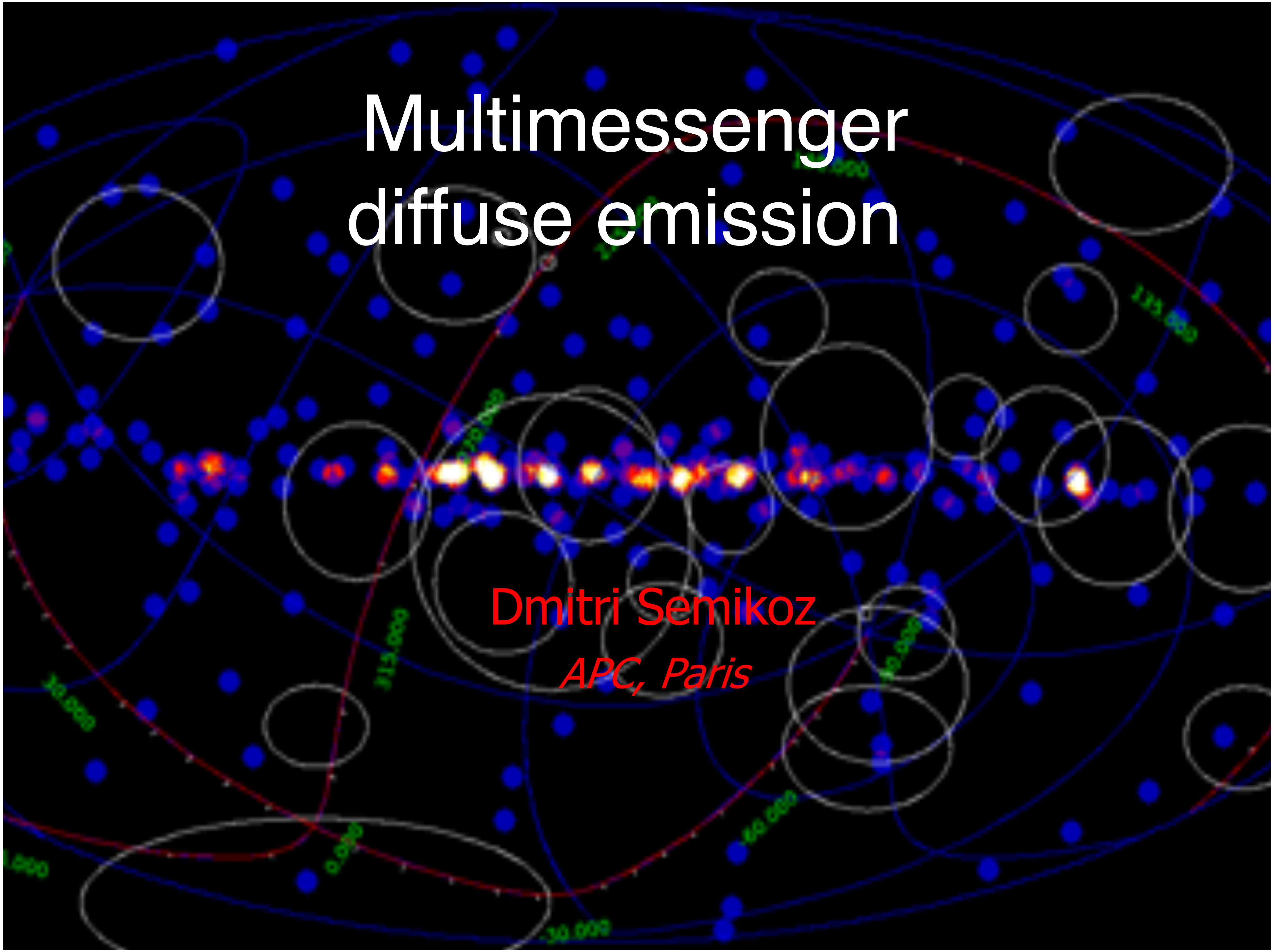
Multimessenger diffuse emission

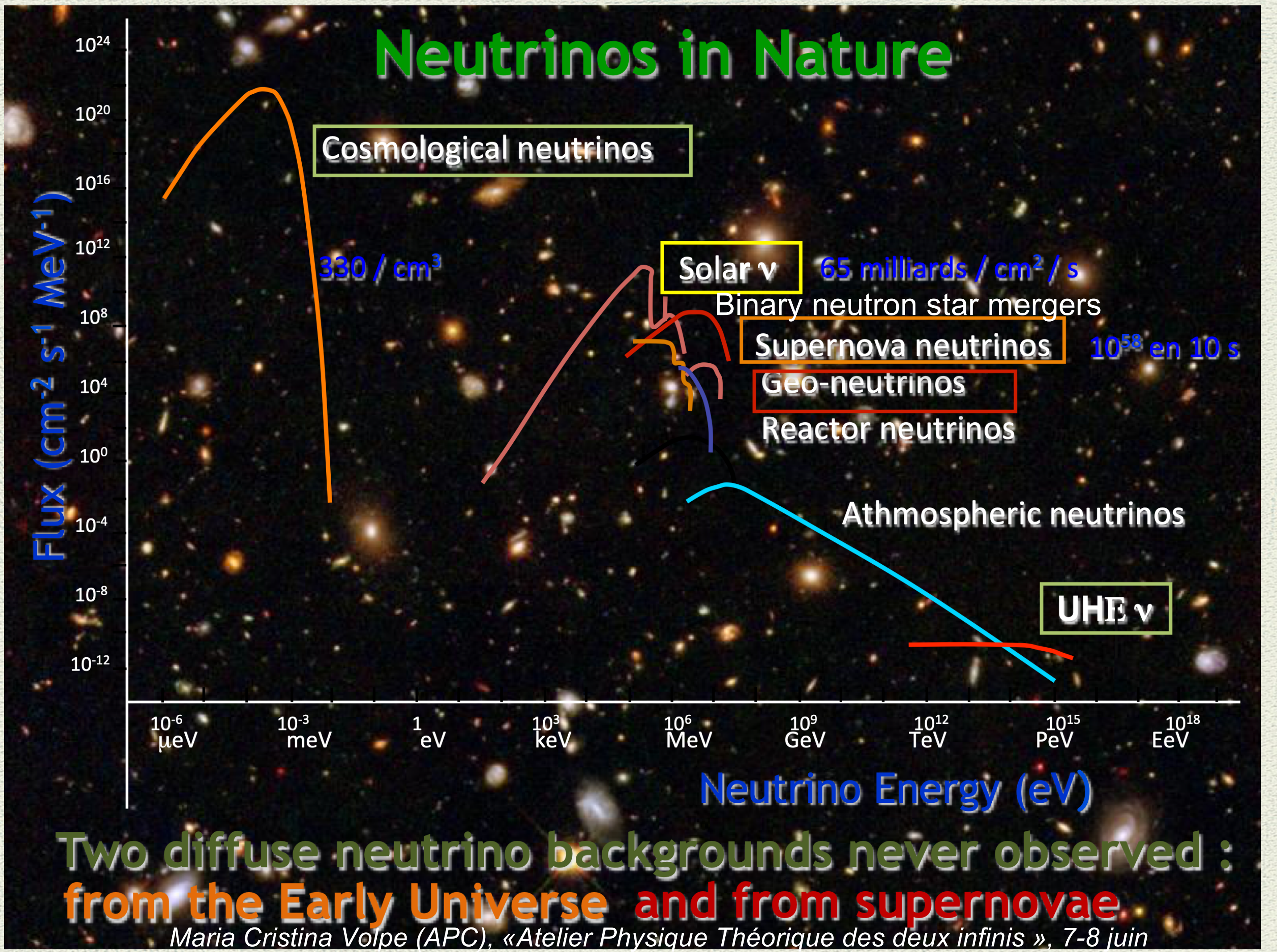


Dmitri Semikoz

APC, Paris

Plan

- Neutrinos from SN explosions and binary NS (C.Volpe)
- High energy neutrinos and gamma-rays in Galaxy
- New measurements of Tibet and expectations for LHAASO
- New cosmic ray, gamma-ray and neutrino model
- Conclusions



Neutrinos in Nature

Two diffuse neutrino backgrounds never observed :
from the Early Universe and from supernovae

Maria Cristina Volpe (APC), «Atelier Physique Théorique des deux infinis », 7-8 juin

Neutrinos from dense astrophysical environments

Core-collapse supernovae

Supernovae : massive stars with M > 8 M_{sun}
They undergo gravitational collapse at the end of their life.

Supernovae emit the gravitational binding energy 10^{53} ergs in 10 s, as neutrinos and antineutrinos of all flavors

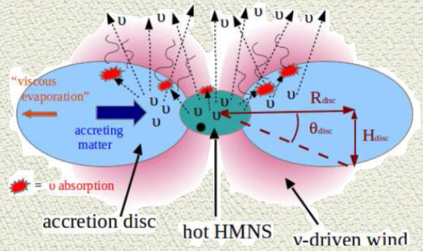
SN1987A- LMC

- On the 23rd of February 1987, Sk-69° 202 exploded in the Large Magellanic Cloud at 50 kpc
- 25 events observed, in KII, IMB, BST
  Hirata et al, 1987, Bionta et al, 1988, Alekseev et al, 1988
- Prompt explosion model discarded. Colgate and White, 1966
  Delayed shock model favored. Bethe and Wilson, 1985
  Loredo and Lamb, 2002
- Currenty multi-dimensional supernova simulations available, with convection, turbulence, realistic neutrino transport and nuclear networks.
  Bruenn et al, 2020, Janka 2017, ...

Wealth of information on non-standard neutrino properties, particles or interactions and on astrophysics

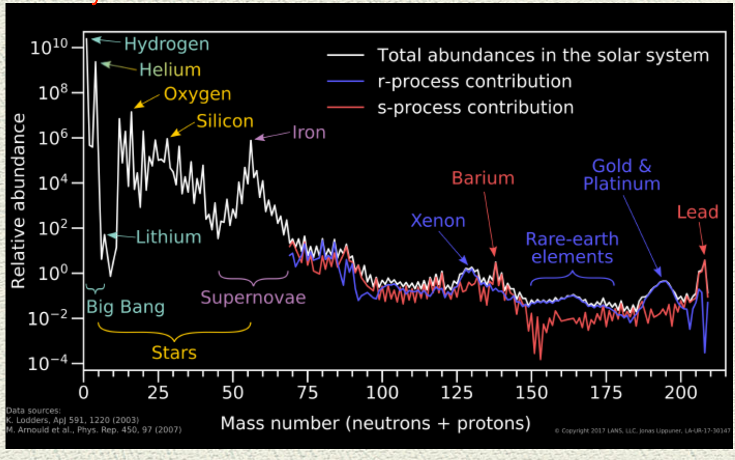
Neutrinos from dense astrophysical environments

Binary neutron star (BNS) mergers remnants



Perego et al, 2014

CCSNe and BNS are candidate sites for r-process nucleosynthesis.



- **GW170817 :** First measurement of gravitational waves from a binary neutron star merger, in coincidence with a short gamma ray burst and a kilonova.

Abbot et al, 2017

- **Electromagnetic emission** powered by the decay of radioactive elements, with lanthanide free ejecta (blue component of the signal) and ejecta with lanthanides (red component).

Indirect evidence for r-process elements in BNS.

Vilar et al, 2017; Tanaka et al, 2017; Aprahamian et al, 2018; Nedora et al, 2021, ...

Neutrino properties and flavor mechanisms impact r-process nucleosynthesis

Maria Cristina Volpe (APC), «Atelier Physique Théorique des deux infinis », 7-8 juin

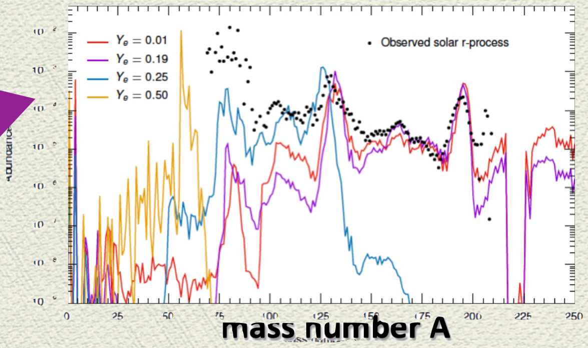
Neutrino from dense environments :
From theory to observations

For the future measurements

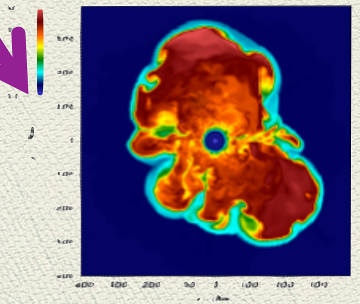
- the discovery of the diffuse supernova neutrino background **- Super-K + Gd**
- an (extra)galactic supernova - 10^{4-6} events **-SNEWS, Hyper-K, JUNO**

Understanding
the role of neutrinos
and of flavor conversion
in dense environments
important

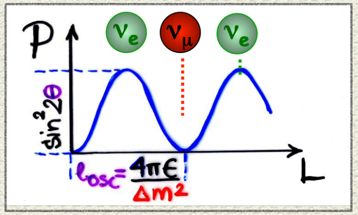
The site(s) for the r-process ?



Supernova explosion mechanism ?



Mueller et al, 1705.00620



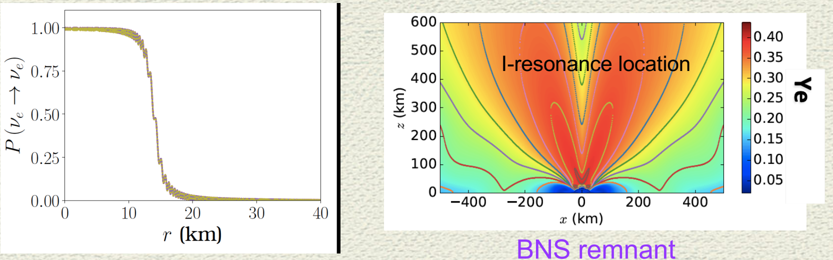
more complex than vacuum oscillations…

Maria Cristina Volpe (APC), «Atelier Physique Théorique des deux infinis », 7-8 juin

Theoretical and phenomenological aspects of neutrino (astro)physics

- In astrophysical and cosmological environments, neutrinos modifies their flavor due to coupling to
  - matter
  - shock waves and turbulence
  - neutrino self-interactions
  - non-standard neutrino properties (e.g. sterile neutrinos, neutrino magnetic moments, …) or interactions.

I-resonance due to non-standard interactions



BNS remnant

Chatelain, Volpe, PRD98 (2018)

- Evolution equations (mean-field, extended mean-field, quantum kinetic equations) can be derived using different approaches and the connections uncovered between a weakly interacting gas of neutrinos and antineutrinos propagating in a dense environment and other many-body systems in nuclear physics and condensed matter, using e. g. the BBGKY hierarchy.

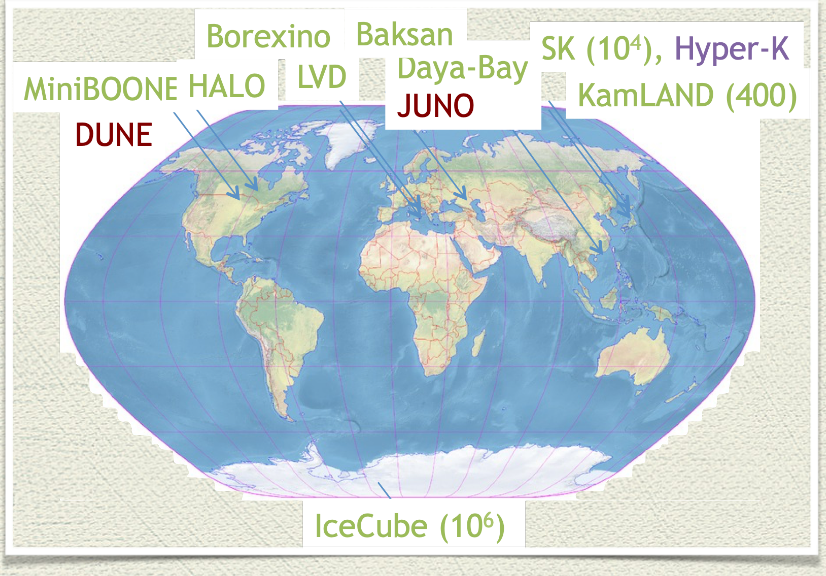
Volpe, Väänänen, Espinoza, PRD87, 2013; Väänänen, Volpe, PRD88, 2013

- Neutrino properties and flavor evolution impacts r-process nucleosynthesis, future observations of neutrinos from a(n) (extra)galactic supernova and the diffuse supernova neutrino background, and potentially also the supernova dynamics (explosion mechanism not yet understood).

