SuGAR MADISON 2024

SEARCHING FOR THE SOURCES OF GALACTIC COSMIC RAYS

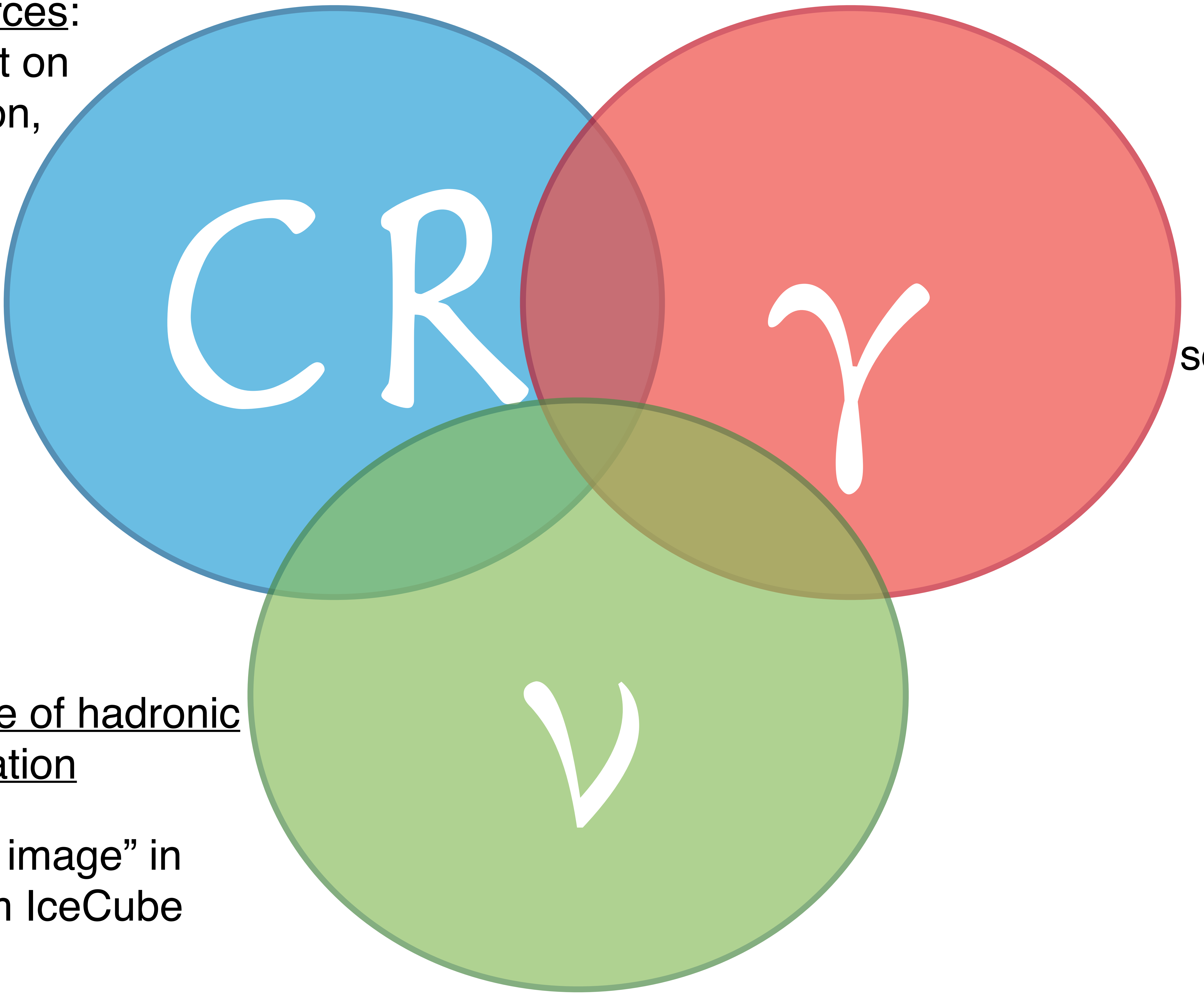
OCTOBER 14-17

NSF ICECUBE WIPAC WARF Wisconsin Alumni Research Foundation

(AN ATTEMPT OF)SUMMARY

SEARCHING FOR THE SOURCES OF GALACTIC COSMIC RAYS

<u>Primary particle from sources</u>:
spectral features give hint on acceleration, propagation, source population



<u>Gammas tracers of CR:</u>

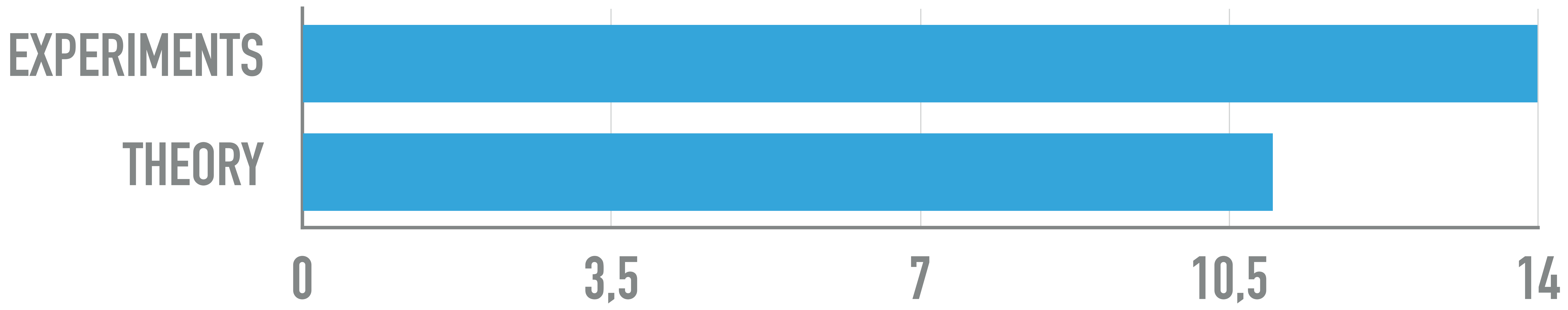
Many bright unidentified sources & new sourse classes with E> 100 TeV measurements

<u>Undeniable prove of hadronic acceleration</u>

First “galactic image” in neutrinos from IceCube

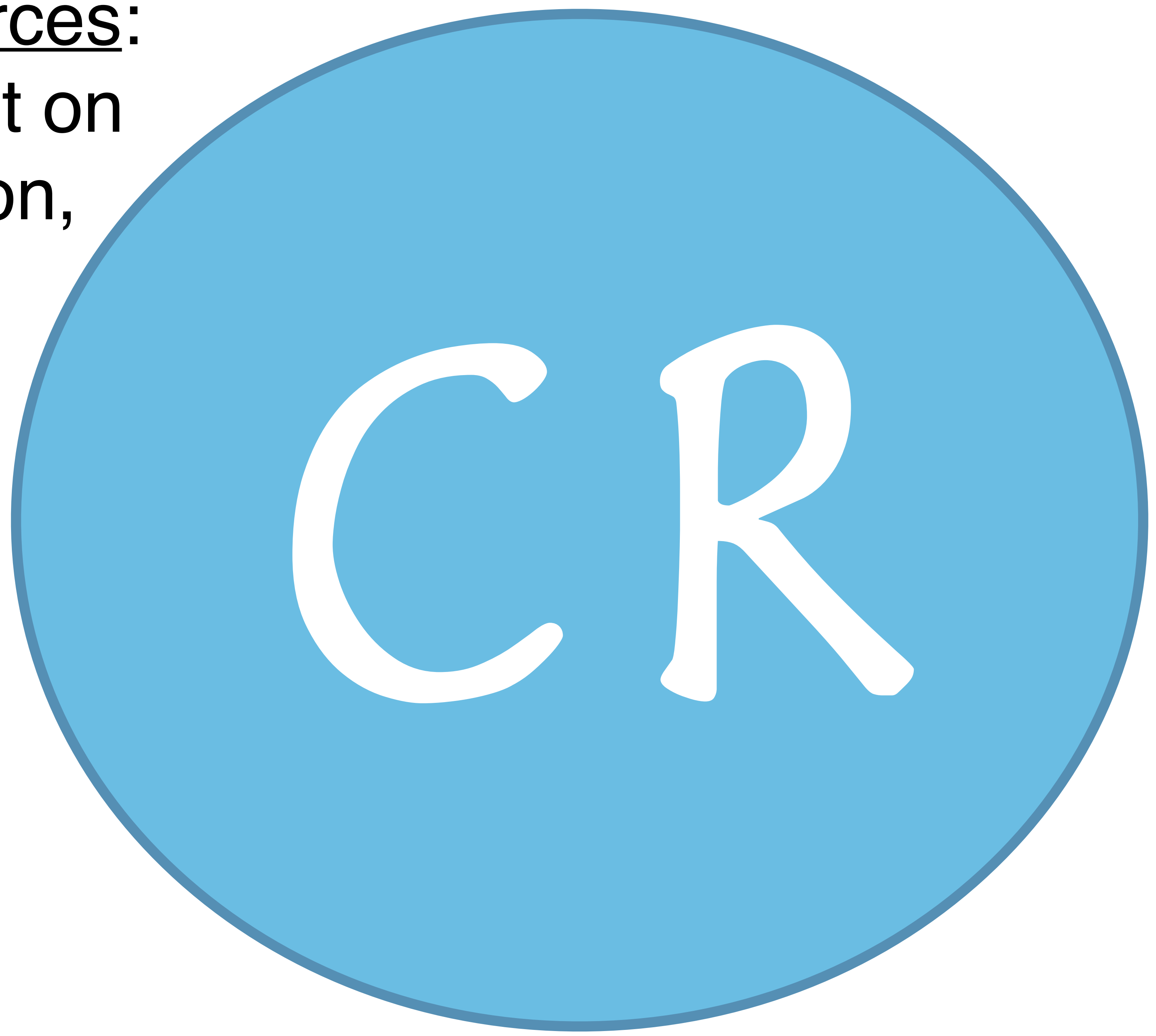
Different messengers provide different aspect of Galactic cosmic rays accelerators (see N. Park’s talk)

TALKS AND TOPICS – THE PERFECT BALANCE



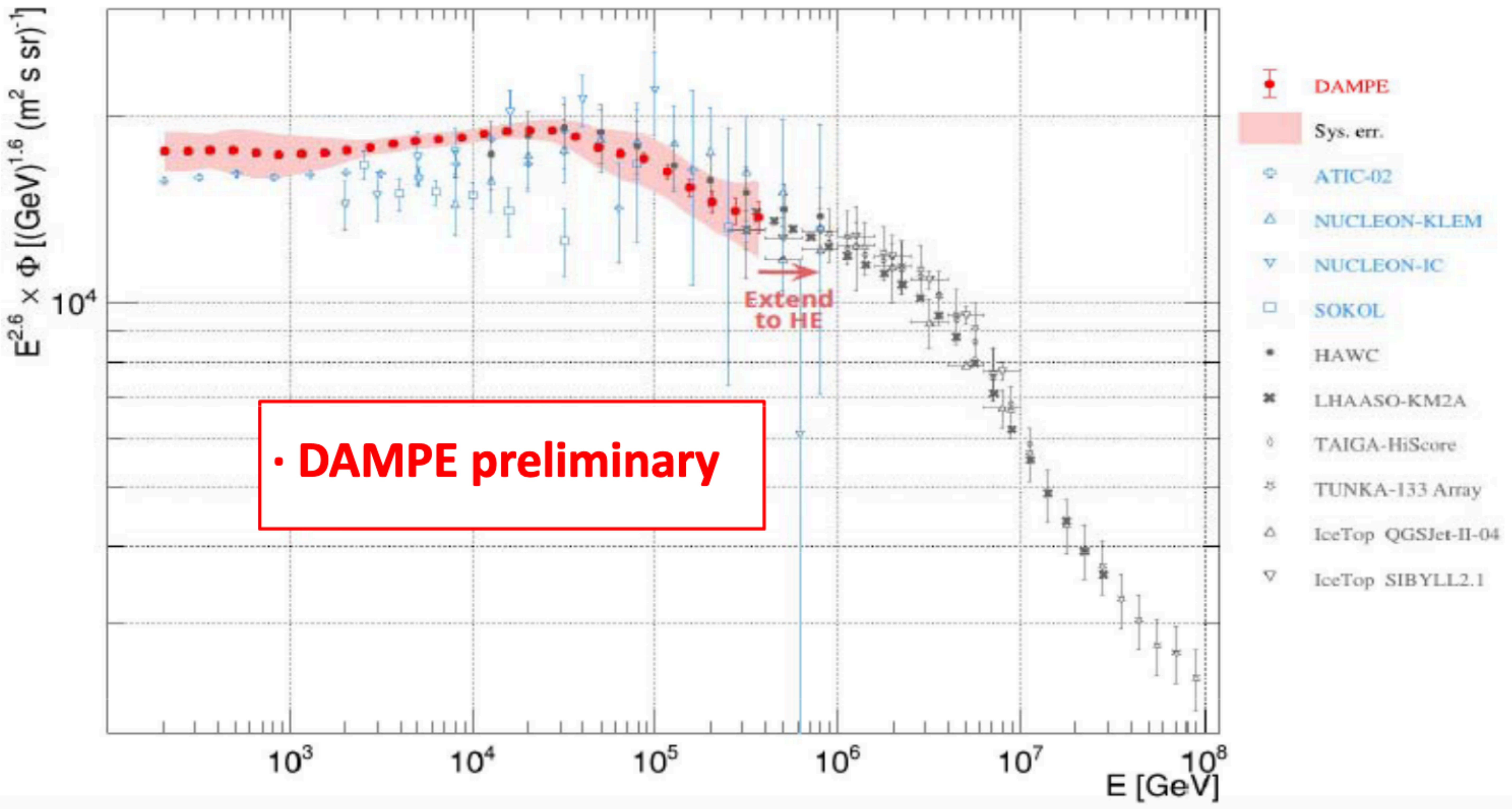
- More instruments online measuring new structures in spectrum at the knee region and beyond.
- Anisotropy in CR: is it related to mass composition?
- SNR as sources of CR? Other possibilities: Star cluster maybe?
- Amazing gamma-ray observations: PeVatrons and several unidentified sources in our galaxy.
- Neutrino starting to deliver results: observation of the galactic plane.
- 2 panel discussions (current and future status of the field).

Primary particle from sources: spectral features give hint on acceleration, propagation, source population

