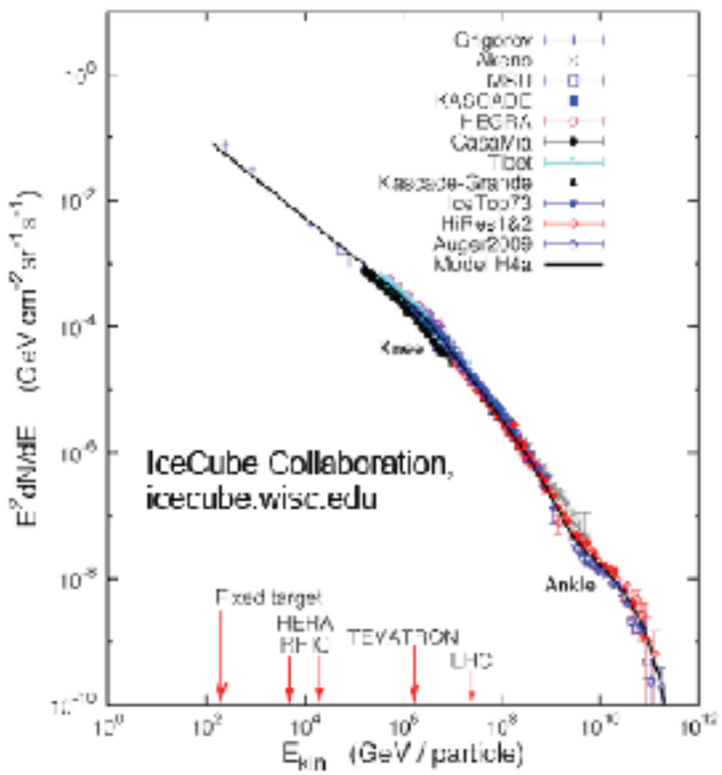
VERS UNE ASTRONOMIE NEUTRINO AVEC IceCube+ANTARES+KM3NeT

DAMIEN DORNIC (CPPM)

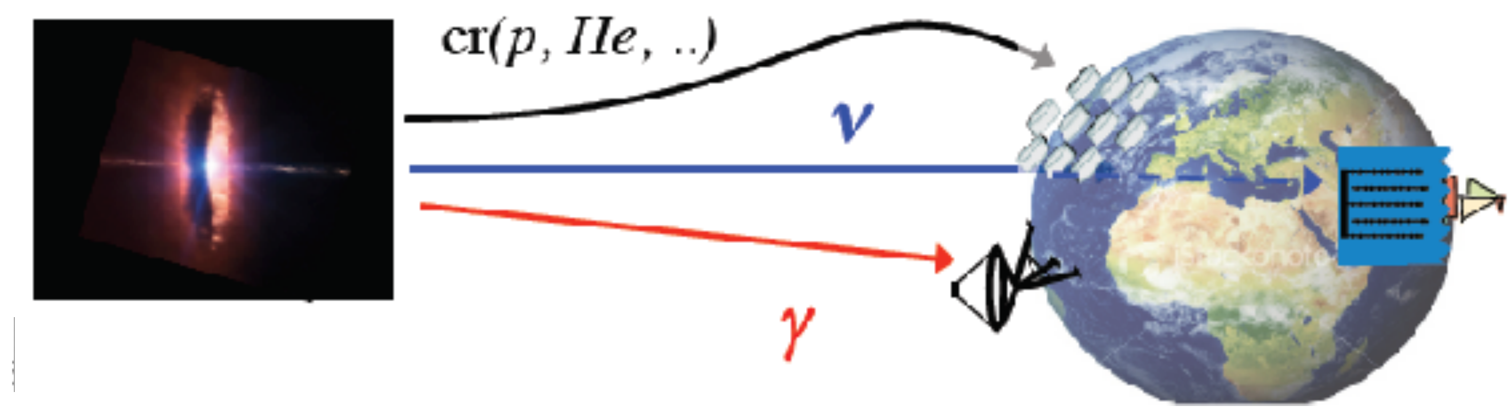
CFR Cos: Meeting de la communauté de recherche sur le rayonnement cosmique

APC - 26-28 mars 2018

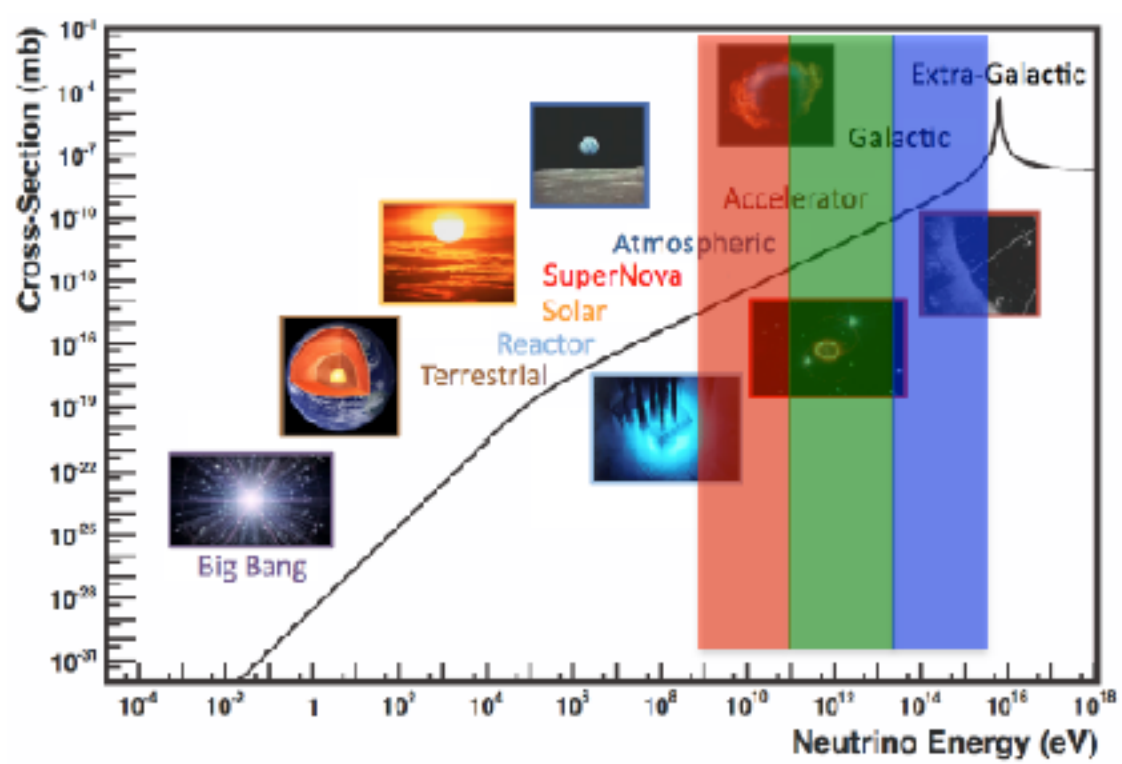
NEUTRINO AS COSMIC MESSENGER



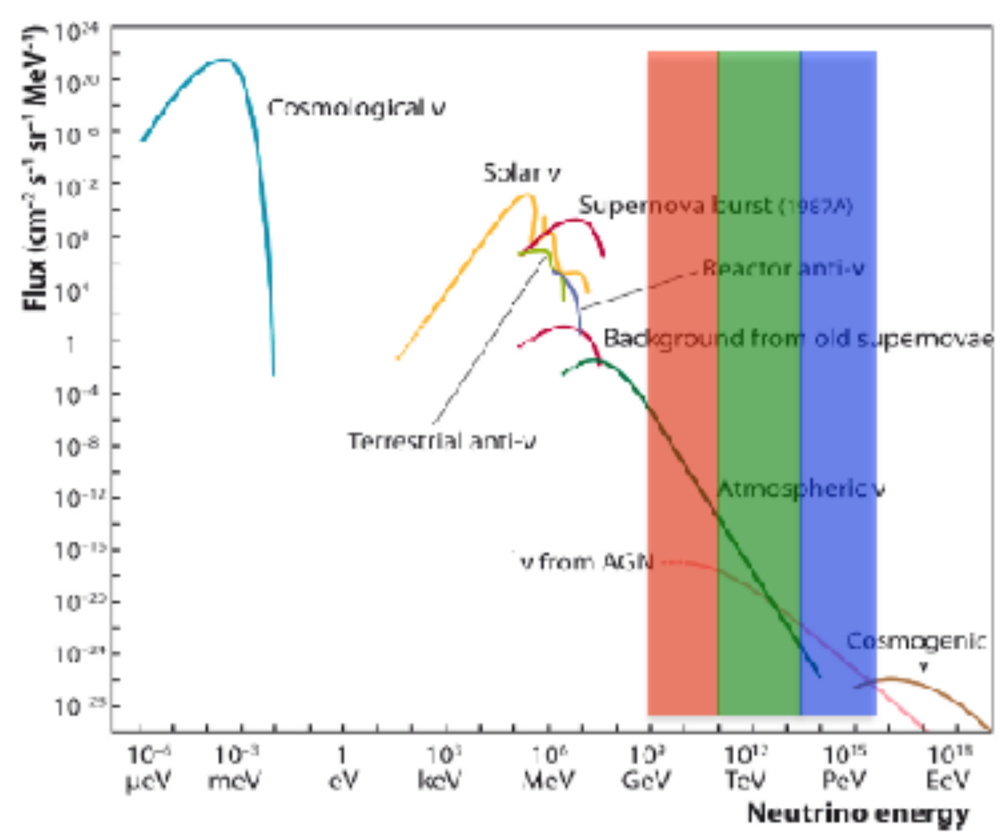
Neutrinos: smoking gun for cosmic-ray interactions



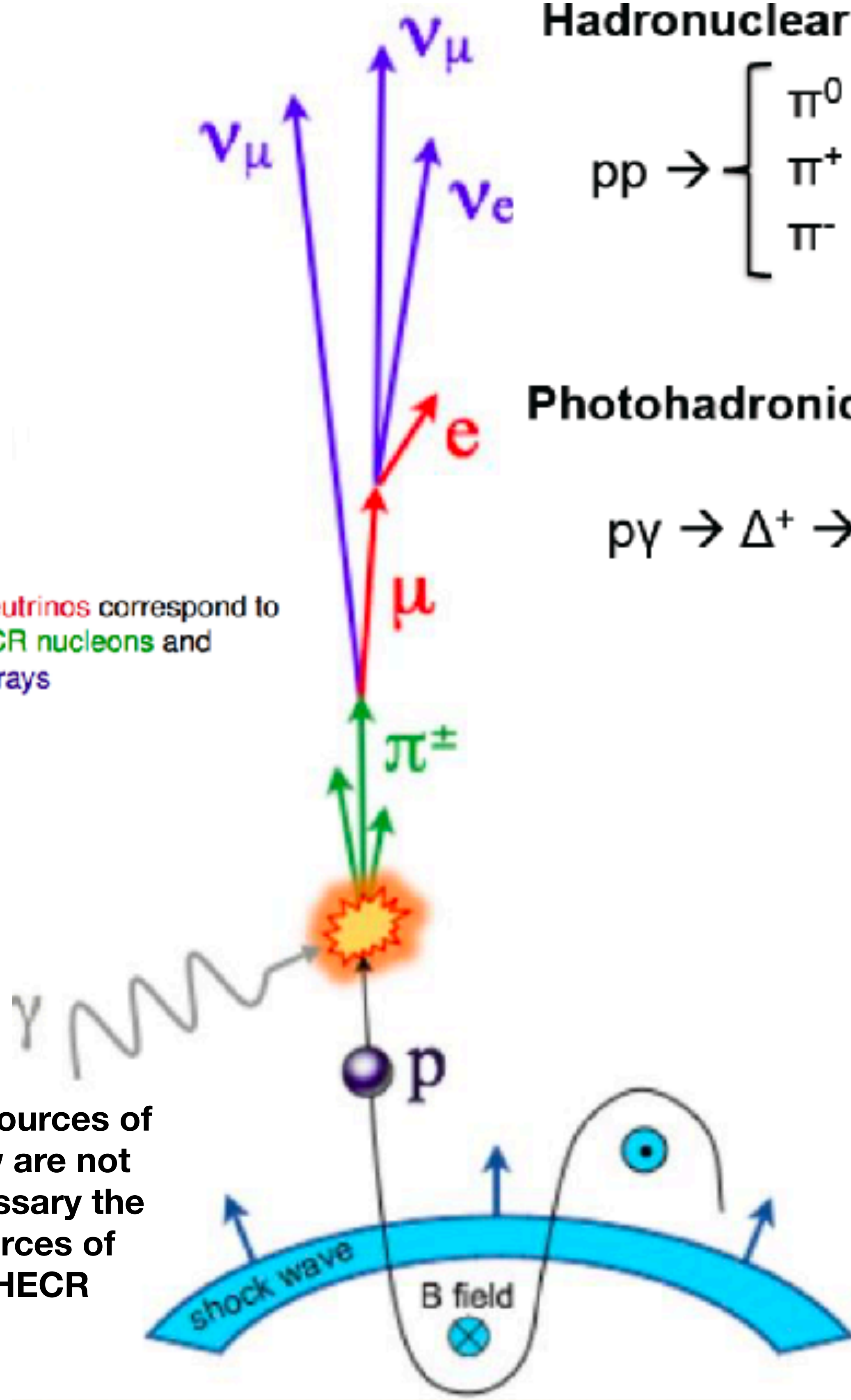
- 3 GeV – 1 TeV: atmospheric neutrinos, dark matter… ORCA
- 100 GeV - 30 TeV: various galactic (TeV gamma) sources ANTARES
- 30 TeV – 3 PeV: IceCube signal (astrophysical flux) ARCA



Formaggio & Zeller, RevModPhys 84 (2012) 1307



HE NEUTRINO PRODUCTION

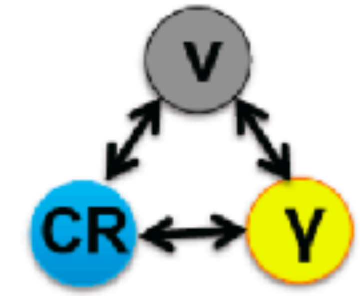


1 PeV neutrinos correspond to
20 PeV CR nucleons and
2 PeV γ-rays

The sources of HE ν are not necessary the sources of UHECR

Hadronuclear (e.g. star burst galaxies and galaxy clusters)

$$pp \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\,\gamma \\ \pi^+ \rightarrow \mu^+\,\nu_\mu \rightarrow e^+\,\nu_e\,\nu_\mu\,\bar{\nu}_\mu \\ \pi^- \rightarrow \mu^-\,\bar{\nu}_\mu \rightarrow e^-\,\bar{\nu}_e\,\bar{\nu}_\mu\,\nu_\mu \end{cases}$$



Photohadronic (e.g. gamma-ray bursts, active galactic nuclei)

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\,\pi^0 \rightarrow p\,\gamma\,\gamma \\ n\,\pi^+ \rightarrow n\,\mu^+\,\nu_\mu \rightarrow n\,e^+\,\nu_e\,\bar{\nu}_\mu\,\nu_\mu \end{cases}$$

cosmic ray + gamma

cosmic ray + neutrinos

Neutrino flavour ratio at source:

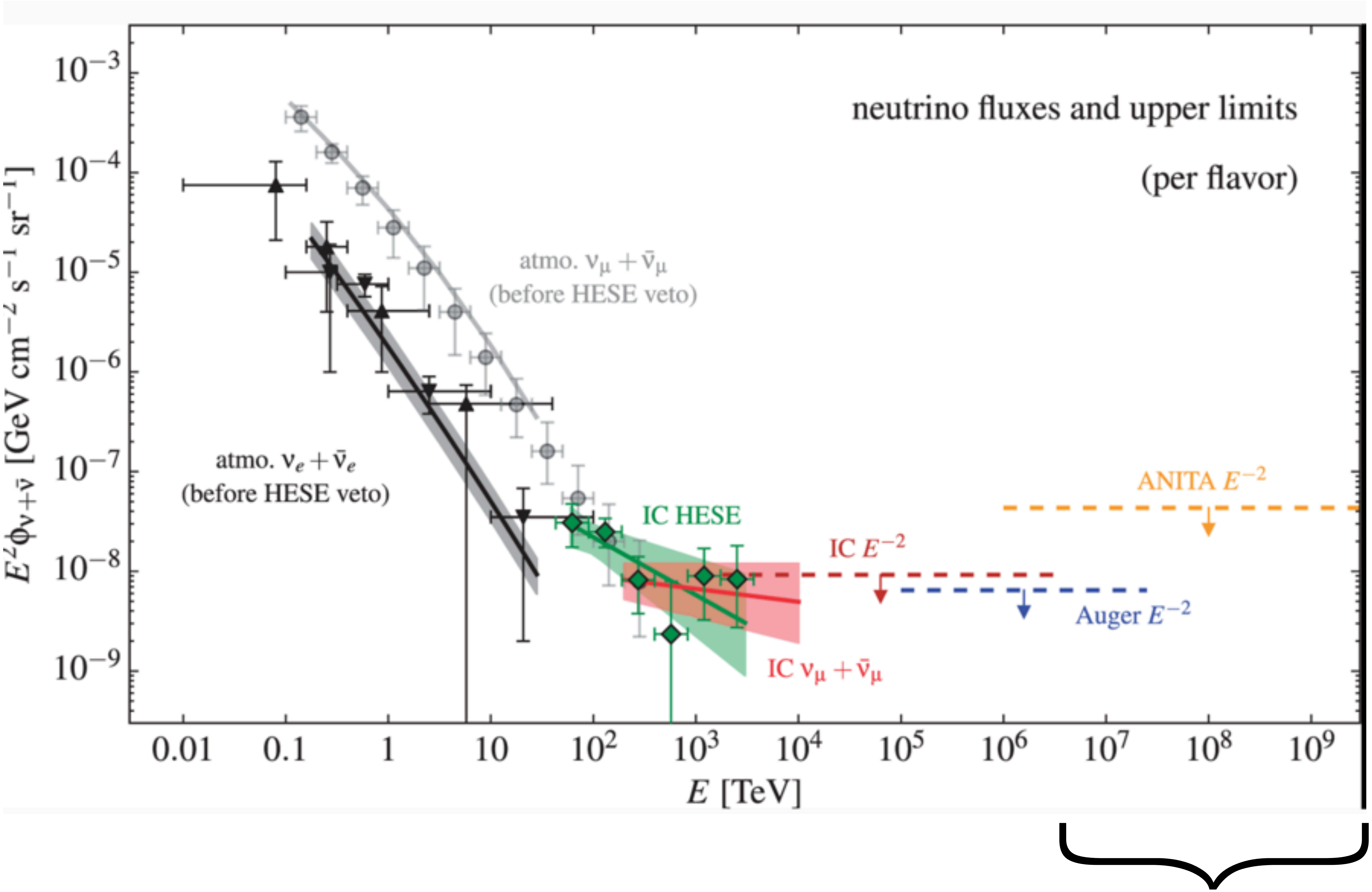
pion-muon decay

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

Oscillations average out over cosmic baselines

$$\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$$

HE NEUTRINO FLUXES

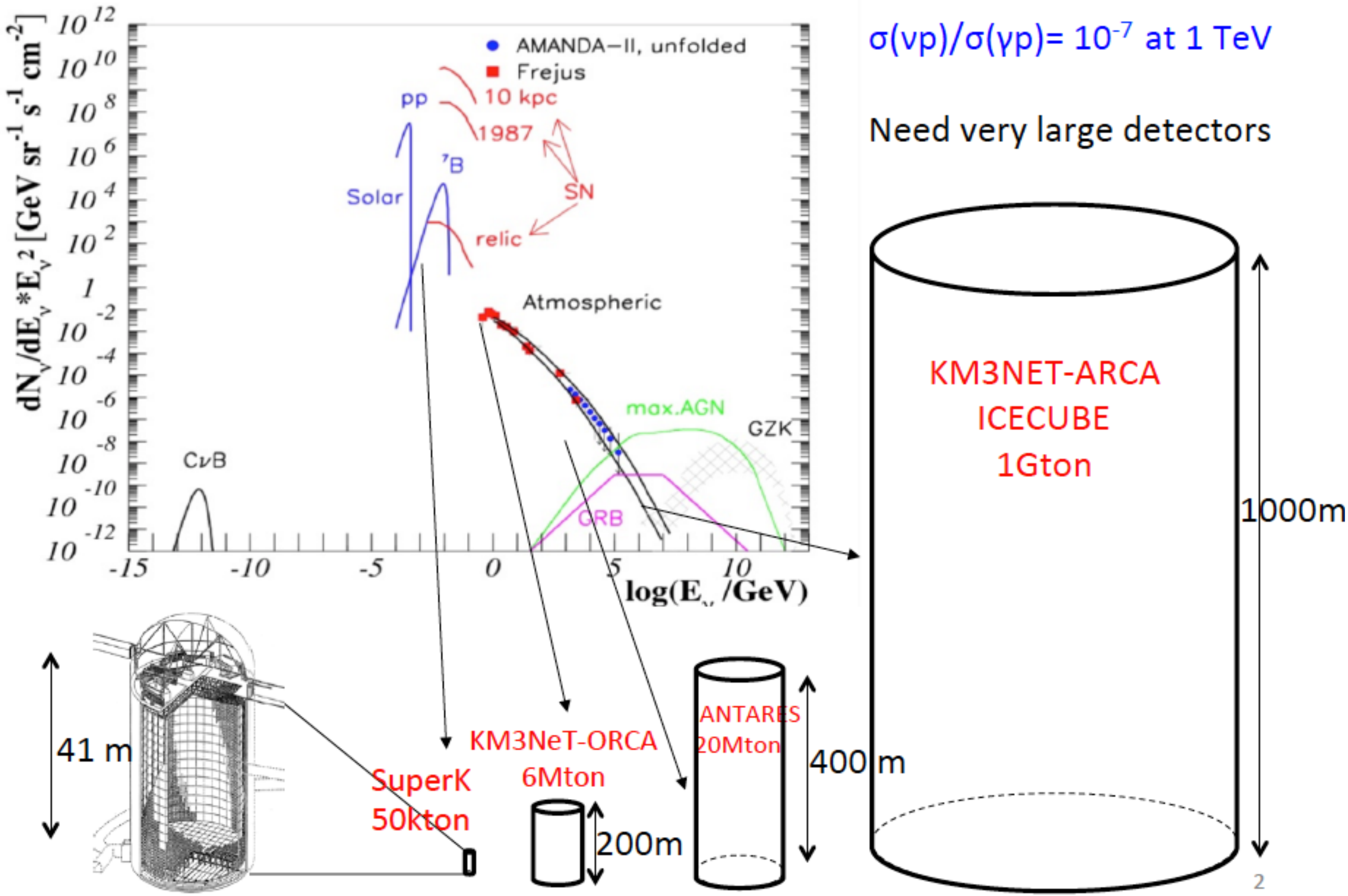


Cf O. Martineau's talk

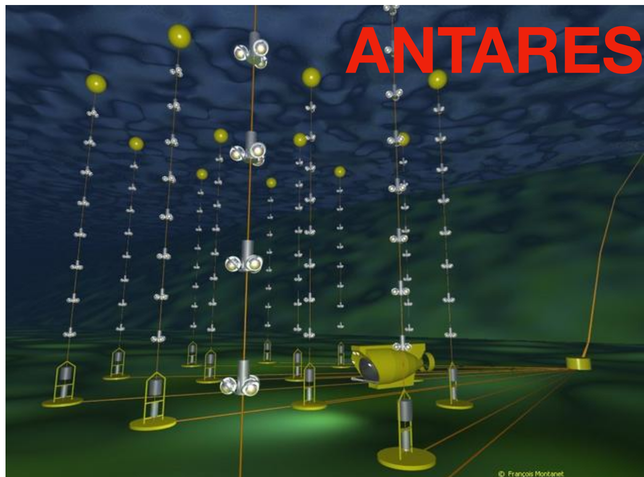
HE NEUTRINO DETECTORS

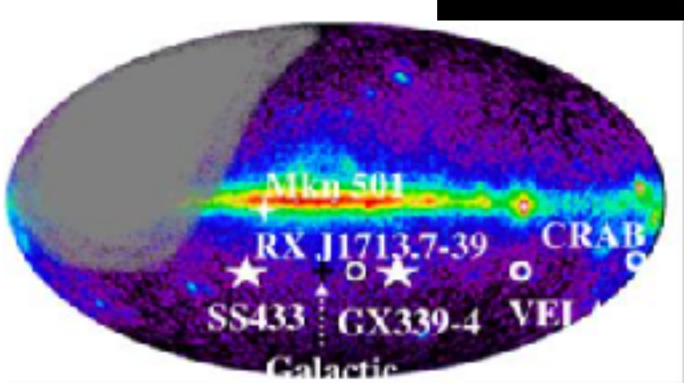
$\sigma(\nu p)/\sigma(\gamma p) = 10^{-7}$ at 1 TeV

