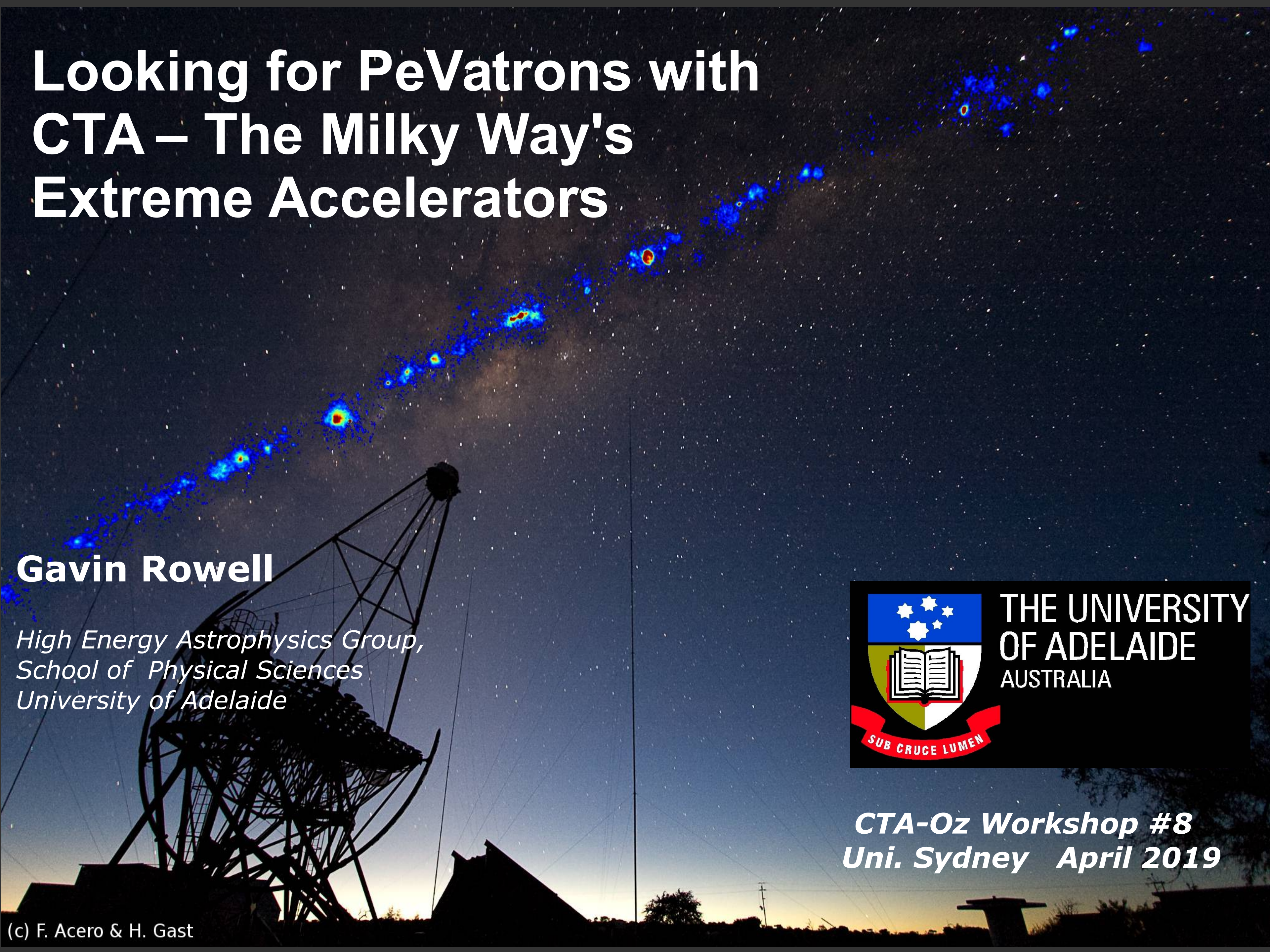
Looking for PeVatrons with CTA – The Milky Way's Extreme Accelerators



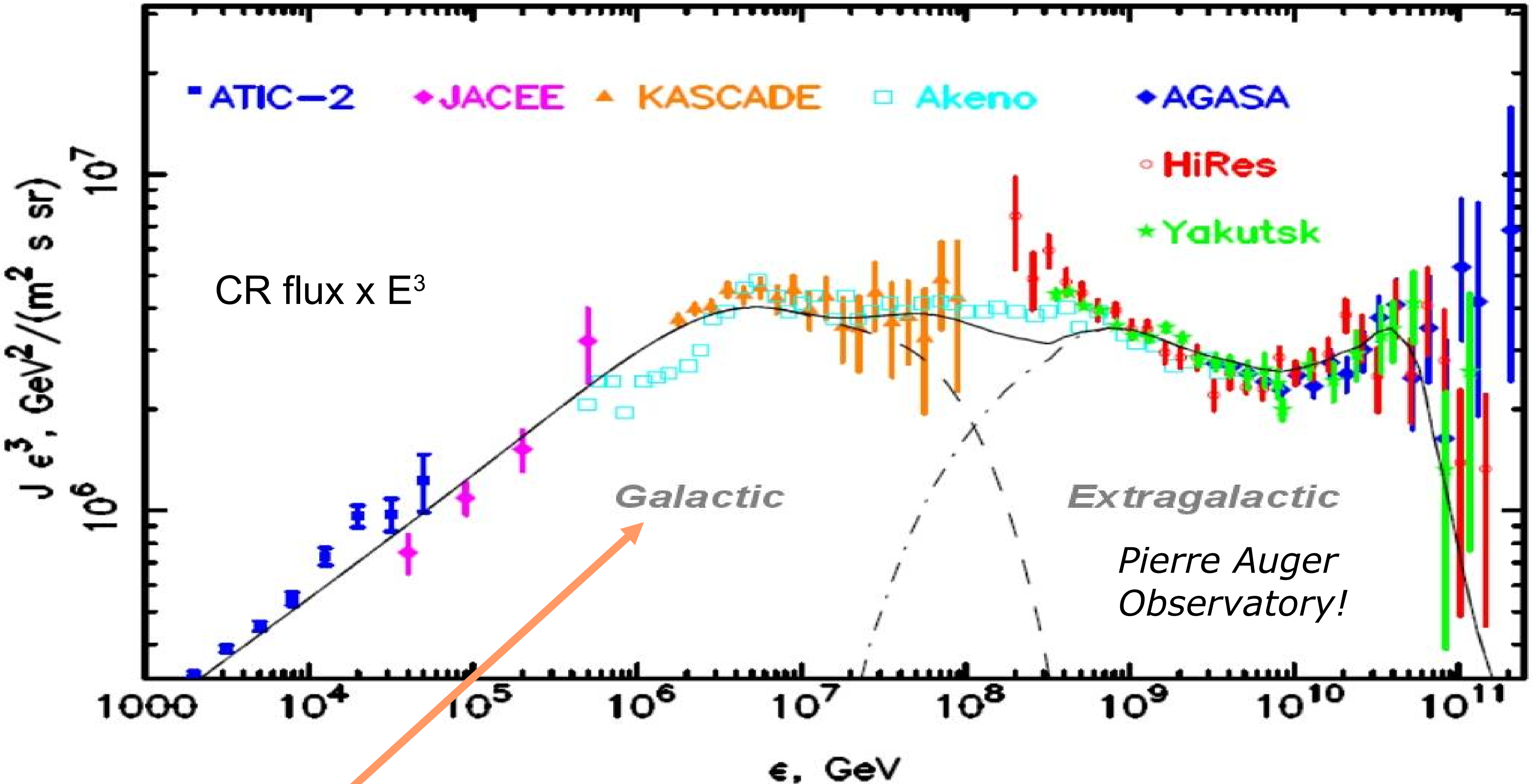
Gavin Rowell

High Energy Astrophysics Group,
School of Physical Sciences
University of Adelaide

THE UNIVERSITY OF ADELAIDE
AUSTRALIA
SUB CRUCE LUMEN

CTA-Oz Workshop #8
Uni. Sydney April 2019

Cosmic-Ray (CR) Energy Spectrum



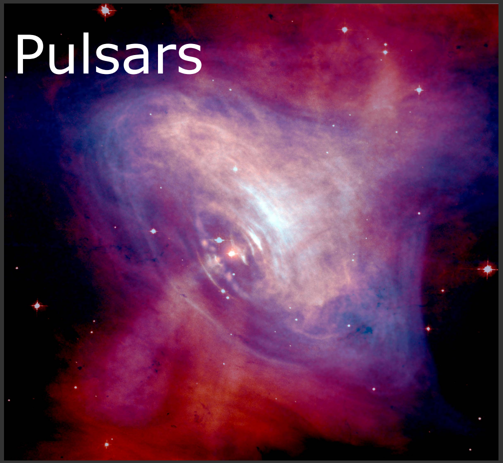
Where and how are CRs accelerated?

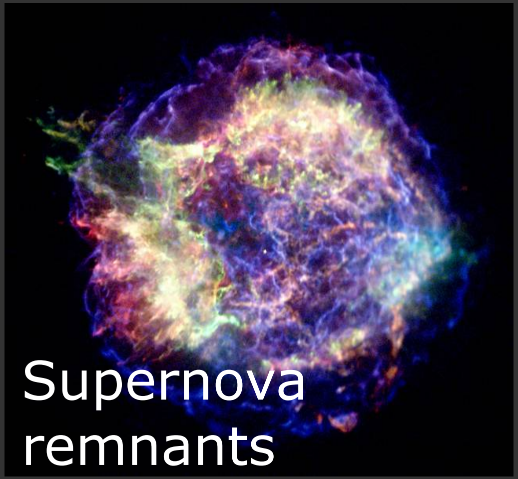
Galactic CR energy budget

L_{CR} ~ 10^{42} erg / s

Since the discovery of CRs in 1912, still no clear origin. In recent years we are gathering clues......

Some (potential) Cosmic-Ray and Electron Accelerators





All are extreme environments!

Acceleration of CRs above the knee (10^{15}~10^{18} eV)

A Major Mystery in High Energy Astrophysics
The Milky Way's highest energy particles!

- Diffusive Shock Acceleration Theory E_{max} ~ few x 10^{15} eV
  (Drury 1983, Lagage & Cesarsky 1983, Hillas 2006 for review)

Some ideas..... eg.

- Magnetic field modification B>100 μG (Bell & Lucek 2001)
  → Young SNRs (<1000 yrs old)

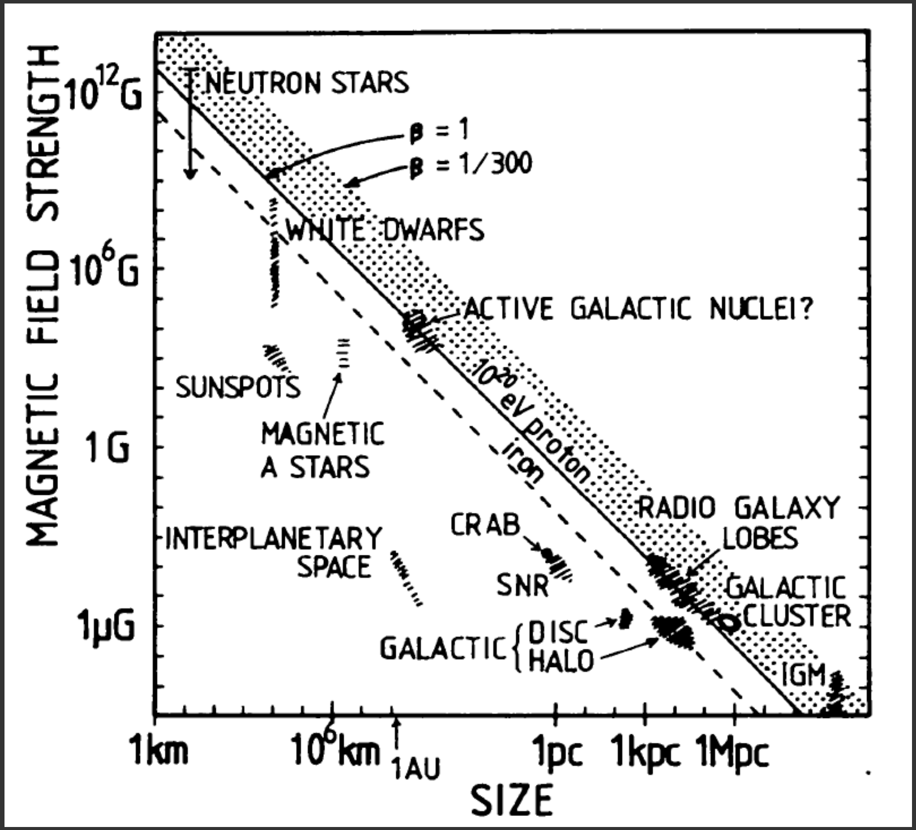
- Re-acceleration of Galactic Cosmic Rays (Jokipii & Morphill 1985, Voelk & Zirakashvili 2001)

- Acceleration by Galactic GRBs – Hypernovae
  (Wick, Dermer, Atoyan 2004)

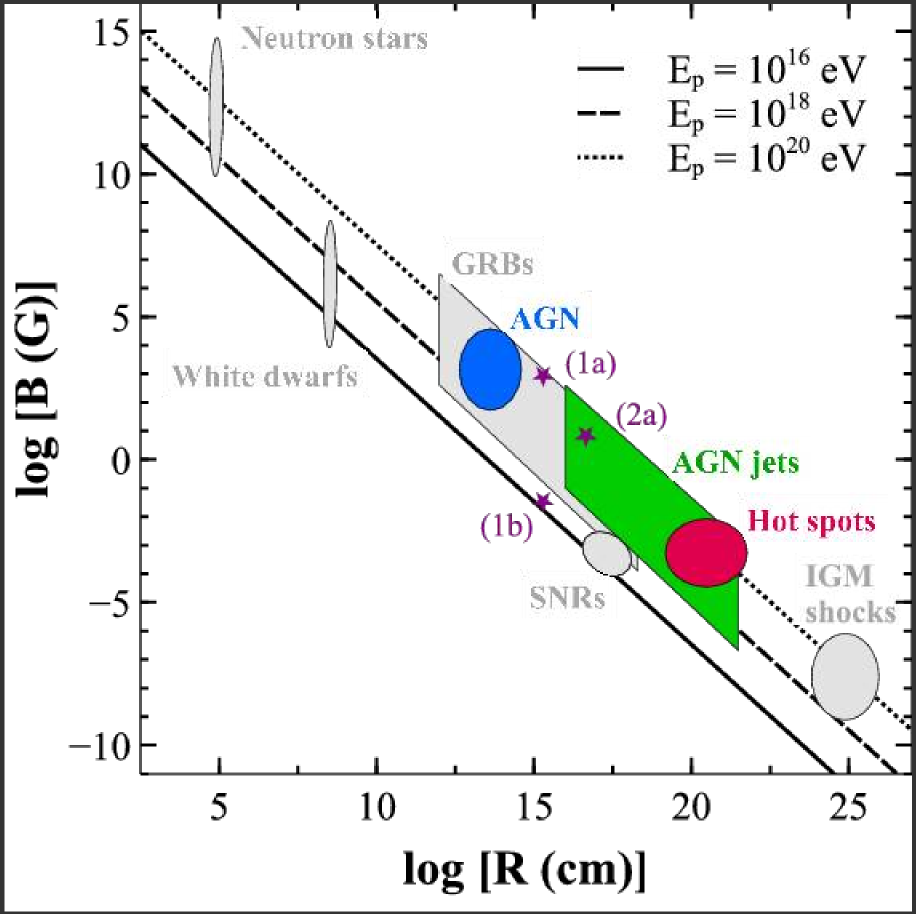
- Large-scale galactic shocks from Superbubbles via
  multi SNR, multi stellar winds from OB assoc.
  (Drury 2001, Bykov 2001, Parizot 2004)

The "Hillas Plot" - Max particle energy   1 PeV = E_{15}

Hillas 1984 Ann. Rev. Astron. Astrophys. 22, 425



$$B_{\mu G} L_{pc} > 2E_{15}/Z\beta$$



Jacobsen 2015 MNRAS 451, 3649

Galactic **TeVatrons** and **PeVatrons**

What are the particle accelerators to E ~ 10^{15} eV (1 PeV)?

