

Credit Spitzer Cocoon Legacy

Hunting for PeVatrons in the Galaxy

us Seminar 17.02.2022

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THE FOLLOWING SLIDES ARE A BIASED OVERVIEW



WARNING

**VIEWER DISCRETION
IS ADVISED**

Outline

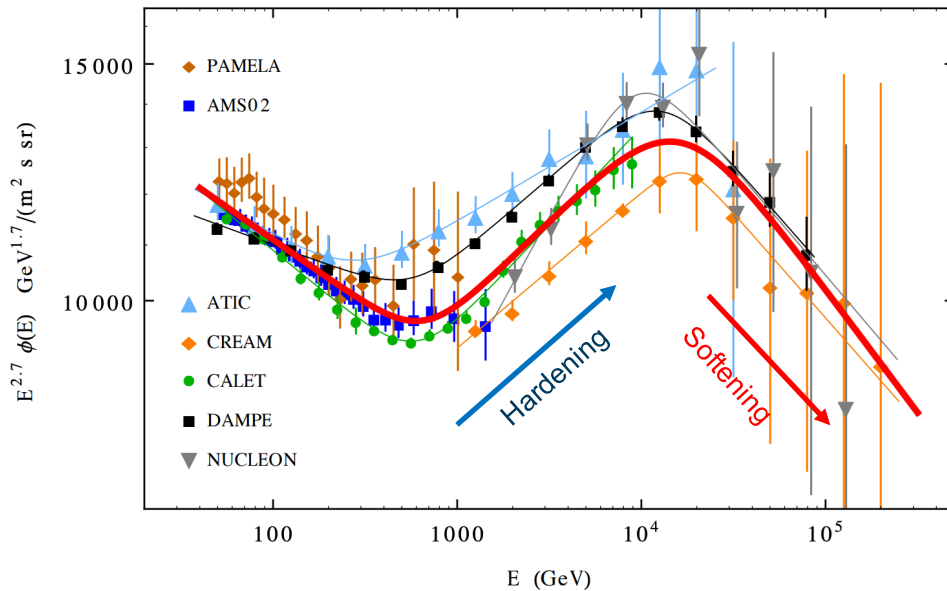
- Motivations
 - the origin of the cosmic ray flux
 - the nature of the most extreme particle accelerators
- γ -ray signatures of particle accelerators
- The search for the Galactic PeVatrons
 - Testing the SNR paradigm
 - Gamma-ray signatures of PeVatrons in MC close to SNRs
 - Galactic Centre
 - Star Clusters
 - Gamma-ray binaries

The leptonic part of the cosmic ray spectrum

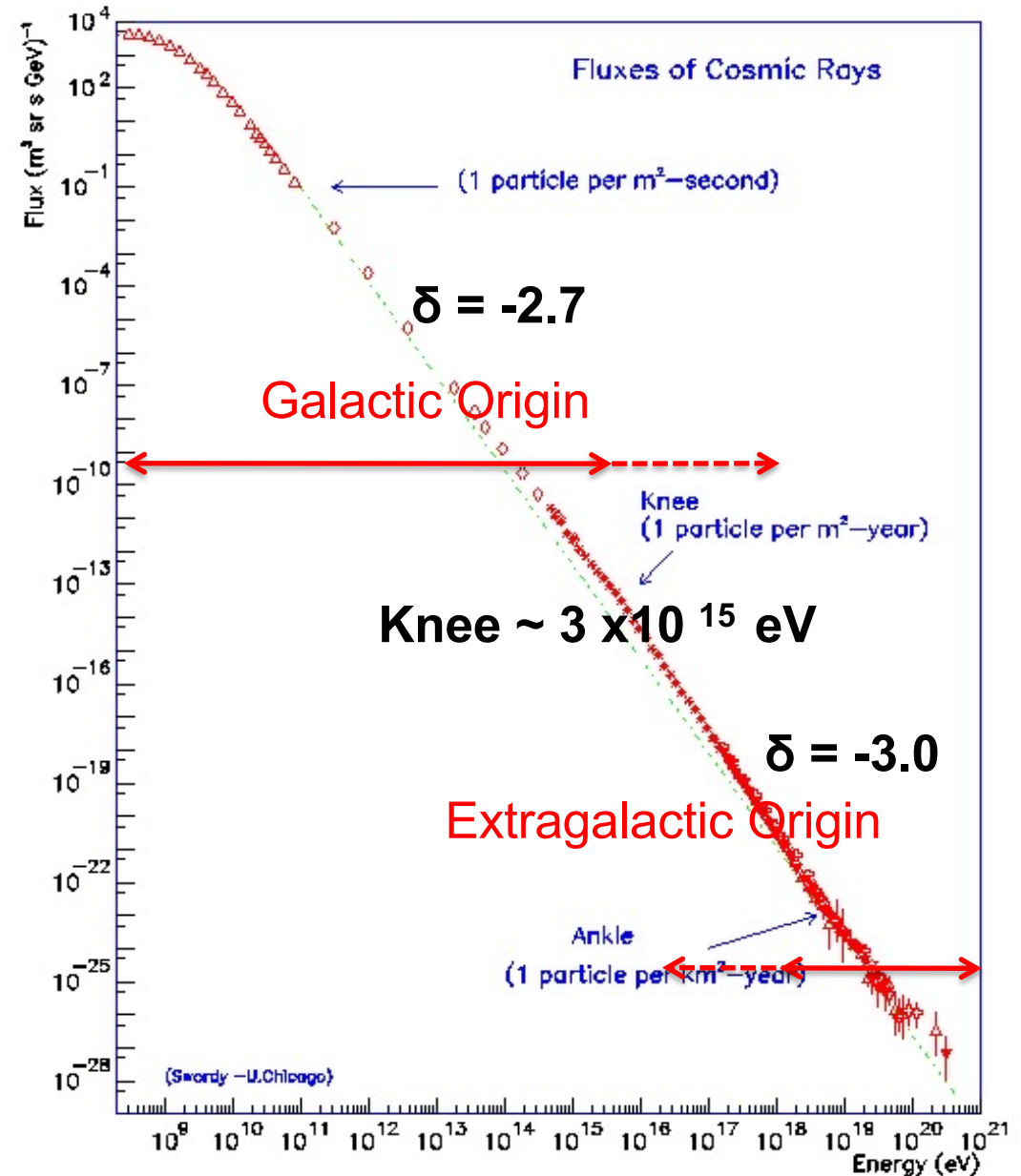
- Future

The cosmic ray flux at Earth

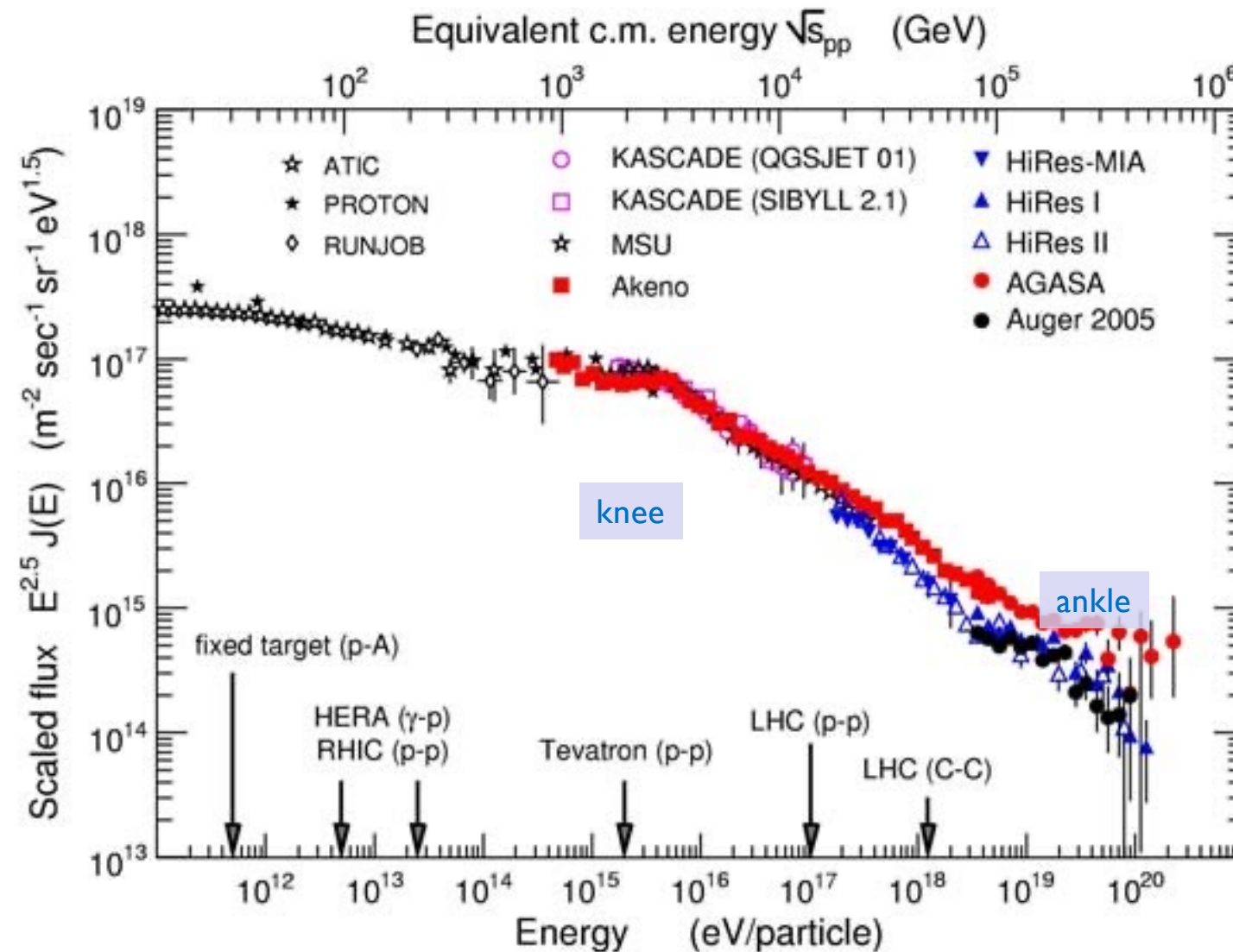
- 90% protons, 9% helium, 1% electrons
- Almost featureless spectrum



. Cronin, T. Gaisser, S. Swordy, Sci. Amer. 276 (1997) 44.



The cosmic ray flux at Earth



- $< 10^{15}$ eV Gal CRs
- $10^{15} - 10^{18}$ eV - transition region
- $> 10^{18}$ ExtraGal CRs

Theoretical challenges :

- ✓ sources of particles $> 10^{15}$ eV : **PeVatrons**
- ✓ sources of particles $> 10^{20}$ eV : **ZeVatrons**

Objectives : understand the origin of the local cosmic ray flux and the physics of the extreme particle accelerators, which inject the relativistic non-thermal plasma known as cosmic rays.

Extreme Particle Accelerators

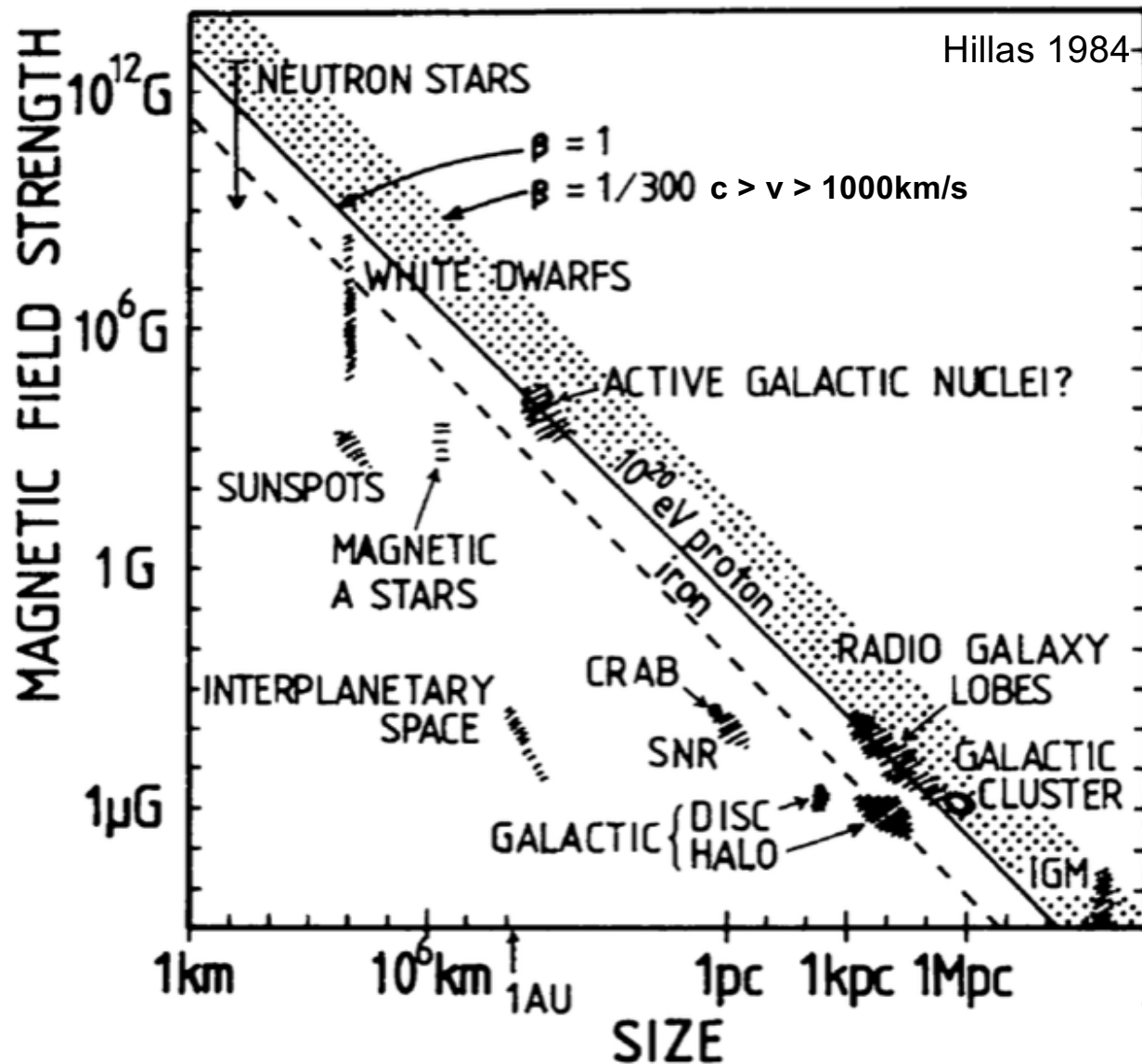
Accelerators with **efficiency close to 100%**

- fraction of the astrophysical source energy converted in non-thermal particles close to 100% (examples: PWNe and SNRs)
- acceleration rate close to the maximum rate allowed in electrodynamics and MHD (examples: Crab and sources of 10^{20} eV protons)

$$dE/dt = q c E = \eta q c B \quad \eta = E_{\text{eff}}/B \leq 1$$

$\eta \rightarrow 1$ extreme accelerator

Hillas criterion



Particles acceleration as long as $r_L < R$

$$r_L \approx \frac{1}{Z} \left(\frac{E}{10^{15} \text{ eV}} \right) \left(\frac{B}{\mu\text{G}} \right)^{-1} \text{ pc}$$

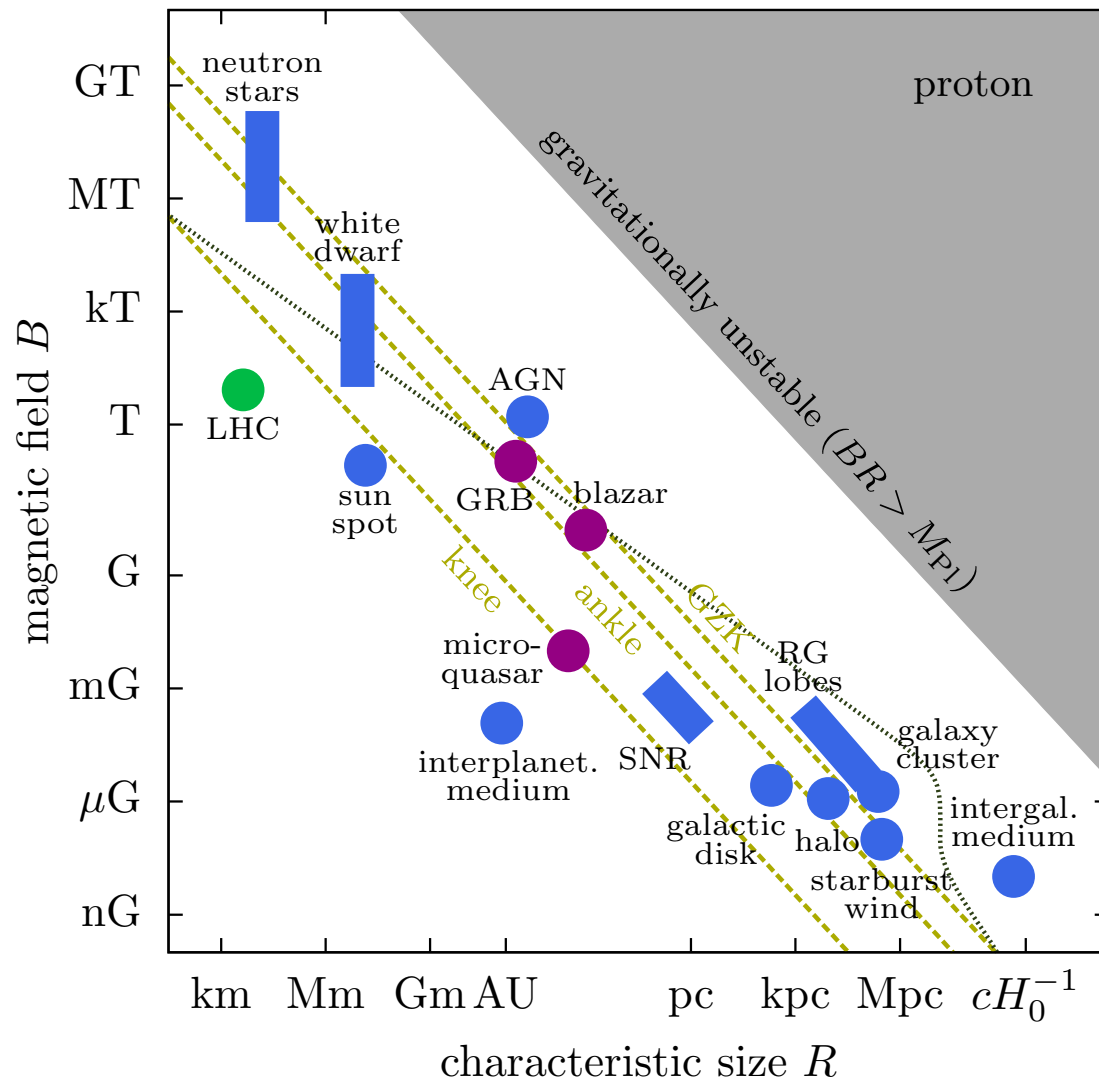
$$E_{\text{max}} \cong Z \beta \left(\frac{B}{\mu\text{G}} \right) \left(\frac{R}{\text{pc}} \right) 10^{15} \text{ eV}$$

Energy losses or even only curvature losses reduce the max energy achievable

Ultra-relativistic bulk flows can help reach the highest energies

Hillas criterion

Dova, 2016



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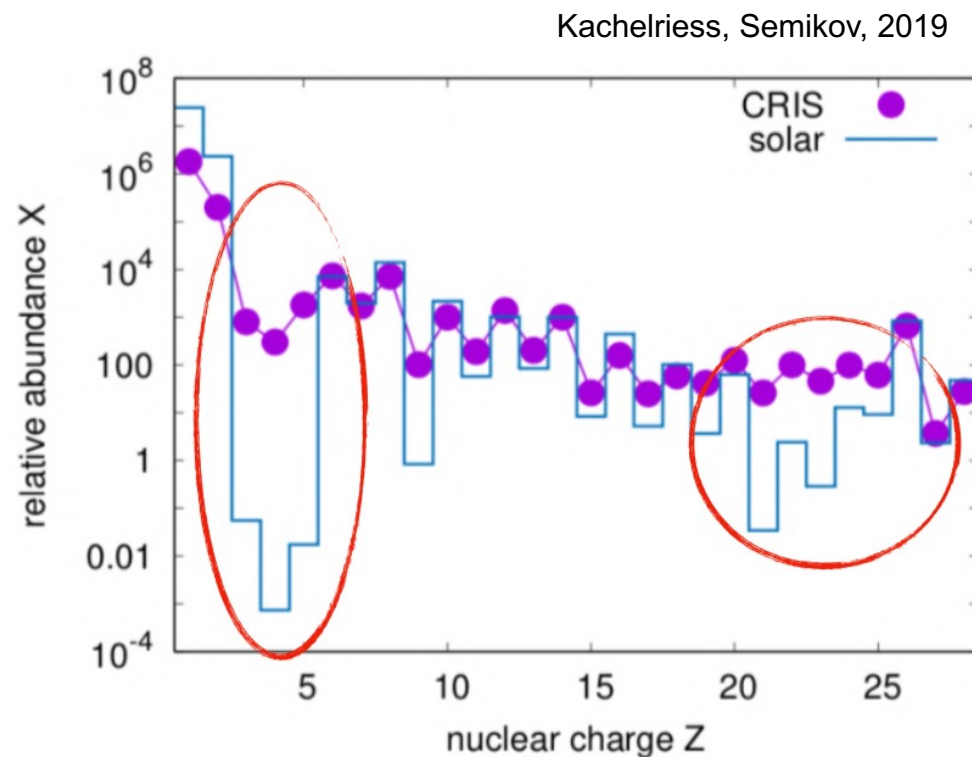
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Energy losses or even only curvature losses reduce the max energy achievable

Ultra-relativistic bulk flows can help reach the highest energies

Cosmic Ray Abundances < 100 GeV

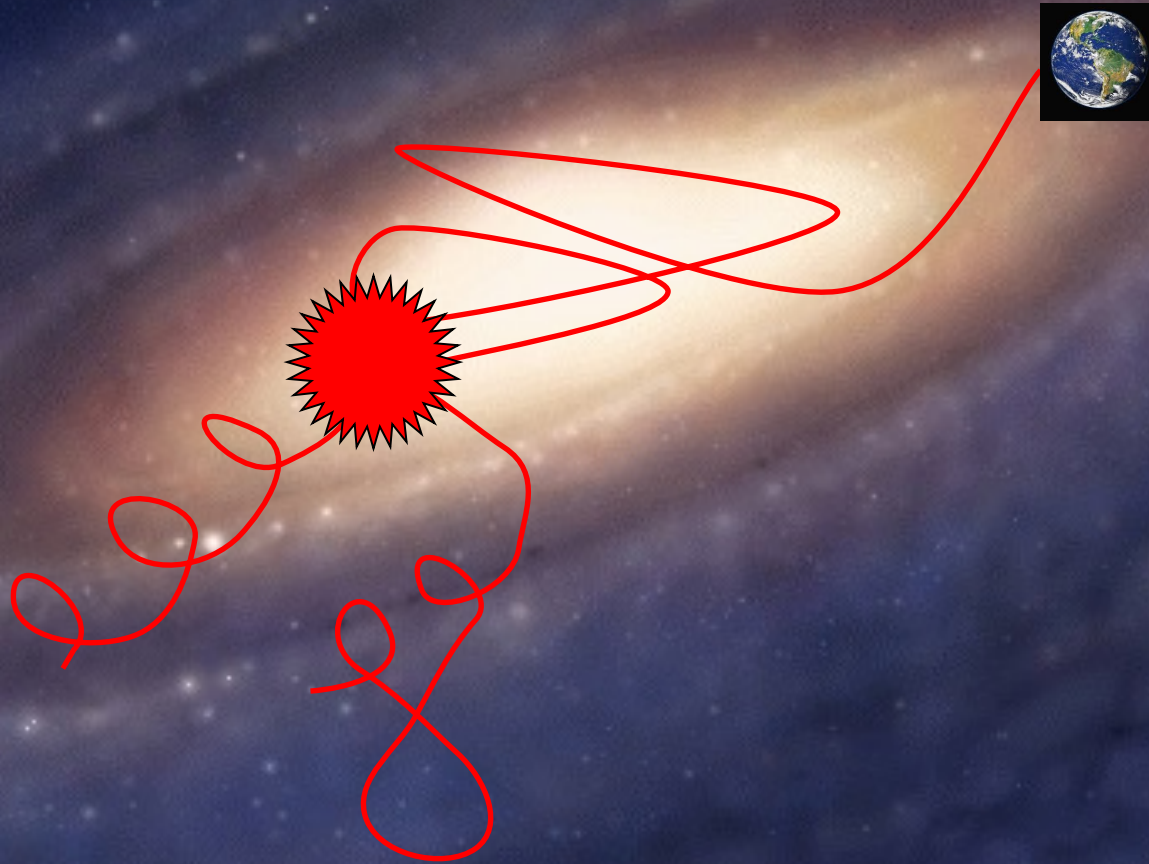
- Secondary particle production (B/C ratio) implies CR pass through 5-10 g/cm² in lifetime
 - Average Galactic plane density of 1 H atom/cm³ implies CR traverse 1000 kpc for a lifetime of **3×10^6 yr**
 - Ratio decreases with energy implies higher energy CR escape Galaxy more quickly
- Long lived radioactive isotope (e.g. Be¹⁰) implies even longer lifetime so CR spend considerable time in Galactic halo



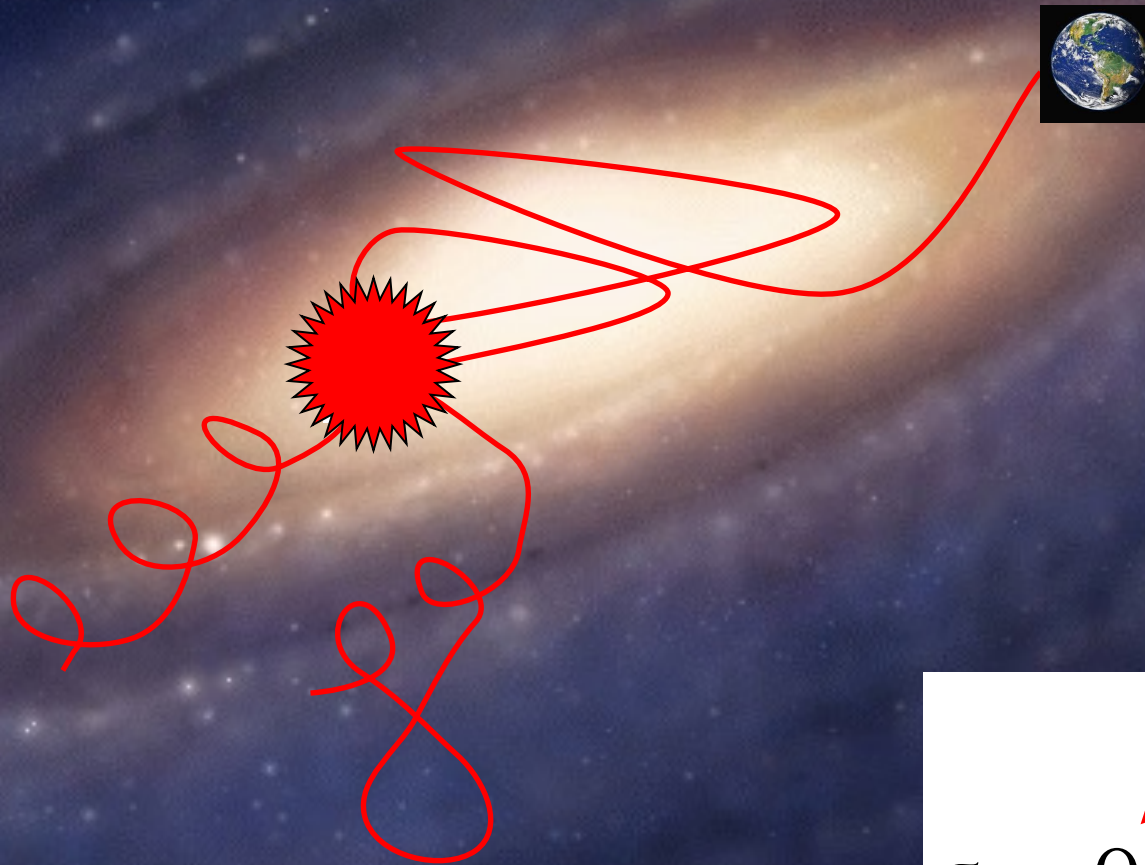
Astrophysics with CRs ?

