High-energy neutrinos
Diffuse flux and sources

Damien Dornic (CNRS/CPPM)

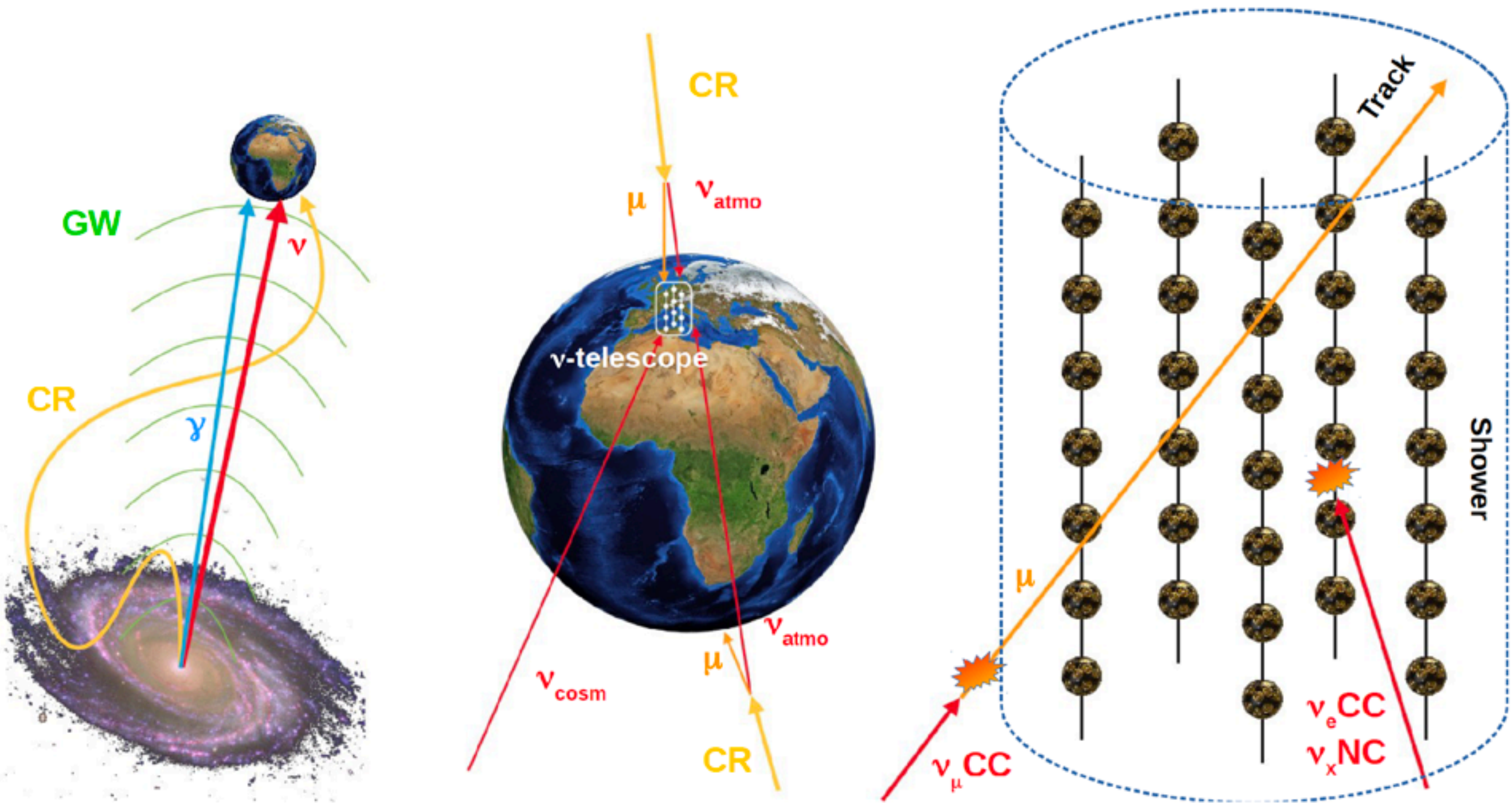
Open questions for neutrino astrophysics ?

- ➡ **Origin, acceleration mechanisms and cosmic evolution of high-energy cosmic rays: galactic/extragalactic**
- ➡ **Study of galactic (and extragalactic?) propagation of CR with neutrinos as tracers**
- ➡ **Origin of IceCube diffuse HE astrophysical neutrinos**
- ➡ **Which mechanism is responsible for the neutrino emission p-p or/and p-ɣ? Which is the flavor composition ?**
- ➡ **Are neutrinos and gammas/CR observed from the same sources?**
- ➡ **Which is the contribution of neutrino from the Galactic plane ?**
- ➡ **Disentangle astrophysical models with multi-messenger observations: i.e., GRBs with GW, HEN and traditional astronomy (important also in case of no ν observation)**
- ➡ **Test the neutrino sector of the SM and BSM physics**

Strength of the multi-messenger ?

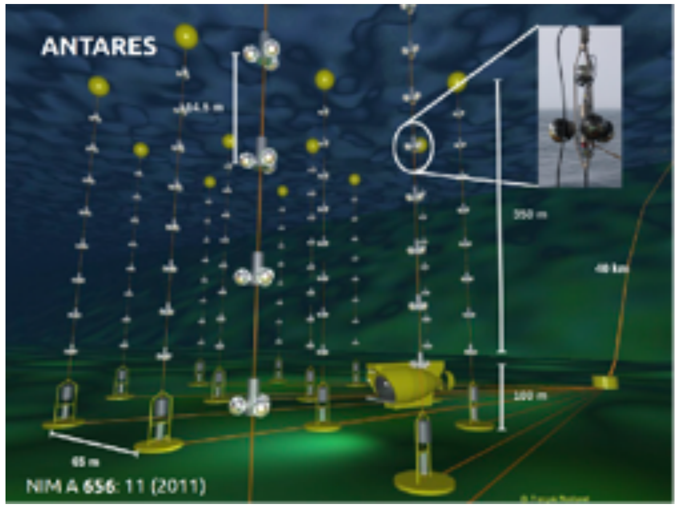
- GW170817, IC170922 have demonstrated the capabilities of doing real-time multi-messenger follow-ups
- Most of the HE sources are time-dependent, flux quickly varying
- Determine the astrophysical nature on the basis of one event
- Provide accurate positions (redshift, host measurements)
- Simultaneous observations of transient phenomena by pointing instruments (so important for the modelisation)

Neutrino astronomy in a nutshell

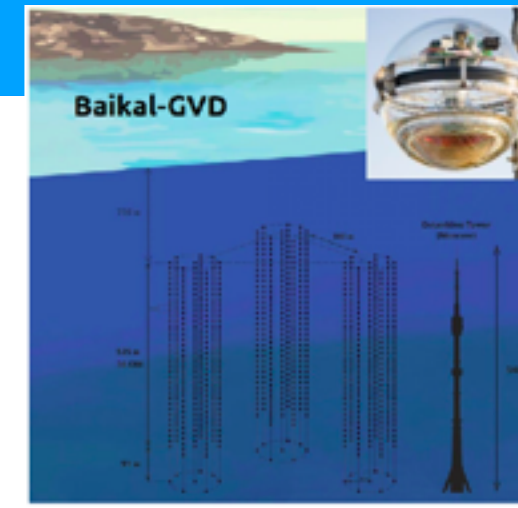


Large volume of deep ice/water

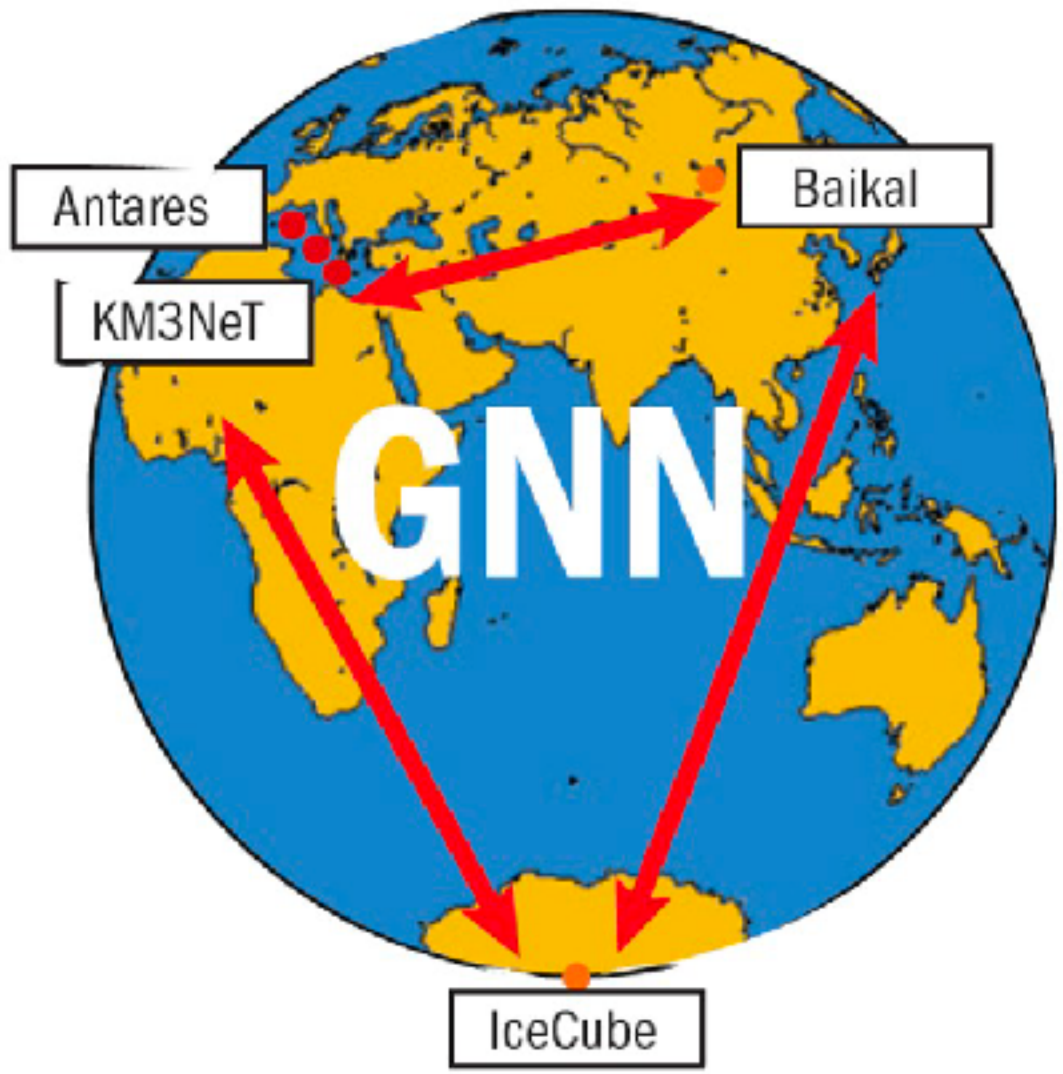
High-energy neutrino detectors

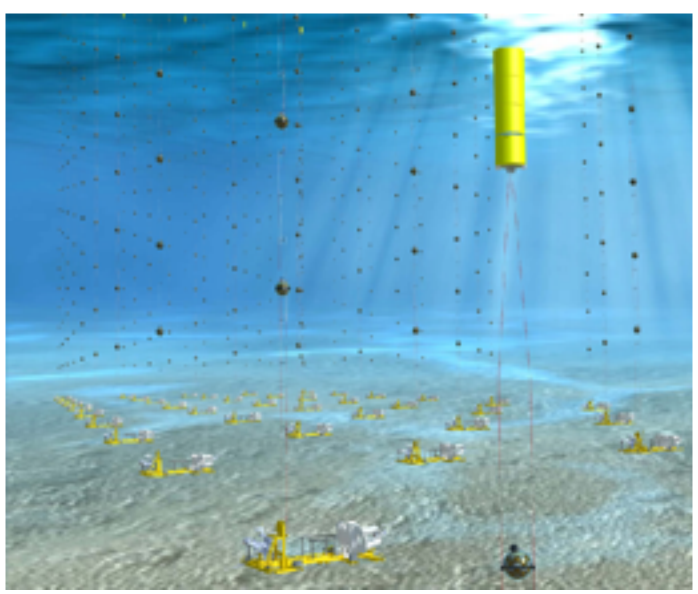


0.01 km³ telescope (12 DUs)
12+ yrs of continuous data taking in the Mediterranean Sea

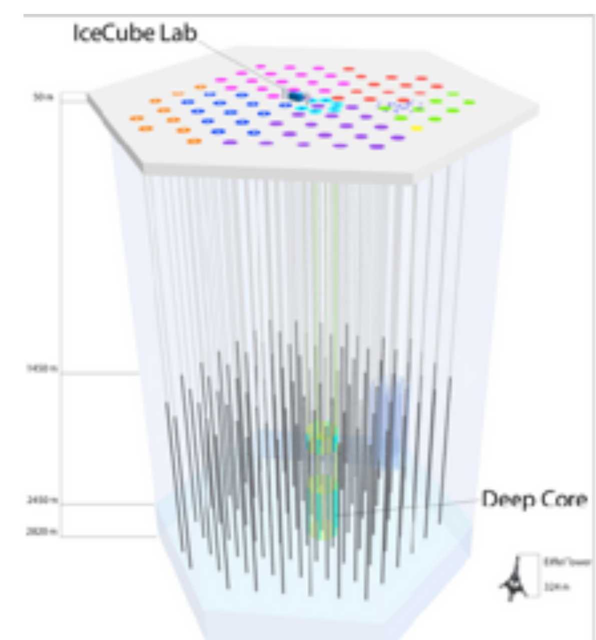


1 km³ telescope, in operation
5 clusters (0.3 km³)
2+ yrs of continuous data taking in the Baikal lake.



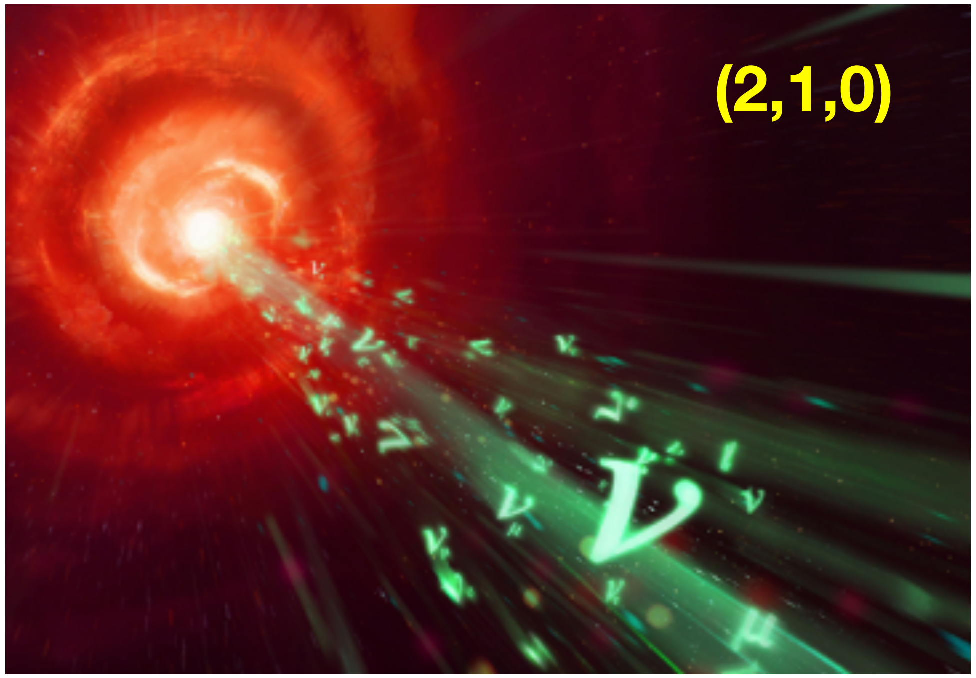


ORCA: 8 Mt detector (115 DUs)
ARCA: ~1 km³ telescope (230 DUs)
~1 yr of data taking in the Mediterranean Sea



