CTAO
Cherenkov Telescope Array Observatory

Non-jetted Galactic Science

Rubén López-Coto, IAA-CSIC

CTAO School, 18/05/26

VHEGA
IAA Instituto de Astrofísica de Andalucía
Excelencia Severo Ochoa

~~Non-jetted~~ Very High Energy Galactic Science

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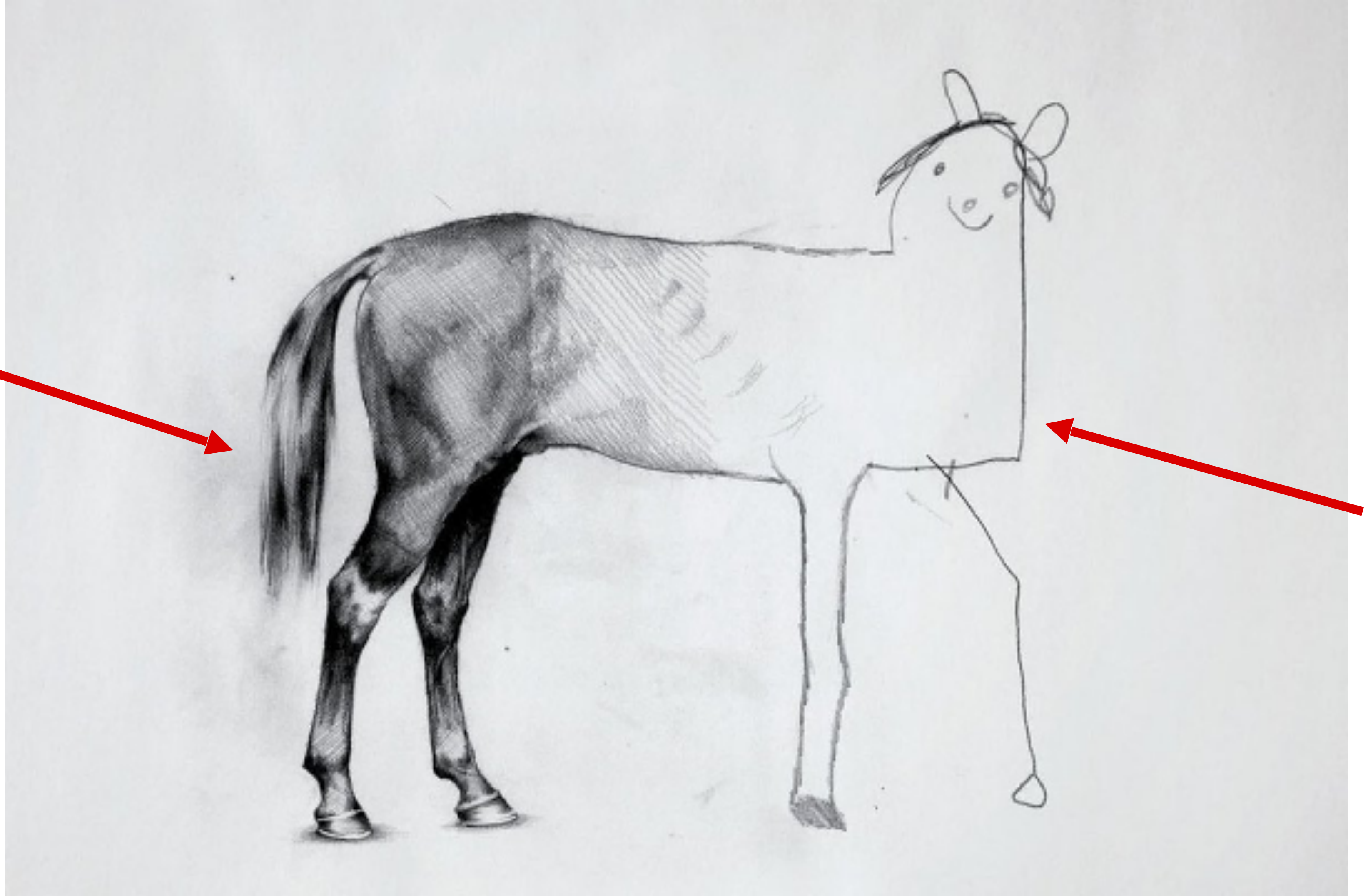
CTAO School, 18/05/26

Who am I?

- Staff Researcher at IAA-CSIC (Granada, Spain)
- Worked at IFAE (Spain), MPIK (Germany), INFN (Italy)
  - CTAO, LST, MAGIC, HESS, HAWC, SWGO…
  - Focus on Galactic Science
- Current CTAO Consortium Physics coordinator

This course

3 months ago when David wrote me



Literally one hour ago

This course

3 months ago when David wrote me

Literally one hour ago

Special thanks to E. de Oña Wilhelmi, A. Moralejo, J. Hinton, M. Ribó… from whom I ~~stole~~ borrowed some slides

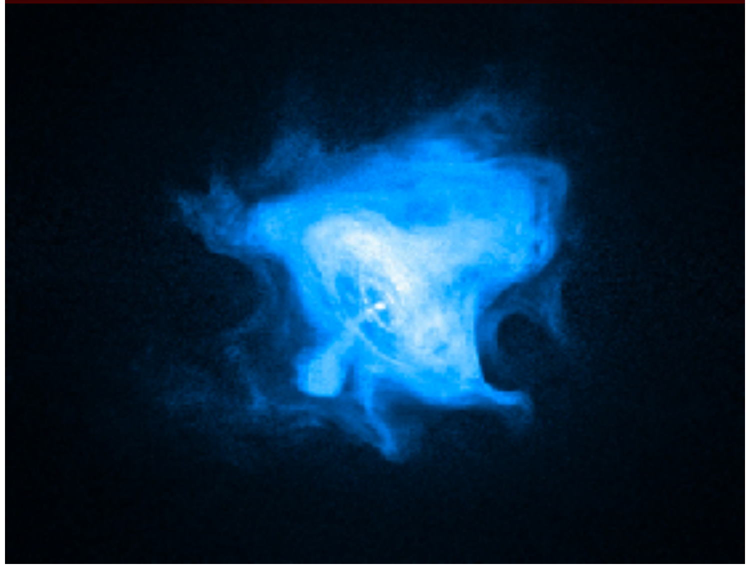
(Very) High energy astrophysics

- To radiate high-energy gamma rays, particles (electrons and protons) have to be accelerated to TeV energies or more:
    - extreme gravitational, magnetic and electric fields
    - very dense radiation fields
    - relativistic speeds (black hole jets and pulsar winds) shock waves (SNRs), highly excited (turbulent) media, etc…
    - Their study involves rich interdisciplinary teams
    - Generates new statistical problems (very large and very small number of events)
    - Is one of the most attractive topics to reach the general public.
- Includes: X-ray astronomy, gamma-ray astronomy (MeV-TeV), neutrino astronomy, gravitational wave astronomy, cosmic ray astrophysics, and cosmology.

Thermal vs Non-thermal universe

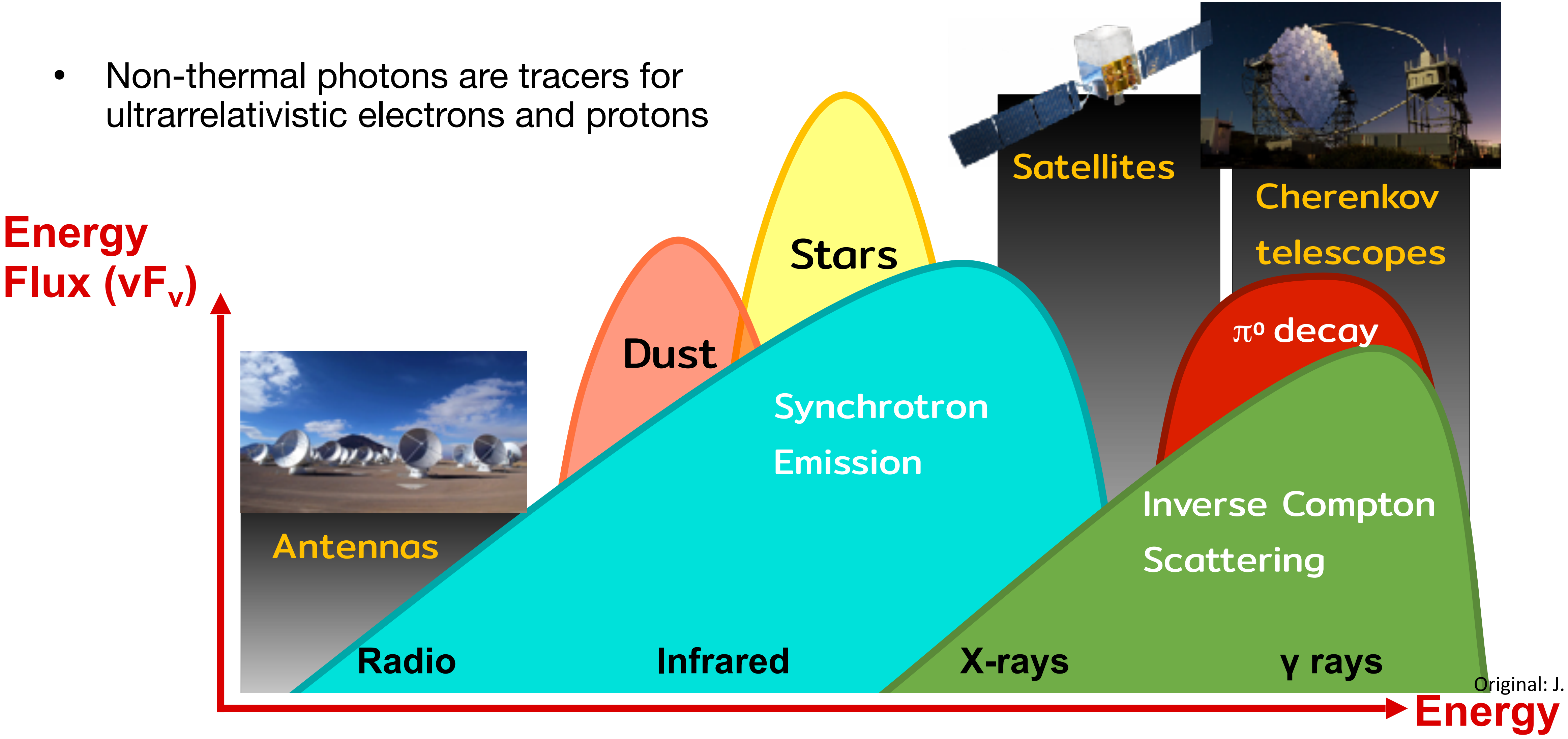
- The thermal universe
  - Stars burning nuclear fuel
  - Dust and gas scattering stellar radiation
  - The Cosmic Microwave Background

- The non-thermal universe
  - There are some energies that cannot be reached by any object emitting radiation due to their temperature.
  - Produced by high energy particles that emit radiation when interacting with magnetic fields or in particle collisions



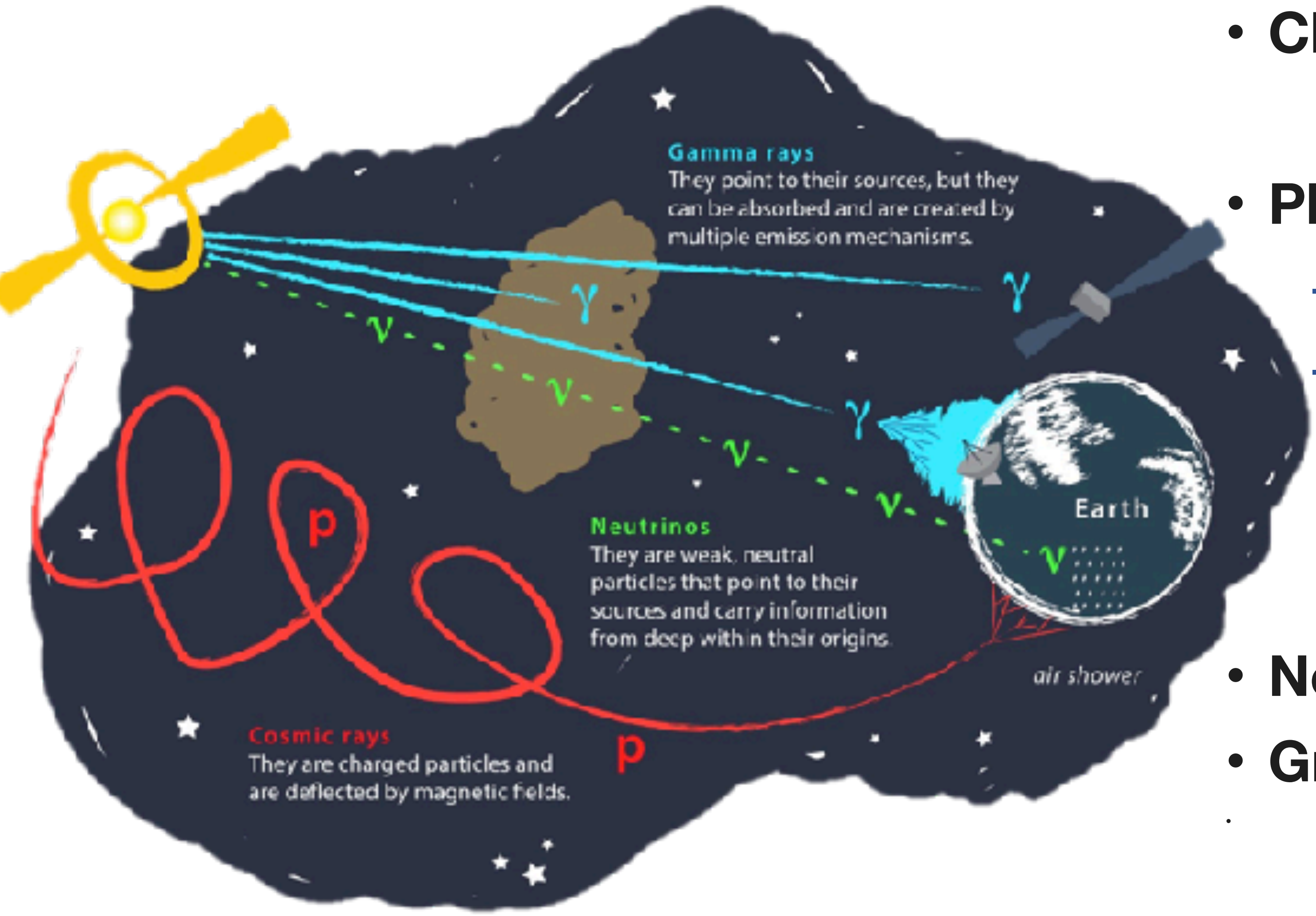
The non-thermal Universe

- Non-thermal photons are tracers for ultrarrelativistic electrons and protons



Original: J. Hinton

Messengers of the non-thermal universe

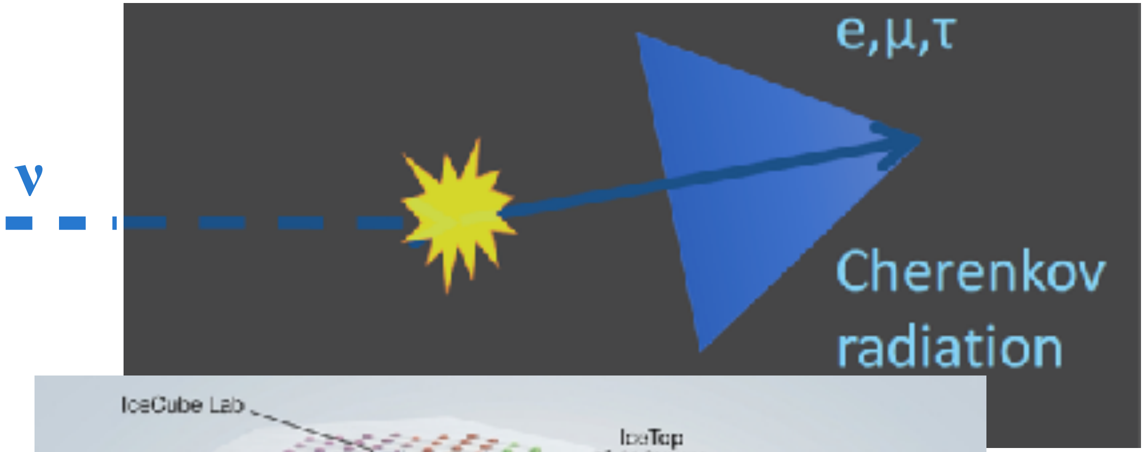


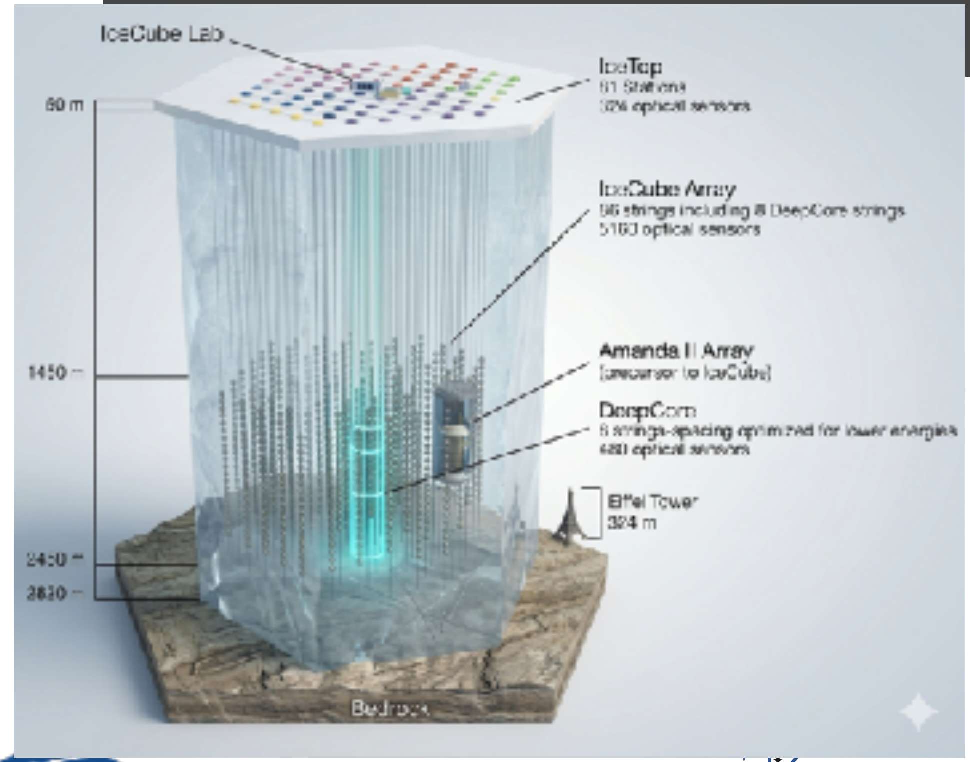
- **Charged particles: Cosmic Rays**
- **Photons**
  - from protons: pion-decay: $\pi^0 \rightarrow \gamma\gamma$
  - from electrons:
    - Inverse Compton Scattering: $e^{\pm}\gamma \rightarrow e^{\pm}\gamma$
    - Synchrotron radiation
    - Bremsstrahlung
- **Neutrinos**
- **Gravitational waves**

Messengers: Cosmic Rays

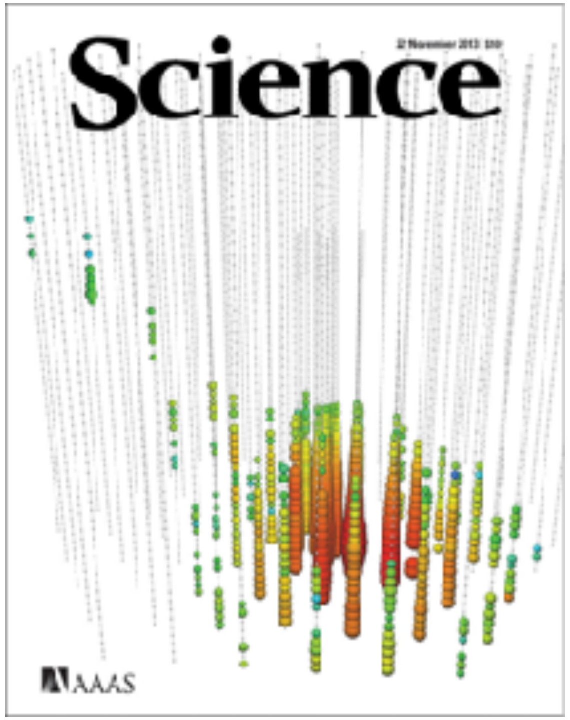
- In 1912, Viktor Hess made a series of balloon flights measuring the amount of radiation
- He measured that **ionization increased with height.**
- He concluded that the increase of the ionization with height is due to a radiation coming from above, and thought that this radiation had extra-terrestrial origin.
- He received the Nobel Prize in 1936 for this discovery

Messengers: Neutrinos

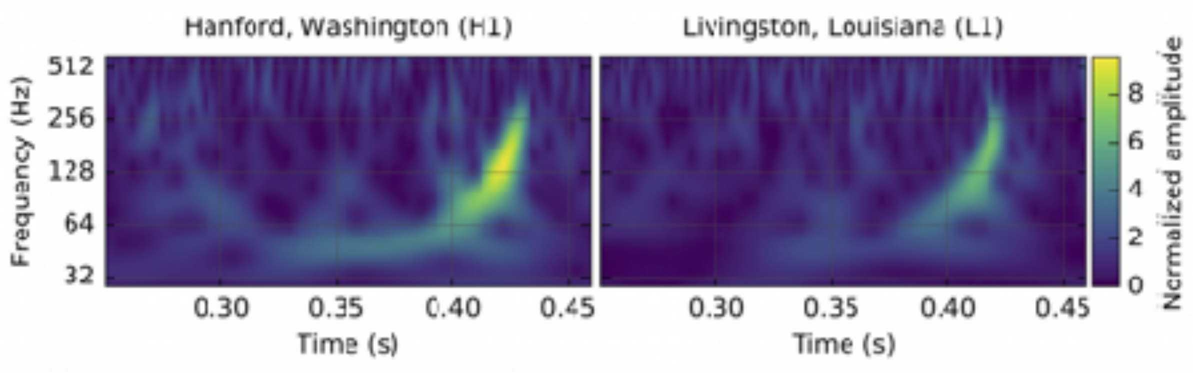




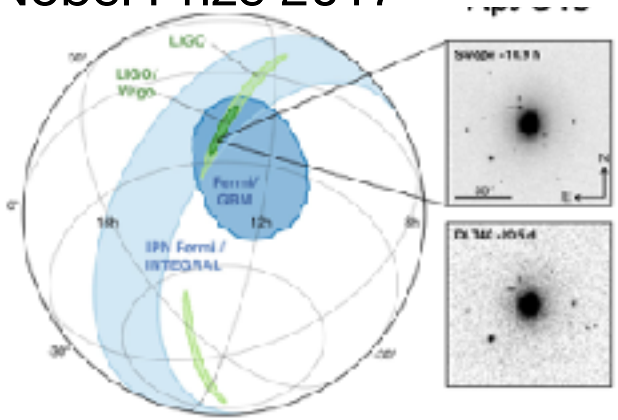
- Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector (22 Nov. 2013)



Messengers: Gravitational Waves

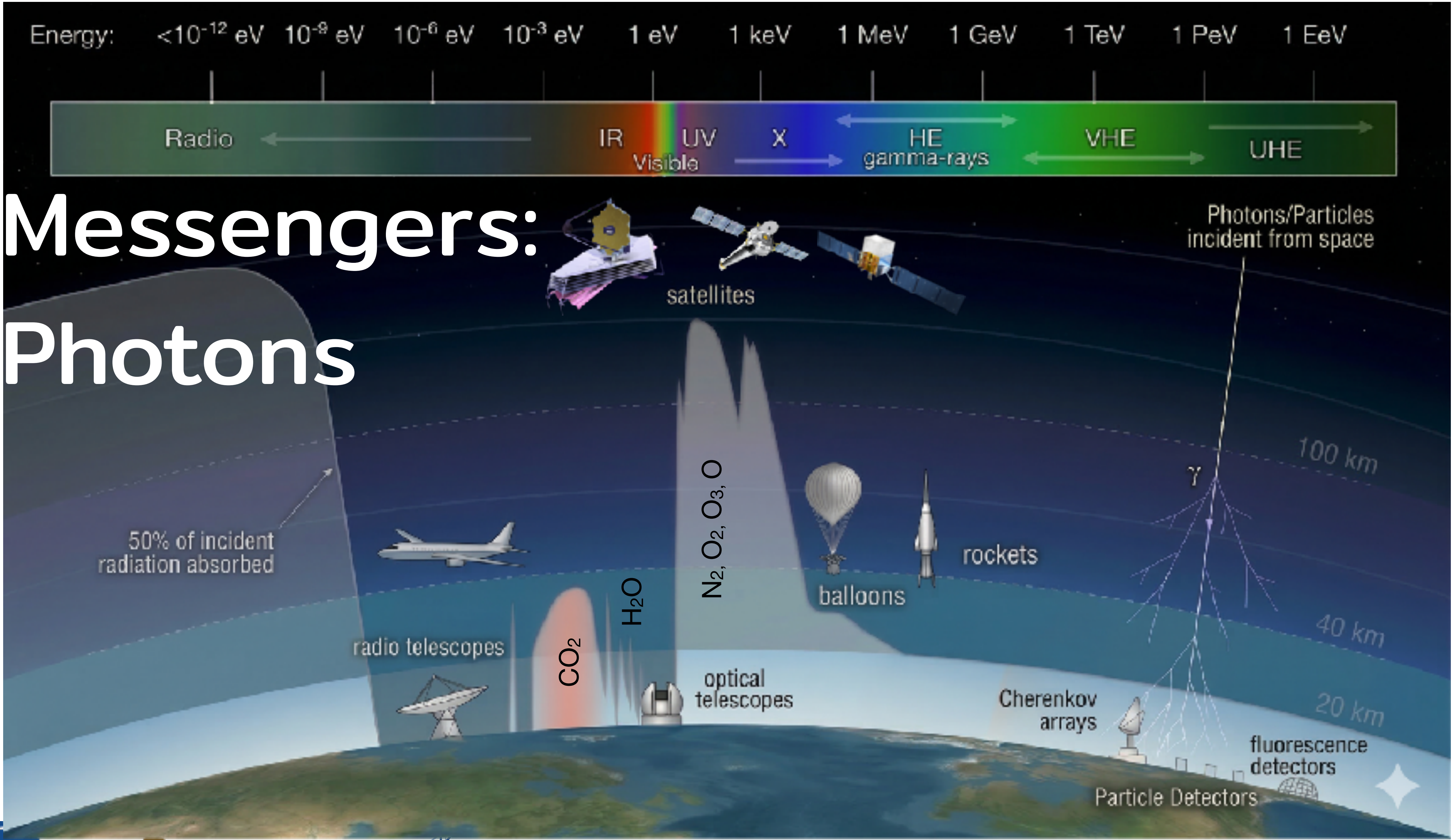


GW150914: the first binary black hole (BBH) -> Nobel Prize 2017



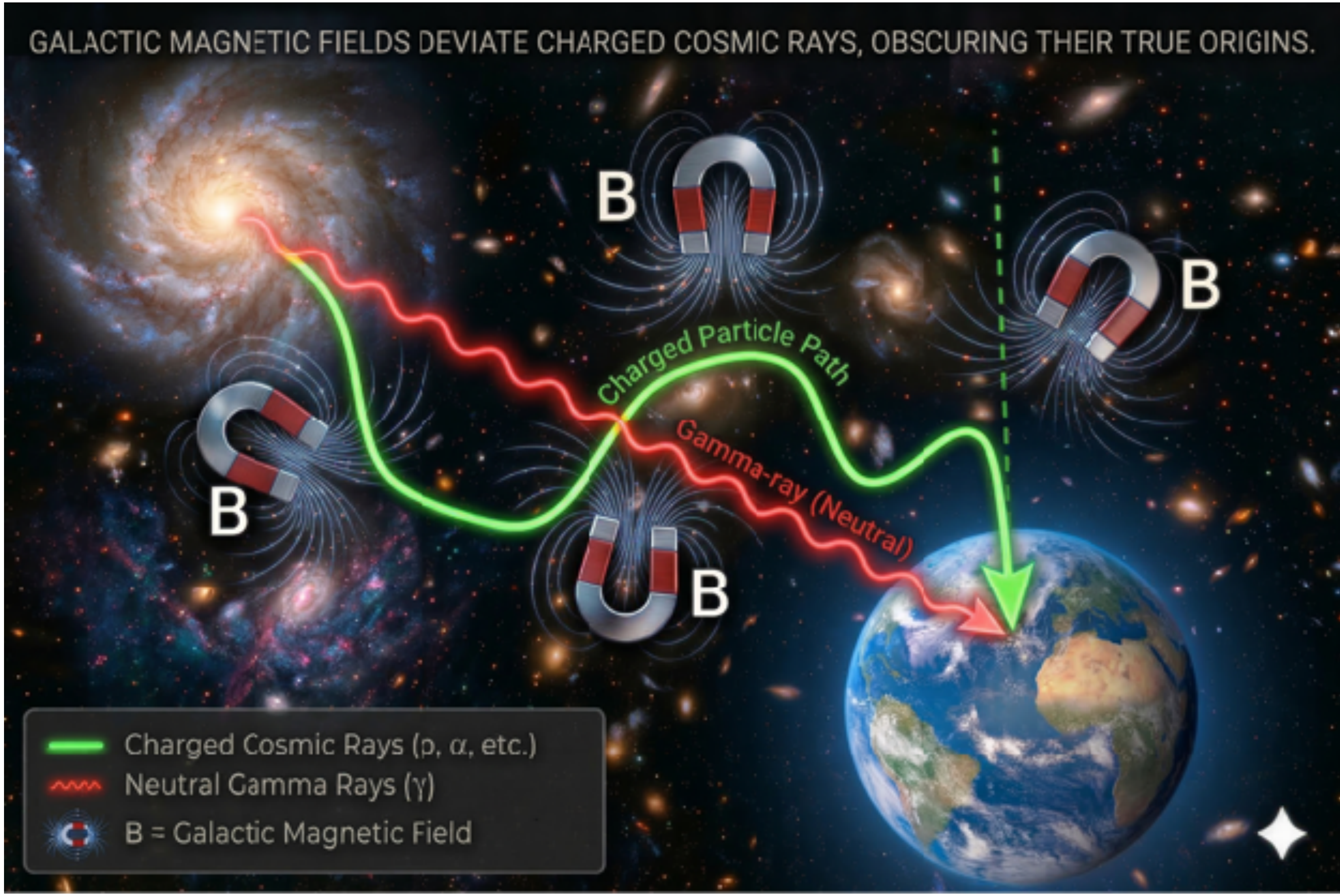
- 17 August 2017: LIGO+VIRGO detection of gravitational wave event: **GW170817** (Phys. Rev. Lett. 119)
- Time profile consistent with merger of neutron-star binary
- **GRB 170817A** detected at t = 1.7 s after coalescence, and consistent direction by Fermi-GBM and INTEGRAL (ApJ 848)
- Extensive multi-wavelength follow-up led, 11 h later, to precise localization with optical telescopes of the origin: galaxy NGC 4993 (z=0.009, 40 Mpc)
- No detection by Fermi-LAT or Cherenkov telescopes

Messengers: Photons



Importance of the non-thermal EM Window

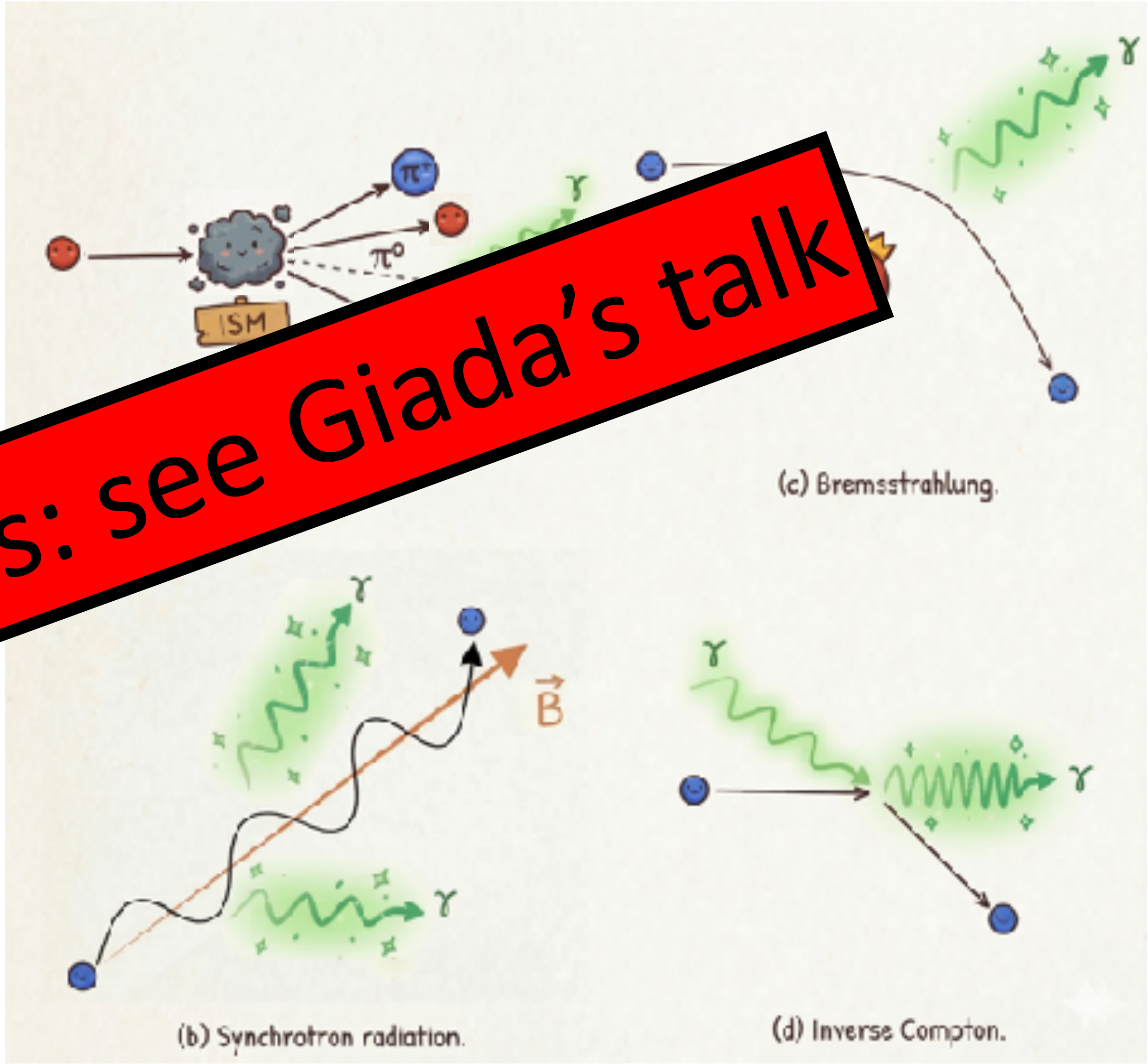
- If we want to understand the origin, evolution and current state of the universe, we need to have a deep knowledge of the non thermal part of the it.
  - Cosmic ray origin cannot be pinpointed towards their sources because they are deflected by magnetic fields
  - Solution: study the neutral products generated at the sources: the **photons**
  - To go to the most extreme accelerators, we need to most extreme photons: the **gamma rays**



Non-thermal radiation mechanisms

- Pion Decay
  - Flux proportional to gas density
  - Spectrum ~follows primary spectrum
- Synchrotron
  - Charged particles moving in a magnetic field
- Bremsstrahlung
  - Emissi … king
- Inverse C … attering
  - Strongly suppressed by the Klein-Nishina mechanism at high E

For further details: see Giada’s talk

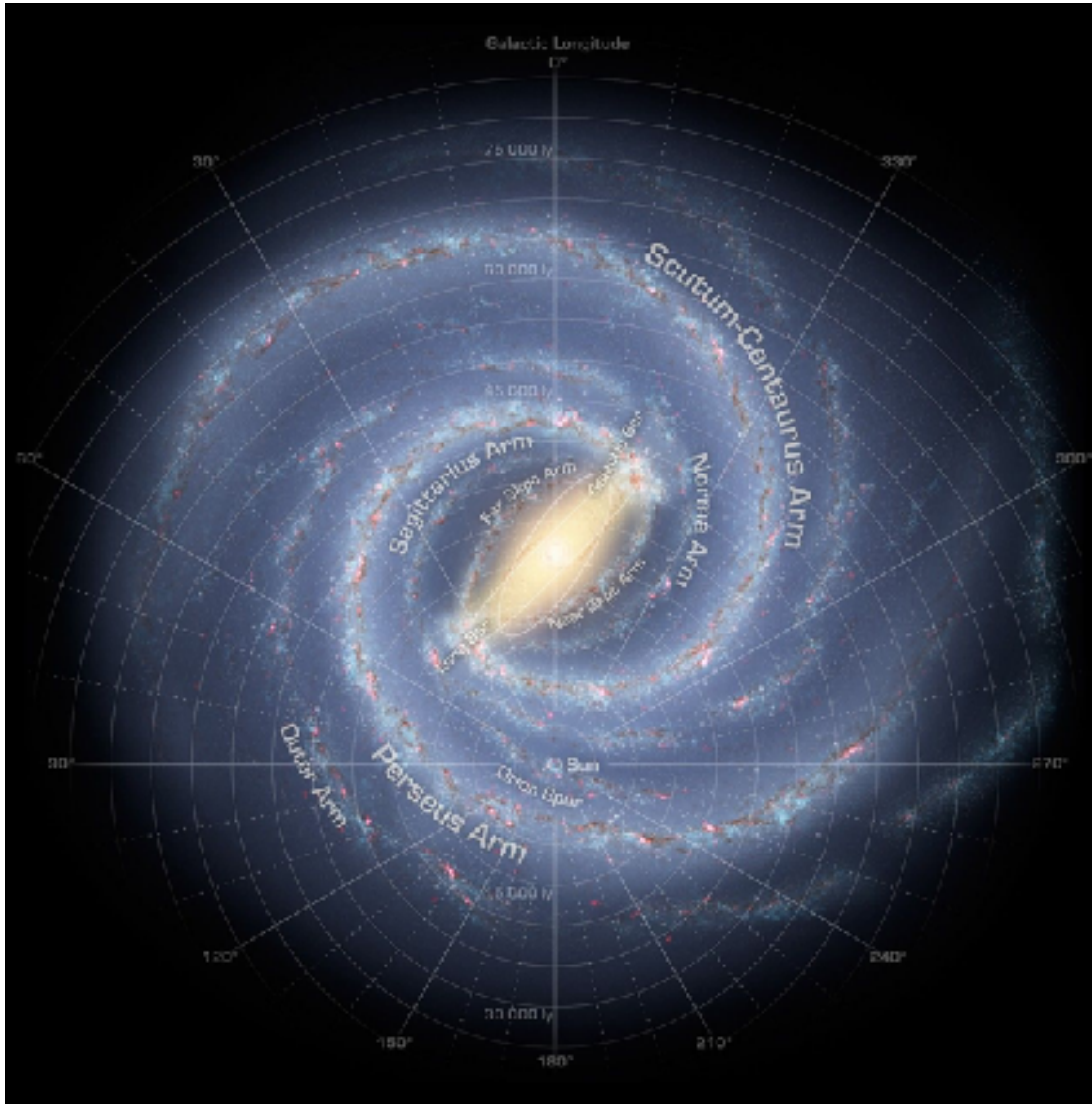


Our Galaxy

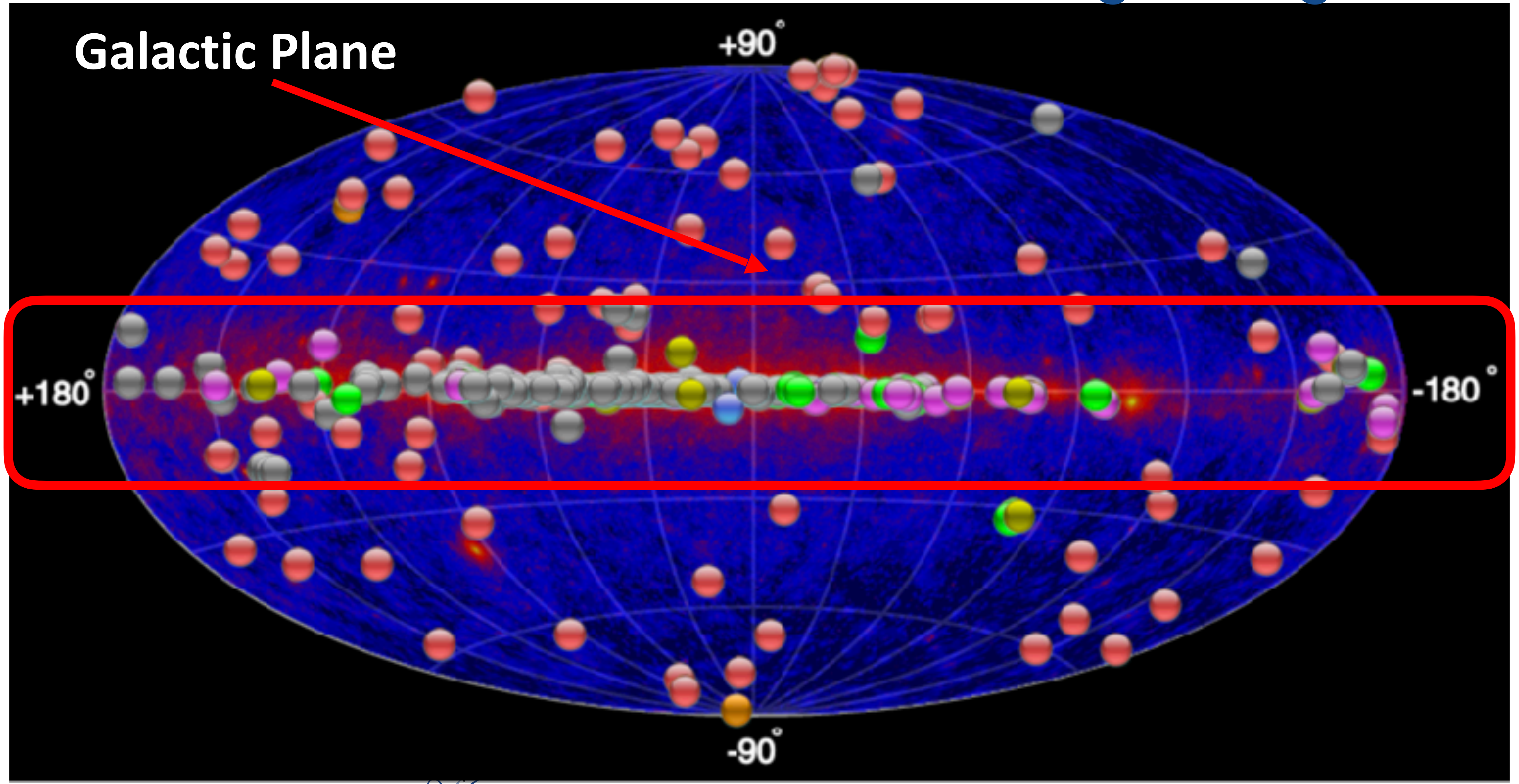
Rare Photograph of The Milky Way viewed from Mars

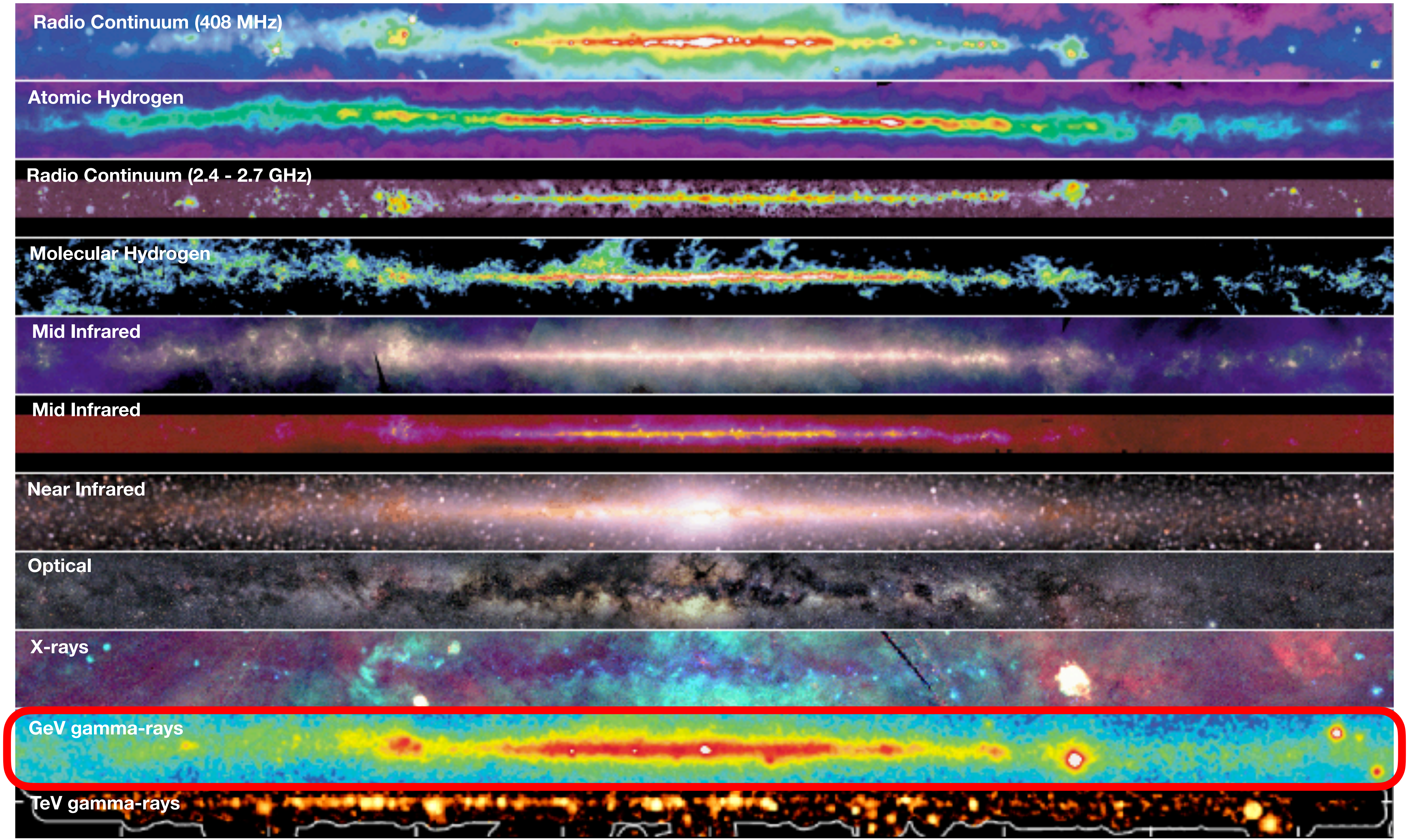
Research topics in VHE Galactic science

- Acceleration and propagation of CRs
  - Galactic CRs :
    - Luminosity, maximum energy, propagation
    - Hadronic accelerators
    - Leptonic accelerators
- Understanding the media in which CRs propagate
  - Targets: Clouds and photon fields
- Sources(!)

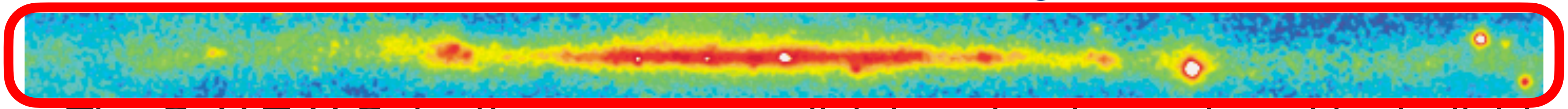


The TeV Gamma-ray sky

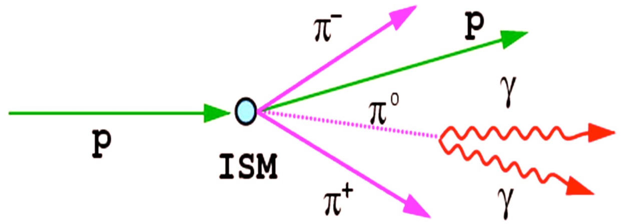


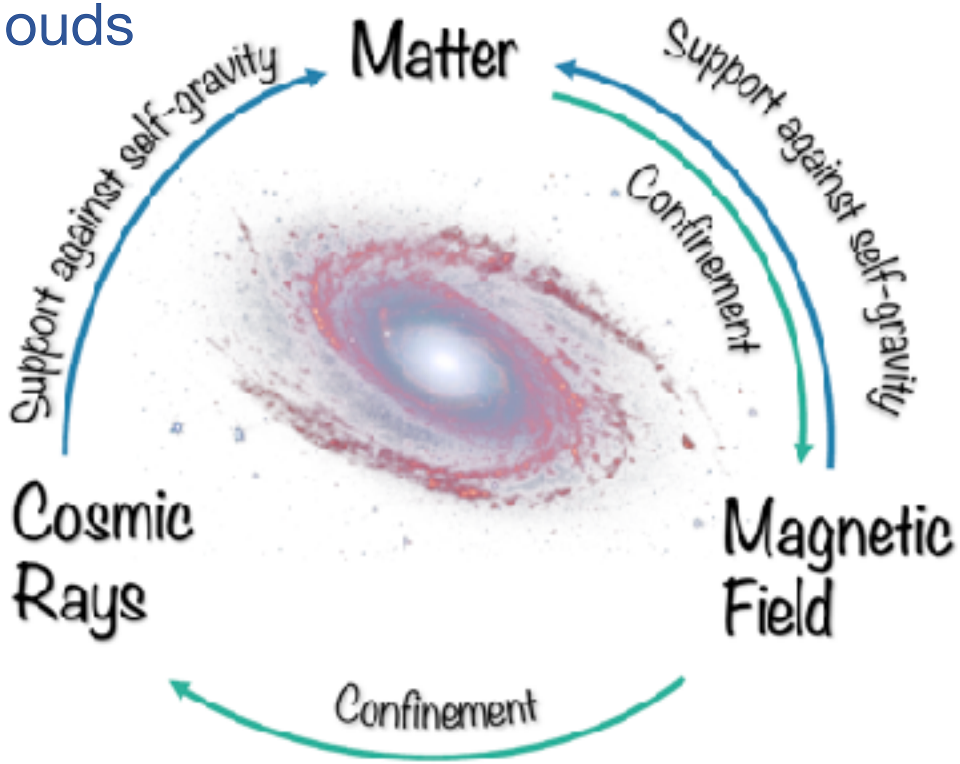

Radio Continuum (408 MHz)
Atomic Hydrogen
Radio Continuum (2.4 - 2.7 GHz)
Molecular Hydrogen
Mid Infrared
Mid Infrared
Near Infrared
Optical
X-rays
GeV gamma-rays
TeV gamma-rays

Galactic Gamma-ray disk



- The GeV-TeV Galactic gamma-ray disk is not only produced by individual sources, but by **diffuse emission**
  - resulting from the interaction of cosmic rays (mostly p's) with the interstellar medium (ISM), e.g. atomic H, molecular clouds



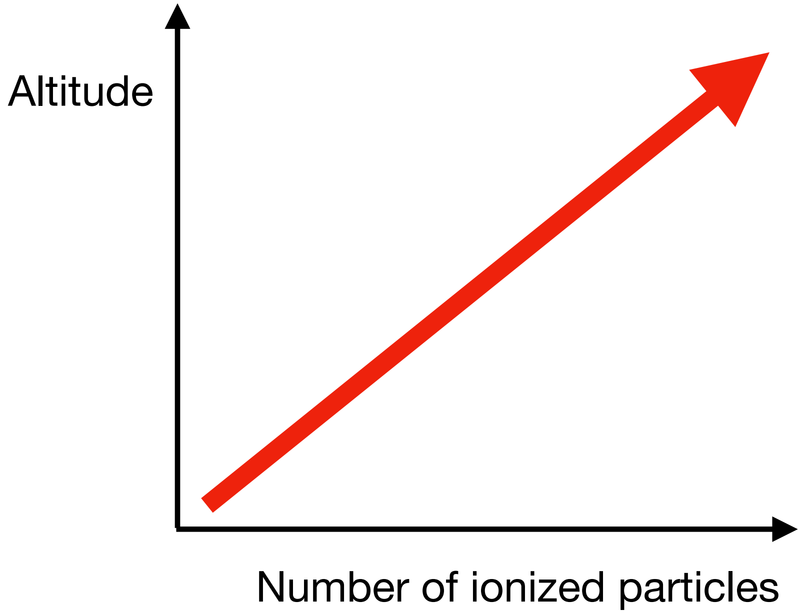


- Insterstellar Medium composition:
  - Matter,
  - Cosmic Rays
  - Magnetic Field
- Dynamic balance processes triggers instabilities in the Galaxy structure
  - $\omega_{CR} \sim \omega_B \sim \omega^{turb}_{gas} \sim 1$ eV/cm^3

Galactic Cosmic Rays

The experiment: a balloon flight

- Viktor Hess (1912)
  - Measured a radiation of very high penetrating power enters our atmosphere from above



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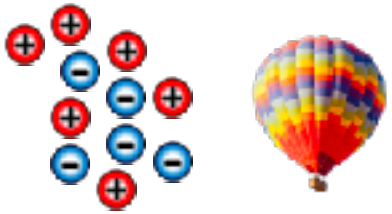


- Initially considered to be some type of radiation (Robert Millikan, 1926):

COSMIC RAYS

- But in reality:

cosmic rays are **charged particles** coming from outside the Earth

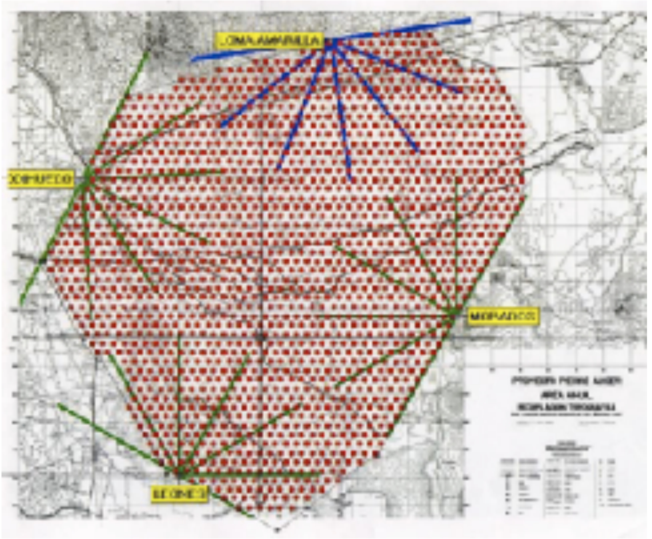
Cosmic rays: Detection

Energy < ~PeV

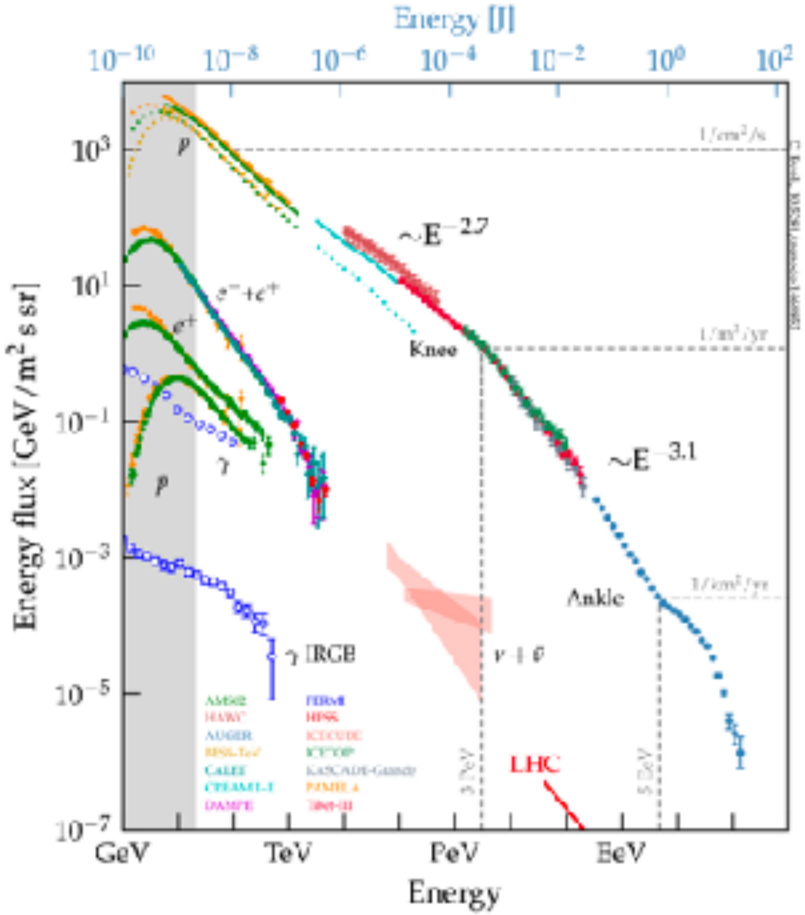
- Not such large collection areas needed
- Satellite or balloon experiments
- AMS, CALET, DAMPE…

Energy > ~PeV

- Very large areas needed
- Extended air showers detecting the secondary particles produced in the shower.
- KASCADE, Auger, Telescope Array…

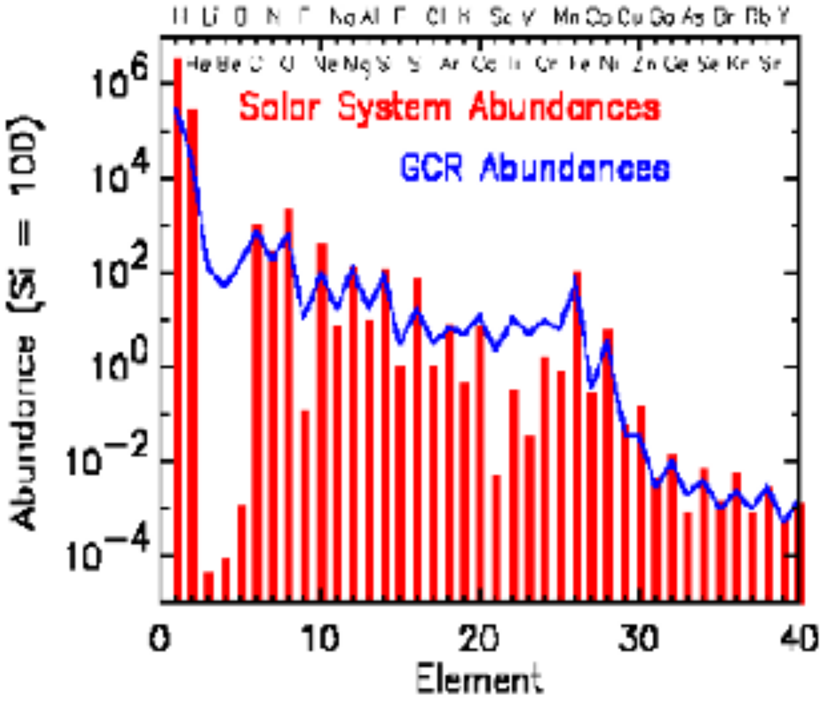


Cosmic rays: Spectrum



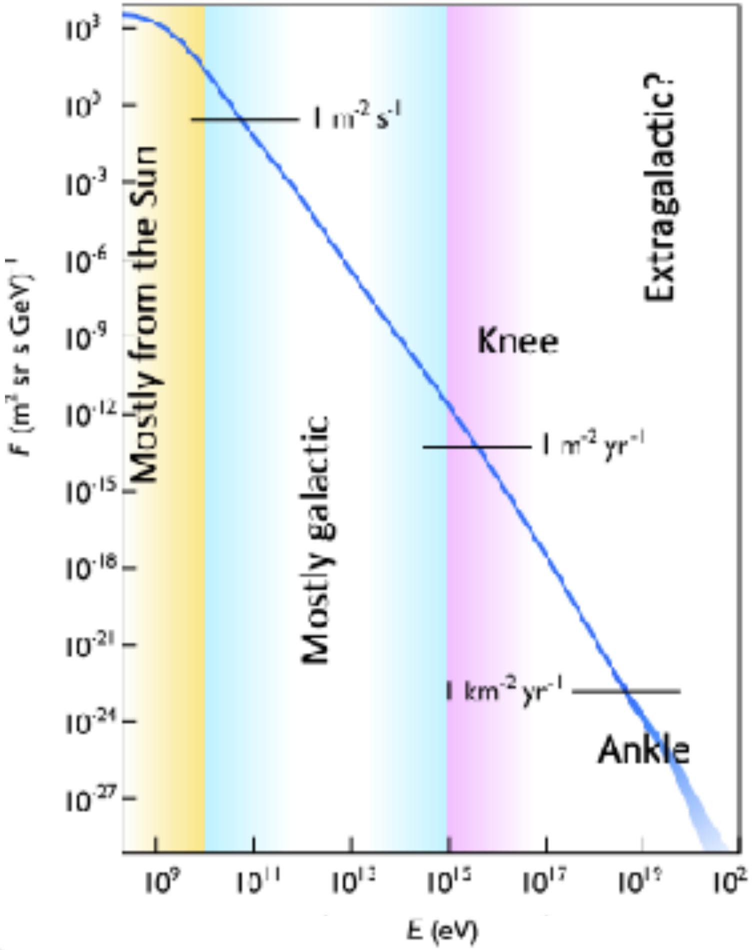
- Spectrum and composition measured by satellites, balloons and extended air shower arrays.

Cosmic rays: Composition



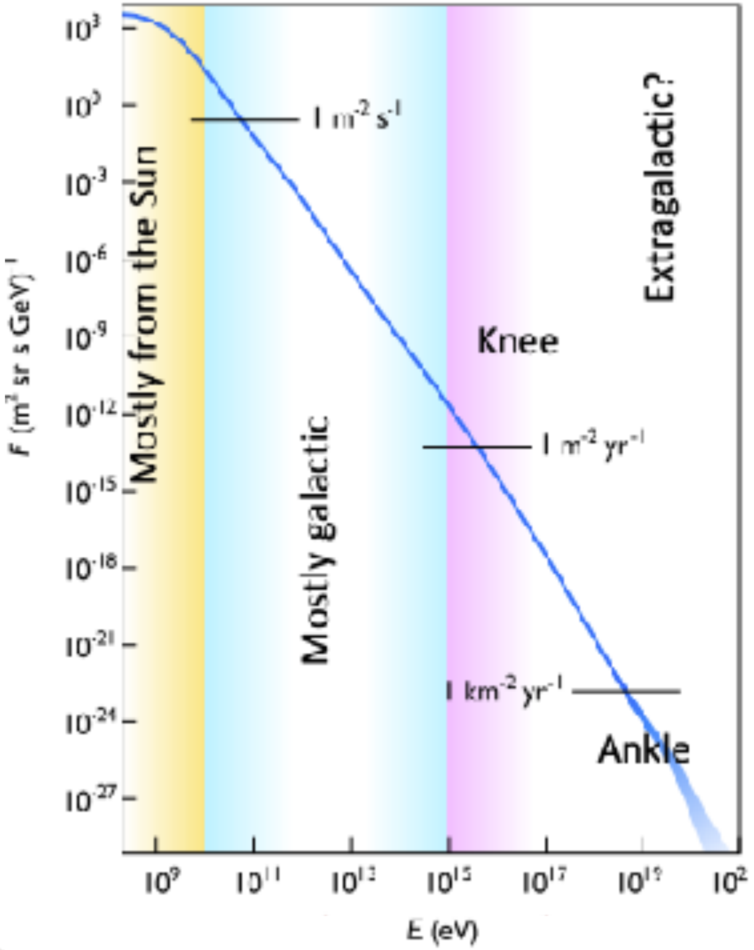
- Spectrum and composition measured by satellites, balloons and extended air shower arrays.
- Composition:
  - 90% Protons
  - 9% Helium nuclei
  - 1% Heavier nuclei, electrons, positrons, antiprotons, …

Cosmic rays: Origin



- Spectrum and composition measured by satellites, balloons and extended air shower arrays.
- Composition:
  - 90% Protons
  - 9% Helium nuclei
  - 1% Heavier nuclei, electrons, positrons, antiprotons, …
- Different origin:
  - Solar (E < 1 GeV)
  - Galactic (1 GeV < E < ~PeV)
  - Extragalactic (E > PeV)

Cosmic rays: Origin



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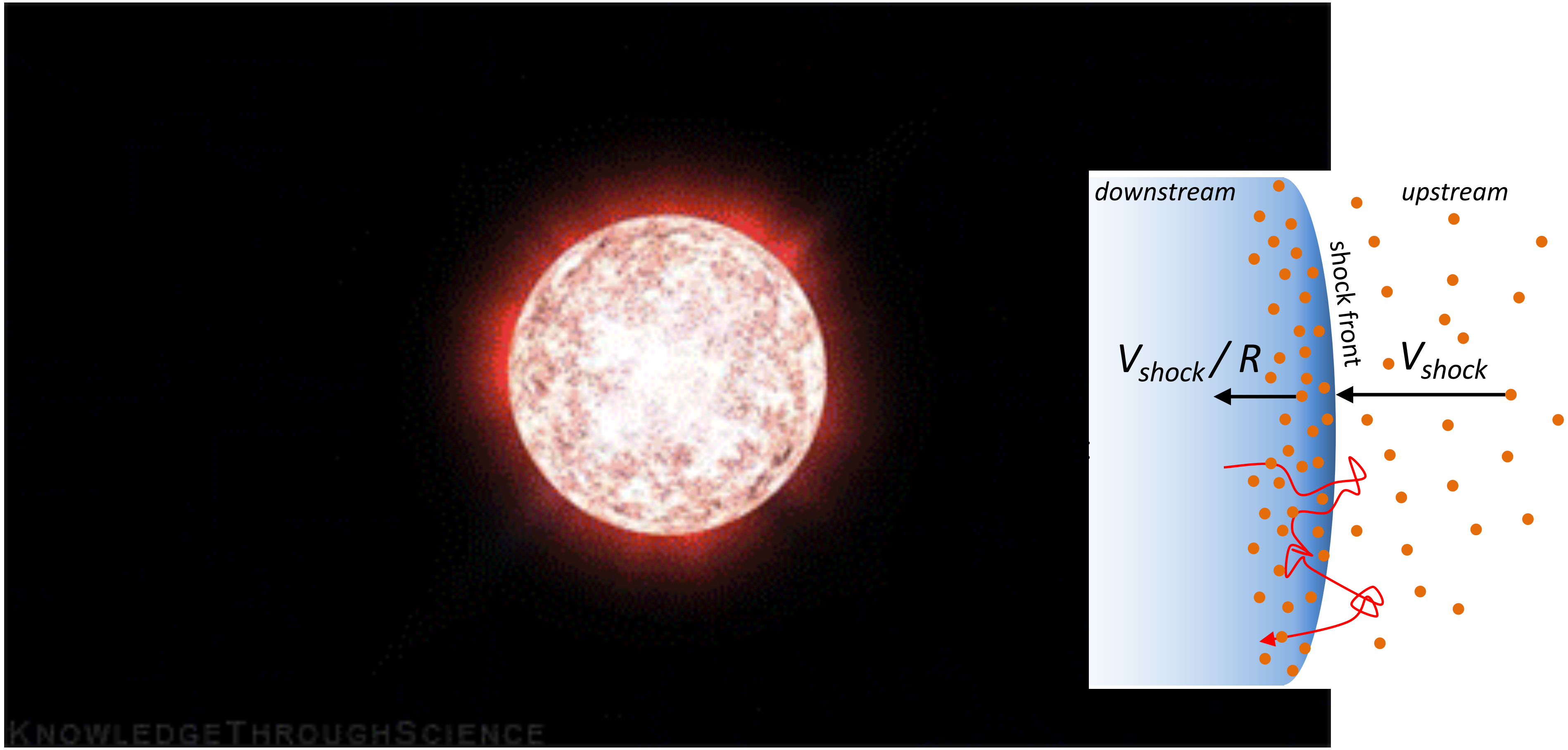
  -

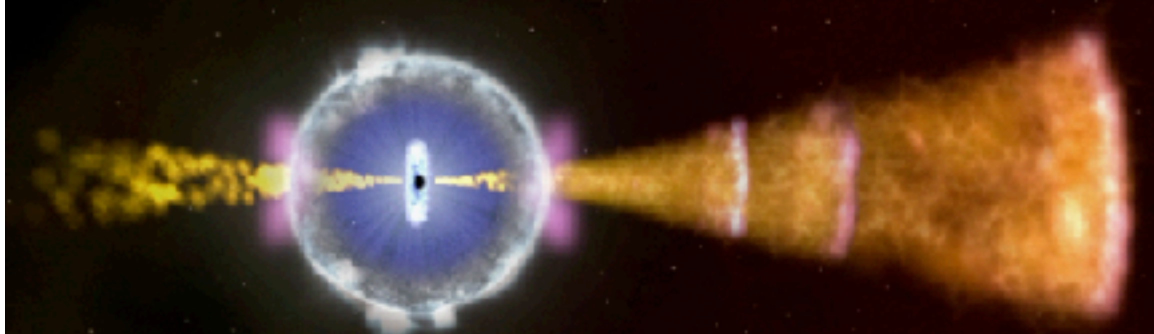
What is the origin of Galactic Cosmic Rays?

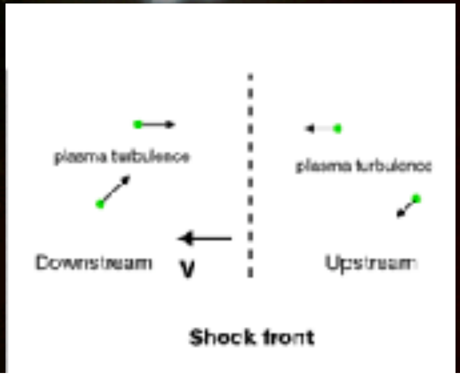
How are CRs accelerated?

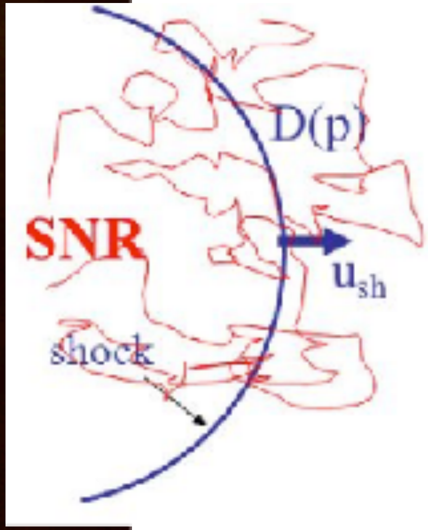


How are CRs accelerated?

Fermi first order acceleration





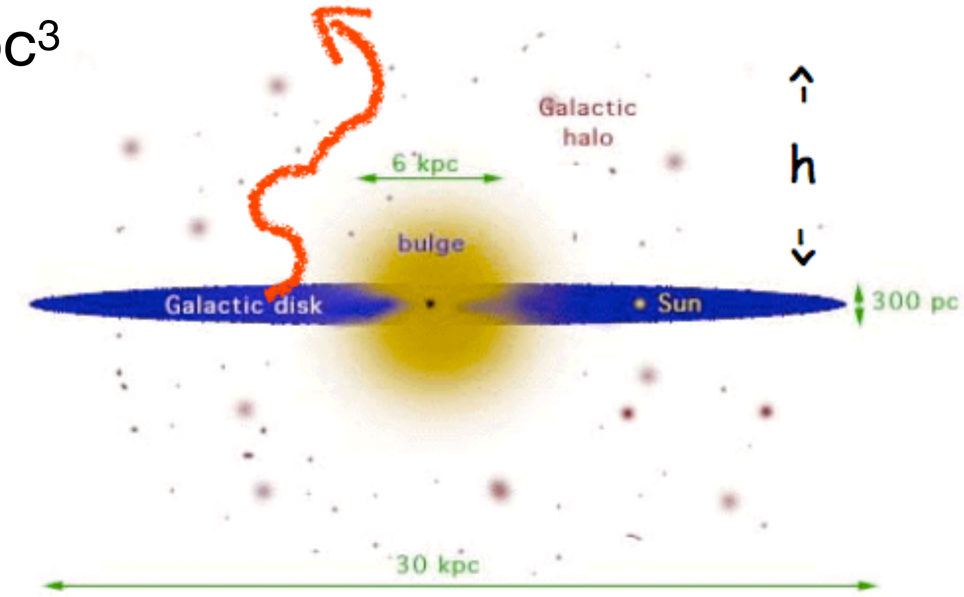


A power law of index ~2 is the expected energy spectrum from Diffusive Shock Acceleration (Fermi mechanism)

Galactic CR luminosity

- Energy Density of CRs u_{CR}~1 eV/cm^3
- Volume of the Galaxy $V_{gal} = \pi R_{disk}^2(2h) \sim 3\text{x}10^{11}$ pc^3
- Luminosity $L=u_{CR}*V_{gal}/t_{CR}$
- CR confinement time t_{CR}~10^7 yrs:

  $L=u_{CR}*V_{gal}/t_{CR} = 5\text{x}10^{40}$ erg/s



We need Galactic accelerators that can provide the right energy budget, up to PeV energies, at the required rate to make the distribution homogeneous.

Galactic CR luminosity

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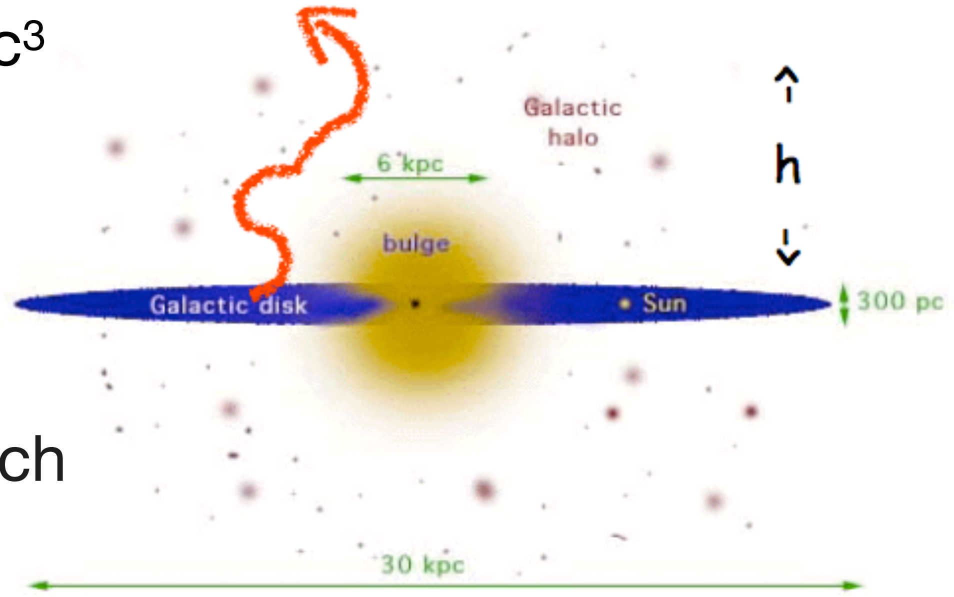


- Assuming 2-3 SNe in the galaxy every century, each of them providing 10^{51} erg, the average kinetic energy from all of them would be ~ 10^{42} erg/s
  - SNe could account for all CRs, if O(0.01) of their kinetic energy goes into CR acceleration
- Aim: observe **Supernova Remnants** (SNRs) and search for evidence of acceleration of **hadrons**, if possible up to PeV energies (**PeVatrons**)

CR Maximum energy: Hillas criterium

- What is the maximum energy a particle can reach?
  - Acceleration is always carried out by an **electric field**
  - For a particle with charge q, moving a distance L
    - $E = q|\vec{E}|L$
  - We can define the acceleration **efficiency** as:
    - $\eta = \vec{B}/\vec{E}$
  - then:

$$E = q\eta BL$$

q = Charge

L = Size of the source

B = Magnetic field in the source

Magnetic field and **size of the source**:
These two values define the maximum energy

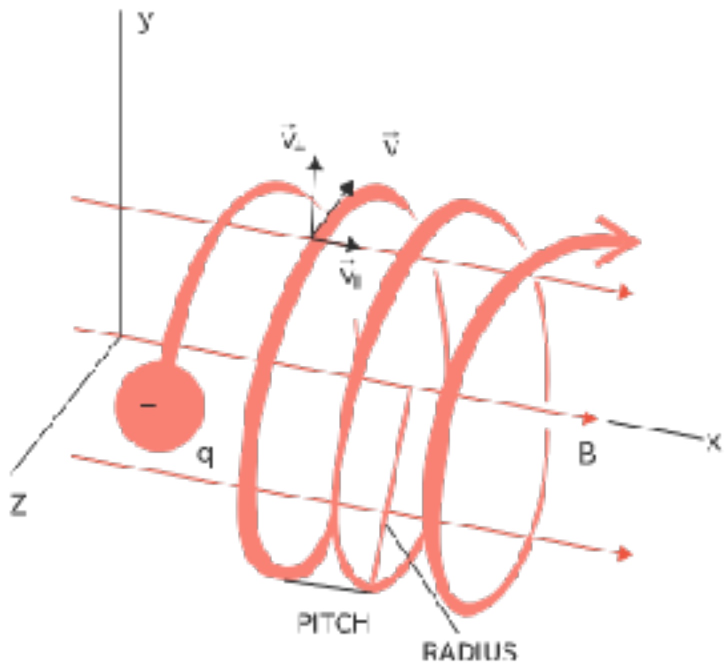
CR Maximum energy: Hillas criterium

- We can derive the same condition considering confinement: the Larmour radius of the particle should be smaller than the size of the accelerator

R_L (=E/qB) < R => $E_{max} = \Gamma qBR$

$$E = q\ u\ R\ B$$

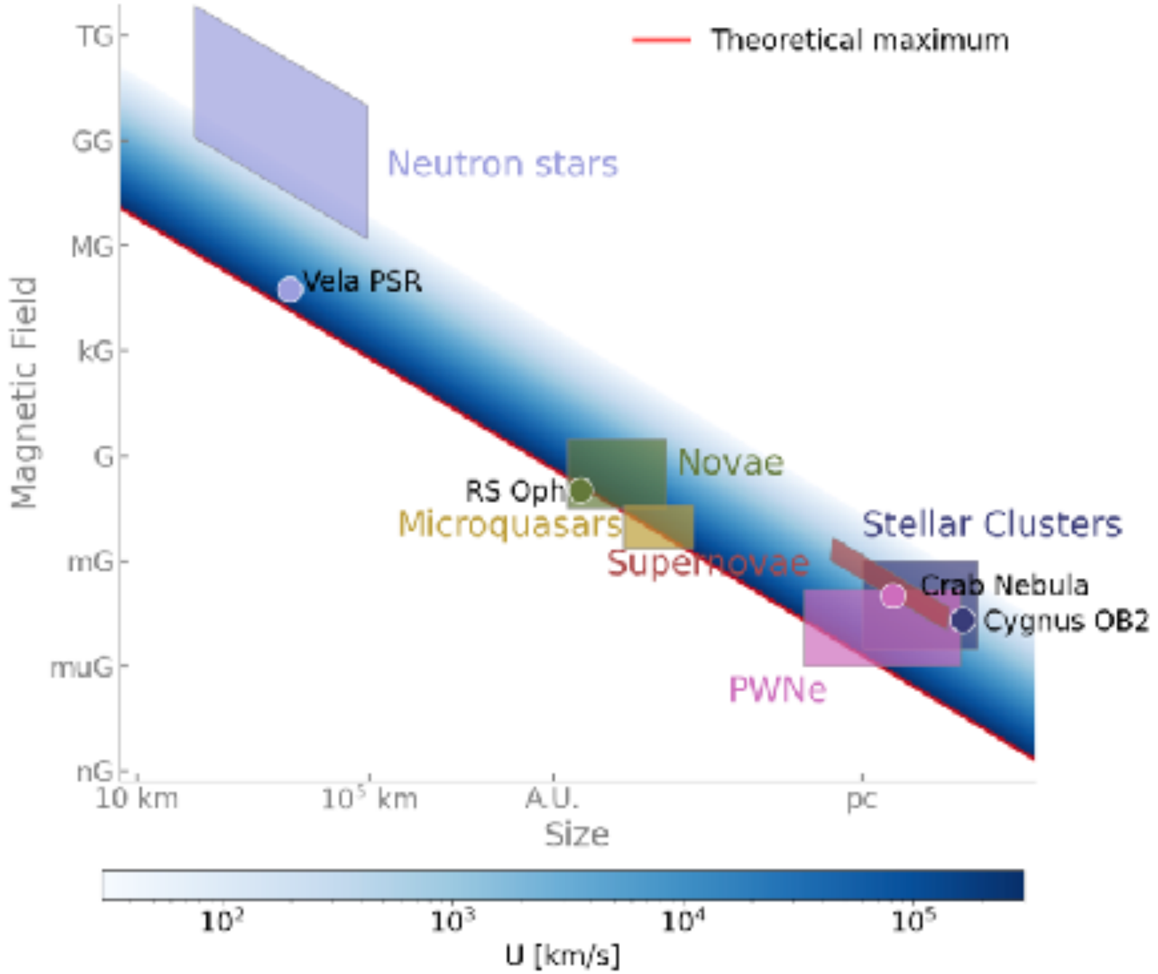
Speed — Radius — Magnetic Field



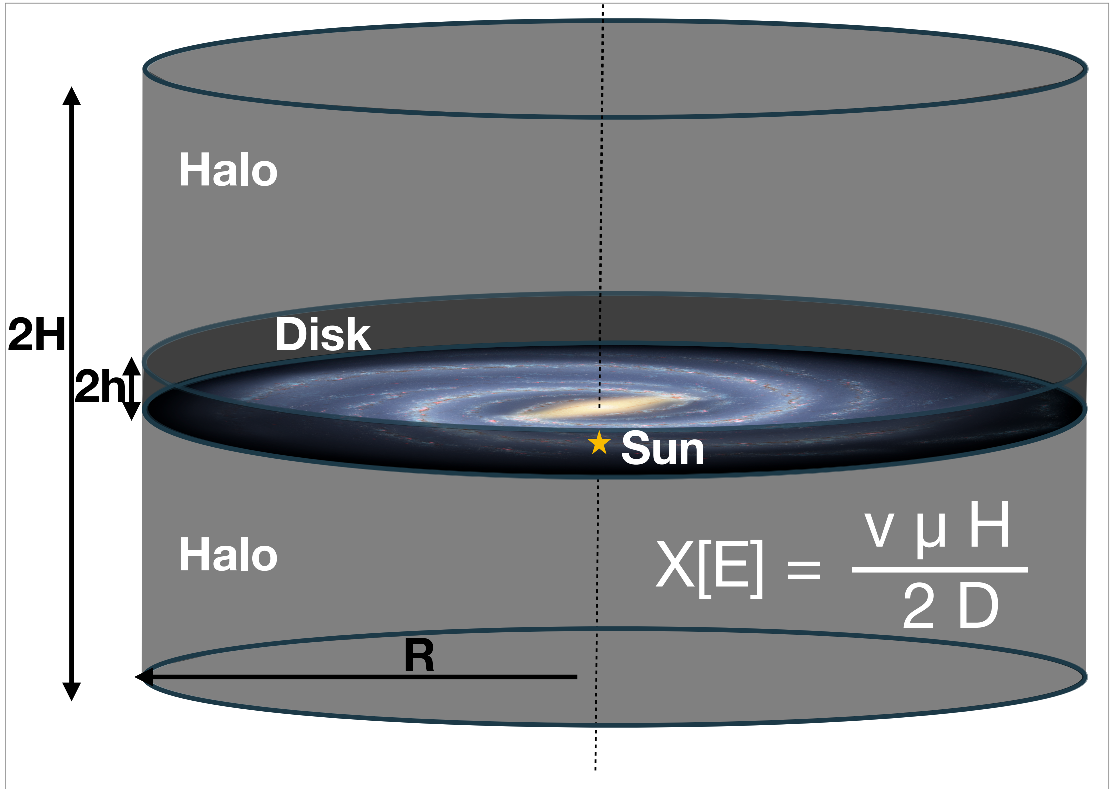
Cosmic Ray maximum energy

- One can write the maximum energy for a proton/electron in a handy way:

$$E_{max} \approx 1 \left(\frac{u}{10^3\ \mathrm{km/s}}\right)\left(\frac{R}{\mathrm{pc}}\right)\left(\frac{B}{\mu\mathrm{G}}\right)\ \mathrm{TeV}$$

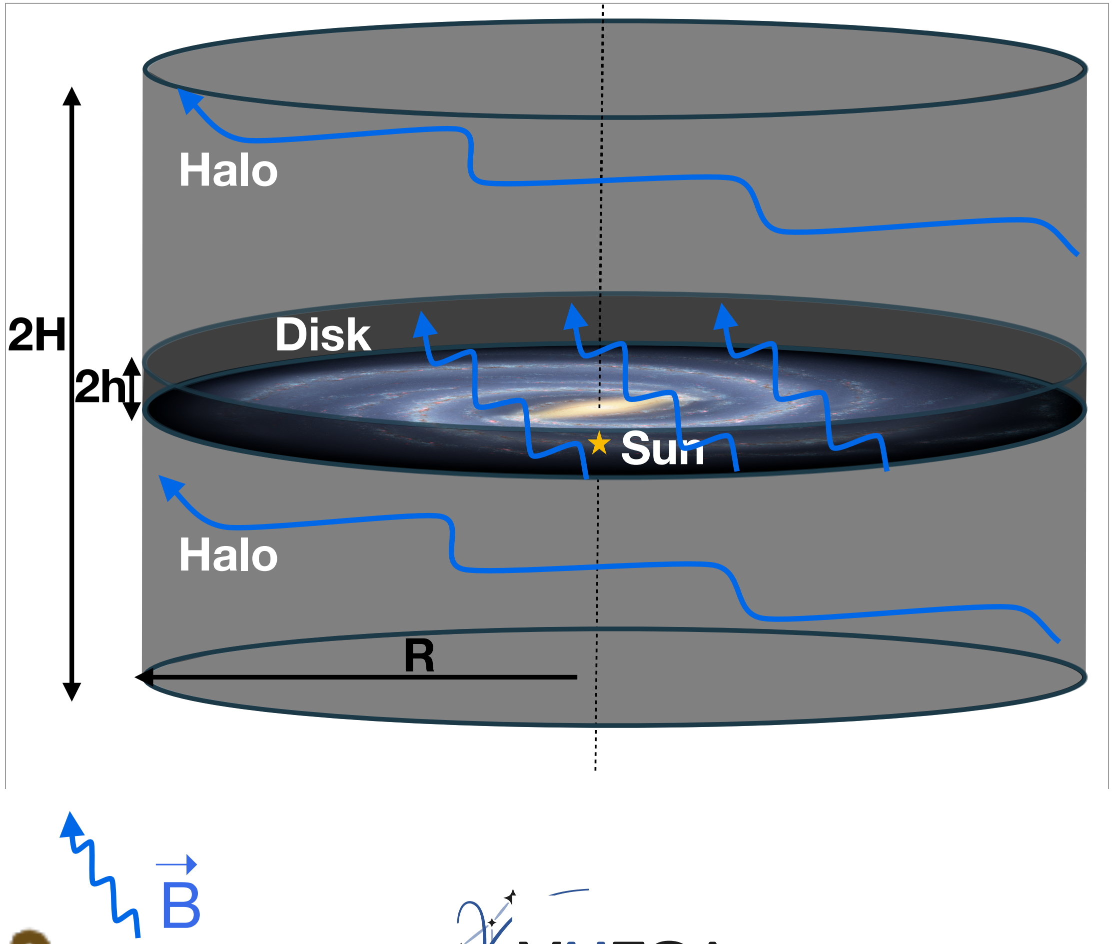


Cosmic Ray propagation



- CRs **diffuse** in the galactic *disk* (the region where the gas is contained) and *halo*
- Galactic **winds** and **reacceleration** are also powering the propagation of CRs
- Grammage X ~ 10 g/cm^2 at 1 GeV/nucleon

Cosmic Ray propagation



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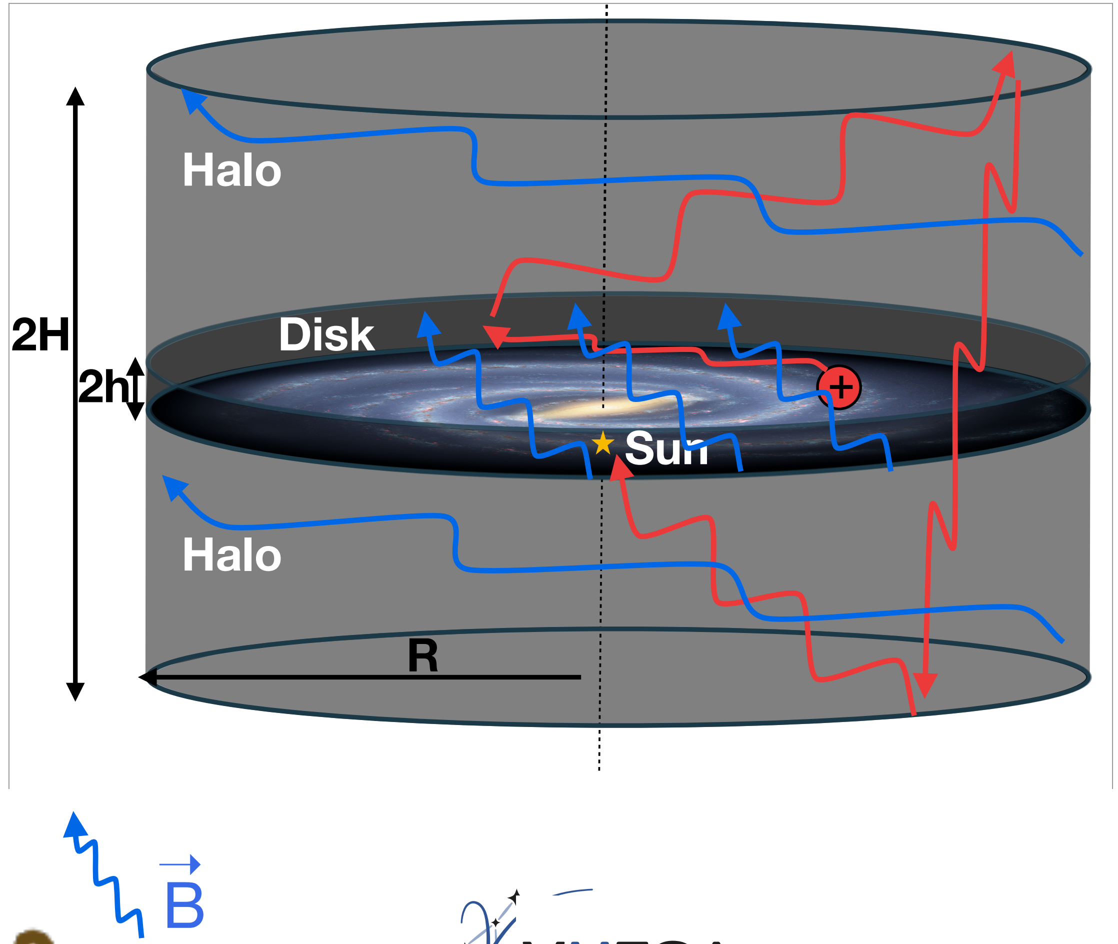

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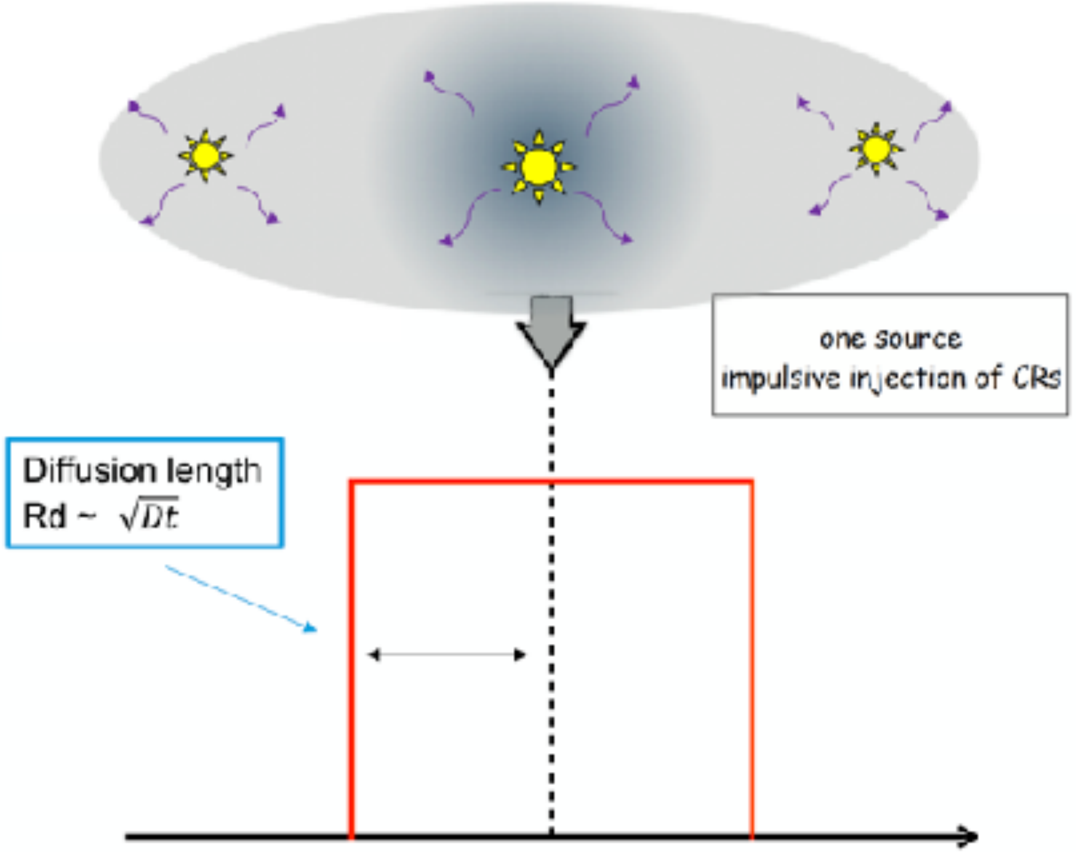
Cosmic Ray propagation

$dN/dE \sim \dot{Q}/D(E) \sim E^{-(\alpha + k\delta)}$ k=3/2, 1

$D(E) = Do(E/Eo)^{\delta}$, Do ~$10^{28\text{-}30}$ cm^2s^{-1}



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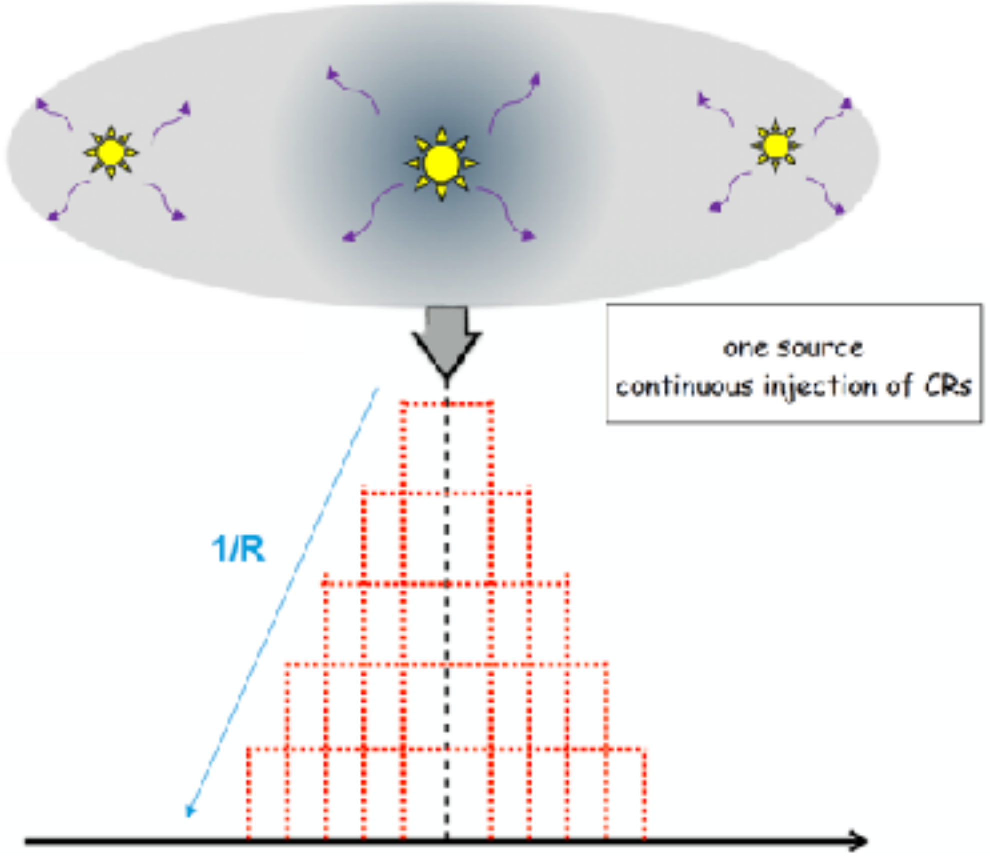

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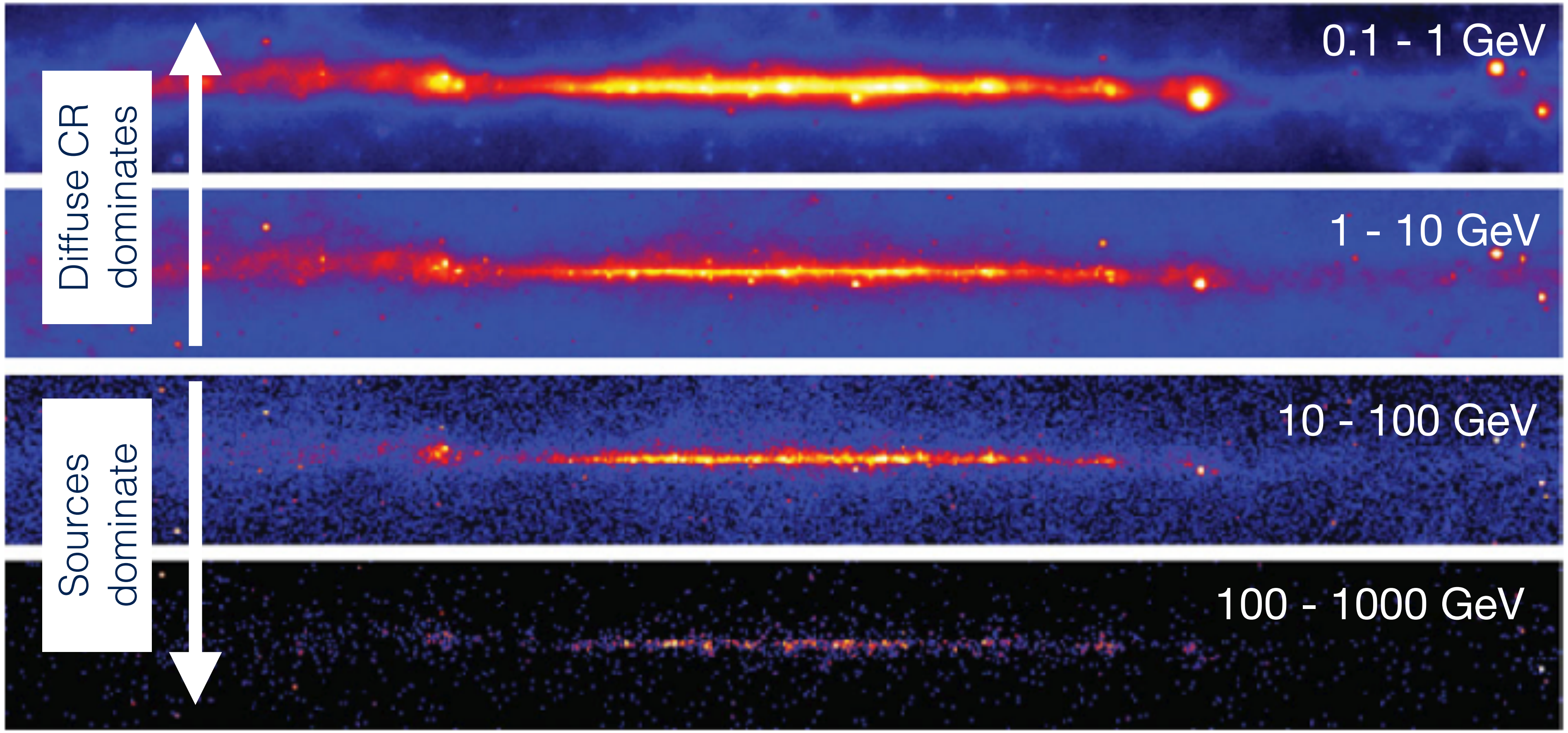

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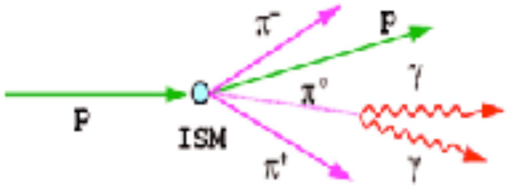
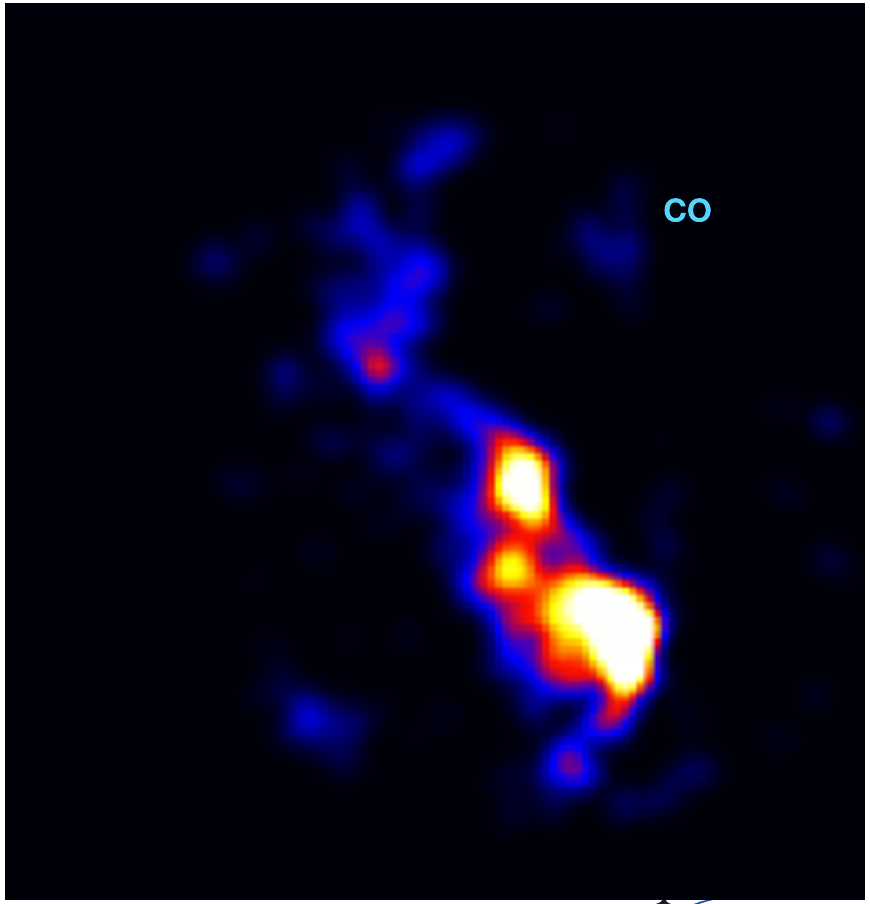
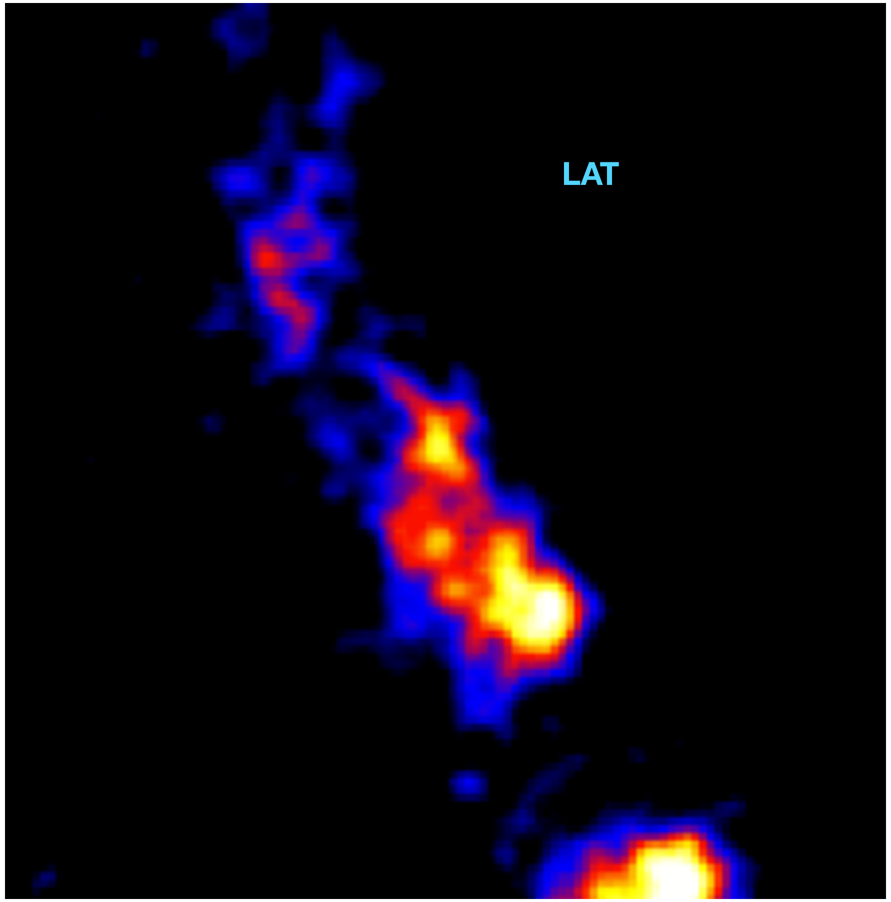


Understanding the ISM / photon fields & the molecular content

Target [p]

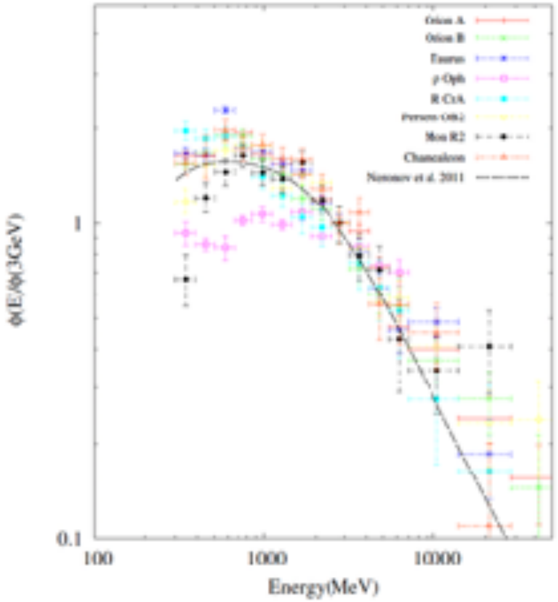


CRs [p]

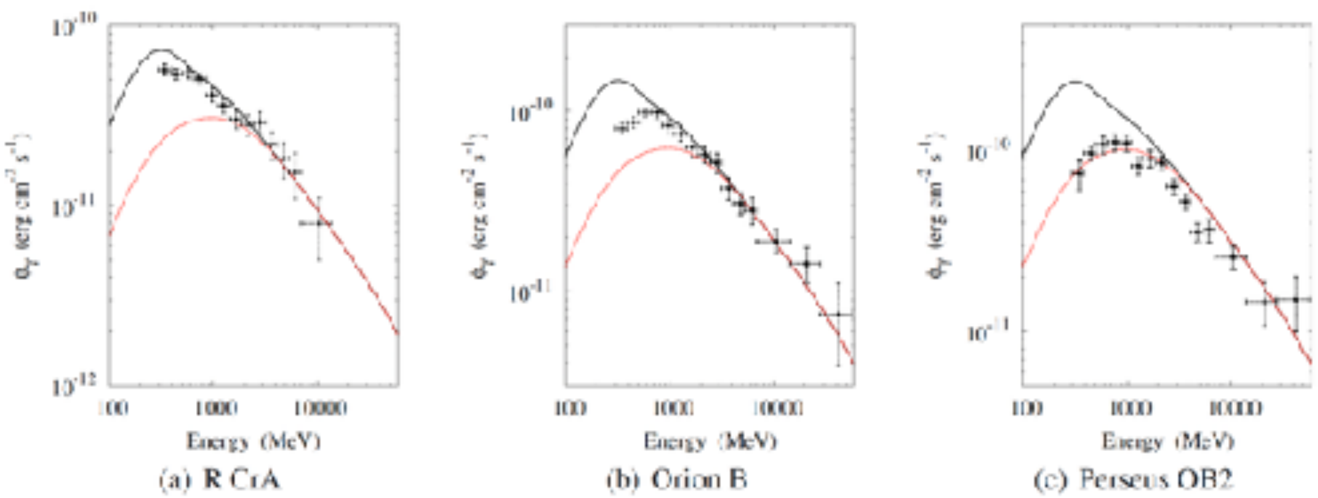


Cosmic Ray propagation

Understanding the ISM / photon fields & the molecular content



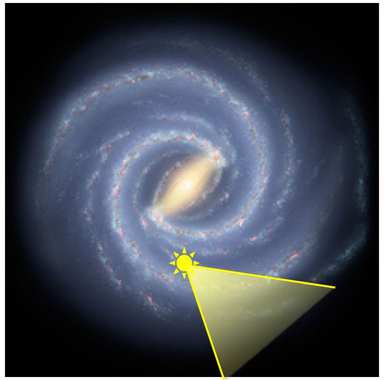
Yang, de Oña Wilhelmi, Aharonian 2014



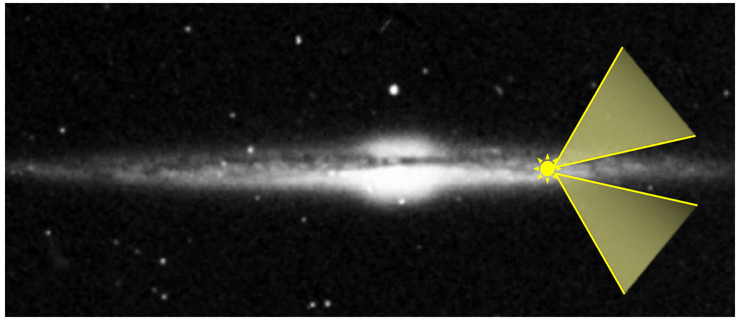
- > 20 GeV: good agreement with CR spectrum measured at Earth
- Low energy part shows differs from cloud to cloud (deviating for pure power law)
- Related to different environment (local acceleration, low CR penetration effects, modulation effects?)

