High-energy neutrinos from the Galaxy: expectations and experimental results

Silvia Celli
silvia.celli@roma1.infn.it

Sapienza University of Rome and INFN

Neutrino properties and their interactions

- Elementary **weakly interacting** subatomic particle;

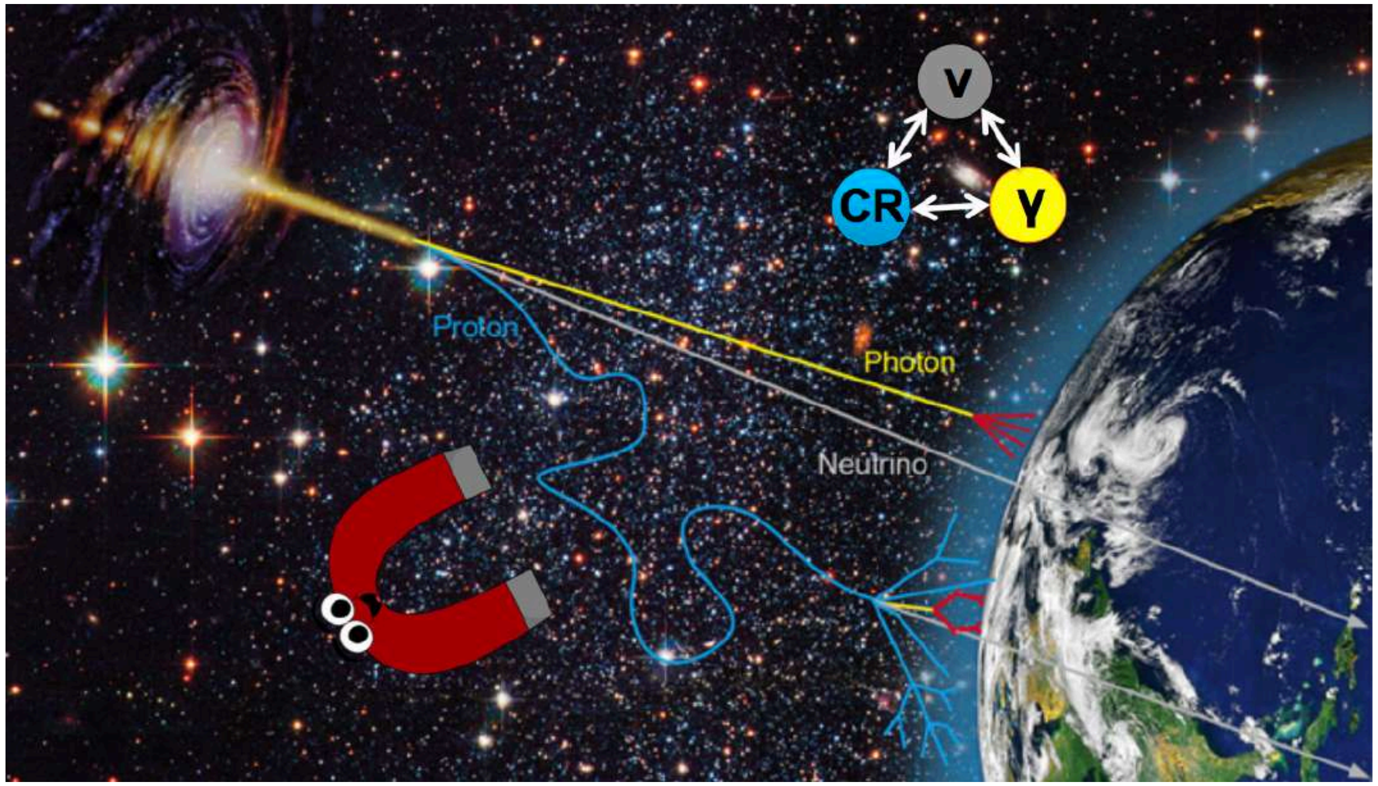
- Tiny mass: **< 0.8 eV/c^2** (KATRIN Coll. 2022);

- **Three flavor eigenstates**: electron (v_e), muon (v_μ), tau (v_τ);

- **Everywhere**:
  340 v/cm^3 in the Universe [E~0.0002 eV]
  10^{11} v/cm^2/s solar neutrinos at Earth [E < few MeV] $\longrightarrow$ 10^{14} v/s through our body;

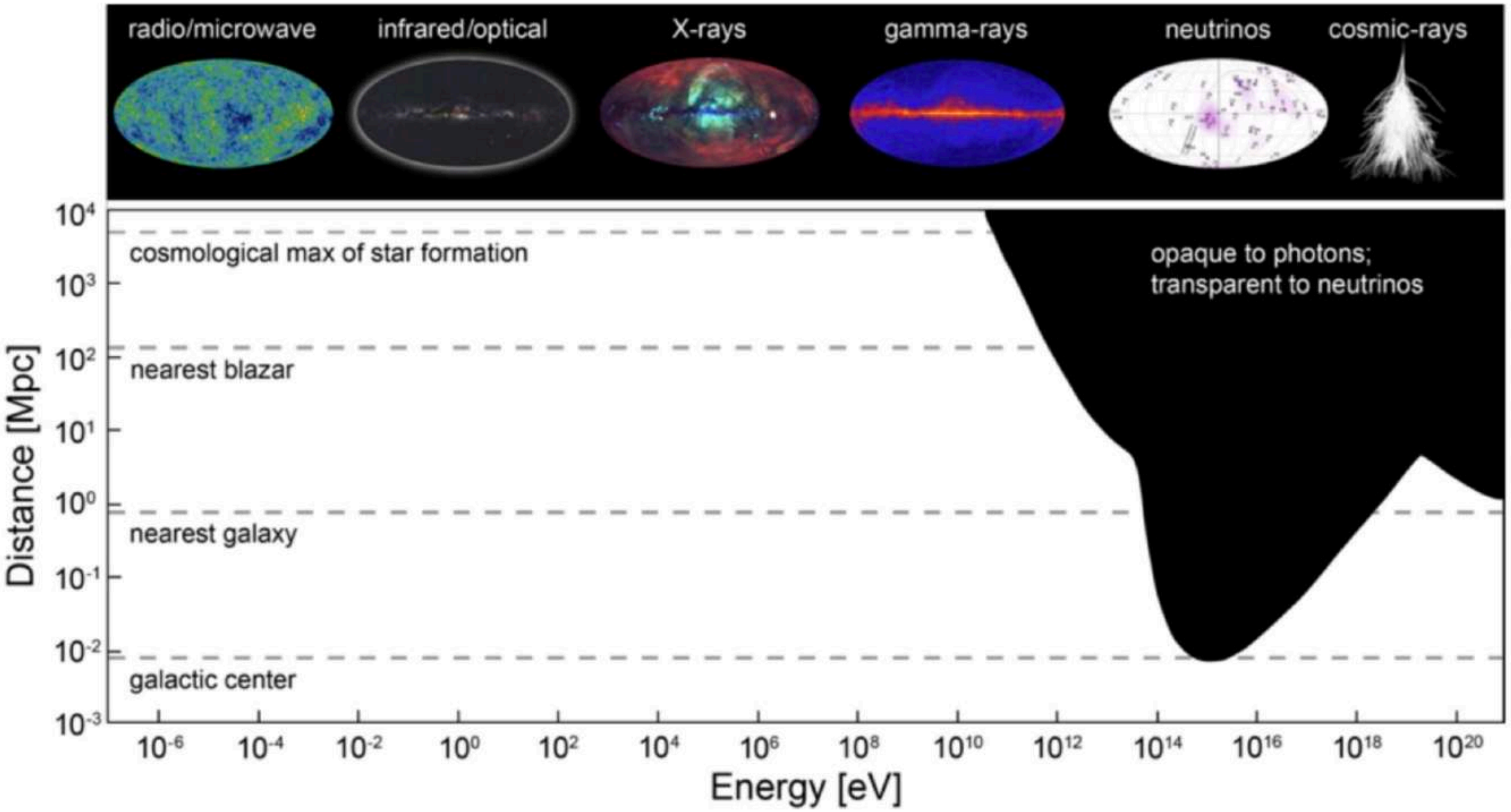
- Probably the **second most common** particle in the Universe (dark matter?).

The multi-messenger search for CR sources



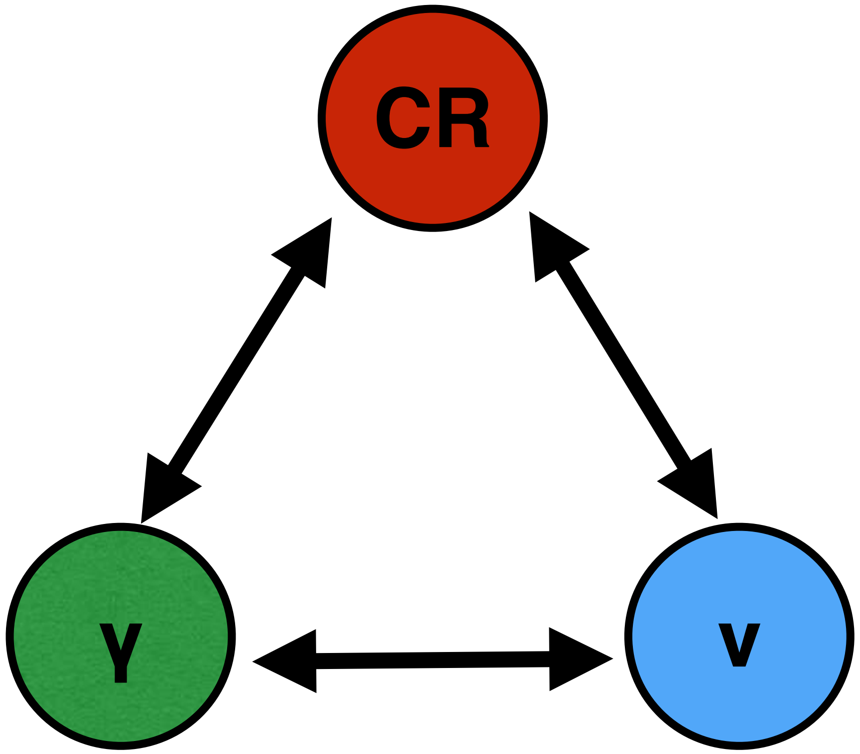
- **Why neutrinos?**
  - stable
  - electrically neutral
  - weakly interacting

→ can reach Earth undeflected from cosmological distances



The search for CR sources

Gamma rays and **neutrinos**
as messengers of
cosmic-ray accelerators



- **leptonic production** is realized at **CR-electron** collisions with matter (bremsstrahlung) and/or radiation fields (inverse Compton) and/or magnetic fields (synchrotron);
- **hadronic production** is realized at **CR-proton** collisions with matter (“pp”) and/or radiation fields (“pγ”), mostly via meson production.

Neutrinos only from hadronic mechanisms,
gamma rays from both.

Hadronic interaction channels

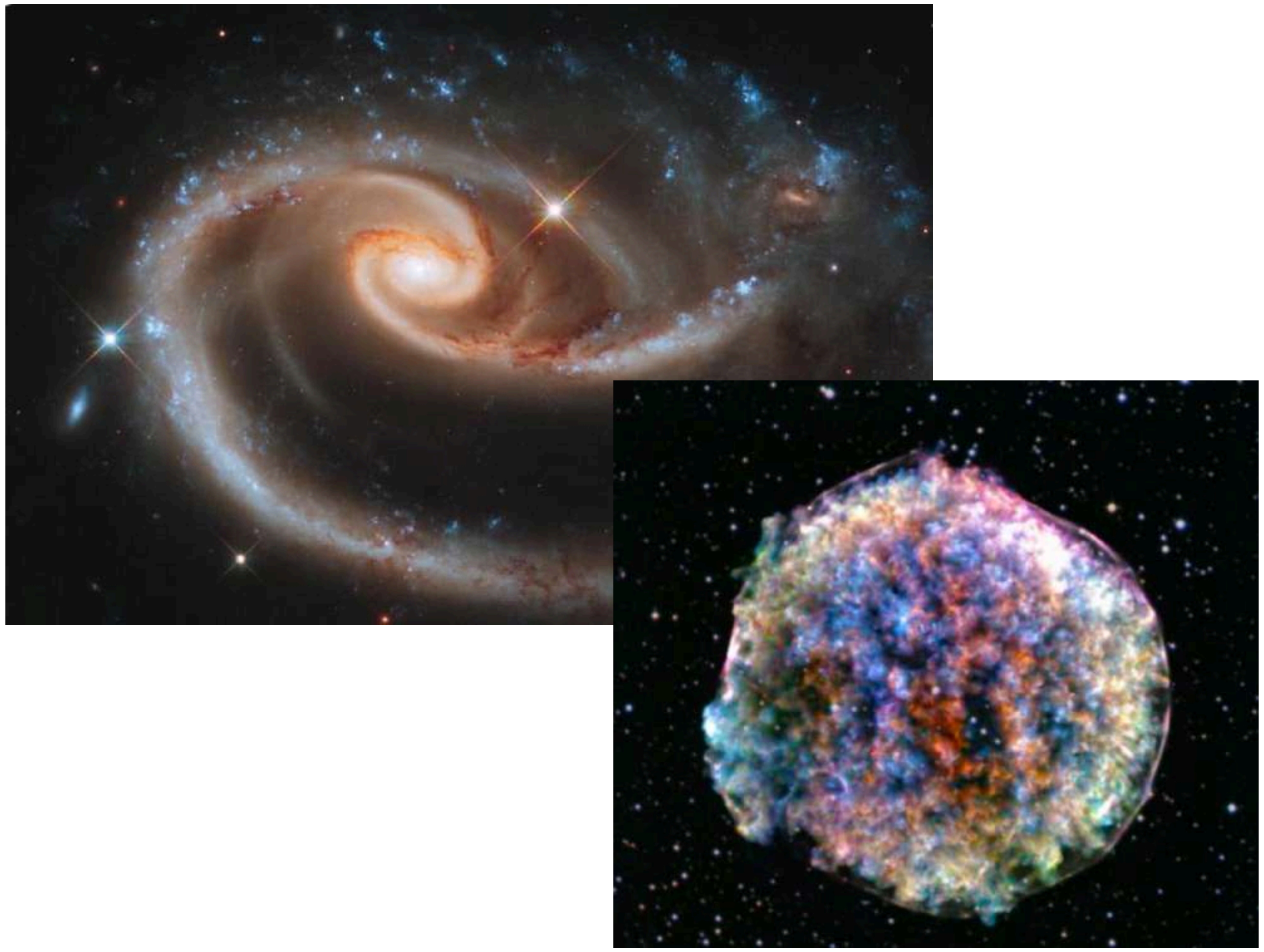
pp interaction:

- accelerated protons
- dense target matter field

$$p + p \longrightarrow \begin{cases} p + p + \pi^0 \\ p + n + \pi^+ \end{cases}$$

“CR reservoir”

e.g. SBG, SNR



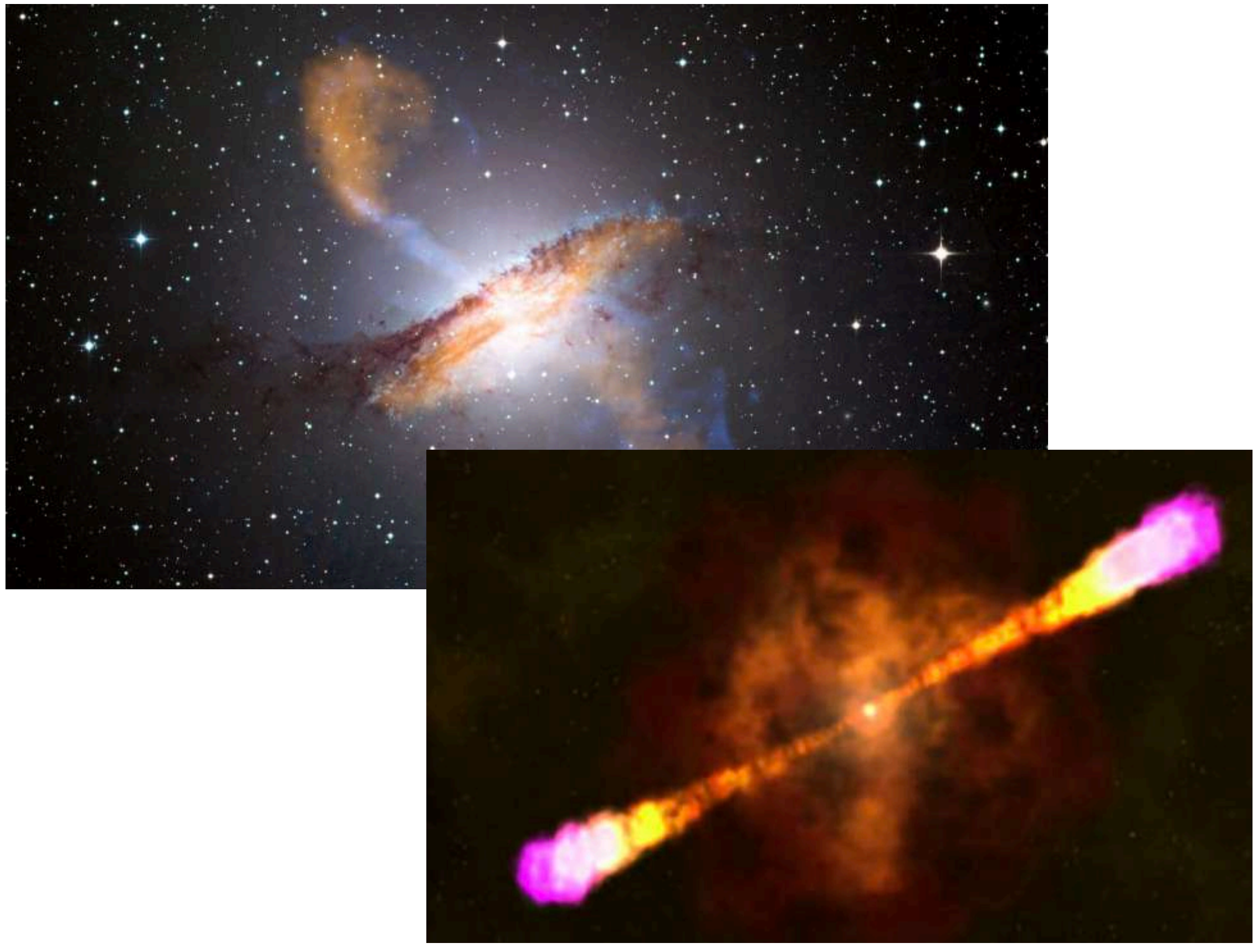
pγ interaction:

- accelerated protons
- dense target radiation field

$$p + \gamma \xrightarrow{\Delta^+} \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

“CR accelerators”

e.g. AGN, GRB



Hadronic interaction channels

pp interaction:
- accelerated protons
- dense target matter field

pγ interaction:
- accelerated protons
- dense target radiation field

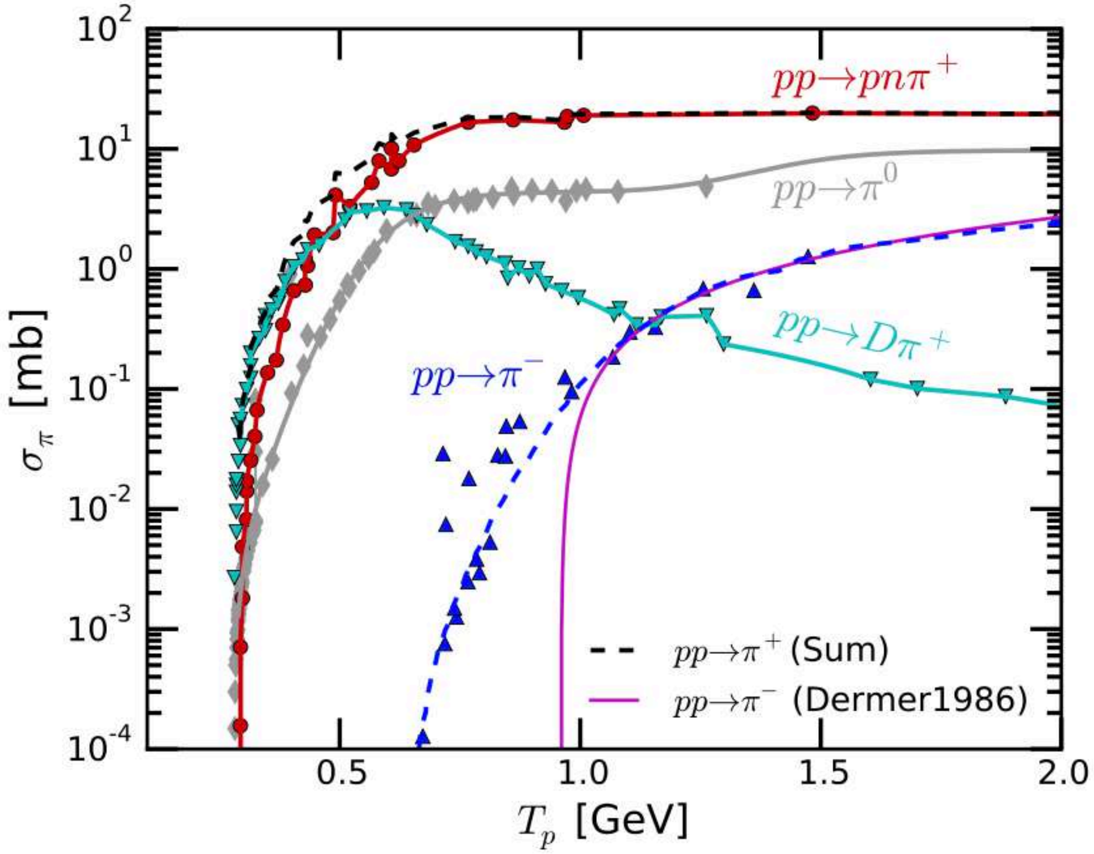
$$p+p \longrightarrow \begin{cases} p+p+\pi^0 \\ p+n+\pi^+ \end{cases}$$

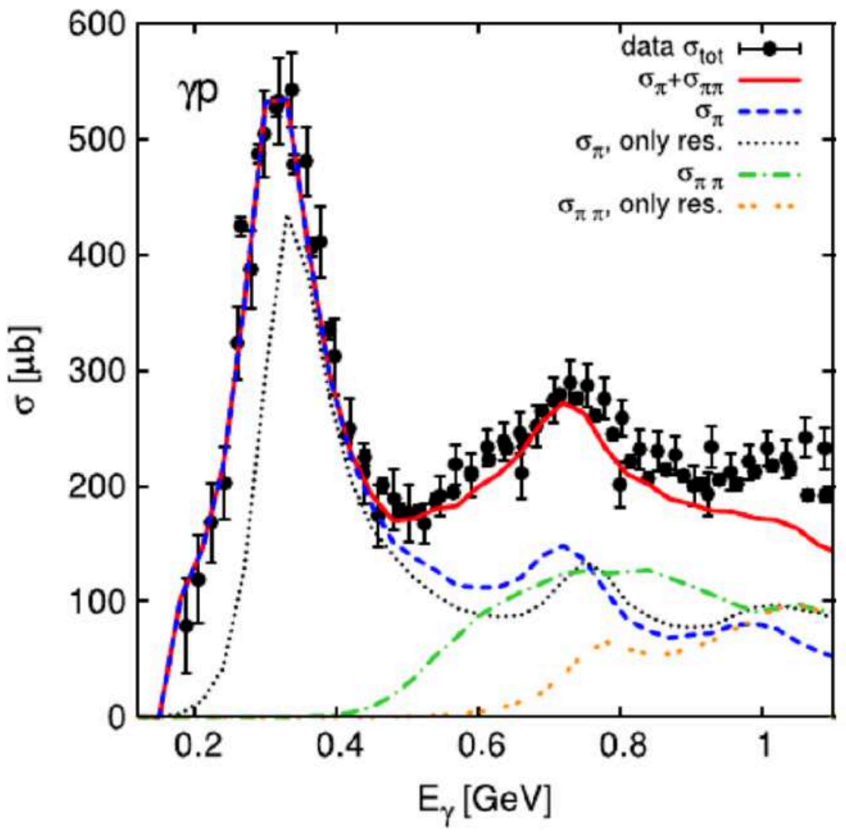
$$p+\gamma \xrightarrow{\Delta^+} \begin{cases} p+\pi^0 \\ n+\pi^+ \end{cases}$$

$$E_\gamma \simeq E_\mathrm{p}/10$$

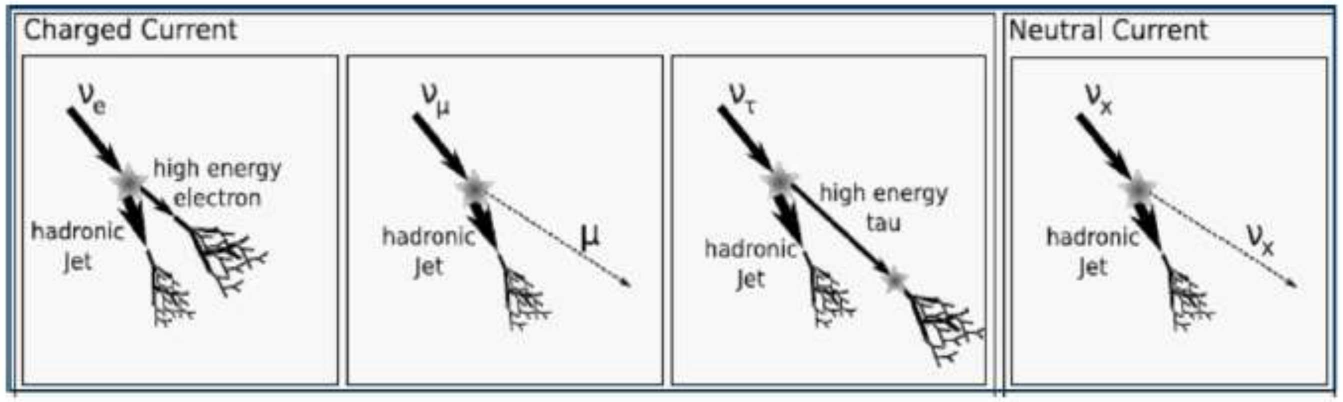
$$E_\nu \simeq E_\mathrm{e} \simeq E_\mathrm{p}/20$$

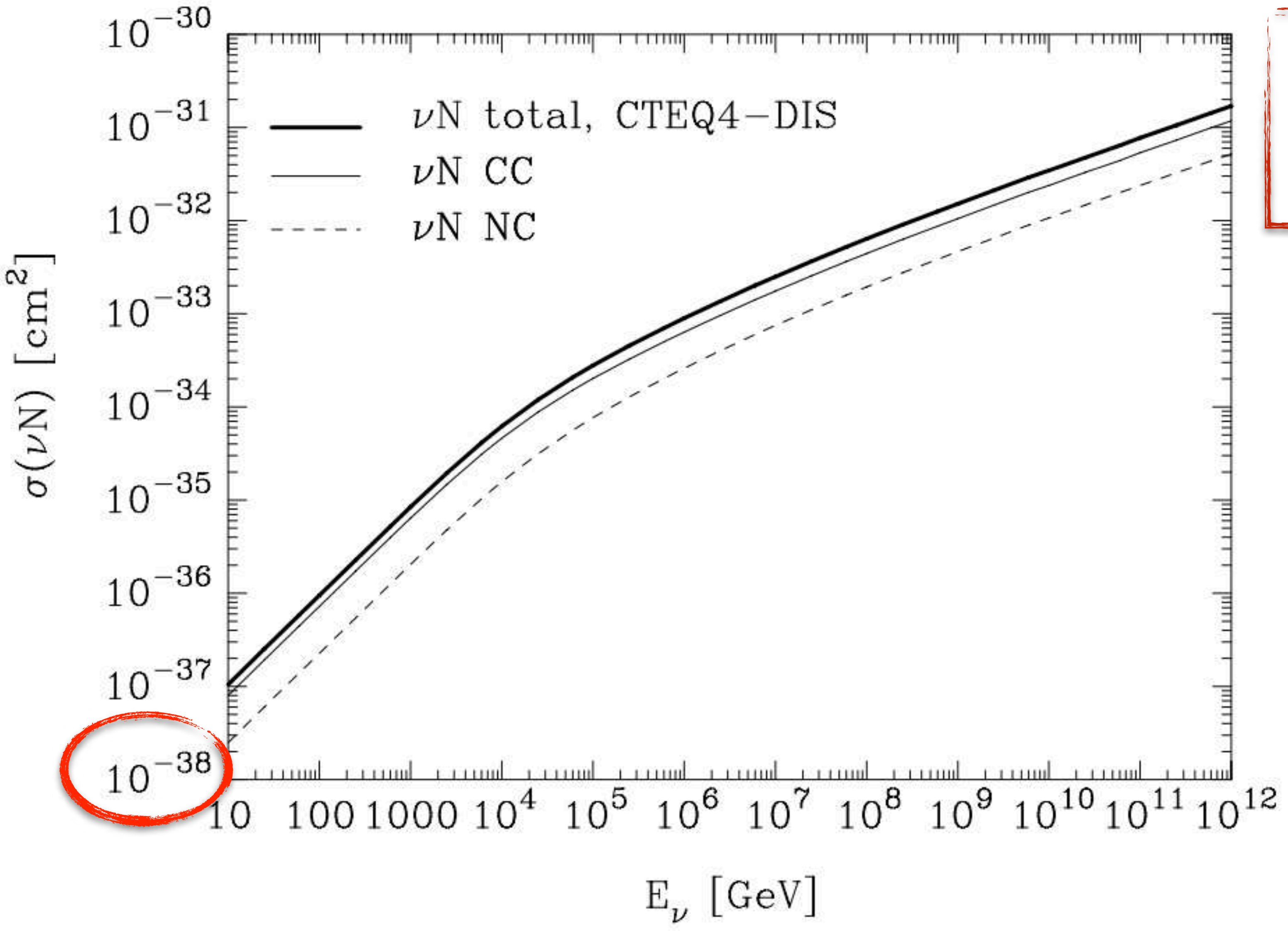
$$\pi^0 \longrightarrow \gamma + \gamma$$
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu \longrightarrow e^+ + \nu_e + \overline{\nu}_\mu + \nu_\mu$$
$$\pi^- \longrightarrow \mu^- + \overline{\nu}_\mu \longrightarrow e^- + \overline{\nu}_e + \nu_\mu + \overline{\nu}_\mu$$





Neutrino properties and their interactions





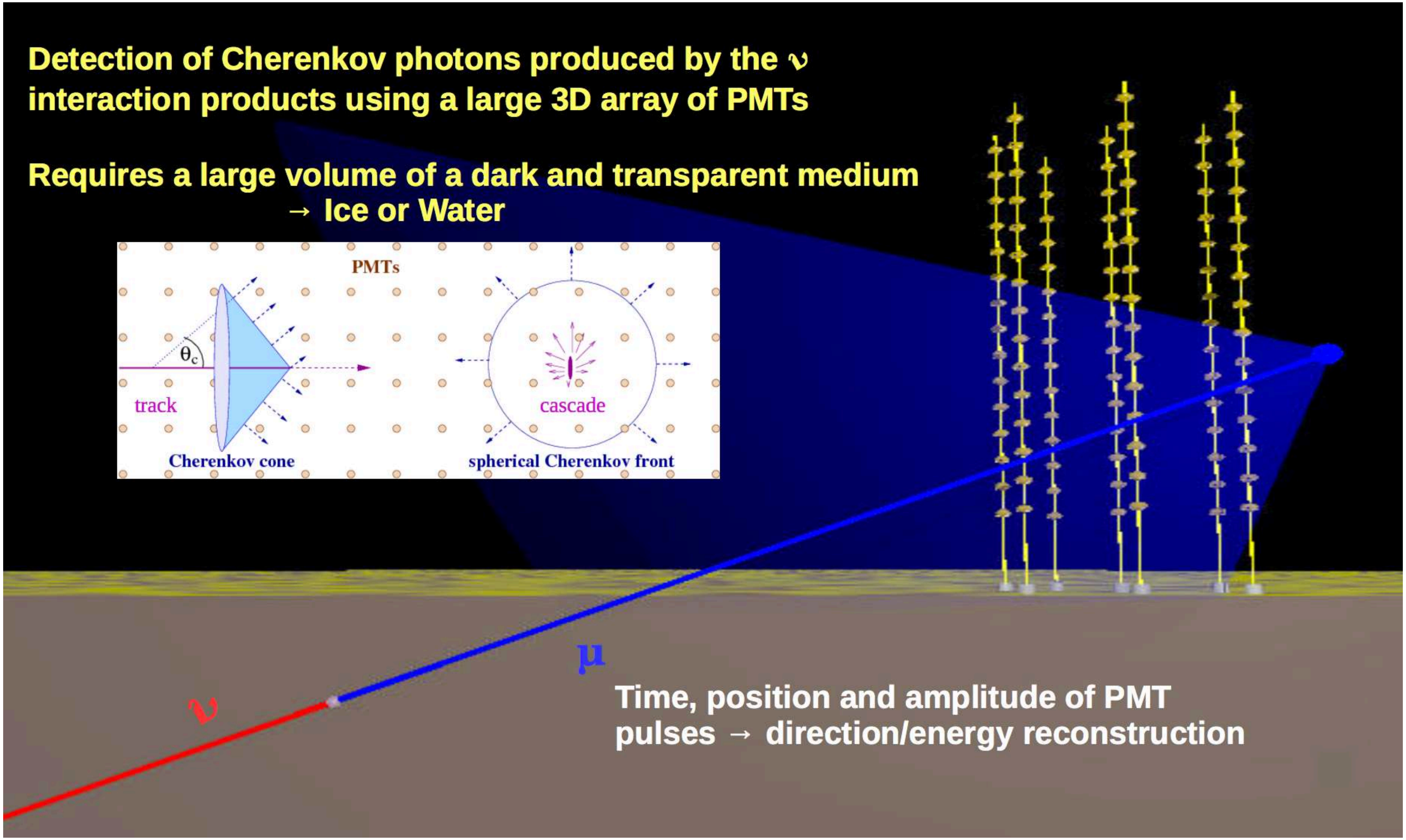
$\sigma_{\nu N} \sim 10^{-38}$ cm^2 @ 1 GeV

$\sigma_{\nu p} / \sigma_{\gamma p} \sim 10^{-7}$ @ 1 TeV

- Very faint event rates require to instrument large volumes ⟶ **natural medium** is ideal
- Products of neutrino interaction observed through Cherenkov light induced by ultra-relativistic propagation in medium ⟶ **transparent medium** is needed

The Cherenkov technique for neutrino detectors

Looking for lepton tracks from **ν** ⟶ **lepton** conversion



Detection of Cherenkov photons produced by the ν interaction products using a large 3D array of PMTs

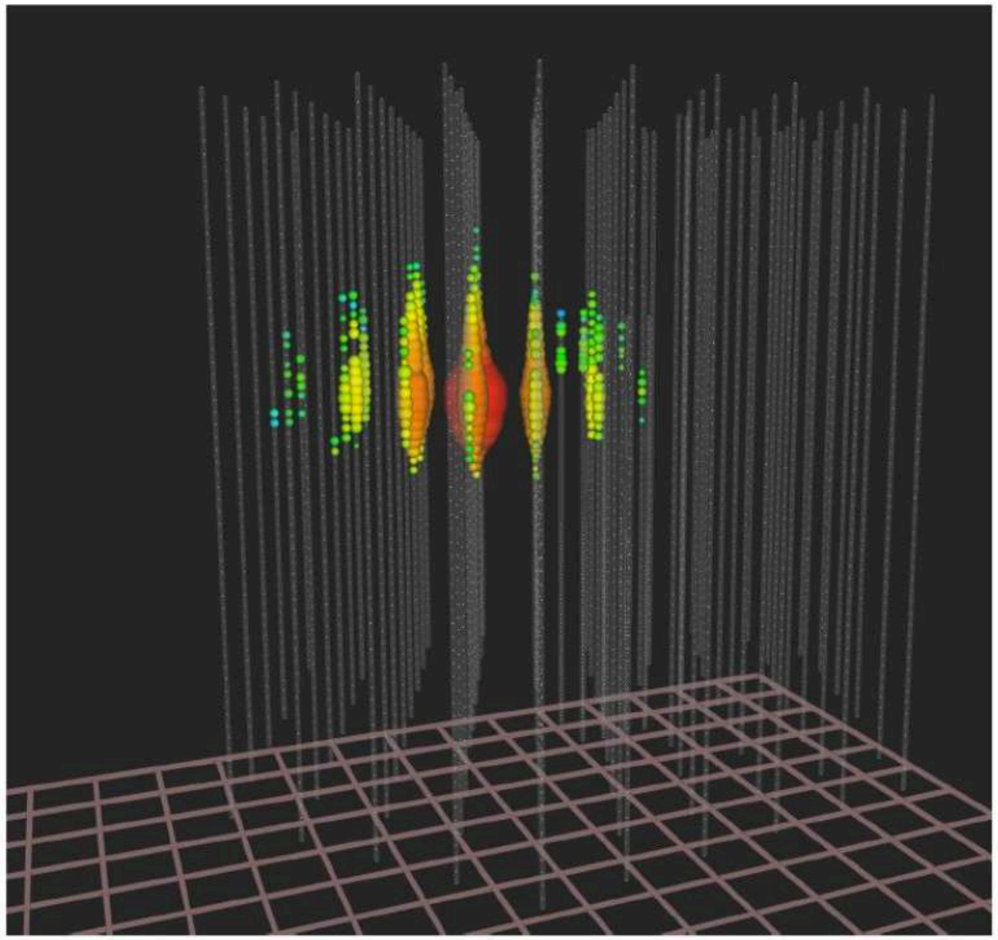
Requires a large volume of a dark and transparent medium → Ice or Water

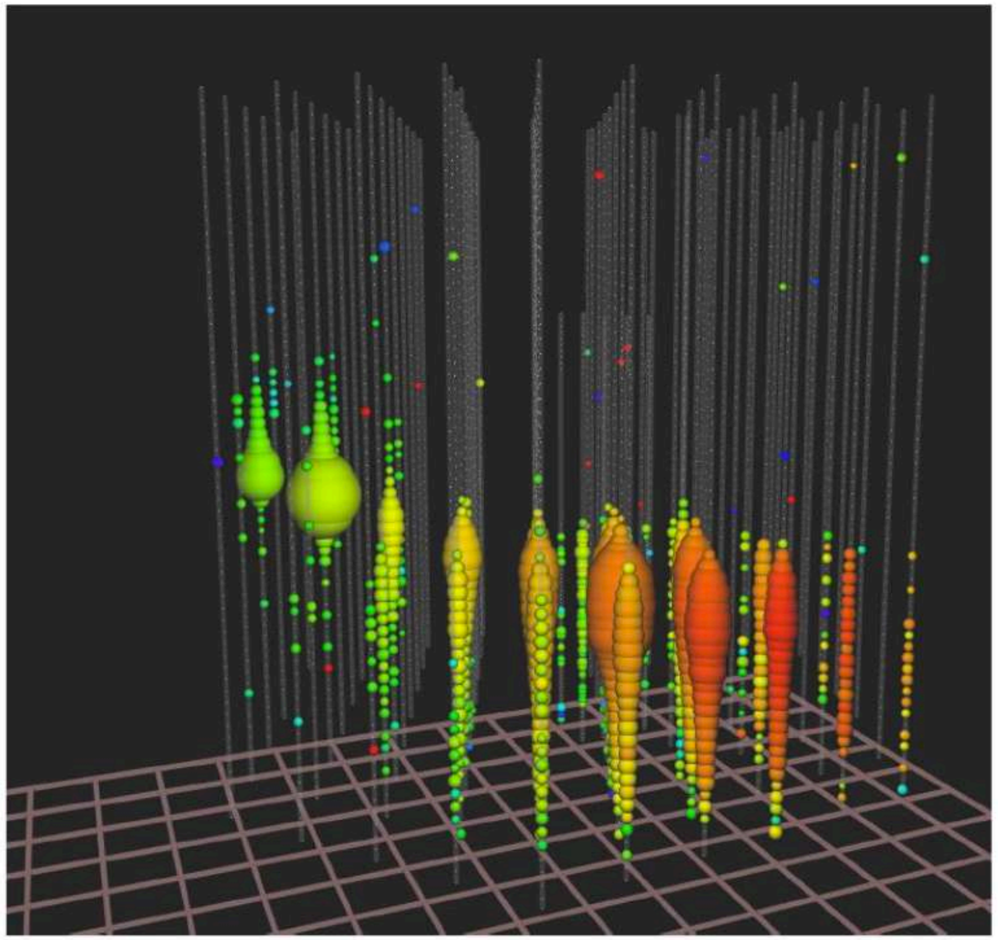
Time, position and amplitude of PMT pulses → direction/energy reconstruction

