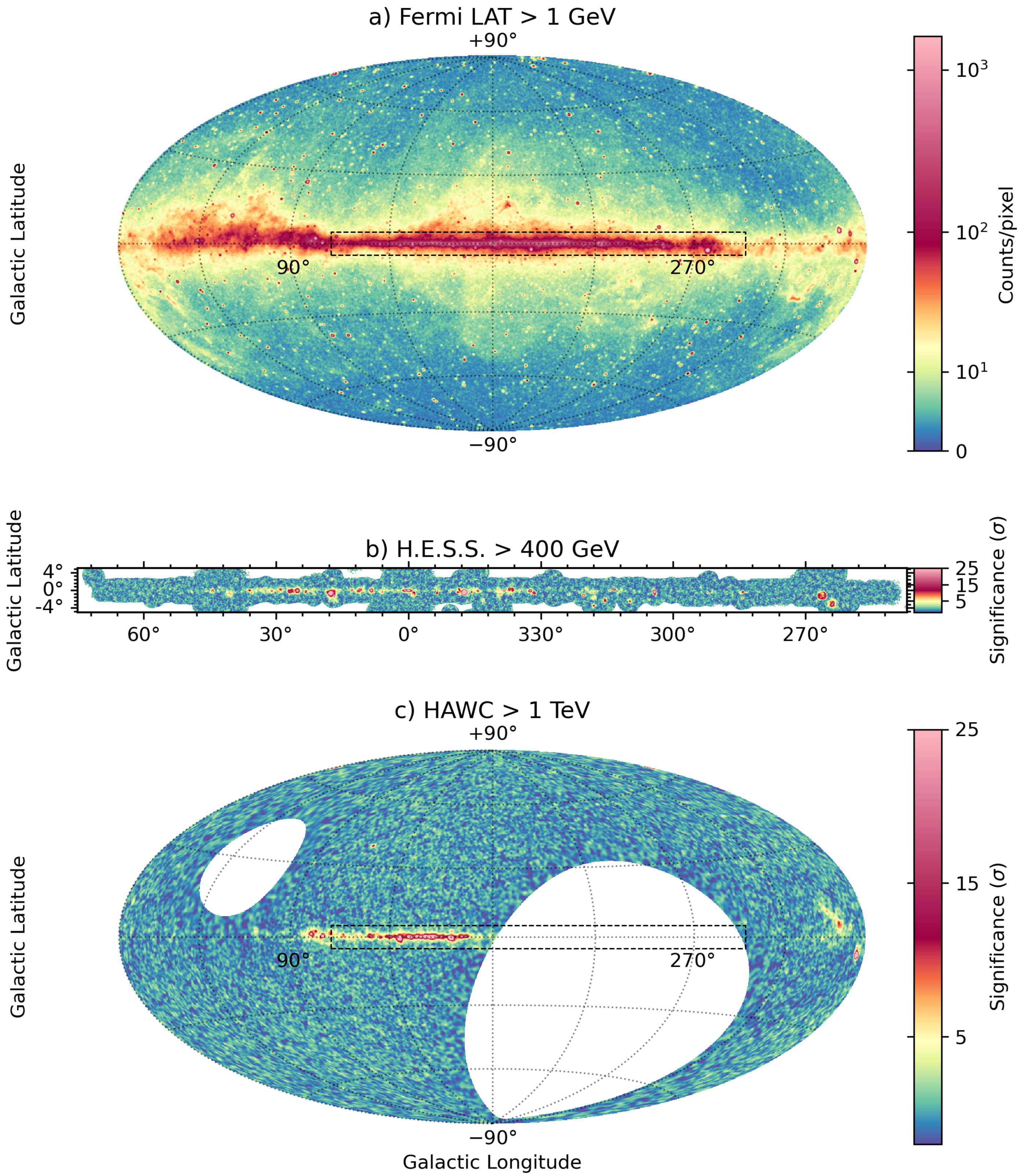


A whirlwind tour of the Milky Way in gamma rays

Luigi Tibaldo
luigi.tibaldo@irap.omp.eu

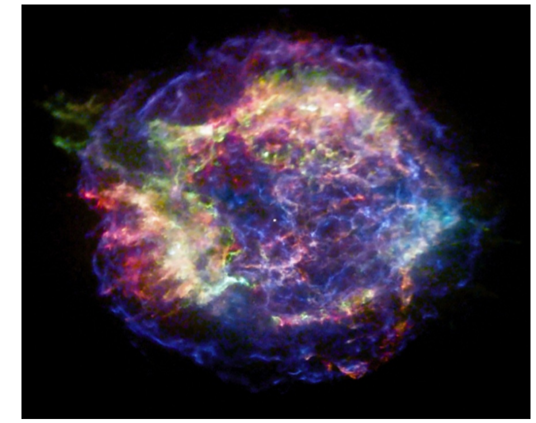
IRAP, Université de Toulouse, CNRS, UPS, CNES

International Conference
on the Physics of the two Infinities
Kyoto
March 2023

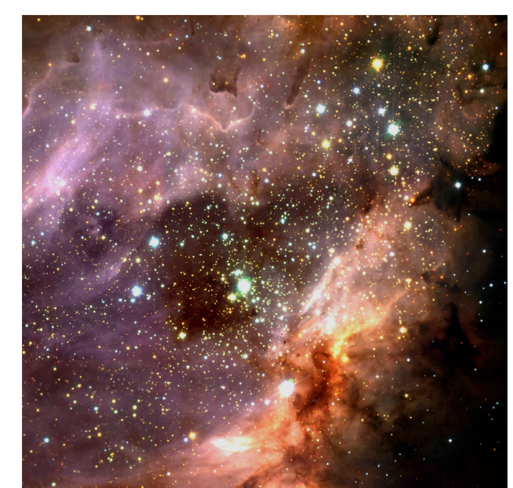
- Introduction
- The census of Galactic gamma-ray sources
- The two ends of the gamma-ray spectrum
- A few more recent highlights
- Exotic emitters
- What's next?

Coming of age of gamma-ray astronomy

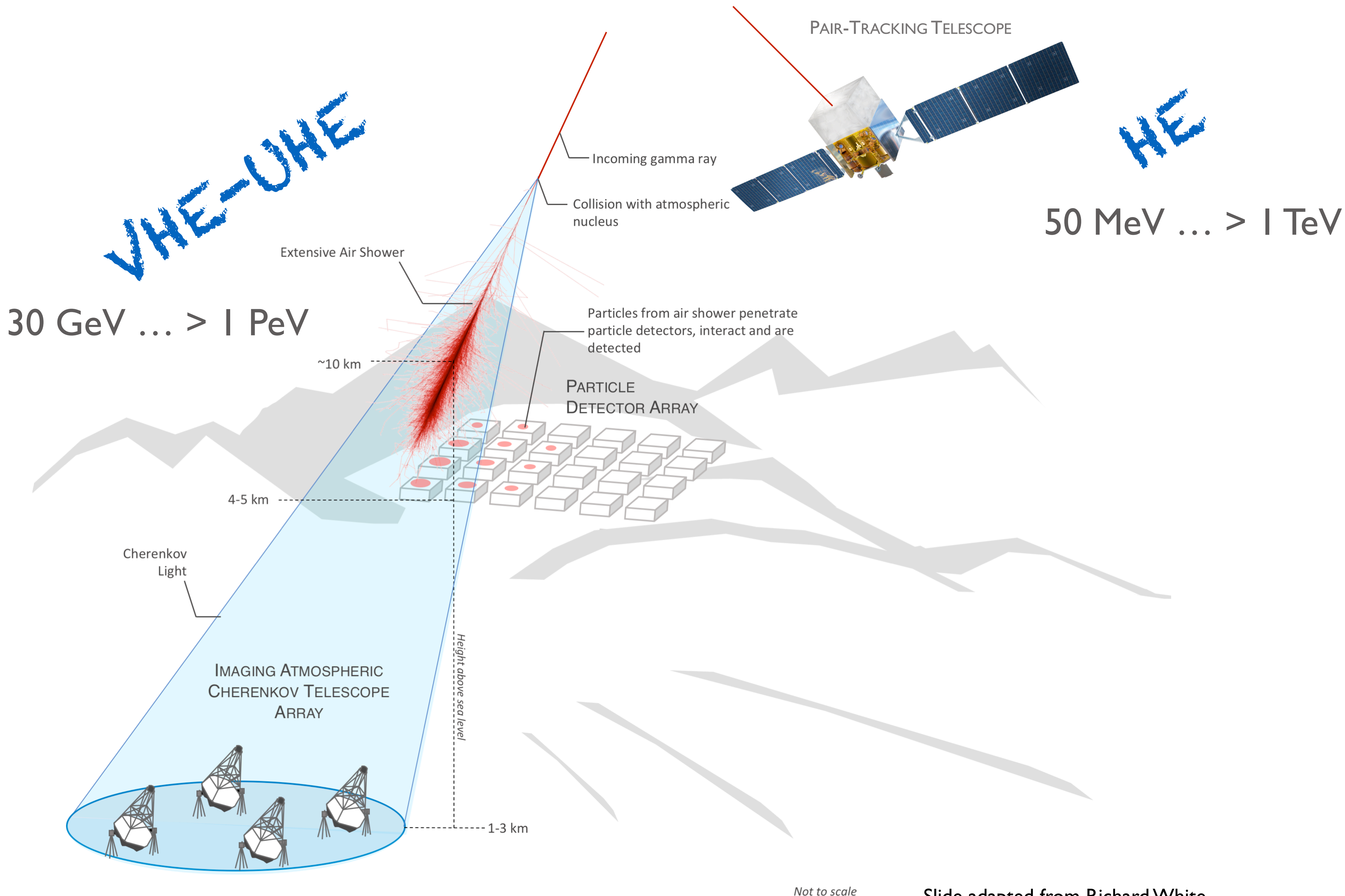
- original motivation: find the sources of Galactic cosmic rays (CRs), probably supernova remnants (SNRs)
- today astonishing variety of sources, of which many in the Milky Way



