UNIVERSITÉ
DE GENÈVE
FACULTÉ DES SCIENCES
Département de physique
nucléaire et corpusculaire

Gamma rays as tracer for cosmic rays

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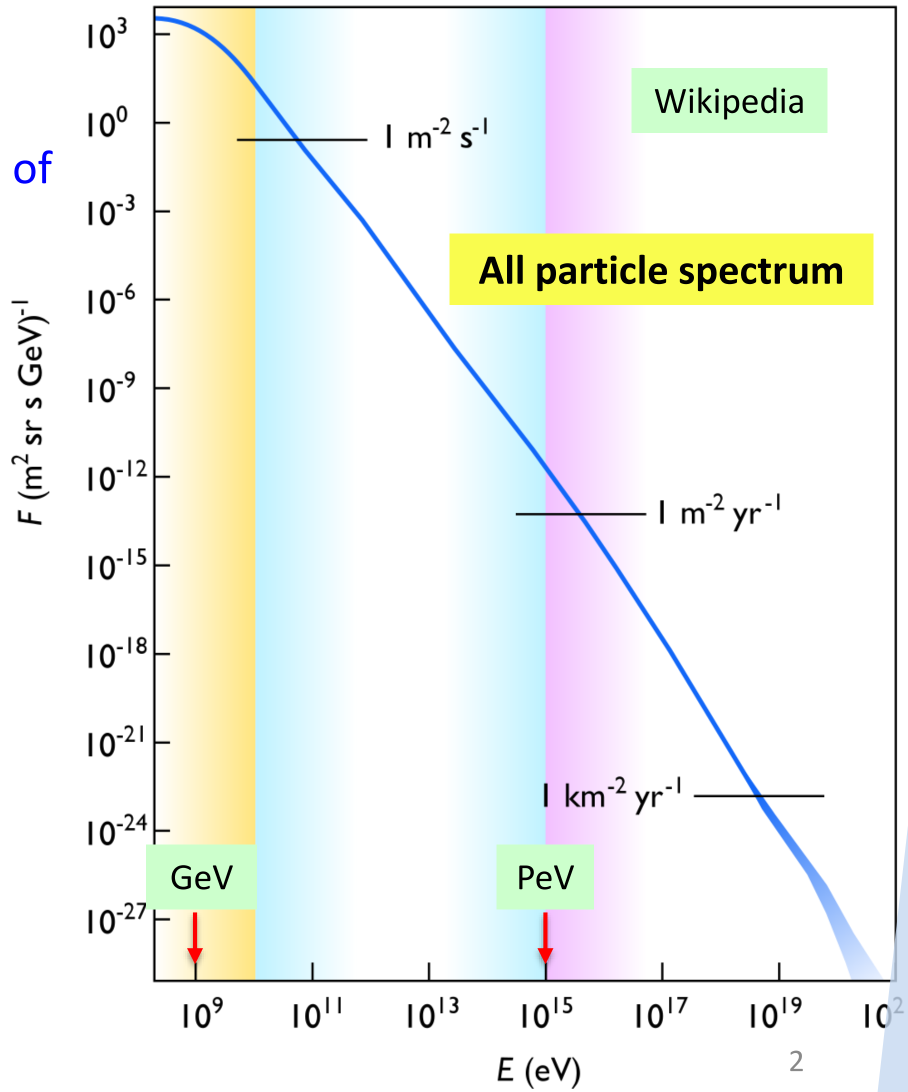
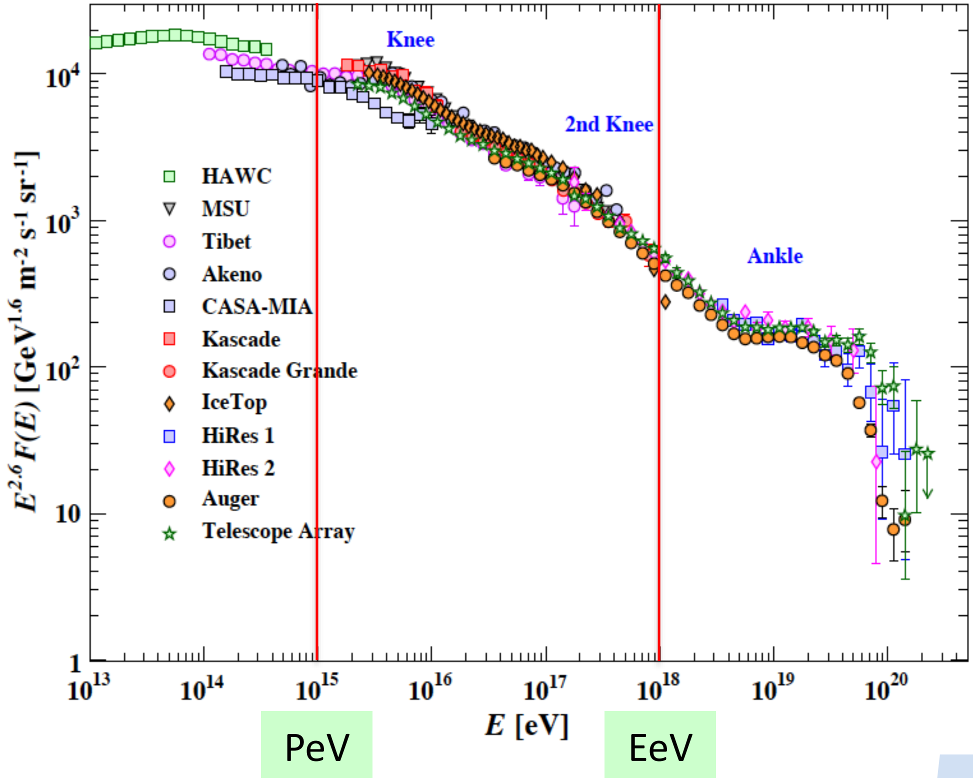
Introduction

- Cosmic rays in general refers to high energy charged particles originated outside the Solar system
  - p, He, and heavier nuclei, antiproton
  - But also electron and positron!
- Observed spectrum covers 12 orders of magnitude in energy and 30 orders in flux
  - **UHECR: > 100 TeV (0.1 PeV)**
  - **VHECR: 100 GeV - 100 TeV**
  - Multiple sources and processes
  - Modulated by propagation effects
- The origins of cosmic rays can only be truly resolved by a multi-messenger and global approach
  - Precise spectral and elemental measurements of cosmic rays
  - **Gamma rays (CTA, …)**
  - Neutrino
  - Gravitational wave