- Shell Type Supernova Remnants? $L_{All-SNR} \sim \text{few} \times 10^{42}$ erg s^{-1}

W_{CR} ~ 10^{50} erg per SNR

$$E \approx 1(B/\text{mG})(\Delta T/100 \text{ years}) \text{ PeV}$$

- Pulsar Wind Nebulae?

Pulsar *spin-down* power $\dot{E} = I\omega\dot{\omega} \sim 10^{32}$ to $\sim 10^{39}$ erg s^{-1}

- Pulsars? Rotating dipole B $E_{max} \approx 8 \times 10^{20} Z(B/10^{13}\text{G})(\omega/3000\text{Hz})^2$ eV

- WR, O & B stars, Massive Stellar Clusters, Massive Star Formation?

Stellar wind KE $L_w = \frac{1}{2}\dot{M}v_\infty^2$

B-star L_w ~10^{34-35} ***erg/s***

WR star L_w **~ 10^{38-39} erg/s**

- X-Ray Binaries, Microquasars, Active galaxies (AGN)?

Accretion power $L_{acc} = \eta c^2 \dot{M}/2$ η=10 to 20%

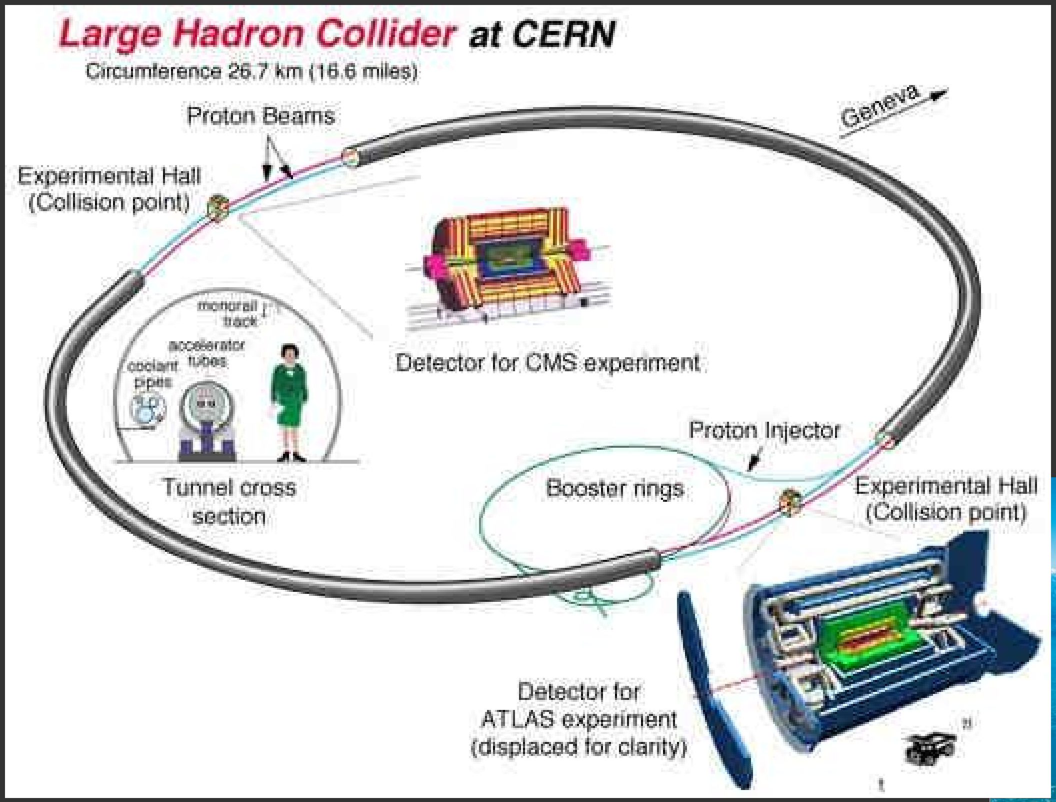
Galactic $L_{acc} \sim 10^{40}$ erg s^{-1} **AGN** $L_{acc} \sim 10^{46}$ erg s^{-1}

PeV cosmic-rays:

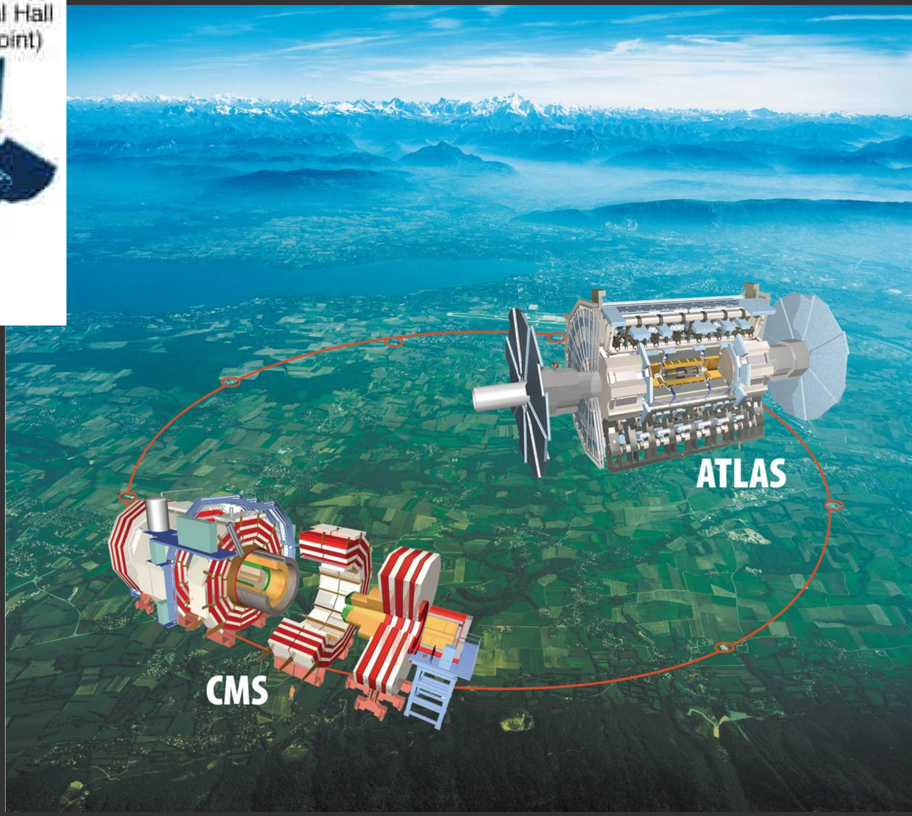
- Show you what the accelerator is capable of
  (just like a car at ful throttle..)

→ constraints on fundamental parameters
  e.g. B field, shock speed....

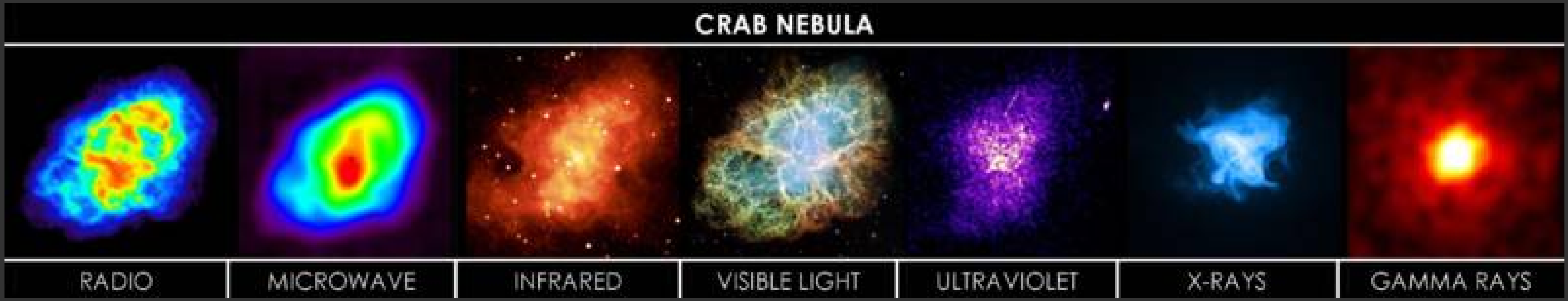
A (very) local PeVatron

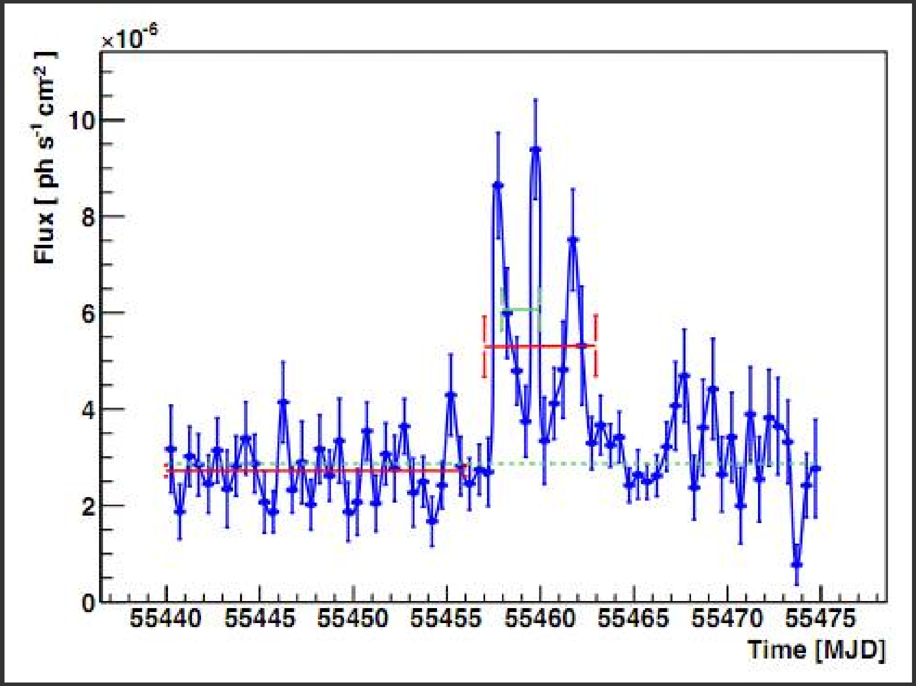


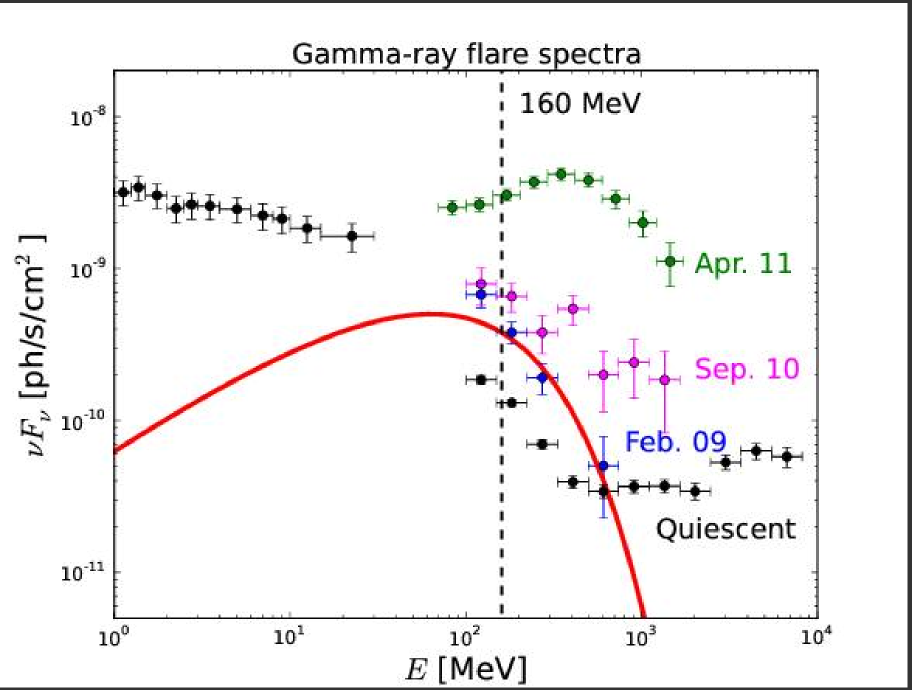
In centre of mass frame
$E_p \sim 100$ PeV



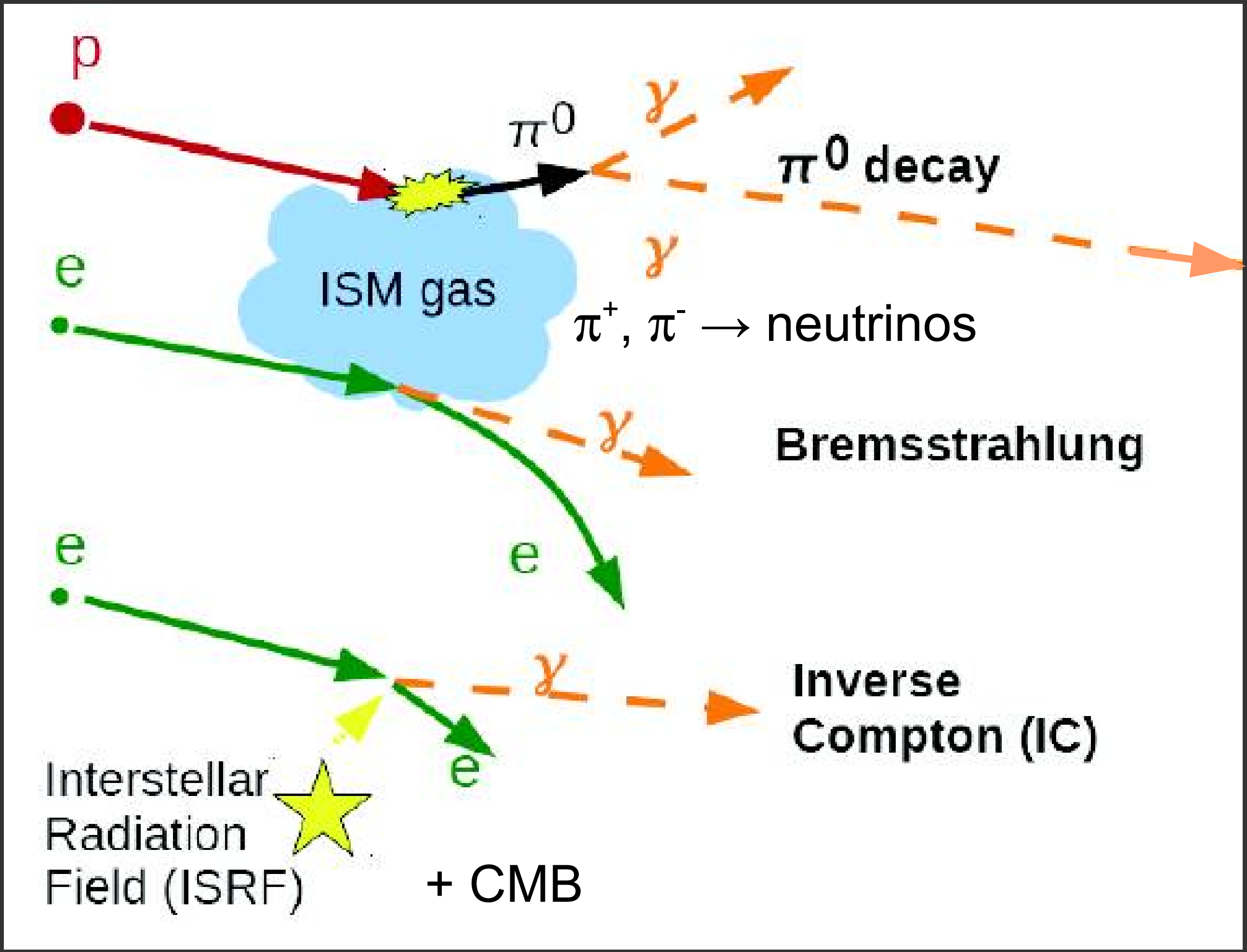
A (2kpc distant) PeVatron – Crab Nebula
- PeV electrons (GeV synchrotron emission)
(GeV flaring Buehler etal 2014)







Gamma Rays & Neutrinos from multi-TeV particles



$E_p \sim 10\ E_\gamma$

Protons: Gamma-rays and gas targets are generally spatially correlated
(need to map atomic and molecular ISM)

Electrons: Gamma-ray (IC) + X-ray, radio emission (synch.) coupled
(Bremss. usually minor)

Synergies with interstellar gas surveys

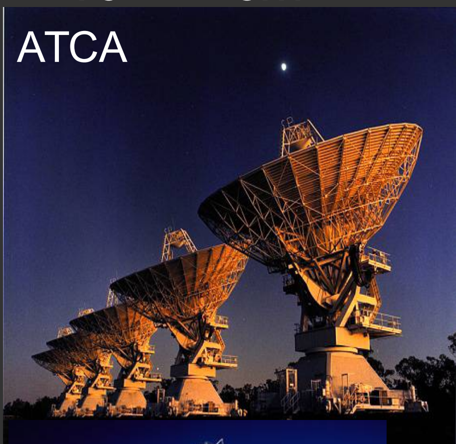
www.atnf.csiro.au/research/HI/sgps

HI (atomic H), OH, CS

Gas density

$\sim 10^{1 \text{ to } 4}$ cm^{-3}

ATCA



Parkes

CSIRO

GASKAP

CO

$\sim 10^{3}$ cm^{-3}

NANTEN Submillimeter Observatory

なんてん電波天文台

国立天文台 NAOJ National Astronomical Observatory of Japan

THz (Antarctica & High-alt)

[CI] + [CII]

CO, NH_3, CS, SiO...