Slide adapted from Rene Ong



Observation techniques



Slide adapted from Richard White

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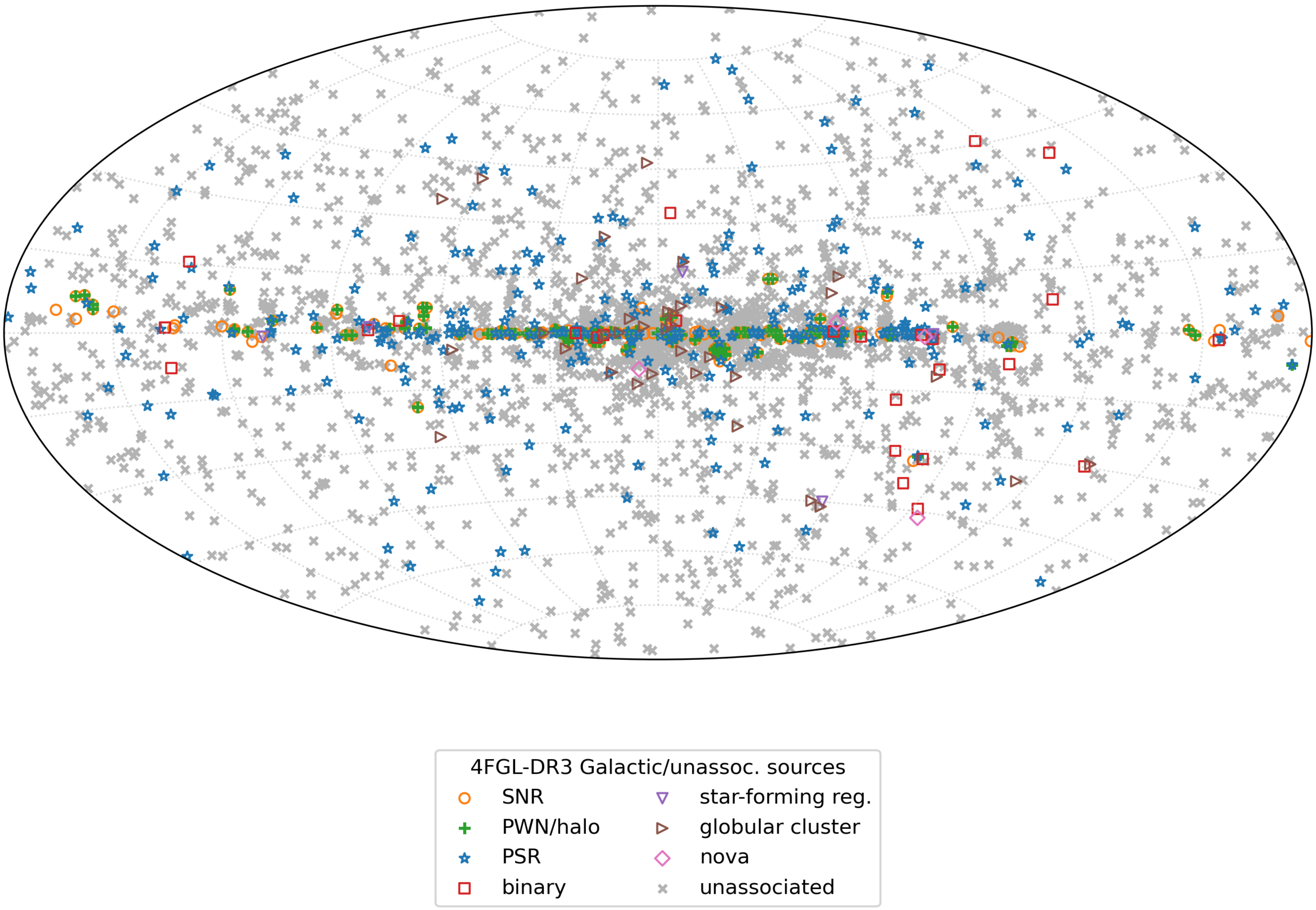
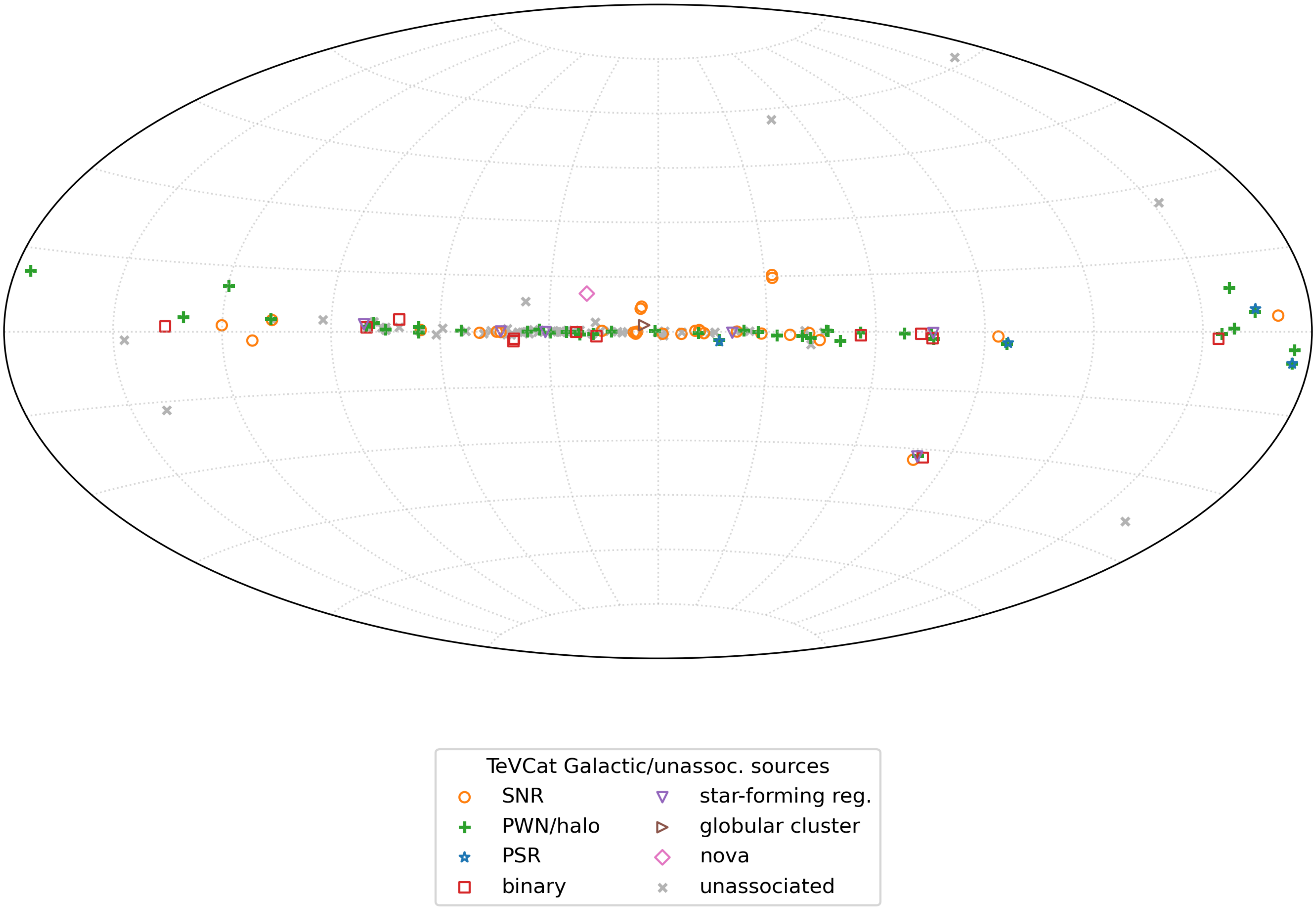
HE sources



4FGL-DR3 Galactic/unassoc. sources
SNR
PWN/halo
PSR
binary
star-forming reg.
globular cluster
nova
unassociated

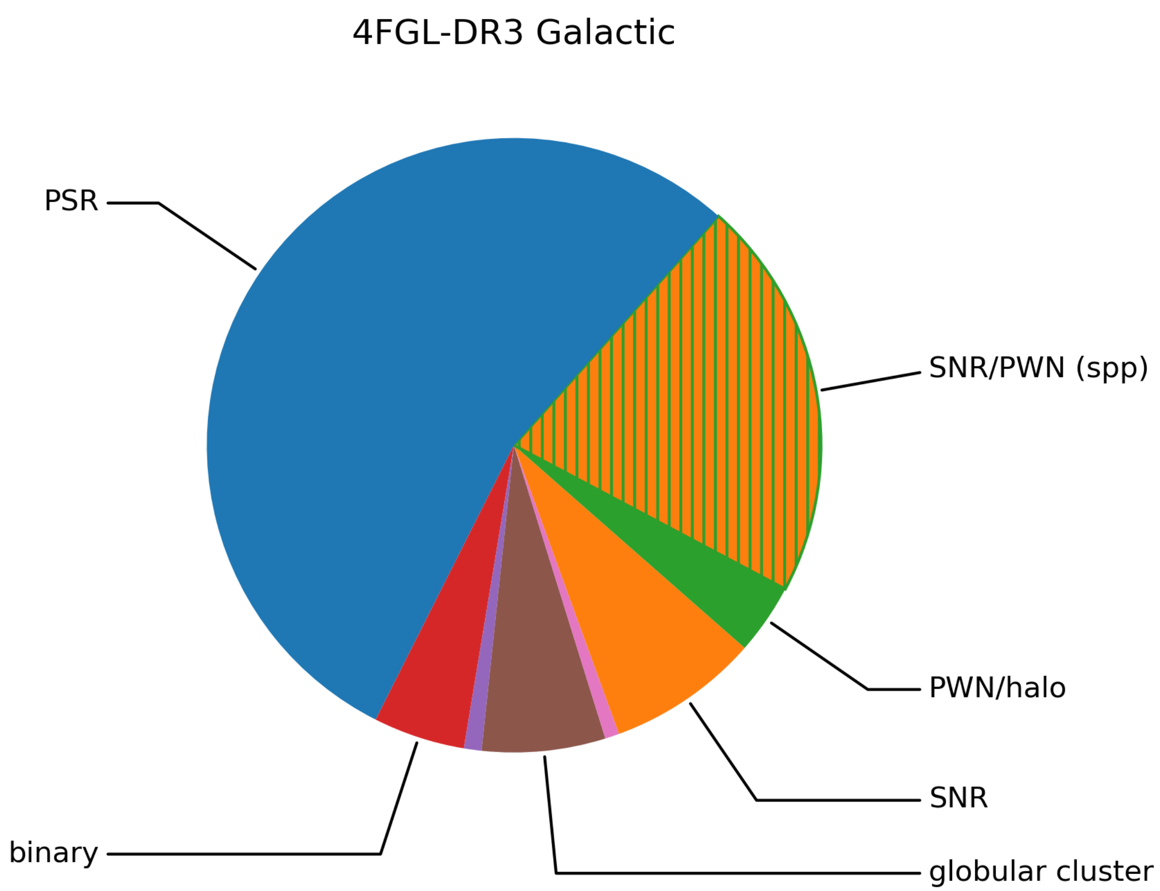
VHE/UHE sources

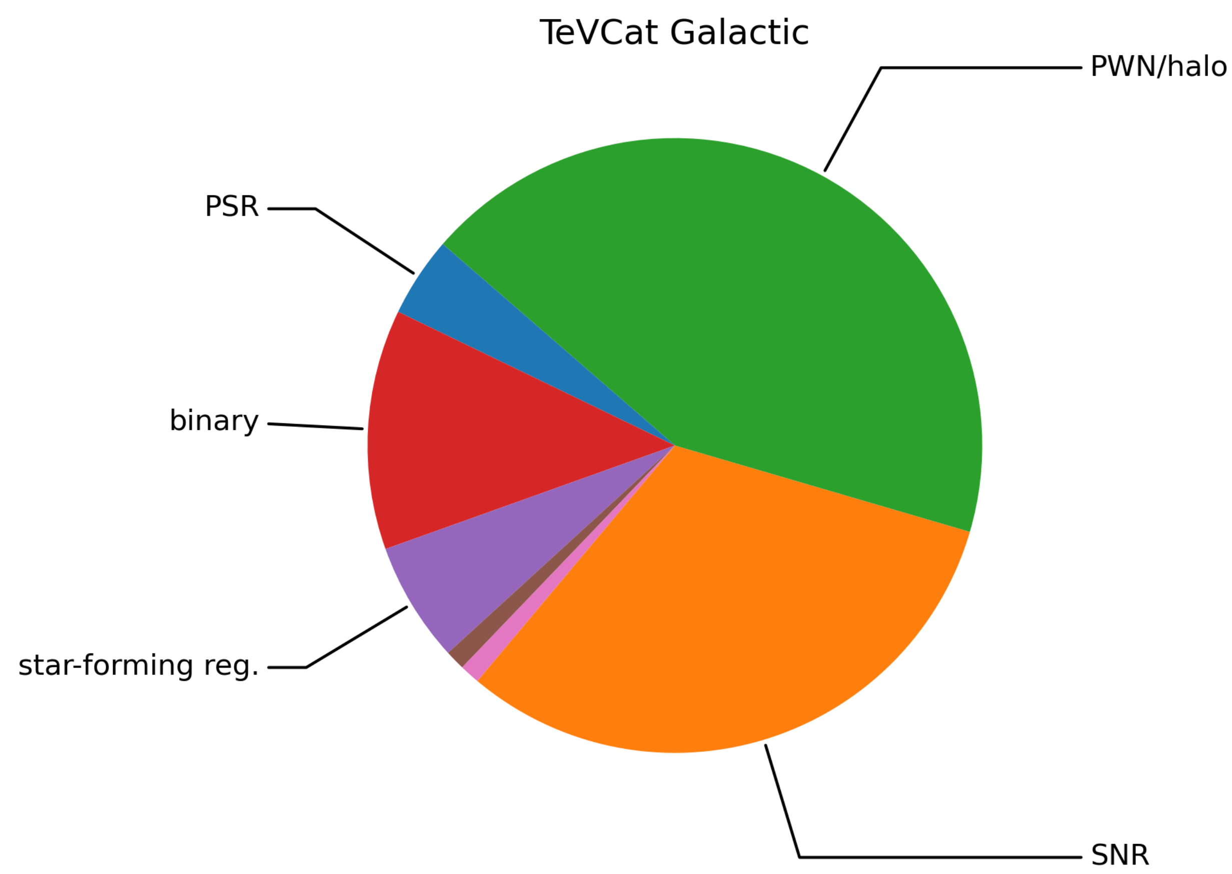
Thanks to D. Horan and S. Wakely for sharing TeVCat data



HE and VHE source classes

Thanks to D. Horan and S. Wakely for sharing TeVCat data



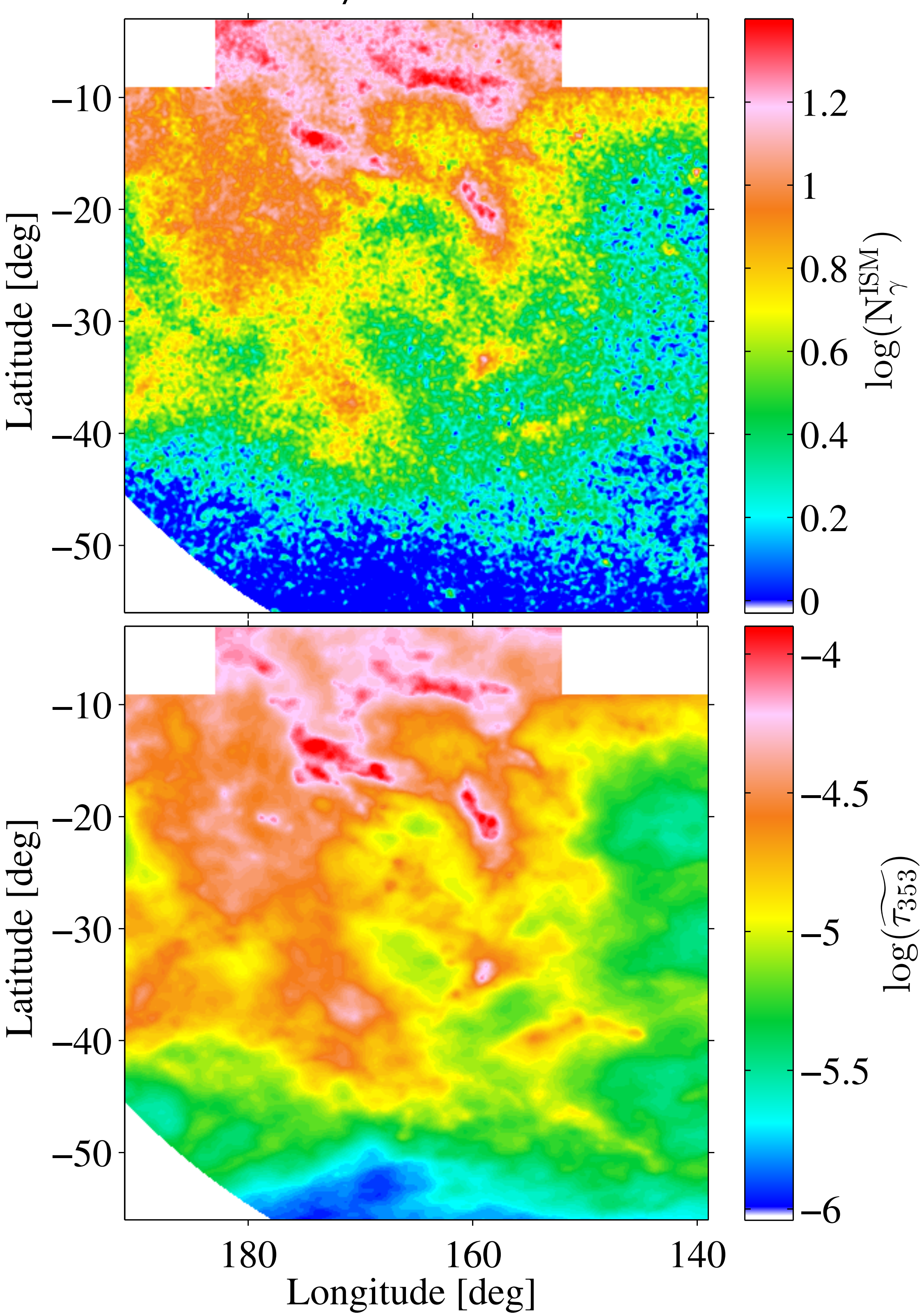


Source diversity → particle acceleration and transport in a variety of astrophysical conditions and environments.

