Searching for PeVatrons in the Galaxy

Igor Oya, DESY
VHEPU, Quy Nhon, 17-8-2018

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

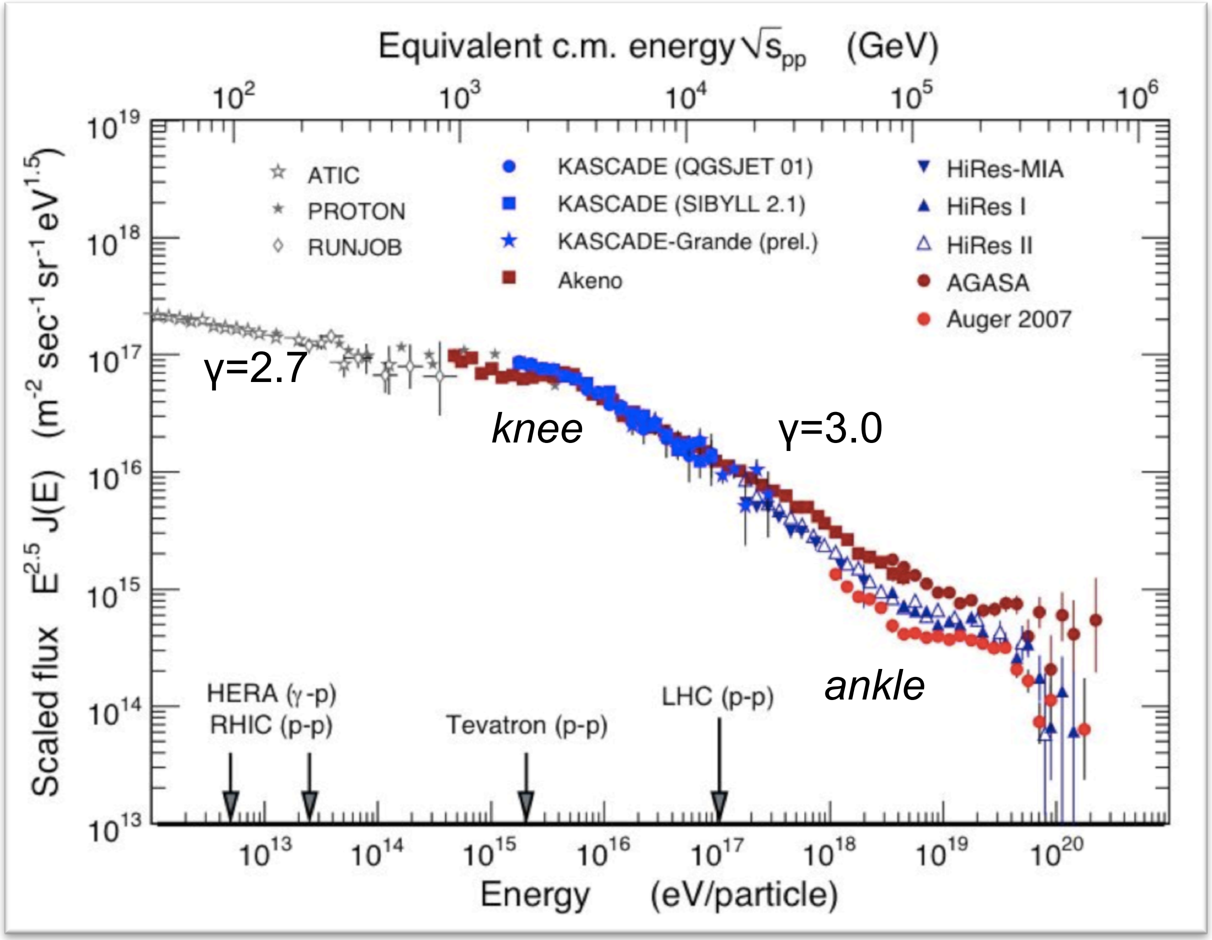
Cosmic Rays

a 100-year-old mystery

- High energy cosmic particles, Cosmic Rays (CR) continuously arriving on Earth (*V. Hess, 1912*)

- Almost a single power law spectrum, with
  - a knee at few PeVs
  - ankle at ~10 EeV

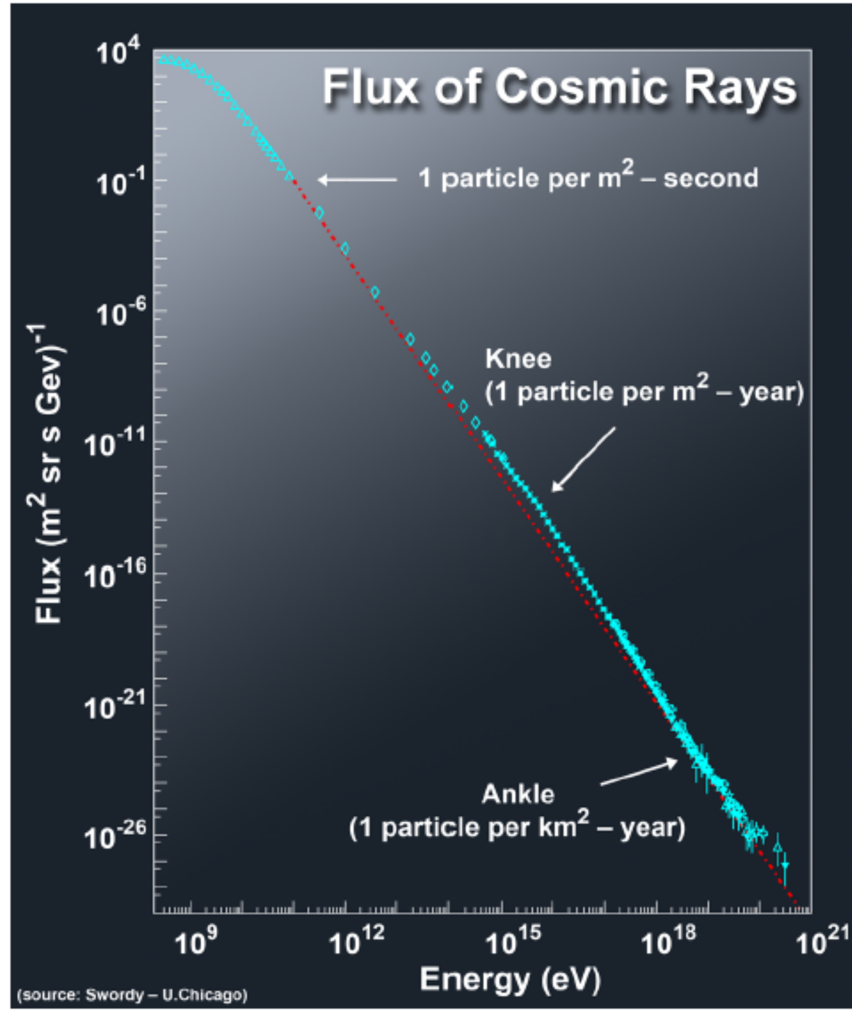
- 89% protons, 9% helium, 1% electrons



Cosmic Rays

a 100-year-old mystery

- CRs up to the knee → Galactic origin (accelerated in galactic objects such as Supernova Remnants (SNRs)).
- CRs between the knee and the ankle → Unclear (thought to be Galactic but the energies are too high for being produced in the SNR shocks)
- CRs beyond the ankle → extra-Galactic.
- Galactic CR energy budget: $L_{CR} \sim 10^{40} – 10^{41}$ erg / s



$$J_{\odot}^{(\mathrm{p})} = 1.8 \times E_{\mathrm{GeV}}^{-2.7} \quad \mathrm{GeV}^{-1}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{cm}^{-2}$$

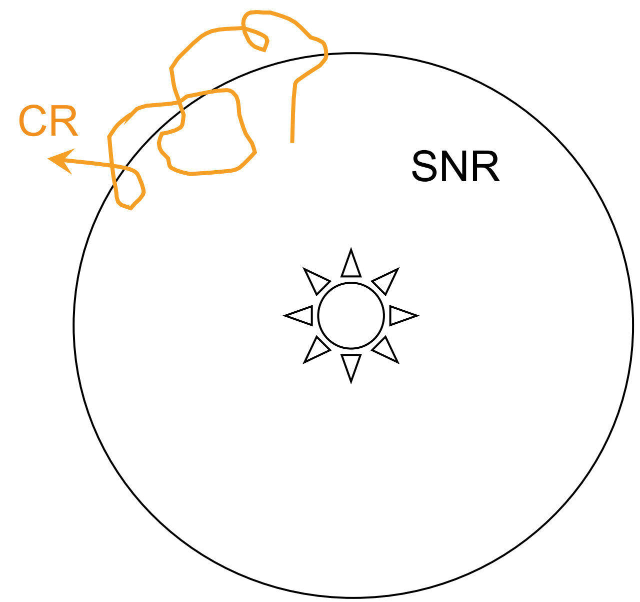
Why are CRs interesting?

- Energy density of Galactic CRs comparable to starlight, magnetic fields, and gas kinetic energy
  - These are all tightly connected
  - CRs carry energy throughout galaxies
  - CRs closely connected to evolution of stars and galaxies
- CRs provide insights in evolution of massive stars
  - Death (supernova remnants)
  - Life (winds from massive stars)
  - Birth (perhaps) signaling onset of fusion/stellar winds
  - Initiate astro-chemistry → key ingredient for life?!
- CRs trace outflows and jets
  - Jets, pulsar winds, accretion, GRBs, …

Standard Model of CRs

How are particles accelerated up to ~1 PeV?

- Standard model: SNRs accelerate cosmic rays up to the knee:
  - W_{CR} ~ 10^{50} erg per SN (~10 % of total SN budget)
  - With a rate of 1/30 years and available energy SNs could produce the necessary power to sustain the Galactic CR population
- Diffusive Shock Acceleration (DSA) predicts and E^{-2} spectrum and is compatible with ~10% efficiency for the acceleration process
- E^{-2} type spectrum to very high energies
- Acceleration of highest energy CR in early stages of SNR
- Other possible contributors to Galactic CRs:
  - Galactic Centre (GC), Microquasars, superbubles, pulsars/plerions, OB, W-R Stars, …



Standard Model of CRs

How are particles accelerated up to ~1 PeV?