Maria Cristina Volpe (APC), «Atelier Physique Théorique des deux infinis », 7-8 juin

Waiting for the next (extra)galactic supernova

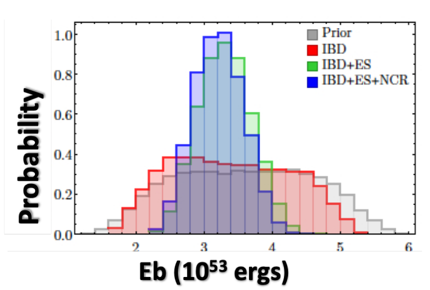
- Expected events for a supernova in our galaxy (10 kpc) up to 10^6



- Detection channels : scattering on protons, electrons, nuclei. Sentivity to all flavors, time and energy signal will be measured.

Scholberg, «the Supernova Early Warning System (SNEW), 1999; SNEWS 2.0, 2021

- A likelihood analysis of the events in a galactic supernova shows the gravitational binding energy can be reconstructed with 11% accuracy in Super-K, 3% accuracy in Hyper-K



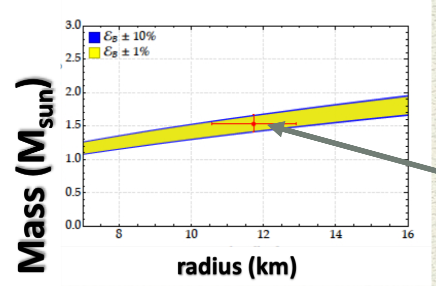
Gallo Rosso, Vissani, Volpe, JCAP11, 2017; JCAP 04, 2018

Fit to EOS for NS

$$\frac{\mathcal{E}_B}{Mc^2} \approx \frac{(0.60 \pm 0.05)\,\beta}{1 - \beta/2}, \qquad \beta = \frac{GM}{Rc^2},$$

Lattimer, Prakash

compactness



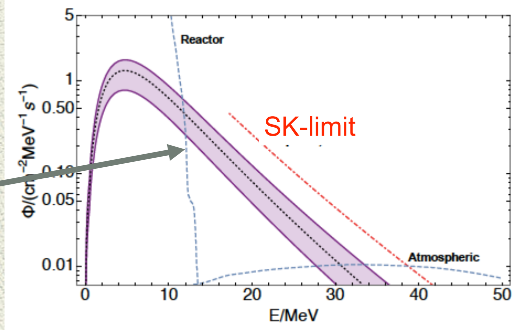
A star like SN1987A

Crucial information on non-standard neutrino properties, particles, interactions, on explosion dynamics, star location and properties

Maria Cristina Volpe (APC), «Atelier Physique Théorique des deux infinis », 7-8 juin

The upcoming discovery of the diffuse supernova neutrino background

theoretical band
includes uncertainty
on supernova rate
and failed supernovae



Priya and Lunardini JCAP 2017

- The DSNB is sensitive to :

  > <u>the fraction of failed supernovae</u>,

  > <u>non-standard neutrino properties</u> (e.g. decay)

  > flavor conversion phenomena - MSW, shock waves and self-interaction effects.

Galais, Kneller, Gava, Volpe, PRD 2010

- The DSNB neutrino flux depends on the core-collapse supernova rate (related to the star formation rate), the supernova neutrino fluxes integrated over redshift

$$F_\alpha(E_\nu) = \int dz \left| \frac{dt}{dz} \right| (1+z) R_{\rm SN}(z) \frac{dN_\alpha(E'_\nu)}{dE'_\nu},$$

$$E'_\nu = (1+z)E_\nu,$$

redshifted neutrino energy
mostly sensitive to z = 0,1,2

- **Predictions close to the current SK limit.**
  Tens (SK+Gd) to hundreds (Hyper-K) events expected (10 years).

SK+Gd experiment started (August 2020), JUNO under construction, Hyper-K approved (2020)

Conclusions and perspectives

- Neutrino flavor evolution in dense environments is still an open problem.

  Last two decades have brought key steps forward, showing the richness of this complex domain, uncovered a variety of flavor conversion mechanisms, the last being fast modes.

Flavor conversion impacts r-process nucleosynthetic abundances and supernova neutrinos fluxes, important for observations.

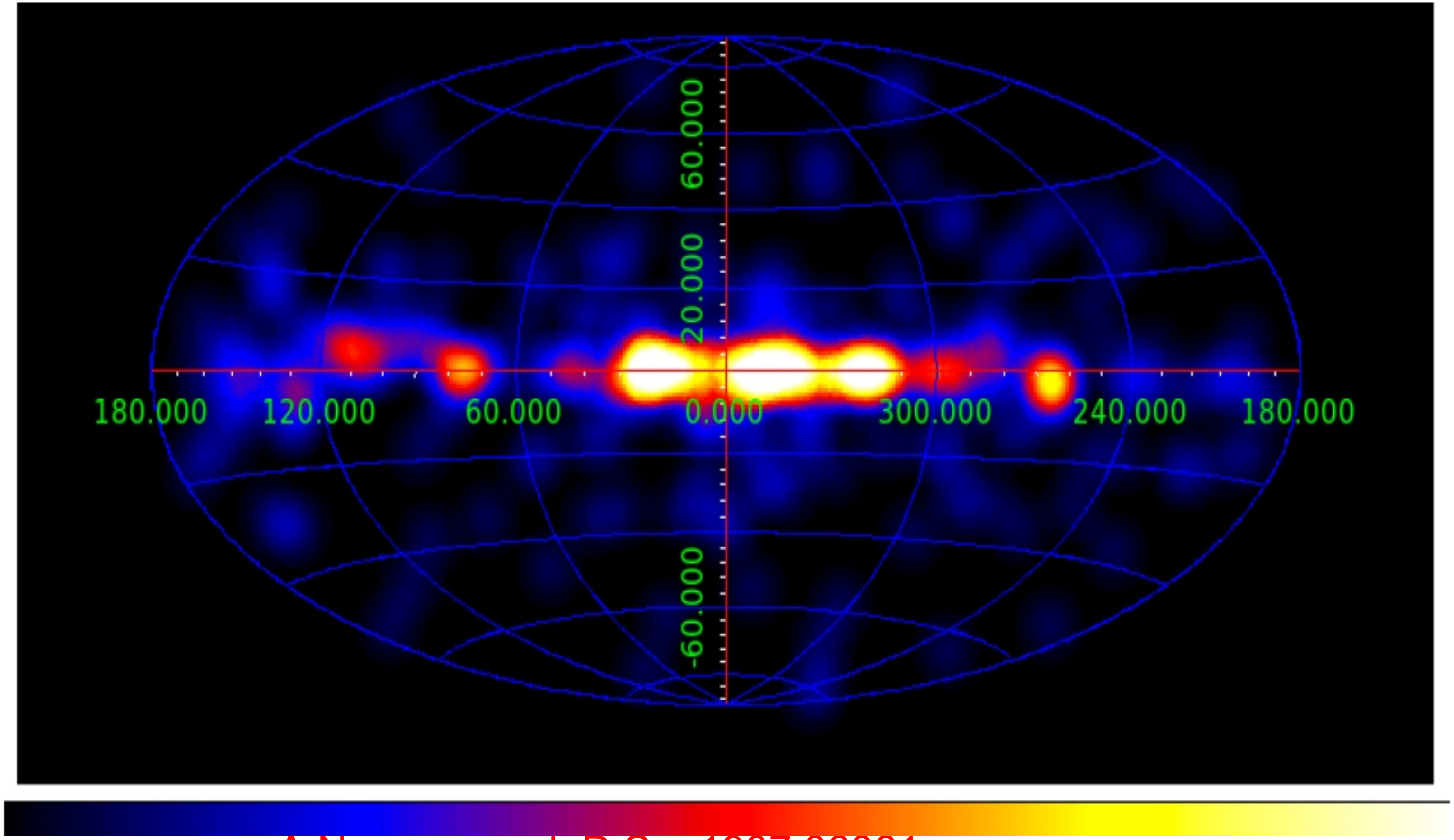
- Numerous open questions need to be fully addressed, including the interplay between flavor and collisions, the impact of fast modes, the role of decoherence and of strong gravitational fields, the final impact on observations.

- Waiting for the next supernova and for the discovery of the diffuse supernova neutrino background which will bring key information on core-collapse supernova rate, on the fraction of failed supernovae, on non-standard neutrino properties and on flavor evolution.