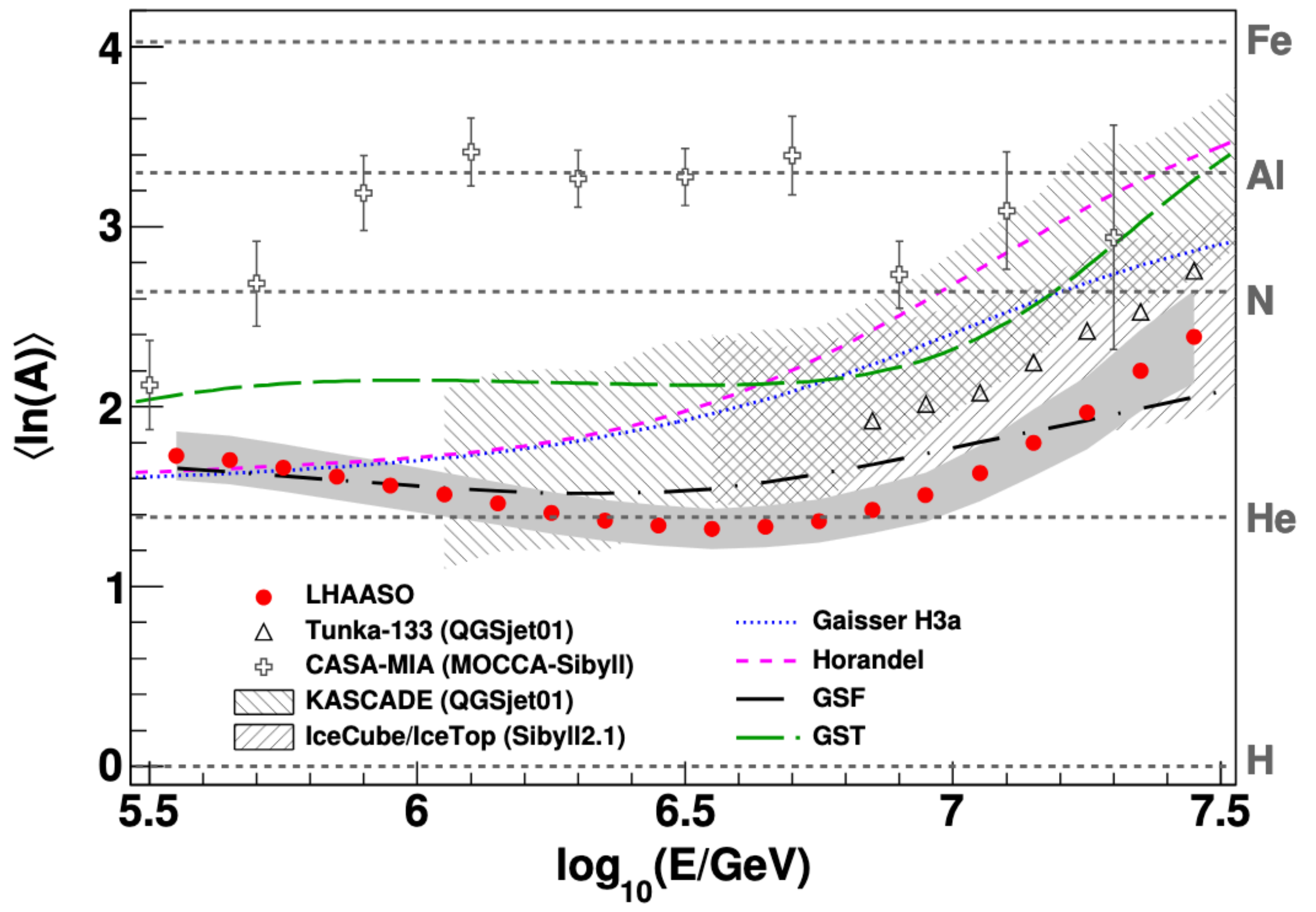


DIRECT MEASUREMENTS FROM SPACE – ALL PARTICLE SPECTRUM

Primary CR carry information about sources, propagation and acceleration process

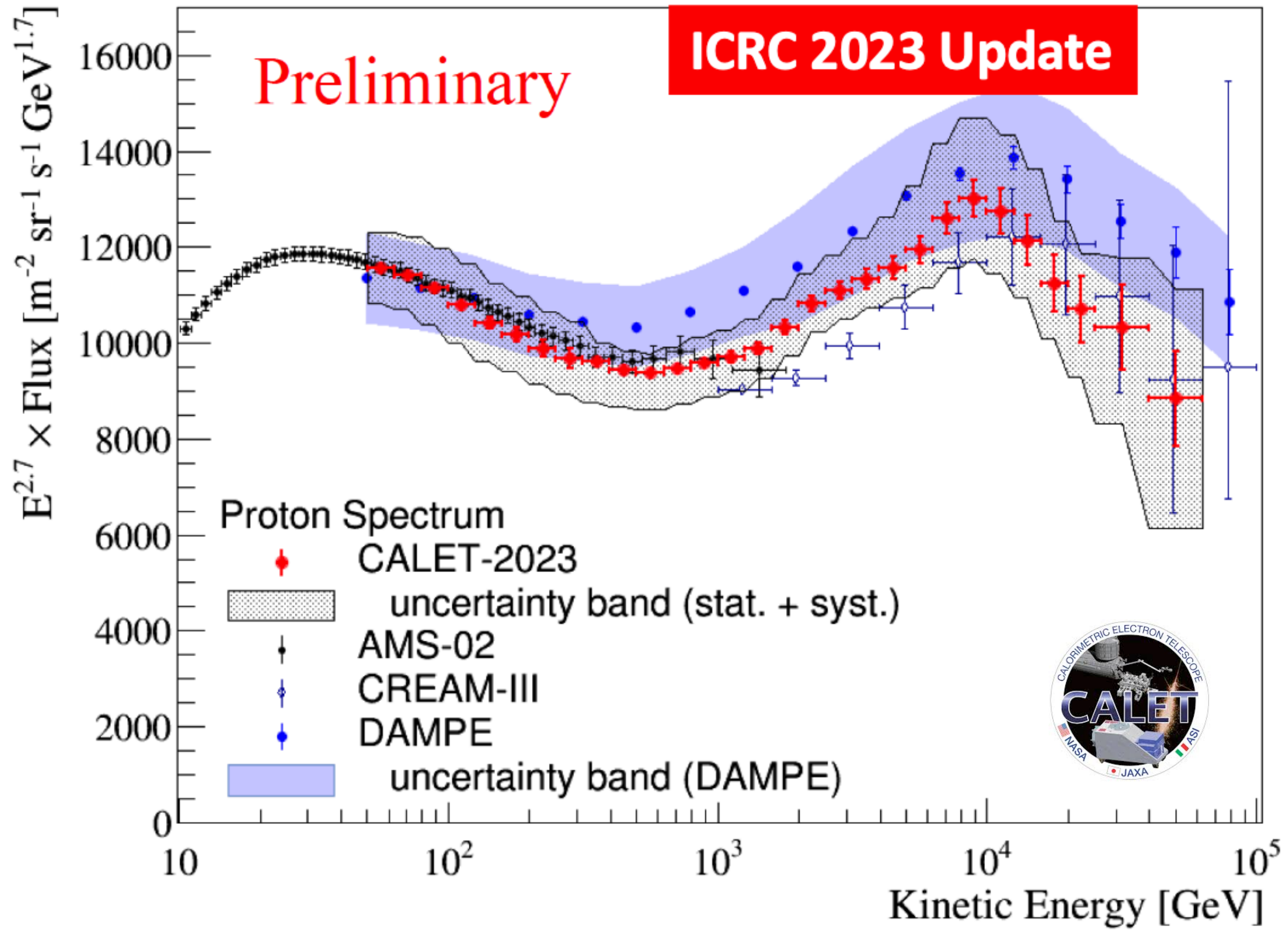


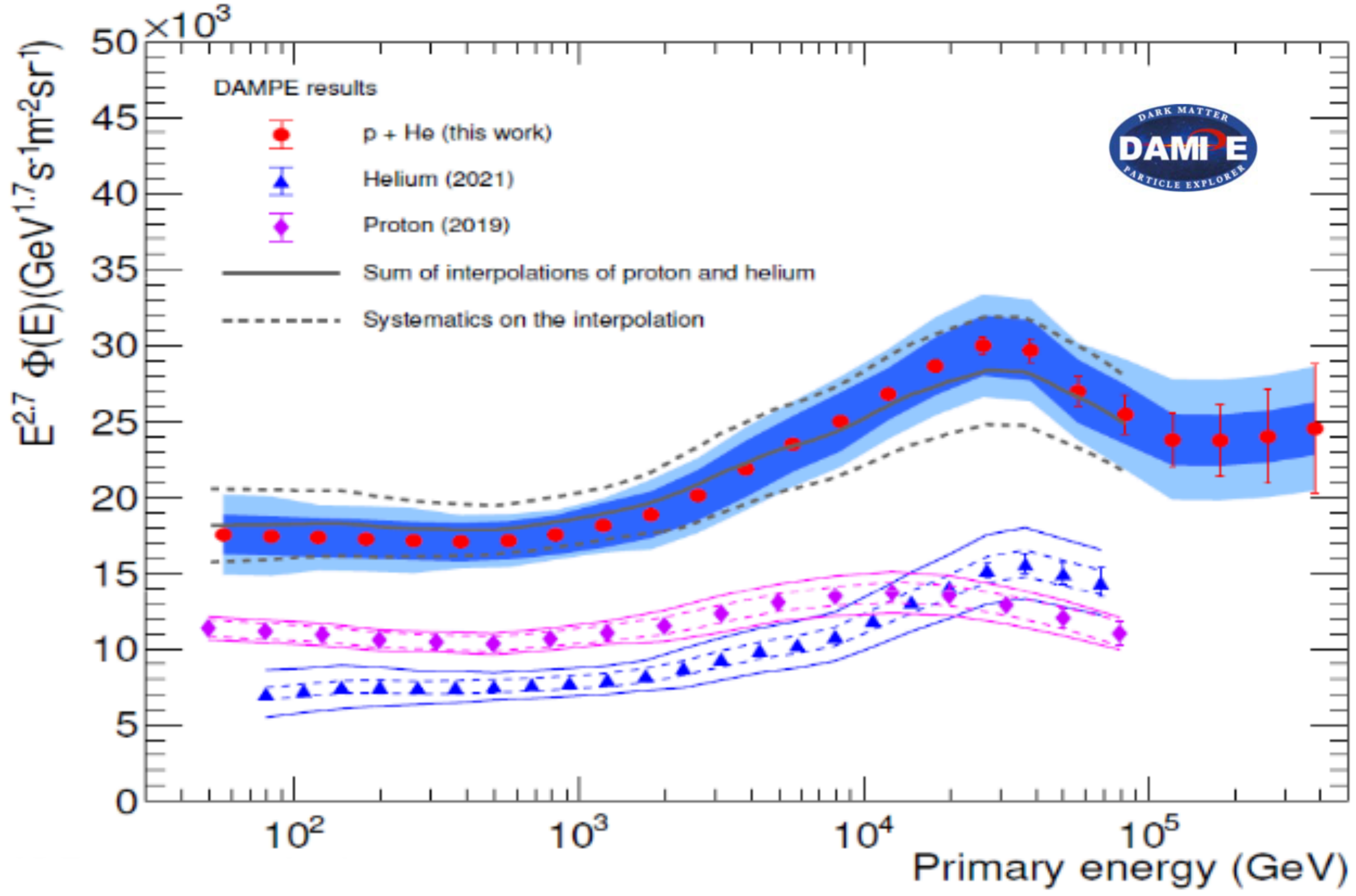
A single measurement across almost 4 orders of magnitude from DAMPE connecting direct and indirect measurements!

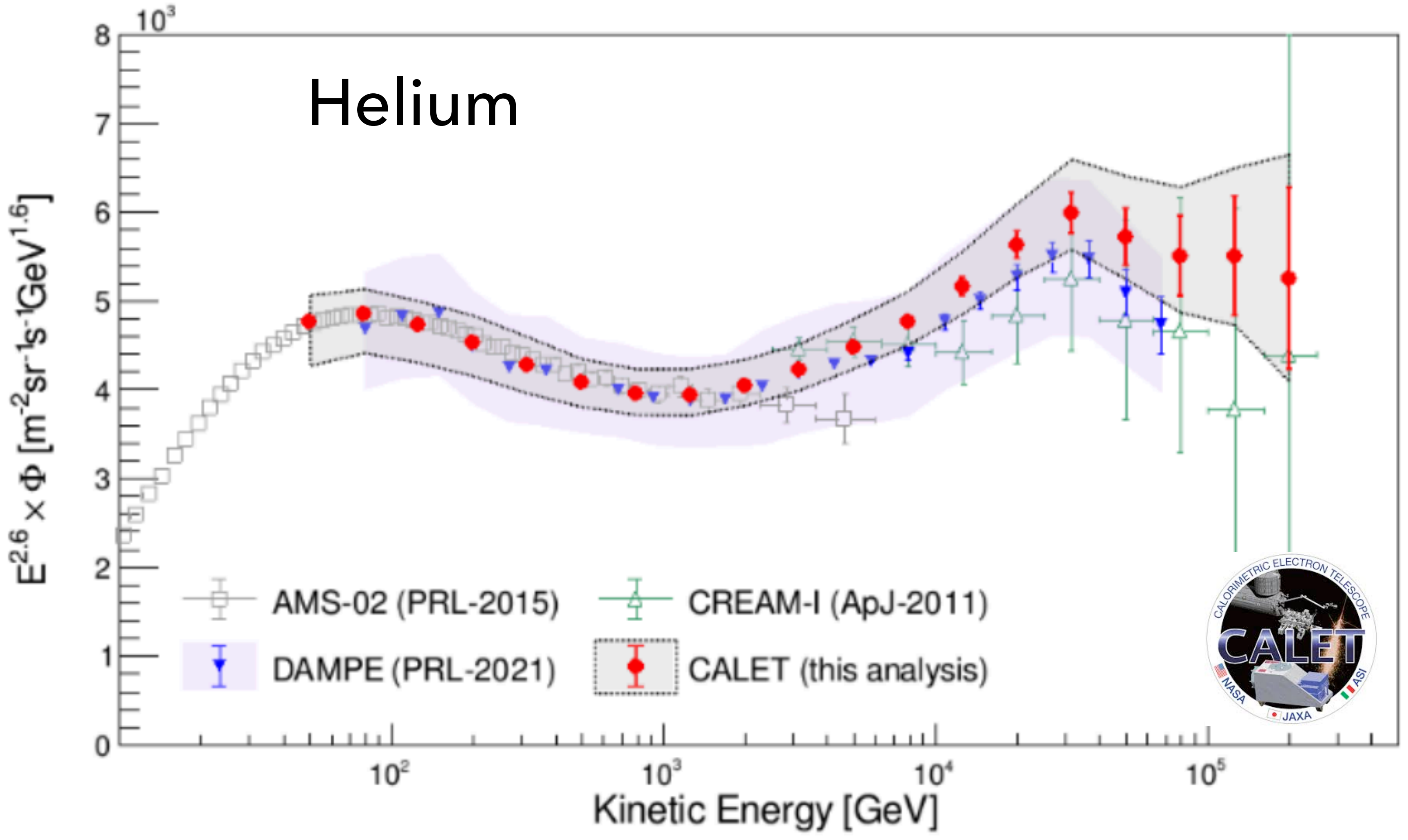


Change in composition around the knee: hint of different classes of sources with different E_{max}?

NEW SPECTRAL FEATURES IN THE KNEE REGIONS (p, He and p+He)







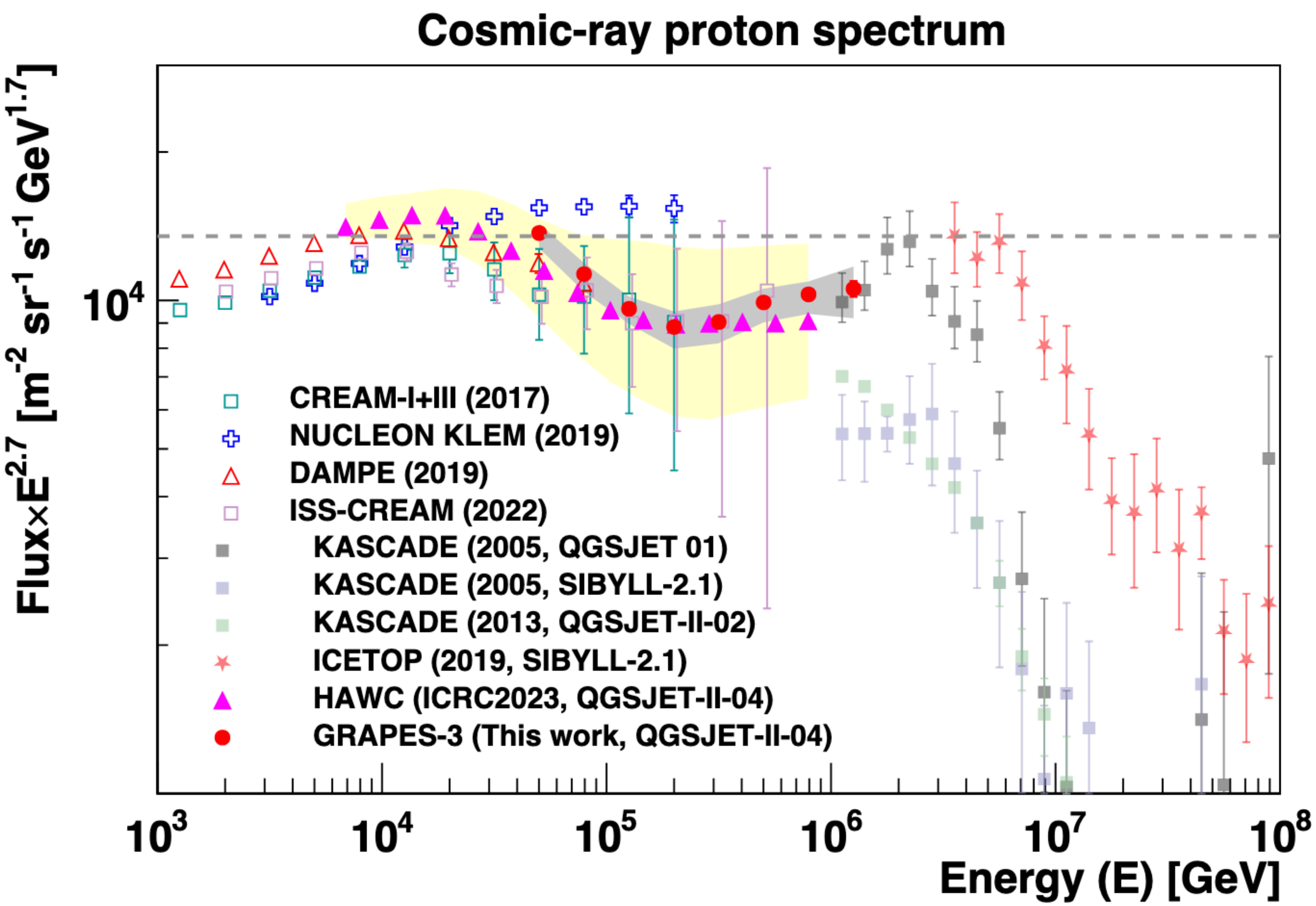
- change in spectral features can point to several sources/source type generating galactic CR.
- The proton spectrum shows a hardening around 550 GeV and a softening around 9.8 TeV
- The helium spectrum shows a hardening around 330 GeV/n (1319 GeV) and a softening around 8.3 TeV/n (33.2 TeV) suggesting Z dependence.
- The proton to helium ratio decreases as a function of energy and rigidity.
- Measurement of p+He confirms the softening and suggest a hardening around 100 TeV.

SPECTRAL MEASUREMENT BY GROUND BASED EXPERIMENTS

P. Mohanty's talk

CONNECTING TO THE SPACE-BASED MEASUREMENTS

- GRAPES-3 observation show proton spectrum continuing and then hardening at 165 TeV
- Spectrum in agreement with HAWC observation.