1 km³ telescope (86 DUs)
10+ yrs of continuous data taking in the South Pole

All-flavour neutrino detection

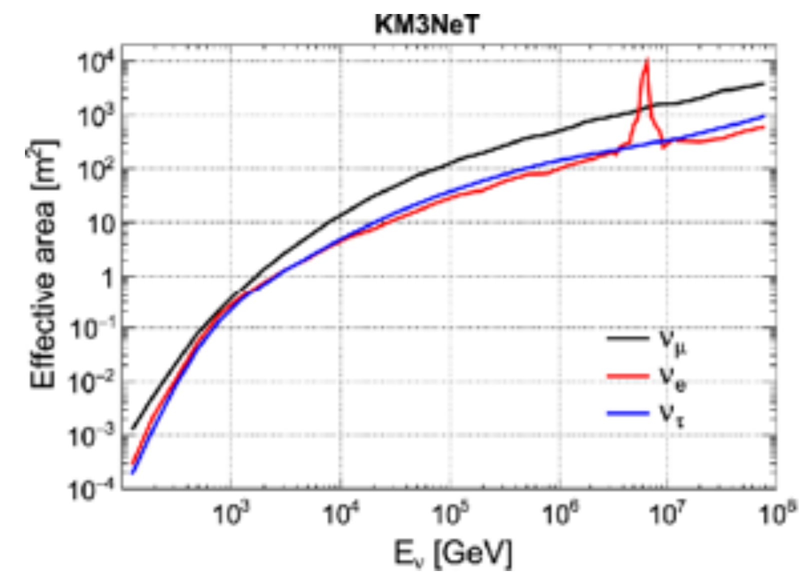


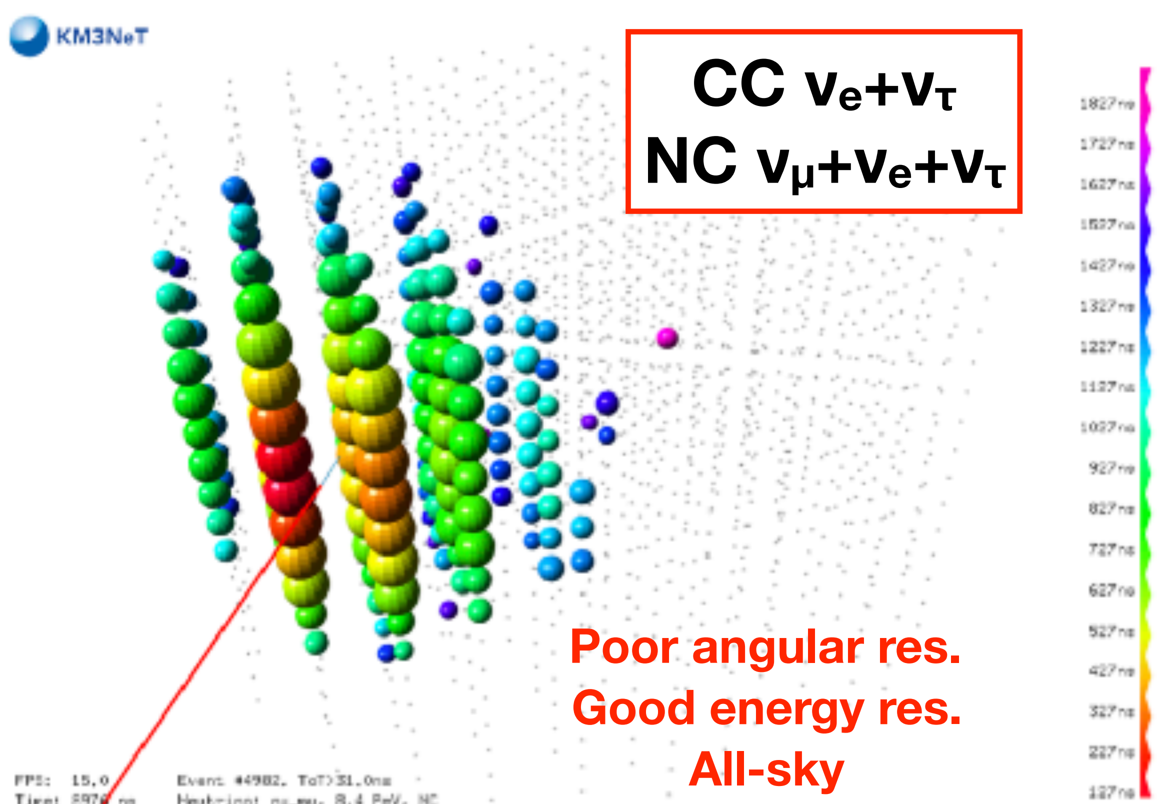
New physics ?

Oscillation

(1,1,1)

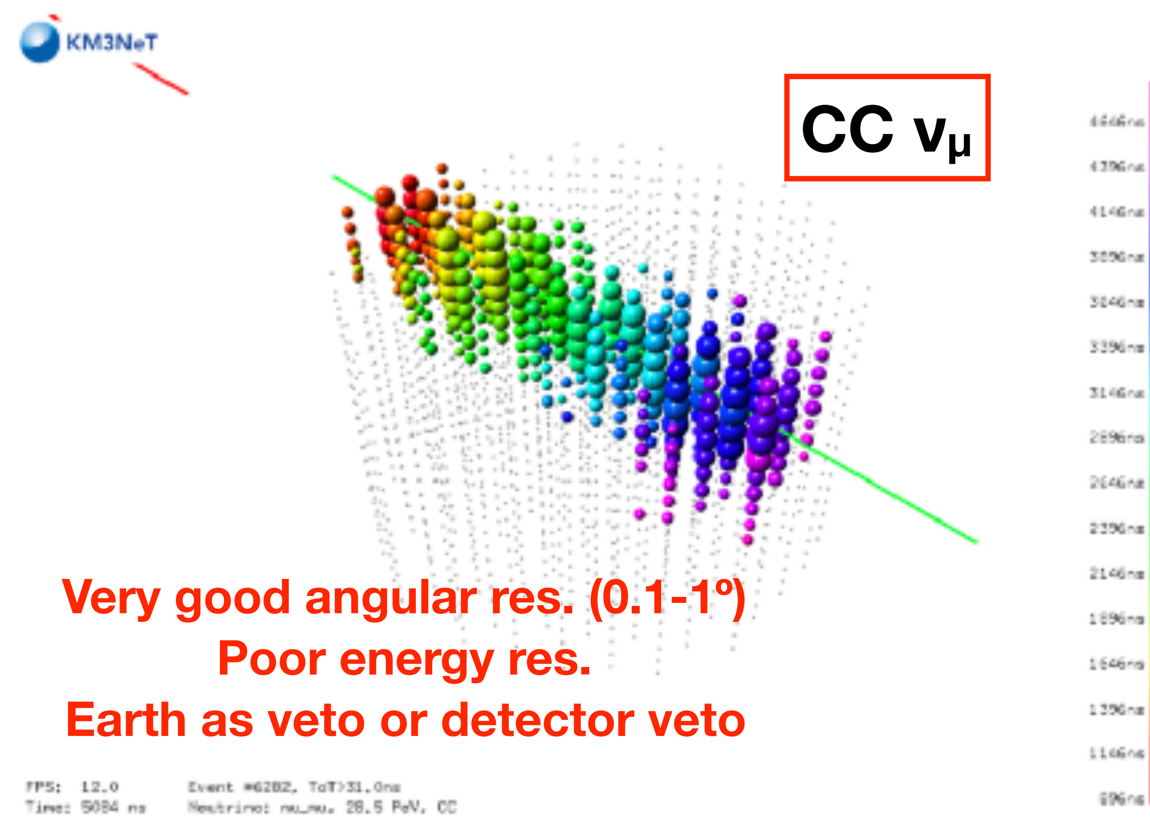
Each neutrino flavour brings information
$\Longrightarrow$ All-flavour astronomy





CC $\nu_e+\nu_\tau$
NC $\nu_\mu+\nu_e+\nu_\tau$

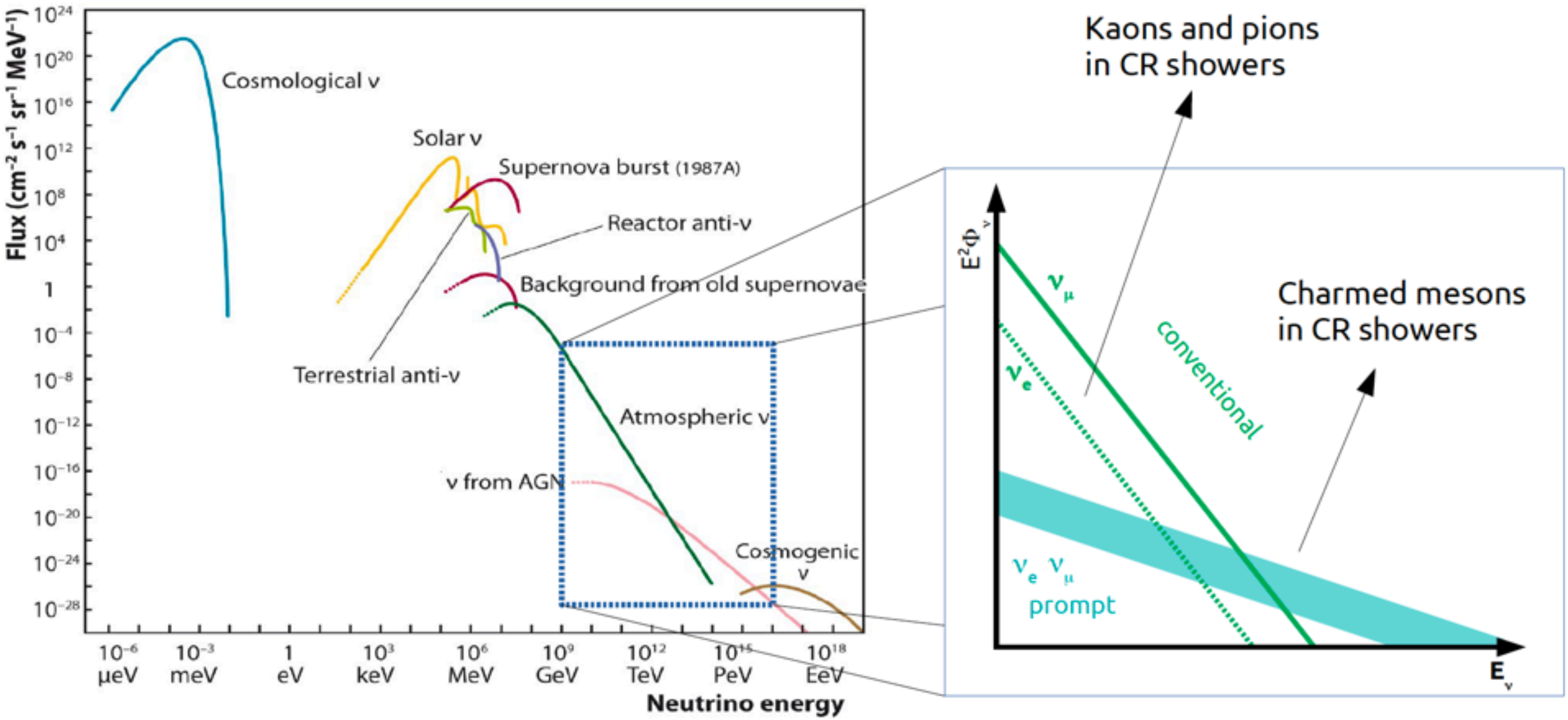
Poor angular res.
Good energy res.
All-sky



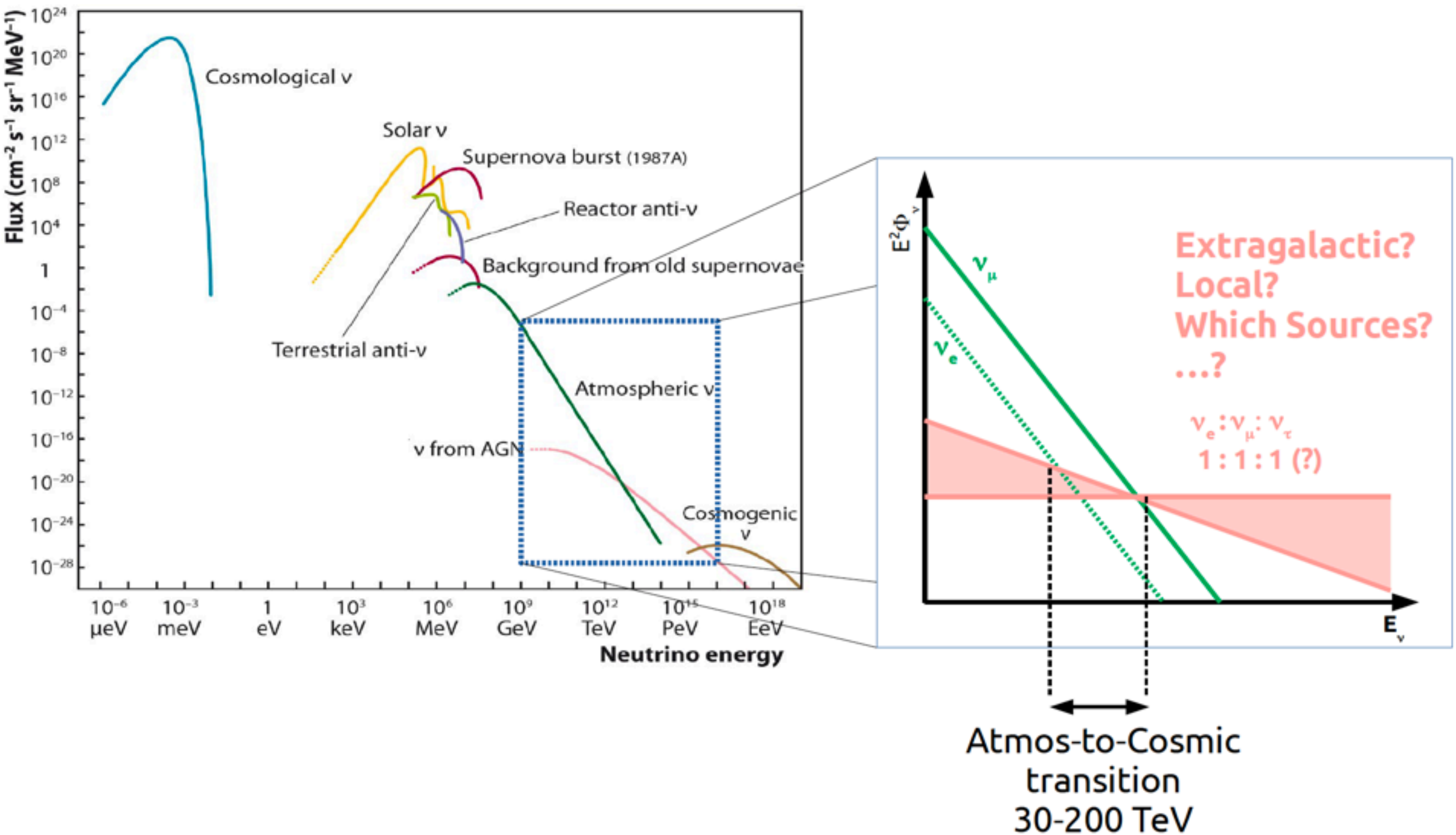
CC ν_μ

Very good angular res. (0.1-1°)
Poor energy res.
Earth as veto or detector veto

High-energy neutrino fluxes



High-energy neutrino fluxes

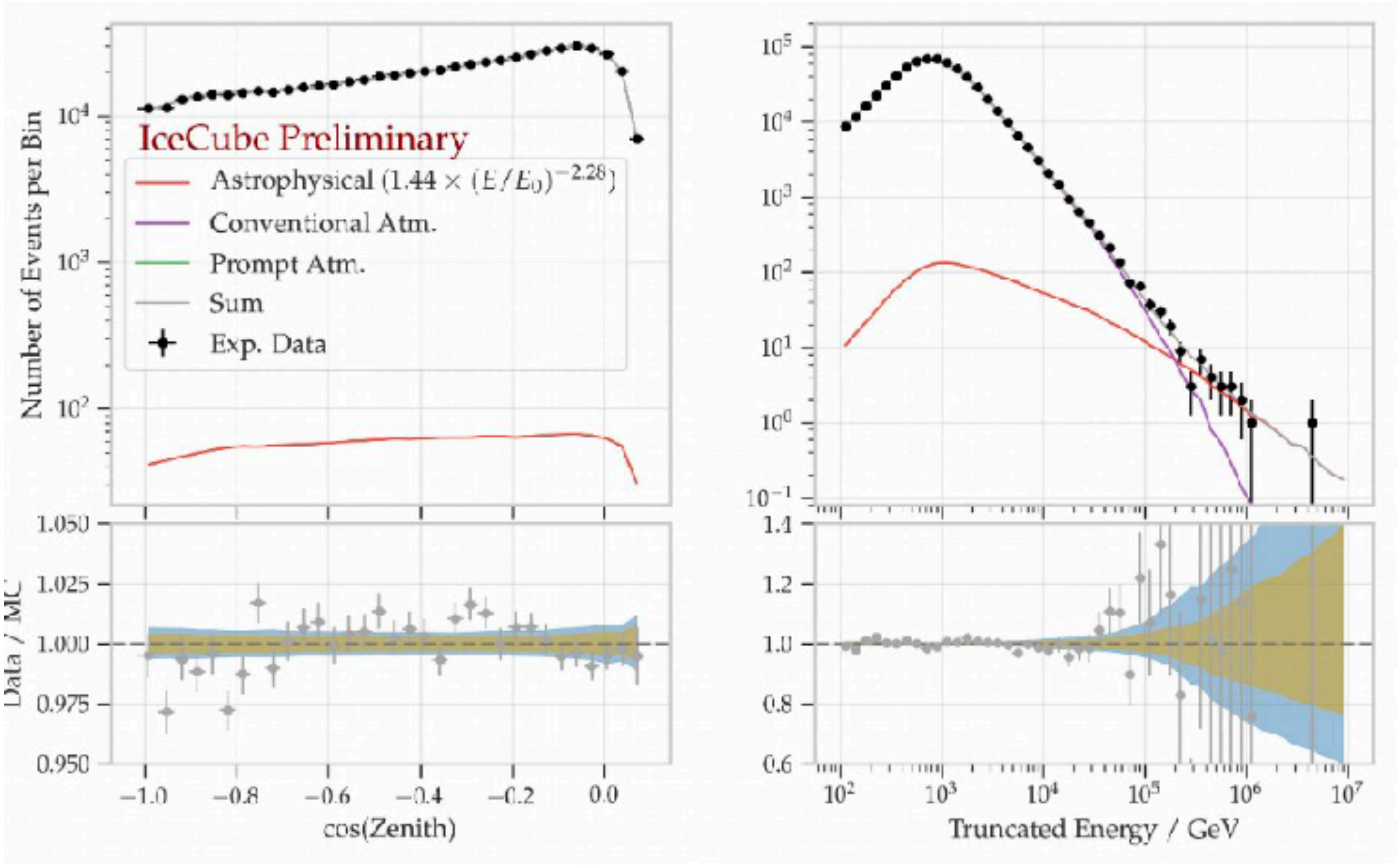


Diffuse neutrino fluxes detected by IceCube

PoS(ICRC2019)1017

The track sample (9.5 years)