Cosmic Ray propagation

Understanding the ISM / photon fields & the molecular content

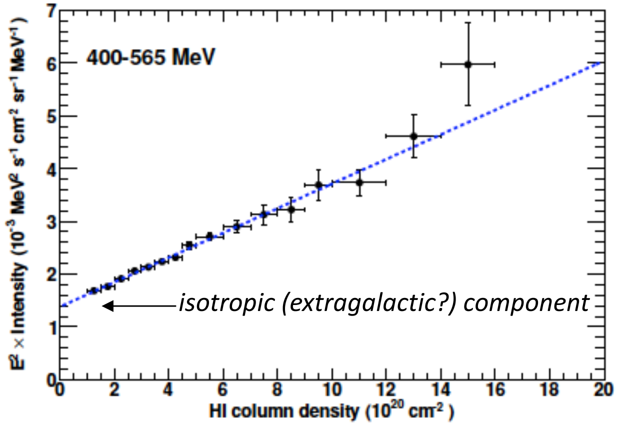


longitude: 200º to 260º

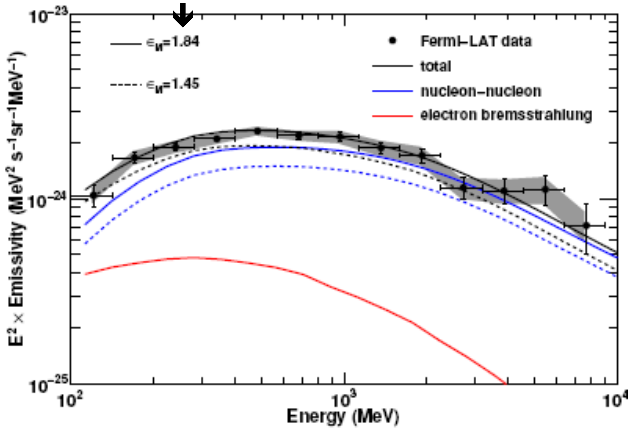


latitude: 22º to 60º (+ & -)

Abdo et al., ApJ, 703, 1249, 2009



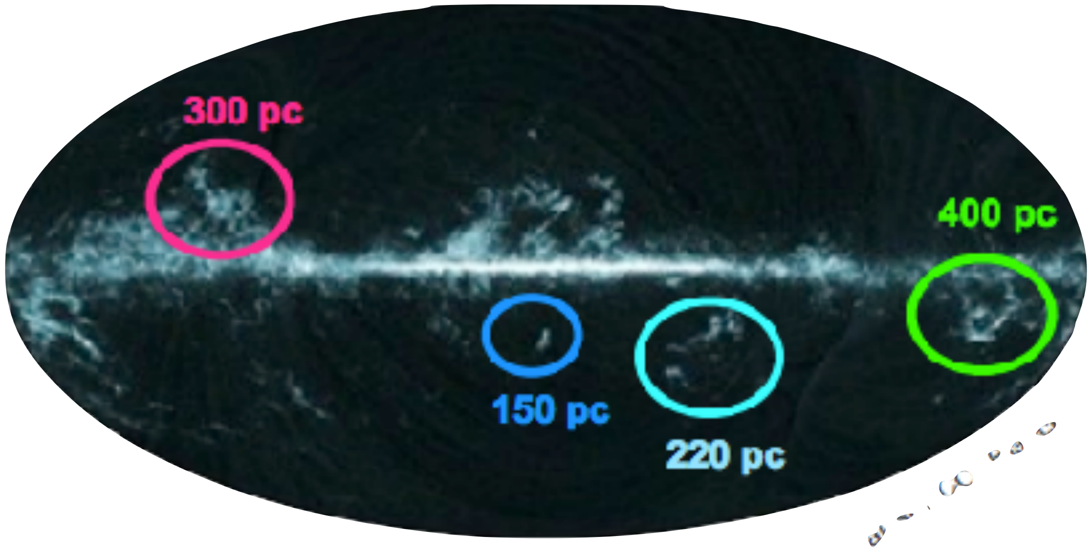
enhancement factor from CRs heavier than p

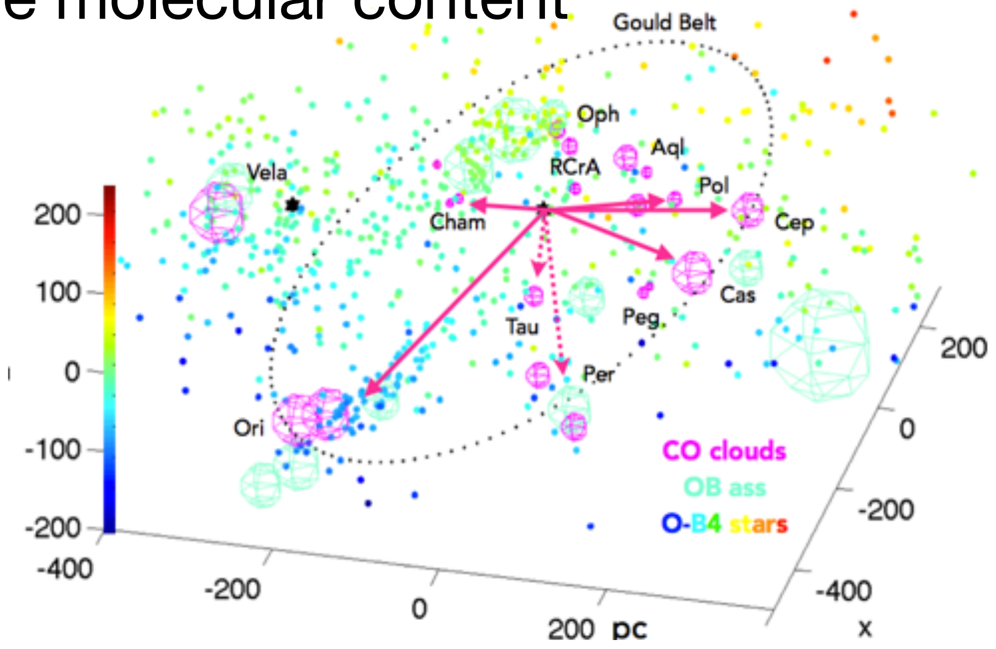


- The gamma-ray intensity exhibits a linear correlation with the atomic gas column density
- The flux of CR nuclei is consistent (10%) with 1 kpc with the one measured locally at the Earth

Cosmic Ray propagation

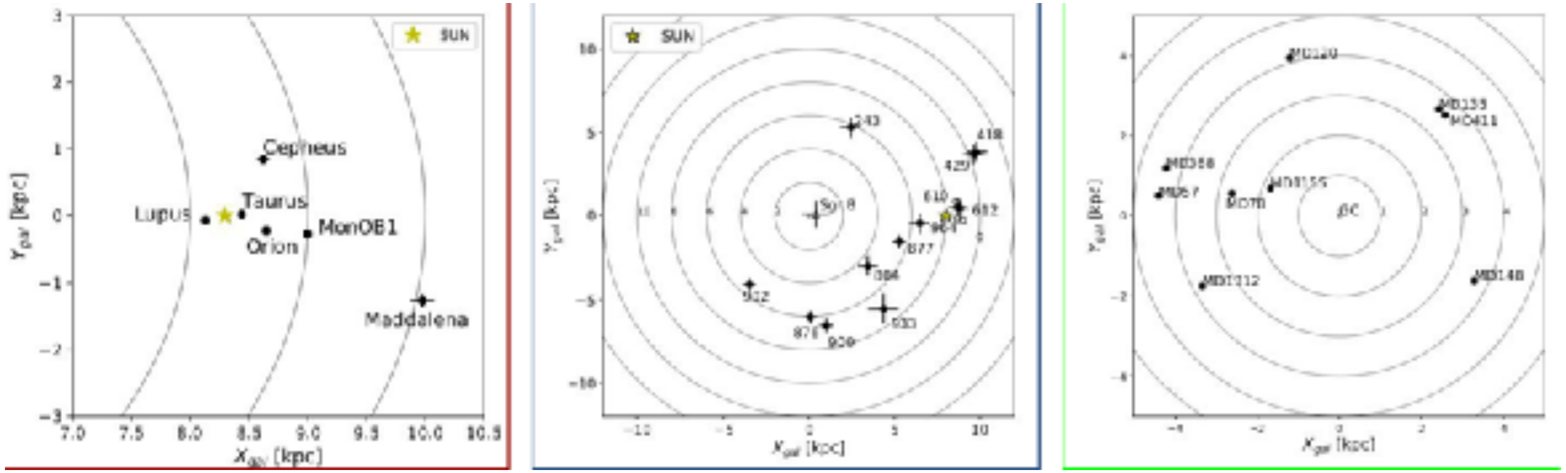
Understanding the ISM / photon fields & the molecular content

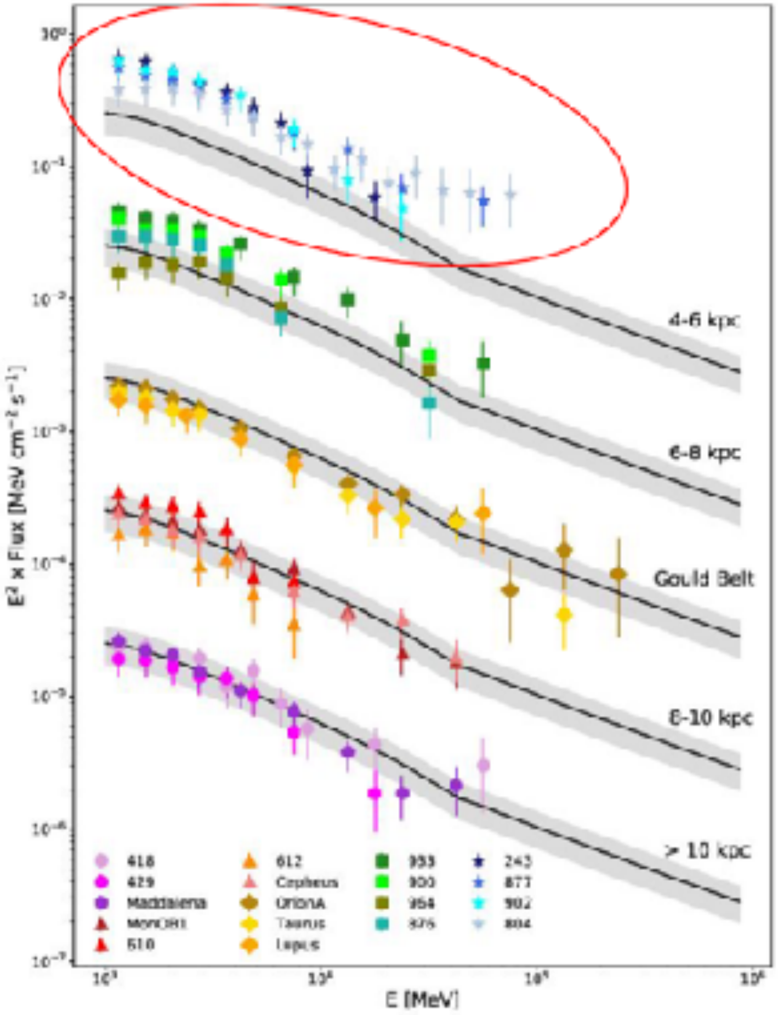




- Using massive clouds are barometers for determine the pressure (energy density) of CRs
- Large number of photons to determine the spectrum with accuracy
- Nearby and dense clouds

Cosmic Ray propagation





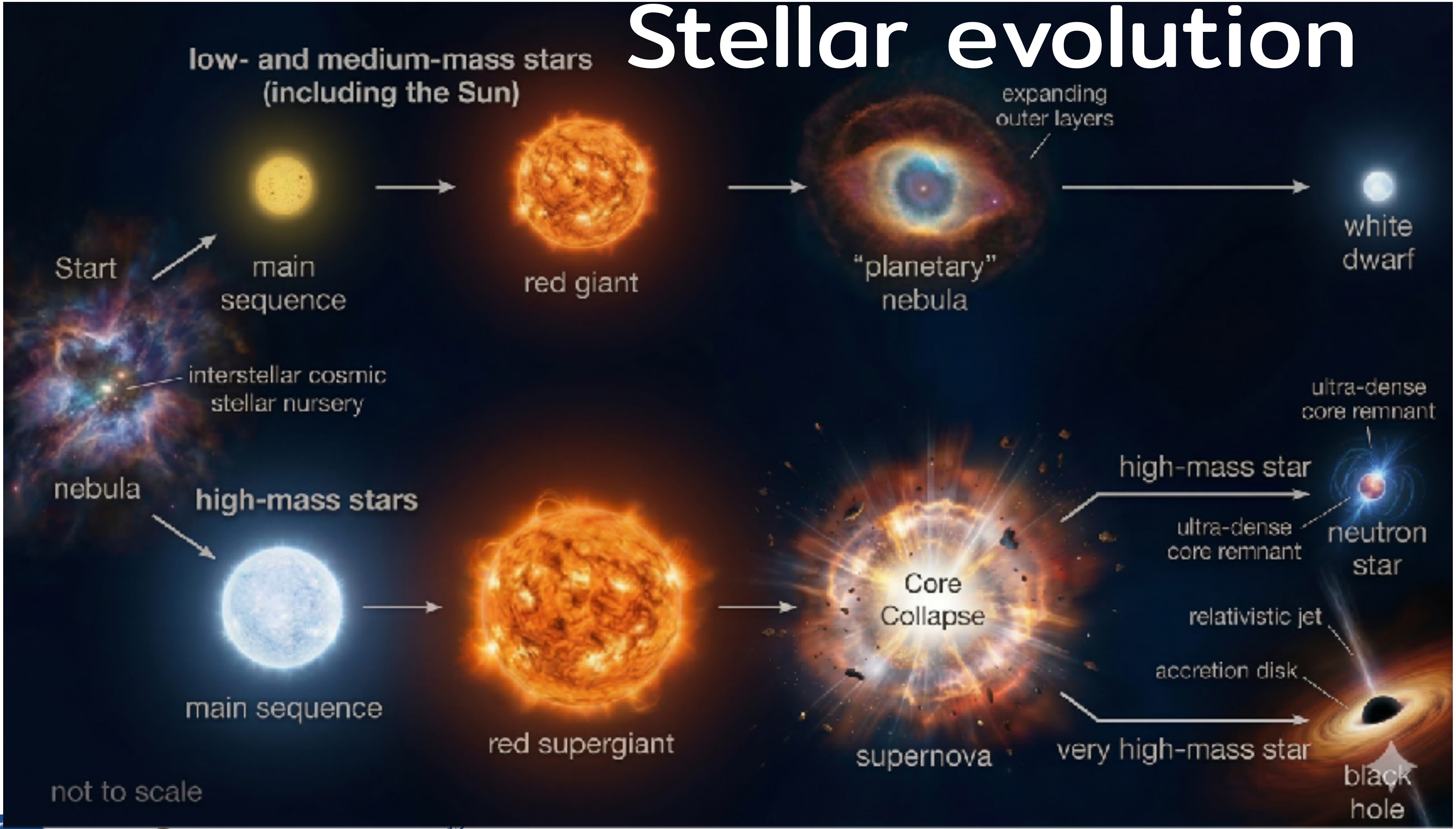
Peron et al 2021

- Probing the CRs at different locations far from the Earth
- Analysis of molecular clouds provide localized information on the CR spectrum far from Earth
- Results from GMCs show deviations from the local

emissivity only in the inner Galaxy, around 4-6 kpc. The deviations are fluctuating, discouraging a global variation

Supernova Remnants

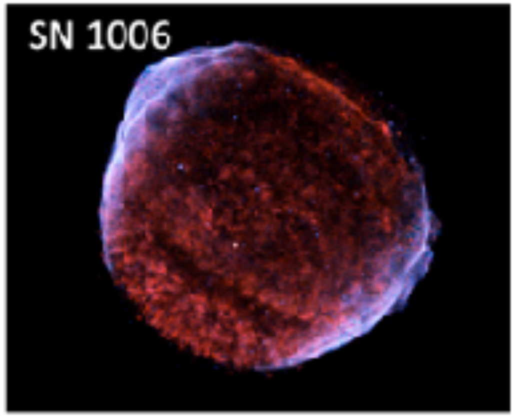
Stellar evolution



Supernova Remnants

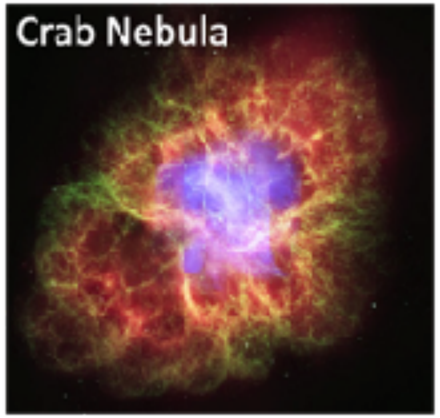
- **Shell-type SNR:** what we see is the shock of the SN ejecta on the surrounding medium
- **Pulsar-Wind Nebulae** (PWN, also called "plerions"): a bright nebula, *powered* by a pulsar
- **Composite:** both the shell and the wind nebula are visible

Shell-type



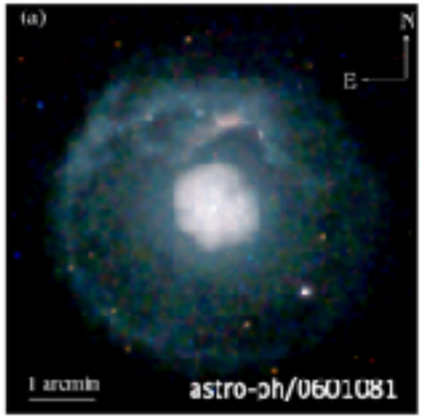
79%

PWN



5%

Composite PWN+shell



12%

SNR Evolution

Free Expansion

$R \sim t$, $M_{ej} >> M_{ISM}$, < 200-300 yrs
$v \sim 5000$ km/s - 10000 km/s
$M_{ej} \sim$ few $M_{\odot}$ - 1 $M_{\odot}$

PeVatron Phase

Adiabatic (Sedov-Taylor)

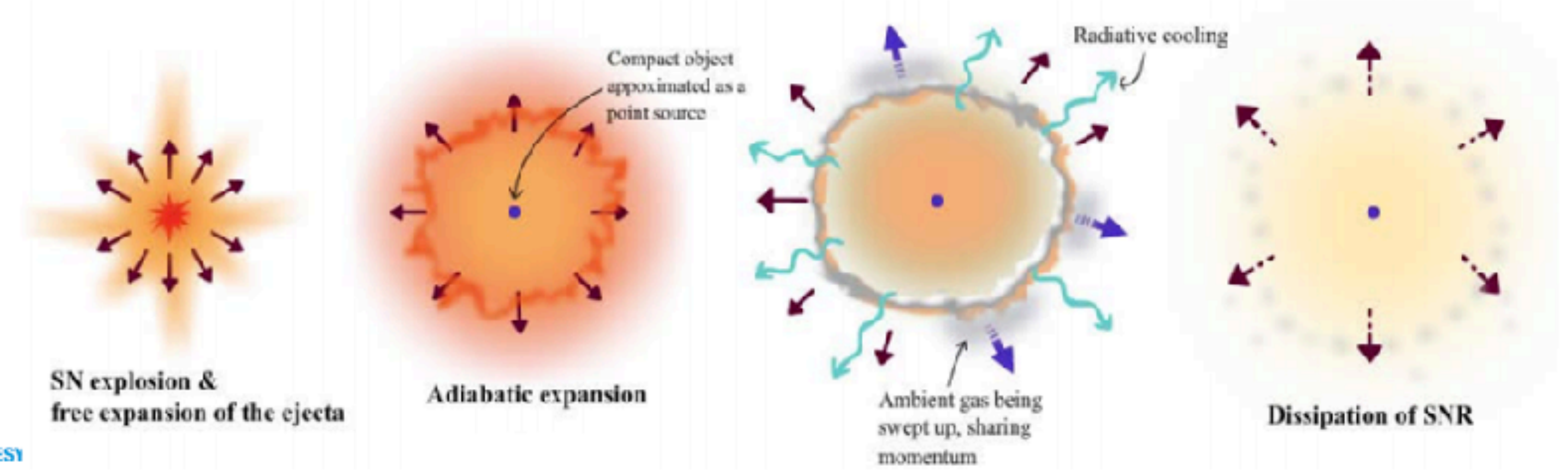
$R \sim t^{2/5}$, $M_{ej} \sim M_{ISM}$, 10^4yrs
$t_{cool} >> t_{dyn}$ ⇒Adiabatic Expansion

Highest Gamma-ray Luminosity

Radiative

Dissipation into ISM v_{sh} ~200 km/s

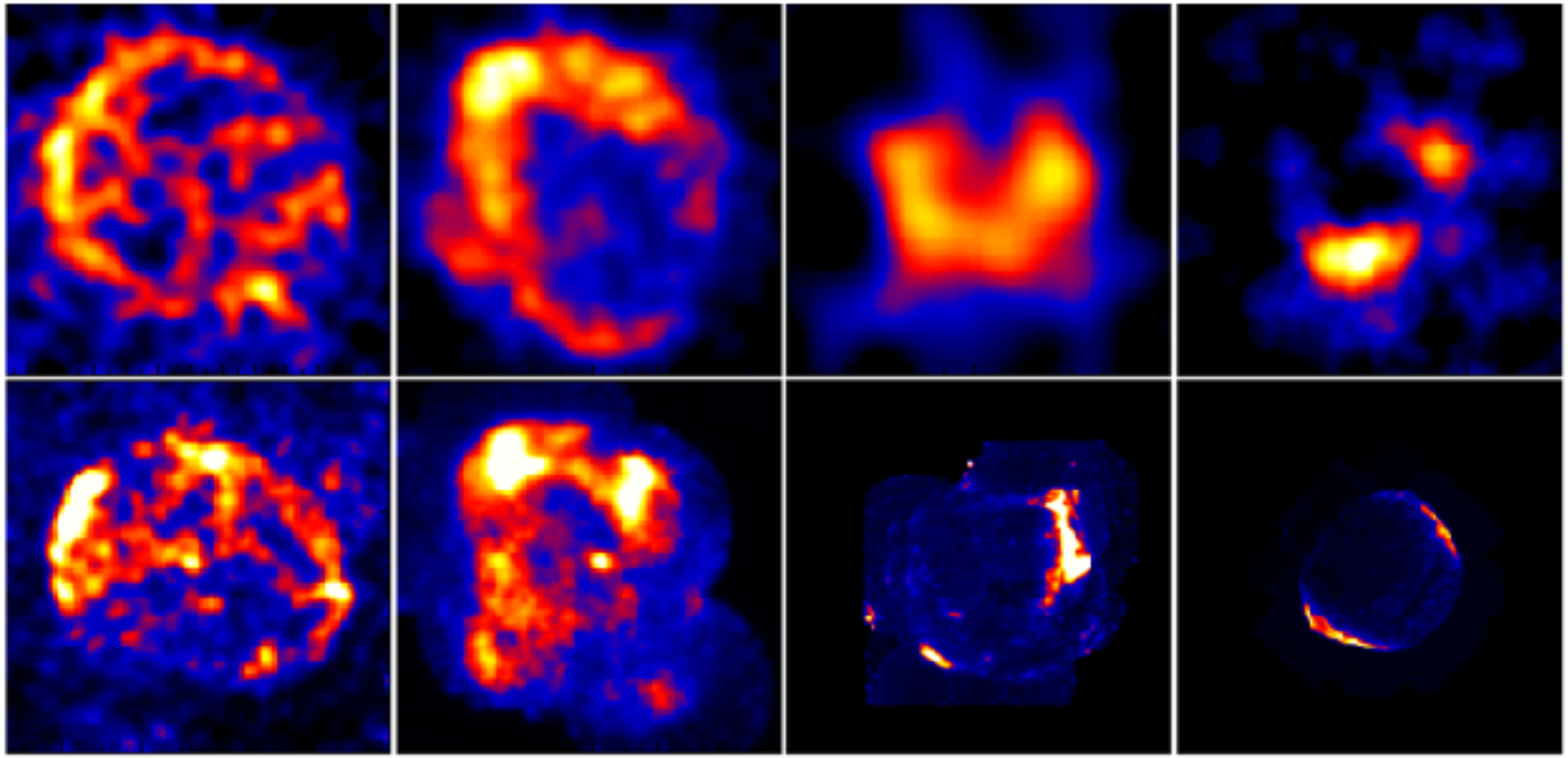
CR Propagation



DESY Page 4

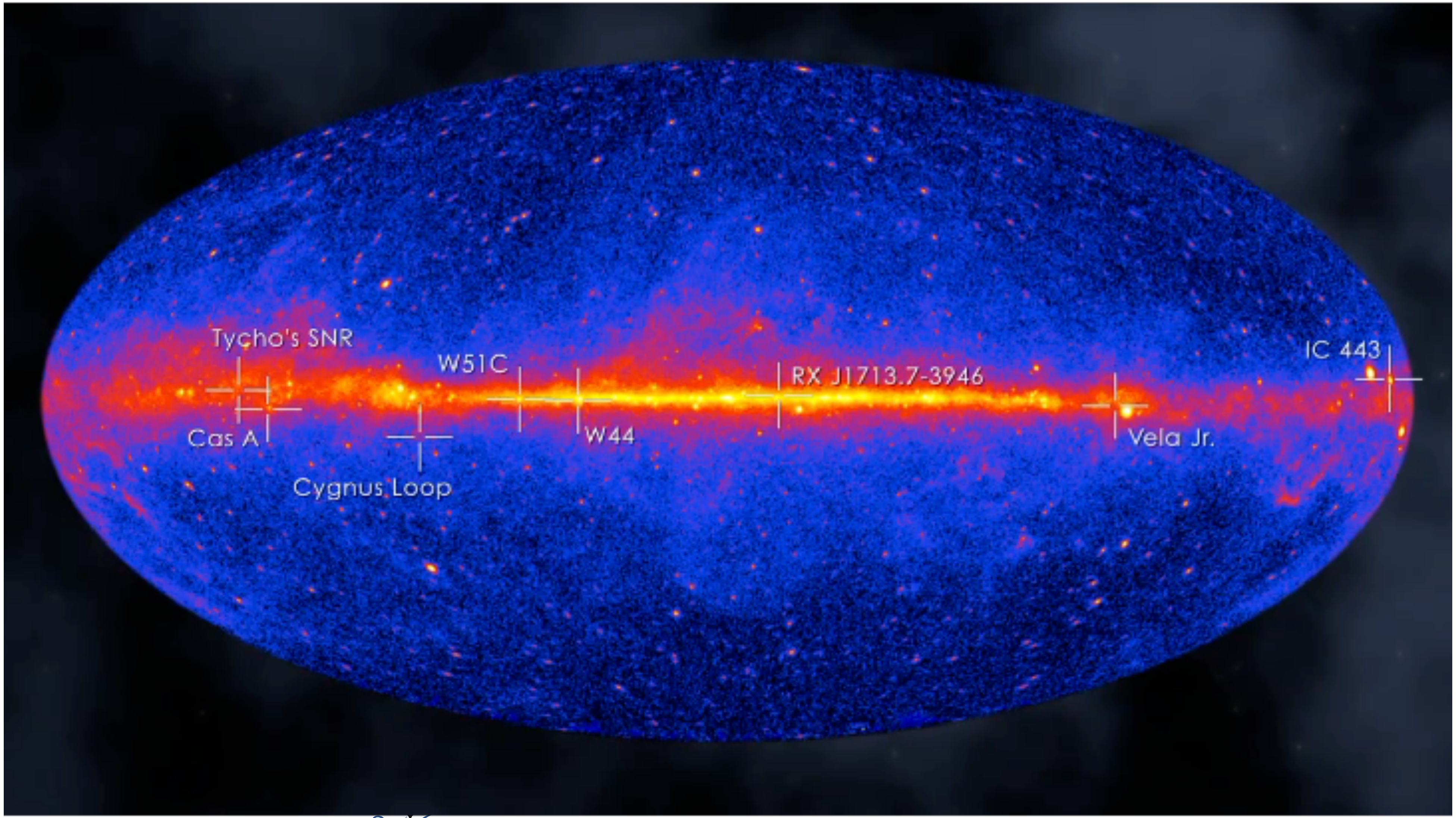
Supernova Remnants

Gamma rays



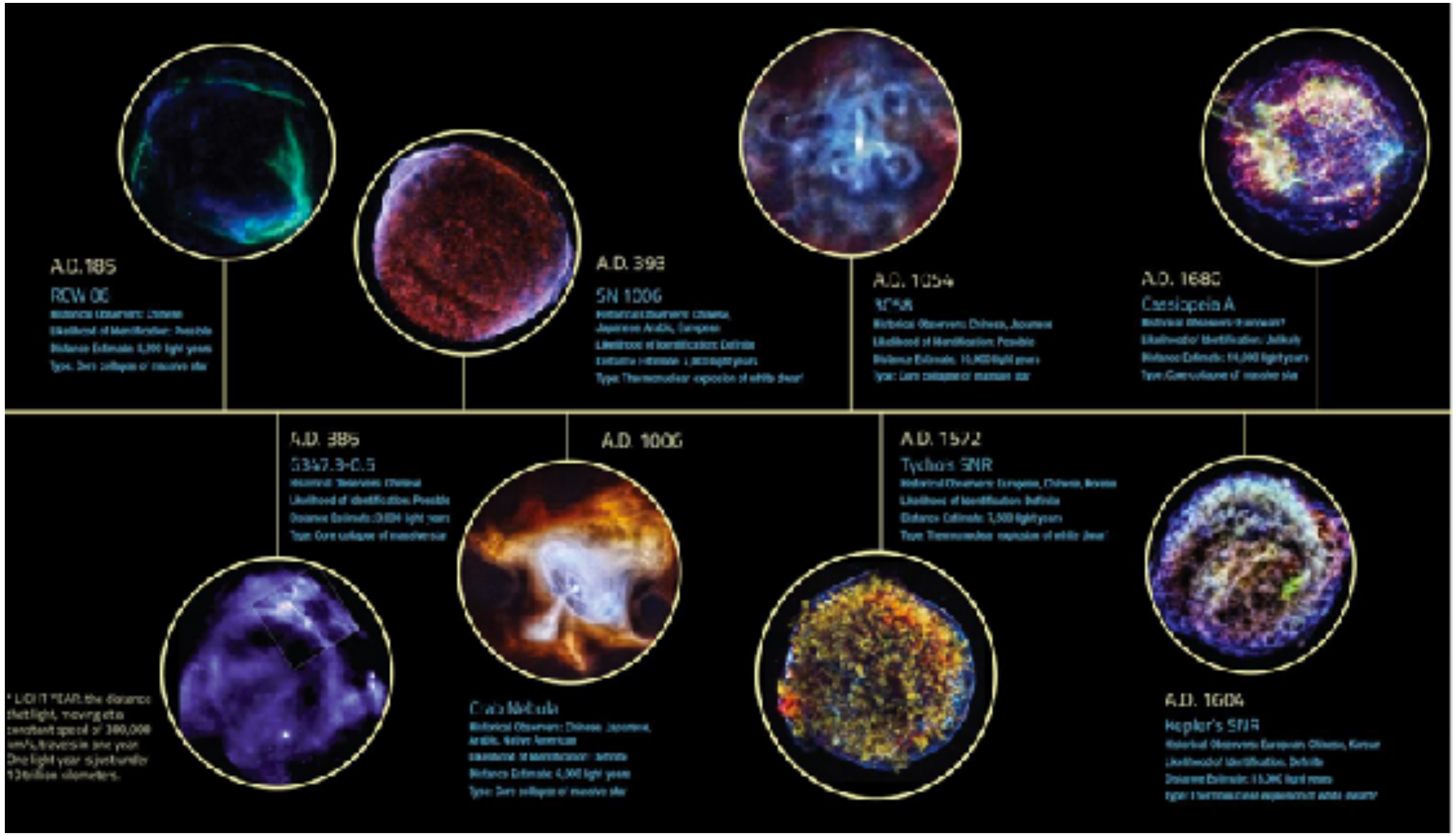
X-rays

Supernova Remnants



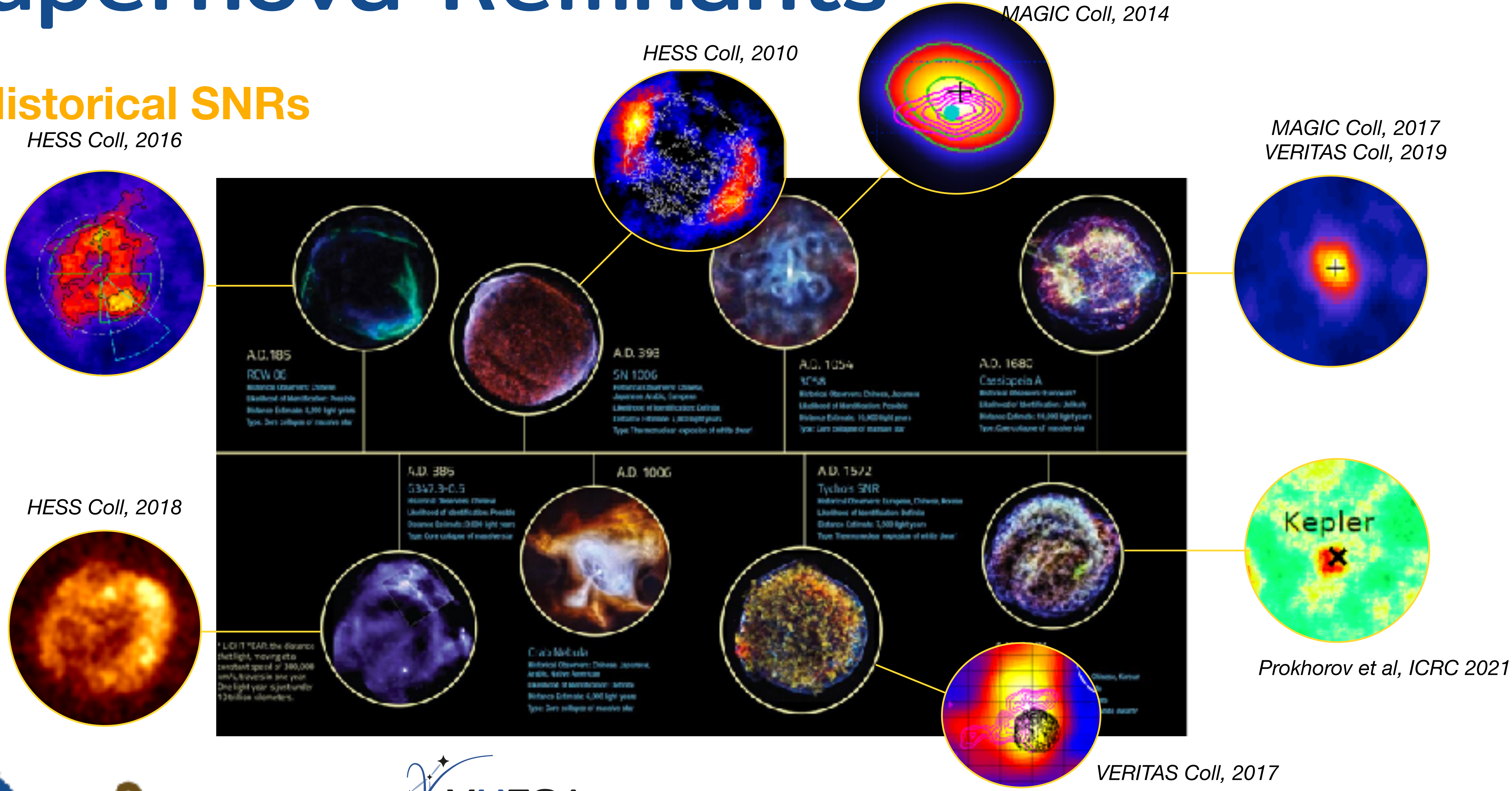
Supernova Remnants

Historical SNRs



Supernova Remnants

Historical SNRs



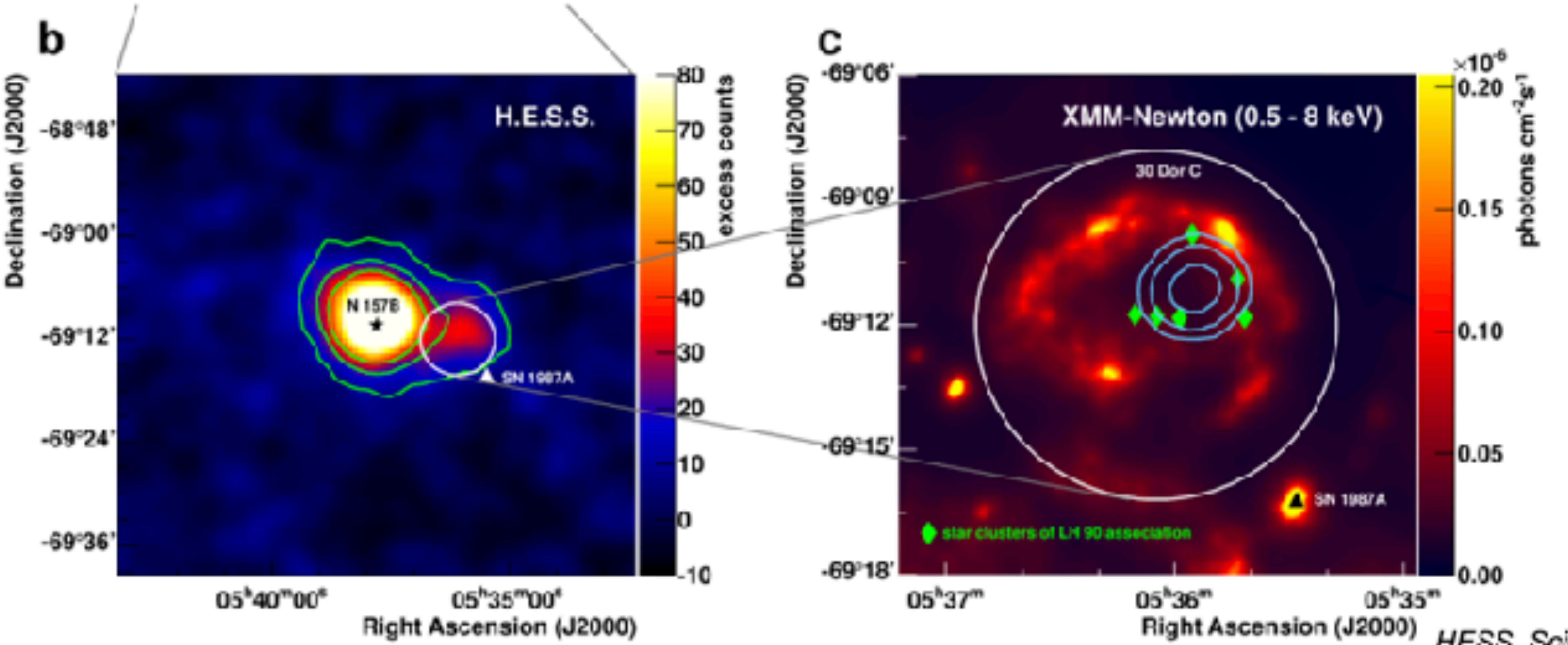
CR accelerators: SNRs

Free Expansion: PeVatron Phase ?

SN 1987A

L (>1 TeV) < 2.2×10^{34} erg/s => W_{pp}(n ~10^3-10^4 cm^{-3}) < $1.4 \times 10^{48} f^{-1}$ erg

For f ~ 0.2 (spherical symmetric distribution) => W_{pp} < 9×10^{48}erg (1% to nuclei)



HESS. Science 2015

Page 5

CR accelerators: SNRs

$t_{syn} \sim 1/5\, B_{mG}^{-1.5} E_{KeV}^{-0.5}$ years

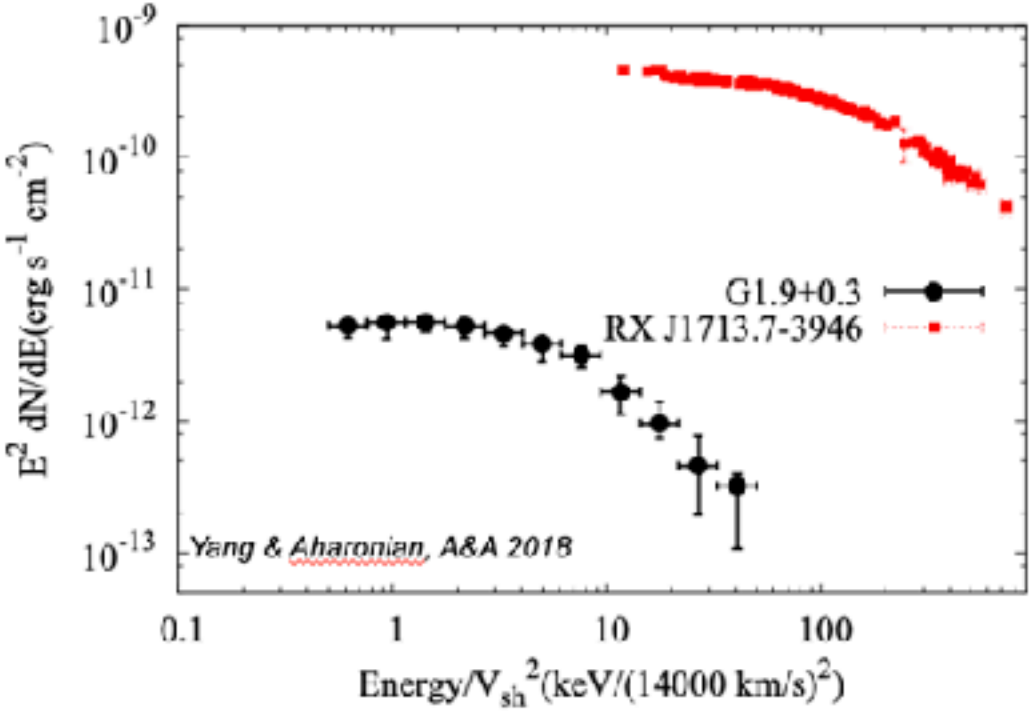
$t_{acc} \sim \eta B_{mG}^{-1.5} E^{0.5} V_{3000}$ years

Free Expansion: PeVatron Phase ?

In strong fields, the maximum Eo results from $t_{cool} = t_{acc}$ => $E_c \propto B^{-1/2} v_{sh}$ => $E_m \propto E_o B^{1/2} \propto v_{sh}$

SNR G1.9+0.3

- Youngest SN in our Galaxy (age ~150 yrs)
- Fast shock v_{sh} ~ 14000 km/s (=> E_o ~ 10 keV)
- Chandra+nuStar: Cutoff at 1.5 keV
  => Not an efficient accelerator
- Was it a PeVatron?



CR accelerators: SNRs

Free Expansion: PeVatron Phase ?

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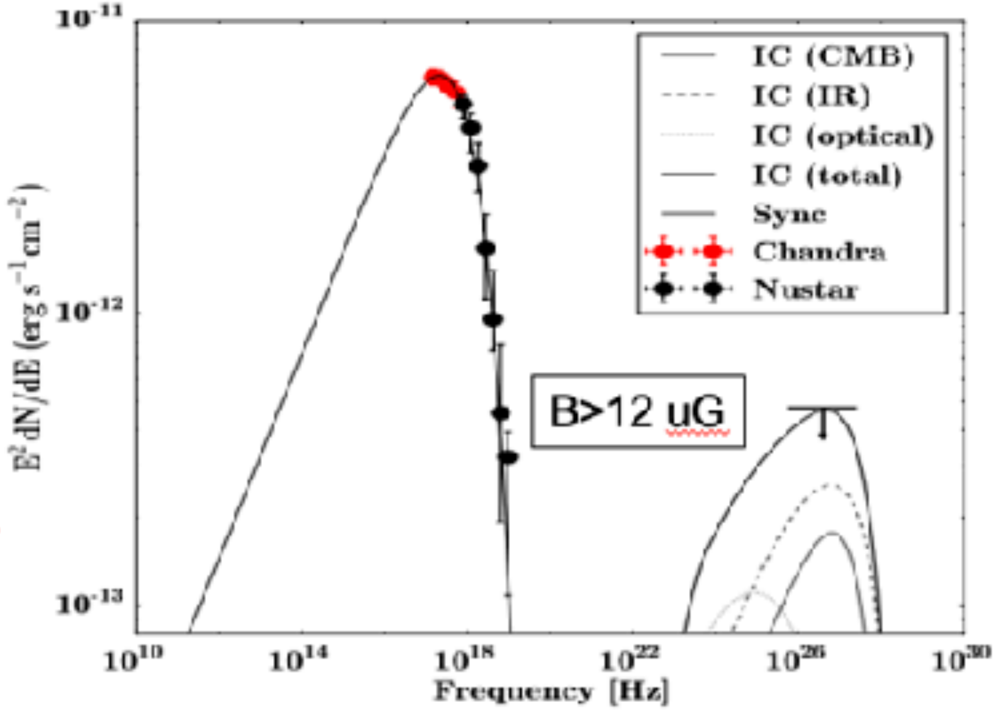
- Fast shock v_{sh} ~ 14000 km/s (=> E_o ~ 10 keV)
- Chandra+nuStar: Cutoff at 1.5 keV
  => Not an efficient accelerator
- Was it a PeVatron?
  Run-away protons R(D=10^{30}cm2/s) <~30pc => 10 arcmin
- W_p(n~100 cm^{-3})<10^{45} erg/s

$R_d = \sqrt{2Dt_{cool}}$



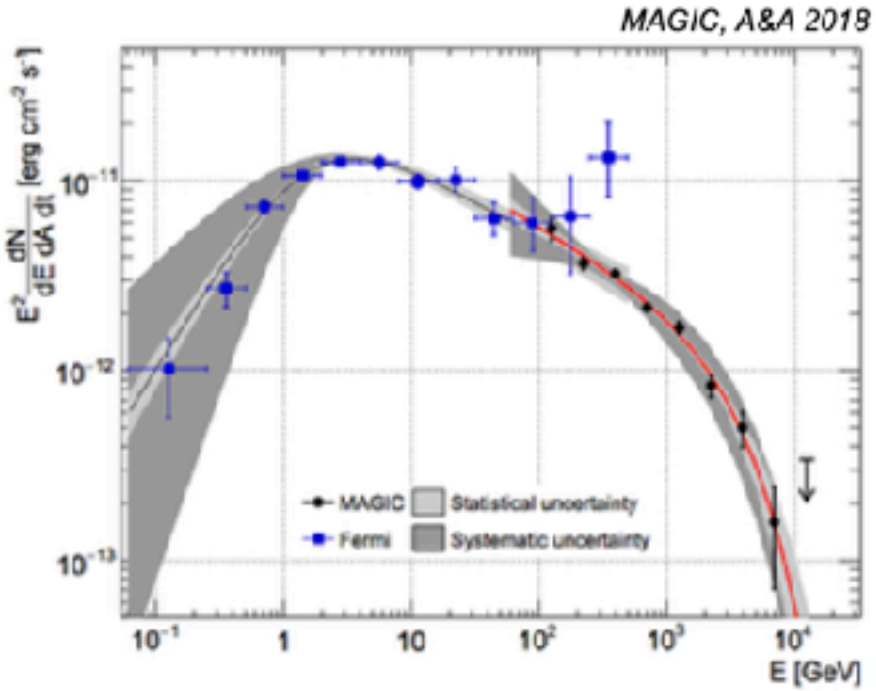
Yang & Aharonian, A&A 2018

CR accelerators: SNRs

Sedov-Taylor phase: Maximum of the gamma-ray emission?

Cassiopeia A

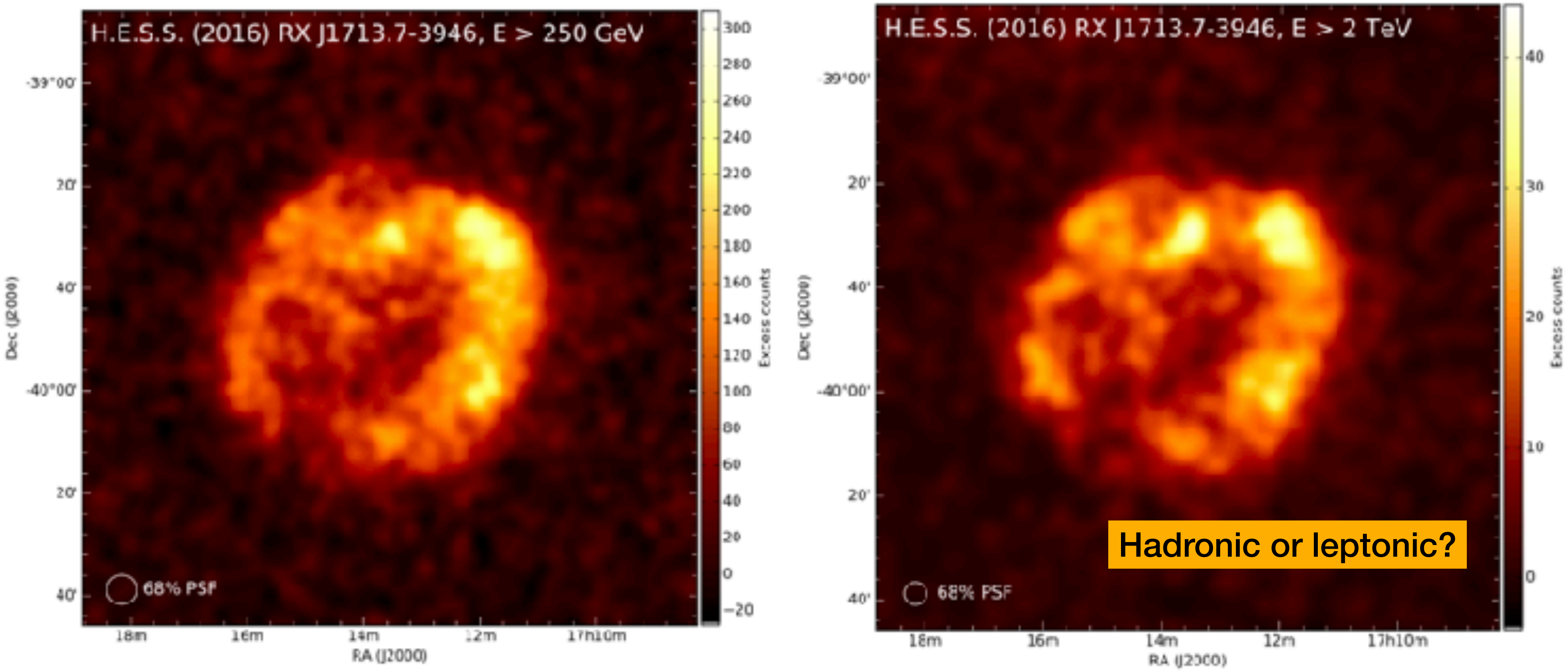
- Age ~ 340 yrs
- Fast shock v_{sh} ~ 5000 km/s
- Highly turbulent Bfield ~ 0.2-0.3 mG
- Ecut = 3.5 TeV
  - Composition: can reduce gamma efficiency by factor 2(
  - Spectrum dominated by plateau, shell higher cut off?



CR accelerators: SNRs

Sedov-Taylor phase: Maximum of the gamma-ray emission?

HESS, A&A 2018

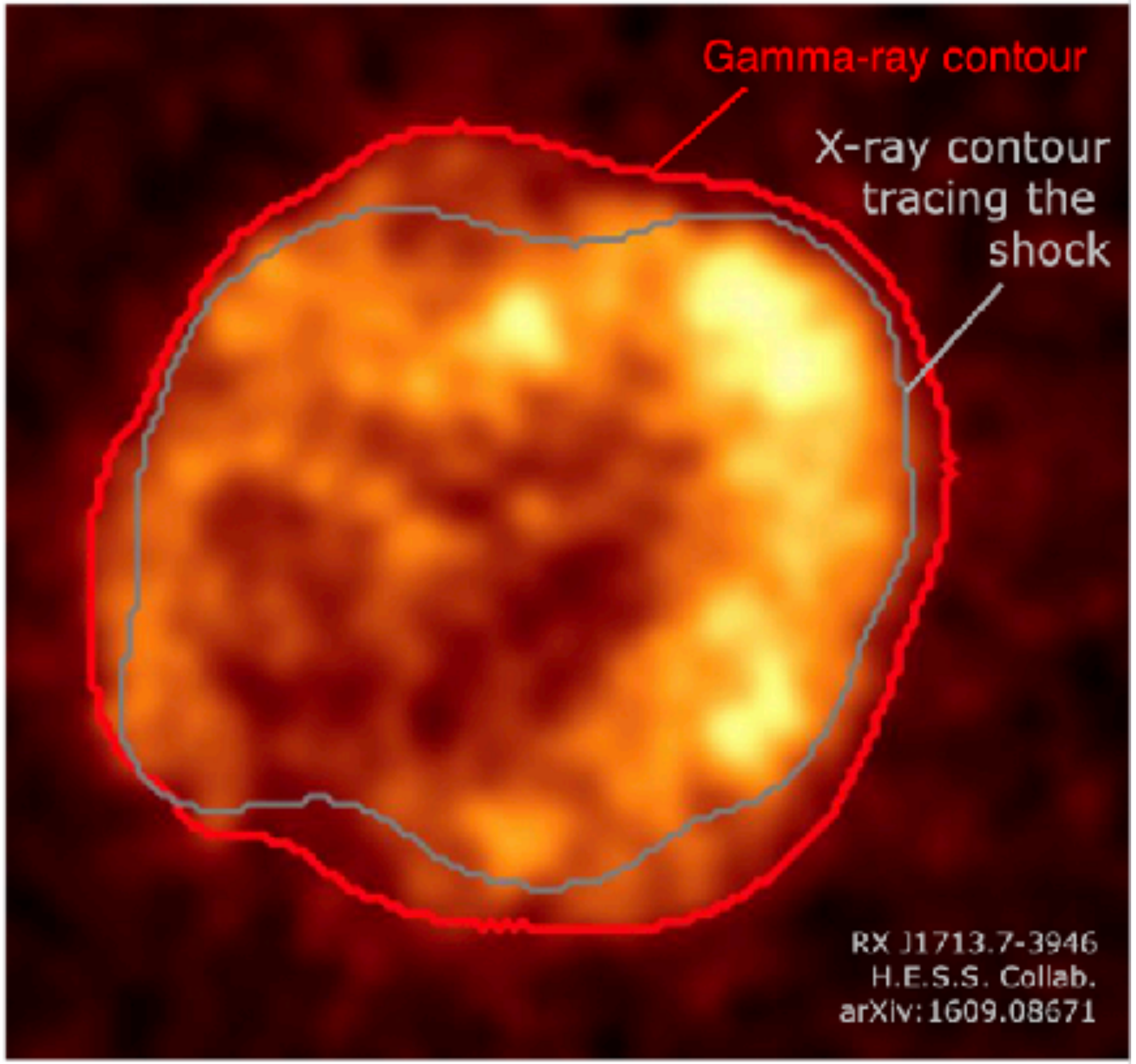


CR accelerators: SNRs

Recognized as essential feature: CR escape from remnants
e.g. Malkov et al., arXiv:1207.4728

→ CR current generates turbulent magnetic fields that are crucial for the acceleration

→ PeV cosmic rays only contained during the first O(100) years (?)

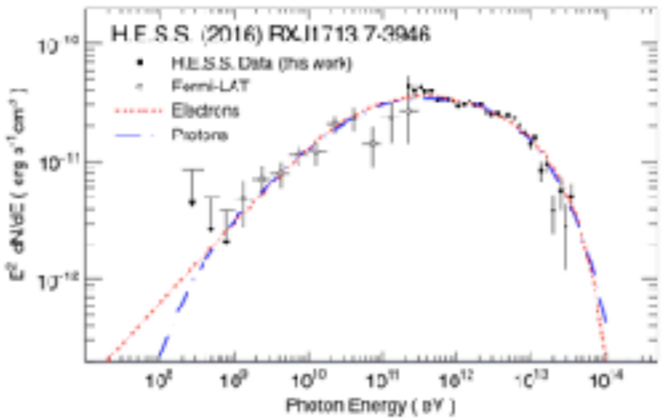


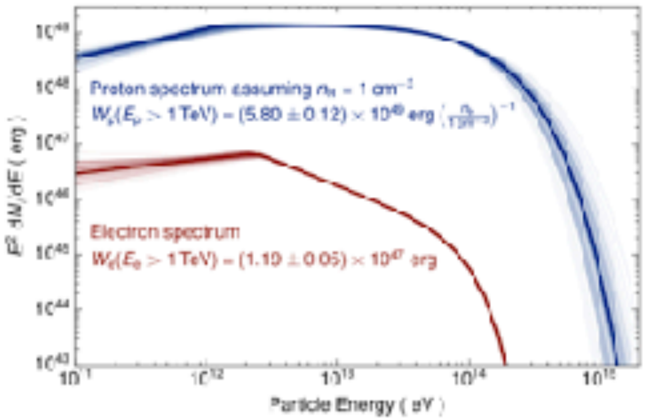
CR accelerators: SNRs

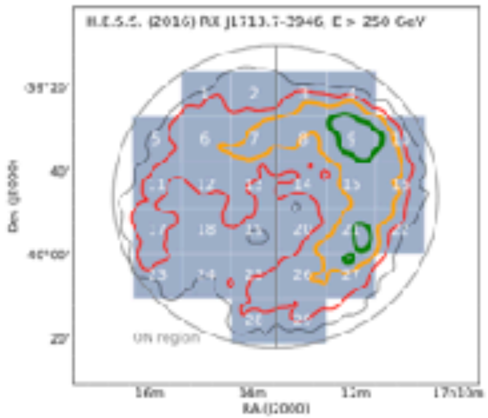
HESS, A&A 2018

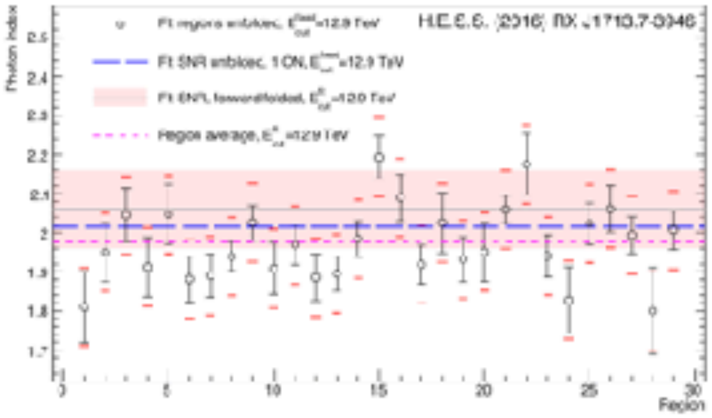
Sedov-Taylor phase: Maximum of the gamma-ray emission?

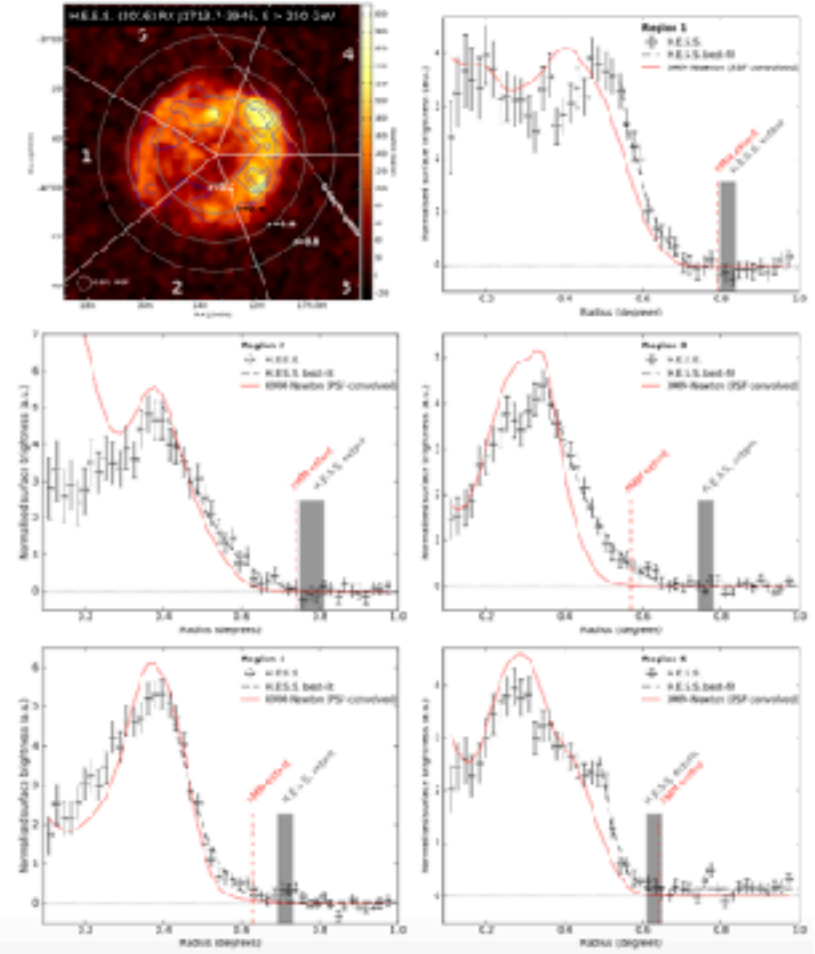
Did particles run-away?







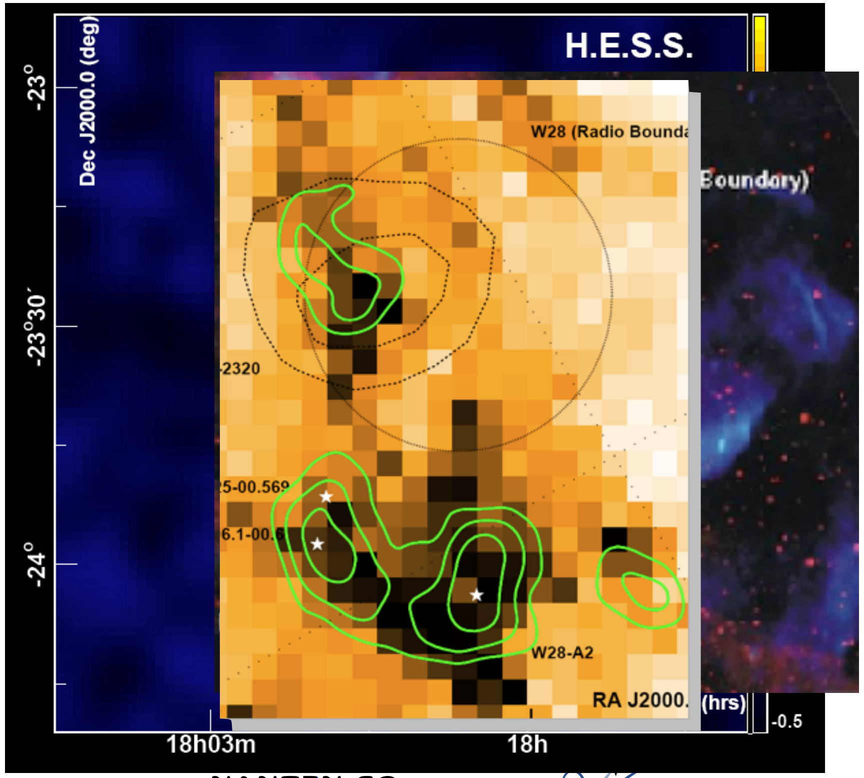


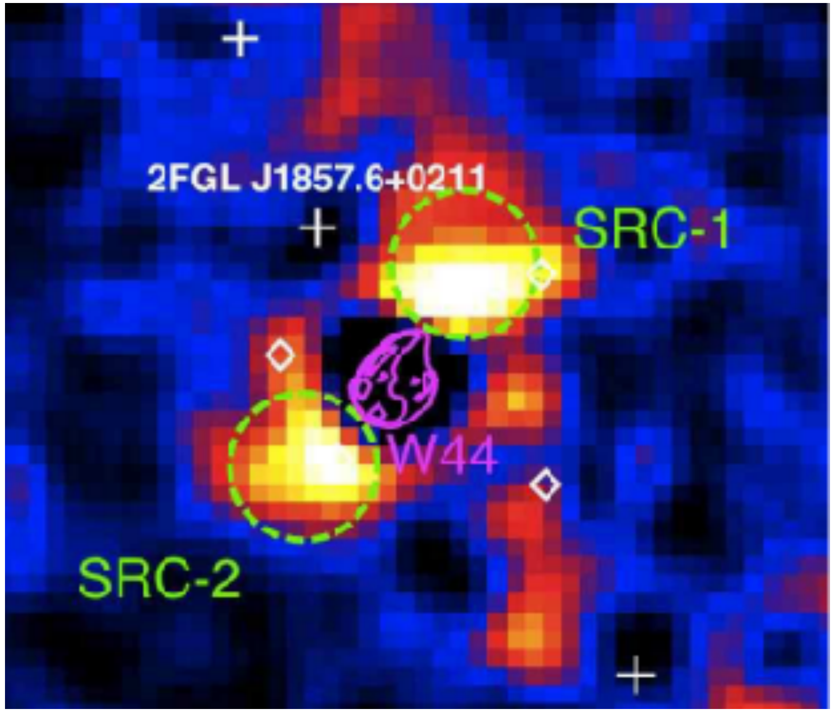


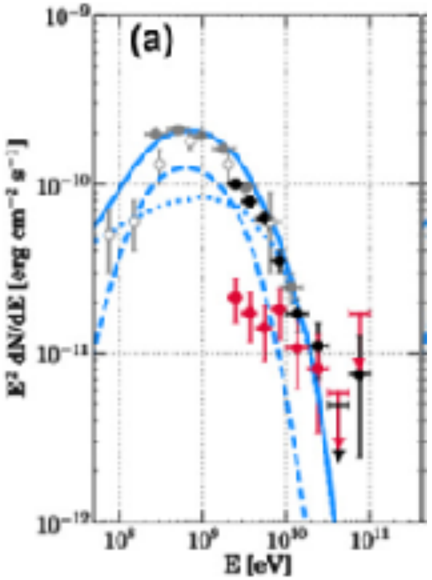
CR accelerators: SNRs

Radiative phase: Old CRs reservoirs? Observations of the CR pion peak

Morphological and High resolution spectroscopic Studies





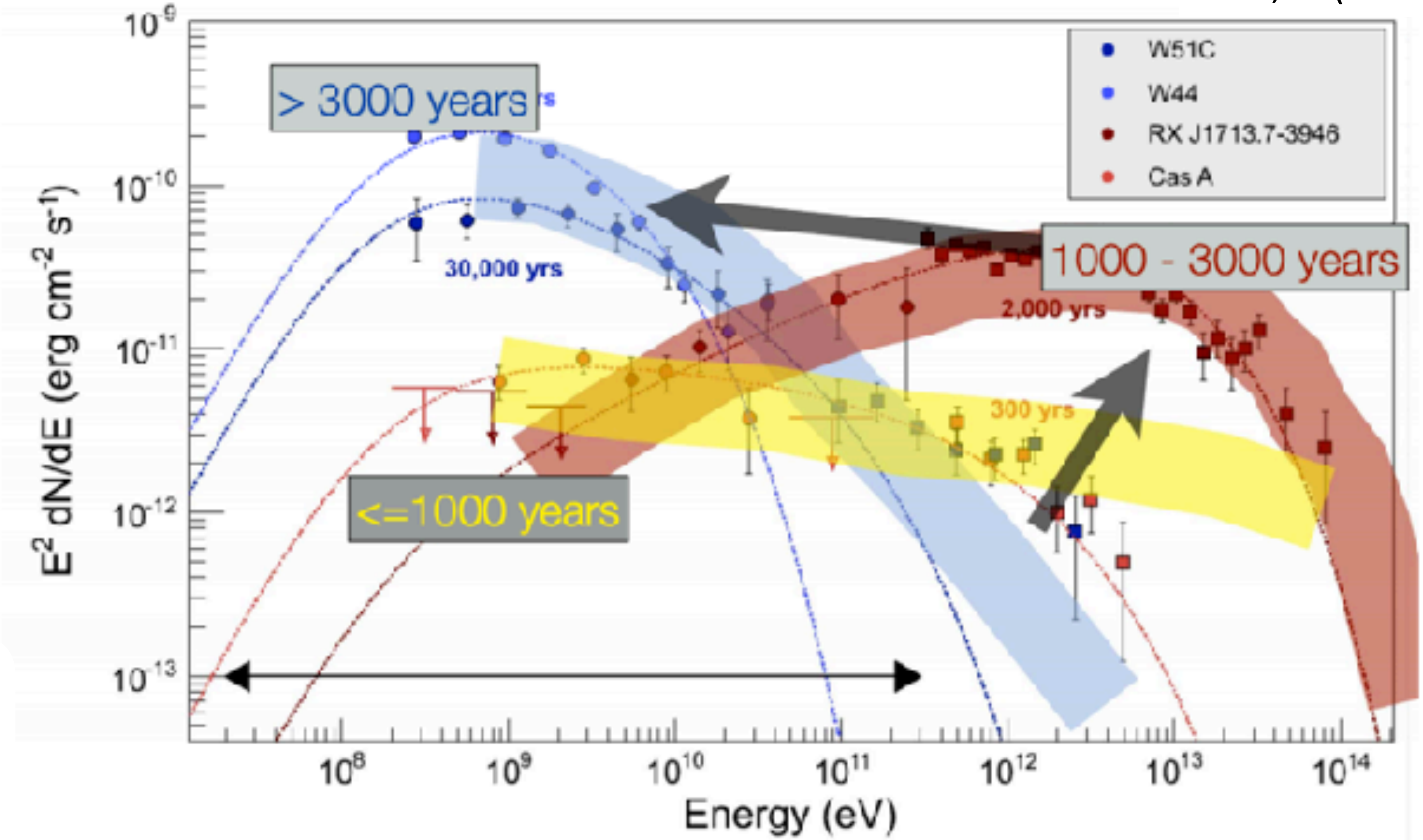


Looks like it in some old SNRs at low energies, but still, no trace of PeV energies

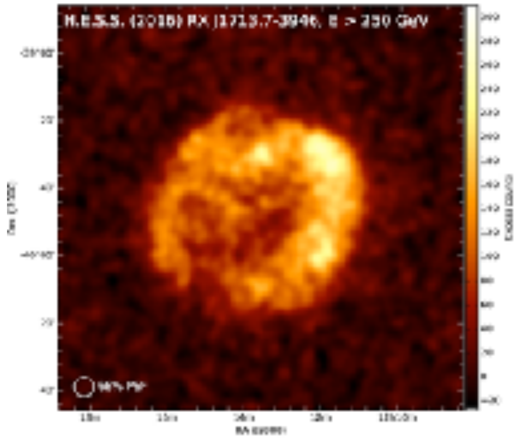
CR accelerators: SNRs

Radiative phase: Old CRs reservoirs? Observations of the CR pion peak

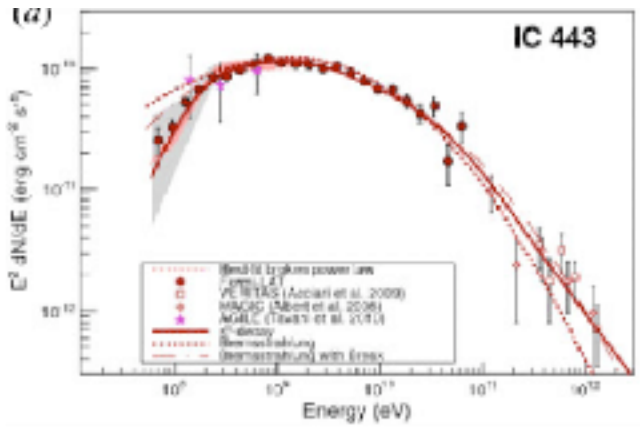
Funk, S. (2015)

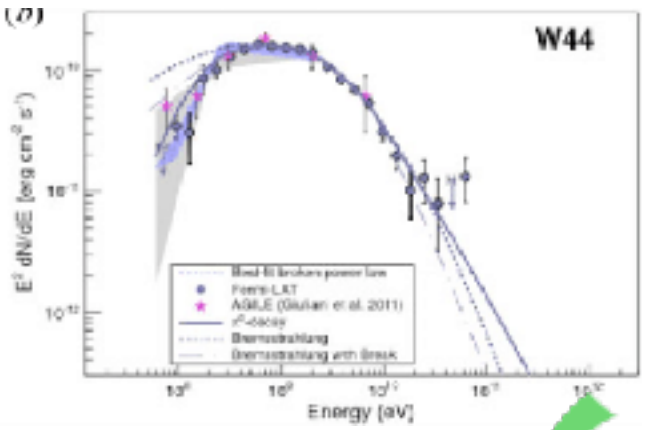


CR accelerators: SNRs



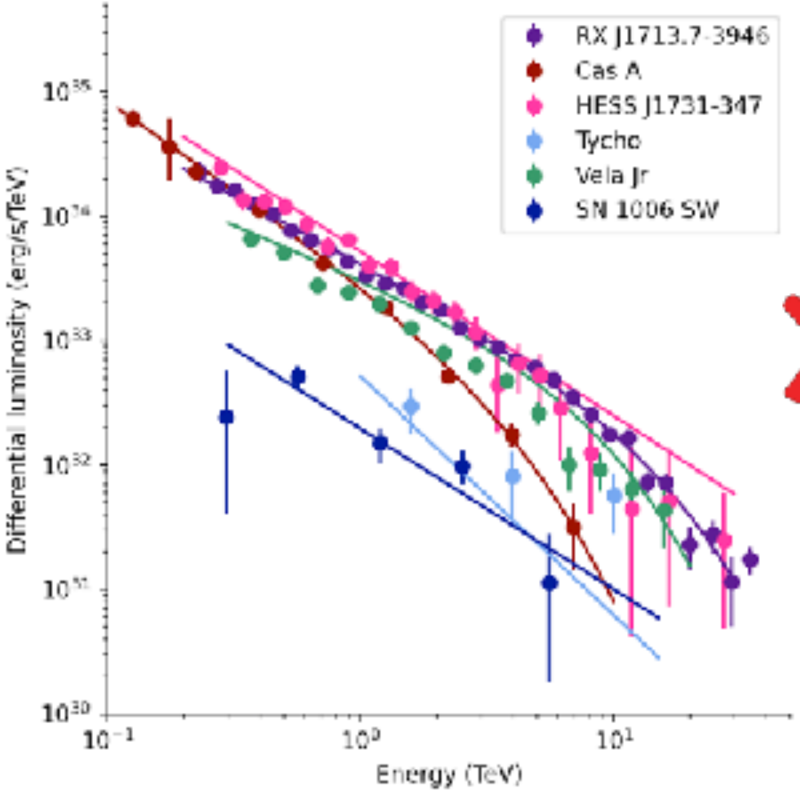
We detect TeV gamma-ray shells





We detect GeV gamma-ray shells & pion-bump

But…energy cutoff at a few tens of TeV => no PeV CRs



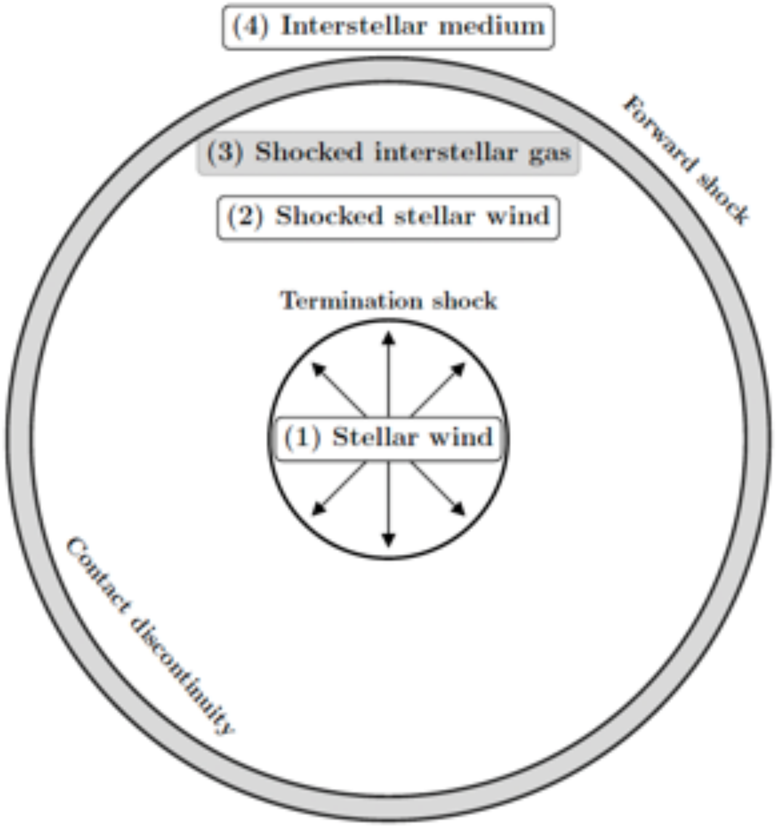
Stellar Clusters

CR accelerators: Stellar Clusters

JWST view of 30 Doradus

- Different definitions of what a stellar cluster is.
- Usually defined based on gravitational boundedness of a star population.
- Born in regions of cold Giant Molecular clouds

CR accelerators: Stellar Clusters



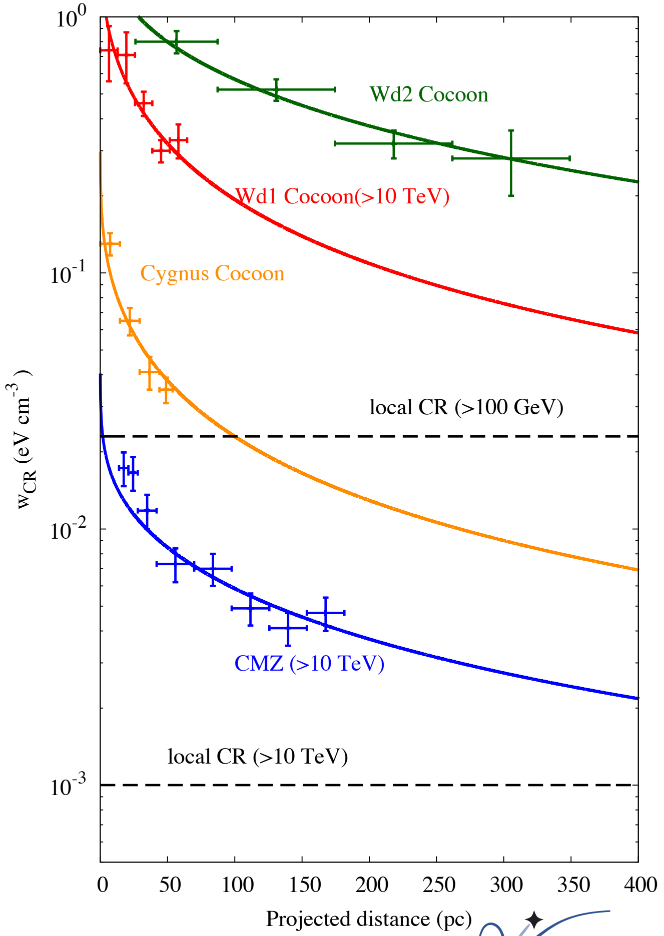
Sketch of a Stellar cluster wind bubble.

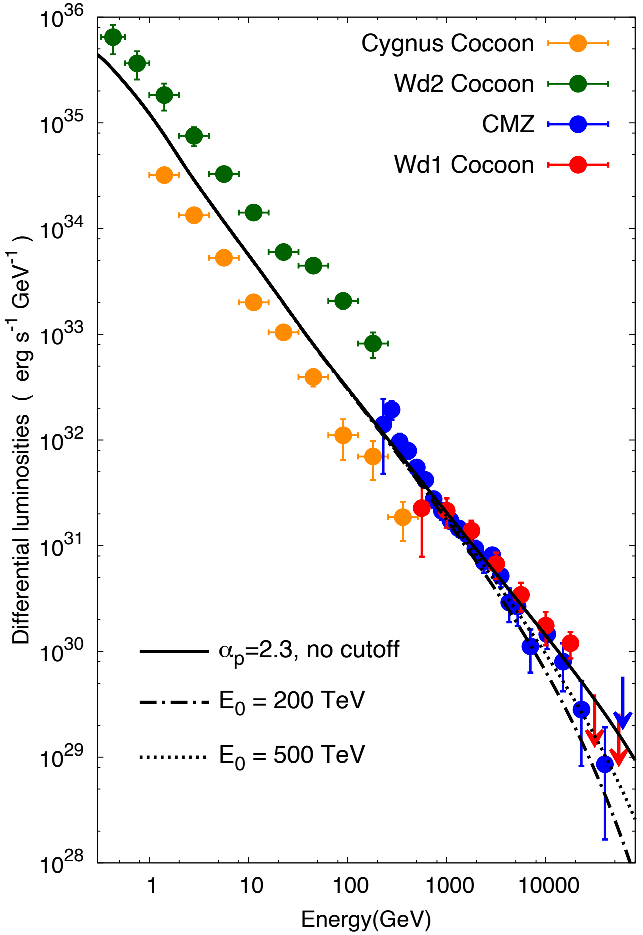
- Young Massive stellar clusters are perfect PeVatron candidates
  - young enough to have few supernovae
  - massive enough to produce significant CR acceleration

CR accelerators: Stellar Clusters

- Exciting observations reviving stellar clusters as PeVatrons

Aharonian, F. et al., 2019



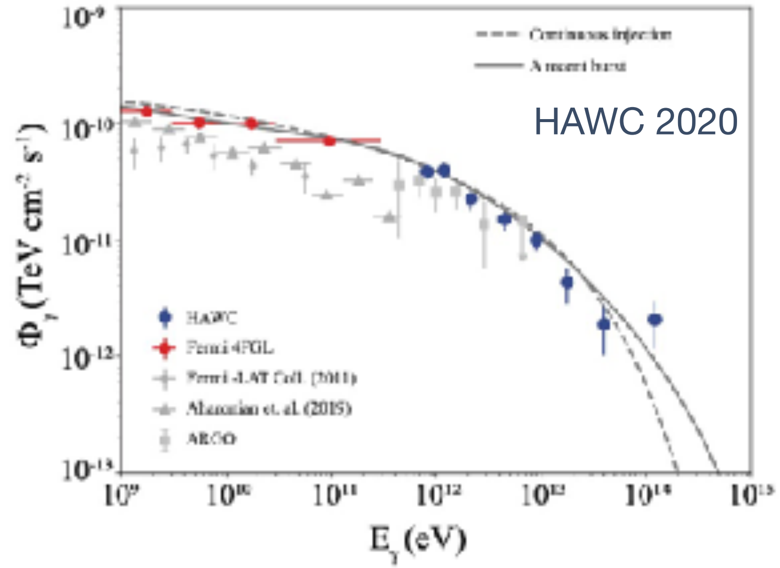


- 1/r morphology points towards a continuous particle injection by a central source

CR accelerators: Stellar Clusters

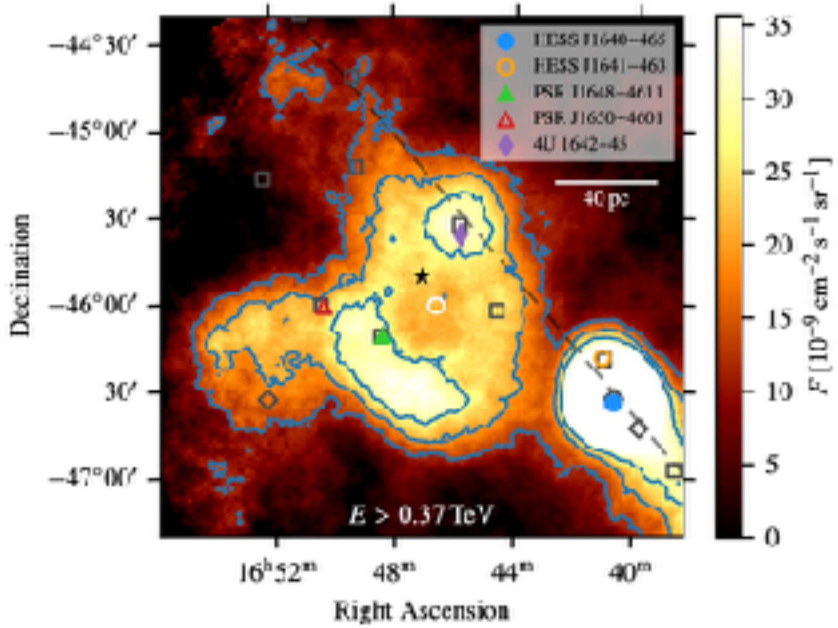
Experimental evidences:

- Cygnus Cocoon accelerates particles up to ~hundreds of TeV (or even up to PeV!)



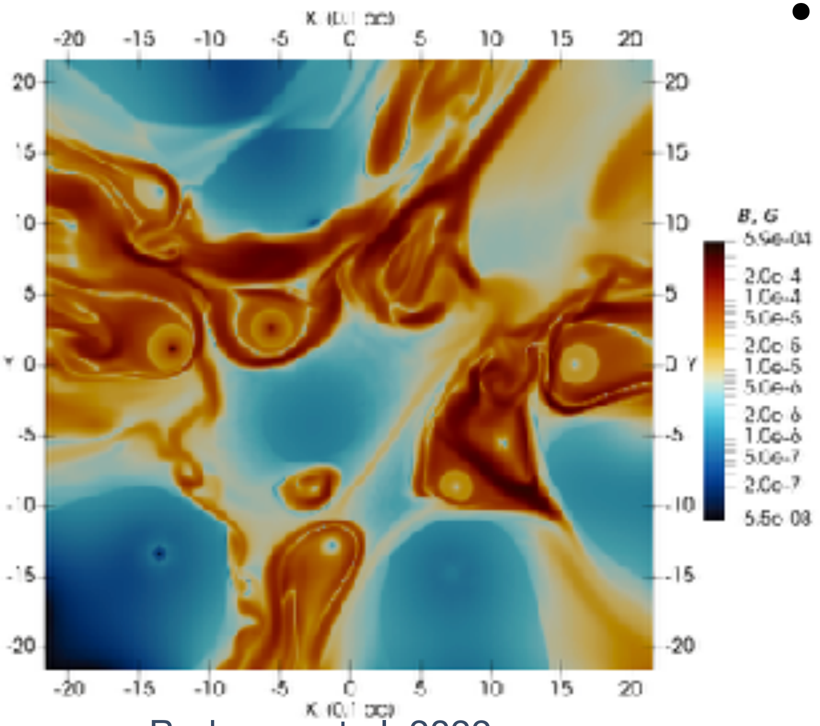
HAWC 2020

- Westerlund 1 shows a complex morphology
- Emission may be explained by leptons accelerated in the region [Härer et al. 2023]



HESS 2022

CR accelerators: Stellar Clusters



Badmaev et al. 2022

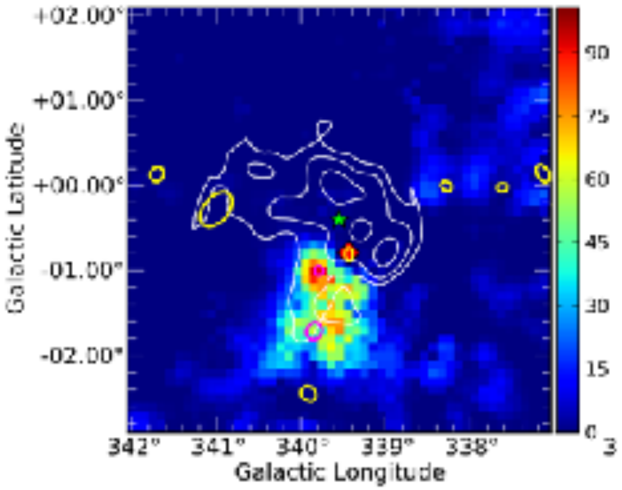
- Backed up by **theoretical** works:
  - Large magnetic fields and size
  - Fast outflows as in SNRs
  - Energetics << than in SNRs

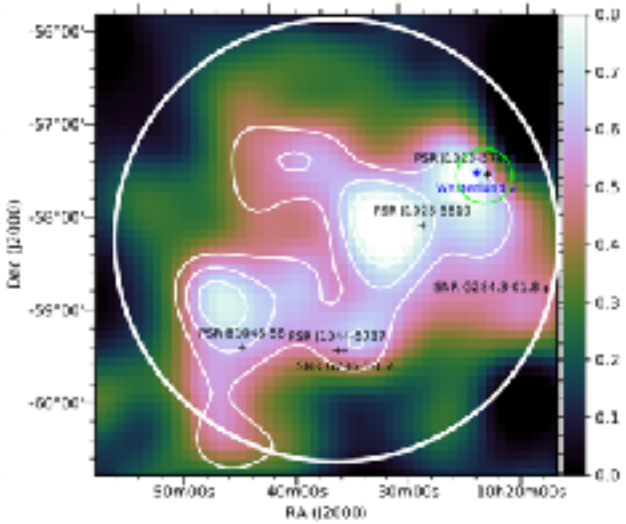
Hillas Criterium:

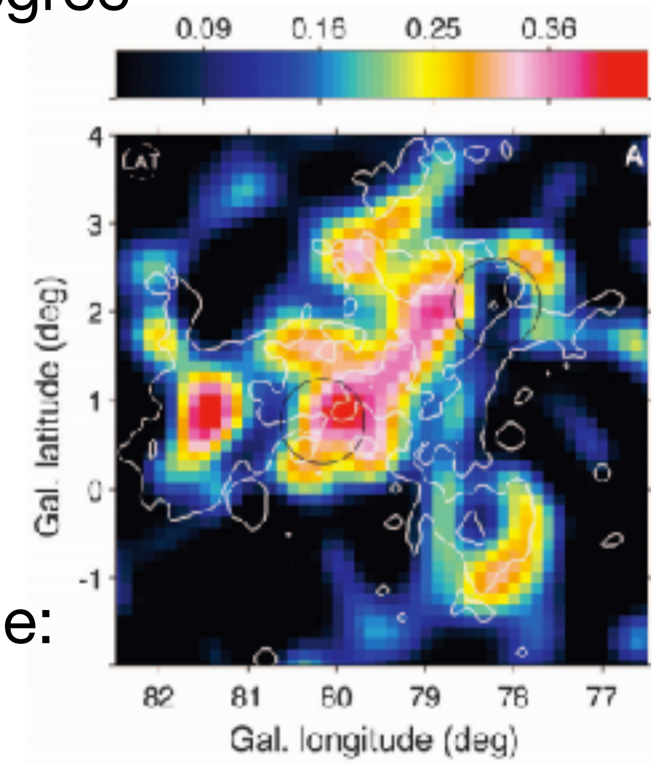
$$E_{max} \sim \left(\frac{q}{c}\right) B_s u_s R_s$$

CR accelerators: Stellar Clusters

- Acceleration in clusters: wind-wind, clusters, collective effects
- Energy reservoir ~$10^{38\text{-}39}$ erg over ages of $T \geq 10^6$ years
- In the GeV range: huge structures covering few degree



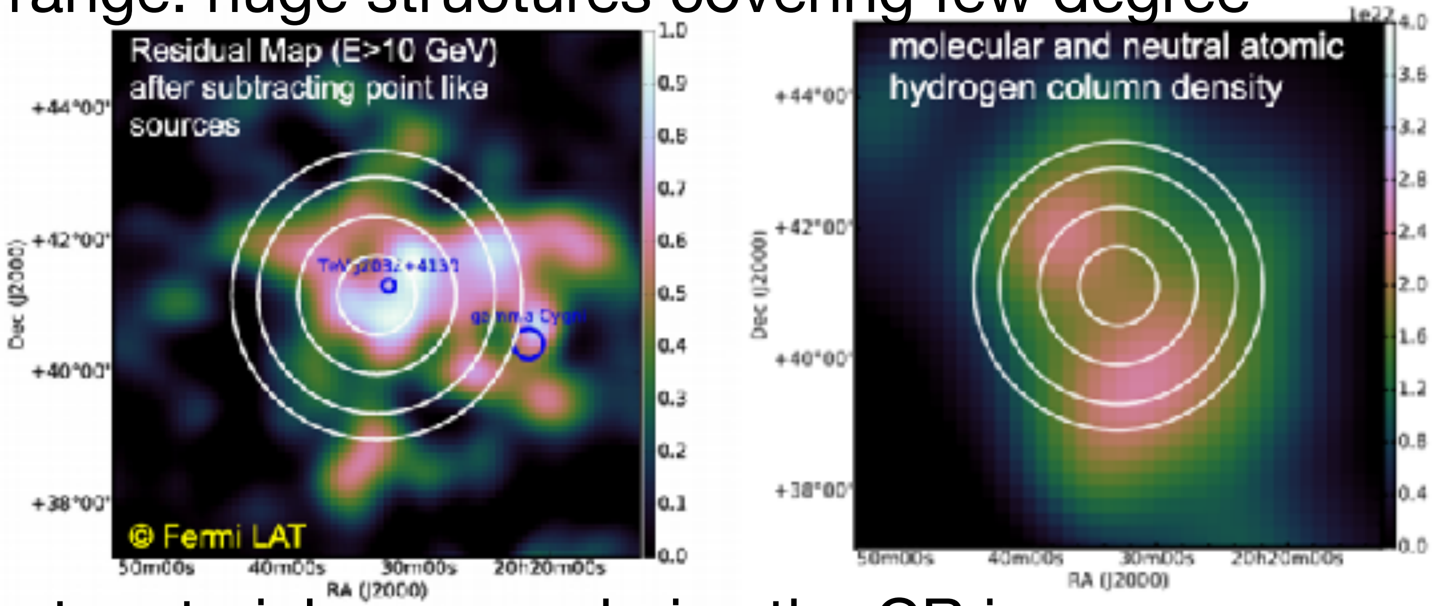




- Knowing the target material, we can derive the CR image:
  - Planck free-free (HII) and CfA (CO) maps.
  - In the GeV range: huge structures covering few degrees

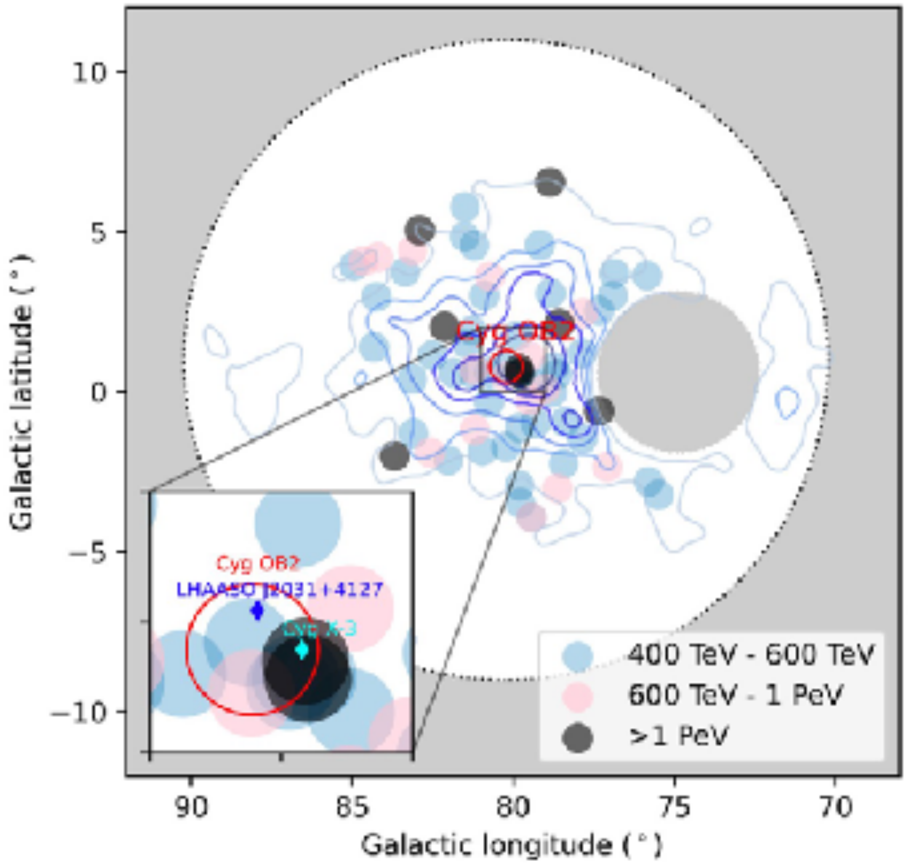
CR accelerators: Stellar Clusters

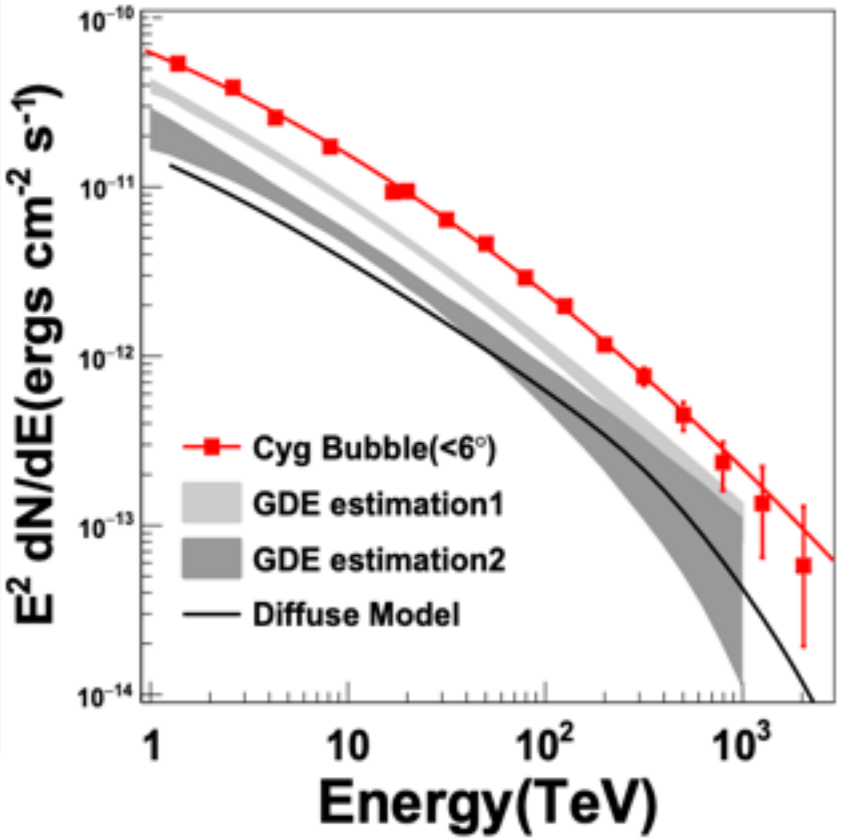
- Other accelerators - Old massive Stars (wind-wind, clusters, collective effects)
- Energy reservoir ~10^{38-39} erg over ages of T≥10^{6} years
- In the GeV range: huge structures covering few degree



- Knowing the target material, we can derive the CR image:
  - Planck free-free (HII) and CfA (CO) maps.
  - In the GeV range: huge structures covering few degrees

Cygnus Cocoon





- LHAASO measures >PeV emission coming from the Cygnus Cocoon region
- Claims a super-PeV acceleration in the region
- Unclear what is the origin of the accelerated particles

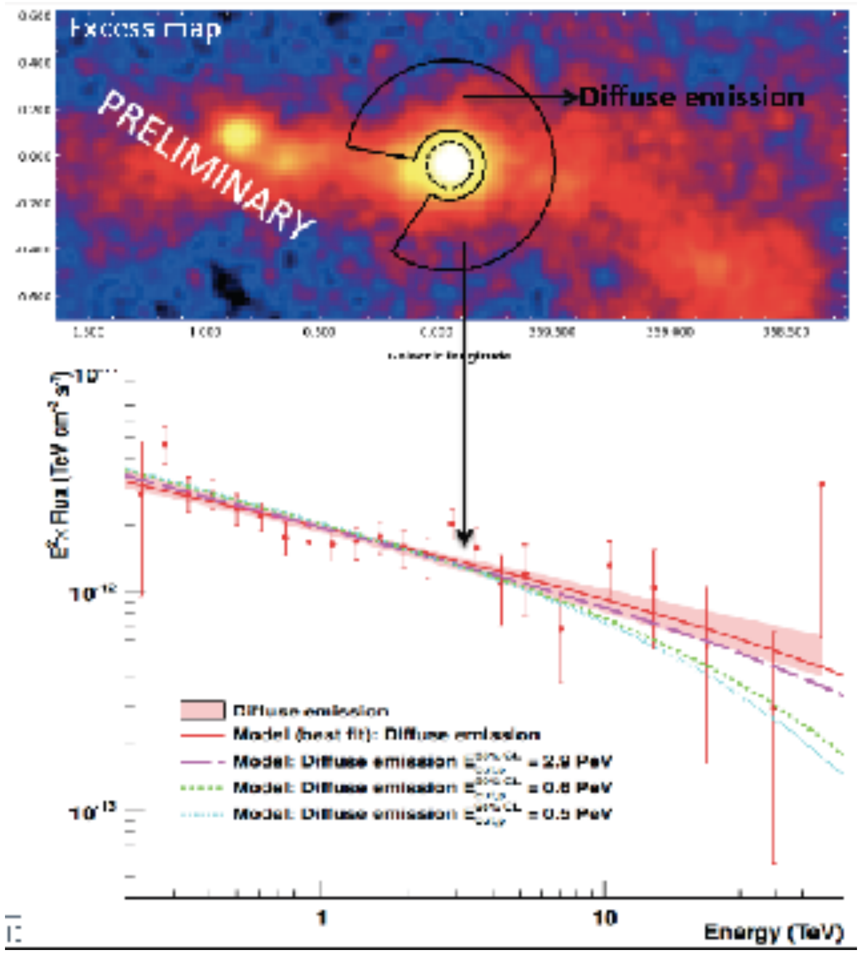
Galactic Center

Galactic center

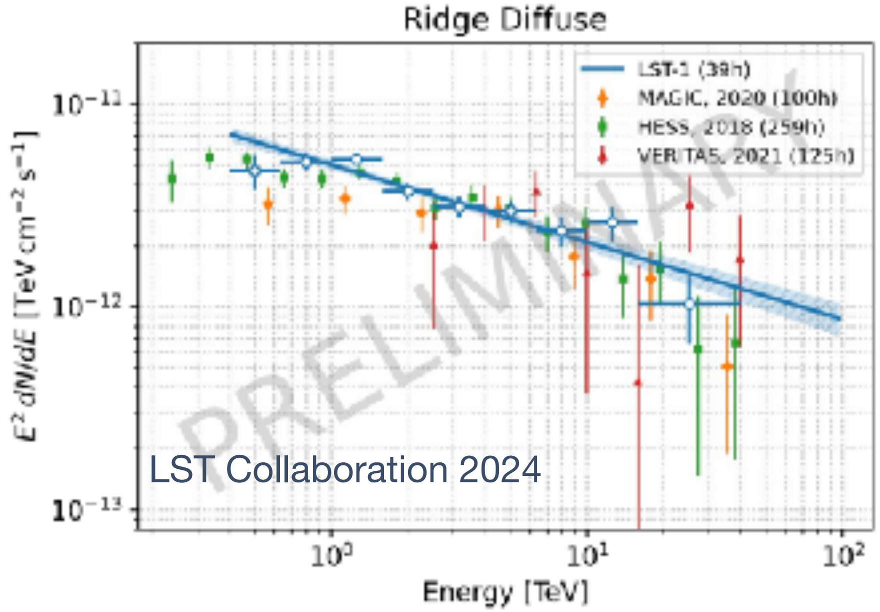
- Supermassive Black Hole at the center of the Milky Way (mass ~ 4 x 10^6 solar masses)

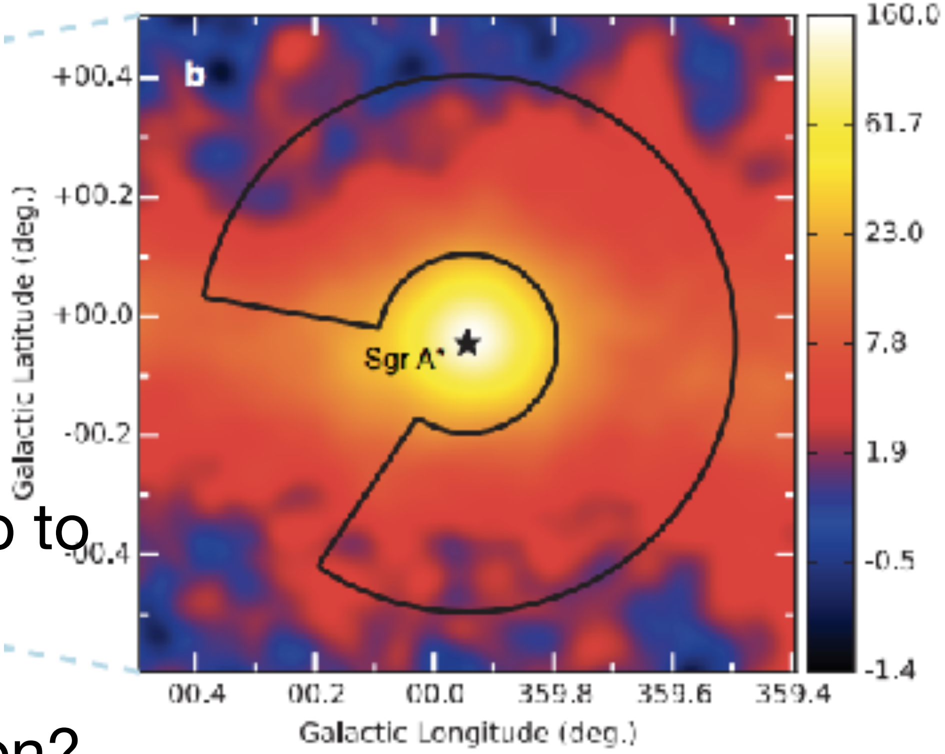
- VHE gamma rays measured above 40 TeV from diffuse emission

- Diffuse emission shows no cut-off
  - constant injection and diffusion for > 1 kyrs
  - emission likely due to propagation of protons from central black hole
  - parent proton population up to 1 PeV with a ~2σ significance: **first detection of a PeVatron**



PeV acceleration?

