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Young SNR Cassiopeia A as a PeVatron: some observational constraints

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LHAASO collaborations

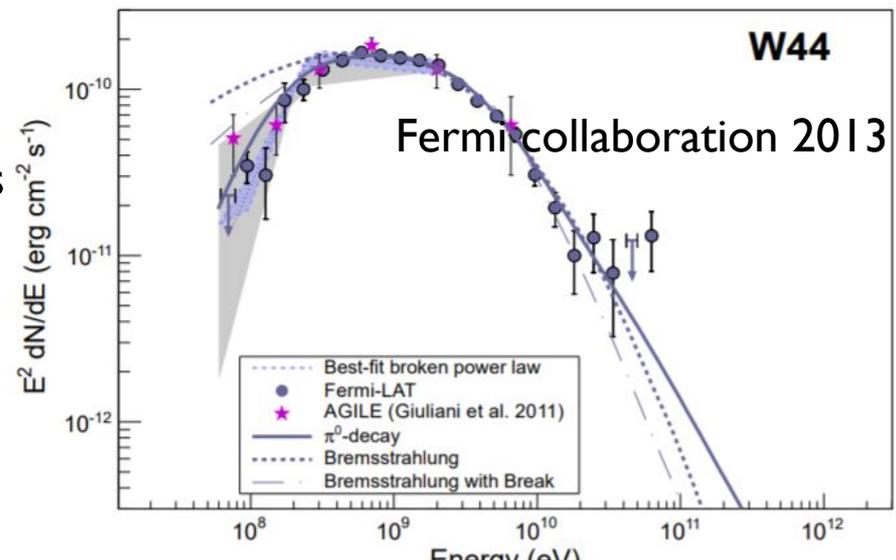
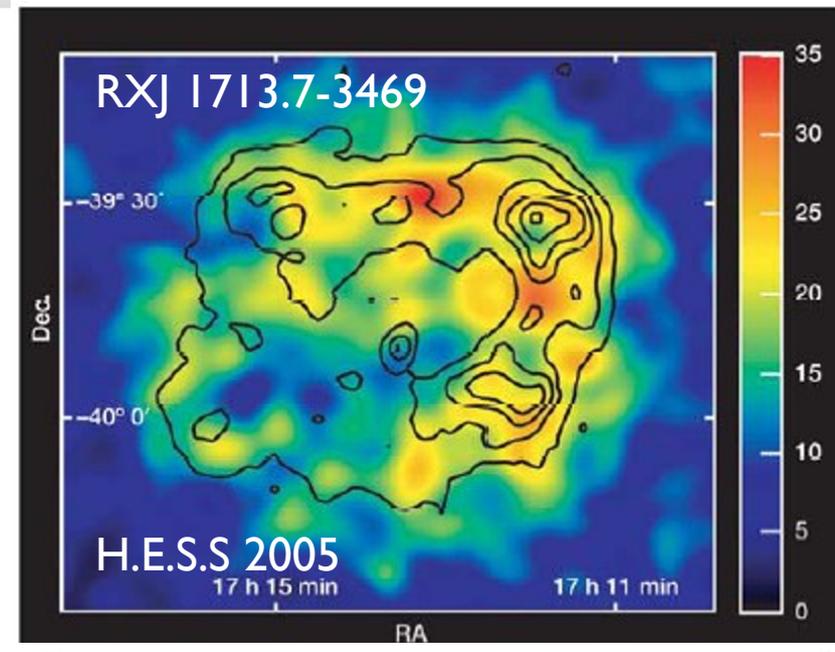
[ApJL, 961 \(2024\), 43](#)