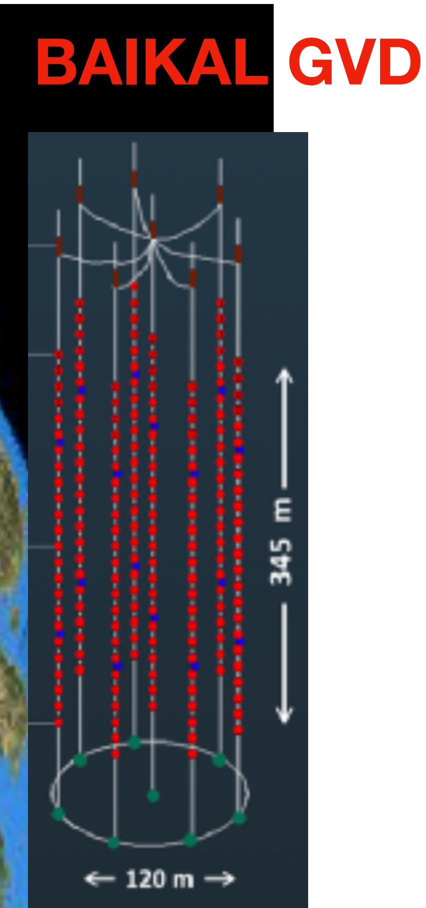
Need very large detectors

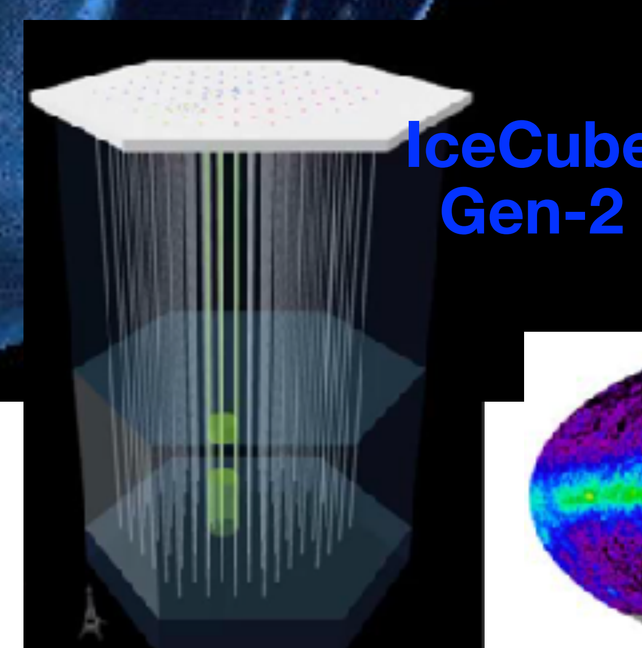


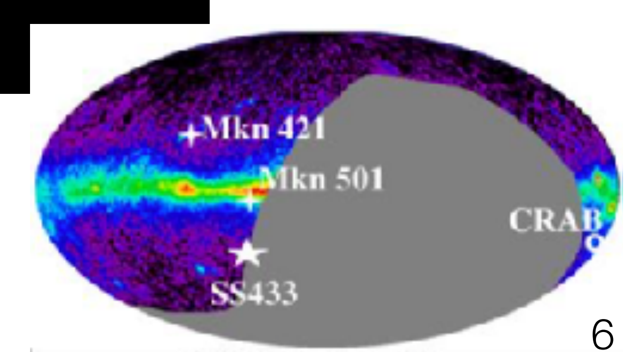
HE NEUTRINO DETECTORS





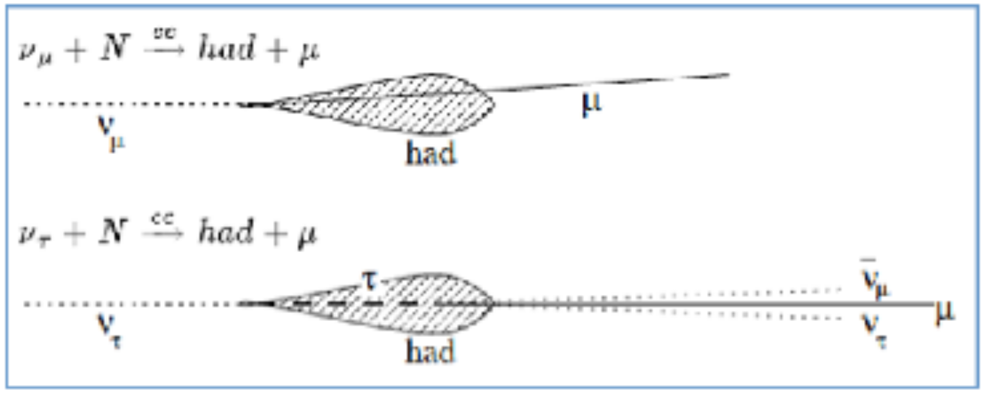






<u>GNN</u>: Global Neutrino Network linked all HE neutrino telescopes + provide framework for regular combined meetings and combined analysis

ALL-FLAVOR NEUTRINO TOPOLOGIES

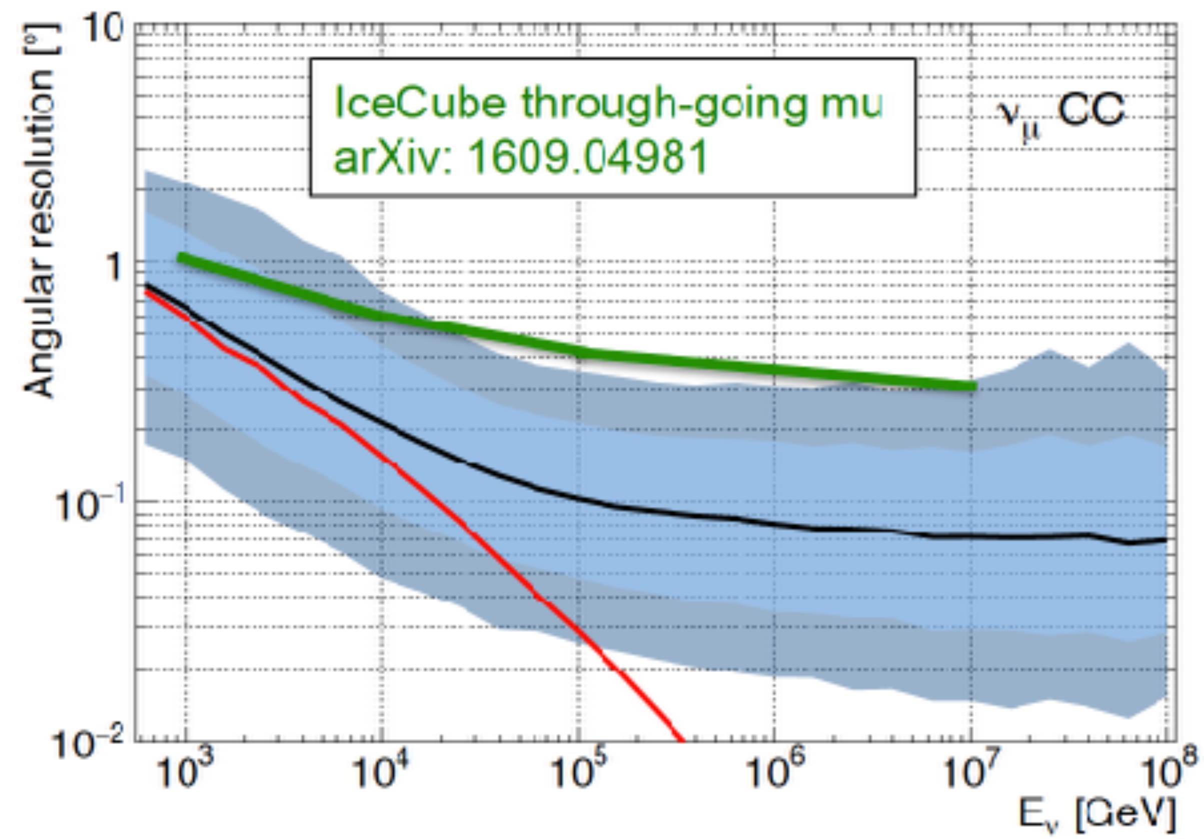


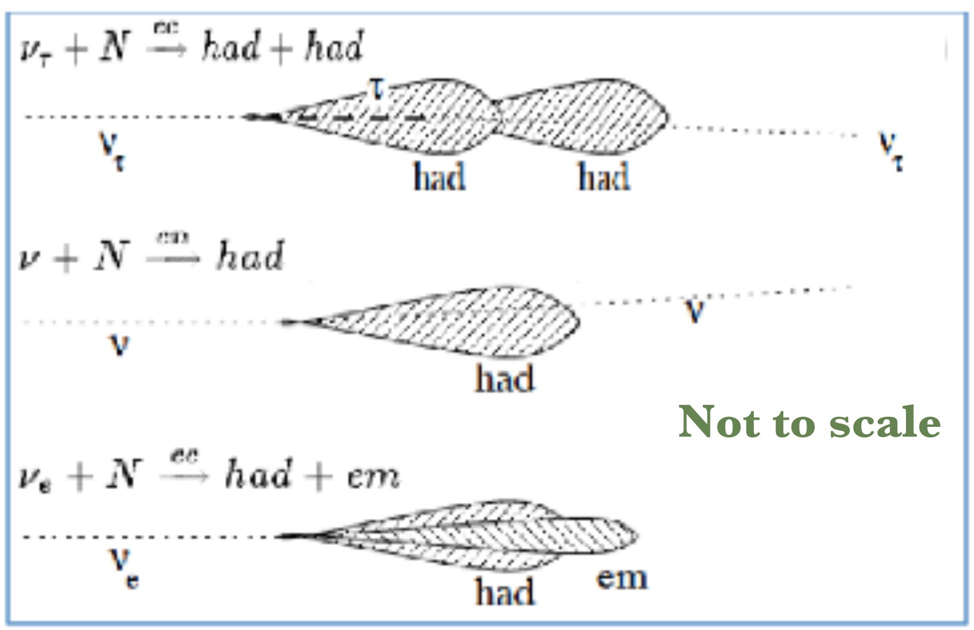
- Direction:

➡ Gal. srcs: 0.2° at 10TeV [0.4° for ANTARES]

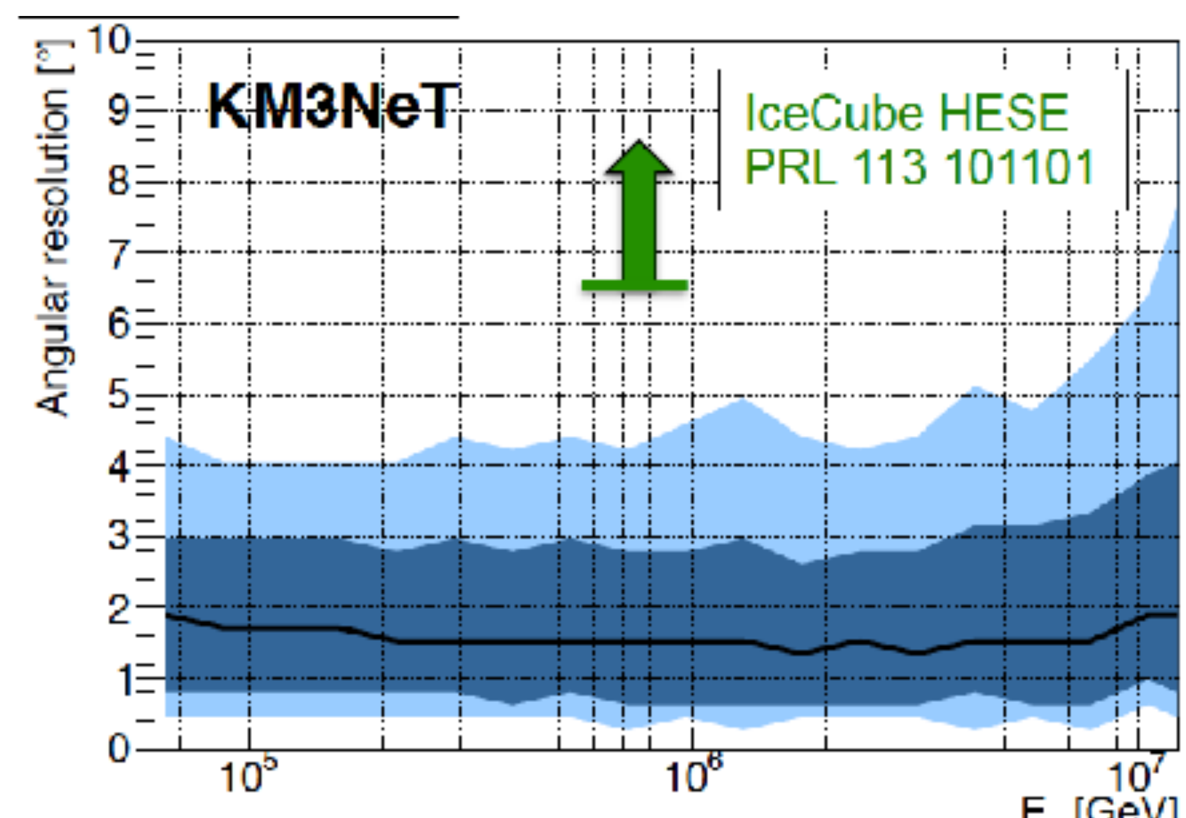
➡ Extra-gal. srcs: 0.1° at 100TeV [0.3° for ANTARES]

- Energy: 0.27 in Log10(E)

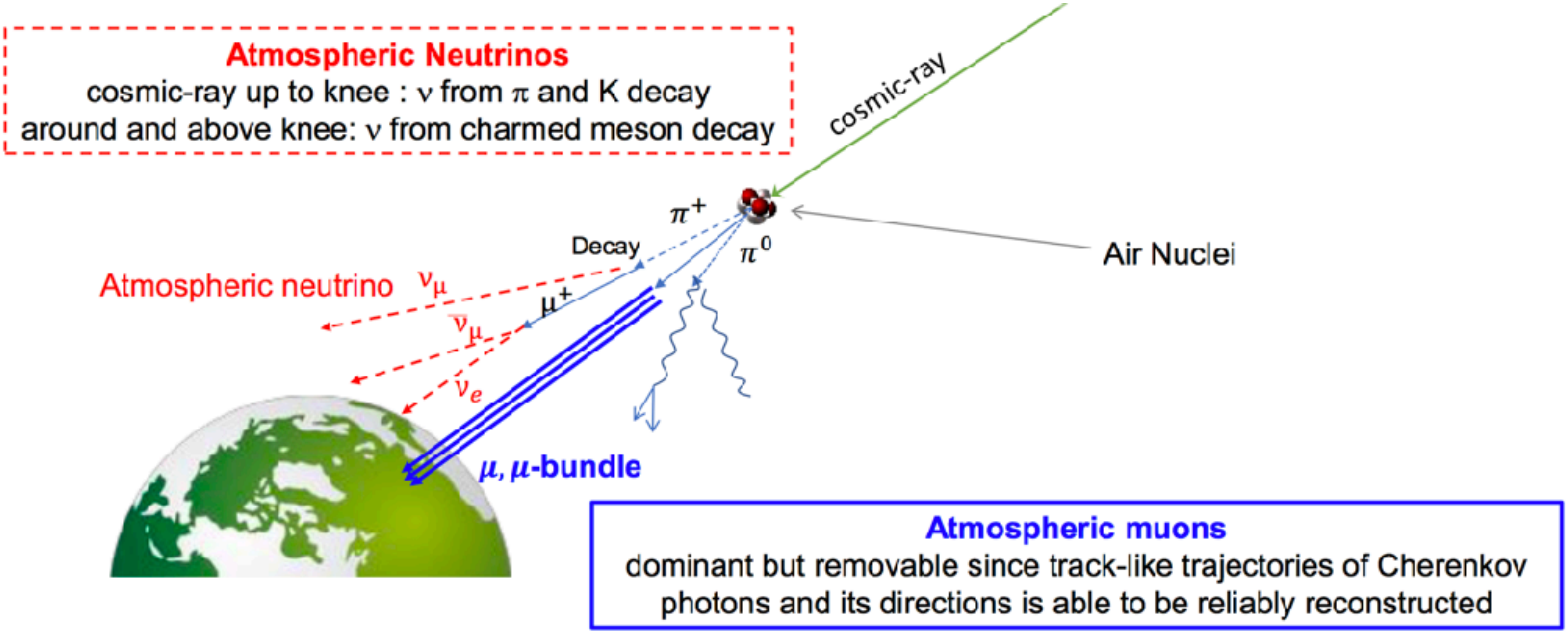




- Vertex: 6-8m (long), 0.5m (perp)
- Direction: ~1.5° [3° for ANTARES]
- Energy: 5%



LARGELY DOMINATED BY ATM BKG



<u>To have better discovery potential:</u>

- **Have the lowest angular precision (tracks)**
- **Have the lowest background contamination (cascades)**
- **Search for time+space-correlations**

THE ICECUBE SIGNAL

6 year HESE analysis (ICRC 2017)