Diffuse emission

Anticenter clouds: *Fermi* vs *Planck*

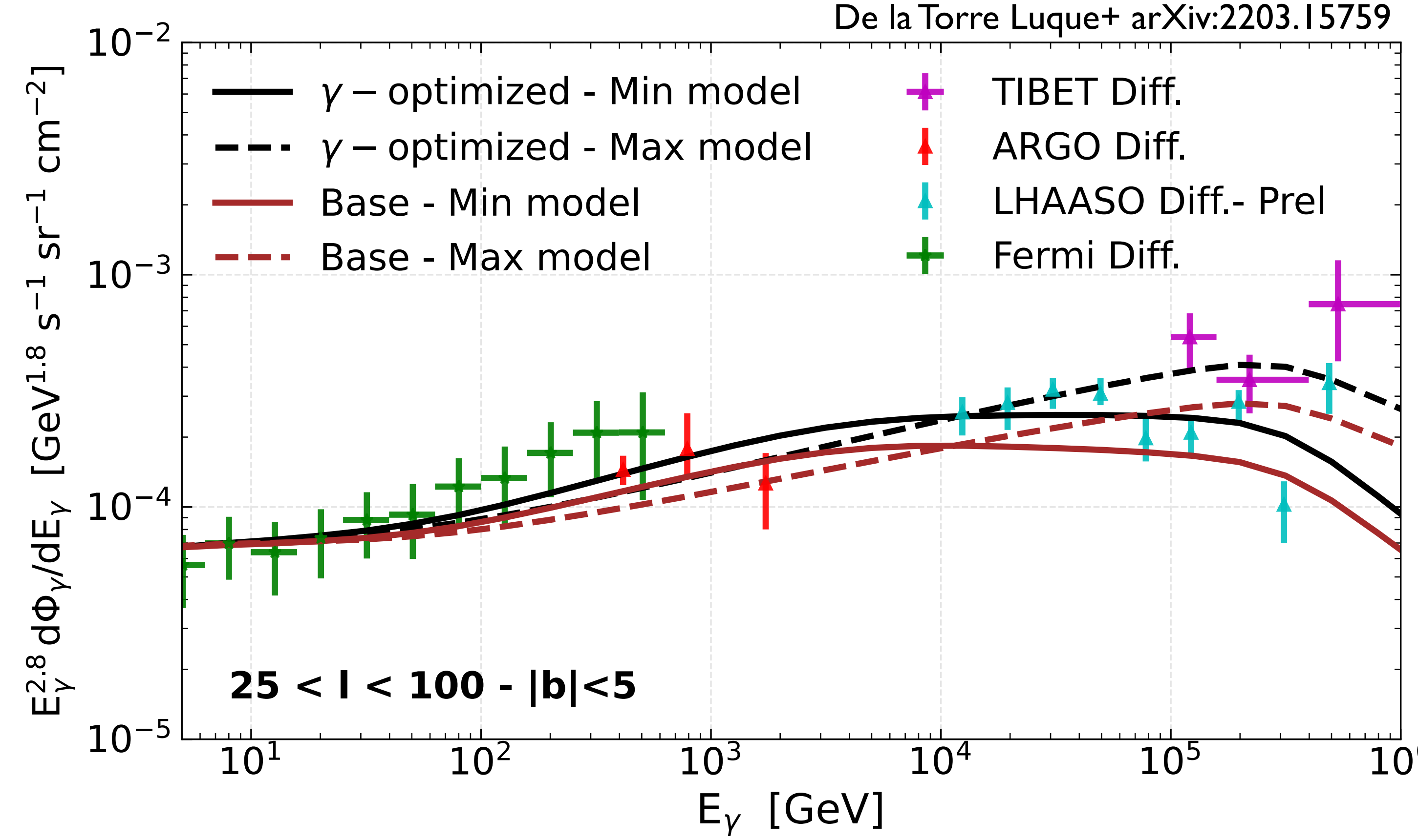
Remy+ 2017 A&A 601 A78



- GeV: good correlation of gamma rays and interstellar matter → CR interactions

- Diffuse emission (not related to individual sources) detected from sub-MeV to sub-PeV energies: CR emission or unresolved sources?

De la Torre Luque+ arXiv:2203.15759



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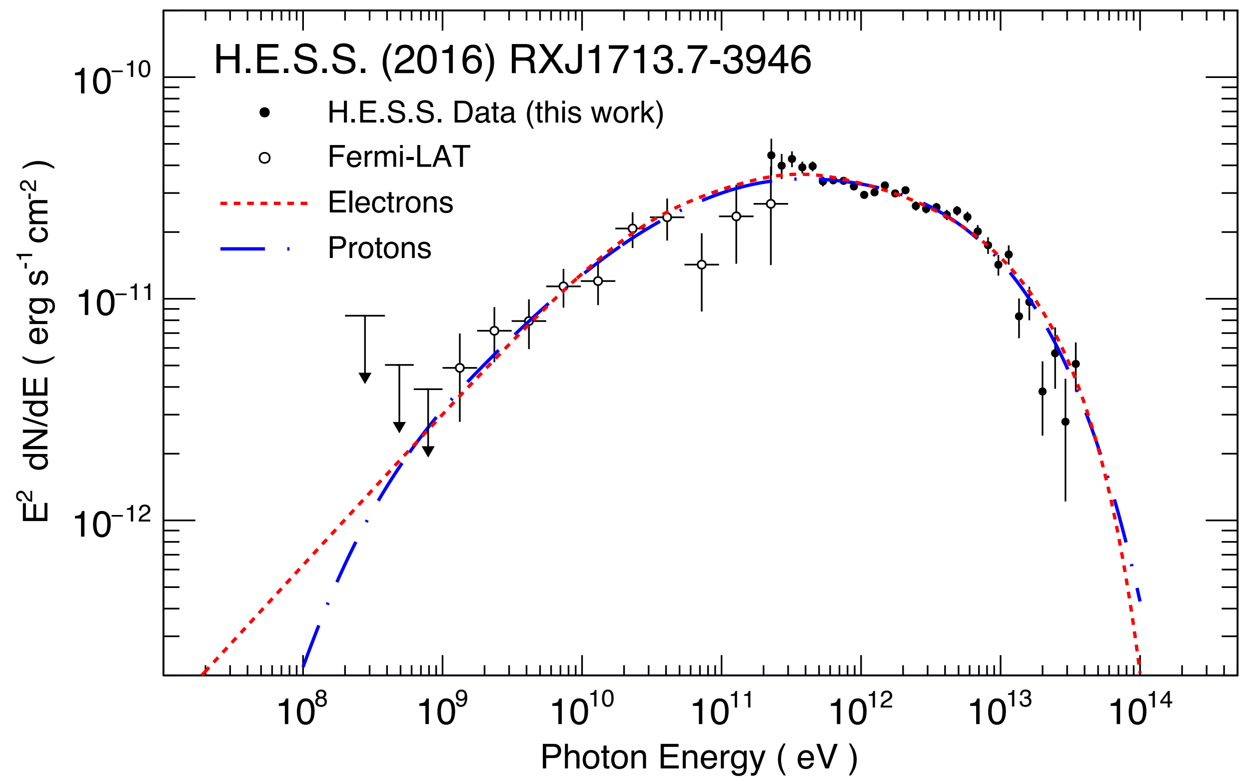
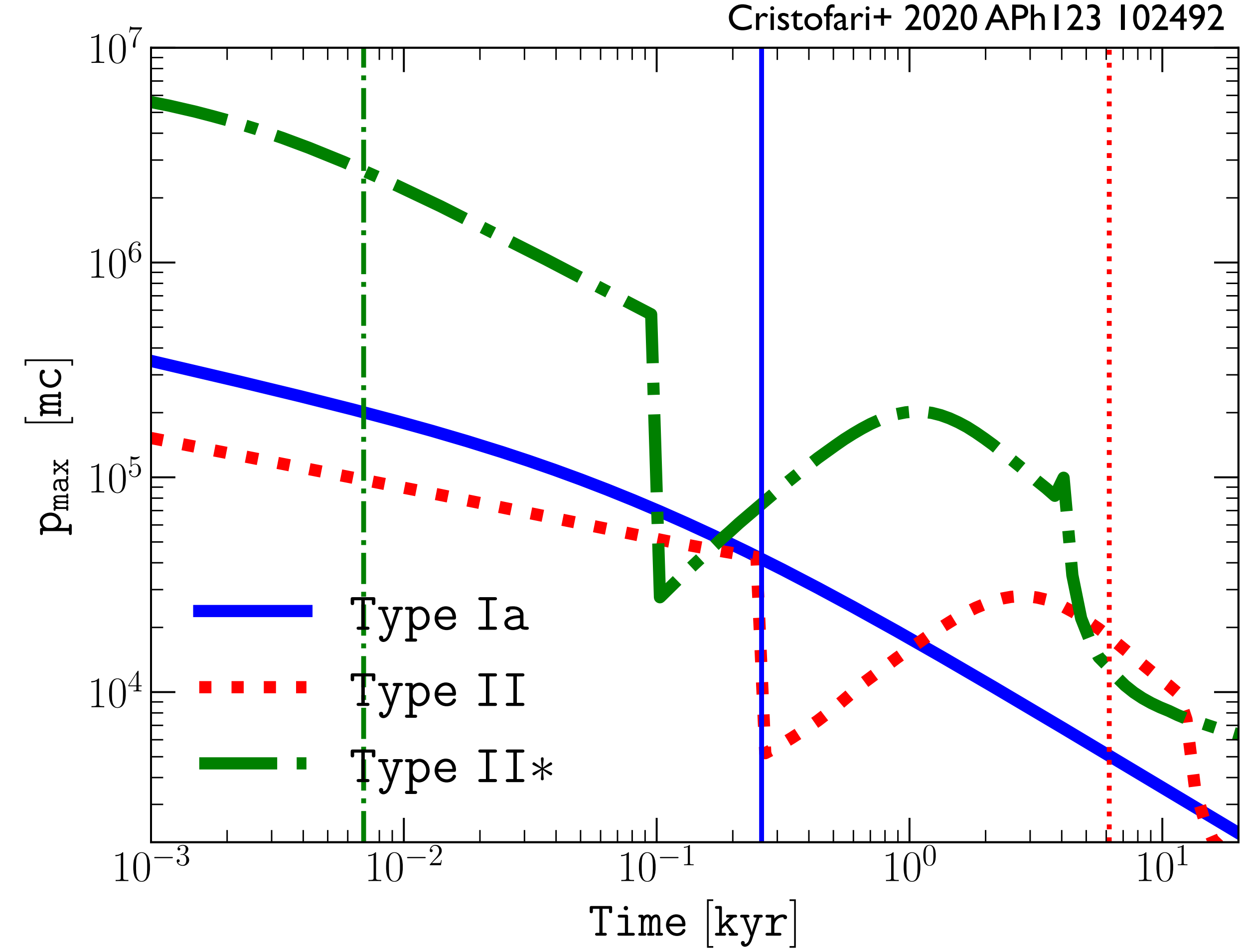
The PeV frontier

- Difficult to accelerate nuclei to PeV in the Milky Way
- SNRs challenged
  - observations: steep spectra, cutoffs
  - theory: maximum energy < PeV with rare exceptions
- Was generally believed
  - leptonic accelerators cannot produce effectively > 100 TeV gamma rays due to Klein-Nishina suppression
  - very rare gamma-ray sources > 100 TeV will pinpoint sources of CR nuclei in the Galaxy