Gamma-ray and neutrino sky above 1 TeV

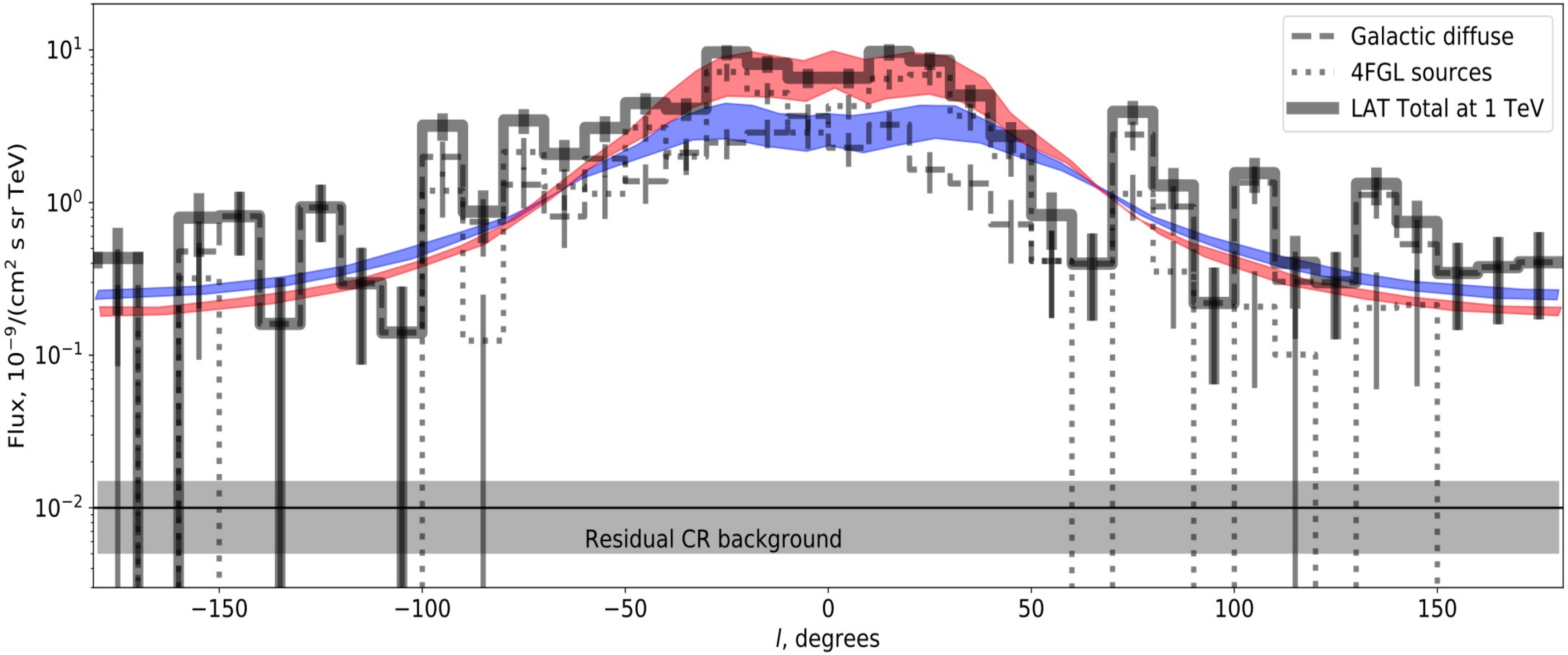
Sky map E> 1TeV

10 years Fermi



A.Neronov and D.S. , 1907.06061

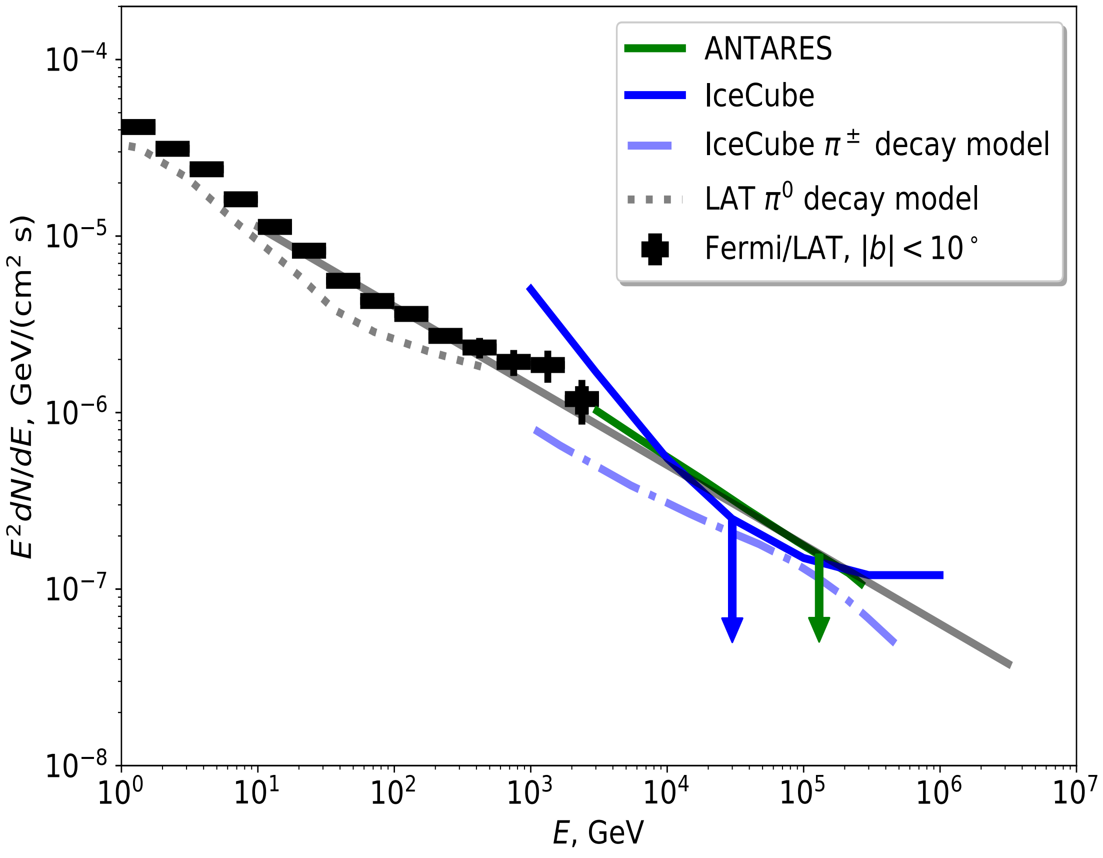
Galactic Plane |b|<2 deg, 1 TeV



Red and blue lines: model predictions from Cataldo et al , 1904.03894

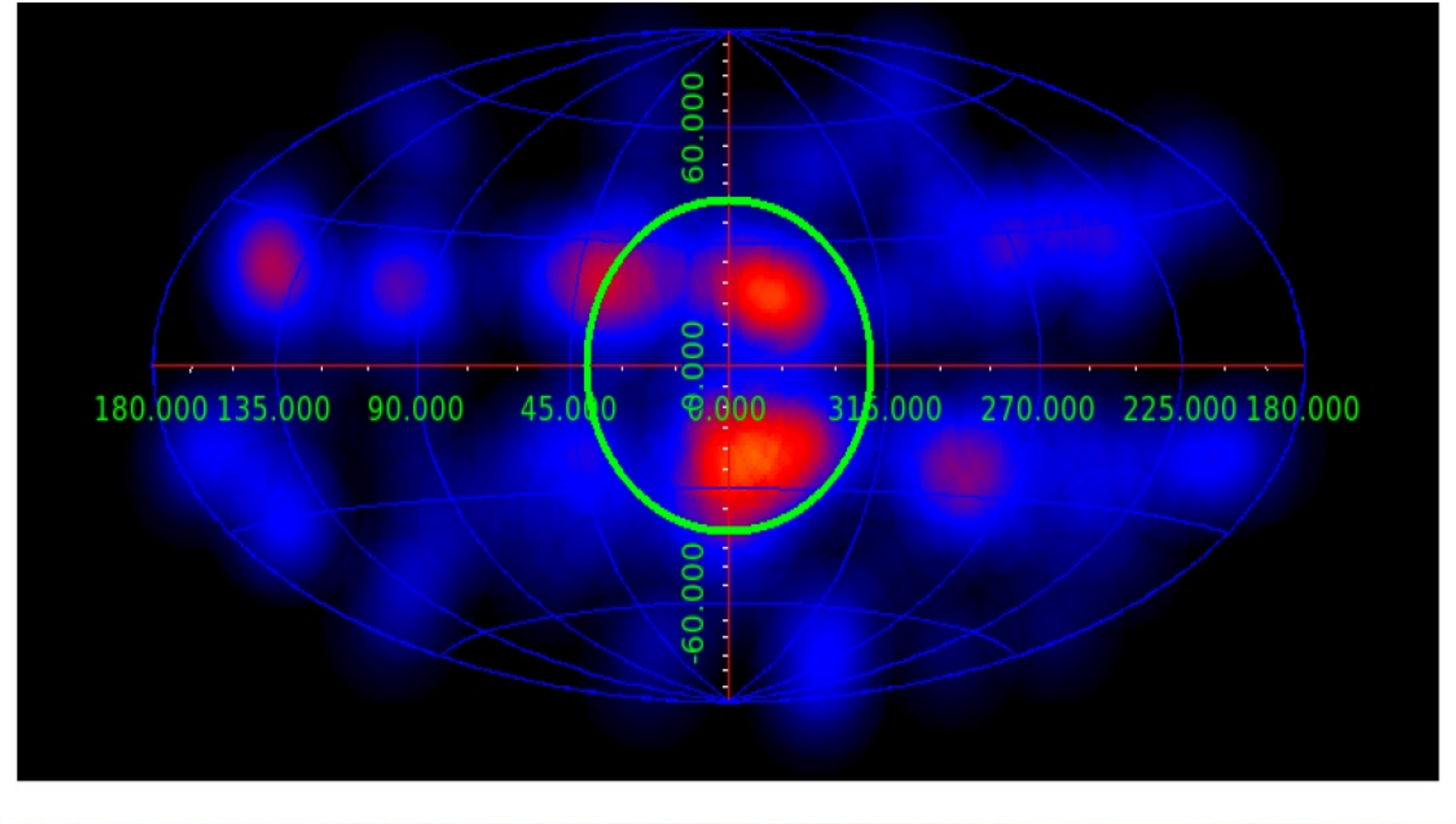
A.Neronov and D.S. , 1907.06061

IceCube + Fermi LAT Galactic plane



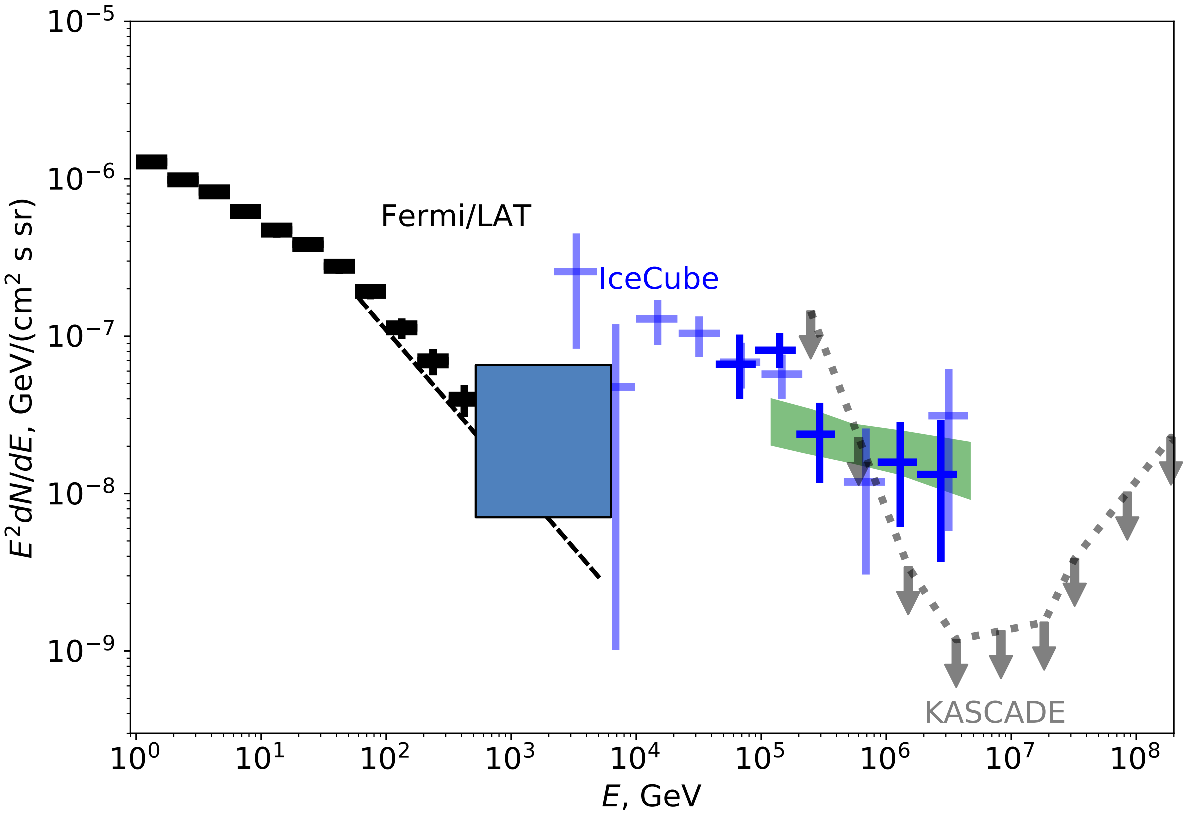
A.Neronov, M.Kachelriess and D.S. , arXiv:1802.09983

Sky map E> 1TeV
no galactic plane |b|> 10 deg



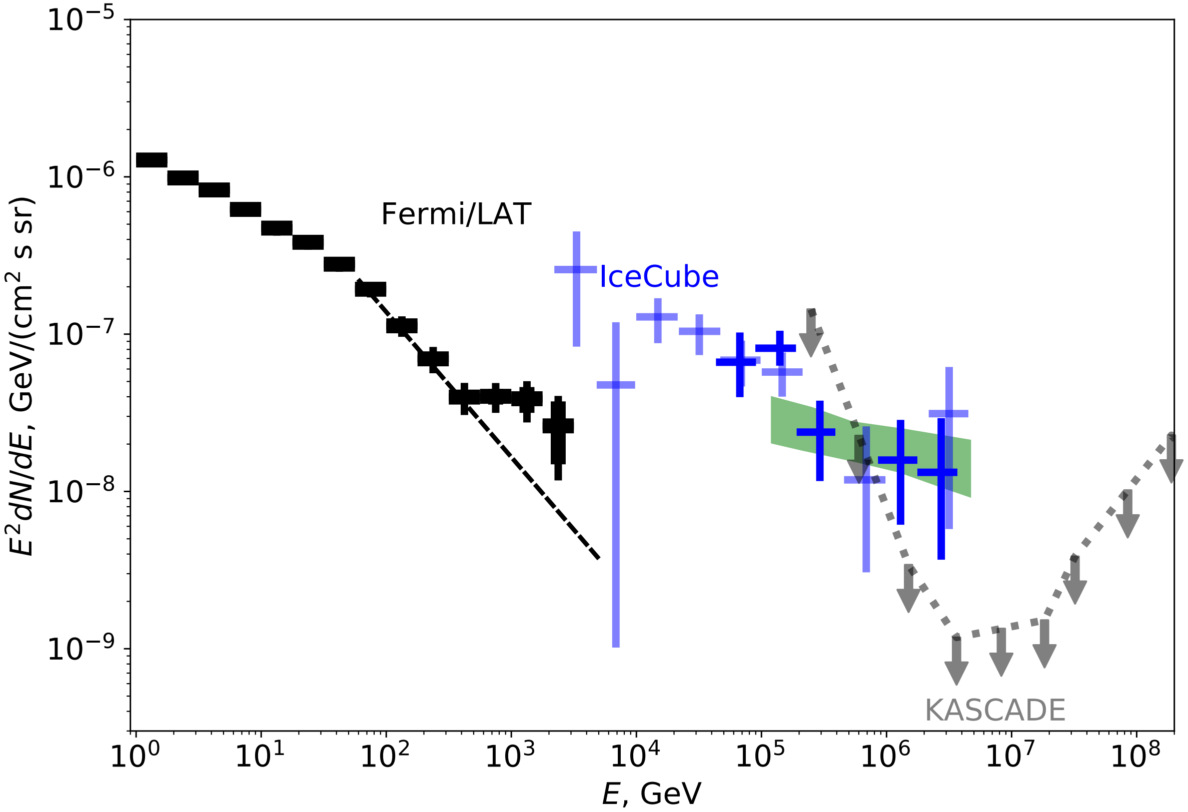
A.Neronov and D.S. , 1907.06061

IceCube + Fermi LAT high galactic latitude |b|>20 deg



A.Neronov, M.Kachelriess and D.S. , arXiv:1802.09983

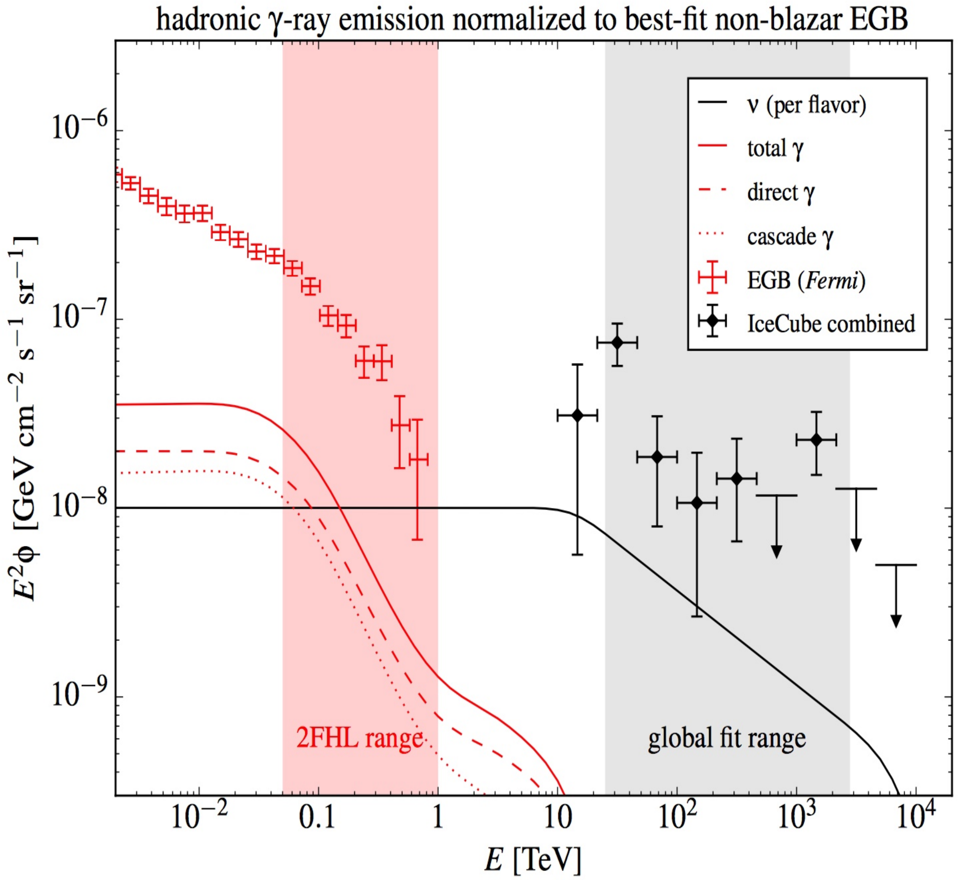
IceCube + Fermi LAT high galactic latitude |b|>20 deg



A.Neronov, M.Kachelriess and D.S. , arXiv:1802.09983

A.Neronov and D.S. , 1907.06061

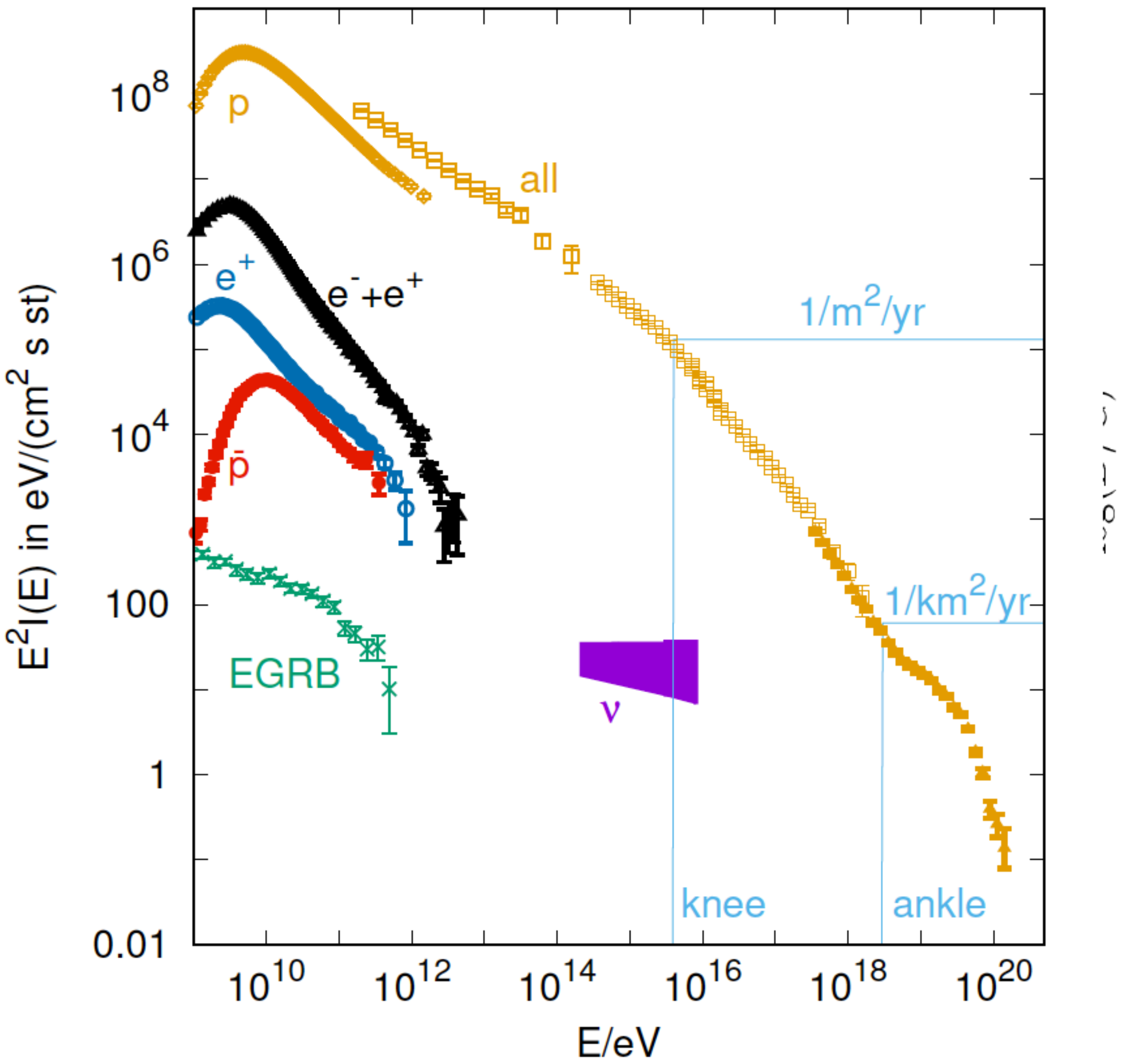
Self-consistent extragalactic sources: if not Fermi blazars



[Bechtol, MA, Ajello, Di Mauro & Vandenbroucke'15]

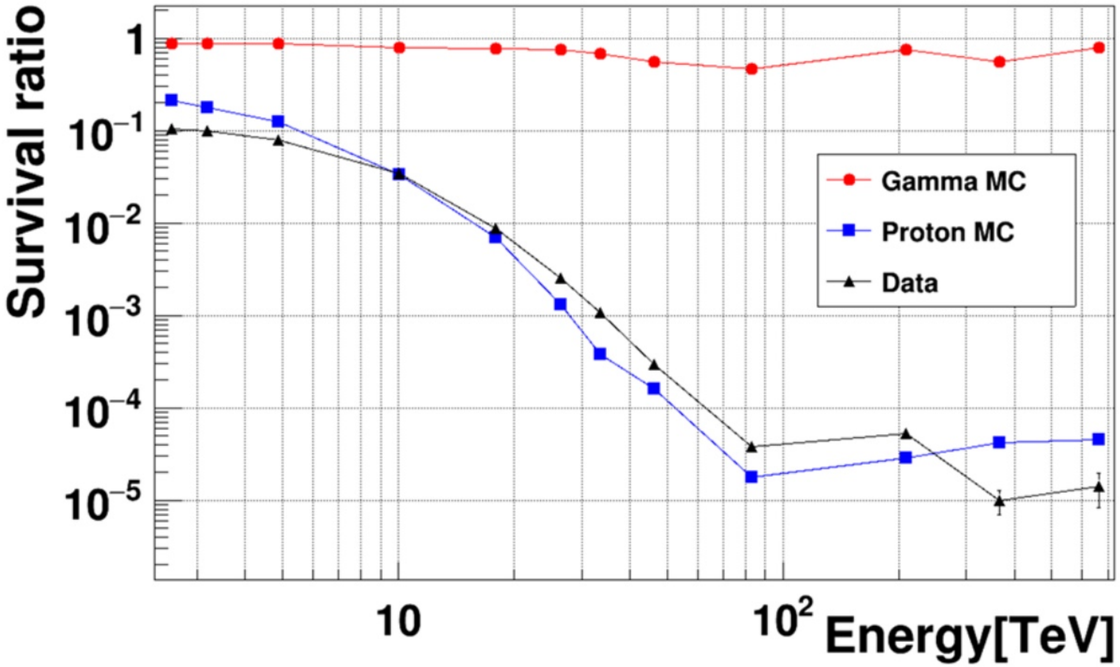
Gamma-ray sky at 10-100 TeV with HAWC and LHAASO