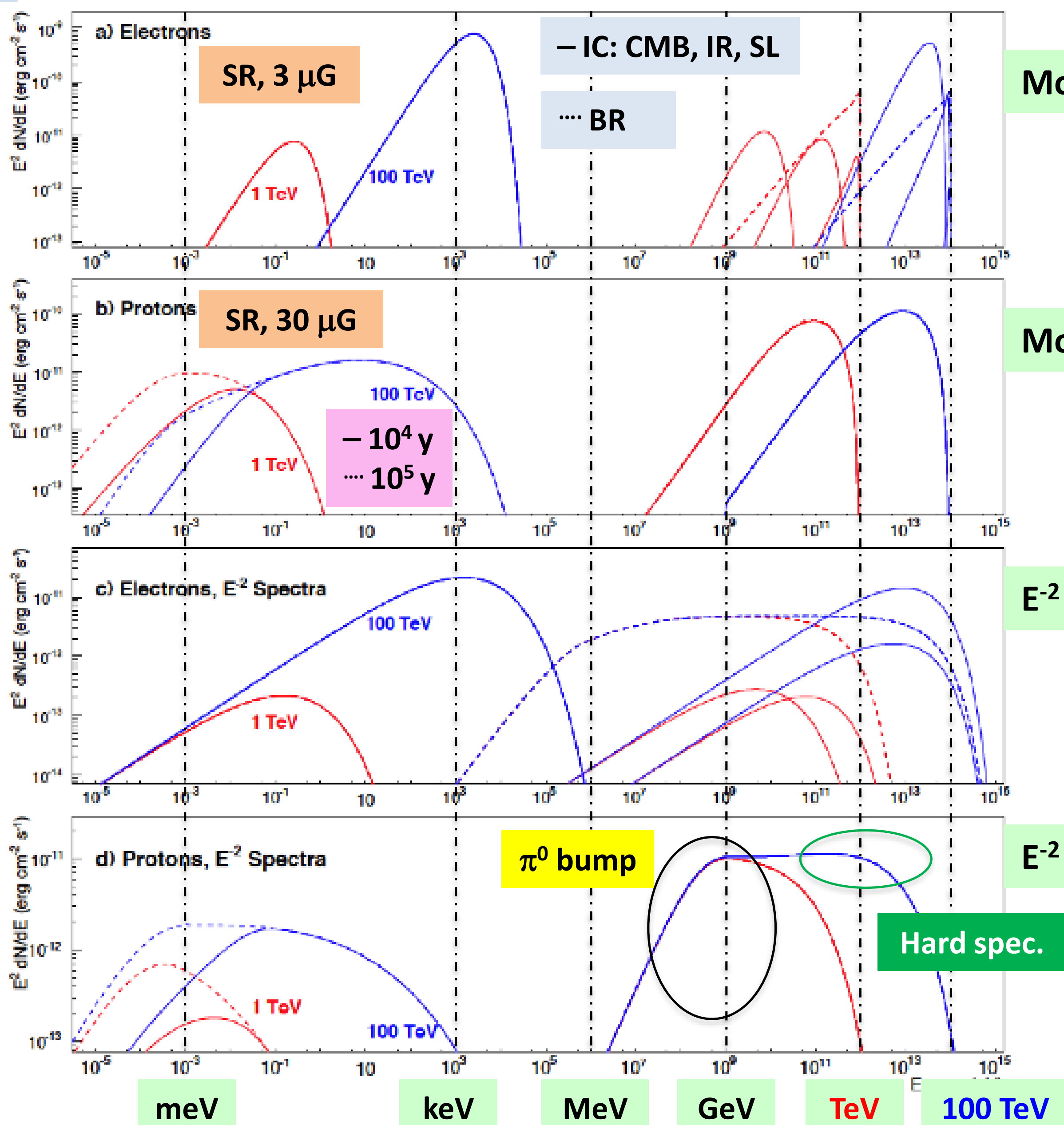
Cosmic rays: around and above the knee (UHECR)

- Because of the Earth atmosphere only particles above ~100 TeV (the "knee" region) can be precisely measured by ground detectors
  - Extended Air Shower detectors: AUGER, TA, HAWC, …
  - Composition measurement difficult, but mass groups possible/improving
- What is behind the observed spectral features?
  - Transition between galactic and extragalactic sources
    - acceleration - confinement - interaction
  - Composition change?
- Gamma rays as tracers of cosmic rays
  - CR + p/γ -> π^0 + X -> $\gamma\gamma$ + X
  - Typically E_γ ~ 0.1 E_{CR}
  - Need spectral features to identify "hadronic" gamma-rays
    - w.r.t "leptonic" gamma-rays, e.g. IC, SR, BR
  - Observed gamma ray spectrum is a convolution of the CR spectrum and π^0 production/decay, as well as injection and cooling effects



“Leptonic” vs “Hadronic” gamma rays

Hinton & Hofmann, Annu. Rev. Astron. Astrophys. 47, 523 (2009).



Mono-E electron: 1 TeV/100 TeV

Mono-E proton: 1 TeV/100 TeV

E^{-2} electron with cut-off: 1 TeV/100 TeV

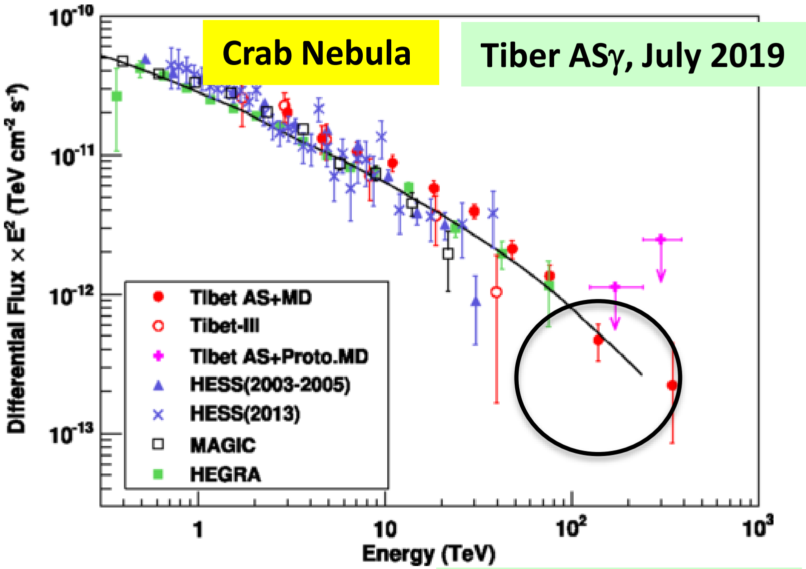
E^{-2} proton with cut-off: 1 TeV/100 TeV