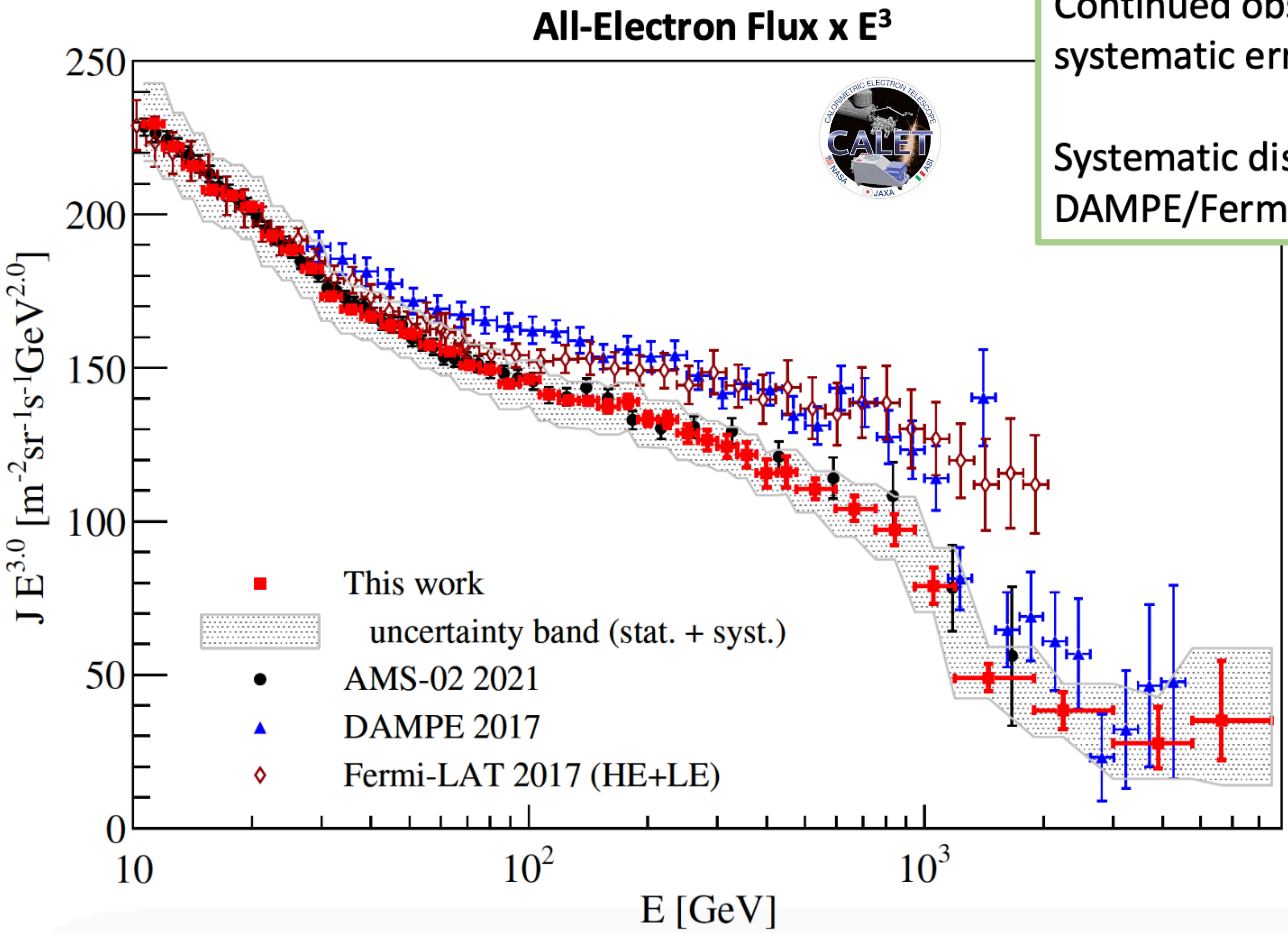


OTHER ELEMENTS

- B/C, B/O -> tracer of diffusion in the galaxy -> break observed required a change in transport
- Be/B -> clock sensitive to the diffusion time: fit to AMS data requires a Galactic Halo size of ~5kpc (big uncertainties in cross section).
- Complex antimatter (antideuterium and antihelium) are tracers for DM annihilation (see T. Linden's talk)
- positron excess explained as contribution from pulsars and their TeVHalos (see D. Hooper's talk)
- antihelium candidates found in AMS-02 (<2020 data).

COSMIC RAY ALL ELECTRON SPECTRUM

Experiments should work together to figure out the disagreement!



Continued observation has reduced statistical and systematic errors in the all-electron spectrum.

Systematic discrepancy between CALET/AMS-02 and DAMPE/Fermi-LAT persists beyond tabulated error.

At ~1 TeV energies, electrons have…

- diffusion length ~ 1 kpc
- characteristic lifetime ~ 100 kyr

(both decreasing with energy)

→ Expected cutoff around 1 TeV based on decrease in number of contributing sources significant in measurement

- Nearby accelerators could leave observable features in the spectrum in the TeV region

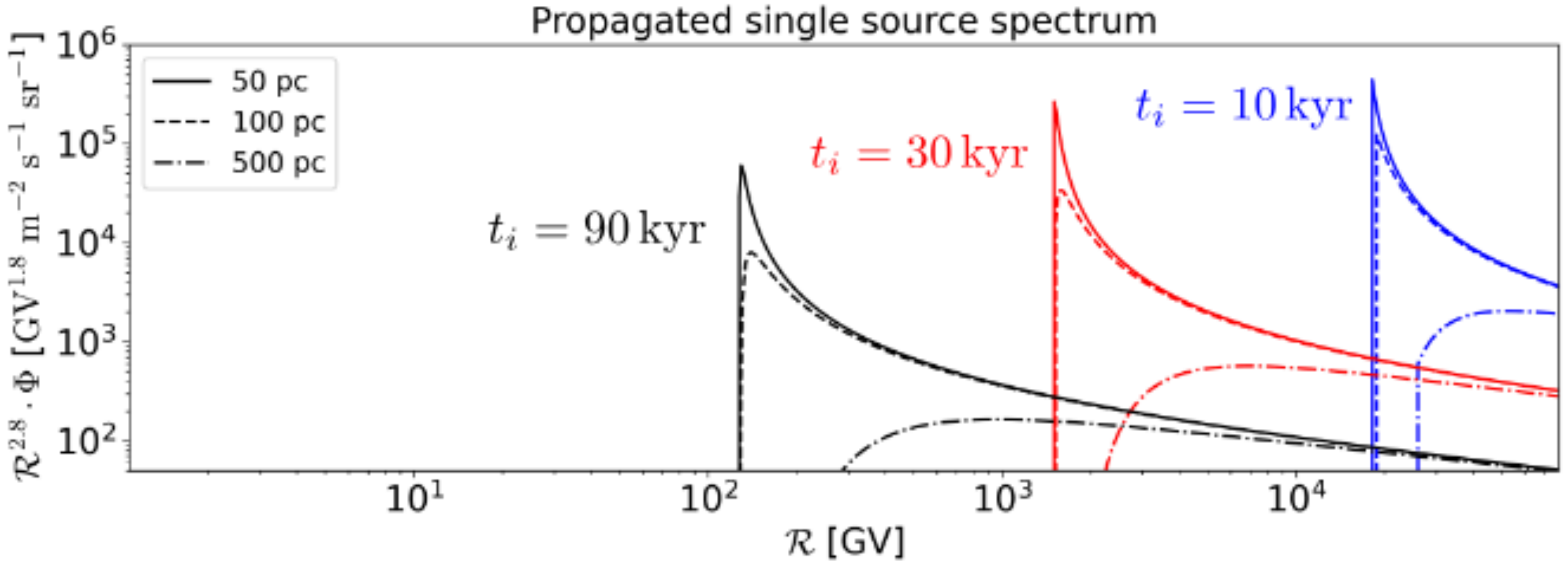
CREDIT: COSMIC RAY ENERGY DEPENDENT INJECTION TIME – P. MERTSCH

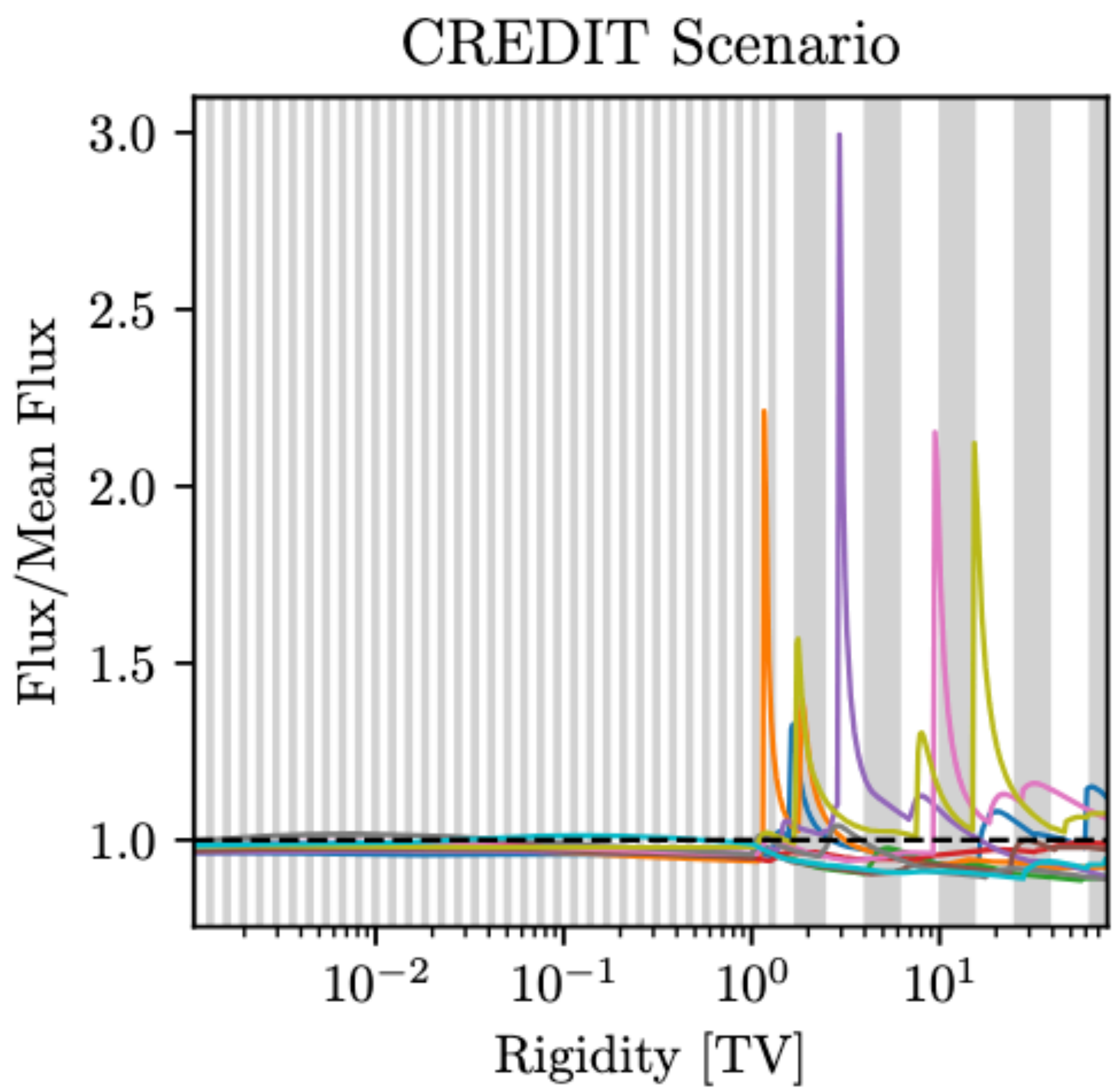
Predicting novel features by combining standard ingredients (supernova paradigm and B-field enhancement by Bell instability)

CR escape at different time because of the time dependence of B-field amplification: highest energies escape earlier.

1. CREDIT scenario

→ Investigate sources

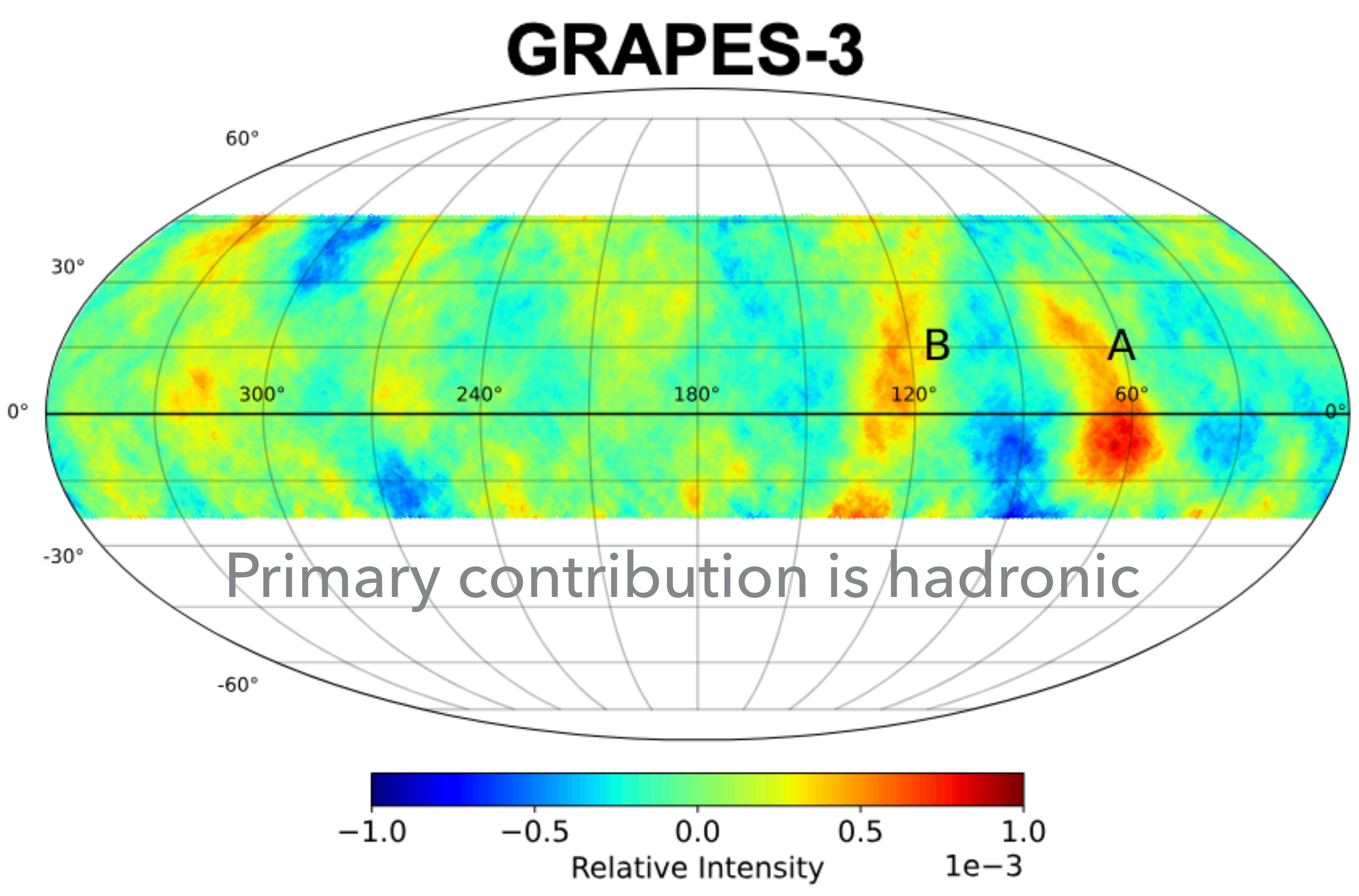


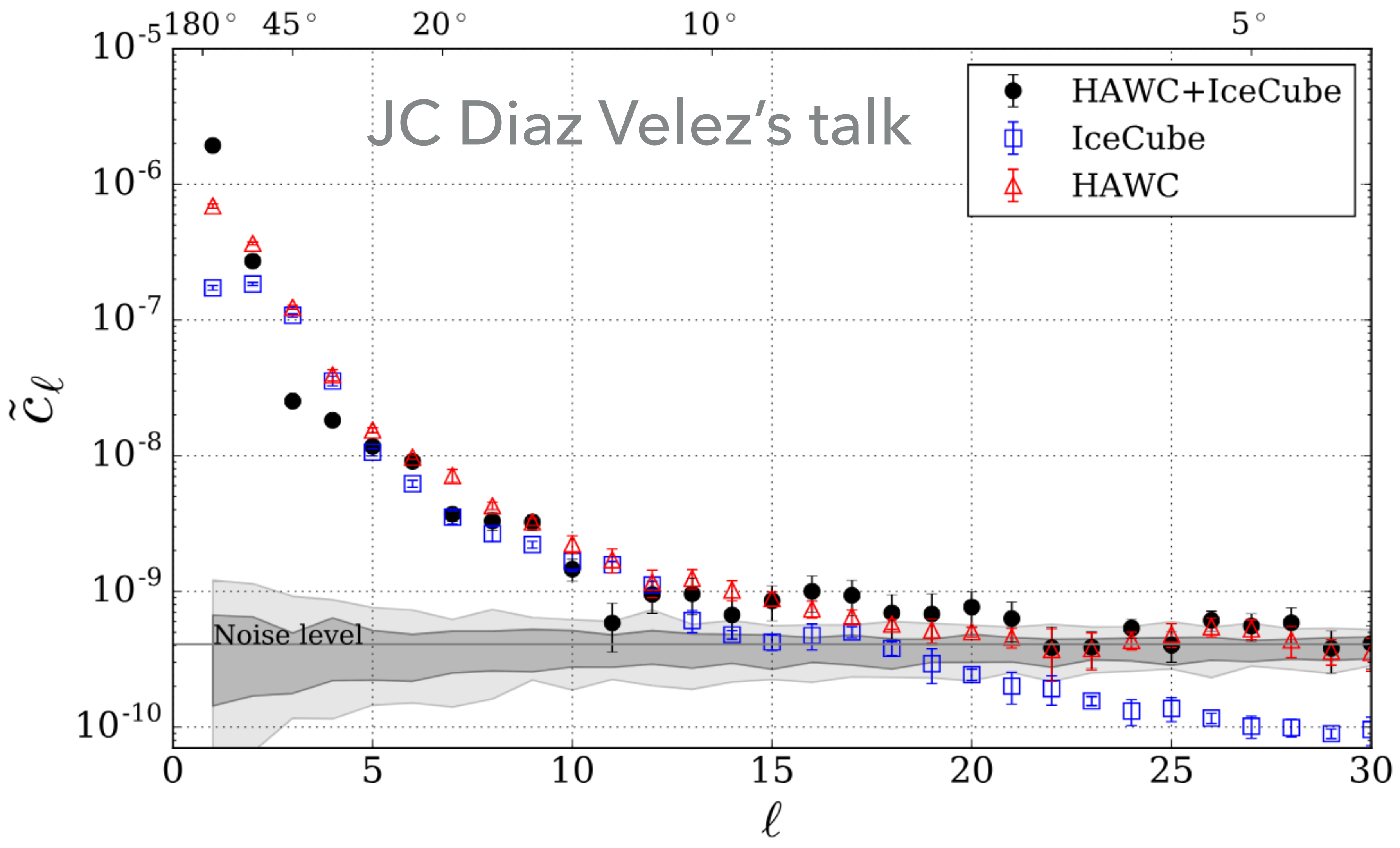


Classifier (decision tree) used on data: model is testable and can disentangle between different scenarios.