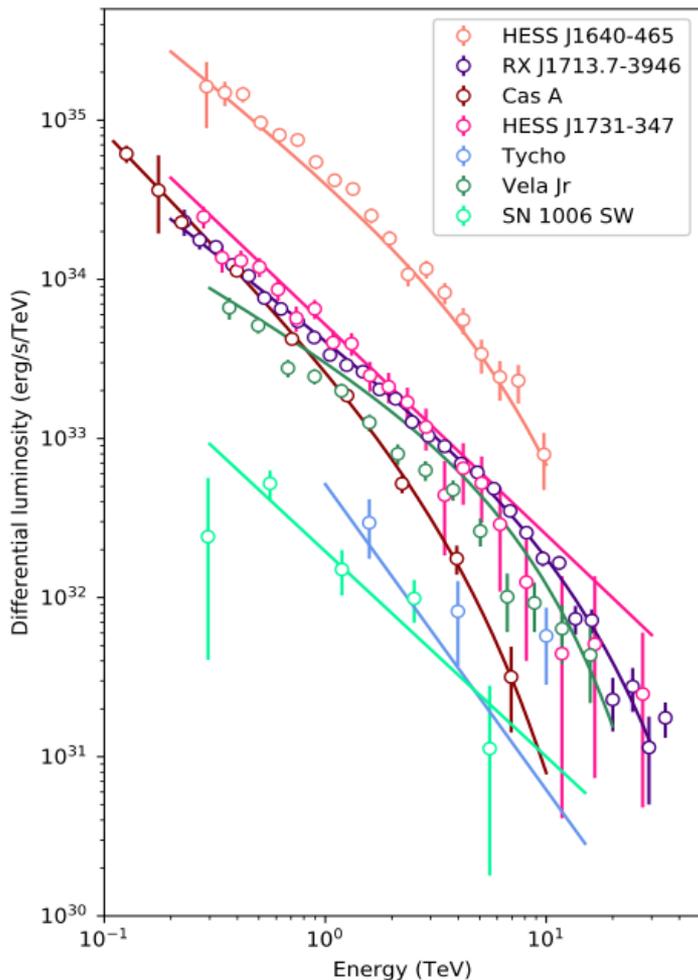
SNRs as CR source/Pevatrons



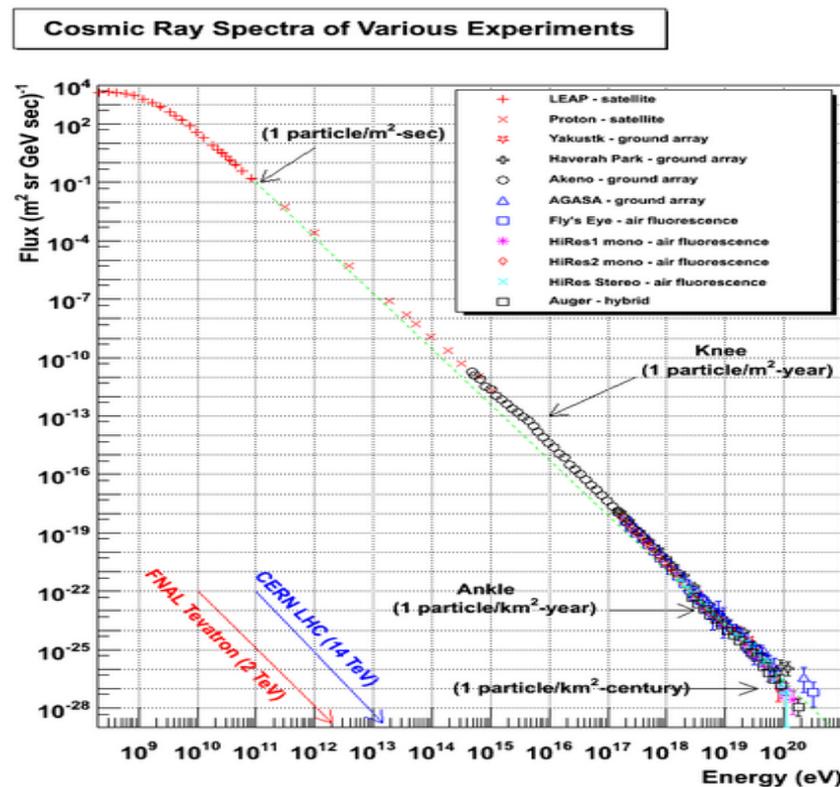
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- Powerful enough to account for all Galactic CRs
- DSA efficient enough to extract 10% of Kinetic power
- Magnetic amplification observed (x-ray filaments)
- Gamma-ray observations reveal strong proof/hints
- Clear Pion-decay feature in mid-age SNRs (AGILE and Fermi LAT)
- Break at ~ 10 GeV, Cannot account for all CRs up to PeV





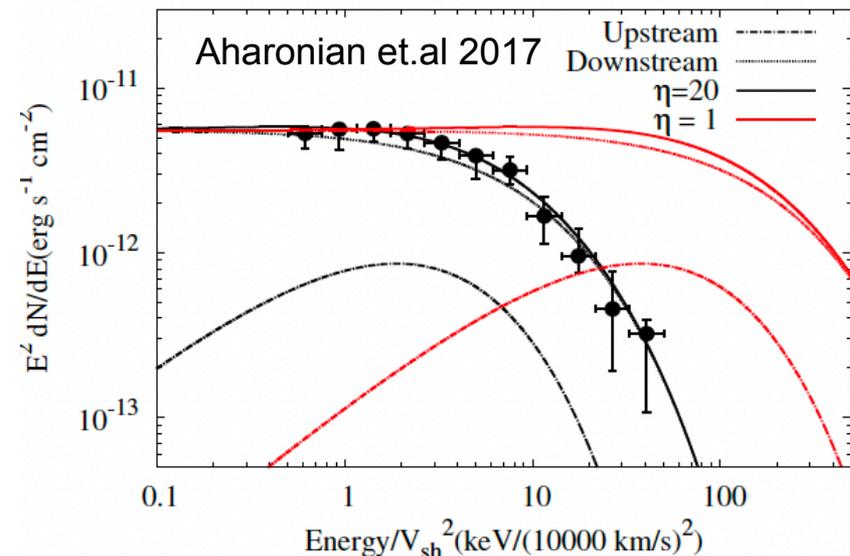
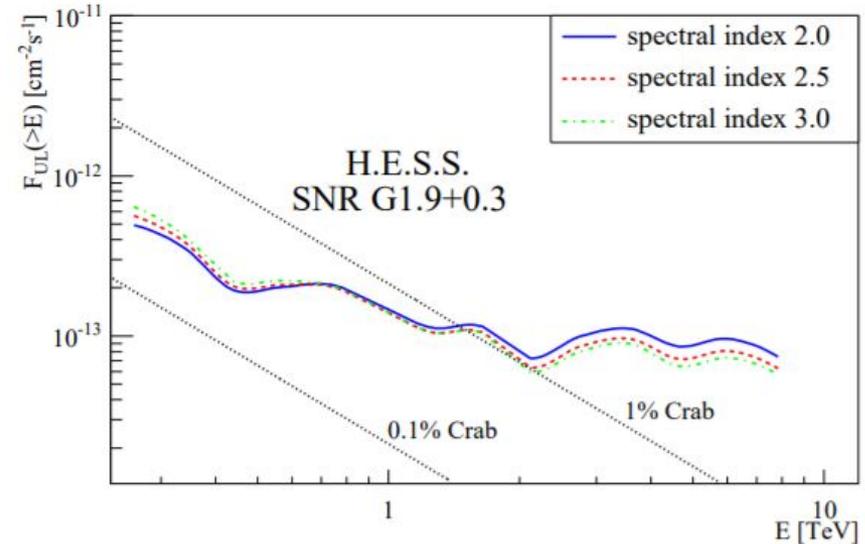
- All young SNRs show soft spectrum or early cutoff at ~ 10 TeV
- corresponding to CR energy of 100 TeV
- Hard to address a single power law spectrum of CRs up to PeV



Very young SNRs?



- The youngest SNR in the Galaxy:
G1.9+0.3, $t \sim 100$ yr
- VHE protons cannot propagate more than 30 pc.
- HESS reveals $L(>1 \text{ TeV}) < 1e32 \text{ erg/s}$ can be used to set limit on proton energy budget.
- Considering a high density in the vicinity (near GC), the total energy on VHE protons are below $1e45 \text{ erg}$. Not enough to account for the CR flux up to the knee.
- X-ray observations also reveal a low acceleration efficiency



X-ray observations on G1.9+0.3 (Aharonian, Sun & Yang 2017)