- High quality information about the **locally** measured primary and secondary components of CRs
- CR factories can be revealed only by neutral & stable astronomical messengers: photons and neutrinos
- Charged CRs do not provide information about the acceleration sites

Acceleration and transport in the Galaxy

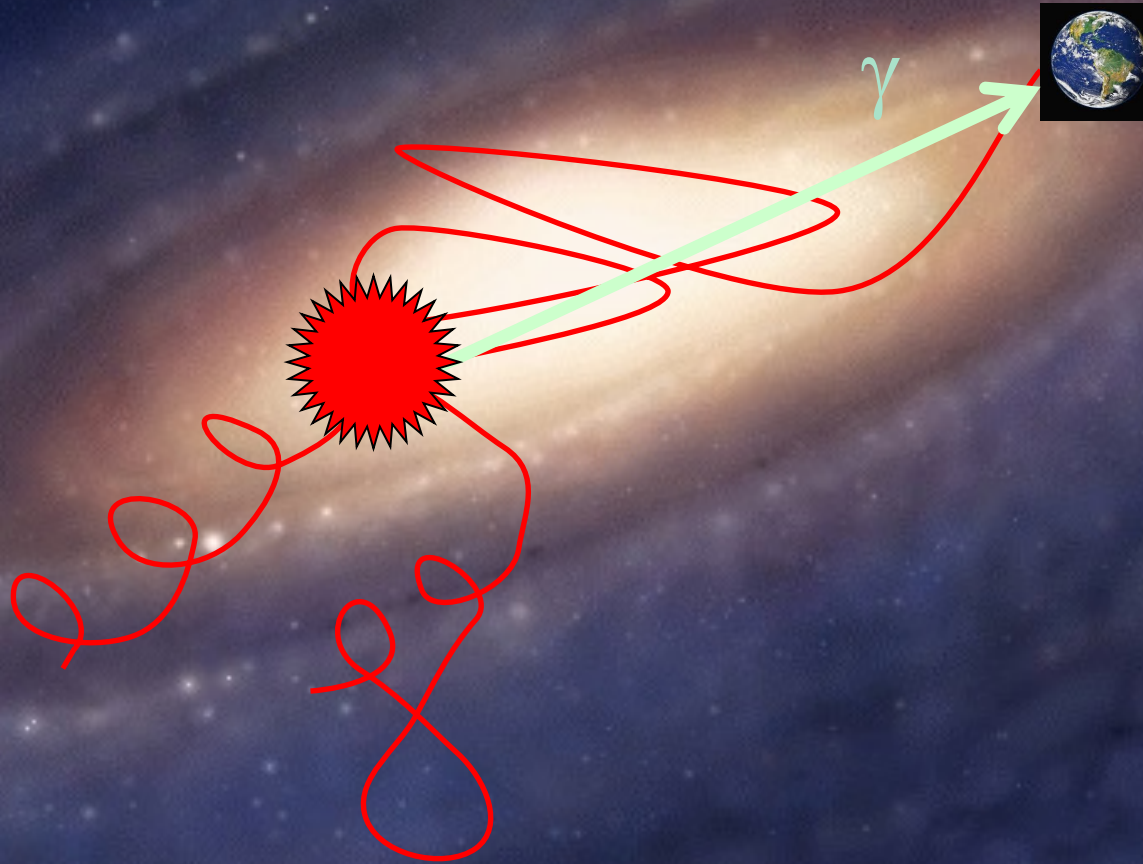


Acceleration and transport in the Galaxy



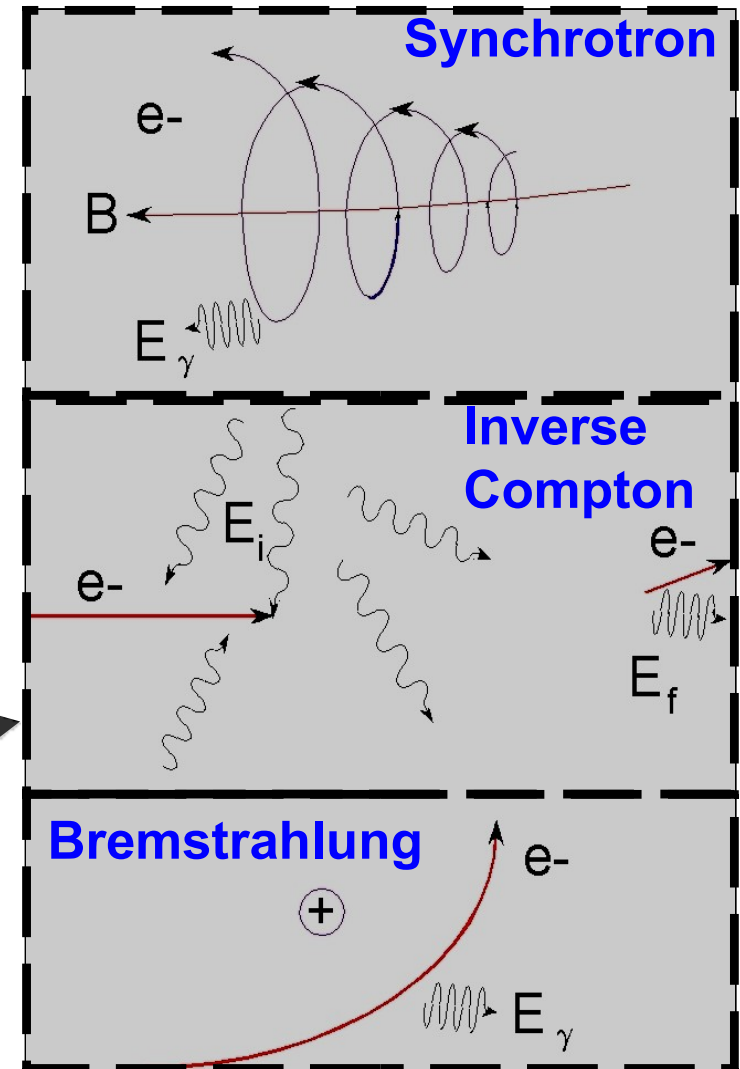
$$\begin{aligned} Q_{\text{source}} &\propto E^{-2 \text{ to } -2.4} \\ \tau_{\text{escape}} Q_{\text{source}} &\propto \frac{dN_{\text{observed}}}{dE_{\text{observed}}} \\ \tau_{\text{escape}} &\propto E^{-0.3 \text{ to } -0.7} \end{aligned}$$

Acceleration and transport in the Galaxy



Gamma-ray Emission : a probe of CR origin and propagation

- CRs + gas $\rightarrow \pi^0 \rightarrow 2 \gamma$
 - CRs + gas $\rightarrow \pi^+ + \pi^- \rightarrow \nu$
- CR signatures for γ -rays
 - Morphology
 - Spectrum
- *But electrons produce gamma-rays, too and very efficiently through IC and bremsstrahlung.*



γ -ray signatures of PeVatrons

$$CRs(1\text{ PeV}) + gas \rightarrow \pi_0 \rightarrow \gamma\gamma (\sim 0.1\text{ PeV})$$

$$CRs + gas \rightarrow \pi^-\pi^+ \rightarrow \nu$$

Roughly hundred TeV γ -rays

The γ radiation is hadronic

Ideally, estimate of energetic input in accelerated particles -

$$L_{\gamma} \propto W_p t^{-1} \propto W_p n$$

Detecting 100 TeV photons means that there are PeV particles colliding off gas target. The emission does not necessarily coincide with the location of the particle accelerator.

Gamma-Ray Observatories

Wide FOV continuous operation

Satellites



**AGILE
EGRET
Fermi-LAT**

Space-based

EAS



**Milagro
Tibet AS γ
ARGO-YBJ
HAWC, LHAASO**

Ground-based

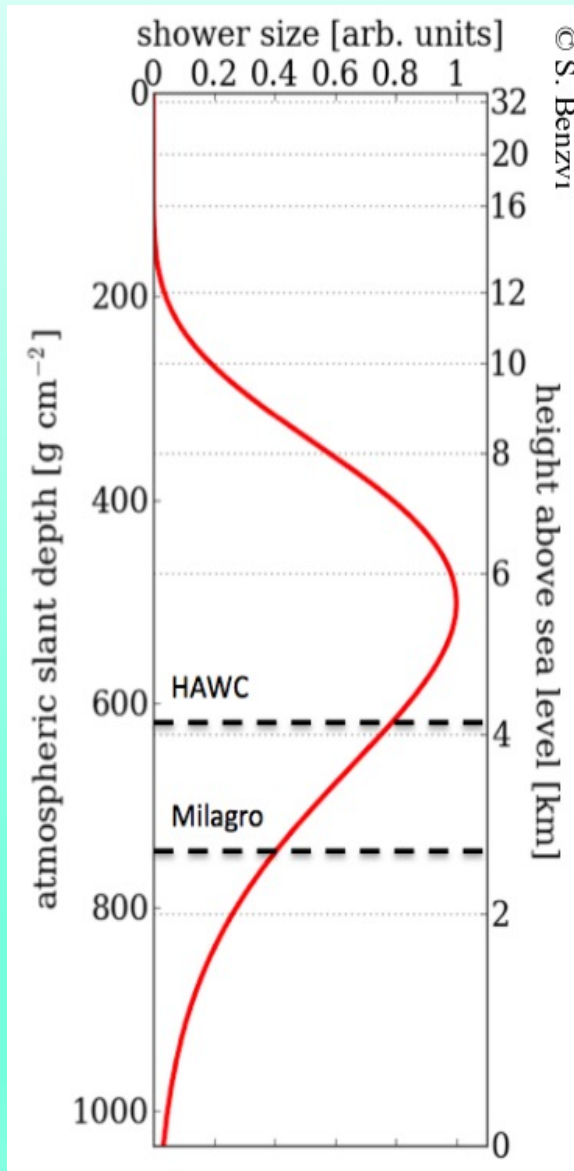
TeV sensitivity

IAC

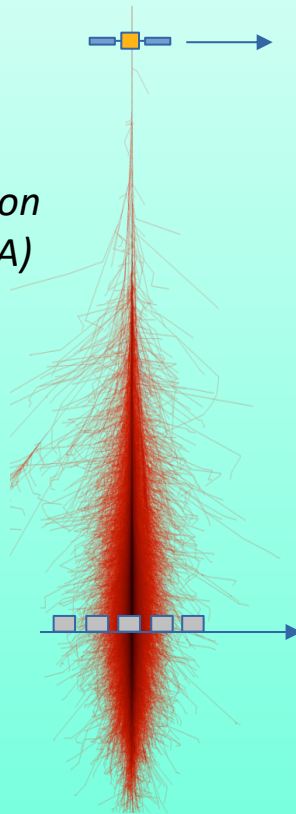


**H.E.S.S.
MAGIC
VERITAS
CTA**

High Energy Gamma-Ray Detectors



Simulation
(CORSIKA)



**Wide Field of View,
Continuous
Operations**

**Satellite
Detector**



**Extensive Air Shower (EAS)
Detector**



TeV Sensitivity

**Imaging Atmospheric Cherenkov
Telescope (IACT)**

SNRs as major suppliers of Galactic CRs

SNR hypothesis based on two arguments:

SNRs provide adequate conditions to have efficient CR acceleration

SN explosions – 10^{51} erg – can sustain the Gal CR population

Observationally

Evidence of CR acceleration up to PeV energies in SNRs ?

Fraction of SN burst energy budget in CRs ?

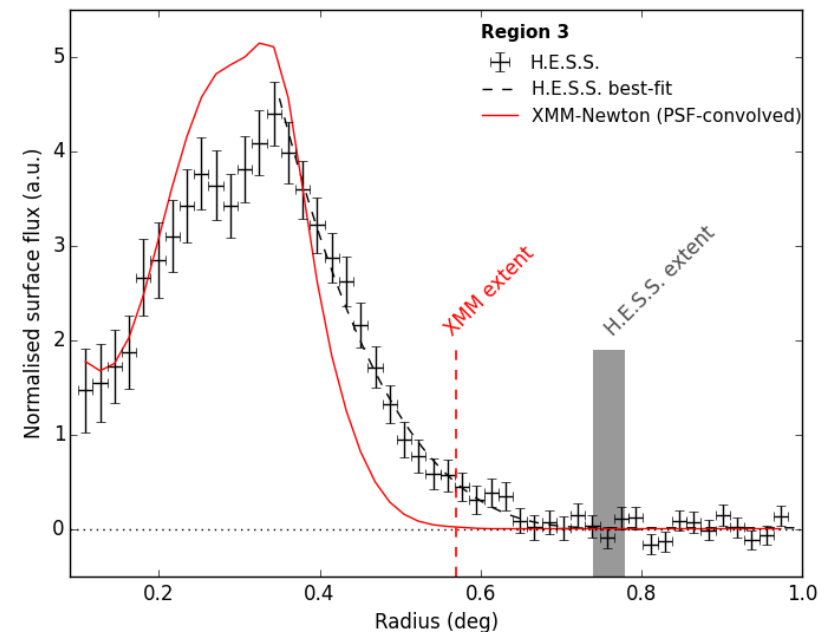
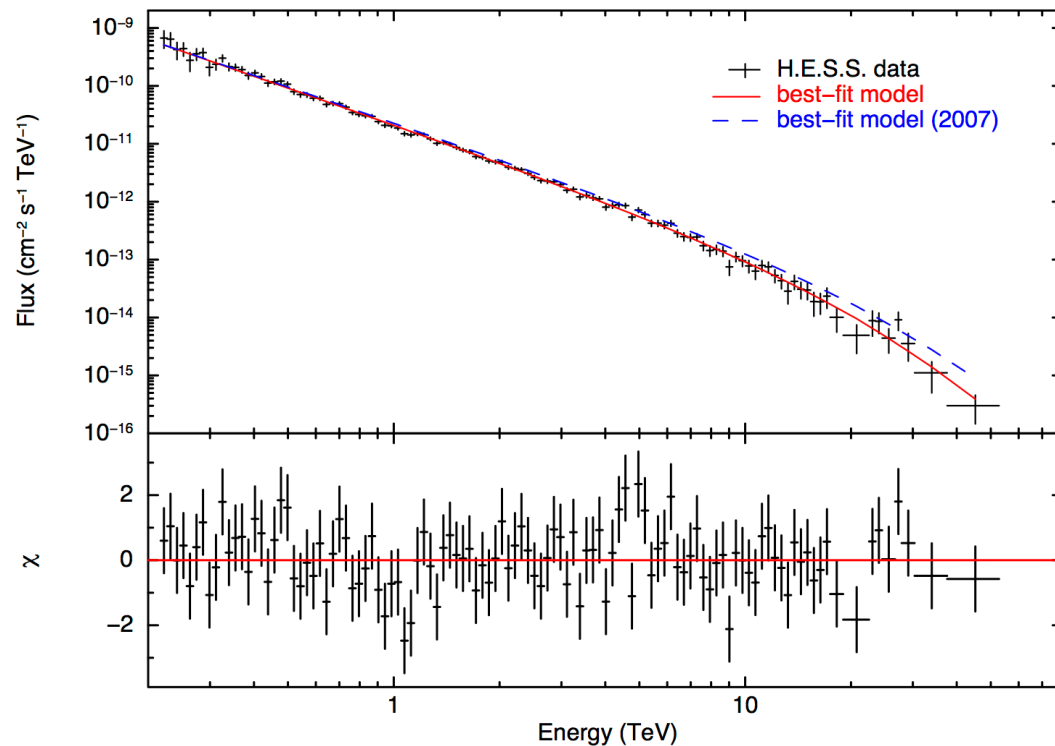
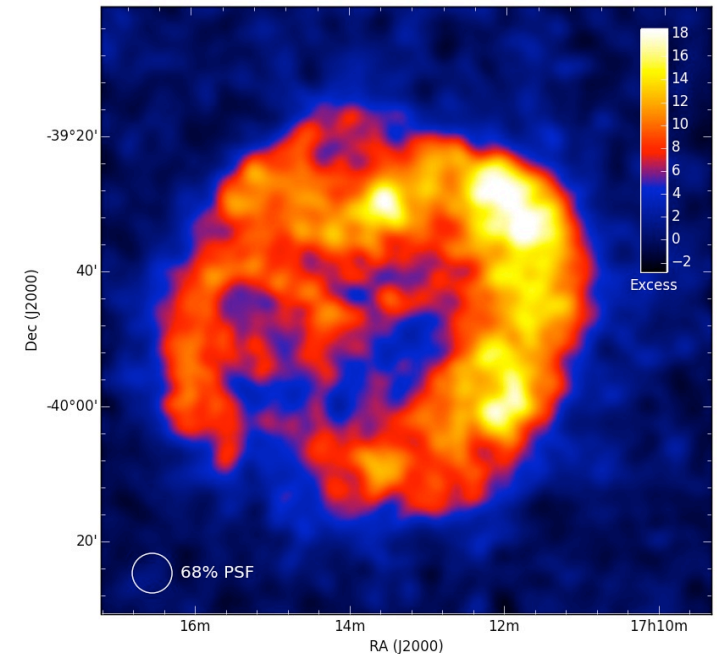
The first suspects: young SNRs

Young (~ 1.5 kyr) and nearby (~ 1 kpc) SNR

First, and brightest resolved TeV shell

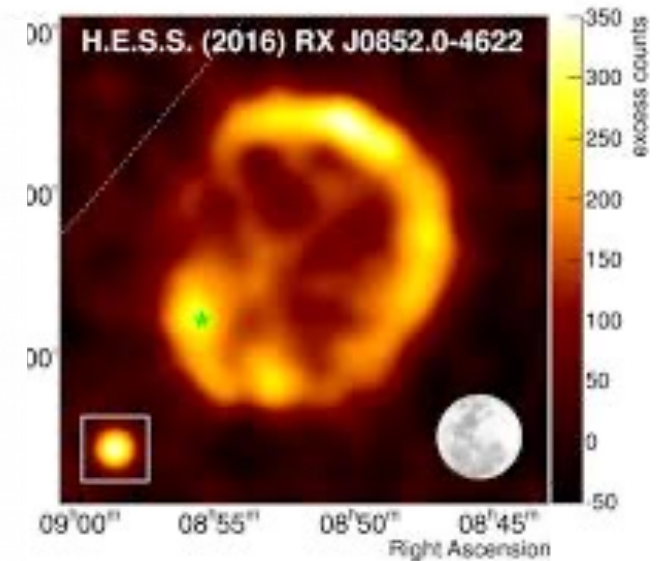
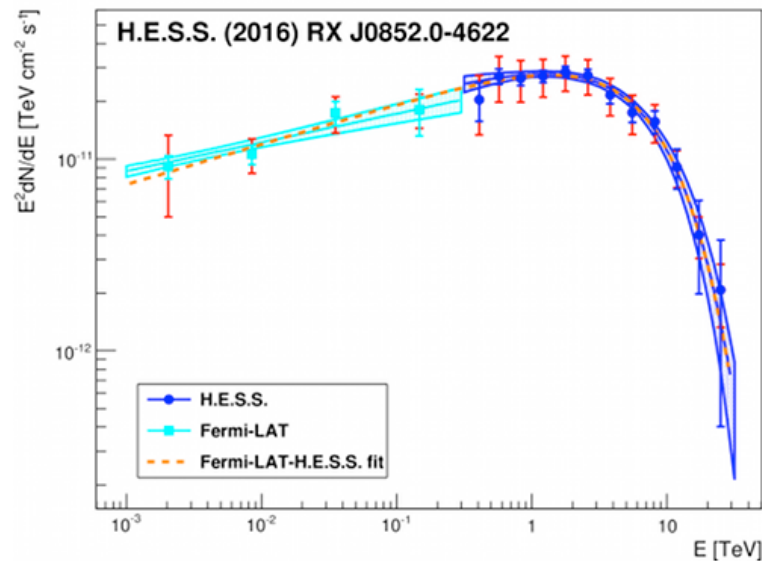
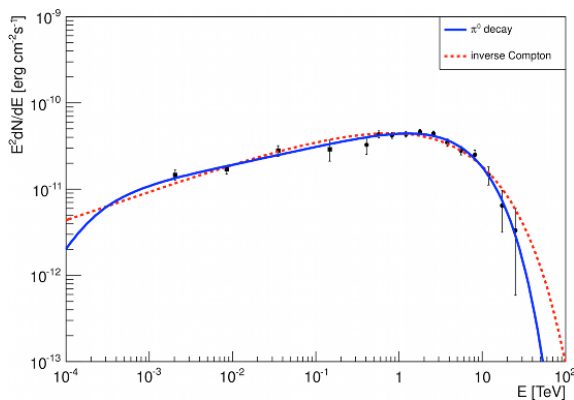
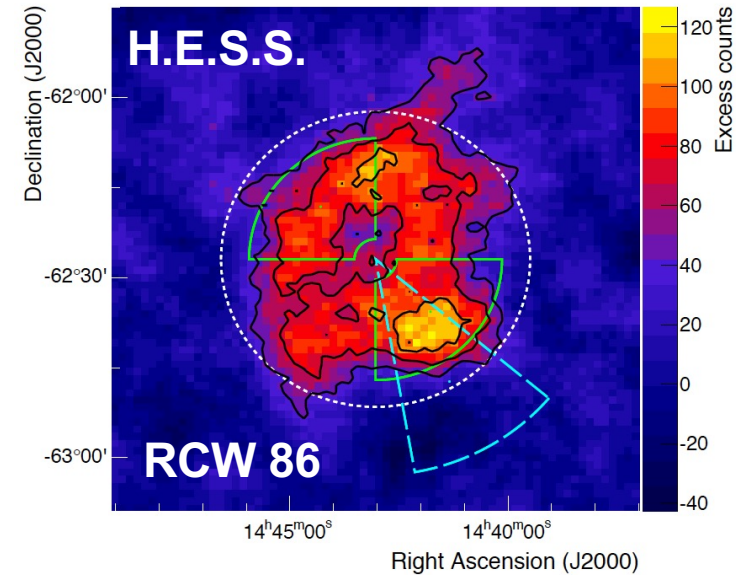
10 years of H.E.S.S. data

- Factor 2 improvement in statistics over last publication ($> 27\,000$ γ 's)
- Spectrum up to ~ 50 TeV: cuts off ~ 12 TeV
- Spatially resolved spectra!



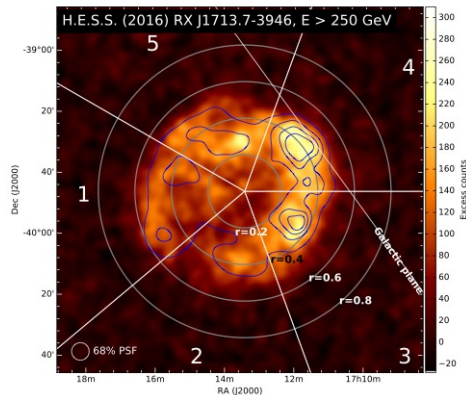
Two famous shell-type SNRs resolved with H.E.S.S.

- Vela Junior:
deep analysis reveals a cutoff at 6.7 TeV
- RCW 86:
deep exposure **confirms** TeV shell appearance
 - Good correlation between TeV and hard X-ray (IC vs. synchrotron), likely leptonic dominated, $B \sim 20 \mu\text{G}$
 - Steepening in the spectrum $\sim 3 \text{ TeV}$



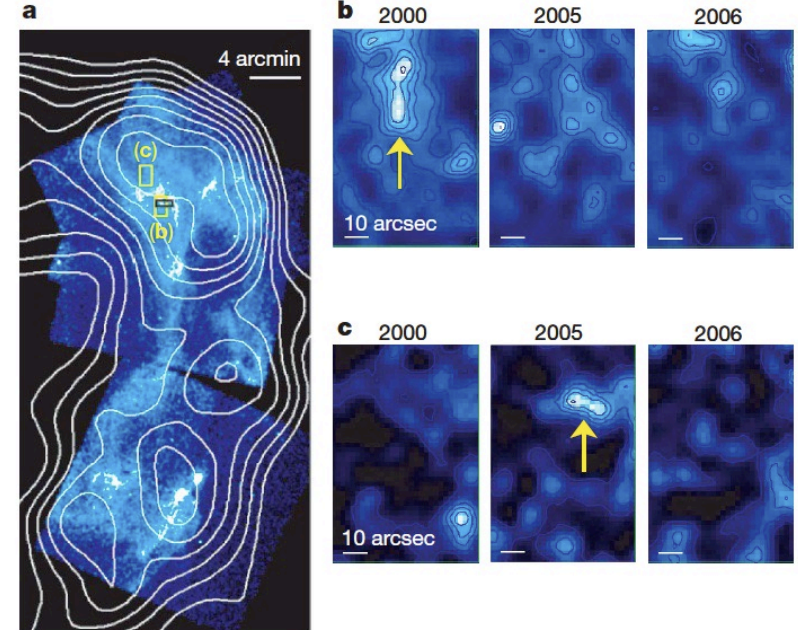
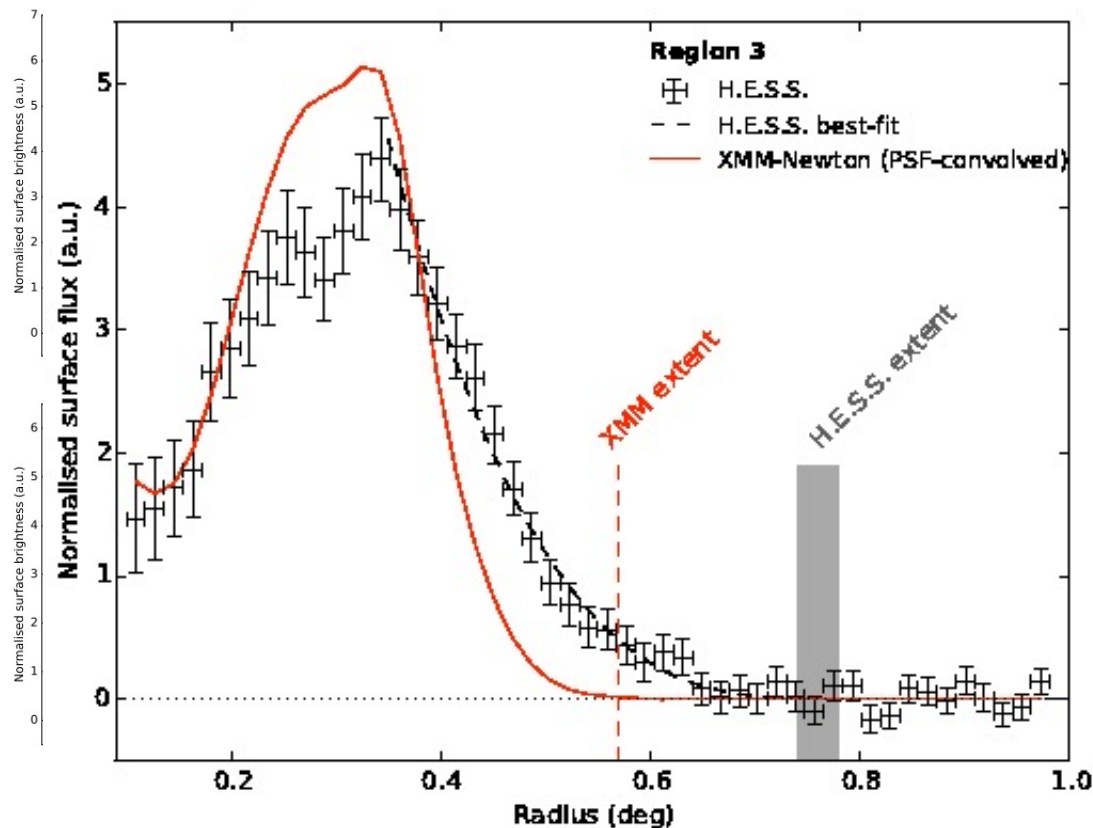
X-ray - TeV correlation

Uchiyama, et al Nature 2007



Correlation X-ray TeV images electrons
Are accelerated in the shell up to
hundreds
TeV.