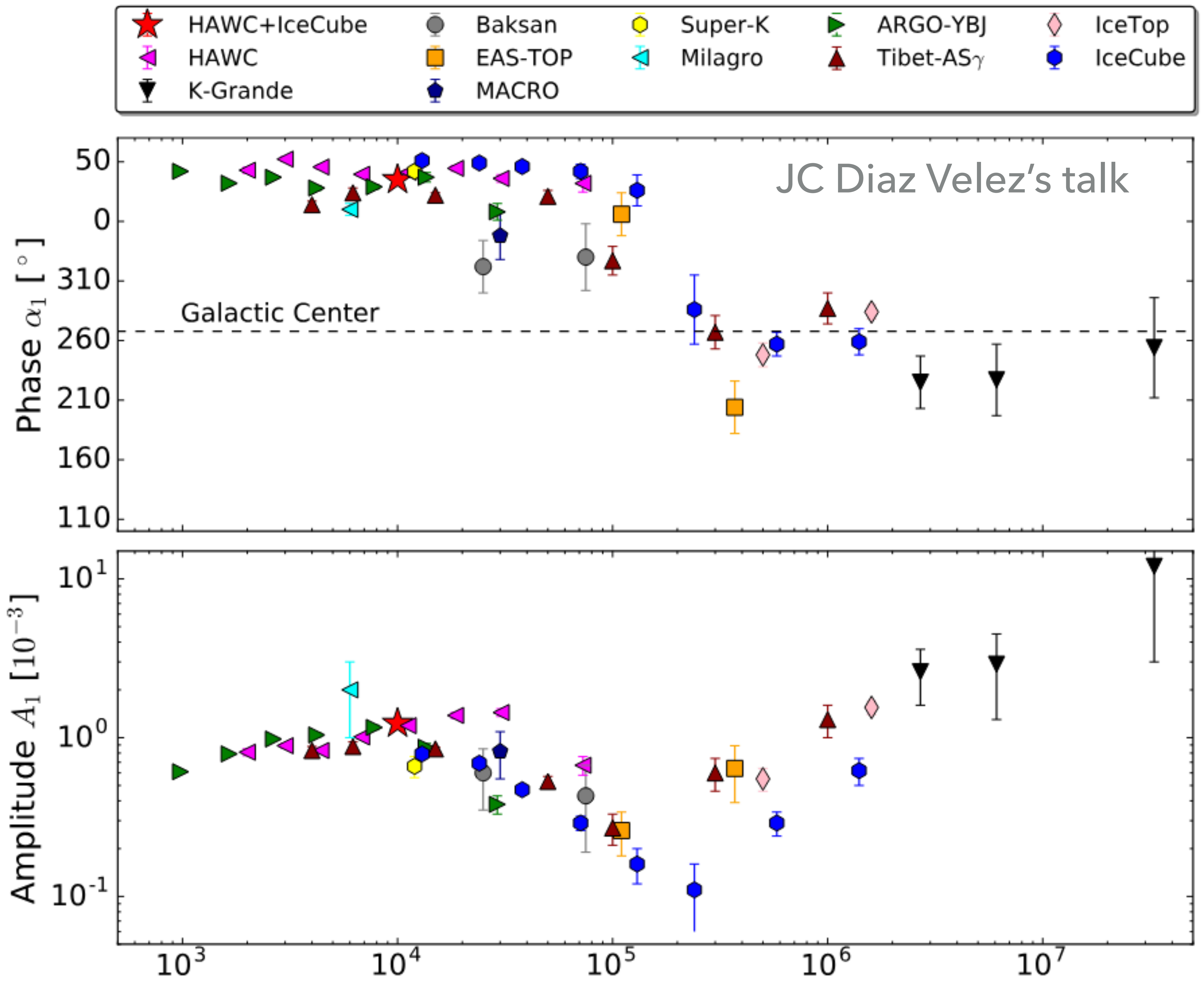
ANISOTROPY

Observed at different scales and energies from several experiments in the 2 hemispheres

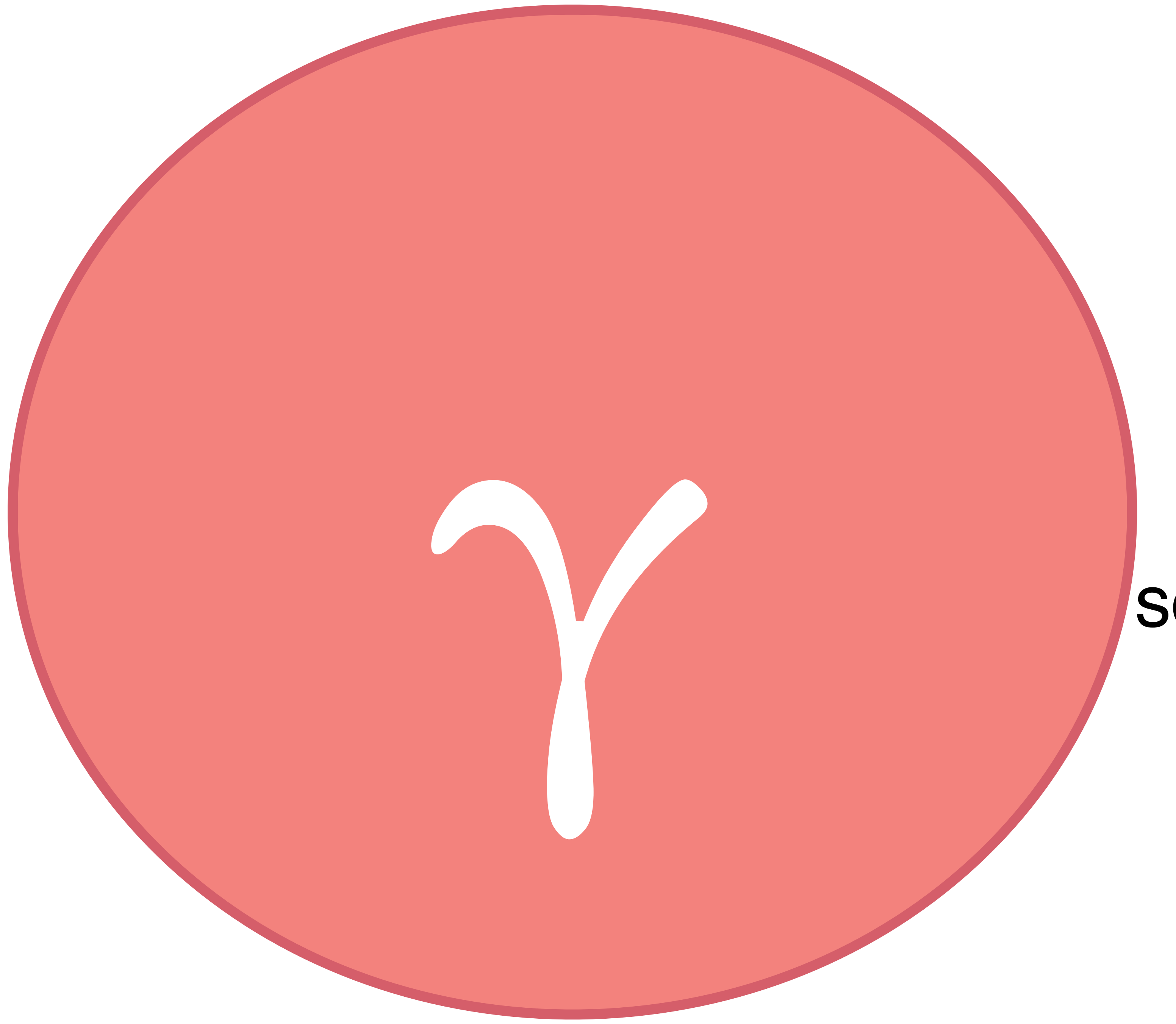




The existence of local TeV accelerators could explain change of the phase and amplitude of dipole anisotropy.



Speculations: change in phase follow the same trend as new features of proton spectrum at the new (different populations?).



<u>Gammas tracers of CR:</u>

Many bright unidentified sources & new sourse classes with E> 100 TeV measurements

ARE THERE PEVATRONS IN OUR GALAXY?

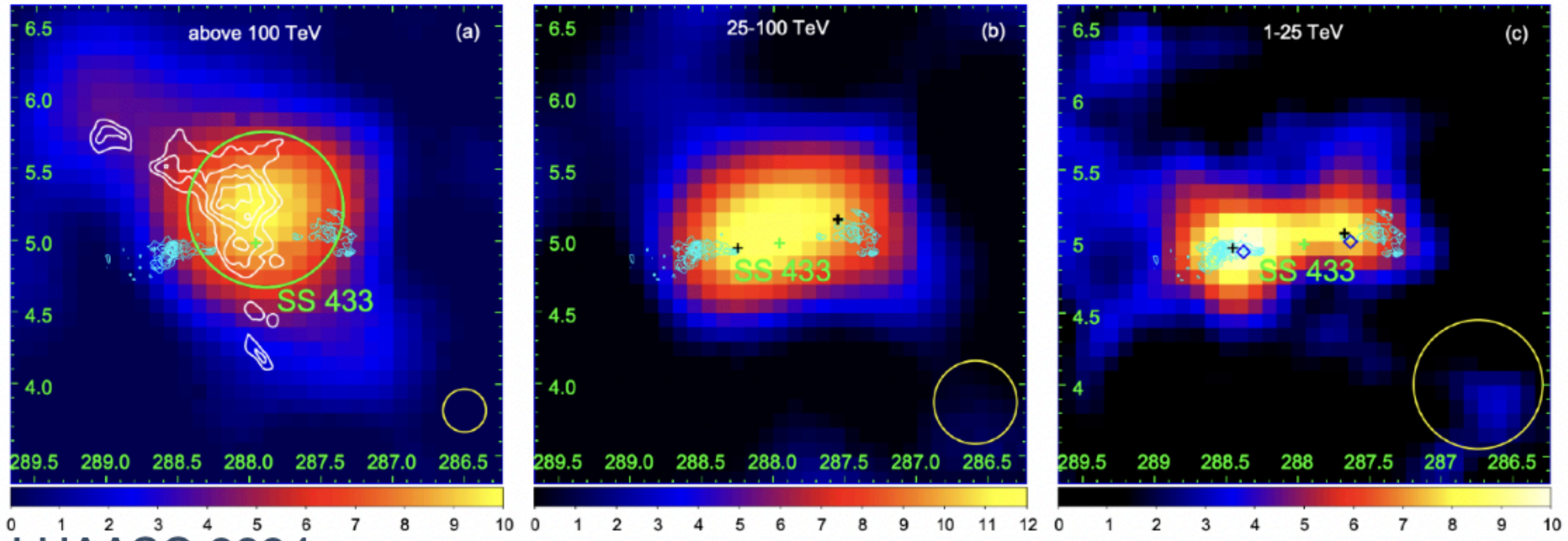
Definition of a PeVatron: “**A PeVatron is a source that is able to accelerate particles with a spectrum that shows a substantial suppression with respect to its low energy power law extrapolation in the region of PeV energies**” (from Blasi’s talk)

Meaning that we are looking for hard (slope ~2) power law gamma ray spectrum with a suppression in the region of hundreds of TeV.

ARE THERE PEVATRONS IN OUR GALAXY?

Z. Cao's talk

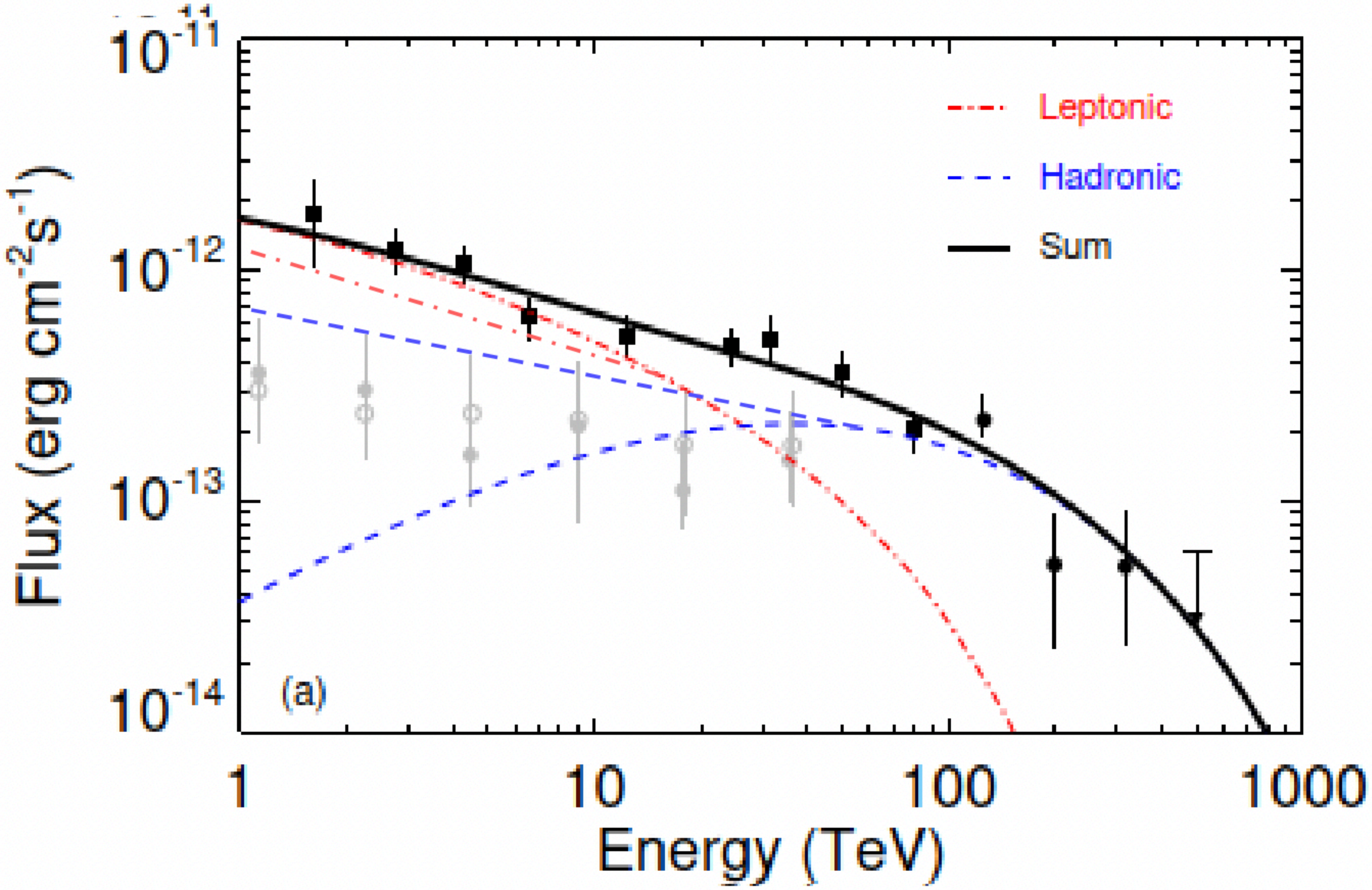
Microquasars SS433



LHAASO 2024

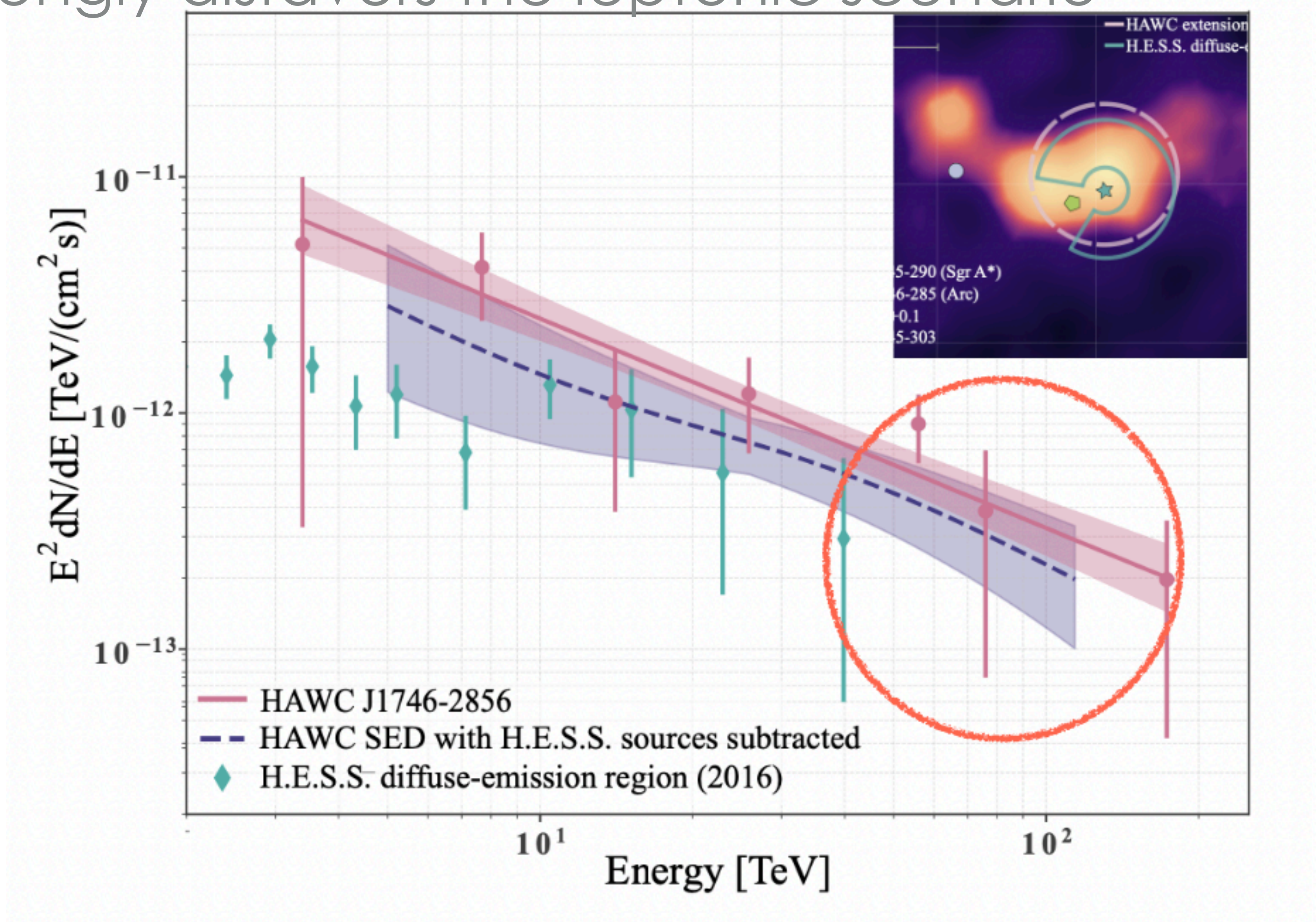
LHAASO: morphology coincident with the molecular clouds (no longer with jets like seen by HESS at lower energies). **Hint to hadronic process.**

