Neutrino fluxes from different classes of galactic sources

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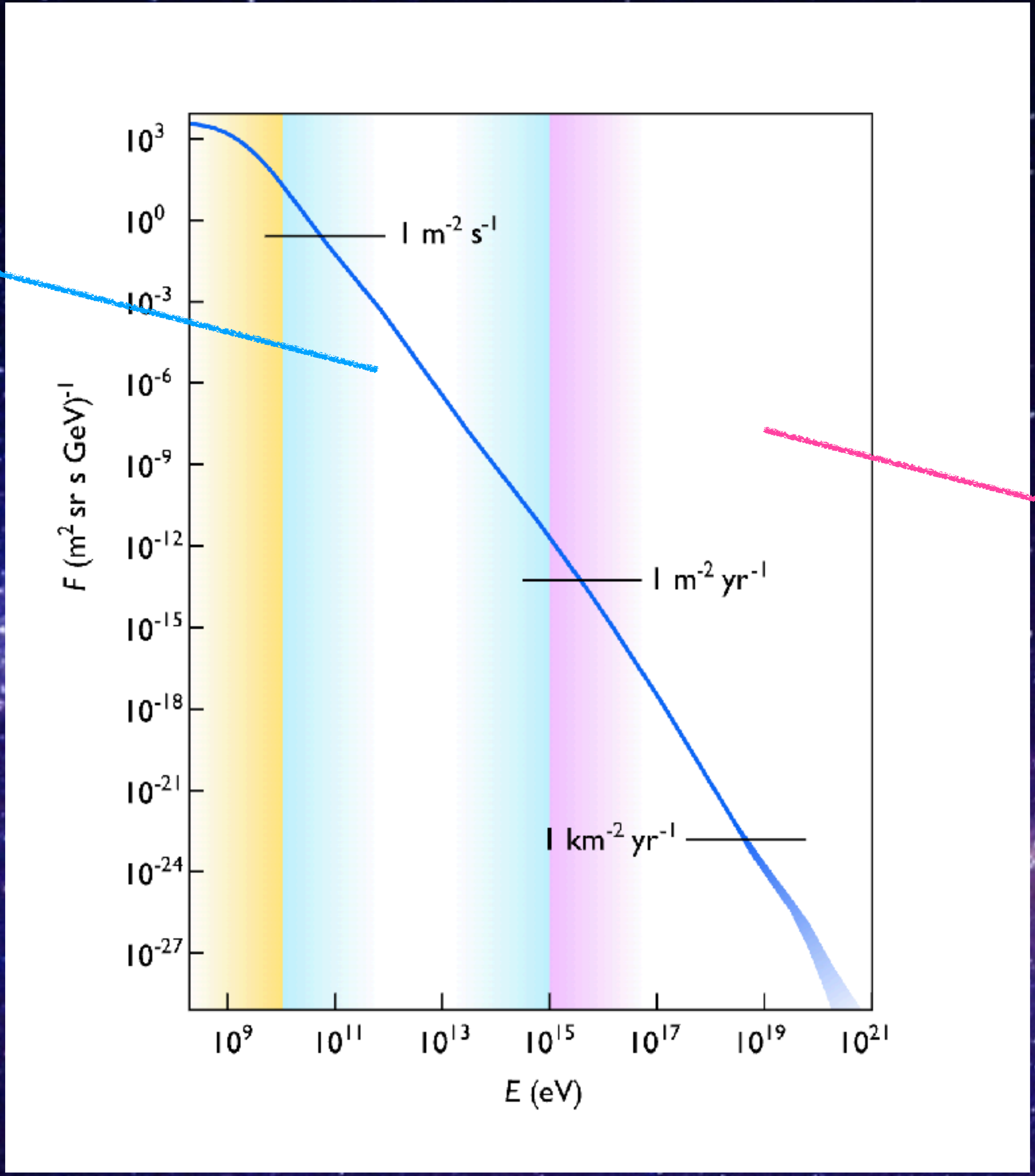
Astro-ph 2403.05288

Cosmic rays energy spectrum



Galactic

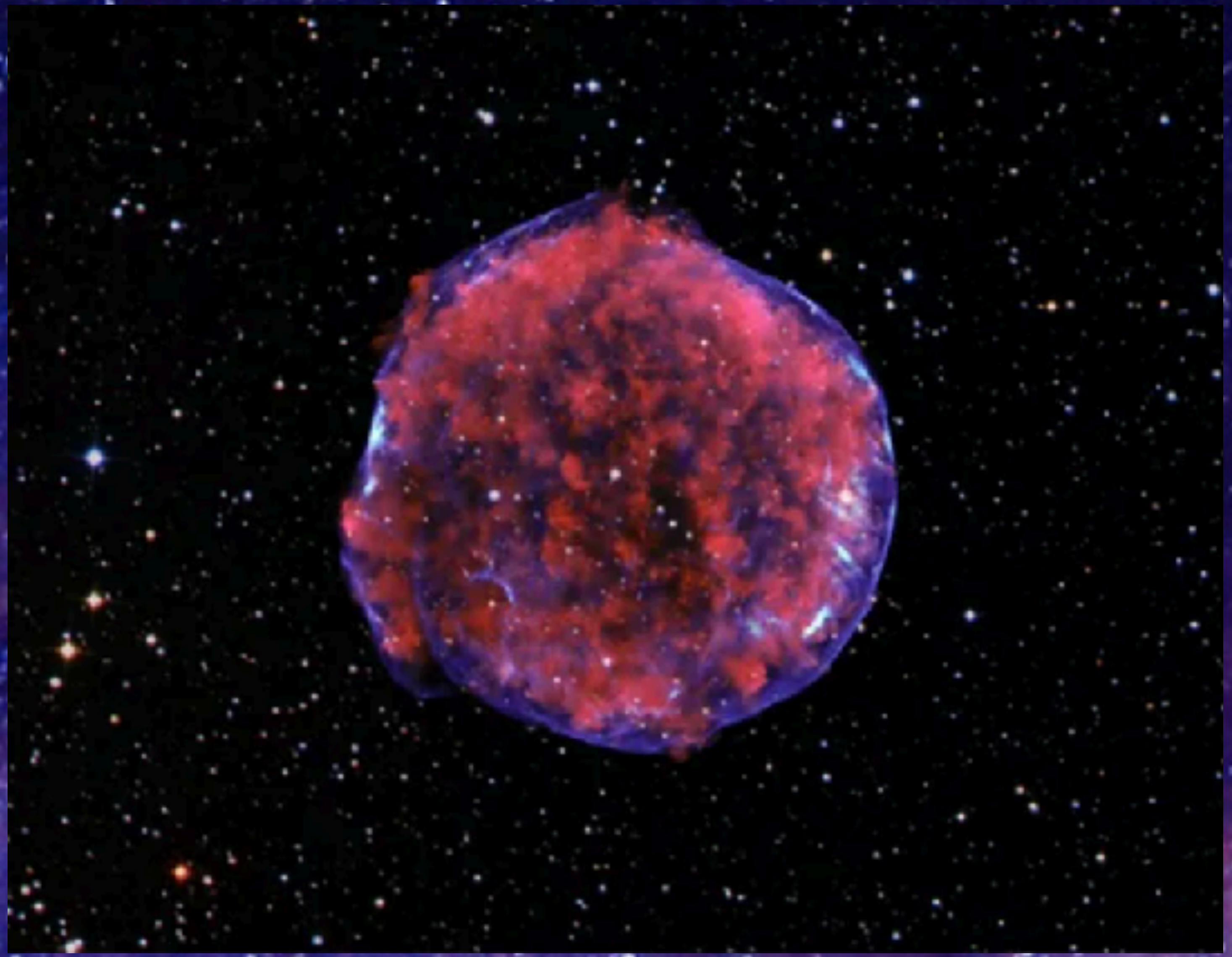
Extra - Galactic

Galactic sources

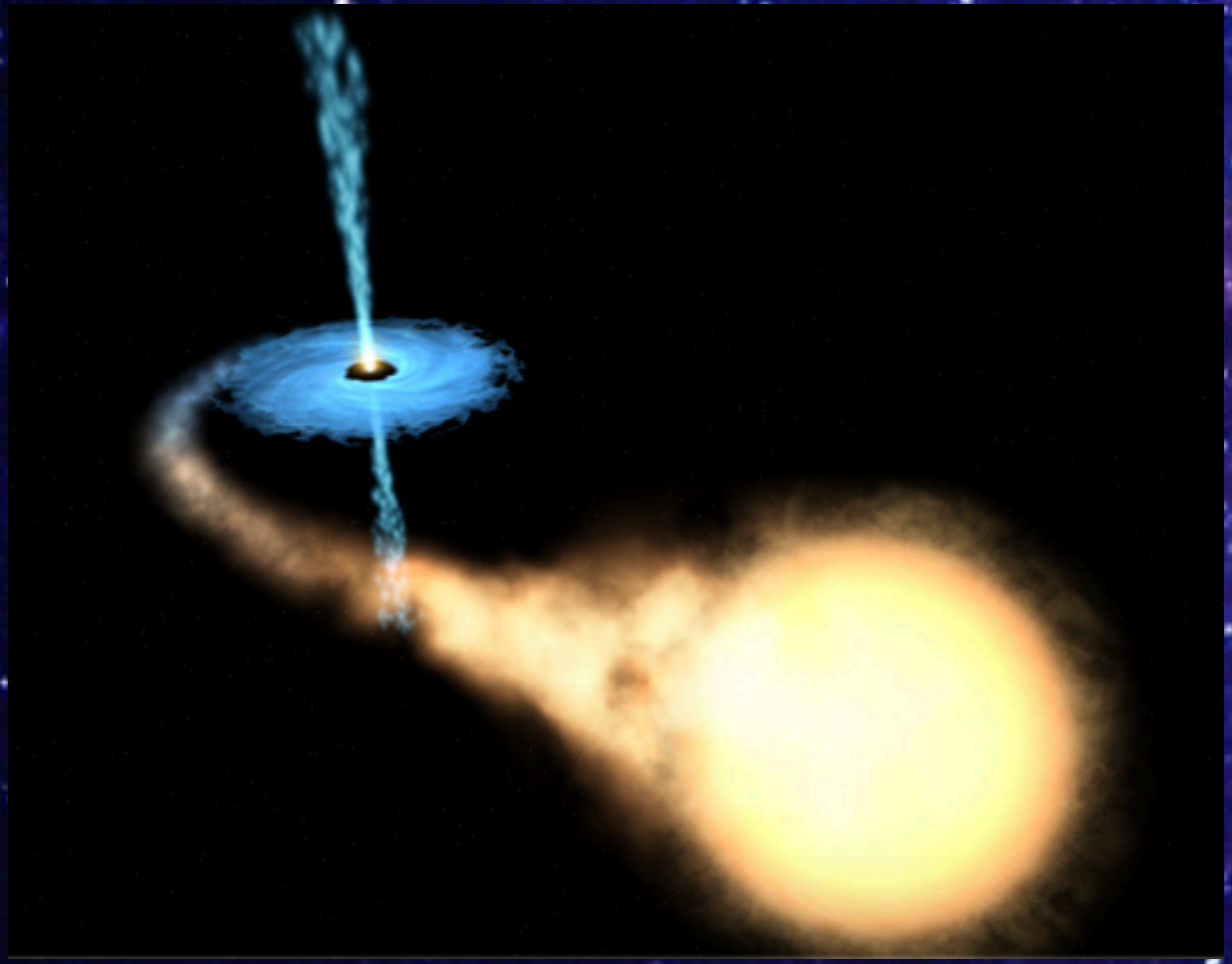
are expected to accelerate cosmic rays (CRs) up to a maximum energy of 1-10 PeV.

