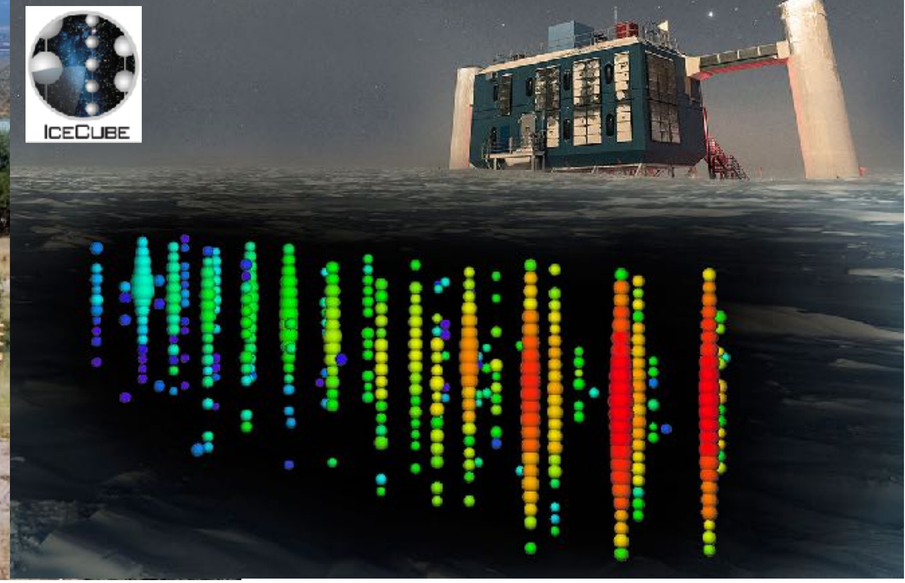


Multi-messenger search for the hadronic accelerators in our Galaxy

Nahee Park

Queen's UNIVERSITY

SuGAR MADISON 2024

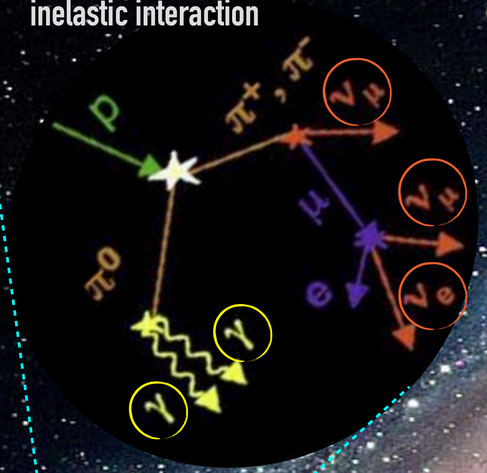
SEARCHING FOR THE SOURCES OF GALACTIC COSMIC RAYS

OCTOBER 14-17

NSF ICECUBE WIPAC WARF

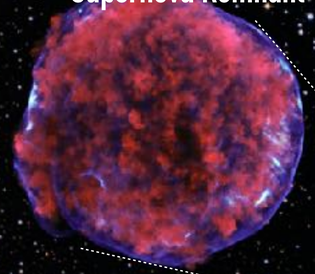
Origin of Galactic Cosmic Rays?

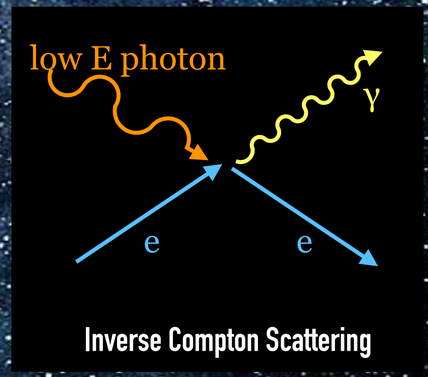
proton-proton
inelastic interaction



Cosmic ray sources

Supernova Remnant





γ (gamma-ray)

ν(neutrino)

p+

Multi-Messsenger Observations

Cosmic-rays are bending inside the magnetic field.

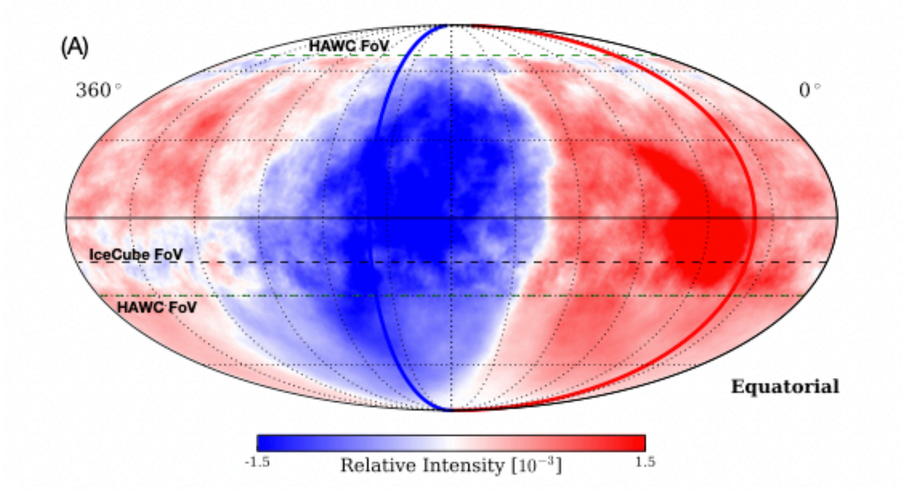
Gamma-rays are generated by both leptons & hadrons!

VHE neutrino are generated only by hadrons!

Searches for the origin of Galactic Cosmic Rays

Cosmic Rays

- ☑ **Spectra**
- ☑ **Composition**
- ☐ **Directionality**



Gamma Rays

- ☑ **Spectra**
- ☐ **Composition**
- ☑ **Directionality**

- Emission can be leptonic
- Brightness of the emission is environment dependent (no target = no emission)

Neutrinos

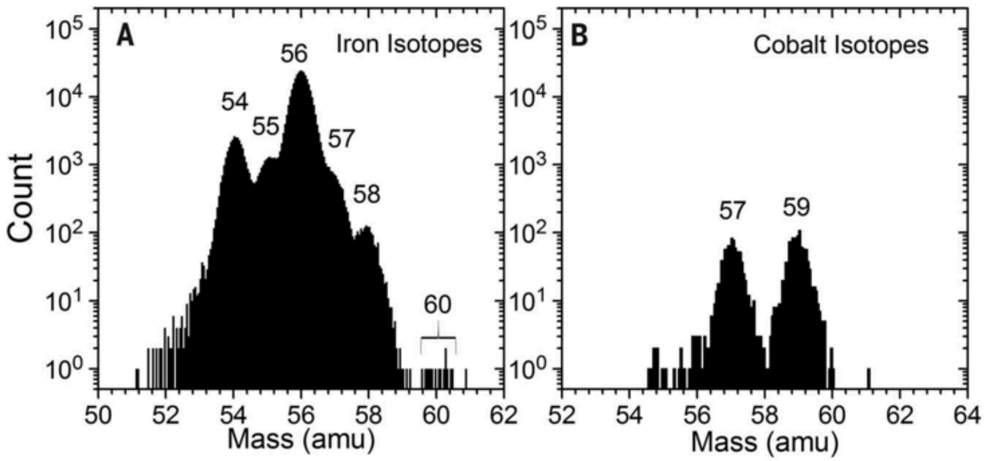
- ☑ **Spectra**
- ☐ **Composition**
- ☑ **Directionality**

- Super hard to detect
- Brightness of the emission is environment dependent (no target = no emission)

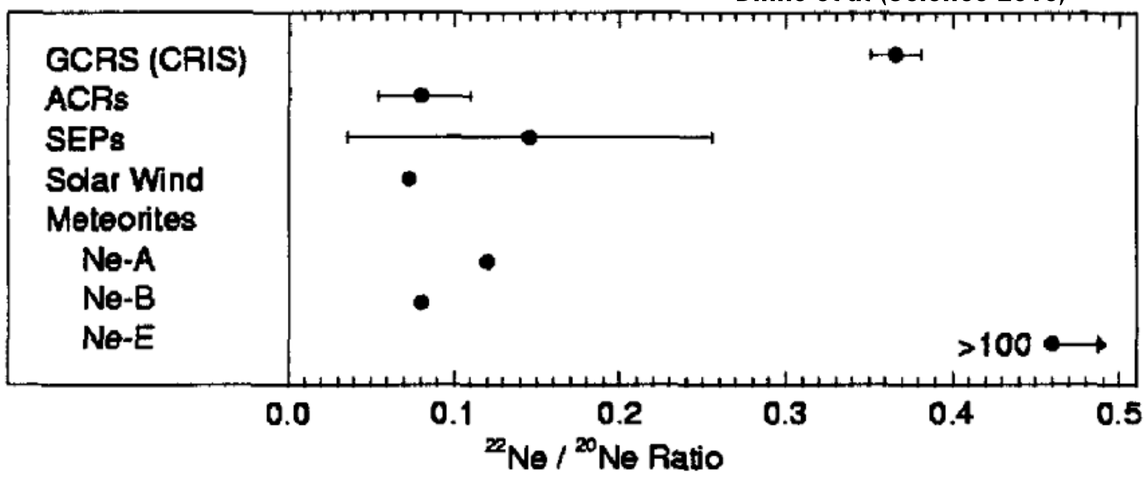
Origin of Cosmic Rays w/ Cosmic rays

Through elemental abudance

ACE/CRIS: E~few 100 MeV/n

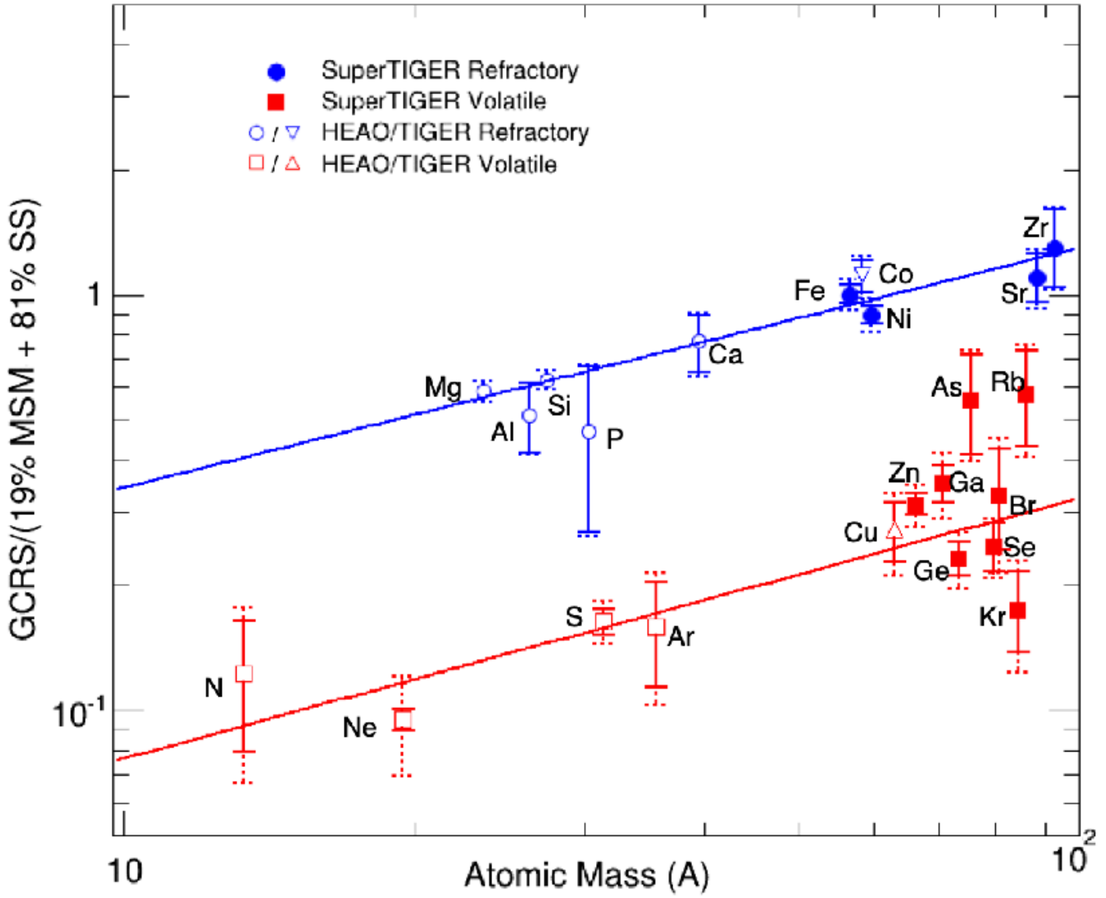


Binns et al (Science 2016)



Binns et al (ACE/CRIS) (Adv. Space Res. 2001)