- CR sources above the knee at ~3 PeV
- Total luminosity $L_p \sim 10^{38}$ erg/s $f_{\mu Q} \sim 10$
- Explains the CR flux around the Earth



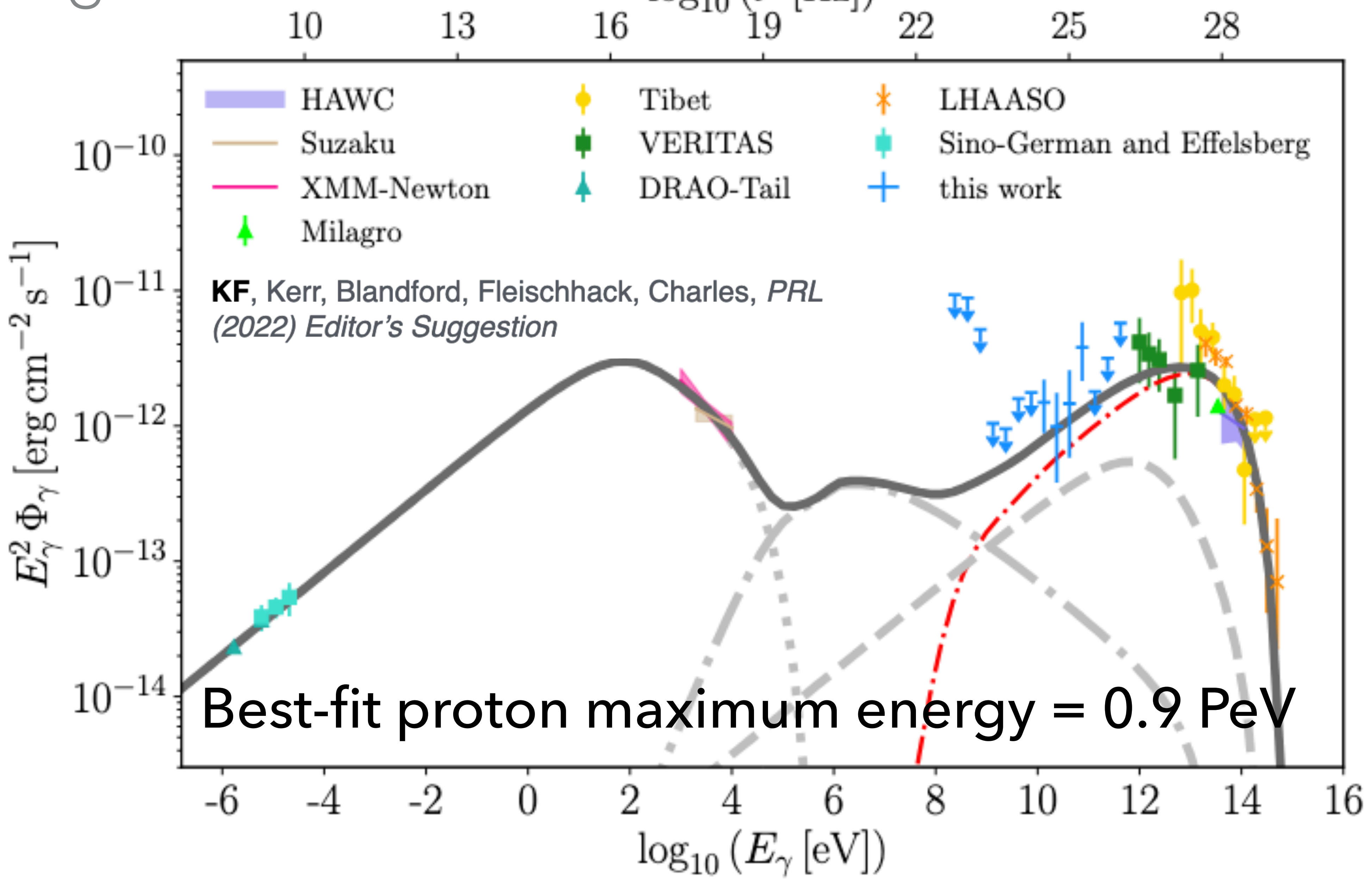
Galactic center

Due to the extension of the source and electron cooling time, the detection of emission to energies >100 TeV thus strongly disfavors the leptonic scenario



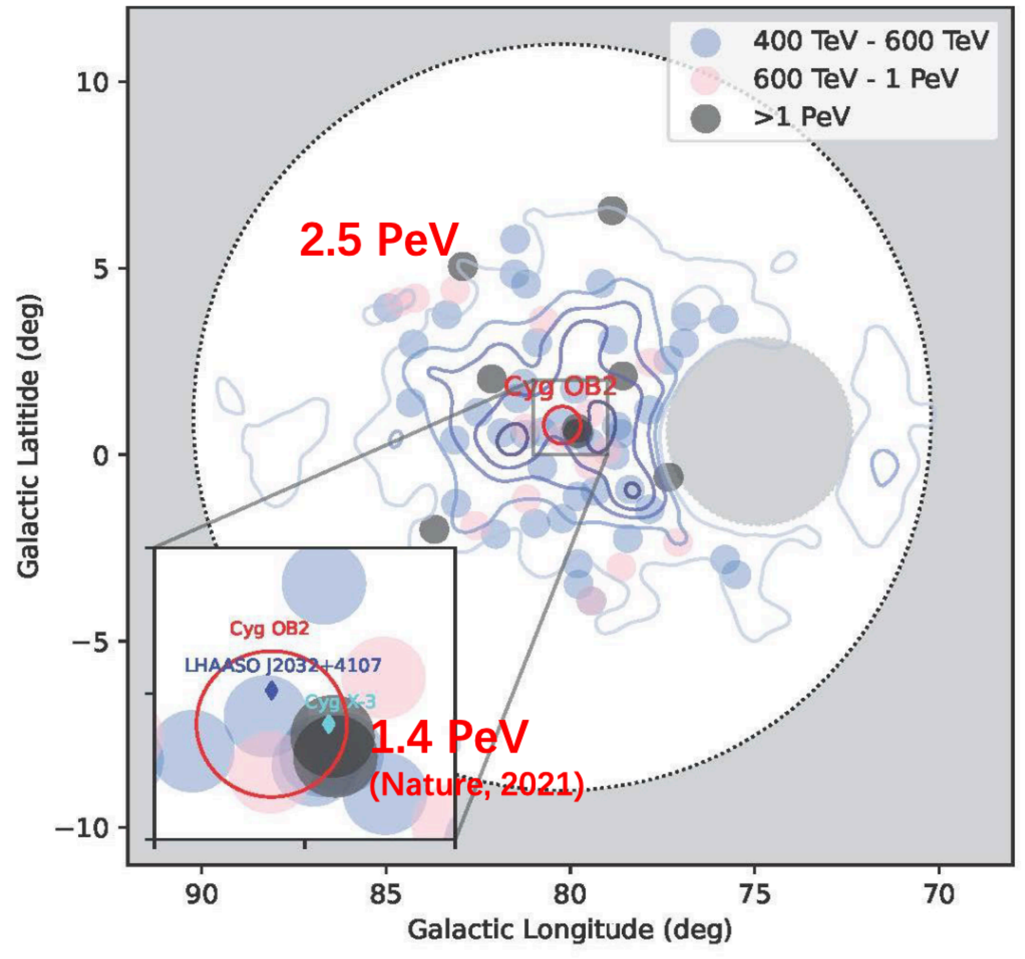
SNR G106.3+2.7 - first PeVatron SNR candidate

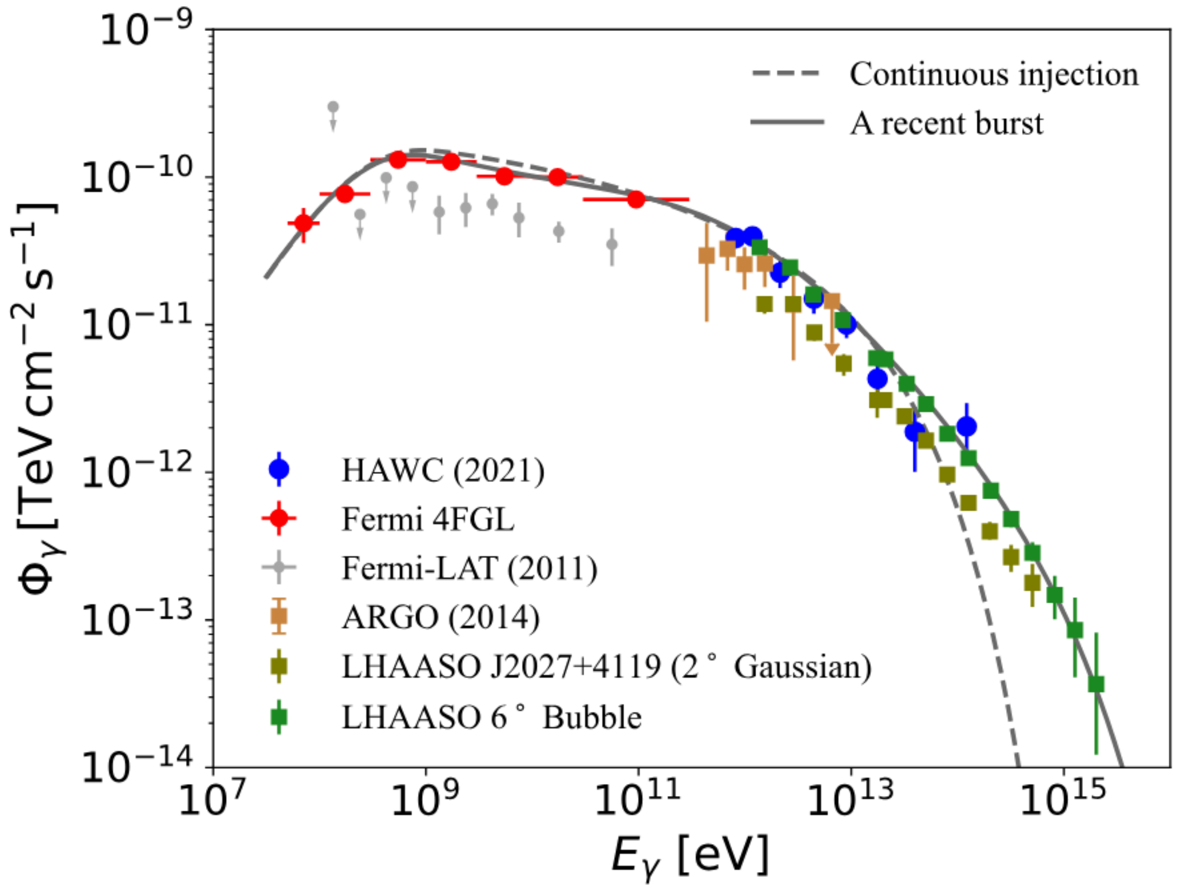
Model with proton contribution is favored at >5 σ significance



Cygnus Cocoon - LHAASO detection up to **2.4 PeV**!

Gamma rays are likely from protons accelerated by stellar wind





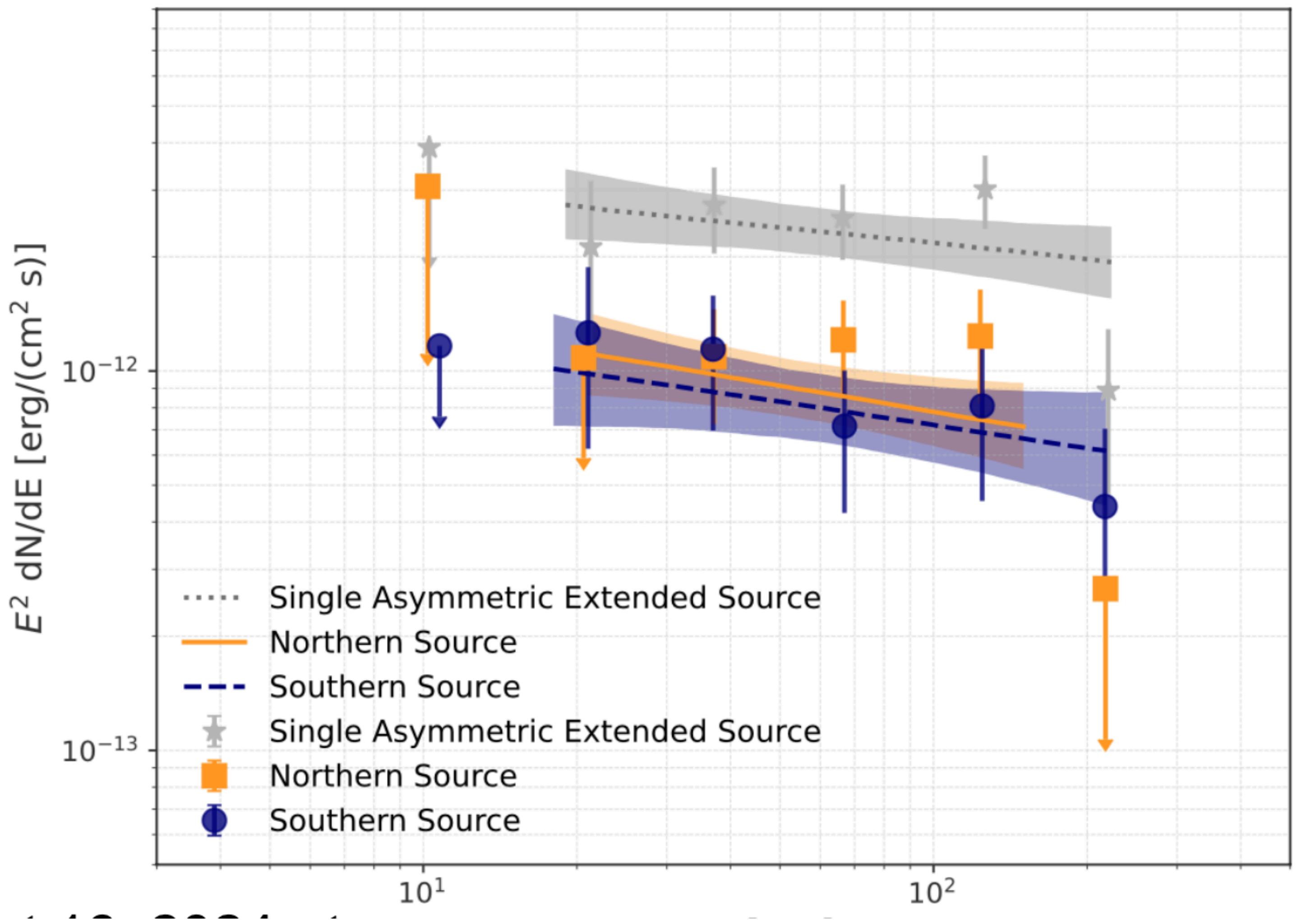
LHAASO Collaboration, Science Bulletin (2024)

KF & Halzen, 2404.15944

V4641 - newly discovered binary

Among the hardest source ever detected by air shower gamma-ray observatories.

Difficult to explain as leptonic due to diffusion over 100pc (size of the bubbles)



ARE THERE PEVATRONS IN OUR GALAXY?

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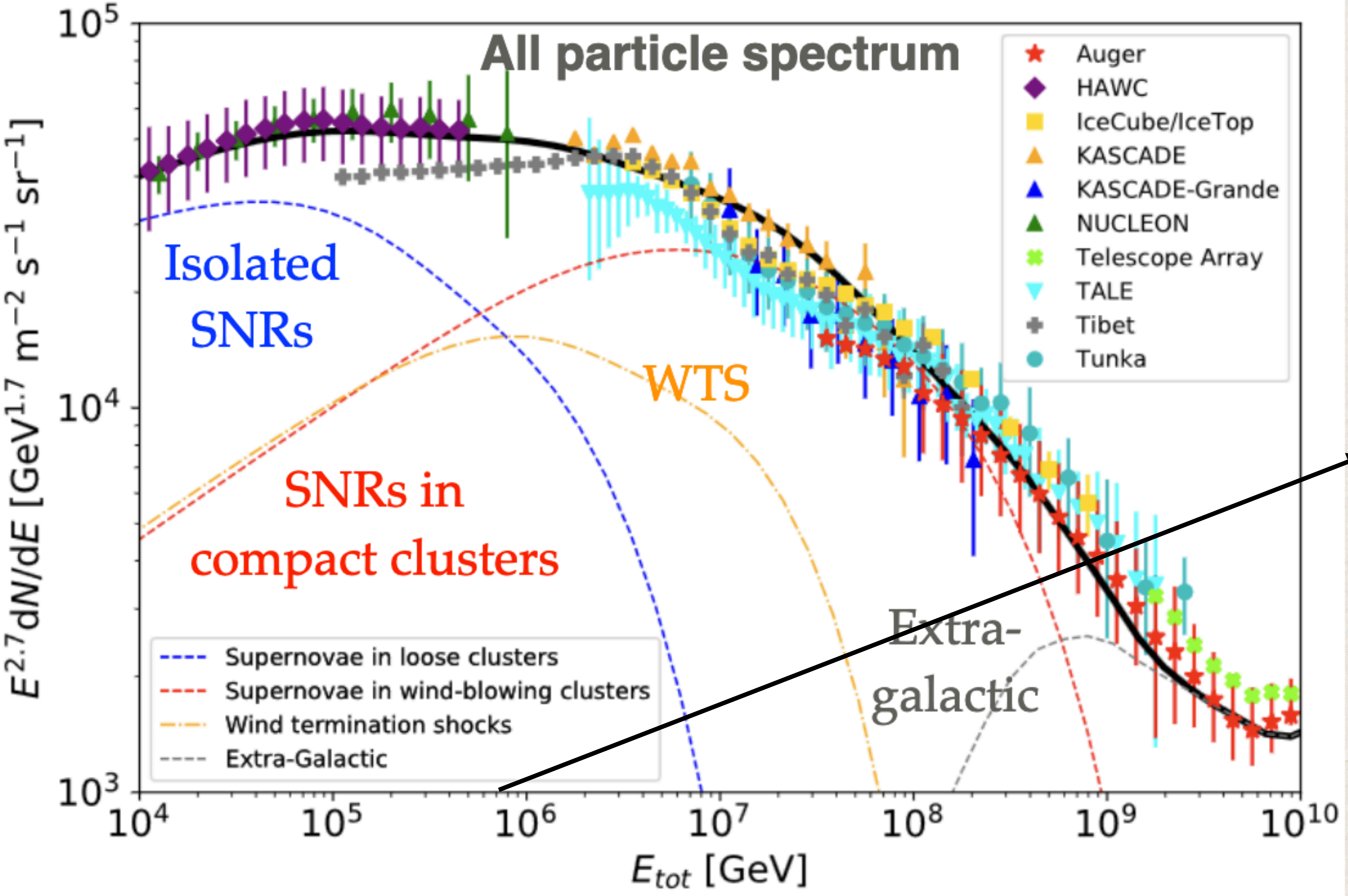
Meaning that we are looking for hard (slope ~2) power law gamma ray spectrum with a suppression in the region of hundreds of TeV.