80(+2) events

Bkg: 15.6+11.4-3.9 atm nu + 25.2+/-7.3 atm mu

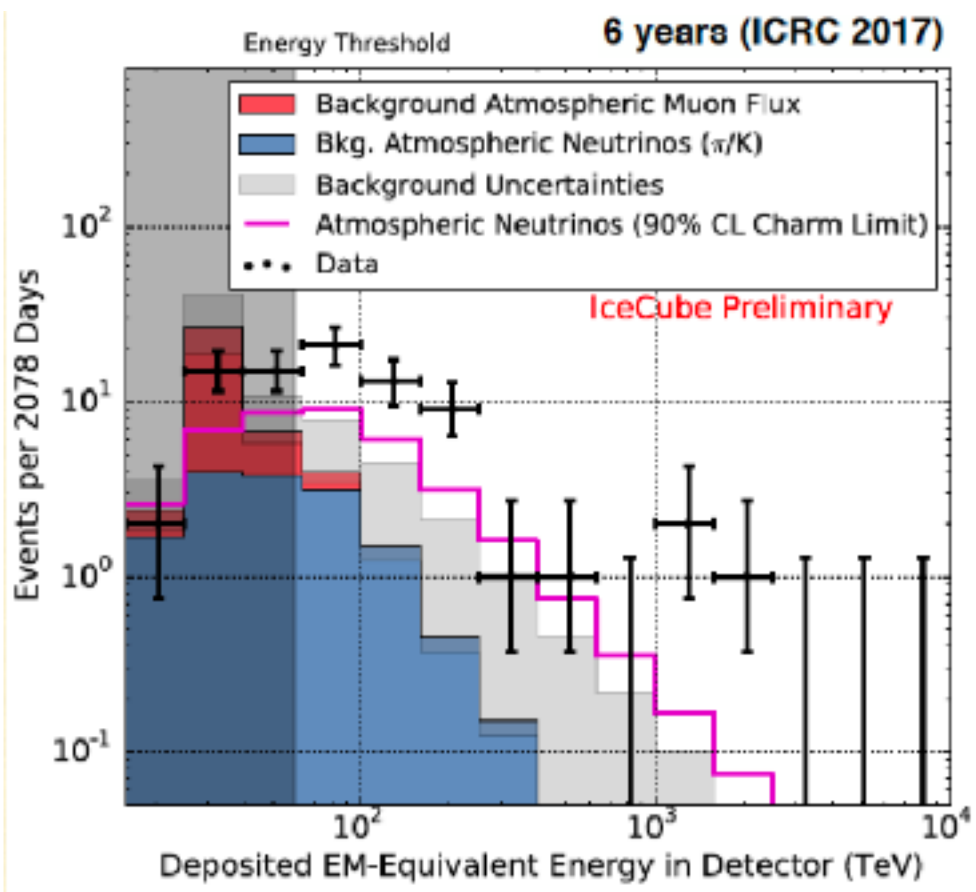
Hemipshere North and South

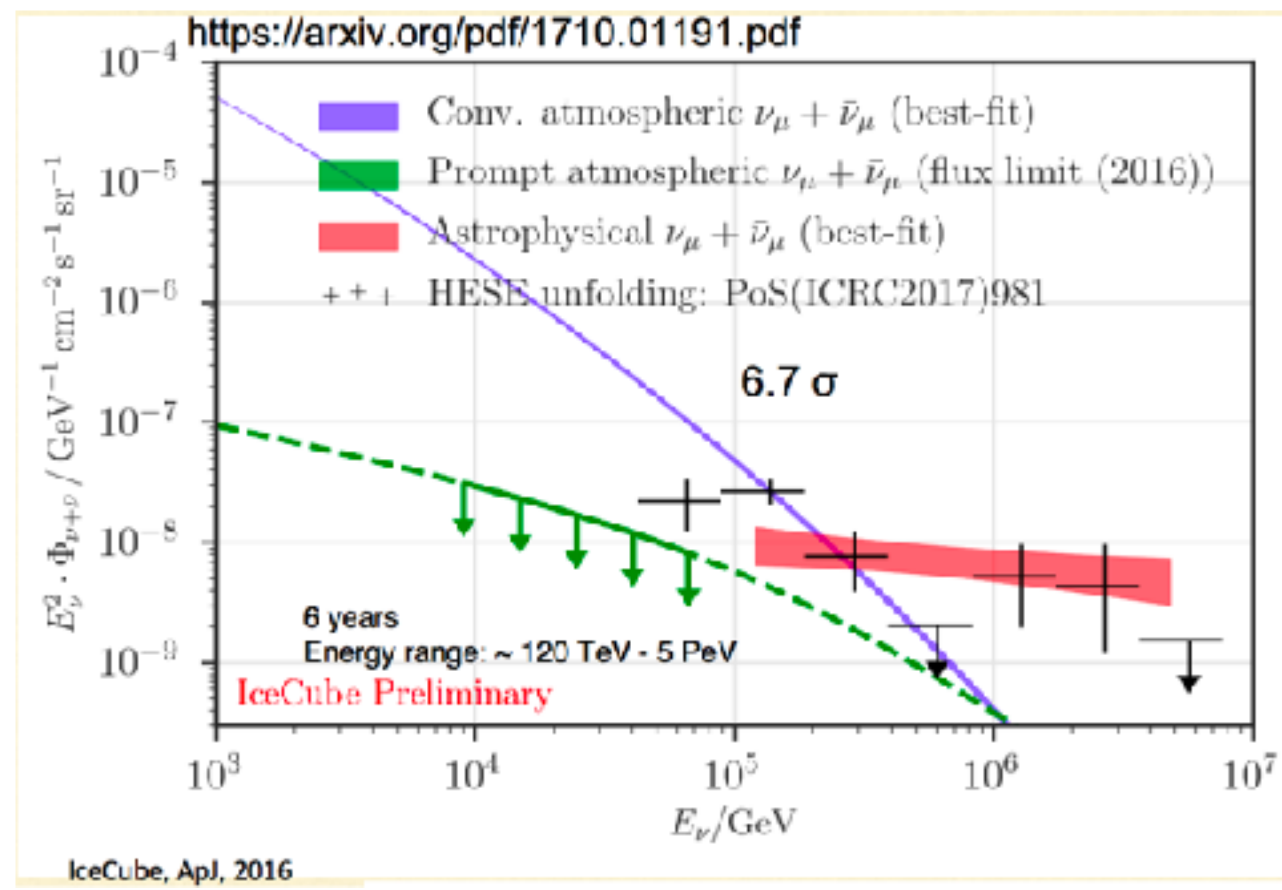
E_{th}: 60 TeV

8 year upgoing muon

E_{th}: 200 TeV

E_{event} >5 PeV !





Significance: 6.5 sigma

Spectra: $E^{-2.92(+0.33\ -0.29)}$

Significance: 6.7 sigma

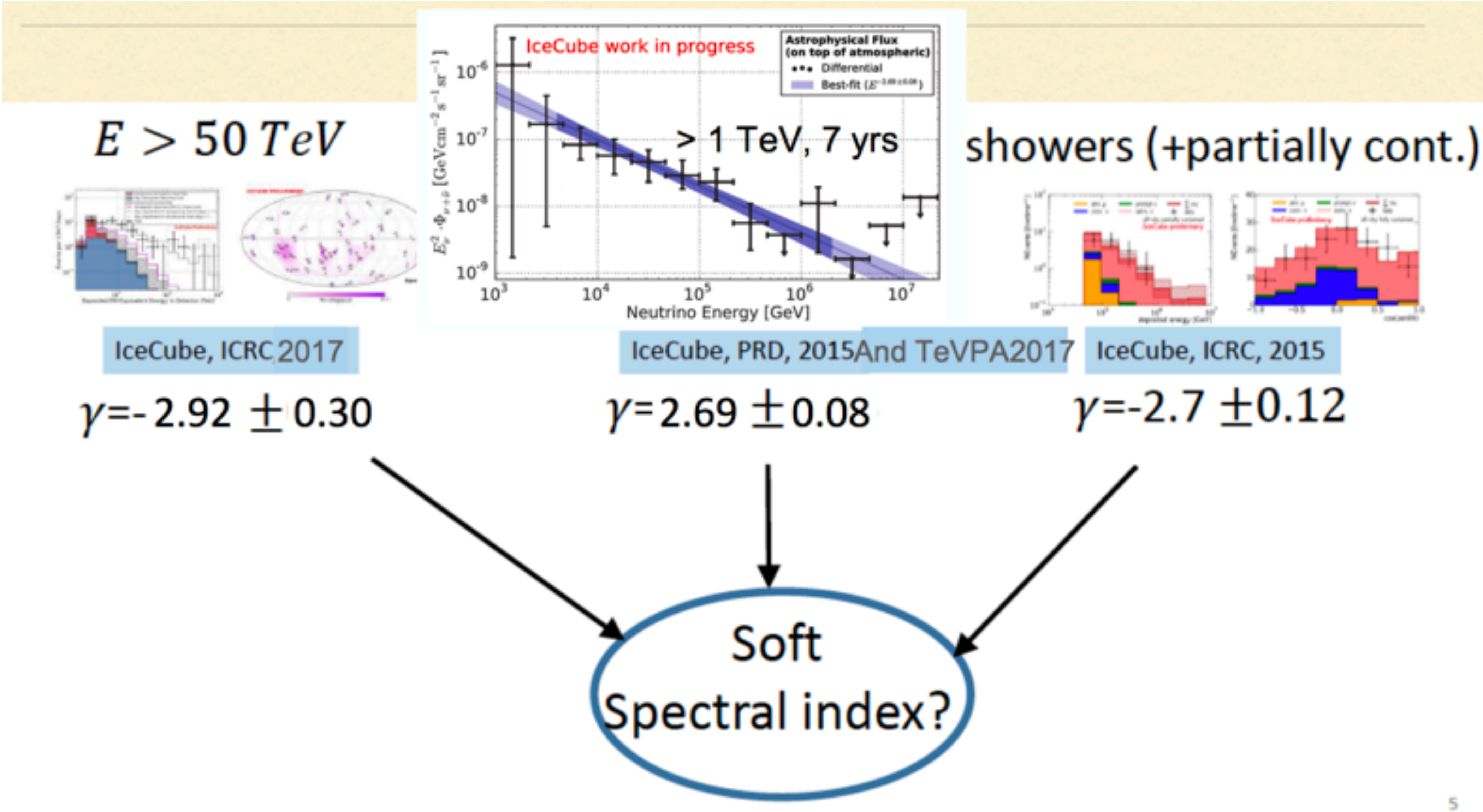
Spectra: $E^{-2.19(+/-0.10)}$

➡ Indication of a break in spectrum? (energy threshold different)

➡ Indication of galactic and extra-galactic components? (different hemispheres)

THE ICECUBE SIGNAL

Last update for the starting track analysis



Analysis	Index	Normalization @ 100 TeV	Significance (σ)	Energy range
HESE 6 yr	2.92 ± 0.3	2.46 ± 0.8	8	60 TeV to 3 PeV
Northern tracks 6 yr	2.19 ± 0.10	1.01 +0.26 -0.23	6.7	119 TeV to 4.8 PeV
Cascades 4 yr	2.48 ± 0.08	1.57 +0.23 -0.22	4.7 (2 year)	10 TeV to 1 PeV
Global fit	2.50 ± 0.09	2.2 ± 0.4		25 TeV to 2.8 PeV

THE ICECUBE SIGNAL

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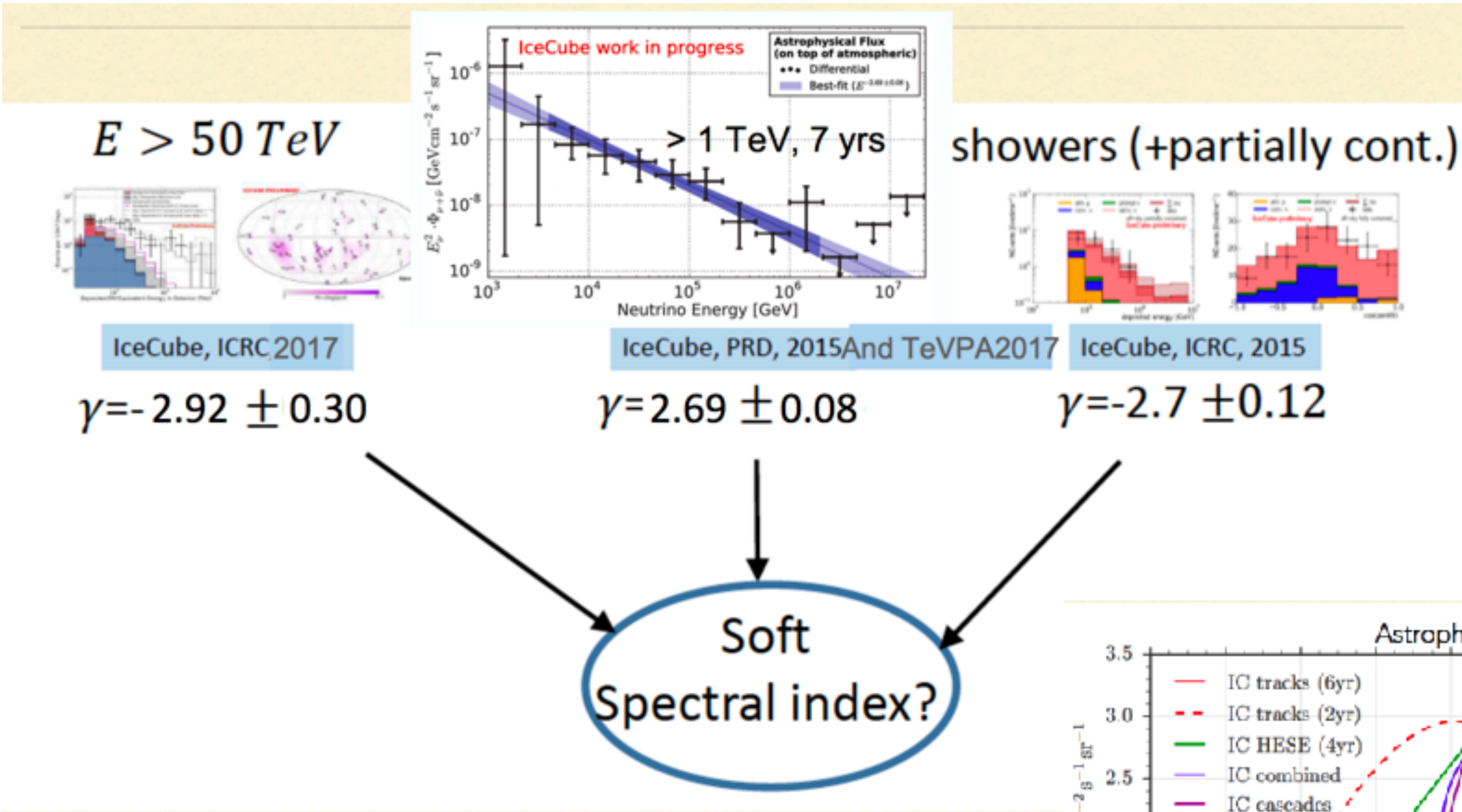
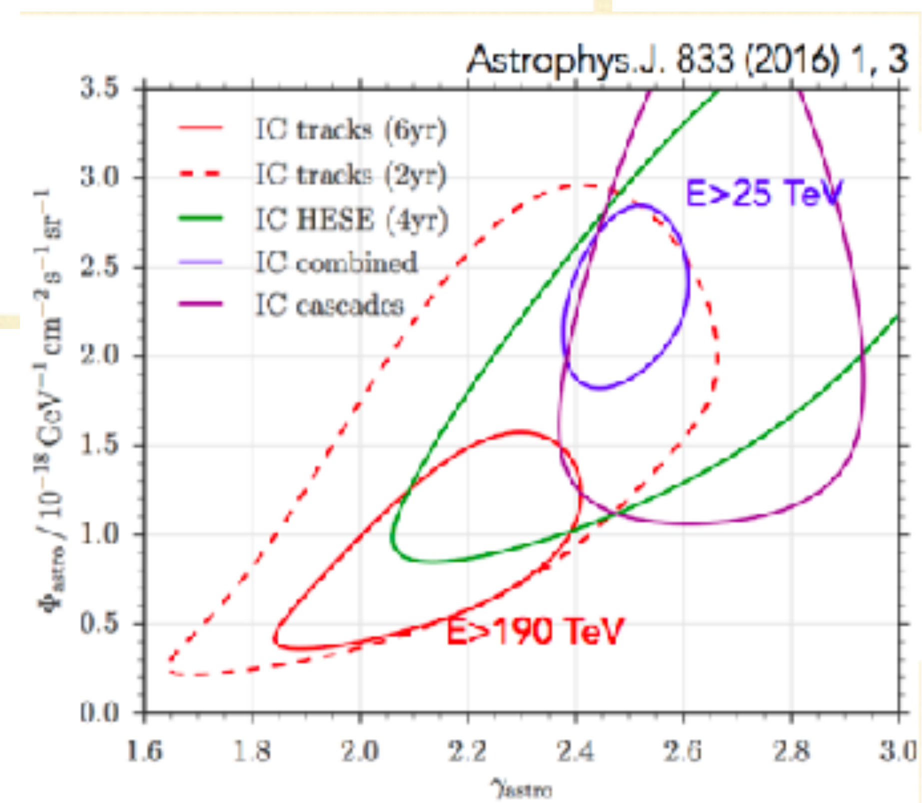
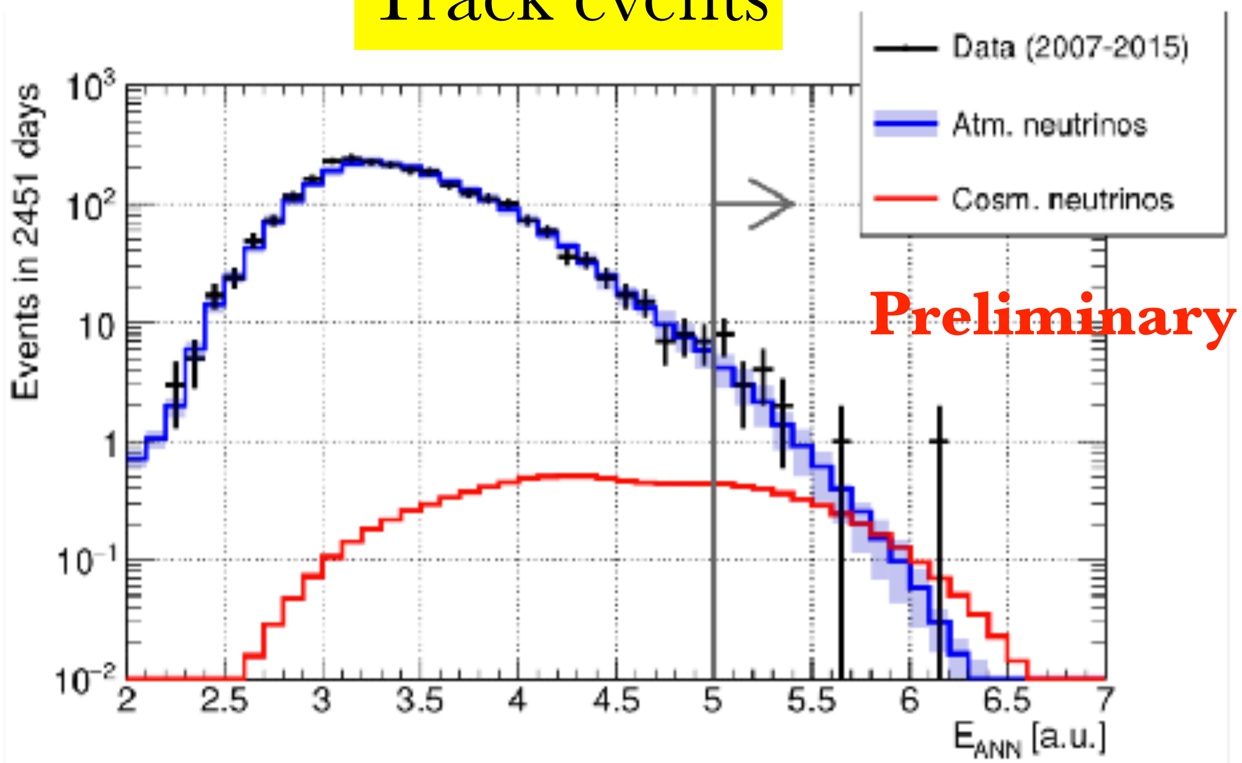




- ➡ Indication of a break in spectrum? (energy threshold different)
- ➡ Indication of galactic and extra-galactic components? (different hemispheres)

ANTARES DIFFUSE RESULTS

Track events



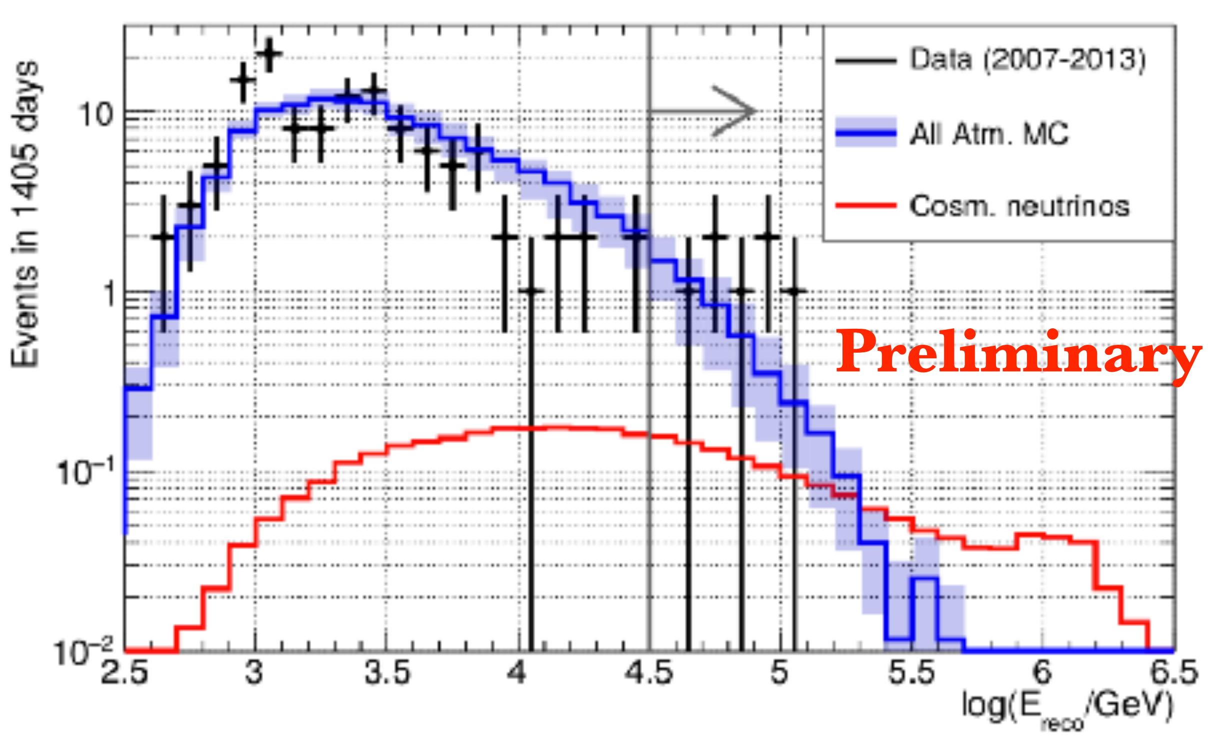
All-sky / All-flavor neutrino search

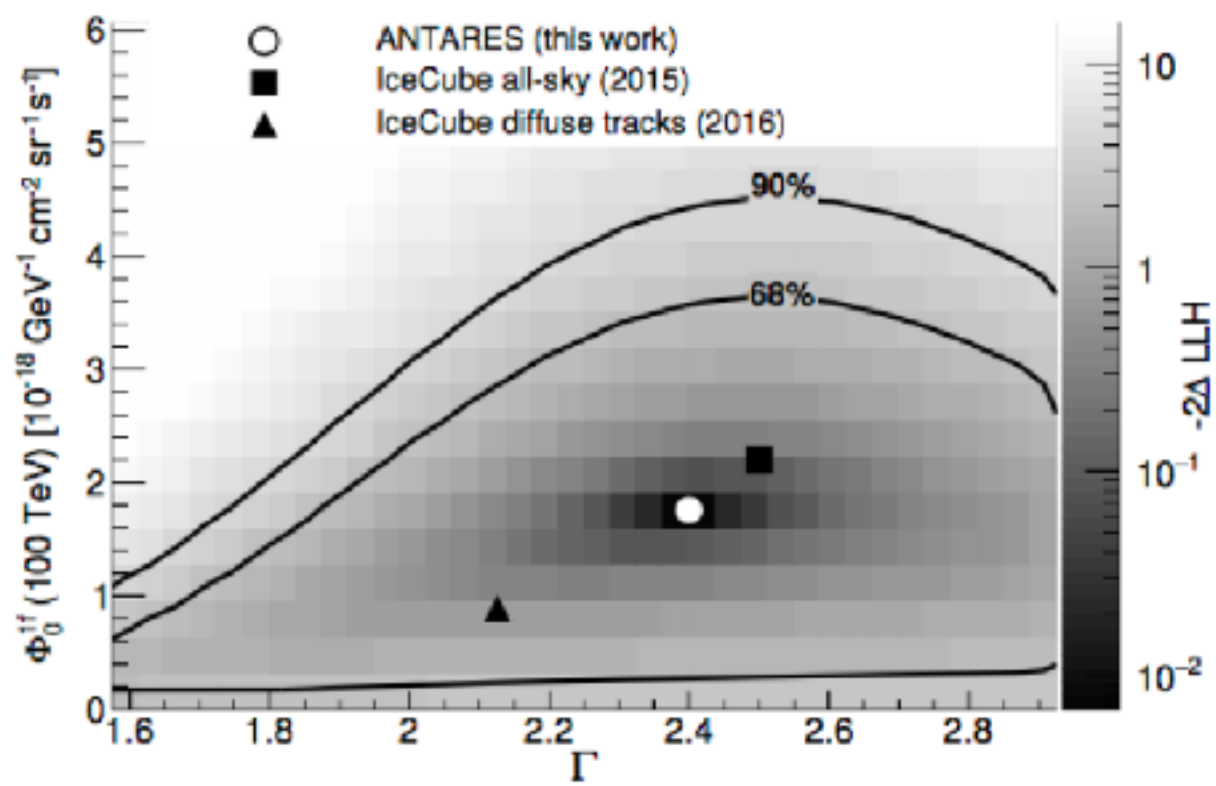
- Look for excess above a given E_{th}
- 9 (7) yrs of data for tracks (cascades)