H.E.S.S. collab. (2018) A&A 612 A6



Cristofari+ 2020 APh123 102492



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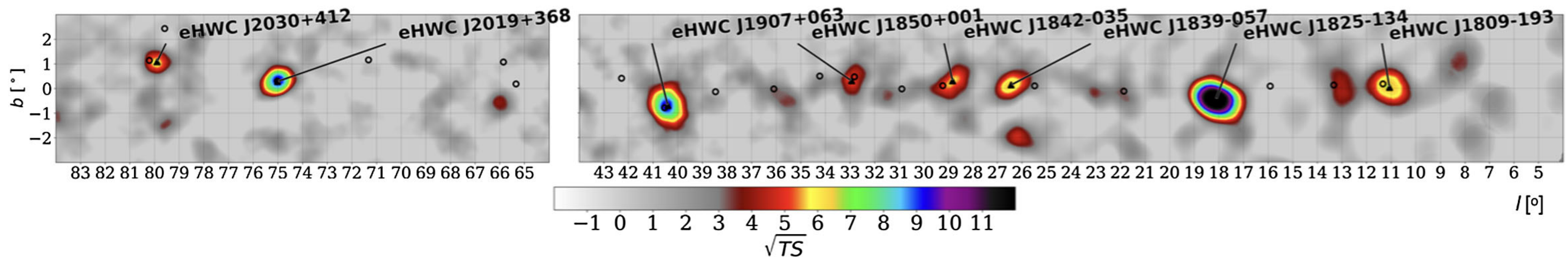
A wealth of UHE sources

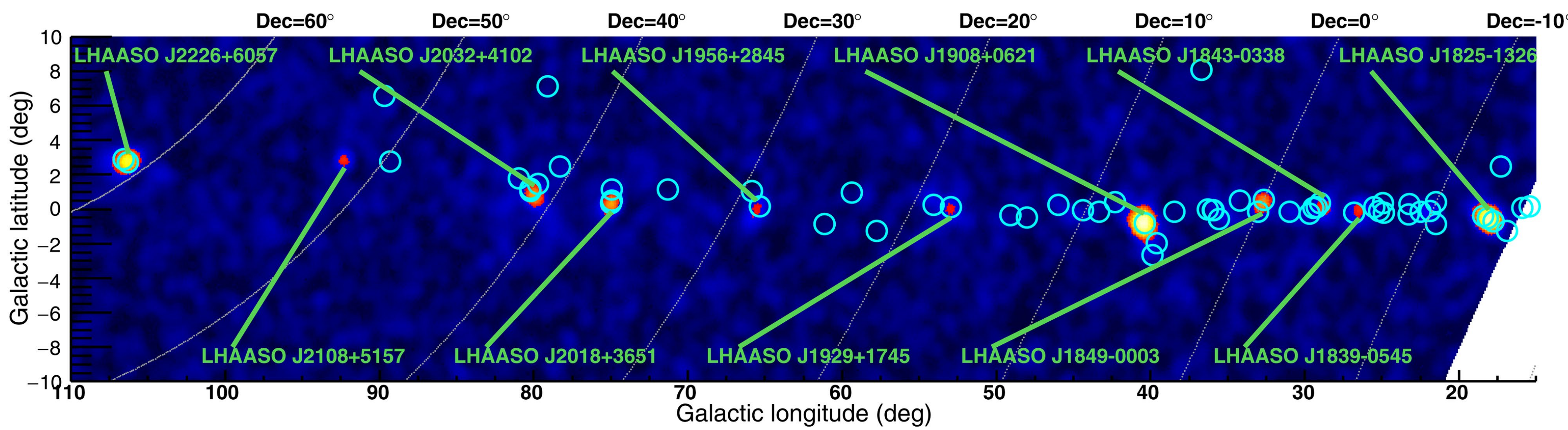
Significant emission > 56 TeV

HAWC collab. (2020) PRL 124 021102



Significant emission > 100 TeV

Cao+ (2021) Nature 594 33

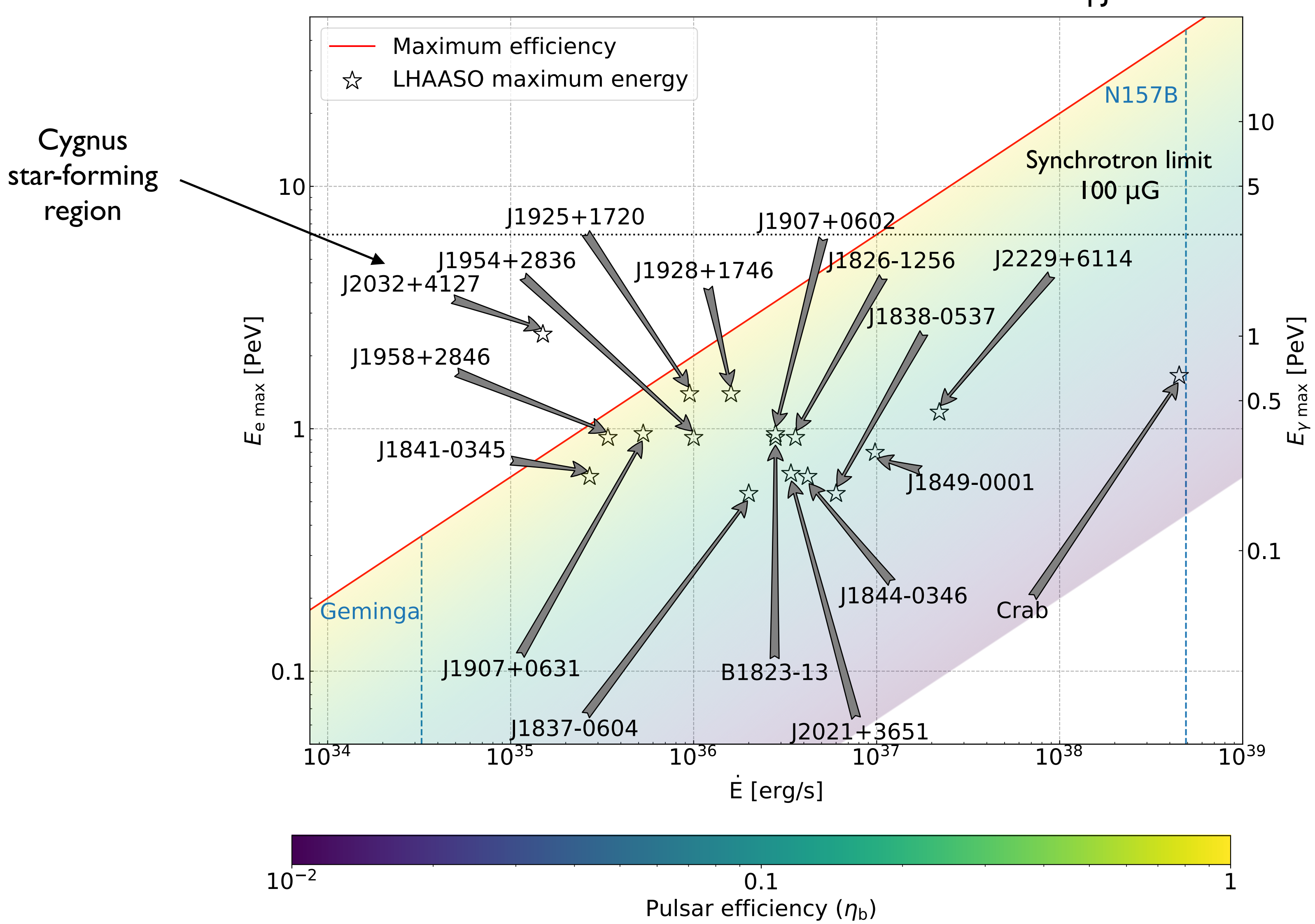


- Technological advantage of LHAASO: underground μ detectors
- Maximum photon energies 200 TeV-1.4 PeV
- Few spectral measurements: cutoff region?

Could UHE sources be leptonic?

- Maximum photon energy mostly consistent with limit from pulsar potential drop
- Emission > 100 TeV can be expected if energy losses dominated by IC (intense radiation fields)

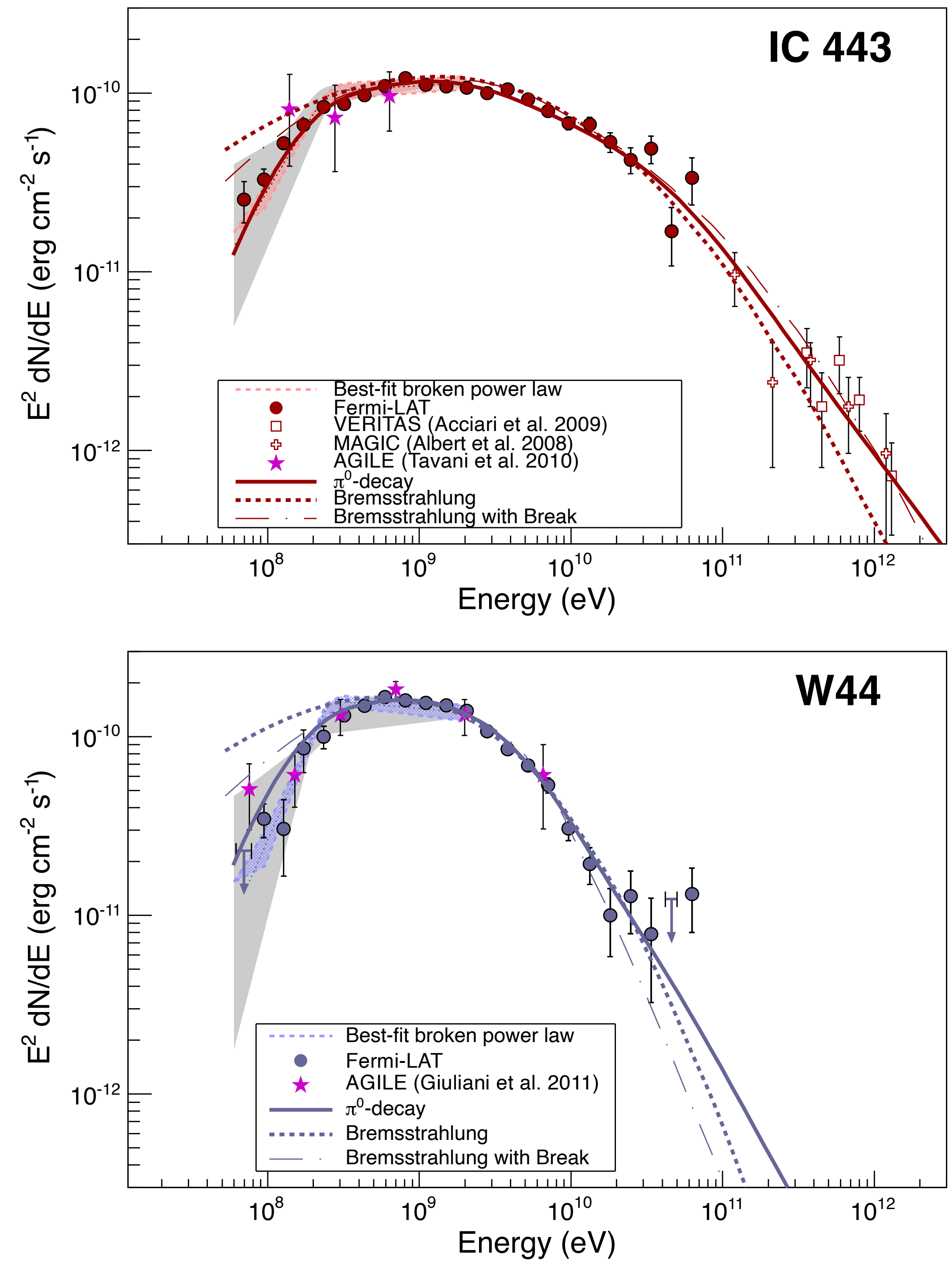
de Oña Wilhelmi+ 2022 ApJL 930 1 L2



The pion bump

- CR protons interactions produce gamma rays via pion decay
  - spectrum peaks at ~70 MeV in pion rest frame
  - characteristic spectral turn-over below few hundred MeV in observer frame
- Signature of nuclei acceleration
- First detected in a a few SNRs by *Fermi* LAT and AGILE