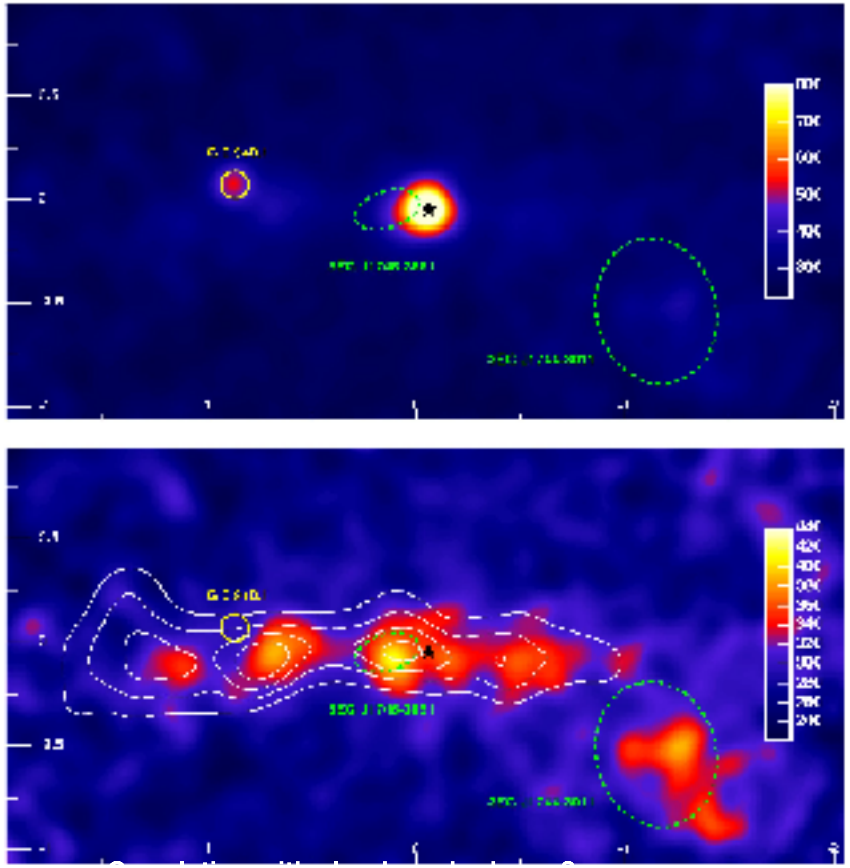




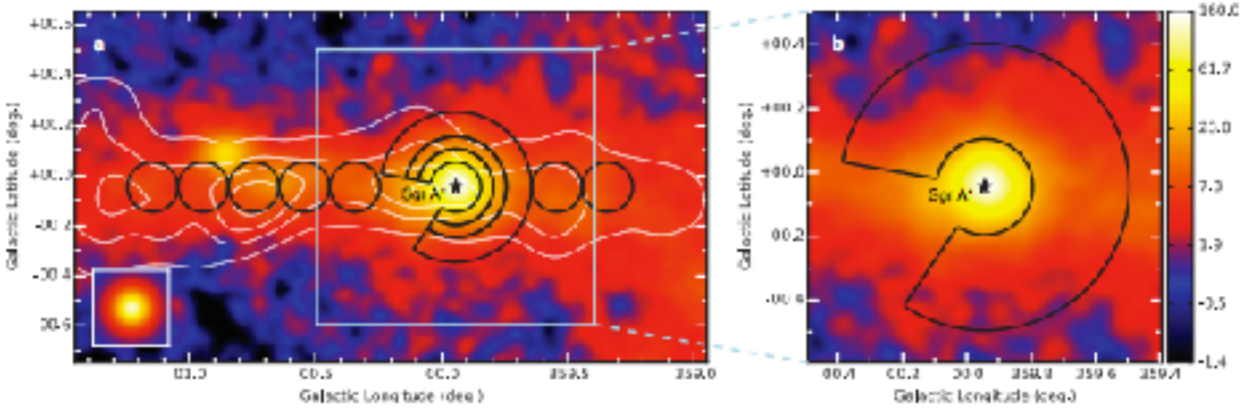
- Continuous injection of protons into CMZ up to PeV :
  - a PeVatron(s) within 10 pc of GC
- SMBC in GC (Sgr A*) operating as a PeVatron? or acceleration happening elsewhere?

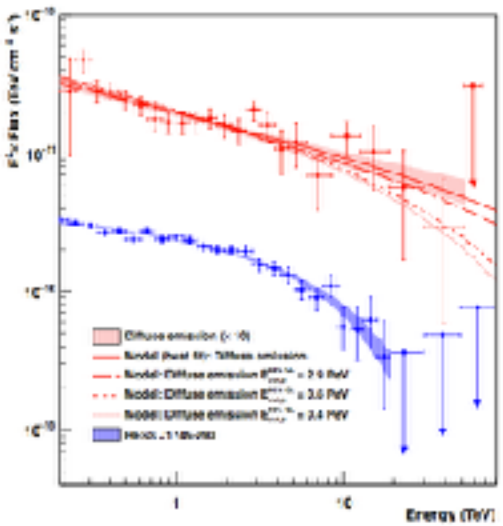
CR accelerators: Galactic Center

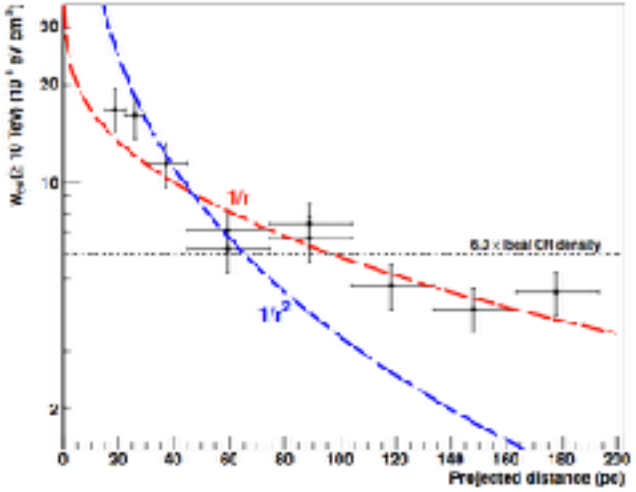
- In the TeV regime:



- Constant injection and diffusion for > 1 kyrs







CR accelerators: Galactic Center

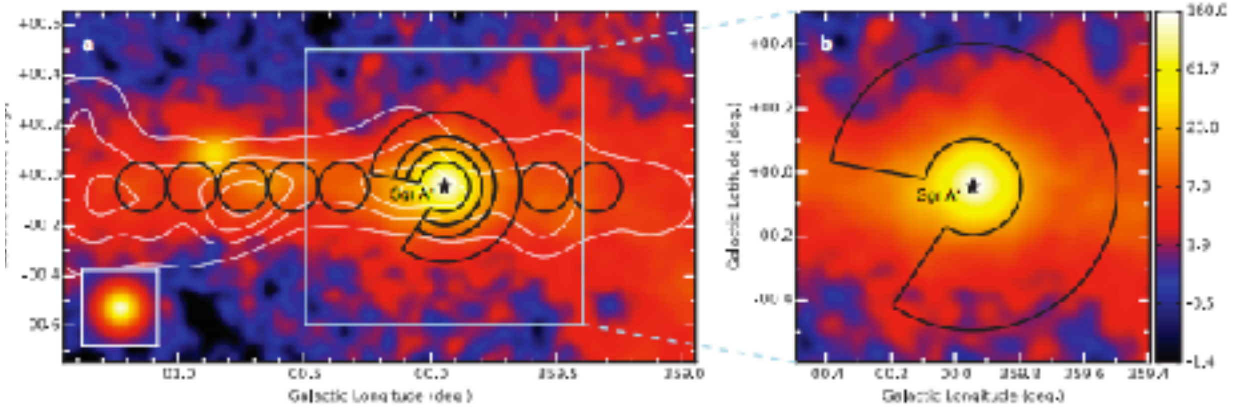
- Constant injection and diffusion for > 1 kyrs

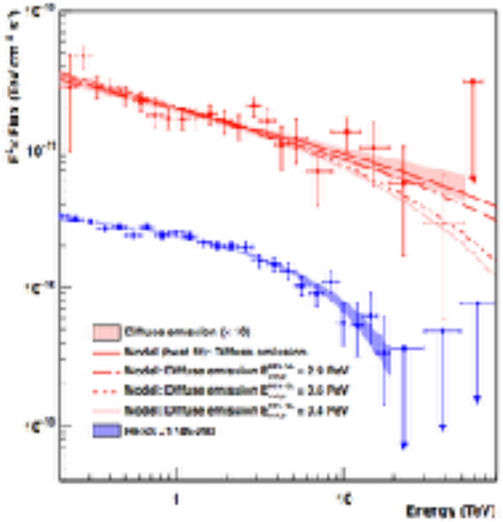
The injection time should be larger than the escape one:

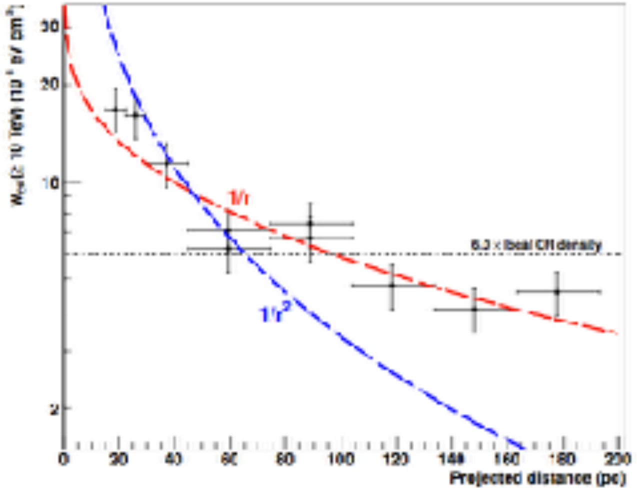
$$\Delta t \geq t_{\rm diff} \approx R^2/6D \approx 2 \times 10^3 (D/10^{30}\ {\rm cm^2 s^{-1}})^{-1}\ {\rm yr},$$

$$Q_{\rm p}(\geq 10\ {\rm TeV}) \approx 4 \times 10^{37} ({\rm D}/10^{30}\ {\rm cm^2 s^{-1}})\ {\rm erg/s}$$

Rather modest injection for thousands of years:
- Galactic center?
- Stellar clusters in the inner region?







VHEGA

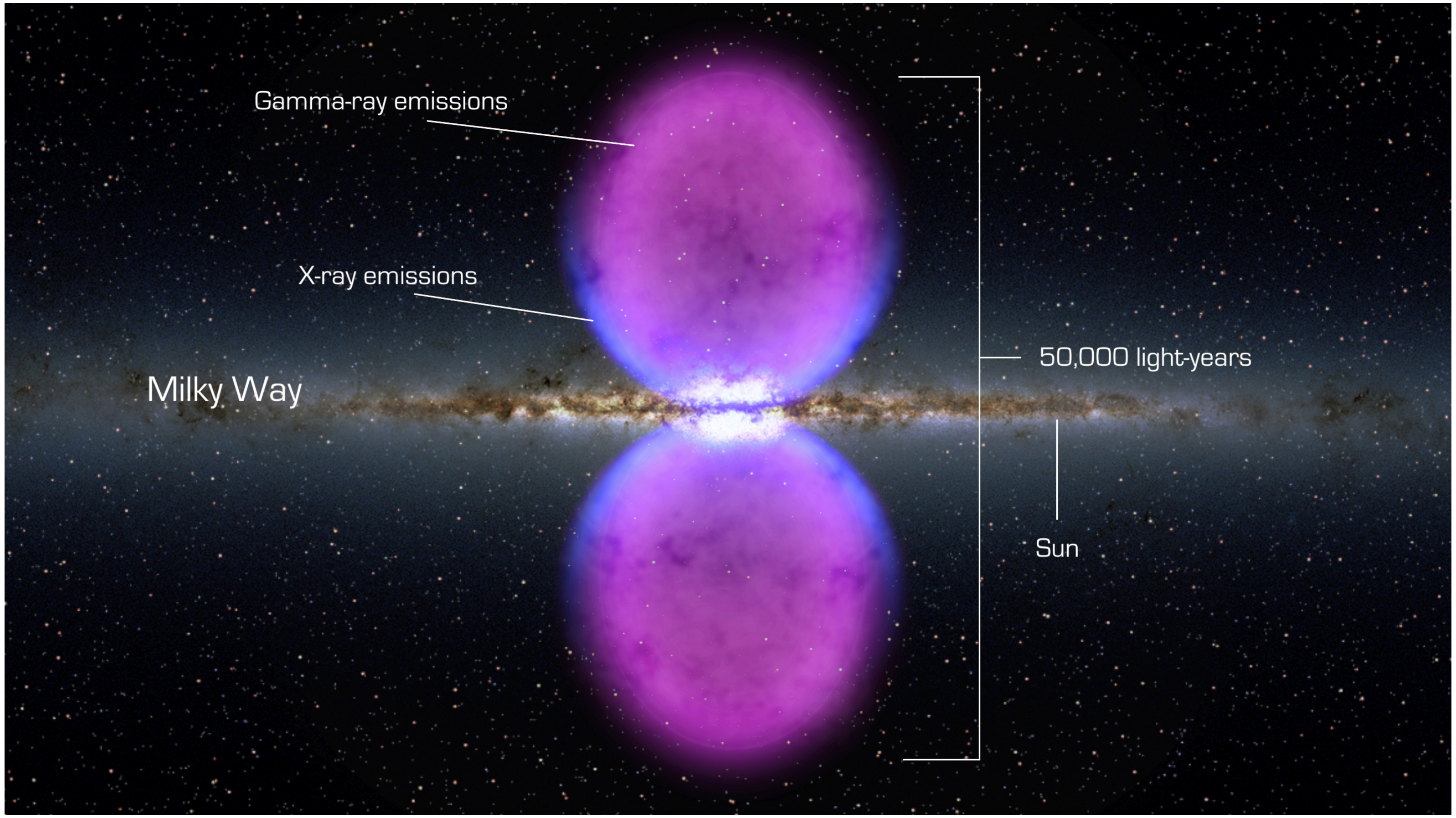
R. ... D

CR accelerators: Galactic Center

Fermi Bubbles

- **Energetics** - Outburst-like event /slow outflows
  - $E_{kin} = 3x10^{54}$ erg
    $L_{IR} \sim 1.6x10^{42}$ erg/s

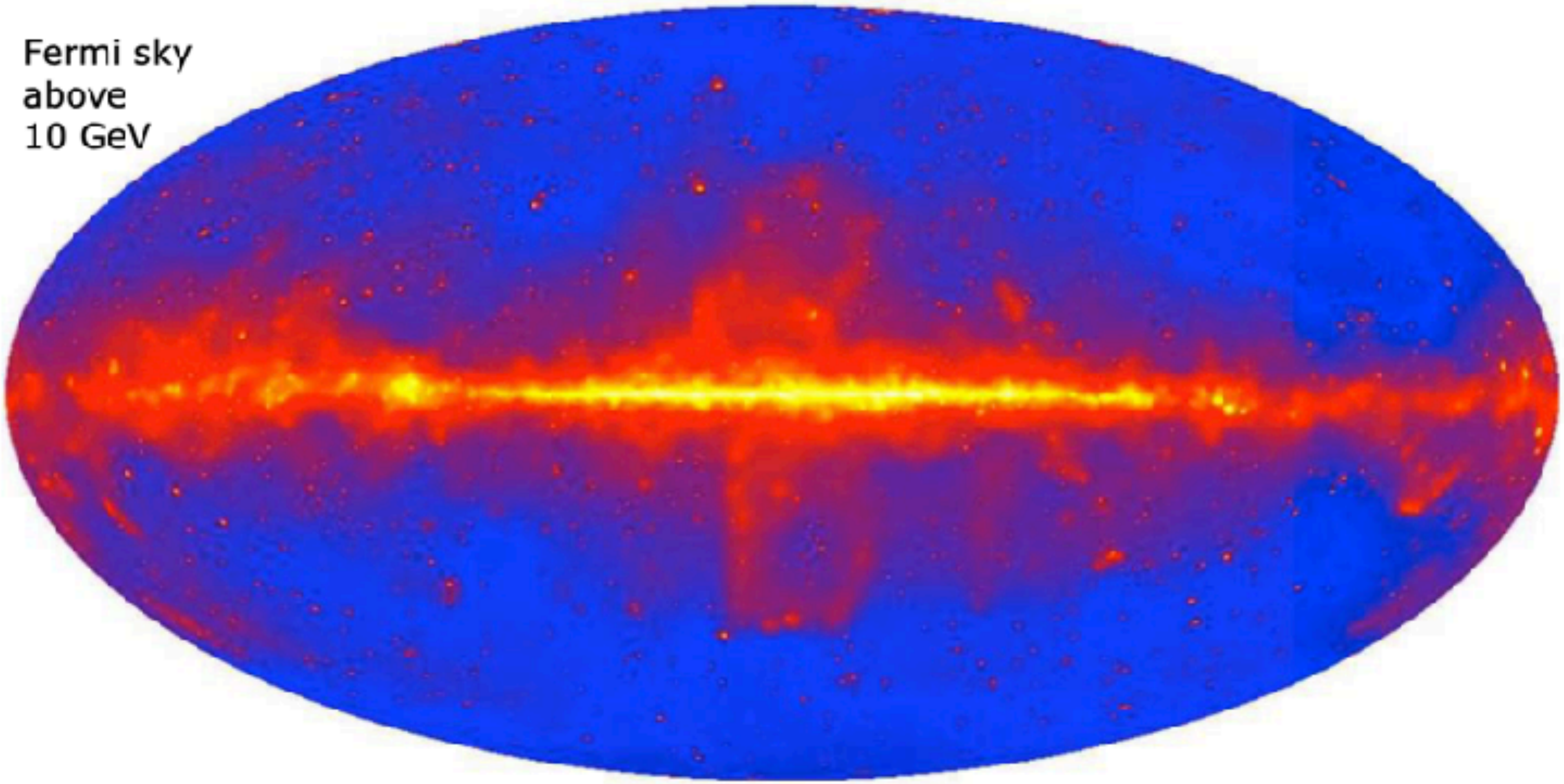
- Is there any indication of such behaviour?



CR accelerators: Galactic Center

- In the GeV regime:

Fermi Bubbles

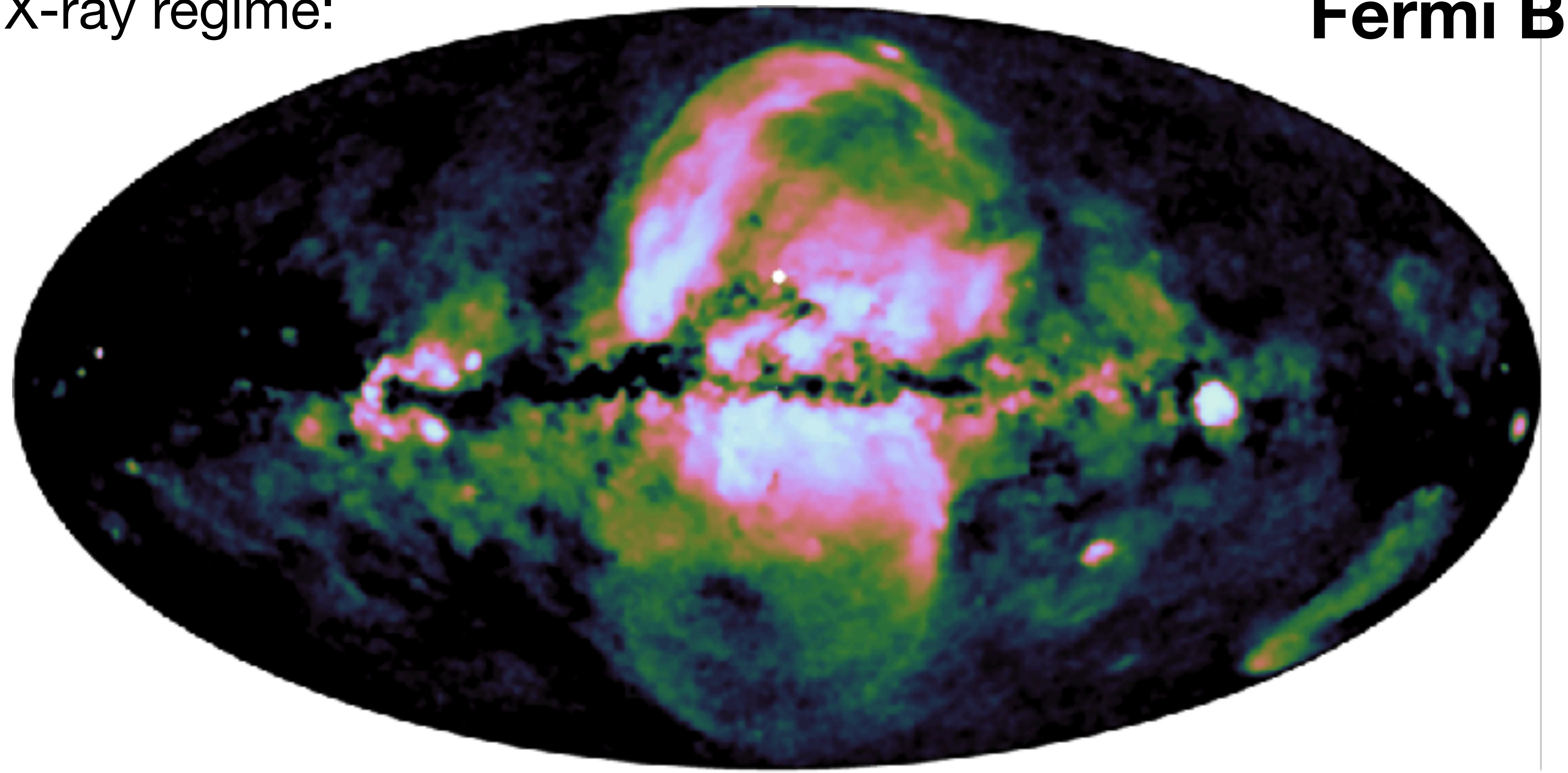


CR accelerators: Galactic Center

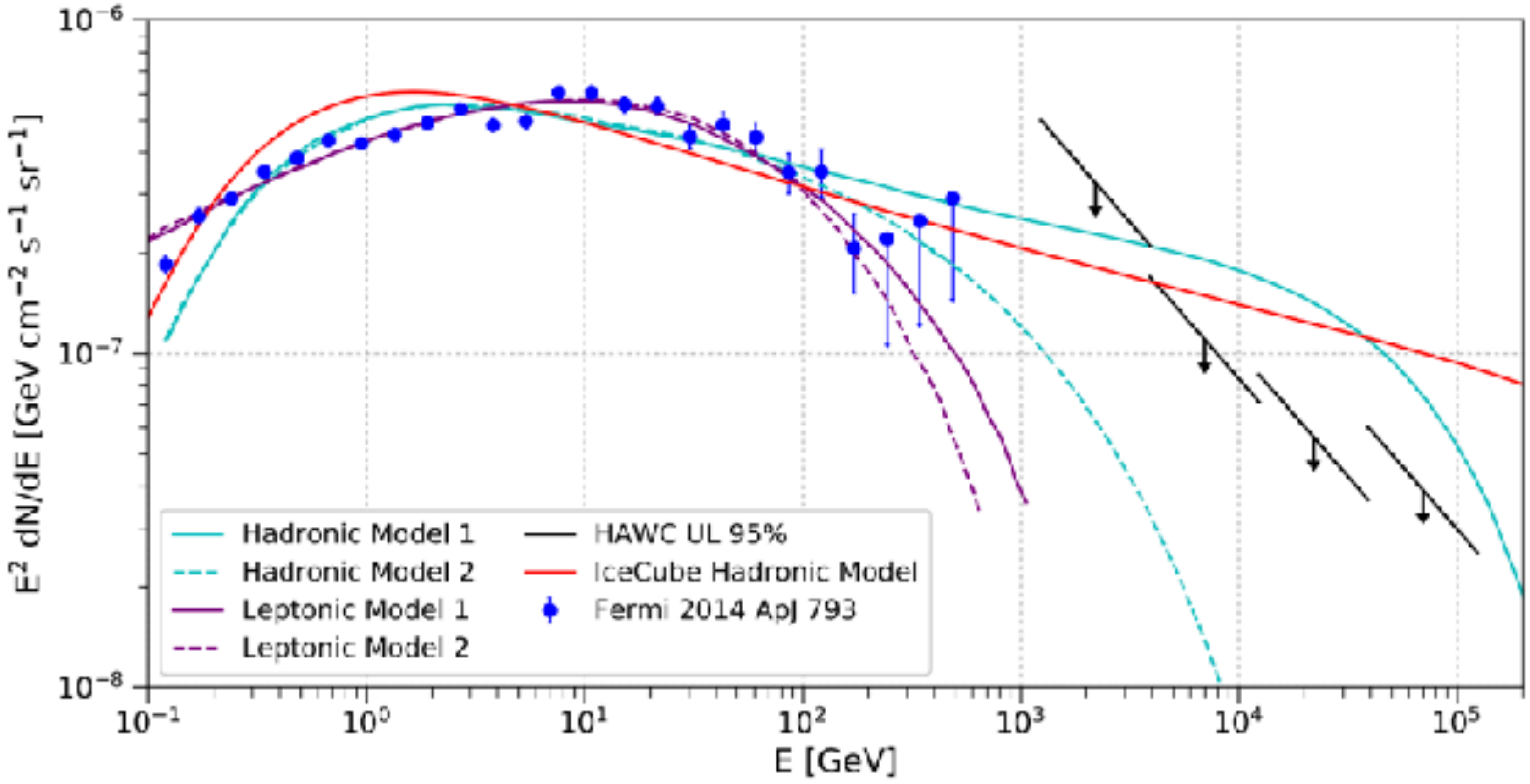
- In the X-ray regime:

eROSITA (0.6-1 keV)

Fermi Bubbles



CR accelerators: Galactic Center



- Fermi spectrum vs HAWC upper limits

Pulsars and their environments

What is the interest of these sources?

- Gamma rays: They are the most powerful steady (up to >PeV energies), nearby accelerators.
  - PWNe also constitute the most numerous population in the VHE.

- Cosmic rays: Primarily lepton accelerators.
  - Contribution to Galactic Cosmic ray fluxes.
  - Only confirmed PeVatron up to now was the Crab Nebula => are all extreme accelerators in the Milky Way leptonic?

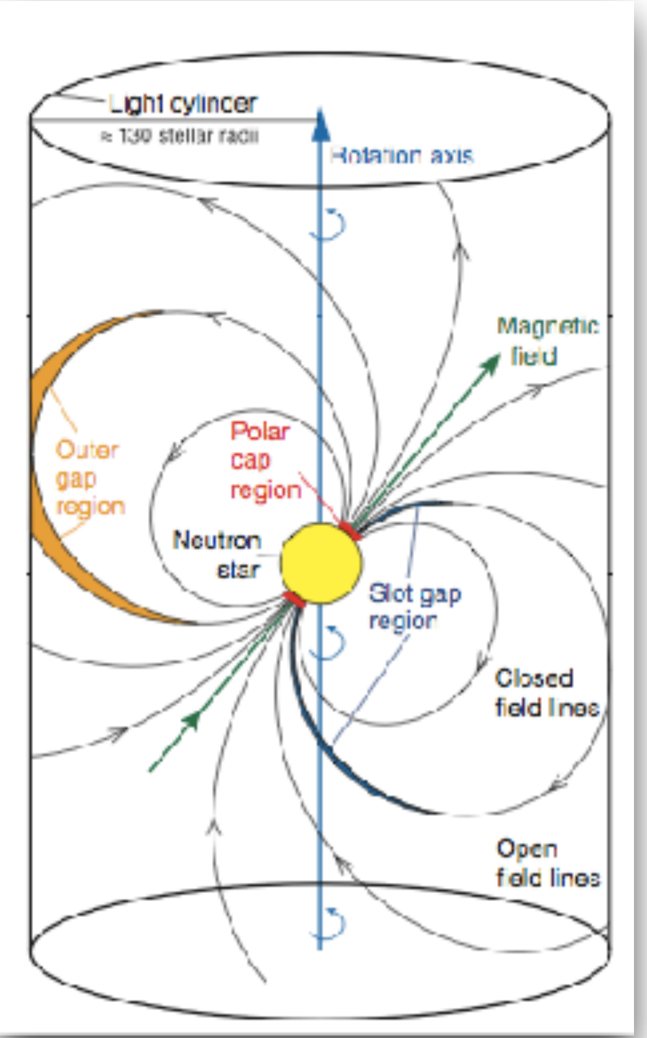
- Pulsar Physics: PWNe enclose most of the energy released by a pulsar.

- Plasma Physics: They last thousands of years, providing clues about historical evolution of radiative plasma and transport of particles/fields.
  - In comparison with other sources of relativistic magnetised plasma, PWNe can be resolved in great detail and shine in almost all wavelengths

- Surprises: PWN flares! -> efficient & rapid particle acceleration.

Neutron stars

- Rapidly rotating highly magnetized stars composed by neutrons.
- If the primary source of emission is the rotational energy, they are known as **pulsars**.
- We detect pulsed emission ranging from radio to VHE gamma rays.
- $e^{\pm}$ plasma fills the magnetosphere and co-rotates with the pulsar.



Neutron stars

- Rapidly rota
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- If the primar
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- We detect p   b
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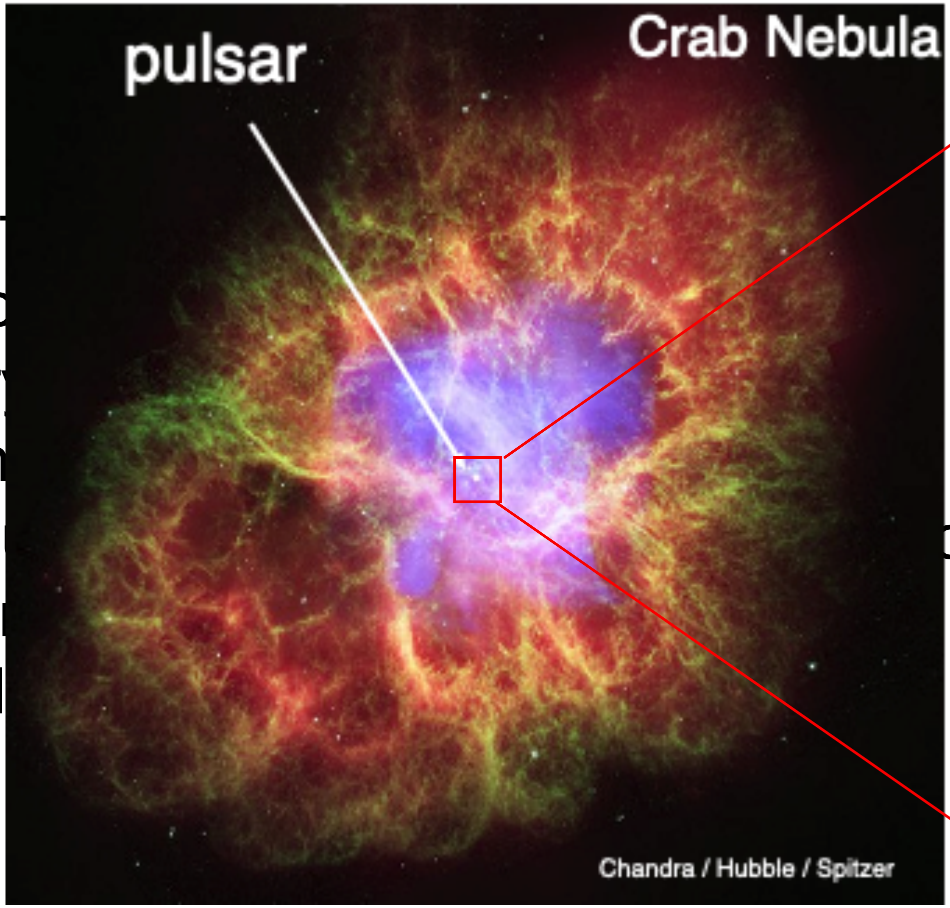
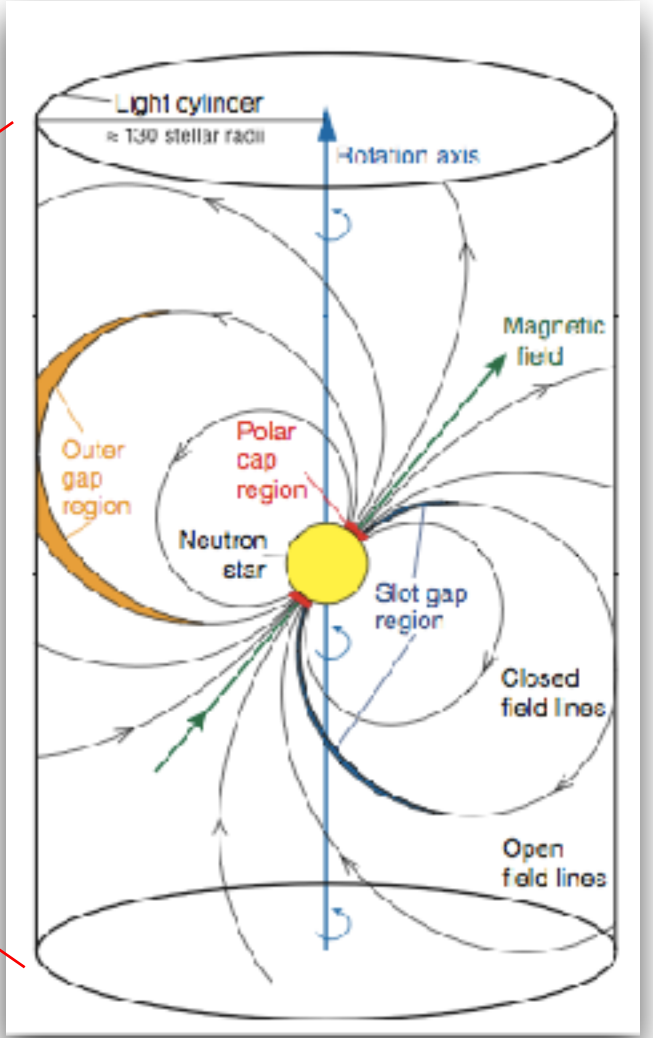
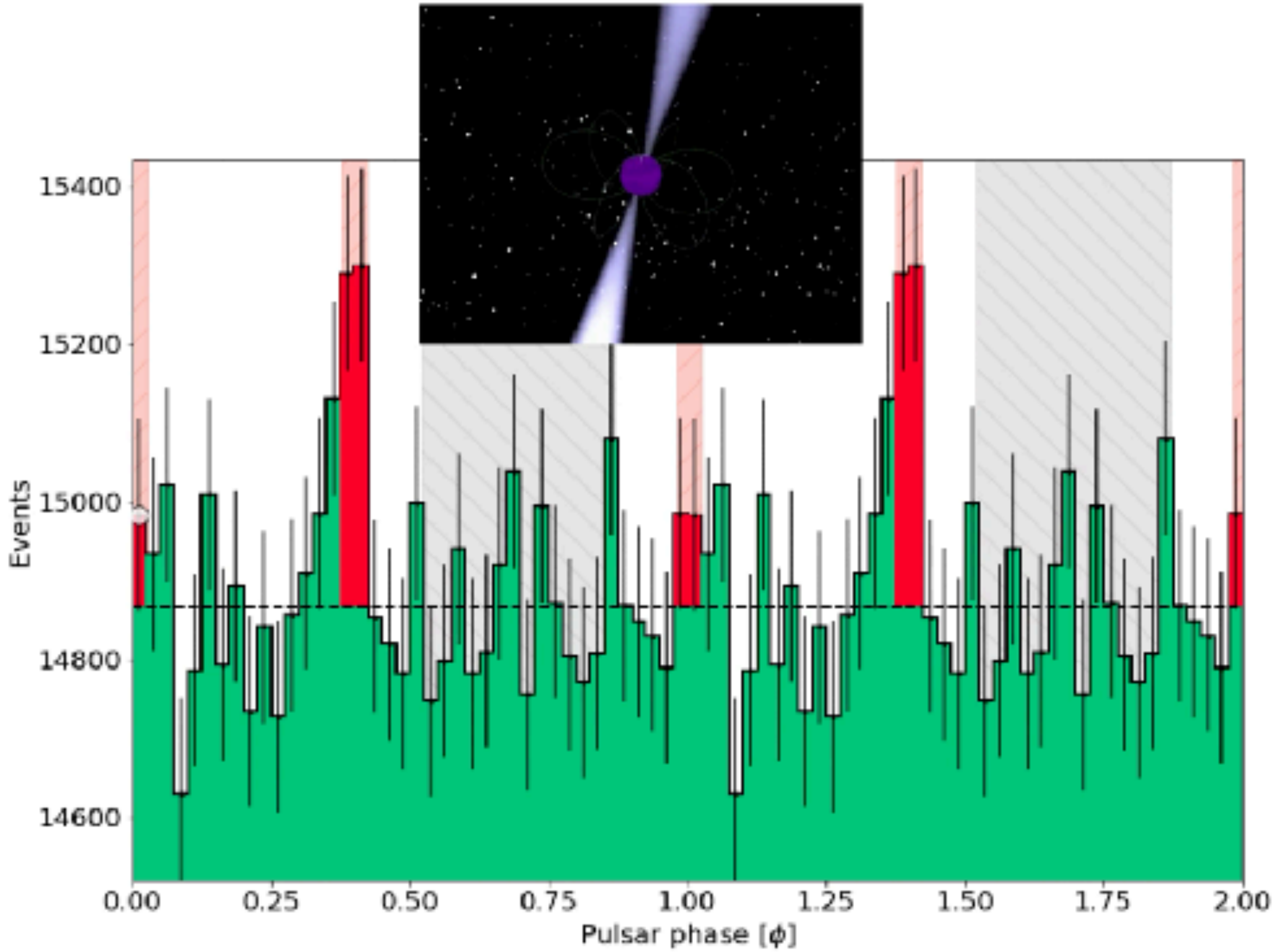




A pulsar is like a lighthouse!

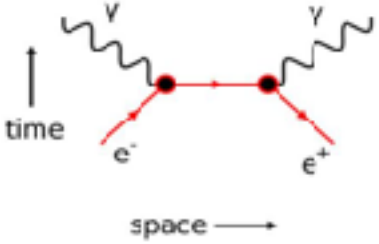


Phaseogram of the Crab pulsar as seen by the Large-Sized Telescope of CTA:
https://www.cta-observatory.org/lst1-detects-vhe-emission-from-crab-pulsar/

High energy radiation from pulsars

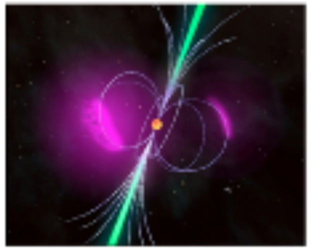
Energy source

Acceleration mechanism

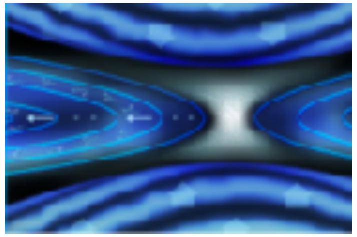


γ-ray production mechanism

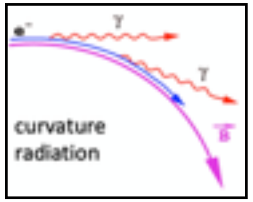
γ rays

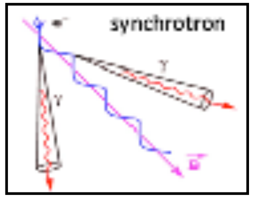


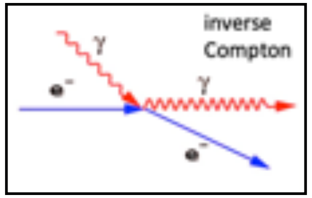
Pulsars

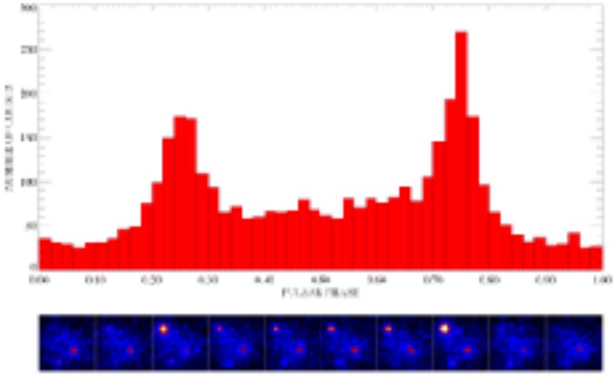


Rotating B-field
Magnetic reconnection
Poynting fluxes

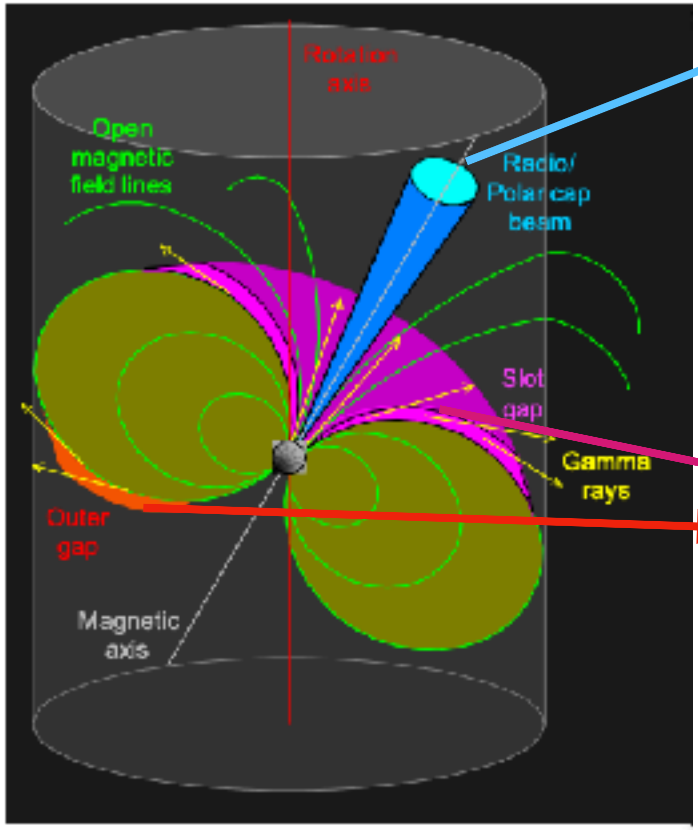








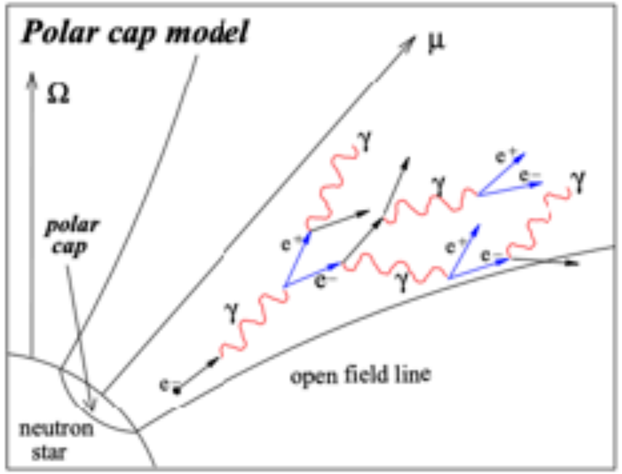
High energy radiation from pulsars

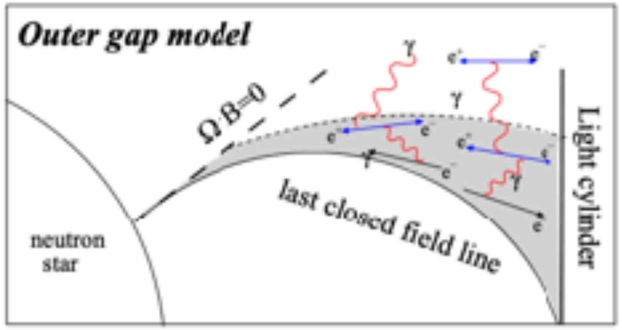


[Many !]

Super-exponential cutoff (magnetic absorption)

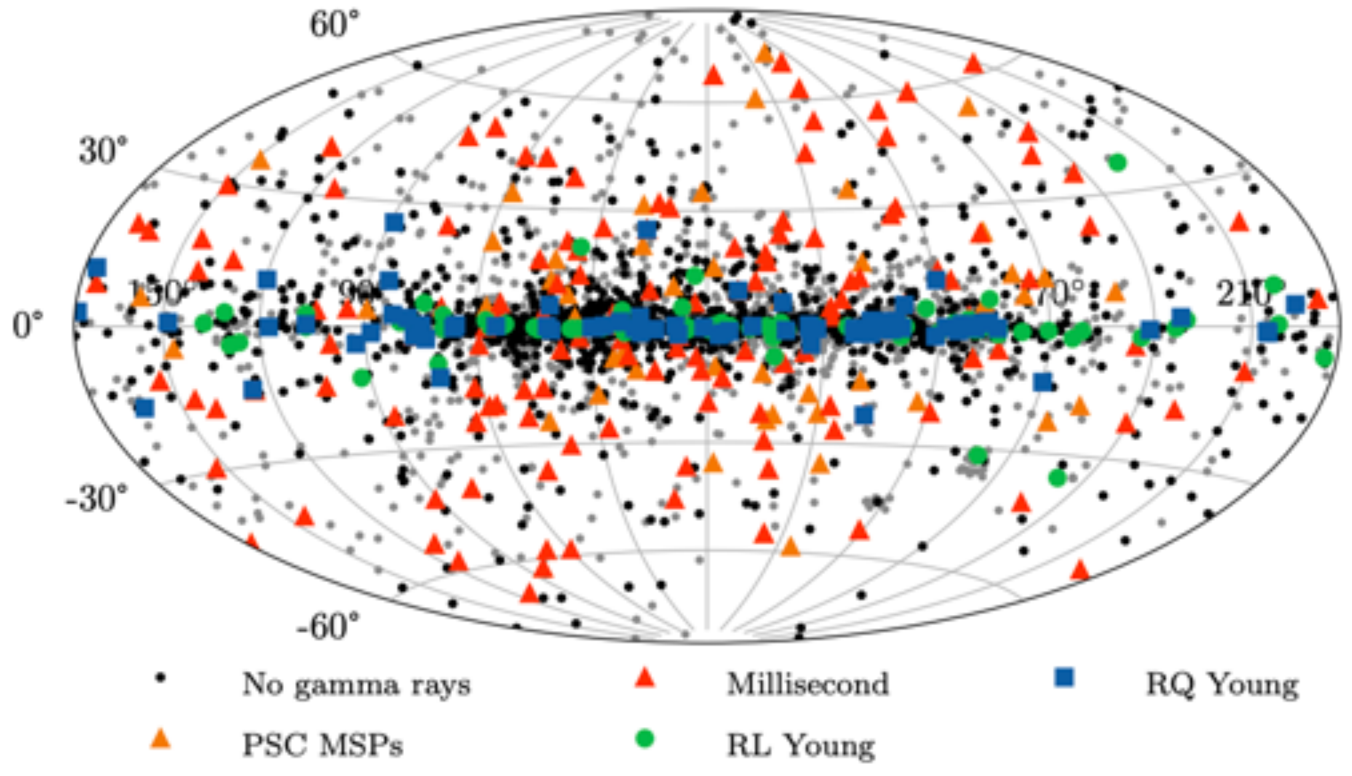
Exponential cutoff (photon-photon absorption)

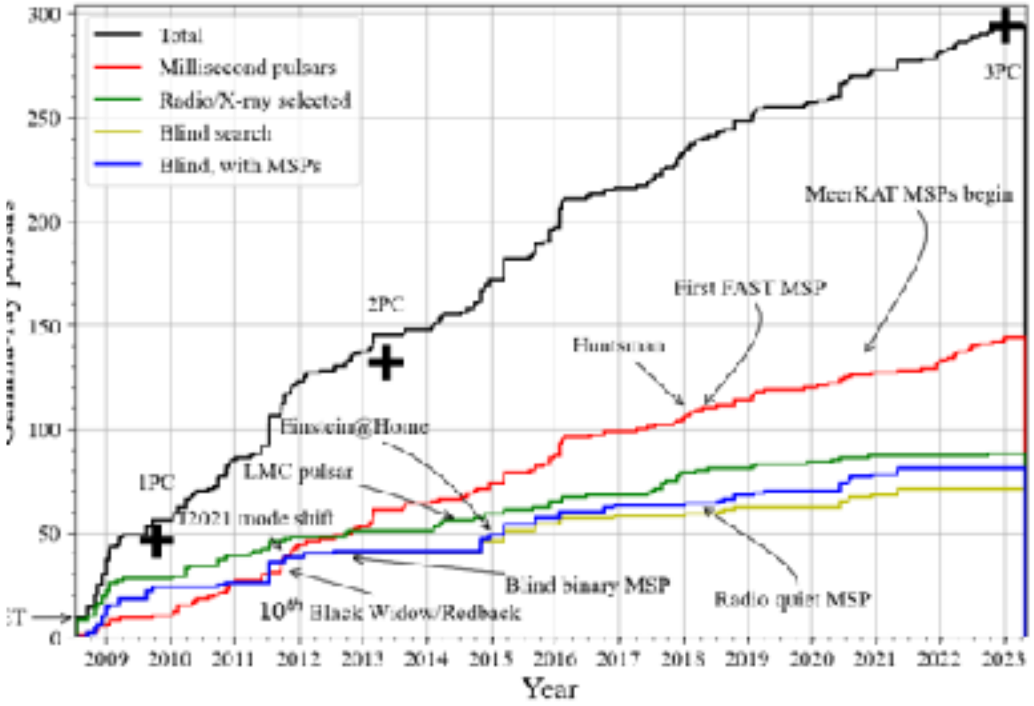




Compact objects: GeV and TeV Pulsars

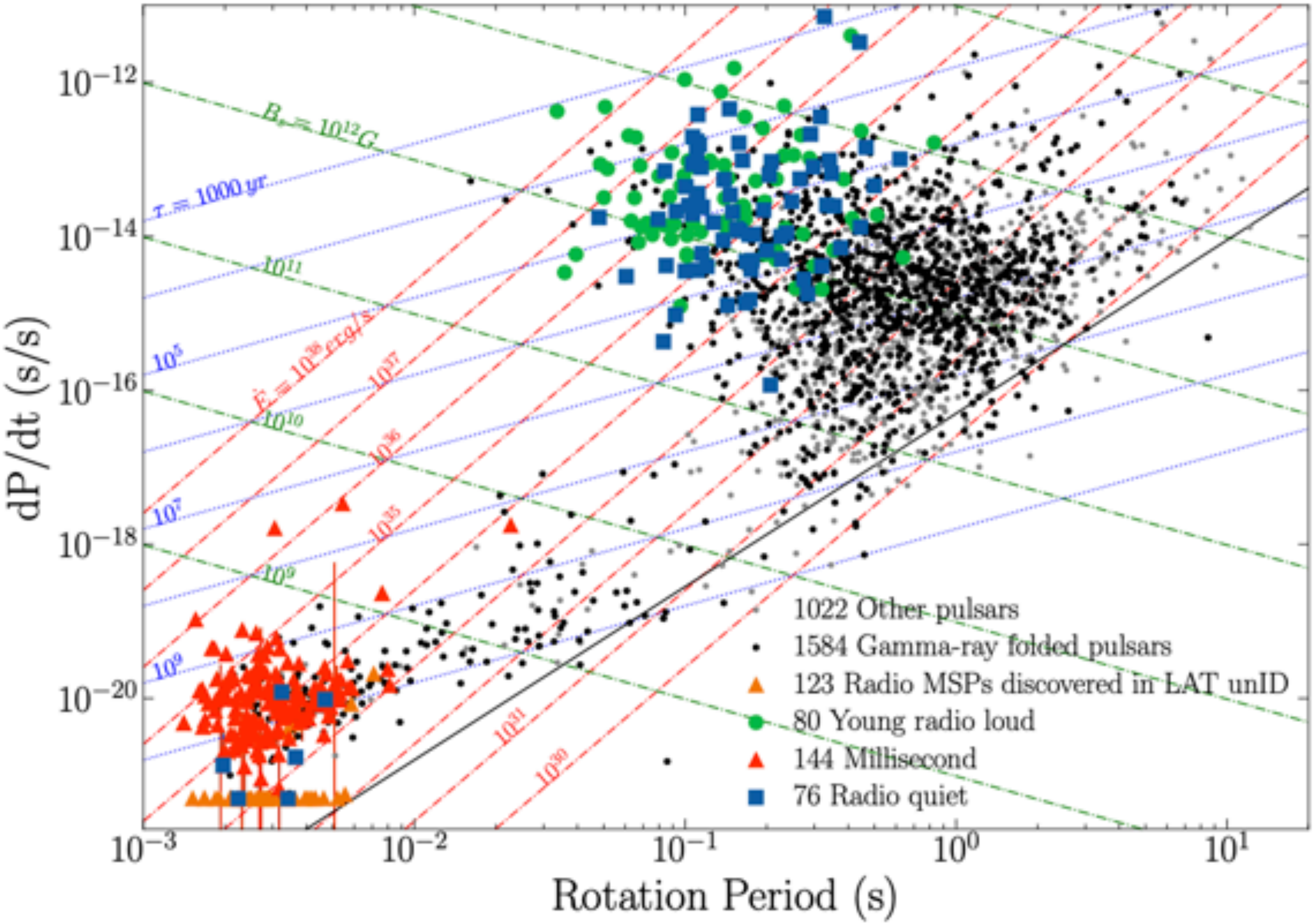
- Many pulsars (>300) identified at GeV energies
- Only a few (4(?)) by imaging atmospheric Cherenkov telescopes



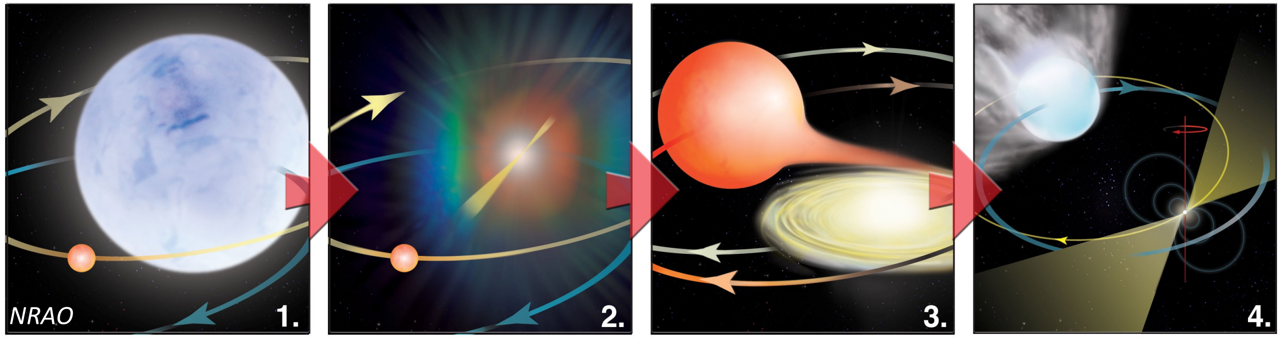


Compact objects: GeV and TeV Pulsars

- P - Pdot diagram
- Most pulsars are "**young**"
  - Their emission is powered by their rotational energy
  - they have not been reaccelerated/recycled

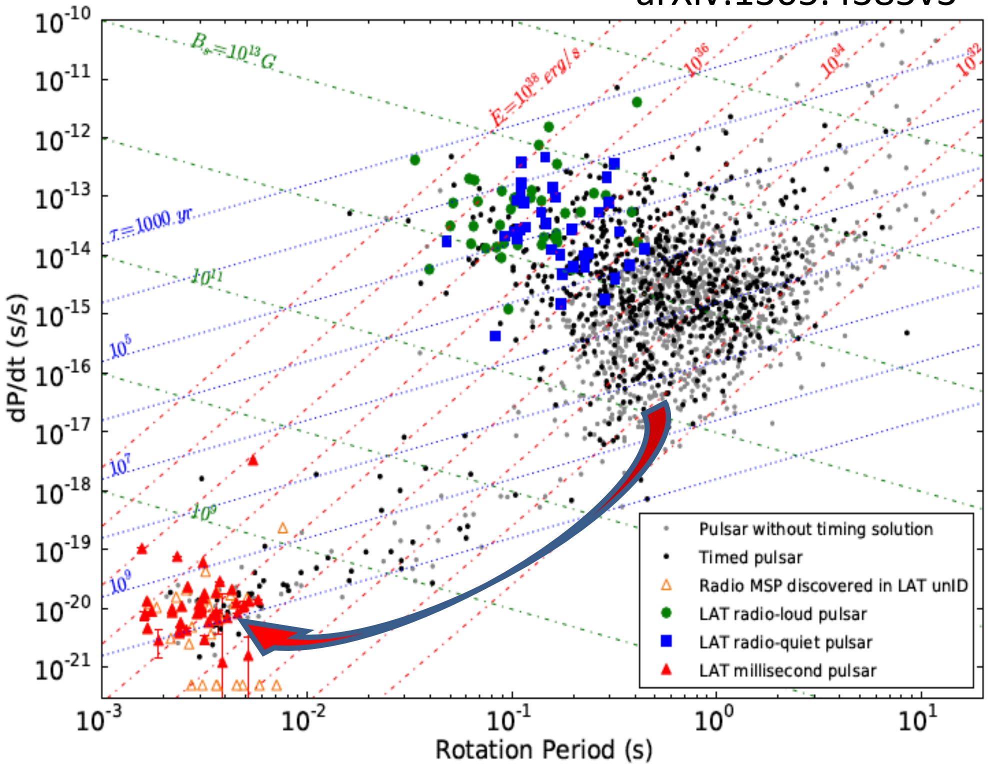


Millisecond pulsars



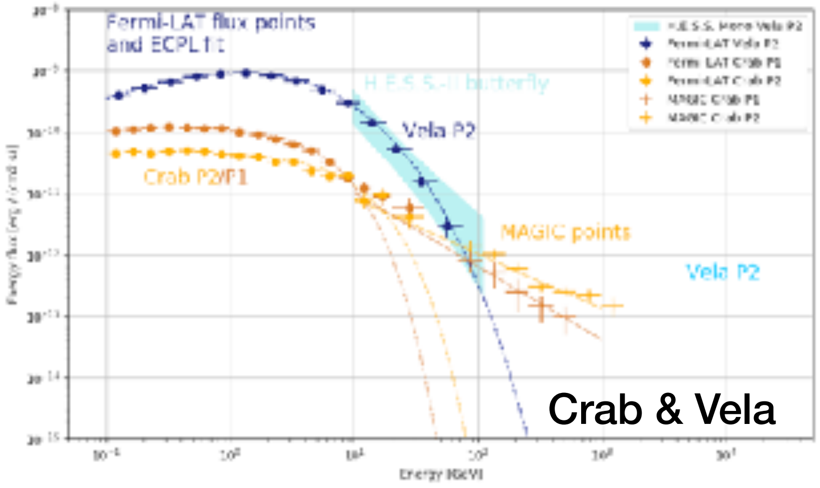
- Very old pulsars *recycled* through accretion from a companion star (leading to a gain of angular momentum)
- Often found in globular clusters (since they are old and dense)

arXiv:1305.4385v3

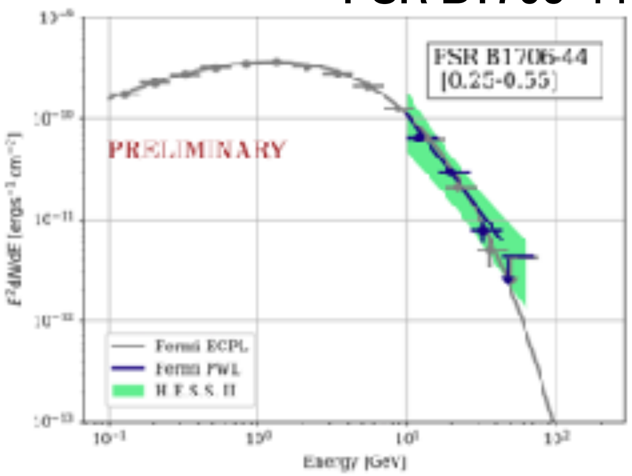


VHE gamma-ray radiation from pulsars

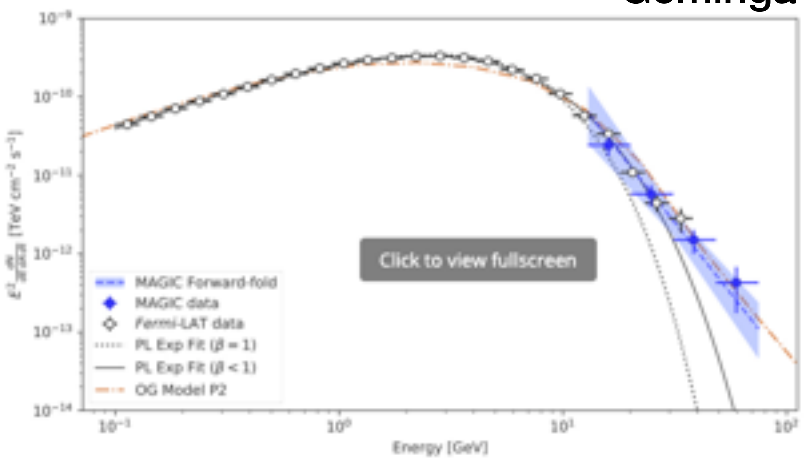
- Comparison of the different pulsars detected at VHE



PSR B1706-44



Geminga

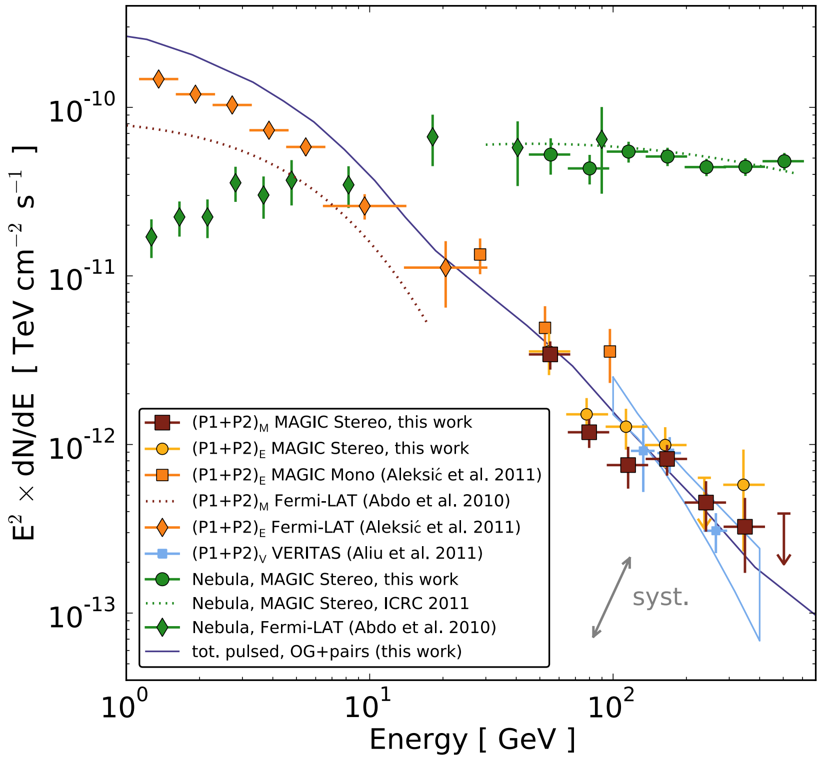


Young, bright GeV pulsar (~10^3 yrs)
High magnetic field (~5x10^{6-9} G @ LC)
Large low-energy photon field (FIR)
Simultaneous light curve across the em spectrum

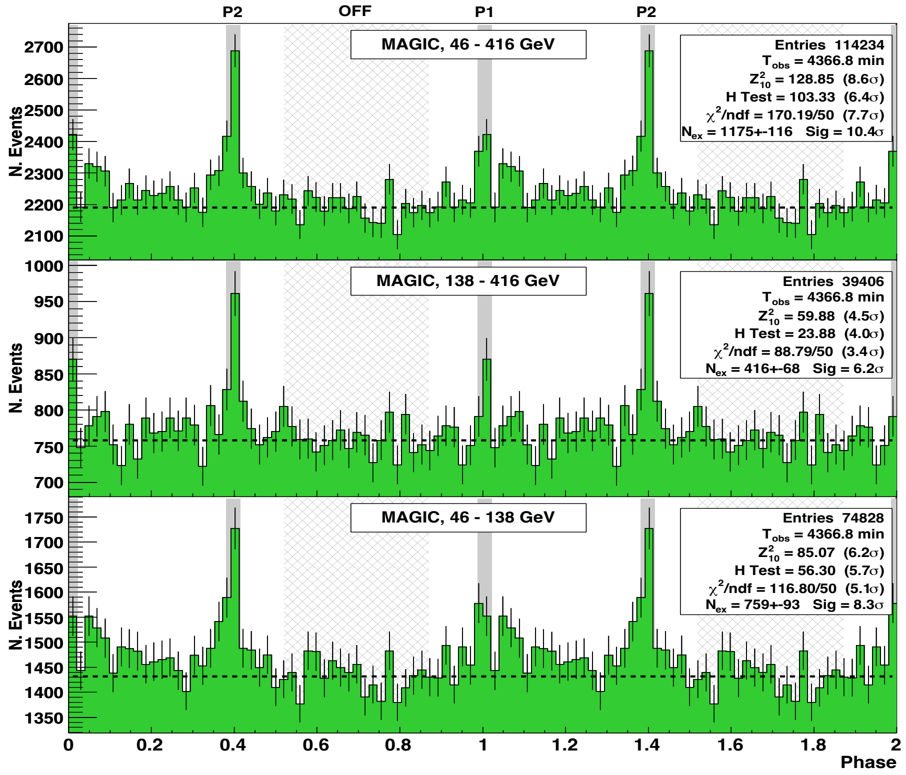
Old, bright GeV pulsar (~10^4-10^5 yrs)
Low(er) magnetic field (~5x10^5 G @LC)
Large low-energy photon field (FIR)

Crab Pulsar

- MAGIC discovered pulsed gamma-ray emission above 25 GeV (Science, 2008, 322, 1221).



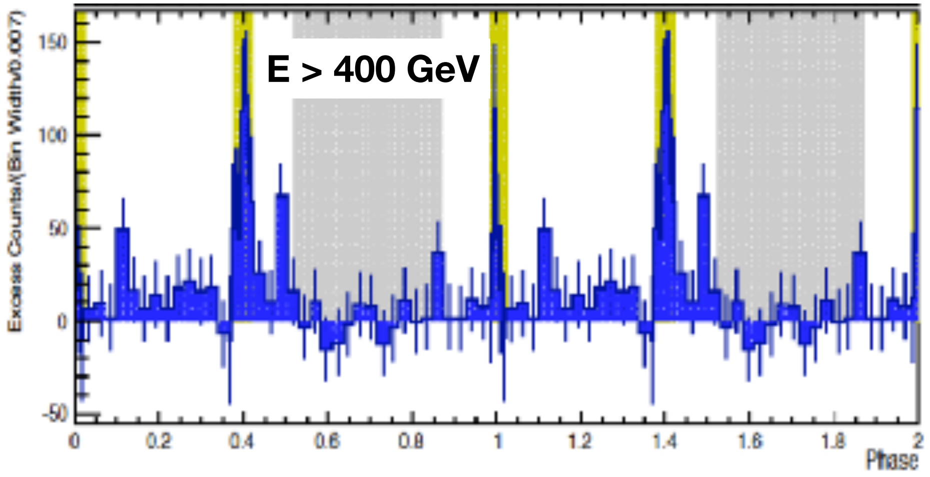
J. Aleksić et al. (MAGIC Coll.), A&A. 540 (2012) 69

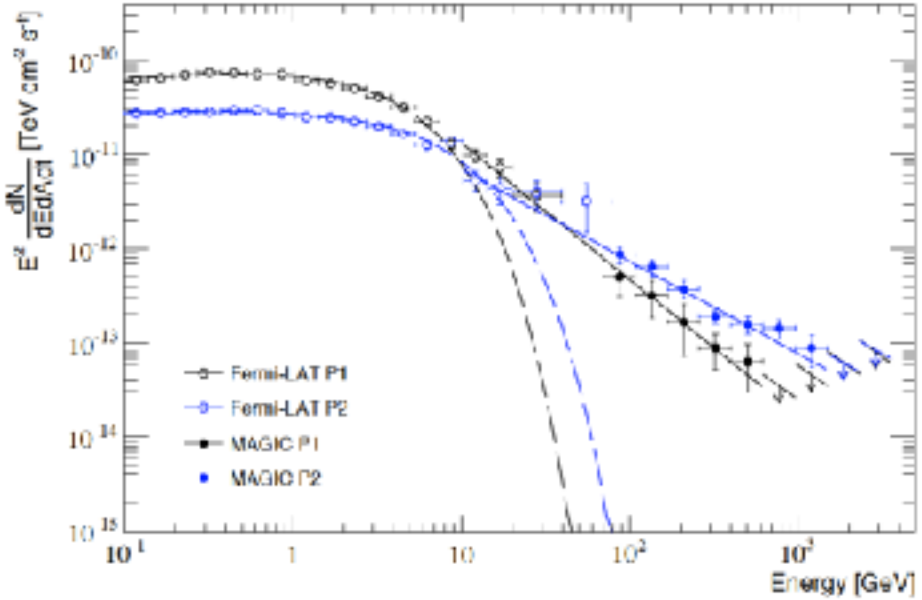


- VERITAS detected this emission above 100 GeV (Science, 2011, 334, 69)
- MAGIC extended the spectrum up to 400 GeV (A&A, 2012, 540, 69) and separately measured the spectrum of P1 and P2.

Highest energy pulsations

- Extension of the spectrum of the pulsed signal up to TeV energies

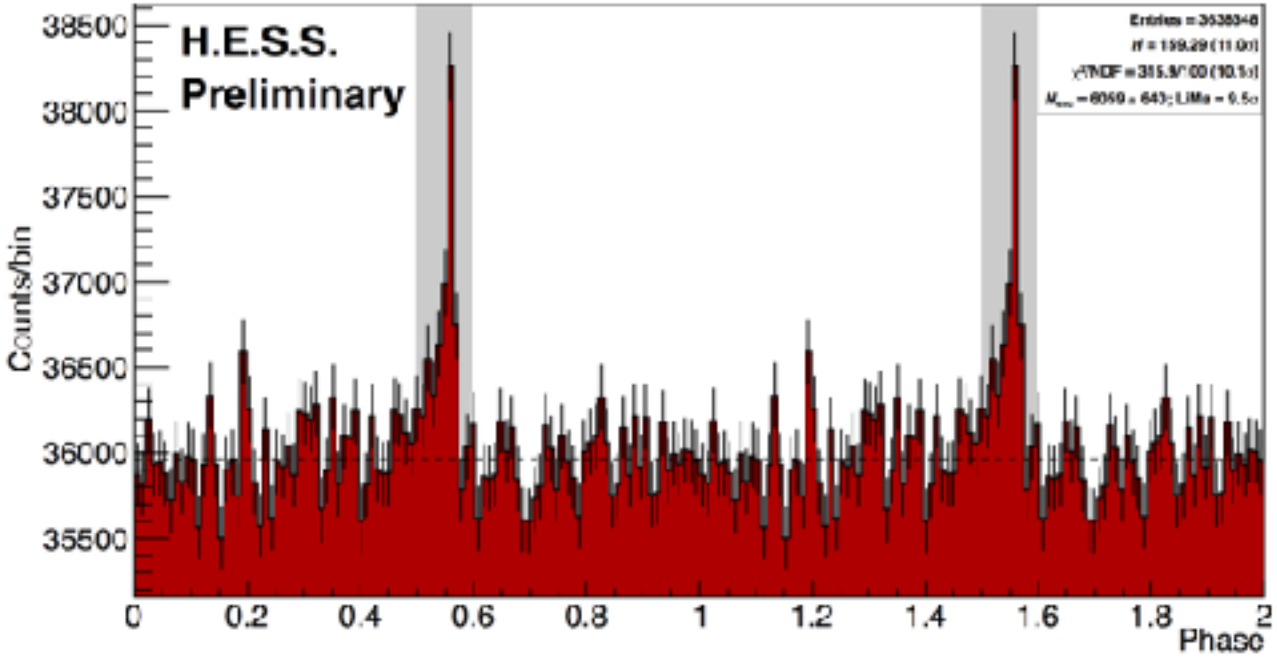




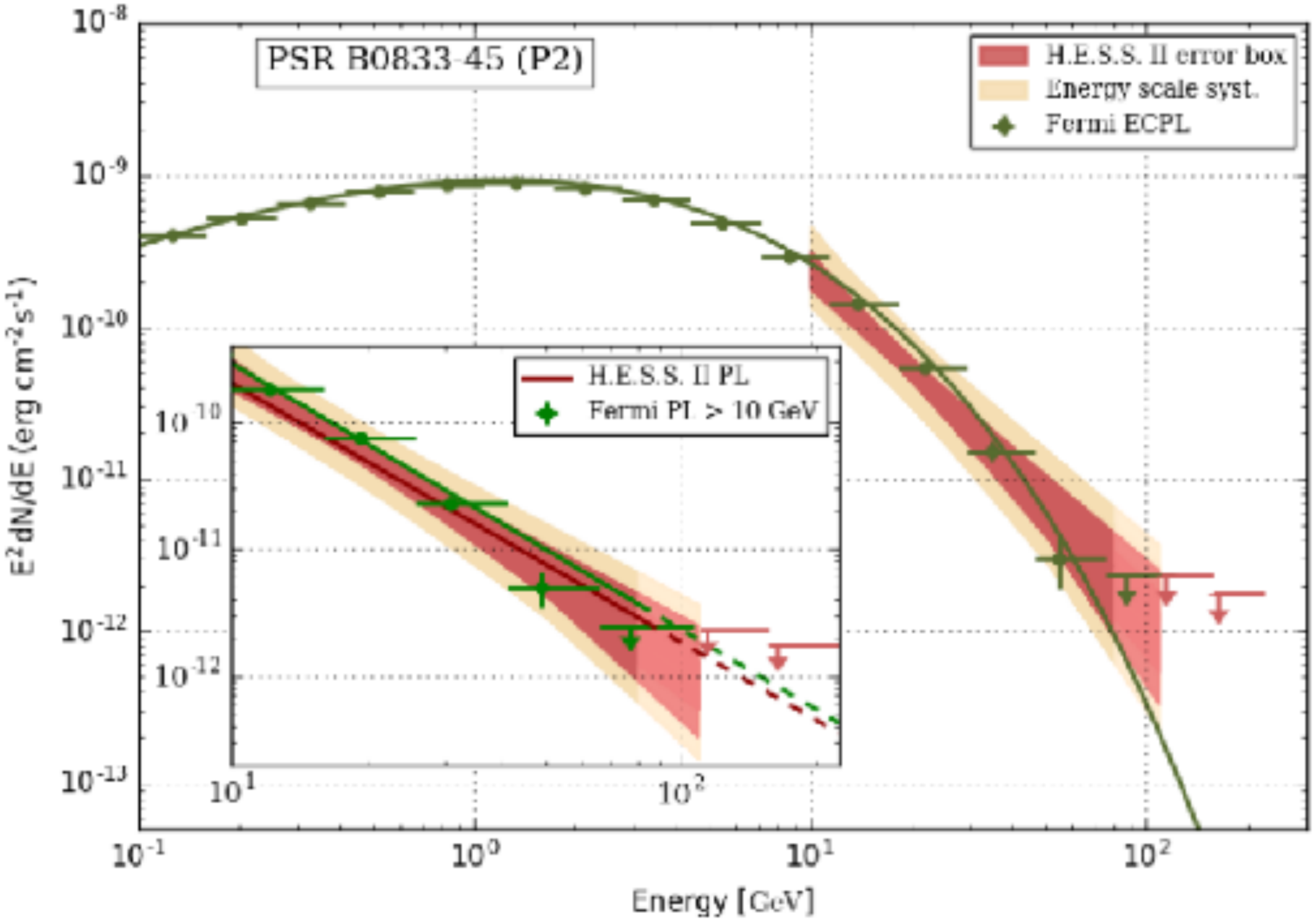
- Challenging all the currently existing models!
- No explanation for the spectrum+pulse profile

Vela: The second pulsar at VHE

- Second VHE γ-ray pulsar detected
- Deep observation campaign currently performed to unveil the maximum energies reached by the pulsed emission

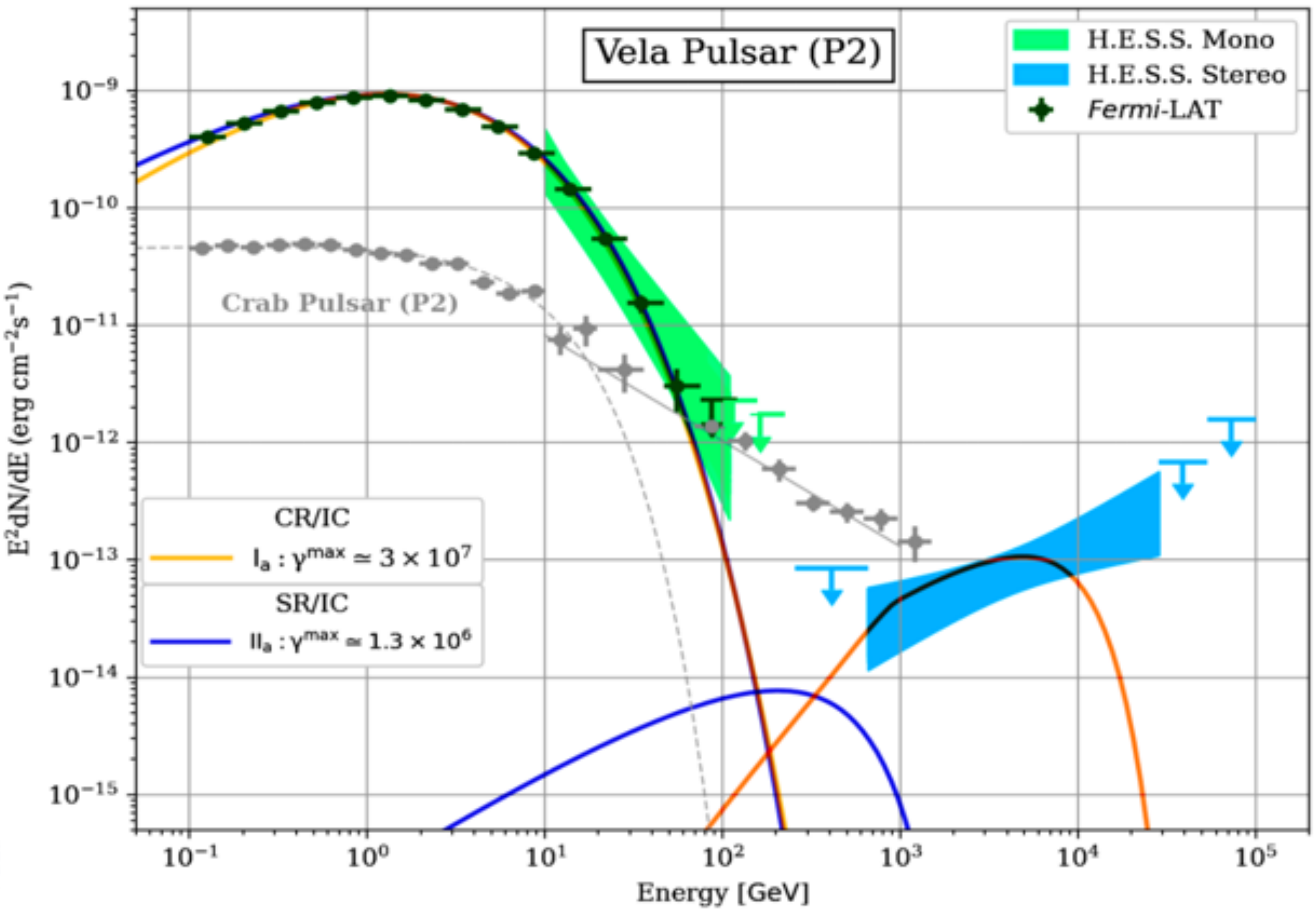


Vela: The second pulsar at VHE



- Spectrum measured between ~10-100 GeV
- Power-law continuation of the Fermi spectrum?

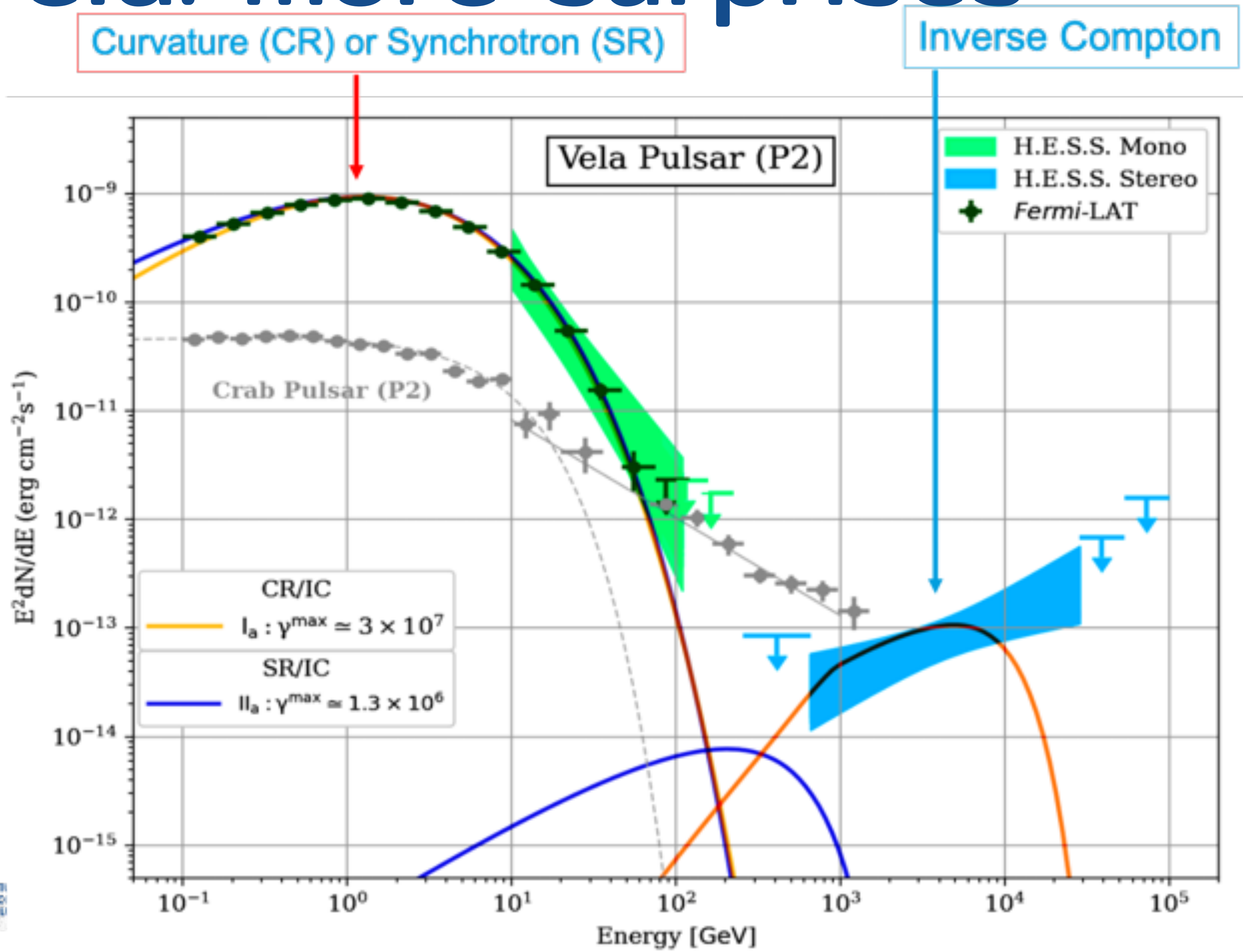
Vela: more surprises



Multi-TeV pulsed emission reaching 20 TeV (!)

Second component different from the lower energy one.

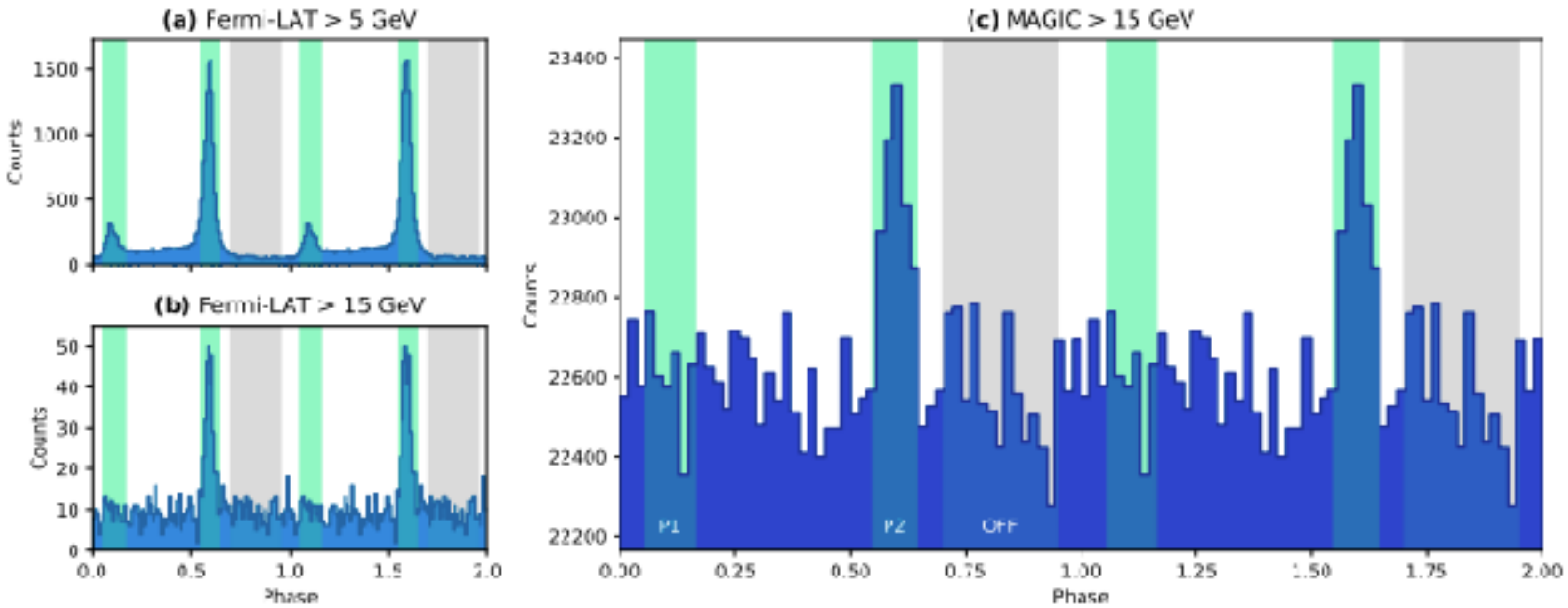
Vela: more surprises



Multi-TeV pulsed emission reaching 20 TeV (!)

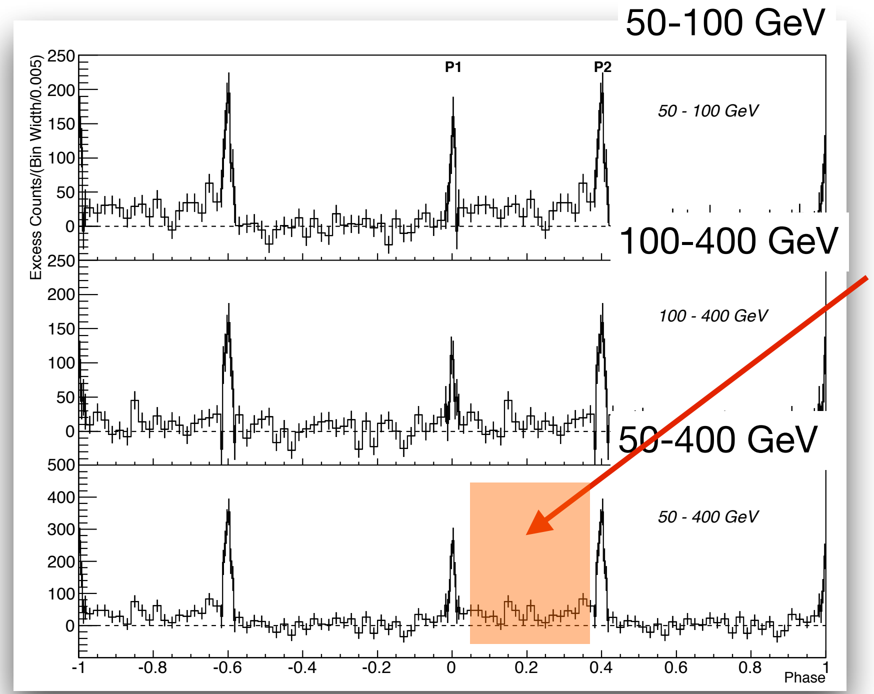
Second component different from the lower energy one.

Geminga pulsar

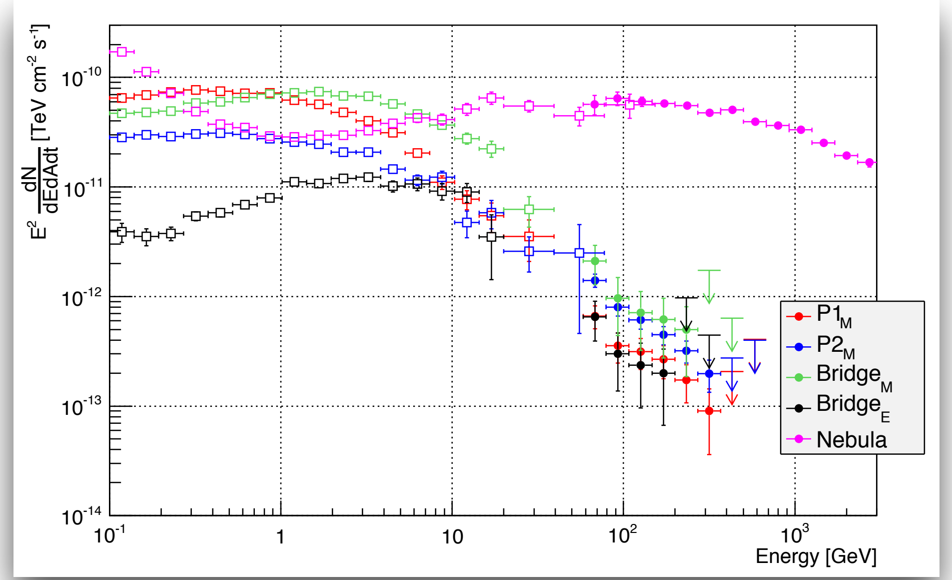


- 3rd pulsar measured by an IACT
  - Detection between 15 and 80 GeV.
  - P2 detected with significance > 6 sigma.
  - First middle-age pulsar (age ~ 300 kyr) detected to emit at such high energies.

Crab Bridge emission



- MAGIC discovered VHE emission from the bridge region between the two peaks extending beyond 100 GeV



- The bridge emission was detected with a significance above 6 σ for energies above 50 GeV

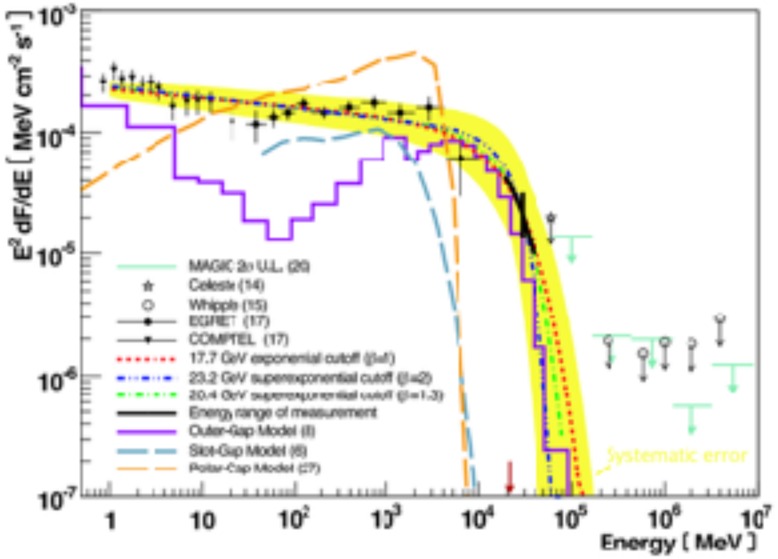
High energy radiation from pulsars

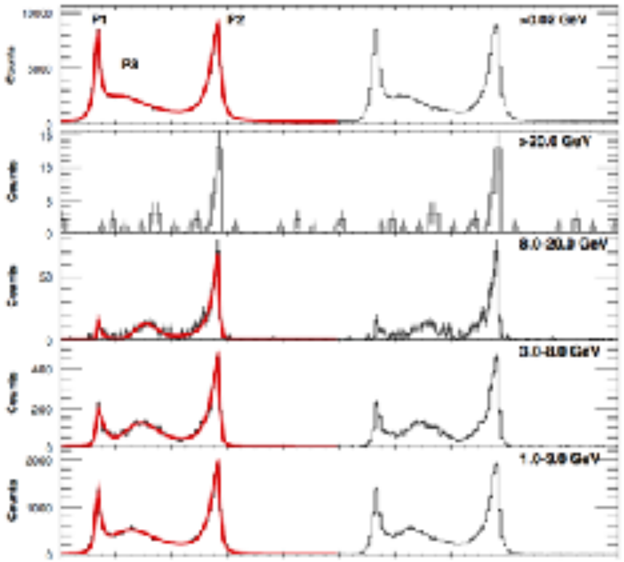
- Not super-exponential
- Not large differences for different magnetic fields Up in the magnetosphere

- Evolution of the peaks
  - *Caustic* of different size?

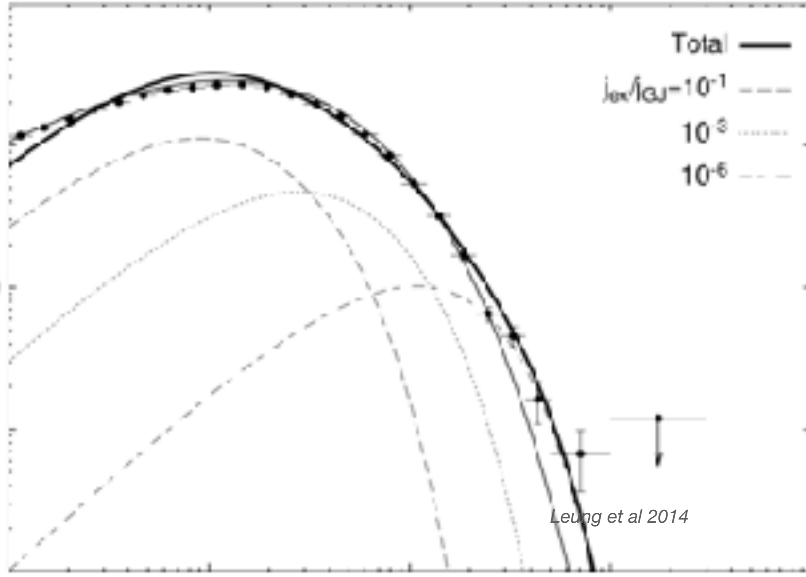
- Deficit at <1 GeV when assuming pure curvature radiation
  - synchrotron contribution?

MAGIC Collaboration 2008





LAT Collaboration 2008

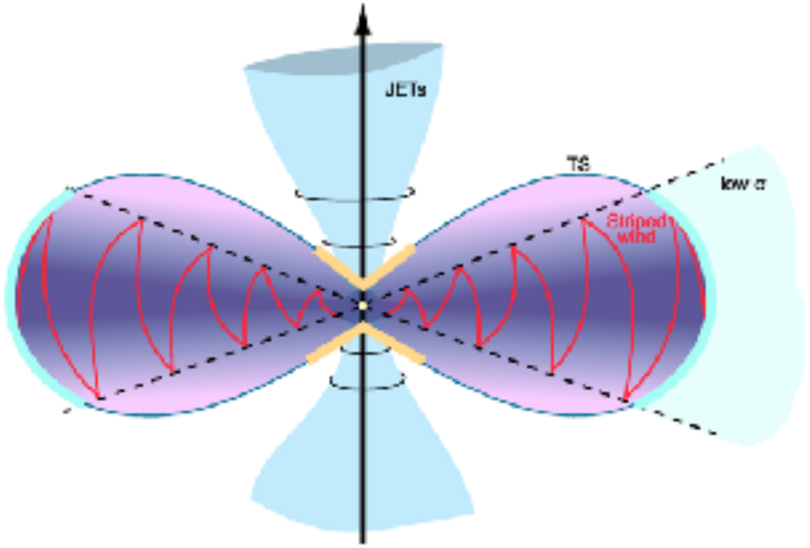


Leung et al 2014

and much more about LCs and transitional behaviour…

High energy radiation from pulsars

- A number of bright pulsars detected in the TeV regime
  - Where is the emission produced?
  - What energies can pulsars reach?



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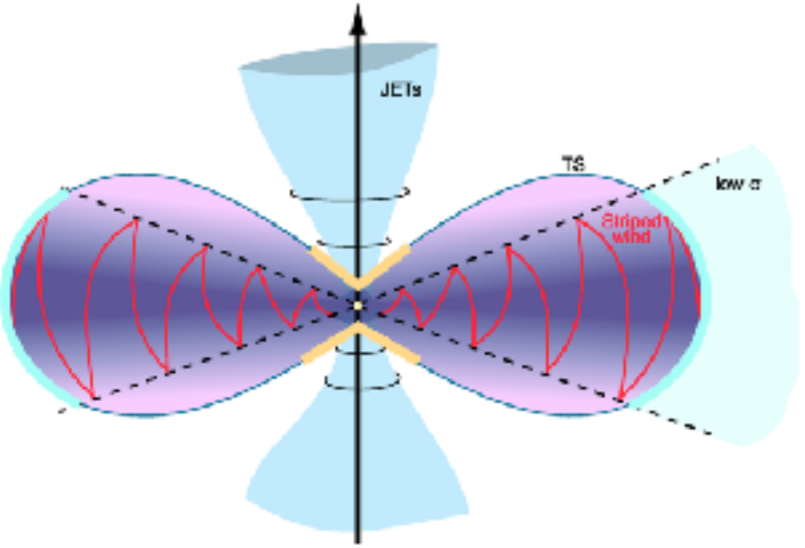
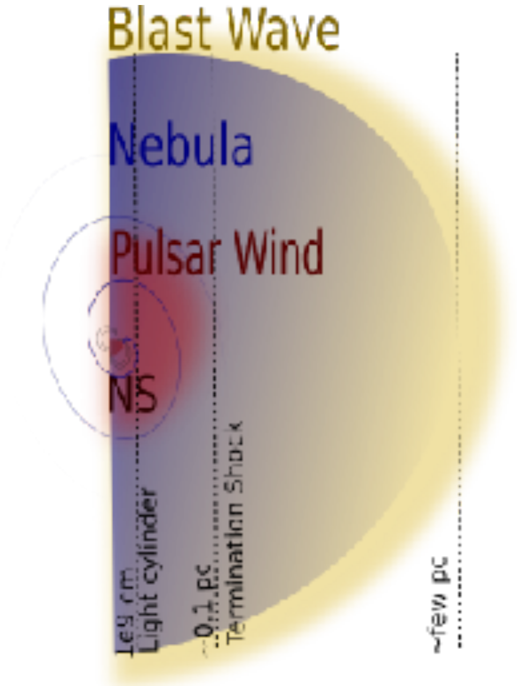




The maximum energy:

$$E_{max} = q\eta_e B_{TS} R_{TS},$$

The magnetic density is a fraction of the pulsar wind energy flux:

$$\frac{B_{TS}^2}{8\pi} = \eta_B \frac{\dot{E}}{(4\pi R_{TS}^2 c)}$$

Then the Emax:

$$E_{max} \approx 2\,\eta_e\,\eta_B^{1/2}\,\dot{E}_{36}^{1/2}\ \text{PeV}$$

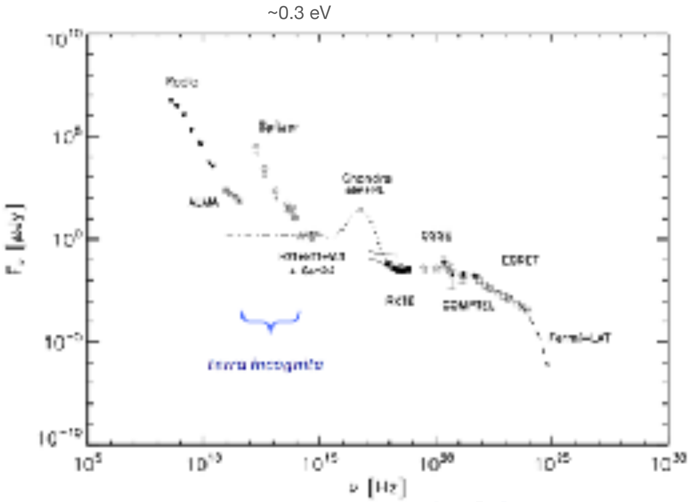
and if CMB (only target >100 TeV)

$$\boxed{E_e \simeq 2.15 E_{\gamma,15}^{0.77}\ \text{PeV}}$$

$$E_{\gamma\ max} \approx 0.9\,\eta_e^{1.3}\,\eta_B^{0.65}\,\dot{E}_{36}^{0.65}\ \text{PeV}$$

High energy radiation from pulsars

- The light curve in the GeV and TeV agree and we observe the same tendency (i.e. peak ratio, width evolution)
  - Same electron/positron ($e^{\pm}$) population
- Sizeable low energy photon fields
  - susceptible of being up-scattered to high energies
- The exponential cutoff seems to be favoured
  - A clear second component = Inverse Compton on soft photon fields



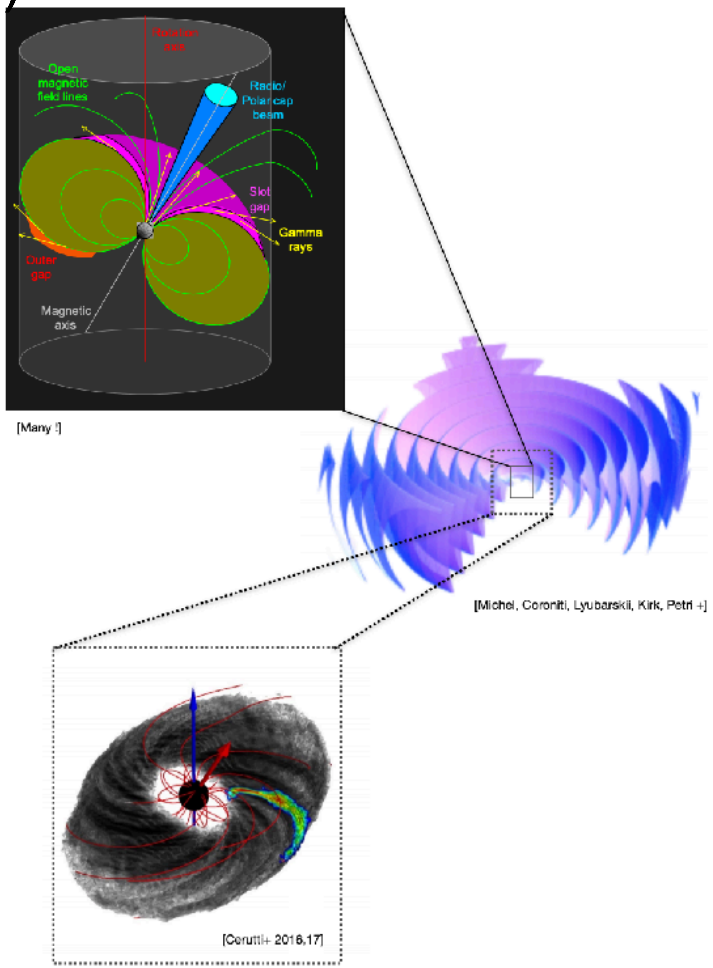
- Inverse Compton in Thomson regime if b<<1
  $b \approx 15\ E_{e,TeV} E_{target\_ph,eV}$
  => Klein-Nishina regime dominant (1-20 TeV)

  Two implications for the electron spectrum
  $E = \Gamma m_e c^2$

  => $\Gamma = 4 \times 10^7$ (20 TeV)
  => $\Gamma = 2 \times 10^6$ (TeV)

High energy radiation from pulsars

- **Within the magnetosphere** (or rather within the gaps):
  - Electrons are accelerated in gaps through $E_{\parallel} = \eta B$
  - HE => CR radiation
  - VHE => IC on low-energy photon target



High energy radiation from pulsars

- **Within the magnetosphere** (or rather within the gaps):
  - Electrons are accelerated in gaps through $E_{\parallel} = \eta B$
  - HE => CR radiation
  - VHE => IC on low-energy photon target

$\eta \lesssim 10\,\%$

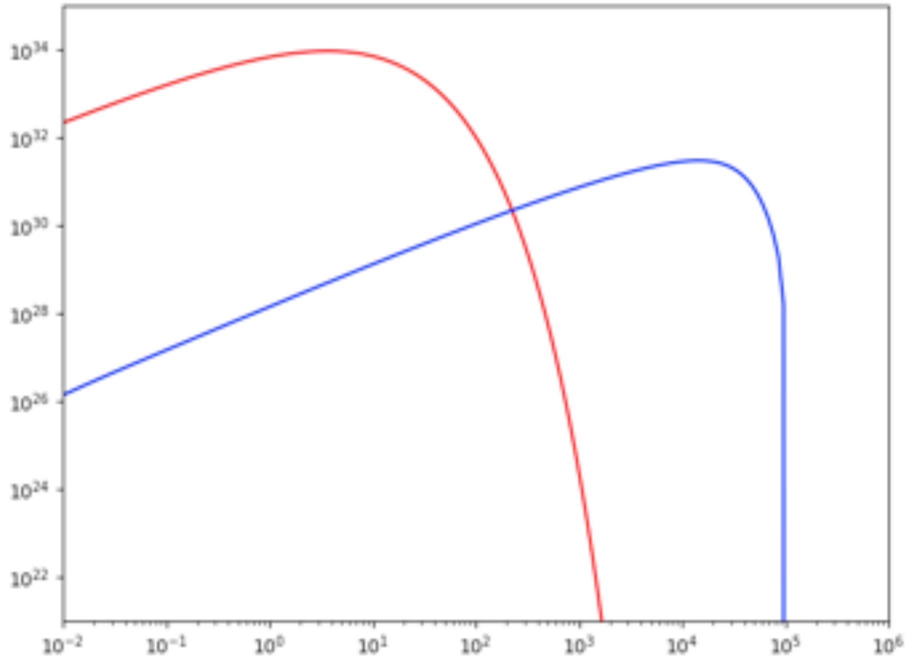
gain rates
$$-\frac{dE}{dt} = e\,c\,\eta\,B$$

energy loss
$$-\frac{dE}{dt} = \frac{2}{3}\frac{e^2 c}{R_c^2}\Gamma_e^4$$

Using Vela values

$$\Gamma_e \approx 4.2 \times 10^7\,\xi^{1/2}\eta_{-1}^{1/4}$$

$\Gamma_e = 4 \times 10^7$ (20 TeV) from TeV

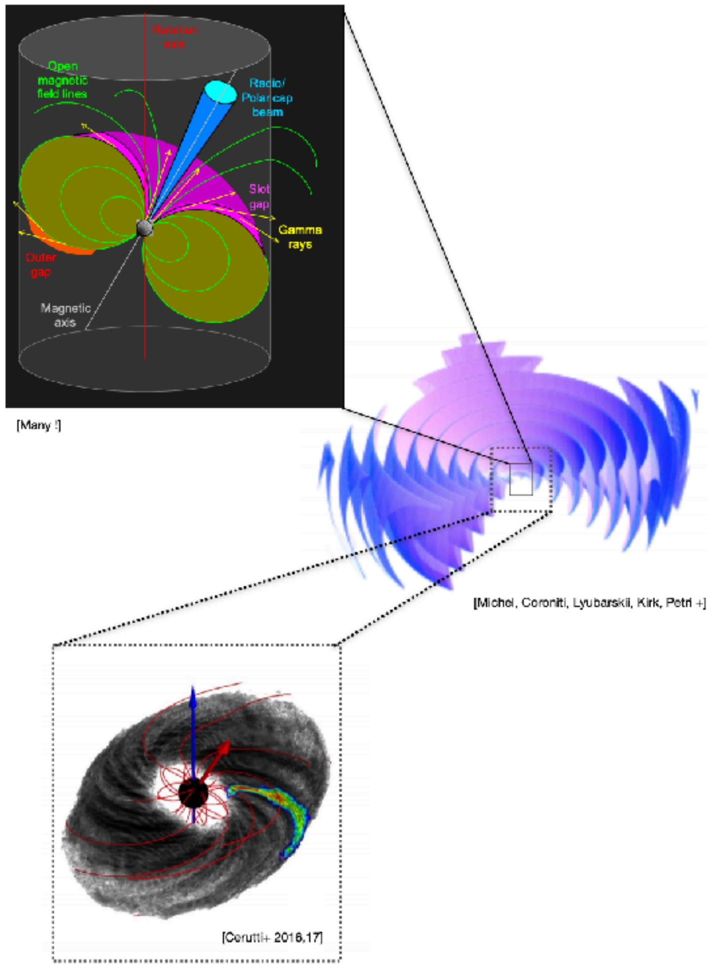


$$R_C = \xi R_{LC} = \xi(cP/2\pi) \Rightarrow \xi > 1$$

Acceleration & Emission beyond the magnetosphere

High energy radiation from pulsars

- Inverse Compton: only depends on the photon field (known) and electron population
- Same electron population produces GeV (same light curve)
- GeV emission can be attributed to:
  - Curvature radiation (CR)
  - Synchrotron emission (SYN)
    =>non-ideal MHD plasma to go beyond ~160 MeV!