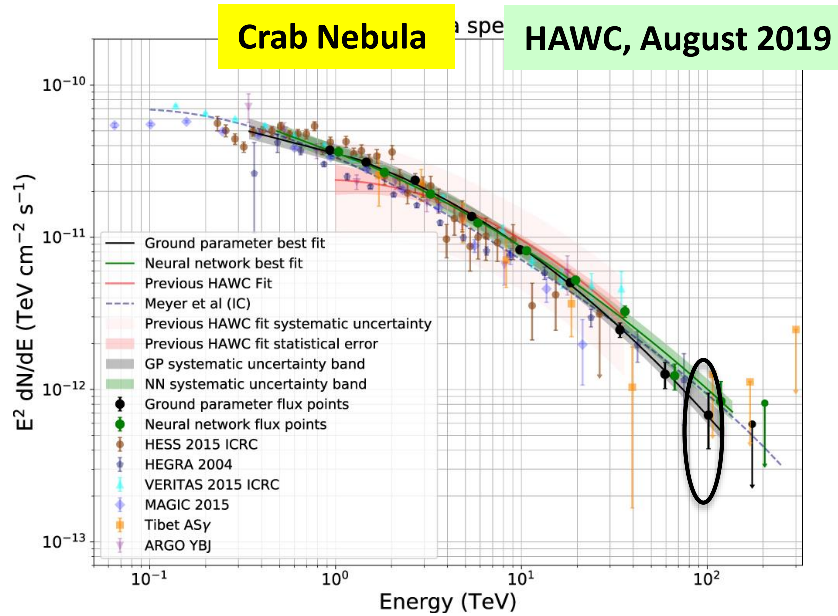
Complex picture, need

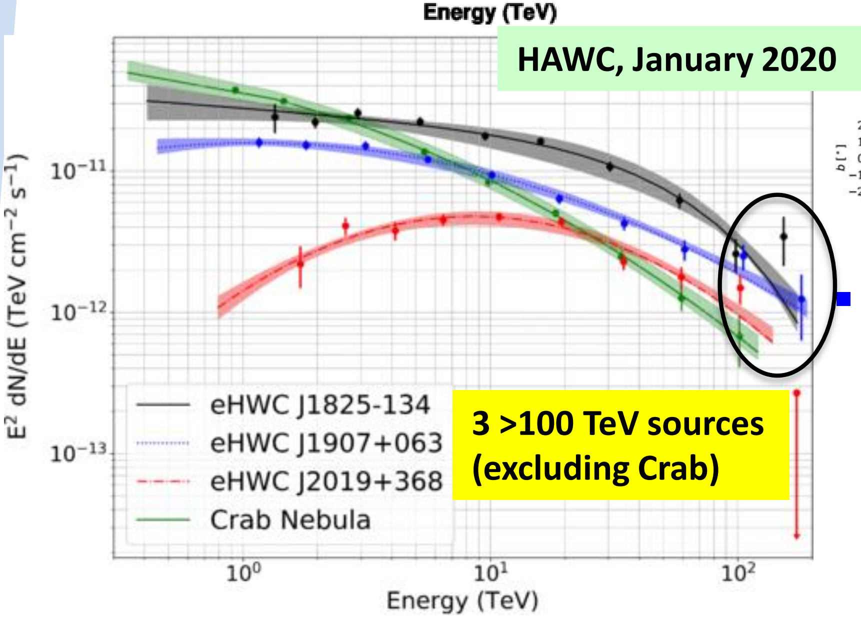
- Wide energy range
- Good energy resolution
- Good imaging

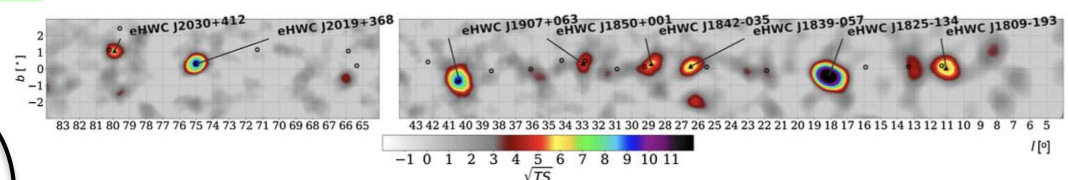
Multi-TeV gamma-ray sources: hunting ground for PeVatrons

