

Non-jetted Galactic Science

Rubén López-Coto, IAA-CSIC
CTAO School, 18/05/26



VHEGA



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

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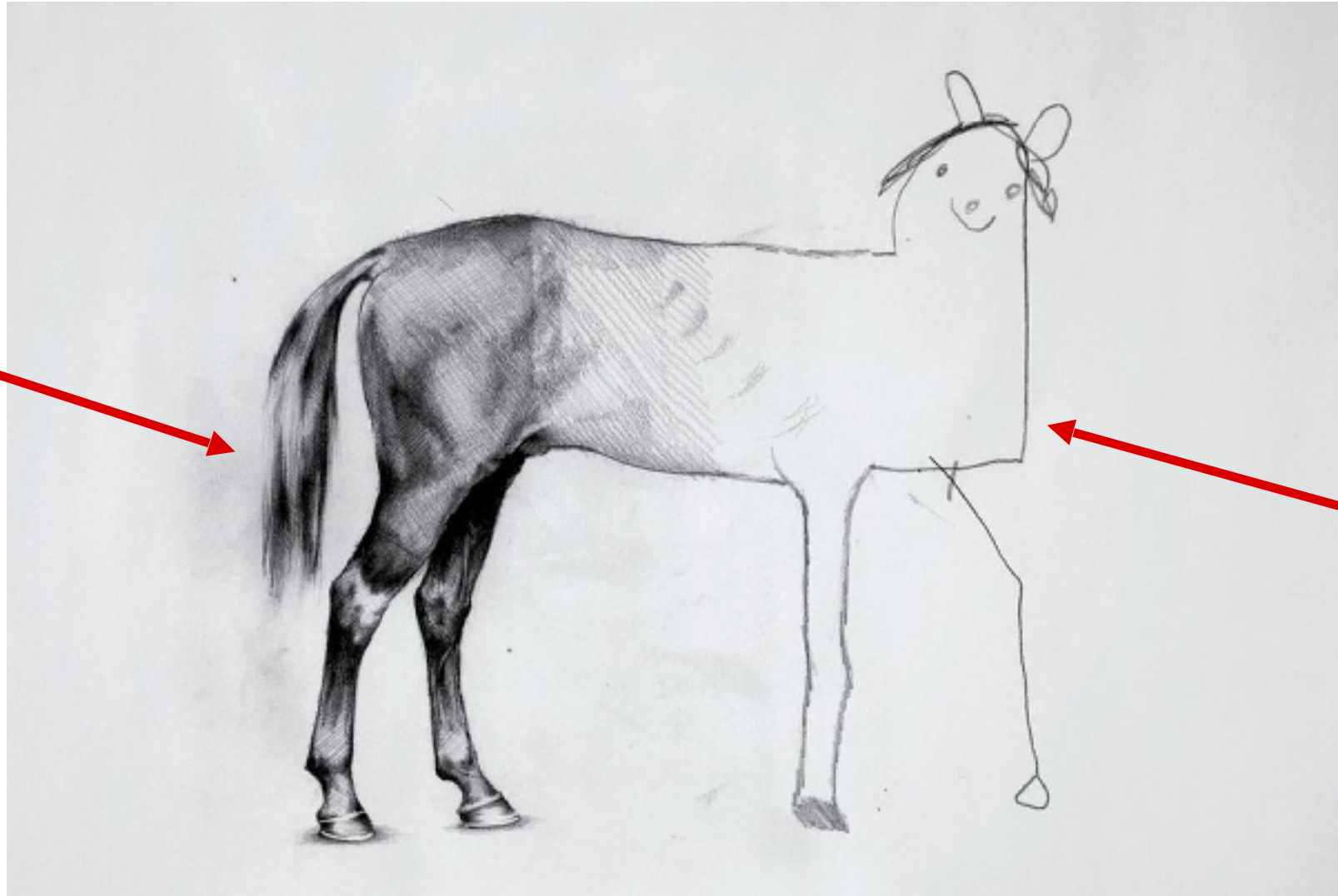
Who am I?



- 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

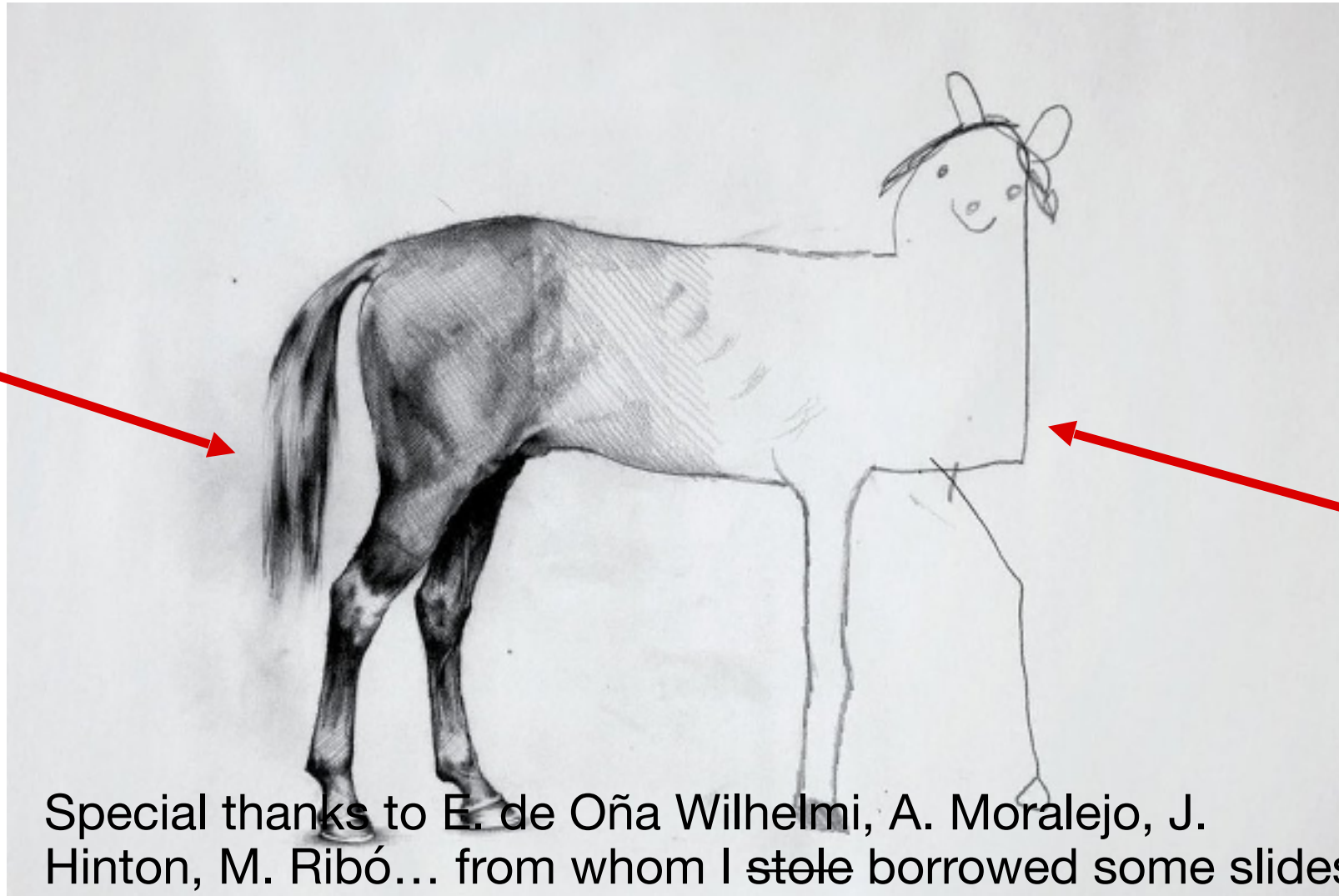
3 months ago
when David
wrote me



Literally one
hour ago

This course

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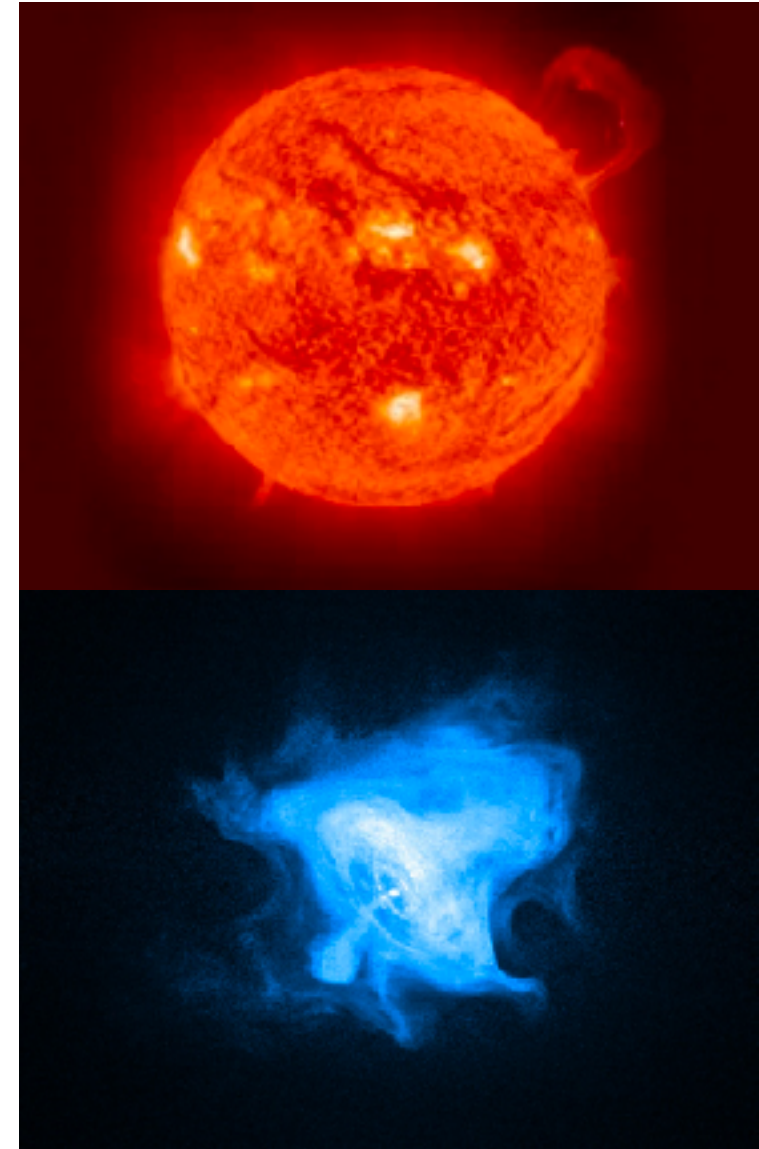
Special thanks to E. de Oña Wilhelmi, A. Moralejo, J. Hinton, M. Ribó... from whom I stole borrowed some slides

(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.

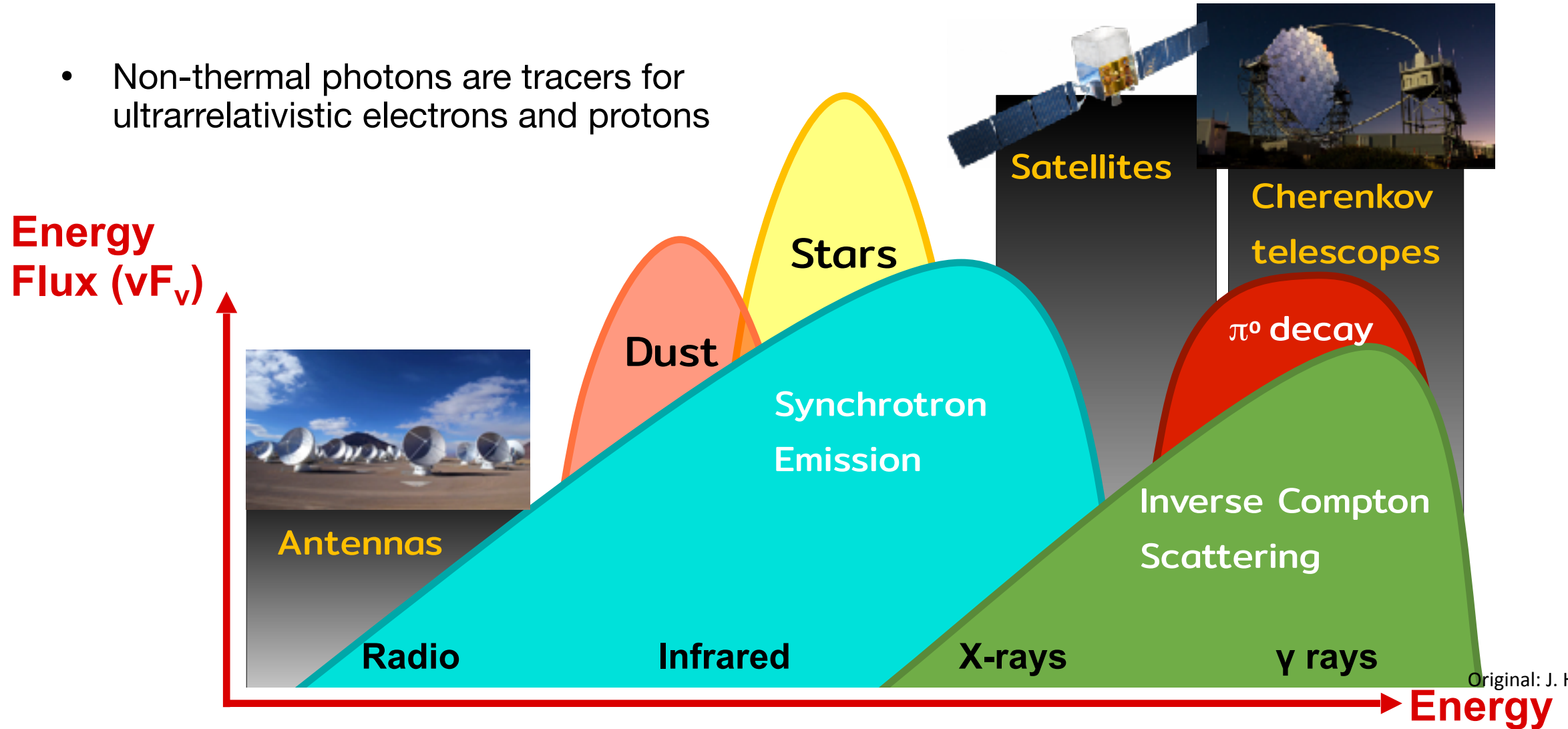
Thermal vs Non-thermal universe

- 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

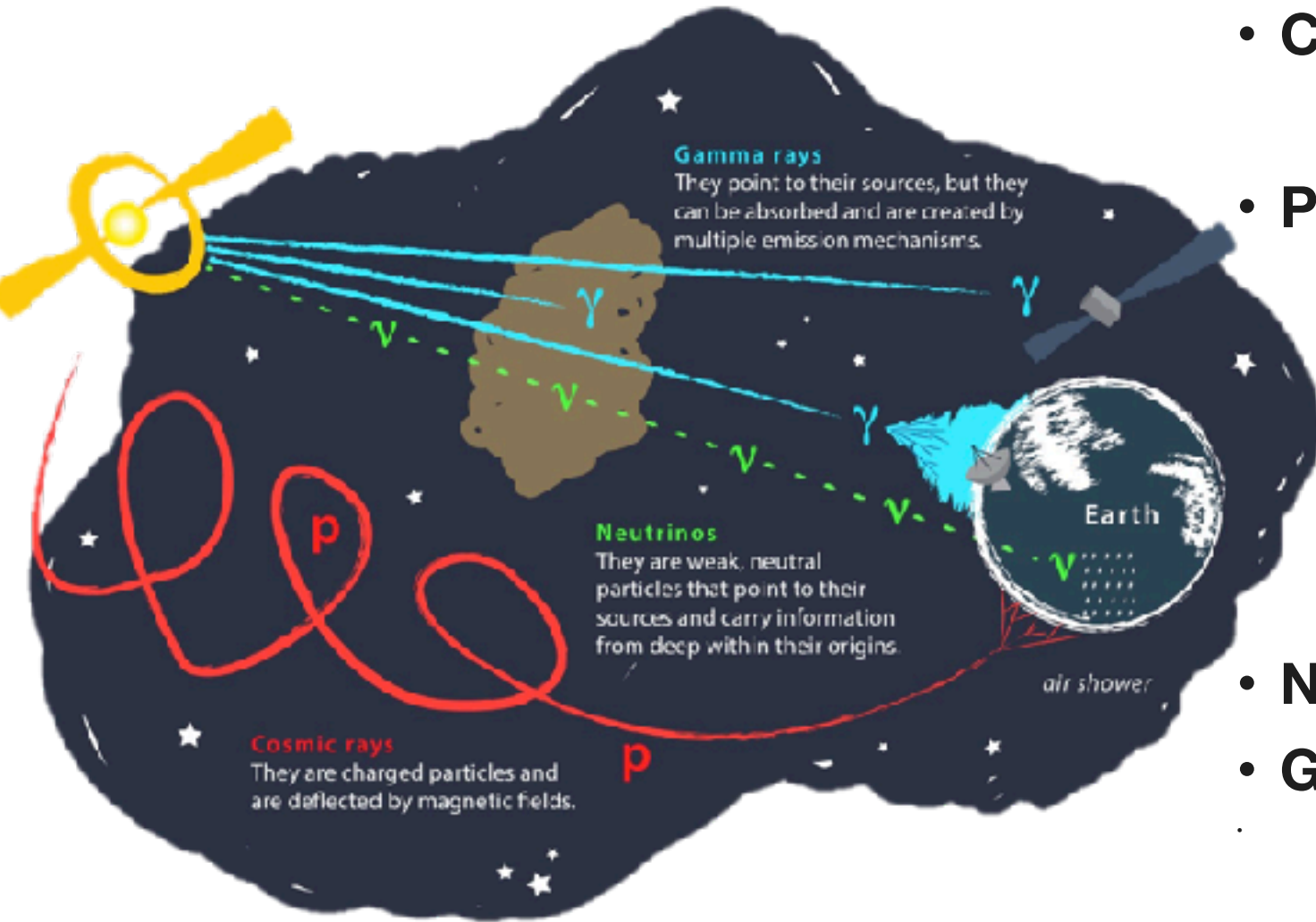


The non-thermal Universe

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



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**

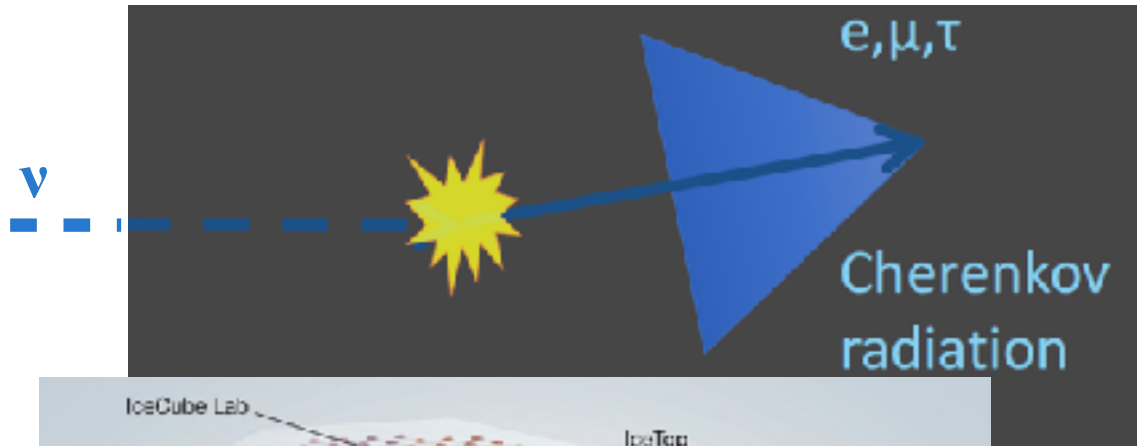
- **Gravitational waves**

Messengers: Cosmic Rays

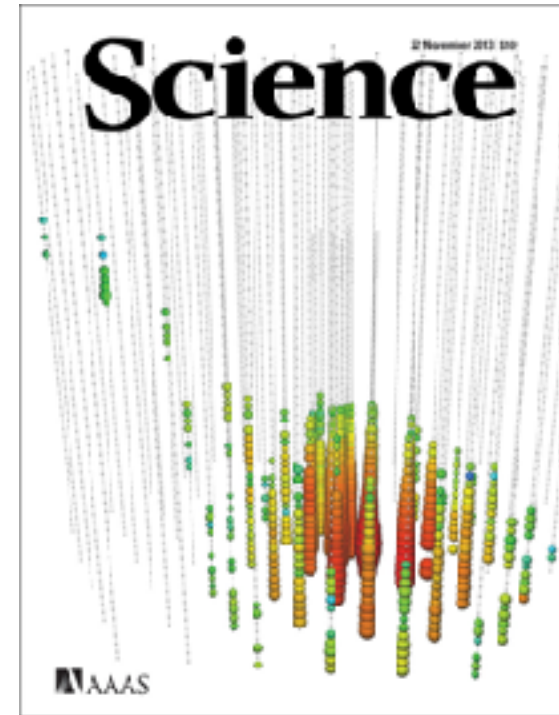
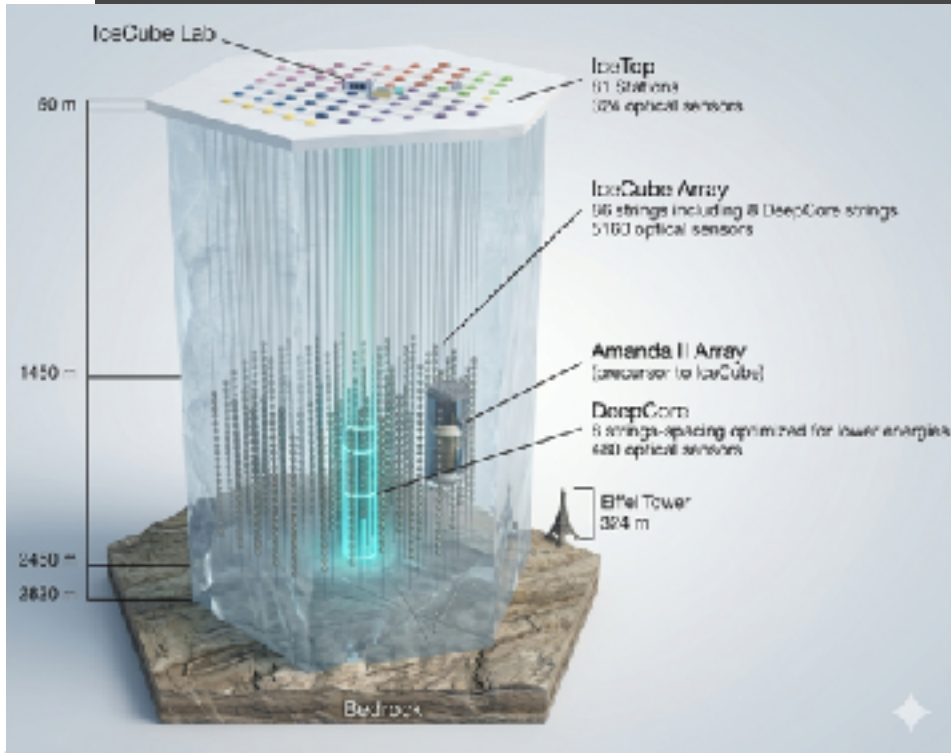


- In 1912, Viktor Hess made a series of balloon flights measuring the amount of radiation
- He measured that **ionization increased with height.**
- He concluded that the increase of the ionization with height is due to a radiation coming from above, and thought that this radiation had extra-terrestrial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

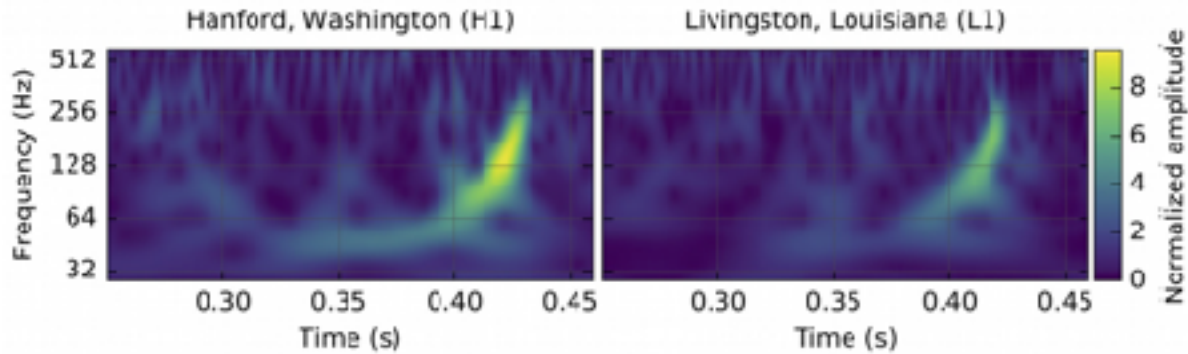
Messengers: Neutrinos



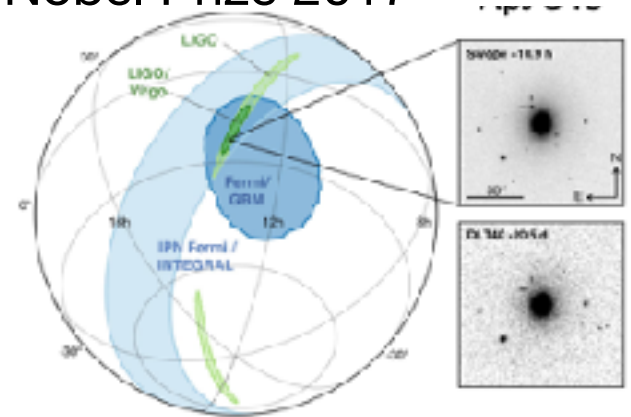
- Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector (22 Nov. 2013)



Messengers: Gravitational Waves



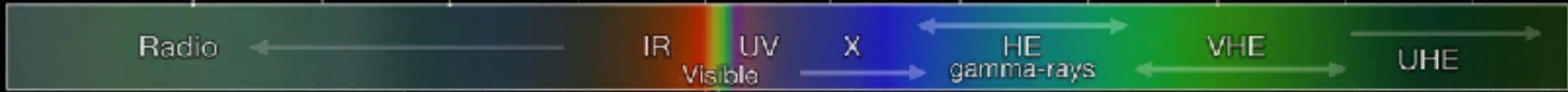
GW150914: the first binary black hole (BBH)
-> Nobel Prize 2017



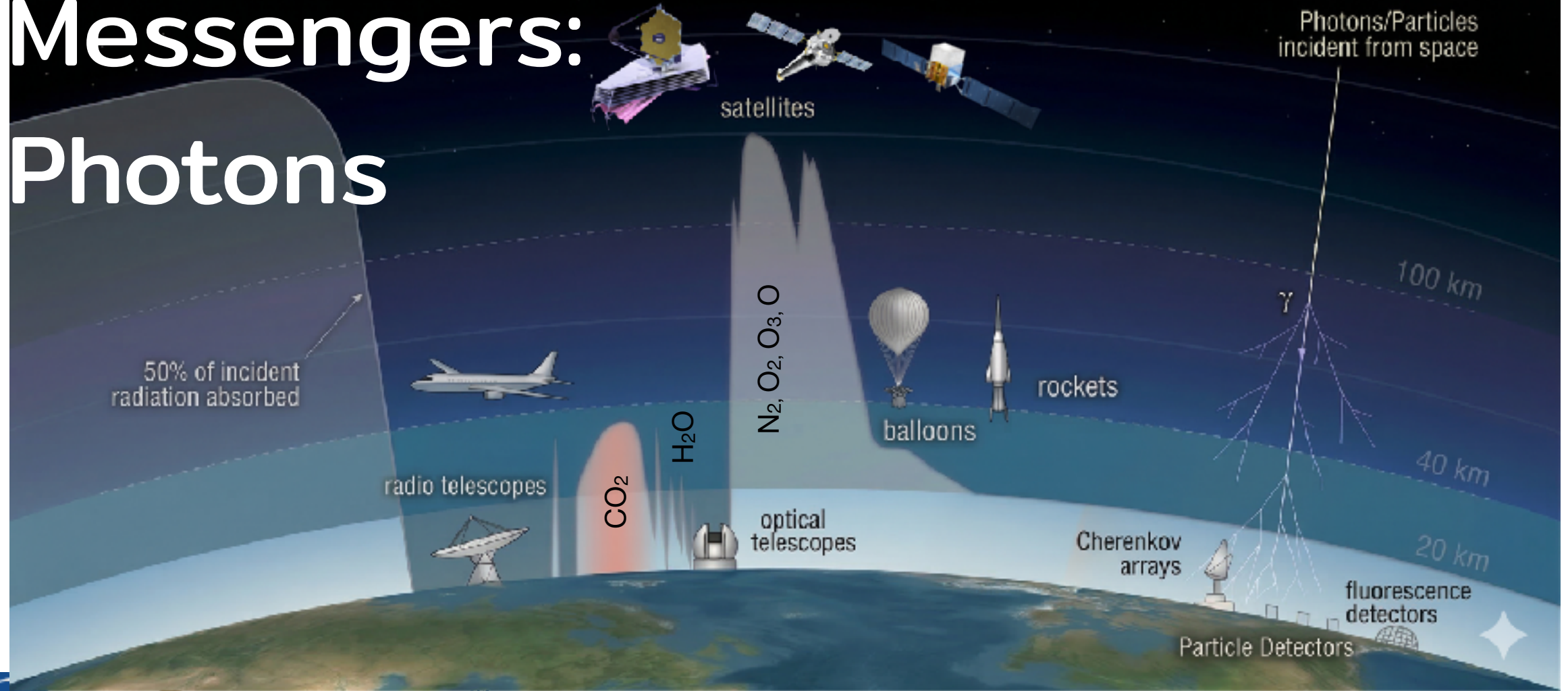
- 17 August 2017: LIGO+VIRGO detection of gravitational wave event: **GW170817** (Phys. Rev. Lett. 119)
- Time profile consistent with merger of neutron-star binary
- **GRB 170817A** detected at $t = 1.7$ s after coalescence, and consistent direction by Fermi-GBM and INTEGRAL (ApJ 848)
- Extensive multi-wavelength 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



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

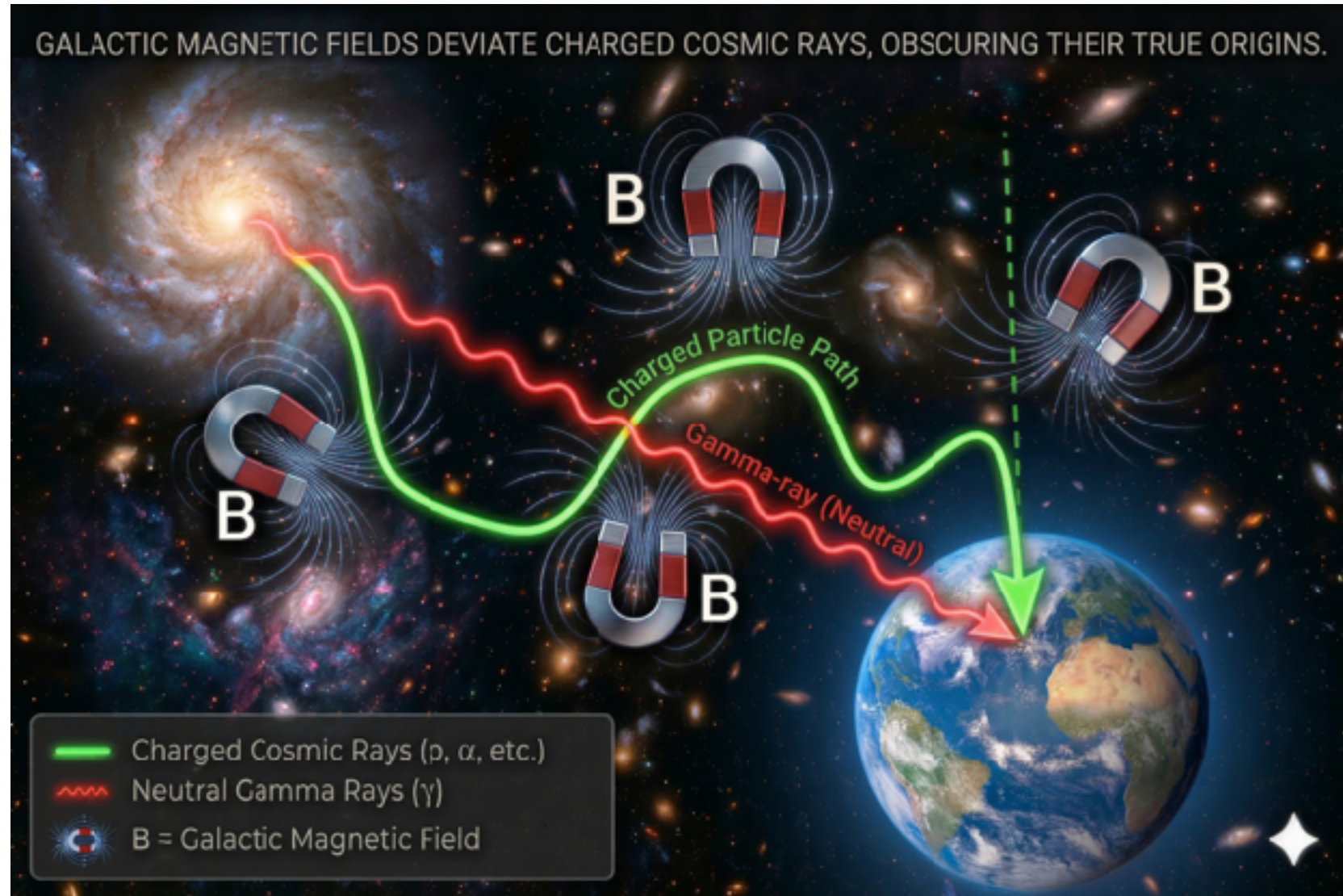


Messengers: Photons



Importance of the non-thermal EM Window

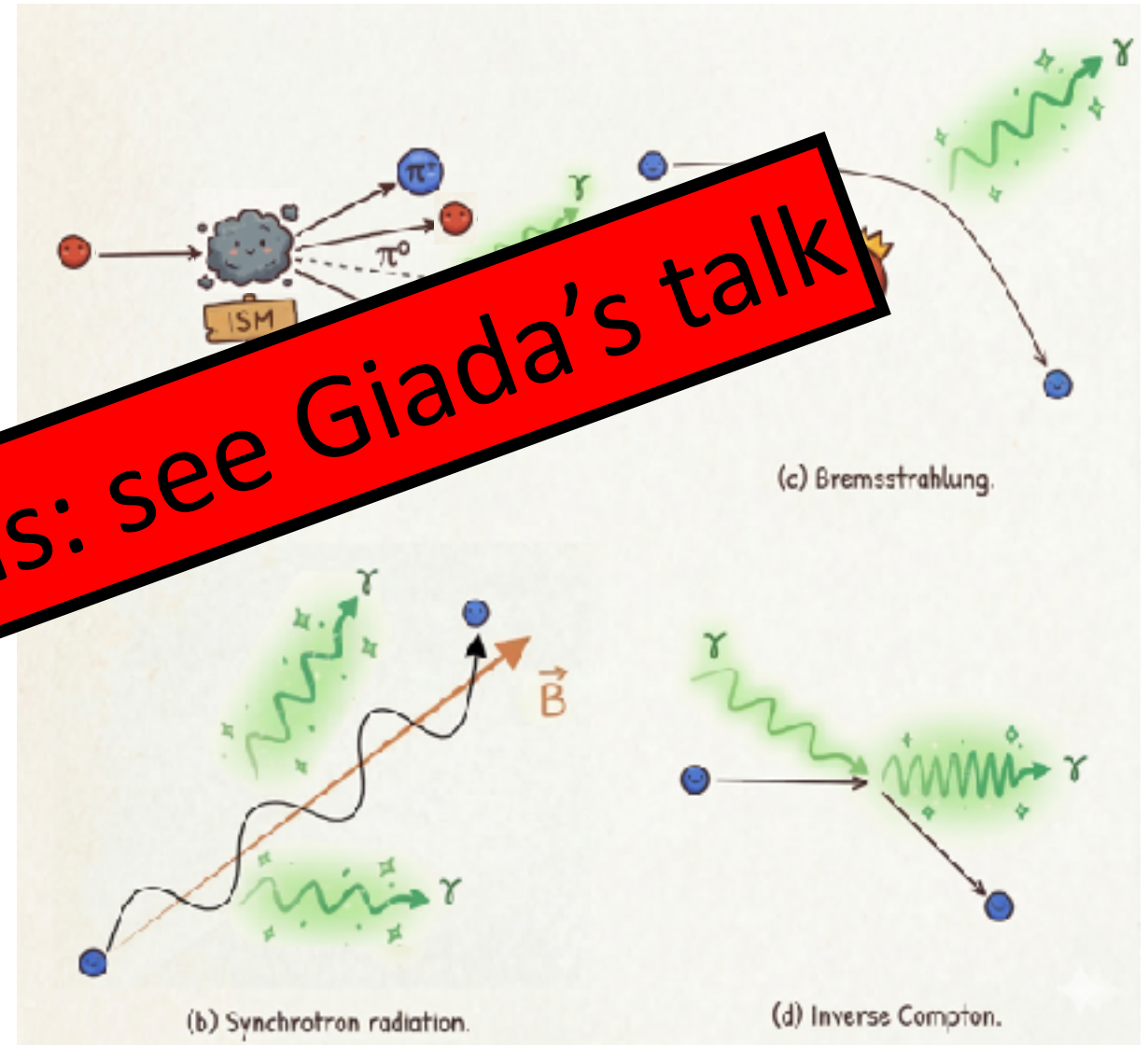
- If we want to understand the origin, evolution and current state of the universe, we need to have a deep knowledge of the non thermal part of the it.
 - Cosmic ray origin cannot be pinpointed towards their sources because they are deflected by magnetic fields
 - Solution: study the neutral products 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
 - Emission from braking
- Inverse Compton Scattering
 - Strongly suppressed by the Klein-Nishina mechanism at high E

For further details: see Giada's talk



Our Galaxy

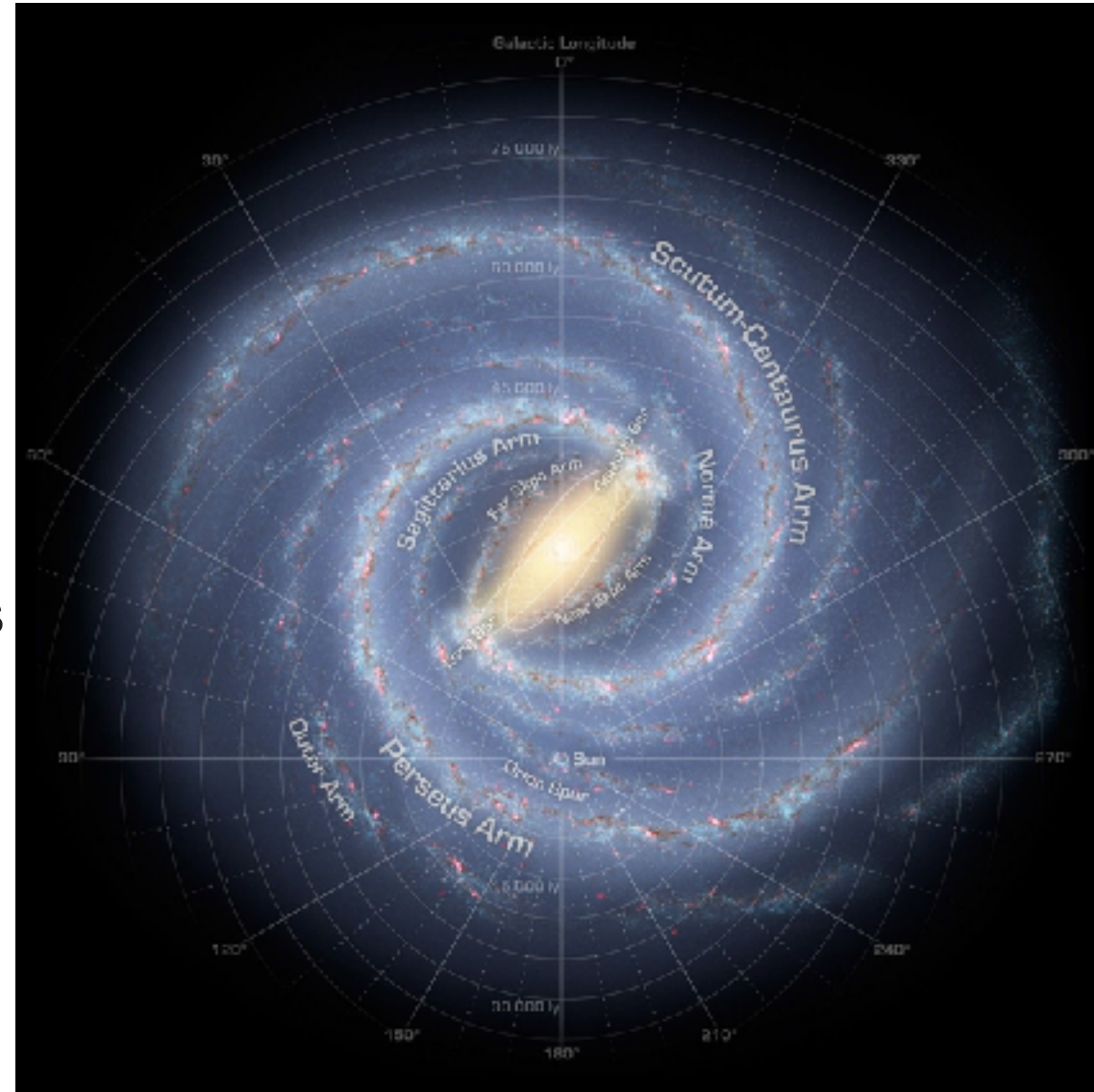


Rare Photograph of The Milky Way viewed from Mars

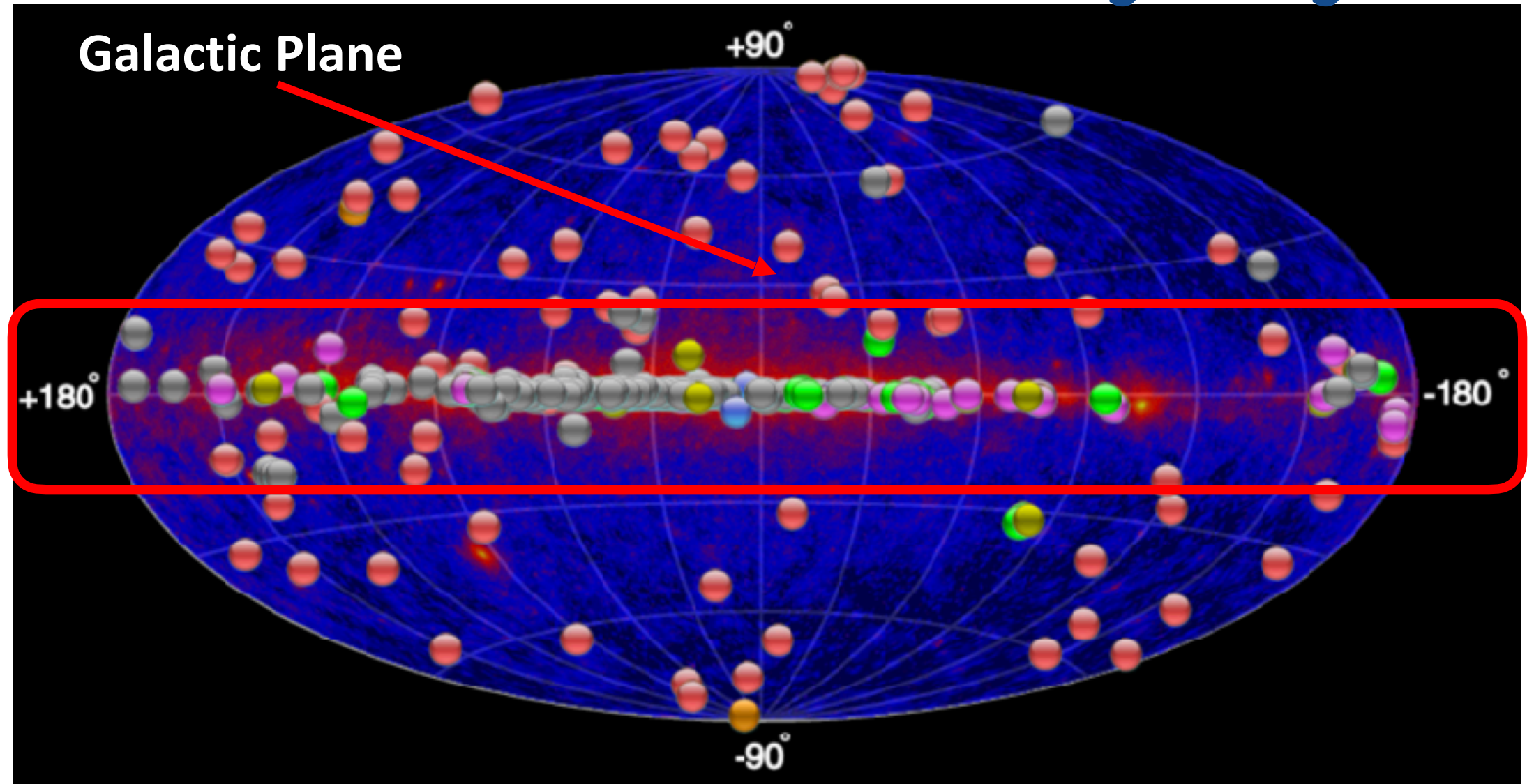


Research topics in VHE Galactic science

- 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

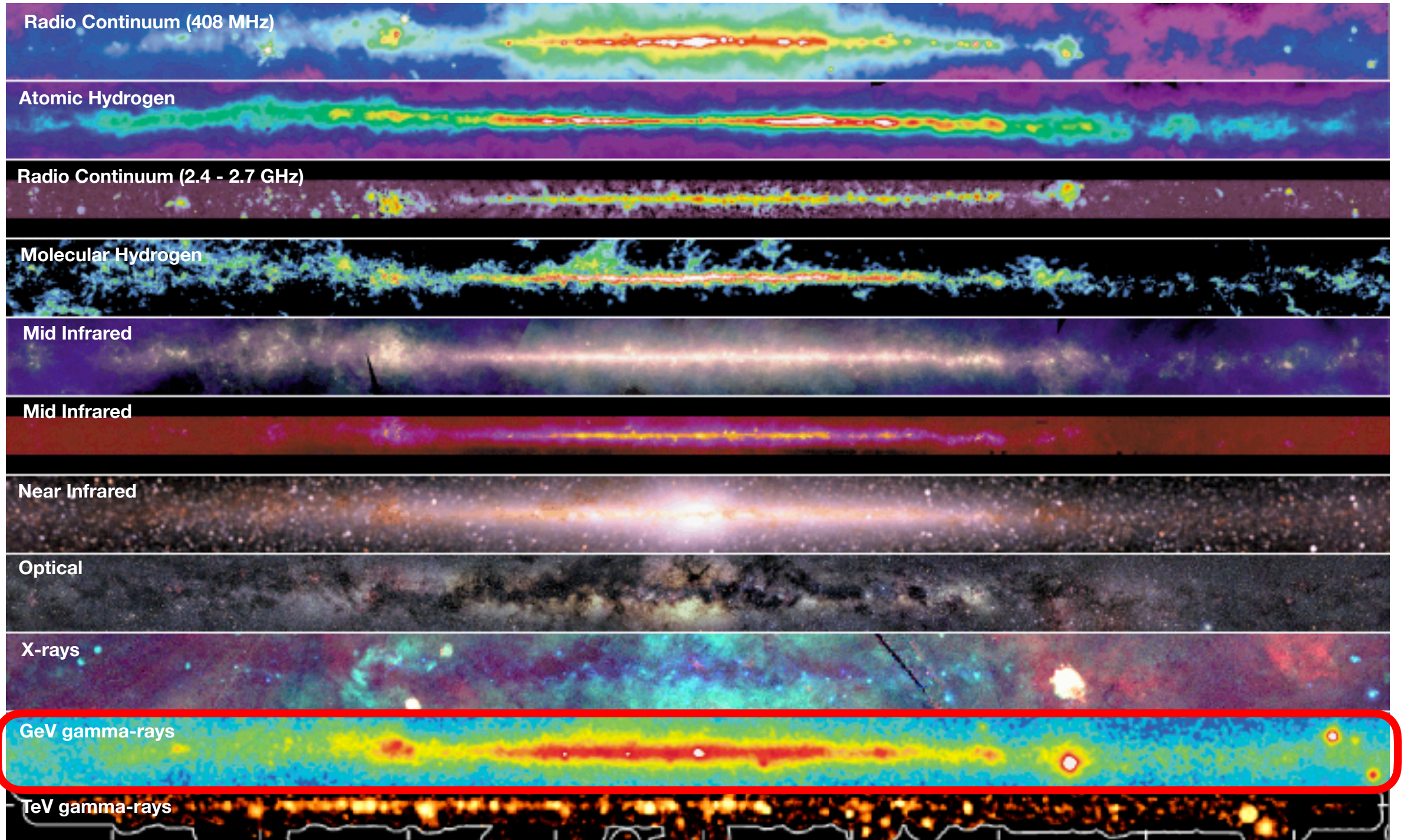
Near Infrared

Optical

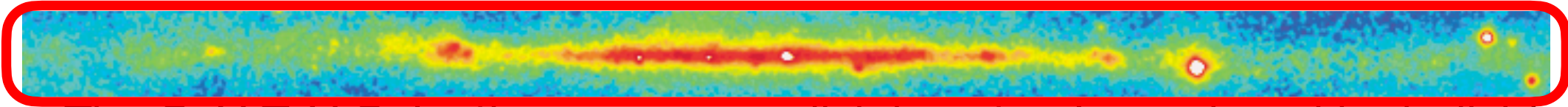
X-rays

GeV gamma-rays

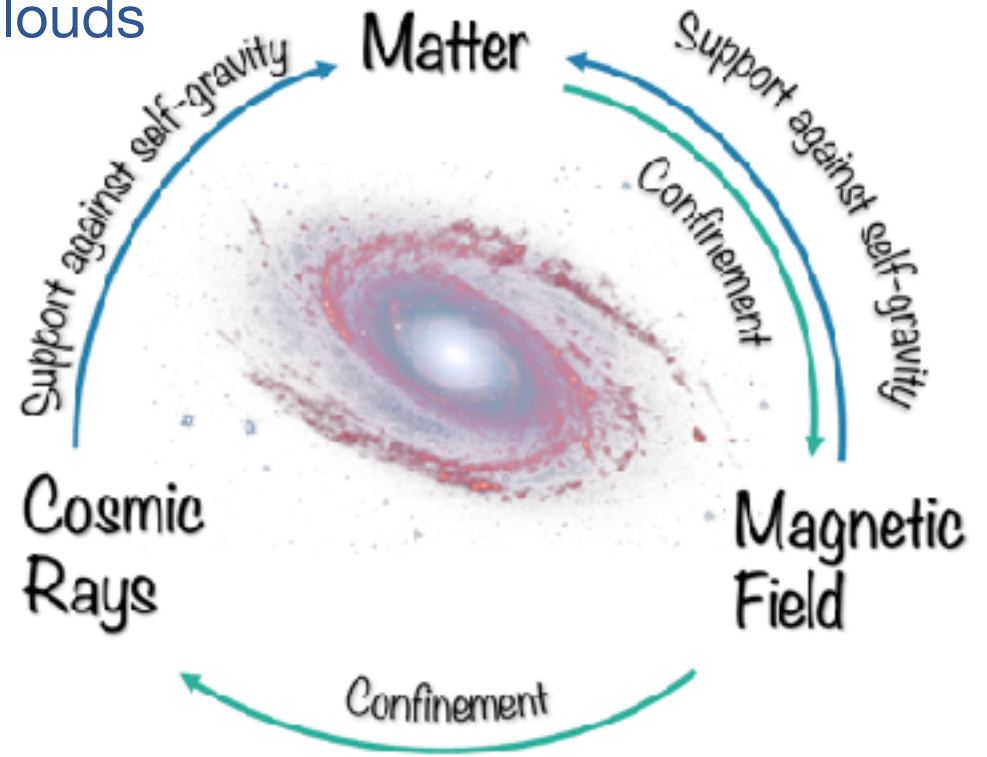
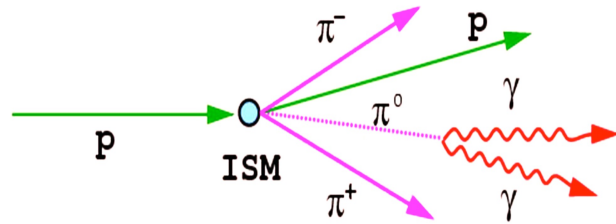
TeV gamma-rays



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



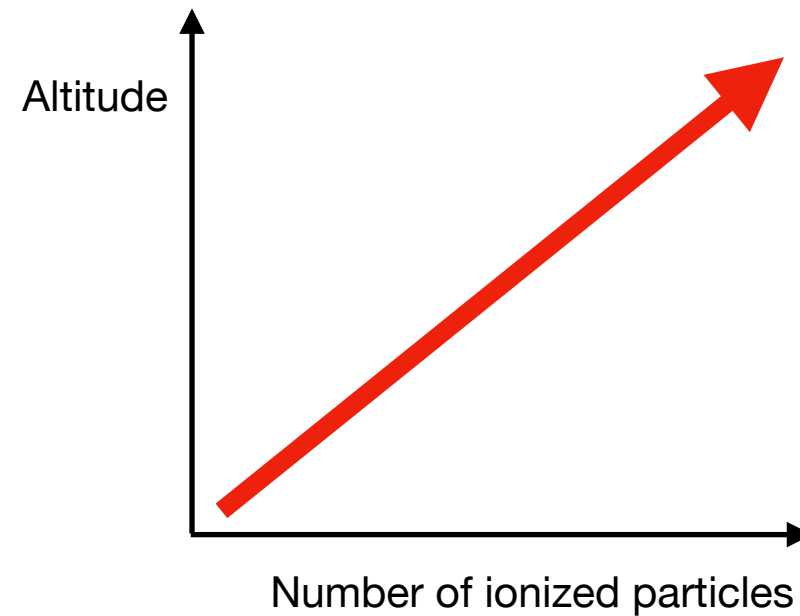
- Interstellar Medium composition:
 - Matter,
 - Cosmic Rays
 - Magnetic Field
- Dynamic balance processes triggers instabilities in the Galaxy structure
 - $\omega_{CR} \sim \omega_B \sim \omega_{turb} \text{ gas} \sim 1 \text{ eV/cm}^3$

Galactic Cosmic Rays

The experiment: a balloon flight



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

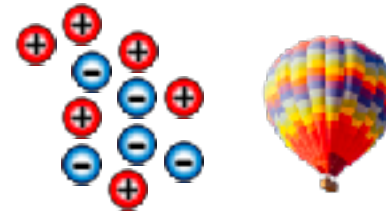


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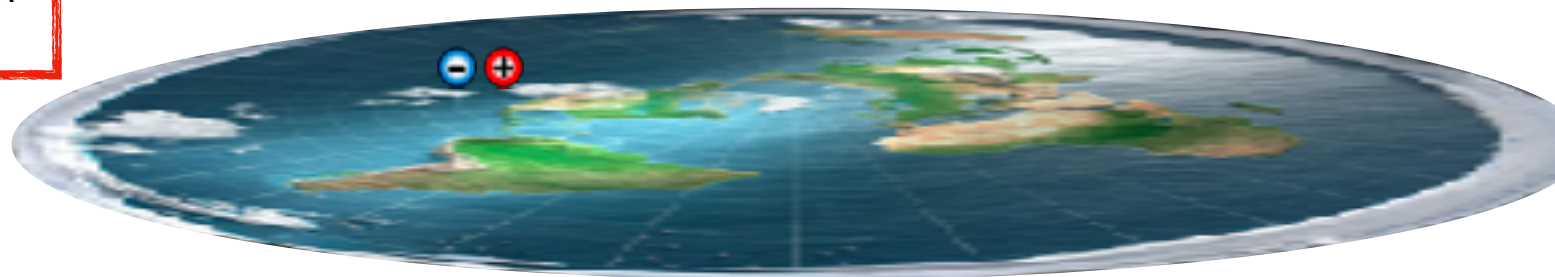
- Initially considered to be some type of radiation (Robert Millikan, 1926):

COSMIC RAYS



- But in reality:

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



Cosmic rays: Detection

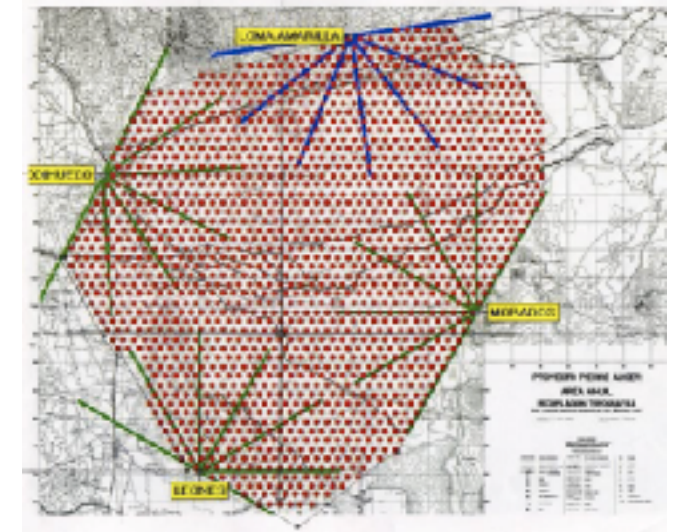
Energy < ~PeV

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

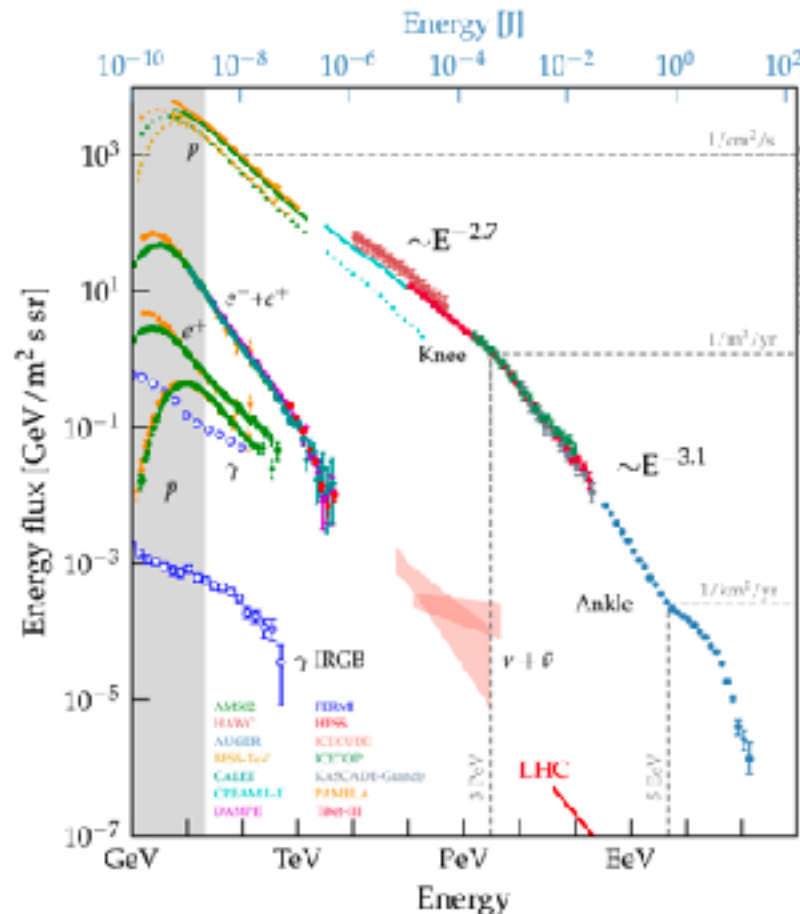


Energy > ~PeV

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

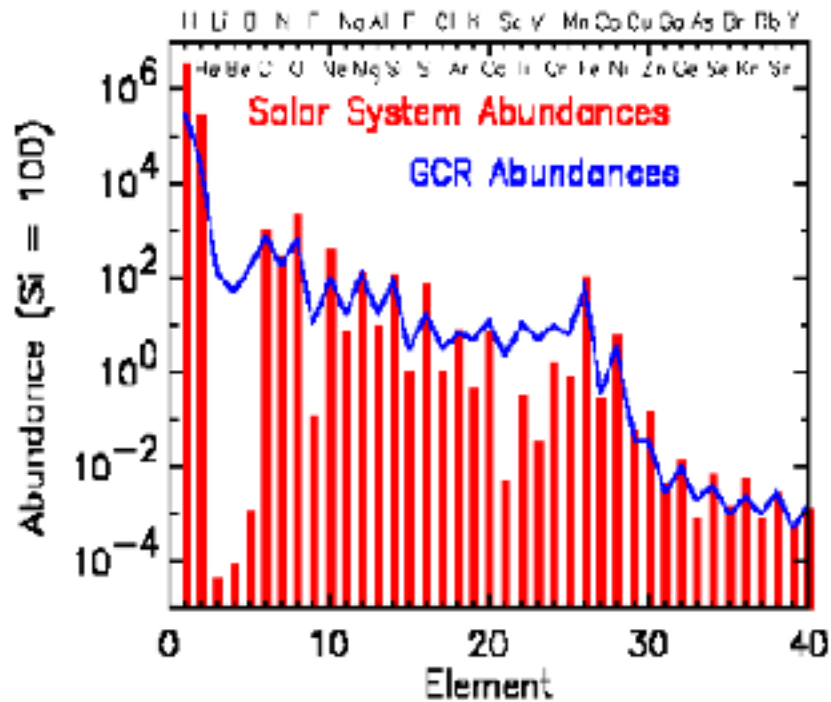


Cosmic rays: Spectrum



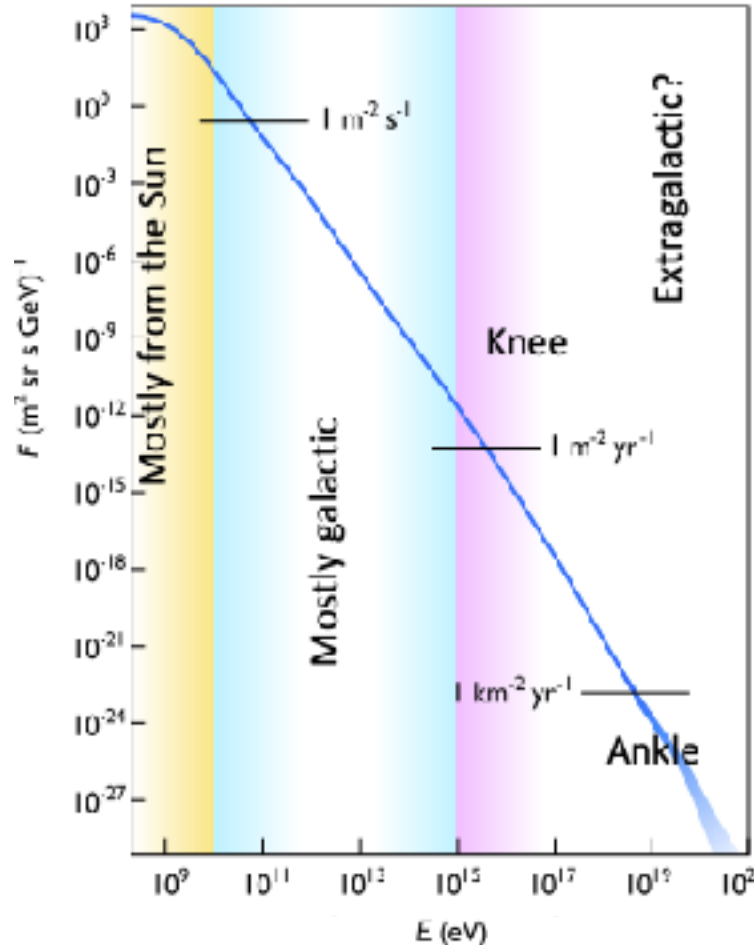
- Spectrum and composition measured by satellites, balloons and extended air shower arrays.

Cosmic rays: Composition



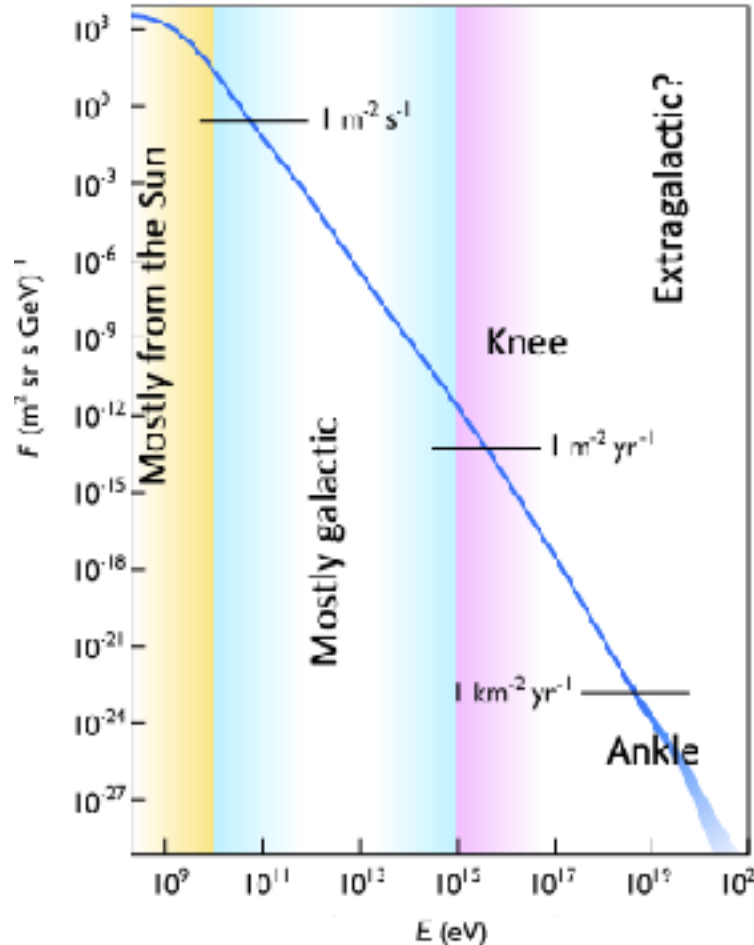
- Spectrum and composition measured by satellites, balloons and extended air shower arrays.
- Composition:
 - 90% Protons
 - 9% Helium nuclei
 - 1% Heavier nuclei, electrons, positrons, antiprotons, ...

Cosmic rays: Origin



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

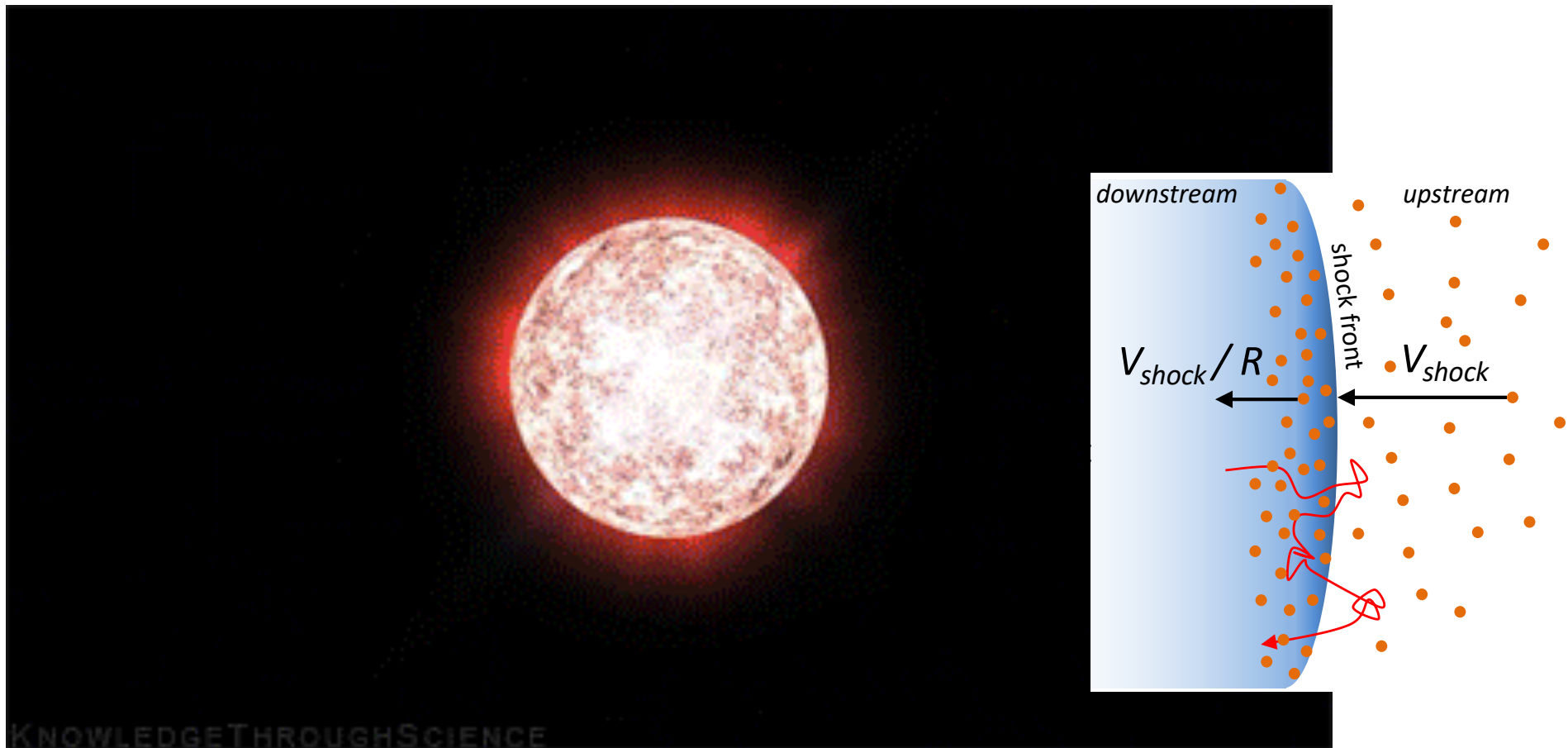
Cosmic rays: Origin



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What is the origin of Galactic Cosmic Rays?

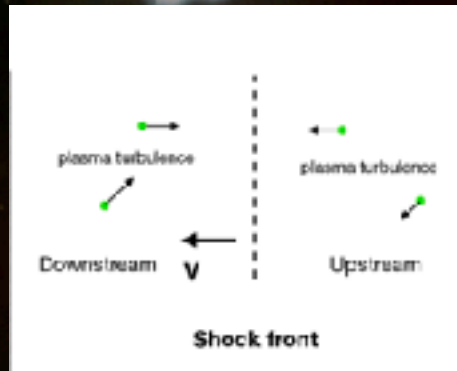
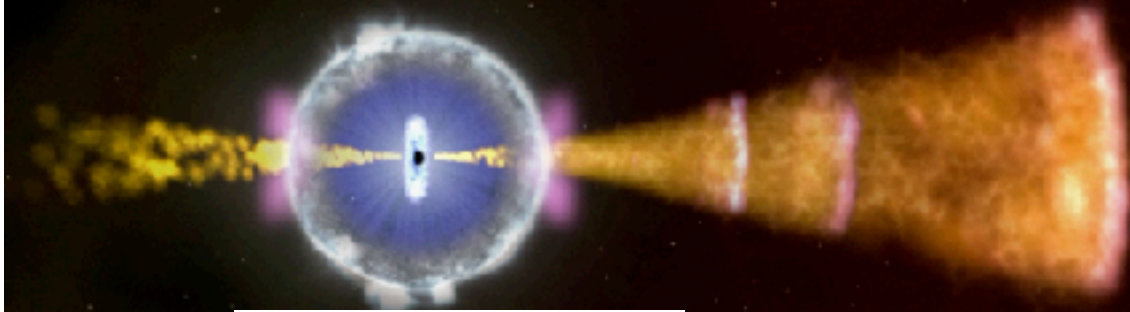
How are CRs accelerated?



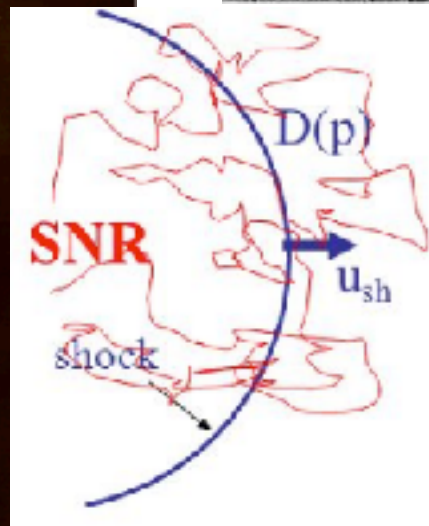
How are CRs accelerated?