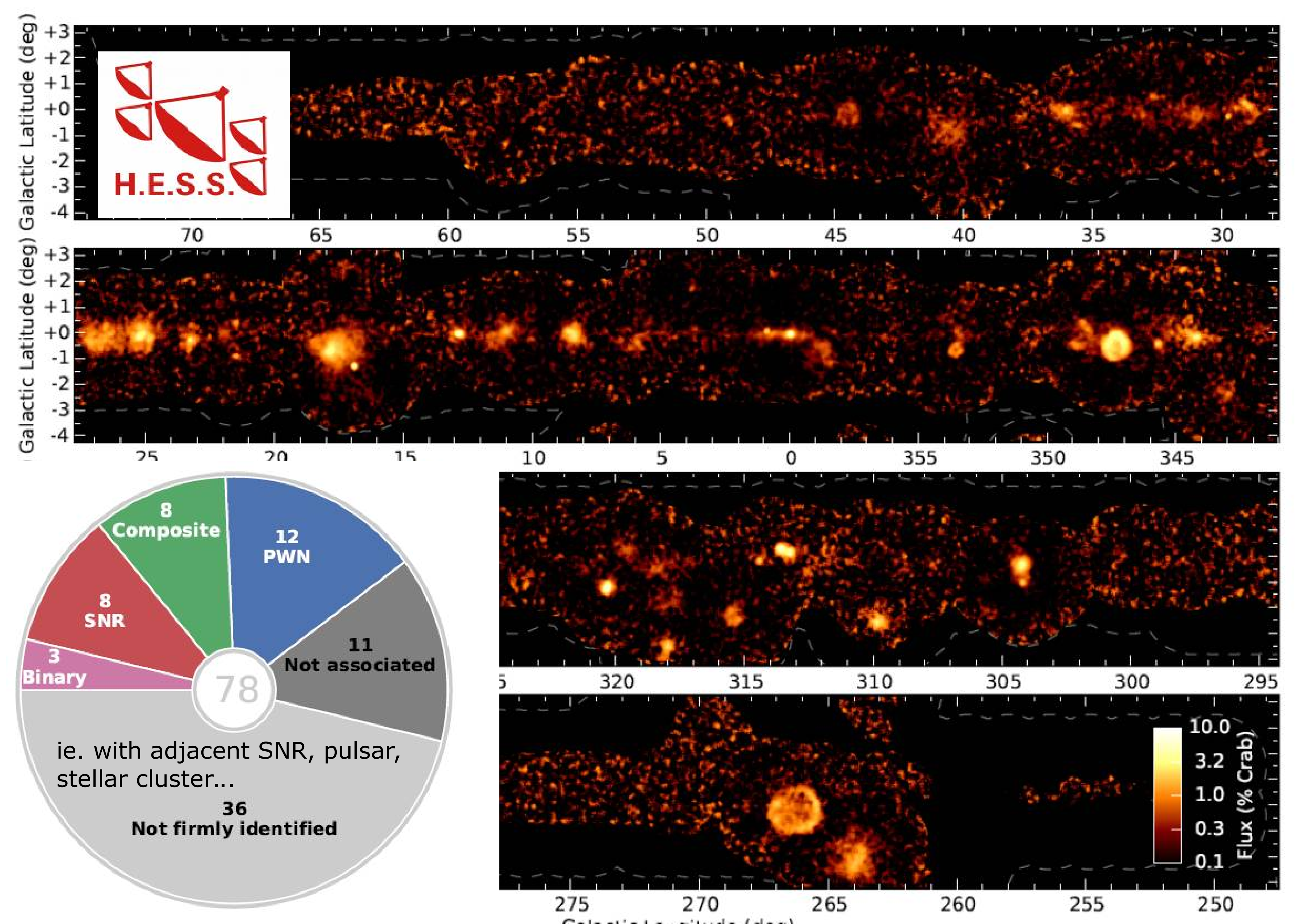
$>10^{3 \text{ to } 4}$ cm^{-3}

Mopra Telescope

CSIRO

HESS Galactic Plane Survey (HGPS)
→ 78 sources (13 new sources)

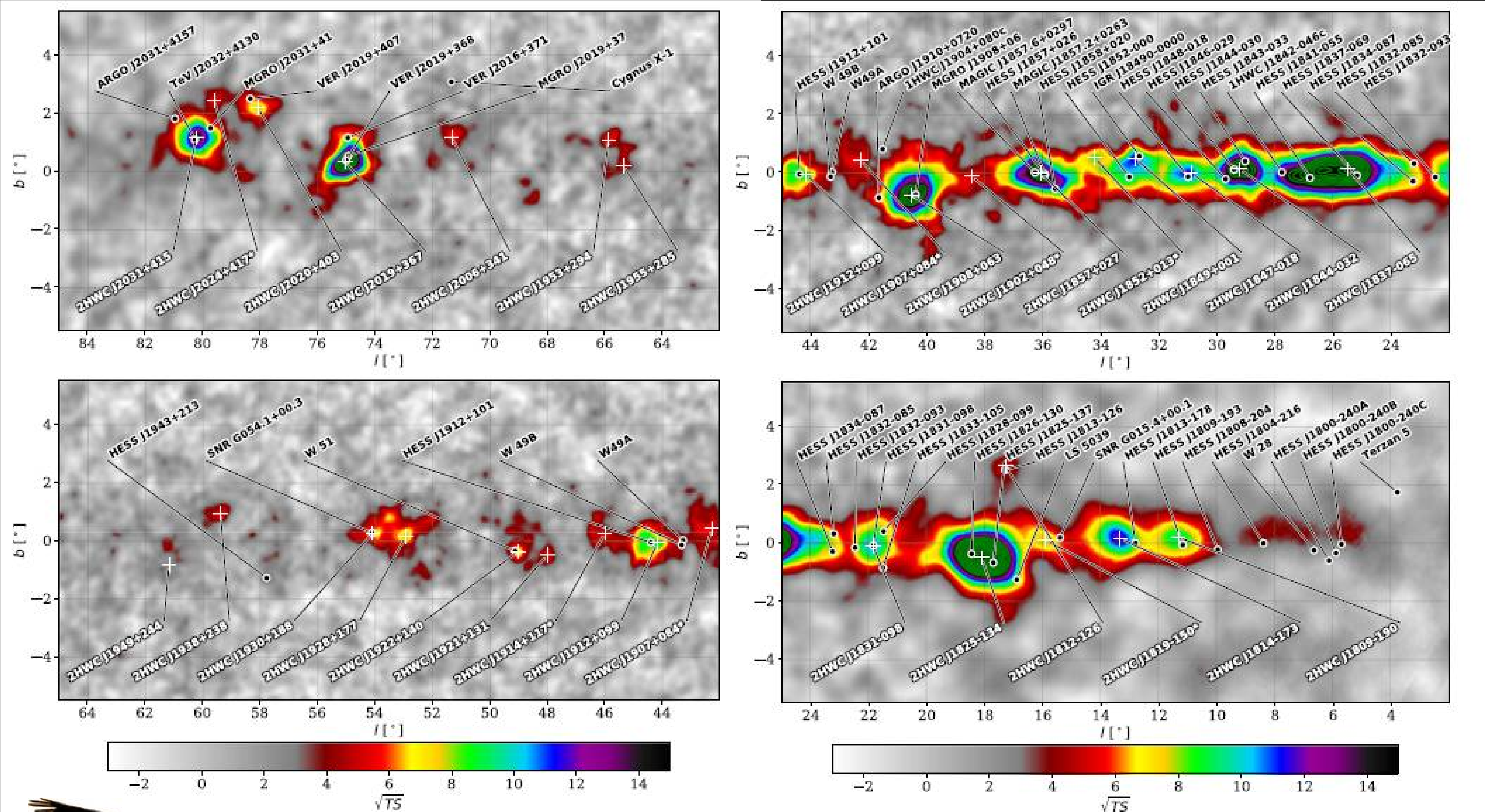
Deil et al 2015, HESS 2018



HAWC Galactic Plane Survey (2HWC)

→ 39 sources (17 new sources)

Abeysekara etal (HAWC) 2017



Some new sources with no <10 TeV counterparts, and some > 20 TeV emission. → Very hard spectra?

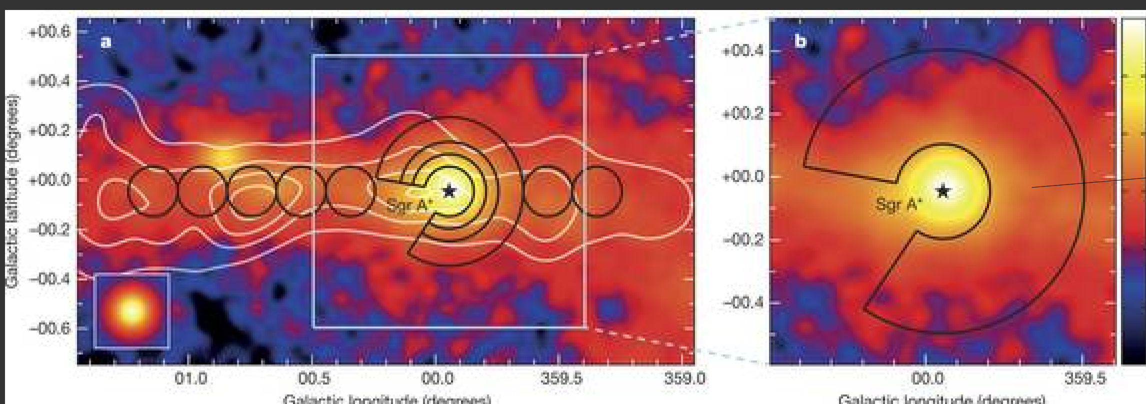
→ PeVatrons?

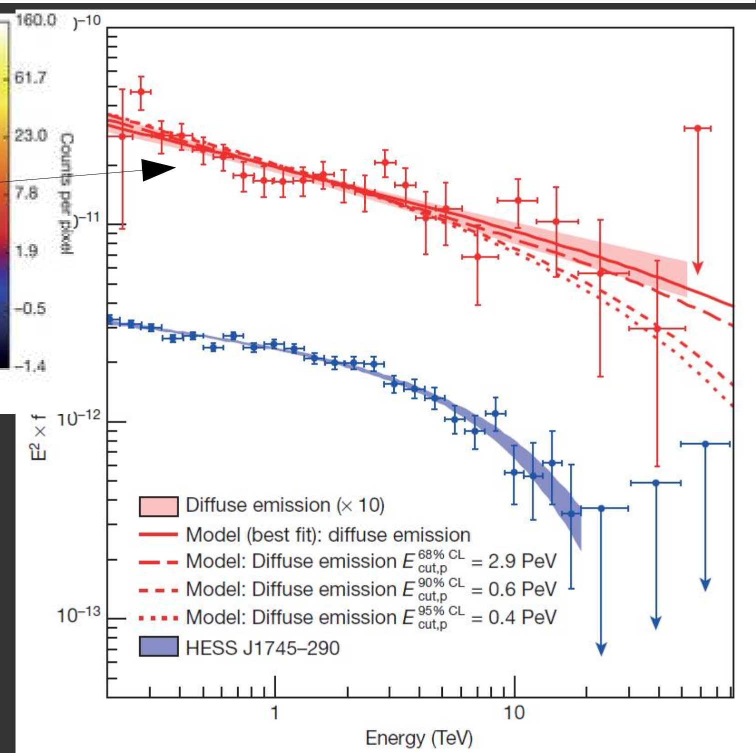
LETTER

doi:10.1038/nature17147

Acceleration of petaelectronvolt protons in the Galactic Centre

HESS Collaboration*



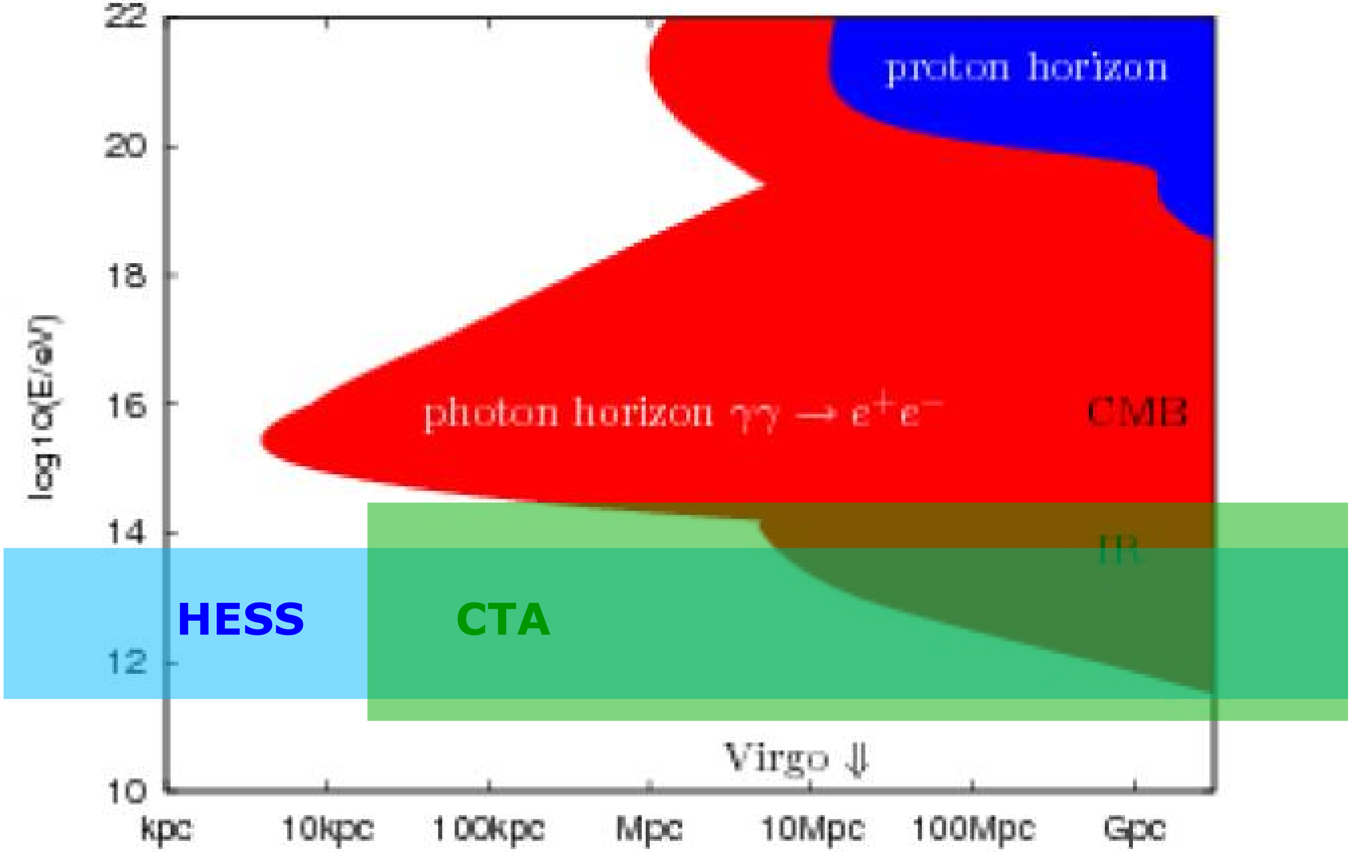


- TeV gammas from diffuse region 70pc
- Spectral cutoff ~ PeV energies

→ Continous CR injector over ~few1000yr
→ Central BH most likely accelerator
→ Could explain galactic CRs >0.1 PeV
  if BH more active in past.
  (SNRs may still contribute some PeV CRs)