Earth used as a shield against CR muons → cosmic excess at the highest energies (>100 TeV) in the Northern sky



$\boxed{\phi^{1f}(100TeV) = (1.44 \pm 0.25)10^{-18}(GeVcm^2ssr)^{-1} \,.\, \Gamma = 2.28 \pm 0.09}$

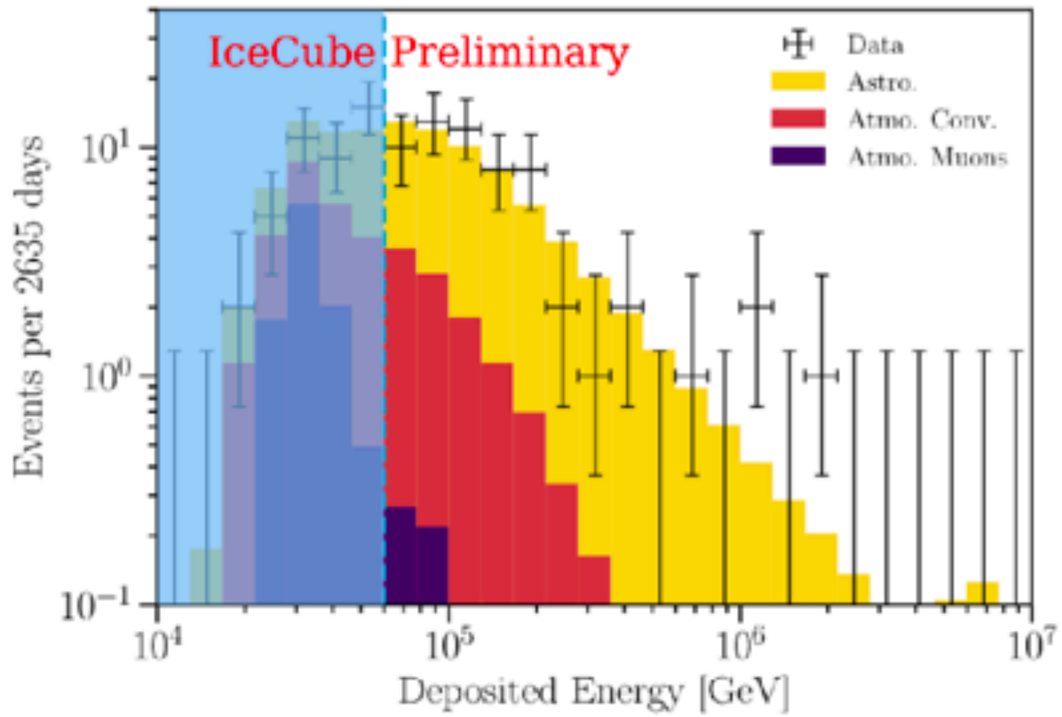
+ Null-prompt component is fitted

Diffuse neutrino fluxes detected by IceCube

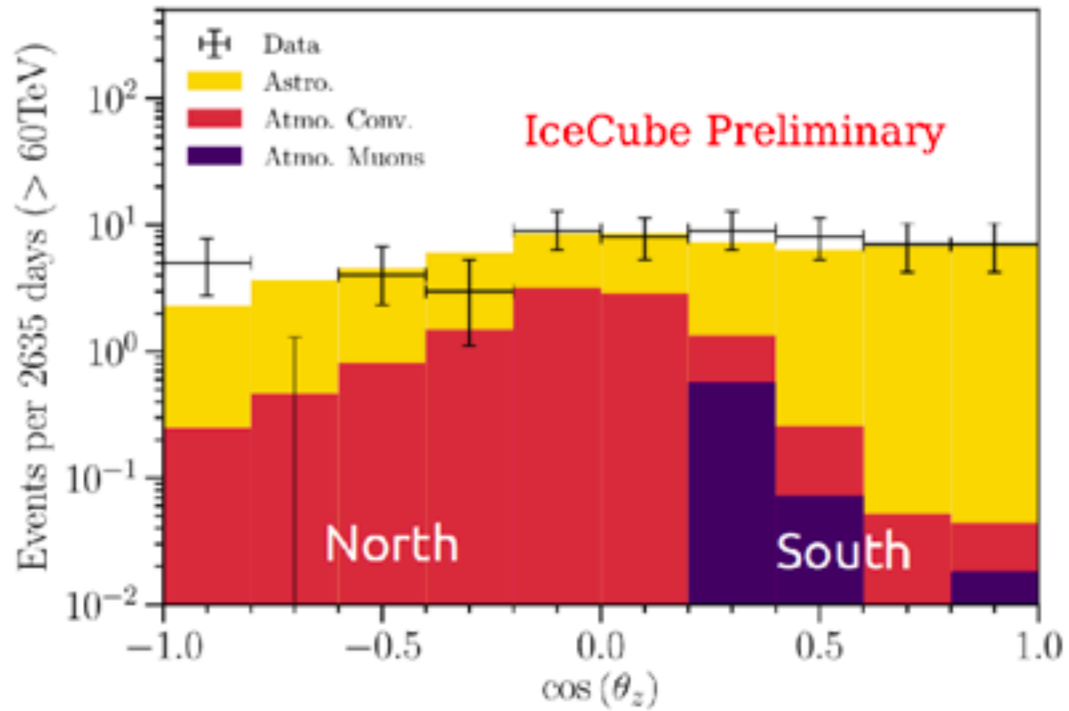
PoS(ICRC2019)1004

The HESE sample (7.5 years)

Too soft?



Compatible with isotropy



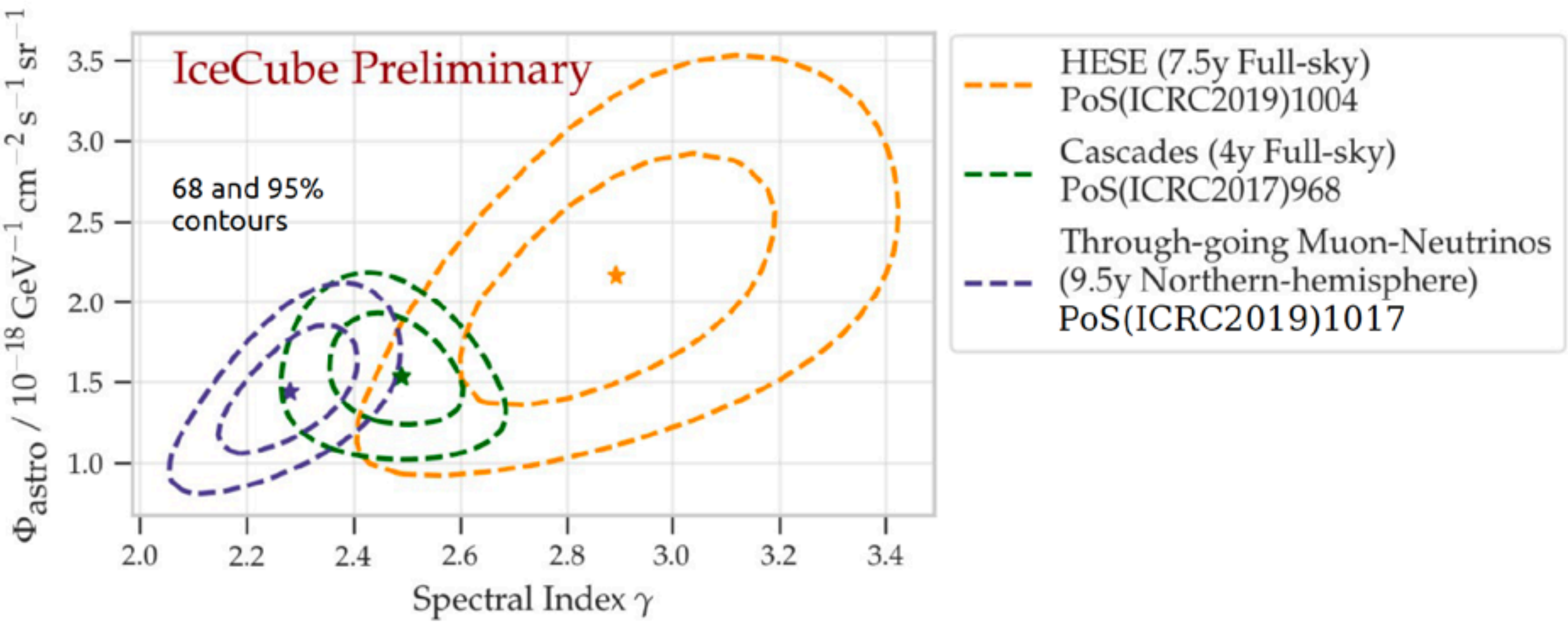
$$\boxed{\phi^{1f}(100TeV) = (2.15^{+0.5}_{-0.15})10^{-18}(GeVcm^2ssr)^{-1} \,.\, \Gamma = 2.9 \pm 0.2}$$

+ Null-prompt component is fitted

$\Longrightarrow$ Compatible with isotropy but too soft spectrum ?

High-energy starting events above 60 TeV (all-sky search)
– Southern sky accessible (veto)
– Northern sky more opaque (absorption)

Diffuse neutrino fluxes detected by IceCube

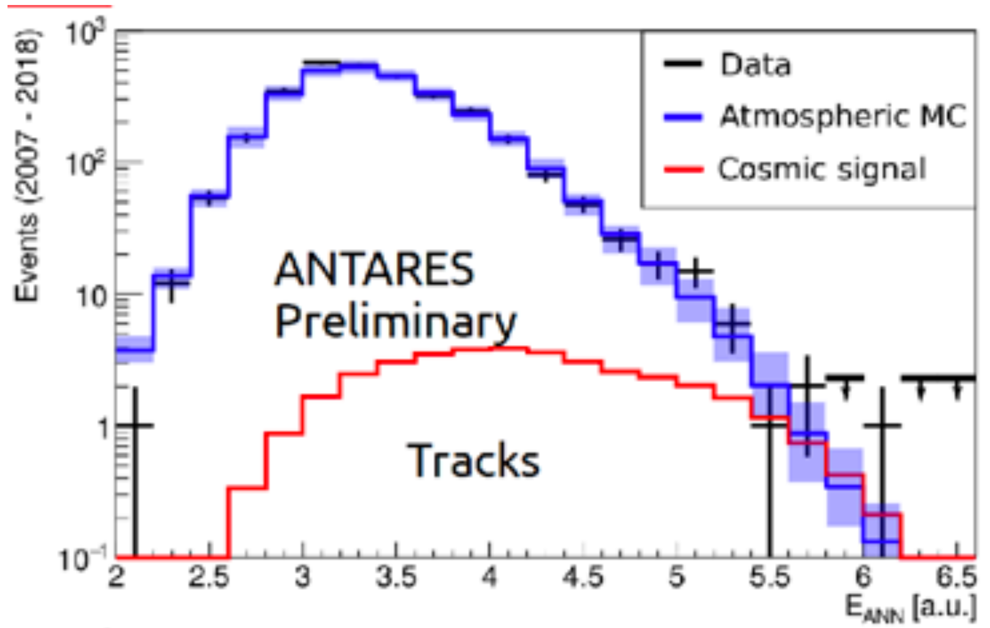


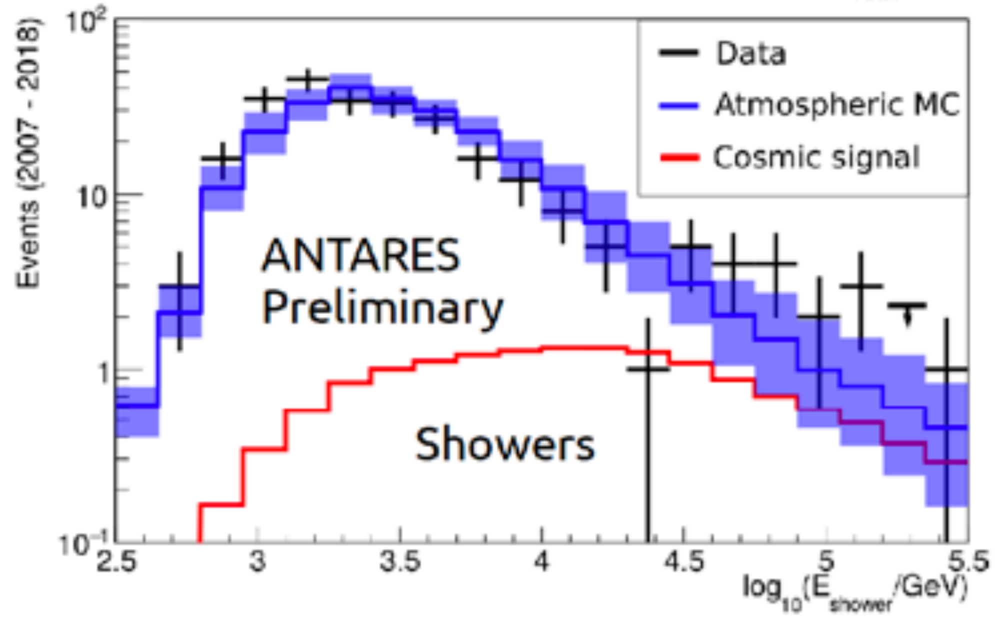
Single power law? Statistics not enough to distinguish between different models.