Fermi first order acceleration

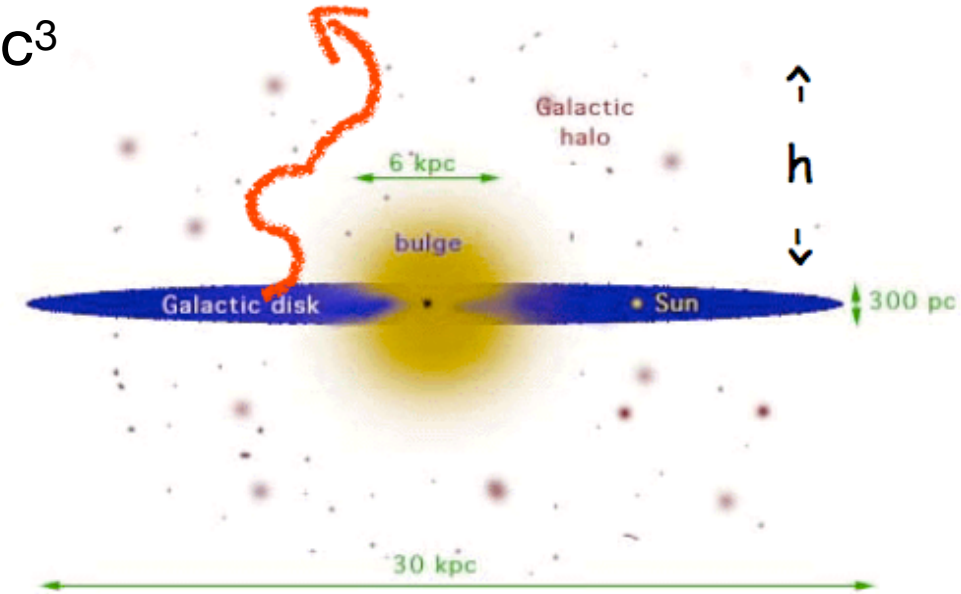


A power law of index ~ 2 is the expected energy spectrum from Diffusive Shock Acceleration (Fermi mechanism)



Galactic CR luminosity

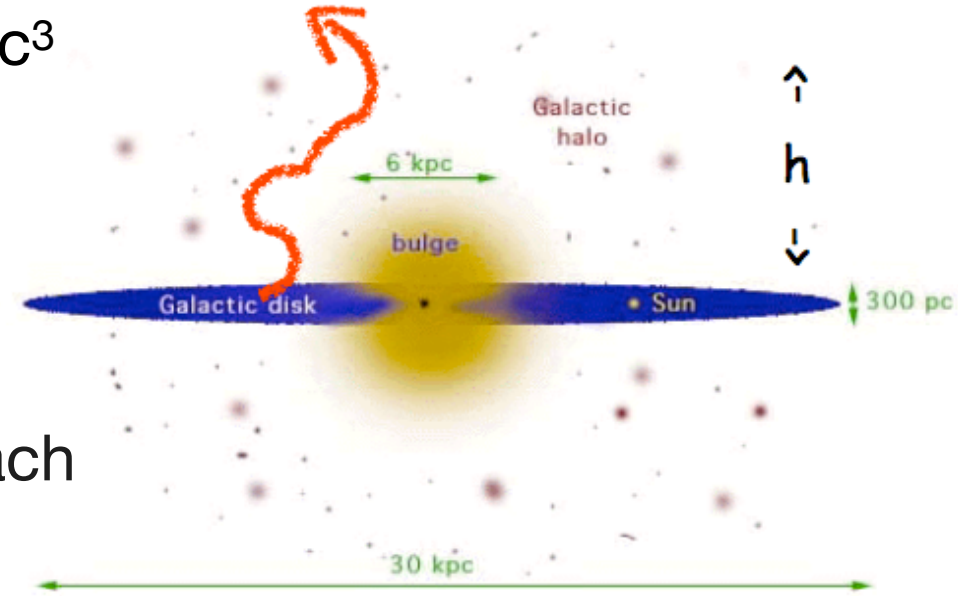
- Energy Density of CRs $U_{CR} \sim 1 \text{ eV/cm}^3$
- Volume of the Galaxy $V_{gal} = \pi R_{disk}^2(2h) \sim 3 \times 10^{11} \text{ pc}^3$
- Luminosity $L = U_{CR} * V_{gal} / t_{CR}$
- CR confinement time $t_{CR} \sim 10^7 \text{ yrs}$:
 $L = U_{CR} * V_{gal} / t_{CR} = 5 \times 10^{40} \text{ erg/s}$



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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 $L = U_{CR} * V_{gal} / t_{CR} = 5 \times 10^{40} \text{ erg/s}$
- 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 $\sim 10^{42} \text{ erg/s}$
 - 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:

q = Charge

L = Size of the source

B = Magnetic field in the source

$$E = q\eta BL$$

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

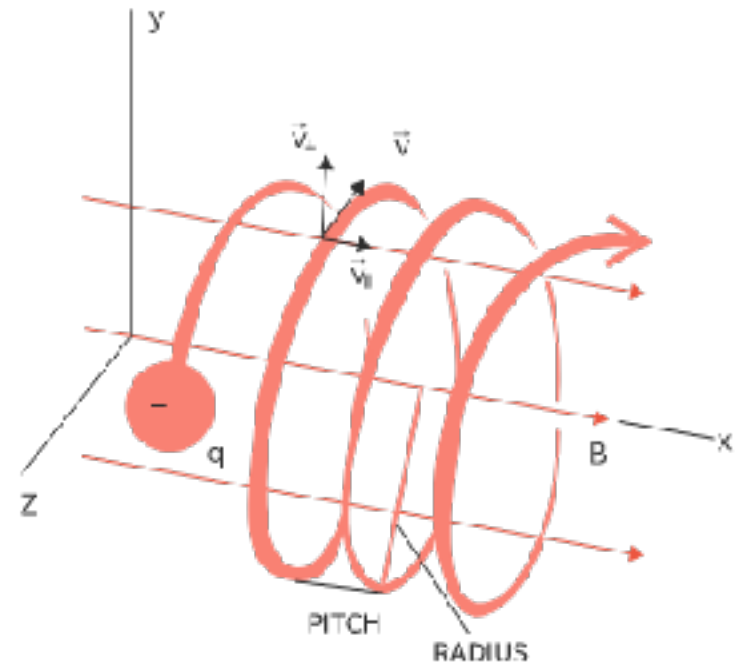
CR Maximum energy: Hillas criterium

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

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

$$E = q u R B$$

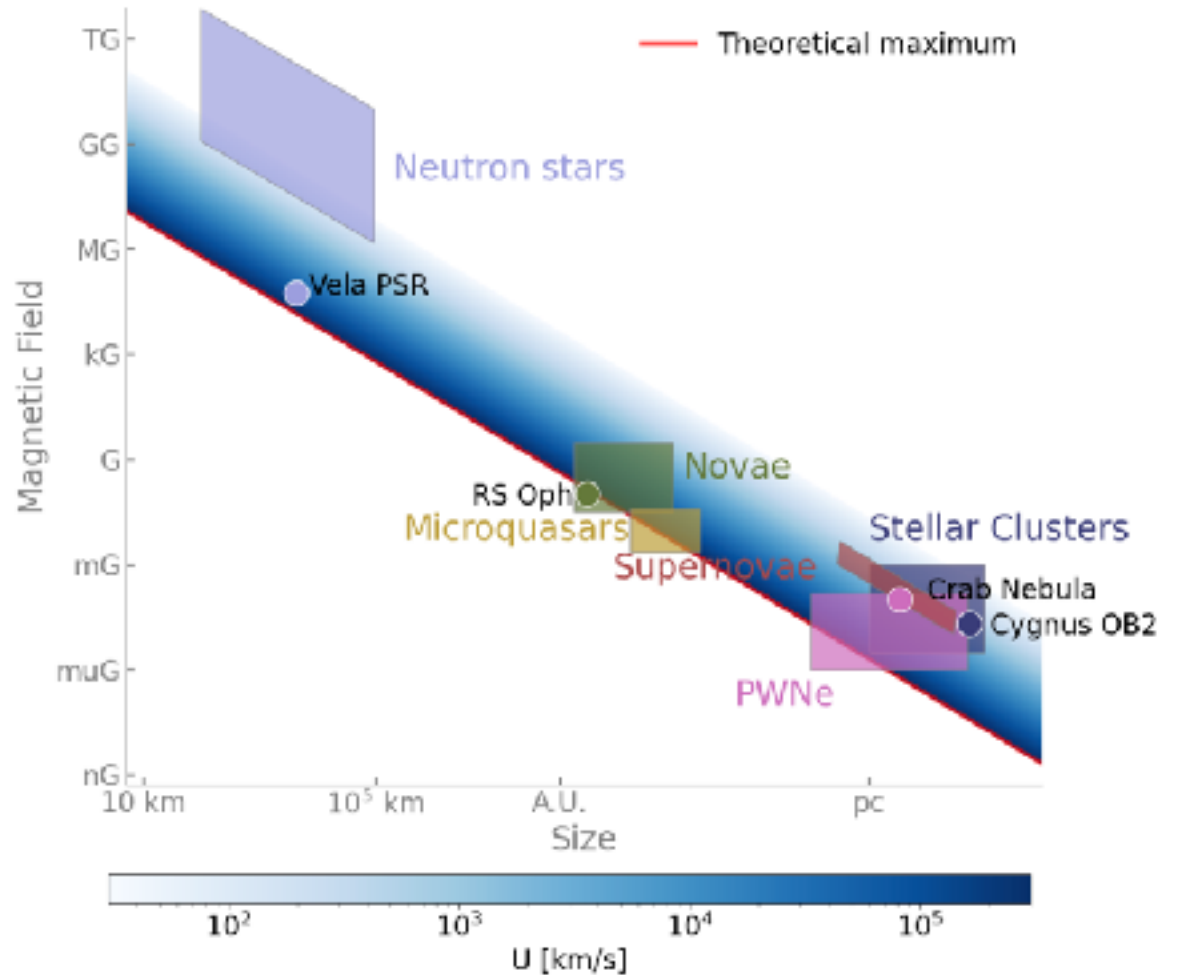
Speed Radius Magnetic Field



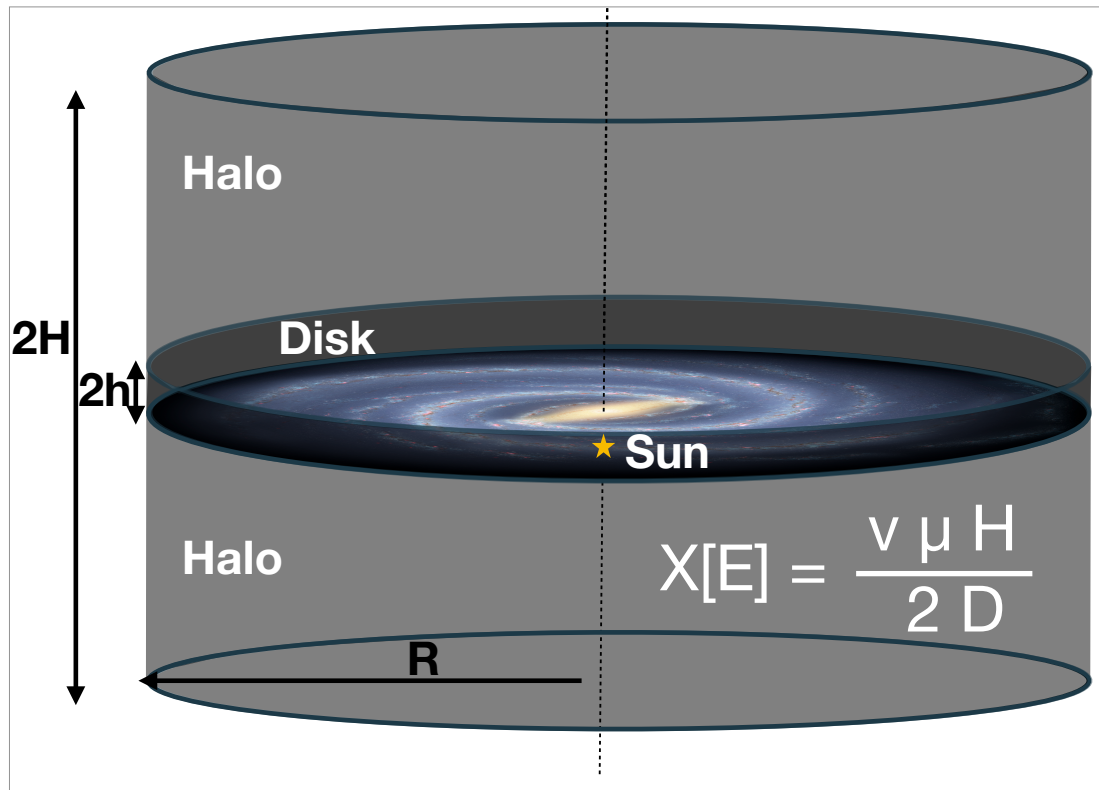
Cosmic Ray maximum energy

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

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

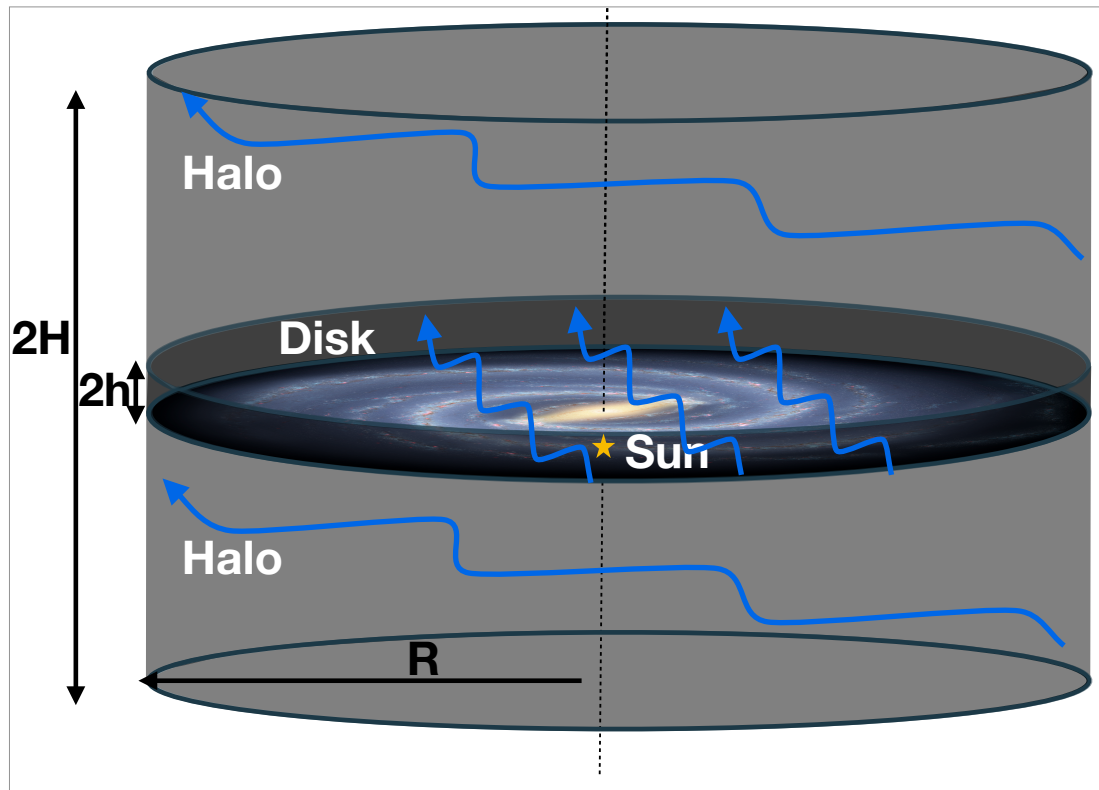


Cosmic Ray propagation



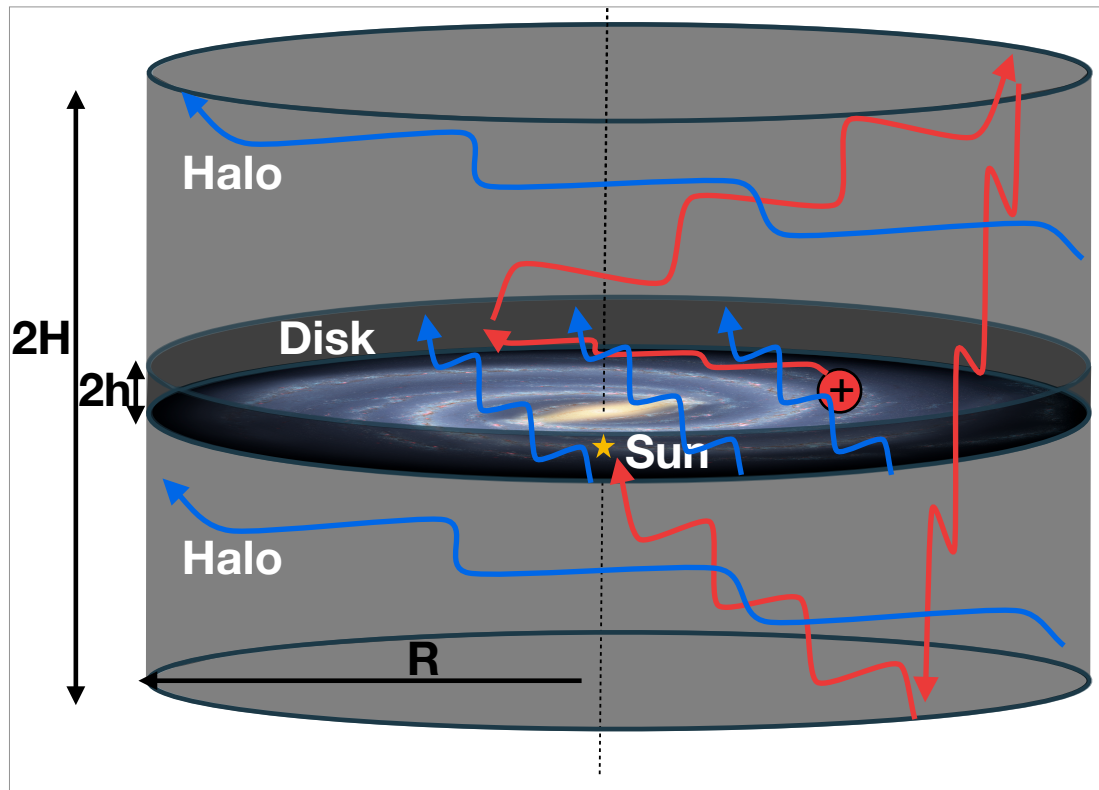
- CRs **diffuse** in the galactic *disk* (the region where the gas is contained) and *halo*
- Galactic **winds** and **reacceleration** are also powering the propagation of CRs
- Grammage $X \sim 10 \text{ g/cm}^2$ at 1 GeV/nucleon

Cosmic Ray propagation



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Cosmic Ray propagation

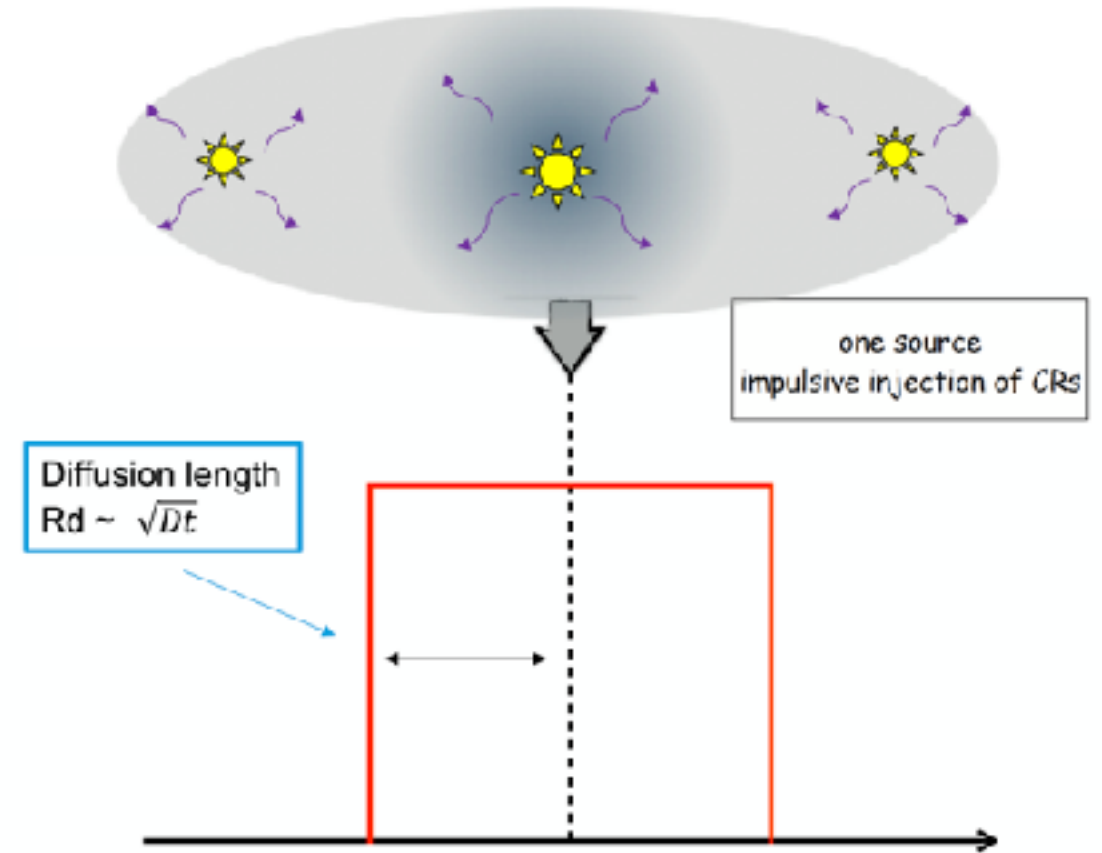


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Cosmic Ray propagation

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

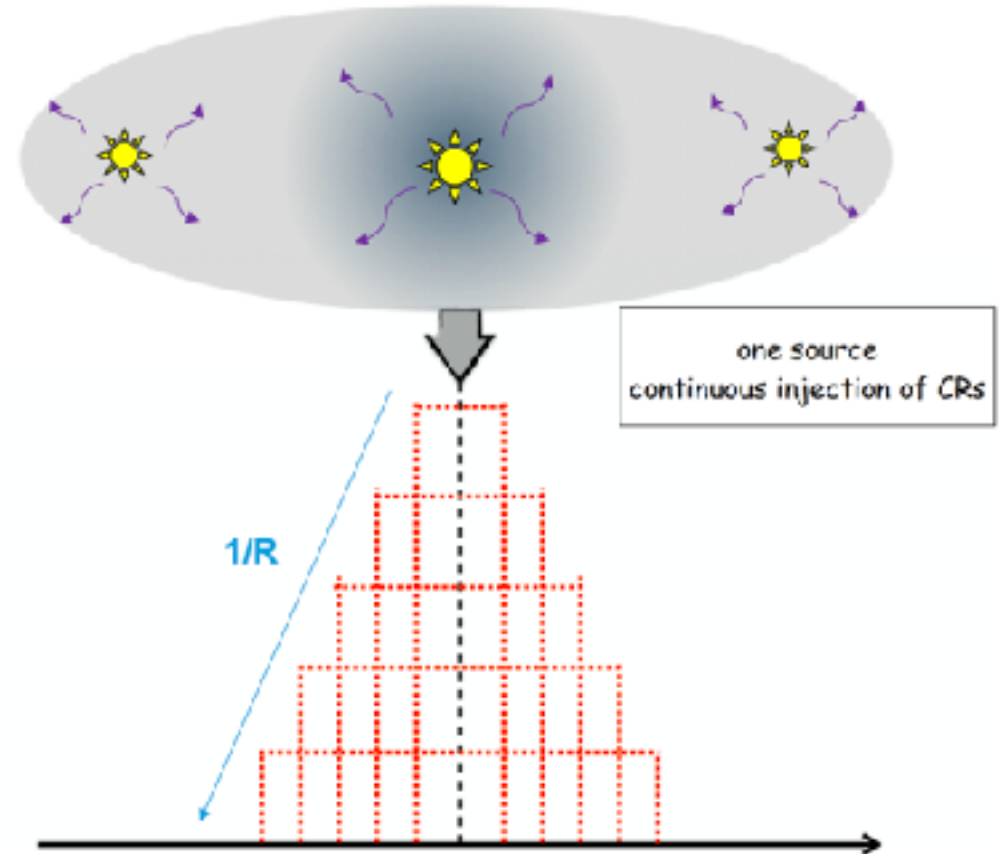
$$D(E) = D_0(E/E_0)^\delta, \quad D_0 \sim 10^{28-30} \text{ cm}^2\text{s}^{-1}$$



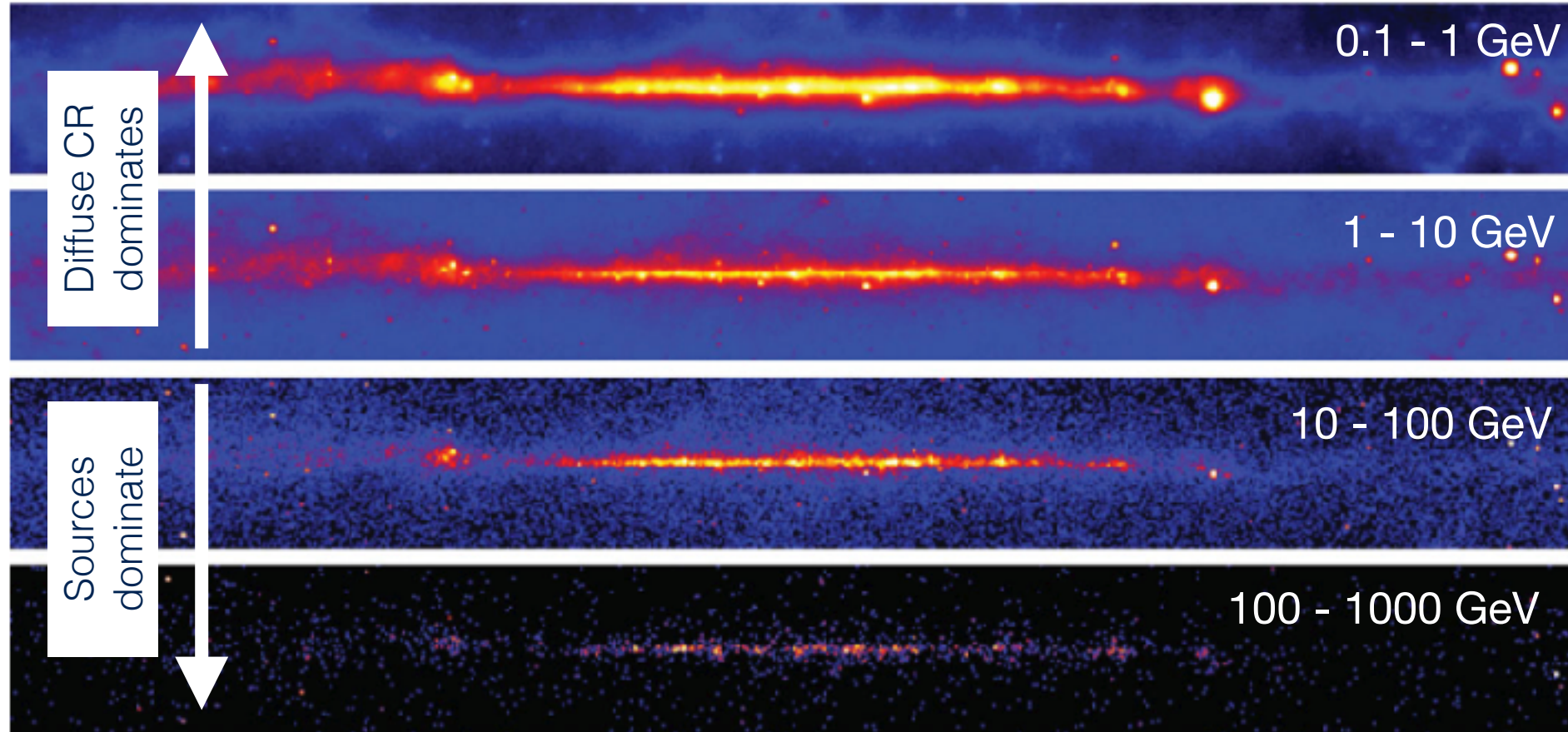
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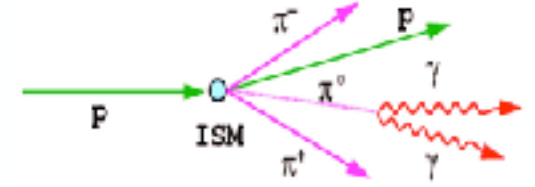
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Cosmic Ray propagation

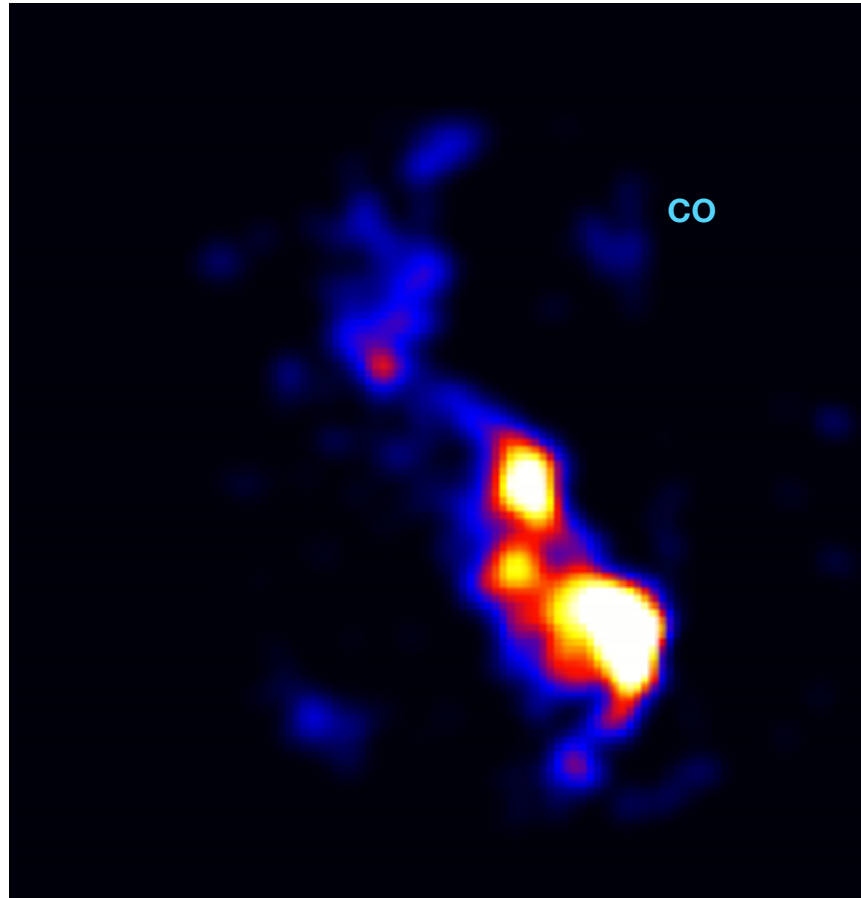


Cosmic Ray propagation

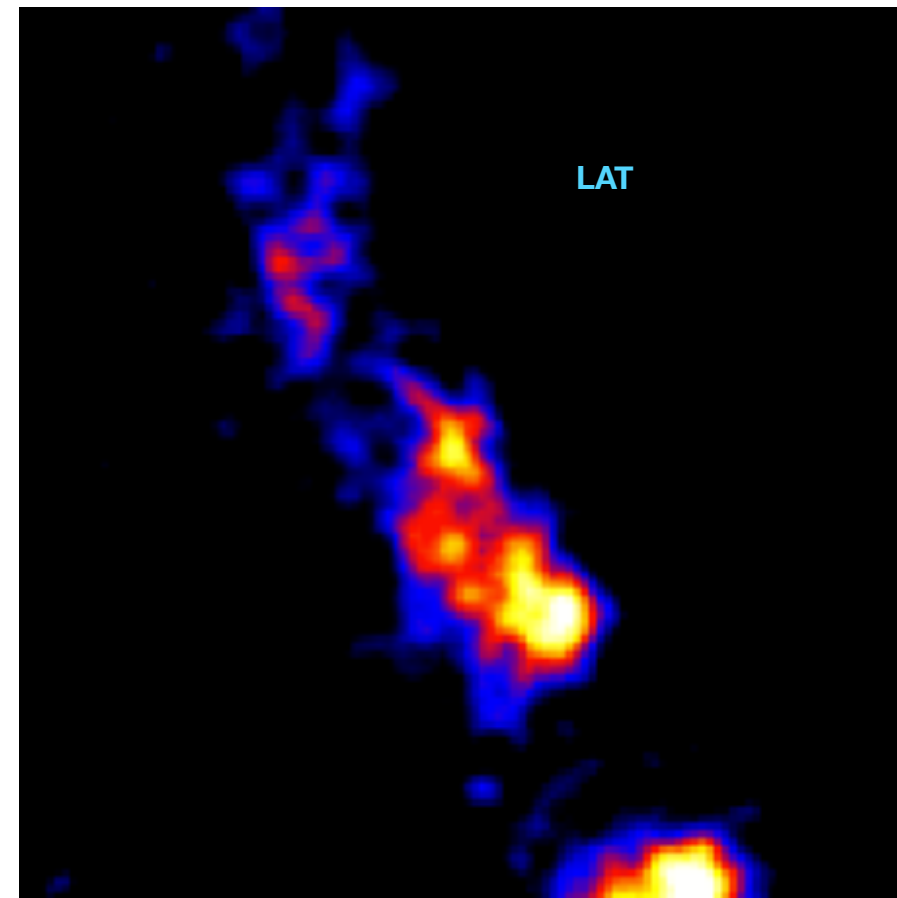


Understanding the ISM / photon fields & the molecular content

Target [p]

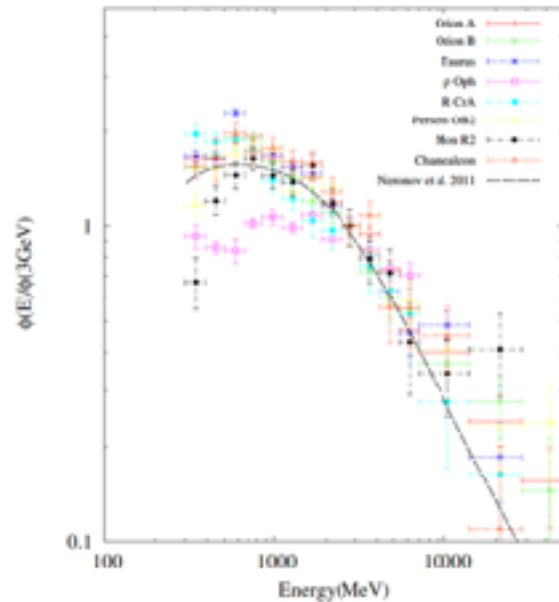


CRs [p]

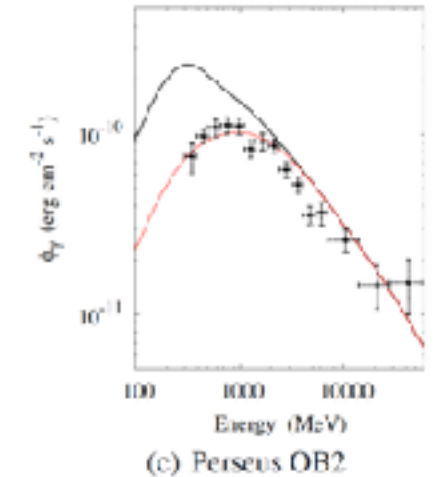
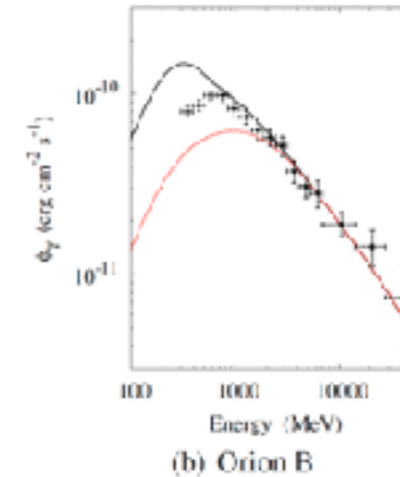
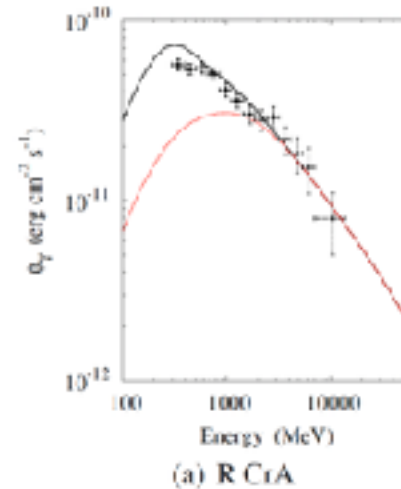


Cosmic Ray propagation

Understanding the ISM / photon fields & the molecular content



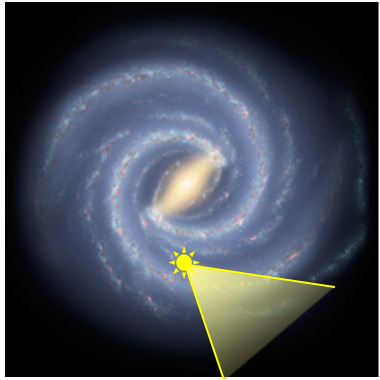
Yang, de Oña Wilhelmi, Aharonian 2014



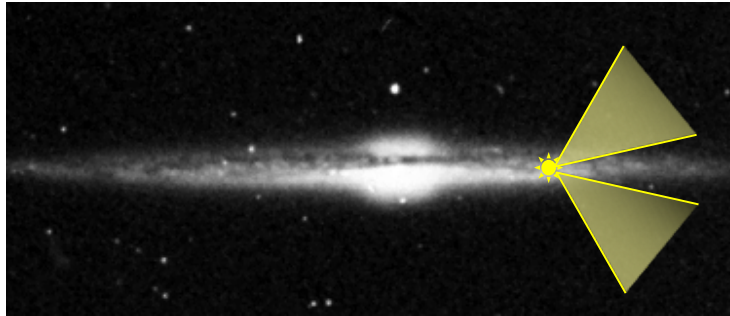
- > 20 GeV: good agreement with CR spectrum measured at Earth
- Low energy part shows differs from cloud to cloud (deviating for pure power law)
- Related to different environment (local acceleration, low CR penetration effects, modulation effects?)

Cosmic Ray propagation

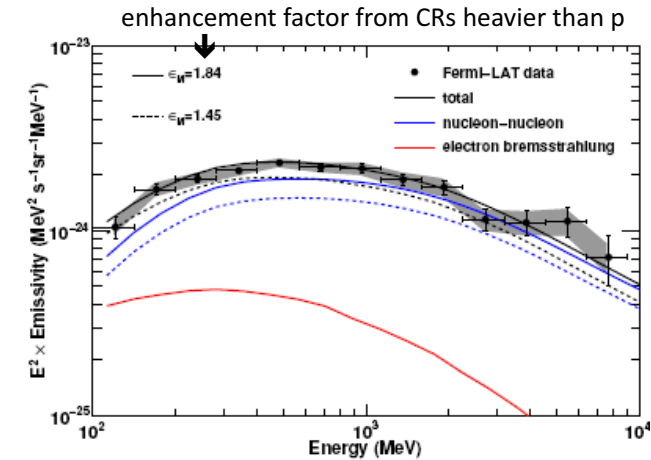
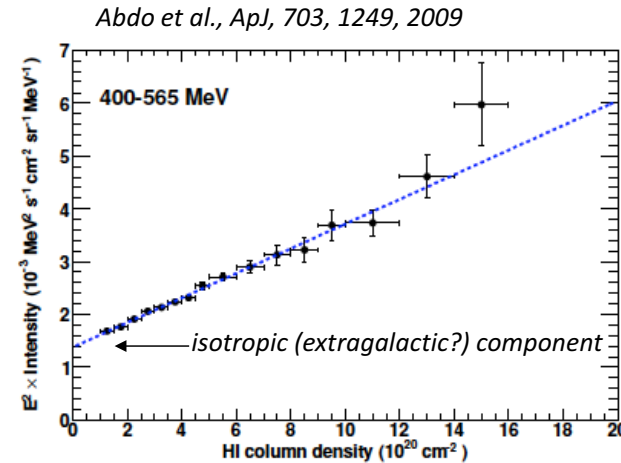
Understanding the ISM / photon fields & the molecular content



longitude: 200° to 260°



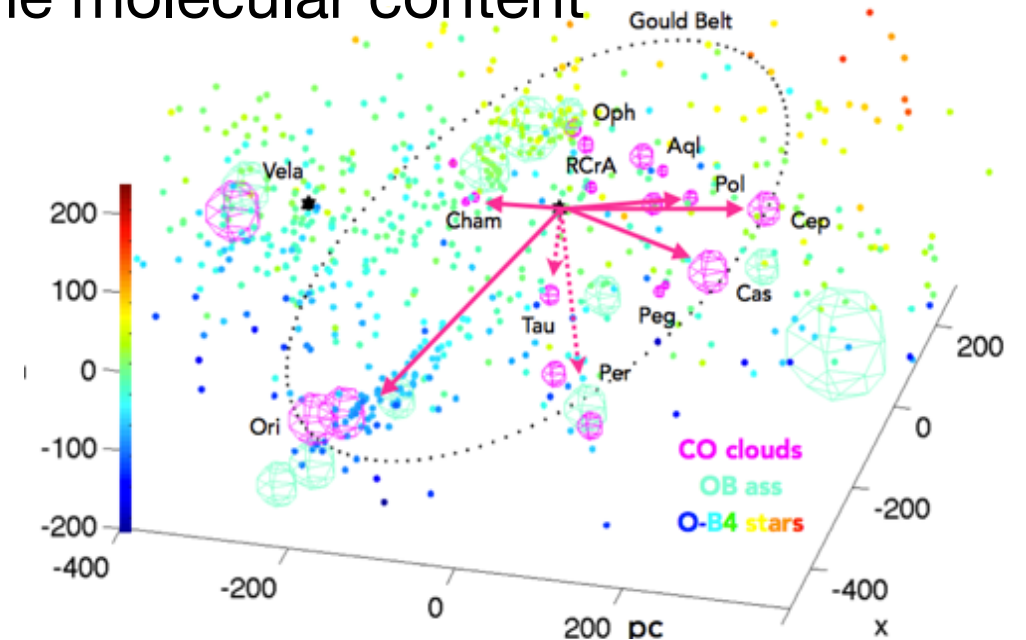
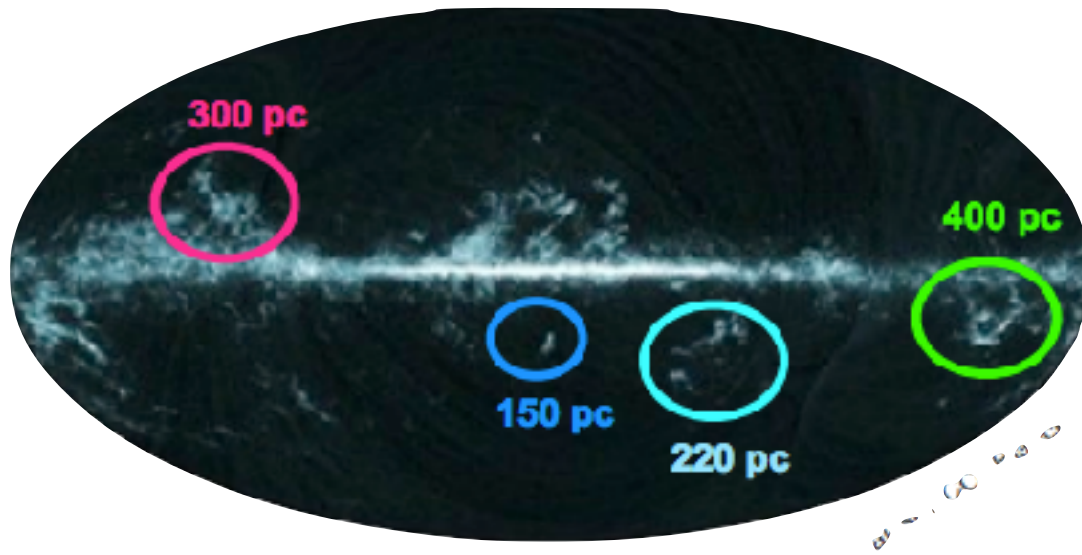
latitude: 22° to 60° (+ & -)



- 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

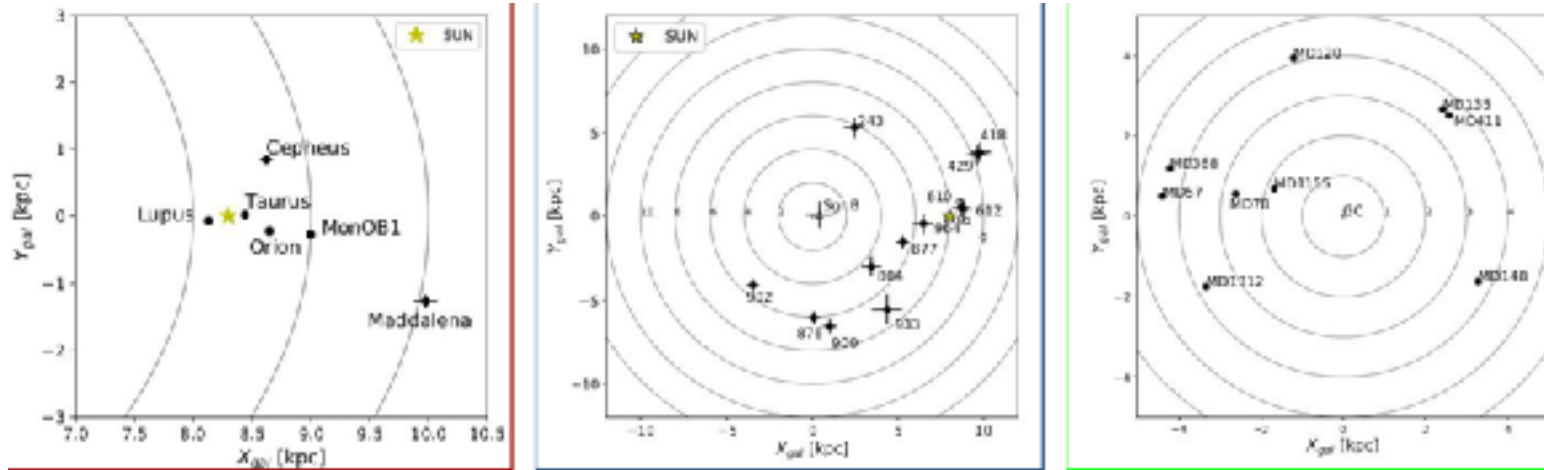
Cosmic Ray propagation

Understanding the ISM / photon fields & the molecular content

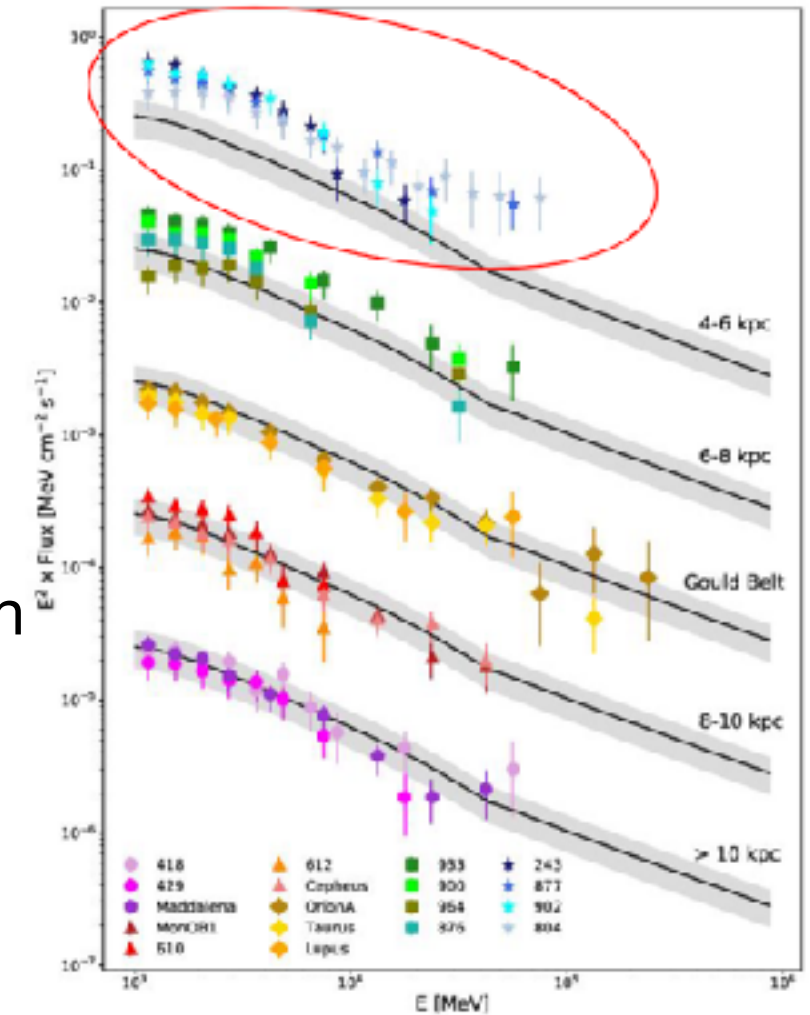


- Using massive clouds are barometers for determine the pressure (energy density) of CRs
- Large number of photons to determine the spectrum with accuracy
- Nearby and dense clouds

Cosmic Ray propagation



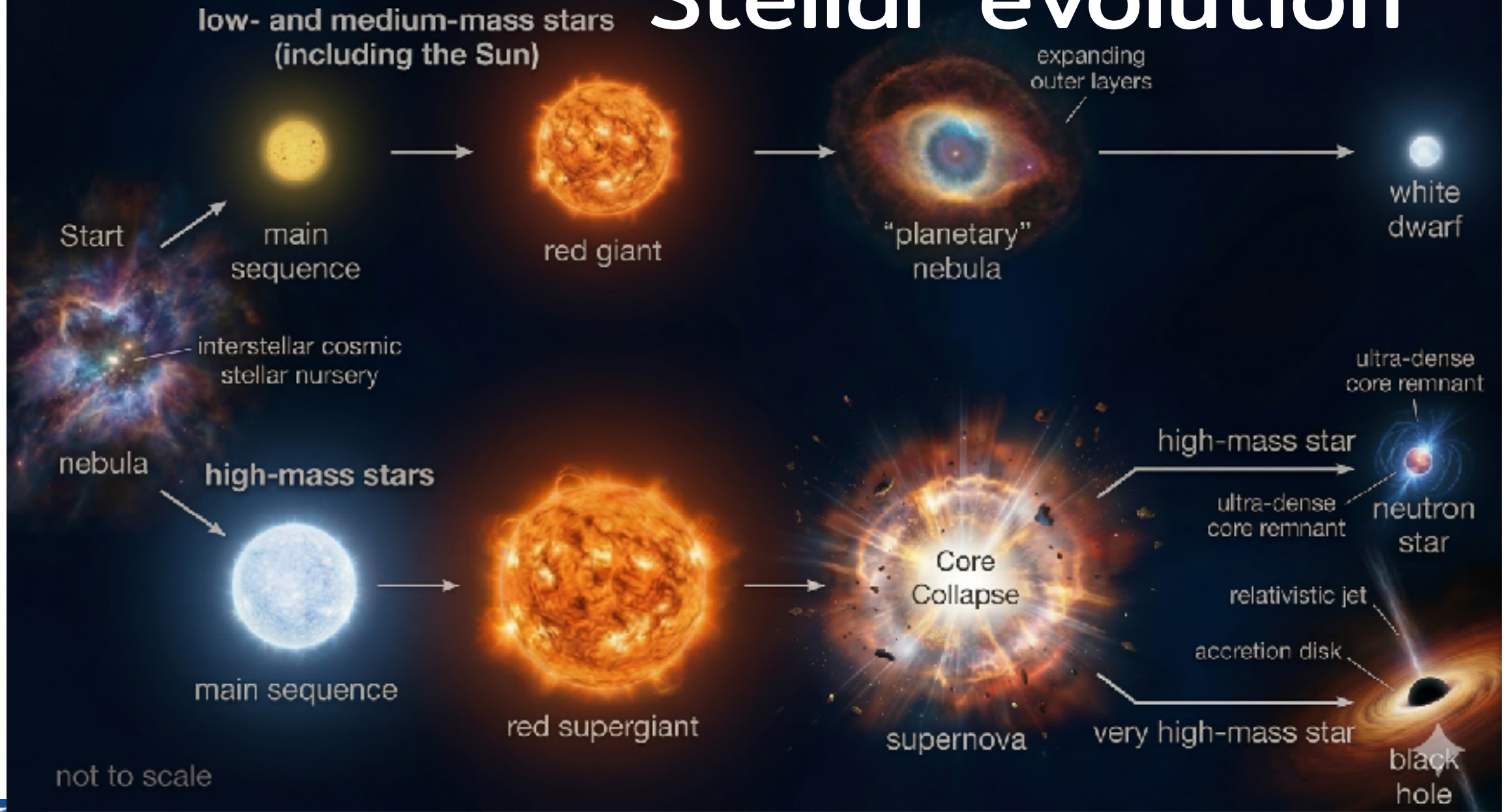
- Probing the CRs at different locations far from the Earth
- Analysis of molecular clouds provide localized information on the CR spectrum far from Earth
- Results from GMCs show deviations from the local emissivity only in the inner Galaxy, around 4-6 kpc. The deviations are fluctuating, discouraging a global variation



Peron et al 2021

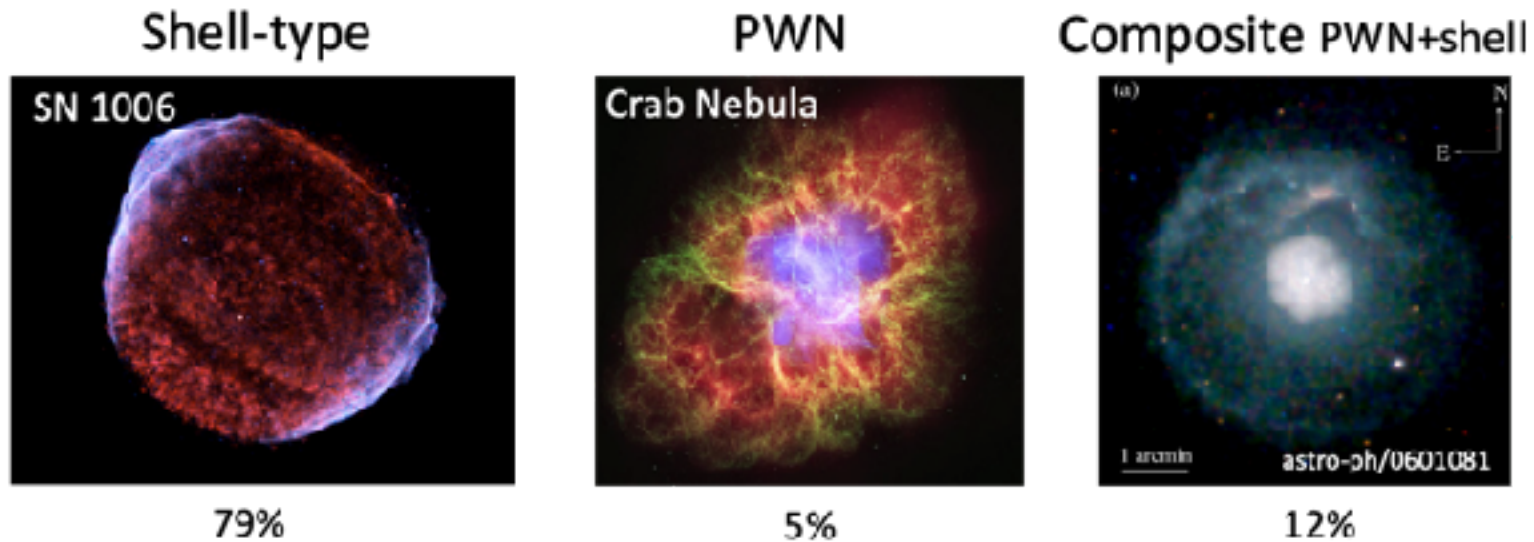
Supernova Remnants

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



SNR Evolution

Free Expansion

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

Adiabatic (Sedov-Taylor)

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

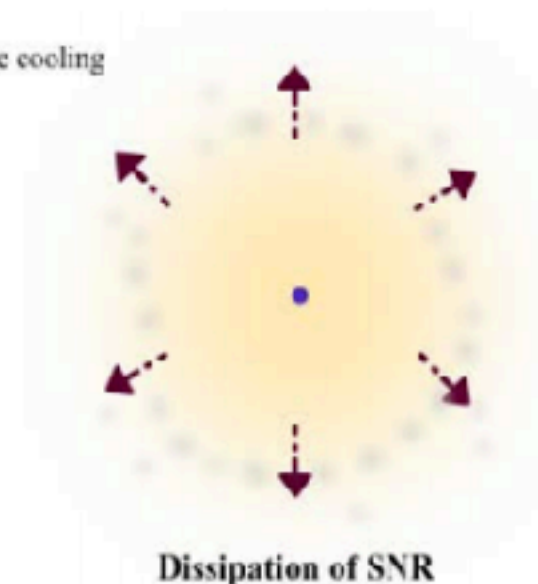
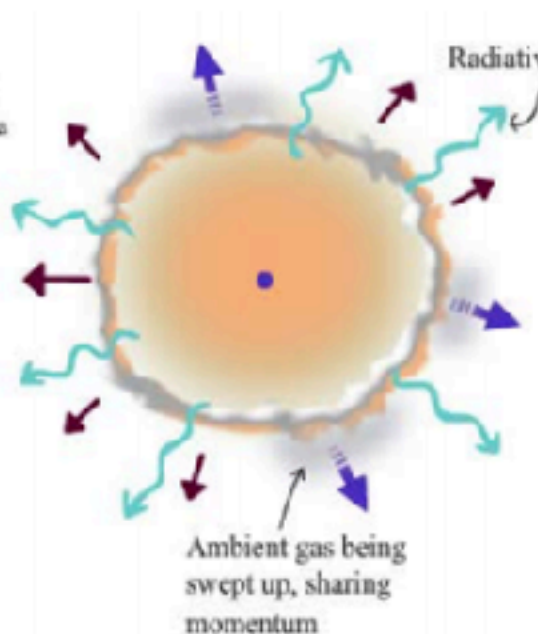
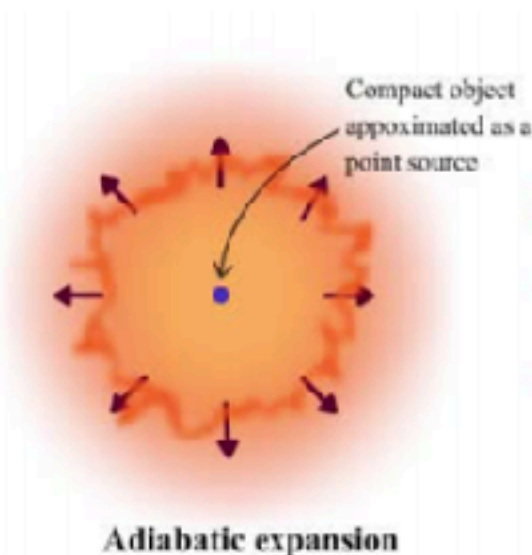
Radiative

Dissipation into ISM $v_{sh} \sim 200$ km/s

PeVatron Phase

Highest Gamma-ray Luminosity

CR Propagation

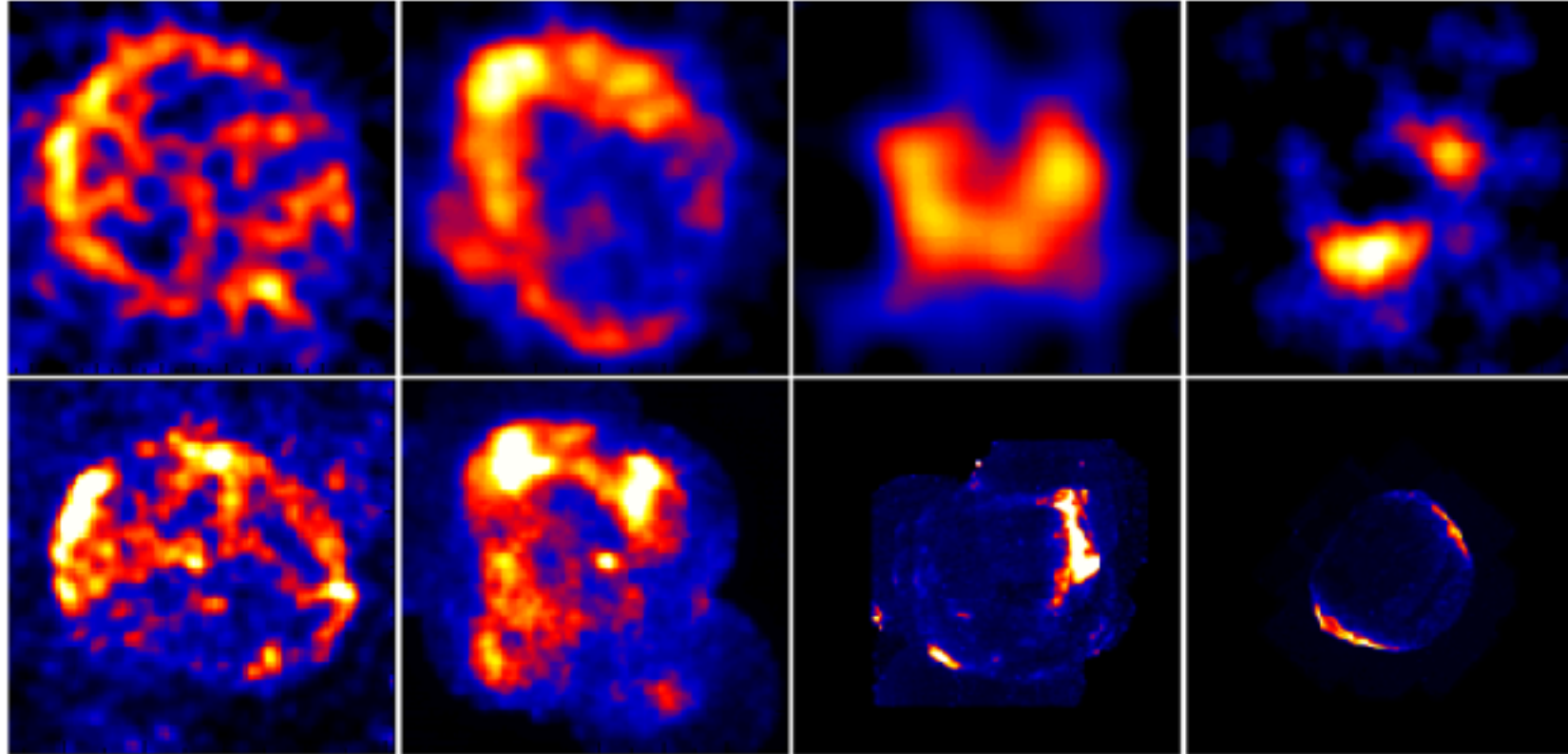


DESY

Page 4

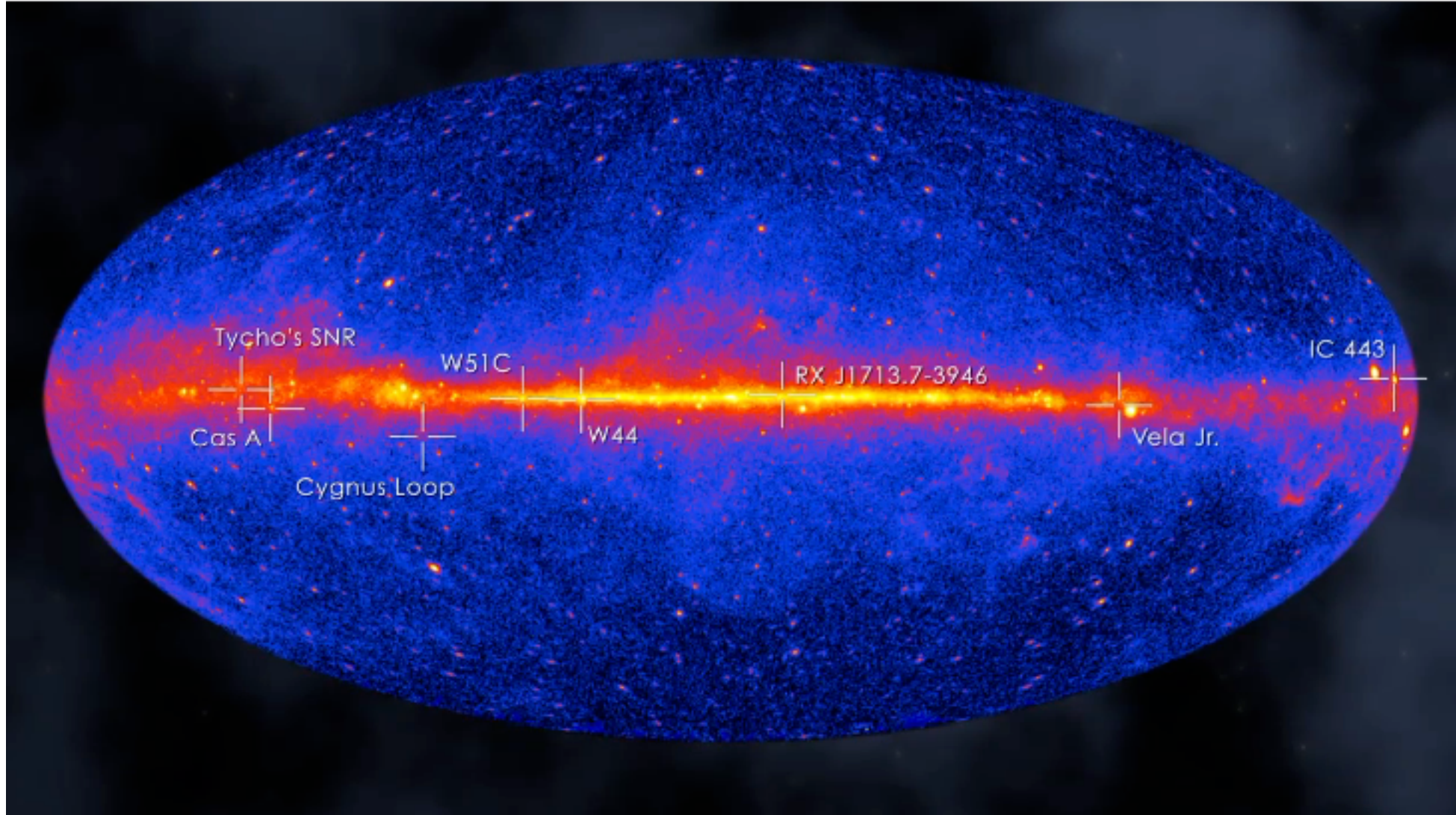
Supernova Remnants

Gamma rays



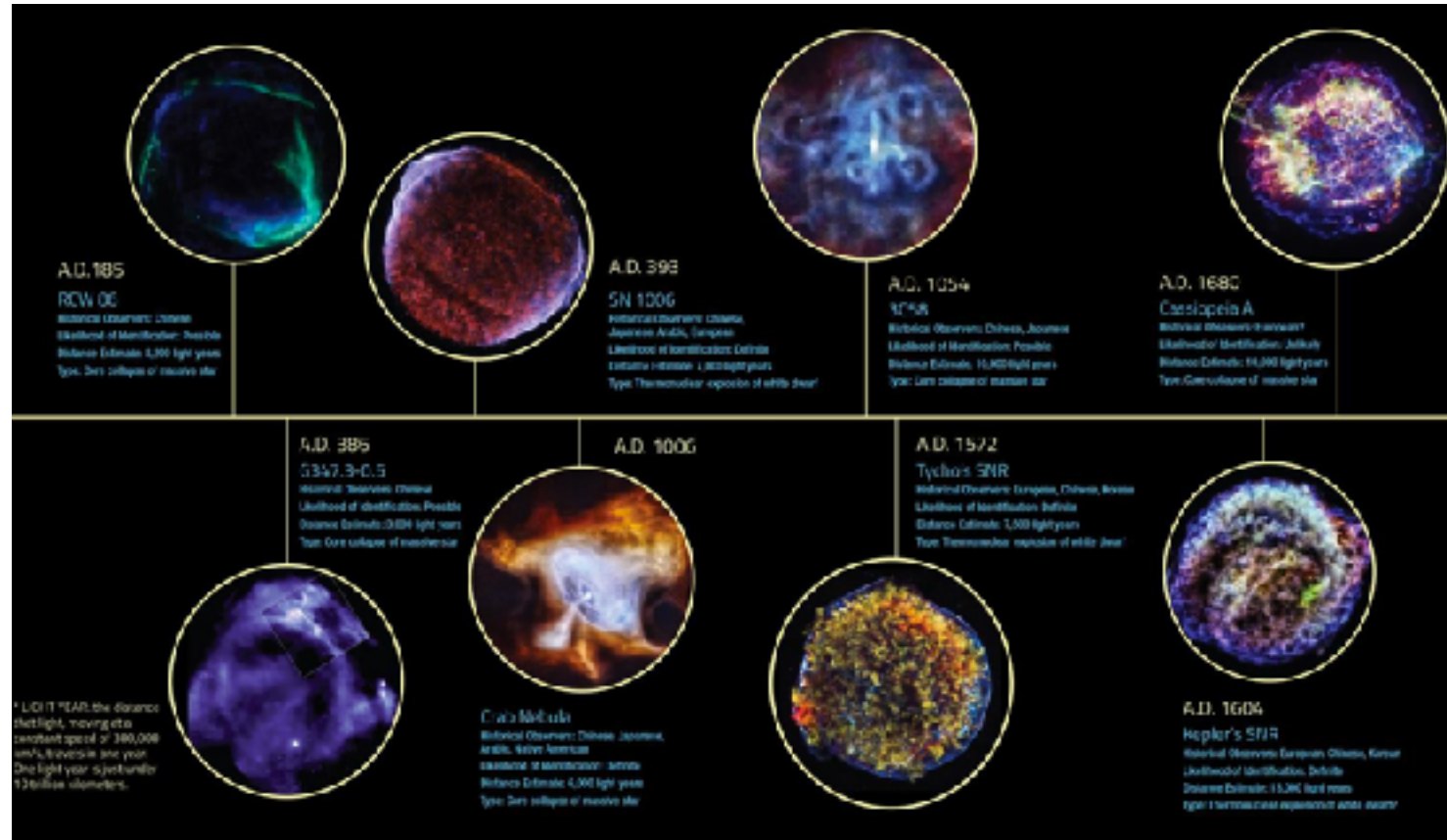
X-rays

Supernova Remnants



Supernova Remnants

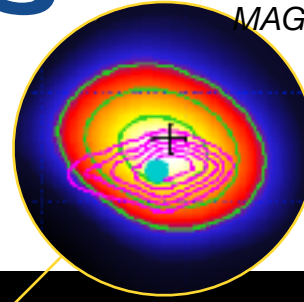
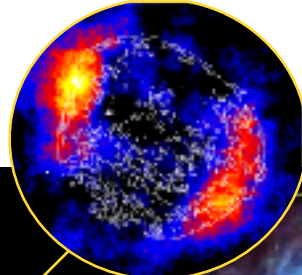
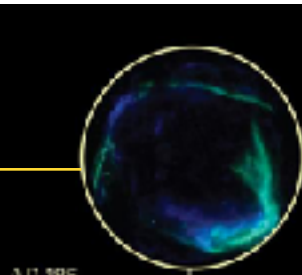
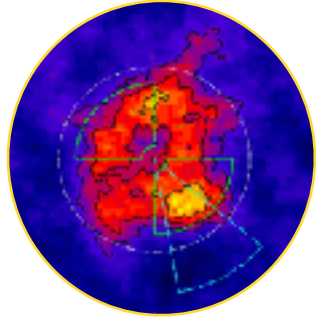
Historical SNRs



Supernova Remnants

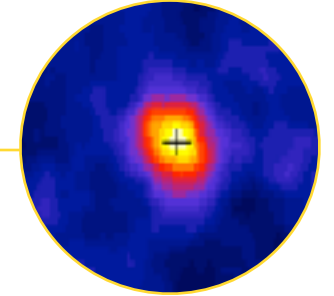
Historical SNRs

HESS Coll, 2016

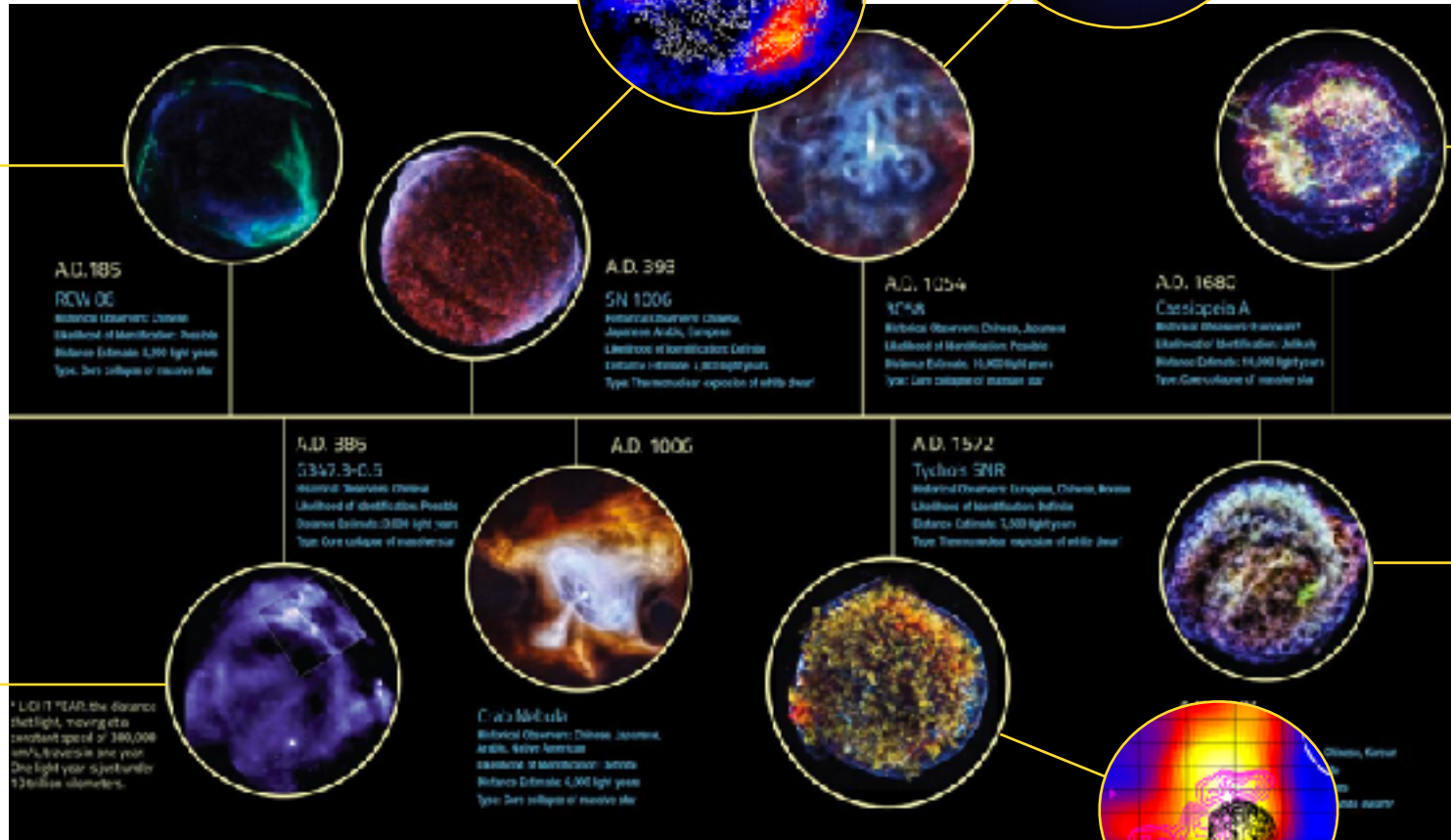
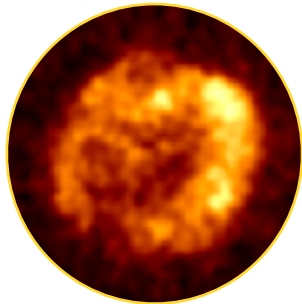


MAGIC Coll, 2014

MAGIC Coll, 2017
VERITAS Coll, 2019



HESS Coll, 2018



Prokhorov et al, ICRC 2021

VERITAS Coll, 2017

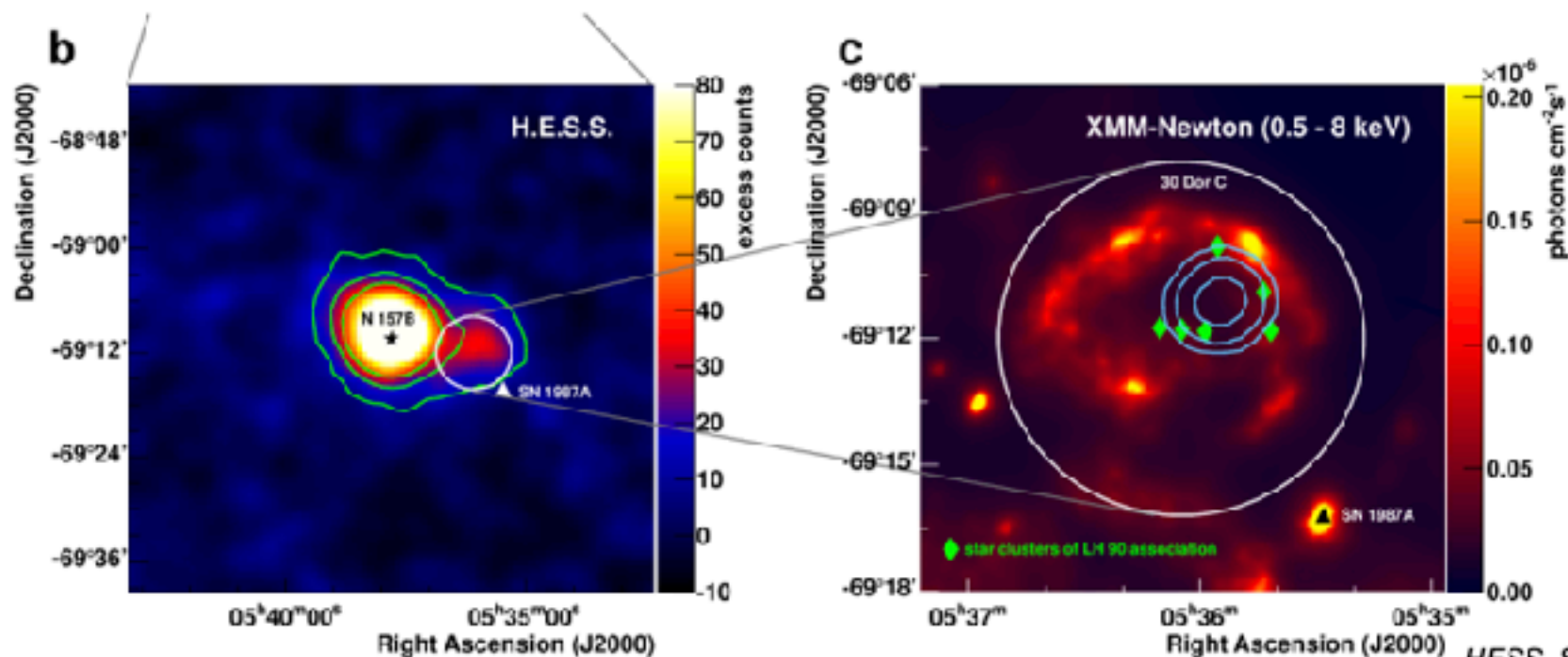
CR accelerators: SNRs

Free Expansion: PeVatron Phase ?

SN 1987A

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

$$\text{For } f \sim 0.2 \text{ (spherical symmetric distribution)} \Rightarrow W_{pp} < 9 \times 10^{48} \text{ erg (1\% to nuclei)}$$



CR accelerators: SNRs

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

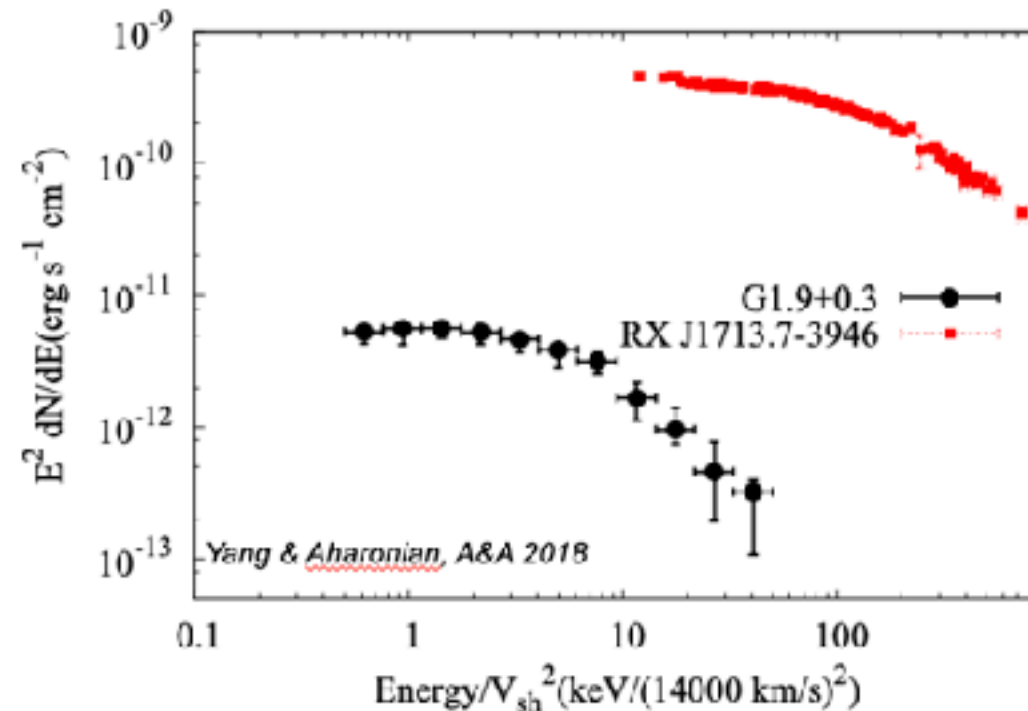
$$t_{\text{acc}} \sim \eta B_{\text{mG}}^{-1.5} E^{0.5} V_{3000} \text{ years}$$

Free Expansion: PeVatron Phase ?

In strong fields, the maximum E_0 results from $t_{\text{cool}} = t_{\text{acc}} \Rightarrow E_0 \propto B^{-1/2} v_{\text{sh}} \Rightarrow E_m \propto E_0 B^{1/2} \propto v_{\text{sh}}$

SNR G1.9+0.3

- Youngest SN in our Galaxy (age ~ 150 yrs)
- Fast shock $v_{\text{sh}} \sim 14000$ km/s ($\Rightarrow E_0 \sim 10$ keV)
- Chandra+nuStar: Cutoff at 1.5 keV
 \Rightarrow Not an efficient accelerator
- Was it a PeVatron?



CR accelerators: SNRs

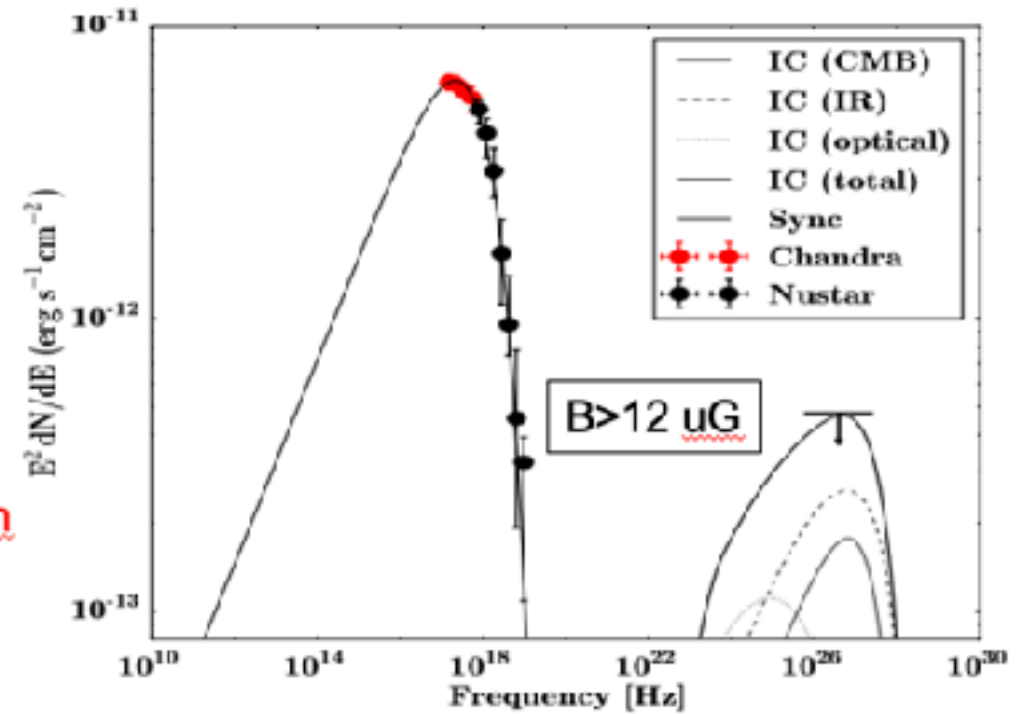
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 \Rightarrow Not an efficient accelerator
- Was it a PeVatron?
Run-away protons $R(D=10^{30} \text{cm}^2/\text{s}) \ll 30 \text{pc} \Rightarrow 10$ arcmin
- $W_p (n \sim 100 \text{cm}^{-3}) < 10^{45}$ erg/s

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



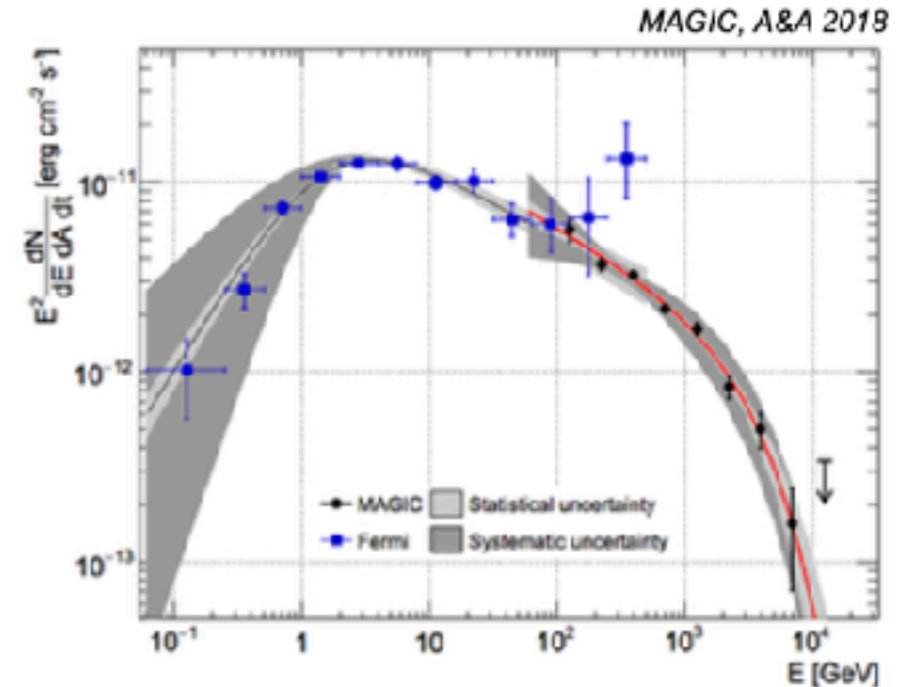
Yang & Aharonian, A&A 2018

CR accelerators: SNRs

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

Cassiopeia A

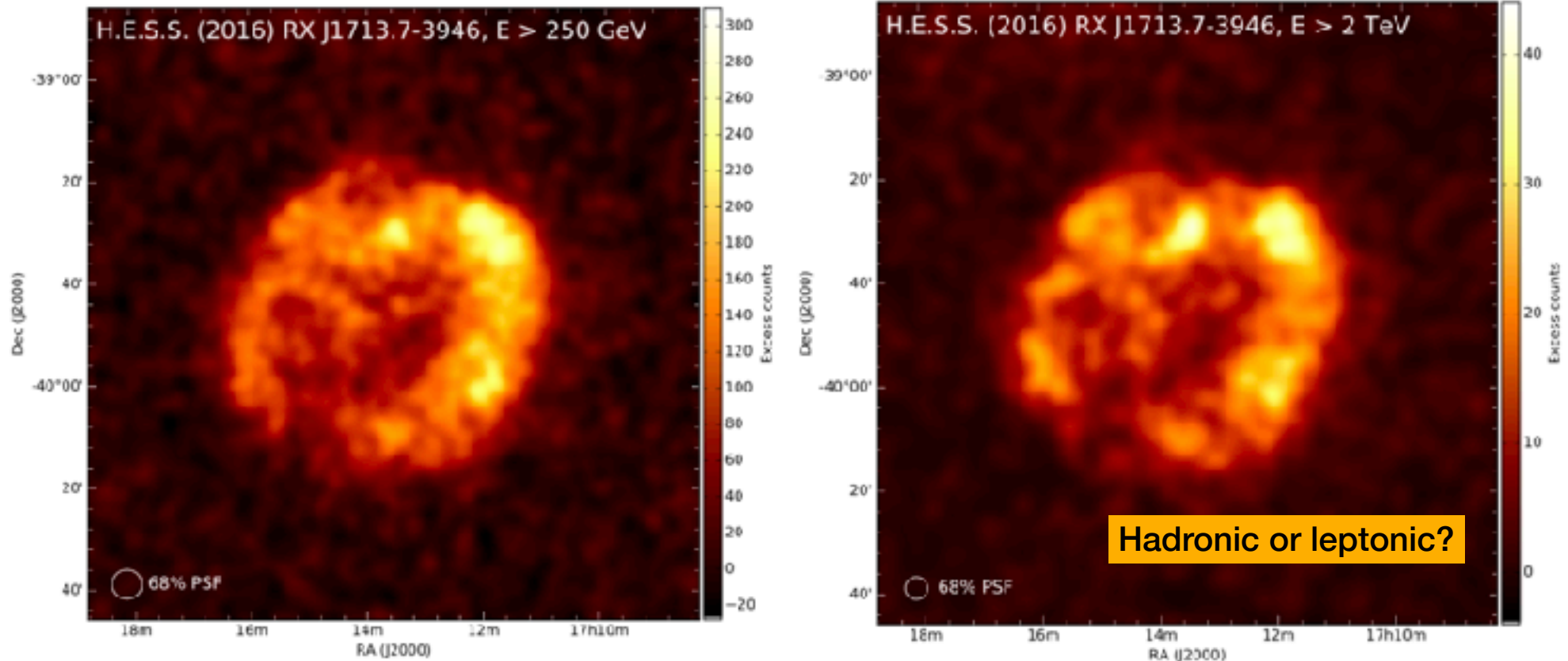
- Age ~ 340 yrs
- Fast shock $v_{sh} \sim 5000$ km/s
- Highly turbulent Bfield ~ 0.2-0.3 mG
- Ecut = 3.5 TeV
 - Composition: can reduce gamma efficiency by factor 2!
 - Spectrum dominated by plateau, shell higher cut off?