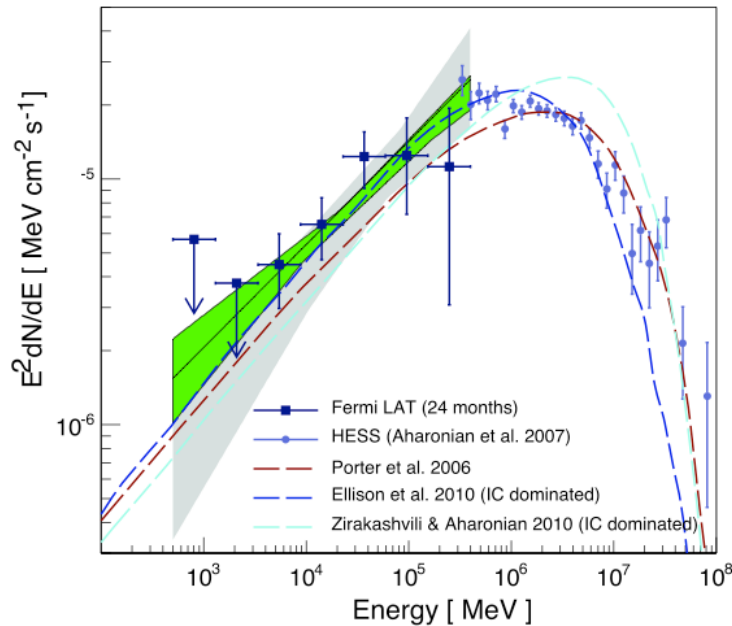
, however TeV extends beyond X-ray
shell at all energies. Interpretation :
VHE CRs are leaving the main shock
Region or particle acceleration in shock
precursor



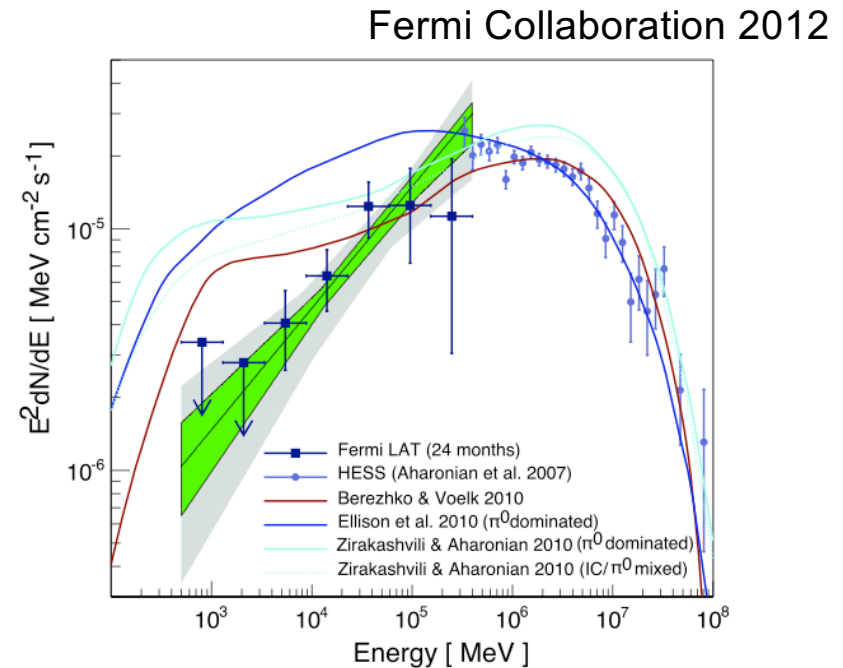
increase - particle acceleration
flux decrease - synchrotron cooling

both require B-field of order 1 mG in
hot spots and, most likely, 100 μ G
outside. Supporting amplification of B-
field through non-resonant streaming
instability

Fermi Spectra of RXJ1713-3946



leptonic models

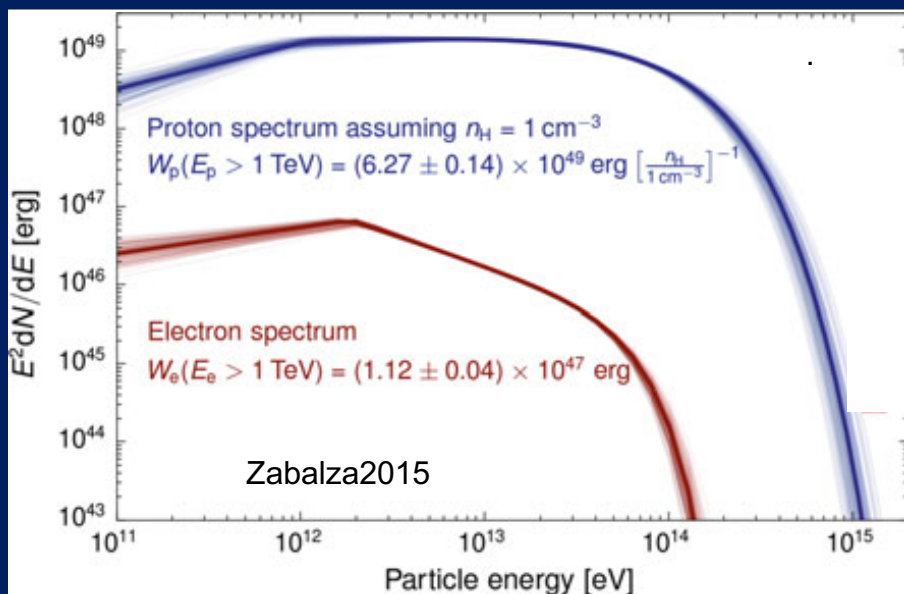
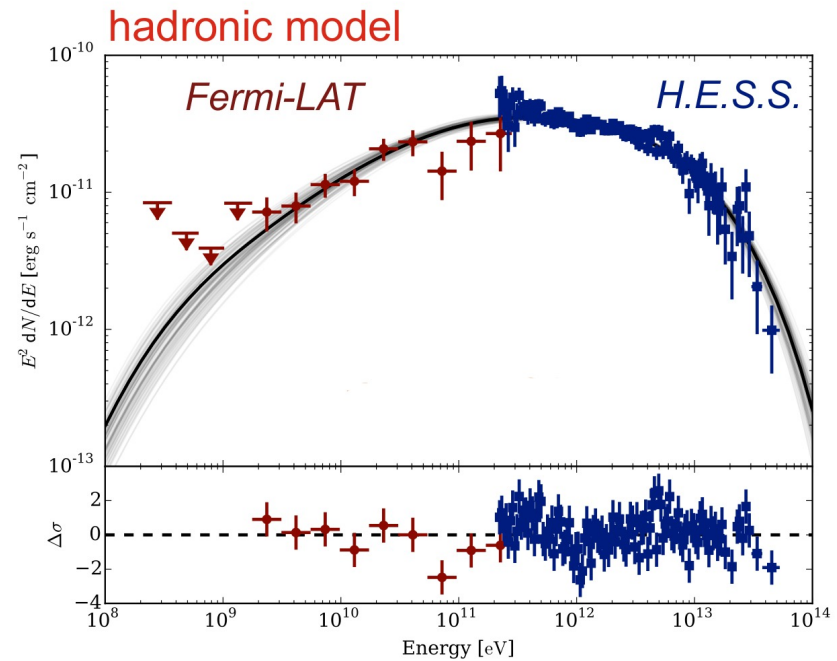
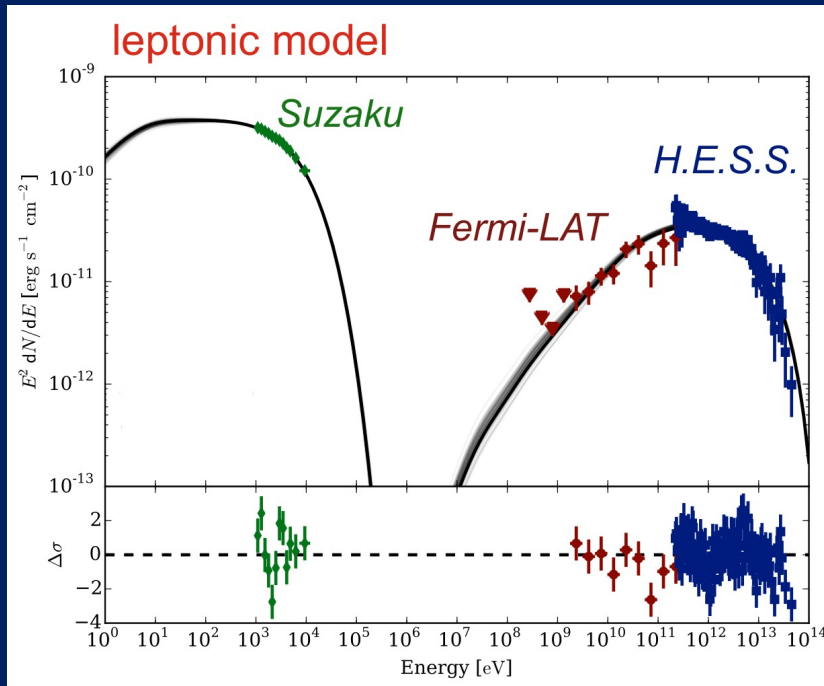


hadronic models

Does this speak against hadronic models ?

- GeV and TeV fluxes are from the same region ?
- What about if the proton spectra are hard? nonlinear theories do predict very hard spectra with $\alpha \rightarrow 1.5$

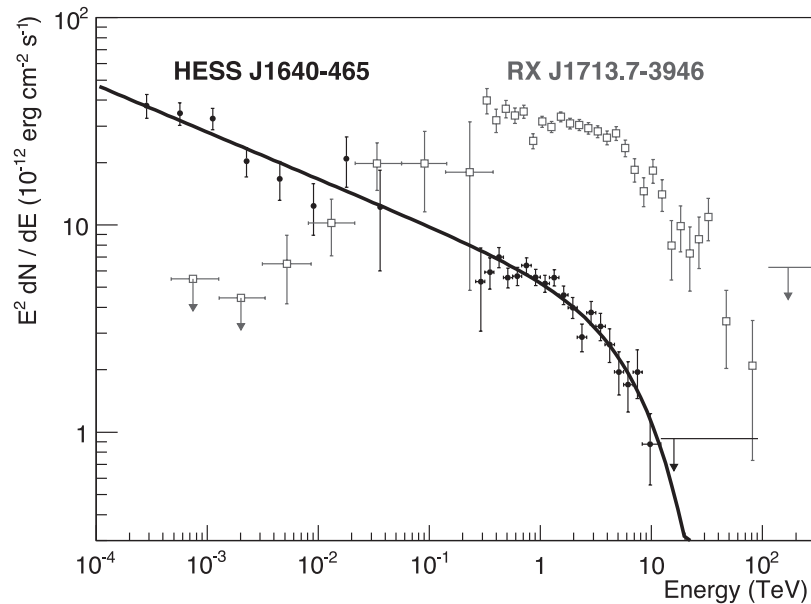
Hadronic or leptonic ?



Both hadronic and leptonic can explain the GeV to TeV emission

The content in accelerated hadrons is unknown because of the uncertainty in the estimate of the gas density

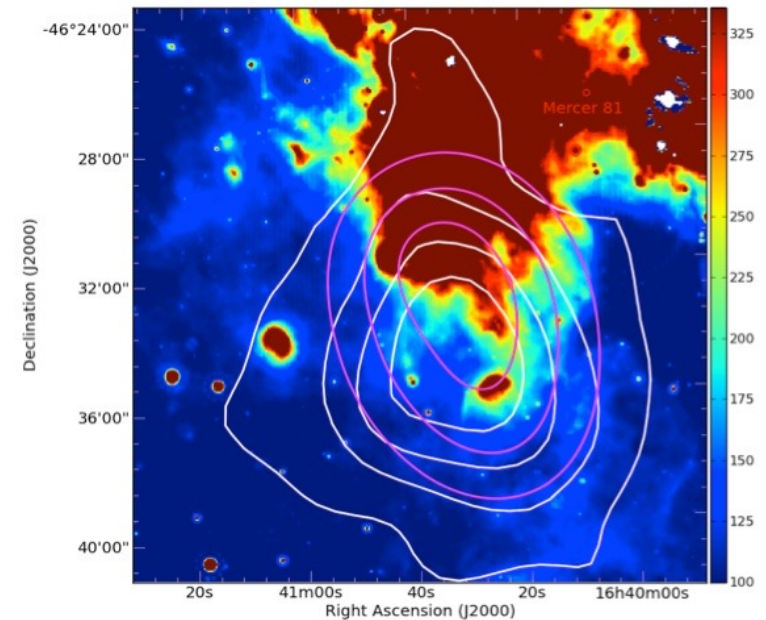
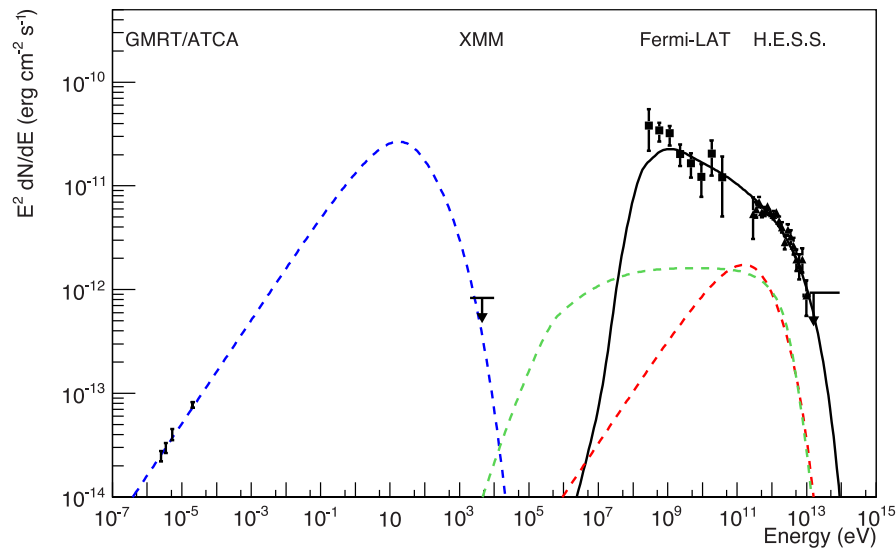
An exceptionally bright SNR G338.3-0.0



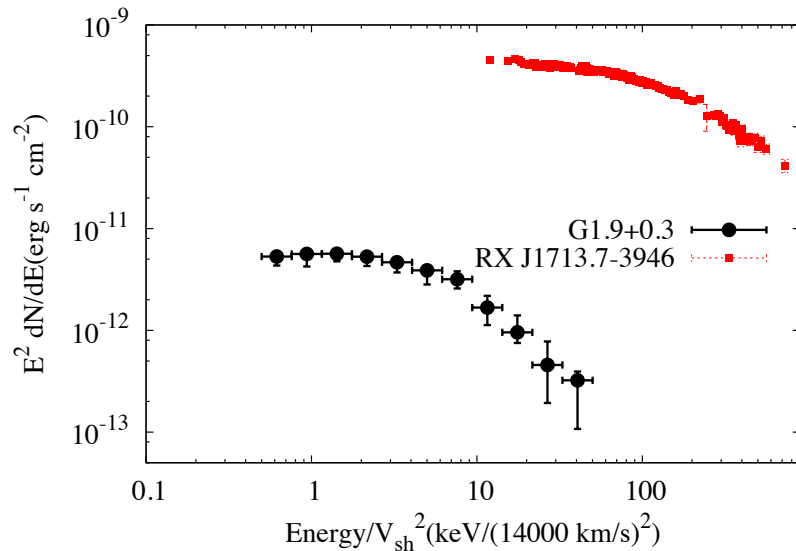
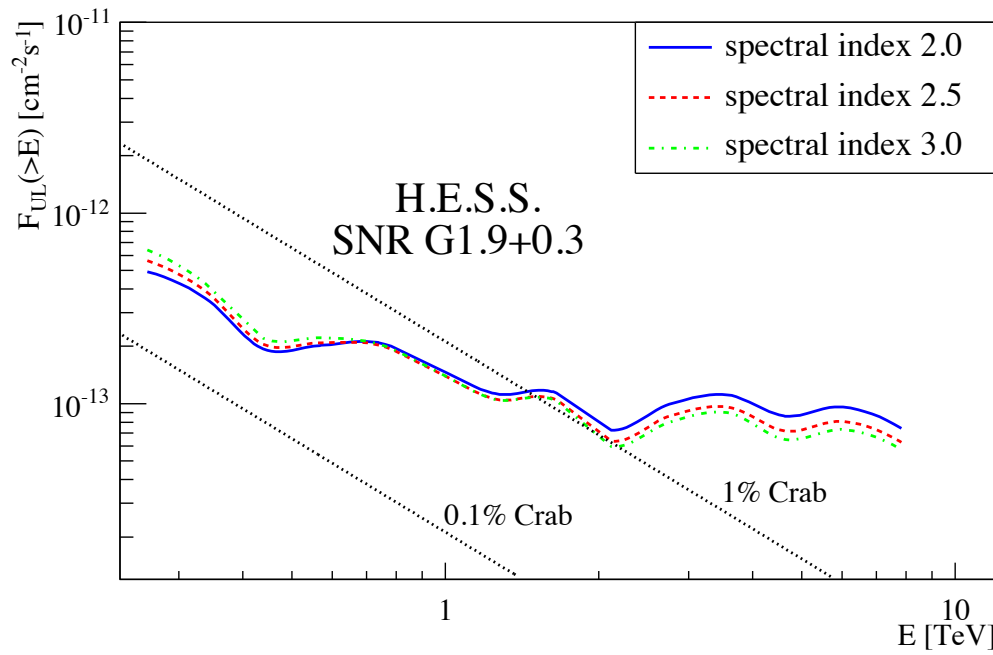
Core collapse SNR from a massive star. Strong winds have created a cavity surrounded by high density shell

L_γ at TeV close to 10^{35} erg/s
 $W_p = 4 \cdot 10^{52} (d/10 \text{ kpc}) (n/1 \text{ cm}^{-3})^{-1}$ erg
 erg $\rightarrow$ rich target density $\rightarrow$ optimism for detecting more of these objects with CTA

The Spitzer MIPS $24\mu\text{m}$ images show abundance of interstellar dust and HII region. Gas density up to 600 cm^{-3}



The youngest SNR in the Galaxy: G1.9+0.3

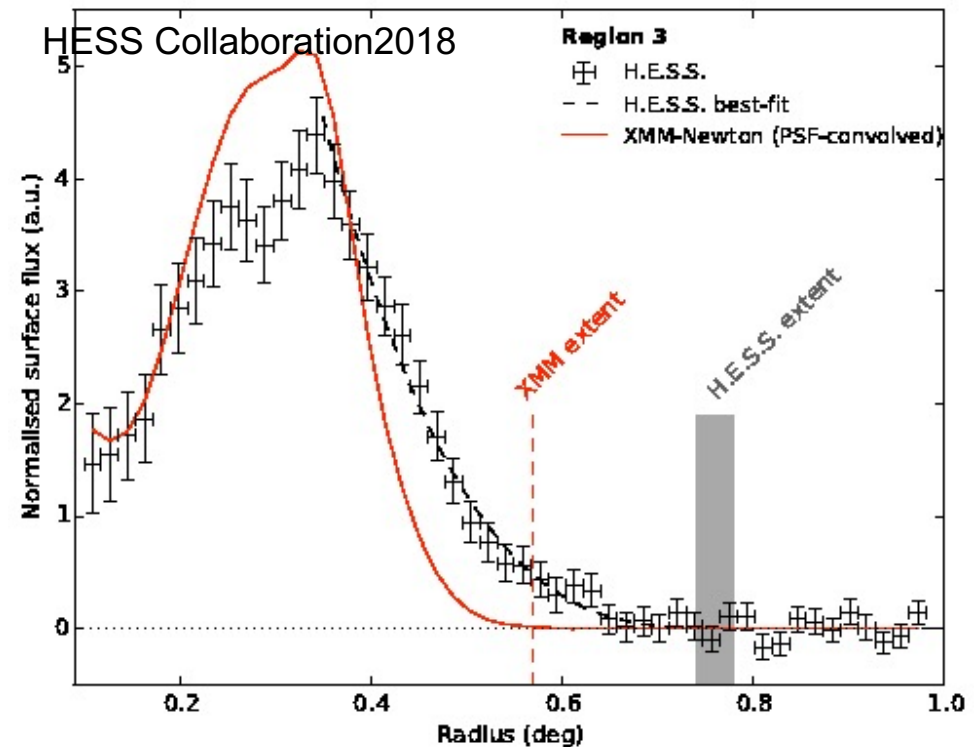
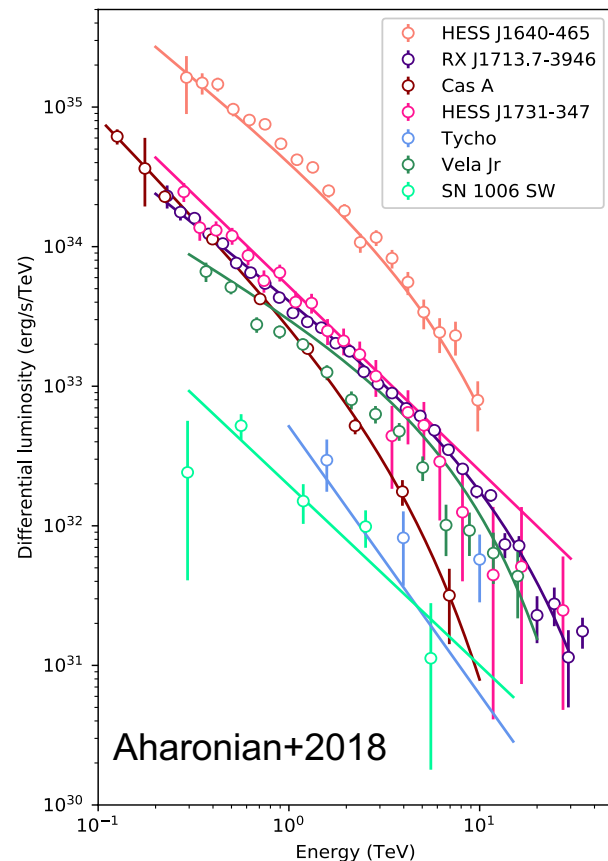


- non thermal dominated youngest SNR
- age ~ 150 -220 yr
- highest energy protons cannot propagate beyond several pc.
- $L_{\text{HESS}}(>1 \text{ TeV}) < 1e32 \text{ erg/s} \rightarrow W_{pp} < 10^{45} \text{ erg}$
- Shock speed 14000 km/s, Expected in Bohm regime synch peak at 20 keV instead only 1 keV - not efficient accelerator

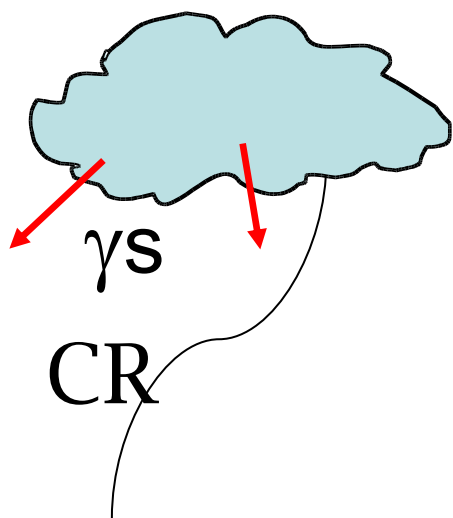
Sun, Yang, Aharonian, 2018

Spectra of young SNRs

- Cutoffs in the spectra of famous young SNRs at few TeVs. Particle acceleration proceeds up to 100 TeV. No indication of particle acceleration proceeding up to the knee
- SNRs thought to act as PeVatrons only during the early phases. Small chance to detect SNRs when they are PeVatrons. Maybe PeVatron gamma-ray signatures from nearby clouds illuminated by runaway CRs



PeVatron signatures from nearby molecular clouds

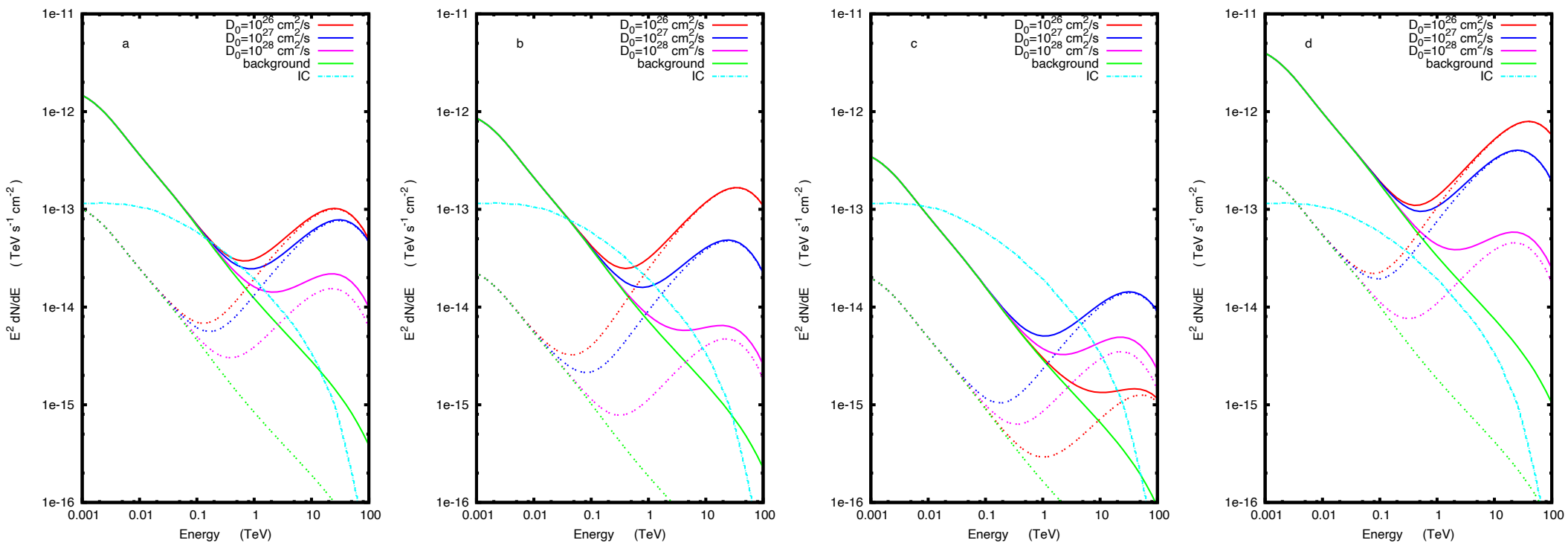


γ detections

mm/cm/IR detections

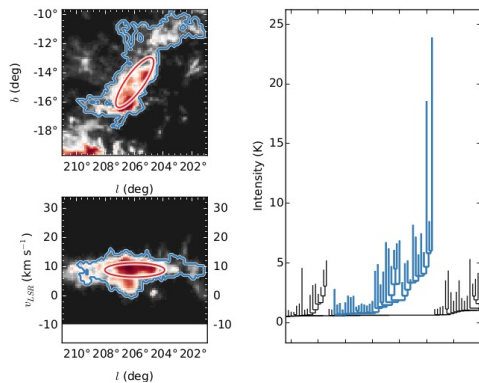
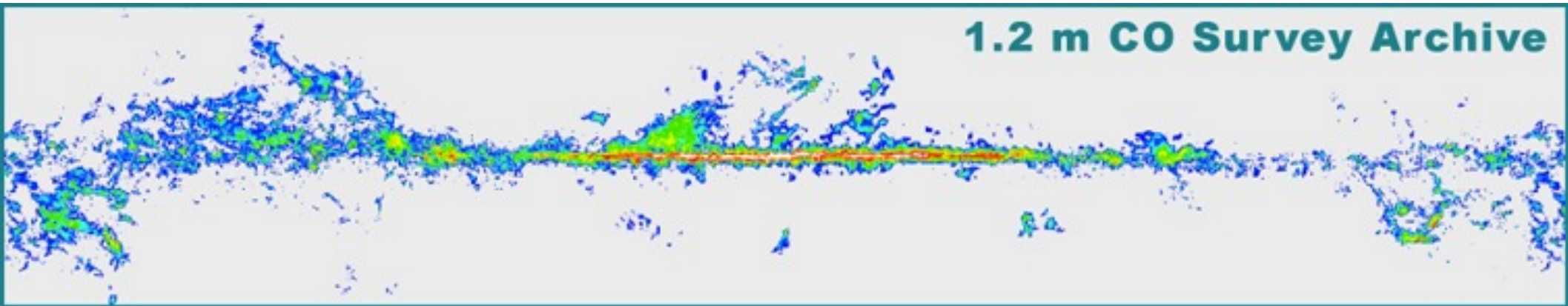
$$F_{\gamma}(E_{\gamma}) \propto c(\delta) \times N_{CR} E_{CR}^{-\delta} \left(\frac{M_{cl}}{d^2} \right)$$

Casanova+2010

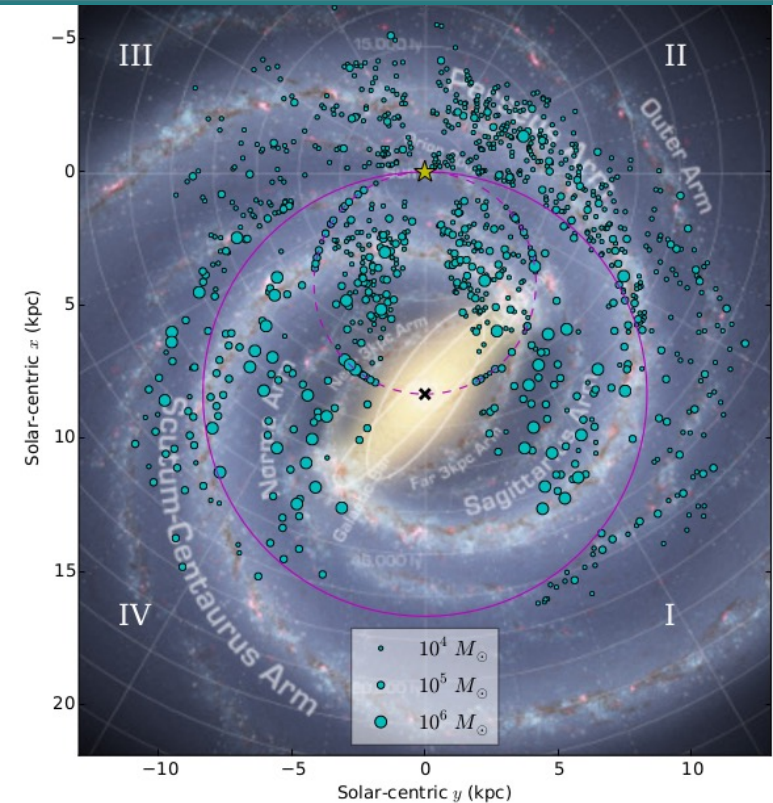
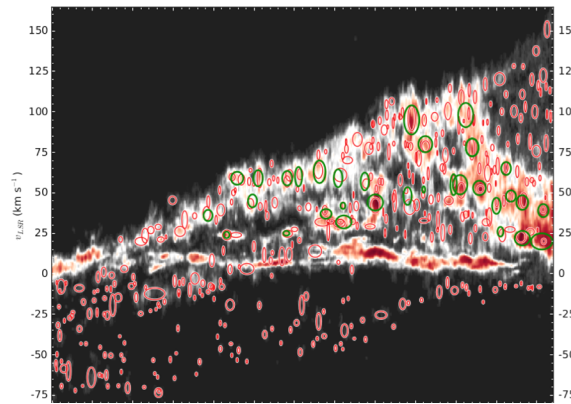
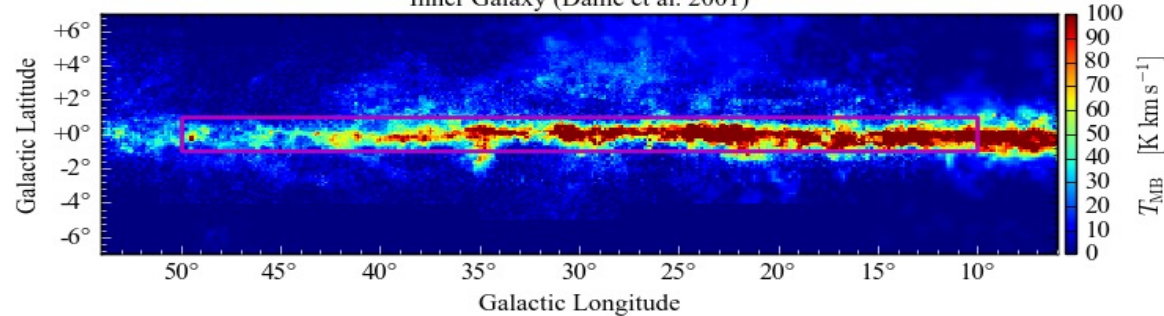