Neutrino event topology

Isolated neutrinos
interacting in the detector

Muon tracks





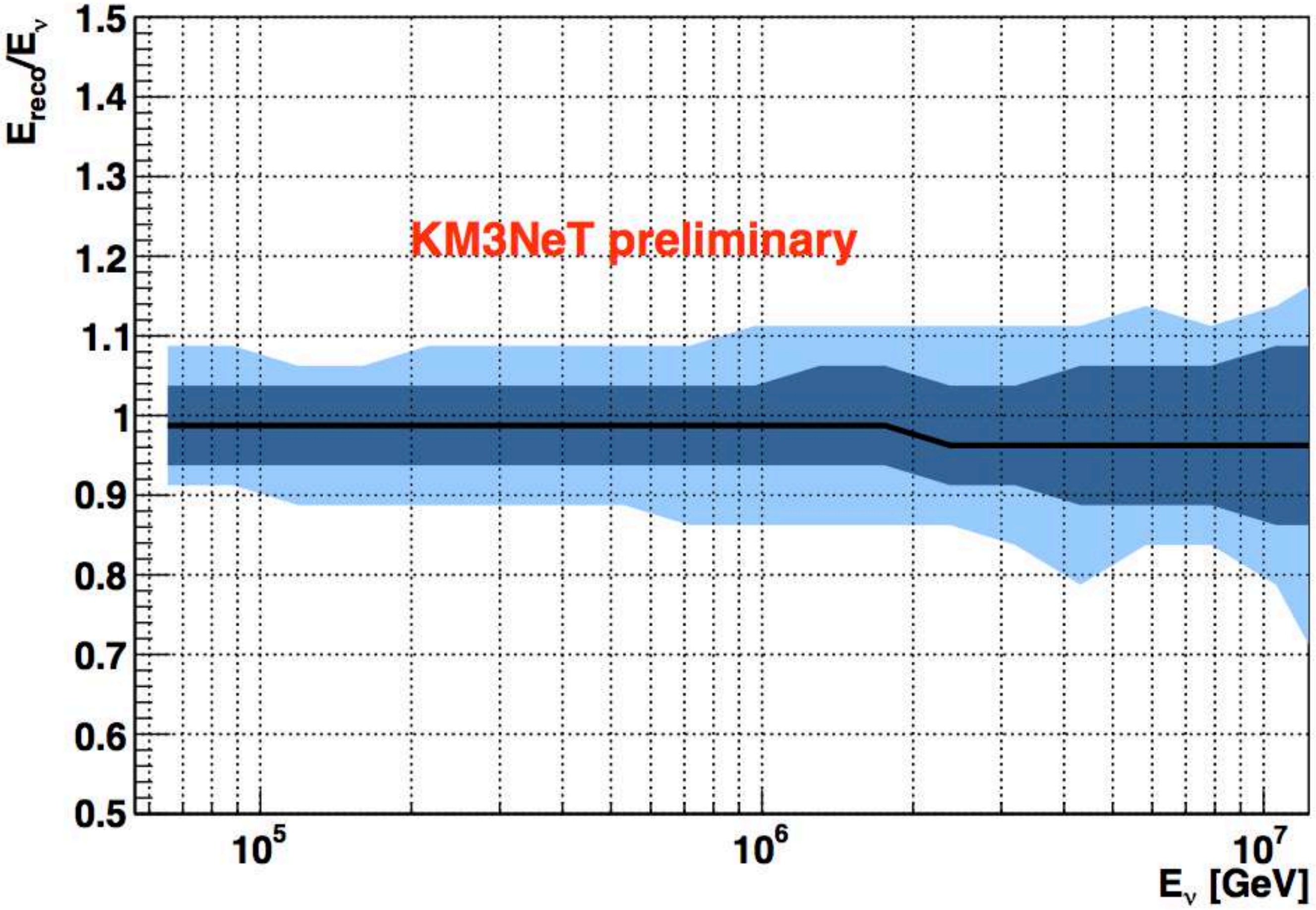
Calorimetry + all flavors

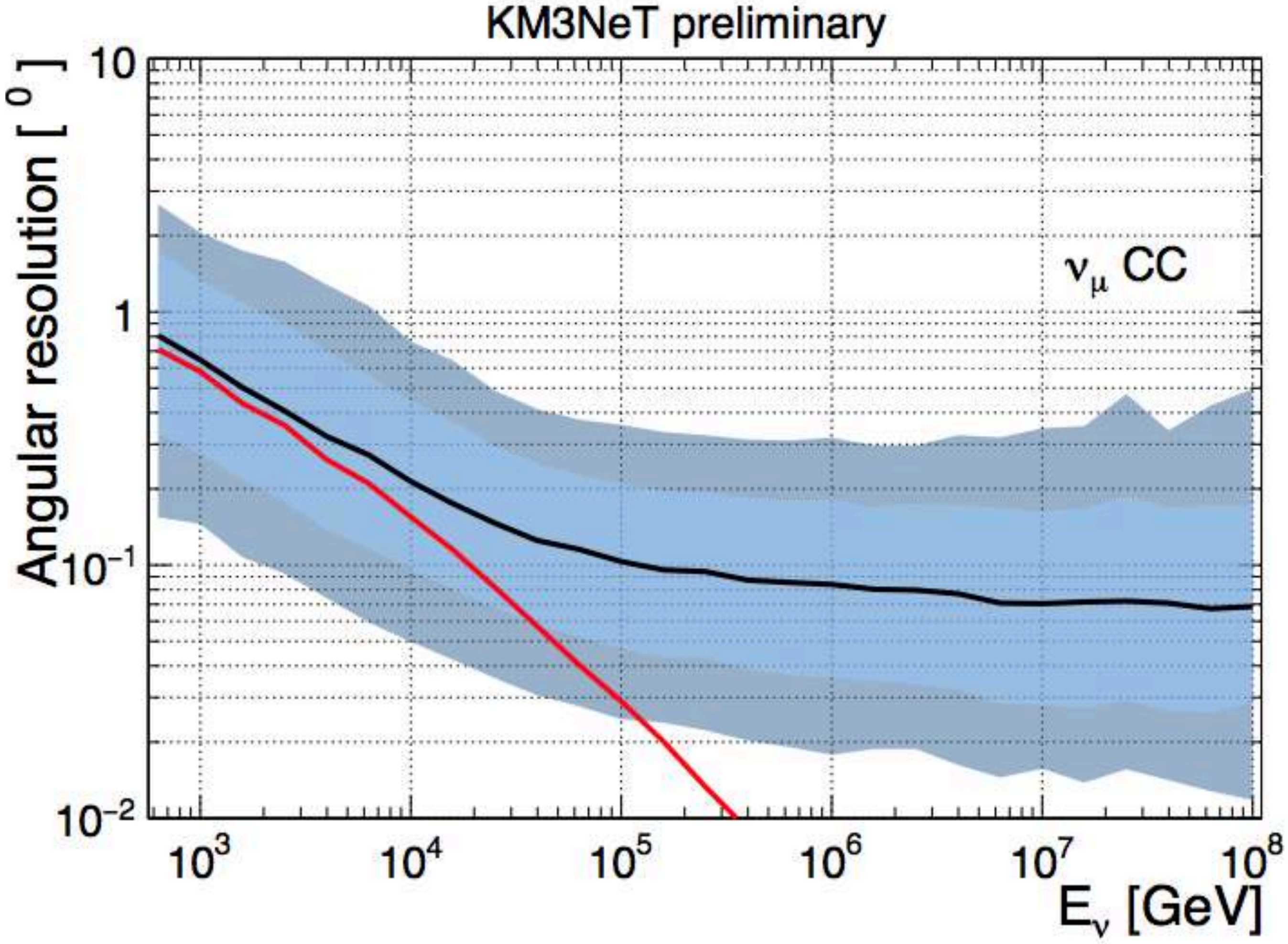
Astronomy: angular resolution

Neutrino event topology

Isolated neutrinos
interacting in the detector

Muon tracks



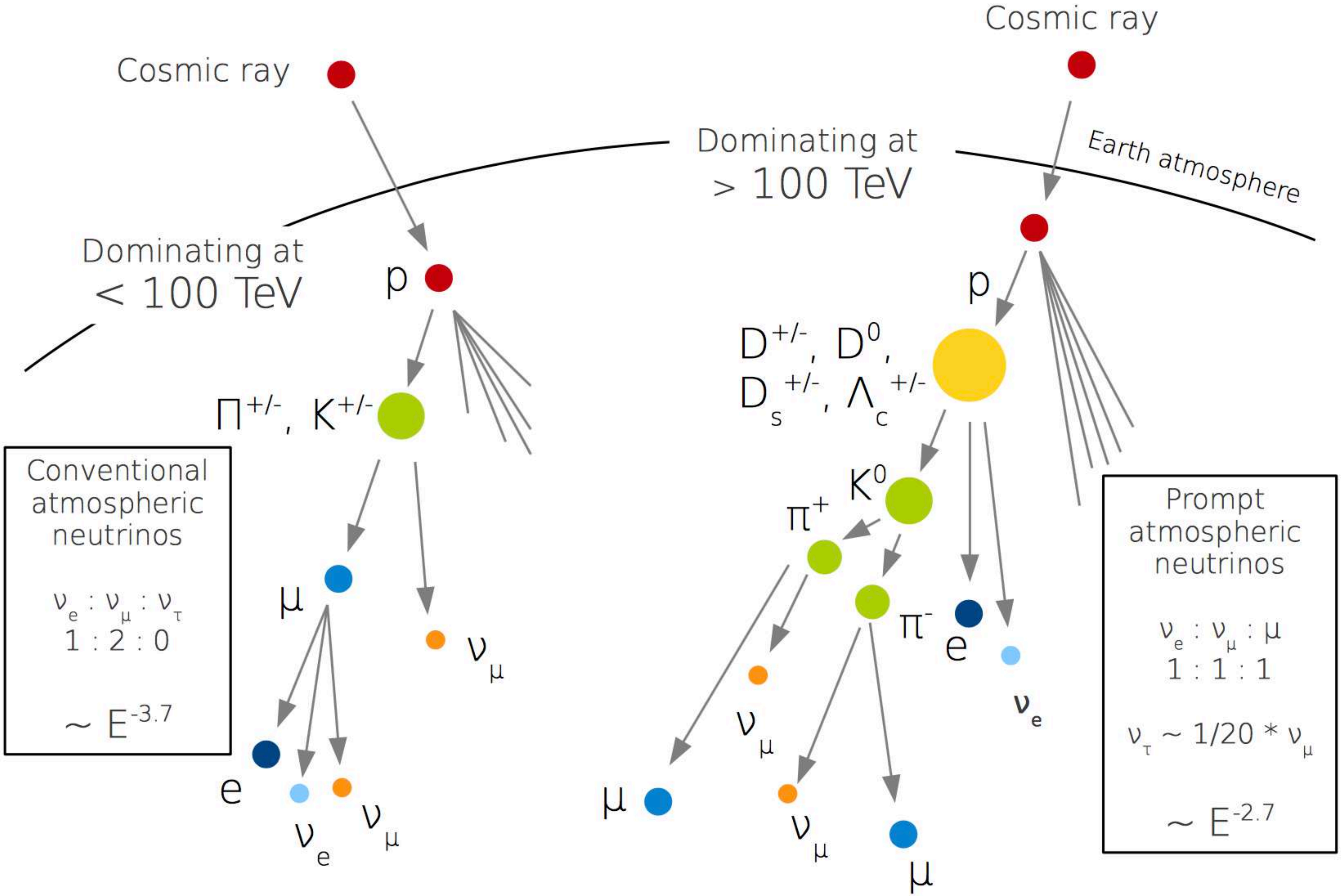


Calorimetry + all flavors

Astronomy: angular resolution

Adrian-Martinez et al. [KM3NeT Coll.],
J. Phys. G: Nucl. Part. Phys. 43 (2016)

The atmospheric background



Dominating at
< 100 TeV

Dominating at
> 100 TeV

Conventional
atmospheric
neutrinos

$\nu_e : \nu_\mu : \nu_\tau$
1 : 2 : 0

$\sim E^{-3.7}$

Prompt
atmospheric
neutrinos

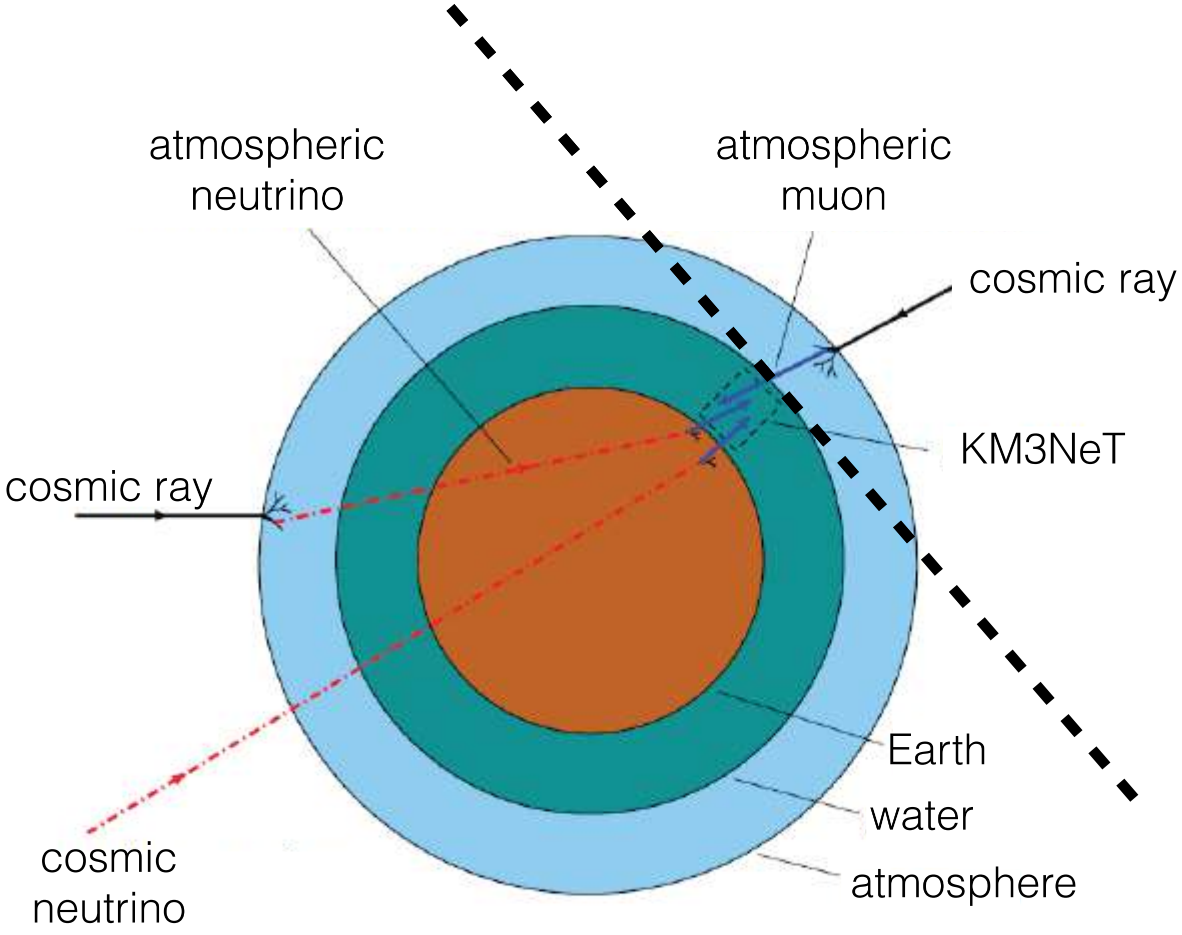
$\nu_e : \nu_\mu : \mu$
1 : 1 : 1

$\nu_\tau \sim 1/20 * \nu_\mu$

$\sim E^{-2.7}$

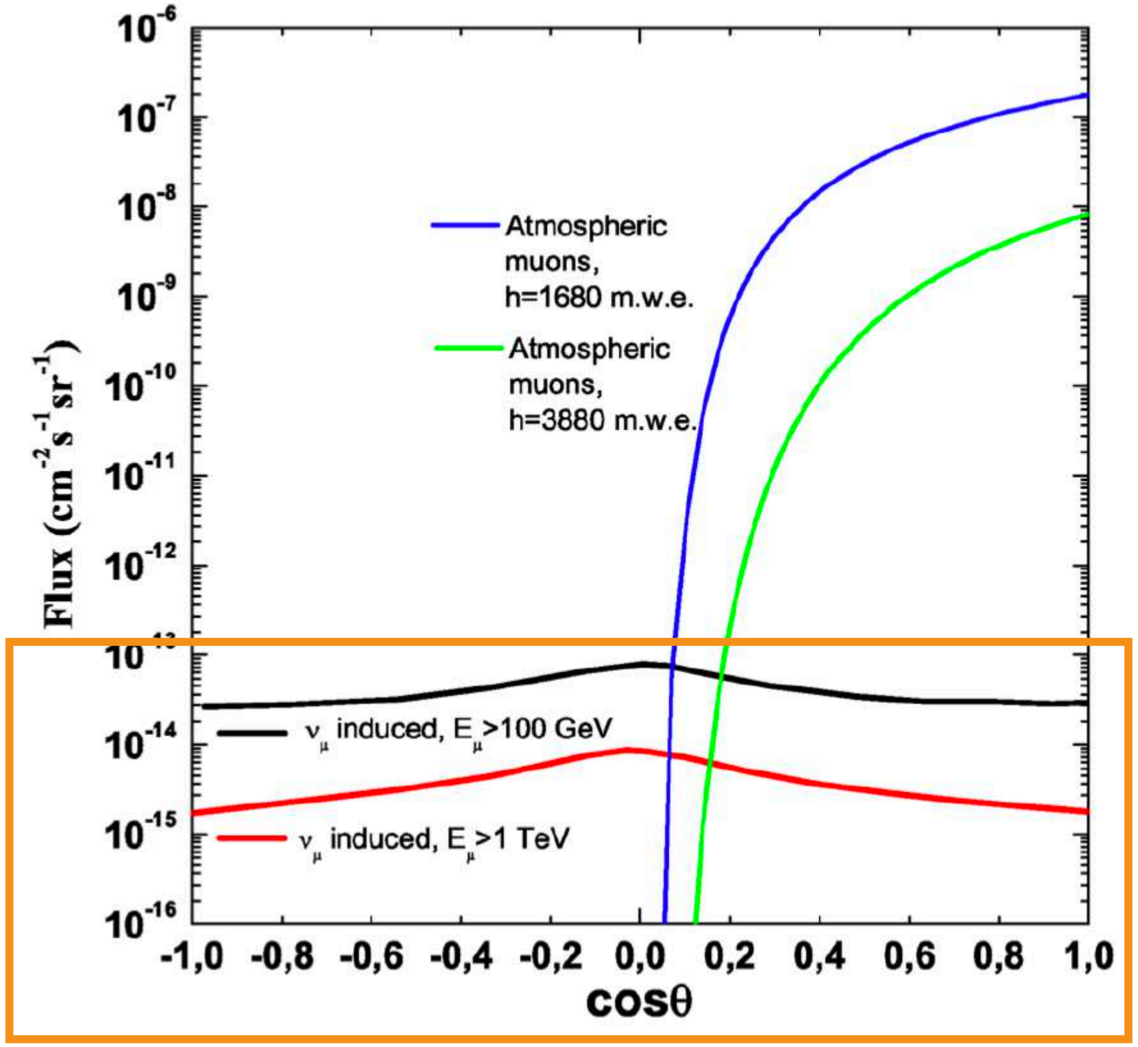
The atmospheric muon background

$$\boxed{\nu_\mu N \longrightarrow \mu X}$$



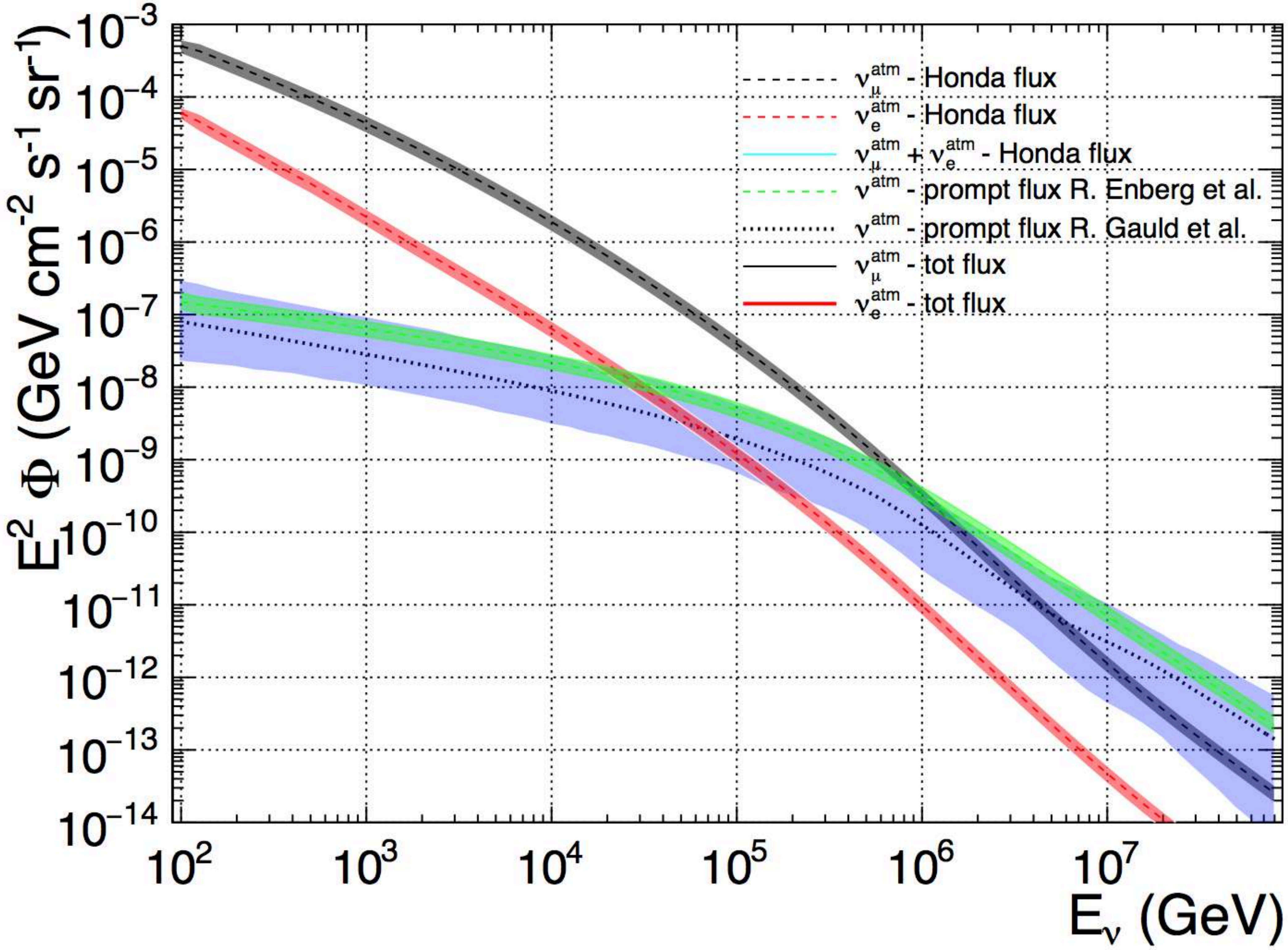
Experimental challenge

atm μ : atm ν: cosmic ν =
10^{10} : 10^4 : 1



**residual background
from atmospheric neutrinos,
suppressed by event selection
and spectroscopic studies**

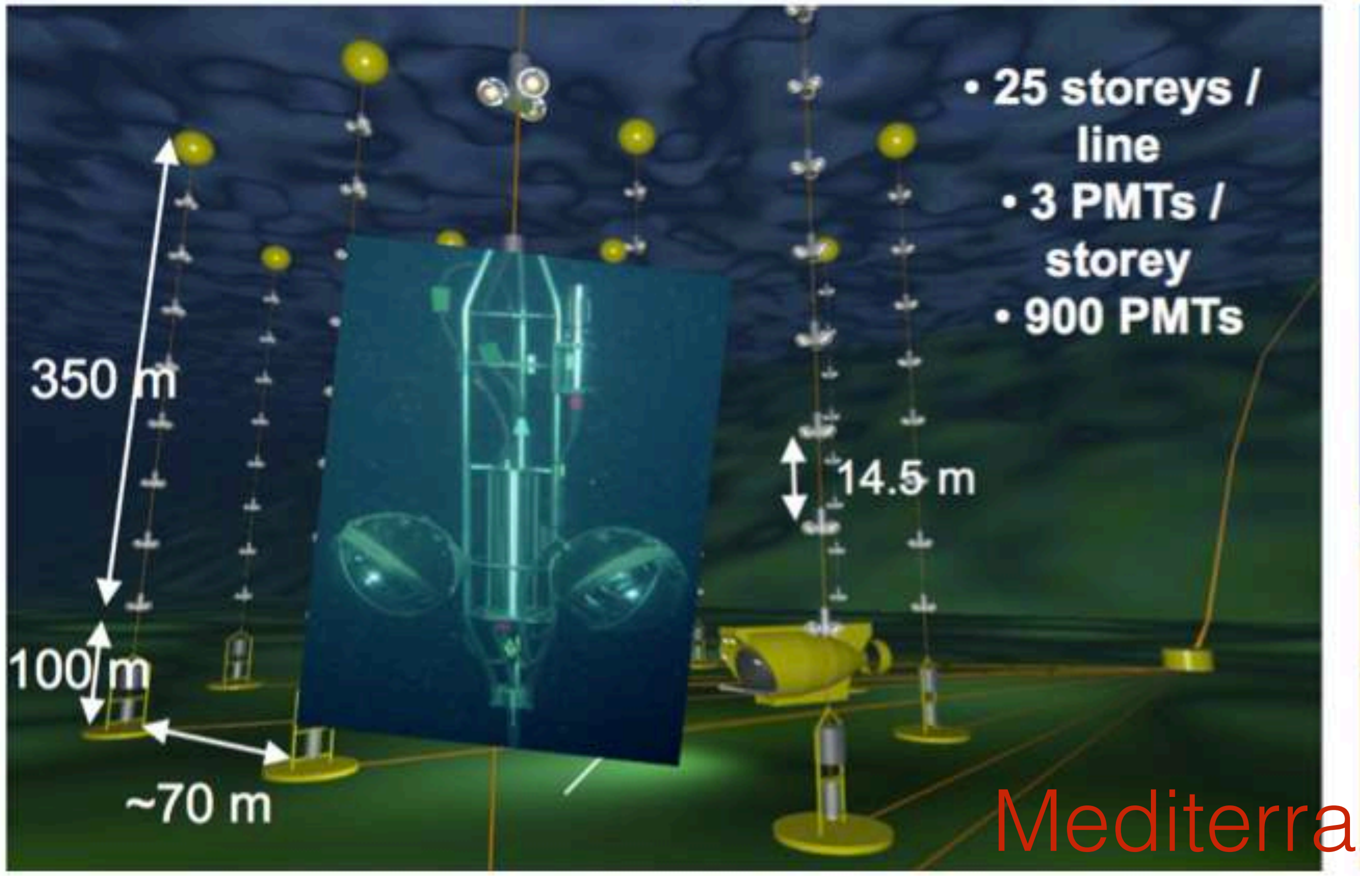
The atmospheric neutrino background



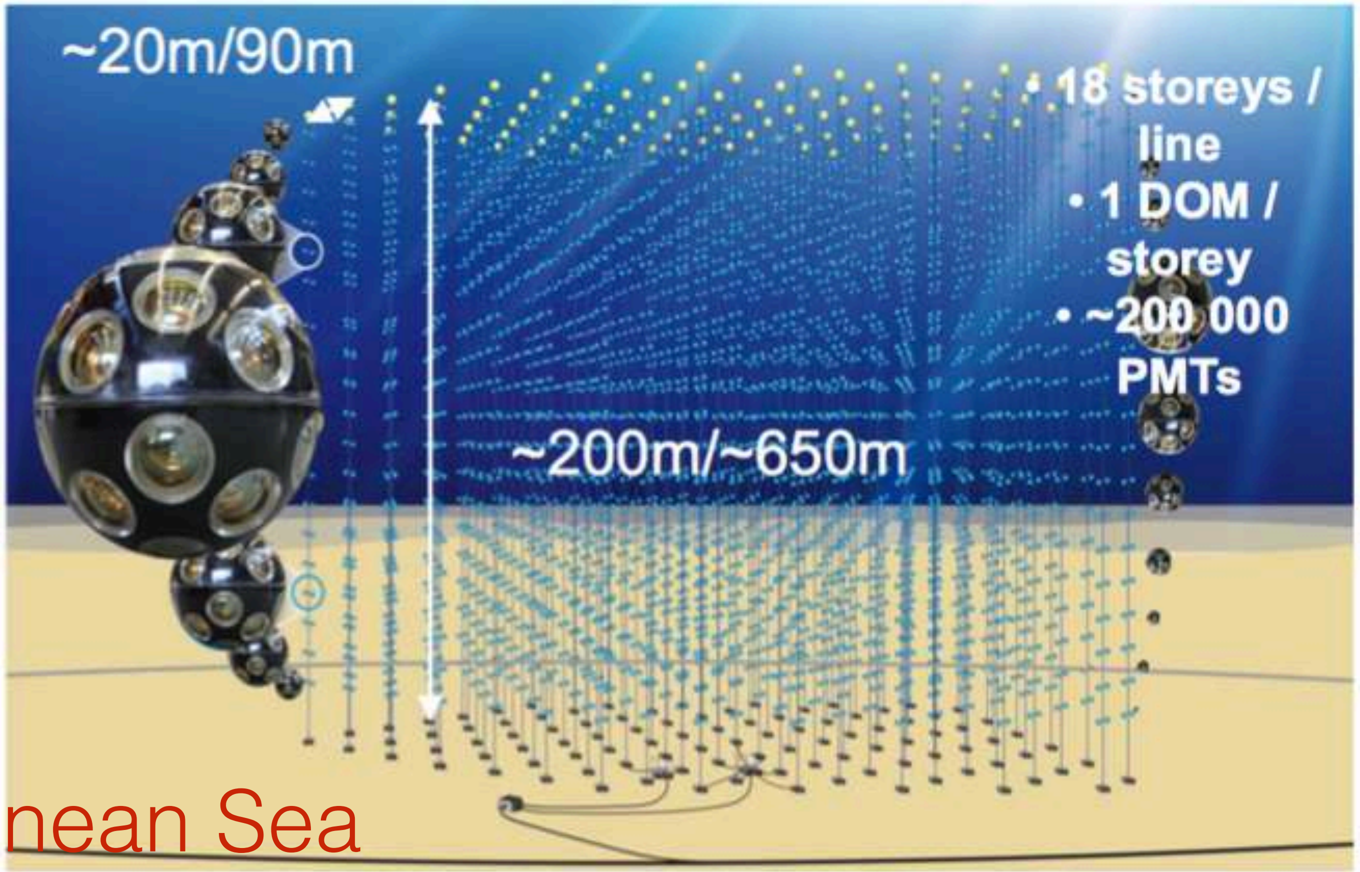
Adrian-Martinez et al. [KM3NeT Coll.],
J. Phys. G: Nucl. Part. Phys. 43 (2016)

Neutrino telescopes around the world

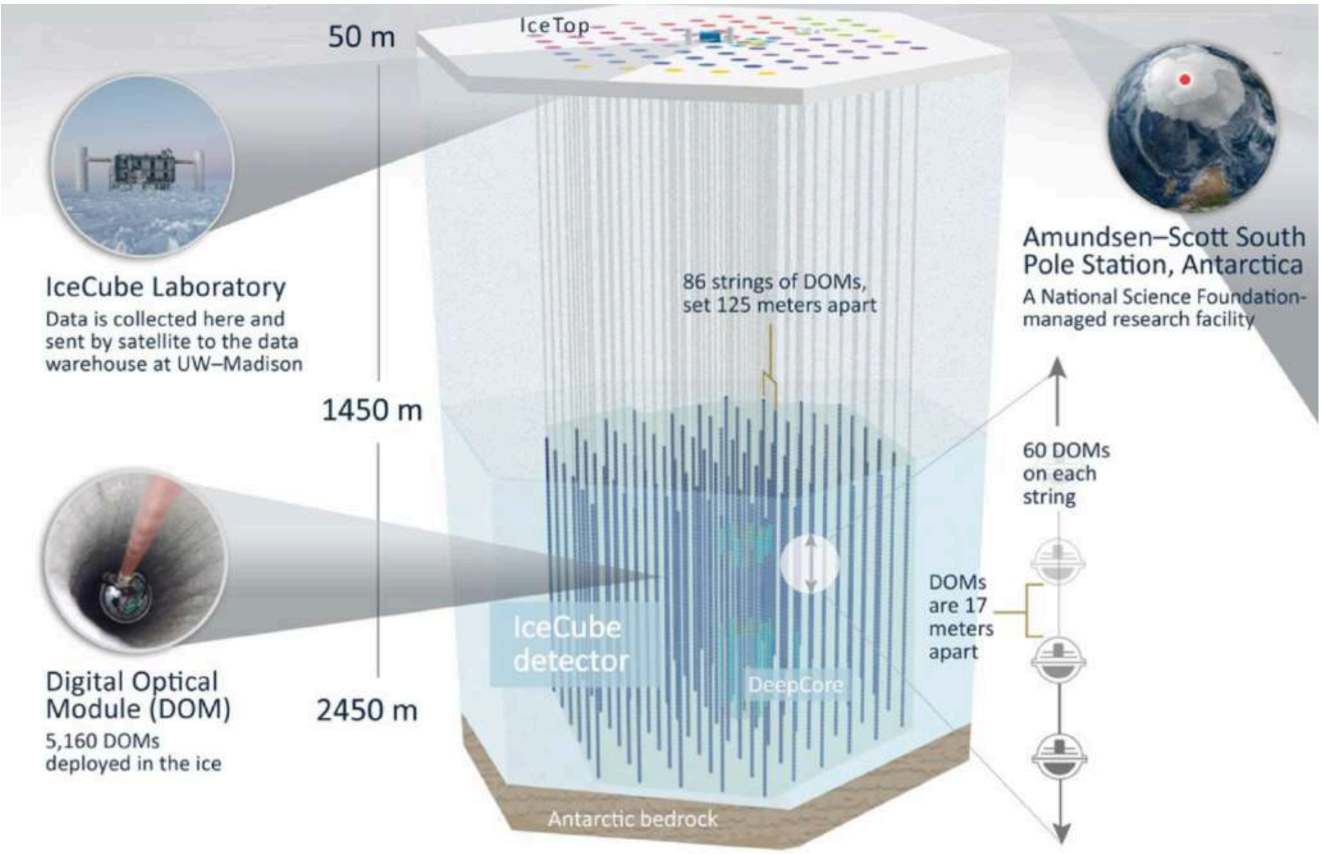
ANTARES Complete since 2008



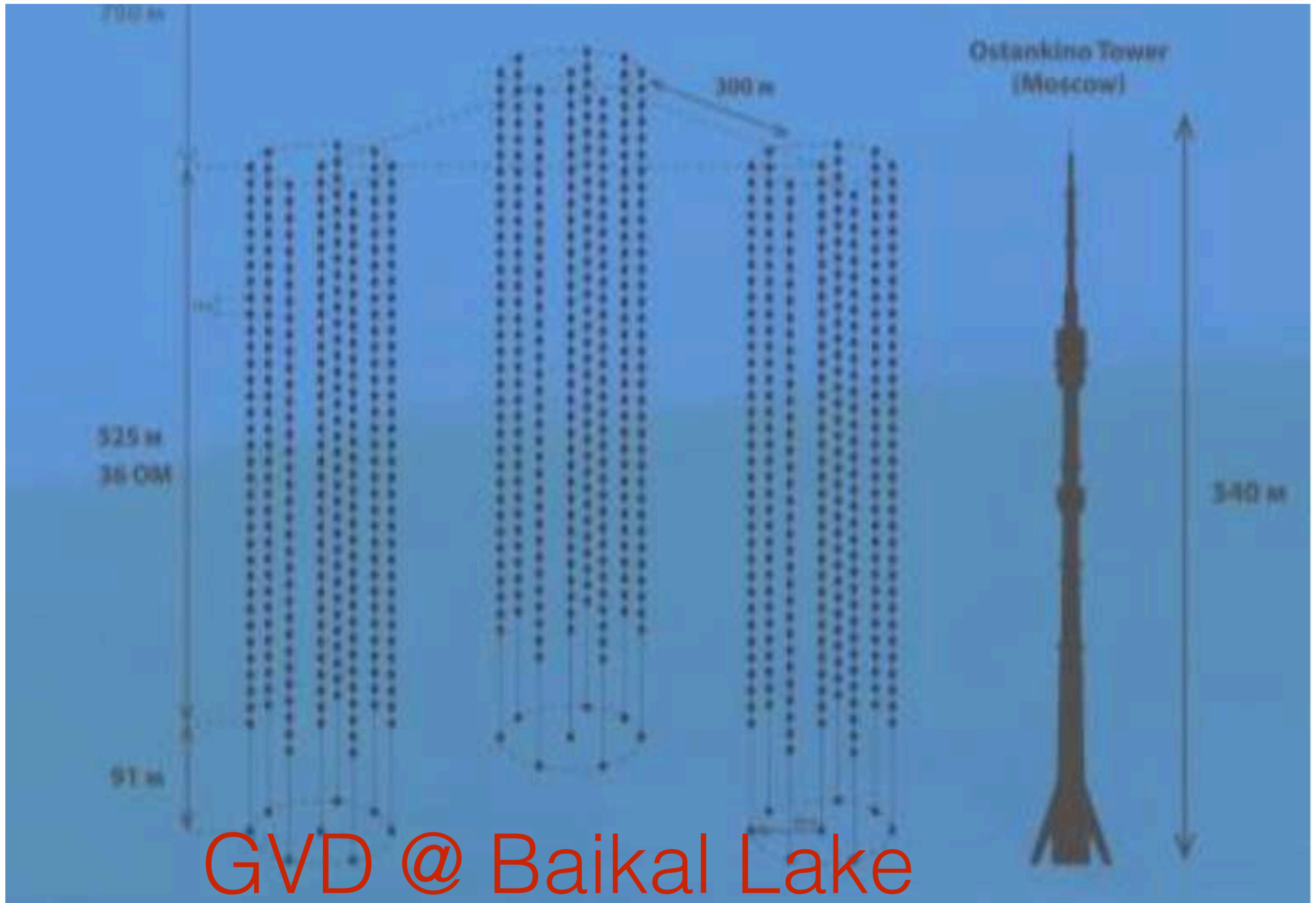
KM3NeT Under Construction



Mediterranean Sea



IceCube @ South Pole

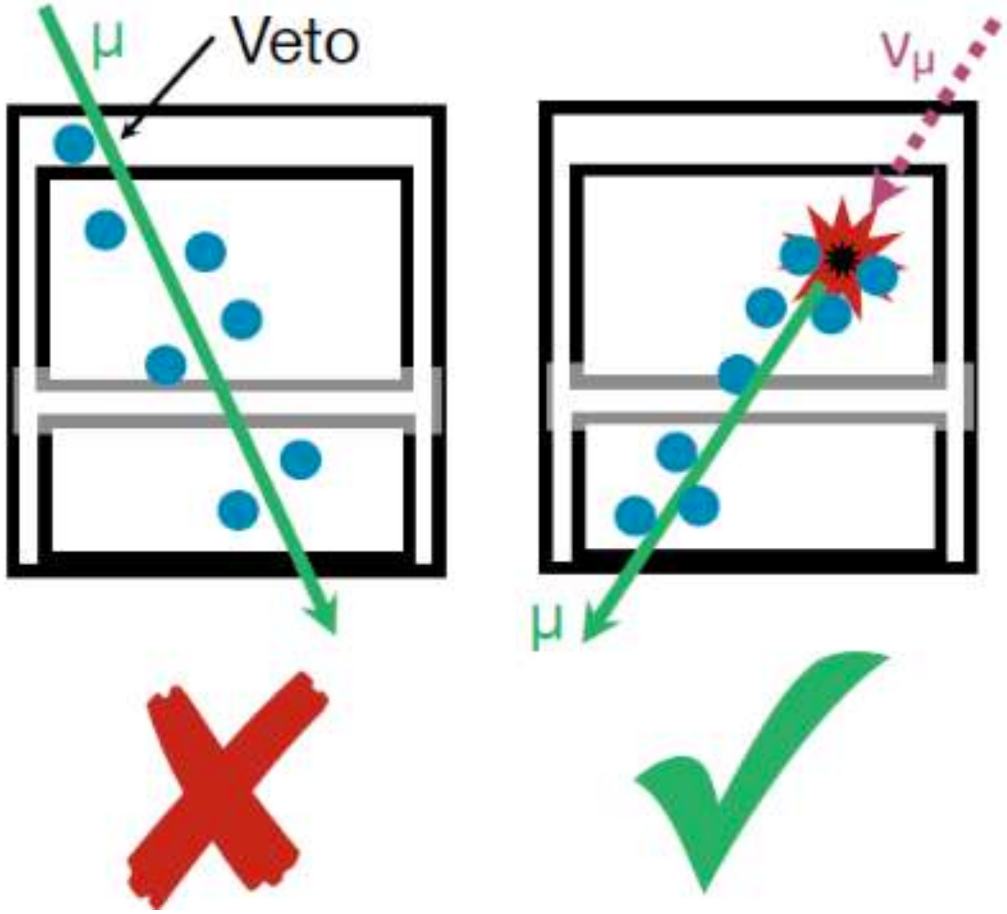


GVD @ Baikal Lake

Atmospheric neutrino veto: HESE

"Vetoing the muon produced by the same parent meson decaying in the atmosphere"

$$\pi \longrightarrow \mu^{atmo} + \nu_\mu^{atmo}$$



- Detects penetrating muons
- Reduced effective volume (400 MTon)
- Sensitive to all flavors
- Sensitive to the entire sky