TIGER/SuperTIGER: E~few GeV/n

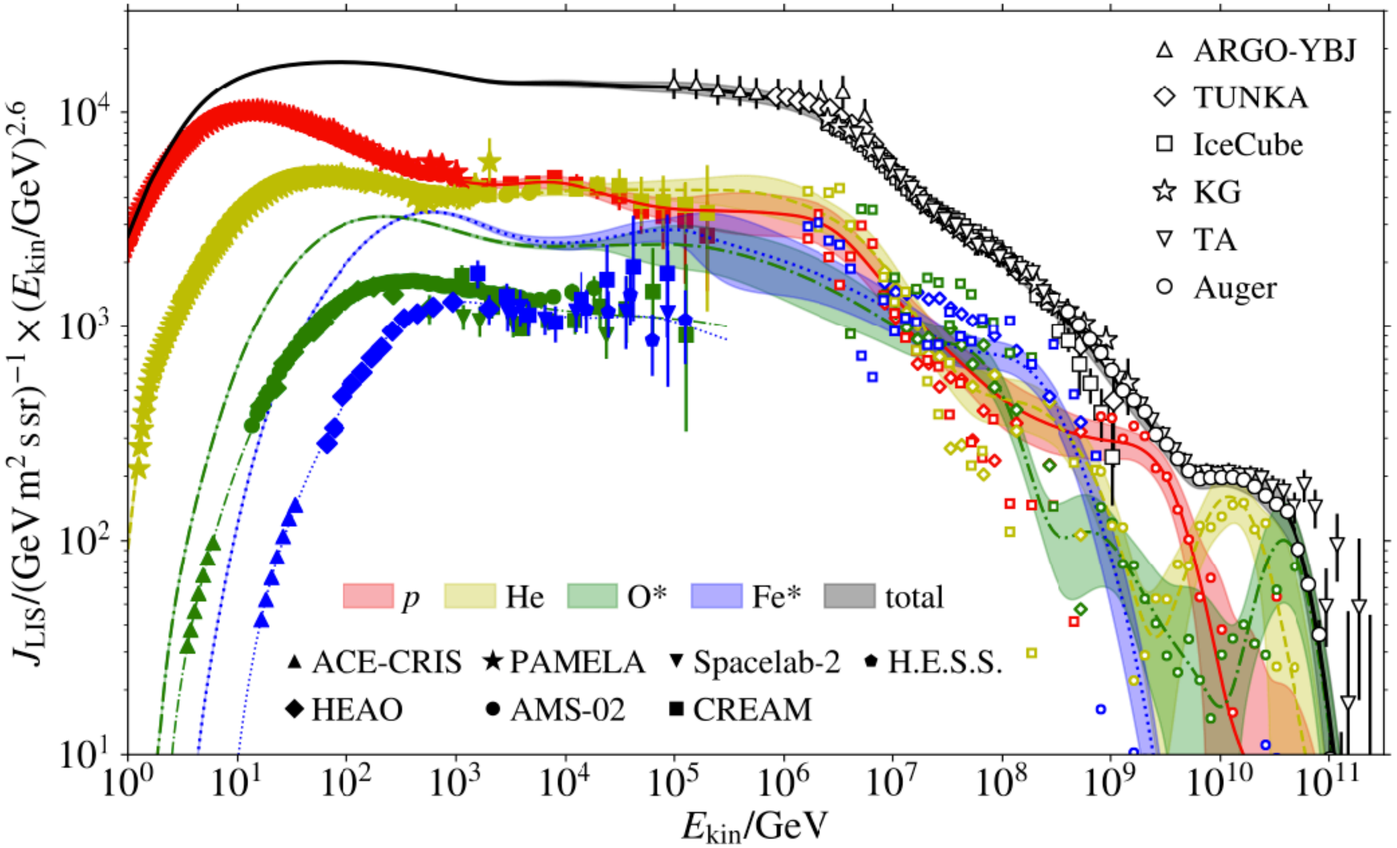


Murphy et al (ApJ 2016)

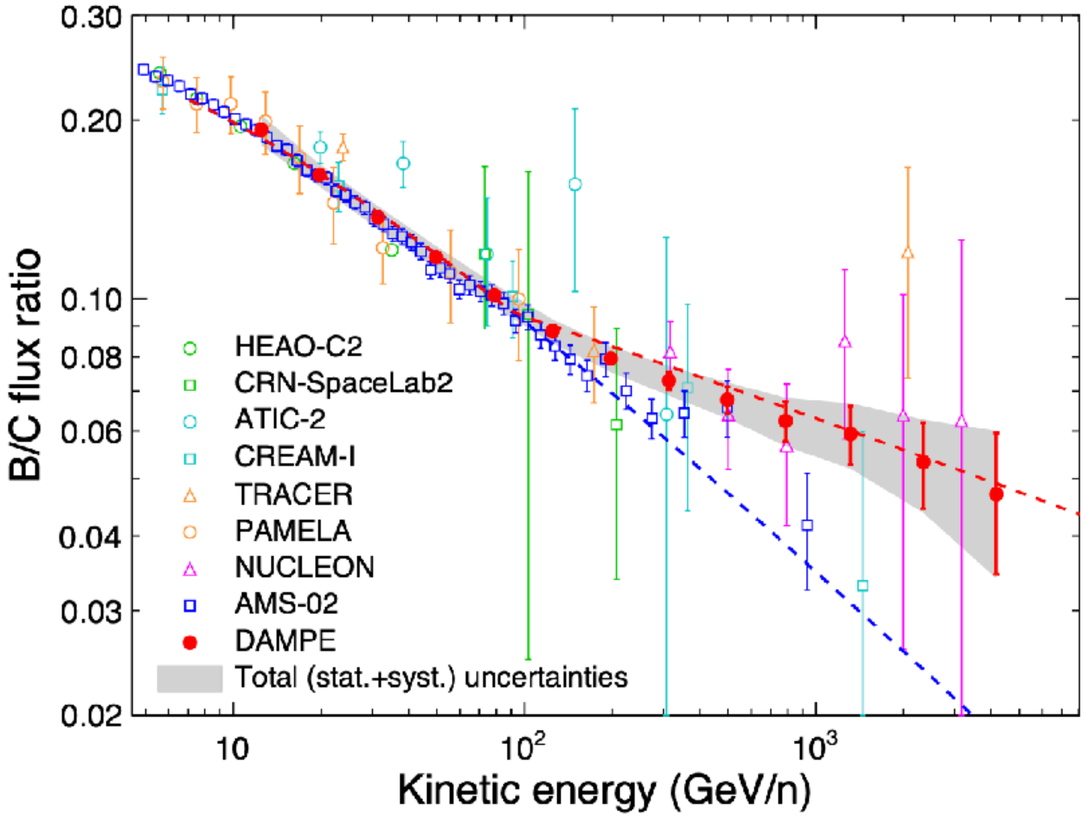
Origin of Cosmic Rays w/ Cosmic rays (2)

Through elemental spectra

....It is complicated...



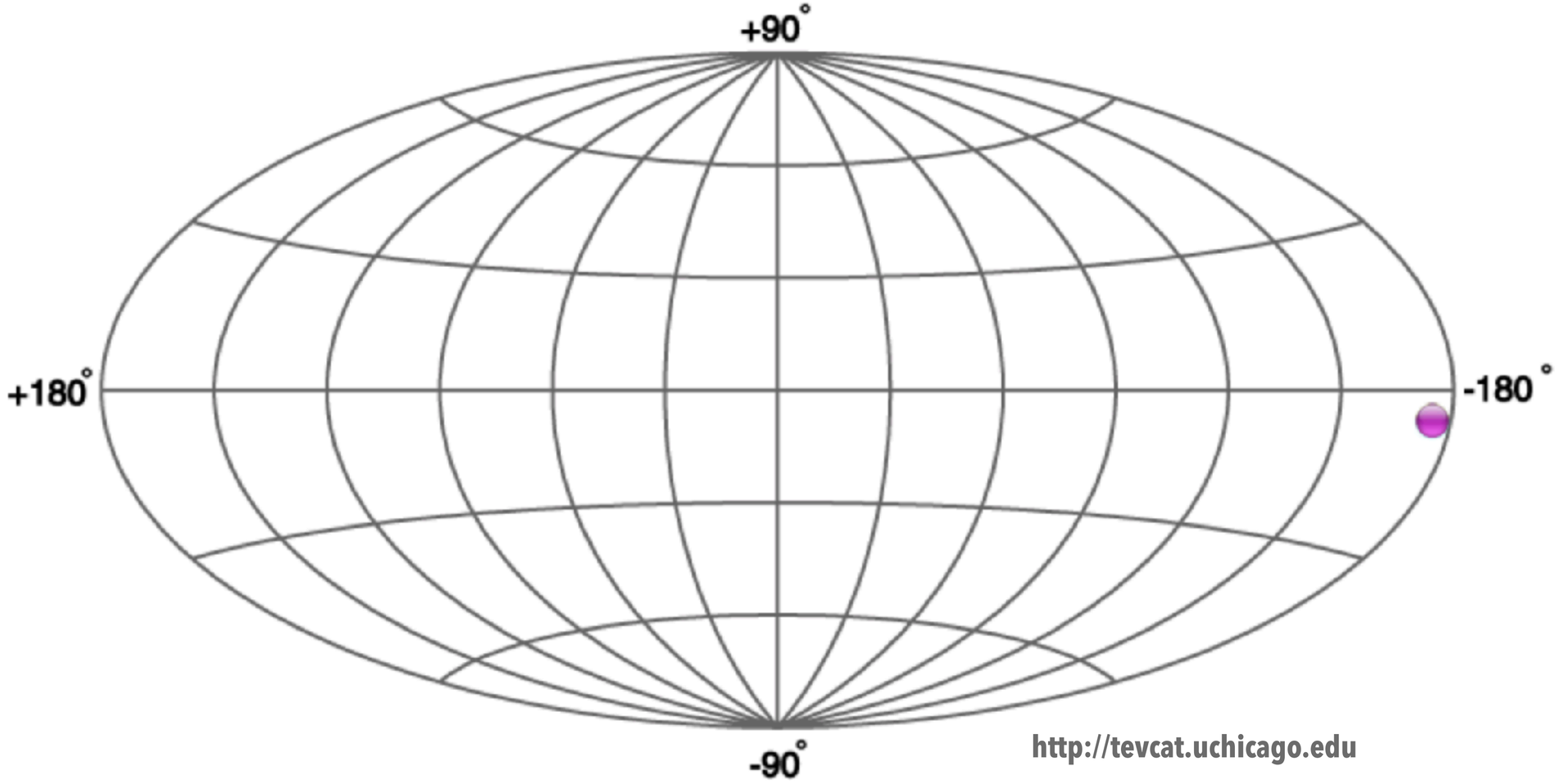
Hembinsky (ICRC 2017)



DAMPE (Sci. Bulletin 2022)

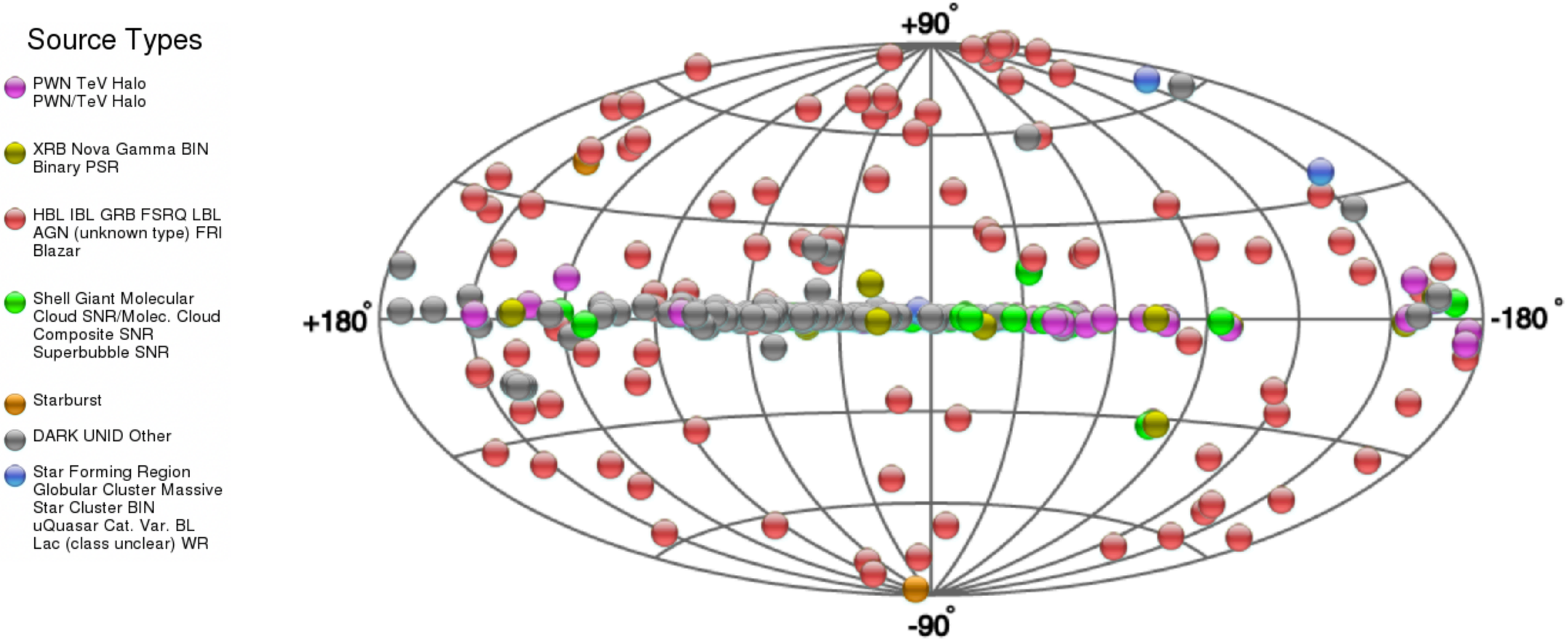
Origin of Cosmic Rays w/ Gamma rays

Gamma-ray sky (w/ 10^{11} higher energy than visible light) in 1987: 1 source



Origin of Cosmic Rays w/ Gamma rays

Gamma-ray sky (w/ 10^{11} higher energy than visible light) in 2024:
>200 sources



2018: first detection of microquasar jet interactions

2019: first detection of GRB

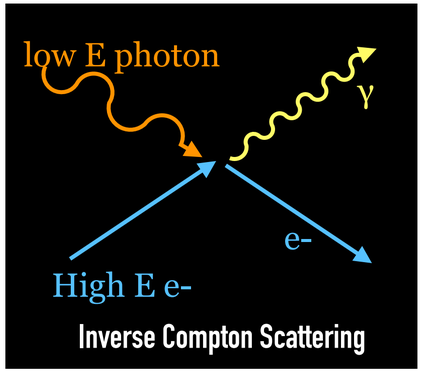
2021: first detection of Nova

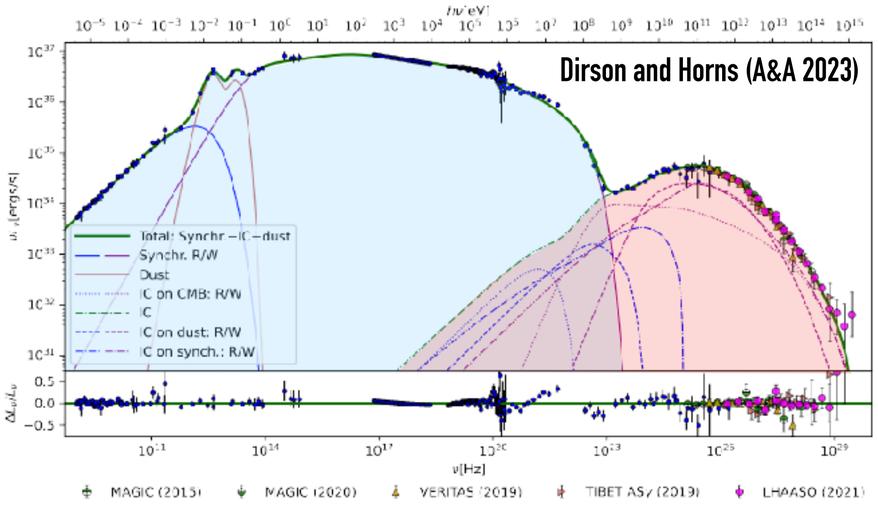
http://tevcat.uchicago.edu

Gamma ray sky: bright with leptonic emission

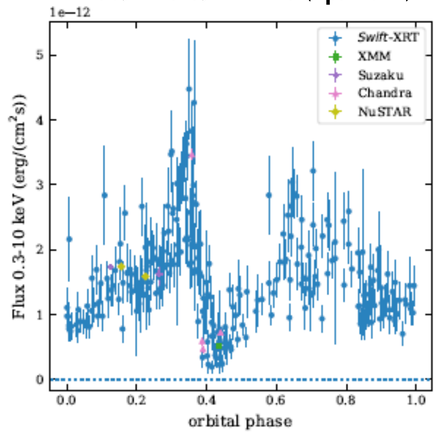
Very High Energy gamma-ray sky is bright with leptonic emission!