Candidate neutrino sources

Pulsar Wind Nebulae (PWN)



Supernova Remnants (SNR)



Microquasar (MQ)

Novae

Neutrino and high energy photon flux

Particles accelerated in galactic astrophysical sources may interact with the matter and/or with photons present in the source

$$p + p \rightarrow \pi^0, \pi^+\pi^-, K^0, K^+, K^-, p, n \ldots$$

$$p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0, n + \pi^+$$

$$\pi^0 \rightarrow \gamma\gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$$

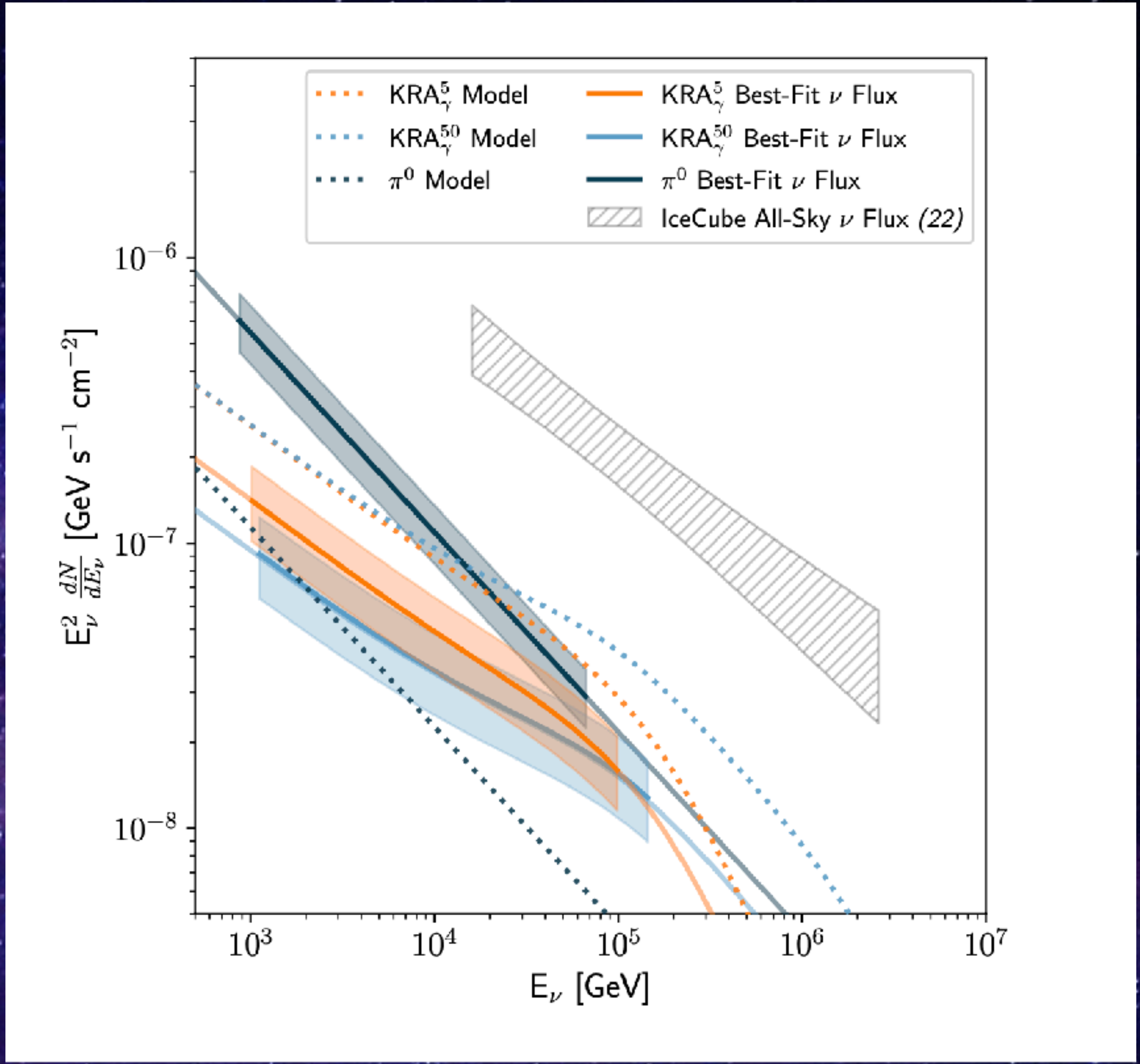
Correlated production of neutrinos and γ-rays opens up the opportunity for multi-messenger searches

Assuming neutrino flux equal to γ-rays

$$\frac{dN_{\nu+\bar{\nu}}}{dE_{\nu+\bar{\nu}}} \simeq \frac{dN_\gamma}{dE_\gamma}$$

Latest results on the galactic neutrino flux

IceCube observation of a diffuse neutrino emission from the Galactic plane at a 4.5 σ level of significance.

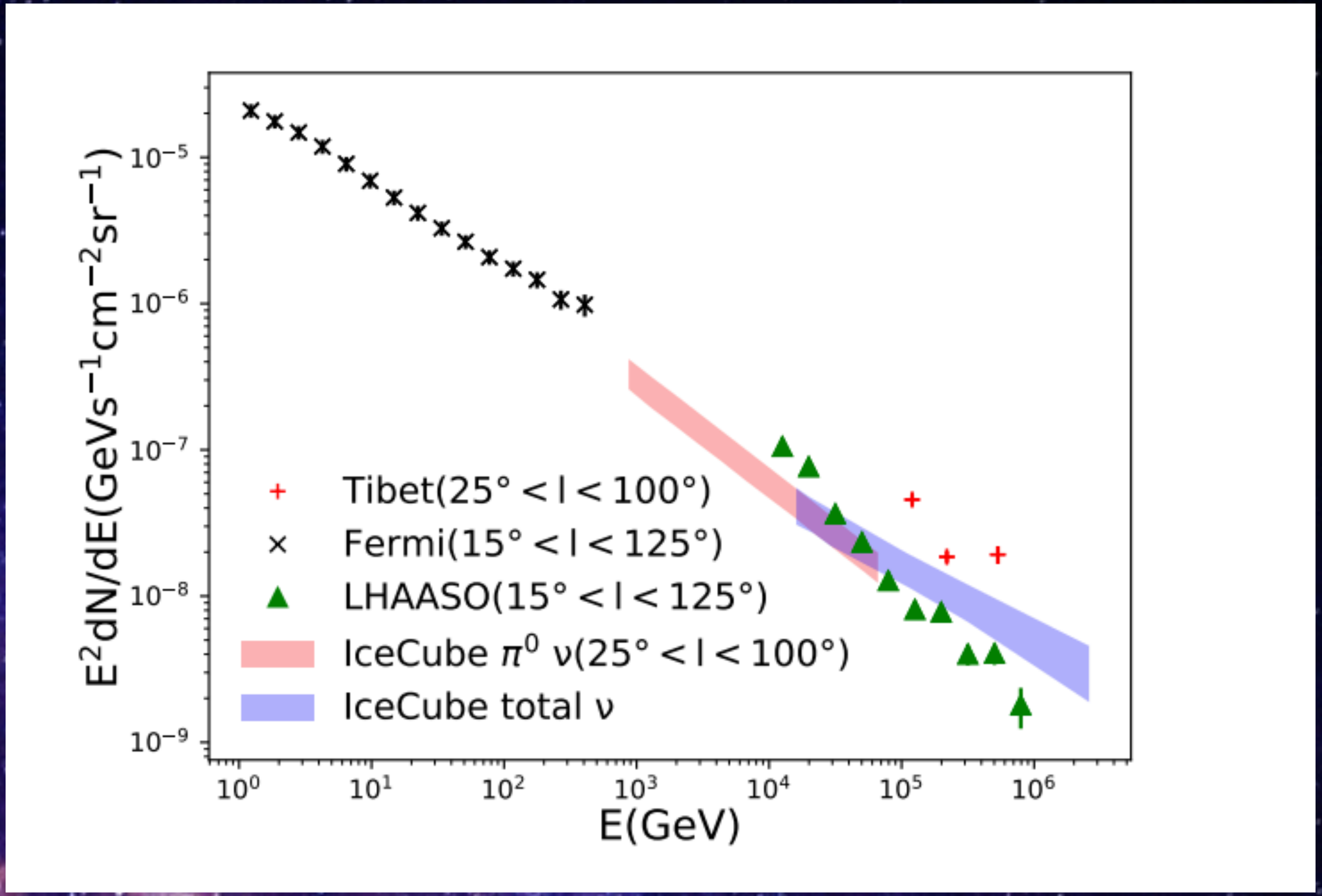


Abbasi, R., Ackermann, M., Adams, J., et al. 2023, Science, 380, 1338, doi: 10.1126/science.adc9818

Evidence of a hadronic component in the TeV emission

The Galactic plane has been observed in γ-rays by Fermi-LAT, by the Tibet ASγ up to 1 PeV and by the LHAASO experiments.

- **Extra unresolved sources are needed to explain the LHAASO measurements in the γ-ray spectrum.**
- **A hadronic component responsible for the high energy emission cannot be excluded.**



Shao, C., Lin, S., & Yang, L. 2023, Phys. Rev. D, 108, L061305, doi: 10.1103/PhysRevD.108.L061305

If part of the diffuse γ-ray emission observed in our galaxy is due to hadronic processes, a correlation with a diffuse neutrino flux emission is expected.

Selected catalog from TeVCat

Criteria:

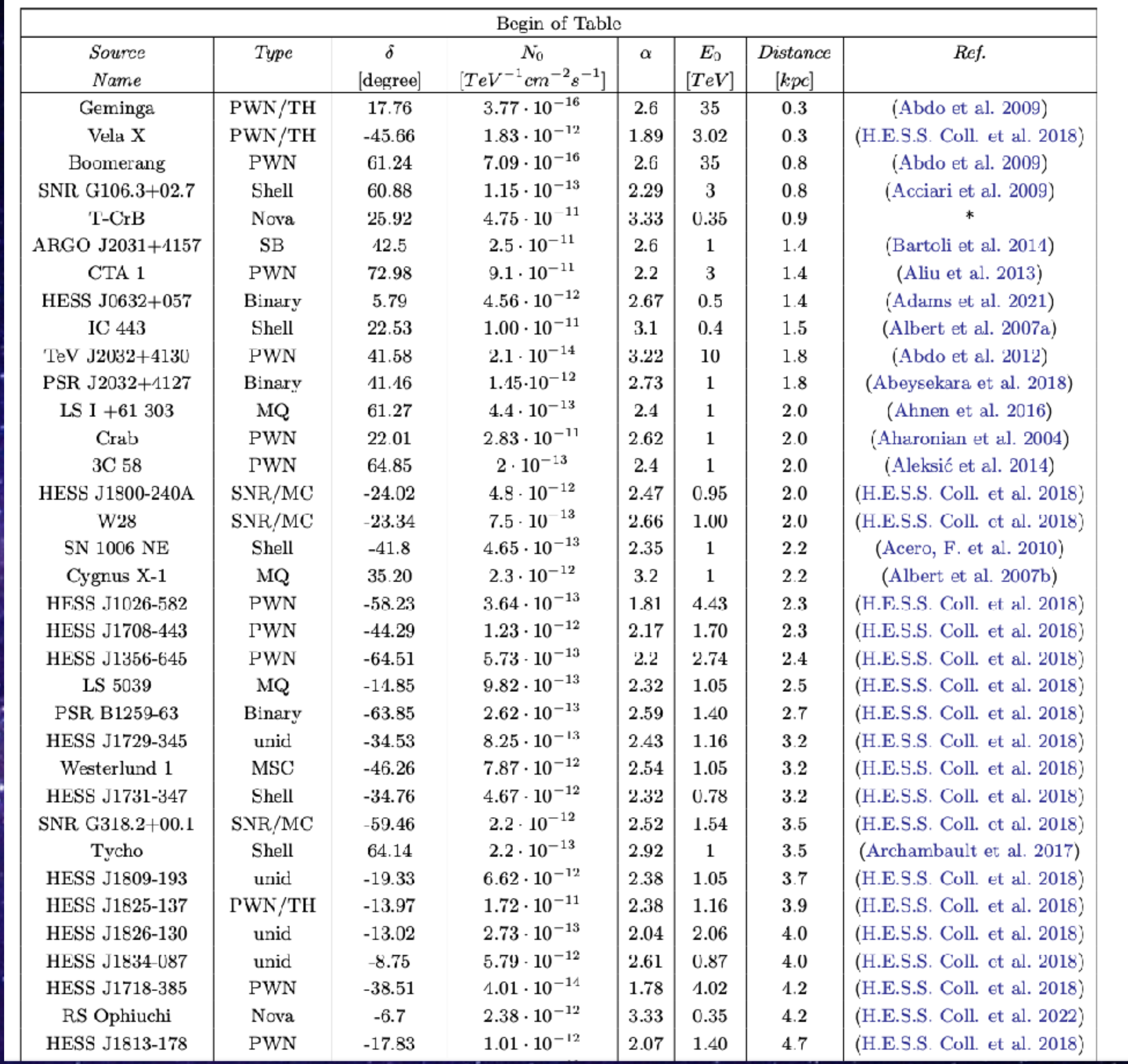
- TeV Observations
- Power Law Spectrum

$$\frac{dN}{dE} = N_0\left(\frac{E}{E_0}\right)^{-\alpha}$$

M = 60 number of sources

$$N_0 \sim 4 \cdot 10^{-12} TeV^{-1} cm^{-2} s^{-1}$$

$$\alpha \sim 2.5$$

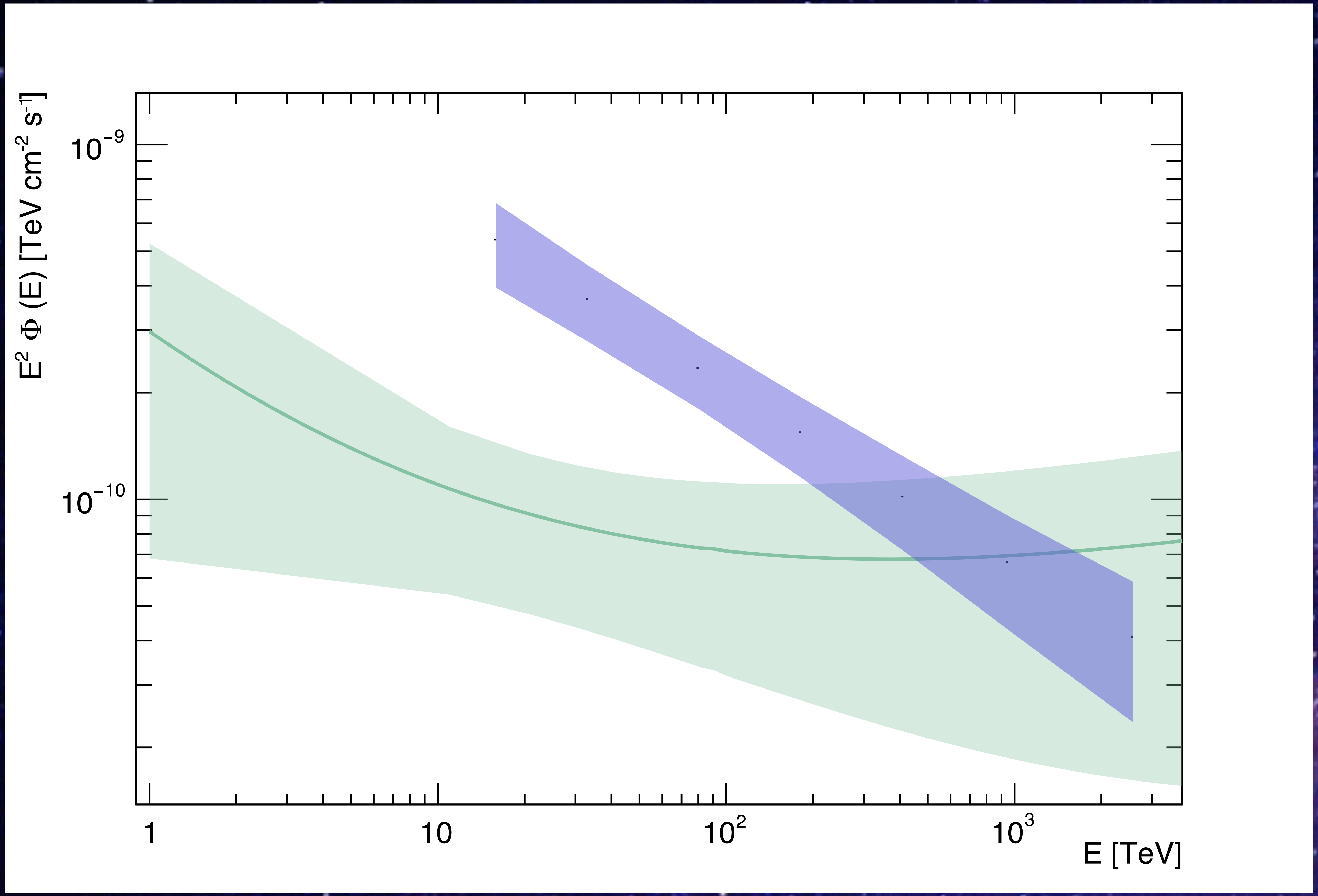


Begin of Table

Source Name	*Type*	δ [degree]	N_0 $[TeV^{-1}cm^{-2}s^{-1}]$	α	E_0 $[TeV]$	*Distance* $[kpc]$	*Ref.*
Geminga	PWN/TH	17.76	$3.77 \cdot 10^{-16}$	2.6	35	0.3	(Abdo et al. 2009)
Vela X	PWN/TH	-45.66	$1.83 \cdot 10^{-12}$	1.89	3.02	0.3	(H.E.S.S. Coll. et al. 2018)
Boomerang	PWN	61.24	$7.09 \cdot 10^{-16}$	2.6	35	0.8	(Abdo et al. 2009)
SNR G106.3+02.7	Shell	60.88	$1.15 \cdot 10^{-13}$	2.29	3	0.8	(Acciari et al. 2009)
T-CrB	Nova	25.92	$4.75 \cdot 10^{-11}$	3.33	0.35	0.9	*
ARGO J2031+4157	SB	42.5	$2.5 \cdot 10^{-11}$	2.6	1	1.4	(Bartoli et al. 2014)
CTA 1	PWN	72.98	$9.1 \cdot 10^{-11}$	2.2	3	1.4	(Aliu et al. 2013)
HESS J0632+057	Binary	5.79	$4.56 \cdot 10^{-12}$	2.67	0.5	1.4	(Adams et al. 2021)
IC 443	Shell	22.53	$1.00 \cdot 10^{-11}$	3.1	0.4	1.5	(Albert et al. 2007a)
TeV J2032+4130	PWN	41.58	$2.1 \cdot 10^{-14}$	3.22	10	1.8	(Abdo et al. 2012)
PSR J2032+4127	Binary	41.46	$1.45 \cdot 10^{-12}$	2.73	1	1.8	(Abeysekara et al. 2018)
LS I +61 303	MQ	61.27	$4.4 \cdot 10^{-13}$	2.4	1	2.0	(Ahnen et al. 2016)
Crab	PWN	22.01	$2.83 \cdot 10^{-11}$	2.62	1	2.0	(Aharonian et al. 2004)
3C 58	PWN	64.85	$2 \cdot 10^{-13}$	2.4	1	2.0	(Aleksić et al. 2014)
HESS J1800-240A	SNR/MC	-24.02	$4.8 \cdot 10^{-12}$	2.47	0.95	2.0	(H.E.S.S. Coll. et al. 2018)
W28	SNR/MC	-23.34	$7.5 \cdot 10^{-13}$	2.66	1.00	2.0	(H.E.S.S. Coll. et al. 2018)
SN 1006 NE	Shell	-41.8	$4.65 \cdot 10^{-13}$	2.35	1	2.2	(Acero, F. et al. 2010)
Cygnus X-1	MQ	35.20	$2.3 \cdot 10^{-12}$	3.2	1	2.2	(Albert et al. 2007b)
HESS J1026-582	PWN	-58.23	$3.64 \cdot 10^{-13}$	1.81	4.43	2.3	(H.E.S.S. Coll. et al. 2018)
HESS J1708-443	PWN	-44.29	$1.23 \cdot 10^{-12}$	2.17	1.70	2.3	(H.E.S.S. Coll. et al. 2018)
HESS J1356-645	PWN	-64.51	$5.73 \cdot 10^{-13}$	2.2	2.74	2.4	(H.E.S.S. Coll. et al. 2018)
LS 5039	MQ	-14.85	$9.82 \cdot 10^{-13}$	2.32	1.05	2.5	(H.E.S.S. Coll. et al. 2018)
PSR B1259-63	Binary	-63.85	$2.62 \cdot 10^{-13}$	2.59	1.40	2.7	(H.E.S.S. Coll. et al. 2018)
HESS J1729-345	unid	-34.53	$8.25 \cdot 10^{-13}$	2.43	1.16	3.2	(H.E.S.S. Coll. et al. 2018)
Westerlund 1	MSC	-46.26	$7.87 \cdot 10^{-12}$	2.54	1.05	3.2	(H.E.S.S. Coll. et al. 2018)
HESS J1731-347	Shell	-34.76	$4.67 \cdot 10^{-12}$	2.32	0.78	3.2	(H.E.S.S. Coll. et al. 2018)
SNR G318.2+00.1	SNR/MC	-59.46	$2.2 \cdot 10^{-12}$	2.52	1.54	3.5	(H.E.S.S. Coll. et al. 2018)
Tycho	Shell	64.14	$2.2 \cdot 10^{-13}$	2.92	1	3.5	(Archambault et al. 2017)
HESS J1809-193	unid	-19.33	$6.62 \cdot 10^{-12}$	2.38	1.05	3.7	(H.E.S.S. Coll. et al. 2018)
HESS J1825-137	PWN/TH	-13.97	$1.72 \cdot 10^{-11}$	2.38	1.16	3.9	(H.E.S.S. Coll. et al. 2018)
HESS J1826-130	unid	-13.02	$2.73 \cdot 10^{-13}$	2.04	2.06	4.0	(H.E.S.S. Coll. et al. 2018)
HESS J1834-087	unid	-8.75	$5.79 \cdot 10^{-12}$	2.61	0.87	4.0	(H.E.S.S. Coll. et al. 2018)
HESS J1718-385	PWN	-38.51	$4.01 \cdot 10^{-14}$	1.78	4.02	4.2	(H.E.S.S. Coll. et al. 2018)
RS Ophiuchi	Nova	-6.7	$2.38 \cdot 10^{-12}$	3.33	0.35	4.2	(H.E.S.S. Coll. et al. 2022)
HESS J1813-178	PWN	-17.83	$1.01 \cdot 10^{-12}$	2.07	1.40	4.7	(H.E.S.S. Coll. et al. 2018)

Galactic neutrino flux

Contribution of the galactic sources to the diffuse flux detected by IceCube

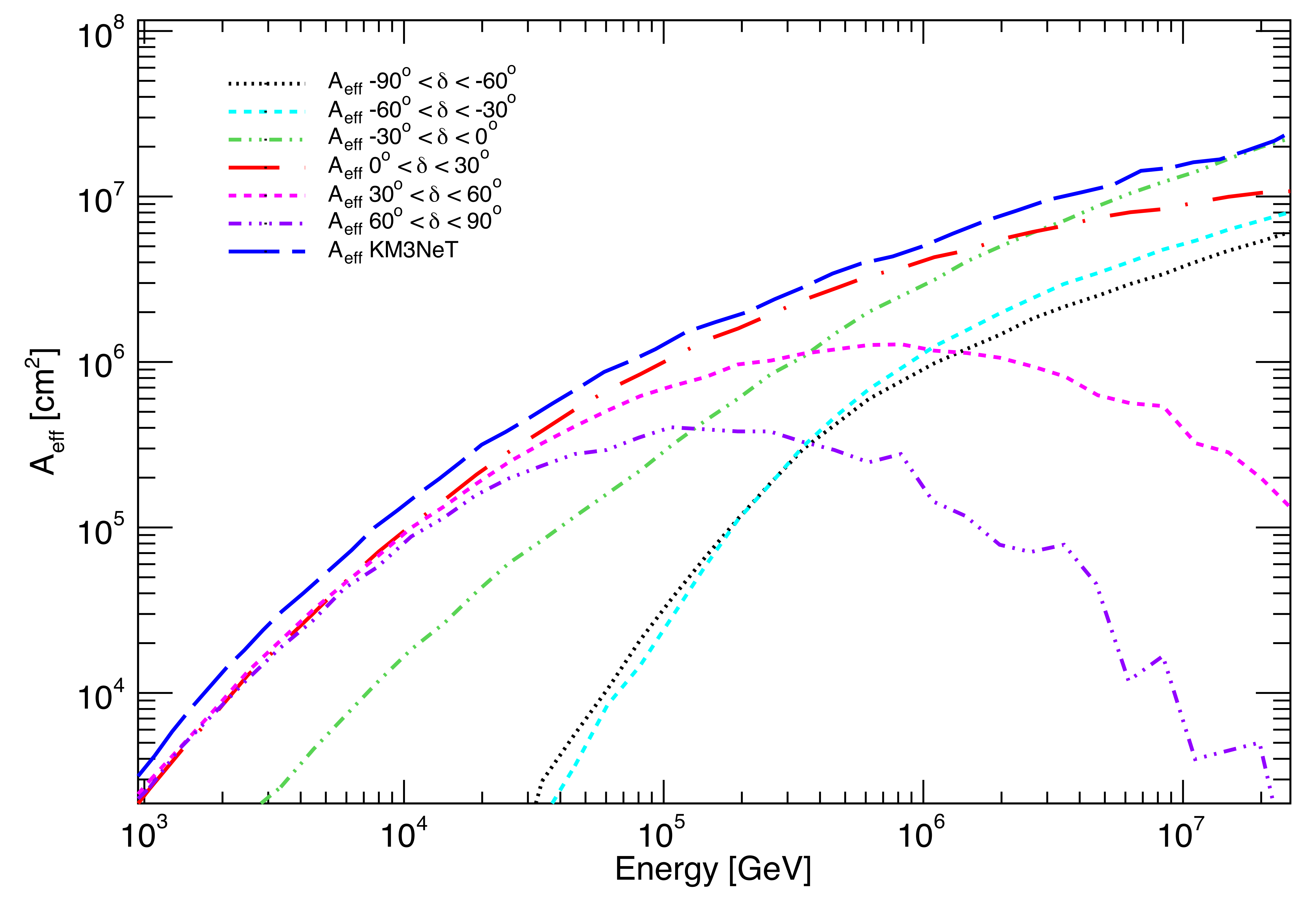


$$\left(\frac{dN}{dEdSdt}\right)_{TOT} = \sum_{i=1}^{M} N_{0,i}\left(\frac{E}{1TeV}\right)^{-\alpha_i}$$

M = 60 number of sources

The galactic flux estimated in this work is ~ 20% of the IceCube All-Sky ν Flux for E~10 TeV

Icecube expected events from point like Galactic sources



$$n^{IC}_{events} = \int_{E_1}^{E_2} T \frac{dN_\nu}{dE_\nu} A(E_\nu, \delta) dE_\nu$$

T = 1 year

Track like events

ARCA expected events from point like Galactic sources

KM3NeT visibility $V(\delta)$

$$n_{events}^{ARCA} = \int_{E_1}^{E_2} T \frac{dN_\nu}{dE_\nu} A(E_\nu) V(\delta) dE_\nu$$