📕 Schonert et al., PRD 79 (2009) 4

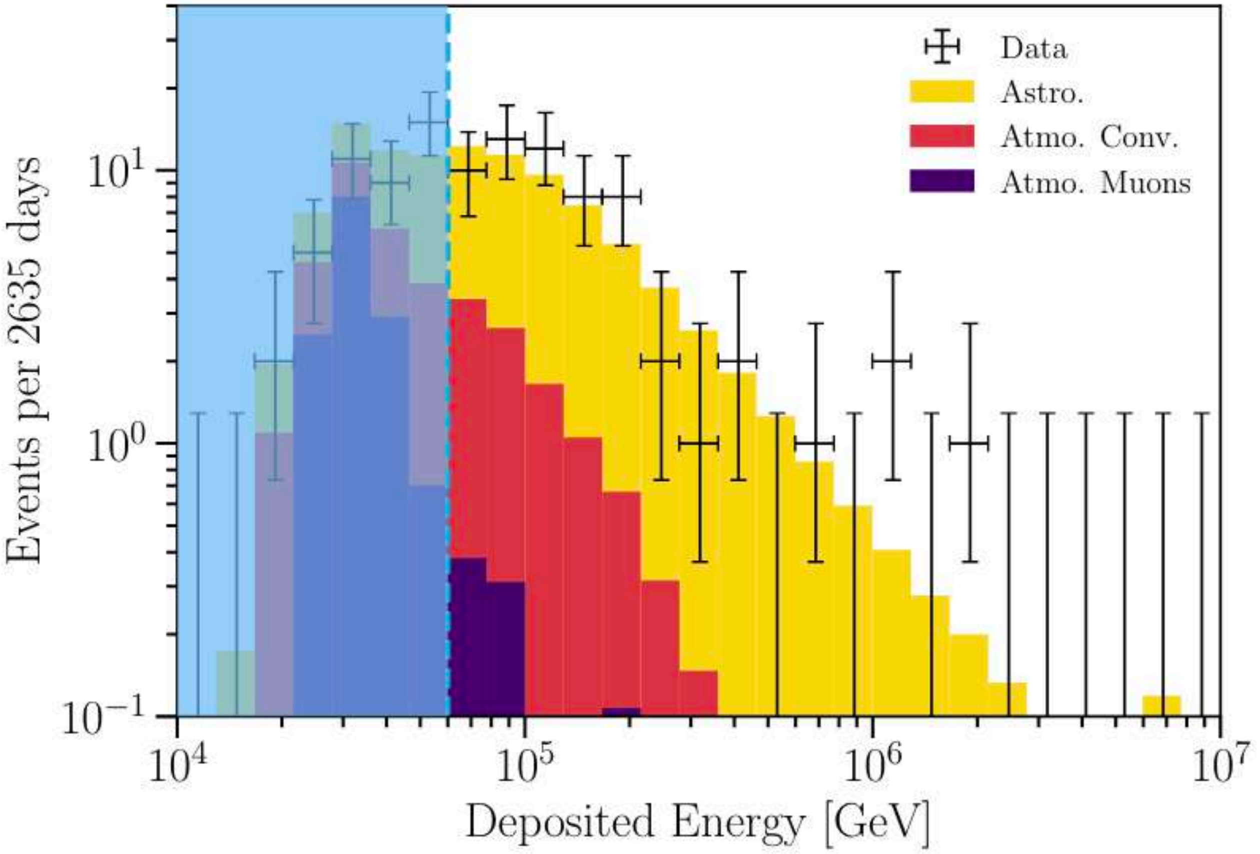
$\boxed{E_\nu > 60\,\mathrm{TeV}}$ in IceCube

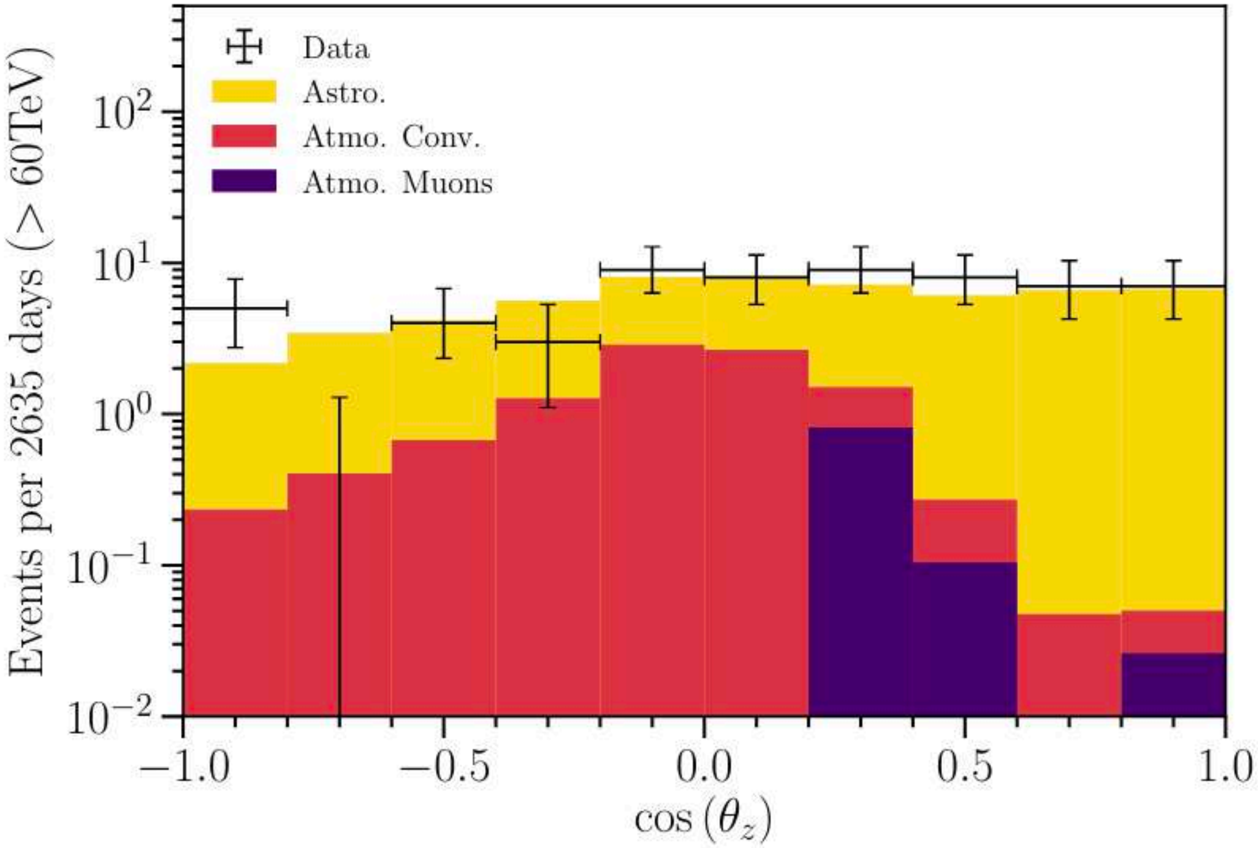
The cosmic neutrino signal

High Energy Starting Events (HESE)

all sky (but mostly from the Southern Hemisphere), 7.5 yrs

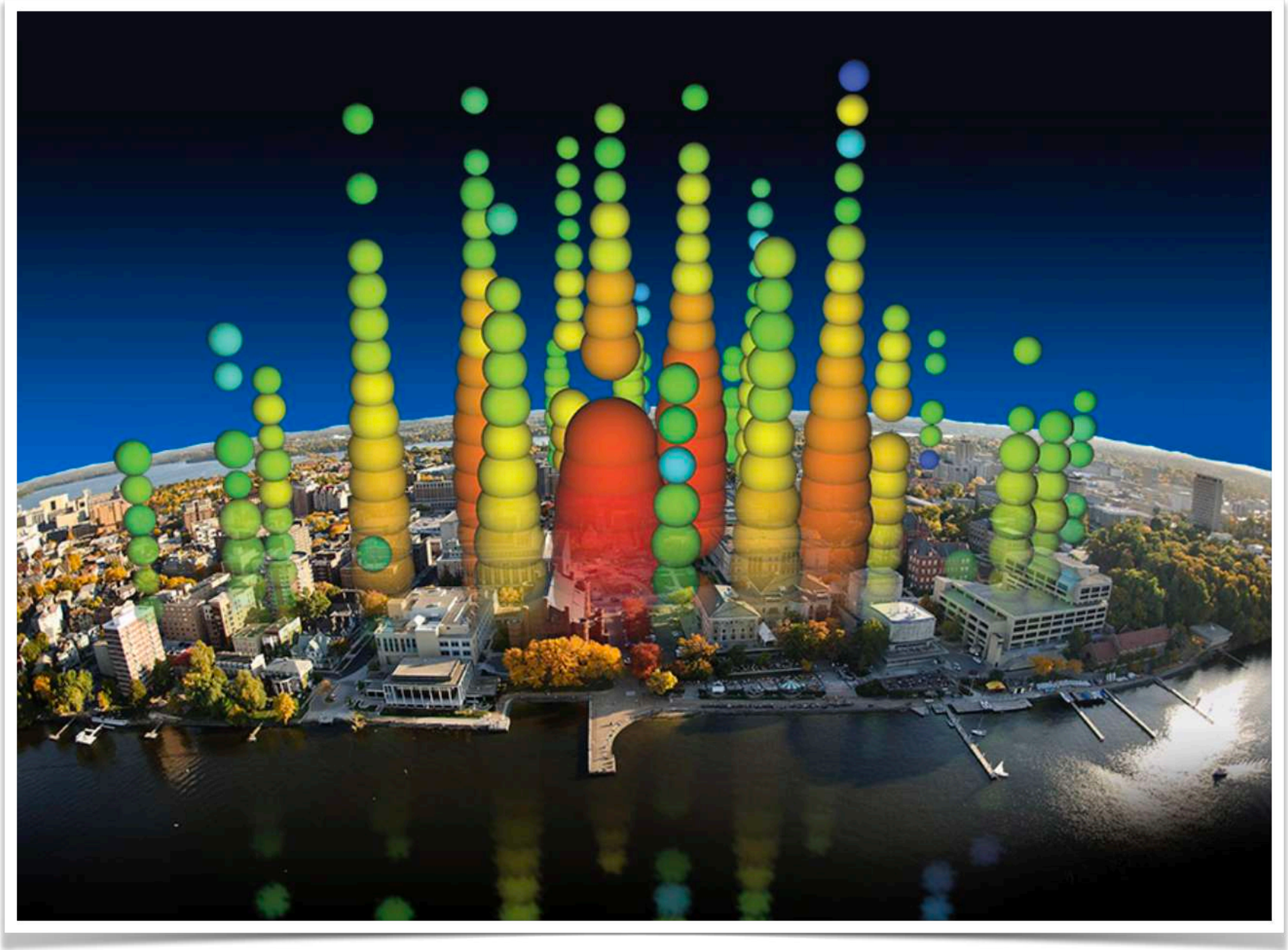
$$\frac{d\Phi_{6\nu}}{dE} = (6.37^{+1.46}_{-1.62}) \cdot 10^{-18} \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-(2.87^{+0.21}_{-0.19})} \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$





Abbasi et al. [IceCube Coll.], PRD 104 (2021) 022002

The cosmic neutrino signal



PeV ν_e (shower) event, > 300 sensors,
> 10^5 photo-electrons reconstructed

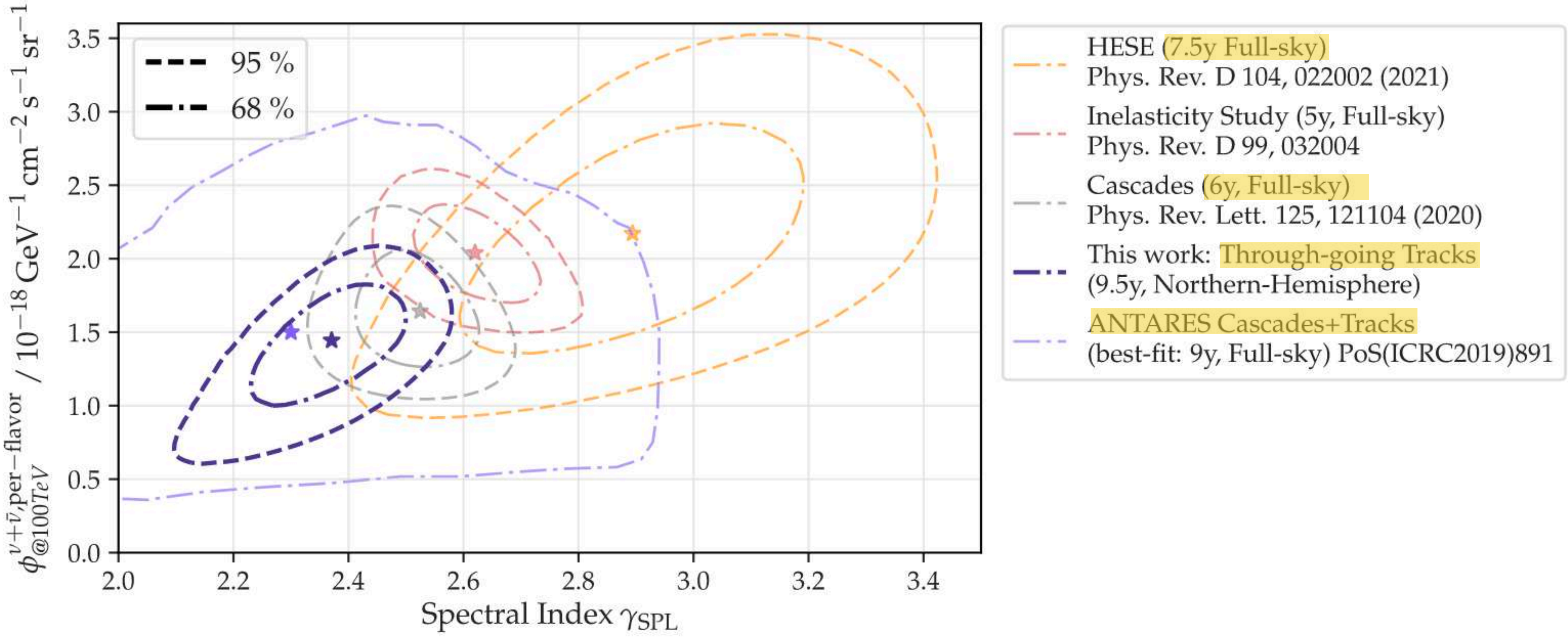
The cosmic neutrino signal

Up-going Muons from 2009-2018 IC data

(through+starting with zen>85°):

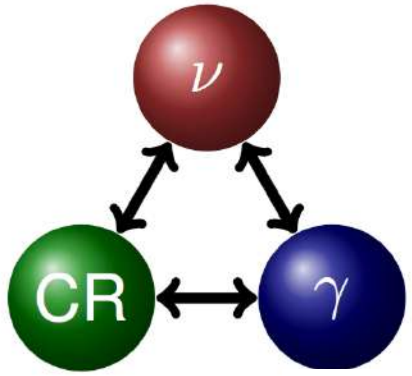
a view on the Northern Hemisphere

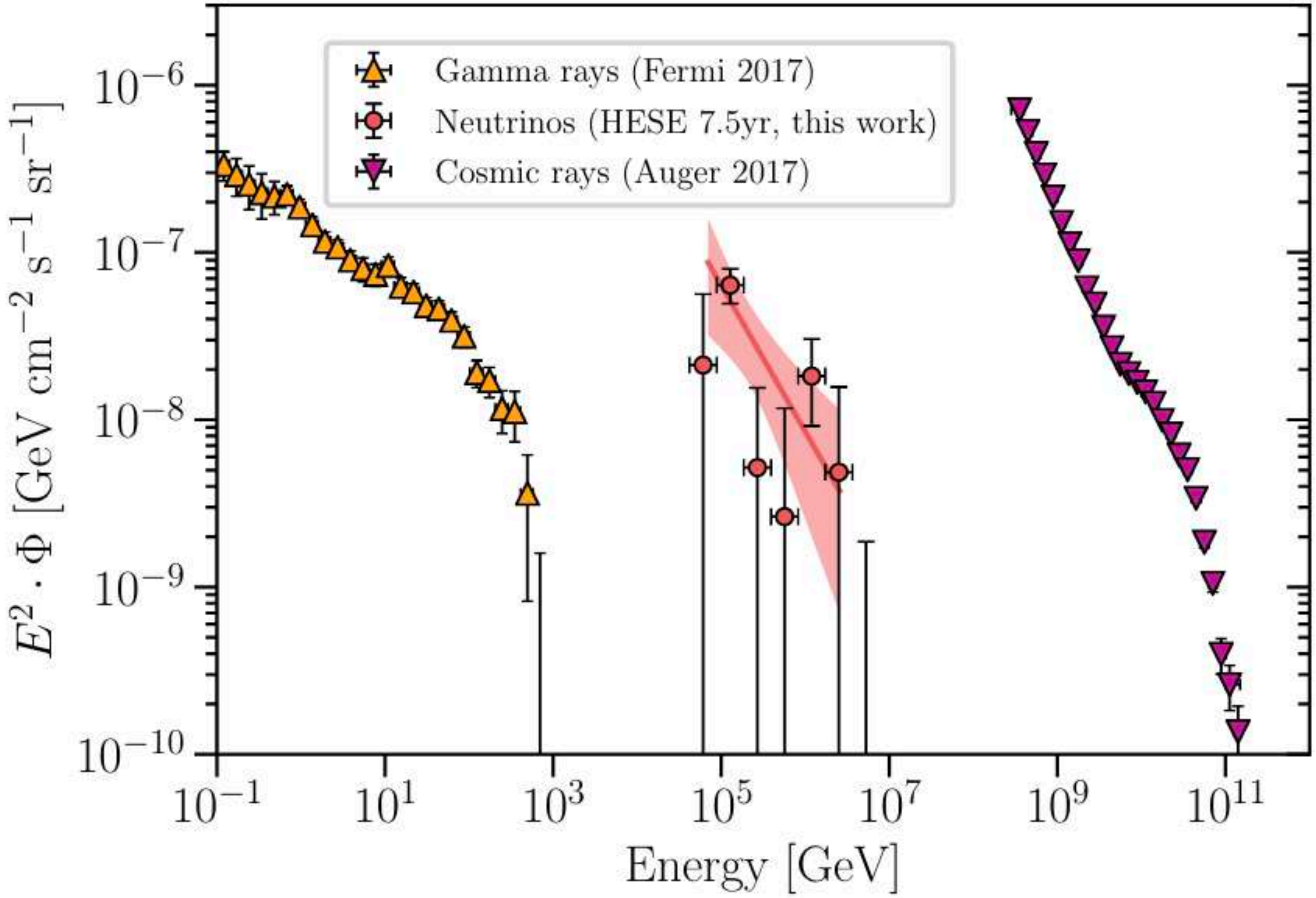
$$\frac{d\Phi_{\nu+\bar{\nu}}}{dE} = (1.44 \pm ^{0.25}_{0.26}) \cdot 10^{-18} \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-2.37\pm0.09} \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$



Abbasi et al. [IceCube Coll.], ApJ 928 (2022) 50

The non thermal Universe in the multi-messenger framework



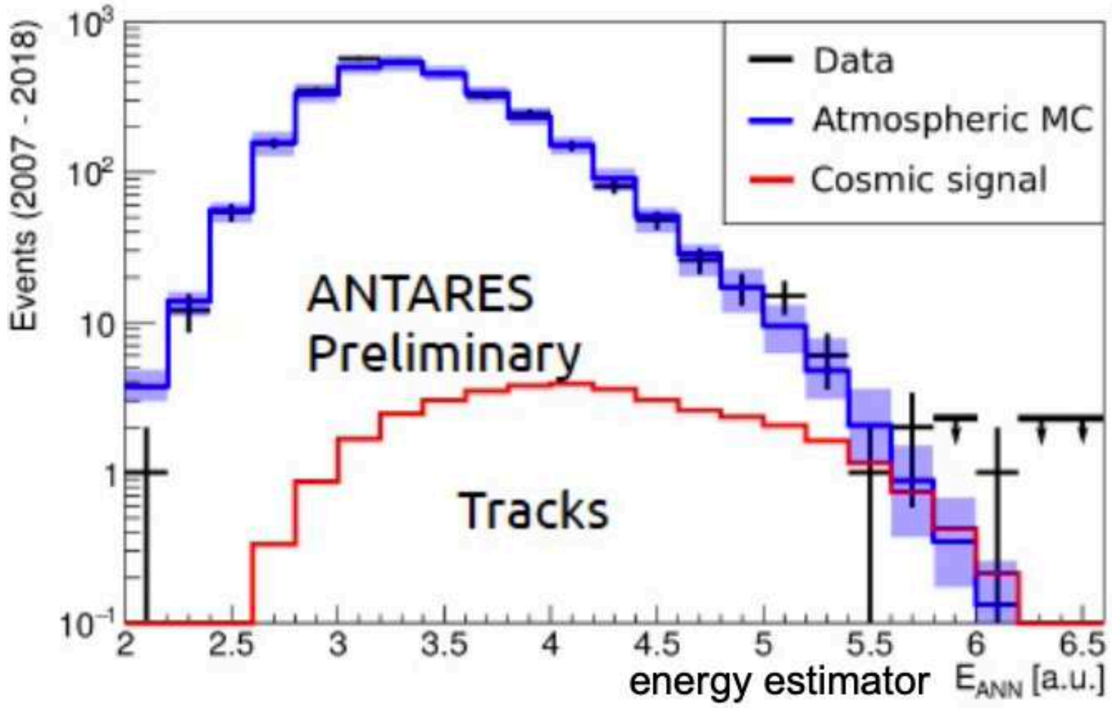


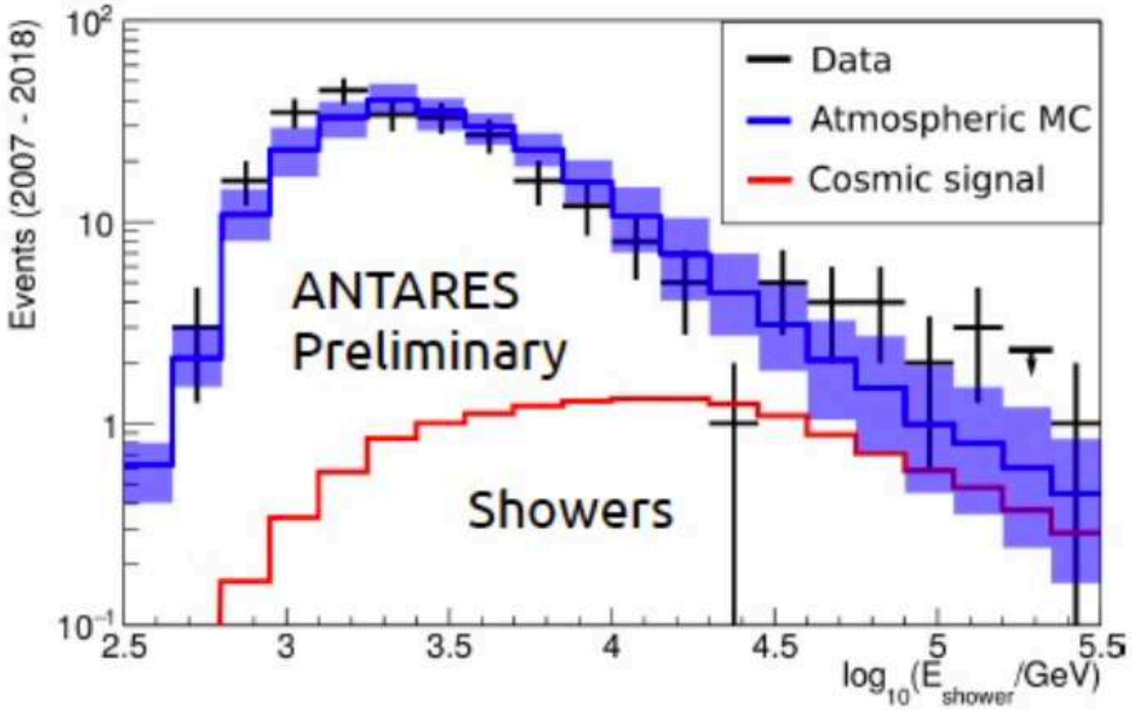
Abbasi et al. (IceCube Coll.), PRD 104 (2021) 2

ANTARES all sky diffuse flux

- Looking for an excess above a given energy threshold
- Combined track and shower sample
- **Data (2007-2018): 50 events** (27 tracks + 23 showers)
- **Background expectation (atm. flux including prompt): 36.1 ± 8.7** (19.9 tracks and 16.2 showers), stat+syst

RESULTS NOT REALLY CONSTRAINING, BUT FULLY COMPATIBLE WITH ICECUBE



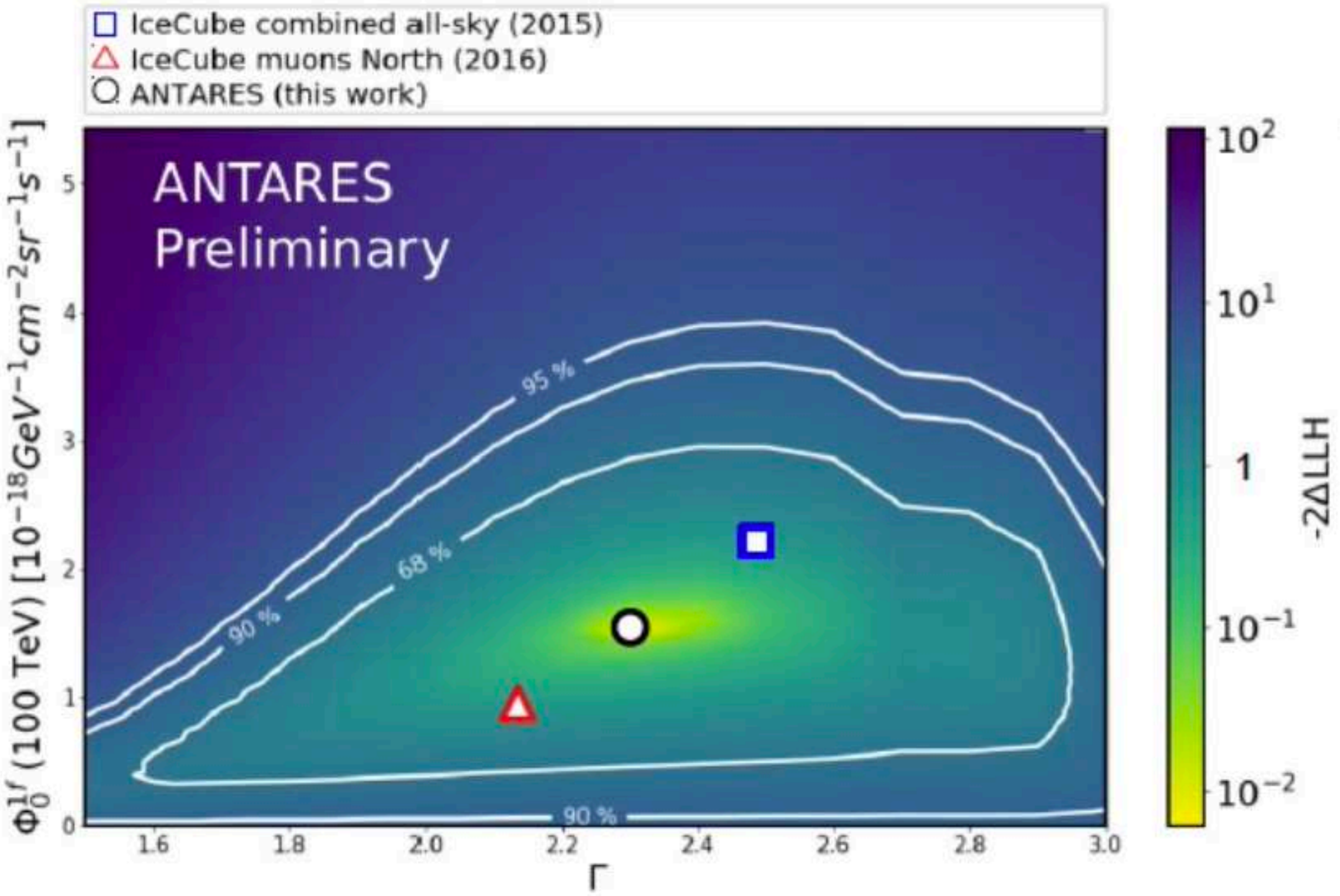


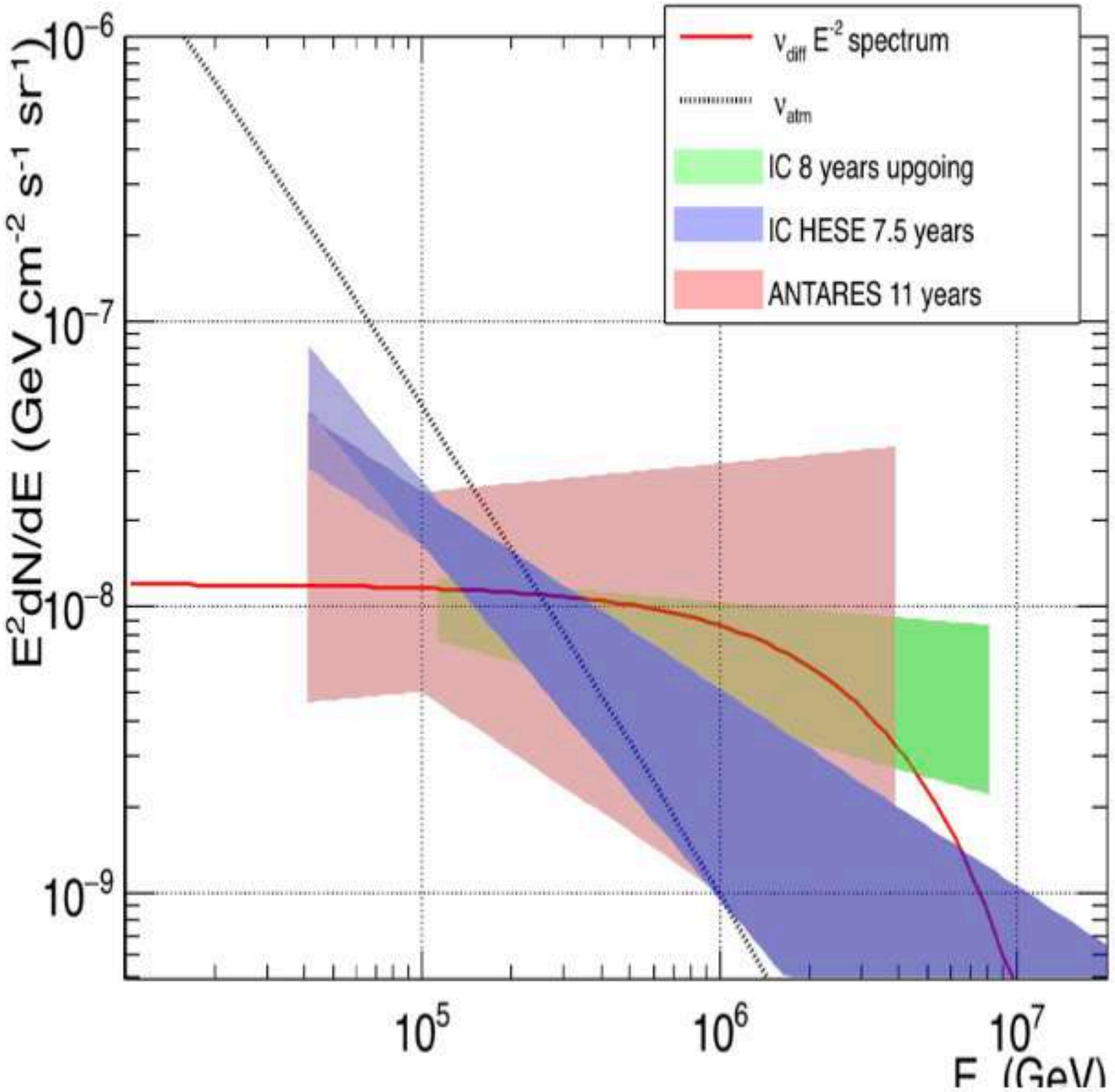
Fusco et al [ANTARES Coll.], PoS ICRC(2019) 891

ANTARES all sky diffuse flux

- Combined tracks+showers likelihood fit
- Cosmic flux: $\boldsymbol{\phi_{100\ \mathrm{TeV}} = (1.5 \pm 1.0) \times 10^{-18}\ \mathrm{GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}}$

  $\boldsymbol{\Gamma = 2.3 \pm 0.4}$

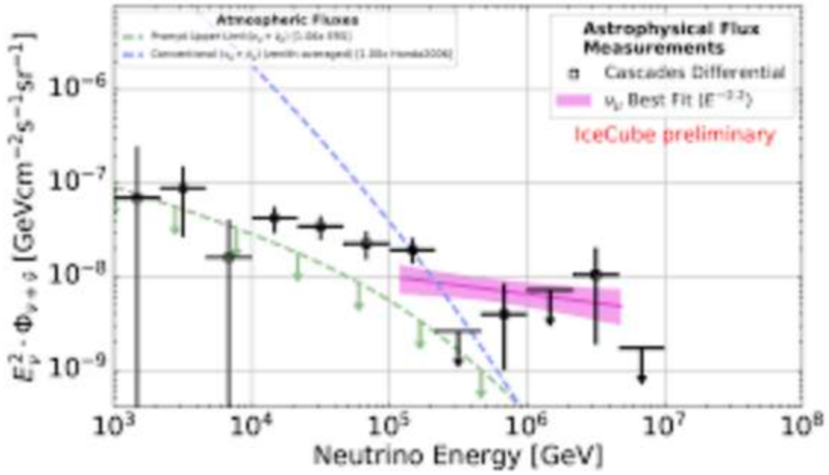




Fusco et al [ANTARES Coll.], PoS ICRC(2019) 891

Where do cosmic neutrinos come from?

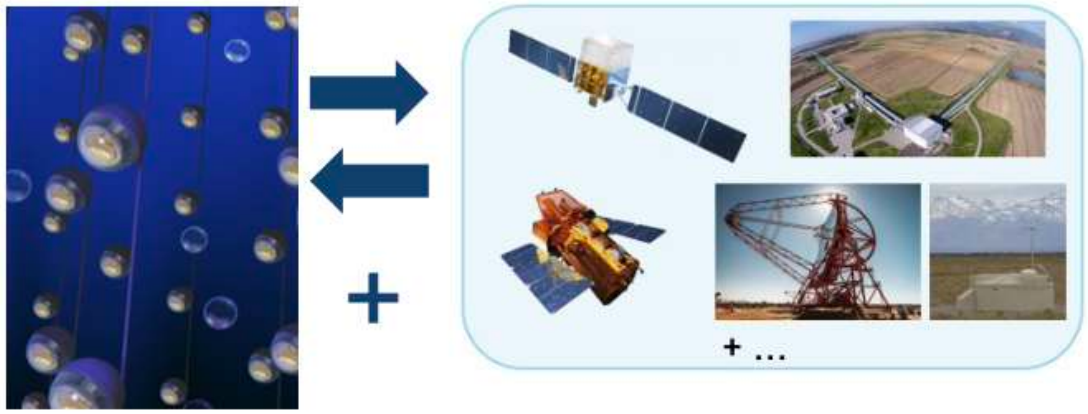
Diffuse flux searches



→ low latitude Galactic Plane excess (4.1σ)?

Kovalev et al., arXiv:2208.08423

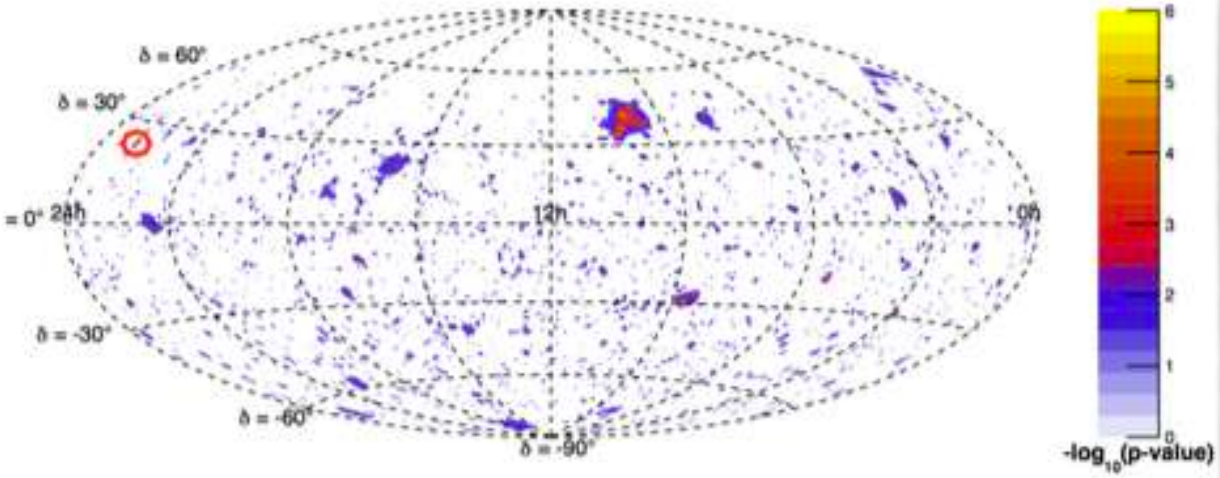
Multi-messenger search



IC170922A alert → TXS 0506+056

Aartsen et al. [IceCube Coll.], Science 361 (2018)

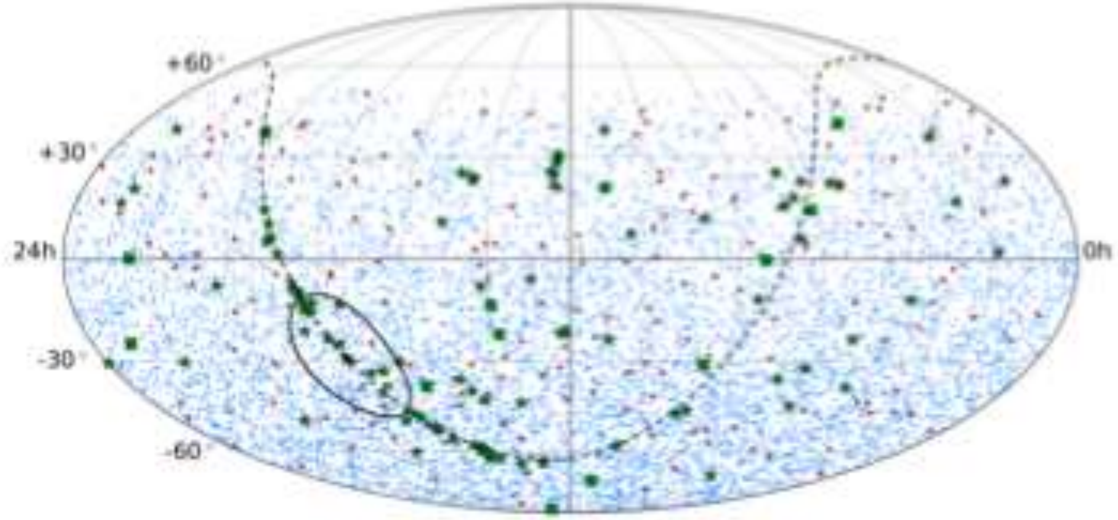
Point source search (auto-correlation)



→ mild excess (2.9σ) in IC data from **NGC1068**

Aartsen et al. [IceCube Coll.], PRL 124 (2020) 051103

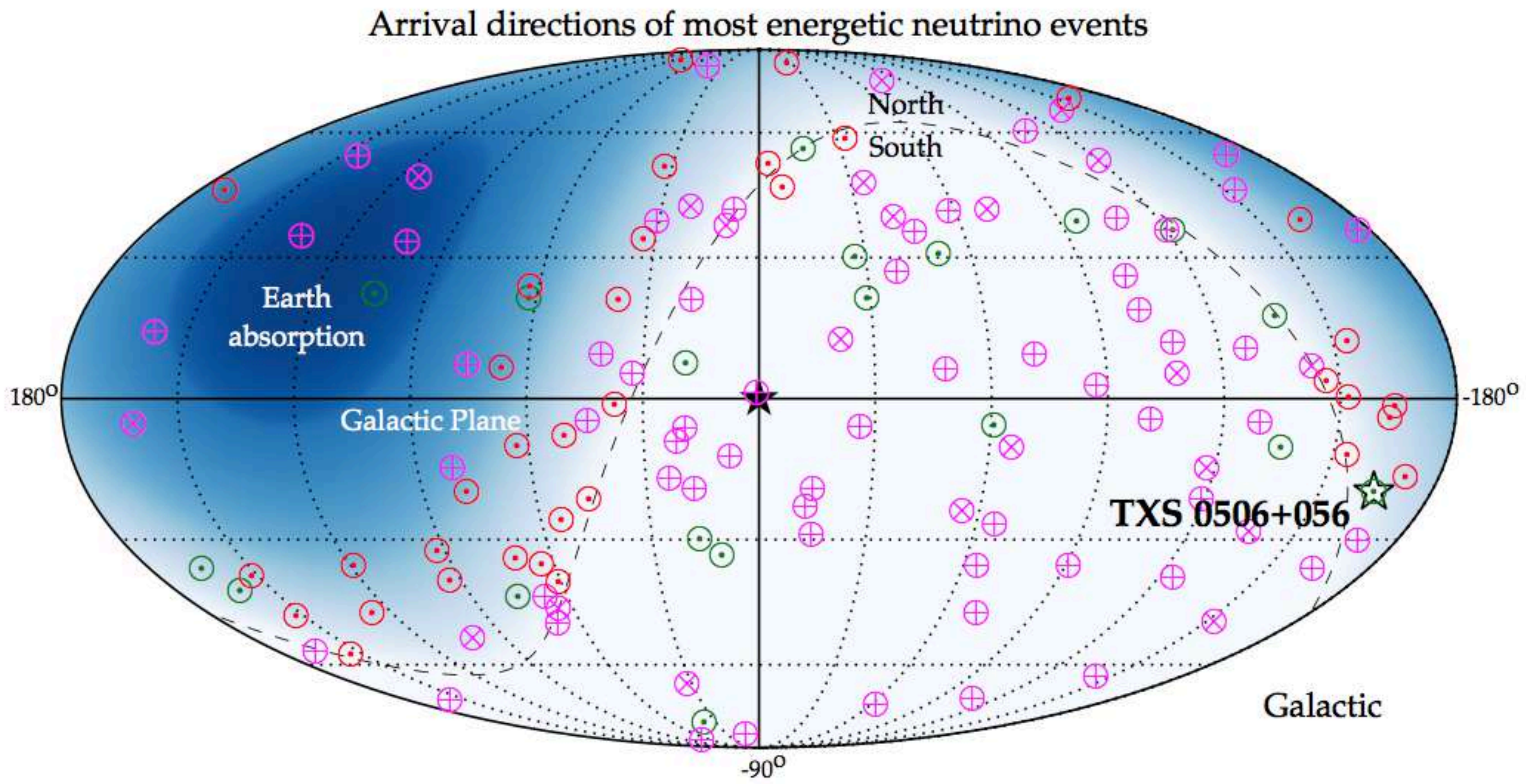
Point source search (catalog search)



→ correlation among IC data from Southern Hemisphere and blazar catalog?