The Gamma-Ray Horizon ($\tau(E) = 1$)

Distance for absorption factor $\exp(-\tau(E)) = 1/e$:



ISRF – Interstellar Radiation Field

from Porter etal 2017 ApJ 86, 67

R12 – Robitaille etal 2012
F98 – Freudenreich 1998

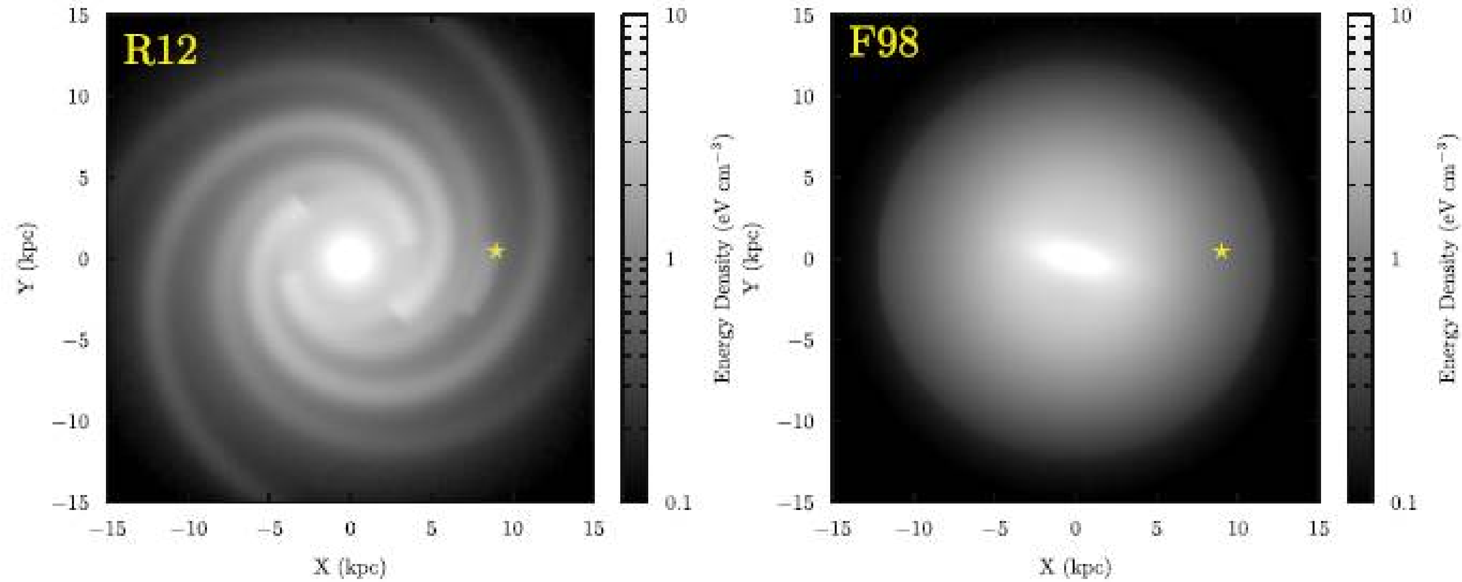


Figure 7. Integrated ISRF energy densities in the Galactic plane for the R12 (left) and F98 (right) models. The yellow star marks the location of the solar system in each panel. Note that the energy density saturates the scale in and about the GC for both models.

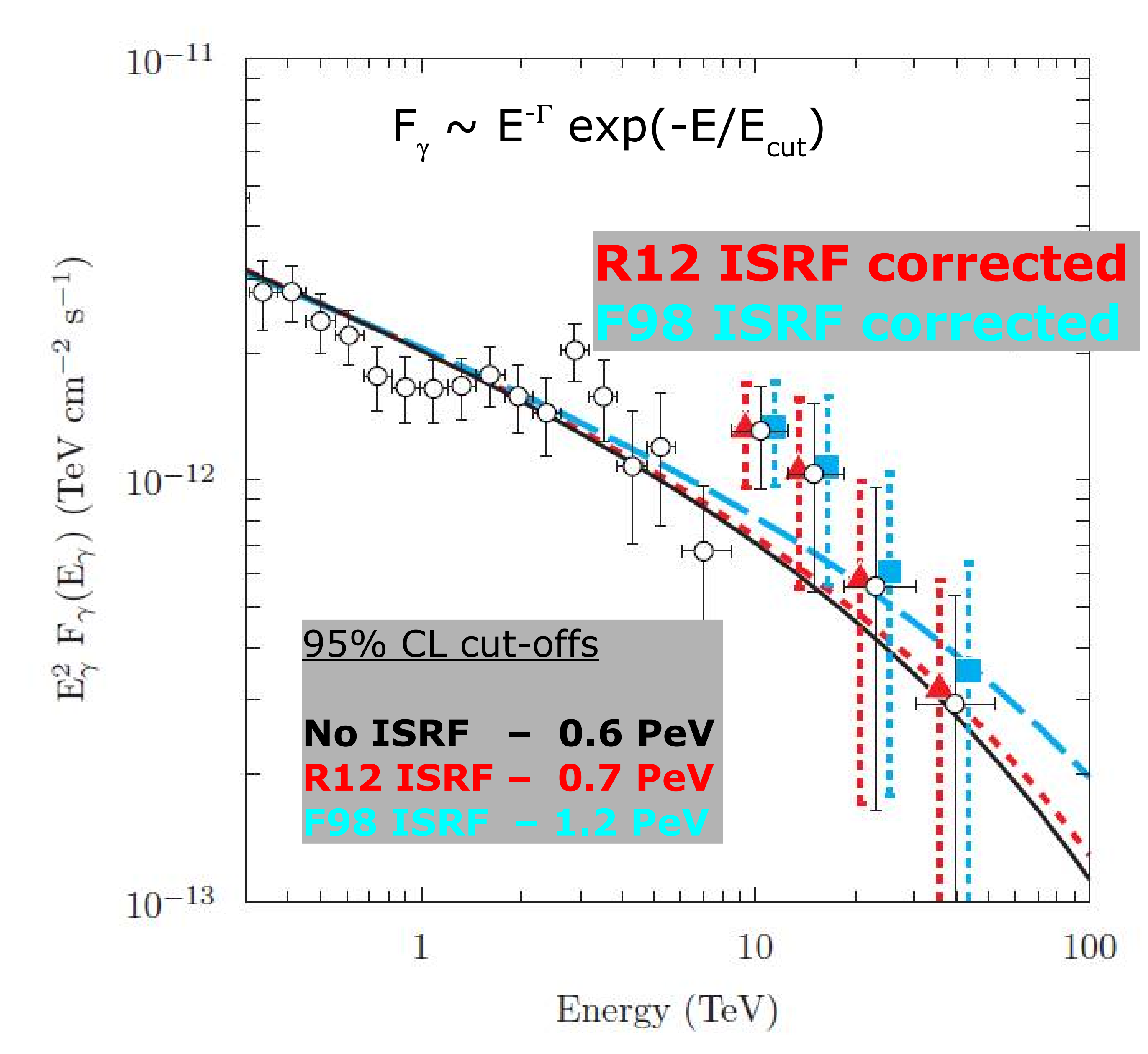
ISRF photons from heated dust. 2D distributions depends on the 3D distribution of IR photons.

Limiting cases
– IR in spiral arms (R12) Low
– IR in central bar and halo (F98) High

Porter, Rowell etal 2018 Phys Rev D 98, 041302

Re-fit cut-off CLs to the ISRF-corrected fluxes using the naima package.

Cut-off ~2x higher

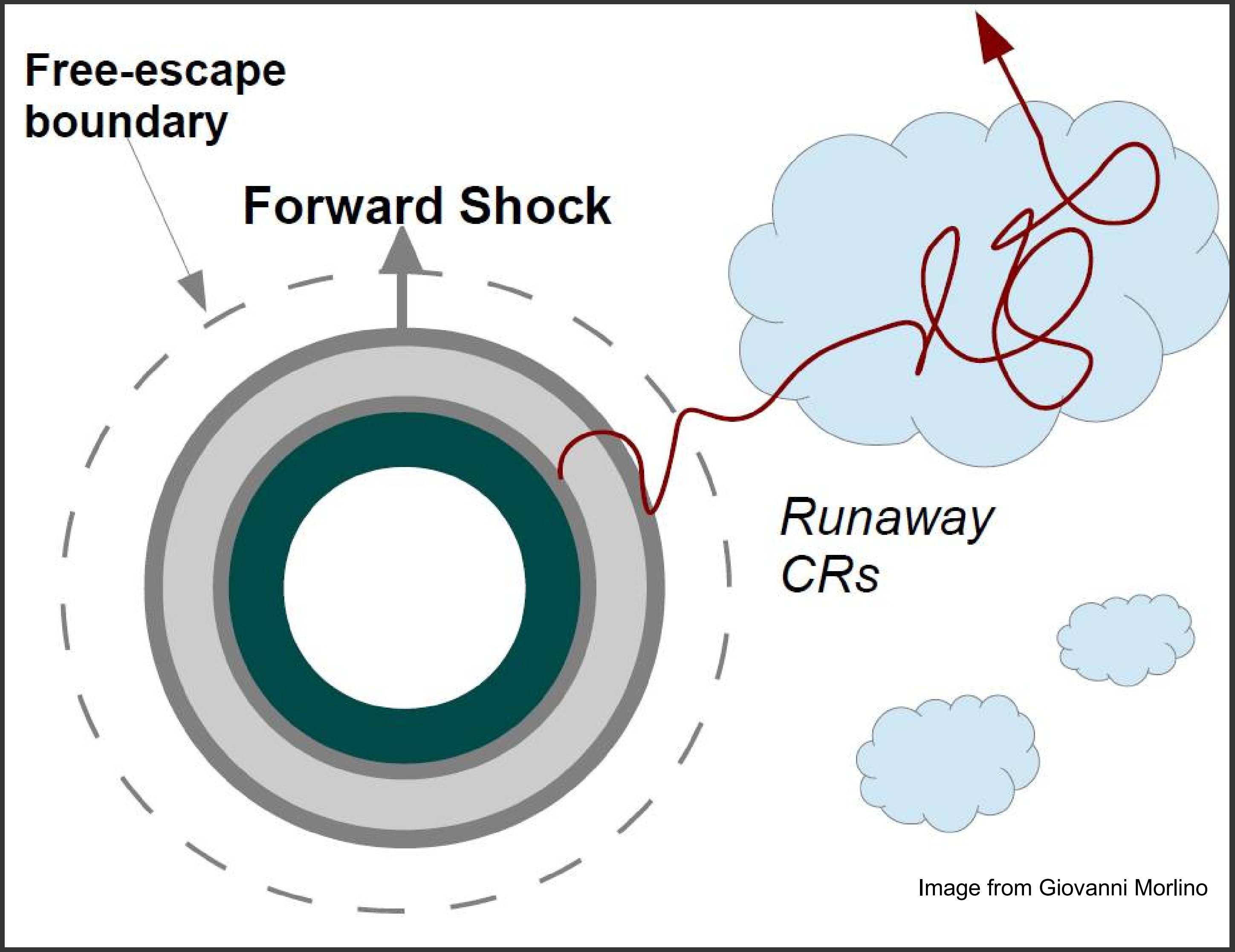


Note: 68% CL cut-offs = 2.7 / 3.9 / 5.6 PeV for no-ISRF / R12/ F98

Diffusive shock acceleration (DSA) in Supernova Remnants

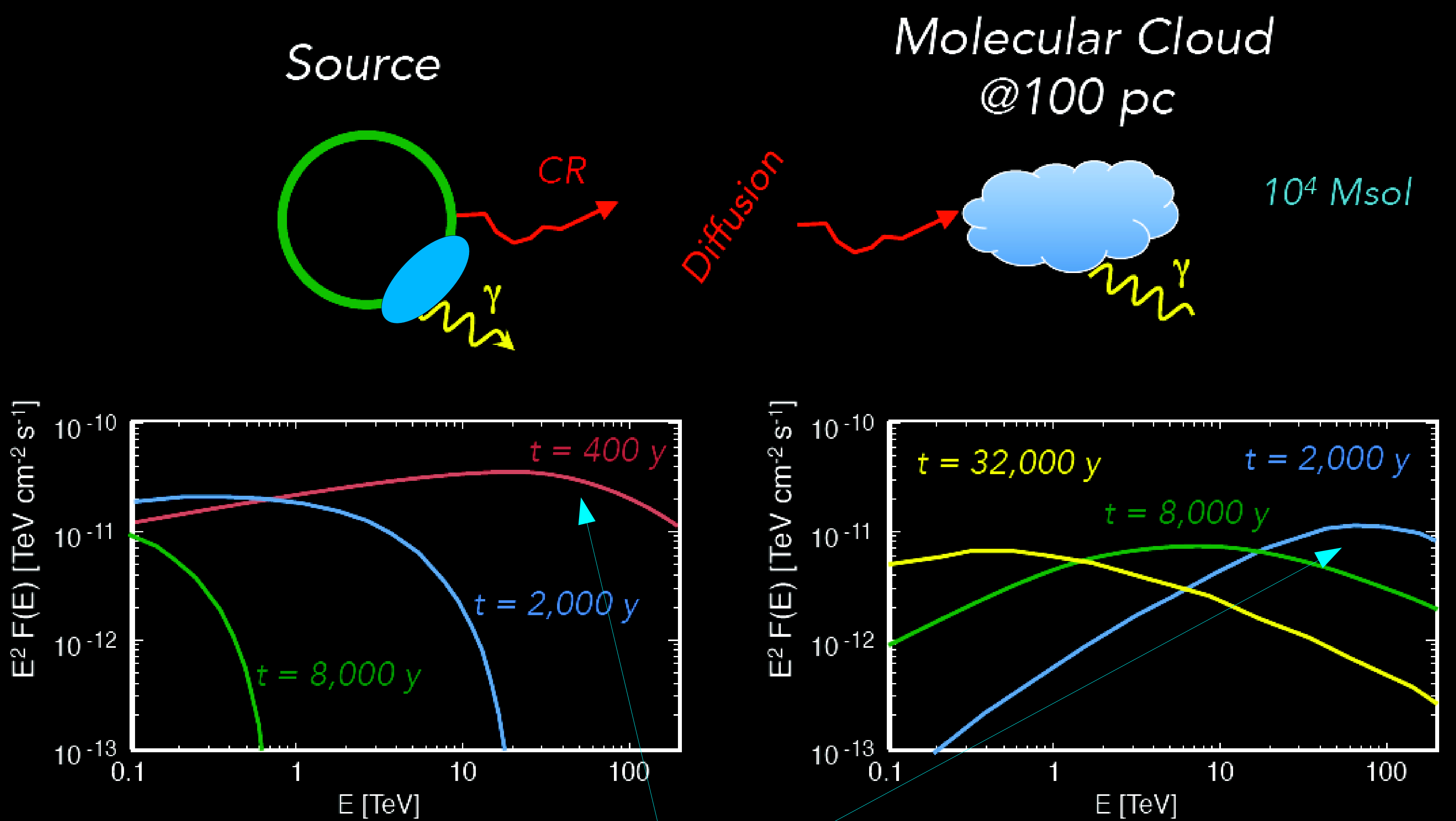
- Highest energy PeV cosmic-rays accelerated first and escape first
- PeV CRs also propagate (run away) fastest:

Diffusion distance ~ sqrt[2D(E)t] for diffusion coeff D(E) ~ $E^{0.3 \text{ to } 0.7}$



Gamma-ray spectra from local and escaped CRs

e.g. Aharonian & Atoyan 1996



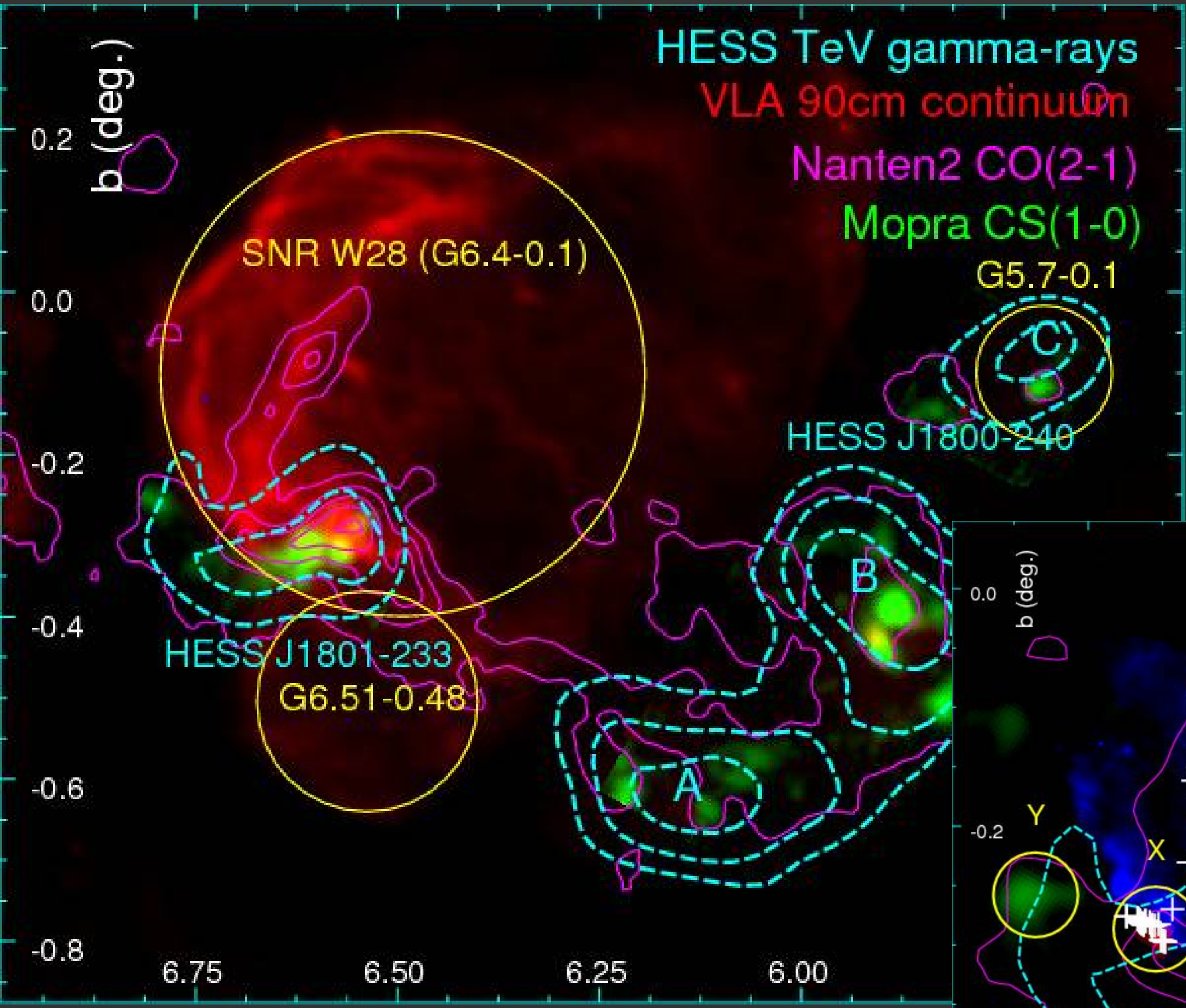
From Gabici & Aharonian (2007)

Slide from Richard White

→ Ideal way to search for PeVatrons! (E_γ > 100 TeV or E_p > 1 PeV)

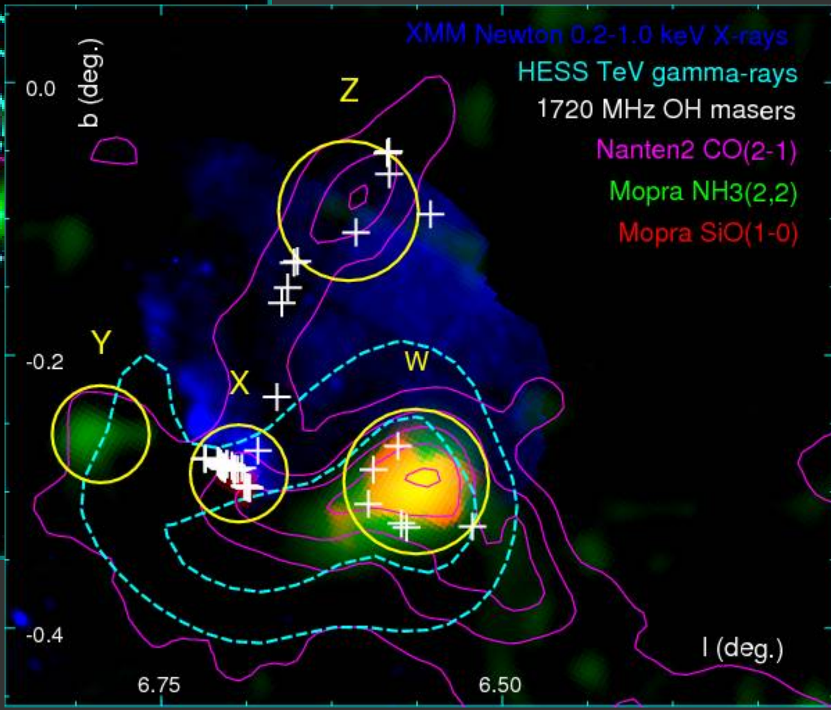
Mature SNR W28 – Radio to TeV

HESS 2008, Niicholas etal 2011, 2012, Maxted etal 2017

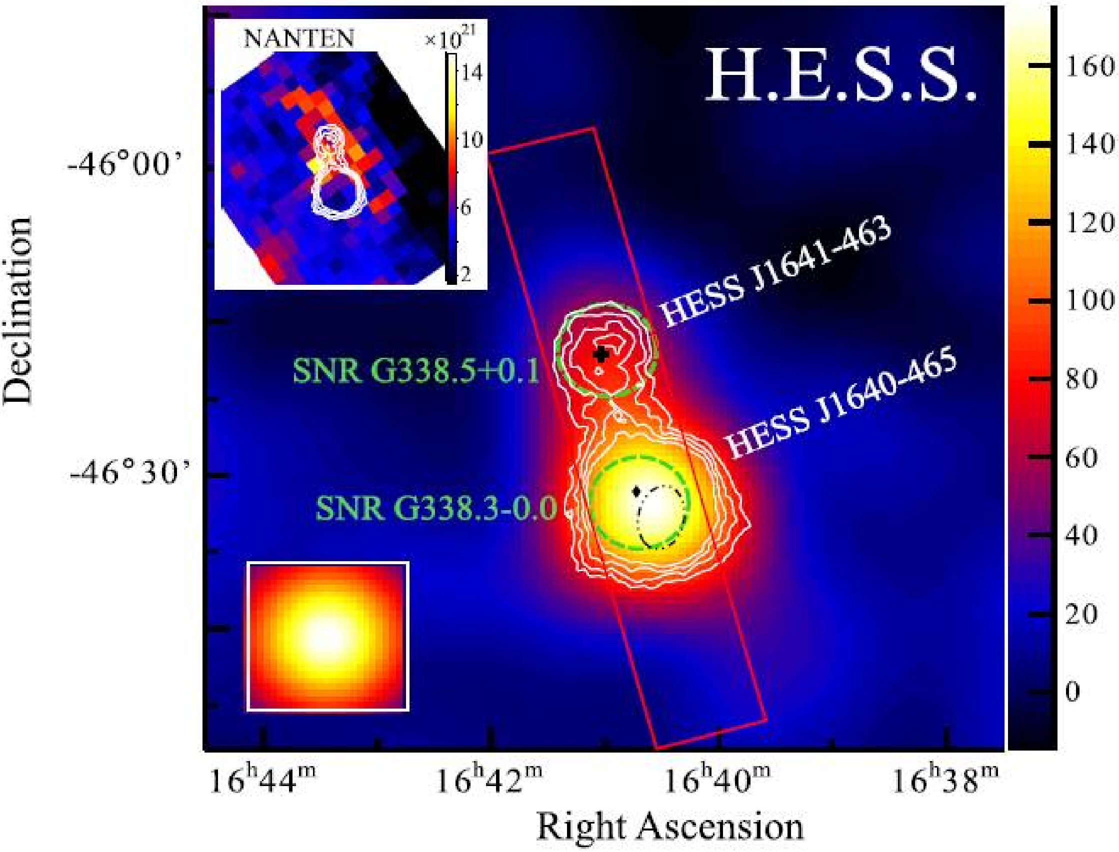


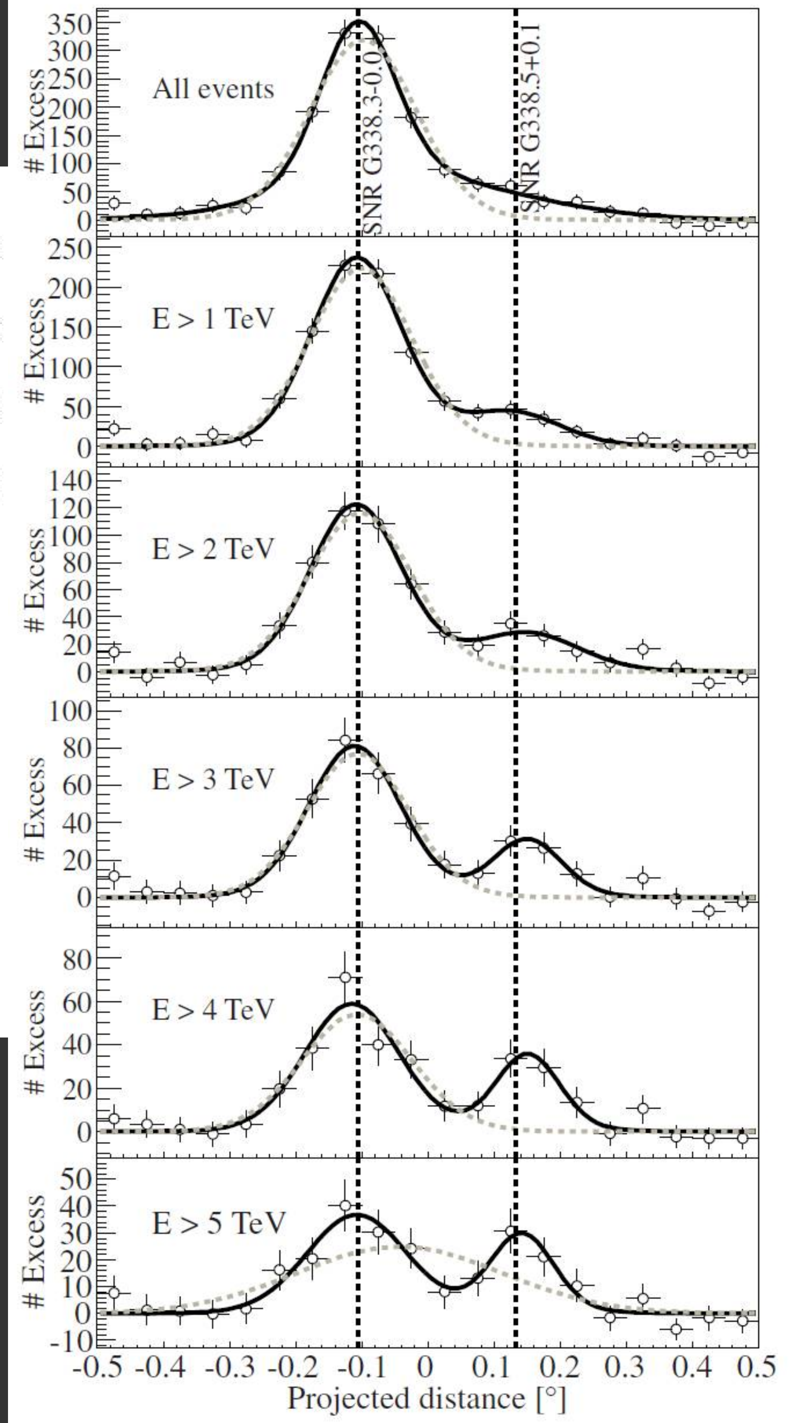
Mature (>10^4 yr) SNR

Adjacent ISM but TeV spectrum steep → PeV CRs have left the scene



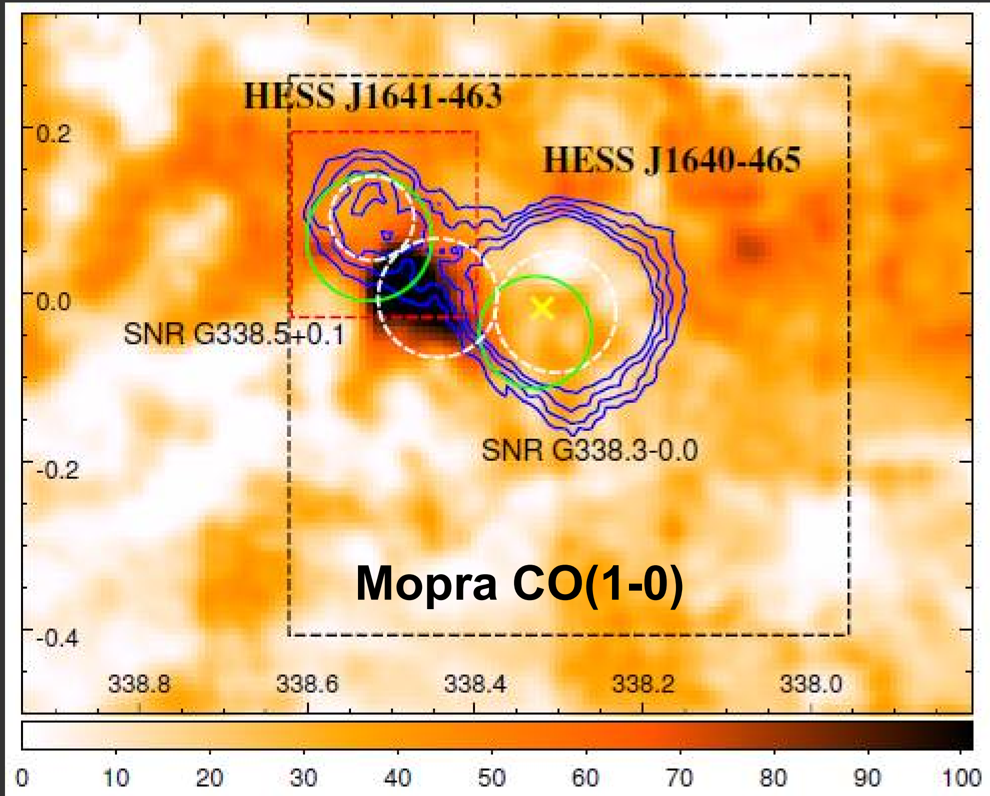
HESSJ1641-463
A Galactic PeVatron?