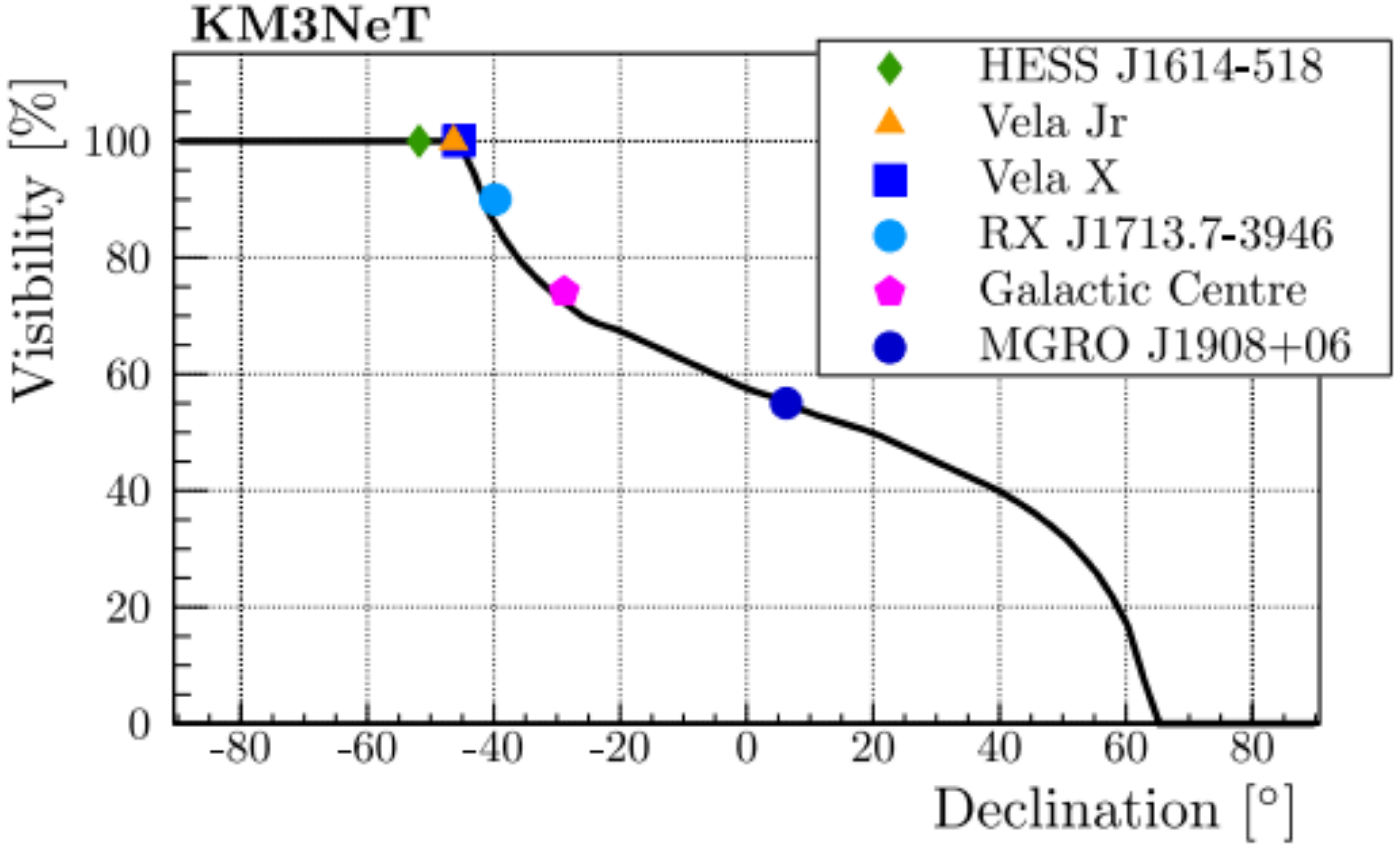


Fig. 1. Source visibility for KM3NeT/ARCA as a function of declination for a zenith cut of 10° above the horizon (black line). The markers represent the visibility of the specific sources discussed in this paper according to their declination and the zenith cuts used in the analyses (see Table 2 for the individual zenith cuts).

Aiello, S., Akrame, S. E., Ameli, F., et al. 2019, Astroparticle Physics, 111, 100, doi: 10.1016/j.astropartphys.2019.04.002

Background: atmospheric neutrinos

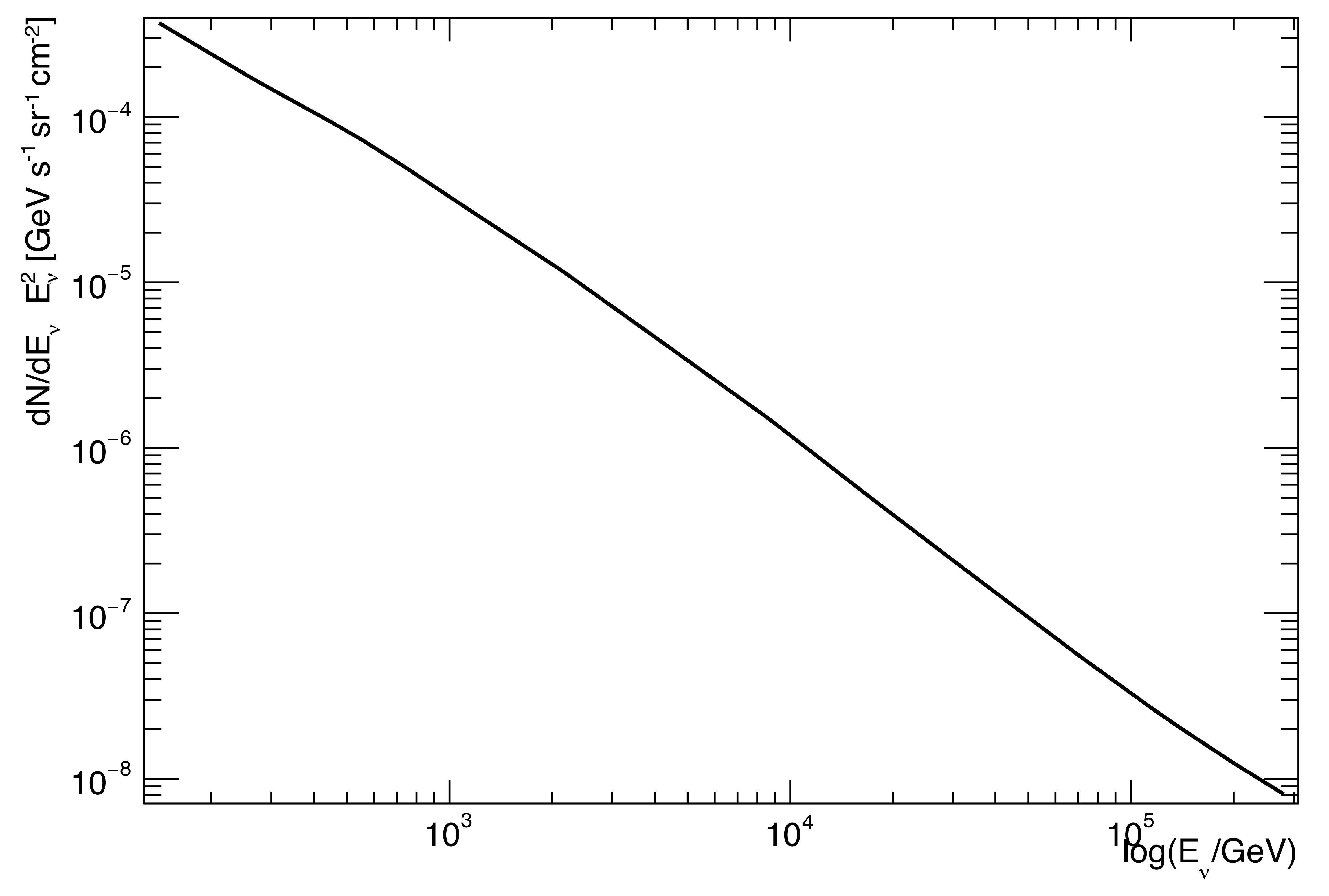
$$\Phi_{\nu_\mu,atm}(E_\nu) = 2.64 \cdot 10^{-8} E_\nu^{-3.4} cm^{-2} s^{-1} sr^{-1} TeV^{-1}$$

In this computation we consider an opening angle $\alpha = \pm 5^o$ around the source.

$$n_{BG}^{IC} = \int_{\Delta\Omega} \int_{E_1}^{E_2} 2T \frac{d\Phi_\nu}{dE_\nu d\Omega} A(E_\nu, \delta) dE_\nu d\Omega$$

$$n_{BG}^{ARCA} = \int_{\Delta\Omega} \int_{E_1}^{E_2} 2T \frac{d\Phi_\nu}{dE_\nu d\Omega} A(E_\nu) V(\delta) dE_\nu d\Omega$$

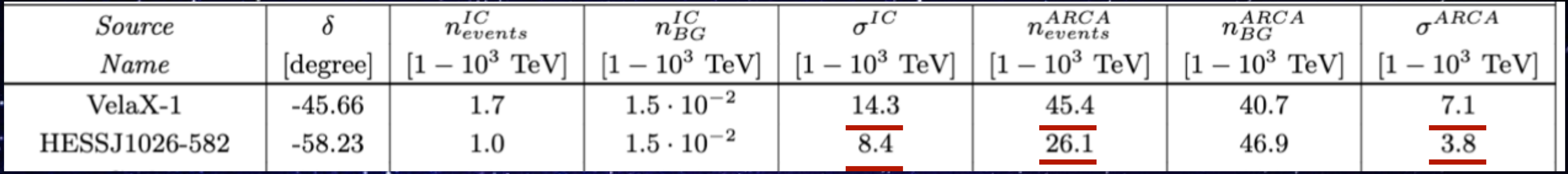
This is a conservative choice that could be improved by the experiments with the better knowledge of the detector.



R. Abbasi *et al.* (IceCube Collaboration) Phys. Rev. D 83, 012001

Promising sources

$$\sigma_i = \frac{n_{events,i}}{\sqrt{n_{BG,i}}}$$



Source Name	δ [degree]	n^{IC}_{events} $[1-10^3$ TeV]	n^{IC}_{BG} $[1-10^3$ TeV]	σ^{IC} $[1-10^3$ TeV]	n^{ARCA}_{events} $[1-10^3$ TeV]	n^{ARCA}_{BG} $[1-10^3$ TeV]	σ^{ARCA} $[1-10^3$ TeV]
VelaX-1	-45.66	1.7	$1.5 \cdot 10^{-2}$	14.3	45.4	40.7	7.1
HESSJ1026-582	-58.23	1.0	$1.5 \cdot 10^{-2}$	8.4	26.1	46.9	3.8

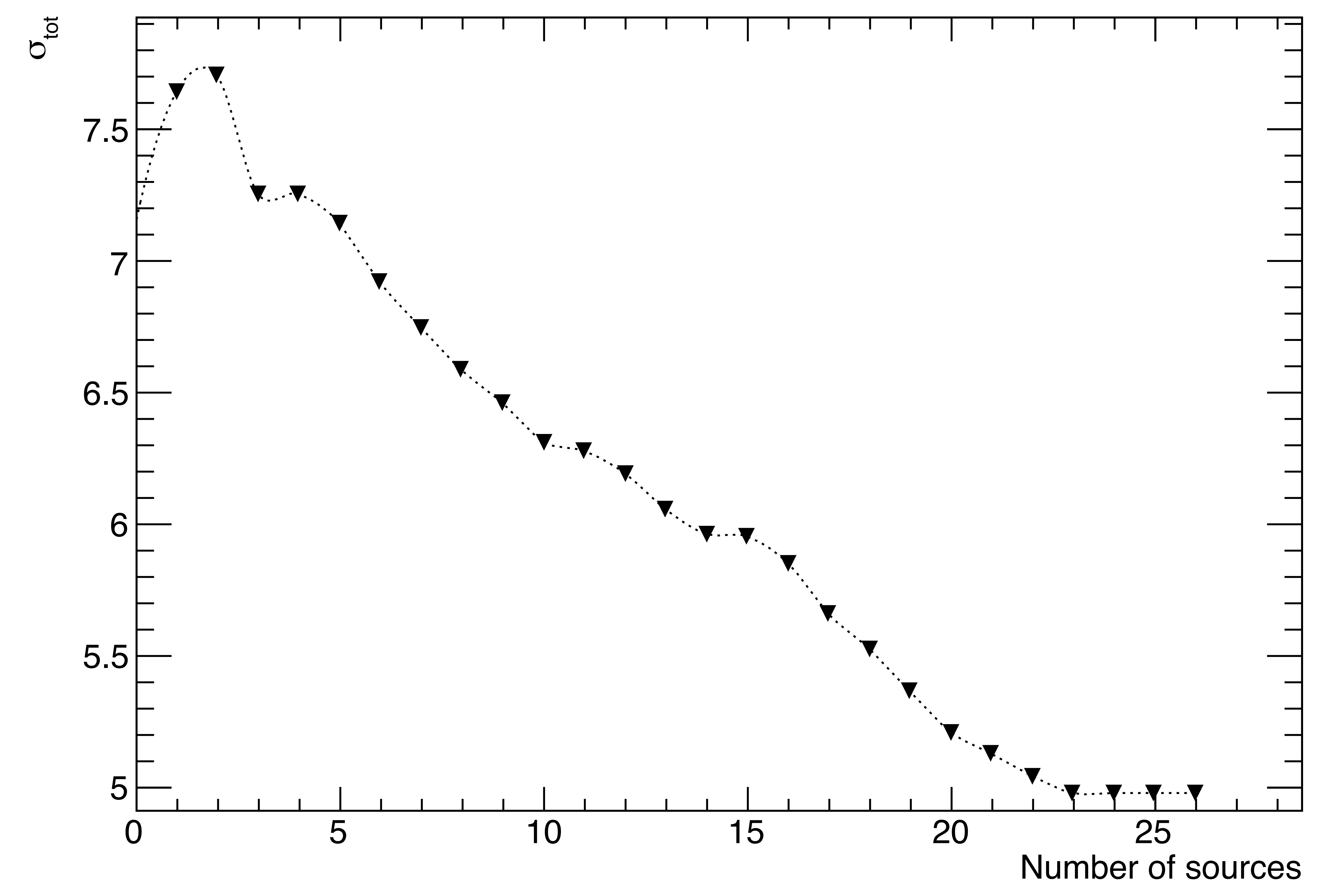
VelaX-1 and HESS J1026-582 for which the expected number of neutrino signal events in the KM3NeT/ARCA telescope is >3 and the $\sigma_i > 3$.