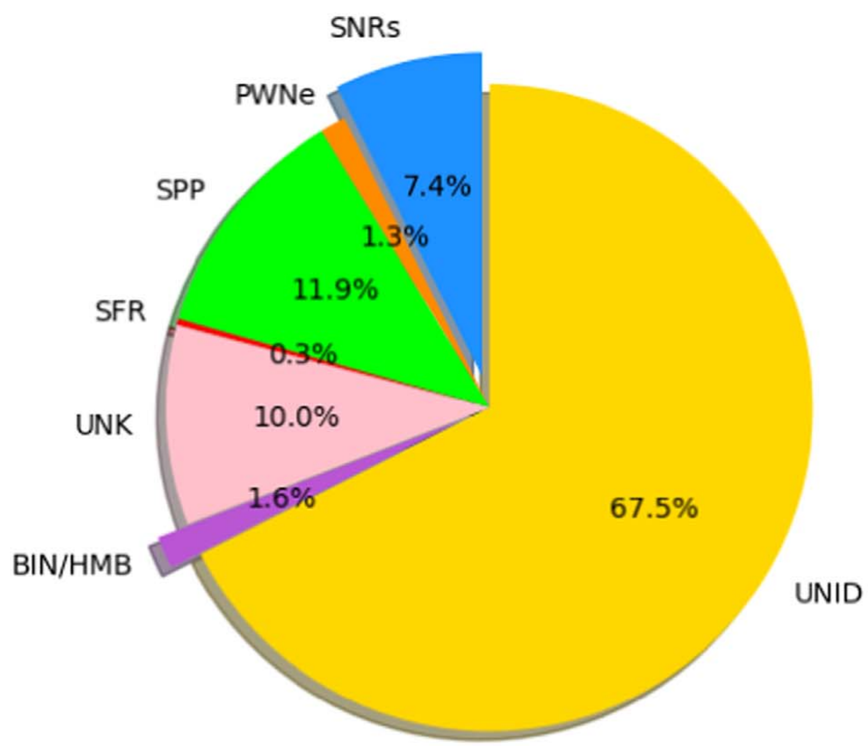
Ackermann+ (2013) Science 339 6121 807



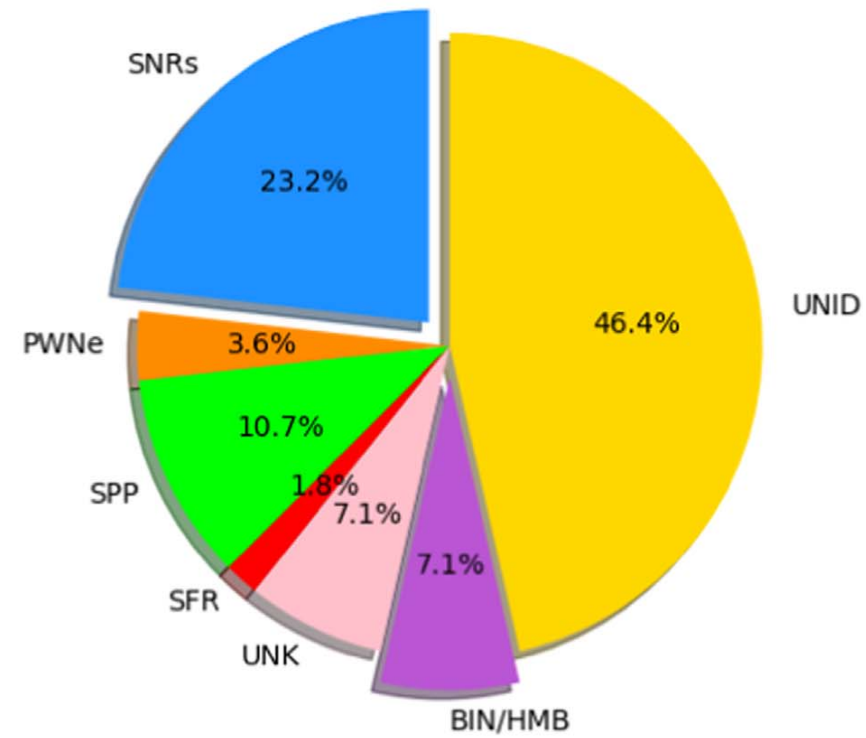
Systematic search for the pion bump

- 56 4FGL sources with significant spectral turnover
- SNRs are the dominant class (13 sources)
- Also four binaries and the Cygnus star-forming region

Sources studied



Sources with confirmed
low-energy spectral turn-over



Abdollahi+ (2022) ApJ 933 204A

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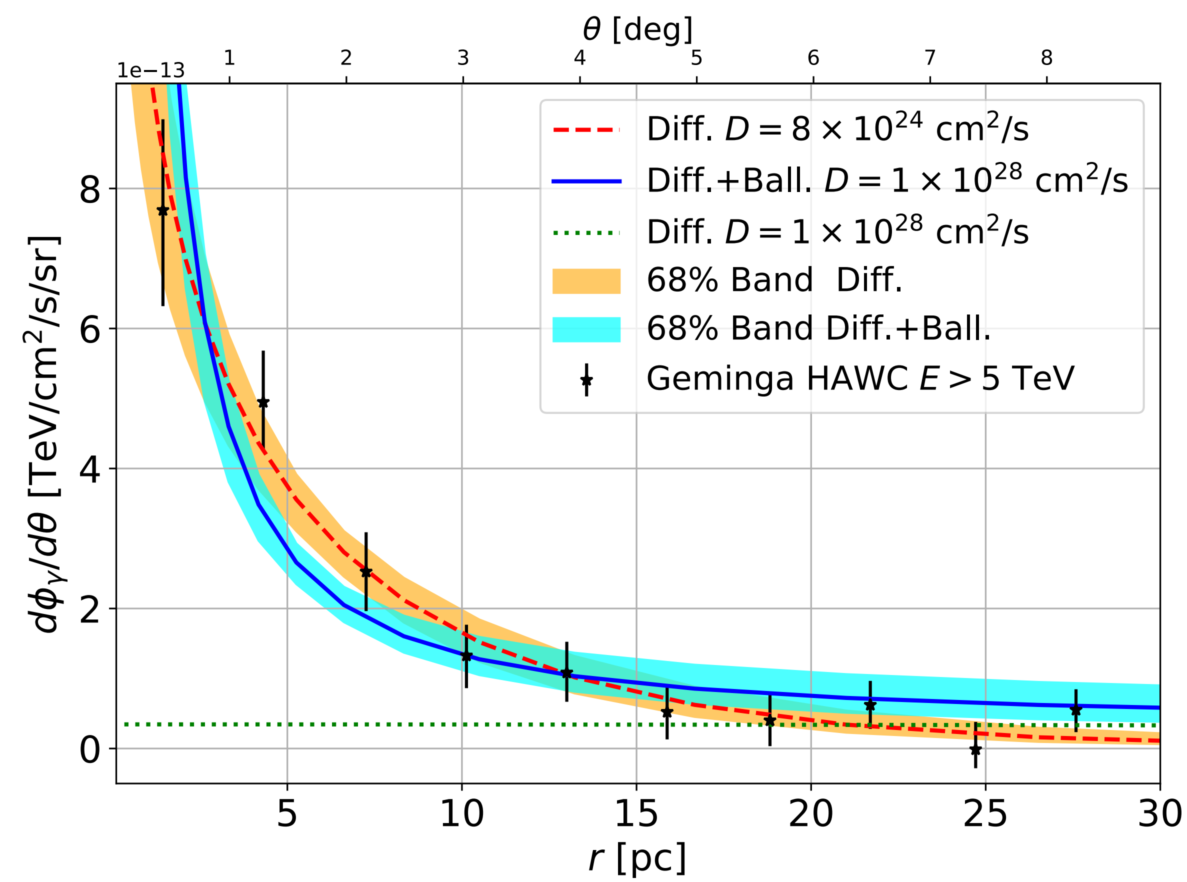
Pulsar halos

- HAWC: Geminga and PSR B0656+14 (> 100 kyr)
- Particles free from PWN
  - diffusion suppressed by ~100 w.r.t. Galactic "average"
  - or combination of ballistic + "average" diffusion?
- Few more candidates at TeV (transitional objects?) and tentative detection of Geminga halo with Fermi
- Suppression of diffusion coefficient?
  - additional turbulence of kinetic or fluid origin
  - reduced turbulence coherence length (< 5 pc)
- Contributions to source populations and diffuse emission?

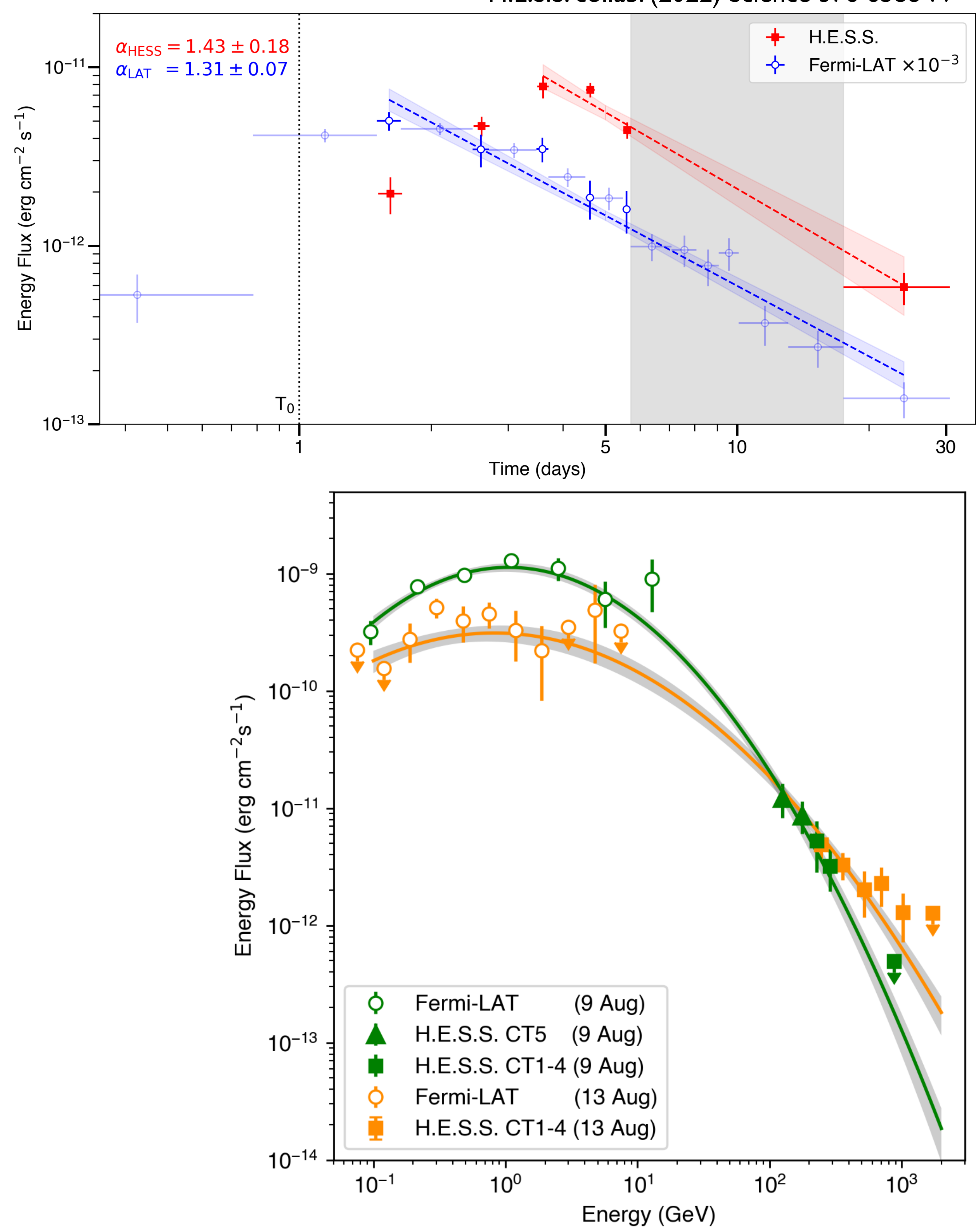
Recchia+ 2021 PRD 104 12 123017



The nova RS Ophiuchi

- thermonuclear explosions in the outer layers of white dwarfs due to accretion from companion star: believed to accelerate particles up to few tens GeV
- recent detection of gamma rays from RS Ophiuchi by H.E.S.S., MAGIC, CTA LST-1 at 0.06-1 TeV
- post-shocked medium's internal energy converted to accelerated protons > 1 TeV with efficiency > 10%
- consistent with theoretical limit for the maximum achievable particle energy via diffusive shock acceleration