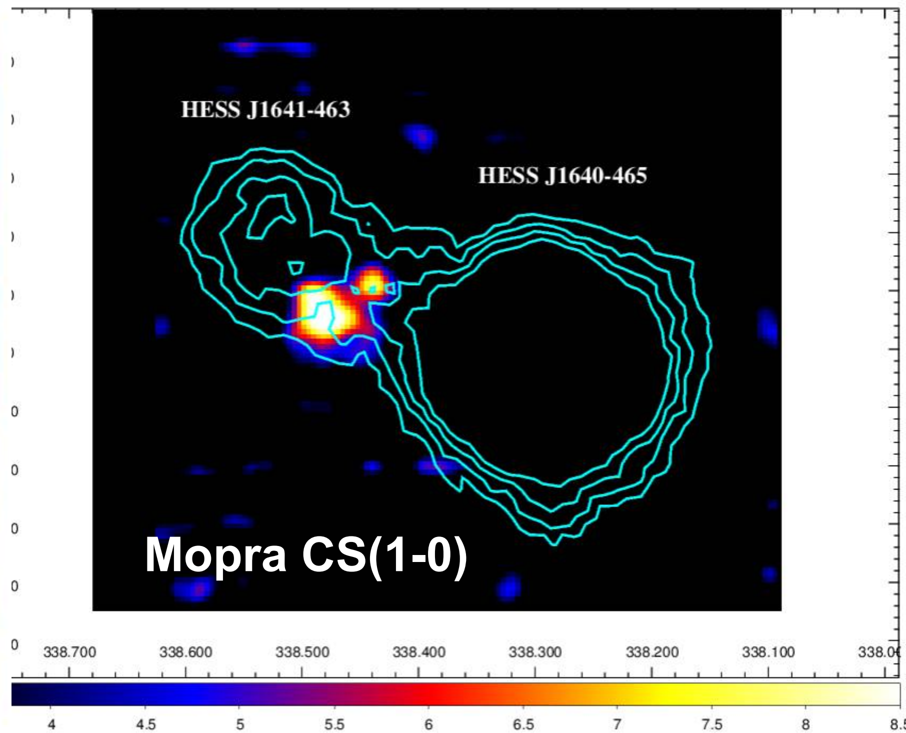




Does HESSJ1641 result from cosmic-rays escaping SNR G338.3?

Hard-spectrum source HESSJ1641
(HESS Coll. 2015)

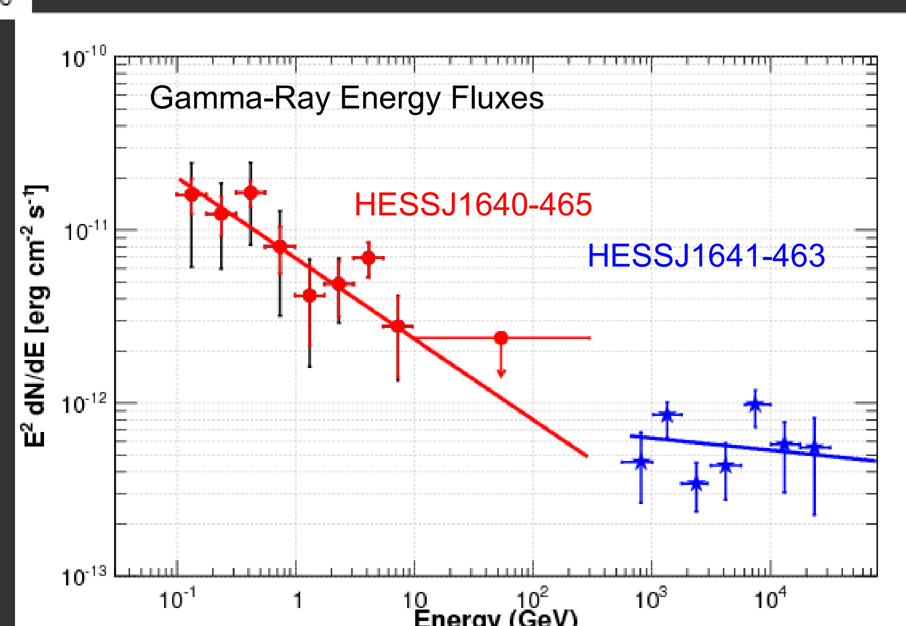




ISM studies by Lau etal 2016

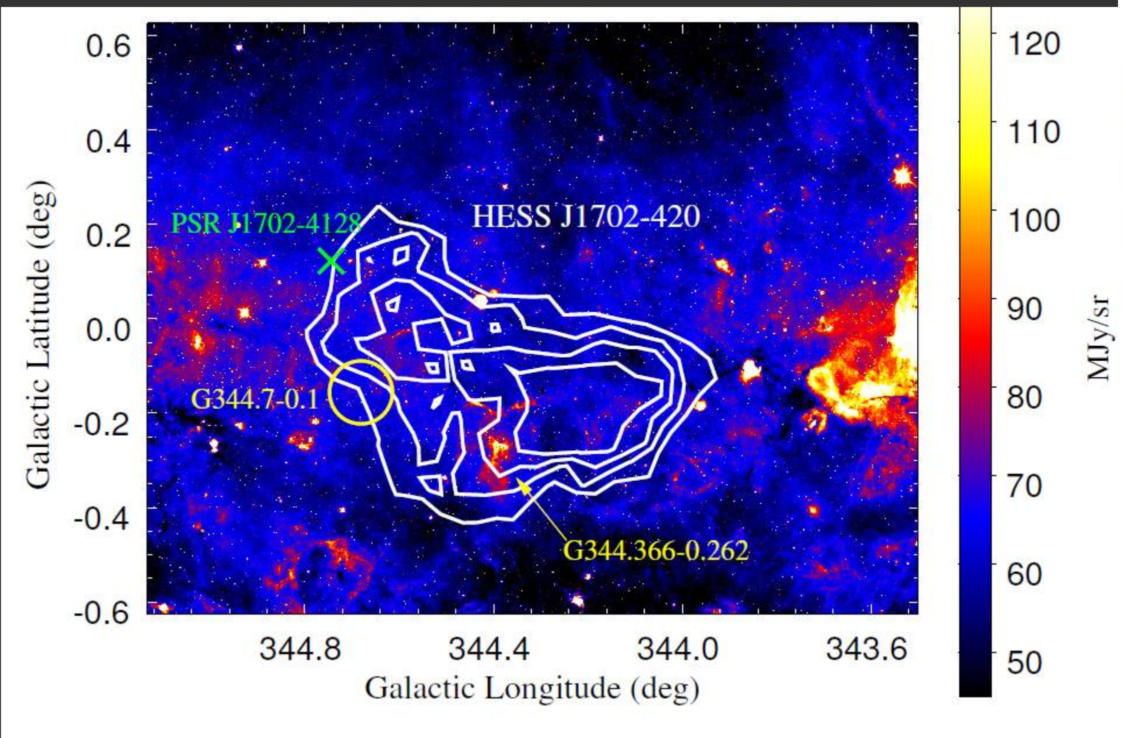
- High average ISM density >100/cc

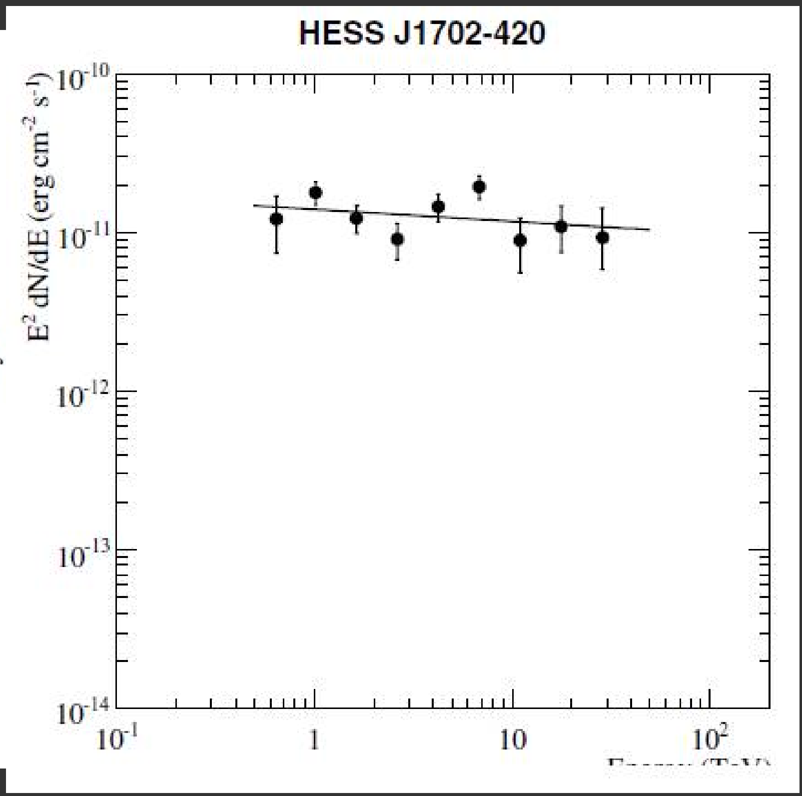
- Dense gas ($>10^4$/cc) bridge between TeV sources



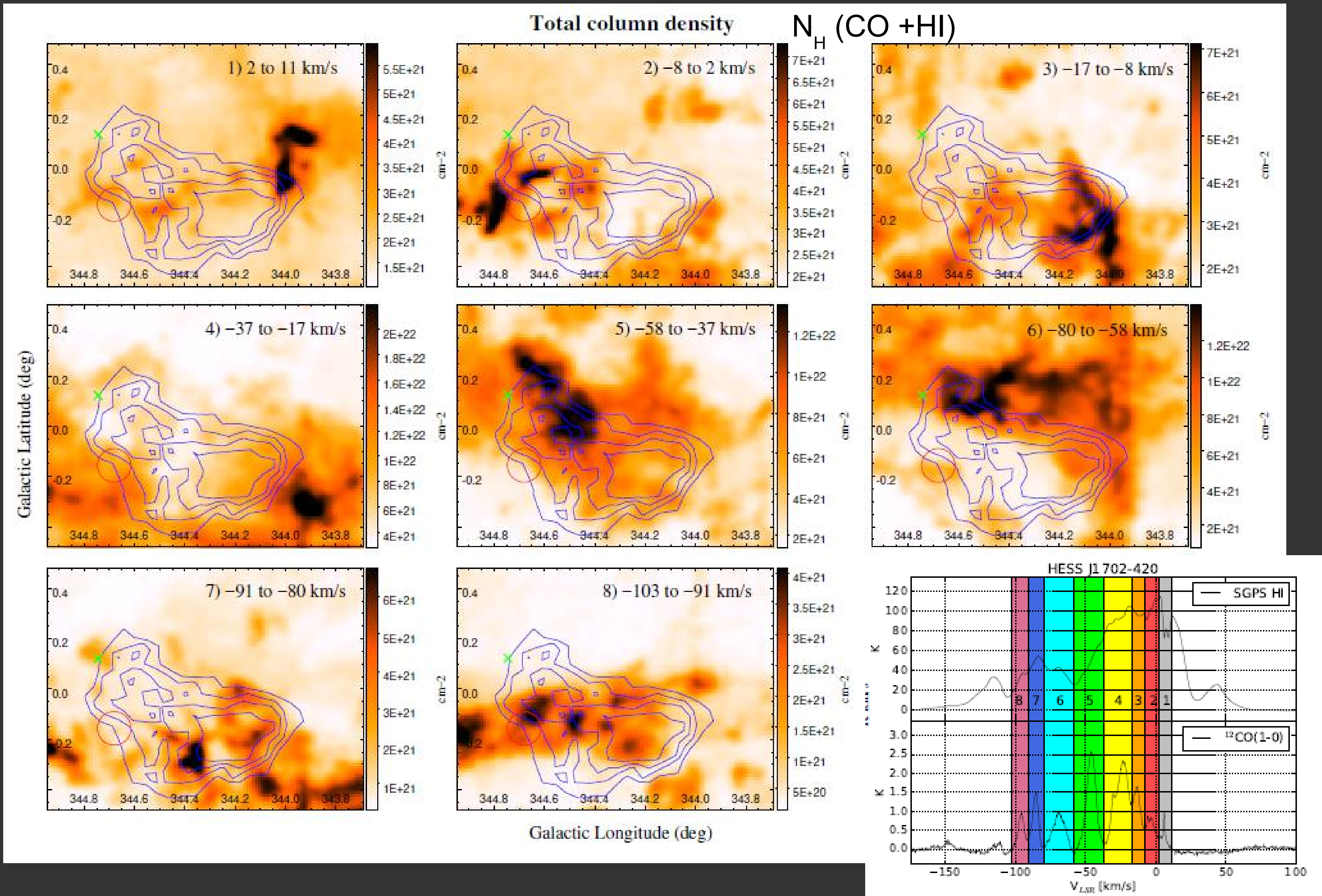
HESSJ1702-420   Another Galactic PeVatron?