Both the sources in principle could have been already detected by Icecube since the $\sigma_i > 7$ but the expected number of events is very low.

In the future, KM3NeT will be able to detect or to put strong constraints on the hadronic component of these brightest sources.

Stacking of sources in KM3NeT/ARCA

The neutrino detection capability can be greatly increased by virtually overlapping several sources in the same position (stacking)

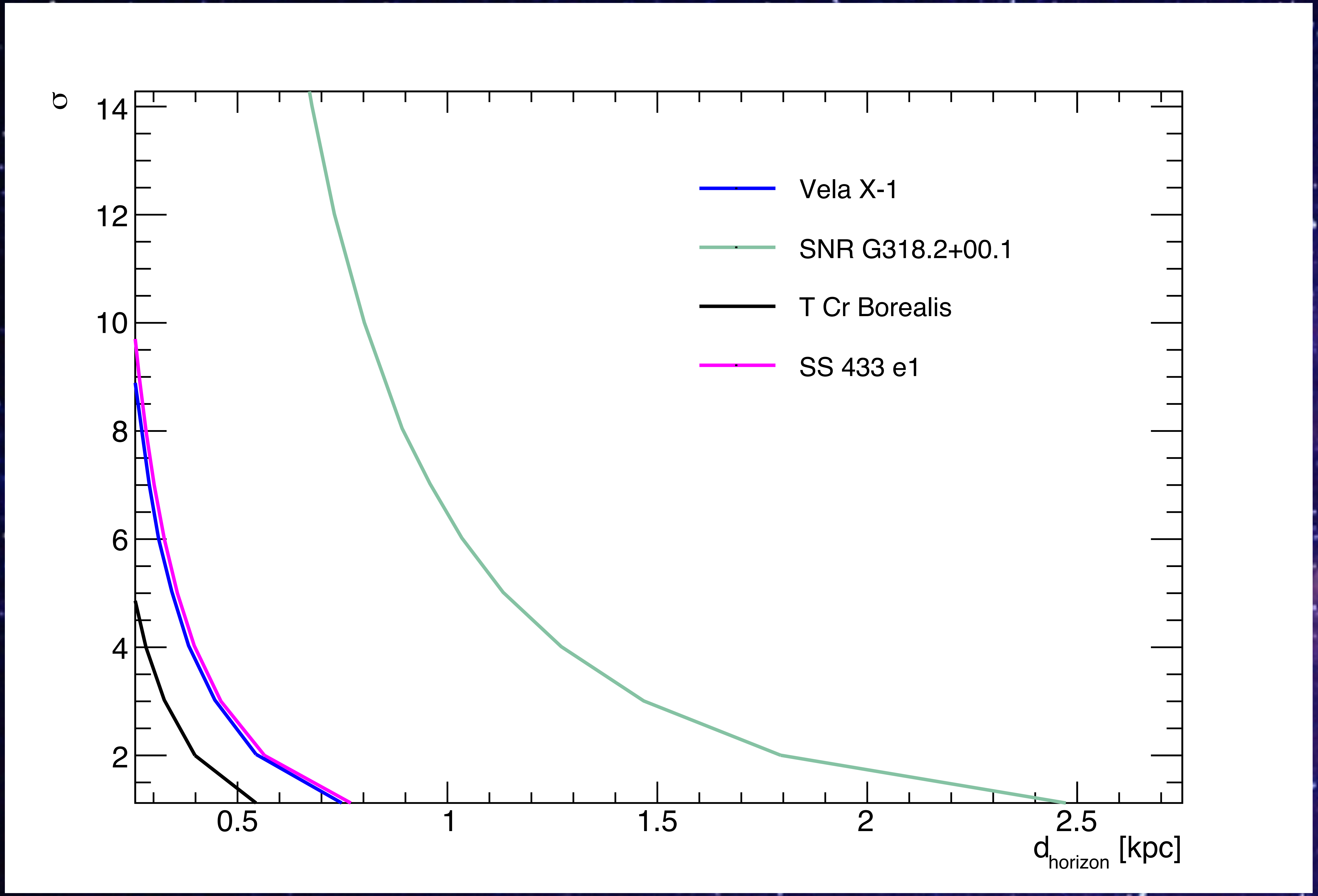


We perform a stacking analysis on a single category of sources, in particular we select a sample containing M=25 PWN and PWN/Halo since they have the highest level of significance

We find that with data sample accumulated by KM3NeT/ARCA telescope in 1 year, by stacking ~ 3 sources, we achieve a significance value $\sigma \sim 7.5$

Horizon distance

KM3NeT sensitivity as function of the distance in kpc evaluated for different classes of sources:



$$\sigma = \frac{n_{events}}{\sqrt{n_{BG,Ref}}} = \frac{T}{\sqrt{n_{BG,Ref}}} \frac{d^2_{Ref}}{d^2_{horizon}} \int \frac{dN_{Ref}}{dEdS} A(E_\nu) dE_\nu$$

For each class we selected the source with the higher sensitivity:

- PWN: Vela X-1
- SNR: SNR G318.2+00.1
- MQ: SS 433 e1
- Novae: TCrBorealis

Conclusions & future prospectives

The estimate number of expected neutrinos from the galactic sources has been performed without considering any specific physical model for the source to produce the TeV fluxes.

- **If the entire TeV emission is due to the hadronic component, the galactic sources can contribute to the diffuse neutrino flux detected by IceCube at the level of $\sim 20\,\%$ up to ~ 10 TeV and at $\sim 50\,\%$ at higher energies.**

- **Considering the fact that part of the TeV emission could also be caused by leptonic mechanism inside the sources, our results may be considered as an upper limit on the hadronic contribution to the high energy photon emission.**

Conclusions & future prospectives

The estimate number of expected neutrinos from the galactic sources has been performed without considering any specific physical model for the source to produce the TeV fluxes.

- Even if all the TeV emission is due to the hadronic processes, no galactic source is detectable by IceCube in 1 year of data taking.
- Some sources may be detectable by KM3NeT/ARCA in 1 year, in particular, the most promising ones result to be PWN type, i.e. Vela X-1 with a significance $\sigma \sim 7$ and HESS J1026-582 with a significance $\sigma \sim 4$.

Conclusions & future prospectives

- If KM3NeT/ARCA will not detect neutrino from these promising sources, constraints will be put on the hadronic component responsible of the γ-ray high energy emission.

- Applying the stacking procedure to the most promising galactic neutrino sources, PWN/PWN TeV Halo, in 1 year KM3NeT should be able to detect with $\sigma \sim 7.5$ a neutrino flux from the stacking of at least 3 PWN/PWN TeV Halo.

- We estimate the maximum distance at which each type of galactic source can be detected in 1 year by KM3NeT/ARCA and we find that $d_{horizon} < 3$ kpc for all kind of sources. The best candidates result to be the SNR sources.

Future investigations are needed to determine which are the sources responsible of IceCube diffuse flux and to constrain the hadronic component responsible to the γ-ray TeV emission.

תודה רבה!

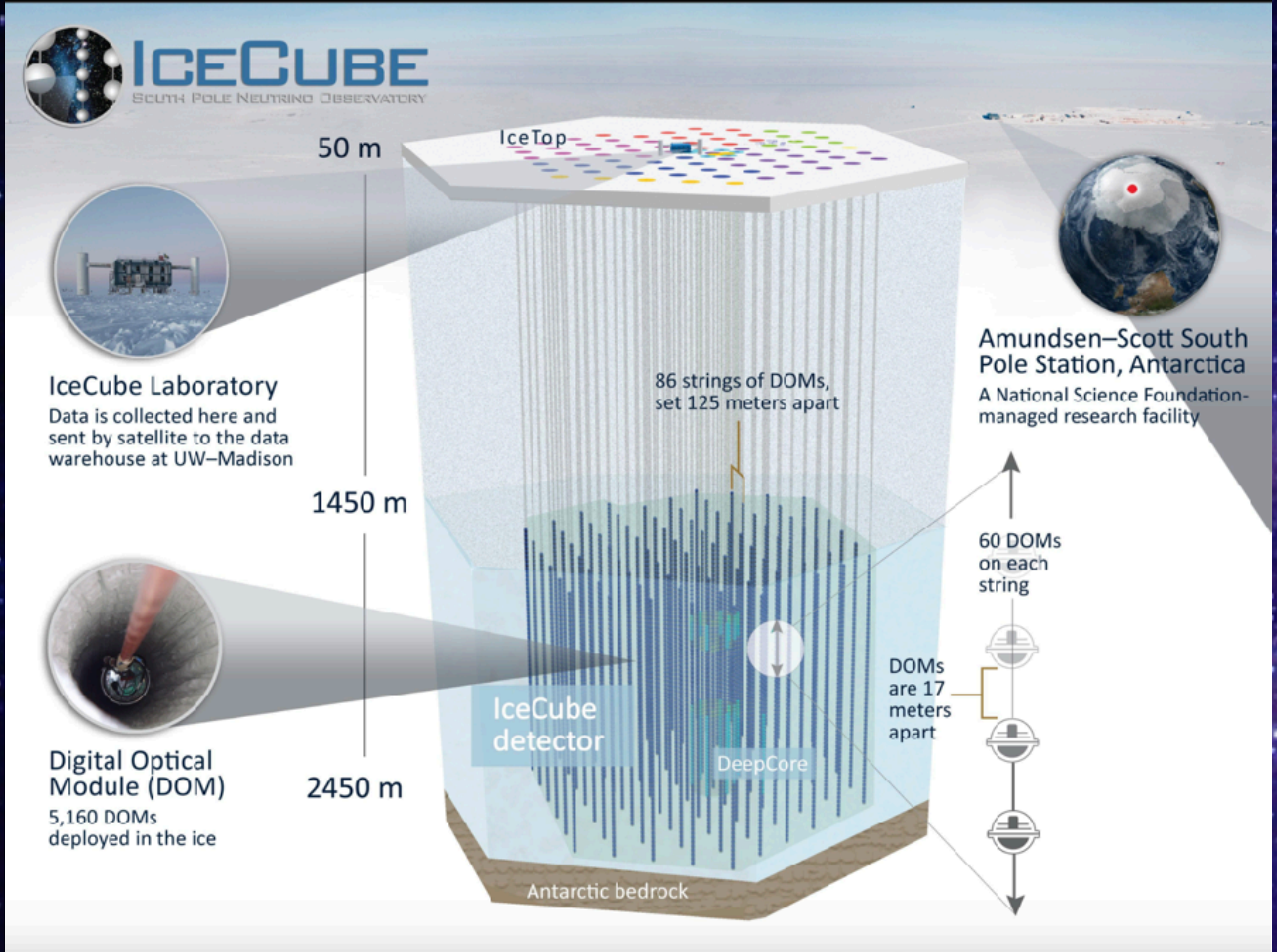
Grazie!

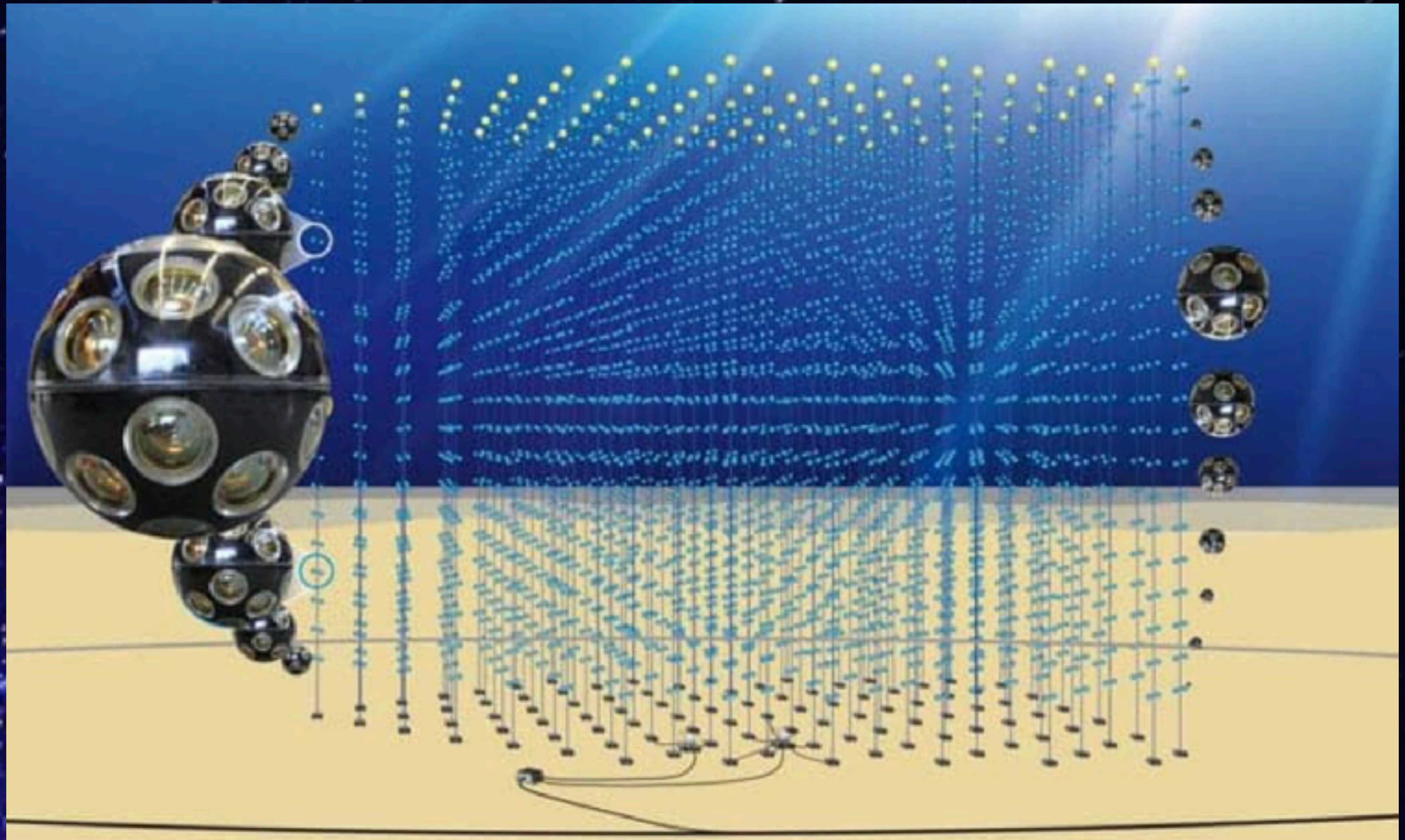
Thank you!