Buson et al., ApJ 933 (2022) L43

The cosmic neutrino signal



⊙ tracks ⊗ HESE tracks ⊕ HESE cascades ⊙ public alerts

Ackerman et al., Bull. Am. Astron. Soc. 51 (2019) 185

Anisotropic contributions from the Galaxy

Two main sources of (**pp**) neutrinos are:

1. Diffuse emission along the **Galactic Plane**, originated in **CR collisions with target gas density** ⟶ could provide constraints about the CR distribution;

Pagliaroli et al., JCAP 11 (2016) 004

2. Emission from **Galactic population of sources** ⟶ could help localizing the accelerators responsible for the CR flux and understanding the relative contribution of sources wrt diffuse emission.

Lipari & Vernetto, PRD 98 (2022) 4

Both can be constrained from gamma-ray counterpart:

$$\begin{aligned} \varphi_{\gamma,\mathrm{tot}} &= \varphi_{\gamma,\mathrm{diff}} + \varphi_{\gamma,\mathrm{S}} + \cancel{\varphi_{\gamma,\mathrm{IC}}} \\ \varphi_{\nu,\mathrm{tot}} &= \varphi_{\nu,\mathrm{diff}} + \varphi_{\nu,\mathrm{S}} \end{aligned}$$

negligible above few GeV

from CR collisions

resolved + unresolved sources

Diffuse emission from the Galactic Plane

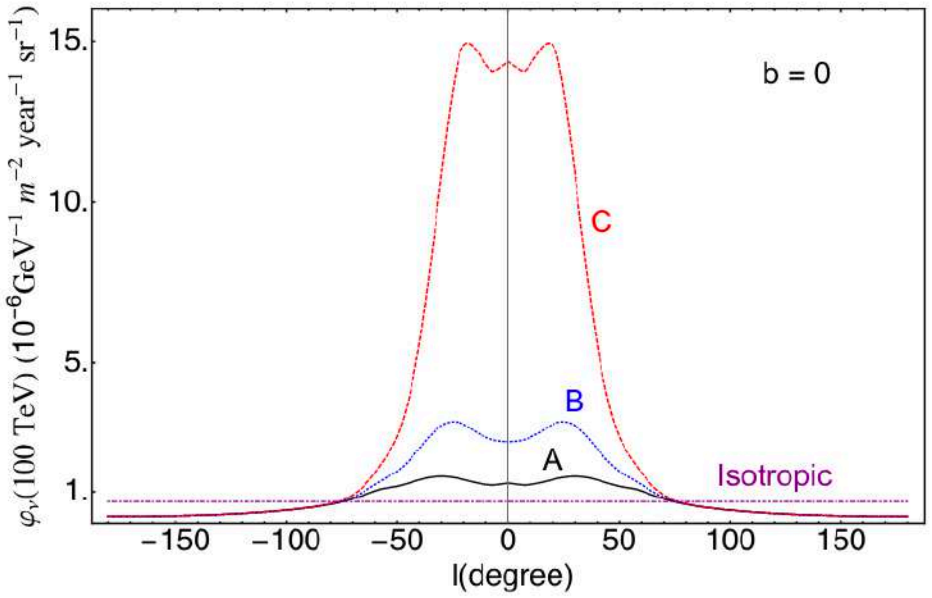
$$\varphi_\nu(E_\nu,\hat{n}_\nu) = \frac{1}{3}\sum_{\ell=e,\mu,\tau}\left[\int_{E_\nu}^{\infty} dE\ \frac{d\sigma_\ell(E,E_\nu)}{dE_\nu}\int_0^\infty dl\,\underbrace{\varphi_{\rm CR}(E,\mathbf{r}_\odot+l\,\hat{n}_\nu)}_{\text{CR density}}\,\underbrace{n_{\rm H}(\mathbf{r}_\odot+l\,\hat{n}_\nu)}_{\text{Gas density}}\right]$$

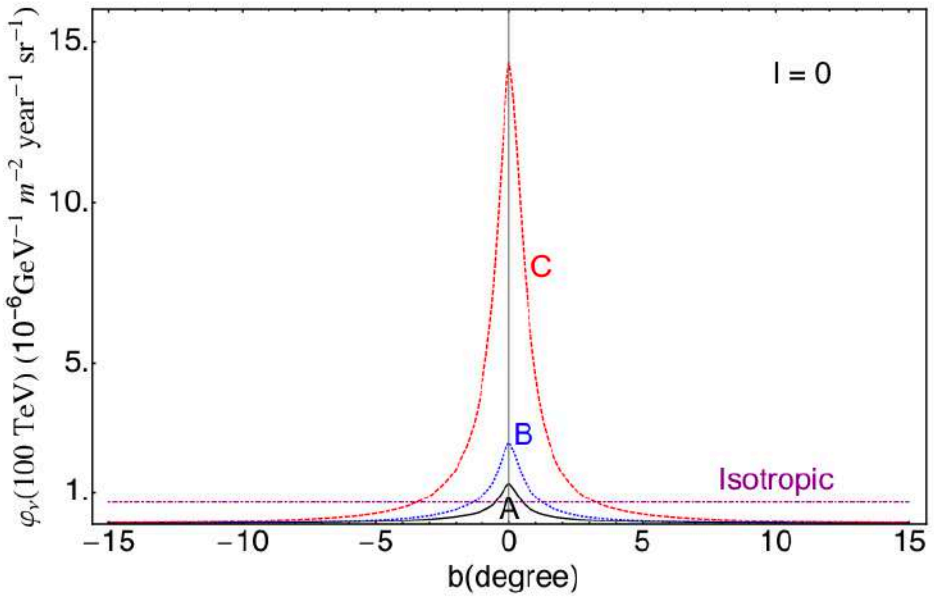
$$\varphi_{\rm CR}(E,\mathbf{r}) = \begin{cases} \varphi_{\rm CR,\odot}(E) & Case\ A \\ \varphi_{\rm CR,\odot}(E)\,g(\mathbf{r}) & Case\ B \\ \varphi_{\rm CR,\odot}(E)\,g(\mathbf{r})\,h(E,\mathbf{r}) & Case\ C \end{cases}$$

homogenous CR density all along the Plane

CR density following the SNR distribution

CR density with r-dependent slope (KRA$_\gamma$)





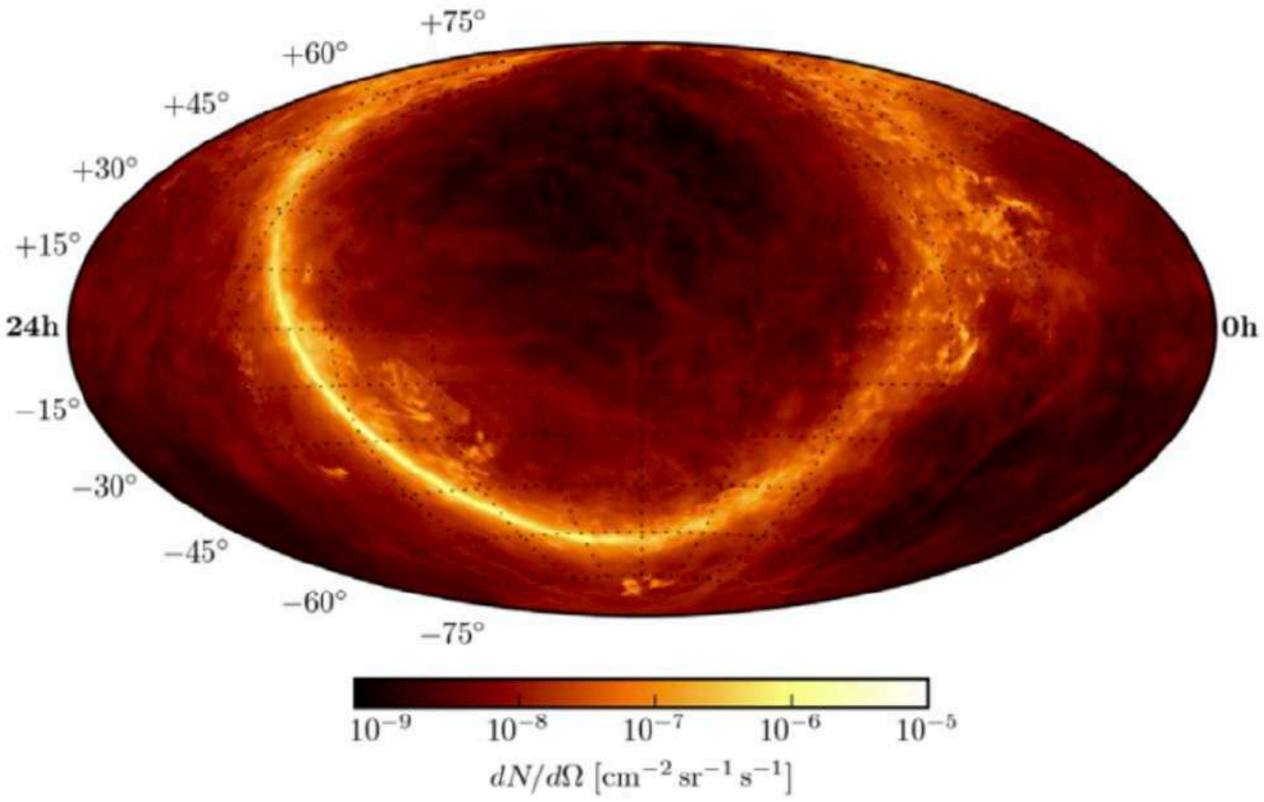
Event rates expected in IceCube:

	N/T – counts · y^{-1}			
	Showers	*Tracks*	*North*	*South*
Case A	0.40	0.07	0.18	0.29
Case B	0.50	0.09	0.20	0.39
Case C	1.01	0.19	0.27	0.92
Isotropic	8.33	1.61	4.13	5.80

⟶ **A narrow region of the GP exists where diffuse dominates over isotropic emission (|l|<70° and |b|<3°, in the most optimistic case C)**

Pagliaroli et al., JCAP 11 (2016) 004

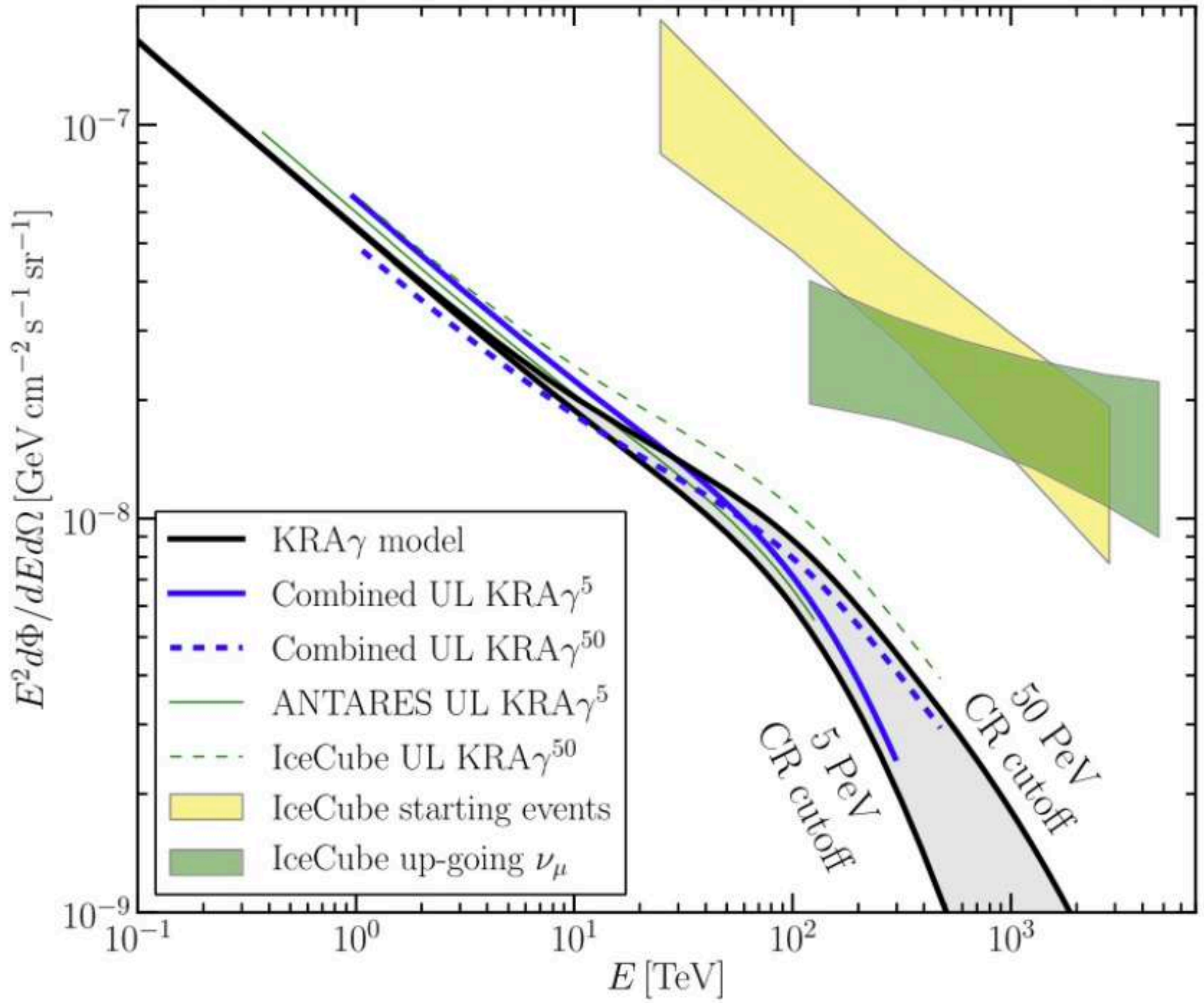
Galactic diffuse neutrino flux



Expected neutrino flux from the KRAγ model

Search for correlation of neutrinos with the template map of emission from the Galactic Plane based on spatial distribution of Fermi/LAT & HAWC gamma-ray data

Joint **ANTARES+IceCube** constraints on the Galactic diffuse neutrino emission



Sensitivities and Results of the Analysis on the KRA$_\gamma$ Models with the 5 and 50 PeV Cutoffs

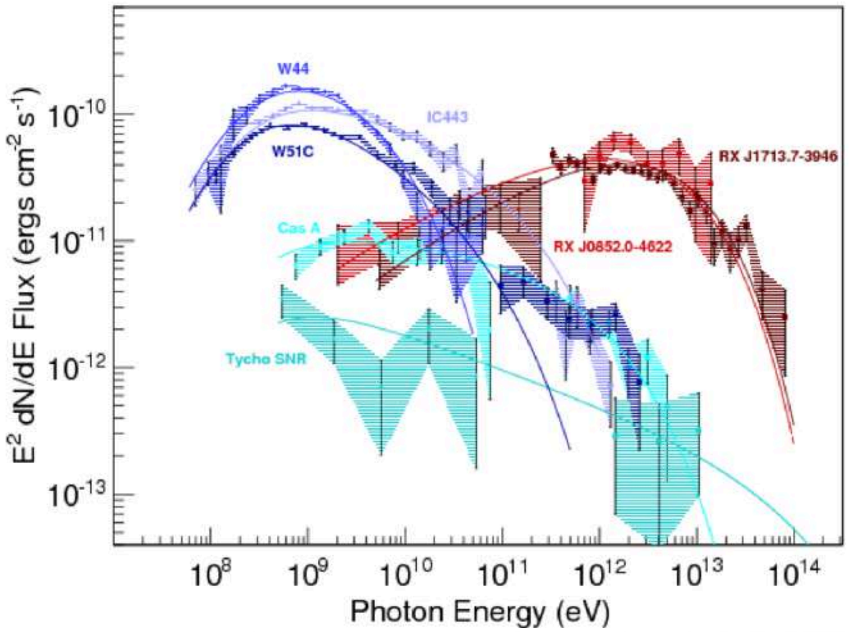
Energy Cutoff	Sensitivity [$\Phi_{\mathrm{KRA}_\gamma}$]			Fitted Flux [$\Phi_{\mathrm{KRA}_\gamma}$]	p-value [%]	Upper Limit (UL) at 90% CL [$\Phi_{\mathrm{KRA}_\gamma}$]
	Combined	ANTARES	IceCube			
5 PeV	0.81	1.21	1.14	0.47	29	1.19
50 PeV	0.57	0.94	0.82	0.37	26	0.90

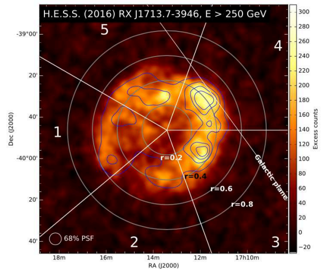
Combined data are starting to constrain the models

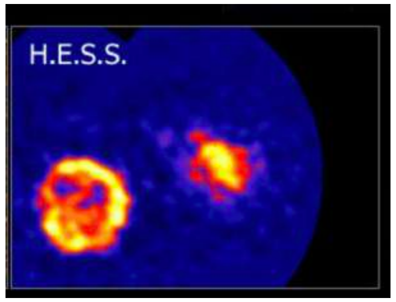
Albert et al., ApJL 868 (2018) 20

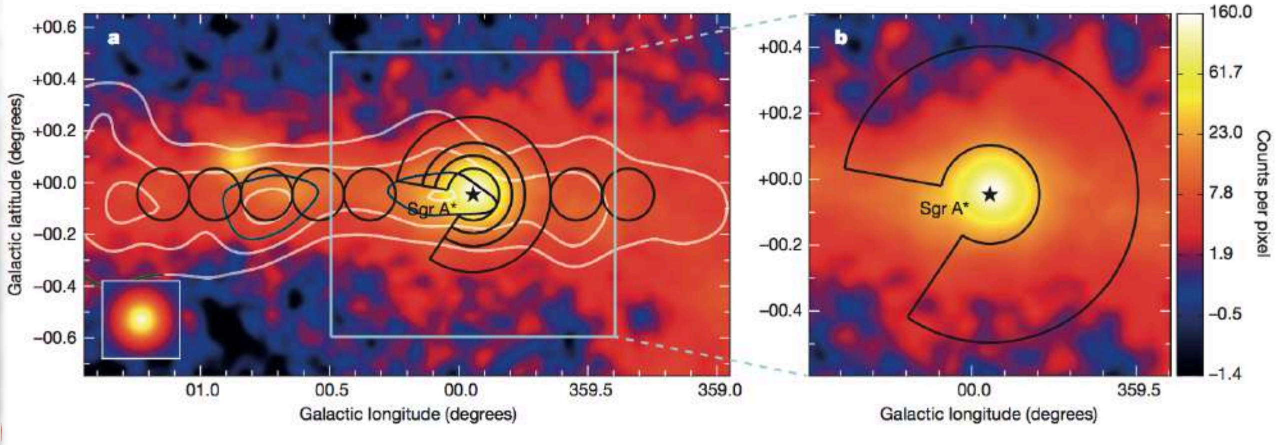
PeVatron candidates in our Galaxy

Supernova remnants



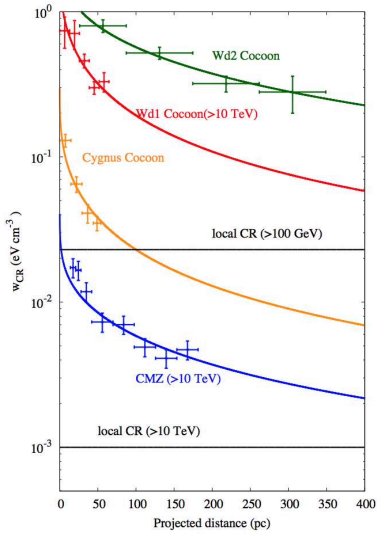






The SMBH @ Galactic Center

Aharonian et al. [HESS Coll.], Nature 531 (2016) 476

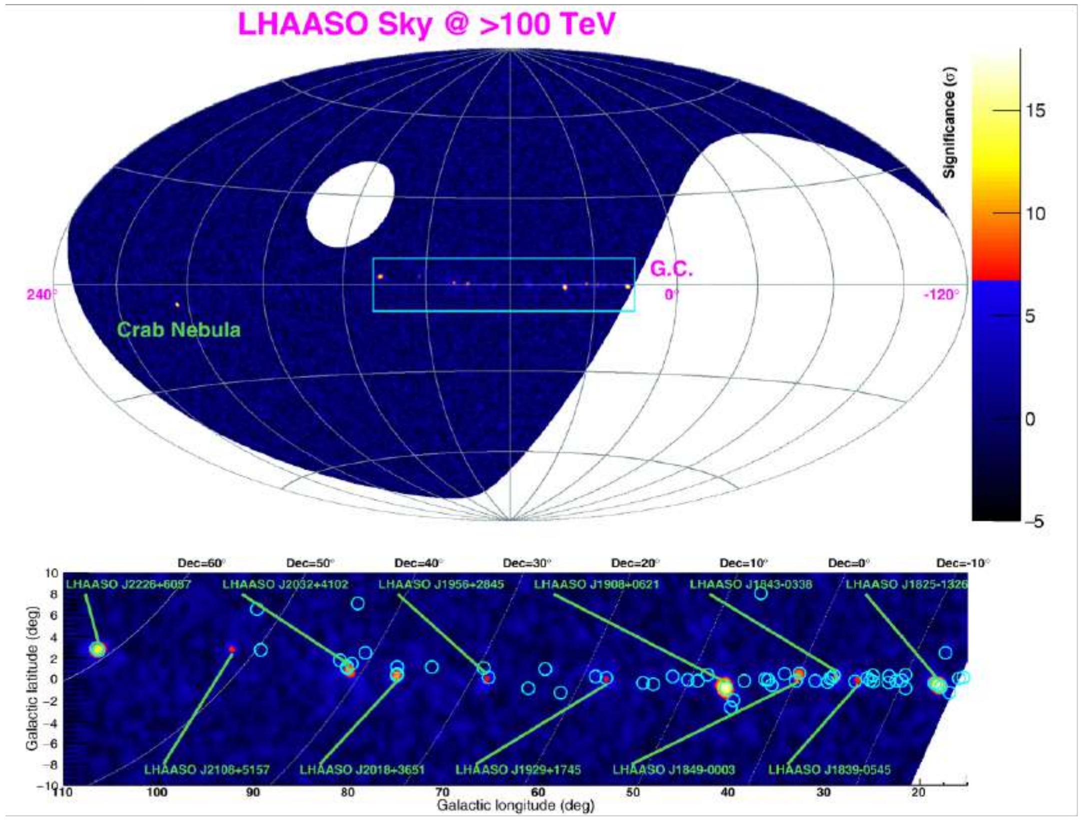


Young and massive stellar clusters

Arches, Quintuplet, Young Nuclear Cluster (CMZ), Cygnus Cocoon, Westerlund 1, 30 Doradus C (LMC)

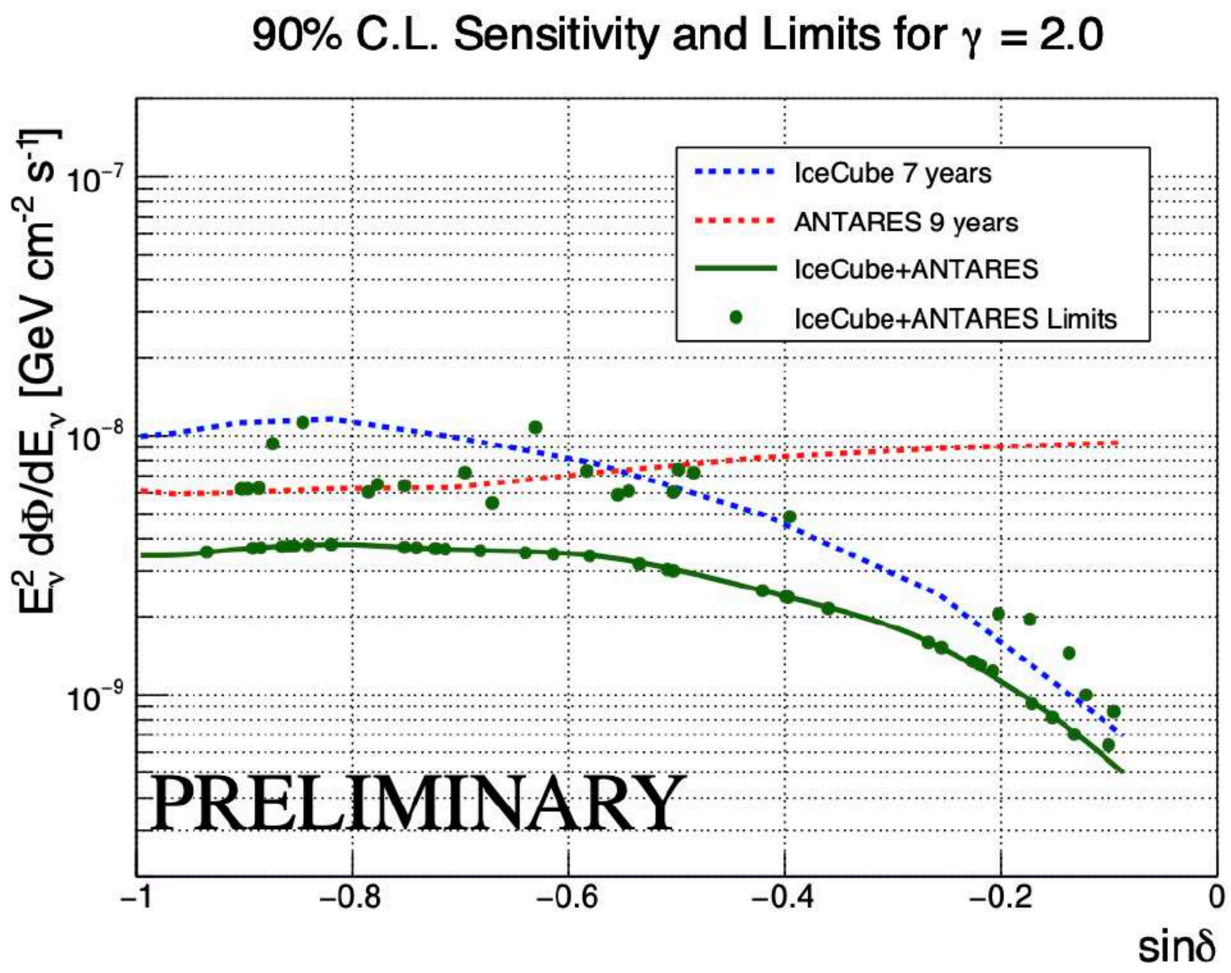
Aharonian et al., Nature Astronomy 3 (2019) 561

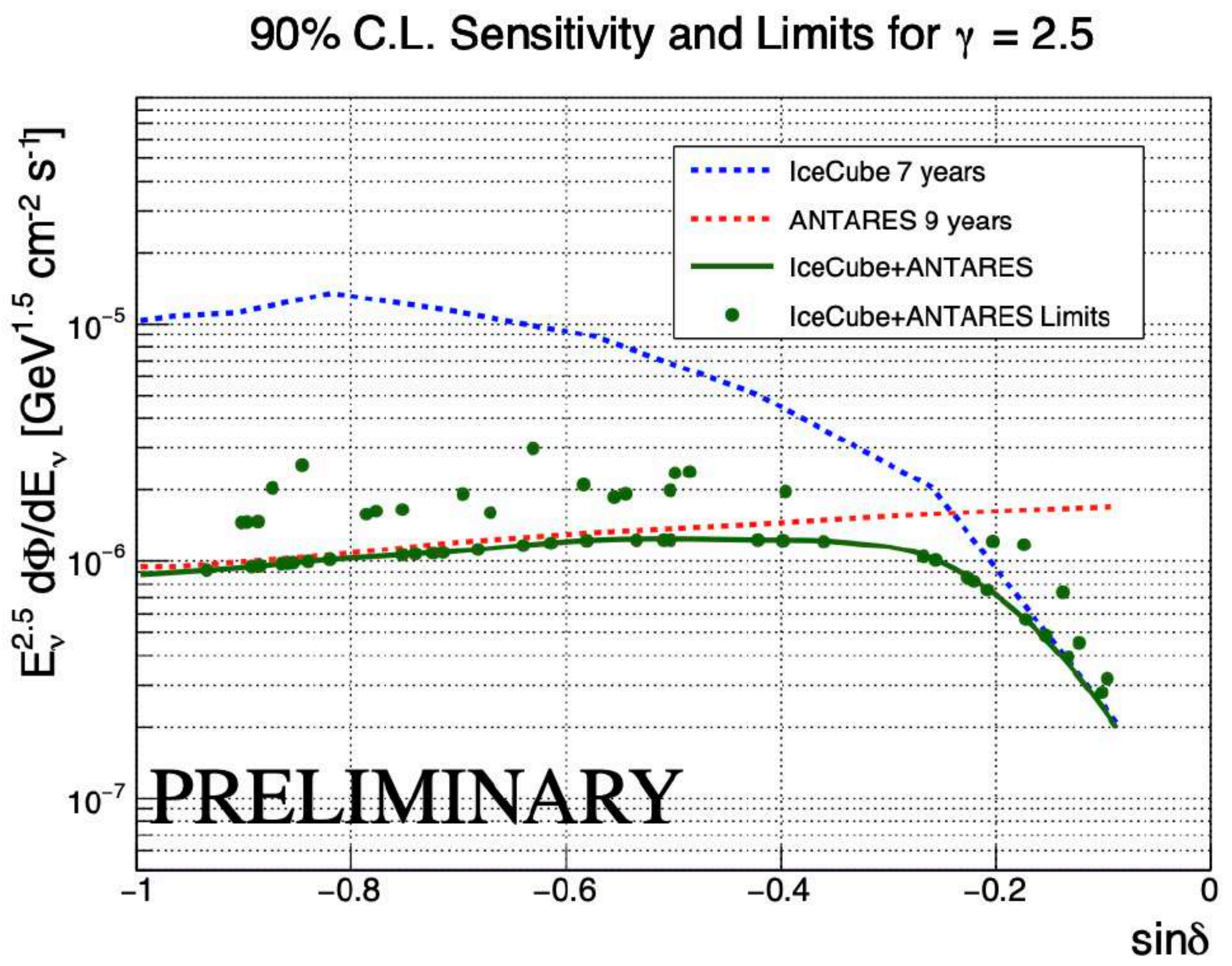
LHAASO



Zhen et al. [LHAASO Coll.], Nature 594 (2021) 33-36

Combined ANTARES+IceCube limits on Southern Hemisphere sources



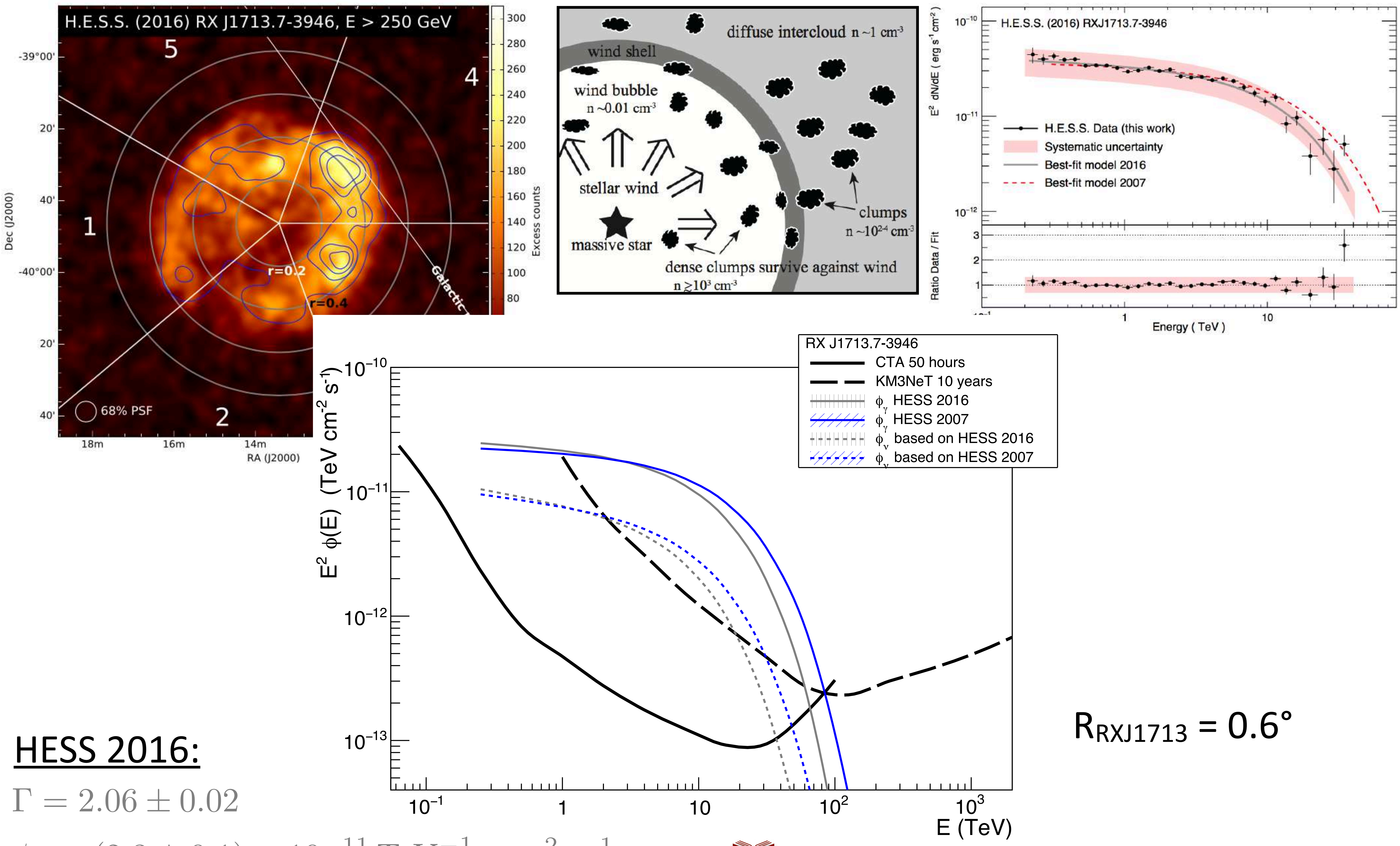


No significant ν-clustering observed in the Southern Hemisphere

Illuminati et al. [ANTARES & IceCube Coll.], ICRC 2019 PoS 919

Galactic contribution (diffuse + sources) expected < 15% above 60 TeV

Neutrinos from the SNR RX J1713.7-3946?