HESS 2008

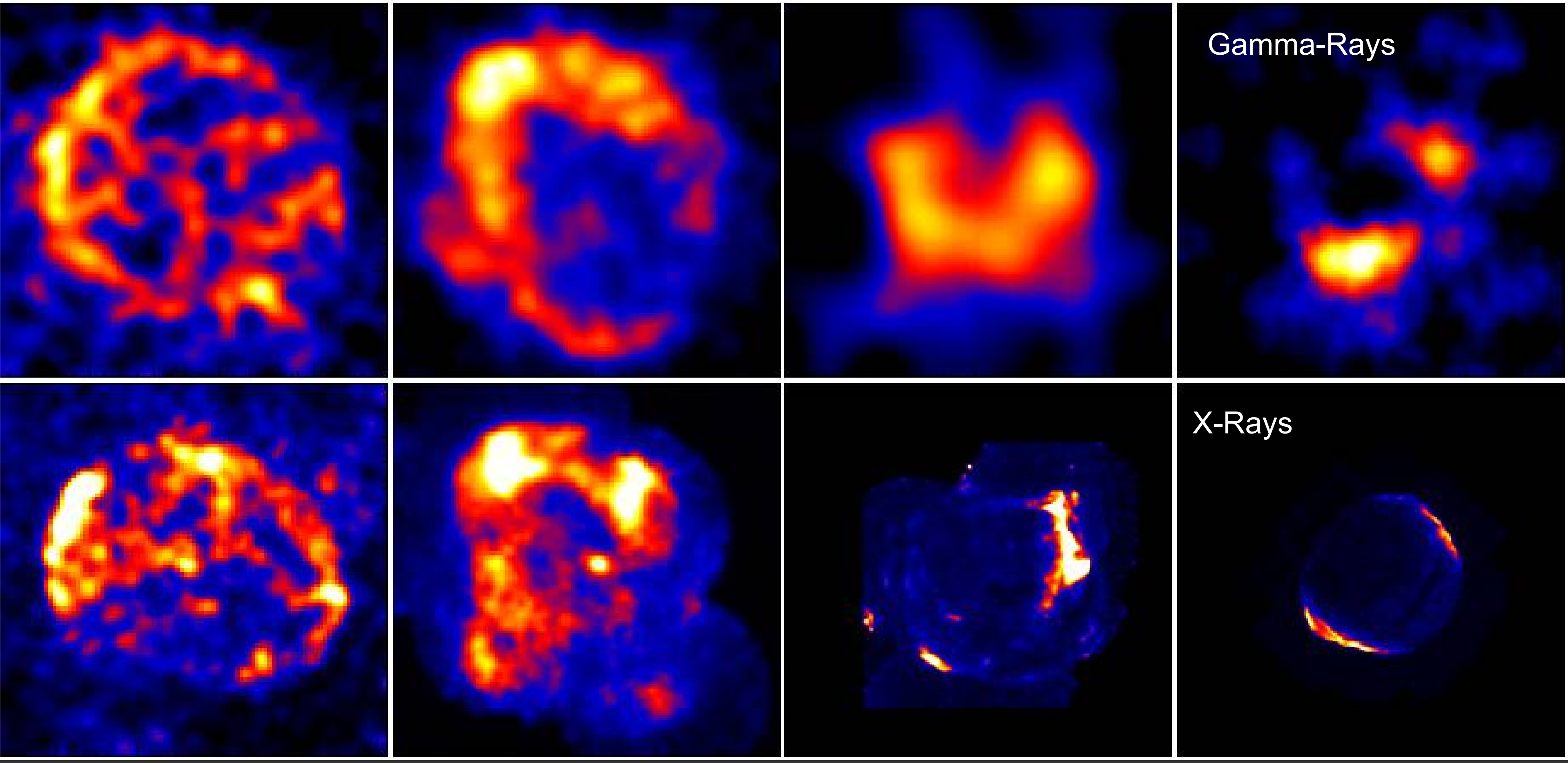




HESSJ1702-420 - Mopra ^{12}CO + SGPS HI   Lau et al 2018

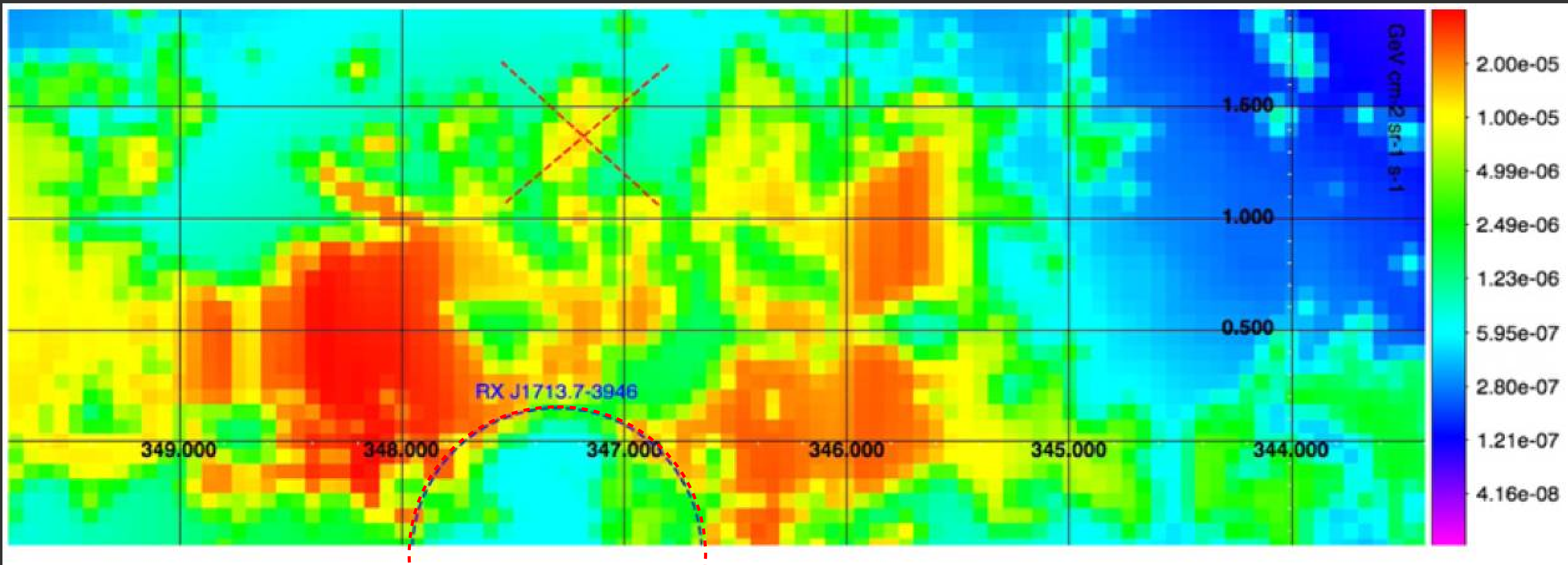


X-Ray-Bright Shell-Type Supernova Remnants
age < few 1000 yr – we expect some PeV CRs here!



→ **Evidence for multi-TeV CRs *and* electrons**

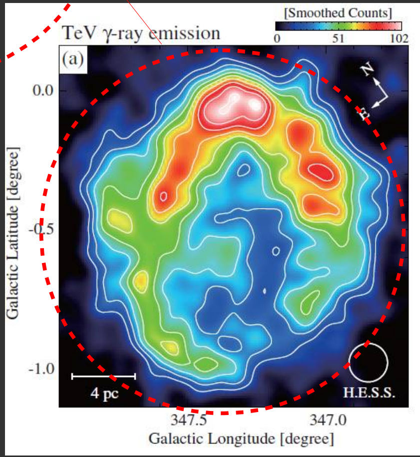
Simulated TeV gamma-ray emission (units $GeV/cm^2/s/sr$) from CRs escaping SNR RXJ1713.7-3946 (Acero etal 2013)



Based on Casanova etal 2010 (with Nanten CO(1-0) data)

$D \quad = 10^{28}(E/10GeV)^{0.5}\ cm^2/s$

$E_{escape} \sim 500\ (t/100\ yr)^{-0.43}\ TeV$



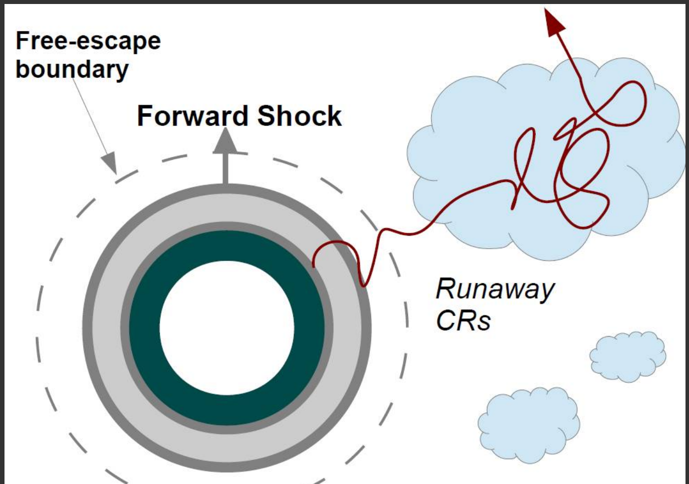


Image from Giovanni Morlino

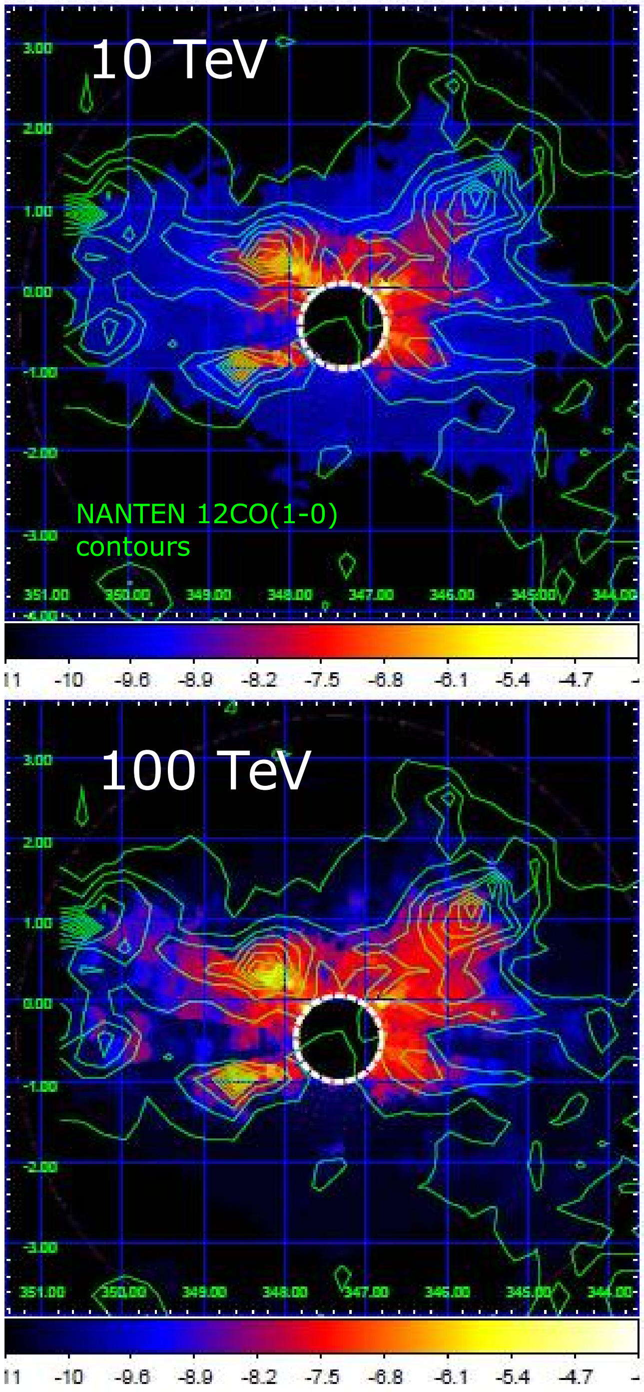
Simulated TeV gamma-ray emission ($GeV/cm^2/s/sr$) from CRs escaping SNR RXJ1713.7-3946 (P. Marinos Hons. Thesis 2018)

As per Casanova etal 2010 but with difusion coefficient depending on cosmic-ray enegy E and B.

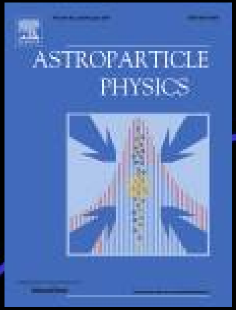
$$D(E_P, B(r)) = \chi D_0 \left(\frac{E_P/\mathrm{GeV}}{B/3\,\mu\mathrm{G}} \right)^{0.5} \quad [\mathrm{cm}^2\,\mathrm{s}^{-1}],$$

$$B \sim 10(n / 300\mathrm{cm}^{-3})^{0.65} \mu\mathrm{G}$$

Gabici etal 2007, Crutcher 2010



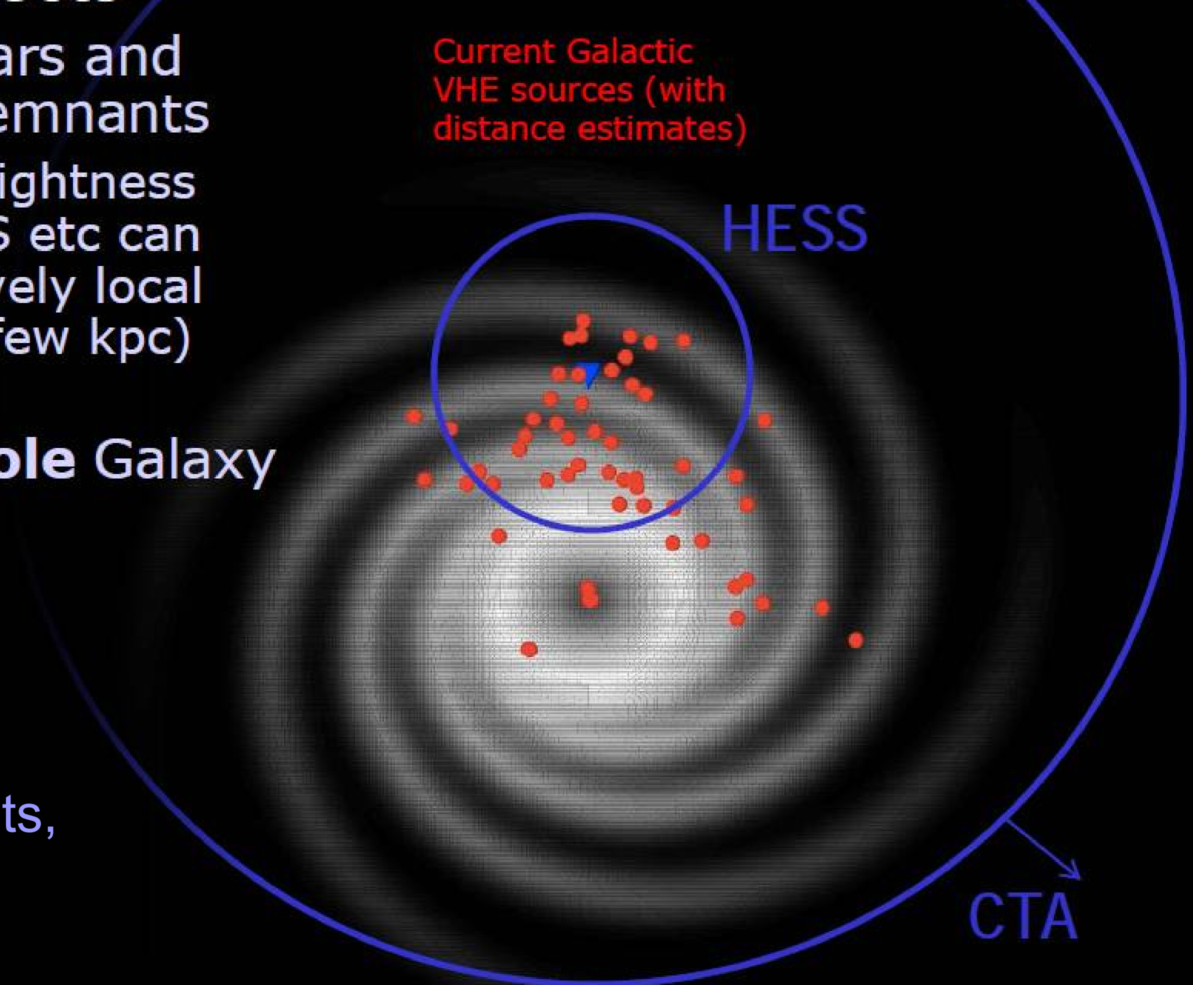
CTA Science



Special Issue Vol 43, Pg 1-356 (Mar 2013)

EU ESFRI Roadmap – same rank as SKA!

- e.g. Galactic objects
  - Newly born pulsars and the supernova remnants
    - have typical brightness such that HESS etc can see only relatively local (typically at a few kpc) objects
  - CTA will see **whole** Galaxy
- Survey speed ~300×HESS



Extragalactic

AGN z>0.5, GRBs, Star-bursts, Gal. clusters, AGN haloes..