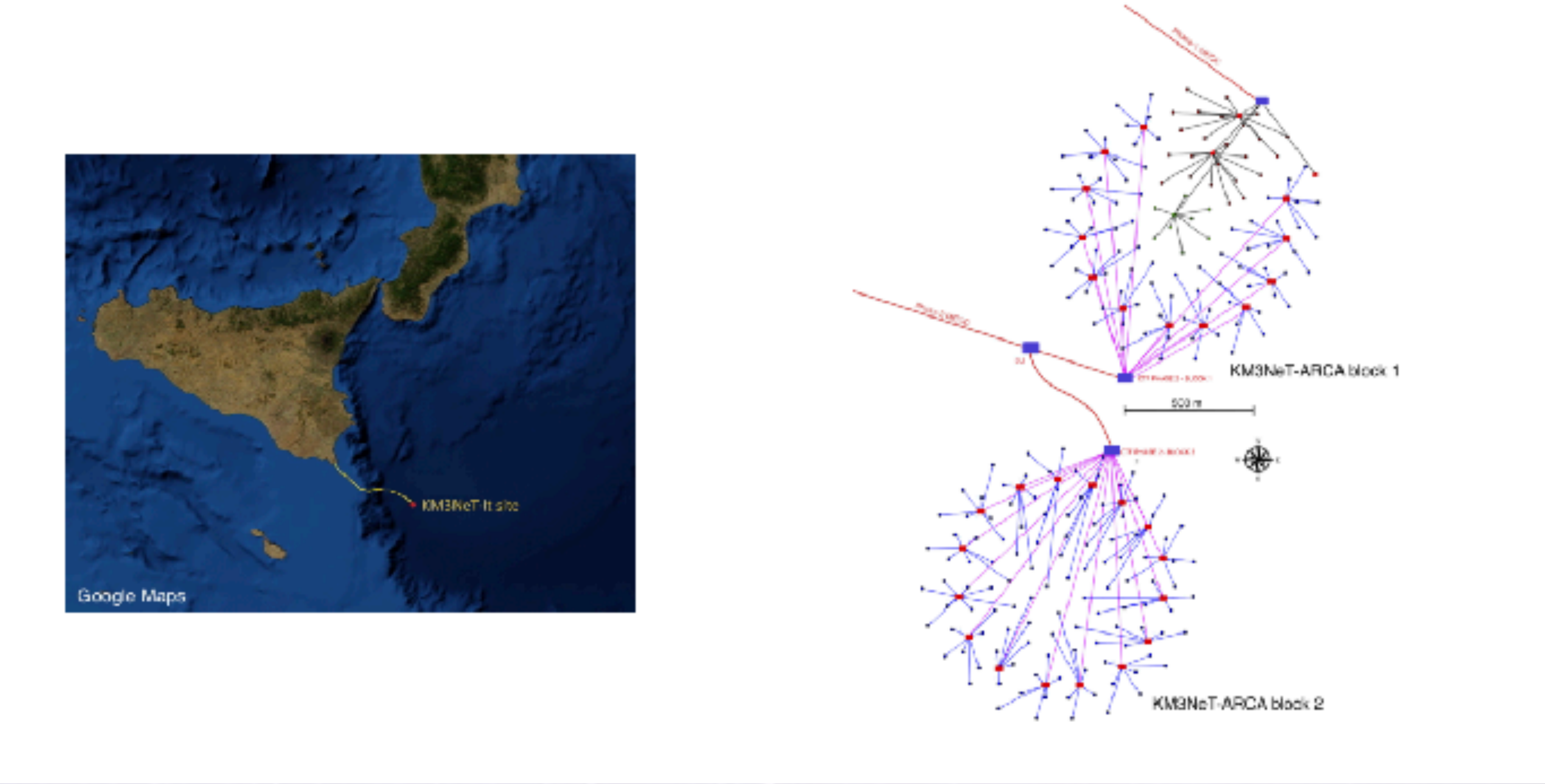
Backup slides

Neutrino Telescopes

Icecube







KM3NeT/ARCA

Introduction

Large part of our knowledge about the universe derives from the observation of electromagnetic signals: radio waves, infrared, visible light, ultra violet, X-rays and the powerful **γ-rays.**

Other astrophysical signals to investigate the cosmos:

- Cosmic Rays (CRs),
- Neutrinos
- Gravitational Waves (GW)

In particular **Ultra High Energy Cosmic Rays (UHECRs)**, i.e. particles with energy above $5\cdot10^{18}$ eV arriving from directions roughly isotropic on the sky, could provide relevant information about the **acceleration mechanisms** that occur inside astrophysical sources.

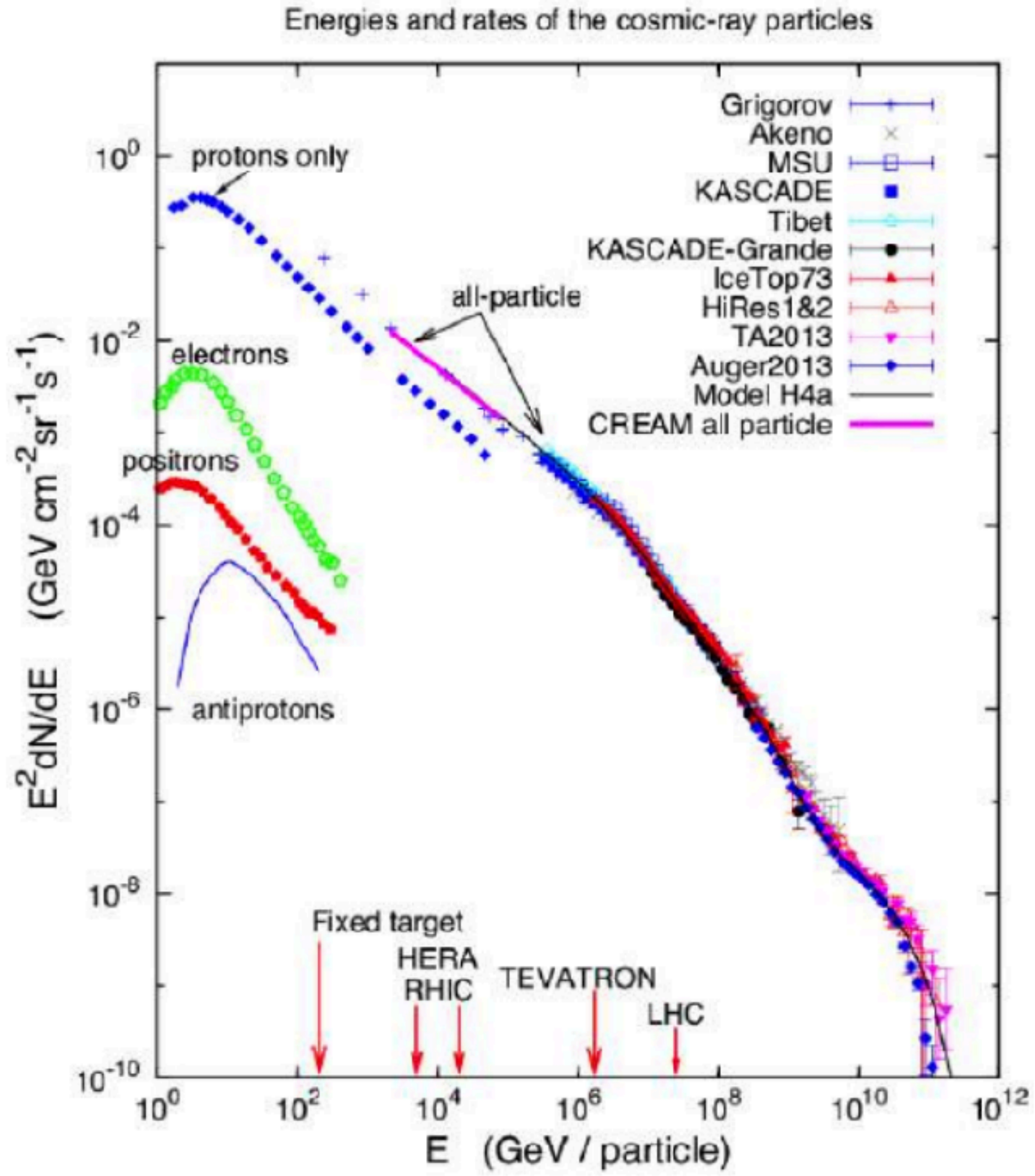
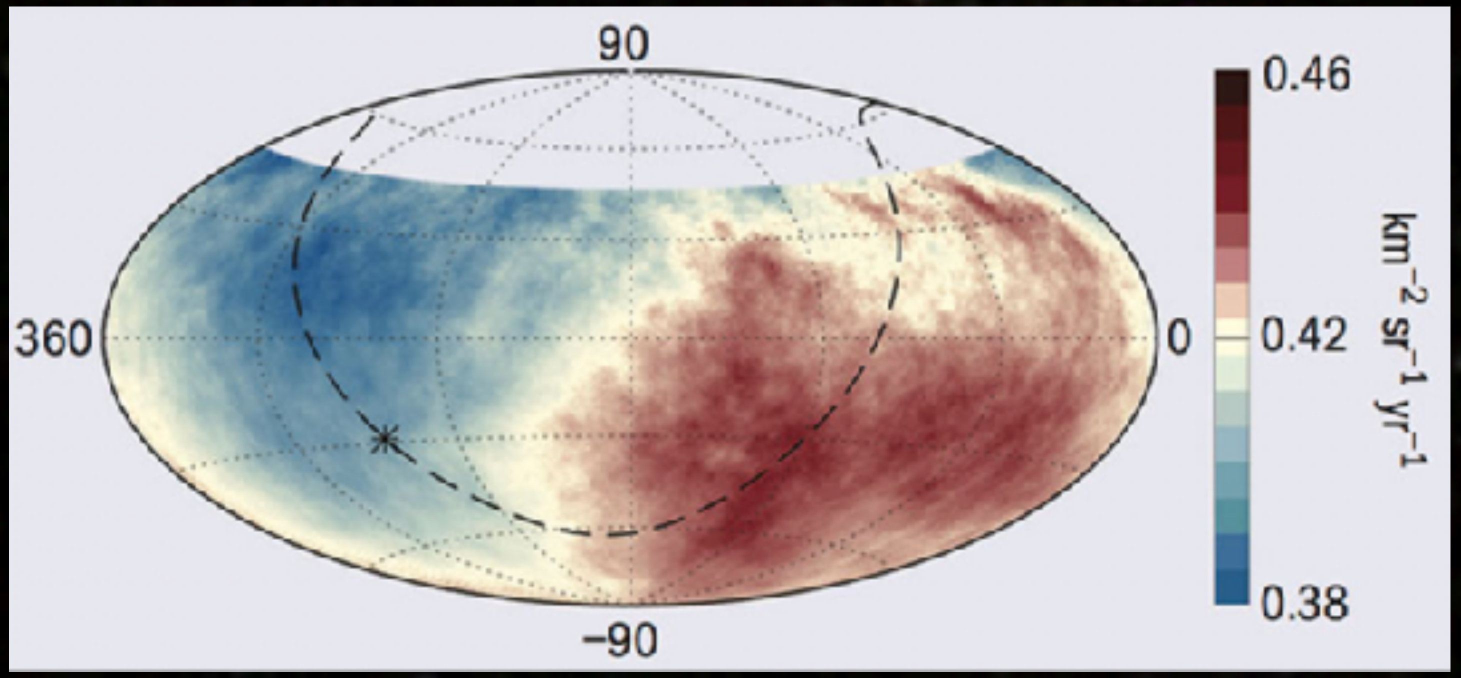


Figure 1.1. All-particle spectrum of CRs. Credits: T. Gaisser.