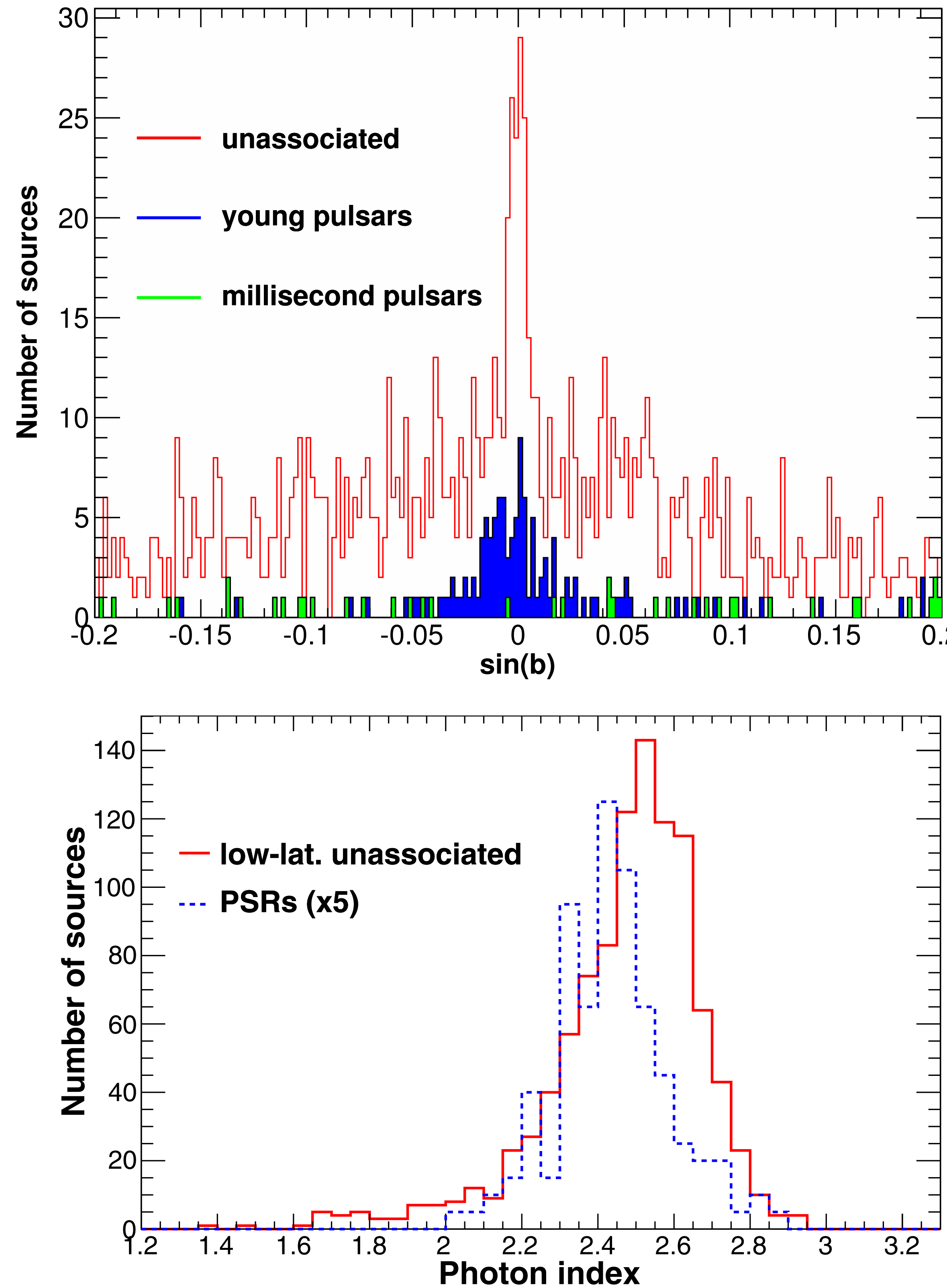
H.E.S.S. collab. (2022) Science 376 6588 77



Low-b 4FGL-DR3 unassociated sources

- Excess of soft sources in the Galactic plane
- Clustering
- Mismodeling of diffuse emission?
  - large-scale regions of fresh CR injection
  - missing gas
- abundant, entirely new class of sources???

Abdollahi+ (2022) ApJS 260 53



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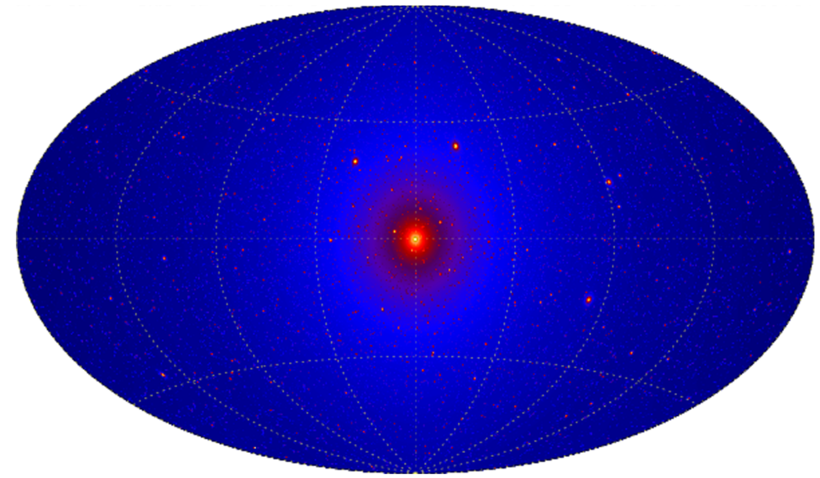
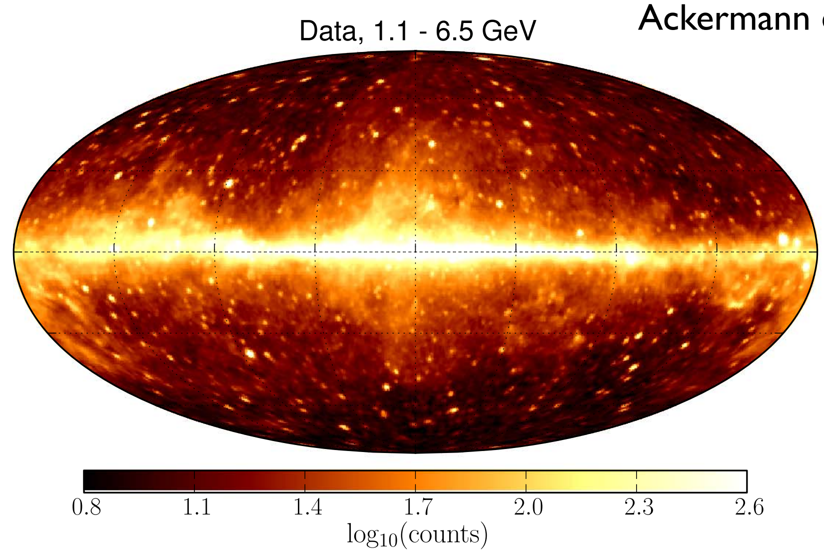
The Galactic center GeV excess

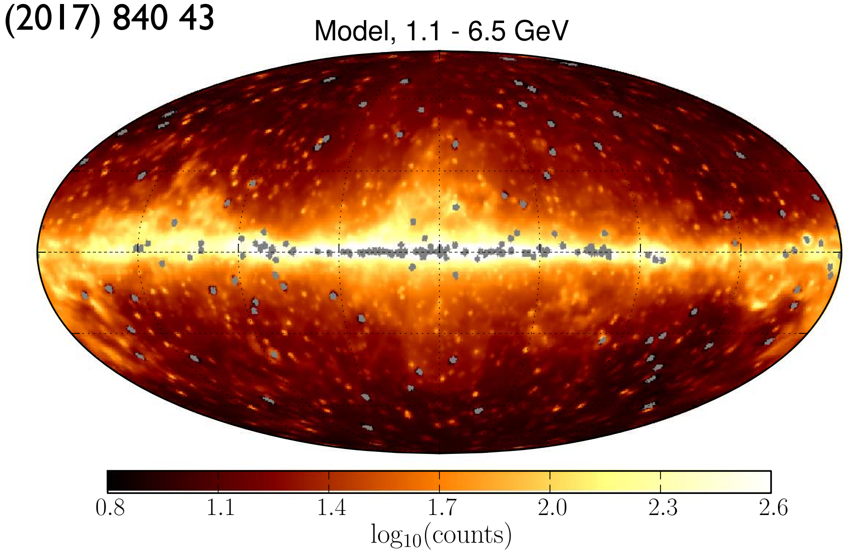
- Weakly Interacting Massive Particles (SUSY) as dark-matter (DM) candidates
  - can decay or self-annihilate into gamma-rays
  - signal maximal towards Galactic center (GC)
- Excess of GeV emission at the GC detected by *Fermi*-LAT

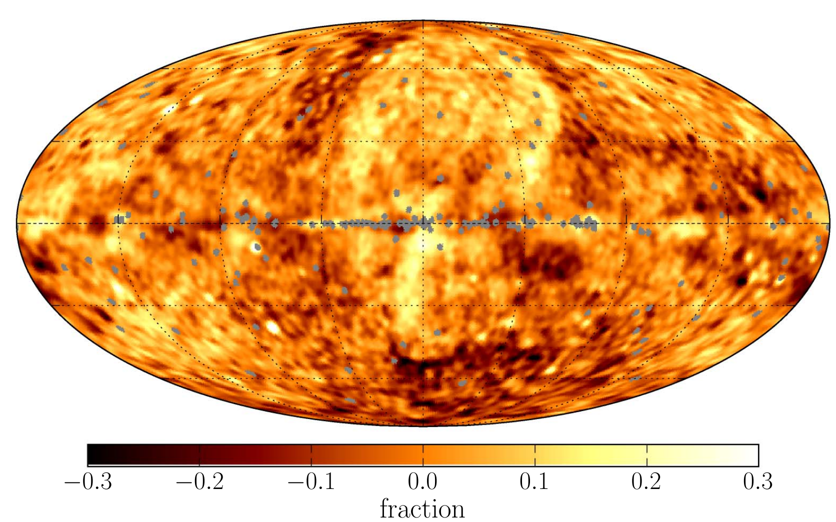
Mock image of gamma-ray emission from DM
Pieri et al. (2011) PRD 83 2 023518

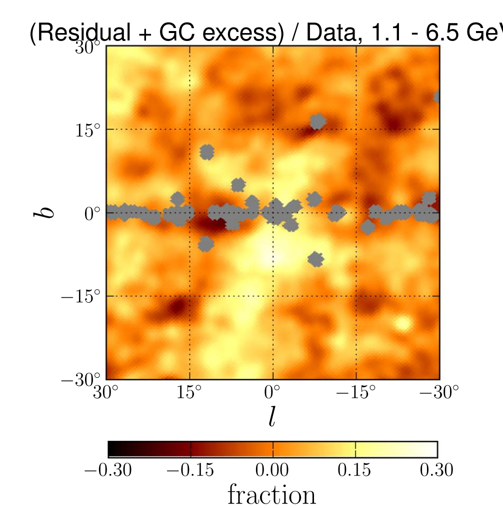


Ackermann et al. (2017) 840 43









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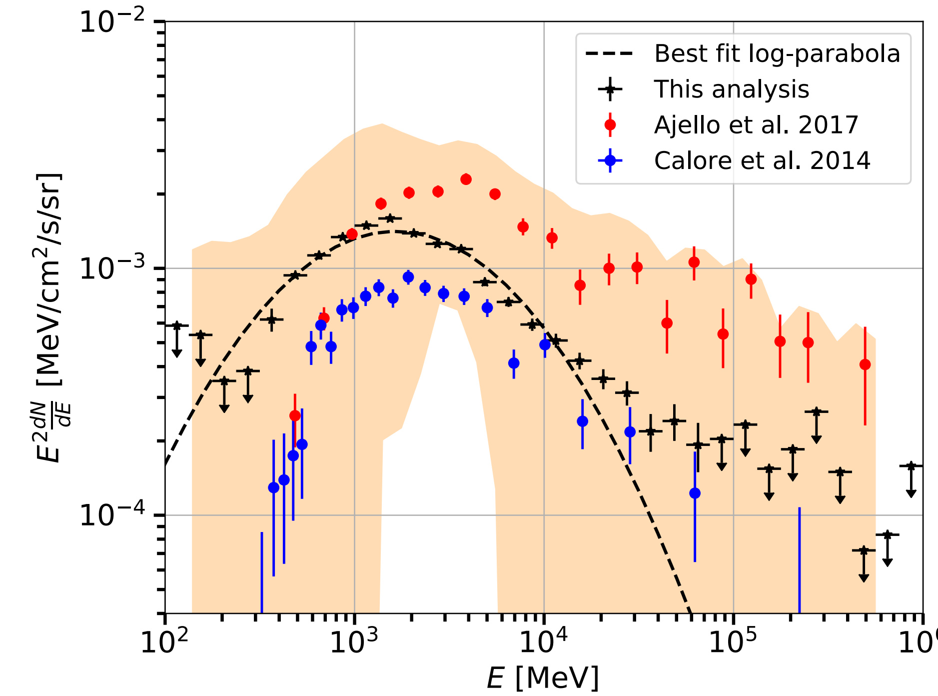
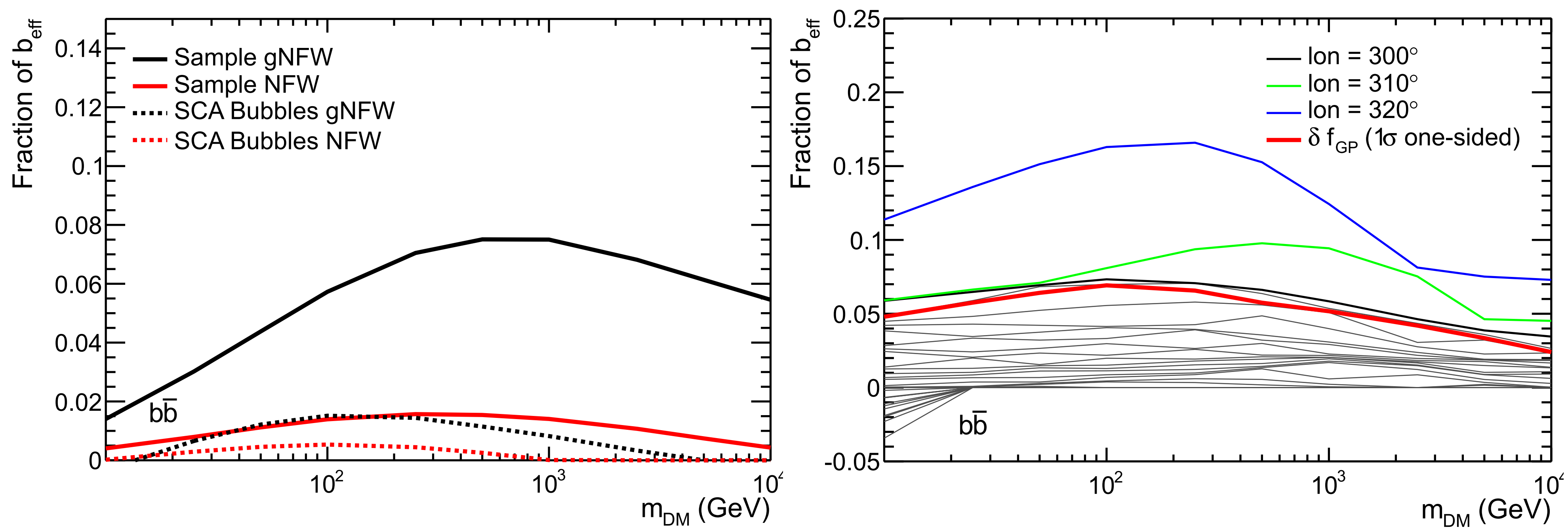
The Galactic center GeV excess