SNR have the energetic budget but they don’t reach the maximum energy or only a few can do that.

Gaining momentum: two source population hypothesis (stellar clusters / SNR in stellar clusters / microquasars)

YOUNG STELLAR CLUSTERS AS CR SOURCES

Attempt to explain the all-particle spectrum with a combination of isolated SNRs + wind termination shock + SNR in compact clusters



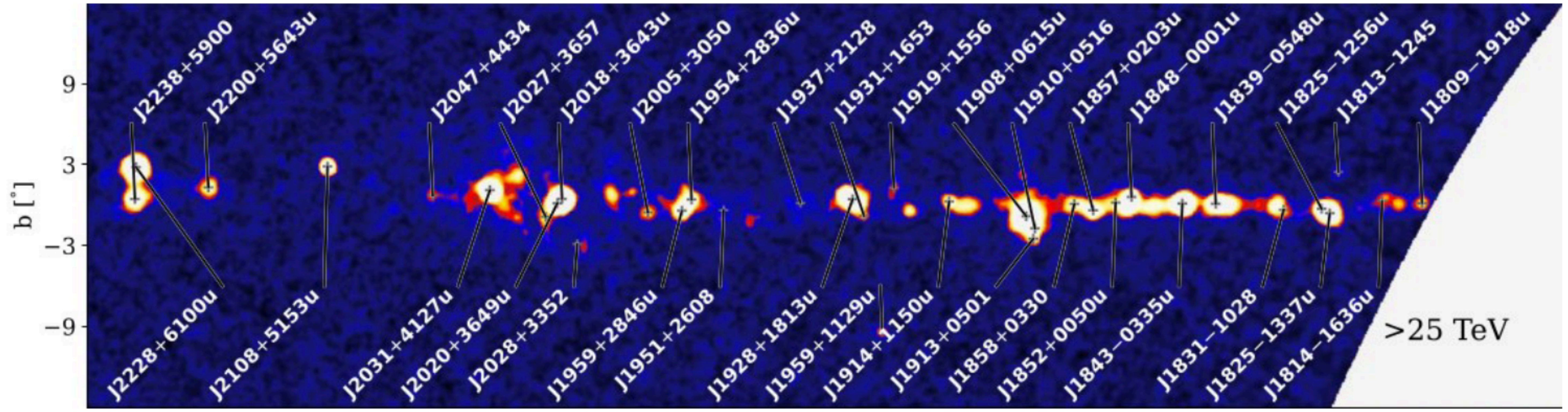
second component kicking in at > hundreds TeV

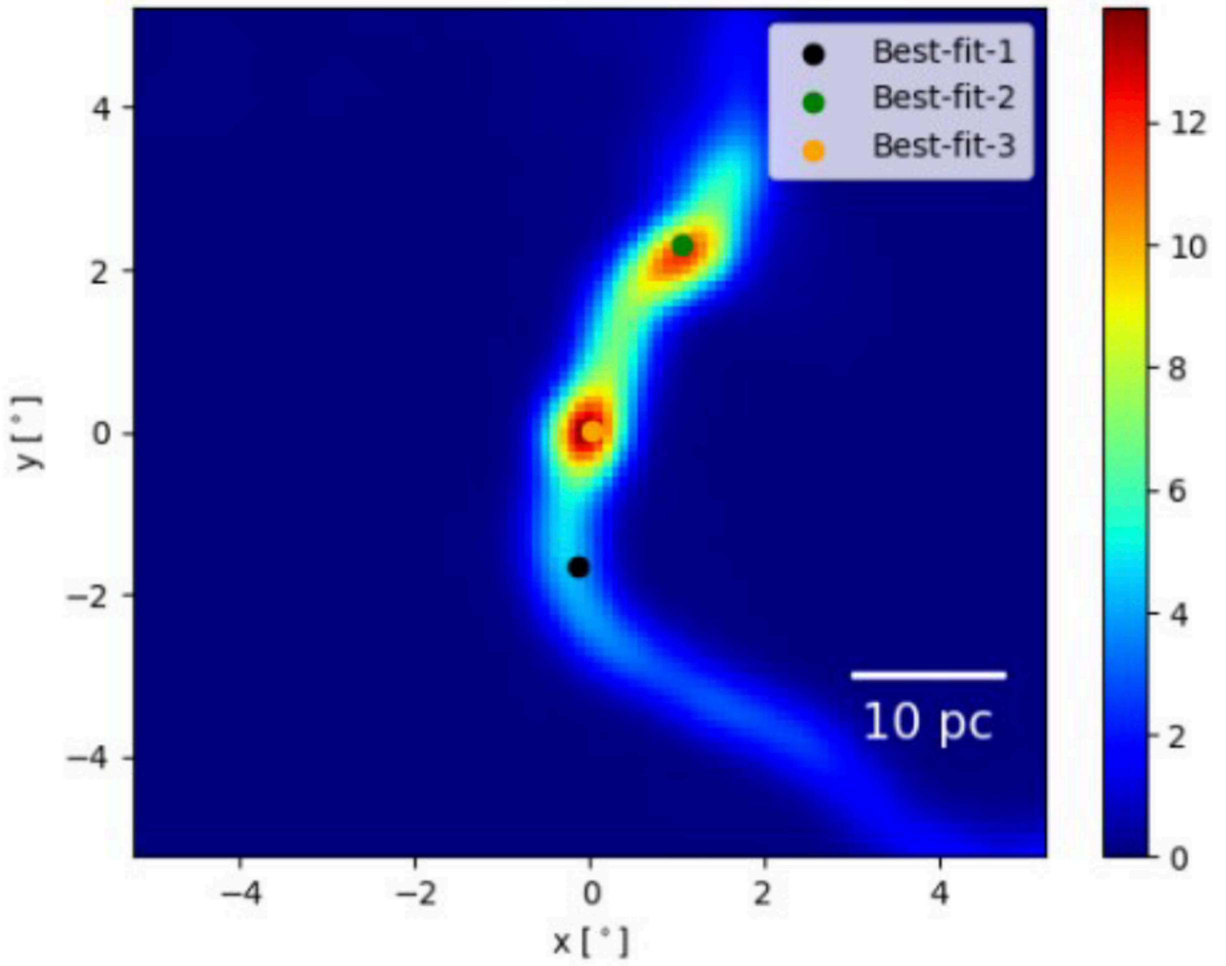
LHAASO SOURCE SHAPE EXPLAINED BY ANISOTROPIC DIFFUSION IN ISOTROPIC (KOLMOGOROV) TURBOLENCE

G. Giacinti's talk

LHAASO Collaboration, ApJS 271, 25 (2024)

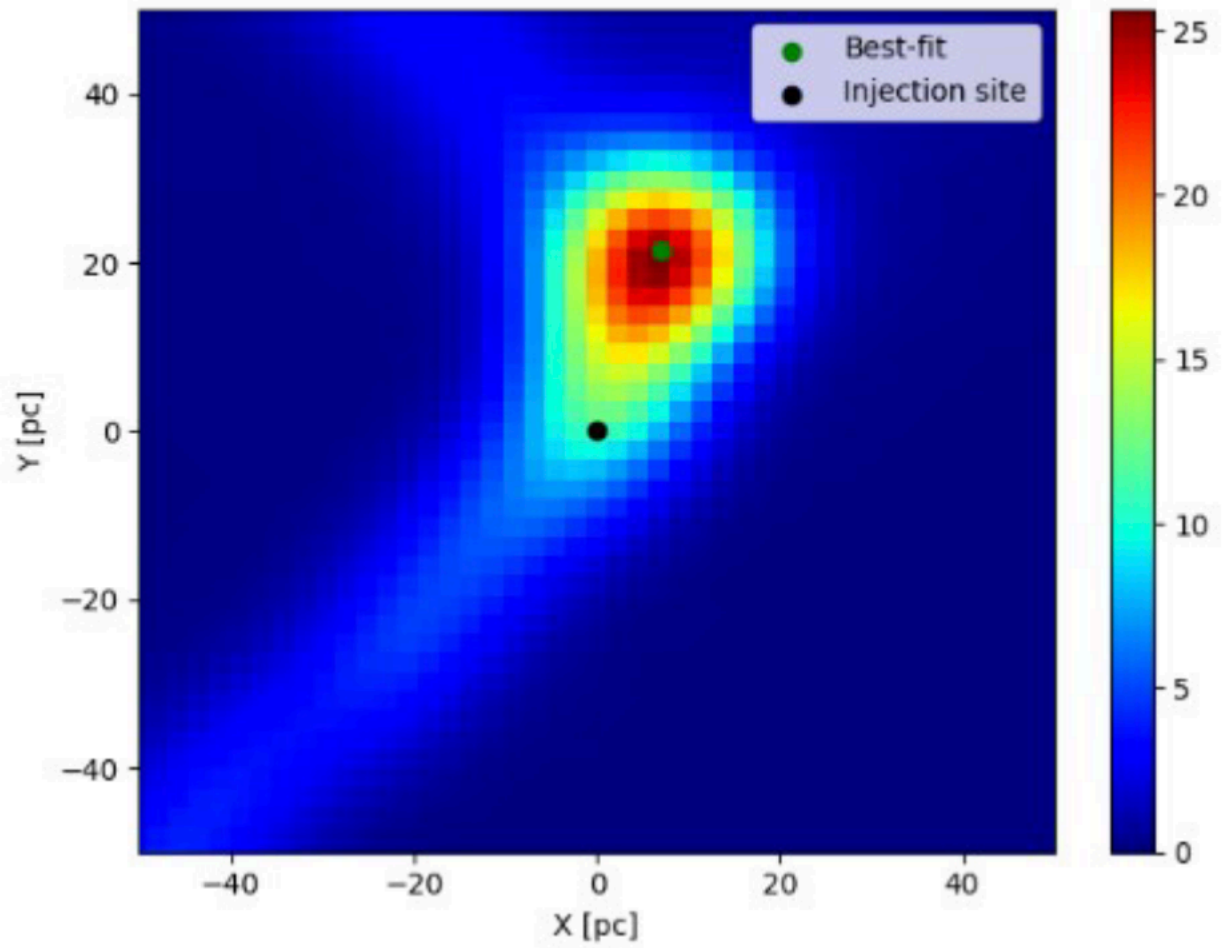
Many **extended sources** w/ **irregular shapes:**





"Mirage" sources may appear around (and far from) astrophysical sources where the magnetic field bends inwards/outwards, wrt/ observer

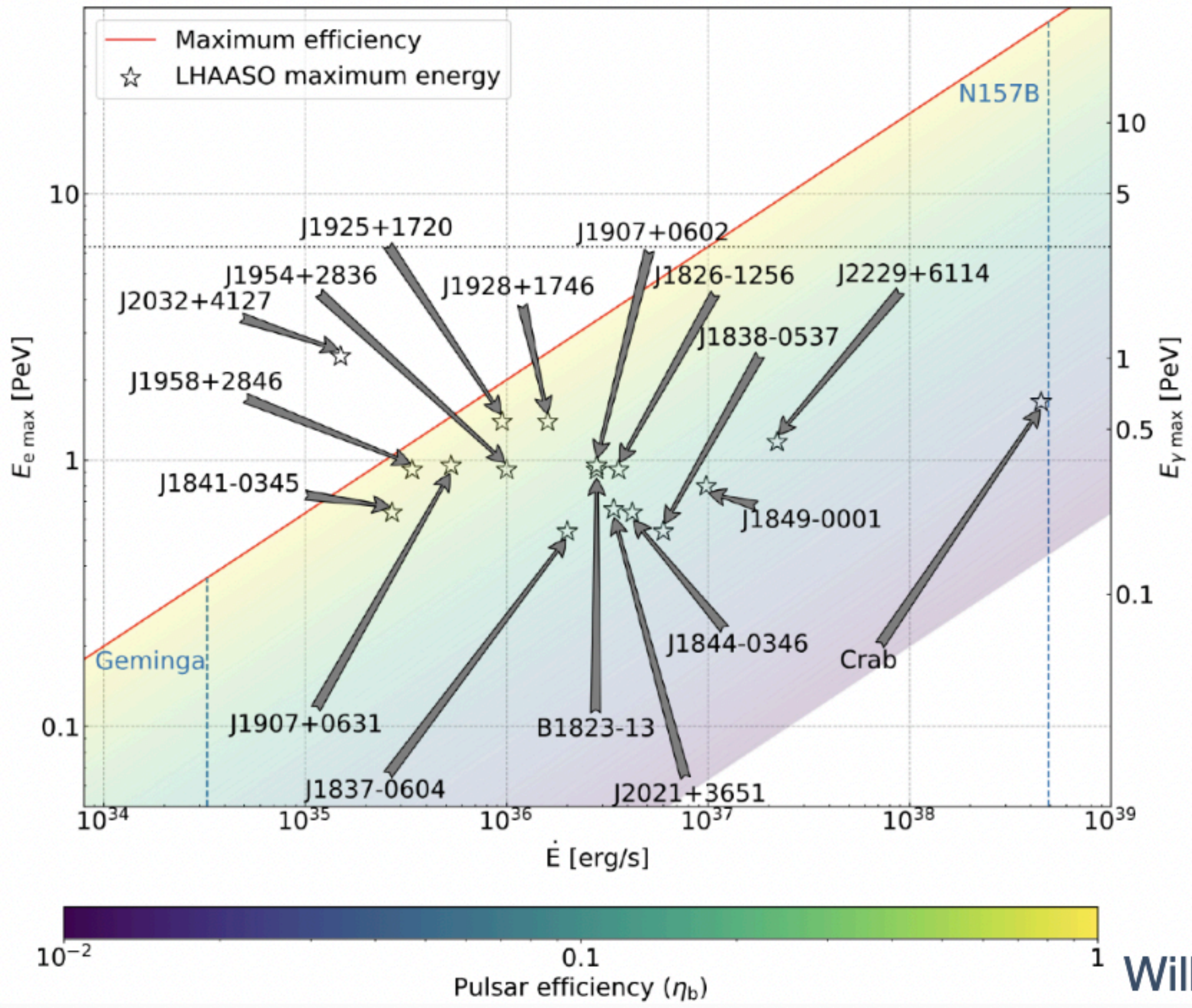
Large offsets may exist between the real source and the detected source, due to B-field structure in the ISM around the source.



Do not forget leptons

R. López-Coto's talk

- Leptonic CR accelerators known since several decades
  - Can most of the gamma-ray sources emitting in the ~hundreds of TeV gamma-ray energy range be explained via leptonic emission? => YES!