Small tension between the different diffuse analyses (but still compatible at 95% CL) $\Longrightarrow$ different sky, extragalactic/galactic components, dominant sources, systematics…

Diffuse neutrino fluxes detected by ANTARES

PoS(ICRC2019)891





3380 days of livetime

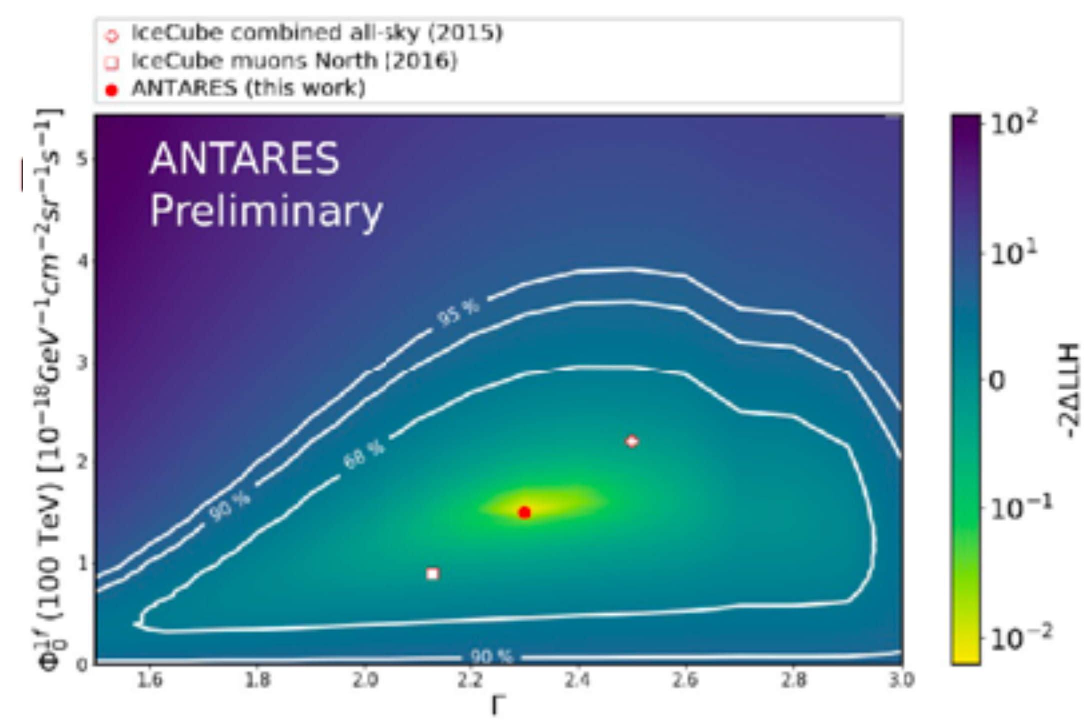
Considering the HE tail (~1% highest E)

→ **data: 50** events
(**27** tracks + **23** showers)

→ **bkg MC: 36.1 ± 8.7** (stat.+syst.)
(**19.9** tracks and **16.2** showers

→ **signal MC: ~10 events expected**
(**4.5** tracks and **5.5** showers)

Null-cosmic excluded at 90% C.L.
1.8σ excess

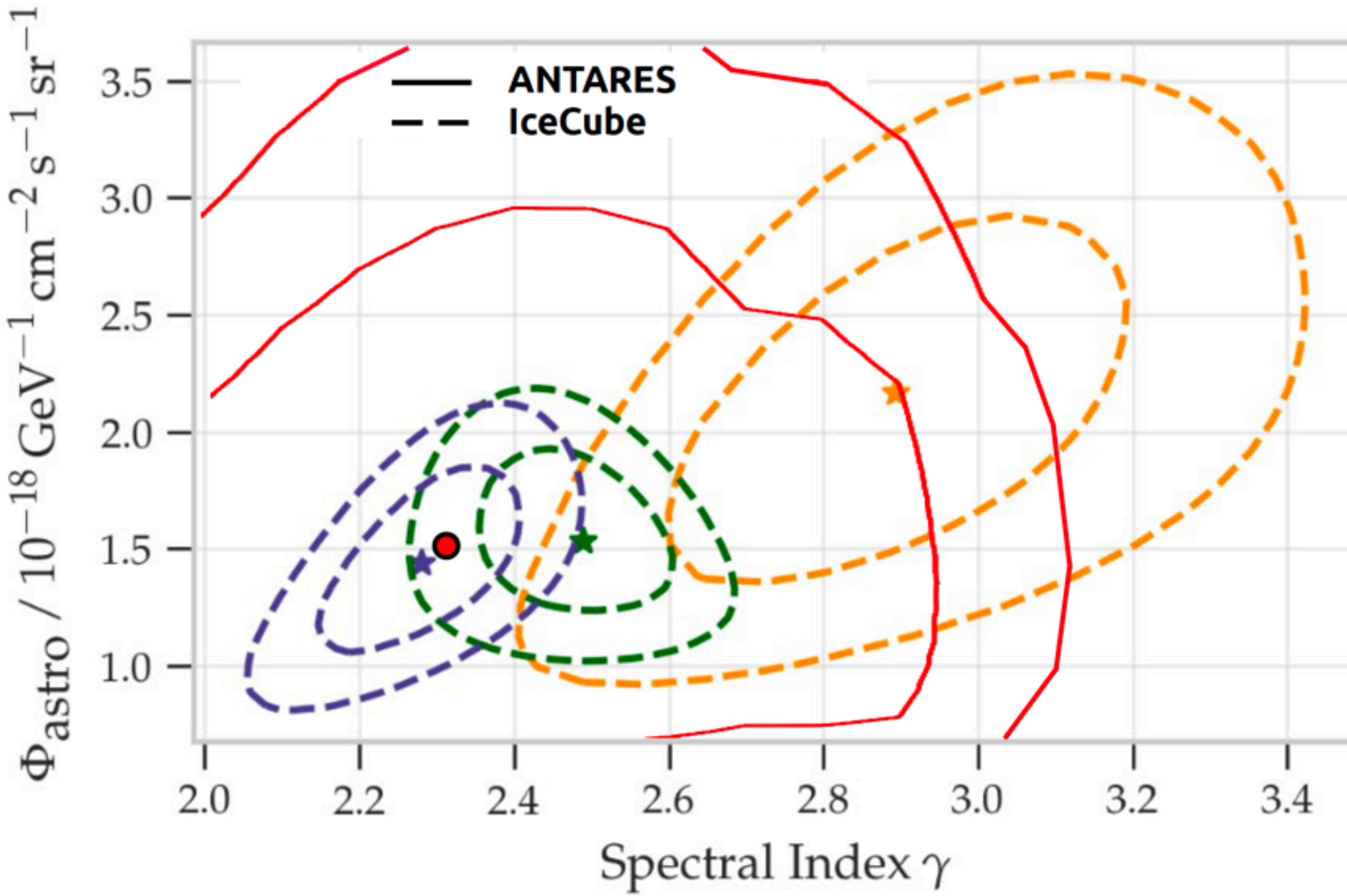


Combining shower+track (Southern sky)

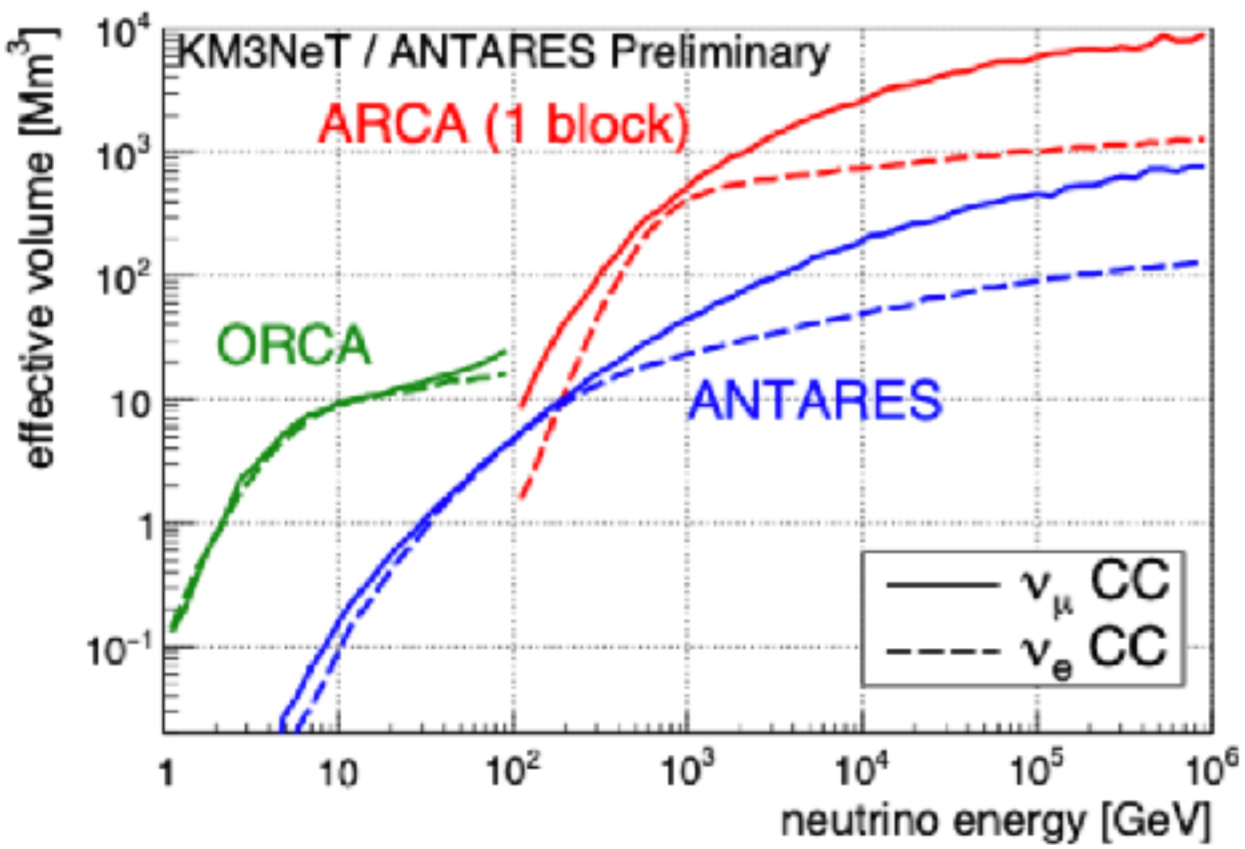
$$\boxed{\phi^{1f}(100TeV) = (1.5 \pm 1.0)10^{-18} - \Gamma = 2.3 \pm 0.4}$$

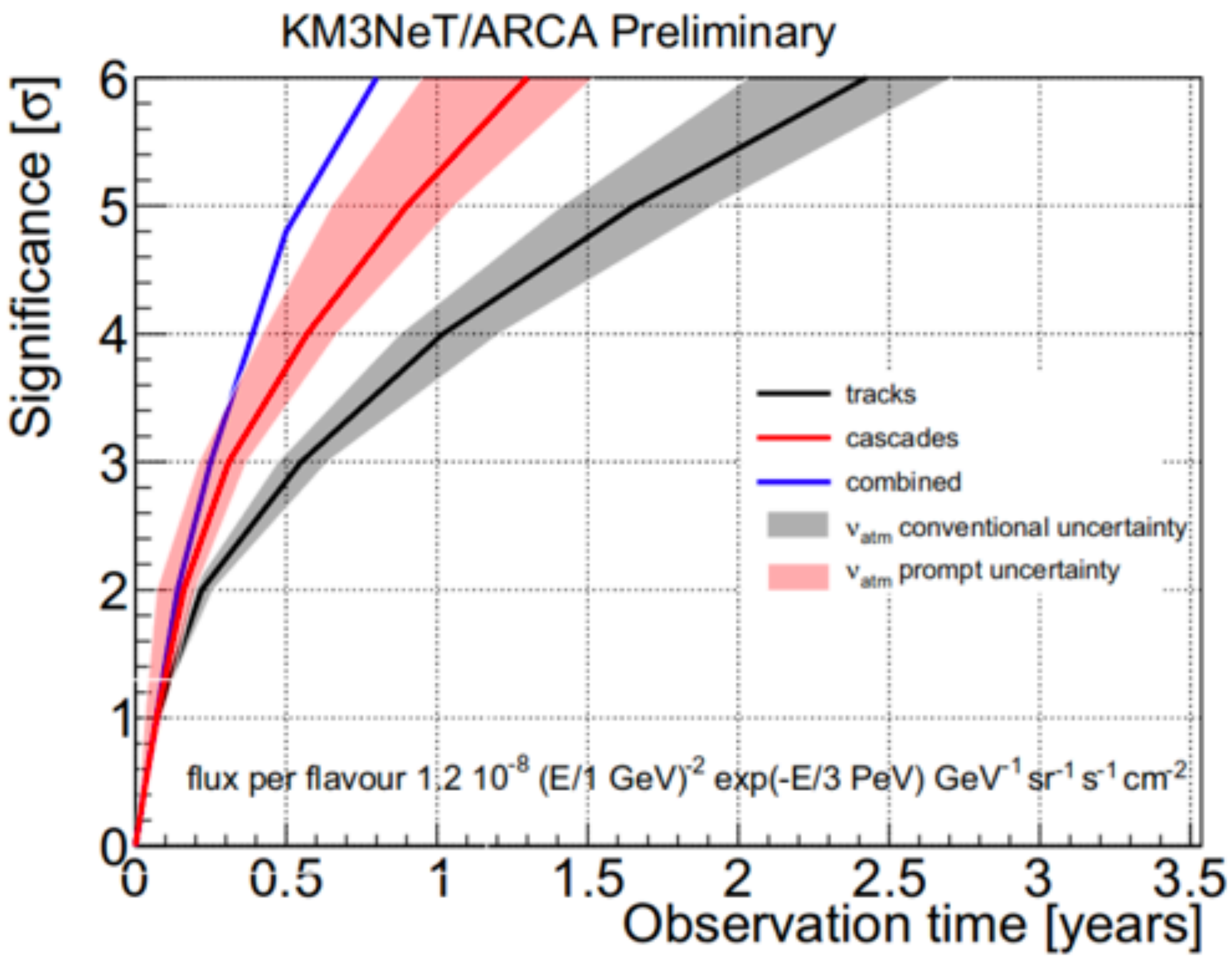
Tracks	Showers
Φ^{1f}(100 TeV) = $(0.8^{+0.5}_{-0.4})\ 10^{-18}$	**Φ^{1f}(100 TeV) = (2.1±0.8) 10^{-18}**
$\Gamma = 2.0^{+0.8}_{-0.4}$	**Γ = 2.4±0.4**

Diffuse neutrino fluxes IceCube+ANTARES



Diffuse flux predictions for KM3NeT





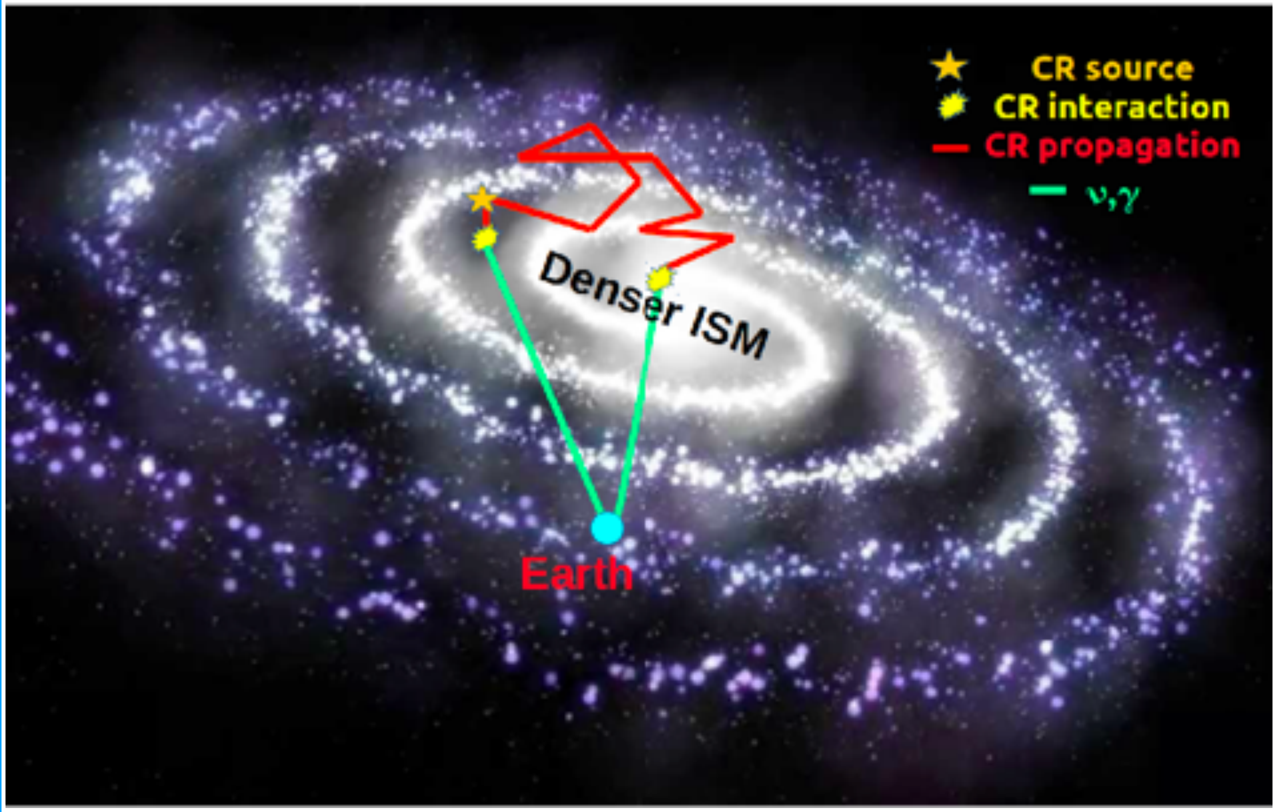
With KM3NeT/ARCA, high sensitivity to HE neutrino cosmic flux (optimization for intermediate energies)