CR accelerators: SNRs

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

HESS, A&A 2018



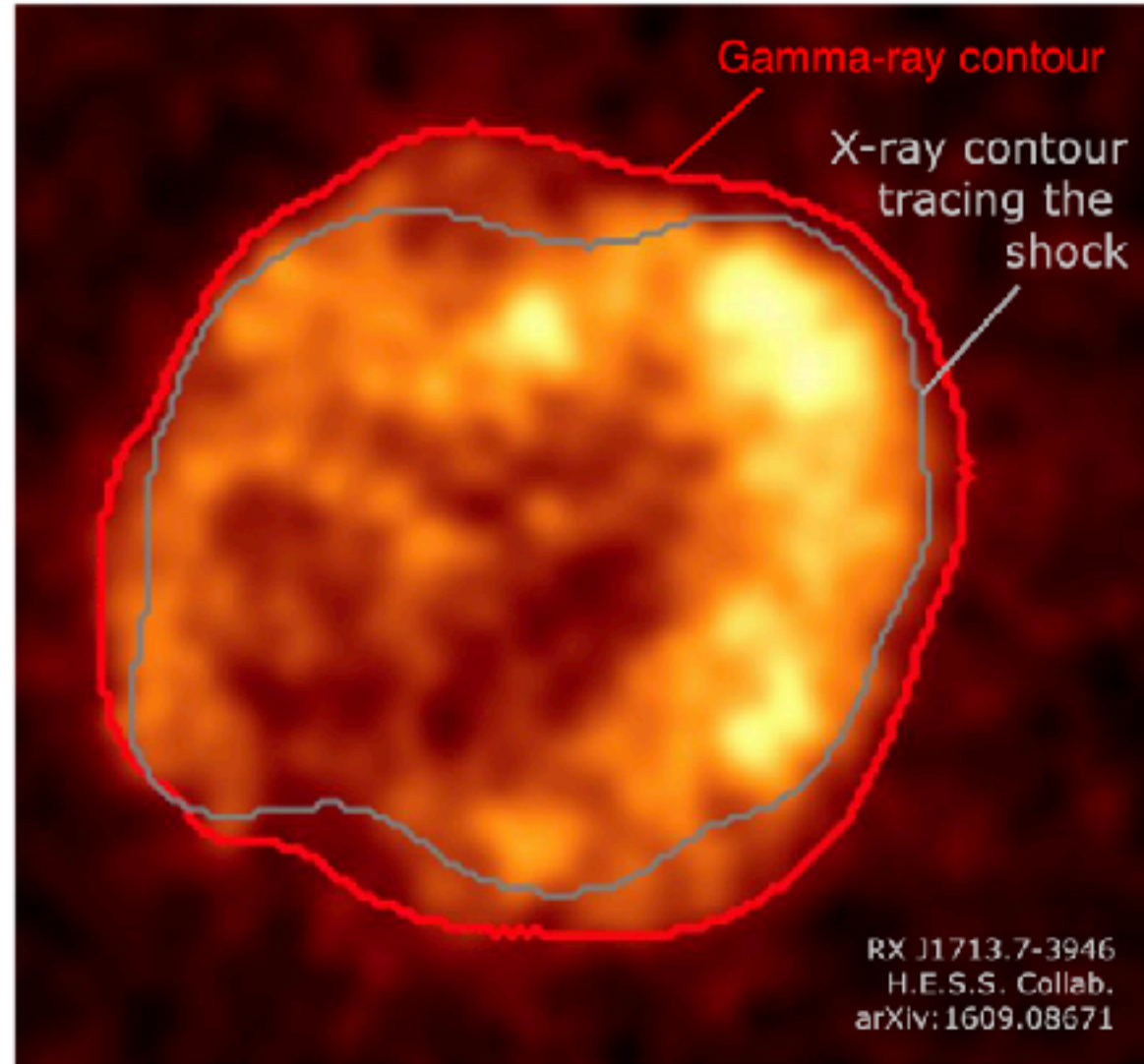
CR accelerators: SNRs

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

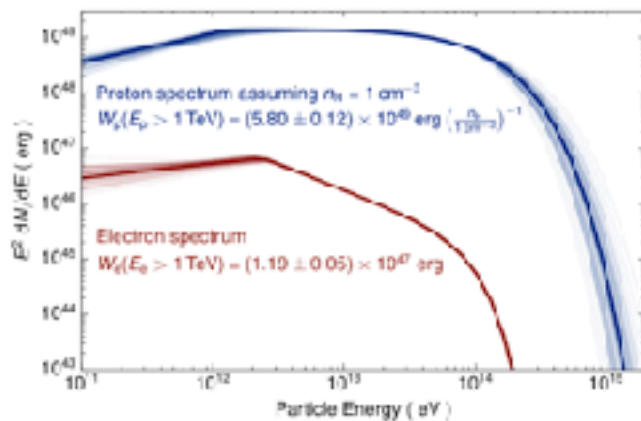
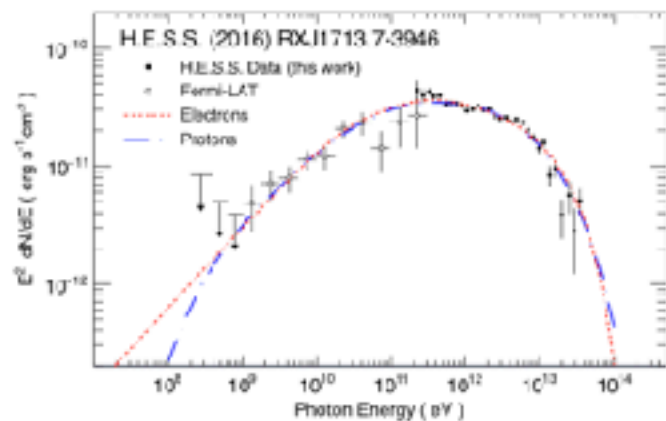
→ PeV cosmic rays only contained during the first $O(100)$ years (?)



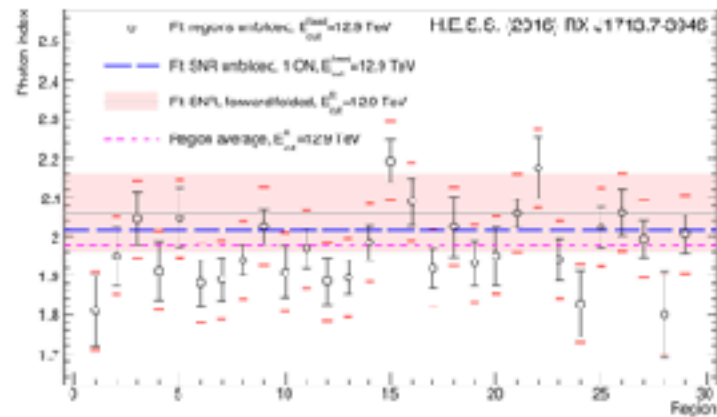
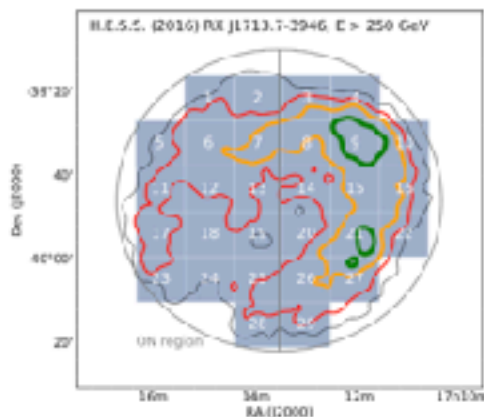
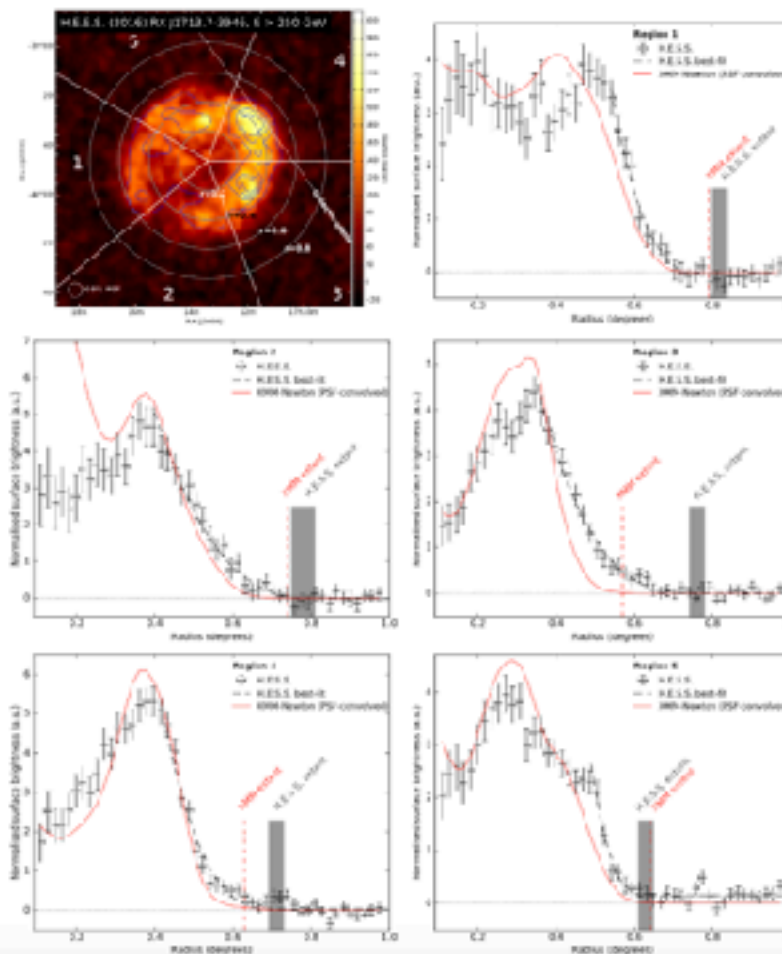
CR accelerators: SNRs

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

Did particles run-away?



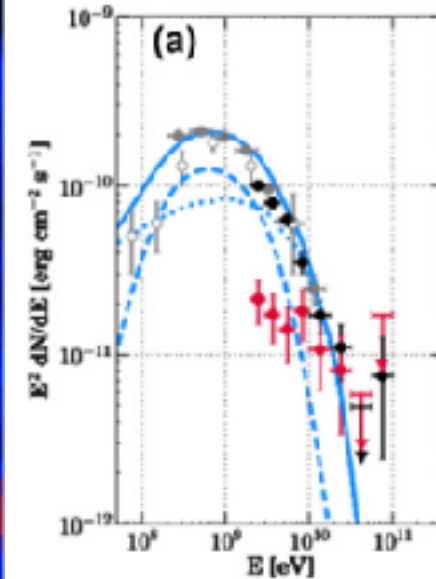
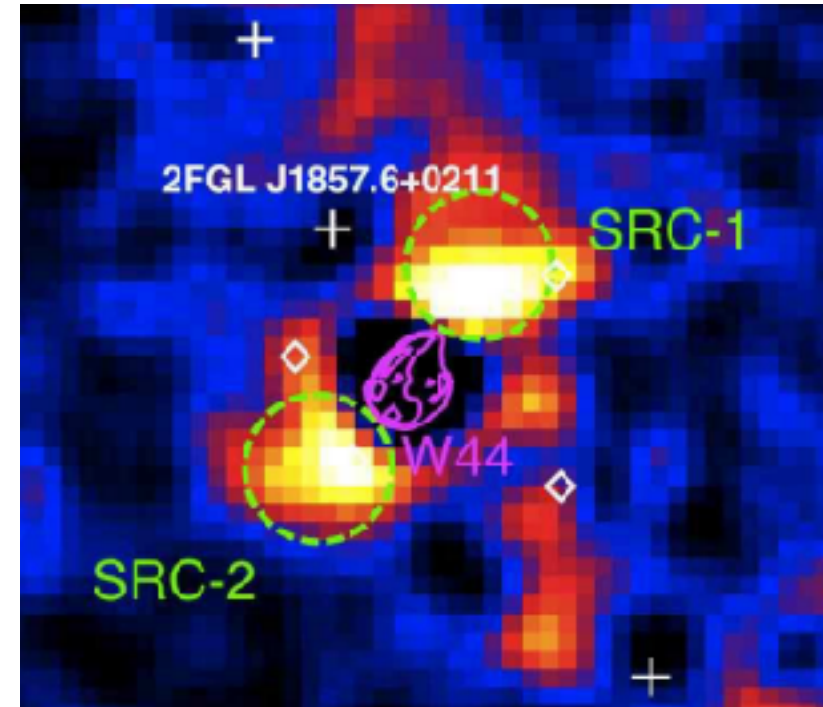
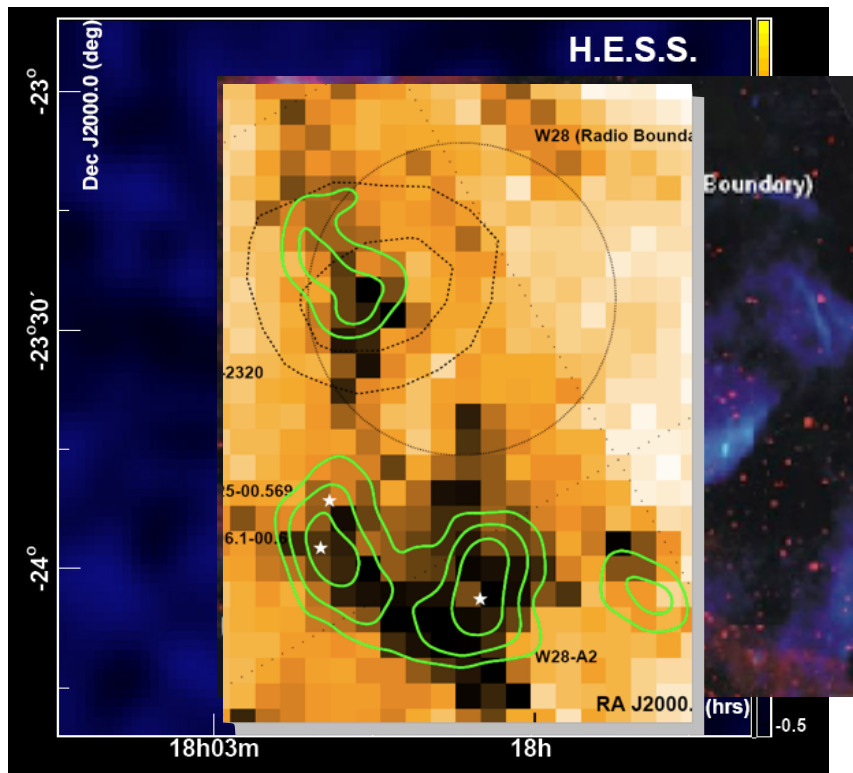
H.E.S.S., A&A 2018



CR accelerators: SNRs

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

Morphological and High resolution spectroscopic Studies

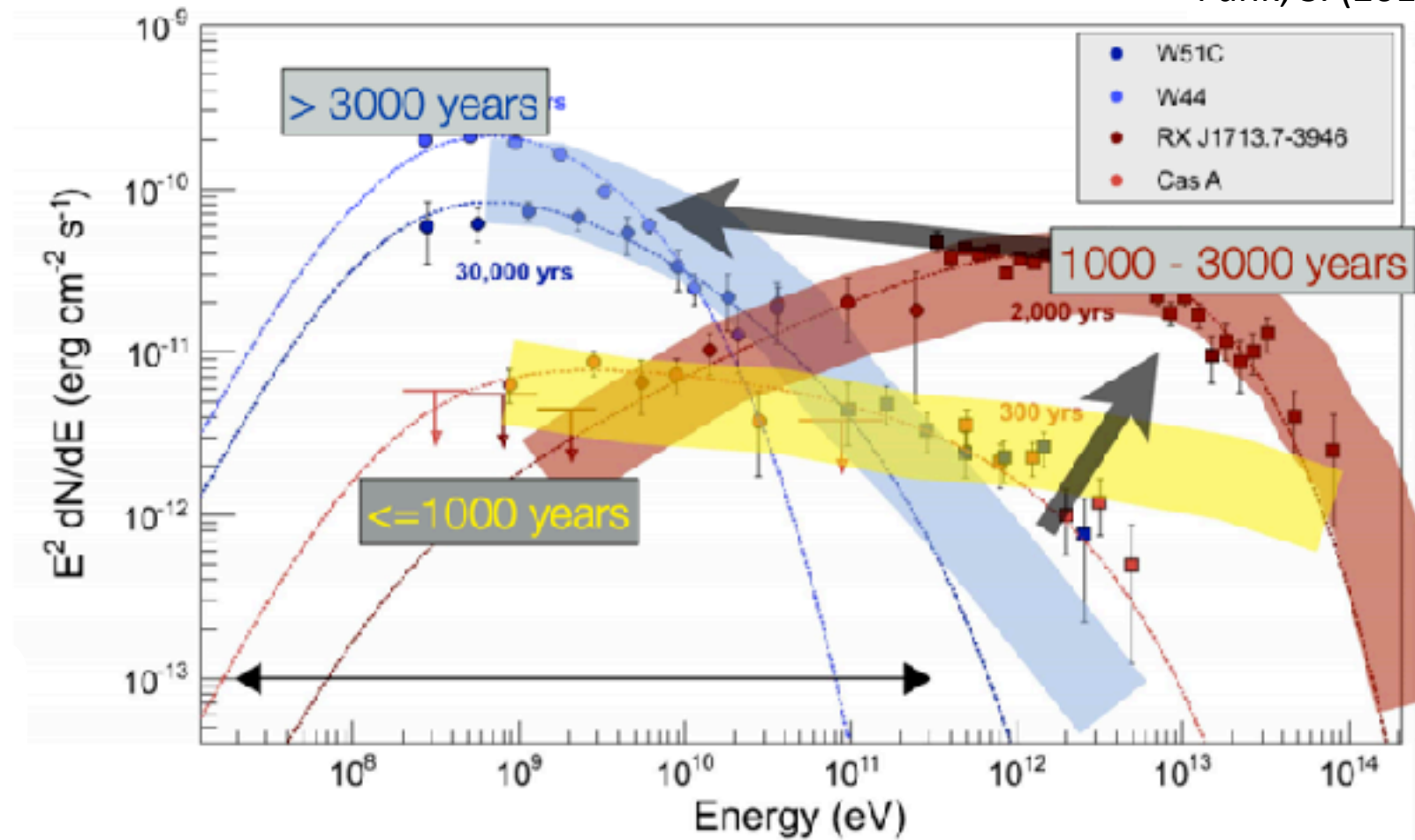


Looks like it in some old SNRs at low energies, but still, no trace of PeV energies

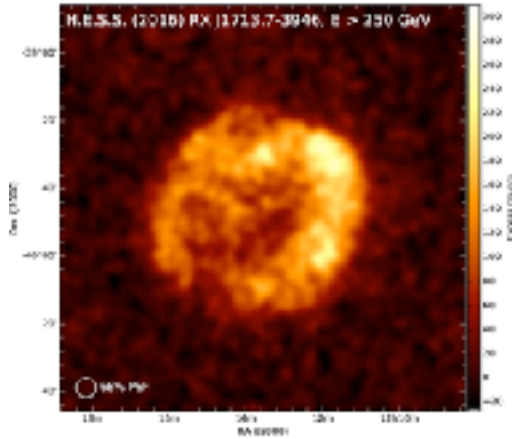
CR accelerators: SNRs

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

Funk, S. (2015)



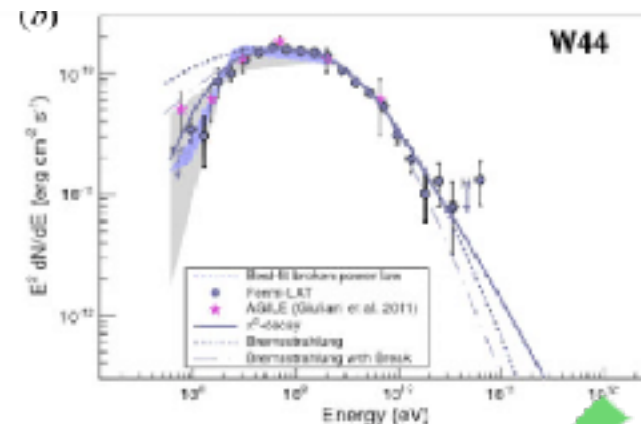
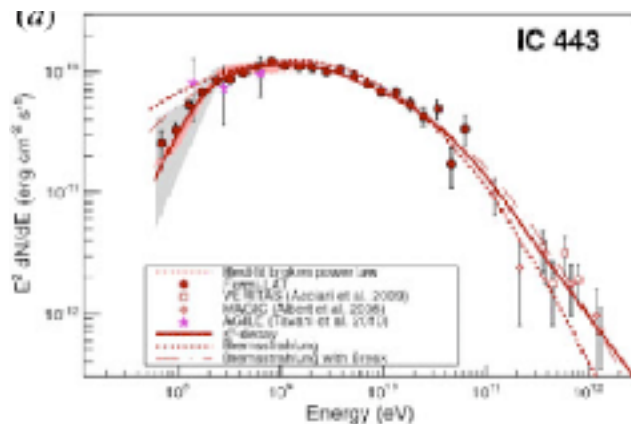
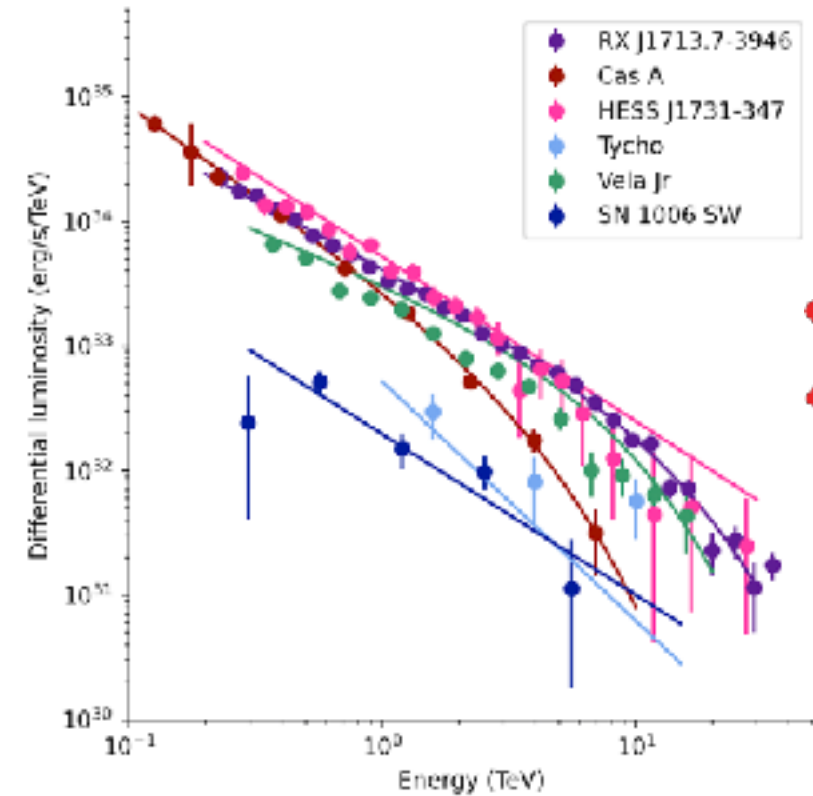
CR accelerators: SNRs



We detect TeV gamma-ray shells



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



We detect GeV gamma-ray shells & pion-bump



Stellar Clusters

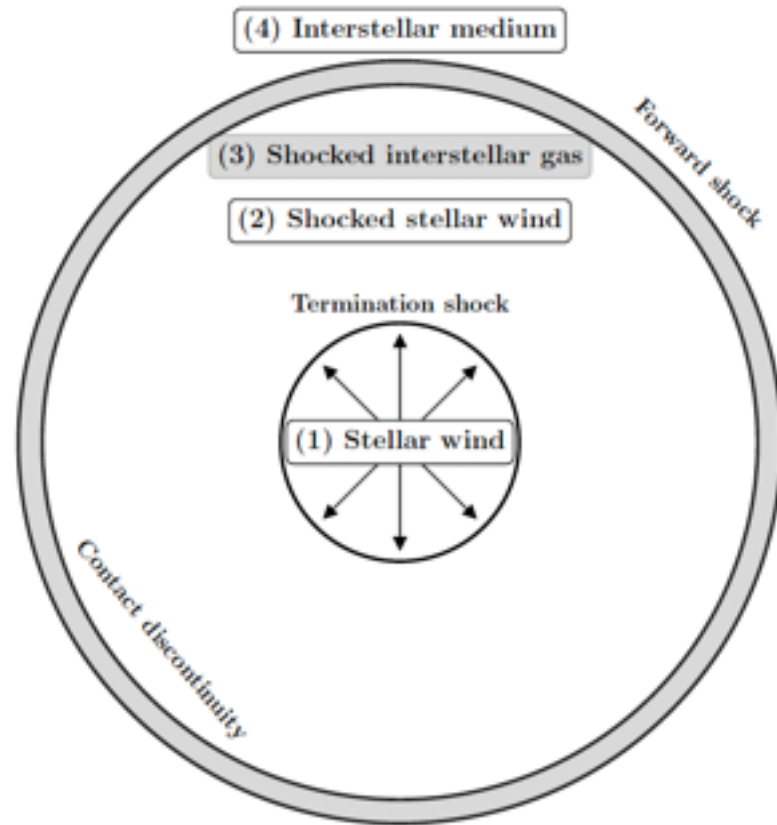
CR accelerators: Stellar Clusters



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

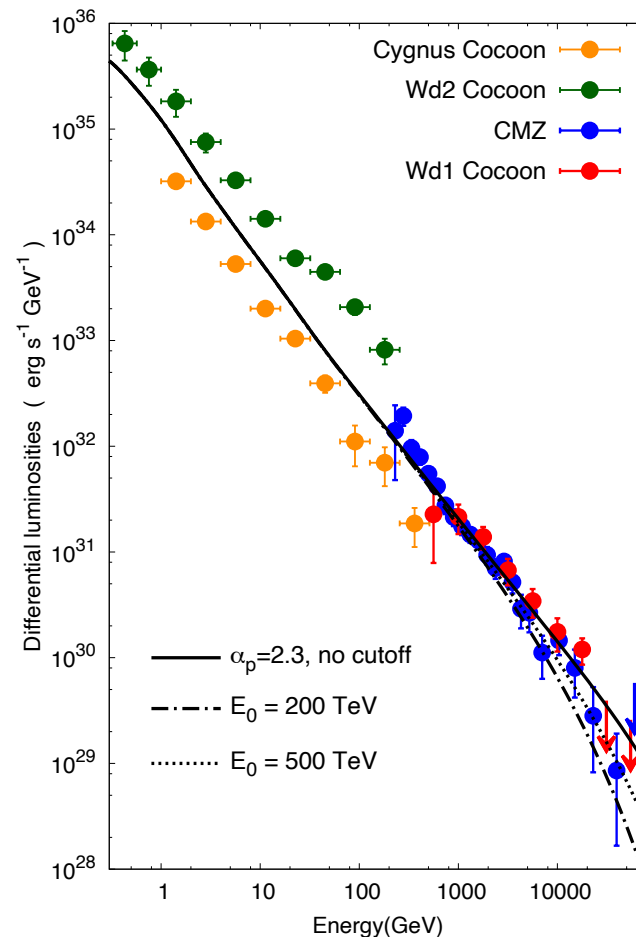
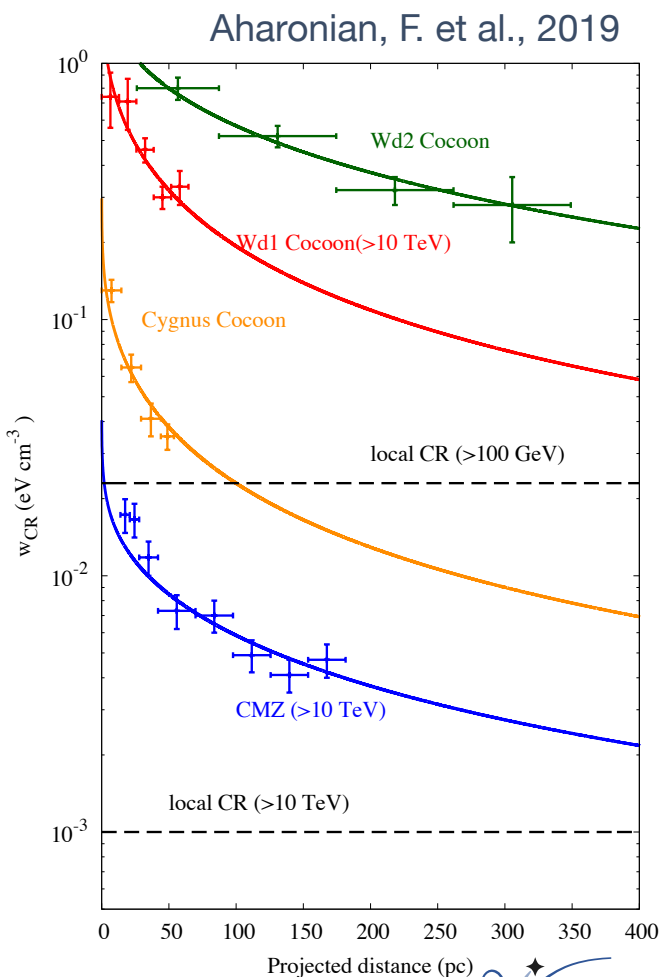


- Young Massive stellar clusters are perfect PeVatron candidates
 - young enough to have few supernovae
 - massive enough to produce significant CR acceleration

Sketch of a Stellar cluster wind bubble.

CR accelerators: Stellar Clusters

- Exciting observations reviving stellar clusters as PeVatrons

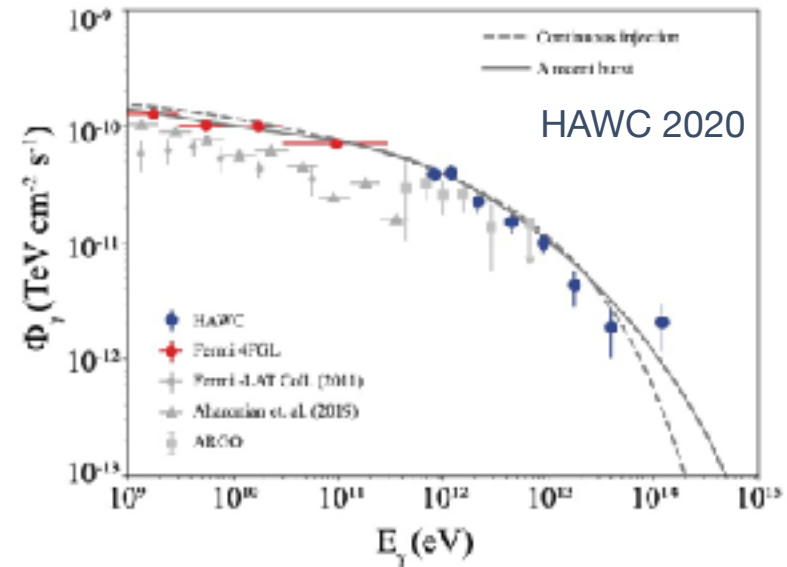
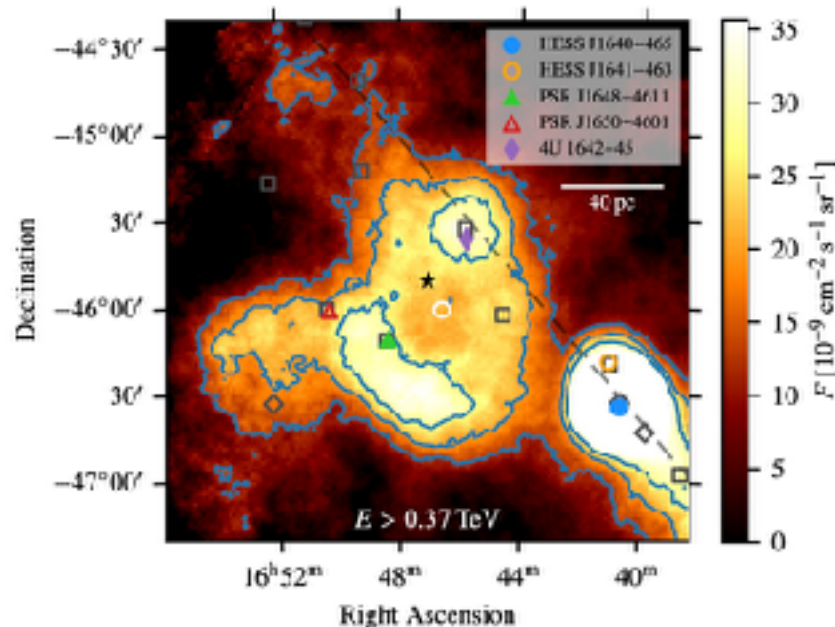


- $1/r$ morphology points towards a continuous particle injection by a central source

CR accelerators: Stellar Clusters

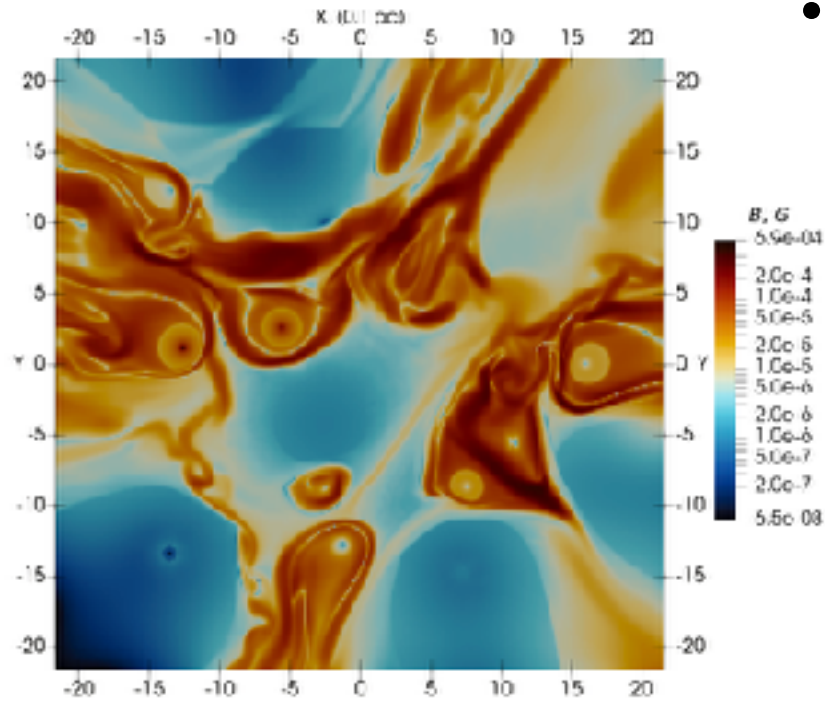
Experimental evidences:

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



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

CR accelerators: Stellar Clusters



Badmaev et al. 2022

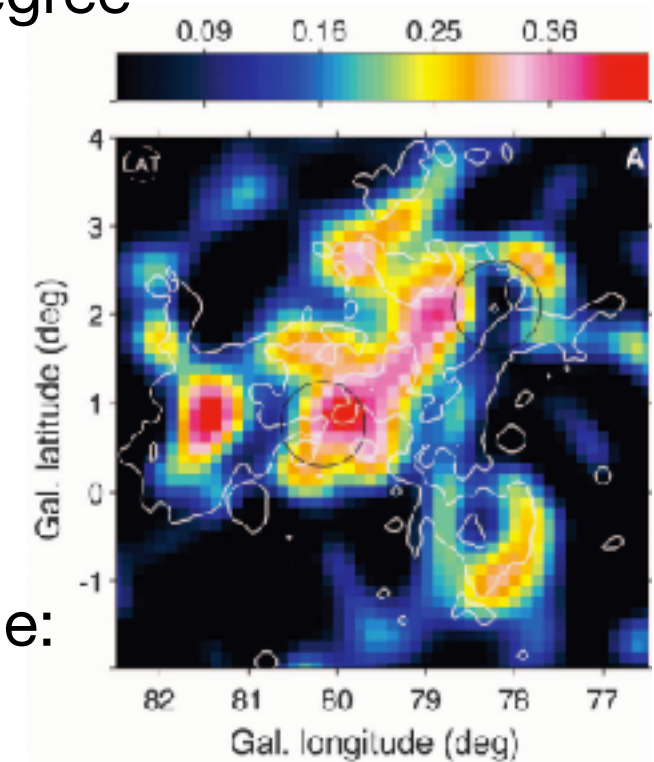
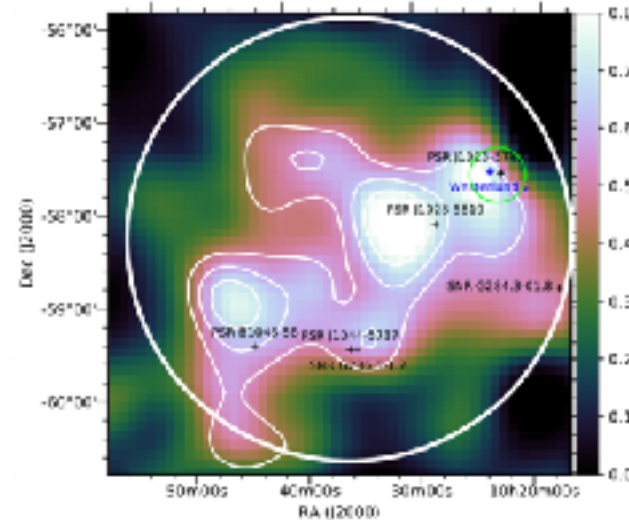
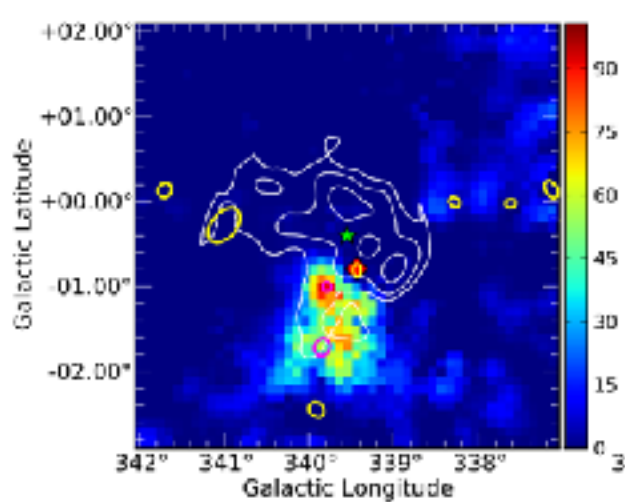
- Backed up by **theoretical** works:
 - Large magnetic fields and size
 - Fast outflows as in SNRs
 - Energetics \ll than in SNRs

Hillas Criterium:

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

CR accelerators: Stellar Clusters

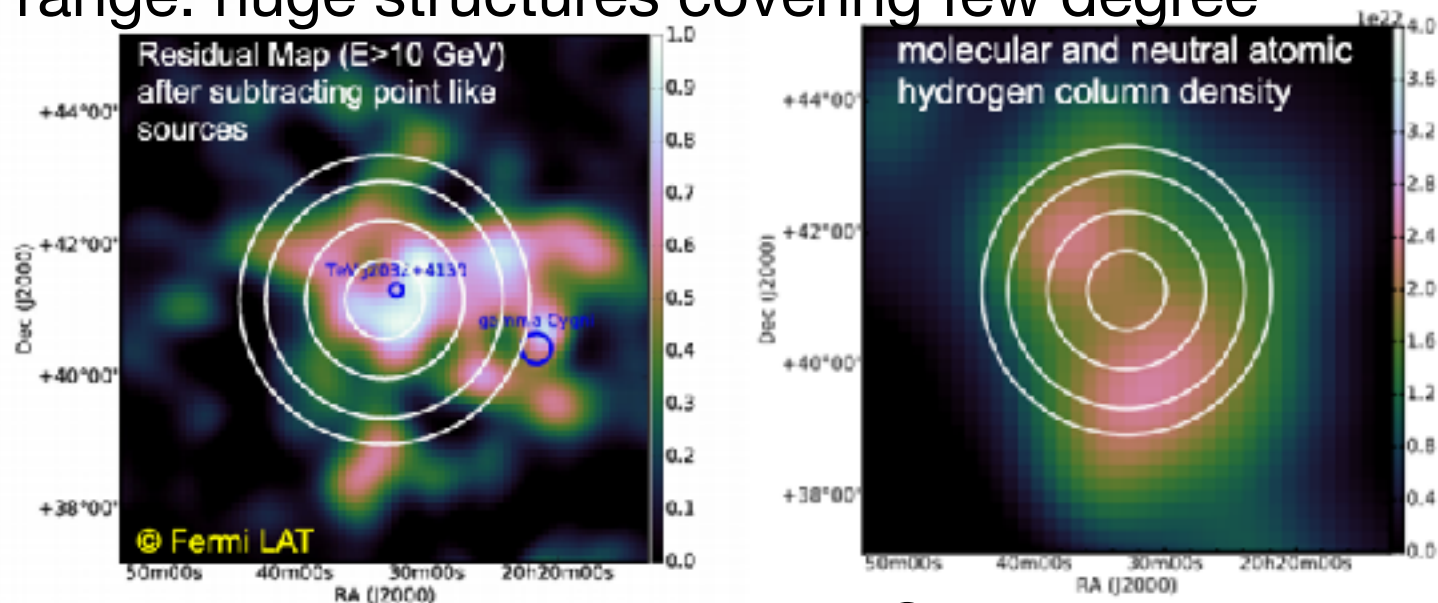
- Acceleration in clusters: wind-wind, clusters, collective effects
- Energy reservoir $\sim 10^{38-39}$ erg over ages of $T \geq 10^6$ years
- In the GeV range: huge structures covering few degree



- 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

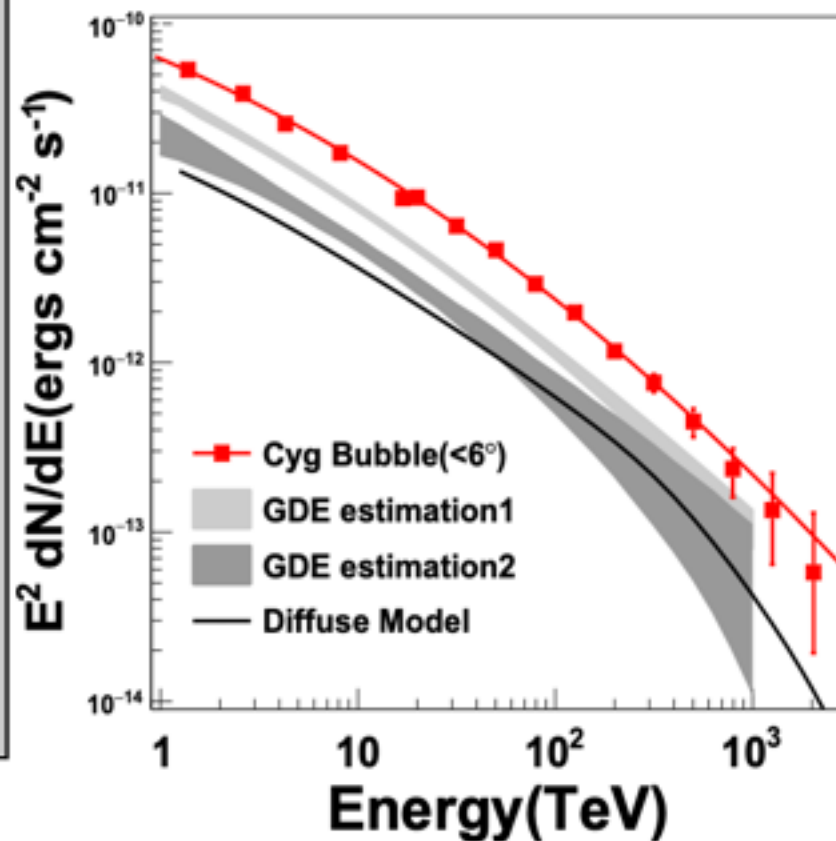
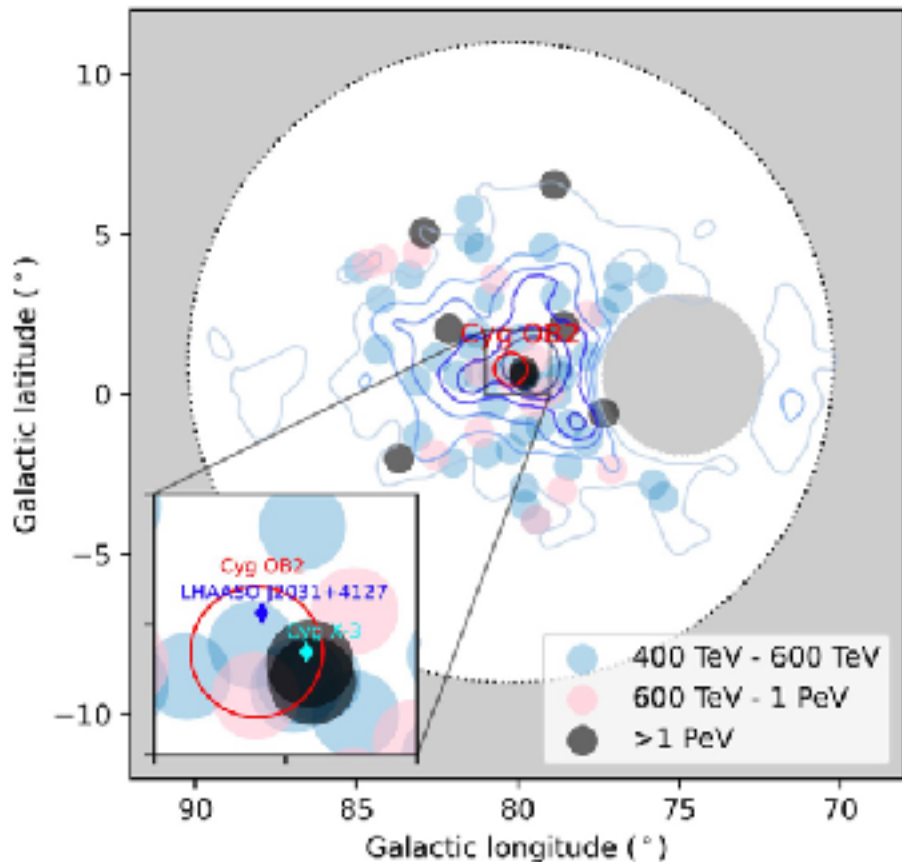
CR accelerators: Stellar Clusters

- Other accelerators - Old massive Stars (wind-wind, clusters, collective effects)
- Energy reservoir $\sim 10^{38-39}$ 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

Cygnus Cocoon

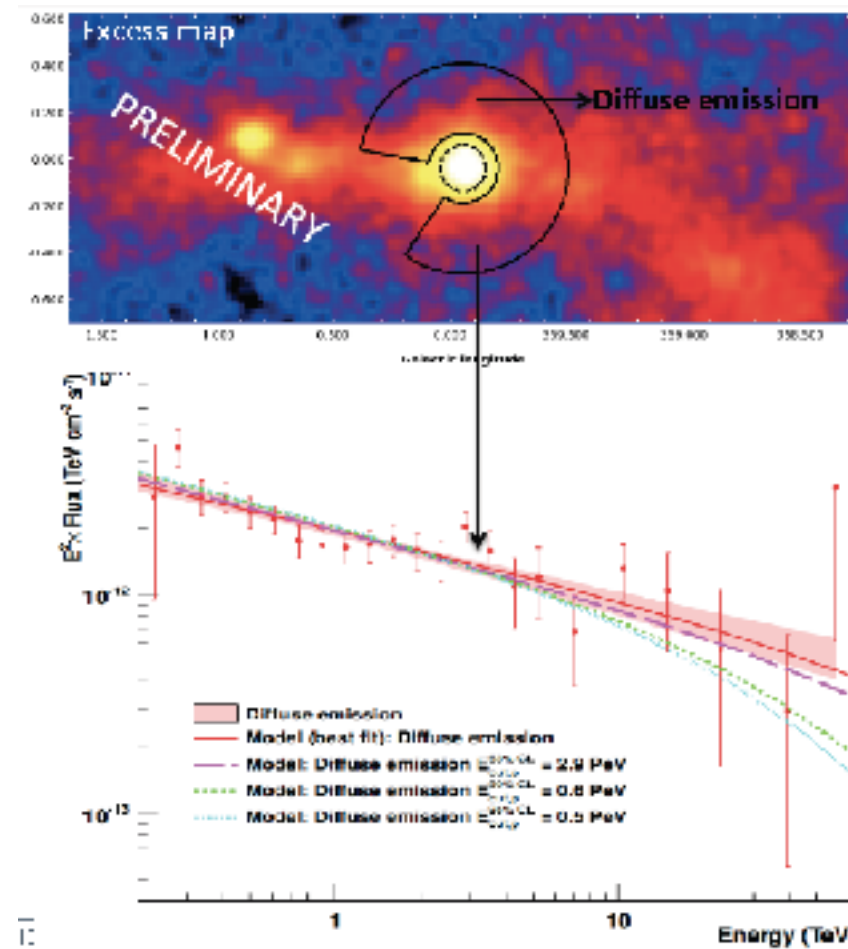


- LHAASO measures $>$ PeV emission coming from the Cygnus Cocoon region
- Claims a super-PeV acceleration in the region
- Unclear what is the origin of the accelerated particles

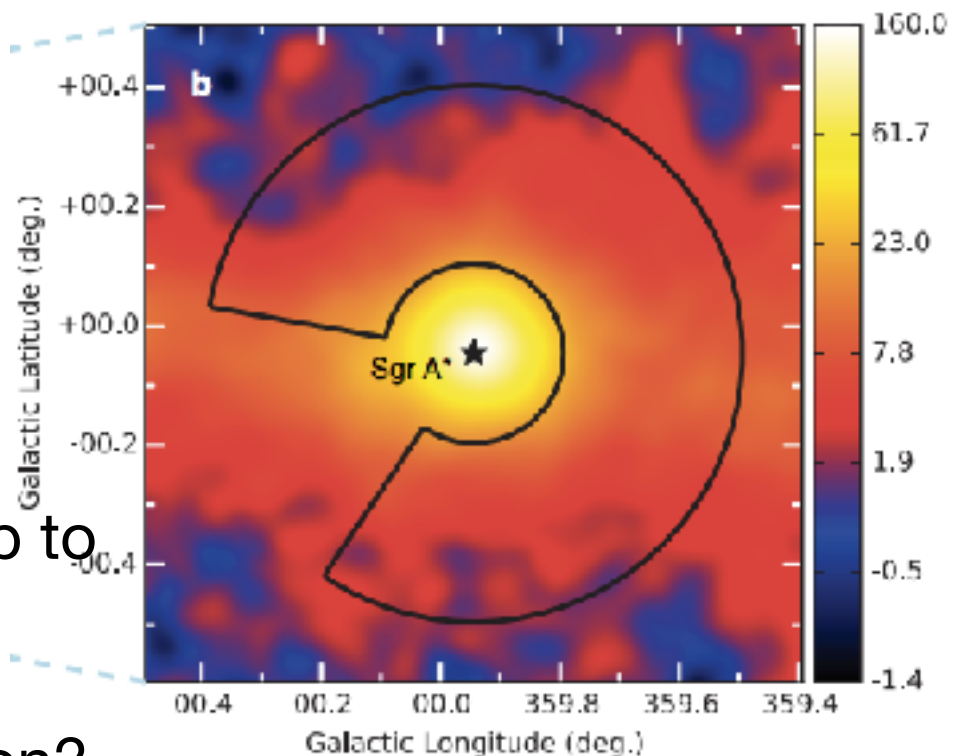
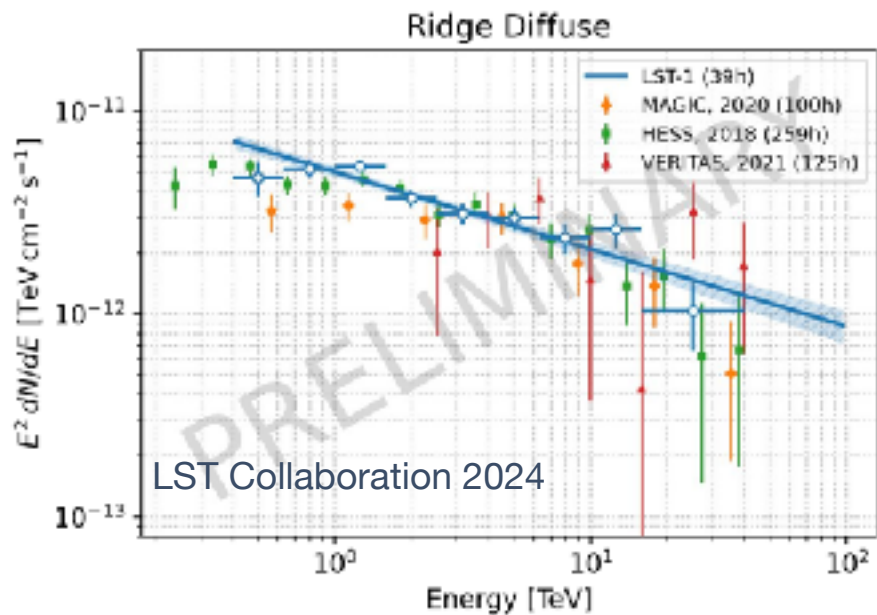
Galactic Center

Galactic center

- Supermassive Black Hole at the center of the Milky Way (mass $\sim 4 \times 10^6$ 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 $\sim 2\sigma$ significance: **first detection of a PeVatron**



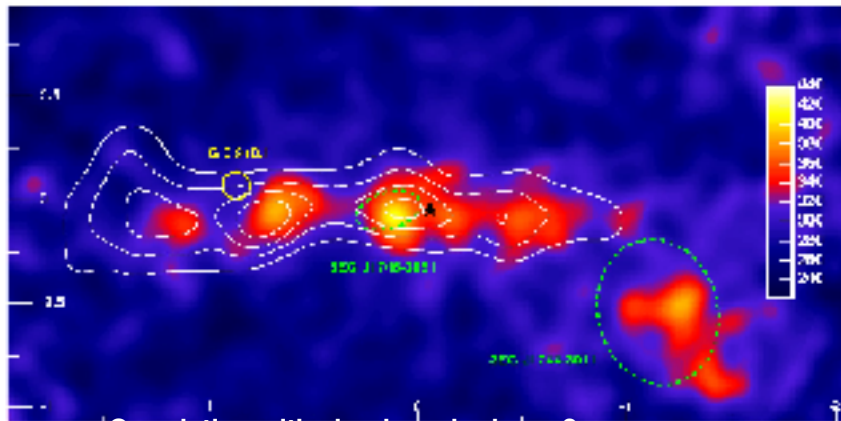
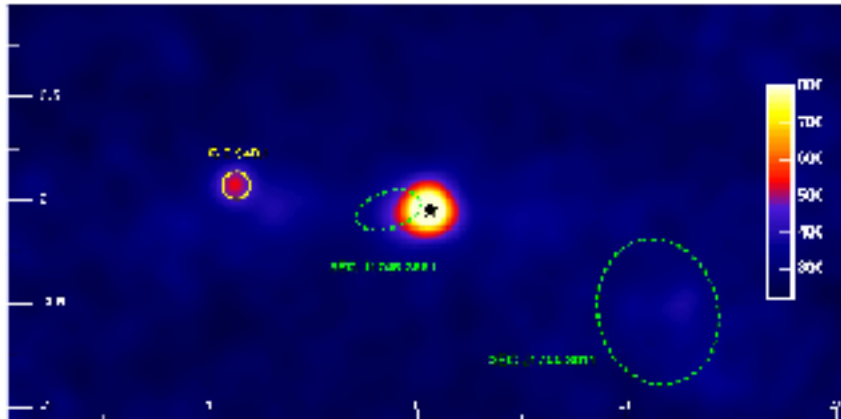
PeV acceleration?



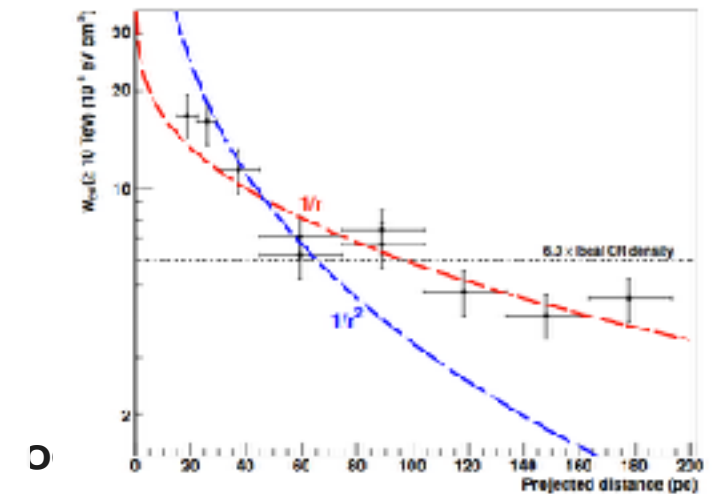
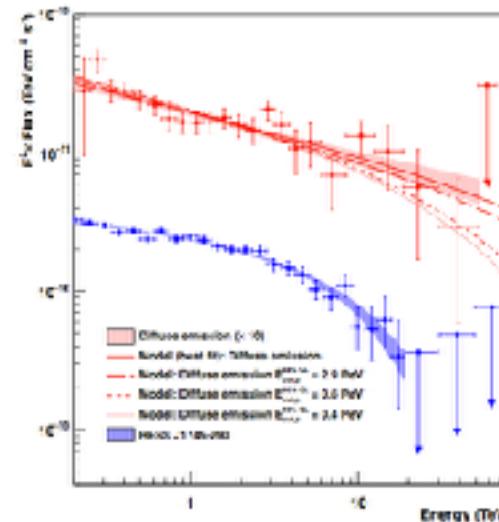
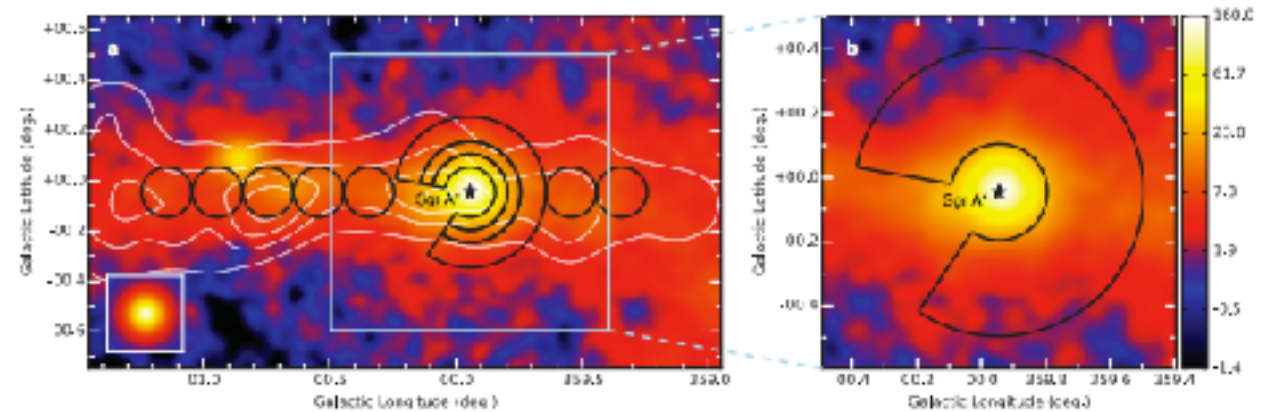
- Continuous injection of protons into CMZ up to PeV :
 - a PeVatron(s) within 10 pc of GC
- SMBC in GC (Sgr A*) operating as a PeVatron?
or acceleration happening elsewhere?

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

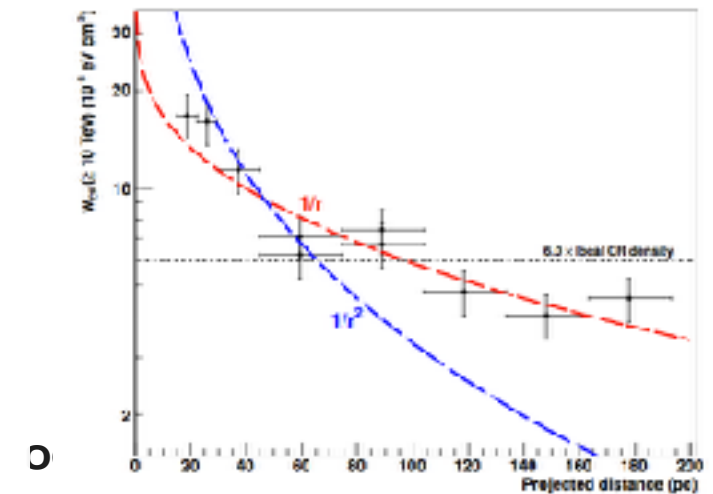
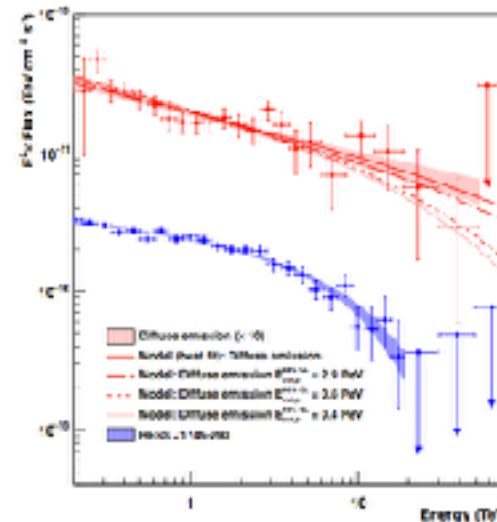
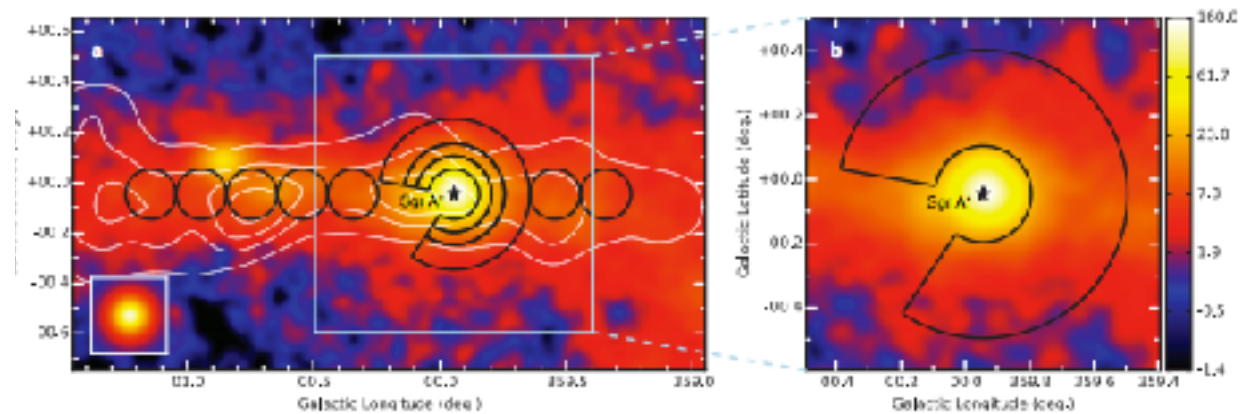
The injection time should be larger than the escape one:

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

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

Rather modest injection for thousands of years:

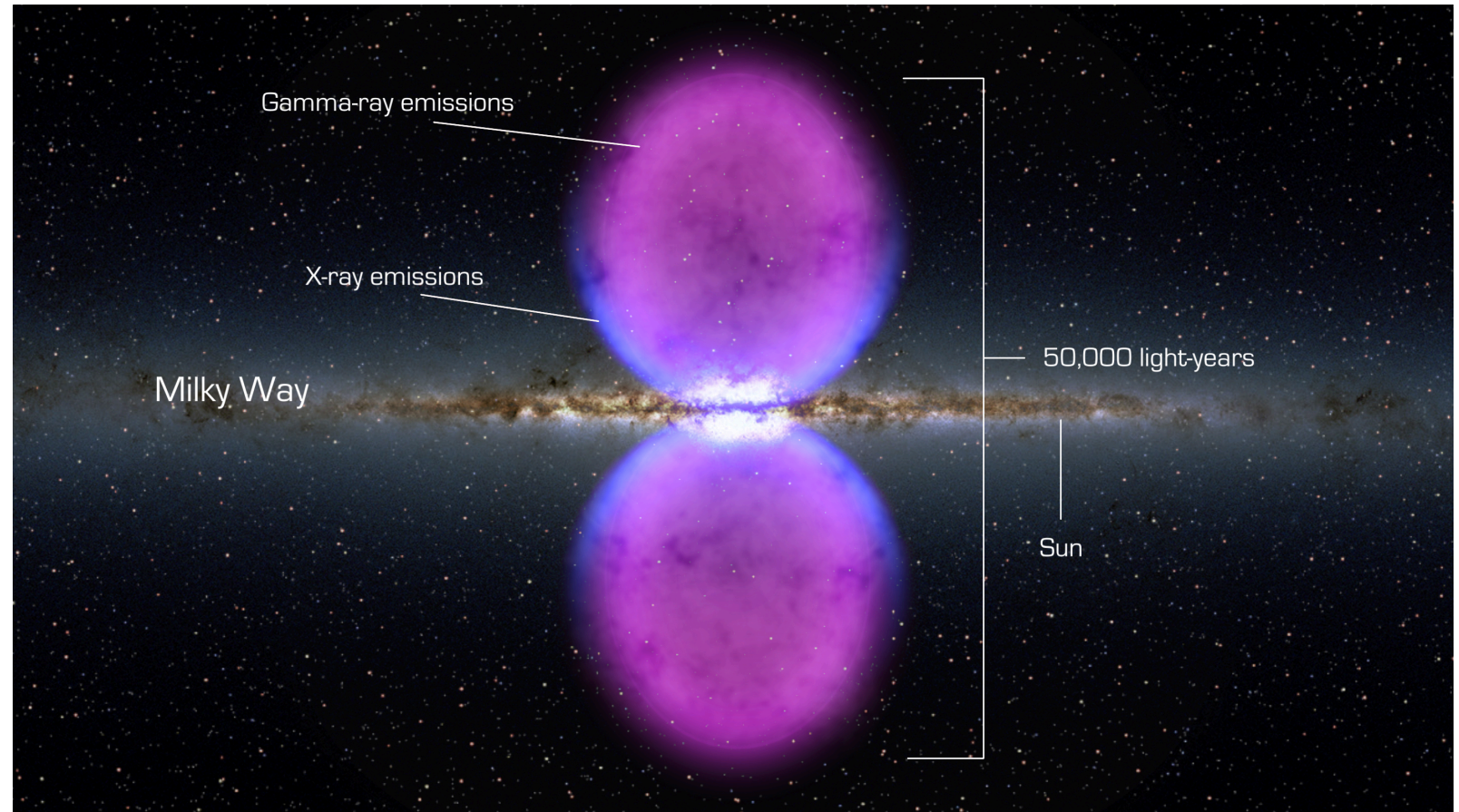
- Galactic center?
- Stellar clusters in the inner region?



CR accelerators: Galactic Center

Fermi Bubbles

- **Energetics** - Outburst-like event /slow outflows
 - $E_{\text{kin}} = 3 \times 10^{54}$ erg
 - $L_{\text{IR}} \sim 1.6 \times 10^{42}$ erg/s
- Is there any indication of such behaviour?

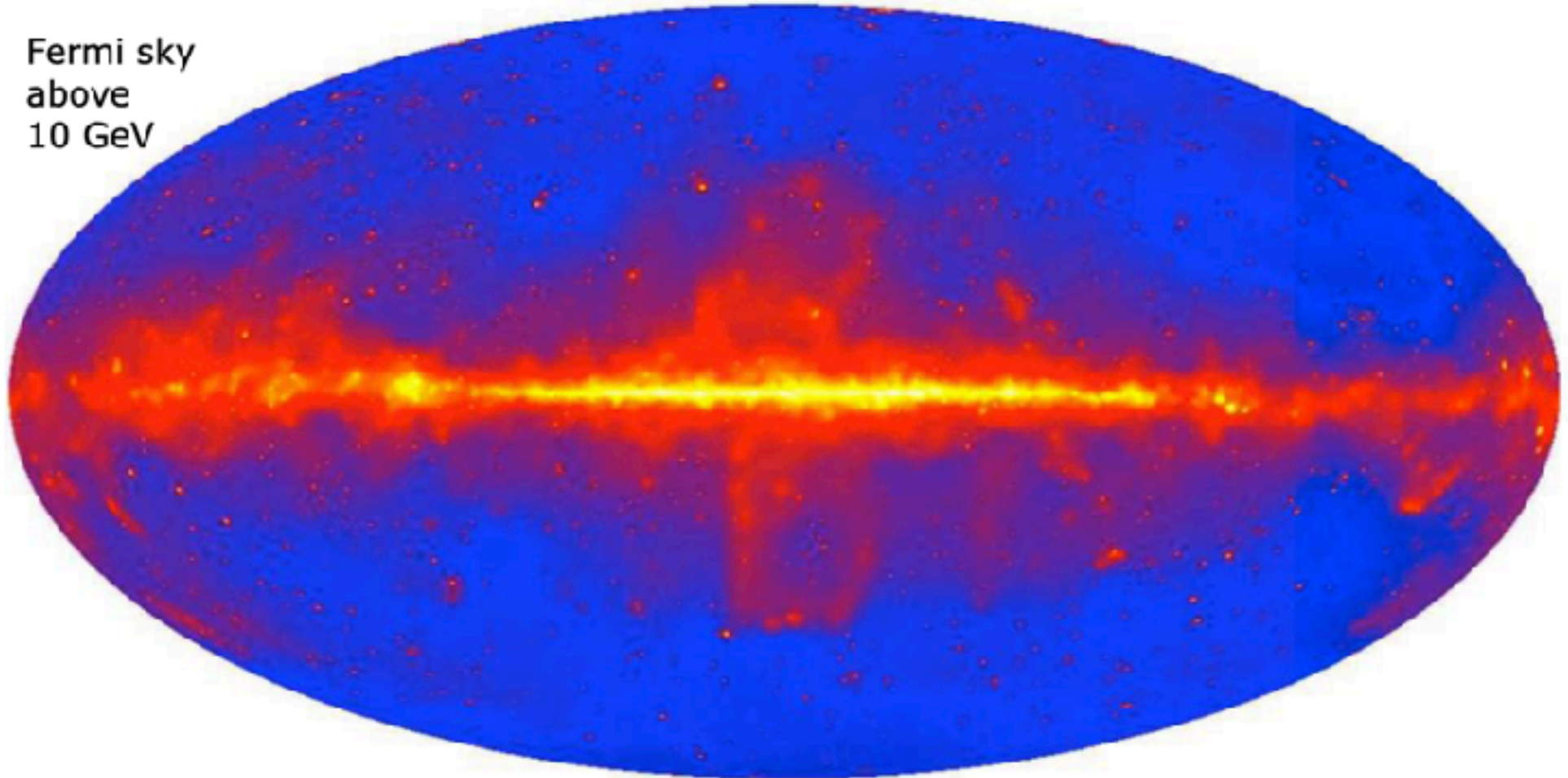


CR accelerators: Galactic Center

- In the GeV regime:

Fermi Bubbles

Fermi sky
above
10 GeV

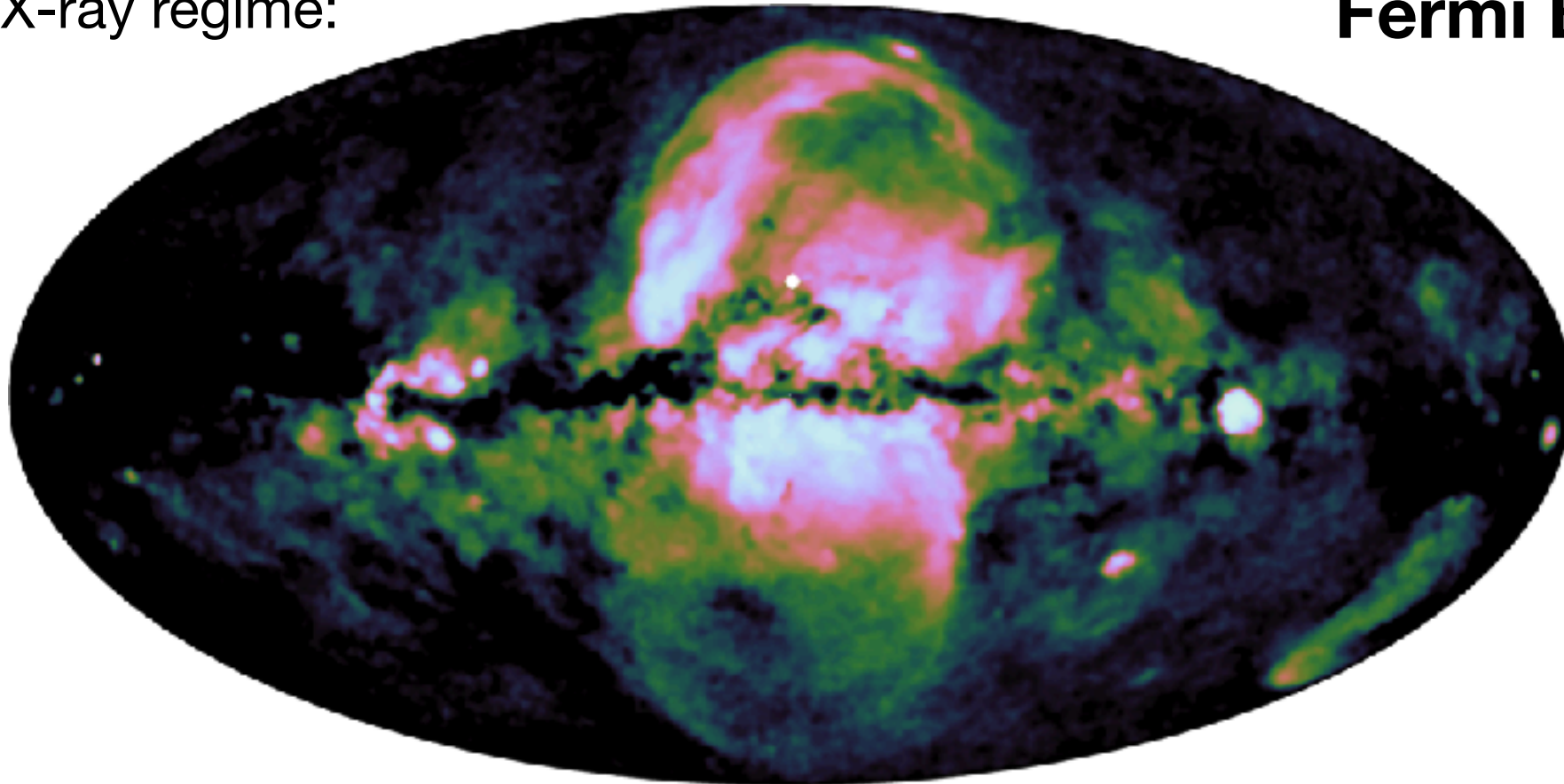


CR accelerators: Galactic Center

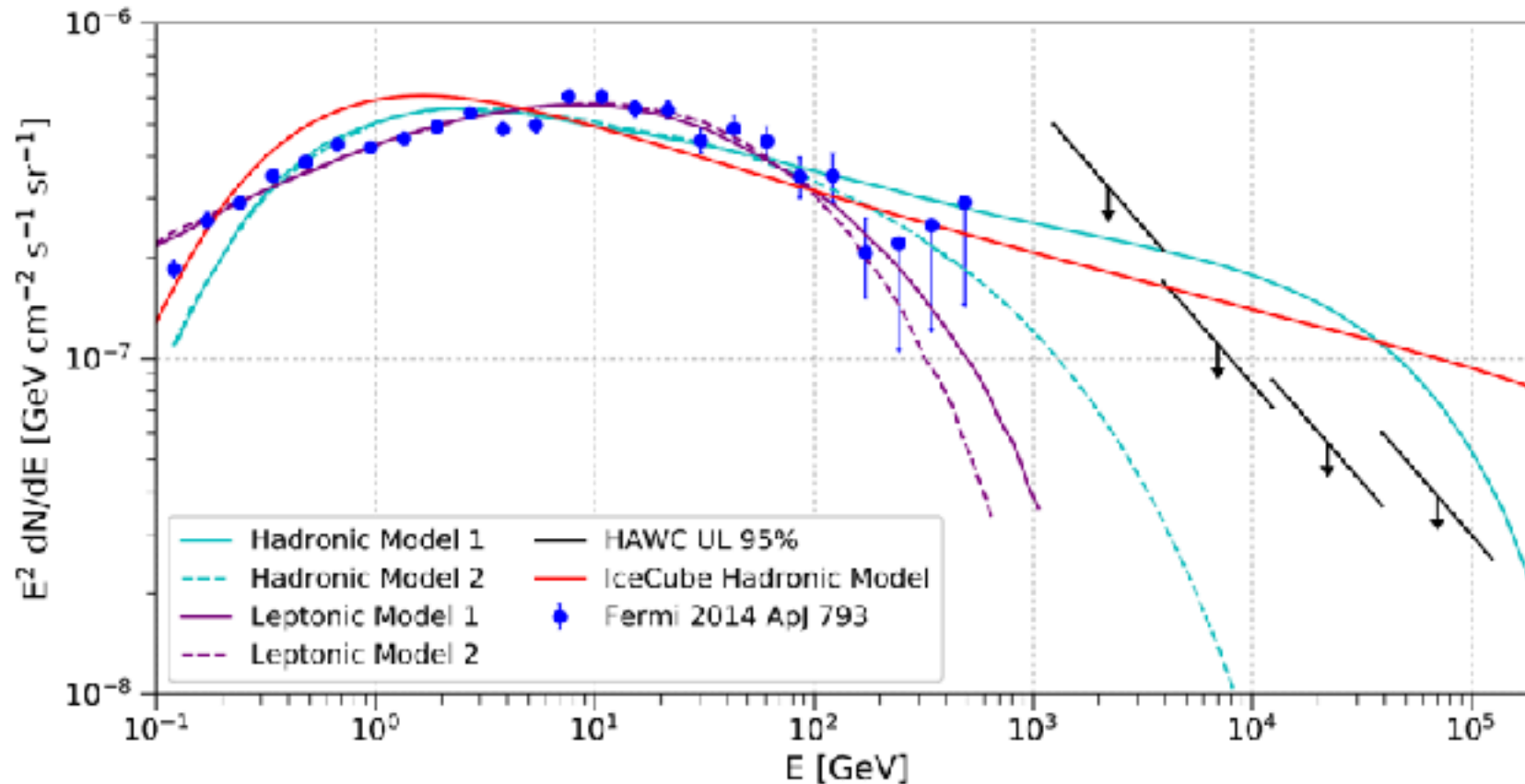
- In the X-ray regime:

eROSITA (0.6-1 keV)

Fermi Bubbles



CR accelerators: Galactic Center



- Fermi spectrum vs HAWC upper limits

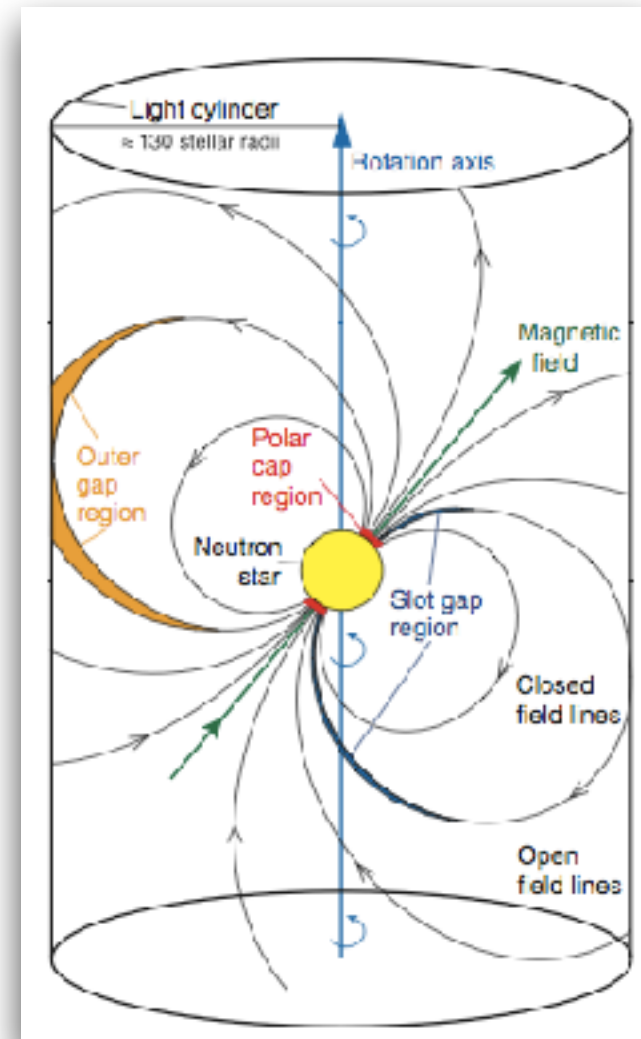
Pulsars and their environments

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.