	Bkg expectation	Signal exceptation	Nb events measured
Track	**13+/-3**	**3**	**19**
Shower	**5+/-2**	**1.5**	**7**

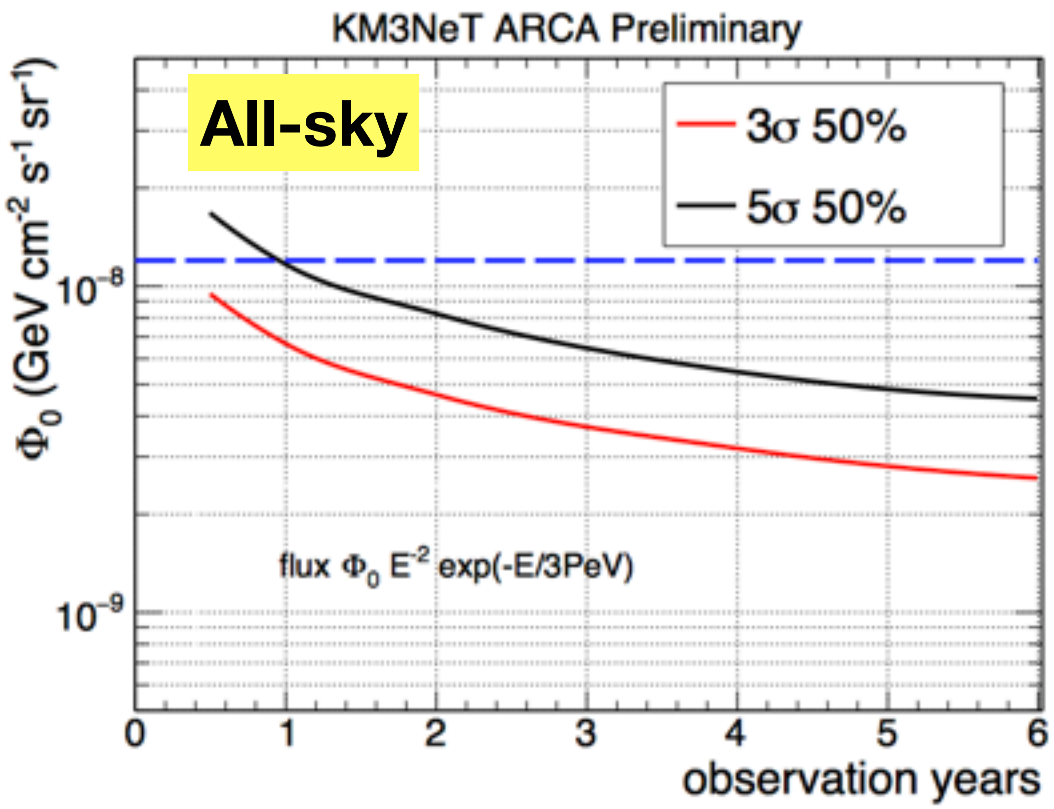
=> Small excess (not significant)

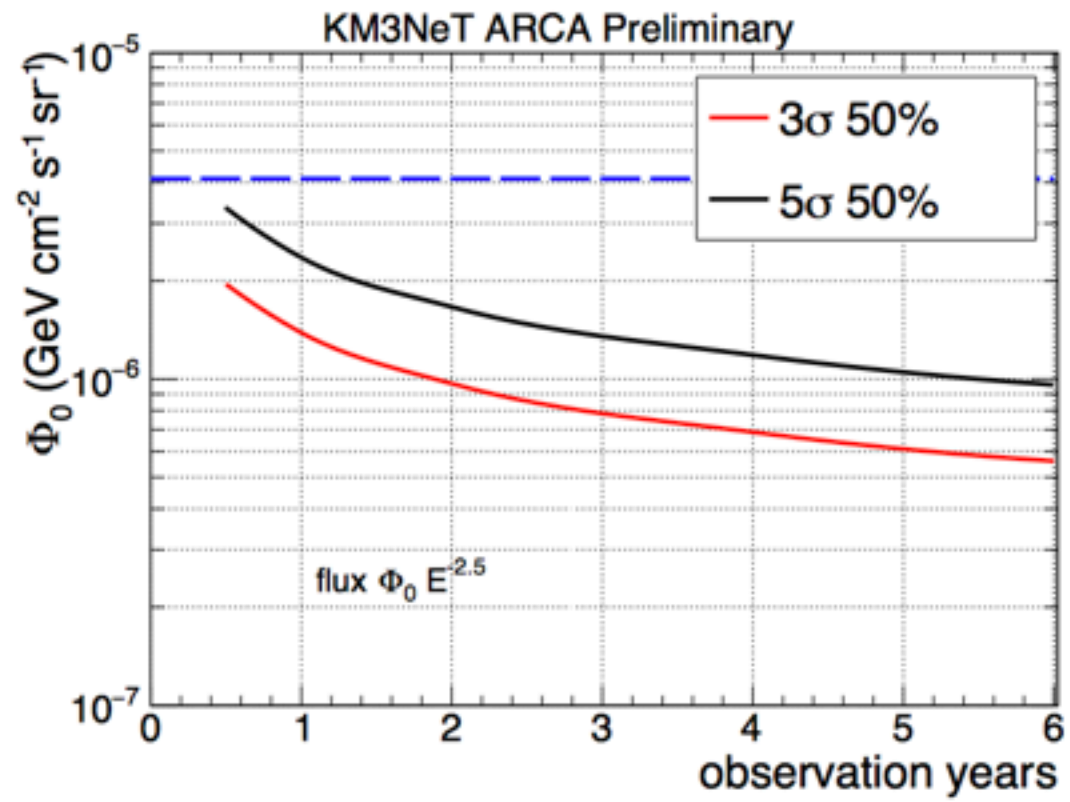
Cascade events





KM3NeT: DIFFUSE FLUX

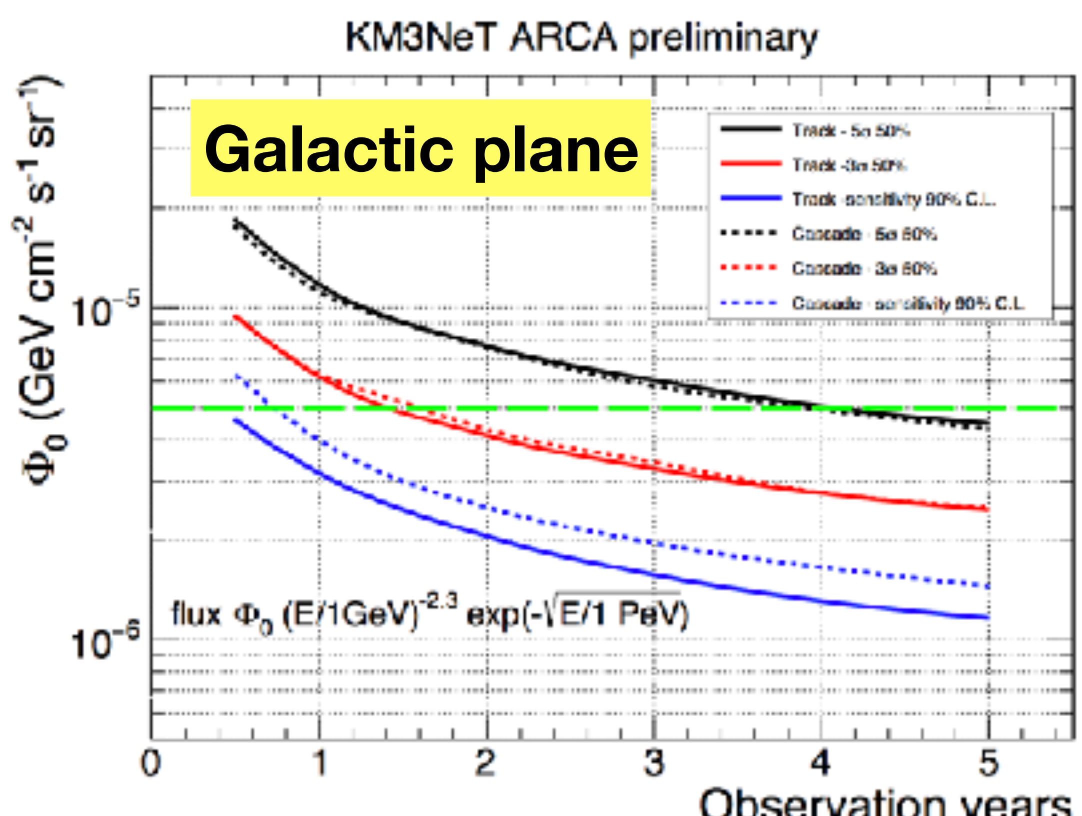




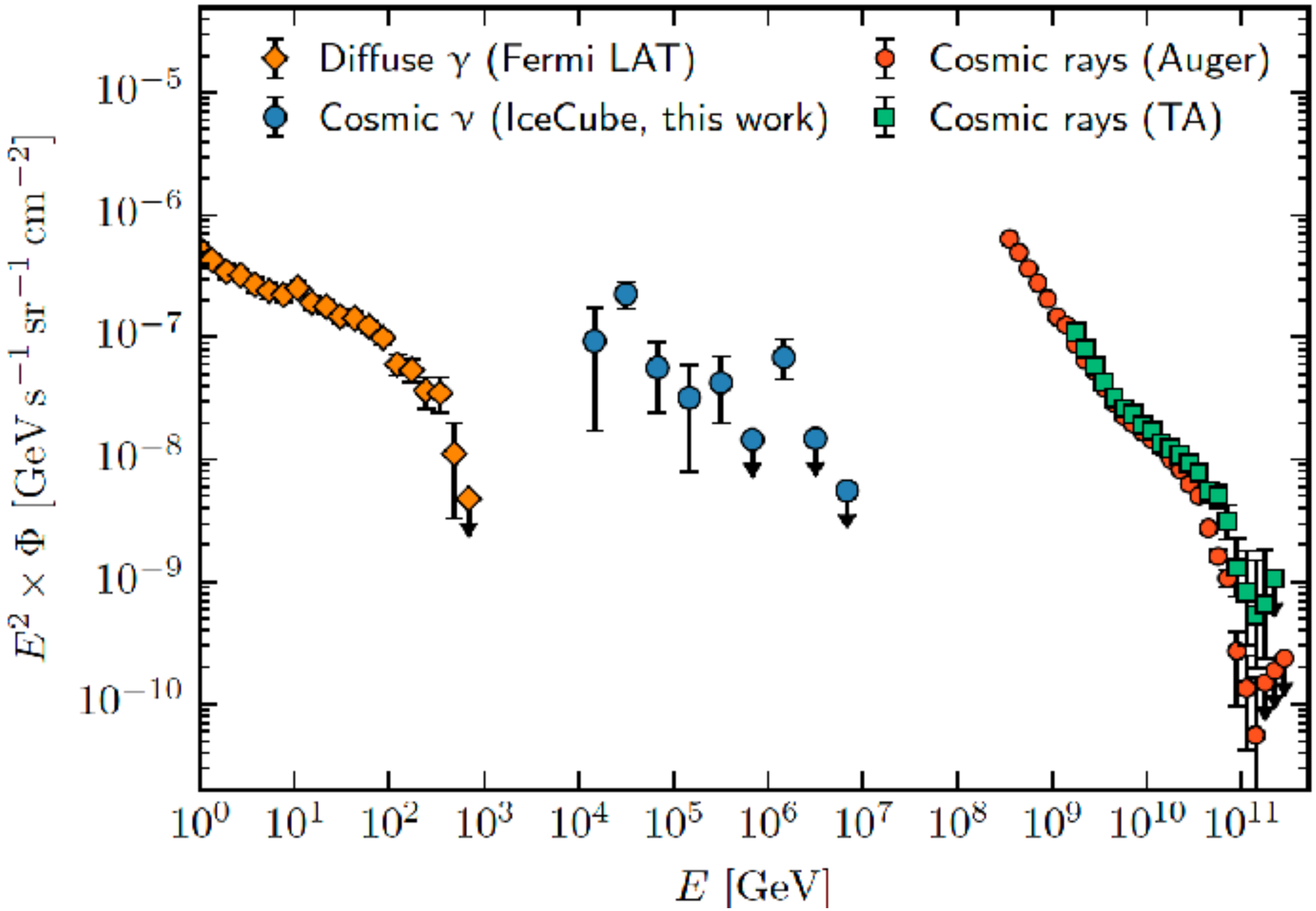
KM3NeT/ARCA is expected to observe the IC signal in less than 1 yr.

➡ Precise characterization (spectral shape, flavor composition, anisotropy)

➡ Excellent sensitivity in the galactic plane: identify gal/extra-gal components ?



γ-ν-RC DIFFUSE FLUXES



⇒ **Energy density of neutrinos in the non-thermal Universe is the same or higher as that in Fermi gamma-rays.**

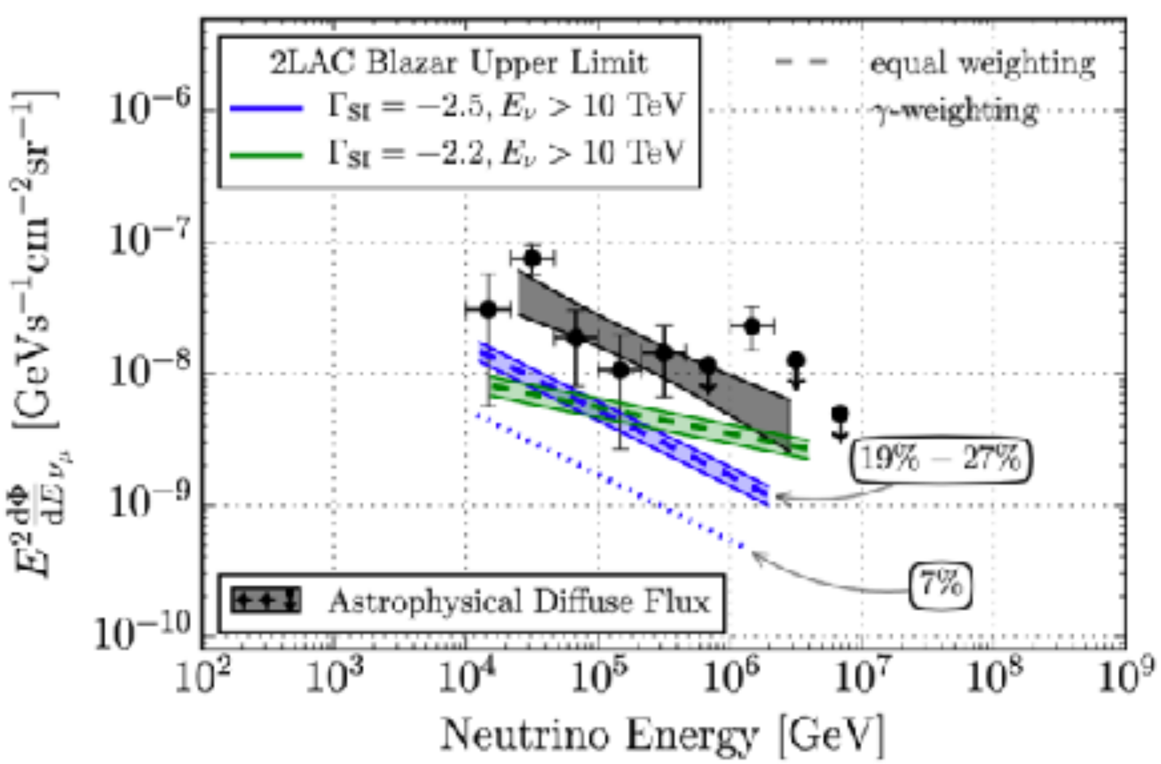
⇒ **Common sources ?   Fermi/LAT γ-ray flux dominated by AGN/blazars (~ 85%)**

POPULATION STUDIES

Blazar space correlation

(862 ‘2LAC’ blazars)

Contribution max of the 2LAC blazars < 27% (10 TeV - 2 PeV), assuming equal weighting among blazars and single power-law with γ = –2.5.



7% of neutrino signal assuming ν flux ⇔ γ-ray flux

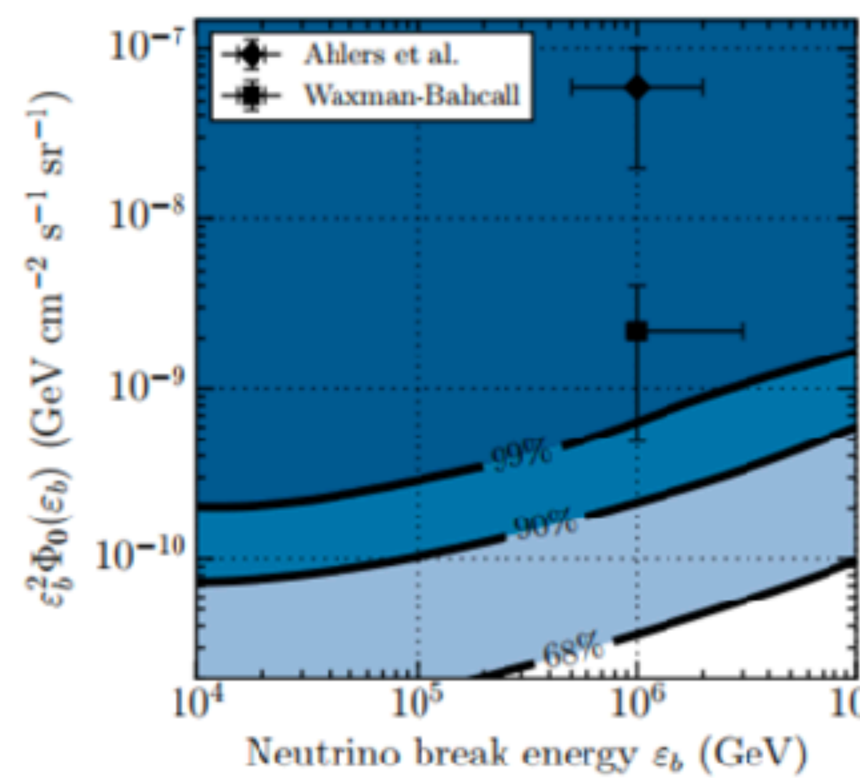
(correlation with 2FHL: < few % of the IC flux)

Astrophysical Journal 835 (2017) 1

GRB time/space correlation

contribute **no more than 1%** of the observed diffuse flux

$$\Phi_\nu(E_\nu) = \Phi_0 \times \begin{cases} \varepsilon_b^{-1} E_\nu^{-1}, & E_\nu \le \varepsilon_b \\ E_\nu^{-2}, & \varepsilon_b < E_\nu \le 10\varepsilon_b \\ E_\nu^{-4}\,(10\varepsilon_b)^2\,, & 10\varepsilon_b < E_\nu. \end{cases}$$



(1172 GRBs - benchmark parameters)

arXiv:1702.06868

POPULATION STUDIES

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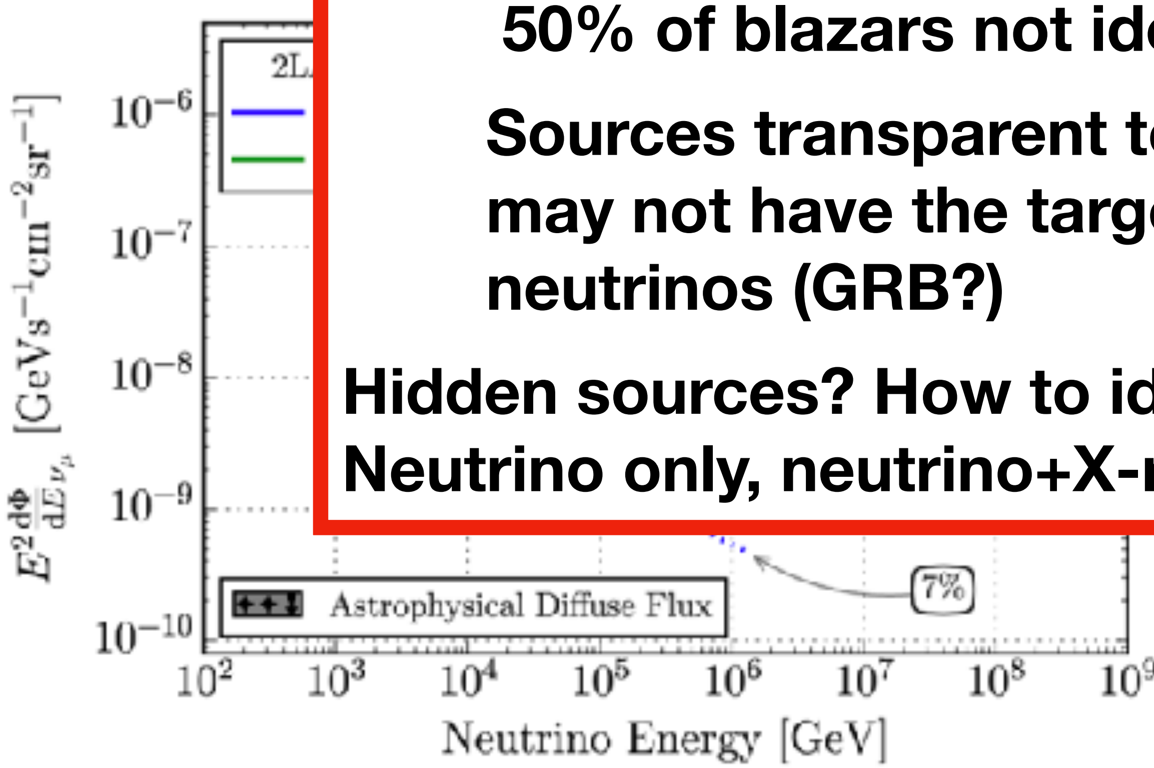
Contribution max of the 2LAC blazars < 27% (10 TeV - 2 PeV), assuming equal weighting among blazars and single power



BUT, neutrinos originate from a larger volume

50% of blazars not identified

Sources transparent to high energy gamma rays may not have the target density to produce neutrinos (GRB?)