- electron acceleration is cooling limited
- synchrotron cutoff in X-ray band only depends on shock speed and diffusion coefficient (confinement/acceleration efficiency)

$$\epsilon^2 \frac{dN}{d\epsilon} \propto \epsilon^2 (\epsilon/\epsilon_0)^{-1} [1 + 0.38(\epsilon/\epsilon_0)^{0.5}]^{11/4} \exp[-(\epsilon/\epsilon_0)^{1/2}] .$$

with

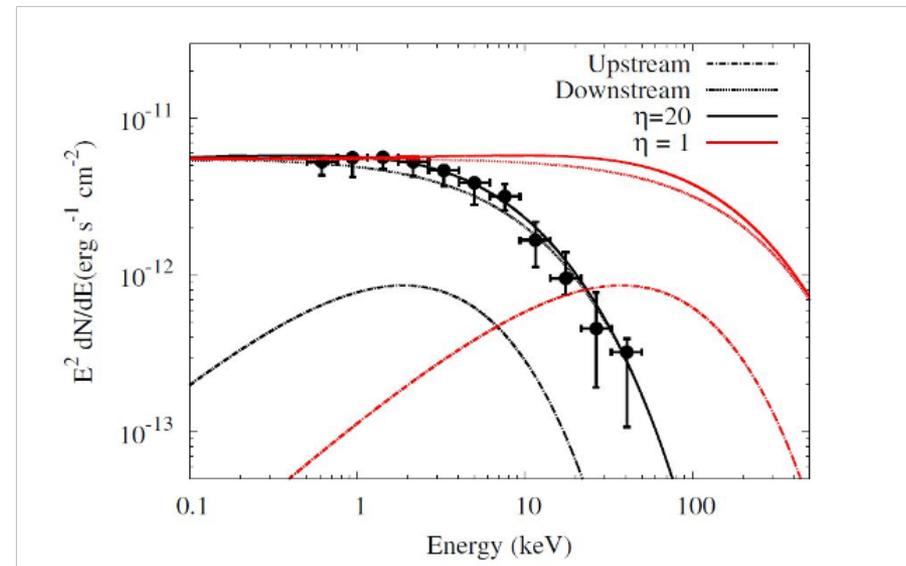
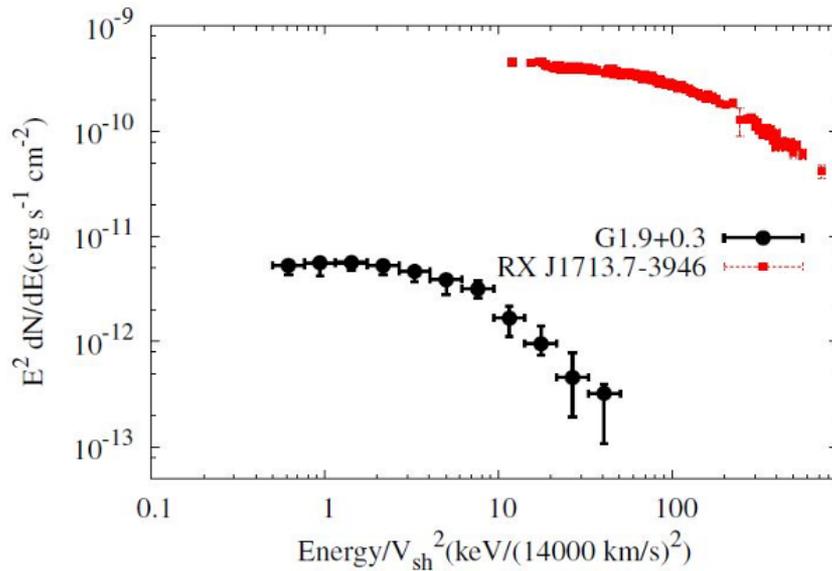
$$\epsilon_0 = \hbar\omega_0 = \frac{2.2 \text{ keV}}{\eta(1 + \kappa^{1/2})^2} \left(\frac{u_1}{3000 \text{ km s}^{-1}} \right)^2 ,$$

Very young SNRs



X-ray observations on G1.9+0.3 (Aharonian, Sun & Yang 2016)

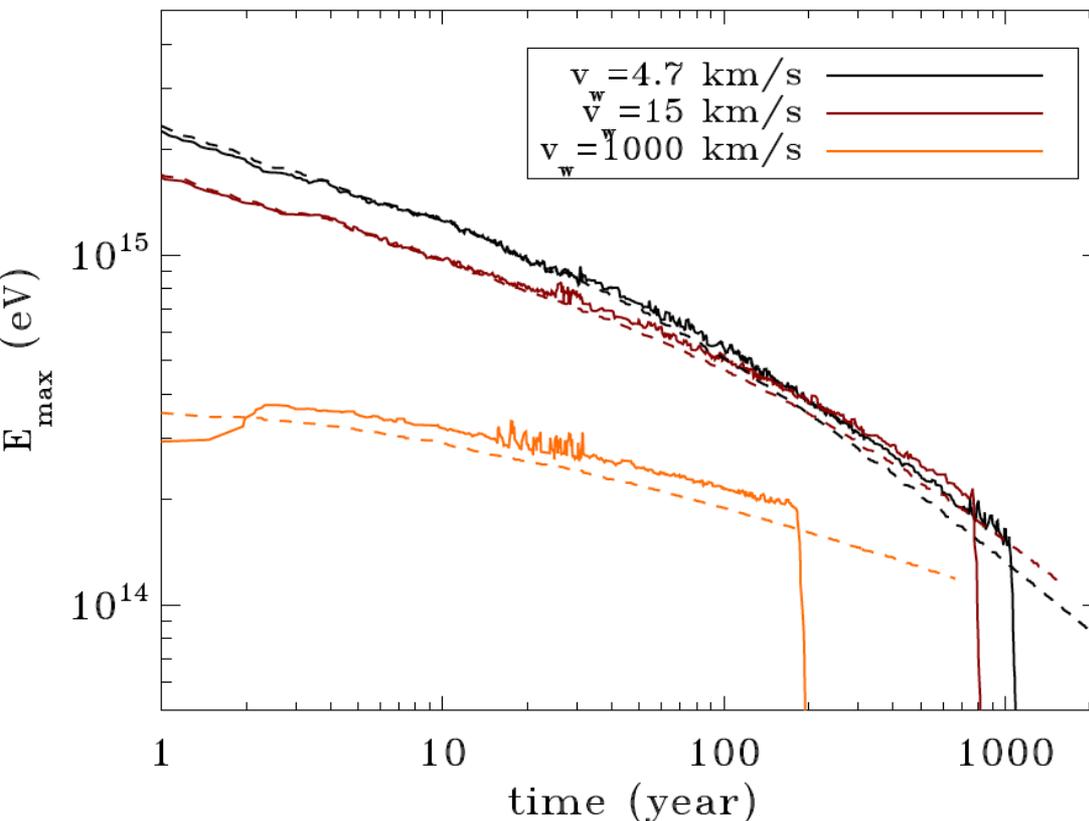
- Shock speed $\sim 14,000$ km/s
- in the Bohm diffusion limit the synchrotron peak should be at around 20 keV but is detected at 1 keV
- Large η derived ($D \sim \eta D_{\text{bohm}}$)
- Not efficient accelerator
- In comparison, RX J1713 and Cas A has a $\eta \sim 1$