- Standard model: SNRs accelerate cosmic rays **up to the knee**: → **Remains to be proven**
  - $W_{CR} \sim 10^{50}$ erg per SN (~10 % of total SN budget)
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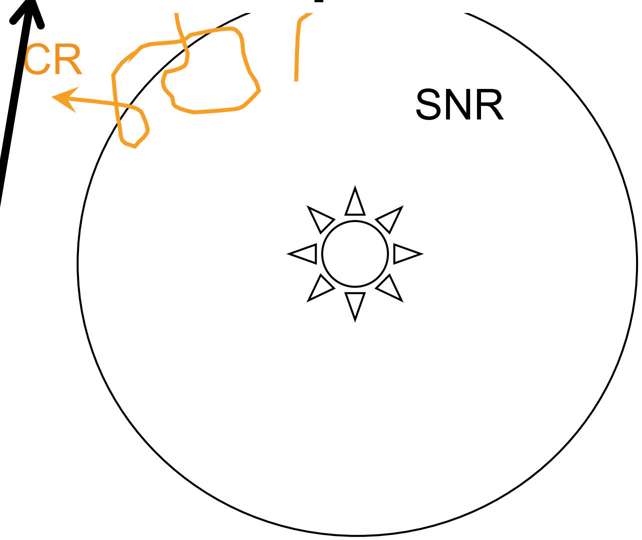
- **Acceleration of highest energy CR in early stages of SNR**



- Other possible contributors to Galactic CRs:
  - Galactic Centre (GC), Microquasars, superbubles, pulsars/plerions, OB, W-R Stars, …

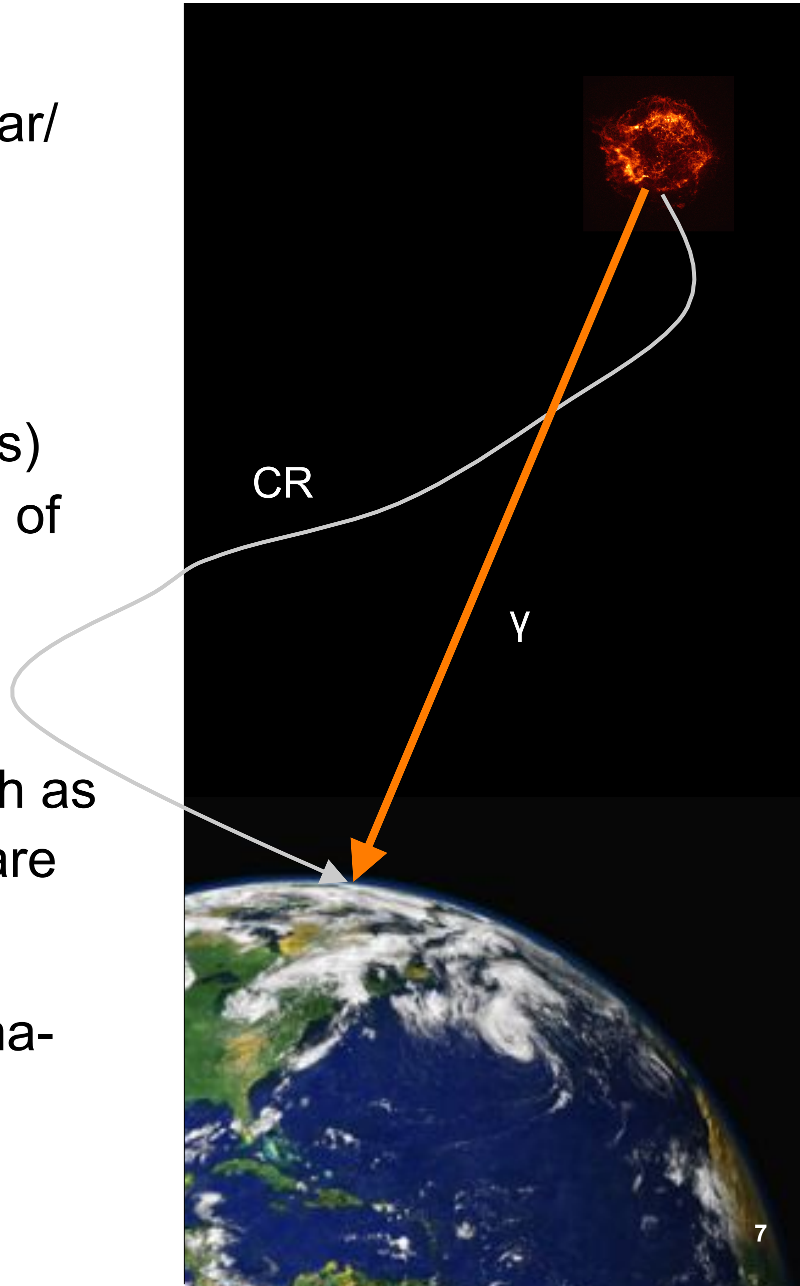
Measuring CR origin

- CR trajectory is deviated due to interstellar/ intergalactic magnetic fields → Indirect detection methods are needed

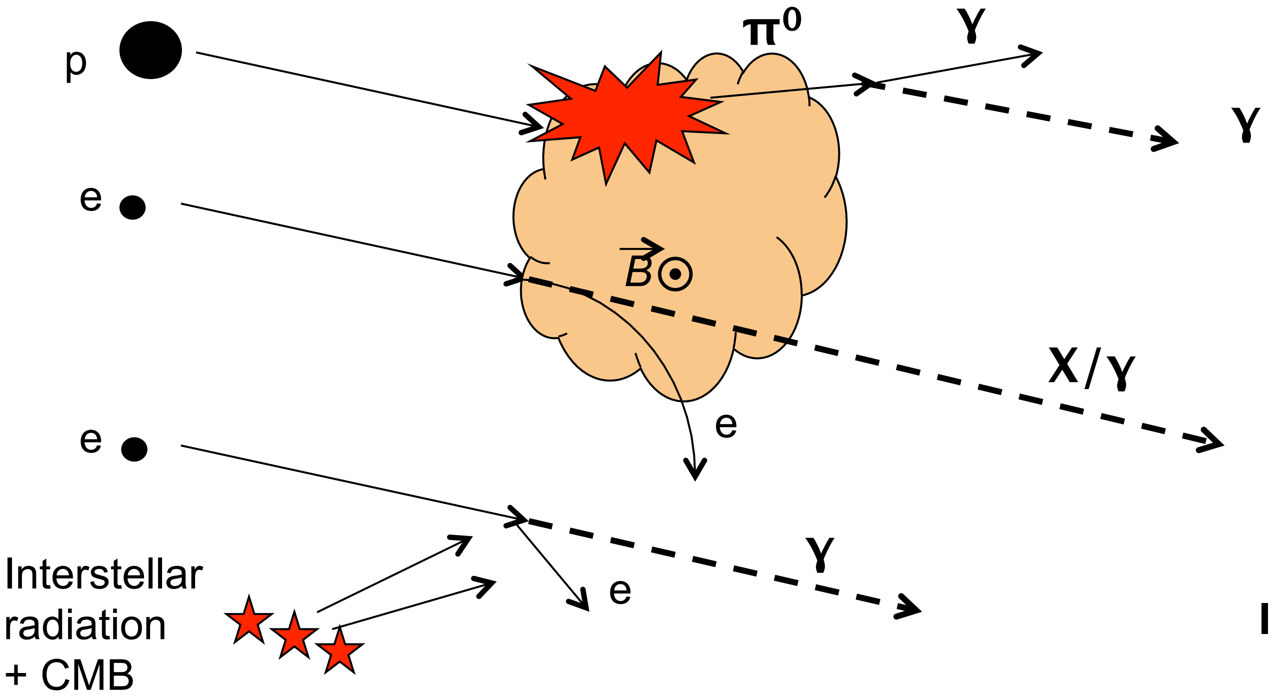
- Neutral messengers (photons & neutrinos) can be used for tracing back to the origin of their astrophysical sources

- Ground-based gamma-ray detectors such as IACTs and water Cherenkov instrument are specially well suited

  → One of the main drivers of VHE gamma-ray astronomy



Gamma Rays from multi-TeV particles

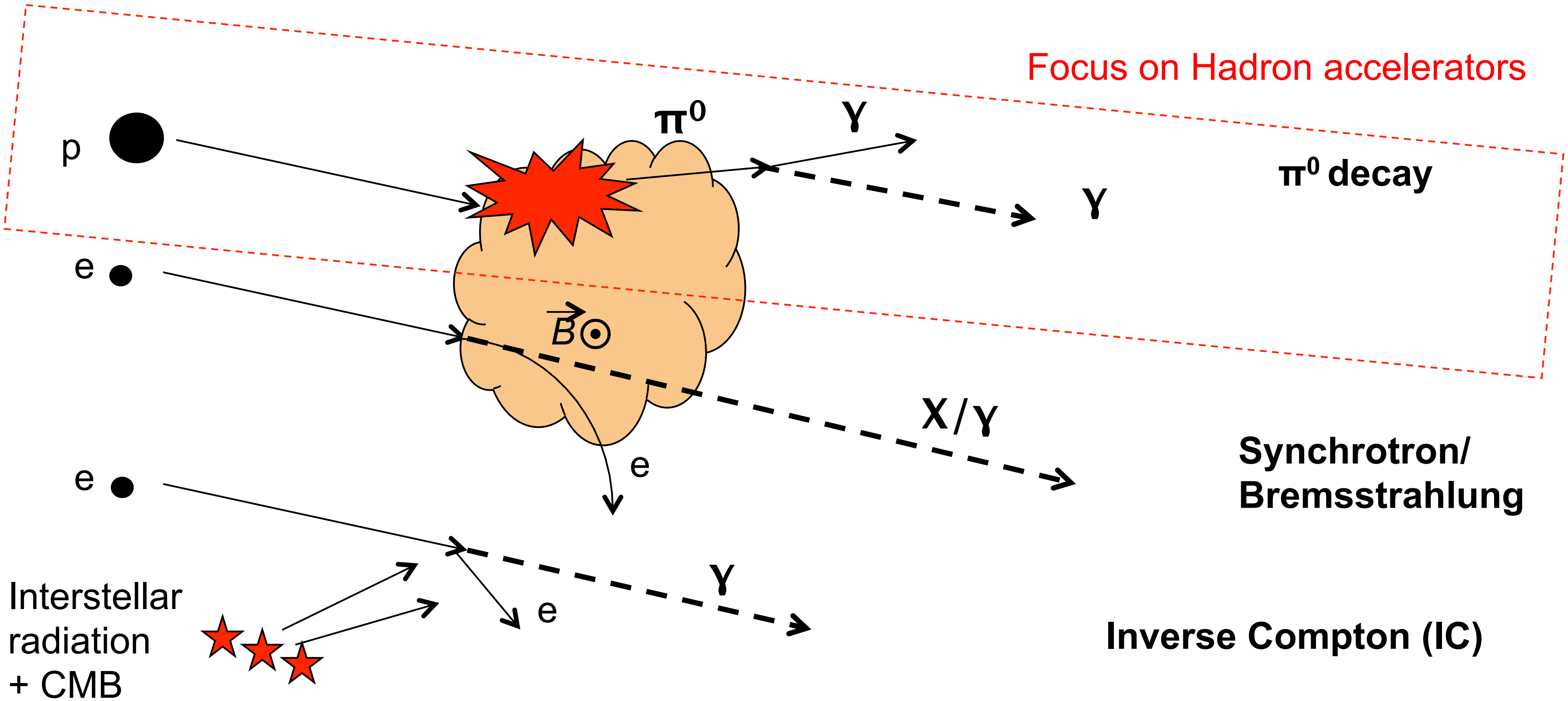


π^0 decay

Synchrotron/ Bremsstrahlung

Inverse Compton (IC)

