Towards Neutrino Astronomy with IceCube+ANTARES+KM3NeT

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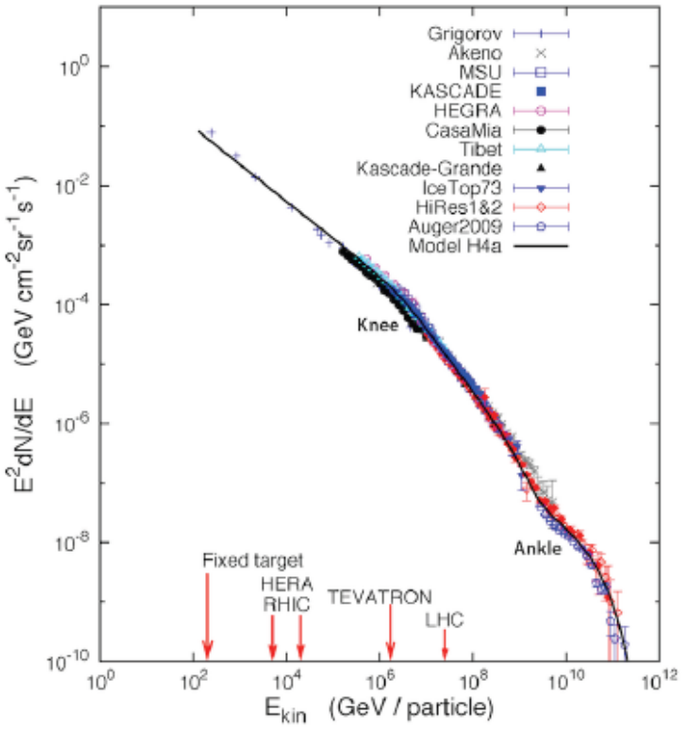
on behalf of Damien Dornic (CPPM)

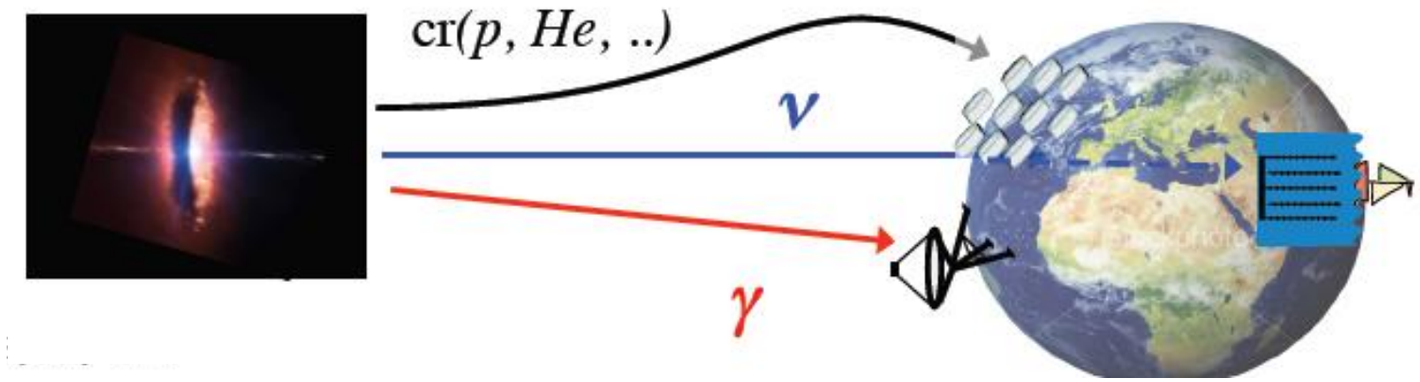
FCPPL meeting @ Marseille

Marseille – 25 May 2018

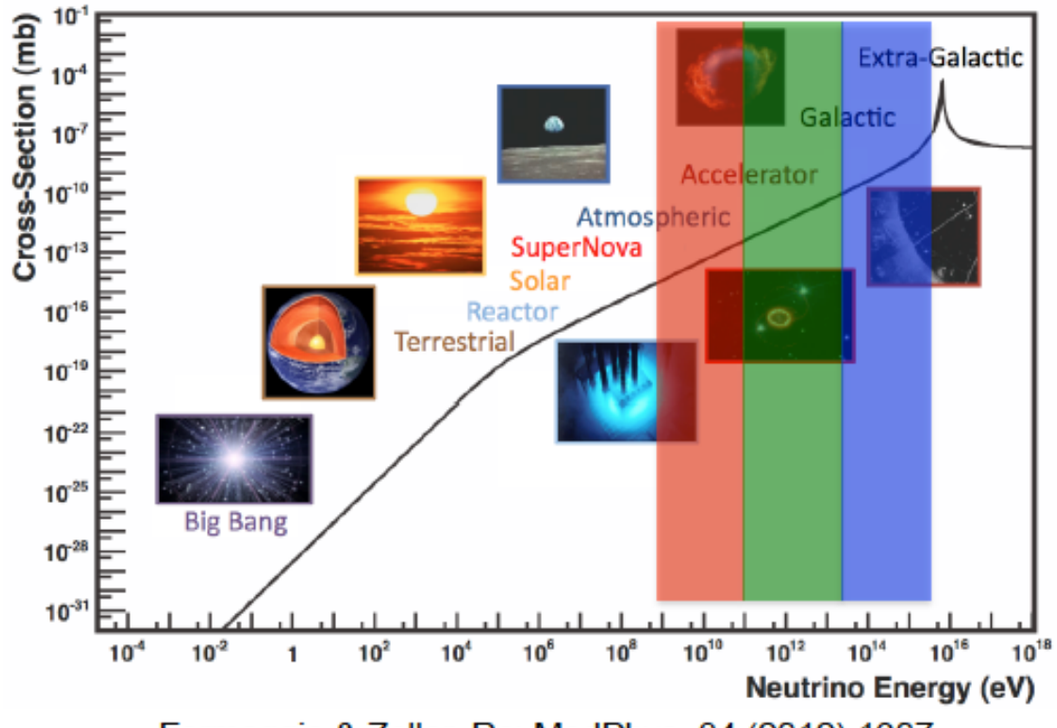
NEUTRINO AS COSMIC MESSENGER



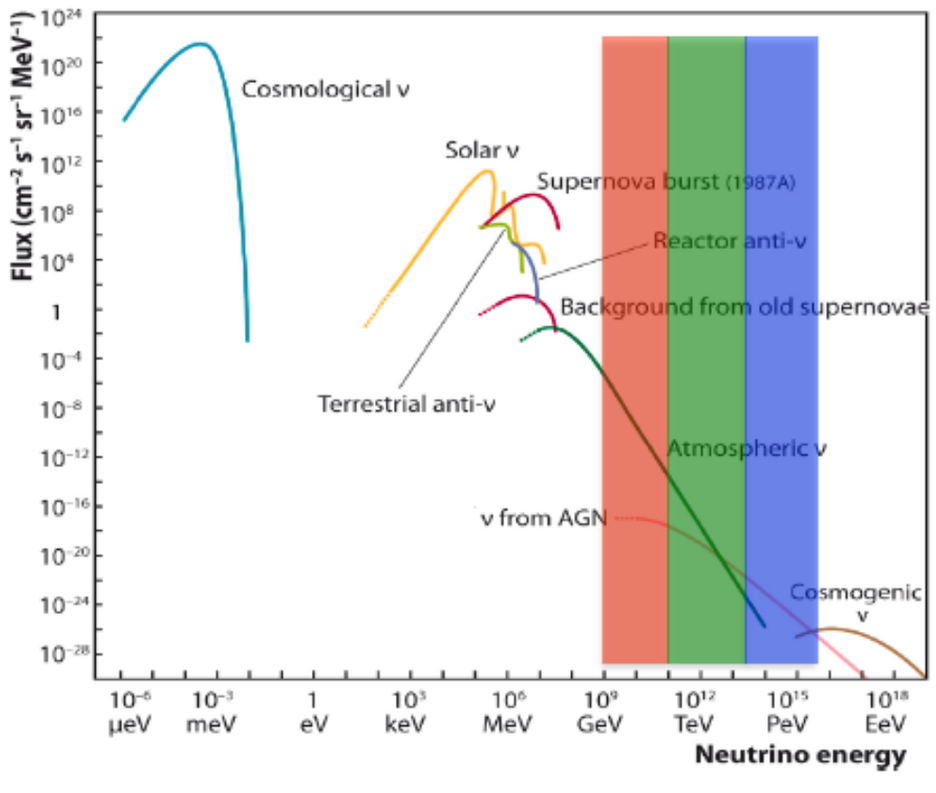
Neutrinos: smoking gun for cosmic-ray interactions



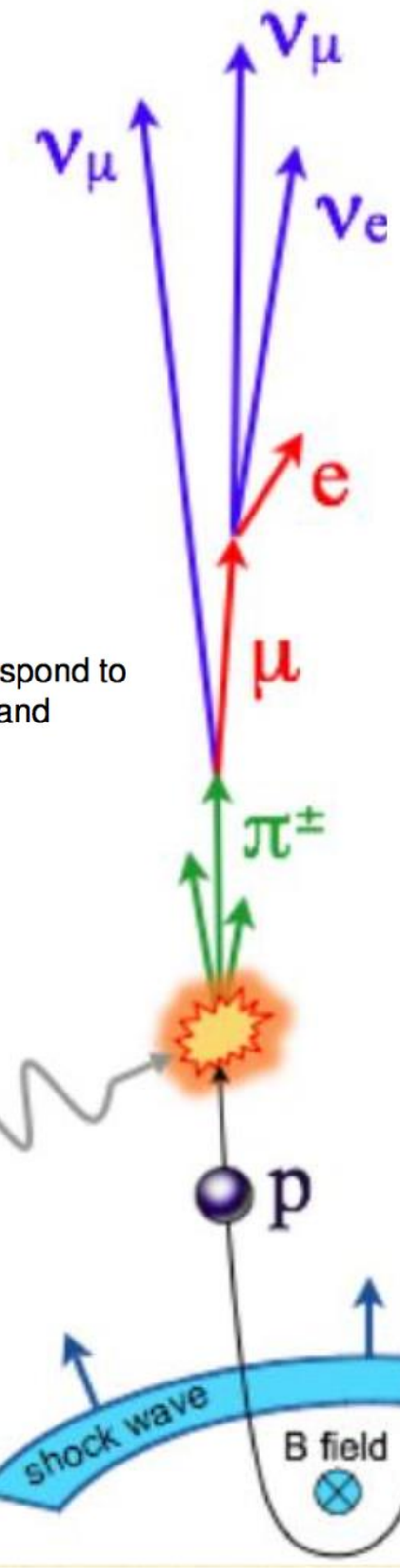
- 3 GeV – 1 TeV: atmospheric neutrinos, dark matter… ORCA
- 100 GeV - 30 TeV: various galactic (TeV gamma) sources ANTARES
- 30 TeV – 3 PeV: IceCube signal (astrophysical flux) ARCA



Formaggio & Zeller, RevModPhys 84 (2012) 1307



HE NEUTRINO PRODUCTION

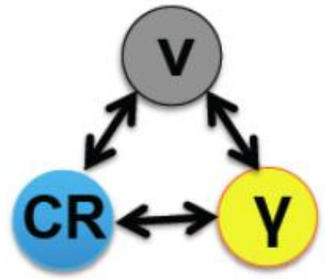


1 PeV neutrinos correspond to
20 PeV CR nucleons and
2 PeV γ-rays

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:

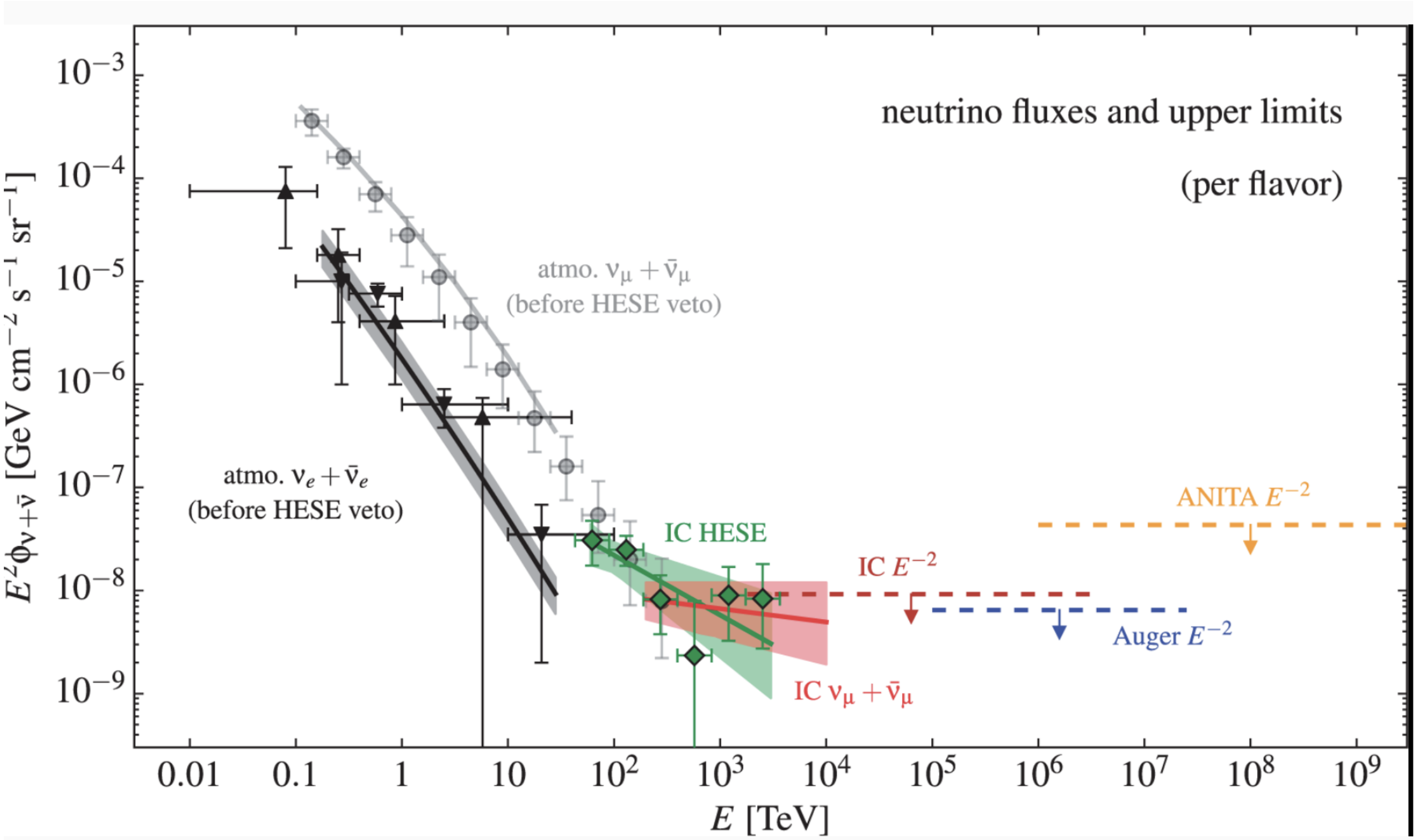
pion-muon decay

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

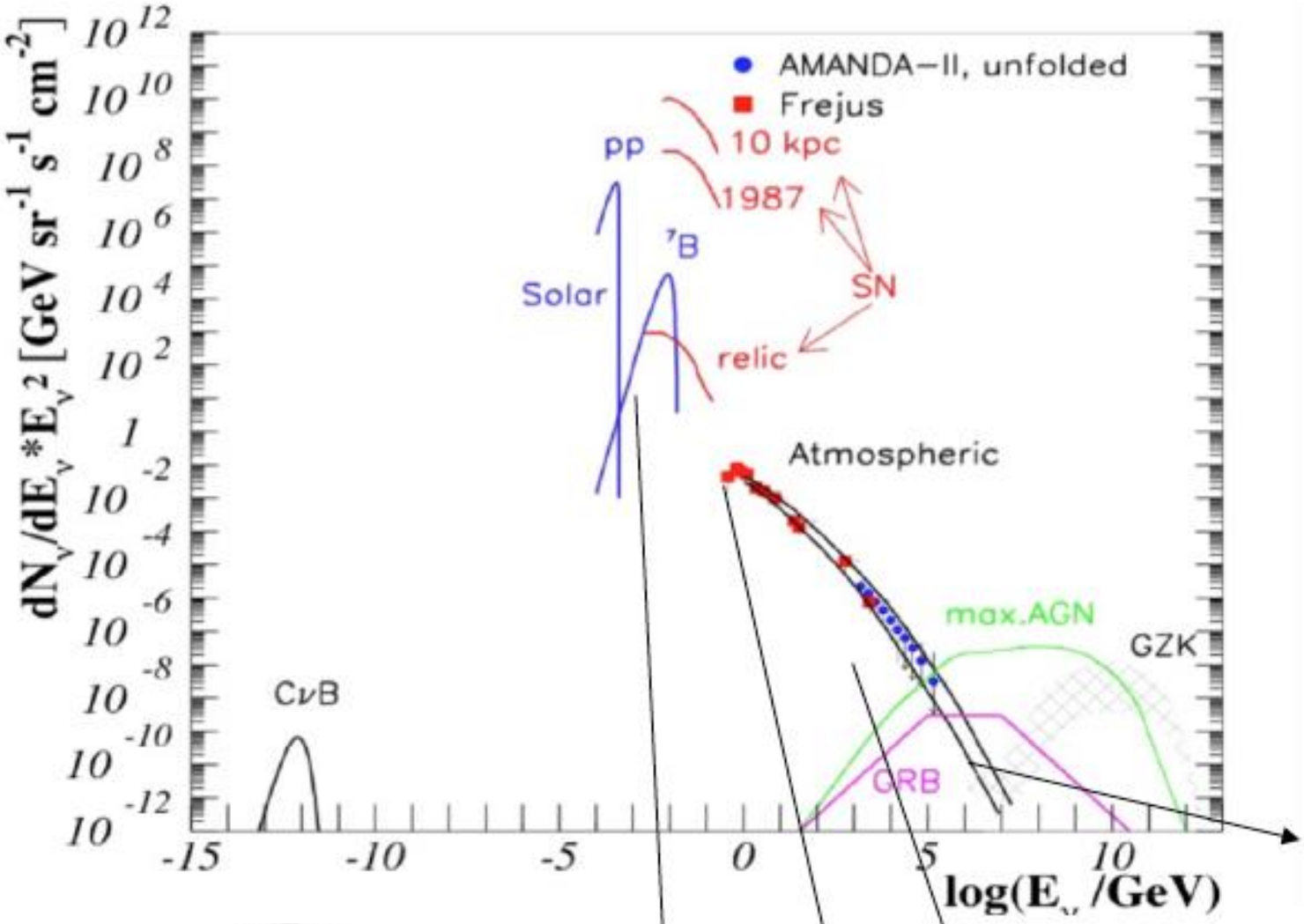
Oscillations average out over cosmic baselines

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

HE NEUTRINO FLUXES

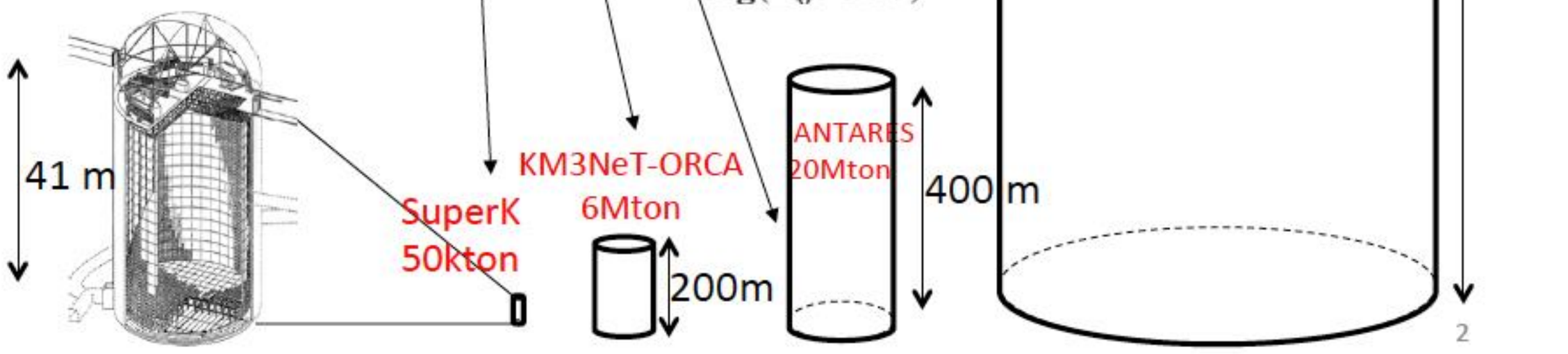


HE NEUTRINO DETECTORS

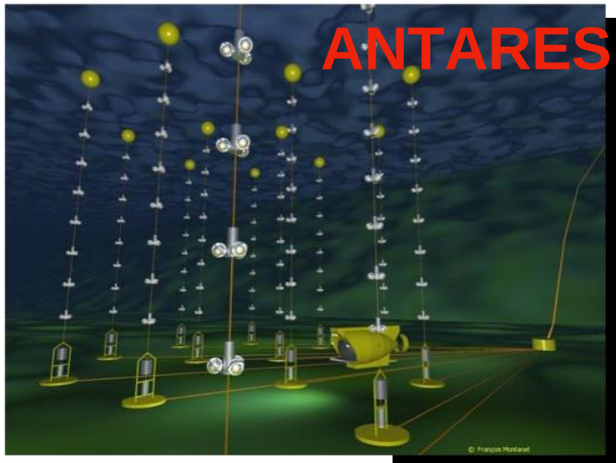


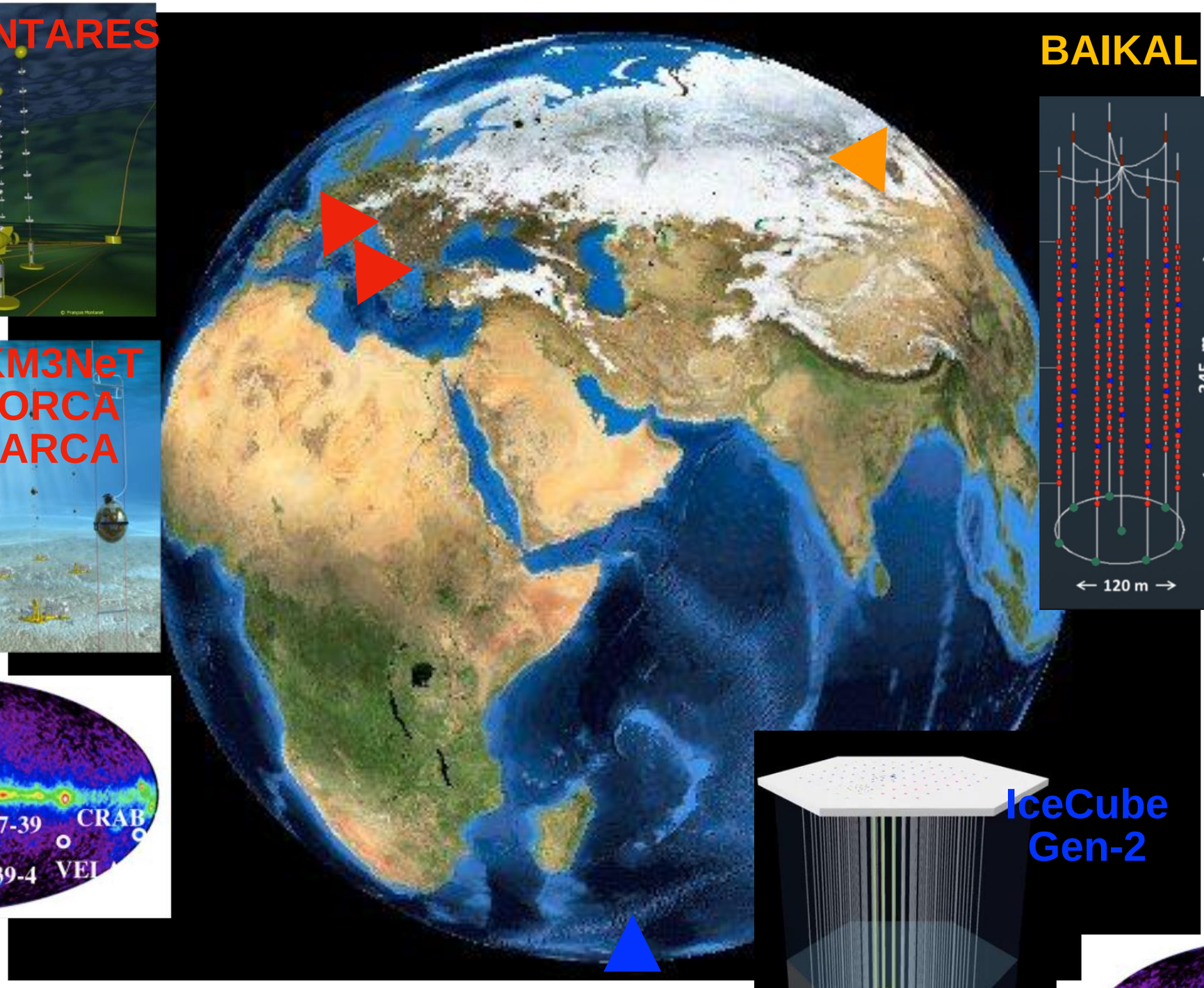
$\sigma(\nu p)/\sigma(\gamma p) = 10^{-7}$ at 1 TeV