Cas A is special



- Dense environment (dense wind in red giant)
- Larger escaping current and more efficient magnetic field amplification
- Higher cosmic ray energy (Schure & Bell 15, Bell et.al 13)



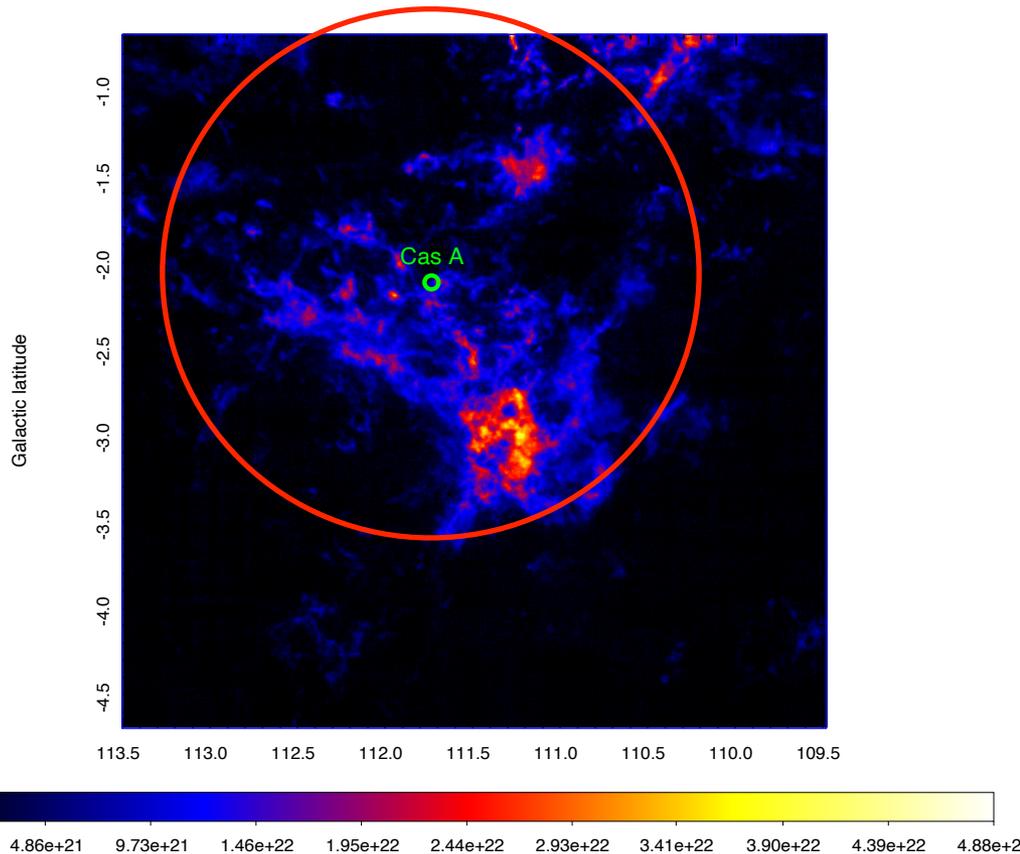
Can be Pevatron at first decade

PeV CRs already escape from the remnant?

Cas A is special



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Giant Molecular clouds in the vicinity
(Ma et.al 2019 MWISP survey)

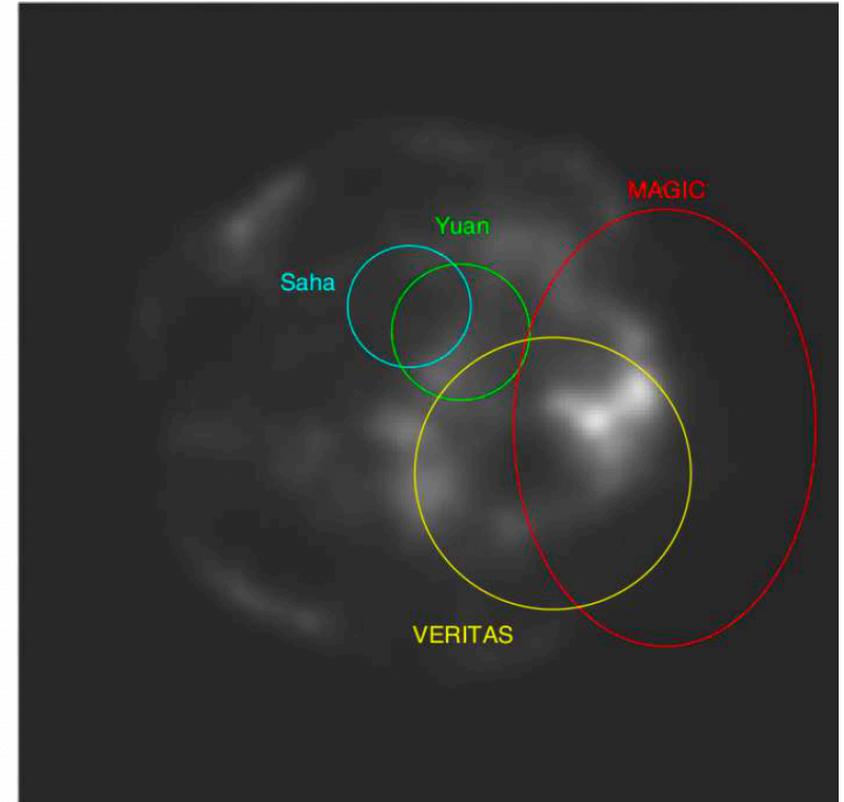
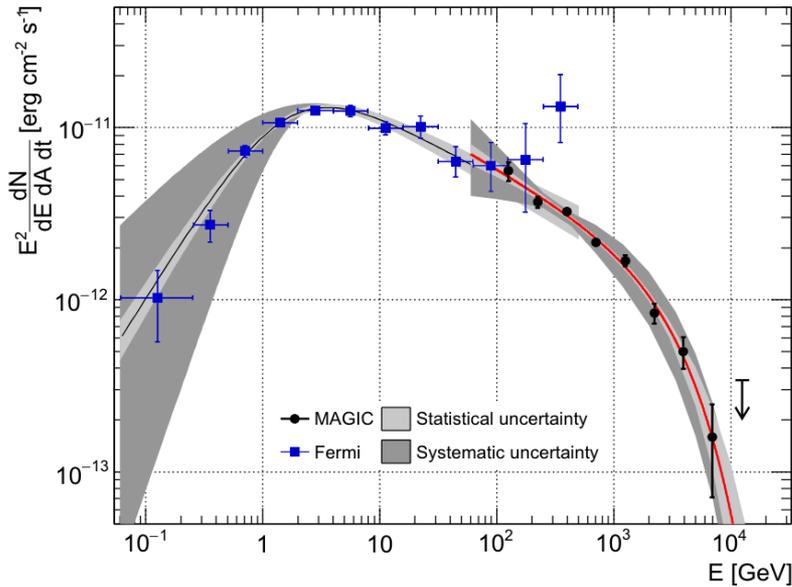
average cubic density $> 10 \text{ cm}^{-3}$

