The search for cosmic neutrino sources

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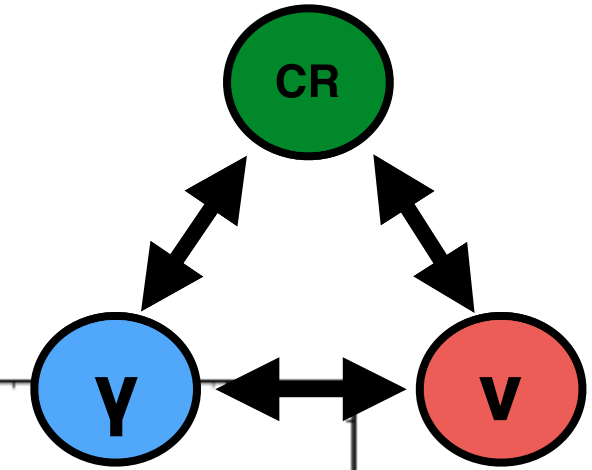
Outline of the talk

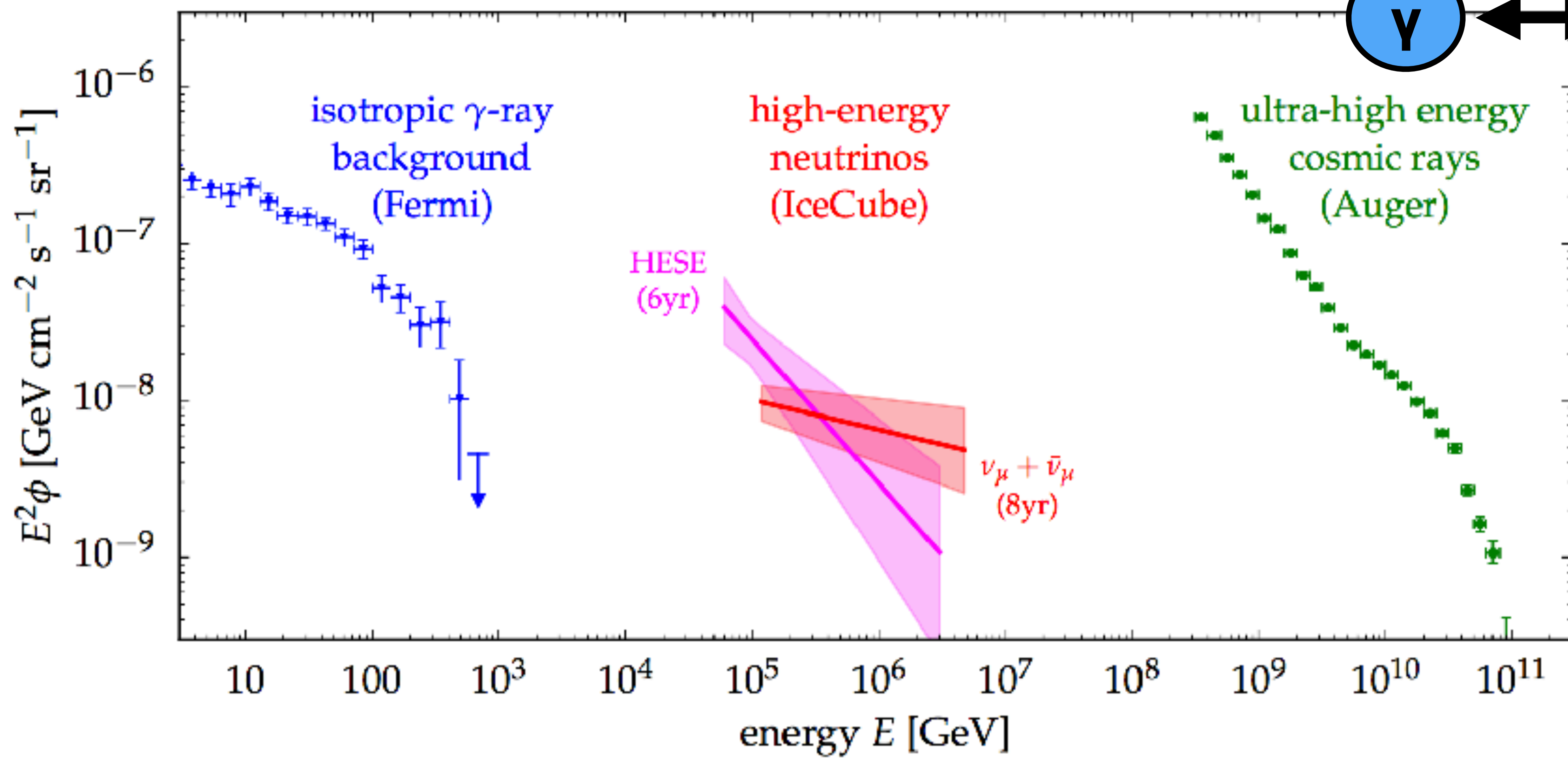
- Introduction to **high-energy neutrino telescopes** (ice-based, sea-based), neutrino **event topology** and **data sets**

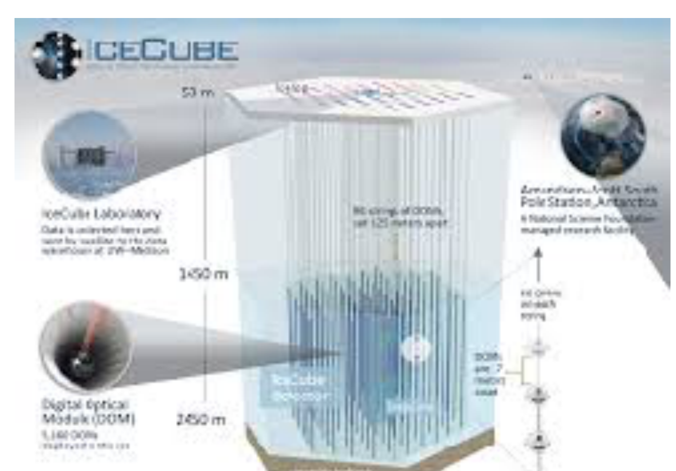
- Status of neutrino astronomy: the observation of a **diffuse cosmic neutrino flux**

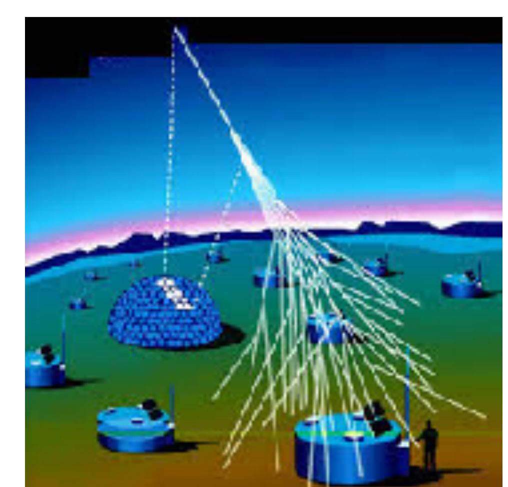
- The search for **neutrino sources**:
  - neutrino production physics;
  - contributions from the Galaxy;
  - extra-galactic candidates.

