Perspective of Detecting Very High Energy Gamma Ray Photons Associated with Neutrinos by LHAASO

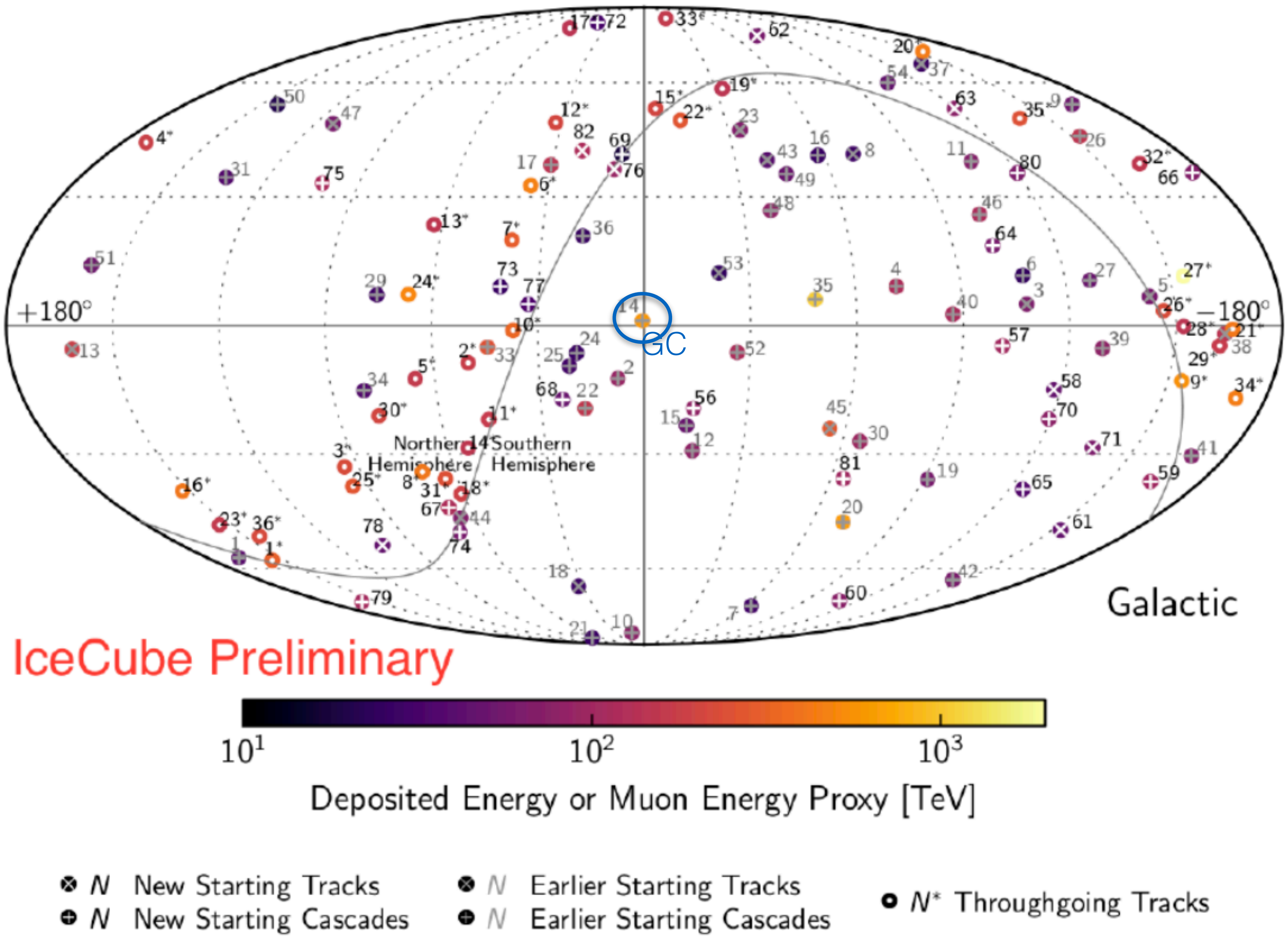
Haoning He （贺昊宁）
PMO / RIKEN

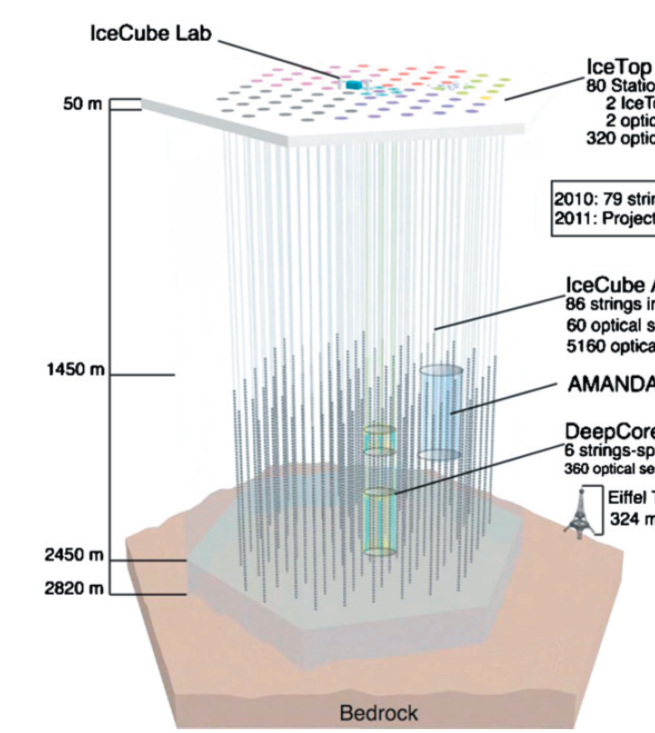
Collaborators: Herman Lee, Shigehiro Nagataki, Alexander Kusenko, Yizhong Fan, Daming Wei

Possible Candidates

- **Extragalactic Sources:** Blazars, GRBs, Galaxy Clusters, Starburst Galaxies
- **Galactic Sources:** The Galactic Plane, CR accelerators+Molecular Clouds, The Galactic Center

The High-Energy Neutrino Sky





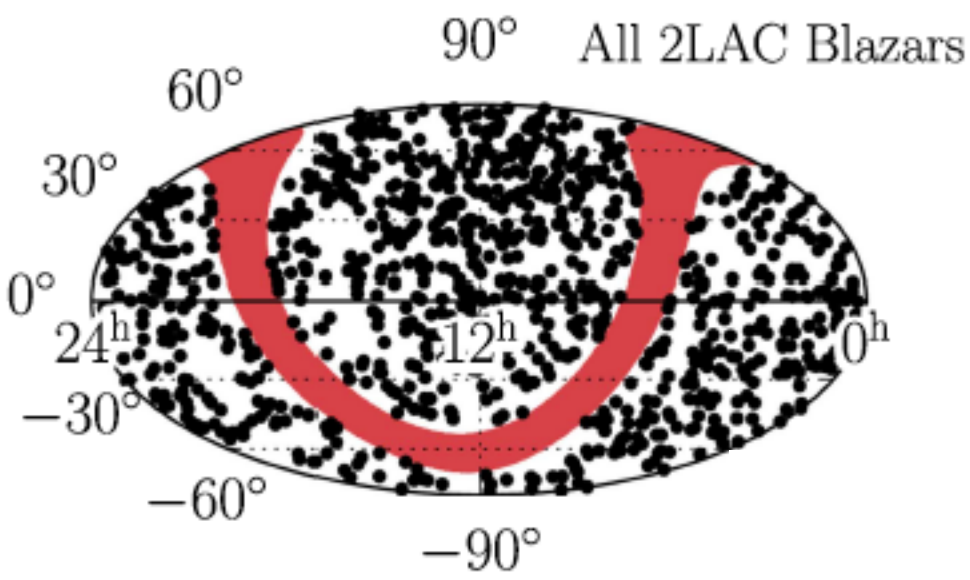
The IceCube @ ICRC 2019

No significant clustering/anisotropy found.

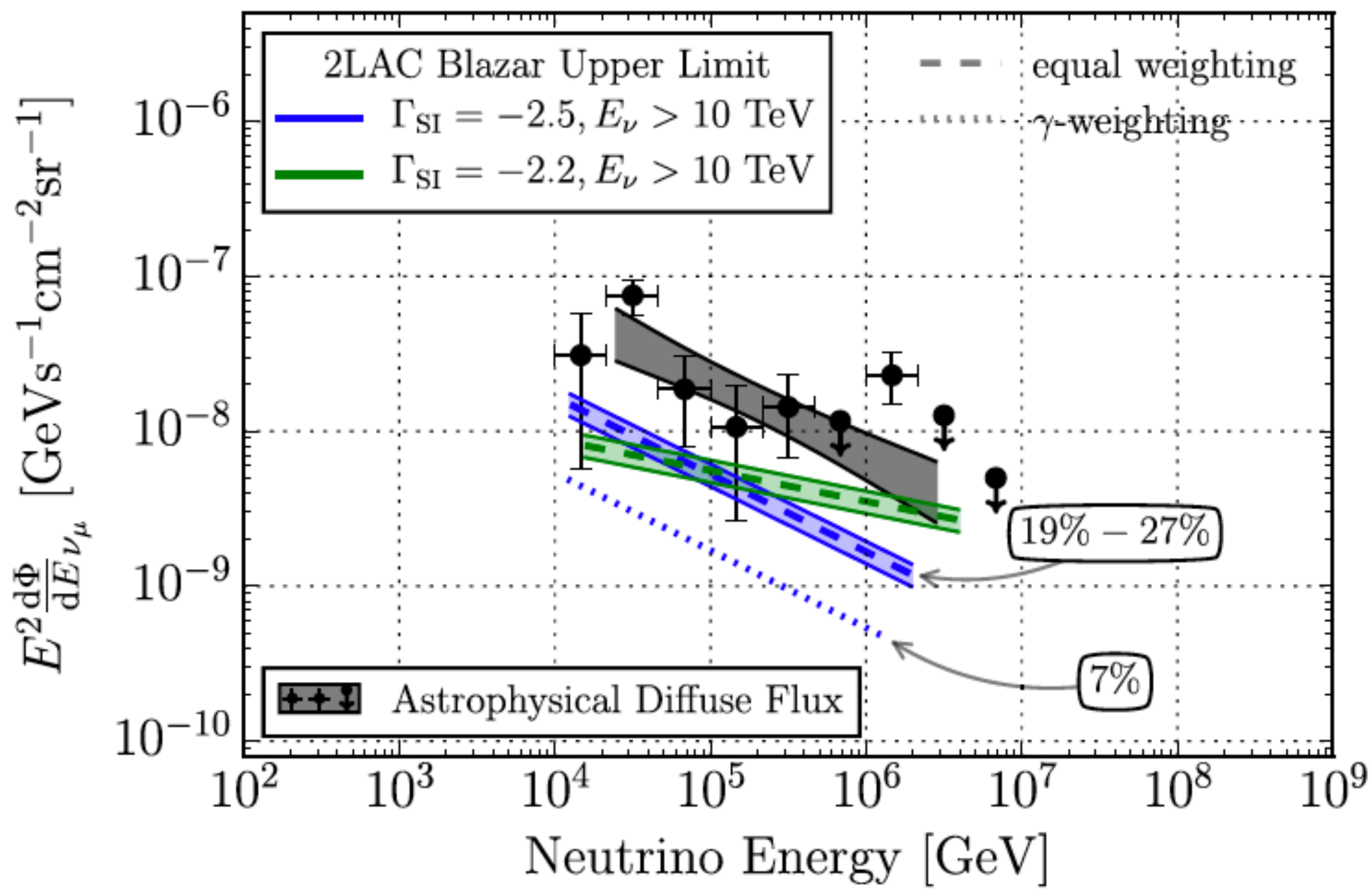
Isotropy: Extragalactic Neutrino Sources

- Blazars
- GRBs
- Choked Jets in Core-Collapse Massive Stars
- AGN cores/outflow
- TDEs
- Galaxy Clusters
- Starforming galaxies / Starburst Galaxies