The CfA Survey of Molecular Gas

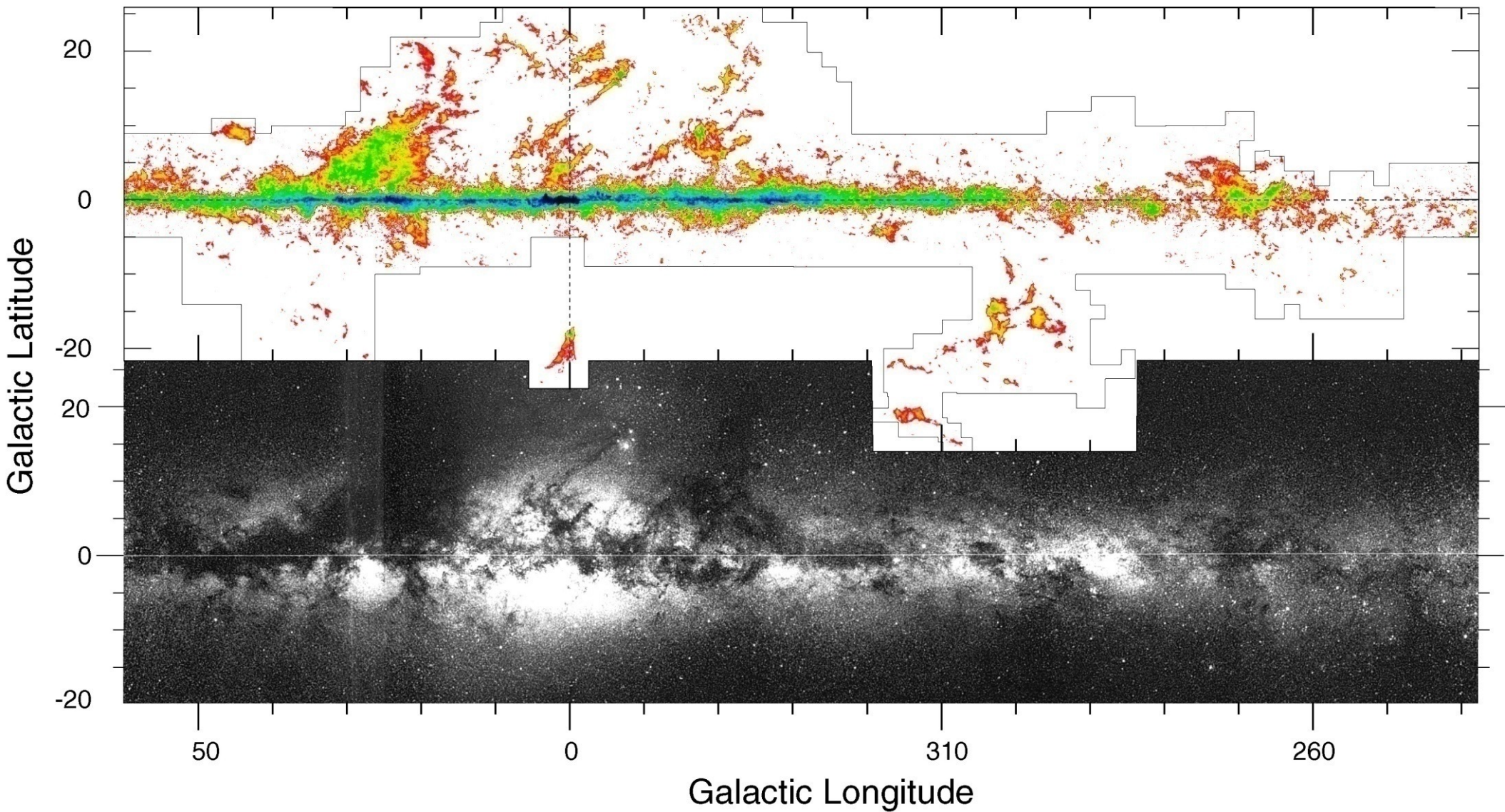
Dame+1987, Dame+2001, Rice+2016



Inner Galaxy (Dame et al. 2001)



The Milky Way in Molecular Clouds (Nanten survey)

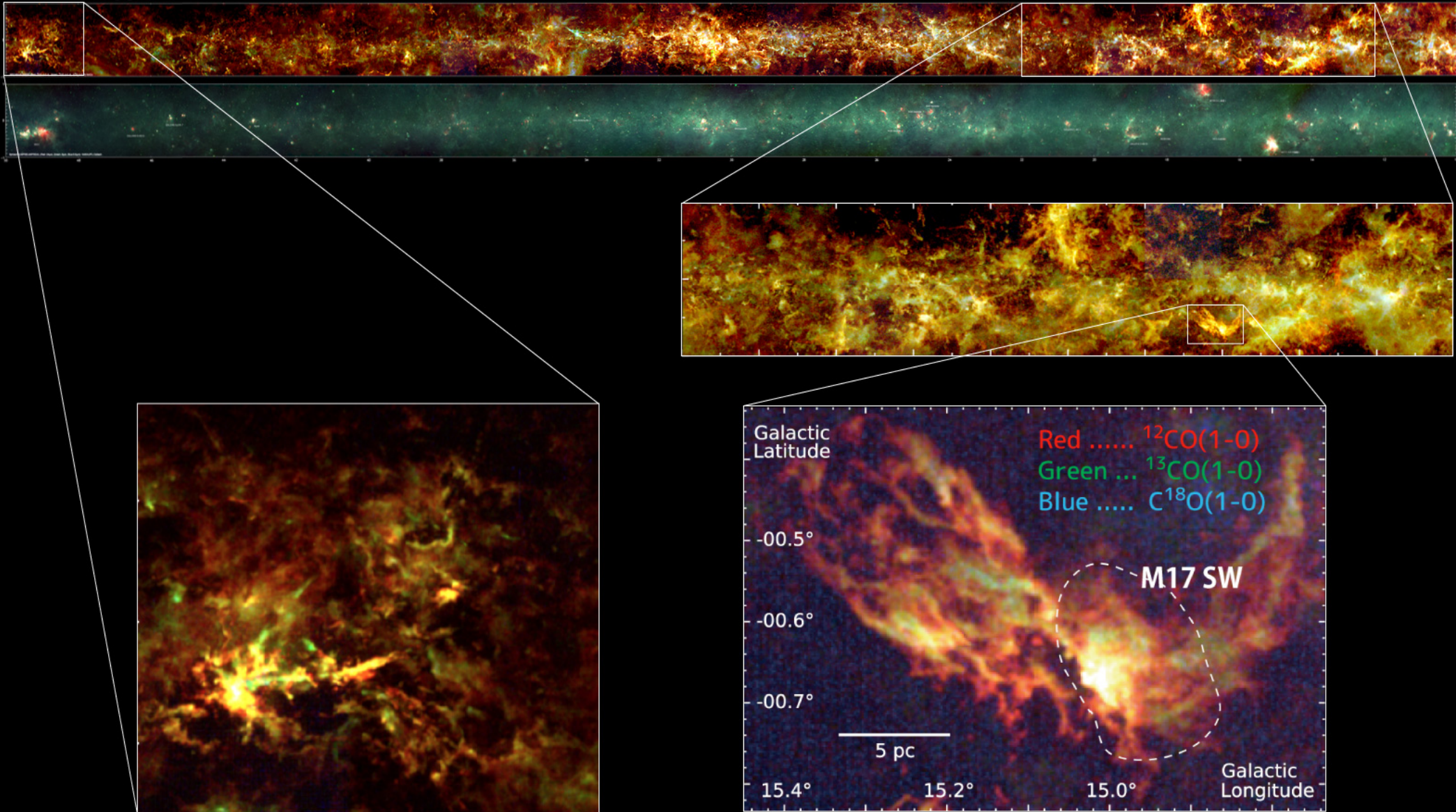


(courtesy: Y. Fukui)

写真：EXPLORING THE SOUTHERN SKY (1988)

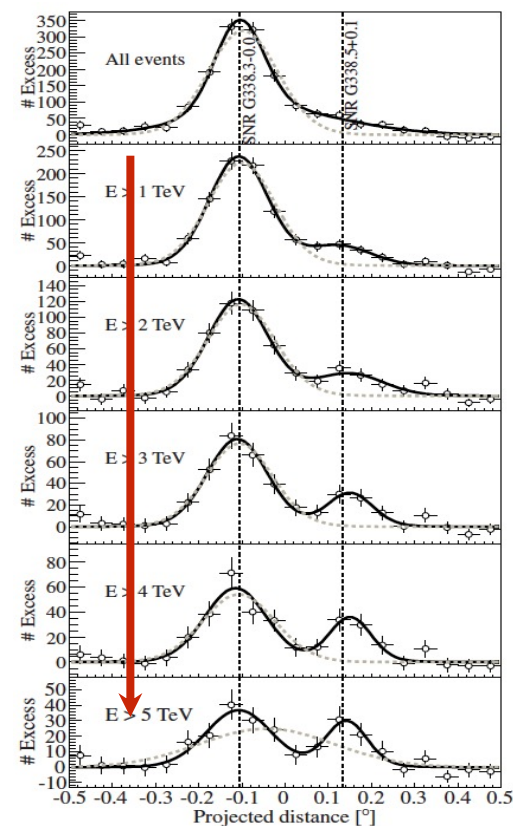
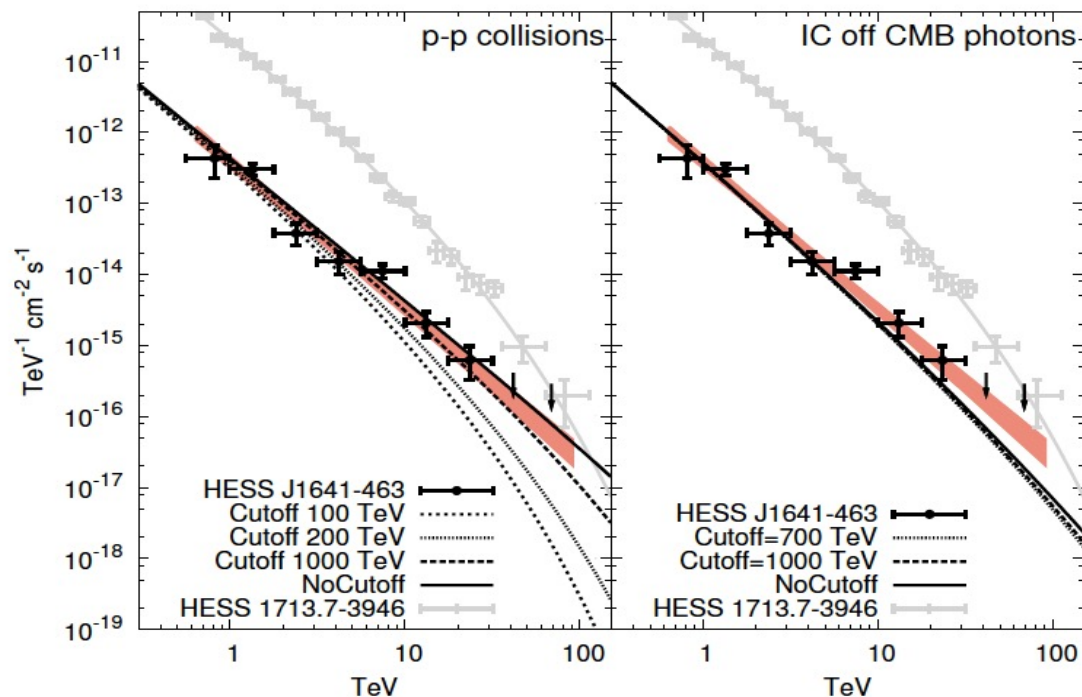
FUGIN

風神 FUGIN FOREST Unbiased Galactic plane Imaging survey with Nobeyama 45-m telescope

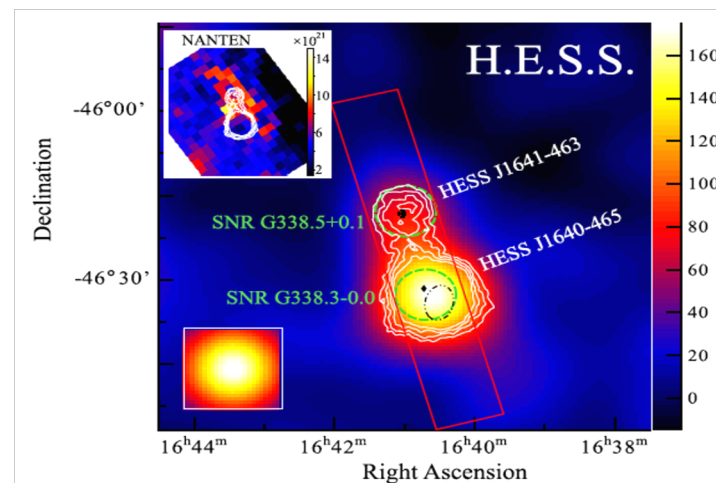


PeV particles illuminating a MC ?

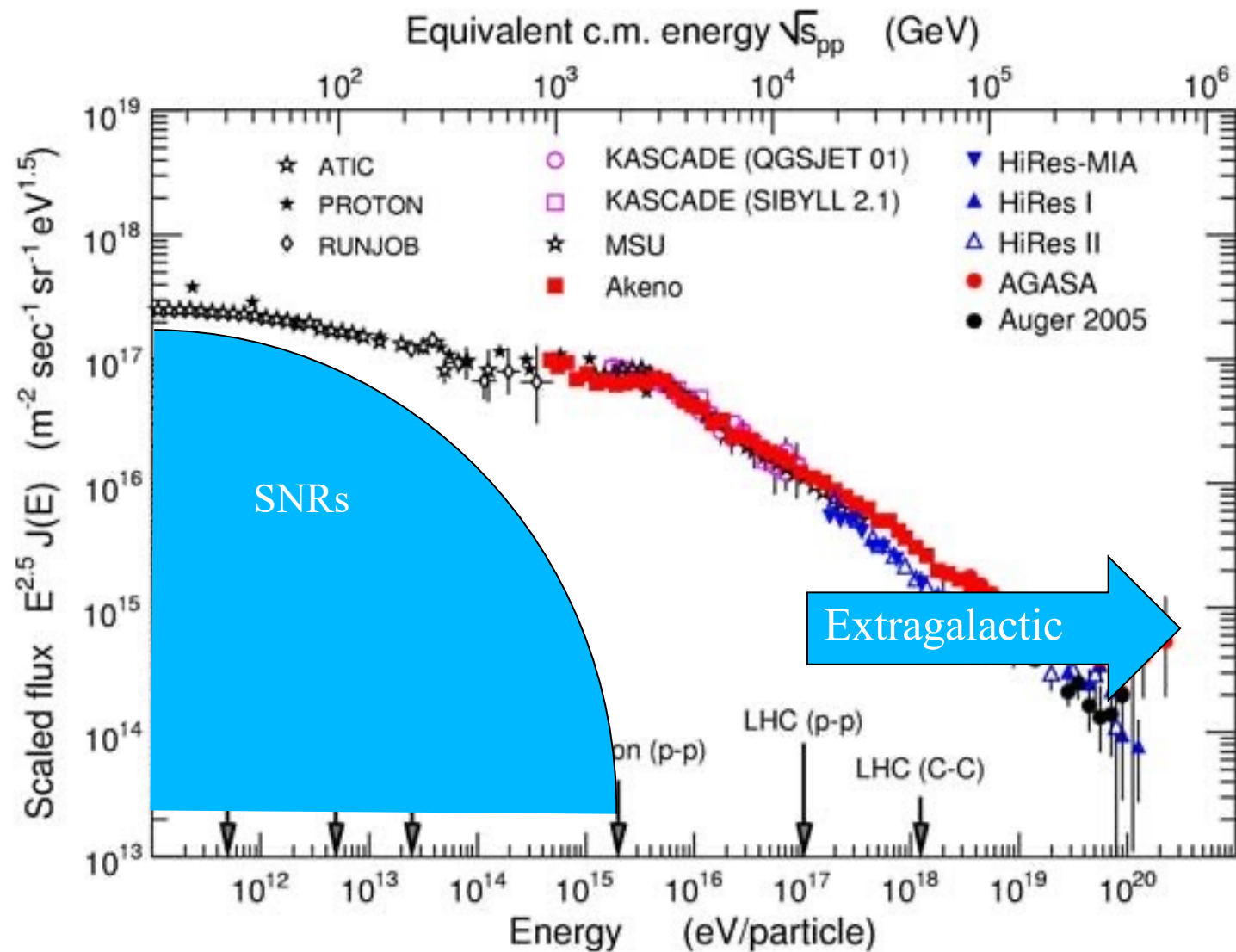
HESS Collaboration 2014



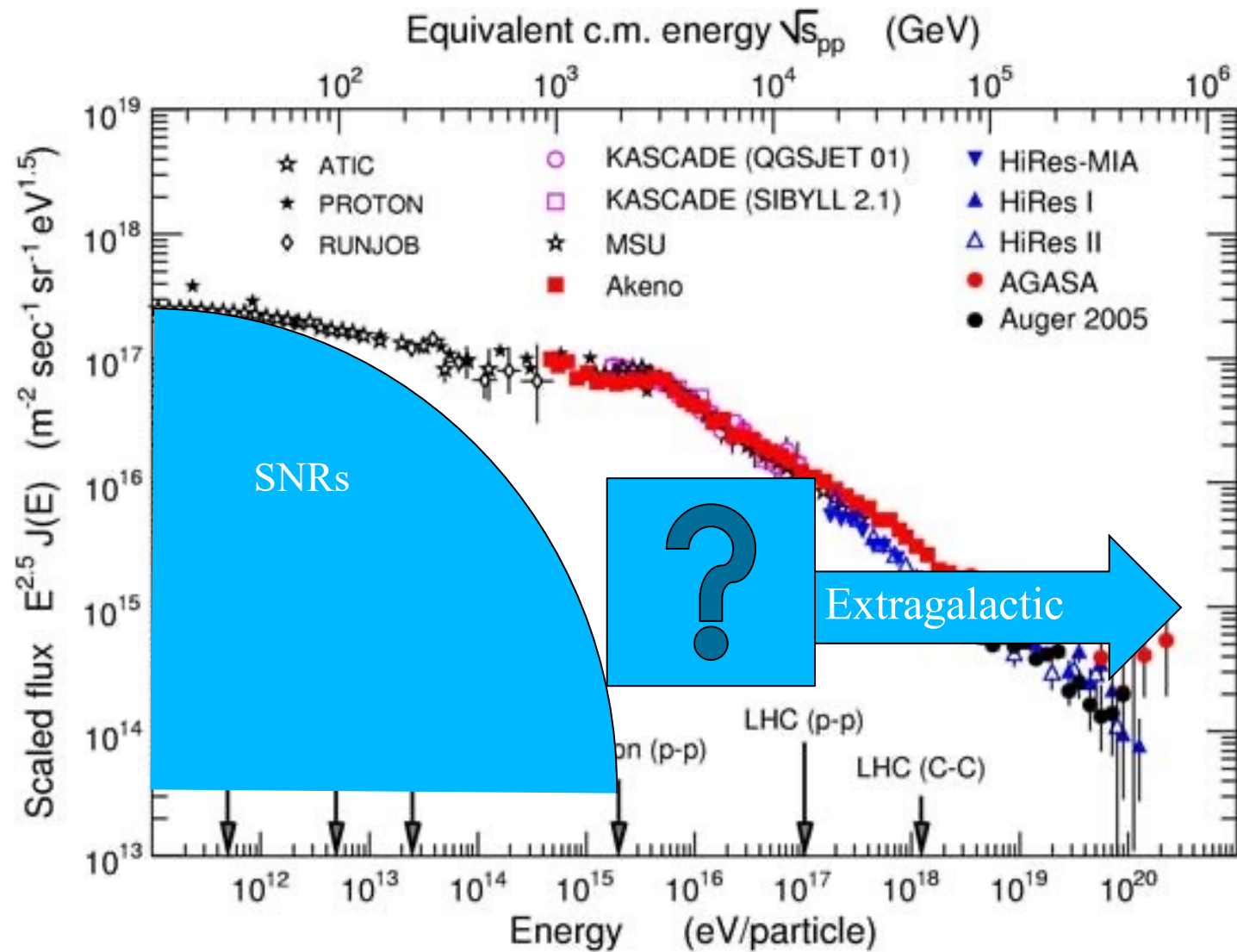
- Very hard spectrum, index 2.07
- No preference for a cutoff
- Lower limit on proton cutoff :100 TeV
- $W_{pp} = 10^{50} \text{ n}^{-1} \text{ erg}$
- Leptonic scenario $\rightarrow E_{\text{cut}} = 700 \text{ TeV}$
- Runaway CRs from HESS J1640-465



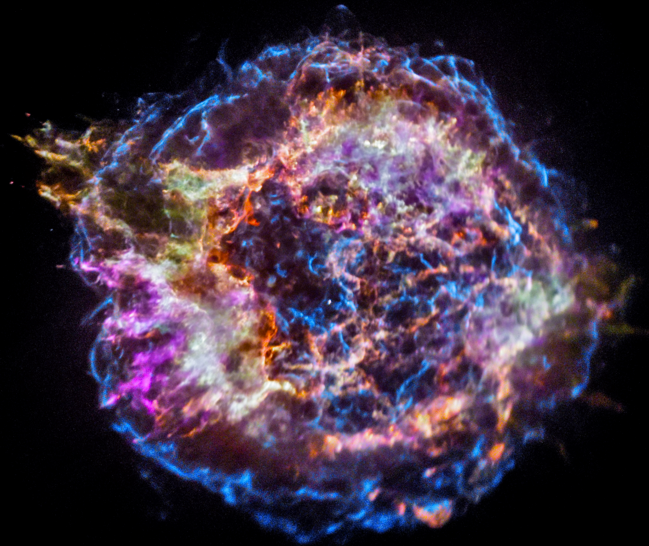
The Cosmic Ray Spectrum at Earth



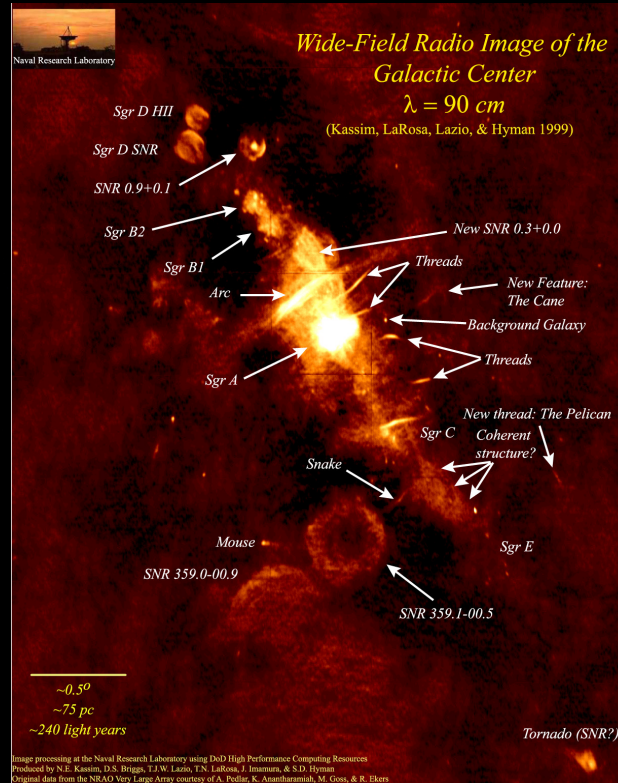
The Cosmic Ray Spectrum at Earth



PeVatron Candidate Source Classes



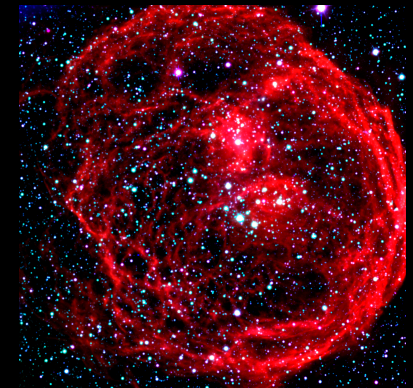
Young SNRs



Galactic Centre

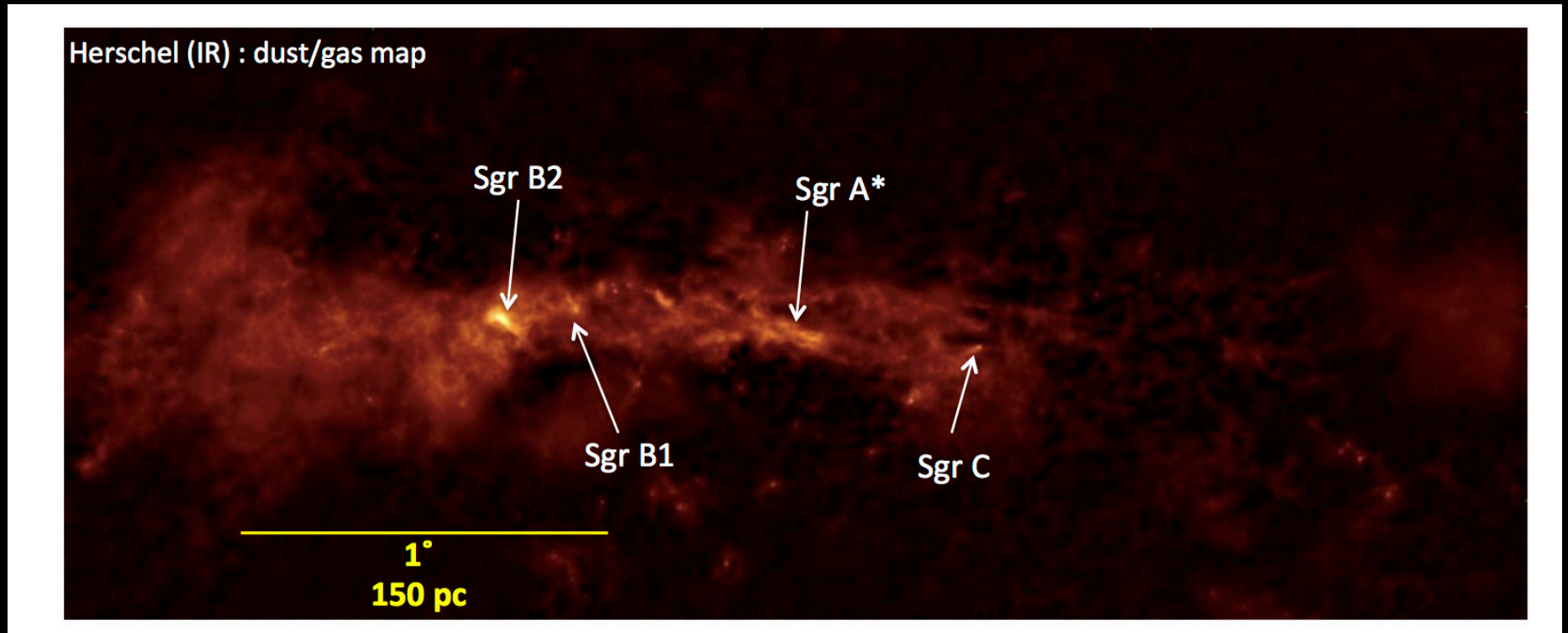


Stellar clusters

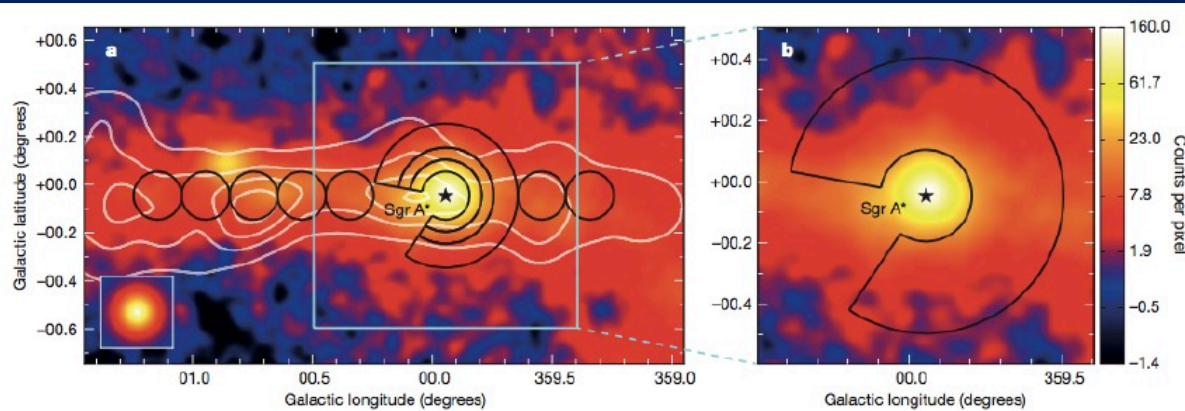


Superbubbles

The Central Molecular Zone (containing 10% of the Galactic gas)



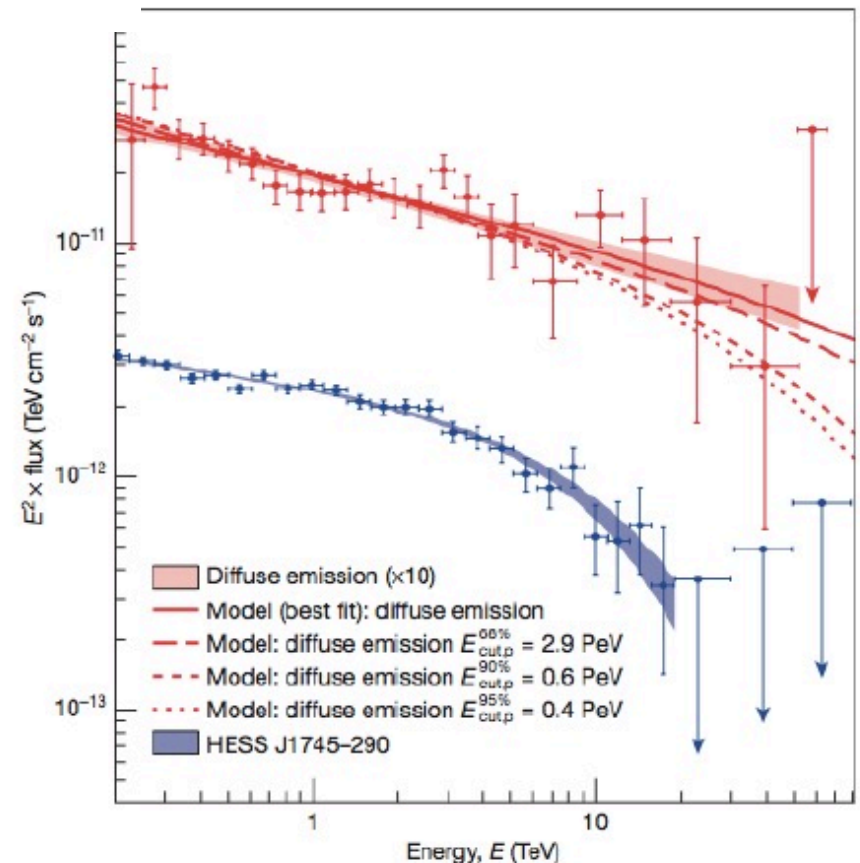
GC PeVatron : Spectral Studies with H.E.S.S.