The multi-messenger framework in the search for CR sources

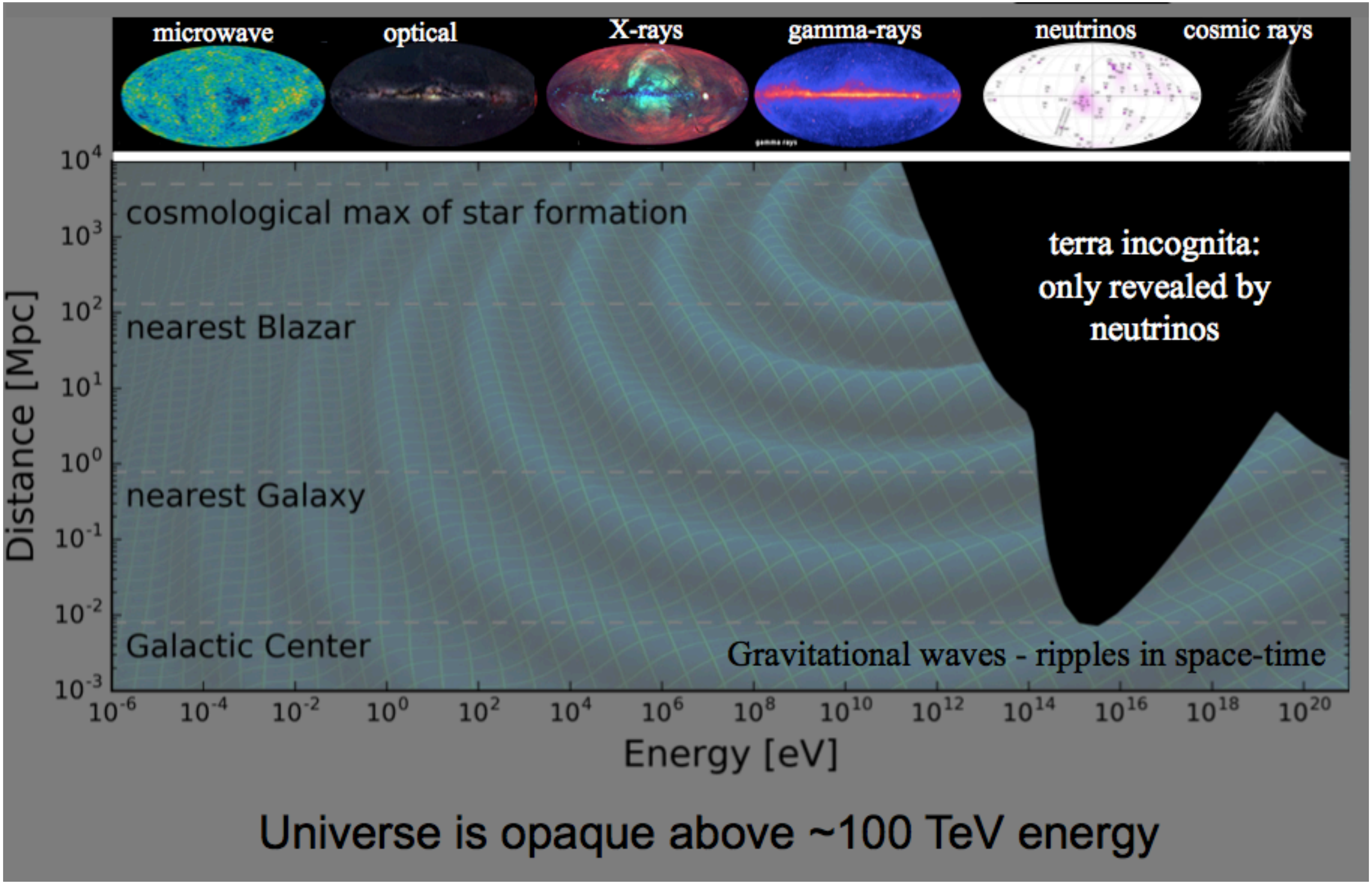






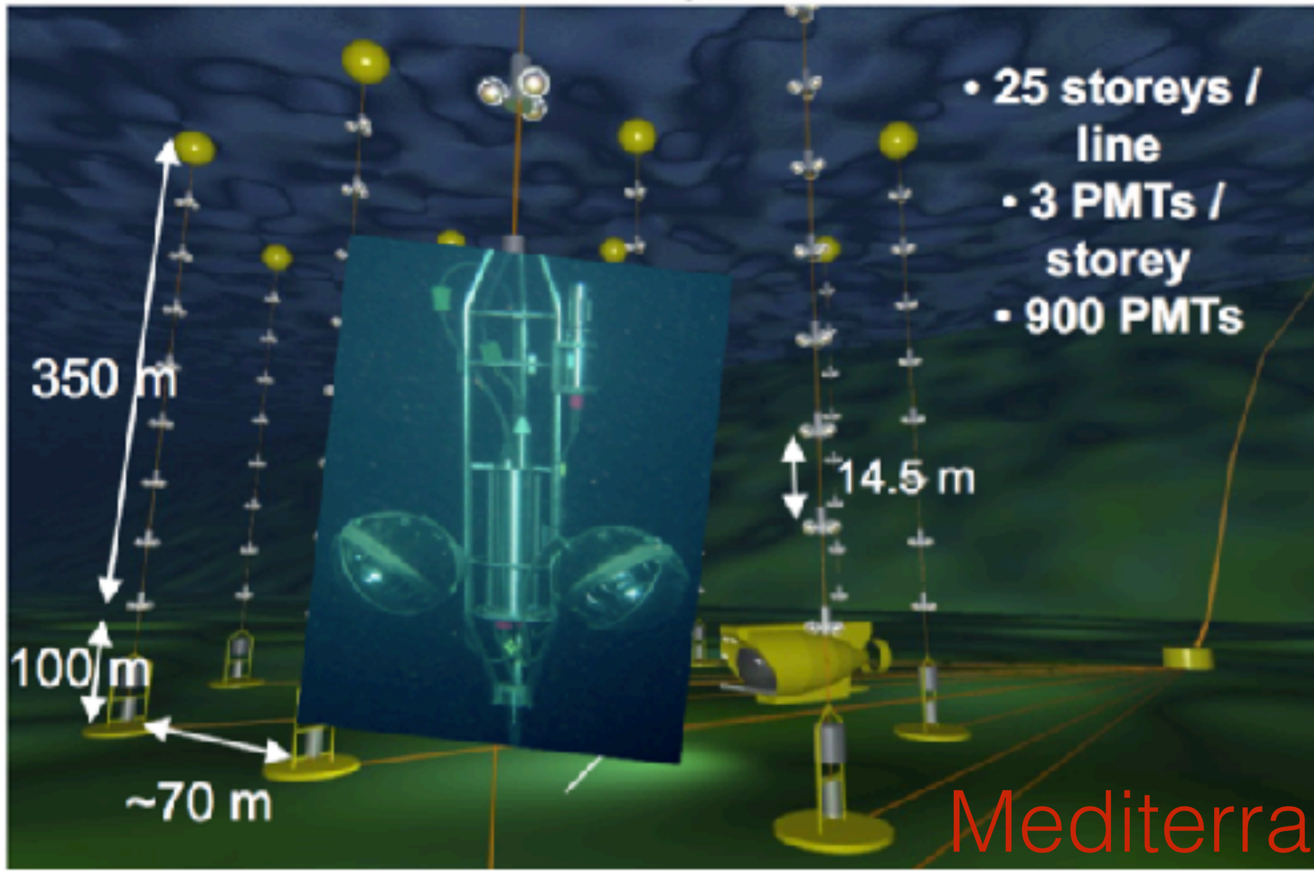


The opaque Universe

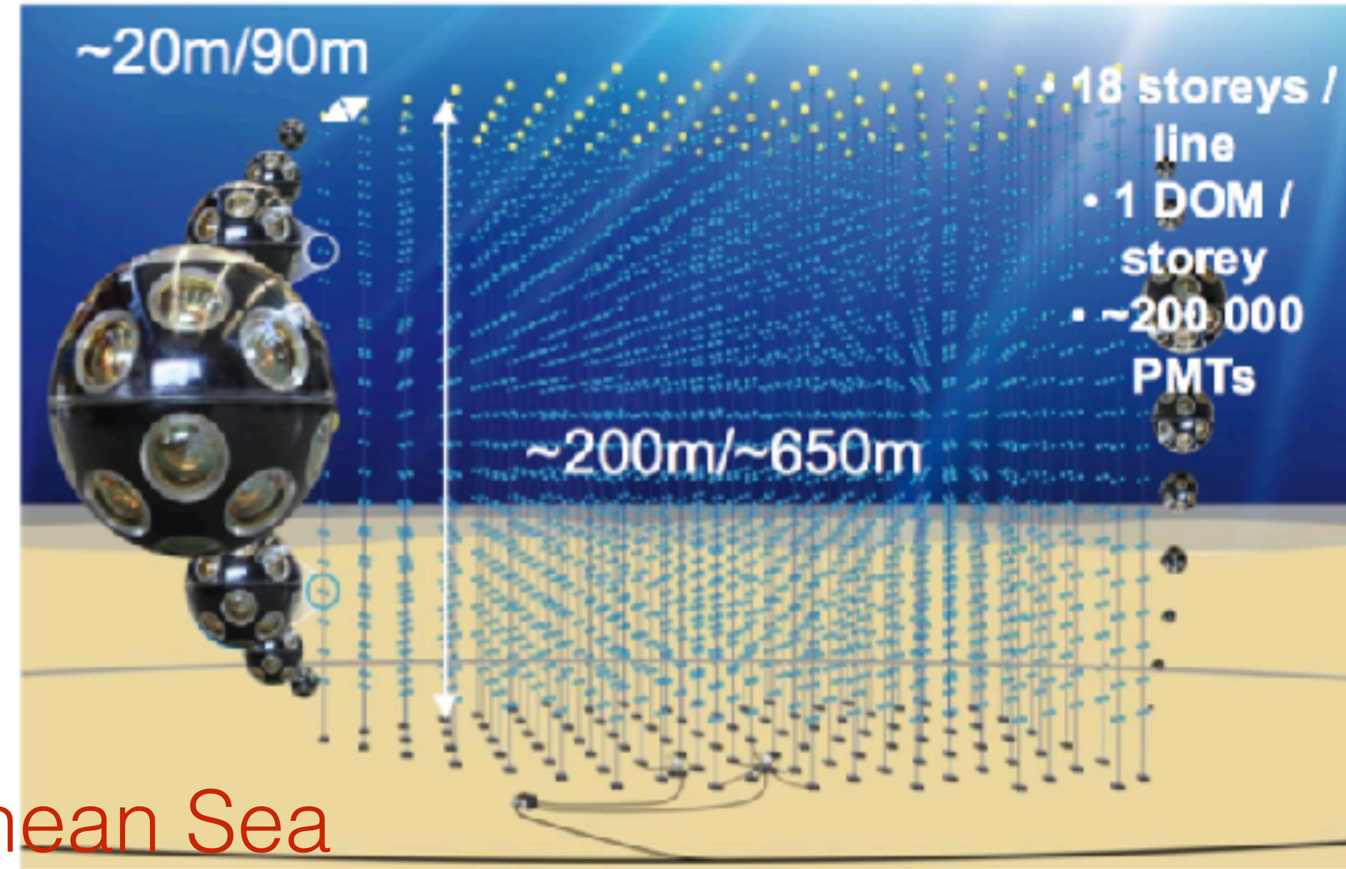


Neutrino telescopes

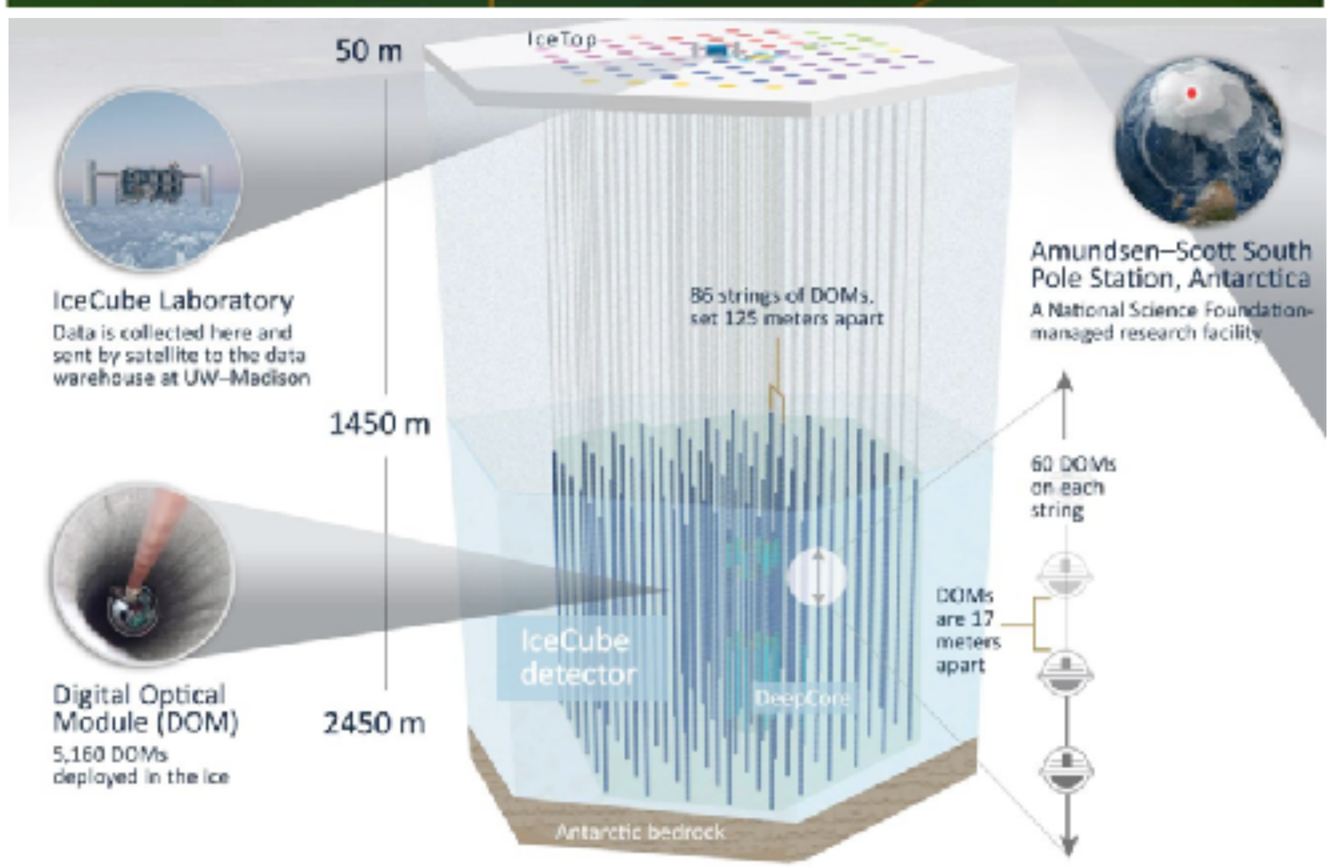
ANTARES Complete since 2008



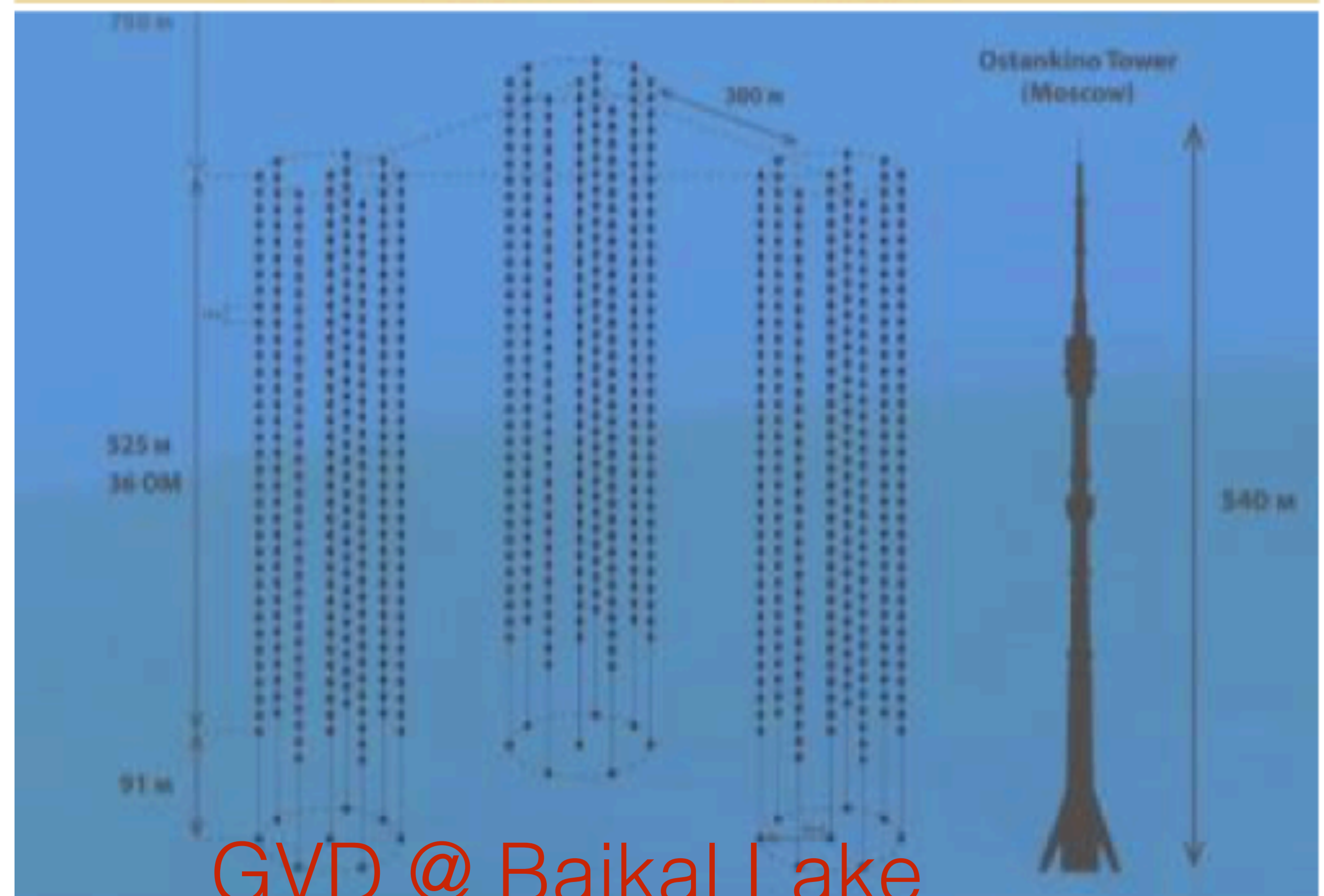
KM3NeT Under Construction



Mediterranean Sea



IceCube @ South Pole



GVD @ Baikal Lake

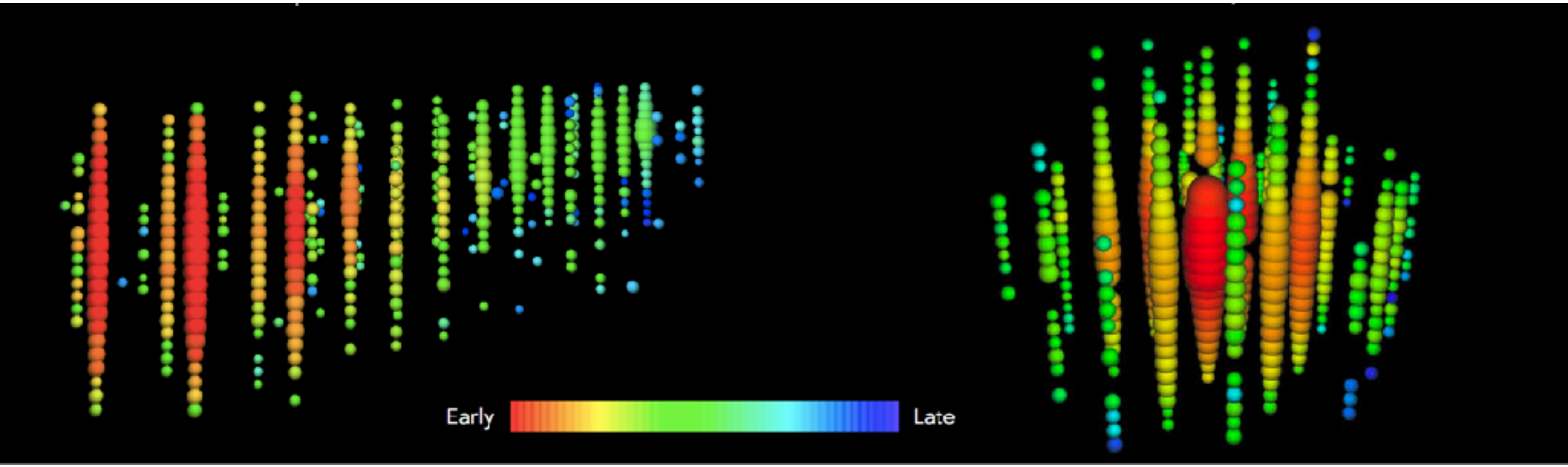
Neutrino event topology

Muon tracks

ν_μ CC interactions

Cascades

NC / ν_τ - ν_e CC



Astronomy

~factor 2 energy resolution

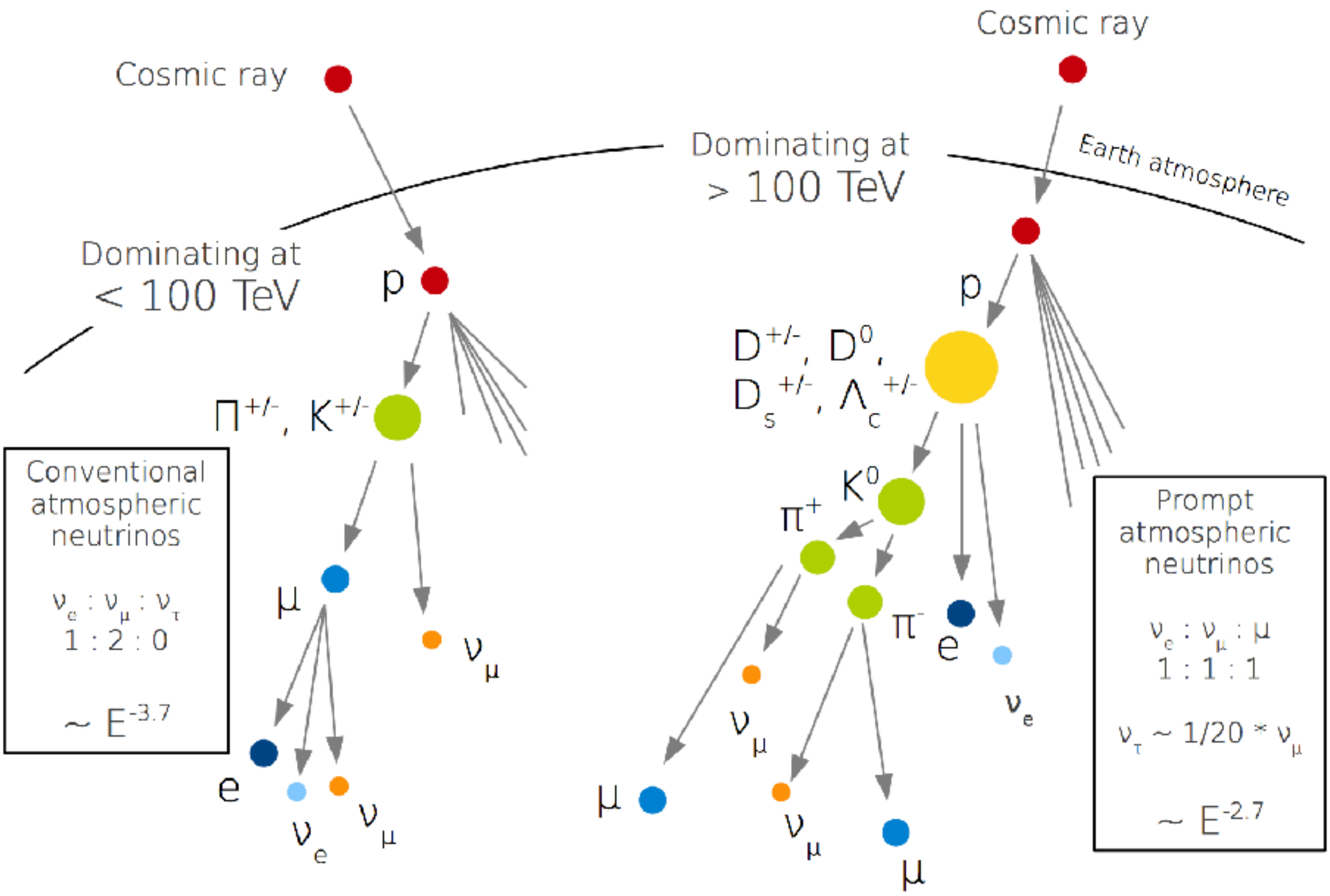
Angular resolution ~0.5° @ 10 TeV

Calorimetry + All flavors

~15% deposited energy resolution

~15° median angular resolution @ 10 TeV

Neutrino background

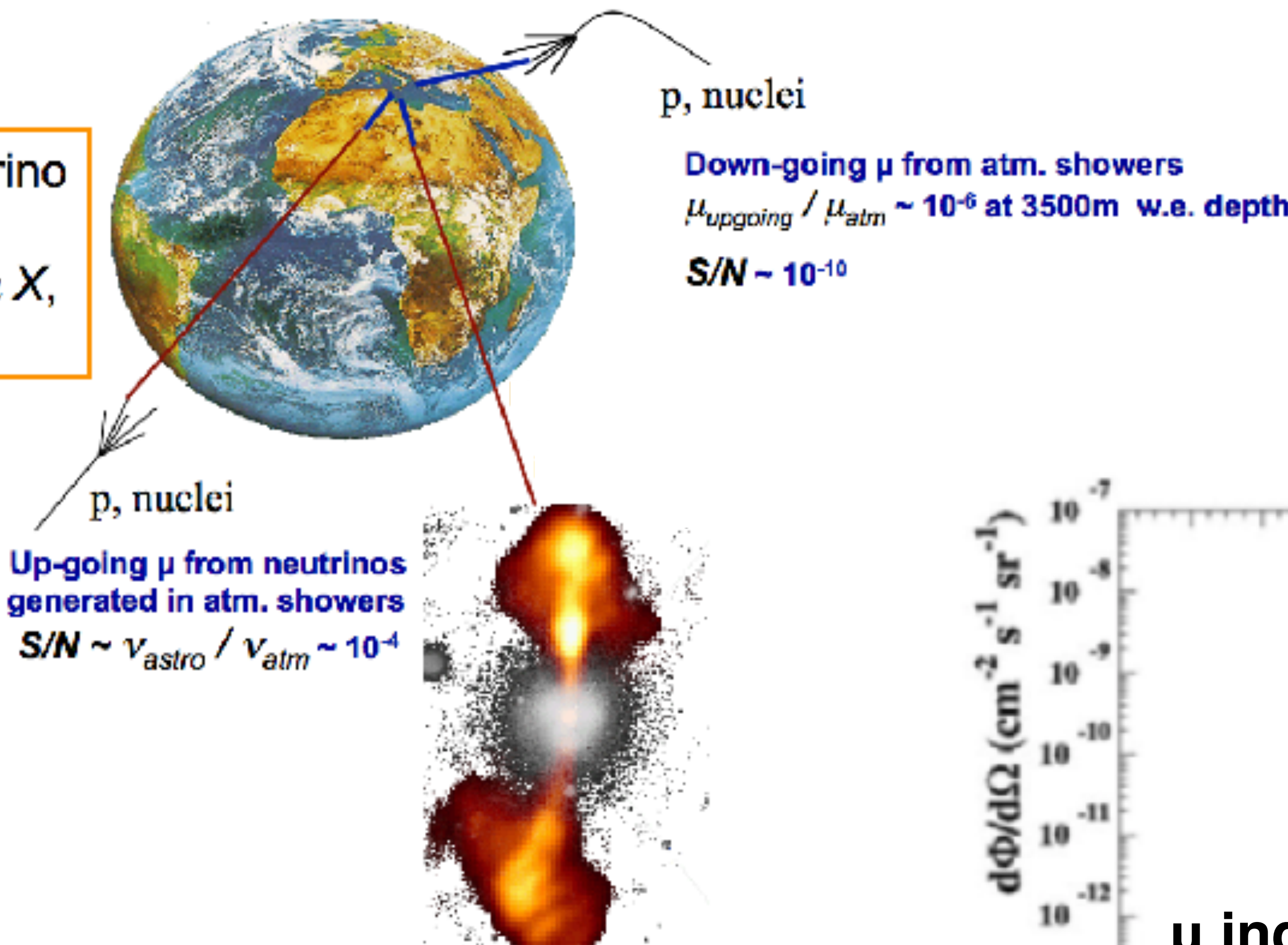


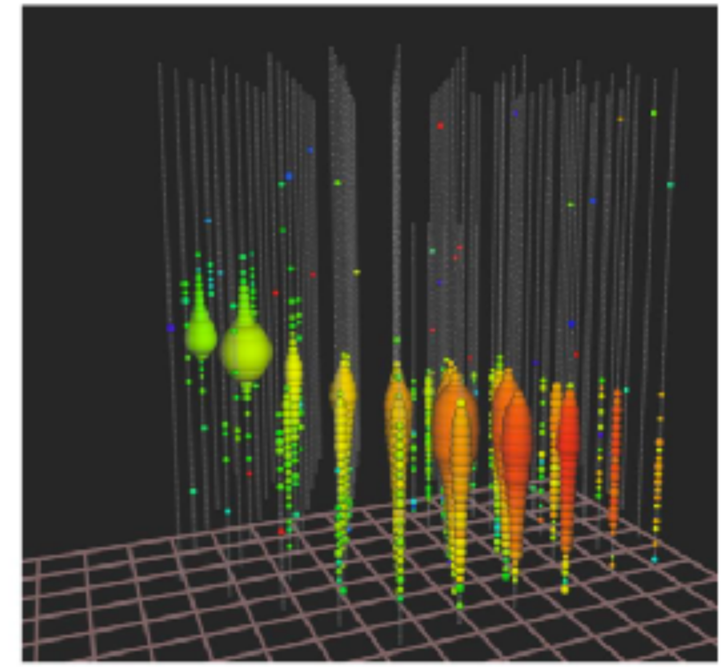
Slide credit: A. Frankowiack

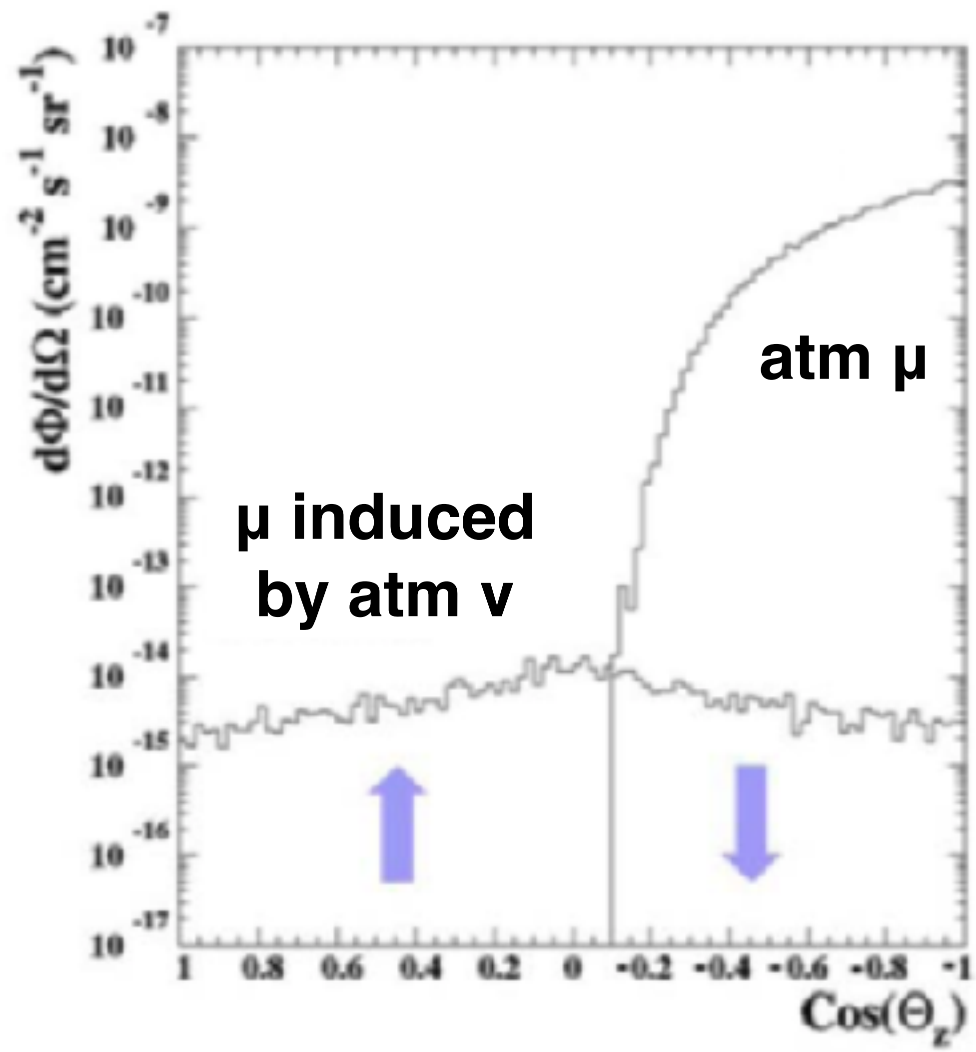
Filtering the atmospheric μ bkg

$$\nu_\mu N \longrightarrow \mu X$$

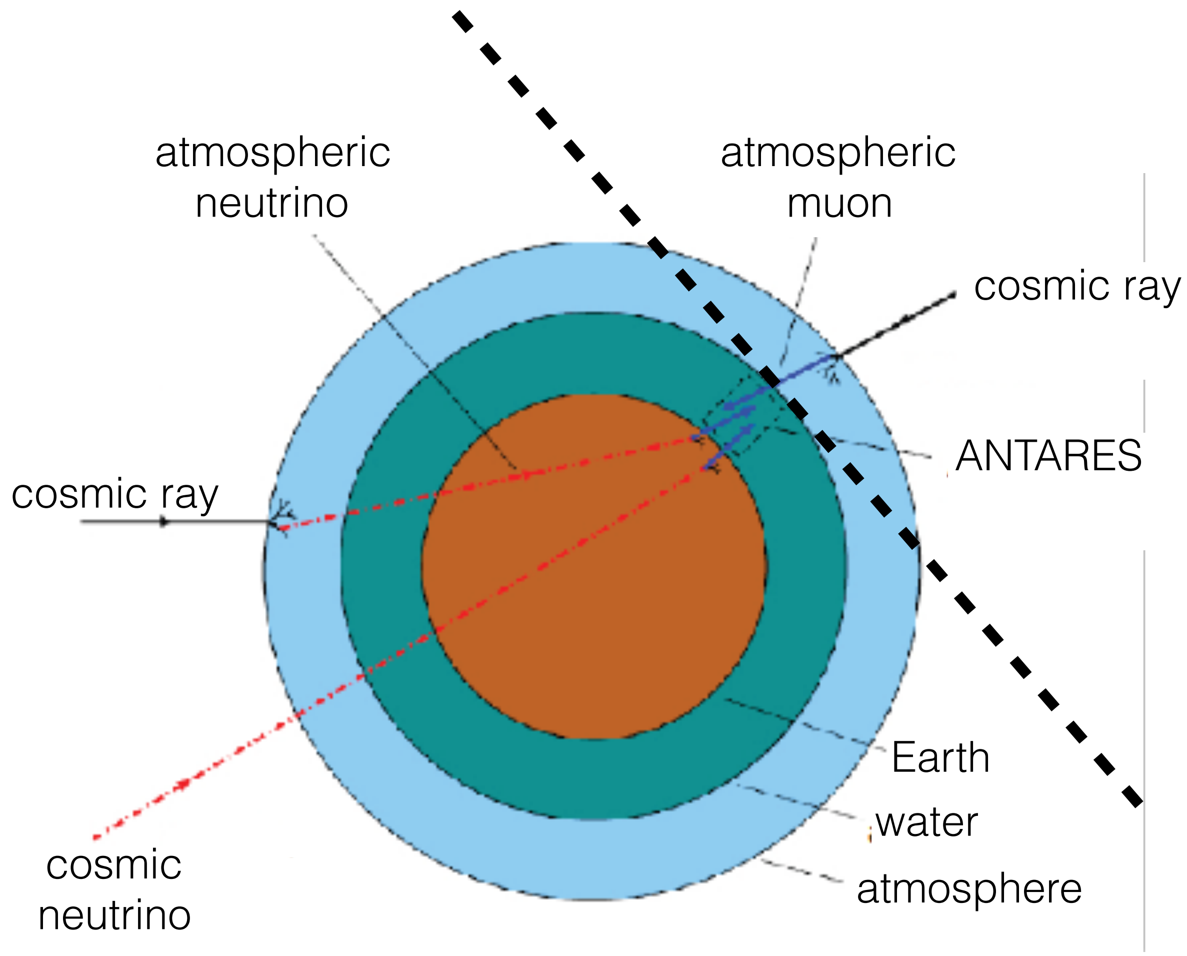
Search for neutrino induced events, mainly $\nu_\mu N \rightarrow \mu X$, up-going