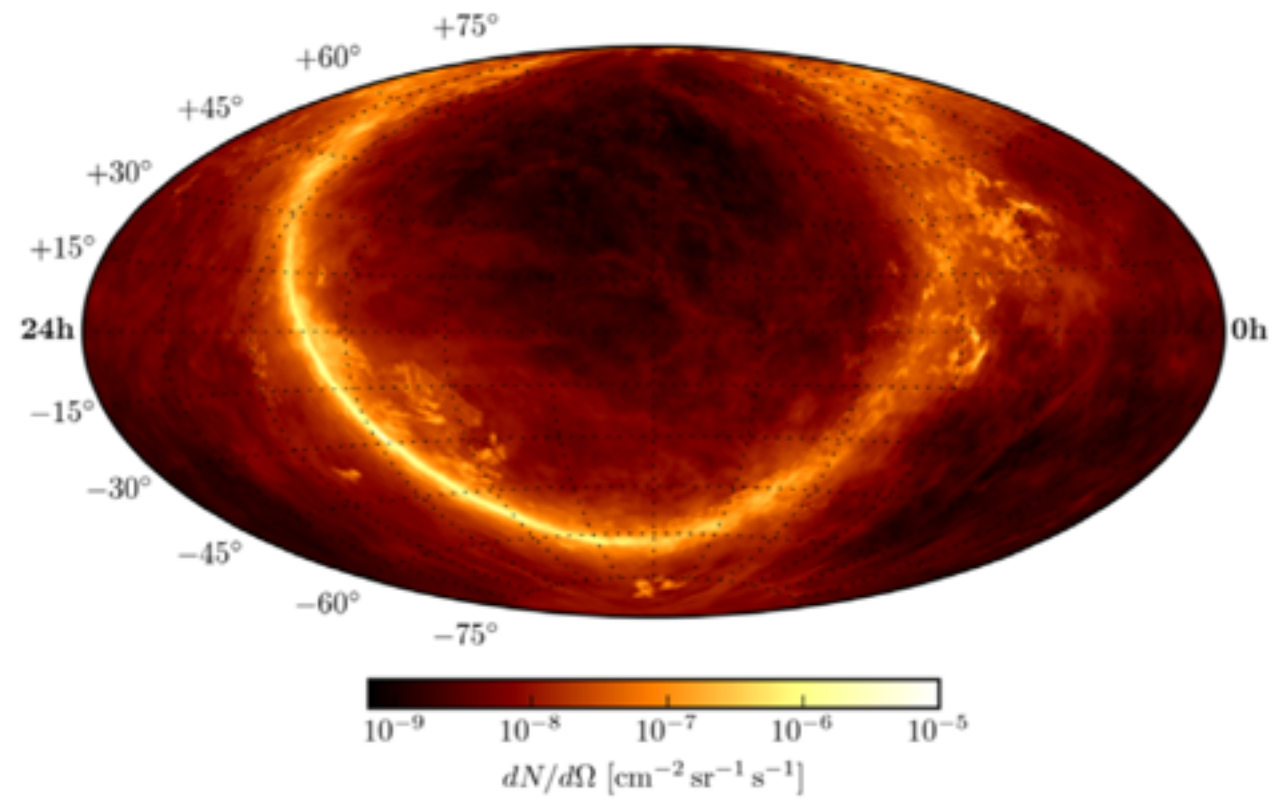
Quick re-discovery of the IceCube diffuse signal with different systematics (detector, background…)

(Cf Talk M. Taiuti on Friday)

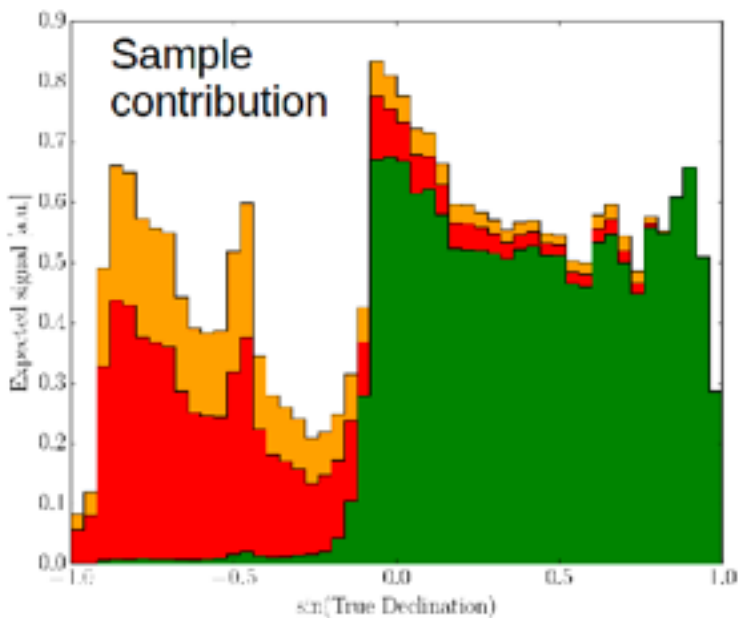
J. Phys. G 43, 8: 084001 (2016)

Galactic neutrino emission



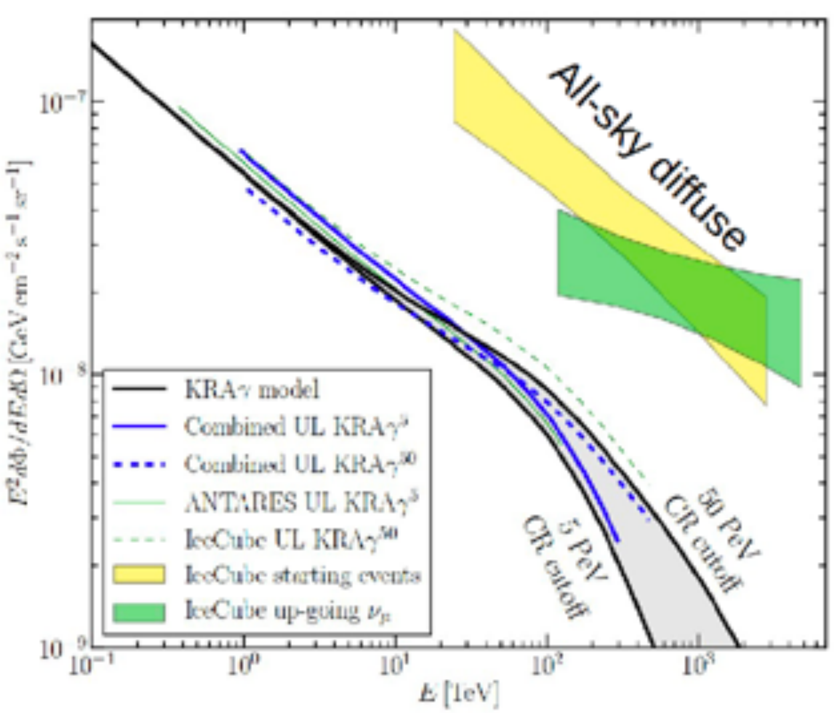


Joint analysis ANTARES (tracks + cascades) and IceCube (tracks)



+ spectral energy distributions are different in the model

No significant excess observed



Low latitude Galactic contribution constrained to 8% of the all-sky flux

Gaggero et al KRA$_\gamma$ model: Radially dependent model for the CR diffusion coefficient and the advective wind. It is tuned on KASCADE(GRANDE)/CREAM data.

Individual sources of neutrinos

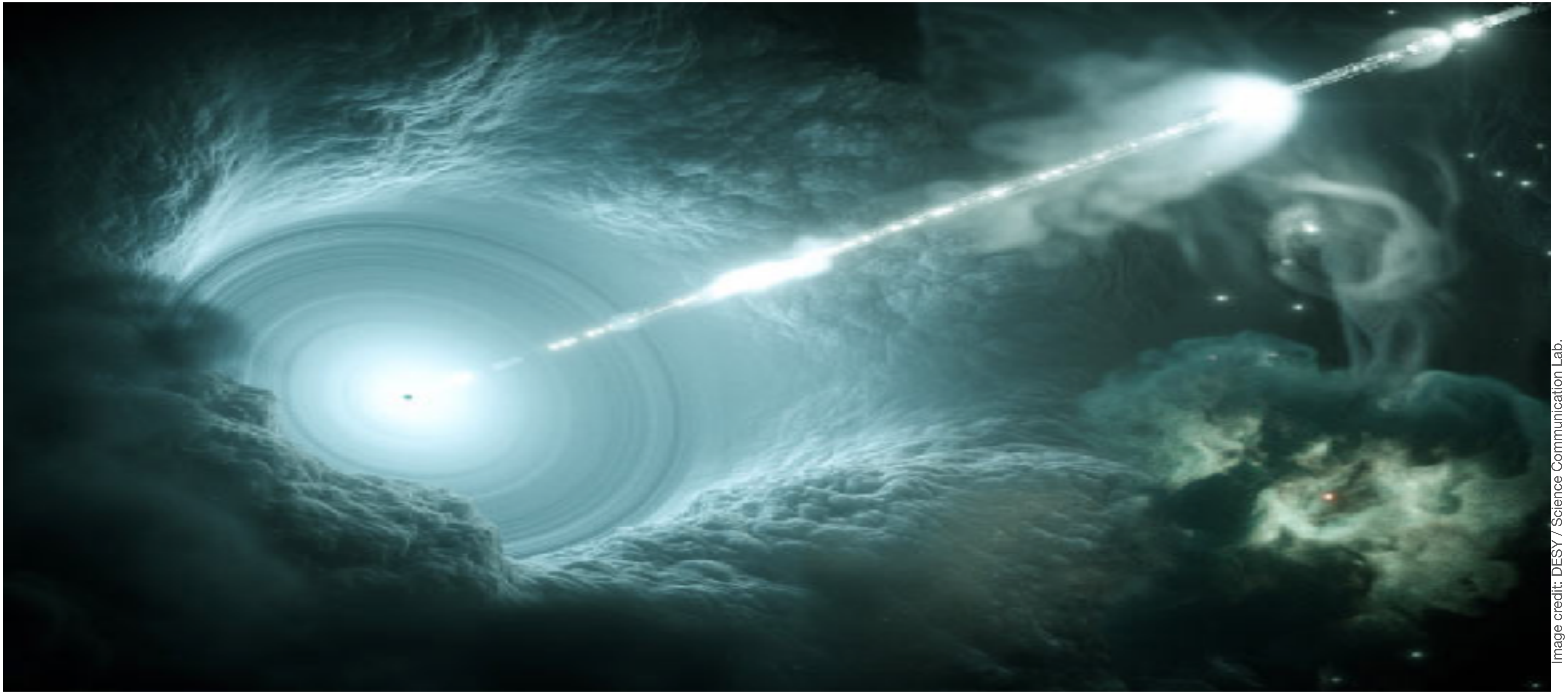


Image credit: DESY / Science Communication Lab.

To look for individual sources on archive:

- All-sky search with no a-priori on the direction, the time and the nature of the source
- Candidate source list (known directions)
- Time-dependent analysis (known time periods and directions)

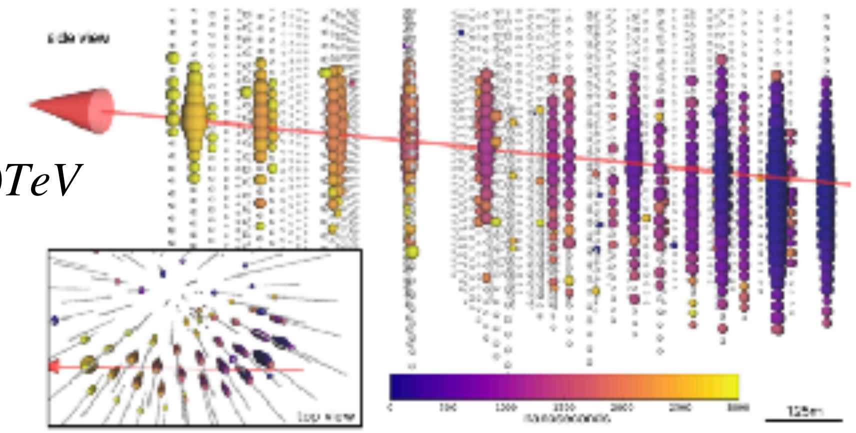
The most efficient way is to be able to associate a small number of neutrinos with a transient phenomena seen at different wavelengths. (cf Talk of E. Blaufuss)

TXS0506+056 seen by IceCube

Neutrinos from the AGN blazar TXS 0506+056

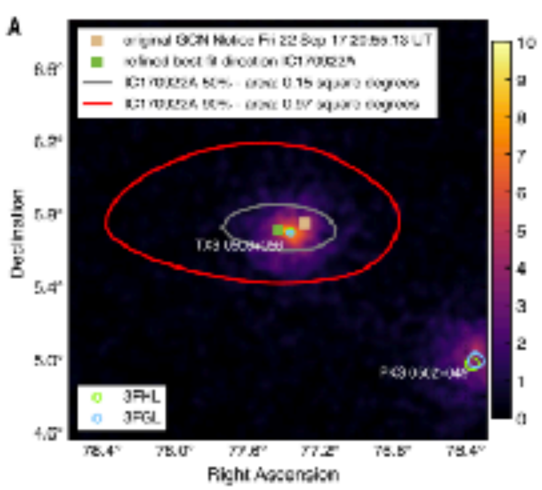
Sept. 22, 2017:
A neutrino in coincidence with a blazar flare

$E_{\nu_\mu} \approx 270TeV$



2014-2015: A (orphan) neutrino flare found from the same object in historical data