Wilhelmi, RLC et al. 2022

<u>Undeniable prove of hadronic acceleration</u>

First “galactic image” in neutrinos from IceCube

FIRST TIME WE SEE STRUCTURE IN THE "GALACTIC" NEUTRINO SKY

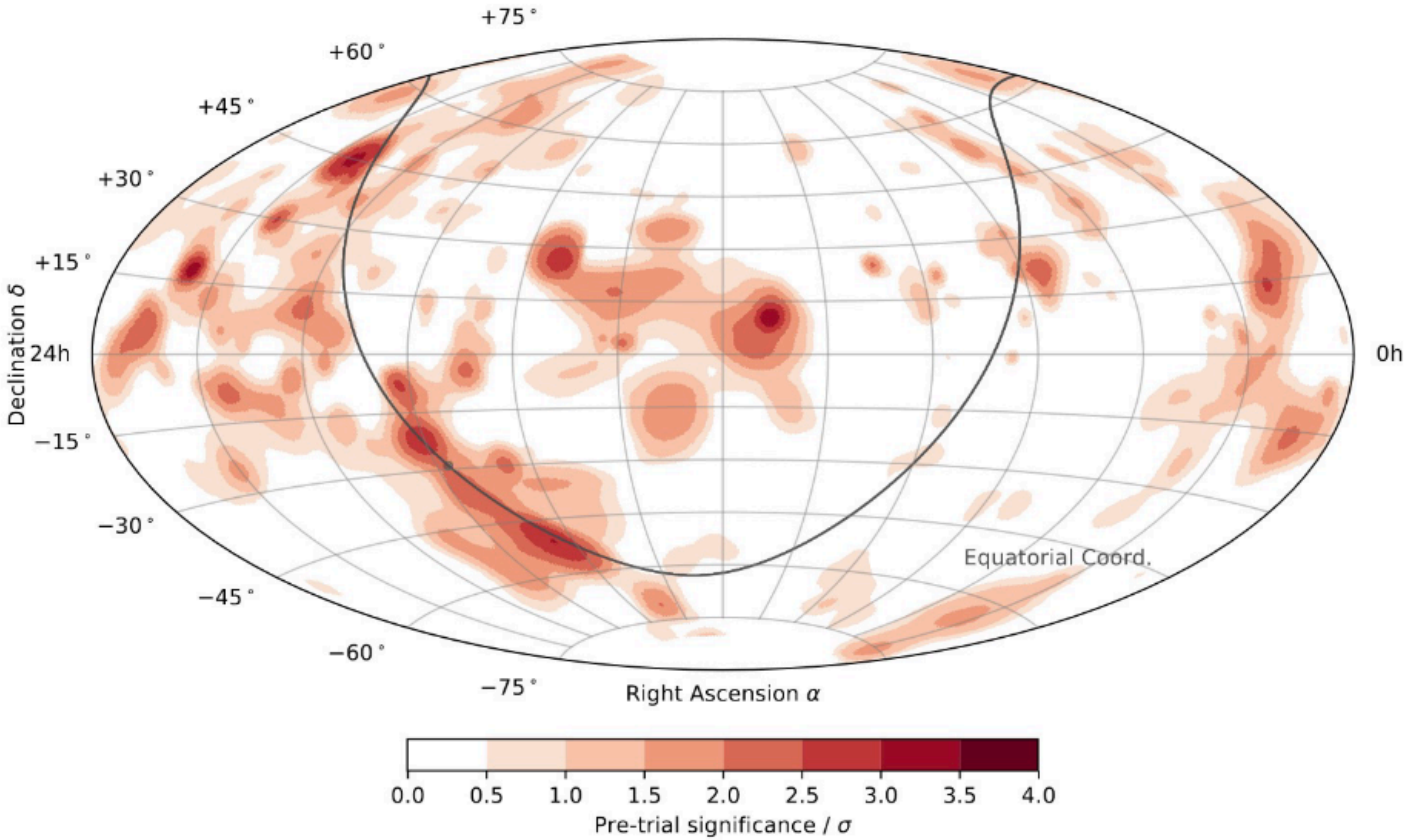
HIGH-ENERGY NEUTRINOS FROM THE GALACTIC PLANE

What is the origin (or more likely, origins) of these neutrinos?

-Cosmic rays scattering with gas in the ISM?

-Cosmic ray accelerators? (supernova remnants, pulsar wind nebulae,…)

Structures in all-sky map seem present but no sources have been observed (yet).

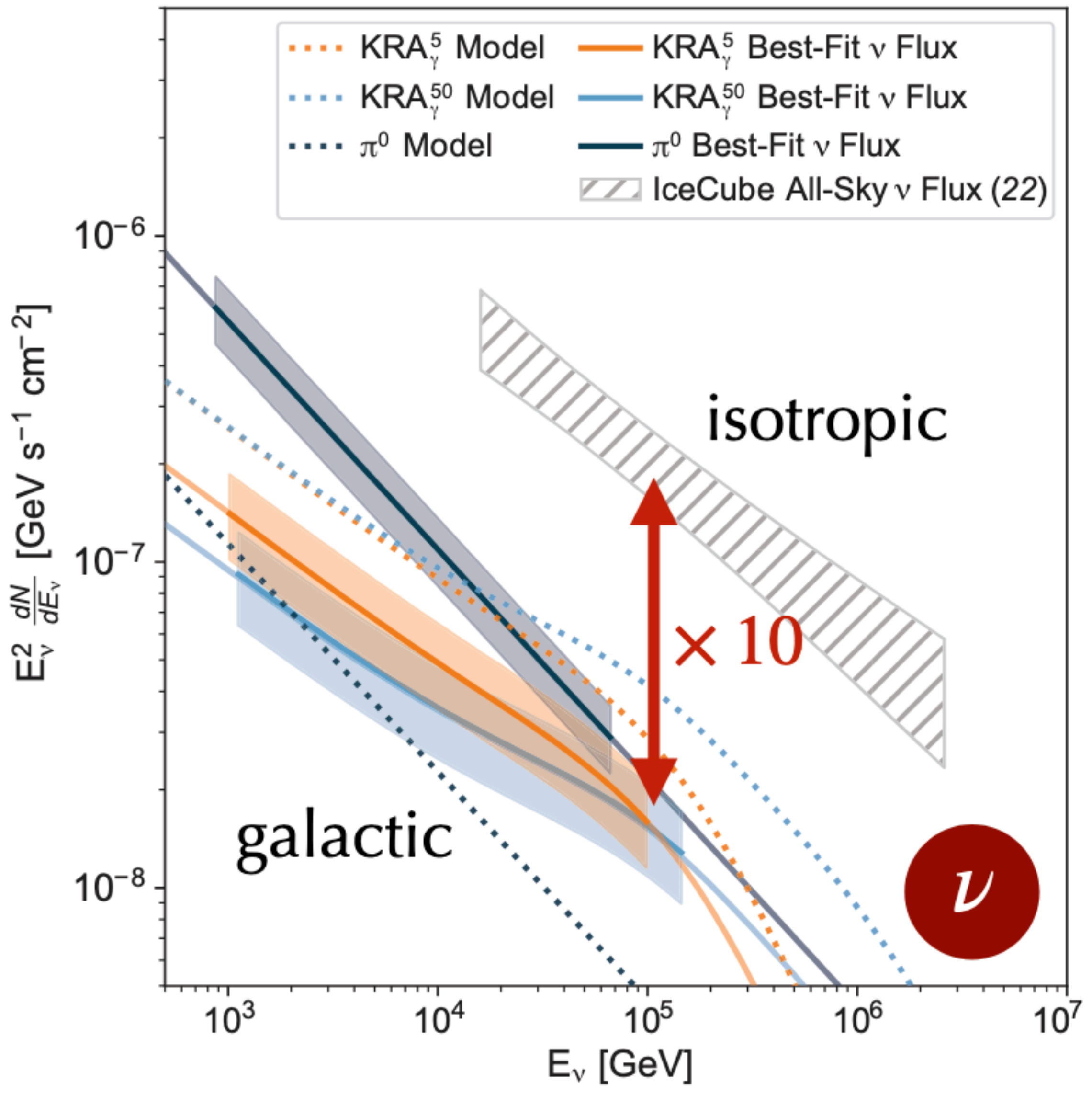


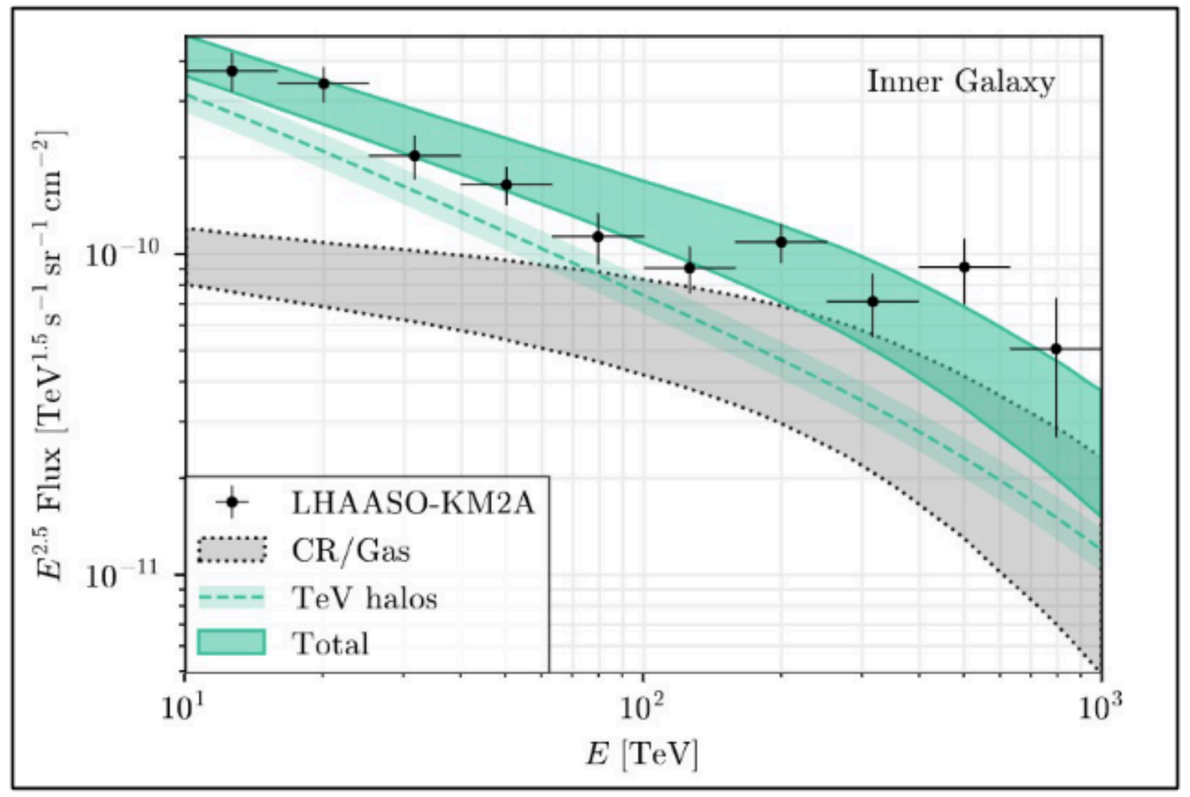
DIFFUSE EMISSION VERSUS SOURCES

K. Fang's talk

D. Hooper's talk

Best-fit normalization of spectra





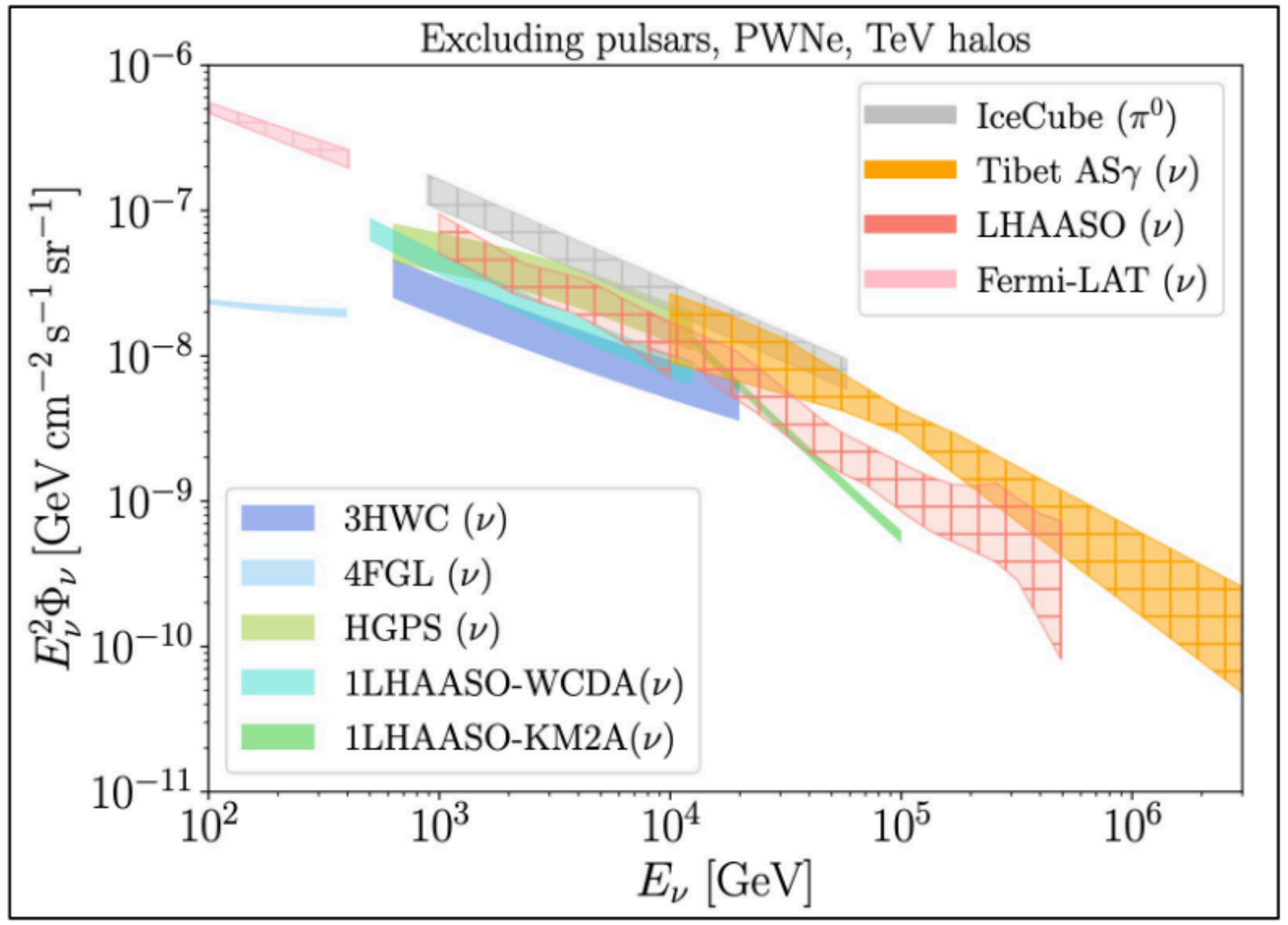
A. Dekker, I. Holst, DH, G. Leone, E. Simon, H. Xiao, arXiv:2306.00051

Gamma-ray diffuse models are consistent with IceCube observations.

Diffuse cosmic ray interactions likely contribute significantly to the Galactic neutrino flux. Most of IceCube's flux must arise from a combination of diffuse cosmic-ray interactions and unresolved sources.

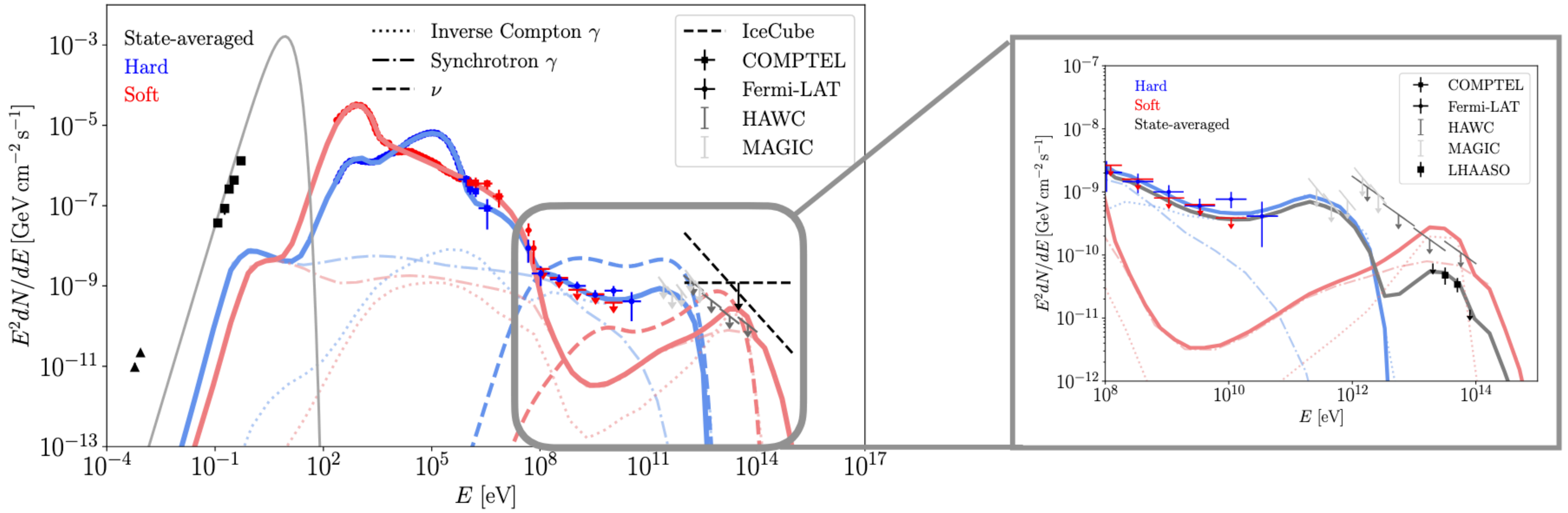
TeV halos (leptonic) appear to be responsible for the observed cosmic-ray positron fraction, and for a significant fraction of the diffuse very high-energy gamma-ray emission that has been observed from the Milky Way

Resolved gamma-ray sources cannot be responsible for most the observed neutrino emission.