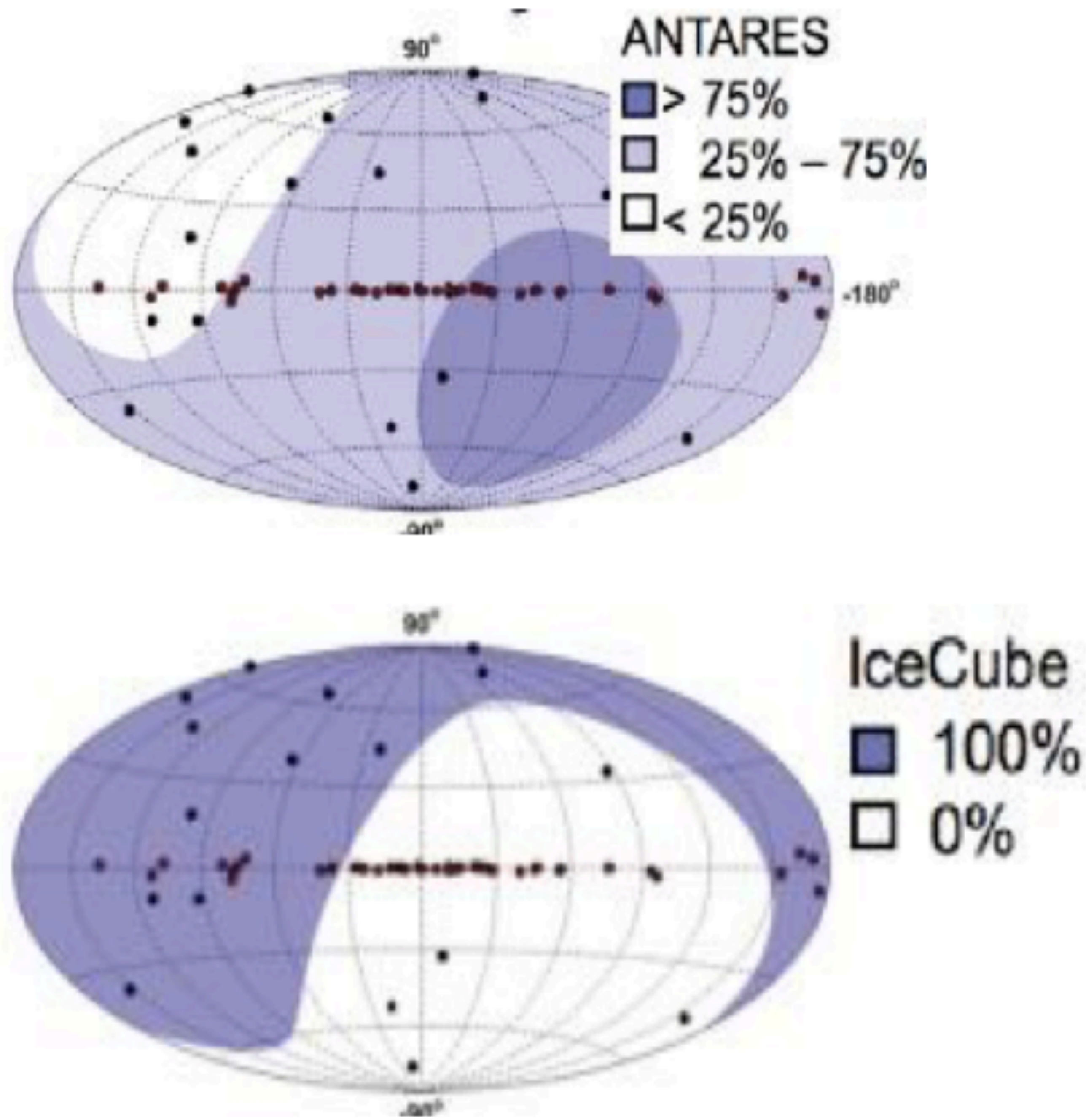




A complementary view of the sky with upgoing events



Visibility

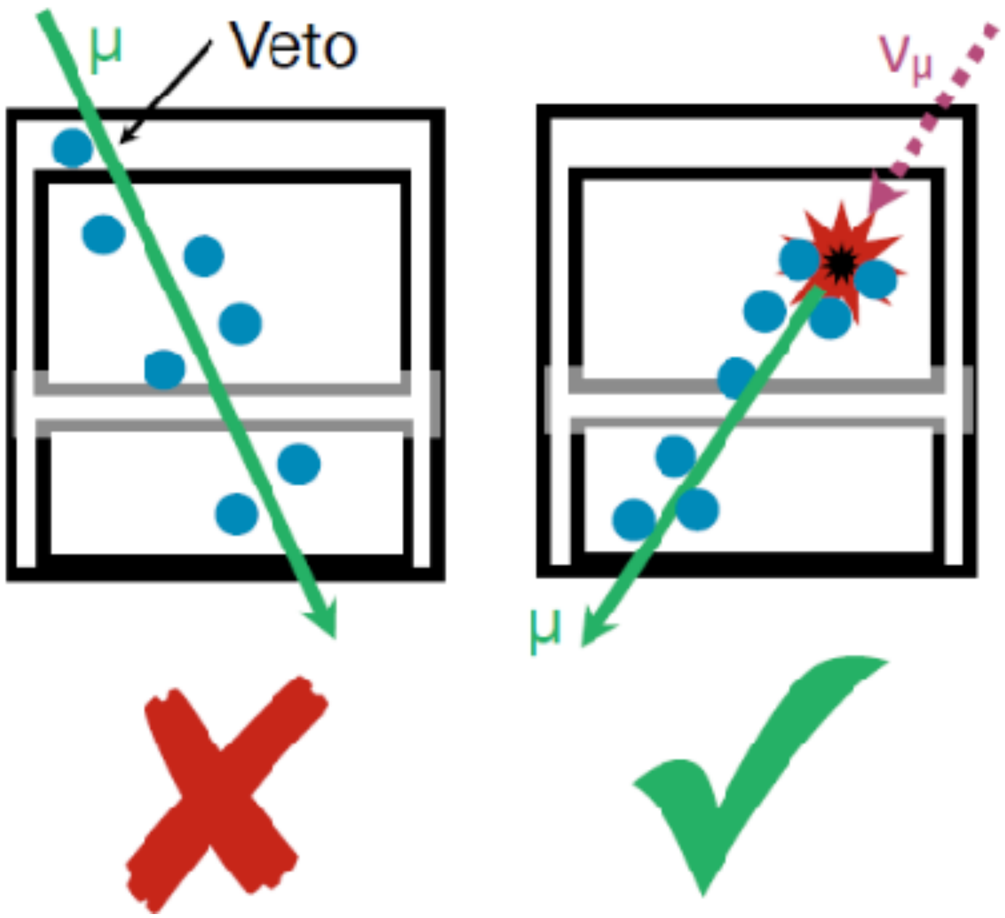


(galactic coordinates)

Filtering the atmospheric ν bkg

"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

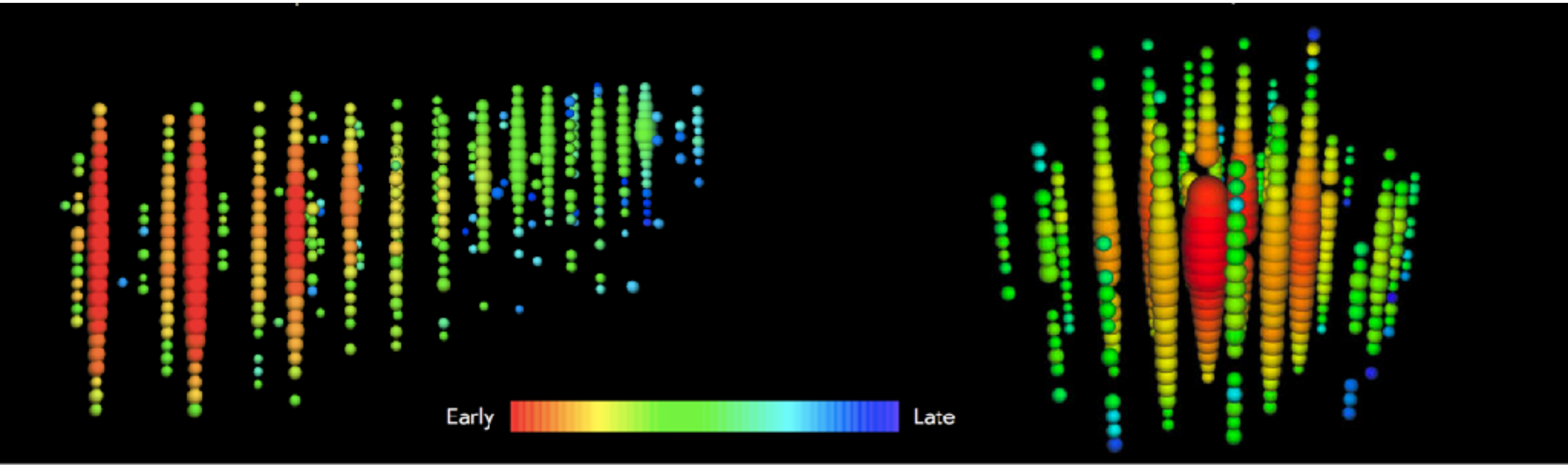
HESE

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

Neutrino event data sets

Through-going muons

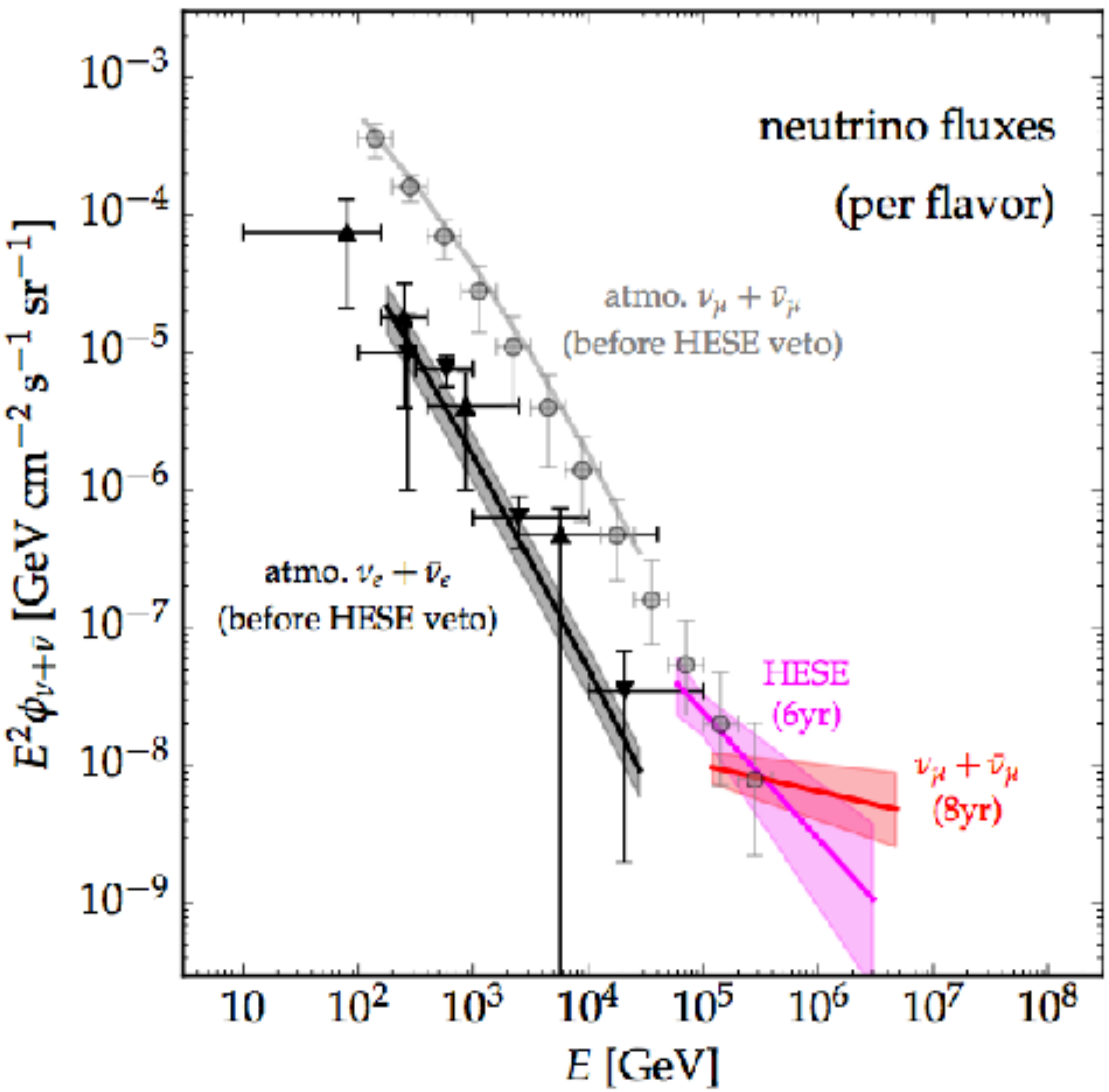
HESE

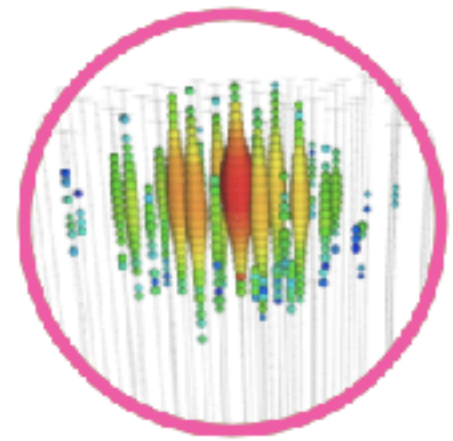


Earth-filtered events —> view from the South Pole is the **Northern Hemisphere**

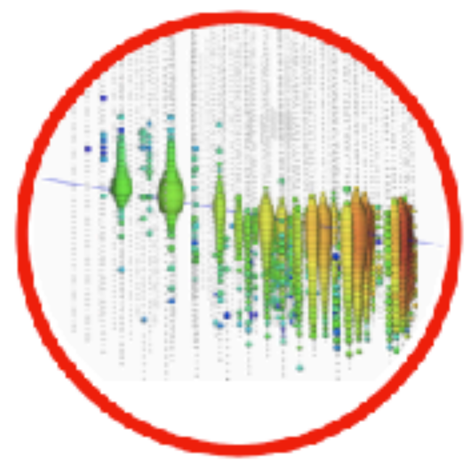
All sky search, but different bkg among tracks and cascades

Status of neutrino astronomy





High-energy starting events (HESE)
Interaction vertex in the detector
All flavor, all sky



Up-going tracks
Muon-dominated
Northern sky

- Astrophysical flux in the 20 TeV - 9PeV range
- Various channels and analysis methods

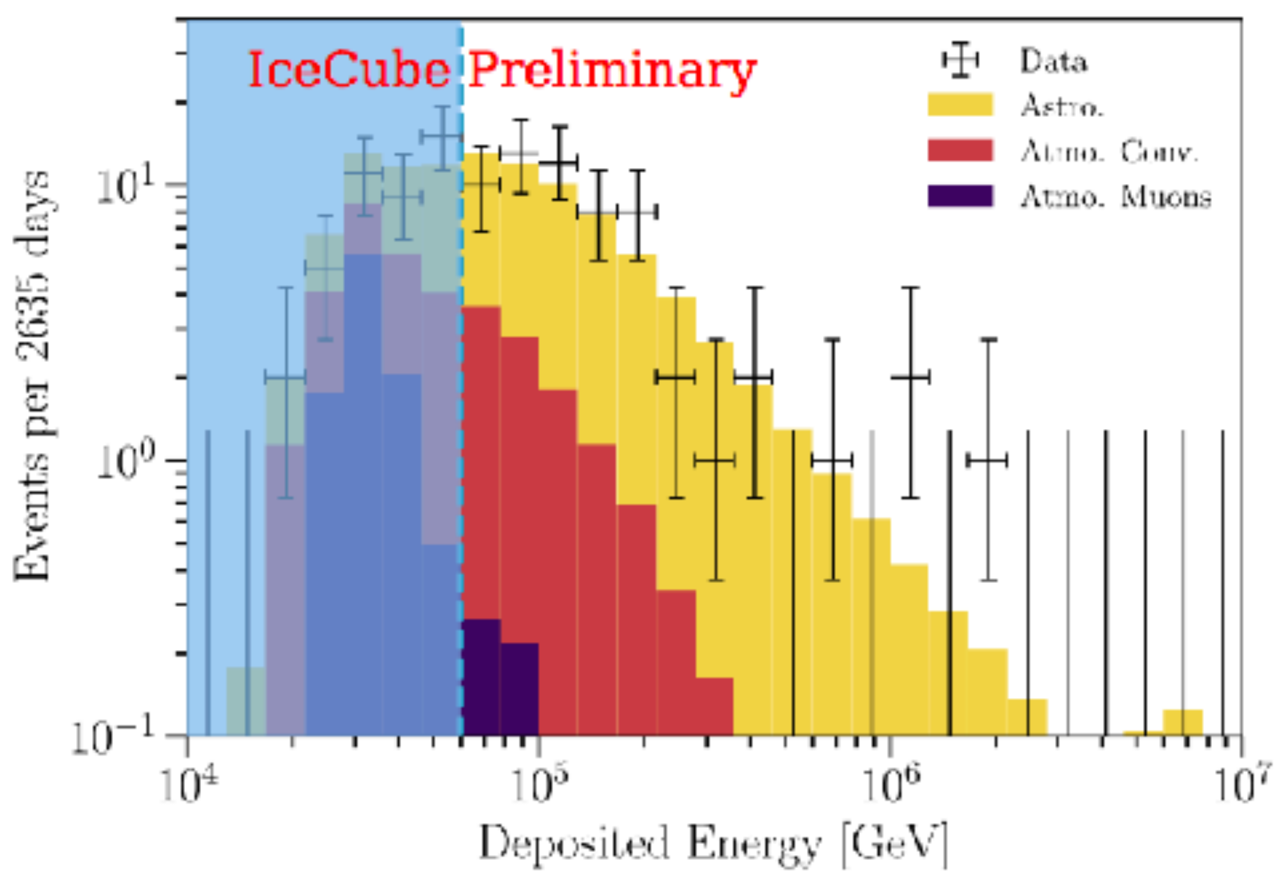
M. Ahlers & F. Halzen, PrPNP 102 (2018) 73A

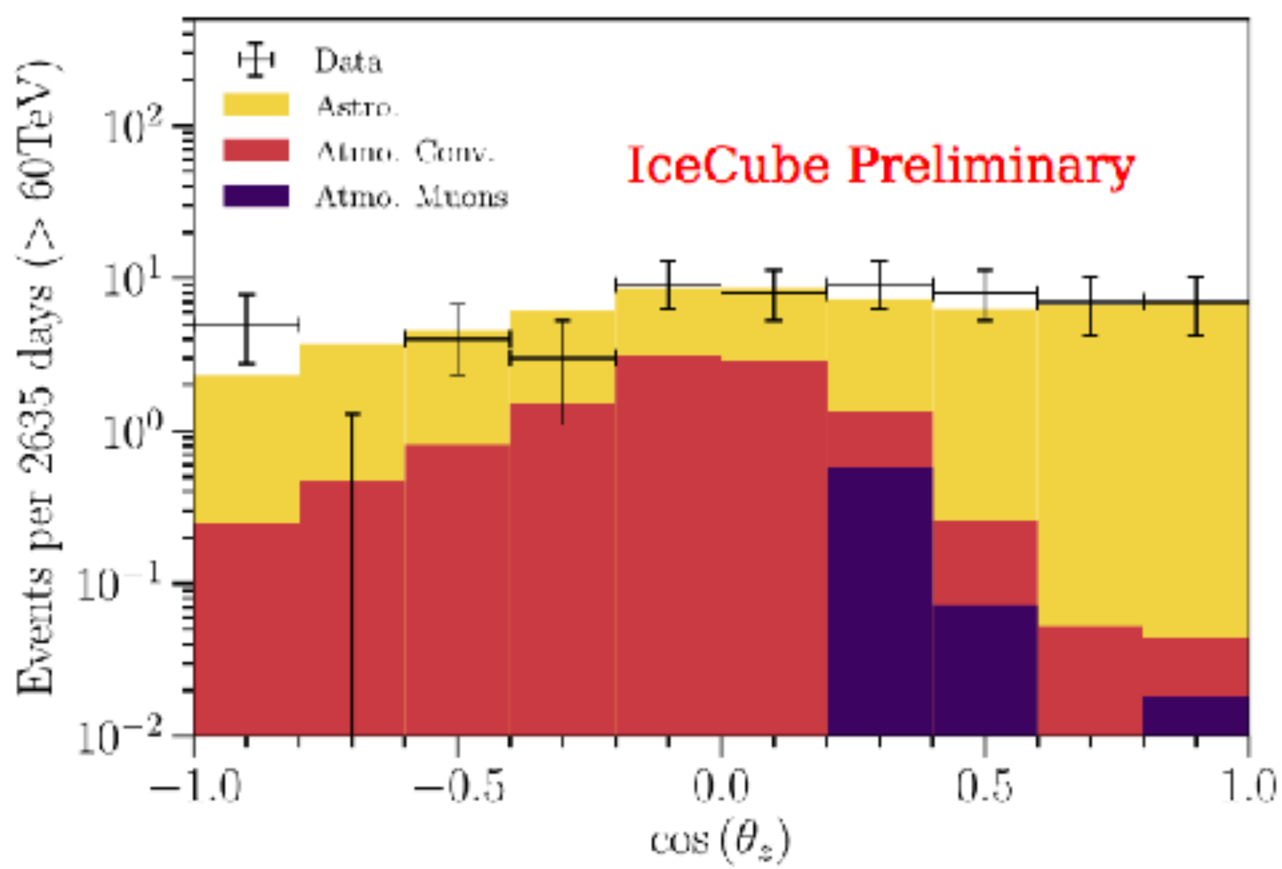
The cosmic neutrino signal

High Energy Starting Events (HESE)

mostly from the Southern Hemisphere

$$\frac{d\Phi_{6\nu}}{dE} = (6.45^{+1.46}_{-0.46}) \cdot 10^{-18} \left(\frac{E}{100\ \text{TeV}}\right)^{-(2.89\pm0.2)} \text{GeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$





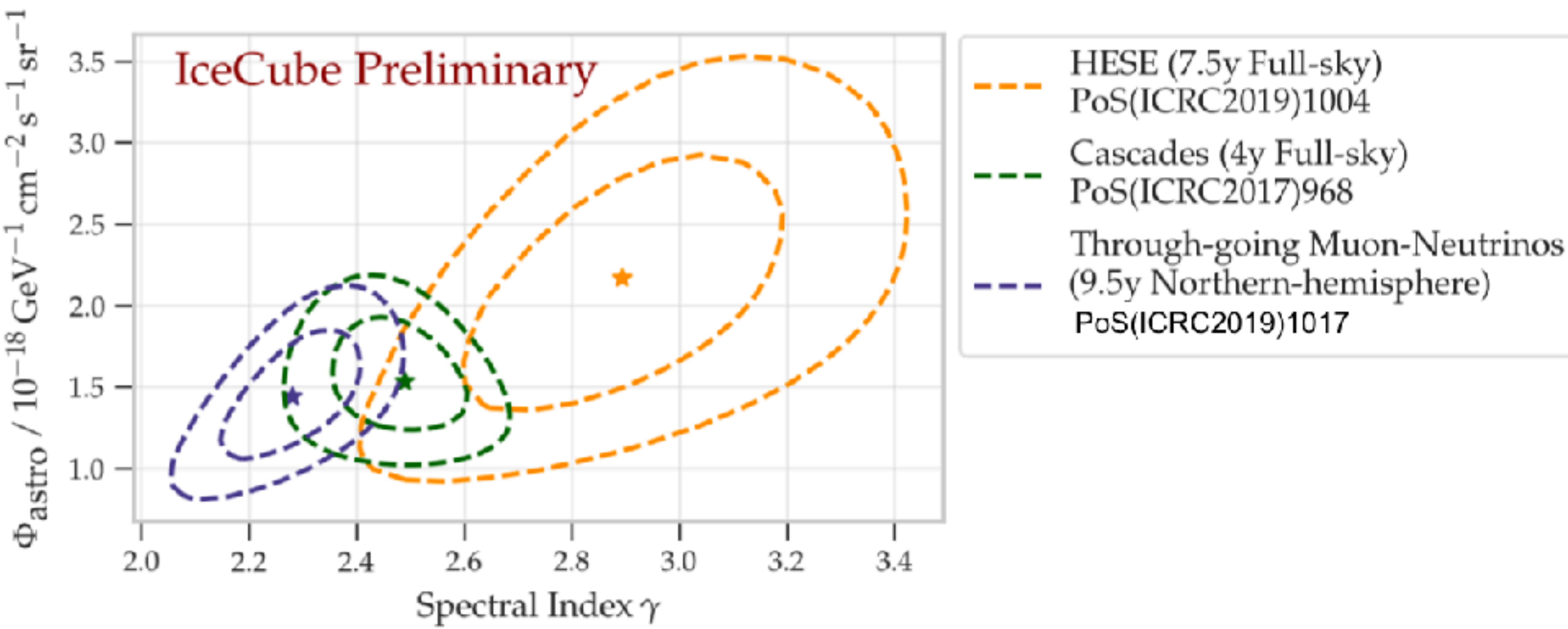
A. Schneider (IceCube Coll.), ICRC 2019, PoS 1004