HESS 2016:

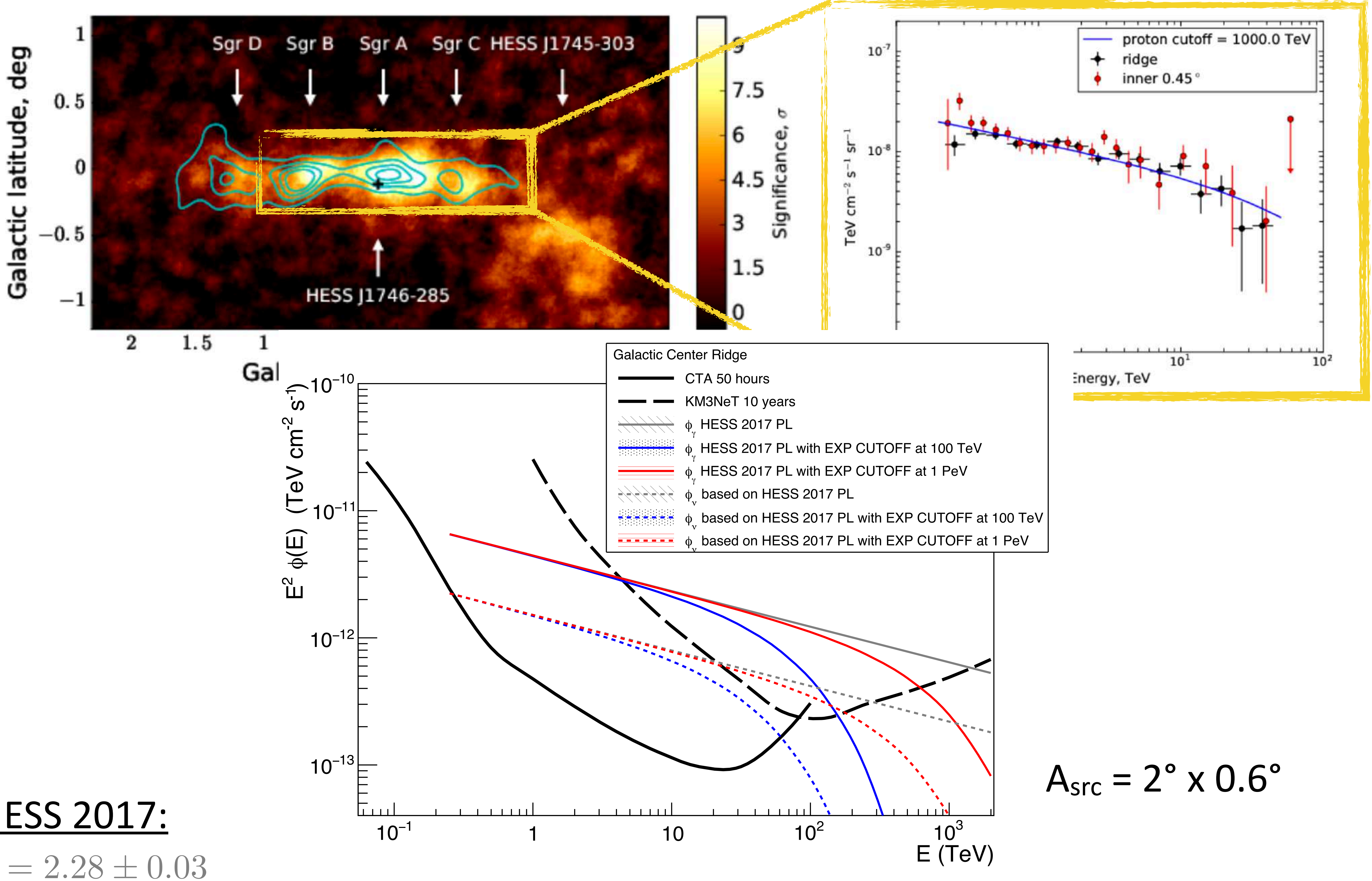
$\Gamma = 2.06 \pm 0.02$

$\phi_0 = (2.3 \pm 0.1) \times 10^{-11}\,\mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

$R_{RXJ1713} = 0.6°$

Ambrogi, Celli & Aharonian, Astropart. Phys. 100 (2018) 69

Neutrino expectations from the GC Ridge



$A_{src} = 2° \times 0.6°$

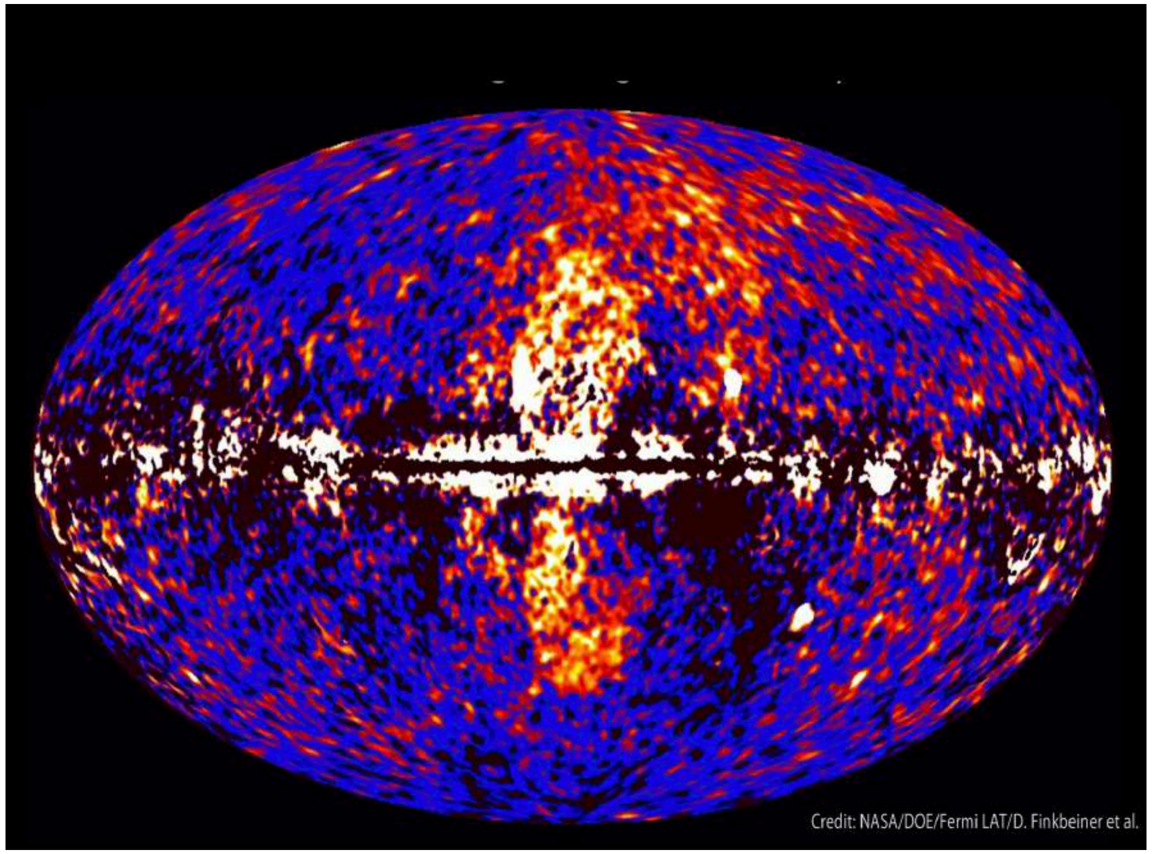
HESS 2017:

$\Gamma = 2.28 \pm 0.03$

$\phi_0 = (1.20 \pm 0.04) \times 10^{-8}\,\mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$

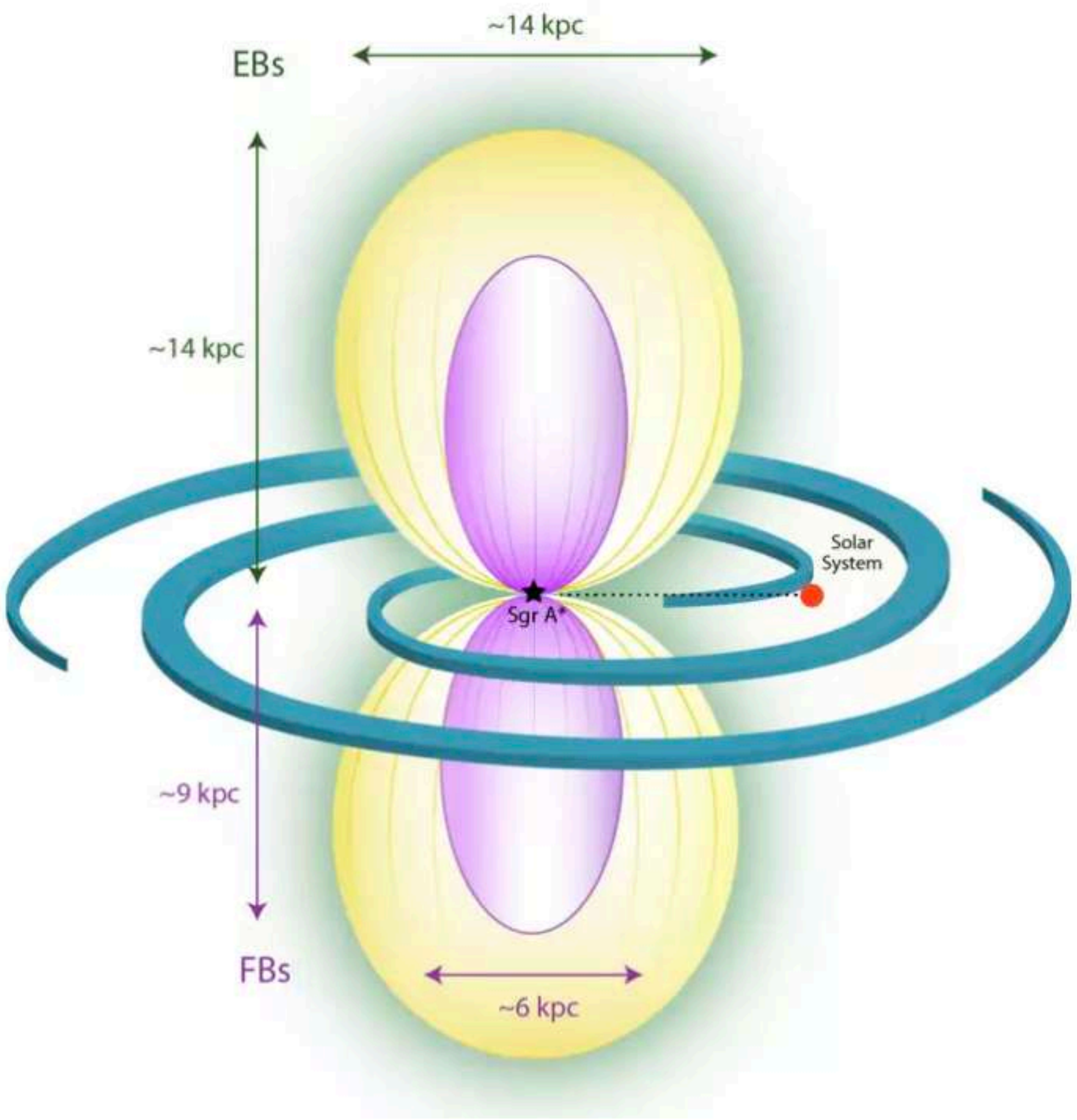
Ambrogi, Celli & Aharonian, Astropart. Phys. 100 (2018) 69

Fermi Bubbles



Fermi-LAT

- Hard and uniform emission observed at HEs, corresponding to a luminosity of **$L_\gamma \sim 4 \times 10^{37}$ erg/s** [1-100 GeV];
- Origin of radiation still under debate;
- Indication for advective CR outflow? Requires hard CR injection in the Galactocentric region (AGN-like, SF?), extremely long trapping timescales (~8 Gyr) and **4×10^{38} erg/s proton power**;
- In situ acceleration (turbulence, shock?) has also been suggested.



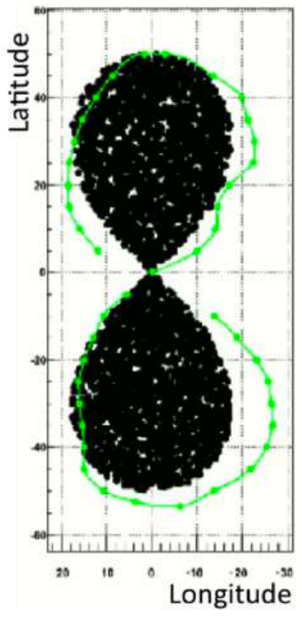
$$E_{max} \simeq Ze\beta BL \simeq 500 \left(\frac{ZB}{5\ \mu\mathrm{G}}\right)\left(\frac{\beta}{0.01}\right)\left(\frac{L}{10\ \mathrm{kpc}}\right) \mathrm{PeV}$$

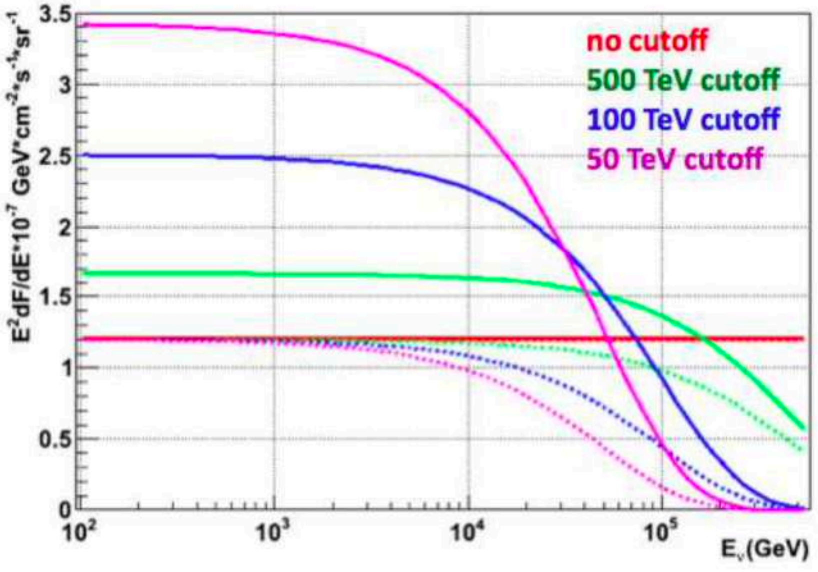
Crocker & Aharonian, PRL 106 (2011) 101102

Taylor & Giacinti, PRD 95 (2017) 023001

Expected neutrinos from Fermi Bubbles

ANTARES LIMITS

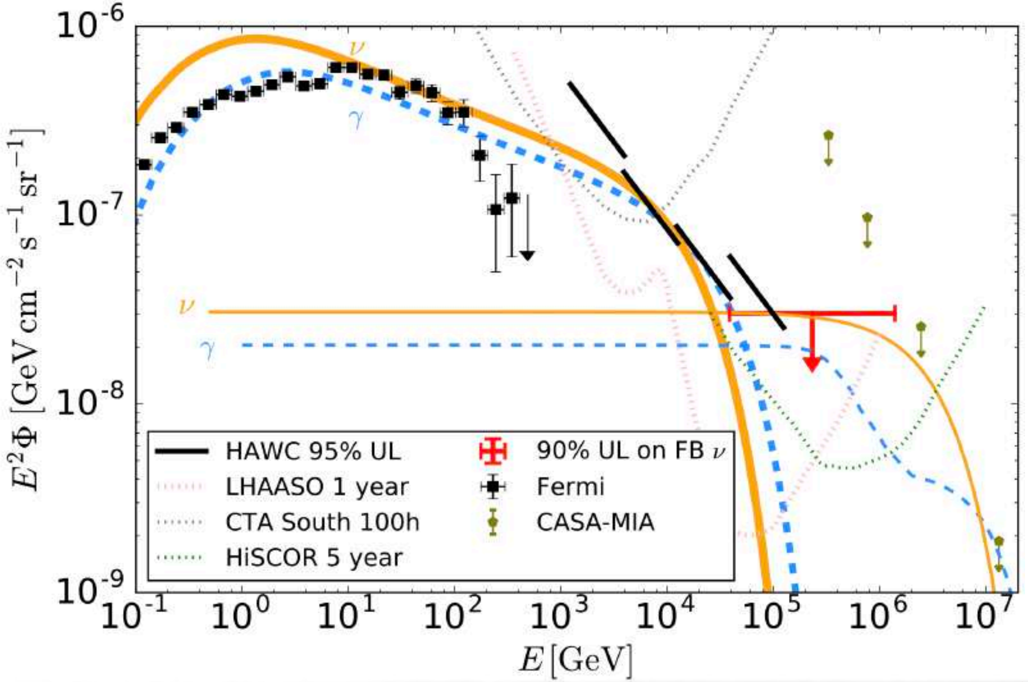


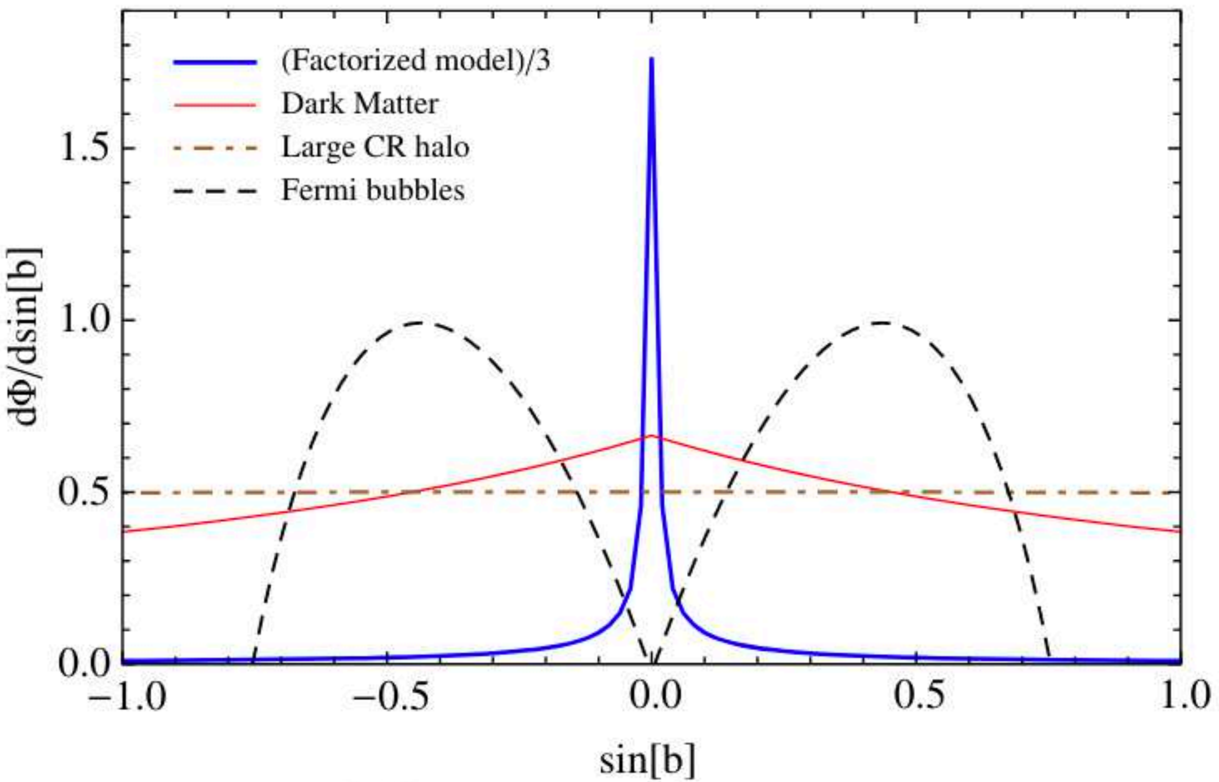


Biagi et al.(ANTARES Coll.), EPJC (2013)

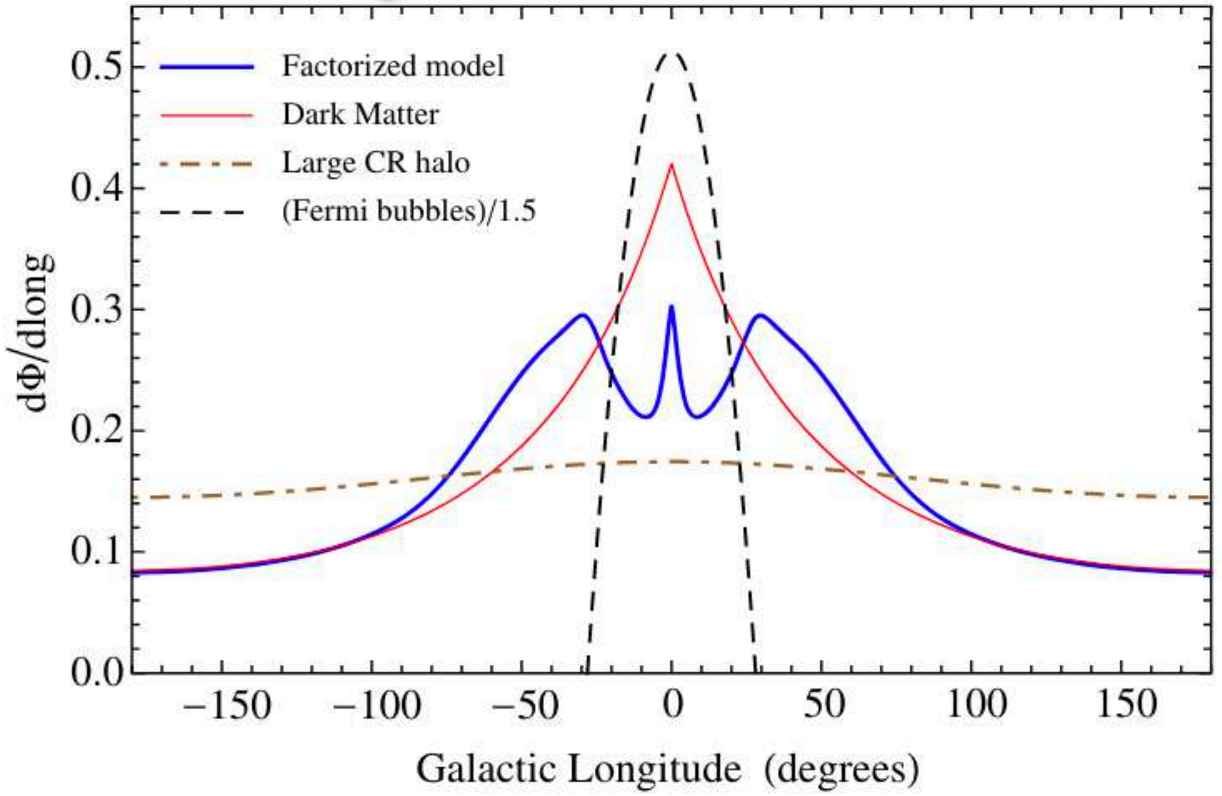
ICECUBE & HAWC LIMITS

Fang et al., PRD 92 (2017) 021301





Lipari & Vernetto, PRD 98 (2022) 4



A comprehensive model

A. Palladino & W. Winter, A&A 615 (2018) A168

- **Atmospheric component: conventional + prompt**

$$\frac{d\phi^{e,\mu}_{\rm atm}}{dE_\nu} = \frac{10^{-18}}{\rm GeV\,cm^2\,s\,sr}\left[F^{e,\mu}_{\rm atm}\left(\frac{E_\nu}{100\ \rm TeV}\right)^{-3.7} + F_{\rm prompt}\left(\frac{E_\nu}{100\ \rm TeV}\right)^{-2.7}\right]$$

$E_\nu \lesssim (0.2-0.5)\mathrm{PeV}$

- **Galactic diffuse component**

$$\frac{d\phi_{\rm Gal}}{dE_\nu} = \frac{F_{\rm Gal}\times 10^{-18}}{\rm GeV\,cm^2\,s\,sr}\left(\frac{E_\nu}{100\ \rm TeV}\right)^{-2.6}\exp\left(-\sqrt{\frac{E_\nu}{150\ \rm TeV}}\right)$$

$E_\nu \lesssim \mathrm{PeV}$

- **Extra-galactic component (pp+pγ)**

$$\frac{d\phi_{\rm pp}}{dE_\nu} = \frac{F_{\rm pp}\times 10^{-18}}{\rm GeV\,cm^2\,s\,sr}\left(\frac{E_\nu}{100\ \rm TeV}\right)^{-2}\exp\left(-\sqrt{\frac{E_\nu}{1\ \rm PeV}}\right)$$

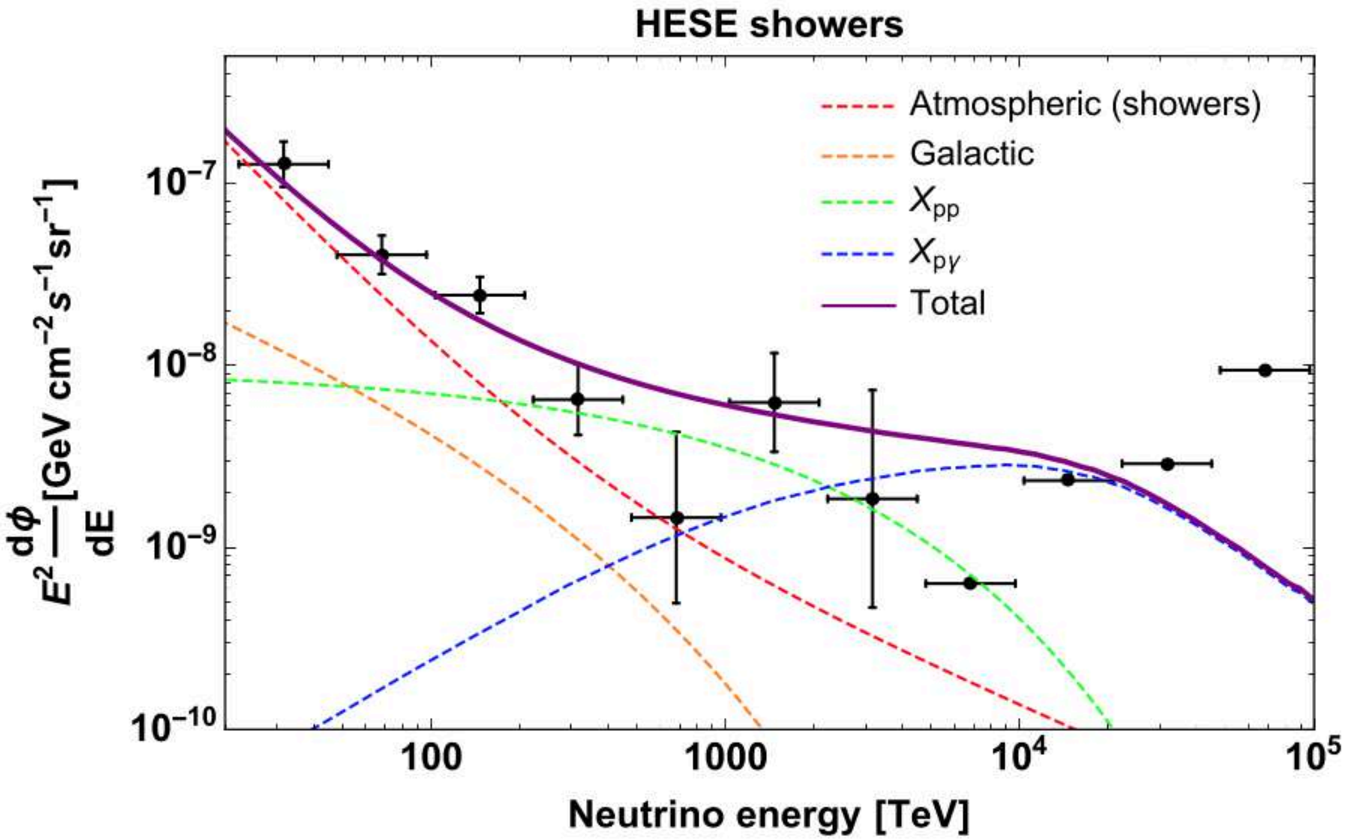
$E_\nu \sim (0.2-2)\mathrm{PeV}$

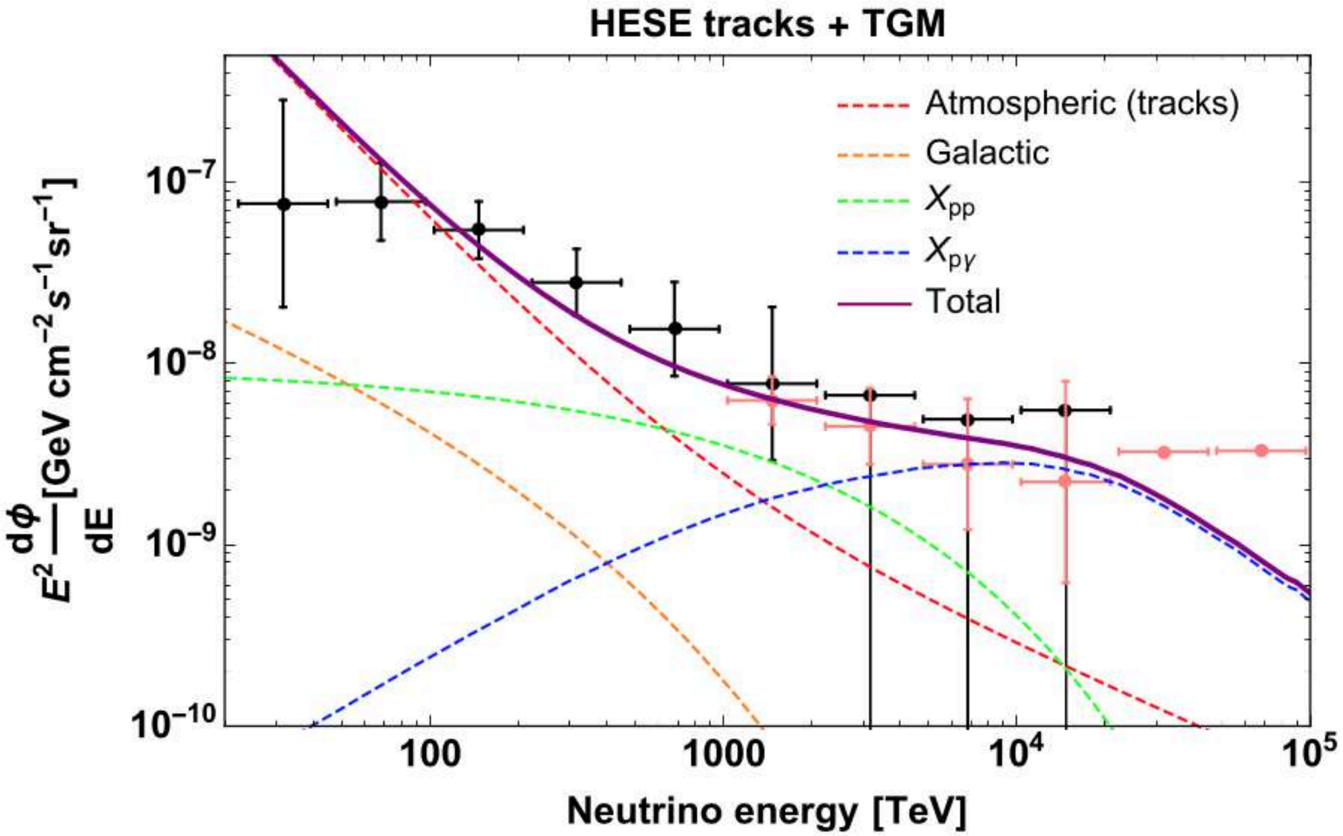
$$\frac{d\phi_{\rm p\gamma}}{dE_\nu} = F_{\rm p\gamma}\frac{d\phi_{\rm TDE}}{dE_\nu}$$

$E_\nu > 2\,\mathrm{PeV}$

A comprehensive model

A. Palladino & W. Winter, A&A 615 (2018) A168





- Residual atmospheric component, passing the veto;
- EG pp-component (e.g. SBGs) consistent with non-blazar limit to EGBR, as well as with lack of multiplets form individual sources;
- EG pγ-component non statistically significant by its own;
- Galactic components contributes ~20% to the total neutrino flux.

Summary & Conclusions

- We are witnessing the birth of **very-high-energy neutrino astronomy,** that has opened a new window into **extreme phenomena**, unaccessible to very-high-energy photons;

- The sources of **diffuse cosmic neutrinos** have not yet been localized nor identified yet: transients? unresolved? gamma-ray opaque?

- Experimental upper limits towards a flux of diffuse neutrinos from the **Galactic Plane** are becoming more and more stringent;

- Neutrinos from **Galactic accelerators** to be investigated with KM3NeT in few years of operation;

- Significant sensitivity improvement expected from **next generation instruments** (KM3NeT, IceCube-Gen2).

Thanks for your kind attention!

BACKUP

ANTARES search for cosmic sources

13 years of data point towards **no significant** excess over background

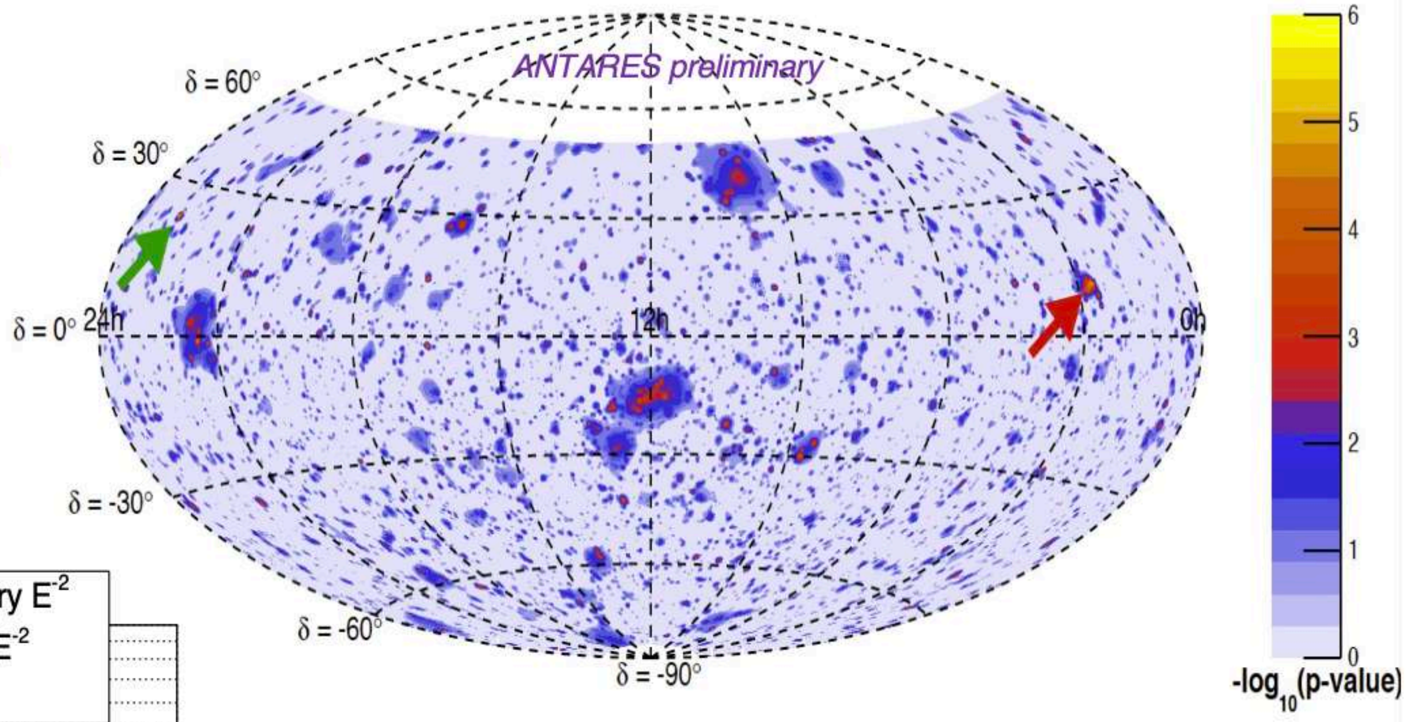
Data set:

Period: from Jan 2007 to Feb 2020

Livetime: 3845 days

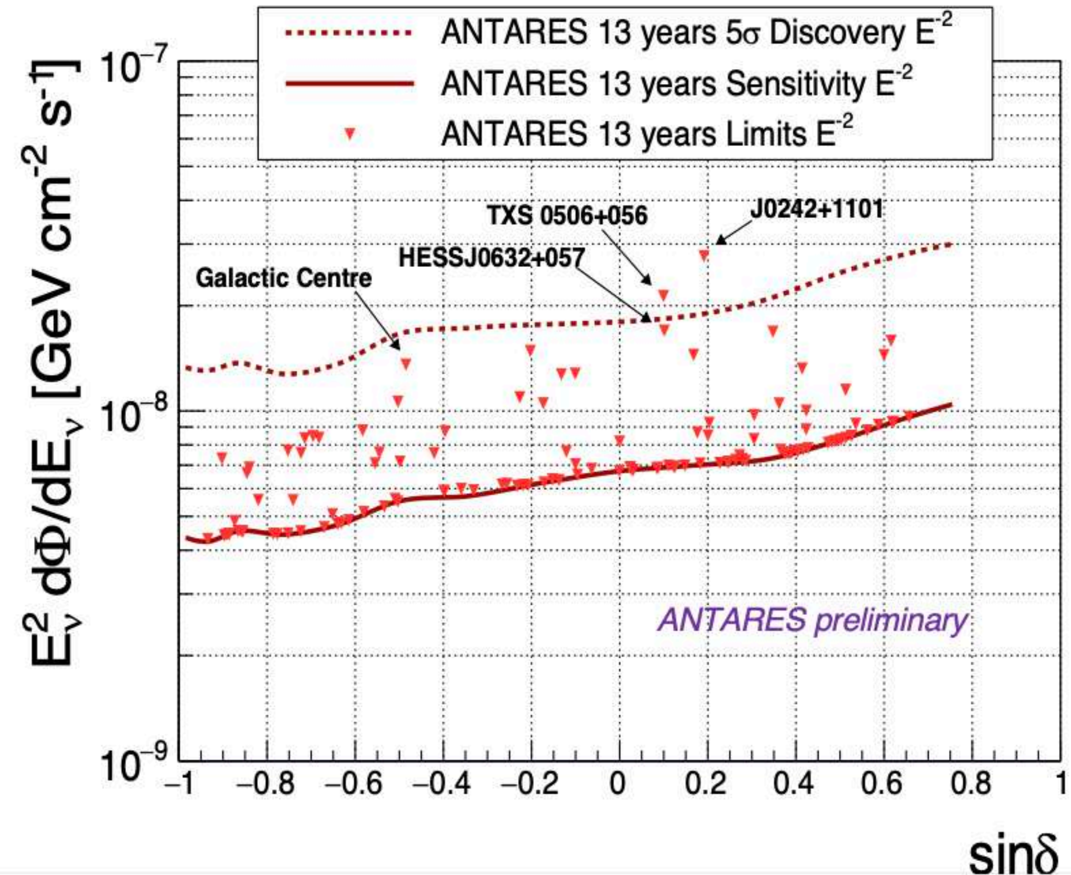
Events: **10162 tracks** and **225 showers**

1. Full-sky search



2. Candidate-list search:

121 investigated sources



Full-sky hottest spot

pre-trial p-value: of 6.8×10^{-6} (4.3σ)

post-trial p-value: of 48%

Illuminati et al. [ANTARES Coll.], ICRC (2021) 1161

Most significant source:

J0242+1101

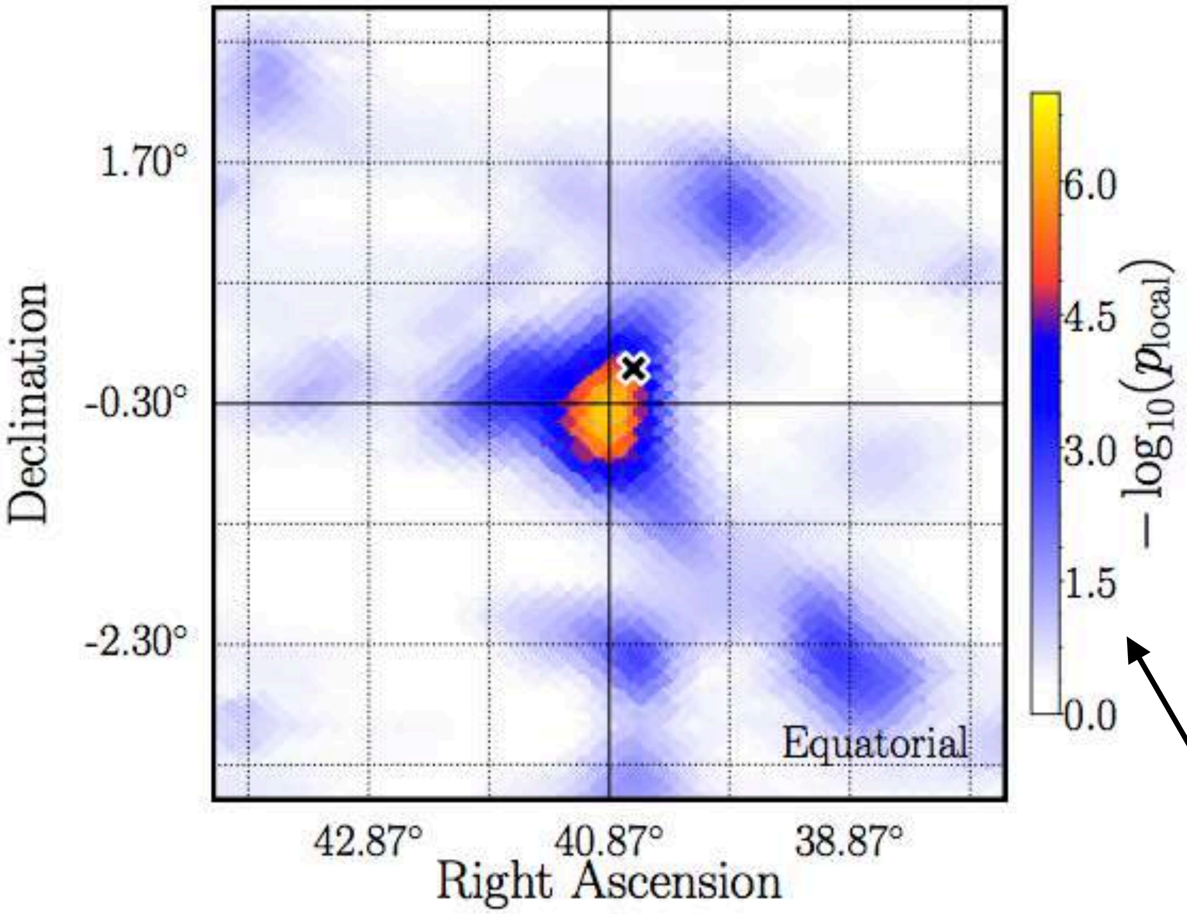
pre-trial significance: 3.8σ

post-trial significance: 2.4σ

IceCube search for cosmic sources

1. Clustering search: **10 years** of data point towards **no significant** excess over background.

M.G. Aartsen et al. [IceCube Coll.], PRL 124 (2020) 051103



A hotspot is seen in the Northern Hemisphere, located 0.35° from the active galaxy **NGC1068**

pre-trial

IceCube search for cosmic sources

2. Catalog search: **110 sources** weighted by their gamma-ray flux (Fermi > GeV). Includes 98 extra-galactic sources (mostly blazars and starburst galaxies), as well as 12 Galactic sources (97 North, 13 South).