The Contribution of Fermi-2LAC Blazars to IceCube diffuse neutrino flux



862 sources



IceCube Collaboration, 2017,ApJ,835,45A

Neutrinos from Blazars

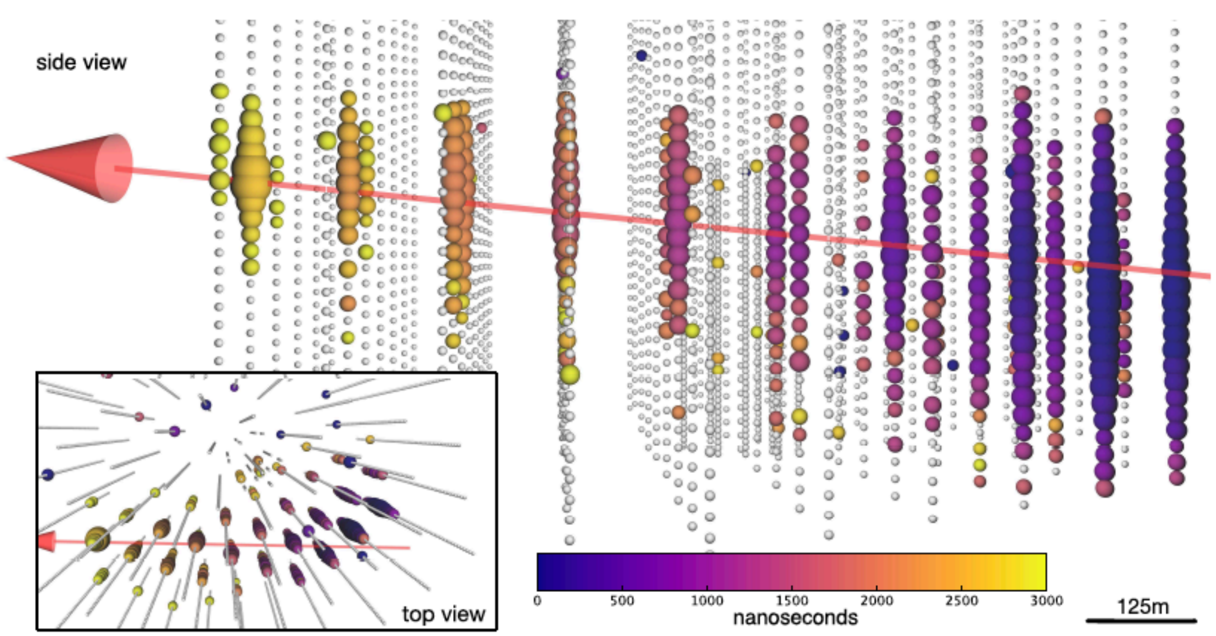
RESEARCH ARTICLE

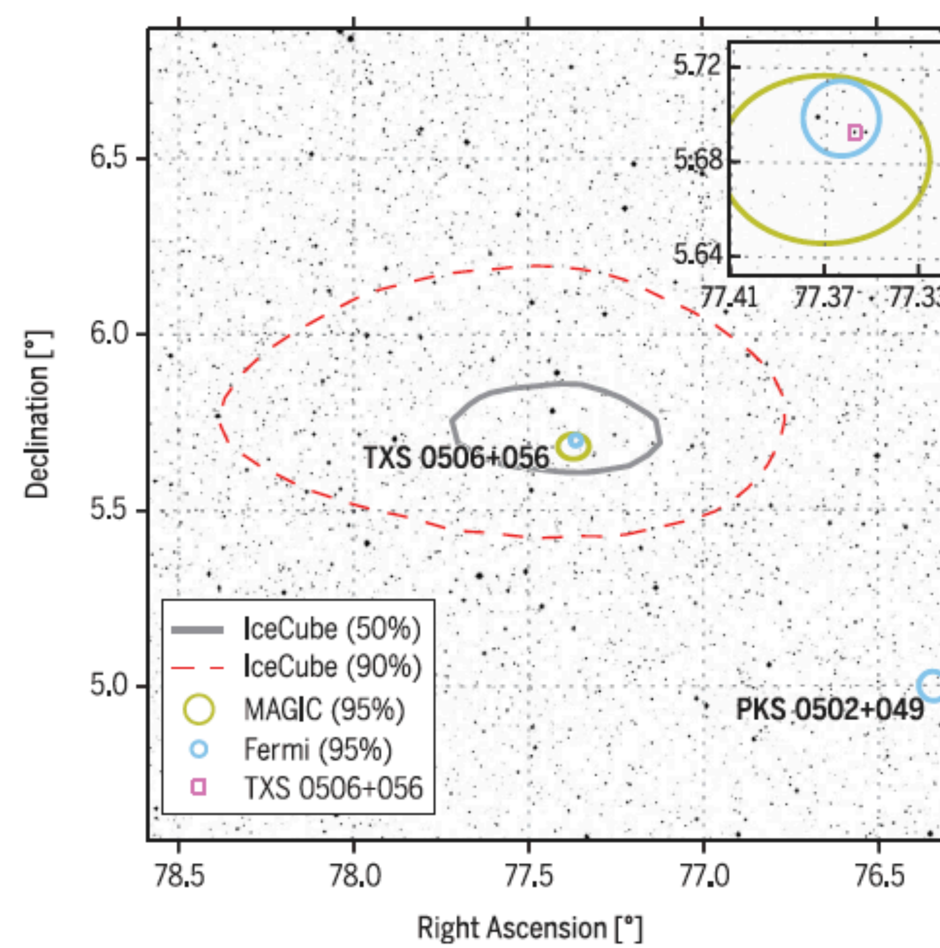
NEUTRINO ASTROPHYSICS

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

The correlation of the neutrino with the flare of TXS 0506+056 is statistically significant at the level of 3 standard deviations (sigma)



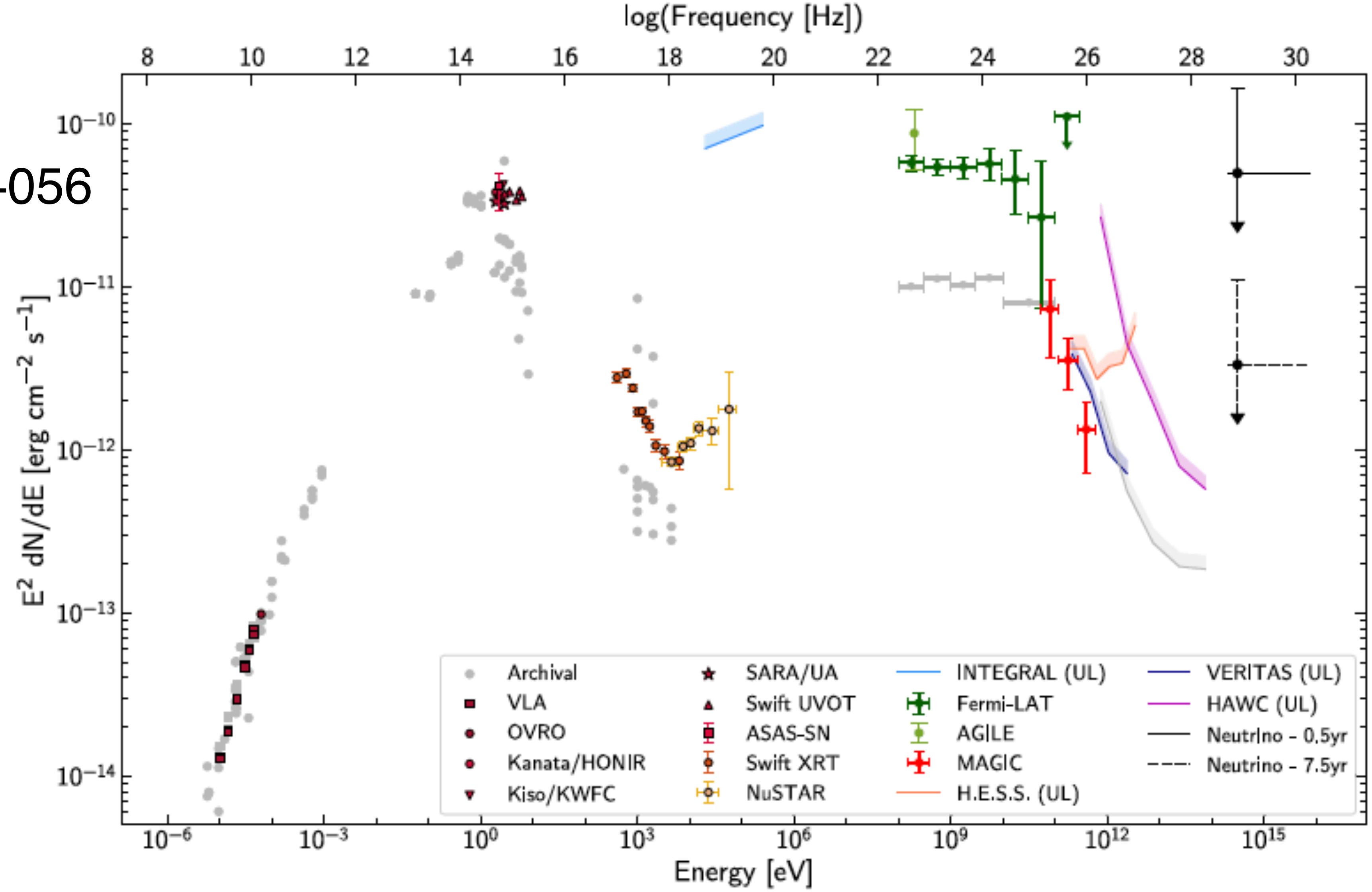


Multimessenger observations of blazar TXS 0506+056. The

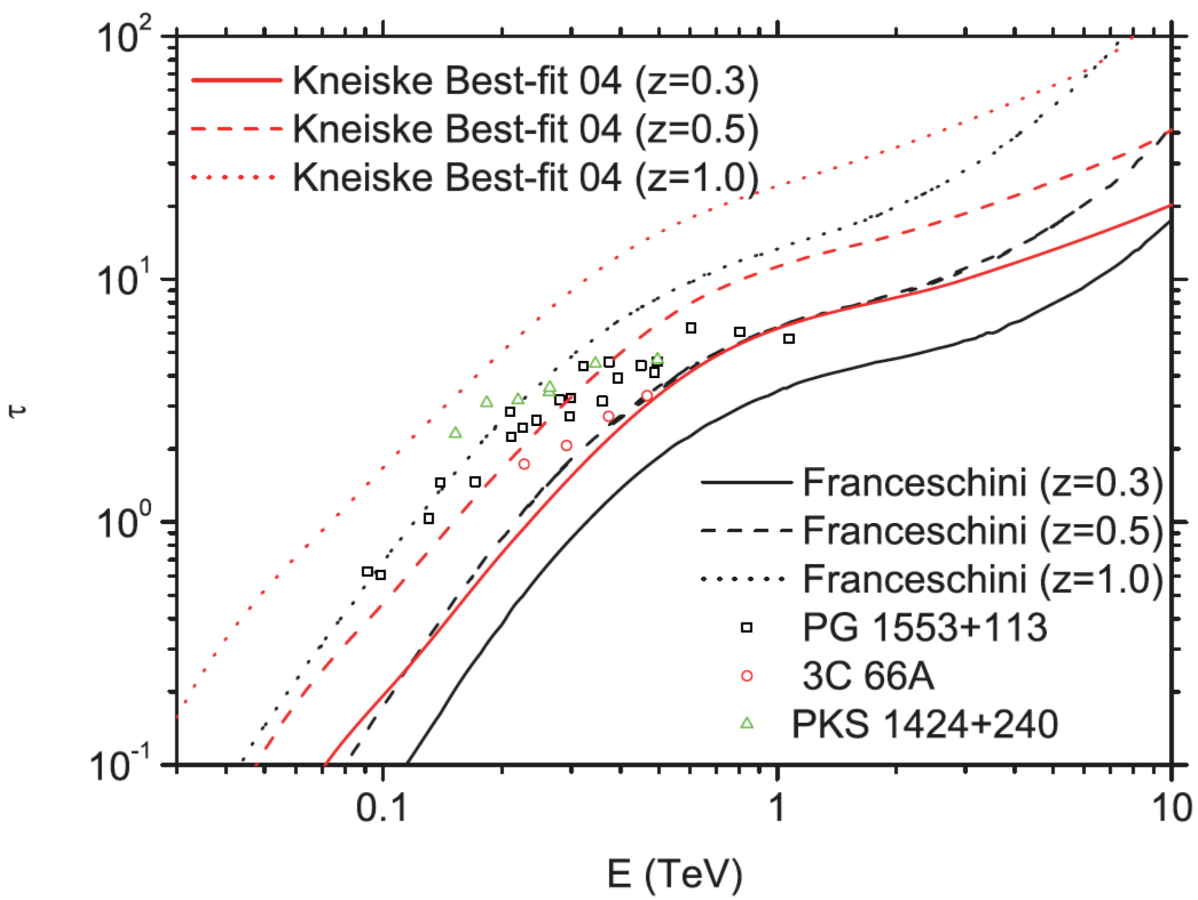
IceCube Collaboration, et al. 2018

The spectrum of TXS 0506+056

Redshift z=0.3365



The IceCube Collaboration, et al. 2018



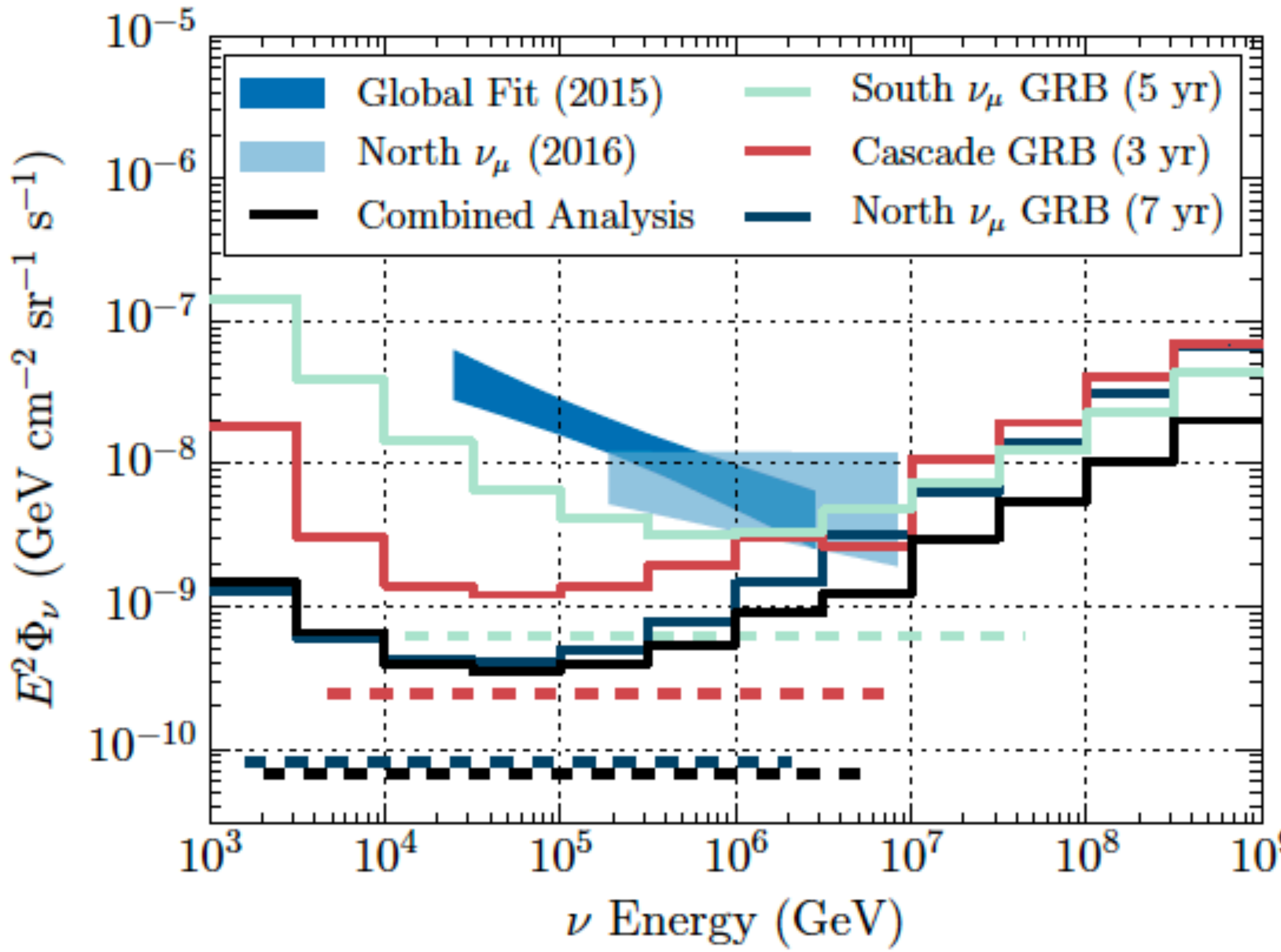
Optical depth for TeV photons

Yang & Wang (2010)

Searching for Neutrinos in Coincidence with GRBs

Short duration
→ minimal background

A number of events were found temporally coincident with these GRBs, but were consistent with background both individually and when stacked together.