The cosmic neutrino signal

Passing Muons

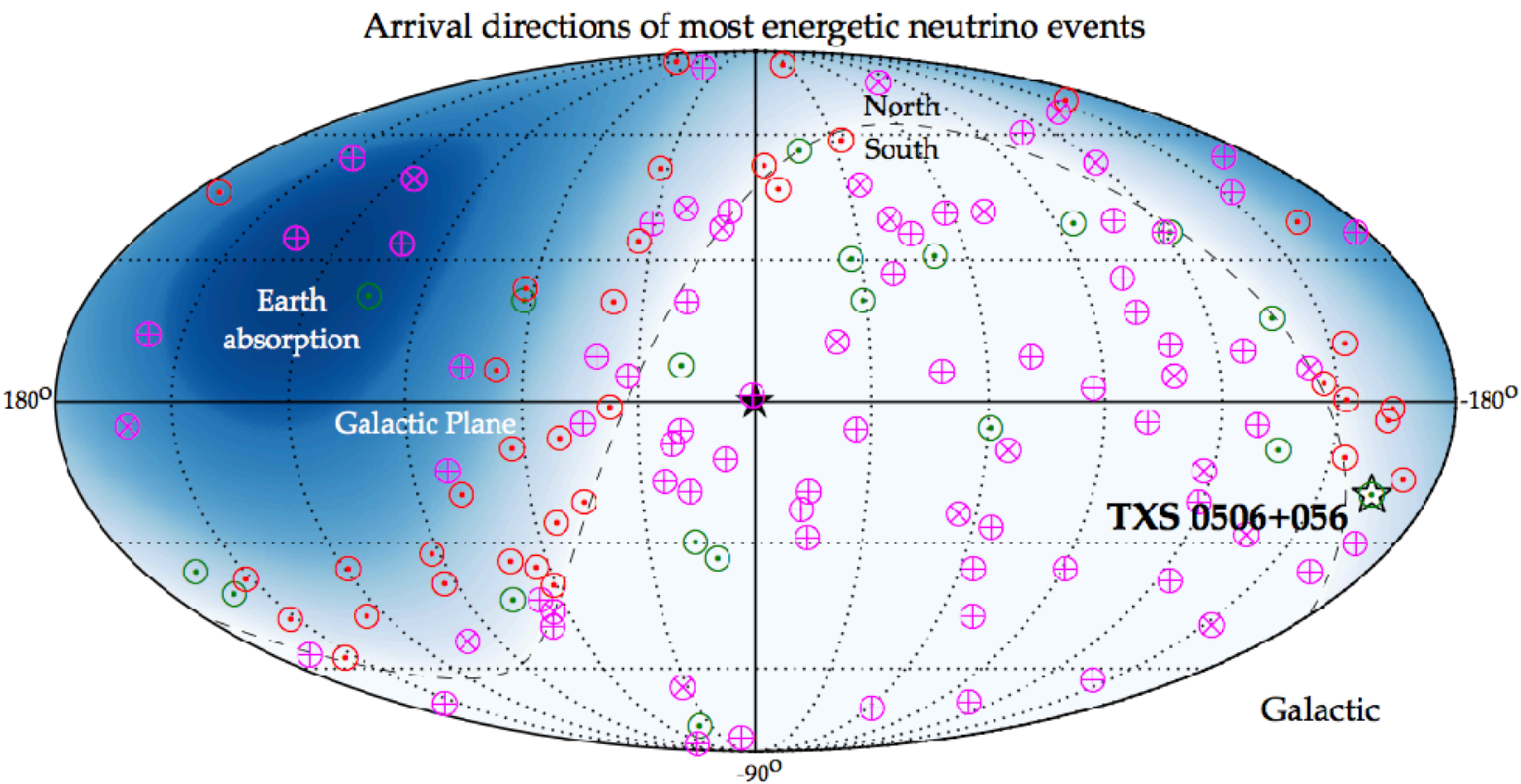
a view on the Northern Hemisphere

$$\frac{d\Phi_{\nu+\bar{\nu}}}{dE} = (1.44\pm^{0.25}_{0.24}) \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-2.28\pm^{0.08}_{0.09}} \cdot 10^{-18}\,\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$



J. Stettner (IceCube Coll.), ICRC 2019, PoS 1017

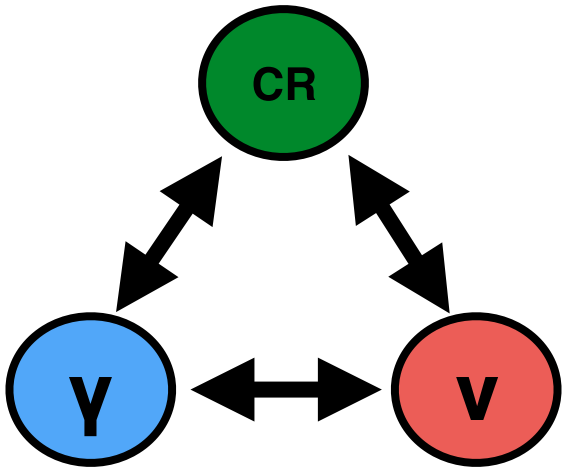
The cosmic neutrino signal



tracks HESE tracks HESE cascades public alerts

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

The search for neutrino sources



Neutrino production channels

pp interaction:

- accelerated protons
- dense target matter field

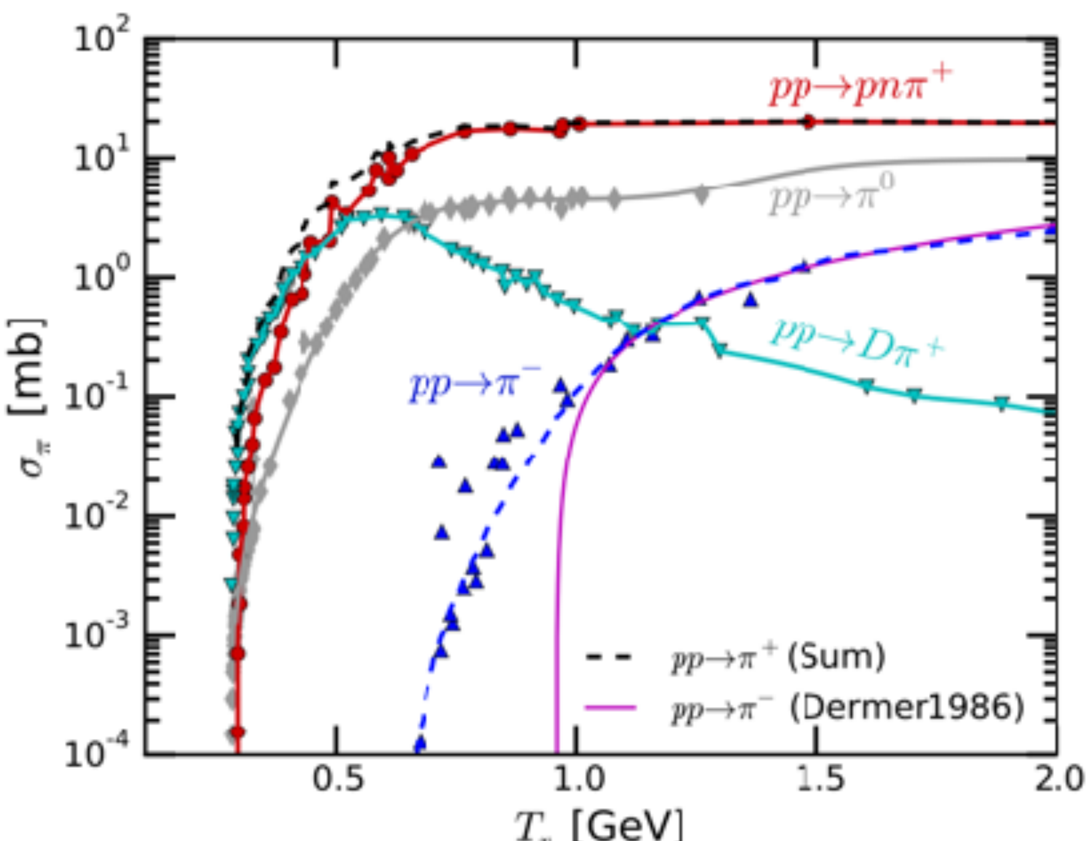
pγ interaction:

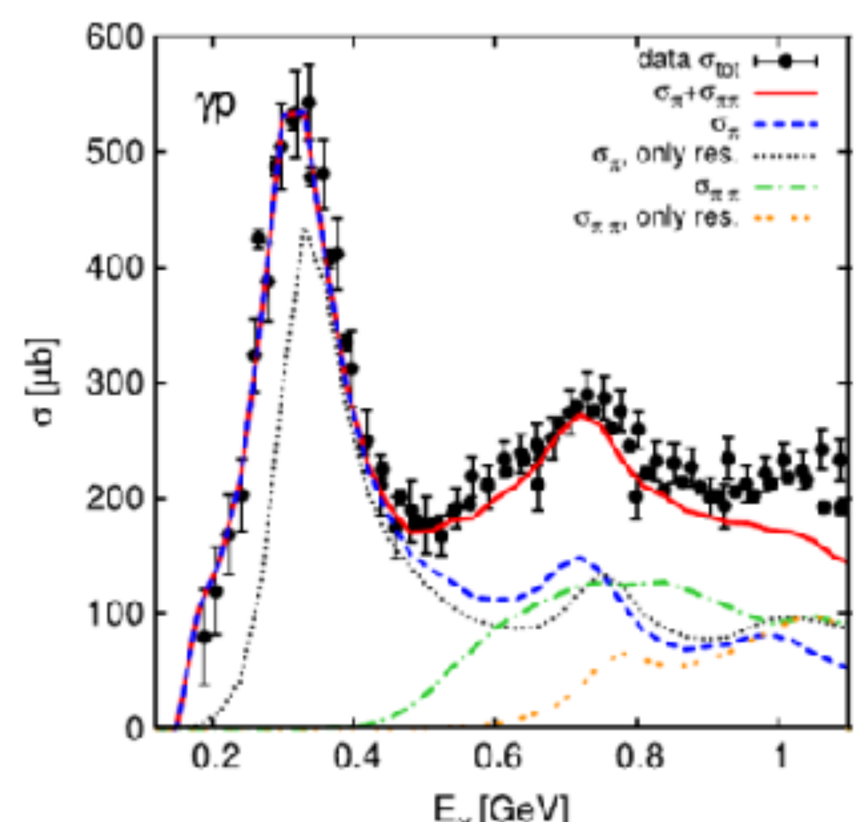
- accelerated protons
- dense target radiation field

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

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

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





Neutrino production channels

pp interaction:

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

"CR reservoir"

e.g. SBG, SNR

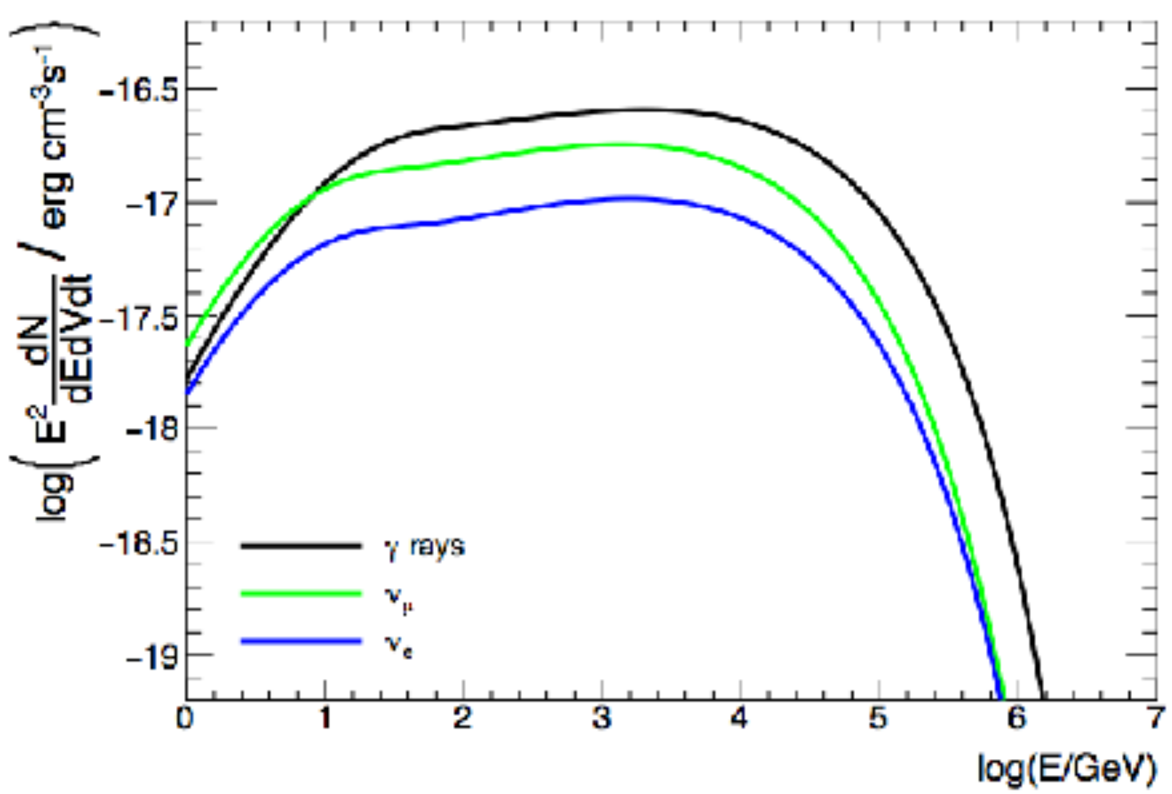
pγ interaction:

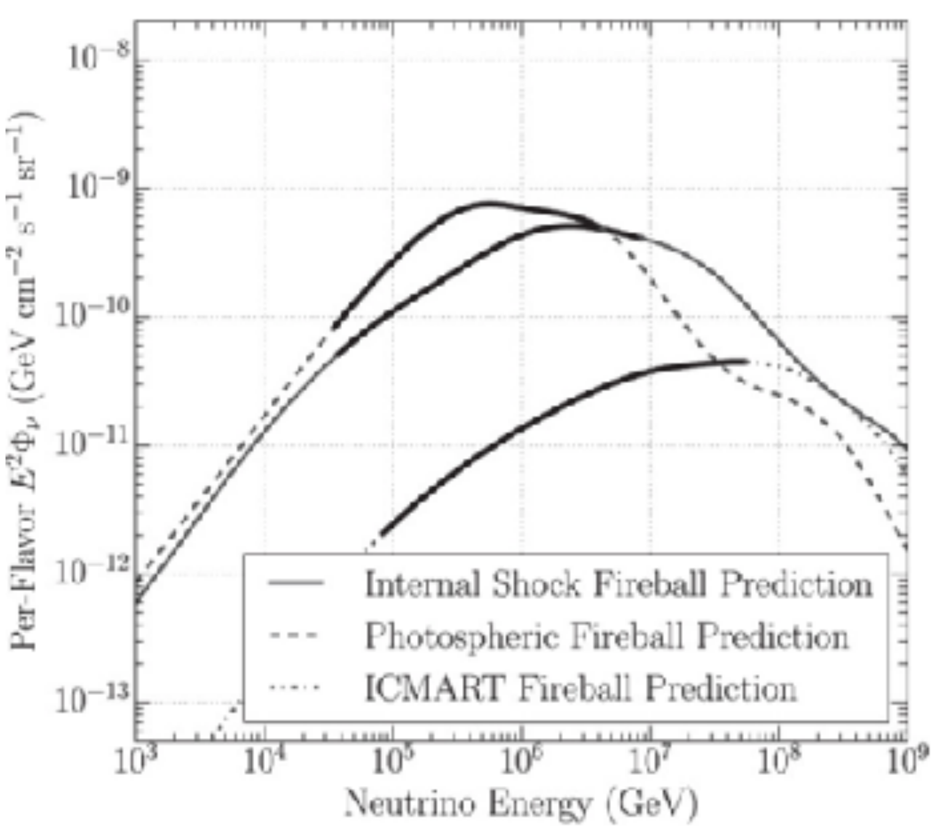
- accelerated protons
- dense target radiation field

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

"CR accelerators"

e.g. AGN, GRB





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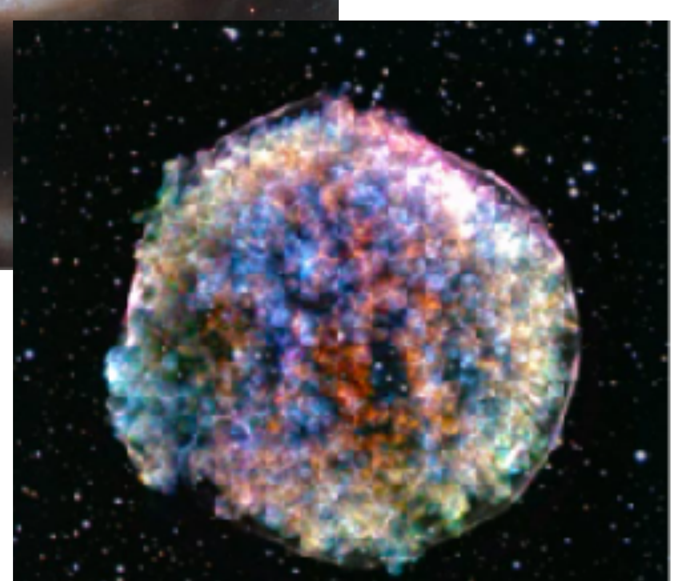


pγ interaction:

- 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

The search for cosmic sources

Several strategies to look for ν-sources:

1. **Clustering** of neutrino events (all-sky scan);

2. **Catalog search**, i.e. at pre-defined sky positions, as indicated by MM studies (typically bright sources in EM wavelengths): e.g. population & stacking analyses;

3. **MM alerts** for extremely energetic events. So far, only this strategy has lead to positive results:

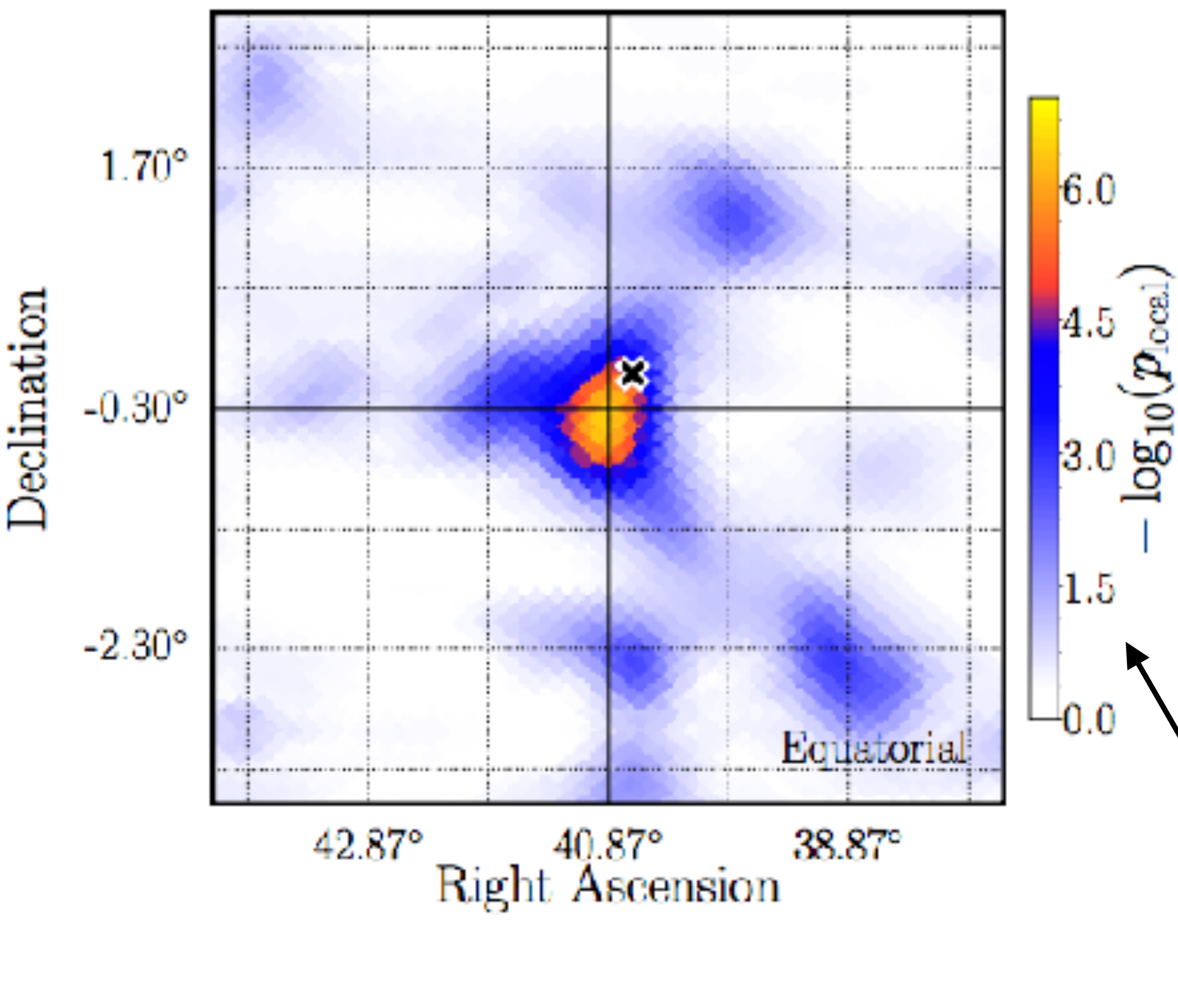
—> **TXS 0506+056** & IC170922A IceCube Coll. et al., Science 361 (2018)

—> **TDE AT2019dsg** & IC191001A R. Stein et al., arXiv:2005.05340

The search for cosmic sources

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

M.G. Aartsen et al., PRL 124 (2020) 051103



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

The 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., 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.