M.G. Aartsen et al. [IceCube Coll.], PRL 124 (2020) 051103

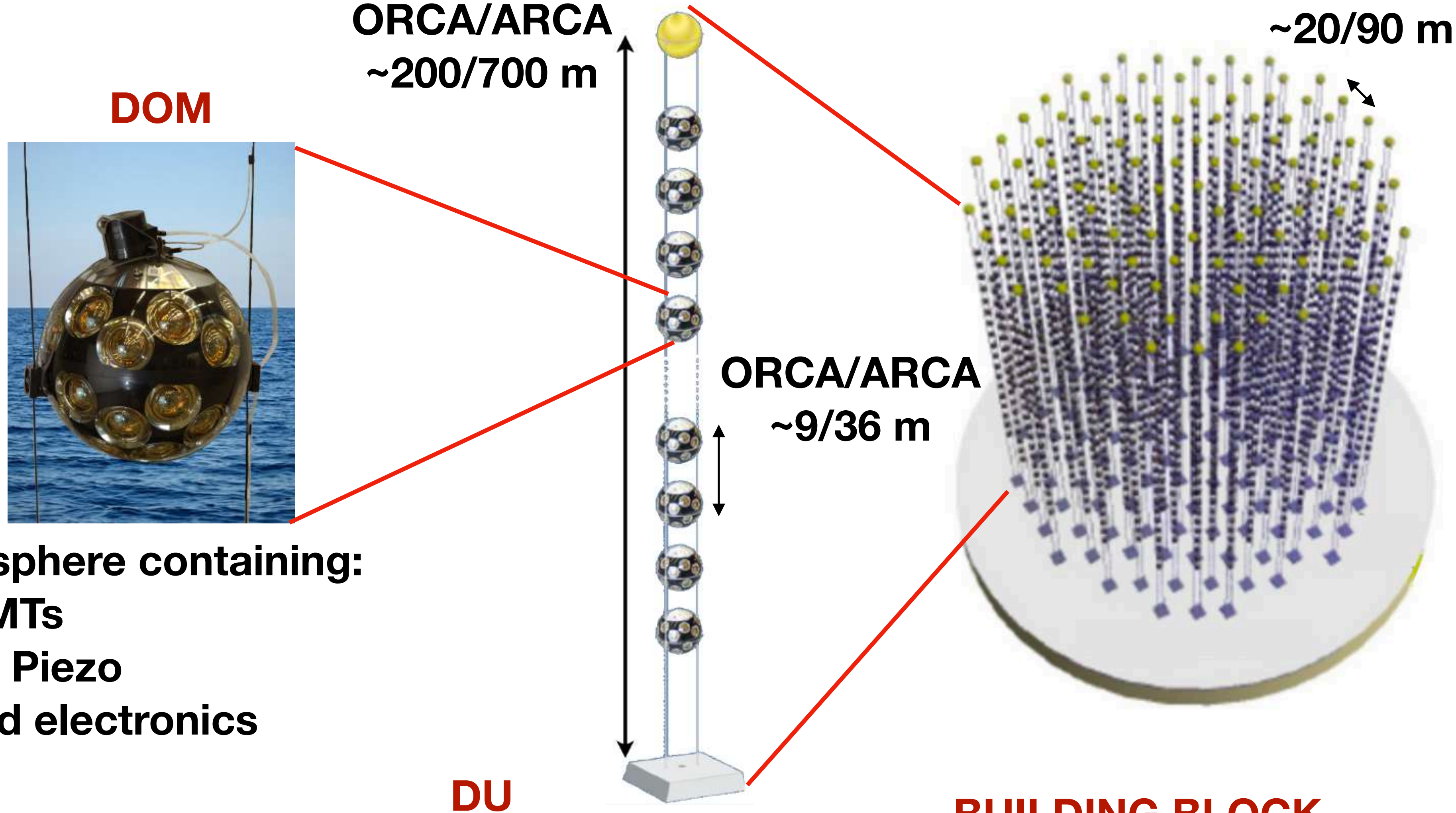
⟶ Northern Catalog filled with 97 objects: most significant excess is located 0.35° from the SBG **NGC1068** (2.9σ post-trial);

⟶ Southern Catalog filled with 13 objects: most significant excess consistent with background.

KM3NeT at a glance

Main detector elements:

- Digital Optical Modules (DOMs)
- Detection Units (DUs)
- Seafloor network: Junction Boxes (JBs) and electro-optical cables



DOM

17” glass sphere containing:

- **31x3” PMTs**
- **LED and Piezo**
- **Front end electronics**

ORCA/ARCA
~200/700 m

ORCA/ARCA
~9/36 m

DU
18 DOMs/DU

ORCA/ARCA
~20/90 m

BUILDING BLOCK
115 DUs/building block

KM3NeT at a glance

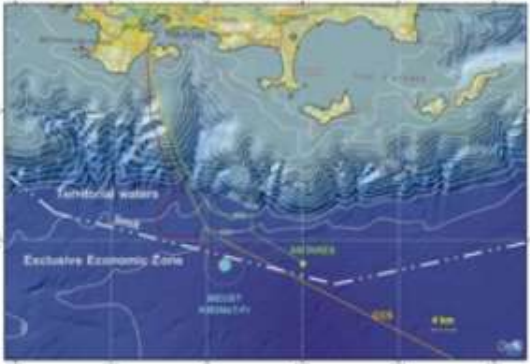
ARCA (1 GTon)

Astroparticle Research
with Cosmics in the Abyss

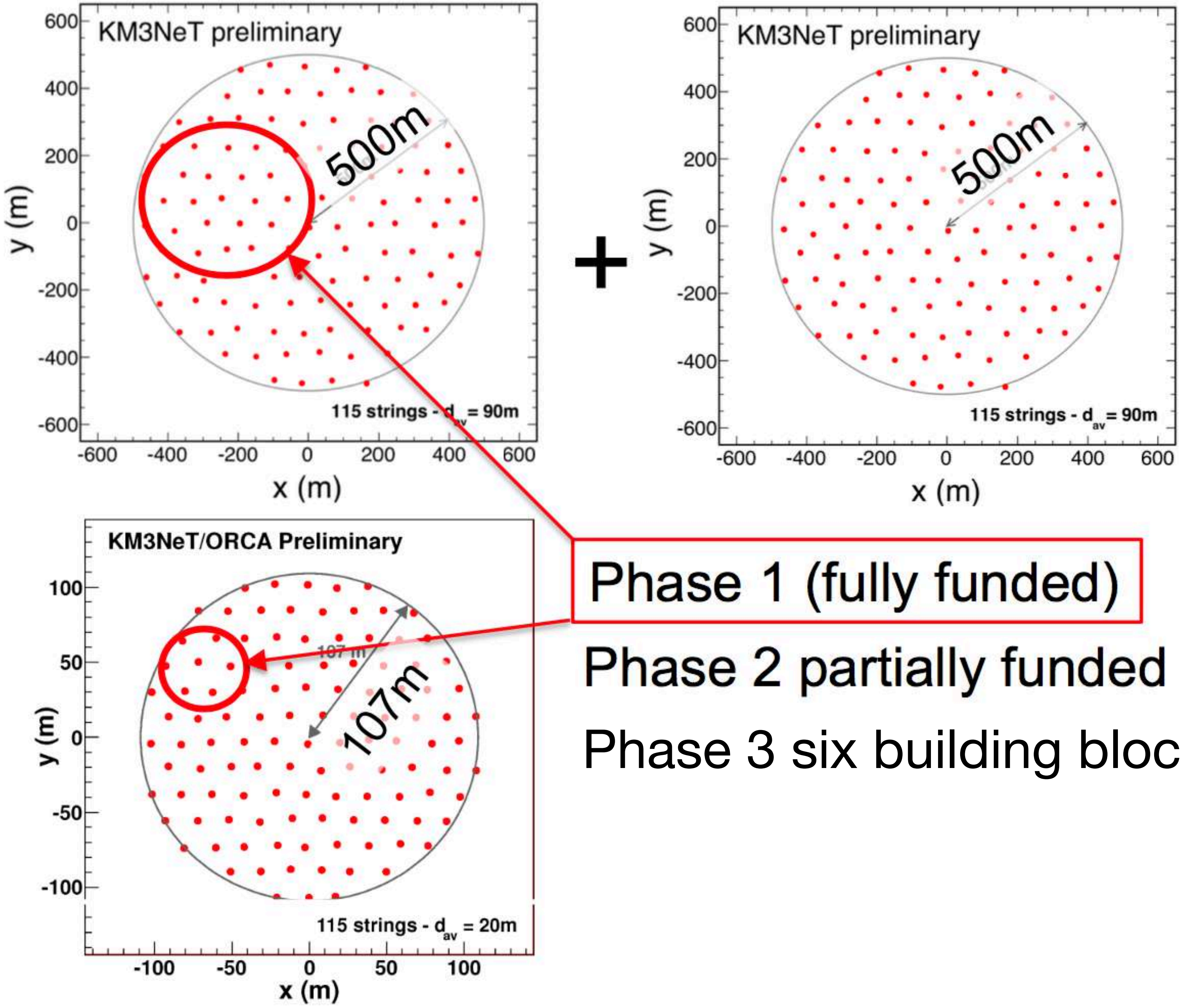
3500 m depth,
offshore Sicily

ORCA (6 MTon)

Oscillation Research
with Cosmics in the Abyss



2500 m depth,
offshore Toulon



Phase 1 (fully funded)

Phase 2 partially funded

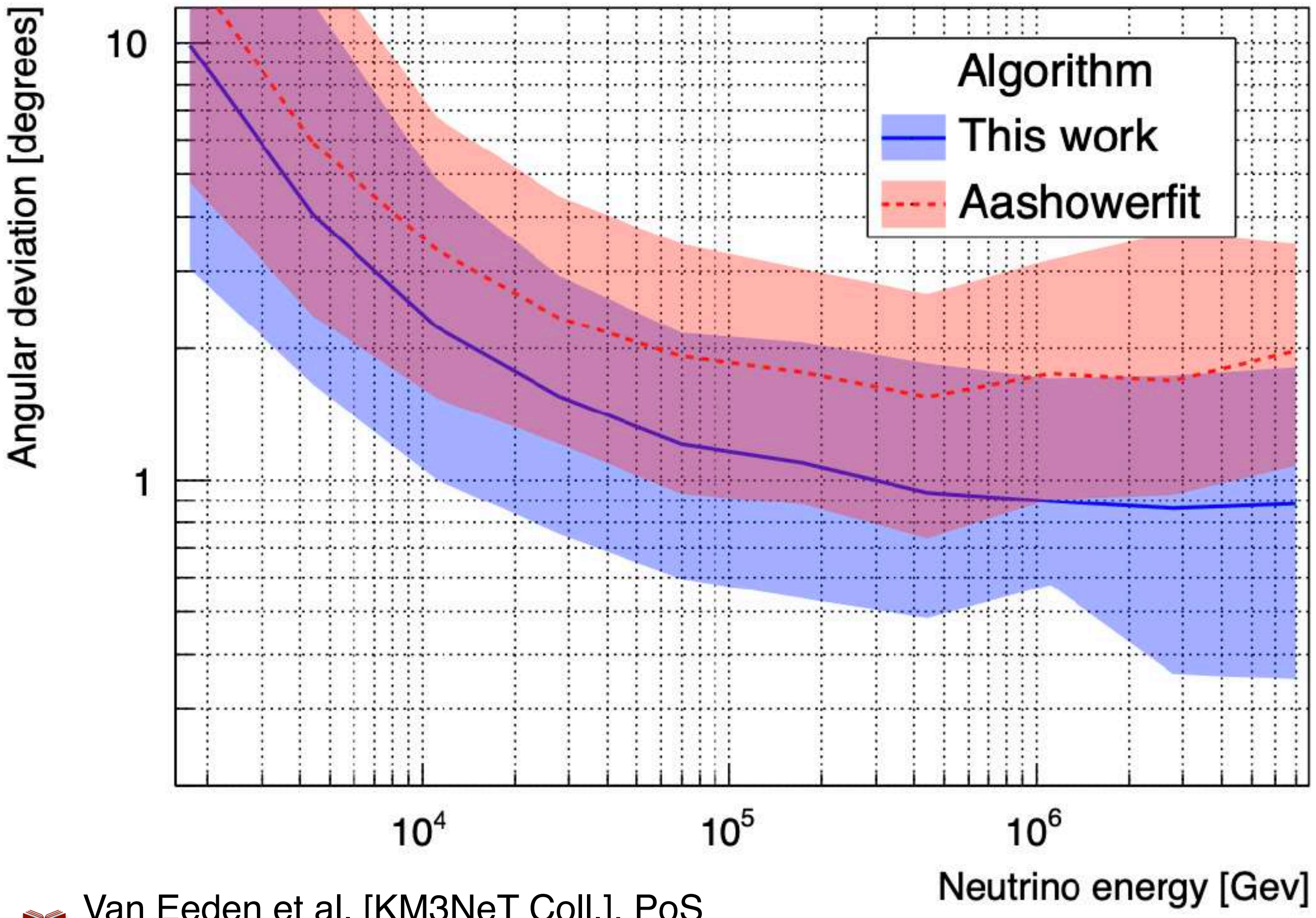
Phase 3 six building blocks

Adrian-Martinez et al. [KM3NeT Coll.], JPGNPP 43 (2016)

Expected performances of the KM3NeT detectors

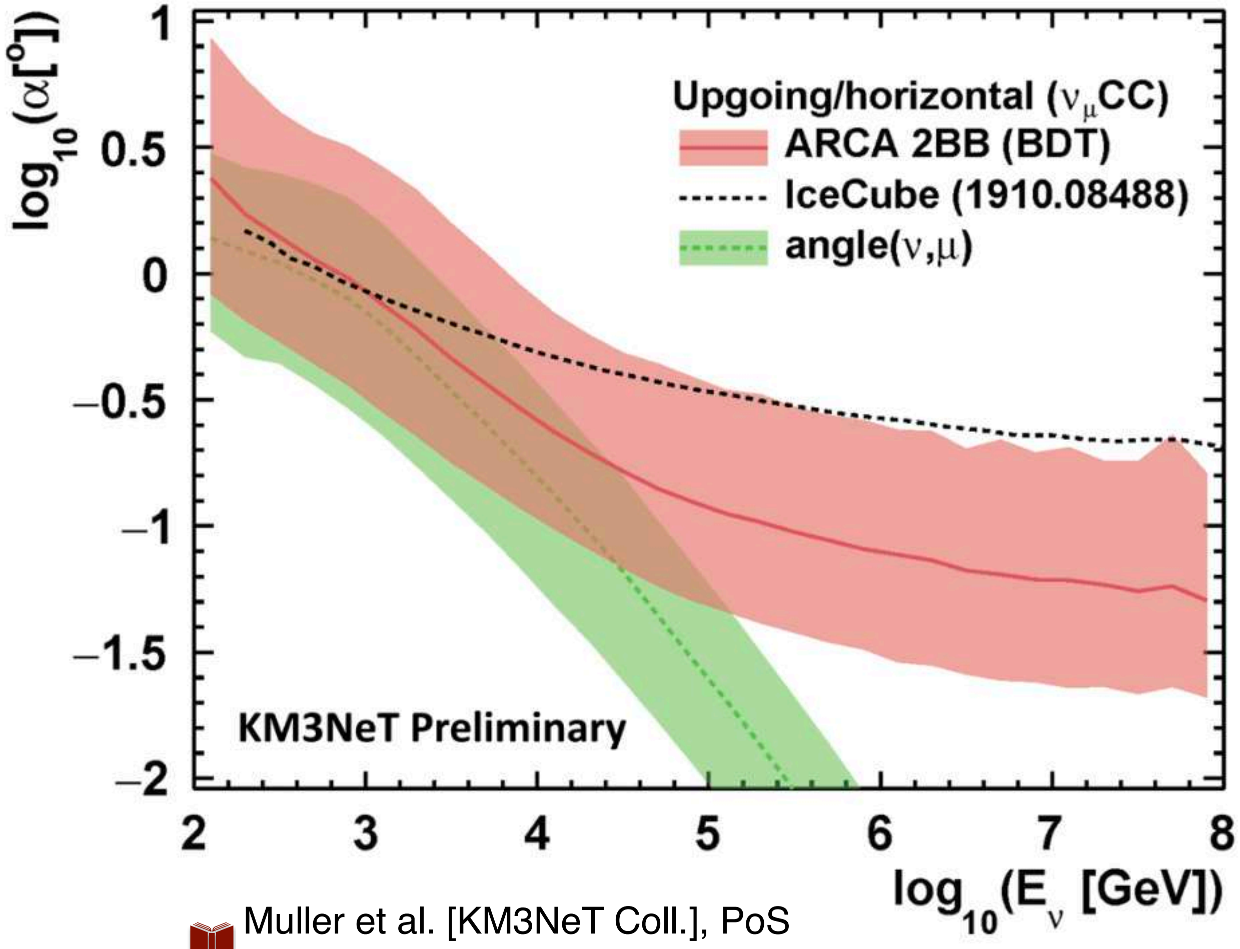
Angular resolution is crucial for astronomical studies

Single cascade events



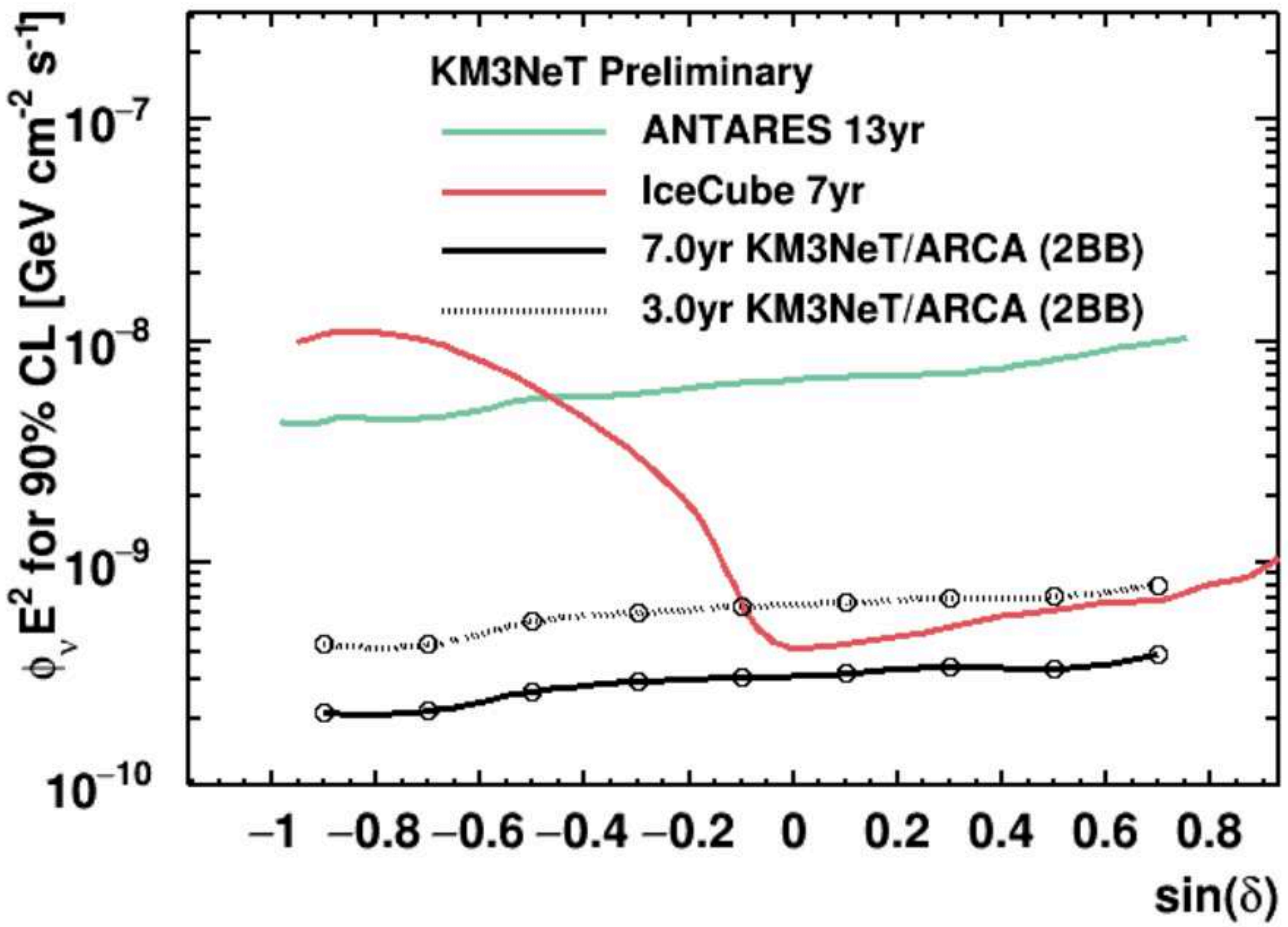
Van Eeden et al. [KM3NeT Coll.], PoS (ICRC2021) 1089

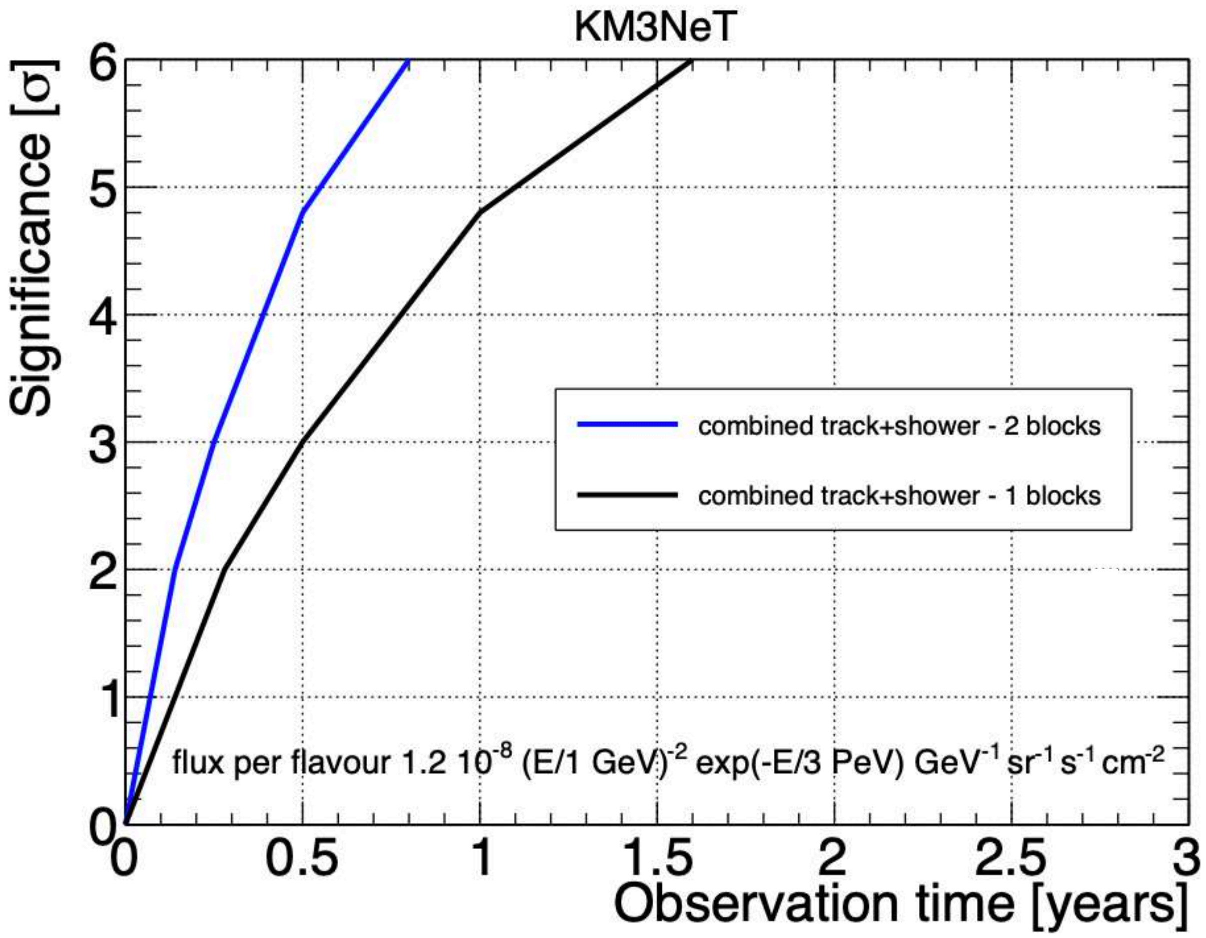
Track like events



Muller et al. [KM3NeT Coll.], PoS (ICRC2021) 1077

Key astrophysical cases: Galactic accelerators & diffuse emission





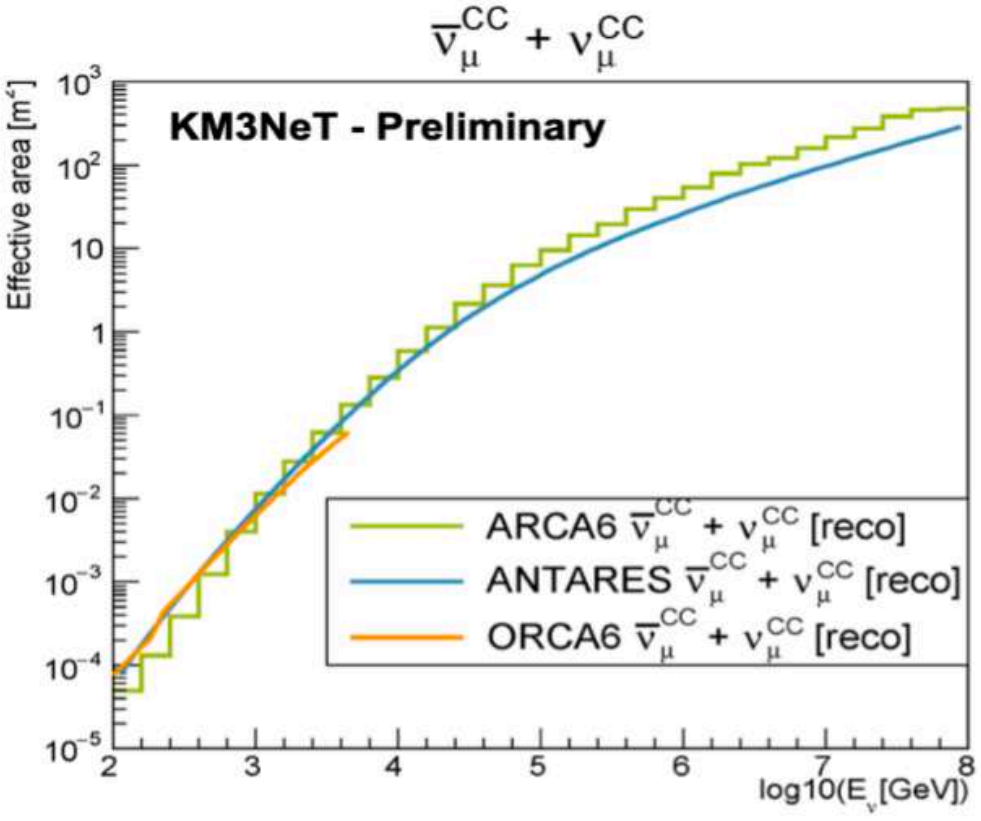
Investigation of neutrino emissions from Galactic sources in few years crucial for unveiling hadronic accelerators!

5σ detection in less than 1 year for 1 building block

Muller et al. [KM3NeT Coll.], PoS (ICRC2021) 1077

Coniglione et al. [KM3NeT Coll.], VLVnT-2021 proceedings, JINST

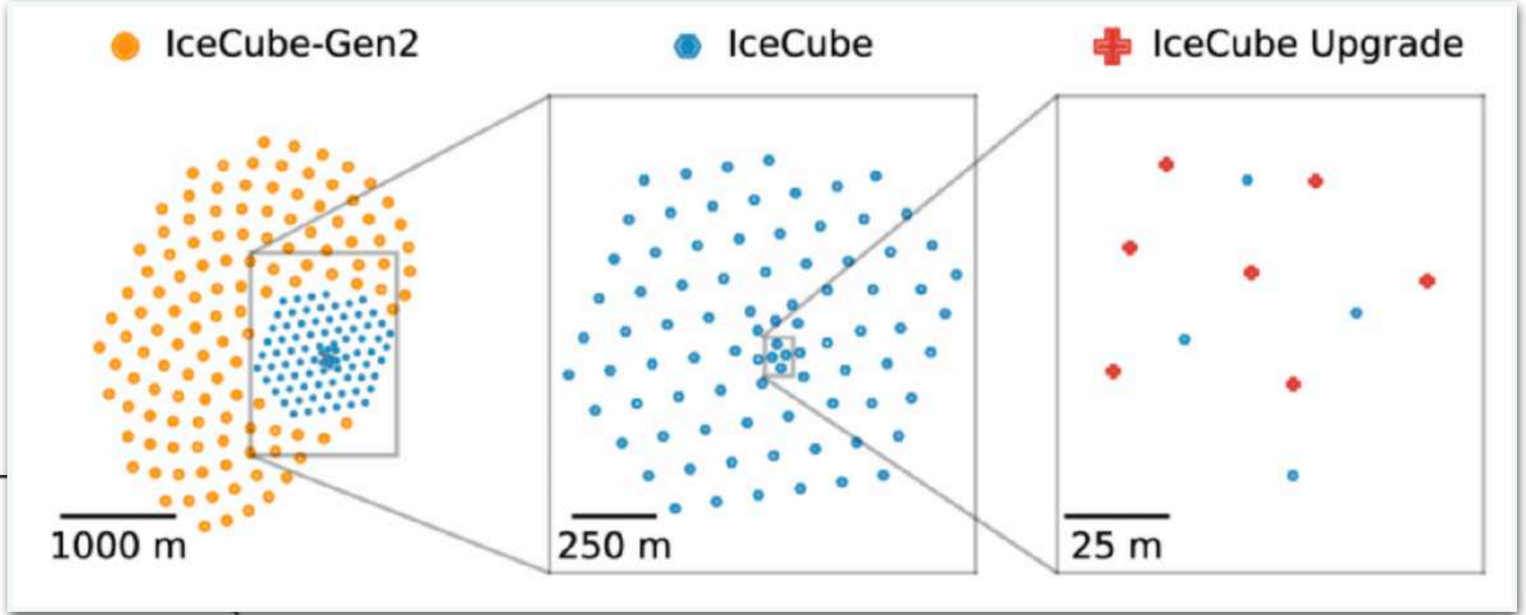
KM3NeT: current status & next milestones

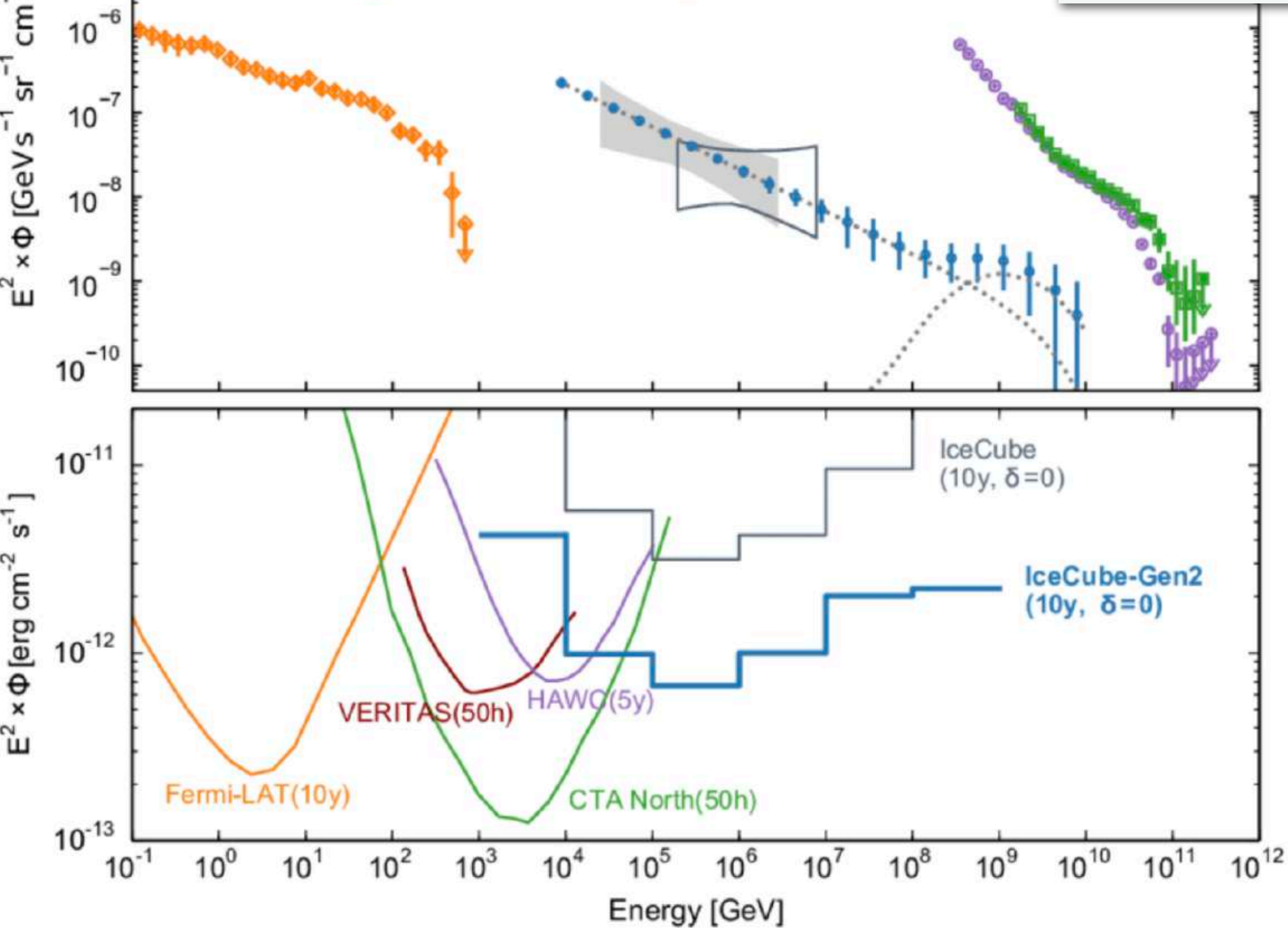


- Since June 2022, both **ARCA** and **ORCA** are operating with **10** strings;
- **Ongoing** sea campaign at both ARCA and ORCA sites.

Detection Units in staging area @ Malta

IceCube-Gen2 Observatory

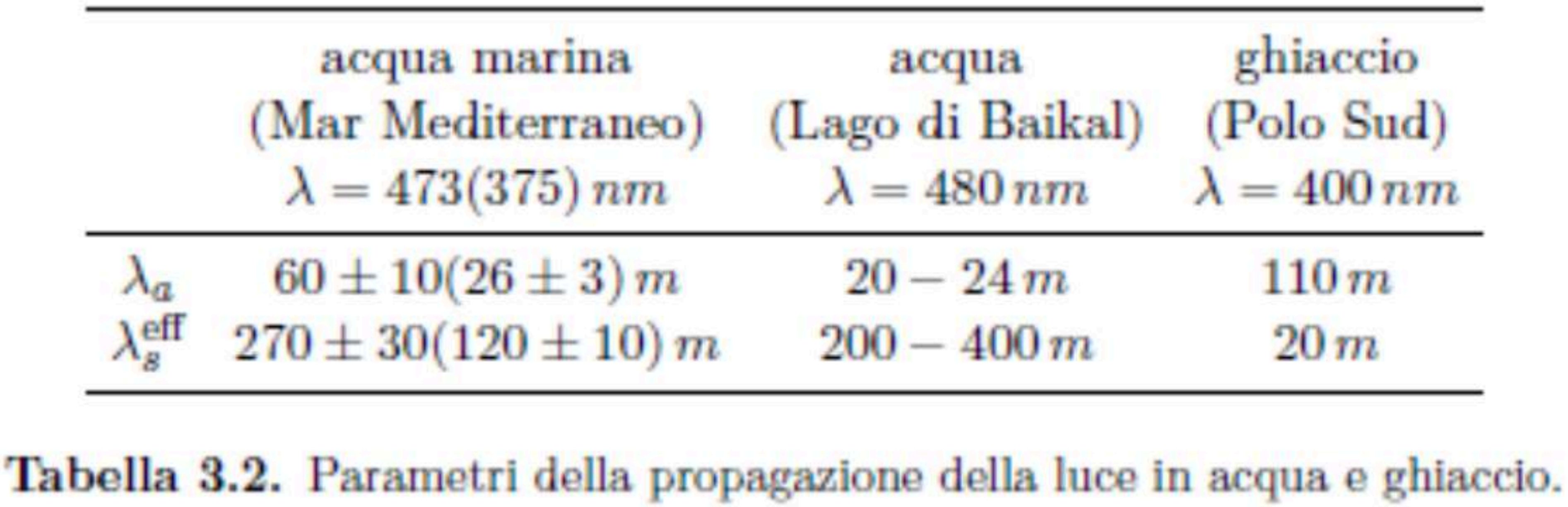




Aartsen et al. [IceCube Coll.], arXiv:1911.02561

- Targeting higher energy neutrinos than IceCube (up to 100 EeV), thanks to radio array;
- **IceCube Upgrade** consists into 7 additional strings hosting a new generation of sensor with increased photocathode area and directional information, improving on angular resolution;
- **IceCube-Gen2** complete design will consist of additional 120 strings;
- ~8 km^3 instrumented volume;
- ~400 M USD facility.

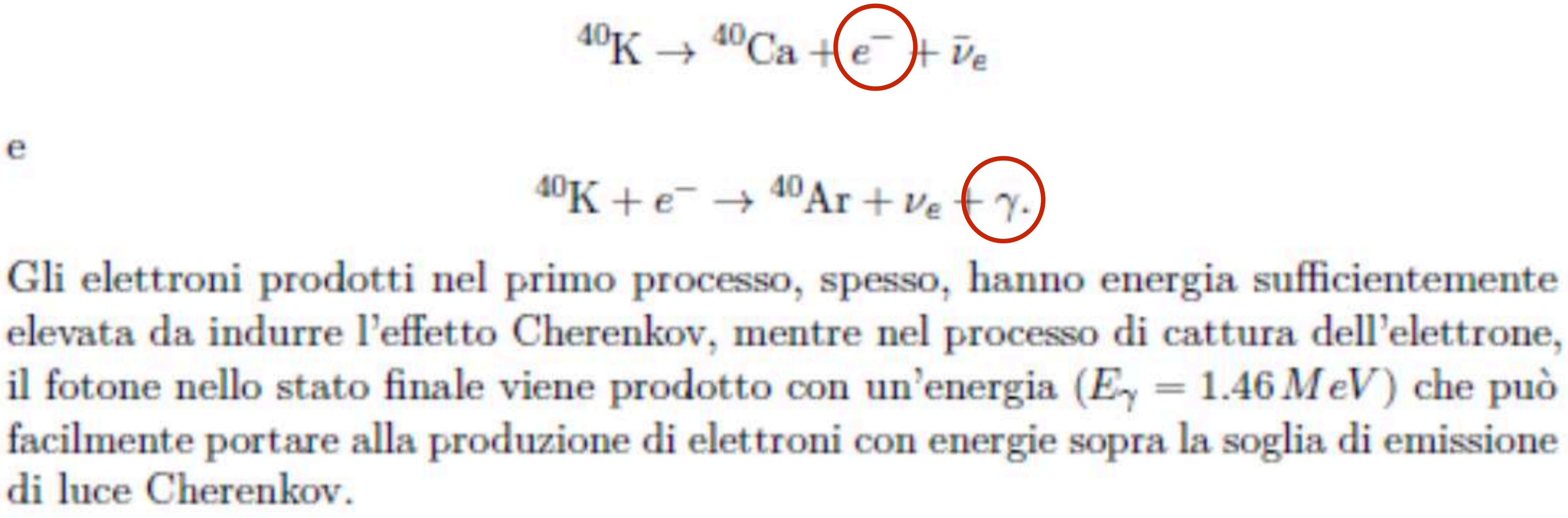
Absorption and scattering: water vs ice



	acqua marina (Mar Mediterraneo) $\lambda = 473(375)\,nm$	acqua (Lago di Baikal) $\lambda = 480\,nm$	ghiaccio (Polo Sud) $\lambda = 400\,nm$
λ_a	$60 \pm 10(26 \pm 3)\,m$	$20 - 24\,m$	$110\,m$
λ_g^{eff}	$270 \pm 30(120 \pm 10)\,m$	$200 - 400\,m$	$20\,m$

Tabella 3.2. Parametri della propagazione della luce in acqua e ghiaccio.