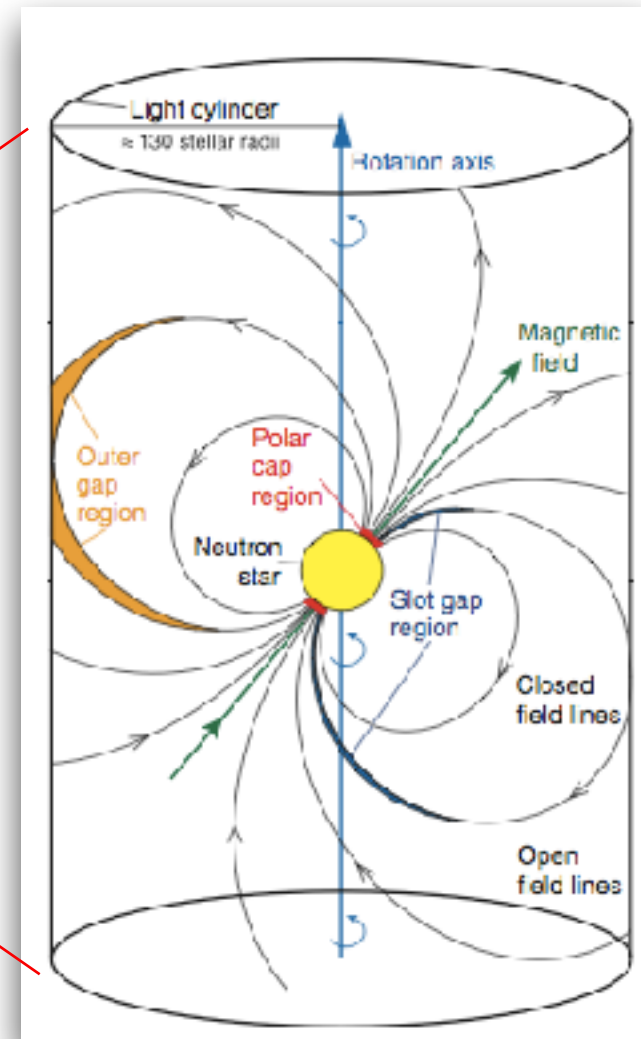
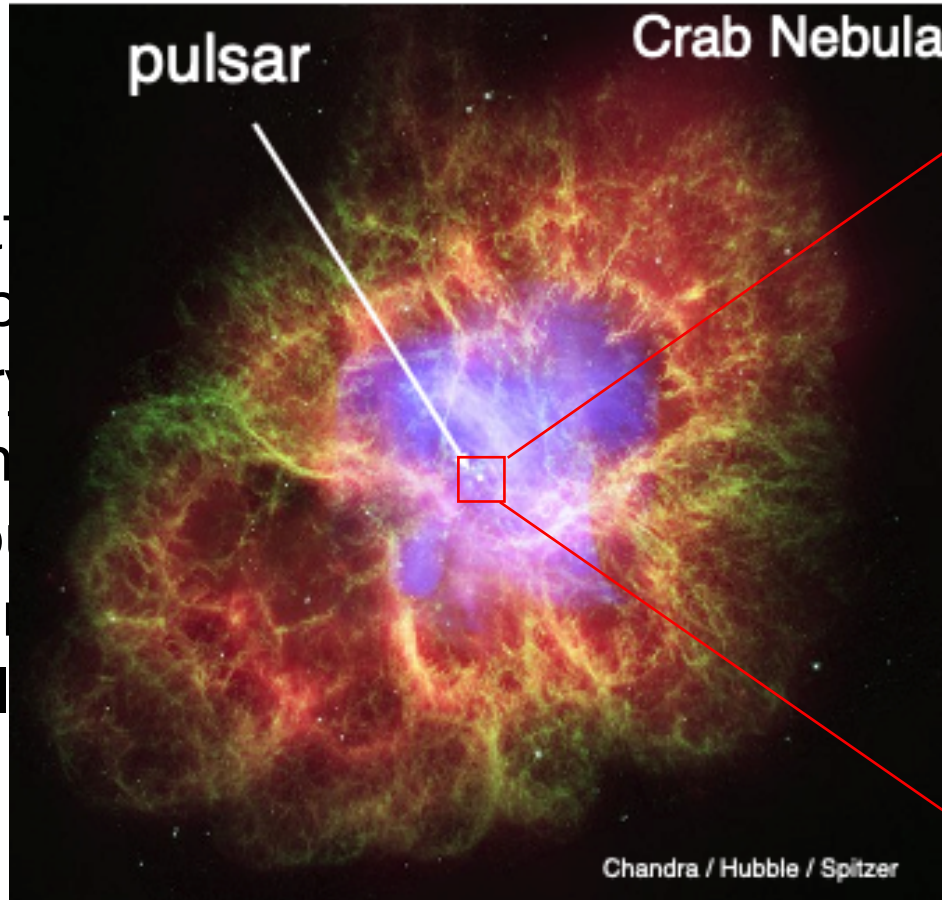
Neutron stars

- 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.

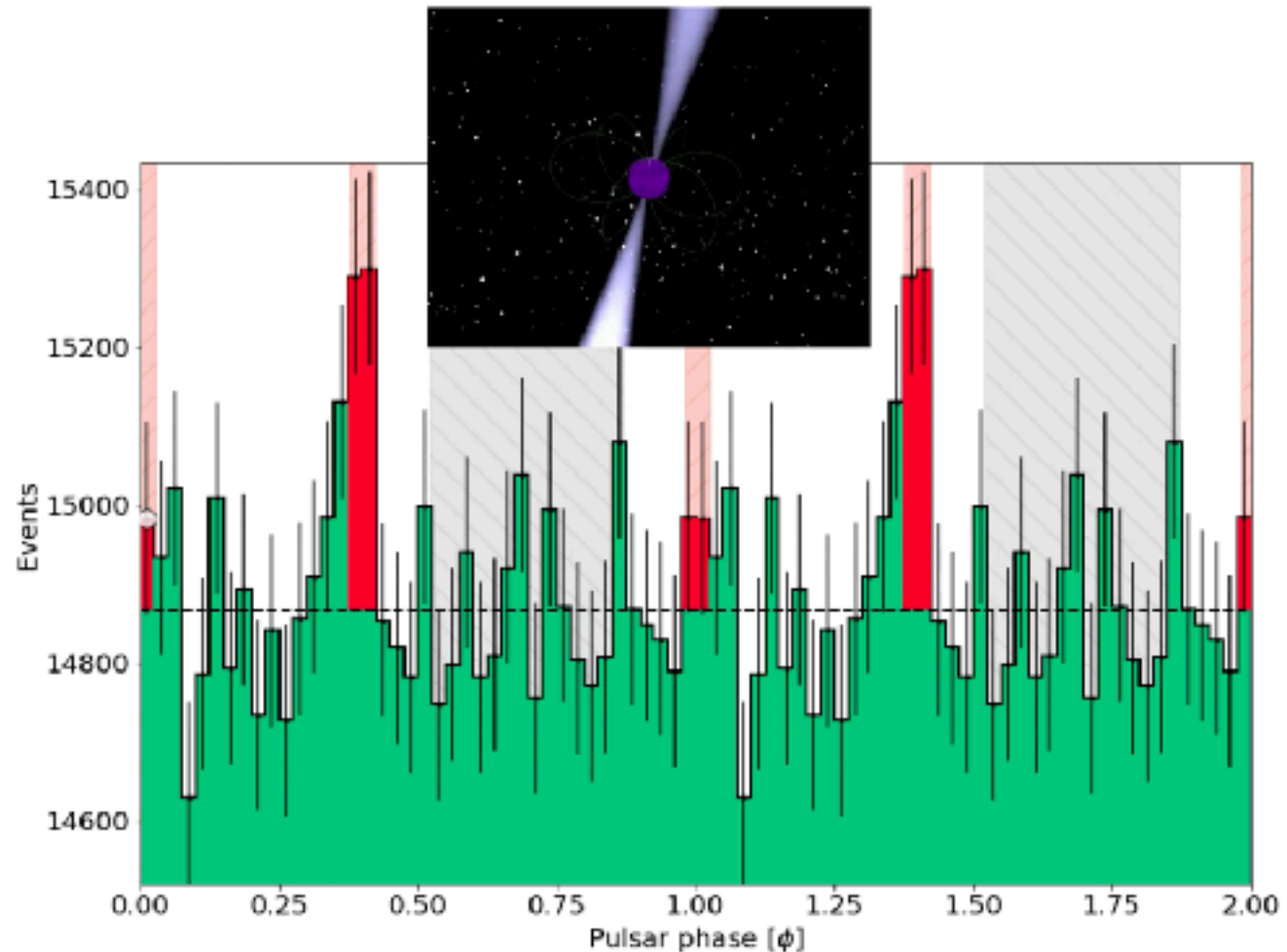


Neutron stars

- Rapidly rotating
- composed by
- If the primary
- rotational energy
- We detect pulsations
- to VHE gamma rays
- e^\pm plasma filament
- rotates with

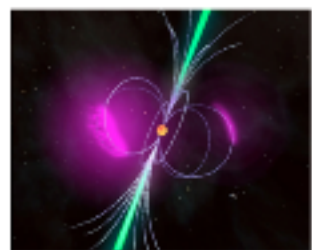
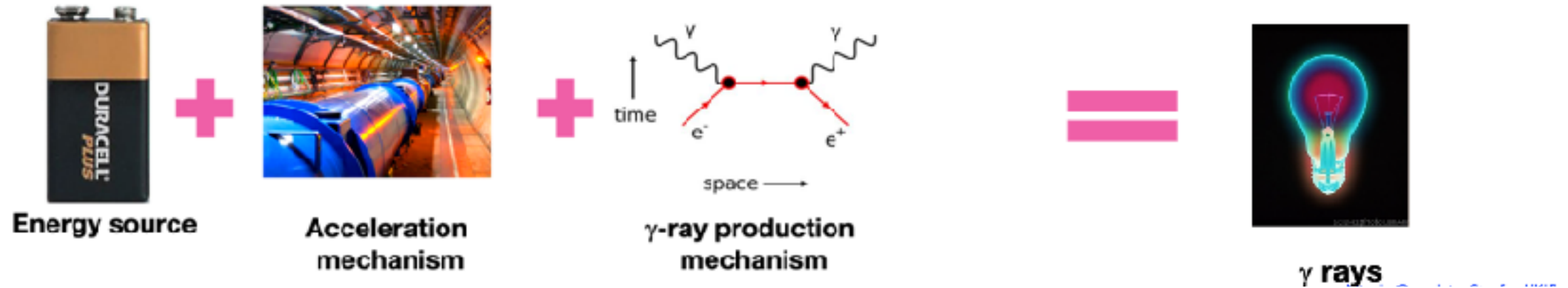


A pulsar is like a lighthouse!

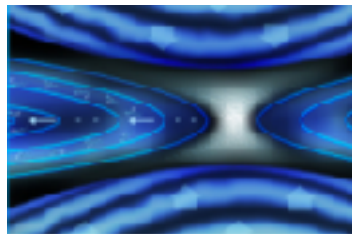


Phaseogram of the Crab pulsar as seen by the Large-Sized Telescope of CTA:
<https://www.cta-observatory.org/lst1-detects-vhe-emission-from-crab-pulsar/>

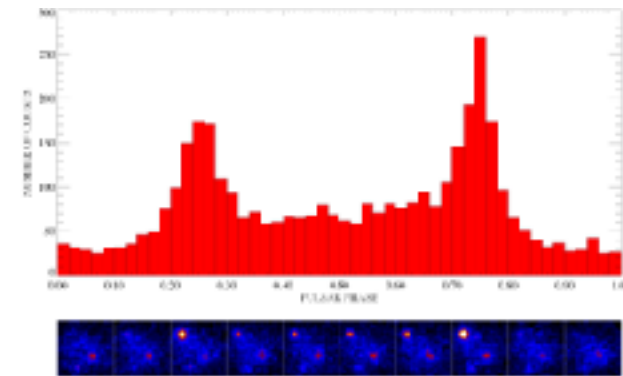
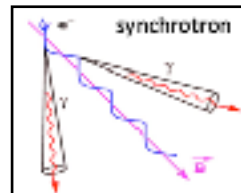
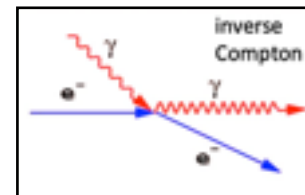
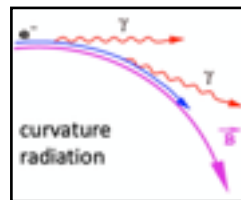
High energy radiation from pulsars



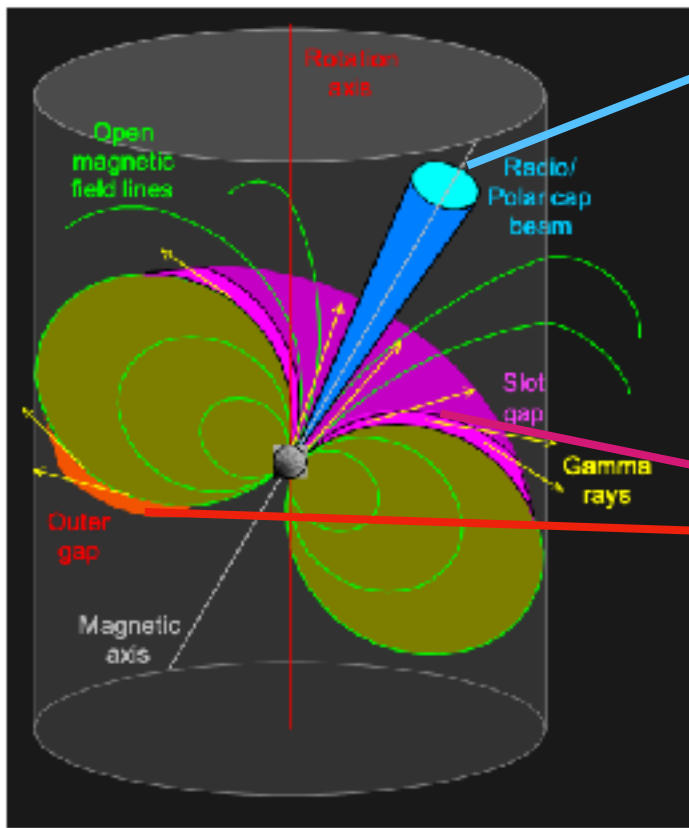
Pulsars



Rotating B-field
Magnetic reconnection
Poynting fluxes



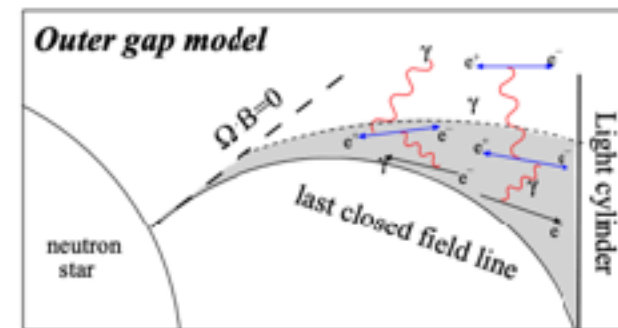
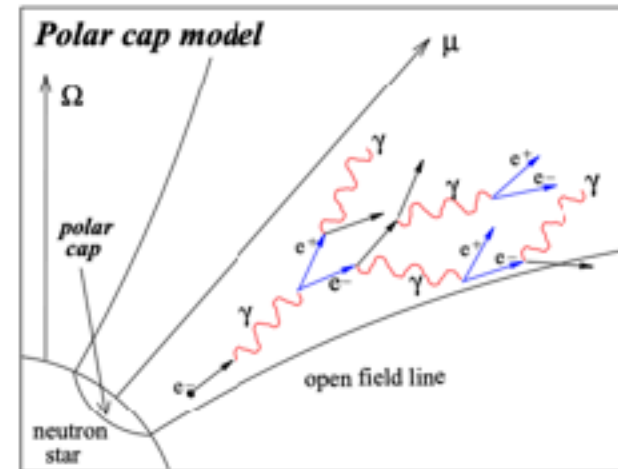
High energy radiation from pulsars



Super-exponential cutoff
(magnetic absorption)

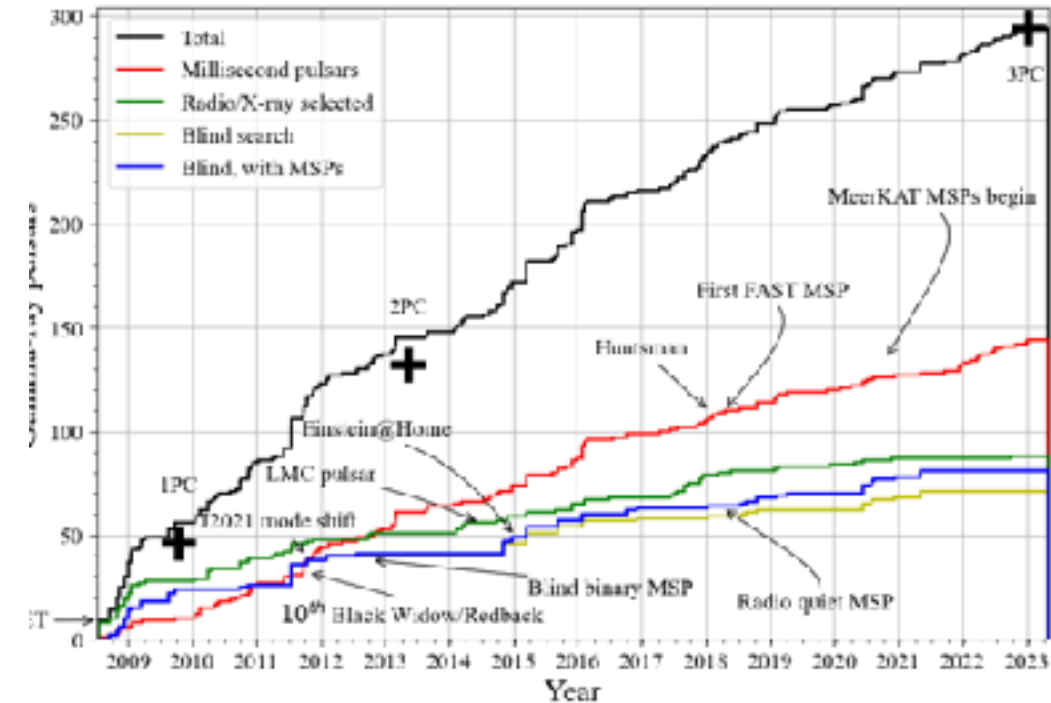
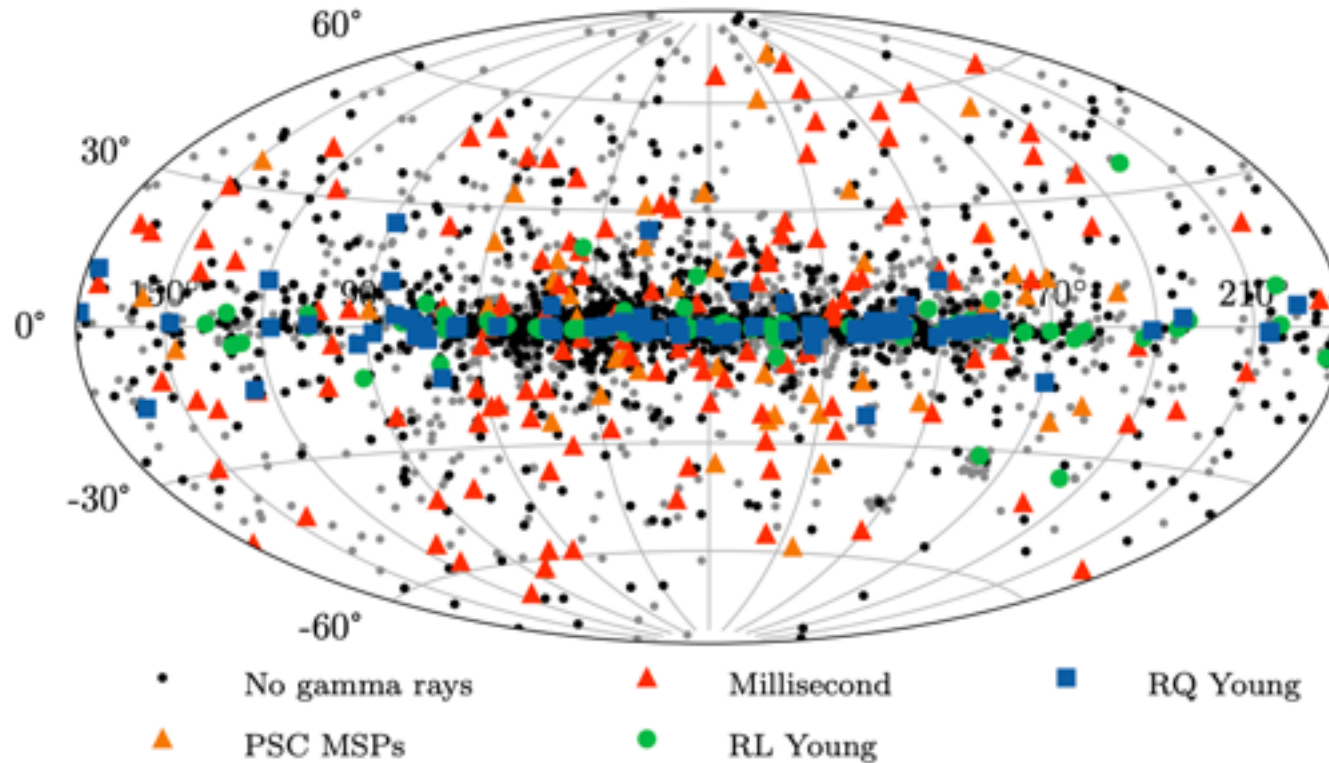
Exponential cutoff (photon-photon absorption)

[Many !]



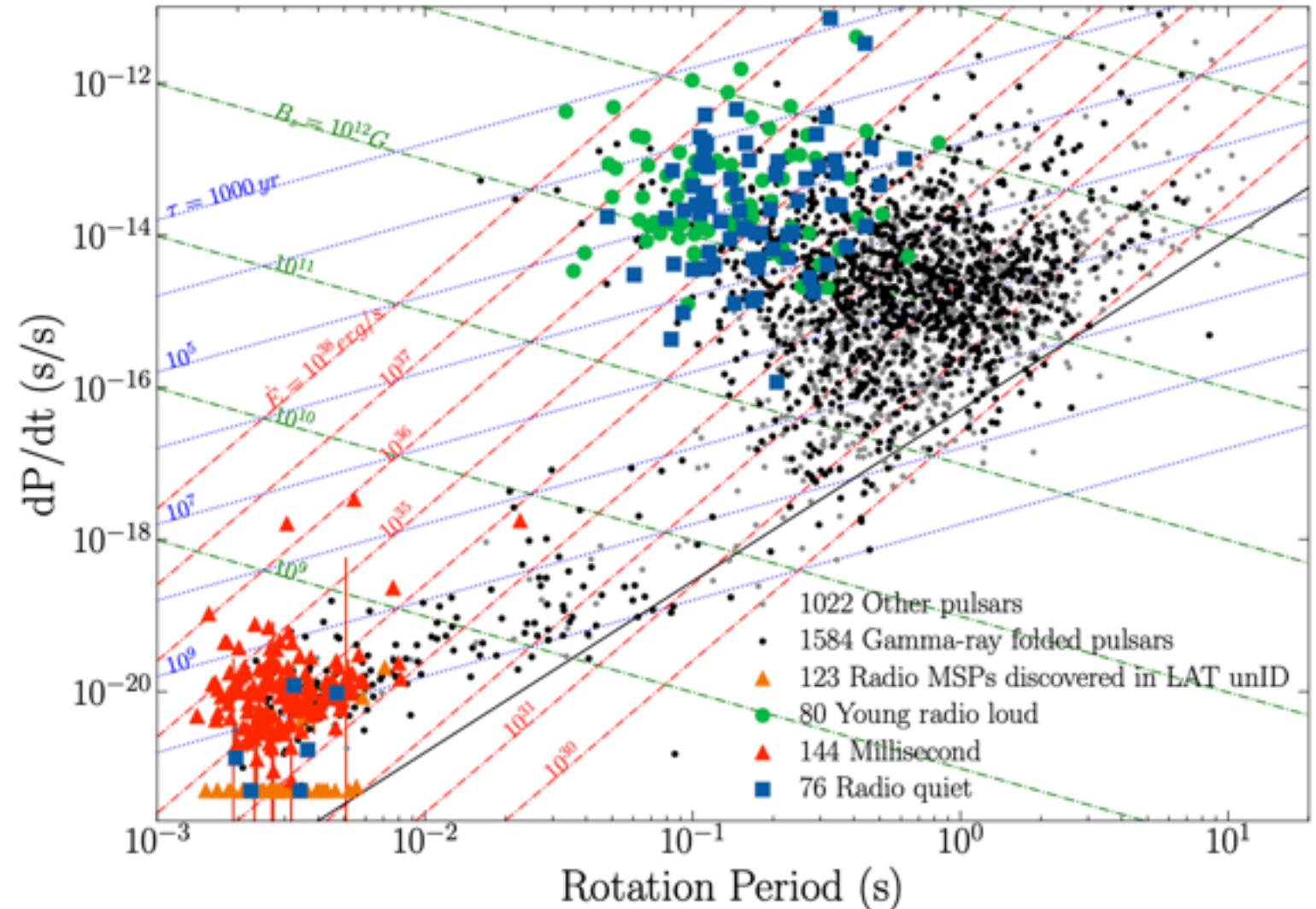
Compact objects: GeV and TeV Pulsars

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

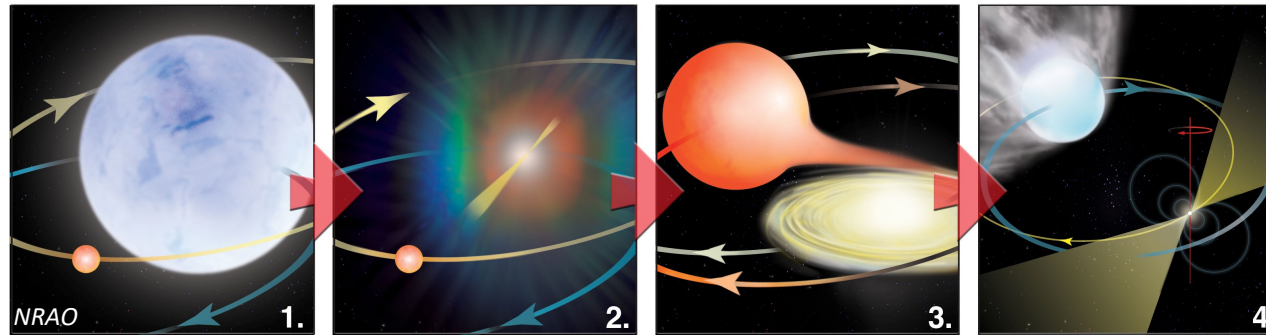


Compact objects: GeV and TeV Pulsars

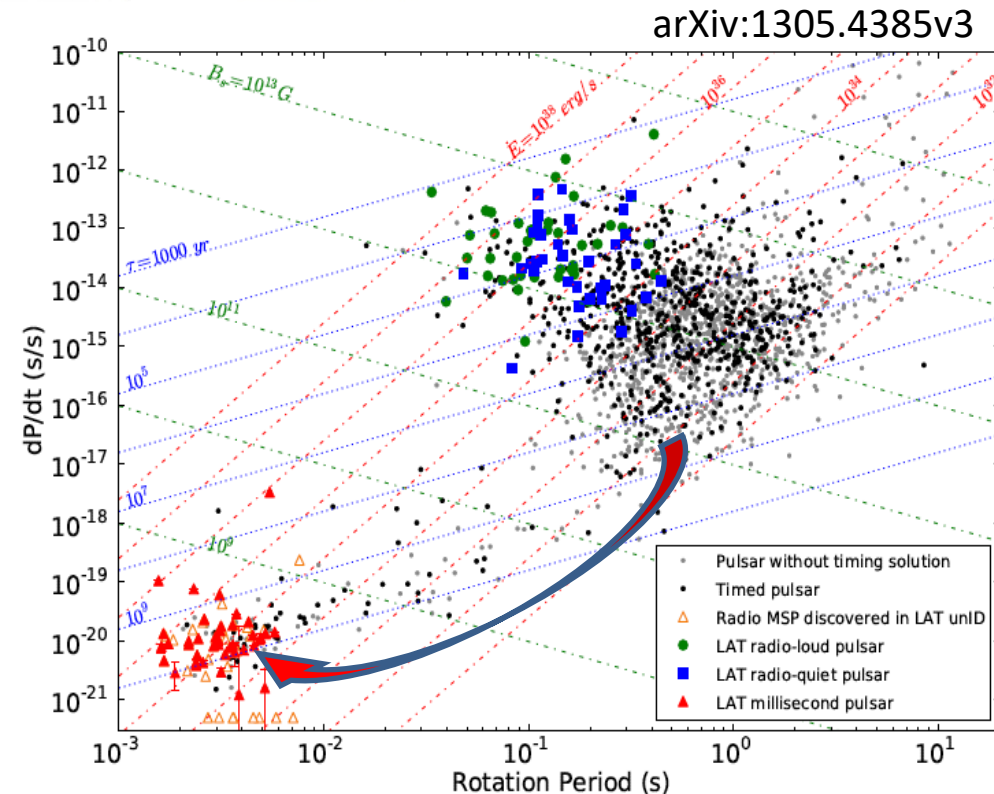
- P - Pdot diagram
- Most pulsars are “young”
 - Their emission is powered by their rotational energy
 - they have not been reaccelerated/ recycled



Millisecond pulsars

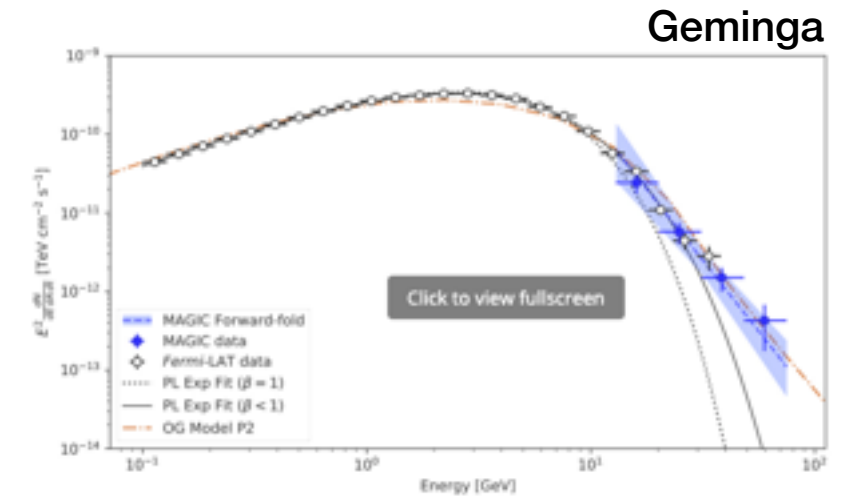
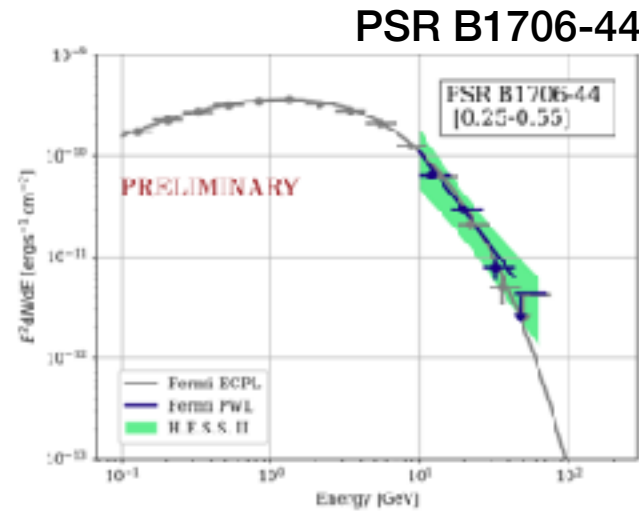
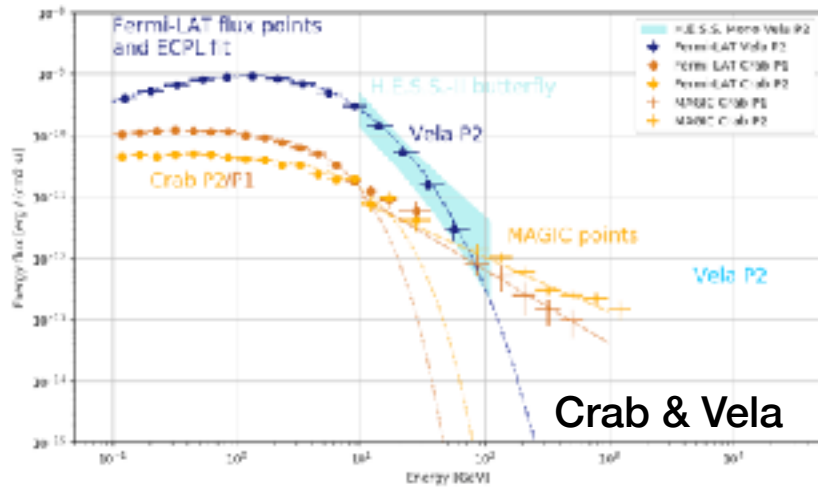


- Very old pulsars *recycled* through accretion from a companion star (leading to a gain of angular momentum)
- Often found in *globular clusters* (since they are old and dense)



VHE gamma-ray radiation from pulsars

- Comparison of the different pulsars detected at VHE

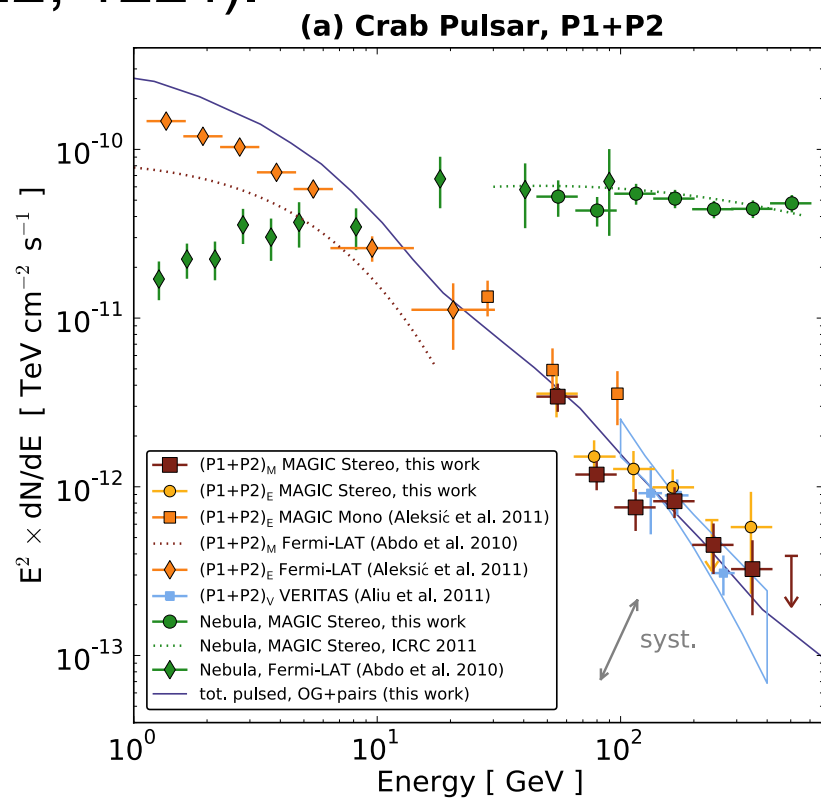


Young, bright GeV pulsar ($\sim 10^3$ yrs)
 High magnetic field ($\sim 5 \times 10^{6-9}$ G @ LC)
 Large low-energy photon field (FIR)
 Simultaneous light curve across the em spectrum

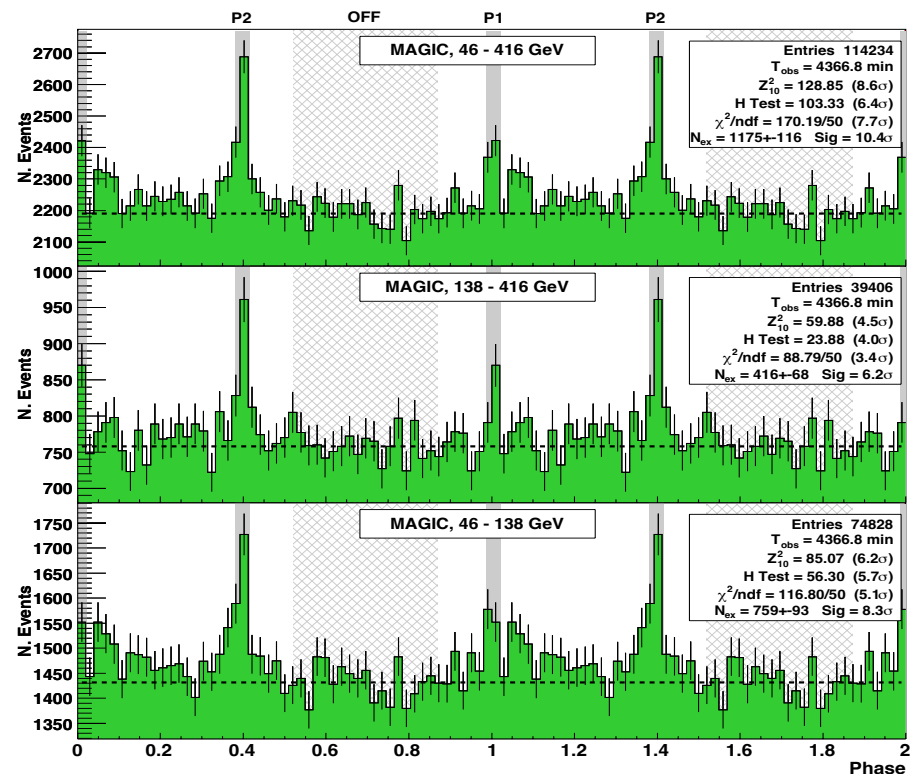
Old, bright GeV pulsar ($\sim 10^4-10^5$ yrs)
 Low(er) magnetic field ($\sim 5 \times 10^5$ G @ LC)
 Large low-energy photon field (FIR)

Crab Pulsar

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



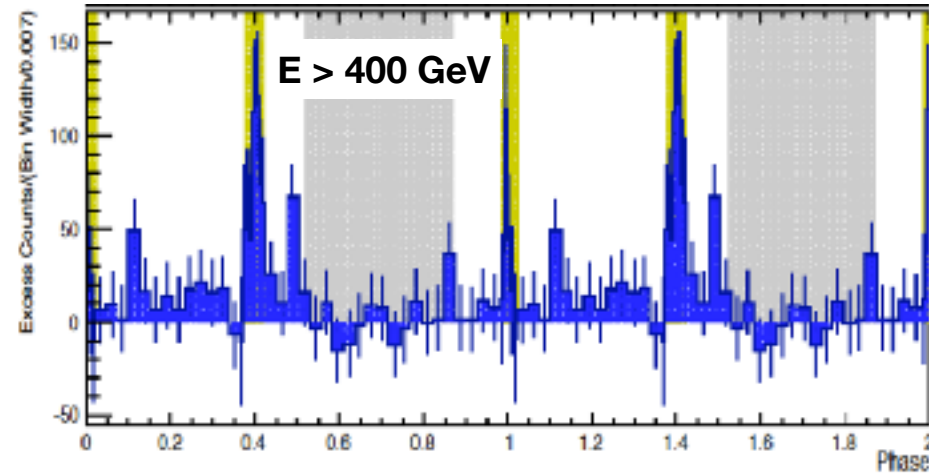
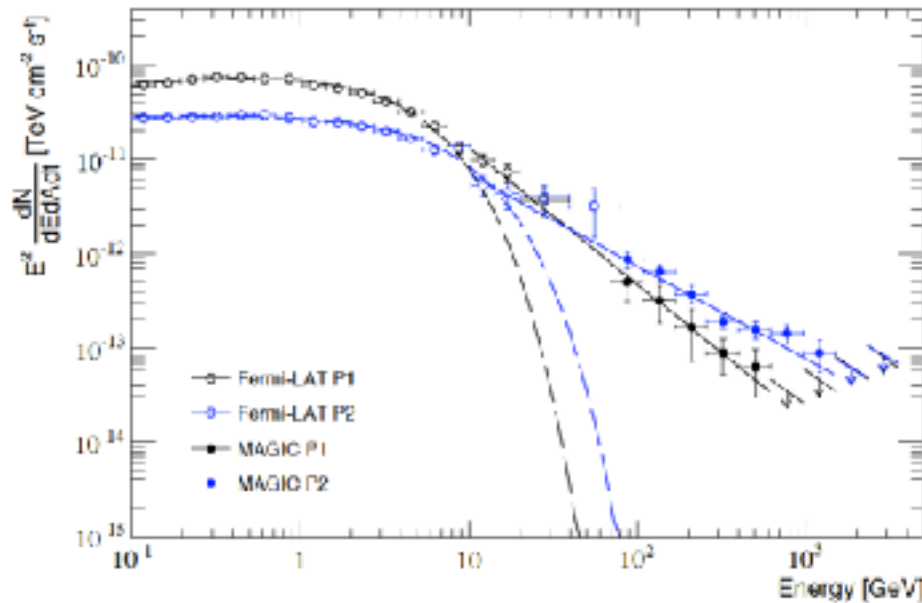
J. Aleksić et al. (MAGIC Coll.), A&A. 540 (2012) 69



- 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

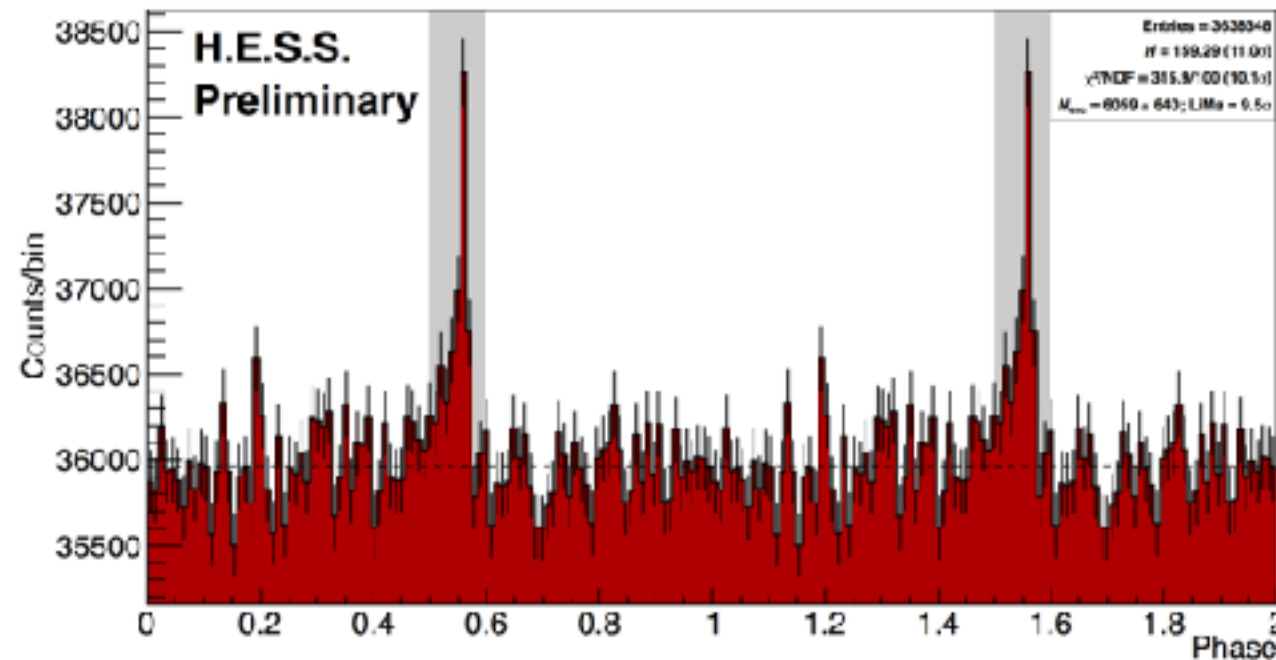
- Extension of the spectrum of the pulsed signal up to TeV energies



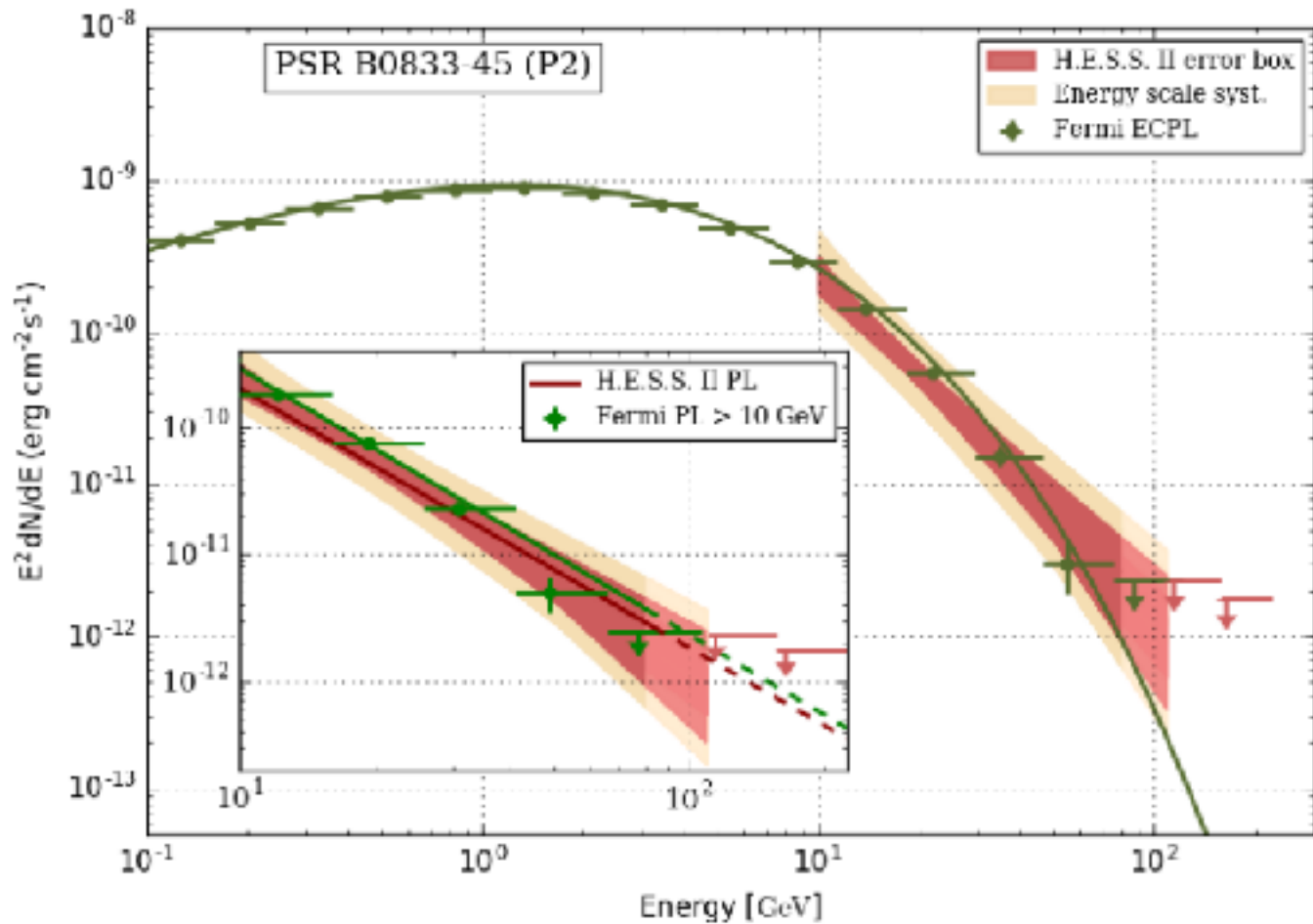
- Challenging all the currently existing models!
- No explanation for the spectrum+pulse profile

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

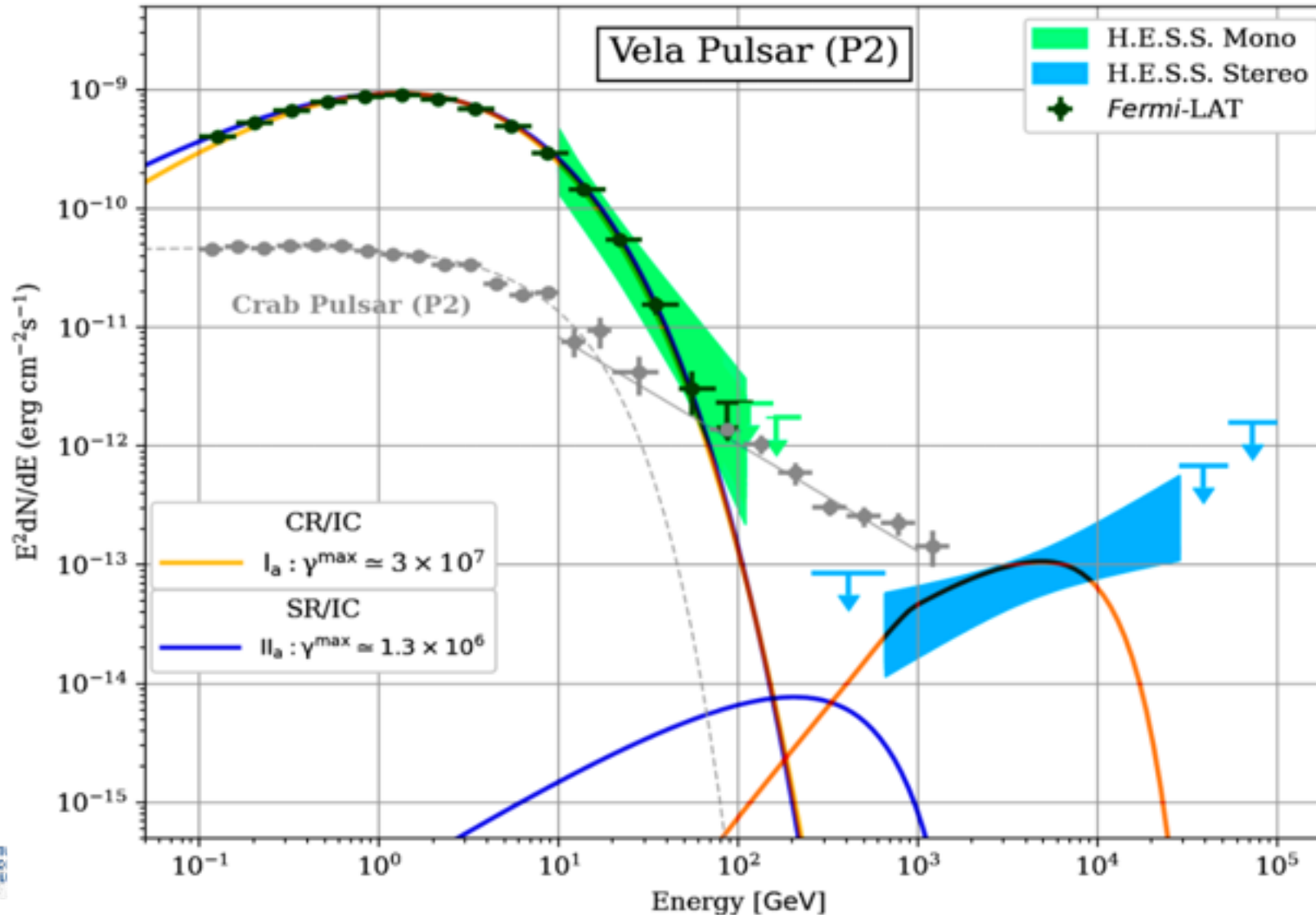


Vela: The second pulsar at VHE



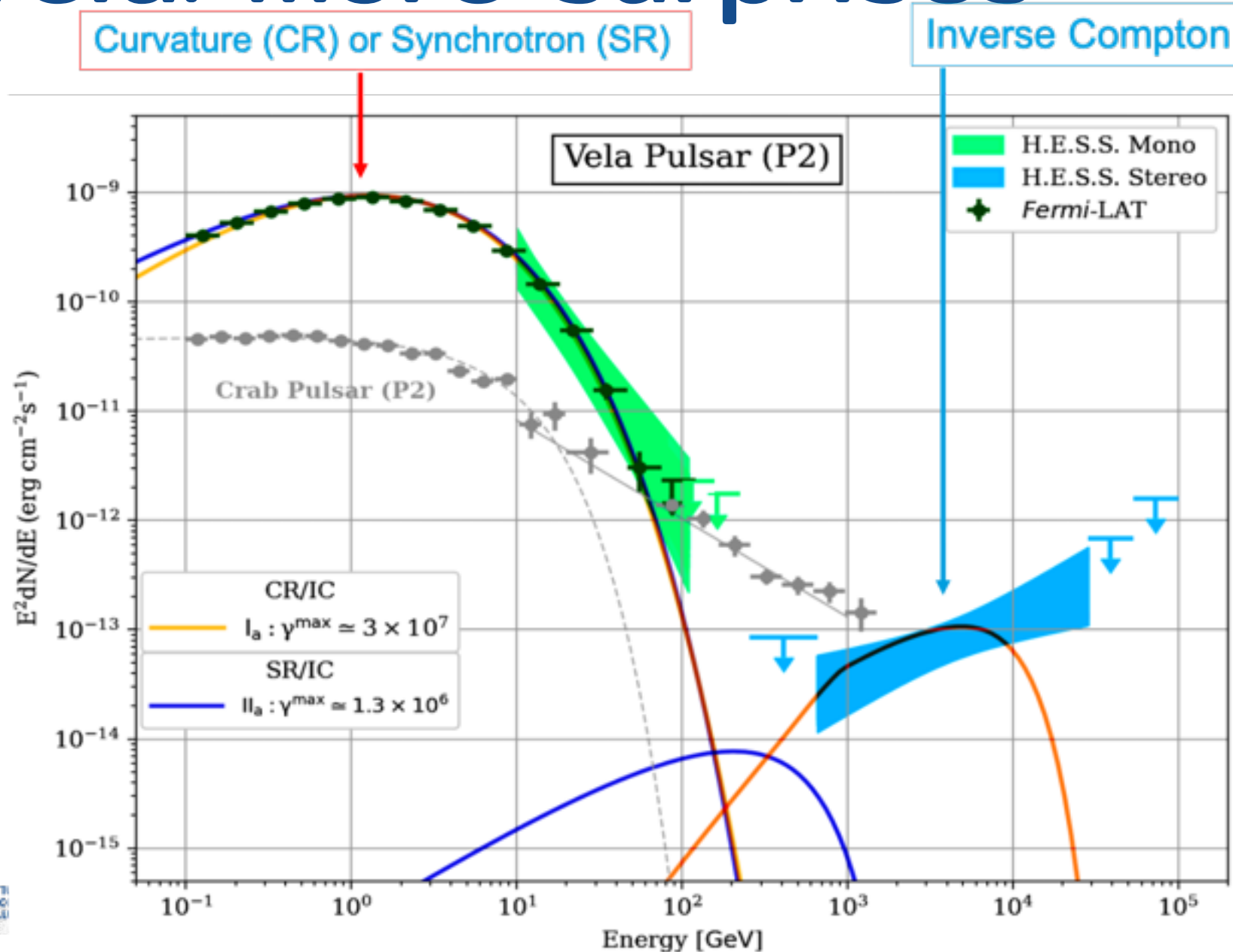
- Spectrum measured between ~ 10 - 100 GeV
- Power-law continuation of the Fermi spectrum?

Vela: more surprises



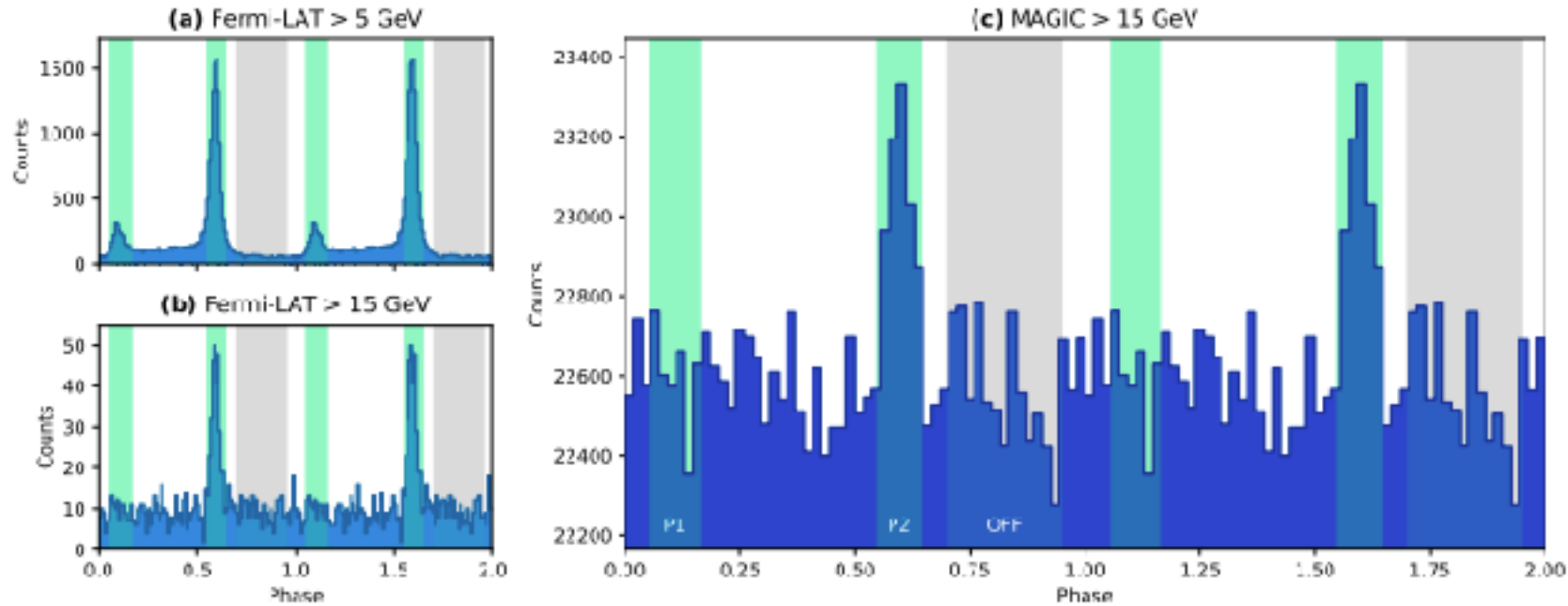
Multi-TeV pulsed emission reaching 20 TeV (!)
Second component different from the lower energy one.

Vela: more surprises



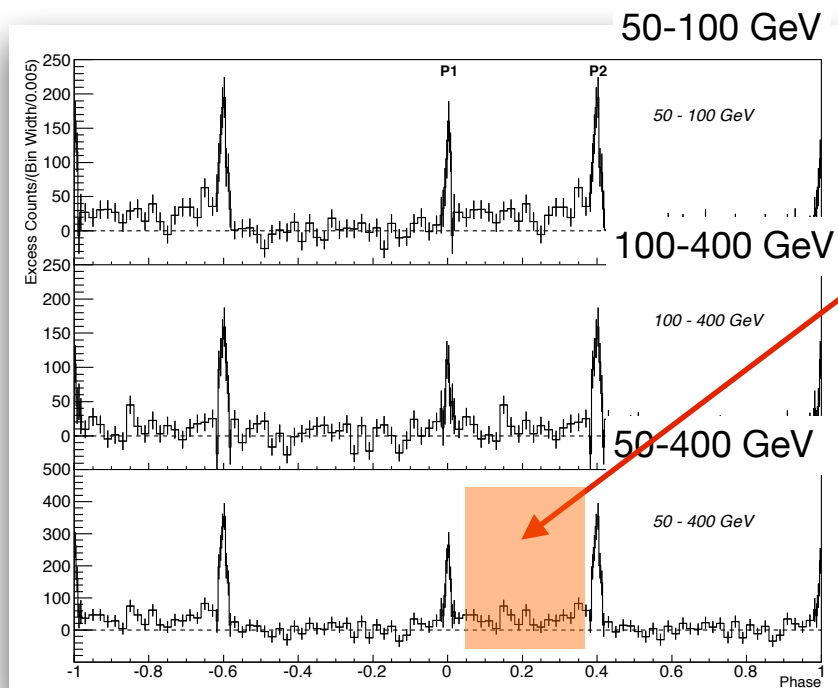
Multi-TeV pulsed emission reaching 20 TeV (!)
Second component different from the lower energy one.

Geminga pulsar



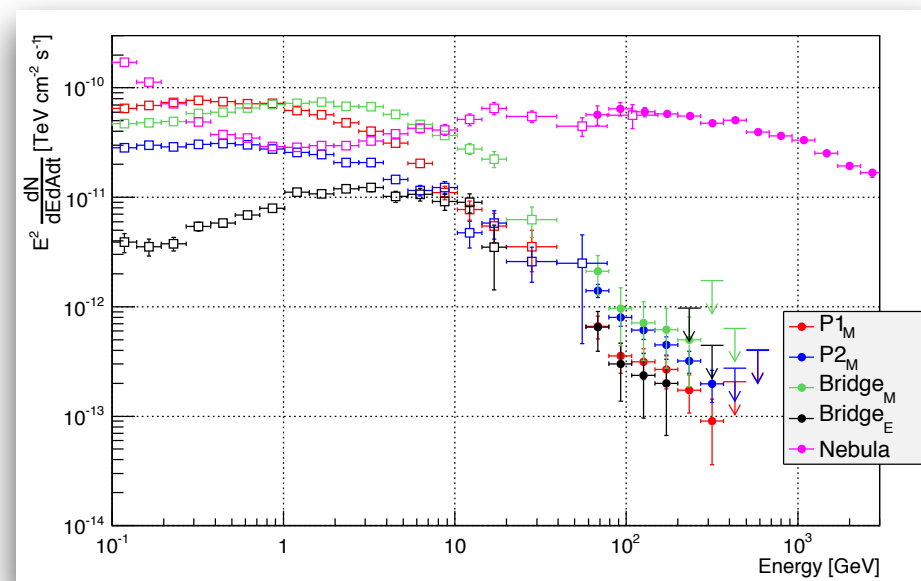
- 3rd pulsar measured by an IACT
 - Detection between 15 and 80 GeV.
 - P2 detected with significance > 6 sigma.
 - First middle-age pulsar (age ~ 300 kyr) detected to emit at such high energies.

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 6σ for energies above 50 GeV

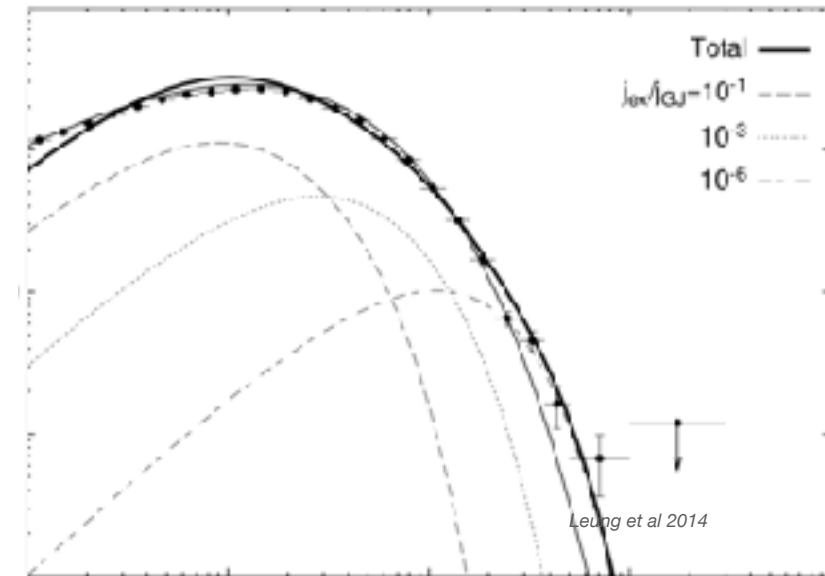
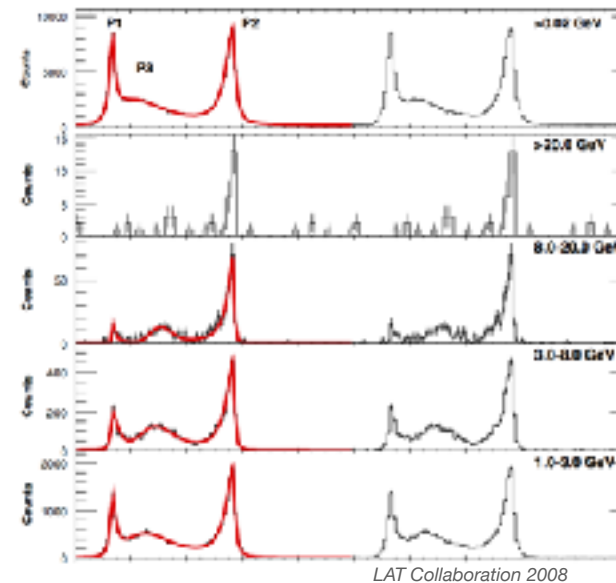
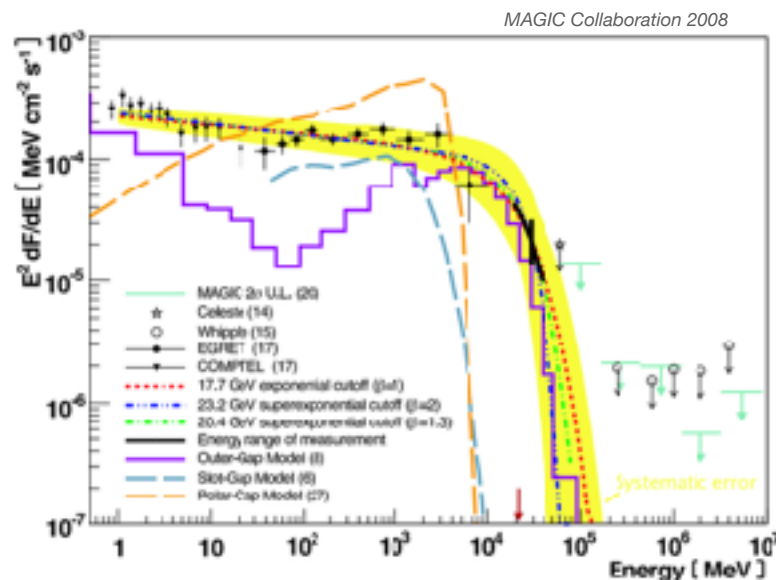


High energy radiation from pulsars

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

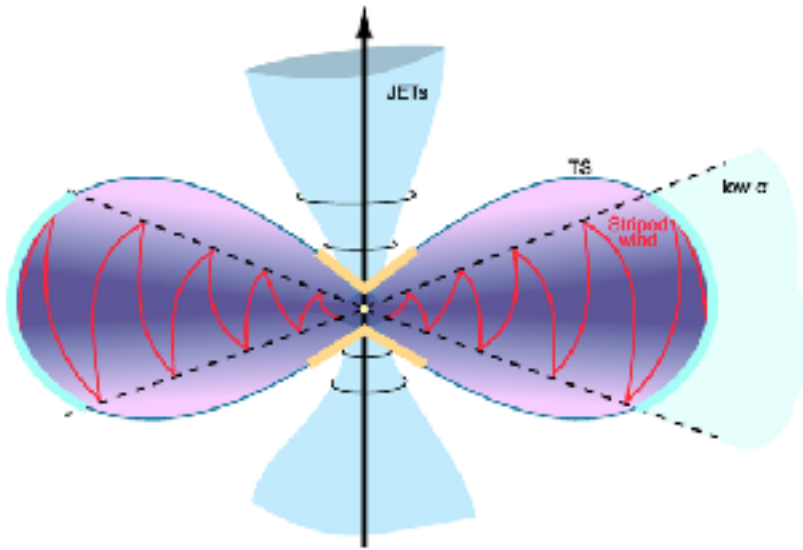
- Evolution of the peaks
 - *Caustic* of different size?

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



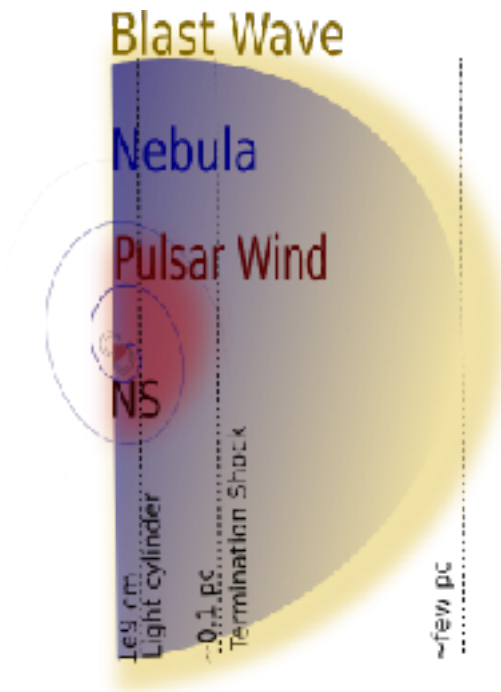
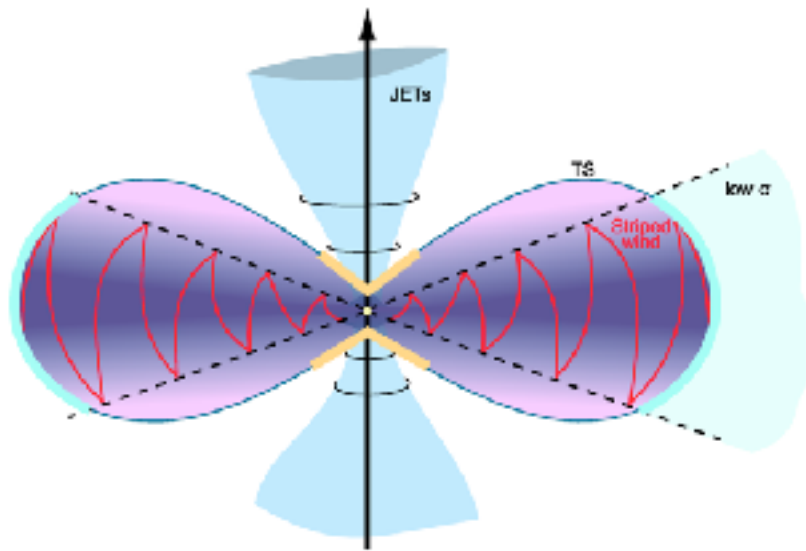
High energy radiation from pulsars

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



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?



The maximum energy:

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

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

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

Then the E_{\max} :

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

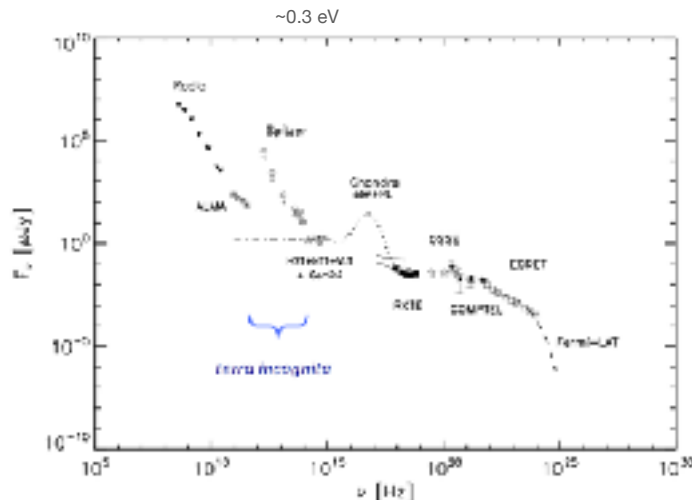
and if CMB (only target >100 TeV)

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

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

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 $b \ll 1$
 $b \approx 15 E_{e, \text{TeV}} E_{\text{target_ph, eV}}$
 \Rightarrow Klein-Nishina regime dominant (1-20 TeV)

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

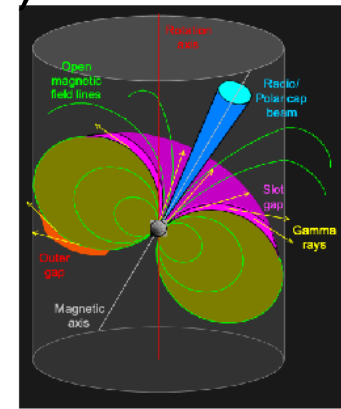
$\Rightarrow \Gamma = 4 \times 10^7$ (20 TeV)

$\Rightarrow \Gamma = 2 \times 10^6$ (TeV)

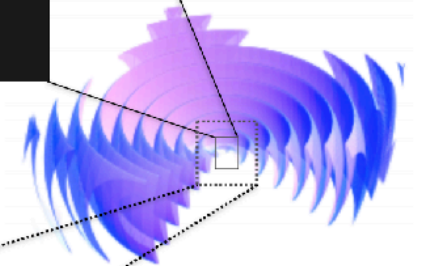
High energy radiation from pulsars

- **Within the magnetosphere** (or rather within the gaps):

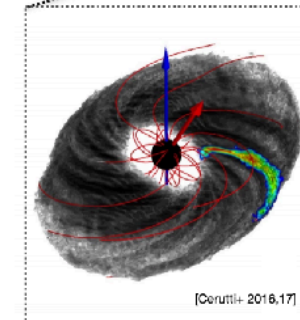
- Electrons are accelerated in gaps through $E_{\parallel} = \eta B$
- HE => CR radiation
- VHE => IC on low-energy photon target



[Many !]



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



[Corutti+ 2016,17]

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

$$\eta \lesssim 10\%$$

Using Vela values

gain rates

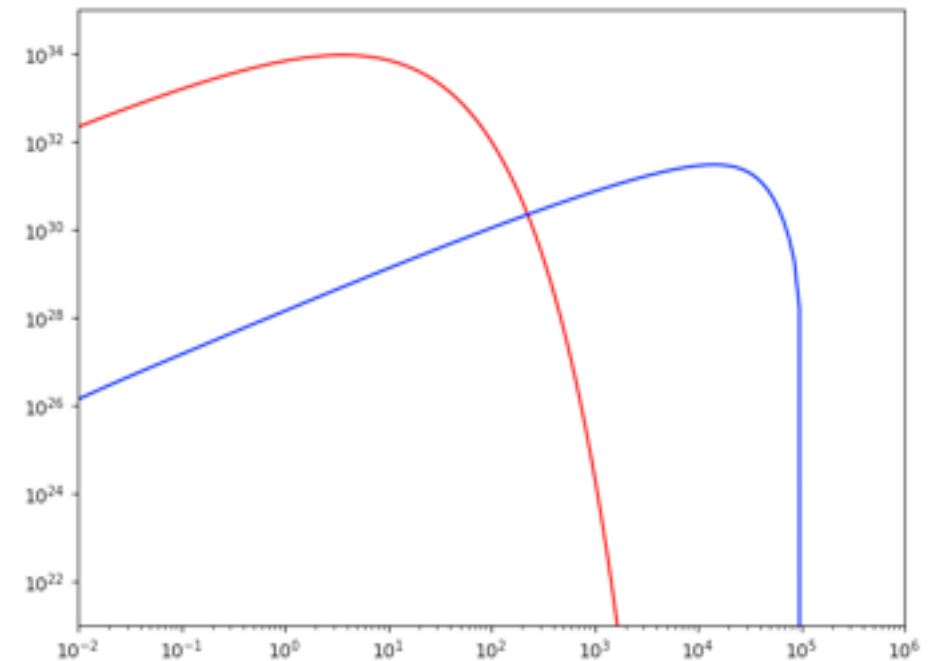
$$-\frac{dE}{dt} = e c \eta B$$

energy loss

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

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

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

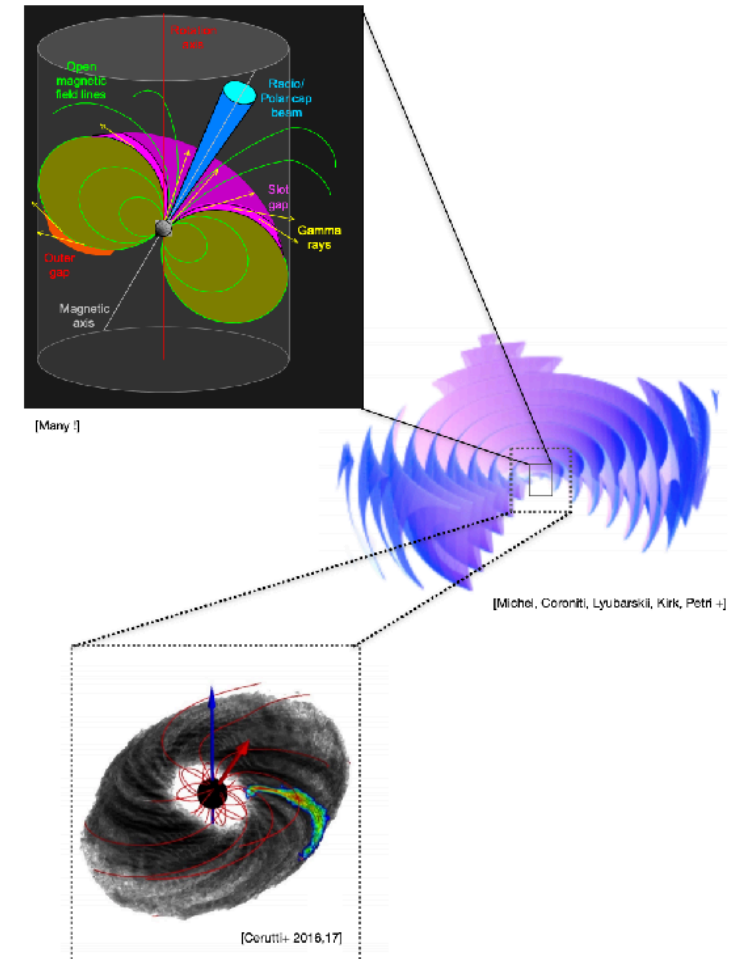


$$R_C = \xi R_{LC} = \xi (cP/2\pi) \Rightarrow \xi > 1$$

Acceleration & Emission beyond the magnetosphere

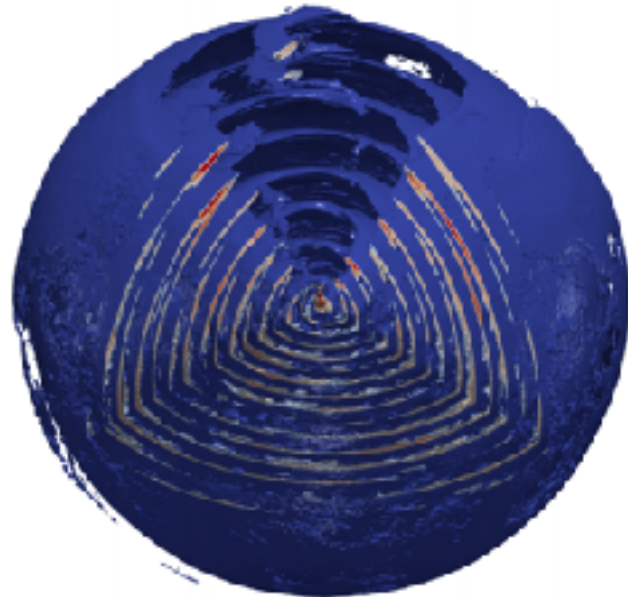
High energy radiation from pulsars

- 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!