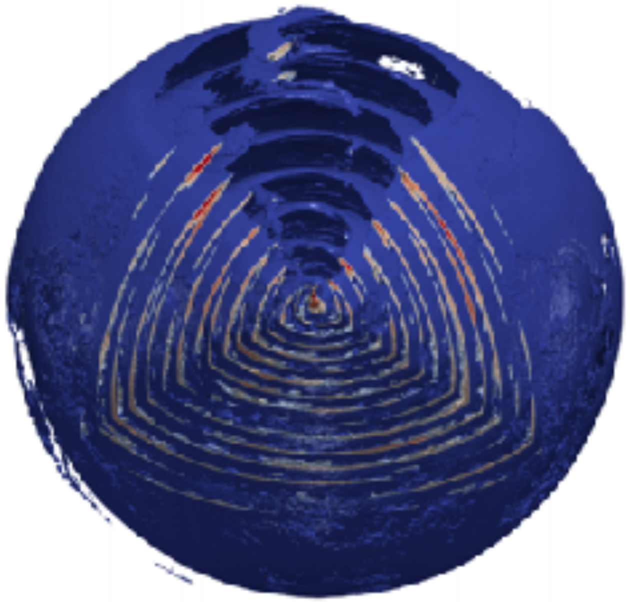
[Many !]

[Michel, Coroniti, Lyubarskii, Kirk, Petri +]

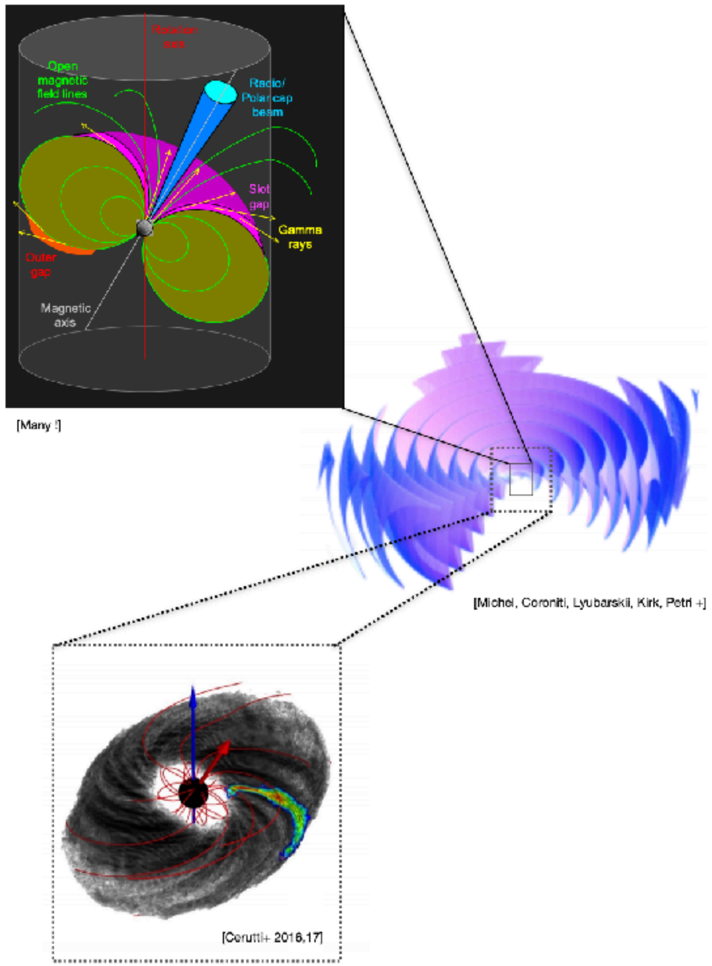
[Cerutti+ 2016,17]

High energy radiation from pulsars

- Beyond the magnetosphere:
  Electrons are accelerated in the wind through magnetic reconnection in the current sheet (CS)
  HE => SYN emission on the CS
  VHE => IC emission on the CS

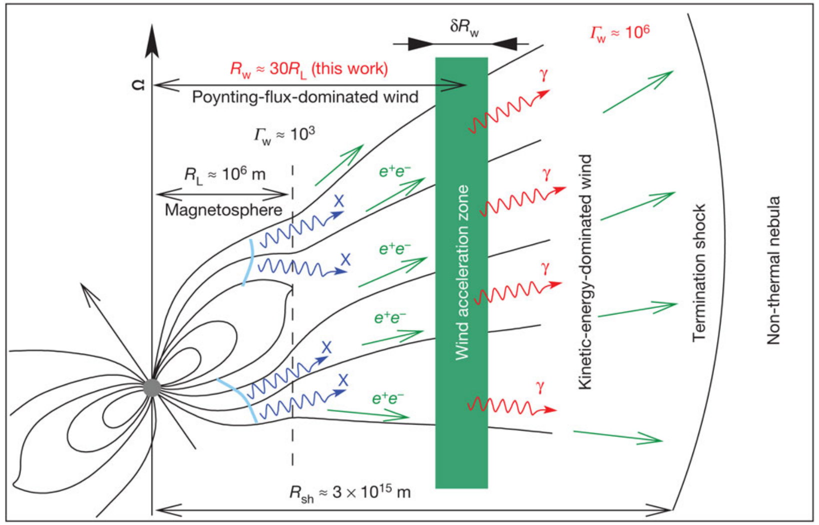


Simulations by Cerruti et al 2020



(A couple of) VHE pulsar models

Cold ultrarelativistic wind

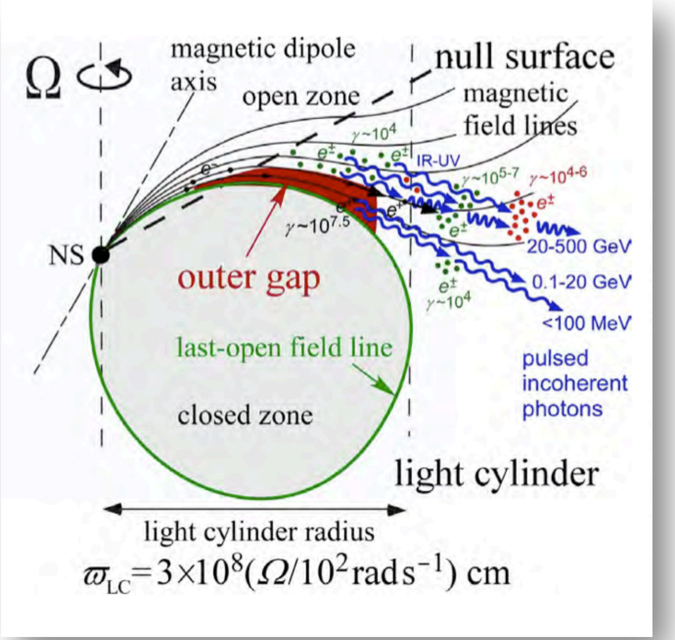


Aharonian, F. et al., Nature 482 (2012) 507

It proposes that VHE gamma-rays are produced in the wind region.

Predicts bridge emission but broader peaks than observed.

Outer gap



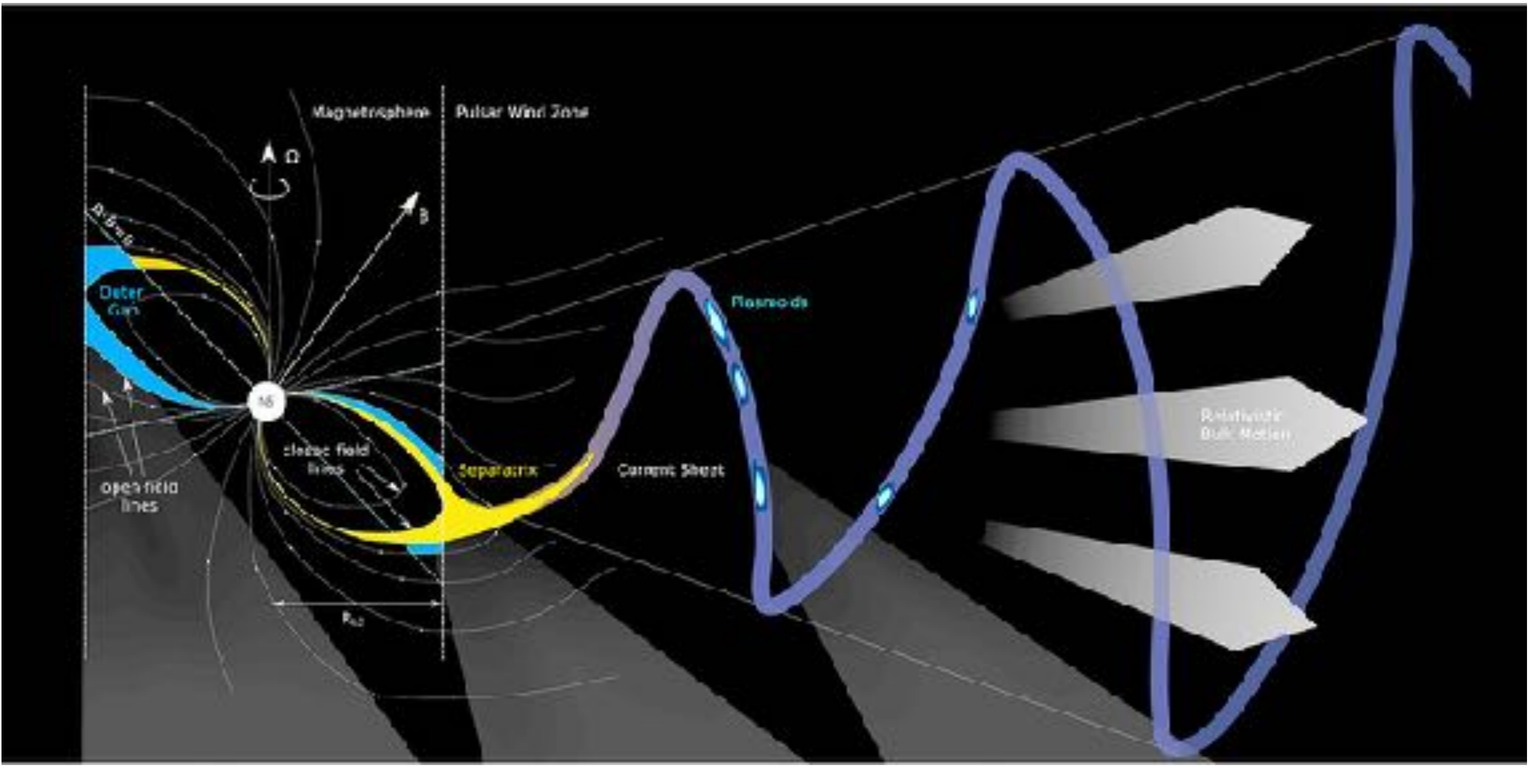
VHE gamma rays are produced inside the magnetosphere in an "outer gap"

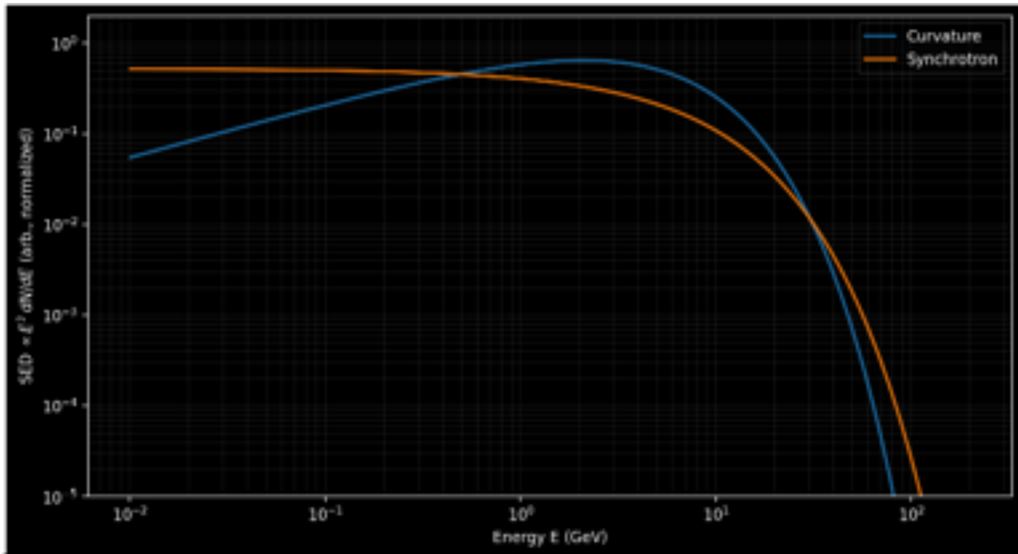
It can explain the spectrum extending up to 400 GeV and also the bridge emission if the magnetic field also has a toroidal component.

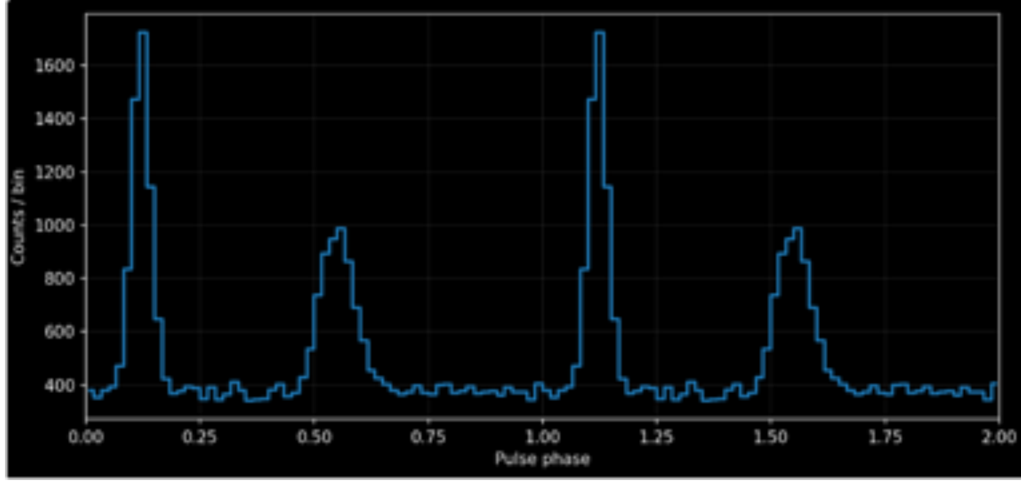
Hirotani, K., ApJ, 733 (2011) L49
Hirotani, K., ApJ, 766 (2013) 98

Multi-TeV energy emission

- To reach multi-TeV energies you need to go large

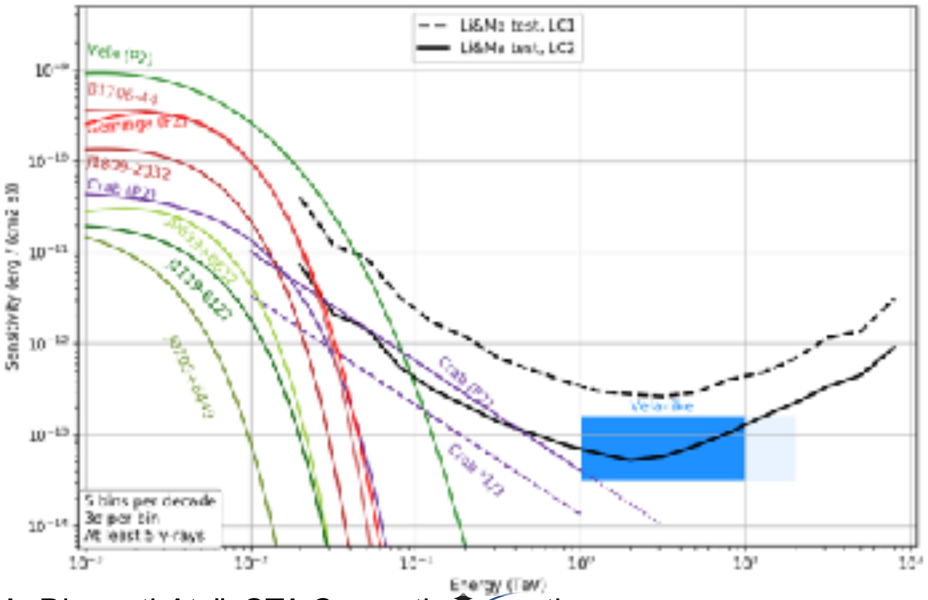




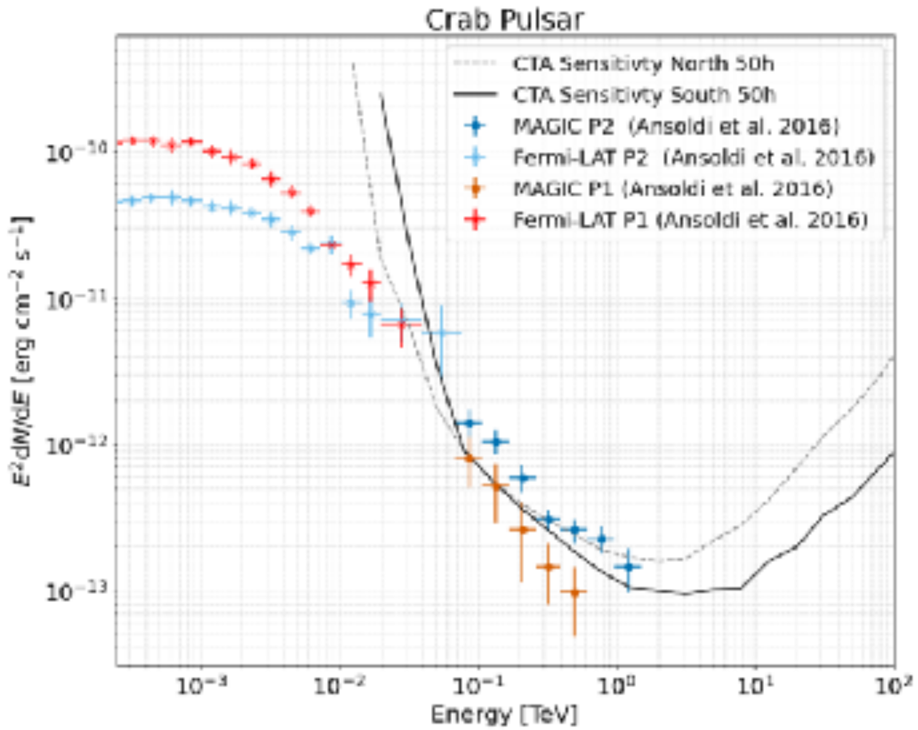


Pulsars: Population studies

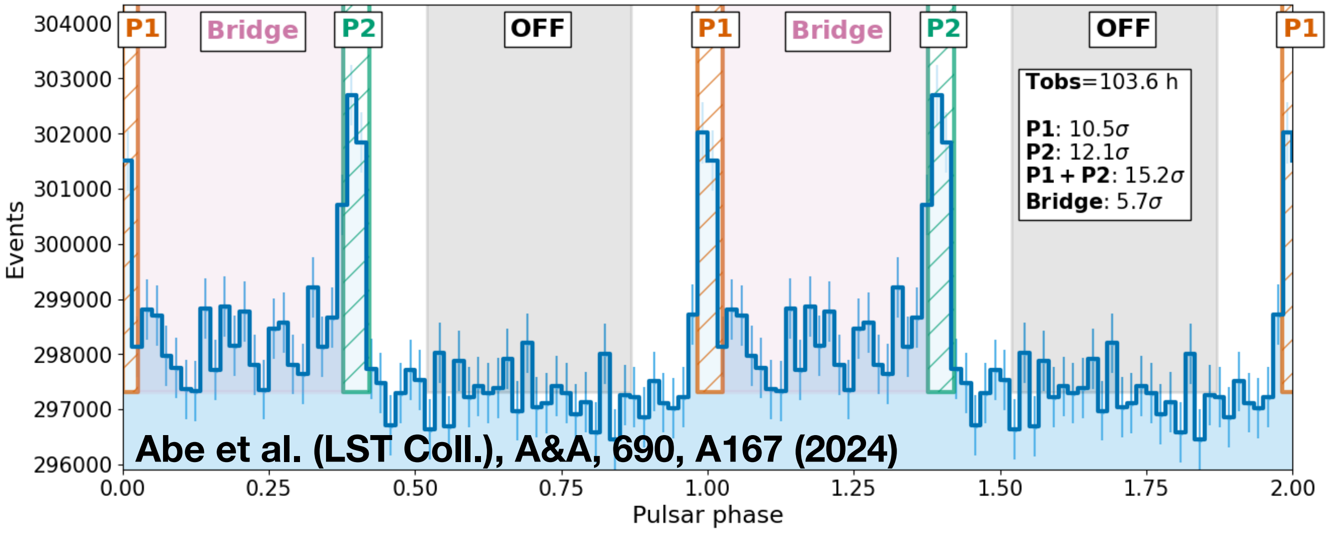
- Emission models at different locations are able to reproduce the emission we observe
- Need to increase the population and the energy range in which these are detected to univocally identify these regions

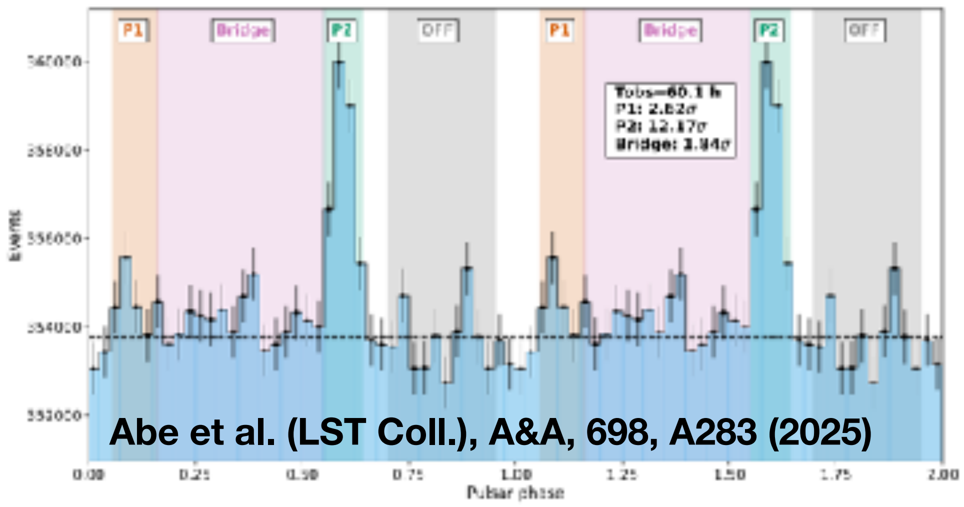


A. Djannati-Ataï, CTA Consortium meeting



Pulsars with LST-1



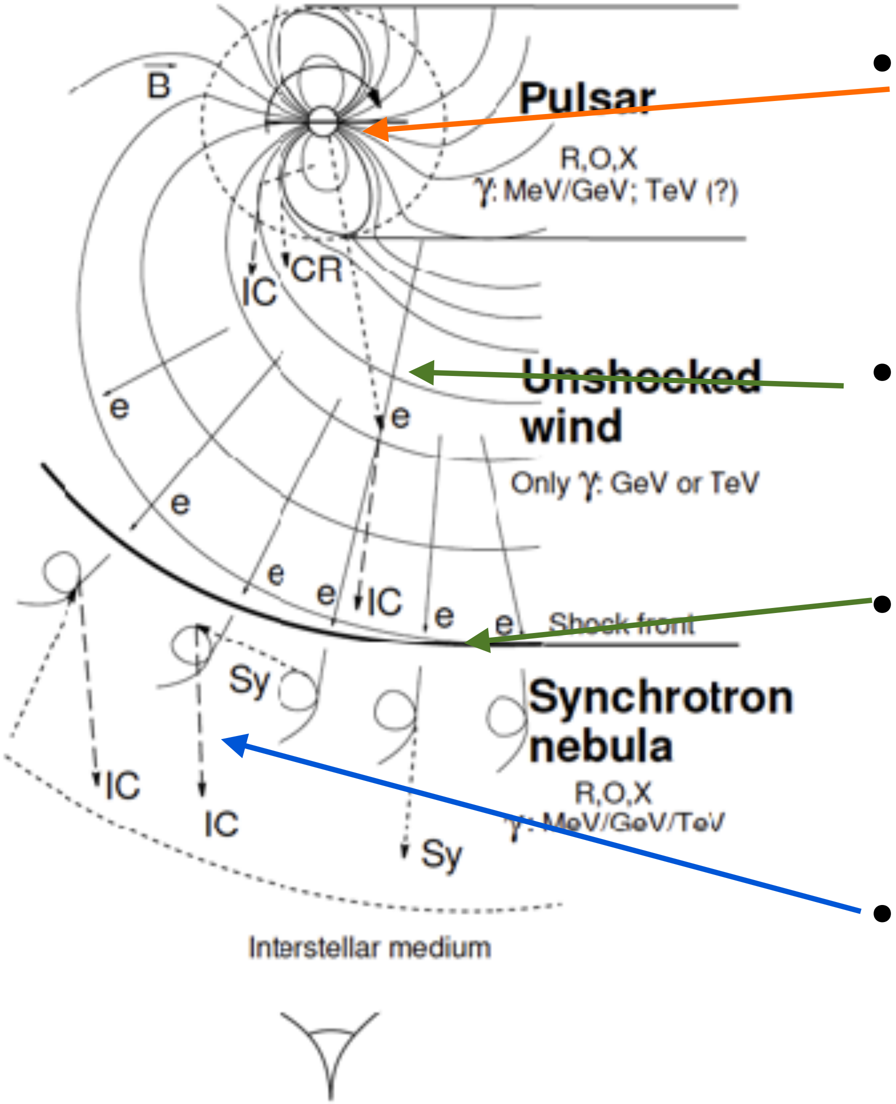


- LST-1 of CTAO measured the **Crab Pulsar** spectrum from few tens of GeV up to hundreds of GeV.

- **Geminga Pulsar** detected above 15(!) GeV

Pulsar Wind Nebulae

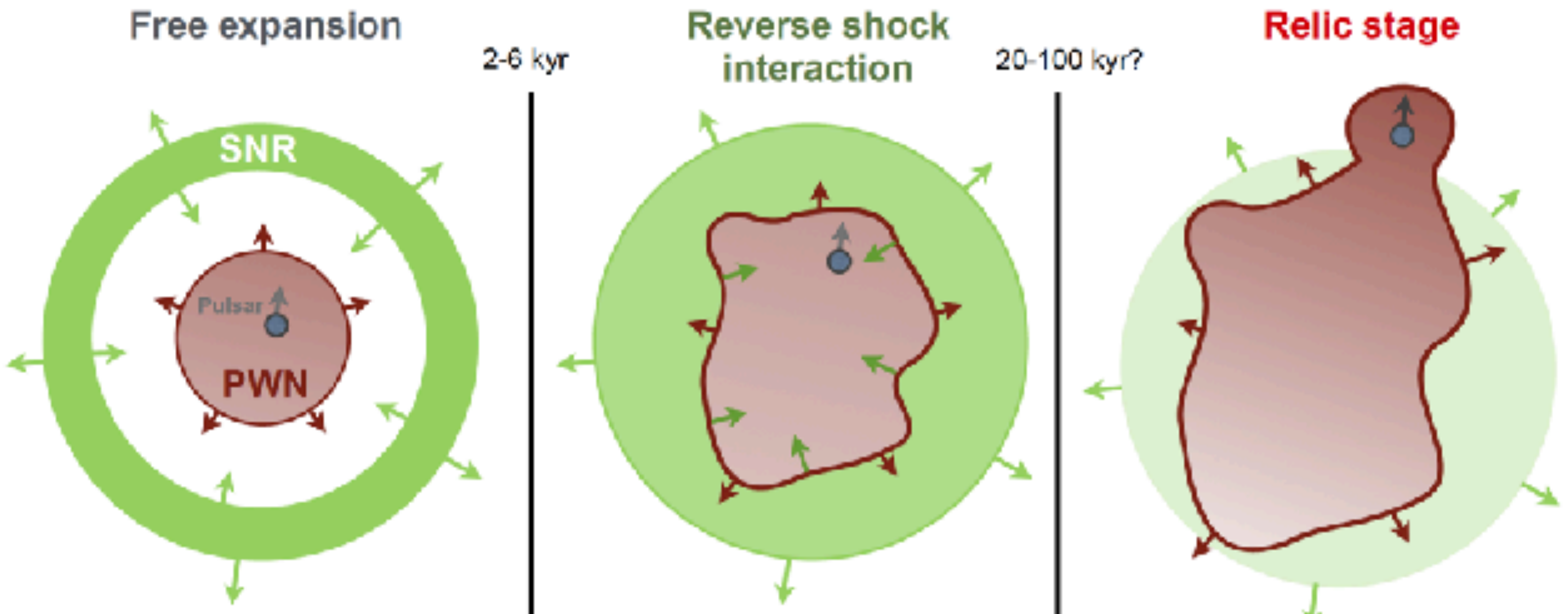
Pulsar wind nebulae



- e± are accelerated in the magnetosphere's gaps.
- Raditionless e± wind.
- Termination Shock (TS) -> e± are decelerated.
- Synchrotron and Inverse Compton (IC) is produced in the nebula.

Pulsar complex evolution

PWN Evolution in a Nutshell



Free expansion

- Easy & independent
- $R \sim t^{6/5}$
- All the Crab wisdom, e.g.
  - Kennel & Coroniti 1984
  - Martin++, 2012
  - ...

Reverse shock interaction

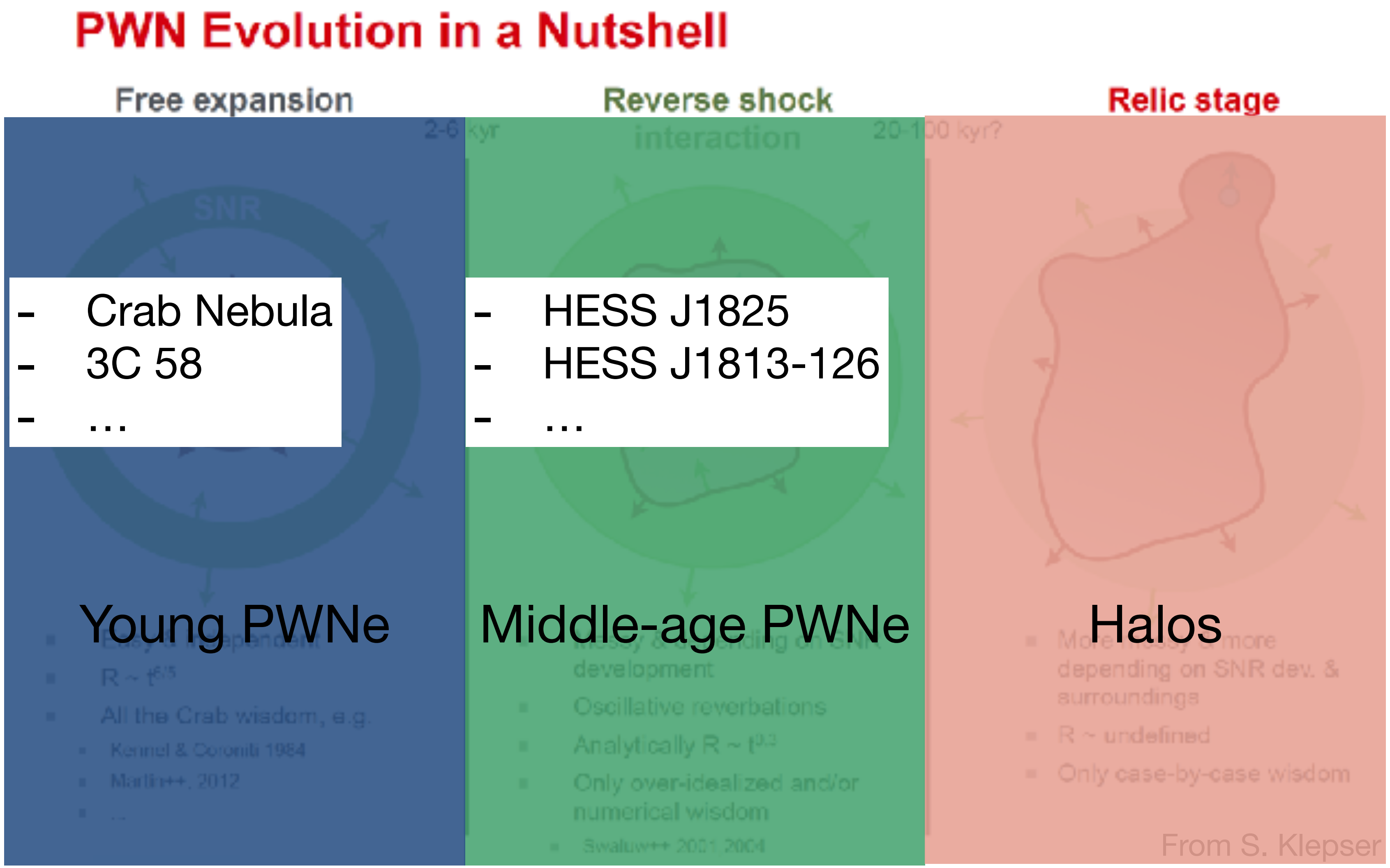
- Messy & depending on SNR development
- Oscillative reverberations
- Analytically $R \sim t^{0.3}$
- Only over-idealized and/or numerical wisdom
  - Swaluw++ 2001,2004

Relic stage

- More messy & more depending on SNR dev. & surroundings
- R ~ undefined
- Only case-by-case wisdom

From S. Klepser

Pulsar complex evolution

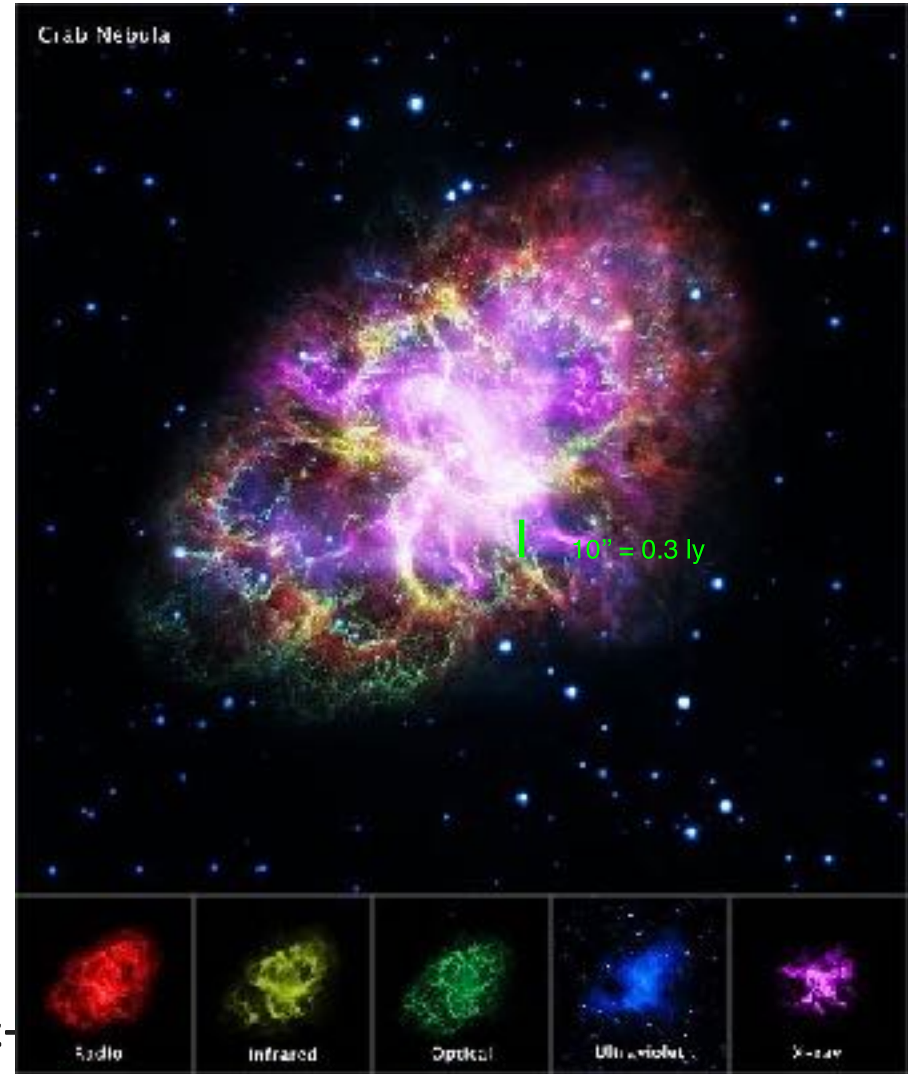


CR Accelerators: Pulsar Wind Nebulae

- The archetype: the Crab Nebula

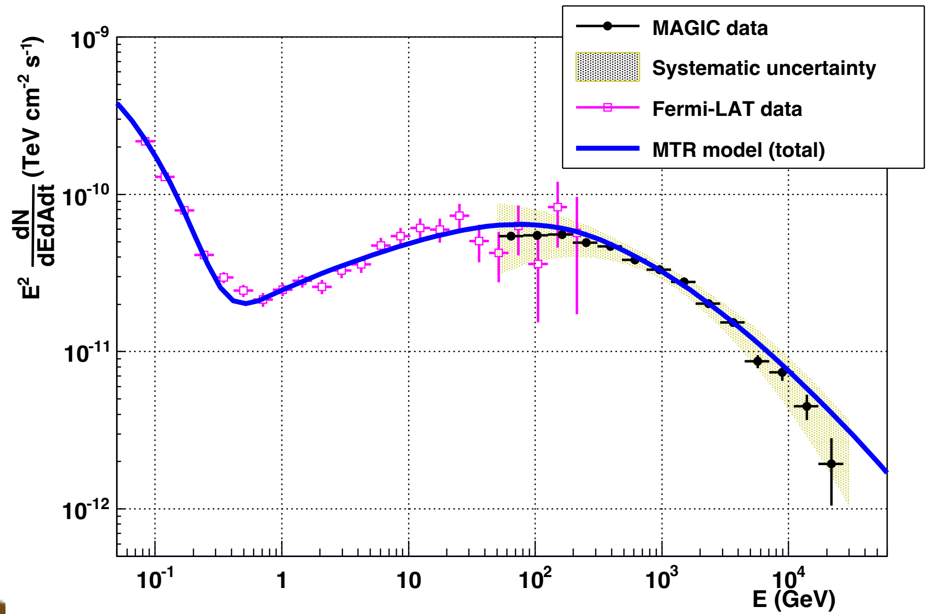
- Bright in many wavelengths

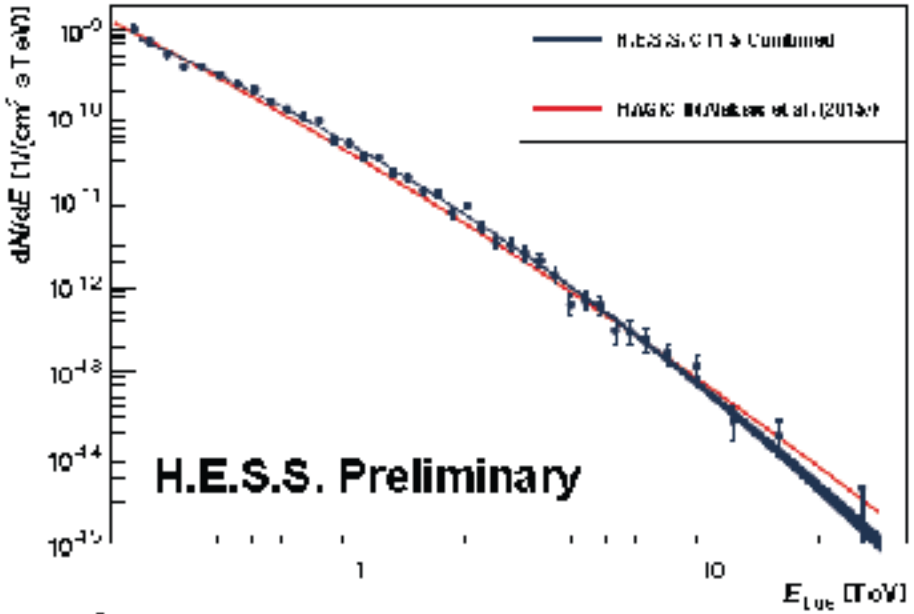
- Different size <=> Different electron population



The VHE gamma-ray calibrator: the Crab Nebula

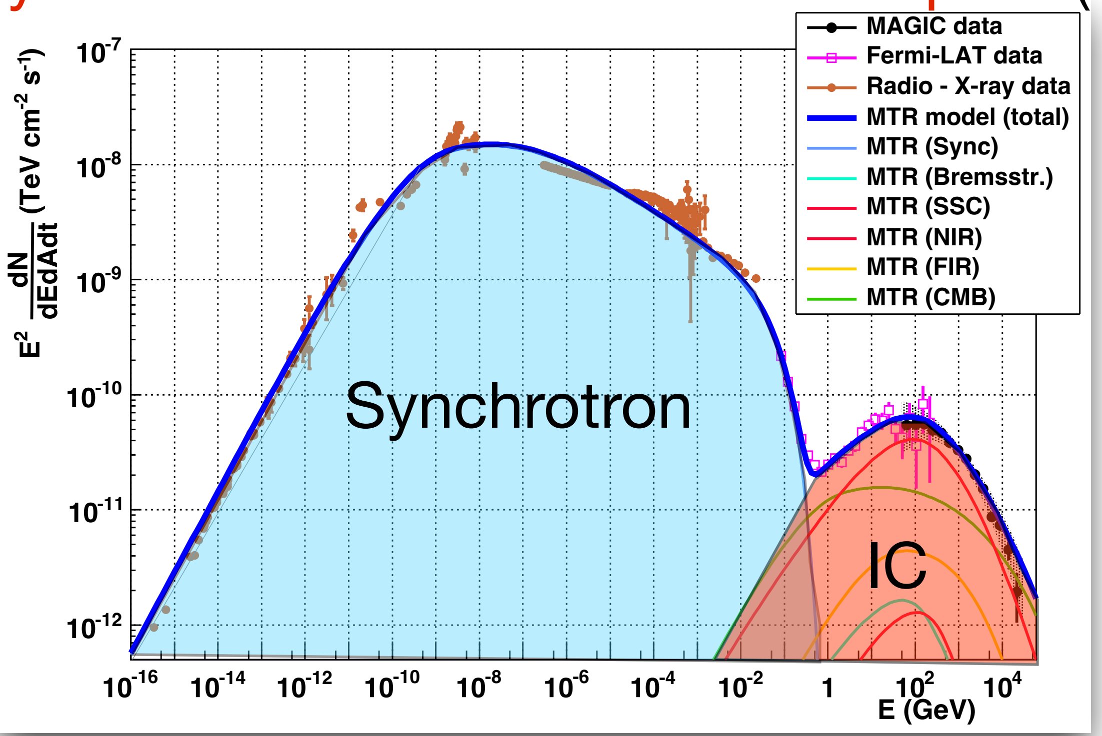
- IACT spectrum extends from 50 GeV to ~30 TeV
- In combination with Fermi-LAT, the IC peak is measured at ~50 GeV
- All the tested models have too simplistic assumptions and none of them can explain the MW spectrum of the Crab nebula





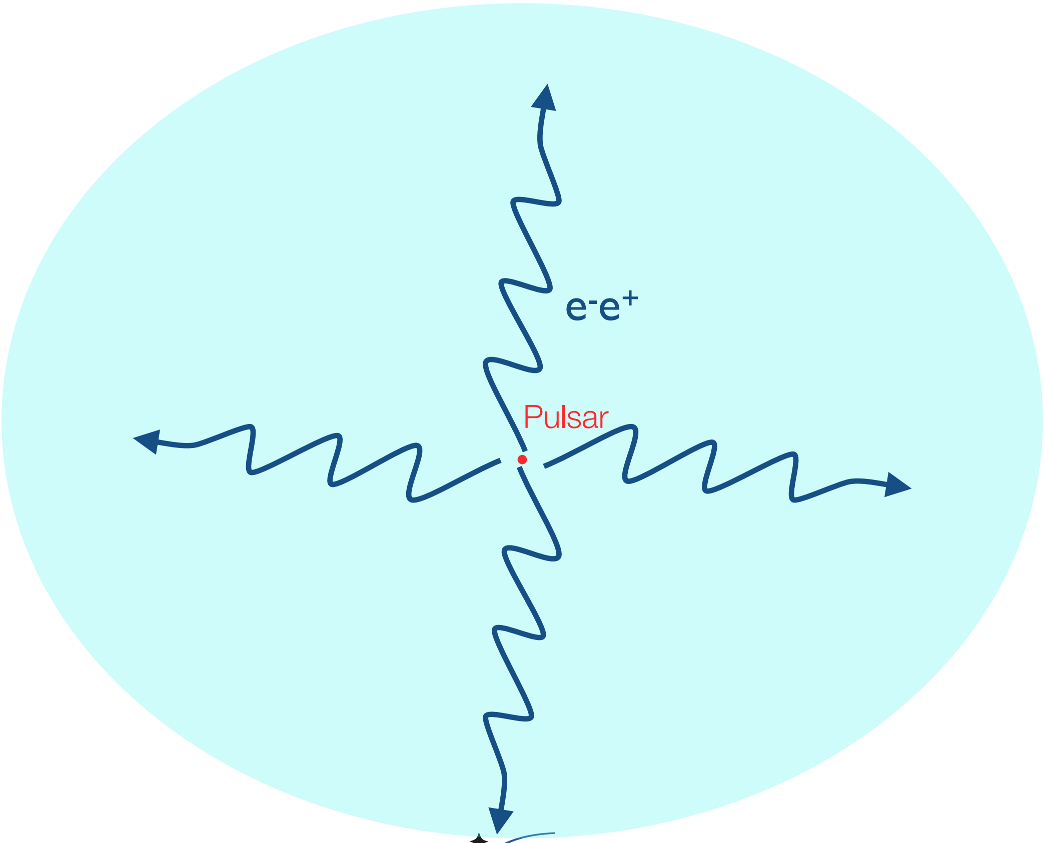
Broadband emission of PWNe

- PWN spectra are composed by two distinct components, the synchrotron and the inverse Compton (IC) part.



- Most popular models:
  - **Magnetohydrodinamic (MHD) models:** Reproduce the morphological and spectral properties through MHD simulations (Kennel & Coroniti, 1984; Meyer et al., 2010).
  - **One-dimensional spectral models:** Reproduce PWN spectra without taking into account the energy-dependence of the PWN morphology (Aharonian et al., 1997; Tanaka & Takahara, 2010; Martín et al., 2012).

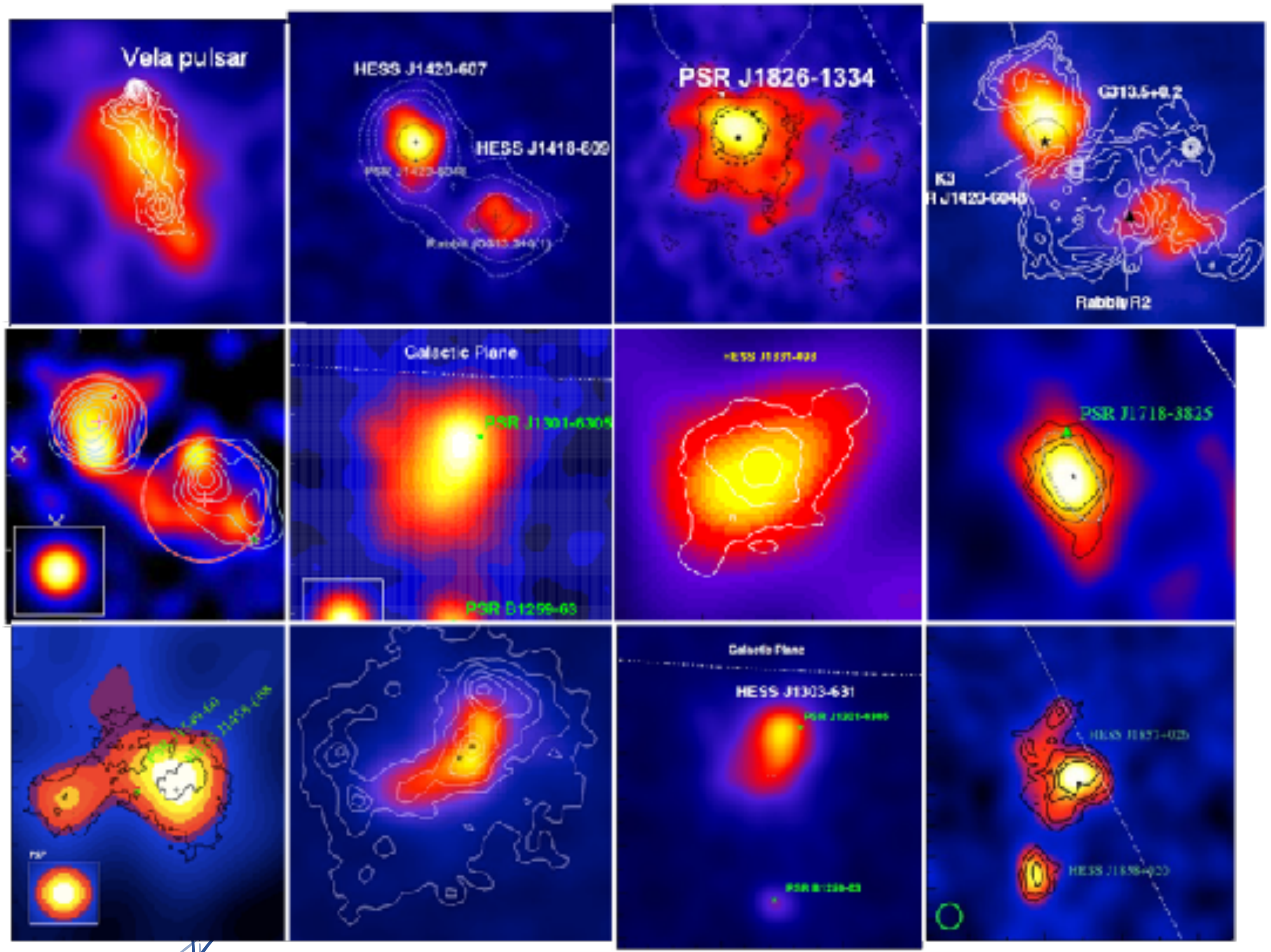
Particle emission of a PWN



- Continuously emitting source assuming a constant injection approach is not valid
  - Pulsars lose its energy as a **dipole**:

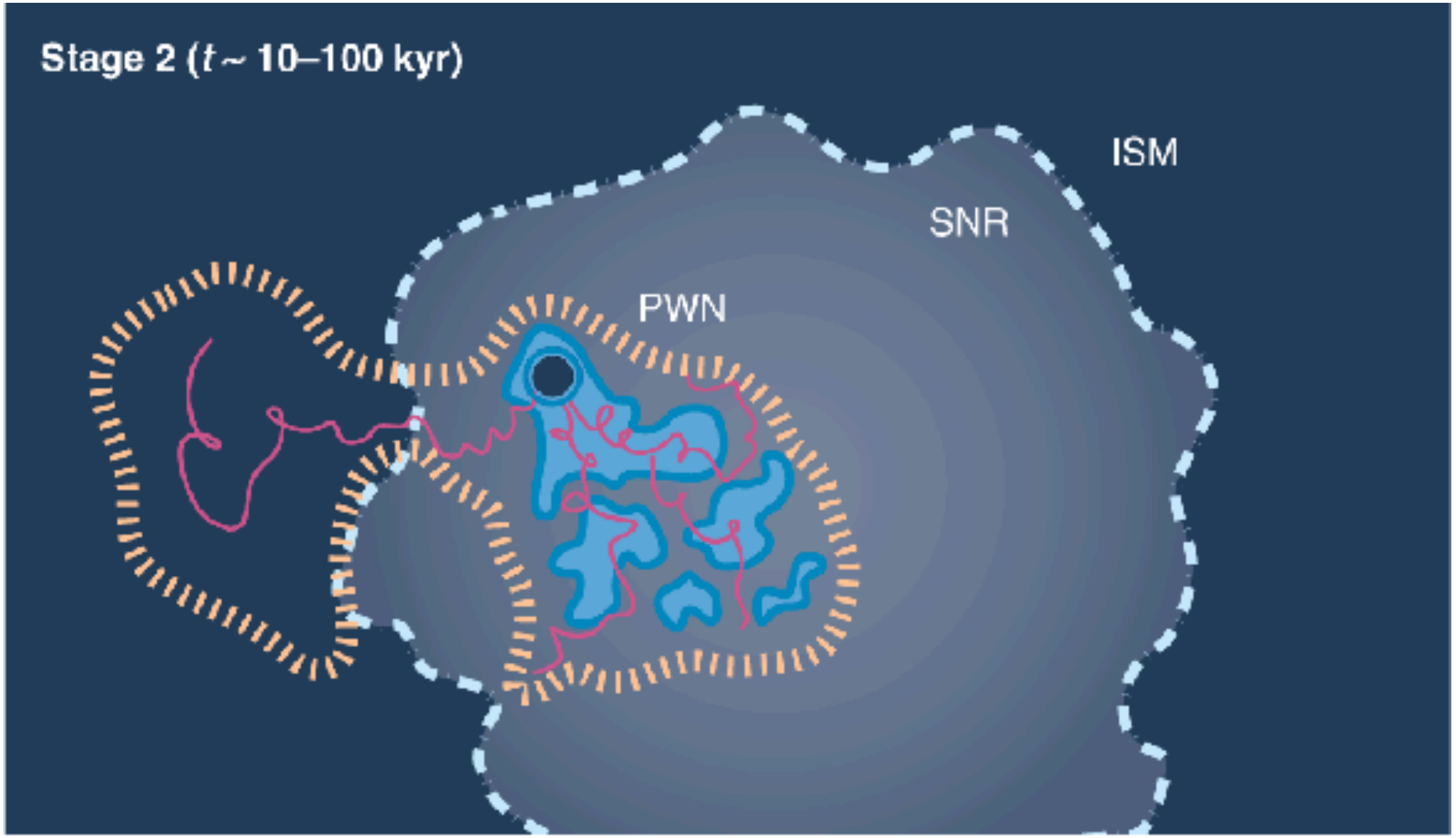
$$L(t) = L_0 \left(1 + \frac{t}{\tau}\right)^{-\frac{n+1}{n-1}}$$

TeV Pulsar Wind Nebulae

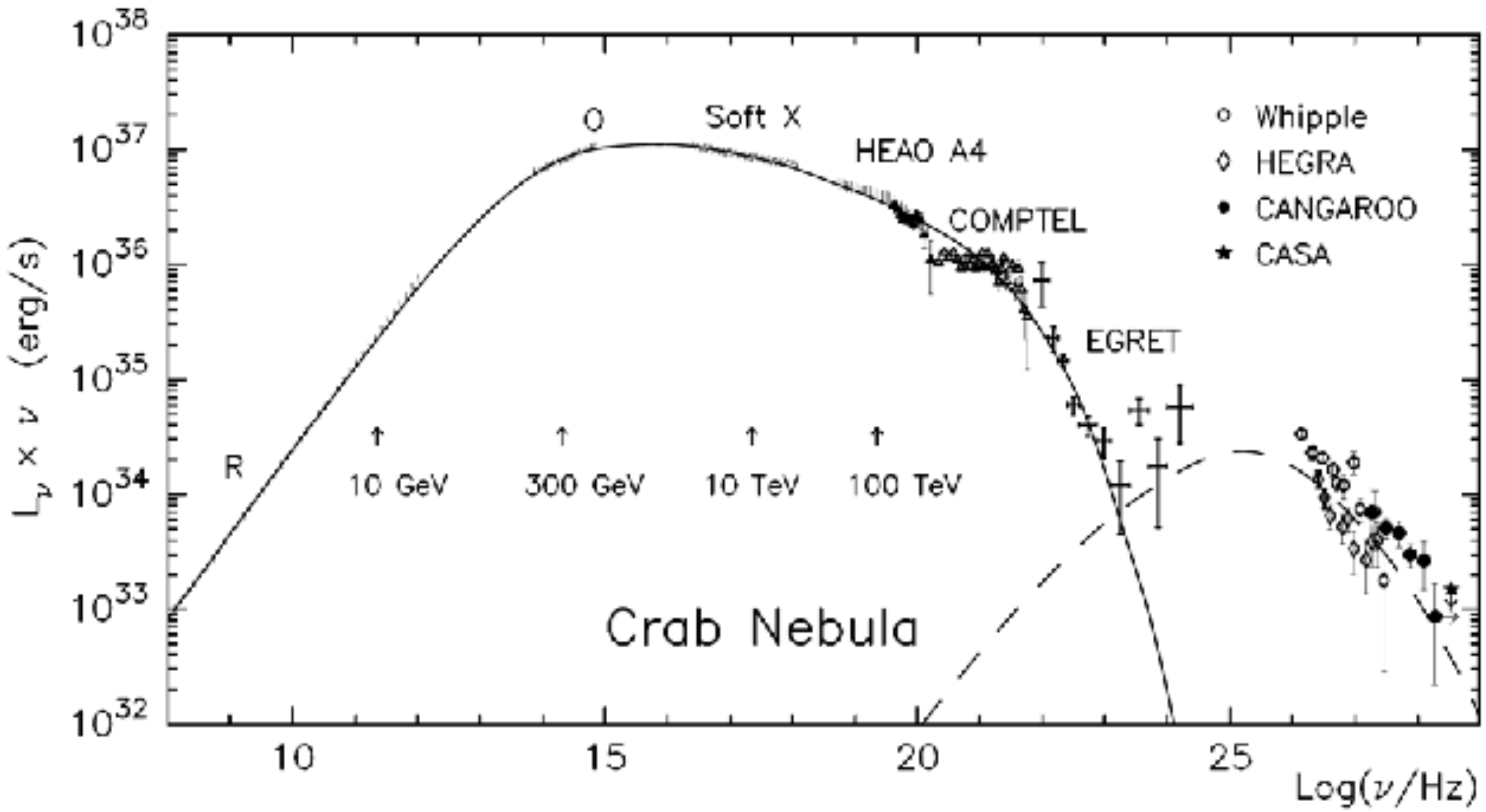


CR Accelerators: Pulsar Wind Nebulae

- The most numerous population in the Galaxy at VHE

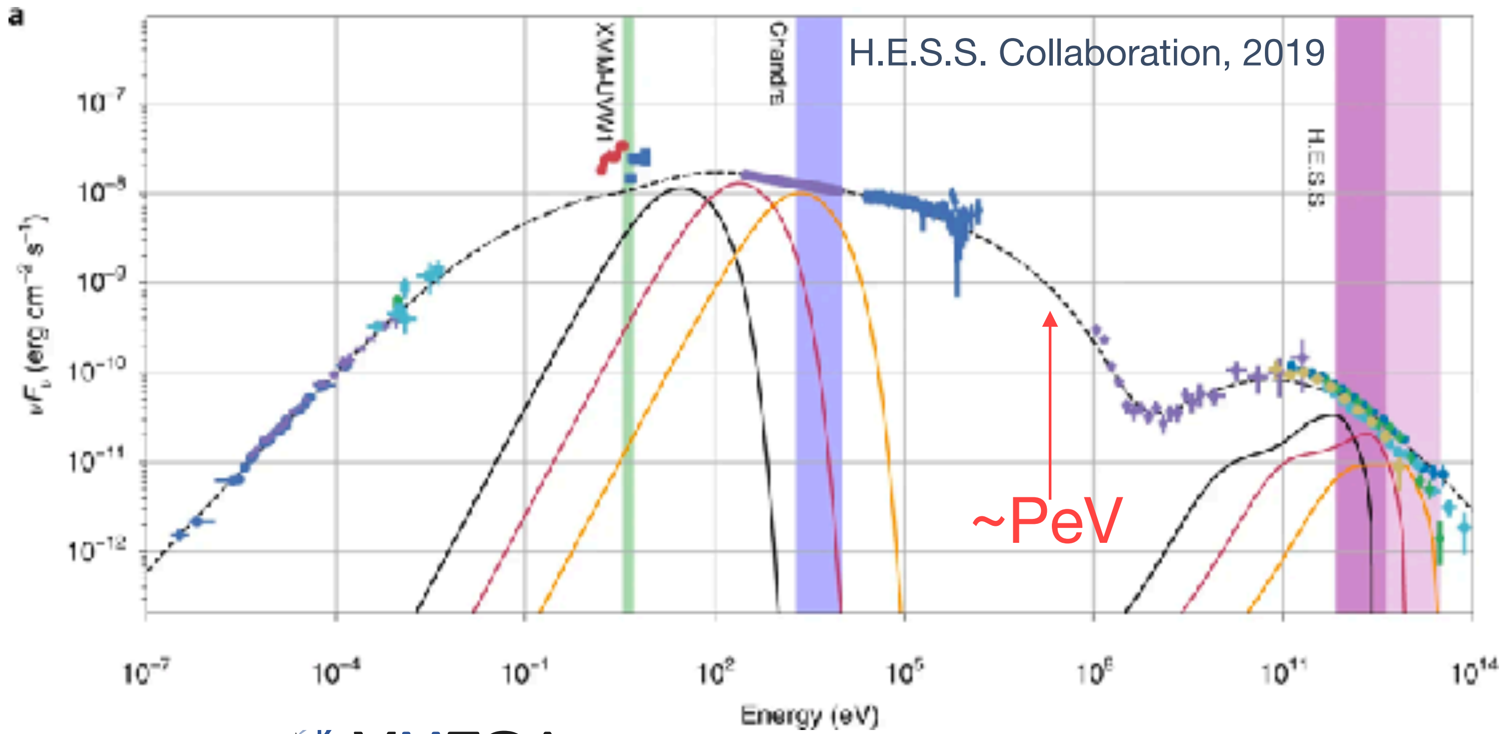


CR Accelerators: Pulsar Wind Nebulae



Leptonic PeVatrons

- Leptonic CR accelerators known since several decades
  - Crab Nebula as an example leptonic PeVatron.



CR Accelerators: Pulsar Wind Nebulae

- Energetics:
  - Syn => Depends on the **magnetic field**

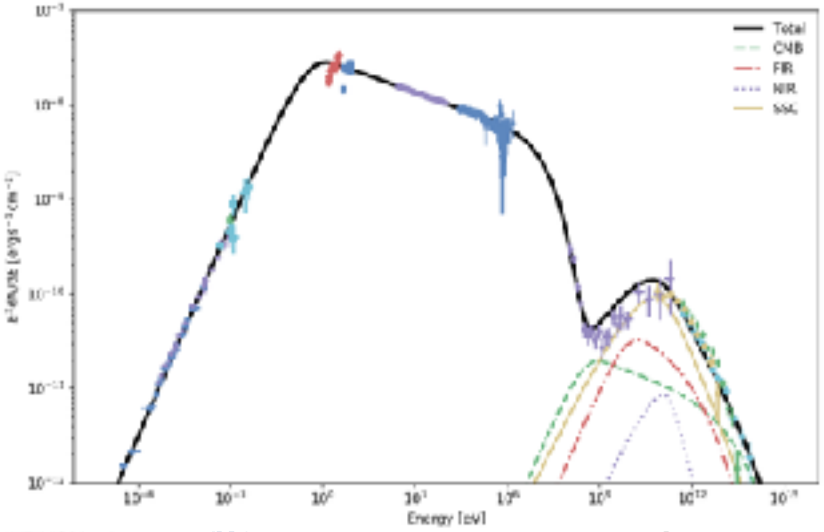
$$\dot{E}_{syn} = -\frac{4}{3}U_B c\gamma^4$$

  - IC => Depends on the **photon field**

$$\dot{E}_{IC} = -\frac{4}{3}U_{ph} c\gamma^2$$

$$\frac{L_1}{L_2} = \frac{\dot{E}_1}{\dot{E}_2}$$

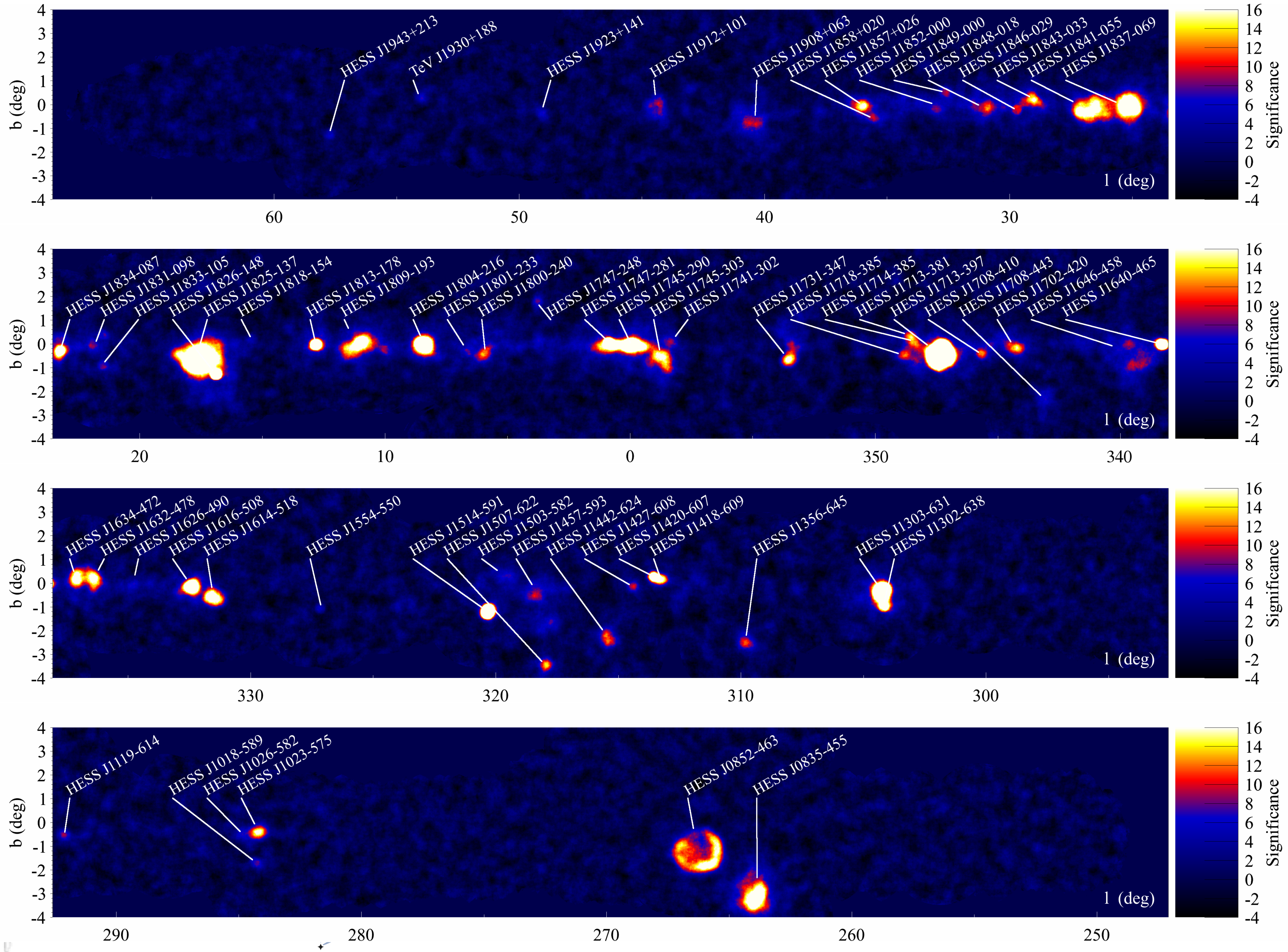
$$\frac{L_1}{L_2} = \frac{U_B}{U_{ph}} = \frac{\frac{B^2}{8\pi}}{\omega_{CMB} + \omega_{FIR} + \omega_{NIR} + \omega_{SYN}}$$



$$\frac{L_{IC}}{L_{syn}} \approx \left(\frac{B}{3\mu G}\right)^{-2}$$

For CMB

B~ 100 uG


HESS J1943+213
TeV J1930+188
HESS J1923+141
HESS J1912+101
HESS J1908+063
HESS J1858+020
HESS J1857+026
HESS J1852-000
HESS J1849-000
HESS J1848-018
HESS J1846-029
HESS J1843-033
HESS J1841-055
HESS J1837-069
HESS J1834-087
HESS J1831-098
HESS J1833-105
HESS J1826-148
HESS J1825-137
HESS J1818-154
HESS J1813-178
HESS J1809-193
HESS J1804-216
HESS J1801-233
HESS J1800-240
HESS J1747-248
HESS J1747-281
HESS J1745-290
HESS J1745-303
HESS J1741-302
HESS J1731-347
HESS J1718-385
HESS J1714-385
HESS J1713-381
HESS J1713-397
HESS J1708-410
HESS J1708-443
HESS J1702-420
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HESS J1640-465
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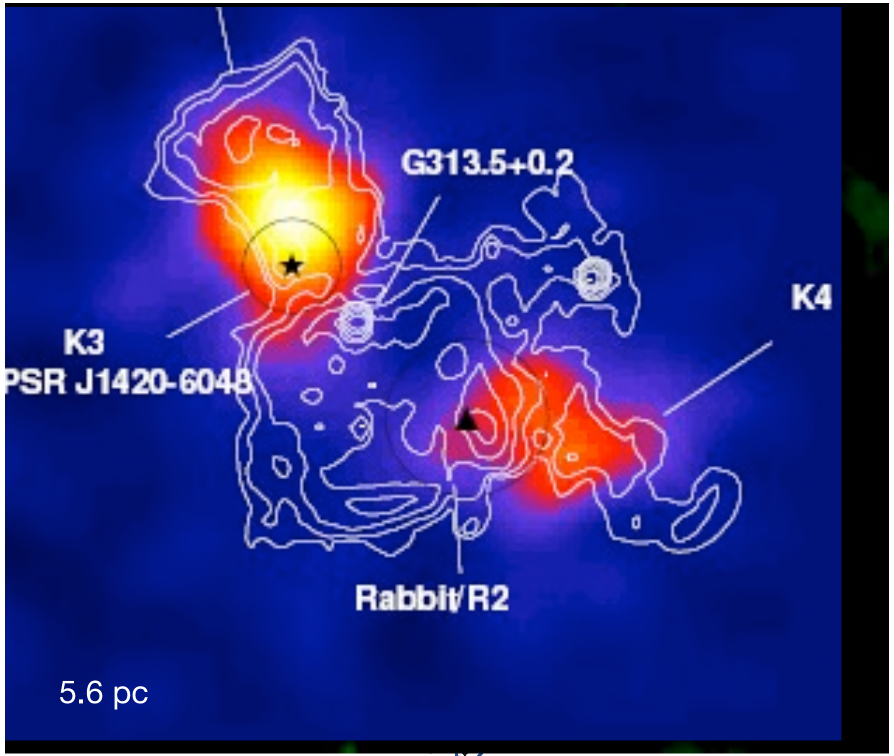
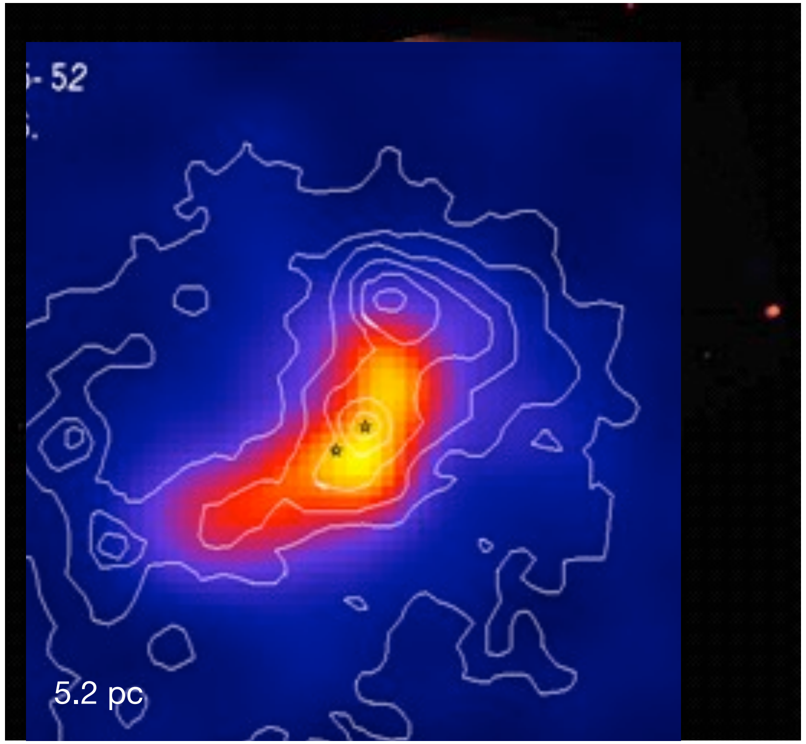
HESS J1616-508
HESS J1614-518
HESS J1554-550
HESS J1514-591
HESS J1507-622
HESS J1503-582
HESS J1457-593
HESS J1442-624
HESS J1427-608
HESS J1420-607
HESS J1418-609
HESS J1356-645
HESS J1303-631
HESS J1302-638
HESS J1119-614
HESS J1018-589
HESS J1026-582
HESS J1023-575
HESS J0852-463
HESS J0835-455
b (deg)
l (deg)
Significance

Accelerators: Pulsar Wind Nebulae

Young PWNe

- Excellent correlation with X-rays (large size compensates sometimes the relatively poor angular resolution ~0.1deg

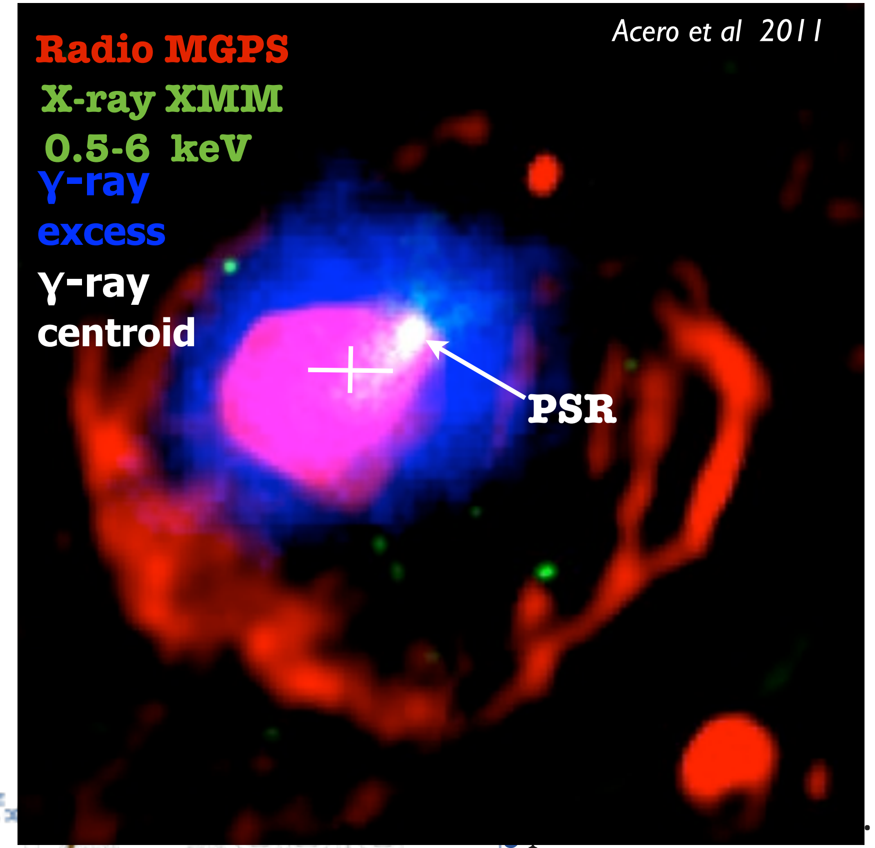


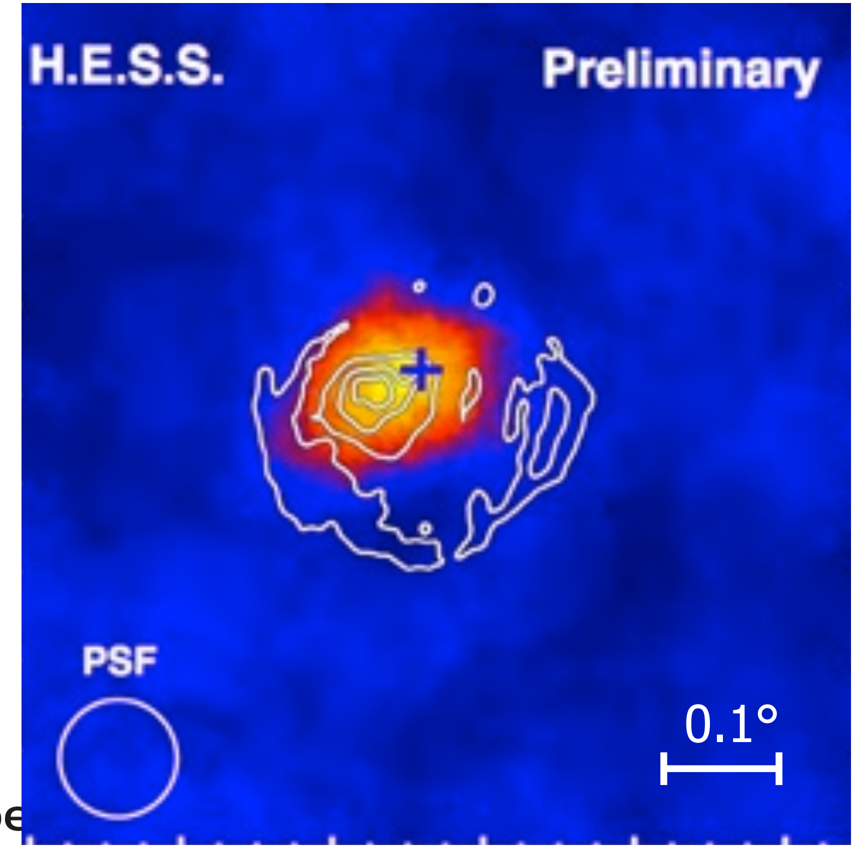


Accelerators: Pulsar Wind Nebulae

Young PWNe

- Very low magnetic fields when comparing with Lx ~ few uG => Far from equipartition

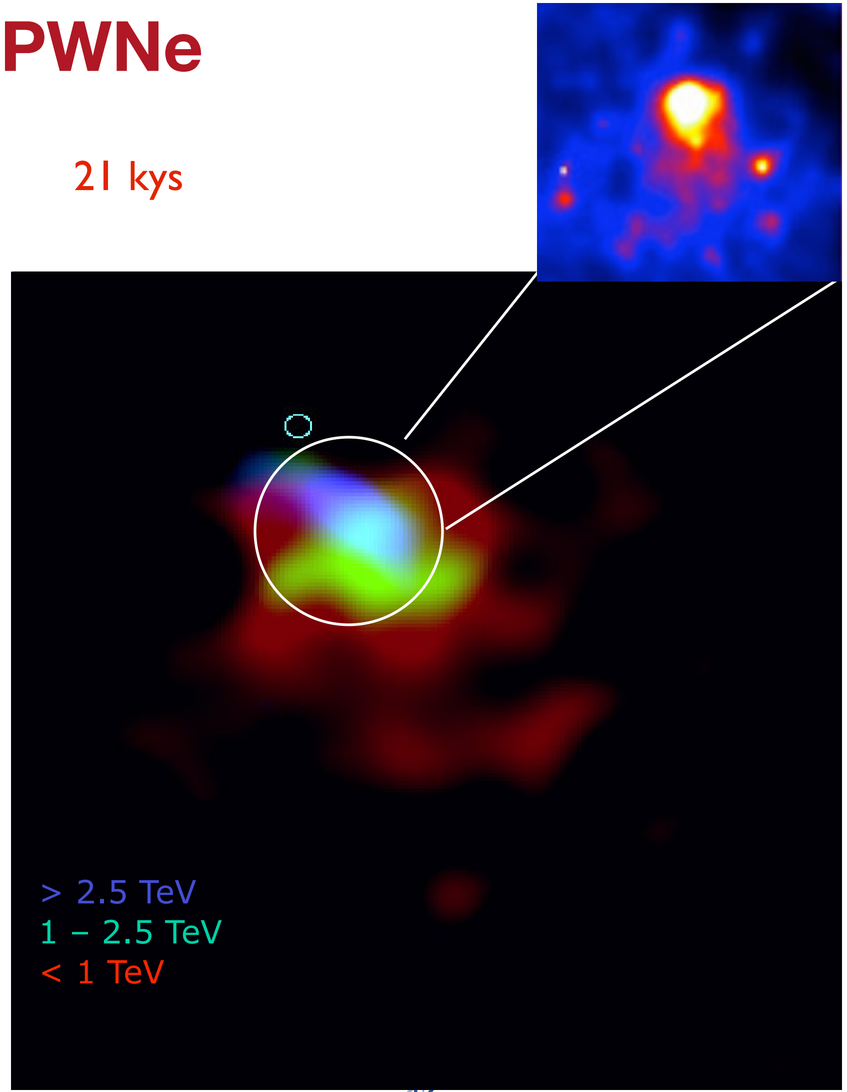


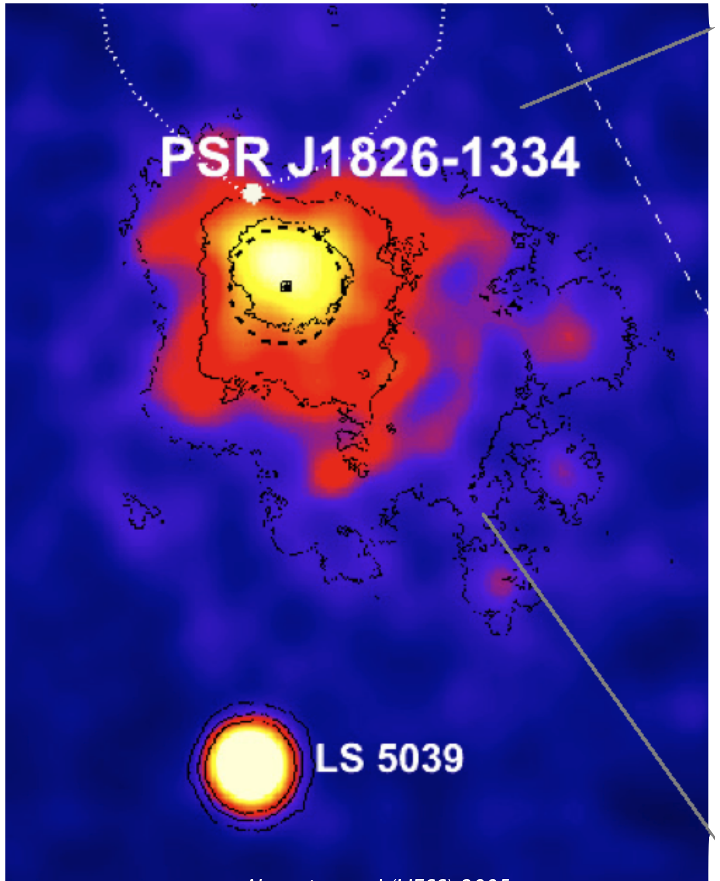


Accelerators: Pulsar Wind Nebulae

Evolved PWNe

21 kys

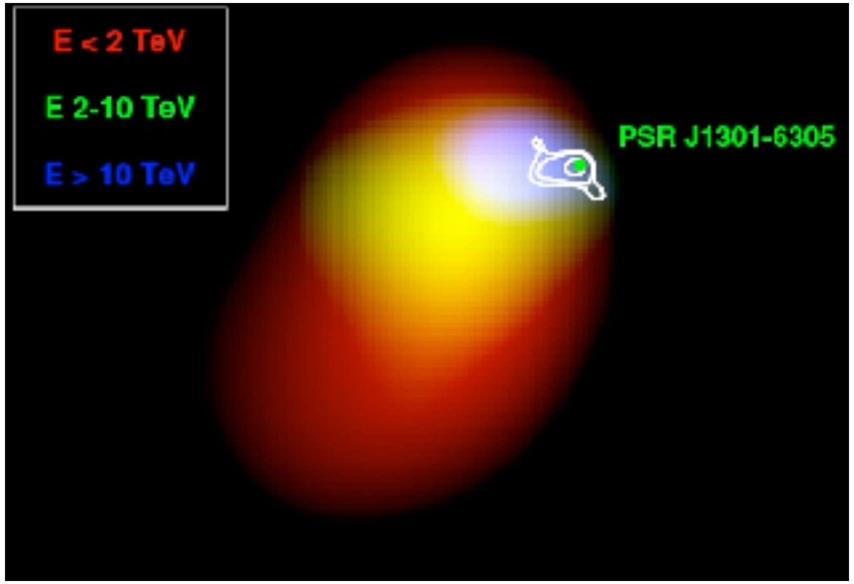


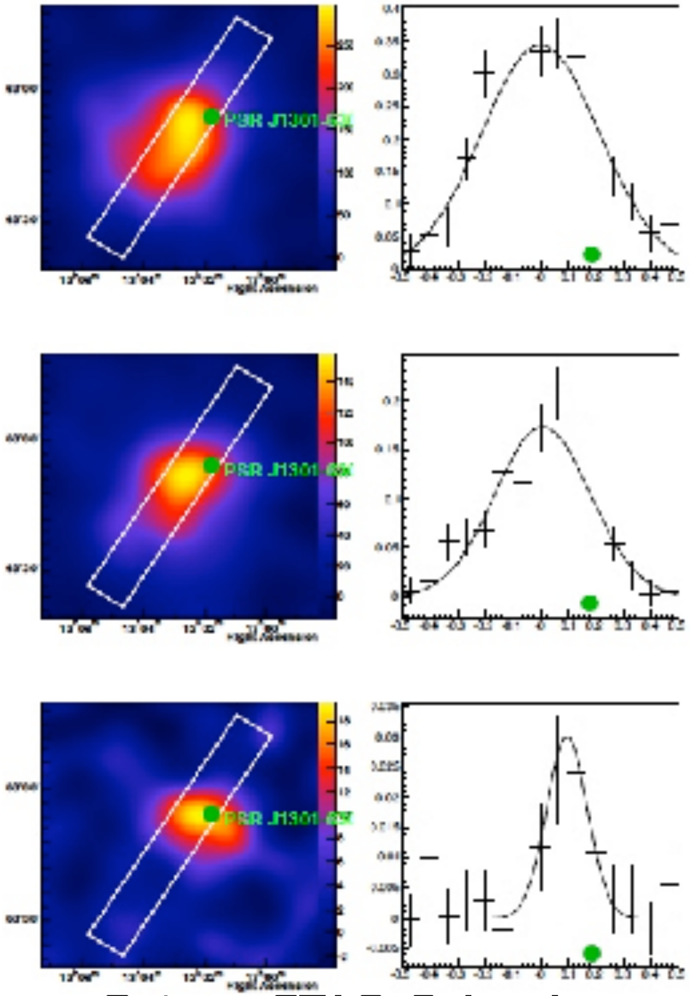


Aharonian et al (HESS) 2005

Accelerators: Pulsar Wind Nebulae

Evolved PWNe





- Shrinking towards high energies
- But keep in mind for evolved systems we mix:
  - Inverse Compton cooling time
  - Diffusion

Accelerators: Pulsar Wind Nebulae

Evolved PWNe

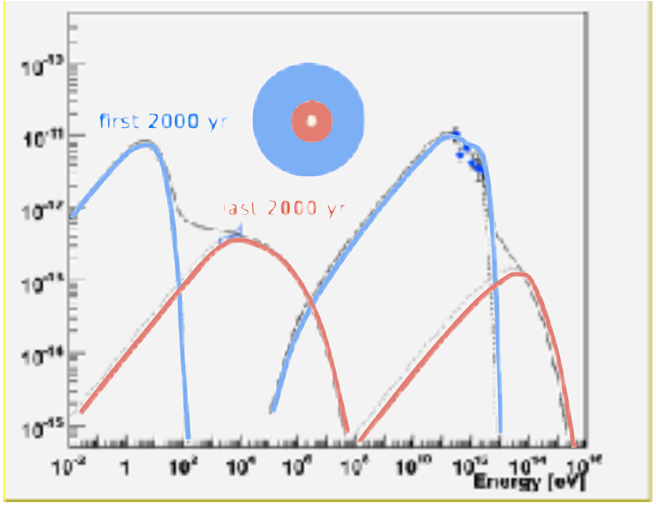
Spectral variation with distance from the pulsar could result from:

- **energy loss of particles during propagation**, with radiative cooling of electrons propagating outward from the pulsar termination shock

- **energy dependent** diffusion or convection **speeds**

- **variation of the shape of the injection spectrum** with age of the pulsar which, after propagation, translates into a spatial variation of spectra.

- If α = electron index -> synchrotron cooling (τ_{syn} ~400 $B^{-2}_{G} E^{-1}_{TeV}$ s)
  $\Delta\alpha = 1 \rightarrow \Delta\Gamma = 1/2$

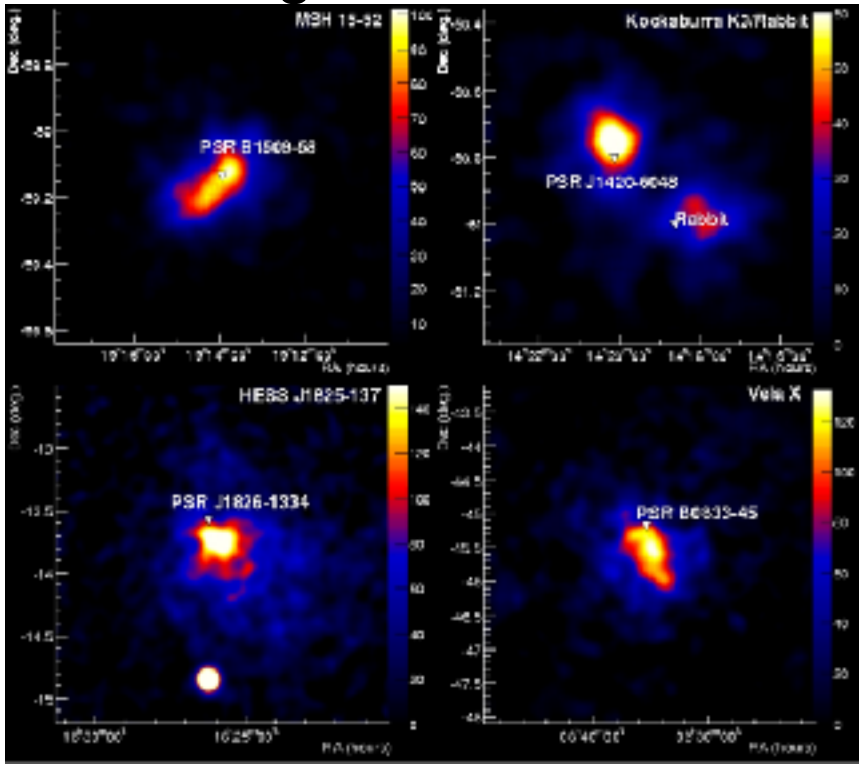


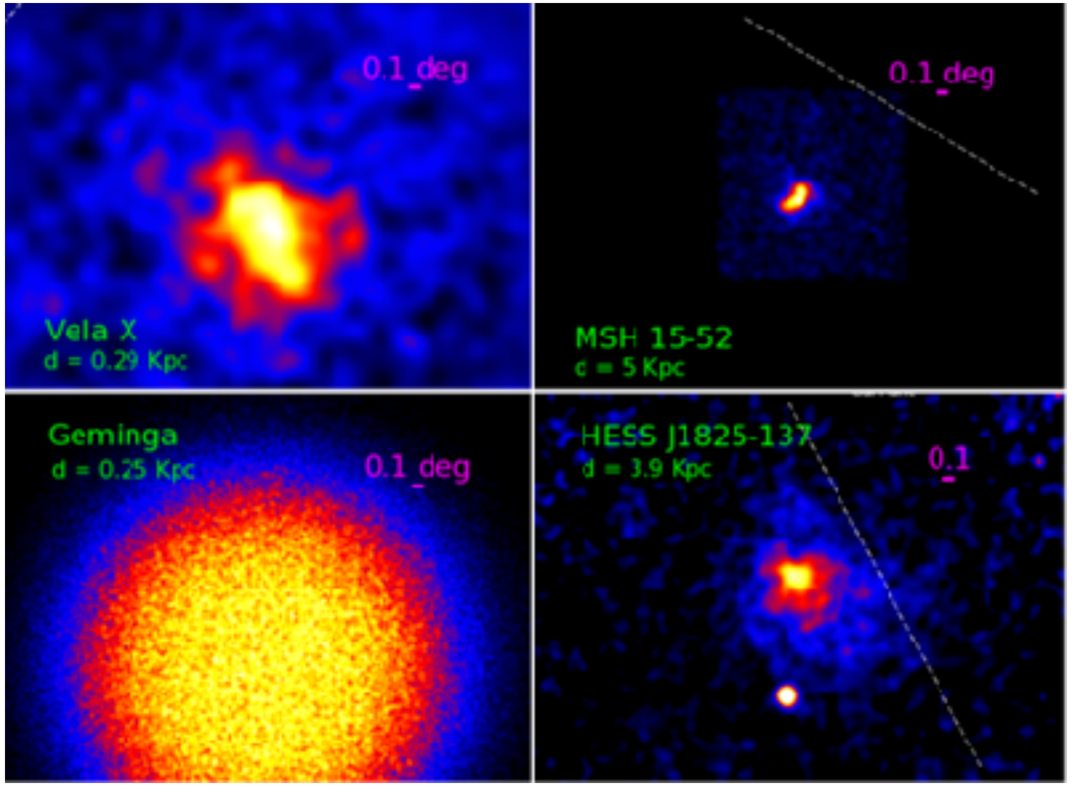
Hofmann 2009

Accelerators: Pulsar Wind Nebulae

Evolved PWNe

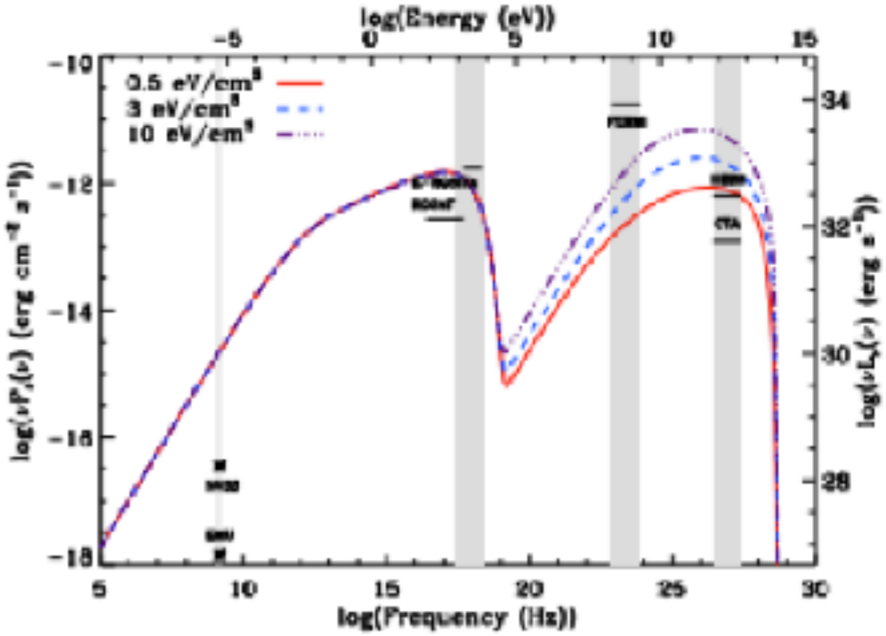
- In comparison with other sources of relativistic magnetised plasma, PWNe can be resolved in great detail

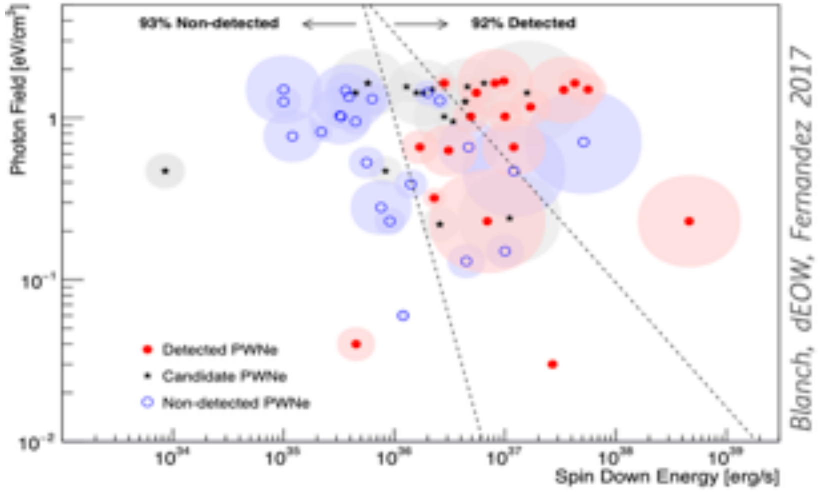


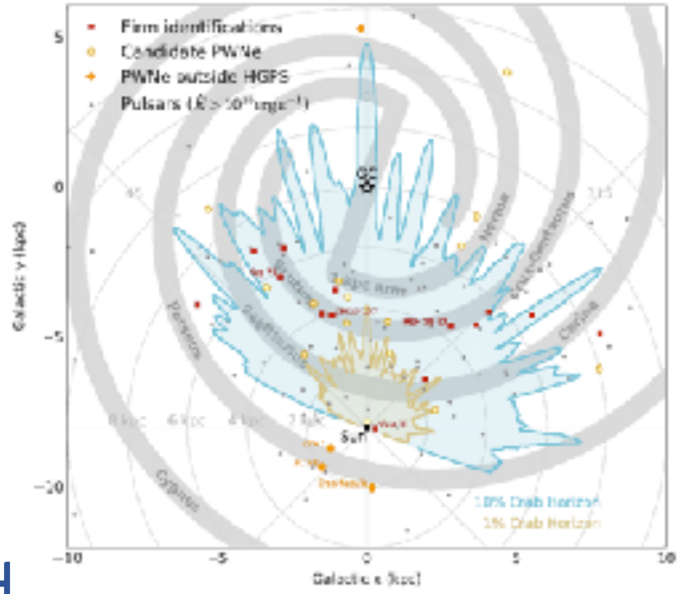


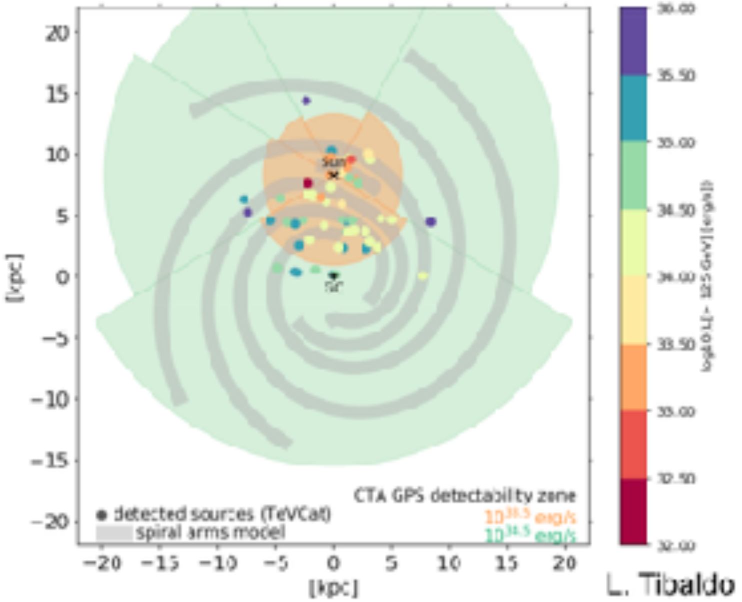
Accelerators: Pulsar Wind Nebulae

Understanding the ISM / photon fields







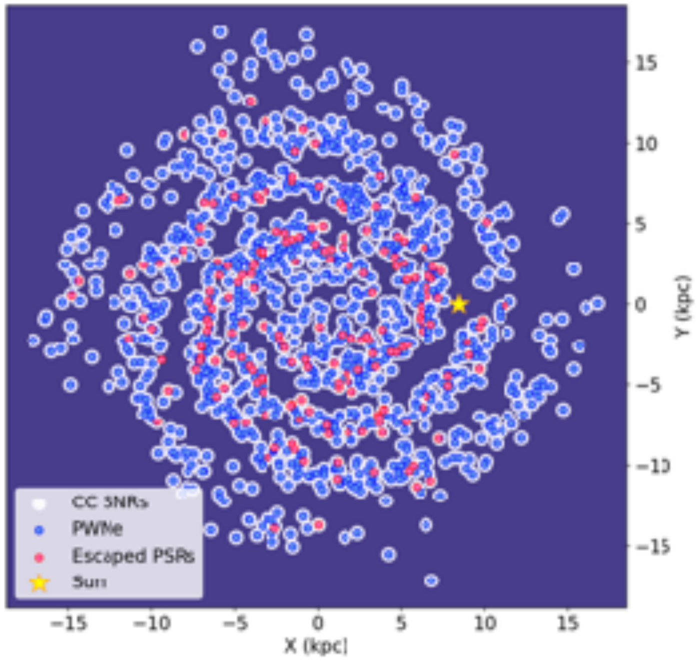


L. Tibaldo

PWNe: Population studies

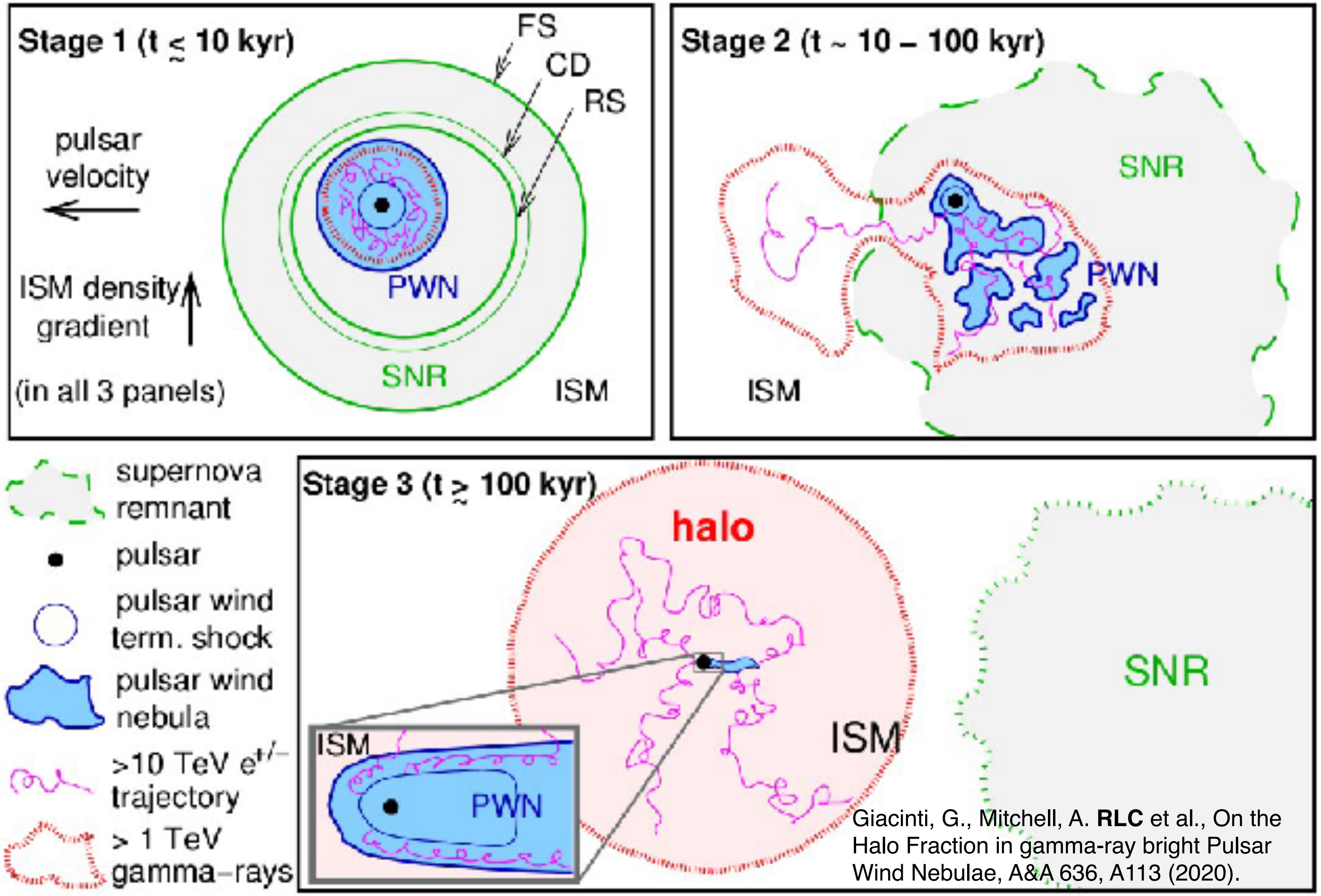
- PWNe will be the dominant sources in gamma rays (de Oña-Wilhelmi et al. 2013, Klepser et al. 2013, Abdalla et al. 2018)
- Current number of detected PWNe: ~30-40
- Estimated number in the first CTAO Galactic Plane Survey: ~200 (Fiori et al. 2022)

- We need to refine radiative models to take into account morphology, reverberation, proper ejecta profiles…
- More information implies a deeper understanding of PWN evolution and emission



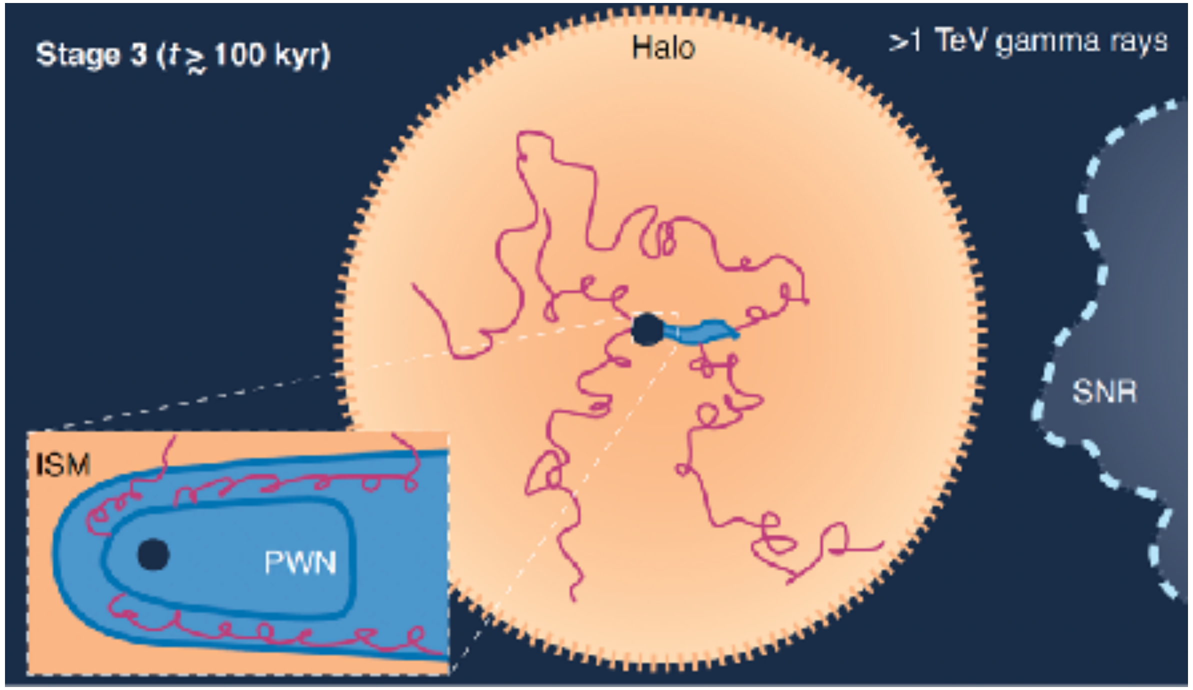
Pulsar Haloes

Definition of Pulsar (TeV) halos

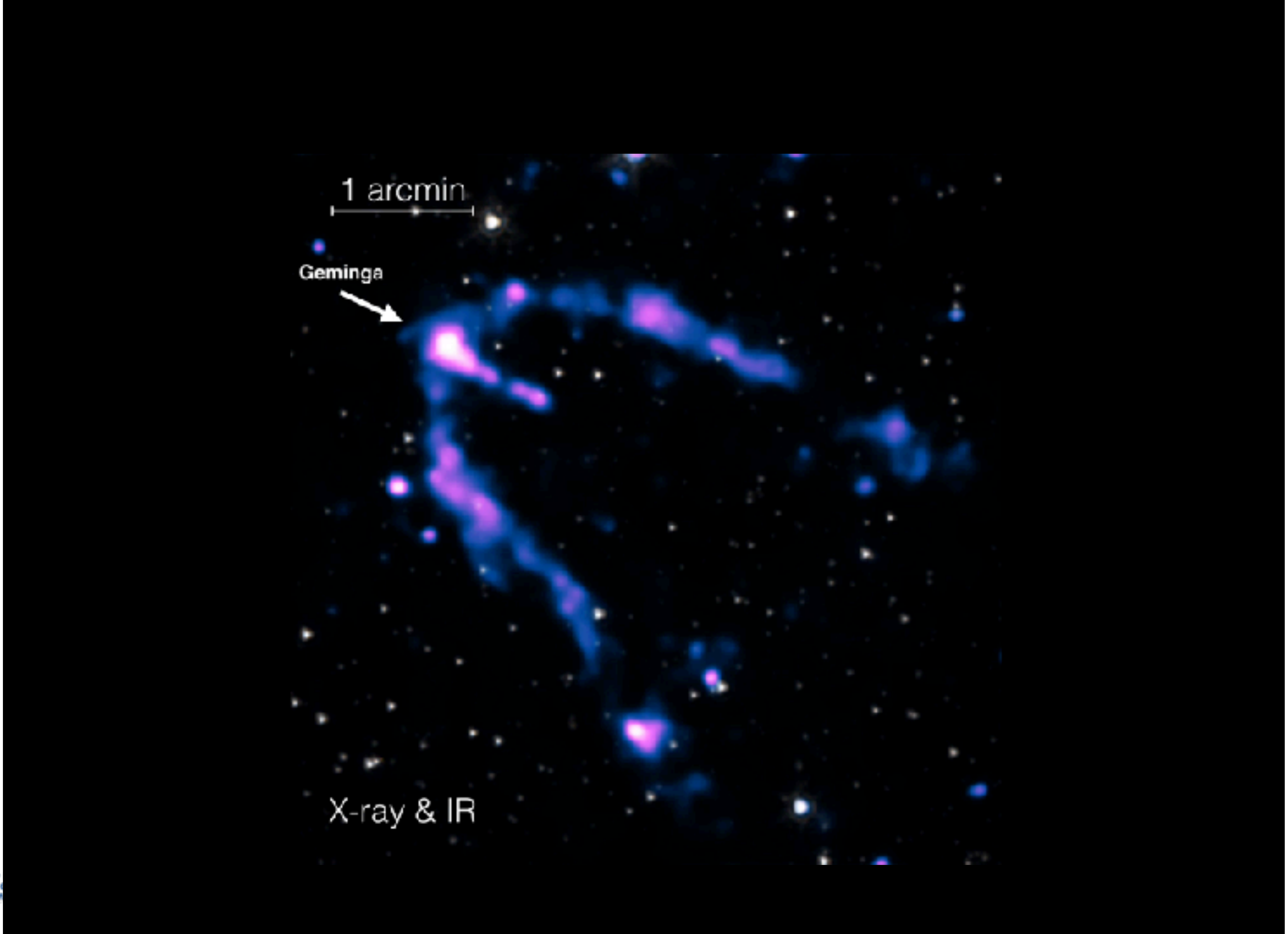


Giacinti, G., Mitchell, A. **RLC** et al., On the Halo Fraction in gamma-ray bright Pulsar Wind Nebulae, A&A 636, A113 (2020).