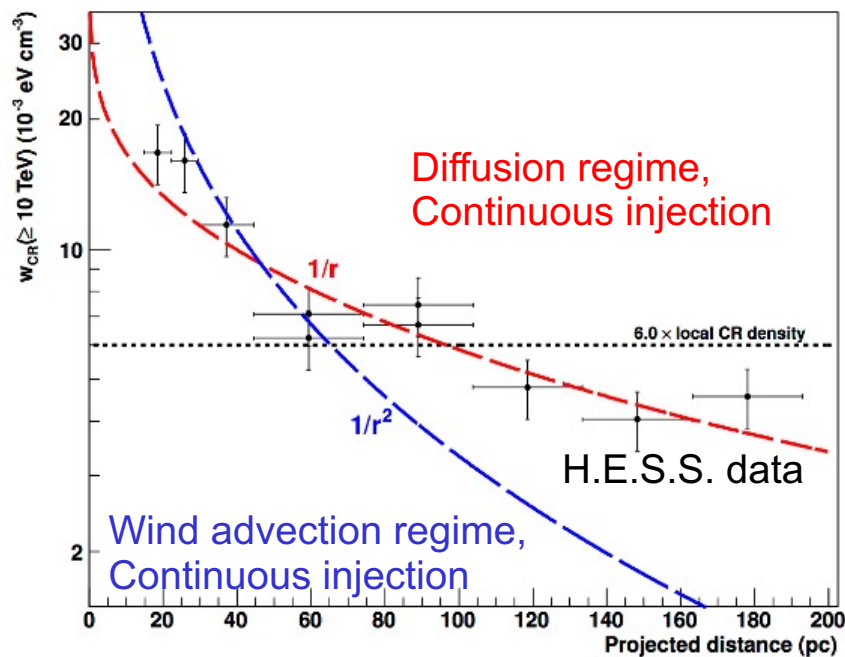
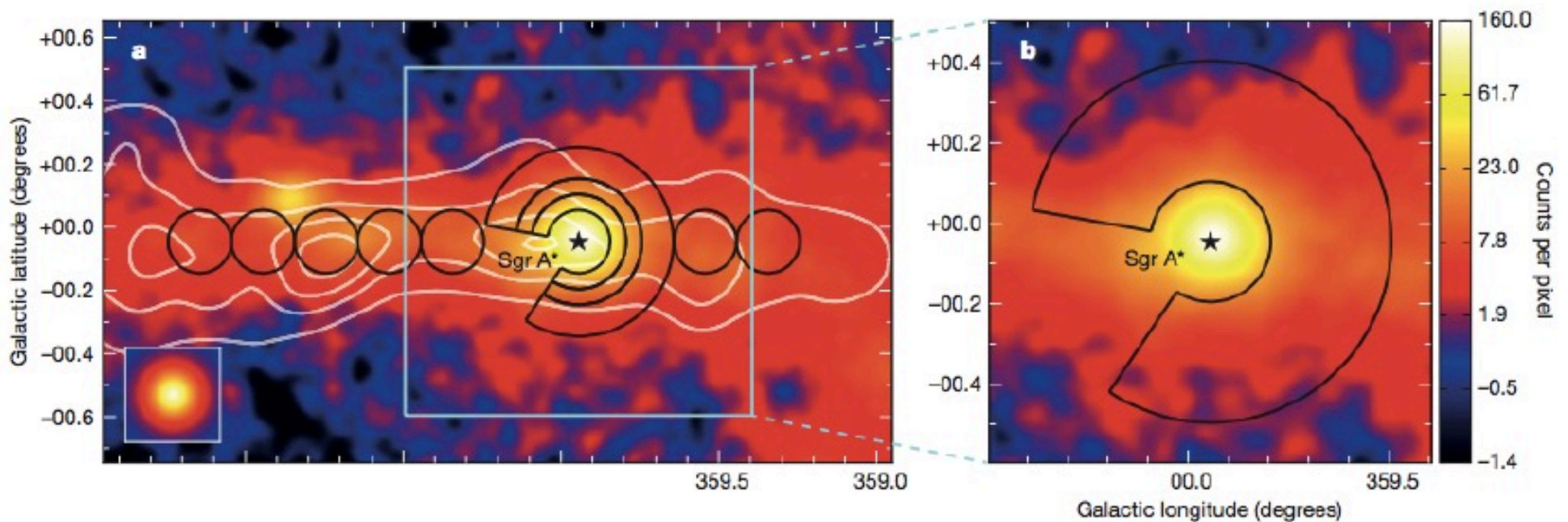
HESS Coll, Nature2016

Point-like, central source on top of extended (ridge) emission

- Central point source: cut-off @ 10 TeV
- Diffuse emission shows no cut-off well > 10 TeV
- Origin of diffuse emission:
 - Interaction of CR (from central BH) with interstellar medium ?
 - CR acceleration in CMZ (and in particular star forming regions) ?



GC PeVatron : Morphological studies



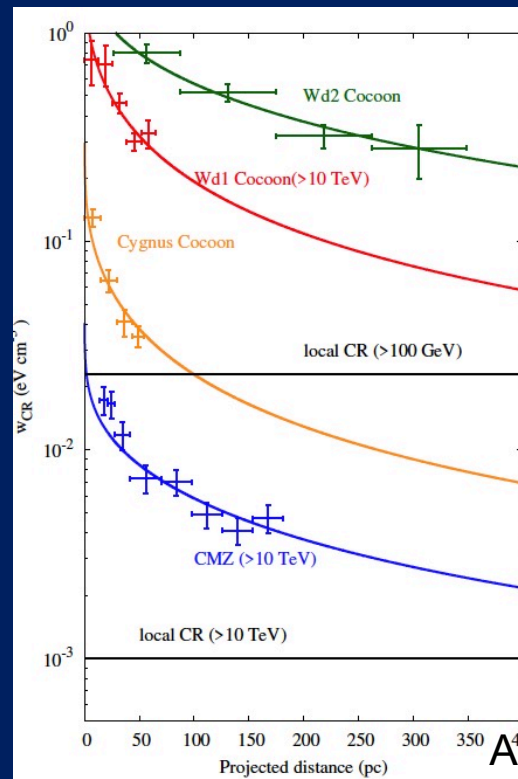
- Emission profile consistent with propagation of protons accelerated continuously from a region $< 10 \text{ pc}$ from GC
- Current bolometric lum of Sgr A* is 100-1000 times less than required to support CR population. PeVatron more powerful in the past ? Other PeVatrons in the Galaxy ?

Young Stellar Clusters

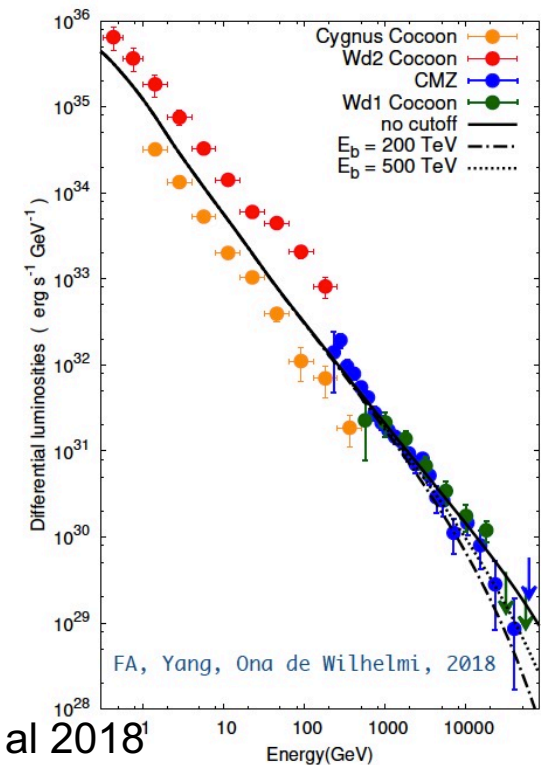
Extended gamma-ray emissions around young star clusters (50 ~ 200 pc). Gamma-ray luminosity $\sim 1e36$ erg/s.

Each source has hard spectrum ~ 2.2 , without cutoff

CR distribution derived by gamma-ray profile and gas distributions. $1/r$ profile implies a continuous injection in the lifetime of clusters

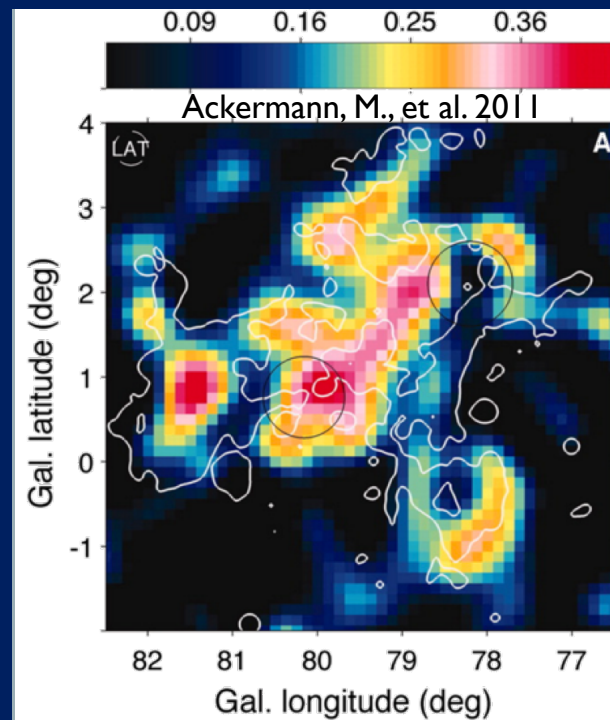
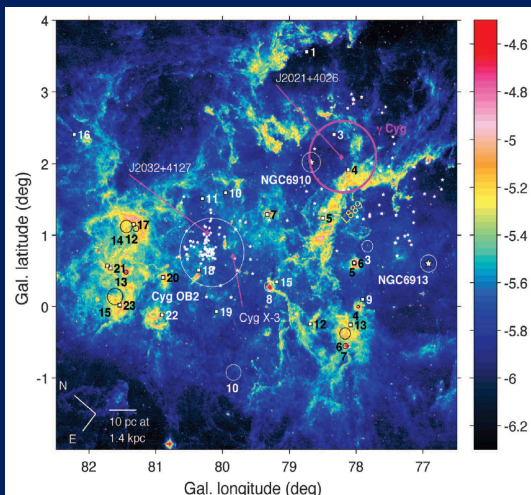


Anahorian et al 2018¹



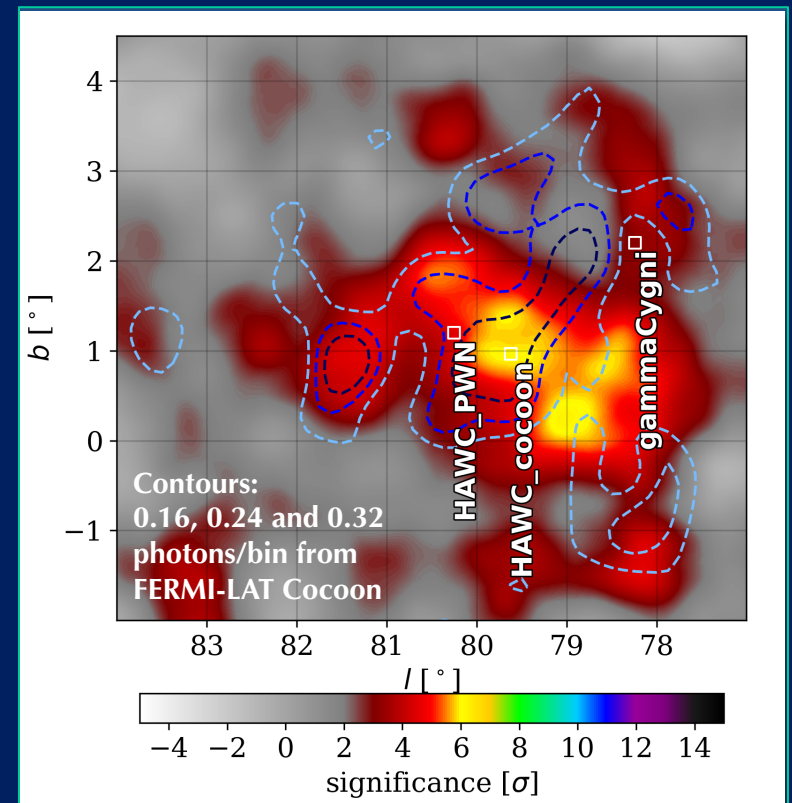
FA, Yang, Ona de Wilhelmi, 2018

Fermi - Argo - HAWC-LHAASO cocoon



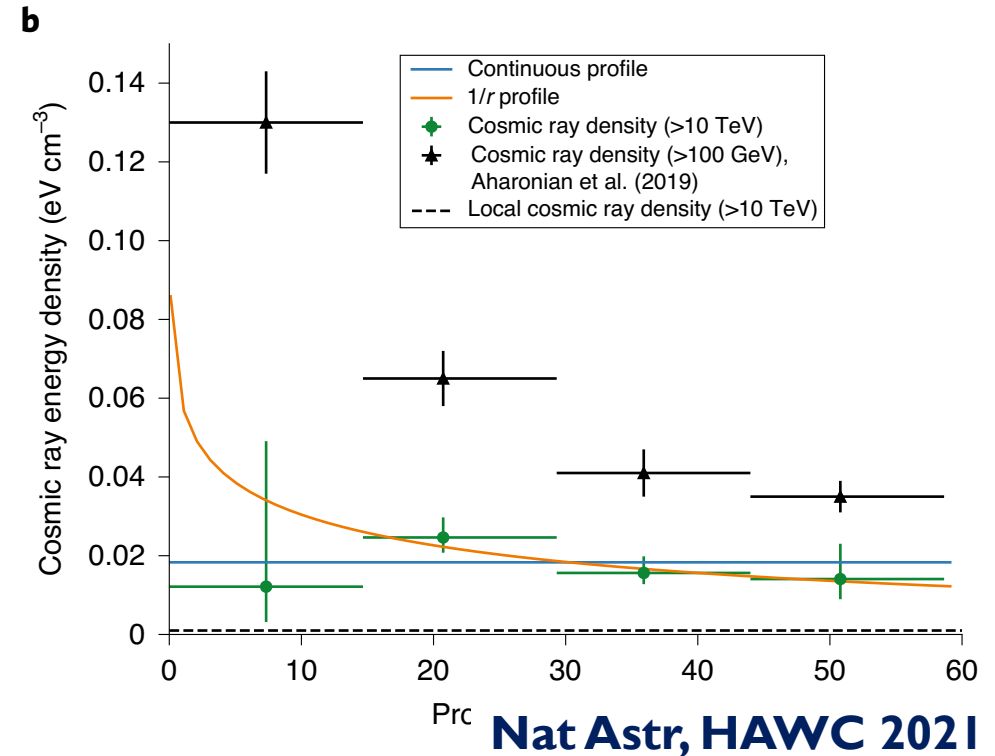
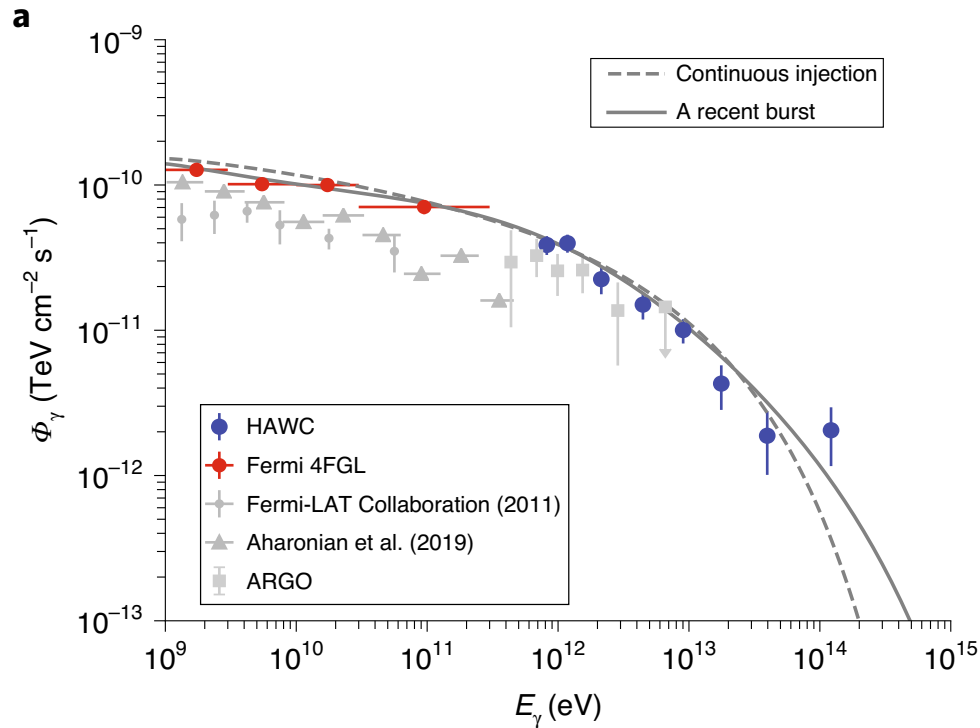
Fermi detected hard and extended emission from Cygnus X, between OB2 and Gamma Cygni SNR

HAWC significance map of the Cygnus Cocoon



HAWC Coll, NatAstr 2021

Cocoon Spectrum and morphology



Unique SFR seen from GeV to PeV energies

Spectral break with respect to Fermi datapoints

CR density > 10 TeV higher than local CR in the whole region

1/r profile would suggest a continuous injection. A constant profile would suggest a recent burst event happened less than 0.1 Myr

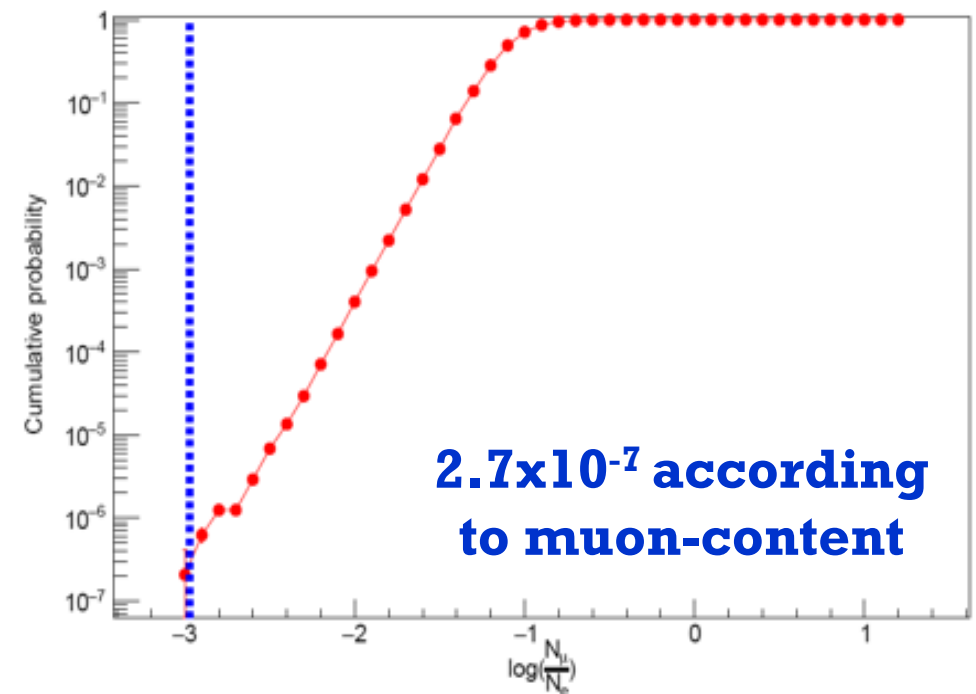
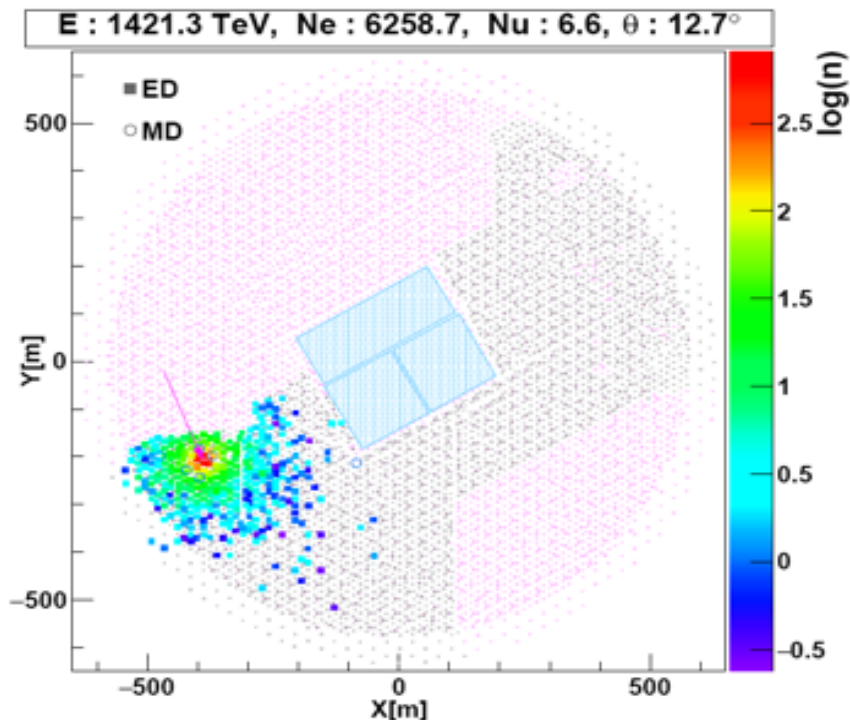
10000 CygOB2 would be required for CRs Galactic population

Highest energy photon



中国科学技术大学
University of Science and Technology of China

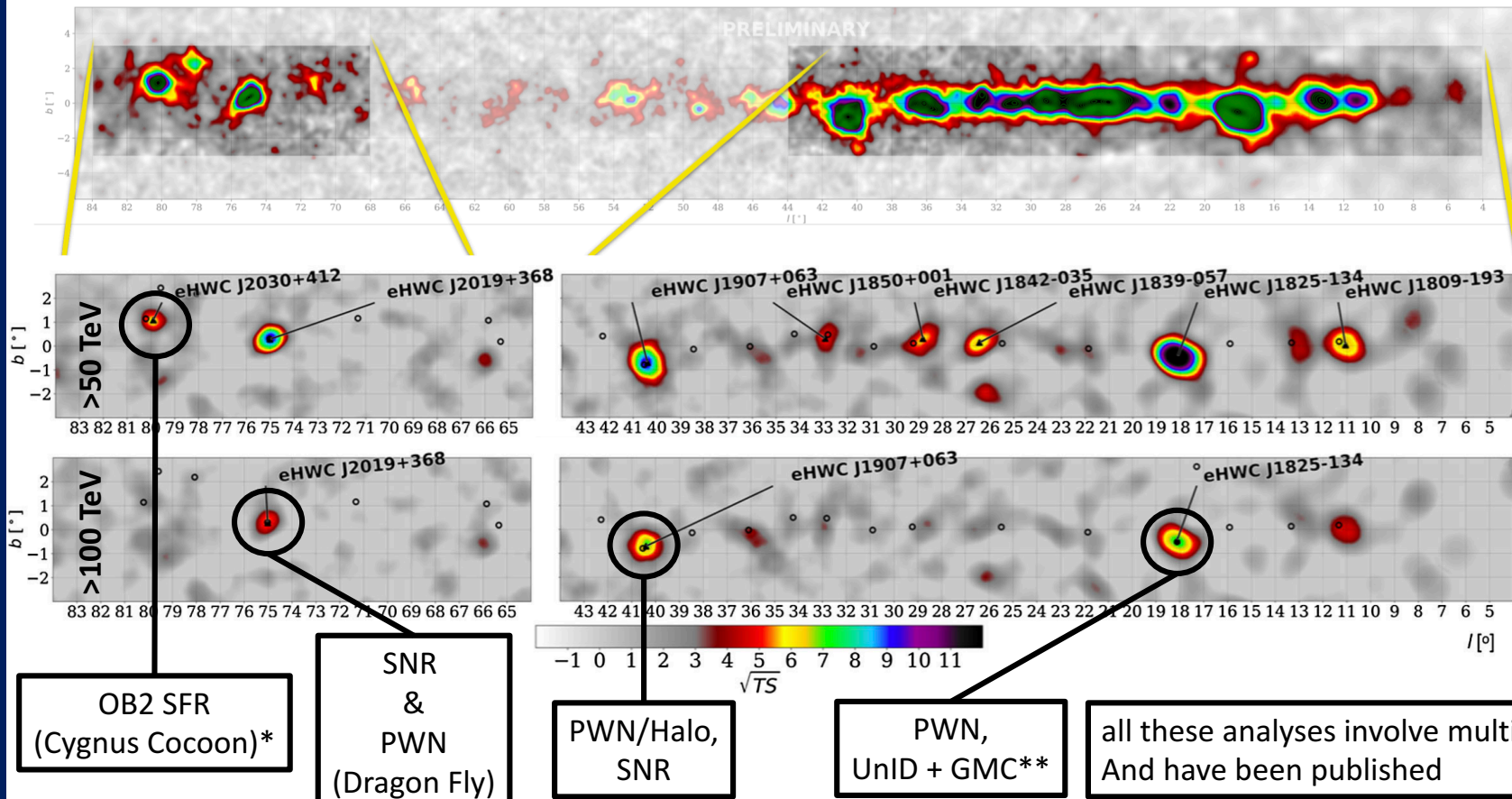
- 1.42 ± 0.13 PeV from the Cygnus region
- Chance probability due to cosmic ray background 0.028%.