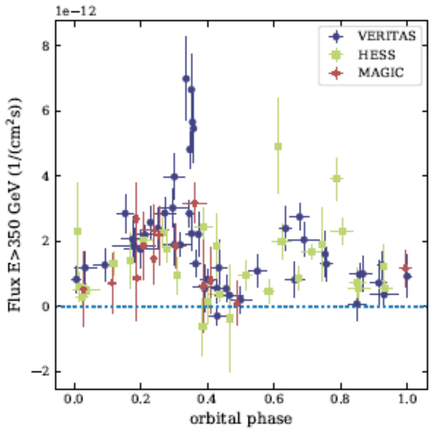
- We know there are high-energy leptonic particles in the Universe
  - Inverse Compton scattering: High-energy leptons scatter the low-energy photons to high-energies

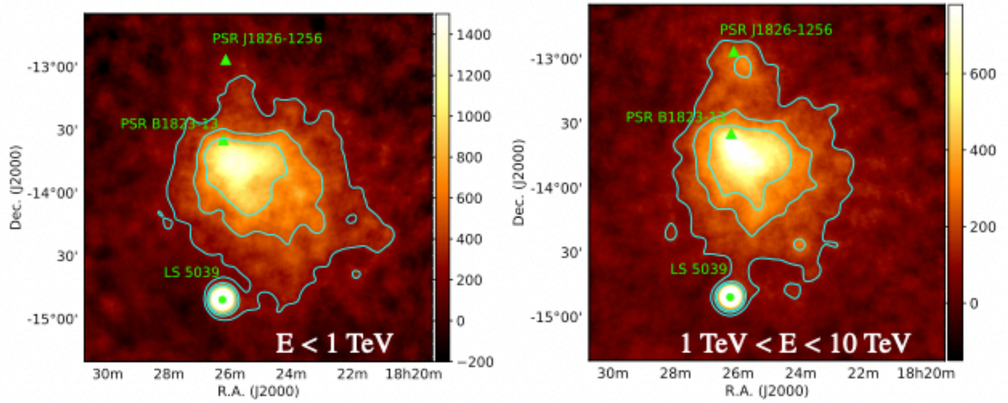


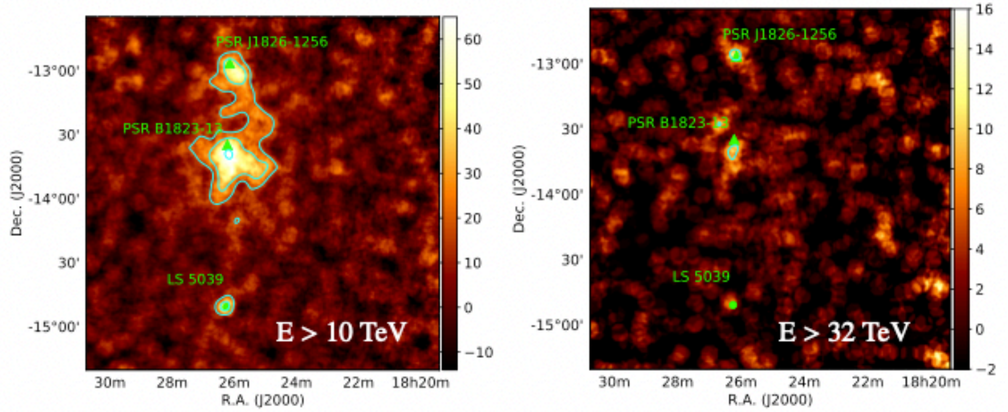


HESS, MAGIC, VERITAS (ApJ 2021)







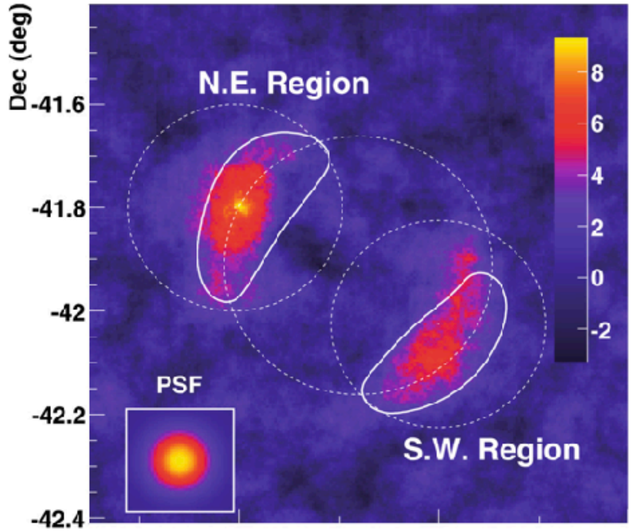


HESS Collaboration (A&A 2019)

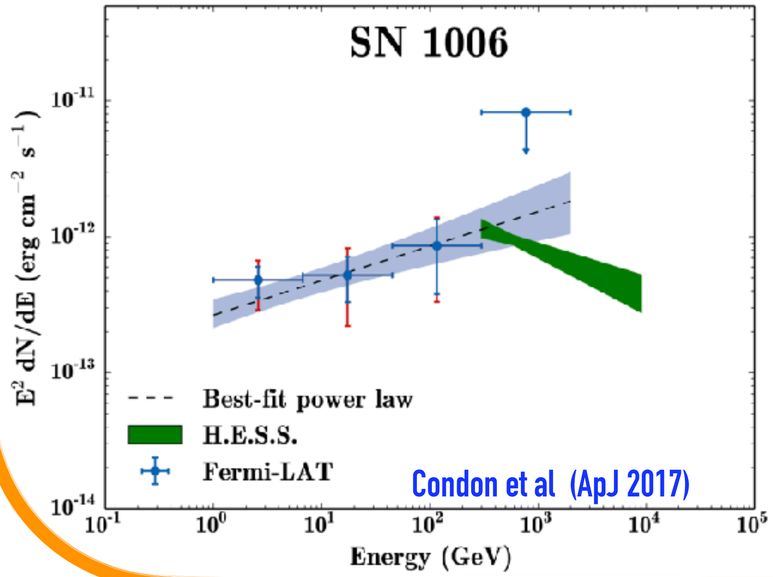
Gamma rays: Sample of Supernova Remnants

Leptonic? Hadrinic?

SN 1006

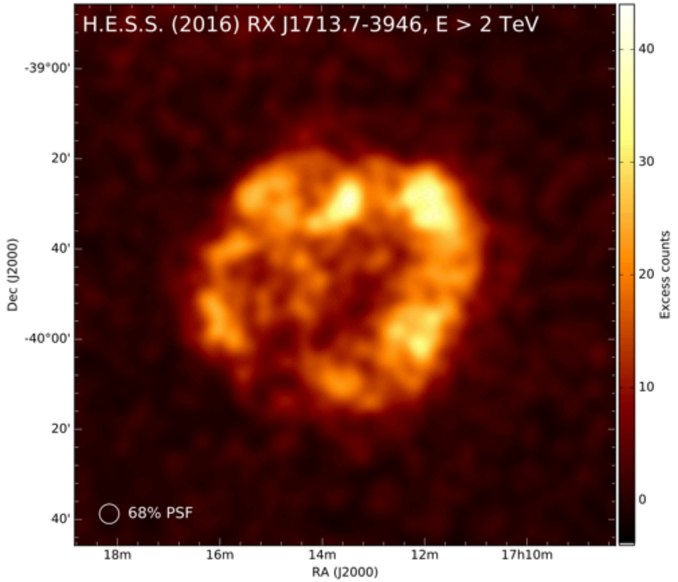


HESS (A&A2010)

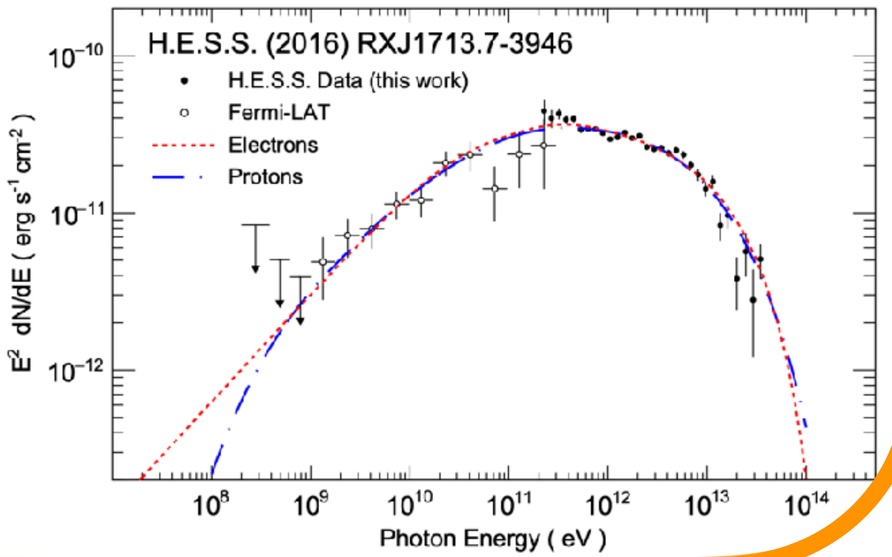


Condon et al (ApJ 2017)

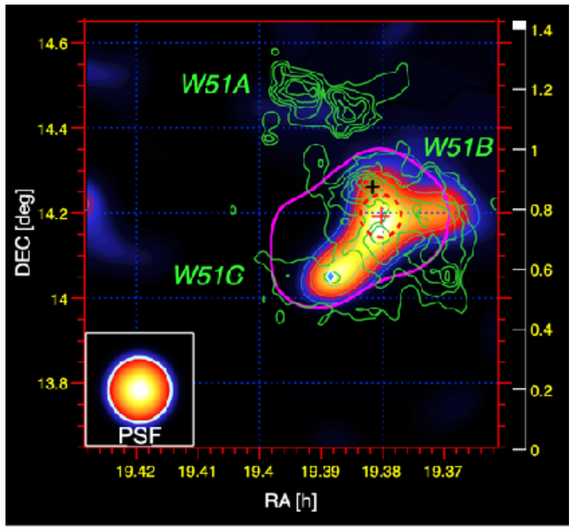
RX J1713.7-3946



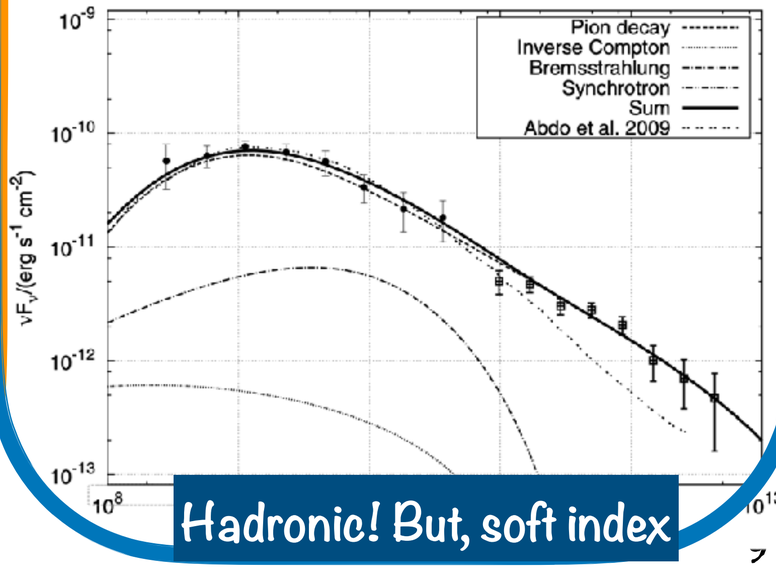
HESS (A&A2016)



W51C



MAGIC (A&A2012)