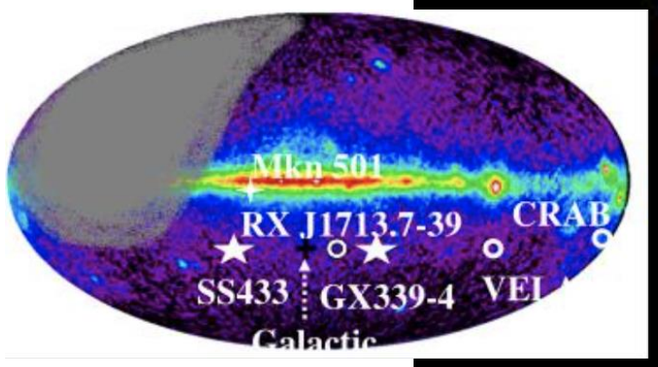
Need very large detectors

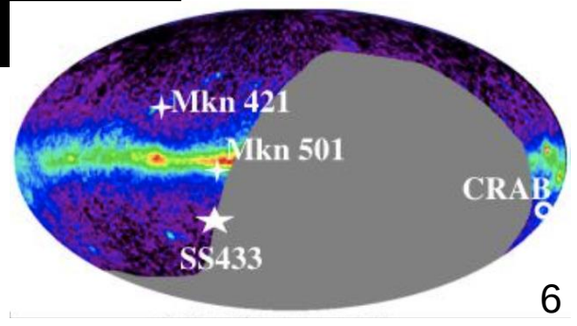


HE NEUTRINO DETECTORS



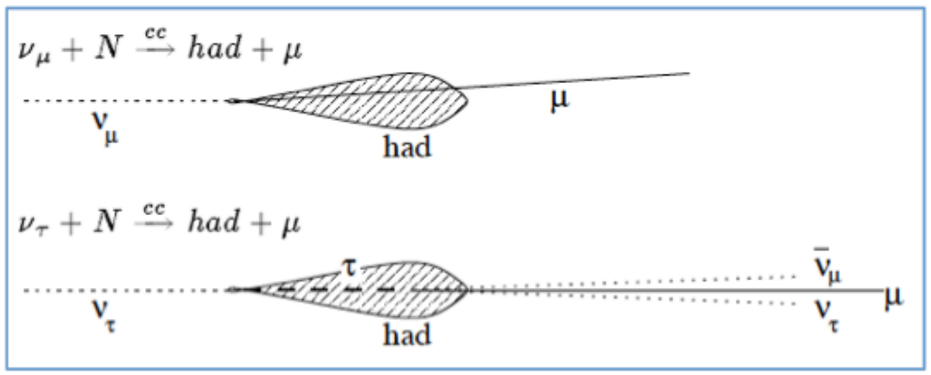




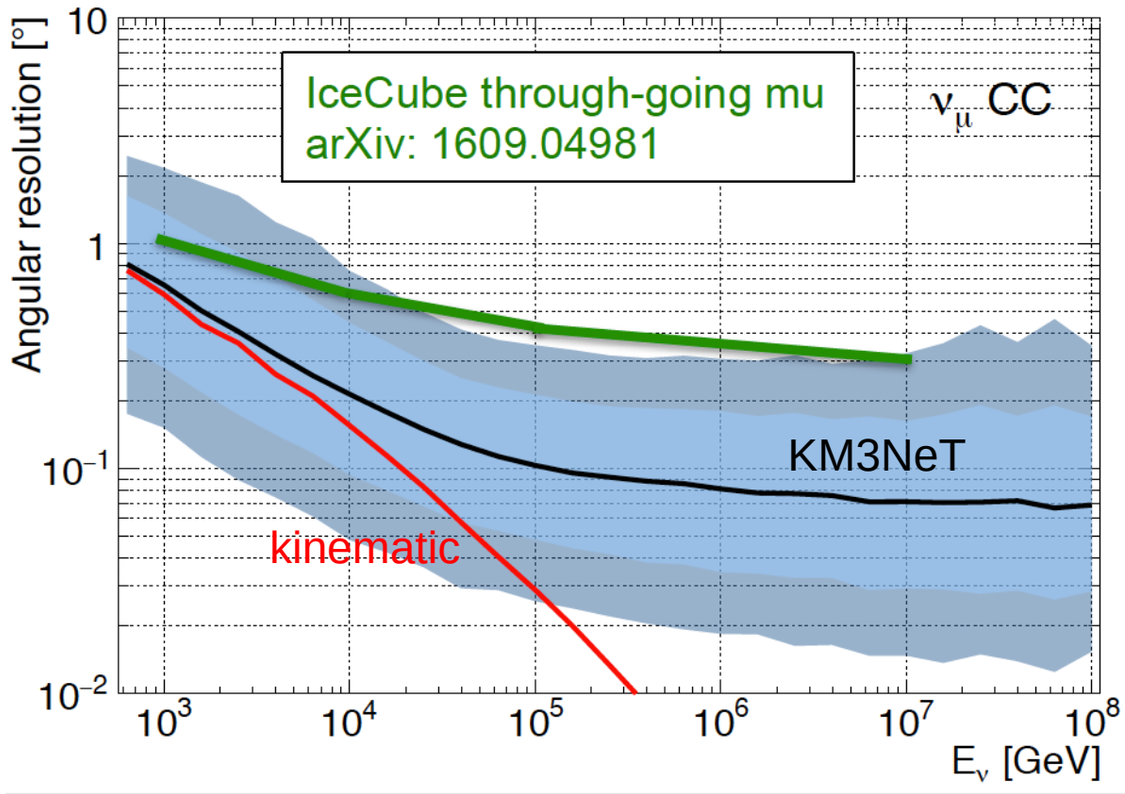


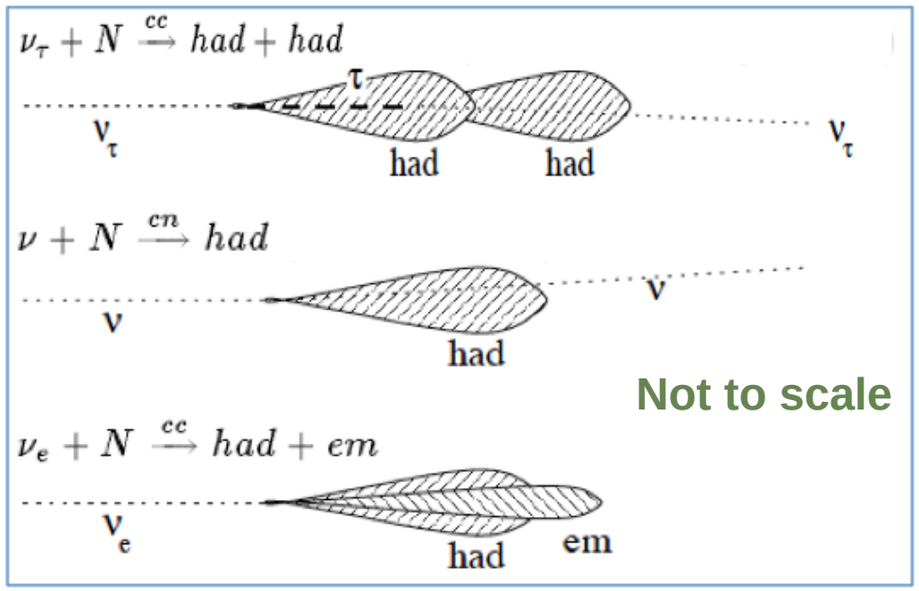
<u>GNN</u>: Global Neutrino Network linked all HE neutrino telescopes + provide framework for regular combined meetings and combined analysis

ALL-FLAVOR NEUTRINO TOPOLOGIES

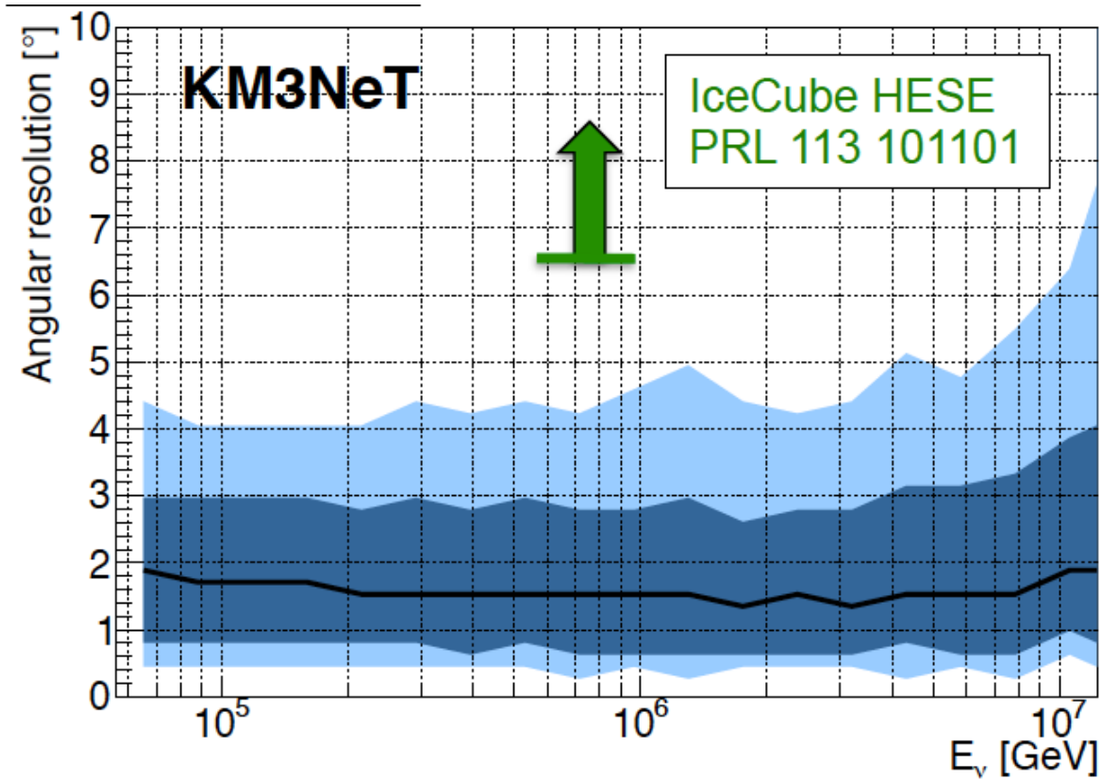


- Direction:
  - ➞ Gal. srcs: 0.2º at 10TeV [0.4º for ANTARES]
  - ➞ Extra-gal. srcs: 0.1º at 100TeV [0.3º for ANTARES]
- Energy: 0.27 in Log10(E)