Multimessenger astronomy

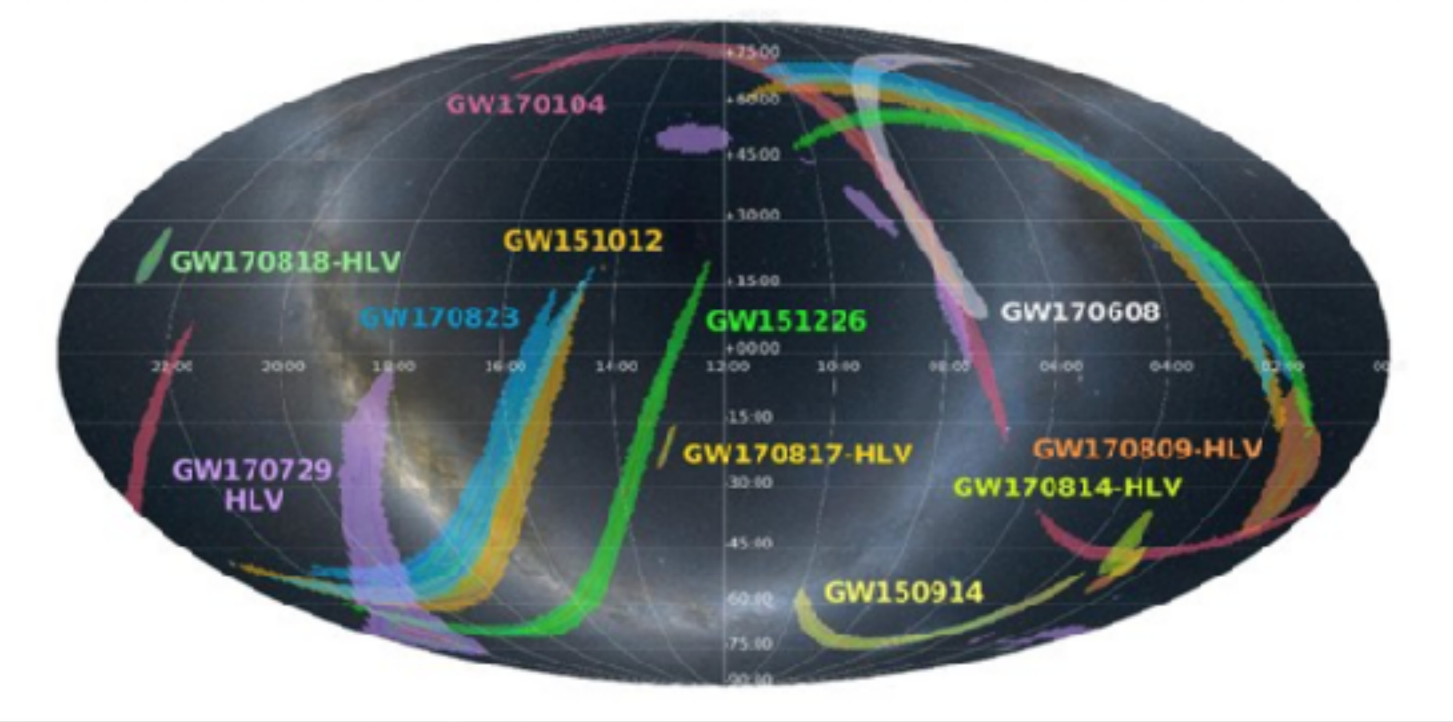
Traditional astronomy is no longer the only way of exploring the Universe