Cosmic rays/ neutrino and gamma



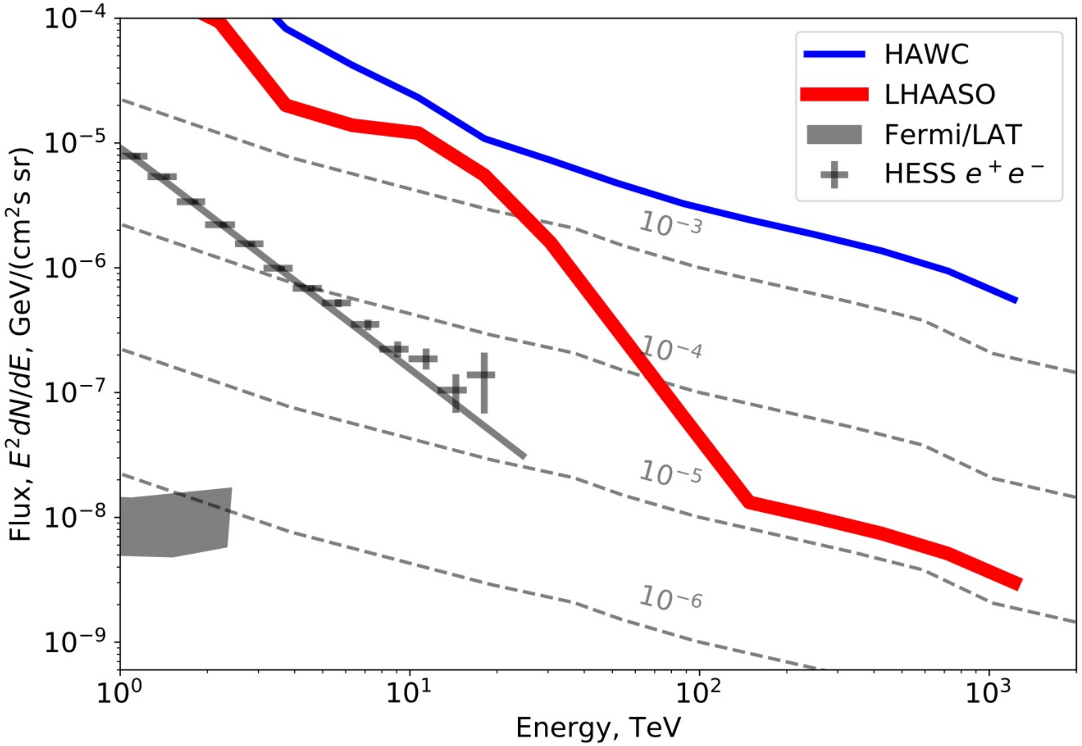
γ/P discrimination of ¼ KM2A

Background rejection >10^4@100 TeV



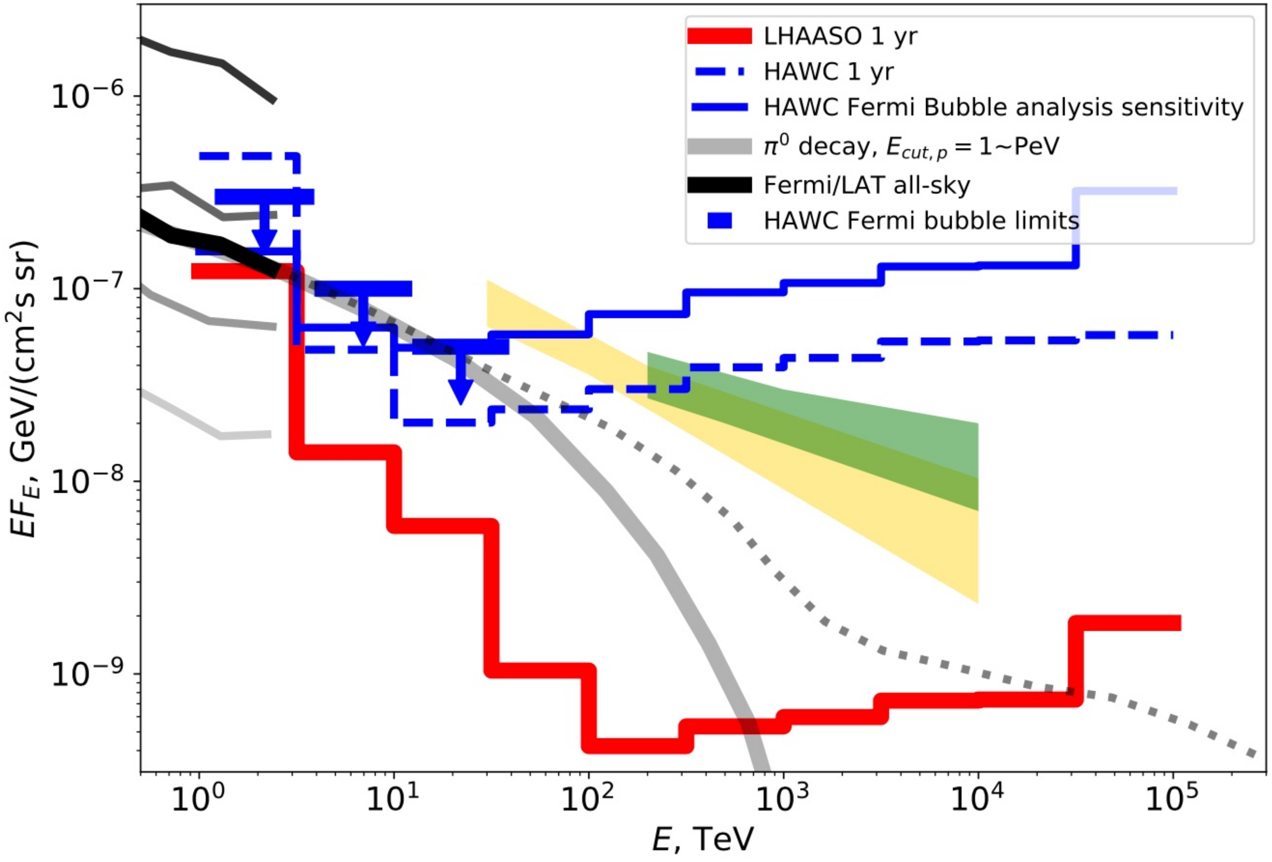
LHAASO meeting Jan 2020

HAWC and LHAASO hadron cut



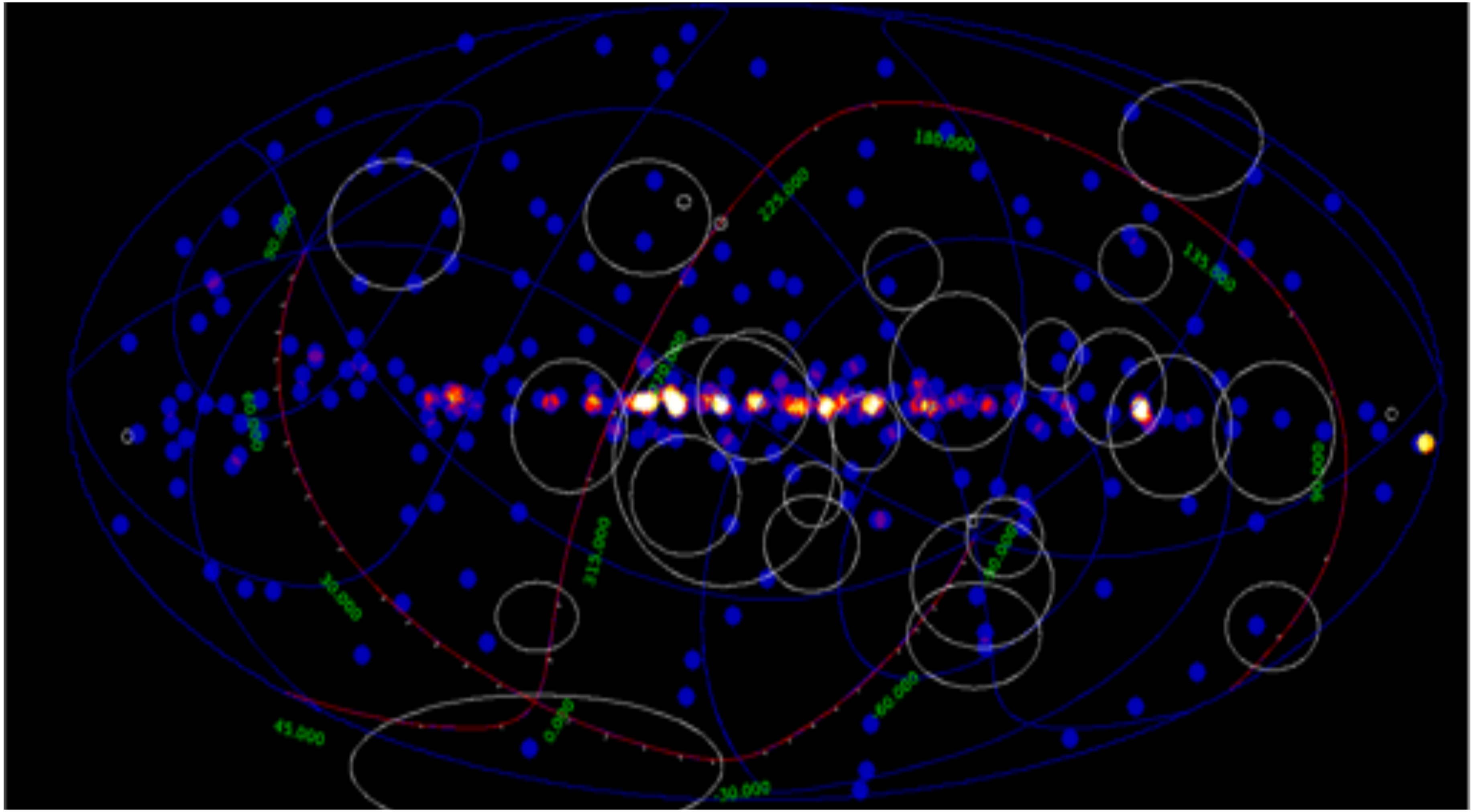
A.Neronov and D.S. , astro-ph/2001.11881

HAWC and LHAASO sensitivity to diffuse gamma



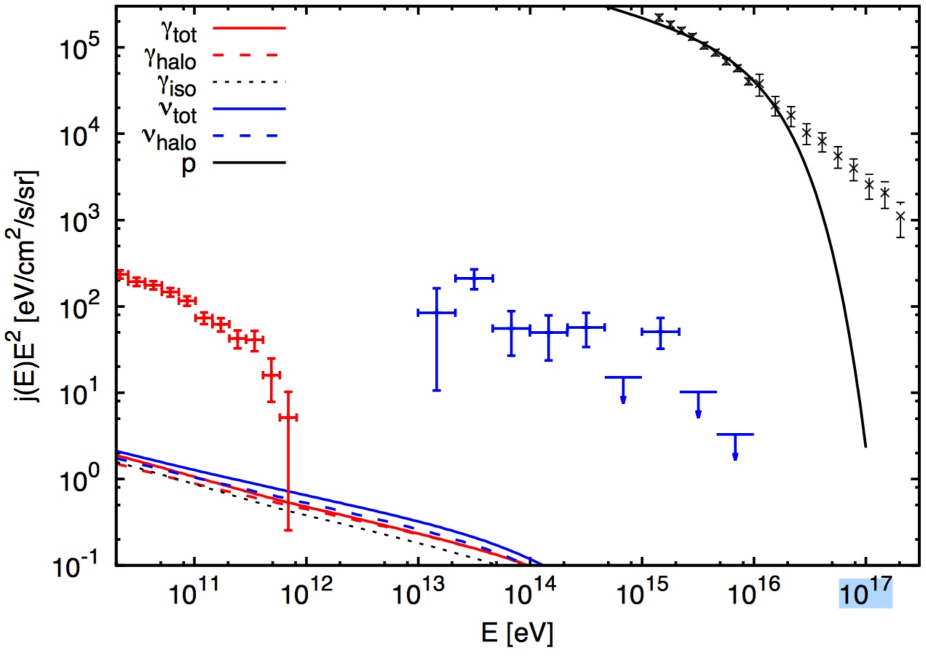
A.Neronov and D.S. , astro-ph/2001.11881

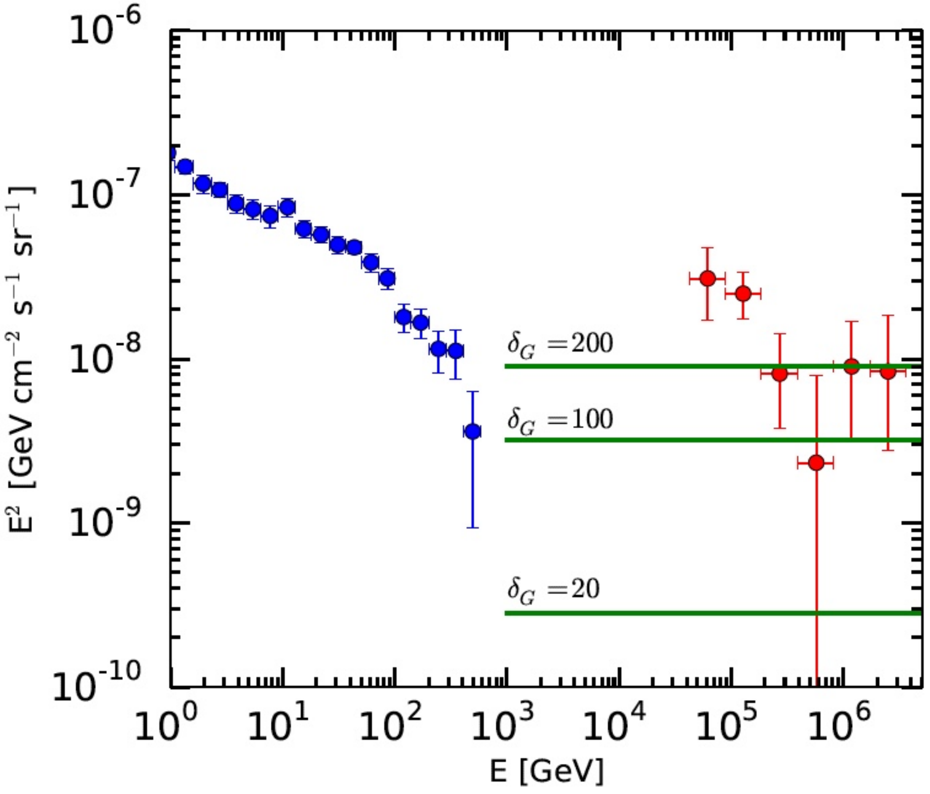
Neutrino and gamma



Neutrinos from Galactic Halo CR

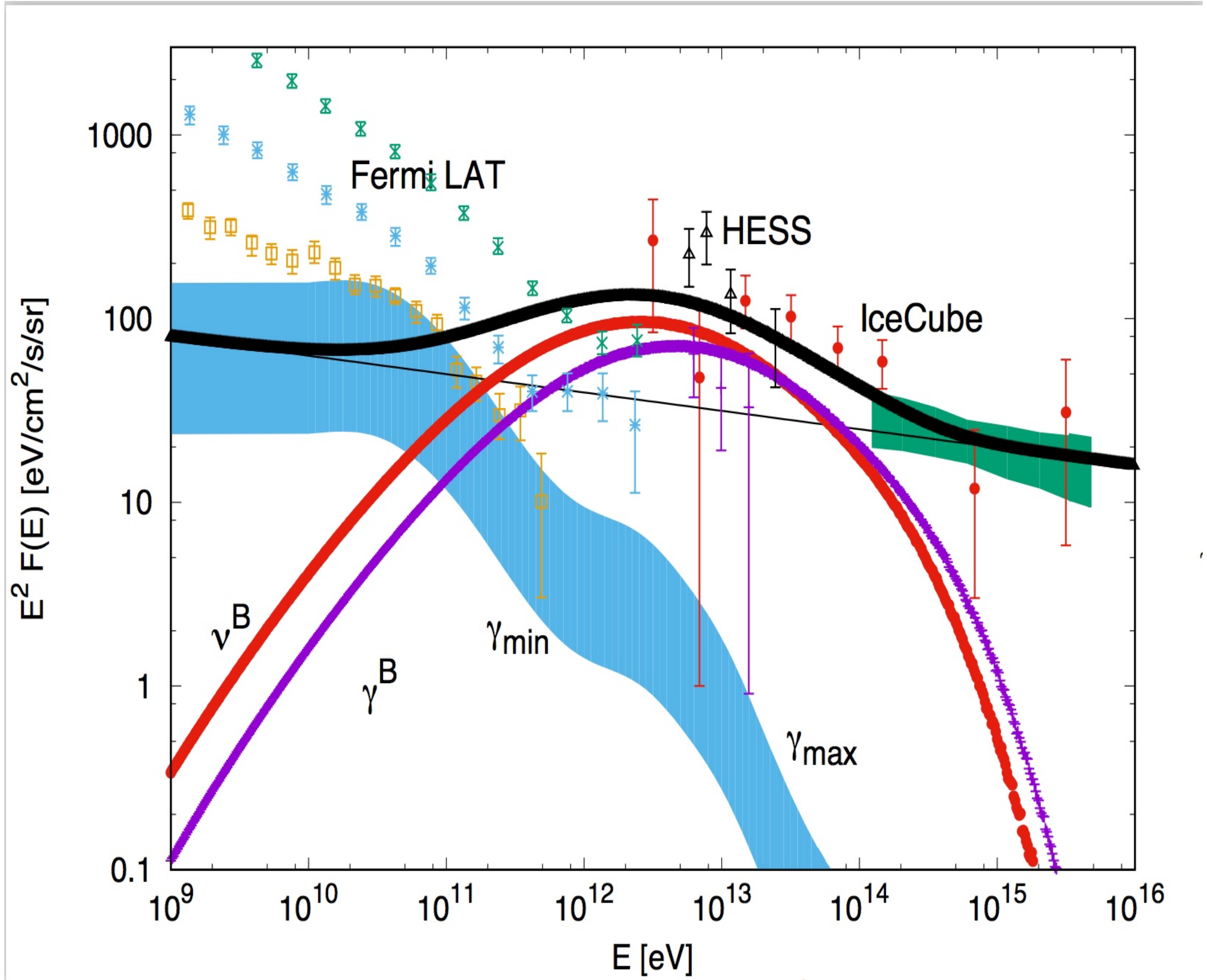
Talk of A.Taylor





A.Taylor, S.Gabici and F.Aharonian, 1403.3206
S.Troitsky and O.Kalashev 1608.07421
P.Blasi and E.Amato , 1901. 03609