Gamma Rays from multi-TeV particles



- Galactic sources accelerating CRs up to PeV energies – *PeVatrons* can be identified and analyzed via the study of gamma-ray emission

Looking for Galactic PeVatrons

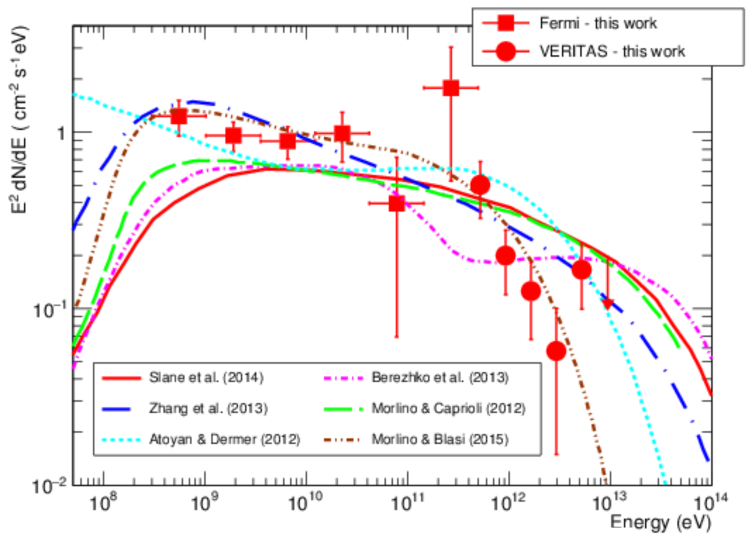
- Many PeVatrons must exist in the Galaxy to explain local cosmic ray flux at the "knee"
- PeVatron candidates
  - Likely proton accelerator site such as a SNR
  - Target dense gas region → Produce VHE gamma rays via pp and then π^0 decay
  - Hard spectral index with no sign cutoff at 10s of TeV
  - Hard X-ray emission from secondary electrons
- Electron accelerators produce TeV gamma rays via IC
  - Also produce keV X-ray synchrotron emission
  - Must be some to explain local CR electrons
  - Would expect co-acceleration with protons, but much more rapid (factor ~100) energy losses
- Spectral study + modeling to distinguish leptonic/hadronic emission

Study with IACTs, water Cherenkov detectors (+HE satellites + MWL)

Are young SNRs PeVatrons?

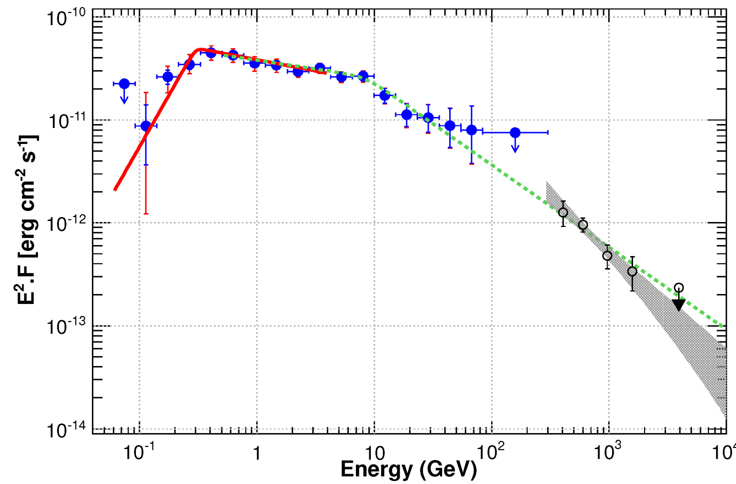
Tycho

VERITAS arXiv:1701.06740



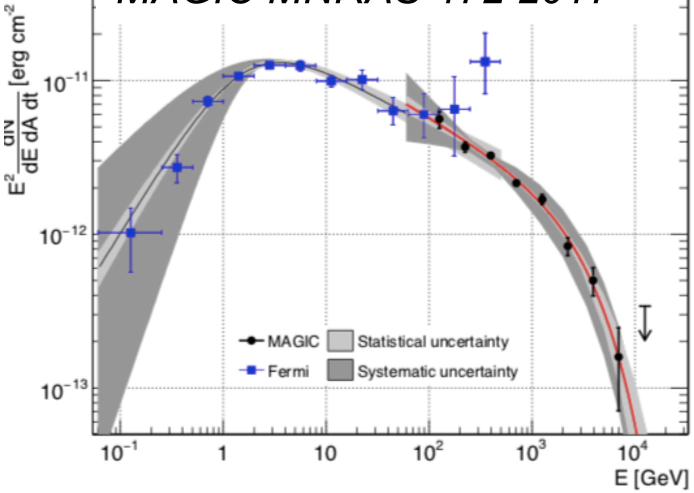
W49B

H.E.S.S. & Fermi A&A 612 (2018)



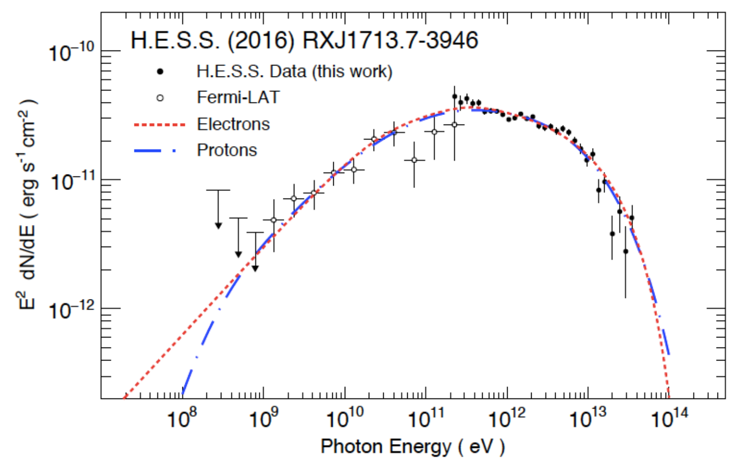
Cas A

MAGIC MNRAS 472 2017



RXJ1713.7-3946

H.E.S.S. A&A Vol. 612 (2018)



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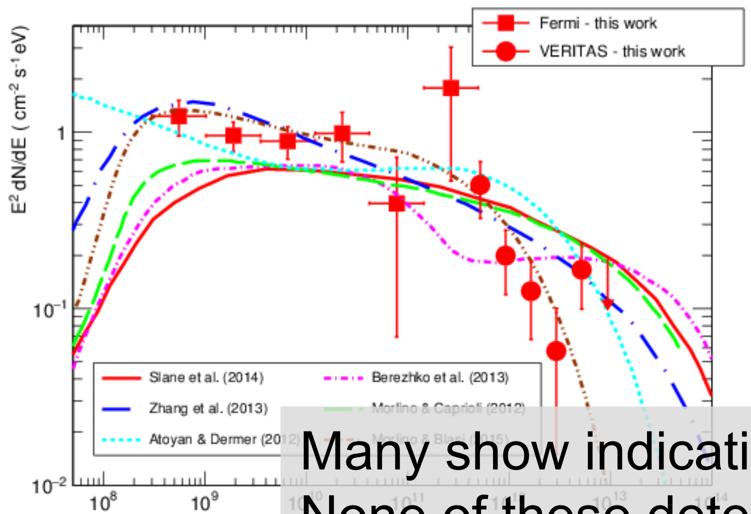

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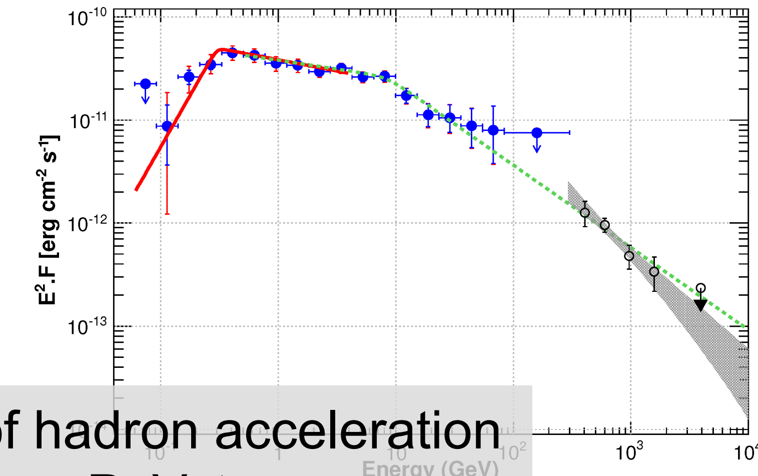


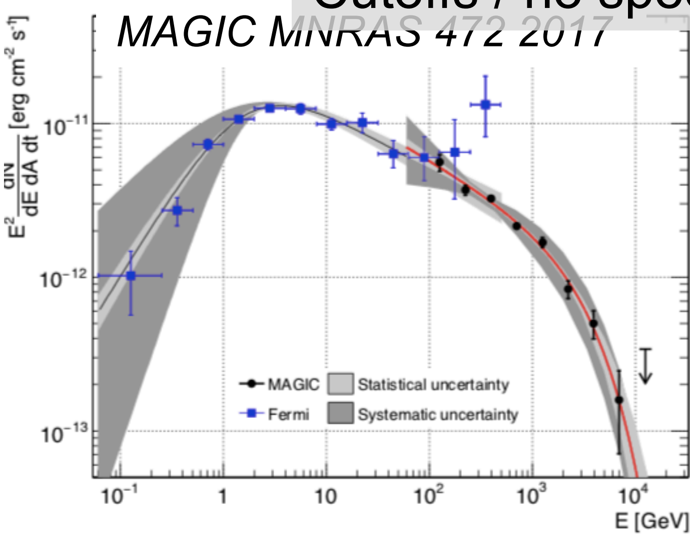
Many show indication of hadron acceleration