Prompt emission from GRBs can produce <1% of the observed neutrino flux.

The IceCube Collaboration
arXiv:1702.06868

Observations on Diffuse Extragalactic Gamma-Ray Background

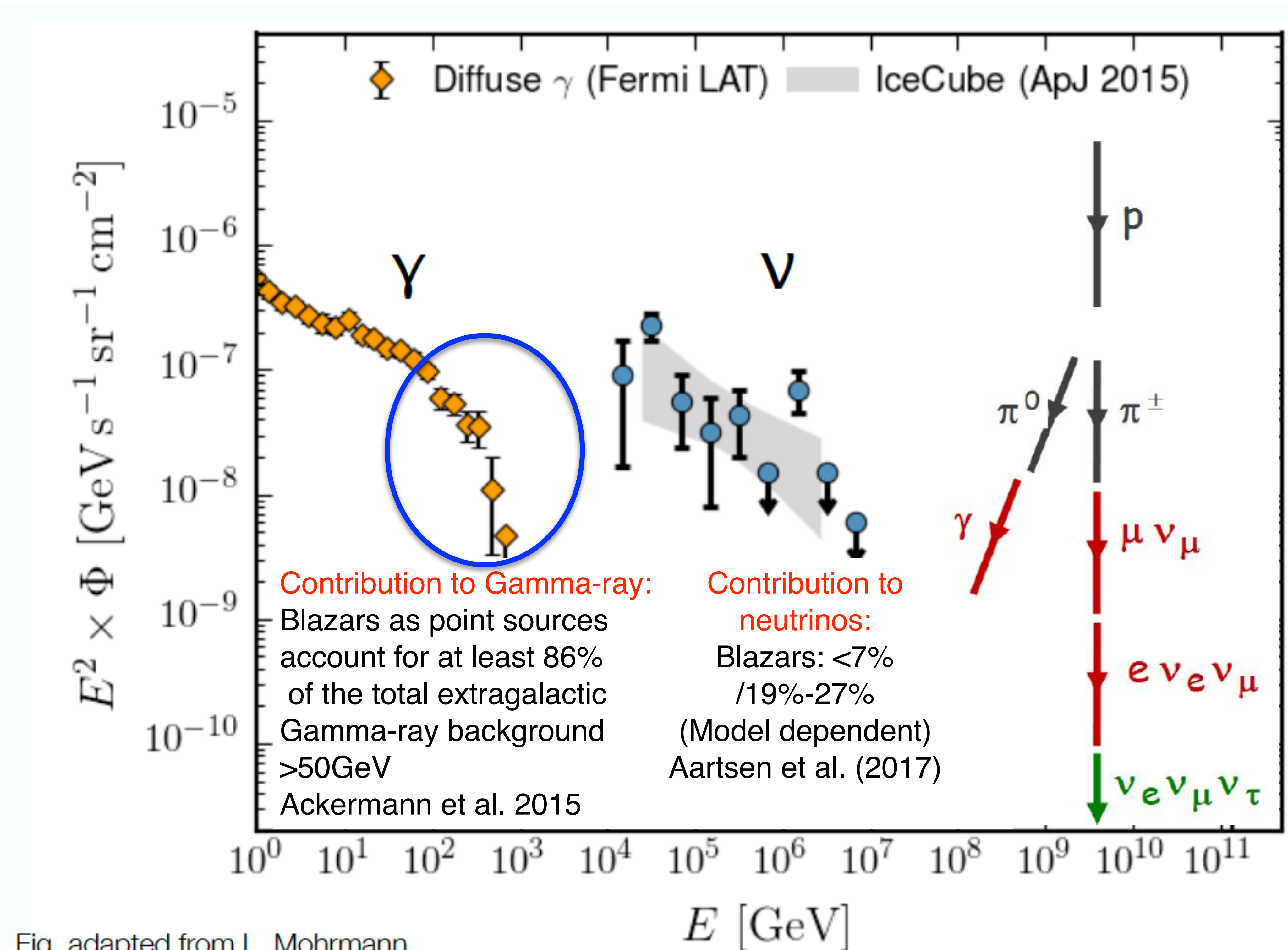


Fig. adapted from L. Mohrmann

Possible Solutions

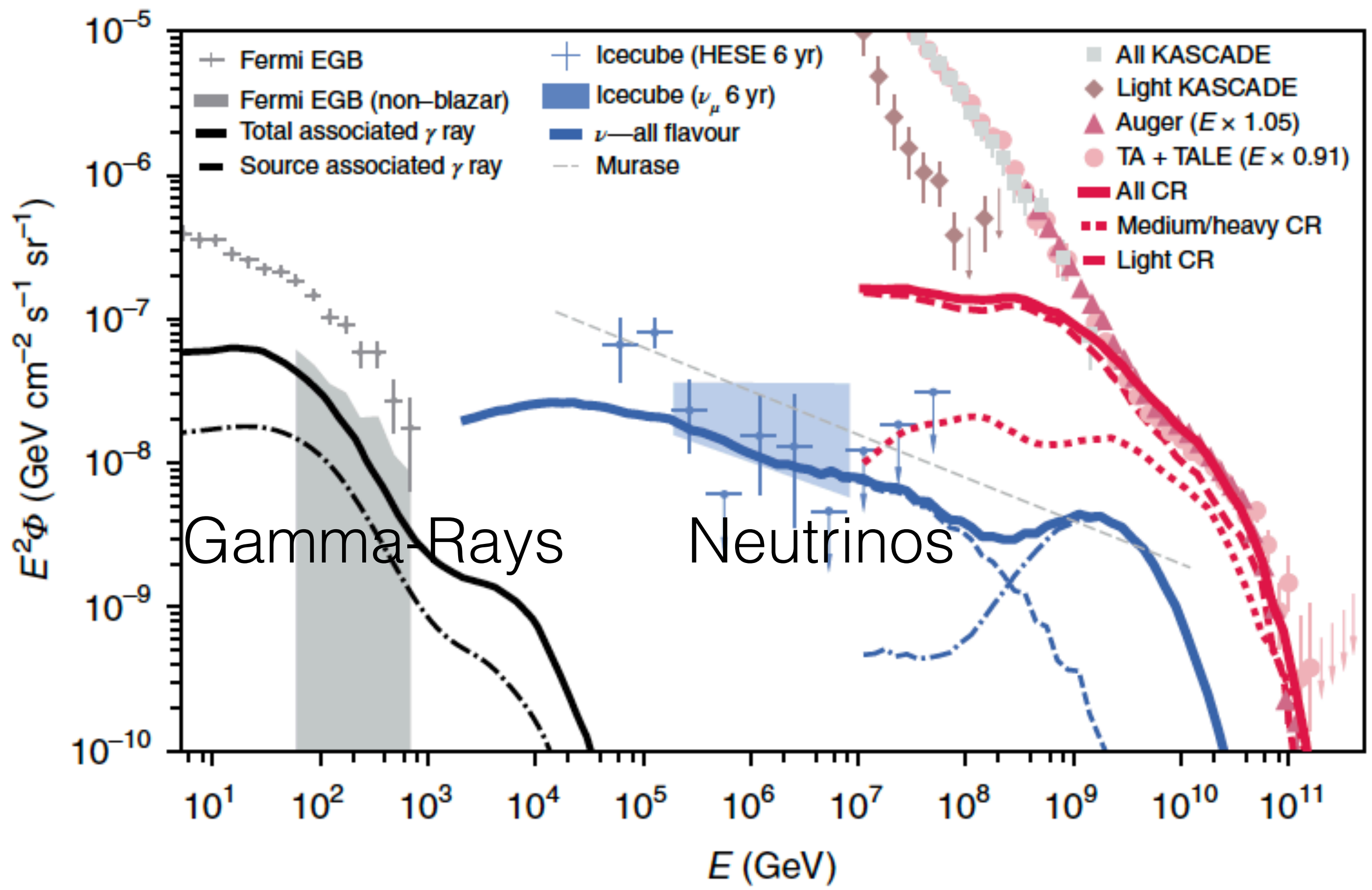
The neutrino sources themselves are opaque to gamma rays (hidden source) or distant:

- choked jets in TDEs of supermassive black holes (Wang & Liu 2016; …)
- choked jets in core-collapse massive stars (Meszaros & Waxman 2001; Razzaque et al.2004; Murase & Ioka 2013; Xiao & Dai 2014; Senno et al. 2016; …)
- AGN cores (Stecker 2005; Murase et al. 2016; …)
- Galaxy Clusters（Fang & Murase 2018…）
- Starburst Galaxies（Chang et al. 2016…）

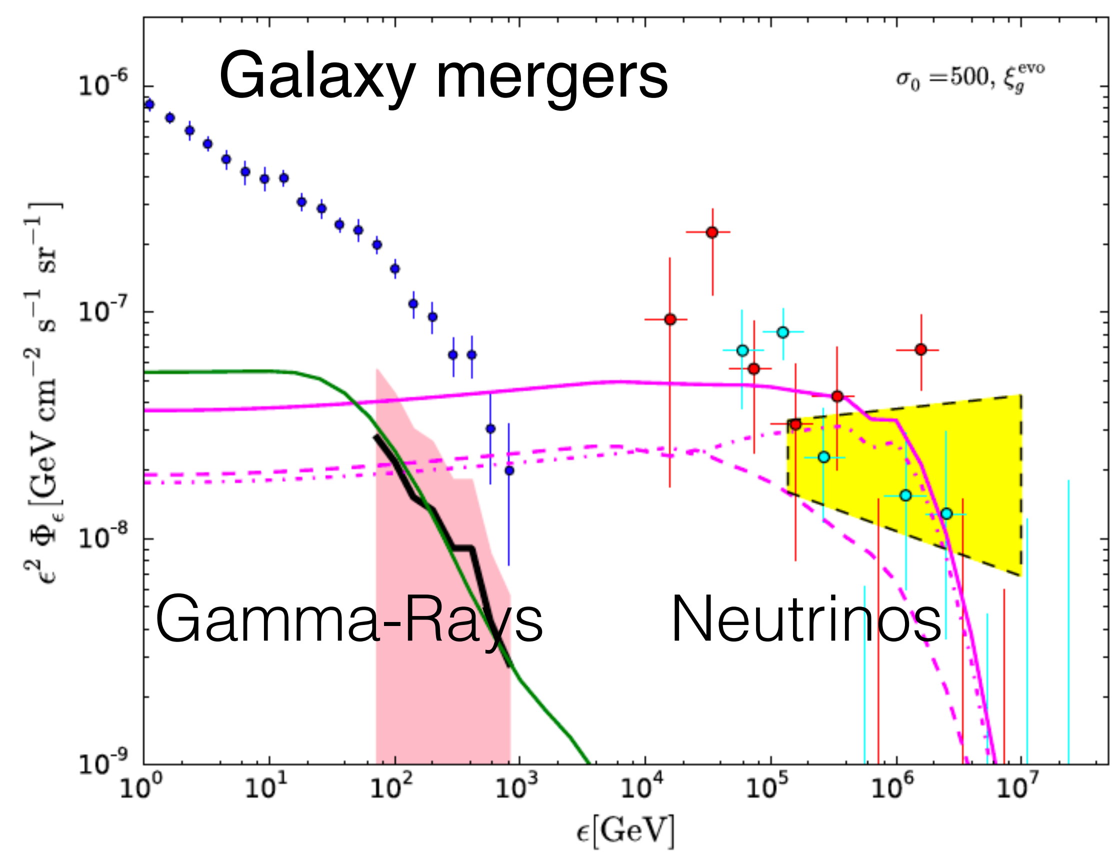
Galaxy Clusters

Cosmic Ray Accelerators in Galaxy Clusters:

1. Large scale accretion shocks/merger shocks
2. AGN jets
3. Other central sources following star formation



Fang & Murase 2018



Yuan et al. 2018

Starburst Galaxies/Star-forming Galaxies

High star formation rate

↓

High Supernova Rate:

$$R_{SN}(z) = 1.2 \times 10^{-2} \rho_{SFR}(z)/M_\odot$$

Fukugita & kawasasi 2007

↓

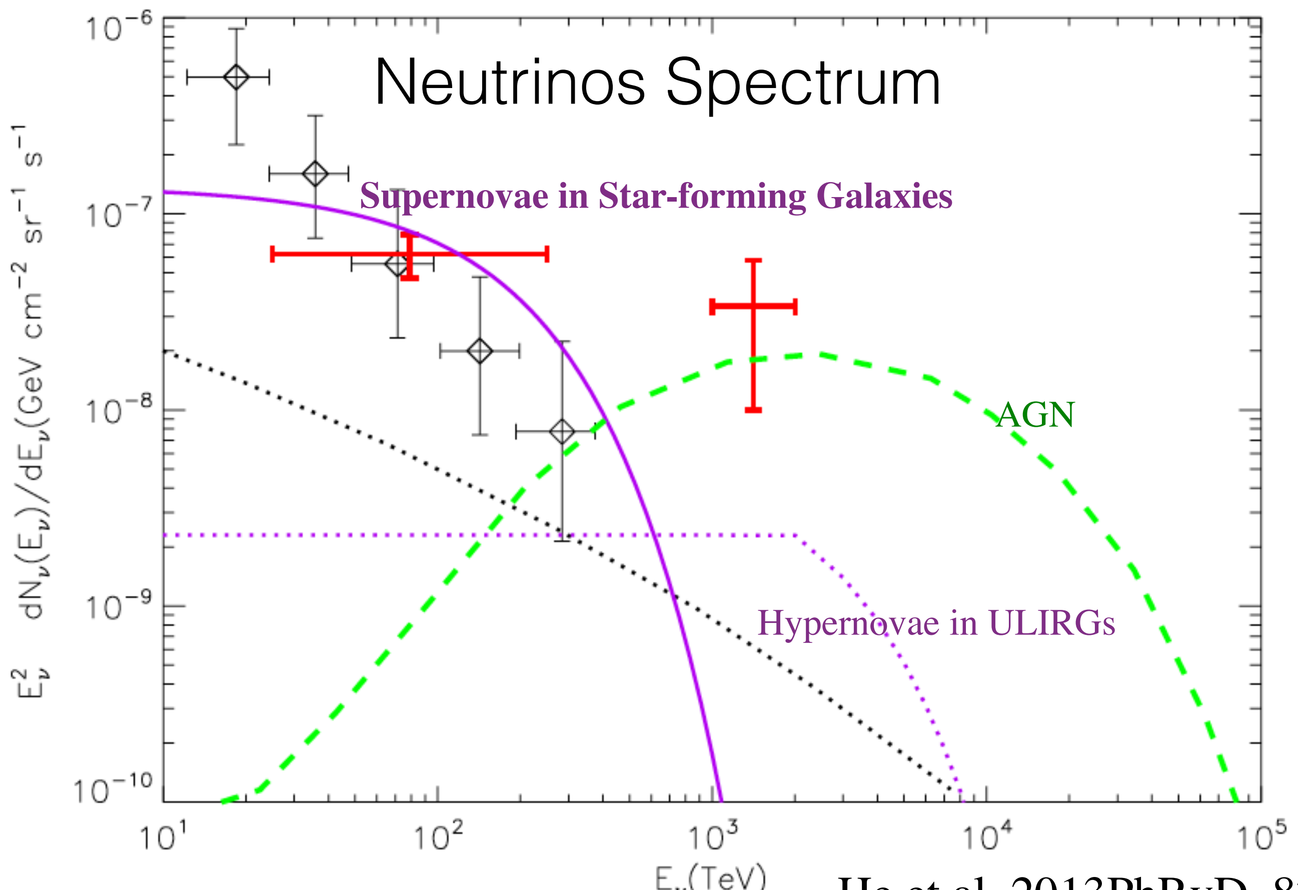
High Hypernova Rate:

$$R_{HN}(z) = f_{HS} R_{SN}(z) \qquad f_{HS} \simeq 0.01$$

Cappelaro et al. 1999
Guetta& Della Valle, 2007

Dense ISM+
Strong Magnetic Field

$\tau_{conf} \geqslant \tau_{loss}$ → pp collission before escaping

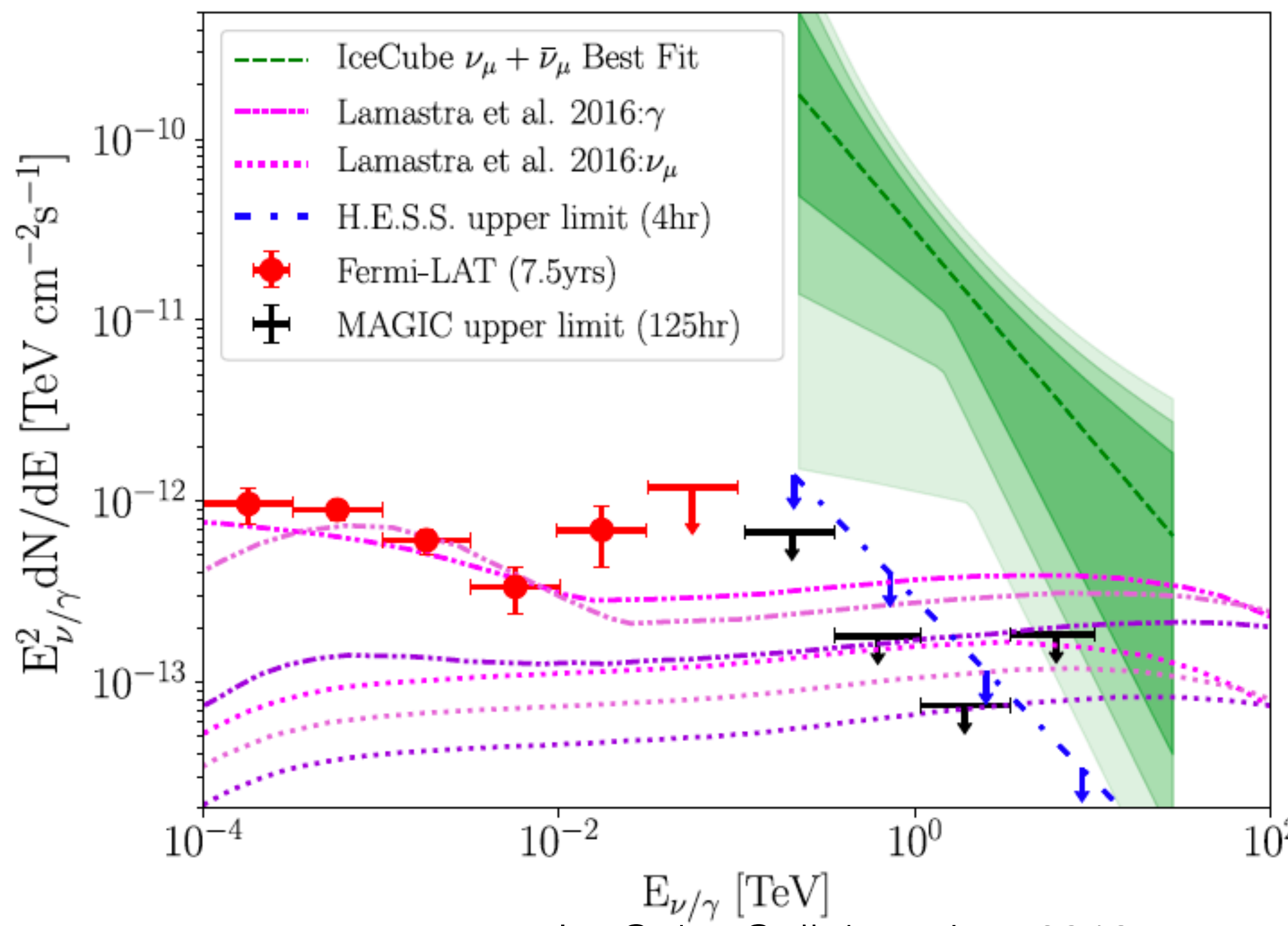


He et al. 2013PhRvD..87f3011H, He et al., 2013arXiv1307.1450H

Nearby Starburst Galaxies

Galaxy name	Distance D(Mpc)	SFR ψ ($M_\odot$ yr^{-1})	SN Rate R_{SN} (century^{-1})	GeV data reference	TeV data reference
M82	3.4 ± 0.9	6.3 ± 0.9	5.7 ± 0.9	Ackermann et al. (2012)	Acciari et al. (2009)
NGC 253	2.5 ± 0.5	2.9 ± 0.4	2.6 ± 0.4	Paglione & Abrahams (2012)	Abramowski et al. (2012)
NGC 4945	3.7 ± 0.8	3.5 ± 1.0	3.2 ± 0.9	Ackermann et al. (2012)	
NGC 1068	16.7 ± 3.0	38 ± 10	35 ± 9	Ackermann et al. (2012)	Aharonian et al. (2005)
Circinus	4.2 ± 0.7	2.1 ± 0.5	1.9 ± 0.5	Hayashida et al. (2013)	
Arp 220	77.0 ± 2.0	188.3 ± 10.0	172.1 ± 9.1	Peng et al. (2016)	VERITAS Collaboration (2015)

Seyfert II (and starburst) Galaxy NGC 1068 shows a 2.9σ deviation from background, in time-integrated neutrino point source searches with 10 years of IceCube data.

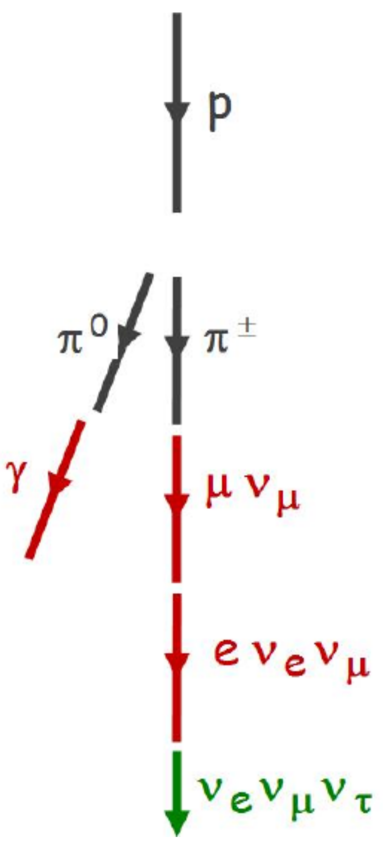


IceCube Collaboration, 2019

Galactic Sources

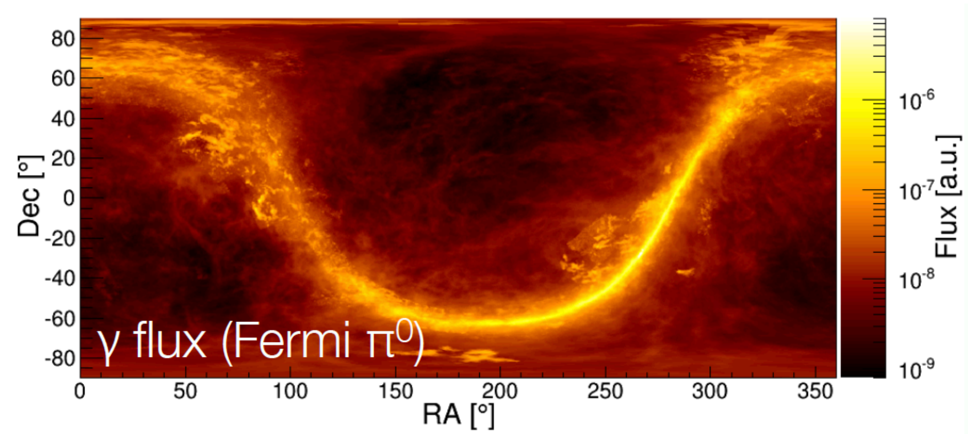
- CR Accelerators (SNR/HNR/Stellar Winds) Accompanied with Molecular Clouds
- PWN
- Fermi Bubble
- Galactic Center
- Galactic Halo
- Galactic Lobe
- Other TeV gamma-ray sources

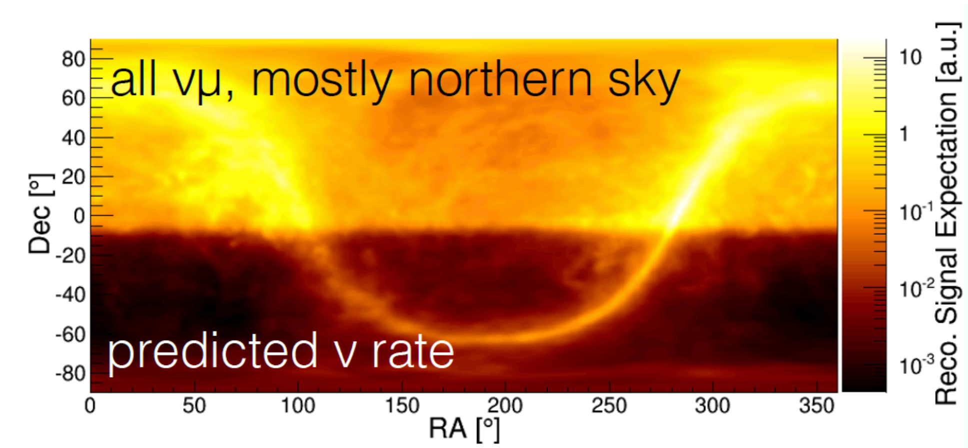
High Energy Neutrinos from the Galactic Plane

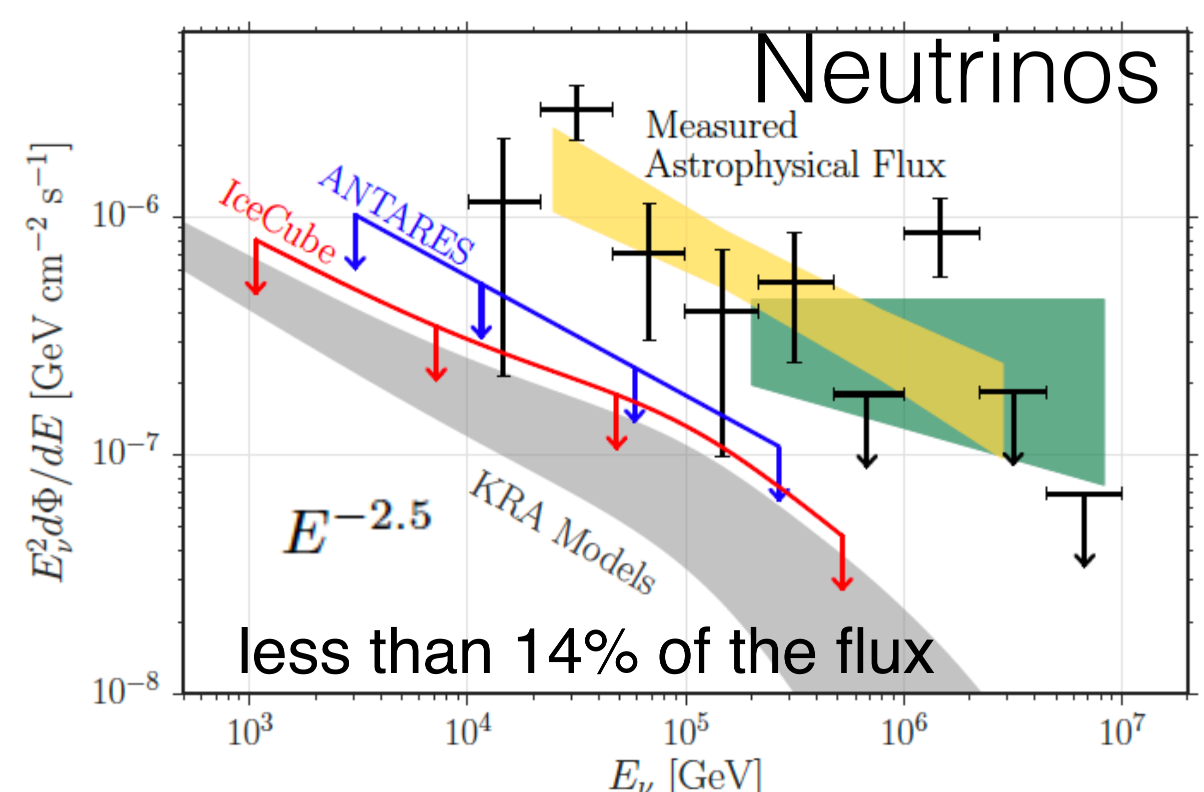


Two Assumptions:

1. Hadronic Origin (pp, or pgamma)
2. Cosmic rays are accelerated to >PeV





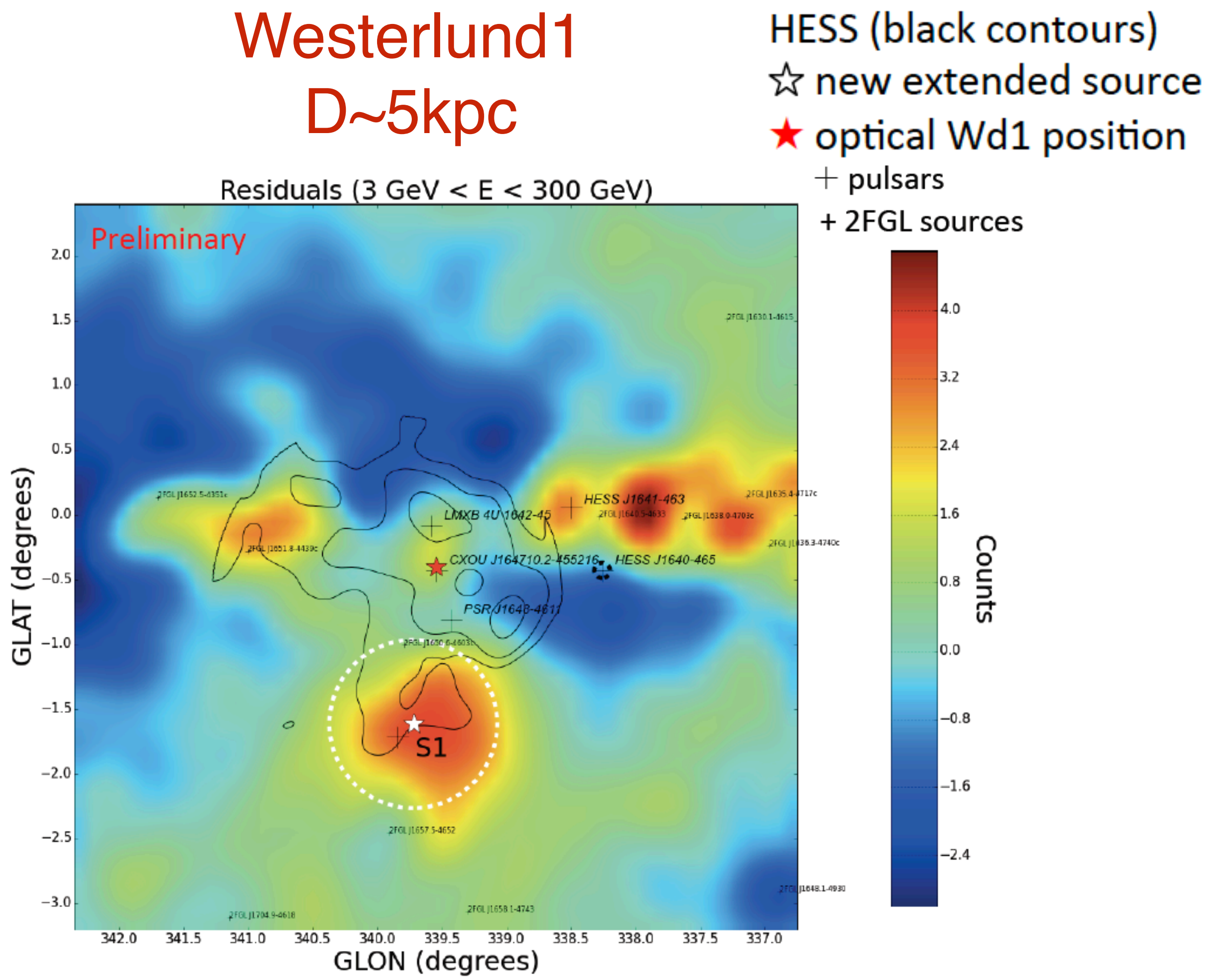


LHAASO template for the Galactic Plane@100 TeV

IceCube Collaboration, ApJ, 849 (2017) 67

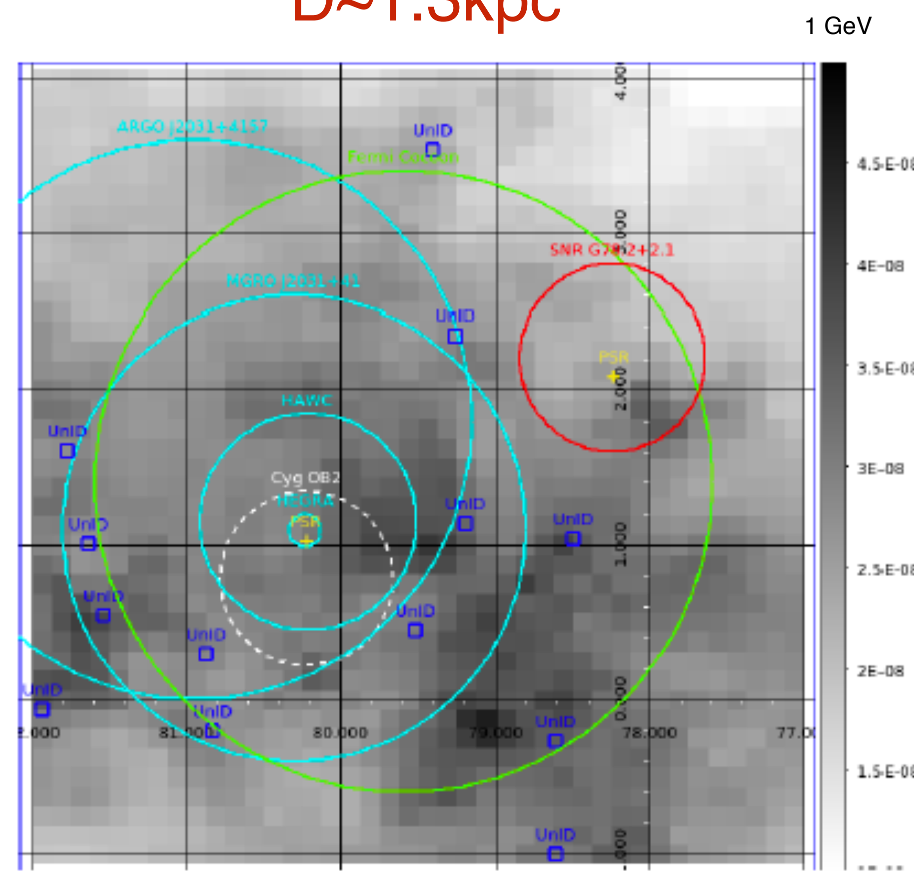
Possible CR Acceleration Sites in the Galaxy

Massive Stellar Cluster
Westerlund1
D~5kpc



Adapted from Brandt's talk at ICRC2017

Starforming Region
Cygnus X
D~1.3kpc



Yoast-Hull et al. 2017

Past massive star explosions/stellar winds+Molecular Clouds

A General Predictions for Neutrinos from PeVatron+MCs

$$n_{\nu_\mu} \simeq \frac{L_\nu/3A_{\rm eff}\Delta t}{ln(10)\epsilon_{\nu_\mu}4\pi d_s^2} = 0.2 \times \frac{E_{\rm inj}}{5\times10^{50}{\rm erg}} M_6 D_{\rm o,29}^{-1.5} T_4^{-1.5} d_{\rm s,1}^{-2} A_{\rm eff,0.5}\Delta t_1$$

@~50TeV

$$\epsilon_\nu^2\frac{dN_\nu}{d\epsilon_\nu} \simeq \frac{L_\nu}{4\pi d_s^2 ln(10)} = 4\times10^{-12}\ {\rm TeV\ cm^{-2}\ s^{-1}} \frac{E_{\rm inj}}{5\times10^{50}{\rm erg}} M_6 D_{\rm o,29}^{-1.5} T_4^{-1.5} d_{\rm s,1}^{-2}$$

He et al. submitted (2020)

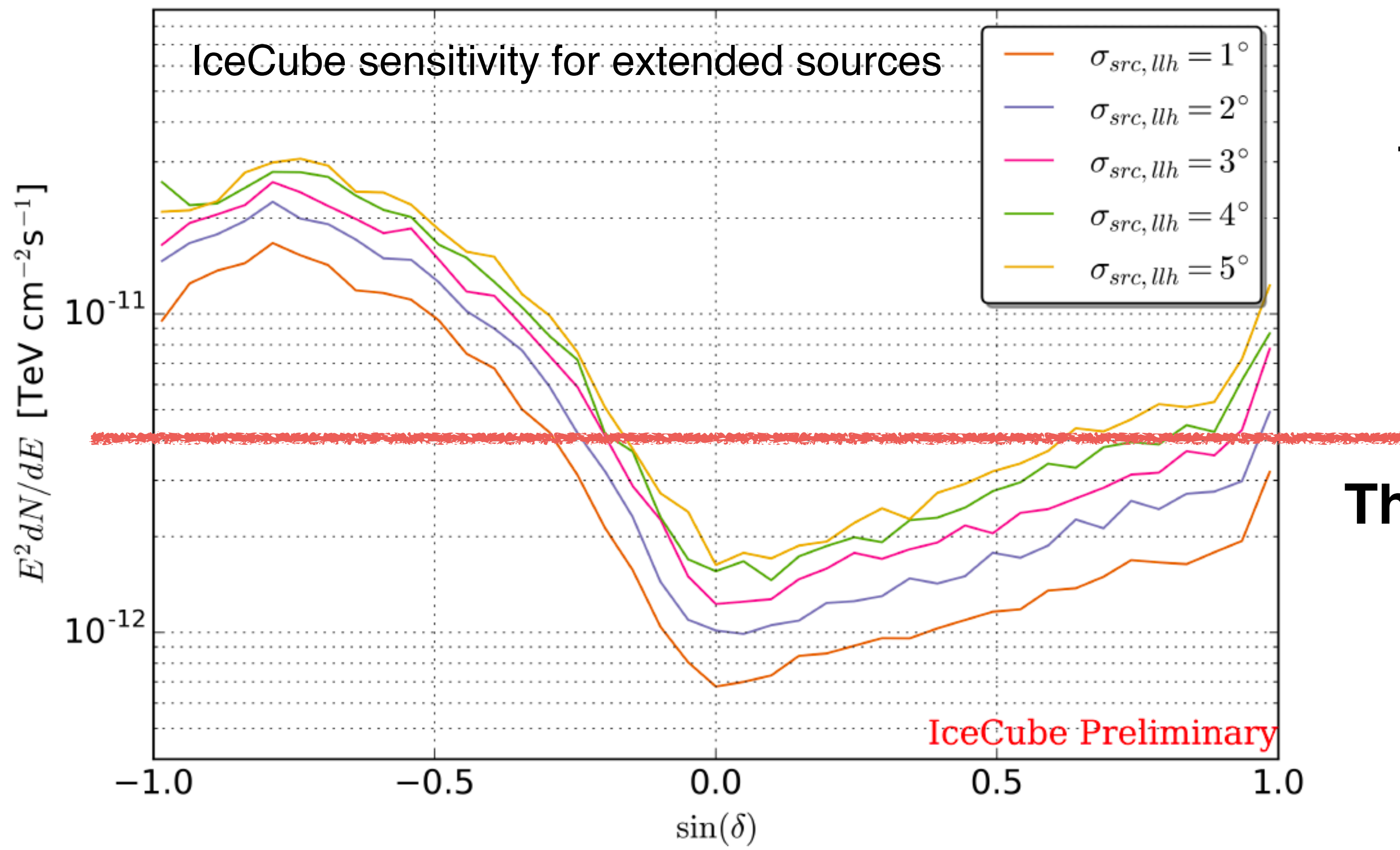


Figure 2: Sensitivity at 90% confidence level for the five extensions considered and an E^{-2} power law spectrum. The best case scenario is assumed, that is when the simulated source extension (σ_{src}) matches exactly the extension of the likelihood scan (σ_{llh}).