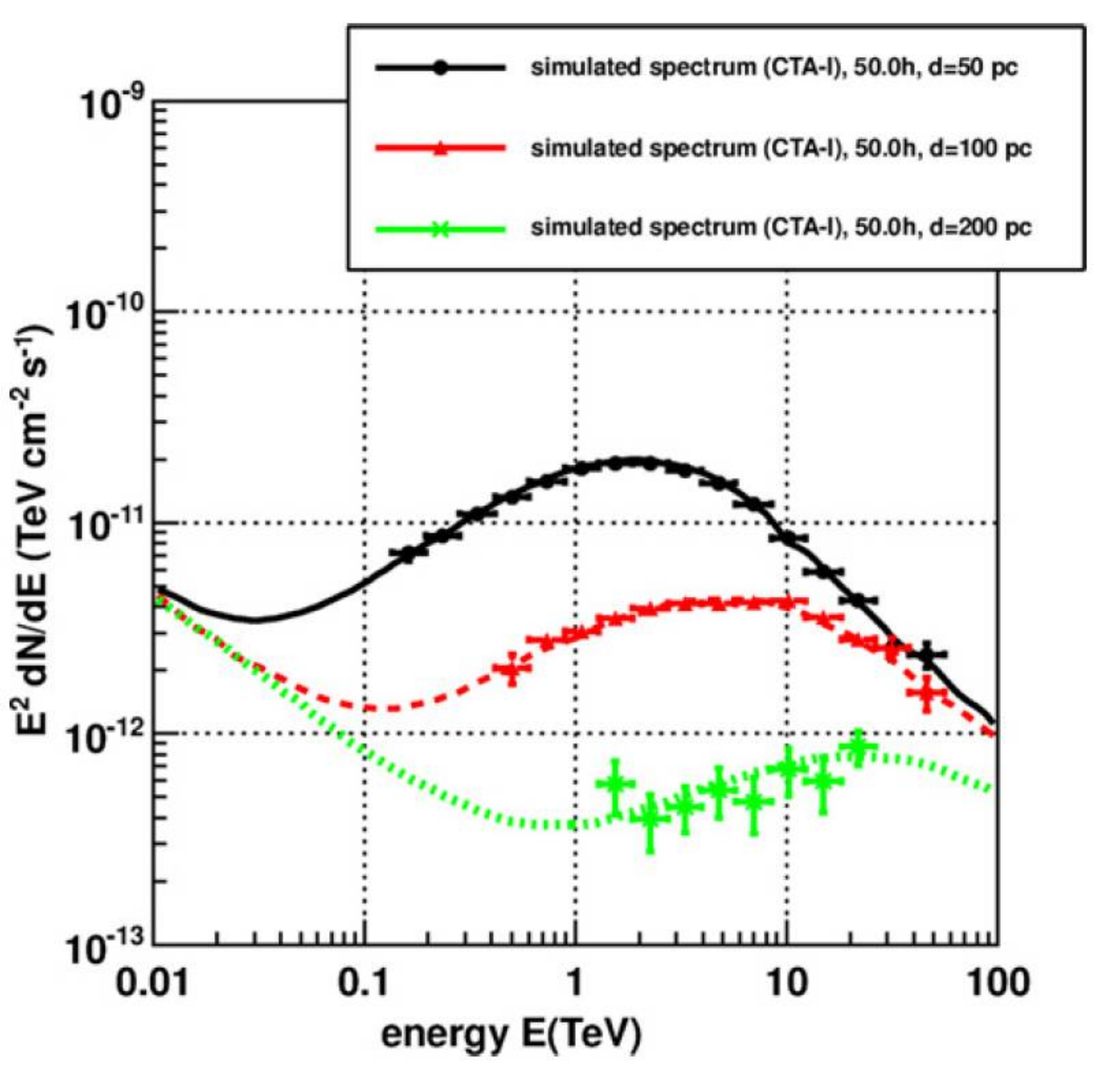
Astro-particle

Dark matter, Lorentz invariance....

Optical

Intensity Interferometry

CTA 50h Observation - CRs escaping SNR (Acero etal 2013)



SNR age 2000 yr

Cloud mass 10^5 M_{sun}

d = 1 kpc

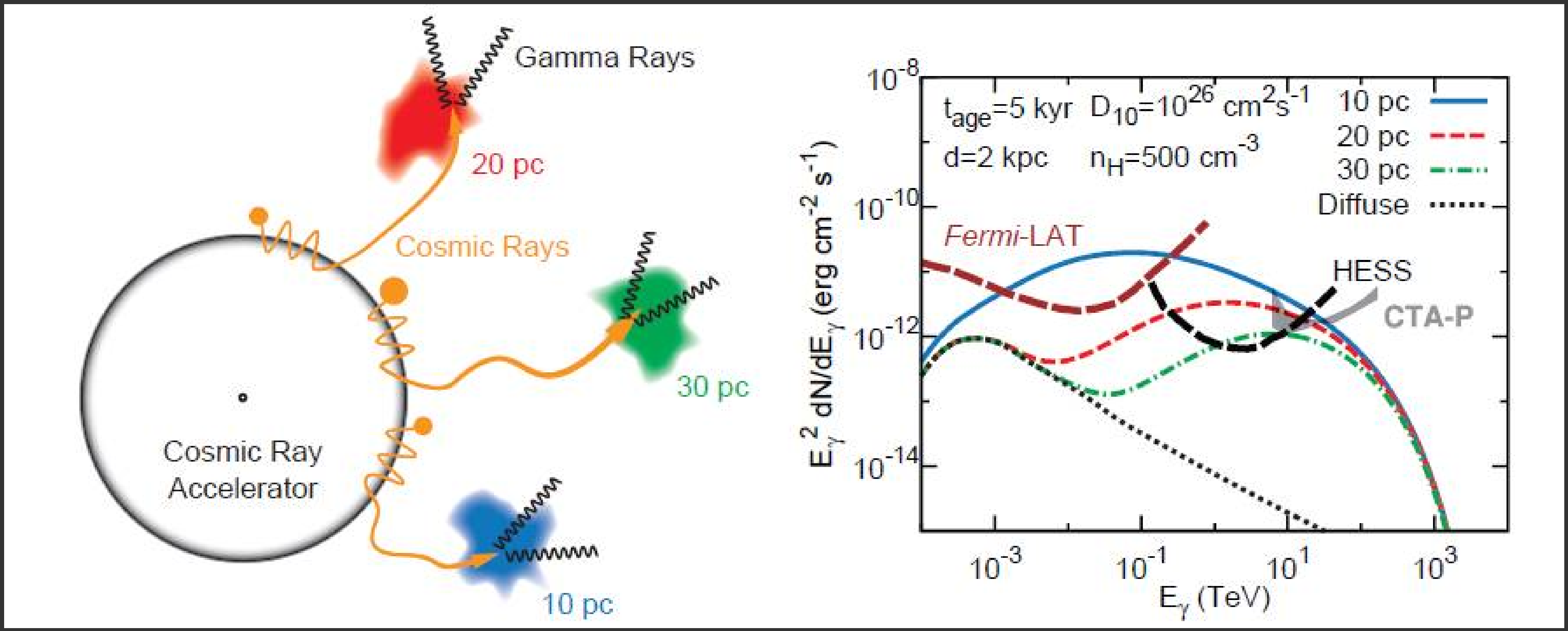
$D=10^{28}(E/10GeV)^{0.5}$ cm^2/s

PeV CRs escape first and arrive at the cloud first!

Ideal way to probe CR PeVatrons

Gamma-ray spectra from local and escaped cosmic-rays

Flux sensitivity (150 hr) for 3 CTA Pathfinder Small Sized Telescopes (CTA-P) at CTA-South site (Chile) – From 2020.



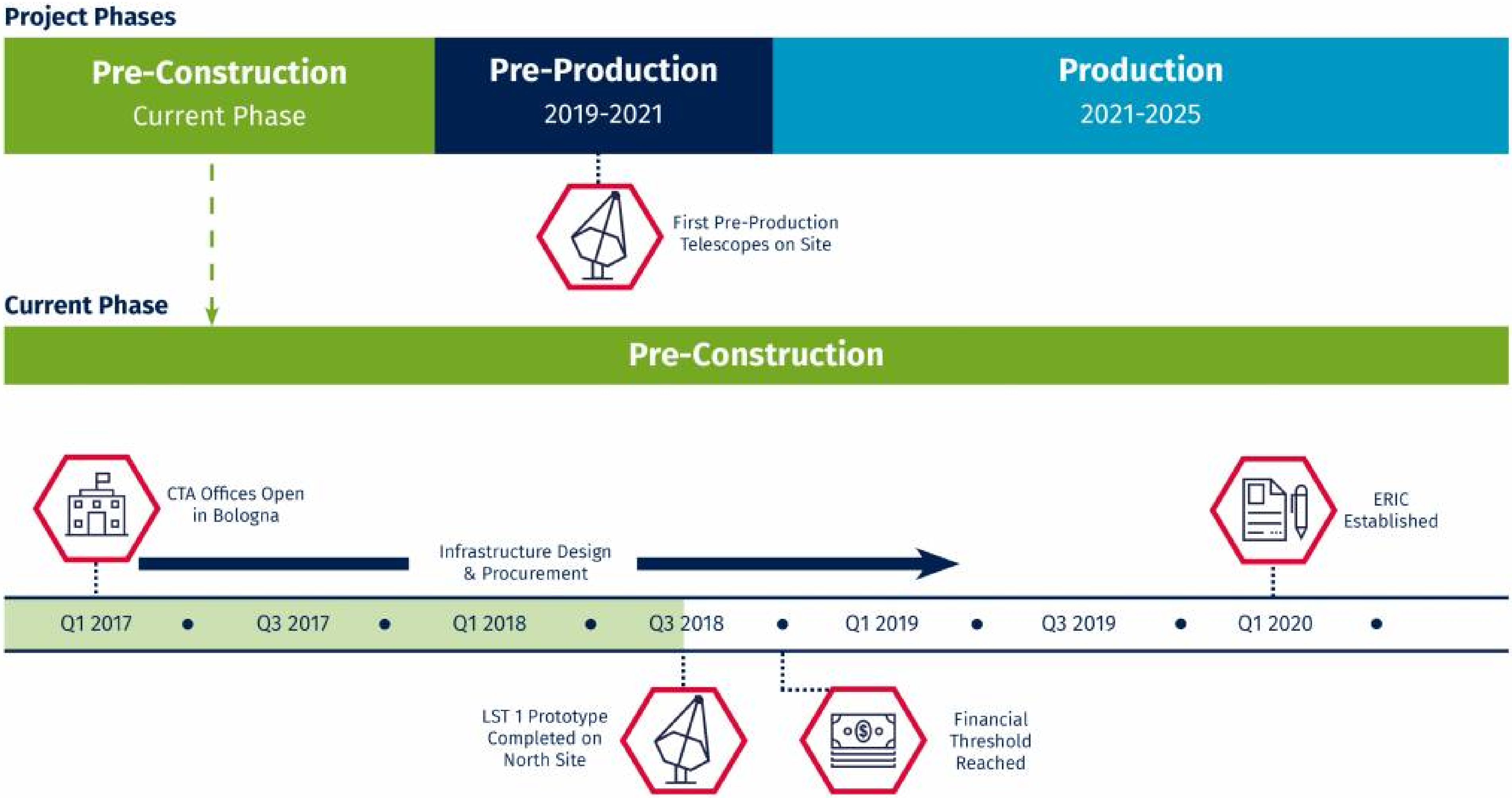
→ Several CTA SSTs can probe the >50 TeV energy range.

→ First detailed search for PeVatrons! (E_p > 500 TeV)

- Examples from HESS/HAWC: HESSJ1641, HESSJ1702, HESSJ1741, Westerlund1, HESSJ1826, HESSJ1908


Thank you..
(c) F. Acero & H. Gast

CTA Timeline (late 2018 status)



Why study cosmic-ray (CRs) and electrons?

- Energy density of galactic CRs similar to that in starlight, magnetic fields, and gas kinetic energy

→ these energy densities are all tightly connected.

→ CRs carry energy throughout galaxies

→ CRs intimately linked to evolution of stars and galaxies

- CRs are a signpost of massive stellar evolution

– death (supernova remnants)

– life (winds from massive stars)

– birth (perhaps) signalling onset of fusion/stellar winds

– initiates astro-chemistry → life!

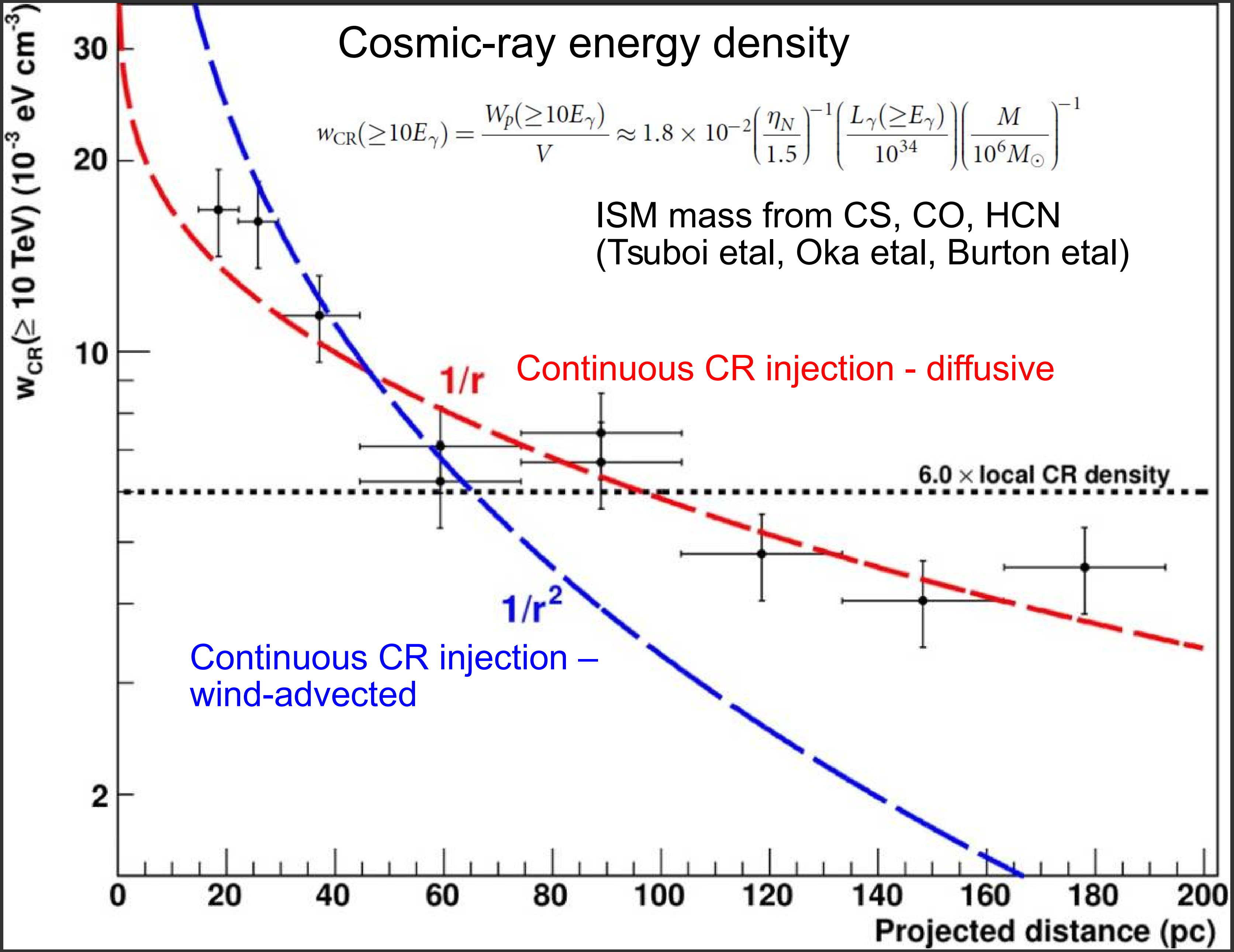
- Where do magnetic fields come? Are they important?

– Magnetic fields can greatly inflence star formation!

– CRs can create magnetic fields - they ionise atoms

- CRs and electrons trace outflows and jets

– jets, pulsar winds, accretion, GRBs-hypernovae.....



Cosmic-ray energy density
$$w_{CR}(\geq 10E_\gamma) = \frac{W_p(\geq 10E_\gamma)}{V} \approx 1.8 \times 10^{-2}\left(\frac{\eta_N}{1.5}\right)^{-1}\left(\frac{L_\gamma(\geq E_\gamma)}{10^{34}}\right)\left(\frac{M}{10^6 M_\odot}\right)^{-1}$$
ISM mass from CS, CO, HCN
(Tsuboi etal, Oka etal, Burton etal)
1/r
Continuous CR injection - diffusive
6.0 × local CR density
$1/r^2$
Continuous CR injection –
wind-advected
$w_{CR}(\geq 10$ TeV) $(10^{-3}$ eV cm$^{-3})$
30
20
10
2
0
20
40
60
80
100
120
140
160
180
200
Projected distance (pc)

GeV-TeV spectra of supernova remnants

Funk et al 2010

If CRs then $E_{CR} \sim 10\, E_{gamma}$