Science 361 (2018) no. 6398, eaat2890

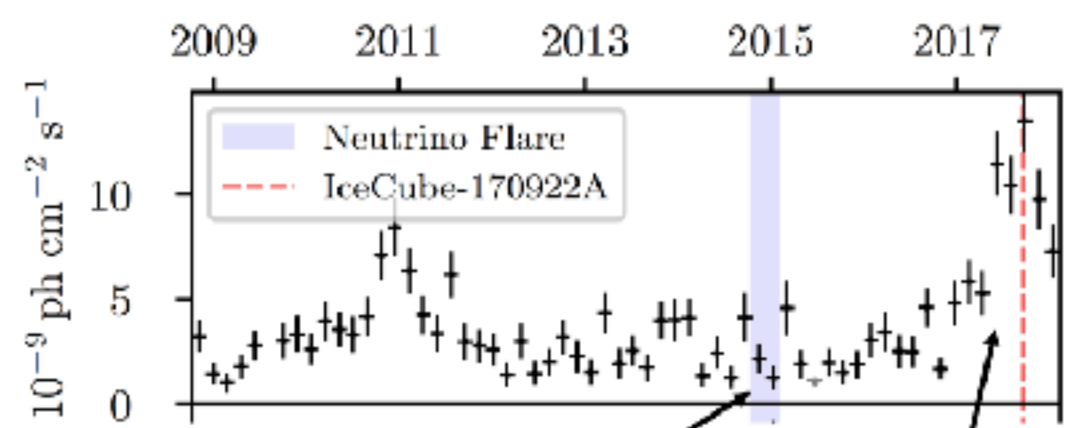


Observed by Fermi-*LAT* and MAGIC

Significance for correlation: 3σ

Science 361 (2018) no. 6398, eaat1378

Fermi-*LAT* data; Padovani et al, MNRAS 480 (2018) 192

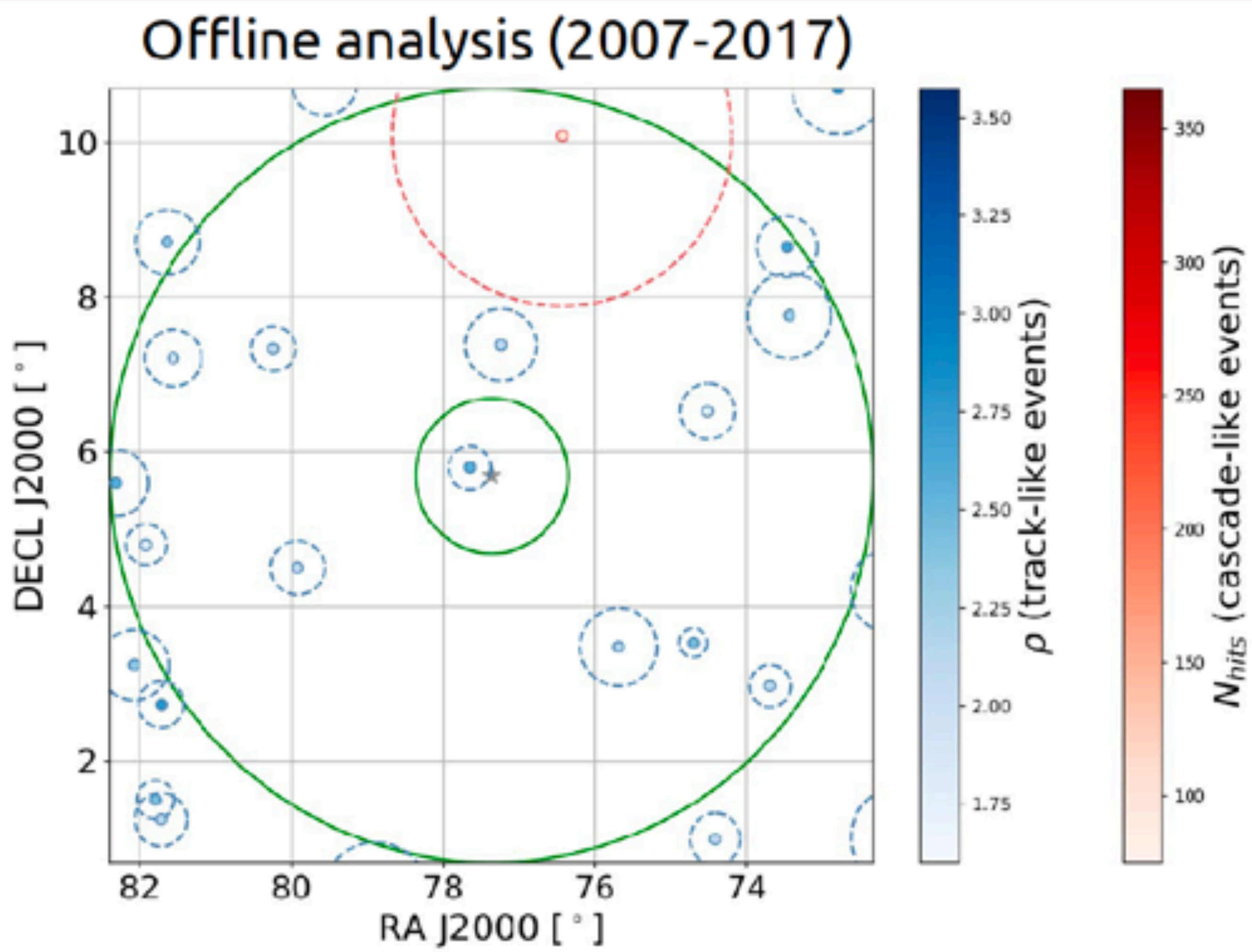


At 2014-15 neutrino flare

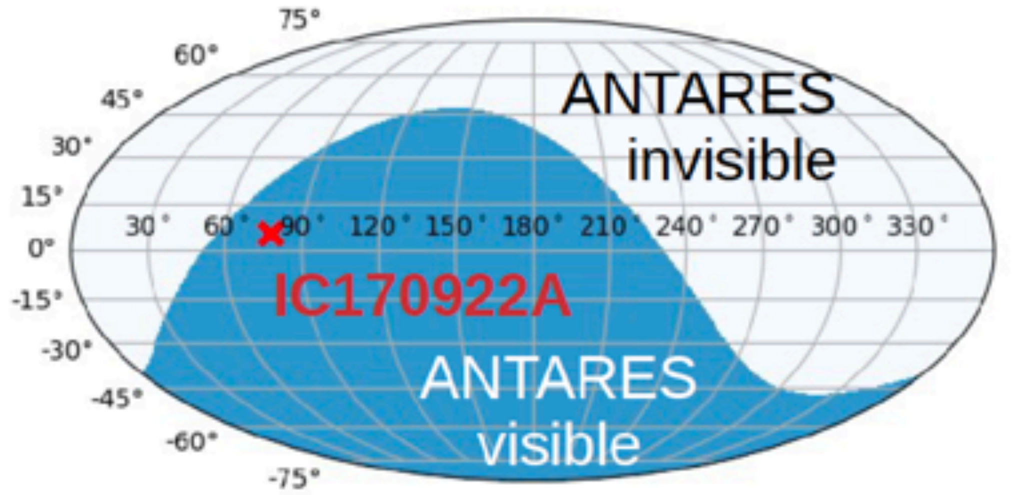
The 2017 flare

Cf Talk of E. Blaufuss on Thursday

TXS0506+056 seen by ANTARES



1.03 signal-like events fitted → p-value = 3.4% (pre-trial)
3rd most significant candidate out of 107*



Online data-stream analysis
→ no coincident event
ATEL #10773 released by ANTARES the following day

+ time dependent search for space-time clustering with the IC neutrino flare – no excess observed

* off the published 2007-2015 analysis; 87% post-trial

ApJ Lett **863** no.2: L30, 2018

Difficult interpretation of TXS0506+056

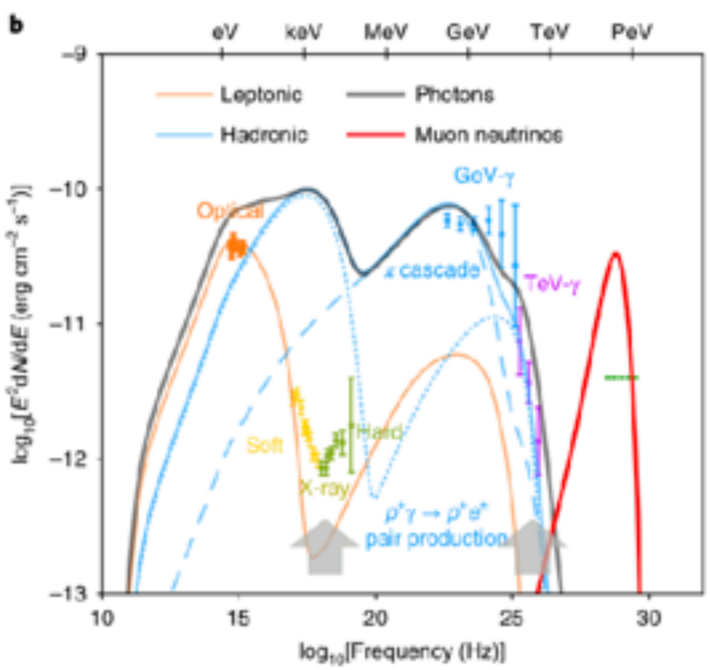
Neutrino production rate ~ Proton density x Radiation density

- Proton density ~ Proton injection x confinement time
- Radiation density given by source luminosity, size, geometry (R', G, Lg, ...)

$$p+\gamma \rightarrow \Delta^{+} \rightarrow \begin{cases} n+\pi^{+} & \Rightarrow \nu \\ p+\pi^{0} & \Rightarrow \gamma \end{cases}$$

1 zone model for 2017 flare

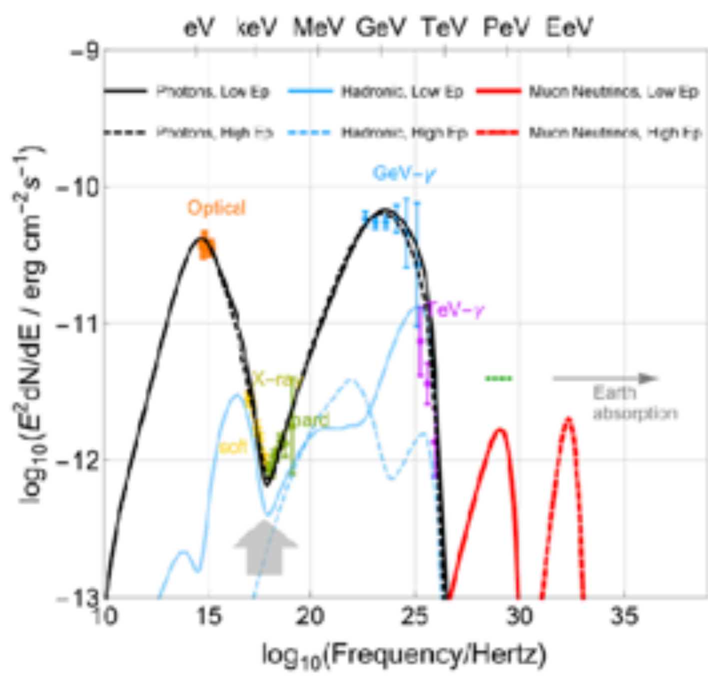
Hadronic (π cascade) models



- Violate X-ray data

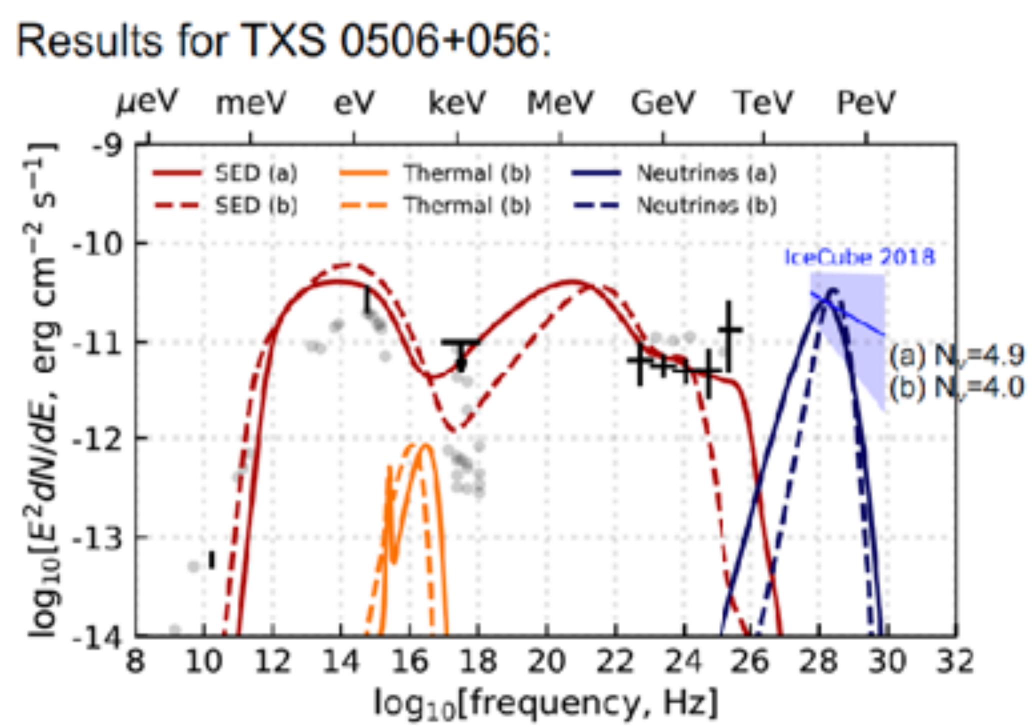
X-ray (and TeV γ-ray) data indicative for hadronic origin

Hybrid or p synchrotron models



- **Violate energetics (L_{edd}) by a factor of a few hundred or significantly exceed ν energy**

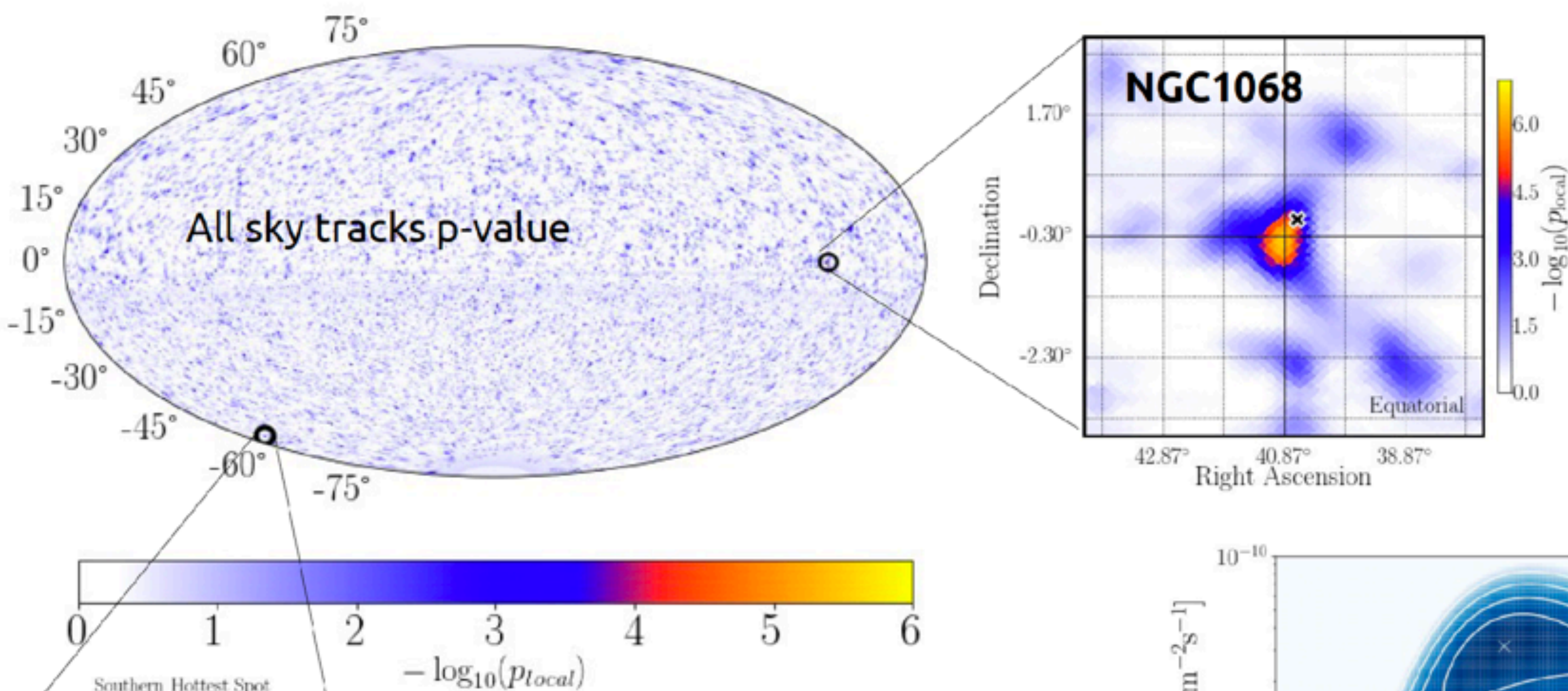
External radiation field for 2014-15 flare

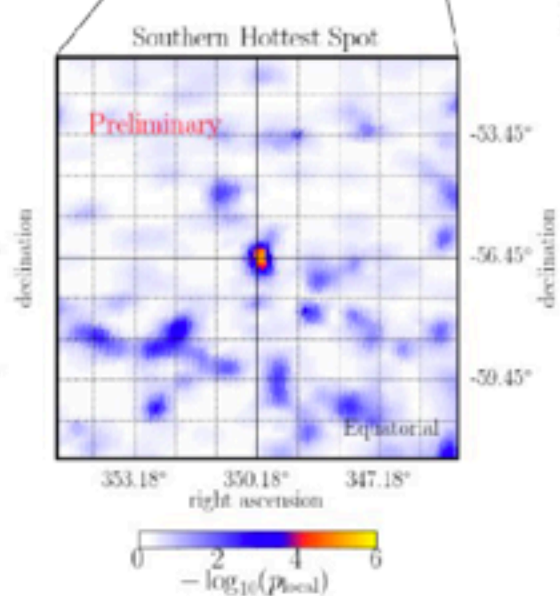


Rodrigues, et al, ApJL 874 (2019) L29; see also Reimer et al, 1812.05654

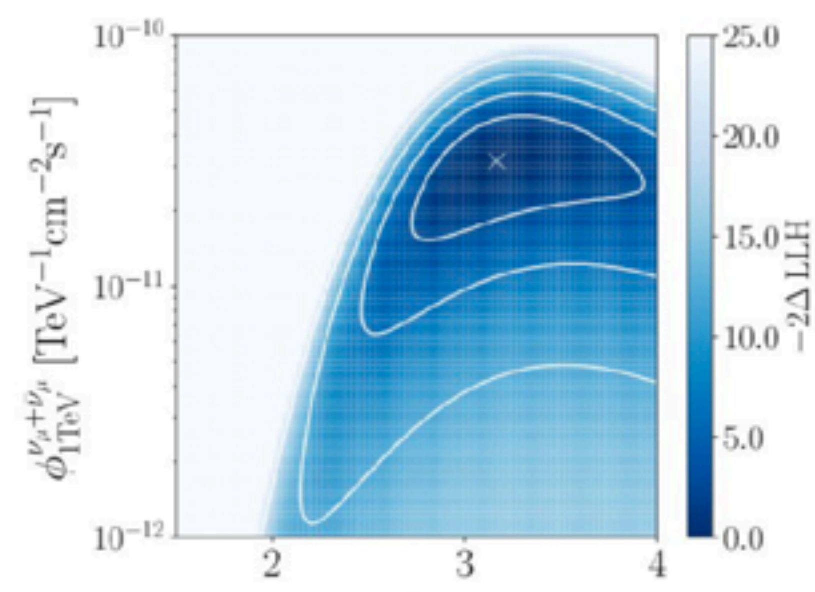
Gao, Fedynitch, Winter, Pohl, Nature Astronomy 3 (2019) 88;
Cerutti et al, 2018; Sahakyan, 2018; Gokus et at, 2018; Keivani et al, 2018