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

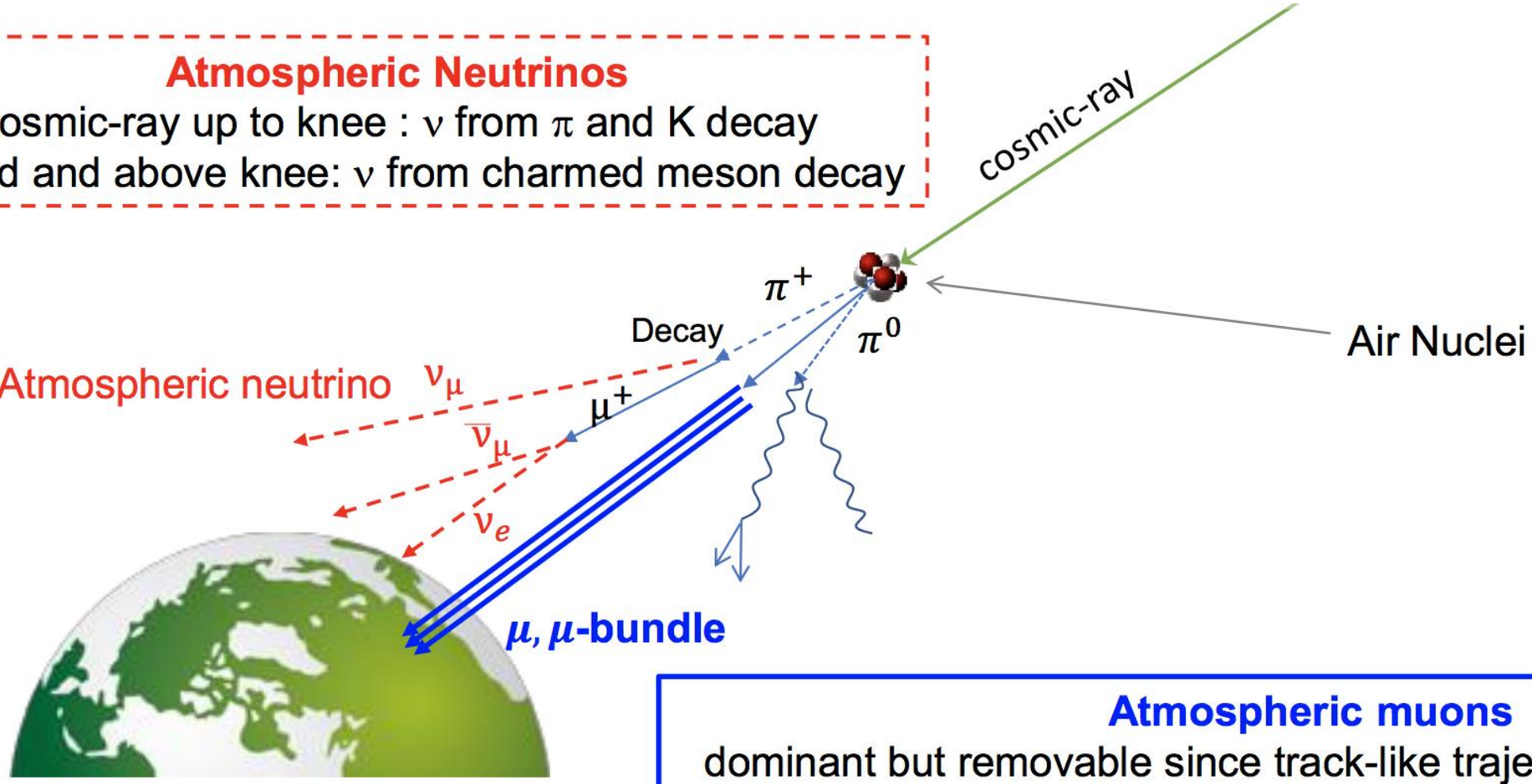


LARGELY DOMINATED BY ATM BKG

Atmospheric Neutrinos

cosmic-ray up to knee : ν from π and K decay

around and above knee: ν from charmed meson decay



Atmospheric muons

dominant but removable since track-like trajectories of Cherenkov photons and its directions is able to be reliably reconstructed

To have better discovery potential:

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

THE ICECUBE SIGNAL

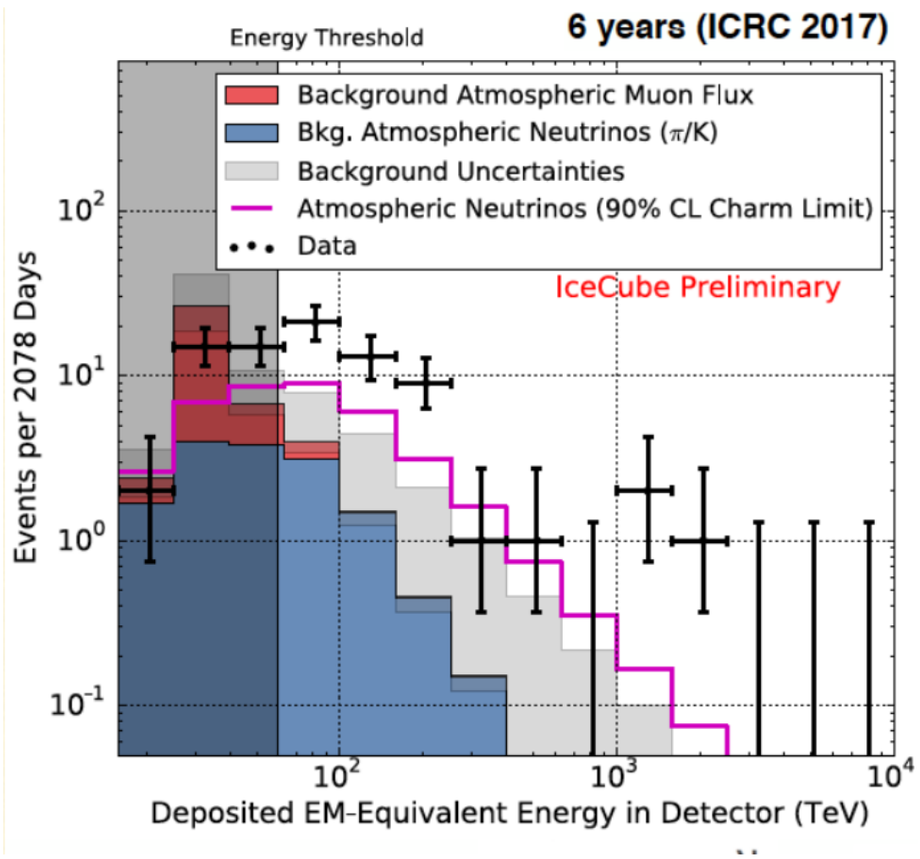
6 year HESE analysis (ICRC 2017)

80(+2) events

Bkg: $15.6^{+11.4}_{-3.9}$ atm ν + 25.2 ± 7.3 atm μ

Hemipshere North and South

E_{th}: 60 TeV



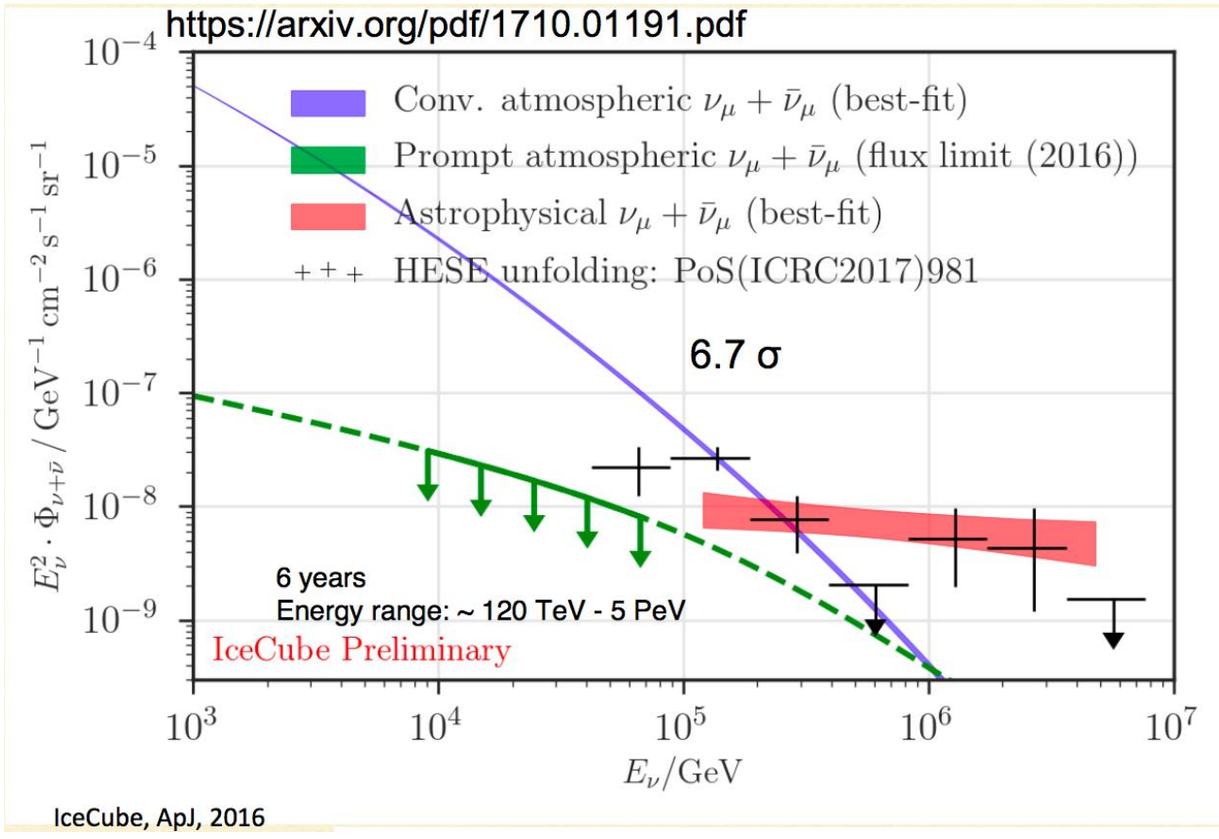
Significance: 6.5 sigma

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

8 year upgoing muon

E_{th}: 200 TeV

E_{event} > 5 PeV !



Significance: 6.7 sigma

Spectra: $E^{-2.19(\pm 0.10)}$

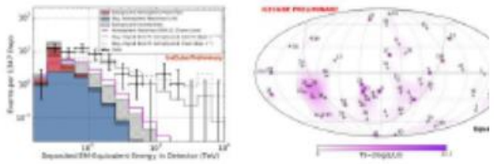
➞ Indication of a break in spectrum? (energy threshold different)

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

THE ICECUBE SIGNAL

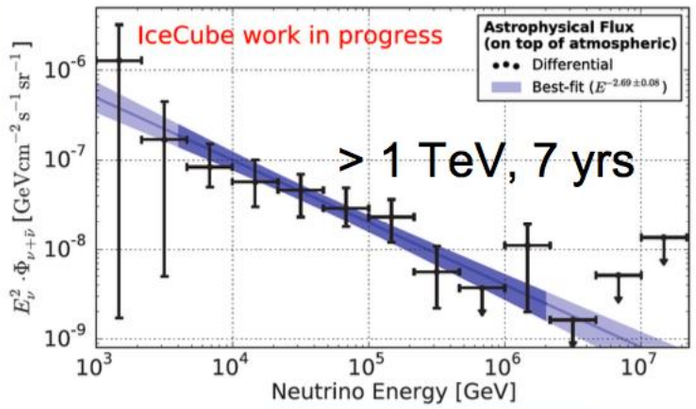
Last update for the starting track analysis

$E > 50\ TeV$



IceCube, ICRC 2017

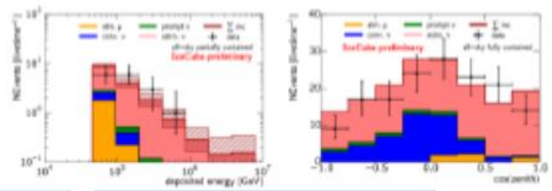
$\gamma = -2.92 \pm 0.30$



IceCube, PRD, 2015And TeVPA2017

$\gamma = 2.69 \pm 0.08$

showers (+partially cont.)