total mass $\sim 10^6$ solar mass

young age (~ 340 yrs), CR still within
100 pc (red circle)

best site to constrain the escaped CRs

Cas A is special

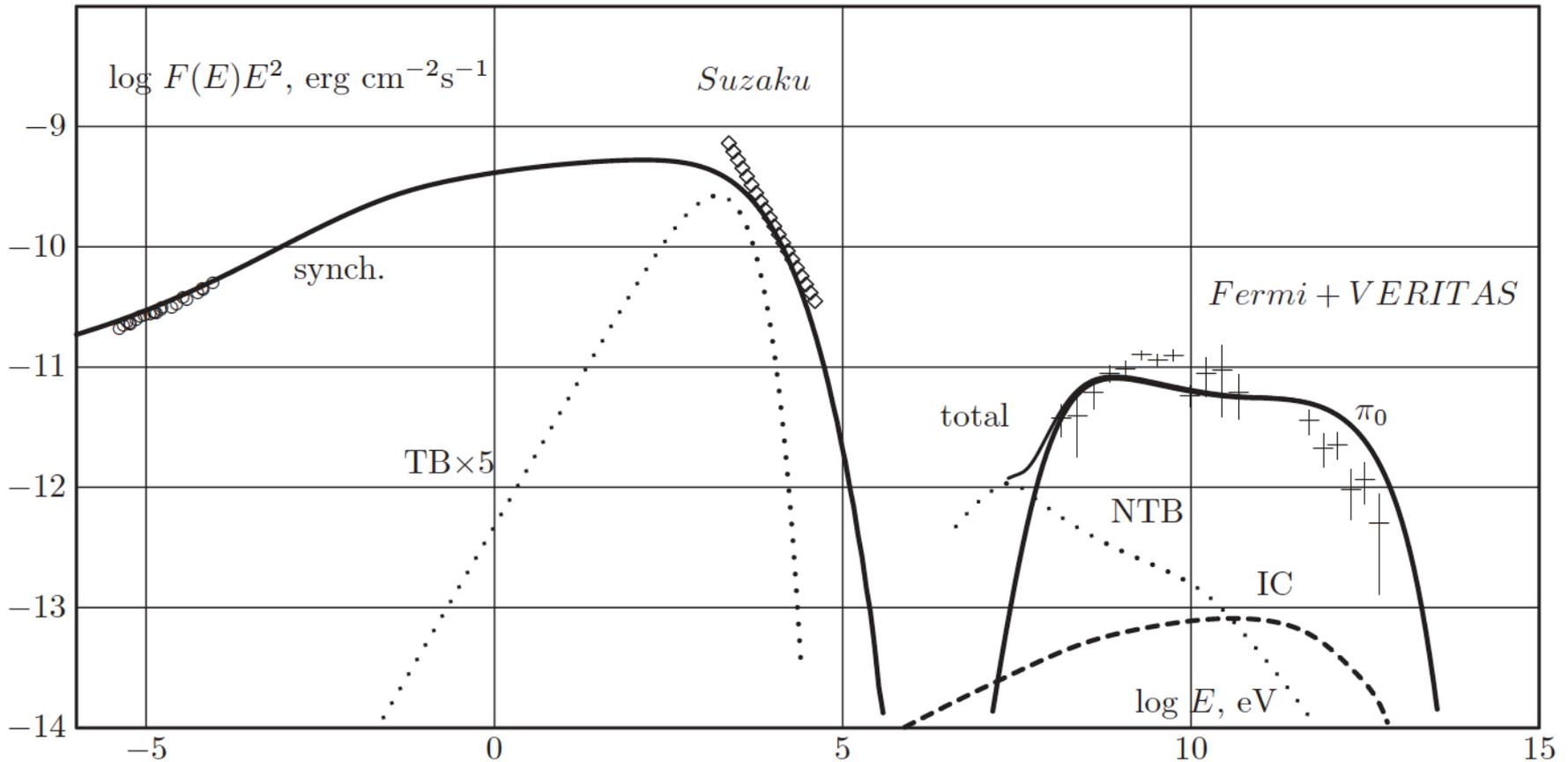


Grefenstette et.al 2015

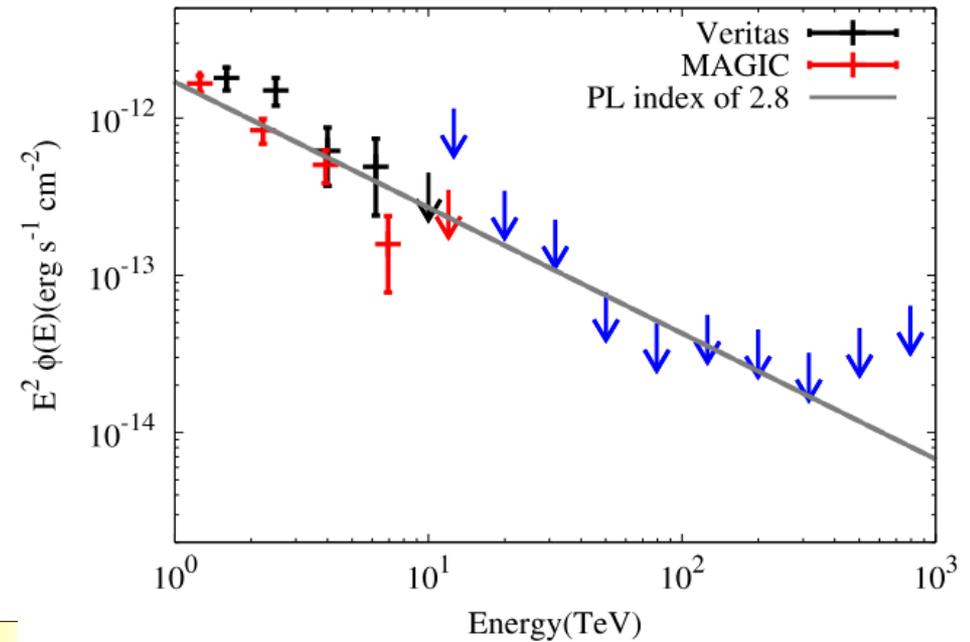
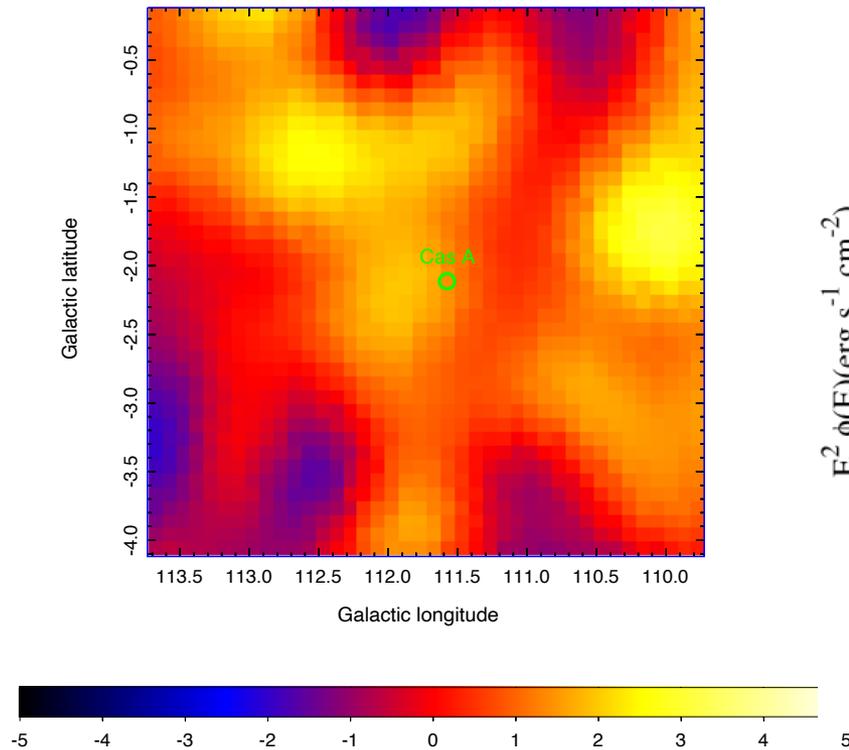
Nustar observations Show clear On-going acceleration (also in Woo et.al 2024)

Magic collaboration 2017 reveal hint for cutoff

Cas A is special



Multi-wavelength fitting, required a acceleration efficiency of more than 20%
(Zirakashvili et.al 2014)



KM2A significance map above 25 TeV