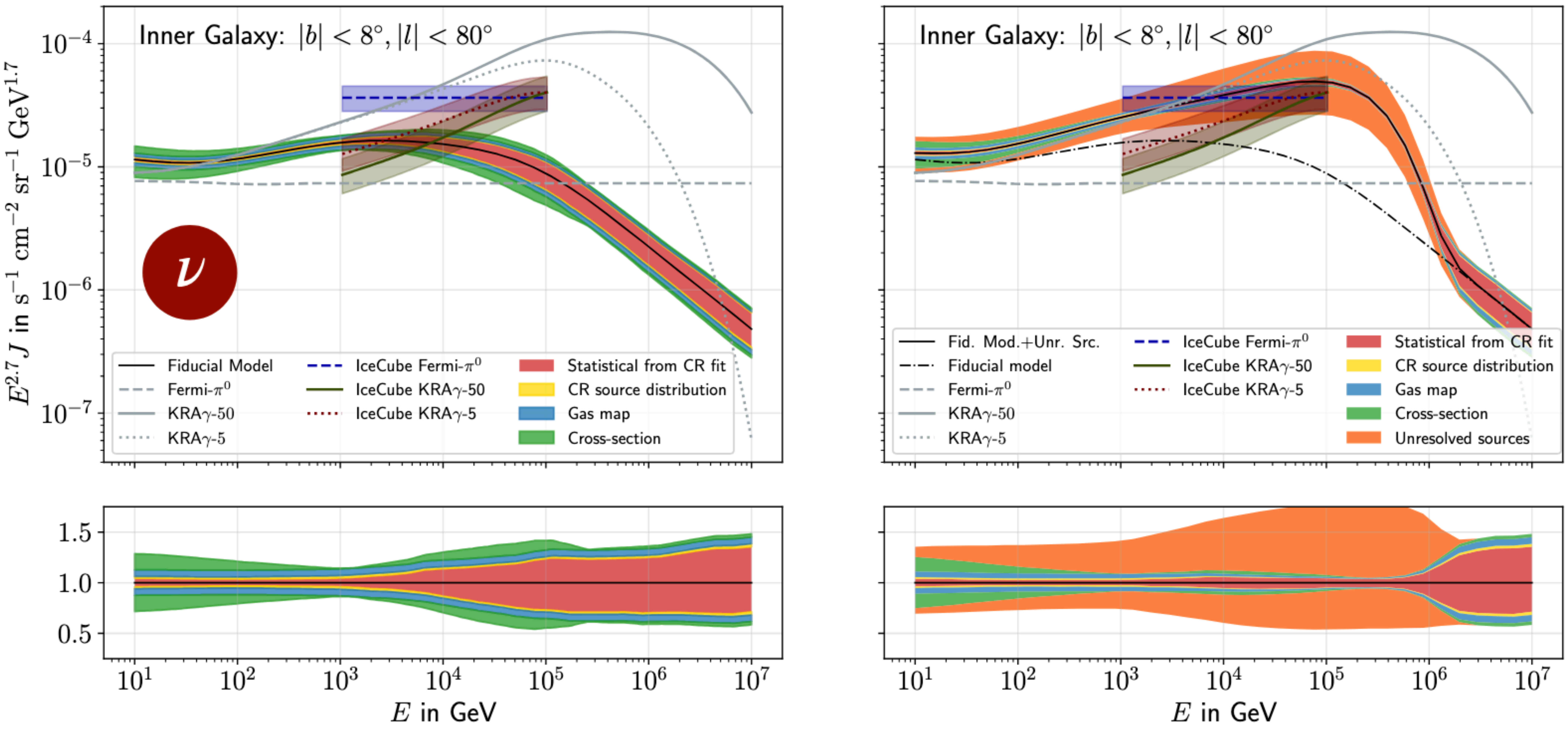


Fang & Murase, arXiv:2307.02905

A population of gamma-ray-obscured neutrino emitters (?)

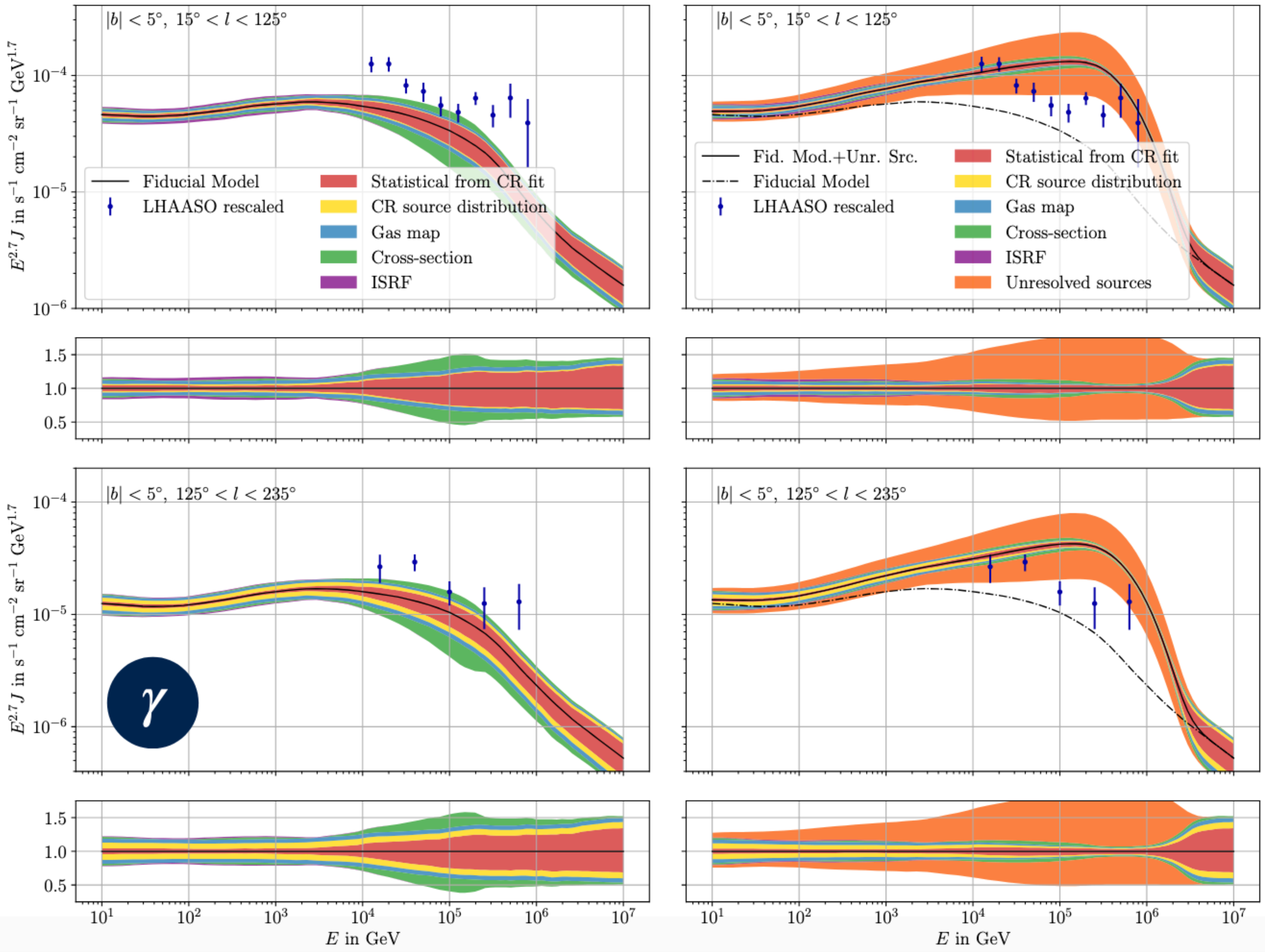


UNRESOLVED SOURCES INCLUDED IN MM FITS



[Schwefer, Mertsch & Wiebusch '23; see also Shao, Lin & Yang'23]

MM FIT INCLUDING LHAASO DIFFUSE EMISSION DATA



[Schwefer, Mertsch & Wiebusch '23]

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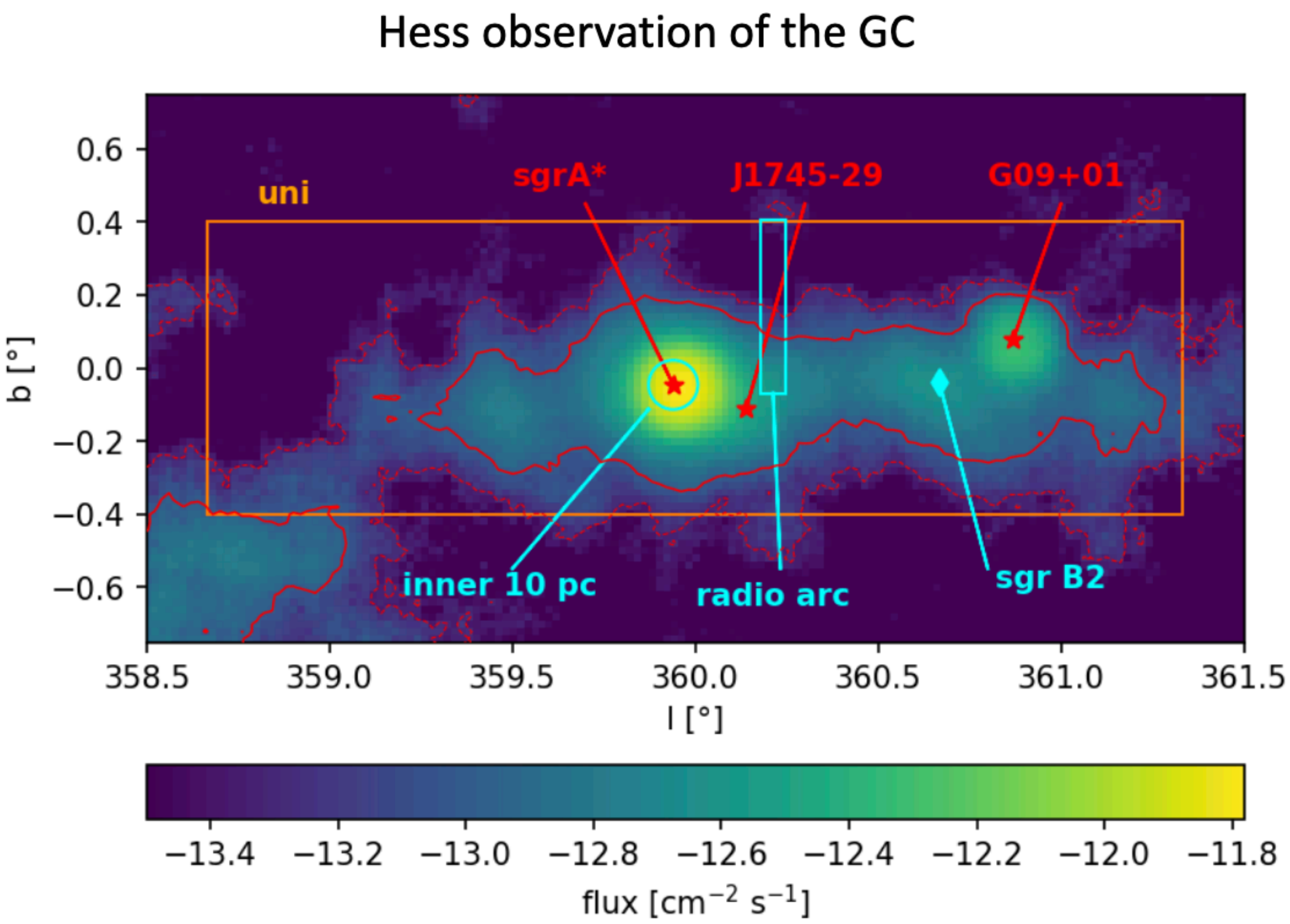
NEW TOOLS FOR MM ANALYSIS

CRPROPA: MM MODELING FOR CR ACCELERATION AND TRANSPORT

L. Merten's talk

- New tools: open source code
- Building blocks
  - CR acceleration (how to get to the knee energies). Several models in CRPropa (stochastic acceleration, diffusive shock acceleration, magnetic reconnection)
  - how to describe the transport of particles (moving away from simplistic diffusion models): Source distribution is relevant for early times but isotropic diffusion is more relevant in longer timescales
  - cosmic ray interaction with ambient photons and matter: pp interaction are under development in CRPropa to get estimate of gamma-ray flux and neutrino flux expected in the galaxy.

Gamma Rays from the Galactic center

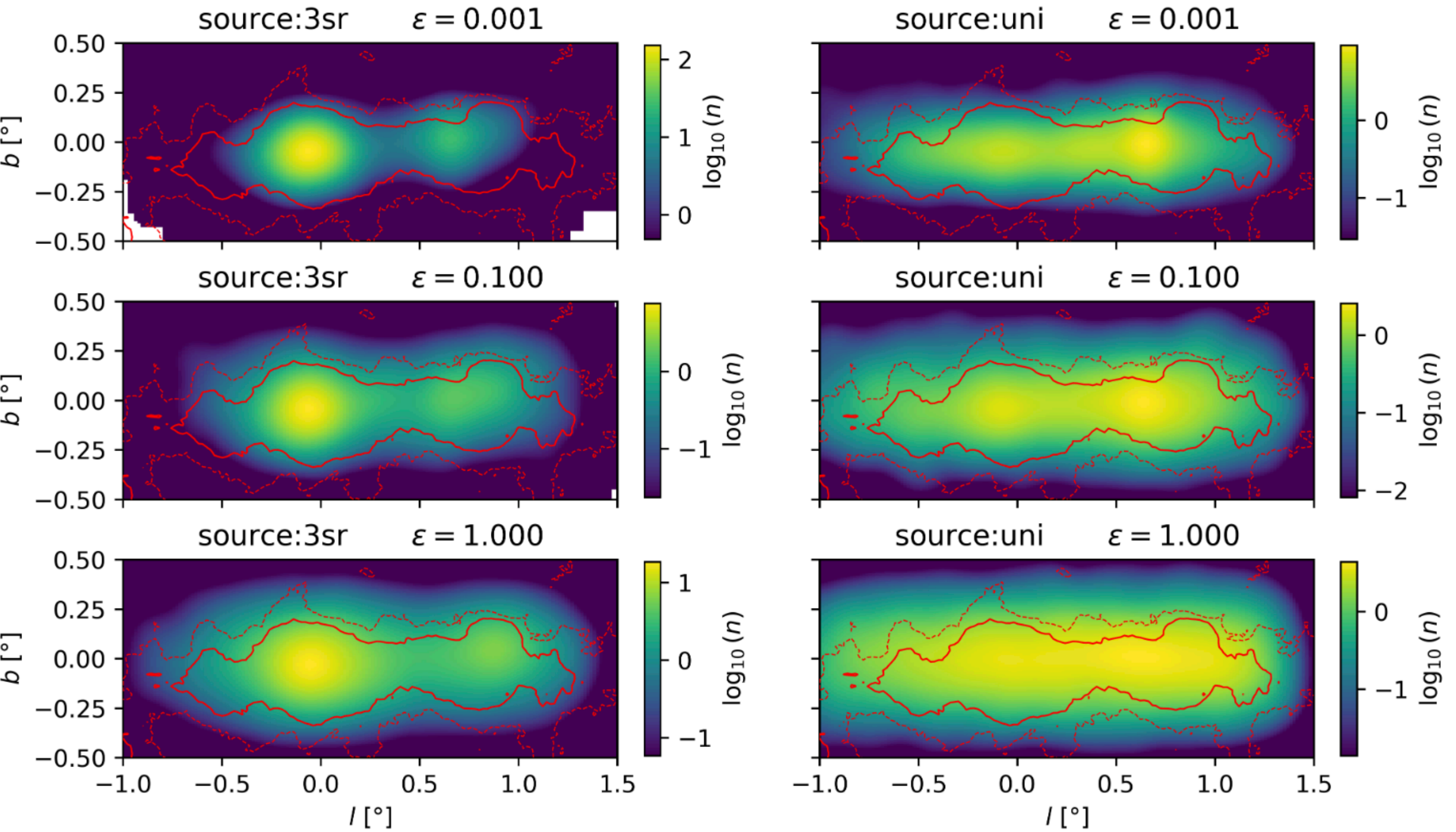


Very high energy gamma-rays observed from the Galactic center

Modeling with CRPropa
- 3D magnetic field structure
- 3D approximation of the target gas densities

Questions
- Influence of the transport model?
- Relevance of source distribution?
- What is the neutrino contribution?

Gamma Rays from the Galactic center



Reduced perpendicular diffusion leads to strong confinement.

Uniform source too strongly confined in Sgr B2.

Best agreement to data for point source + isotropic diffusion

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PANELS

NOTES FROM PANEL DISCUSSION - CURRENT STATUS OF MM ASTROPHYSICS

- The field is lacking of community efforts to plan the future accordingly. Other fields move together to advance knowledge. MM is more for proposal writing than actual common efforts. Messengers move in parallel but not together. We need to do a better job.
- Data sharing is important. Priority should be given to combine data.
- Most exiting things happening in the last years: neutrino flux from the galaxy particularly high, GW, Novae as gamma-ray sources, precision measurement of spectral features in the knee regions, PeV gamma-ray sources.
- We need better measurements to constrain the amount of antimatter component in CR: GAPS in near future
- Exiting future facilities: CTA, SWGO (wide FoV, complementary to IACTs and cross-checks between techniques), IceCube Upgrade to study GeV nu sources (Novae), IceCube-Gen2 at the highest energies for neutrinos. Coverage and redundancy in measurements are key to solve the puzzle.

NOTES FROM PANEL DISCUSSION - FUTURE OF MM ASTROPHYSICS

- WB bound motivated the need of a km3-scale detector to discover the neutrino flux. No surprise of detecting neutrinos.
- However, models were too optimistic: lack of communication with astronomy community
- Before building experiments we ned to ask ourselves what are the questions that we want to answer, what are the models we want to test and how to falsify them.
- How will discrepancies between different experiments be resolved? -> discussions are starting to happen in between collaborations
- We need to build better detectors: direct evidence from experiments at the highest energies drive advancement in the field. Especially, we need better neutrino detectors
- A lot of new experiments in gamma-ray and neutrinos. Not many in direct CR detection. Eextending direct measurements to highest energies should be discussed in US or Europe (only HERD in China).
- Also MeV gamma rays do not have a future mission at the moment.

NOTES FROM PANEL DISCUSSION - FUTURE OF MM ASTROPHYSICS

Q: Is there a measurement you can do to rule out that SNR are the sources of CR? How many neutrinos do we need to discover the sources of CR? How many events? How do we confirm the PeVatrons?
These are answers that should be answered.
A: The goals is not a handful of neutrinos. We need good statistic to do spectral studies. So, better sensitivity and better detector.
Q: Did you do the math to quantify the detector dimension you need for that? Is 10km3 enough? Probably not.
A: The answer is easy: we can translate the gamma-rays we see in the galaxy to neutrinos (assuming the sources are hadronic). That's the optimistic flux.

- There is a need of a focused definition of what are the big questions we need to answer and how we want to answer them: which experiments answer what questions (in principle this should be Astro2020).
- However we need a united front (more organic approach in particle physics that speak with one voice). We haven't convinced people that we can do that efficiently and that we talk to each other.

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take home message

- Beautiful and sometimes surprising observations from the Galaxy (neutrinos, PeVatrons)
- New intriguing features appearing in CR spectrum in the knee region.
- We need to build better detectors but not blindly!
- Community should move together to understand what are the most important questions we would like to answer in the next decade. (good attempt is in Astro2020)

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MM is a powerful “tool” but also a difficult (social) exercise requiring people from different community working together.

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THANK YOU AND SEE YOU AT THE NEXT SuGAR