Hidden sources? How to identify these sources ? Neutrino only, neutrino+X-ray ?

7% of neutrino signal assuming ν flux ⇔ γ-ray flux

(correlation with 2FHL: < few % of the IC flux)

Astrophysical Journal 835 (2017) 1

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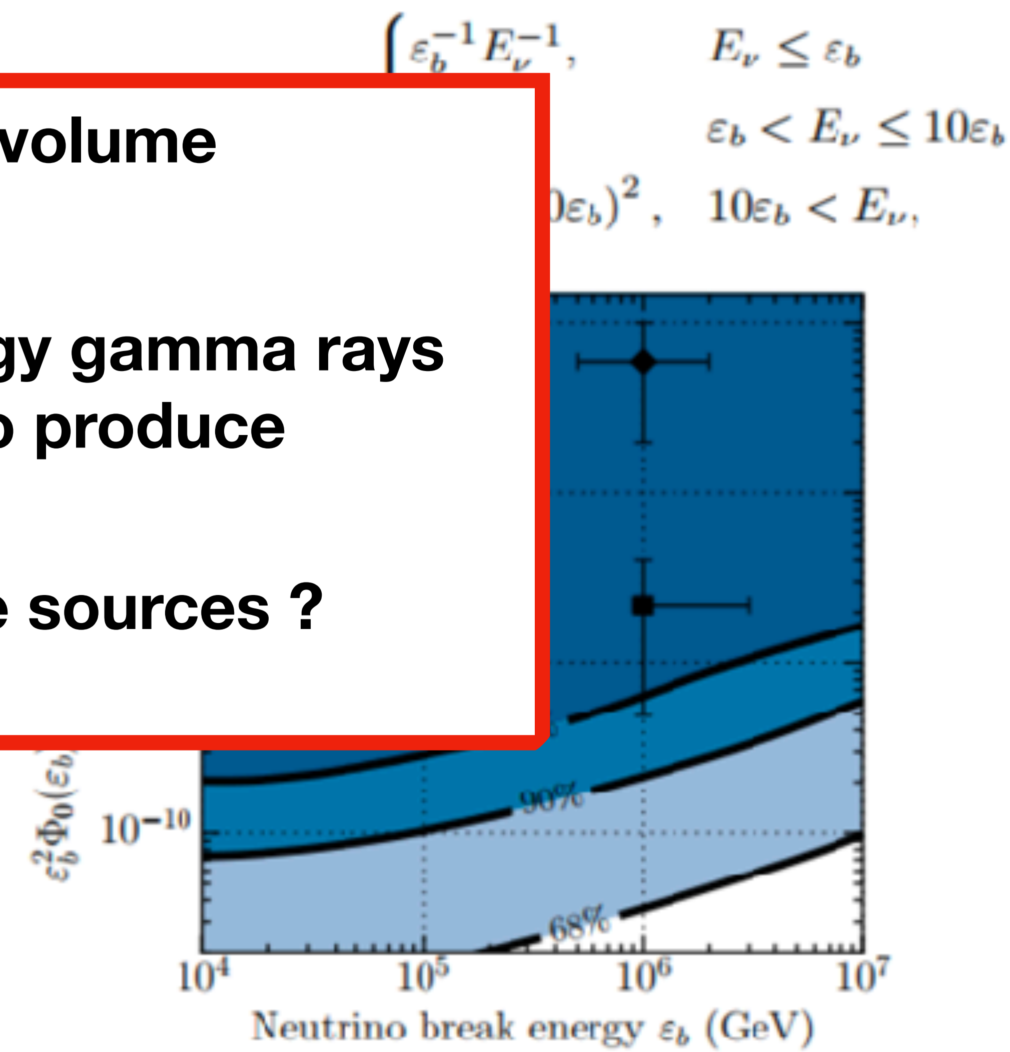

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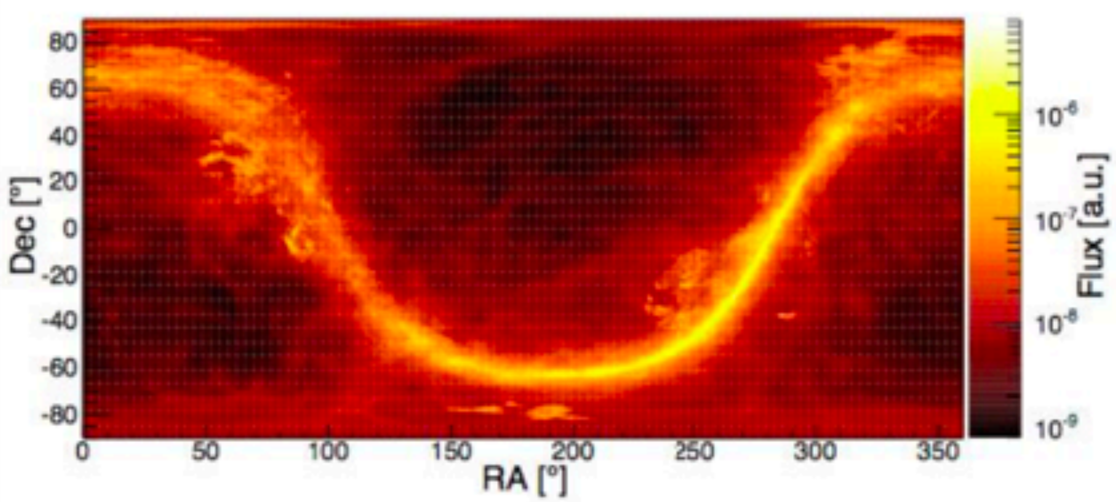
arXiv:1702.06868

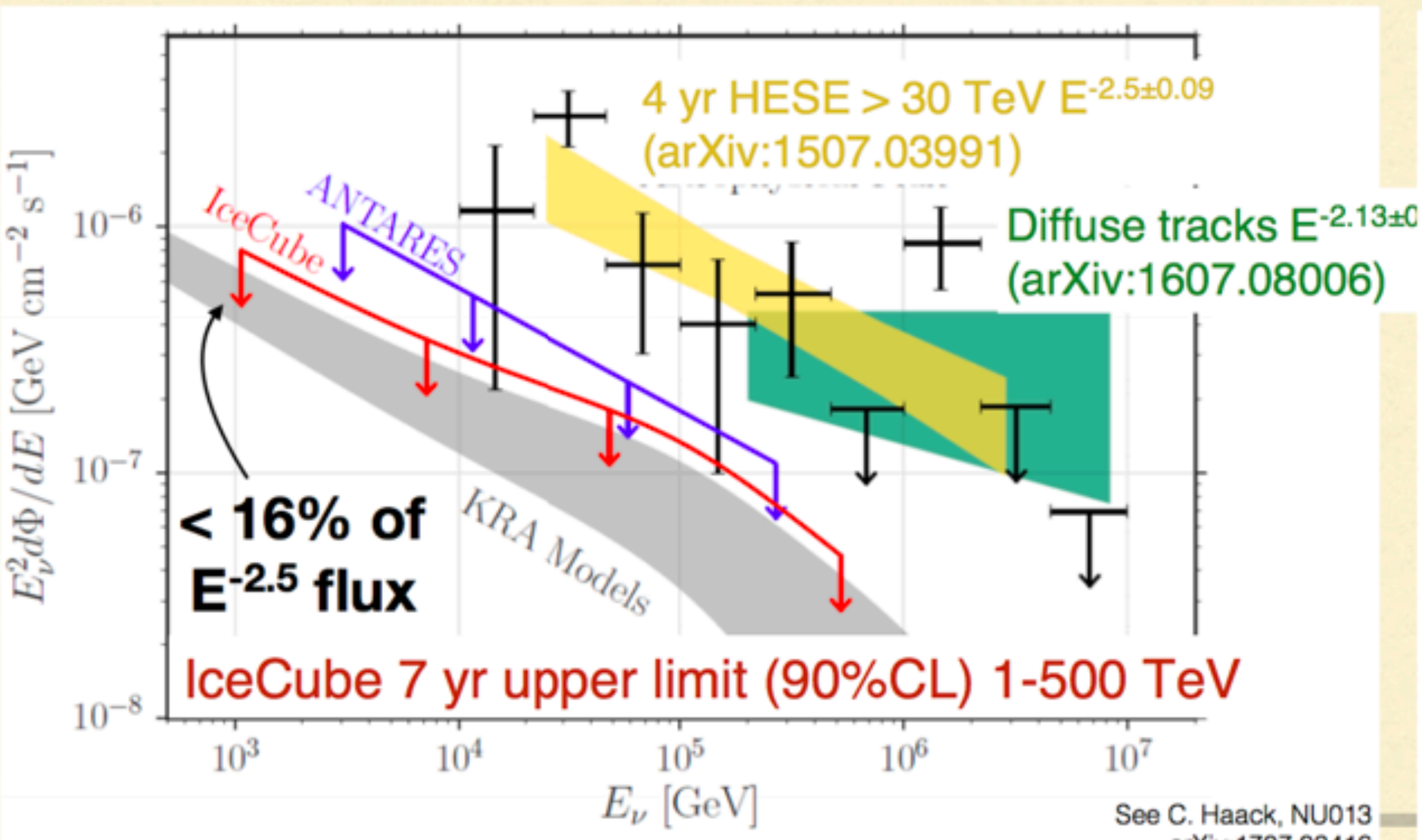
GALACTIC DIFFUSE FLUX



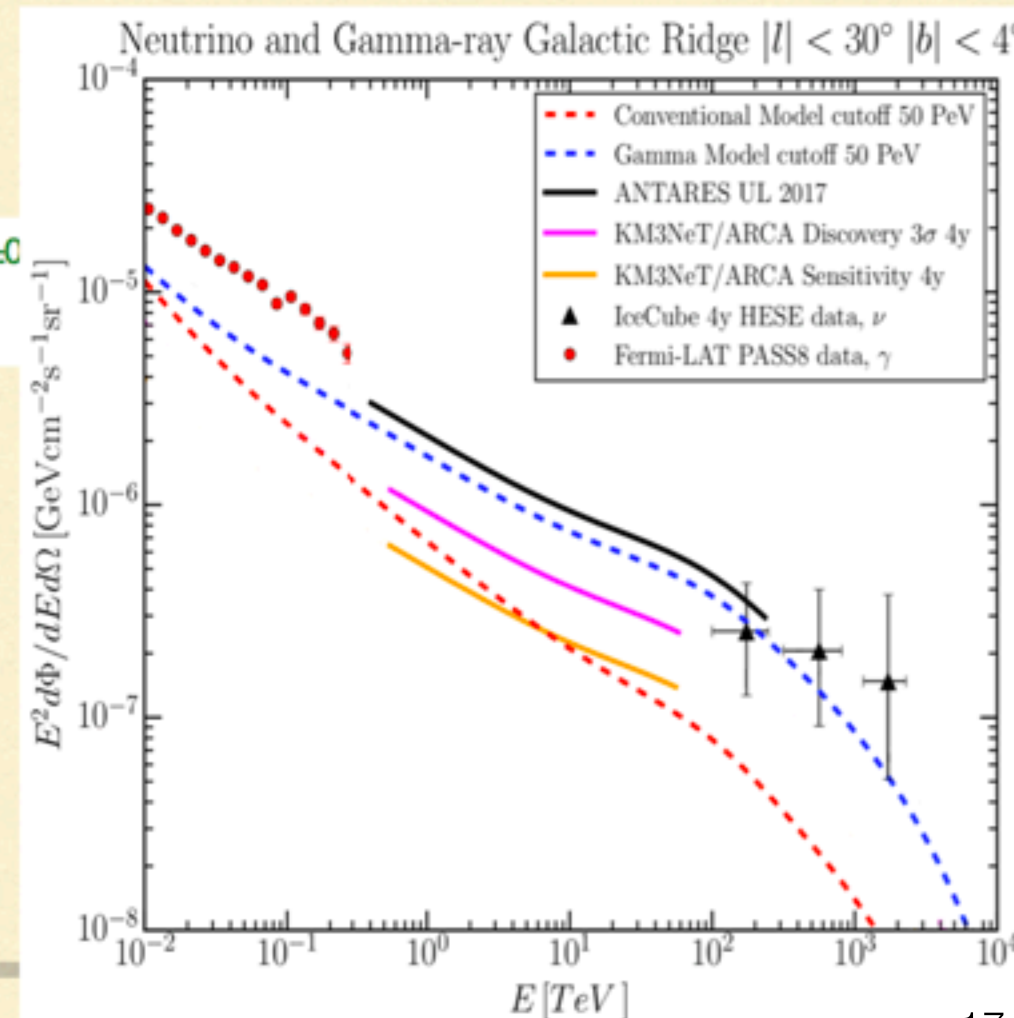
(a) KRA-γ (50 PeV cutoff) template

- Analysis of correlation with template map derived from interstellar gas distribution reproducing Fermi-LAT data Models in Gaggero et al, arXiv:1504.00227
- Only small fraction of signal can originate from CR interactions in the Galaxy. UL for IC and ANTARES 1.2 x KRA-γ (50 PeV)

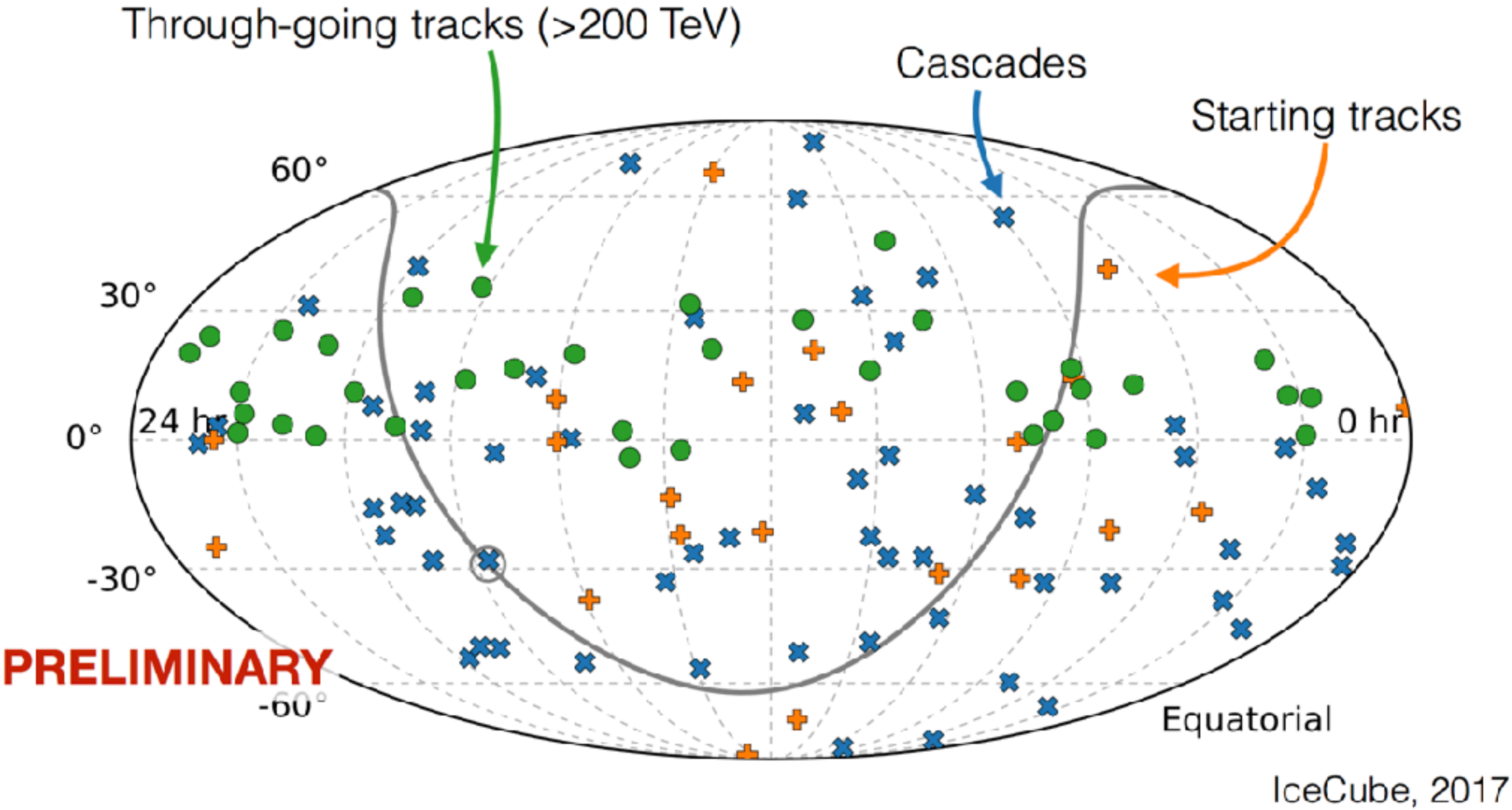
ANTARES arXiv:1602.03036 updated at this conference



See C. Haack, NU013
arXiv:1707.03416



IC NEUTRINO SKYMAP

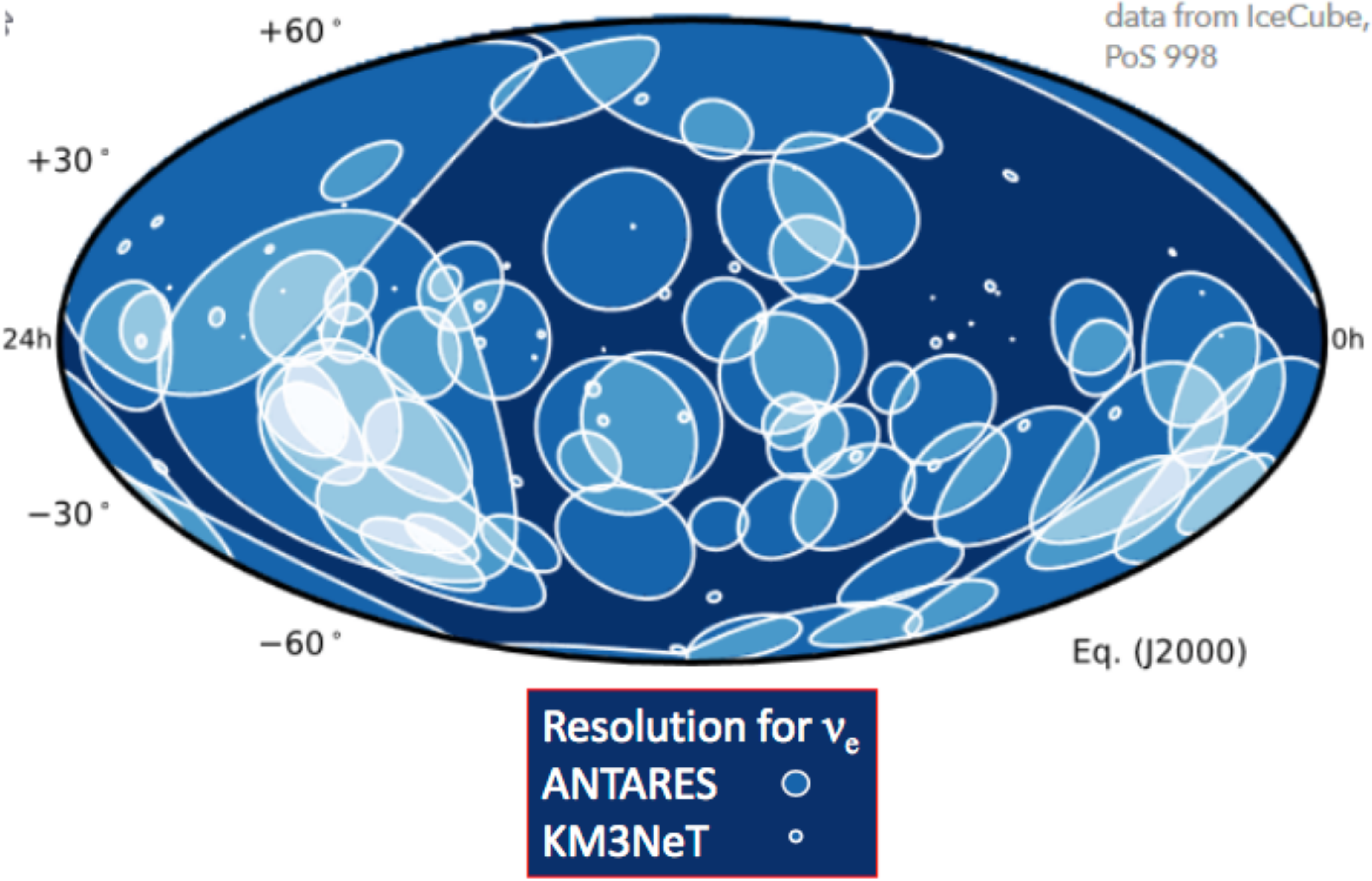


No evidence of clustering in high-energy neutrino directions

mostly isotropic $\Longrightarrow$ neutrinos of extragalactic origin

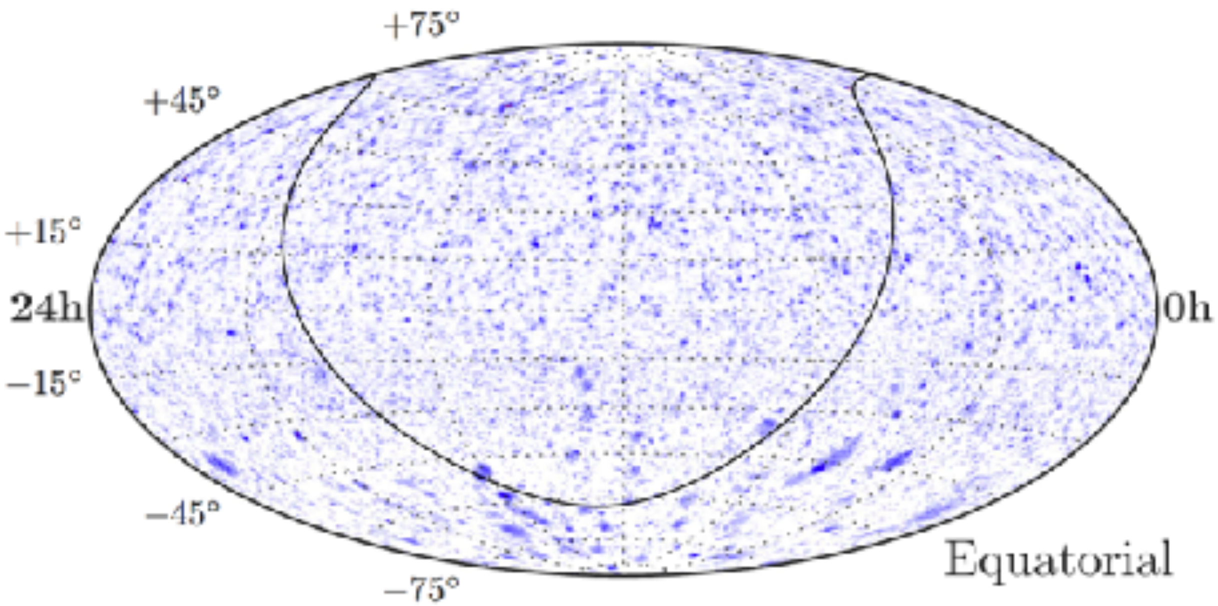
Where are the PeV γ-rays together with PeV neutrinos ?