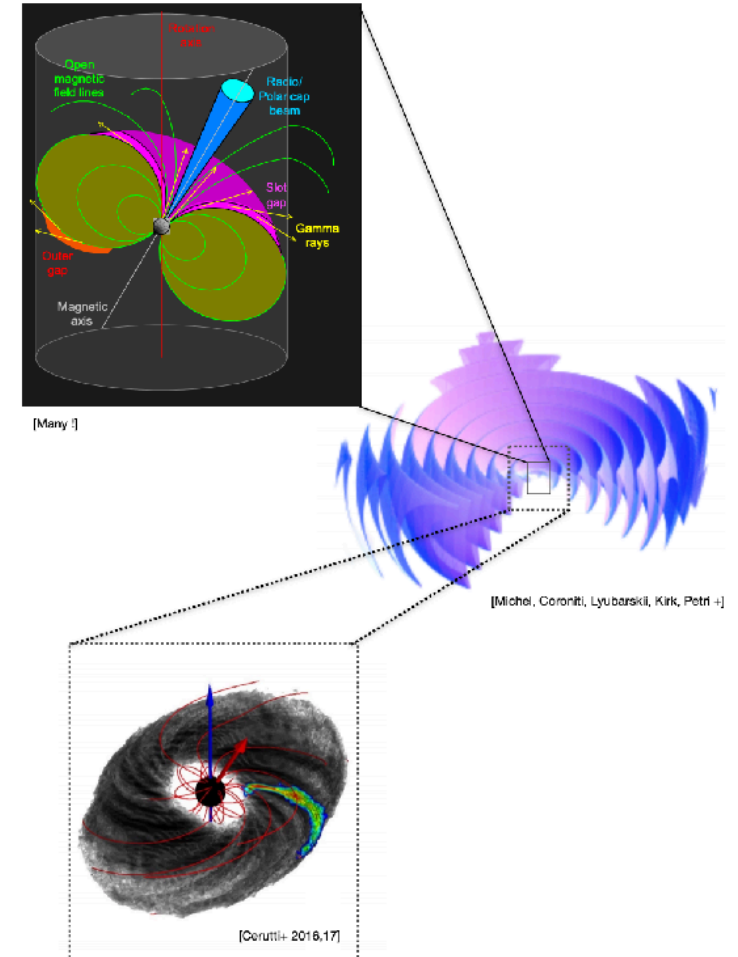


High energy radiation from pulsars

- 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 Cerutti et al 2020



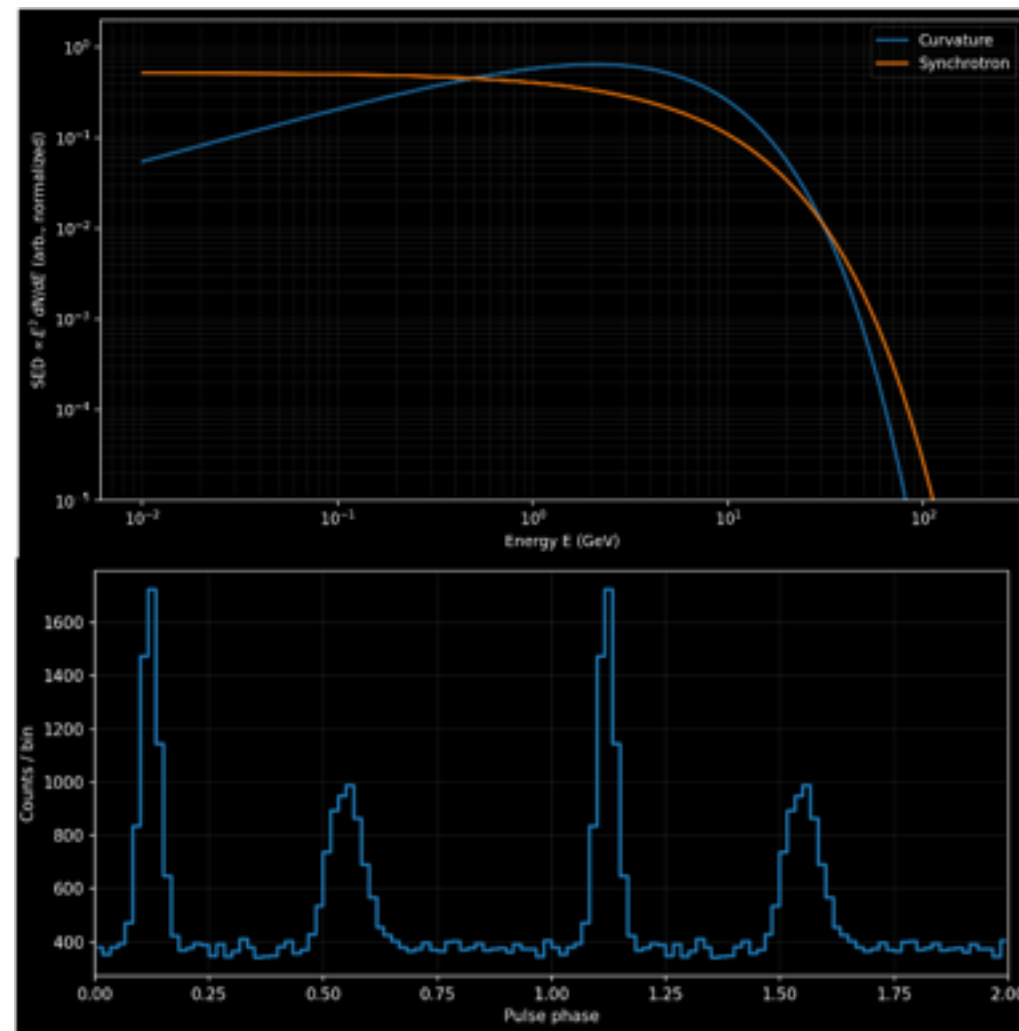
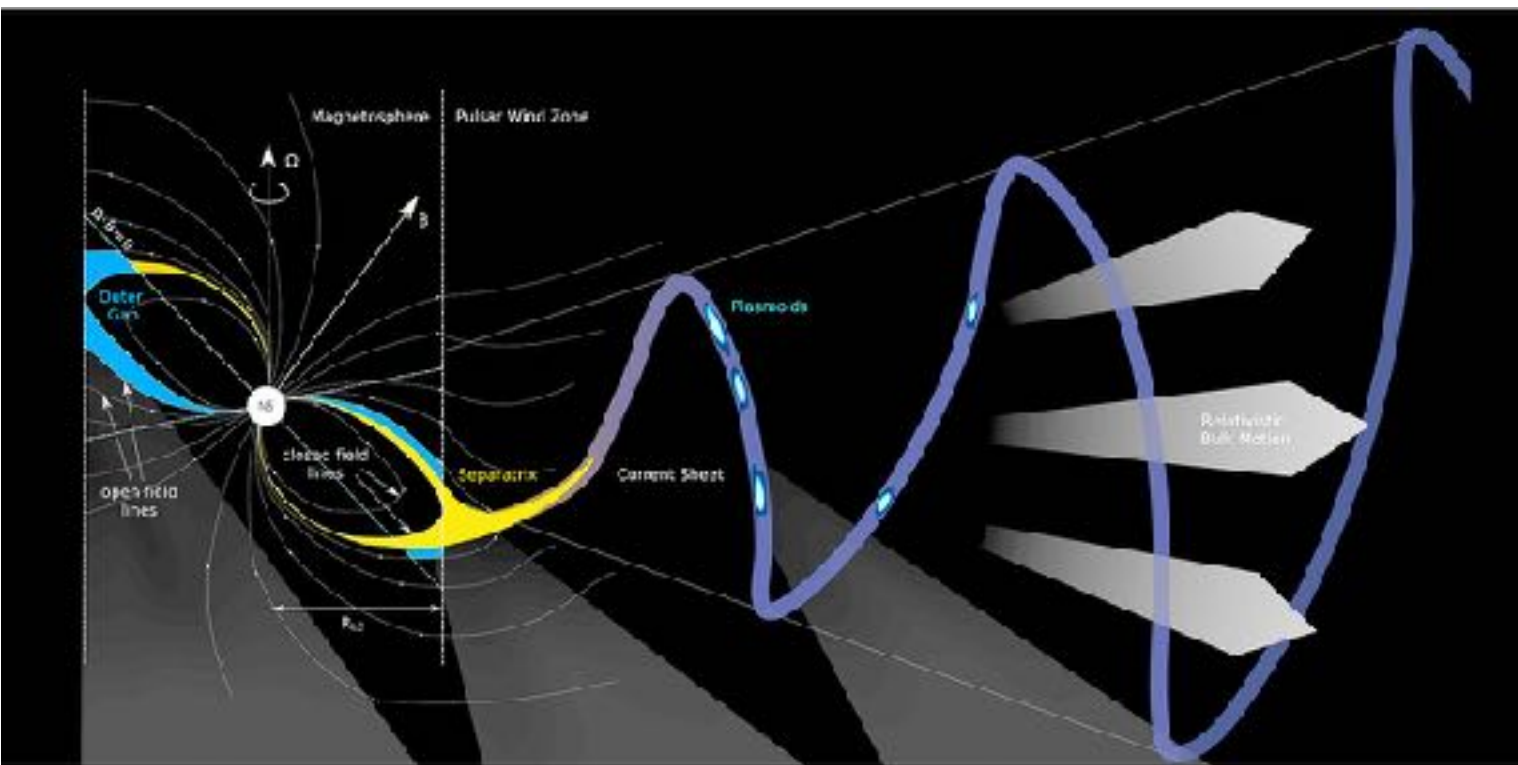
[Many !]

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

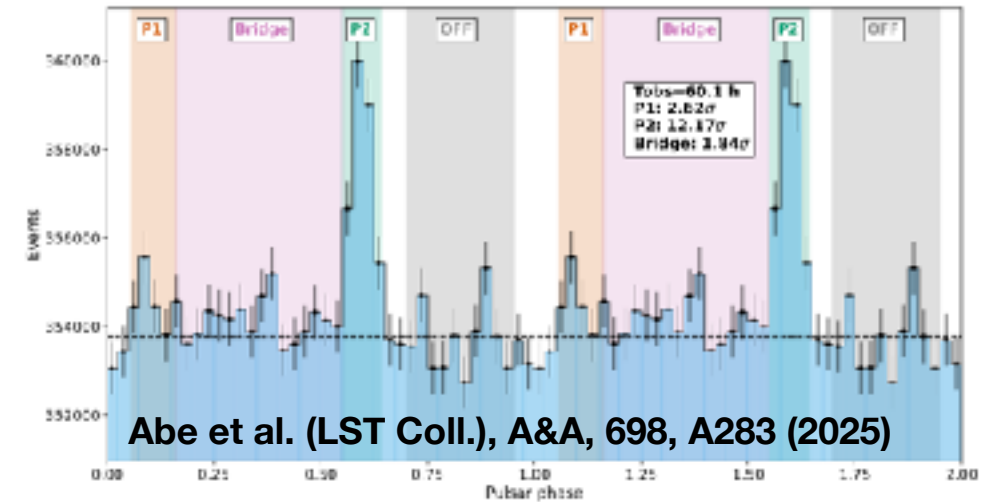
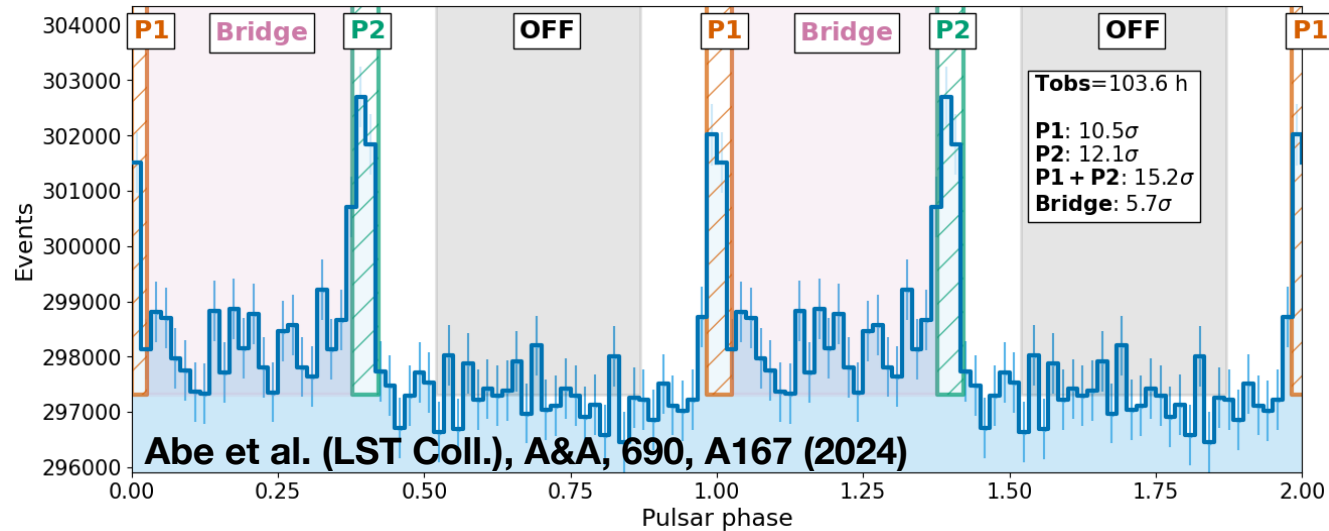
[Cerutti+ 2016,17]

Multi-TeV energy emission

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



Pulsars with LST-1



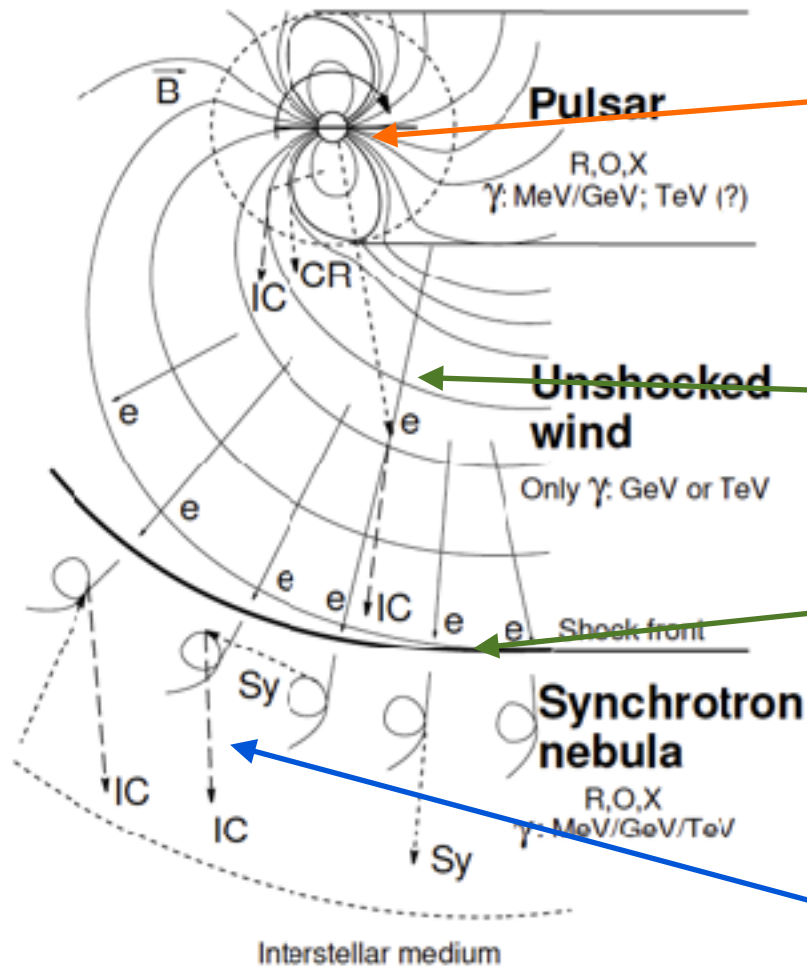
- LST-1 of CTAO measured the **Crab Pulsar** spectrum from few tens of GeV up to hundreds of GeV.

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

Pulsar Wind Nebulae



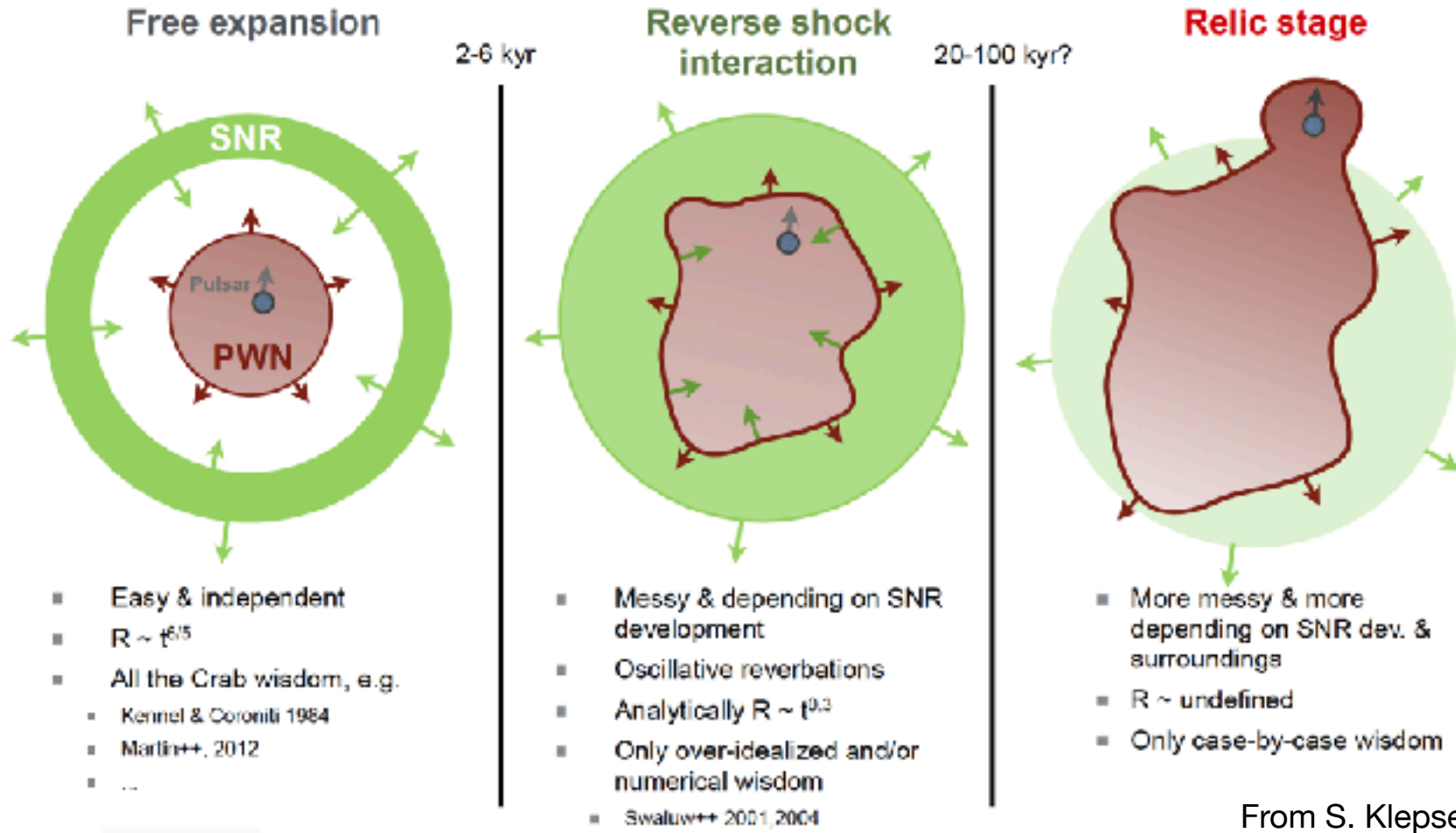
Pulsar wind nebulae



- e^\pm are accelerated in the magnetosphere's gaps.
- Radiationless e^\pm wind.
- Termination Shock (TS) $\rightarrow e^\pm$ are decelerated.
- Synchrotron and Inverse Compton (IC) is produced in the nebula.

Pulsar complex evolution

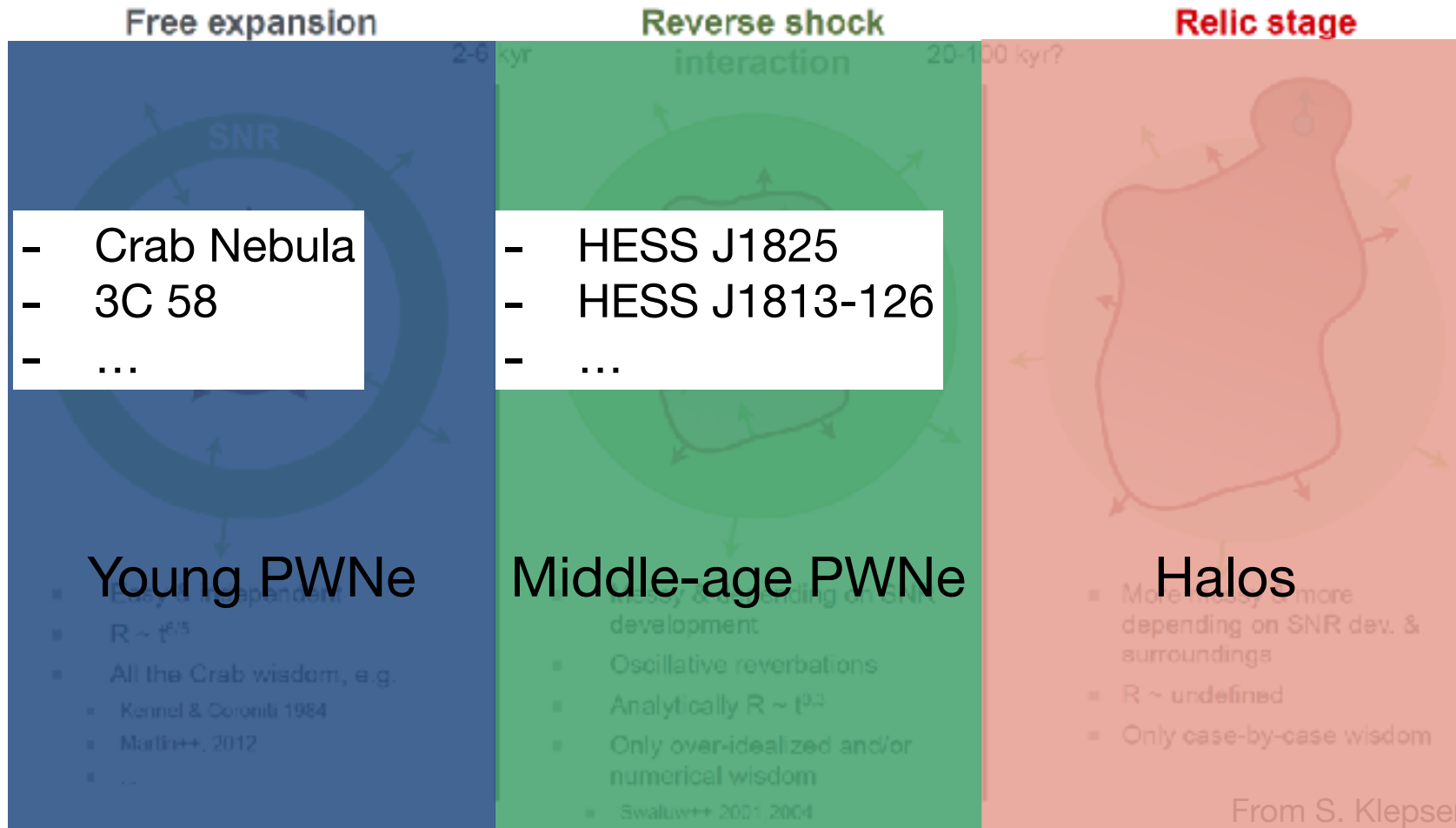
PWN Evolution in a Nutshell



From S. Klepser

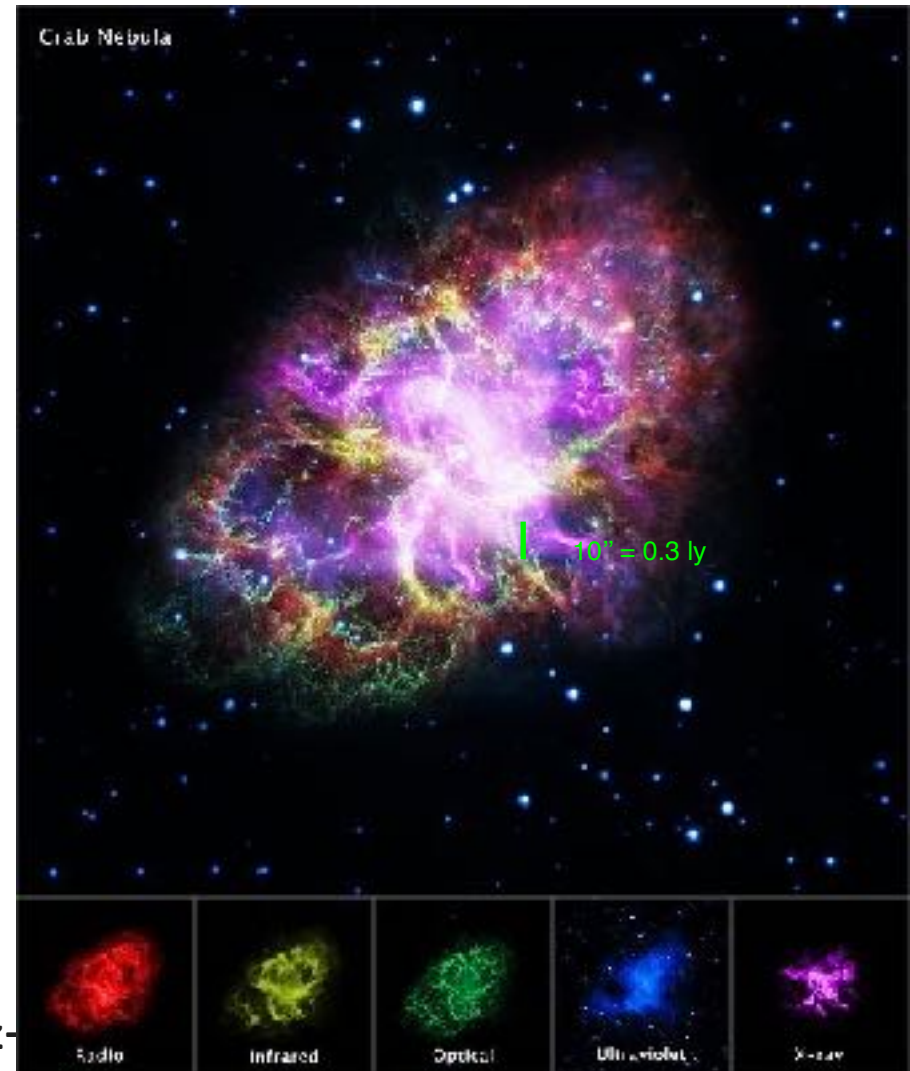
Pulsar complex evolution

PWN Evolution in a Nutshell



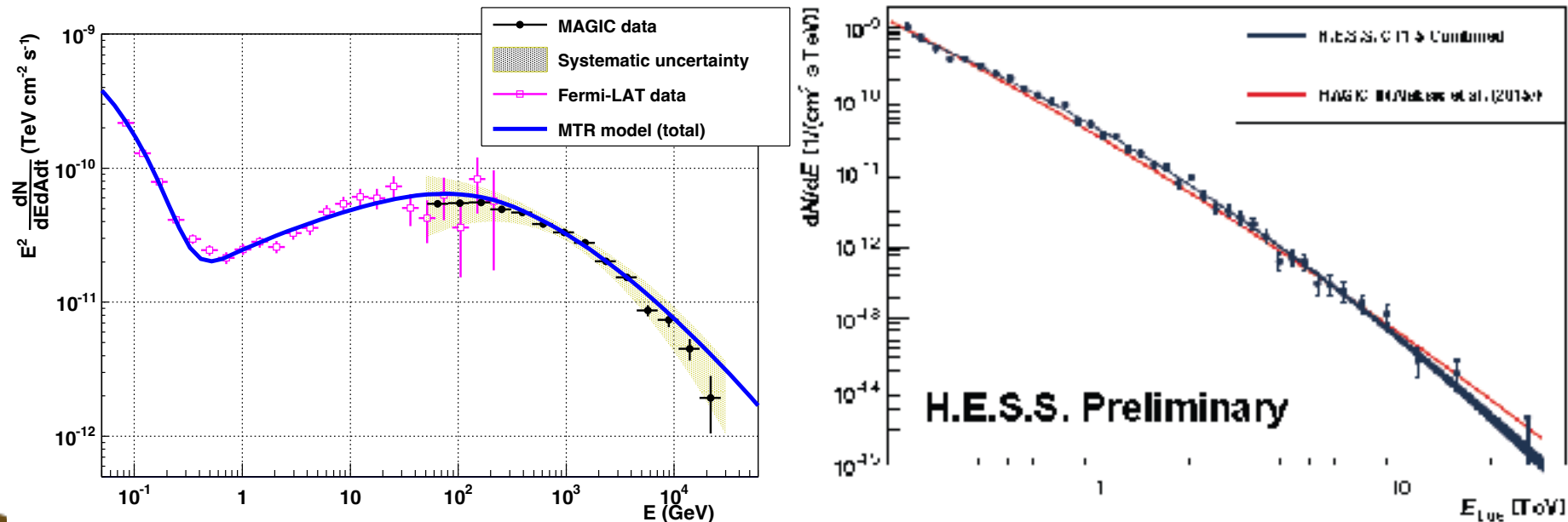
CR Accelerators: Pulsar Wind Nebulae

- The archetype: the Crab Nebula
- Bright in many wavelengths
- Different size \Leftrightarrow Different electron population



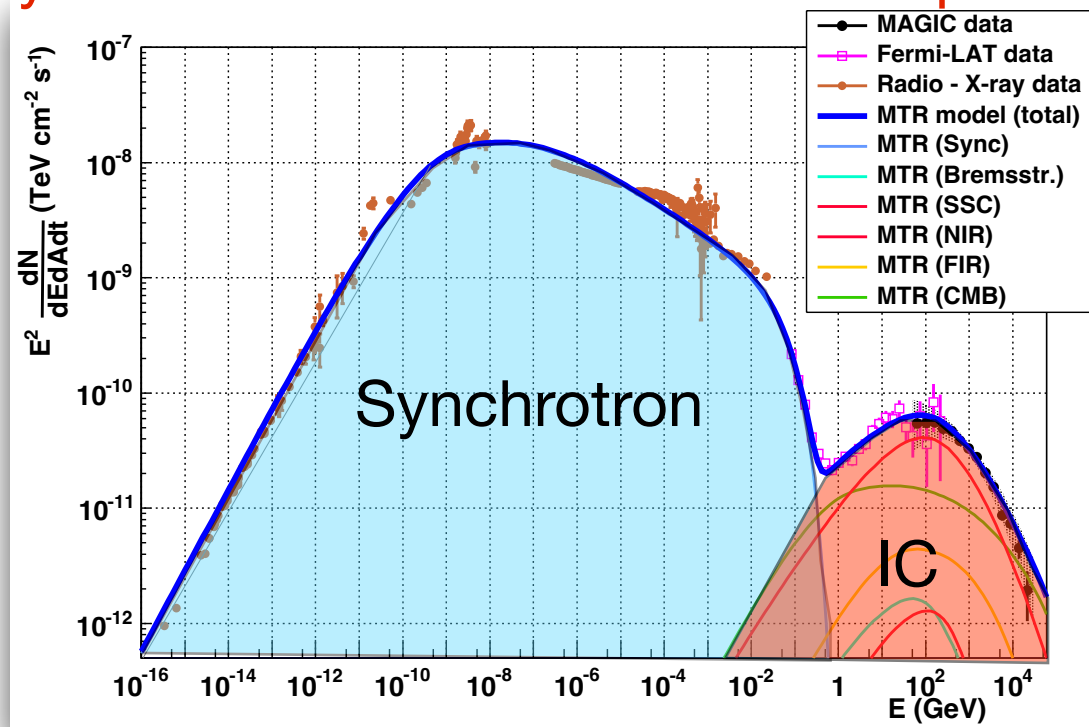
The VHE gamma-ray calibrator: the Crab Nebula

- 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

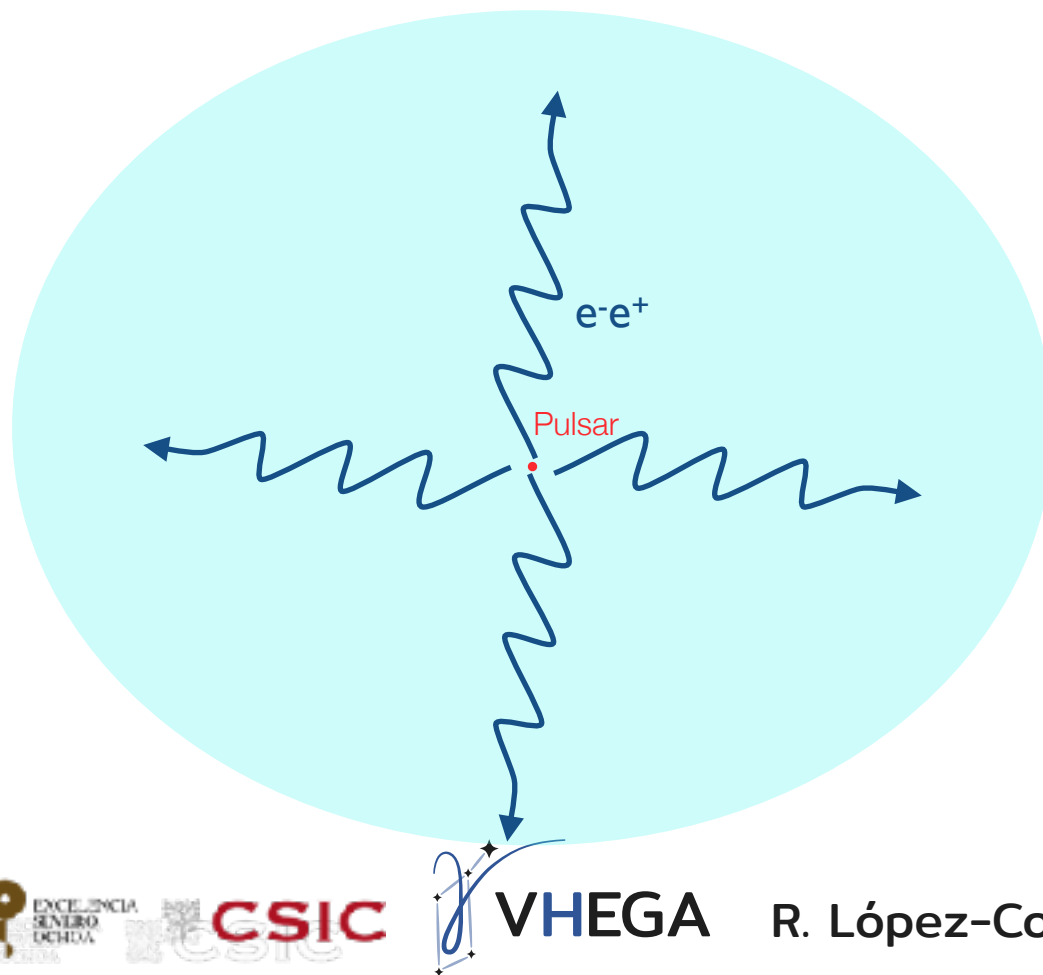
- PWN spectra are composed by two distinct components, the **synchrotron** and the **inverse Compton (IC)** part.



- Most popular models:
 - **Magnetohydrodynamic (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).

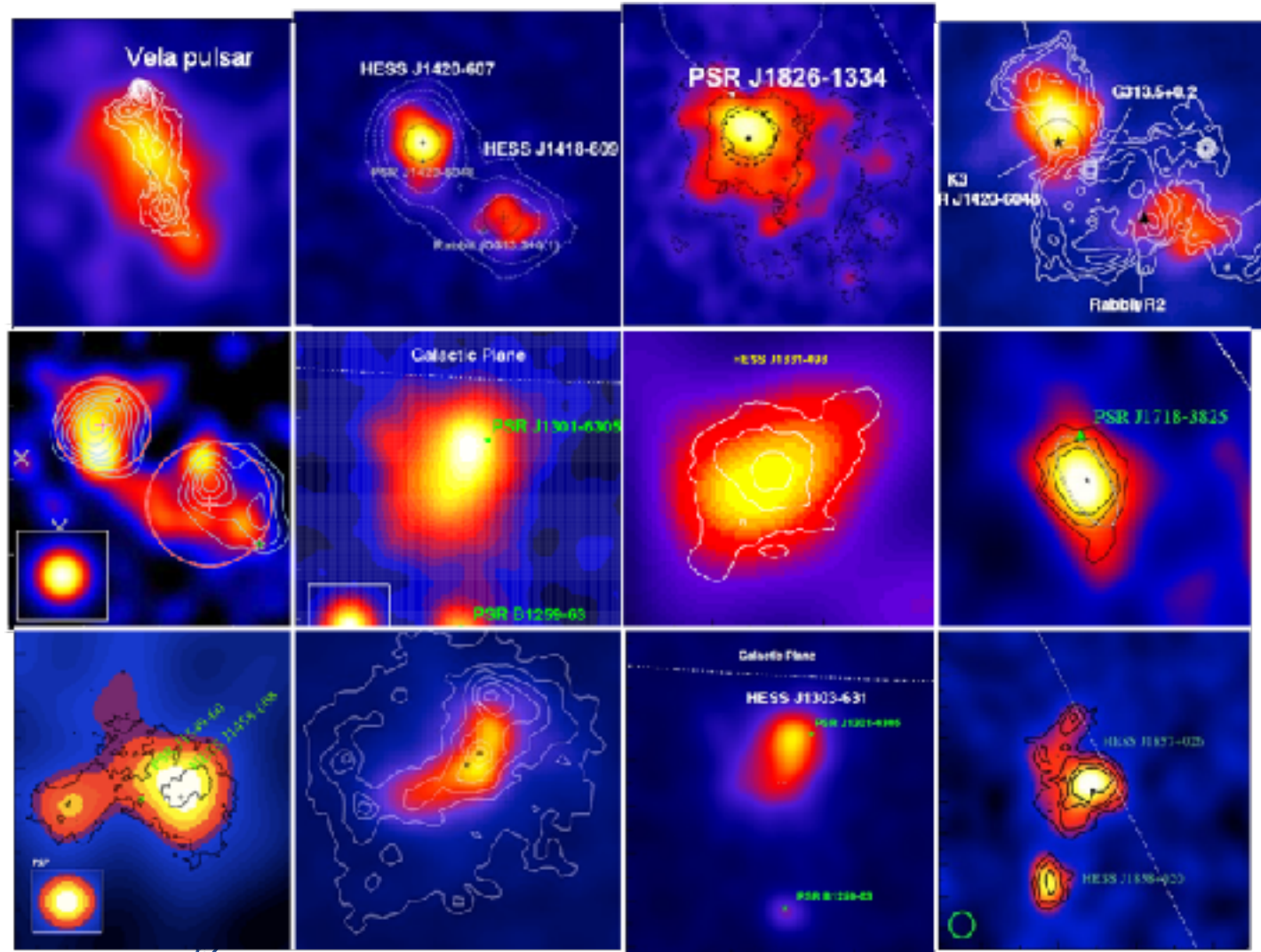
Particle emission of a PWN



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

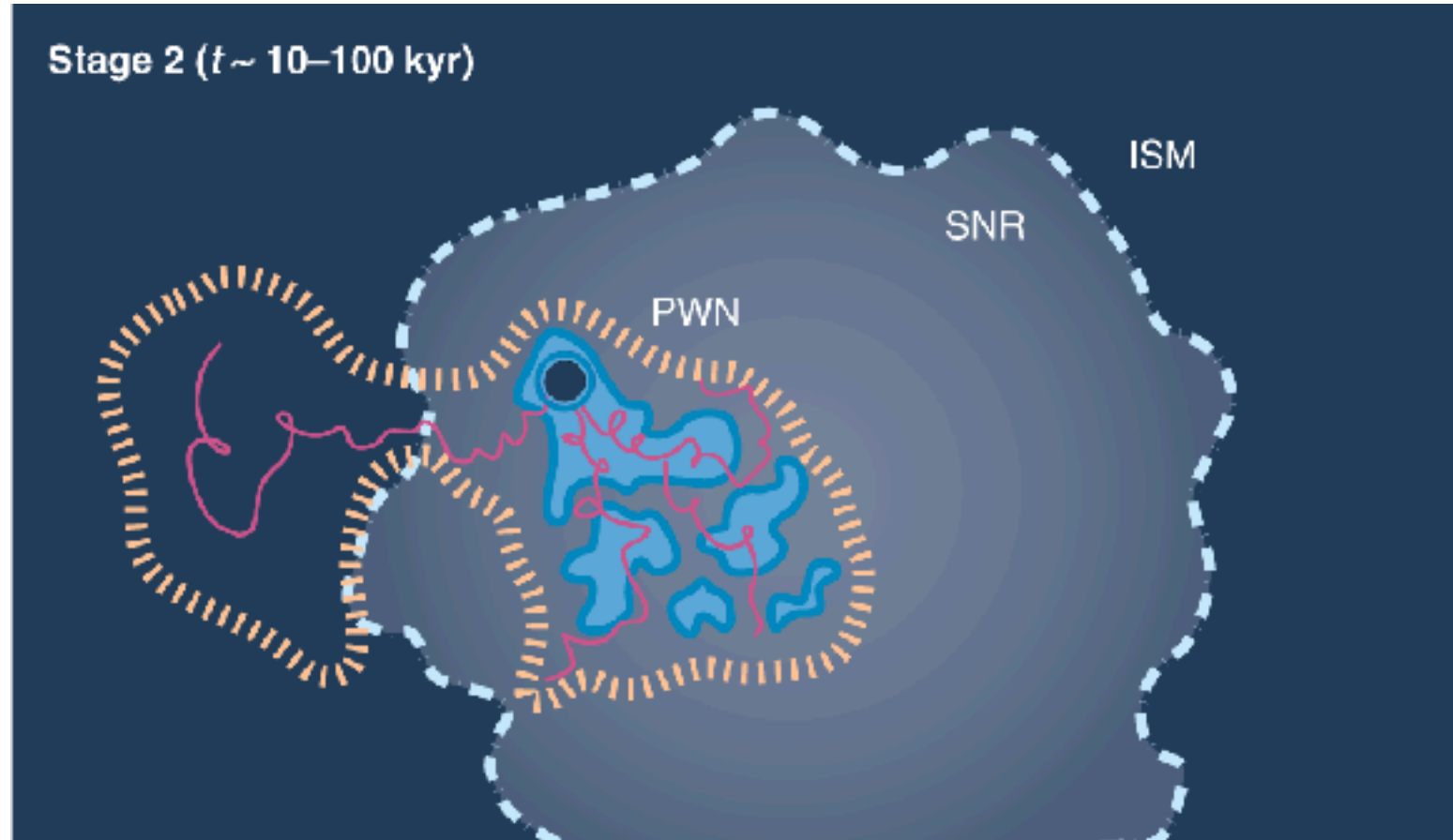
$$L(t) = L_0 \left(1 + \frac{t}{\tau}\right)^{-\frac{n+1}{n-1}}$$

TeV Pulsar Wind Nebulae

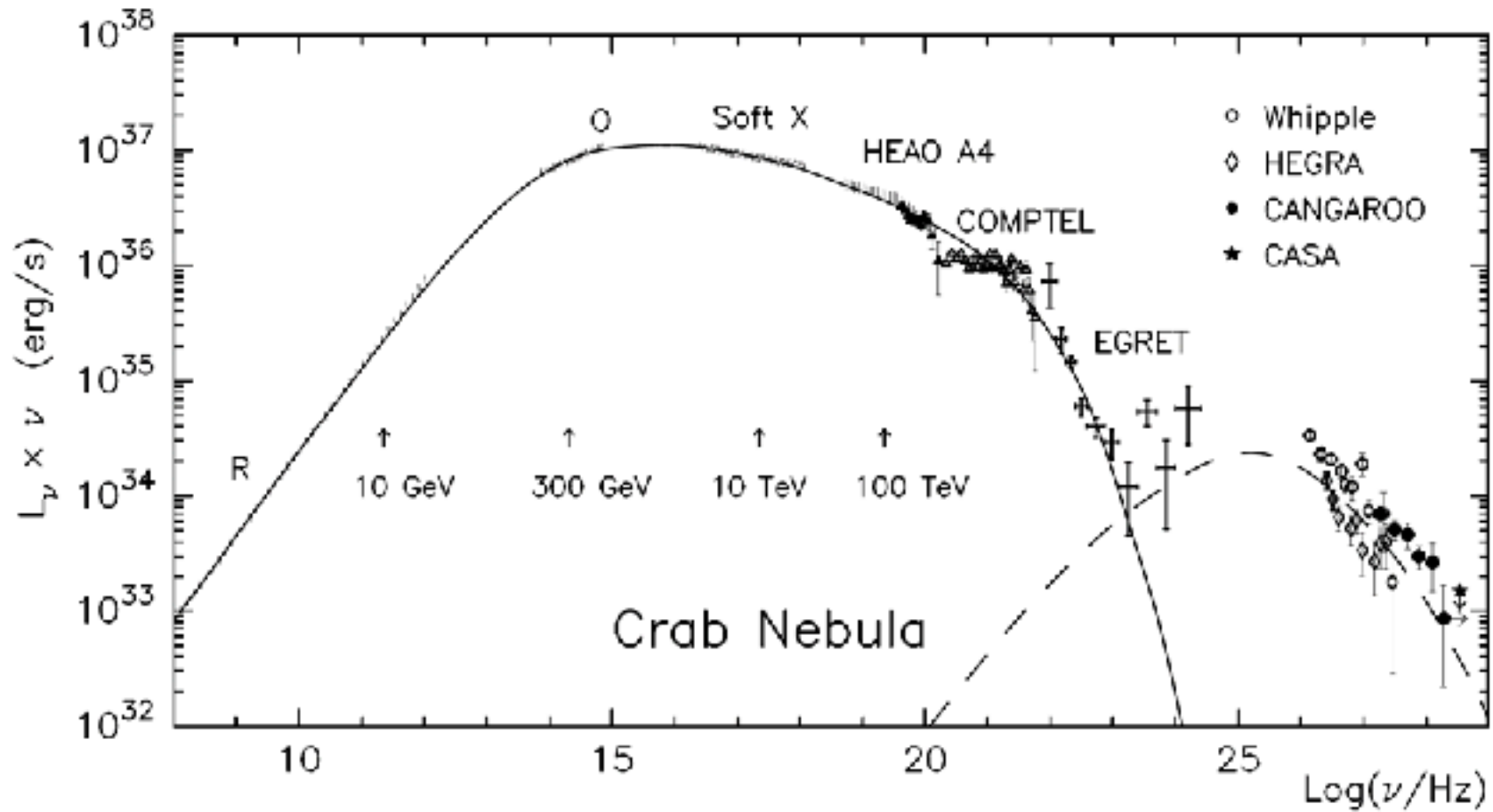


CR Accelerators: Pulsar Wind Nebulae

- The most numerous population in the Galaxy at VHE

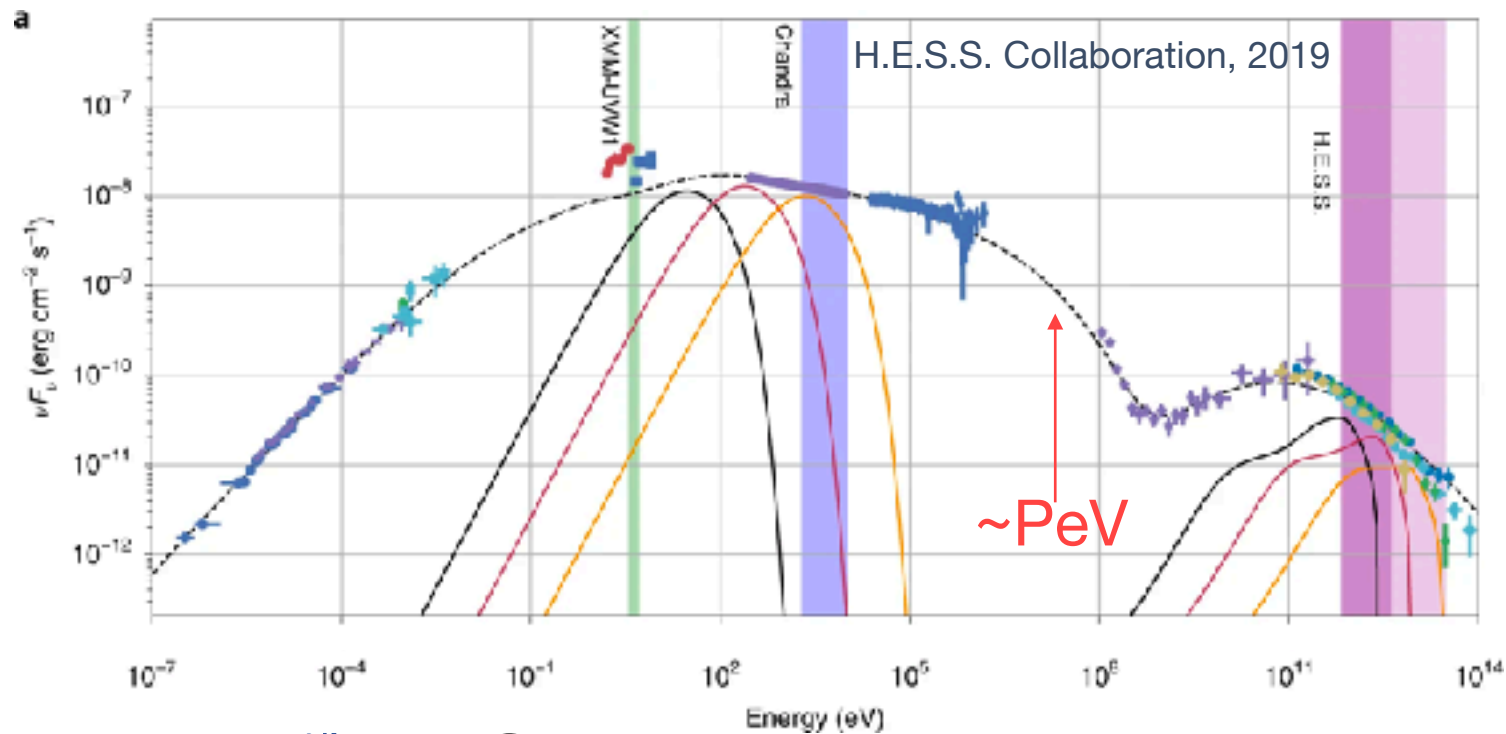


CR Accelerators: Pulsar Wind Nebulae



Leptonic PeVatrons

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



CR Accelerators: Pulsar Wind Nebulae

- Energetics:

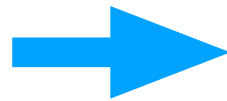
- Syn => Depends on the **magnetic field**

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

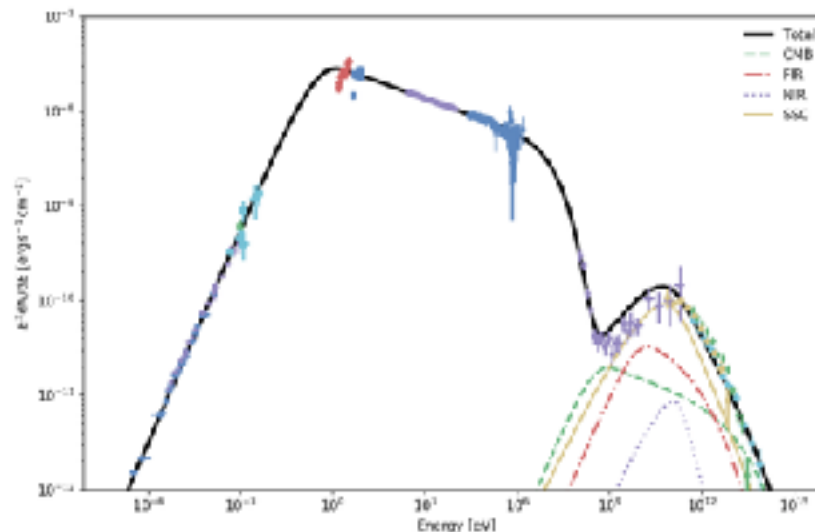
- IC => Depends on the **photon field**

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

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



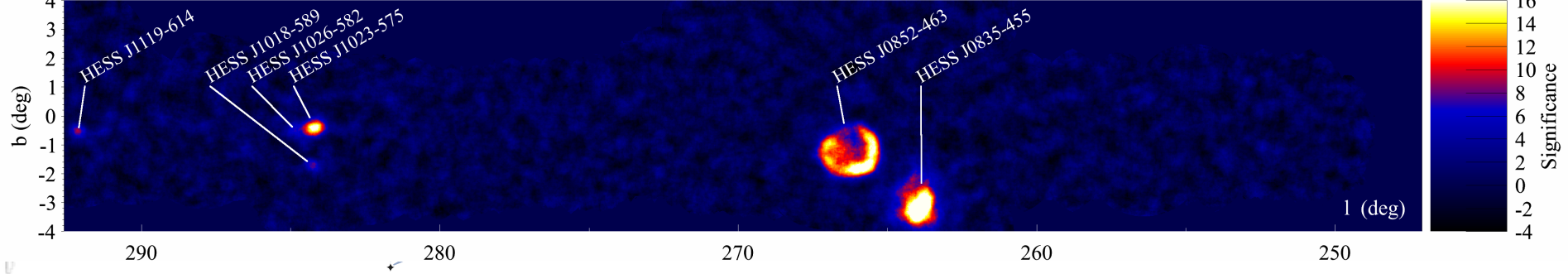
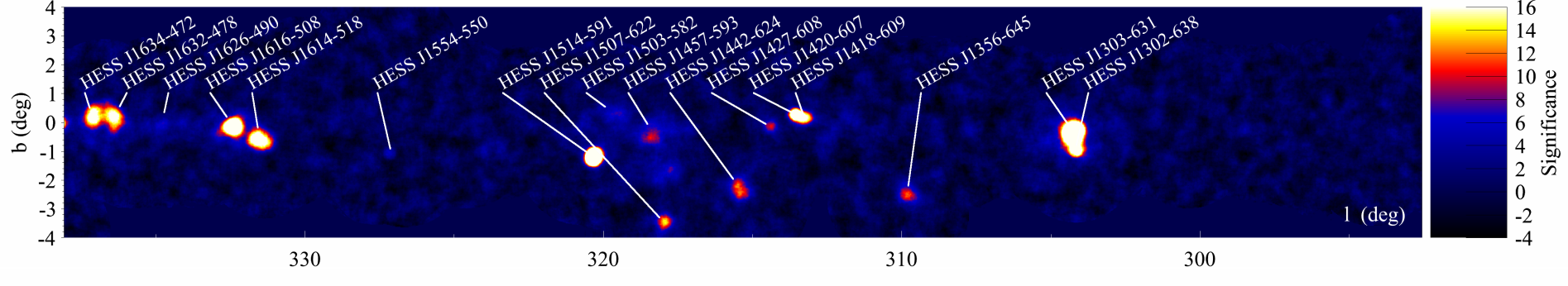
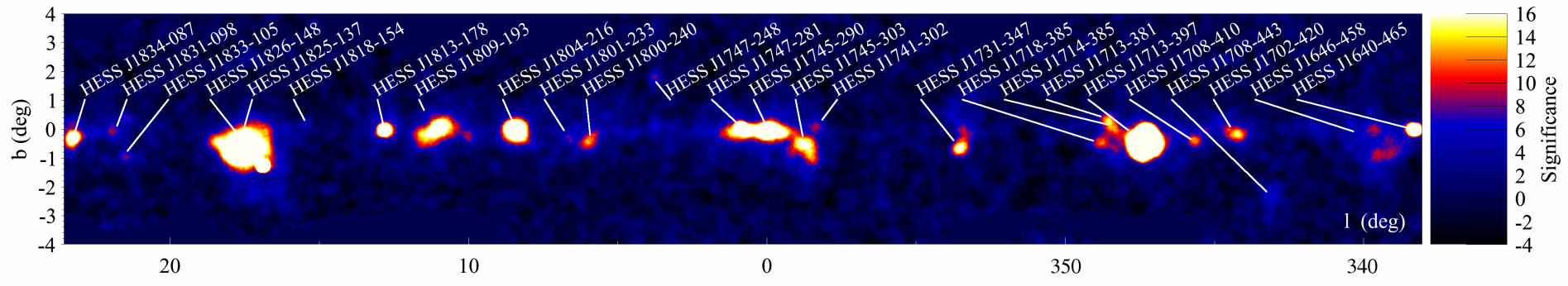
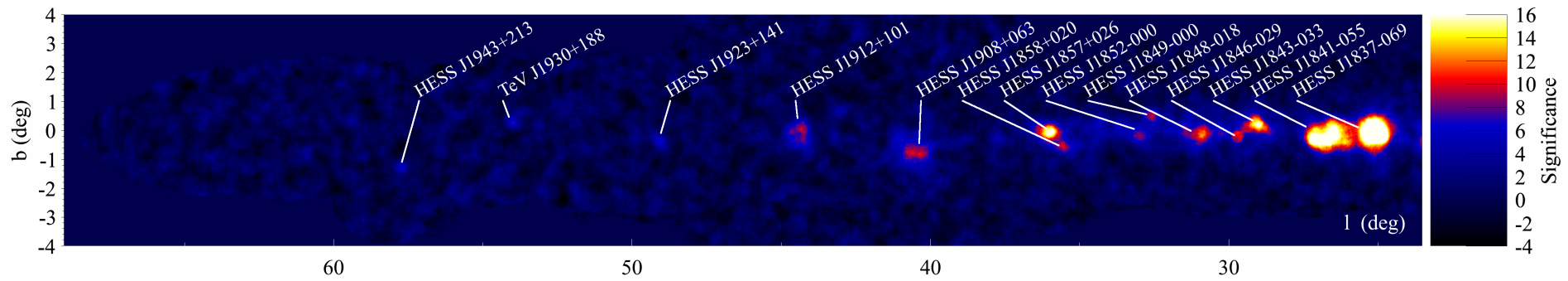
$$\frac{L_1}{L_2} = \frac{U_B}{U_{ph}} = \frac{\frac{B^2}{8\pi}}{\omega_{CMB} + \omega_{FIR} + \omega_{NIR} + \omega_{SYN}}$$



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

For CMB

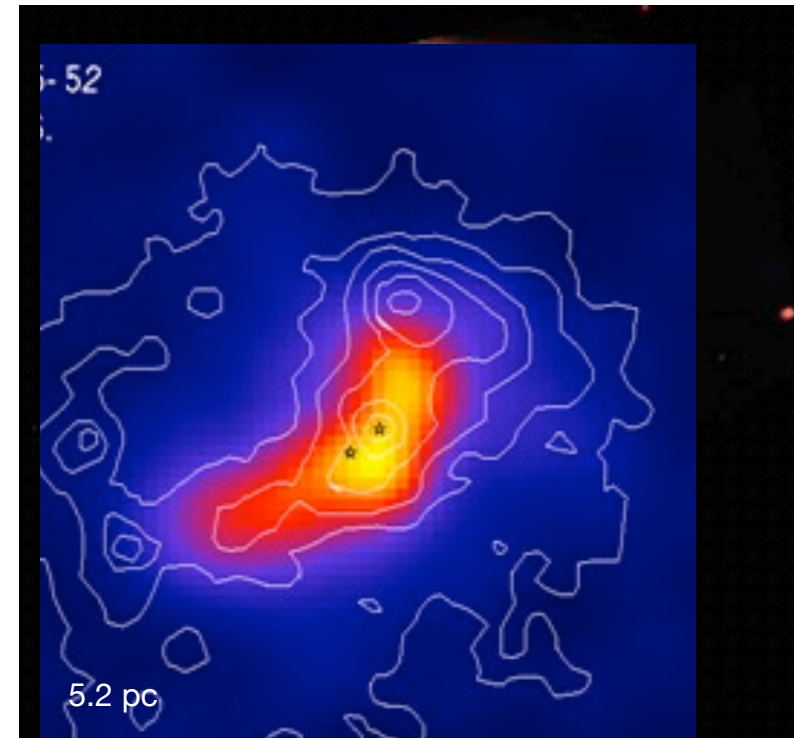
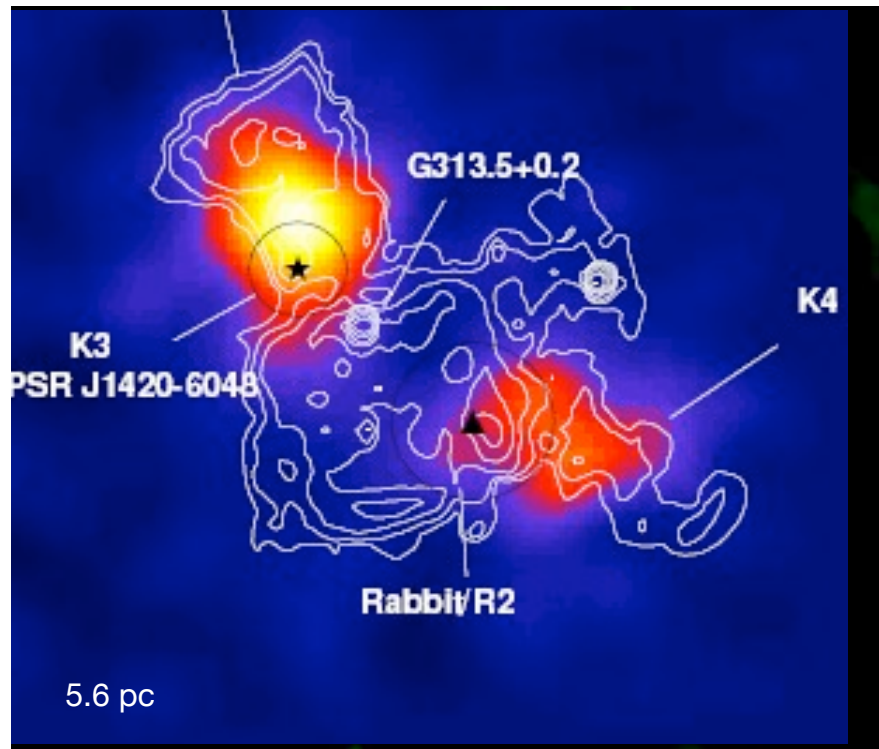
B ~ 100 uG



Accelerators: Pulsar Wind Nebulae

Young PWNe

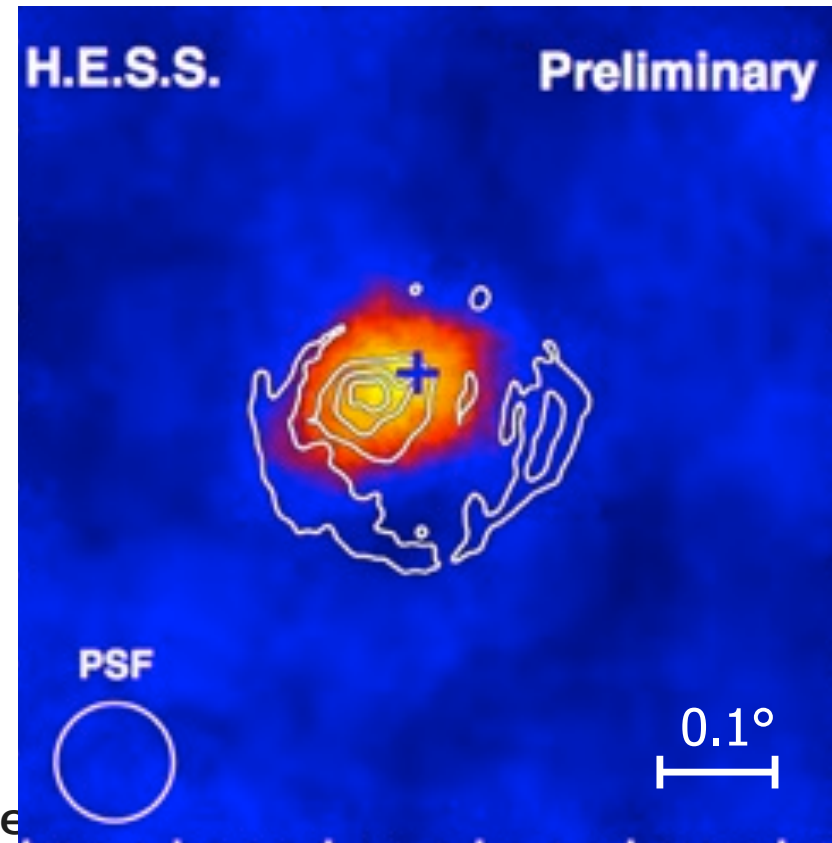
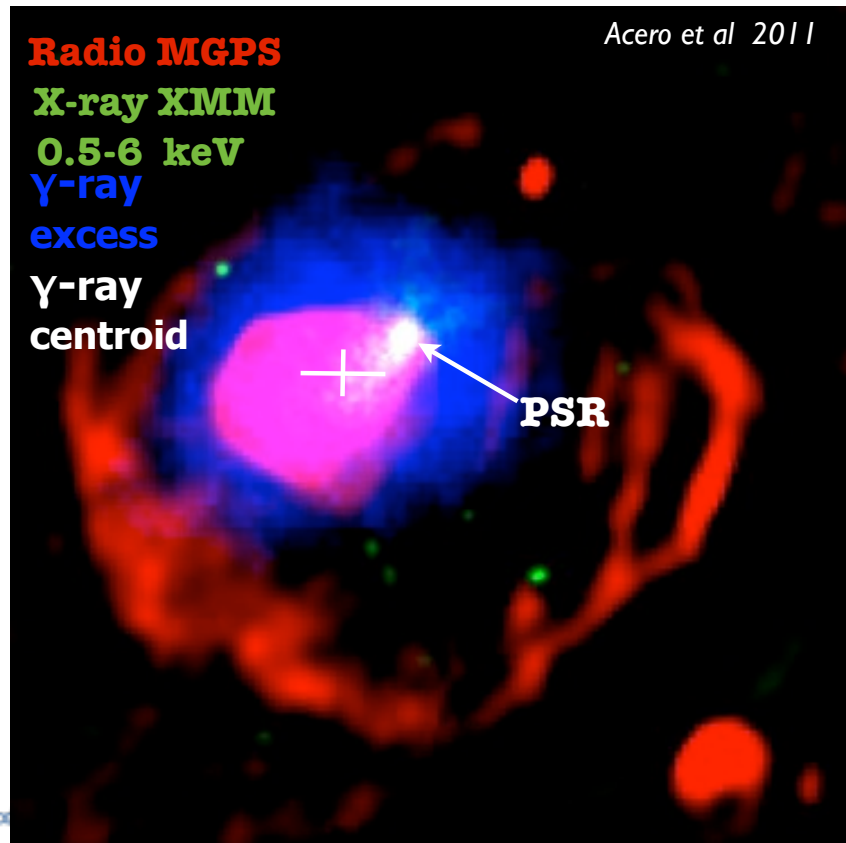
- Excellent correlation with X-rays (large size compensates sometimes the relatively poor angular resolution ~ 0.1 deg)



Accelerators: Pulsar Wind Nebulae

Young PWNe

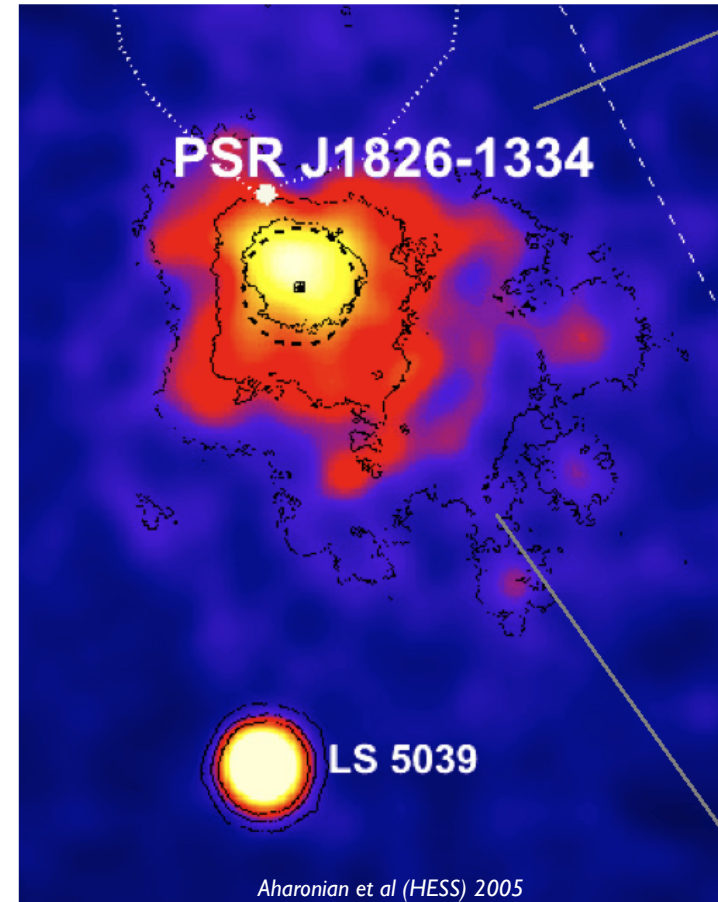
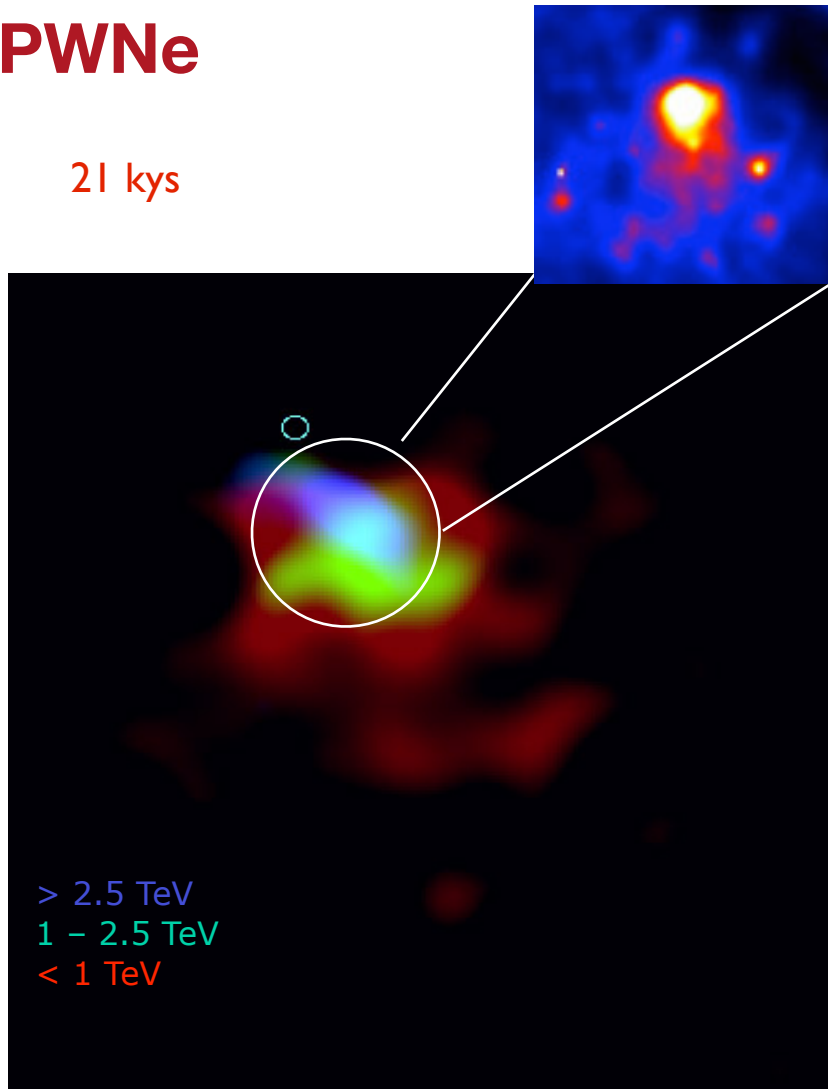
- Very low magnetic fields when comparing with $L_x \sim \text{few } \mu\text{G} \Rightarrow$ Far from equipartition



Accelerators: Pulsar Wind Nebulae

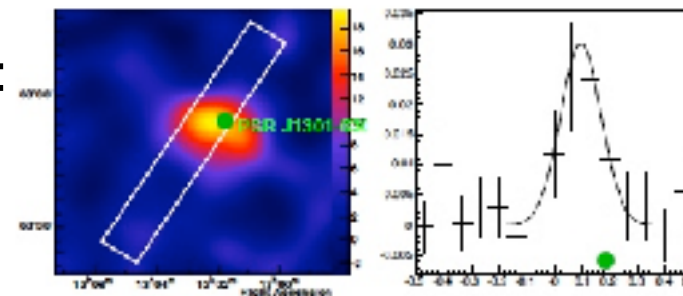
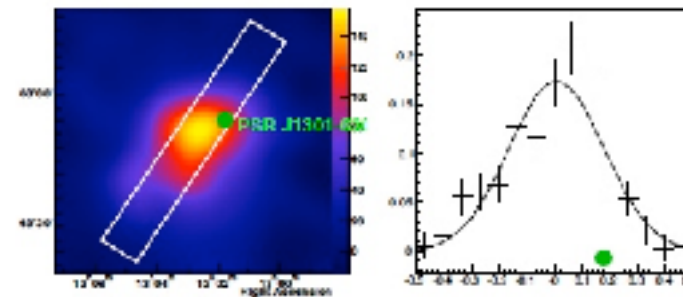
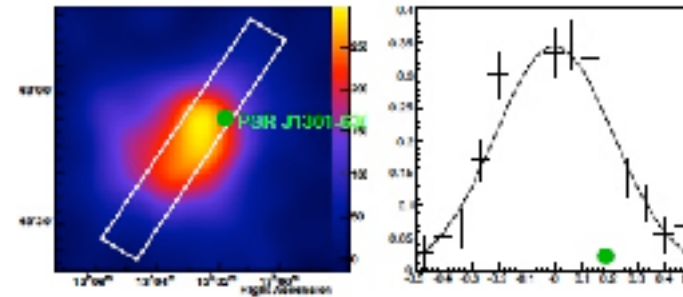
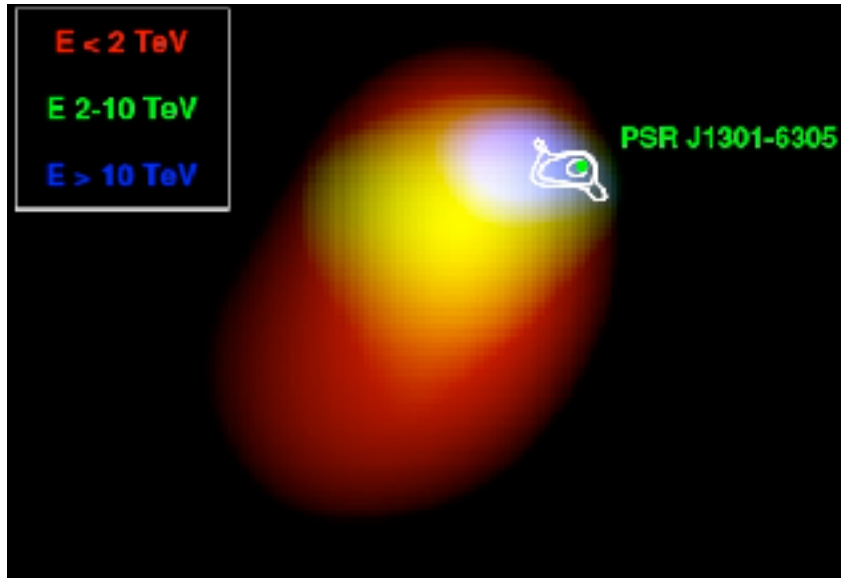
Evolved PWNe

21 kys



Accelerators: Pulsar Wind Nebulae

Evolved PWNe



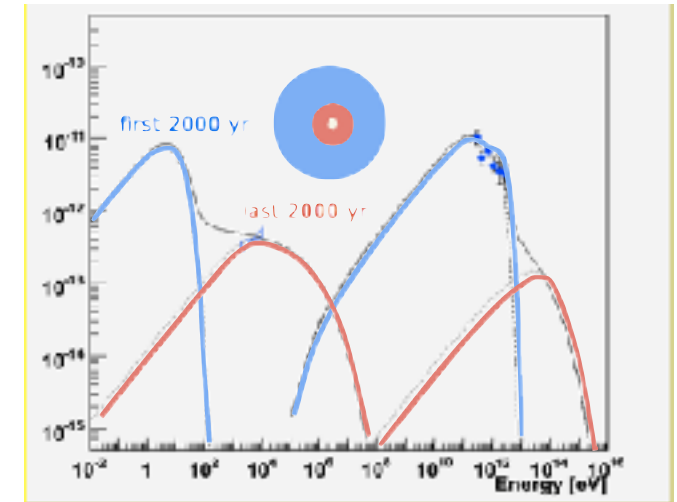
- Shrinking towards high energies
- But keep in mind for evolved systems we mix:
 - Inverse Compton cooling time
 - Diffusion

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.