Pulsar halos

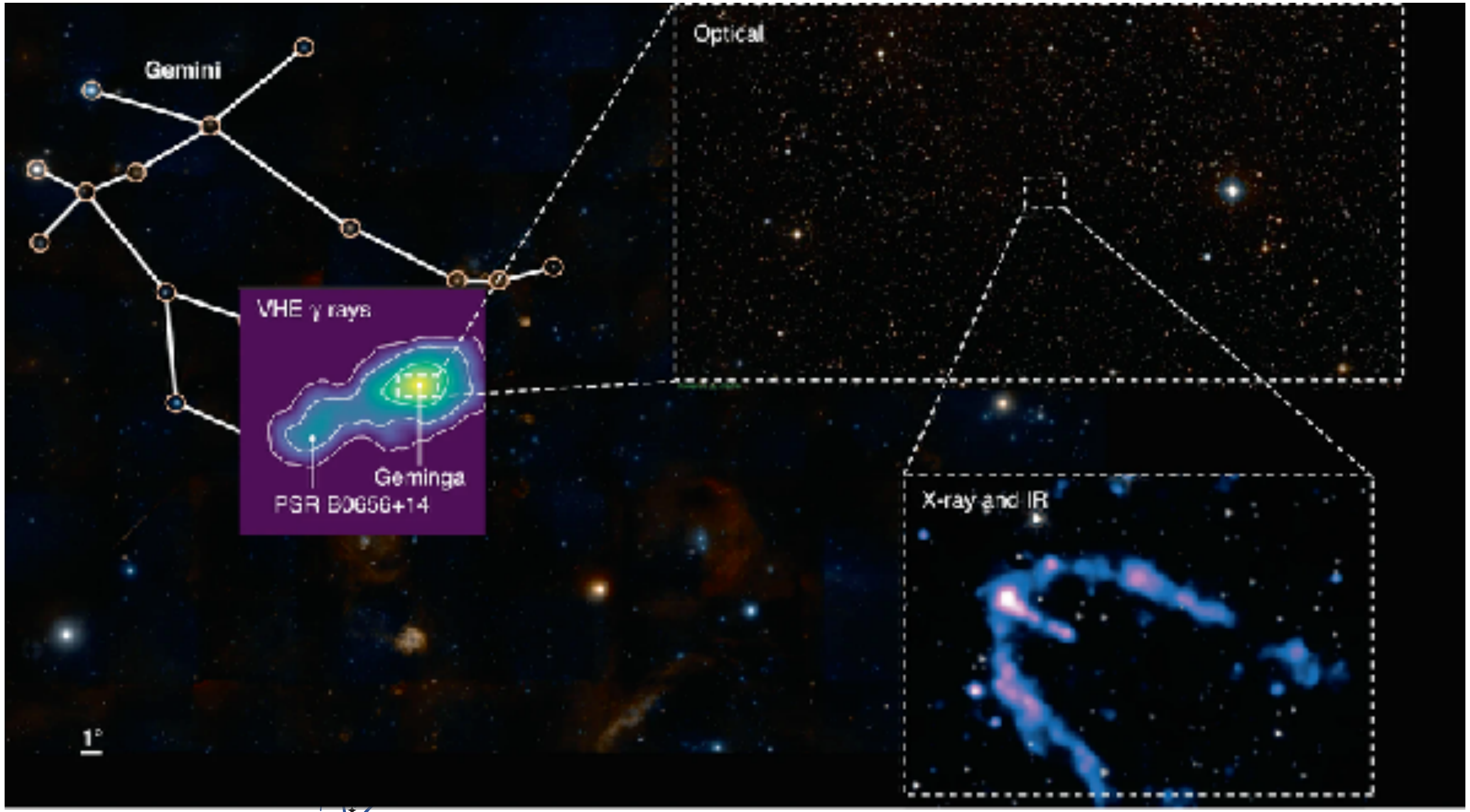


- Bright at multi-TeV energies
- Produced by very high energy electrons (~100 TeV) inverse Compton upscattering CMB.
  - They propagate in a magnetic field that is at least two orders of magnitude more turbulent than that of the ISM.
- Electrons do not dominate over the energetics in the ISM

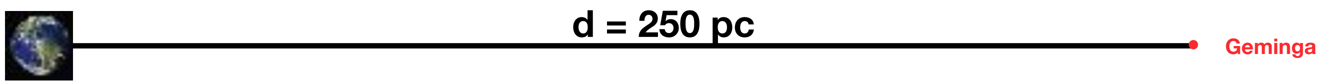

1 arcmin
Geminga
X-ray & IR

Accelerators: Haloes

Halos: Study the diffusion of particles in the Galaxy

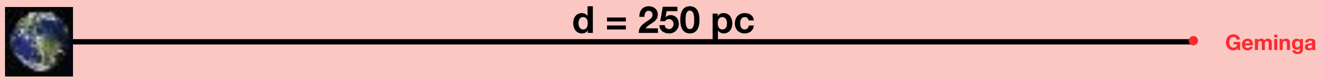


Energetics in Geminga



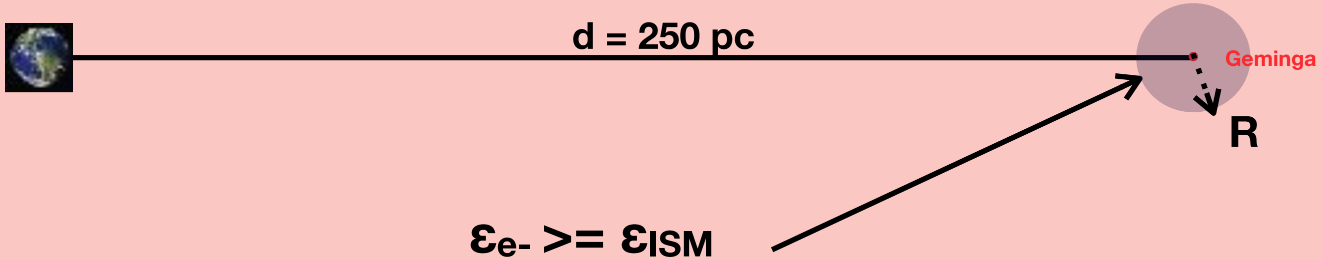
Energetics in Geminga

$\varepsilon_{ISM} \sim 2\text{-}3\ eV/cm^3$



Energetics in Geminga

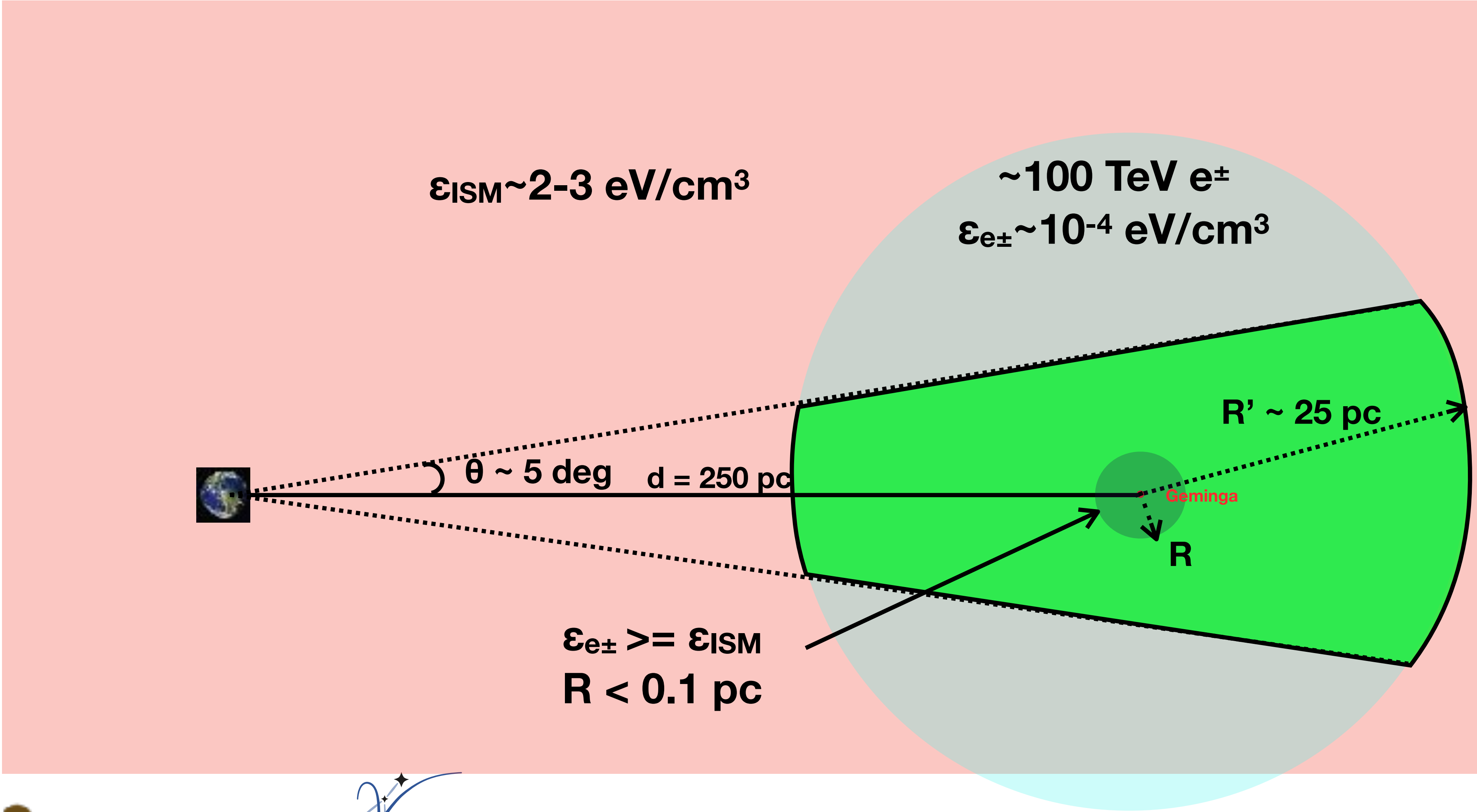
ε_{ISM}~2-3 eV/cm^3



$\varepsilon_{e-} >= \varepsilon_{ISM}$

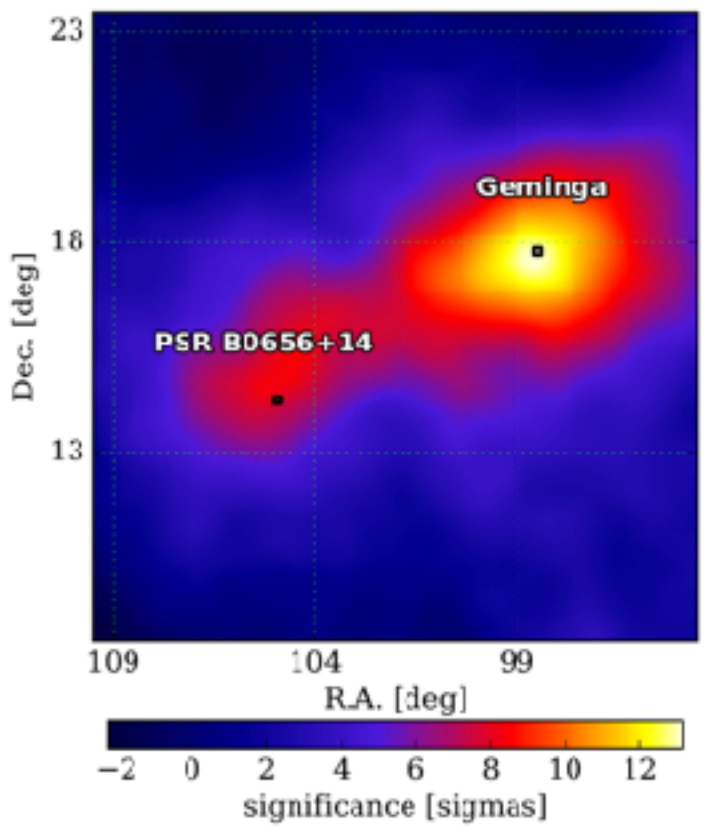
$R < 0.1$ pc

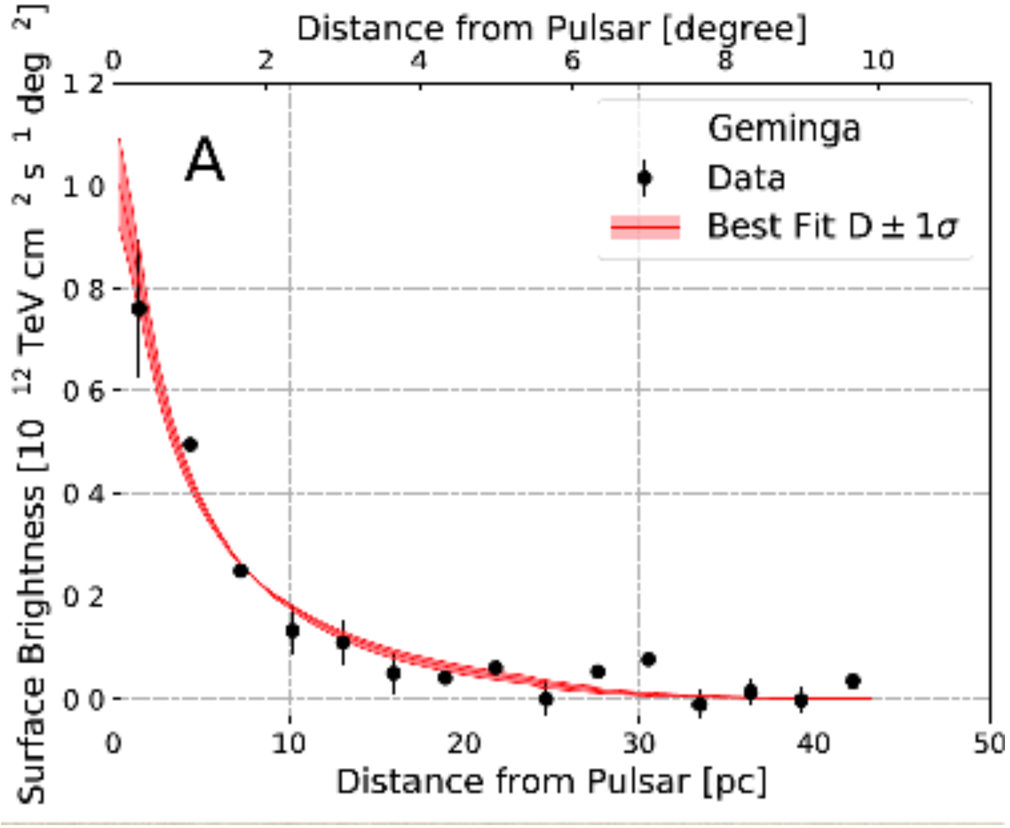
Energetics in Geminga



Accelerators: Haloes

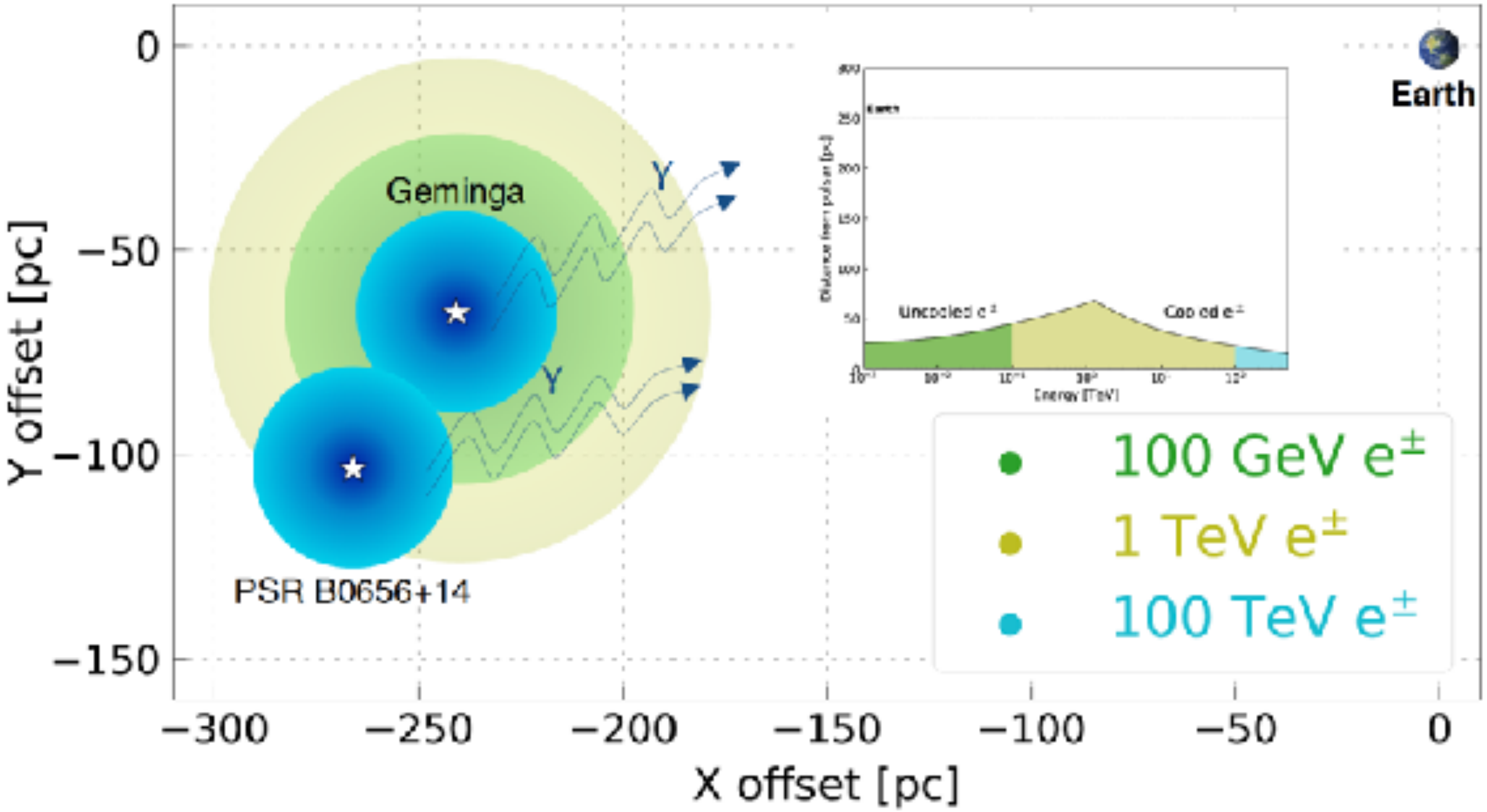
Halos: Study the diffusion of particles in the Galaxy





Accelerators: Haloes

Halos: Study the diffusion of particles in the Galaxy

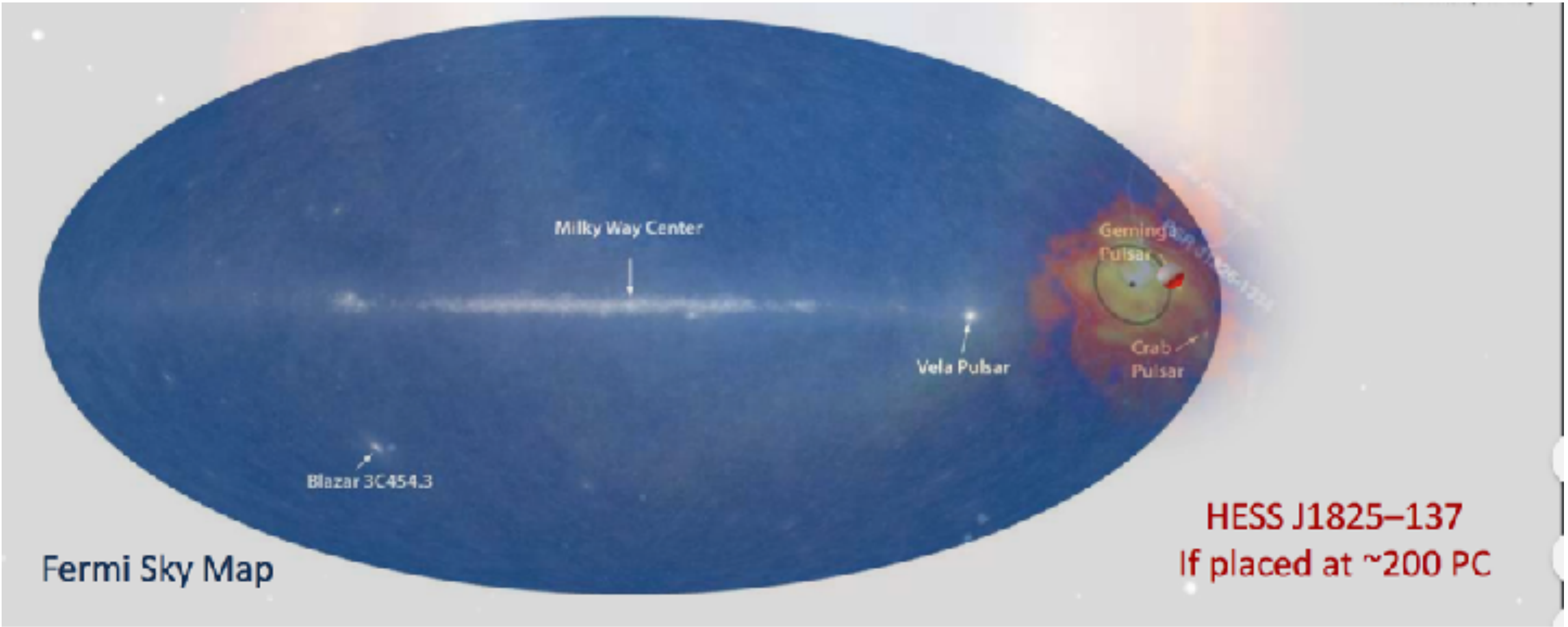


$$D(E) \approx 2 \times 10^{28}\ \mathrm{cm^2\ s^{-1}}\ \xi_{B,0.1}^{-1} \left(\frac{\lambda_{\rm pc}}{E_{\rm TeV}} \right)^{\alpha-1} B_{\mu}^{\alpha-2}$$

D ~ 4.5 x 10^{27} cm^2/s
(mean value in the ISM is ~10^{30} cm^2/s)

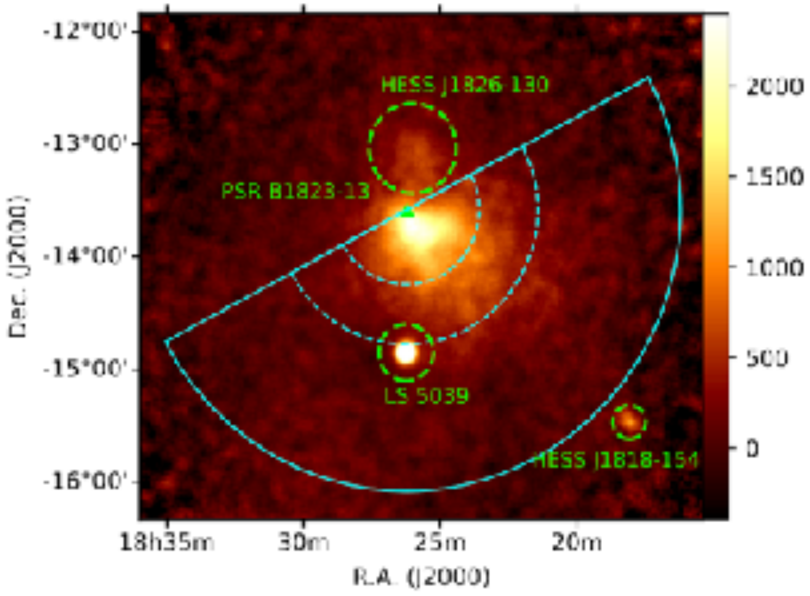
Accelerators: Haloes

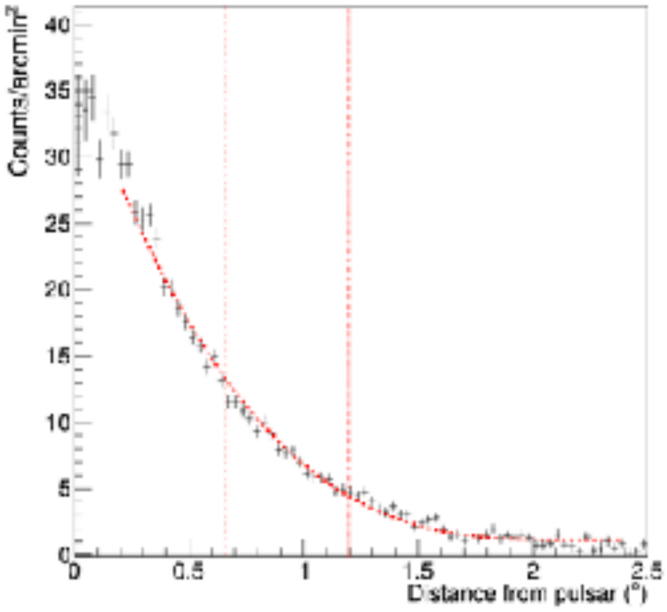
Halos: Study the diffusion of particles in the Galaxy

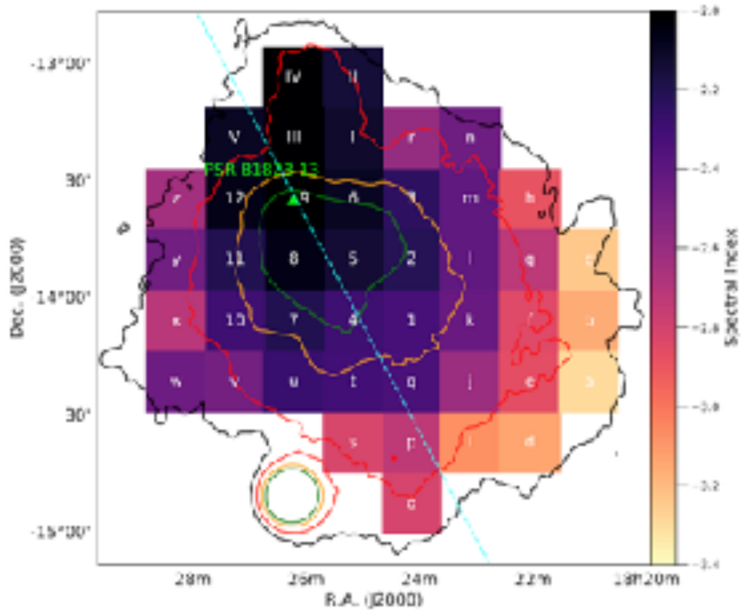


Accelerators: Haloes

Halos: Study the diffusion of particles in the Galaxy

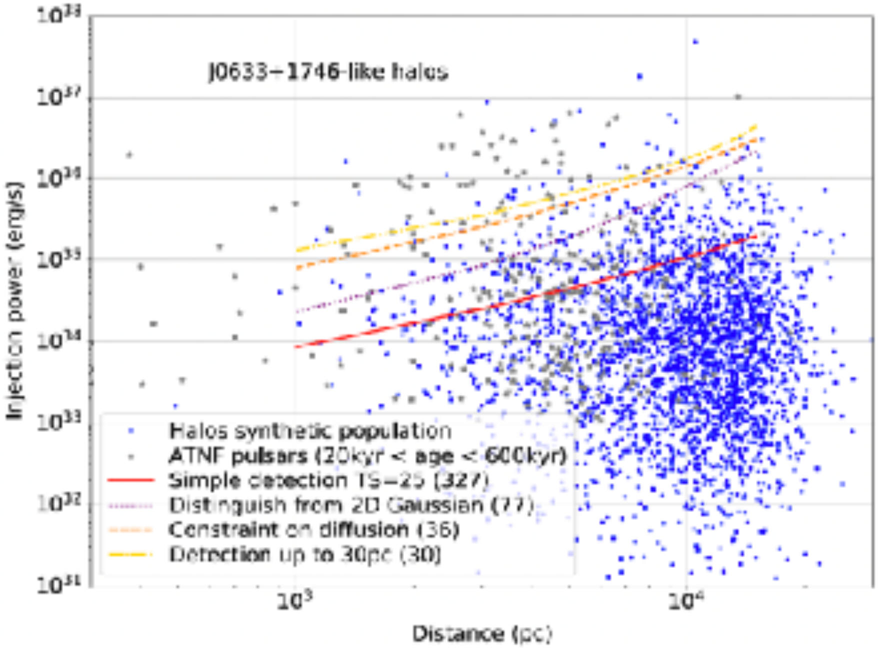




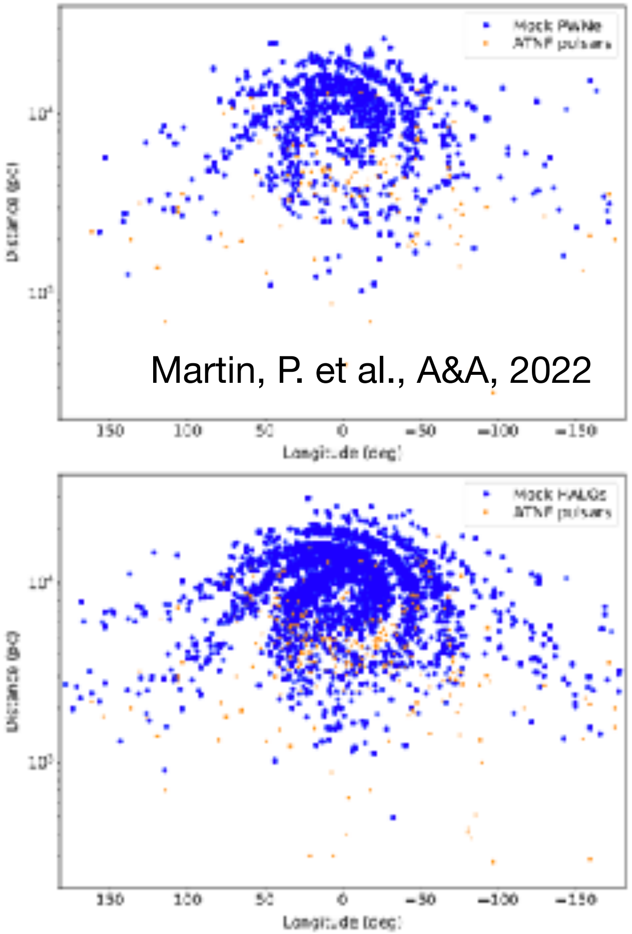


Pulsar Halos: Population Studies

- Recent papers on prospects:
  - Most optimistic scenarios foresee up to 200 halos (!)
  - Detailed characterization is more difficult, only reachable by combining good sensitivity and angular resolution



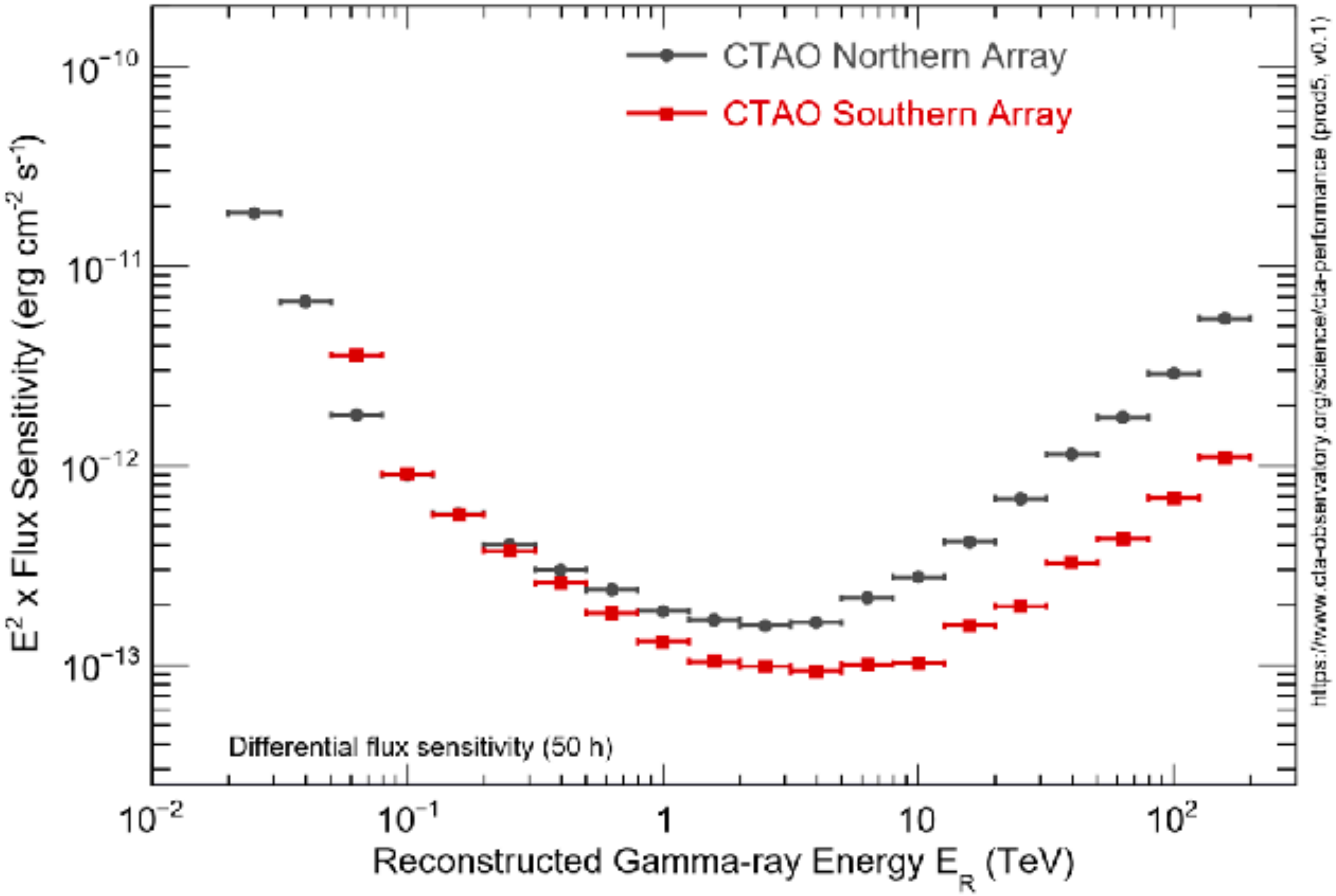
Vodeb, V., Gamma 2022



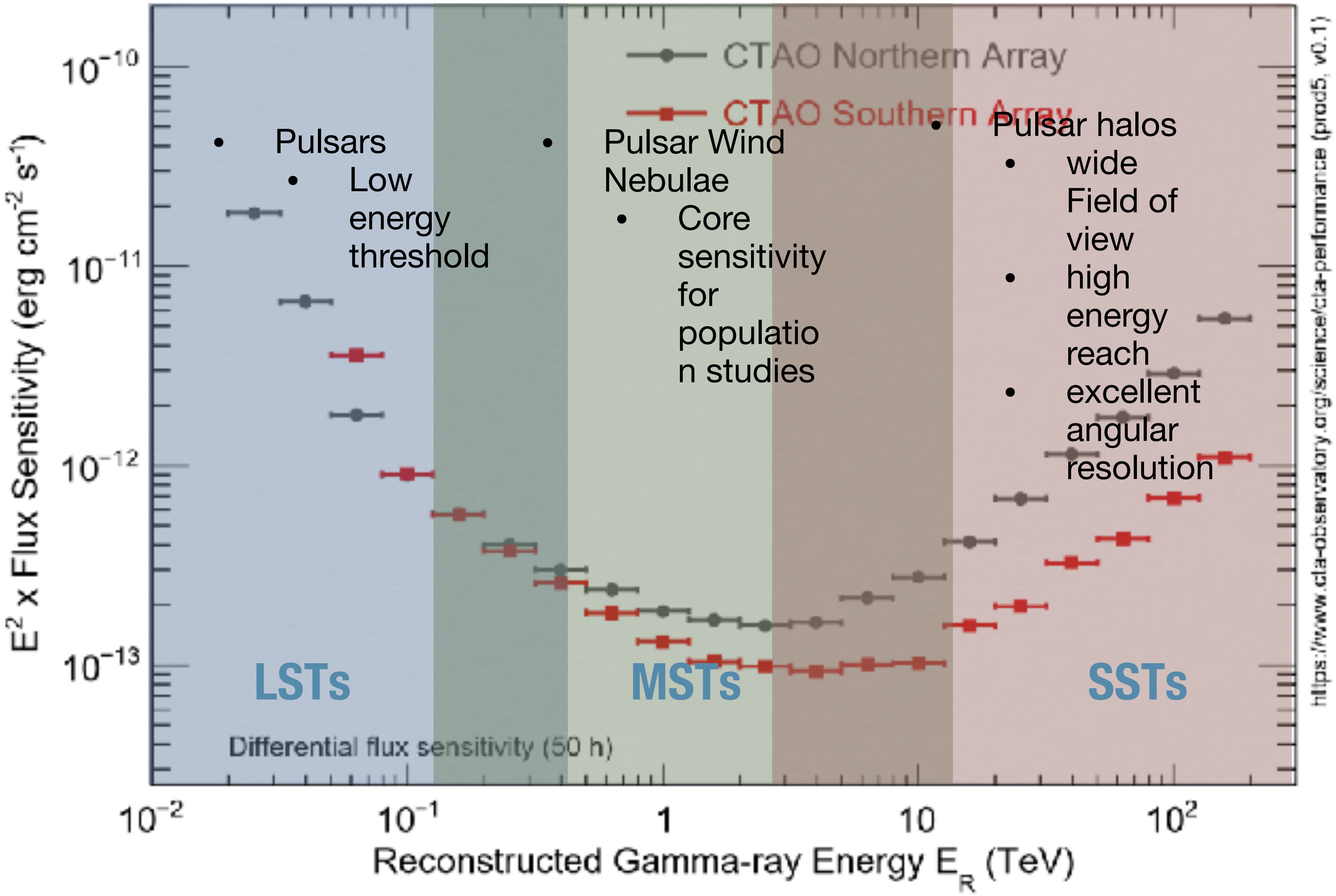
Martin, P. et al., A&A, 2022

Fig. 1: Spatial distribution of mock PWNe and halos in the Galactic plane, for halos with suppressed diffusion region of size 50 pc and diffusion suppression by a factor 500. Overlaid for comparison and cross-check are the positions of a set of pulsars from the ATNF database within the same age ranges (characteristic ages < 100 kyr for PWNe and < 400 kyr for halos).

CTAO Sensitivity



CTAO Sensitivity



- Pulsars
  - Low energy threshold
- Pulsar Wind Nebulae
  - Core sensitivity for populatio n studies
- Pulsar halos
  - wide Field of view
  - high energy reach
  - excellent angular resolution

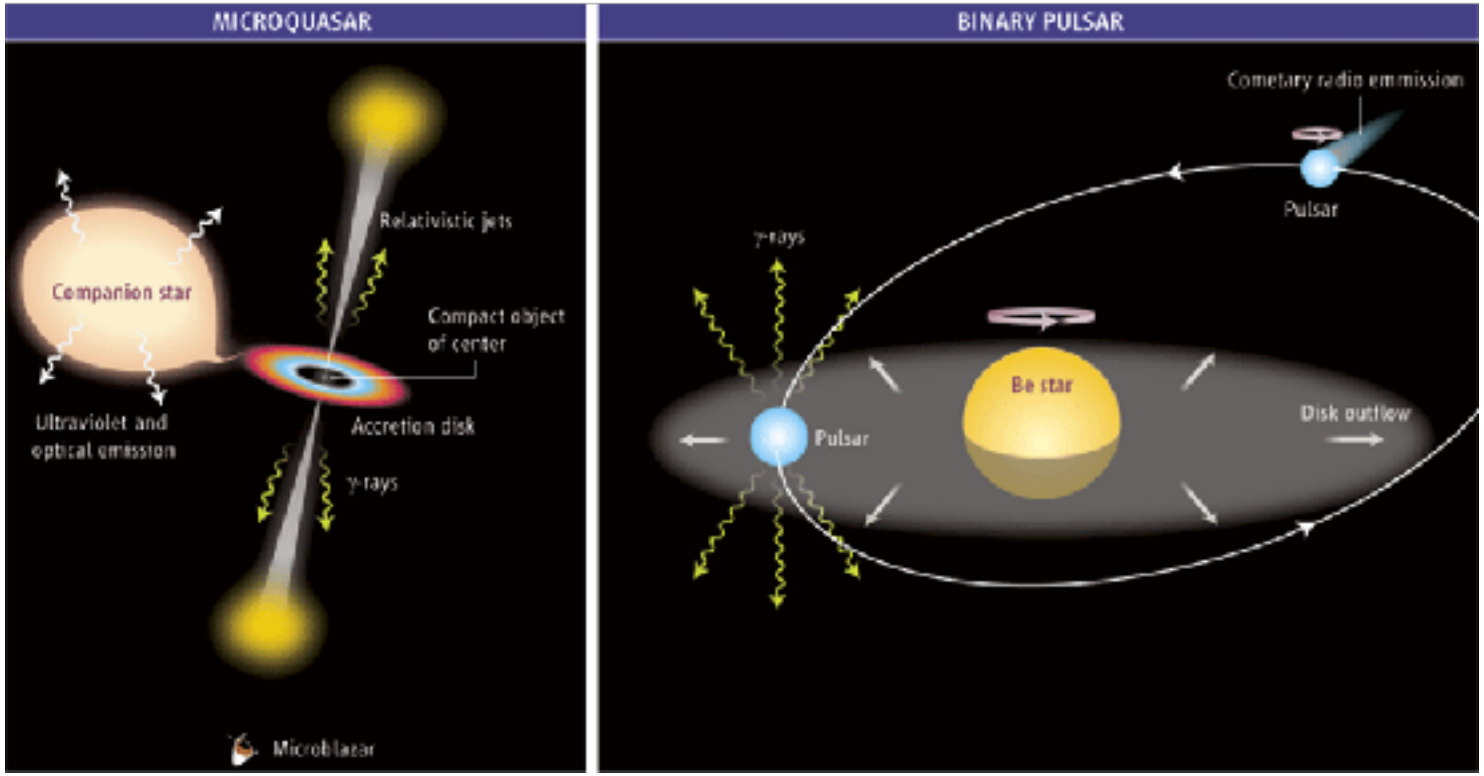
VHE gamma rays - **Future**

what do we want to learn?

Pulsars	PWNe	Halos
• More Pulsars • Extend energy range	• More and more detailed PWNe • Include morphology and evolution in the modeling	• IACT detection and study

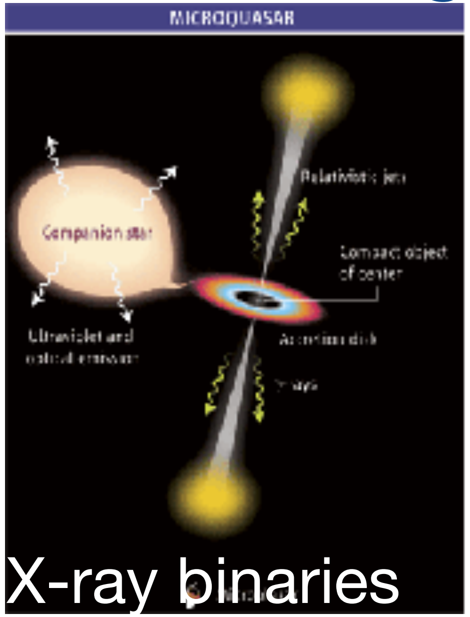
Binary systems

Binary systems

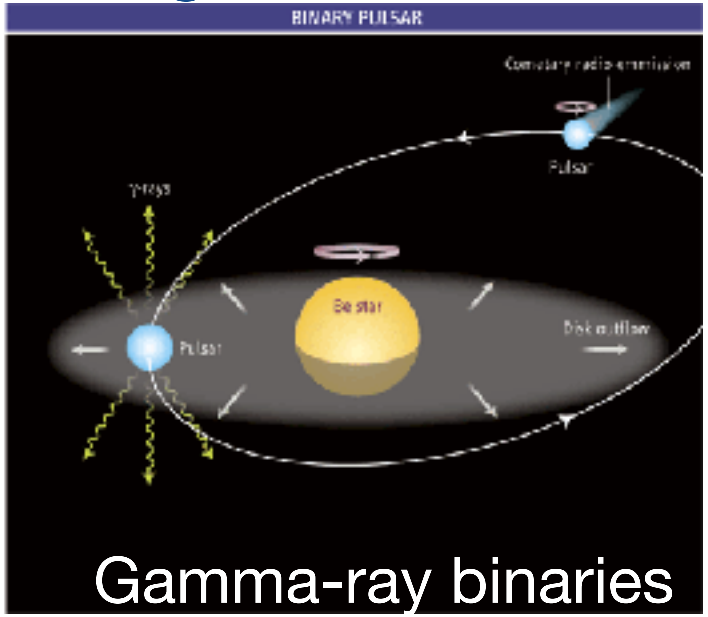


- Composed by a compact object (Neutron star or Black Hole) plus a massive companion

Binary system fauna

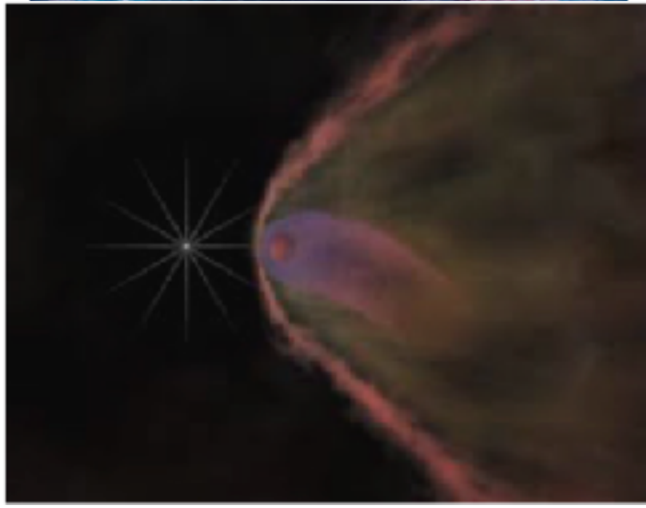


X-ray binaries



Gamma-ray binaries

Colliding wind binaries

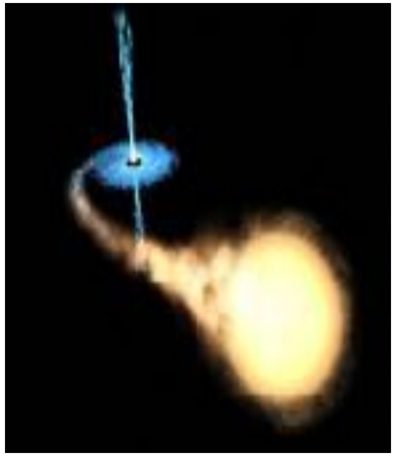


Transitional ms pulsars

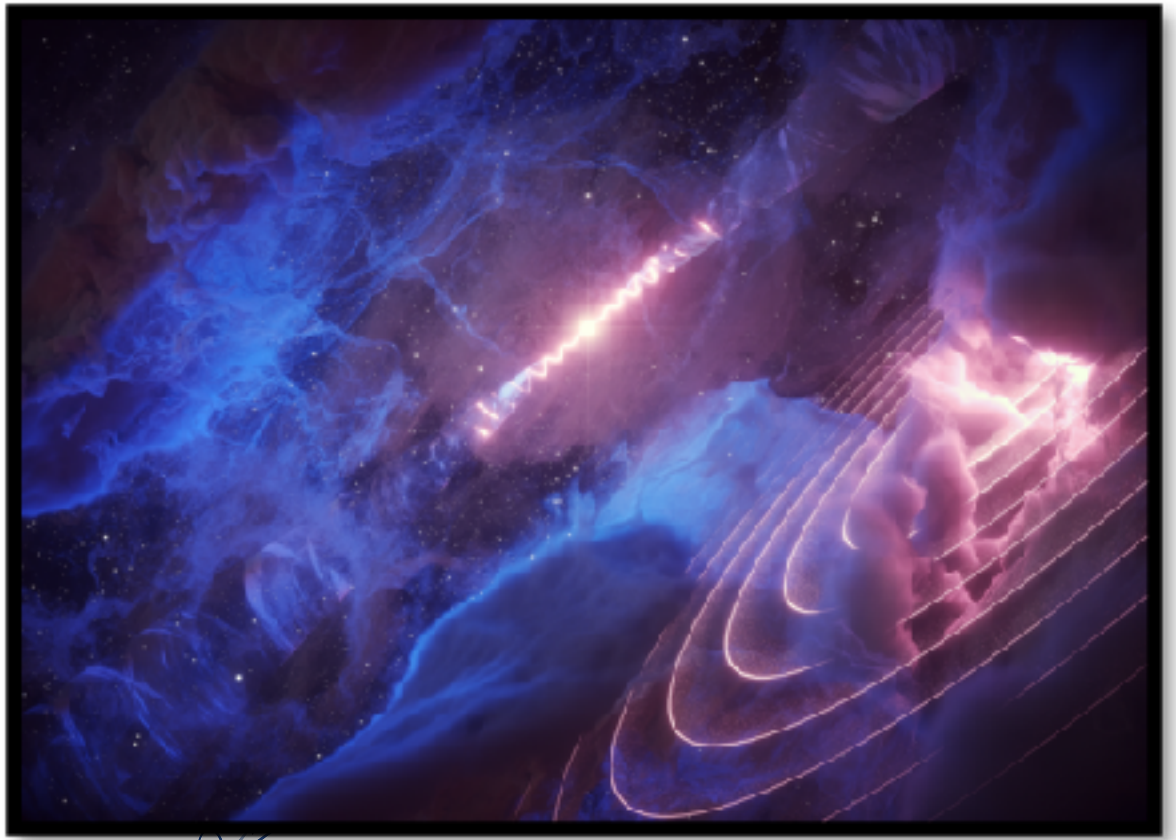
Cataclysmic variable stars

- Novae

Binary systems



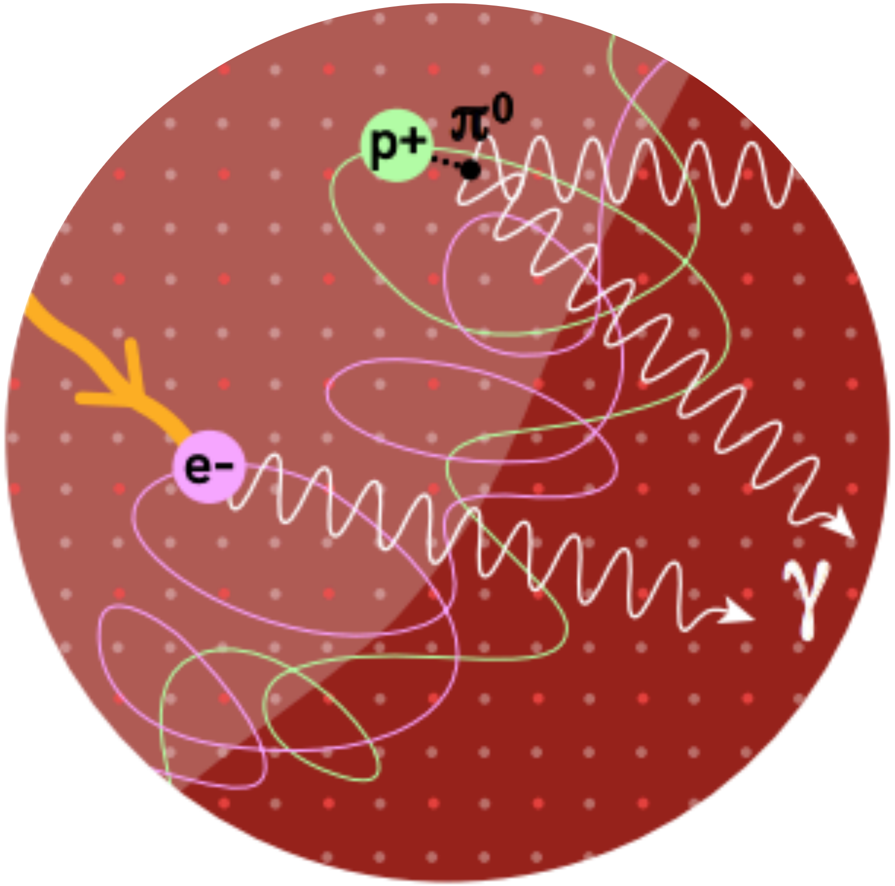
- Photon field enhanced by the massive companion - modulated emission!



Binaries: Leptonic/hadronic acceleration

- Leptonic models: Dominated by Inverse Compton on photon fields
  - Synchrotron Self Compton relativistic in the jets with jet photons.
  - External Compton: relativistic e- in the jets with photon field of companion star

- Hadronic models: Dominated by proton collisions and pion decay
  - Jet interaction with companion stellar wind
  - Jet protons with ISM

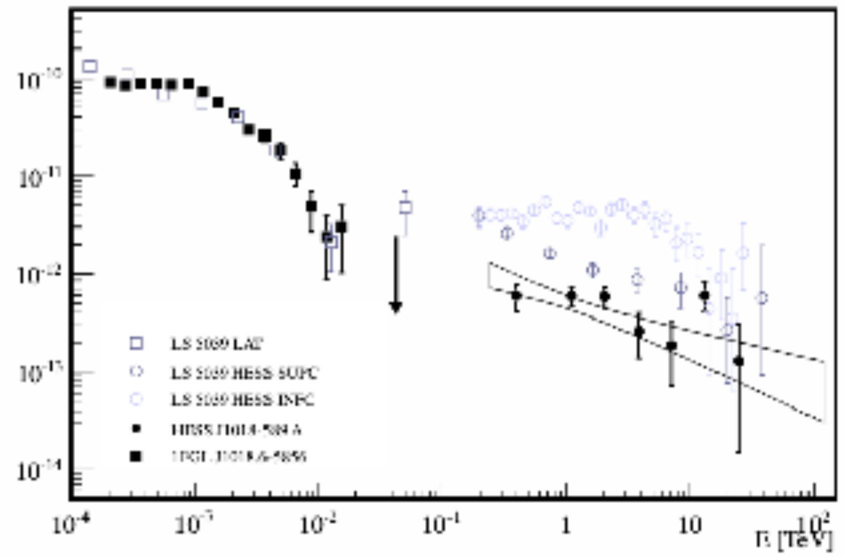


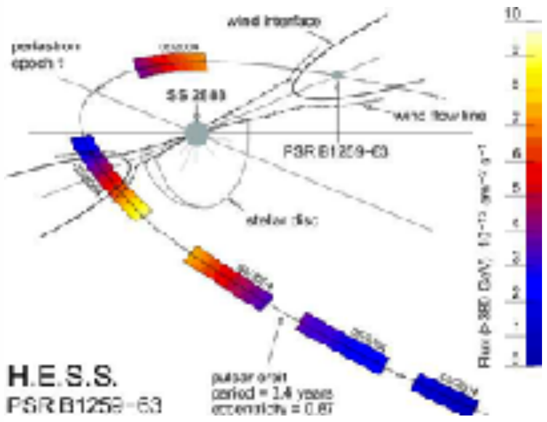
LHAASO 2024

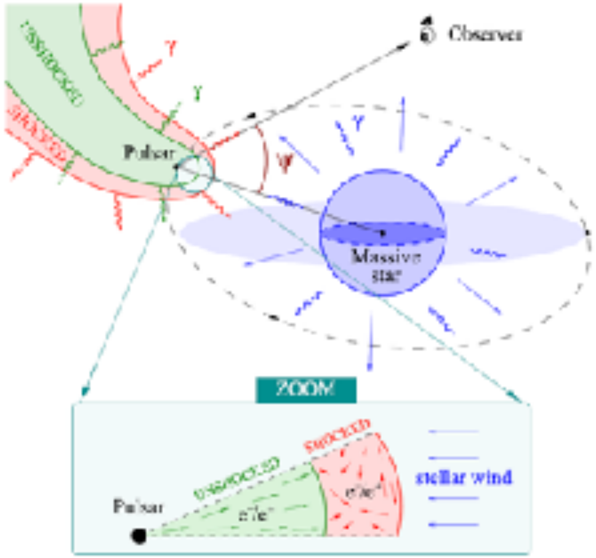
Compact object in binary systems

Gamma-ray Binaries

- GeV and TeV often uncorrelated:
  - Max of orbital light curve
  - Two spectral components
  - Flares and rich phenomenology

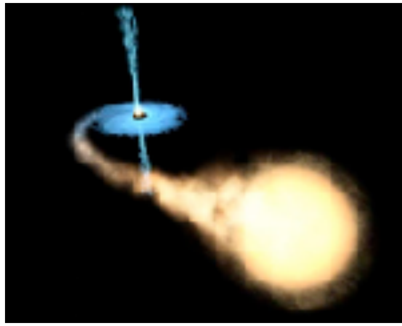






	Flux (% Crab)	D (Kpc)	Flux variability (HE/VHE)	Periodic
LSI +61 303	0-15	2	yes/yes	yes (~1 month)
LS 5039	5-15	2.5	yes/yes	yes (~4 days)
PSR B1259-63	0-10	1.5	yes/yes	yes (~3.4 years)
HESS J0632+057	0-3	1.5	no/yes	yes (~300 days)
...	...	...	...	...

Compact object in binary systems

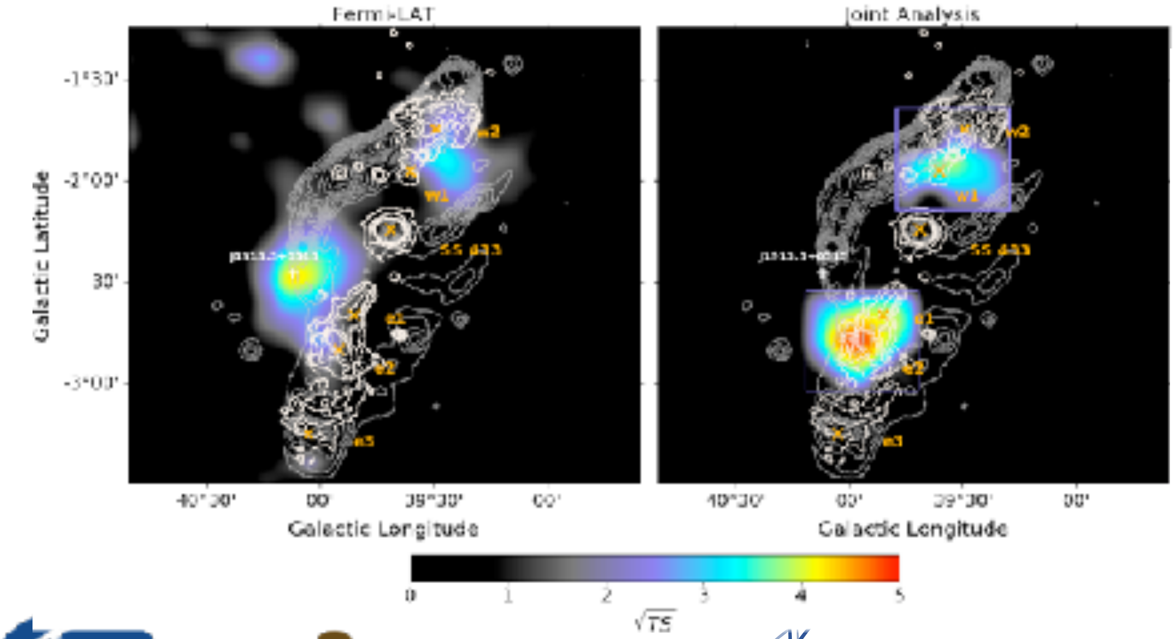


Gamma-ray Binaries

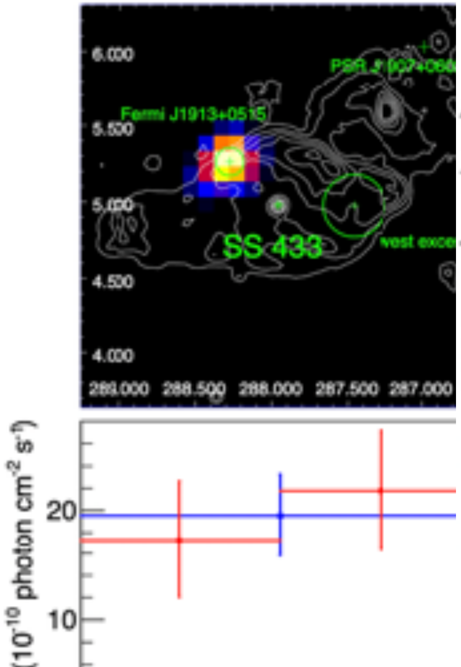
- GeV and TeV often uncorrelated:
  - Max of orbital light curve
  - Two spectral components
  - Flares and rich phenomenology

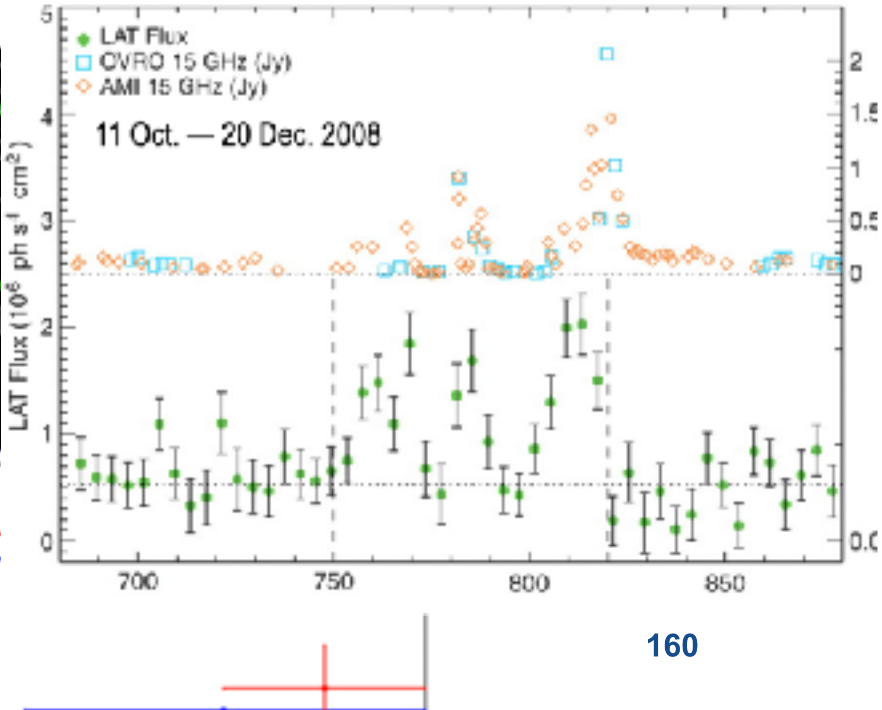
Microquasars

- Black hole + massive companion
- GeV detection associated to X-ray activities
- GeV/TeV detection associated to jets



Li et al, 2020





precessing with a period of 162.250 days

Compact object in binary systems

Gamma-ray Binaries

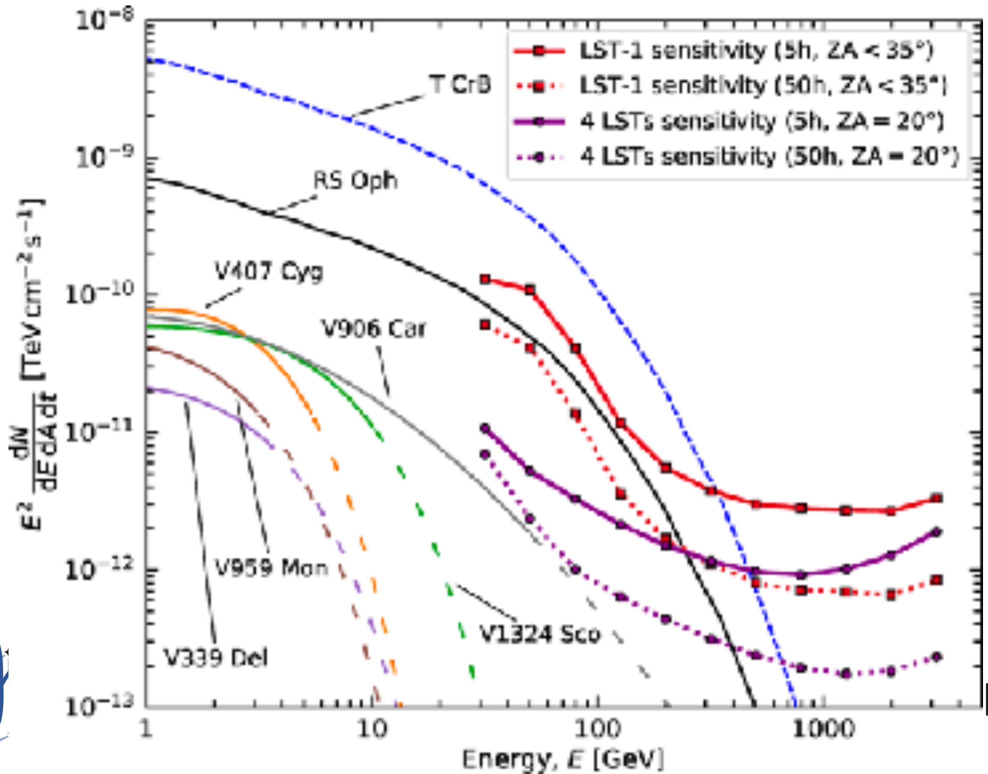
- GeV and TeV often uncorrelated:
  - Max of orbital light curve
  - Two spectral components
  - Flares and rich phenomenology

Microquasars

- Black hole + massive companion
- GeV detection associated to X-ray activities
- GeV/TeV detection associated to jets

Novae

- GeV Detection of a few
- First TeV detection of RS Oph

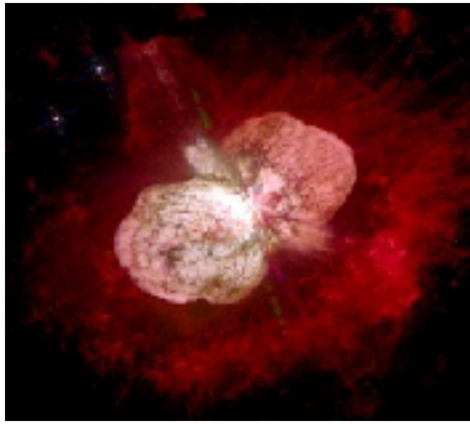


Credit: A. Aguasca-Cabot

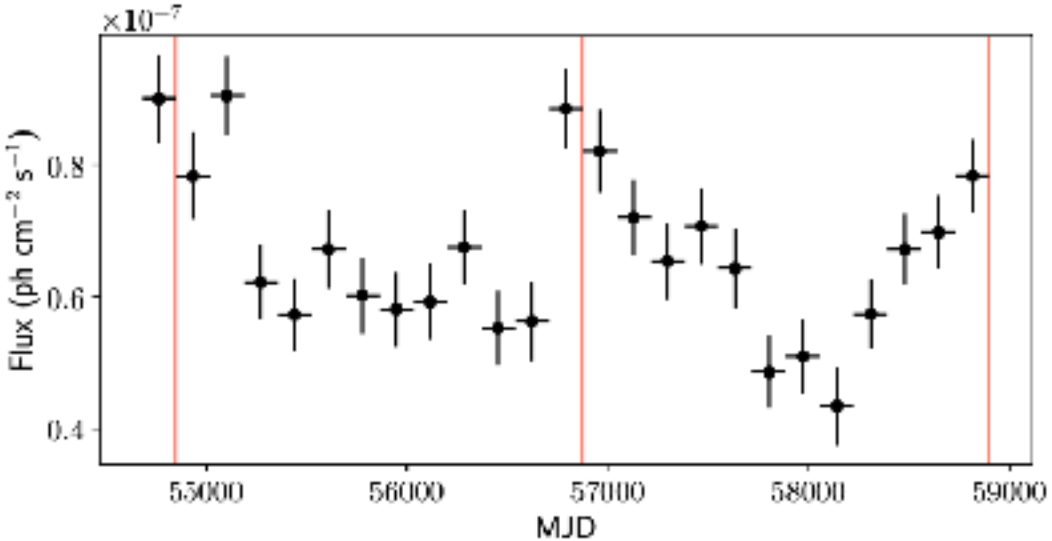
Gamma-ray binaries

- Binary system: massive O/Be star and compact object of unknown nature
  - 9 binary systems detected at GeV and/or TeV energies:
  - 3 contain young non-accreting pulsars: PSR B1259-63, PSR J2032+4127 and LS I +61 303.
- Very different orbital configurations: periods from 4 d to 50 yr and eccentricities from 0.3 to 0.95 => very different separations (0.1-100 AU).
- VLBI observations show extended, cometary tail-like morphologies, sometimes forming bipolar structures like microquasars.
- The X-ray flux is modulated with the orbital period, but with maximum different from the periastron. No clear accretion signatures, no X-ray pulsations.
- GeV spectra can be fitted with a power law + exponential cutoff, like for pulsar magnetospheres, but the emission is variable(!) and periodic.
- TeV emission is periodic and to first order correlated with X-ray emission.

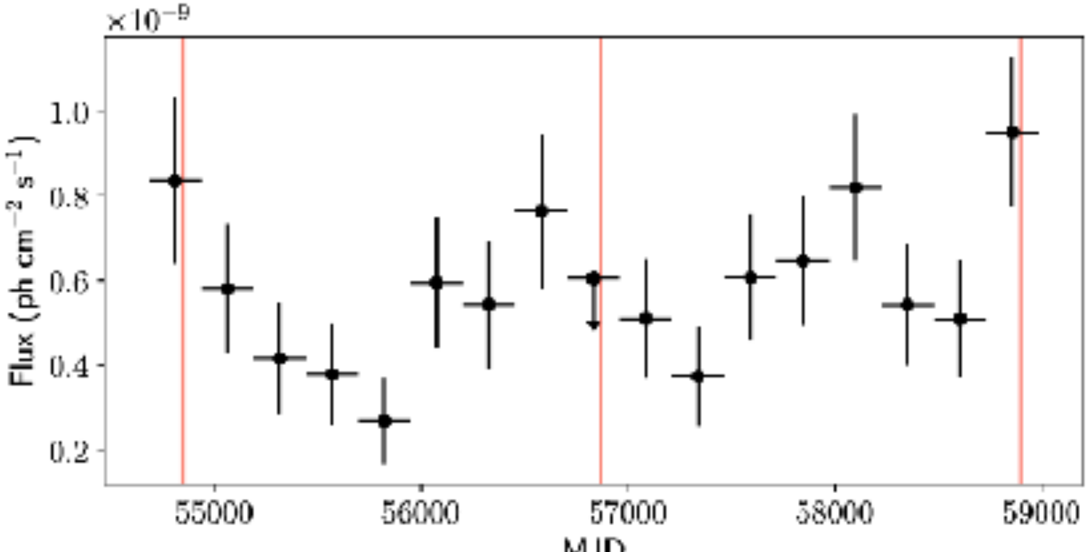
Colliding wind binaries

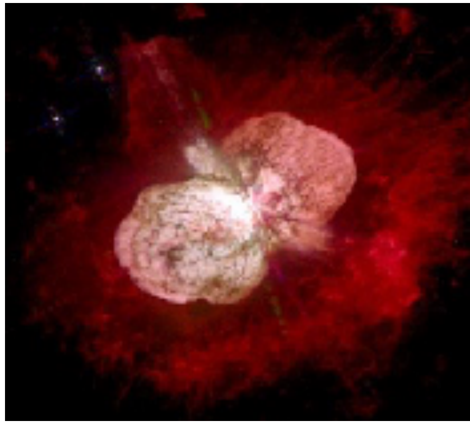


- Eta Carinae
  - Fermi/LAT data during 12yr show 5.5 yr orbital variability in Eta Carinae.
- This can be understood and interpreted in a colliding-wind binary scenario for orbital modulation of the gamma-ray emission.
- The lightcurves change from cycle to cycle.
- The spectral shape in each periastron passage is different.
- These facts strongly suggest that the wind collision region of this system is perturbed from orbit to orbit, affecting particle transport within the shock



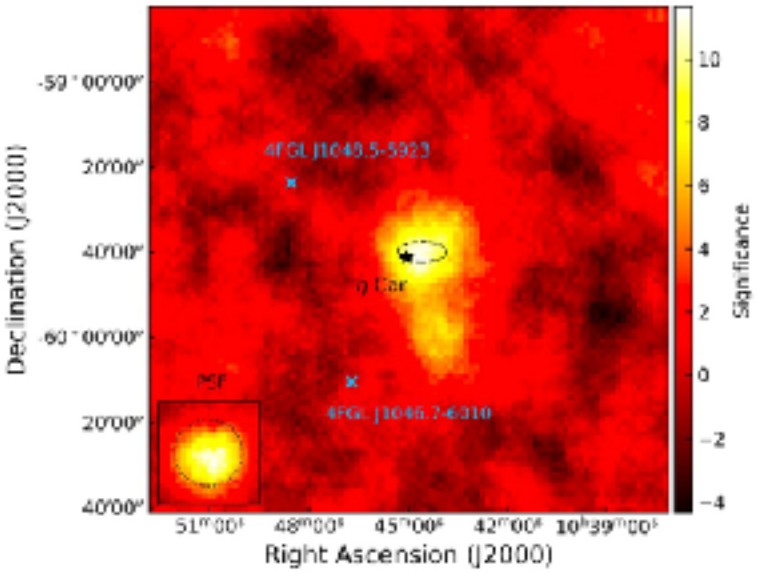
R. López

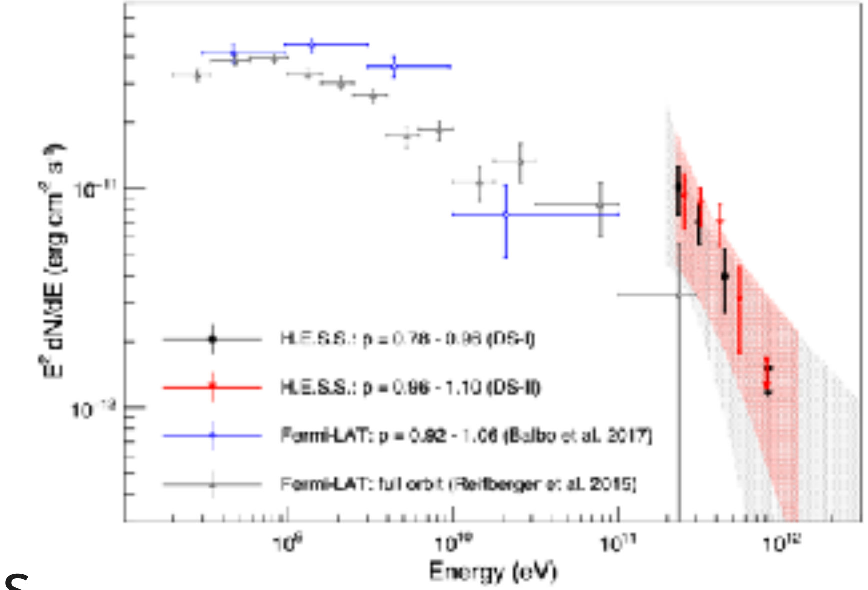




Colliding wind binaries

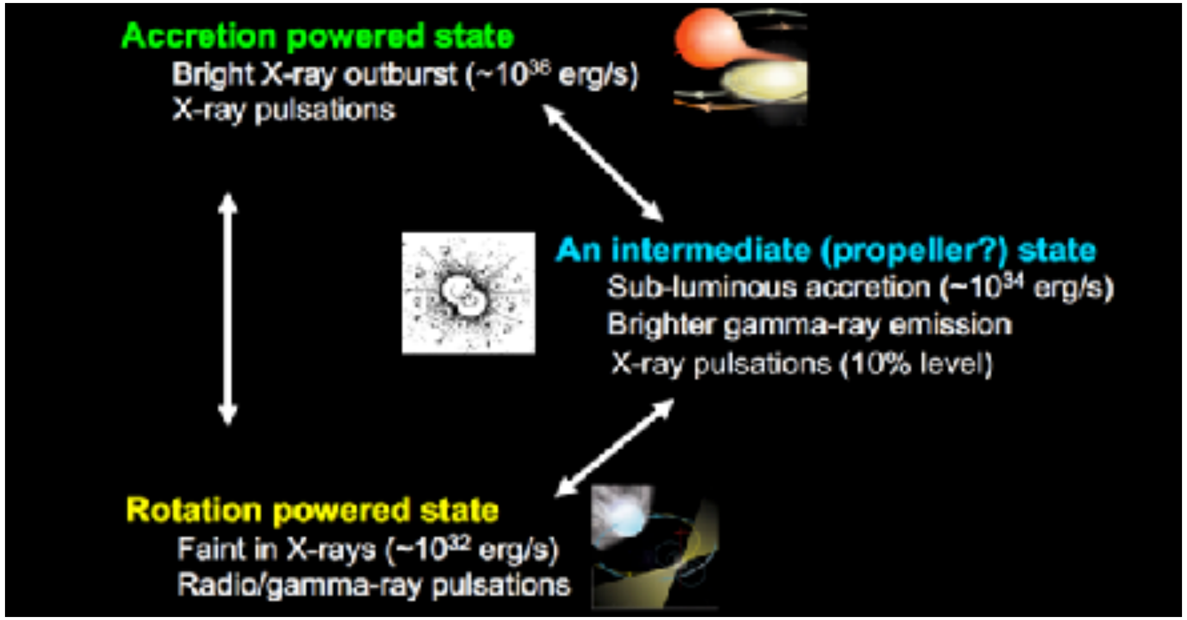
- Eta Carinae
  - HESS detected VHE g-ray emission from Eta Carinae close to periastron.
  - The source is point-like and the spectrum is best described by a power law.
  - The γ-ray spectrum extends up to at least ~400 GeV.
  - n a leptonic scenario this implies B < 0.5 G in the emission region.
  - No indication for phase-locked flux variations is detected in the HESS data. (HESS Collaboration, Abdalla et al. 2020).

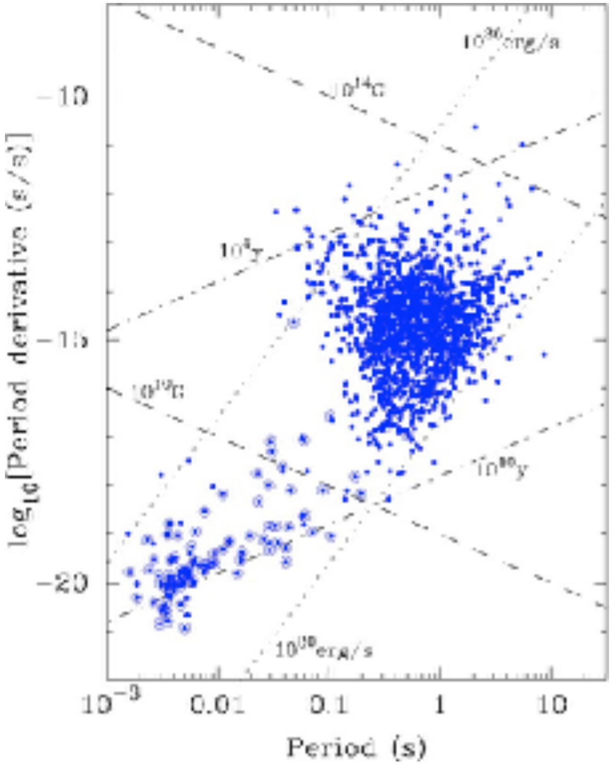




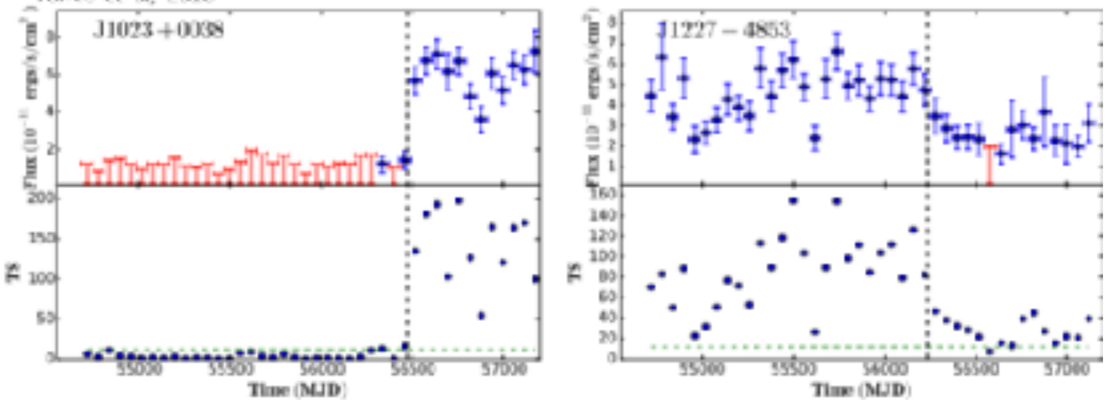
Transitional ms-pulsars

- A game between rotation <=> accretion
- Seen only in the GeV band



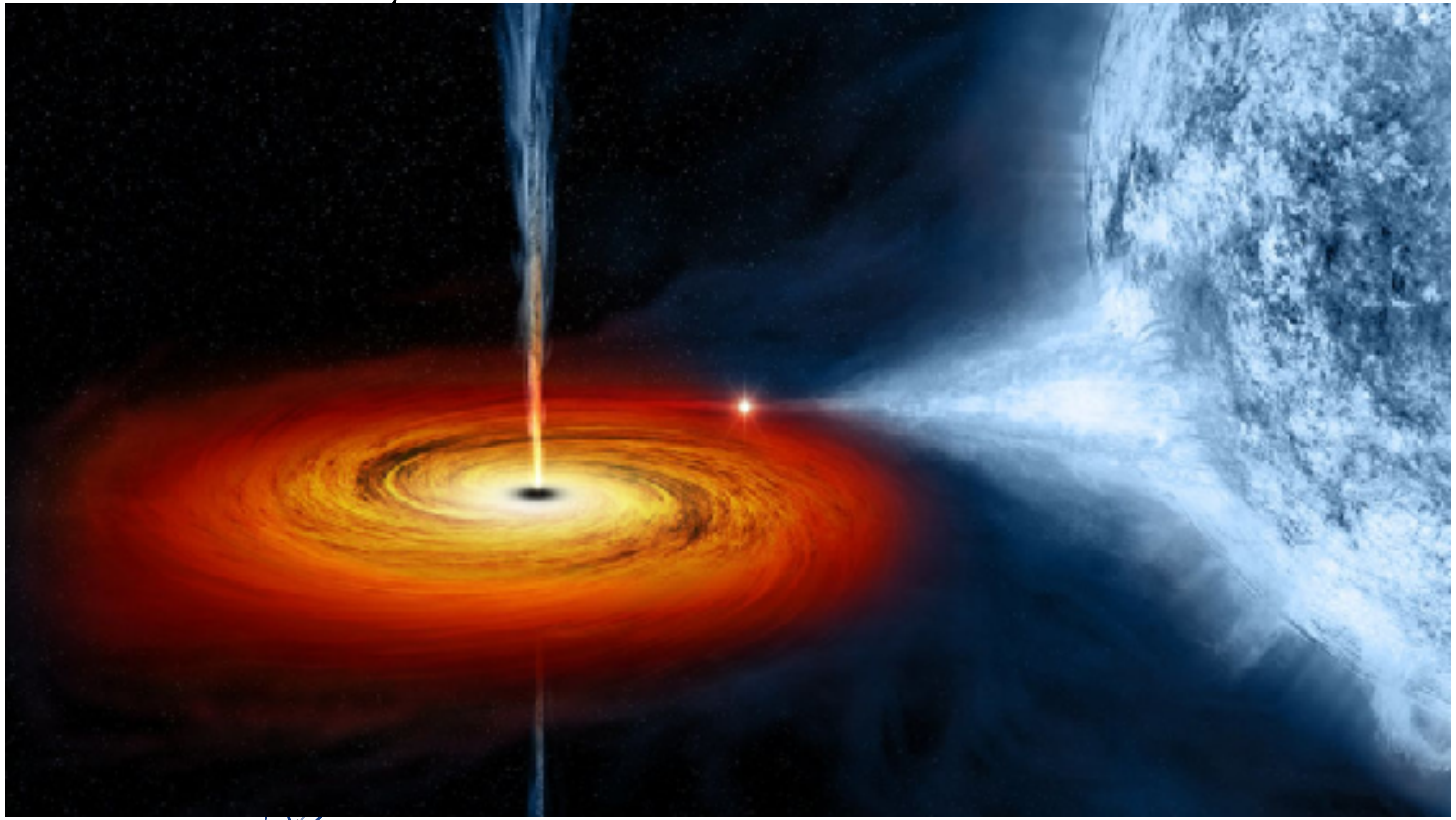


Torres et al. 2016



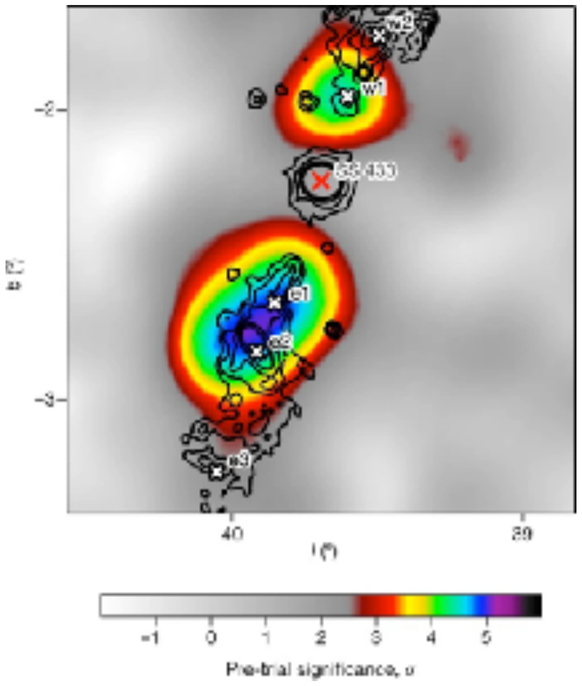
Microquasars

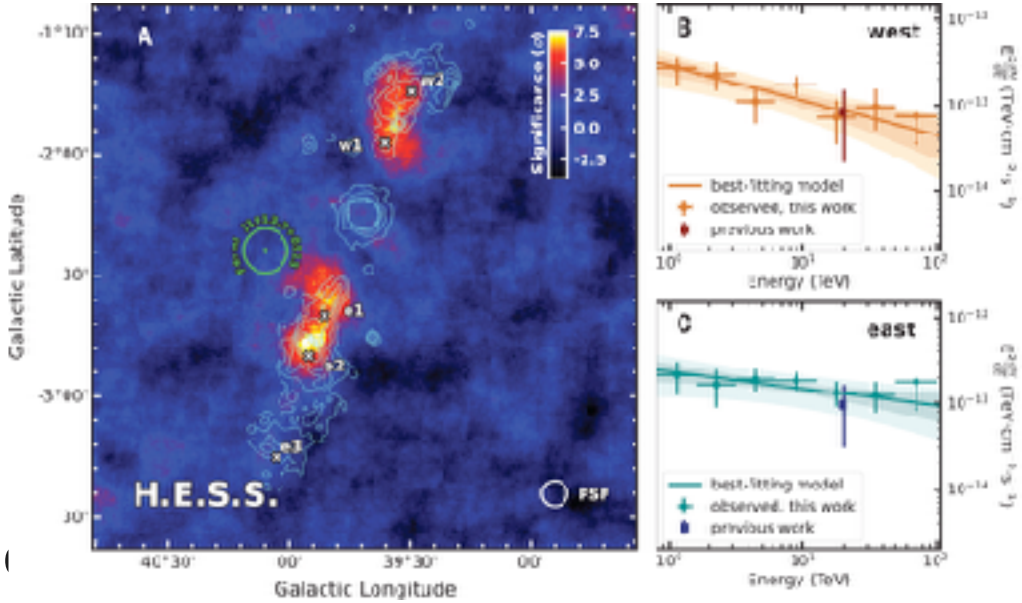
- a.k.a. **X-ray binaries**
- Emission related to jets
- Several possible states, accretion…



Microquasars: SS 433

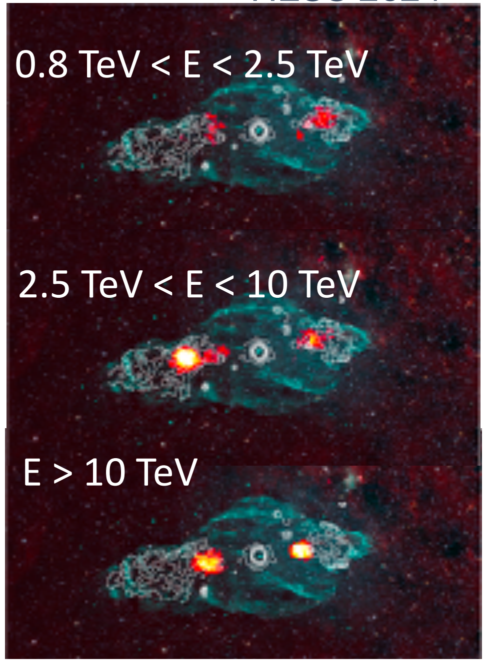
- A-type supergiant orbited by ~BH at 5.5 kpc.
- Super-Eddington accretion. Barion-loaded 0.26c jet.
- Inside theW50 nebula, being distorted by jets.
- multi-TeV detection by HAWC, compatible with
- leptonic scenario with e_- energies up to ~>100 TeV and B=16 µG (Abeysekara et al. 2018).
- TeV detection by H.E.S.S.
- Energy range: 1-50 TeV.
- At ~30 pc from the source on both E andW.
  - Similar shape & spectrum.
  - Spatially consistent with the extended non-thermal X-ray jets. (H.E.S.S. Collaboration et al. 2024).

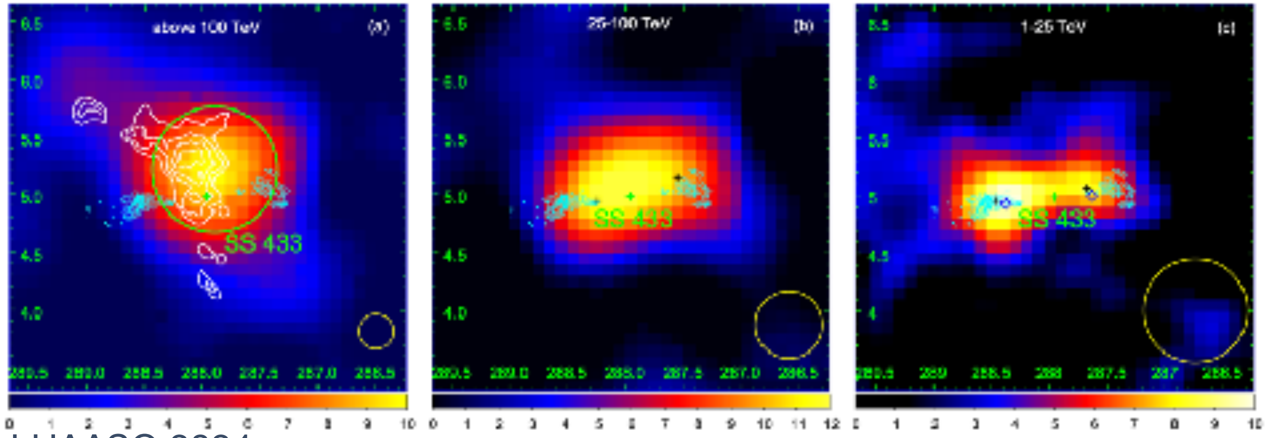




Microquasars: SS 433

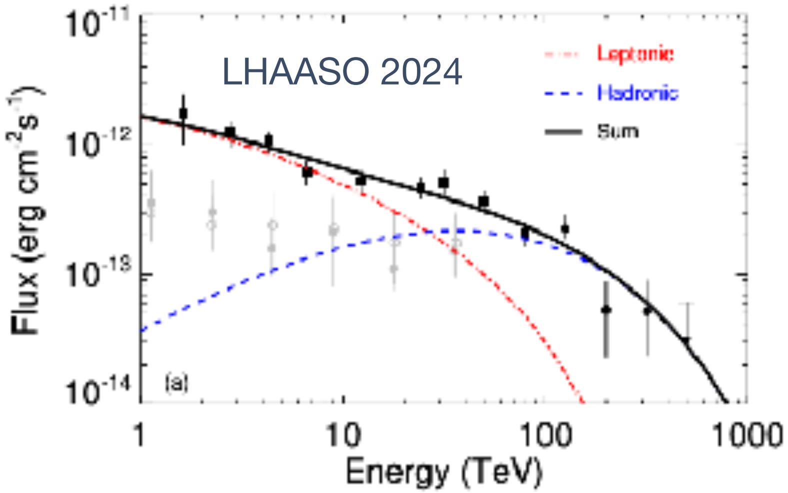
HESS 2024





LHAASO 2024

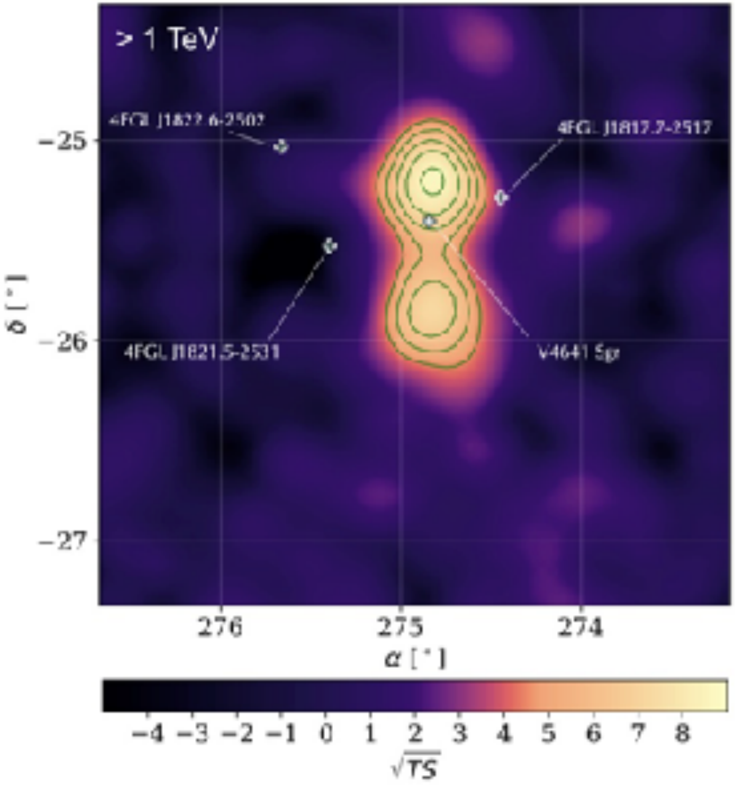
- The microquasar SS 433
  - HAWC/HESS observations favor a leptonic origin of the emission
  - LHAASO sees emission coincident with molecular clouds not coincident with the jets

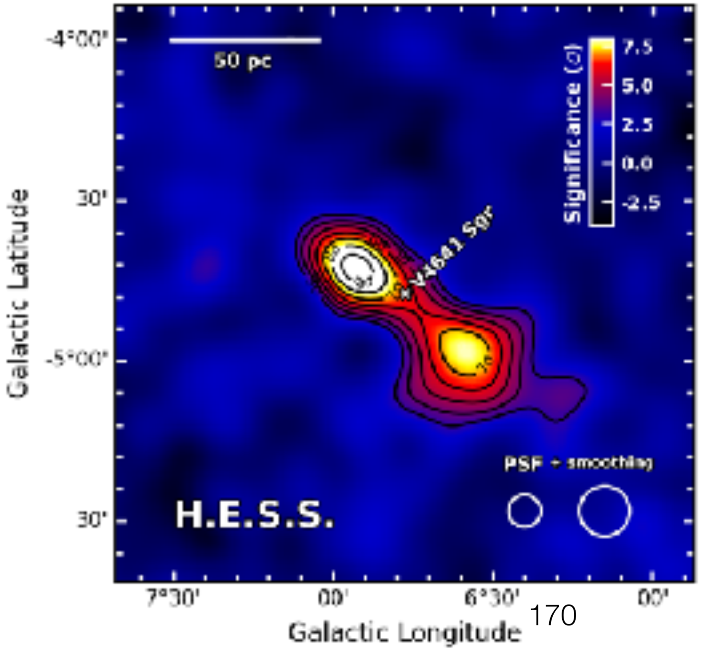


Microquasars: SS 433

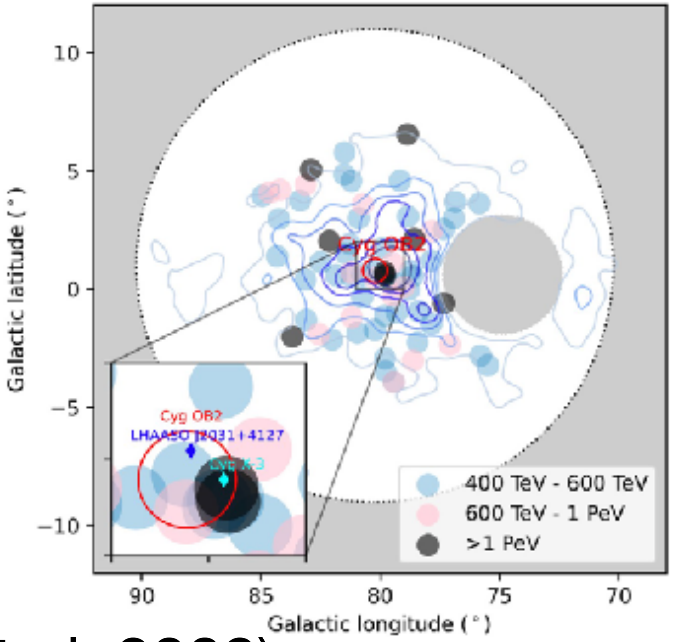
MQs: V4641

- B star of ~3 $M_\odot$ with ~6 $M_\odot$ BH at 6 kpc.
- Super-Eddington accretion. Superluminal 9.5c jets.
- multi-TeV detection significant above 100 TeV
- One or two sources? Spectrum up to >220 TeV.
- Projected in the plane of sky: 30 pc N, 55 pc S.
- What is their real distance? Similar to SS 433? (HAWC Collaboration 2024, talk by Casanova).
- TeV detection by HESS/HAWC/LHAASO





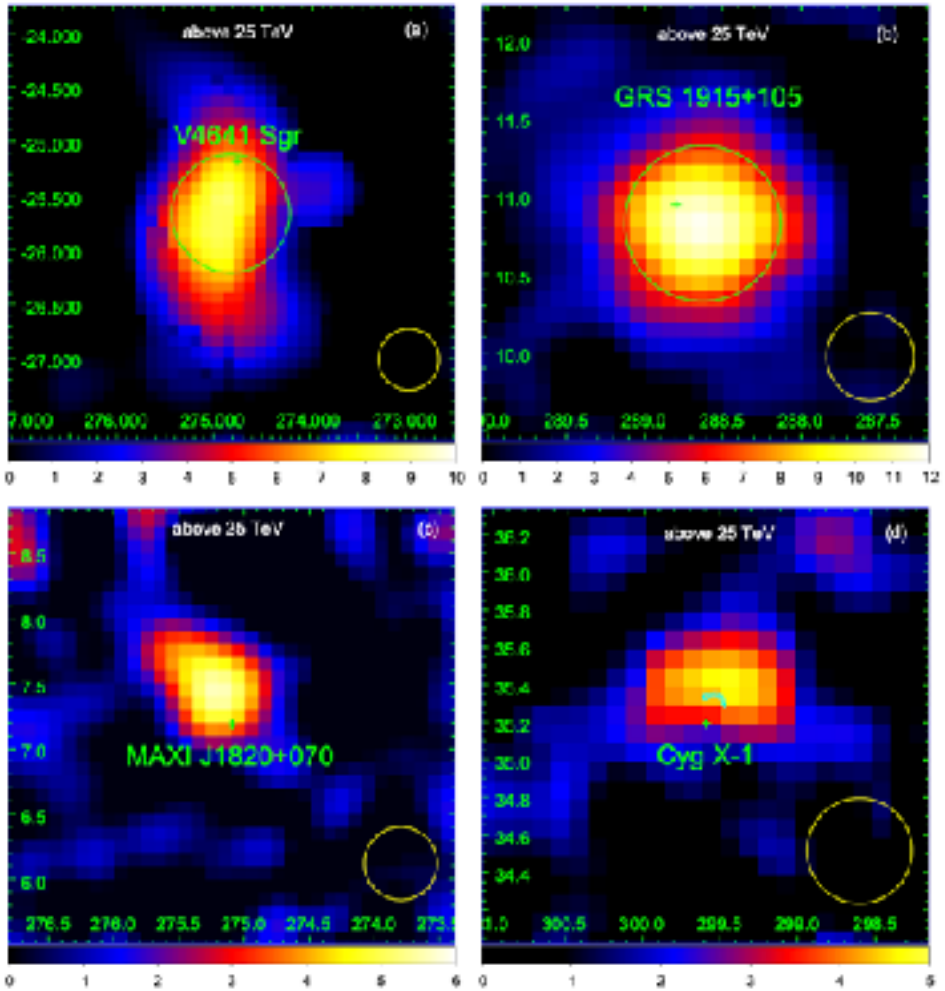
MQ: Cygnus X-3



- WR of ~12 M. with ~7 M. BH at 9 kpc.
- GeV detection during radio flaring periods
- Orbital variability anisotropic IC (Tavani et al. 2009, Abdo et al. 2009).
- Jet i and orbital motion à GeV lightcurve (Dubus et al. 2010, Bednarek 2010).
- ULs at TeV energies from ~60 h of MAGIC obs. (Aleksic et al. 2010).
  - Not very constraining.
  - Cutoff ?
  - gg absorption very relevant!
- See also VERITAS ULs (Archambault et al. 2013).
- UHE: Cyg X-3 in the core of Cygnus bubble(LHAASO Collaboration 2024).