Two scenarios

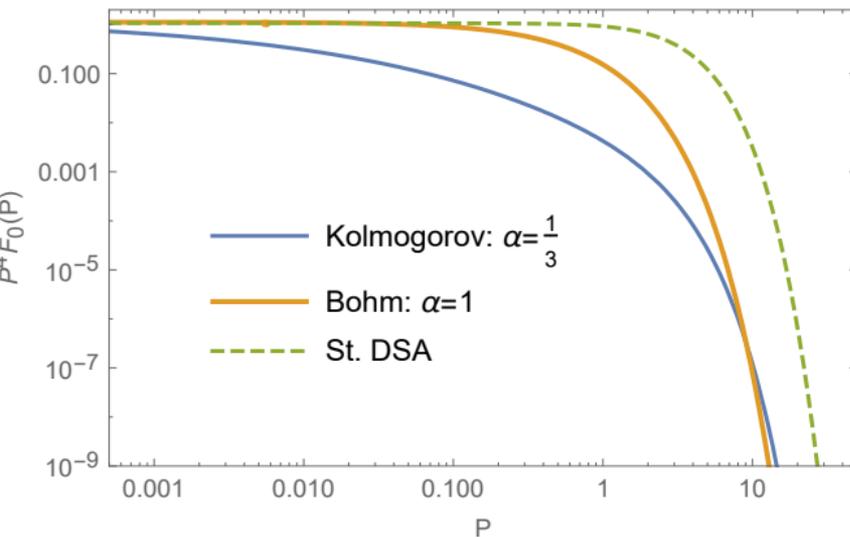


1. Cas A is active PeVatrons (and gamma-ray emitter) with a softer CR spectrum (2.4-2.7). KM2A upper limits for **Point source** at about 100 TeV can give constraints.
2. Cas A was a PeVatron and PeV protons have escaped, the **diffuse emission** around can set upper limit.

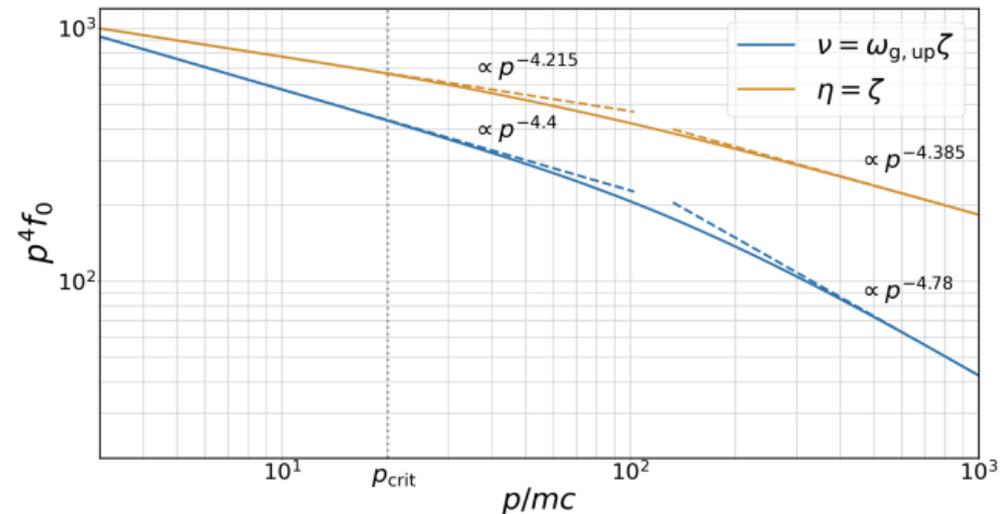
Case I: softer PeVatron



- I. Cas A is active PeVatrons (and gamma-ray emitter) with a softer CR spectrum (2.4-2.7). KM2A upper limits for **Point source** at about 100 TeV can give constraints.