Uncertainties:

The injected energy of CRs

The injected time

The diffusion time

The total mass of MC

The distance of the source

The declination of the Source

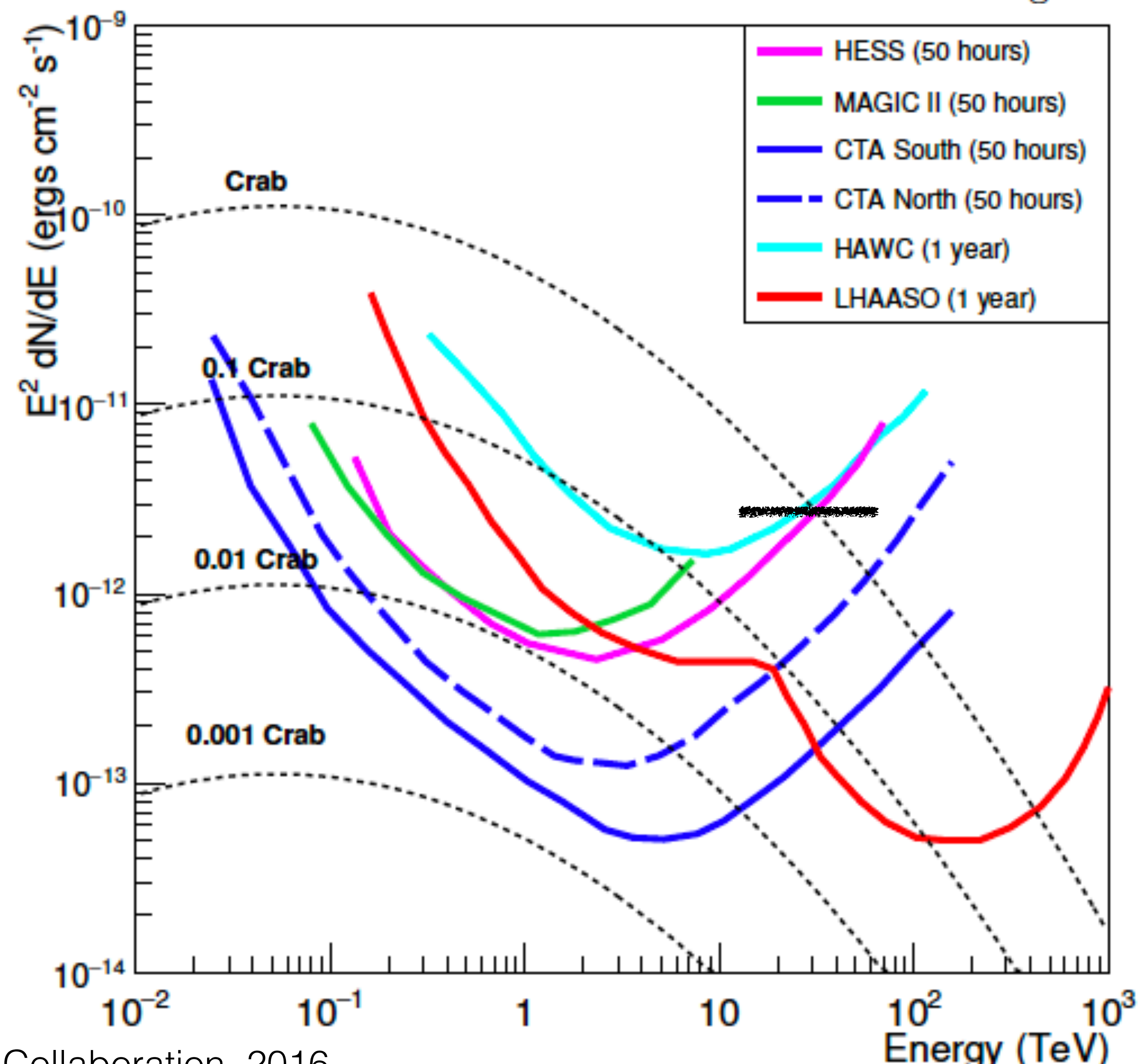
Pinat & Snchez (2018)

A General Gamma-Ray Predictions from PeVatron+MCs

$$\epsilon_\gamma^2 \frac{dN_\gamma}{d\epsilon_\gamma}(\epsilon_\gamma) \simeq \frac{L_\gamma}{4\pi d_s^2 ln(10)} = 3 \times 10^{-12}\ \mathrm{TeV\ cm^{-2}\ s^{-1}} \frac{E_{\rm inj}}{5\times 10^{50}\mathrm{erg}} M_6 D_{\rm o,29}^{-1.5} T_4^{-1.5} d_{\rm s,1}^{-2}$$

The exposure time needed for LHASSO: $t_{\rm LH} = 41\ \mathrm{day} \frac{E_{\rm inj}}{5\times 10^{50}\mathrm{erg}} M_6 D_{\rm o,29}^{-1.5} T_4^{-1.5} d_{\rm s,1}^{-2}$

He et al. submitted (2020)



LHASSO Collaboration, 2016

>10 TeV photons from the Galactic Center

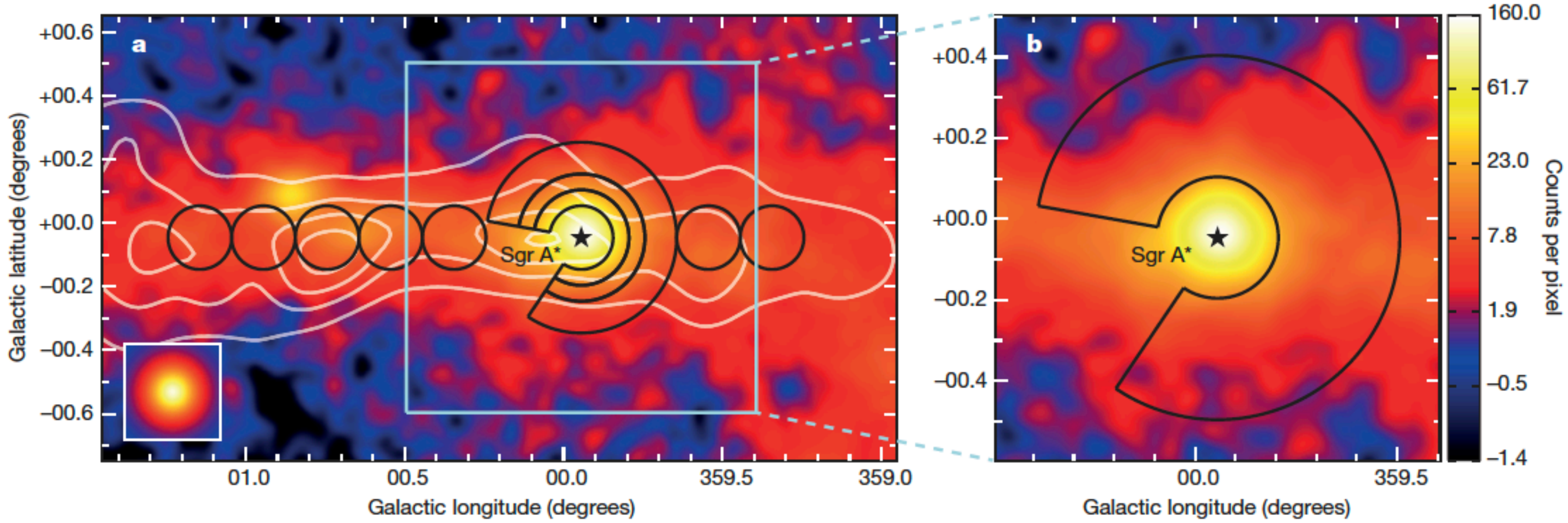


Figure 1 | VHE γ-ray image of the Galactic Centre region. The colour scale indicates counts per 0.02° × 0.02° pixel. **a**, The black lines outline the regions used to calculate the cosmic-ray energy density throughout the central molecular zone. A section of 66° is excluded from the annuli (see Methods). White contour lines indicate the density distribution of molecular gas, as traced by its CS line emission[30]. Black star, location of Sgr A*. Inset (bottom left), simulation of a point-like source. The part of the image shown boxed is magnified in **b**. **b**, Zoomed view of the inner ~70 pc and the contour of the region used to extract the spectrum of the diffuse emission.

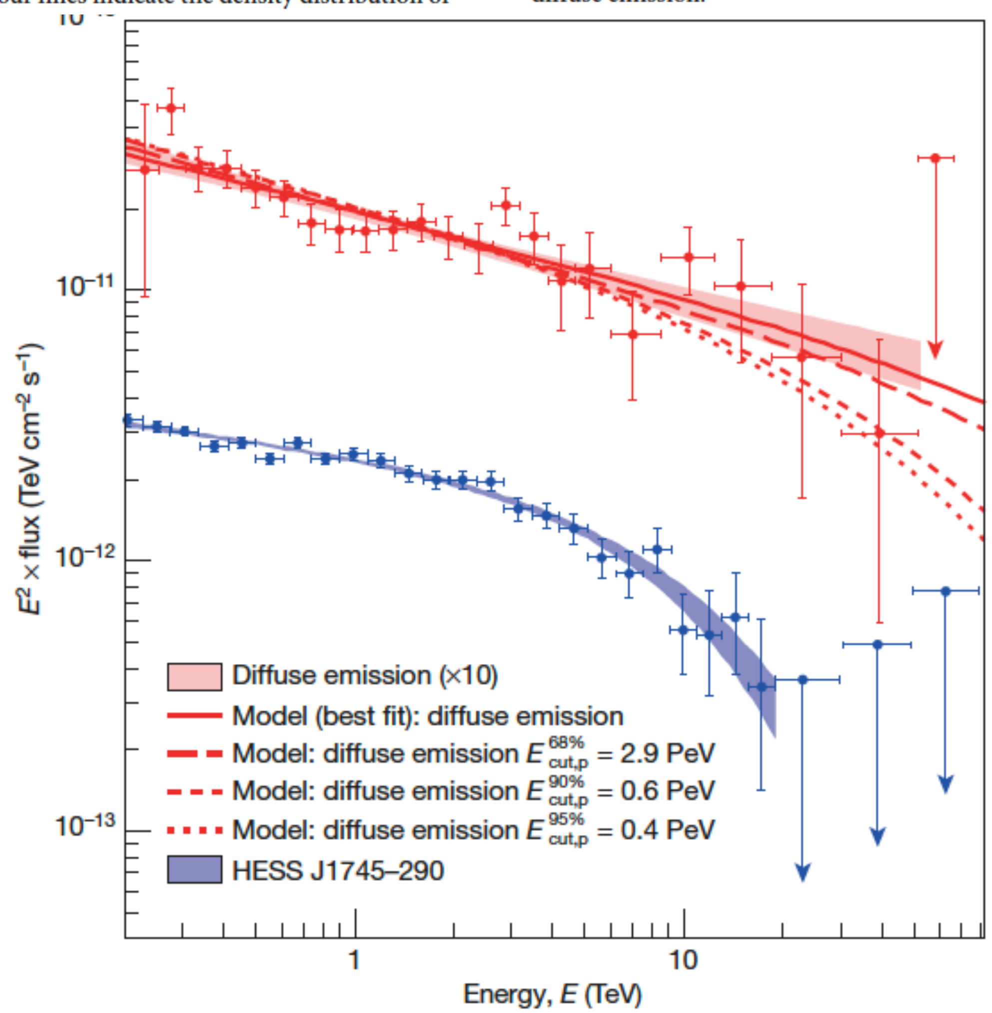


Figure 3 | VHE γ-ray spectra of the diffuse emission and HESS J1745−290. The *y* axis shows fluxes multiplied by a factor E^2, where *E* is the

H.E.S.S. Collaboration, 2016

Cosmic Ray Accelerators in the GC region

Fermi Bubble (Su et al. 2010) → The past star formation activity or the central supermassive black hole activity

A group of massive supergiants and Wolf-Rayet stars (Kauffmann 2017) → A high rate of SNe/HNe/GRBs

The star formation rate in the GC region peaks around 1e5 yr ago

$$\rho_{\rm SFR} = 0.14\ M_\odot\ {\rm yr}^{-1}$$

Yusef-Zadeh et al. (2009) → HNe Rate in the GC region: 1 per 1e5yr

Possible Accelerators in the GC

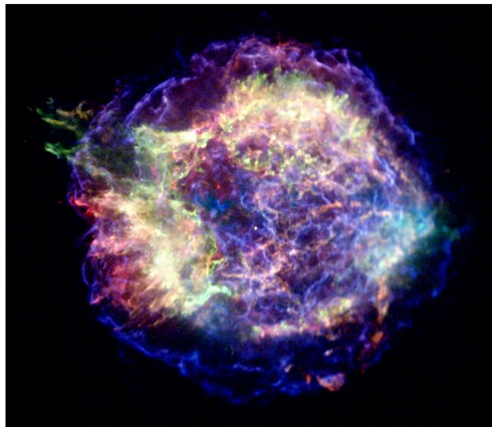
1. Accretion flow or termination of an outflow of Sgr A* (H.E.S.S. Collaboration 2016)