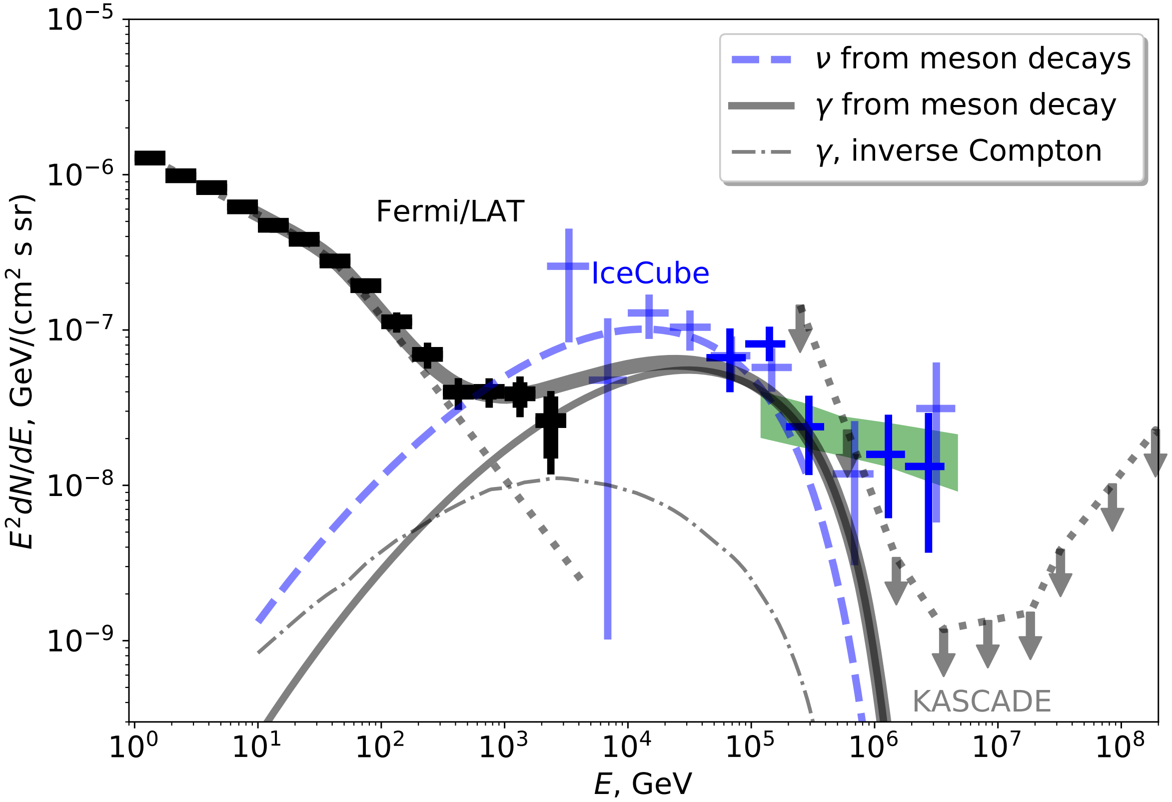
IceCube + Fermi LAT+HESS : local source+Local superbubble



A.Neronov, M.Kachelriess and D.S. , arXiv:1802.09983

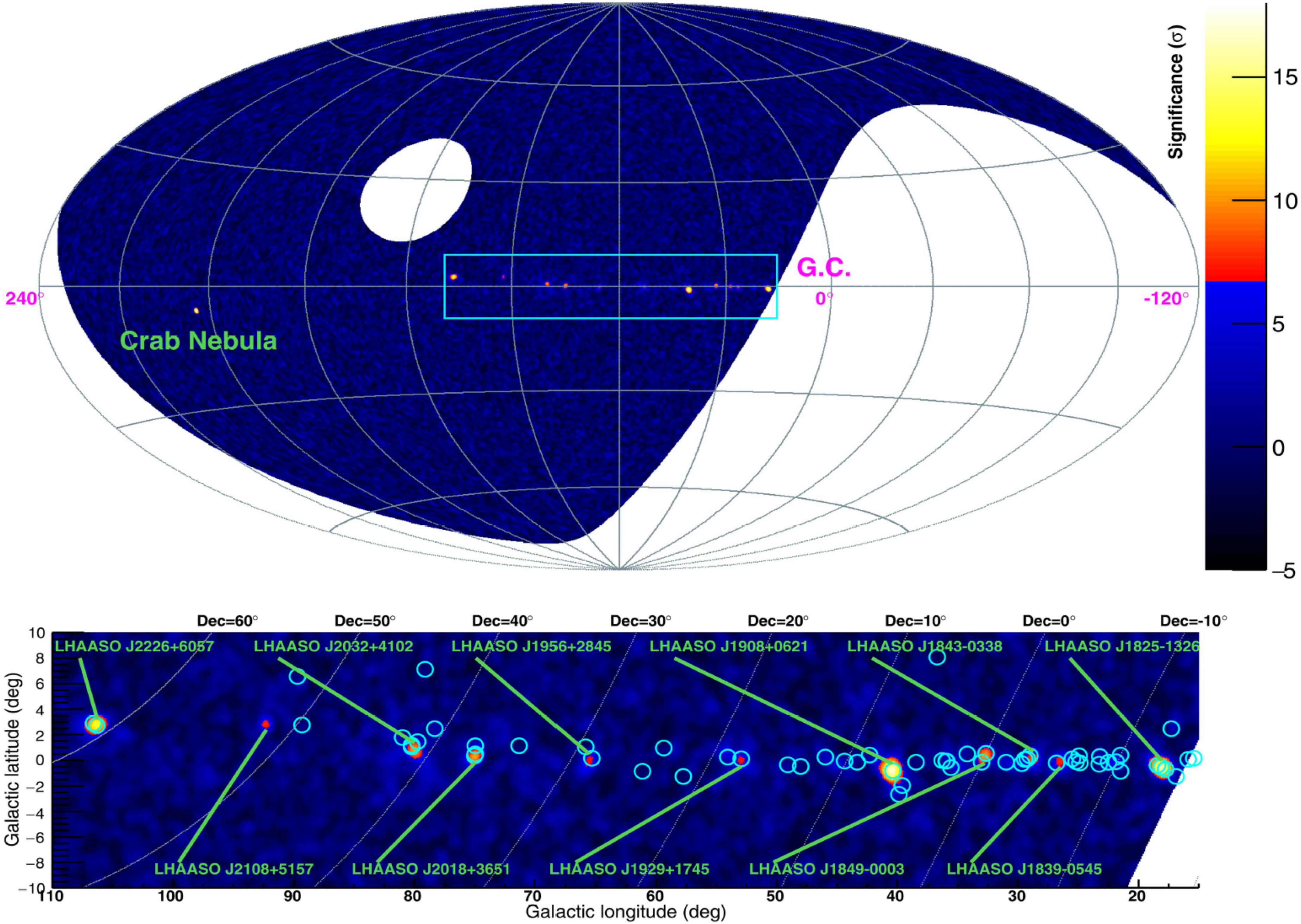
M.Bouyahiaoui, M.Kachelriess and D.S. , arXiv:2001.00768

IceCube + Fermi LAT
Dark Matter m=5 PeV



A.Neronov, M.Kachelriess and D.S. , arXiv:1802.09983

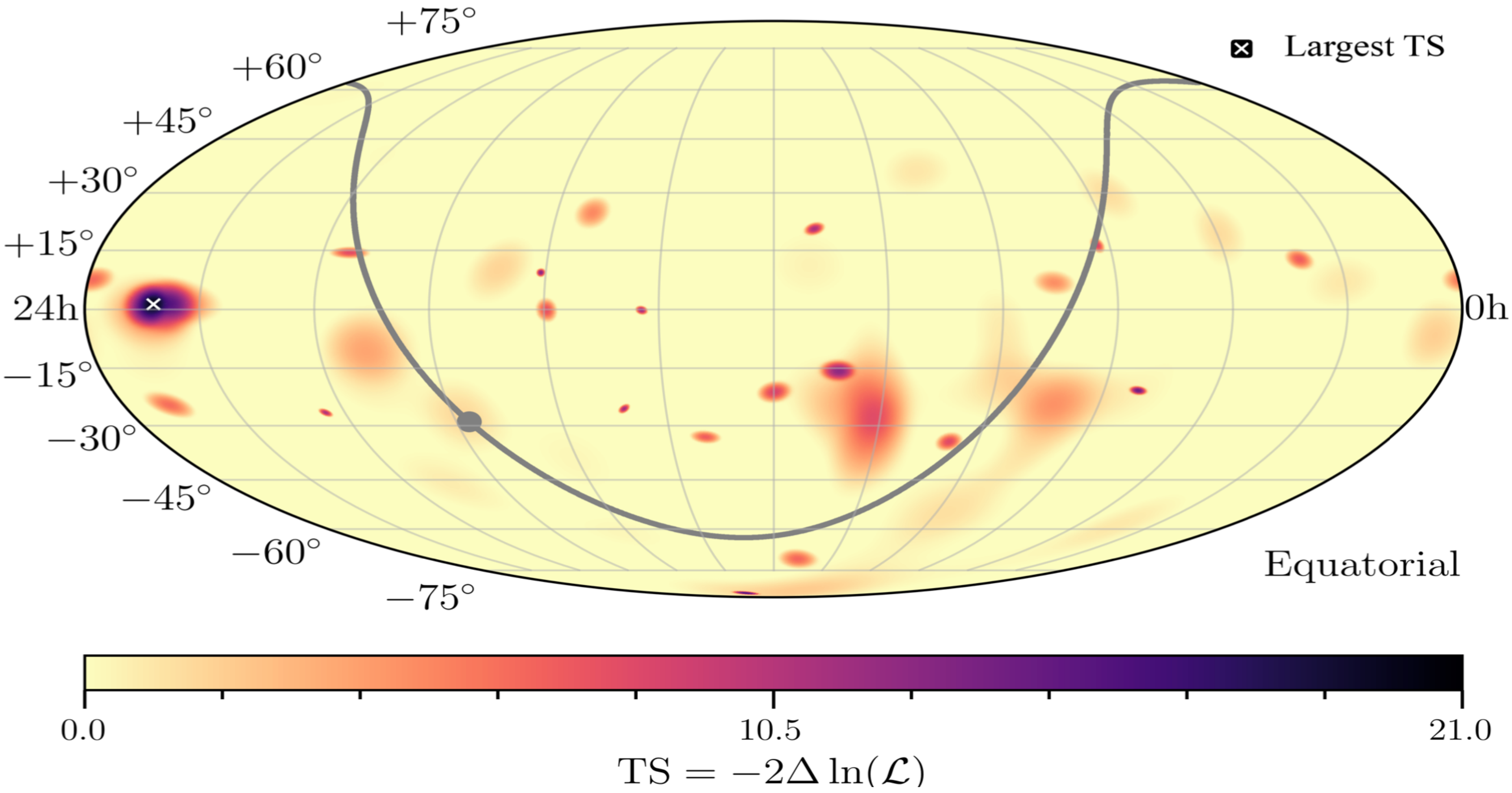
LHAASO Sky @ >100 TeV



Extended Data Fig. 4 | LHAASO sky map at energies above 100 TeV. The circles indicate the positions of known very-high-energy γ-ray sources.