Microquasars++

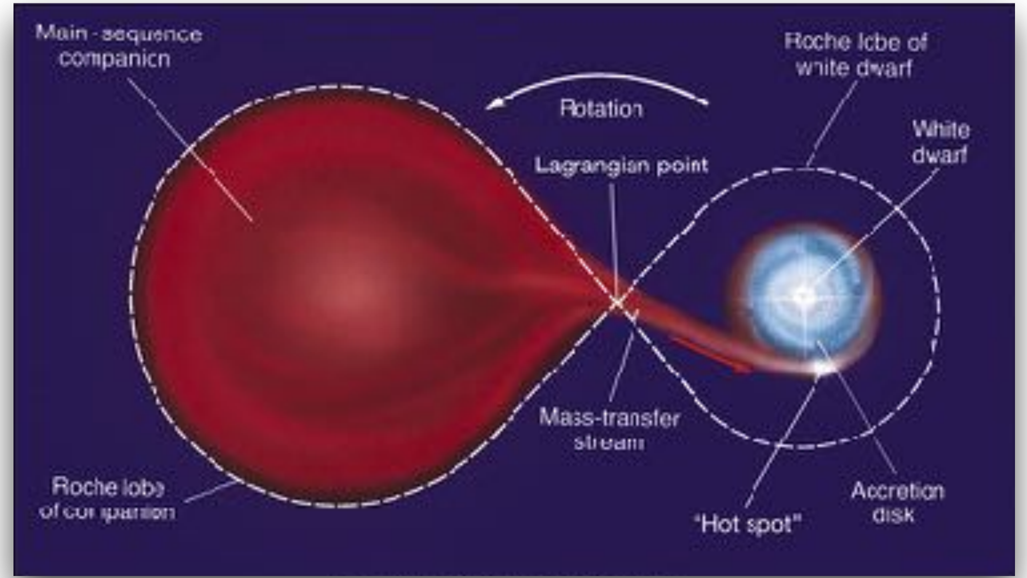
- Gamma rays up to hundreds of TeV detected from 4 additional microquasars
  - GRS 1915, Cyg X-1, MAXI J1820 reach beyond 100 TeV and the origin is under debate
  - V4641 Sgr emission is likely of hadronic origin (claim to be accelerating up to 10 PeV protons!)



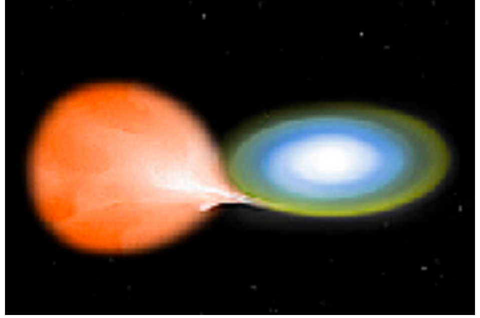
LHAASO 2024

Cataclysmic variable stars

- Cataclysmic Variable (CV) stars: White Dwarf + companion star.
- Outbursts observed at radio, IR, optical and X-ray.
- Recent (~10 years) reports of γ-ray emission by Fermi-LAT.
- They are divided into:
  - Classical Novae (they include symbiotic novae)
  - Recurrent Novae
  - Dwarf Novae
  - Nova-like variables
  - Magnetic CVs

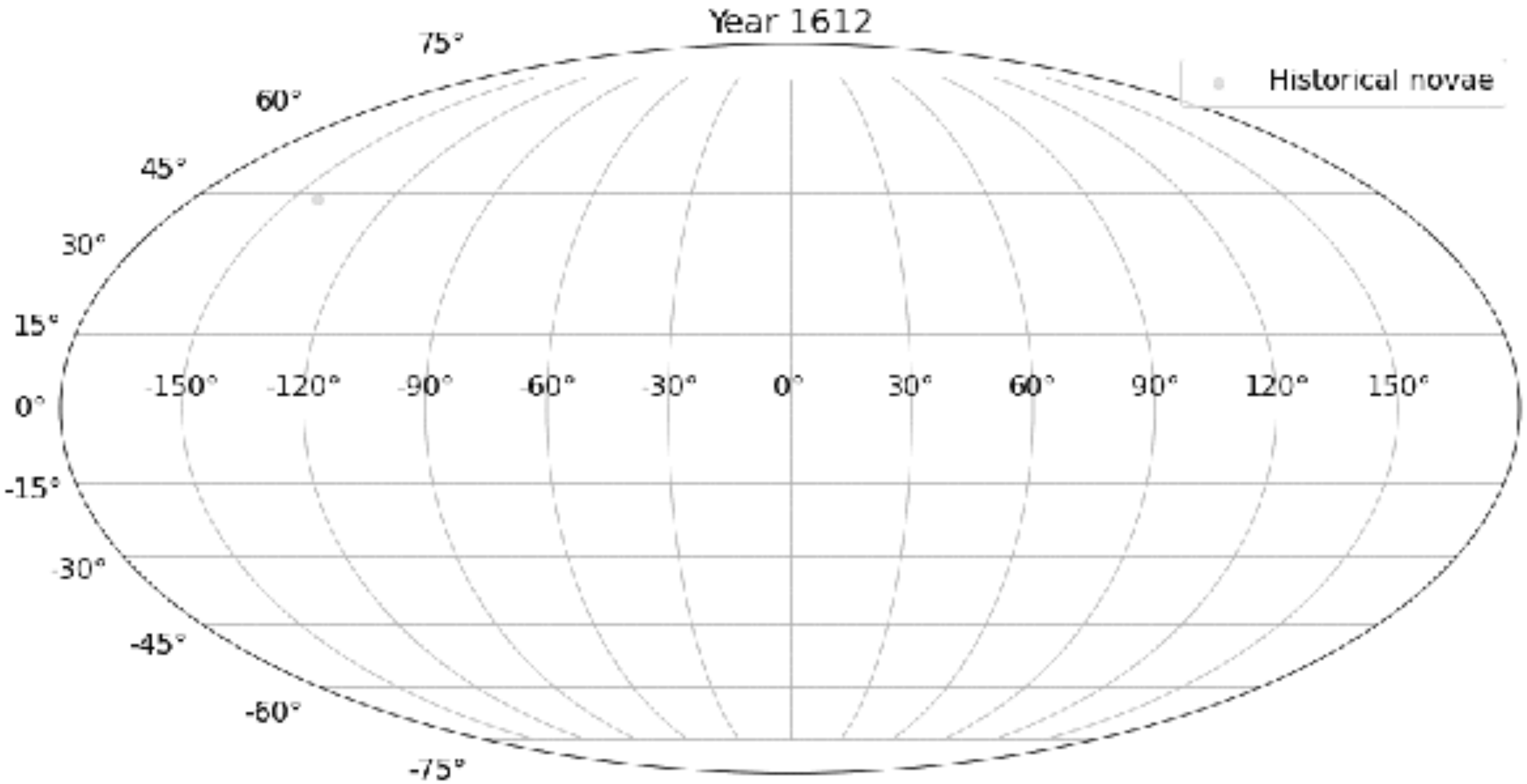


Novae



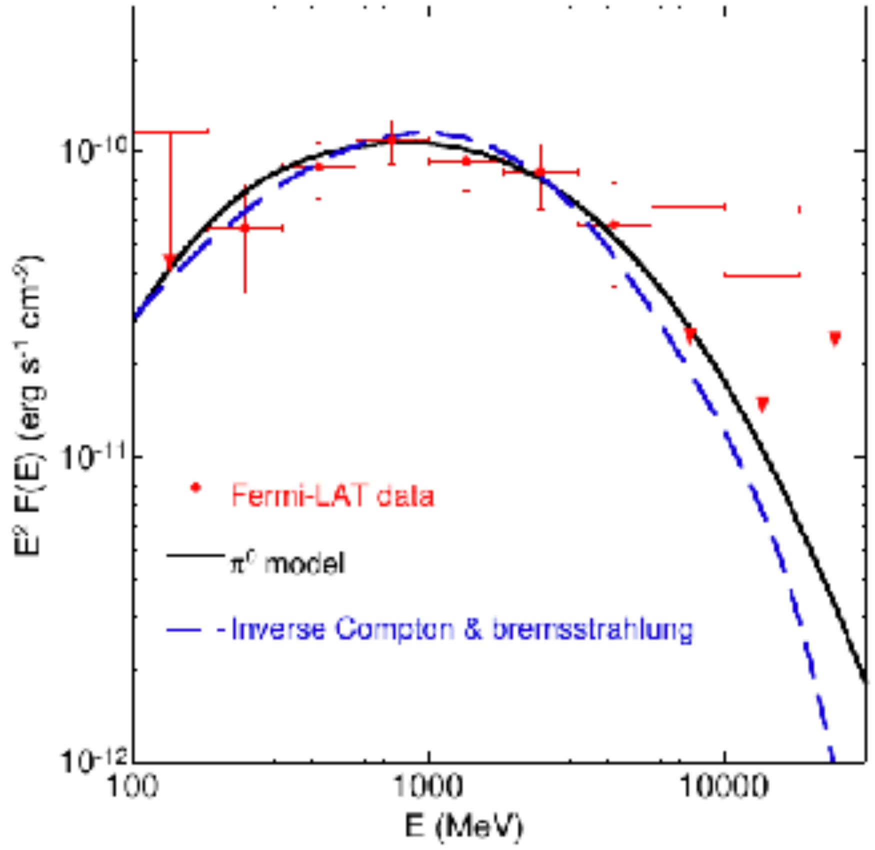
- Thermonuclear explosions caused by accumulation of material from a donor star on the surface of a White Dwarf (WD).
- Novae have been extensively studied in optical, X-rays, radio.
- If donor star is a Red Giant (RG) this can produce a symbiotic binary with the WD immersed in the RG wind.
- There were some expectations that GeV emission might also be produced in shocks of symbiotic novae (e.g. Tatischeff & Hernanz, 2007).

Historical Novae



Novae in Gamma Rays

- Discovered in 2010 with the observation of V407 Cyg
- GeV emission was later also detected for a bunch of classical novae by *Fermi*-LAT
- Both proton (with pp interaction target being the nova ejecta) and electron models have been both possible up to now.
- In August 2021, RS Oph was observed and detected by MAGIC, LST-1 and HESS

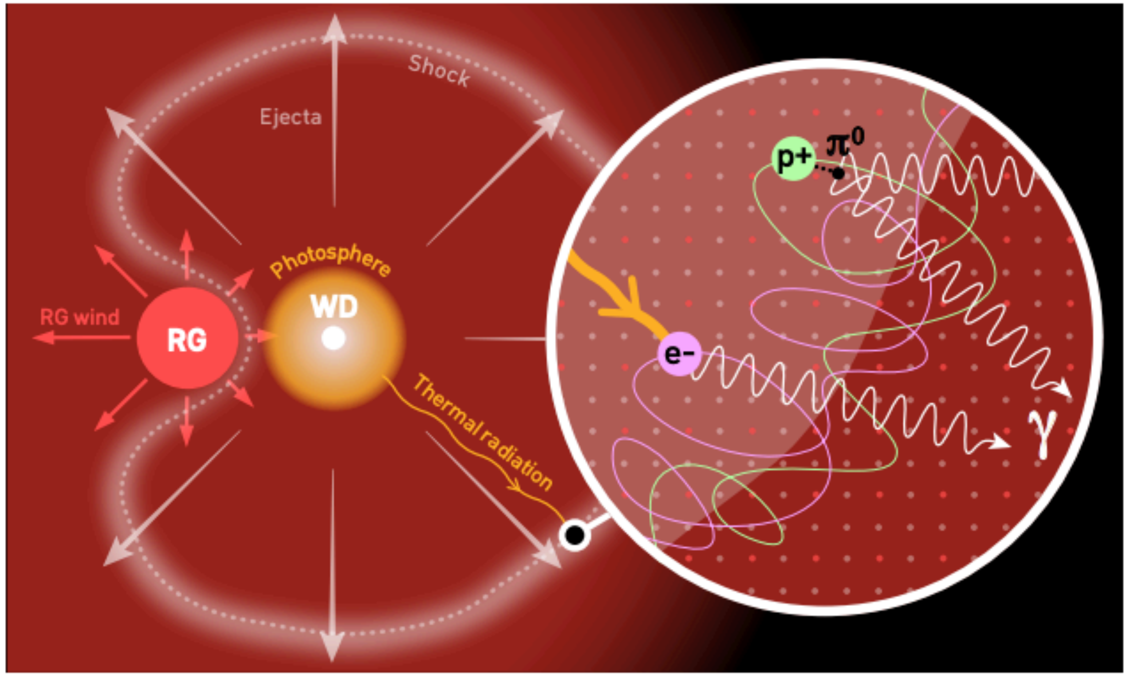


RS Ophiuchi

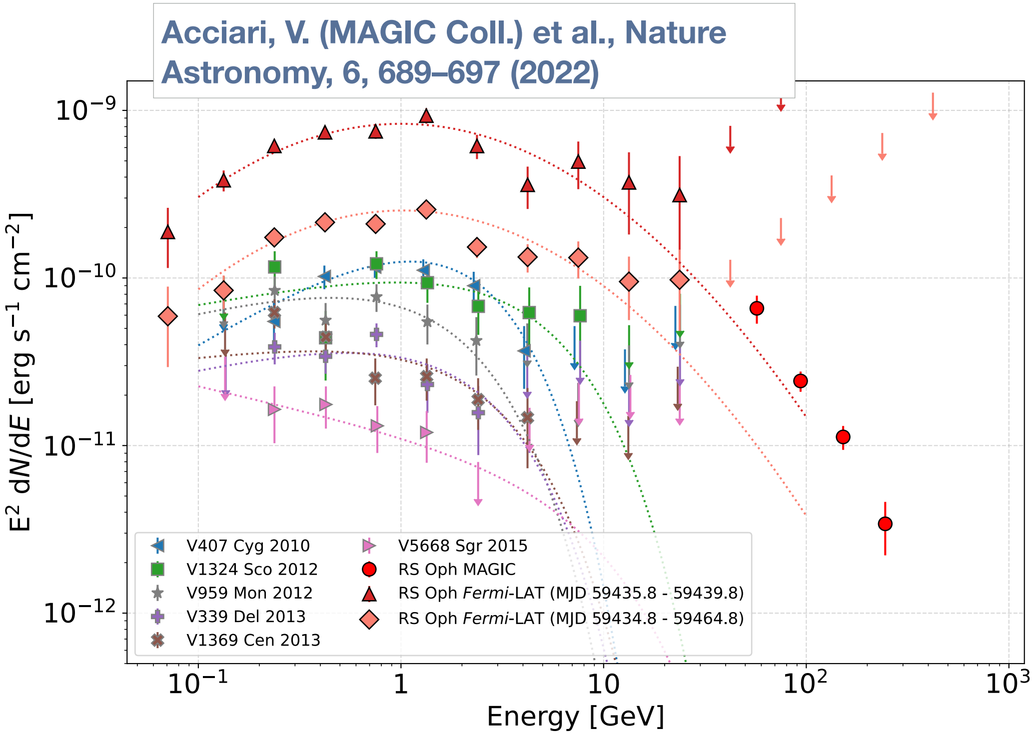
- Recurrent nova in a symbiotic binary
- Outbursts every 15-20 years
- Previous to last outburst in 2006 => no sensitive gamma-ray satellites available
- Distance debated – applied value 2.45 kpc, but values ~1.4 – 4.3 kpc (with various caveats) are reported in the literature
- Latest outburst on 2021.08.08 UT ~22:20
- Detected by *Fermi*-LAT, but also by MAGIC, LST-1 and H.E.S.S.

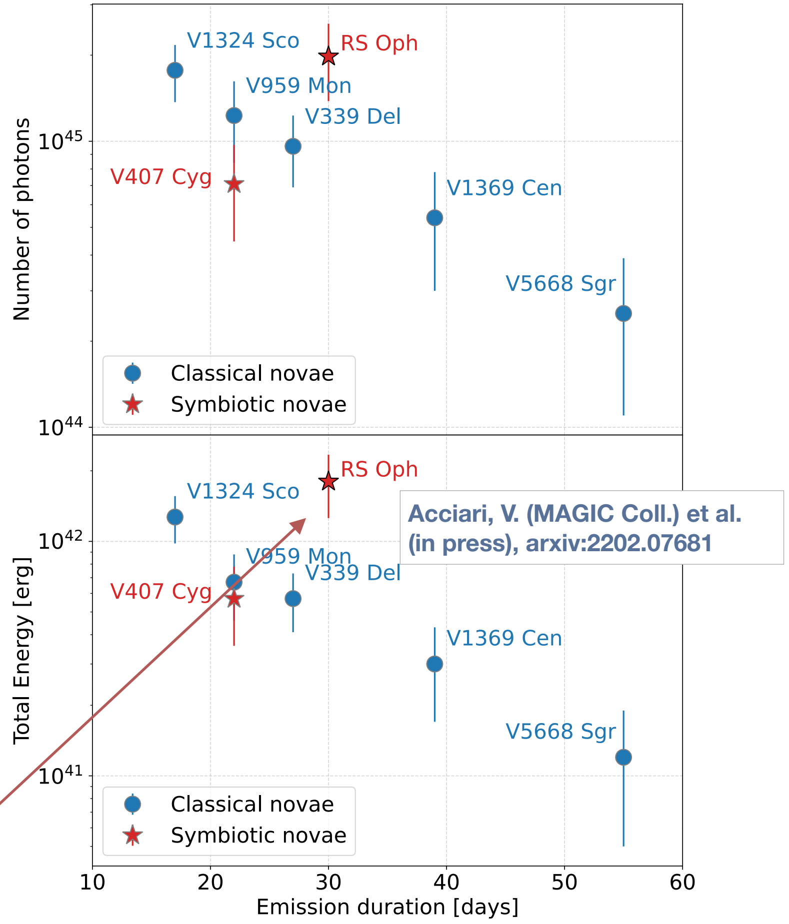
RS Oph in context

- What is happening in RS Oph so special? Why are we seeing it in VHE gamma rays and not all the other novae?



RS Oph in the context of other high energy novae

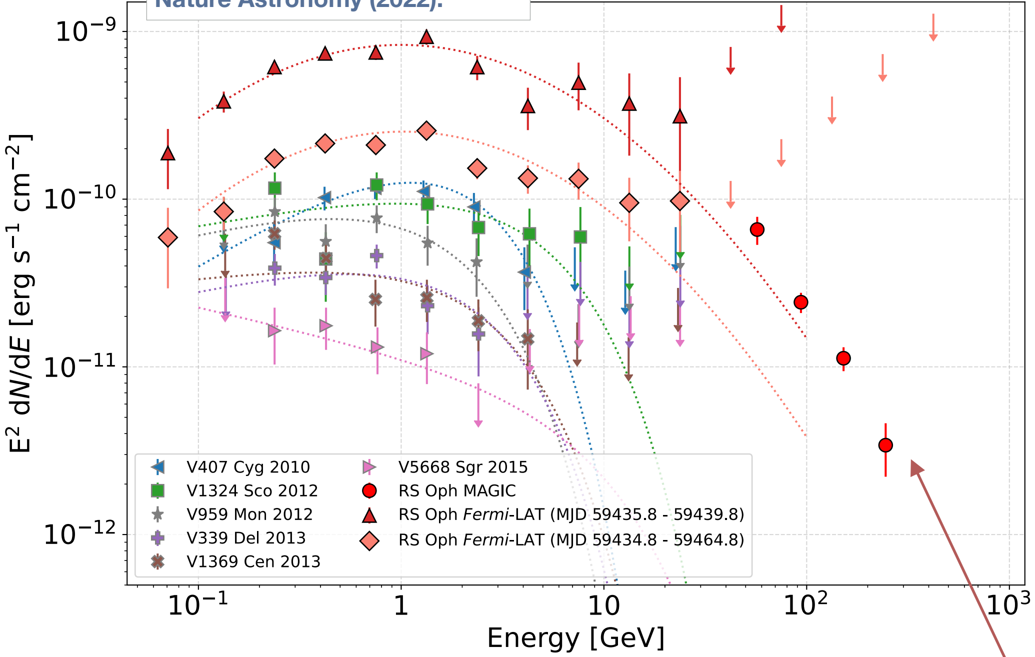


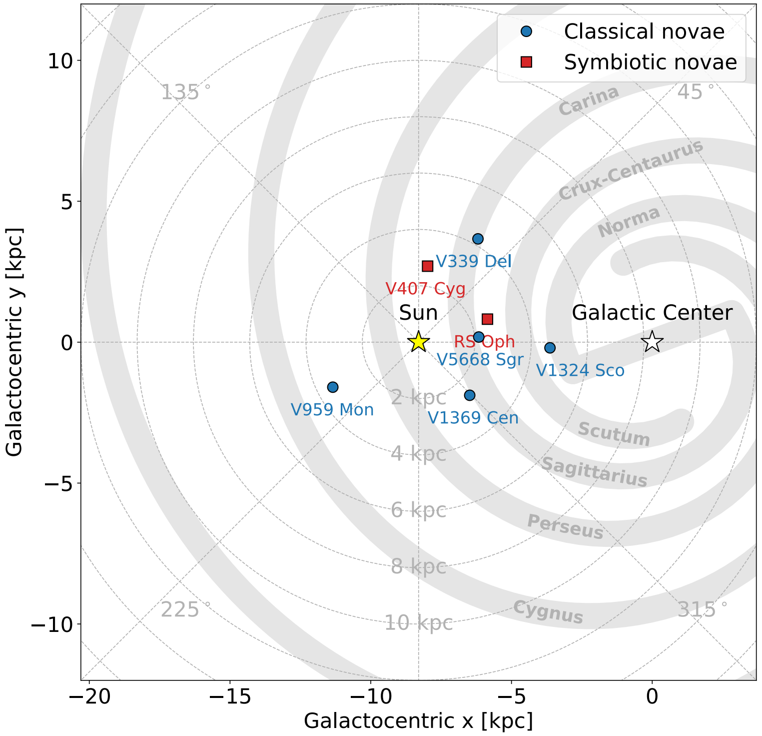


- Several novae detected by *Fermi*-LAT
  - RS Oph is intrinsically the brightest

RS Oph: what was so special about it?

Acciari, V. (MAGIC Coll.) et al., Nature Astronomy (2022).





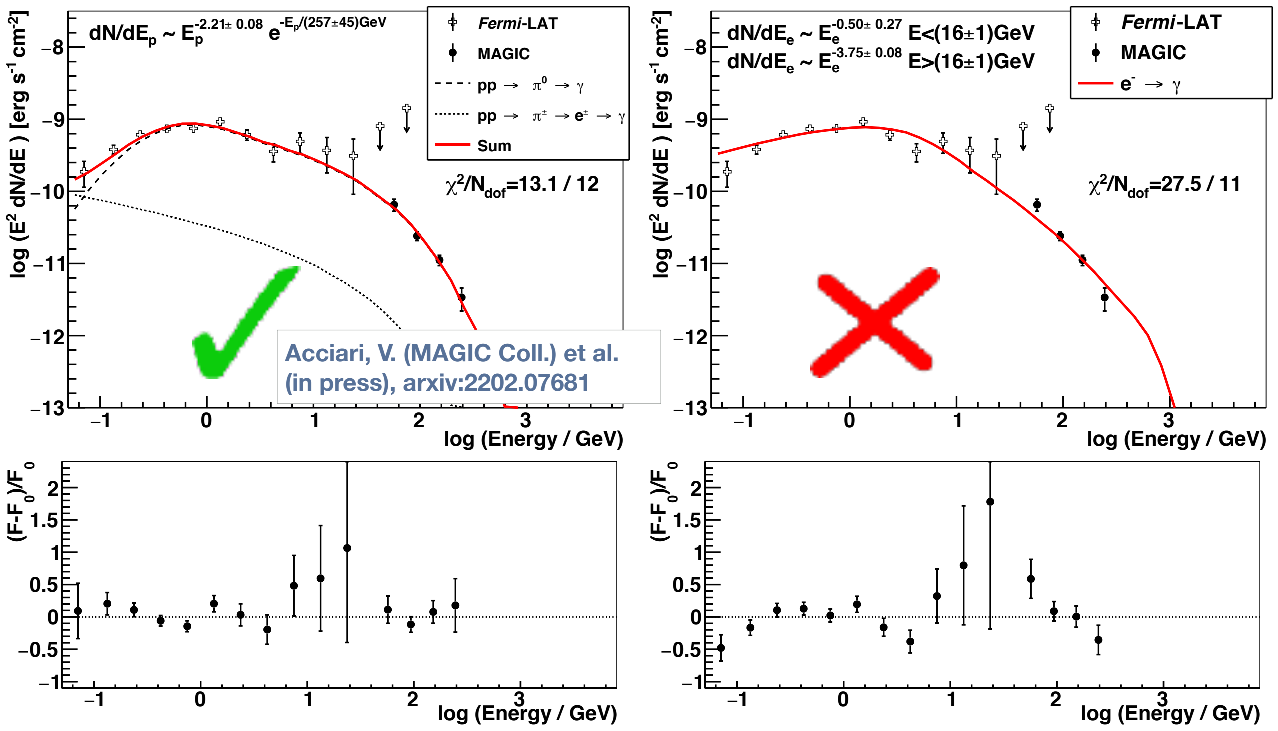
- Several novae detected by *Fermi*-LAT
  - RS Oph is also the one with the highest flux

RS Oph accelerates protons!

[Submitted on 15 Feb 2022 (this version), latest version 22 Feb 2022 (v2)]

Gamma rays reveal proton acceleration in thermonuclear novae explosions

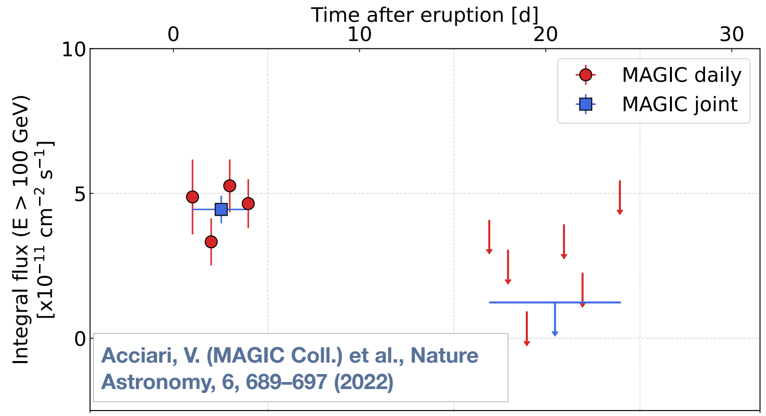
MAGIC Collaboration: V. A. Acciari (1), S. Ansoldi (2,42), L. A. Antonelli (3), A. Arbet Engels (4), M. Artero (5), K. Asano (6), D. Baack (7), A. Babić (8), A.

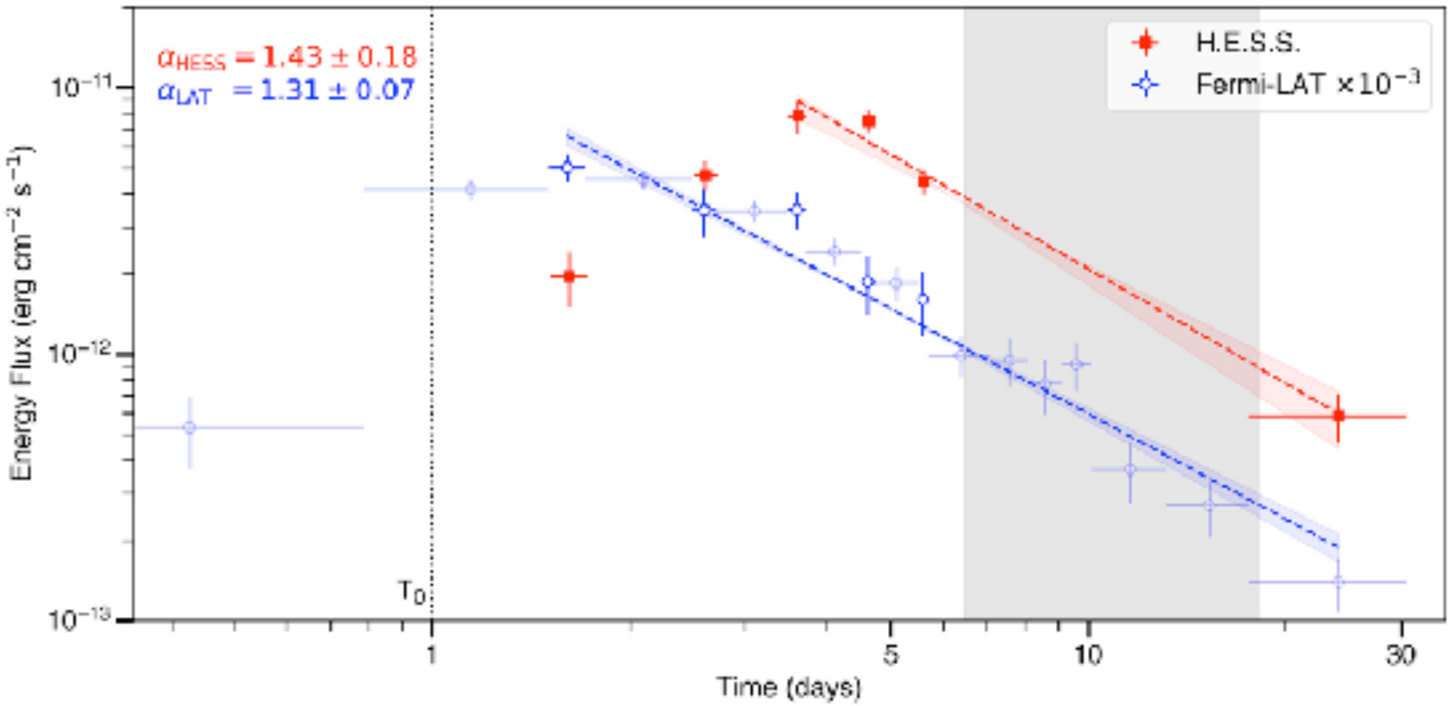


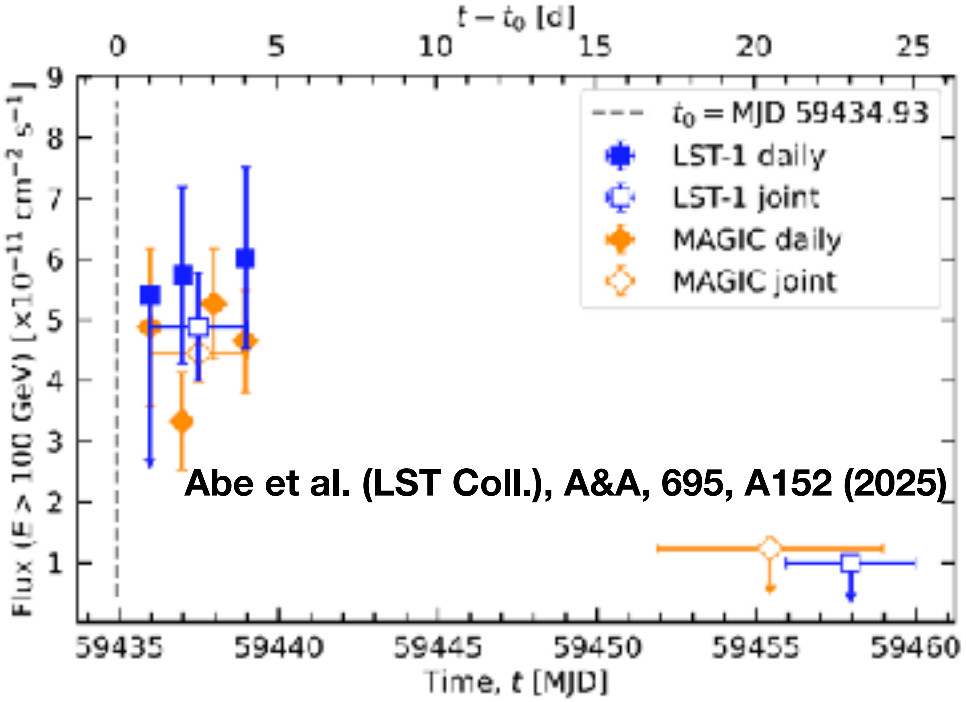
- Rough contributions to galactic CRs of novae w.r.t. supernova remnants is <1%

Multiwavelength Lightcurve

- MAGIC and LST flux is compatible with a constant. HESS claims an exponential decay
- Fast decay in the optical and Fermi.





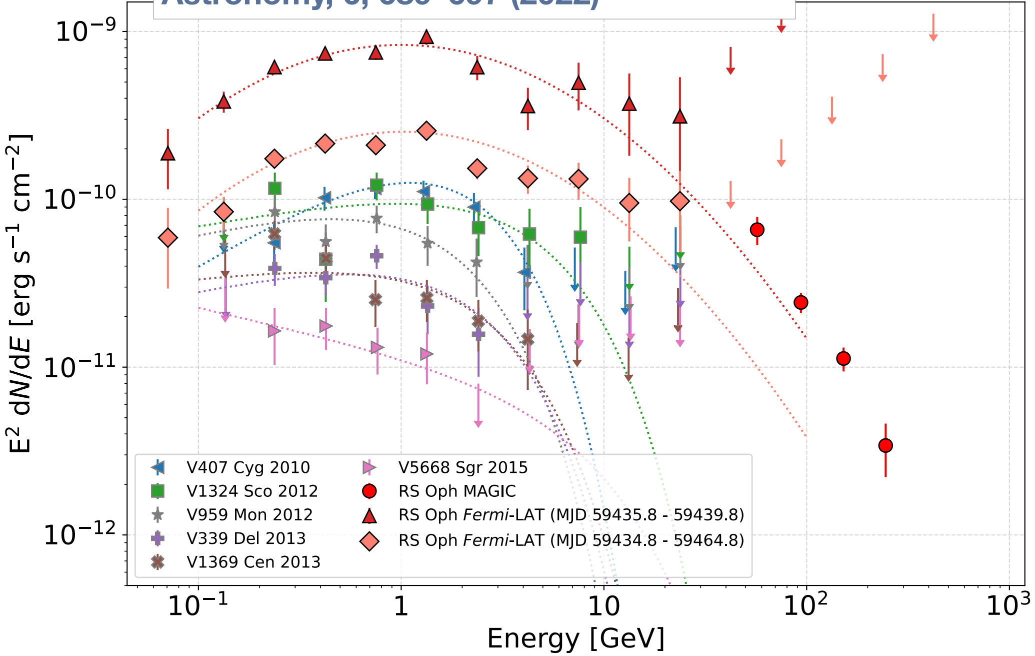


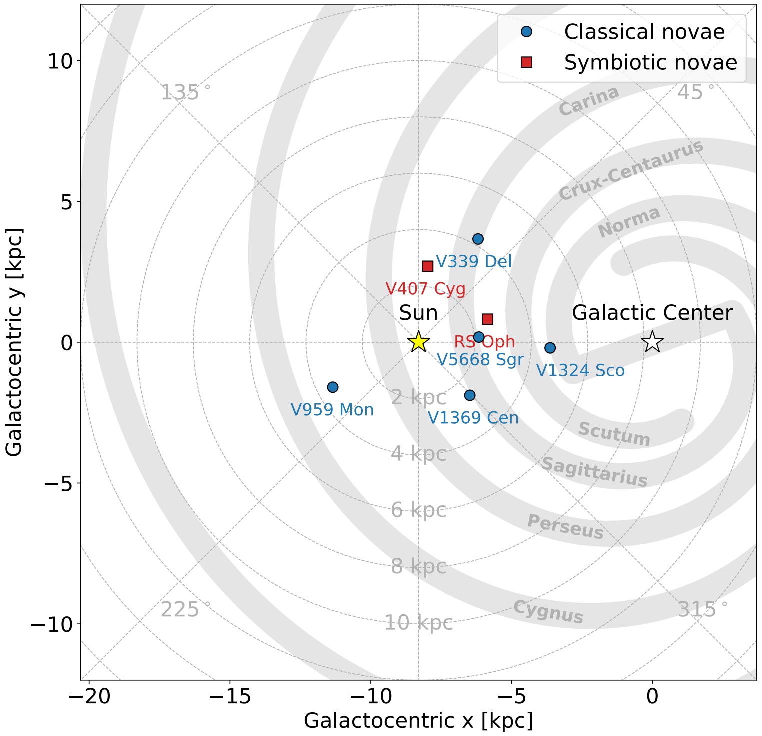
Abe et al. (LST Coll.), A&A, 695, A152 (2025)

MJD

RS Oph in the context of other high

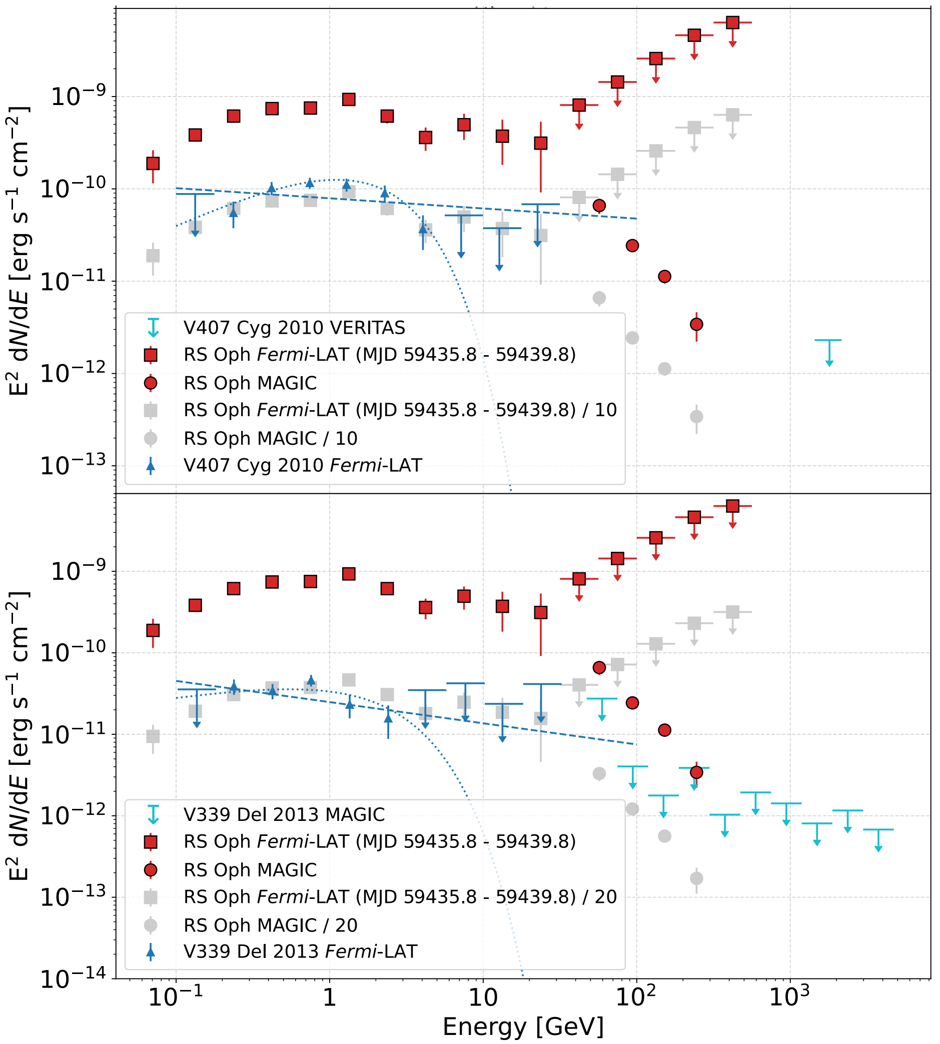
Acciari, V. (MAGIC Coll.) et al., Nature Astronomy, 6, 689–697 (2022)





- Several novae detected by Fermi
  - RS Oph is the one with the highest flux

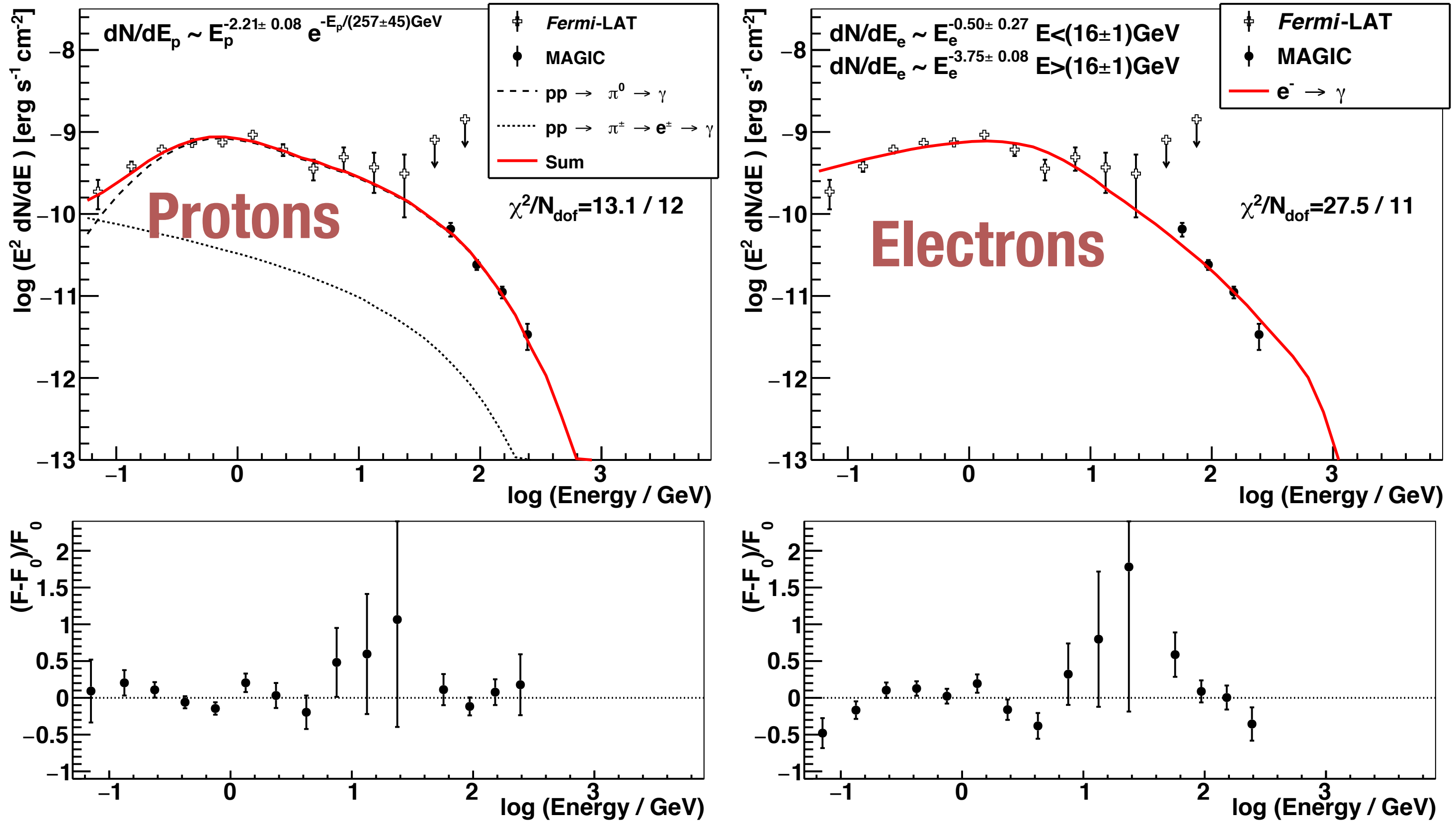
Are other novae also emitting VHE?



- The short answer is that we do not know:
  - Scaling V337 Del and V407 Cyg to the RS Oph level the previous MAGIC and VERITAS U.L. would not be able to constrain RS Oph-like emission.
  - It means that all previous novae may have been emitting at the same level RS Oph emitted, but we did not have the sensitivity to detect them.

Particle acceleration

- So there are some relativistic particles, but…
  - protons or electrons?

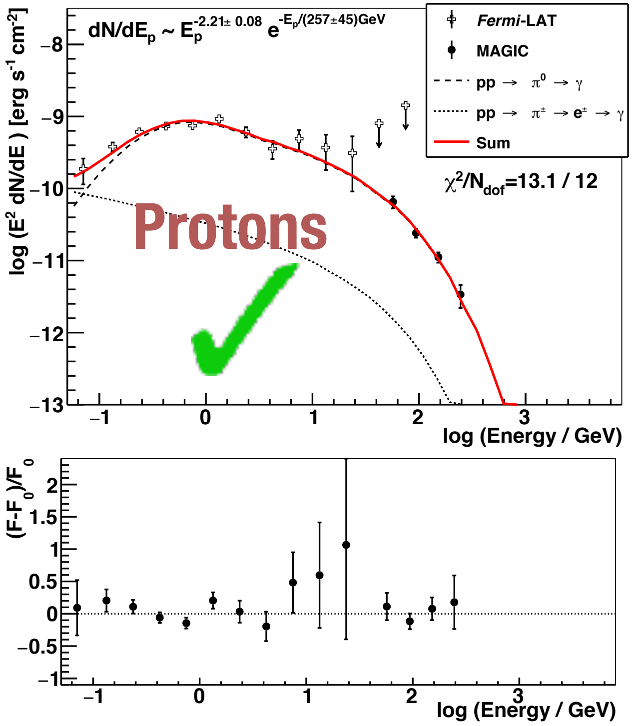


Proton acceleration

[Submitted on 15 Feb 2022 (this version), latest version 22 Feb 2022 (v2)]

Gamma rays reveal proton acceleration in thermonuclear novae explosions

MAGIC Collaboration: V. A. Acciari (1), S. Ansoldi (2,42), L. A. Antonelli (3), A. Arbet Engels (4), M. Artero (5), K. Asano (6), D. Baack (7), A. Babić (8), A.

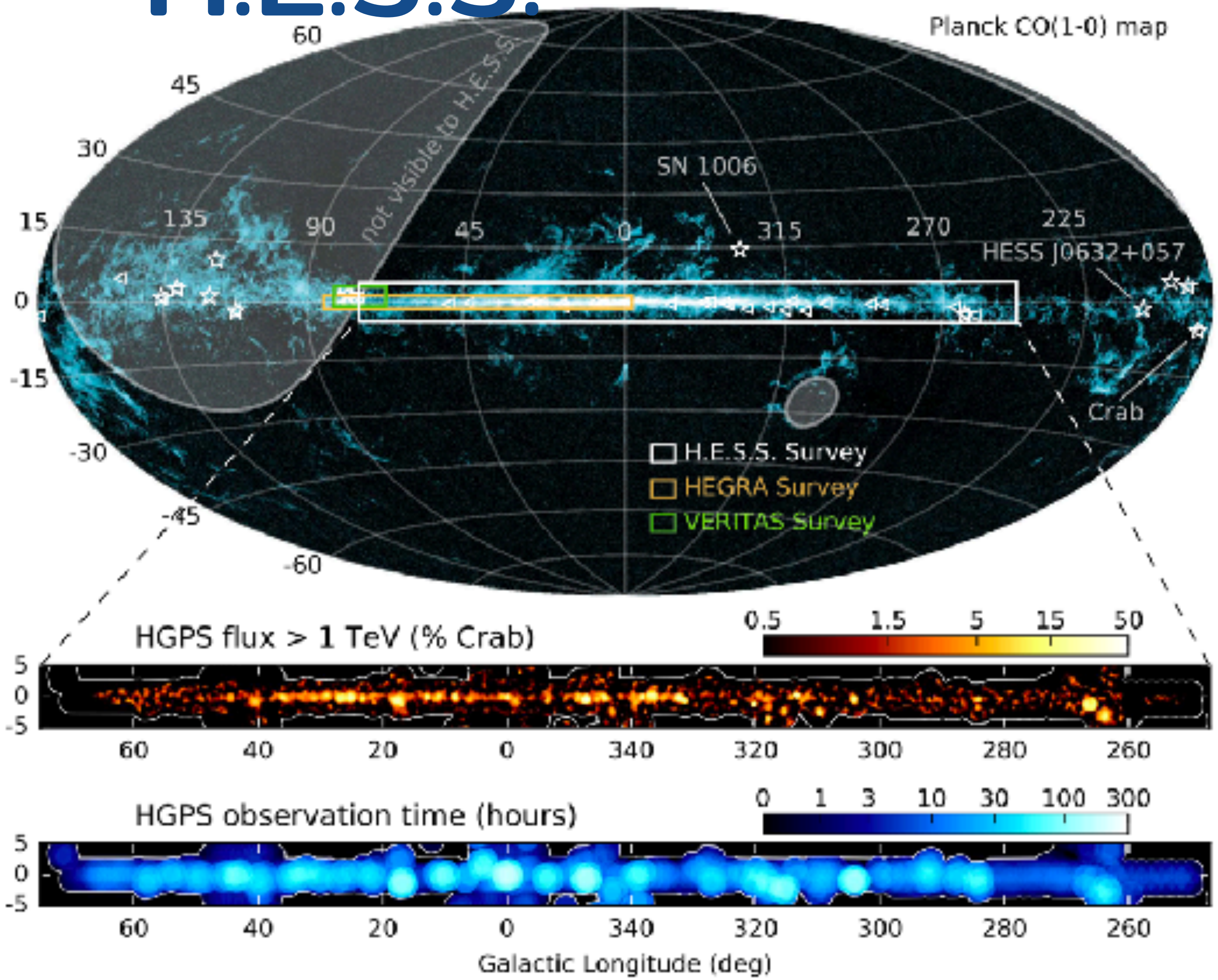


Acciari, V. (MAGIC Coll.) et al., Nature Astronomy, 6, 689–697 (2022)

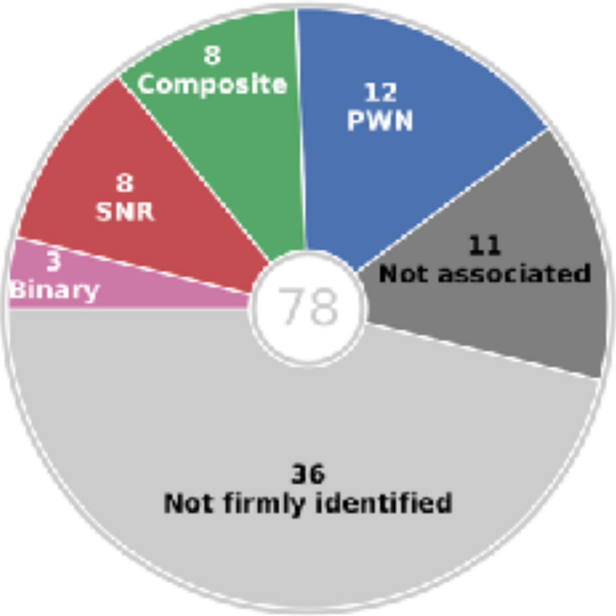
- Protons are favored over electrons because:
  - 1) they can be injected with a natural -2 spectral index
  - 2) the chi2 of the fit is much better for protons over electrons
  - 3) there is a hint of spectral hardening in the energy of the protons => protons do not cool down and their acceleration is not immediate.
  - 4) optical and high energy emission follow a similar decay => IC emission should decay faster because of the photosphere expansion
- These protons would contribute to the sea of Cosmic Rays that we have in the galaxy.
  - The total contribution of novae is in any case < 0.2% compared to that of supernovae (remnants)

Galactic Plane Surveys

The Galactic Plane in Gamma-rays: H.E.S.S.

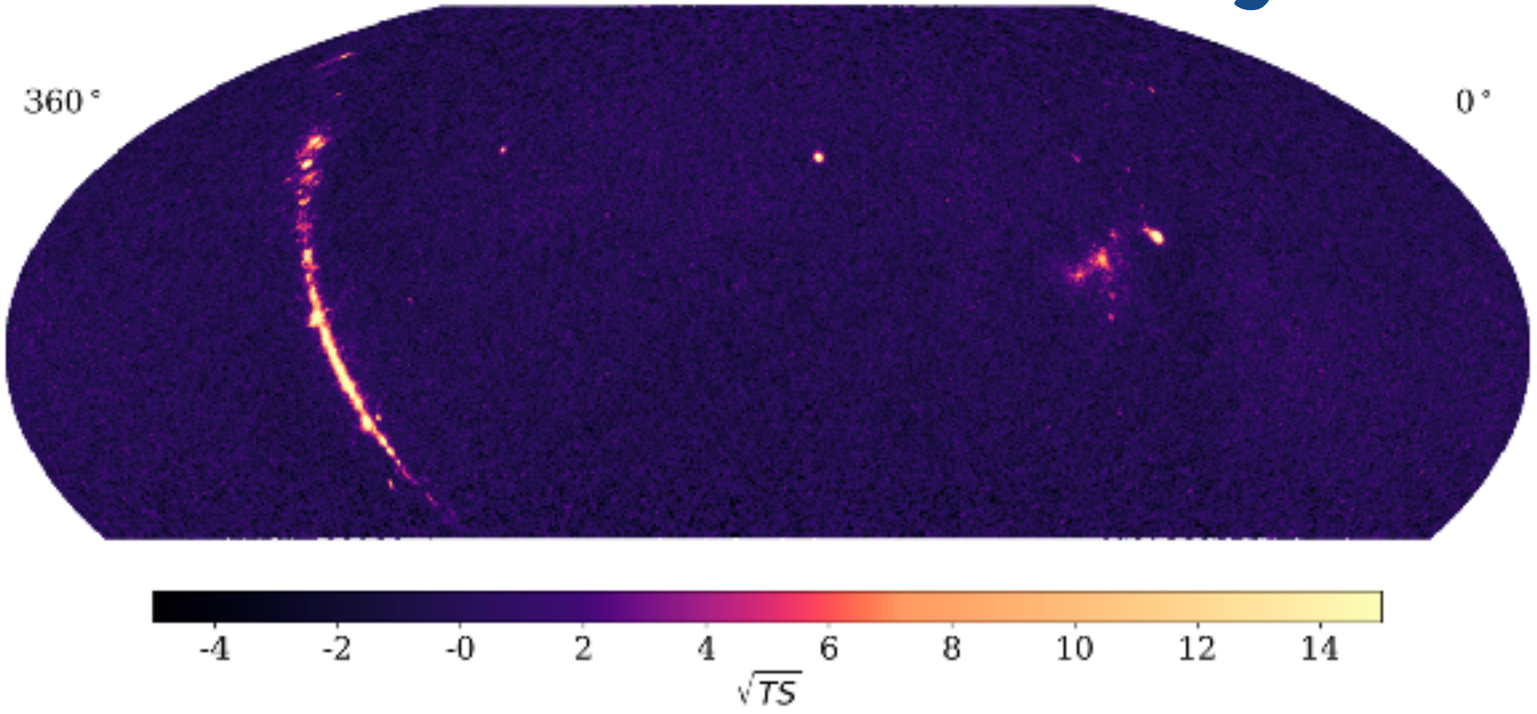


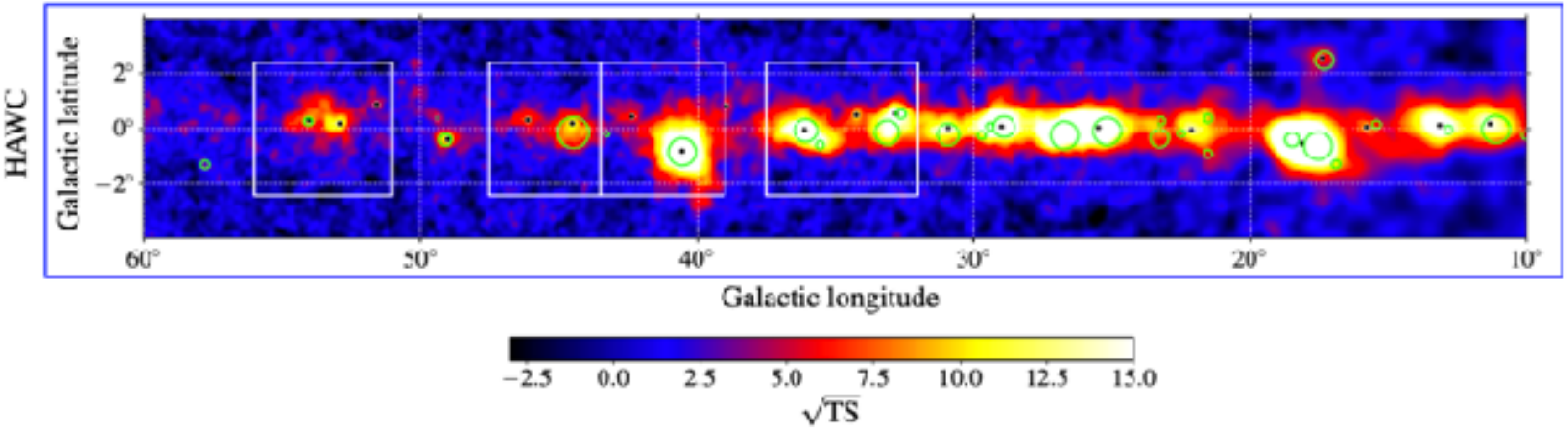
- Final HESS catalog of survey sources
- Data collected 2004 – 2013 (3000 hours)
- Significance and flux maps
- Automatic pipeline for source extraction
- 64 VHE sources
  - + 13 complex sources (e.g. shell SNR) excluded



The Galactic Plane in Gamma-rays: HAWC

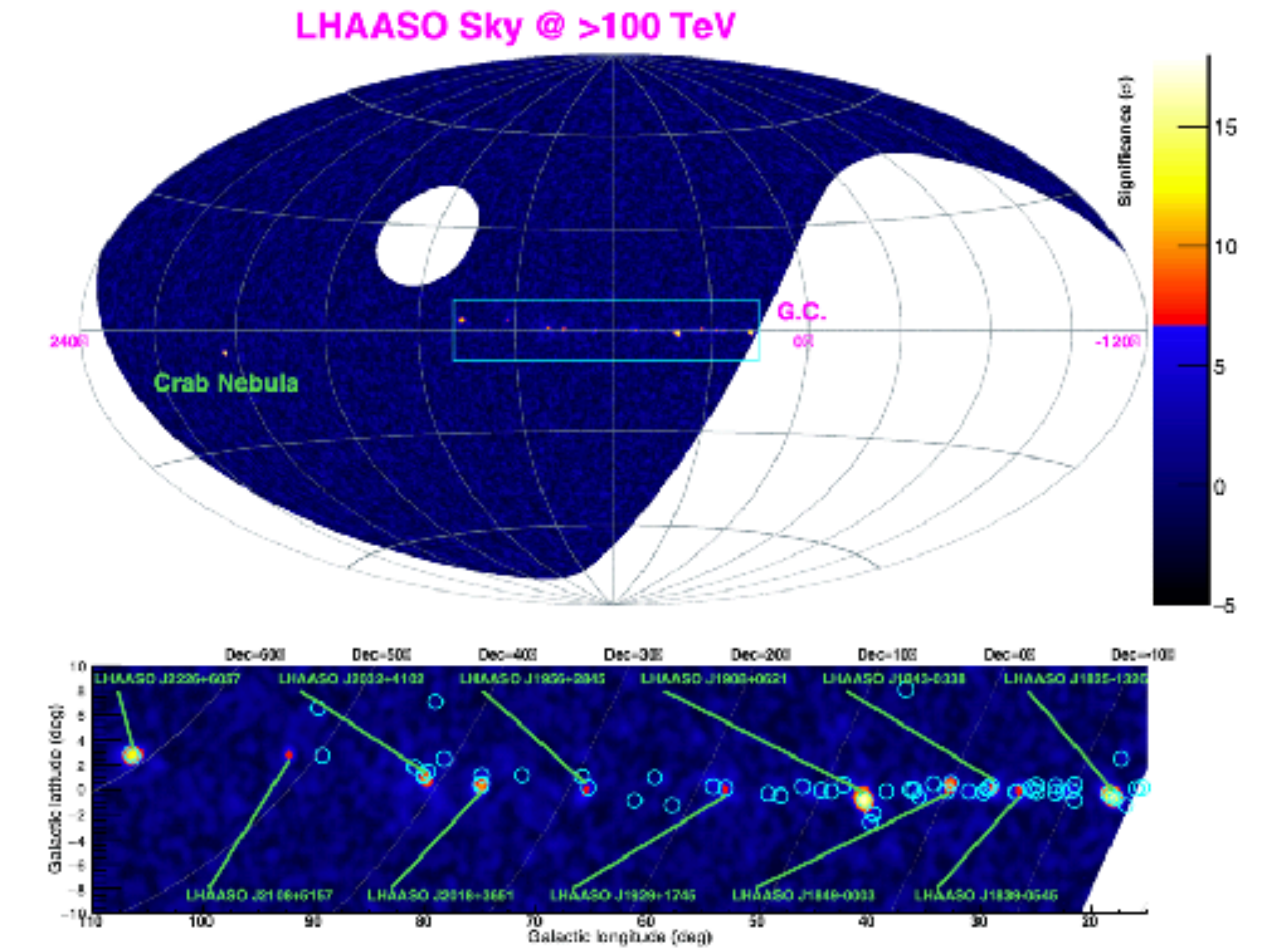
- 7.5 years
- 85 sources
- Energy range > 100 TeV





The Galactic Plane in Gamma-rays: LHAASO

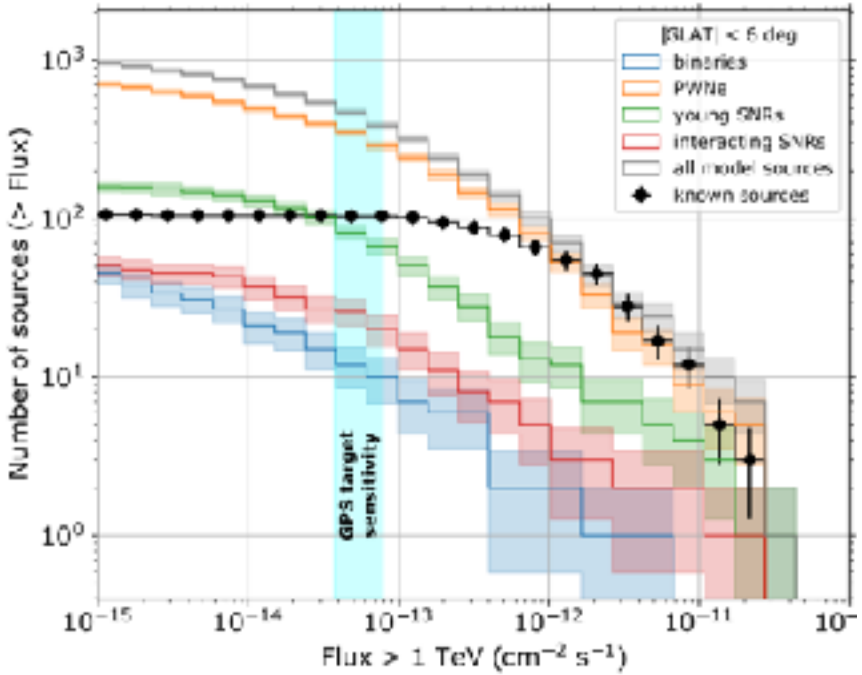
- Ultrahigh-energy photons up to 1.4 petaelectronvolts
- 12 γ-ray Galactic sources (Nature, June 3rd 2021)

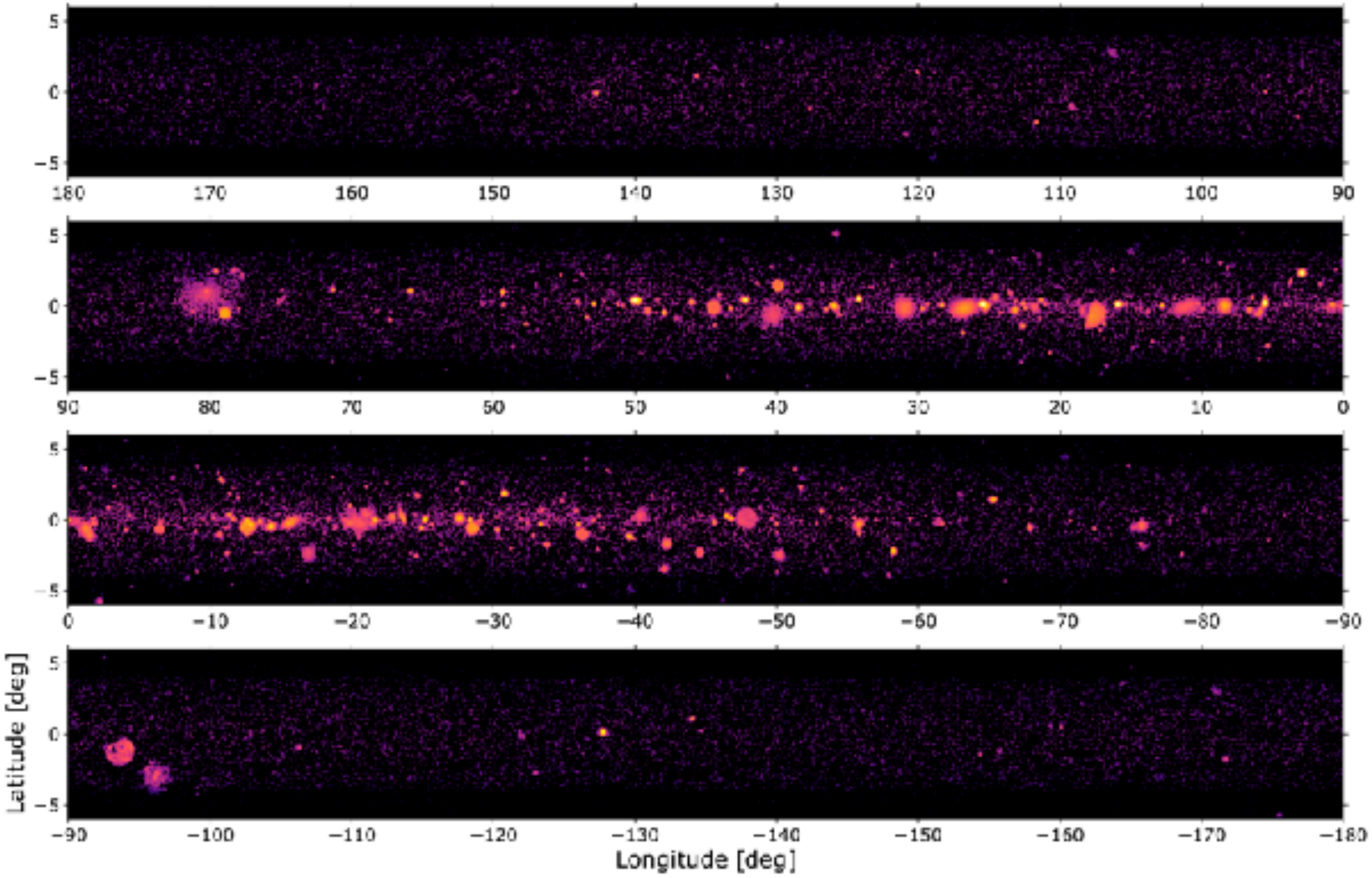


Extended Data Fig. 4 | LHAASO sky map at energies above 100 TeV. The circles indicate the positions of known very-high-energy γ-ray sources.

The Galactic Plane in Gamma-rays: CTAO

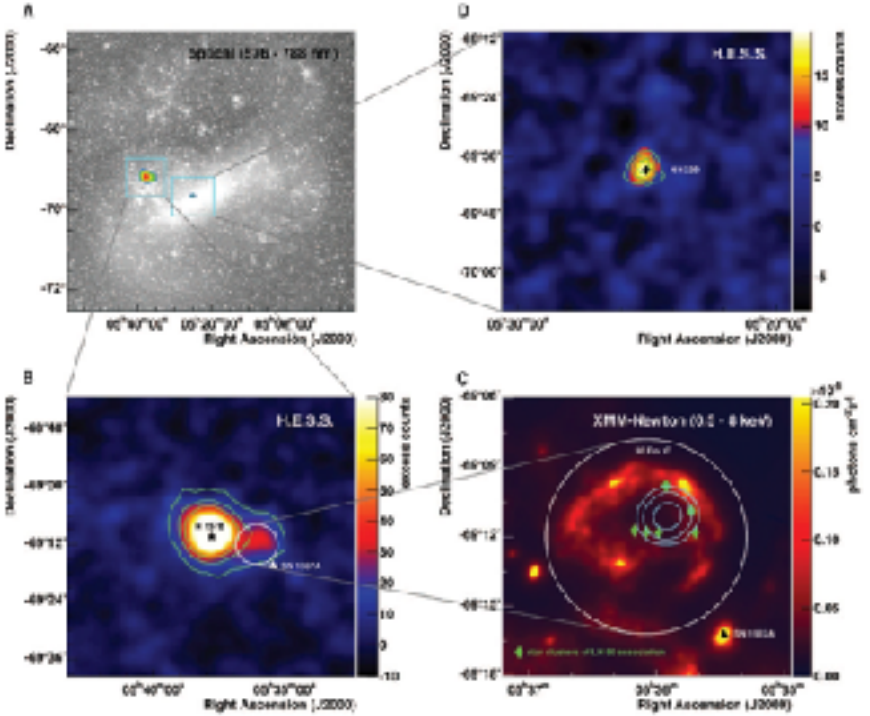
- Expectation to study in detail hundreds of sources





Galactic sources... outside of the galaxy!

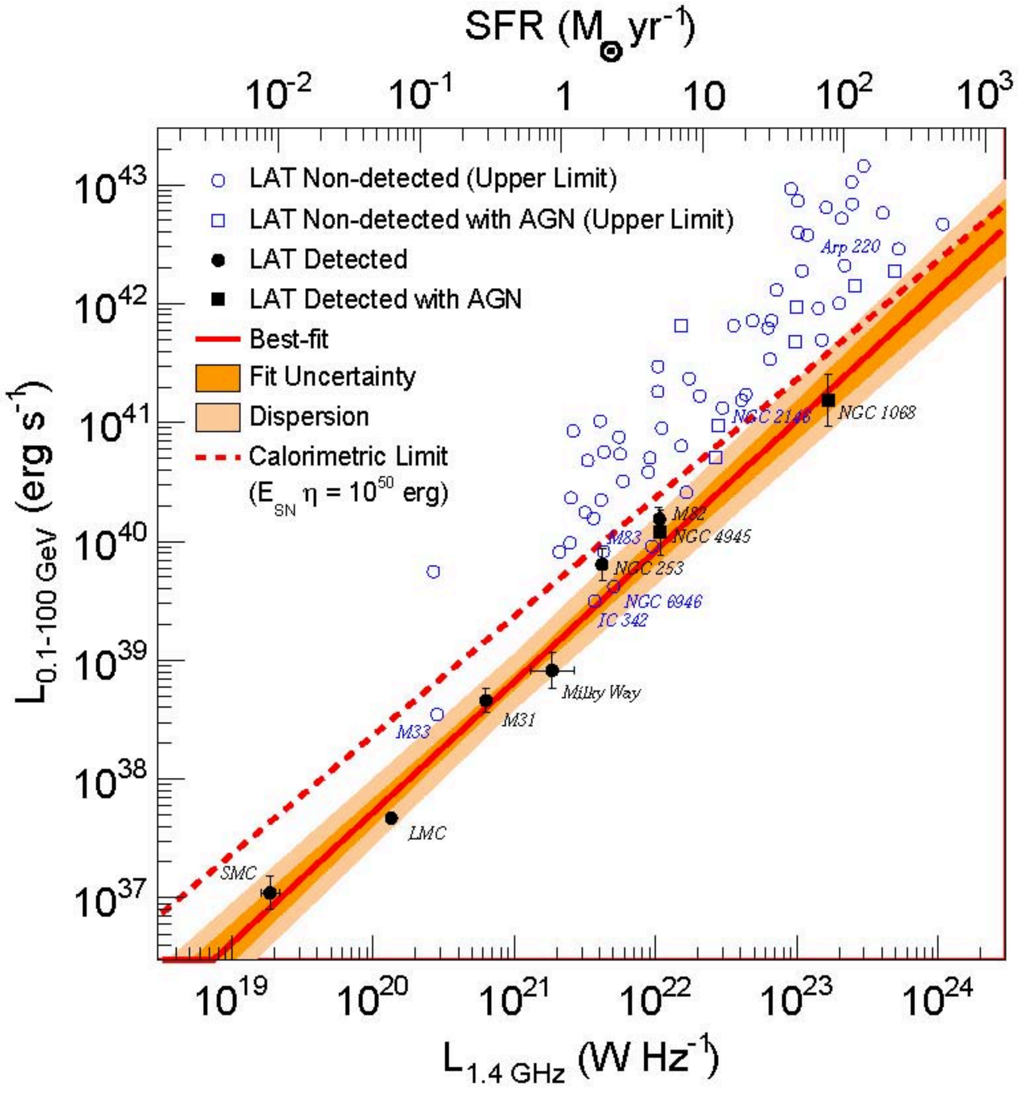
- 3 TeV sources in the Large Magellanic Cloud (LMC):
  - PWN N157B
    - Crab counterpart but low B field
  - 30 Dor C
    - first unambiguous detection of a superbubble in gamma rays
  - N 132D
    - one of the oldest TeV emitting SNRs
- First individual cosmic-ray sources in an external galaxy



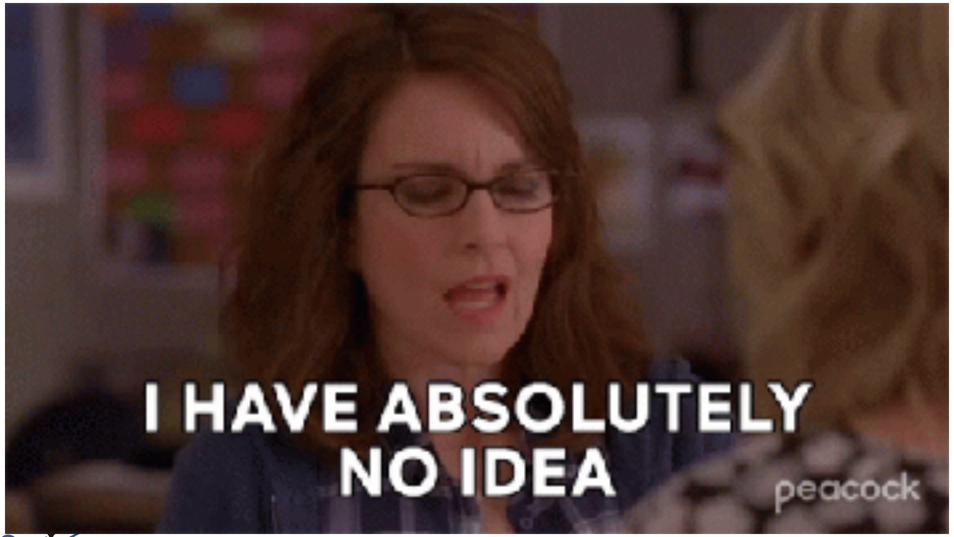
Galactic science in extragalactic objects

- HE gamma-ray emission from star burst Galaxies SBGs and nearby ordinary galaxies (Magellanic clouds, M31) scales quasi-linearly with Star Formation Rates (SFR) derived from IR observations

- Also correlates with radio continuum (from CR electrons)

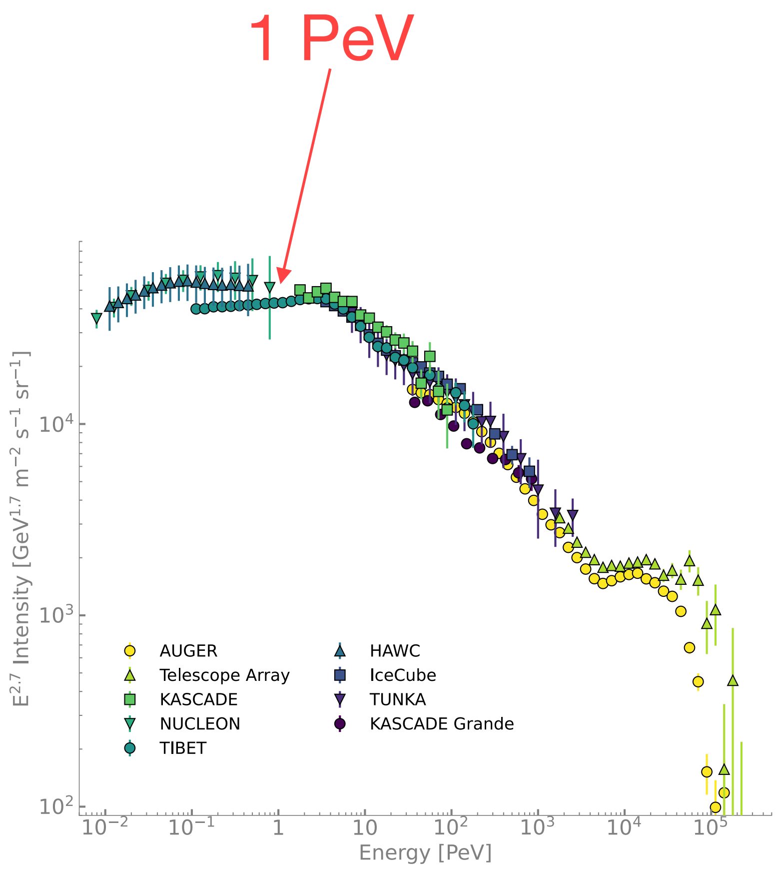


To sum up… what's the Origin of Galactic CRs?



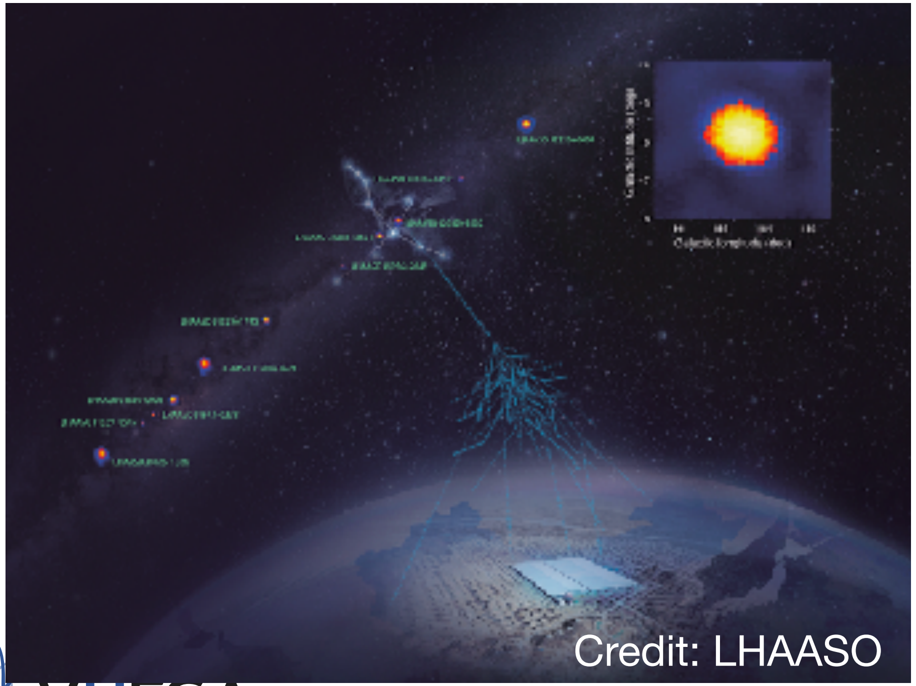
PeVatrons

- The term “PeVatron” usually refers to accelerators which are able to accelerate particles at energies > 1 PeV
  - This definition is independent of the particle nature (electron or heavy nuclei)
- Why are they so important?
  - The change of spectral index at the *knee* points to a change of dominant source accelerator
  - Origin of **Galactic Cosmic rays** => Need to get particles accelerated up to PeV energies.
- Composition at the knee also unknown
  - Maximum rigidity needed depends on composition.



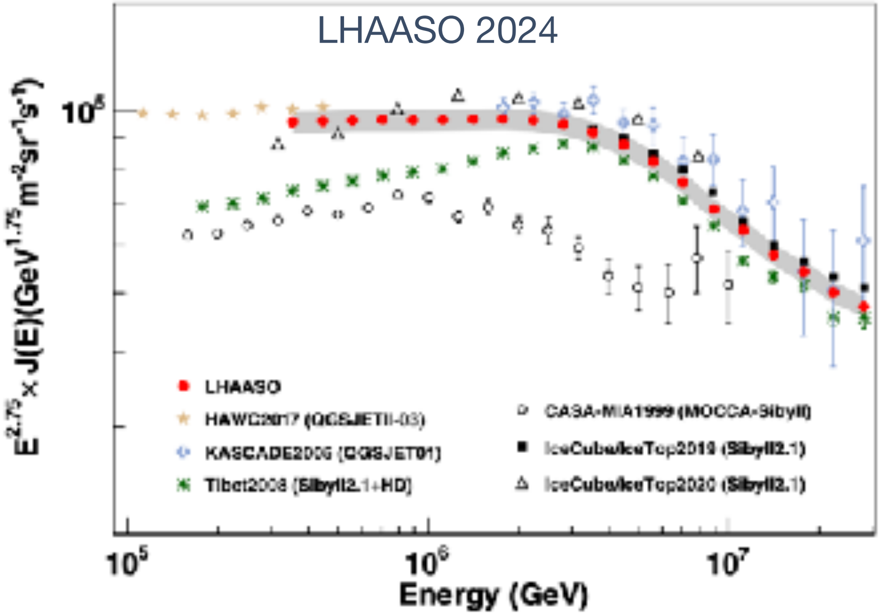
PeVatrons: a hot topic nowadays

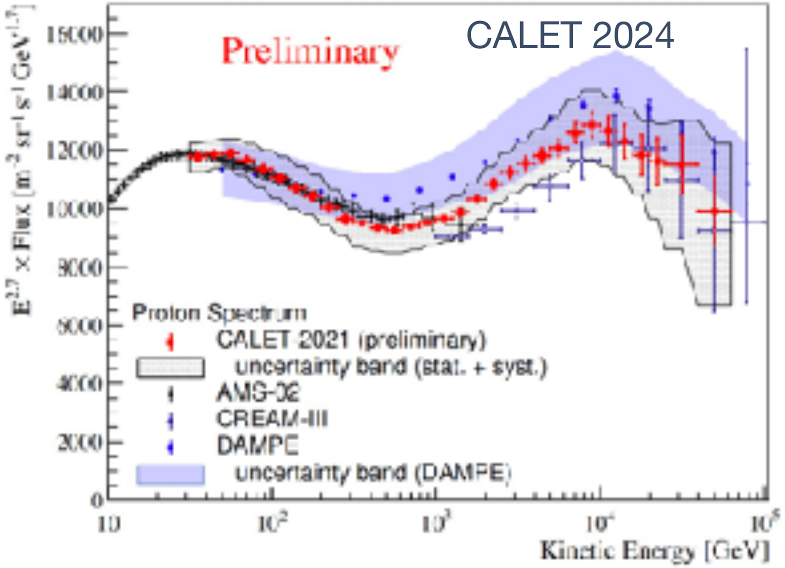
- Latest results from several experiments have increased the interest on the study of PeVatrons
  - SNRs struggle to reach the PeV goal.
  - Star forming regions observed by IACTs and wide FoV instruments.
  - Microquasars???
  - LHAASO results on sources emitting gamma rays up to PeV energies.
    - Are they protons or electrons?


Credit: LHAASO

PeVatrons: a hot topic nowadays

- Particle spectrum shows general trends, but the proton spectrum is subjected to statistics and systematic errors: this could broaden the range of possible PeVatrons.
- Latest results from CALET/DAMPE show that the region below 1 PeV is not as featureless as we thought

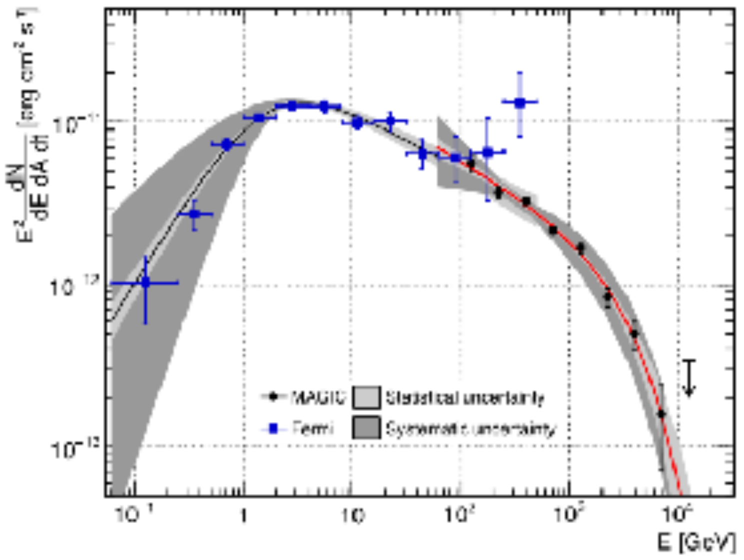




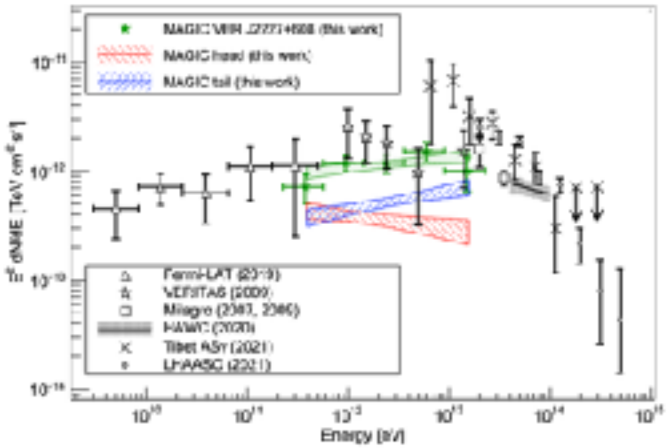
Main candidate: Supernova Remnants

- Most popular historical candidate to explain Galactic Cosmic Rays
  - Phenomenologically favored over the years.
- SNRs provide a huge **energy budget** and enough **number of sources** to explain:
  - The whole galactic hadronic CR flux
  - Anisotropy
- BUT
  - No firm evidence of proton acceleration beyond few hundred TeV.
  - From theory, only powerful and rare SNRs reach PeV energies.
- The Challenge: known SNRs do not seem to be PeVatrons at present

Cas A. MAGIC Collaboration, 2017

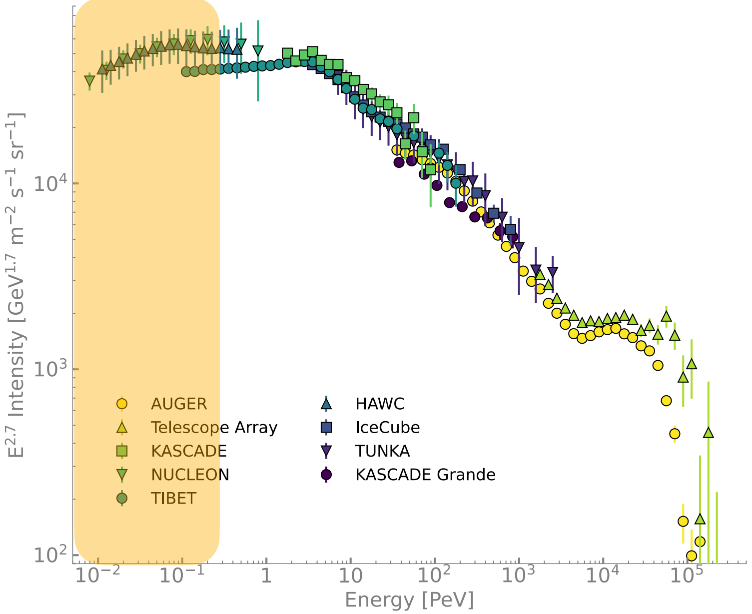


Boomerang, MAGIC Collaboration 2022



The origin of the Galactic Cosmic Rays

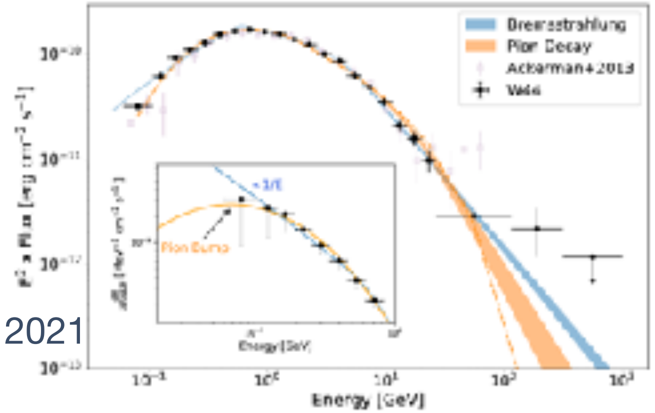
The Sub-PeV regime



- General agreement: most of the low energy particles comes from Supernova Remnants
  - Experimental evidences & theoretically comfortable

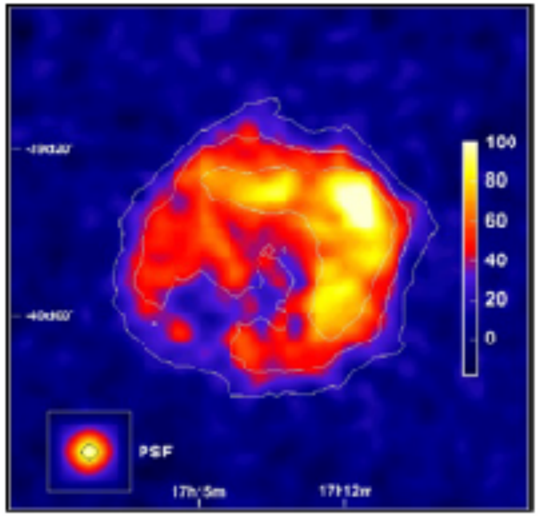
Experimental evidences:

Pion Decay



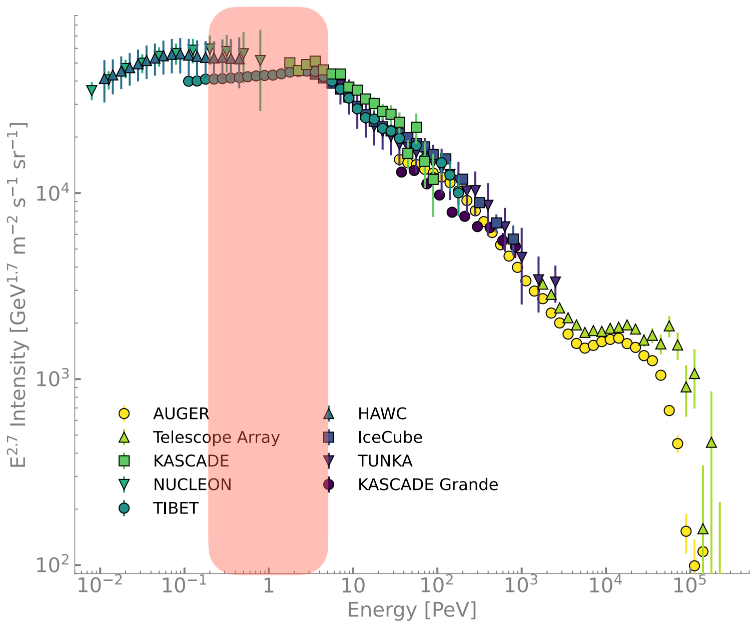
Peron et al. 2021

Morphology

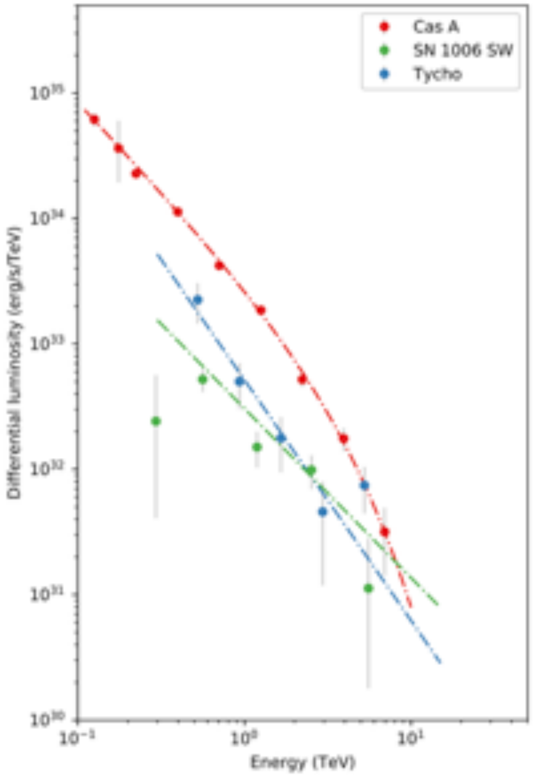


The origin of the Galactic Cosmic Rays

~hundreds of TeV to few PeV



- The challenge to the standard paradigm: known young SNRs do not seem to reach PeV energies

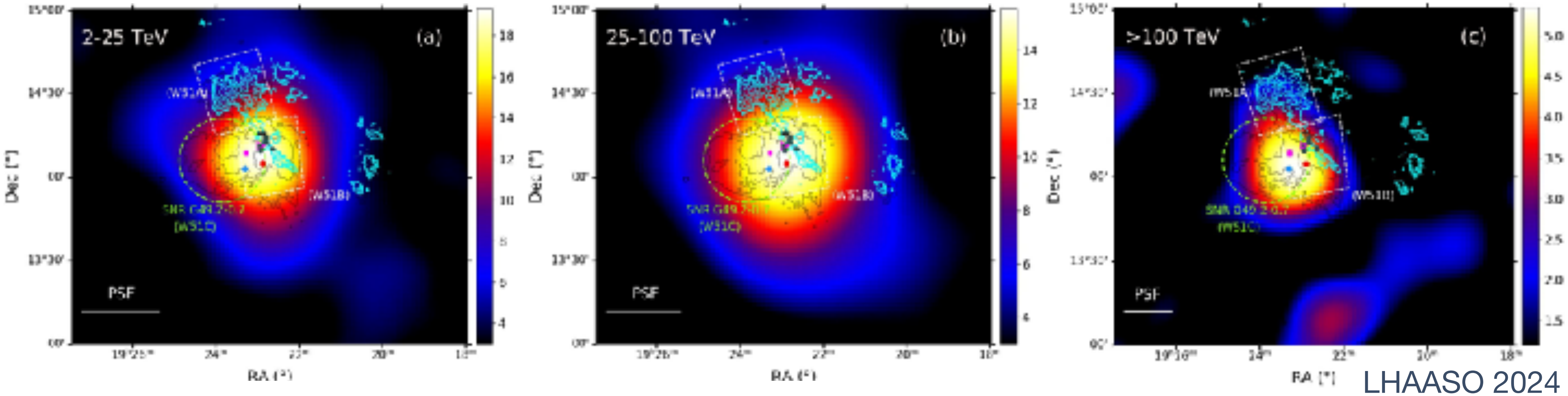


Experimental evidences:

Aharonian, F. et al., 2019

PeV acceleration? in Supernova Remnants

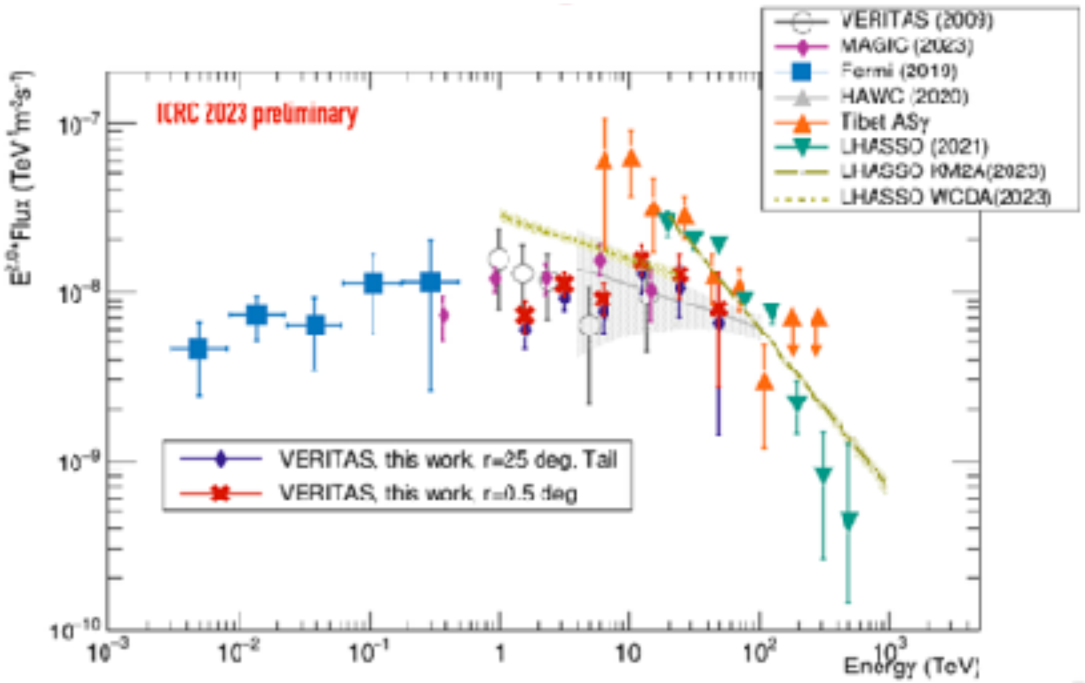
- **W51C** measured by MAGIC, HESS, HAWC, LHAASO… up to ~hundreds of TeV
  - still favoring hadronic models (with cut-off at 400 TeV) to explain the emission
  - approaching (but not reaching) the holy-grail PeV



LHAASO 2024

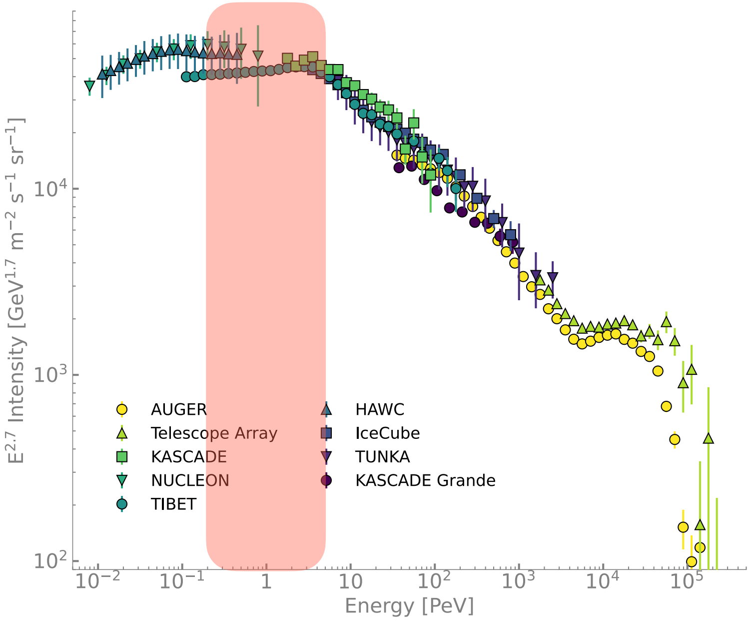
PeV acceleration? in Supernova Remnants

- **SNR G106.3+2.7** (Boomerang)
  - HAWC, VERITAS, MAGIC, LHAASO, Tibet AS-γ…
    - Spectrum measured up to ~500 TeV.
    - Origin unclear



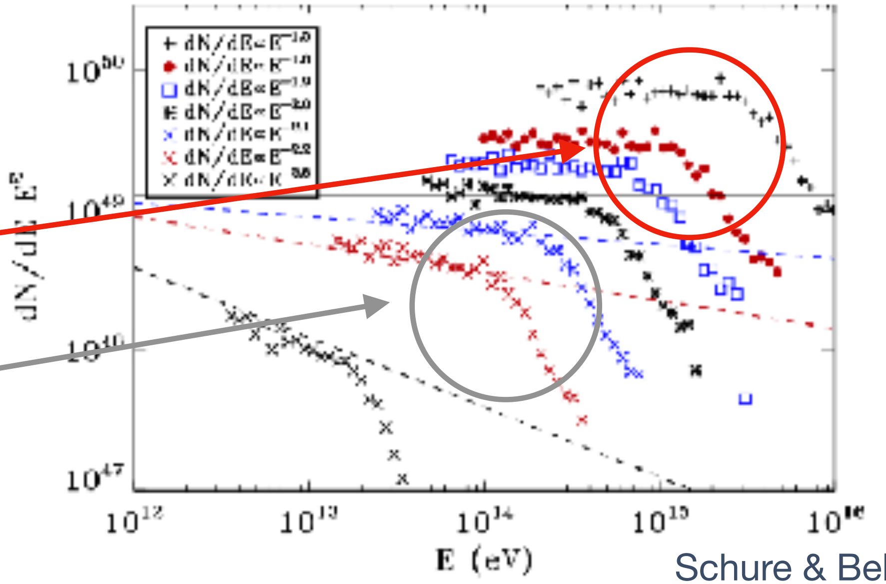
The origin of the Galactic Cosmic Rays

~hundreds of TeV to few PeV



- Theoretical estimations:
  - We need young SNRs in dense winds (type II)
  - We need escape of particles upstream to produce confining magnetic fields

- Knee at the right energy => too hard injection spectrum
- Softer -more natural- injection spectrum => high energies not reached



Schure & Bell 2014

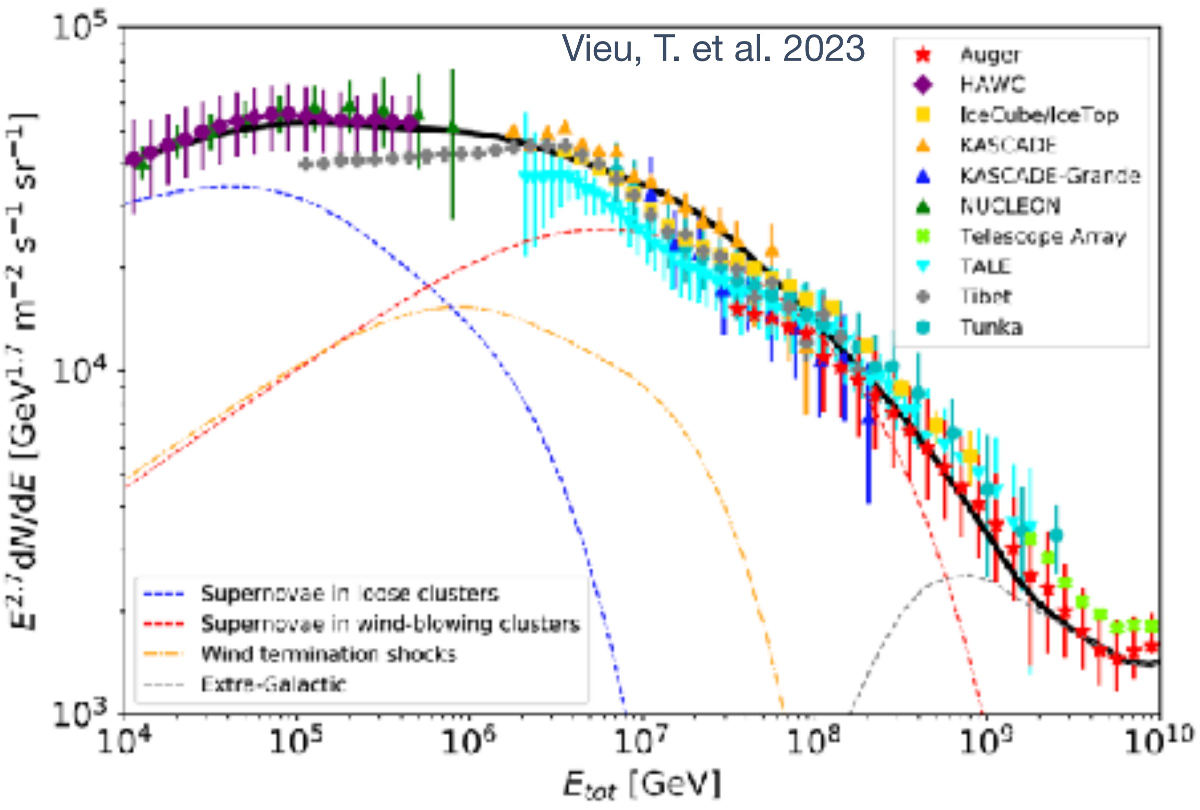
The origin of the Galactic Cosmic Rays

~hundreds of TeV to few PeV

- Possible ideas to solve the problem…

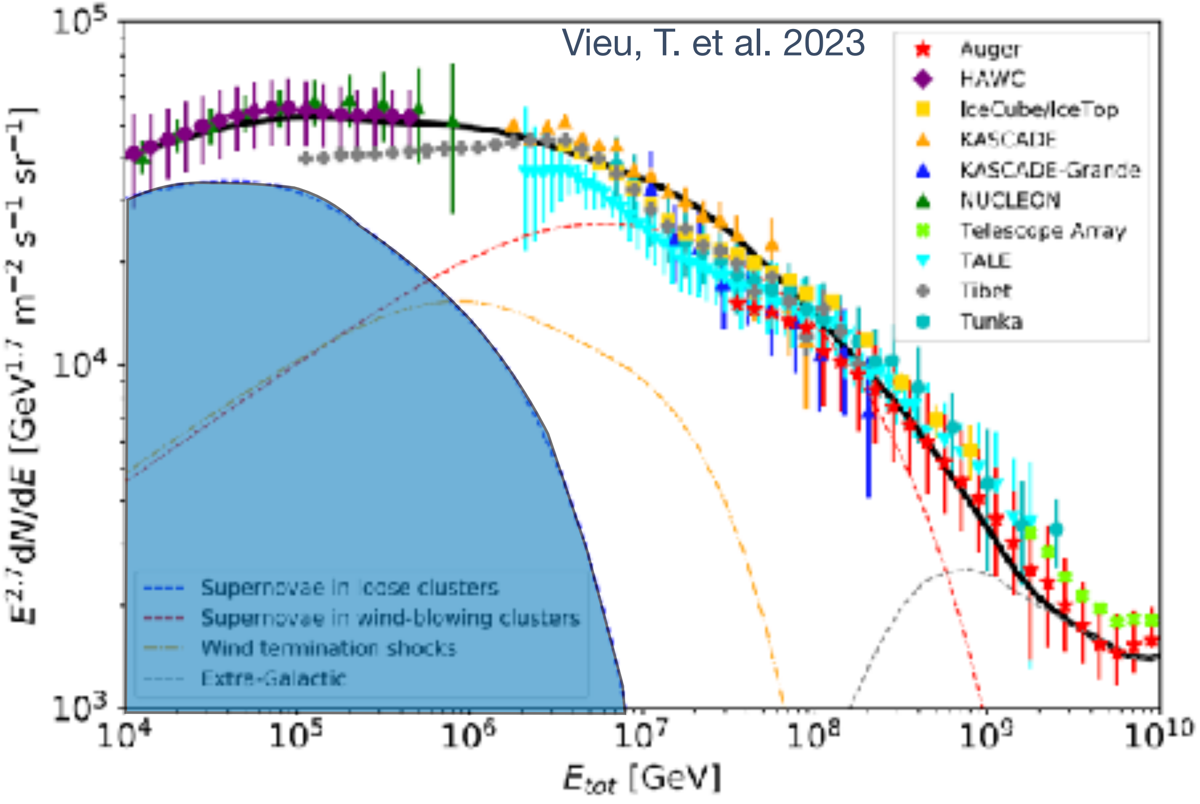
  - Early phase SNRs in the <100 yrs (highest density / fastest shock velocity) are the ones accelerating PeV CRs.
  - SNRs we don't know?
  - Some candidates may reach almost the PeV regime
    - W51C, Boomerang…
  - Two source population hypothesis: a source type that provides the bulk of CRs (SNRs) and another one that provides the highest energies?
    - Other accelerators: Stellar clusters / SNRs in Stellar clusters / Galactic Center / Microquasars / …

Two source population hypothesis



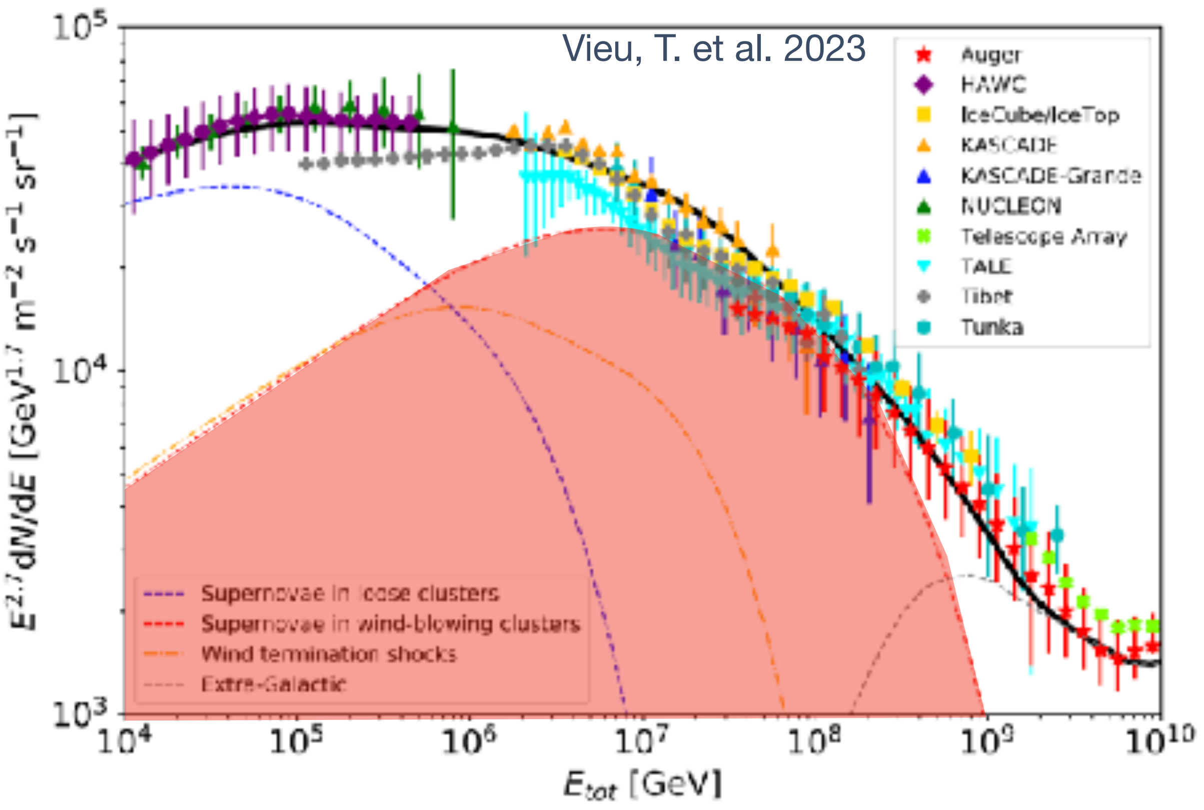
Two source population hypothesis

- Two source population hypothesis: a source type that provides the bulk of CRs (SNRs) and another one that provides the highest energies?