- Properties
  - Spectrum
    - bump at few GeV
    - wild variations depending on background models
  - Morphology
    - Lively debates: centered on the GC? Correlated with mass in the bulge? Smooth or peaky (sources)?
    - May be consistent with DM profile
- Interpretation: DM, ms pulsar population, mismodeled interstellar emission
- Often forgotten: similar excesses found everywhere in the Galactic plane

Di Mauro 2021 PRD 103 6 063029



Ackermann et al. (2017) 840 43



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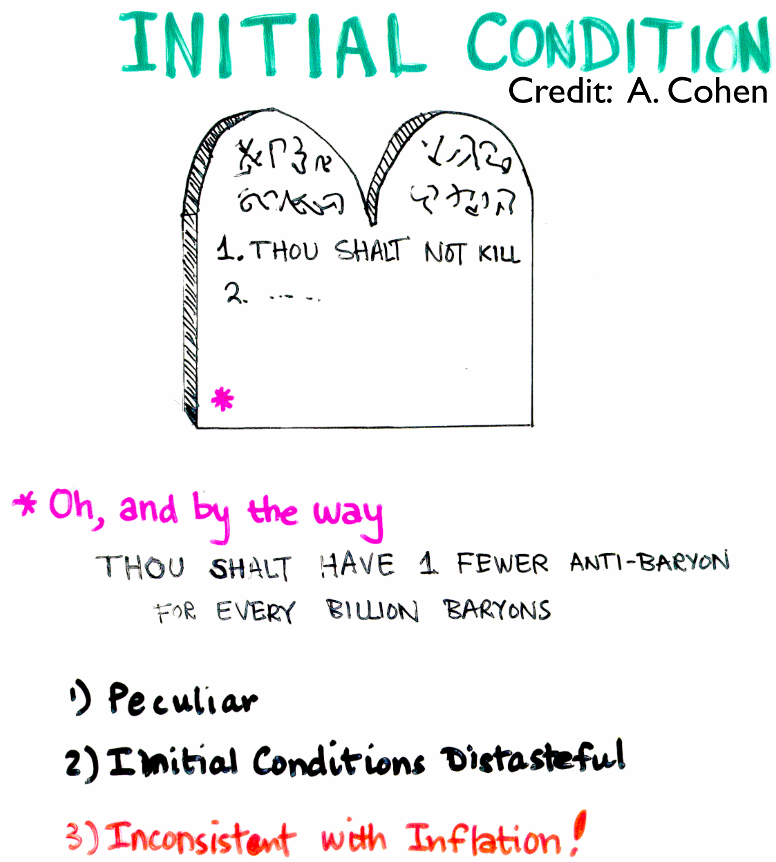
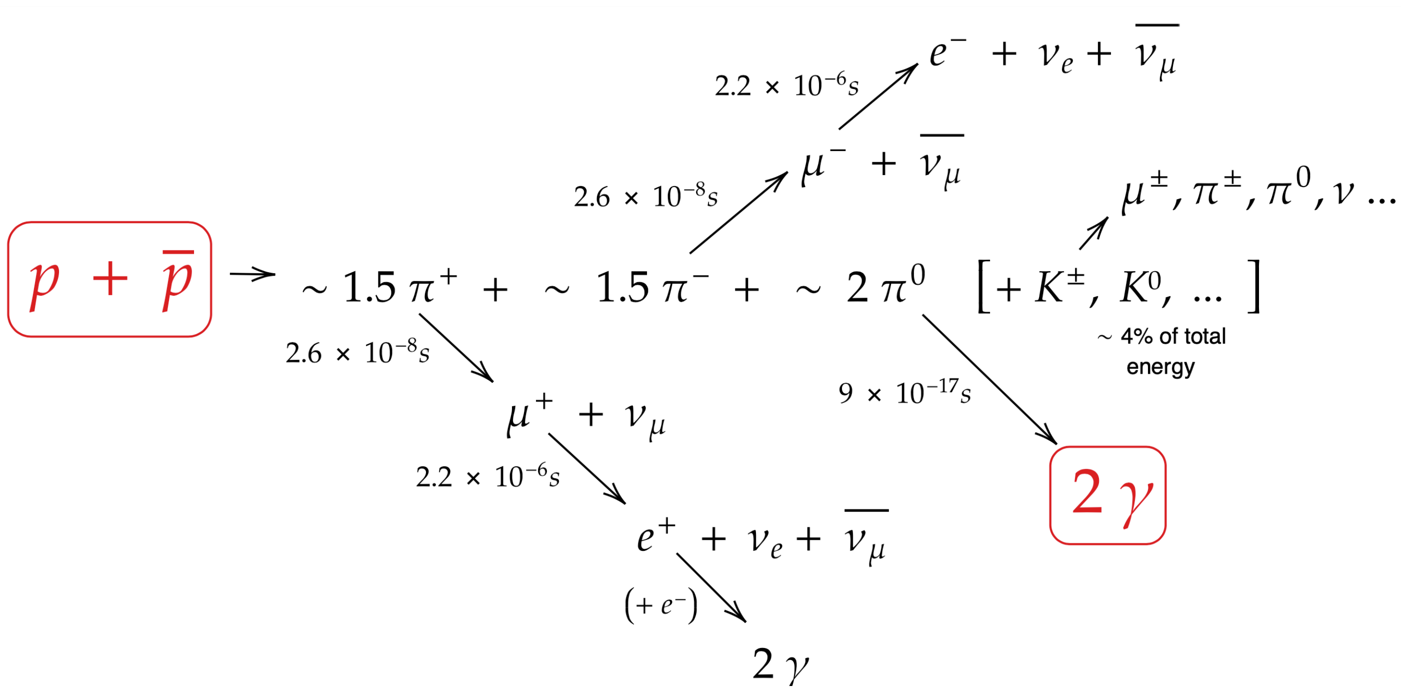
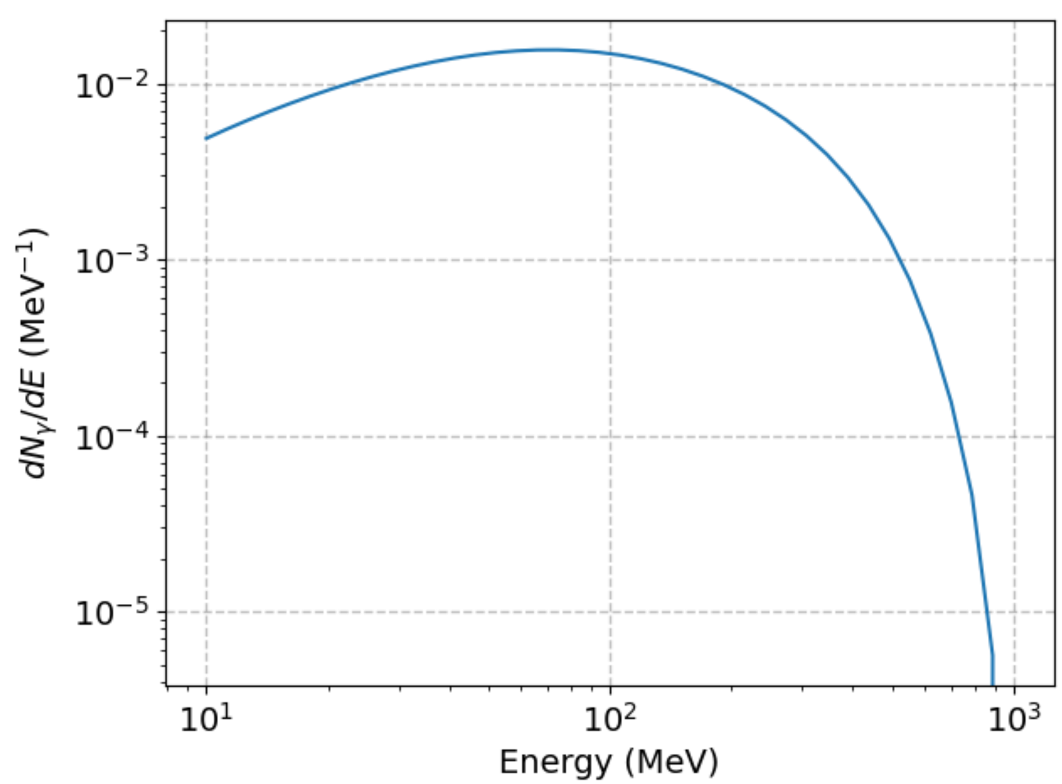
Antimatter and antistars

- Matter-antimatter asymmetry unexplained in standard model: baryogenesis, Dirac-Milne cosmology, CPT-symmetric Universe, …
- Tentative detections of anti-He by AMS-02
  - cannot be produced by CR spallation
  - possible hint of nearby antimatter domain
- Antistars identified as most plausible candidate, can be formed in Affleck-Dine baryogenesis scenario
- Antimatter domain can be sought using its characteristic gamma-ray spectrum





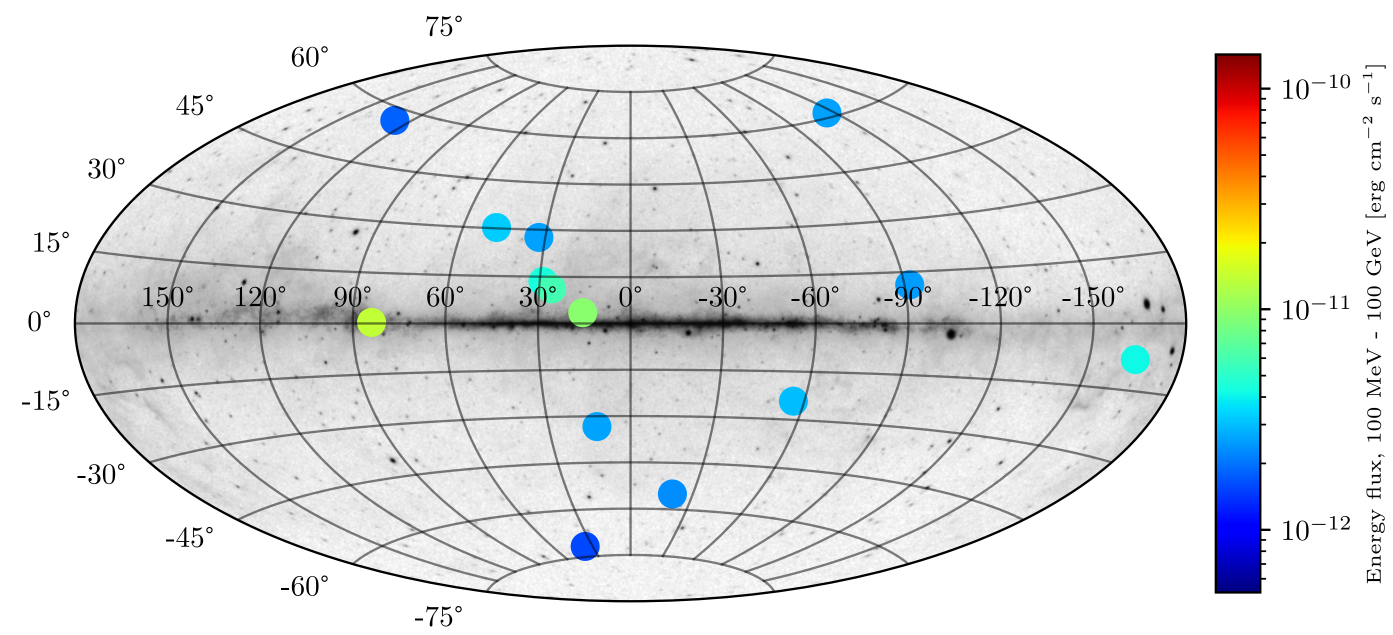
Backenstoss+ (1983) Nucl. Phys. B 228 3 424



Antistar candidates and limits

- 14 candidates selected based on morphology and spectrum among unassociated 4FGL-DR2 sources
- Most likely belonging to standard source classes → upper limits
  - < 2.5 × 10^{-6} antistars/stars for objects with properties similar to young stellar population in the Galactic disk (20 times more stringent than before)
  - new limits for primordial halo antistars with masses > 2 $M_\odot$