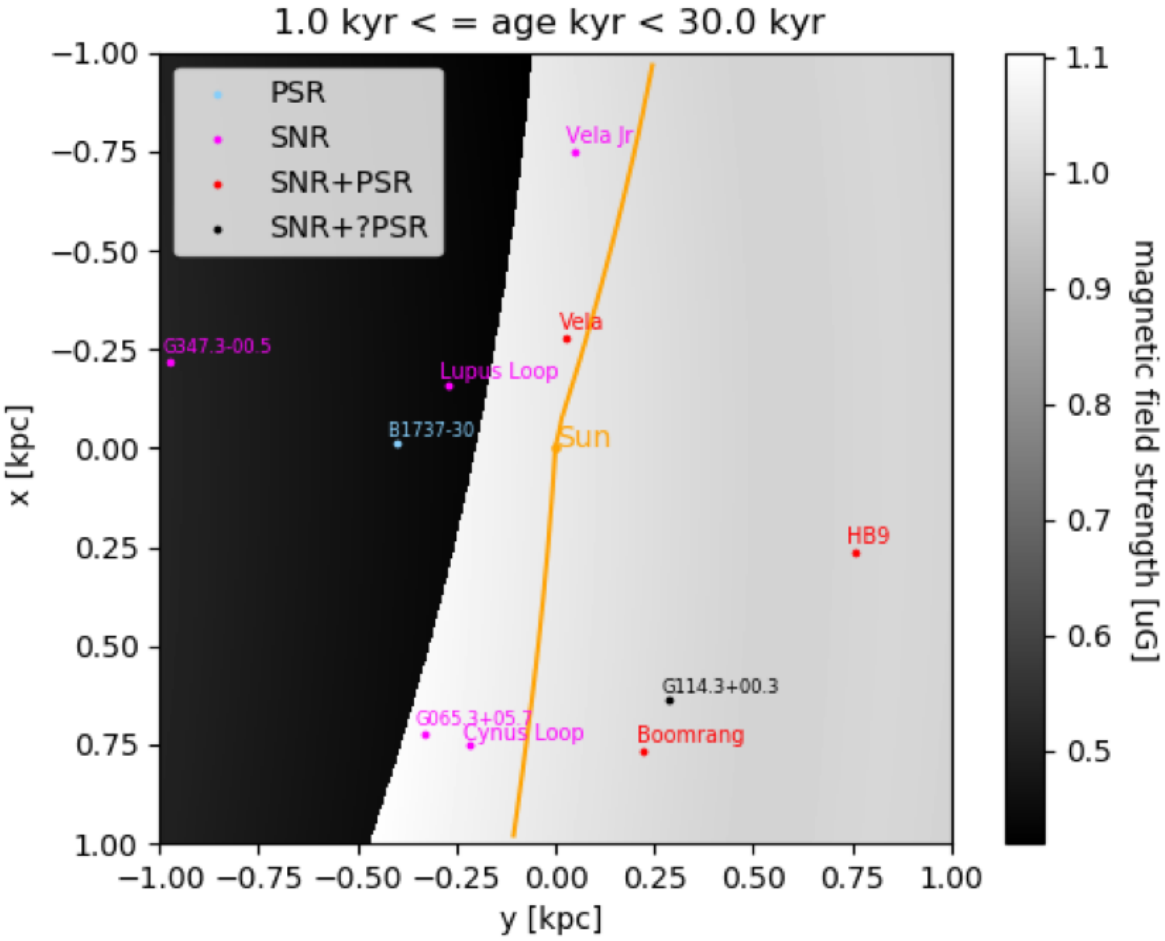
Nature, May 17 2021

Sky map HESE 7.5 years



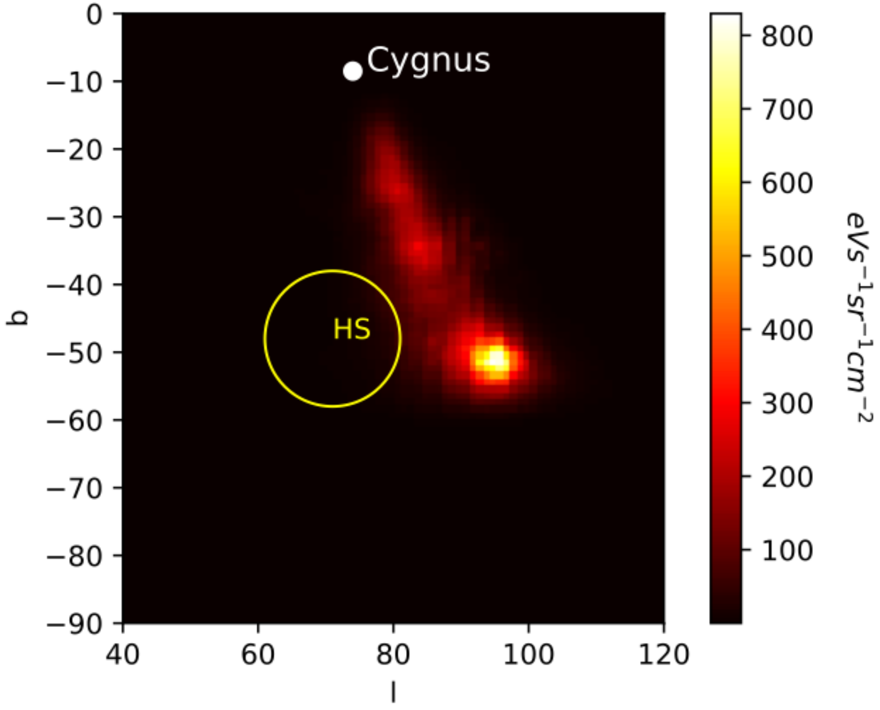
IceCube, astro-ph/2011.03545

Nearby young SN



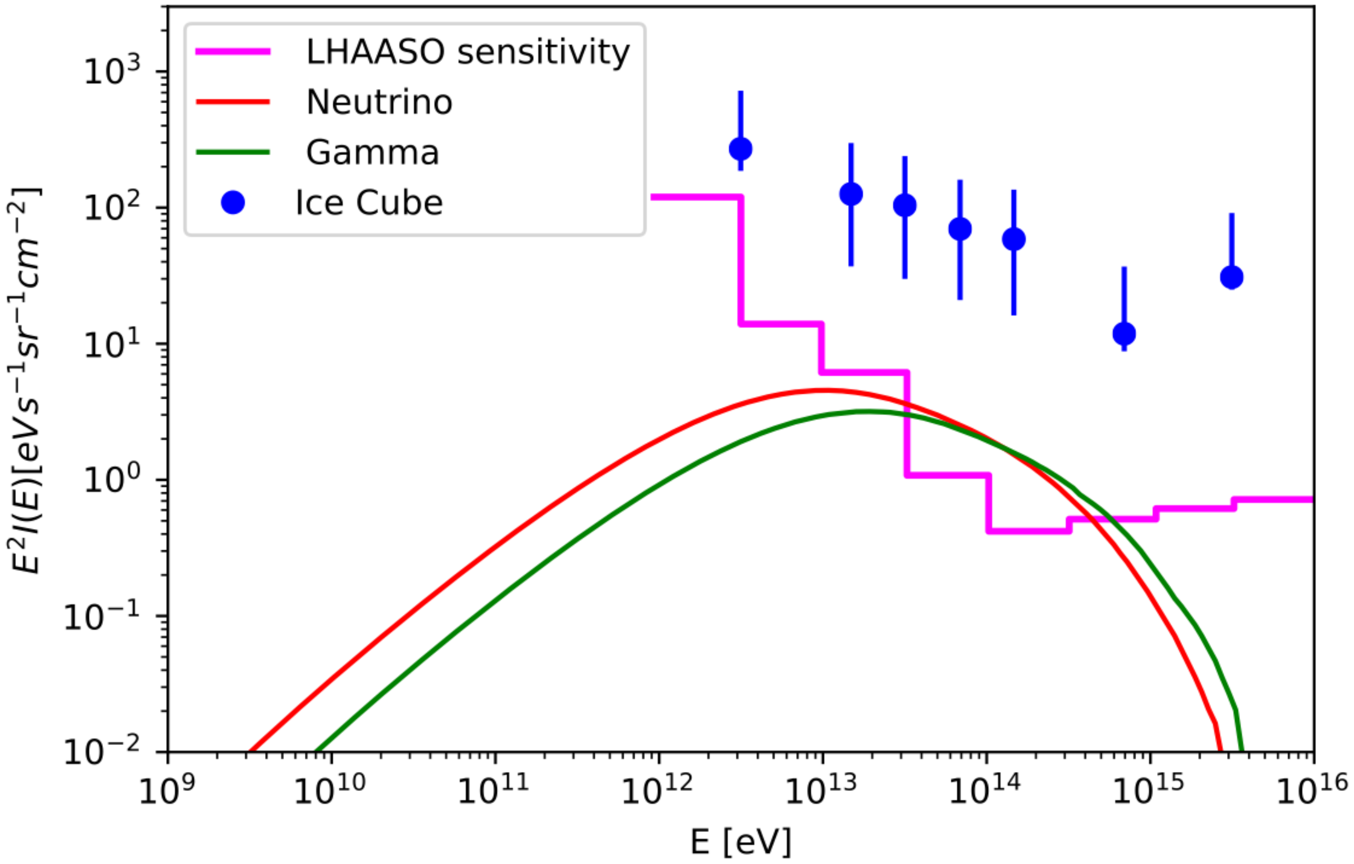
M. Bouyahiaoui, M. Kachelriess, and. D.S. , astro-ph/2001.00768

Cygnus loop neutrinos



M. Bouyahiaoui, M. Kachelriess, and. D.S. , astro-ph/2105.13378

Cygnus loop neutrinos

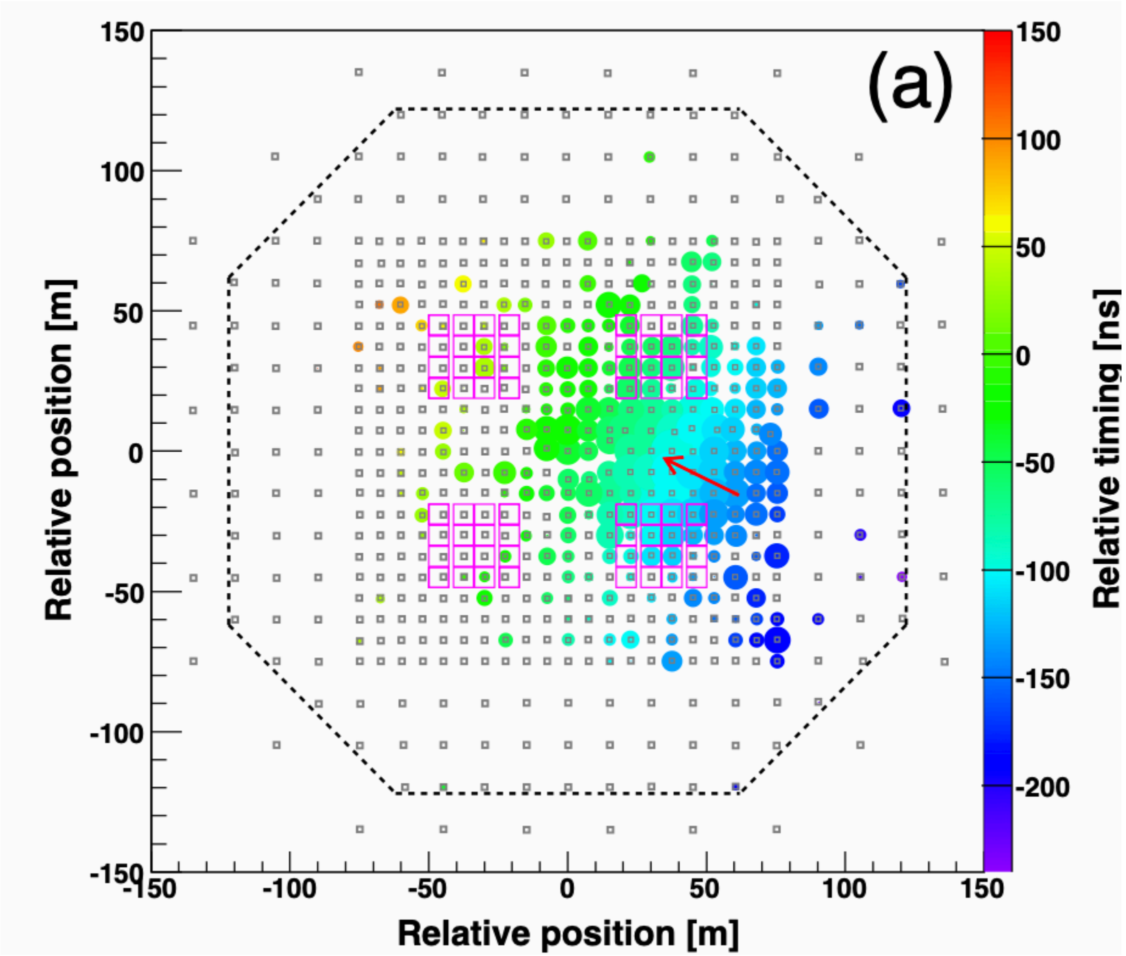


M. Bouyahiaoui, M. Kachelriess, and. D.S. , astro-ph/2105.13378

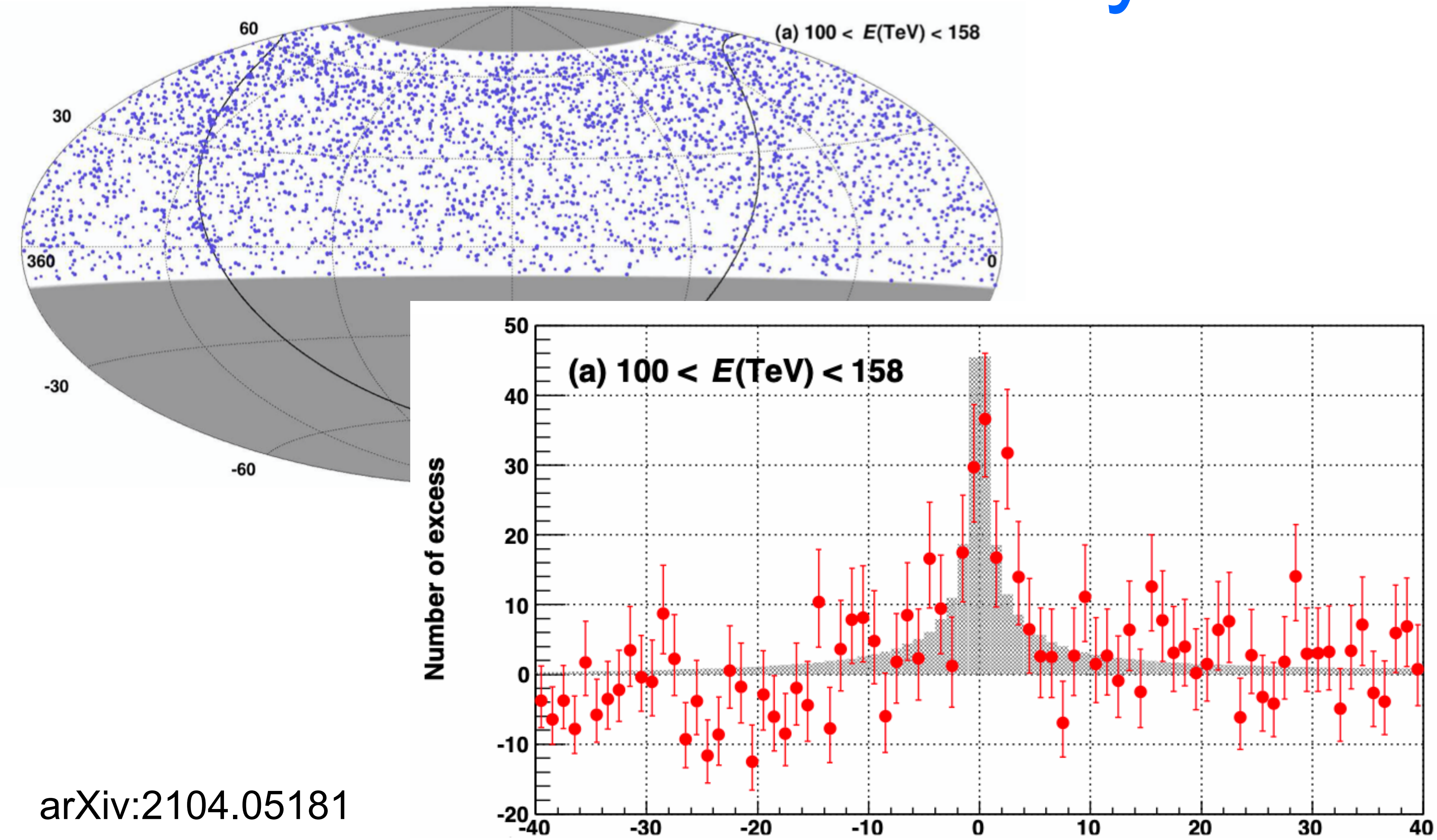
Tibet array measurements of diffuse gamma-ray flux