- A few **>100 TeV** gamma-ray sources reported recently





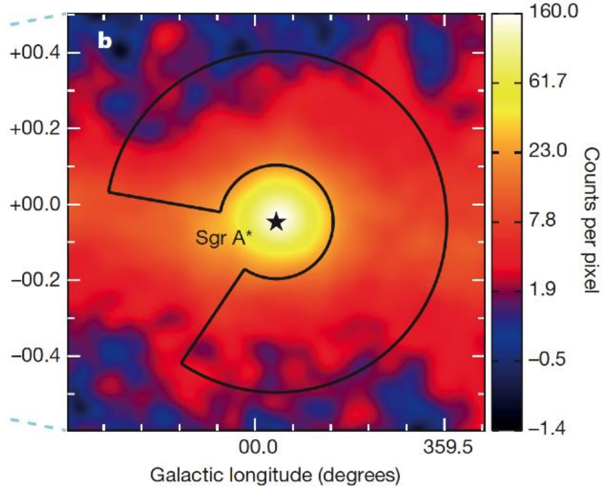




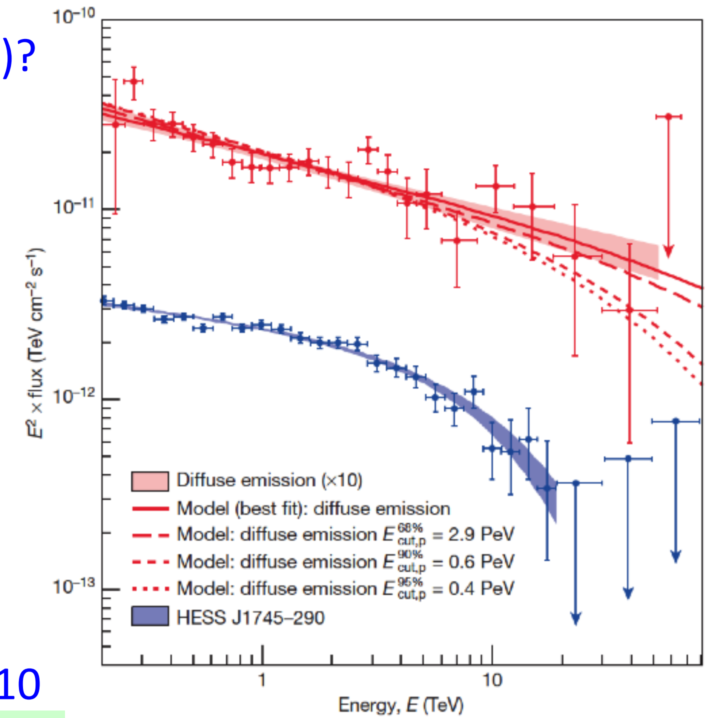
- HAWC: 8 >56 TeV sources (excluding Crab)
  - Extended; Close to the galactic plane (<1°)
  - Consistent with known TeV sources
  - Have nearby pulsar (<0.5°)
  - Pure leptonic cannot be excluded, neither hadronic contribution

Multi-TeV gamma-ray sources: potential PeVatron candidates

- A PeVatron at the Galactic Center (Sagittarius A*)?

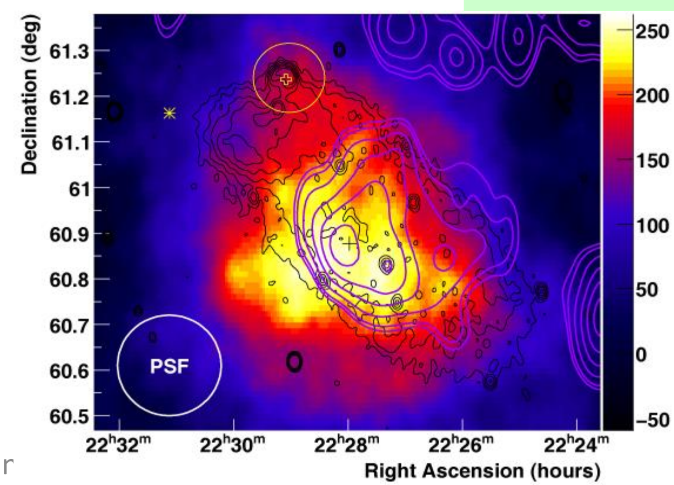


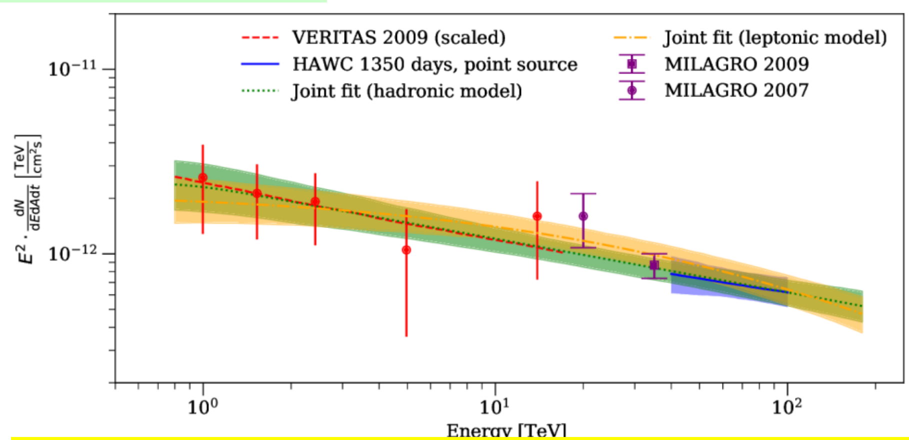
HESS J1745– 290



- SNR G106.3+2.7: VER J2227+608/HAWC 2227+610

HAWC, *Astrophys.J.Lett.* 896 (2020)