Contributions from our Galaxy

Two main sources of (pp) neutrinos are:

1. **Galactic population of sources**, e.g. SNRs if these are responsible for the CR flux observed at Earth;

2. Diffuse neutrinos, originated in **CR collisions with target gas density** located in the Galactic Plane.

Both can be constrained from gamma-ray counterpart:

$$\varphi_{\gamma,\mathrm{tot}} = \varphi_{\gamma,\mathrm{diff}} + \varphi_{\gamma,\mathrm{S}} + \varphi_{\gamma,\mathrm{IC}}$$
$$\varphi_{\nu,\mathrm{tot}} = \varphi_{\nu,\mathrm{diff}} + \varphi_{\nu,\mathrm{S}}$$

from CR collisions ($\varphi_{\nu,\mathrm{diff}}$)

resolved + unresolved sources ($\varphi_{\nu,\mathrm{S}}$)

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

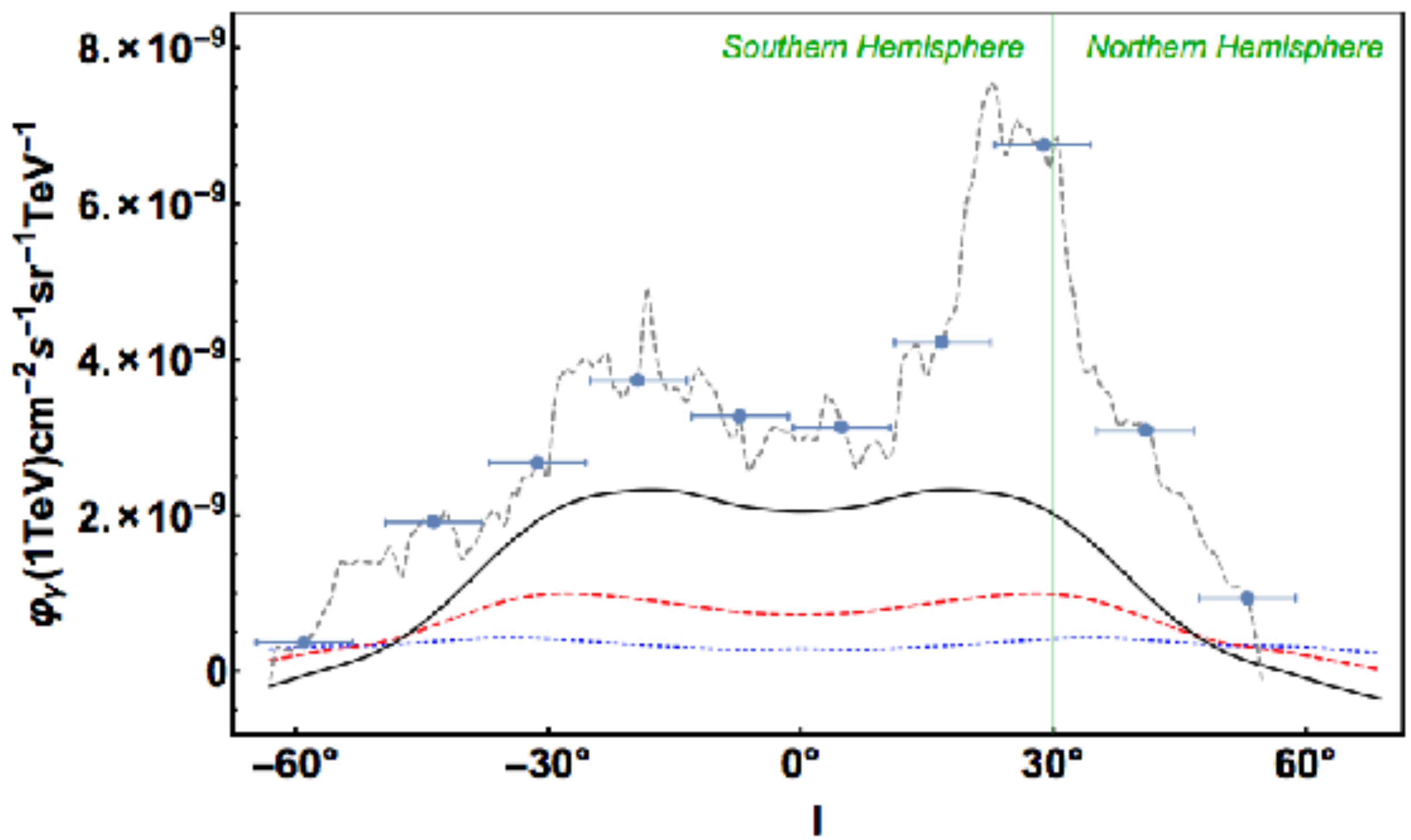
G. Pagliaroli & F. Villante, JCAP 08 (2018) 035

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

A: homogenous CR density all along the Plane

B: CR density following the SNR distribution along the Plane

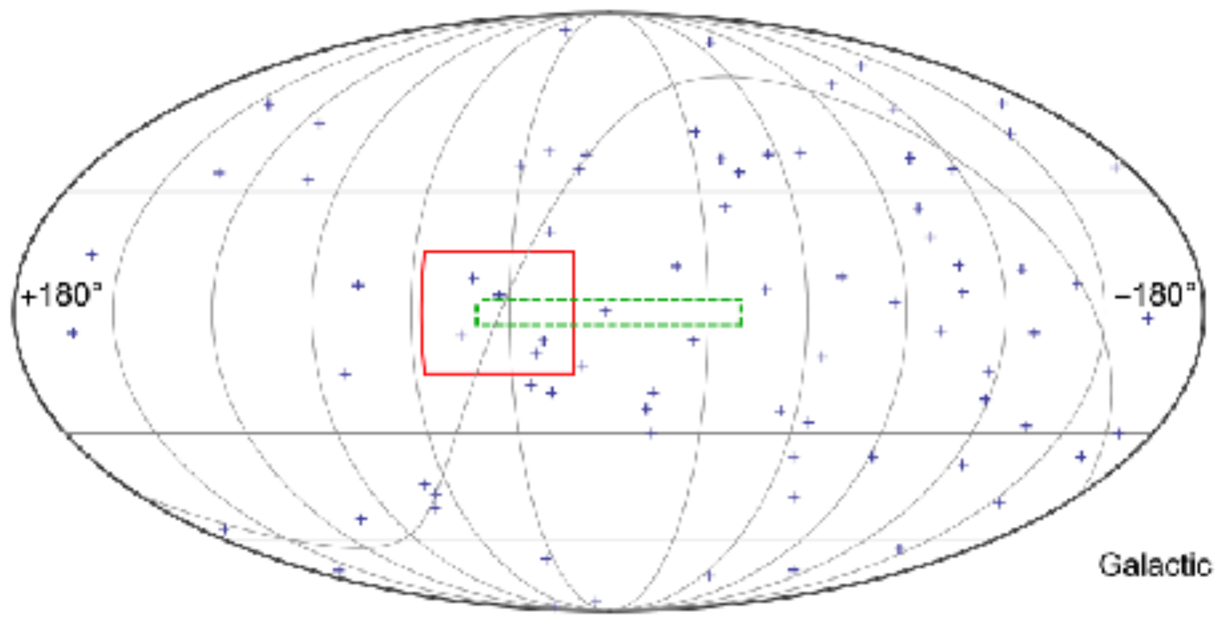
C: CR density with radially dependent spectral index (KRA$_\gamma$)



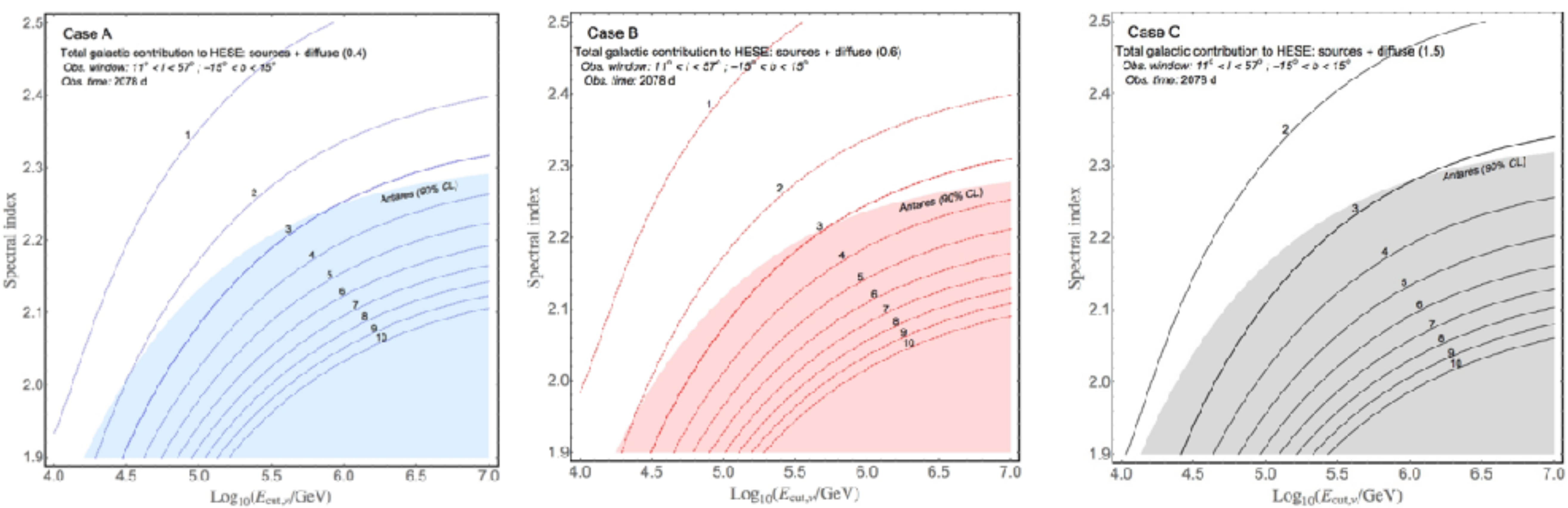
—> non negligible **source contribution**

Contributions from our Galaxy: neutrinos

Extended Hot Region
Galactic Ridge

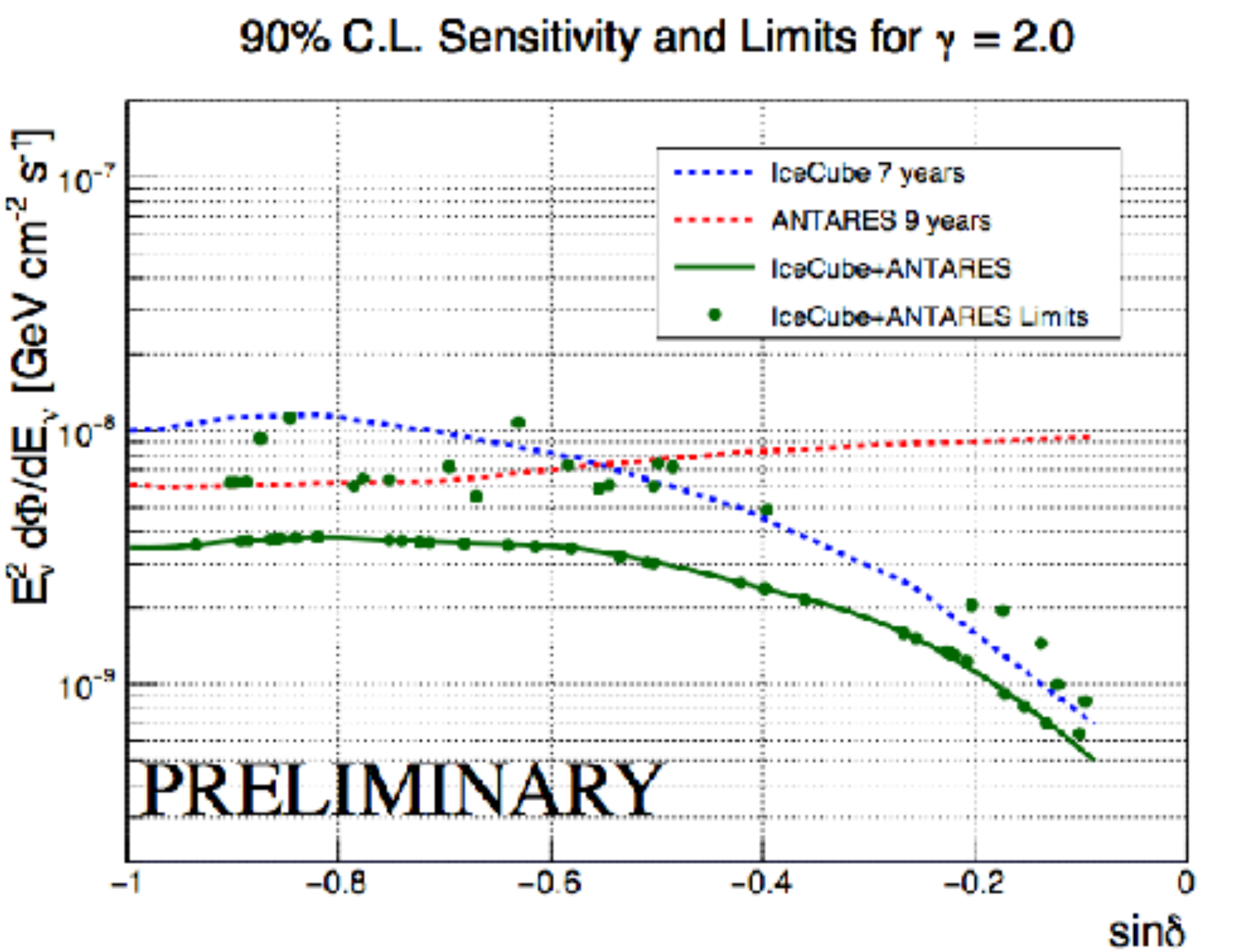


In terms of ν, the spectrum depends on the sources:



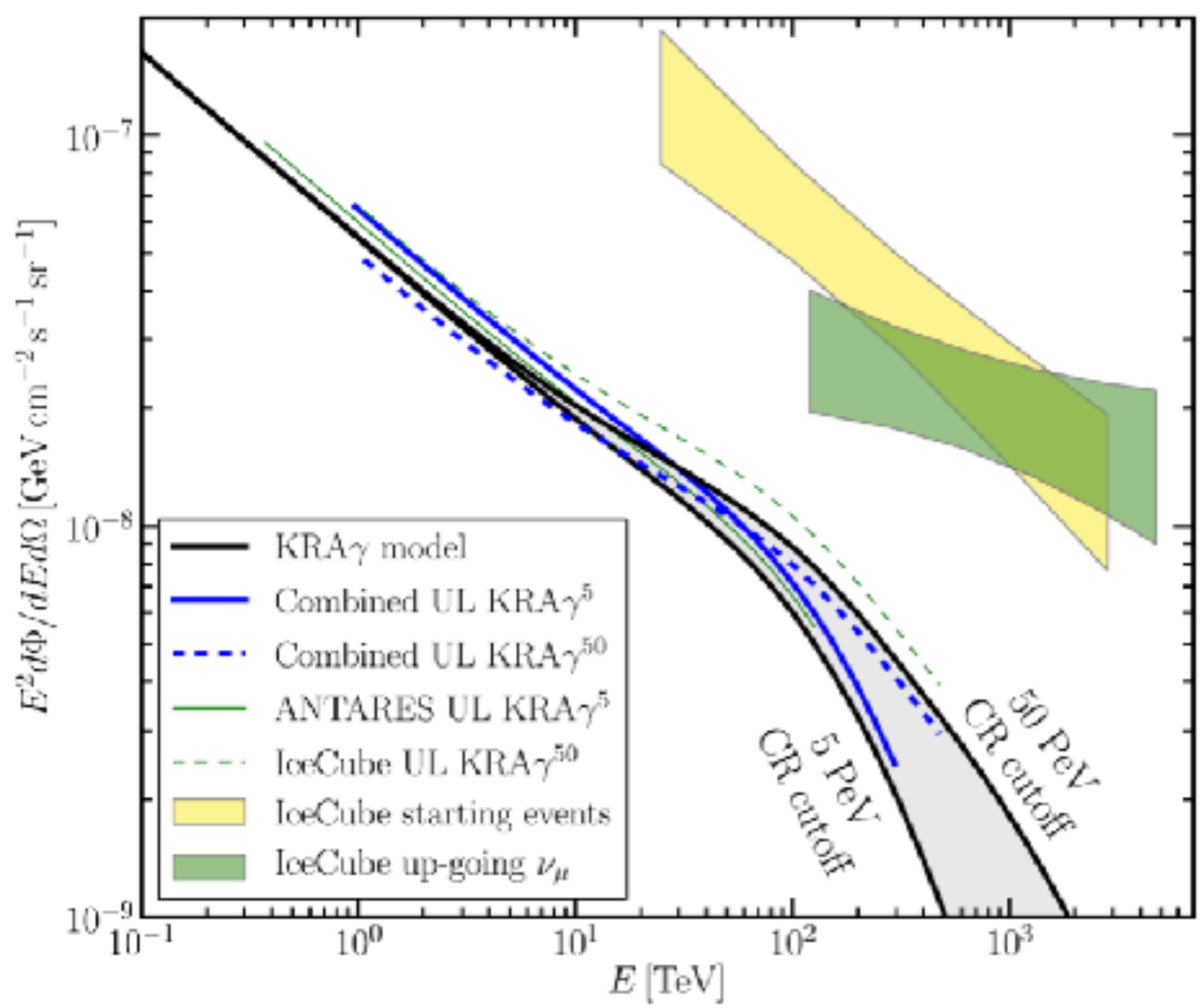
G. Pagliaroli & F. Villante, JCAP 08 (2018) 035

Contributions from our Galaxy: experimental constrains



G. Illuminati et al. (ANTARES+IceCube), ICRC 2019 PoS 919

No significant ν-clustering observed in the Southern Hemisphere



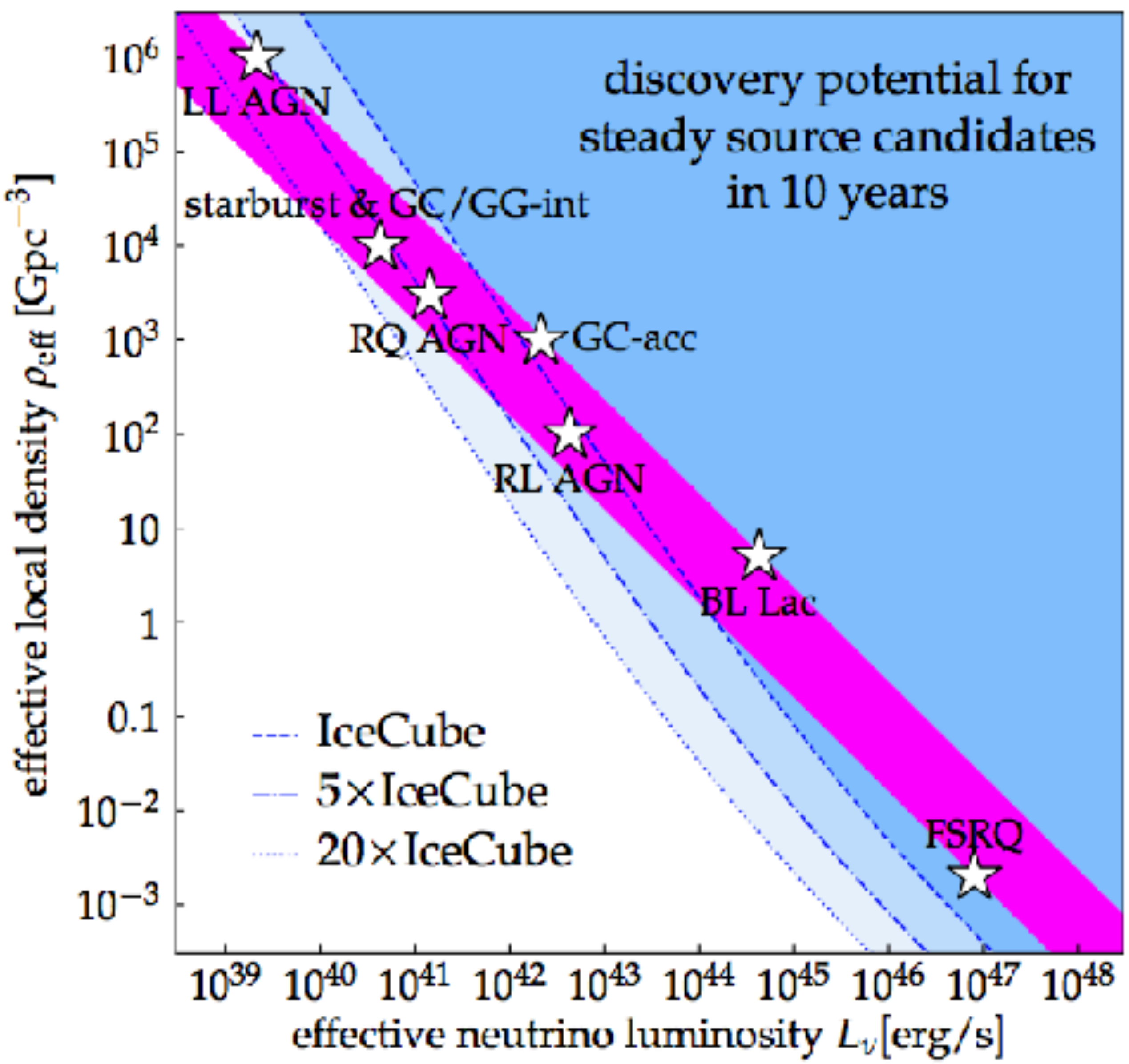
A. Albert et al. (ANTARES+IceCube), ApJ 868 (2018) L20

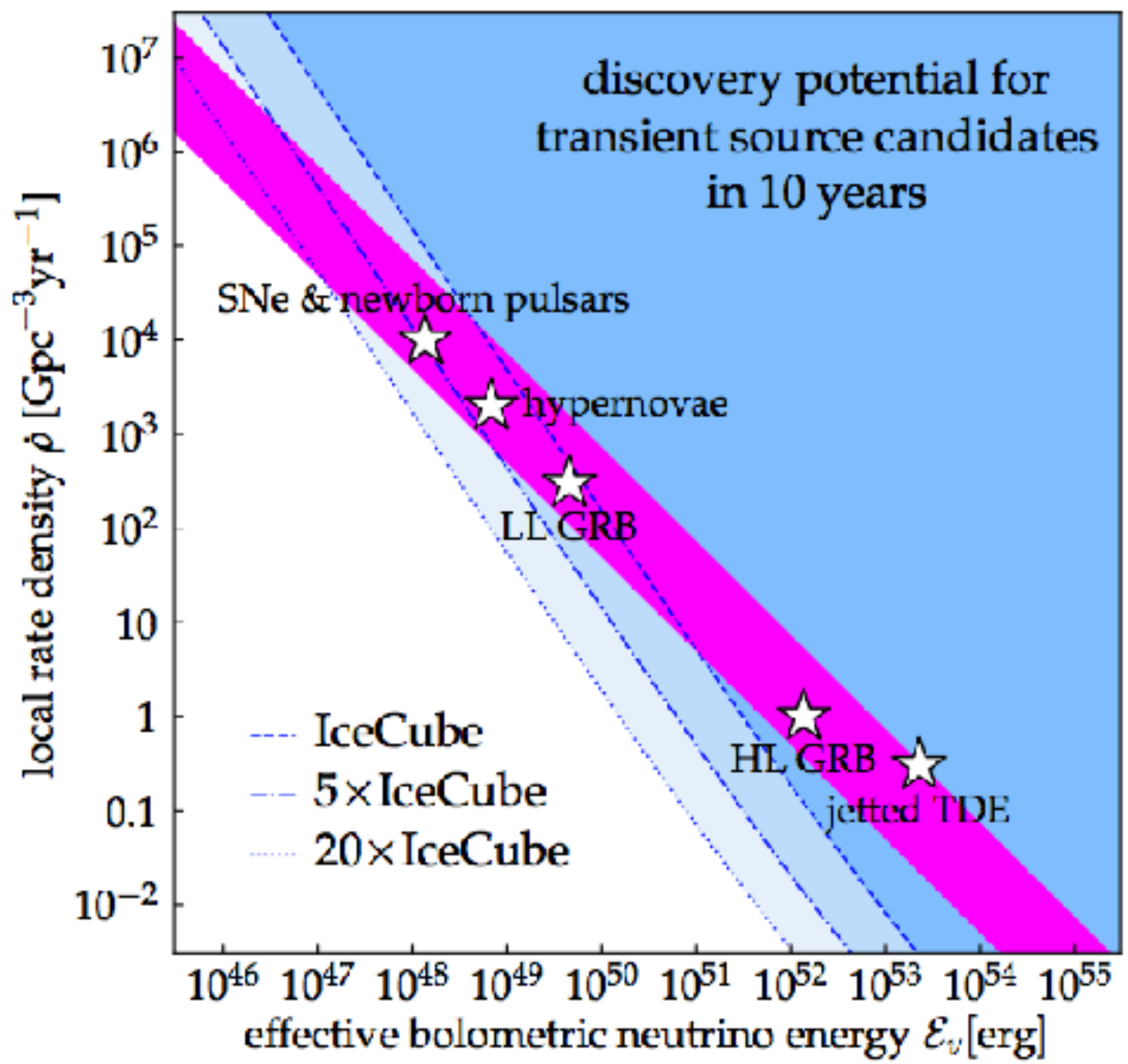
Specific CR model tested in ANTARES+IceCube

Galactic contribution expected < 15% above 60 TeV

Extra-galactic candidate sources

The **isotropic** sky distribution of ν-events points towards an extra-galactic origin of the cosmic flux.