Point-source searches by IceCube



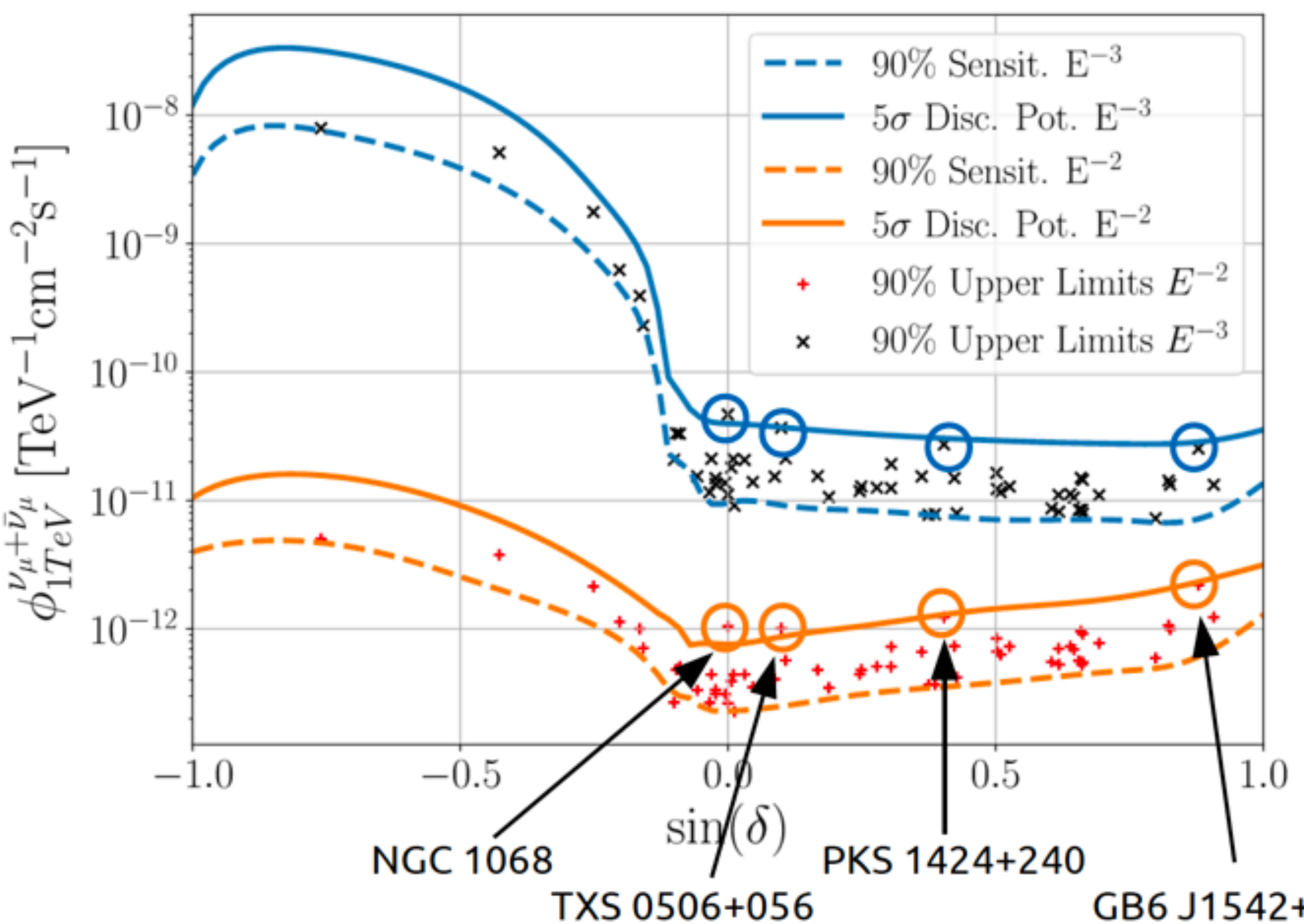


pre-trial p-values
Still not that significant,
but some hints for
clustering



PoS(ICRC2019)851 + arxiv:1910.08488

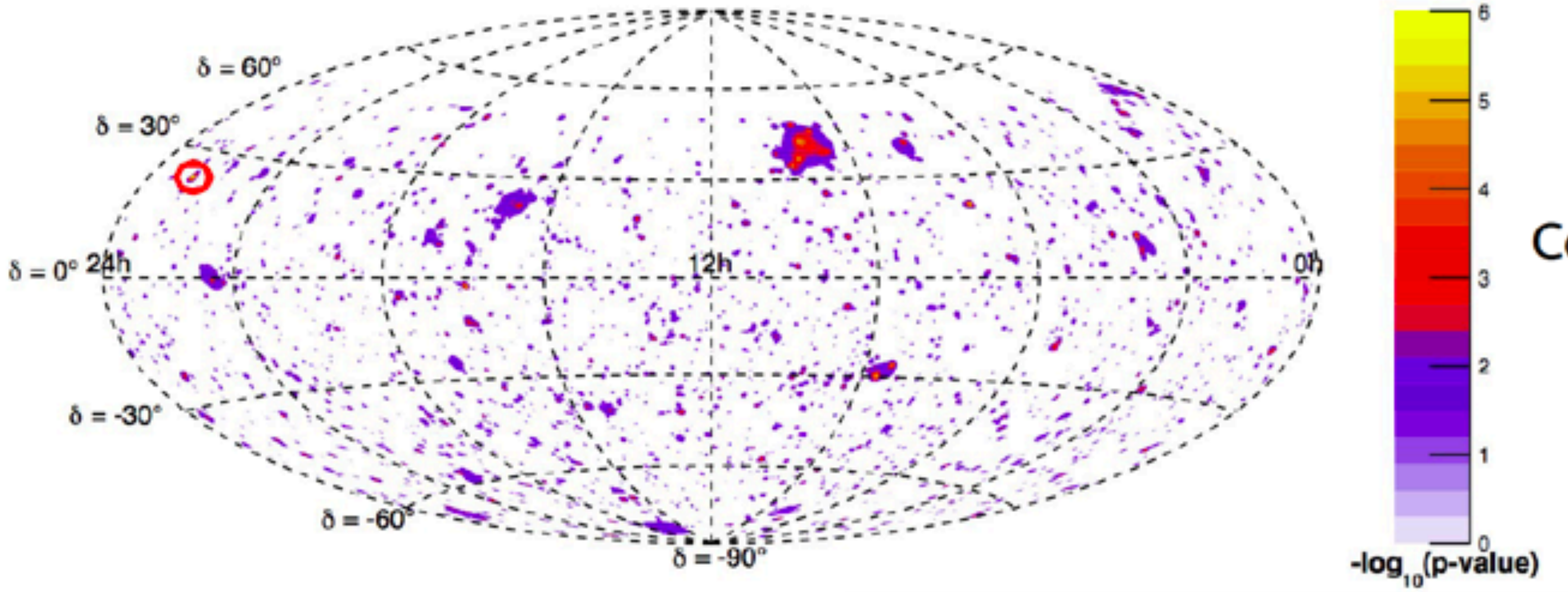
Point-source searches by IceCube



Somewhere between 2-3σ excess

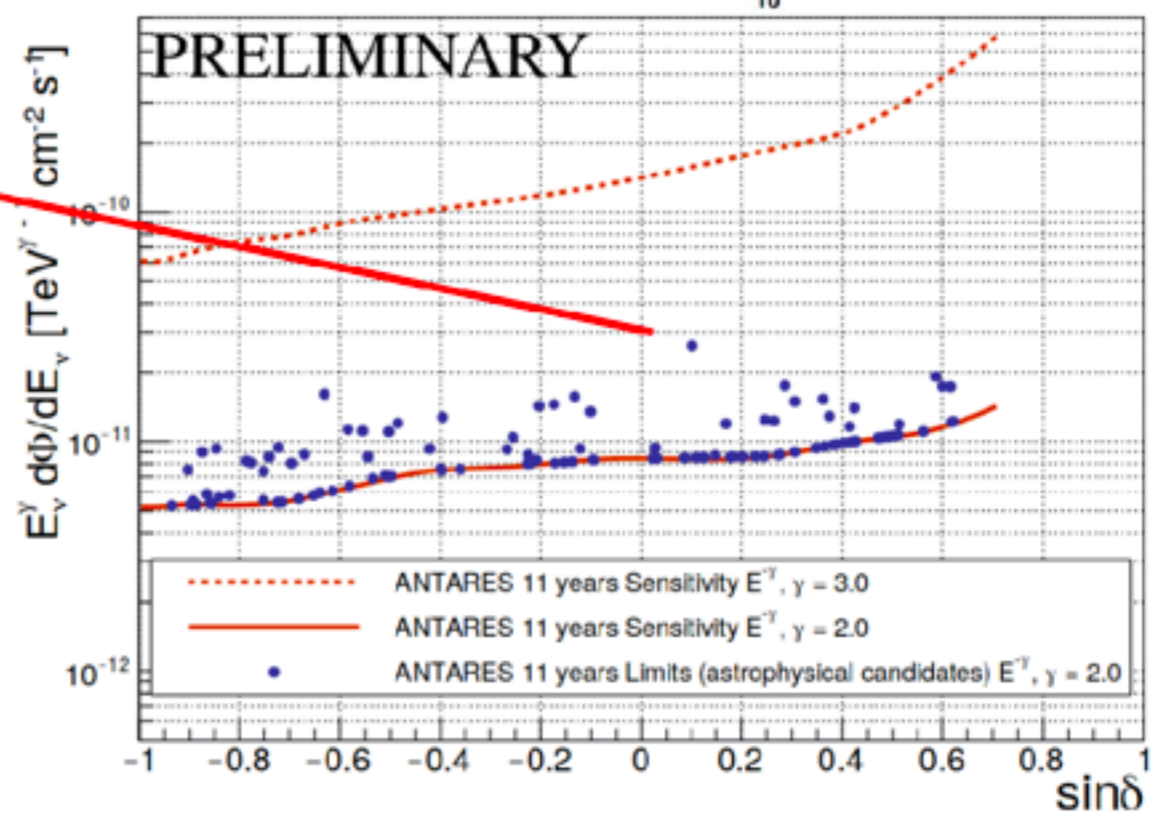
PoS(ICRC2019)851 + arxiv:1910.08488

Point-source searches by ANTARES



Combined tracks + showers

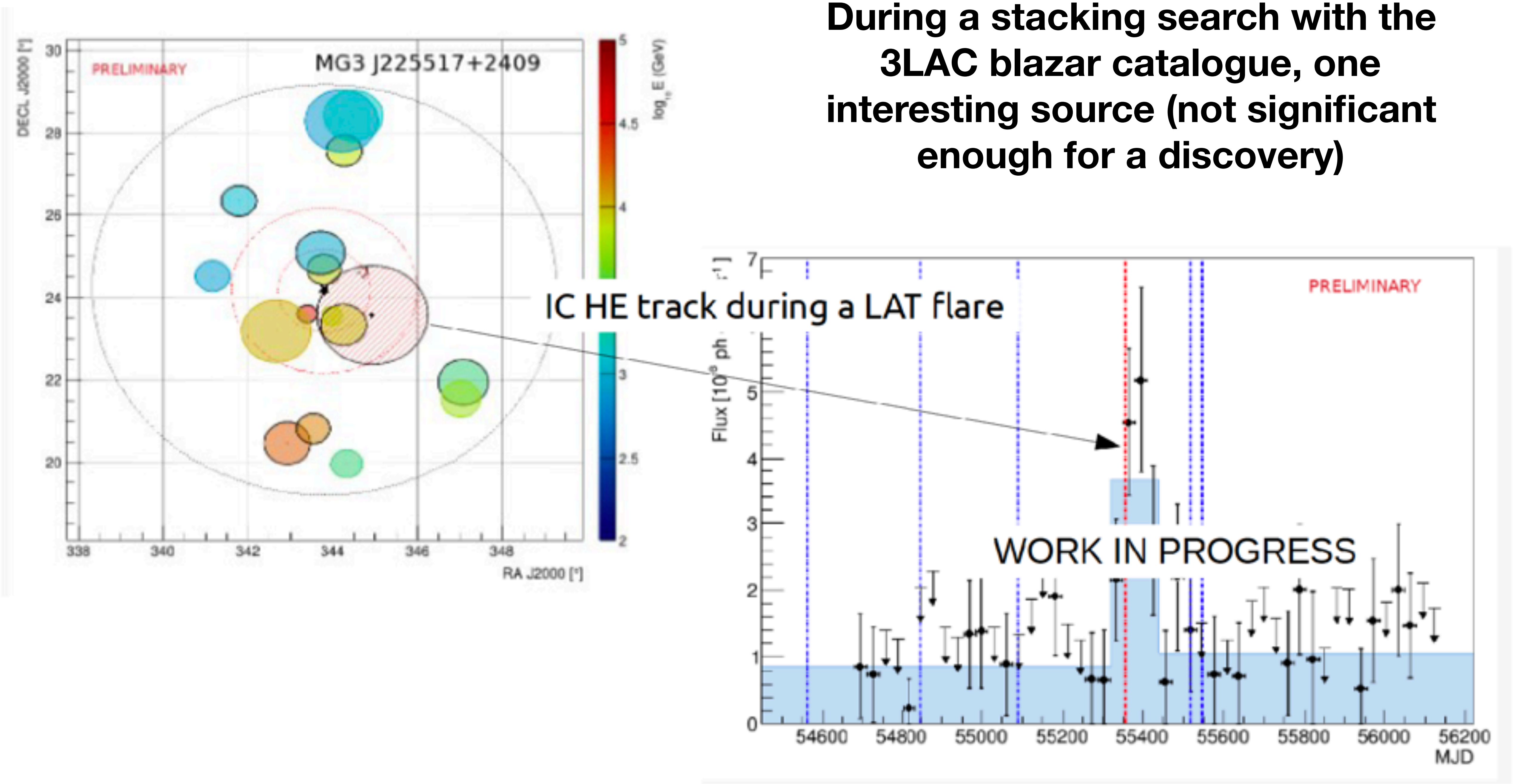
HESSJ0632+057
(α,δ) =(98.24°,5.81°)
1.4σ



Still more sensitive than IceCube for soft spectra in the Southern Sky

PoS(ICRC2019)920

Point-source searches by ANTARES

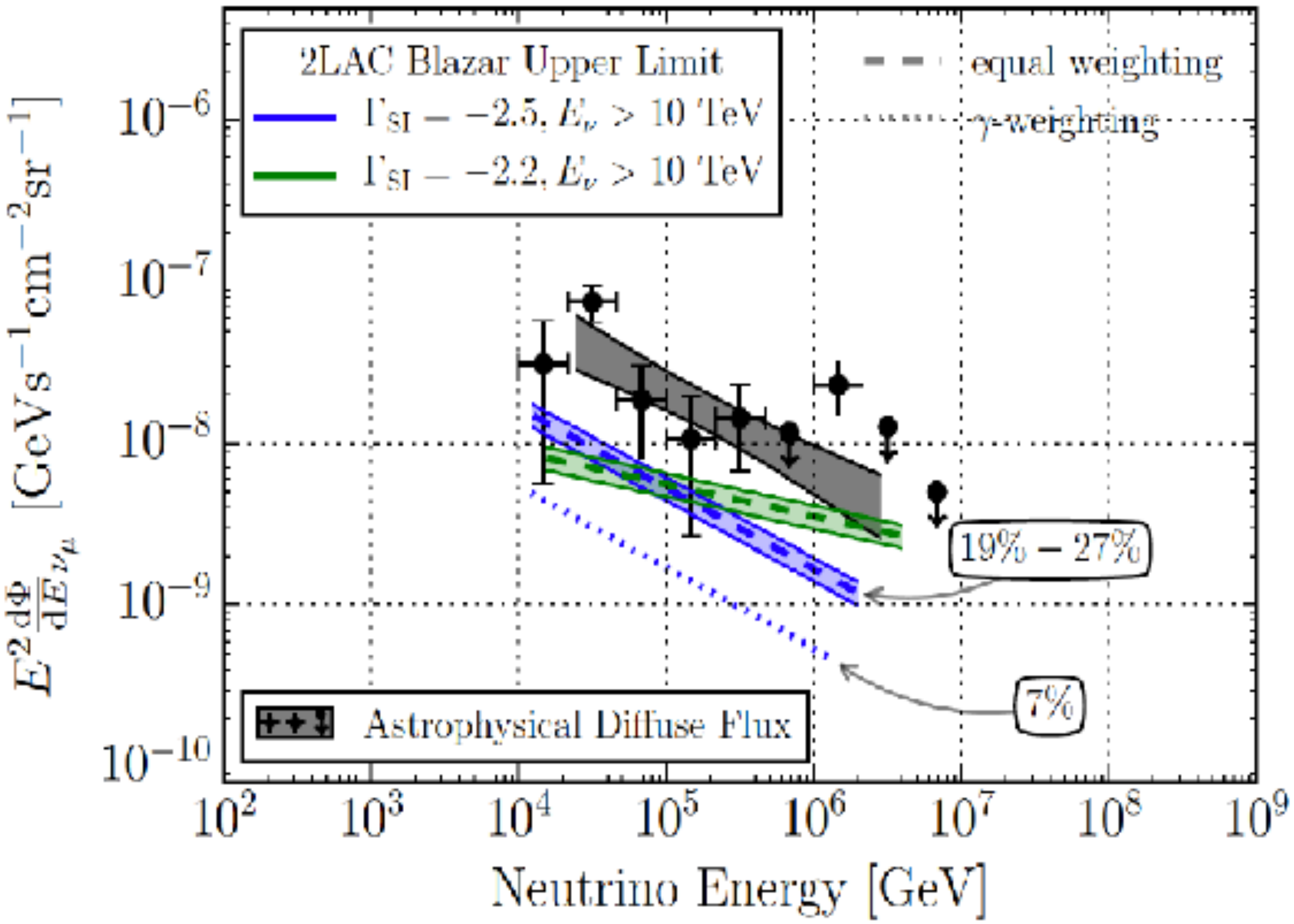


During a stacking search with the 3LAC blazar catalogue, one interesting source (not significant enough for a discovery)

PoS(ICRC2019)840

Are γ-ray blazars the main sources of HE neutrinos ?