Natural background



$$^{40}\text{K} \rightarrow {}^{40}\text{Ca} + e^- + \bar{\nu}_e$$

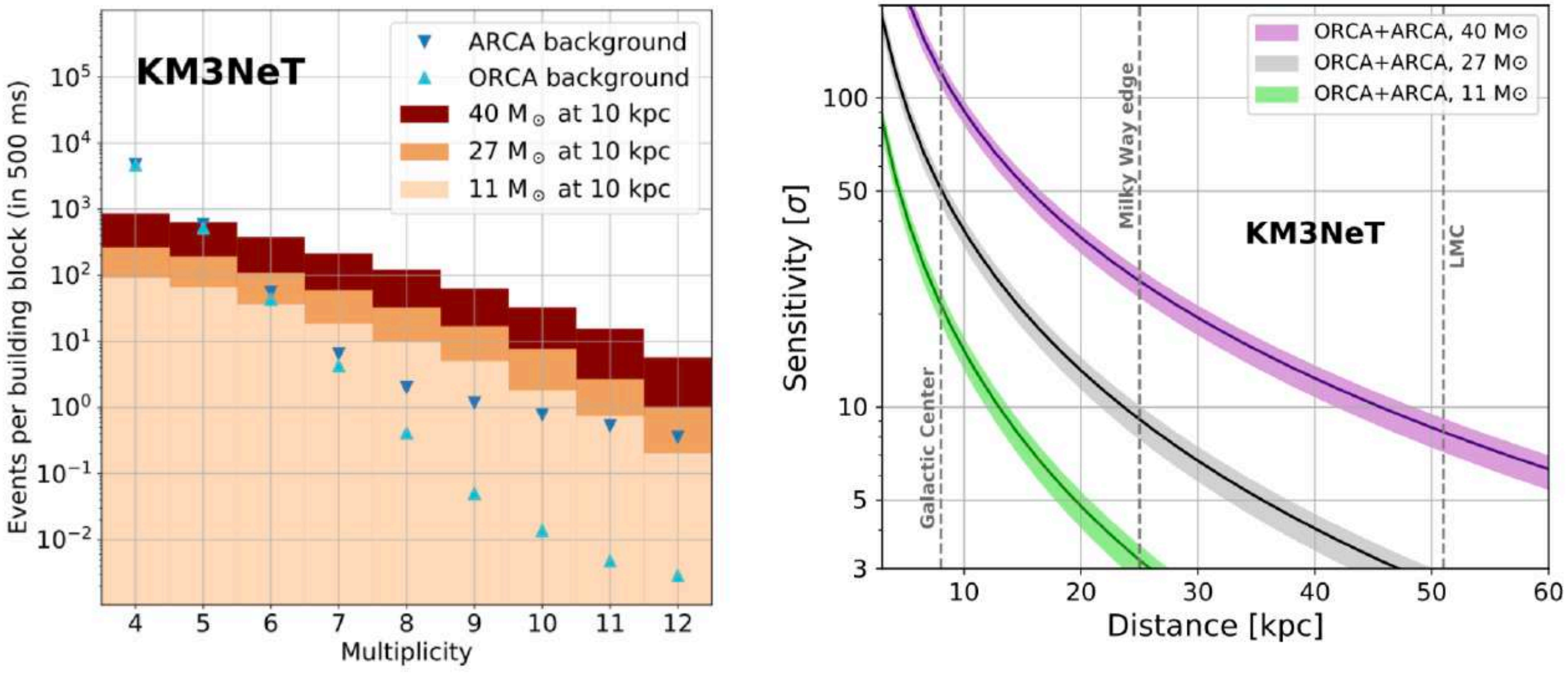
e

$$^{40}\text{K} + e^- \rightarrow {}^{40}\text{Ar} + \nu_e + \gamma.$$

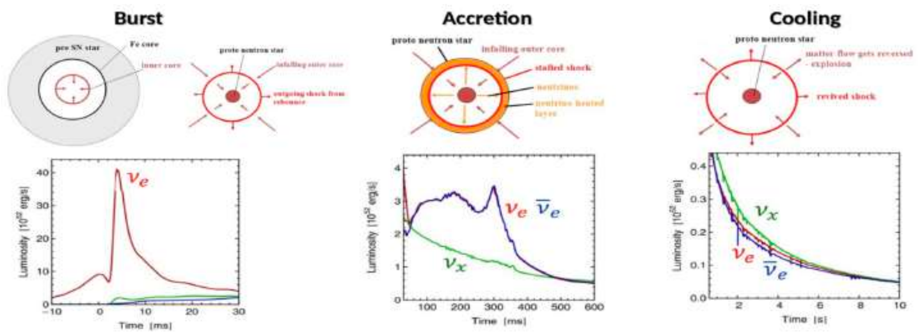
Gli elettroni prodotti nel primo processo, spesso, hanno energia sufficientemente elevata da indurre l'effetto Cherenkov, mentre nel processo di cattura dell'elettrone, il fotone nello stato finale viene prodotto con un'energia ($E_\gamma = 1.46\,MeV$) che può facilmente portare alla produzione di elettroni con energie sopra la soglia di emissione di luce Cherenkov.

KM3NeT detection prospects for the next core collapse Galactic supernova

- Neutrinos below 100 MeV expected at several stages of the stellar collapse
- Main interaction channels in water are IBD of electron antineutrinos with protons, ES on electrons and CC interaction with oxygen nuclei
- Cherenkov signature detected as a population of coincidences in single DOMs



Aiello et al. [KM3NeT Coll.], Eur. Phys. J. C 81 (2021) 445

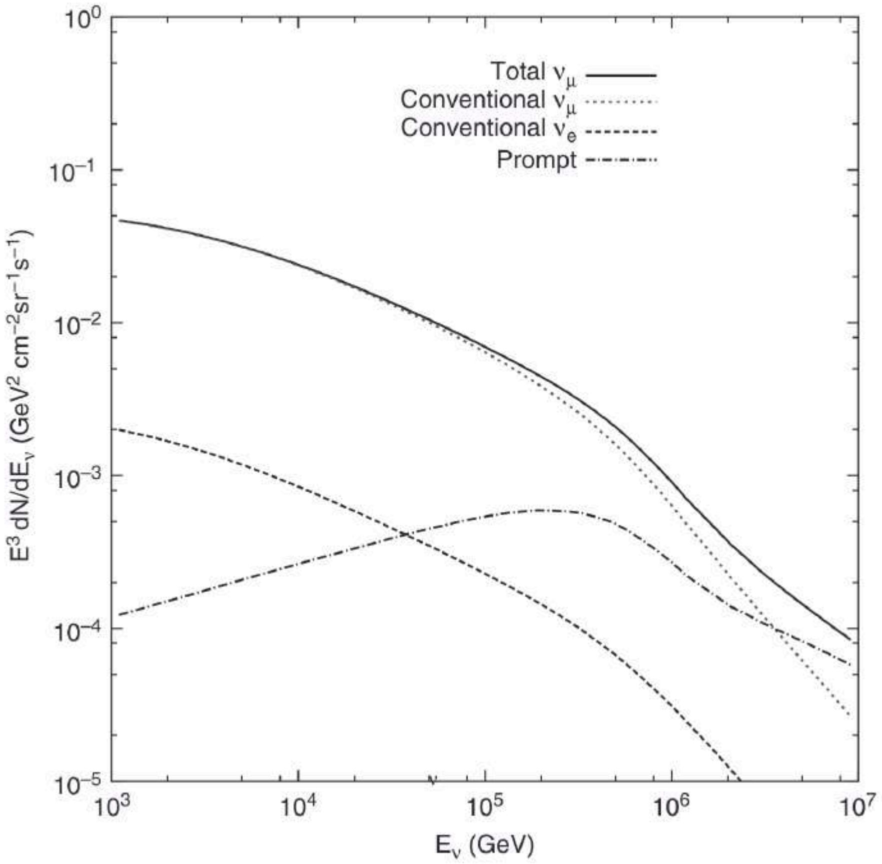


Bendhaman et al. [KM3NeT Coll.], PoS (ICRC2021) 1090

⟶ **ARCA6 and ORCA6 detectors are already sensitive to ~60% of the CCSN Galactic population**

⟶ **Real time alert system is in place within SNEWS since 2019**

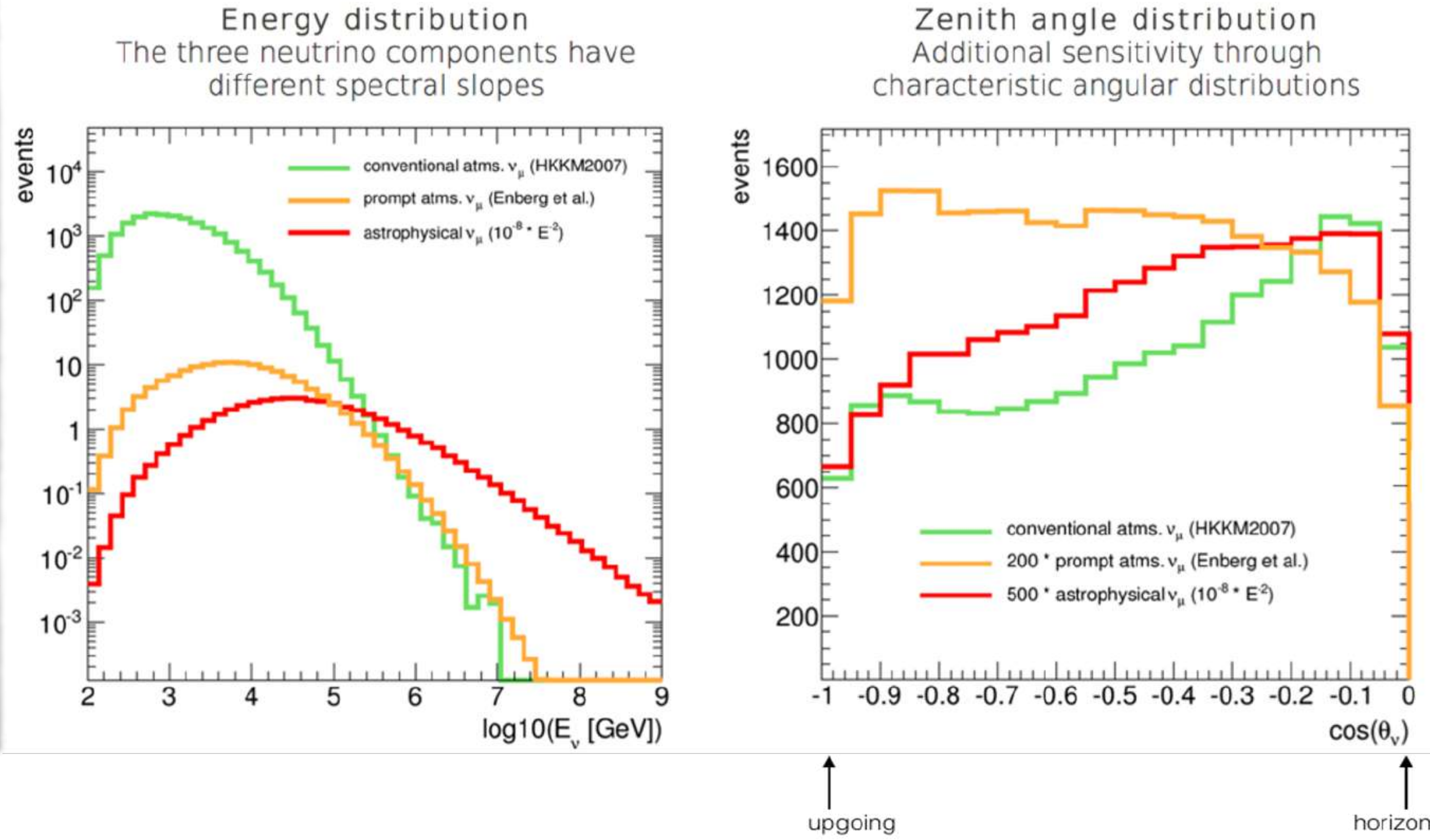
Atmospheric neutrinos



T. Gaisser, R. Engel & E. Resconi,
Cambridge University Press (2016)

per flavor

- **Conventional component**: $E^{-3.7}$, anisotropic
- **Prompt component**: $E^{-2.7}$, isotropic
- **Astrophysical component**: E^{-2}?, isotropic/anisotropic?



Energy distribution
The three neutrino components have different spectral slopes

Zenith angle distribution
Additional sensitivity through characteristic angular distributions

See also C. Mascaretti & F. Vissani, JCAP 08 (2019) 004

Neutrino expectations from the Galactic Halo

$$N_\nu \;\propto\; \sigma_{pp}\,\frac{dN}{dE_{\rm CR}}\;N_H\;\Delta\Omega\;\Delta E_\nu\;\Delta t$$

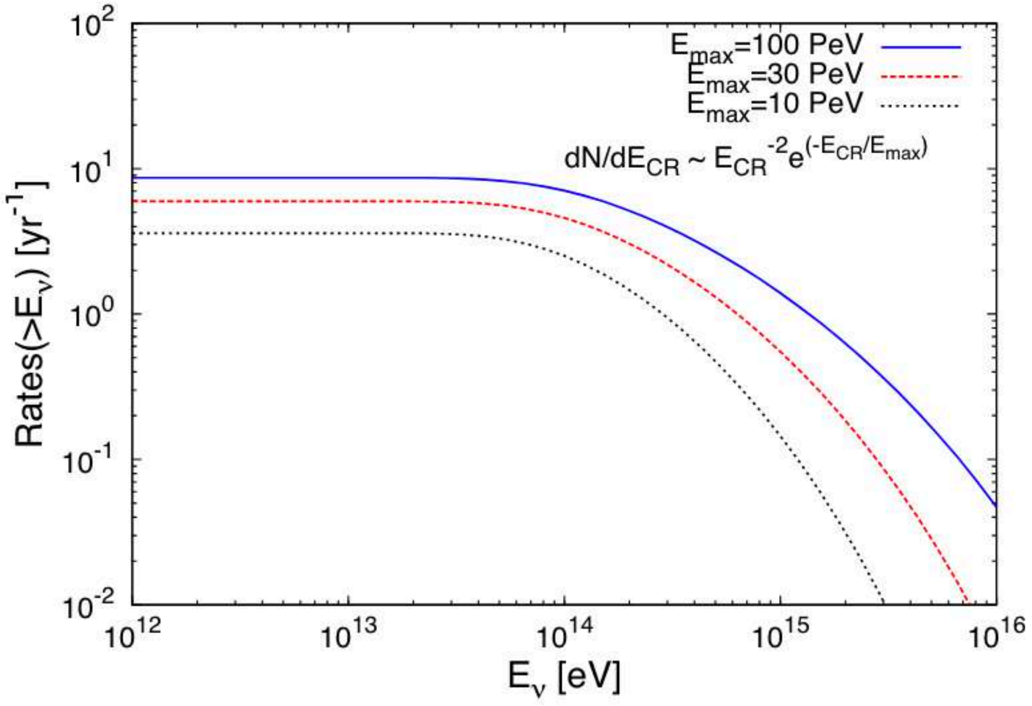
$$\frac{N_\nu^h}{N_\nu^d} \;=\; \left(\frac{n_p^h}{n_p^d}\right)\left(\frac{L^h}{L^d}\right)\left(\frac{\Delta\Omega^h}{\Delta\Omega^d}\right) \approx 0.05\left(\frac{n_{p,-3}^h}{n_{p,0}^d}\right)\left(\frac{L_1^h}{L_1^d}\right)\left(\frac{\Delta\Omega^d}{0.1}\right)^{-1}$$

For constant CR intensity, number of expected neutrinos is dominated by disc unless Galactic halo is very extended (L^h~100 kpc).

In such a case, neutrino luminosity required to explain IC data would amount to

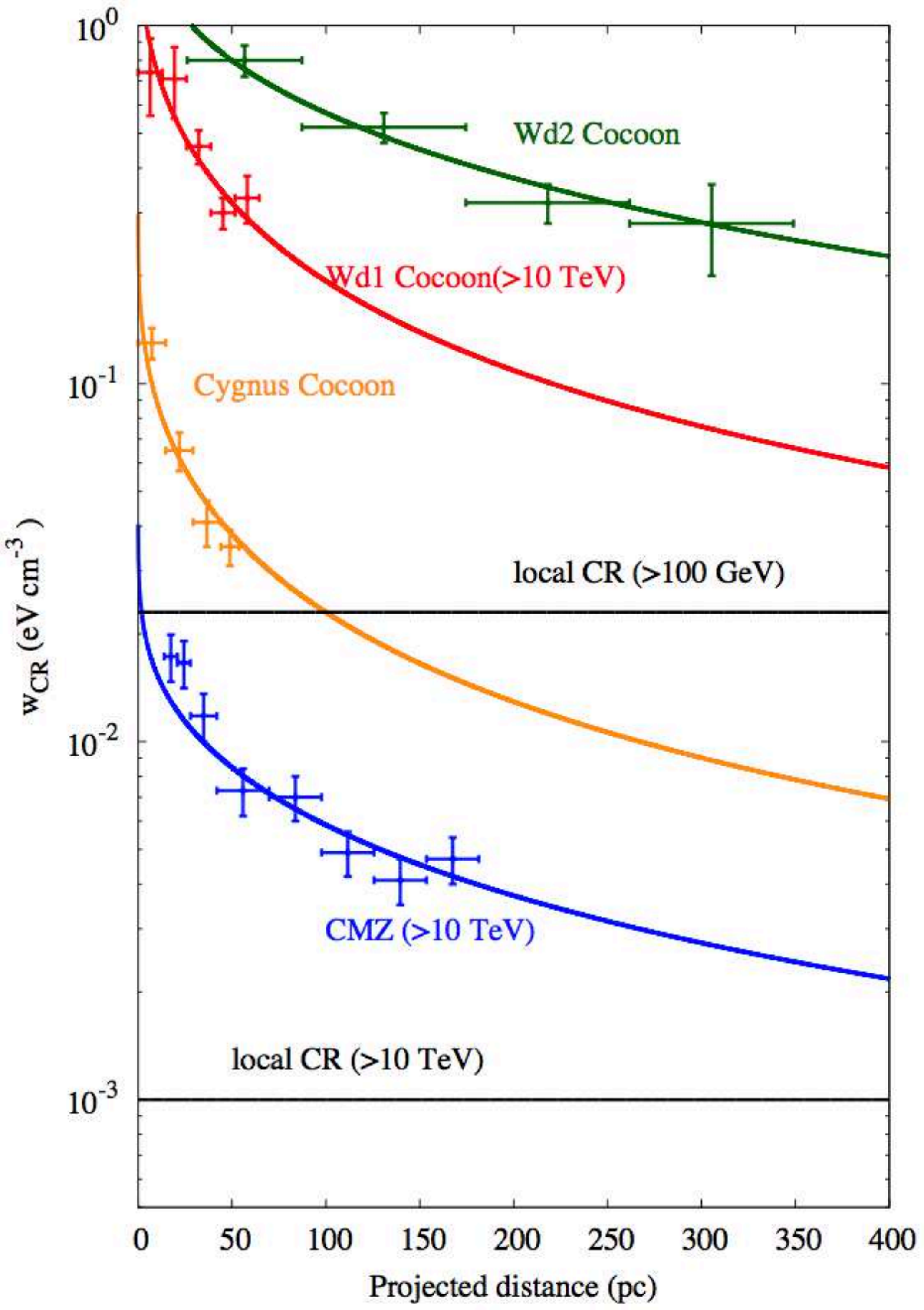
$$L_\nu \simeq 4\pi L_{\rm h}^2 E_\nu F_\nu \simeq 8\times10^{38}\ {\rm erg/s}$$

In a fully dumped scenario ($t_{pp} < t_{esc}$) and K_ν = 0.5, a proton luminosity of **L_p =10^{39} erg/s** would be required.

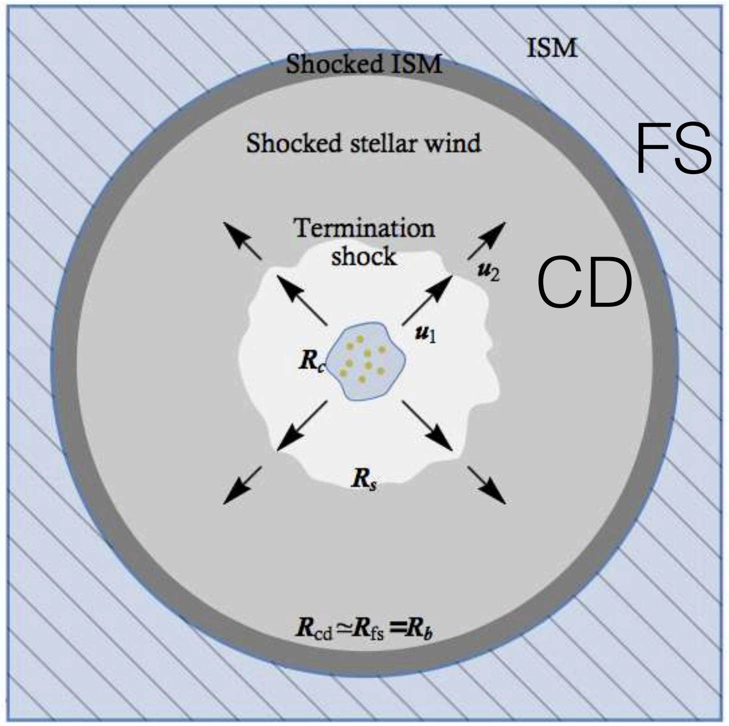


Taylor, Gabici & Aharonian, PRD 89 (2014) 103003

Do massive stellar clusters operate as PeVatrons?

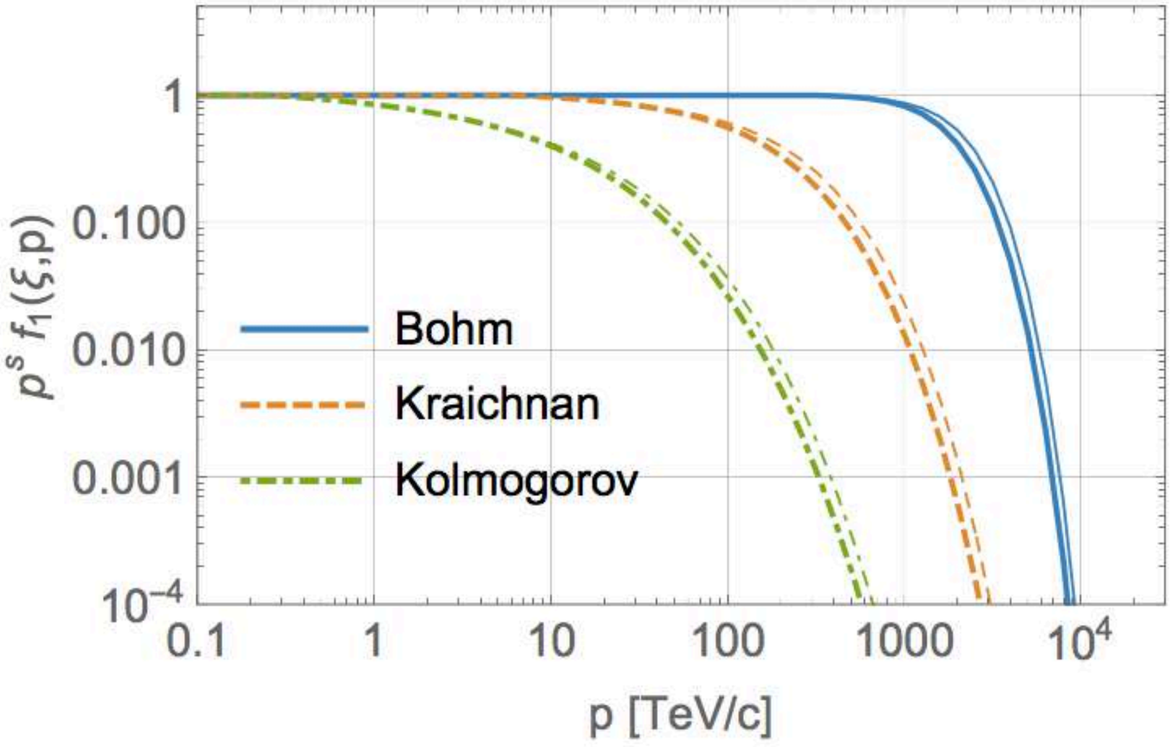


Aharonian et al., Nature Astr. 3 (2019) 561



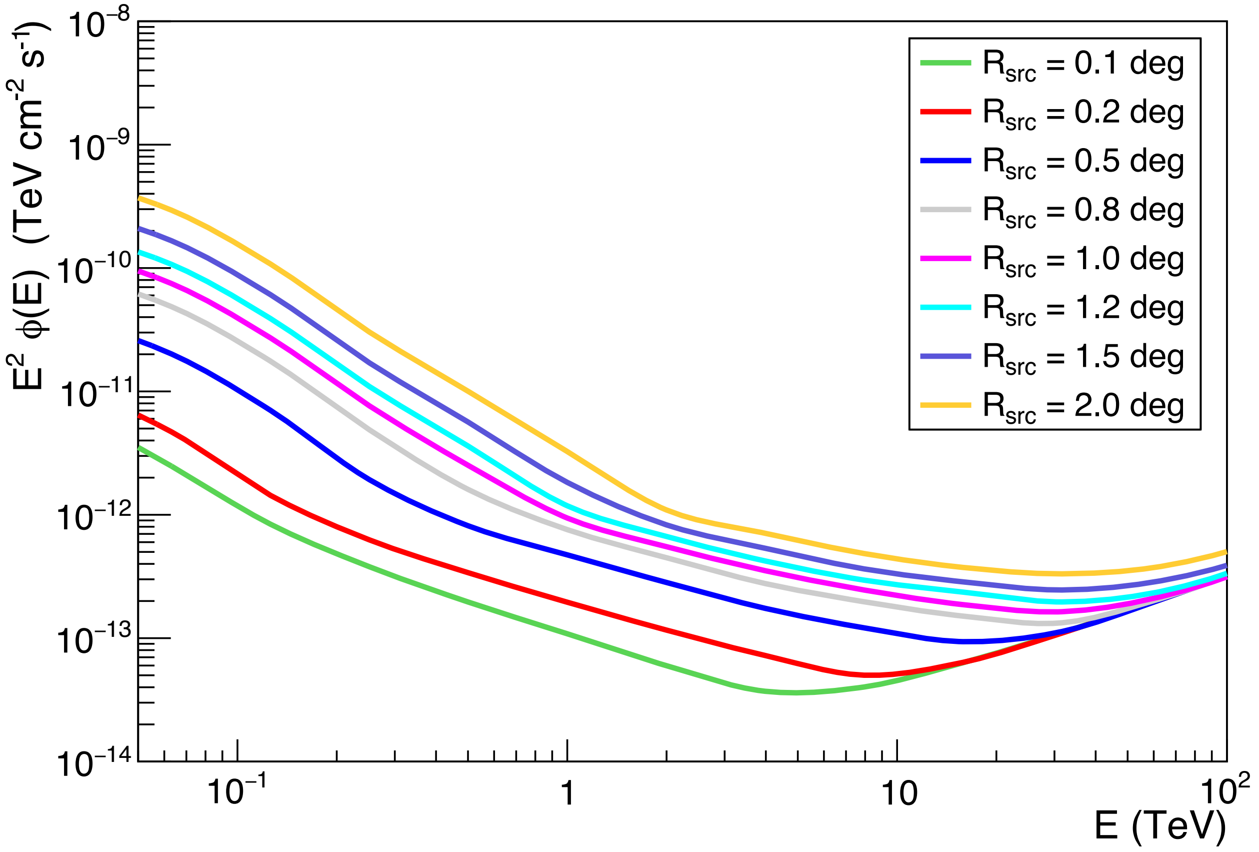
Particle acceleration expected at the **wind termination shock** —> dissipation of the wind energy into magnetic perturbations

Morlino et al., arXiv:2021.09217

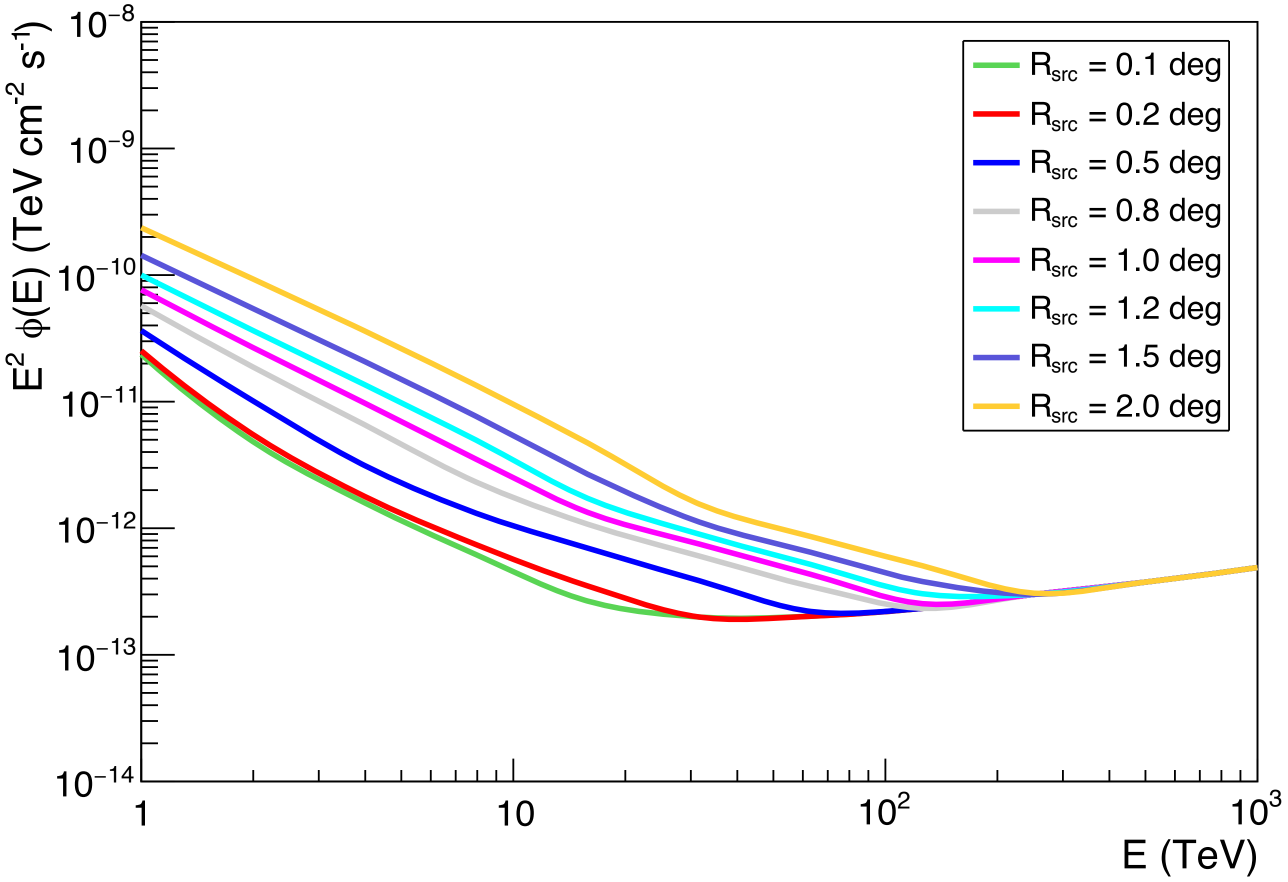


Sensitivity studies to extended sources

CTA 50 hrs

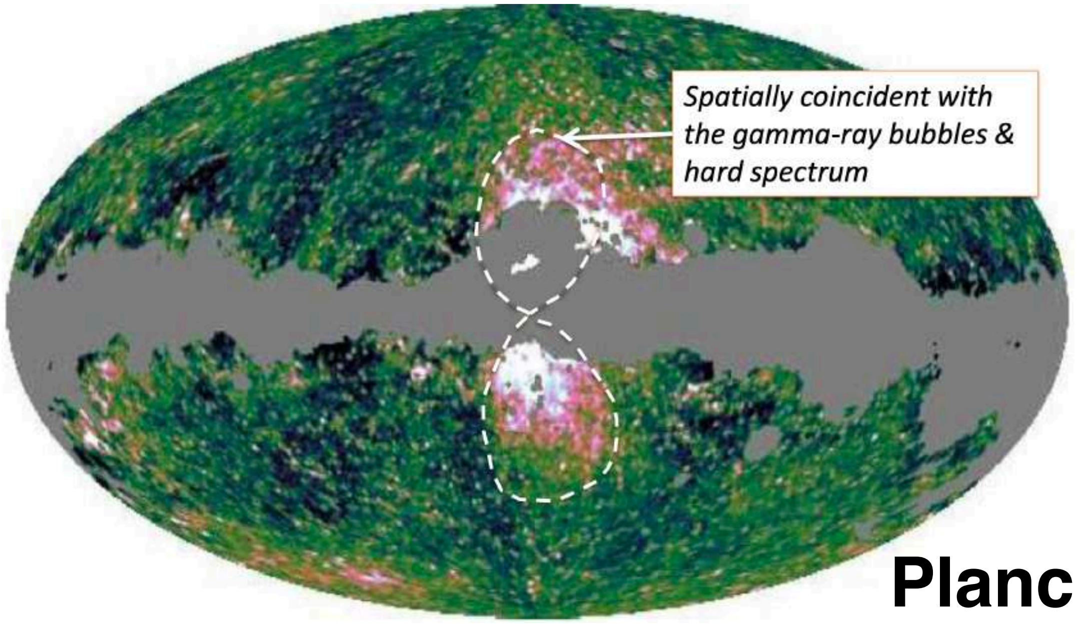


KM3NeT 10 yrs



Ambrogi, Celli & Aharonian, Astropart. Phys. 100 (2018) 69

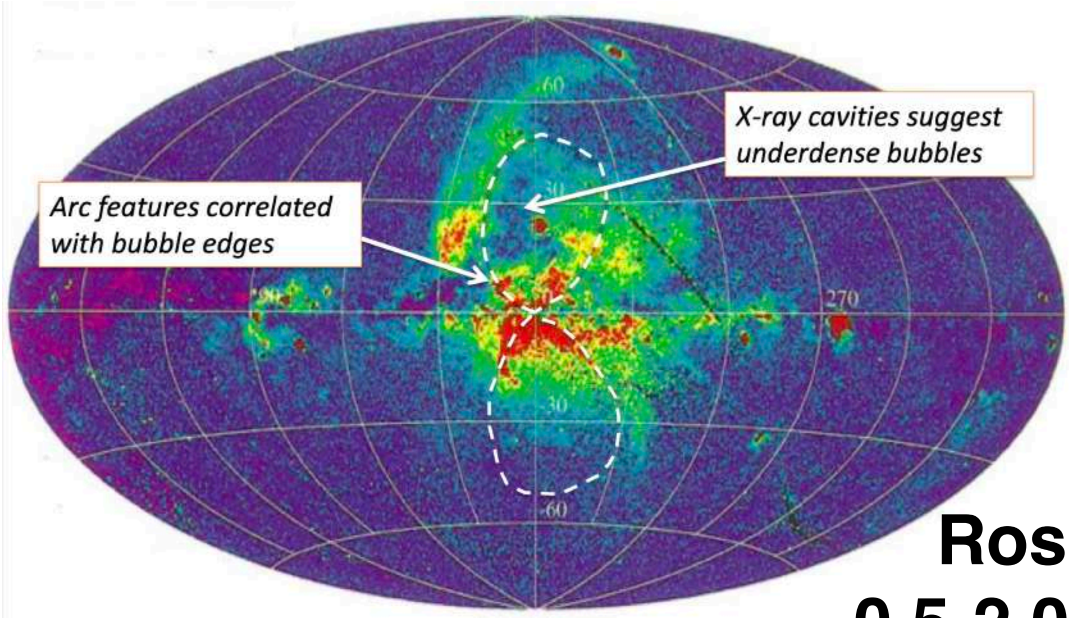
Fermi Bubbles



Spatially coincident with the gamma-ray bubbles & hard spectrum

Planck+WMAP

Finkbeiner, ApJ 614 (2004) 1

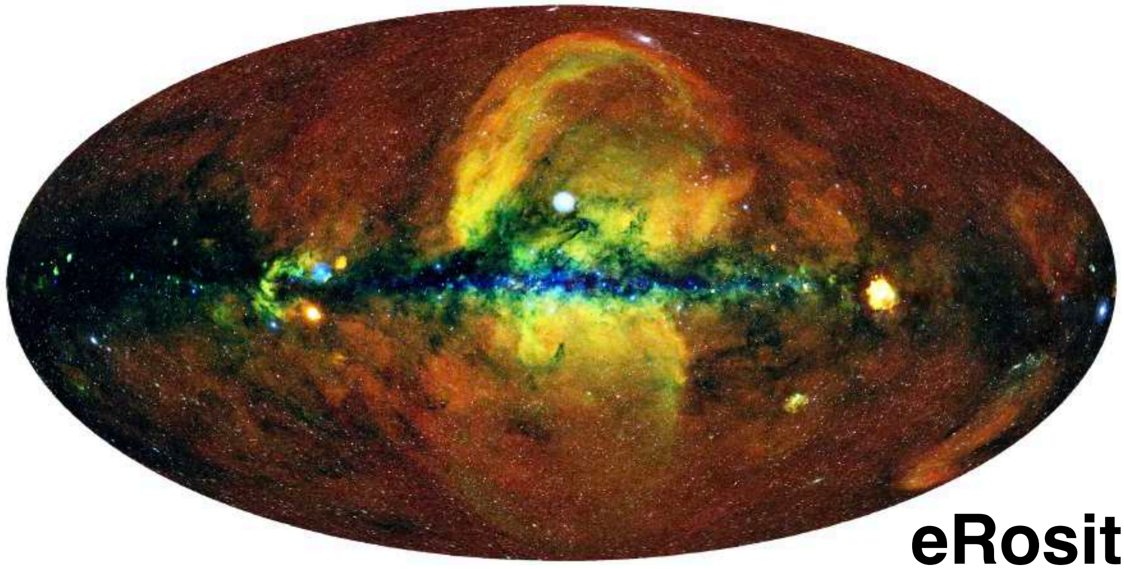


Arc features correlated with bubble edges

X-ray cavities suggest underdense bubbles

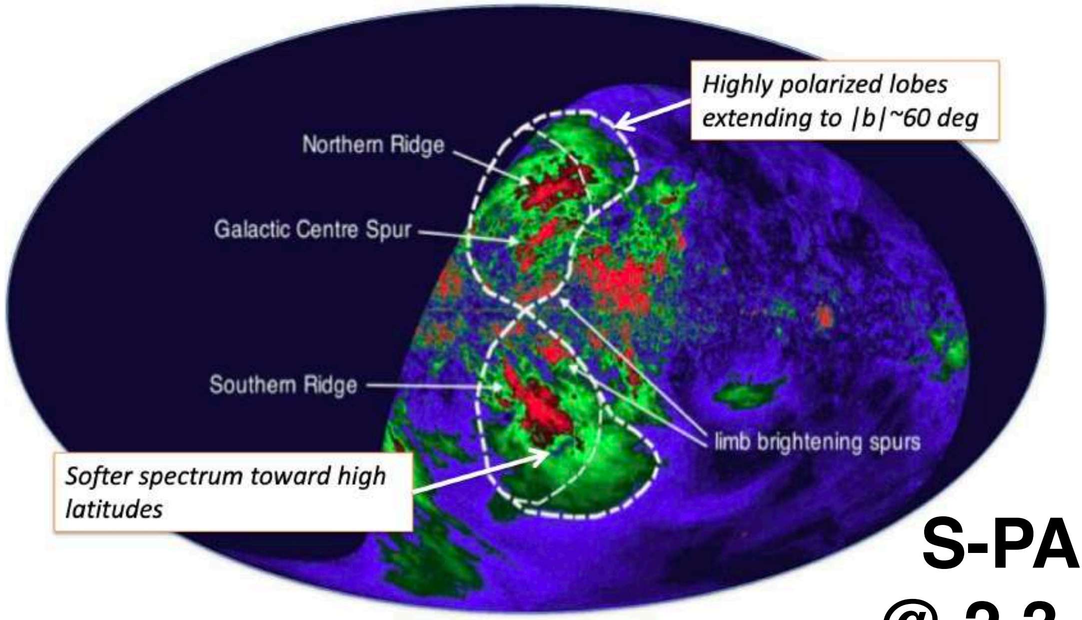
Rosat
0.5-2.0 keV

Snowden et al., ApJ 485 (1997) 1



eRosita
0.3-2.3 keV

Predehel et al., Nature 588 (2020) 277



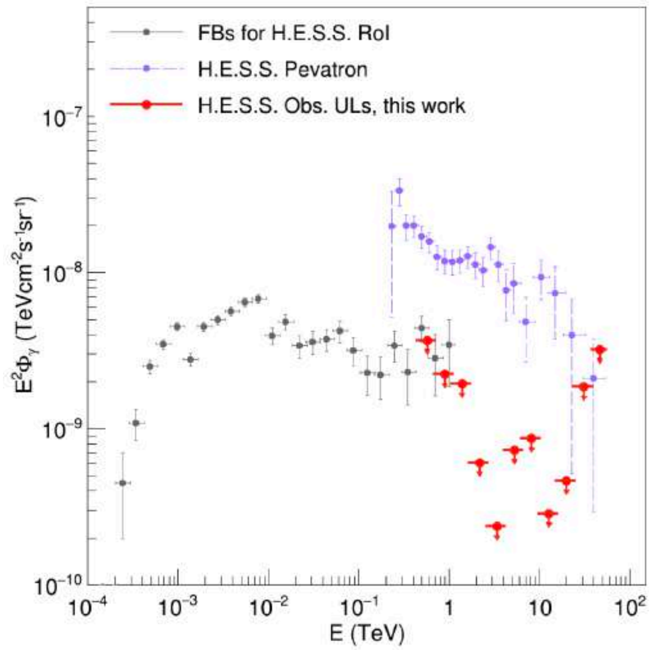
Highly polarized lobes extending to |b|~60 deg