None of these detected as PeVatron

Cutoffs / no spectral points >~ 15 TeV

Cas A

MAGIC MNRAS 472 2017



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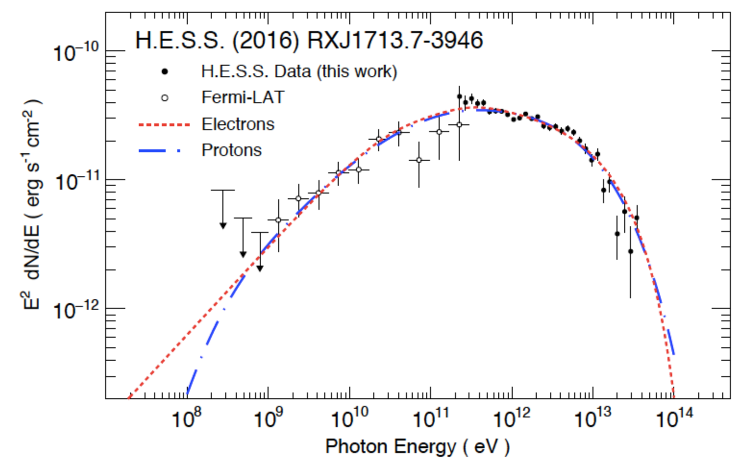
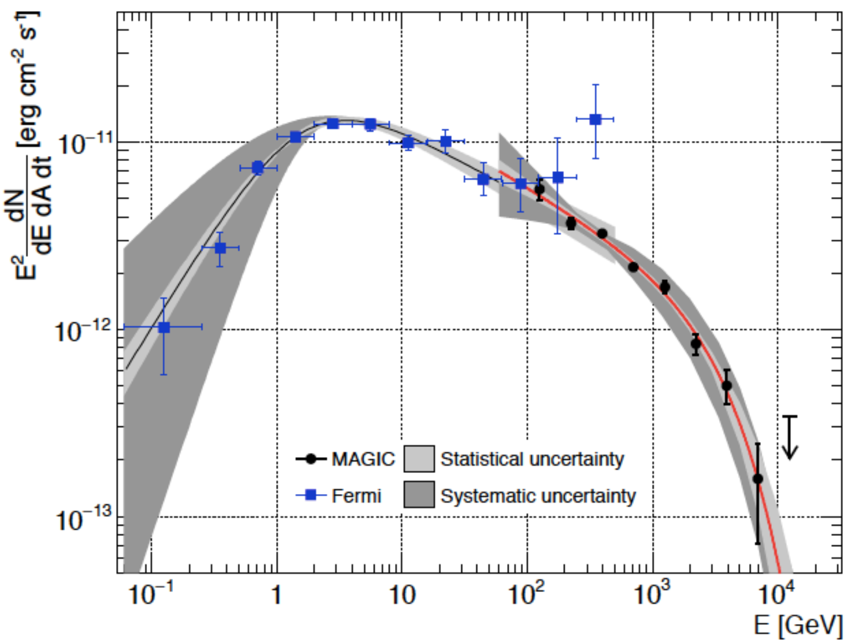


MAGIC studies of Cas A

MAGIC, MNRAS 472 2017

- Cassiopea A (Cas A) would appear as one of the best PeVatron candidates
  - relatively young (about 300 years)
  - largely studied in radio and X-ray bands, which constrains essential parameters for testing emission models.
  - CR accelerator



- However MAGIC team found a significant exponential cut-off at 3.5 TeV
- Assuming hadronic processes no significant cosmic ray diffusion

→ Cas A is not a PeVatron at its present age

The Galactic Centre (I)

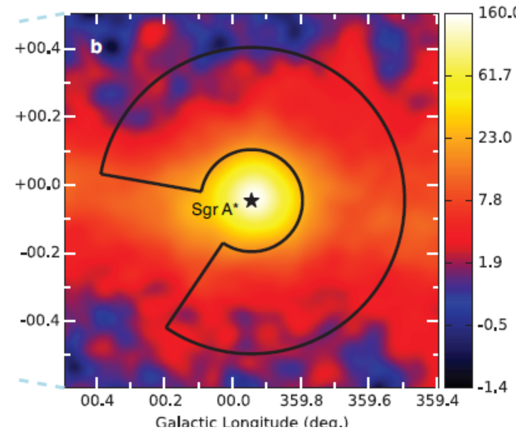
HESS Collaboration, Nature, 531, 476 (2016)

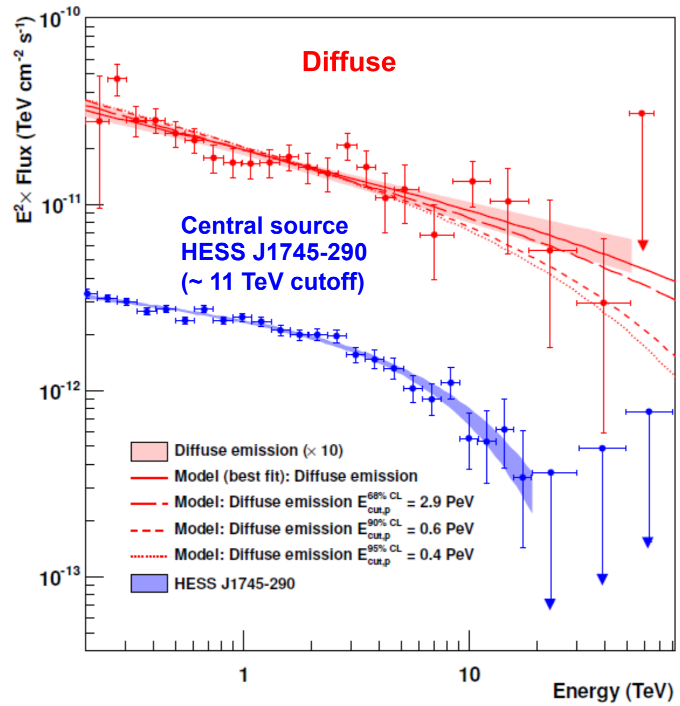
Acceleration of PeV protons in the Galactic Centre

- 220 h observation data
- Hard spectrum diffuse emission around the GC
- The diffuse emission spectrum is a power-law:

$\Phi = (1.92 \pm 0.08_{stat} \pm 0.28_{sys}) \times 10^{-12}$ TeV^{-1} cm^{-2} s^{-1}
$\Gamma = 2.32 \pm 0.05_{stat} \pm 0.11_{sys}$

- Assuming:
  - pp interactions → subsequent π^0 decay
  - a cutoff in the parent proton spectrum → 1σ, 2σ and 3σ cutoff → 2.9 PeV, 0.6 PeV and 0.4 PeV.
- Strongest indication found so far of a VHE cosmic hadronic accelerator operating as a PeVatron.





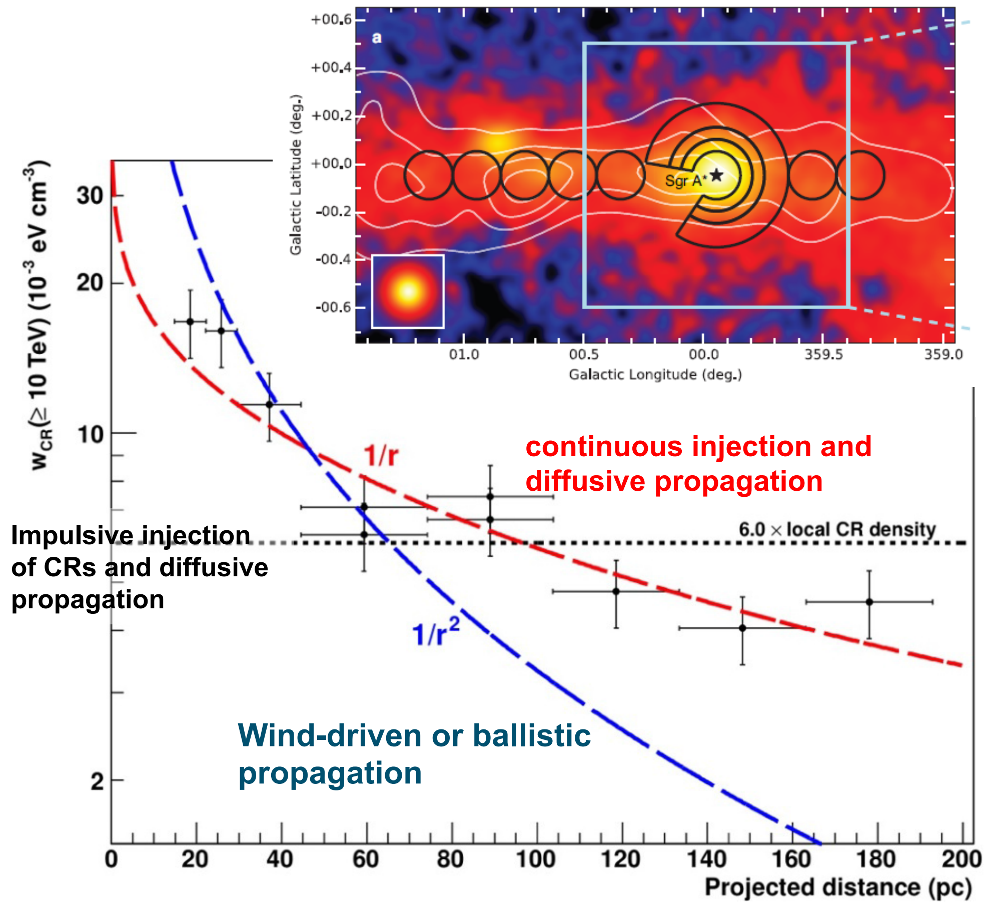
The Galactic Centre (II)

HESS Collaboration, Nature, 531, 476 (2016)

H.E.S.S.