Two source population hypothesis

- Fits CR composition
  - But still to be proven…



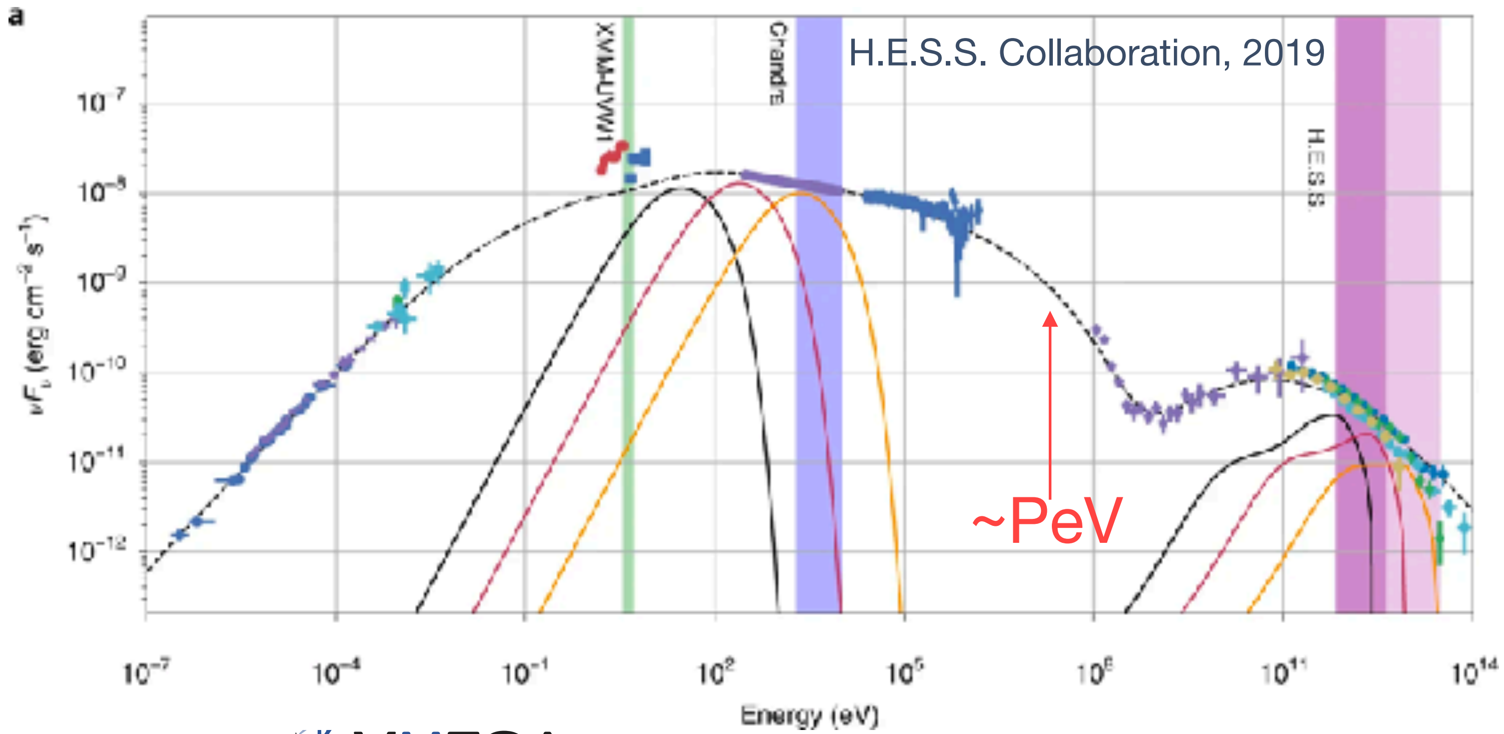
Two source population hypothesis

- Fits CR composition
  - But still to be proven…

- Stellar Cluster: Some problems
  - Radial profile sometimes does not follow 1/r
  - Product of CRs and gas distribution -> Might not strictly have to follow it…
    - Depends on the center of gravity
- Massive clusters are large and messy: difficult to prove the association of gamma rays with the stellar cluster.
  - Better resolution in the gamma-ray instruments and neutrino detectors is needed

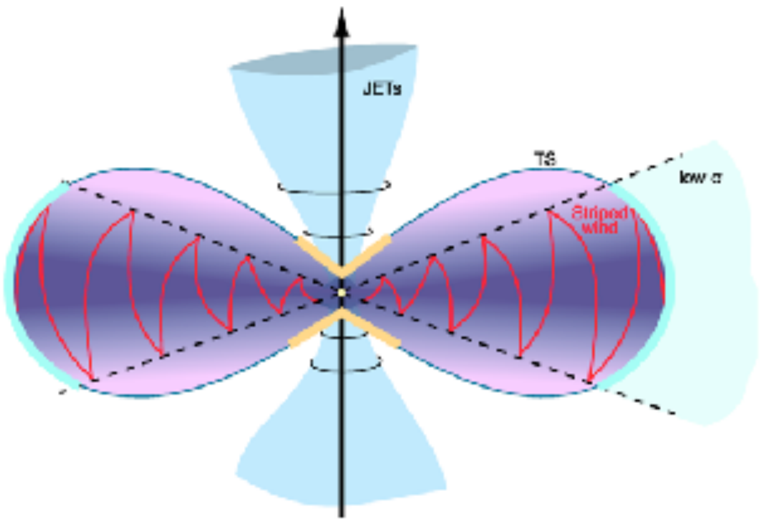
Leptonic PeVatrons

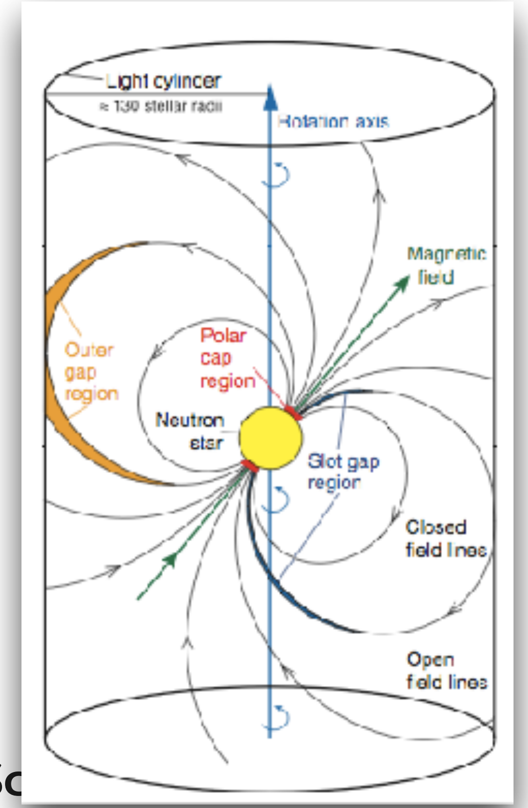
- Leptonic CR accelerators known since several decades
  - Crab Nebula as an example leptonic PeVatron.



The Role of Pulsars/PWNe

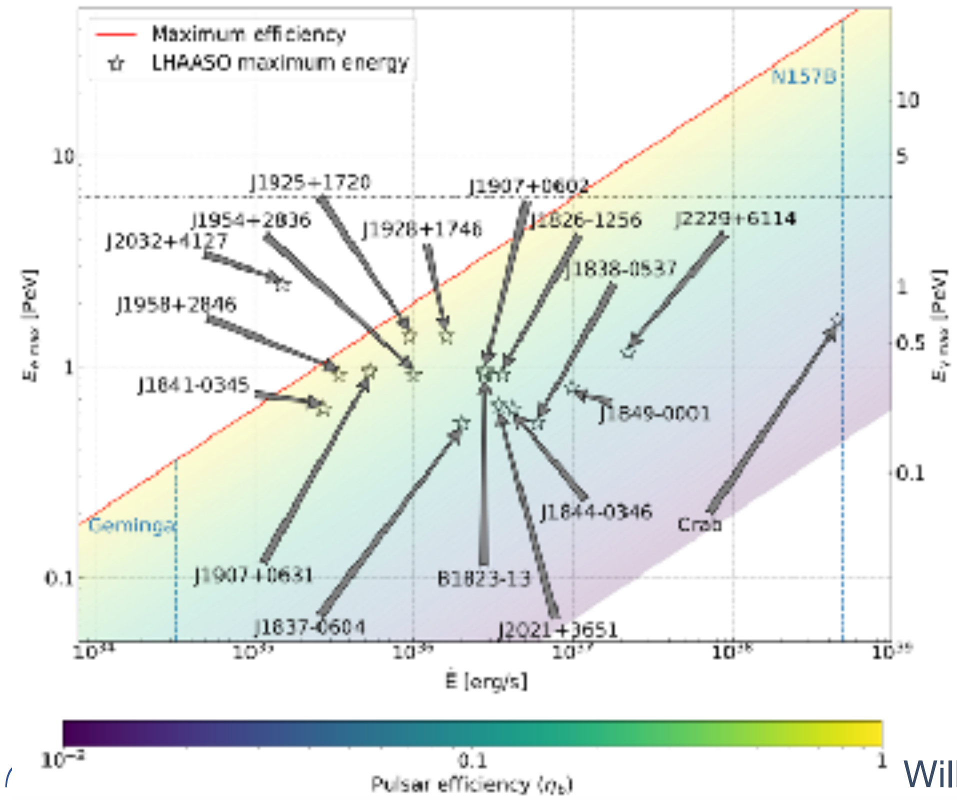
- It is very-well known that electrons and positrons get accelerated in pulsars and their environments
  - Also likely other sources, but these are the primary ones for which we have proof





Do not forget leptons

- Leptonic CR accelerators known since several decades
  - Can most of the gamma-ray sources emitting in the ~hundreds of TeV gamma-ray energy range be explained via leptonic emission? => YES!

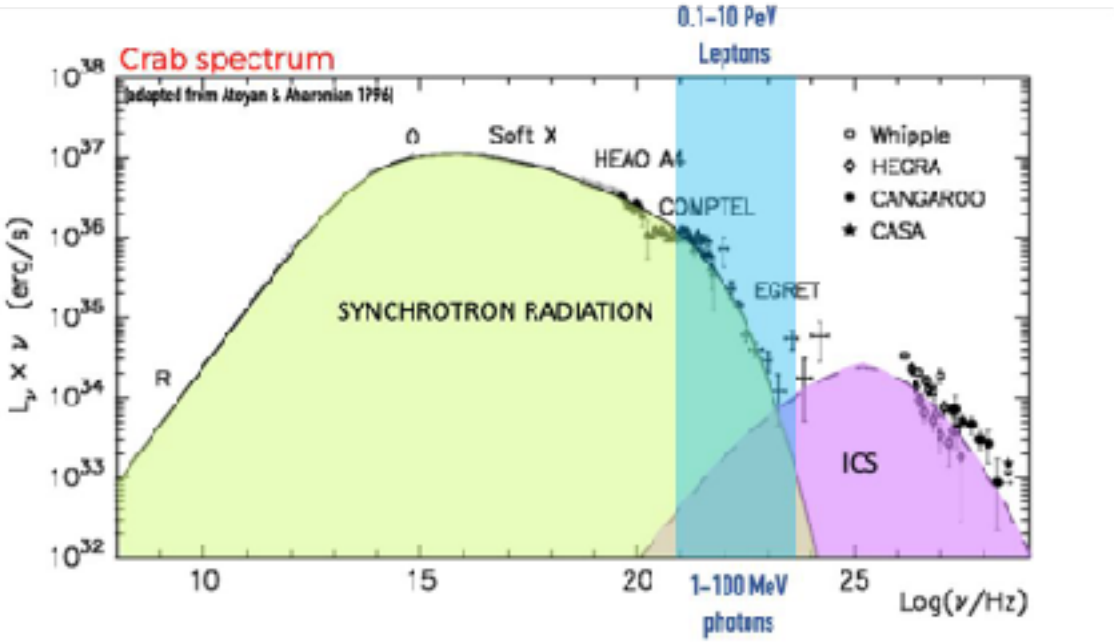


Wilhelmi, RLC et al. 2022

Leptonic PeVatrons

- It is very-well known that electrons and positrons get accelerated in pulsars and their environments
  - Also likely other sources, but these are the primary ones for which we have proof

- The only known PeVatron since many years is the Crab Nebula
  - Can also other sources accelerate particles up to PeV energies?



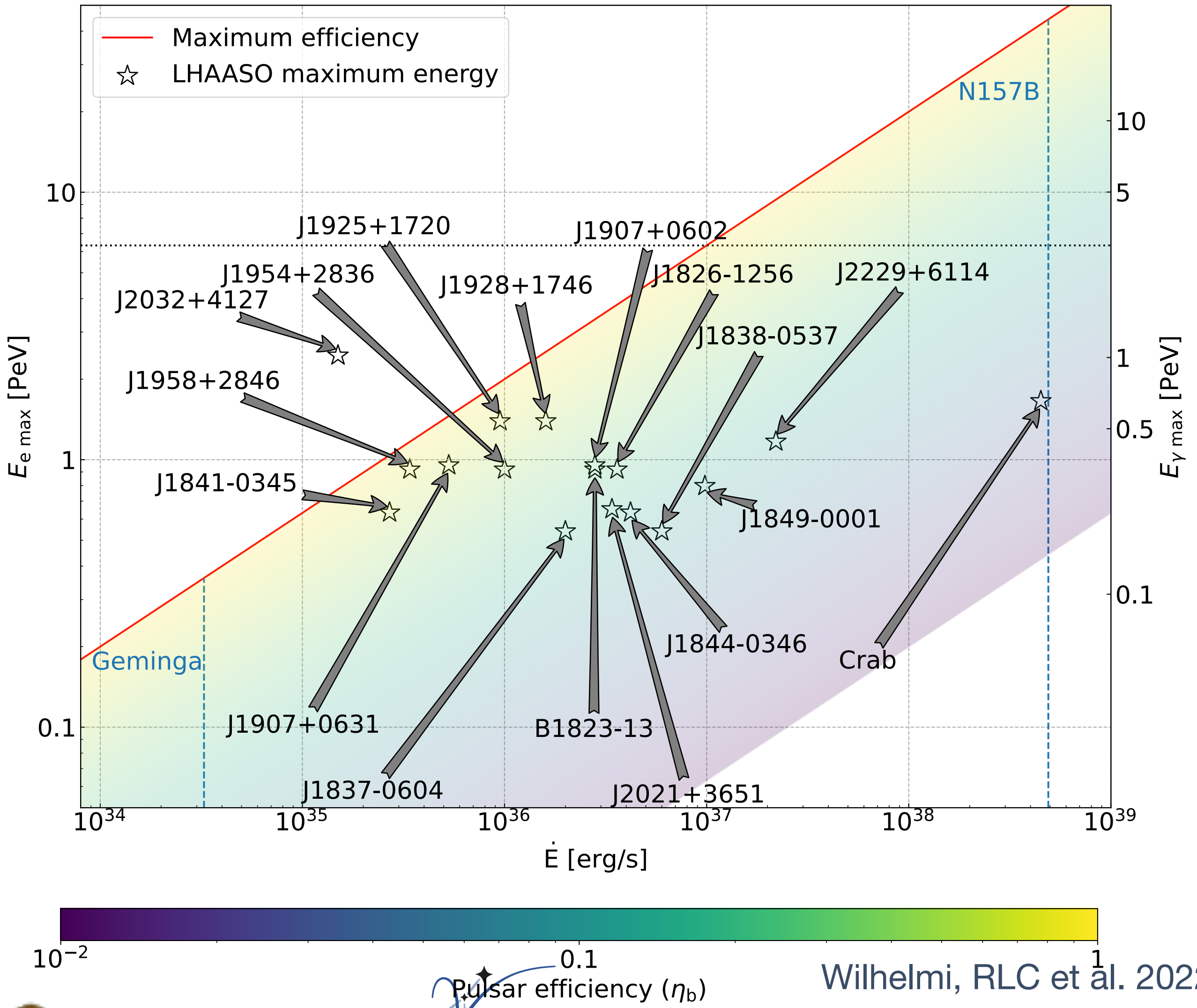
The Role of Pulsars/PWNe

- Our study [Wilhelmi, RLC et al. 2022]:
  - search for pulsars within 1 deg from the location of LHAASO sources.
- Study if these pulsars can provide enough acceleration power to produce the gamma rays detected at E > 1 PeV
  - But we have reasonable doubts about how particles get accelerated by Diffusive Shock Acceleration, which maximum energy they reach and so on, so…
    - What is the energy limit?
- Maximum energy is given by the maximum potential drop that you can get from a pulsar
  - The **potential drop** between the pulsar ($V = (\dot{E}/c)^{1/2}$) and infinity (V=0) gives you the maximum energy that can be reached for individual particles
  - This gives you the maximum energy of electrons, that can be related to the maximum energy of gammas in the Klein-Nishina regime:

$$E_{\gamma,\max} \approx 0.9 \dot{E}_{36}^{0.65} \ \mathrm{PeV}$$

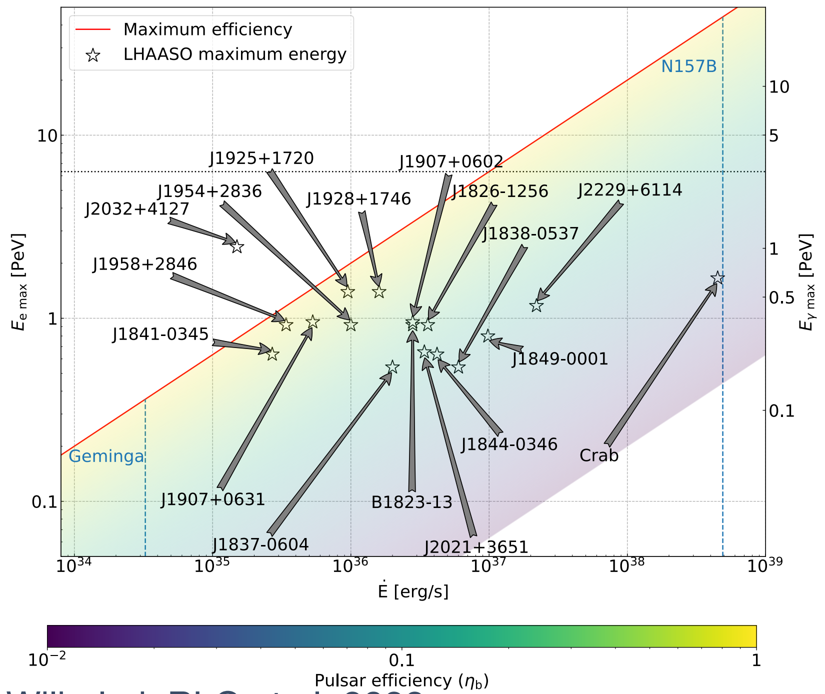
Physical limits

$$E_{\gamma,\max} \approx 0.9\dot{E}_{36}^{0.65}\ \text{PeV}$$



Wilhelmi, RLC et al. 2022

Physical limits



Wilhelmi, RLC et al. 2022

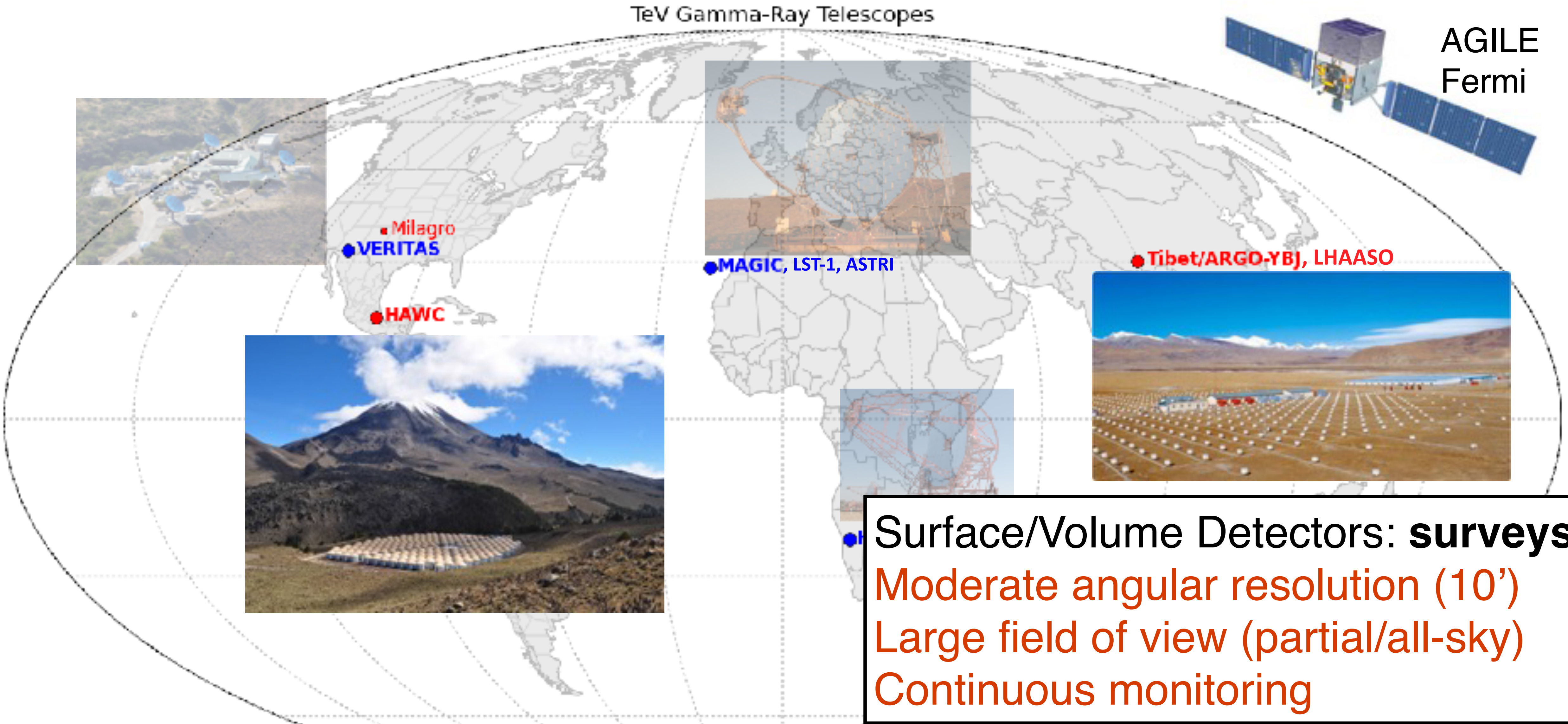
Table 2
LHAASO Ultrahigh-energy Sources and Putative Associated Pulsars, with the Corresponding Constraints on the Maximum Energy and Magnetic Field

LHAASO Source	Pulsar	$E_{\gamma,max}$ (PeV)	E_{max} (PeV)	B_{max} (μG)
J1825-1326	J1826-1256	2.06	3.79	38
	B1823-13	1.77	3.35	14
J1839-0545	J1837-0604	1.44	2.83	33
	J1838-0537	2.78	4.90	$\gg$ 100
J1843-0338	J1841-0345	0.41	1.04	12
	J1844-0346	2.25	4.10	$\gg$ 100
J1849-0003	J1849-0001	3.71	6.26	$\gg$ 100
J1908+0621	J1907+0602	1.77	3.35	30
	J1907+0631	0.63	1.46	9
J1929+1745	J1925+1720	0.91	1.95	9
	J1928+1746	1.26	2.53	14
J1956+2845	J1954+2836	0.94	2.00	37
	J1958+2846	0.47	1.17	22
J2018+3651	J2021+3651	1.99	3.69	102
J2032+4102	J2032+4127	0.28	0.77	7
J2108+5157				
J2226+6057	J2229+6114	5.89	9.36	64

- All sources but two can be explained with the visible pulsars in their neighbor
  - one of them (LHAASO J2108+5157) does not have any associated pulsar
  - the second (LHAASO J2032+4102) has a pulsar not powerful enough to produce the observed gamma-ray emission


Thanks!
Juan Escudero

Gamma-ray astronomy



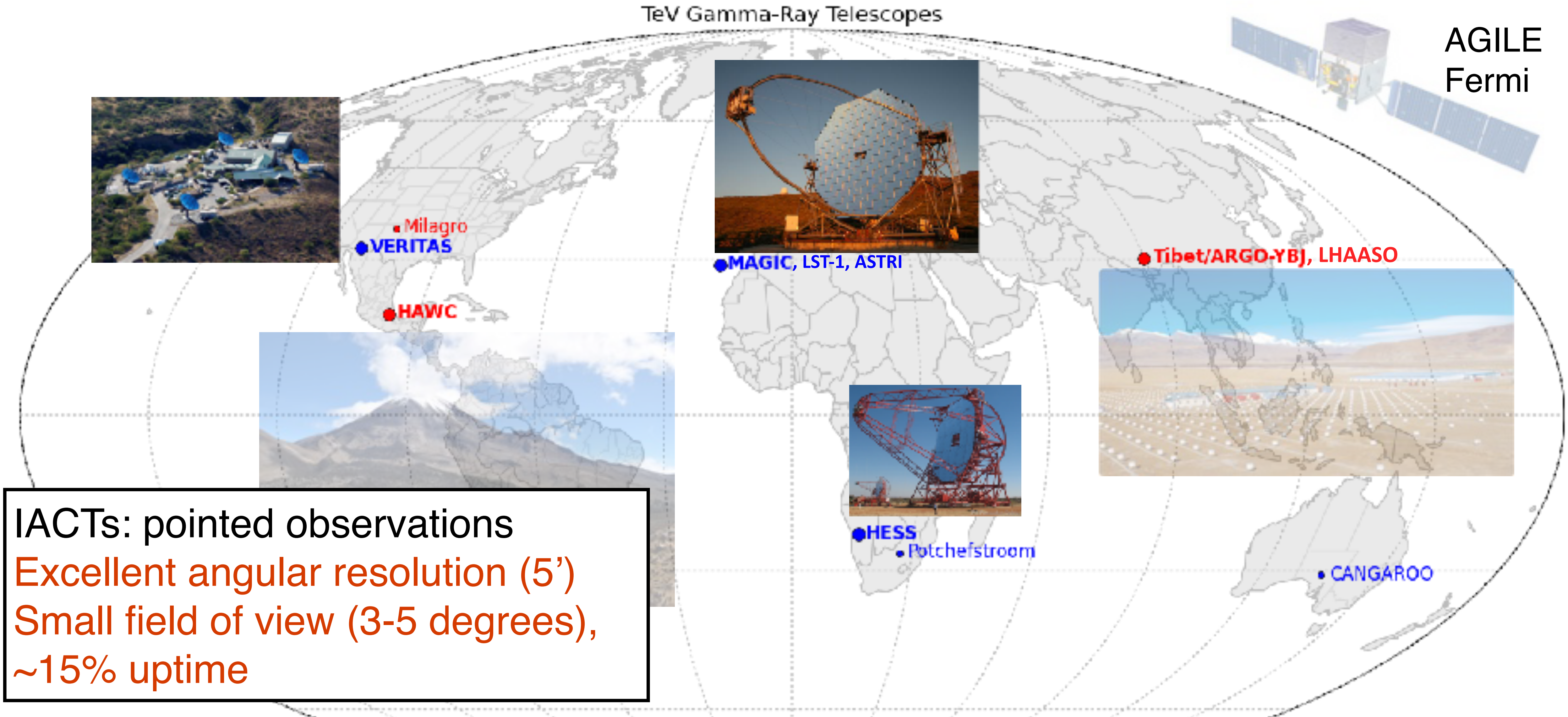
Surface/Volume Detectors: **surveys**

Moderate angular resolution (10')

Large field of view (partial/all-sky)

Continuous monitoring

Gamma-ray astronomy

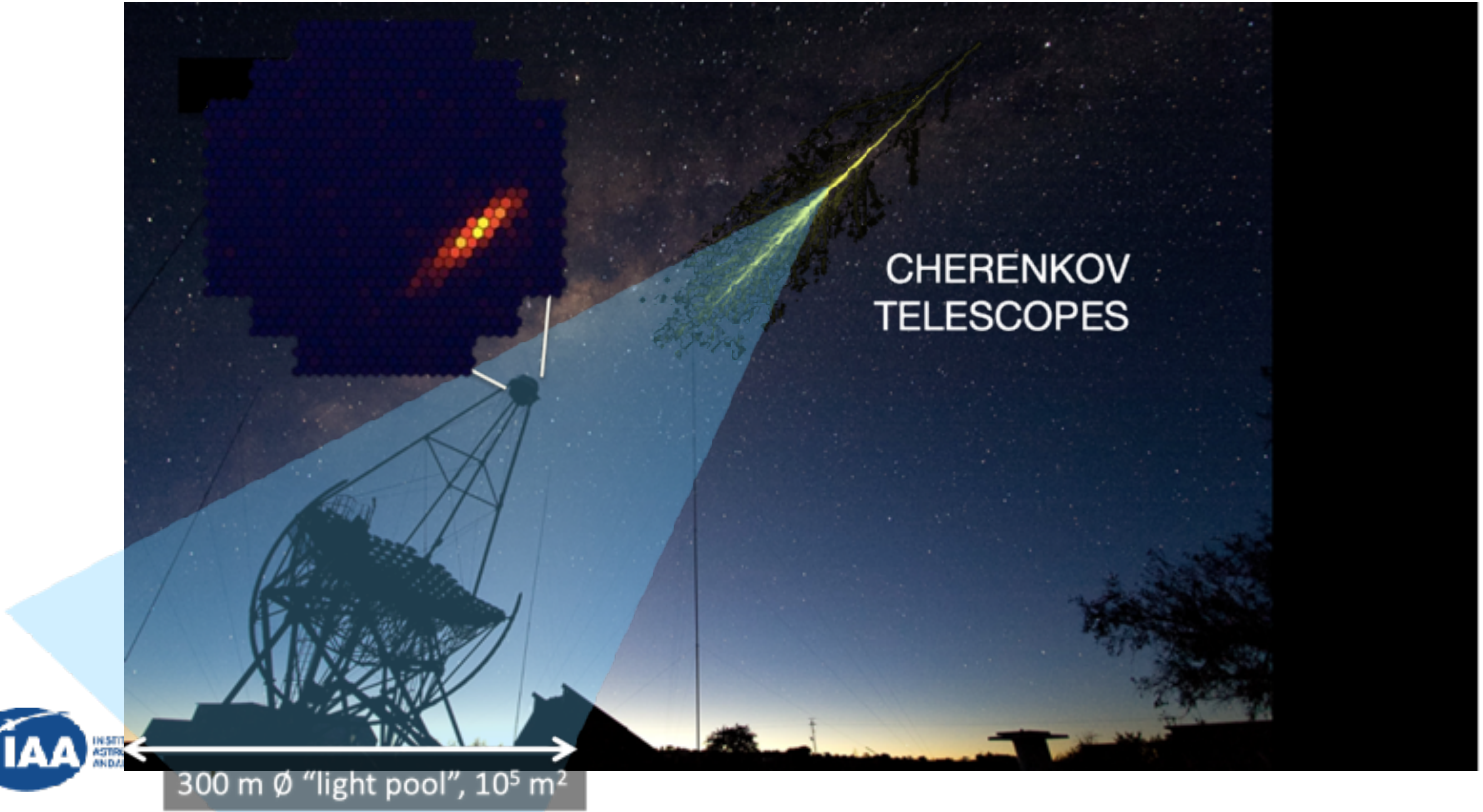


IACTs: pointed observations
Excellent angular resolution (5’)
Small field of view (3-5 degrees),
~15% uptime

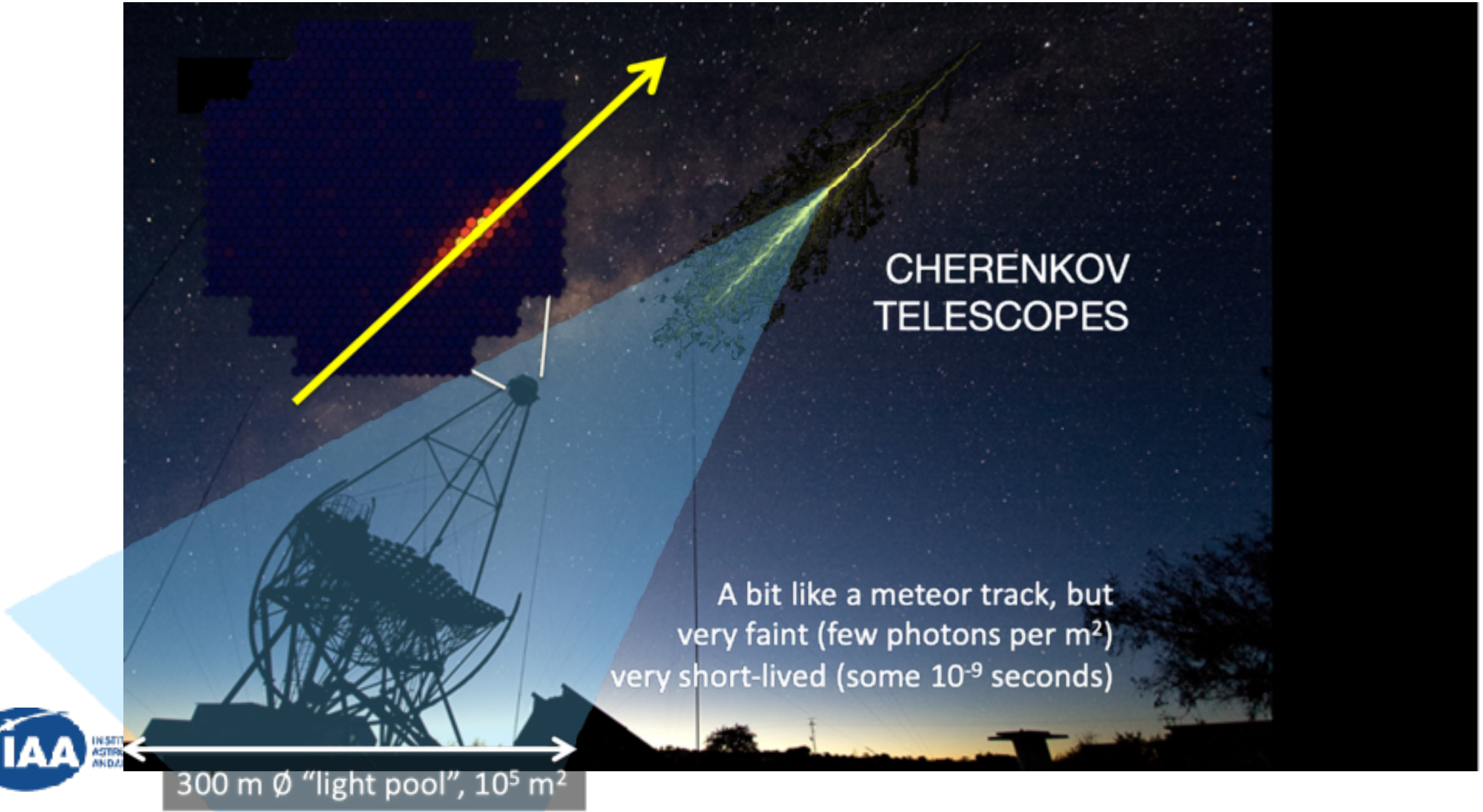
The IACT technique

The IACT technique

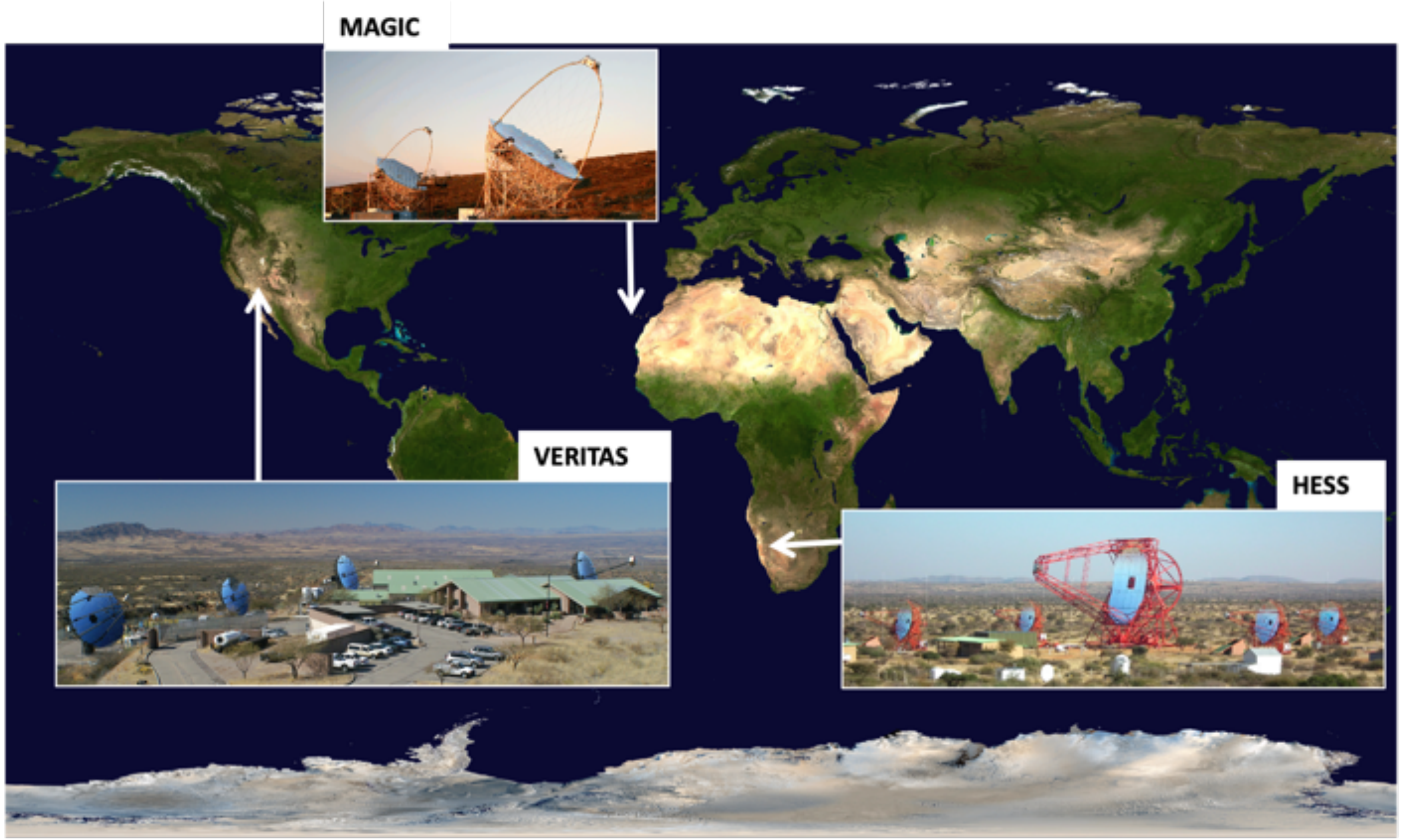
The IACT technique



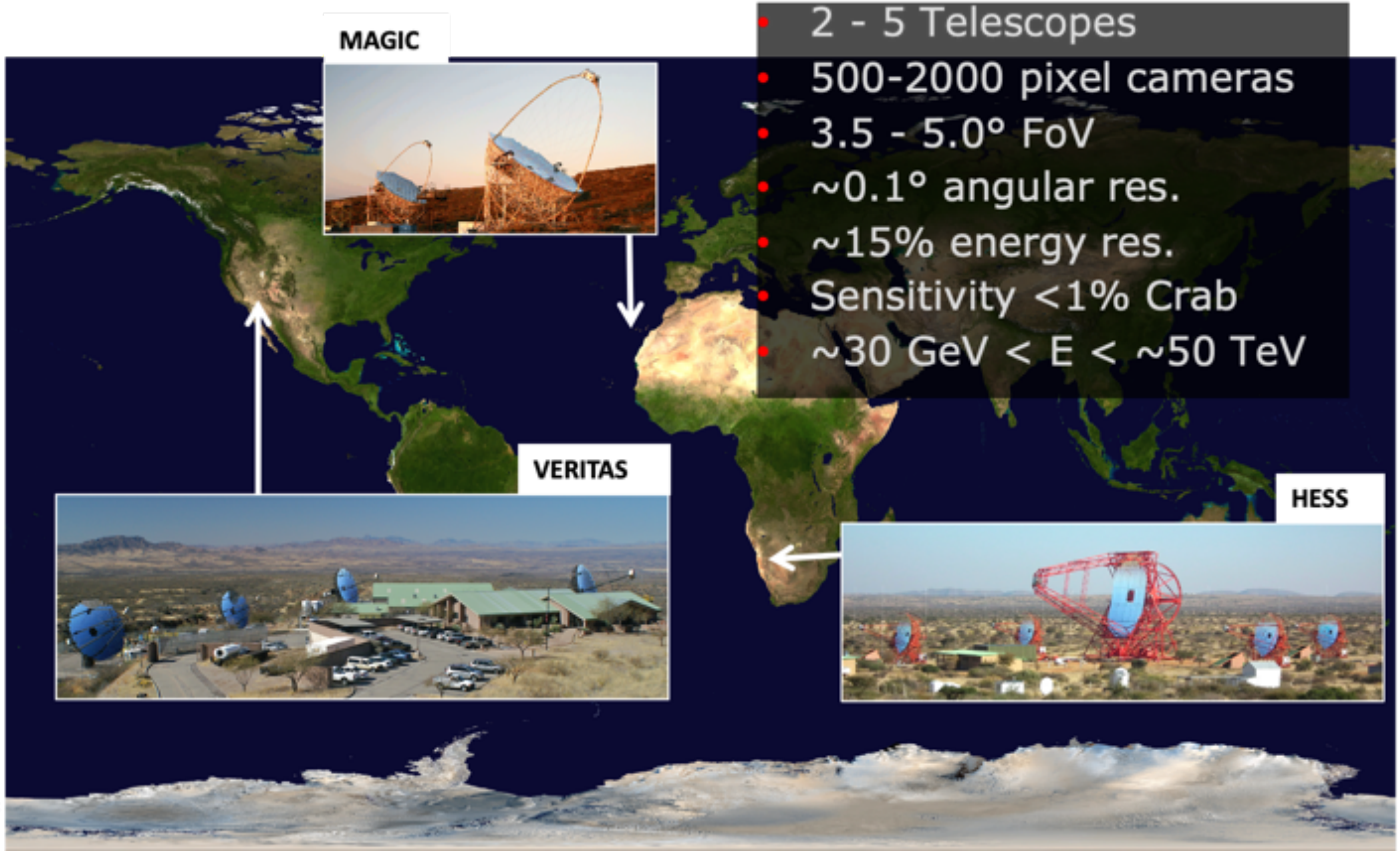
The IACT technique



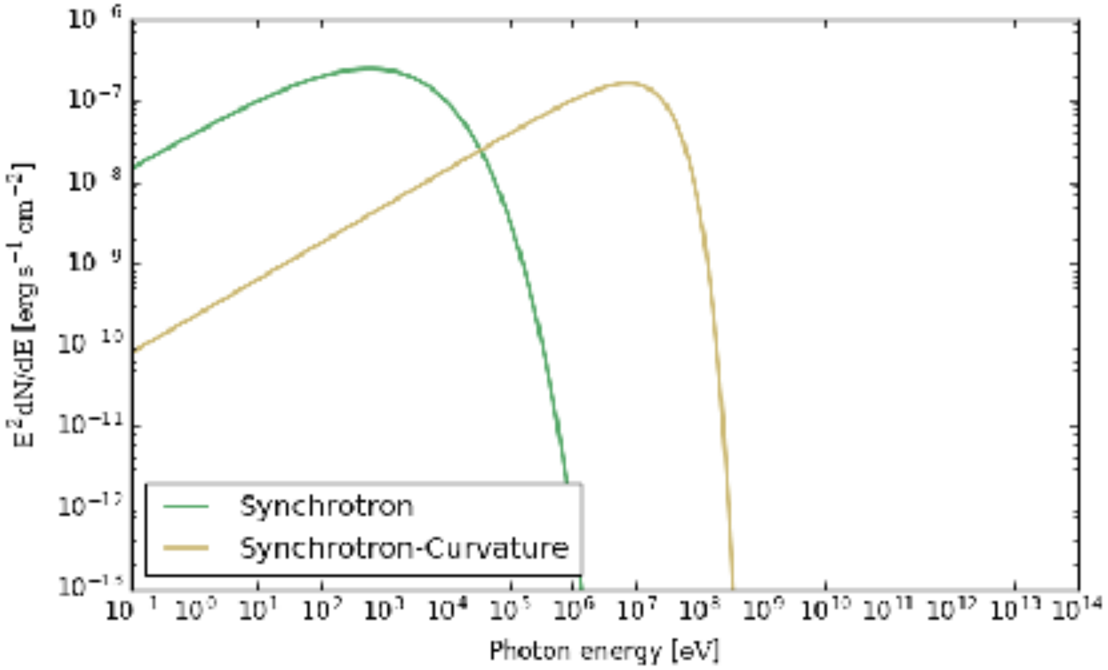
Current IACTs



Current IACTs



Radiation Mechanisms

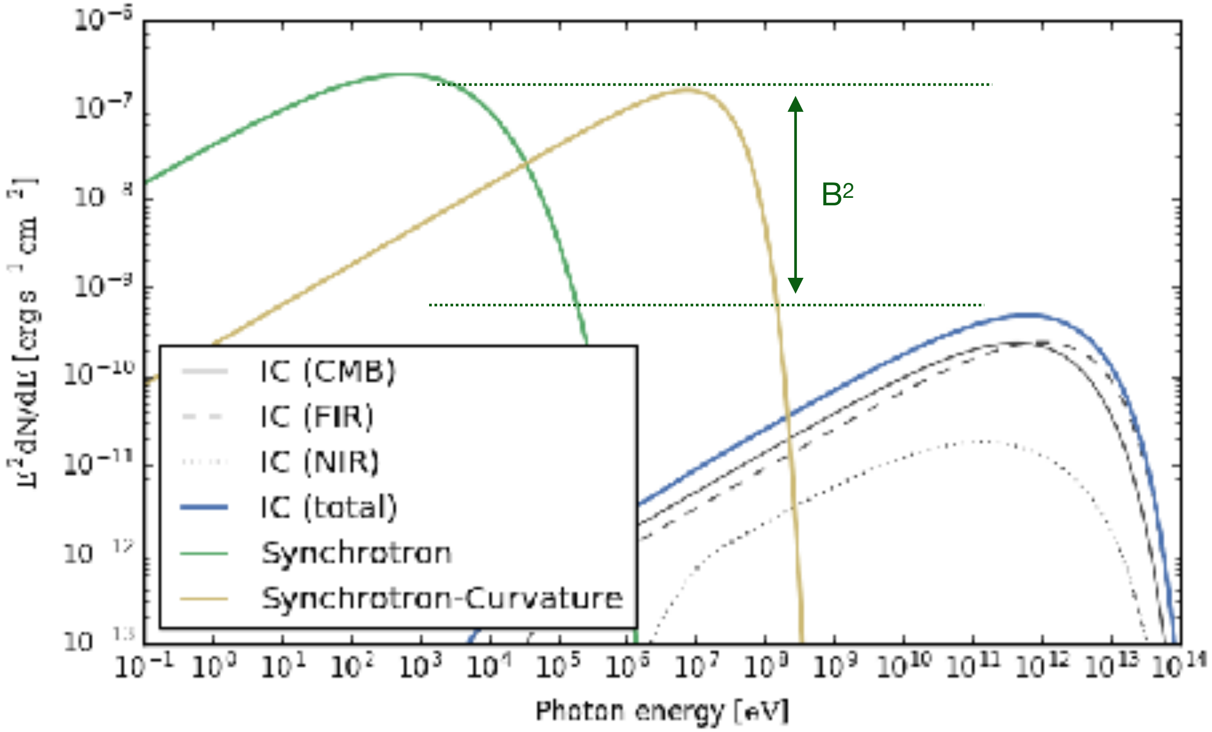


<u>Synchrotron-Curvature</u>

$e^{\pm} + \mathbf{B} \Rightarrow Y + e^{\pm}_{\mathrm{lowerE}}$

$$dN/dE \propto Q(E)t_{\mathrm{loss}}(E) \propto E^{-(s+1)}$$

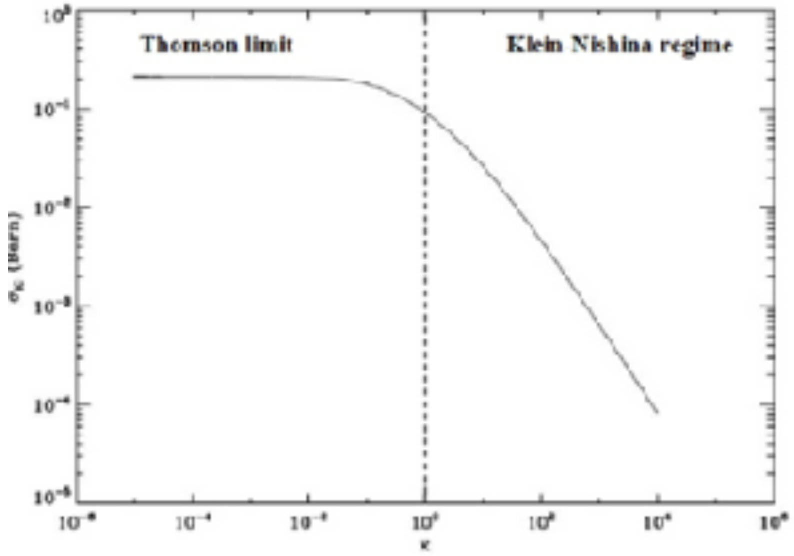
Radiation Mechanisms



<u>Inverse Compton</u>

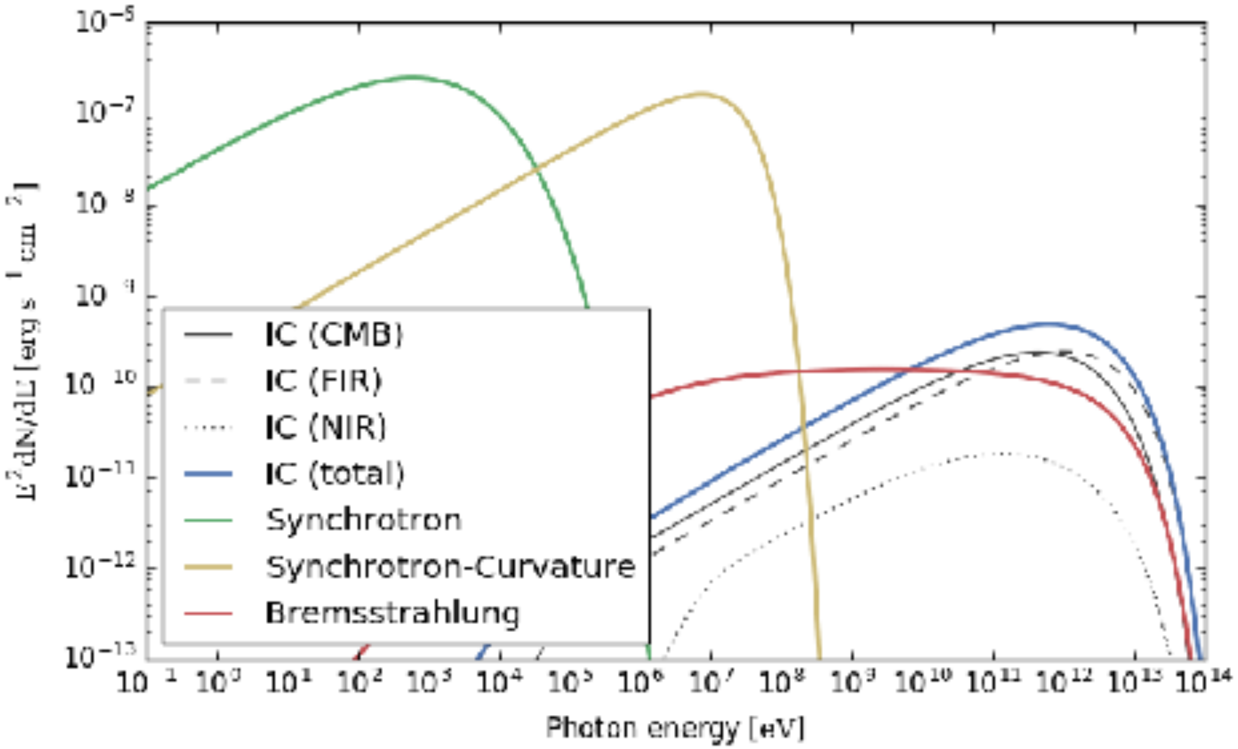
$e^{\pm}_{HE} + \Upsilon_{LE} \Rightarrow e^{\pm}_{lowerE} + \Upsilon_{LE}$

$b = 4EeE_T/m^2c^4$
$b << 1$ Thompson Regime
$b \sim 1$ Klein-Nishina Regime



- Thompson approximation (no relativistic): $\phi \sim E^{-(s+1)/2}$
- Klein-Nishina approximation (relativistic): $\phi \sim E^{-(s+1)}$

Radiation Mechanisms



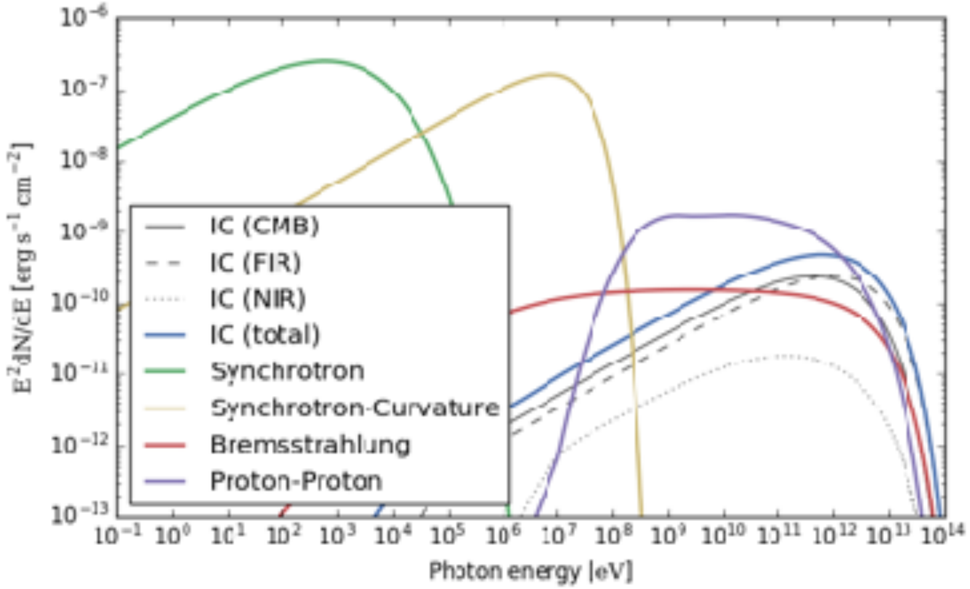
Bremsstrahlung

$e^{\pm} + N(e) \Rightarrow e' \gamma N(e)$, $E\gamma \sim 1/2\ Ee$

Regions of high density:
Galactic Center, dense clouds, SNRs

Pair Production: $\gamma N(e) \rightarrow e+e-\ N(e)$
e+e- annihilations: $e+e- \rightarrow \boldsymbol{\gamma\ \gamma}$ (511 keV line)

Radiation Mechanisms



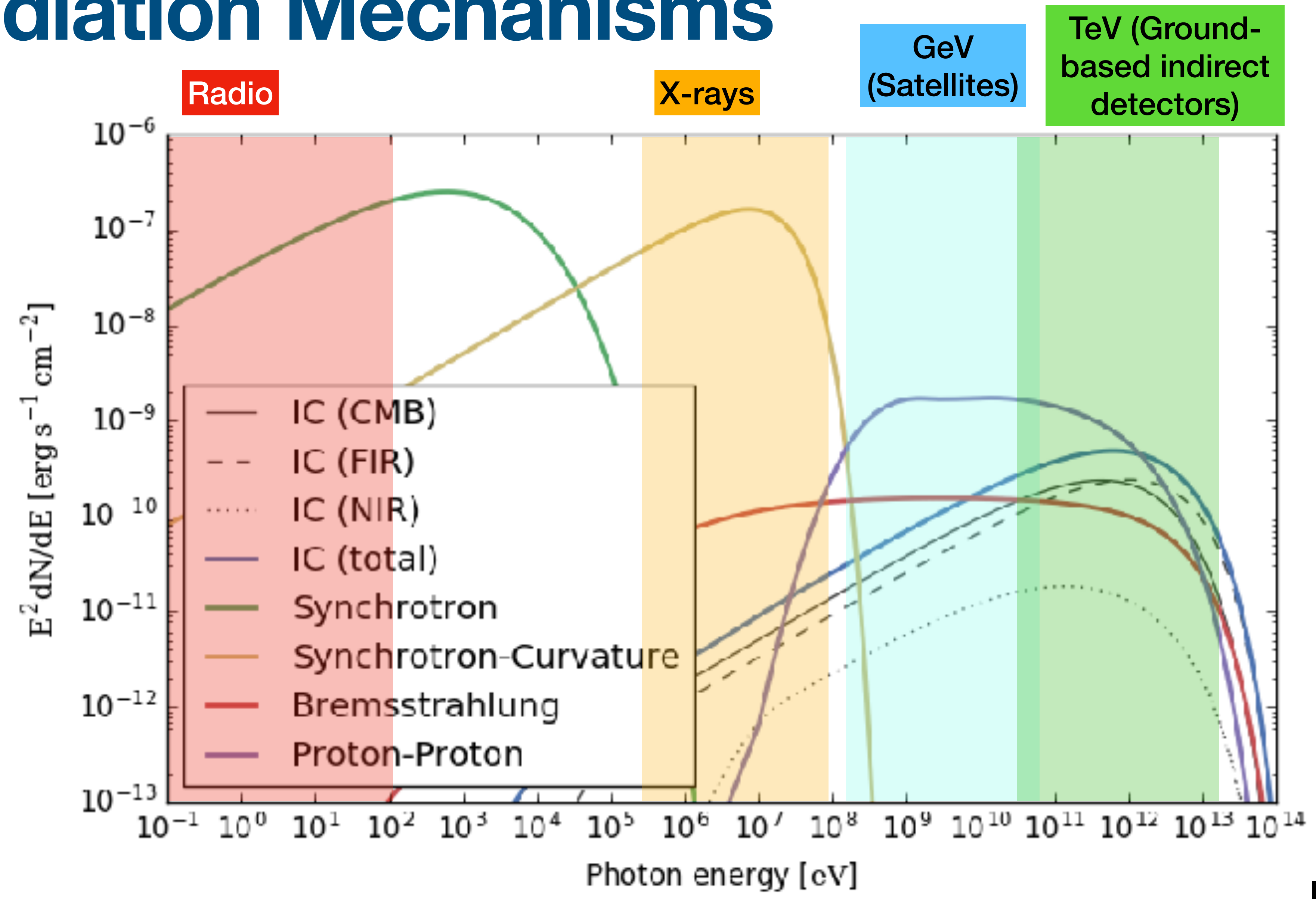
Proton-Proton

$p + p \rightarrow \pi^0 + \chi + \ldots + \pi^{\pm}$

↳ $\gamma + \gamma$ ↳ $\nu_\tau + \nu_e$

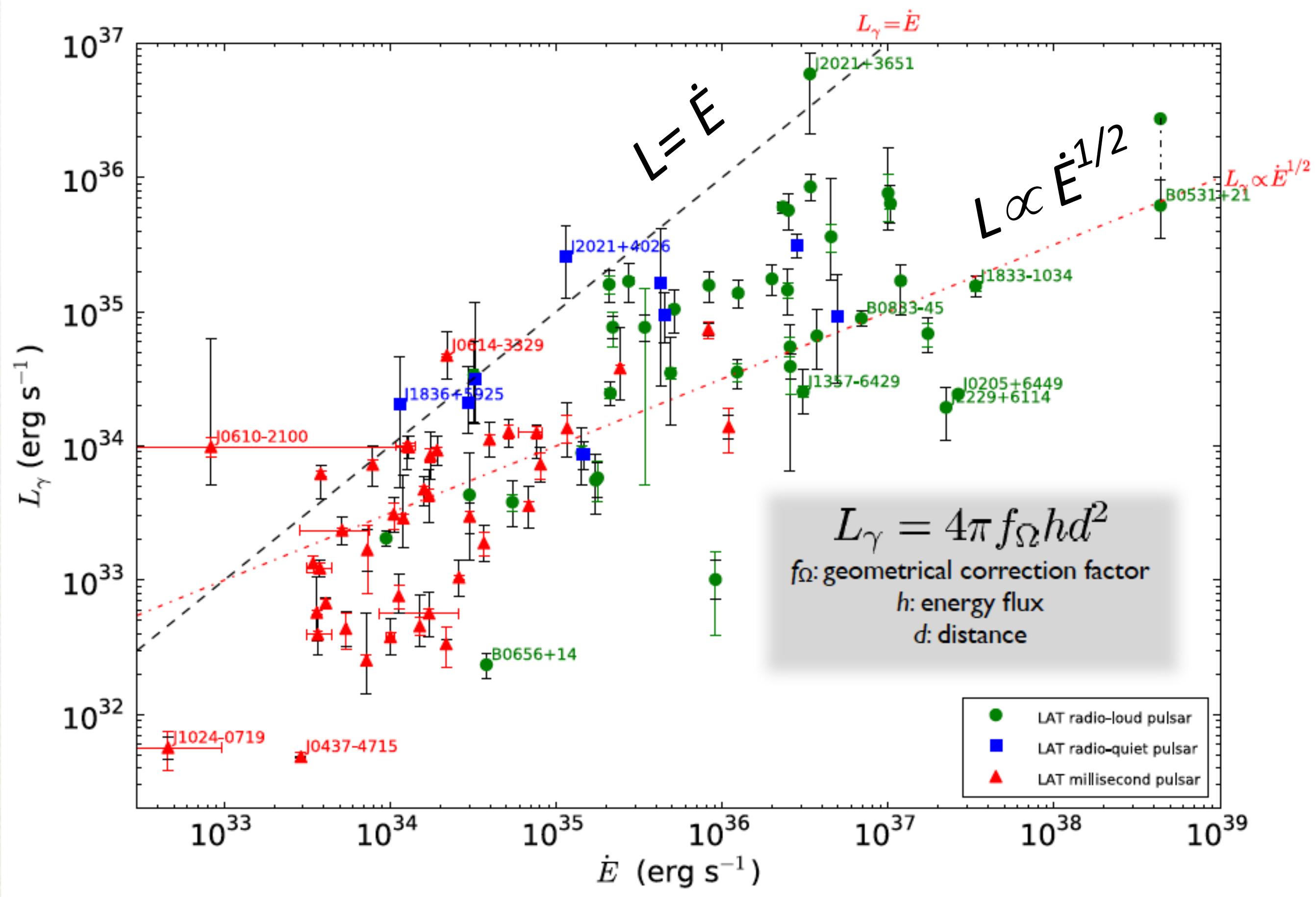
↳ e+, e-

Radiation Mechanisms



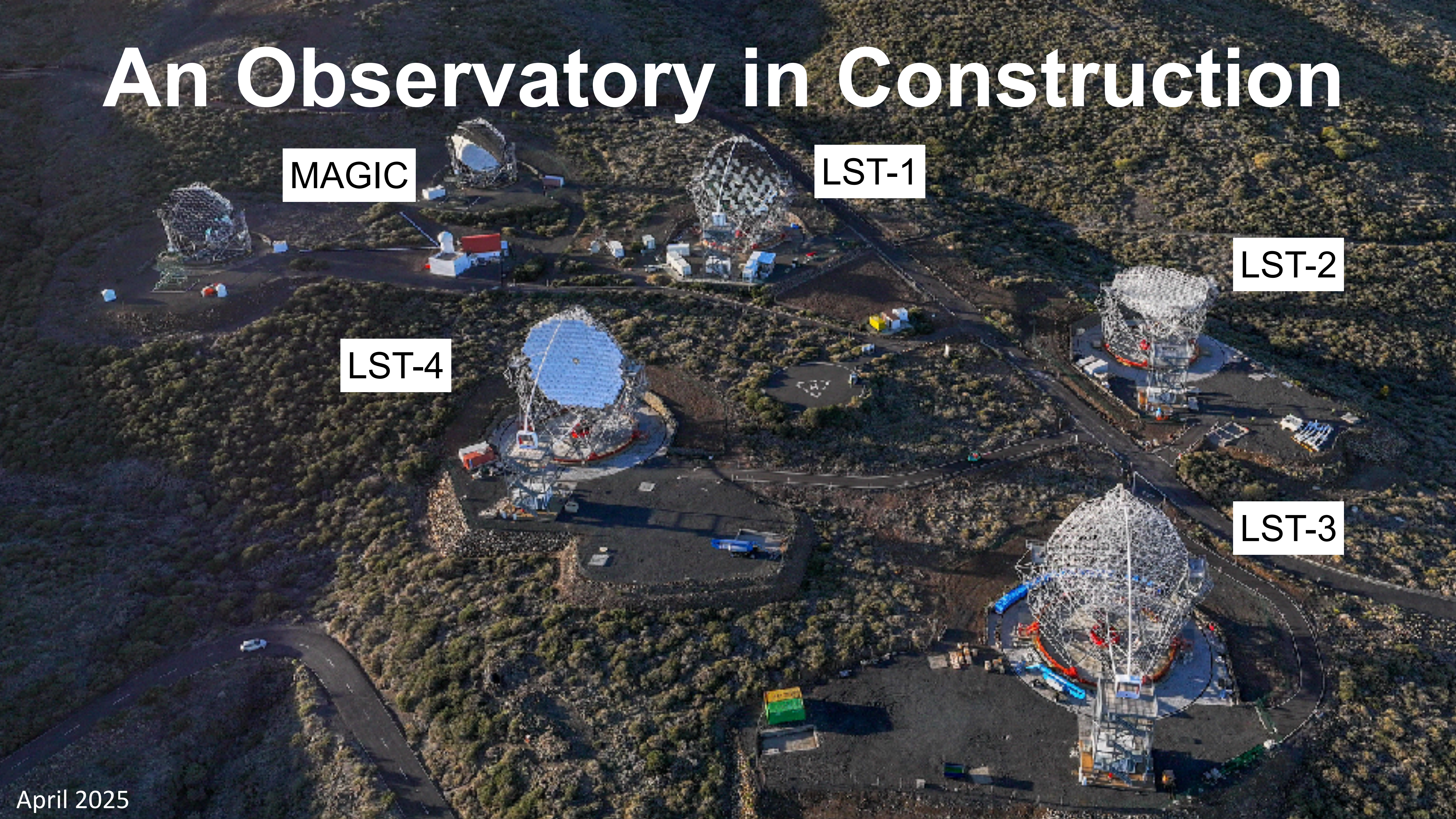
Which Instruments?

Gamma-ray luminosity vs spin-down power

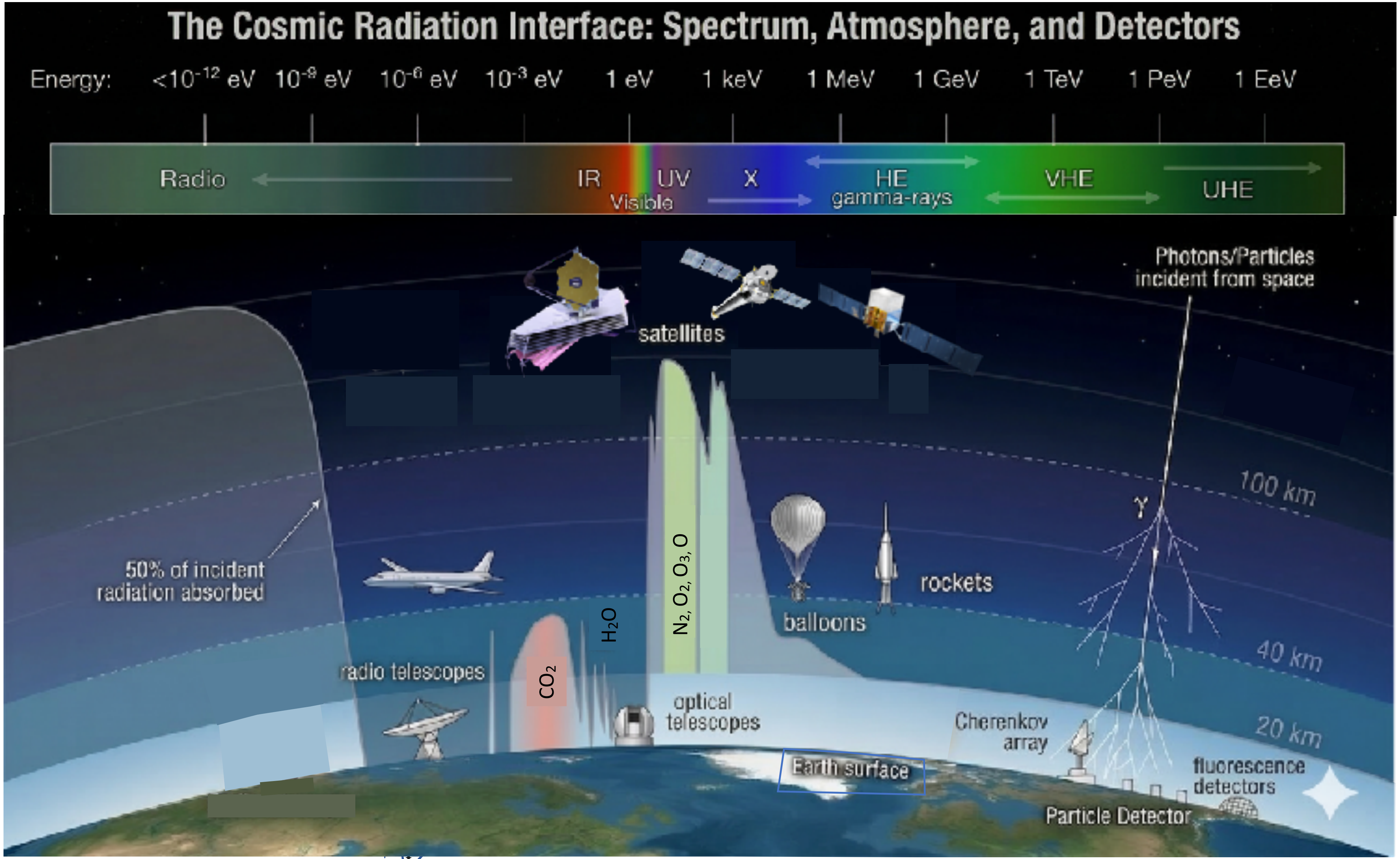


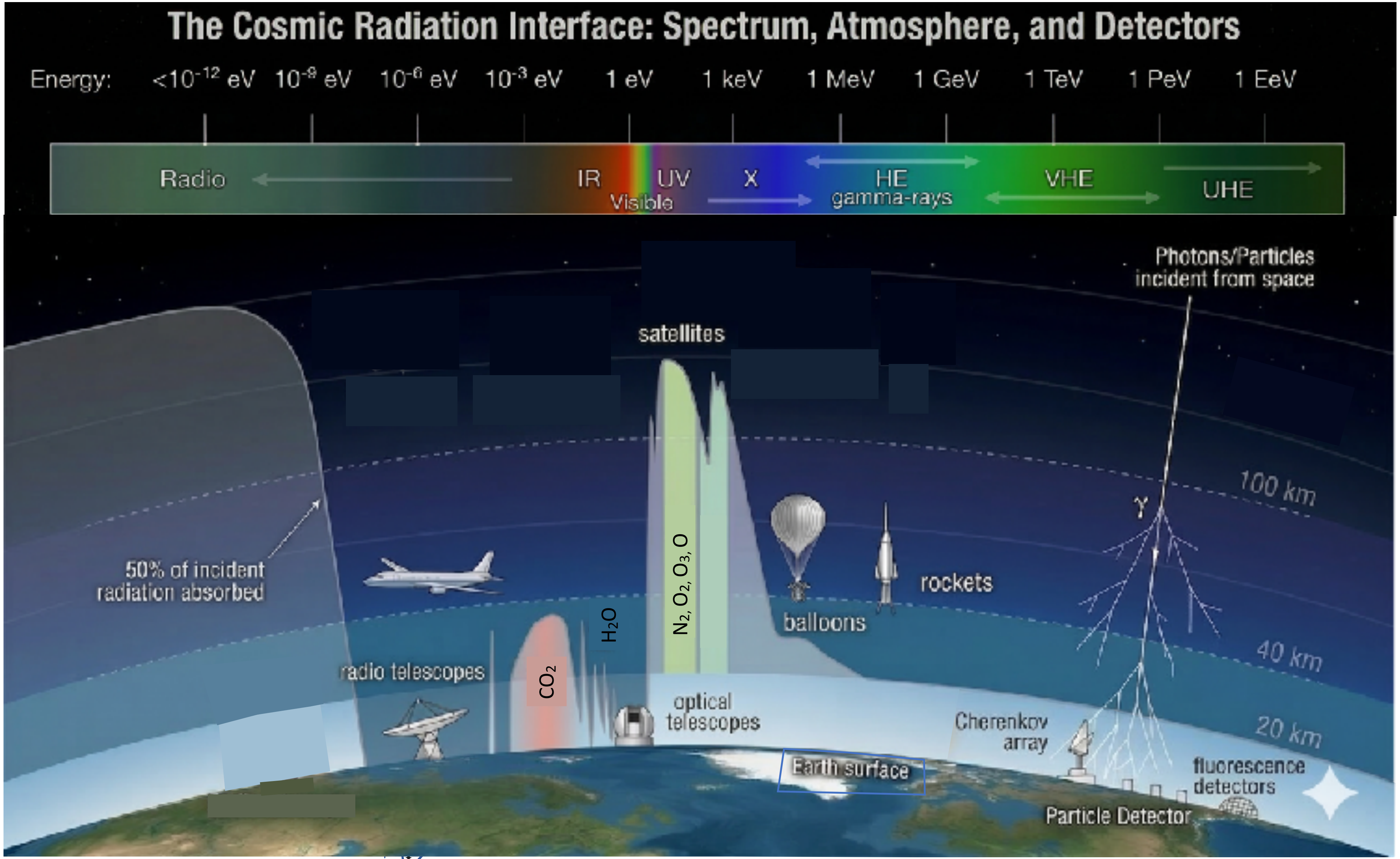
Efficiency of γ-ray production seems to go down with luminosity (but uncertainties are large, e.g. in distance)

An Observatory in Construction



April 2025


The Cosmic Radiation Interface: Spectrum, Atmosphere, and Detectors
Energy: <10^-12 eV 10^-9 eV 10^-6 eV 10^-3 eV 1 eV 1 keV 1 MeV 1 GeV 1 TeV 1 PeV 1 EeV
Radio
IR
Visible
UV
X
HE
gamma-rays
VHE
UHE
satellites
Photons/Particles
incident from space
100 km
γ
50% of incident
radiation absorbed
N_2, O_2, O_3, O
H_2O
CO_2
balloons
rockets
40 km
radio telescopes
optical
telescopes
Cherenkov
array
20 km
Earth surface
fluorescence
detectors
Particle Detector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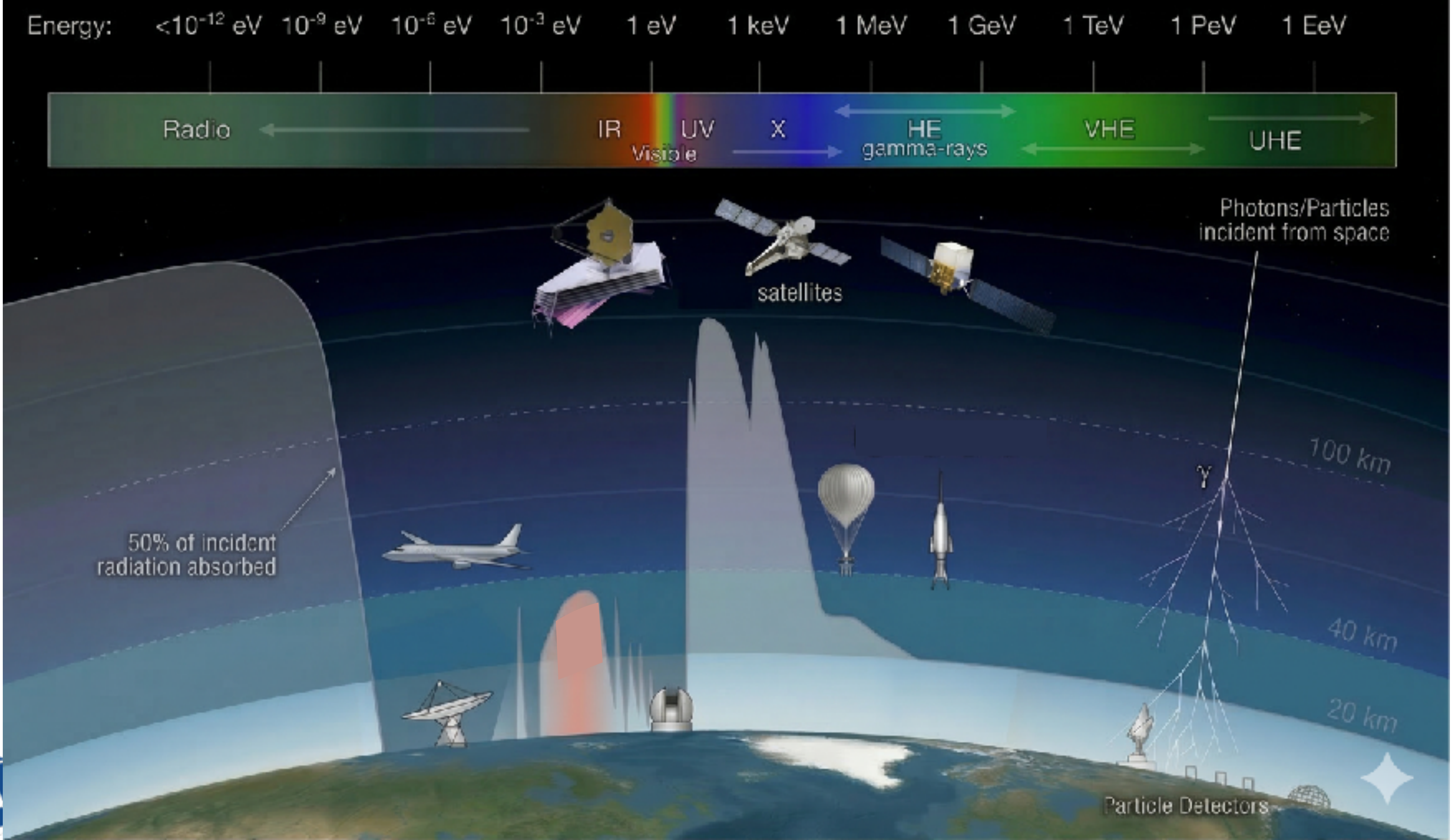

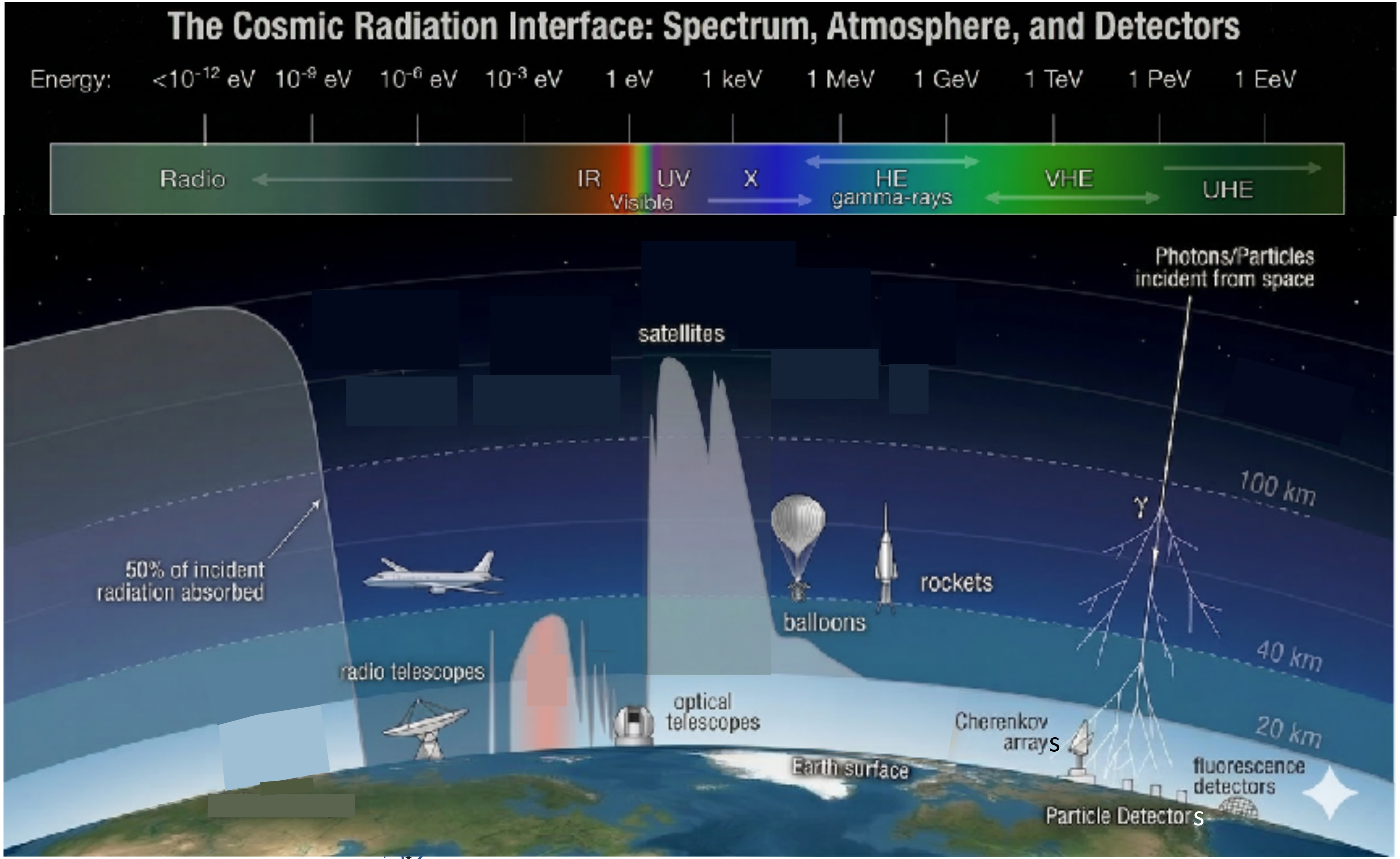
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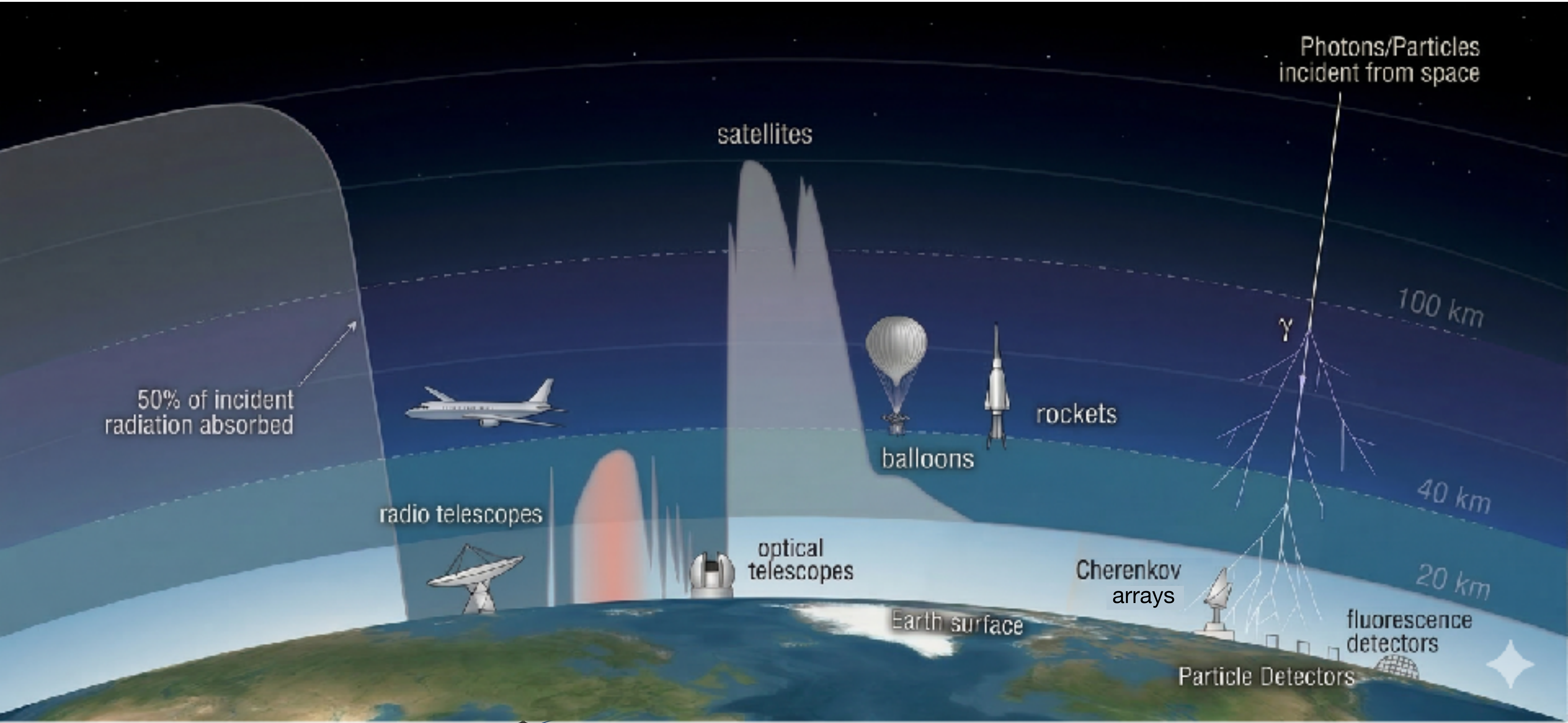
Particle Detectors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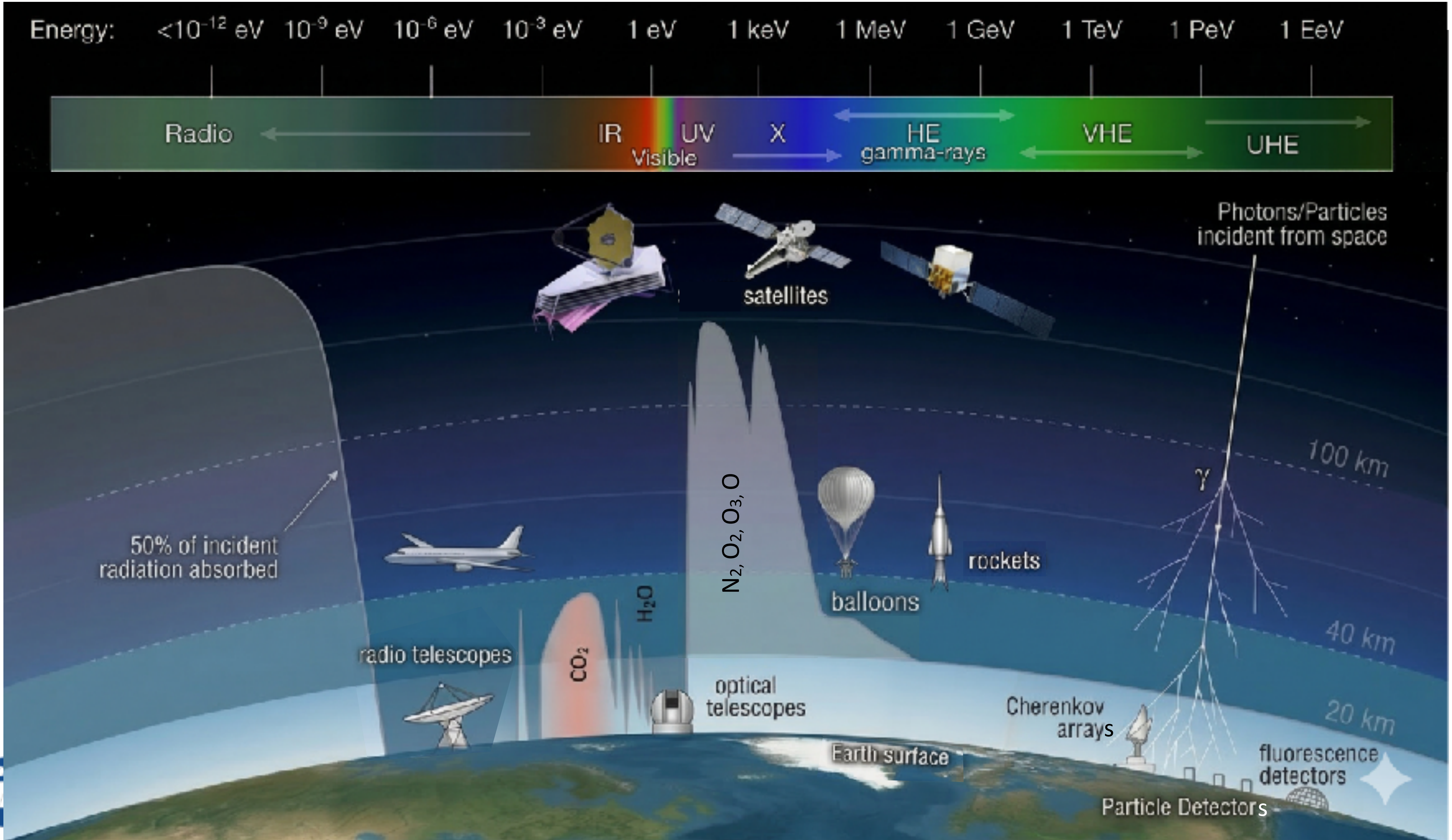

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100 km
40 km
20 km
radio telescopes
CO_2
H_2O
optical telescopes
Cherenkov arrays
Earth surface
fluorescence detectors
Particle Detectors

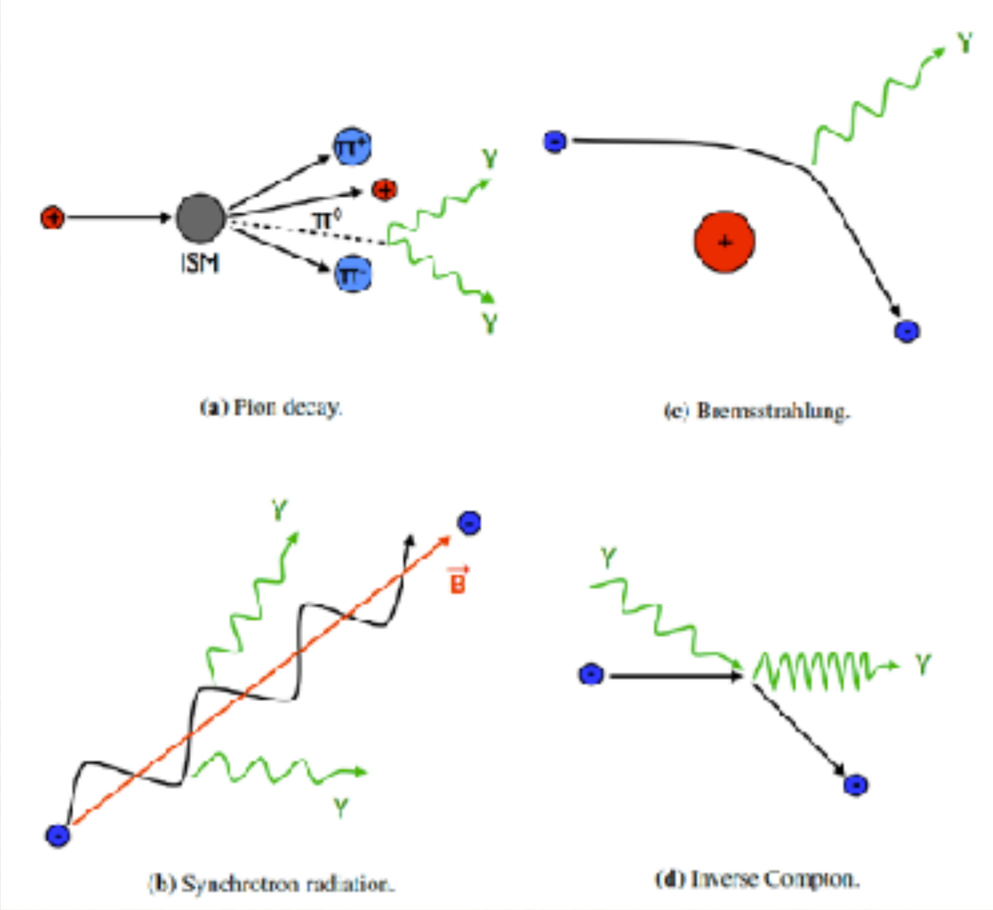
Non-thermal emission mechanisms

- Inverse Compton Scattering
- Strongly suppressed by the Klein-Nishina mechanism at high E

- Proton-Proton
- Flux proportional to gas density
- Spectrum ~follows primary spectrum

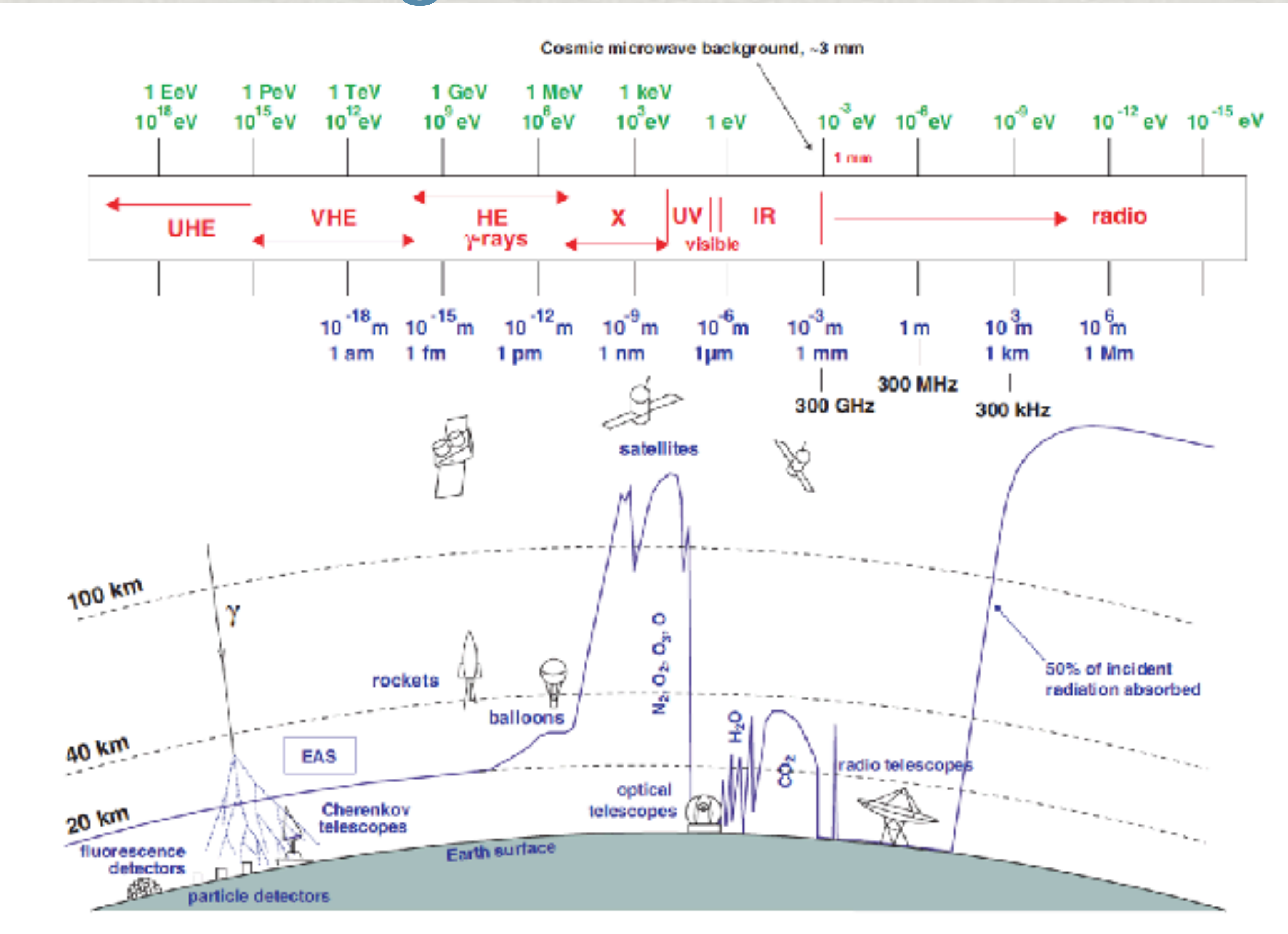
- Synchrotron
- Charged particles moving in a magnetic field

- Bremsstrahlung?
- Need n>200 cm^{-3} for bremsstrahlung to dominate over IC on CMB at 1 TeV

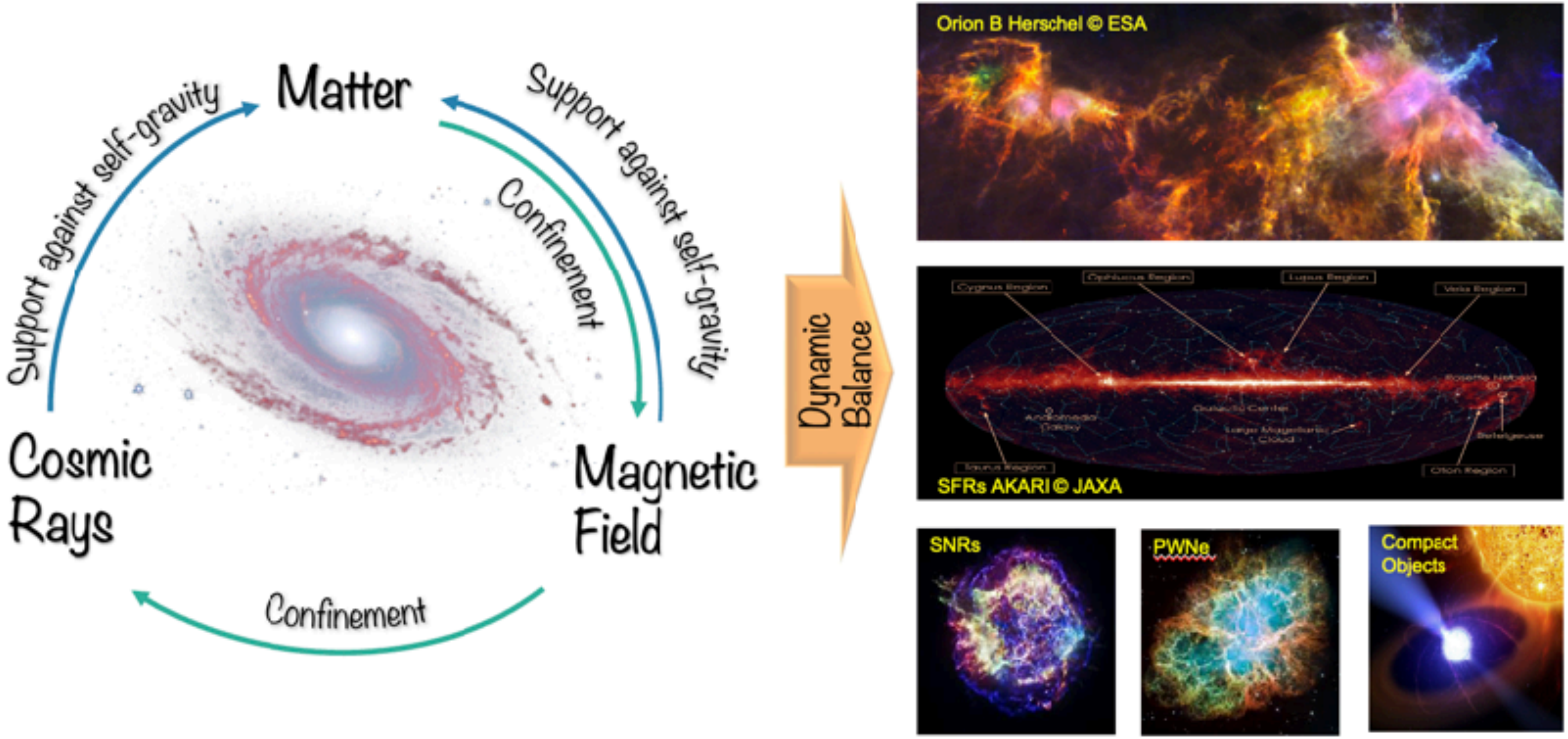


Rubén López-Coto - 21/04/21

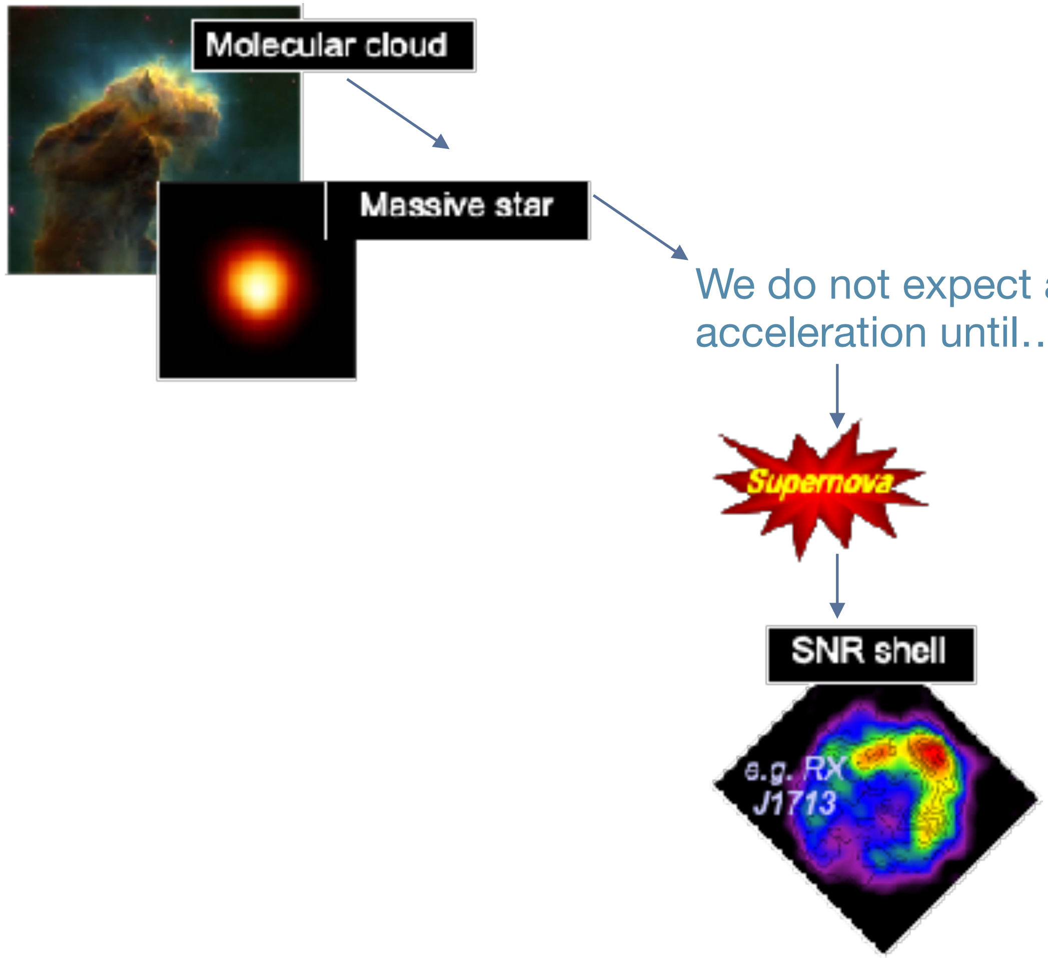
Messengers: Photons.