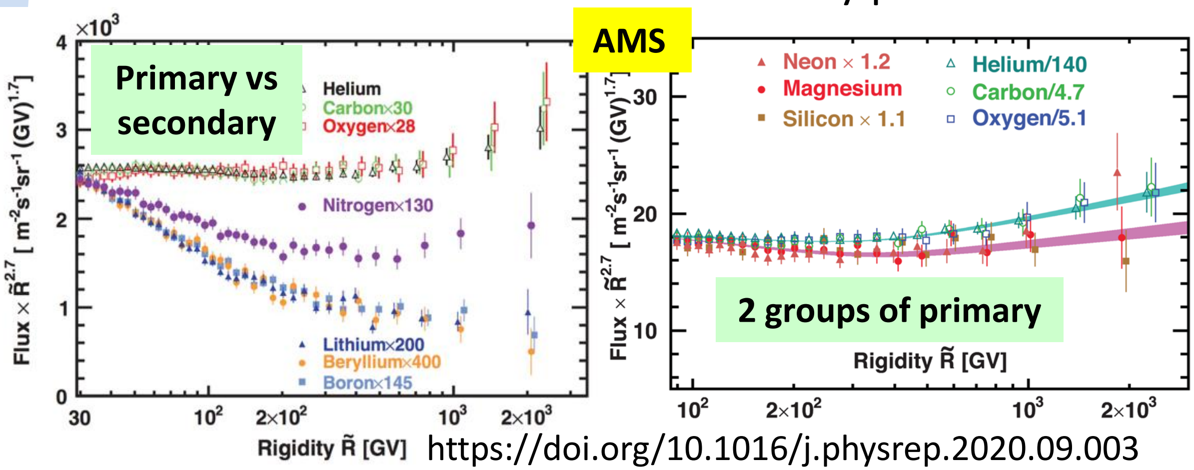


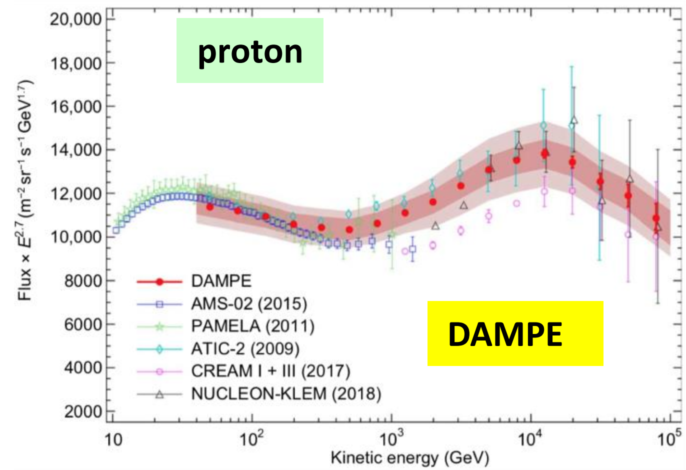
Xir

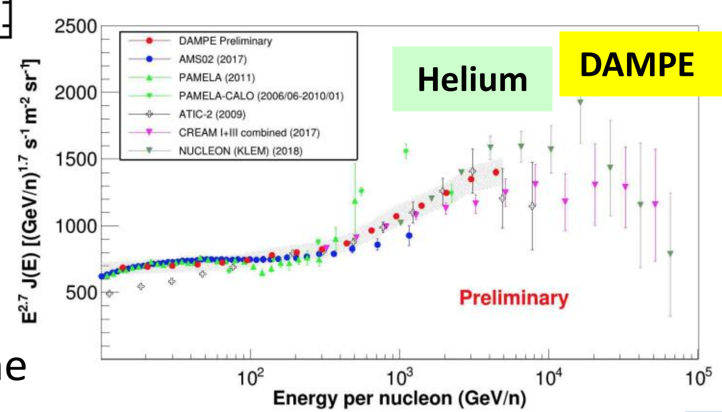
Not yet possible to differentiate hadronic and leptonic origins

VHECR: many breaks from direct detections below the knee

- Precision measurements below the knee become possible with balloons and satellites
  - Many interesting spectral features of individual species are being unveiled between ~0.1 – 100 TeV, and soon to PeV
- Key questions
  - Are the UHE and VHE cosmic rays from the same population? What is the effect of propagation? What is the effect of secondary production?



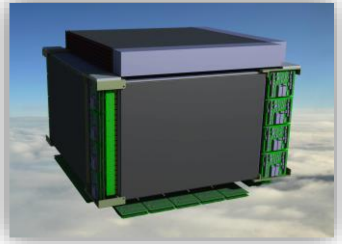




https://doi.org/10.1016/j.physrep.2020.09.003
https://doi.org/10.1103/PhysRevLett.124.211102

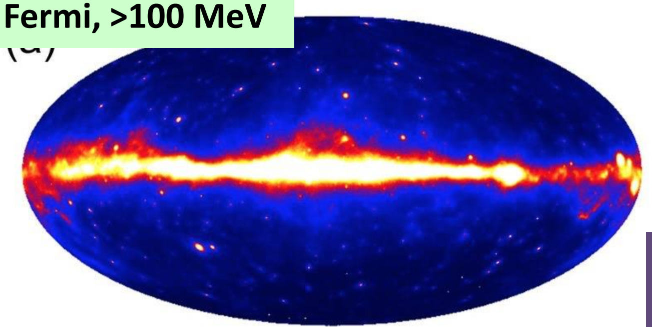
- Parallel to PeVatron hunting, it is a fundamental task for CTA/gamma-ray astronomy to help to resolve these questions
  - Resolve point sources of the dense galactic plane
  - Constraint parameters of propagation models

Cosmic ray and GeV gamma-ray astronomy with HERD

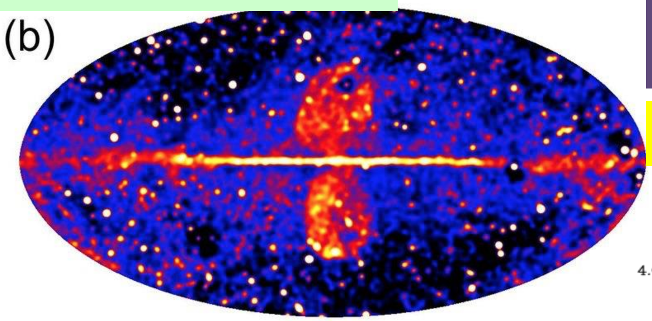


- HERD with 5-side fiber tracker (FIT, developed by DPNC)
  - ~3x better angular resolution than Fermi in the 0.1 - 1 GeV range, large FOV

Fermi, >100 MeV



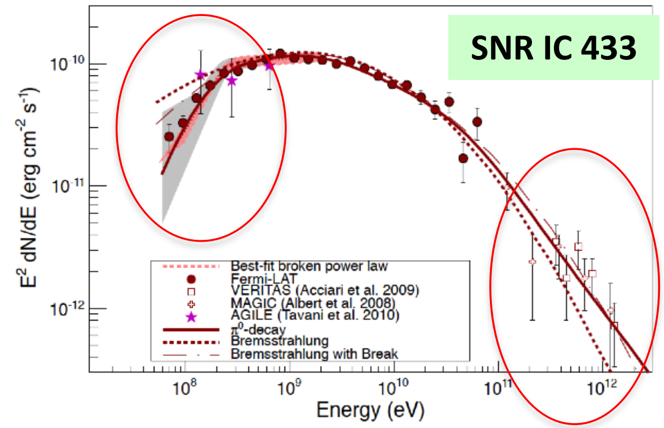
Fermi, >2GeV/>100 MeV



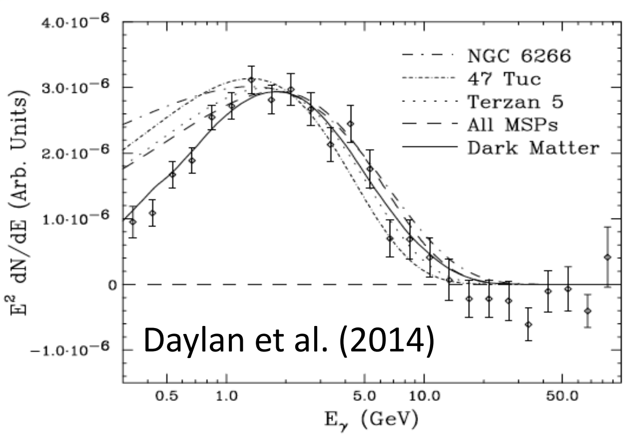
- HERD will resolve large number of sub-GeV sources and measure diffuse flux in the galactic plane
  - Millisecond pulsars (MSP) peaked at ~GeV