IC NEUTRINO SKYMAP

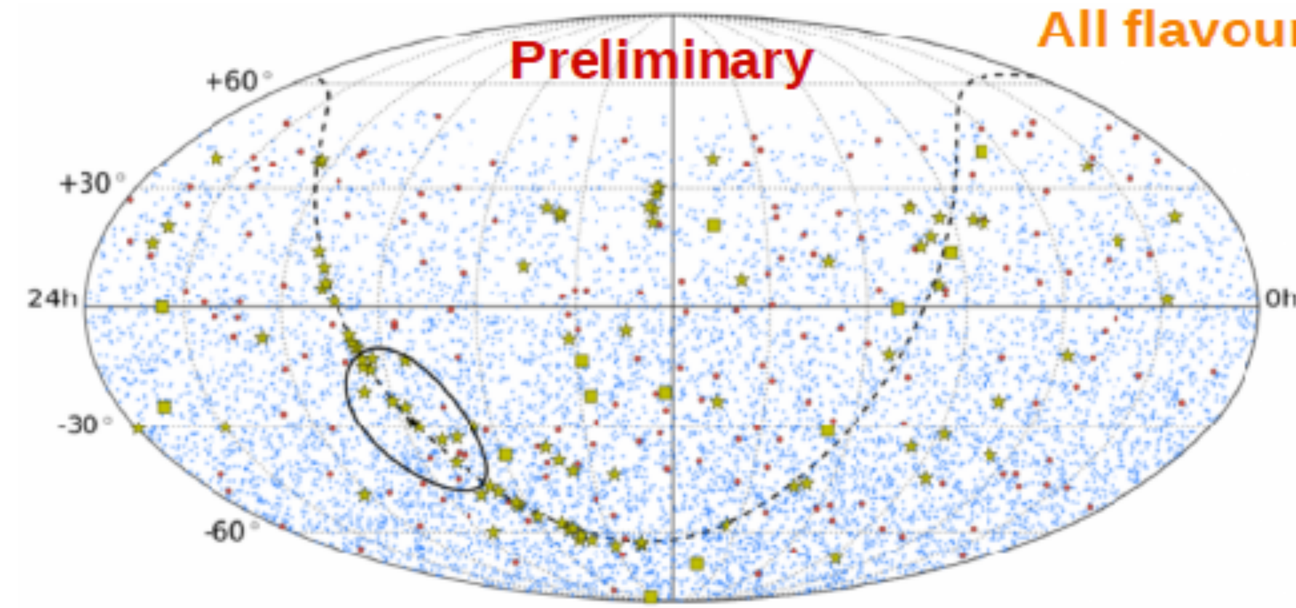


LOOKING FOR POINT-SOURCES

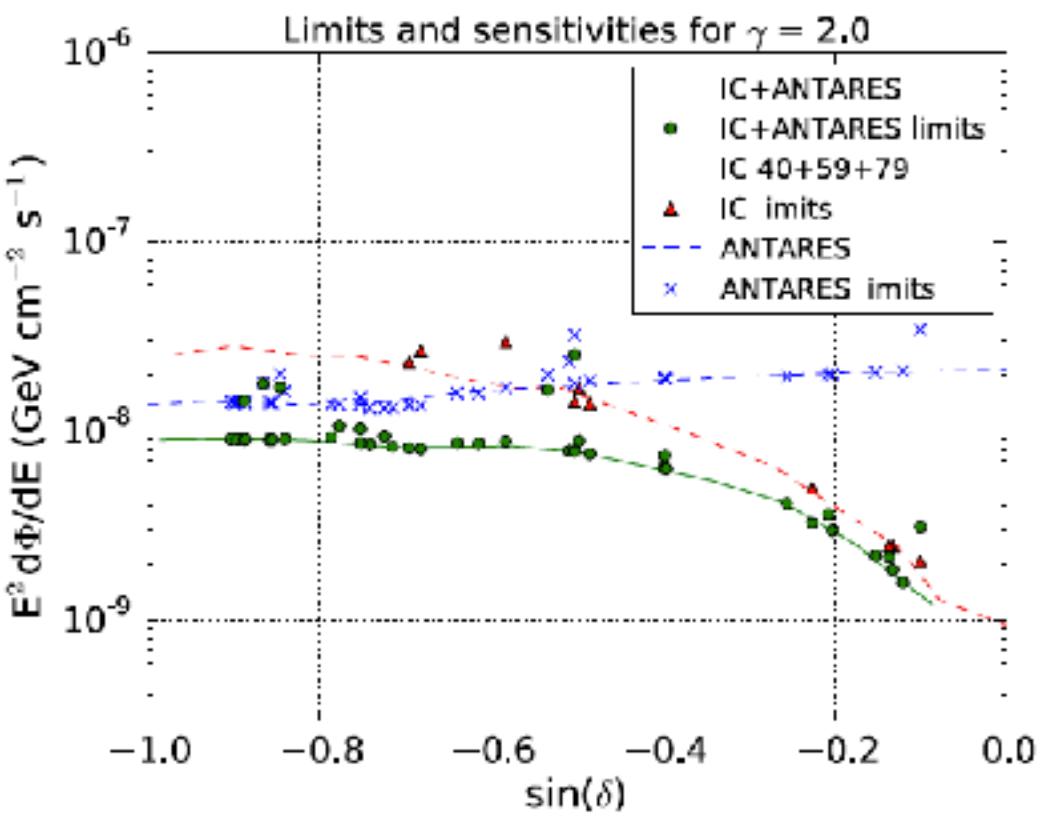
IceCube (7 yrs - tracks)

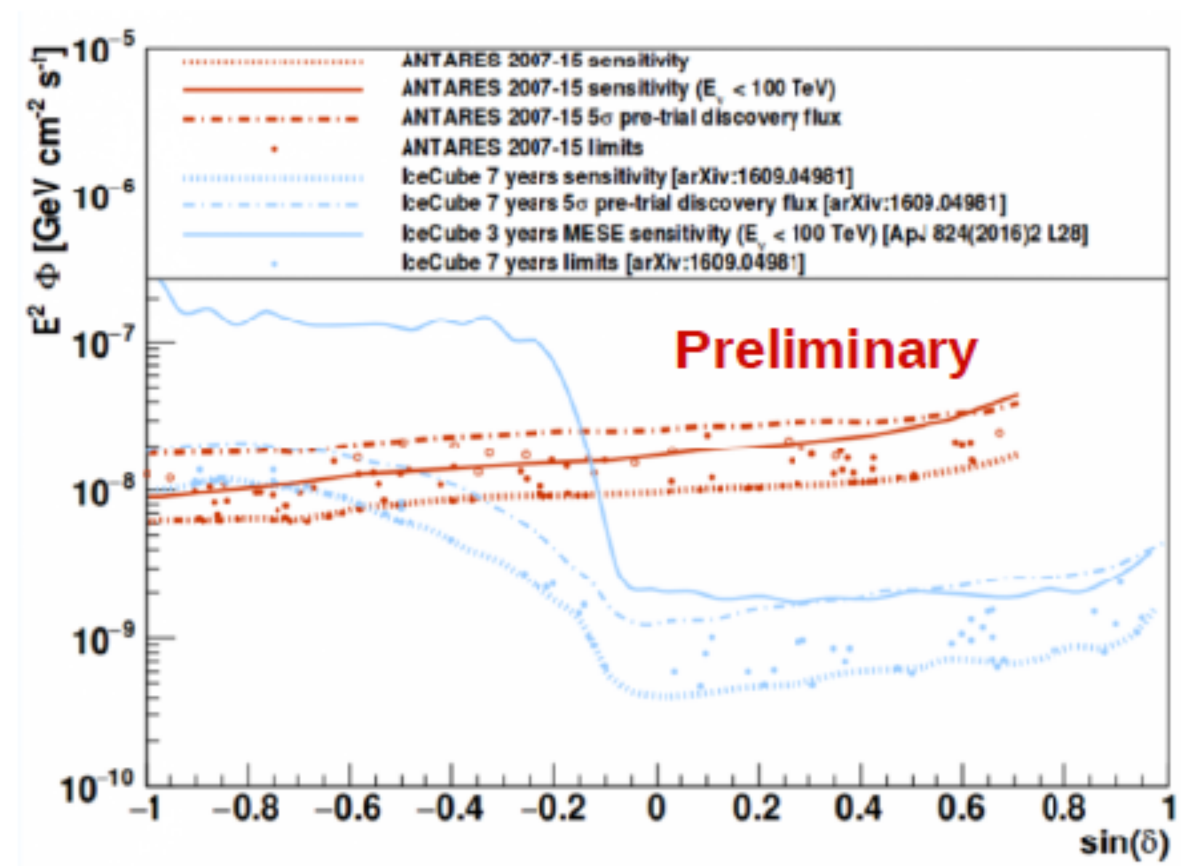


ANTARES



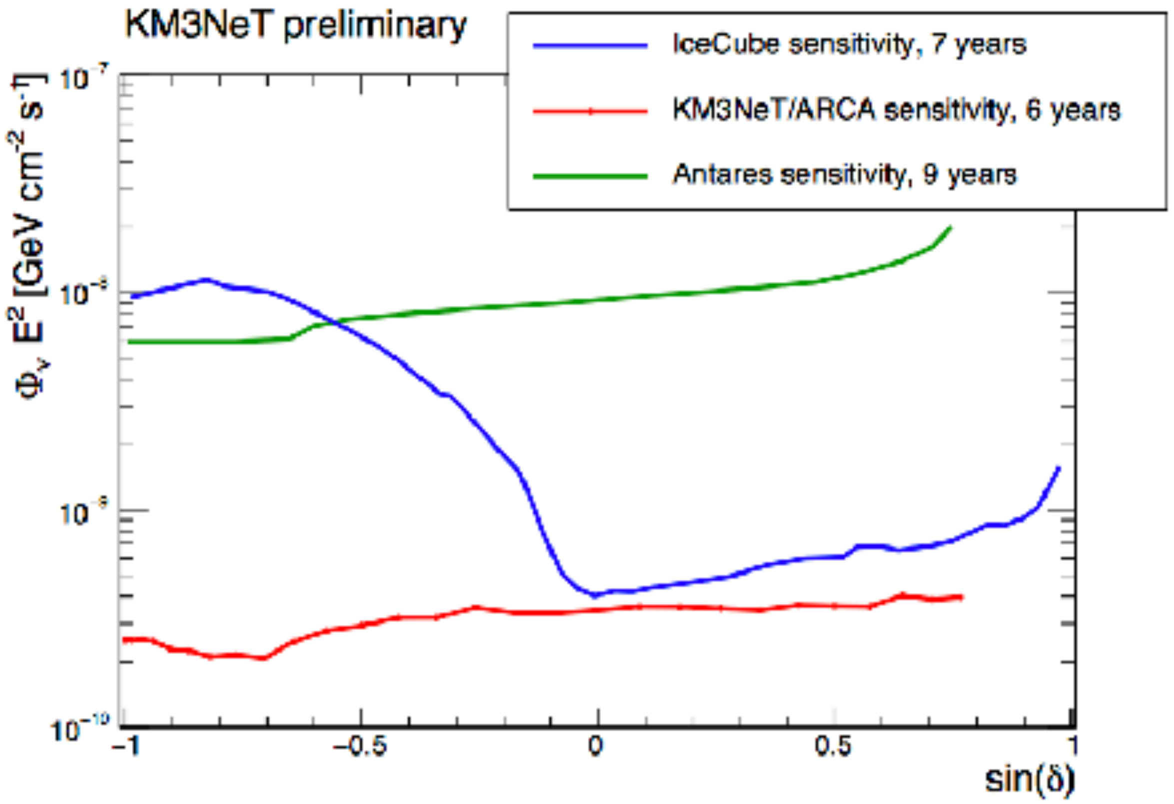
ANTARES+IceCube

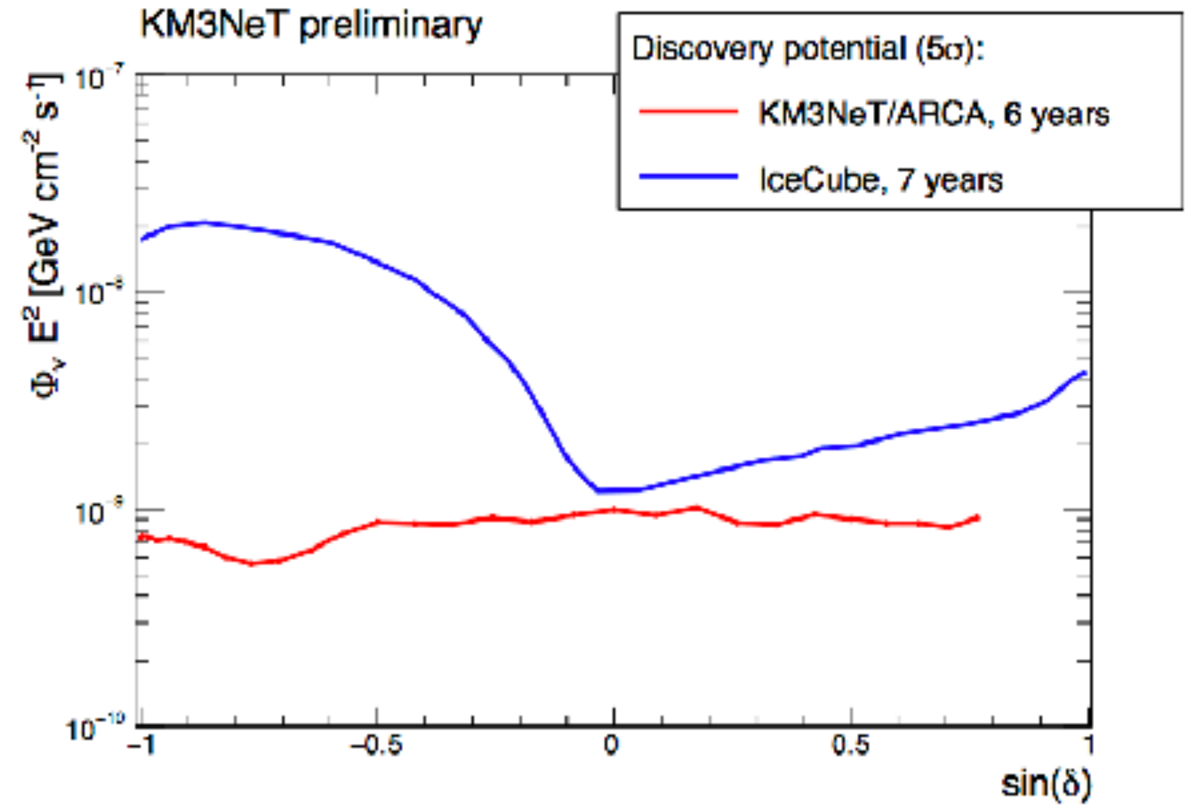




KM3NeT: POINT-SOURCE

Generic source

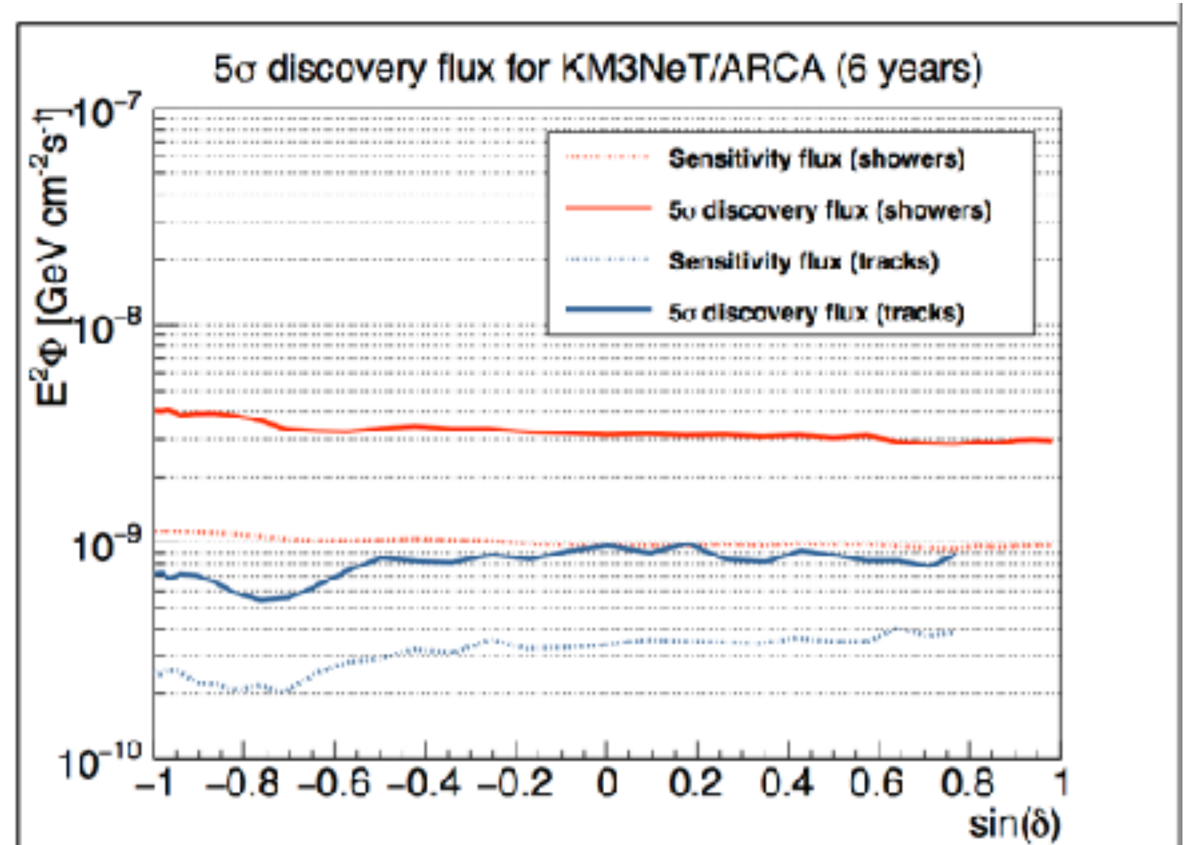




KM3NeT/ARCA is expected to have more than one order of magnitude better sensitivity than IC in the Southern sky.

➡ Due to the quite good angular resolution for cascade events, the point-source search is also very efficient.