2. Sgr A* is a LLAGN and has a Radiatively inefficient Accretion flows (RIAF) (Fujita, Murase, & Kimura, 2017)

3. A tidal disruption event (TDE) caused by Sgr A* (Liu et al. 2016)

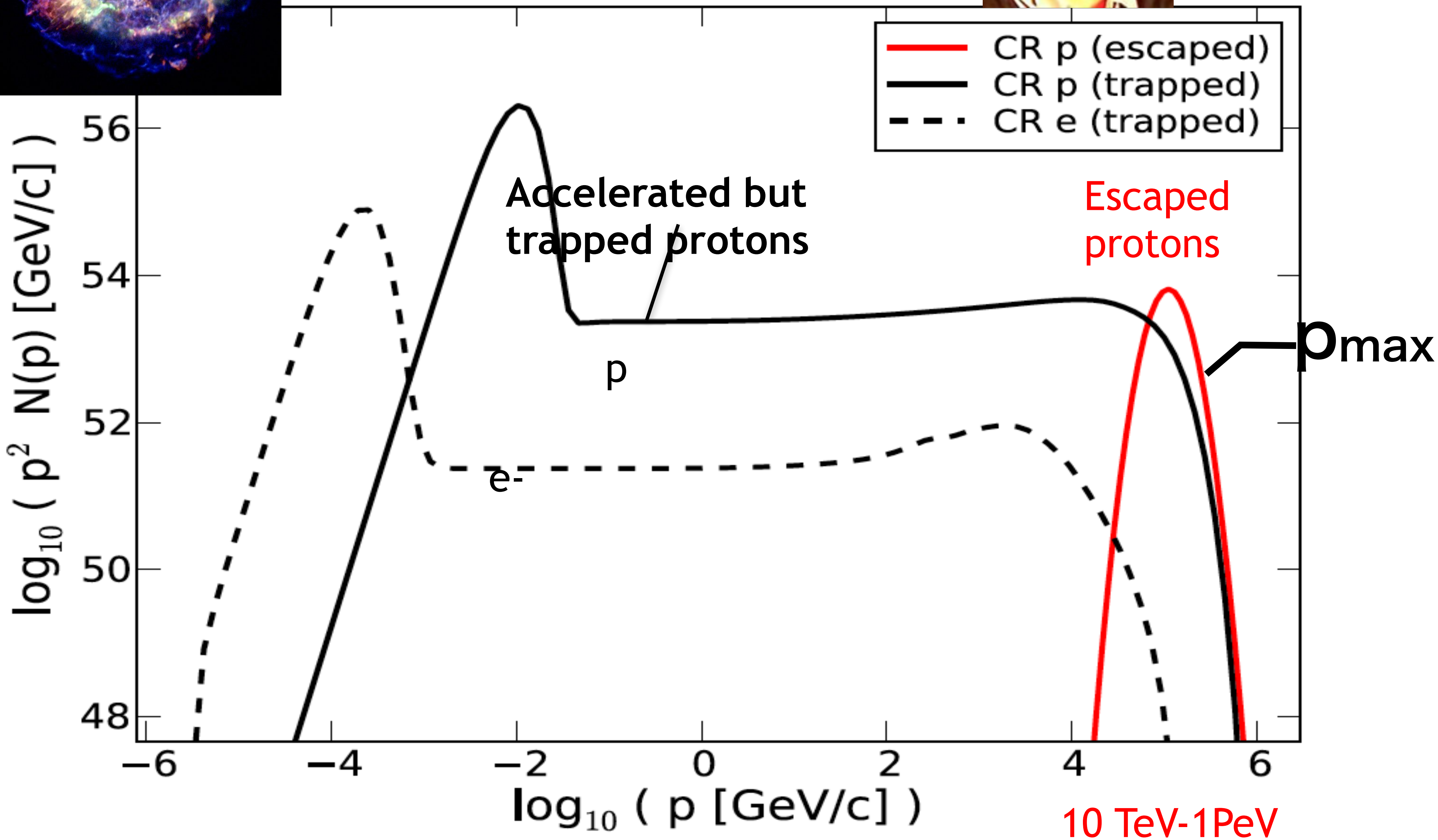
4. A Hypernova Remnant

Non-linear Diffusive Shock Acceleration in SNR/HNR



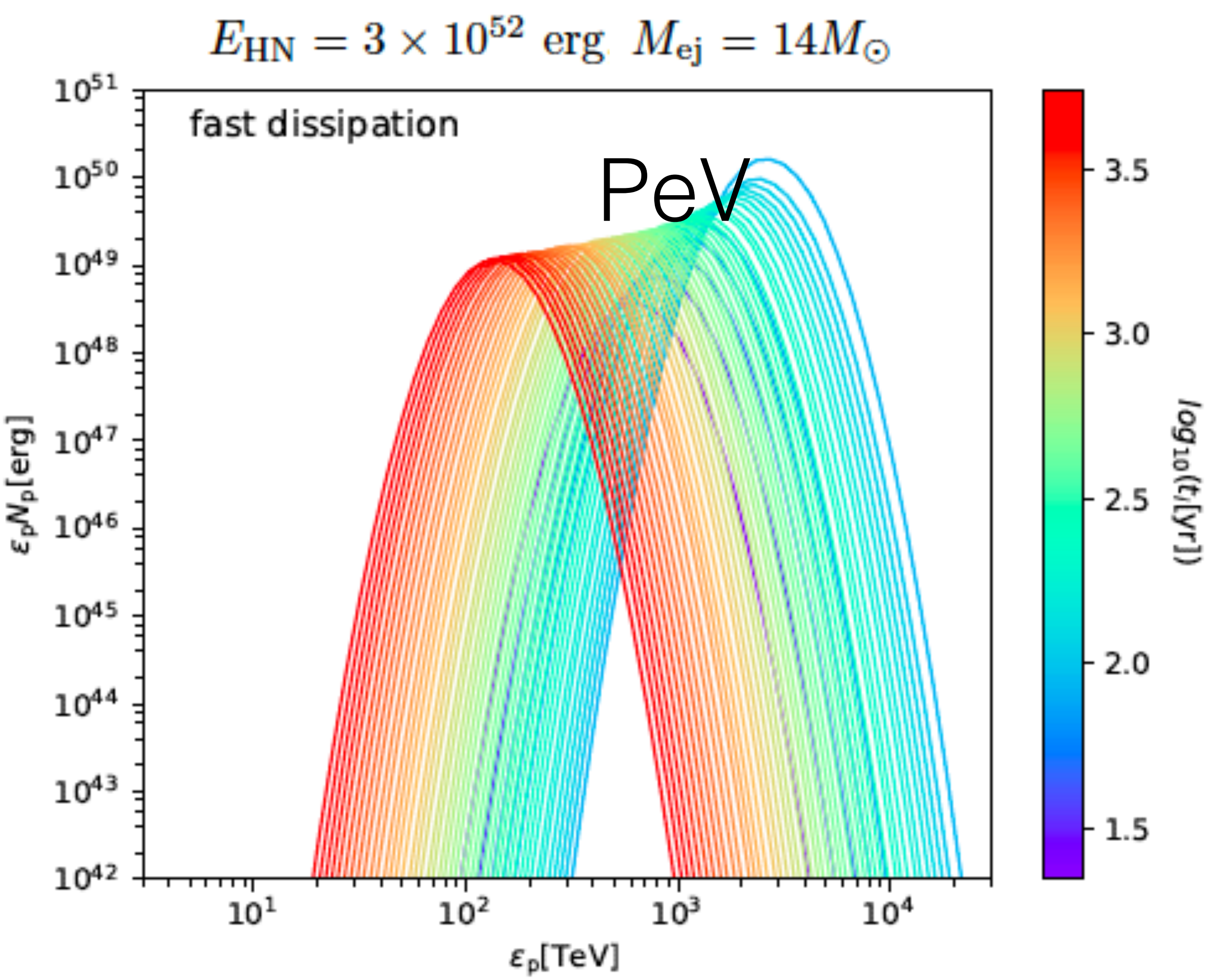
Lee, Ellison & Nagataki (2012)

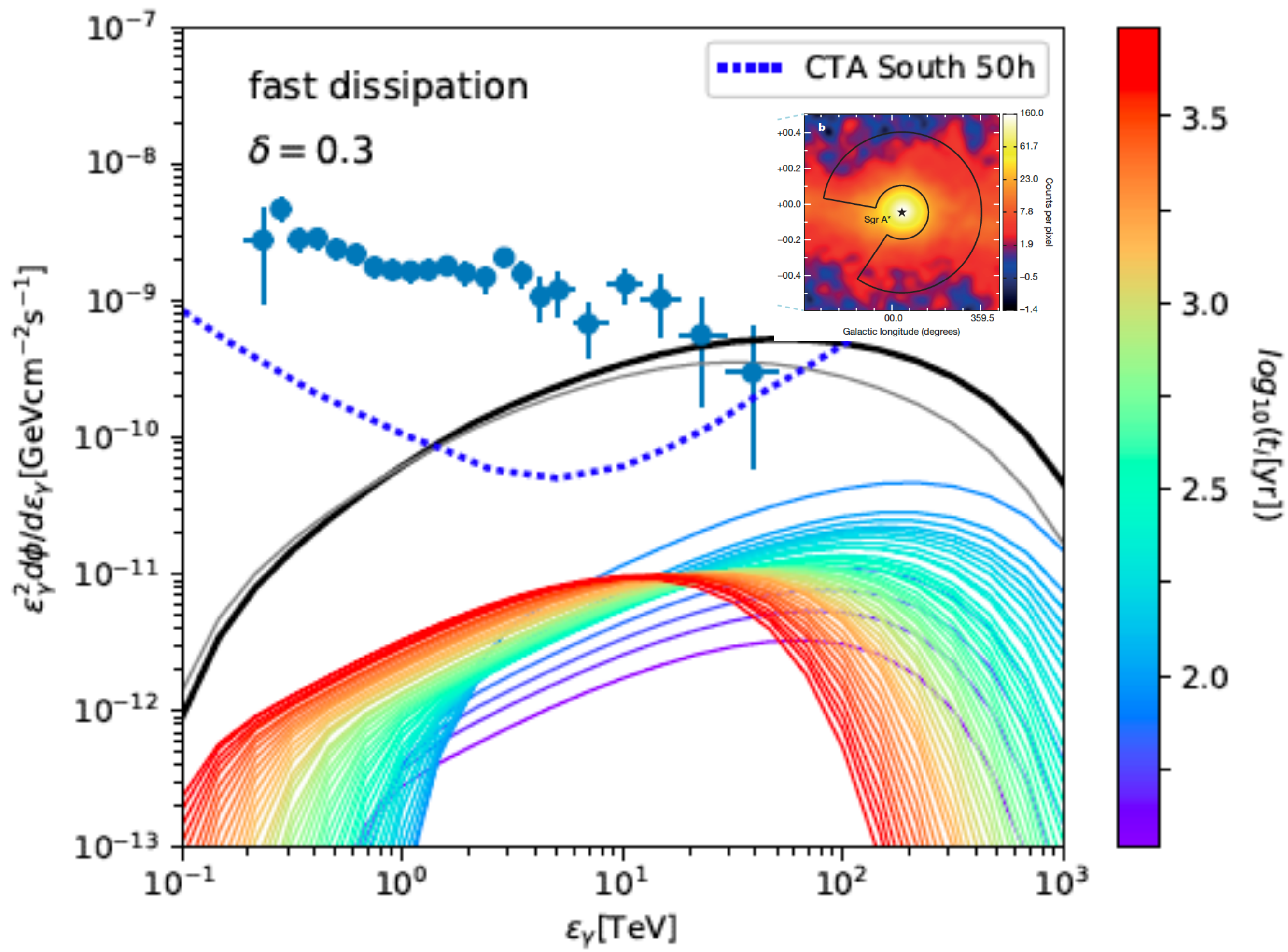
S.H. Lee
(Kyoto University)



Protons that escape from the HNR

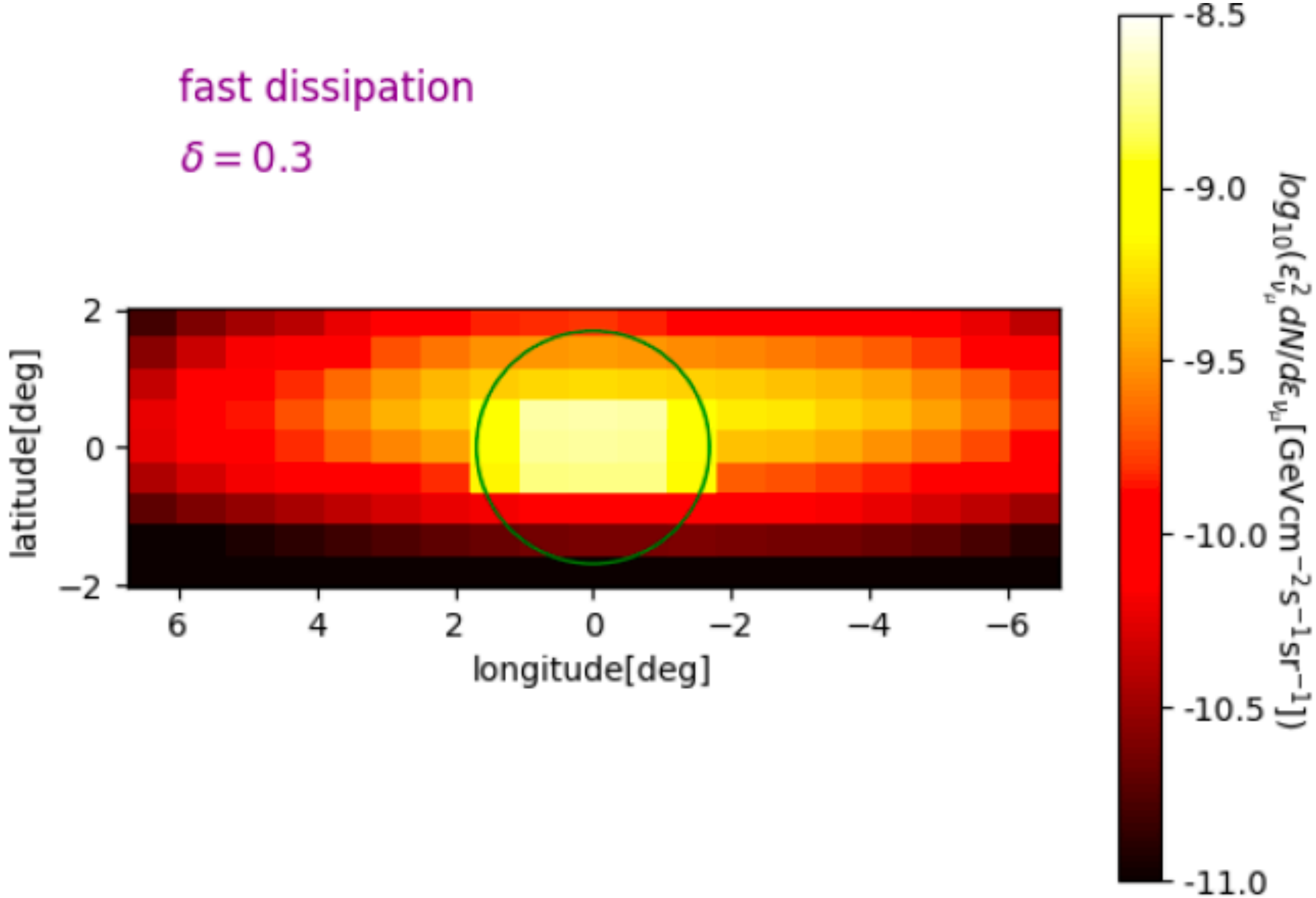
Gamma-Rays from pp inelastic collision between high energy protons and molecular clouds