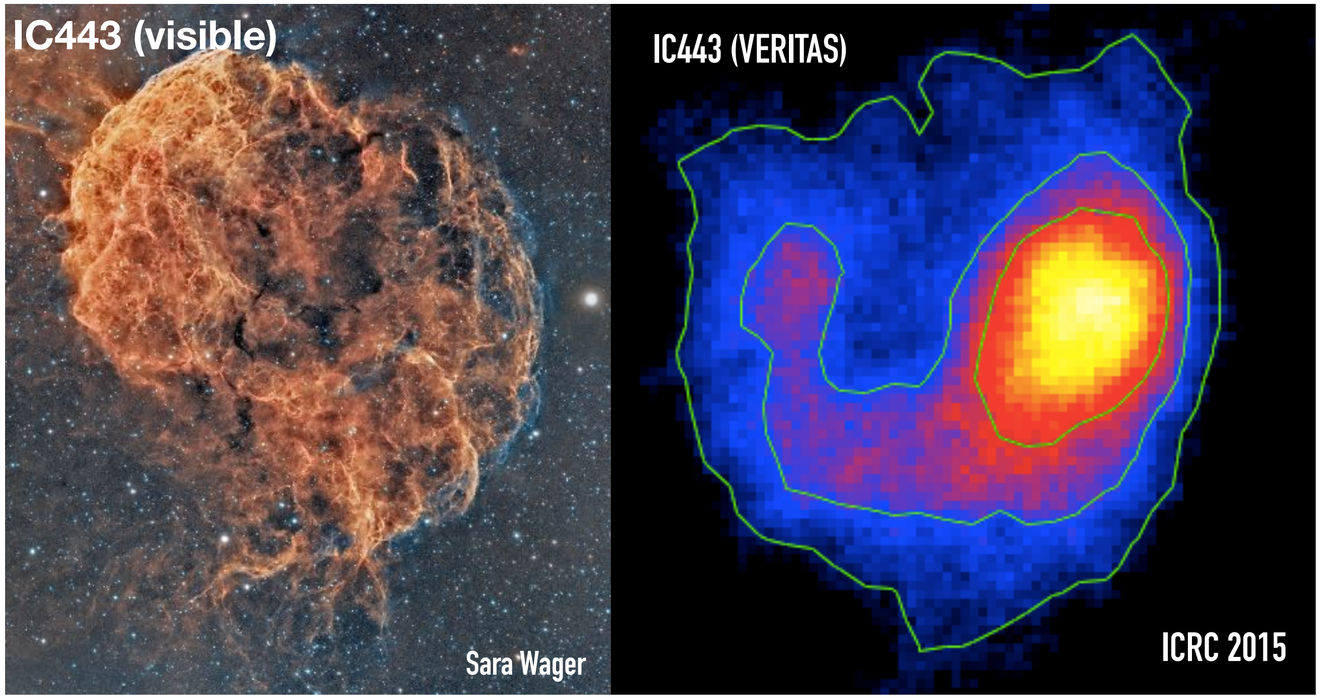
Hadronic! But, soft index

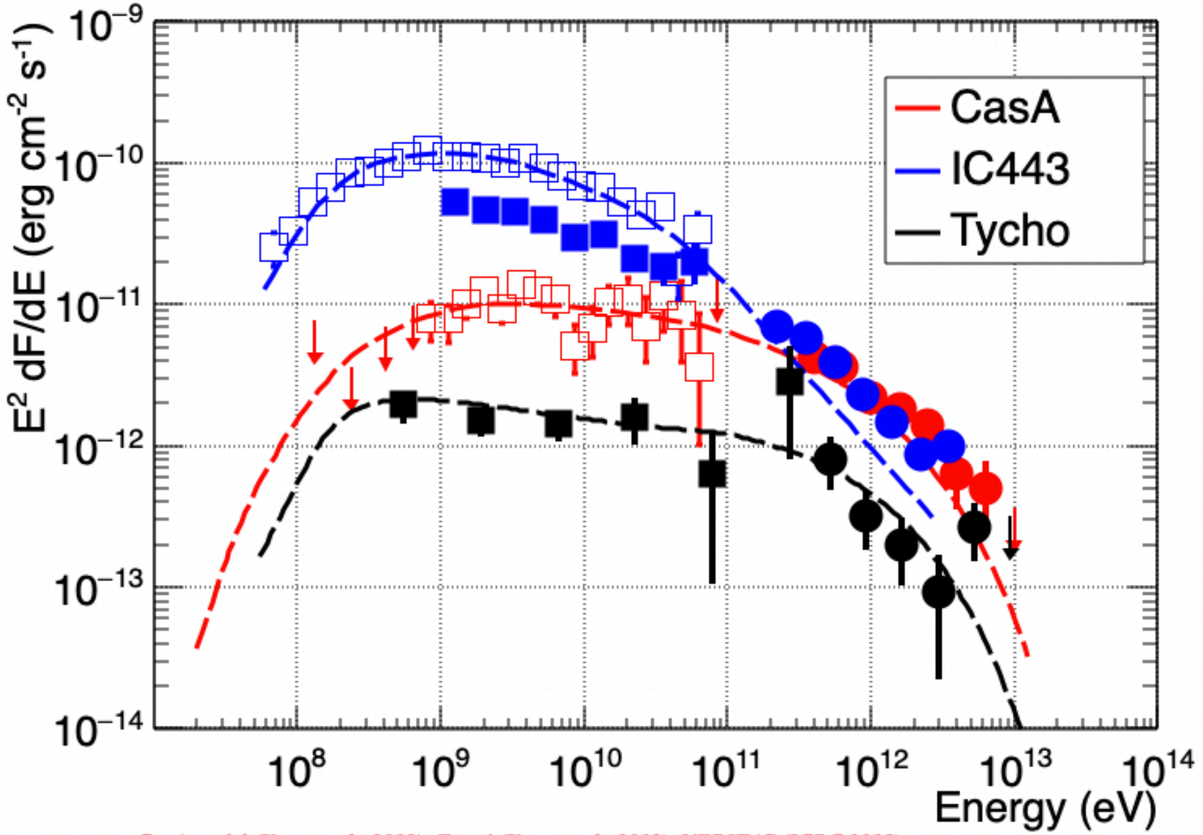
Gamma rays: Not all SNRs are the same

There are hadronic accelerators in our Galaxy

- Sample of hadronic dominated older SNRs (IC 443, W28, W31C) : softer indices
- Hisotric SNRs with a hard index + hadronic origin (CasA, Tycho's SNR)

→ No clear SNRs fits into all criteria we want (hadronic & E_{cutoff}>100 TeV)





CasA model (Yuan et al., 2013), Fermi (Yuan et al., 2013), VERITAS (ICRC 2015)
IC443 model (Ackermann et al., 2013), Fermi (Ackermann et al., 2013), VERITAS (ICRC 2015)
Tycho model (Slane et al., 2014), Fermi (Archambault et al, 2017), VERITAS (Archambault et al, 2017)

Any other hadornic accelerators?

Super bubbles

- 30 Dor C, Cygnus cocoon

Massive star clusters

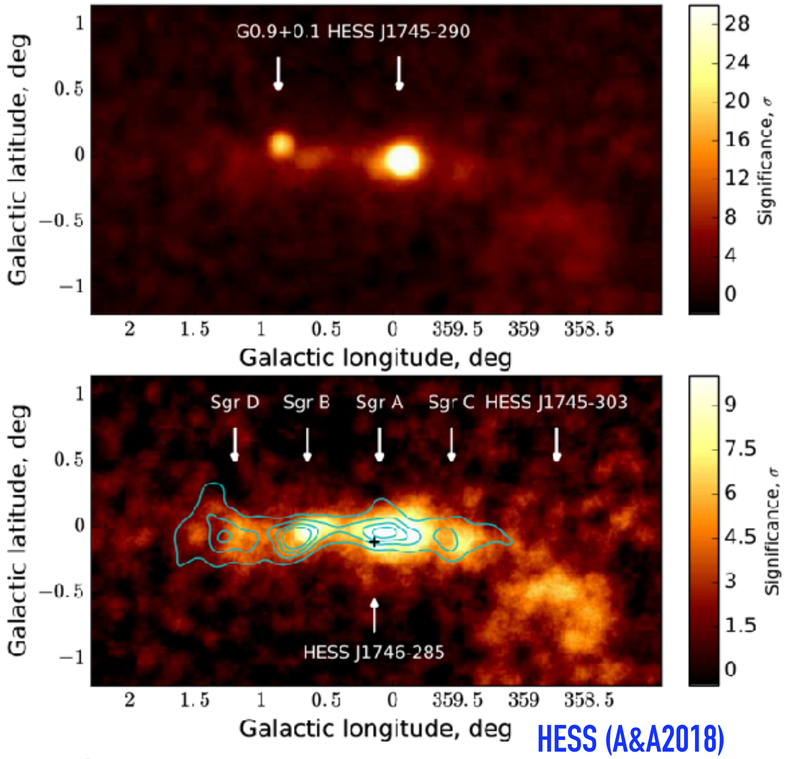
- Westerlund 1

Galactic center

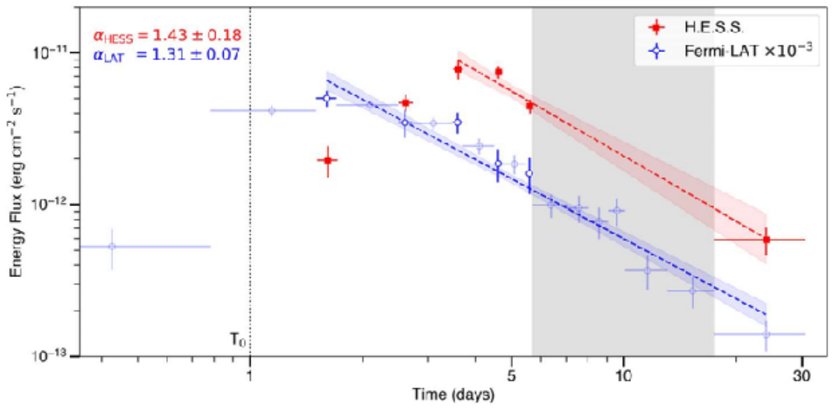
- Ridge emission

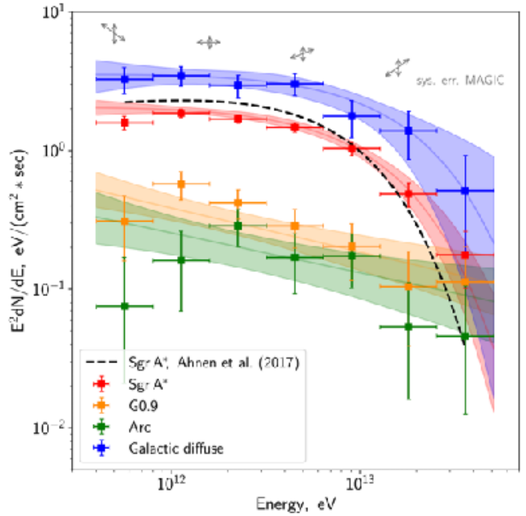
Galactic nova

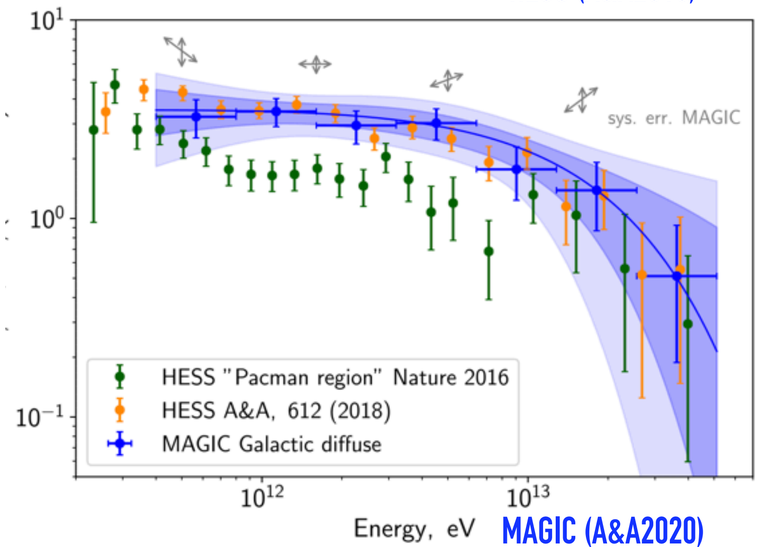
- RS Ophiuchi



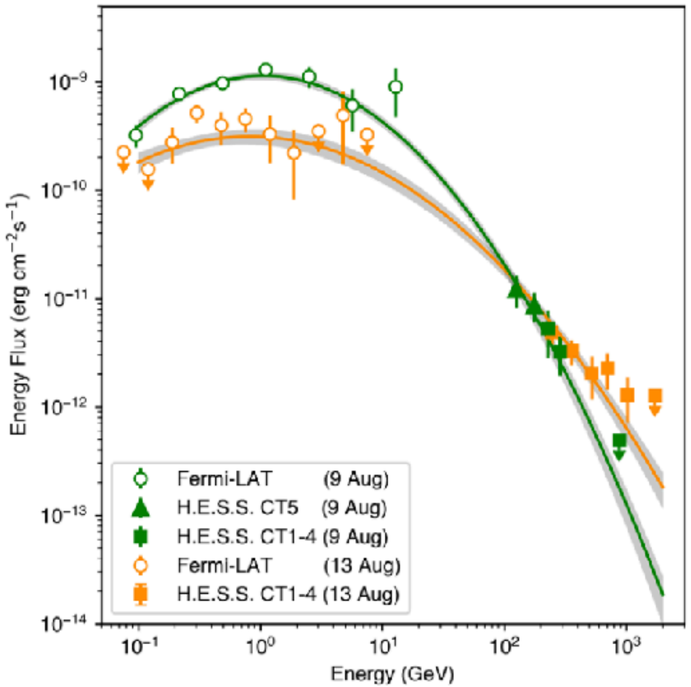
HESS (A&A2018)







MAGIC (A&A2020)

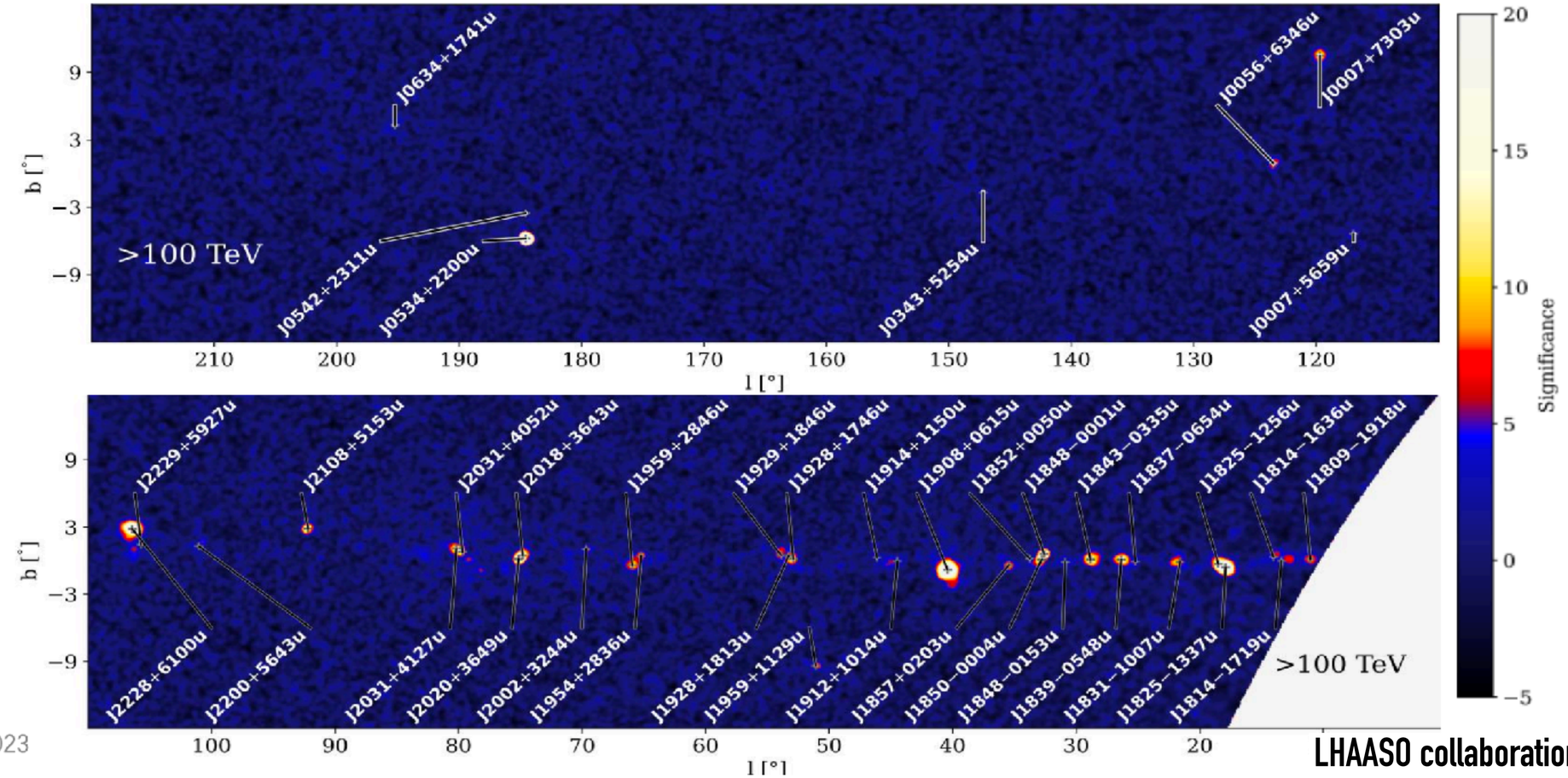


HESS (Science2022)