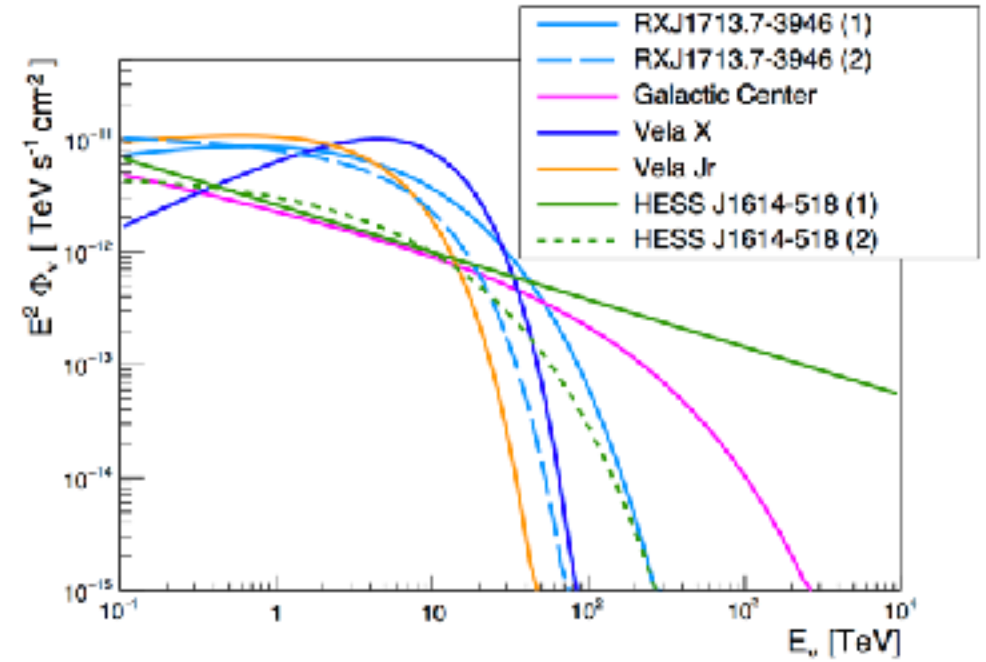
➡ Expected better performances for the transient neutrino sources (GRB, AGN…)



KM3NeT: POINT-SOURCE

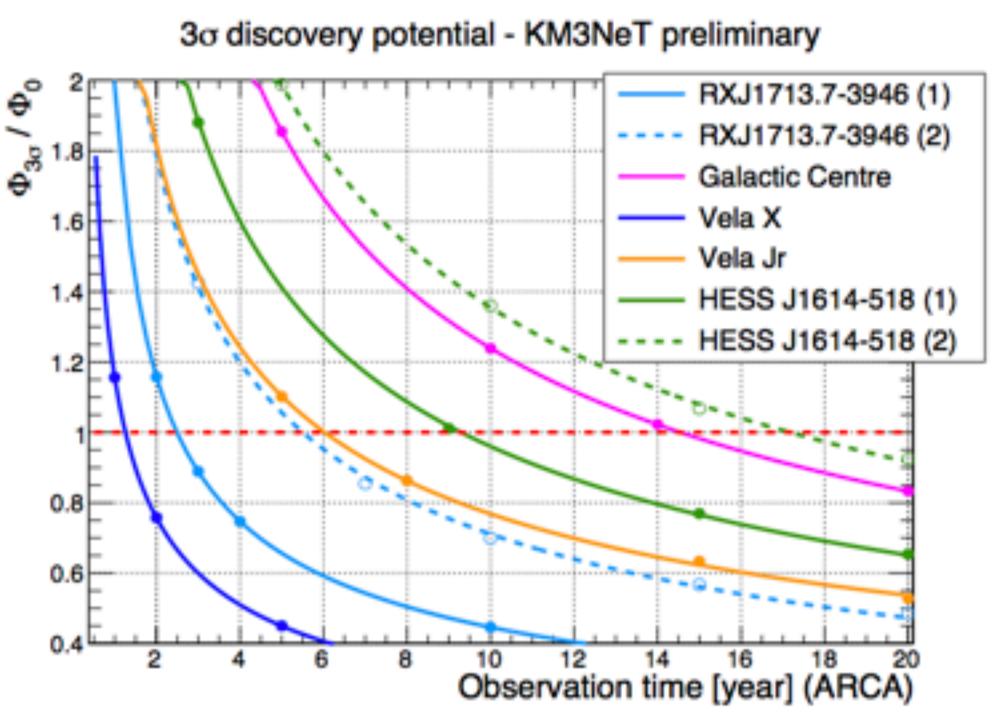
Specific galactic sources

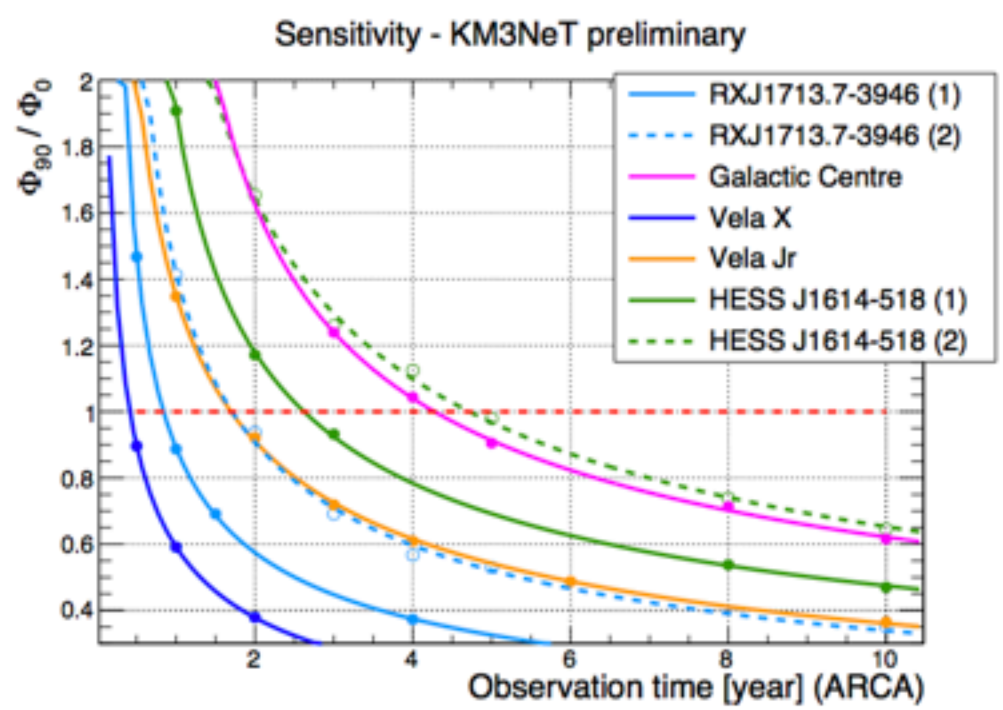
Source	δ	extension	Φ_0	Γ	E_{cut}	β	γ-ray data
RX J1713.7-3946 (1)	-39.77°	0.6°	1.68	1.72	2.1	0.5	[13]
RX J1713.7-3946 (2)	-39.77°	0.6°	0.89	2.06	8.04	1	[14]
Vela X	-45.6°	0.8°	0.72	1.36	7	1	[15]
Vela Jr	-46.36°	1°	1.30	1.87	4.5	1	[16]
HESSJ1614-518 (1)	-51.82°	0.42°	0.26	2.42	-	-	[17]
HESSJ1614-518 (2)	-51.82°	0.42°	0.51	2	3.71	0.5	[17]
Galactic Centre	-28.87°	0.45°	0.25	2.3	85.53	0.5	[18]
MGRO J1908+06 (1)	6.27°	0.34°	0.18	2	17.7	0.5	see text
MGRO J1908+06 (2)	6.27°	0.34°	0.16	2	177	0.5	see text
MGRO J1908+06 (3)	6.27°	0.34°	0.16	2	472	0.5	see text



γ→ν flux conversion:

F. Vissani, *Astropart. Phys. 26* (2006), 310.
F. L. Villante and F. Vissani, *Phys. Rev. D 78* (2008), 103007.
F. Vissani and F. Villante, *Nucl. Instrum. Methods A 588* (2008), 123.

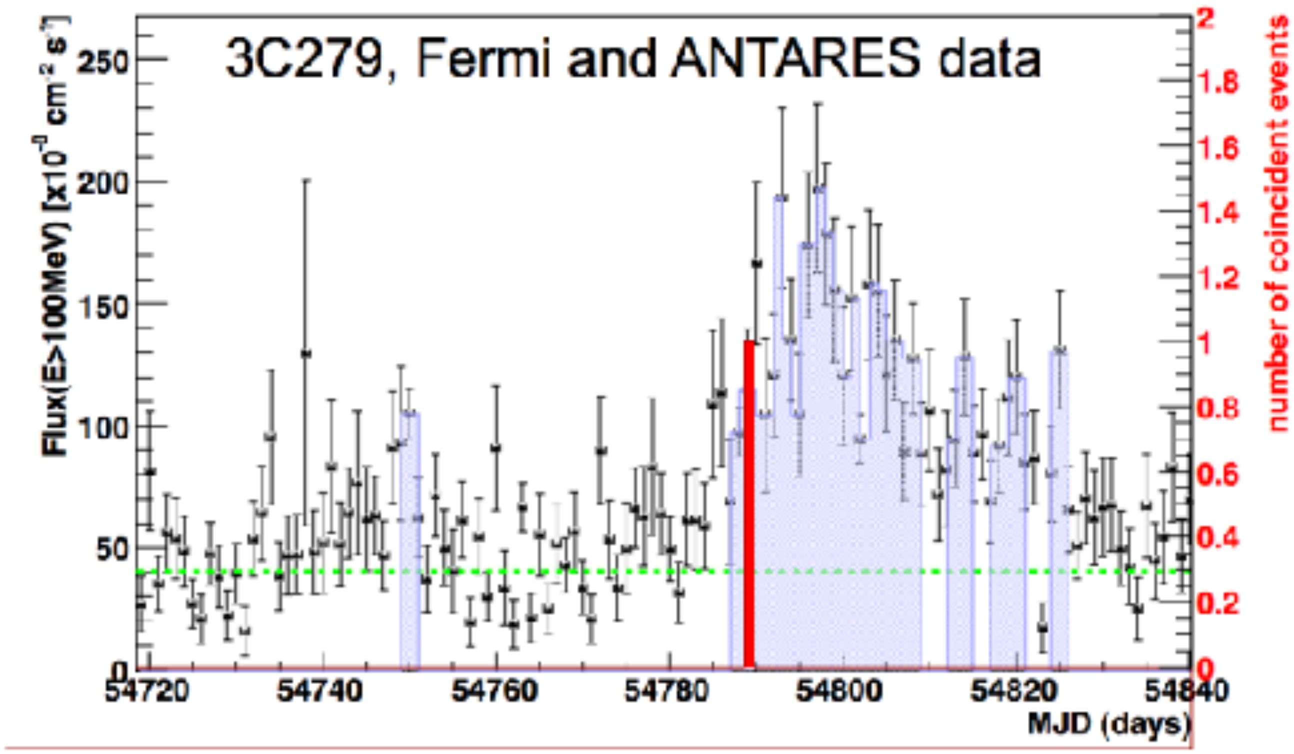




With reasonable 100% hadronic models, large probabilities to observe individual neutrino sources in the Galactic Plane

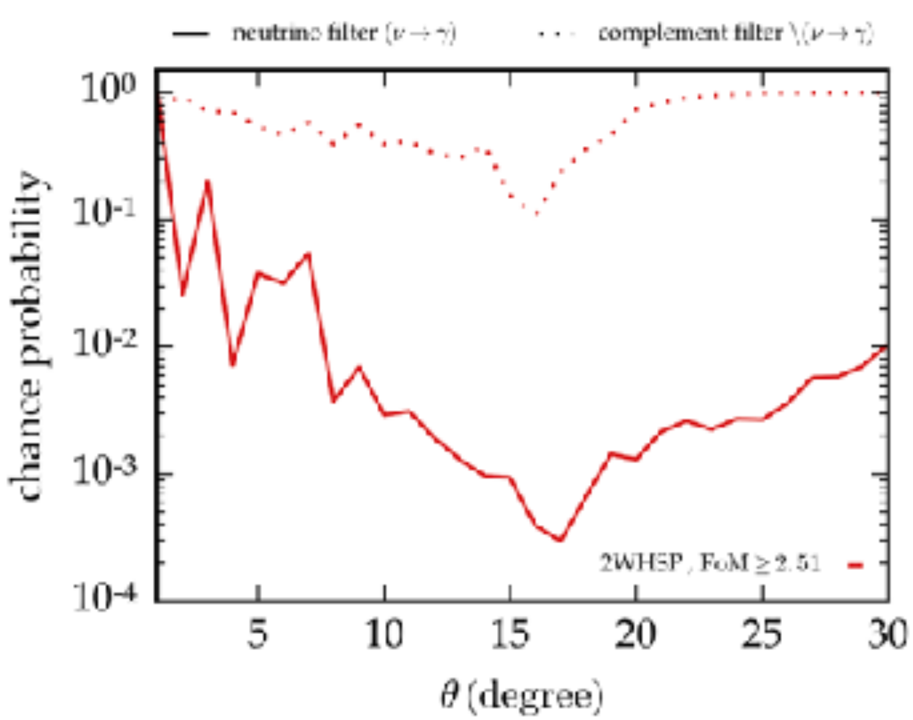
LOOKING FOR VARIABLE SOURCES

- ➡ **No correlation with GRB, FRB**
- ➡ **Few hints with blazars (nothing significant)**
- ➡ **One hint with SN Ic (IC160427)**

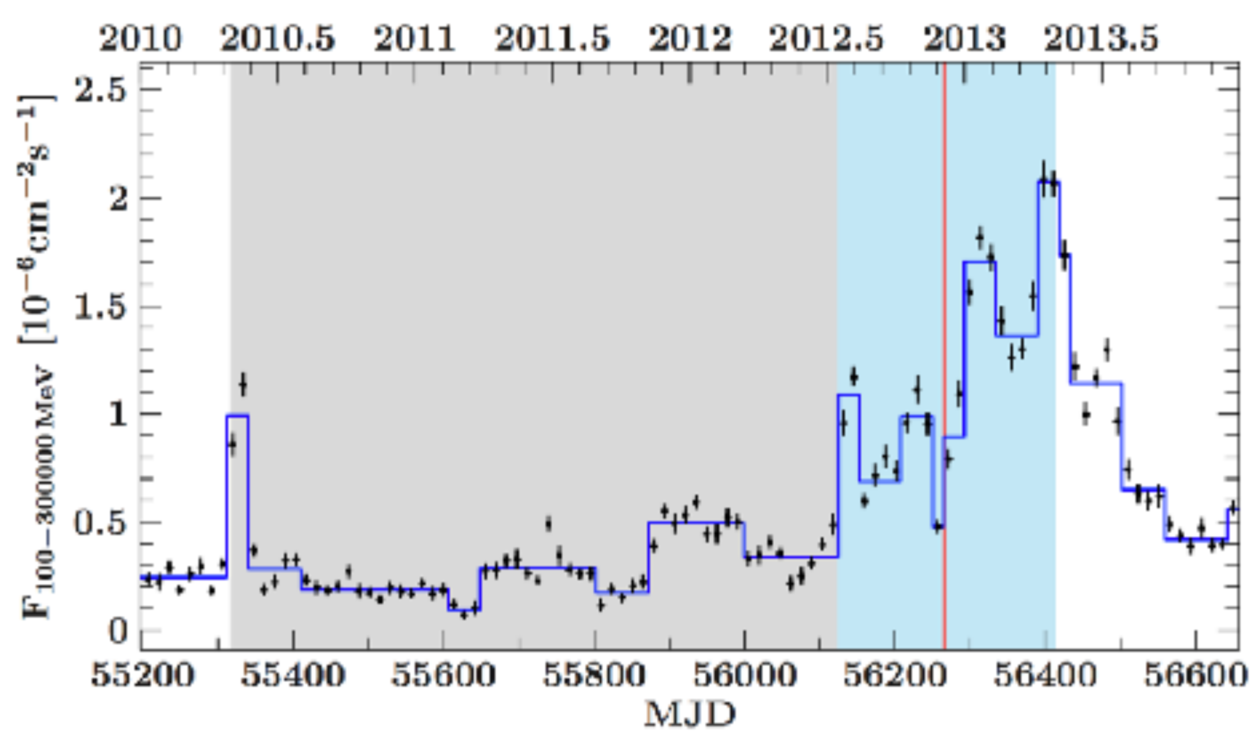


Connection ν-γ-UHECR

Resconi et al 2017, 2.9 sigma correlation with sub-sample of HBLs, IC nu and Auger UHECR



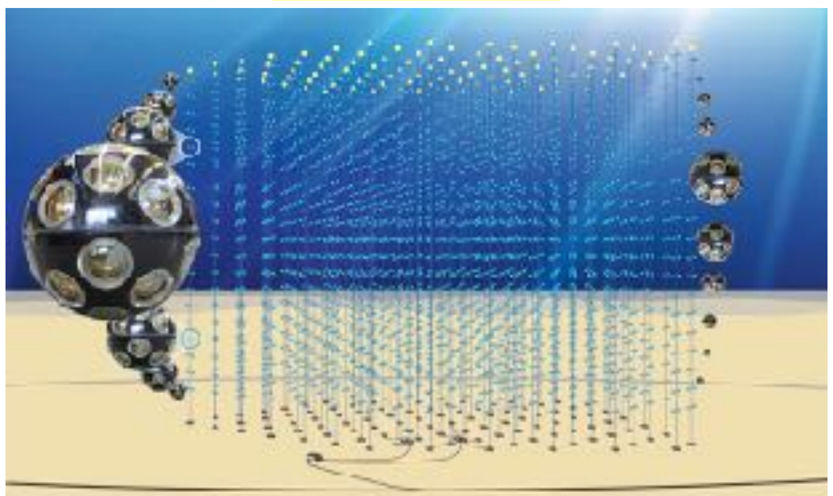
IceCube- Big Bird PKS B1424-418



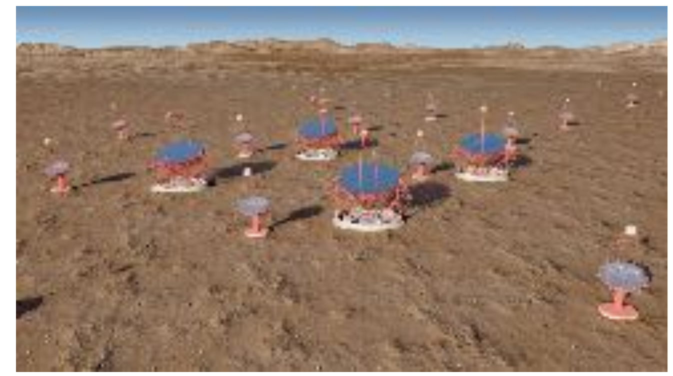
KM3NeT MULTI-MESSENGER PROGRAMS

- Follow-up of neutrino alerts
- Joint sub-threshold analysis

KM3NeT



CTA



LSST

SVOM

HAWC

LIGO/VIRGO

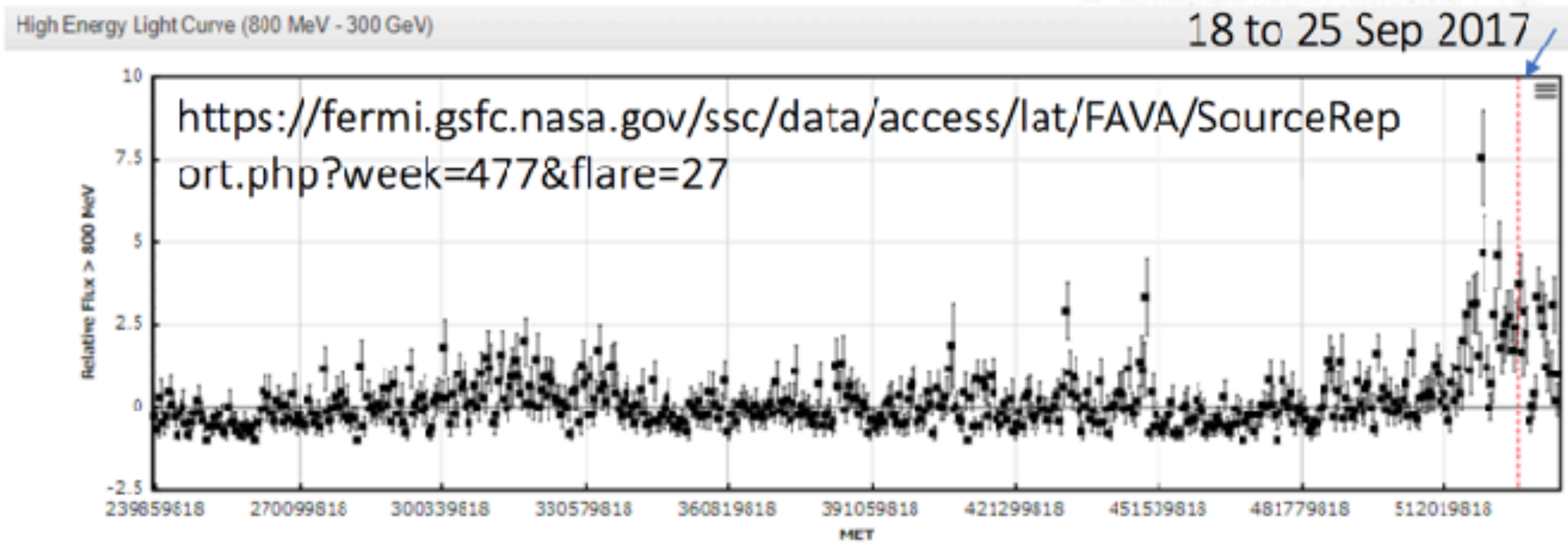
SKA

TAROT

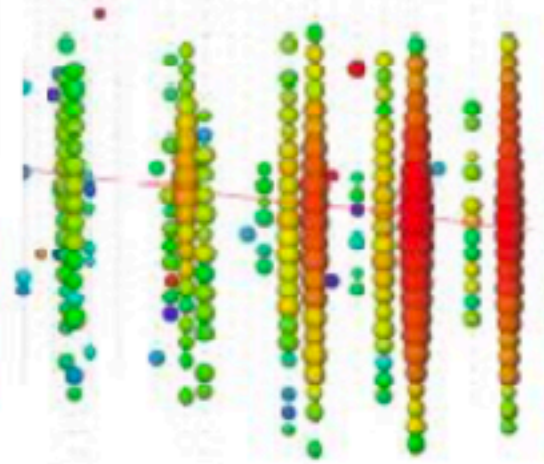
- Follow-up of EM/GW alerts
- Offline time/space correlation search with catalogues (GRB, AGN, XRB, SN, FRB…)

IC170922 / TXS 0506+056 ?