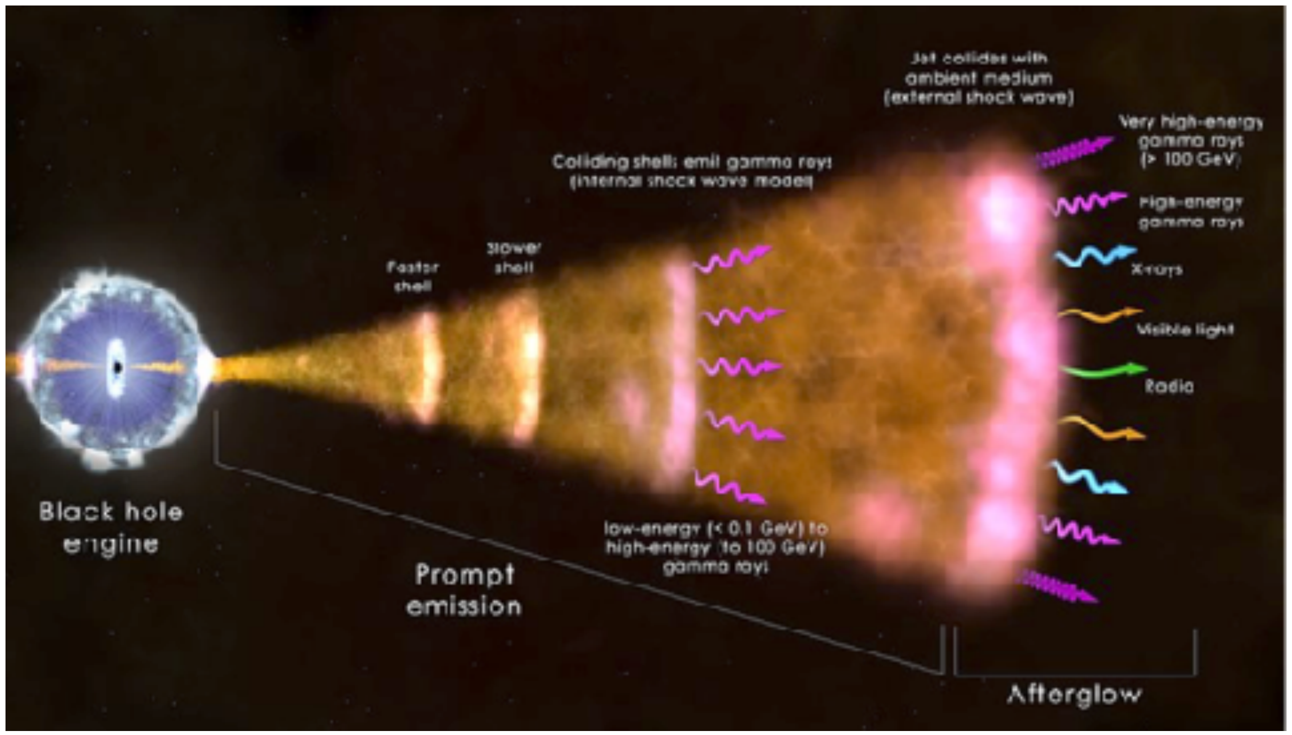




M. Ackerman et al., Bull. Am. Astron. Soc. 51 (2019) 185

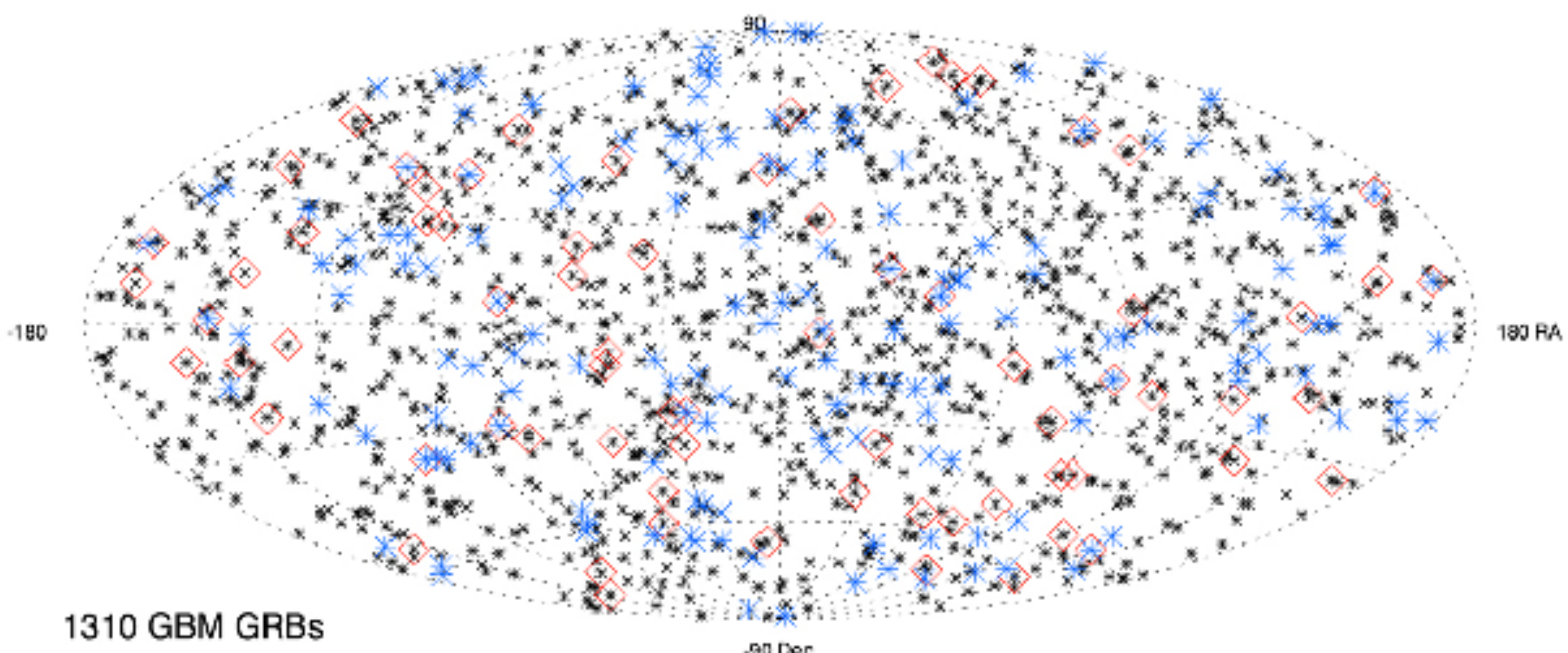
Search for GRB-ν

Promising because of the **transient** nature, that allows to enhance the sensitivity of the search.



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

prompt + afterglow neutrinos

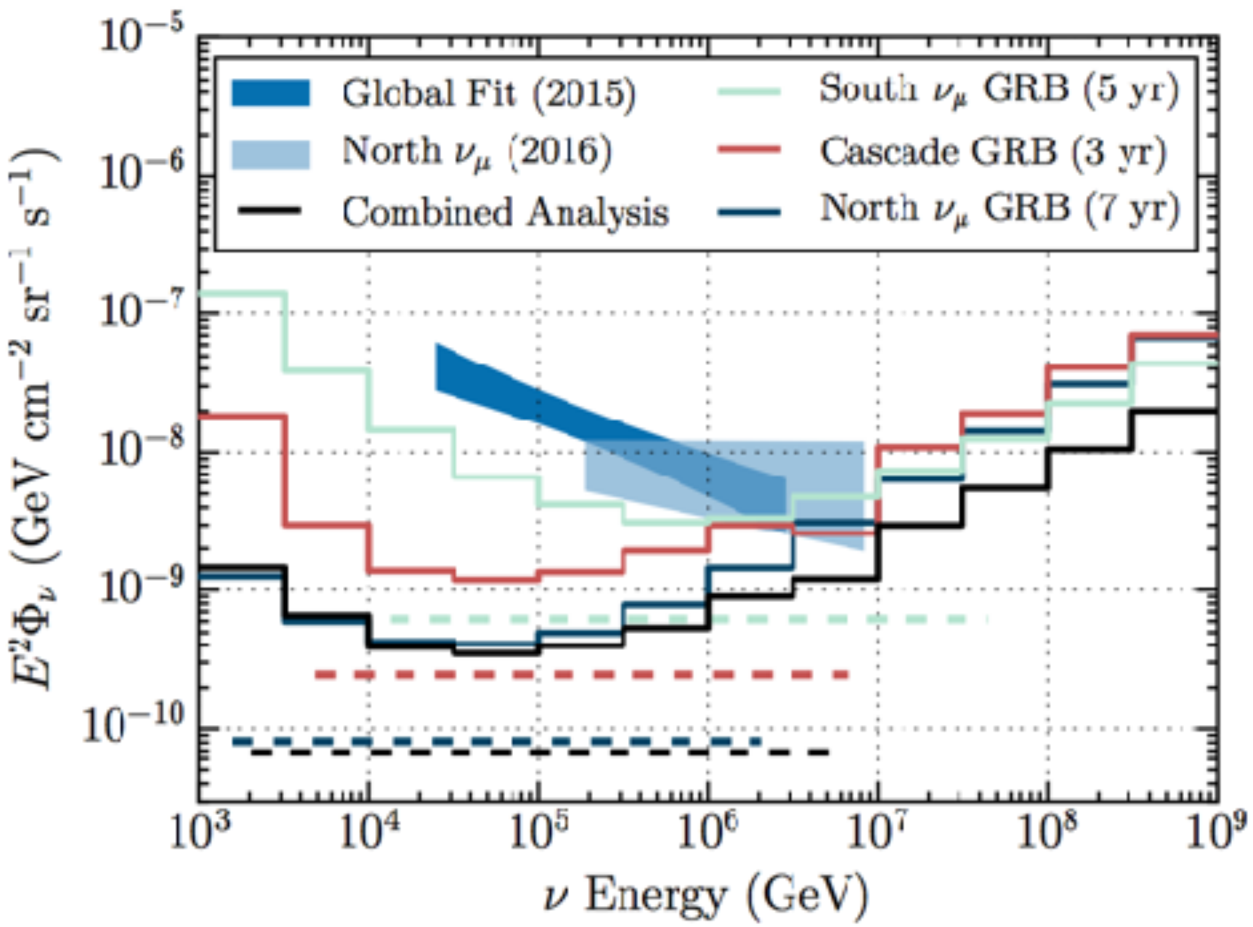


1310 GBM GRBs
174 Swift GRBs
73 LAT GRBs

Credit: Fermi-LAT and GBM Collaborations

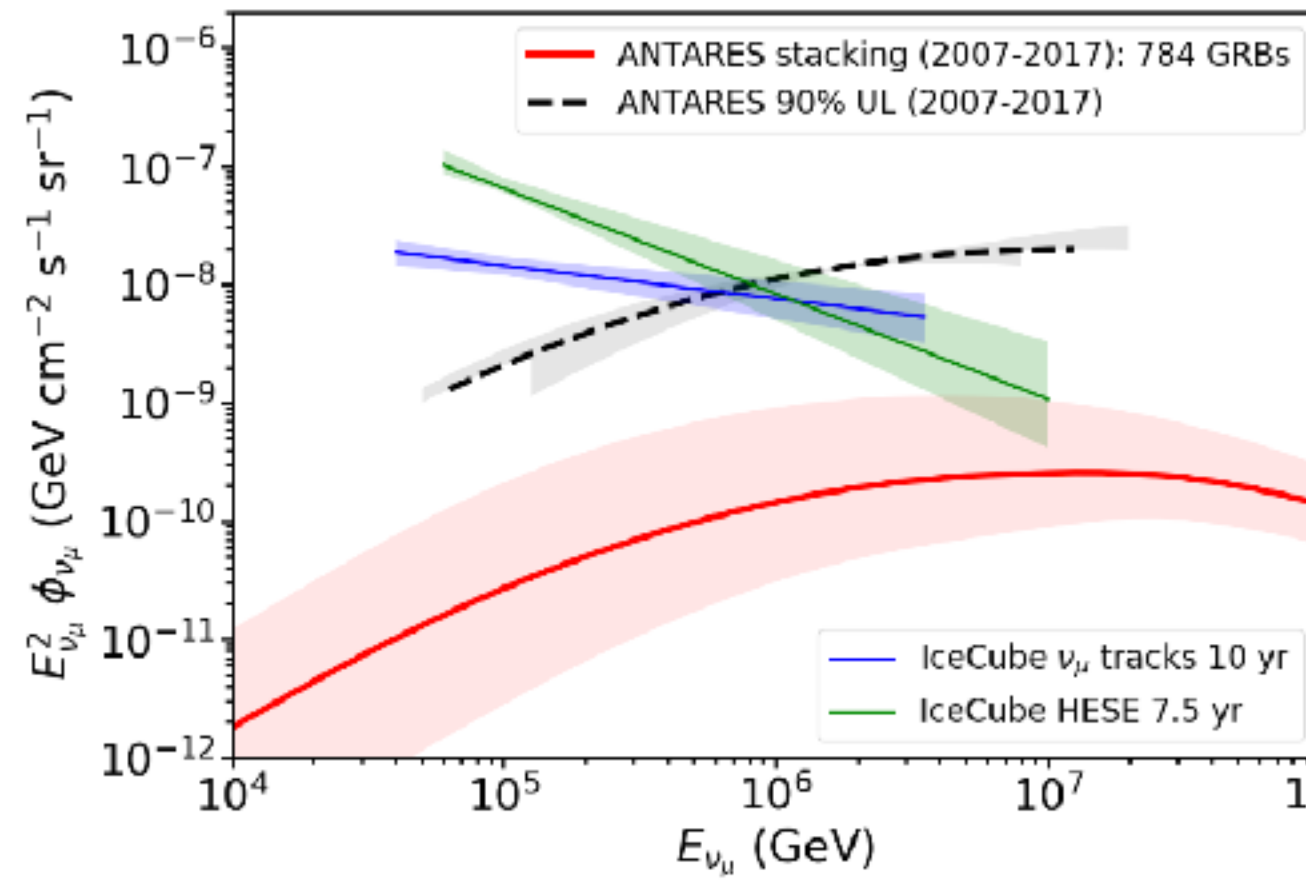
Stacking search for GRB-ν

IceCube



A. Artsen et al. [IceCube Coll.], ApJ 843 (2017) 2

ANTARES



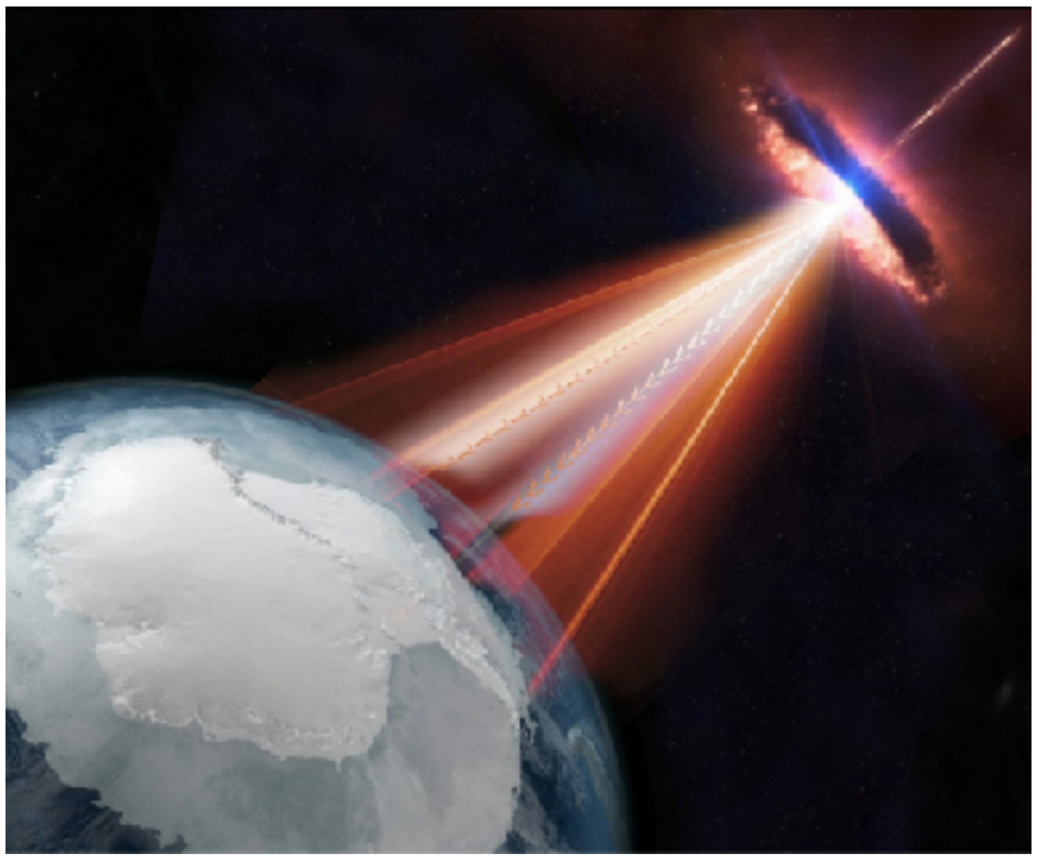
A. Albert et al. [ANTARES Coll.], arXiv:2008.02127

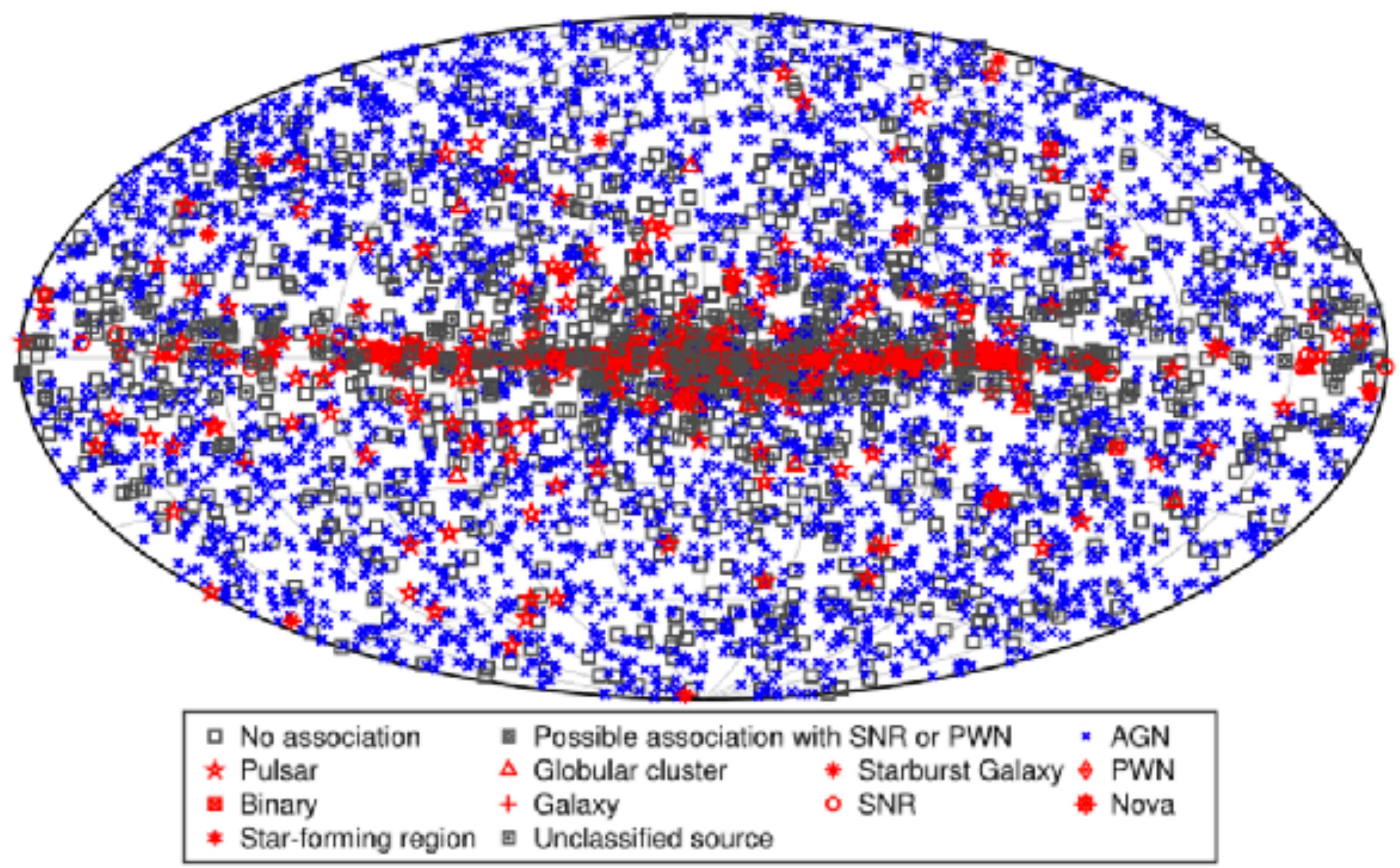
No evidence for time and space coincidences with the prompt emission of GRBs