Gamma rays: Still many unknowns

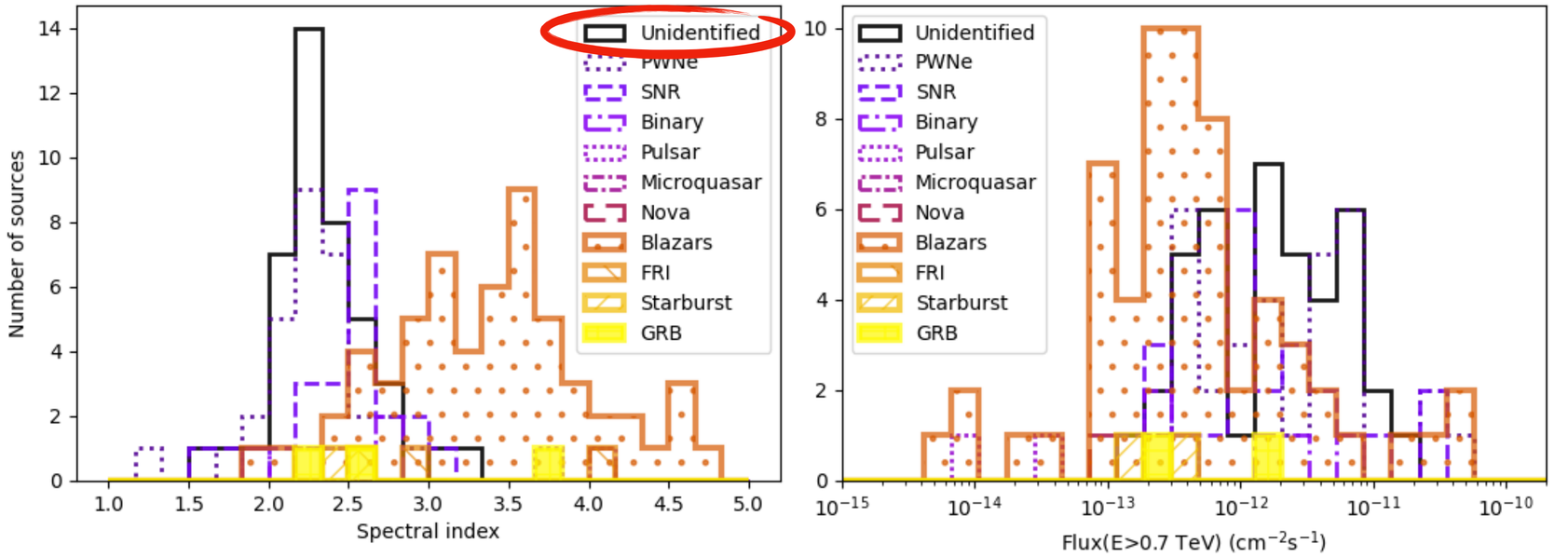
There are a lot of unknowns in our Galaxy…

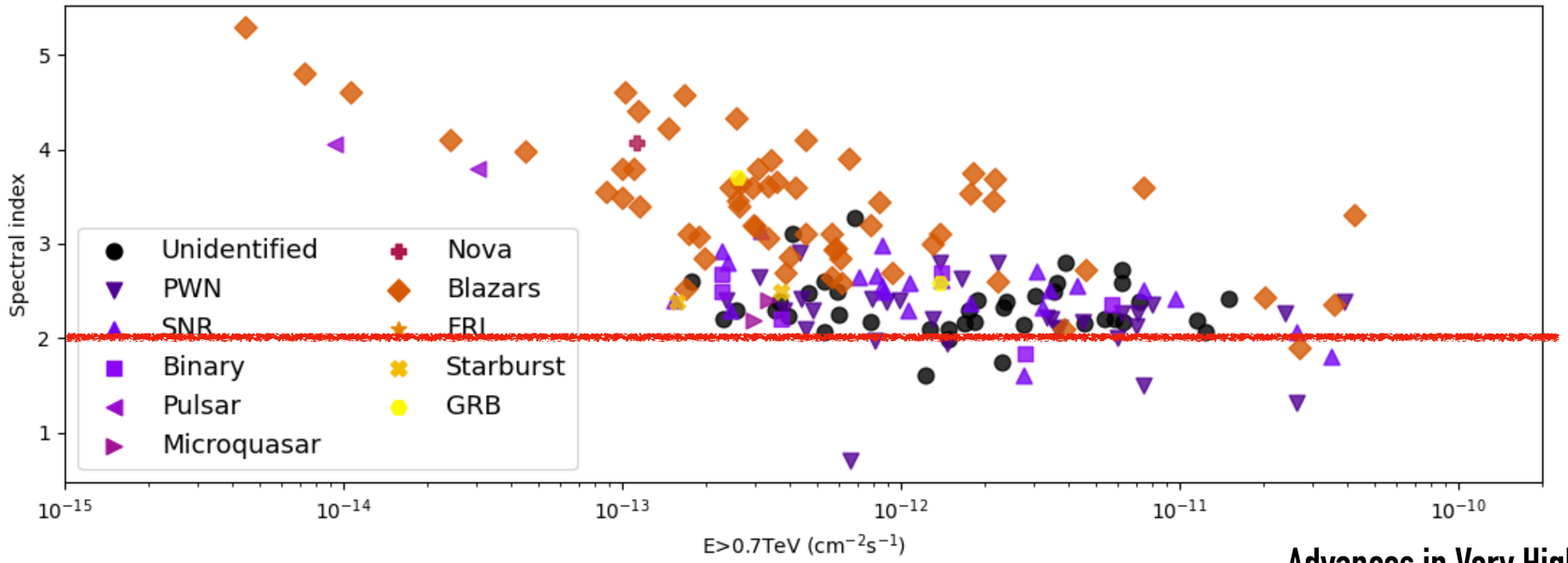
- About 40% of Galactic TeV sources are unidentified sources
- We now have gamma-ray skymap with energies higher than 100 TeV. But, not clear whether these are hadronic emission



LHAASO collaboration 1st catalog (arXiv 2023)

VHE gamma-ray source properties

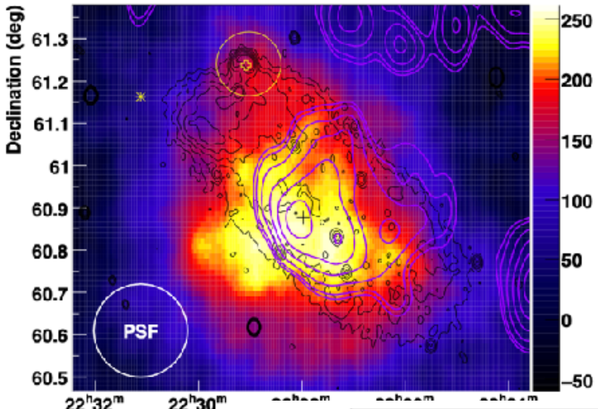


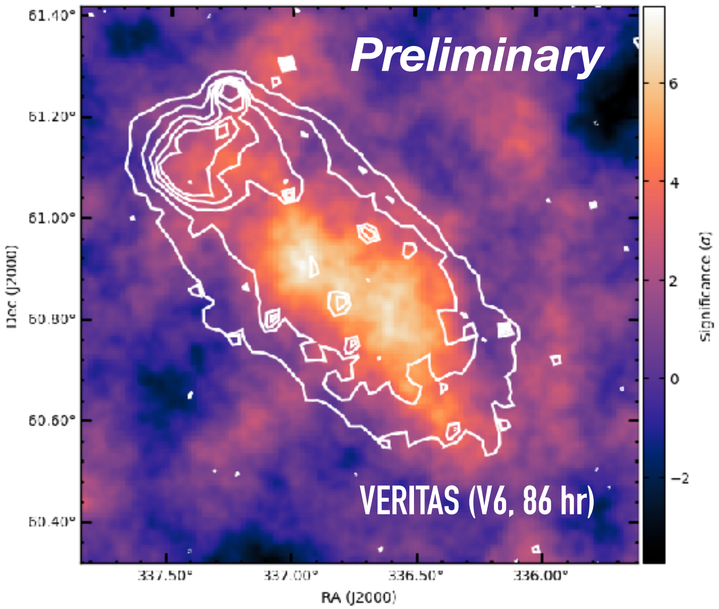


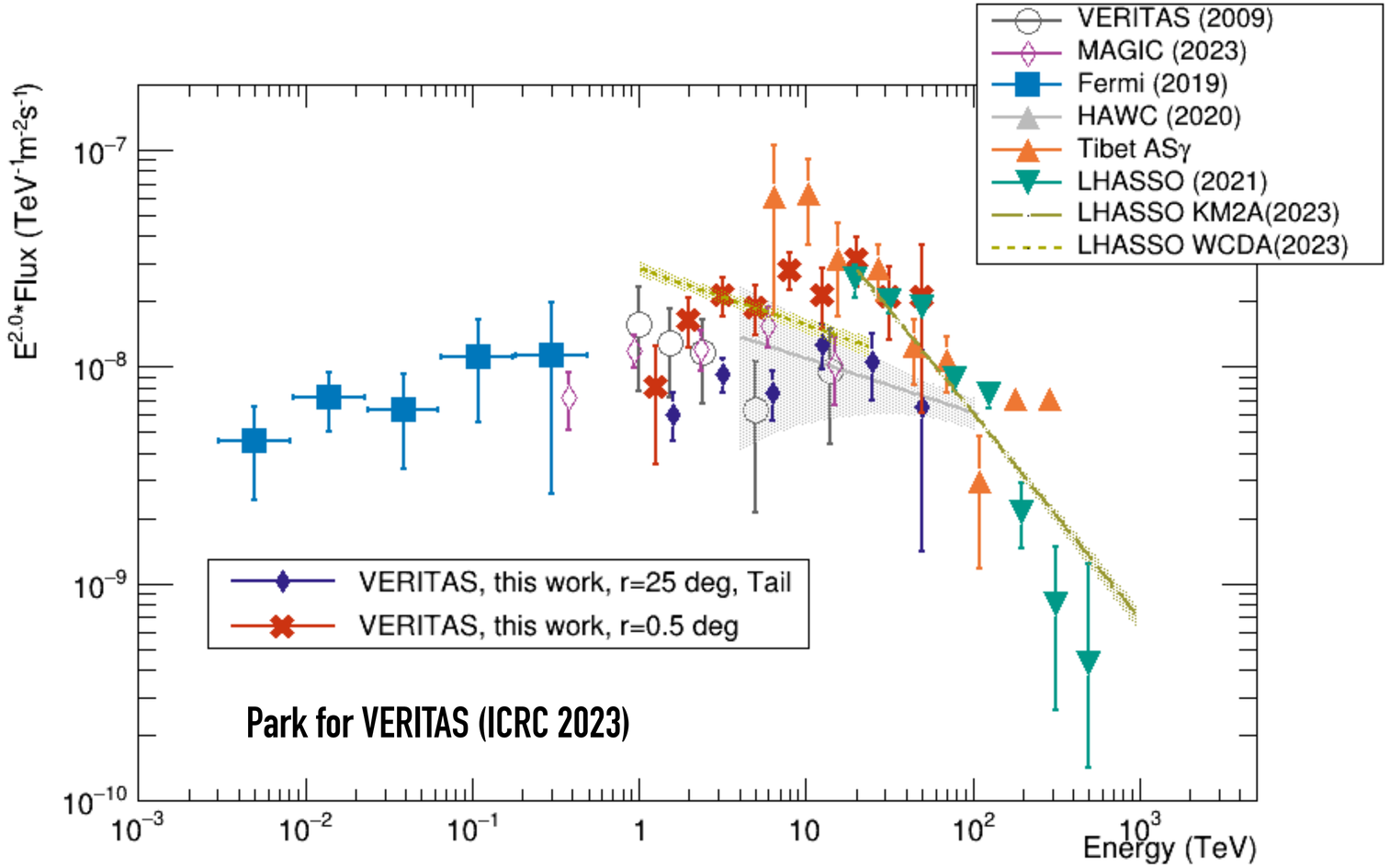
Gamma rays: effort to understand the UIDs...

Not so easy... (e.g. SNR G106.3+2.7 region)

- Not much data in low wavelength, extended emission w/ a hard index from GeV to tens of TeV, ambiguity on the target density,...