IceCube, ICRC, 2015

$\gamma = -2.7 \pm 0.12$

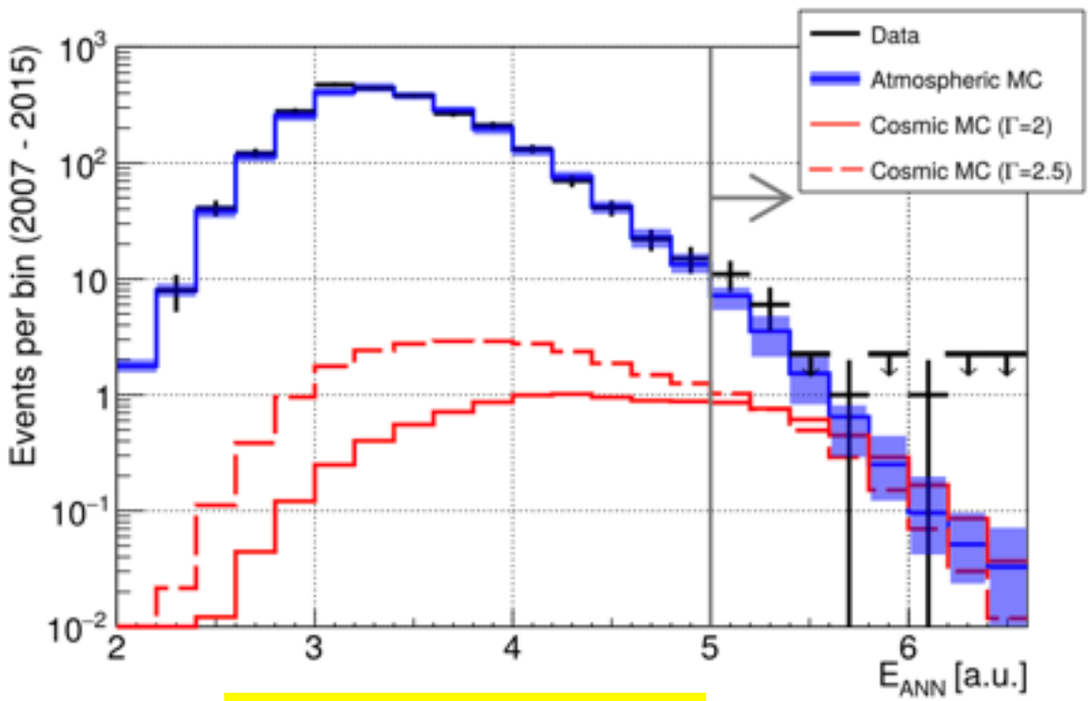
Soft
Spectral index?

5

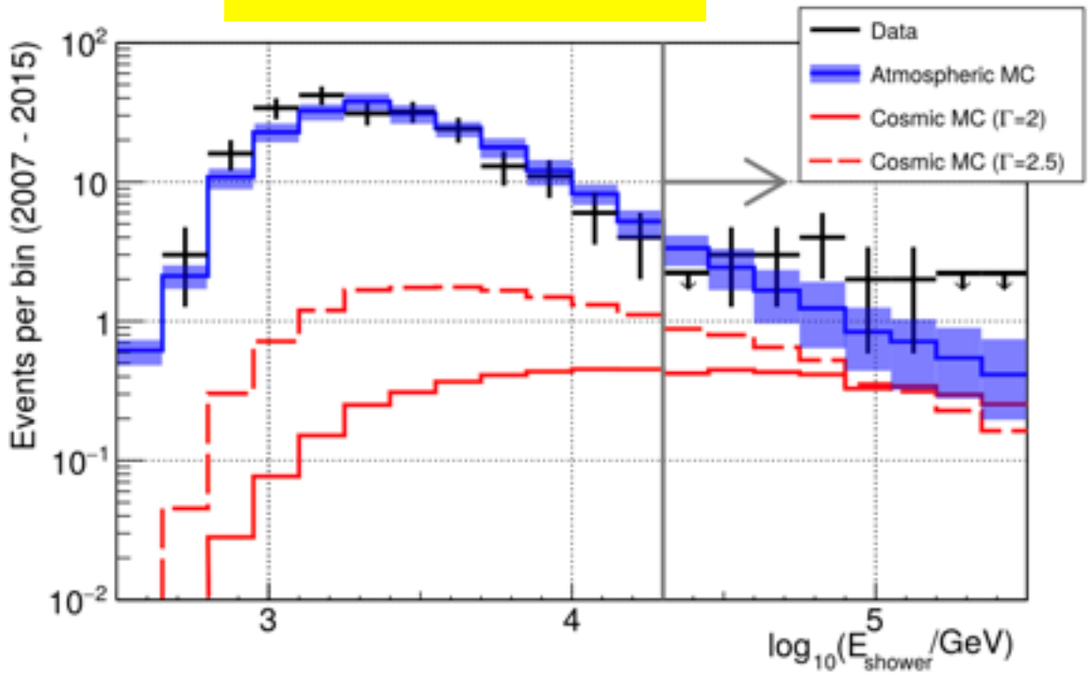
Analysis	Index	Normalization @ 100 TeV	Significance (σ)	Energy range
HESE 6 yr	2.92 ± 0.3	2.46 ± 0.8	8	60 TeV to 3 PeV
Northern tracks 6 yr	2.19 ± 0.10	1.01 +0.26 -0.23	6.7	119 TeV to 4.8 PeV
Cascades 4 yr	2.48 ± 0.08	1.57 +0.23 -0.22	4.7 (2 year)	10 TeV to 1 PeV
Global fit	2.50 ± 0.09	2.2 ± 0.4		25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

ANTARES DIFFUSE RESULTS

Track events



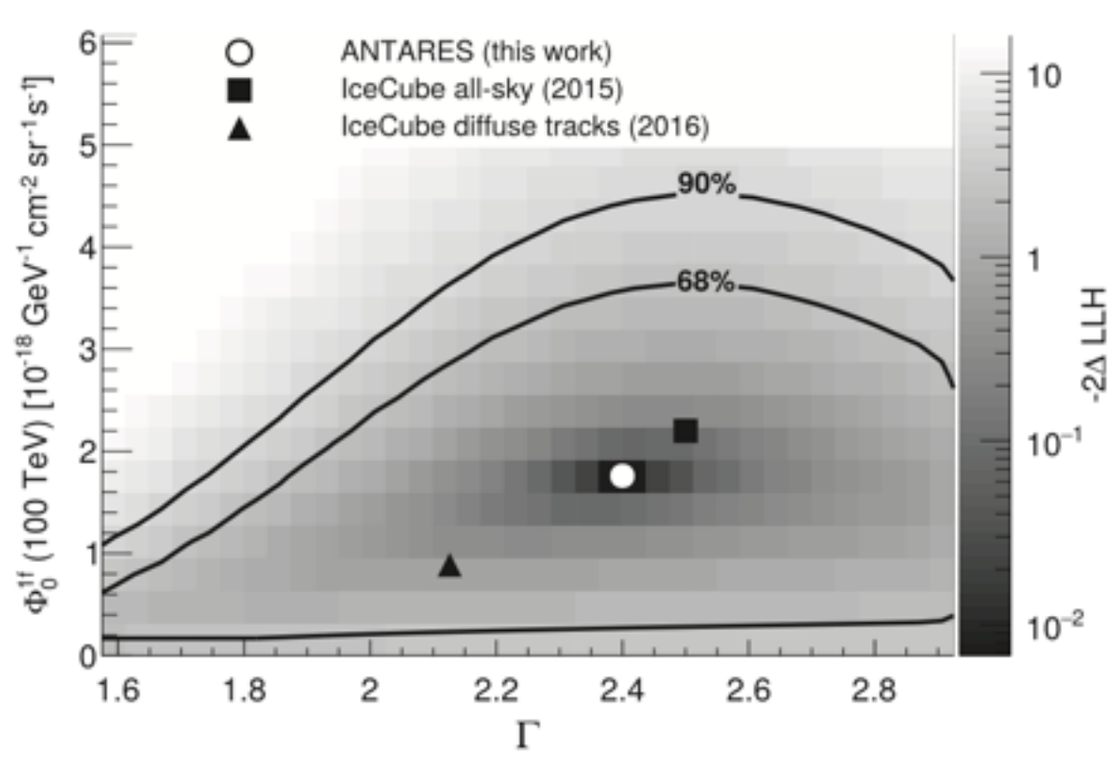
Cascade events



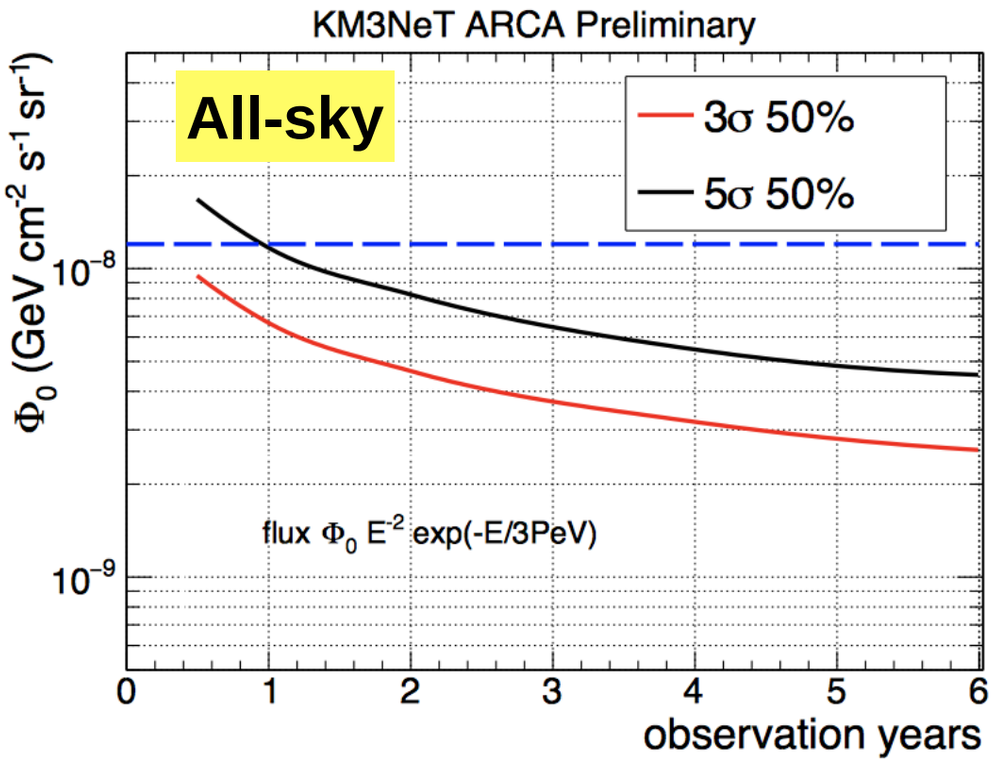
All-sky / All-flavor neutrino search

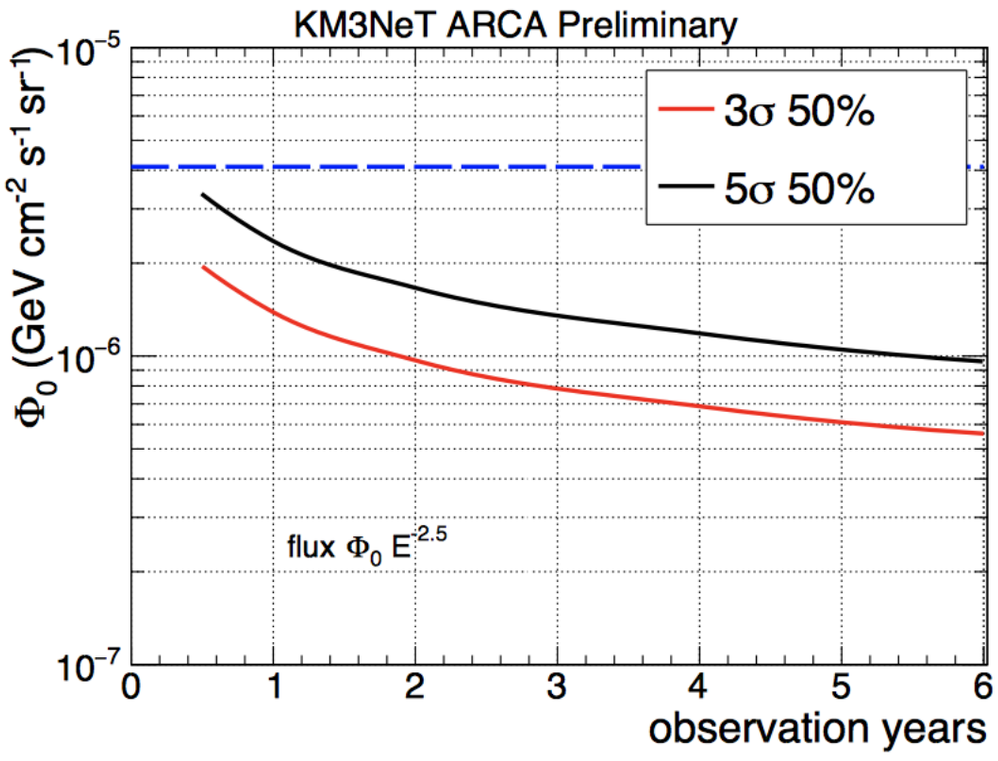
- Look for excess above a given E_{th}
- 9 (7) yrs of data for tracks (cascades)