Acceleration of PeV protons in the Galactic Centre

- Analysis of the ridge emission
- Calculated cosmic-ray energy density profile ∝ L/M
- Continuous CR injector over ~ few 1000 yr
  - Central BH most likely accelerator
- CR power injected ~10^{38} erg/s
- Could explain galactic CRs >0.1 PeV if BH more active in past
- Or additional PeV accelerators in the Galaxy are needed



- Note: interaction of the diffuse Galactic CR population with the local dense gas could be contributing significantly. (D. Grasso presentation on Monday)

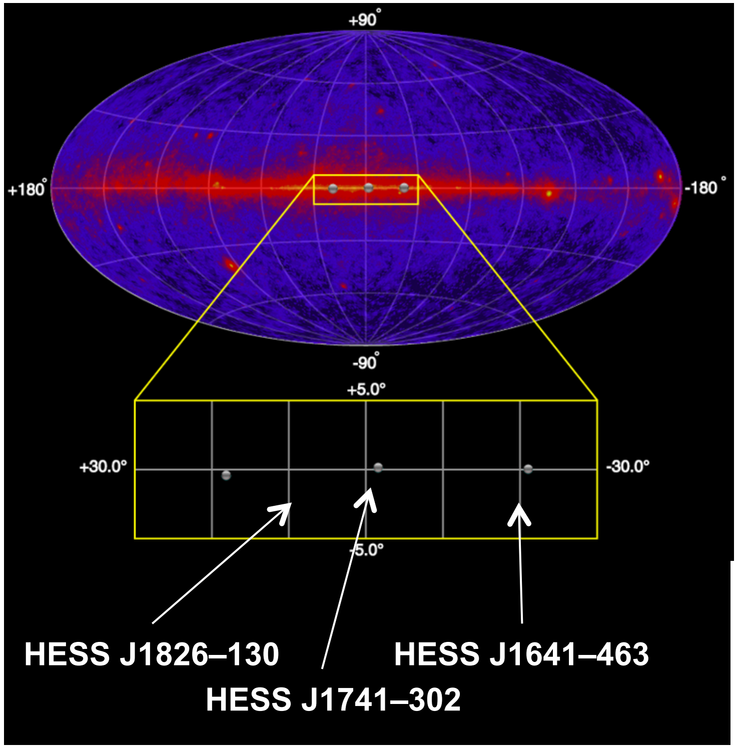
Hard Spectrum H.E.S.S. Sources (I)

EO Angüner et al (HESS), ICRC 2017

- Three unidentified H.E.S.S. sources showed interesting characteristics:

1. Very hard index spectrum
2. Coincident with dense gas regions
3. Do not show variable VHE emission

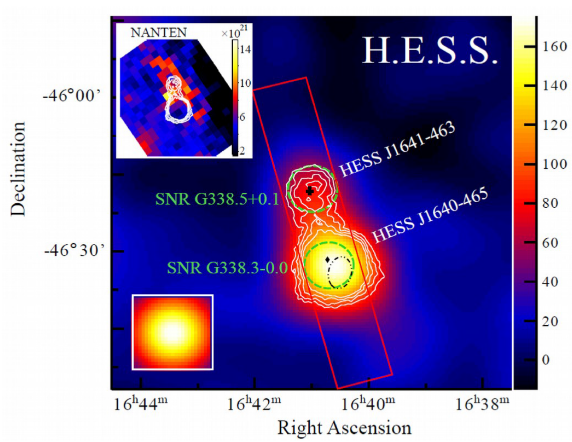
- Are these sources capable of accelerating protons up PeV energies?
- Faint and located near other bright VHE sources, thus their (apparent) emission is contaminated and suffering from source confusion



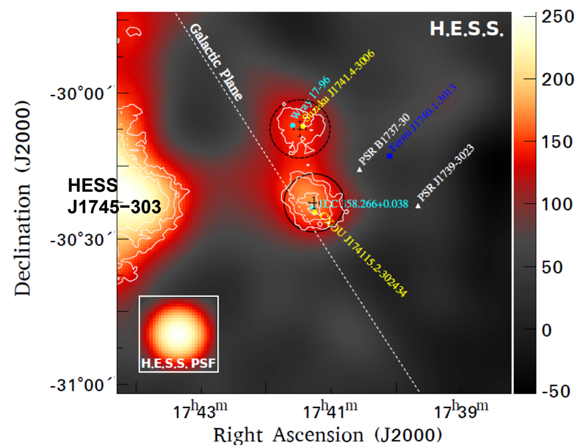
Hard Spectrum H.E.S.S. Sources (II)

HESS, ApJ Letters, 794 (2014)
EO Angüner et al (HESS), ICRC 2017
HESS, A&A 612, A13 (2018)

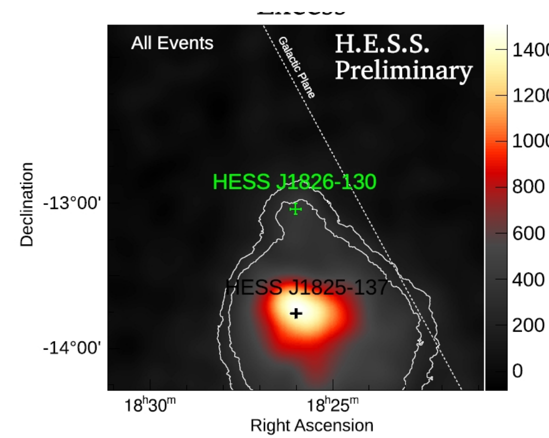
HESS J1641–463



HESS J1741–302



HESS J1826–130

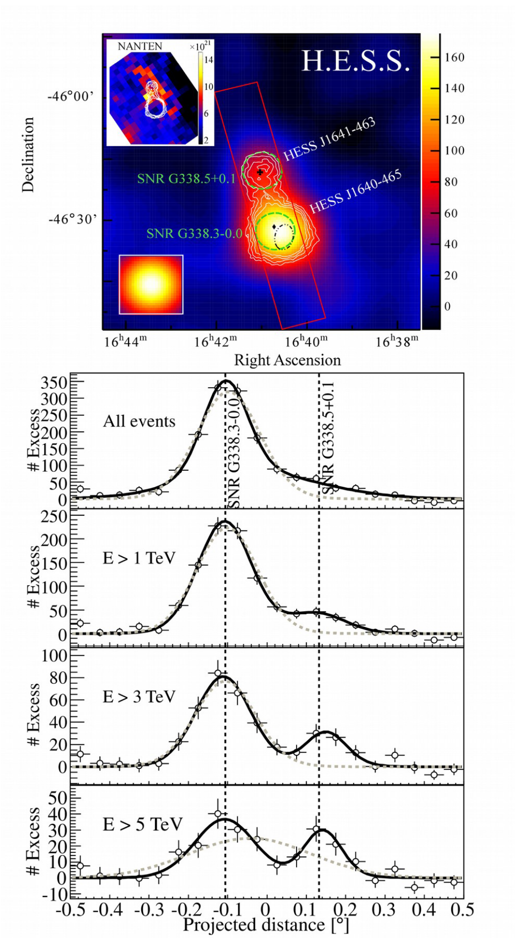


Source Name	Observation Period	Live-time h	Significance σ	Best Fit Position (J2000)	Extension (°)	Source Morphology
HESS J1641−463 (E > 4.0 TeV)	2004 - 2011	72	8.5	R.A.: $16^h41^m2.1^s$ Dec.: $-46°18'13.0''$	0.050 (UL)	Point-like
HESS J1741−302 (E > 0.4 TeV)	2004 - 2013	145	7.8	R.A.: $17^h41^m15.8^s$ Dec.: $-30°22'30.7''$	0.077 (UL)	Point-like
HESS J1826−130 (E > 0.5 TeV)	2004 - 2015	204	21.0	R.A.: $18^h26^m0.2^h$ Dec.: $-13°02'1.8''$	0.17 ± 0.02	Extended

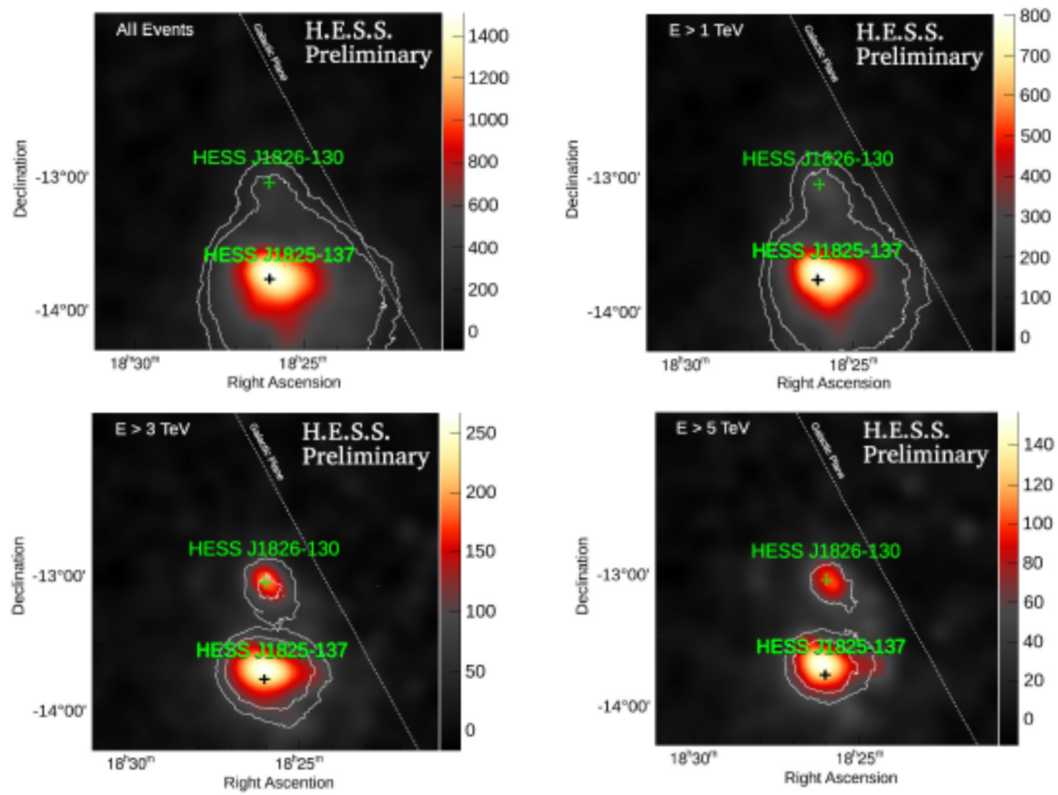
Hard Spectrum H.E.S.S. Sources (III)

HESS, ApJ Letters, 794 (2014)
EO Angüner et al (HESS), ICRC 2017
HESS, A&A 612, A13 (2018)