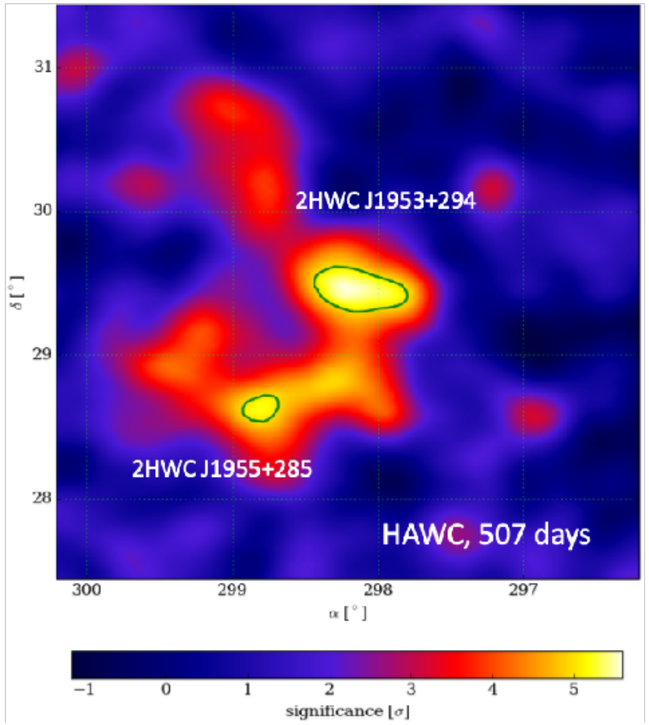


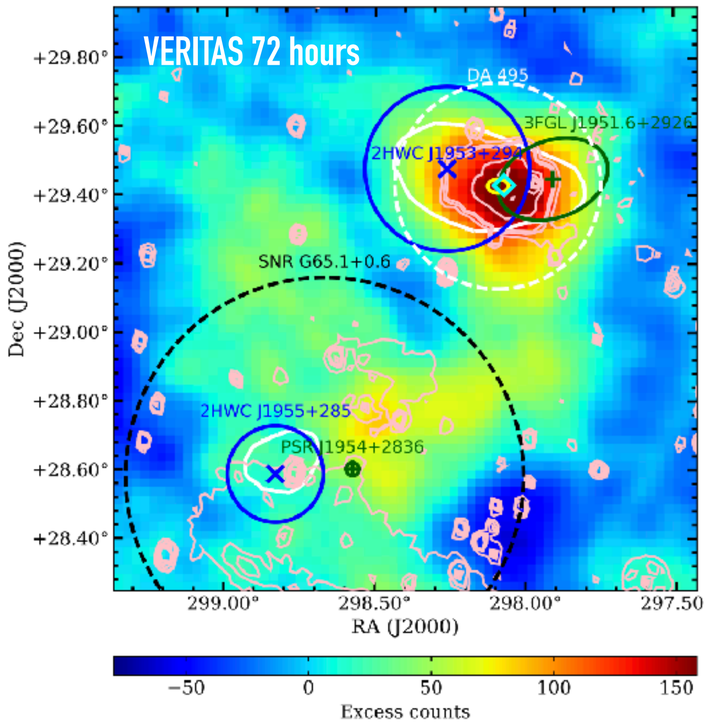


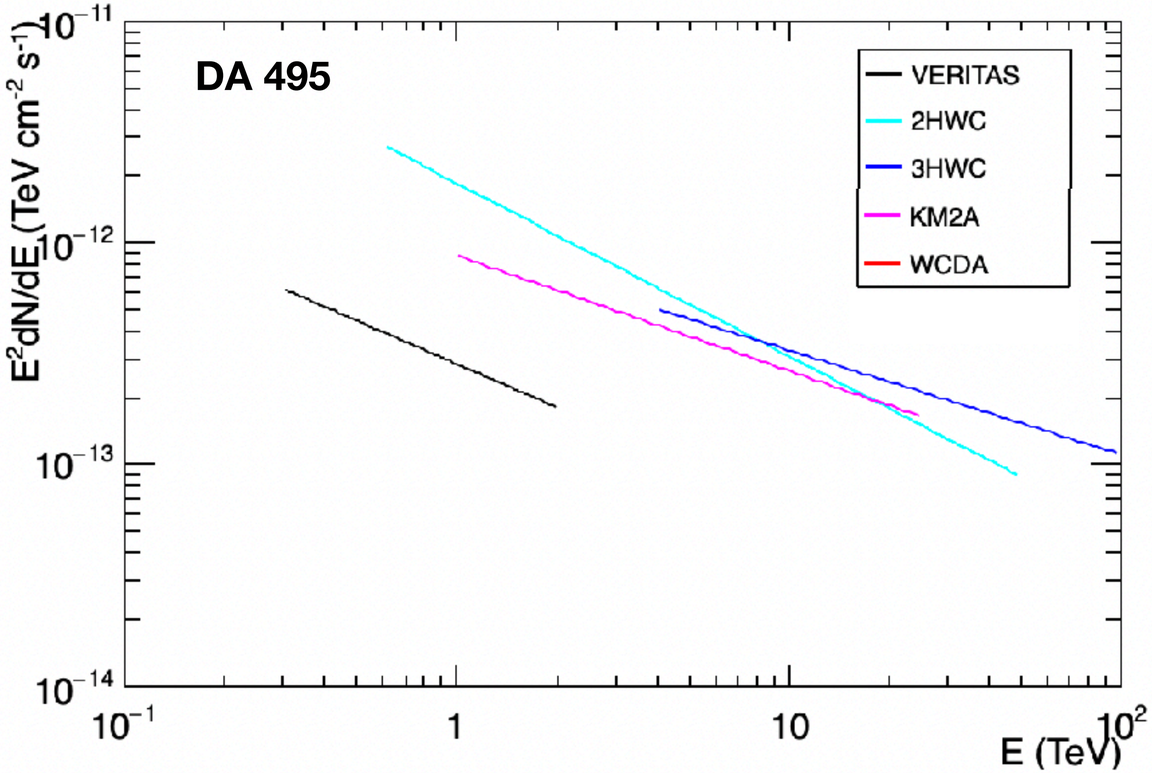
Gamma rays: effort to understand the UIDs...

Synergy between IACTs and ground air shower array experiments, but we need to be careful at comparing the results

- e.g. PWN DA 495 region
  - -VERITAS reports seven times lower flux than HAWC's measurements
    - ✦Discrepancy is largely due to how each instrument handles background and angular resolution of the instruments.
    - ✦HAWC/LHAASO's measurements may be influenced by the flux of nearbv diffused source



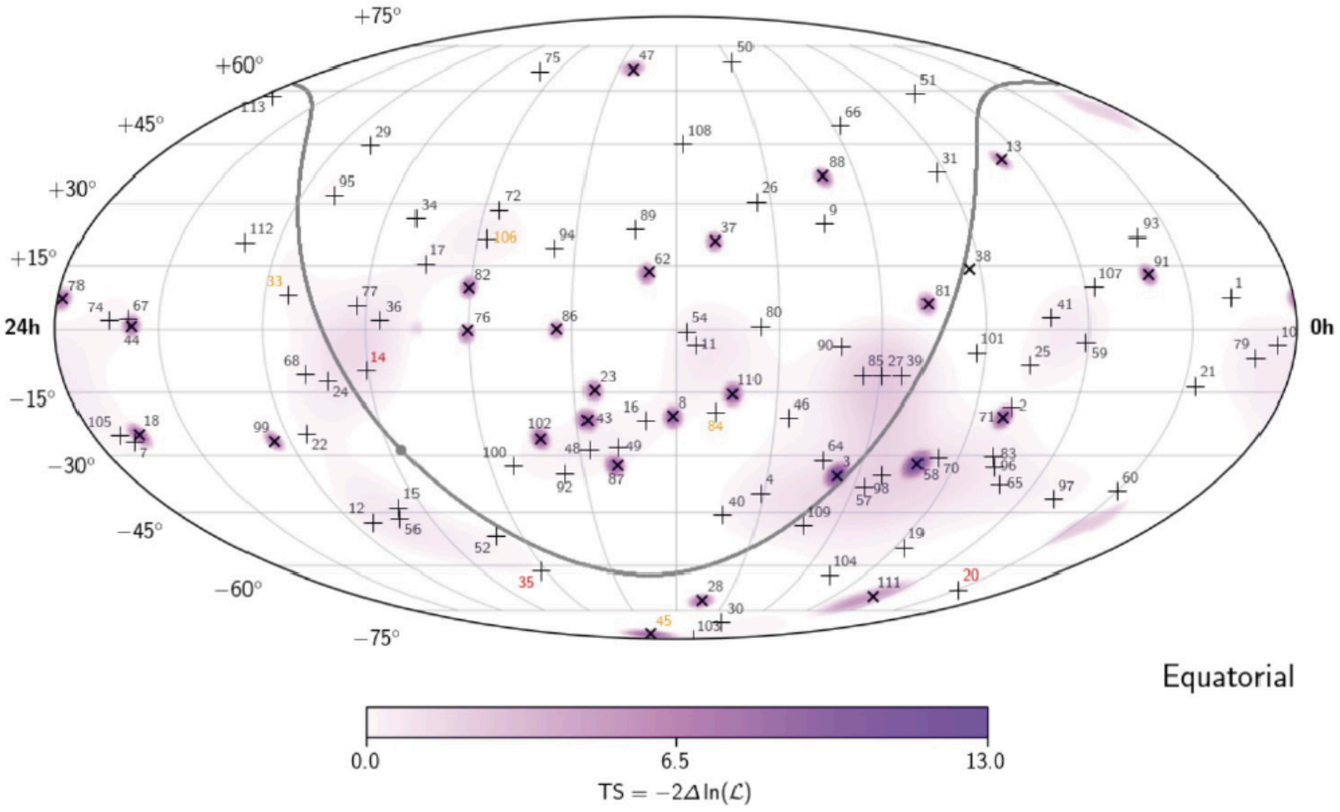




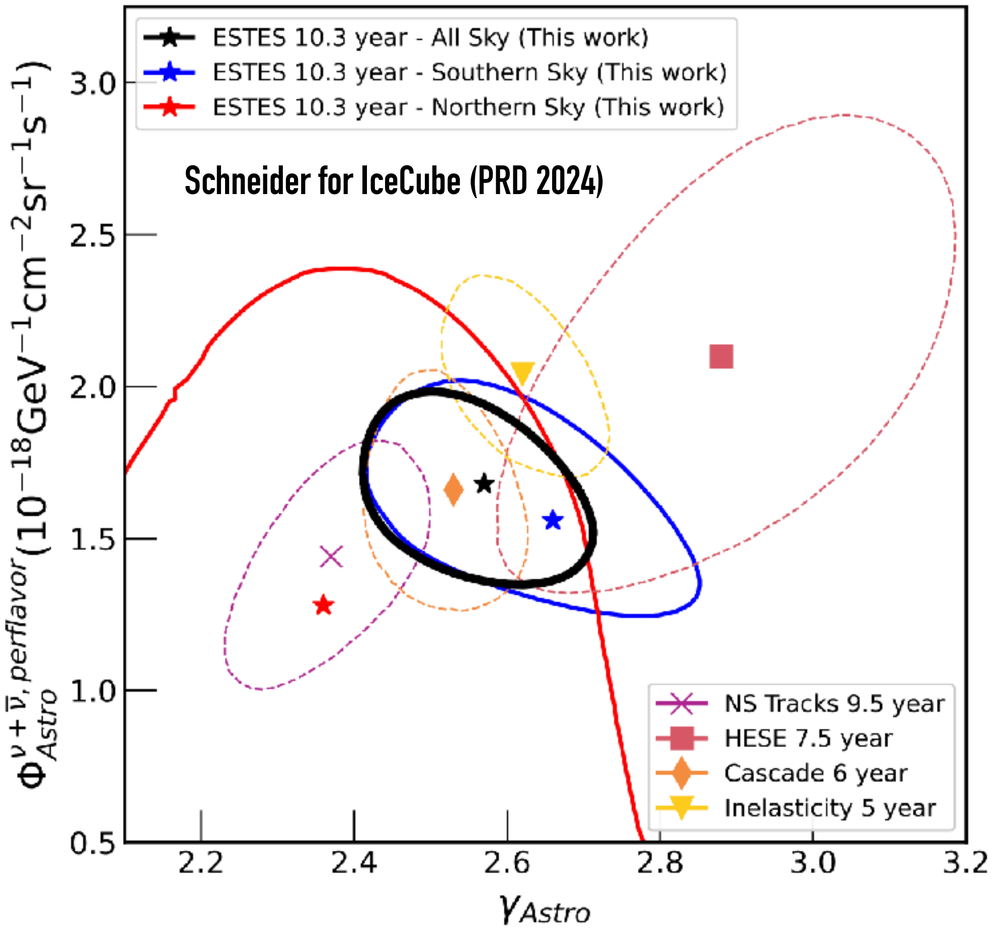
Galactic Cosmic rays: Neutrinos?

Neutrinos are also generated by the cosmic ray interactions!