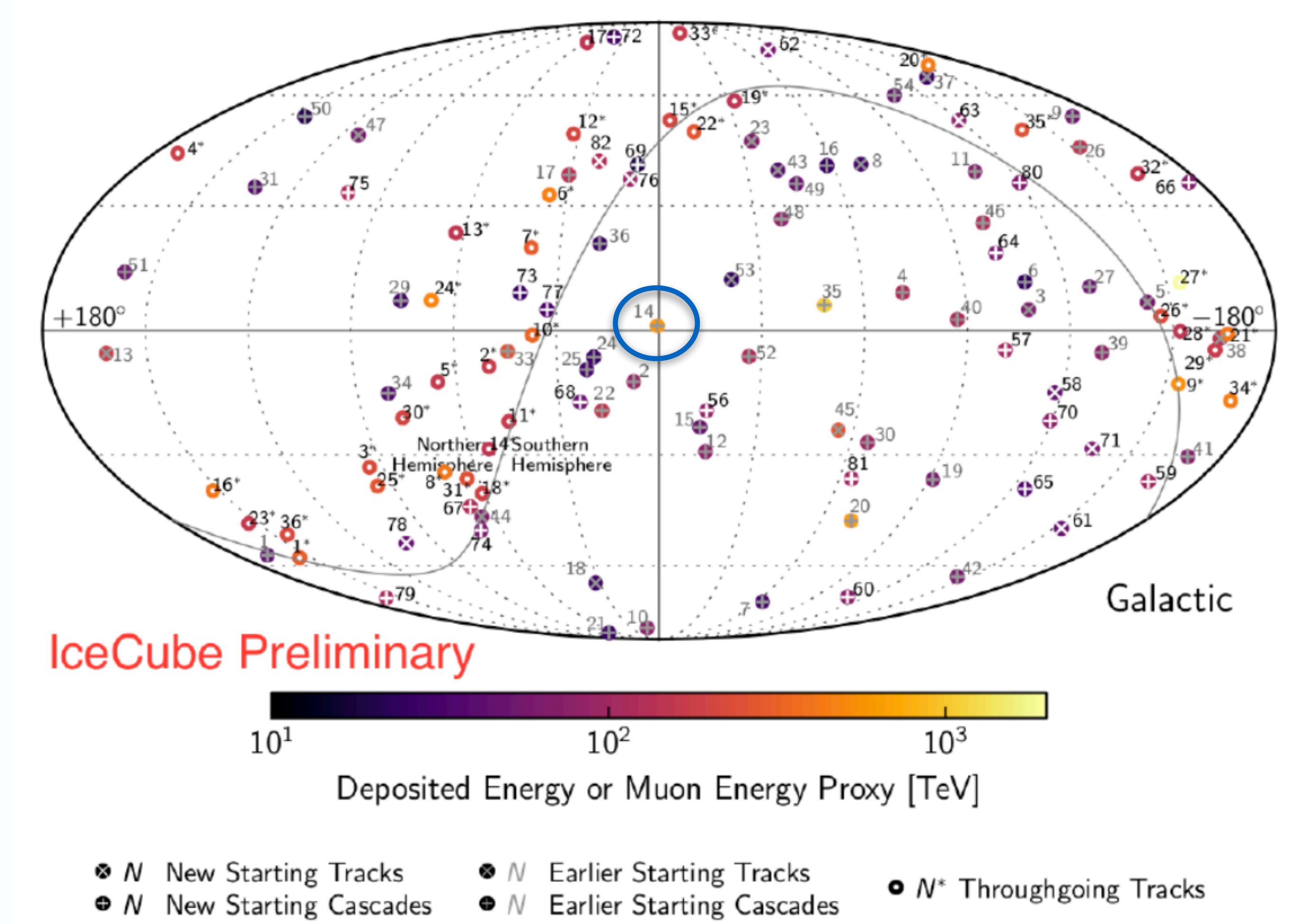
He et al. submitted (2020)

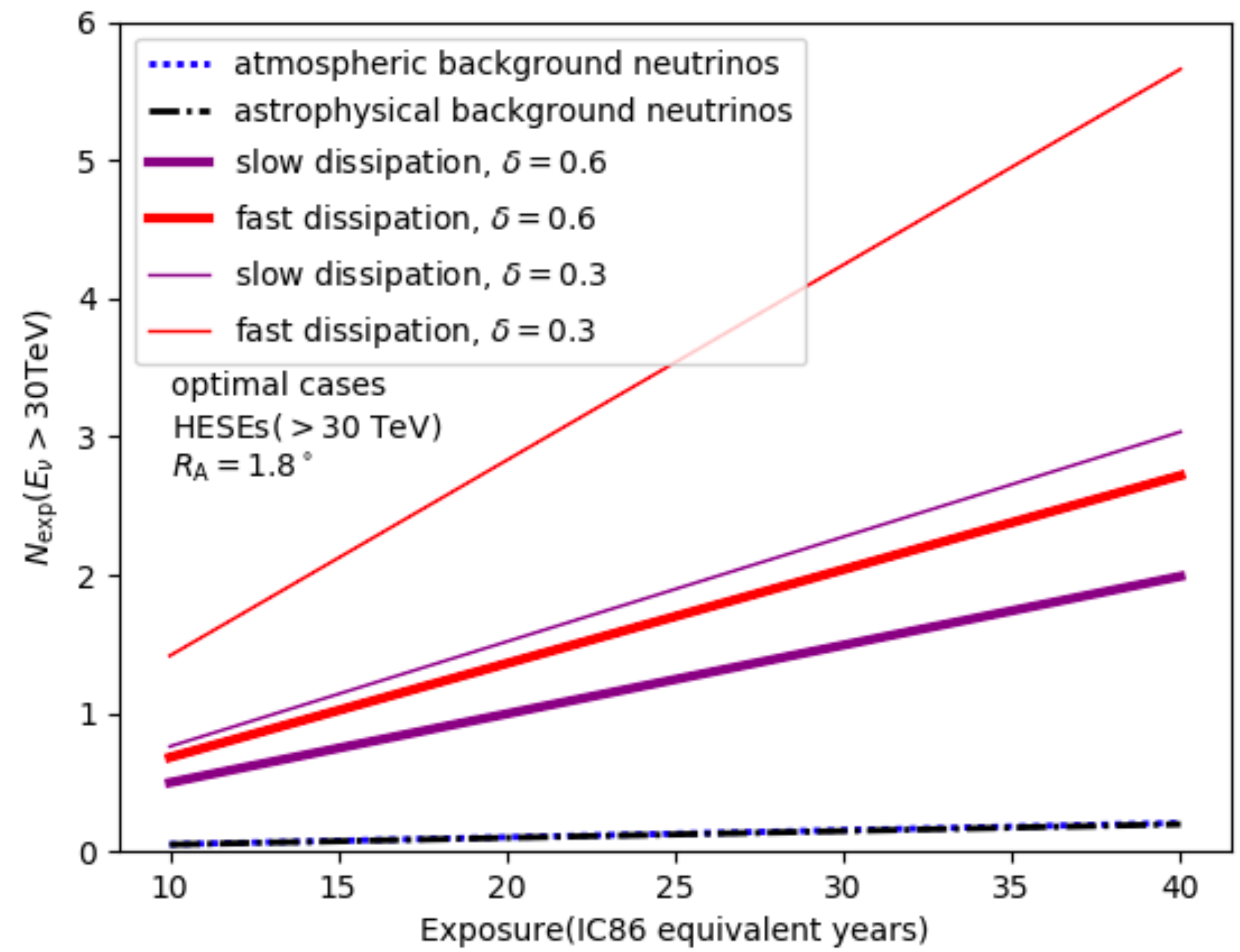
A muon-Neutrino Template of the Galactic Center for IceCube



He et al. submitted (2020)

Expected counts for HESEs





A cascade event with energy of about 1 PeV is reconstructed to point toward 1.2° from the GC with a median angular uncertainty of 13.2° (IceCube Collaboration 2013).

VHE gamma-rays from the GC

The zenith angle of the GC is 65 degree.

The effective area of LHAASO KM2A from the GC direction.

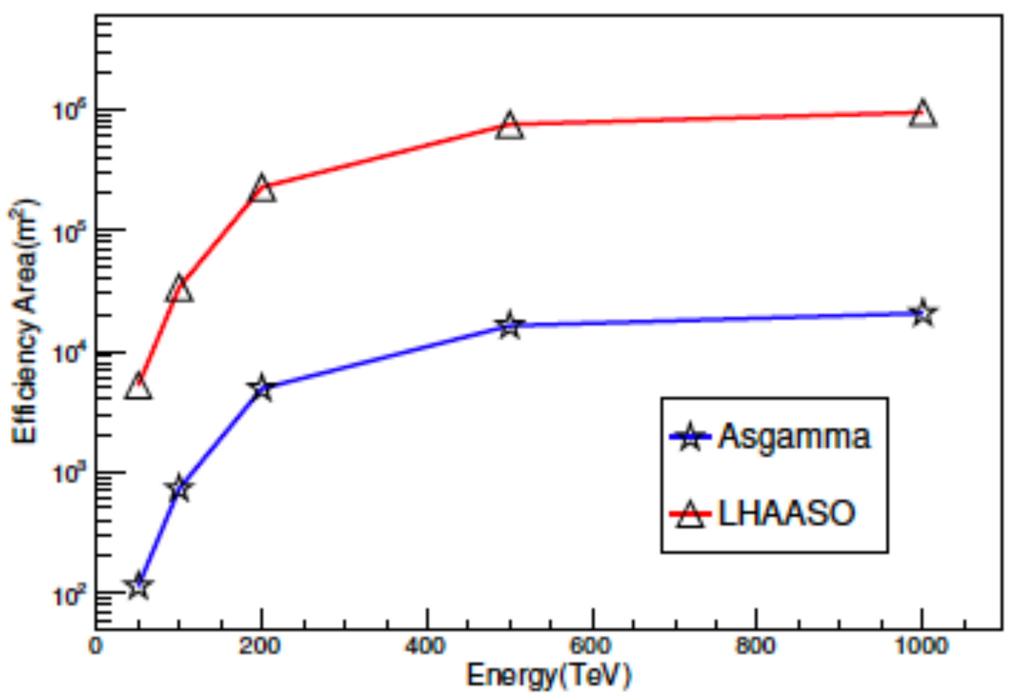
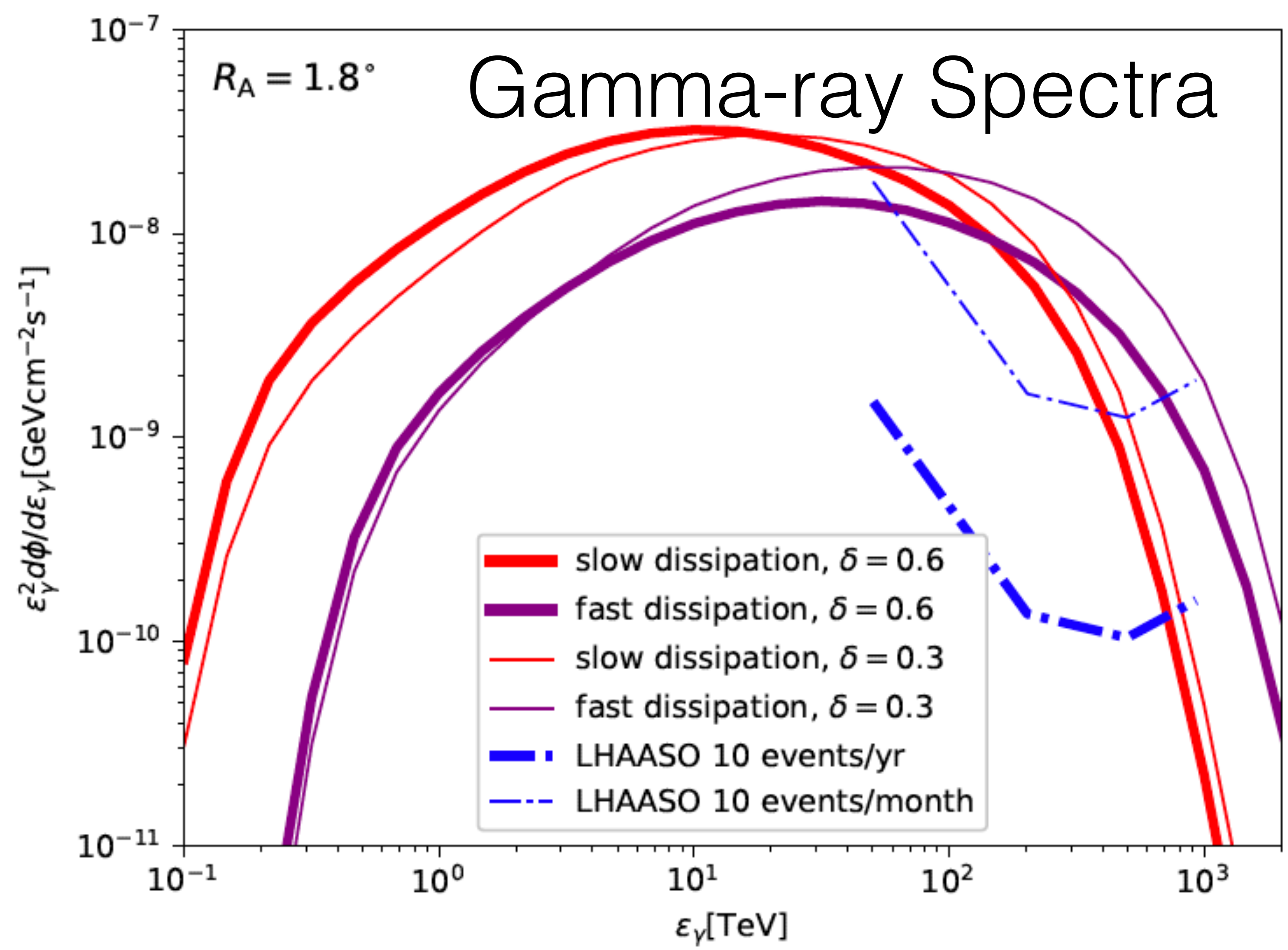


Figure 21: *The effective area of LHAASO for γ-rays from GC direction*

LHAASO White paper (2019)

Owing to the zero background at 100 TeV, 10 gamma-ray events detected can be defined as 5 sigma level.



He et al. submitted (2020)

Prospects

- Searching for spatial and temporal associations between neutrinos and VHE transients (GRBs, or Blazar flares)
- Searching for VHE gamma-rays and neutrinos from nearby galaxy clusters, nearby starburst galaxies
- **Galactic Sources**—SNR/HNR/Stellar Winds+Molecular Cloud Complex in the Galaxy, the Galactic Center
- LHAASO template for the Galactic Plane @ 100 TeV
- IceCube Gen II + KM3Net Observations on neutrinos combining with CTA, HAWC, and LHASSO observations on gamma-rays, with other multi messenger approaches.

Thank you!