HESS J1641–463 (15% > 0.64 TeV)



HESS J1826–130 (40% > 0.4 TeV)



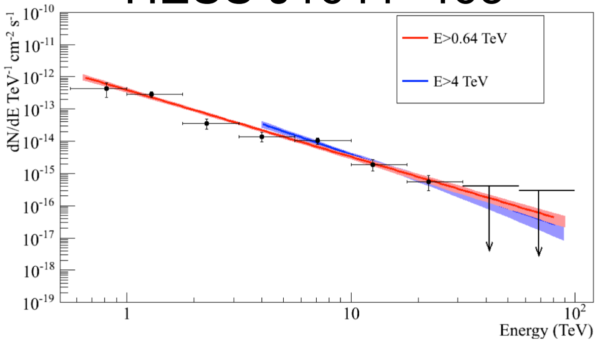
Analysis in energy bands is a powerful technique. Contamination decreases with the increasing energy threshold

Hard Spectrum H.E.S.S. Sources (IV)

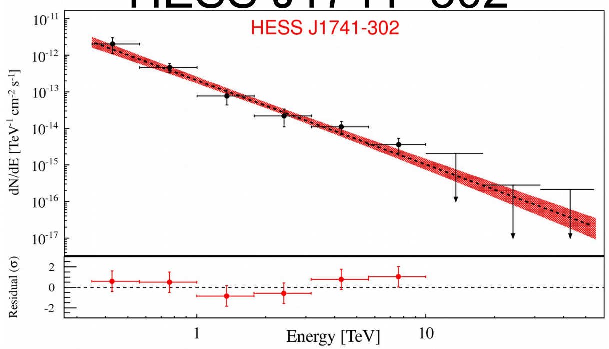
Spectra

HESS, ApJ Letters, 794 (2014)
EO Angüner et al (HESS), ICRC 2017
HESS, A&A 612, A13 (2018)

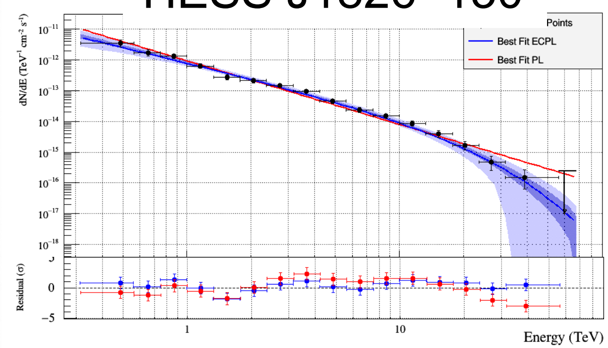
HESS J1641–463



HESS J1741–302



HESS J1826–130



Source Name	Spectral Model	Normalization (at 1 TeV) $10^{-13} \times$ cm^{-2} s^{-1} TeV^{-1}	Index	Cut-off Energy (TeV)	Flux (> 1 TeV) (Crab Unit %)
HESS J1641−463	PL	$3.91 \pm 0.69_{stat} \pm 0.8_{sys}$	$2.07 \pm 0.11_{stat} \pm 0.20_{sys}$	–	1.8
HESS J1741−302	PL	$2.1 \pm 0.4_{stat} \pm 0.4_{sys}$	$2.3 \pm 0.2_{stat} \pm 0.2_{sys}$	–	1.0
HESS J1826−130	ECPL	$8.28 \pm 0.68_{stat} \pm 1.6_{sys}$	$1.66 \pm 0.11_{stat} \pm 0.20_{sys}$	$13.5^{+4.7}_{-2.7}$	4.0

- Low statistics, systematics at higher energies → determining spectral features difficult
- Source contamination may have potentially distort the observed spectra

Hard Spectrum H.E.S.S. Sources (V)

ISM

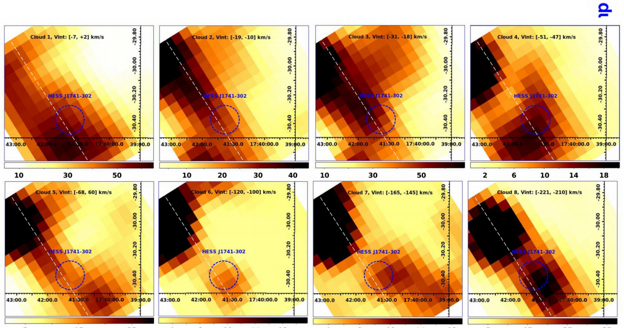
HESS, ApJ Letters, 794 (2014)
EO Angüner et al (HESS), ICRC 2017
HESS, A&A 612, A13 (2018)

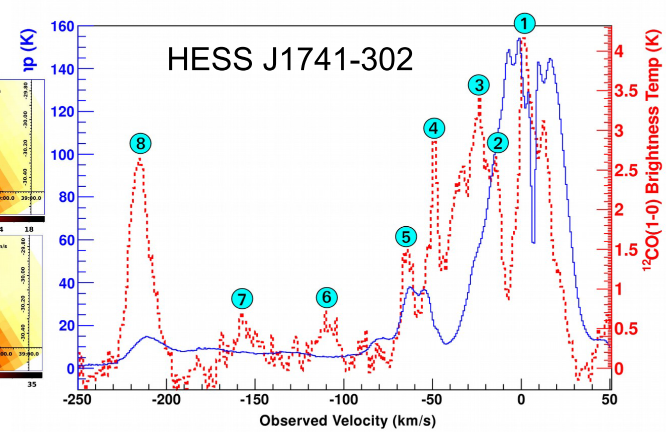
- Distribution of molecular gas is obtained by integrating the ^{12}CO 1 → 0 rotational line emission measured with the NANTEN Sub-millimeter Observatory

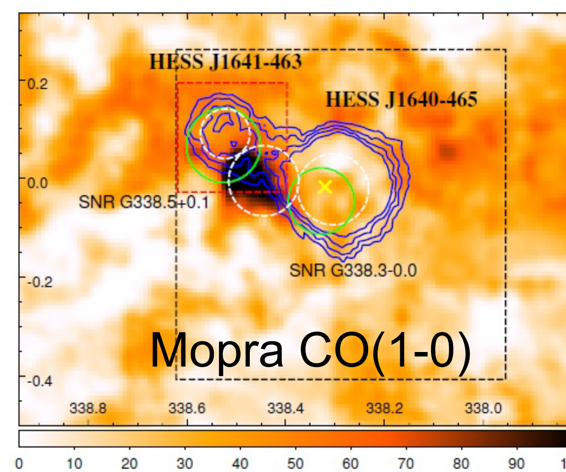
Source	J1641–463	J1741–302	J1826–130
N_{gas} [cm^{-3}]	~100	62 - 380	~600
Mass [10^5 M_{sun}]	~2.4	1.9 – 9.8	3.0
Distance [kpc]	~11	5 – 11.2	3.7 – 4.7

- HESSJ1641 ISM studies by Lau et al, MNRAS 464, 3757
  - High average ISM density >100 cm^{-3}
  - Dense gas (>10^4 cm^{-3}) bridge between TeV sources

HESS J1741-302





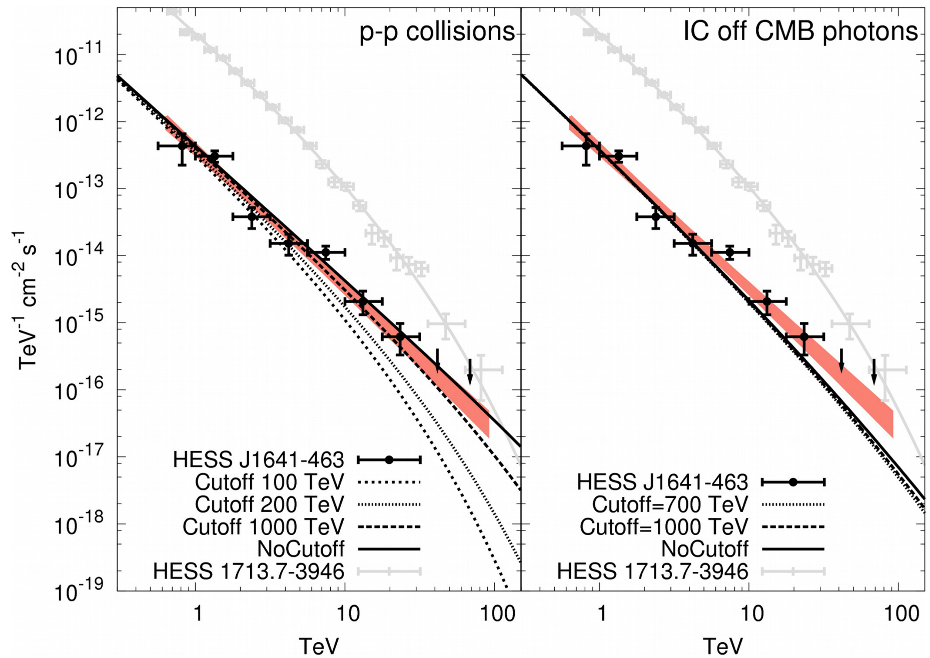


Hard Spectrum H.E.S.S. Sources (V)

Hadronic vs leptonic

HESS, ApJ Letters, 794 (2014)
EO Angüner et al (HESS), ICRC 2017
HESS, A&A 612, A13 (2018)

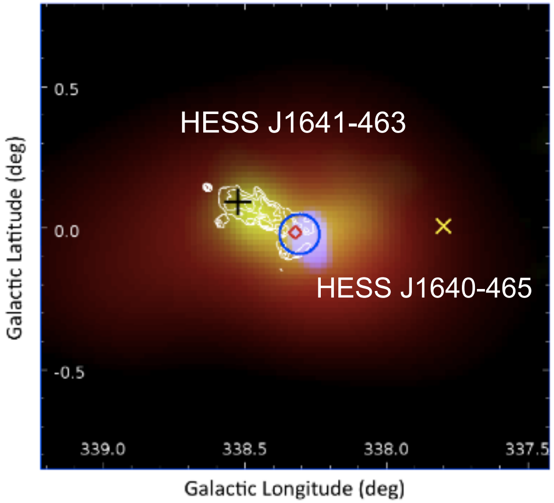
- If hadronic origin + gas regions properties, the parental particle spectra can extend up to at least several hundreds of TeV
  - **HESS J1641–463 → Wpp = 10^{48} erg**
  - **HESS J1826–130 → Wpp = 10^{47} erg**
  - **HESS J1741–302 → Wpp = [7.0 x 10^{46}, 1.5 x 10^{48}]**
- Leptonic origin is not discarded:
  - J1741–302 & J1826–130 could be leptonic
  - J1826–130 Vela X-like spectrum
- HESS J1641-463 case:
  - P-P collisions with a particle index of -2.1 → Protons: 100 TeV (99 CL)
  - IC off CMB photons with index -3.14. Electrons: 700 TeV (99% CL) → strongly disfavored