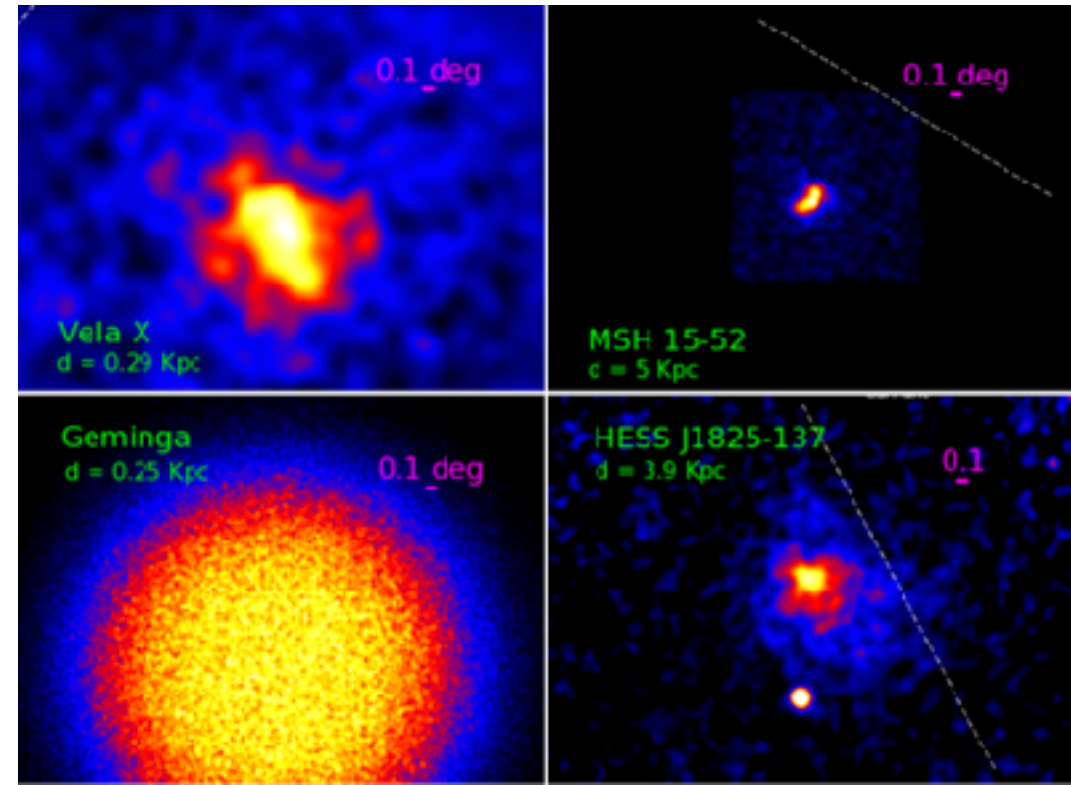
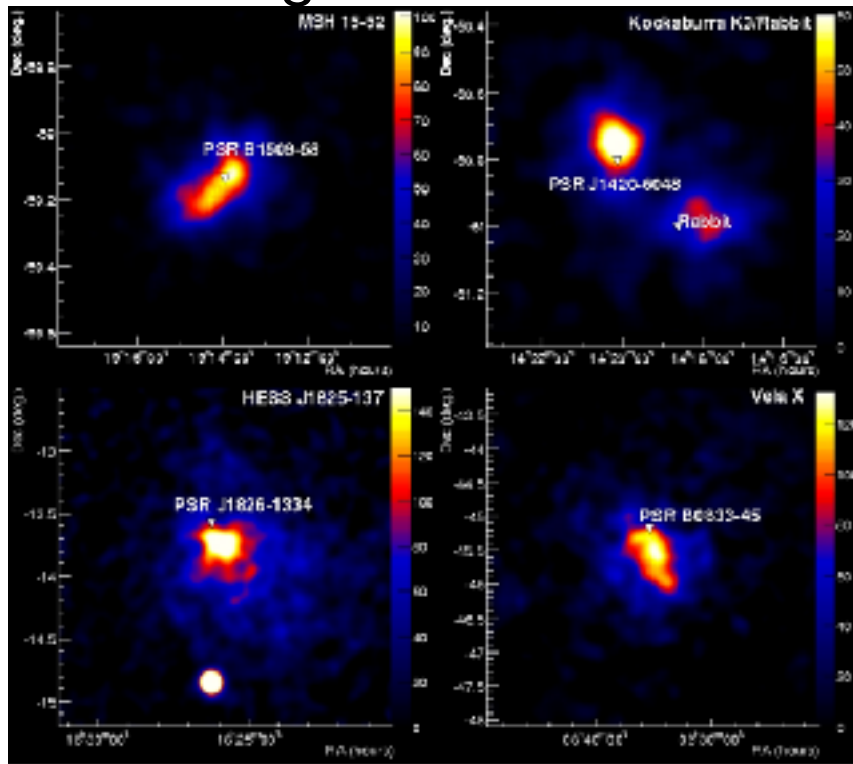
Hofmann 2009

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

Accelerators: Pulsar Wind Nebulae

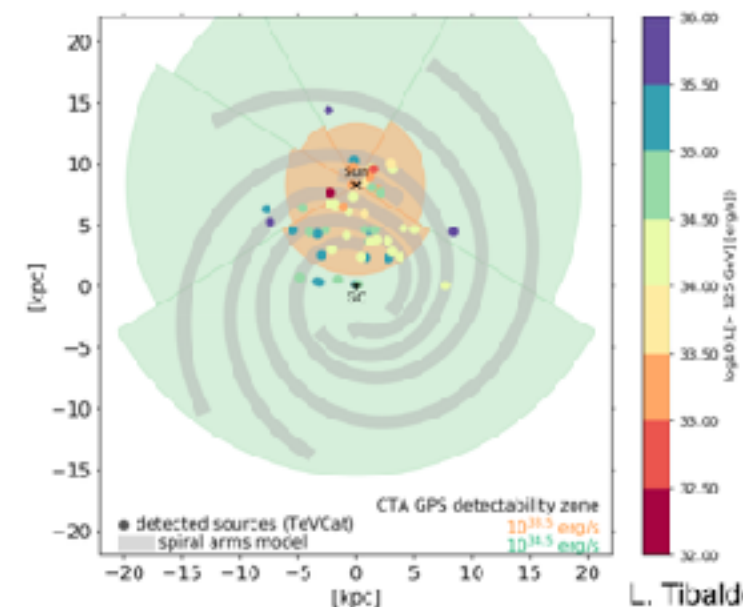
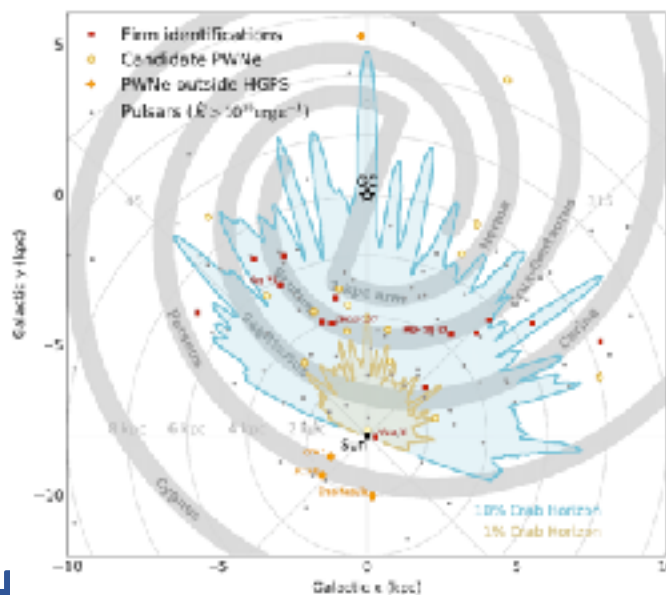
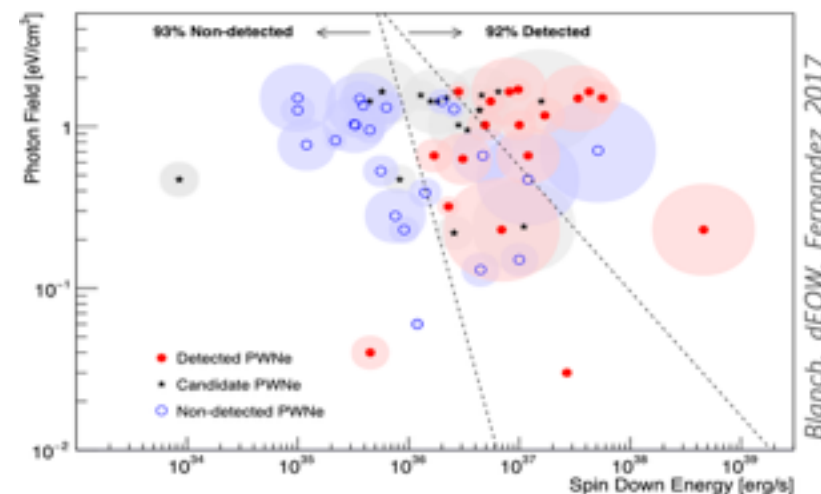
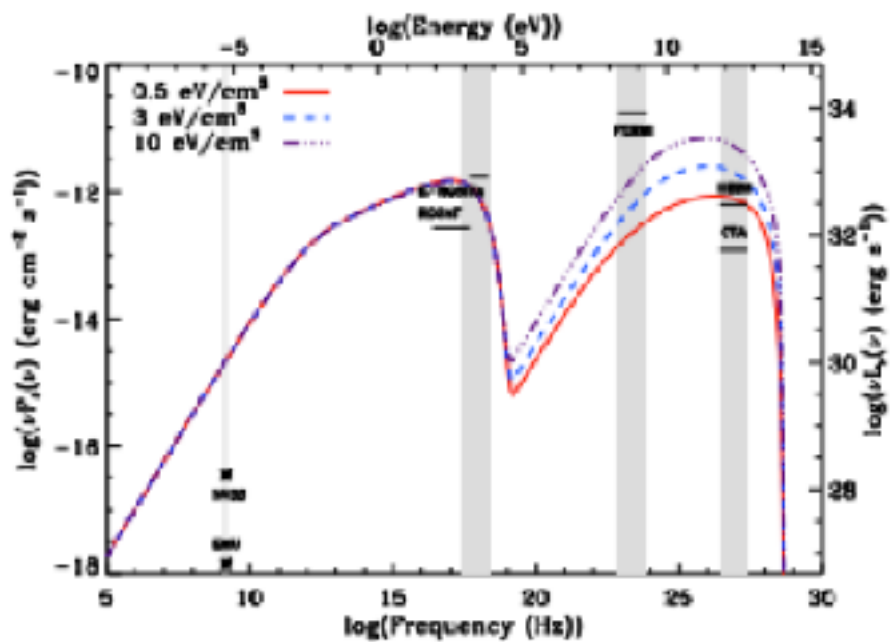
Evolved PWNe

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



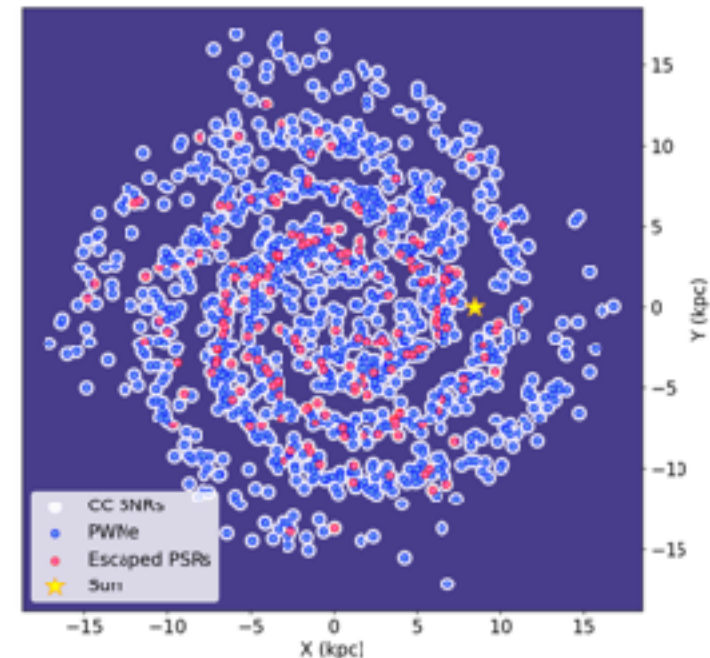
Accelerators: Pulsar Wind Nebulae

Understanding the ISM / photon fields



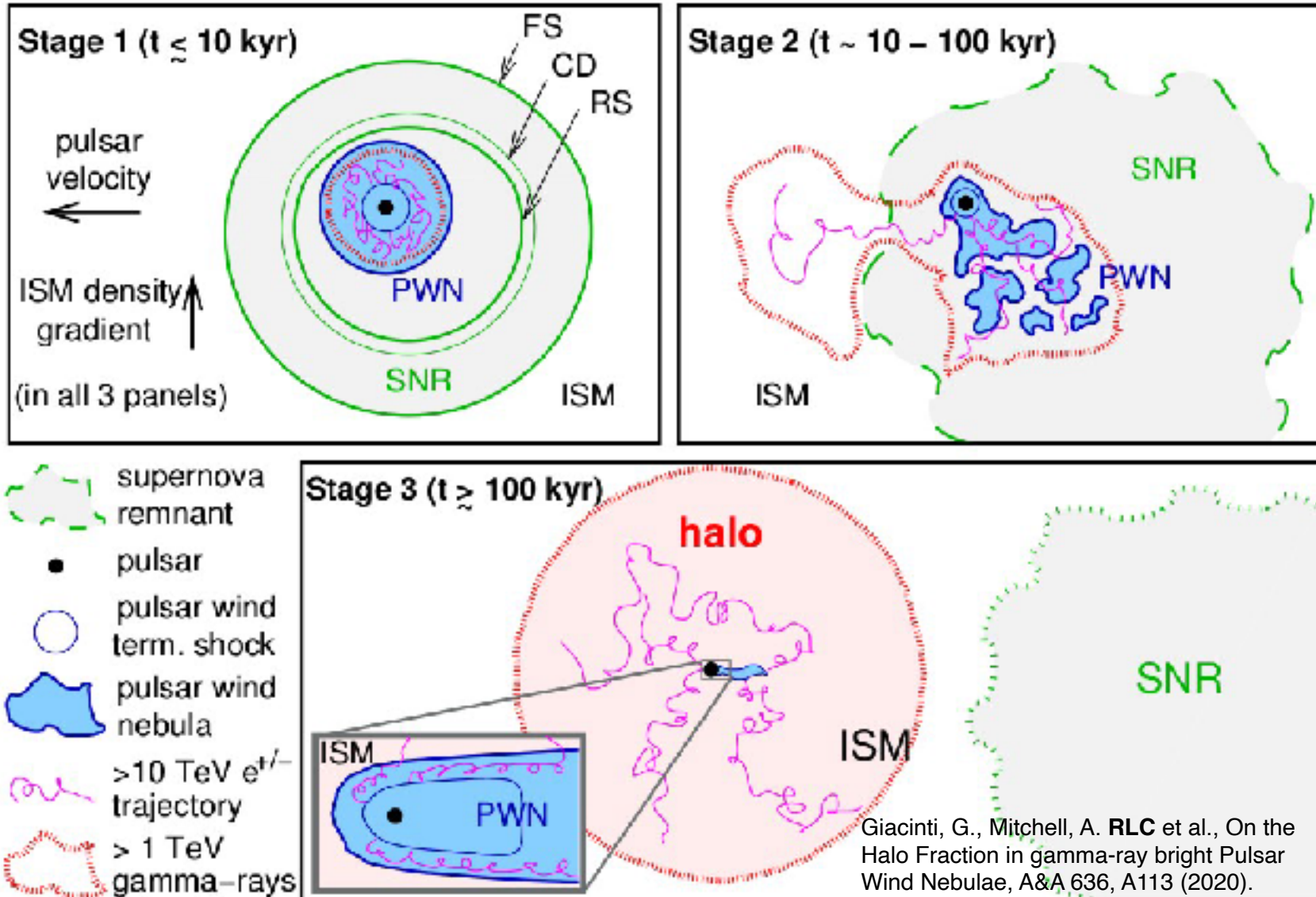
PWNe: Population studies

- 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

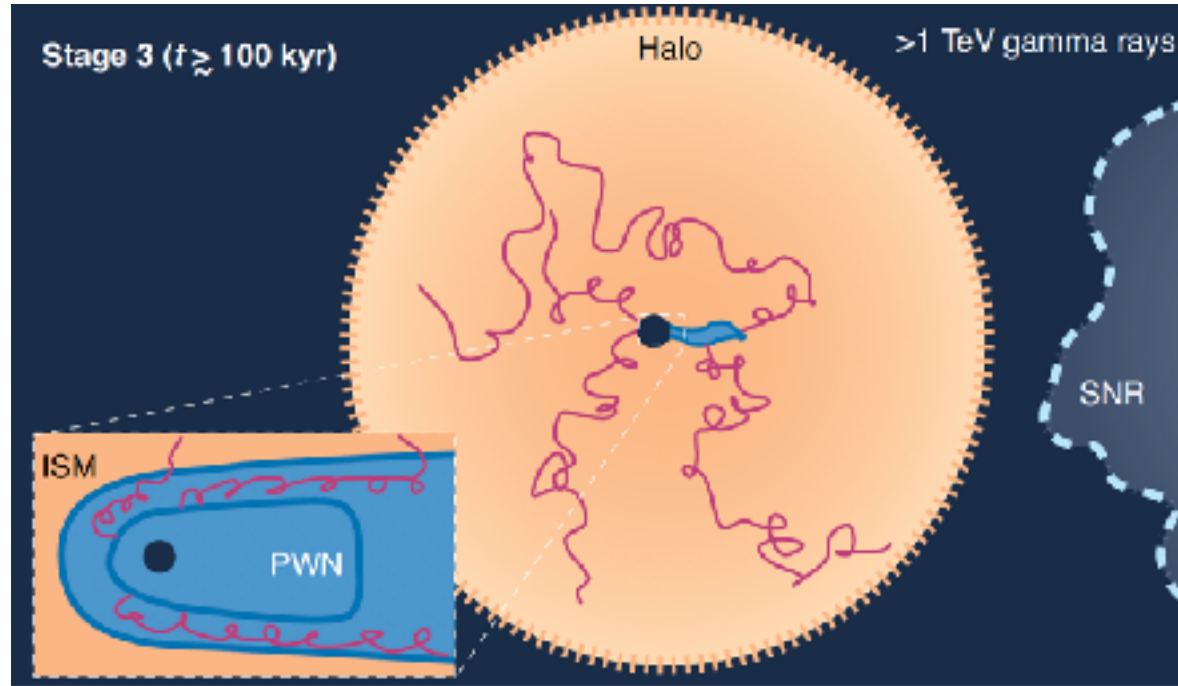


Pulsar Haloes

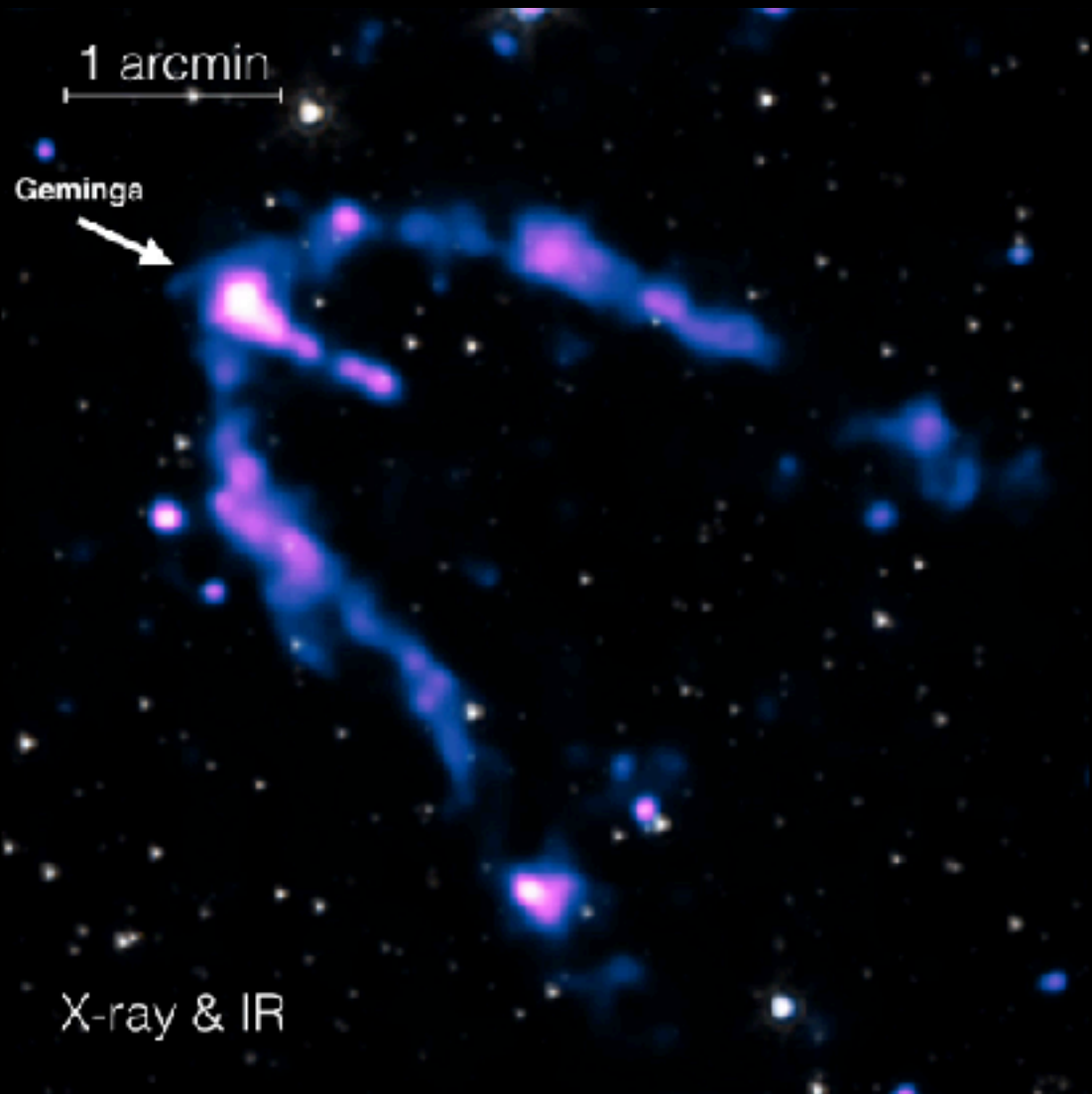
Definition of Pulsar (TeV) halos



Pulsar halos

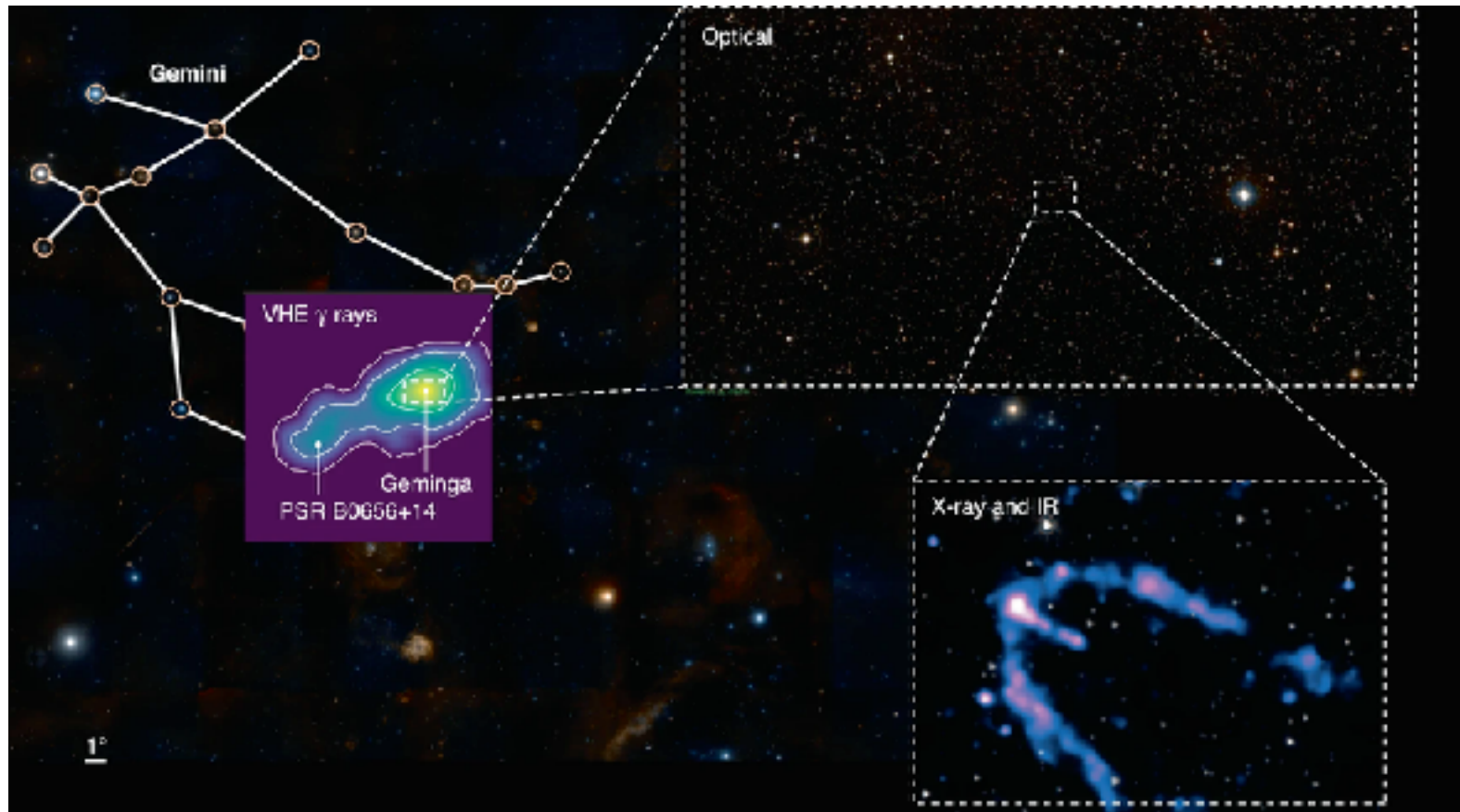


- Bright at multi-TeV energies
- Produced by very high energy electrons (~ 100 TeV) inverse Compton upscattering CMB.
 - They propagate in a magnetic field that is at least two orders of magnitude more turbulent than that of the ISM.
- Electrons do not dominate over the energetics in the ISM



Accelerators: Haloes

Halos: Study the diffusion of particles in the Galaxy



Energetics in Geminga



$d = 250 \text{ pc}$

Geminga

Energetics in Geminga

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

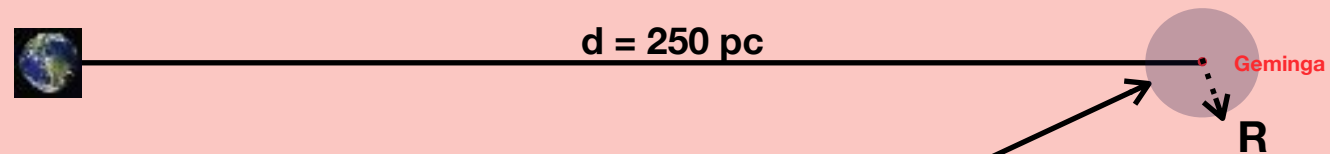


d = 250 pc

Geminga

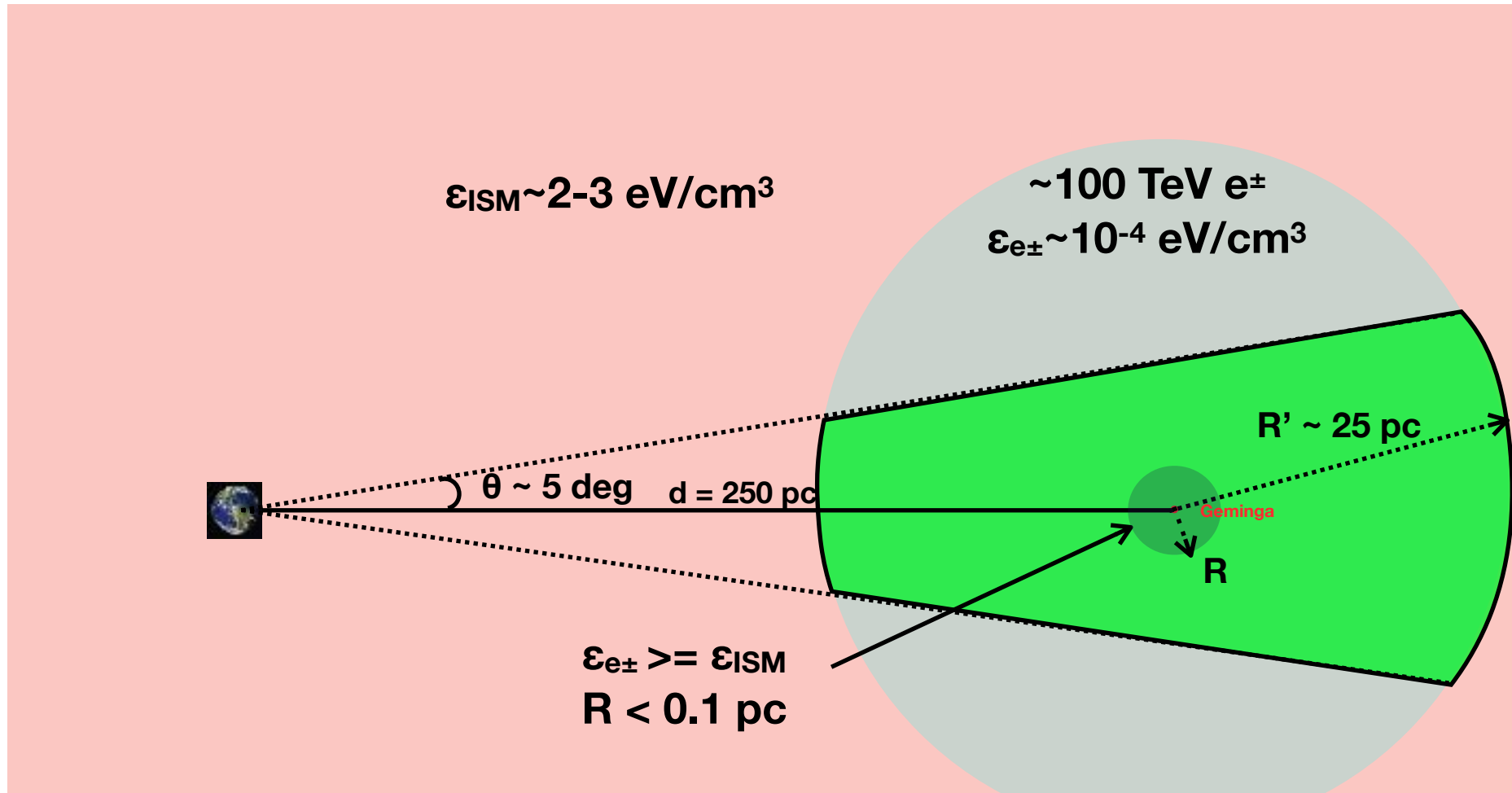
Energetics in Geminga

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



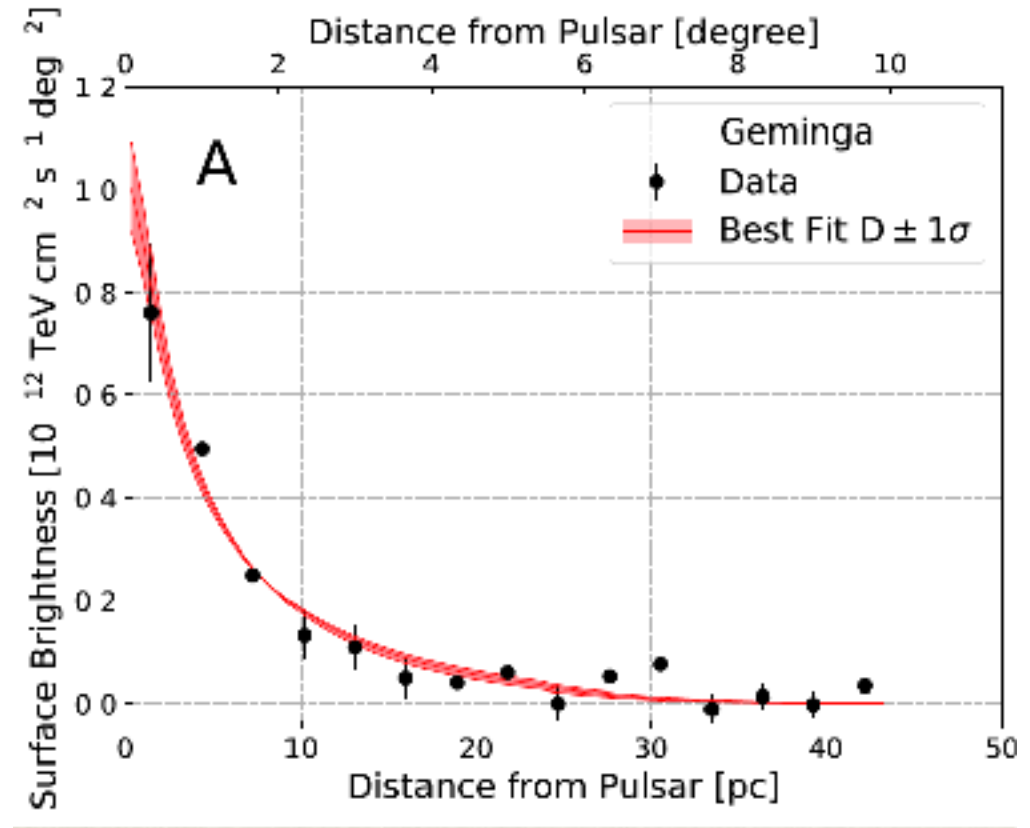
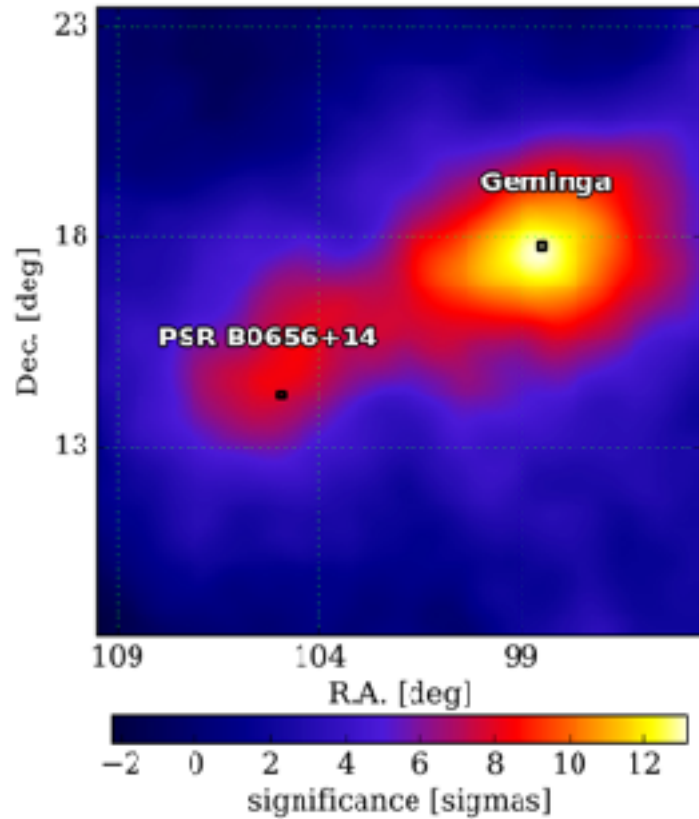
$$\epsilon_{e^-} \geq \epsilon_{\text{ISM}}$$
$$R < 0.1 \text{ pc}$$

Energetics in Geminga



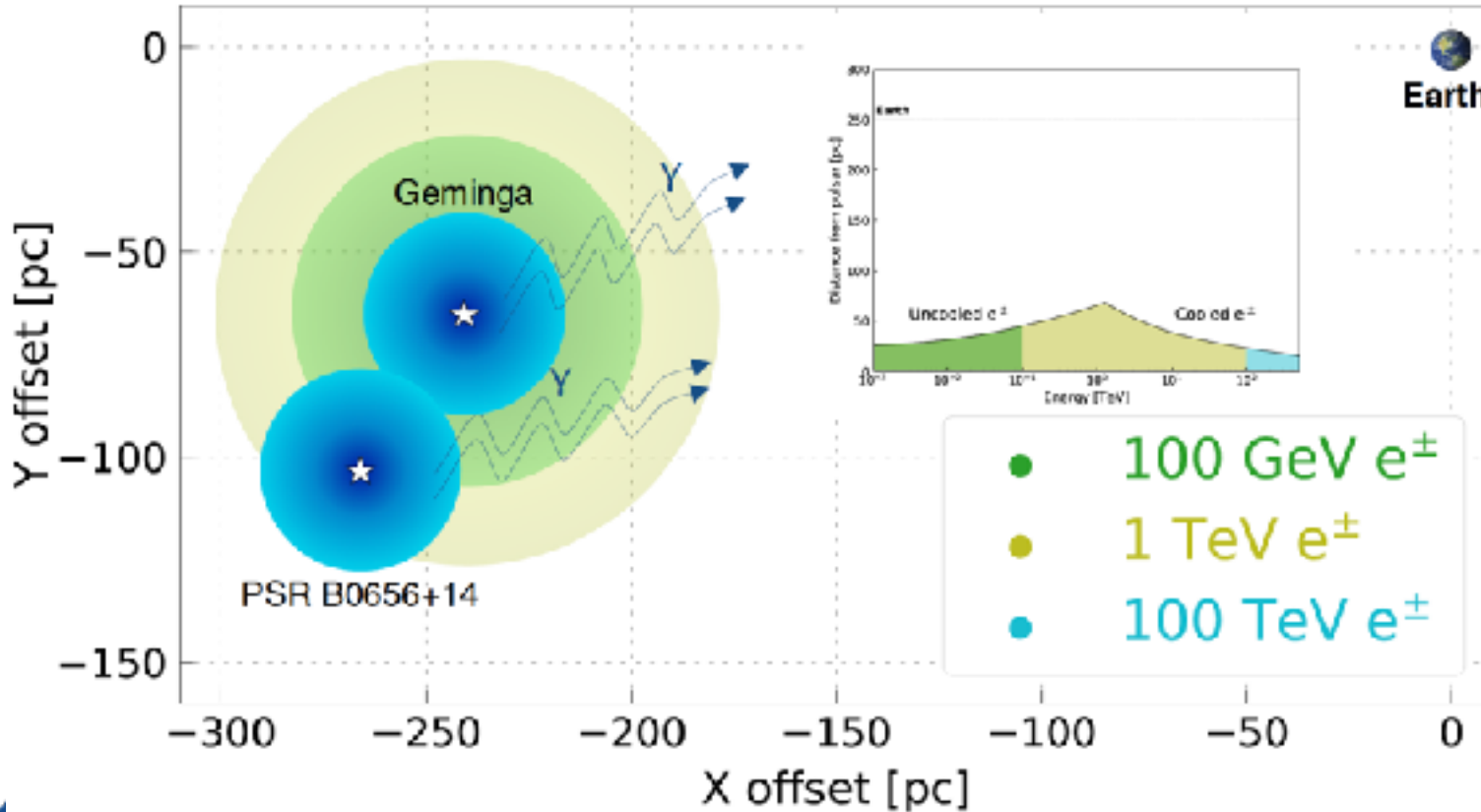
Accelerators: Haloes

Halos: Study the diffusion of particles in the Galaxy



Accelerators: Haloes

Halos: Study the diffusion of particles in the Galaxy

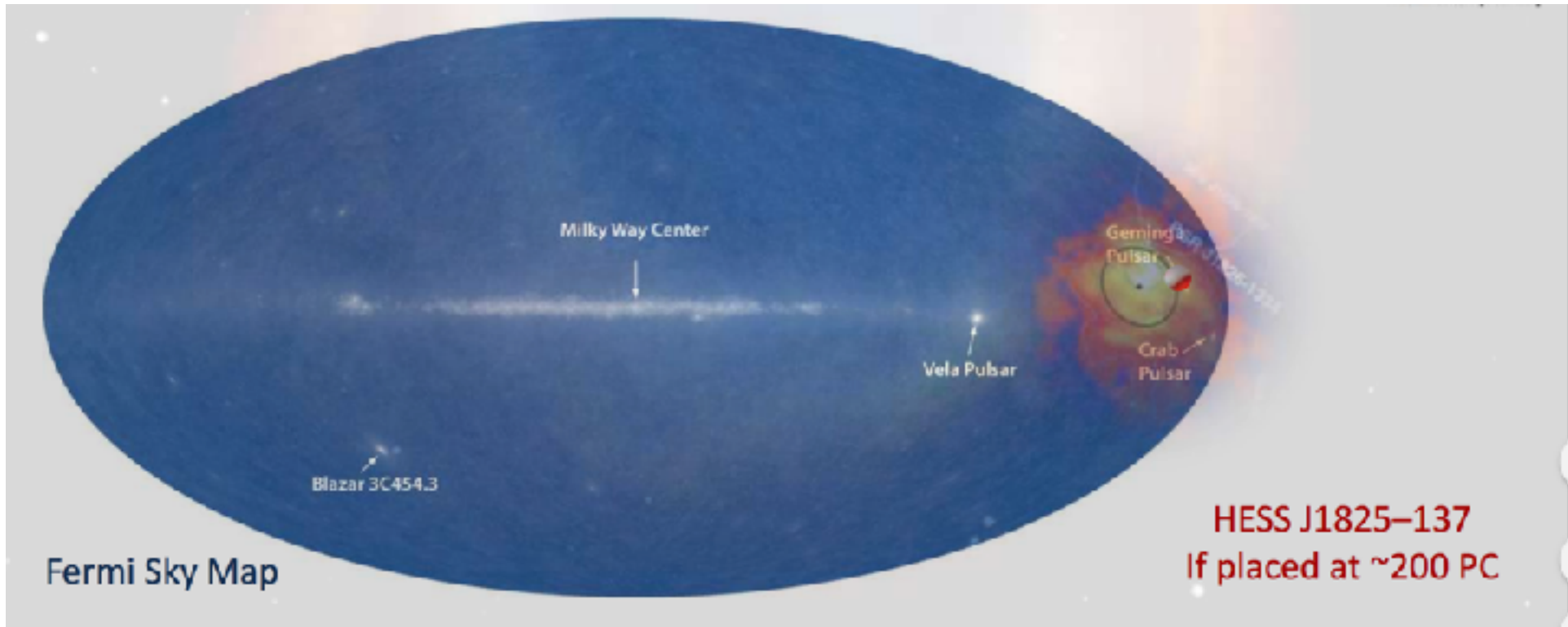


$$D(E) \approx 2 \times 10^{28} \text{ cm}^2 \text{ s}^{-1} \xi_{B,0.1}^{-1} \left(\frac{\lambda_{pc}}{E_{\text{TeV}}} \right)^{\alpha-1} B_{\mu}^{\alpha-2}$$

$D \sim 4.5 \times 10^{27} \text{ cm}^2/\text{s}$
(mean value in the ISM is $\sim 10^{30} \text{ cm}^2/\text{s}$)

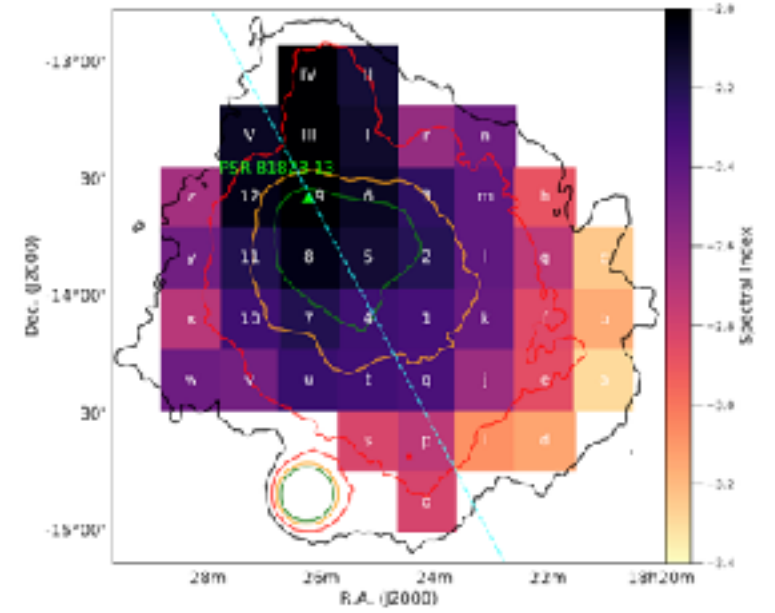
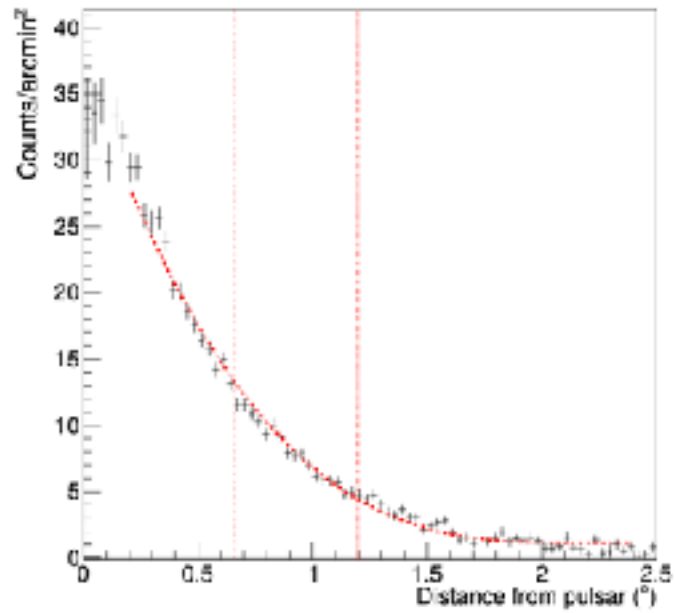
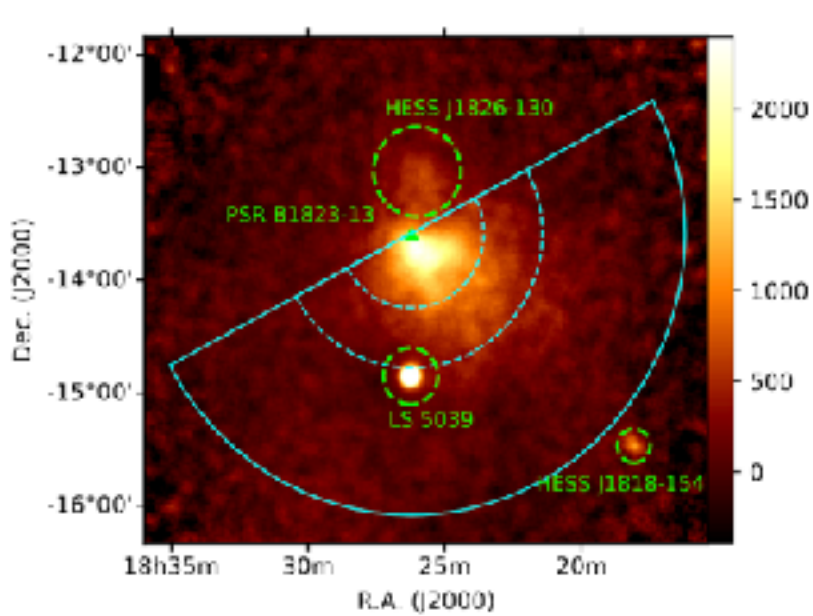
Accelerators: Haloes

Halos: Study the diffusion of particles in the Galaxy



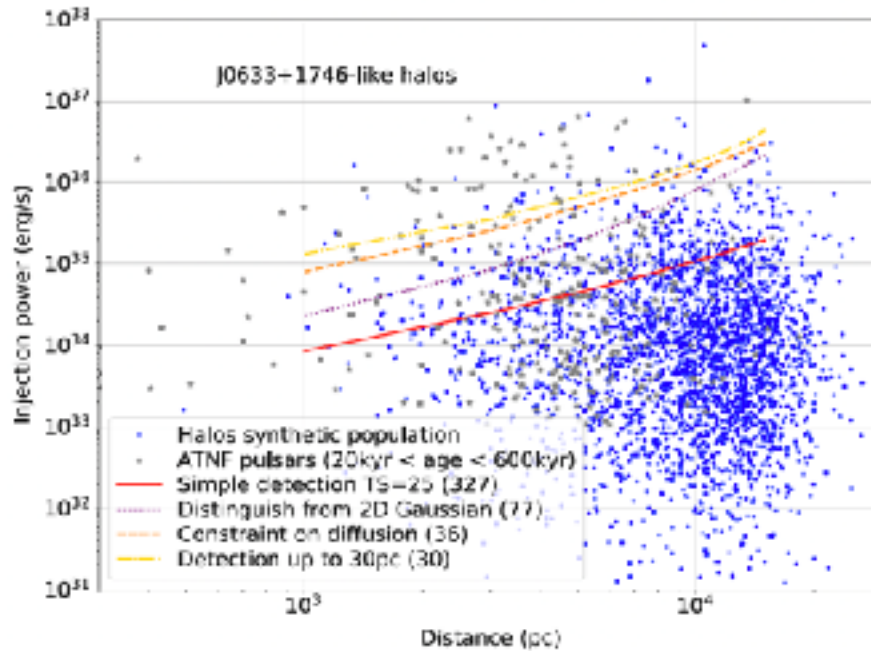
Accelerators: Haloes

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

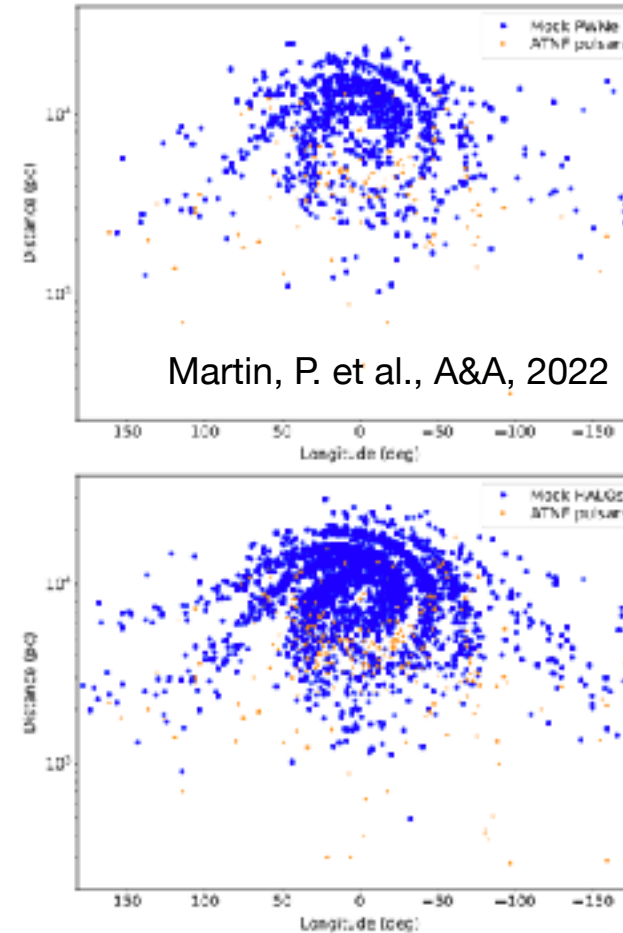
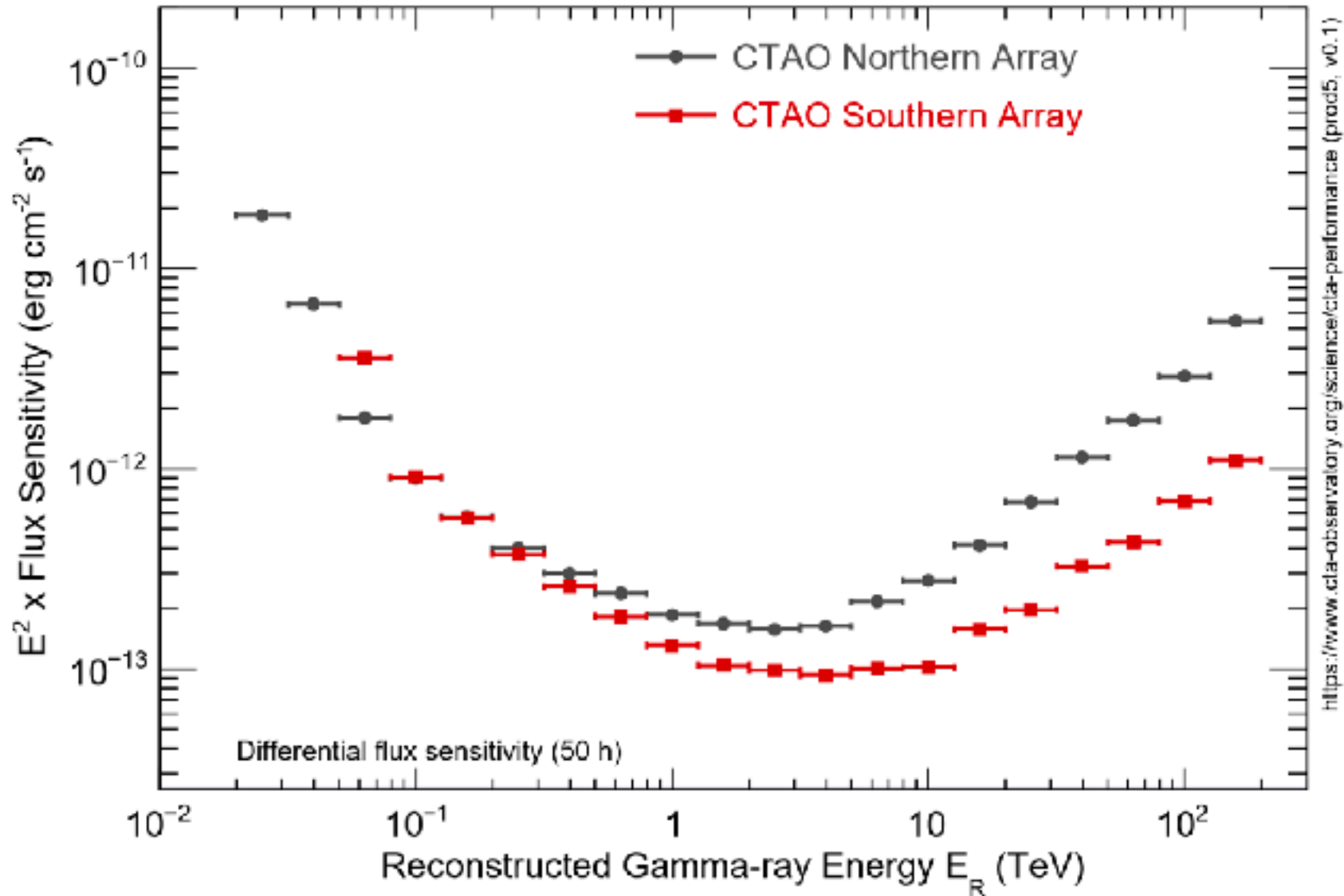
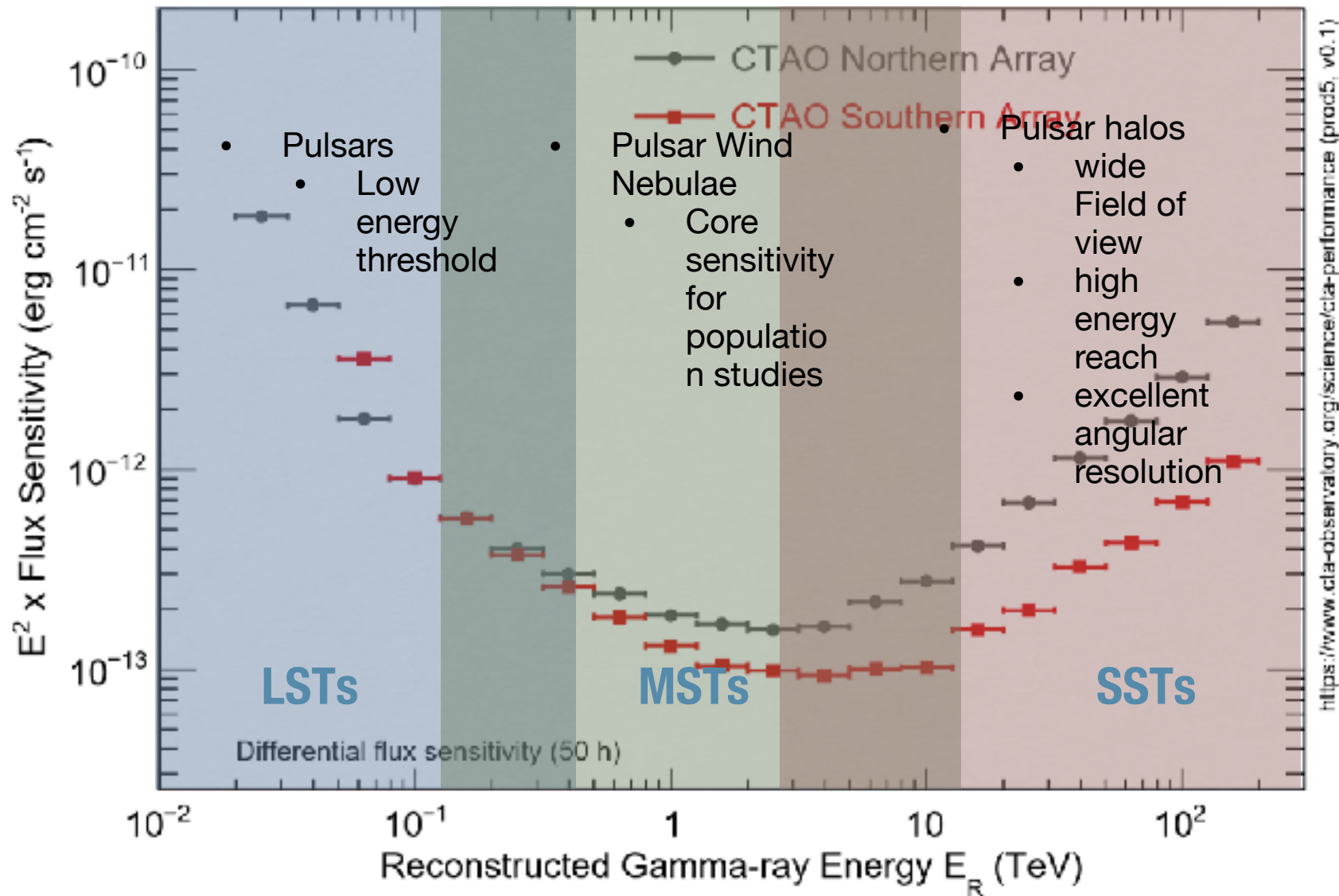


Fig. 1: Spatial distribution of mock PWNe and halos in the Galactic plane, for halos with suppressed diffusion region of size 50pc and diffusion suppression by a factor 500. Overlaid for comparison and cross-check are the positions of a set of pulsars from the ATNF database within the same age ranges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

CTAO Sensitivity



CTAO Sensitivity



VHE gamma rays – **Future**

what do we want to learn?

Pulsars

- More Pulsars
- Extend energy range

PWNe

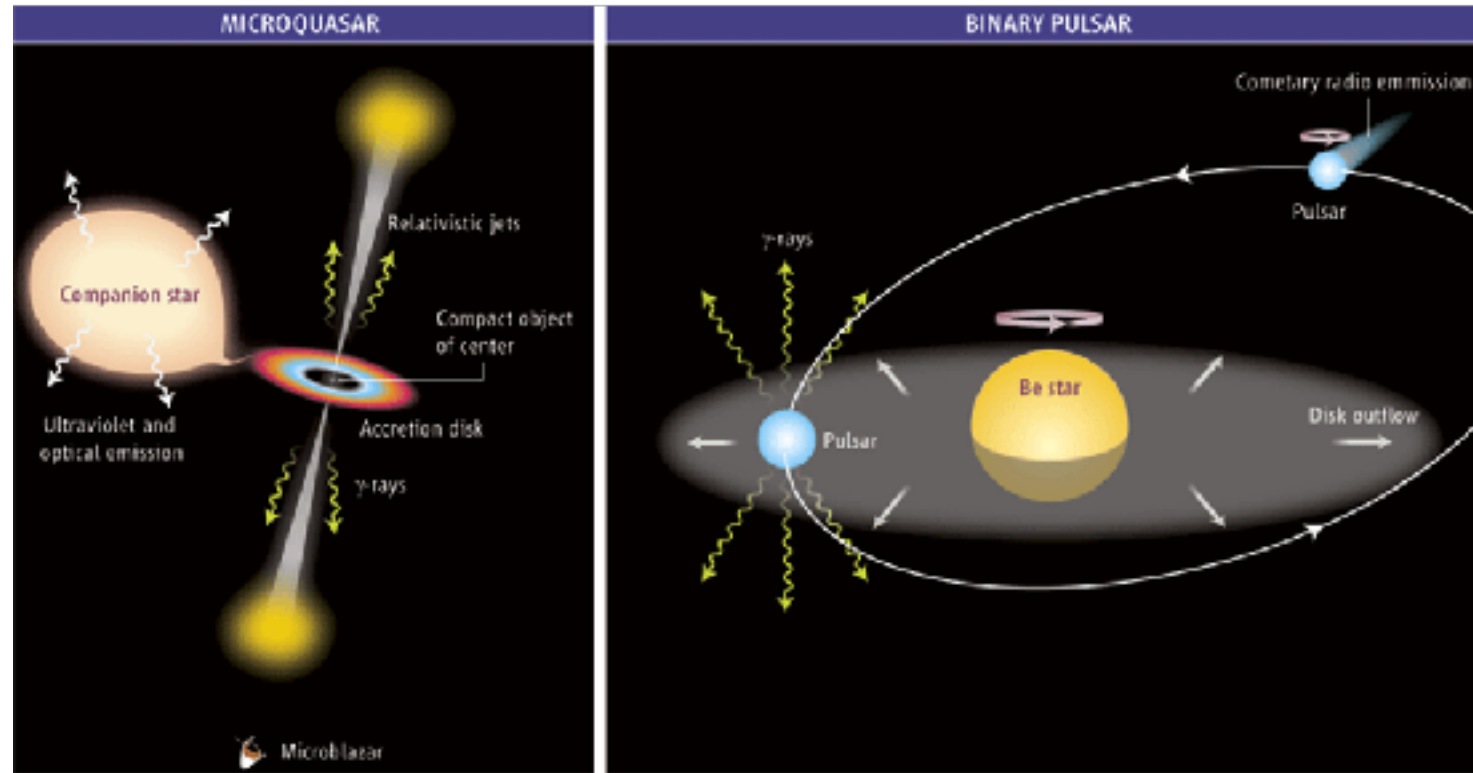
- More and more detailed PWNe
- Include morphology and evolution in the modeling

Halos

- IACT detection and study

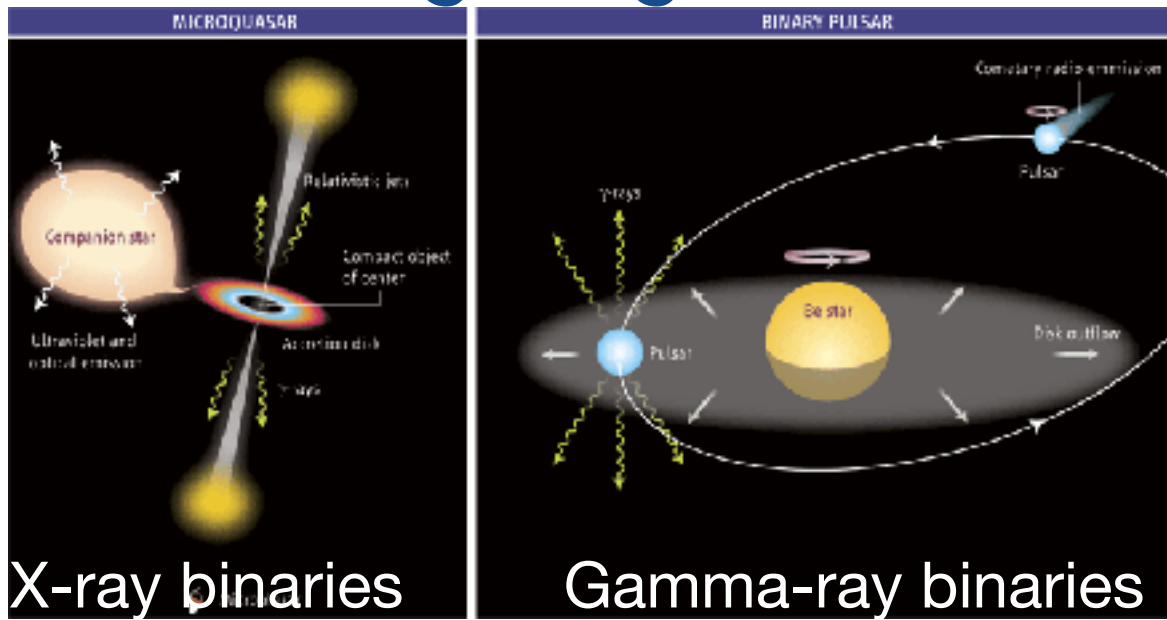
Binary systems

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



Cataclysmic variable stars

- Novae

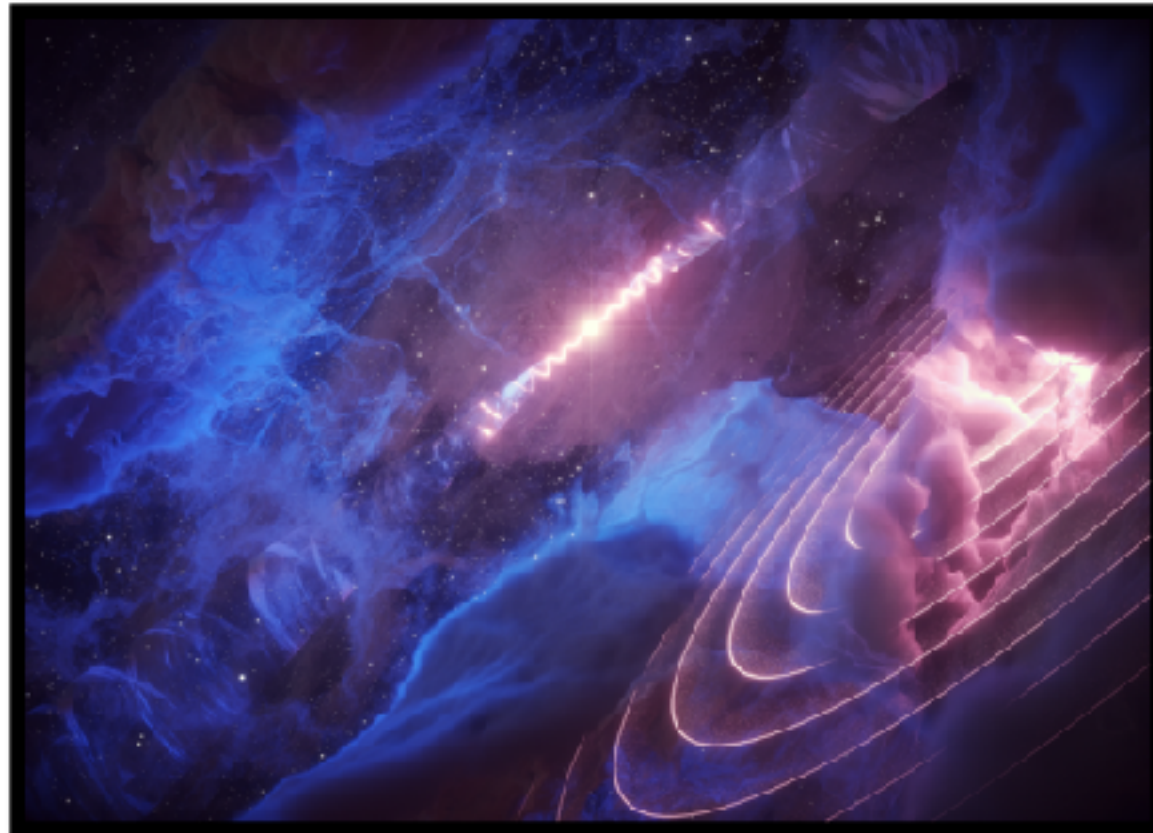
Transitional ms pulsars



Binary systems

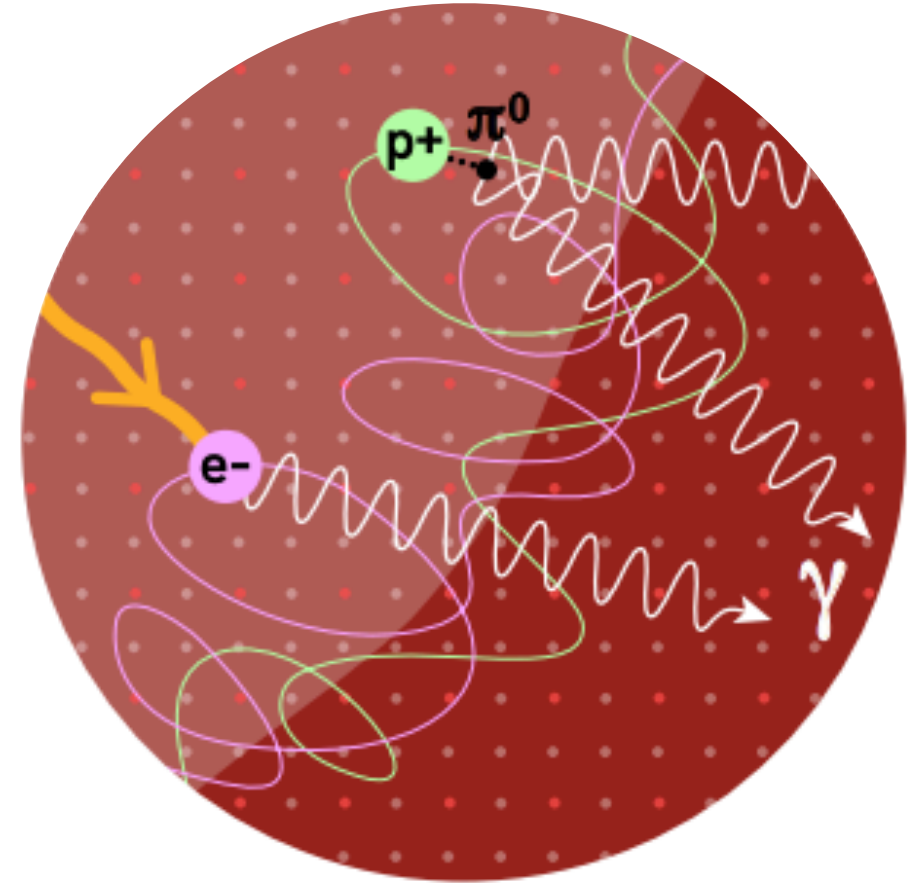


- Photon field enhanced by the massive companion - modulated emission!



Binaries: Leptonic/hadronic acceleration

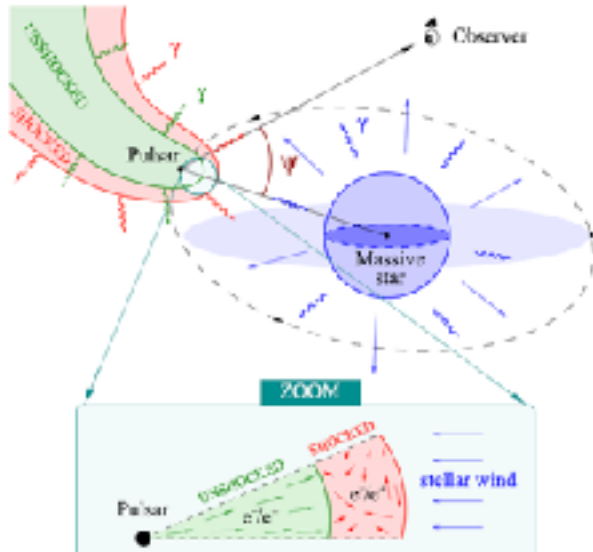
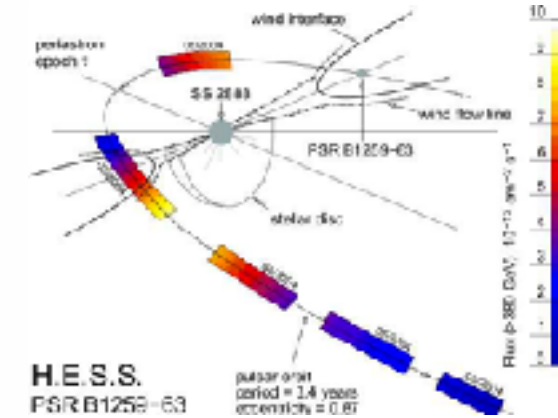
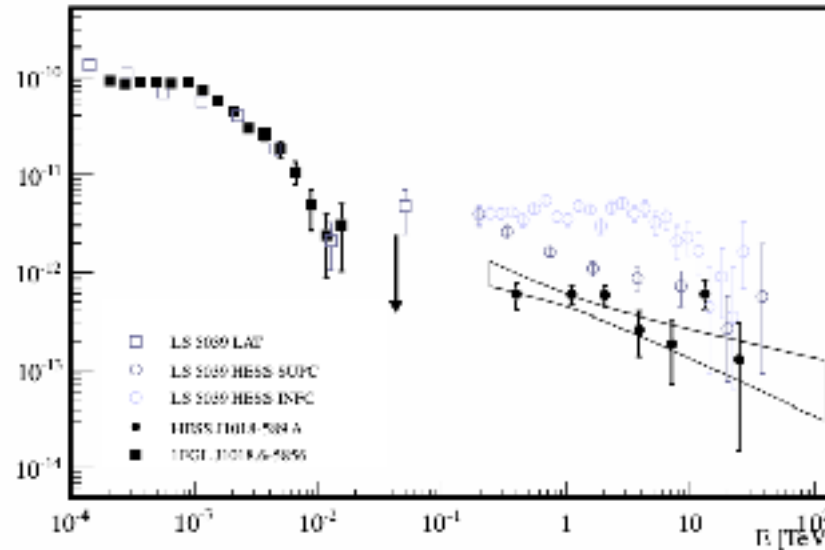
- **Leptonic models:** Dominated by Inverse Compton on photon fields
 - Synchrotron Self Compton relativistic in the jets with jet photons.
 - External Compton: relativistic e^- in the jets with photon field of companion star
- **Hadronic models:** Dominated by proton collisions and pion decay
 - Jet interaction with companion stellar wind
 - Jet protons with ISM



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 (HEATHE)	Periodic
LSI +51 303	0-15	2	yes/yes	yes (~1 months)
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)
...

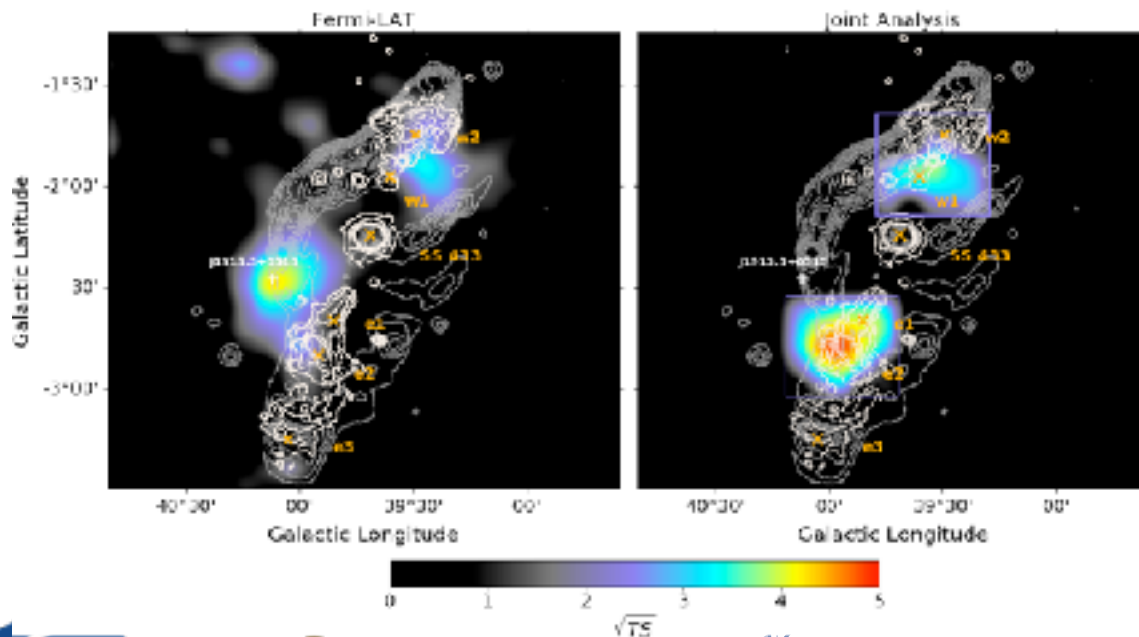
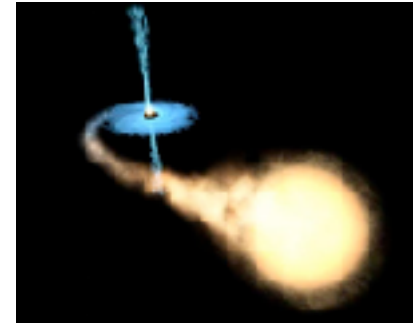
Compact object in binary systems

Gamma-ray Binaries

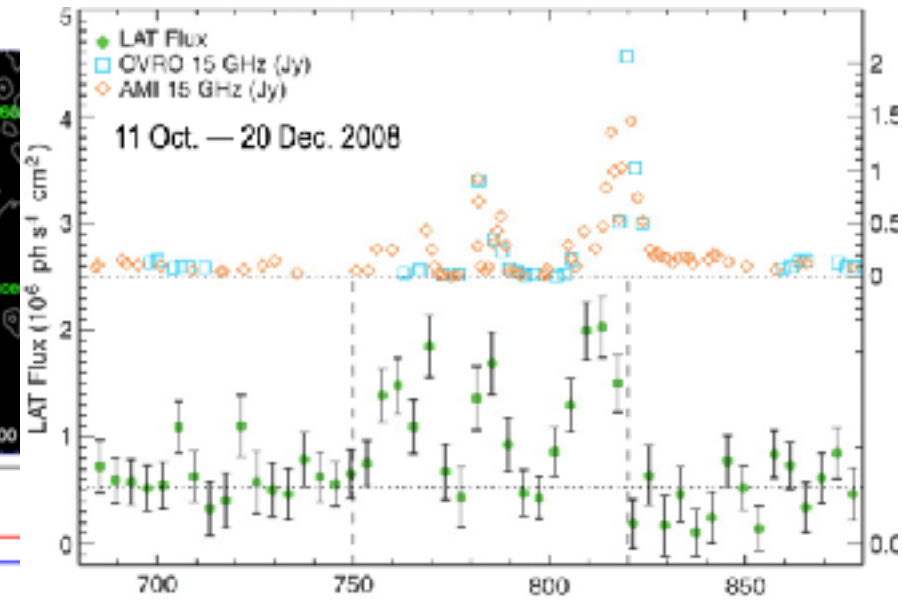
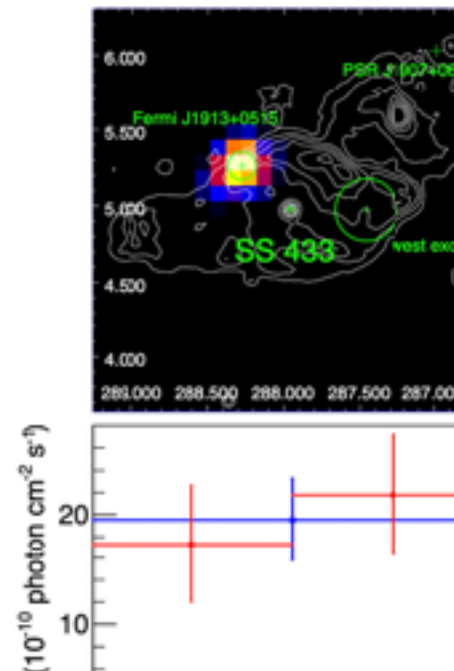
- GeV and TeV often uncorrelated:
 - Max of orbital light curve
 - Two spectral components
 - Flares and rich phenomenology

Microquasars

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



Li et al, 2020



Compact object in binary systems

Gamma-ray Binaries

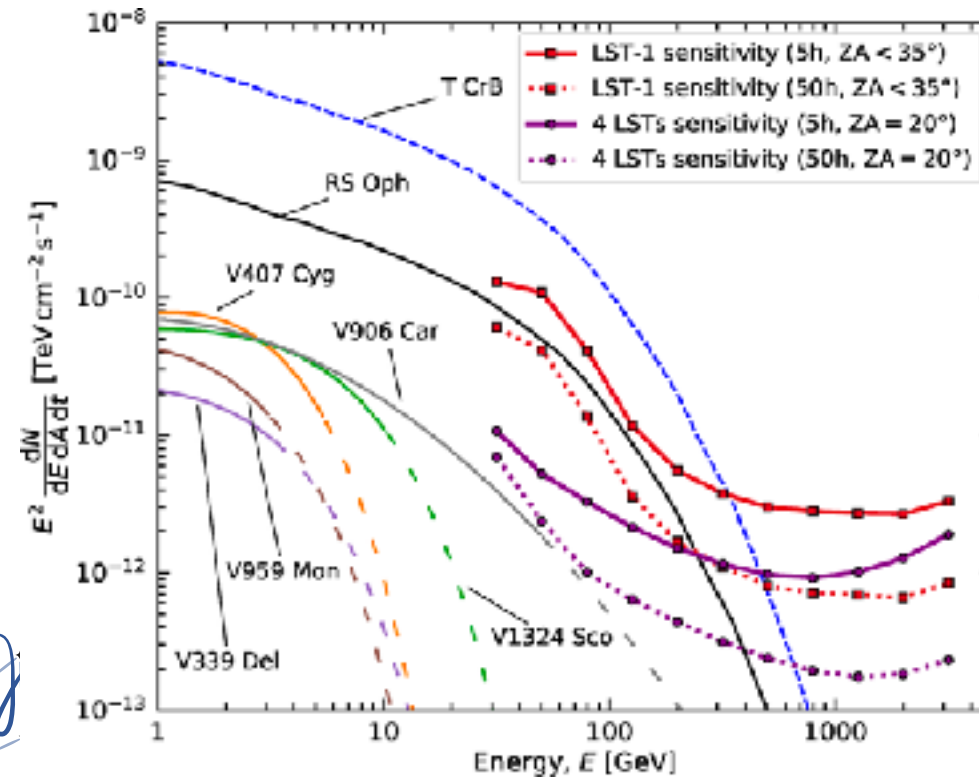
- GeV and TeV often uncorrelated:
 - Max of orbital light curve
 - Two spectral components
 - Flares and rich phenomenology

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



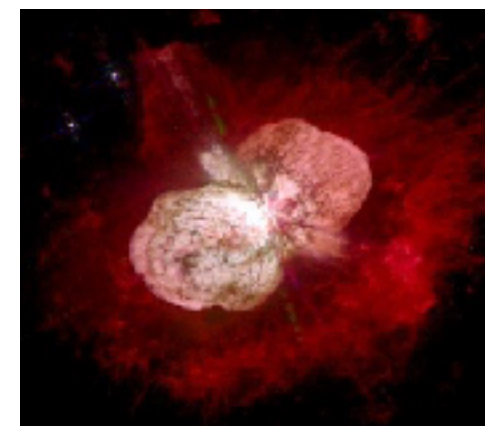
Credit: A. Aguasca-Cabot



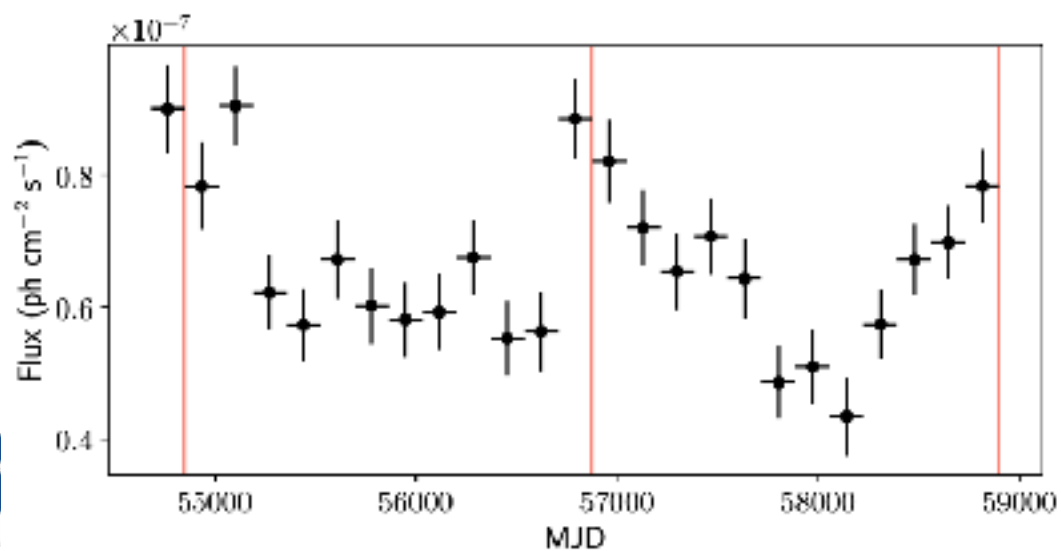
Gamma-ray binaries

- 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.