	Bkg expectation	Signal expectation	Nb events measured
Track	**13.5 ± 4**	**3-3.5**	**19**
Shower	**10.5 ± 4**	**3-3.5**	**14**



KM3NeT: DIFFUSE FLUX

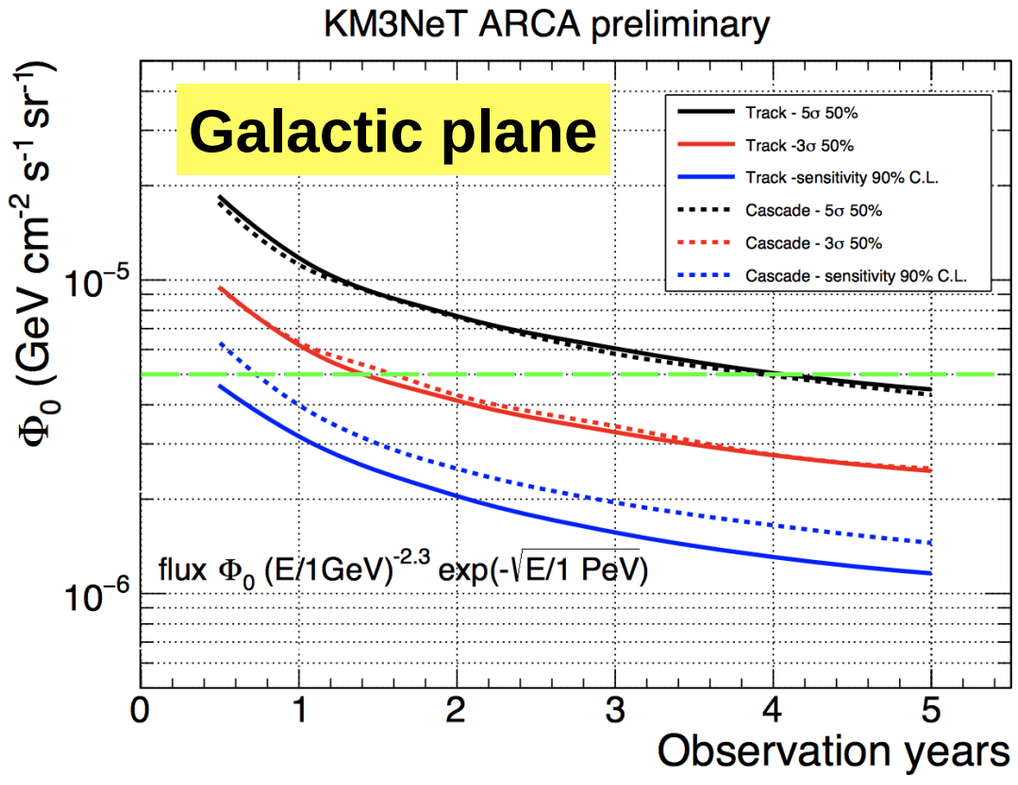




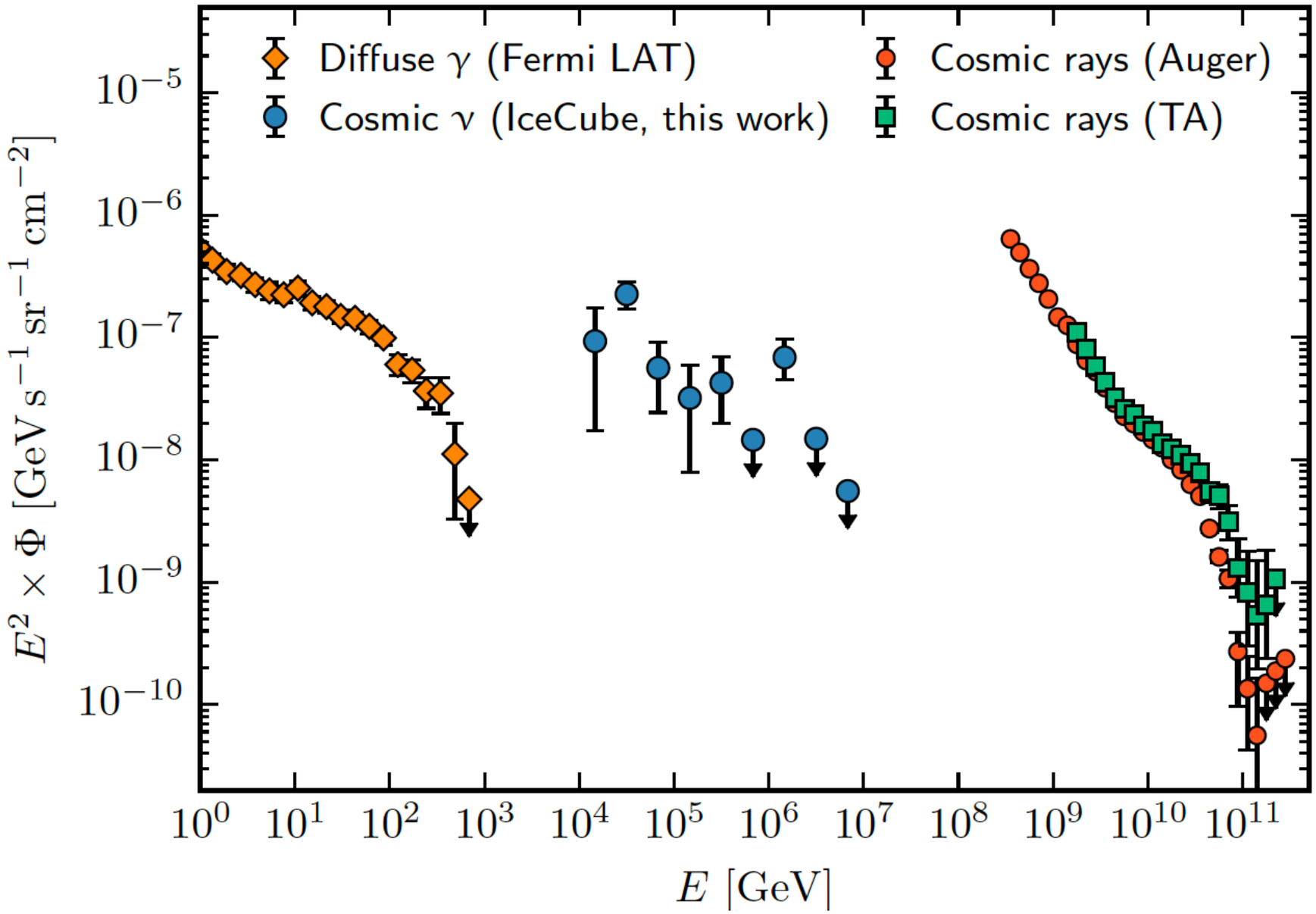
KM3NeT/ARCA is expected to observe the IC signal in less than 1 yr.

➞ 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.

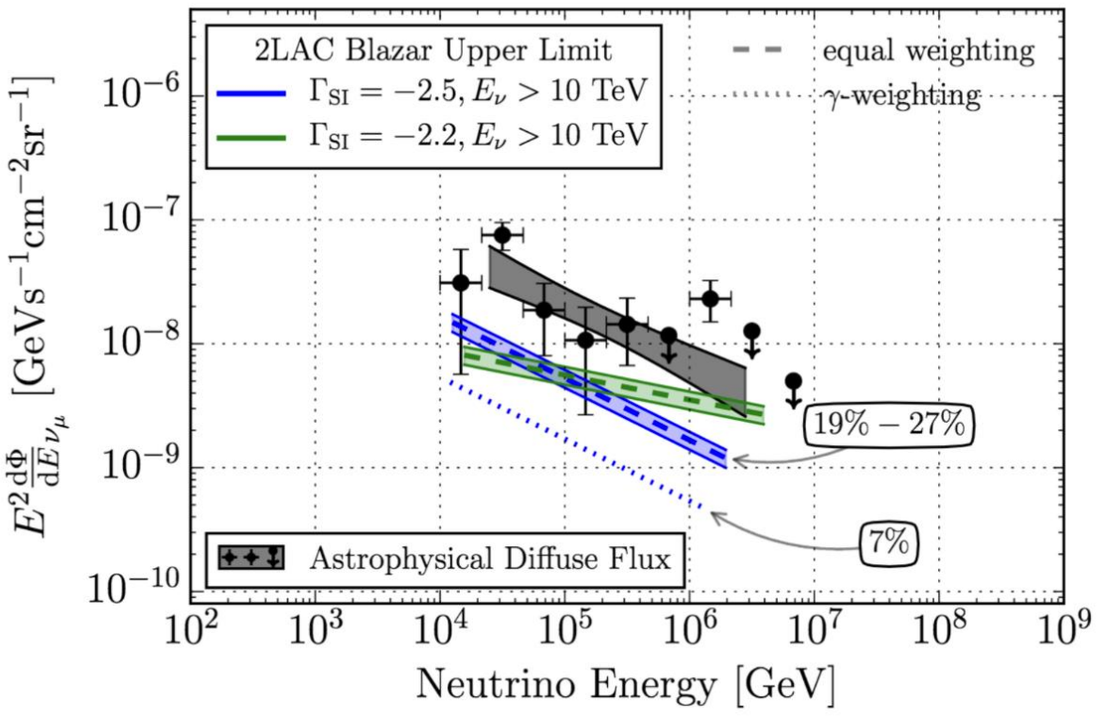
⇒ Common sources ? Fermi/LAT γ-ray flux dominated by AGN/blazars (~ 85%)

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)

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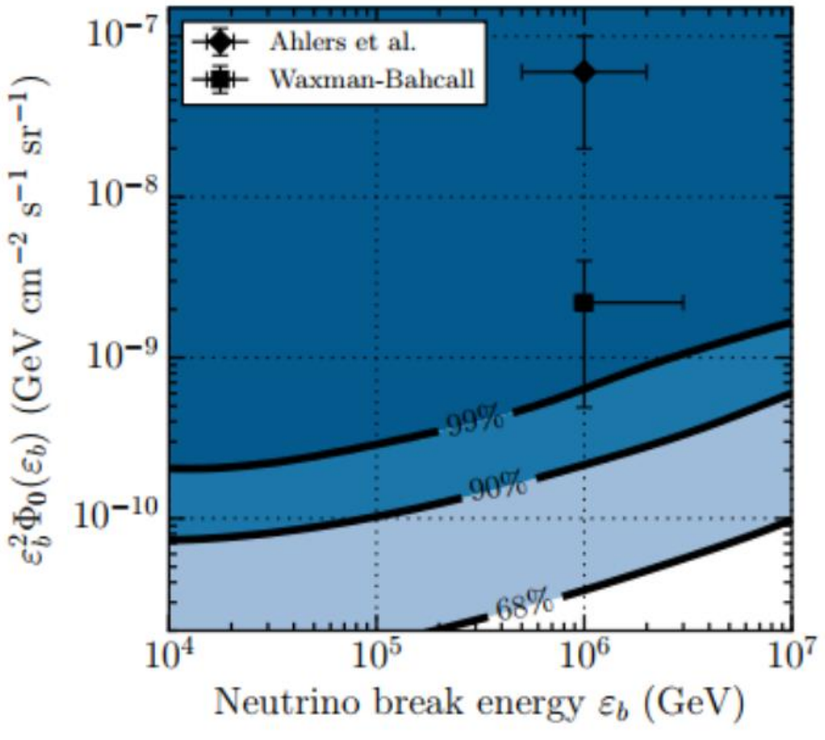
GRB time/space correlation

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

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



(1172 GRBs - benchmark parameters)