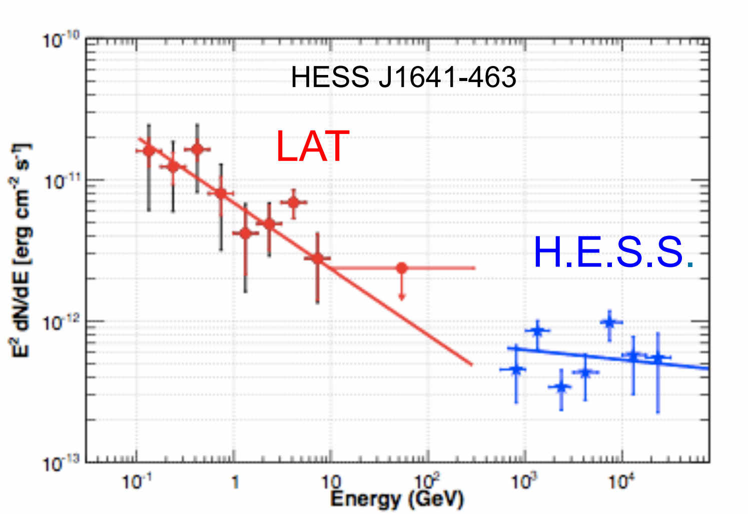


HESS J1641-463 & Fermi-LAT

Fermi-LAT, ApJL, 794, L16, 2014

- Softer spectrum with Γ= 2.47 ± 0.05 ± 0.06.
- The connection the hard H.E.S.S. spectrum remains unclear: two different mechanisms, or overlapping sources?

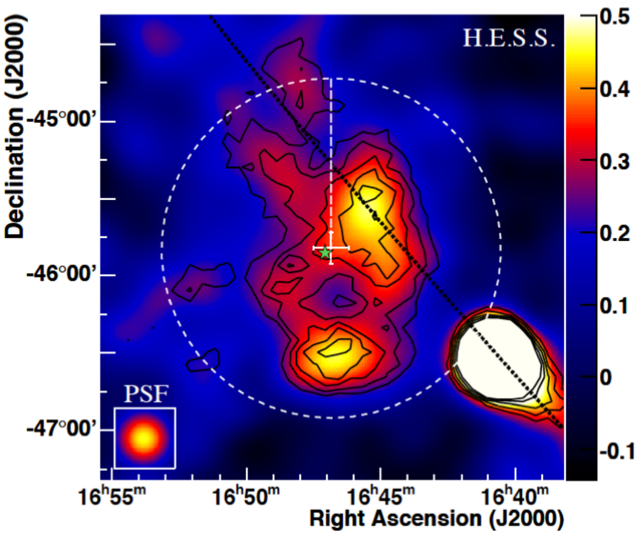


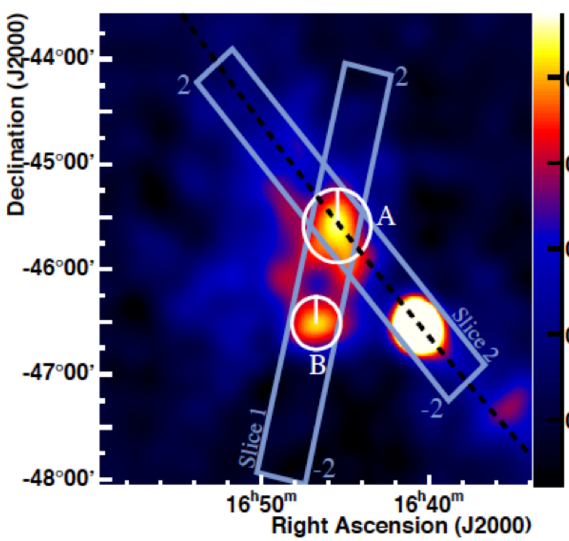


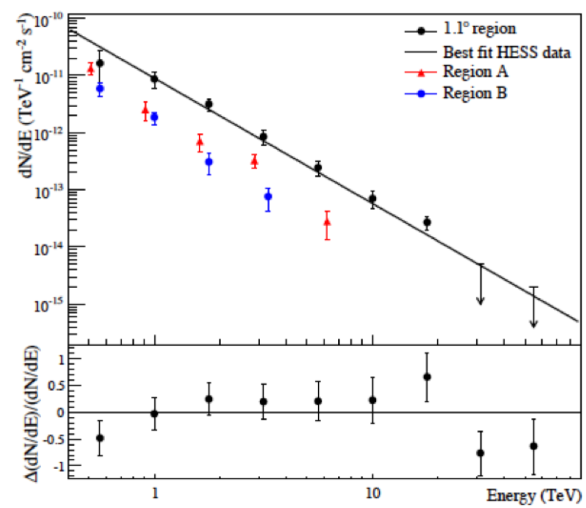
Another candidate from H.E.S.S.: Westerlund 1

H.E.S.S. A&A 537, A114 (2012)

- Massive stellar cluster, superbubble candidate
- Hard power-law index 2.19 +/- 0.08_{stat} +/- 0.20_{syst} at VHEs
- Very extended source 1.1 deg, complicated analysis
- Young massive star clusters plausible PeVatron candidates: See talk of R. Yang
- Deeper study is needed in this and other candidates: Westerlund 2, Cygnus Cocoon, …