Nature 594:33-36 (2021)

Slide by Ruizhi Yang

HAWC survey for Galactic PeVatrons

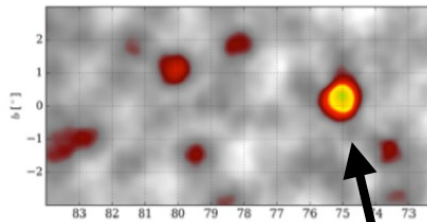


PRL 124, 021102 (2020)

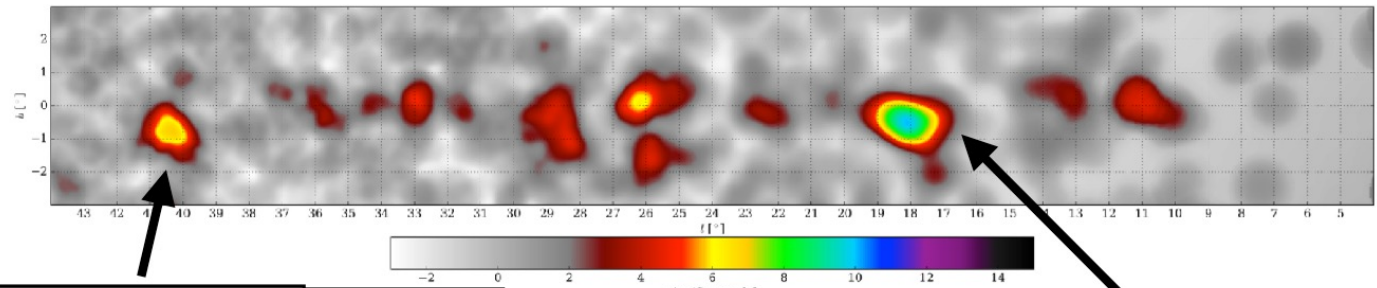
The Galaxy above 56 TeV

Source name	RA (°)	Dec (°)	Extension > 56 TeV (°)	F (10^{-14} ph cm $^{-2}$ s $^{-1}$)	$\sqrt{TS} >$ 56 TeV	nearest 2HWC source	Distance to 2HWC source(°)	$\sqrt{TS} >$ 100 TeV
eHWC J0534+220	83.61 $\pm$ 0.02	22.00 $\pm$ 0.03	PS	1.2 $\pm$ 0.2	12.0	J0534+220	0.02	4.44
eHWC J1809-193	272.46 $\pm$ 0.13	-19.34 $\pm$ 0.14	0.34 $\pm$ 0.13	2.4 $^{+0.6}_{-0.5}$	6.97	J1809-190	0.30	4.82
eHWC J1825-134	276.40 $\pm$ 0.06	-13.37 $\pm$ 0.06	0.36 $\pm$ 0.05	4.6 $\pm$ 0.5	14.5	J1825-134	0.07	7.33
eHWC J1839-057	279.77 $\pm$ 0.12	-5.71 $\pm$ 0.10	0.34 $\pm$ 0.08	1.5 $\pm$ 0.3	7.03	J1837-065	0.96	3.06
eHWC J1842-035	280.72 $\pm$ 0.15	-3.51 $\pm$ 0.11	0.39 $\pm$ 0.09	1.5 $\pm$ 0.3	6.63	J1844-032	0.44	2.70
eHWC J1850+001	282.59 $\pm$ 0.21	0.14 $\pm$ 0.12	0.37 $\pm$ 0.16	1.1 $^{+0.3}_{-0.2}$	5.31	J1849+001	0.20	3.04
eHWC J1907+063	286.91 $\pm$ 0.10	6.32 $\pm$ 0.09	0.52 $\pm$ 0.09	2.8 $\pm$ 0.4	10.4	J1908+063	0.16	7.30
eHWC J2019+368	304.95 $\pm$ 0.07	36.78 $\pm$ 0.04	0.20 $\pm$ 0.05	1.6 $^{+0.3}_{-0.2}$	10.2	J2019+367	0.02	4.85
eHWC J2030+412	307.74 $\pm$ 0.09	41.23 $\pm$ 0.07	0.18 $\pm$ 0.06	0.9 $\pm$ 0.2	6.43	J2031+415	0.34	3.07

Galactic Plane, > 56 TeV (0.5 degree extended source assumed)



MGRO 2019+371



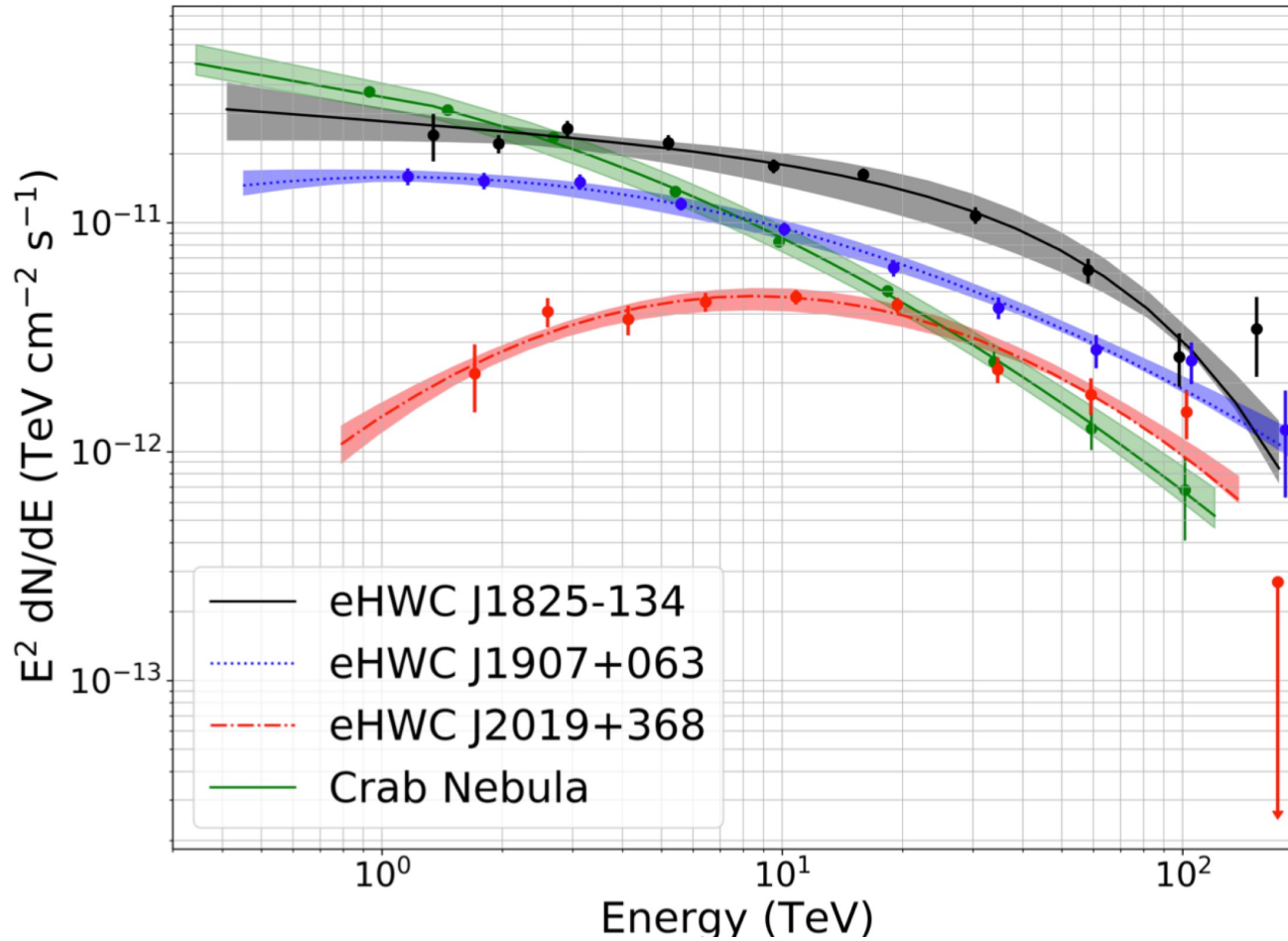
MGRO 1908+06

HESS J1825+137
HESS J1826-130

HAWC Collaboration+20

The Galaxy above 100 TeV: Spectra

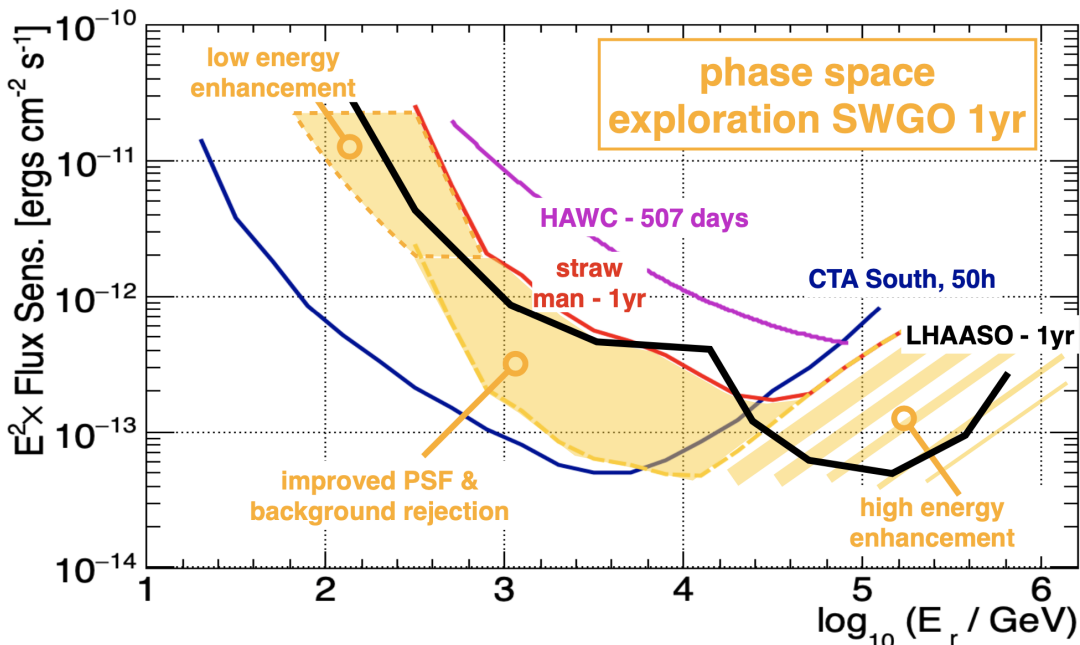
HAWC Collaboration+20



Source	$\sqrt{TS}$	Extension ($^{\circ}$)	$\phi_0 \text{ (} 10^{-13} \text{ TeV cm}^2 \text{ s)}^{-1}$	α	$E_{cut} \text{ (TeV)}$	PL diff
eHWC J1825-134	41.1	0.53 ± 0.02	2.12 ± 0.15	2.12 ± 0.06	61 ± 12	7.4
Source	$\sqrt{TS}$	Extension ($^{\circ}$)	$\phi_0 \text{ (} 10^{-13} \text{ TeV cm}^2 \text{ s)}^{-1}$	α	β	PL diff
eHWC J1907+063	37.8	0.67 ± 0.03	0.95 ± 0.05	2.46 ± 0.03	0.11 ± 0.02	6.0
eHWC J2019+368	32.2	0.30 ± 0.02	0.45 ± 0.03	2.08 ± 0.06	0.26 ± 0.05	8.2

Extrapolating the number of sources

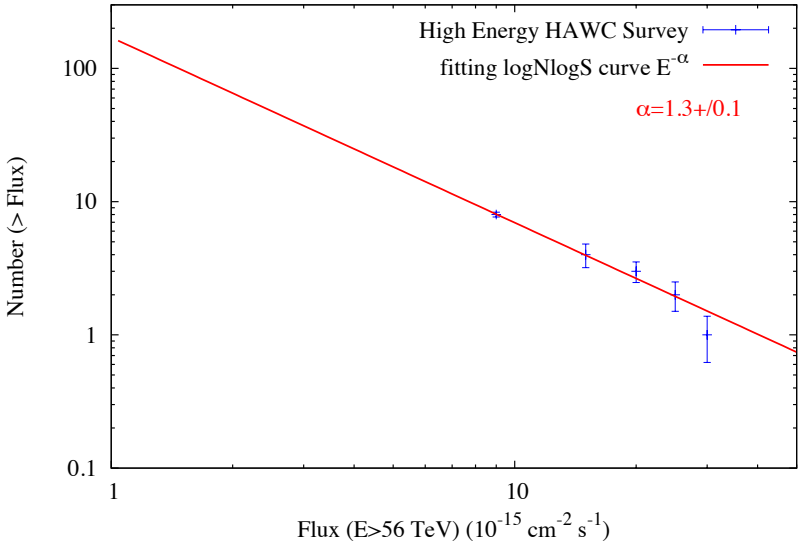
Schoorlemmer, for SWGO Coll 2021



Differential point source sensitivity of several experiments and the phase-space for the design studies for SWGO

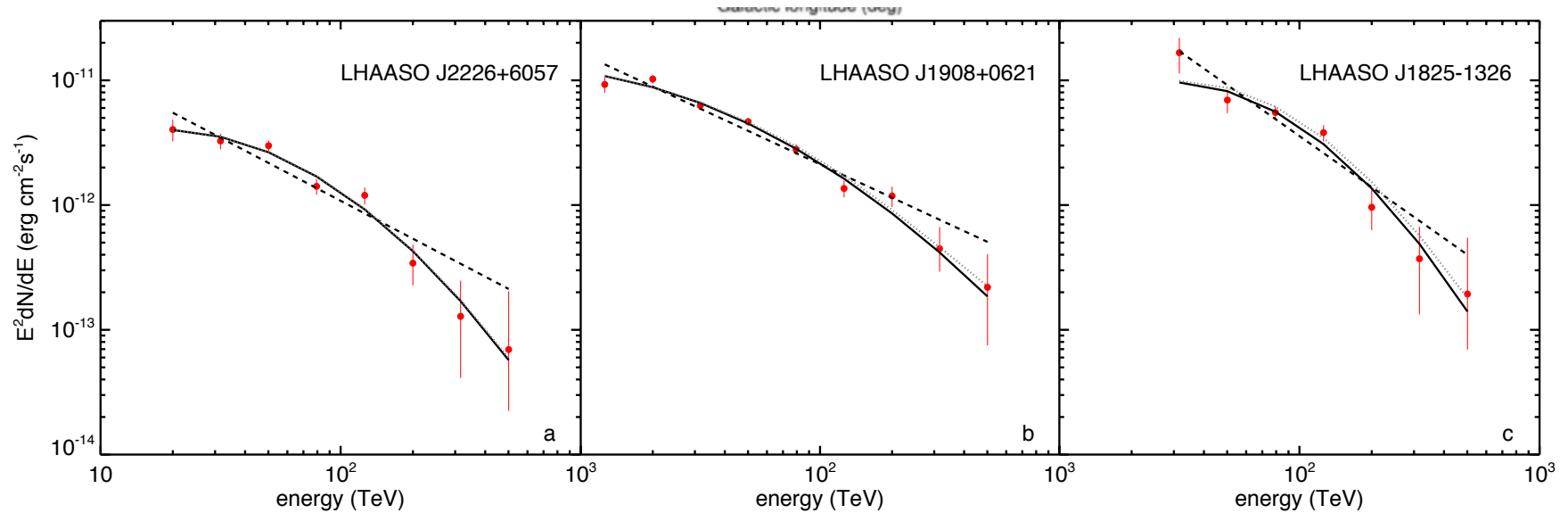
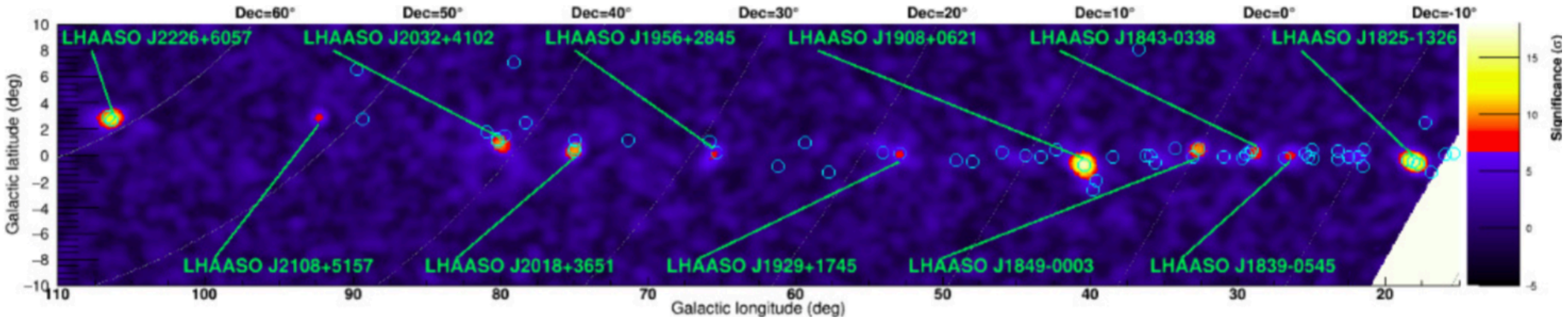
HAWC Collaboration+19

Source	F (10^{-14} ph cm $^{-2}$ s $^{-1}$)	$\sqrt{TS} > 56$ TeV	$\sqrt{TS} > 100$ TeV
eHWC J0534+220	$1.5^{+0.3}_{-0.2}$	11.7	4.27
eHWC J1809-193	$2.6^{+0.7}_{-0.6}$	6.76	4.69
eHWC J1825-134	$5.4^{+0.7}_{-0.6}$	14.0	7.35
eHWC J1839-057	$1.7^{+0.4}_{-0.3}$	6.63	3.03
eHWC J1842-035	$1.7^{+0.4}_{-0.3}$	6.06	2.52
eHWC J1850+001	$1.3^{+0.4}_{-0.3}$	5.18	3.09
eHWC J1907+063	$3.4^{+0.5}_{-0.4}$	10.3	7.17
eHWC J2019+368	1.9 ± 0.3	9.86	5.55
eHWC J2030+412	$1.1^{+0.3}_{-0.2}$	6.16	2.96



1 yr LHAASO Survey

LHAASO Coll Nature 2021



1 yr LHAASO Survey

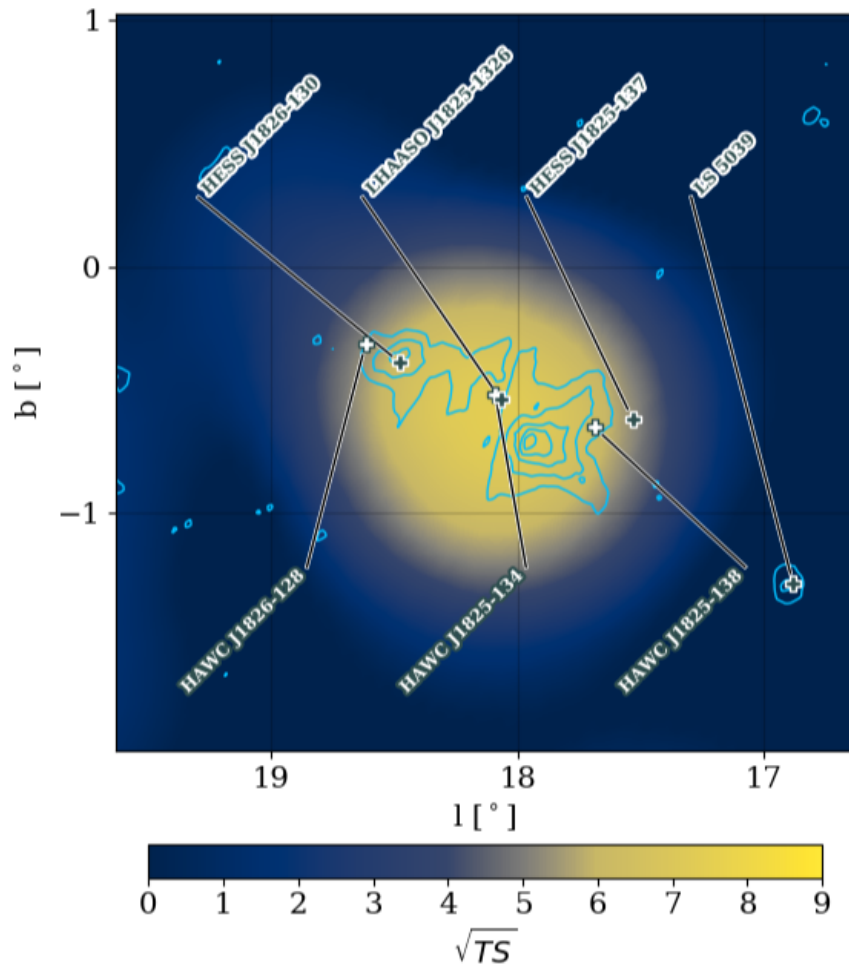
Table 1 | UHE γ -ray sources

Source name	RA (°)	dec. (°)	Significance above 100 TeV ($\times\sigma$)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	-13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	-5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	-3.65	8.5	$0.26 - 0.10^{+0.16}$	0.73(0.17)
LHAASO J1849-0003	282.35	-0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71 - 0.07^{+0.16}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)

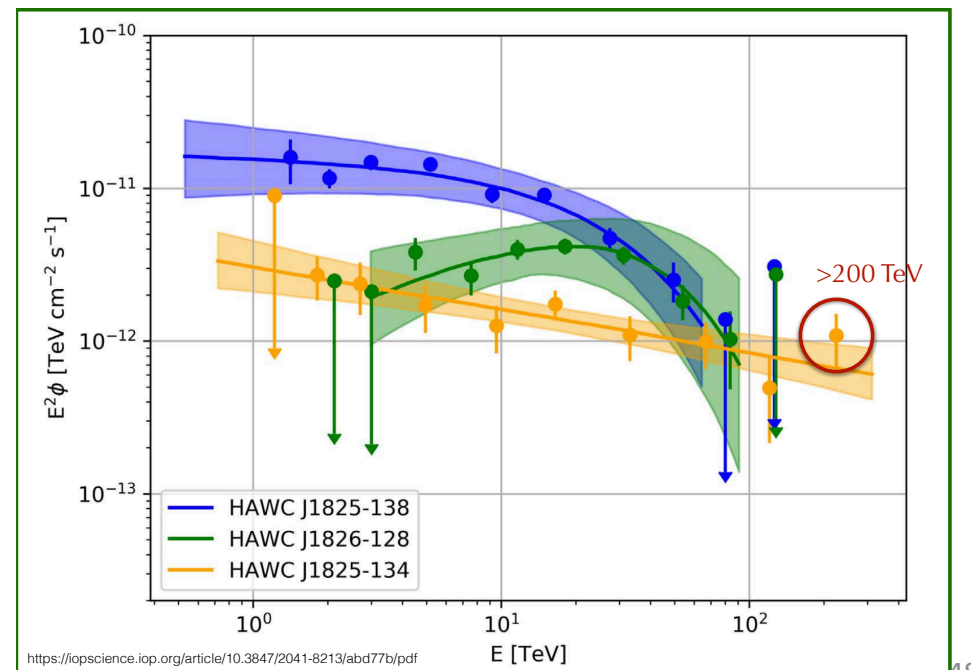
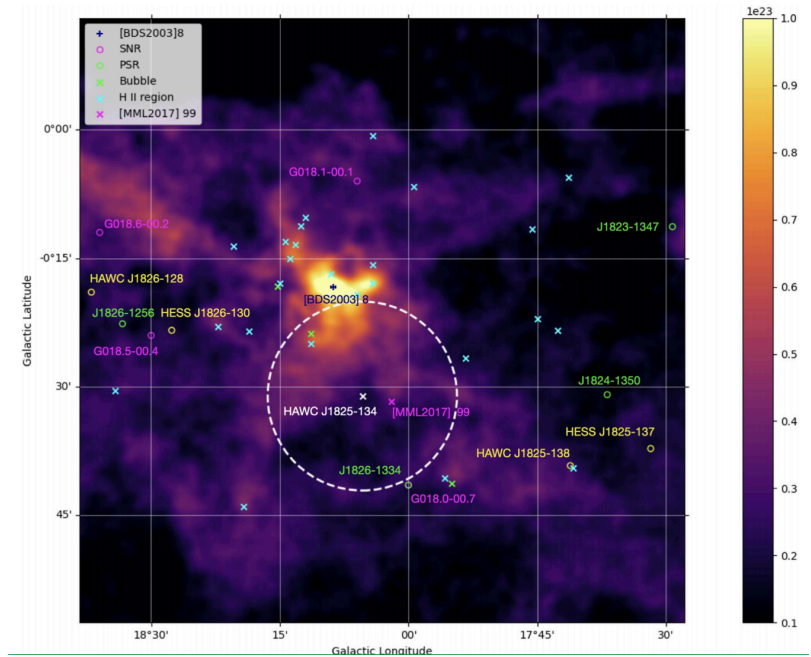
LHAASO Coll Nature 2021

HAWC J1825-134

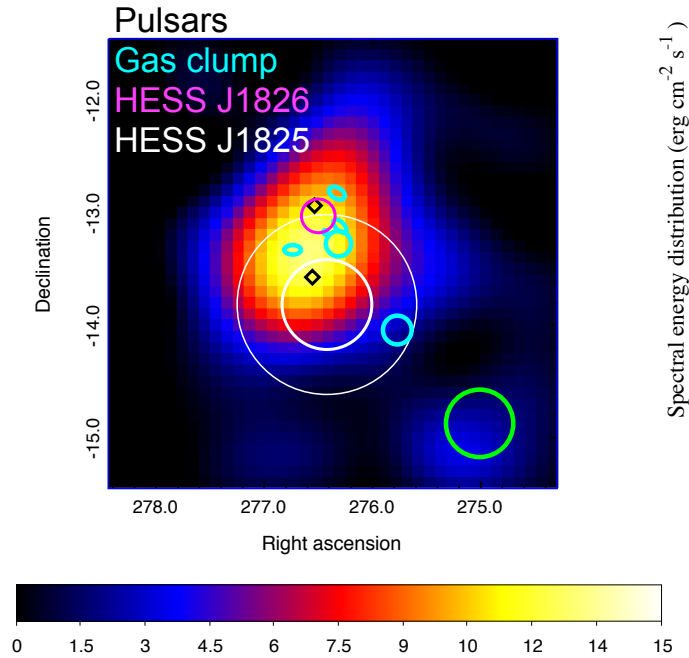
HAWC Coll ApJL 2021



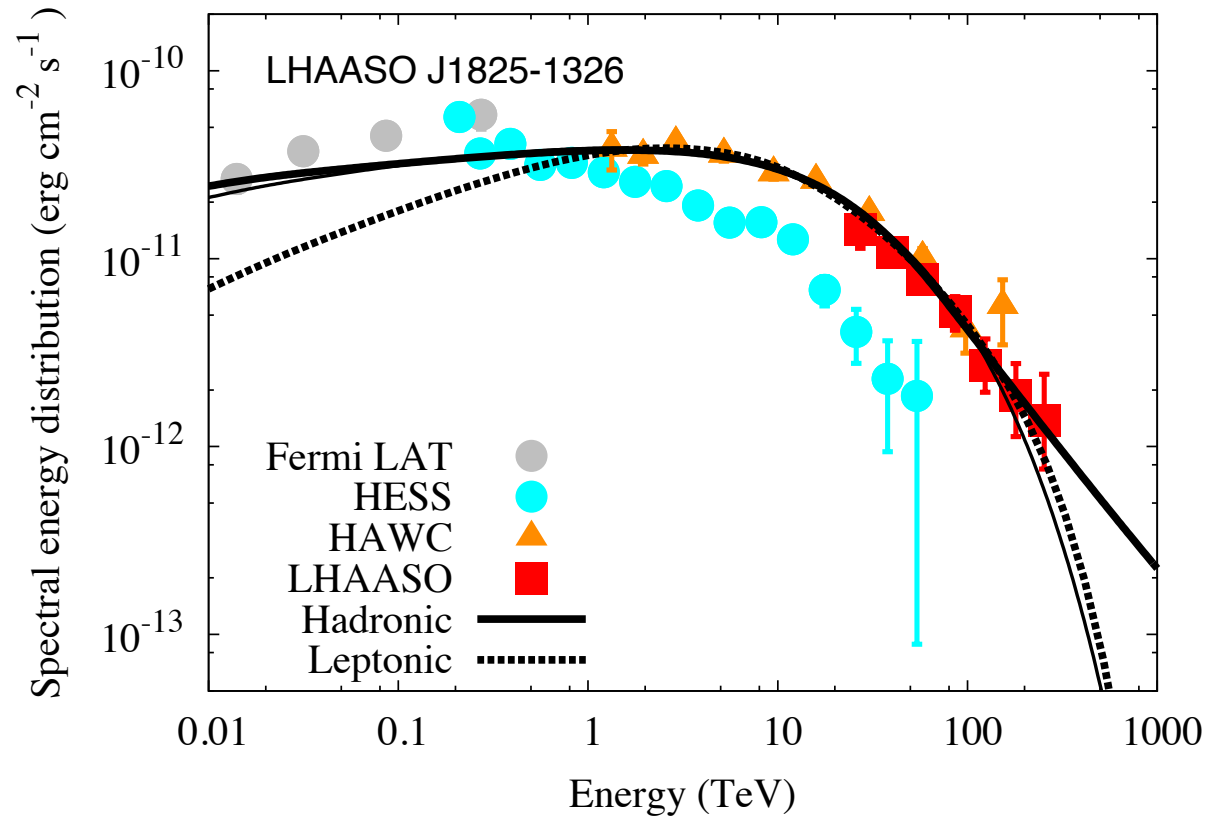
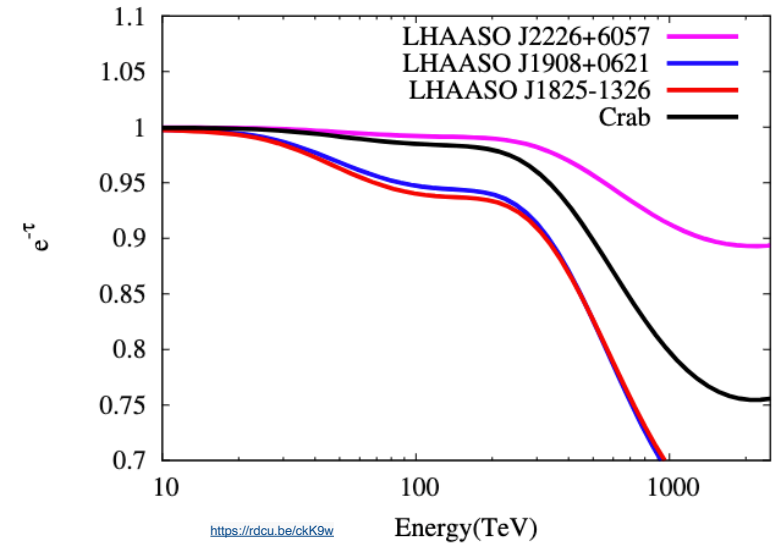
Above 177 TeV