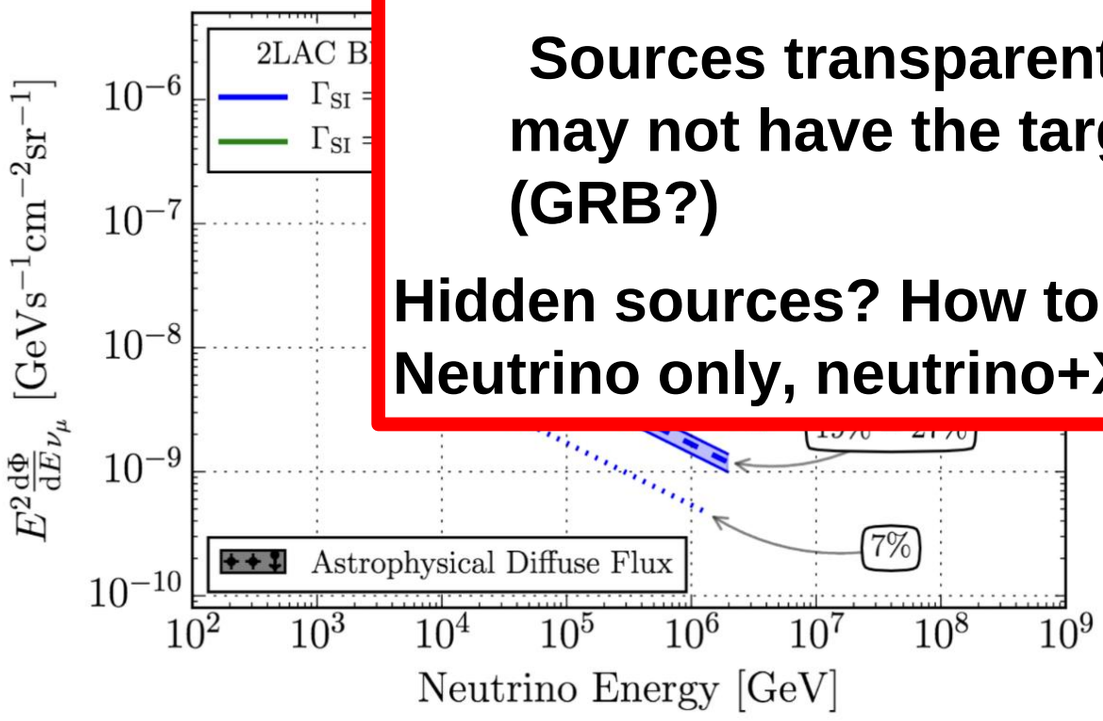
arXiv:1702.06868

POPULATION STUDIES

Blazar space correlation

(862 '2LAC' blazars)

Contribution max of the 2LAC blazars < 27% (10 TeV - 2 PeV), assumin
single power-law



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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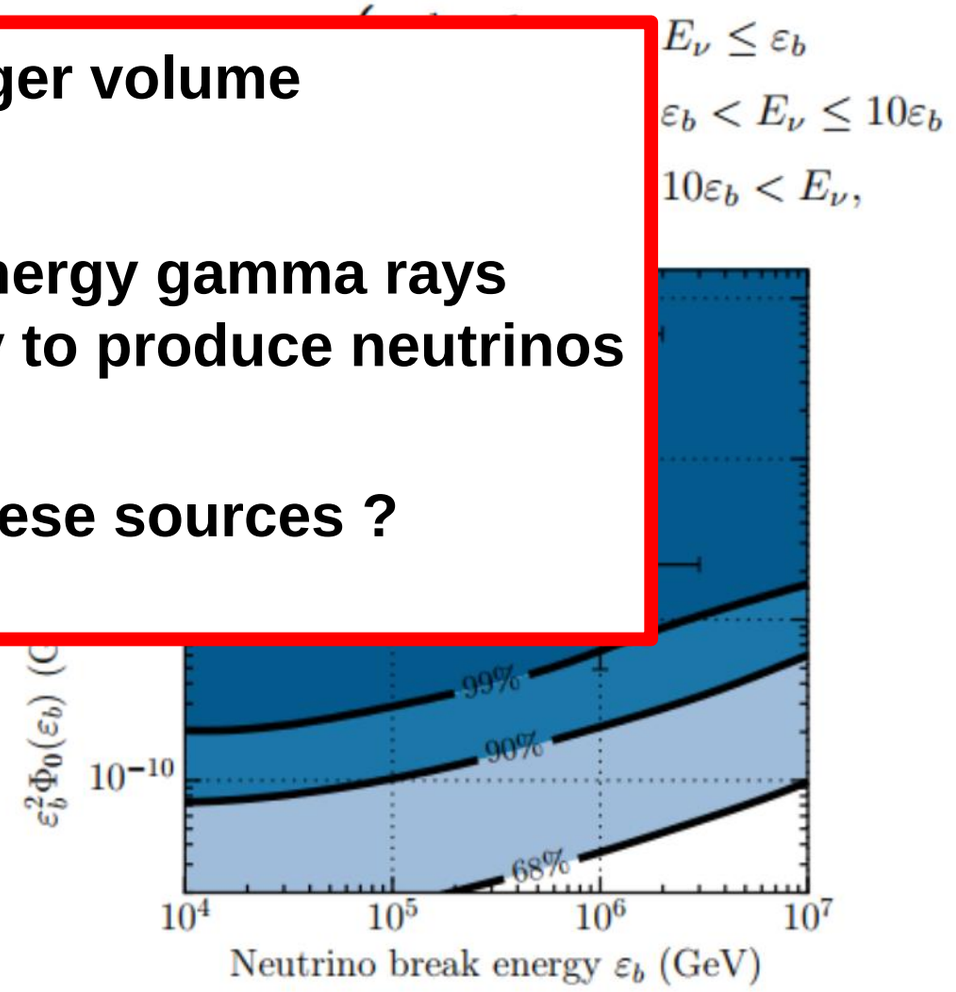

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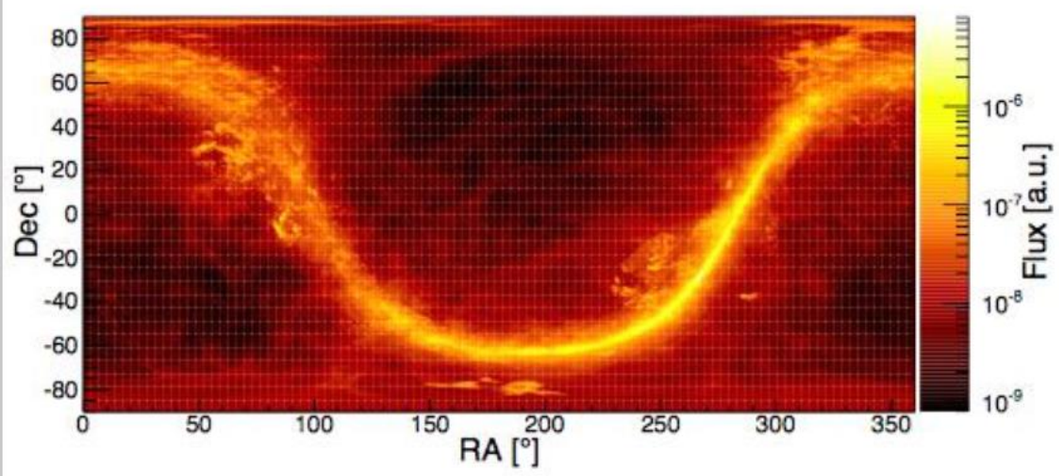
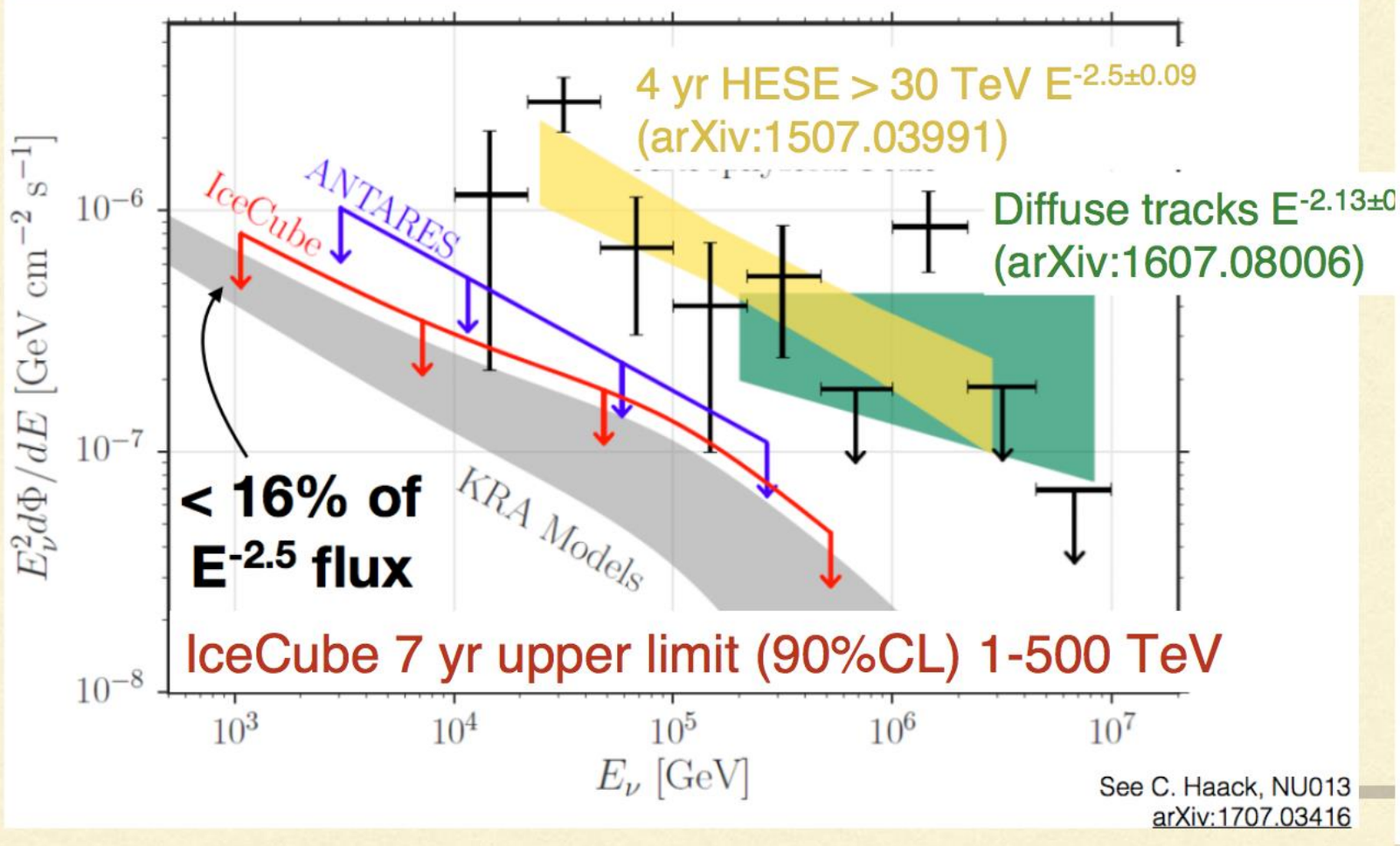
GALACTIC DIFFUSE FLUX