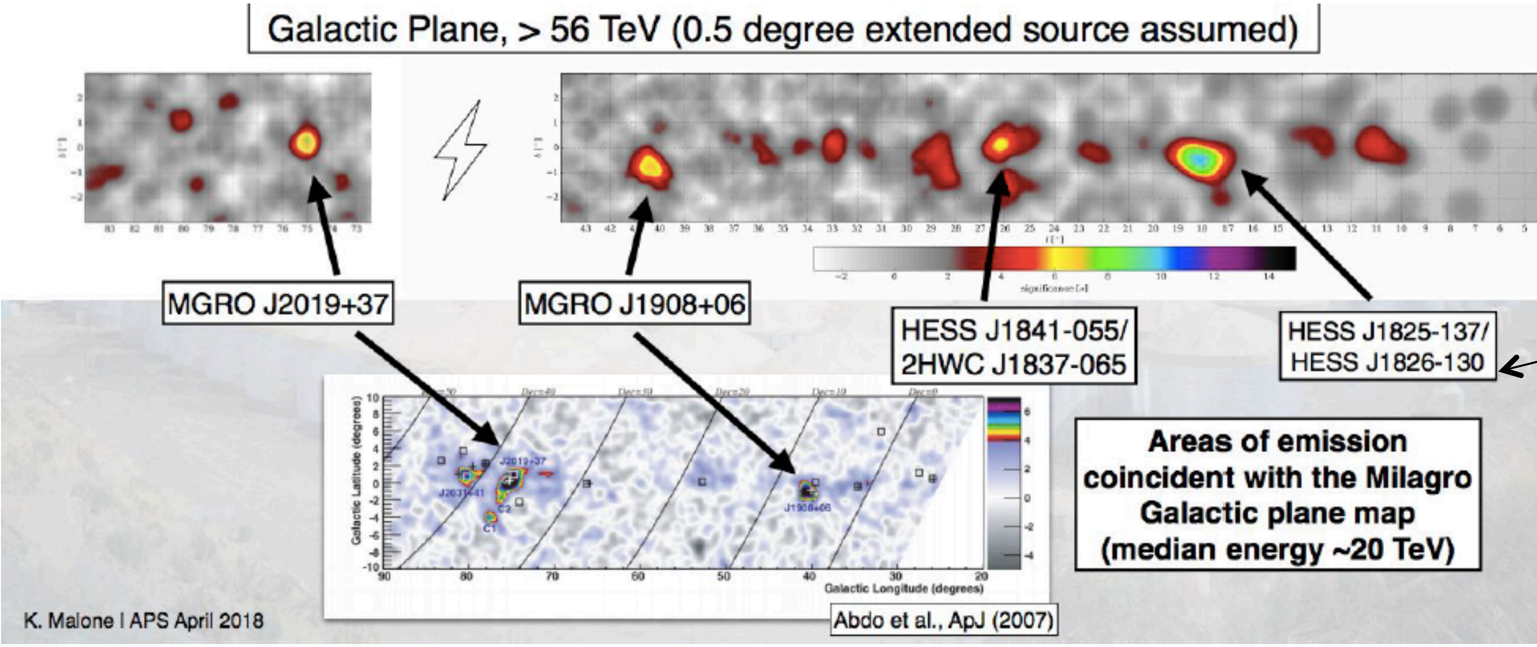






HAWC PeVatron Candidates

Andrea Albert @ CIPANP 2018

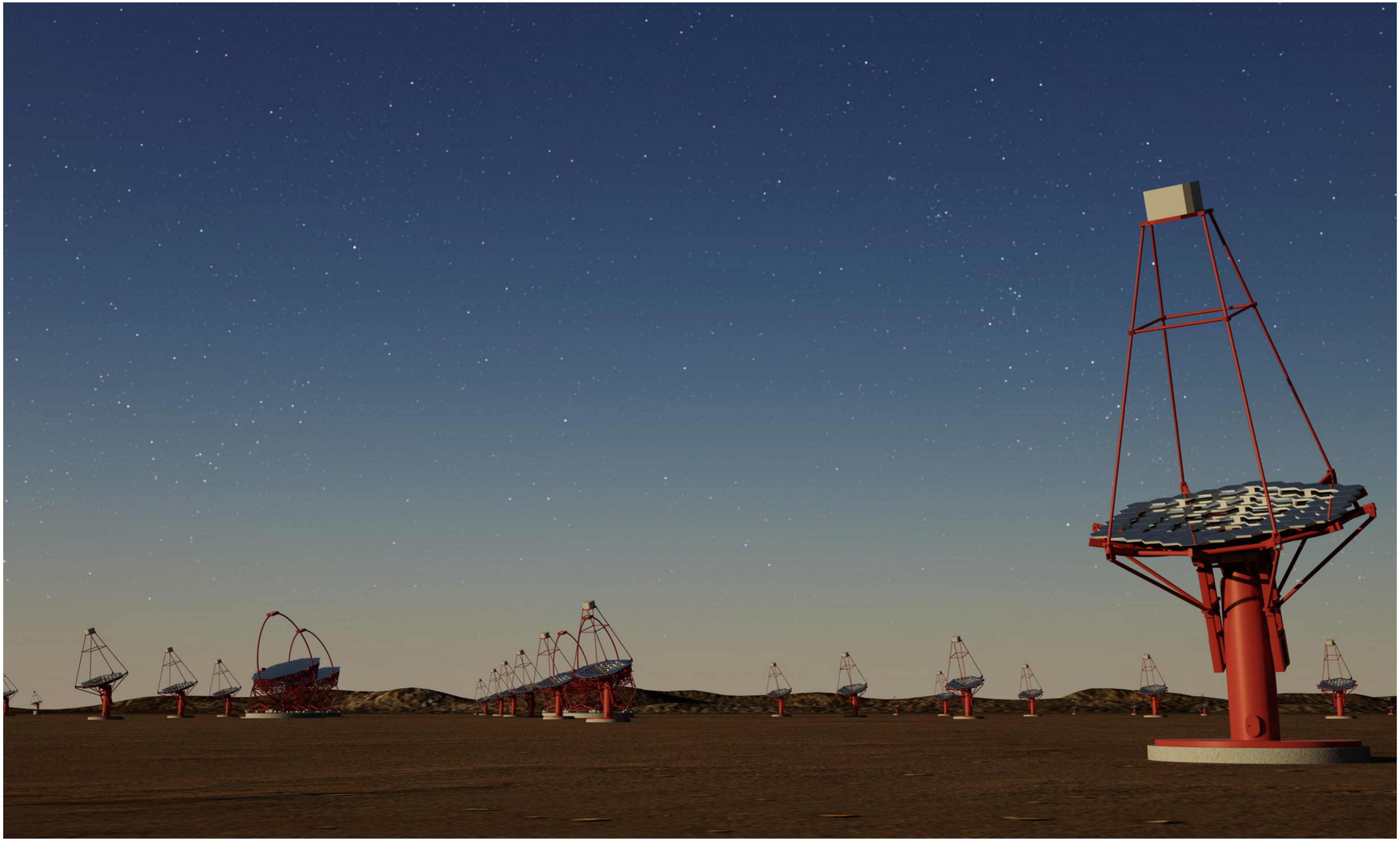


One of the H.E.S.S. hard spectra sources

- Preliminary analysis has found high-energy (>56 TeV) sources
  - PeVatron candidates
  - High-energy sources are coincident with pulsars
  - HAWC team is working in spectral fits
- More info on HAWC sources by Hugo Ayala later today

CTA

A crucial instrument for PeVatron searches

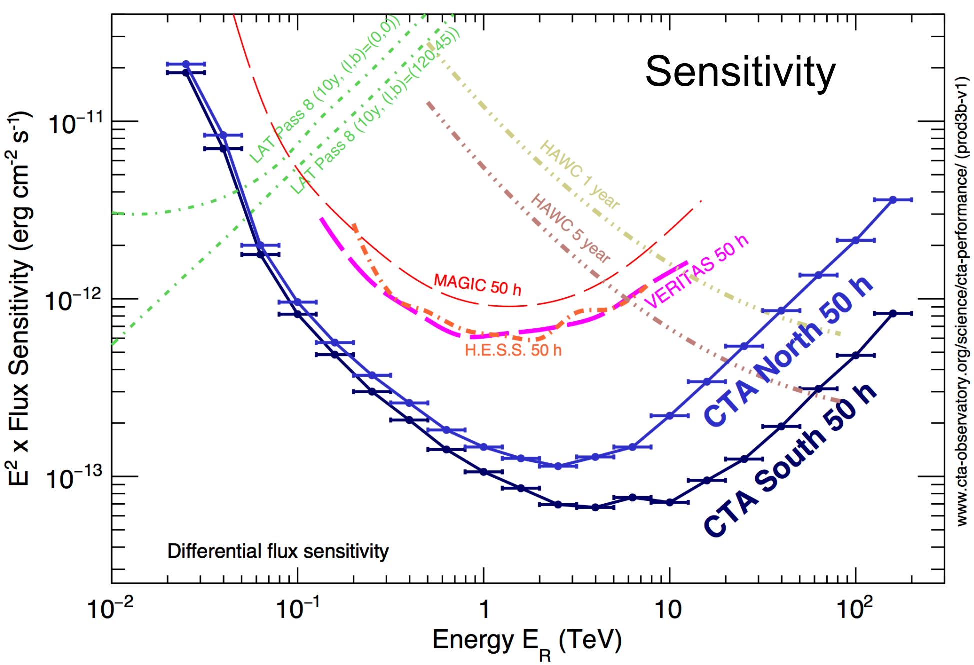


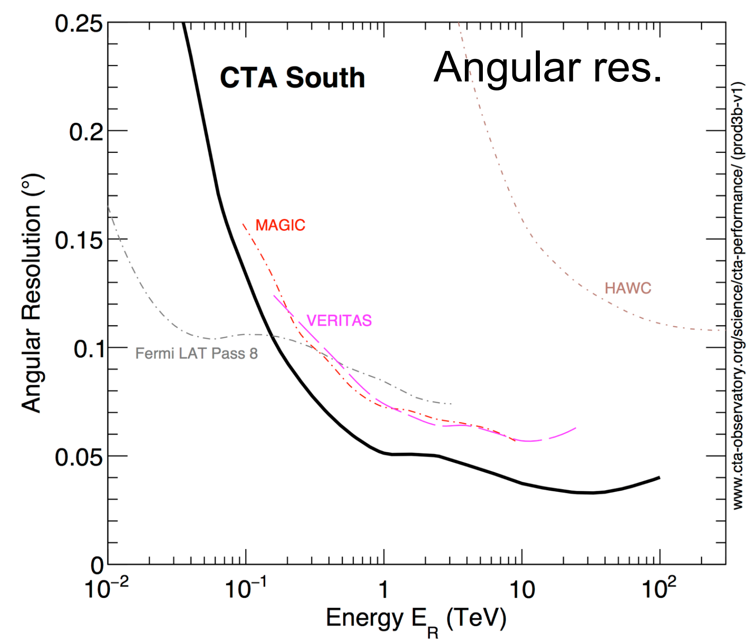
Enhance sensitivity at higher energies

CTA will, w.r.t. current IACT instruments:

- Enhanced energy range, up to 300 TeV
- Enhanced energy and angular resolution
- Reduce source confusion
- Measure with higher precision spectral features such as spectral cutoffs

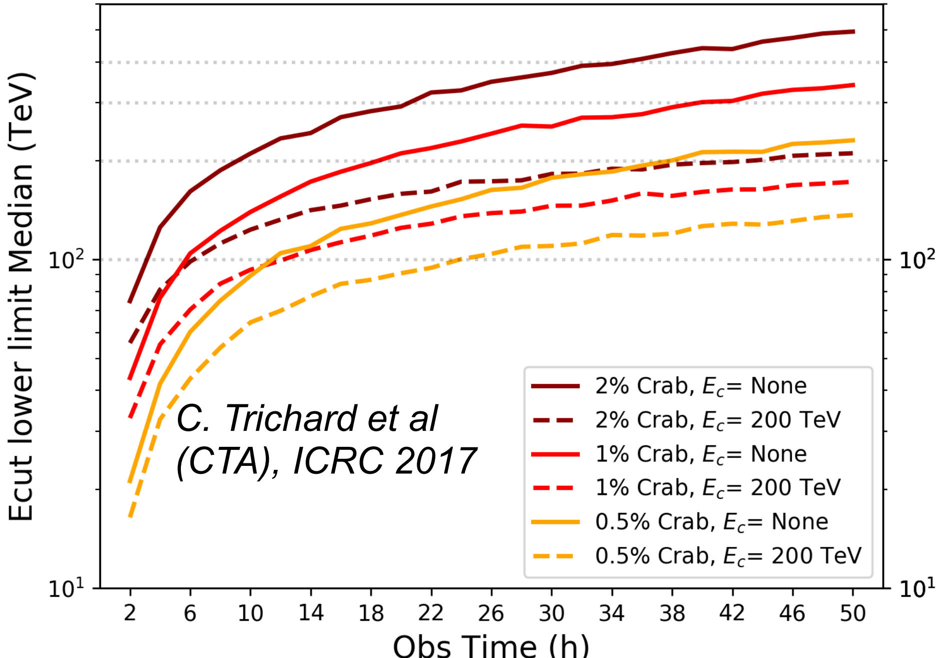
More details on talk of S. Funk yesterday





CTA and PeVatron Searches

- Deeper flux and higher angular resolution to study of the GC
- Extend the search of PeVatrons to the >100 TeV range:
  - Use the CTA Galactic Plane Scan as finder and then follow-up brightest sources with no sign of a cut-off
  - Study H.E.S.S. hard spectrum sources and HAWC candidates
  - Determine spectral cutoff lower limits after a dozen of hours



Summary and Conclusions (I)

- CR population of Galactic origin around 1 PeV (the knee)
  - SNR traditional candidates as originating places
- TeV gamma-ray emission can trace PeV CRs if:
  - Appropriate spectral characteristics e.g. lack of cutoff at tens of TeV
  - Enough target material e.g. in MCs
- SNRs accelerate CRs, but none detected as PeVatron up to now
  - Could not find evidences of for PeVatron nature in young SNRs
  - Alternative accelerators such as massive star clusters?
- Evidences of a PeVatron at the GC:
  - Interpreted as continuous CR injector over ~ few 1000 yr by Sgr A* Central back hole
  - Should be more powerful in the past to account for detected CR flux alone
  - Stronger contribution by CR sea?

Summary and Conclusions (II)

- H.E.S.S. hard spectra sources
  - very hard spectra and coincident dense gas regions
  - scenarios where parental population of hadrons extends up to several hundreds of TeV.
  - may be representing a population of CR accelerators active in the Galaxy
  - alternative leptonic interpretations possible
  - issues: sources confusion, low counts, systematics
- Several PeVatron candidates from HAWC, spectral analysis to come
- Are PeVatron candidates detected by H.E.S.S. and HAWC electron or proton accelerators? Are they PeVatrons?
- Promising future for the Galactic CR accelerators study with CTA

+ SGSO (HAWC South) + Lhaaso + EAS Radio Measurements + MWL +…