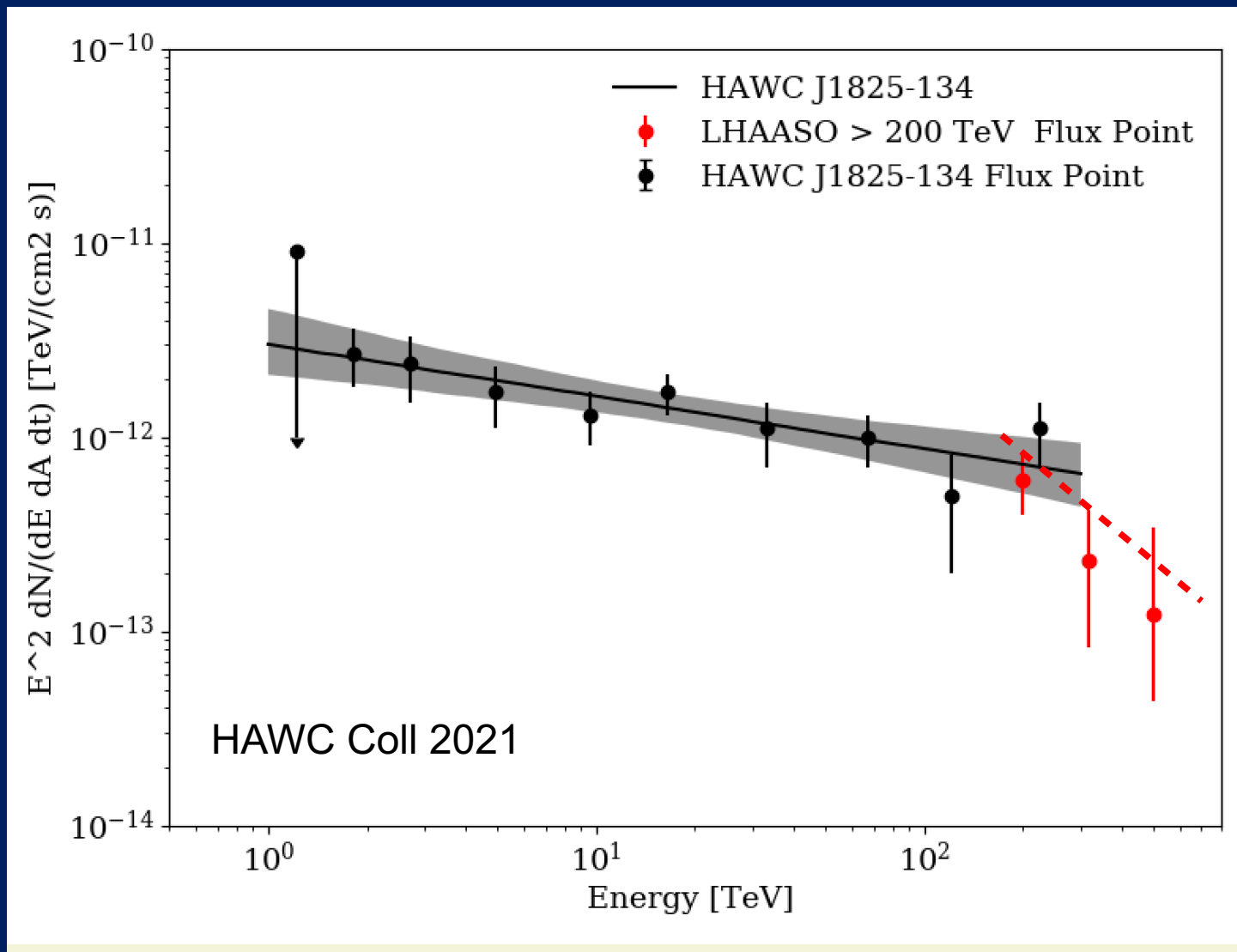
LHAASO J1825-1326



LHAASO Coll Nature 2021



HAWC J1825-134 and LHAASO J1825-136 above 200 TeV

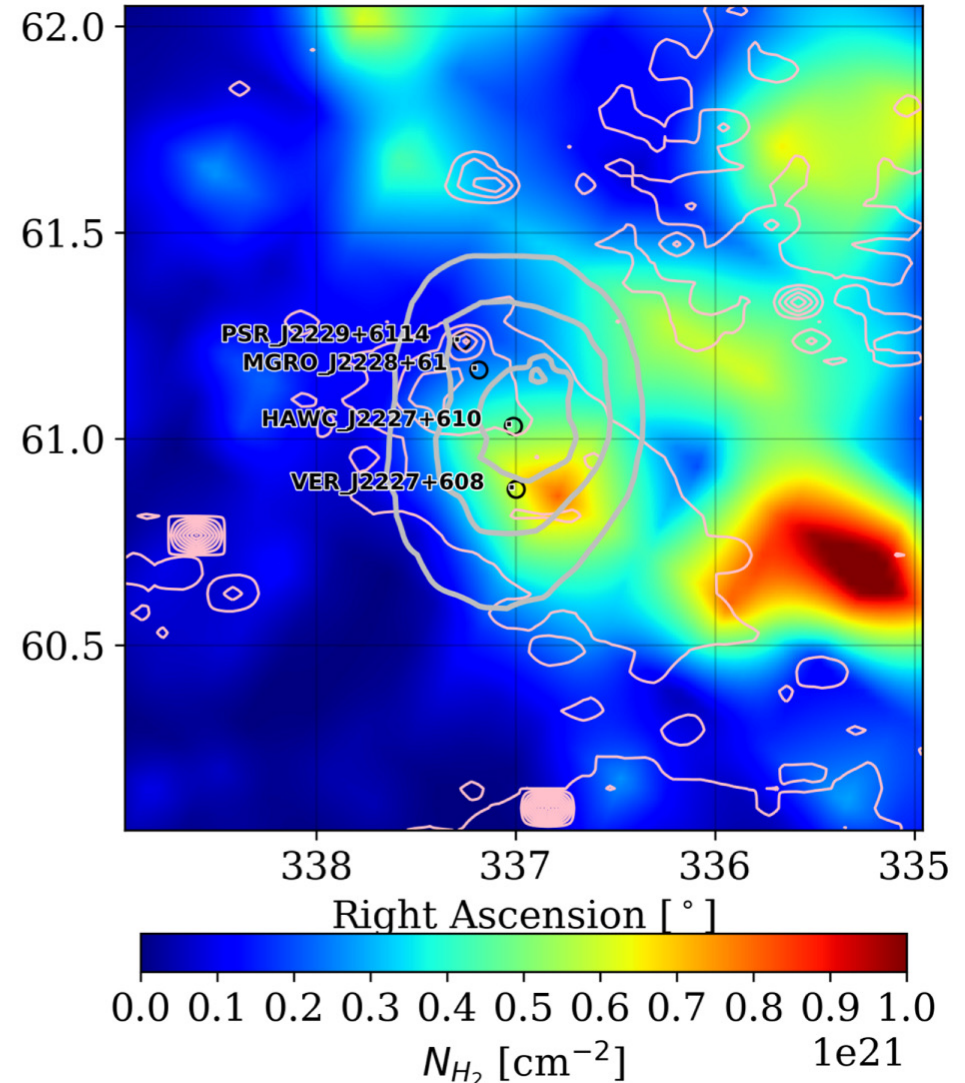


Revisiting the SNR paradigm

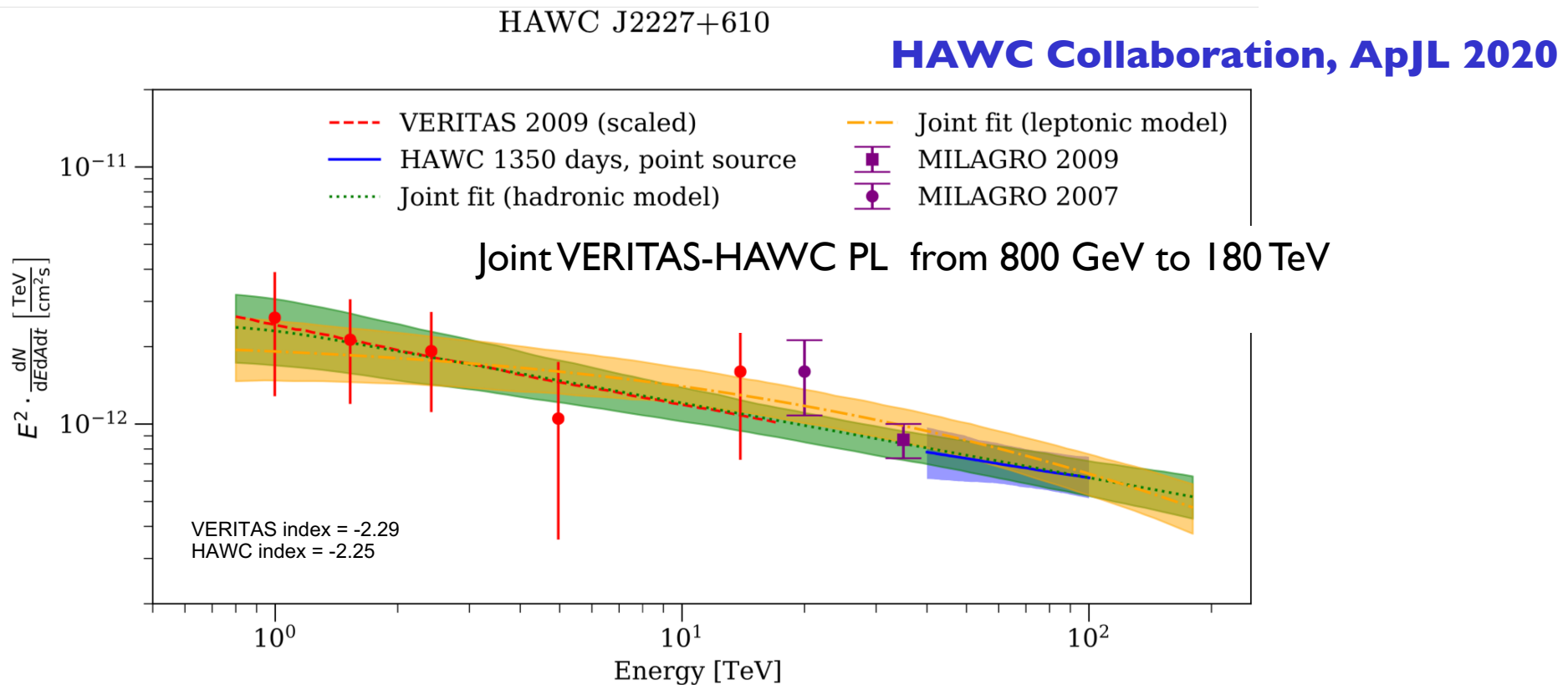
SNR G106.3+2.7: Galactic PeVatron ?

HAWC Collaboration, ApJL 2020

- SNR G106.3+2.7 is a 10kyr comet-shaped radio source at 0.8 kpc
- PSR J2229+6114, seen in radio, X-rays, and gamma rays
- Boomerang Nebula is contained in the remnant
- VERITAS source (energy range 900 GeV – 16 TeV)
- HAWC emission pointlike, morphology compatible with VERITAS source and coincident with a region of high gas density



G106.3+2.7 : a Galactic PeVatron?



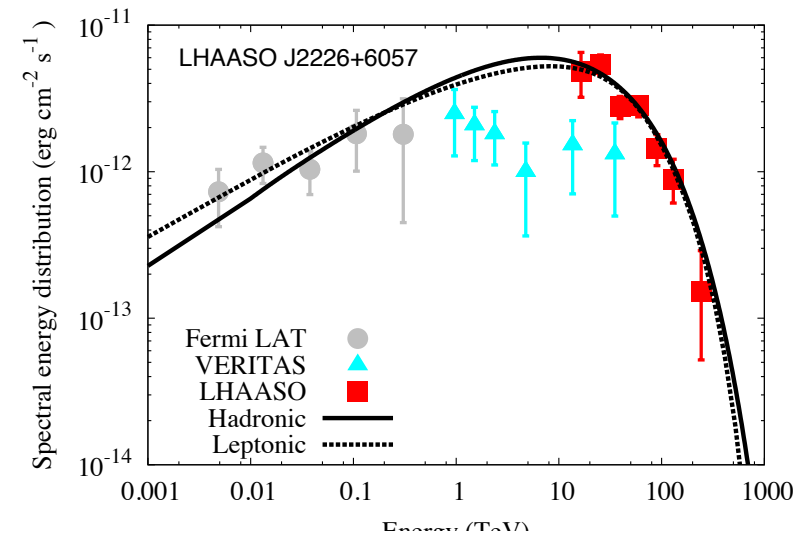
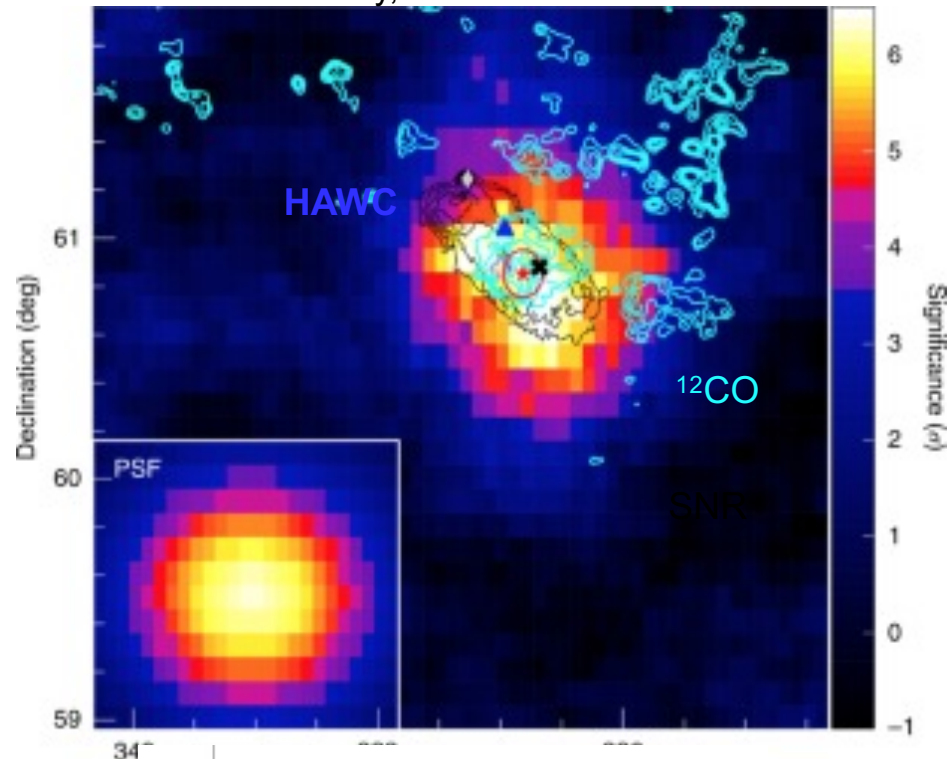
Gamma PL : 2.29, Lower limit on gamma Ecut = 120 TeV

Proton PL : 2.35, Lower limit on proton Ecut = 800 TeV,

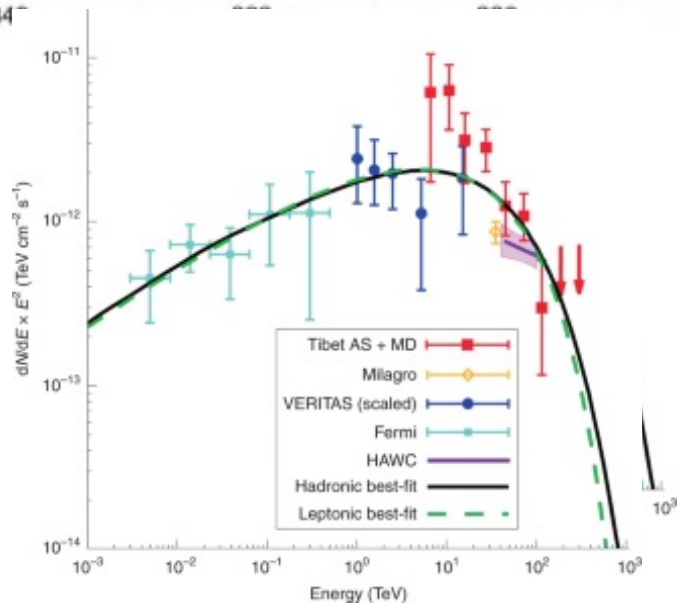
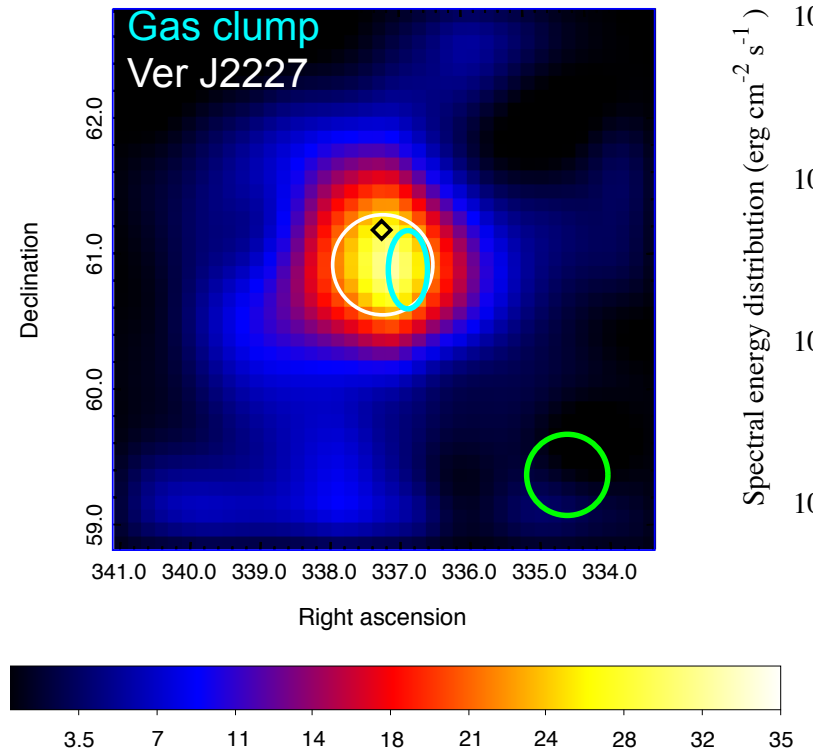
$$W_p = 10^{48} (n/50)^{-1} \text{ erg}$$

G106.3+2.7: a Galactic PeVatron ?

Significance above 10 TeV
Tibet Array, 2021



Pulsar

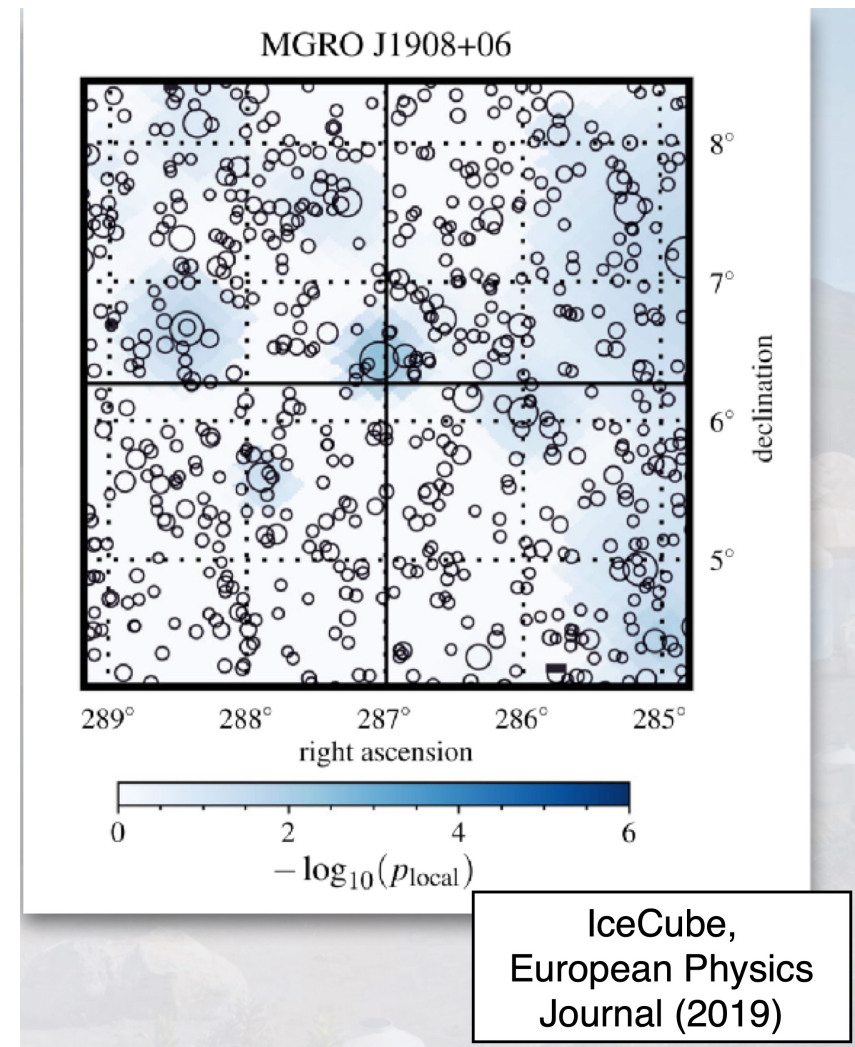


HAWC J1908+06 as neutrino source?

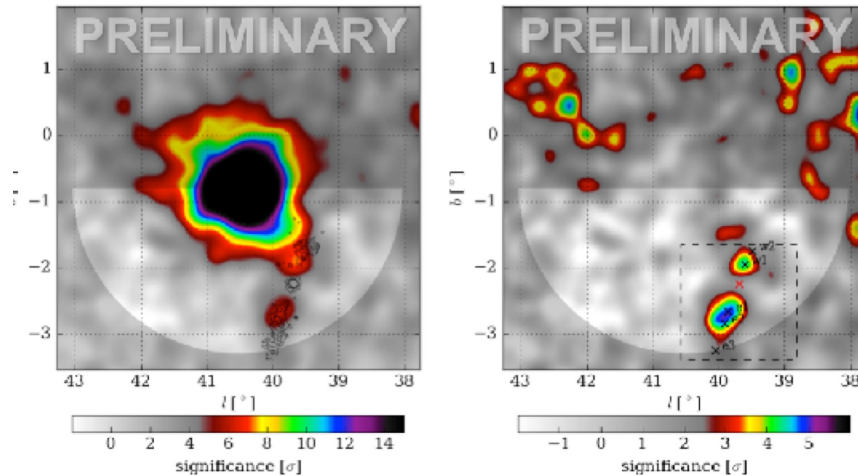
Some HAWC PeV candidates are promising neutrino sources

Neutrinos seen in coincidence with a PeVatron candidate would unambiguously indicate hadronic origin

J1908+06 one of best p-values in IceCube point source searches, although still consistent with background-only hypothesis



Microquasars as gamma-ray sources: SS433 Lobes



- SS 433 is a Galactic micro-quasar observed in radio-X-rays.

- SS433 is a binary system formed by a Supergiant 30 solar masses star and a compact object, either a neutron star or a black hole

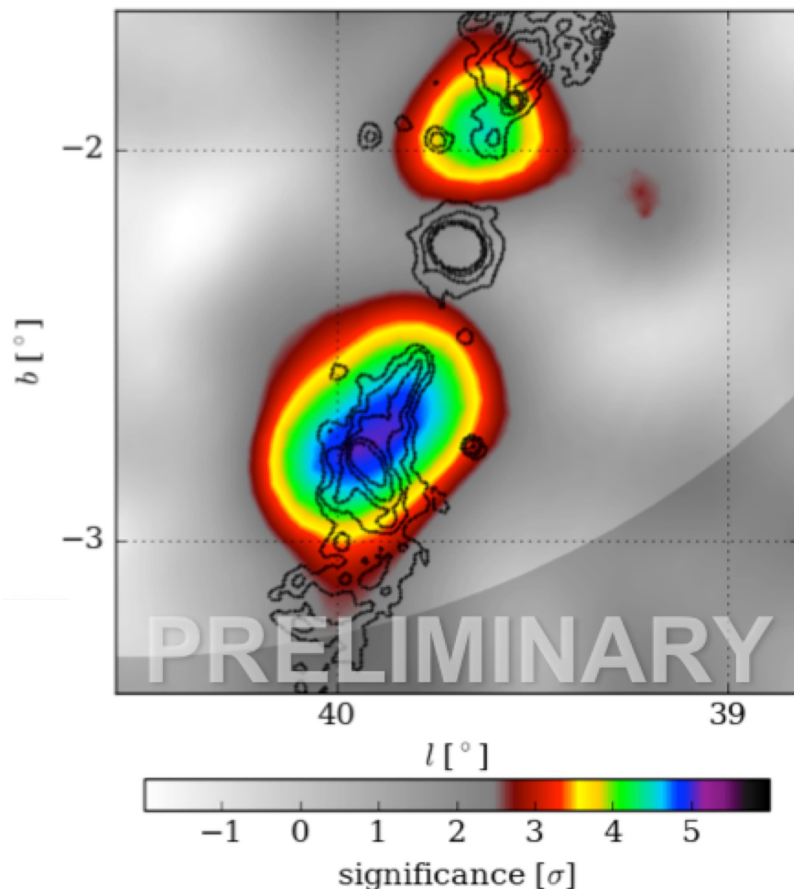
- Two jets, the most powerful known in the Galaxy, extend perpendicular to the line of sight and terminate in W50 nebula and produce western and eastern X-ray lobes

- SS433 jet : 10^{39-40} erg/s

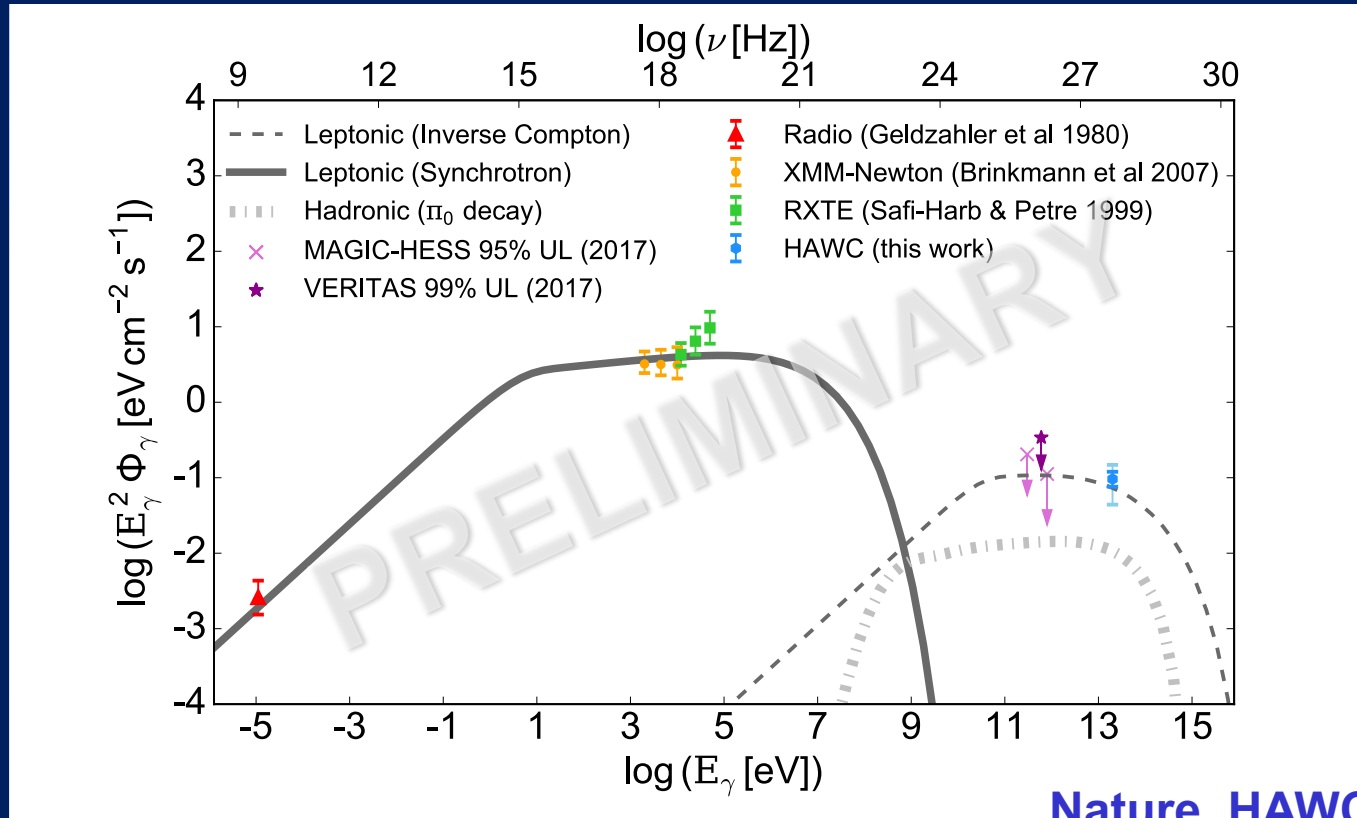
- SS433 jet speed roughly $c/4$

- Baryon loaded

- Particle acceleration is believed to occur at the lobes where strong radiation is expected to be emitted at GeV and TeV energies