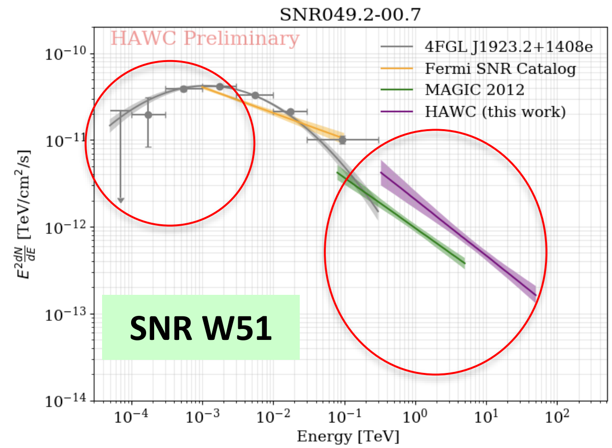
The sub-GeV part of the spectrum is essential to distinguish hadronic and leptonic emission

HERD is complementary to CTA



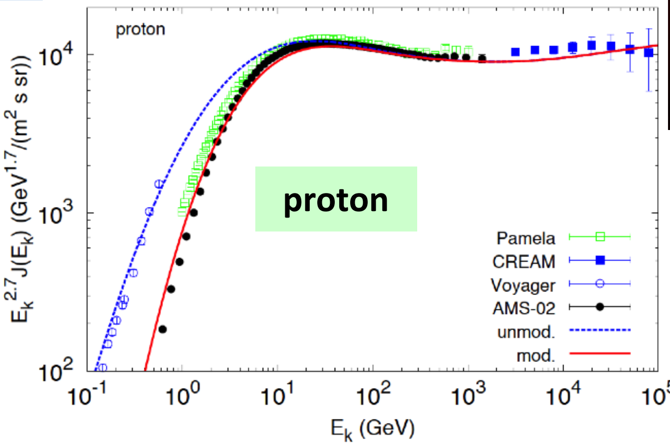
... and to elucidate the origin of the *Galactic Center GeV Excess* (GCE)



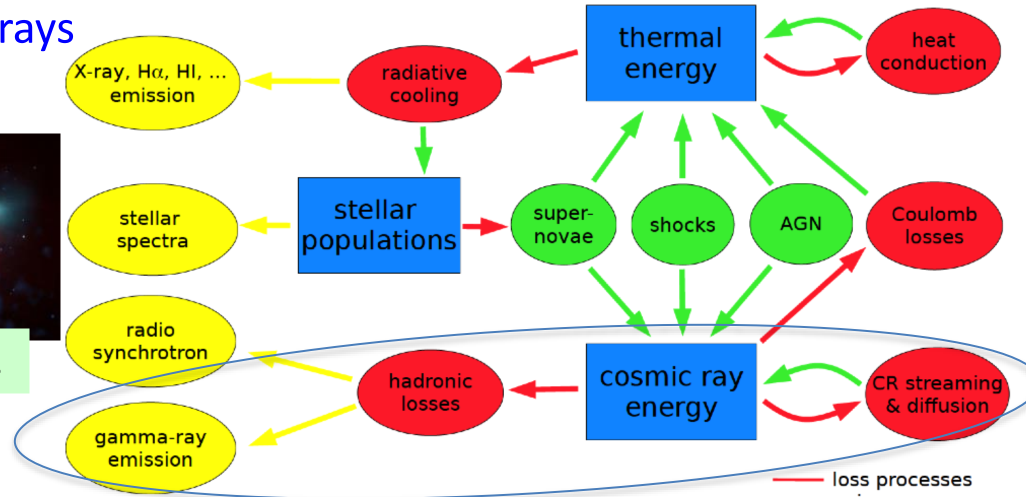


Galactic wind, cosmic ray feedback, non-linear transport

- Strong phenomenological and theoretical arguments support that Galactic winds can be launched by accelerated cosmic rays
  - CR can play a critical role in galaxy formation

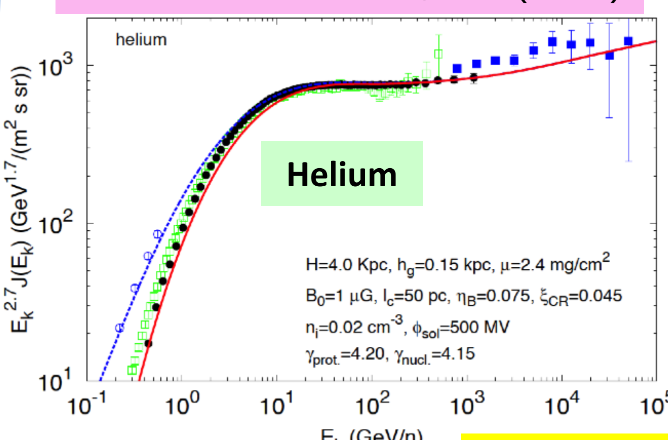


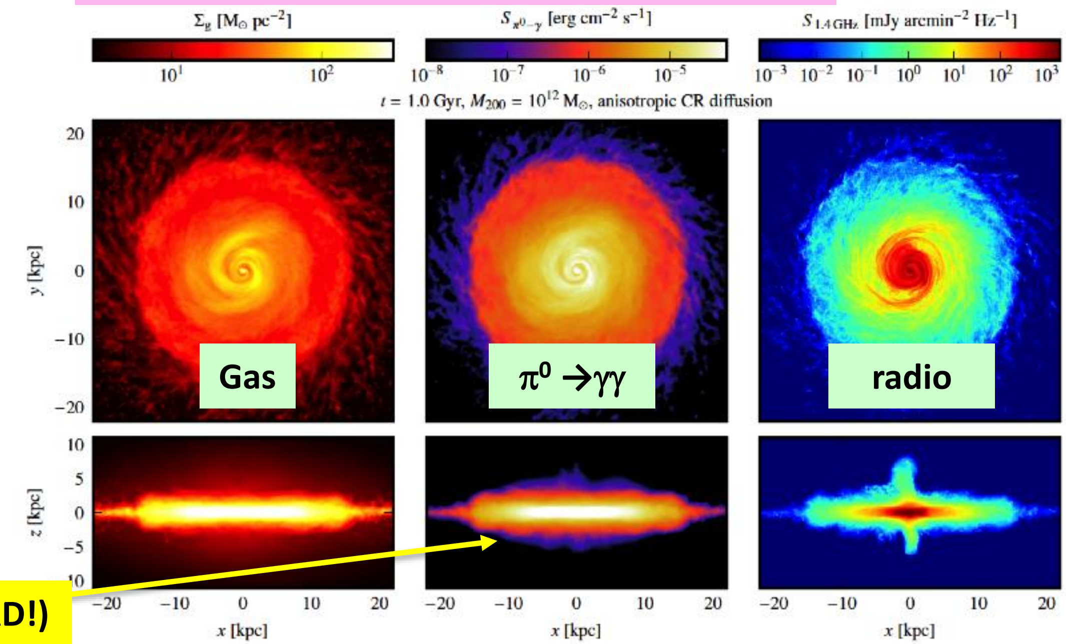
M82



Pfrommer et. al. AIP Conf. Proc., V 1792, 1

Alisio et. al. A&A 583, A95 (2015)





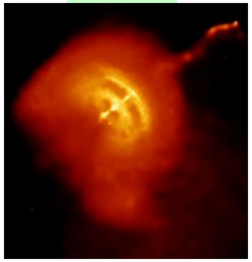
γ-ray > 100 MeV (HERD!)