- Event occurred at 22nd Sept 2017 at 20:54:30 UTC
  - ➤ ***ATel 10791 - Fermi - increased gamma-ray activity of TXS 0506+056***(3FGL J0509.4+0541)



(signalness ~ 50%)
(E proxy ~ 120 TeV)



  - ➤ ***ATel 10817 – The First-time detection of VHE gamma rays by MAGIC***

MAGIC observed this source under good weather conditions for
12 h of observations from September 28th till October 3rd.
...and a 5 sigma detection above 100 GeV was achieved!
The first time measurement of VHE gamma-ray from a direction consistent with a detected neutrino event

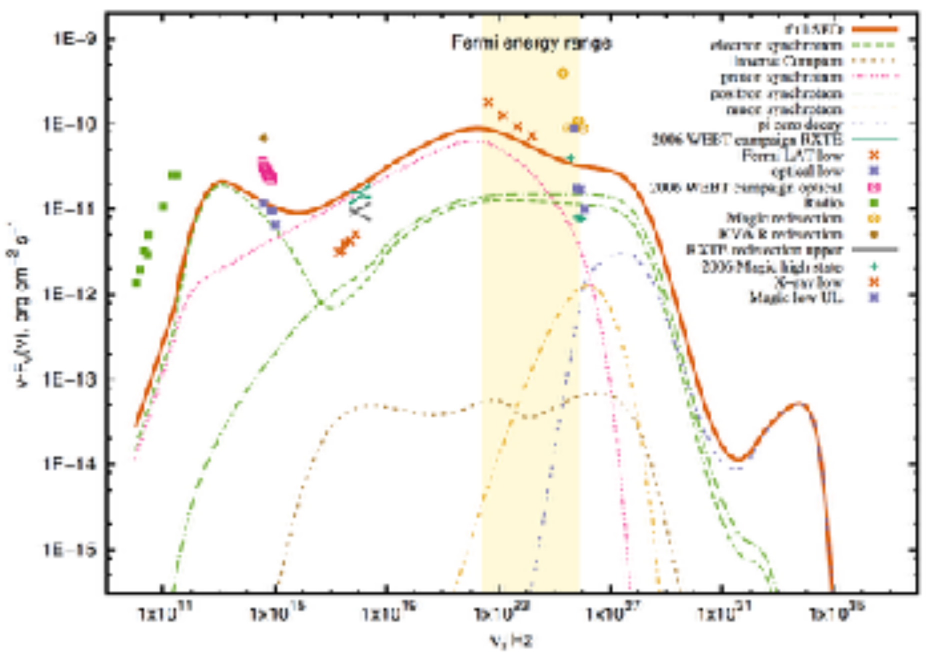
- ***Distance to TXS 0506+056?***

Paiano et al. (2018):the 10.4m Gran Telescopio Canarias, an optical spectroscopy ⇒ z = 0.3365 +/- 0.0010

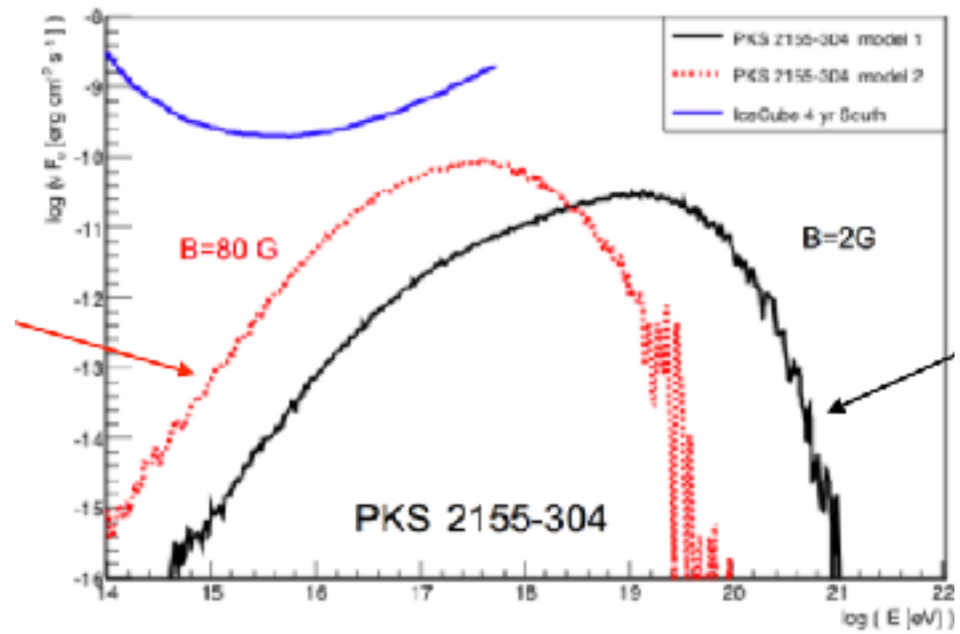
ν PREDICTIONS FOR AGN

For AGN, very few groups are developing lepto-hadronic models:
⇒ Produce very high energy neutrinos >1 PeV

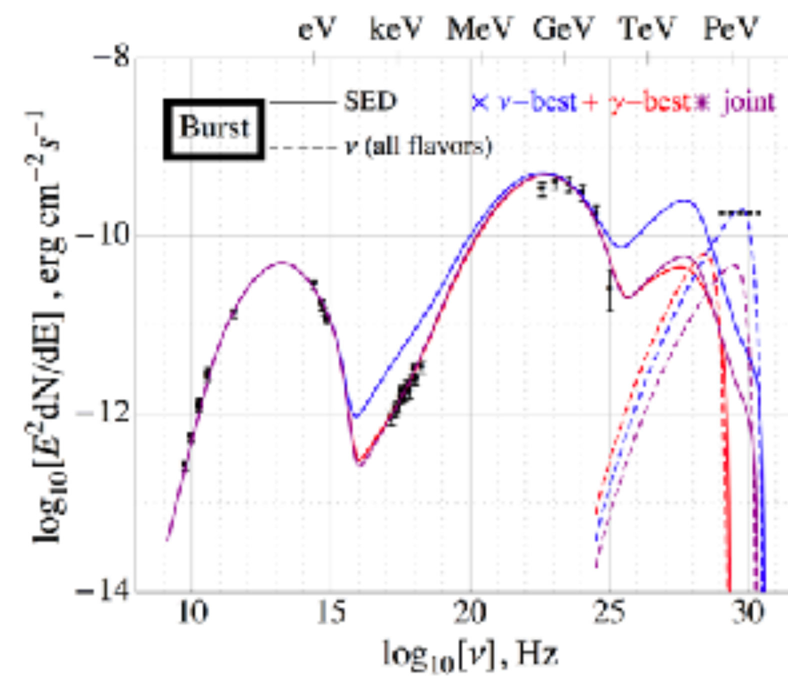
3C279 | **PKS 2155-304** | **PKS B1424-418**



Richter, Spanier, arXiv:1802.08820



Zech, Cerruti, Mazin, A&A 602 (2017) 25



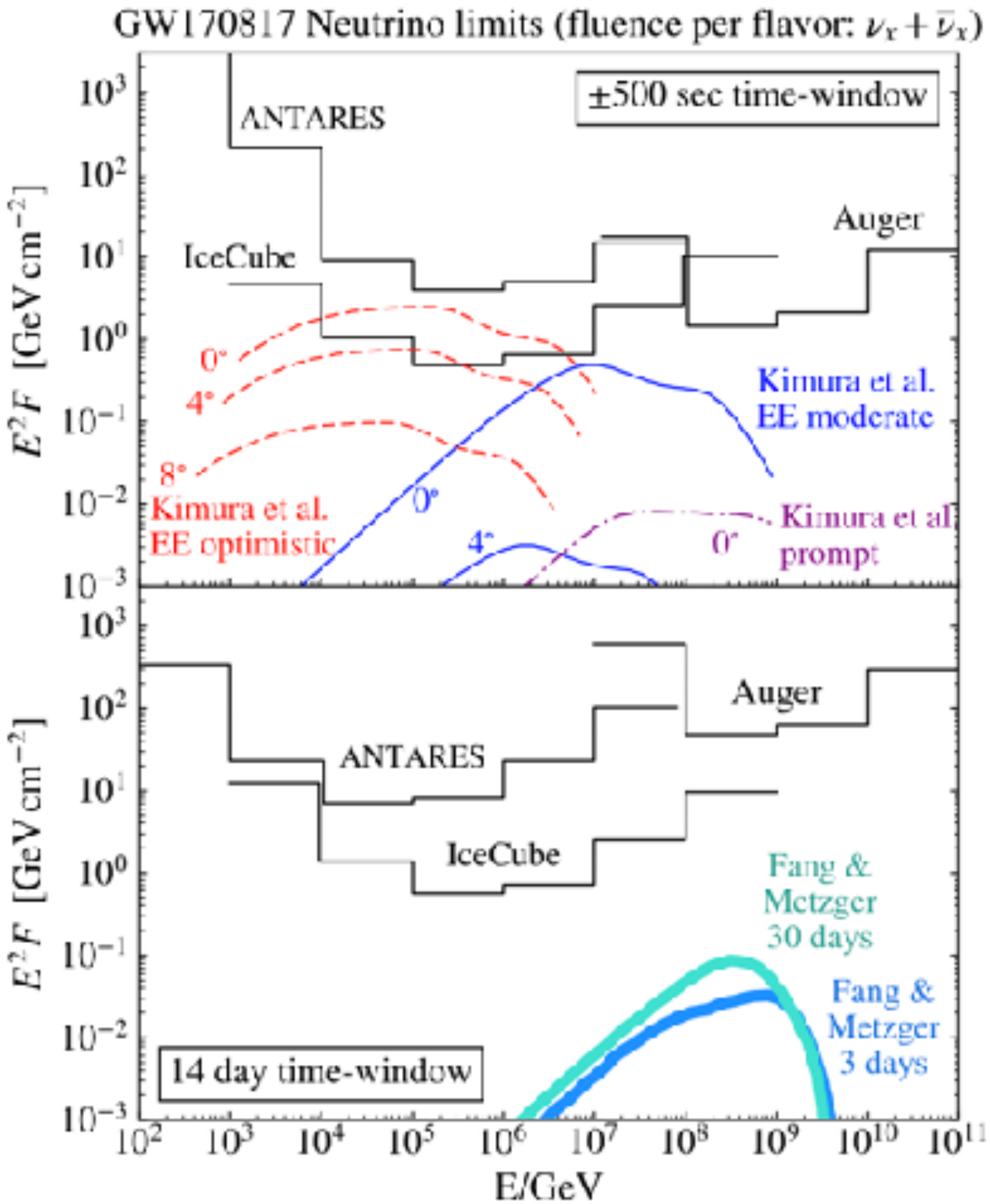
Gao, Paul, Winter, ApJ. 843 (2017) 2

+Winter et al, Böttcher et al., Petropoulou et al. , Zdziarski et al.,

Is it possible to produce intermediate energy neutrinos [1-50 TeV] ?

In which condition ? Correlation with 100 MeV - 10 GeV or 100 GeV - 10 TeV γ-rays ?

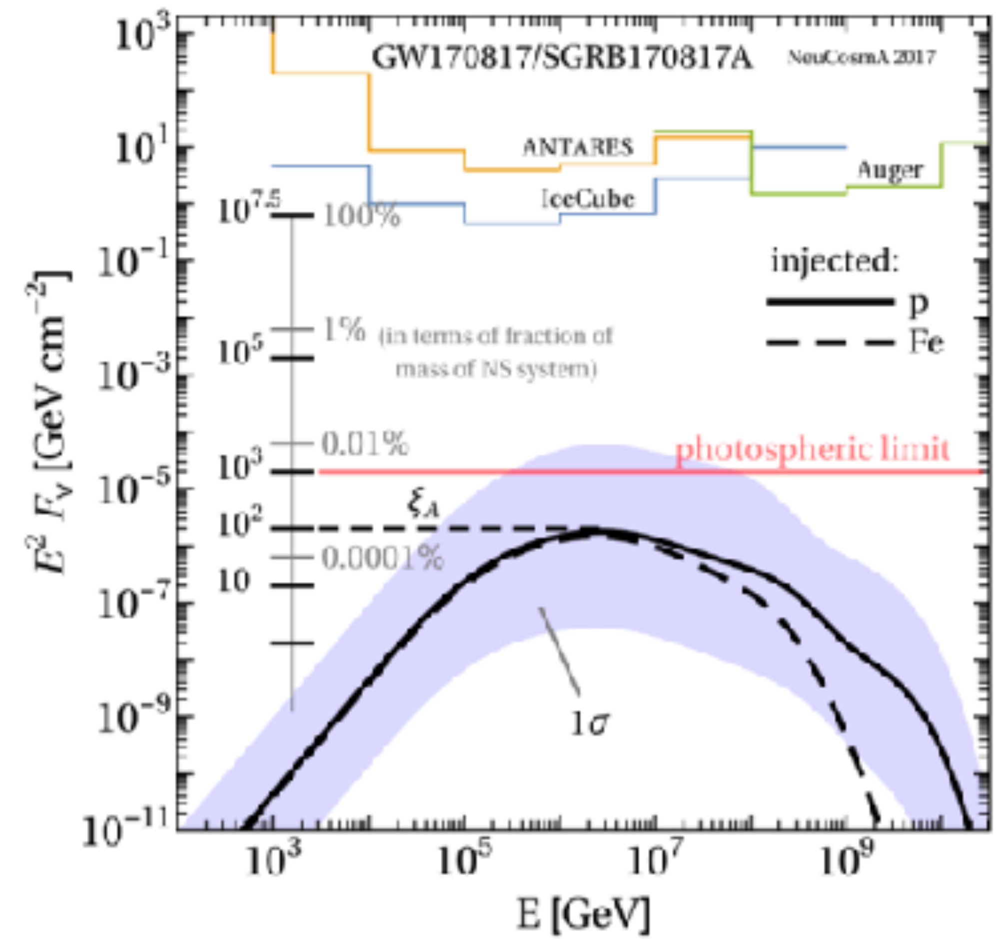
NEUTRINO FROM GRB170817/GW170817 ?



ANTARES, IceCube, Auger, LIGO/VIRGO, ApJ, 850 (2017) L35

Kimura, Murase, Mészaros & Kiuchi, ApJL, 848 (2017) L4

$\neq$



Biehl, Heinze, Winter, arXiv:1712.00449

- ➡ **For this special event, very different computations. Need to be ready for the next interesting events**
- ➡ **Standard GRBs seem to not be efficient neutrino producers. Do we still have a chance to detect individual GRB? Which parameters?**

MODELISATION

➡ To improve discovery potential, need to know where/when to look for neutrino association: correlation with TeV γ-ray?, GeV γ-ray?, X-ray ? Radio flares?

➡ For galactic sources, the sensitivities of future telescopes (ARCA/ Gen-2) are closed to the model predictions, need also more sophisticated models (lepto-hadronic, better implementation of microphysics).

➡ We have few hints that transient/variable sources could brighter HE neutrino sources (blazars, SN…), need to have time-dependent hadronic models (arXiv:1410.5380)

➡ Most of the neutrino predictions are at very high or ultra high energies, need models for intermediate energy range [50 GeV - 50 TeV]

➡ One strength of IceCube is that theoreticians are part of the collaboration. This interaction is quite weak in our collaboration.

[It is free to be observator in the KM3NeT Collaboration]

Summary

Multi-messenger astronomy era ! (GW + neutrino)

- **Diffuse flux of cosmic neutrinos observed by IceCube**
- **Higher level of hadronic activity in the non-thermal universe than previously thought**
- **Sources remain to be identified. Hints are pointing in MM analyses. We are quite closed !**

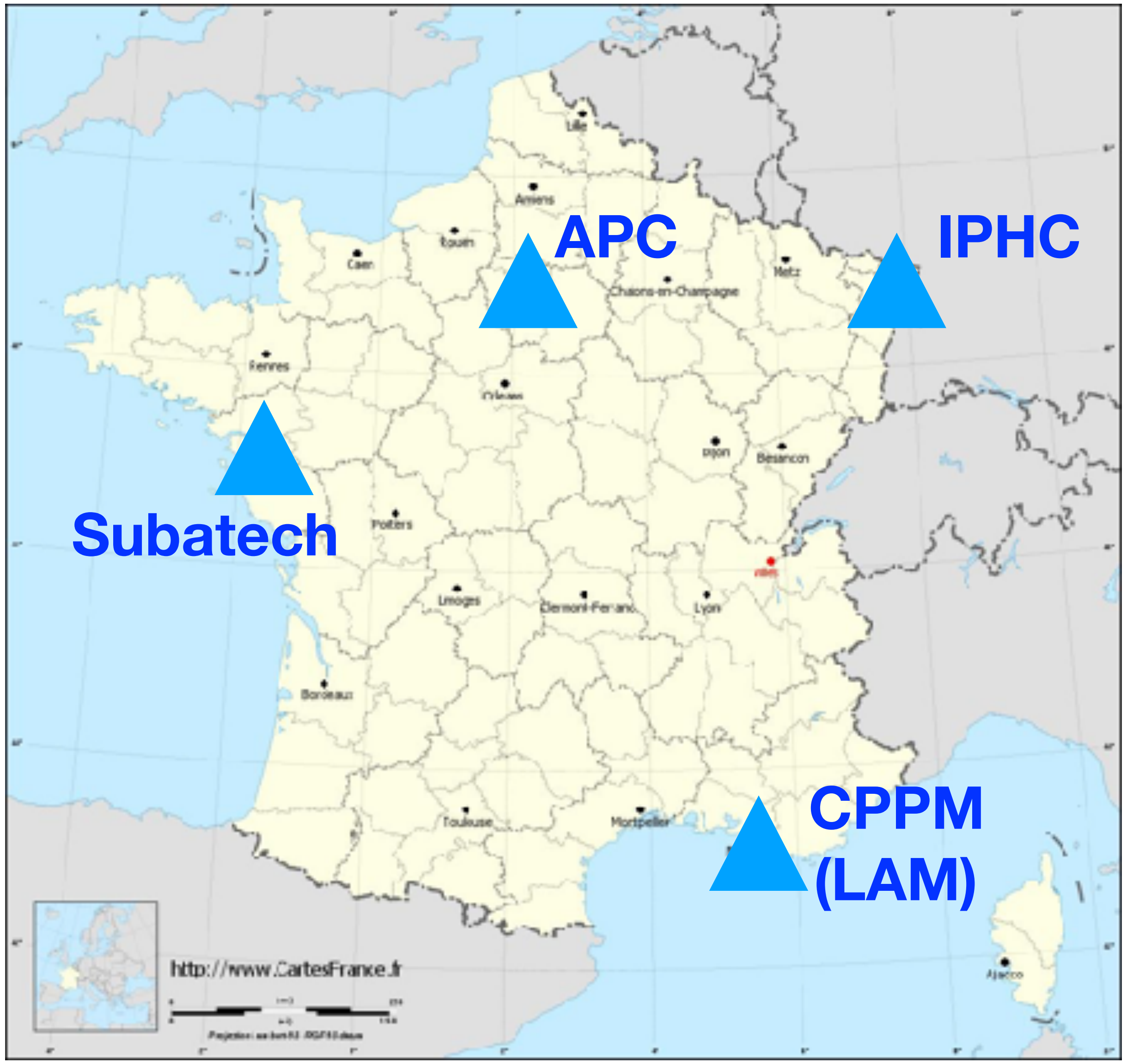
Exciting times ahead !

⇒ KM3NeT: phased approach to next-generation neutrino telescope

ARCA (KM3NeT-It) **for HE neutrino astronomy (tracks & showers)**
ORCA (KM3NeT-Fr) **for measurement of neutrino mass hierarchy**
→ First strings performing well !!!

- **Start to implement the multi-messenger programs in KM3NeT for both ORCA and ARCA based on the successful experience of ANTARES.**
- *The follow-up of gravitational waves have worked very well and the community is organizing itself to get an even better follow-up of GW events. Neutrinos are a bit left in this structurant process. Need to think more in a multi-messenger manner rather than separated the messenger.*

KM3NeT IN FRANCE



In France, 4 groups:

APC, CPPM, IPHC, Subatech

(+LAM, MIO observator)

~ 15 permanent physicians 50/50 between low and high energy activities

KM3NeT is a multi-purpose experiment, we have access to all ORCA/ARCA data.

➡ KM3NeT neutrino data are proprietary but become public after a latency of 2 years after the data taking (except neutrino alerts).

➡ It is free to be observator in the Collaboration [only sign paper with contributions, no shift]

On KM3NeT, we have the responsibilities for:

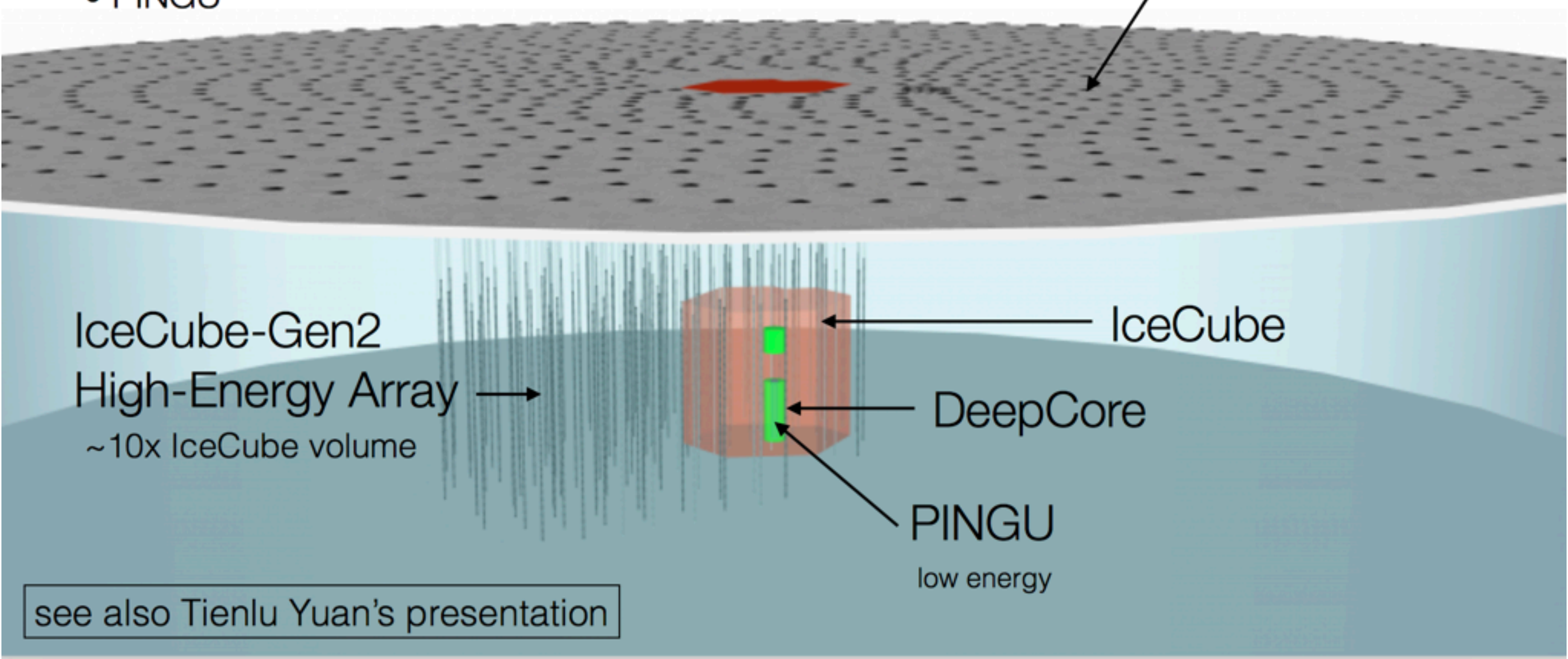
- **Neutrino oscillation group:** PMNS oscillation parameters, neutrino mass hierachy, CP phase
- **Multi-messager group:** time-dependent searches for GRB, AGN, FRB…, real-time alerts, MM analysis (GW, IC, UHECR…), MeV neutrino SNe

The IceCube-Gen2 facility

A wide band neutrino observatory (MeV – EeV) using several detection technologies – optical, radio, and surface veto – to maximize the science

Multi-component observatory:

- IceCube-Gen2 High-Energy Array
- Surface air shower detector
- Sub-surface radio detector
- PINGU



see also Tienlu Yuan's presentation