Dupourqué, LT+ (2021) PRD 103 083016



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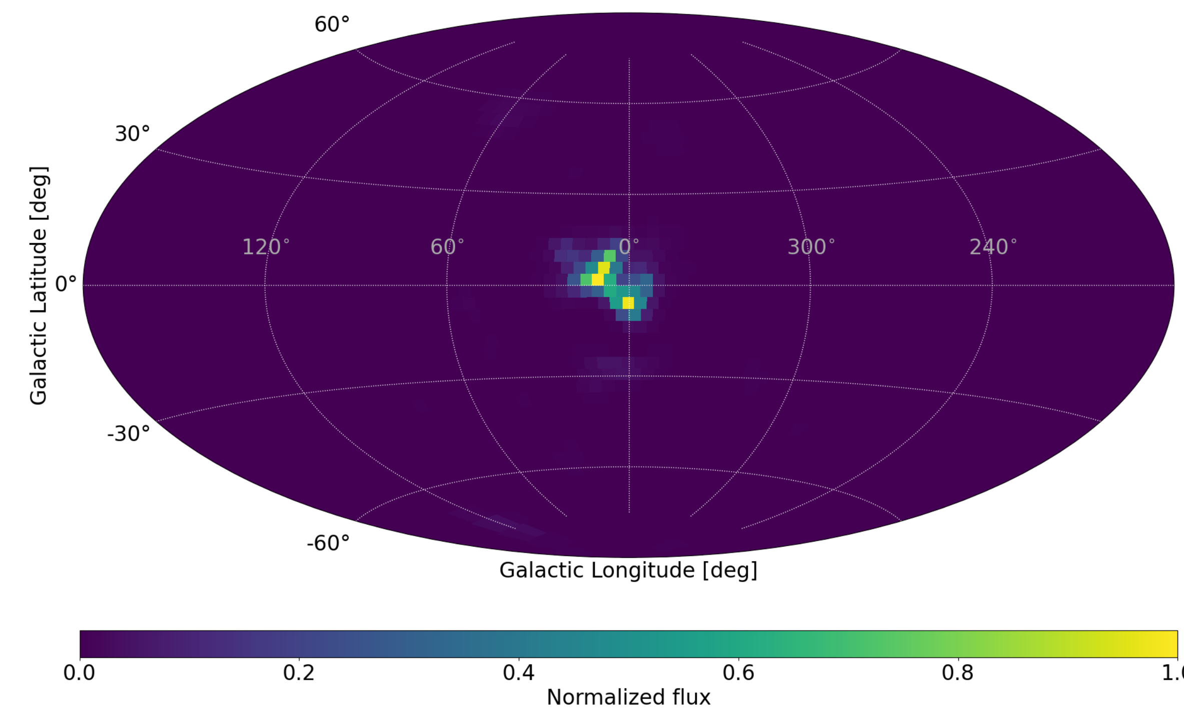
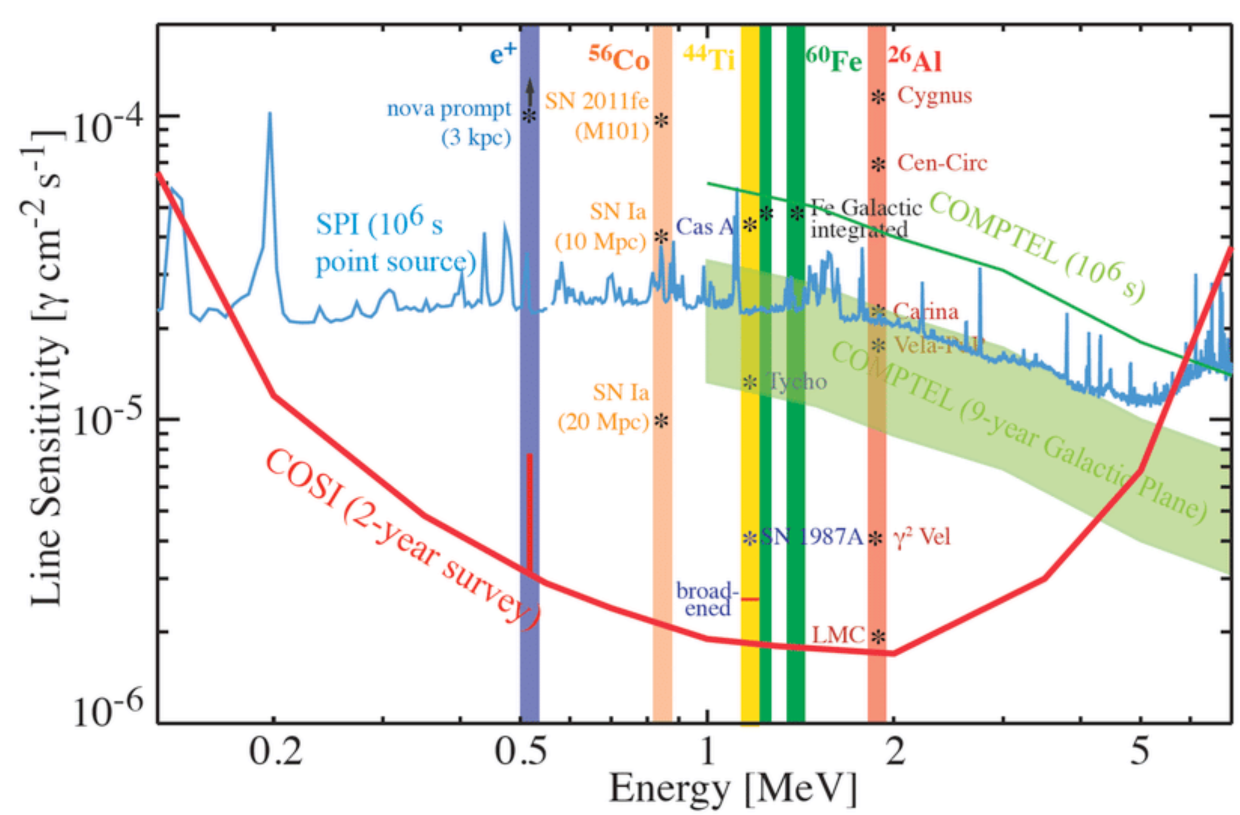
COSI SMEX

- Will make accessible the MeV band again after > 20 years
- Compton telescope based on Germanium cross-strip detectors
- Superpressure balloon → SMEX mission scheduled for launch in 2025
- Imaging + spectroscopy + polarimetry
  - positron origin
  - element formation
  - polarization in PWNe, …

511 keV positron annihilation map
Zoglauer+ 2021 arXiv:2102.13158



Tomsick+ 2020 Astro2020



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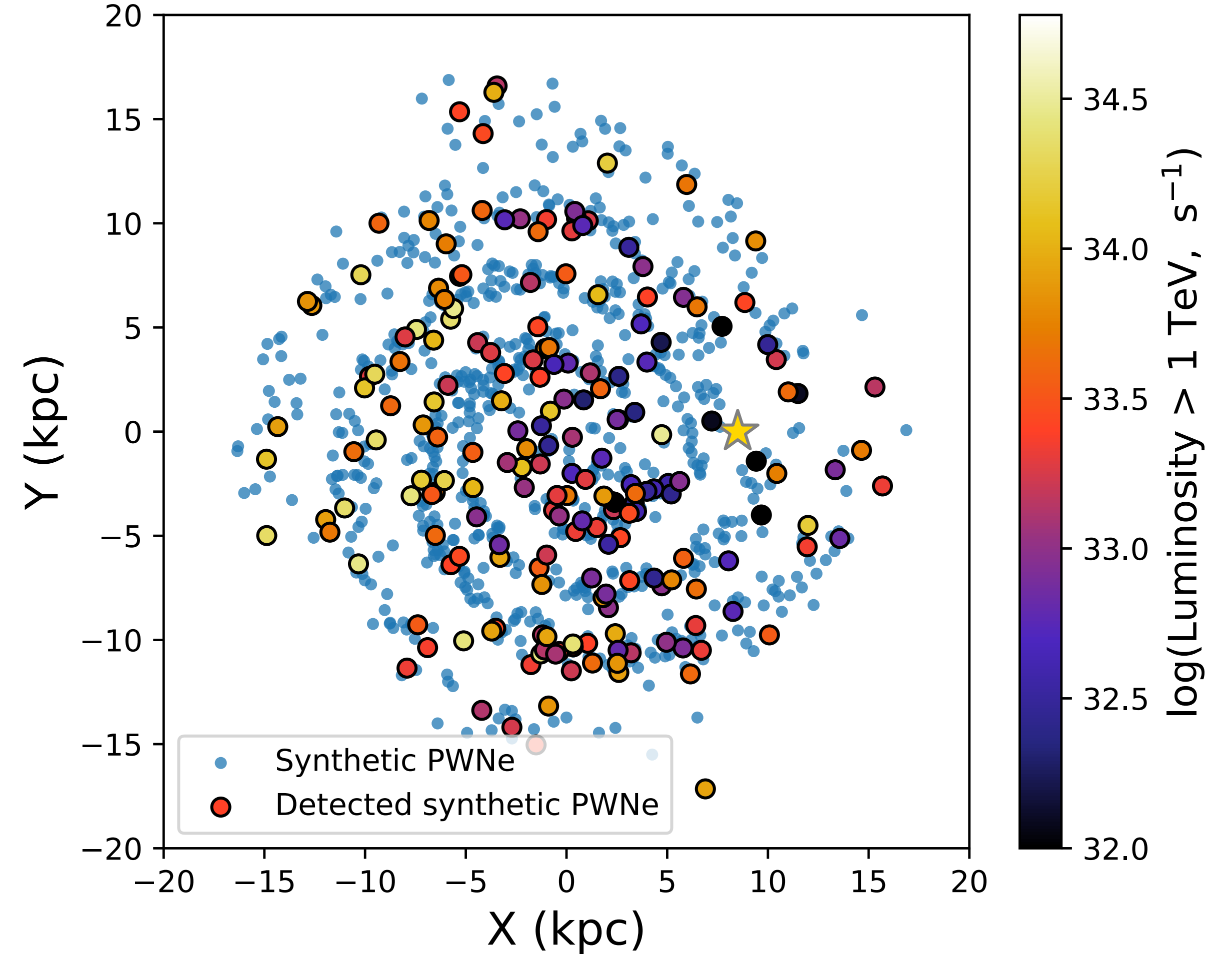
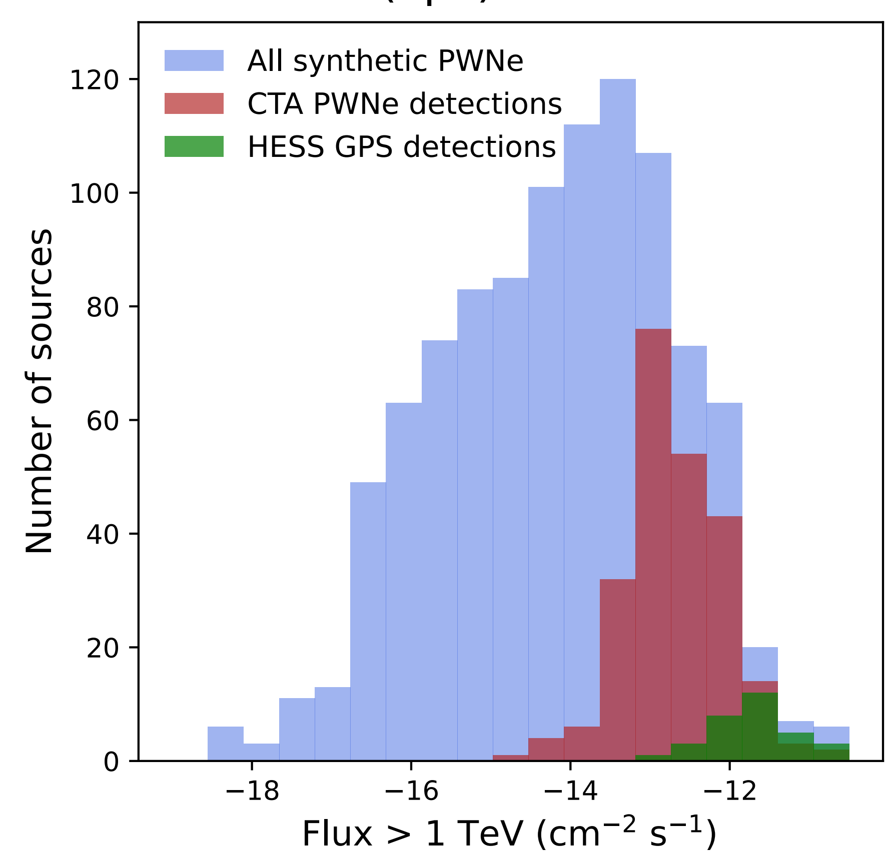
CTAO

- New-generation Cherenkov observatory:
  - two arrays (N: La Palma, Spain, S: Paranal, Chile)
  - > 60 Cherenkov telescopes optimised for different energy ranges
  - construction expected to start in 2023 and last 5 years
- Survey of the entire Galactic plane proposed as Key Science Project: increase by a factor of ~5 the number of sources

Remy, LT+ (2021) 37th ICRC





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Final remarks

- Gamma-ray observations make it possible to study particle acceleration and transport in an ever-increasing variety of astrophysical conditions and environments
- The standard supernova remnant paradigm for the origin of Galactic cosmic rays is challenged: what kind of sources/ acceleration processes contribute for different energies and particle types?
- Gamma-ray observations can also address physics beyond the standard model of particle physics, such as the nature of dark matter and the matter-antimatter asymmetry