Tibet array

- Hadron separation in muon covered area 3400 m2 up to 1/10^6

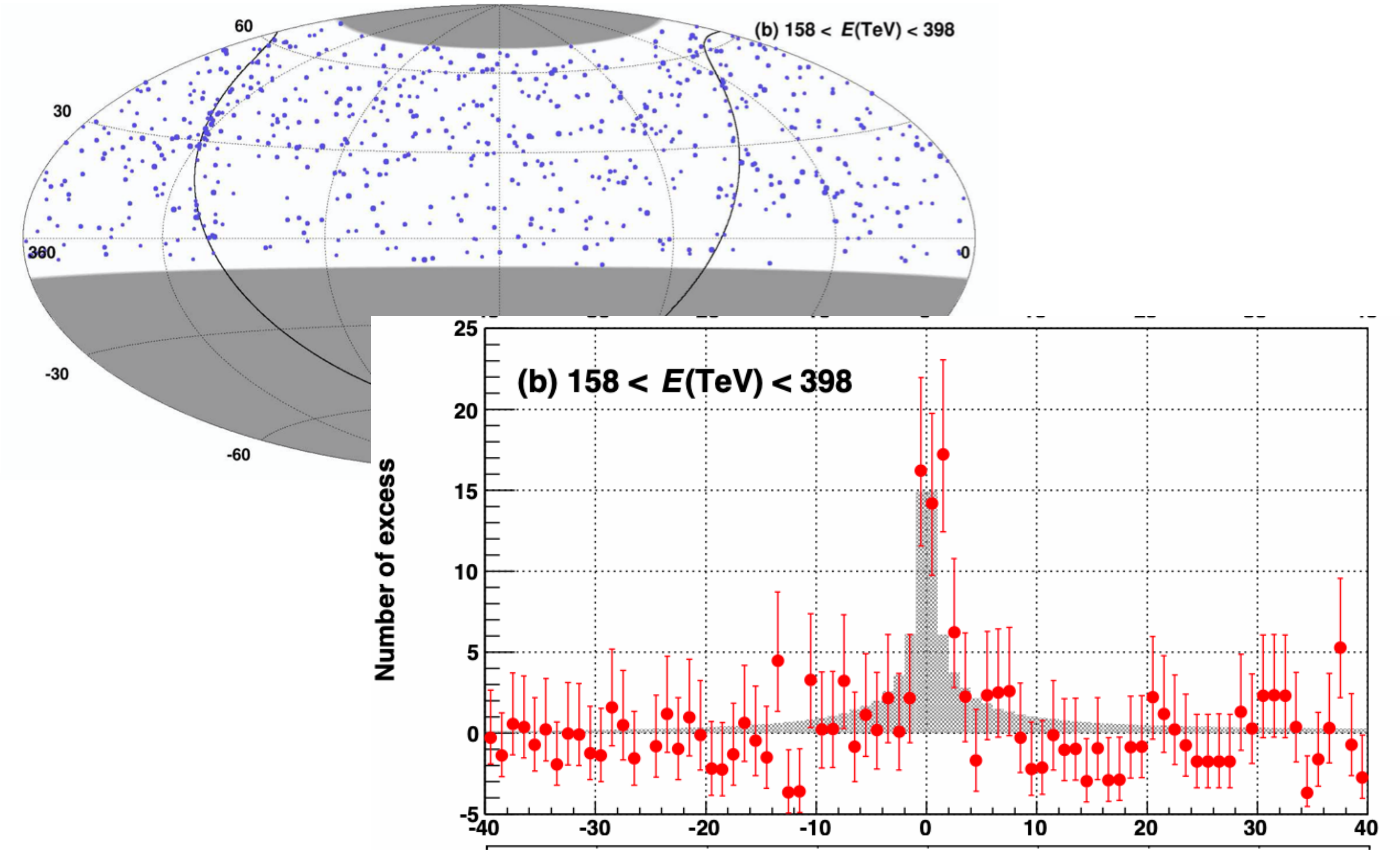


Tibet gamma-ray sky

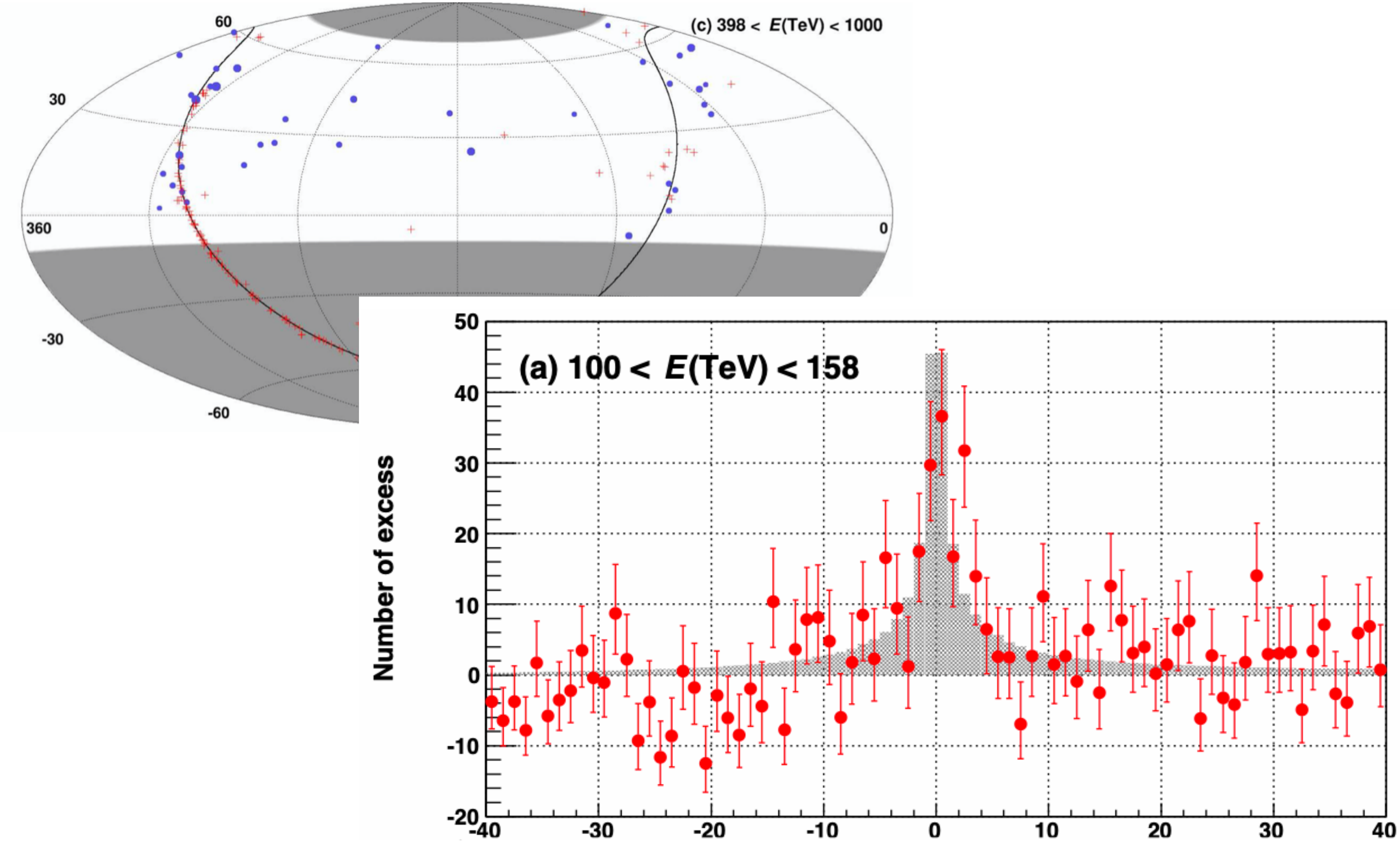


arXiv:2104.05181

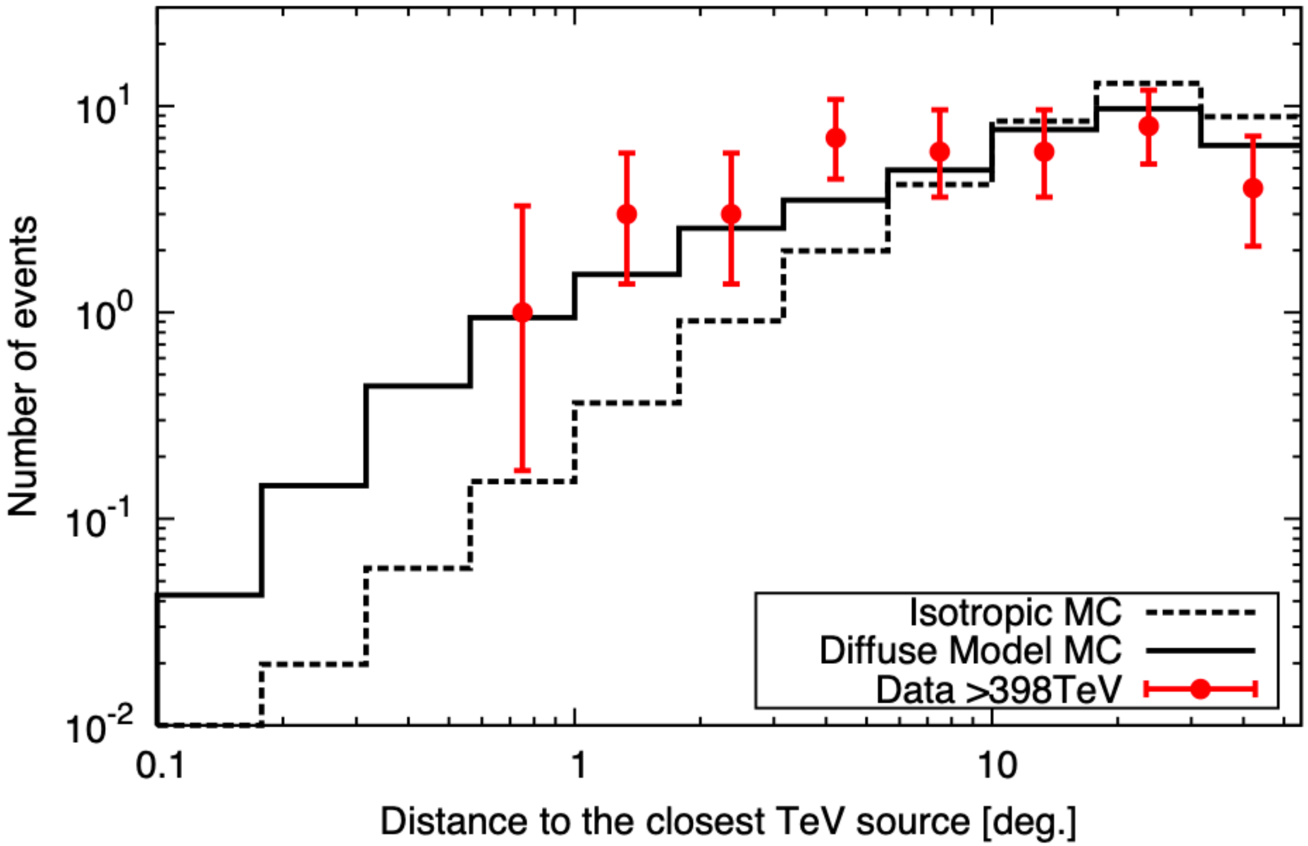
Tibet gamma-ray sky



Tibet gamma-ray sky

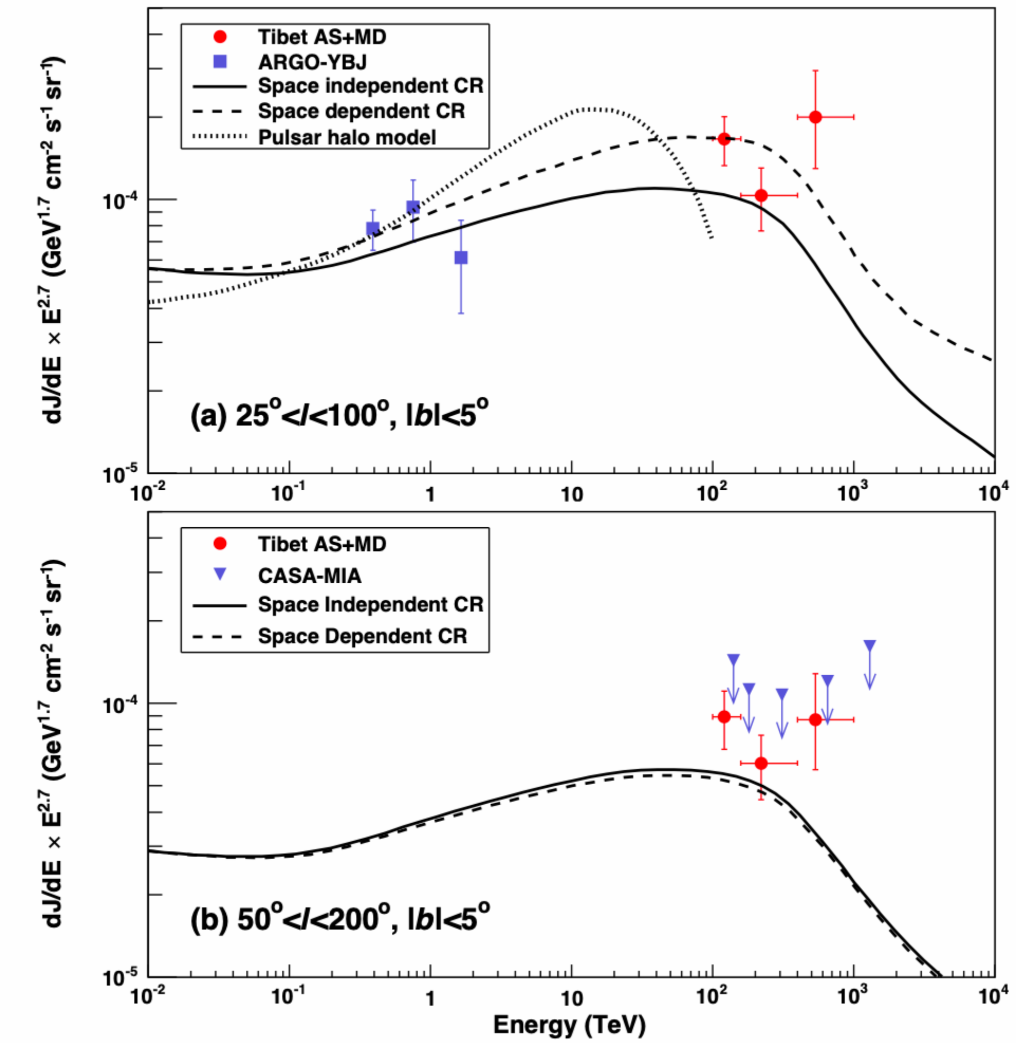


Tibet photons not from point



arXiv:2104.05181

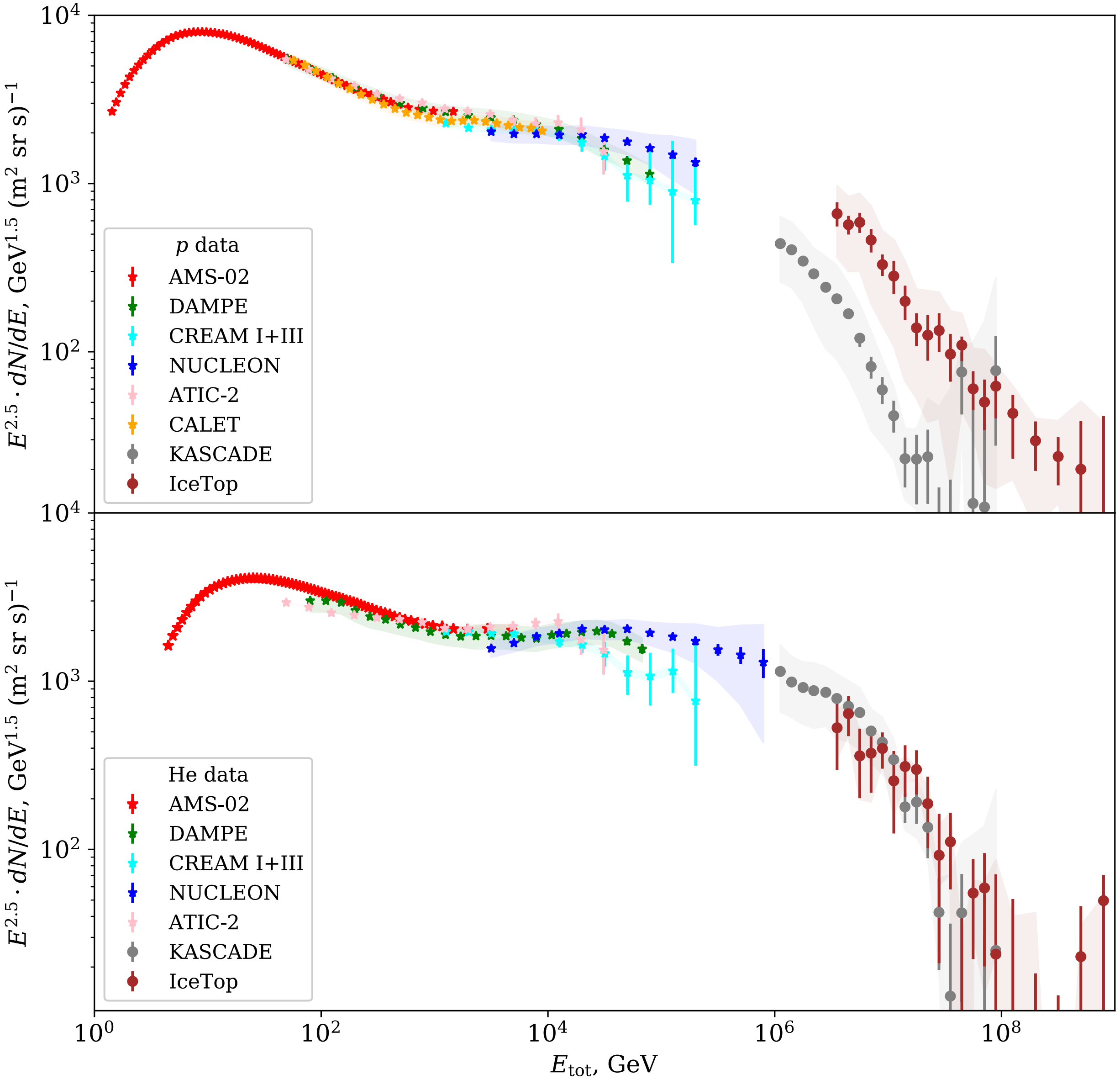
Tibet diffuse gamma-rays



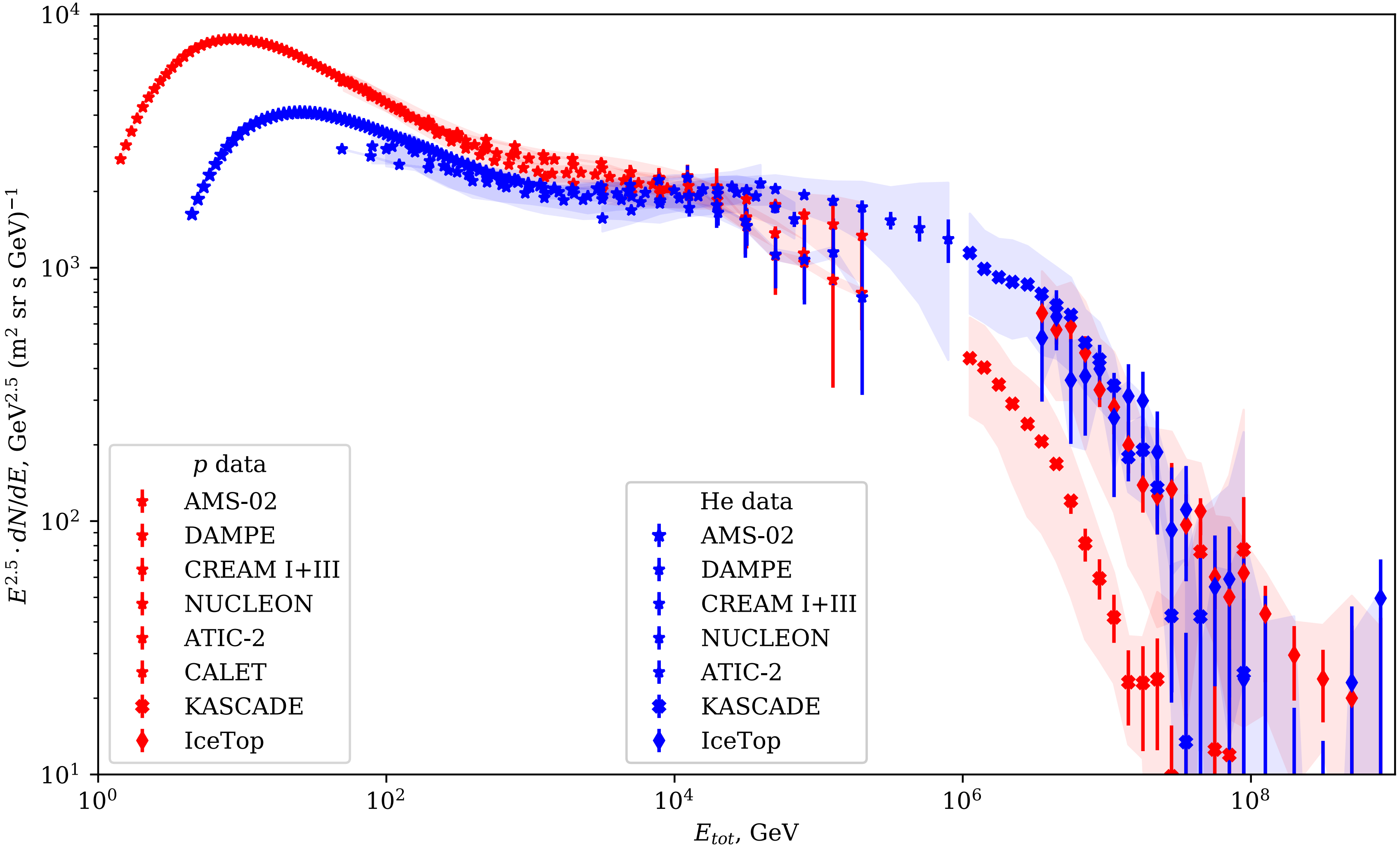
arXiv:2104.05181

Cosmic ray flux in outer Galaxy and predictions for gamma-rays and neutrinos

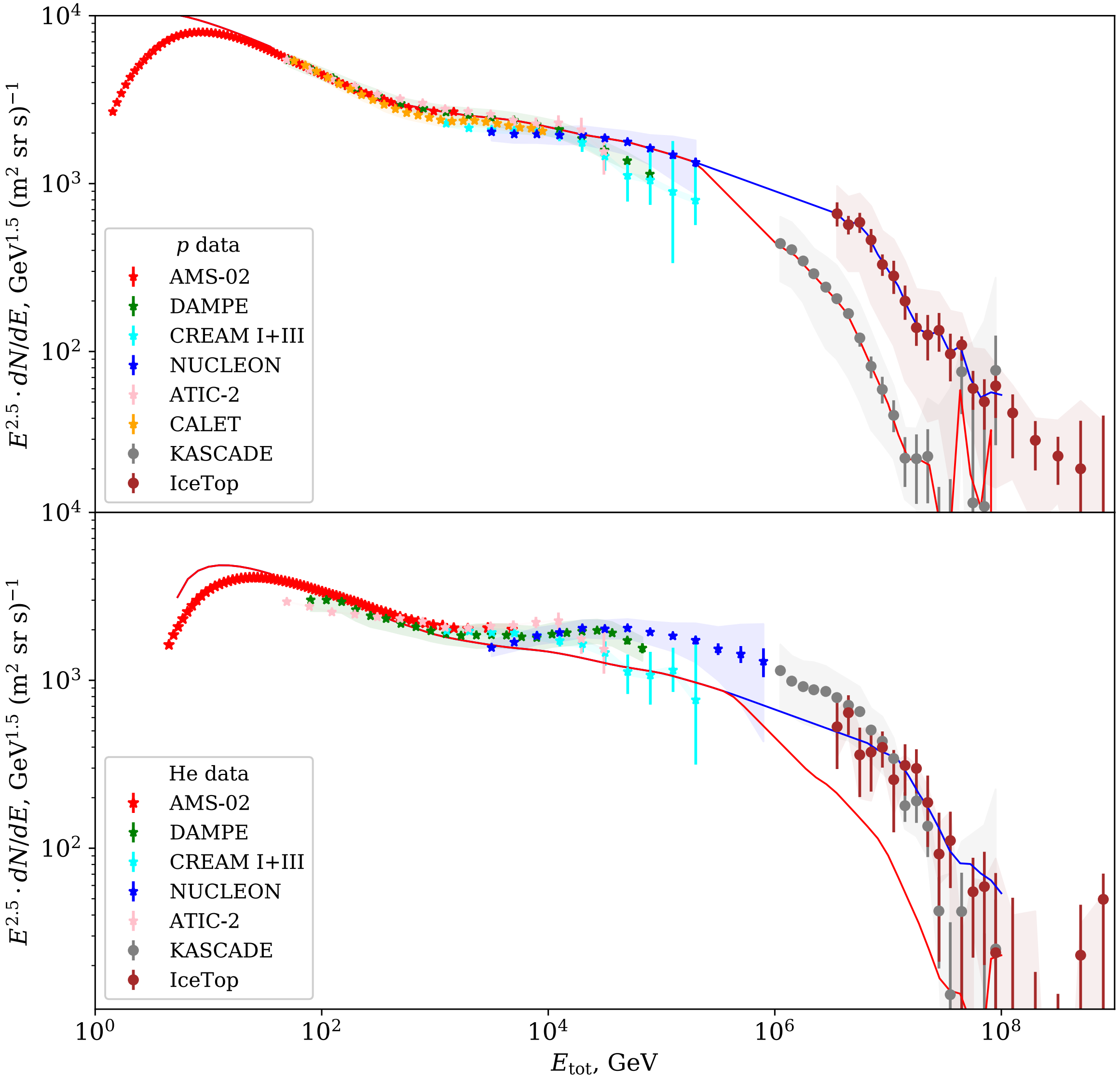
Local cosmic ray flux



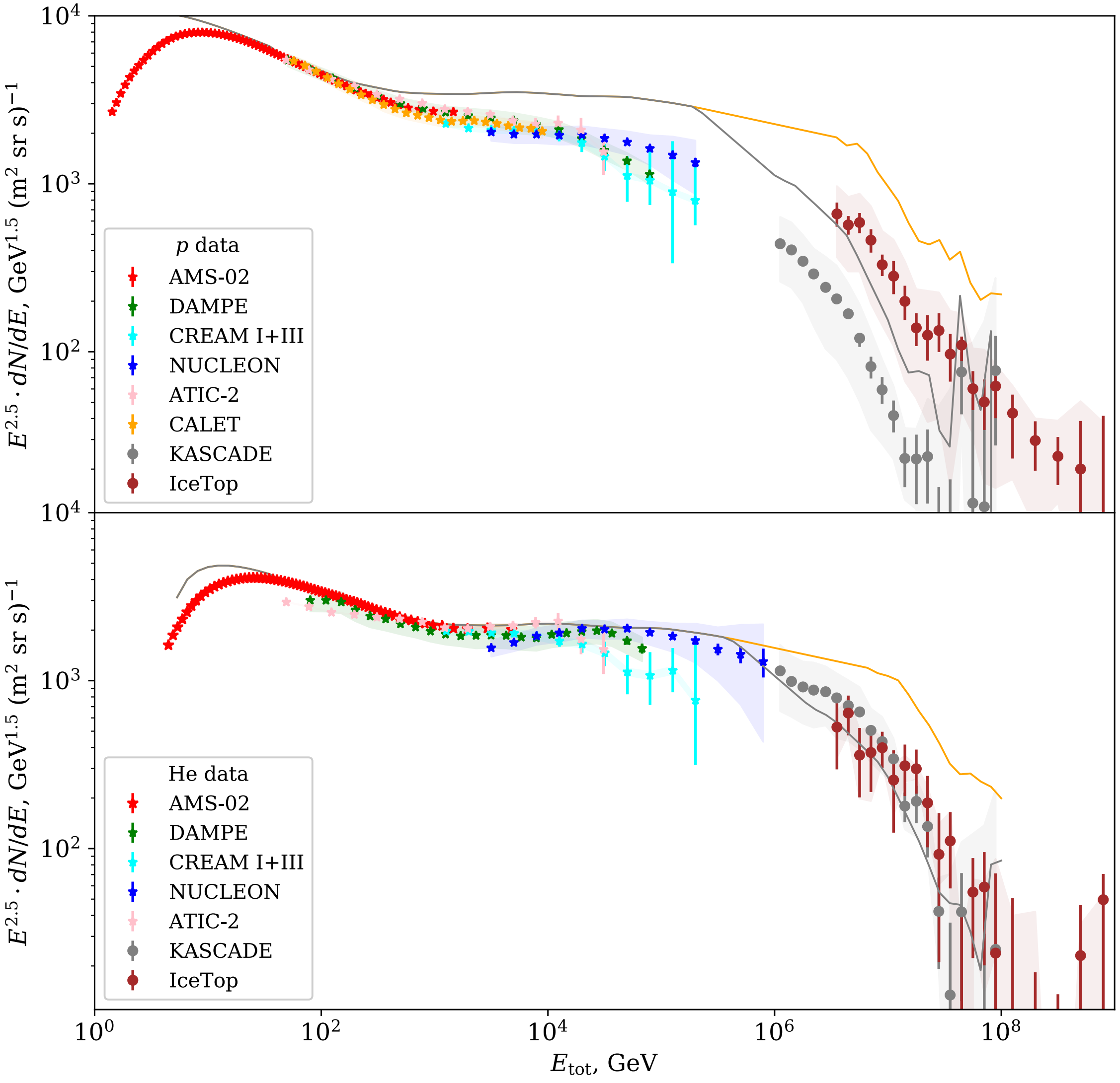
Local cosmic ray flux



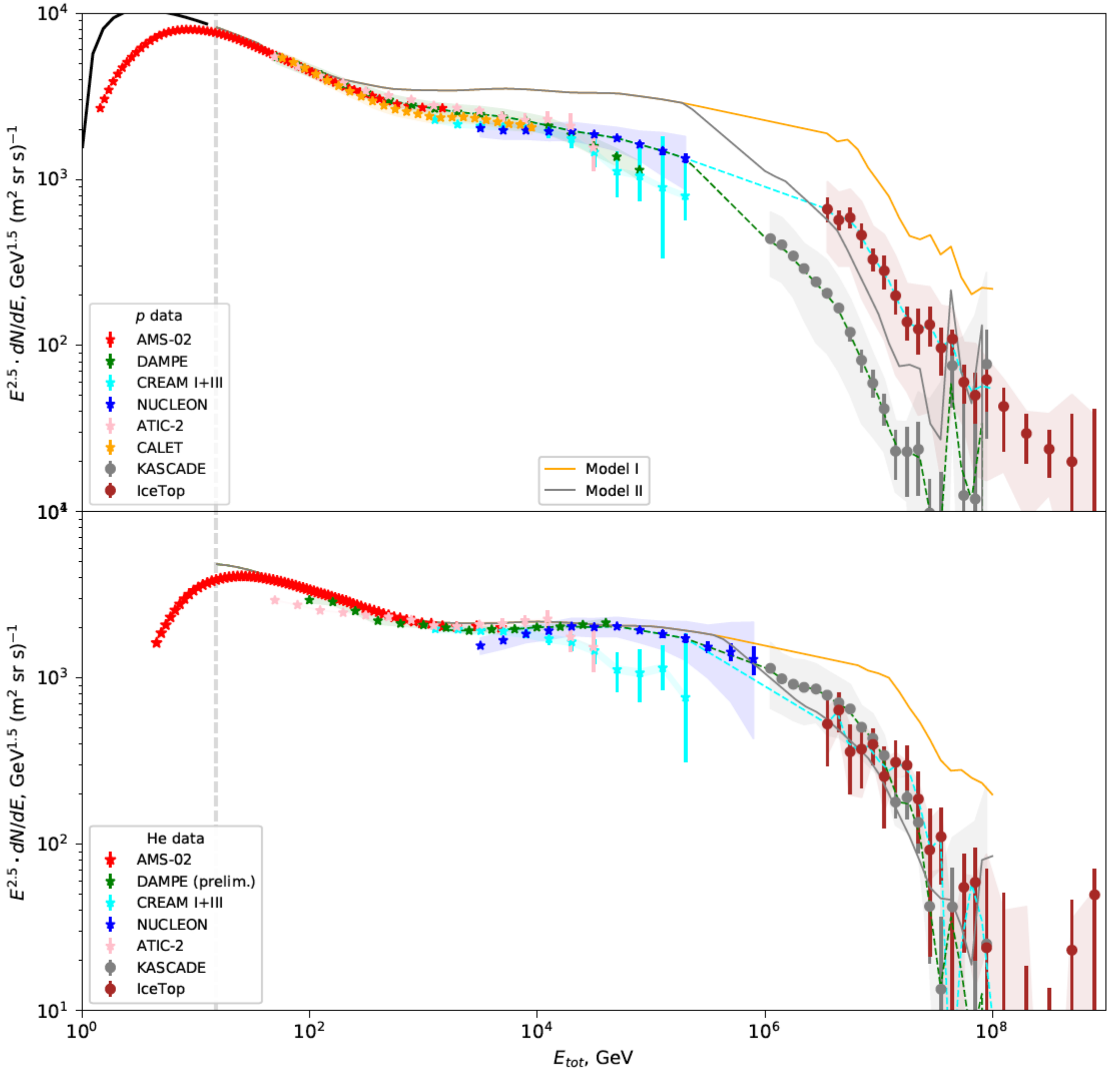
Cosmic ray flux in outer Galaxy is soft as local proton flux



Cosmic ray flux in outer Galaxy is hard as local He flux

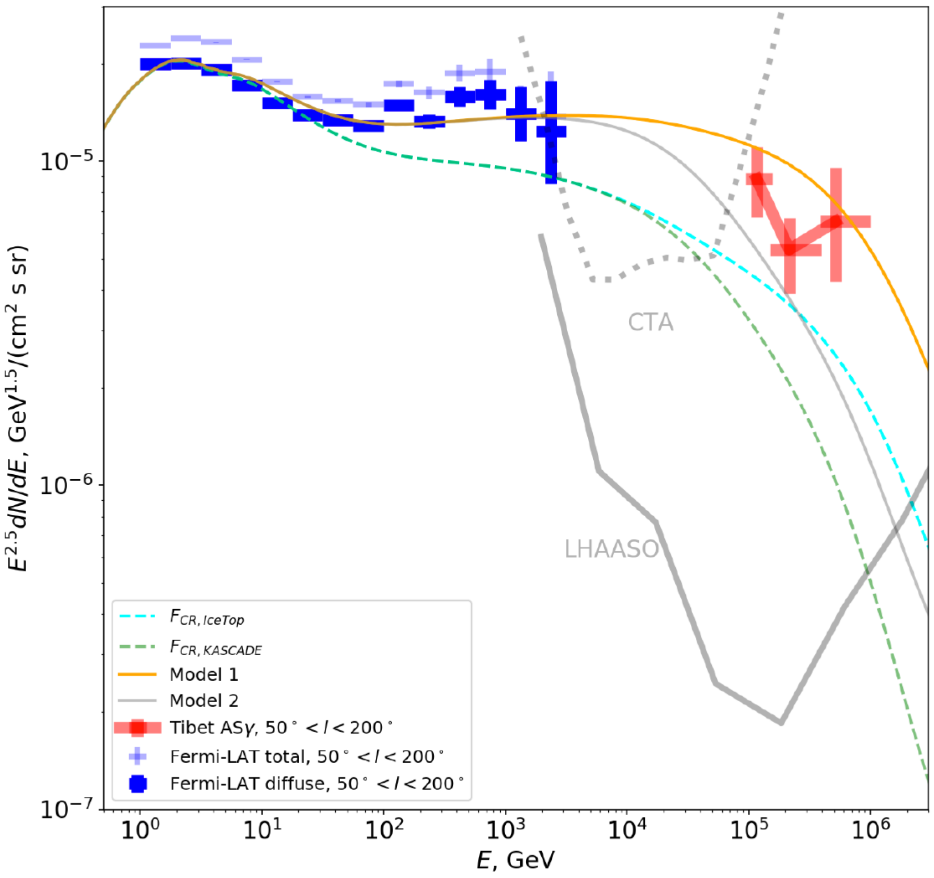


Cosmic ray flux models in outer Galaxy



S.Koldobskiy, A.Neronov and D.Semikoz, arXiv:2105.00959

Gamma-ray flux in outer Galaxy



S.Koldobskiy, A.Neronov and D.Semikoz, arXiv:2105.00959

Open questions for near future study

- Cosmic ray spectrum non-universality in Galaxy, origin of knee, transition to extragalactic CR
- Gamma-ray astronomy at E>100 TeV sources, point and extended sources, leptonic/hadronic sources, diffuse background and relation to cosmic rays and neutrinos
- Neutrino flux from Galaxy, diffused and point sources

Summary

- Gamma-rays and neutrinos in energy range 1 TeV-100 TeV can have common Galactic origin. Several models are exist on the market and can be developed in the furture
- First detection of diffuse gamma-ray background at E>100 TeV by Tibet is keystone for understanding of cosmic ray physics in outer Galaxy. LHASSO with 10 times better sensitivity can do revolution in 100 TeV gamma-ray astronomy
- New model explaining cosmic rays, neutrinos and gamma-rays at multi-TeV-PeV energies is needed.