- Very difficult to detect
- Astrophysical neutrinos: dominated by extragalactic emission



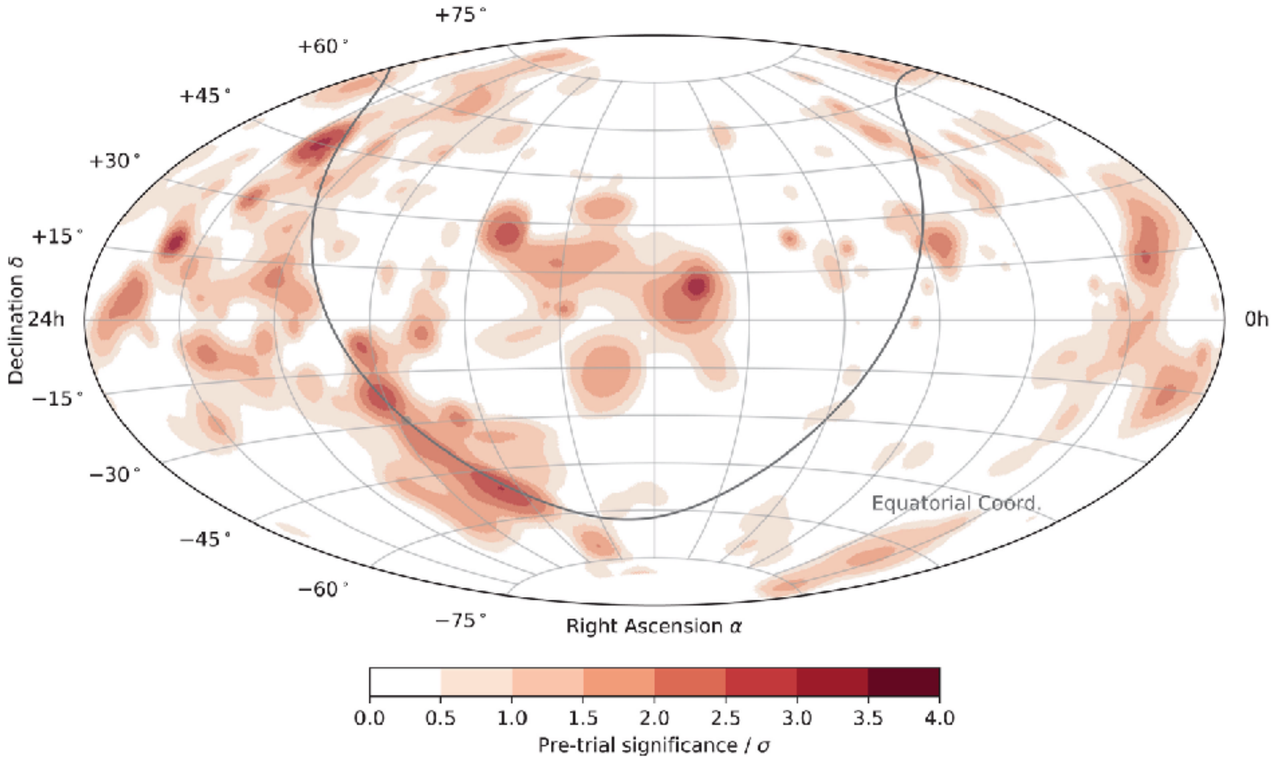
Schneider for IceCube (2018 TeVPA)



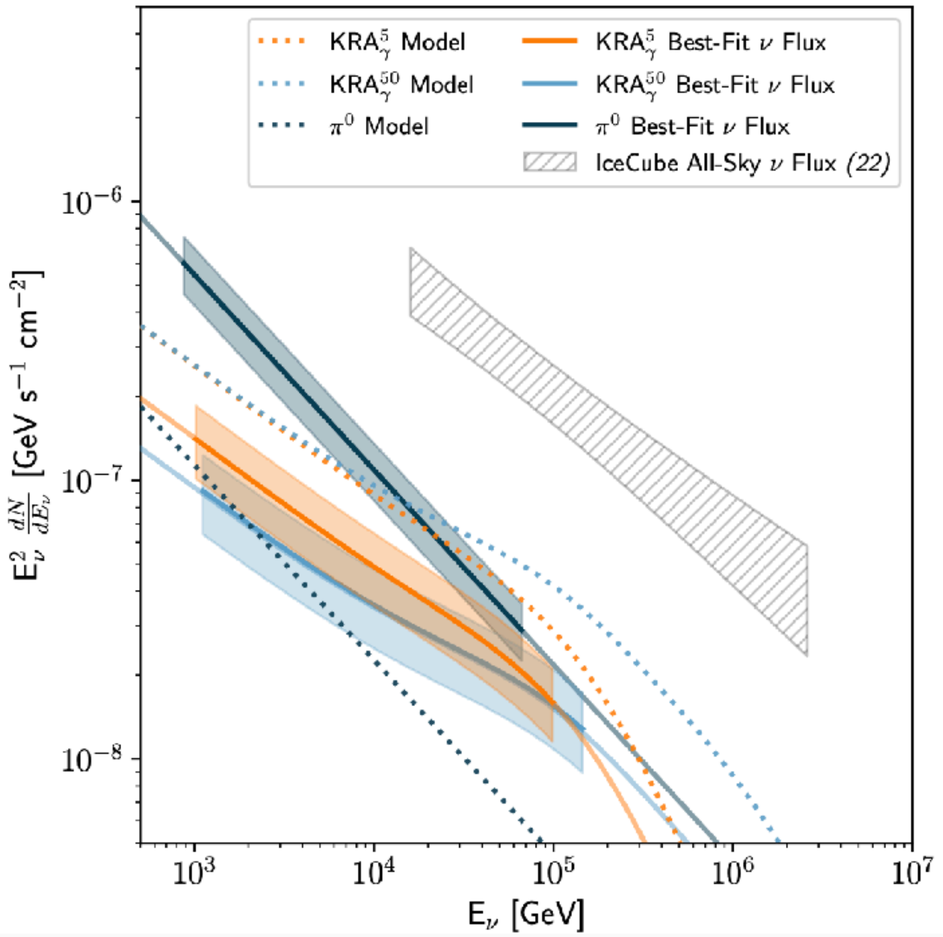
Galactic Cosmic rays: Neutrinos?

Neutrinos are also generated by the cosmic ray interactions!

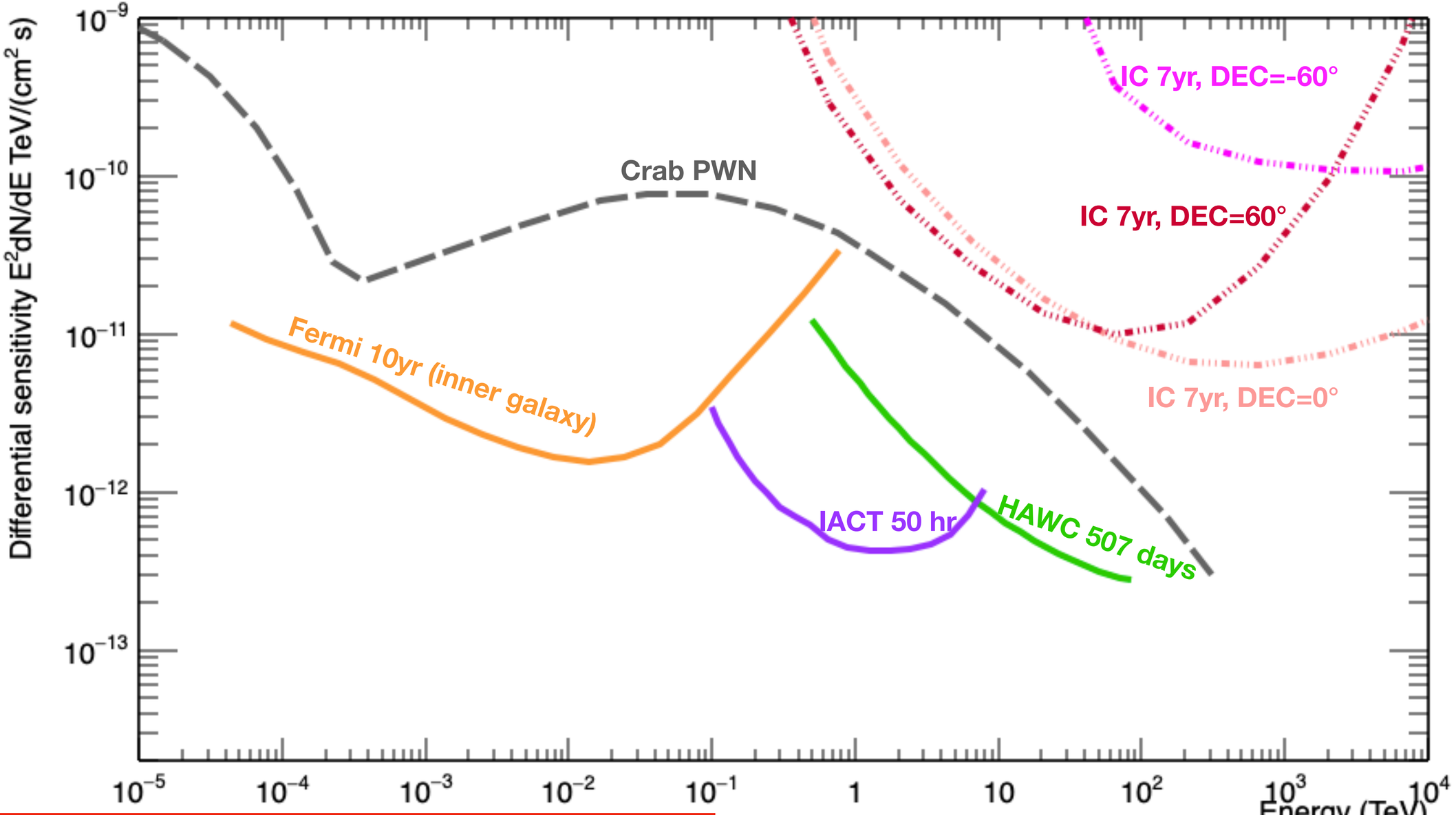
- Very difficult to detect
- Recent progress:IceCube sees Galactic Plane w/ 4.5 σ
  (Not clear how much contamination is due to unidentified sources)



IceCube Collaboration (Science2023)



Sensitivity of Current MM Observations

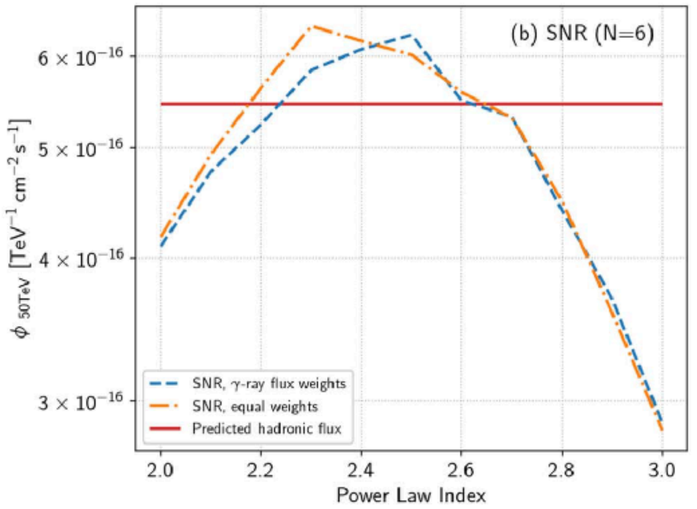


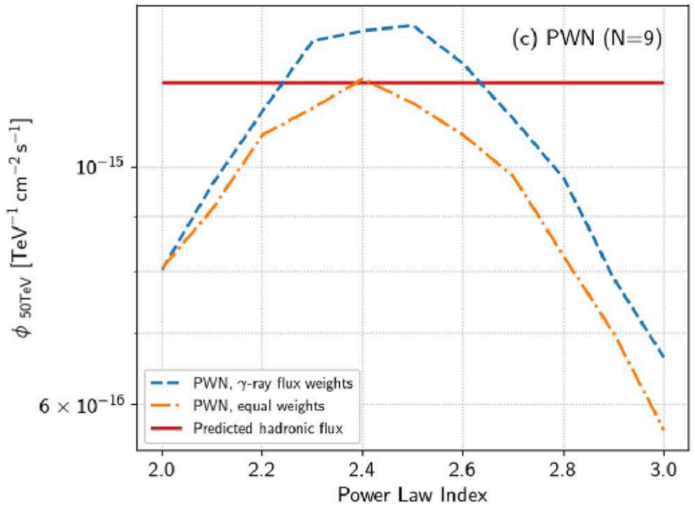
Sorry - didn't have time to update the sensitivity plots….

Still, neutrino observations can be constraining

IceCube's Galactic source studies using LHAASO measurements w/ 11 yr data: Constraining the hadronic fraction of gamma-ray emission

- Crab PWN
  - -Assuming a PL: <59%
  - -Assuming a log parabola: < 84%
- SNR G106.3+2.7 region (LHAASO J2226+6057)
  - -Assuming a PL (w/ index = 3): < 47%
  - -Assuming a log parabola: no constraints
- HESS J1849-000/LHAASO J1849-0008 (UID)
  - -Assuming a PL: <94%





IceCube Collaboration (ApJ 2023)

Summary of Current Status (very personal view)

Cosmic rays

- Many breaks and hardenings

  -some more unknown than others

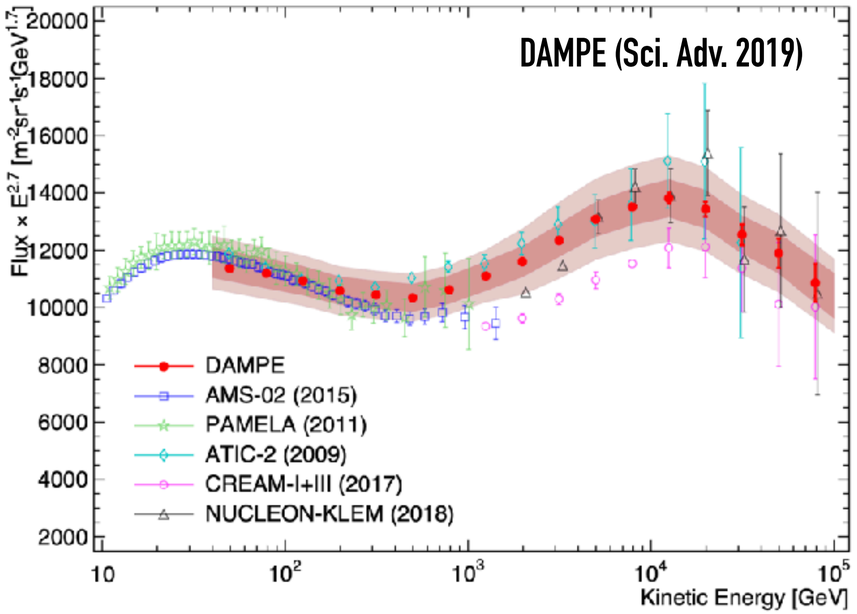
- Low energy (<few GeV): many evidence of influence from massive stars

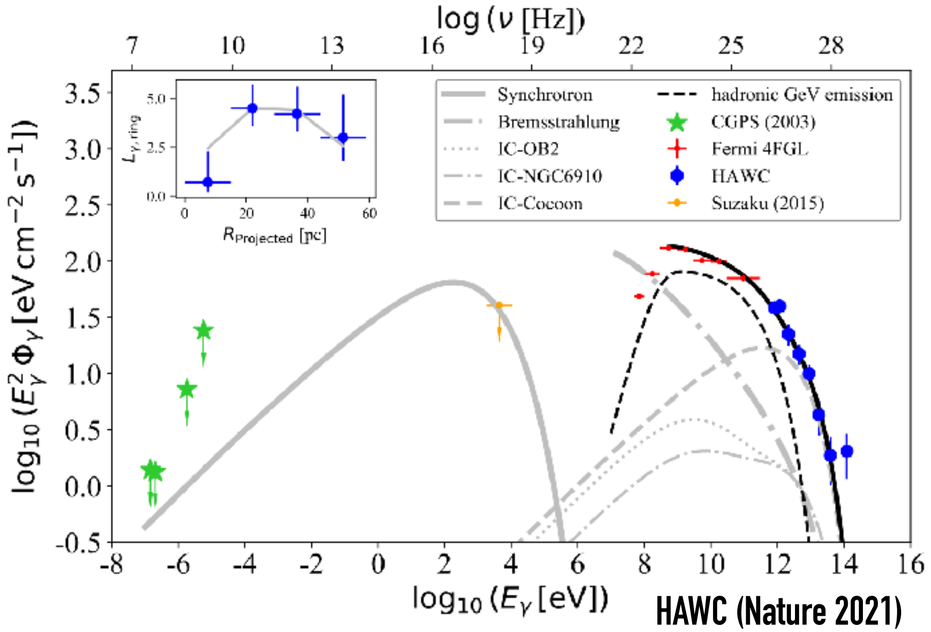
Gamma rays

- SNRs: clear hadronic accelerators. No clear hadronic emitter reaching PeV energy
- Many bright unidenfitied sources & new course classes with E> 100 TeV measurements