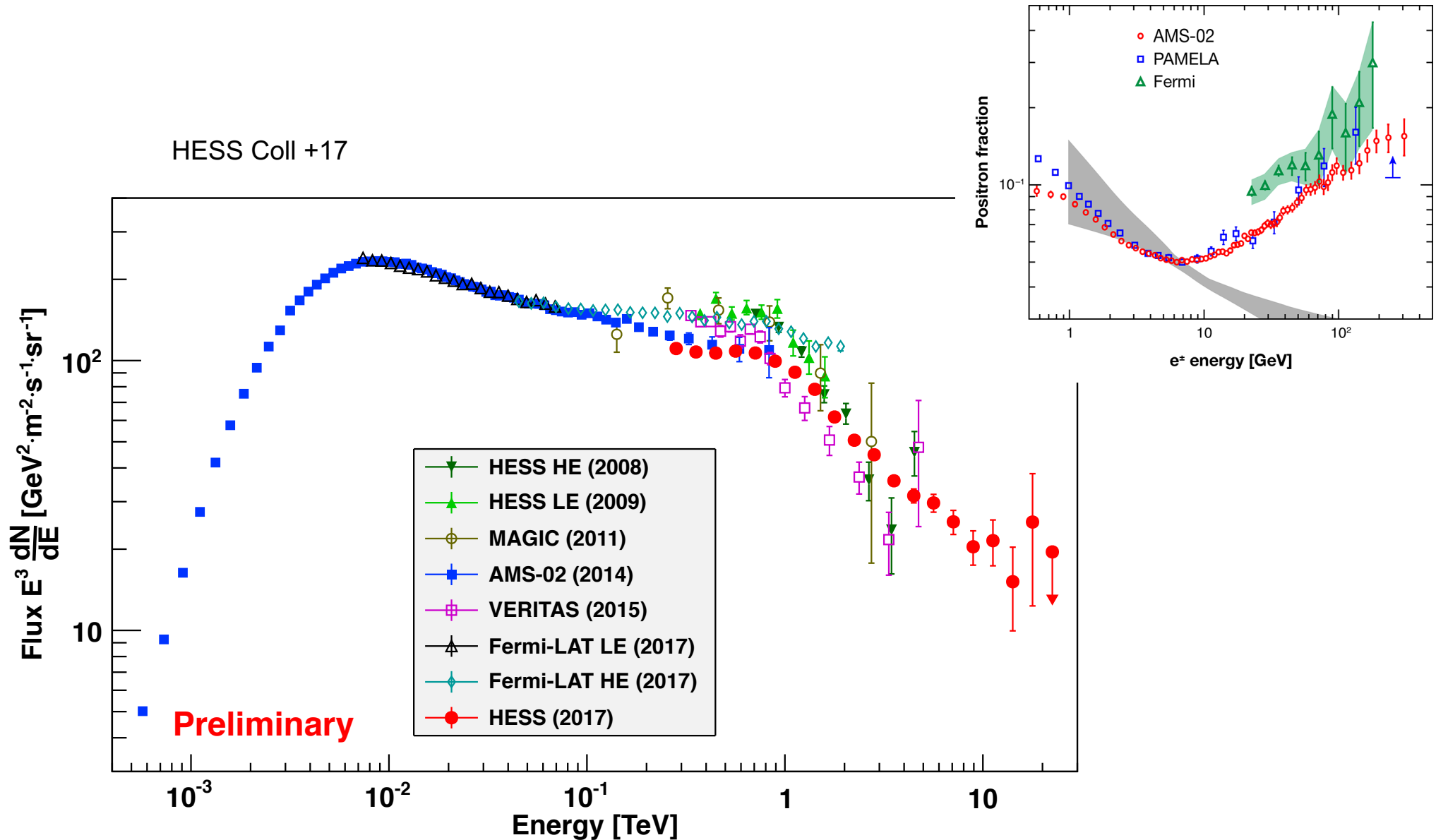


Origin of the emission



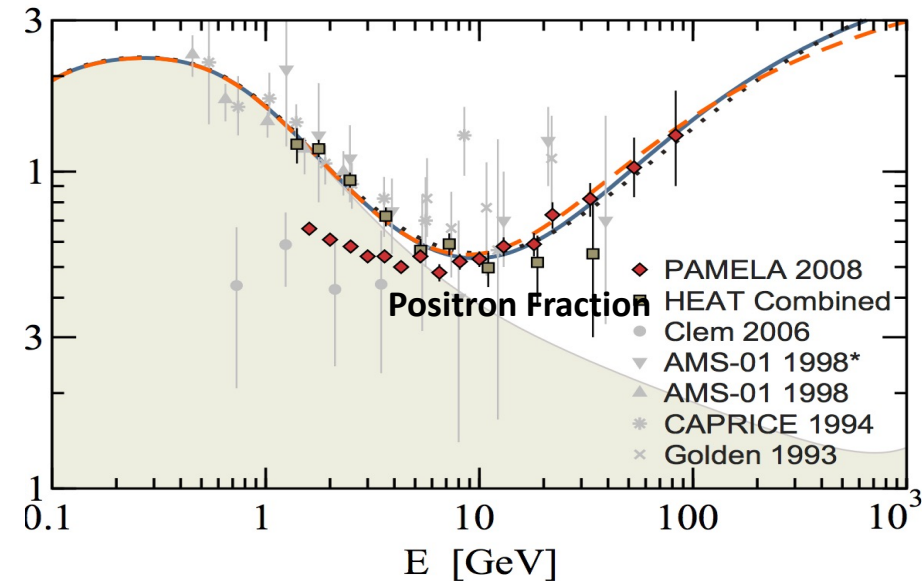
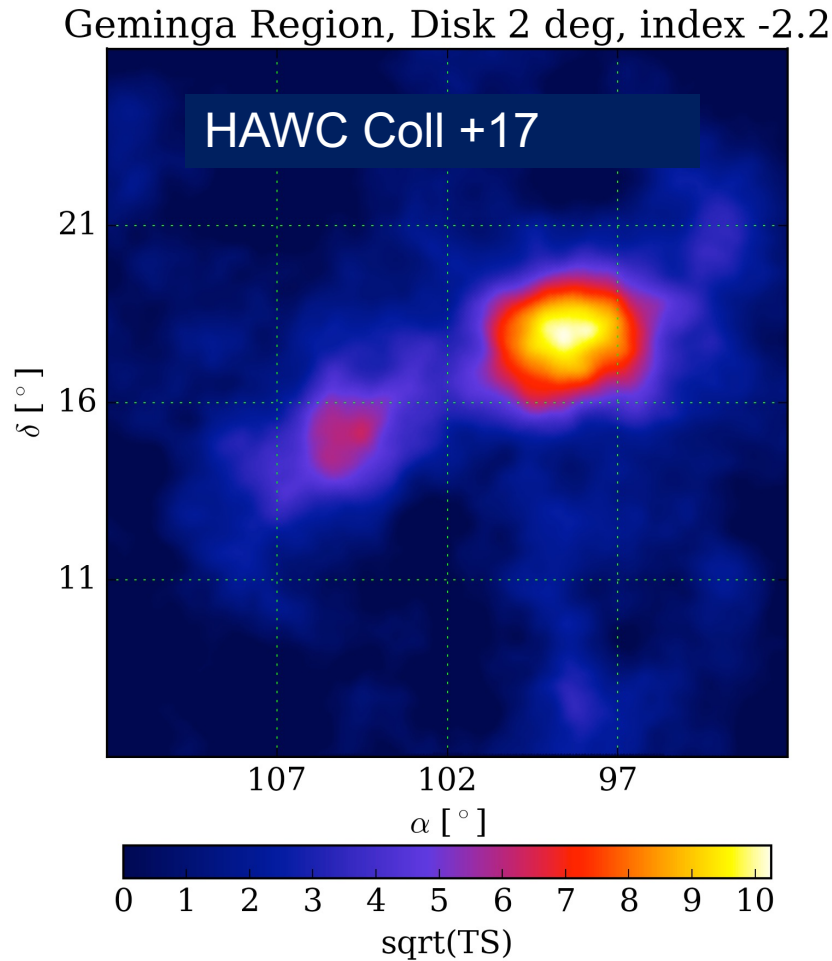
- IC scattering off CMB photons, scattering off optical and infrared suppressed electron acceleration
- Electrons of at least 130 TeV required in a magnetic field of 16 microGauss
- Hadronic emission assumes 10% conversion of jet energy into protons and 0.05 cm $^{-3}$ density

The leptonic part of the CR spectrum



**As for the hadronic part of the spectrum
not only the local flux motivates our searches !**

Geminga-Monogem PWNe

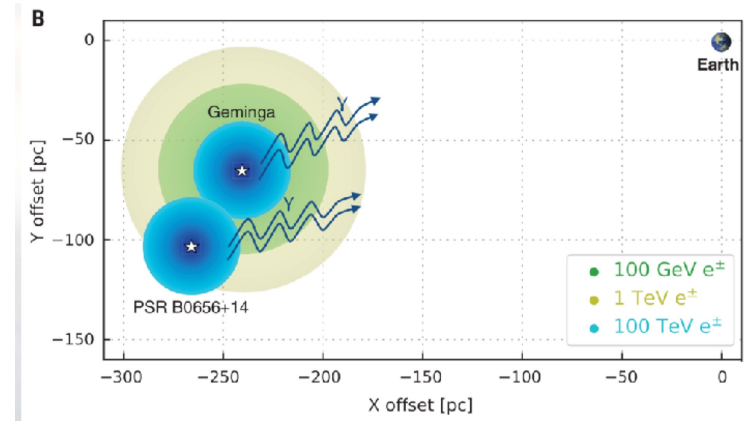
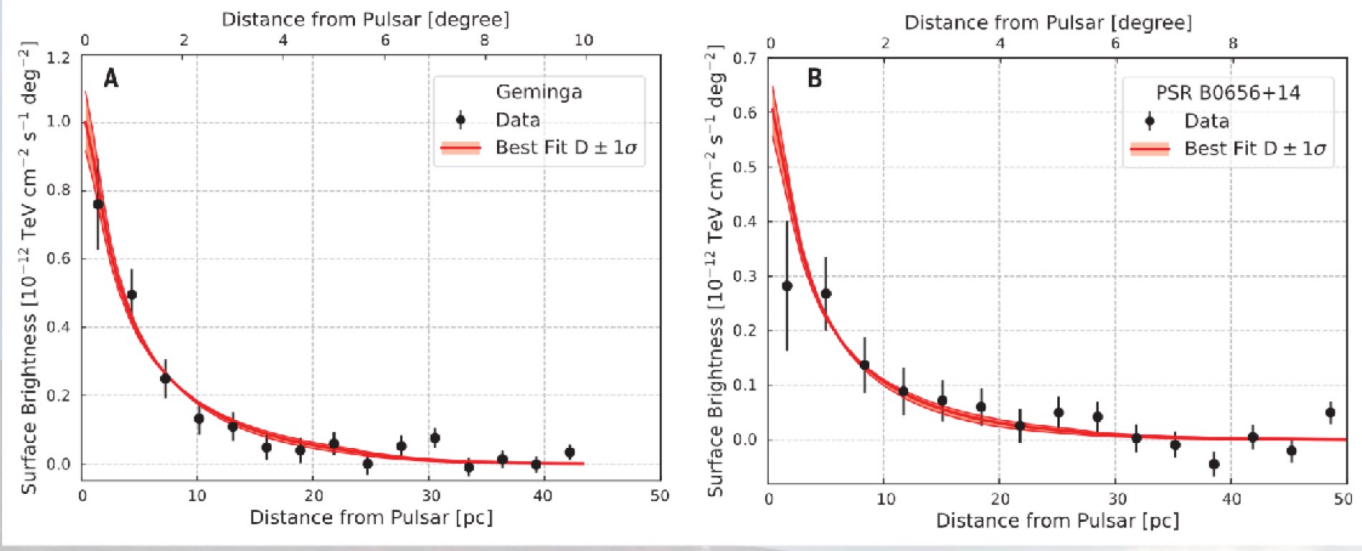


Aharonian+1995, Yuksel+2009

Both pulsars, similar in age and distance, were suggested as major contributors of the positron fraction.

Geminga-Monogem PWNe

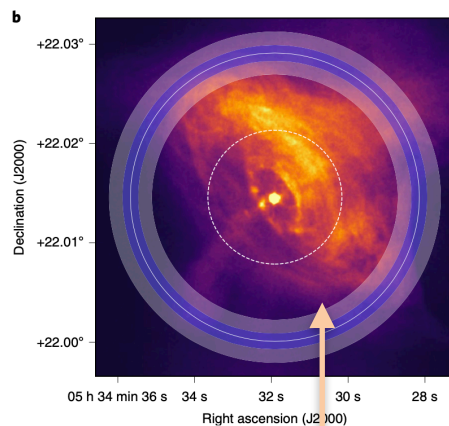
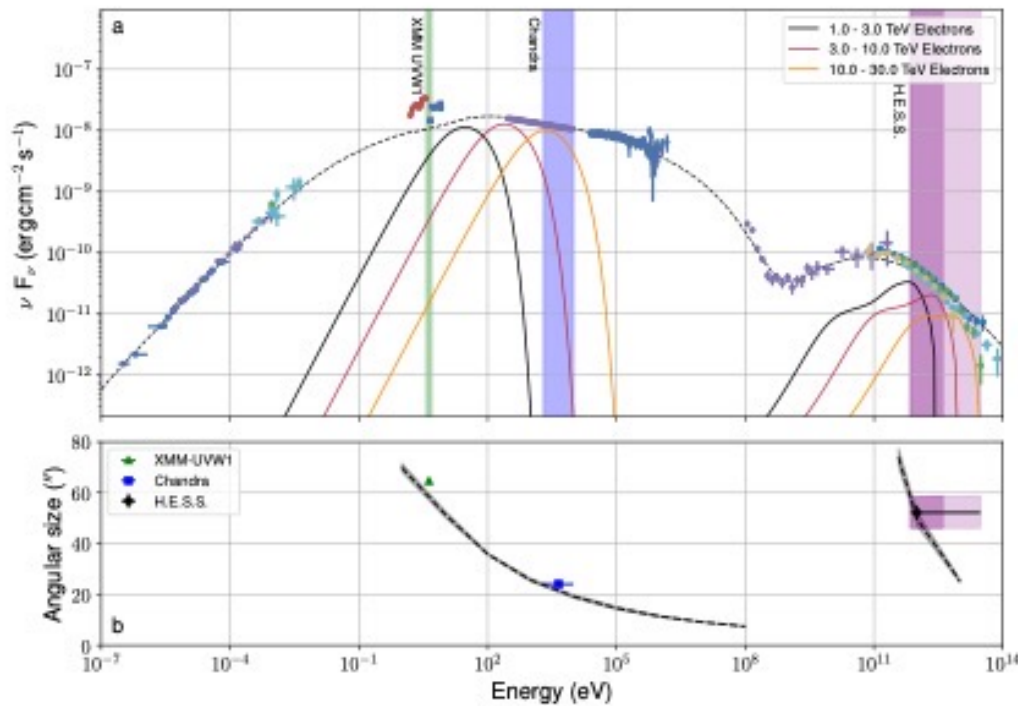
HAWC Coll, Science 2017



- Geminga and Monogem : about 5 deg ext
- Assuming emission from electrons diffusing in the ISM, then direct measurement of particle diffusion
- $D(100 \text{ TeV}) = (4.5 \pm 1.2) 10^{27} \text{ cm}^2/\text{s}$, roughly 100 times smaller than diffusion from B/C ratio

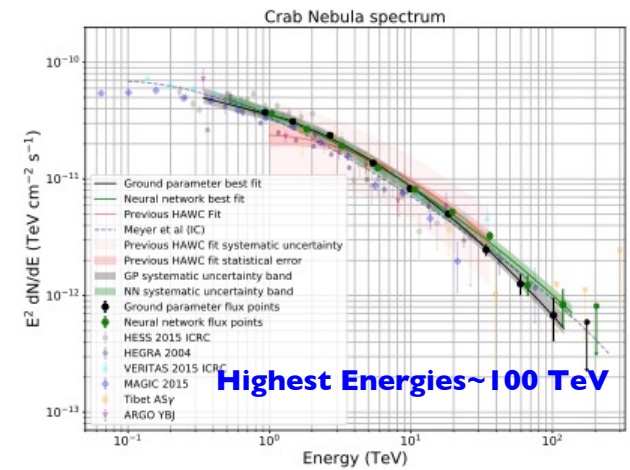
TeV-toPeV photons from the Crab

HESS Collaboration+19

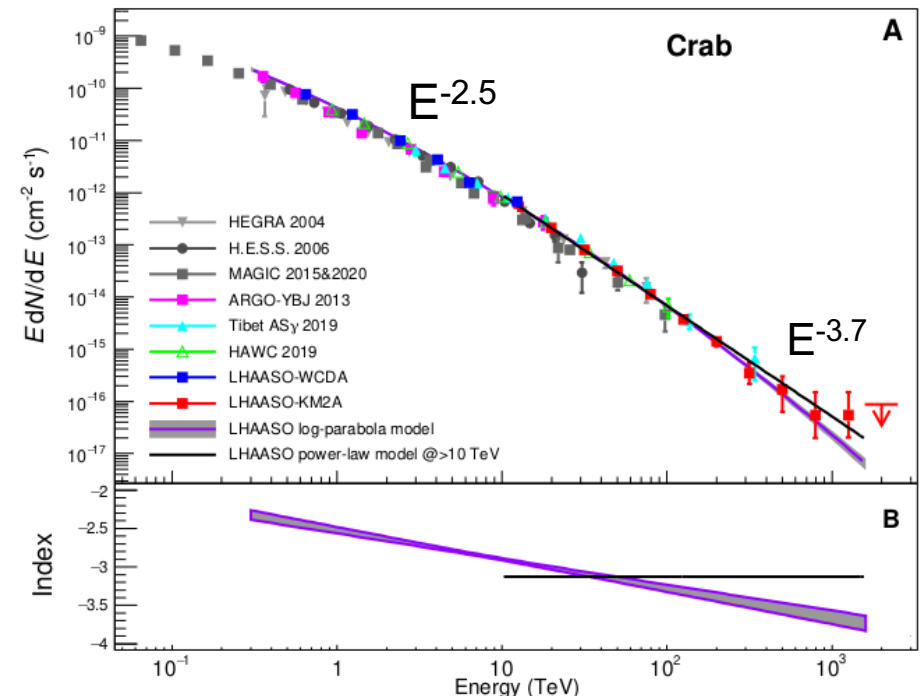


TeV size
50 arcsec

HAWC Collaboration+19

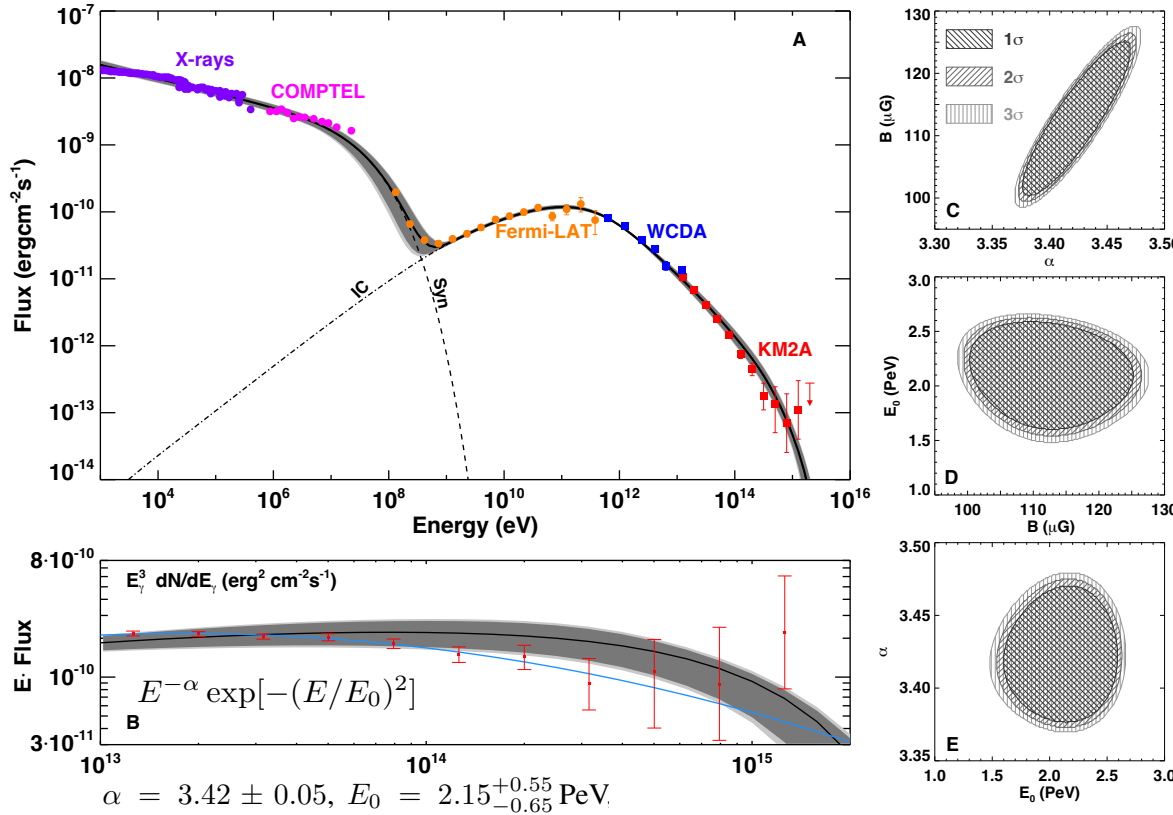


LHAASO Coll +21



IC-synchrotron one zone model

LHAASO Coll +21



KN regime

$$E_e \simeq 2.15(E_\gamma/1 \text{ PeV})^{0.77} \text{ PeV}$$

Same electron population

$$\varepsilon_{\text{syn}} = 9.3(E_\gamma/1 \text{ PeV})^{1.5}(B/100 \mu\text{G}) \text{ MeV}$$

MeV flux not overshoot

$$B = 112^{+15}_{-13} \mu\text{G}$$

Larmor radius constraint

$$(B/100 \mu\text{G})(l/1 \text{ pc}) \geq 0.023(E_\gamma/1 \text{ PeV})^{0.77}$$

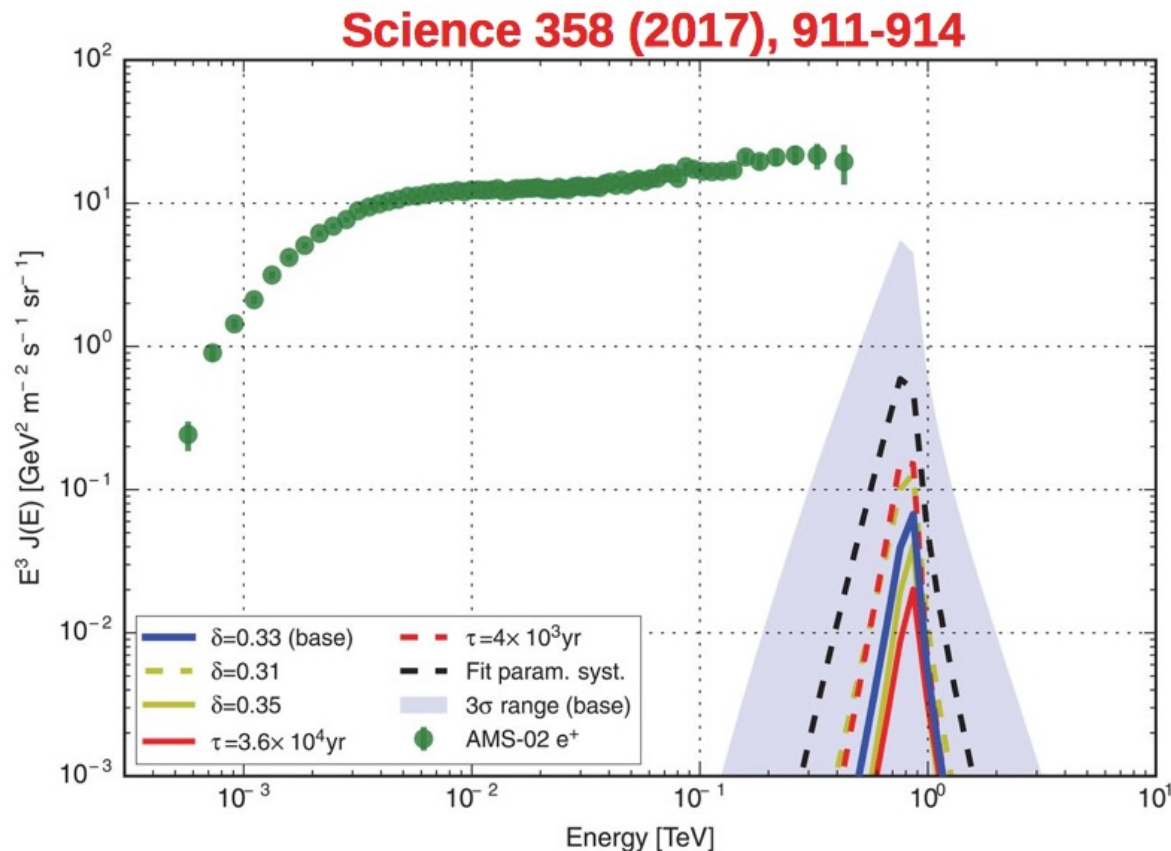
$$l \geq 0.02 \text{ pc}$$

Balance between acceleration and loss rates
E_{max} in gammas = 1.1 PeV

$$E_{e,\text{max}} \approx 5.8\eta^{1/2}(B/100 \mu\text{G})^{-1/2} \text{ PeV}$$

$$\eta = 0.14(B/100 \mu\text{G})(E_\gamma/1 \text{ PeV})^{1.54} \text{ PeV}$$

The positron flux at Earth



RESEARCH

PARTICLE ASTROPHYSICS

Extended gamma-ray sources around pulsars constrain the origin of the positron flux at Earth

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The unexpectedly high flux of cosmic-ray positrons detected at Earth may originate from nearby astrophysical sources, dark matter, or unknown processes of cosmic-ray secondary production. We report the detection, using the High-Altitude Water Cherenkov Observatory (HAWC), of extended tera-electron volt gamma-ray emission coincident with the locations of two nearby middle-aged pulsars (Geminga and PSR B0656+14). The HAWC observations demonstrate that these pulsars are indeed local sources of accelerated leptons, but the measured tera-electron volt emission profile constrains the diffusion of particles away from these sources to be much slower than previously assumed. We demonstrate that the leptons emitted by these objects are therefore unlikely to be the origin of the excess positrons, which may have a more exotic origin.

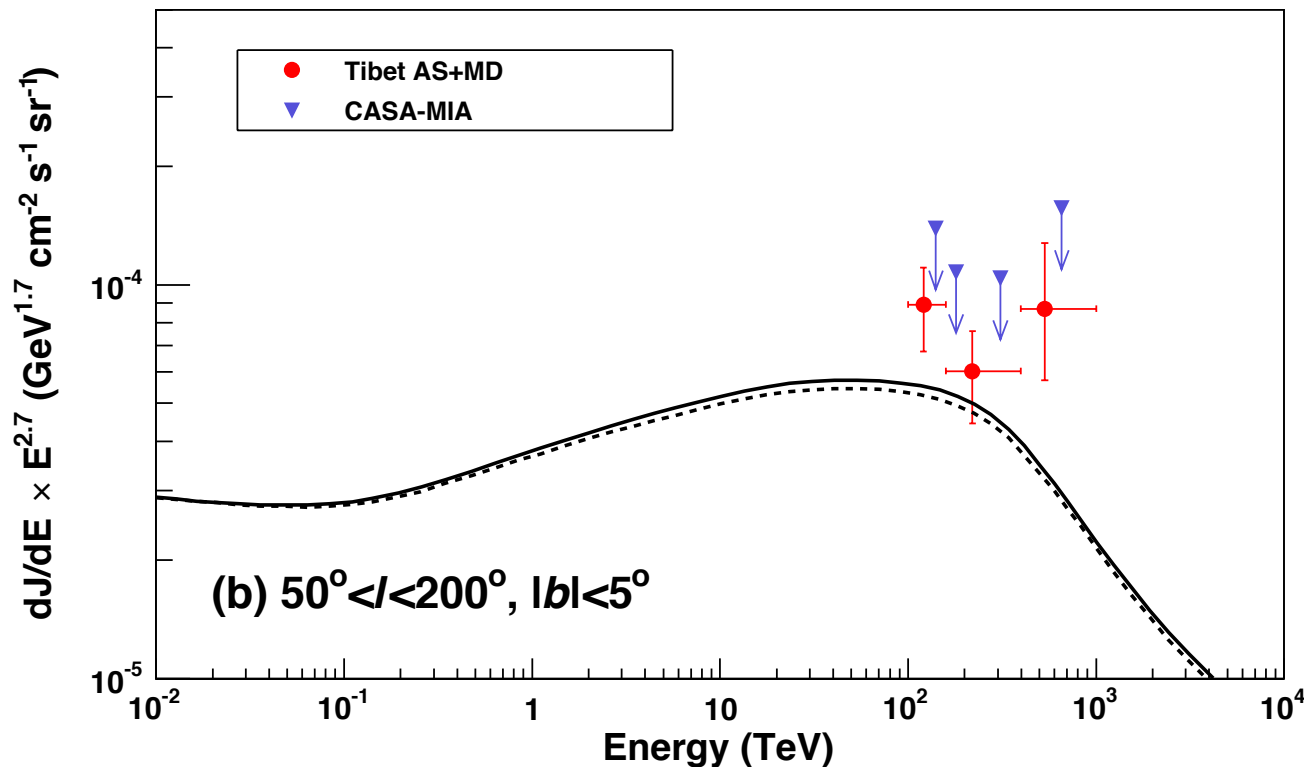
- From the gamma-ray flux and diffuse information (radial profile) we can estimate the flux of electrons/positrons expected at the Earth.
- Under the assumption of isotropic and homogeneous diffusion, these sources are **unlikely to be the main contributors** to the positron excess.

Conclusions and Outlook

- Both target analysis and discoveries in blind surveys showed new source class candidates as Galactic PeVatrons (star clusters, superbubbles, SNRs, gamma-ray binaries....)
- We have **not yet** pinned down the PeVatrons but we now know that the Galaxy is rich in multi-TeV up to PeV gamma-ray sources
- Future : Imaging and wide FoV instruments
 - High discovery potentials with HAWC/LHAASO and SWGO
 - Detailed morphology with HESS/VERITAS/MAGIC and CTA
 - Combined spectra over many ranges in energies from GeV to PeV
 - Gas (great improvements in resolution of surveys in infrared, submm and radio)

Diffuse γ -rays at hundred TeVs

Amenomori+21, Tibet AS



- The fractional source contribution to the diffuse component is estimated to be 13%.
- All events above 398 TeV observed more than 0.5 deg apart from known sources. PeV electrons cannot easily explain such emission
- Above 398 TeV 4 out of 10 events are detected within 4° from the centre of the Cygnus cocoon. If these 4 events are simply excluded, the observed flux at the highest energy agrees with the model prediction.

Prompt X-rays from a PeVatron