less than 10% of the IceCube flux

Search for blazar-ν

Blazars are the most abundant steady source population observed by Fermi



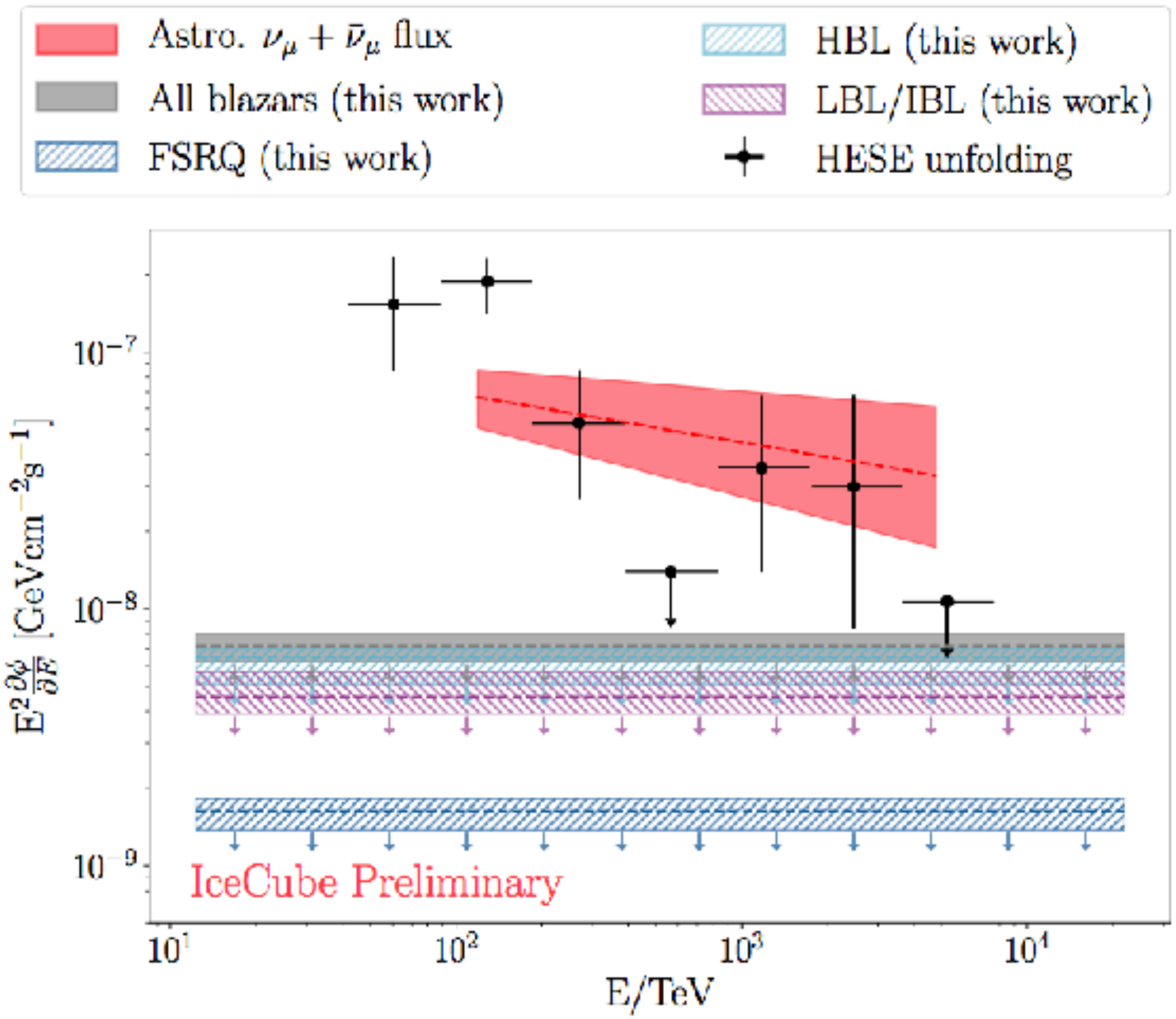


jet radiation field
+ broad line region (FSRQ)

S. Ciprini et al. [Fermi Coll.], APCS 2018 PoS 054

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

Stacking search for resolved blazar



M. Huber et al. [IceCube Coll.], ICRC 2019 PoS 916

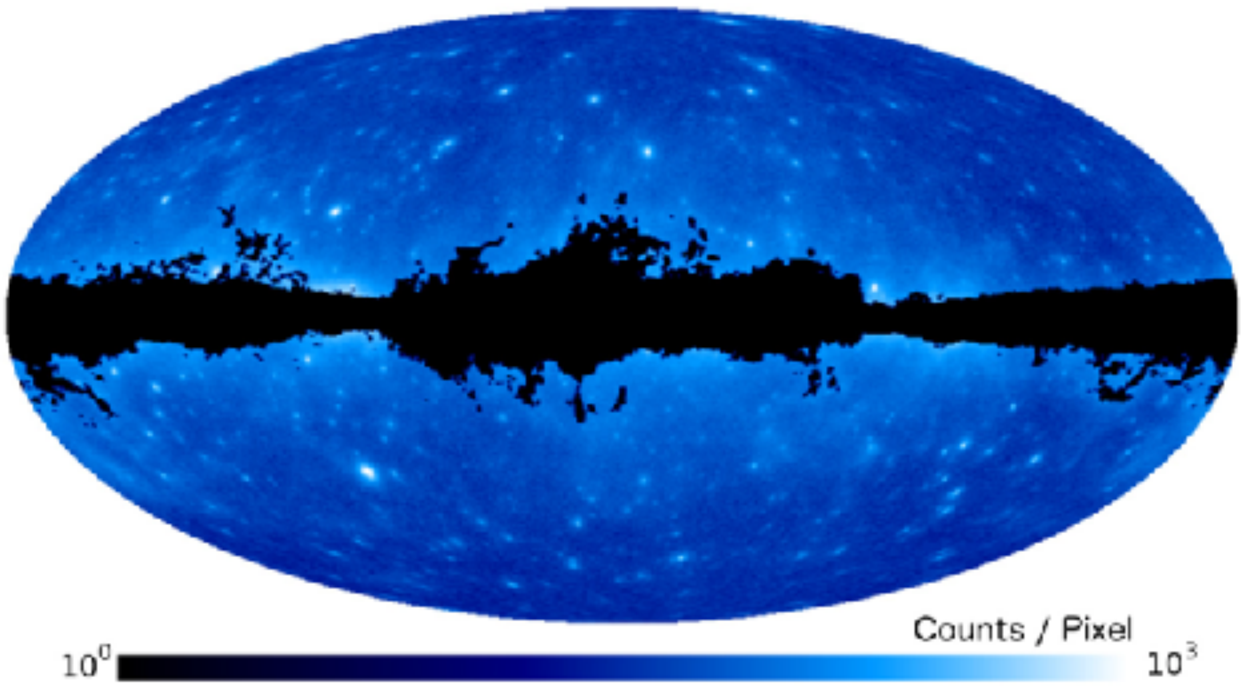
Stacking of 1301 blazars from 3FHL catalog with 8 years of through-going muon tracks (Northern Hemisphere sources)

—> no excess so far

less than ~15% of the IceCube flux

The EGB

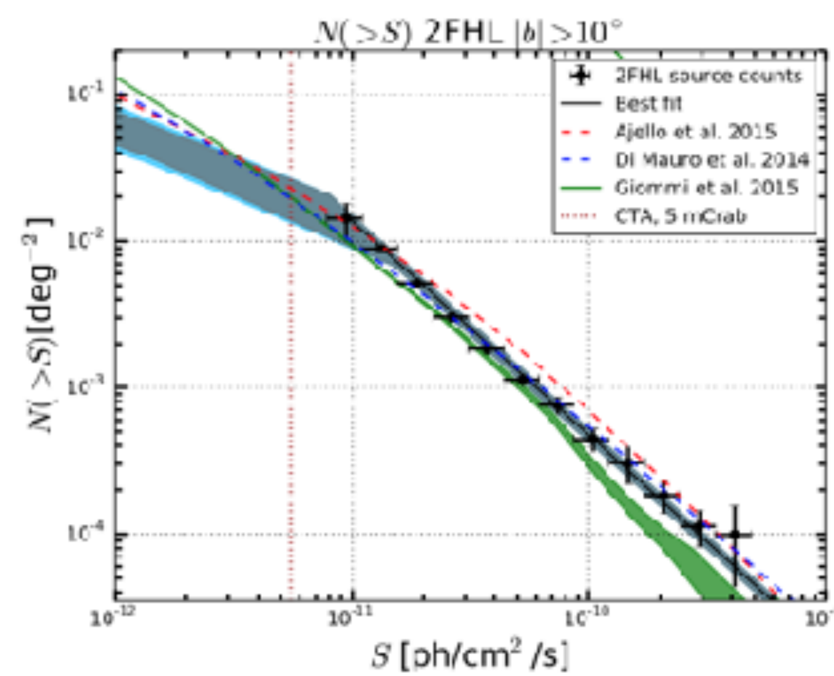
…but many blazars remain so far unresolved



M. Ackermann et al. [Fermi-LAT Coll.], ApJ 799 (2015) 86

The Fermi-LAT Collaboration has estimated that **~ 86± 15 %** of the EGB flux above 50 GeV is provided by sources (blazars)

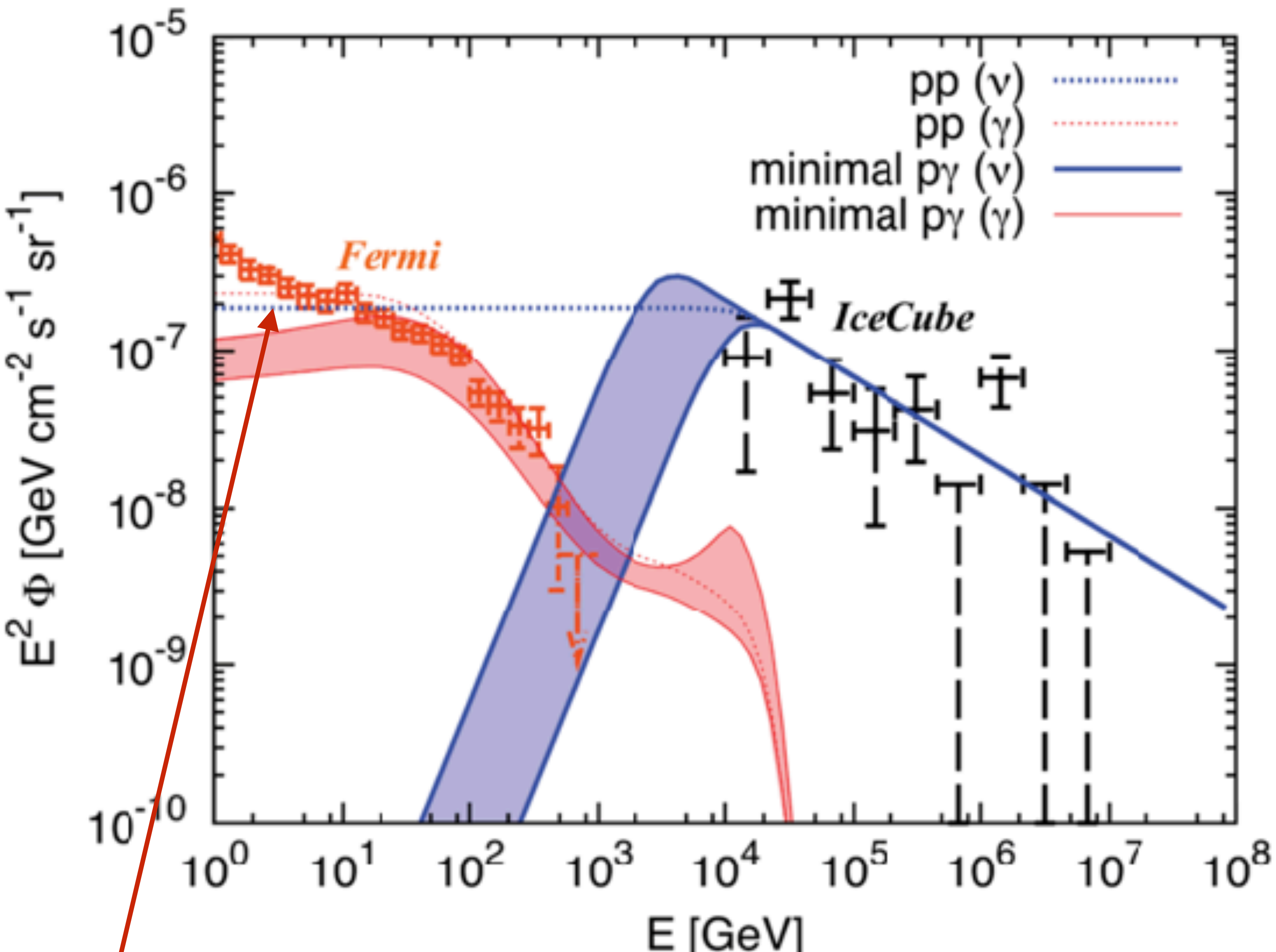
M. Ackermann et al. [Fermi-LAT Coll.], PRL 116 (2016) 151105



…but see also **68 ± 10 %** from Lisanti et al. and **81% (+52,-19)** from Zechlin et al.

Search for EG ν-sources

In a MM framework (sources of gamma rays produce the IC neutrinos) the constraint provided by the **IGRB** should be satisfied.



K. Murase et al., PRL 116 (2016) 071101

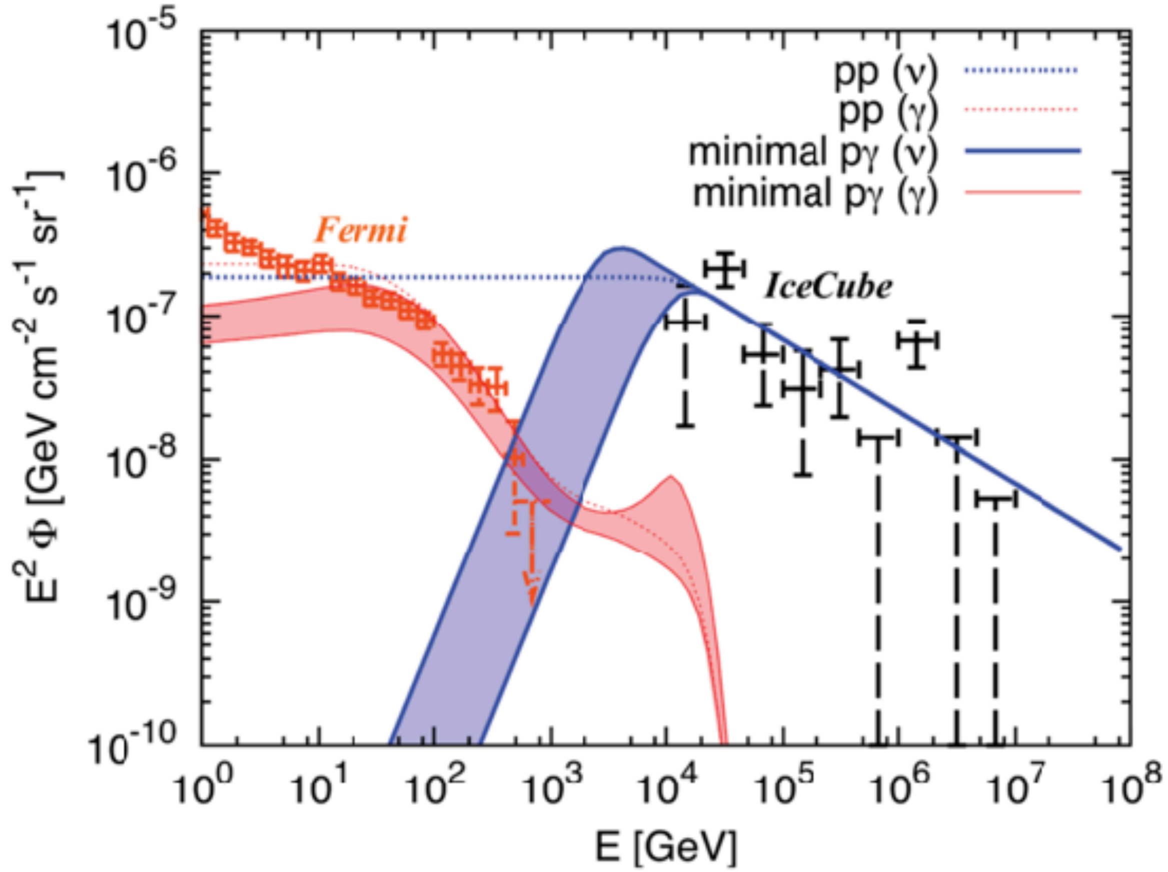
resolved blazars are removed in Fermi data

pp models of the HESE flux in tension with IGRB data

pγ models of the HESE flux less in tension with IGRB data

…but strongly depend on assumption for the radiation field

pγ scenarios for IC-ν



K. Murase & K. Ioca, PRL 111 (2013) 121102

Which radiation field is required to produce 30 TeV νs?

$$\varepsilon_p \approx 20\varepsilon_\nu \approx 0.5\Gamma^2 m_p c^2 \bar{\varepsilon}_\Delta \varepsilon_t{}^{-1}$$

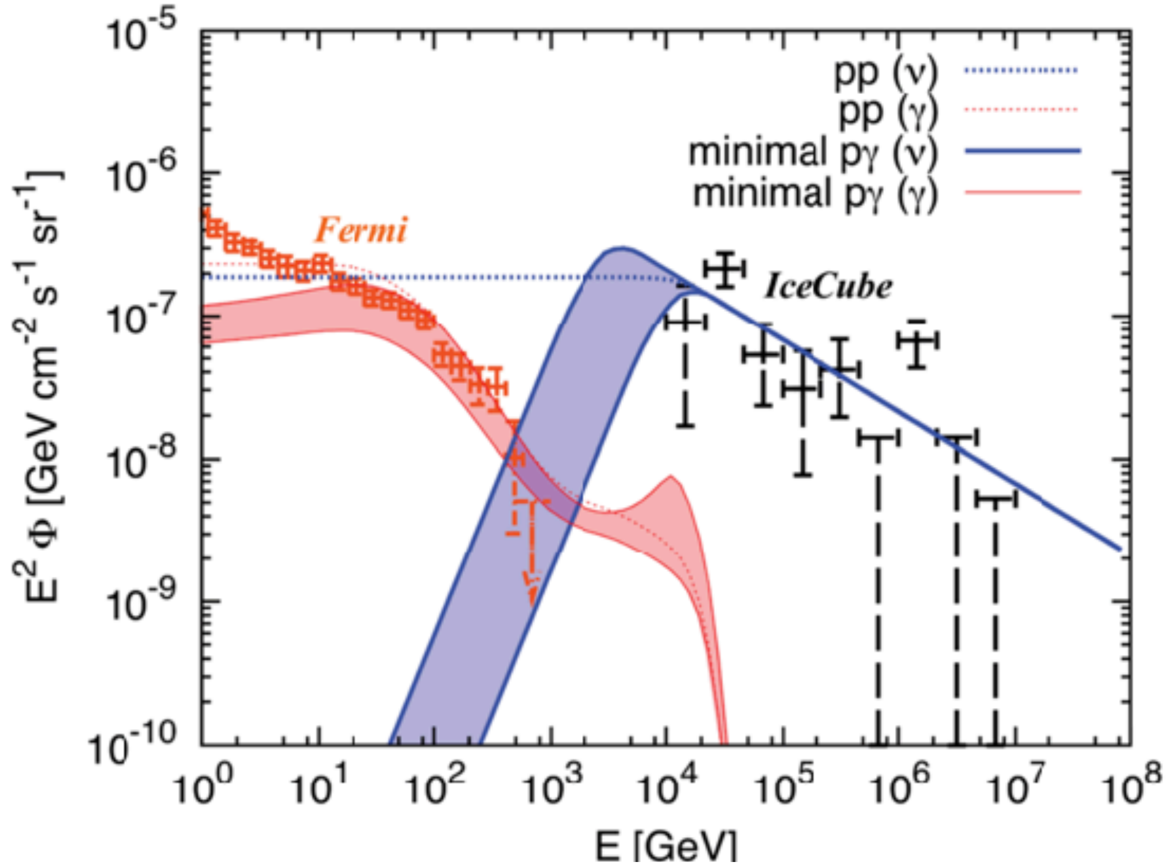
$$\varepsilon_t \sim 20\ \mathrm{keV}(\Gamma/10)^2(\varepsilon_\nu/30\ \mathrm{TeV})^{-1}$$

Are these sources transparent to the (twins) γ rays?

$$\tau_{\gamma\gamma}(\varepsilon_\gamma^c) \approx \frac{\eta_{\gamma\gamma}\sigma_{\gamma\gamma}}{\eta_{p\gamma}\hat{\sigma}_{p\gamma}} f_{p\gamma}(\varepsilon_p) \sim 10\left(\frac{f_{p\gamma}(\varepsilon_p)}{0.01}\right)$$

$$\varepsilon_\gamma^c \approx \frac{2m_e^2c^2}{m_p\bar{\varepsilon}_\Delta}\varepsilon_p \sim \mathrm{GeV}\left(\frac{\varepsilon_\nu}{25\ \mathrm{TeV}}\right)$$

pγ scenarios for IC-ν



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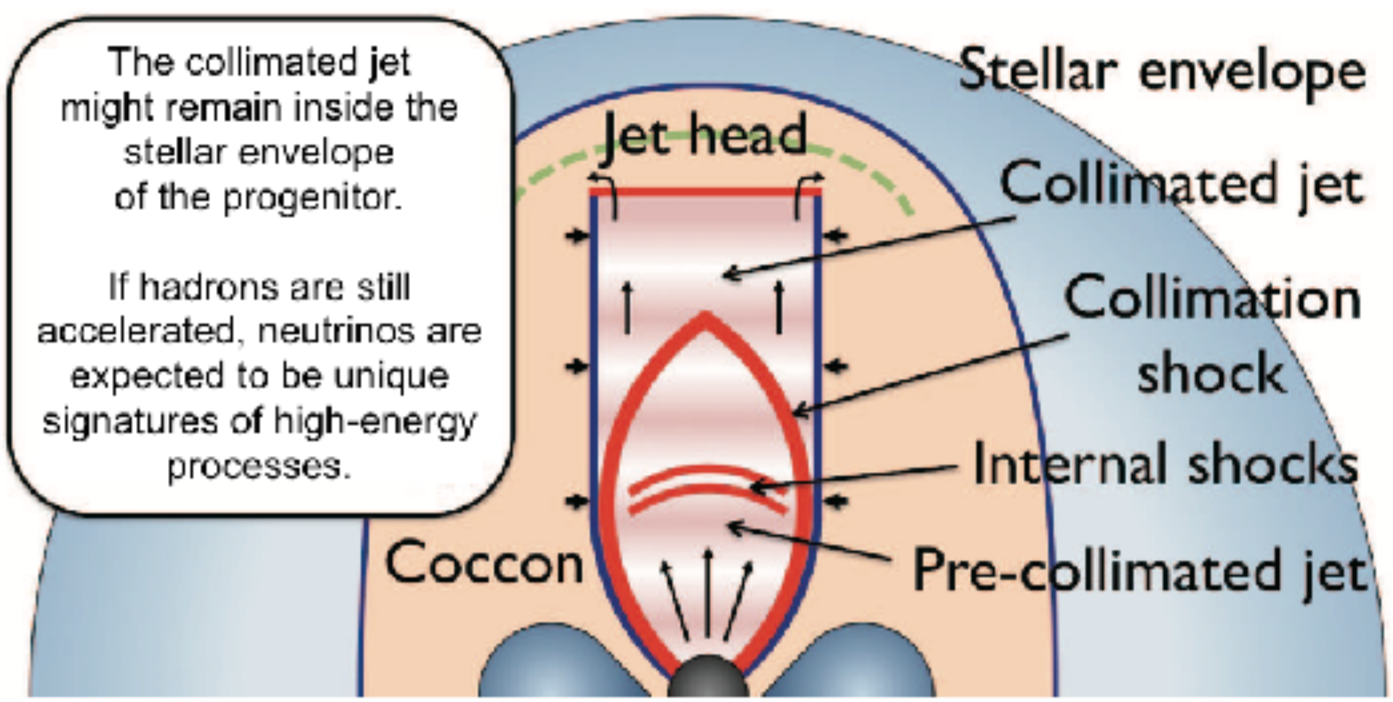


Are these sources transparent to the (twins) γ rays?