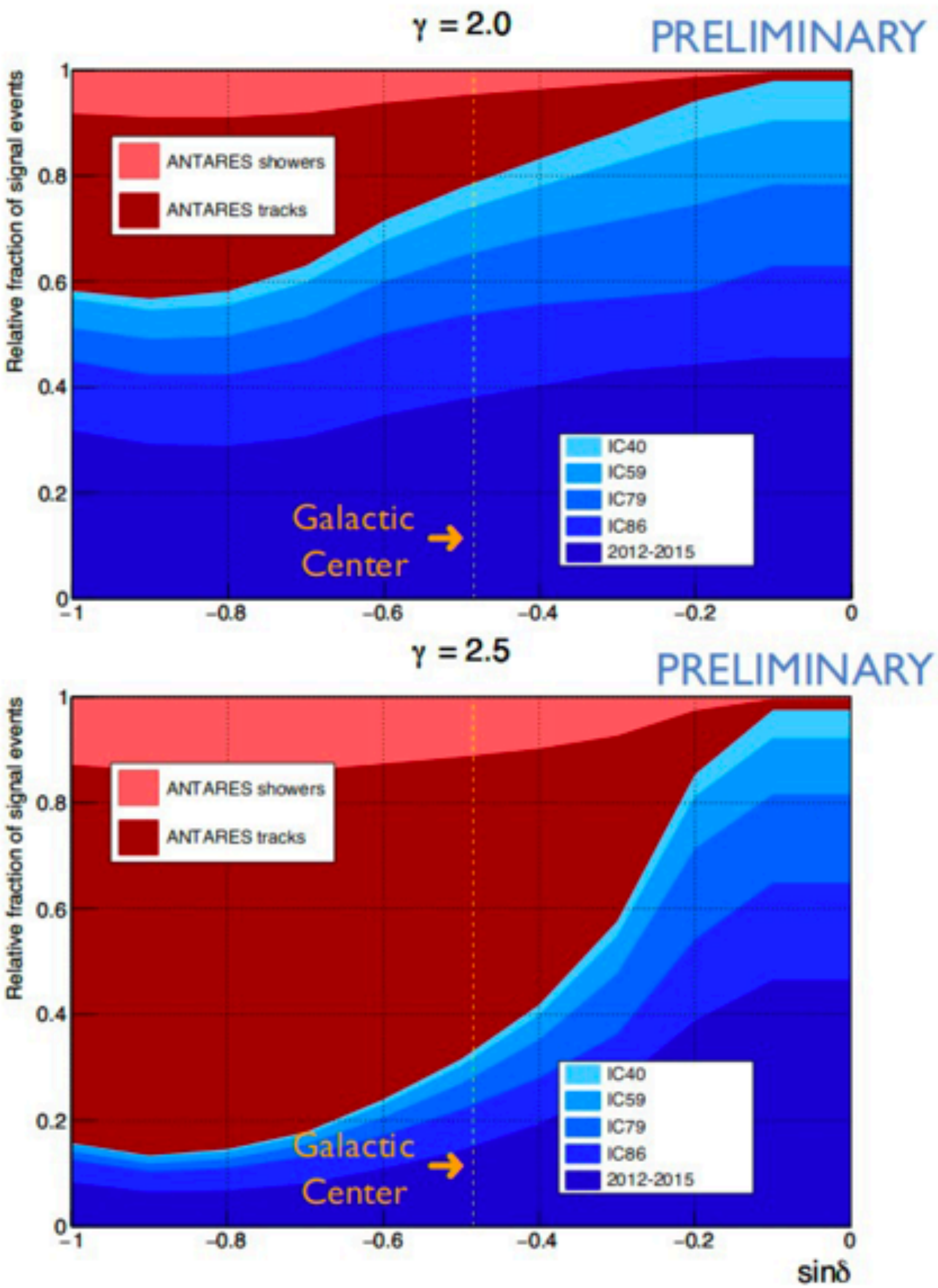
Limits from AGN stacking searches
(→ visible objects)



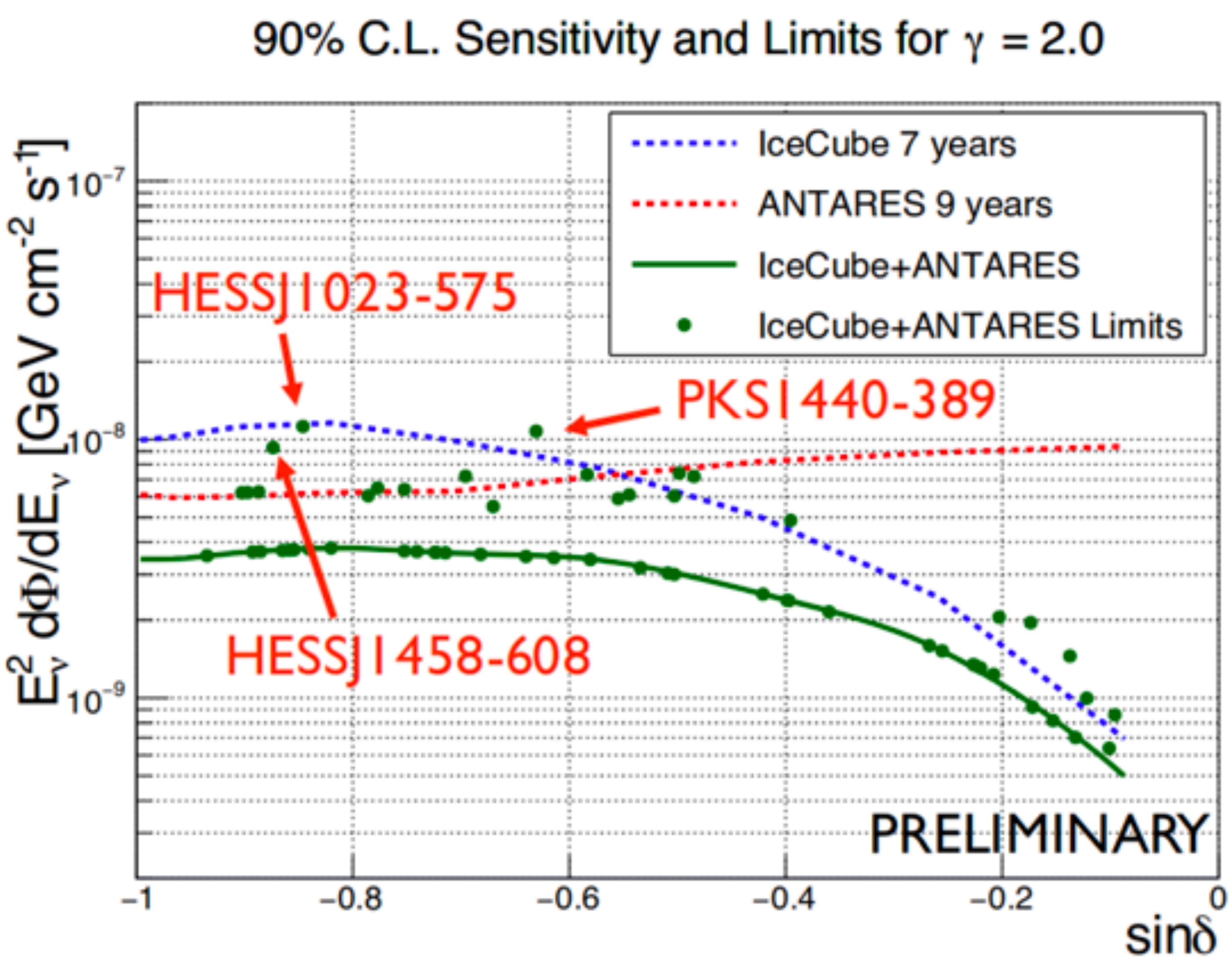
Stacking search with 862 Fermi 2LAC blazars
$\Longrightarrow$ No significant excess.
Upper limit on the steady flux contribution of the resolved blazar (quite dependent on input hypothesis).

IceCube, Astrophys. J. 835 (2017) 45
Palladino, Rodrigues, Gao, Winter, ApJ 871 (2019) 41;
Lower fig. from Petropoulou et al, arXiv:1911.04010
also found in multi-epoch description of TXS 0506+056

Joint PS search by ANTARES+IceCube

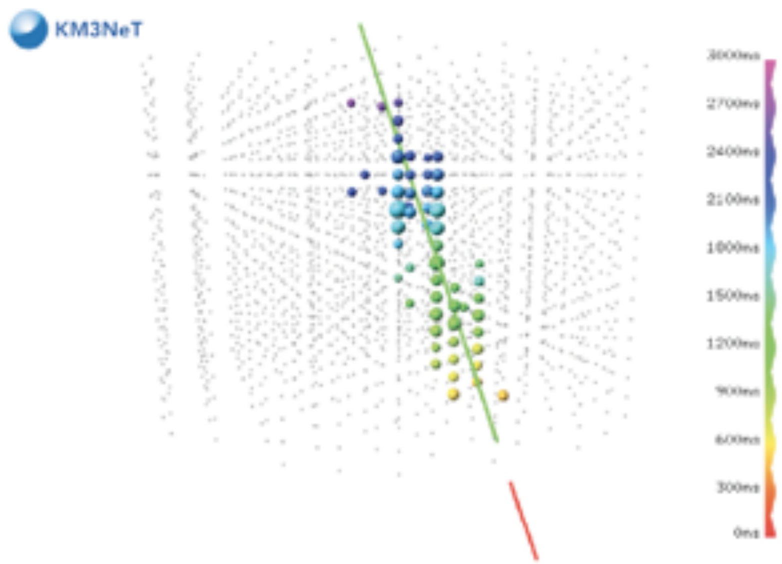


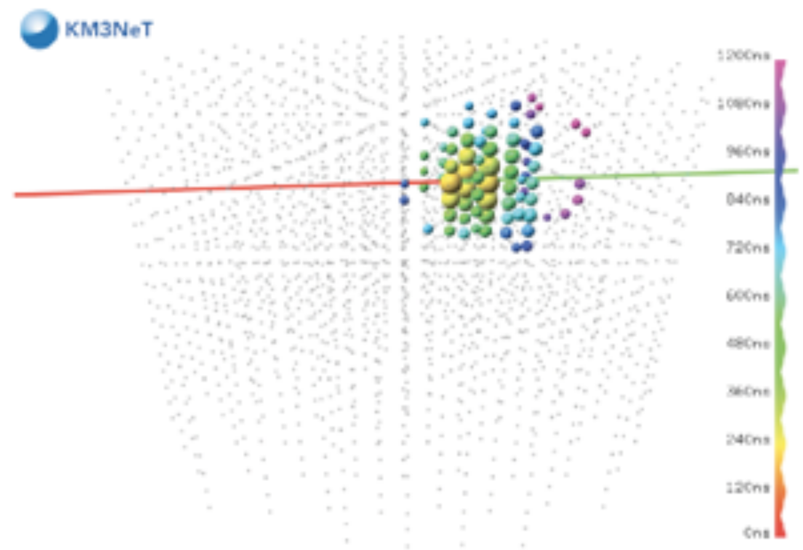
PoS(ICRC2019)919



+ constraints on SgrA* in the backup

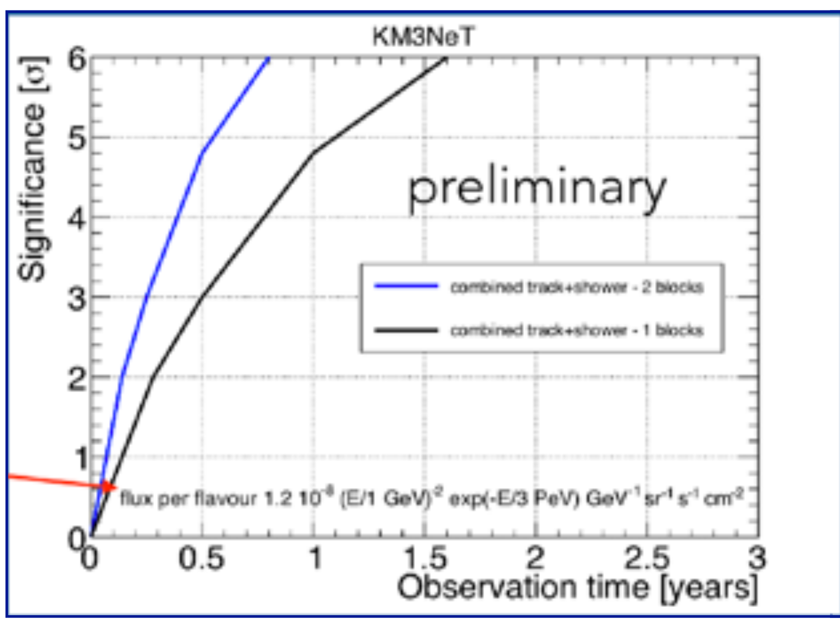
Point-source searches with KM3NeT



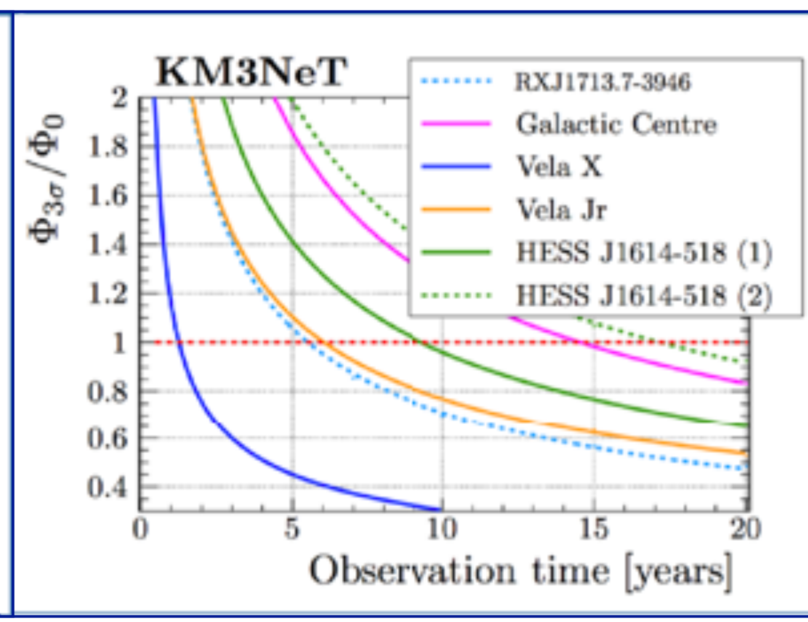


Tracks:
ARCA: < 0.1º (>100 TeV)
ORCA: 1 - 2º (100 GeV - 1 TeV)

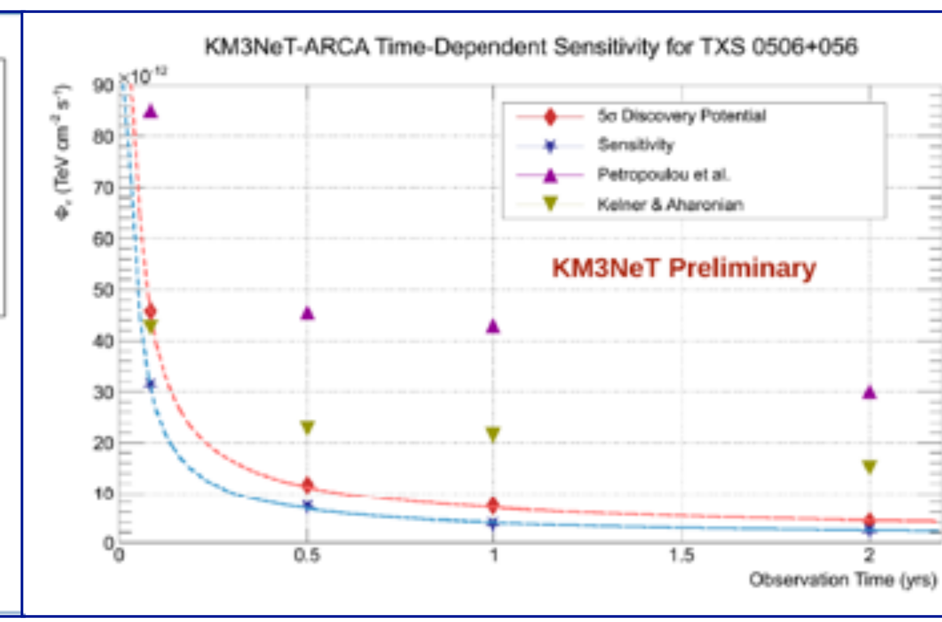
Cascades:
ARCA: < 1.5º (>100 TeV)
ORCA: ~4 - 5º (100 GeV - 1 TeV)



Diffuse ν flux



Galactic sources



Extragalactic sources

Summary

High Energy Neutrinos are opening a new window into the cosmos:

- All-flavor cosmic neutrino diffuse fluxes well established (>8 σ)
- Compelling evidence for the first high-energy neutrino source: a blazar
- Main limitations are the low statistic of neutrinos (Gen2) and the quality of reconstructions (KM3NeT)
- Multi-messenger studies are essential for identification of sources