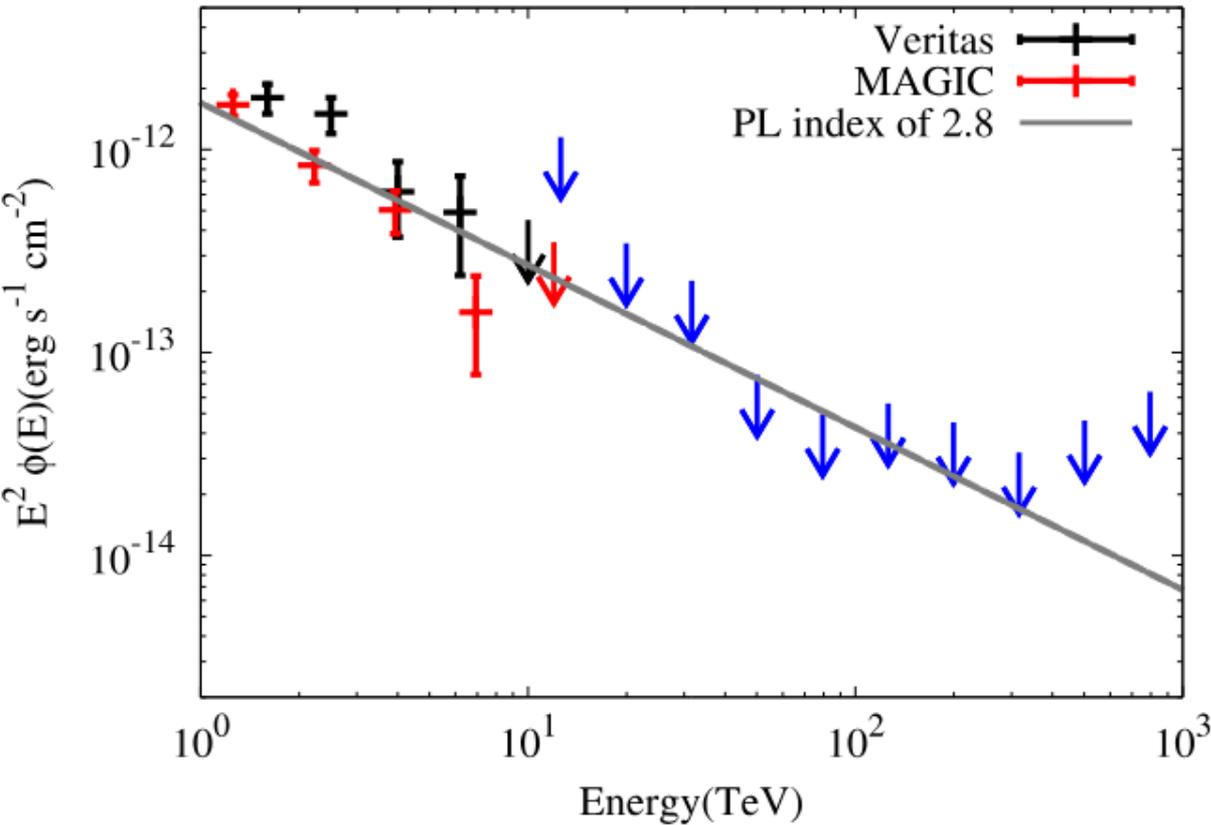
Malkov and Aharonian 2018



Shirin et.al 2025

- Cas A can still be PeVatron, but with a softer injection spectra (2.4-2.7)
- VHE gamma-ray on point source can set stringent upper limit.

Case I: softer PeVatron



The power-law index must be larger than 2.8 (proton index of 2.9)

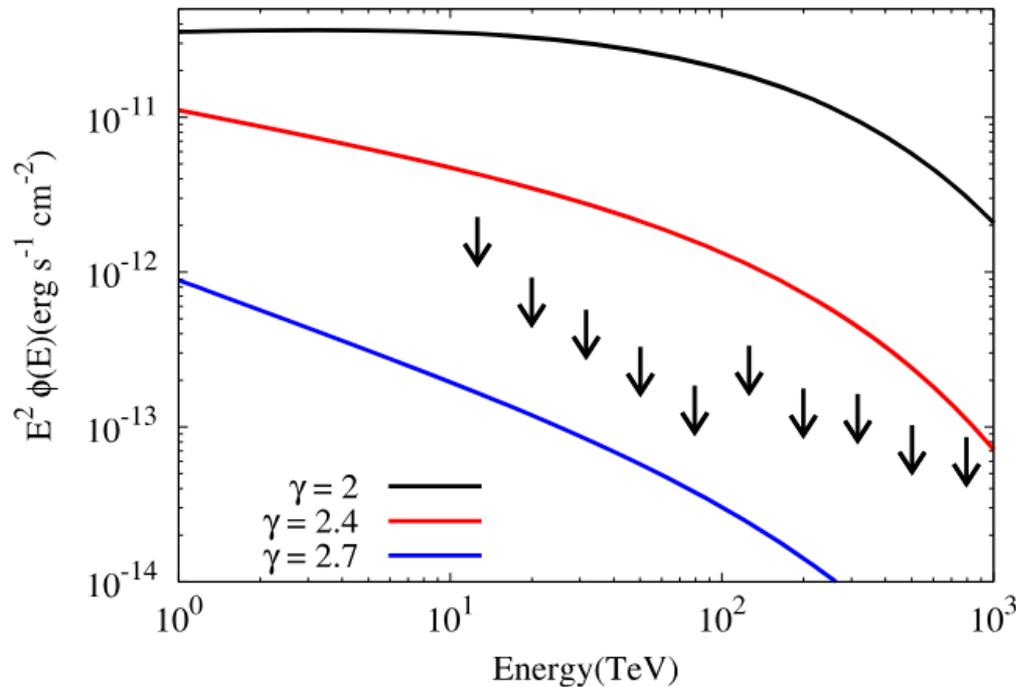


2. Cas A was a PeVatron and PeV protons have escaped, the diffuse emission around can set upper limit:

in any case the diffusion length should be smaller the $c \cdot t \sim 110 \text{ pc} \sim 1.8 \text{ degree}$. The flux upper limit from **1.8 degree disk** region should be the most conservative case.