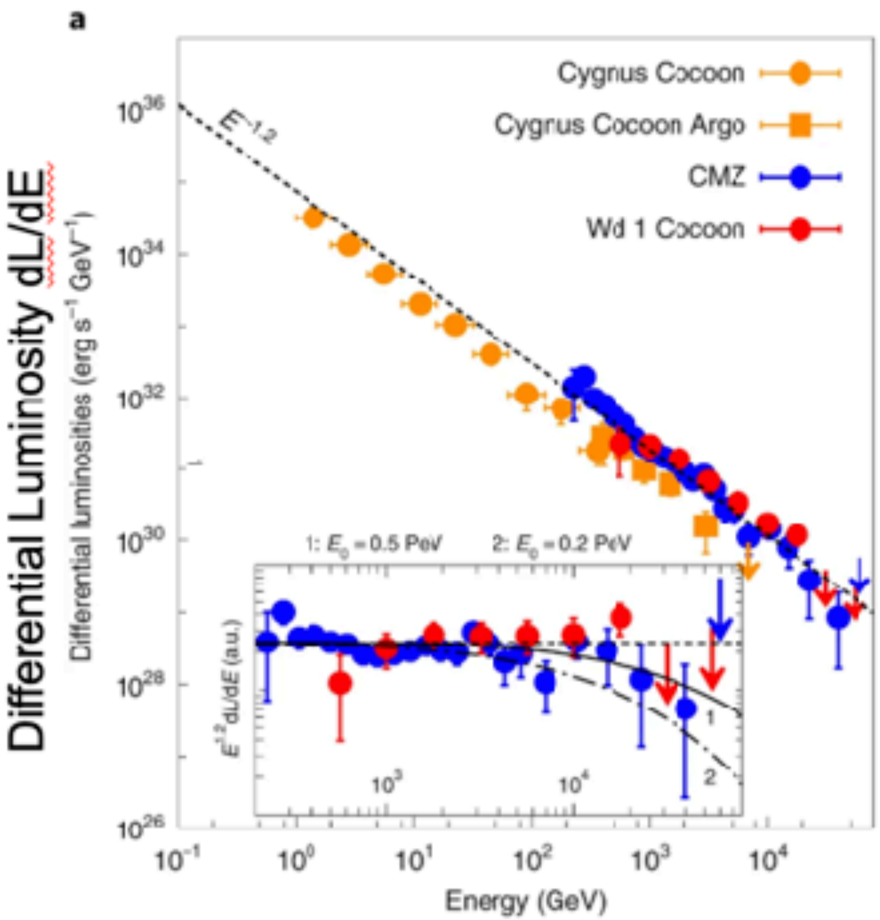
Galactic Gamma-ray disk



Cosmic Ray acceleration



CR accelerators: Stellar Clusters



The spectra (of some of them) extends to high energies

With remarkably similar shape and spectral index (2.2)

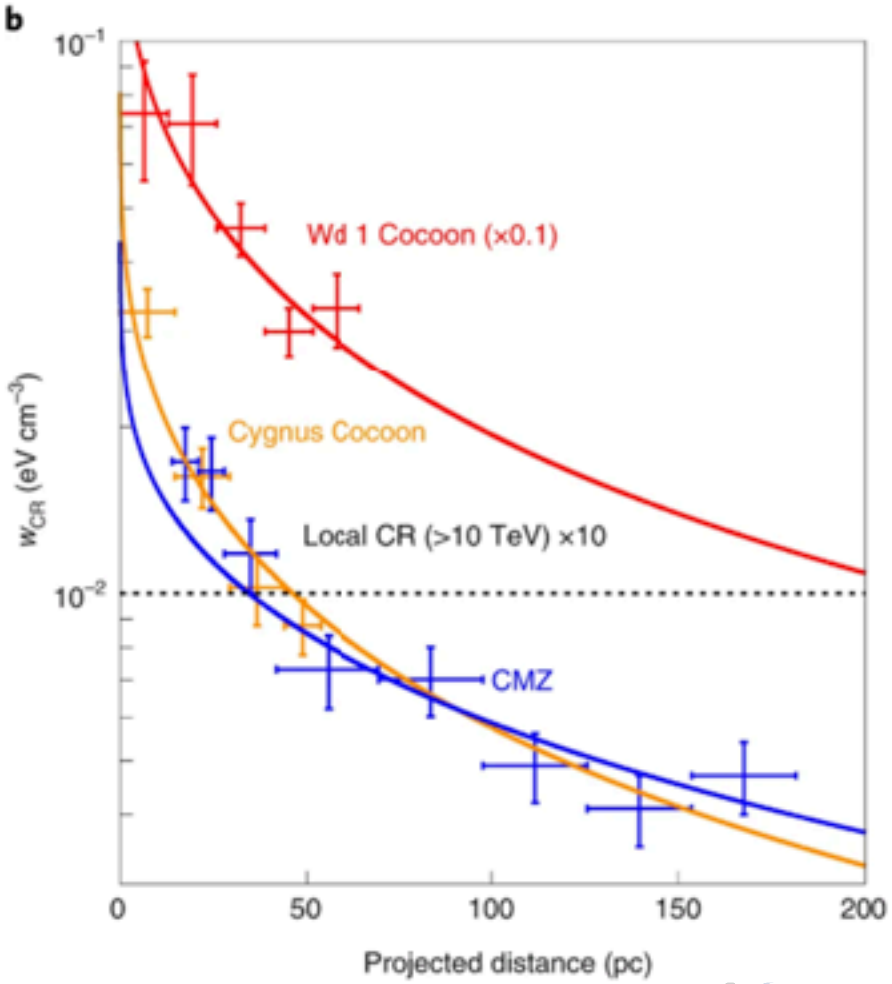
No indication of energy cutoff (with the available statistics)

Proton spectrum described with:

$E^{-2.3}\exp(-E/E_o)$ with E_o = 0.2 (1), 0.5 (2) PeV

=> For Kolmogorov-type turbulence, $D(E) \propto E^{1/3}$, we arrive at a 'classical' E^{-2}-type acceleration spectrum.

CR accelerators: Stellar Clusters



The CR proton radial distribution follows a 1/r line (>10 TeV)
(for the Cygnus Cocoon we extrapolated from LAT energies)

Exceeding the local CR by a factor of 10 (from AMS)

We parametrized the CR density as:

$$w(r) = w_0(r/r_0)^{-1}$$

$$W_p = 4\pi \int_0^{R_0} w(r) r^2 \, dr$$
$$\approx 2.7 \times 10^{47} (w_0/1 \text{ eV cm}^{-3})(R_0/10 \text{ pc})^2 \text{ erg}$$

CR accelerators: Stellar Clusters

We define R as the extension of the source (50 and 300 pc), or more conservatively, the maximum given by the diffusion condition:

$$R_D = 2\sqrt{T_0 D(E)} \approx 3.6 \times 10^3 (D_{30} T_6)^{1/2} \text{ pc}$$

Since W_{CR} cannot be larger than W_{tot} => $f(\geq 10 \text{ TeV}) \approx 1 w_0 D_{30} L_{39}^{-1}$

$$W_{tot} = f L_0 T_0 = 3 \times 10^{52} f L_{39} T_6 \text{ erg}$$

Measuring the Local diffuse coefficient:
if f=10% => D ~10^{28} cm^{-2} s^{-1}

Halos as large as 300 pc and with a density still 2 order of magnitude larger than the local CR density

$$W_p = 4\pi \int_0^{R_0} w(r) r^2 \, dr \approx 2.7 \times 10^{47} (w_0 / 1 \text{ eV cm}^{-3})(R_0 / 10 \text{ pc})^2 \text{ erg}$$

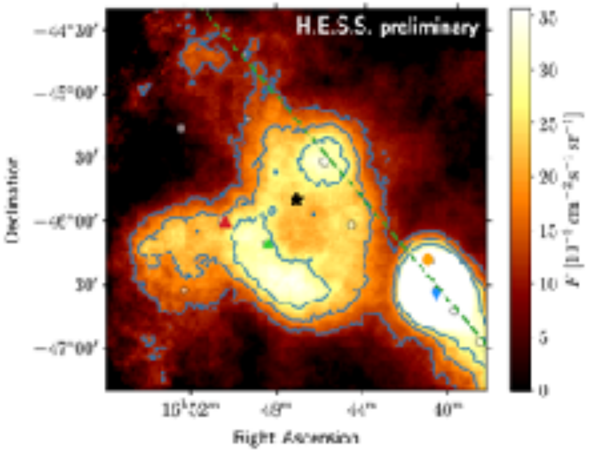
Source	Cygnus Cocoon	CMZ	Wd 1 Cocoon
Extension (pc)	50	175	60
Age of cluster (Myr)[39]	3–6	2–7	4–6
Kinetic luminosity, L_{kin}, of cluster ($erg\,s^{-1}$)	2×10^{38} (ref. 17)	1×10^{39} (ref. 40)	1×10^{39} (ref. 41)
Distance (kpc)	1.4	8.5	4
w_0 (>10 TeV) ($eV\,cm^{-3}$)	0.05	0.07	1.2

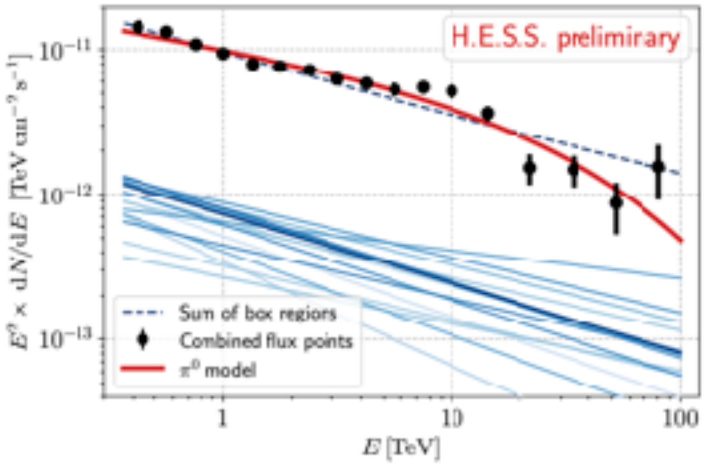
CR accelerators: Stellar Clusters

- What do we see in the VHE with Cherenkov instruments? Look at the most massive SC

Westerlund 1

Mohrmann et al, ICRC 2021





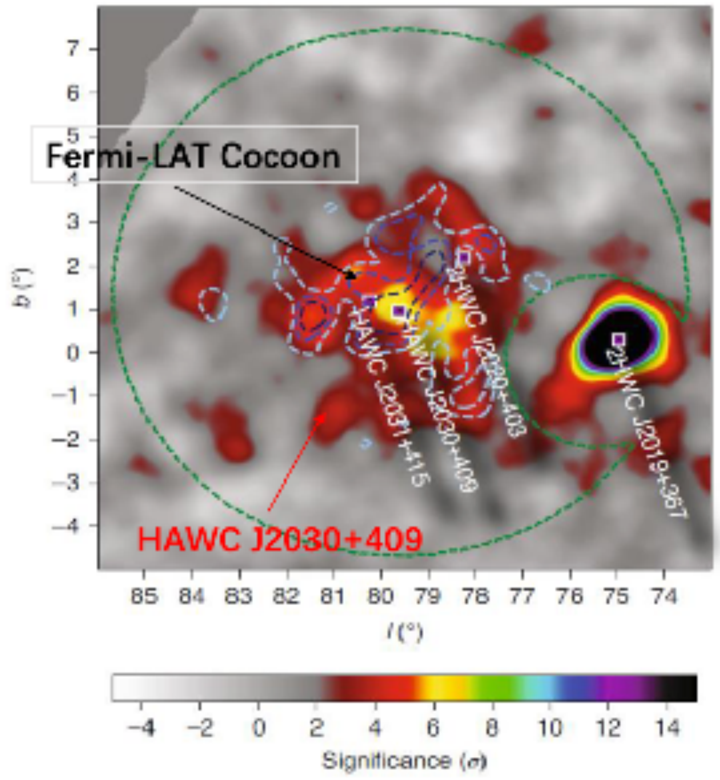
E_c =400($^{+250}_{-130}$) TeV
W_p ~ 5x10^{49} (n/10cm^{-3})(d/3.9 kpc)^2 erg

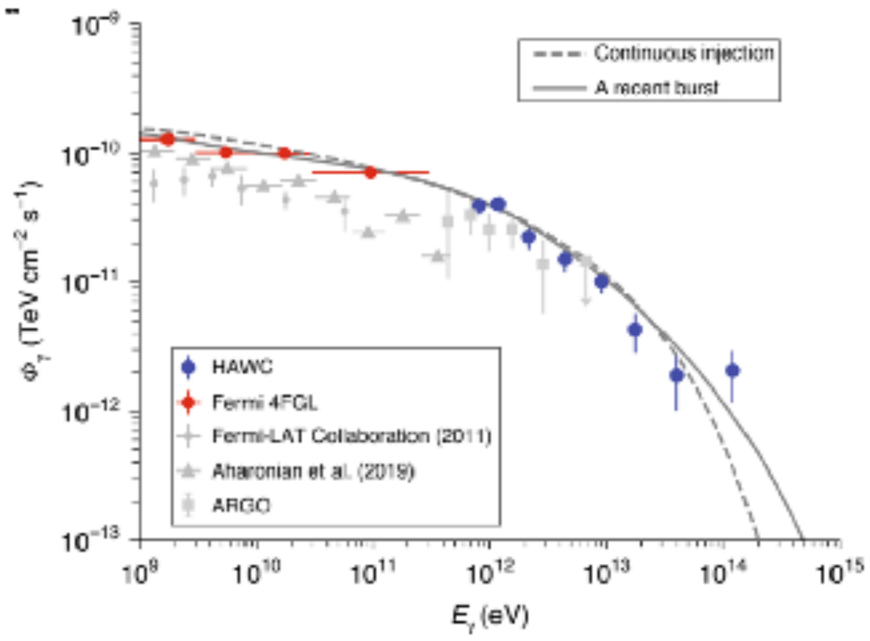
- Complex morphology
- Similar spectra along the 1° (70 pc at 3.9 kpc) source & similar radial profile at different energies
- Dip in the surrounding of Westerlund 1
- Spectrum extends to 100 TeV

CR accelerators: Stellar Clusters

- What do we see in the VHE with Cherenkov instruments?

  Cygnus Region





HAWC 2021 result

Pulsar Wind Nebulae

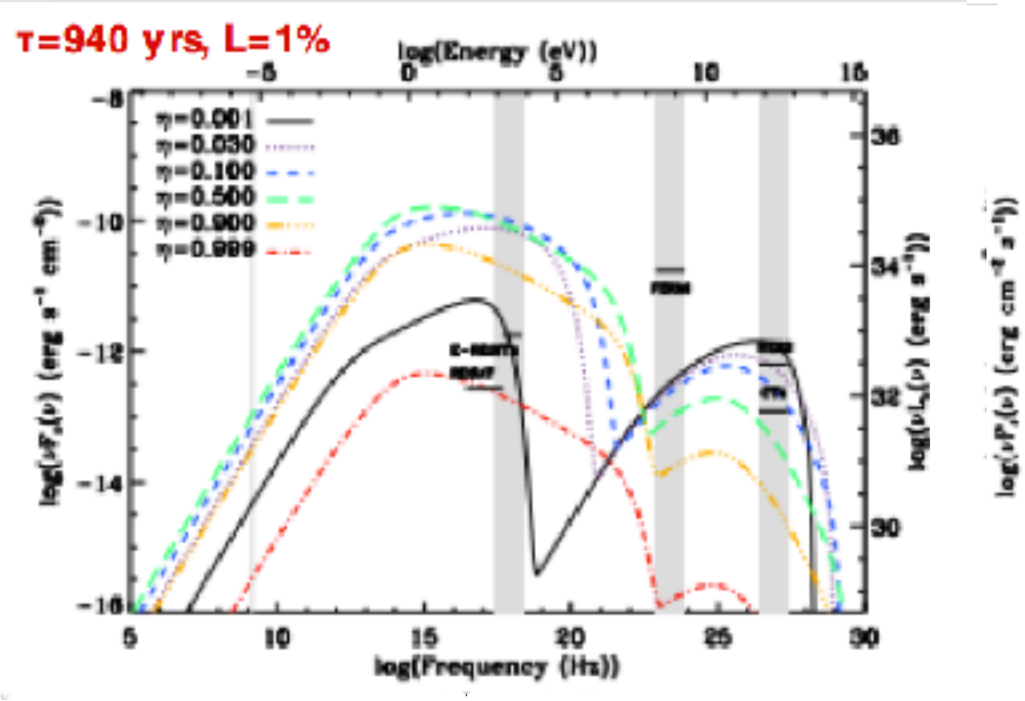
Pulsar

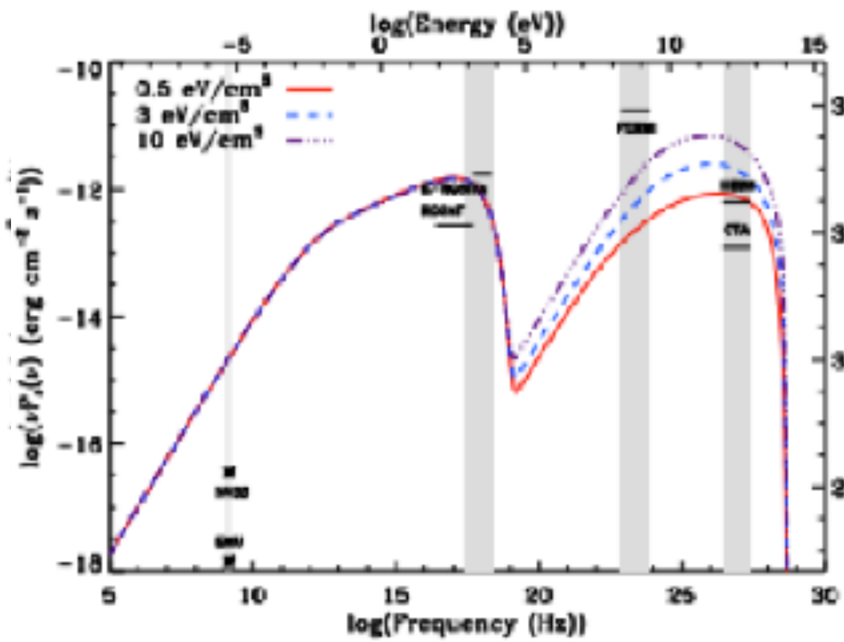
SED depends on:

The age of the pulsar/pwn
The initial spin-down energy
The magnetization fraction (or fraction of energy shared in particles and in magnetic field)

Wind

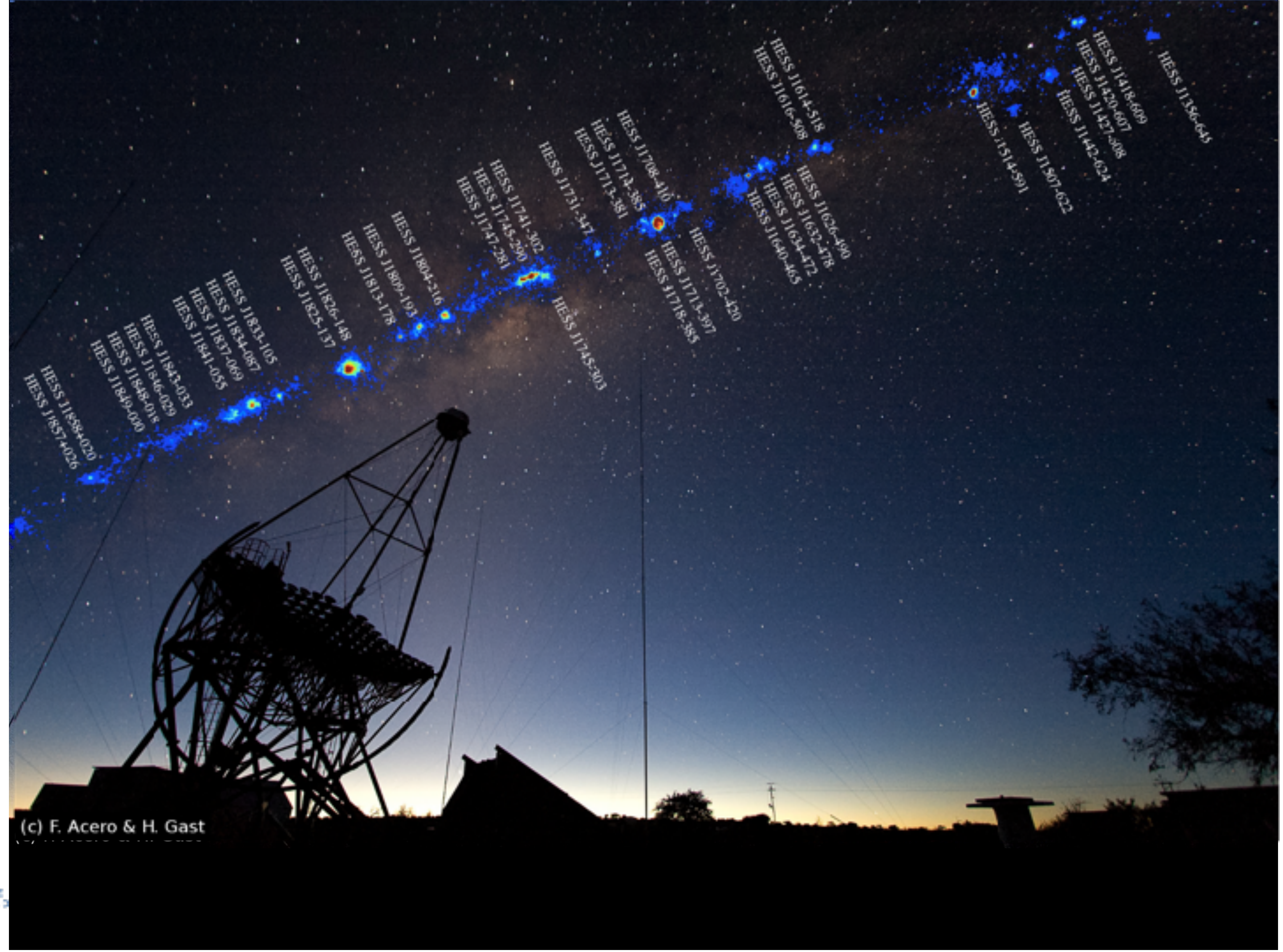
Injection Spectrum
Radiation Field






Optical
© Fabio Acero


Optical
+TeV
(c) F. Acero & H. Gast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HESS J1846-029
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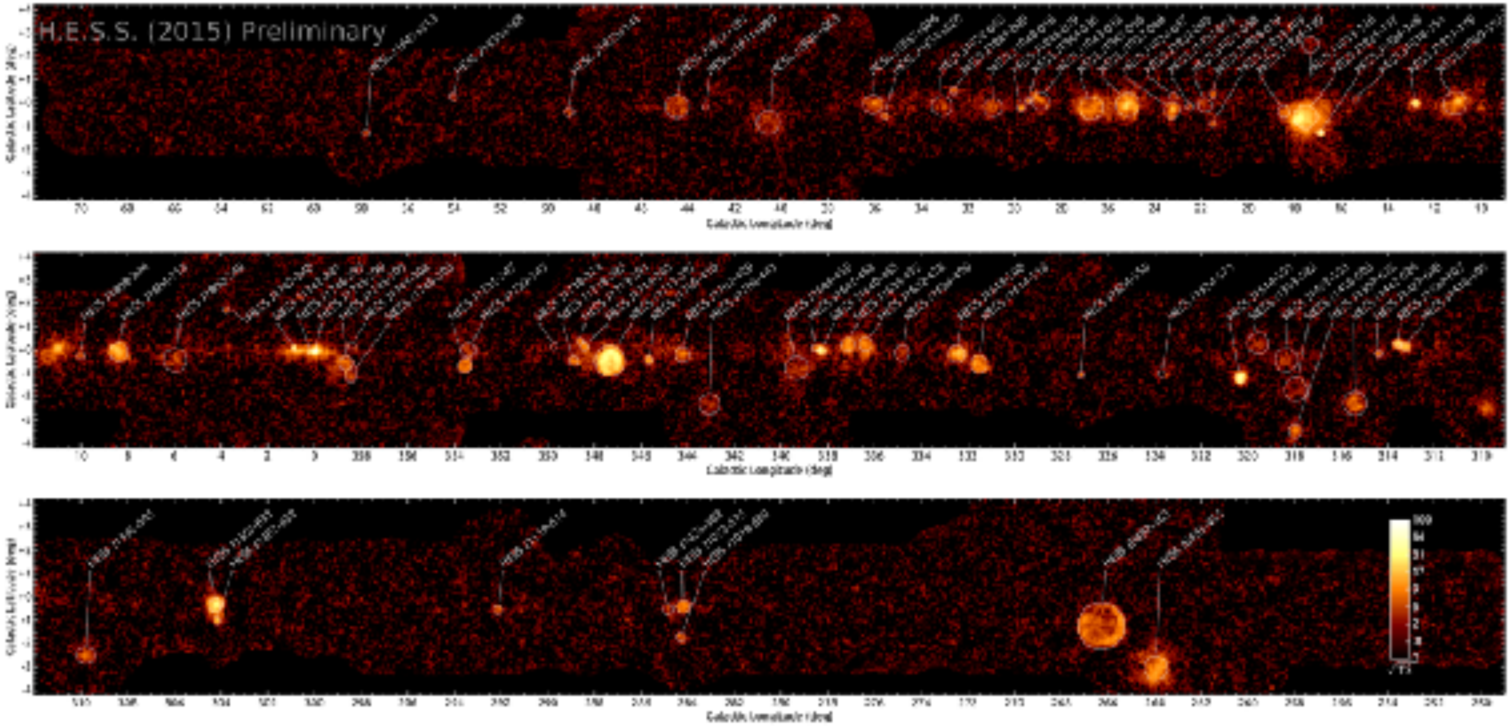
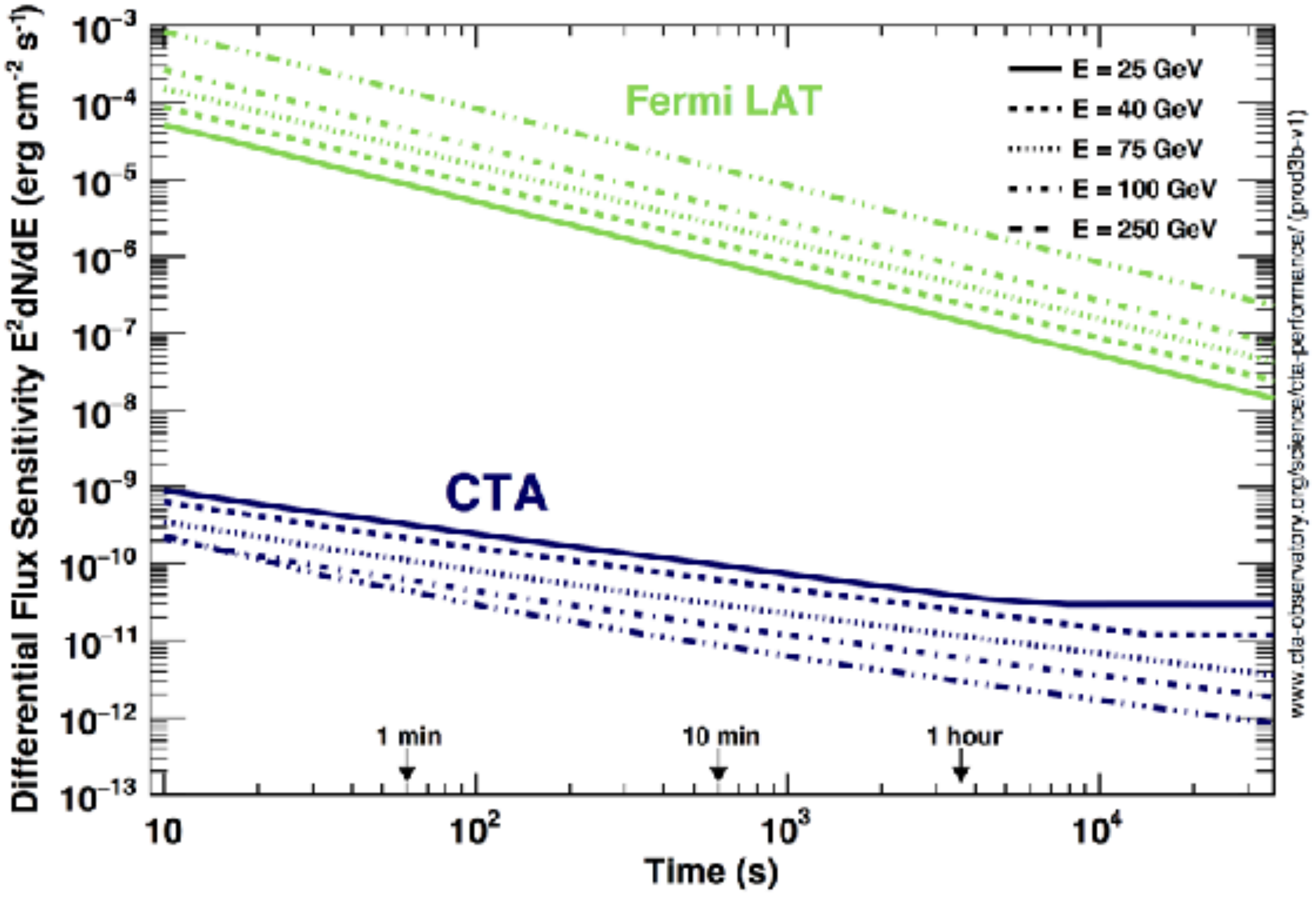
HESS J1841-055
HESS J1837-069
HESS J1834-087
HESS J1833-105
HESS J1825-137
HESS J1826-148
HESS J1813-178
HESS J1809-193
HESS J1804-216
HESS J1747-281
HESS J1745-290
HESS J1741-302
HESS J1745-303
HESS J1731-347
HESS J1713-381
HESS J1714-385
HESS J1708-410
HESS J1718-385
HESS J1713-397
HESS J1702-420
HESS J1640-465
HESS J1634-472
HESS J1632-478
HESS J1626-490
HESS J1616-508
HESS J1614-518
HESS J1514-591
HESS J1507-622
HESS J1442-624
HESS J1427-608
HESS J1420-607
HESS J1418-609
HESS J1356-645
(c) F. Acero & H. Gast

HESS Galactic Plane Survey

- Final HESS catalog of survey sources
- Data collected 2004 – 2013 (3000 hours)
- Significance and flux maps
- Automatic pipeline for source extraction
- 64 VHE sources
  - + 13 complex sources (e.g. shell SNR) excluded

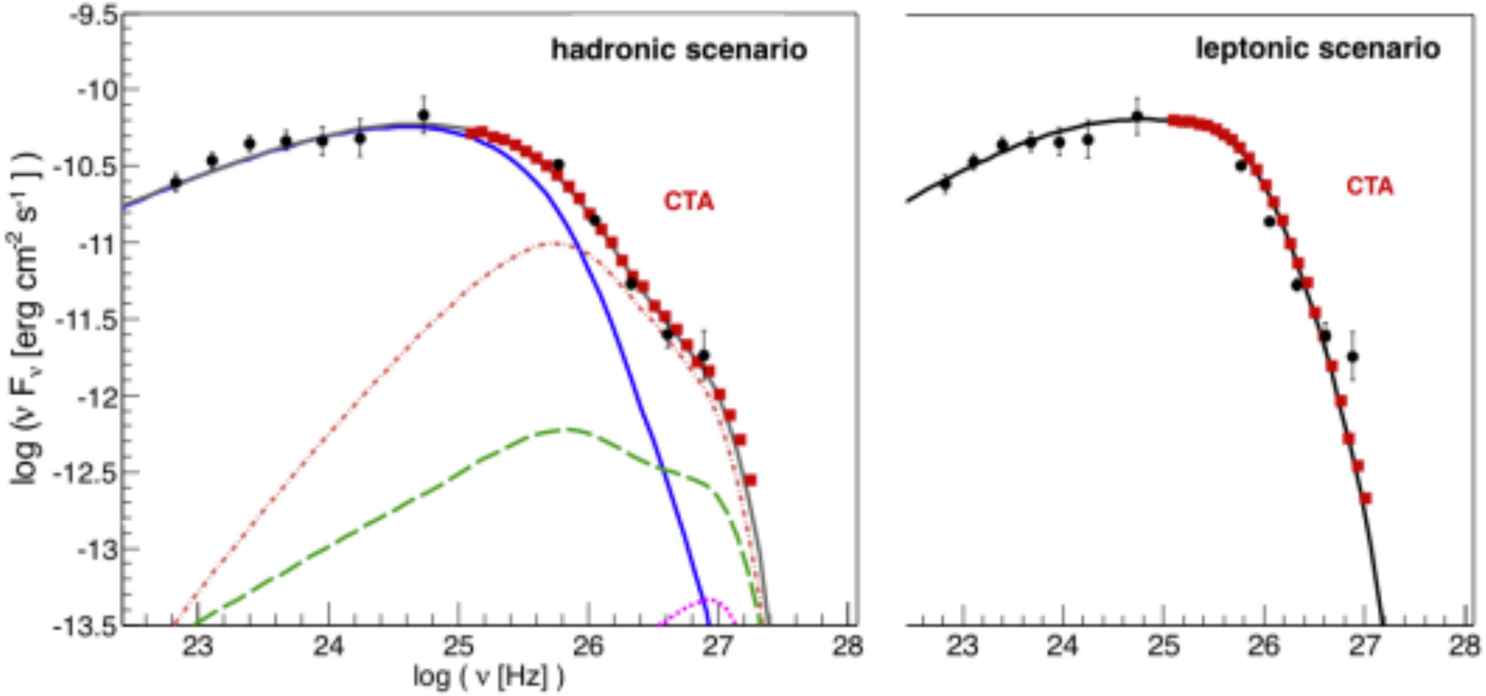


Short-time Scale Capabilities



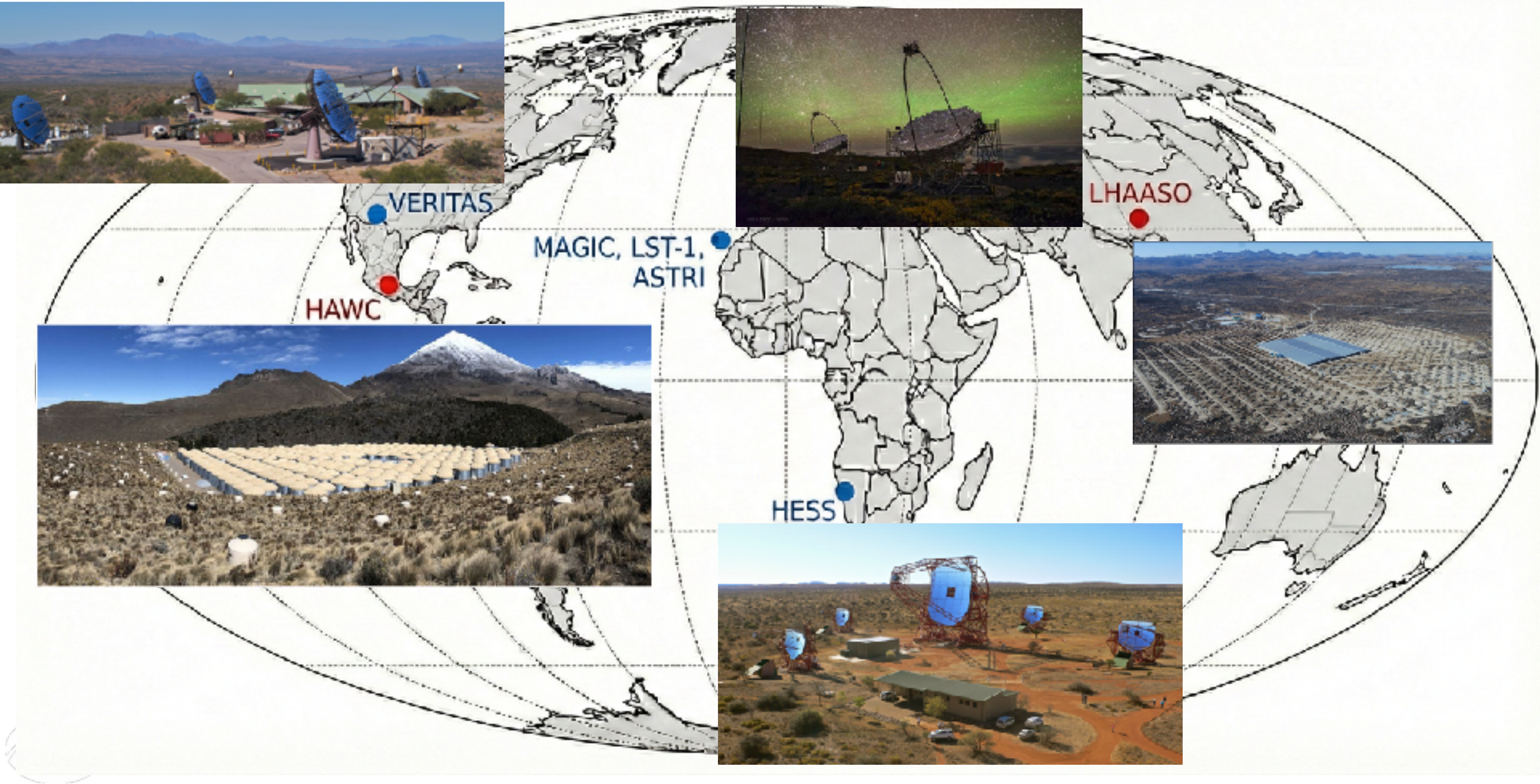
Short-time Scale Capabilities

Distinguish between leptonic and hadronic models



The Future

Current Very High Energy (VHE) Gamma-ray **experiments**



The Future VHE Gamma-ray Observatory

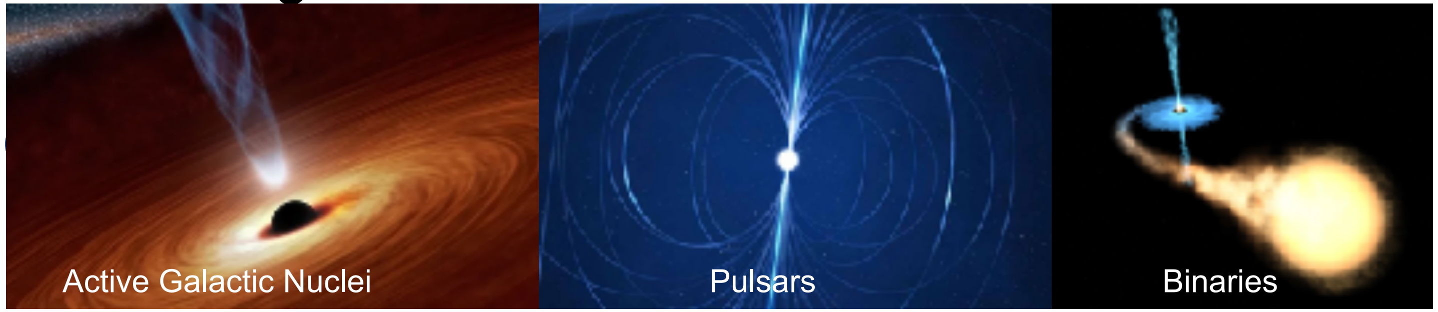
CTAO

The Cherenkov Telescope Array Observatory

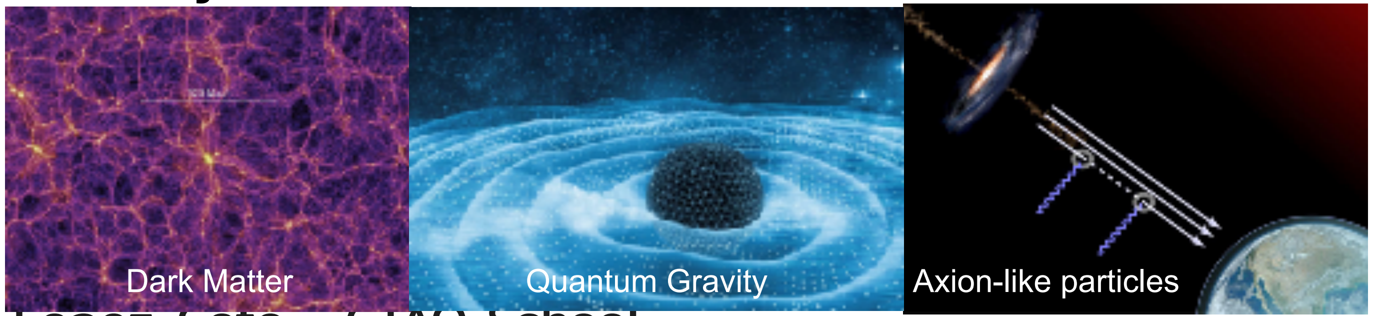
Science Goals

- **Goal 1: Cosmic ray acceleration**
  -
  -
  -

- **Goal 2: Proving extreme environments**
  -
  -
  -



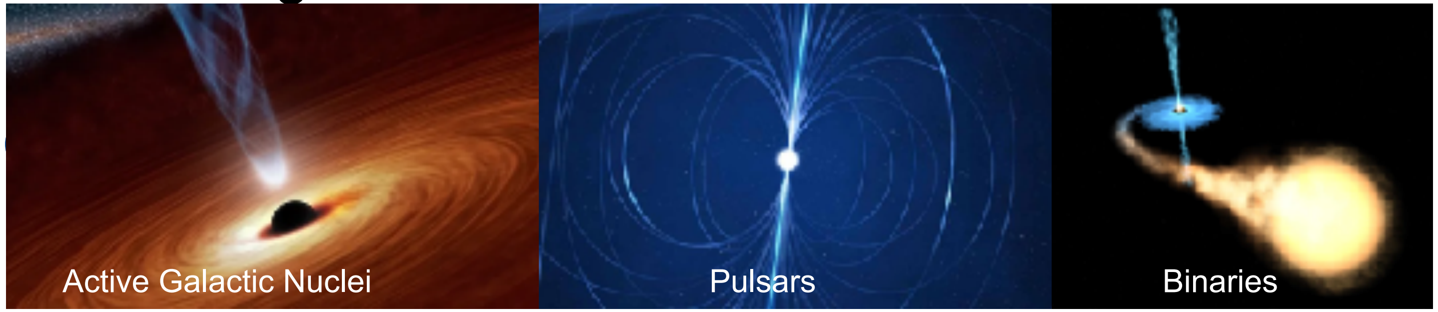
- **Goal 3: Physics frontiers**
  -
  -
  -



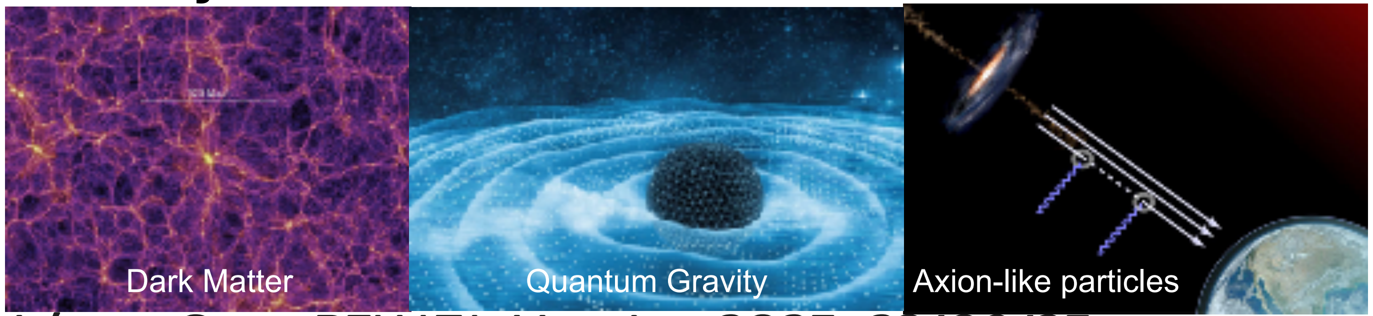
Science Goals

- **Goal 1: Cosmic ray acceleration**
  - How and when are cosmic rays accelerated?
  - How do they propagate?
  - What is their impact in the environment?

- **Goal 2: Proving extreme environments**



- **Goal 3: Physics frontiers**



Science Goals

- **Goal 1: Cosmic ray acceleration**
  - How and when are cosmic rays accelerated?
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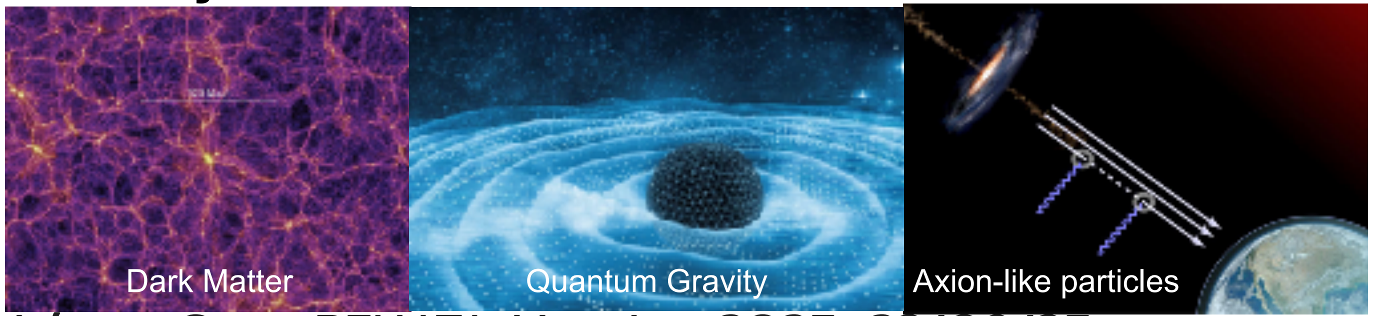
  - What is their impact in the environment?

- **Goal 2: Proving extreme environments**
  - Processes nearby neutron stars and black holes
  - Characterization of jets, relativistic winds and explosions
  - Radiation and magnetic fields in the interstellar medium

- **Goal 3: Physics frontiers**
  -
  -
  -



Science Goals

- **Goal 1: Cosmic ray acceleration**
  - How and when are cosmic rays accelerated?
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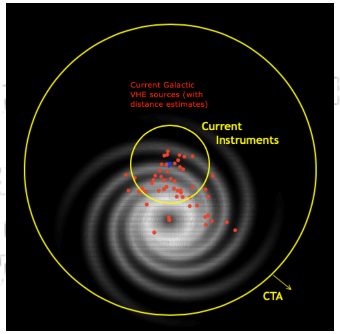
- **Goal 2: Proving extreme environments**
  - Processes nearby neutron stars and black holes
  - Characterization of jets, relativistic winds and explosions
  - Radiation and magnetic fields in the interstellar medium

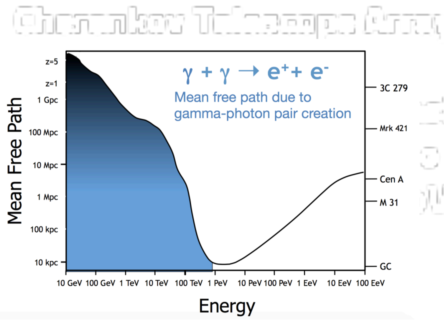
- **Goal 3: Physics frontiers**
  - Dark matter nature
  - Is light speed a constant?
  - Are there particles like axions?

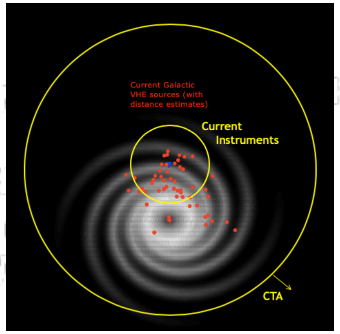
CTAO Design drivers

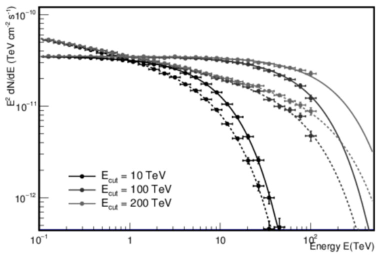


10 x Sensitivity, collection area => Covering all science cases

CTAO Design drivers







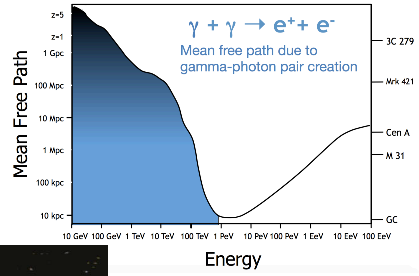
Energies down to 20 GeV
=> Cosmology, Pulsars

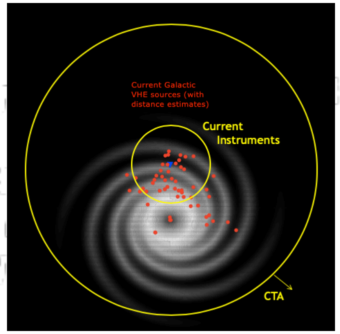
10 x Sensitivity, collection area
=> Covering all science cases

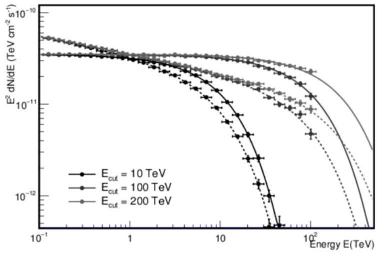
Energies up to 300 TeV
=> PeVatrons

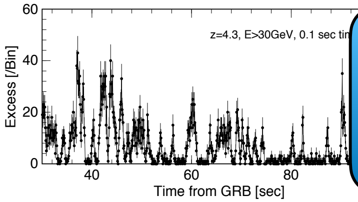
CTAO

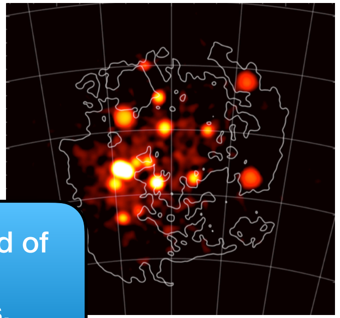
CTAO Design drivers











Energies down to 20 GeV
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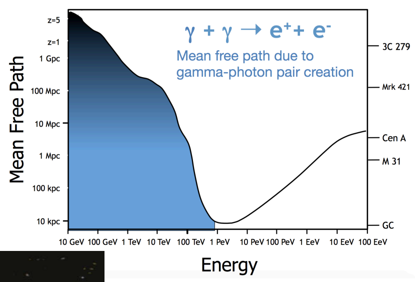
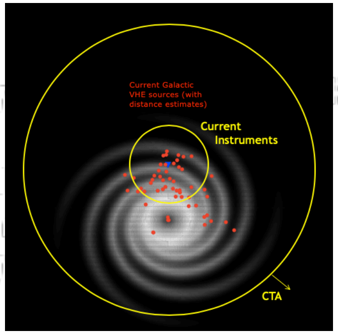
Rapid Slewing in 20 seconds
=> Transients

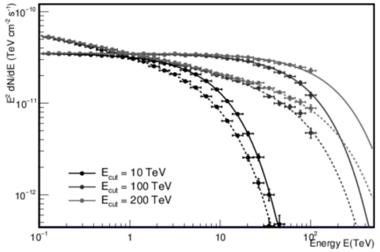
Up to 10º Field of View
=> Surveys, extended objects

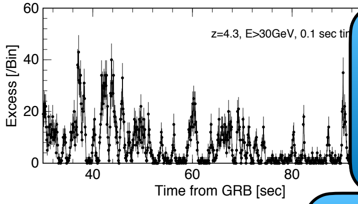
CTAO

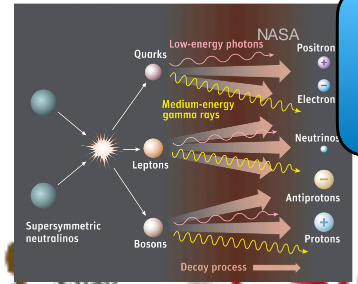
CTAO Design drivers

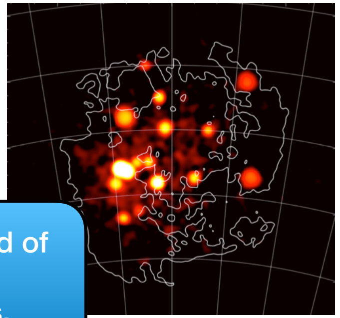


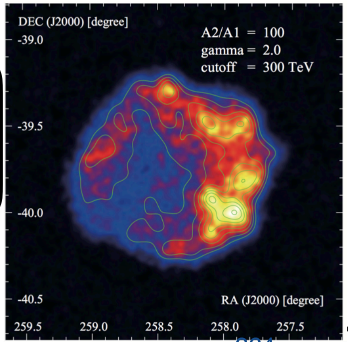












CTAO

10 x Sensitivity, collection area => Covering all science cases

Energies down to 20 GeV => Cosmology, Pulsars

Energies up to 300 TeV => PeVatrons

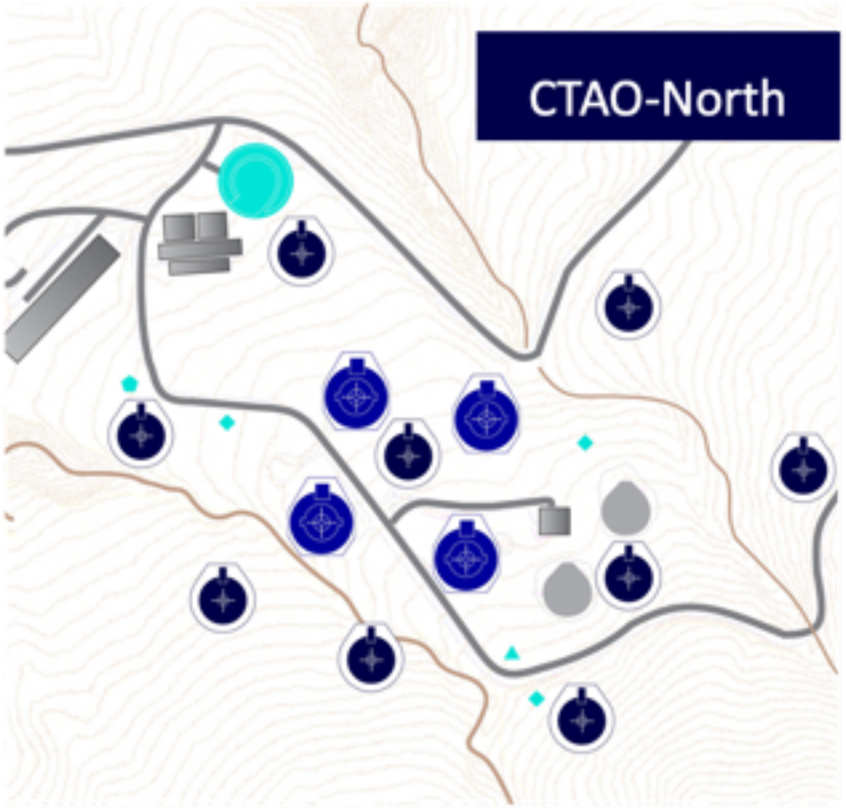
Rapid Slewing in 20 seconds => Transients

Up to 10º Field of View => Surveys, extended objects

10% Energy Resolution => lines, features

Few ' Angular Resolution => morphology

One Open Observatory, two sites



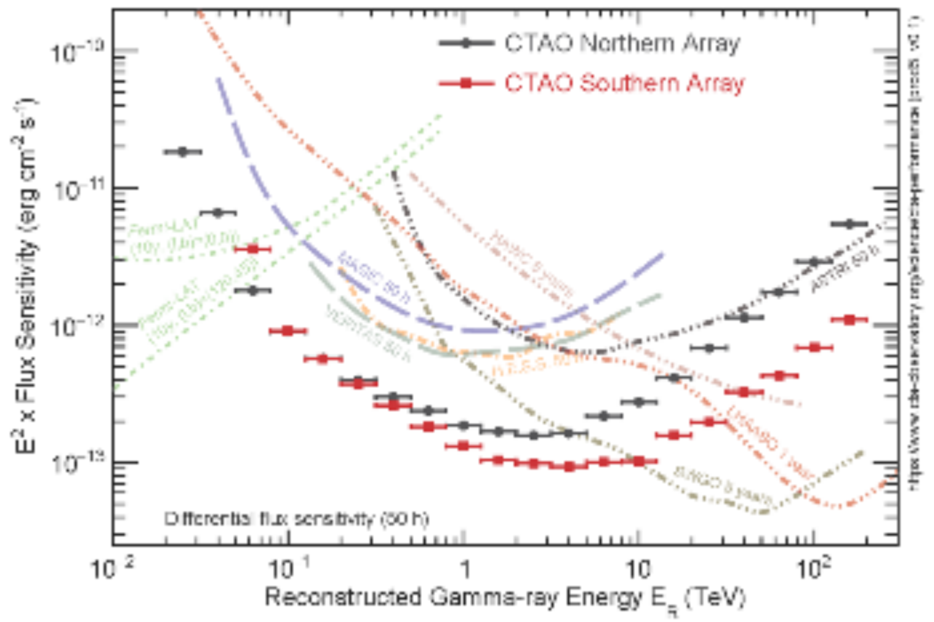
La Palma, Spain

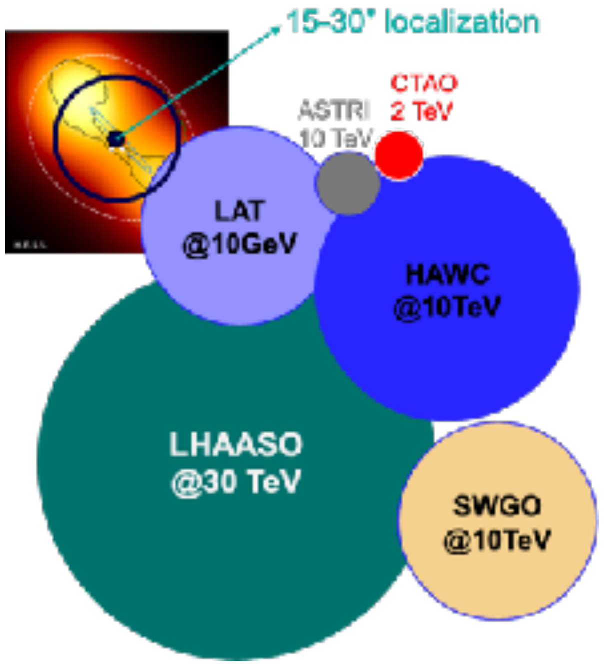
13 telescopes

Paranal, Chile

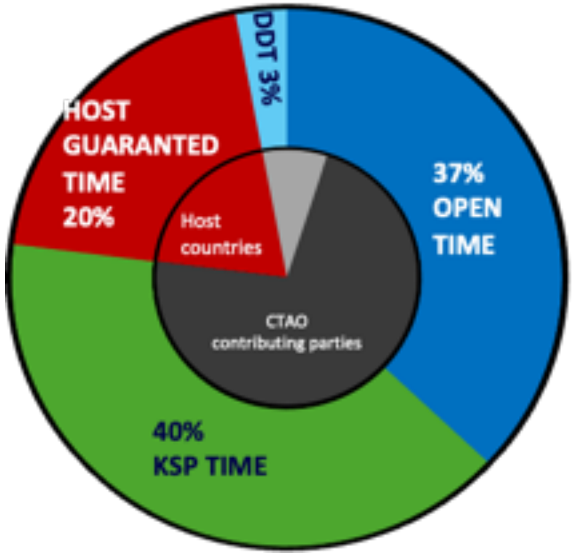
51 telescopes

An Open Observatory

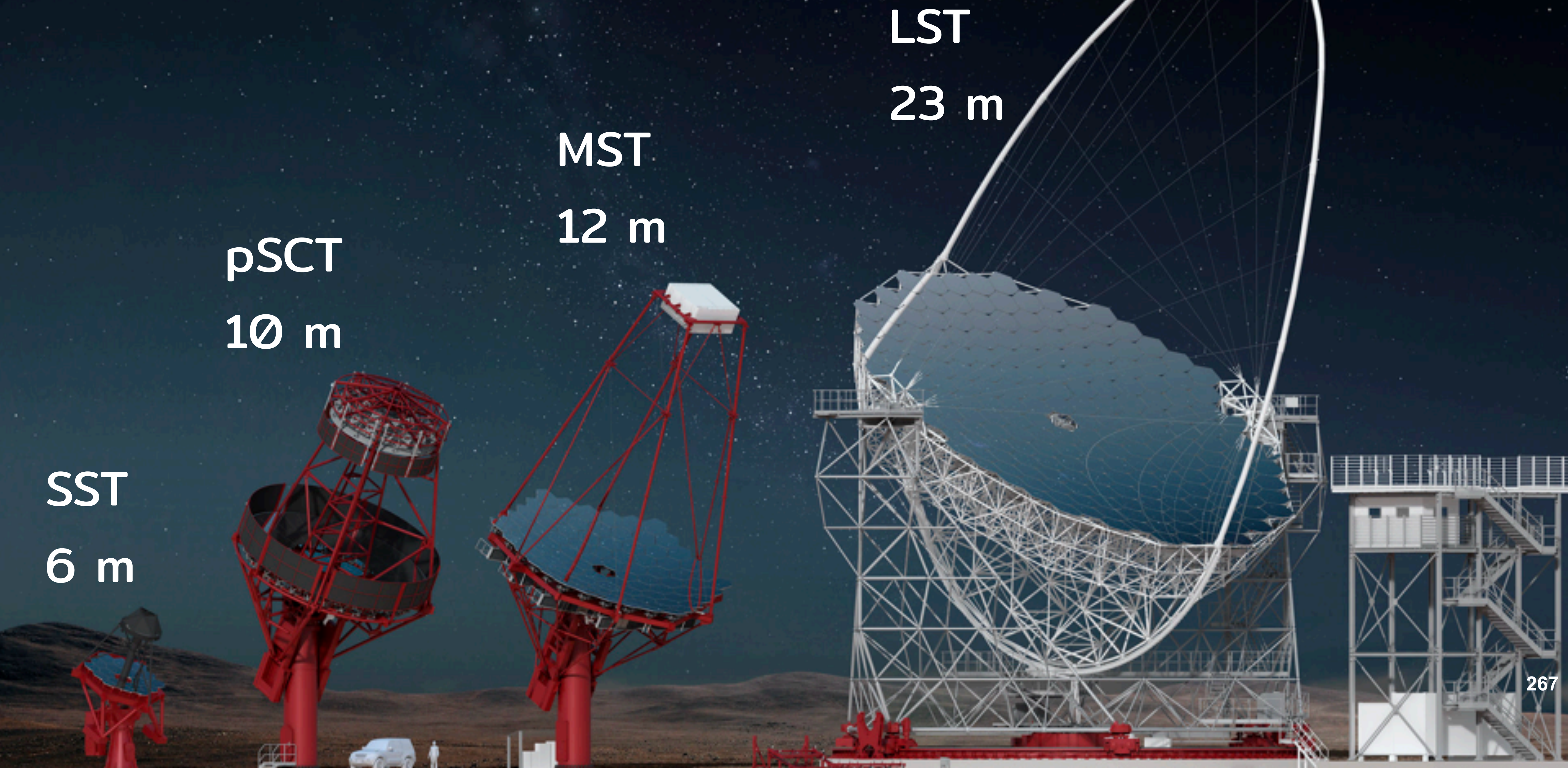




- Proposal-driven, with reserved time for the builder countries



Telescope types



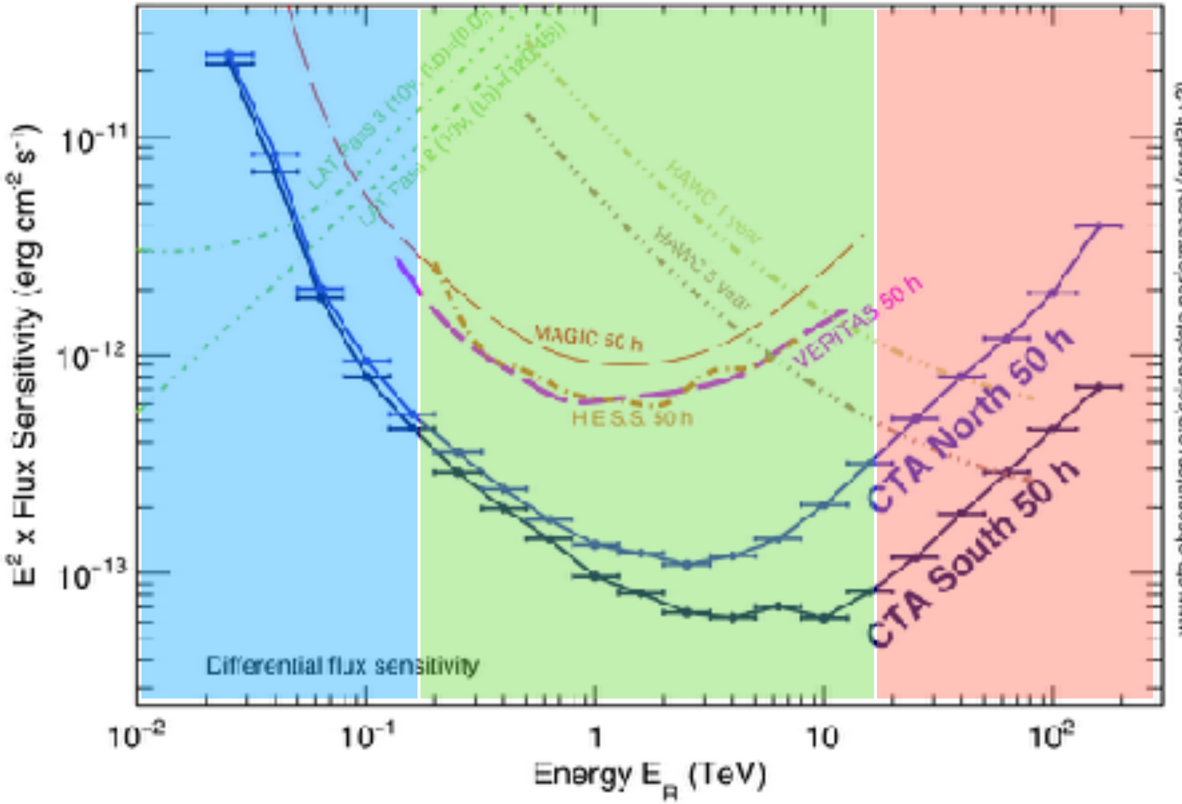
Galactic Physics with CTAO

Boosting:

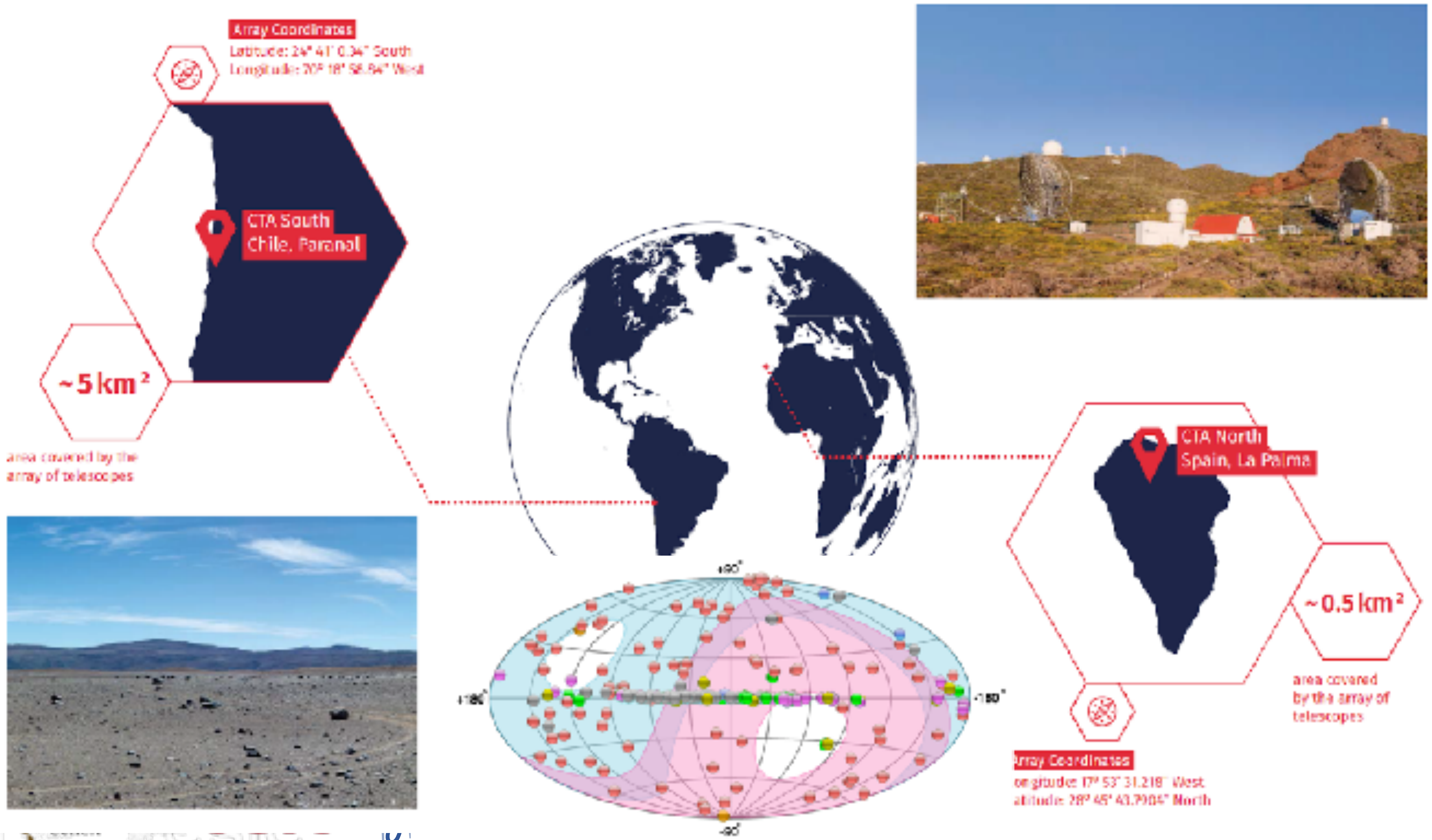
- Increase sensitivity by up to a factor ~6 at 1 TeV
- Increase the detection area for transients and at the highest energies
- Increase the angular resolution/maintaining a large FoV

New:

- Energy coverage: tens of GeV => >100 TeV (~300 TeV)
- 2 Sites, flexibility of operation, allowing for sub-arrays and multi-mode
- Operate as an observatory

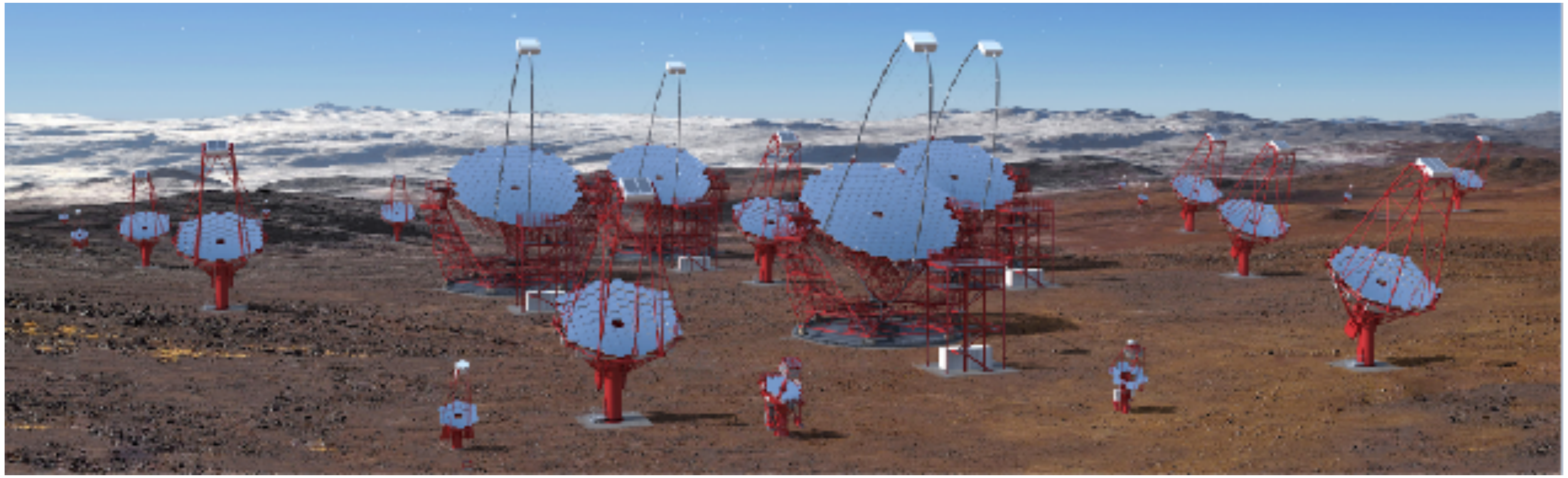


Galactic Physics with CTAO



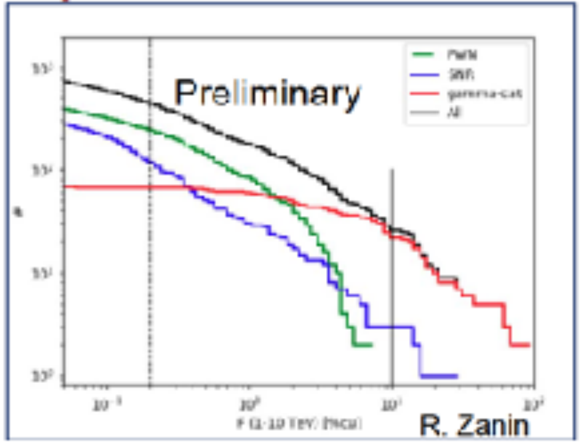
Galactic Physics with CTAO

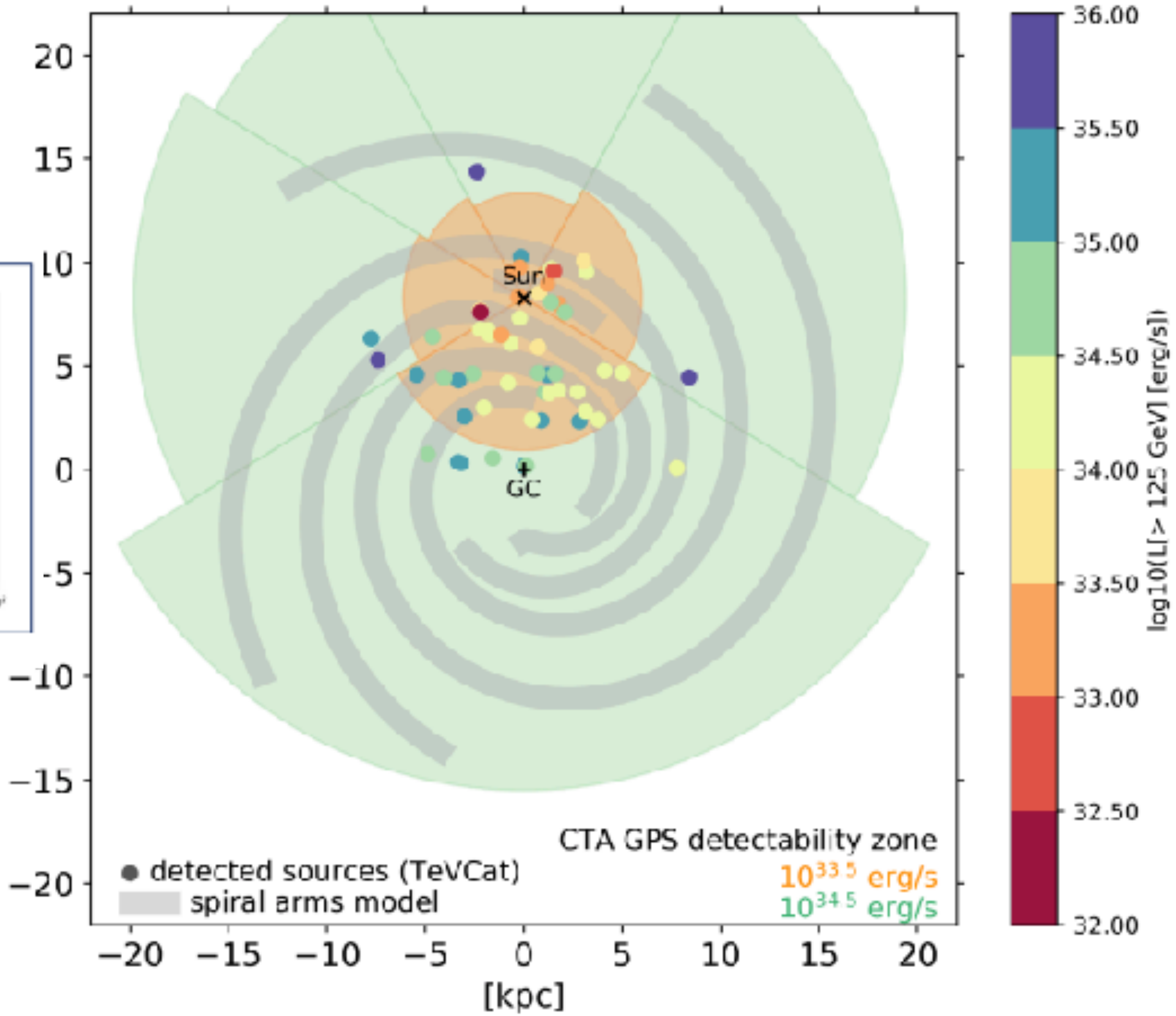
South: 53 telescopes spread out over ~3 km^2 (37 SSTs, 14 MSTs, 2 LSTs(?))



North: 13 telescopes spread out over ~1 km^2 (9 MSTs, 4 LSTs)

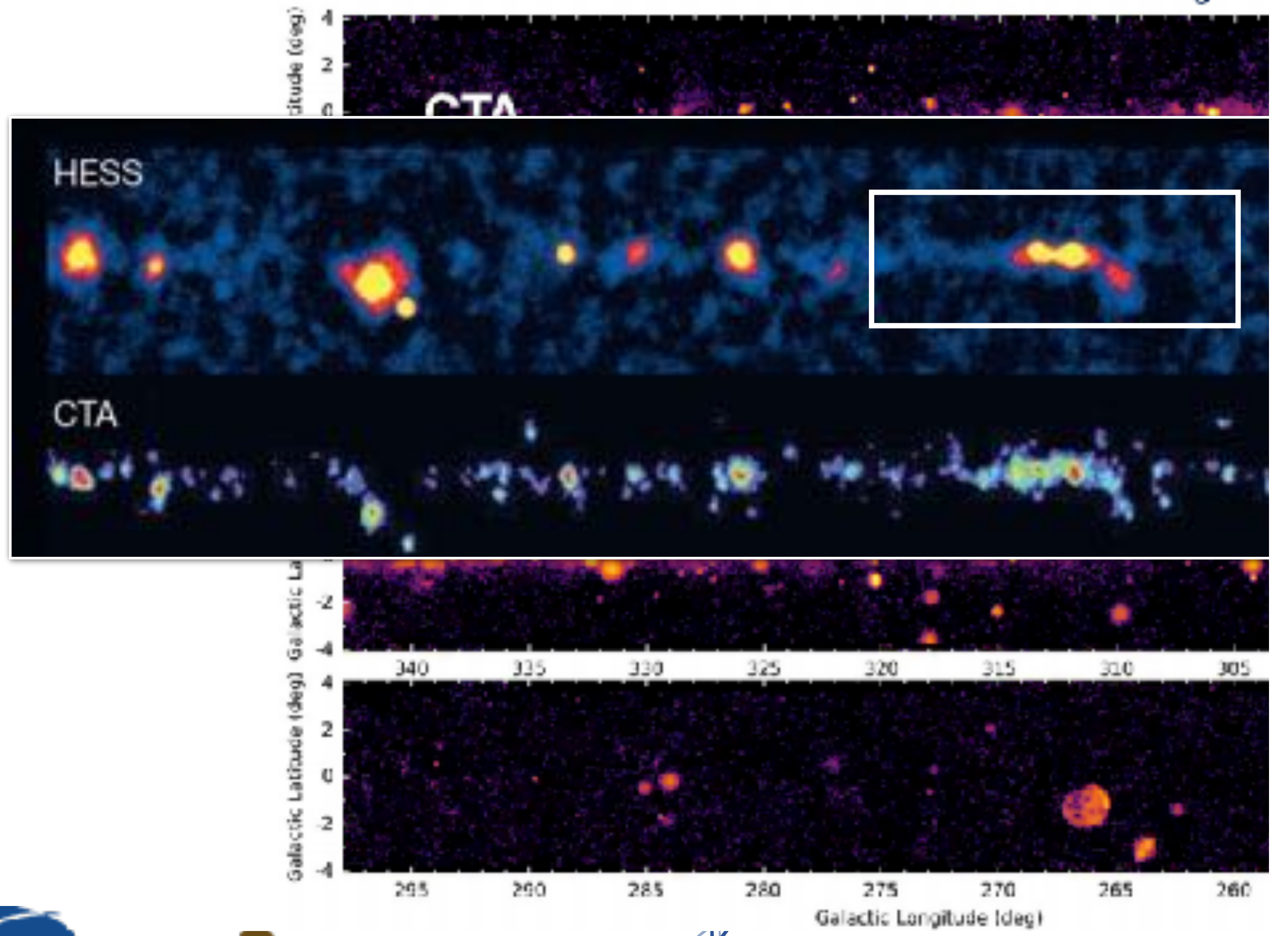
Population Studies

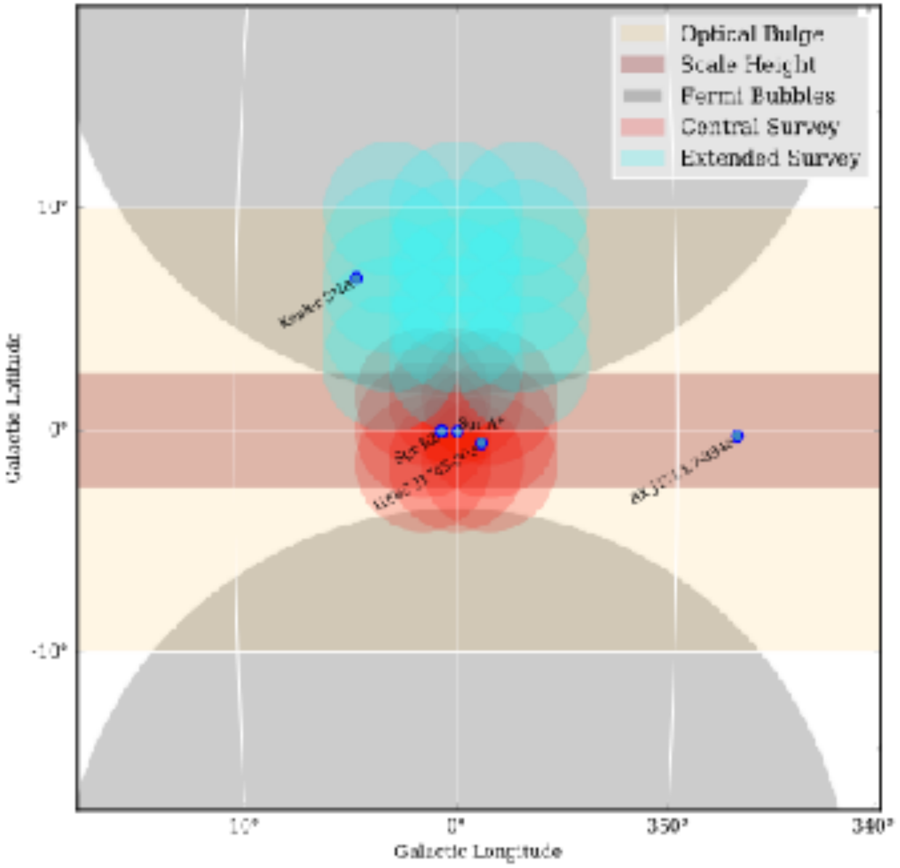


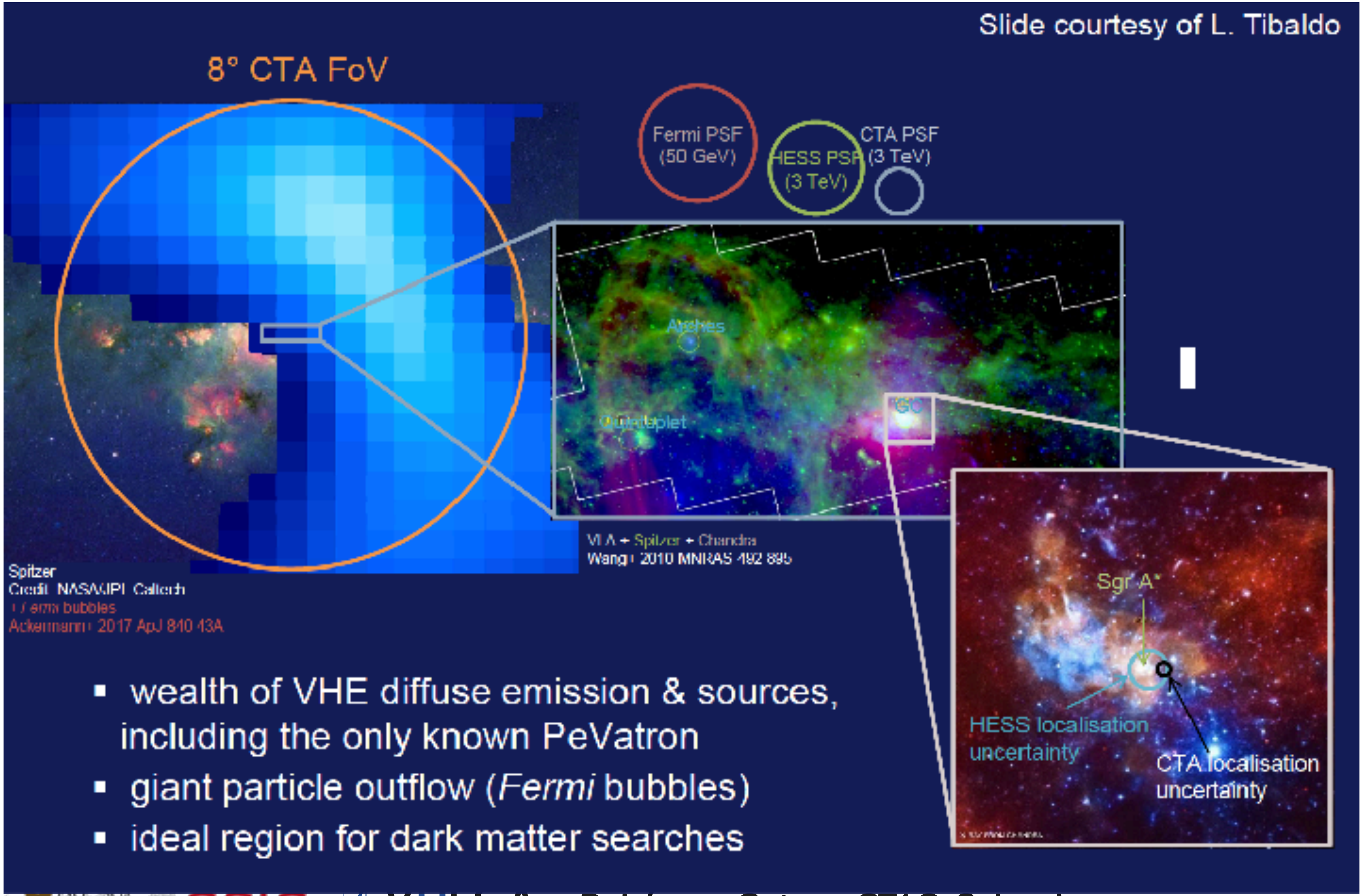


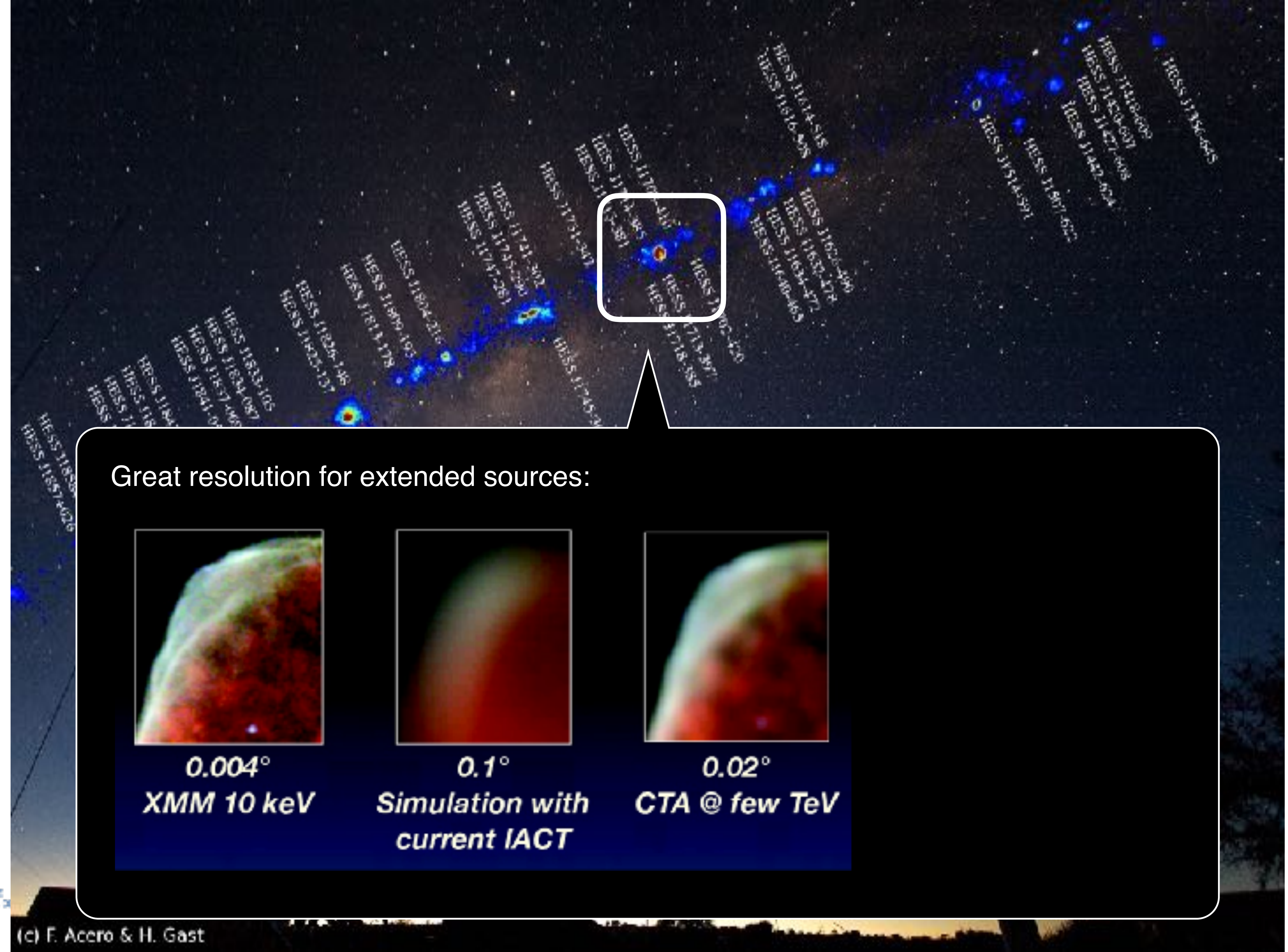
Full galactic plane (1020 h) ~2 mCrab (now ~1-2%Crab)
Deep survey of the Galactic Centre region (300 h on 10°x10° region, 525 h on GC)
The Large Magellanic Cloud (340 h in 6 pointings)

Cutout of CTA GPS from first Data Challenge

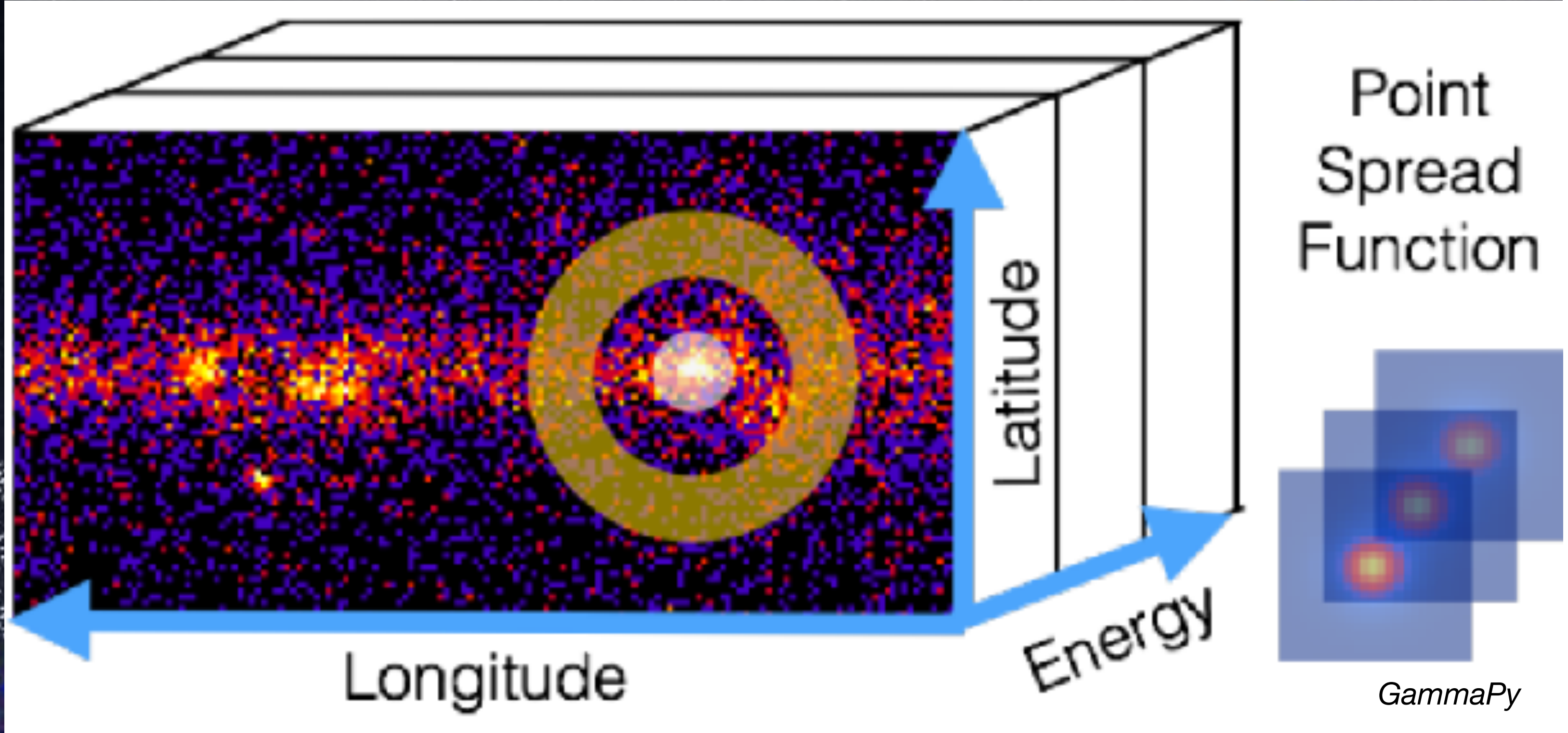


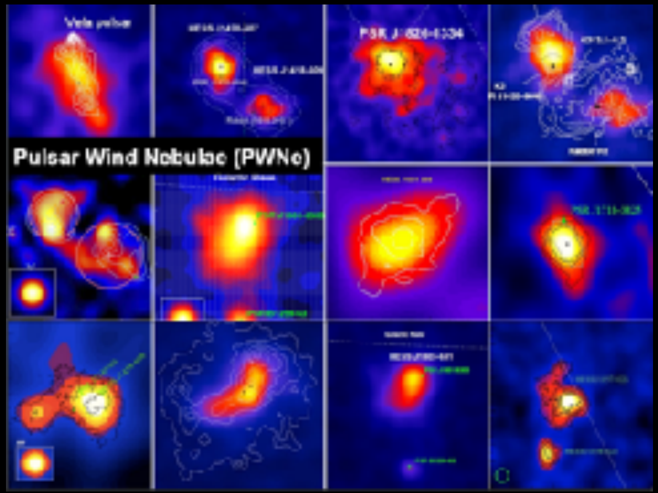



Slide courtesy of L. Tibaldo
8° CTA FoV
Fermi PSF (50 GeV)
HESS PSF (3 TeV)
CTA PSF (3 TeV)
Arches
Quintuplet
GC
Spitzer
Sgr A*
HESS localisation uncertainty
CTA localisation uncertainty
▪ wealth of VHE diffuse emission & sources, including the only known PeVatron
▪ giant particle outflow (*Fermi* bubbles)
▪ ideal region for dark matter searches



(c) F. Acero & H. Gast

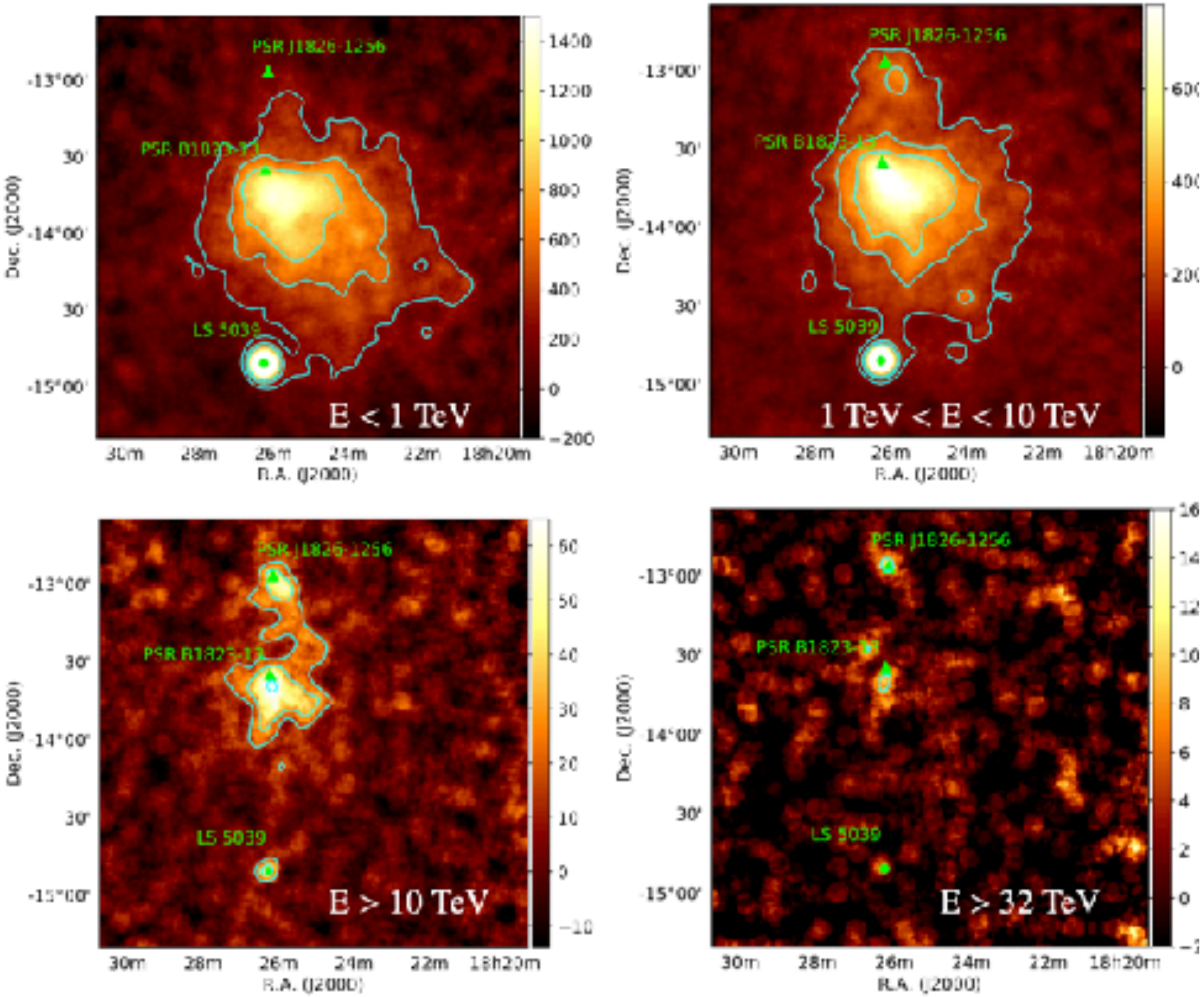


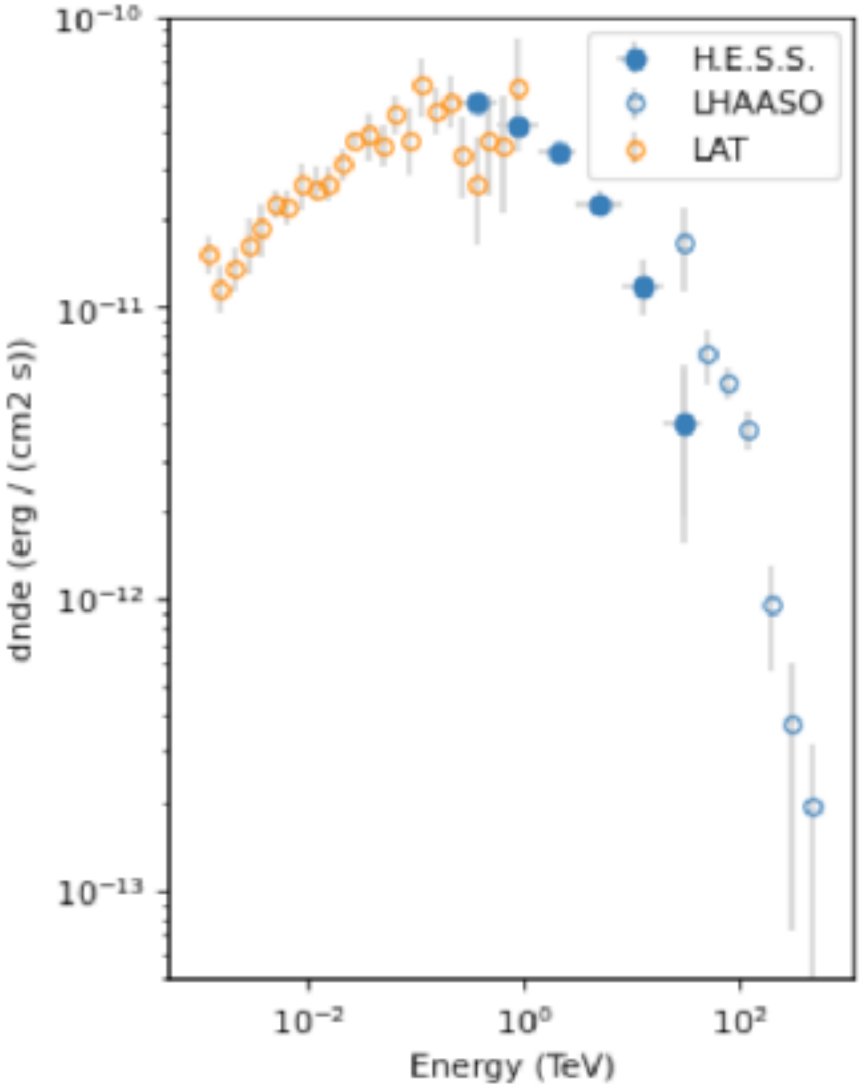


Better resolution, but also better sensitivity
=> More extended sources!

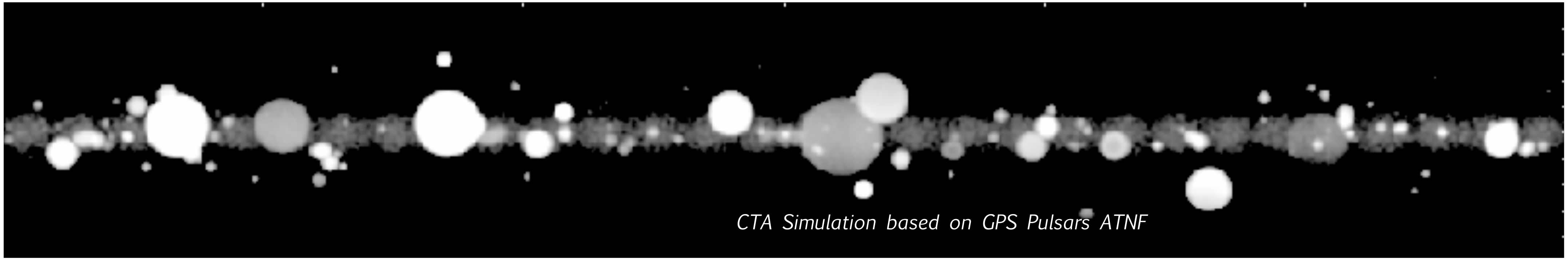
GeV / TeV/ PeV analysis

(c) F. Acero & H. Gast


PSR J1826-1256
PSR B1823-13
LS 5039
E < 1 TeV
1 TeV < E < 10 TeV
E > 10 TeV
E > 32 TeV
Dec. (J2000)
R.A. (J2000)


H.E.S.S.
LHAASO
LAT
dnde (erg / (cm2 s))
Energy (TeV)

Source Confusion



CTA Simulation based on GPS Pulsars ATNF