Cosmic Rays



Pierre Auger Observatory- UHECRs

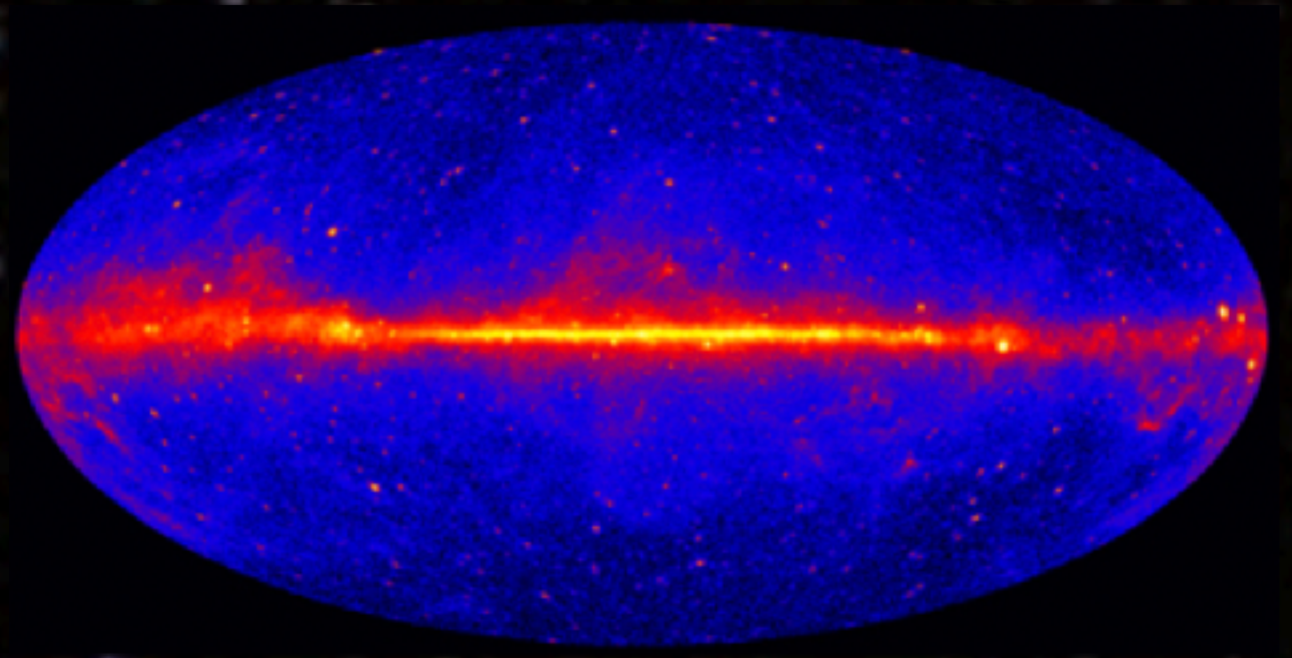
Gravitational Waves



Ligo-Virgo GWs

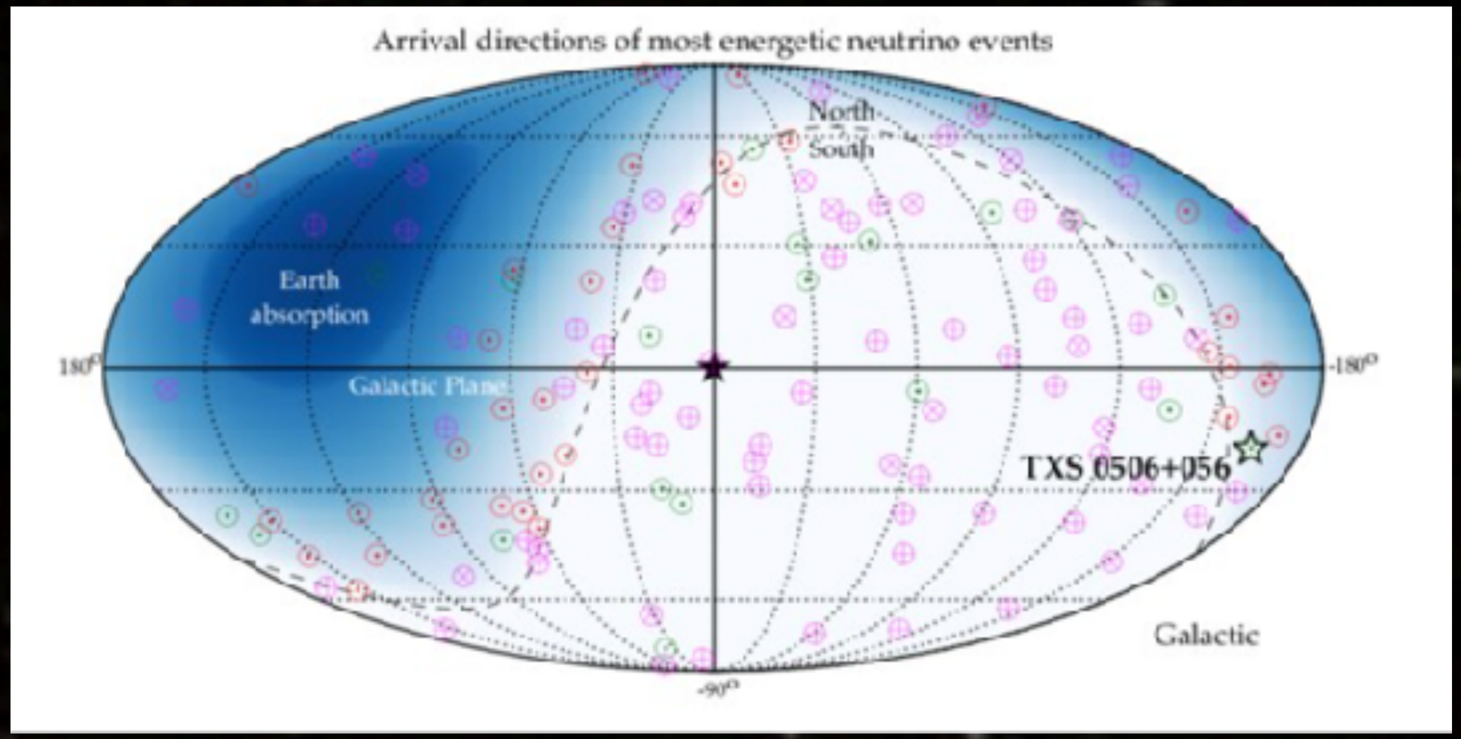
The sky is full of messengers

γ-rays



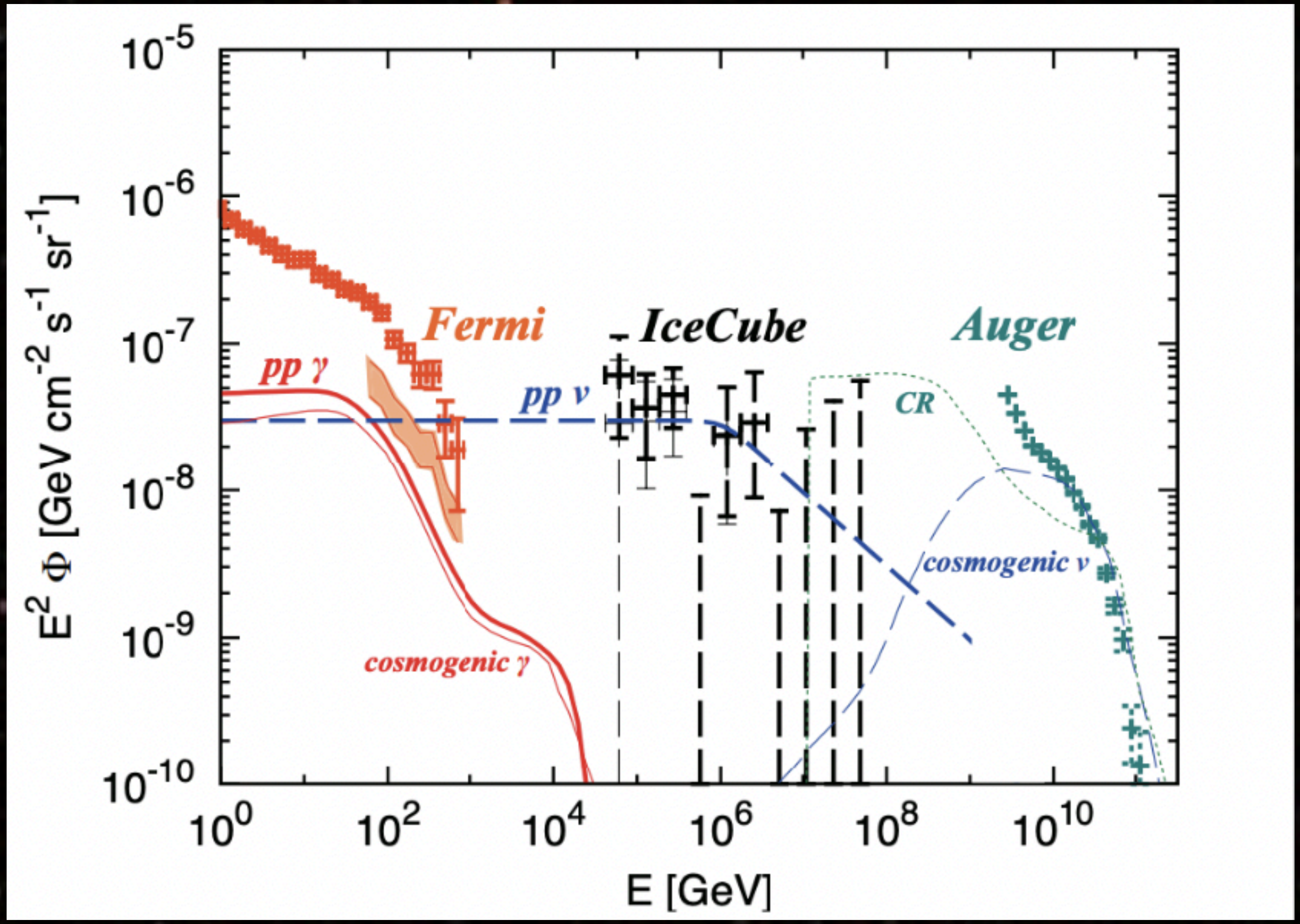
Fermi LAT map
MeV - GeV

Neutrinos



IceCube astrophysical events
TeV-PeV

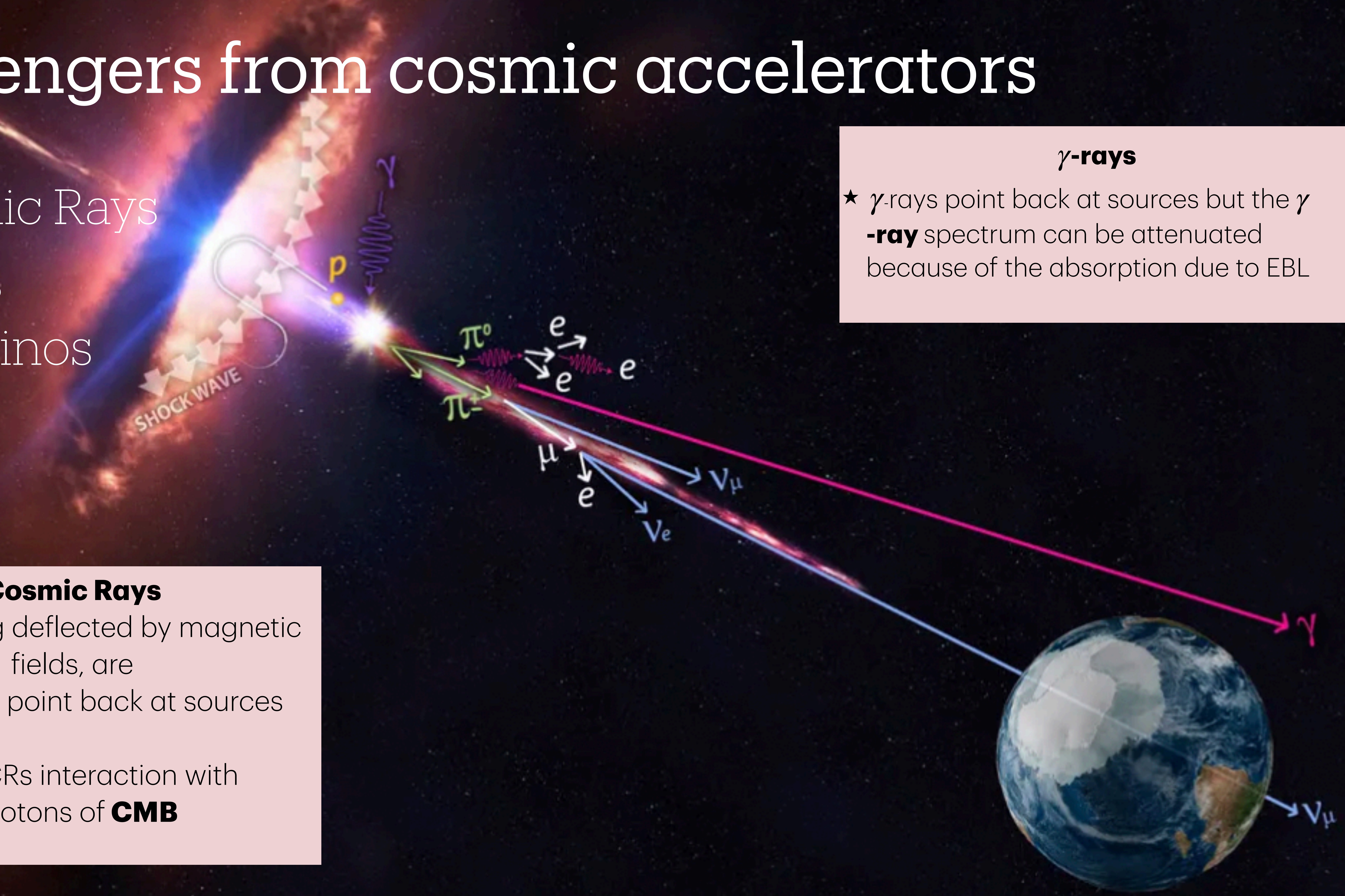
Multimessenger astronomy



The observed energy density carried by the flux of neutrinos in the ~ PeV range turned out to be comparable to those of the diffuse sub-TeV gamma-ray flux and the UHECR flux, so the energy budgets of the three messengers are somehow comparable (Murase and Waxman 2016).

Messengers from cosmic accelerators

- Cosmic Rays
- γ-rays
- Neutrinos



γ-rays

★ γ-rays point back at sources but the γ **-ray** spectrum can be attenuated because of the absorption due to EBL

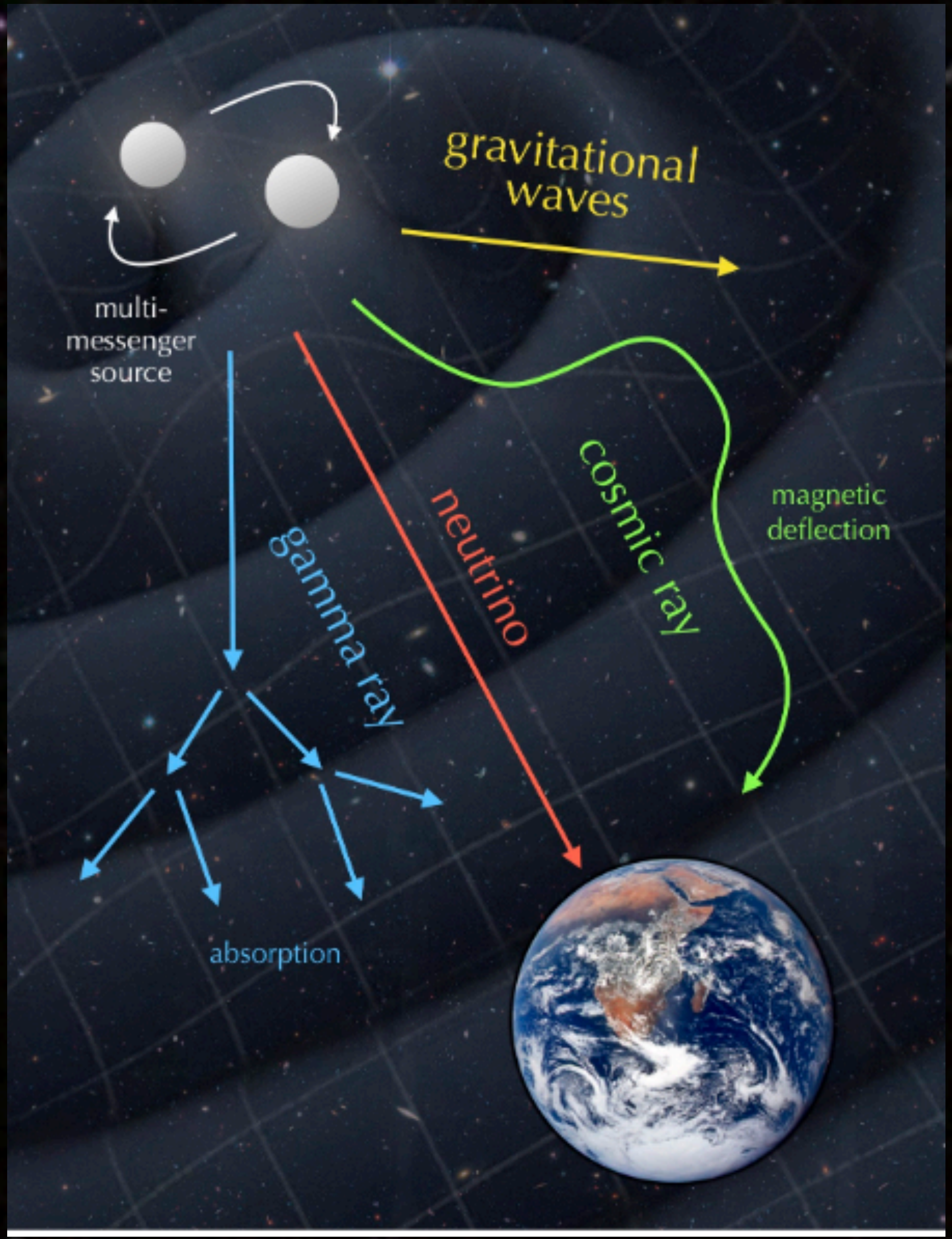
Cosmic Rays

★ **CRs**, being deflected by magnetic fields, are not able to point back at sources

★ UHECRs interaction with photons of **CMB**

Neutrino astronomy

This research is focused on the information we can get by detecting high energy neutrinos originated in astrophysical sources.



Why neutrinos?

Neutrinos are ideal messengers in the search for distant astrophysical objects

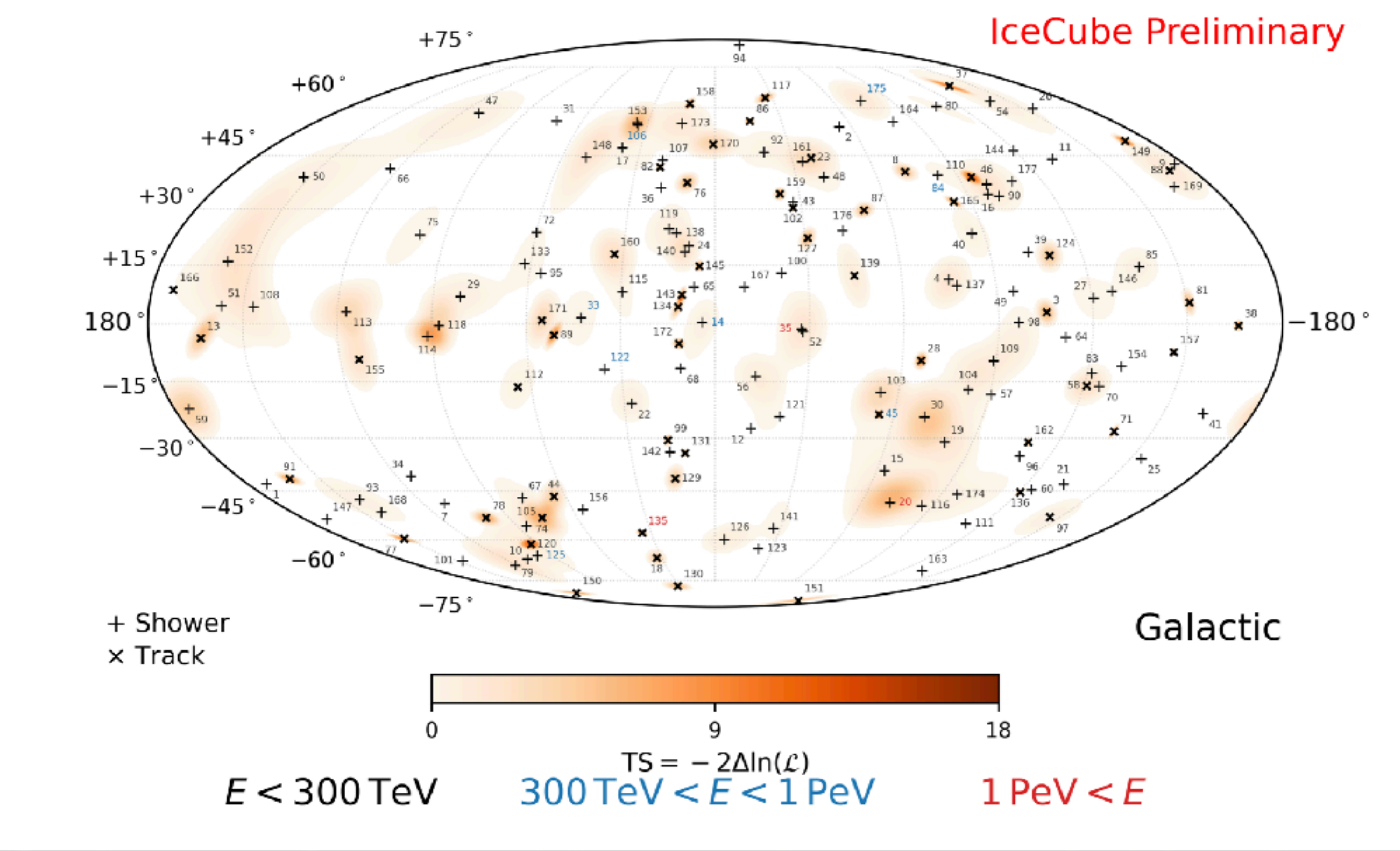
Unique properties of neutrinos:
electrically neutral, stable, and weakly interacting particles

★ No deflection in magnetic field (unlike cosmic rays)
★ No absorption in cosmic backgrounds, as Extragalactic Background Light (unlike gamma-rays)

Astrophysical neutrinos

In 2013, the IceCube Collaboration reported the discovery of cosmic high-energy neutrinos exceeding the expected background (Aartsen, 2013a, 2014a).

Arrival directions of the neutrino events in Galactic coordinates.



The present data show no evidence for neutrino induced event clustering around known astrophysical objects except for two candidates.