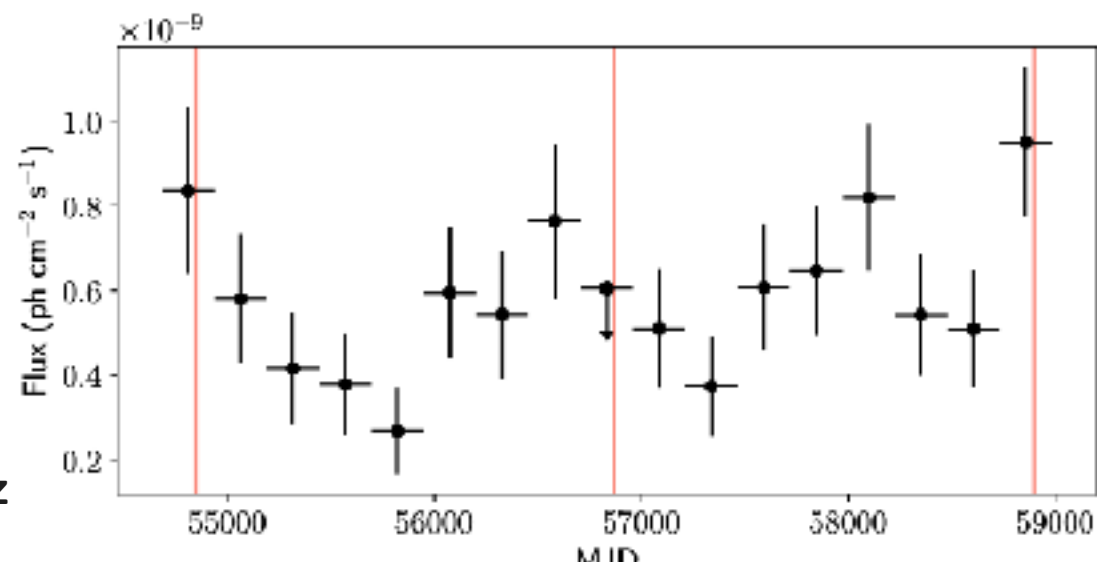
Colliding wind binaries



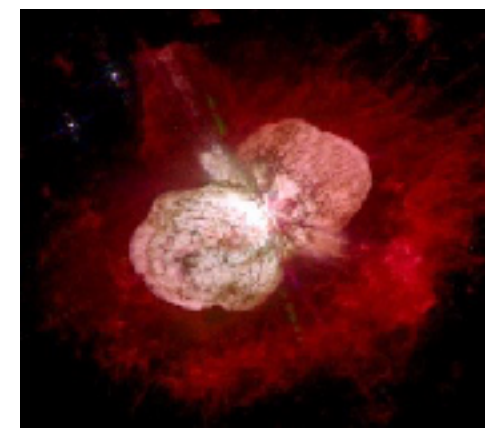
- Eta Carinae
 - Fermi/LAT data during 12yr show 5.5 yr orbital variability in Eta Carinae.
- This can be understood and interpreted in a colliding-wind binary scenario for orbital modulation of the gamma-ray emission.
- The lightcurves change from cycle to cycle.
- The spectral shape in each periastron 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

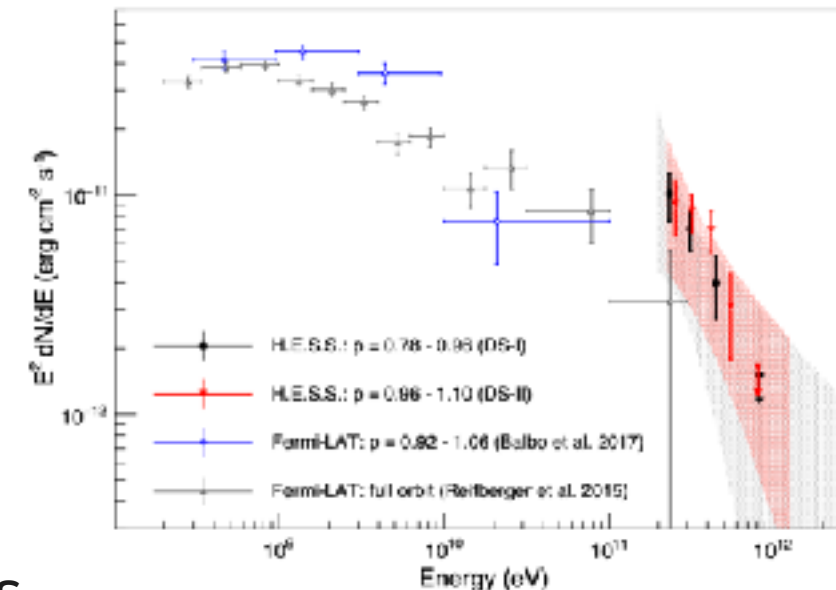
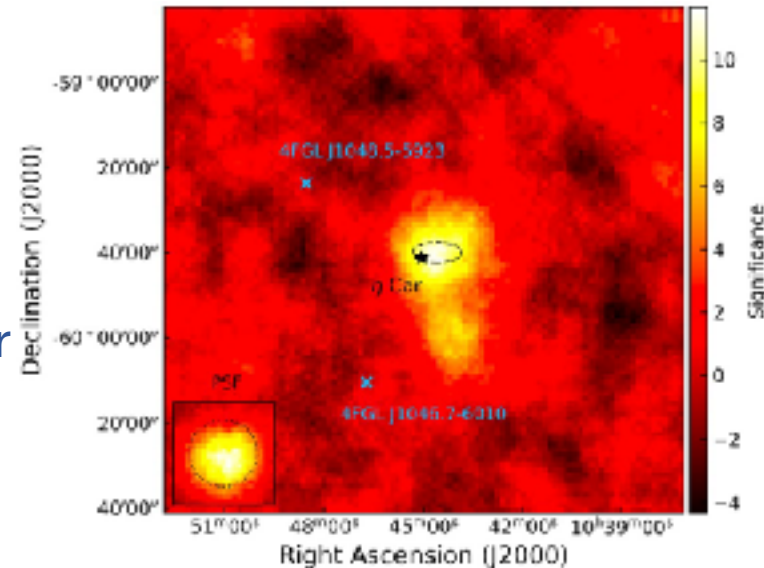


Colliding wind binaries



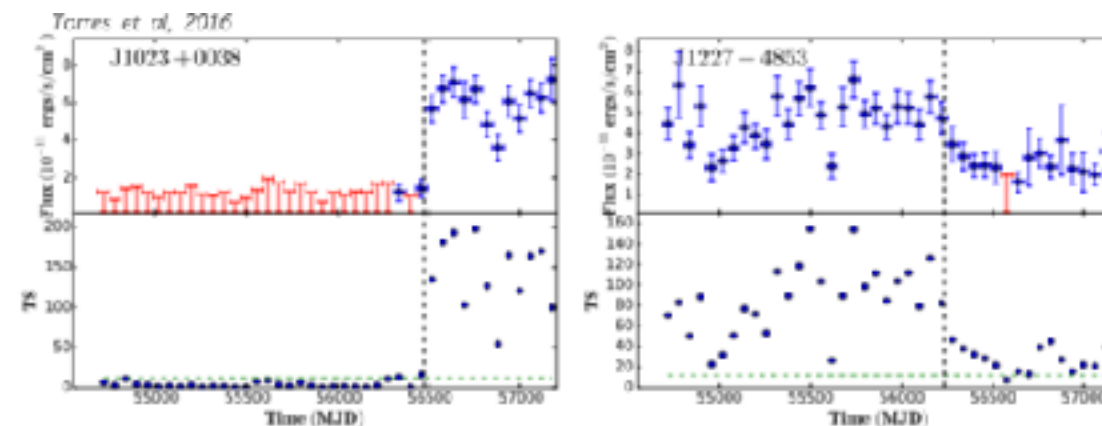
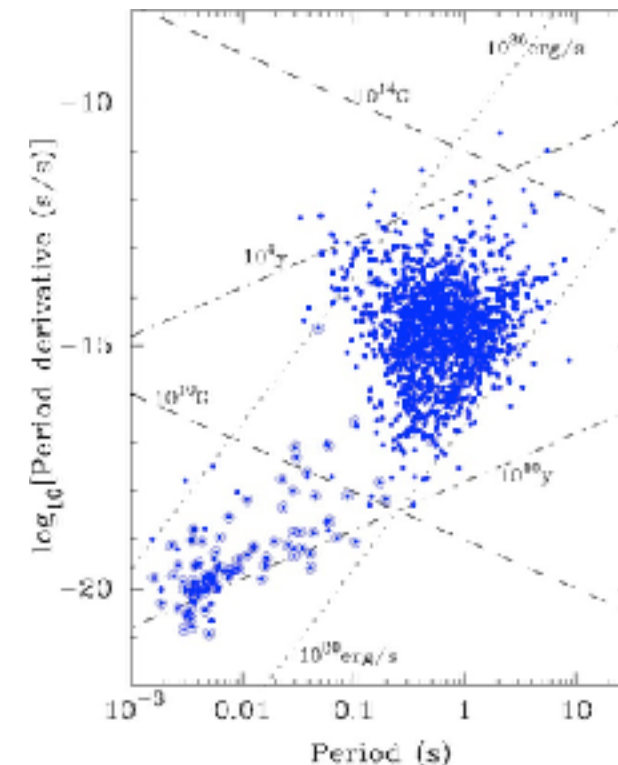
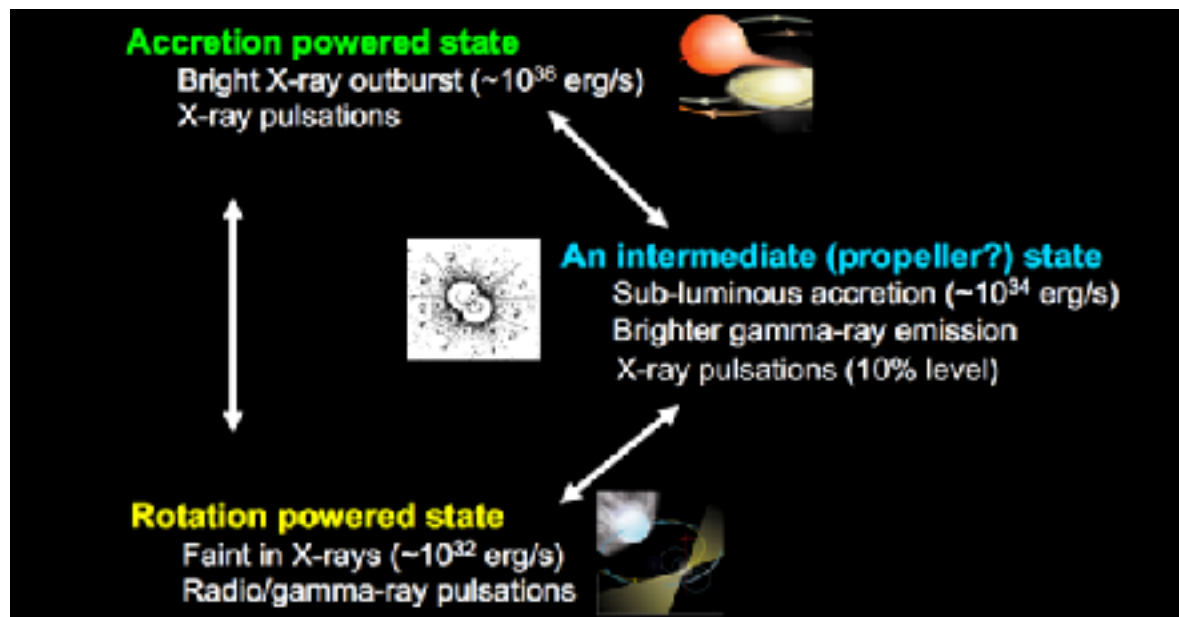
- Eta Carinae

- HESS detected VHE γ -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.
- In 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).



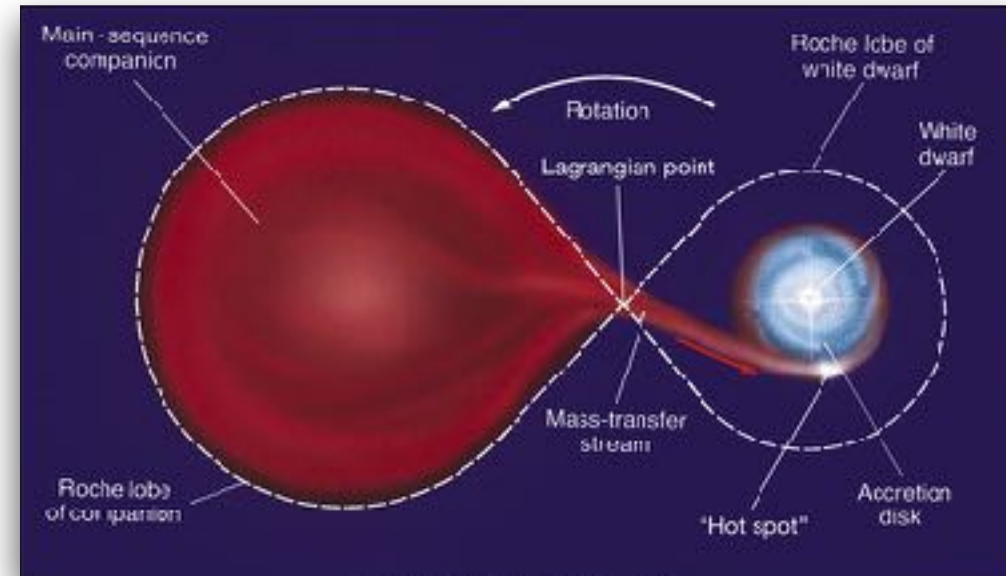
Transitional ms-pulsars

- A game between rotation \Leftrightarrow accretion
- Seen only in the GeV band

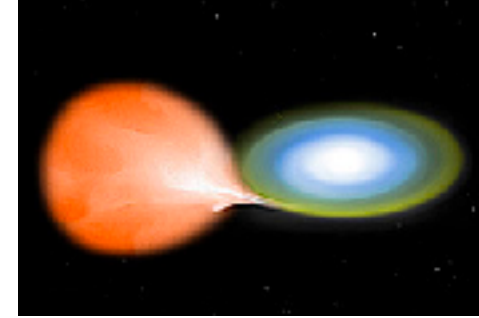


Cataclysmic variable stars

- 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

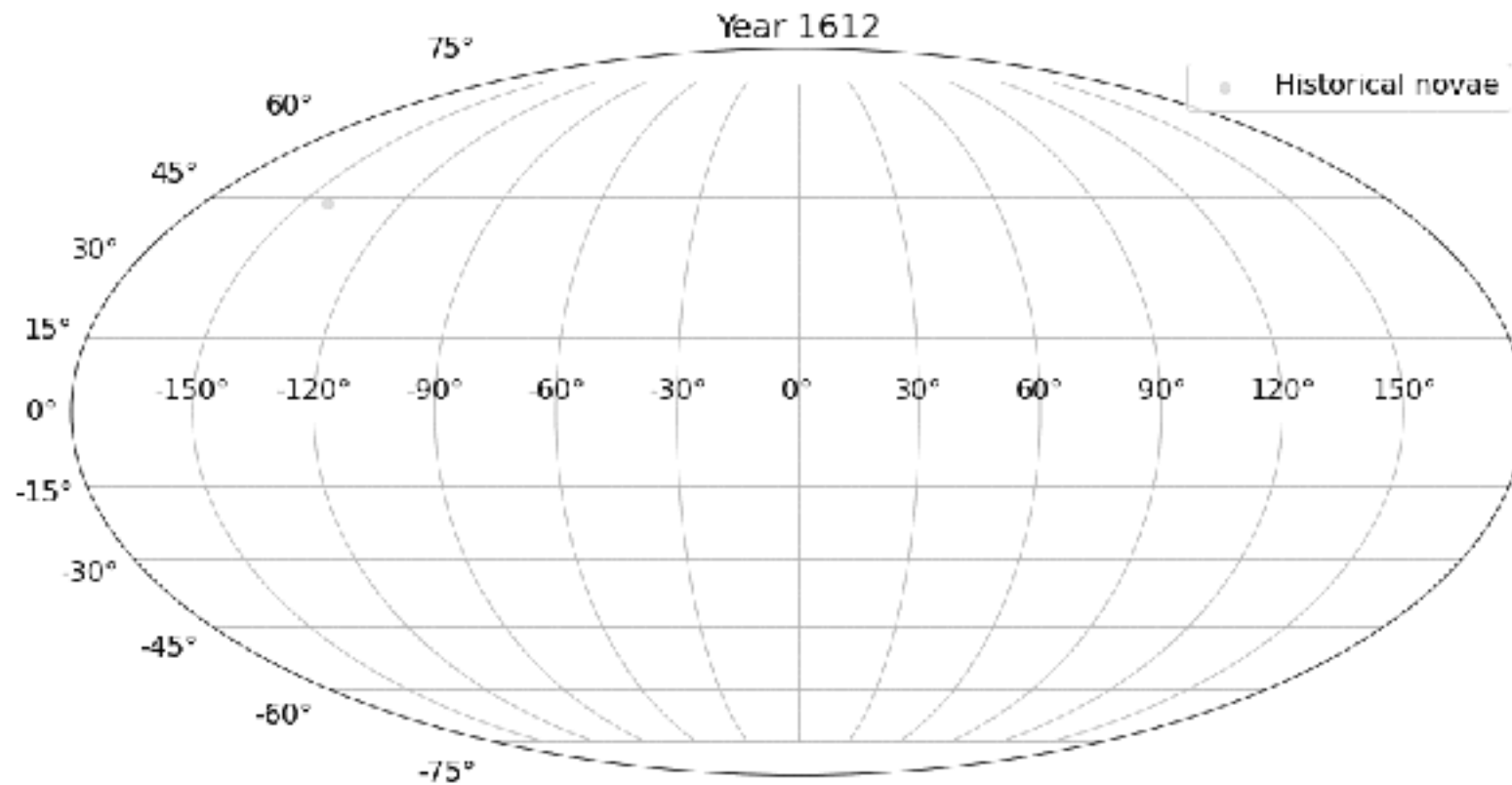


Novae



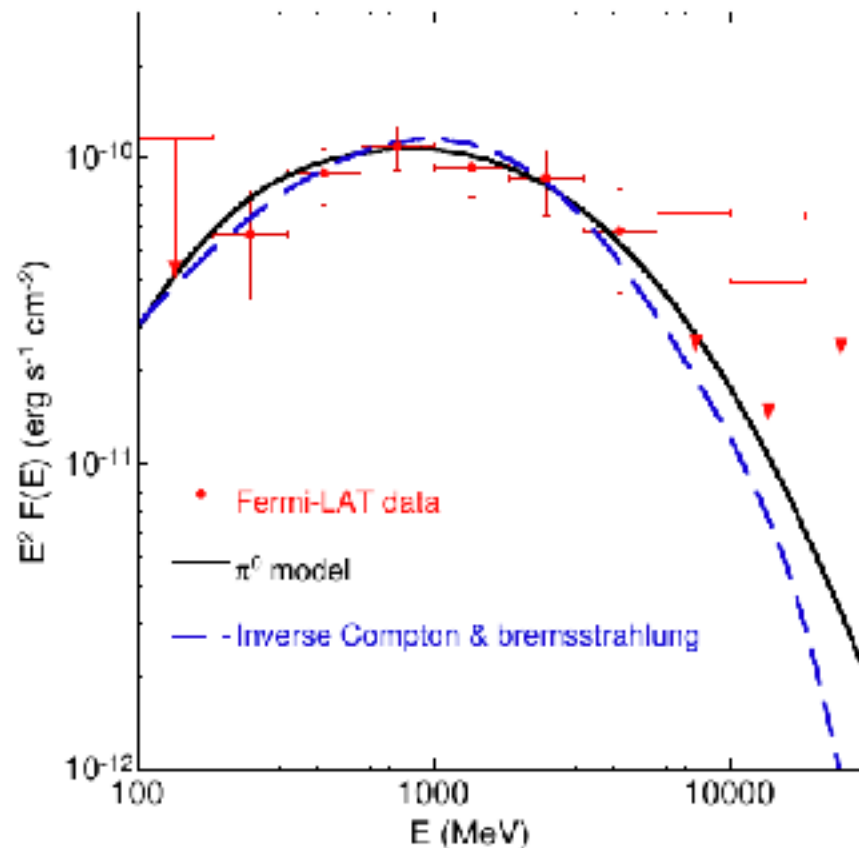
- Thermonuclear explosions caused by accumulation of material from a donor star on the surface of a White Dwarf (WD).
- Novae have been extensively studied in optical, X-rays, radio.
- If donor star is a Red Giant (RG) this can produce a symbiotic binary with the WD immersed in the RG wind.
- There were 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

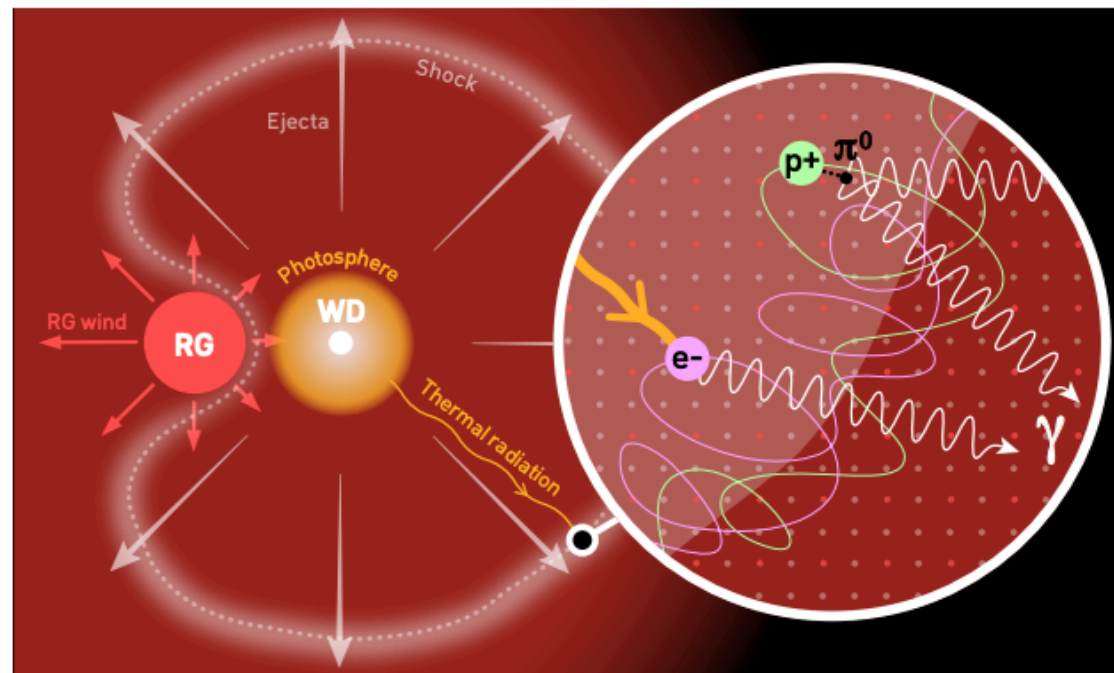


- Recurrent nova in a symbiotic binary
- Outbursts every 15-20 years
- Previous to last outburst in 2006 => no sensitive gamma-ray satellites available
- Distance debated – applied value 2.45 kpc, but values ~1.4 – 4.3 kpc (with various caveats) are reported in the literature
- Latest outburst on 2021.08.08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

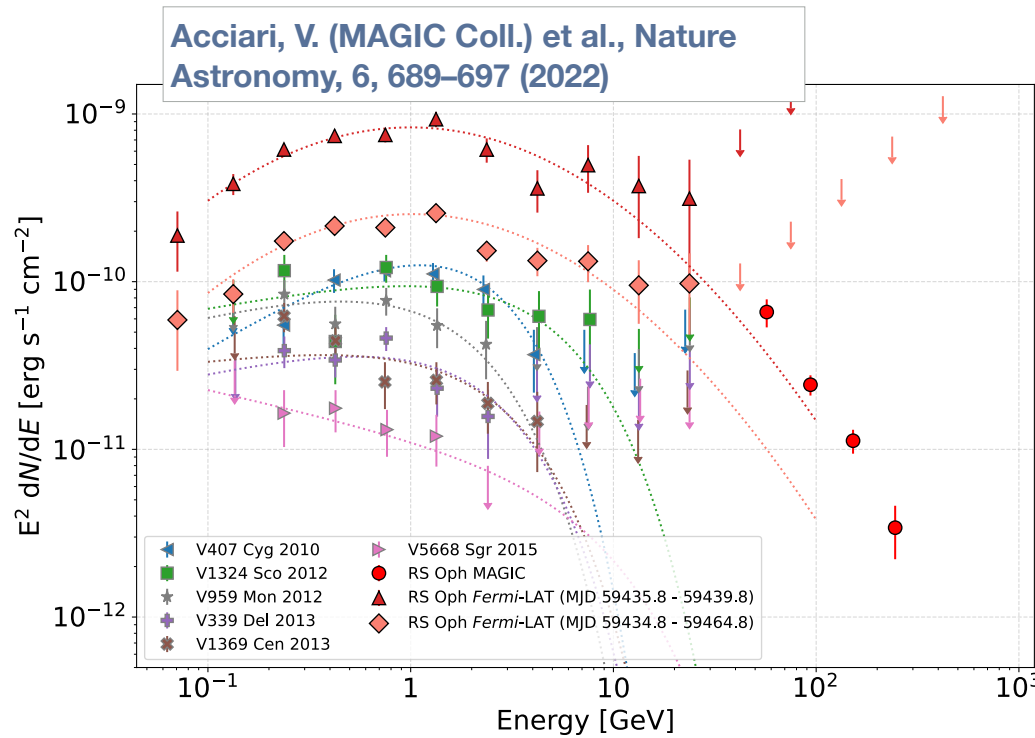


RS Oph in context

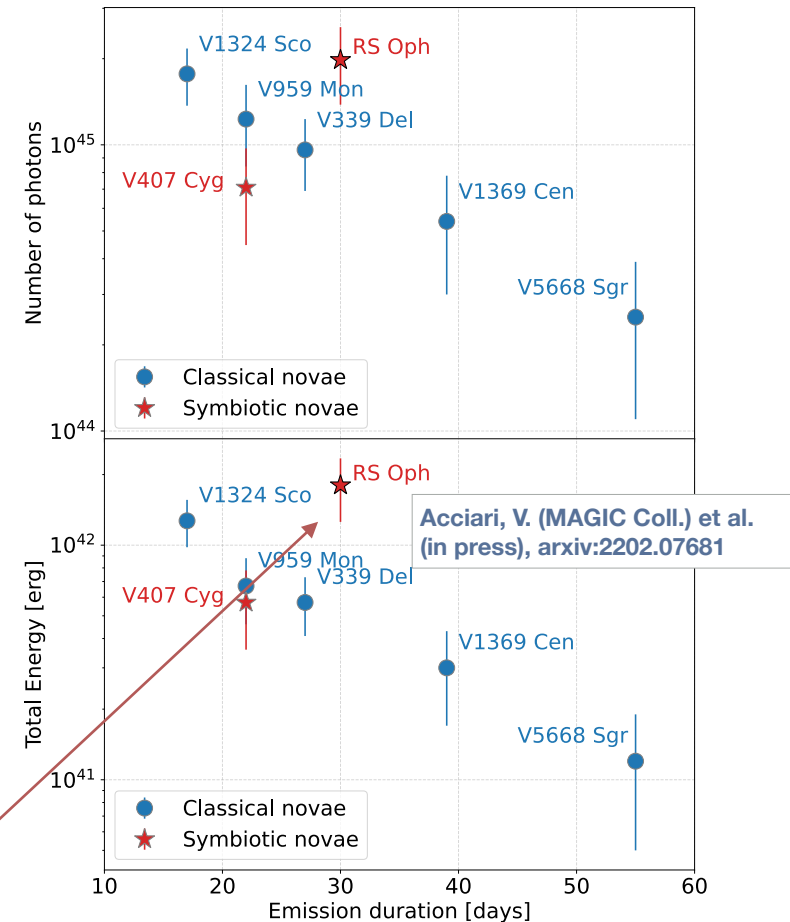
- What is happening in RS Oph so special? Why are we seeing it in VHE gamma rays and not all the other novae?



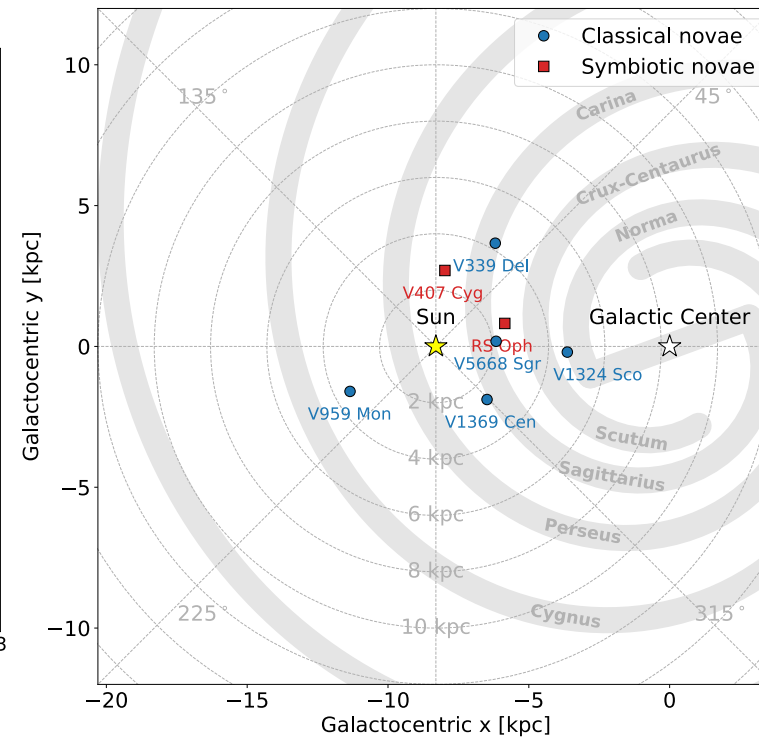
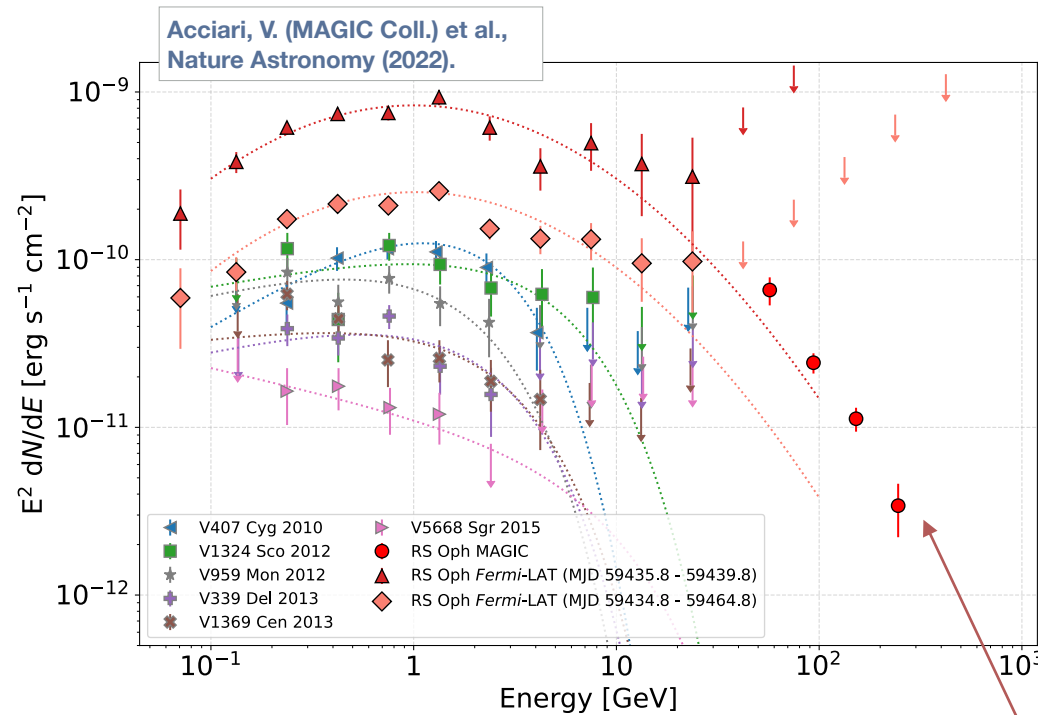
RS Oph in the context of other high energy novae



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



RS Oph: what was so special about it?



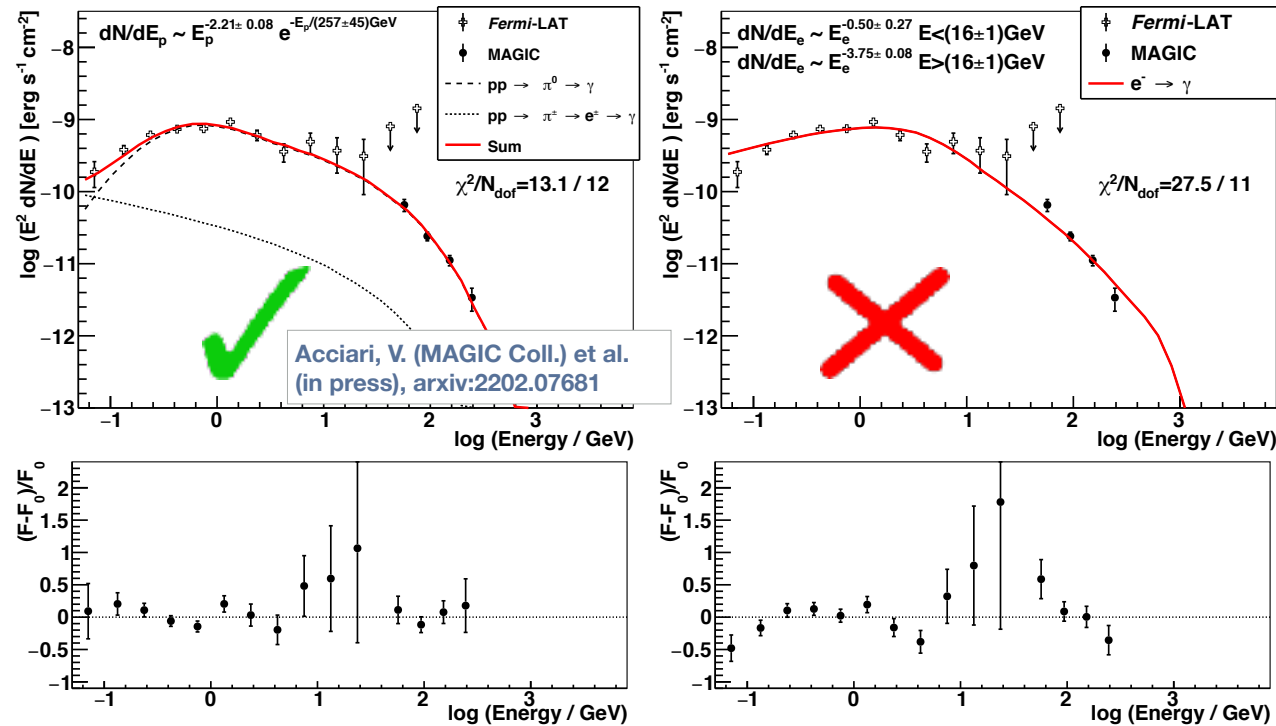
- Several novae detected by *Fermi*-LAT
 - RS Oph is also the one with the highest flux

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

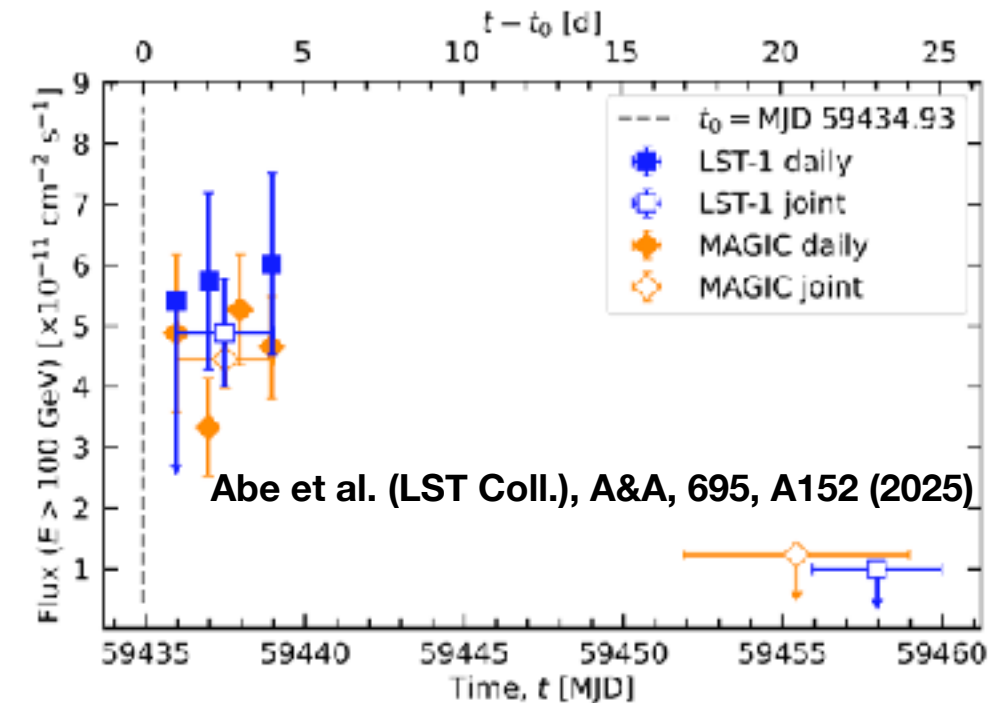
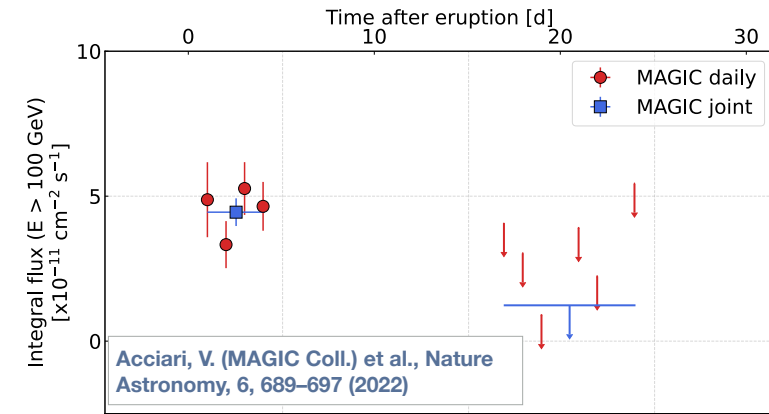
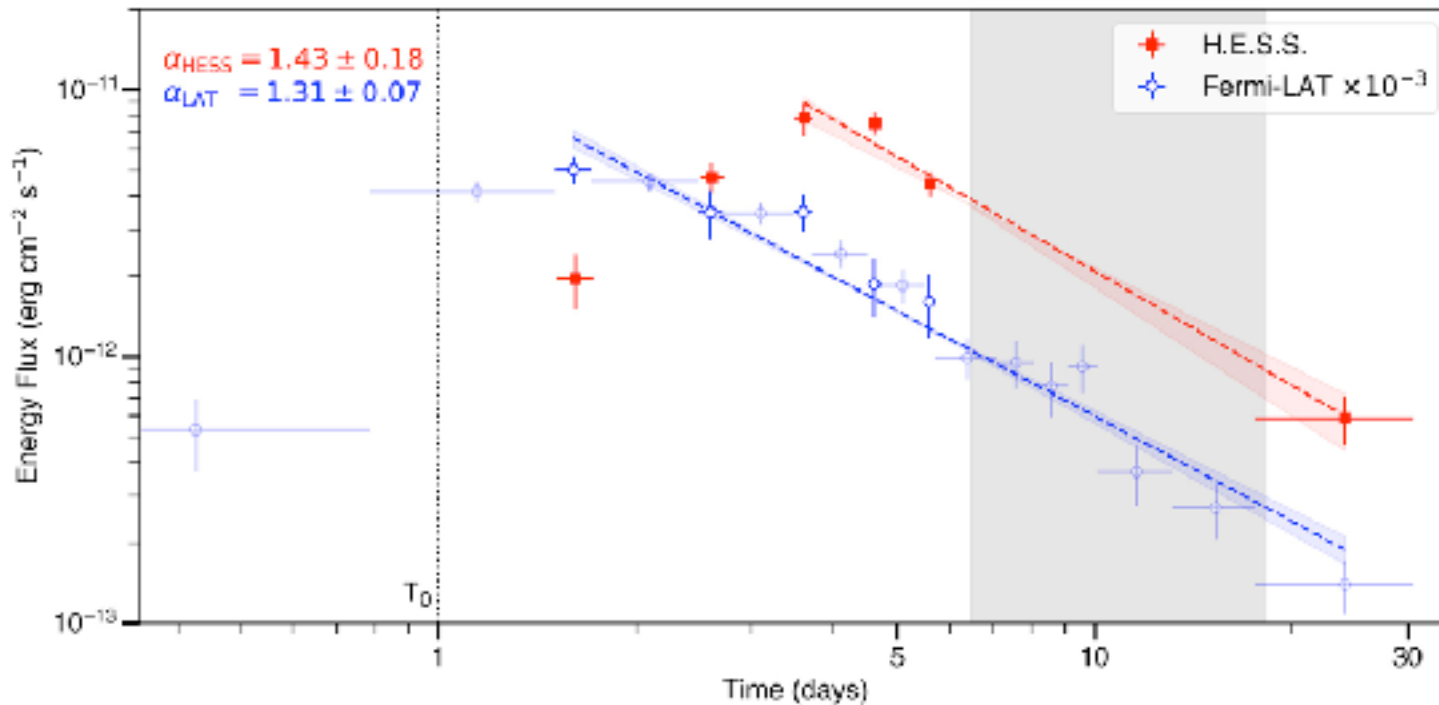
MAGIC Collaboration: V. A. Acciari (1), S. Ansoldi (2,42), L. A. Antonelli (3), A. Arbet Engels (4), M. Artero (5), K. Asano (6), D. Baack (7), A. Babić (8), A.



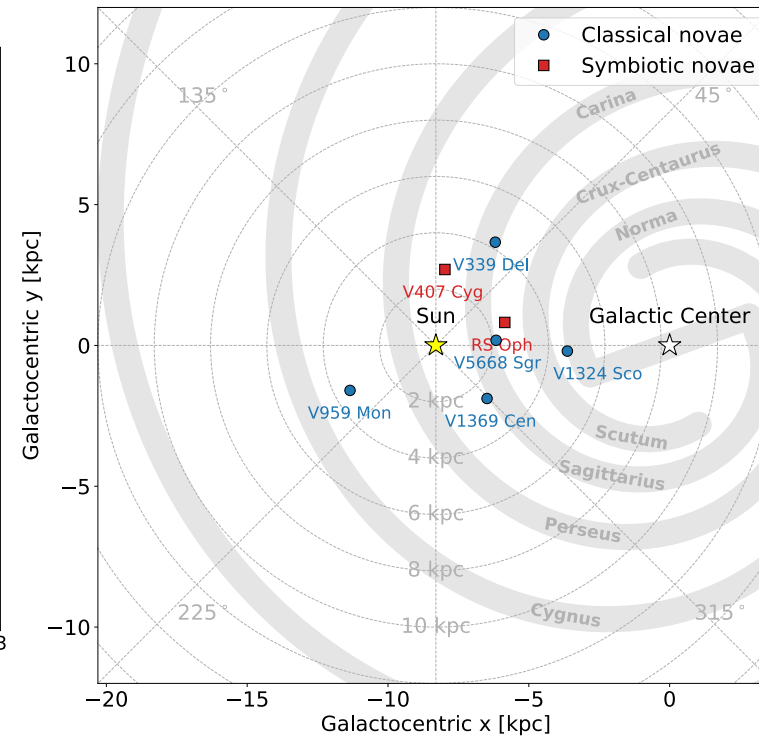
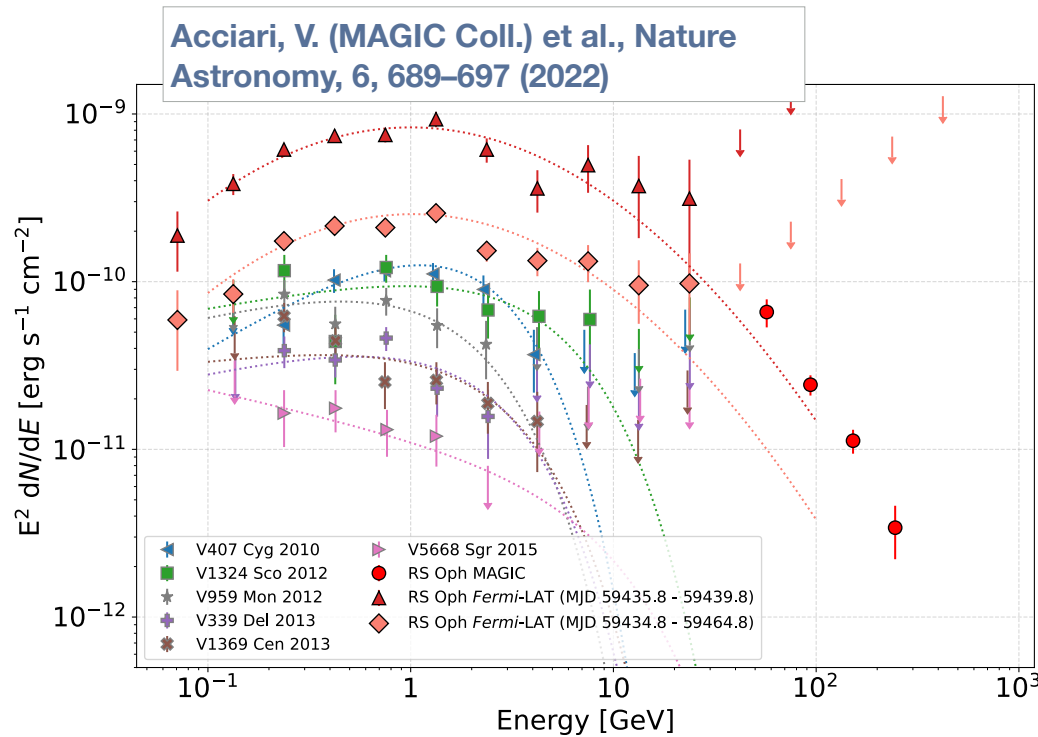
- Rough contributions to galactic CRs of novae w.r.t. supernova remnants is <1%

Multiwavelength Lightcurve

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

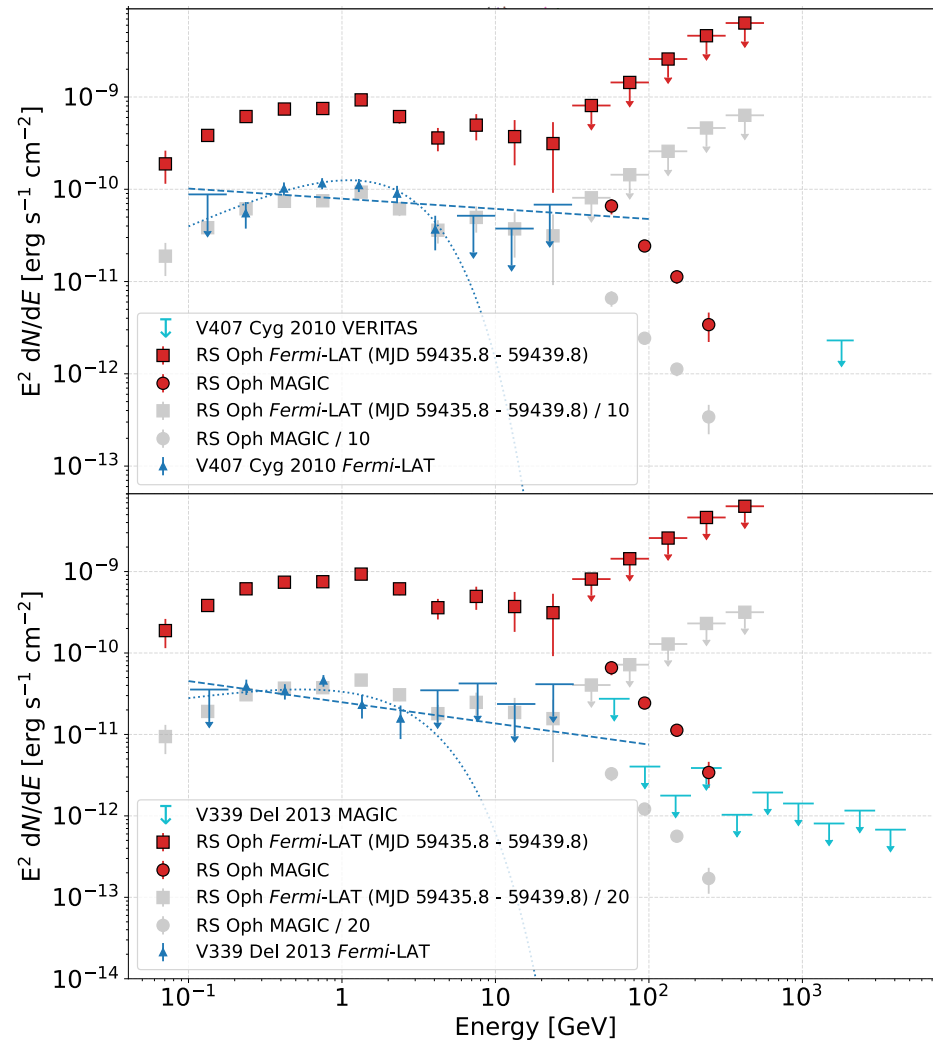


RS Oph in the context of other high energy novae



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

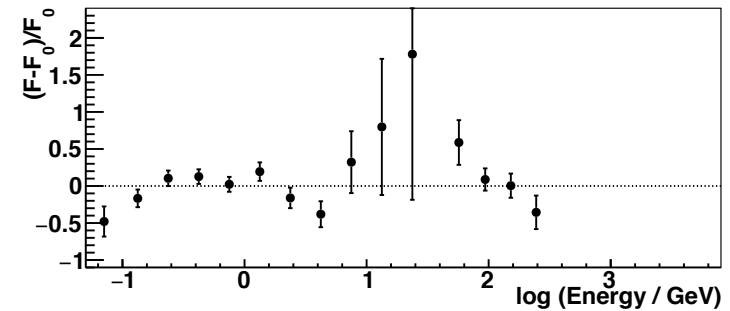
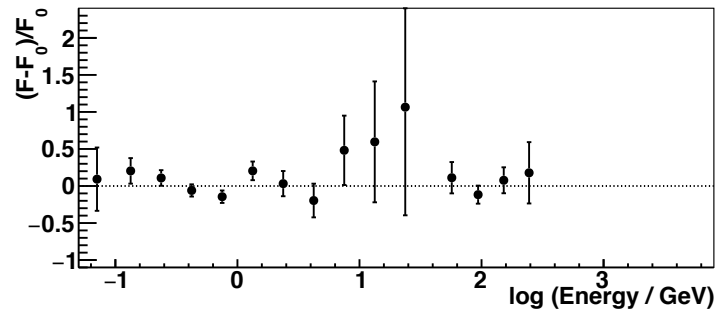
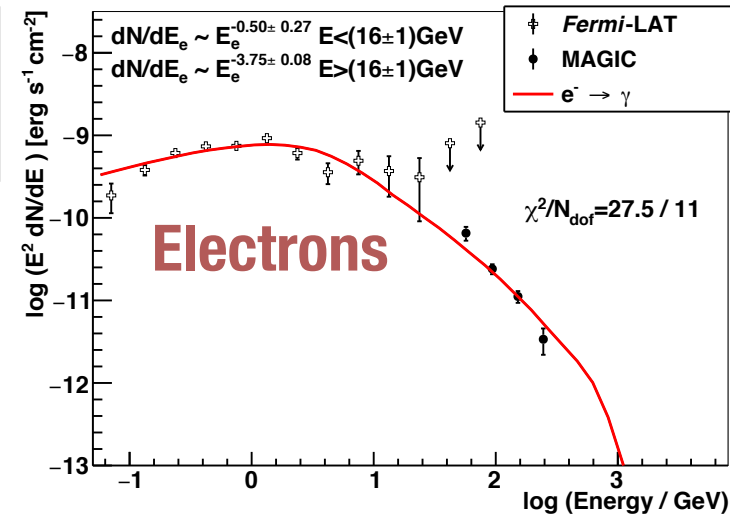
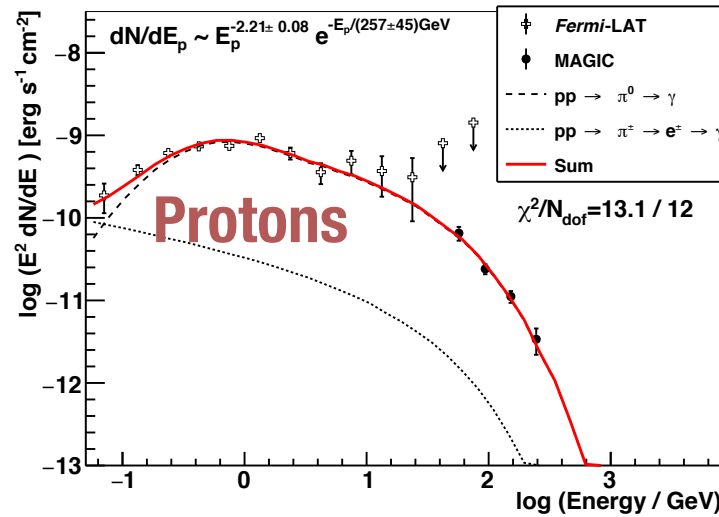
Are other novae also emitting VHE?



- 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?

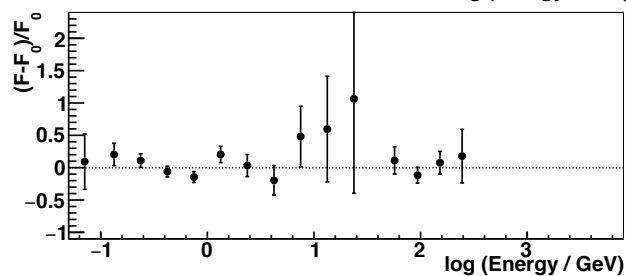
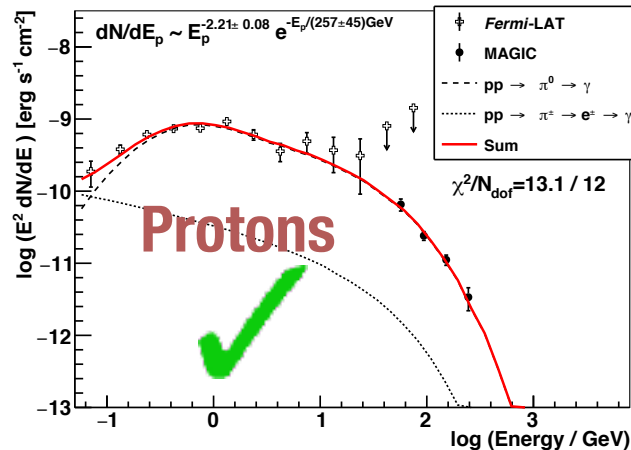


Proton acceleration

[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.

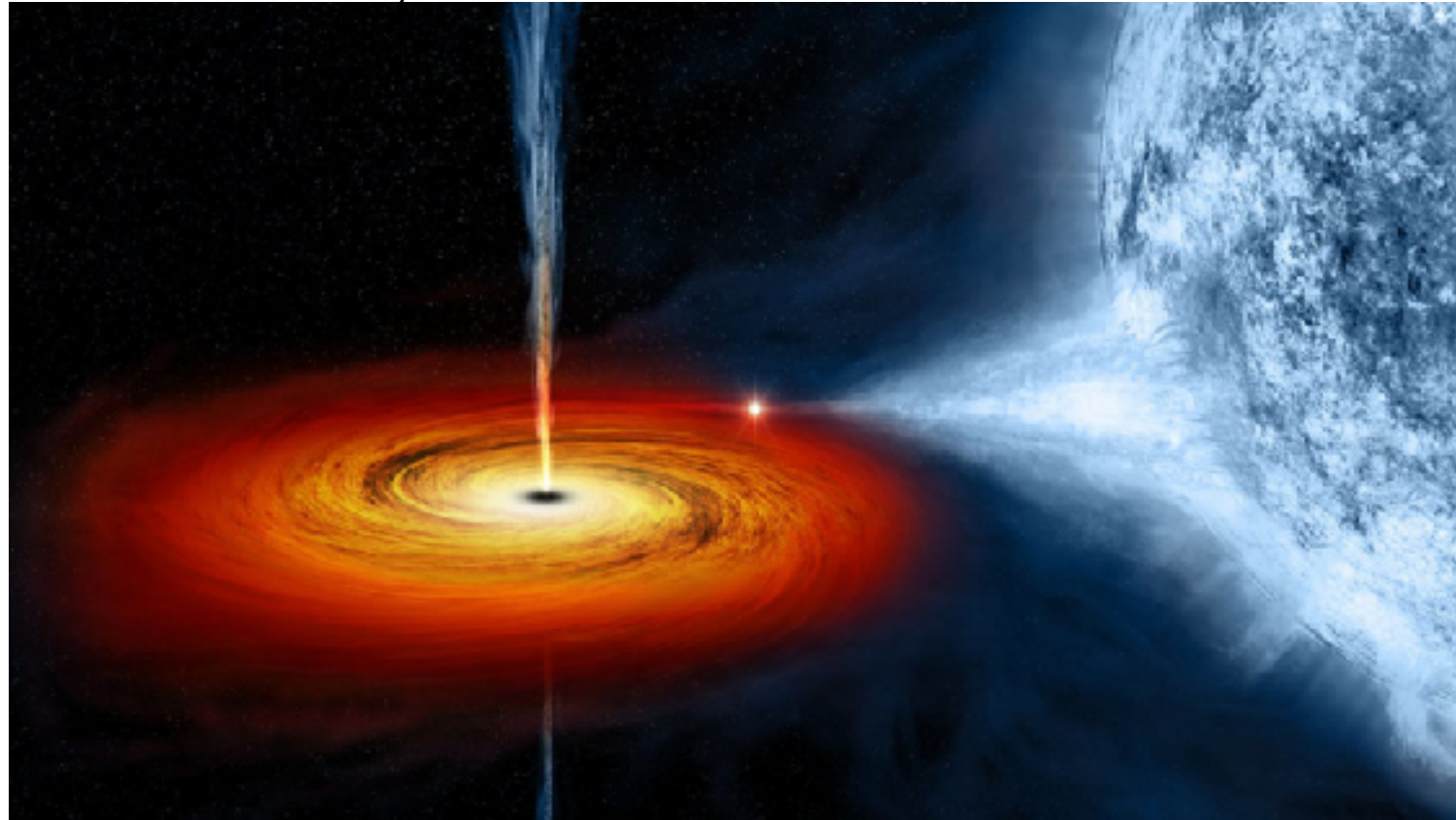


Acciari, V. (MAGIC Coll.) et al.,
Nature Astronomy, 6, 689–697
(2022)

- 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) => they also do not reach the energies needed

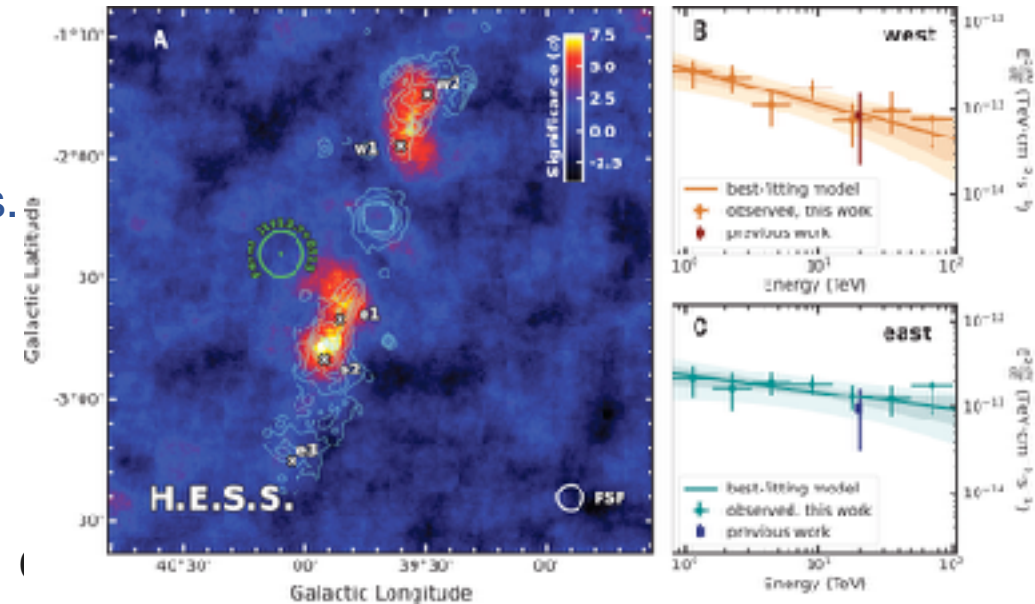
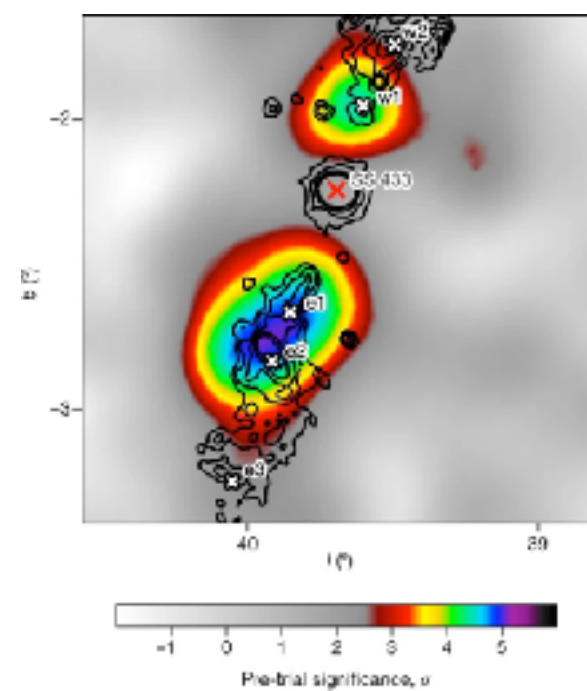
Microquasars

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



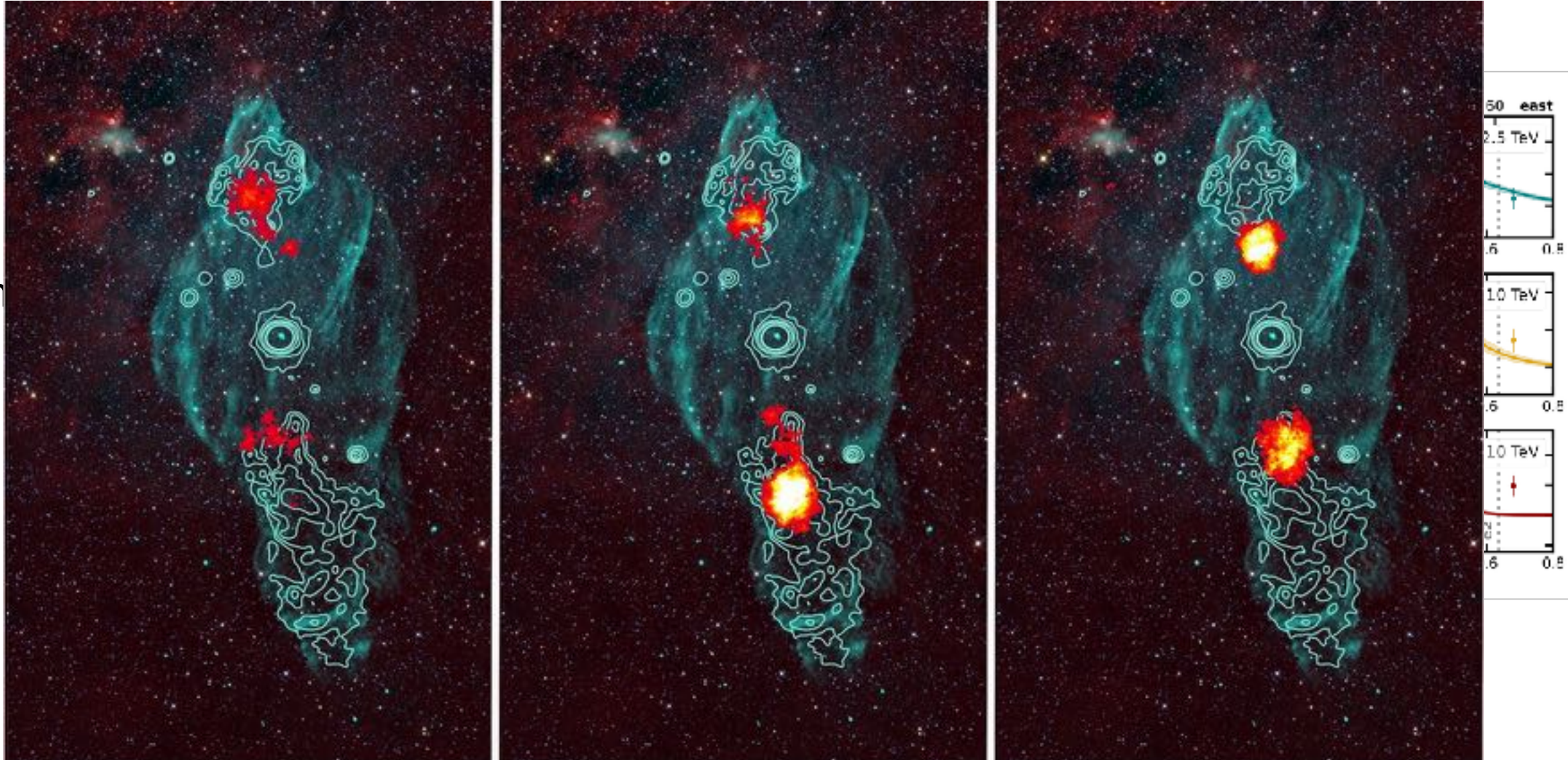
Microquasars: SS 433

- A-type supergiant orbited by \sim BH at 5.5 kpc.
- Super-Eddington accretion. Barion-loaded 0.26c jet.
- Inside the W50 nebula, being distorted by jets.
- multi-TeV detection by HAWC, compatible with leptonic scenario with e- energies up to $\sim >100$ TeV and $B=16 \mu\text{G}$ (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 and W.
 - Similar shape & spectrum.
 - Spatially consistent with the extended non-thermal X-ray jets. (H.E.S.S. Collaboration et al. 2024).

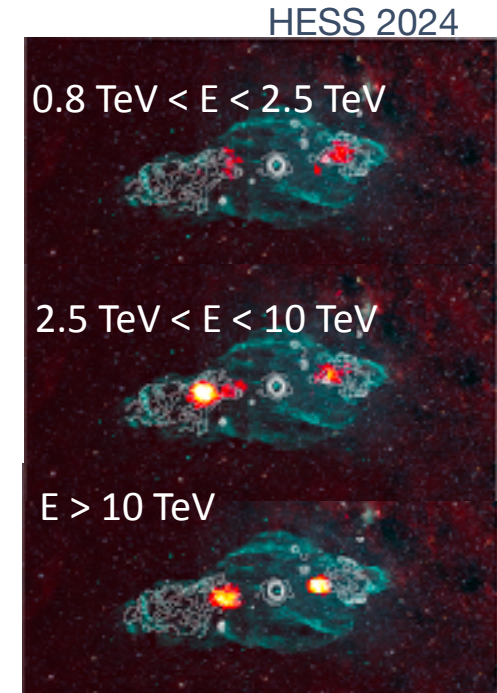
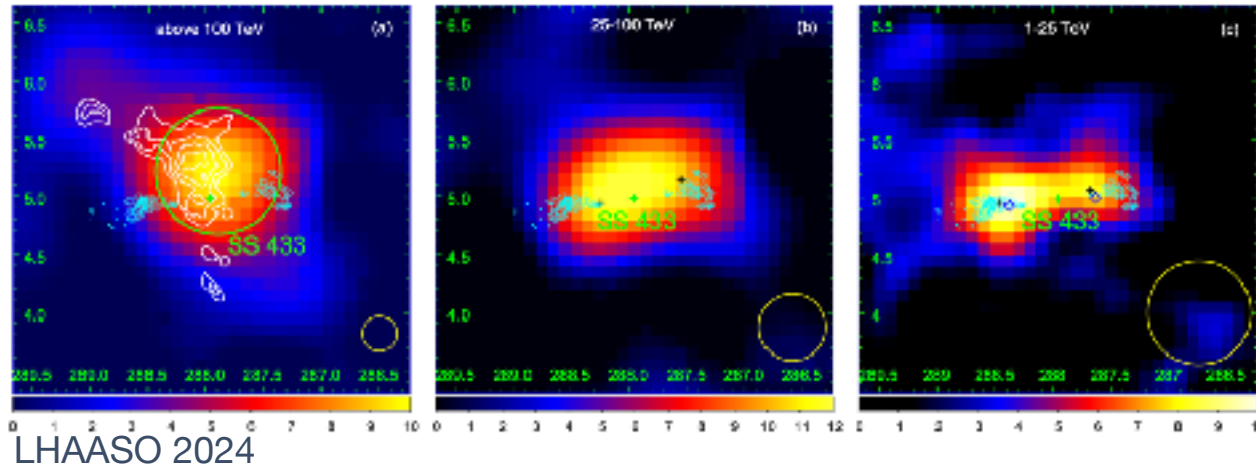


Microquasars: SS 433

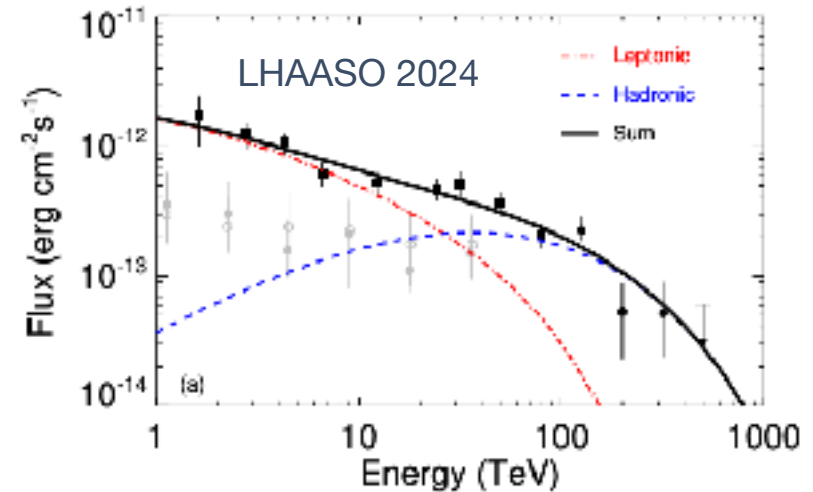
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Microquasars: SS 433



- hundreds of TeV observations
 - HAWC/HESS observations favor a leptonic origin of the emission
 - LHAASO sees emission coincident with molecular clouds => not coincident with the jets

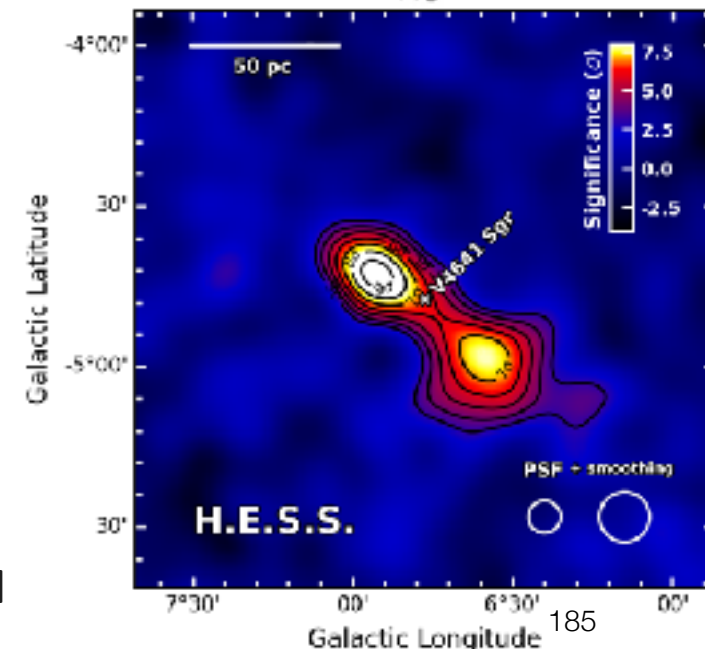
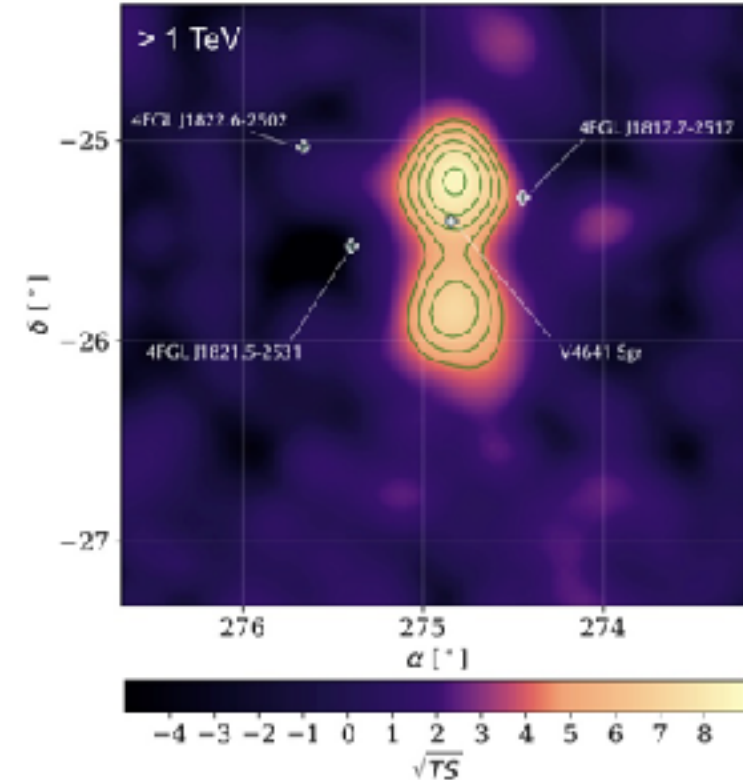


Microquasars: SS 433



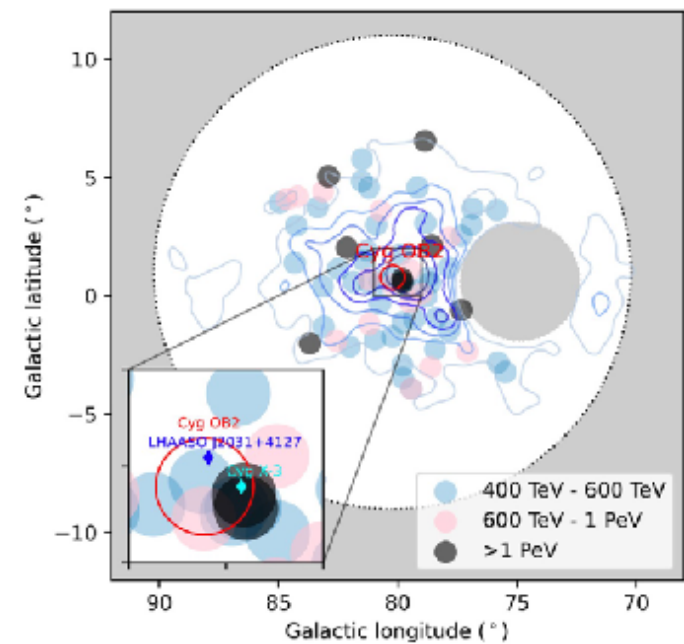
MQs: V4641

- B star of $\sim 3 M$ with $\sim 6 M$ 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?
- TeV detection by HESS/HAWC/LHAASO



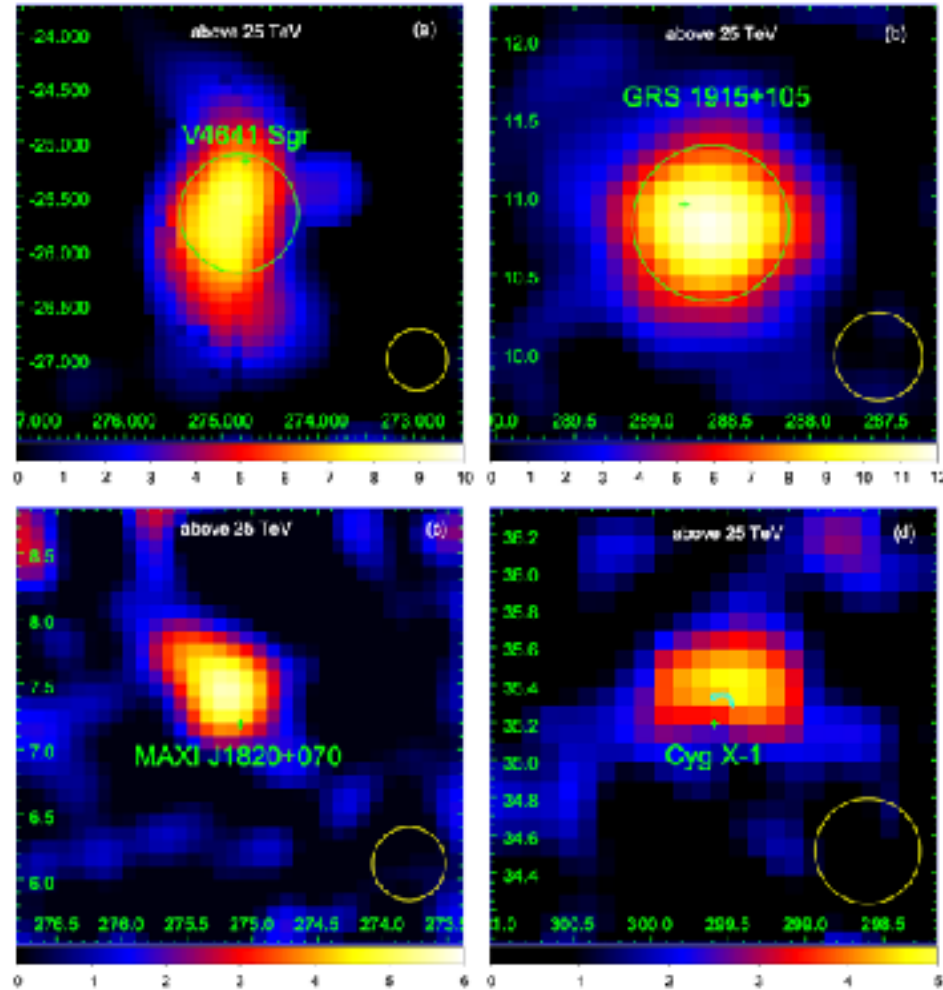
MQ: Cygnus X-3

- WR of $\sim 12 M_{\odot}$ with $\sim 7 M_{\odot}$ BH at 9 kpc.
- GeV detection during radio flaring periods
- Orbital variability anisotropic IC (Tavani et al. 2009, Abdo et al. 2009).
- Jet inclination and orbital motion \Rightarrow 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++

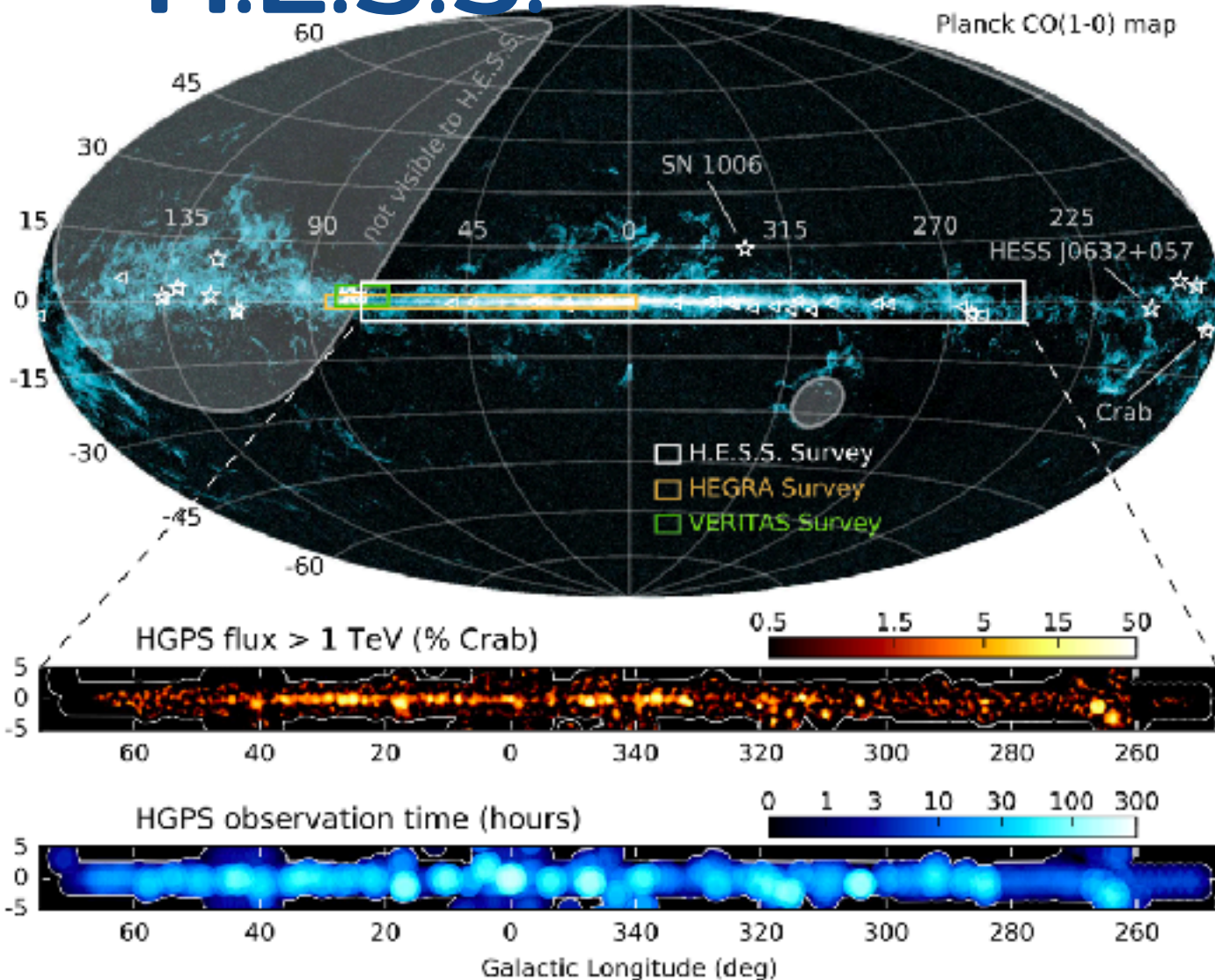
- Gamma rays up to hundreds of TeV detected from 4 additional microquasars
 - GRS 1915, Cyg X-1, MAXI J1820 reach beyond 100 TeV and the origin is under debate
 - V4641 Sgr emission is likely of hadronic origin (claim to be accelerating up to 10 PeV protons!)