Pulsars and Pulsar Wind Nebulae as particle accelerators

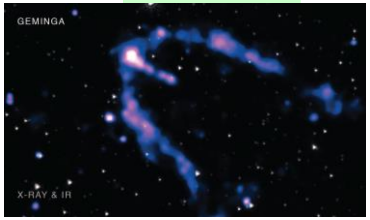
- Relativistic outflows can be efficient and extreme accelerators, and **lepton factories**!
  - **γ → e⁺+e⁻**
  - Could nearby pulsars be sources of high energy electron and positron observed?

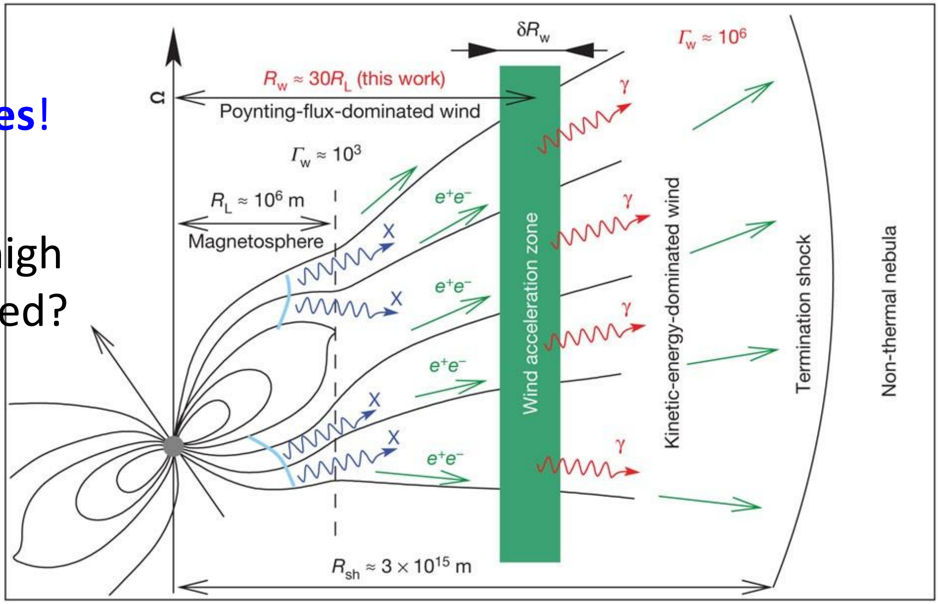
Crab

Vela



Geminga



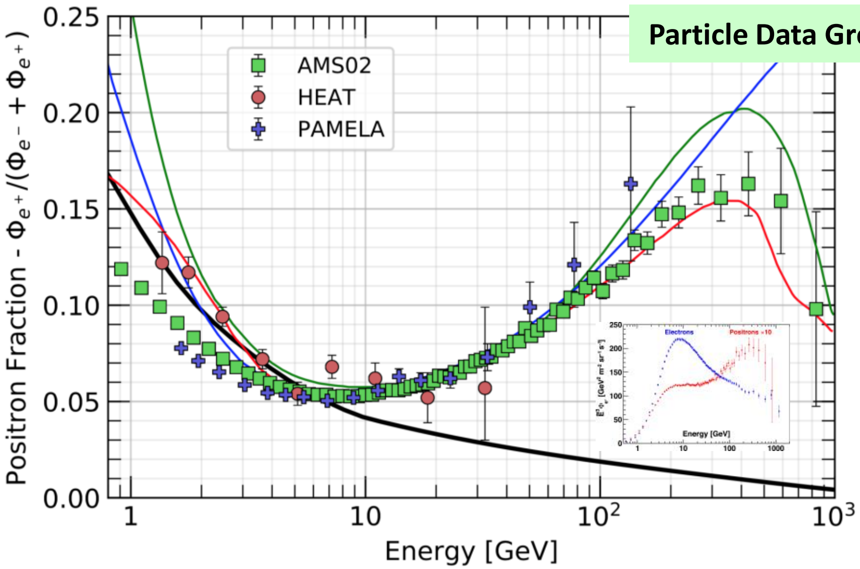


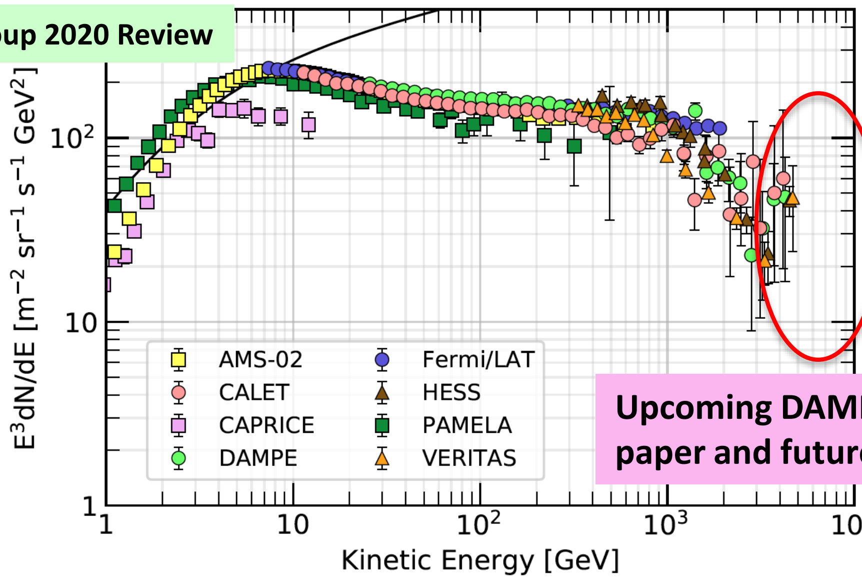
Aharonian *Nature* 482, 507(2012)