NO

The same radiation field acts as a target for pair production

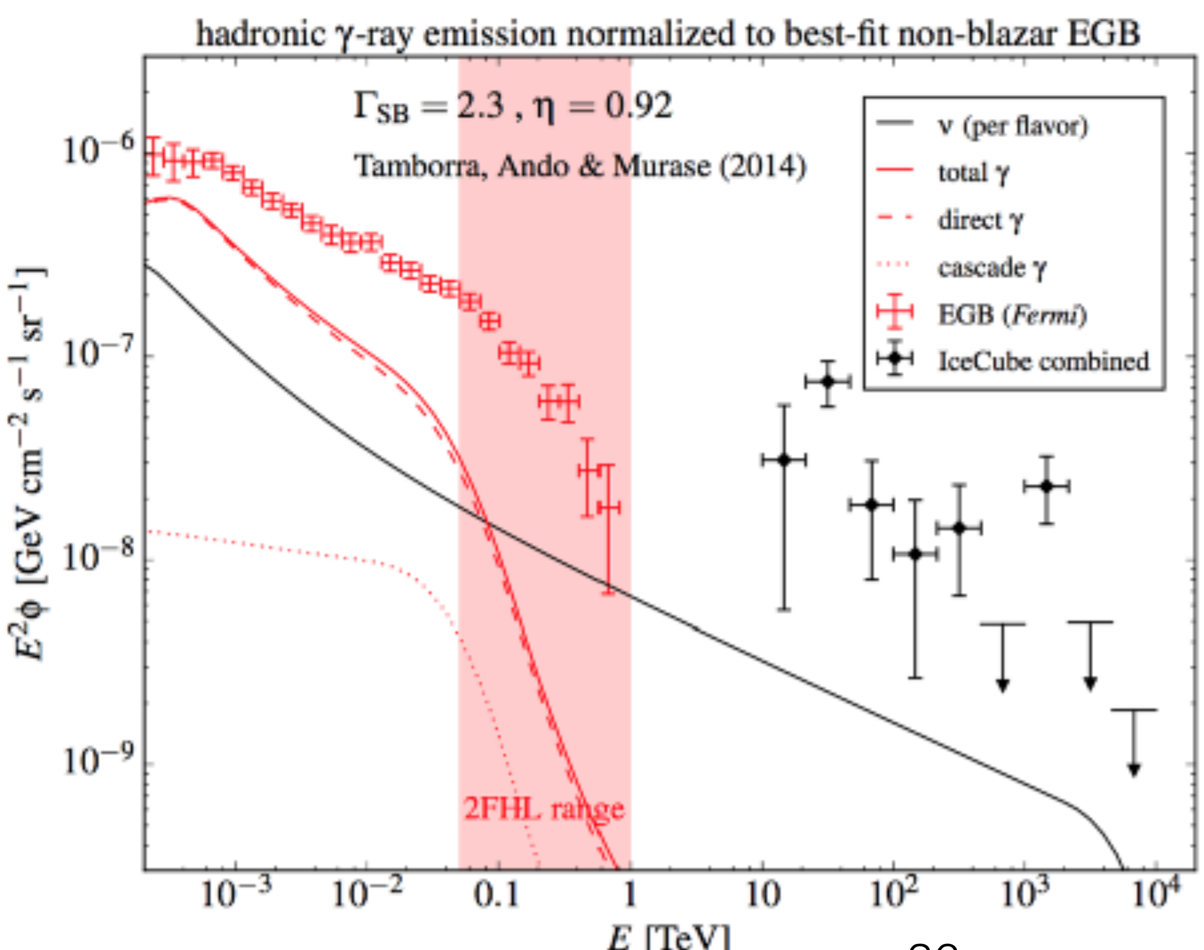
—> chocked GRBs

K. Murase & K. Ioca, PRL 111 (2013) 121102

pp scenarios for IC-ν

STARBURST GALAXIES

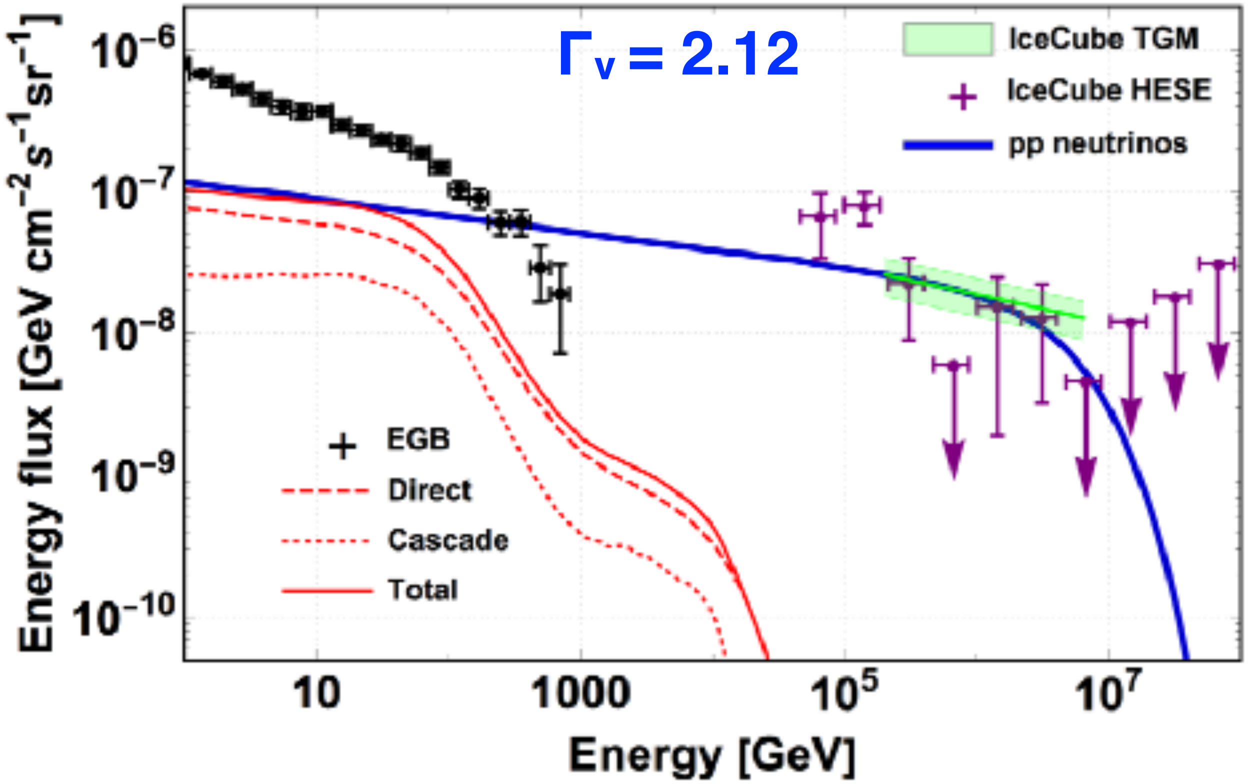
Galaxies with a high star formation rate (~100 x Milky Way) and enhanced gas density —> ideal calorimeters for pp collisions



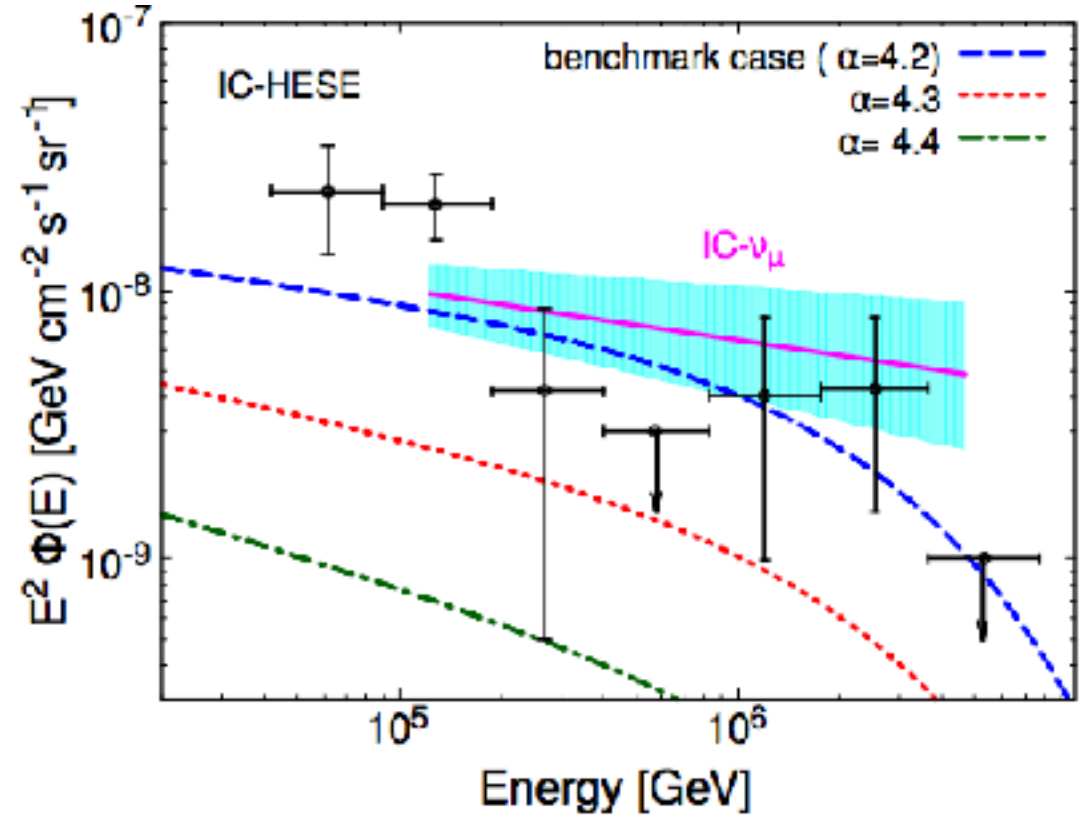
less than ~10% of the HESE flux…

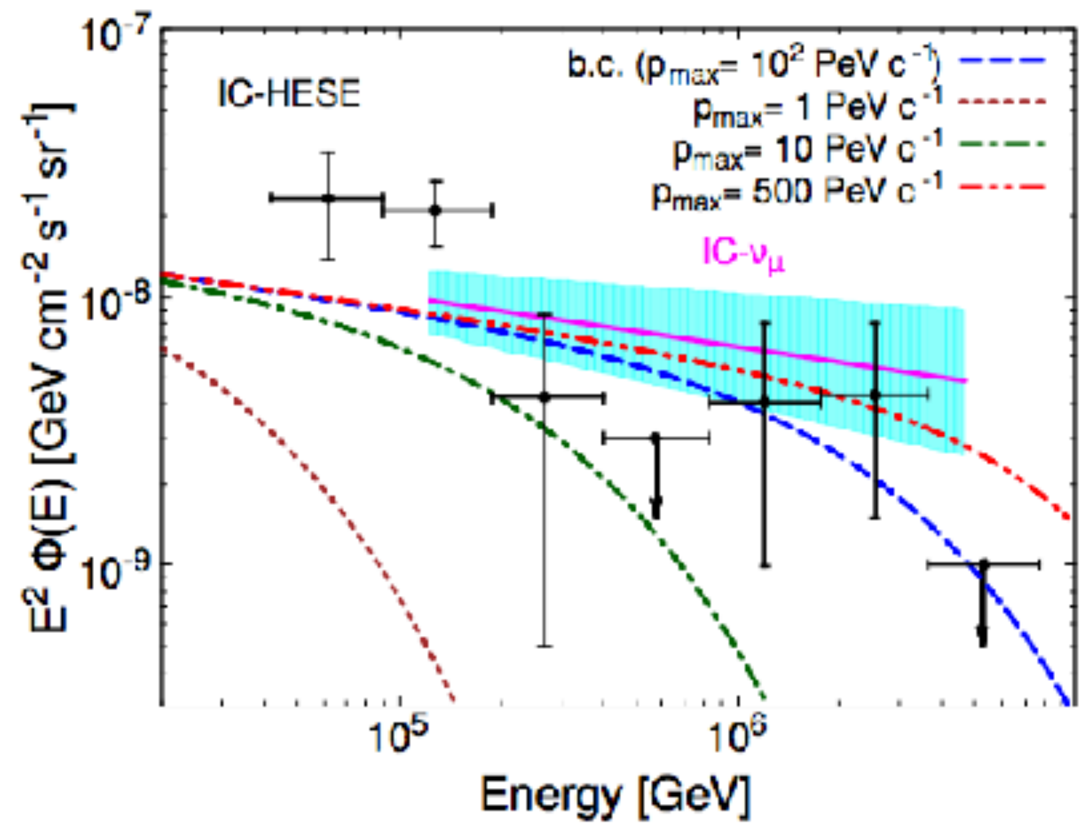
K. Bechtol et al., ApJ 836 (2017) 47

Search for SBG-ν



A. Palladino et al., JCAP 09 (2019) 004





…but emission from SBGs is compatible with the through-going flux

$\Gamma_\nu > 2.3$ excluded @ 5σ

$\Gamma_\nu = 2.15 \pm 0.1$

A. Loeb & E. Waxman, JCAP 0605 (2006) 003

E. Peretti et al., MNRAS 493 (2020) 4

A comprehensive model

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

- **Atmospheric component: conventional + prompt**

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

$E_\nu \lesssim (0.2-0.5)\rm PeV$

- **Galactic component**

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

$E_\nu \lesssim \rm PeV$

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

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

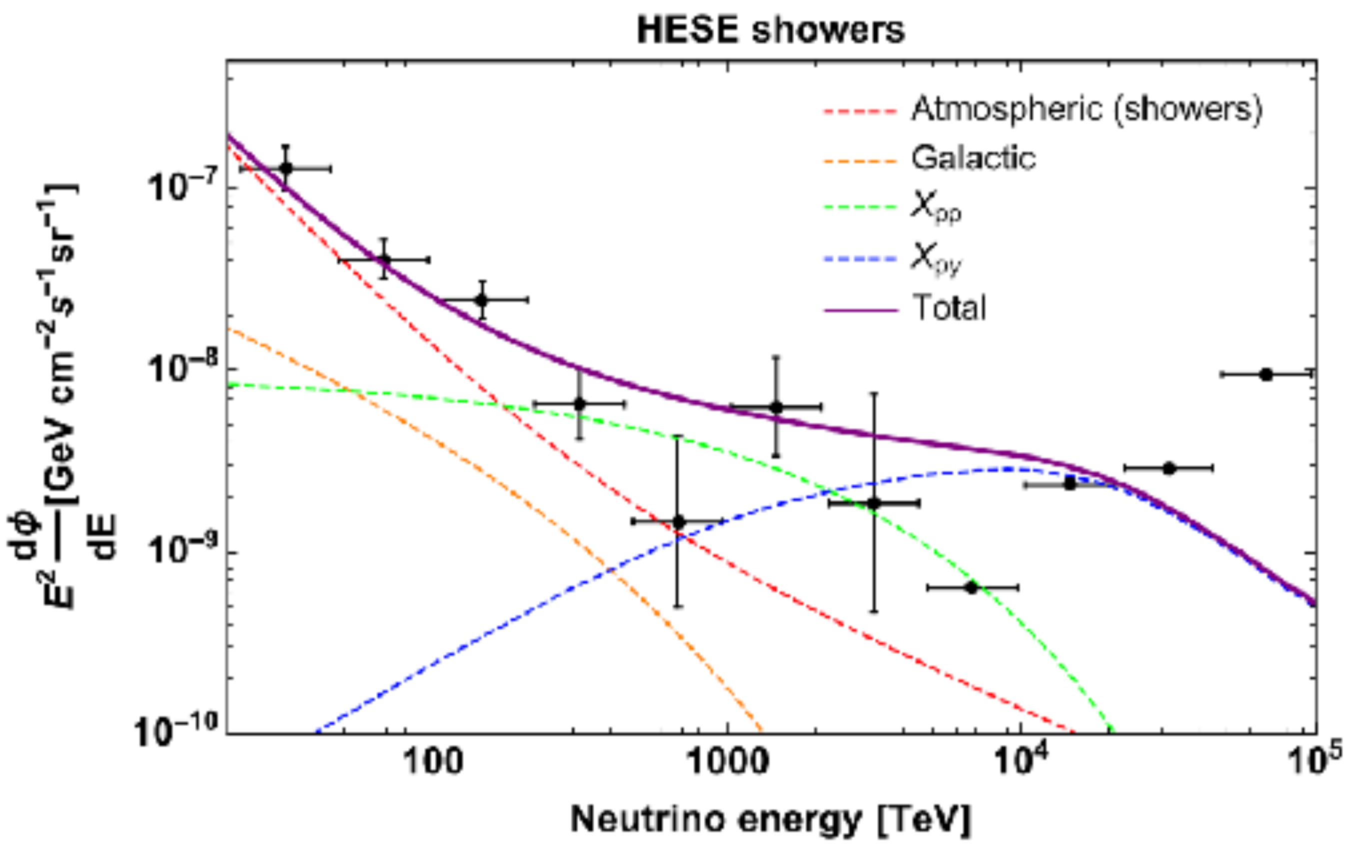
$E_\nu \sim (0.2-2)\rm PeV$

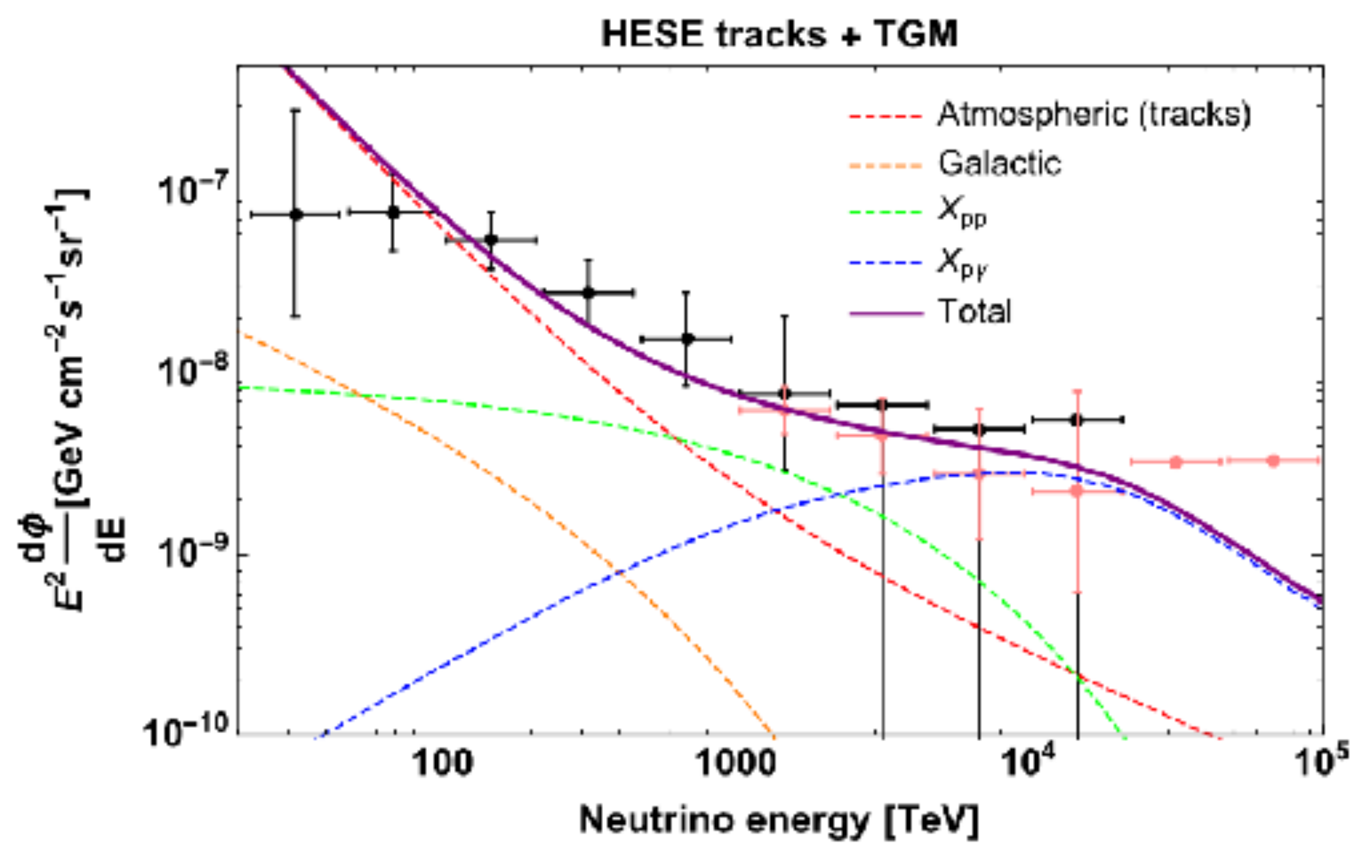
$$\frac{d\phi_{\rm p\gamma}}{dE_\nu} = F_{\rm p\gamma}\frac{d\phi_{\rm TDE}}{dE_\nu}$$

$E_\nu > 2\,\rm PeV$

A comprehensive model

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





—> statistically significant (3.5σ) evidence for pp contribution

Conclusions and outlook

- The **sources** of the high-energy neutrino flux observed by IceCube remain so far **elusive**: unveiling the sources is of utmost importance as neutrinos are powerful probes of CR-related processes;
- The presence of such diffuse flux awaits an **independent confirmation** (ideally from neutrino-telescopes in the Northern Hemisphere, as to properly investigate the Galactic contribution);
- Interesting possibilities are emerging in considering the contribution of **several source classes**;
- **Multi-messenger observations** are key to investigate as much as possible the source activity and reduce the wealth of models on the market.

Thanks for your kind attention