- **How many > 100TeV CRs required?**
- Total CR luminosity $1-3 \times 10^{41} \text{ erg/s}$ above 1 GeV (e.g., Drury 12, from Galprop)
- $1.5 - 5 \times 10^{40} \text{ erg/s}$ for index of 2.0, $1.0-3.0 \times 10^{39} \text{ erg/s}$ for index of 2.4
- Cas A type once per century :
 - ~ $5 \times 10^{49} \text{ erg}$ for index of 2.0
 - ~ $3 \times 10^{48} \text{ ergs}$ for index of 2.4

Case II : PeV CR escaped

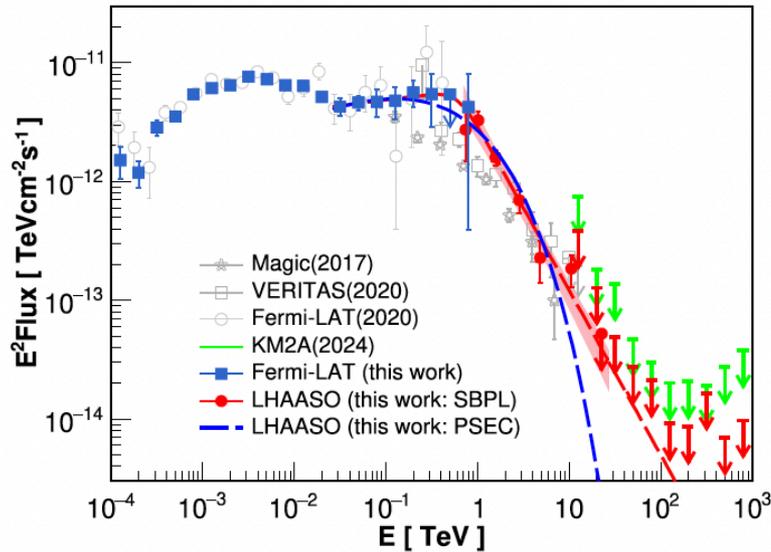


- total CR power above 100 TeV < $3e47$ erg ($n \sim 10 / \text{cm}^3$)
- The required CR power depends on index.
- can only consistent with theoretical requirement with index > 2.6 (assuming Cas A type as the only PeVatron)
- Even for a lower energy density ($n \sim 1 / \text{cm}^3$), injection index > 2.4

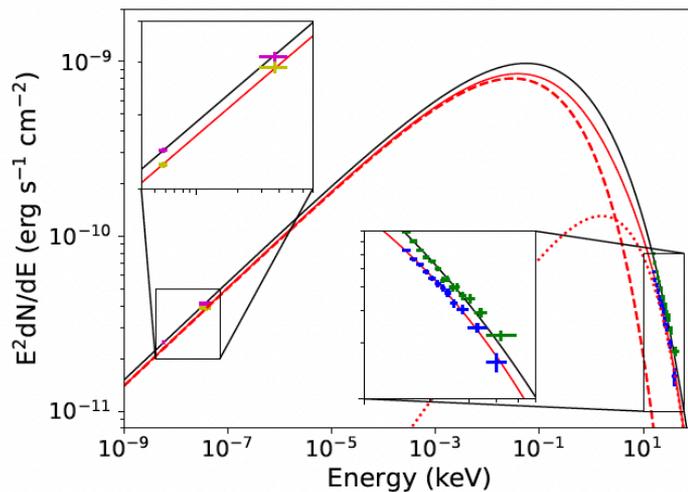


- In most cases there are strong tension with hypothesis that Cas A - type SNRs as major PeVatrons.
- Softer injection spectrum seem feasible, but also require major modification to the current CR propagation model (very soft injection spectrum and different energy dependence in confinement time)
- Our method is very conservative and robust:
Much larger integration area in the the diffusion regime
No GDE are subtracted (GDE impact is also small)

Multi-wavelength

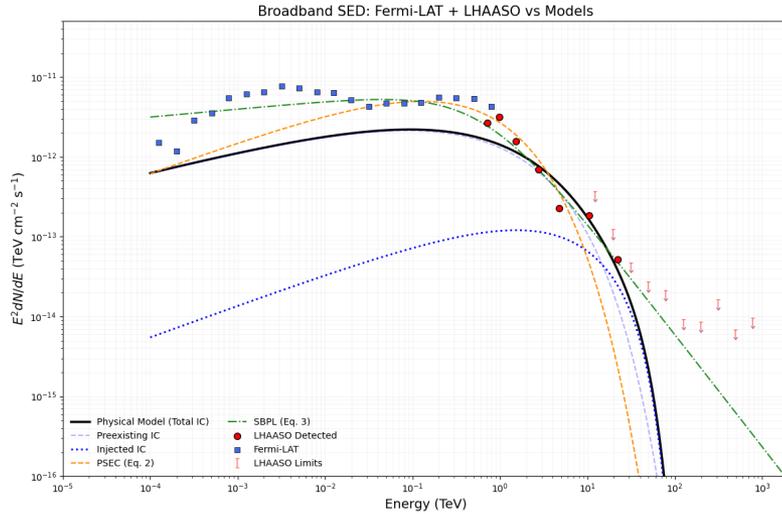


- Fermi LAT/WCDA reveal a bump at GeV-TeV band, a second component? (LHAASO collaboration 2025)

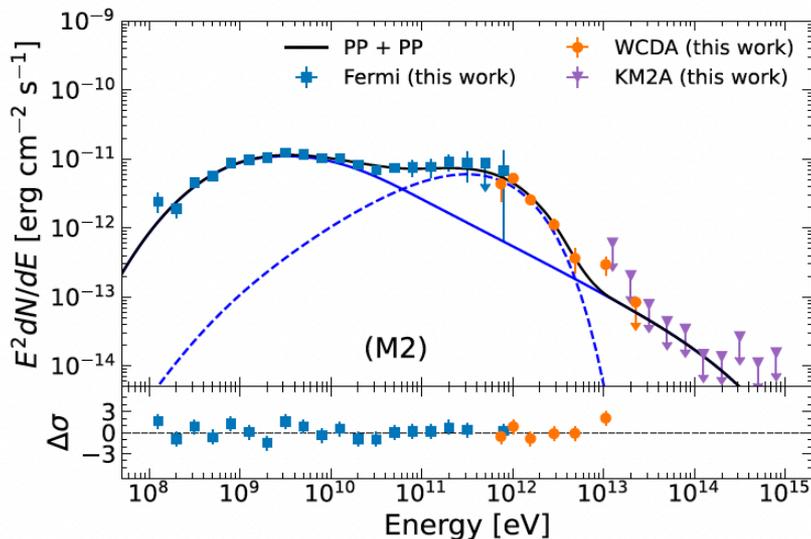


- Nustar reveal on-going acceleration of electrons up to 30 TeV (woo et.al 2024)

Multi-wavelength



- leptonic emission cannot account for the second component
- radio-Nustar reveal a electron spectral index of 2.2, consistent with DSA, but in tension with p-p model, and Soft injection scenario of KM2A study
- cutoff in CRp spectrum (~ 30 TeV) also in slight tension with the electron cutoff (~ 30 TeV)





- KM2A have set stringent limit on the total PeV CRs injected by Cas A
- Soft injection spectrum is still possible, but in tension with X-ray/multiwavelength data