PAMELA and AMS observed a rising e⁺ fraction

DAMPE observed a TeV break of e⁺+e⁻ flux

Particle Data Group 2020 Review



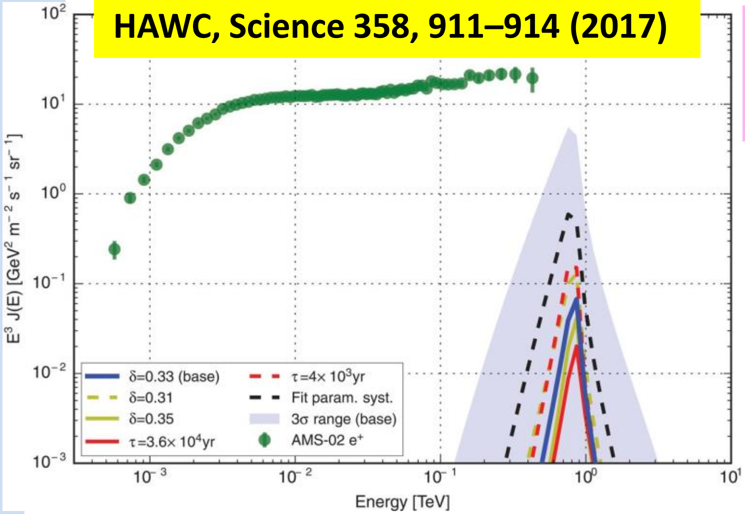


Upcoming DAMPE paper and future HERD

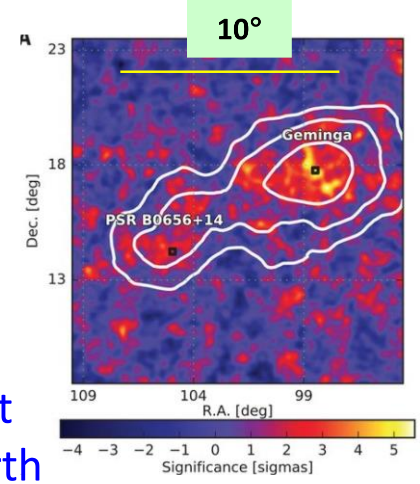
Is the positron excess due to nearby pulsars?

Gamma-ray observations provide very interesting constraints

HAWC, Science 358, 911–914 (2017)



Small zone of TeV γ-ray flux near Geminga and Monogem

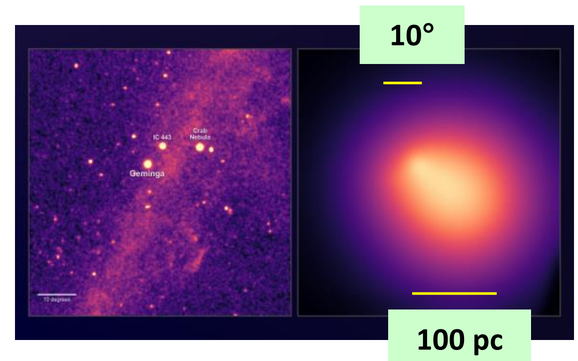


→ small lepton diffusion coefficient

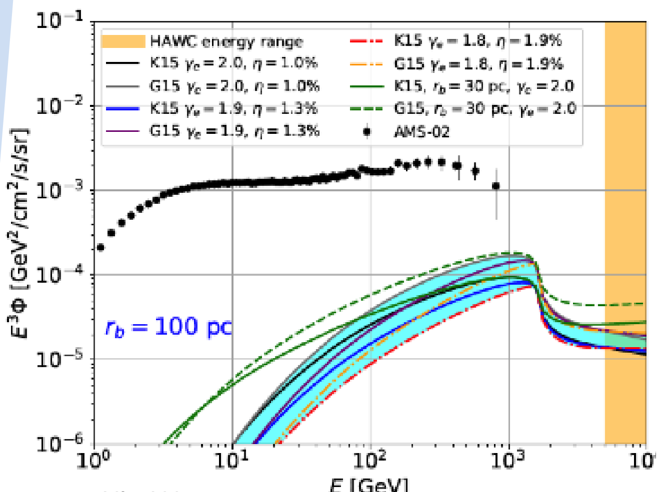
→ constraint on positron flux at Earth

- Leptons from these pulsars are “unlikely to be the origin of the excess positrons, …”

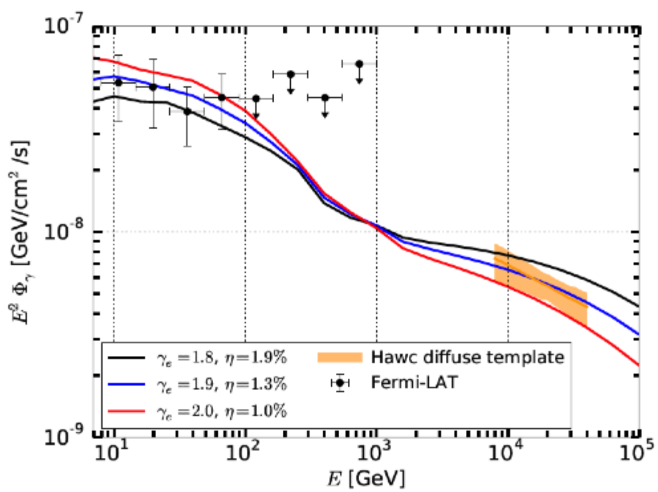
But it is also possible diffusion is less efficient around the source!



Fermi, Phys. Rev. D 100, 123015 (2019)



Large sub-TeV γ-ray bubble around Geminga



Use 2-zone diffusion model

- the cumulative positron emission from Galactic PWNe remains a viable interpretation for the positron excess

Conclusion

- Gamma ray, as tracer for cosmic ray, is a powerful tool to map the cosmic ray acceleration and propagation sites in the Galaxy, and beyond
  - There are recent major progress, and near future major observational capability extension, in cosmic ray observations and gamma ray observations
  - Multi-messenger cosmic ray acceleration and propagation models are fast evolving
- Switzerland is a key player in this global effort through its major hardware contributions and leading roles in data analysis, covering x-ray, gamma ray, cosmic ray, neutrino, and gravitational wave
- **University of Geneva is a center of excellency in multi-messenger astrophysics**
  - Space: AMS, DAMPE, HERD, POLAR-2, …
  - Ground: MAGIC, IceCube, LAHSSO, CTA, …
  - **HERD and CTA concurrently cover gamma-ray sky from 0.1 GeV to ~300 TeV**
    - **Strong complementary/synergy in observation and science**