Neutrinos

- Detection of Galactic plane
- Some constraints for very bright & high-energy gamma-ray sources





HAWC (Nature 2021)

My wish for the future (very personal view)

Cosmic rays

- Let the data continue to lead the way
  - -Better understanding of the propagation (isotope measurements, extend boron to higher energies, …)
  - - Keep extending the composition resolved spectral analysis
  - - Further composition studies

Gamma rays

- Detailed multi-wavelength based studies
  - -Find the origin & emission mechanisms
- Keep searches for new emitters

Neutrinos

- Improve sensitivity
  - -Water/Ice & North/South hemispheres

HELIX Flight 2024

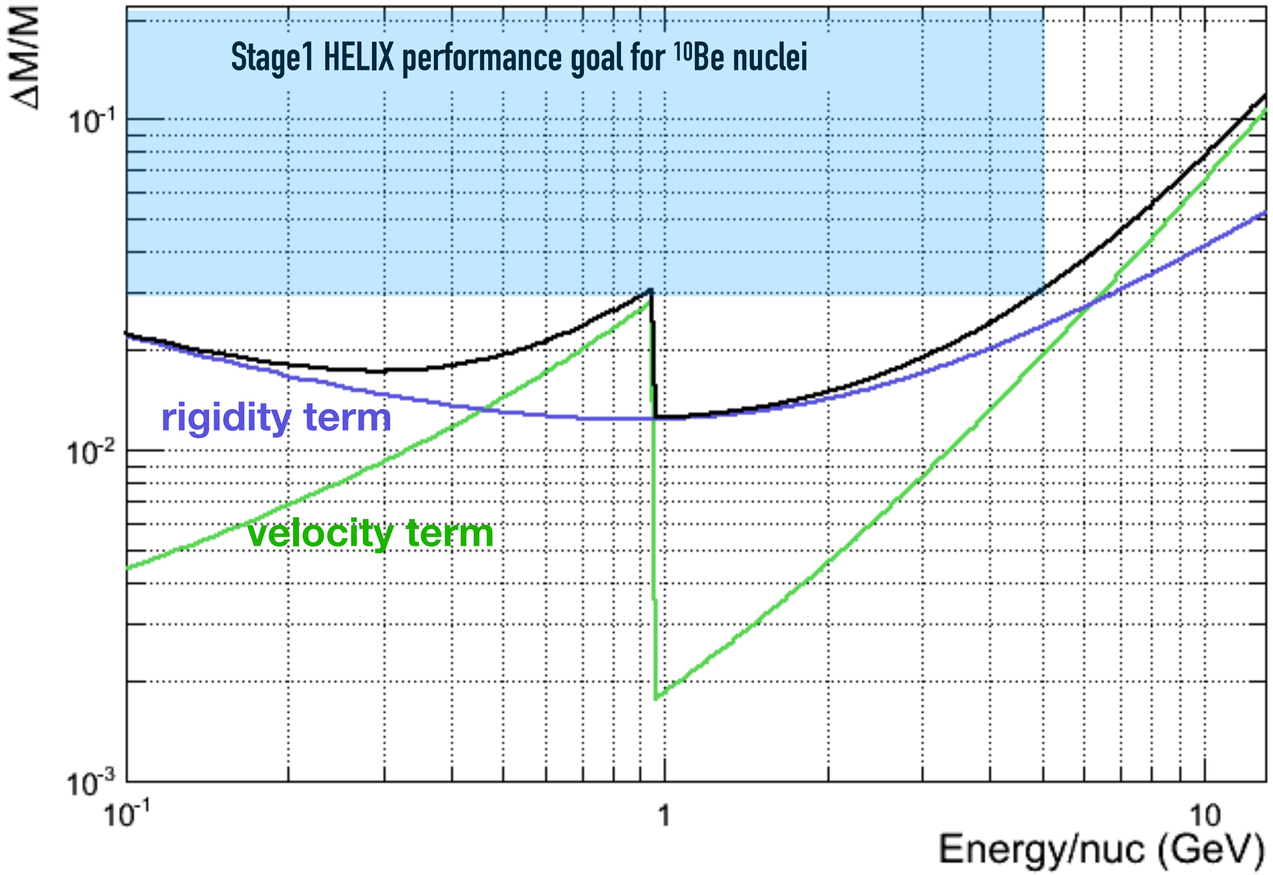
HELIX was successfully launched from Kiruna, Sweden on May 28th, 2024.

https://www.youtube.com/watch?v=PoofJ8al4S4

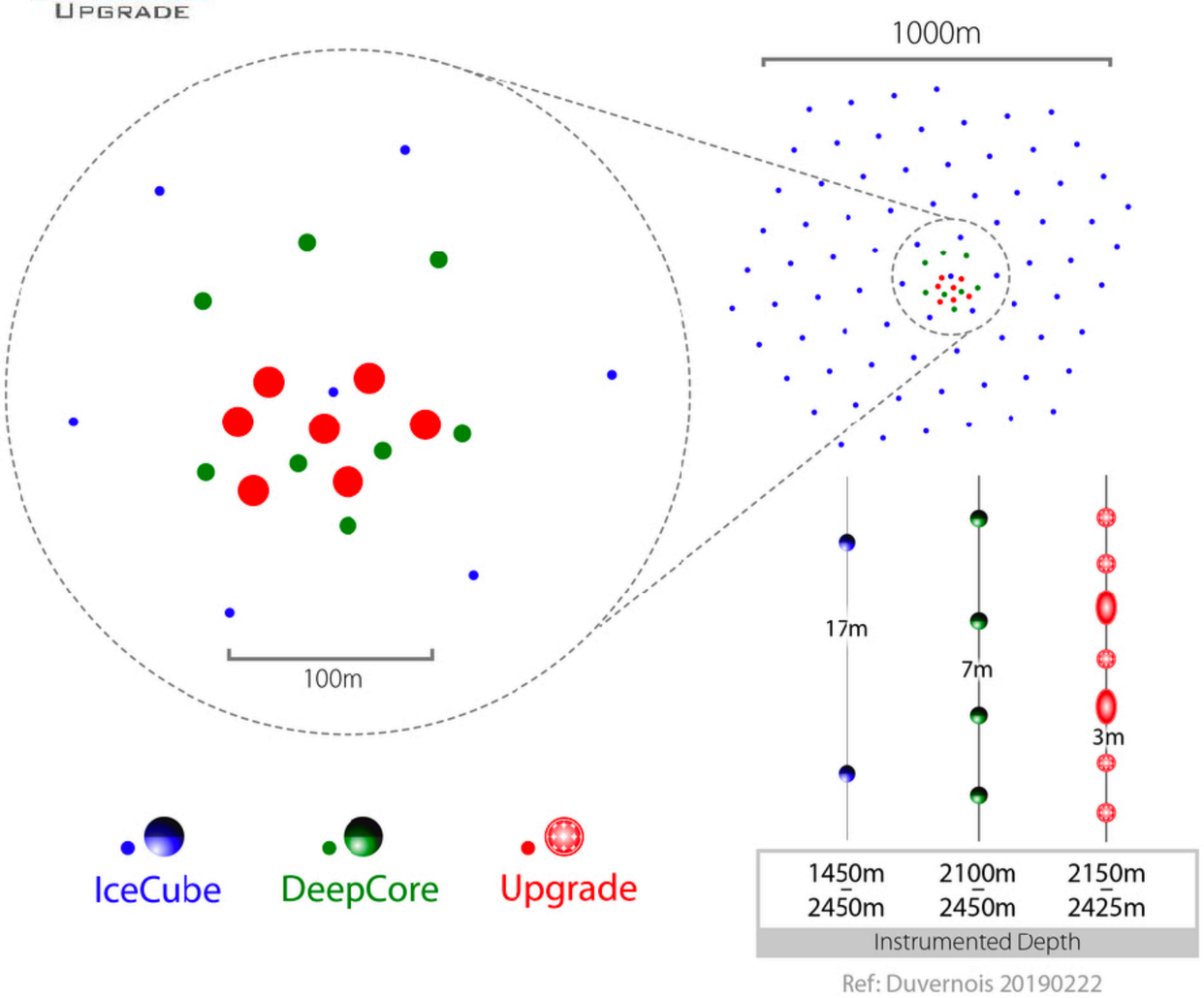
HELIX Stage1 Performance Goals

^{10}Be/^{9}Be ratio up to ~3 GeV/n with Δm/m ~2.5%

- 7-14 day exposure with 0.1 m²sr geometry factor
- Measure the charge of CR up to neon (Z=10)
- Mass resolution of few percentage for light isotopes up to 3 GeV/n



IceCube Upgrade: near future



Goals

- Precision oscillation measurements
- Improved detector calibration
- R&D for IceCube-Gen2

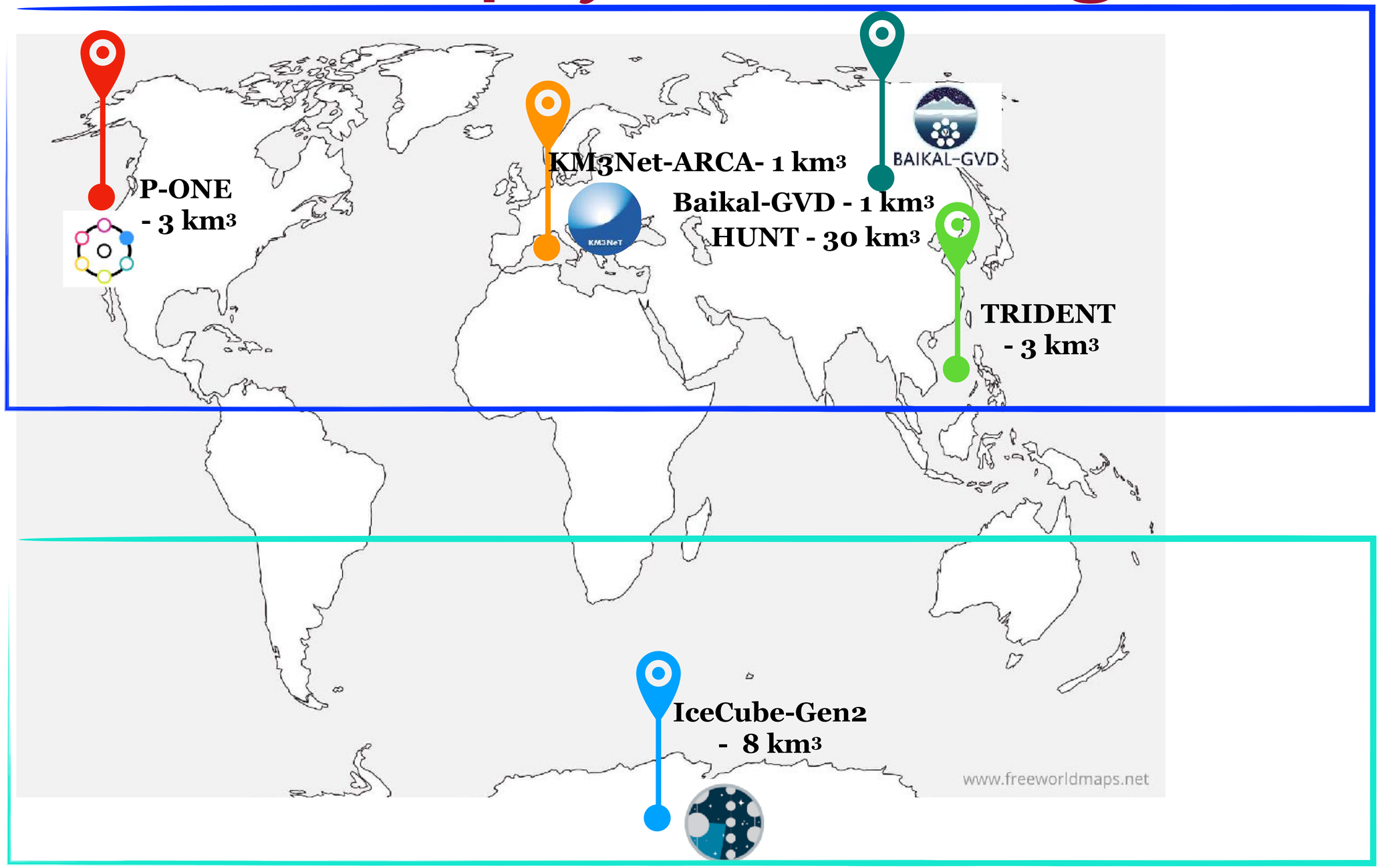
Key features

- > 800 new devices
- Reduced spacing between modules
- Explore deep ice down to 2.6 km

Status

- Pandemic delayed the deployment
- Scheduled to start drilling in 2024-25
  String deployment in 2025-26!

Neutrino Astrophysics: Moving forward



Summary

Different messengers provide different aspect of Galactic cosmic rays accelerators

- However, the overall picture should be consistent
  - Low energy cosmic rays: influence of massive star (WR stars, OB assocations,...)
    - ✦Gamma-ray counterparts?
  - Hadronic cosmic ray accelerators
    - ✦ Expect a hard spectral index (~2.0) w/ high-energy cut-off
      - Young supernovae have lower energy cut-off than expected
      - Potential high-energy emitters: leptonic vs. hadornic? what are their contributions?
    - ✦ Elemental spectral breaks & hardenings before knee regions
      - Propagation? Acceleration? Source population?
    - ✦Neutrino constraints (& detection) would clarify hadronic accelerators