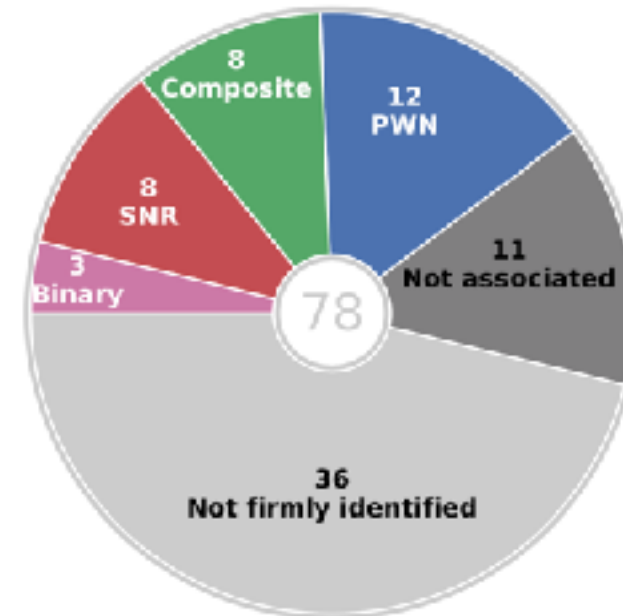
LHAASO 2024

Galactic Plane Surveys

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



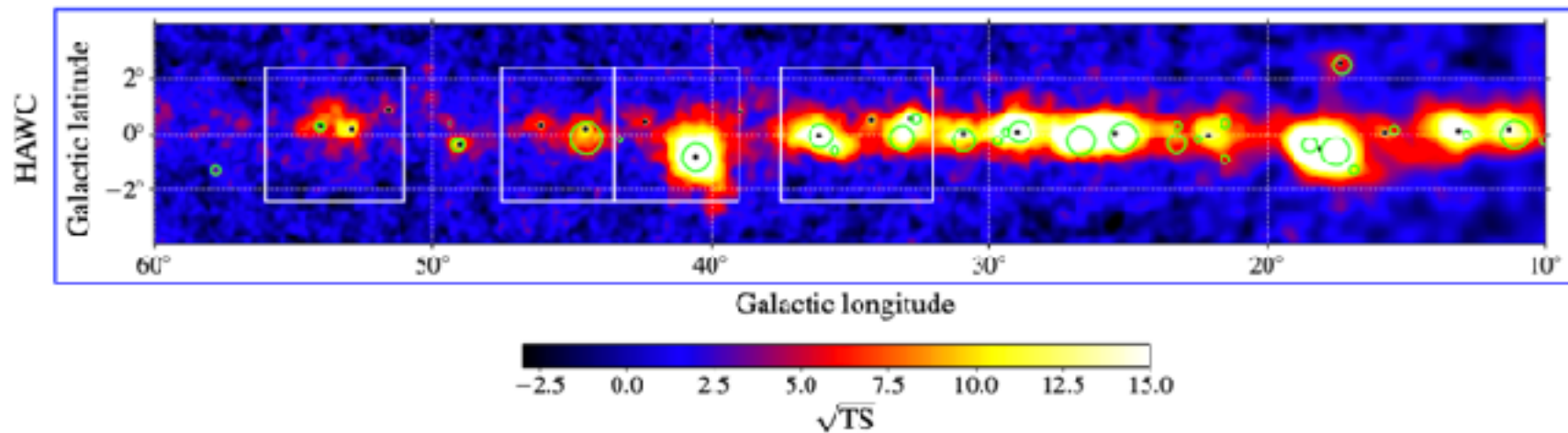
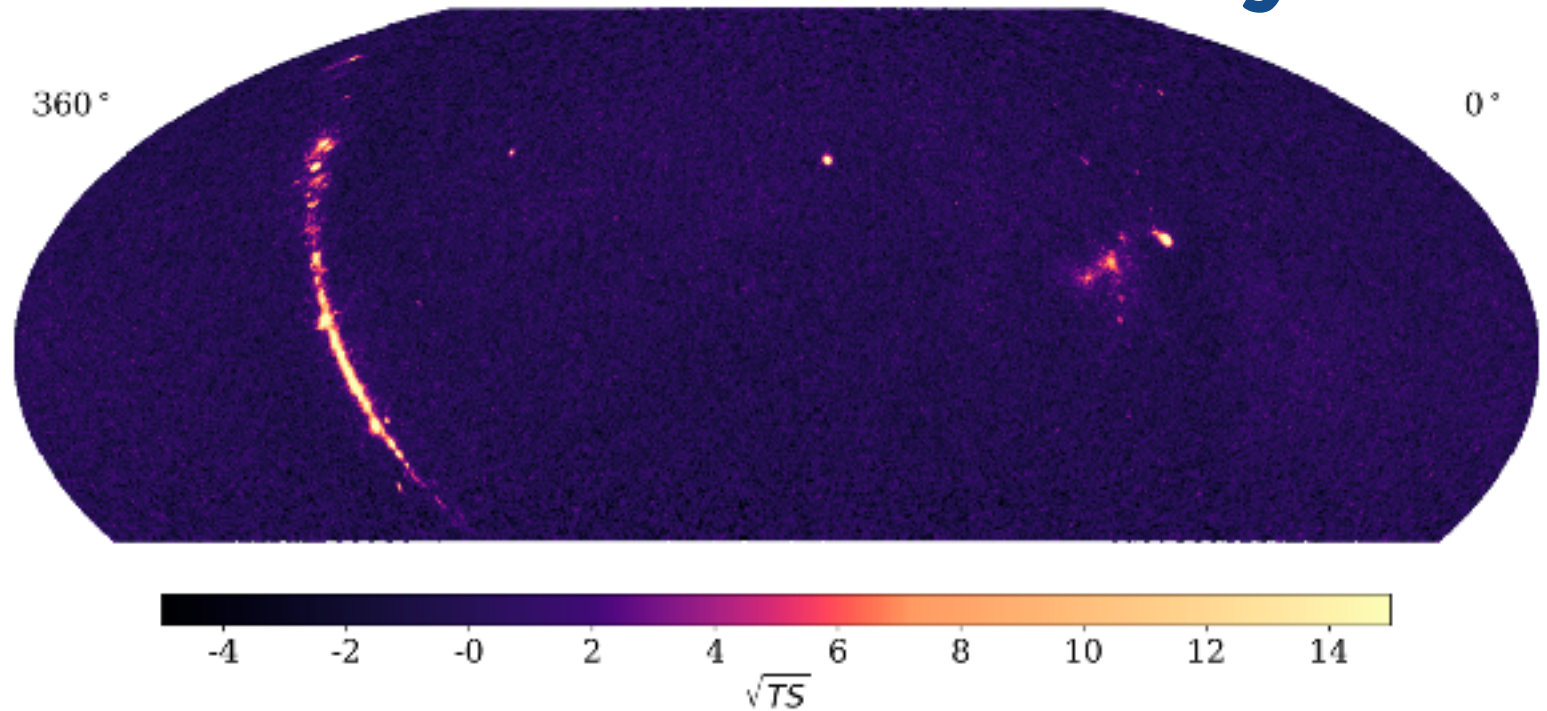
- Final HESS catalog of survey sources
- Data collected 2004 – 2013 (3000 hours)
- Significance and flux maps
- Automatic pipeline for source extraction
- 64 VHE sources
 - + 13 complex sources (e.g. shell SNR) excluded



- (

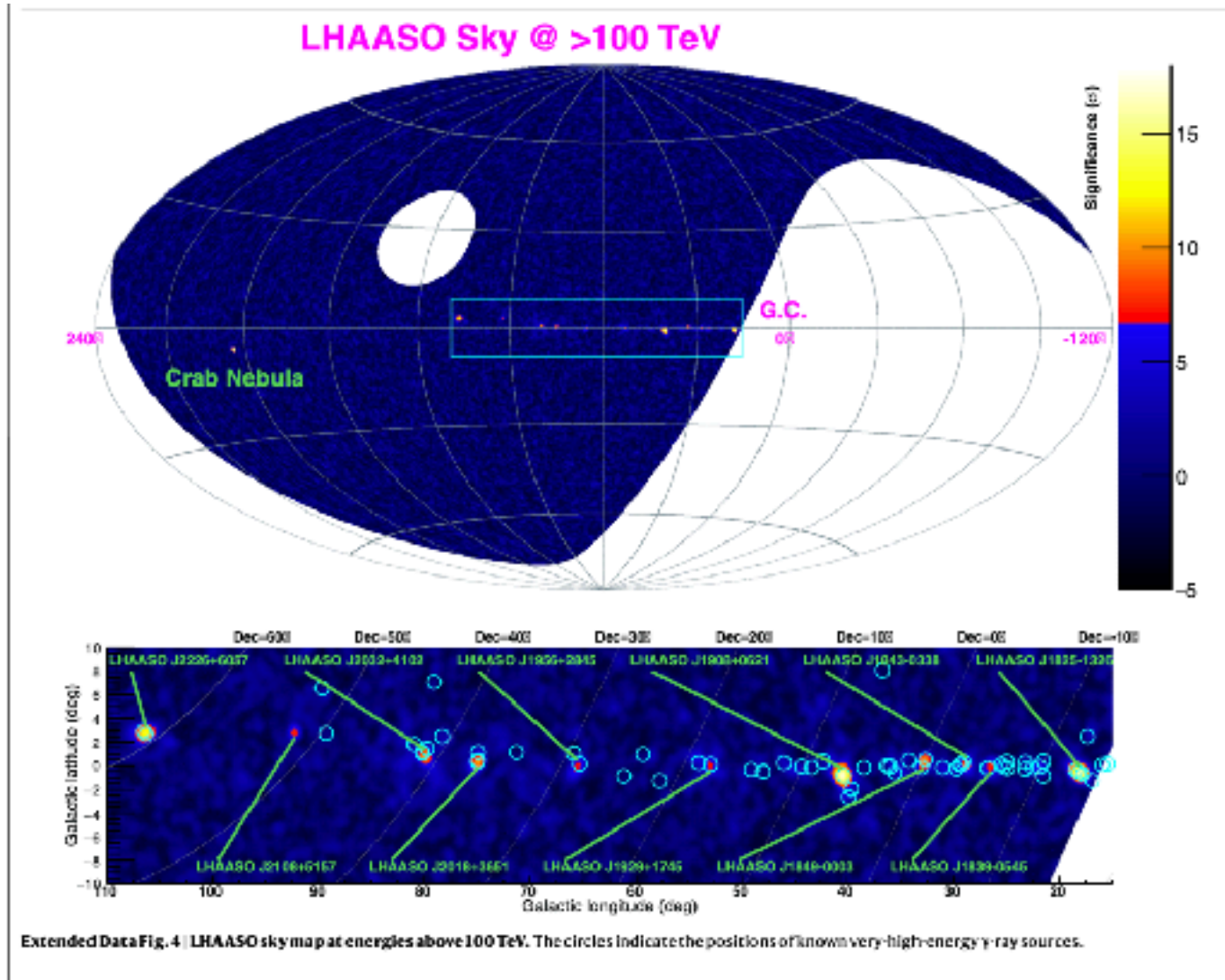
The Galactic Plane in Gamma-rays: HAWC

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



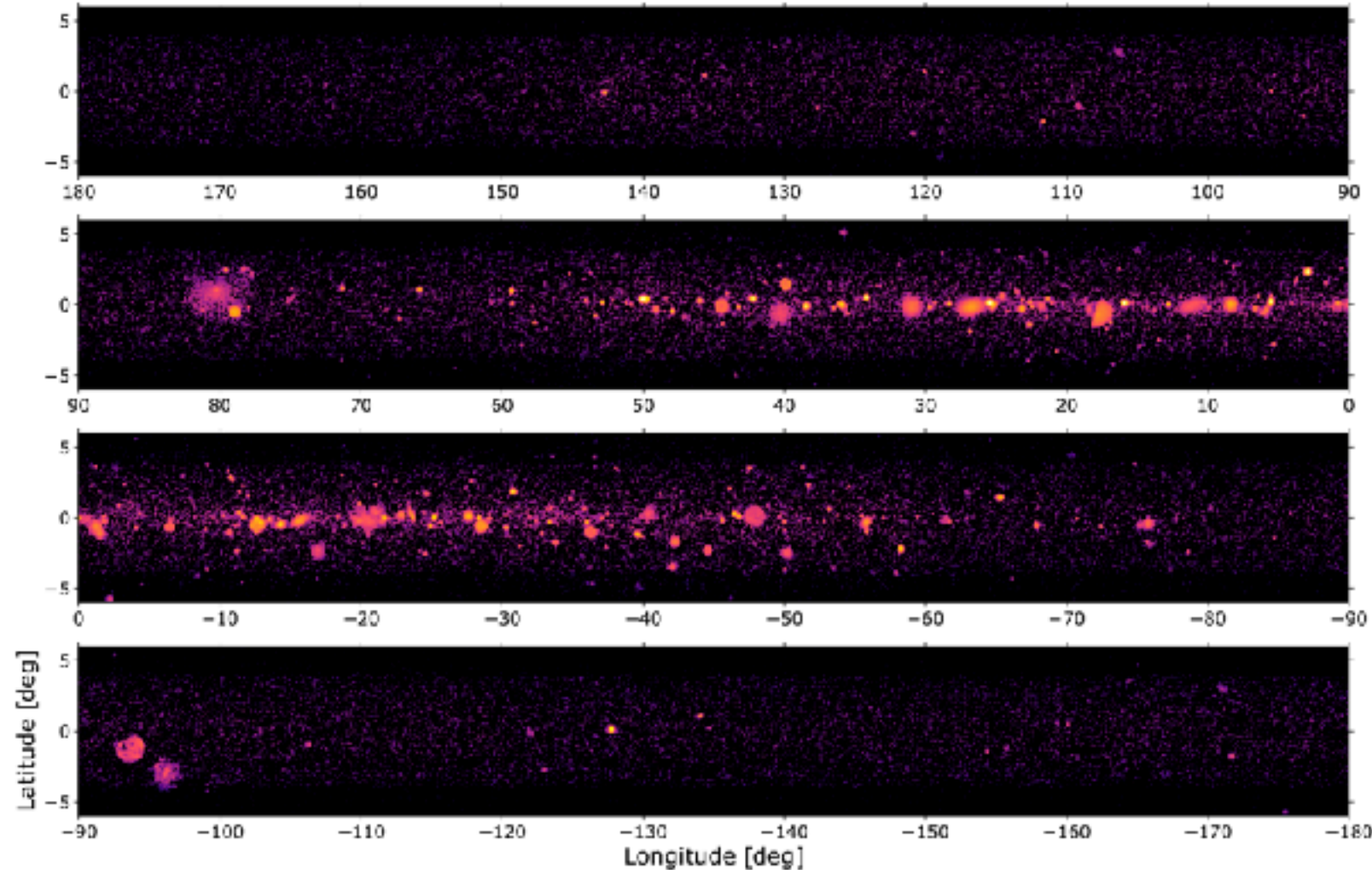
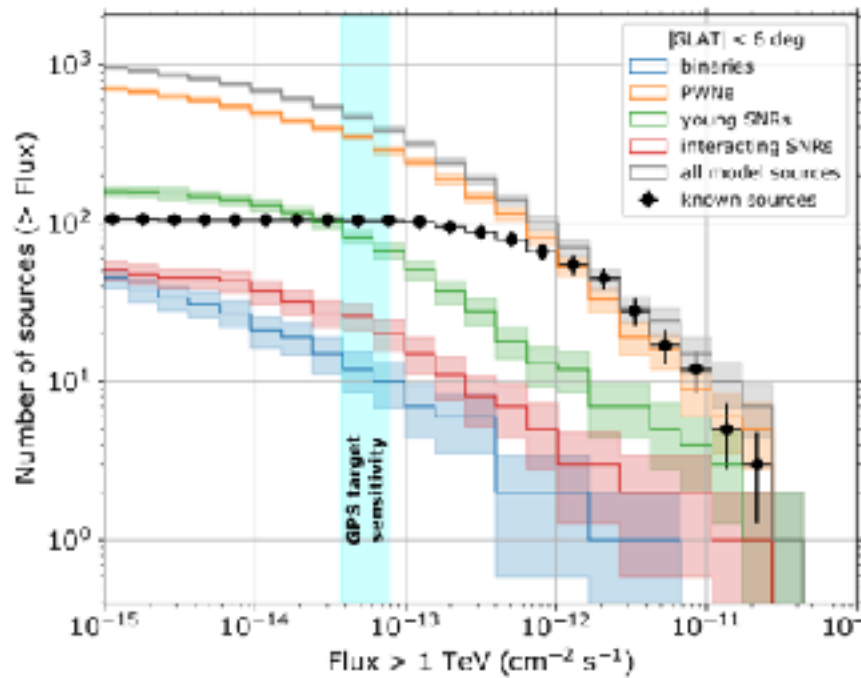
The Galactic Plane in Gamma-rays: LHAASO

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



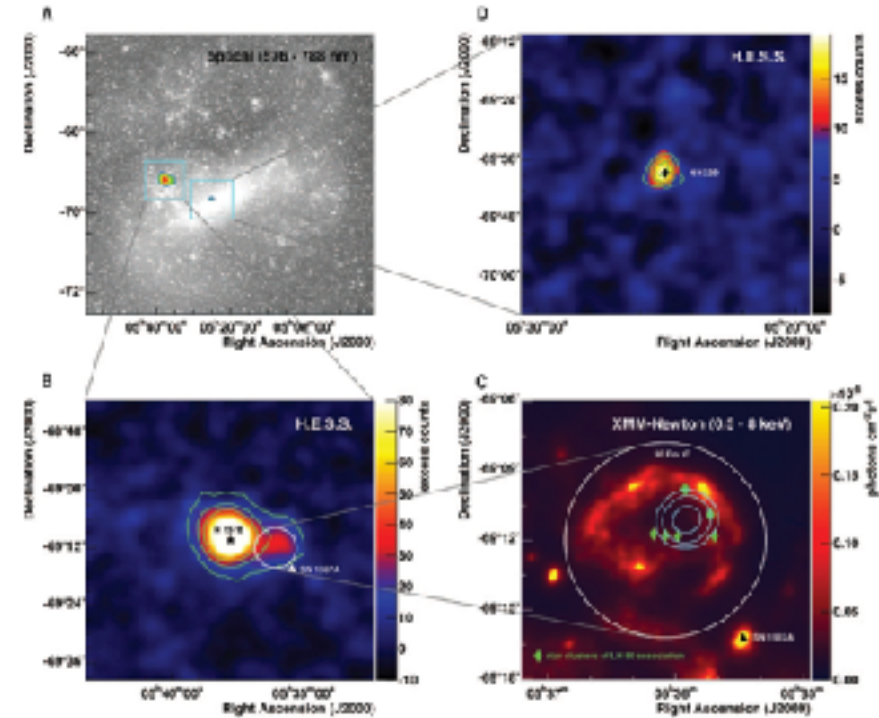
The Galactic Plane in Gamma-rays: CTAO

- Expectation to study in detail hundreds of sources



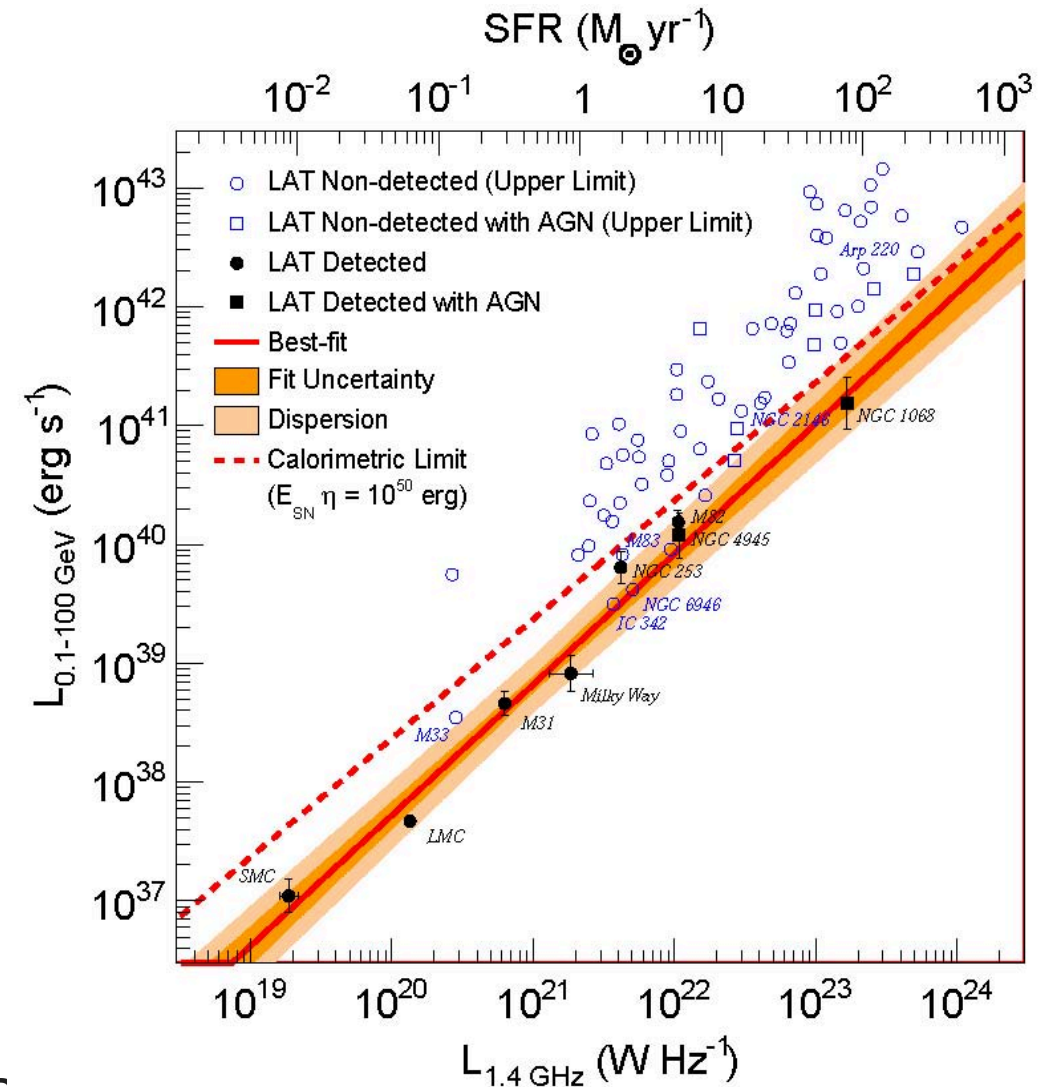
Galactic sources... outside of the galaxy!

- 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

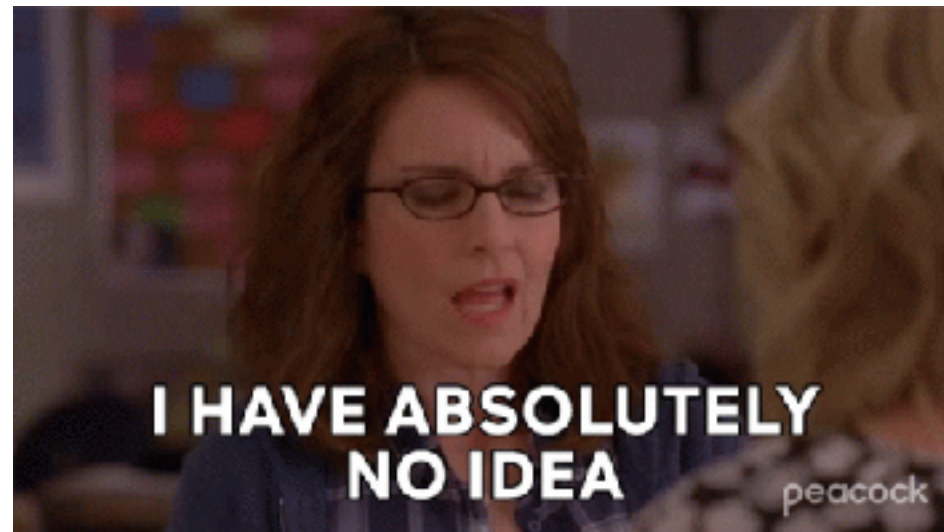


Galactic science in extragalactic objects

- 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)

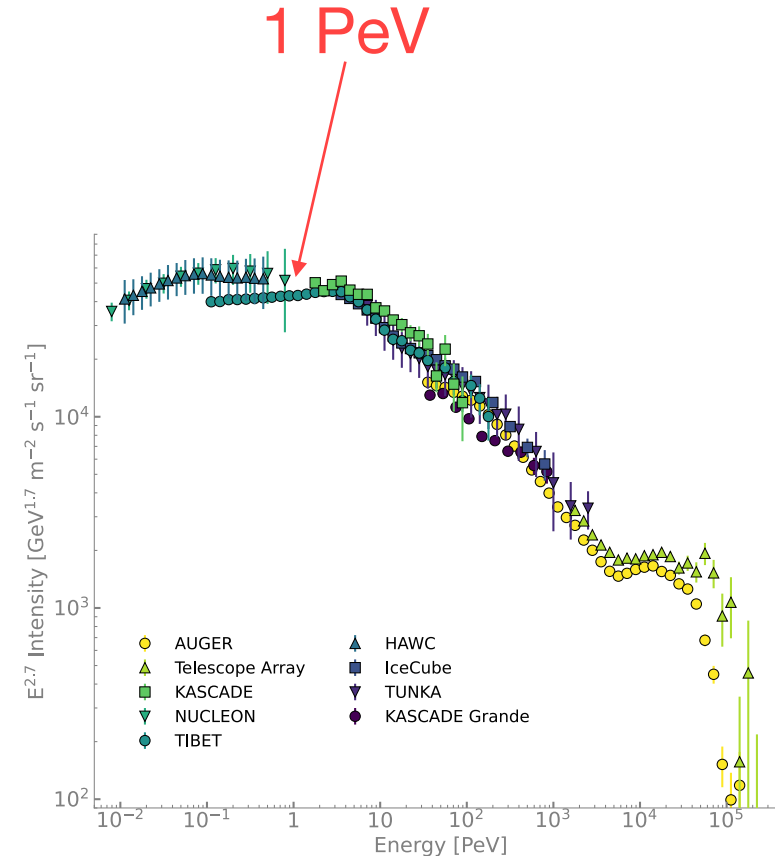


To sum up... what's the Origin of Galactic CRs?



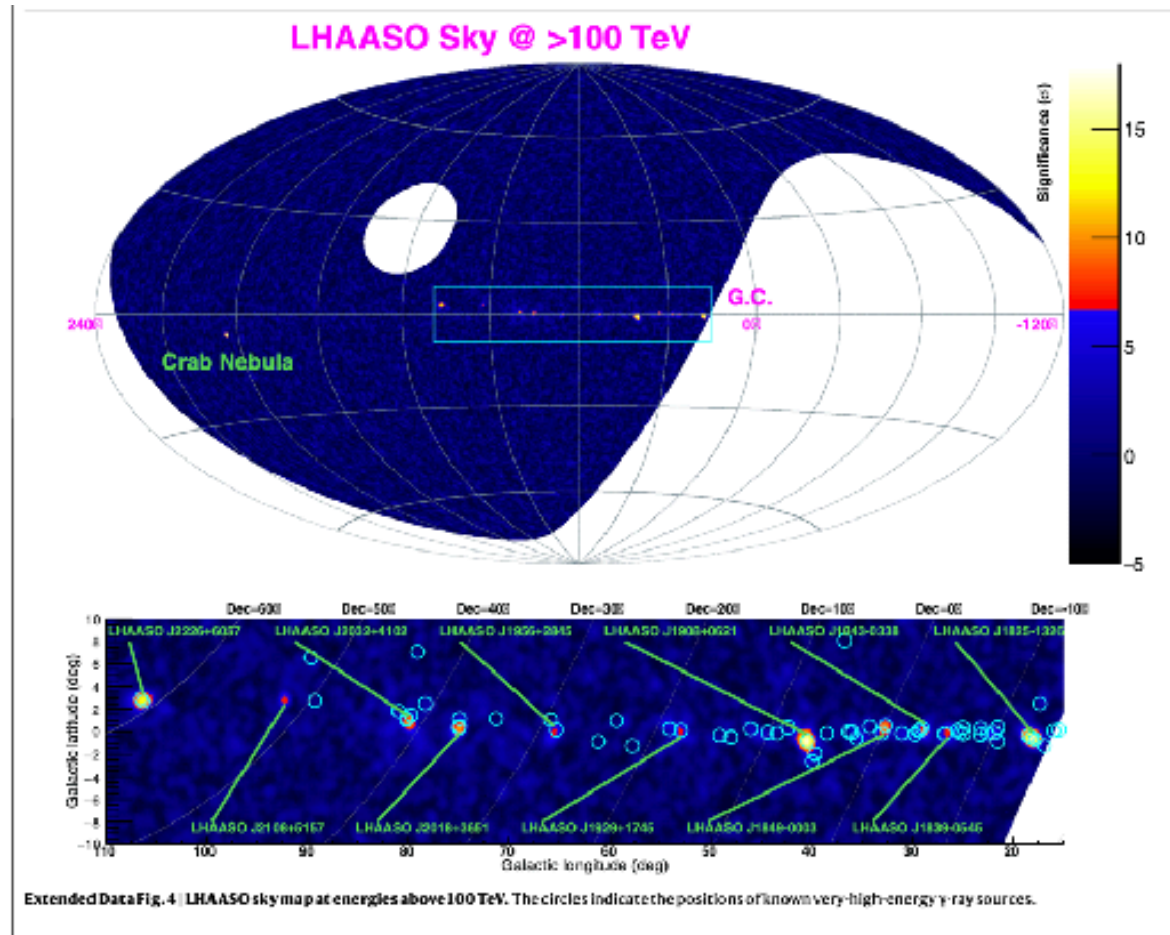
PeVatrons

- 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.



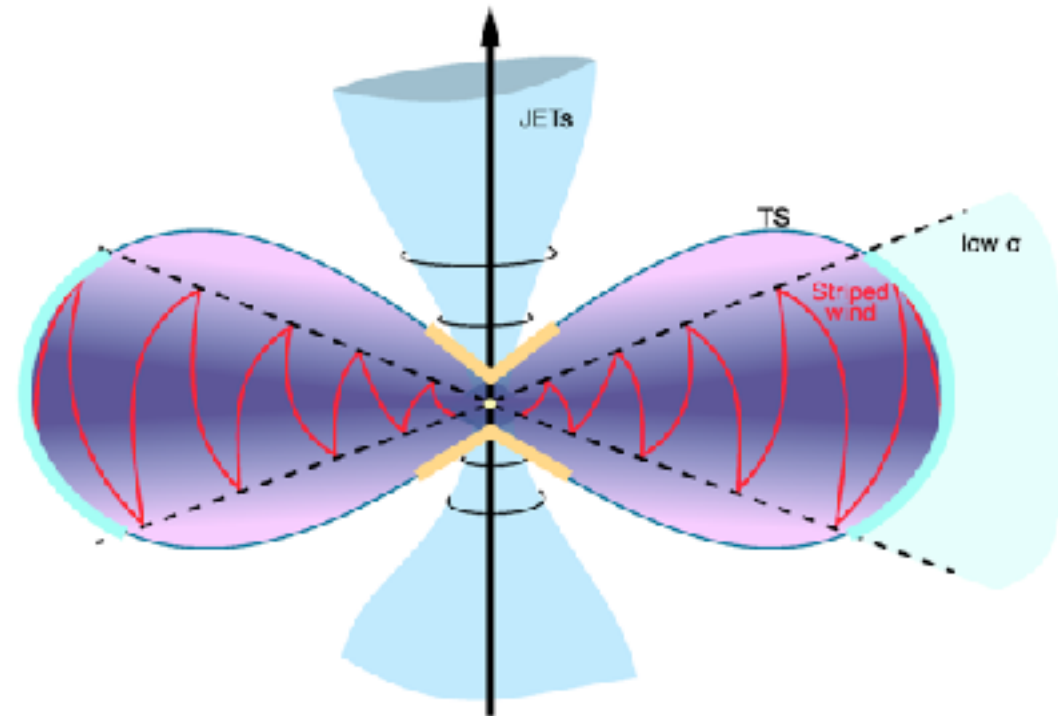
PeVatrons: a hot topic nowadays

- Results from LHAASO catalog have increased the interest on the study of PeVatrons
- Population of sources emitting gamma rays above 100 TeV (and beyond PeV!)



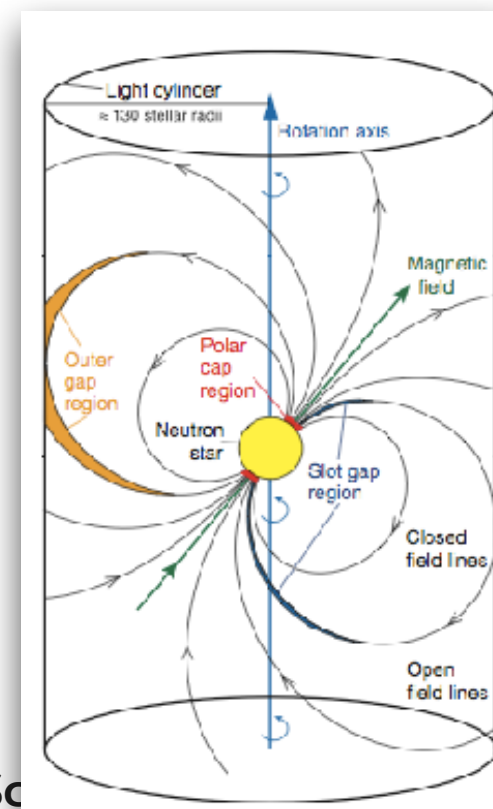
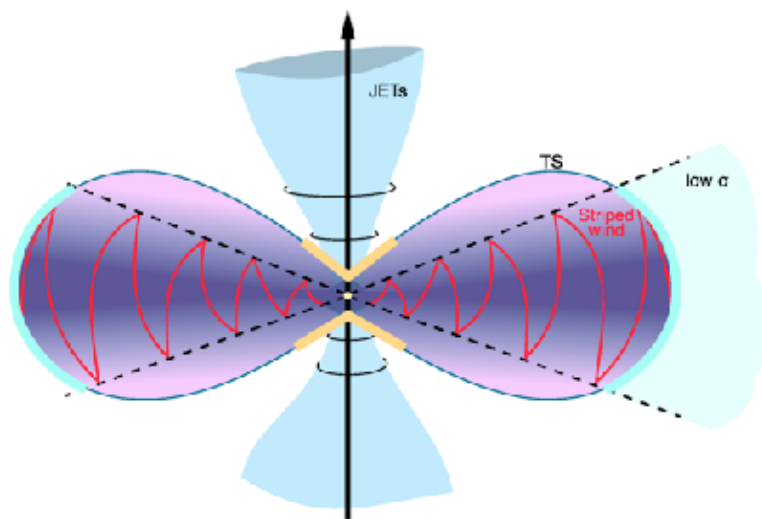
Do not forget leptonic PeVatrons

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



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

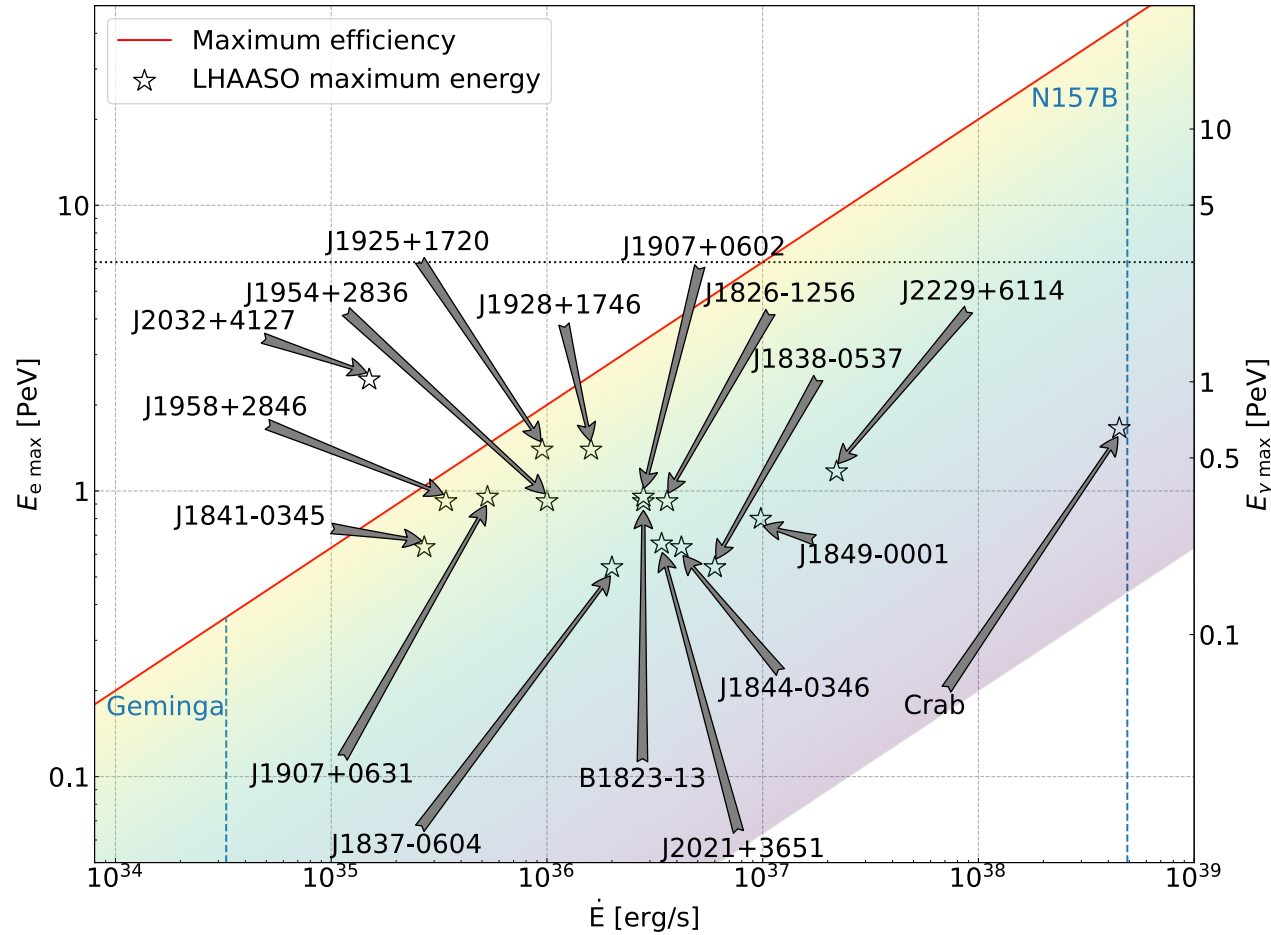


The Role of Pulsars/PWNe

- Have these LHAASO sources any pulsars nearby?
 - 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:

Physical limits

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



Pulsar efficiency (η_b)
VHEGA

Wilhelmi, RLC et al. 2022

R. López-Coto - CTAO School

Physical limits

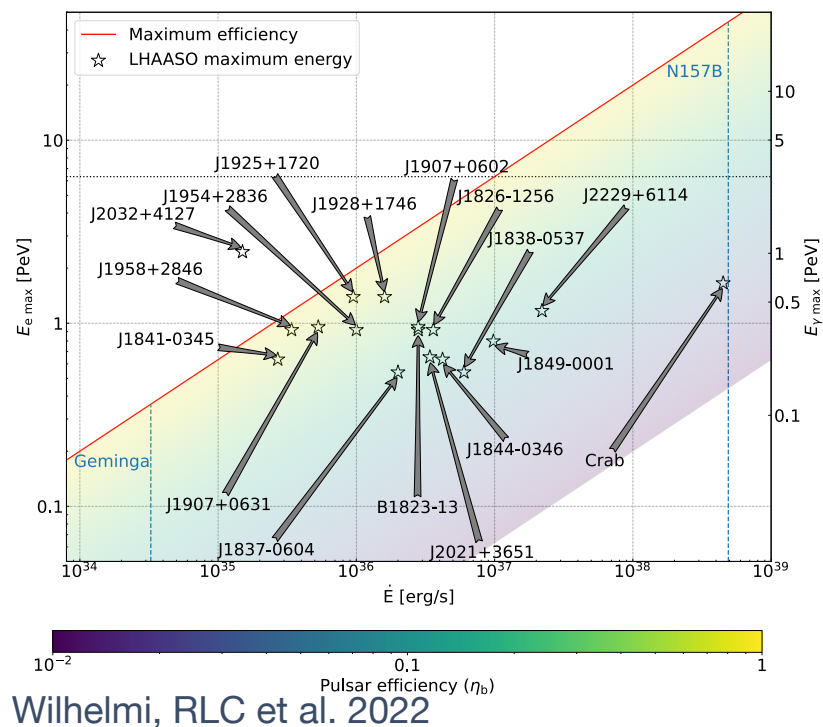


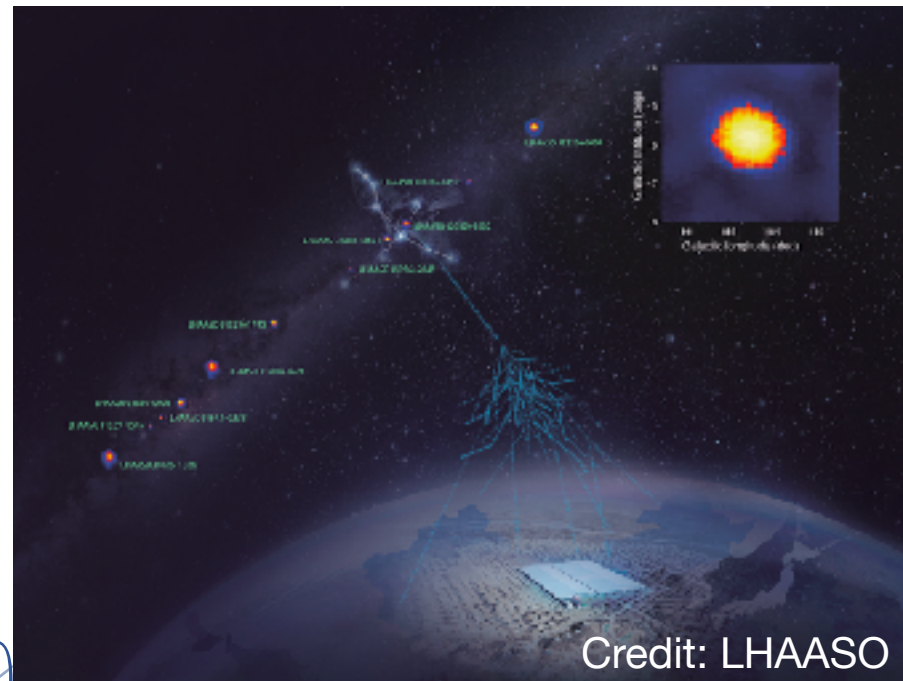
Table 2
LHAASO Ultrahigh-energy Sources and Putative Associated Pulsars, with the Corresponding Constraints on the Maximum Energy and Magnetic Field

LHAASO Source	Pulsar	$E_{\gamma, \text{max}}$ (PeV)	E_{max} (PeV)	B_{max} (μT)
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	≥ 100
J1843-0338	J1841-0345	0.41	1.04	12
	J1844-0346	2.25	4.10	≥ 100
J1849-0003	J1849-0001	3.71	6.26	≥ 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+3631	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

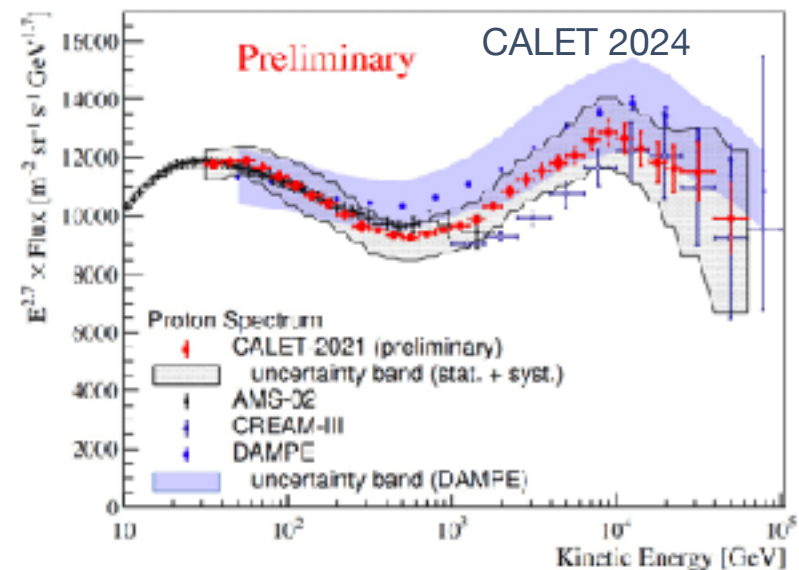
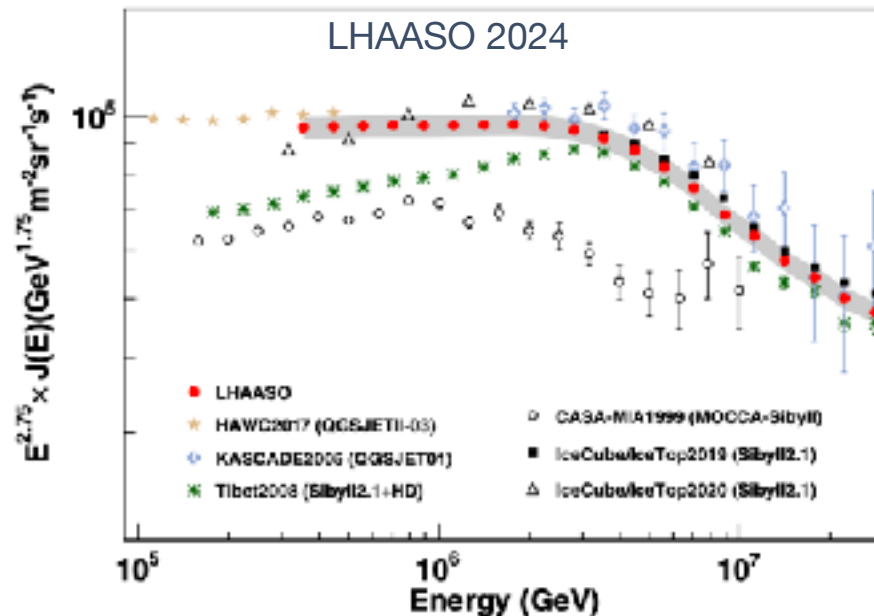
PeVatrons: a hot topic nowadays

- 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?



PeVatrons: a hot topic nowadays

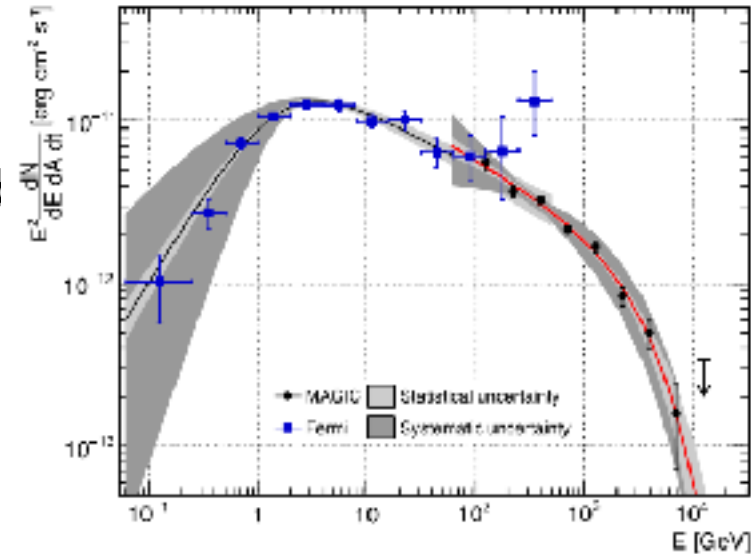
- Particle spectrum shows general trends, but the proton spectrum is subjected to statistics and systematic errors: this could broaden the range of possible PeVatrons.
- Latest results from CALET/DAMPE show that the region below 1 PeV is not as featureless as we thought



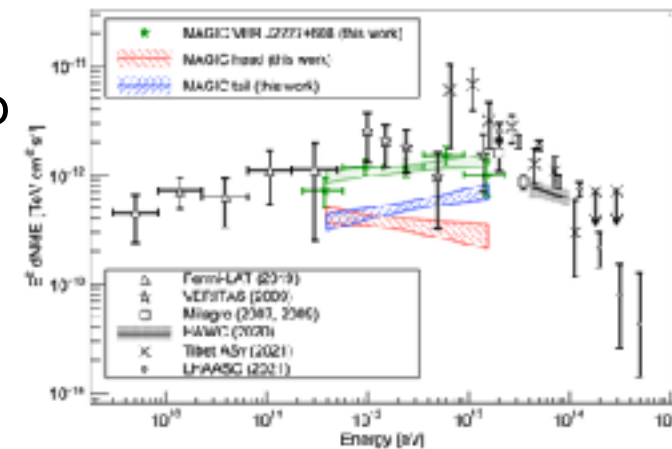
Main candidate: Supernova Remnants

- 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

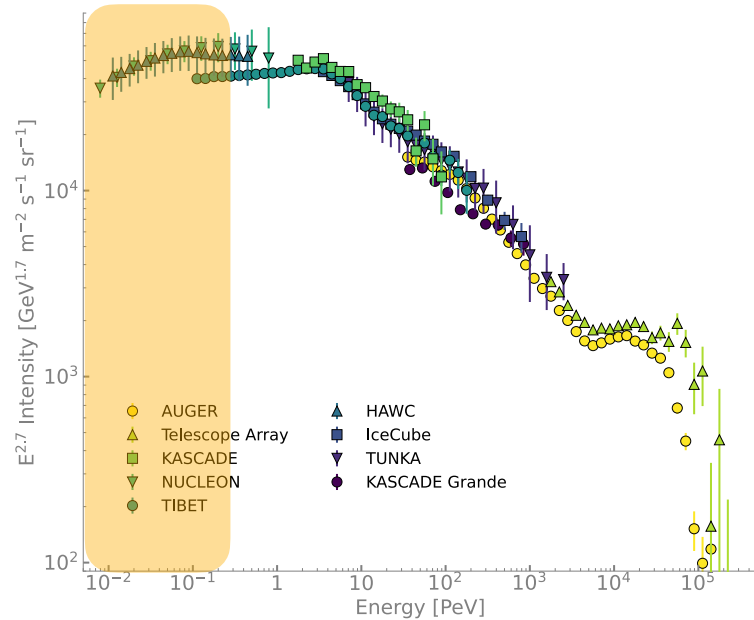


Boomerang, MAGIC Collaboration 2022



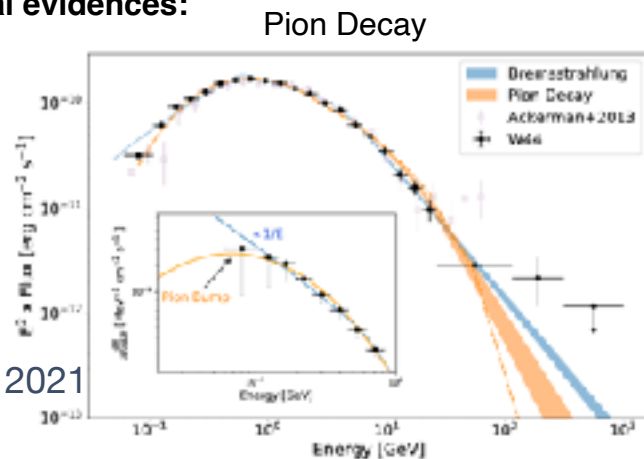
The origin of the Galactic Cosmic Rays

The Sub-PeV regime



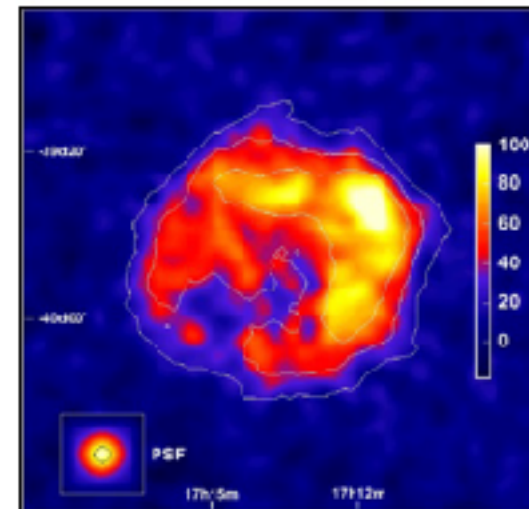
- General agreement: most of the low energy particles comes from Supernova Remnants
 - Experimental evidences & theoretically comfortable

Experimental evidences:



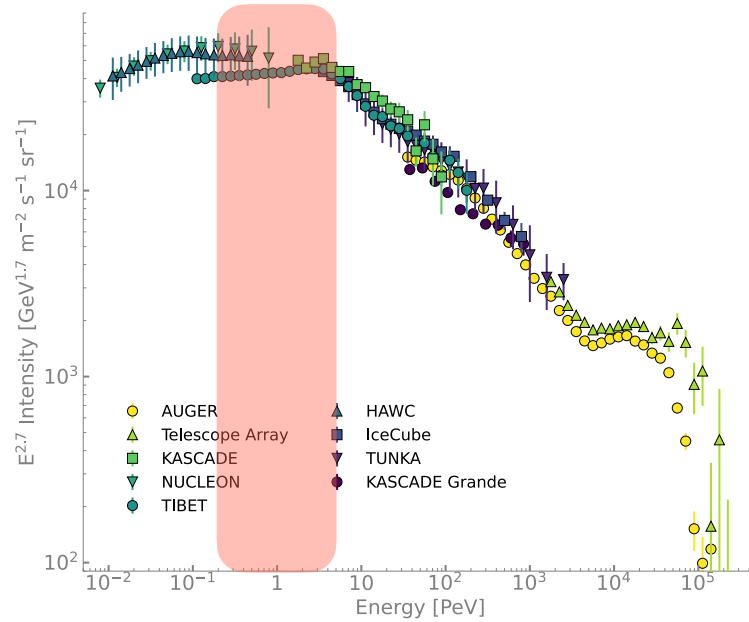
Peron et al. 2021

Morphology

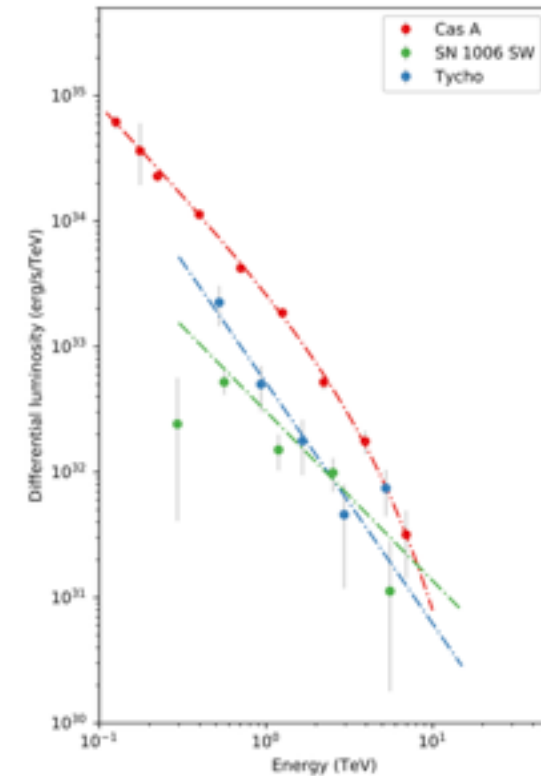


The origin of the Galactic Cosmic Rays

~hundreds of TeV to few PeV



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

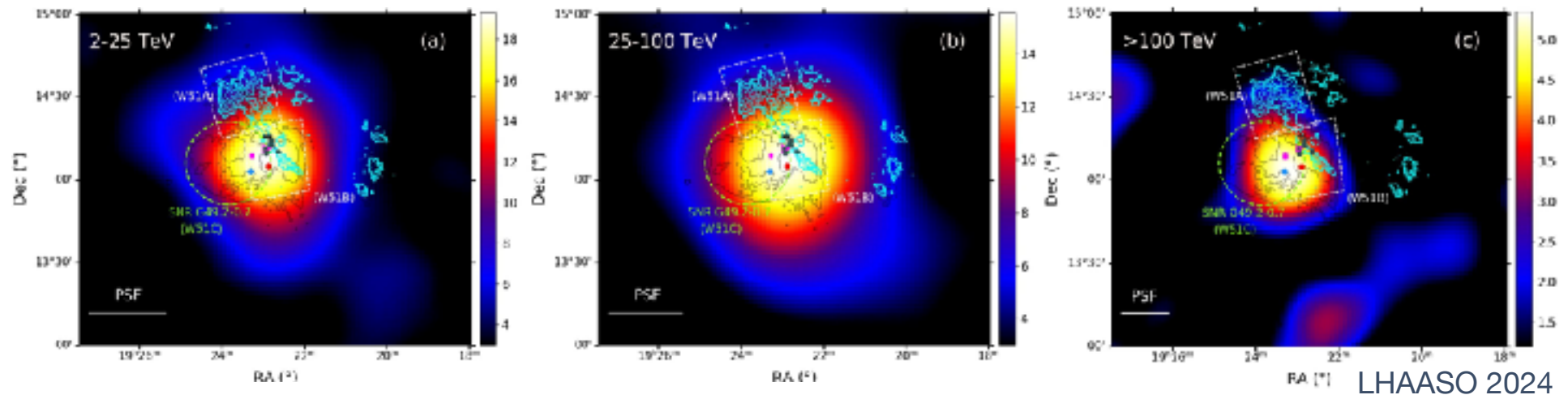


Experimental evidences:

Aharonian, F. et al., 2019

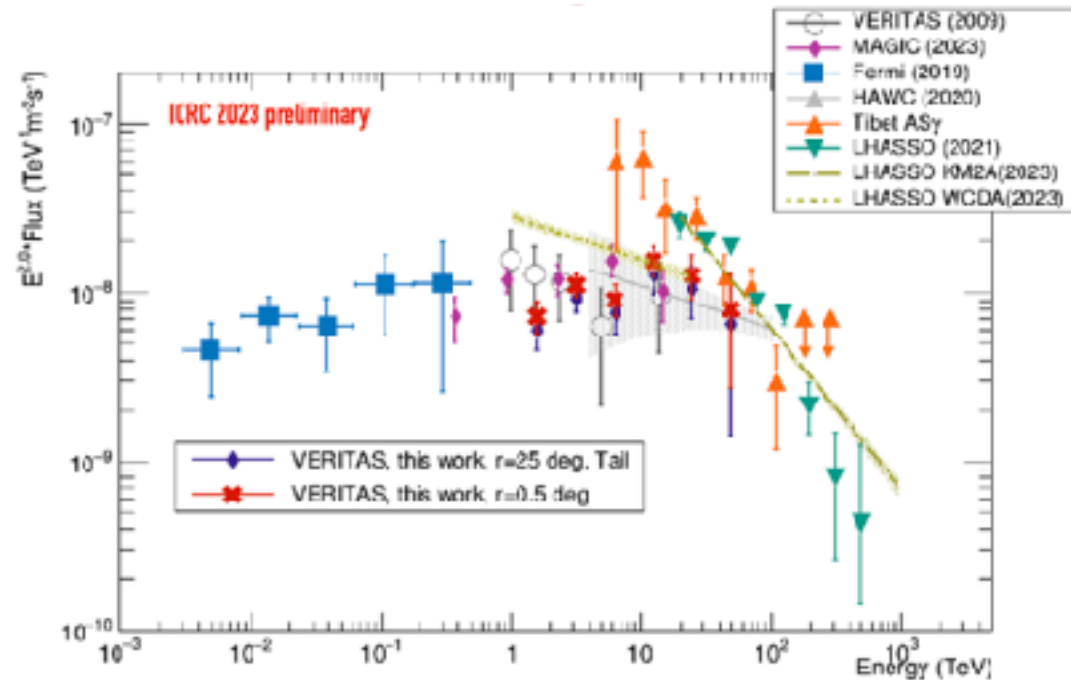
PeV acceleration? in Supernova Remnants

- **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



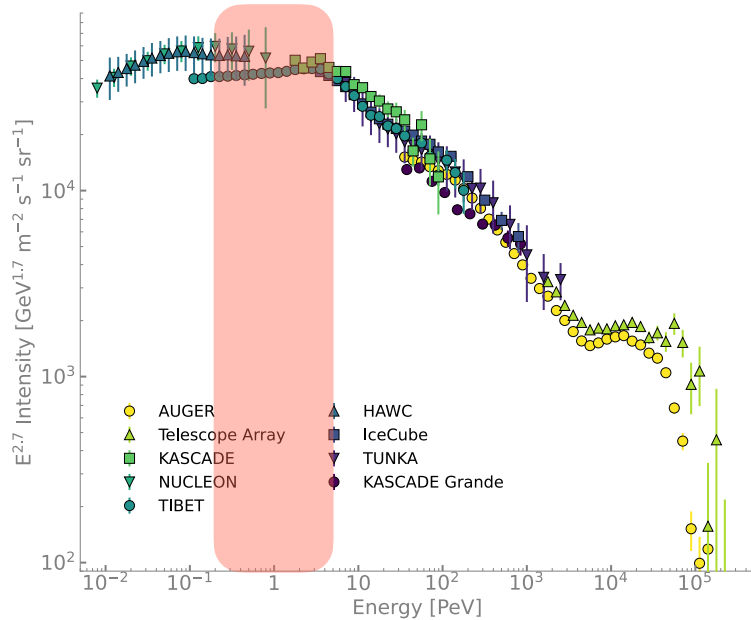
PeV acceleration? in Supernova Remnants

- **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

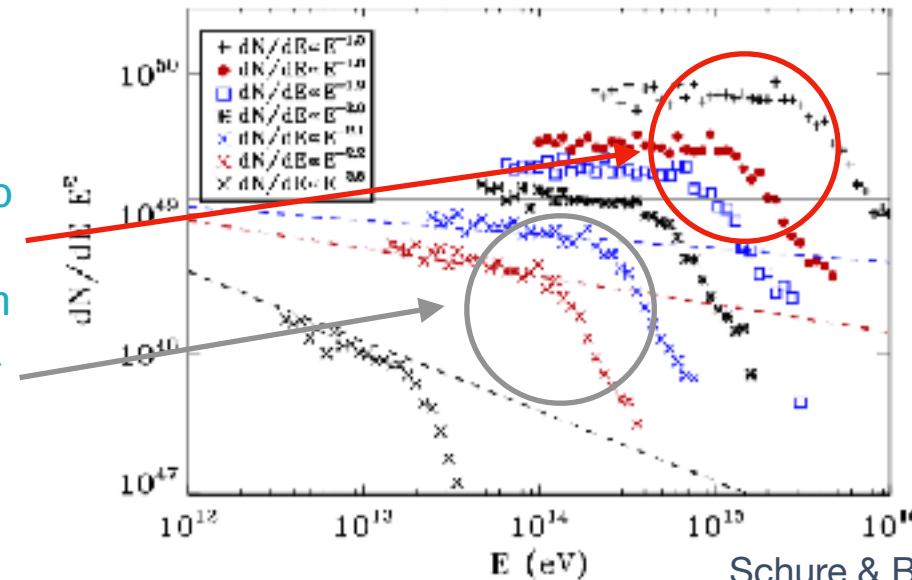
~hundreds of TeV to few PeV



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

Theoretical estimations:

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

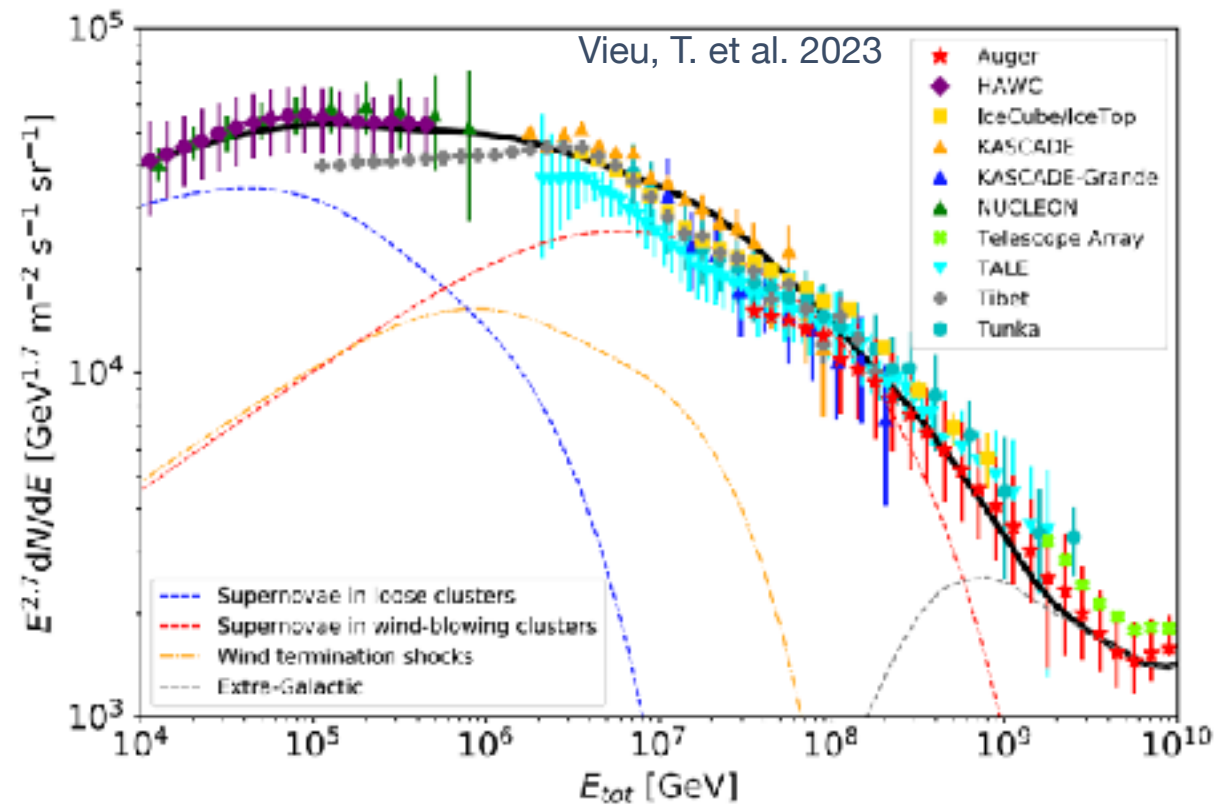


Schure & Bell 2014

The origin of the Galactic Cosmic Rays

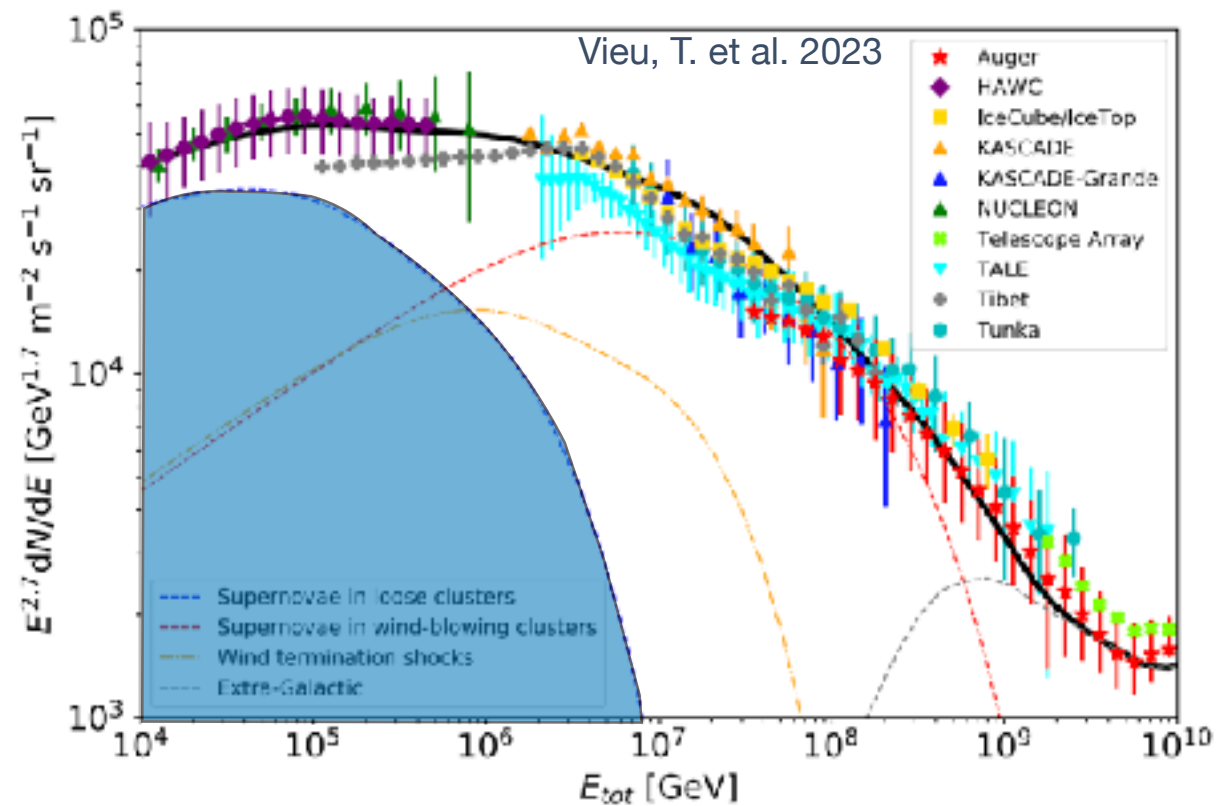
- Possible ideas to solve the problem...
 - Early phase SNRs in the <100 yrs (highest density / fastest shock velocity) are the ones accelerating PeV CRs.
 - SNRs we don't know?
 - Some candidates may reach *almost* the PeV regime
 - W51C, Boomerang...
 - **Two source population hypothesis:** a source 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



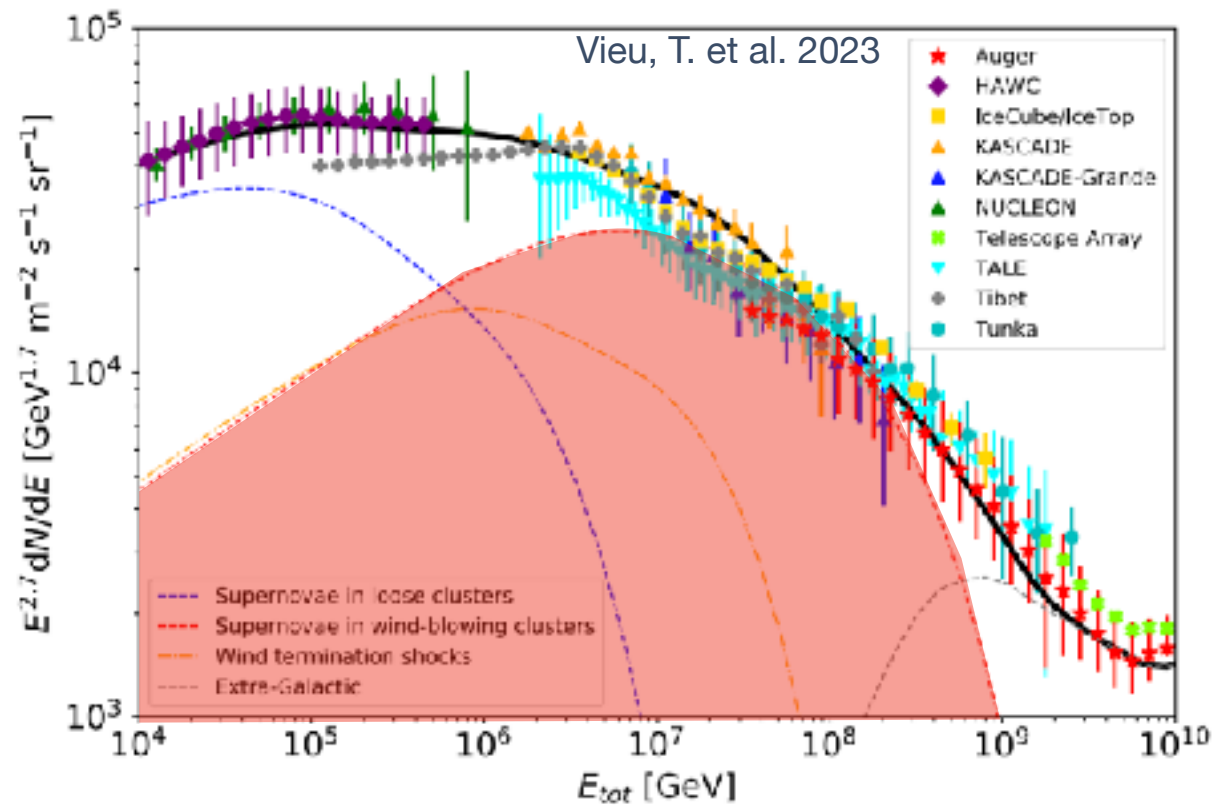
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- Fits CR composition
 - But still to be proven...



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 - Radial profile sometimes does not follow $1/r$
 - Product of CRs and gas distribution -> Might not strictly have to follow it...
- 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

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- Microquasars?
 - Yes, but...what about the anisotropy?

Recap of the course

- Galactic Science?



- Gamma rays on top of X-rays?

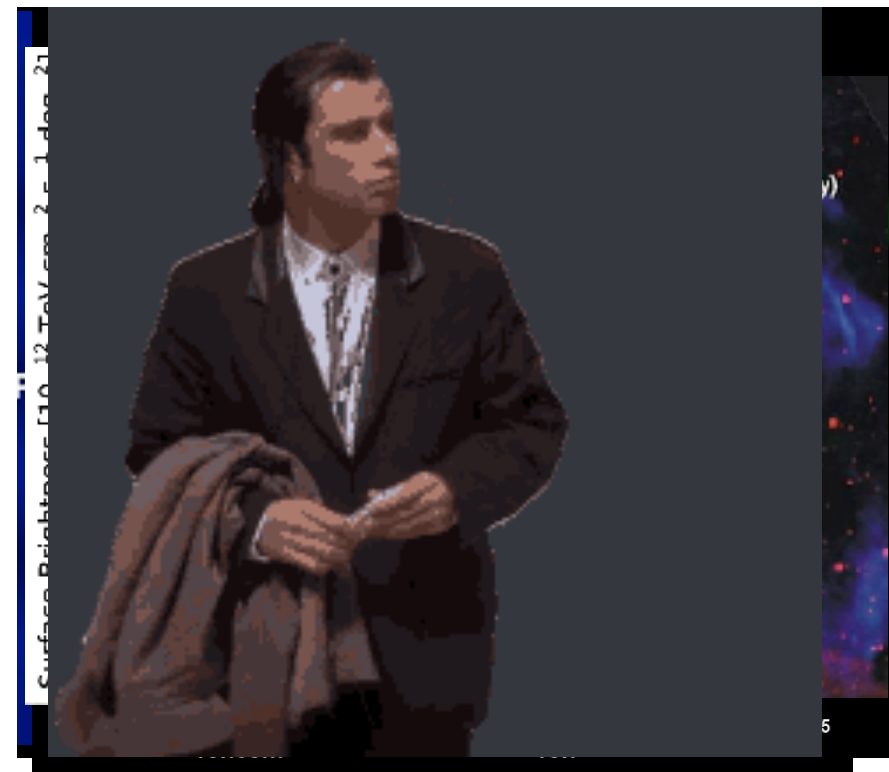
Electrons

- Gamma rays on top of gas?

Protons

- $1/r$? **Diffusion**

- PeVatrons?



Thanks!