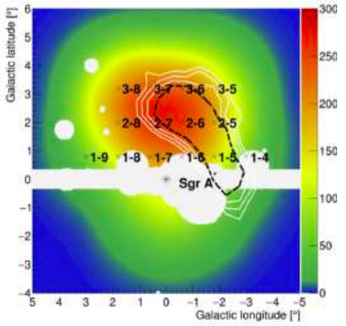
Softer spectrum toward high latitudes

S-PASS
@ 2.3 GHz

Carretti et al., Nature 493 (2020) 66

Expected neutrinos from Fermi Bubbles

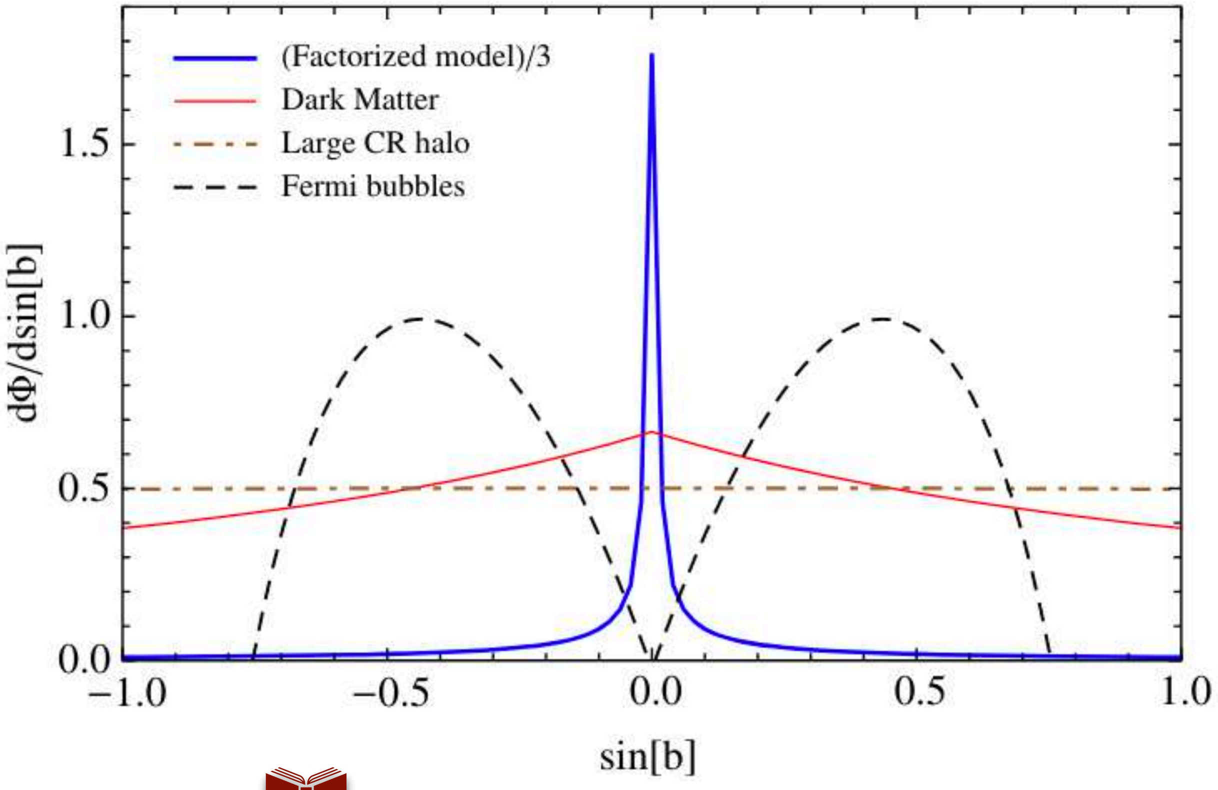




$E_{e,cut}$<9.7 TeV

$E_{p,cut}$<22.9 TeV

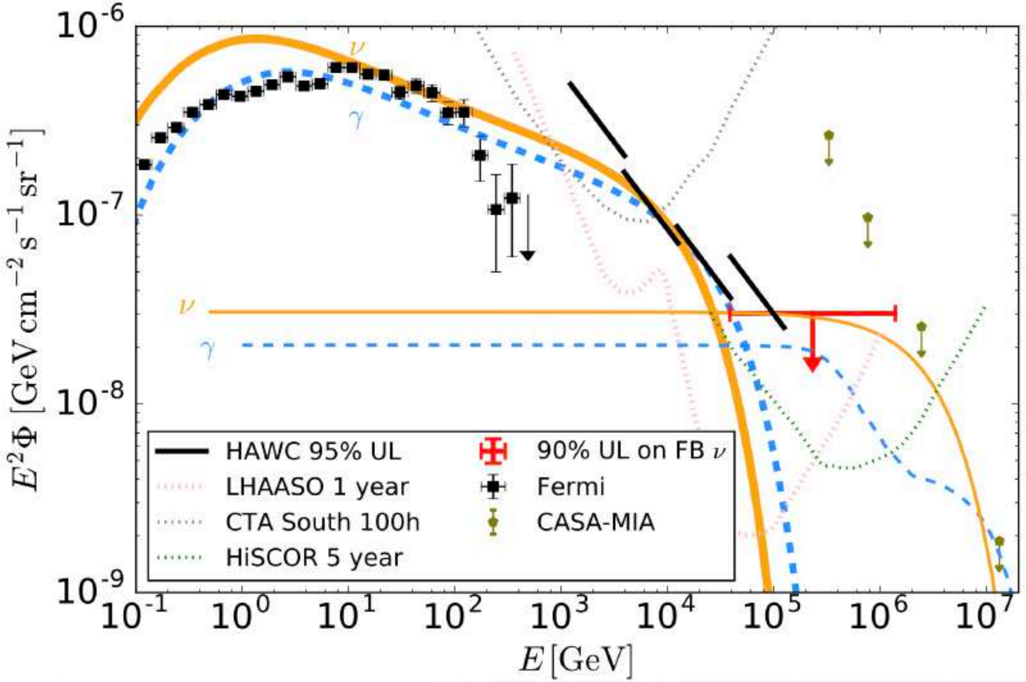
Moulin et al., PoS (2021) 791

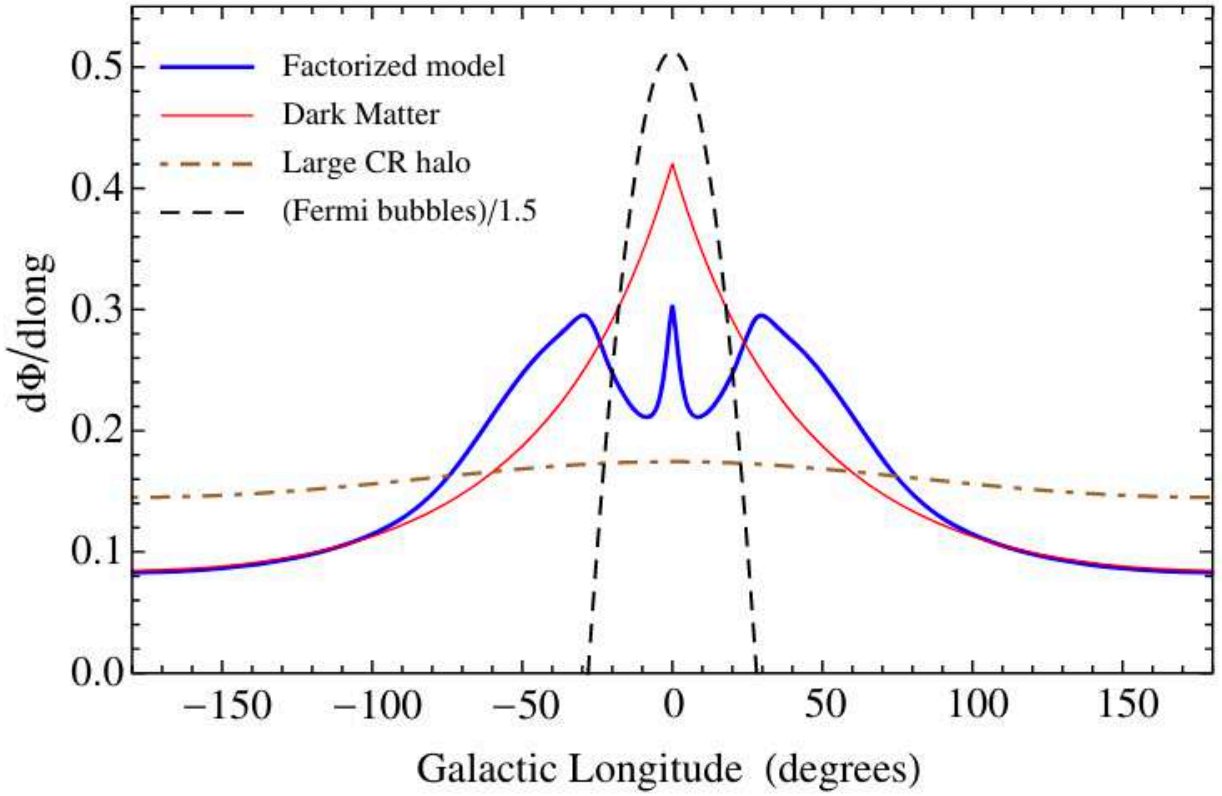


Biagi et al.(ANTARES Coll.), EPJC (2013)

Lunardini et al., PRD 92 (2015) 021301

Feng et al., PRD 92 (2017) 021301





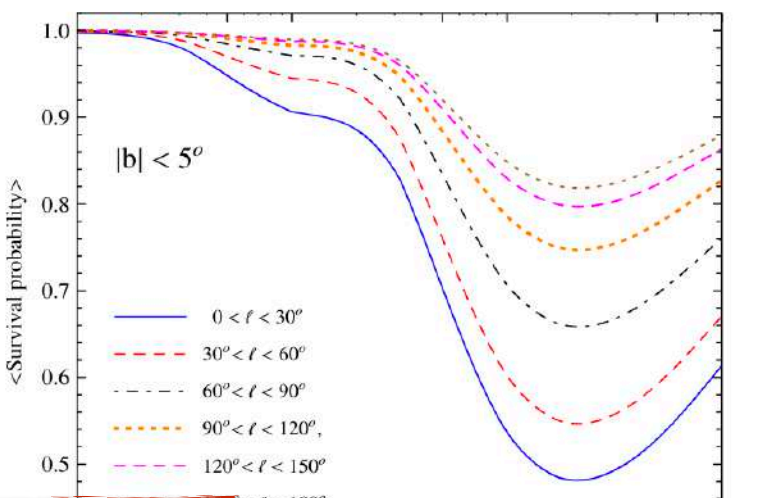
Lipari & Vernetto, PRD 98 (2022) 4

The HE and VHE diffuse gamma-ray flux

Gamma rays at the highest energies propagating through the Galaxy suffer absorption because of e^+e^- pair production:

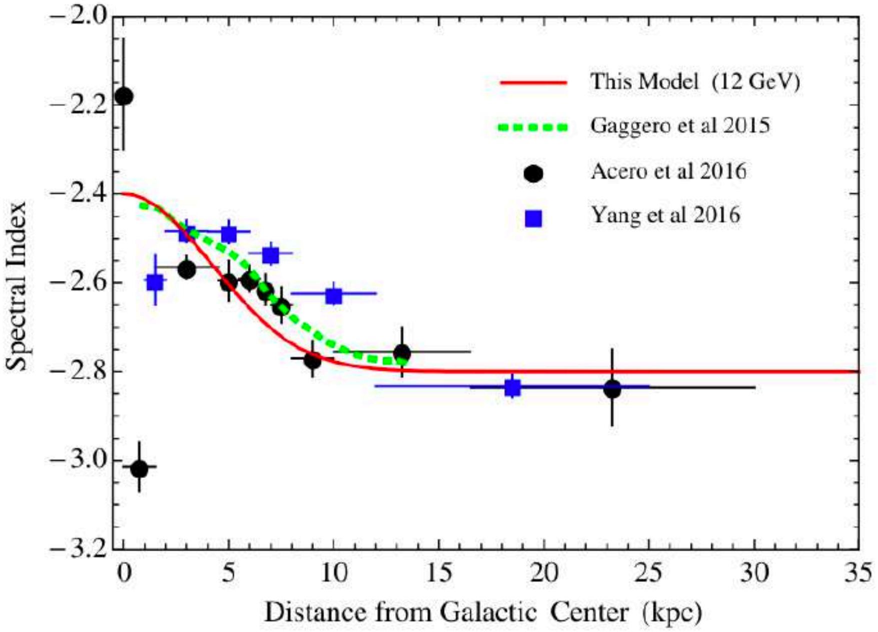
- dust emitting **IR** radiation is mostly effective on **100 TeV** photons
- **CMB** radiation is mostly effective on **2 PeV** photons

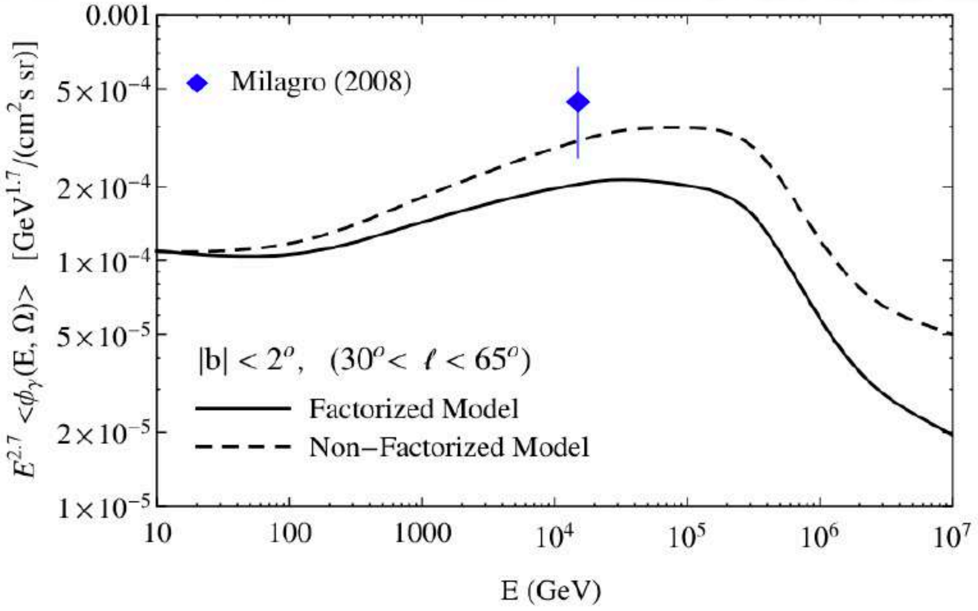
Lipari & Vernetto, PRD 98 (2022) 4

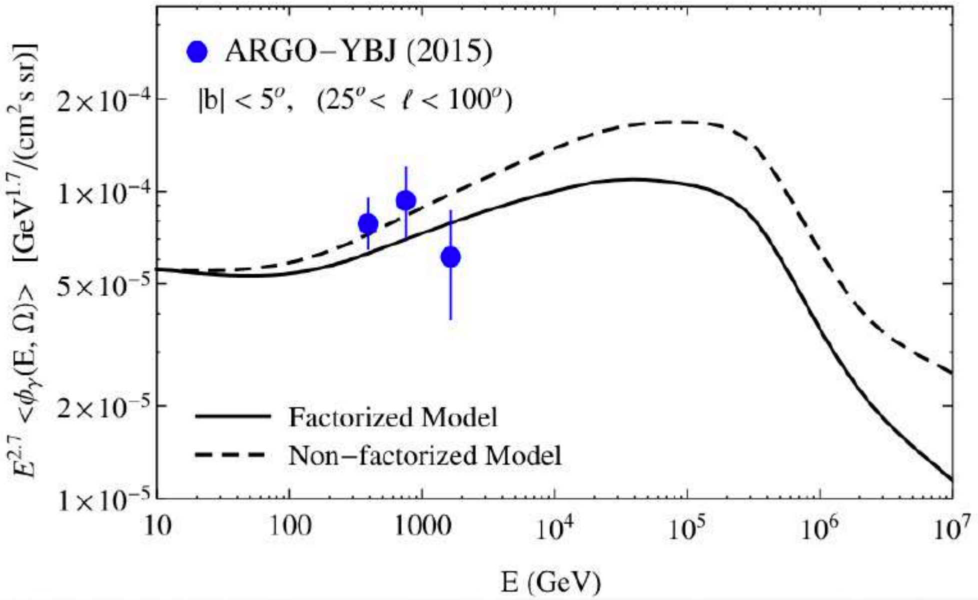


FACTORIZED MODEL: space dependent CR spectrum, exponentially suppressed at high r

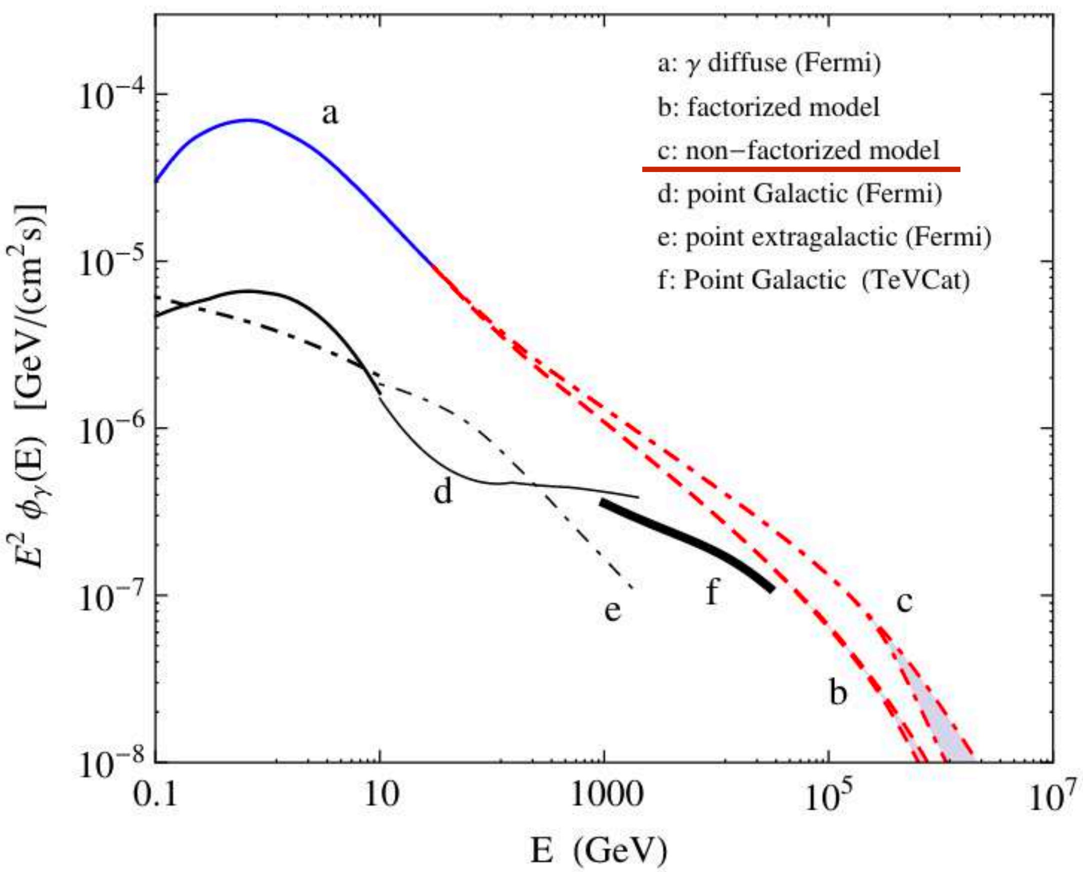
NOT-FACTORIZED MODEL: space dependent CR spectrum, reproducing hardening towards the Galactic Center

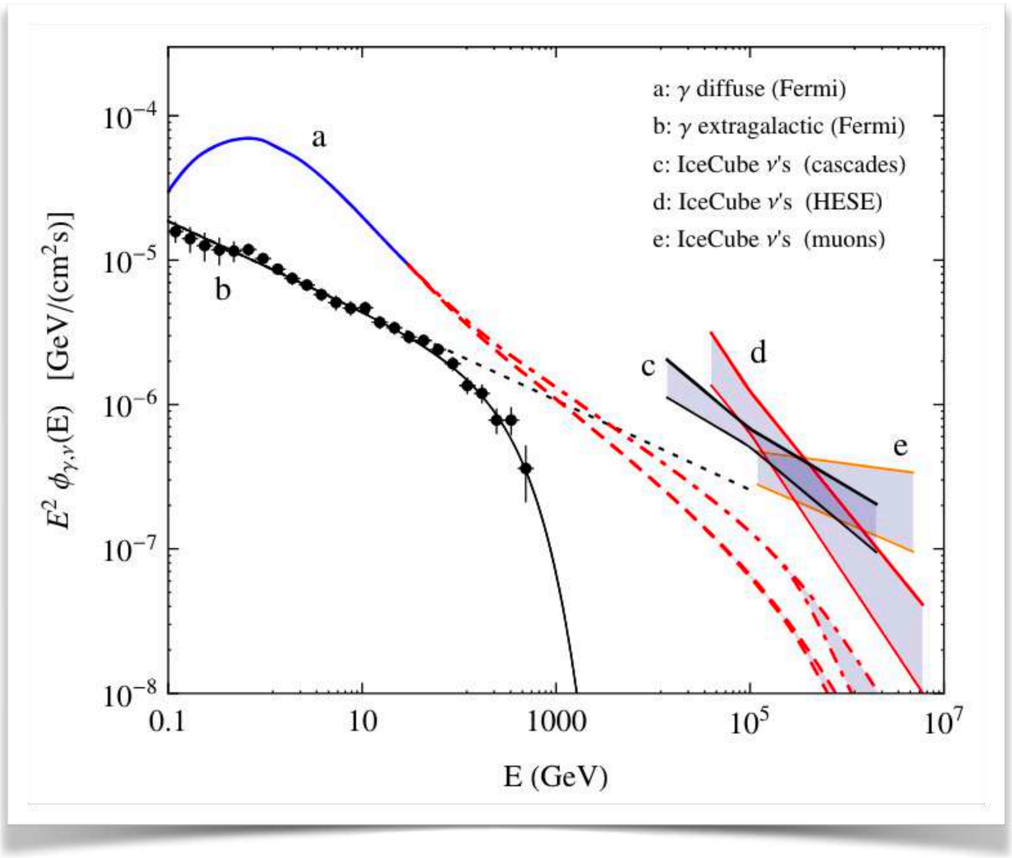


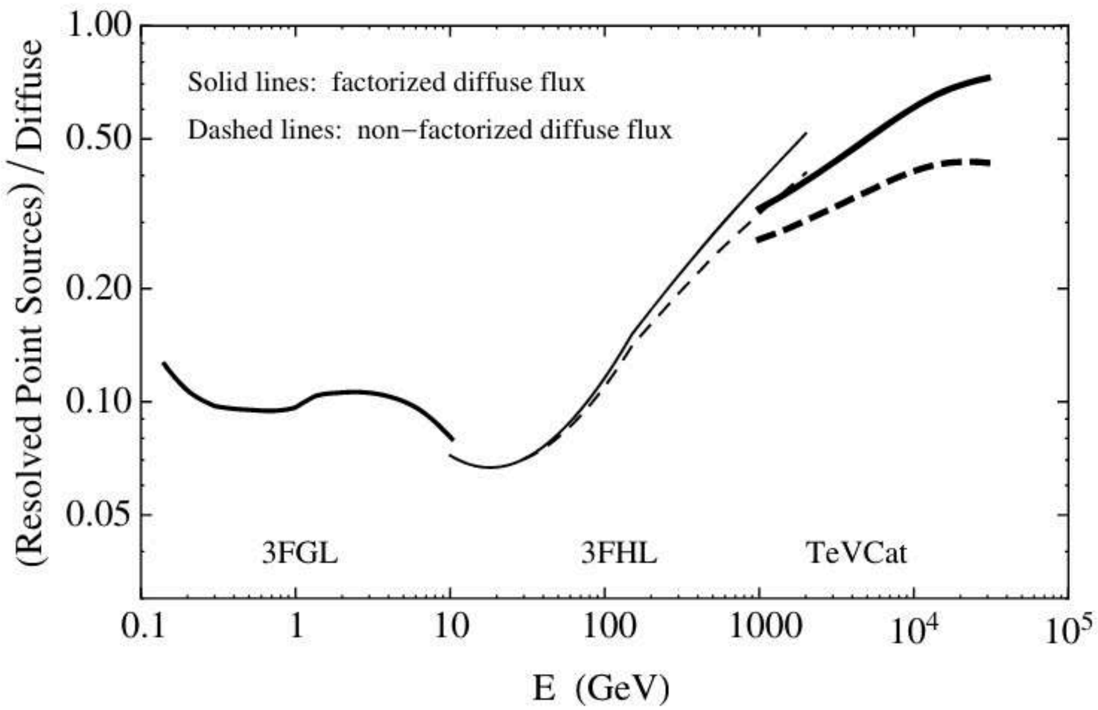




Source contribution in HE & VHE gammas







GeV Galactic sources from Fermi 3FGL and 3FHL
TeV Galactic sources from TeVCat (116 with |b|<10°)

⟶ **ratio among resolved and diffuse grows with energy, from 6% at 10 GeV, to 30-50% at 1 TeV**

⟶ **what about unresolved sources?**
Correct estimation would require knowledge of luminosity function and space distribution of sources

Lipari & Vernetto, PRD 98 (2022) 4

Contributions from our Galaxy: gammas

From the recent Galactic Plane Survey of H.E.S.S.:

$$\varphi_{\gamma,\mathrm{S}} \simeq \varphi_{\gamma,\mathrm{obs}} - \varphi_{\gamma,\mathrm{diff}} = k_\gamma(\hat{n}_\gamma)\left(\frac{E_{\mathrm{obs}}}{\mathrm{TeV}}\right)^{-\alpha_\gamma} \exp\left(-\sqrt{\frac{E_{\mathrm{obs}}}{E_{\mathrm{cut},\gamma}}}\right)$$

can be modeled in the context of CR transport

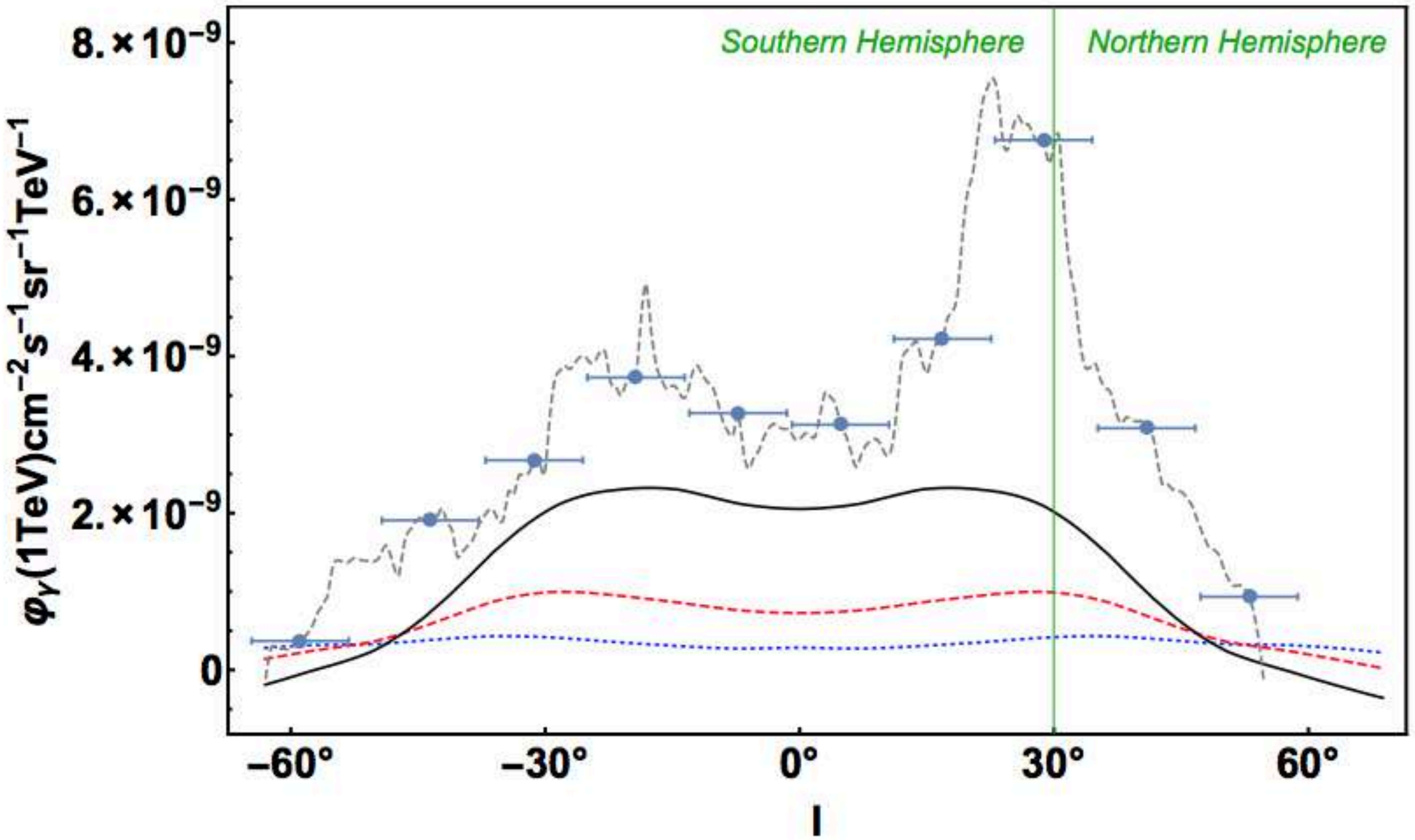
G. Pagliaroli & F. Villante, JCAP 08 (2018) 035

$$\varphi_{\mathrm{CR}}(E,\mathbf{r}) = \begin{cases} \varphi_{\mathrm{CR},\odot}(E) & \textit{Case A} \\ \varphi_{\mathrm{CR},\odot}(E)\, g(\mathbf{r}) & \textit{Case B} \\ \varphi_{\mathrm{CR},\odot}(E)\, g(\mathbf{r})\, h(E,\mathbf{r}) & \textit{Case C} \end{cases}$$

A: homogenous CR density all along the Plane

B: CR density following the SNR distribution along the Plane

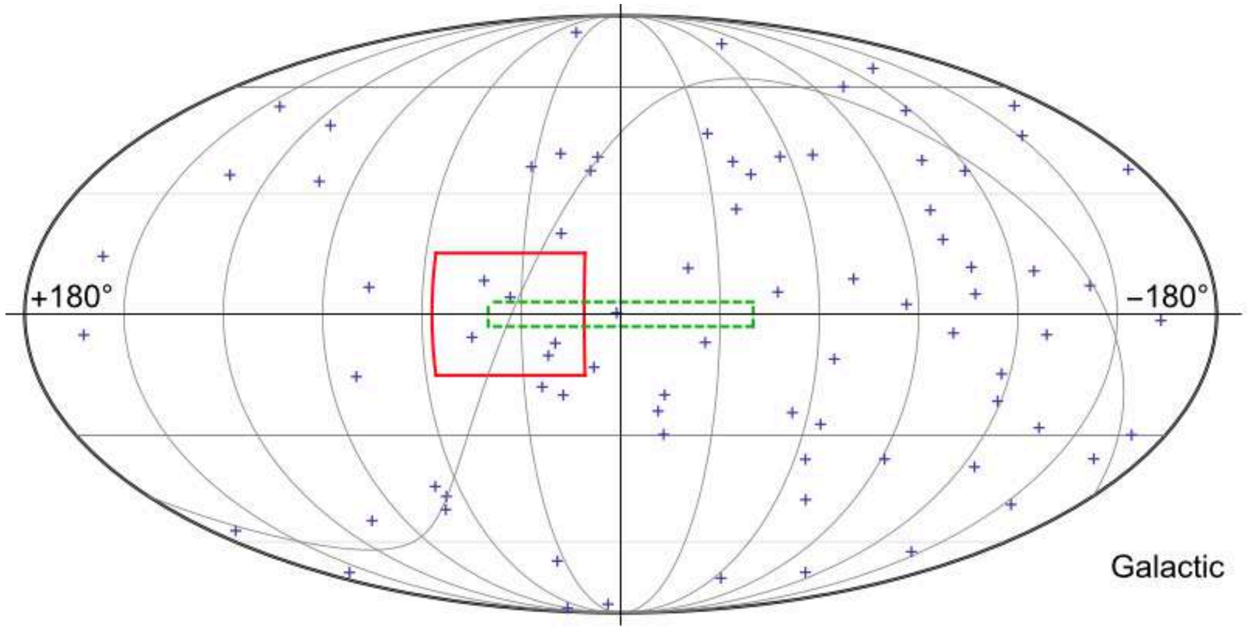
C: CR density with radially dependent spectral index (KRA$_\gamma$)



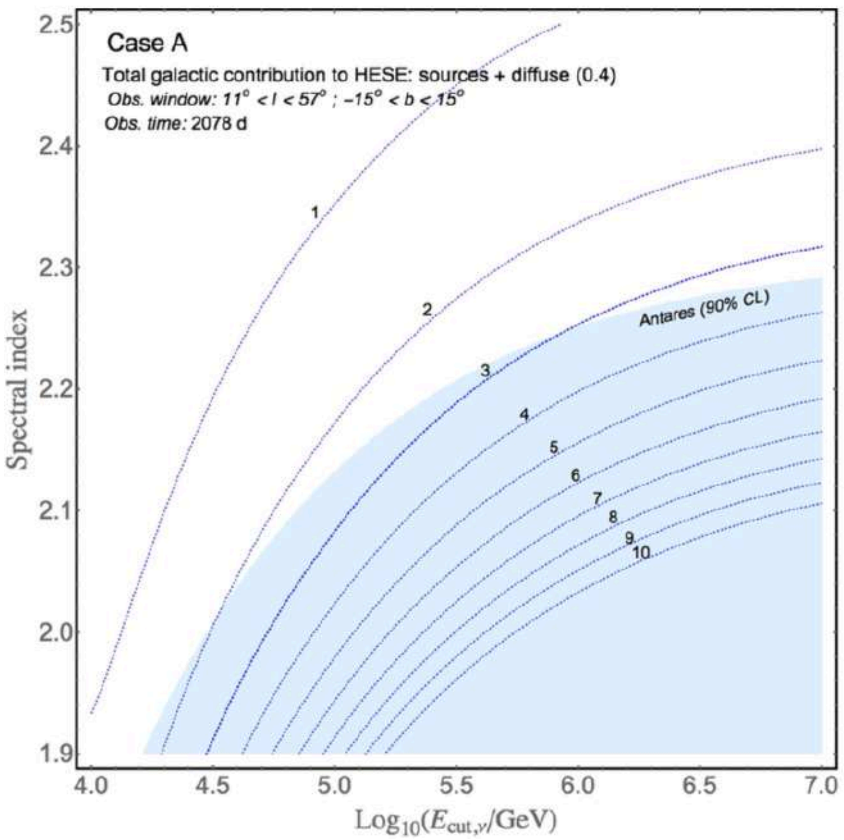
—> non negligible **source contribution**

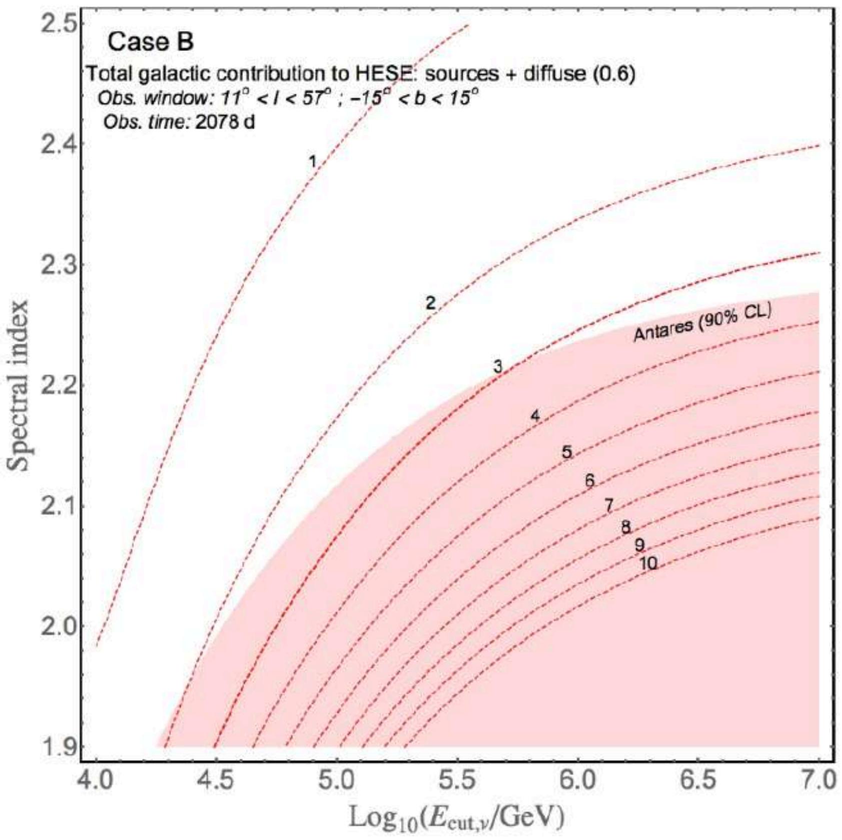
Contributions from our Galaxy: neutrinos

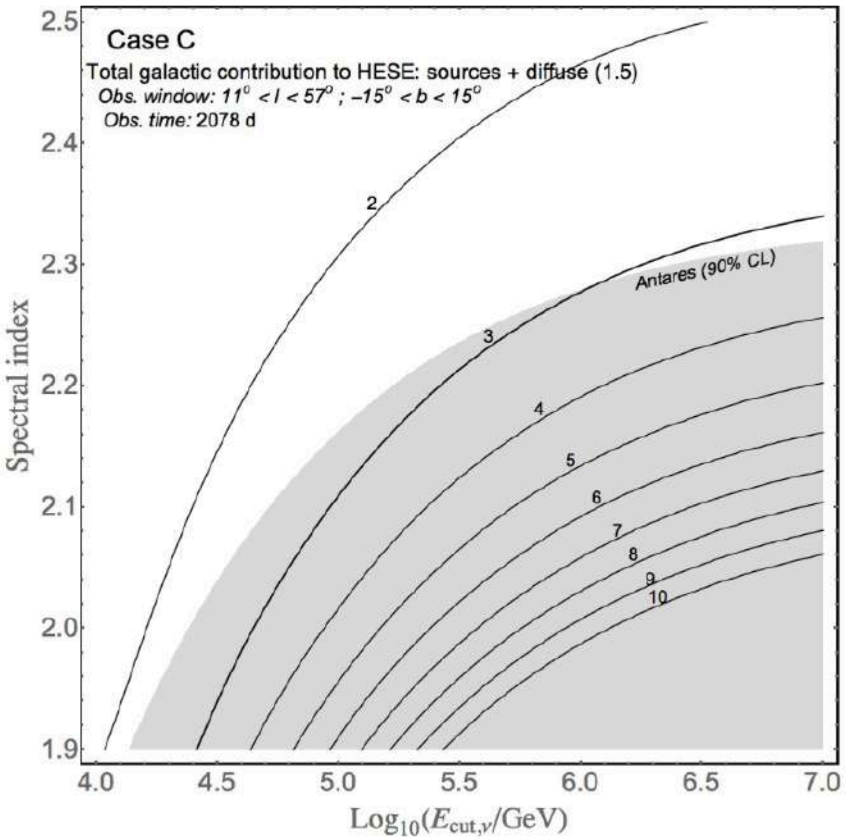
Extended Hot Region
Galactic Ridge



In terms of ν, the spectrum depends on the sources:







G. Pagliaroli & F. Villante, JCAP 08 (2018) 035