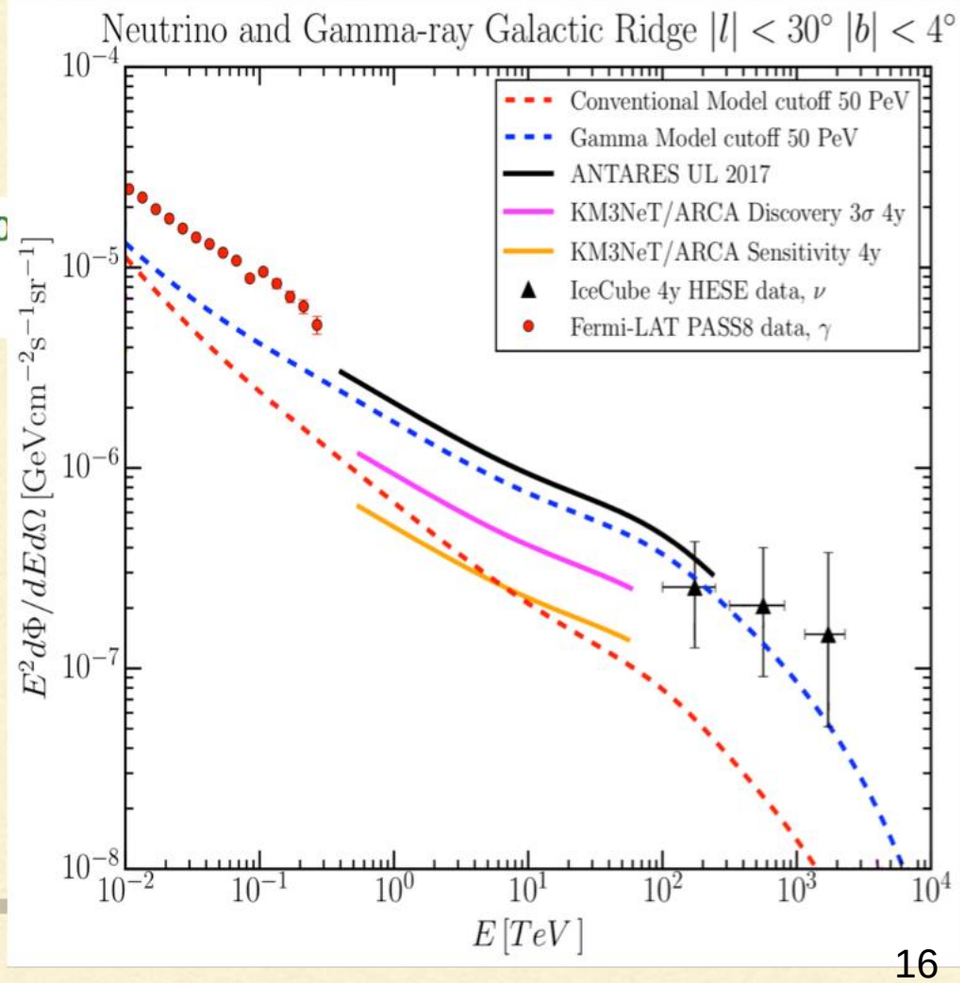


(a) KRA-γ (50 PeV cutoff) template

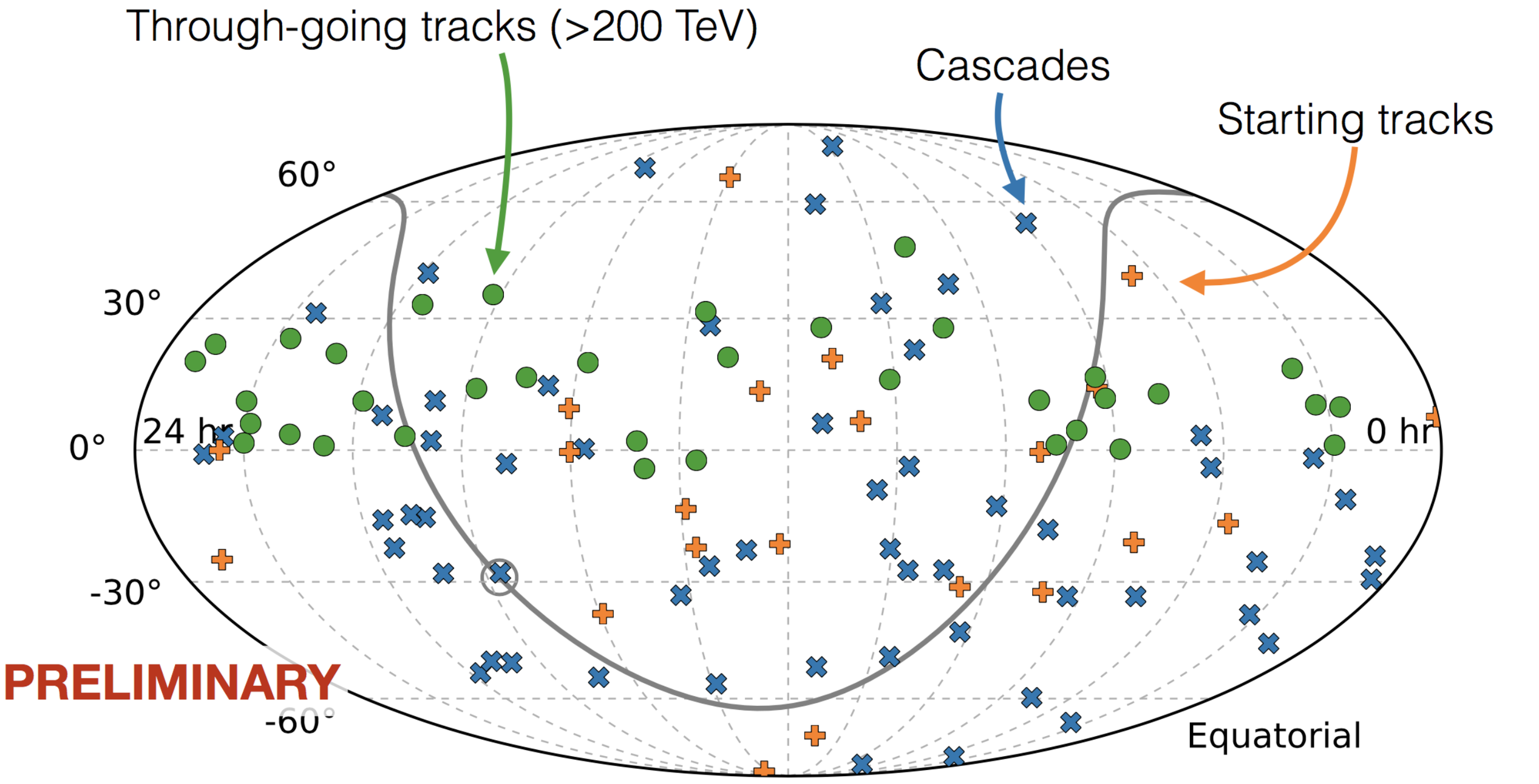
- Analysis of correlation with template map derived from interstellar gas distribution reproducing Fermi-LAT data Models in Gaggero et al, arXiv:1504.00227
- Only small fraction of signal can originate from CR interactions in the Galaxy. UL for IC and ANTARES 1.2 x KRA-γ (50 PeV)



See C. Haack, NU013
arXiv:1707.03416



IC NEUTRINO SKYMAP



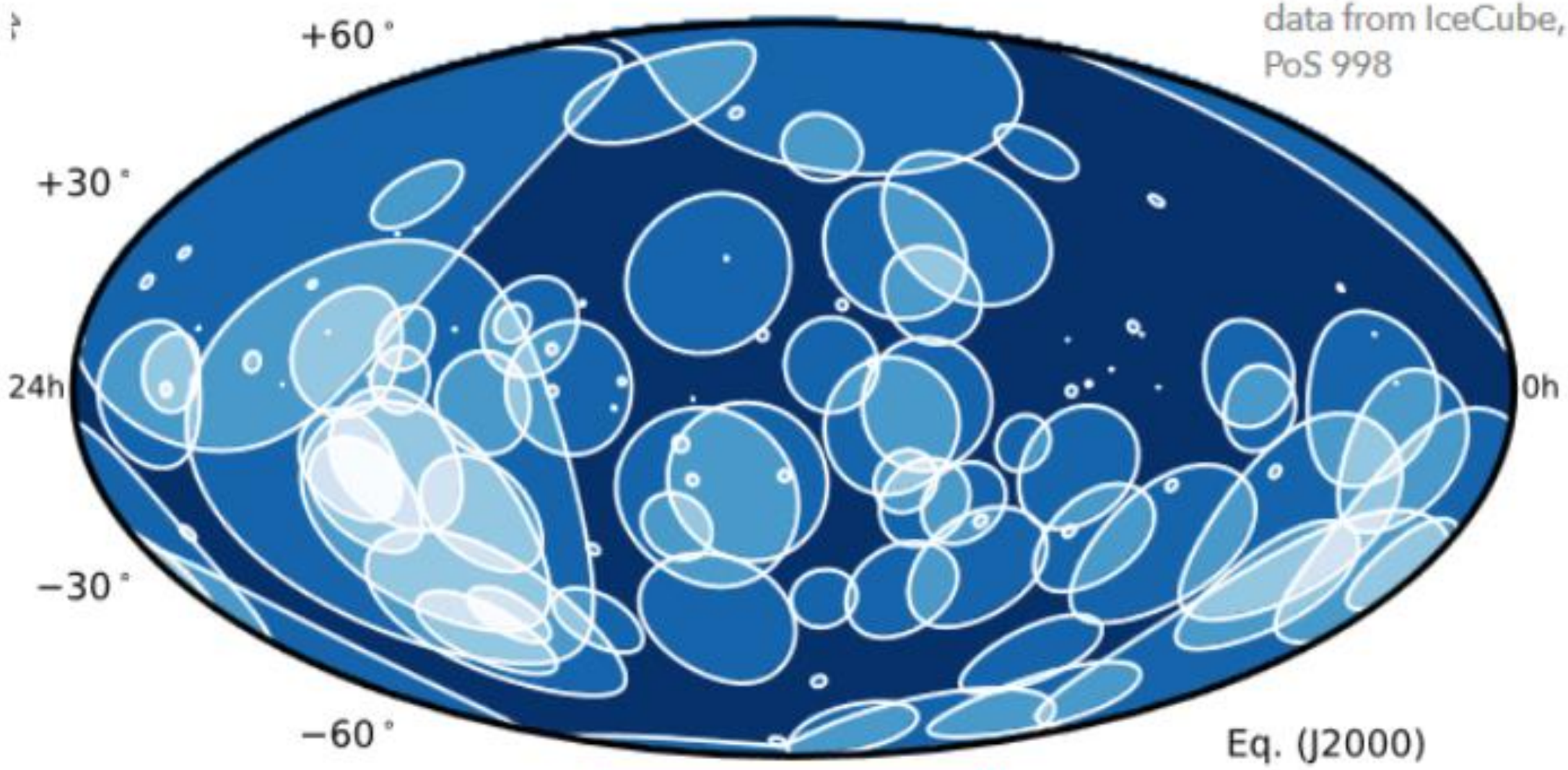
IceCube, 2017

No evidence of clustering in high-energy neutrino directions

mostly isotropic ⟹ neutrinos of extragalactic origin

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

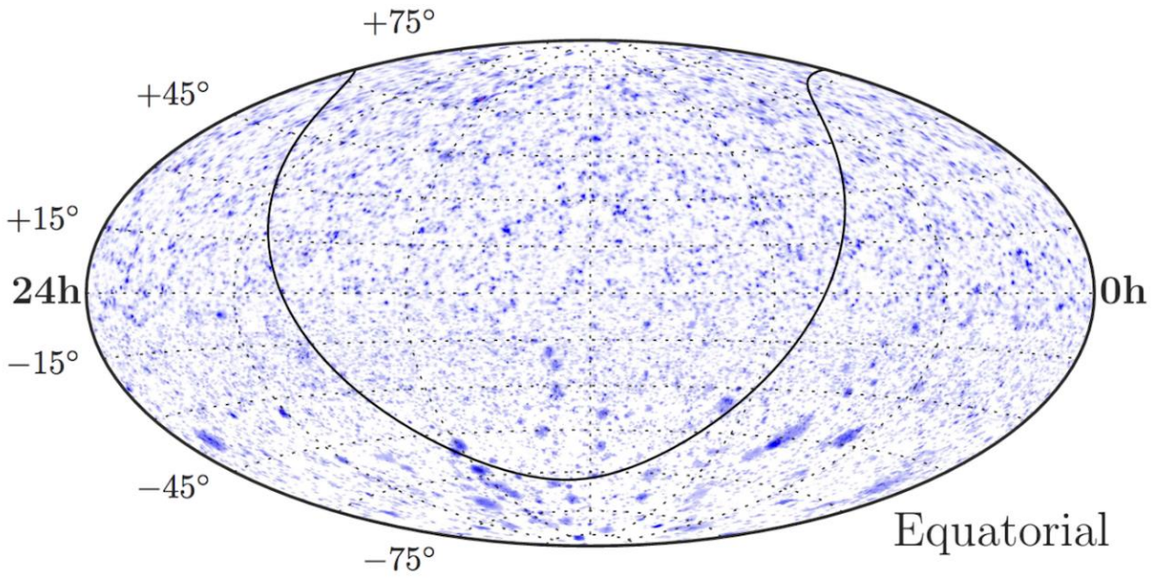
IC NEUTRINO SKYMAP



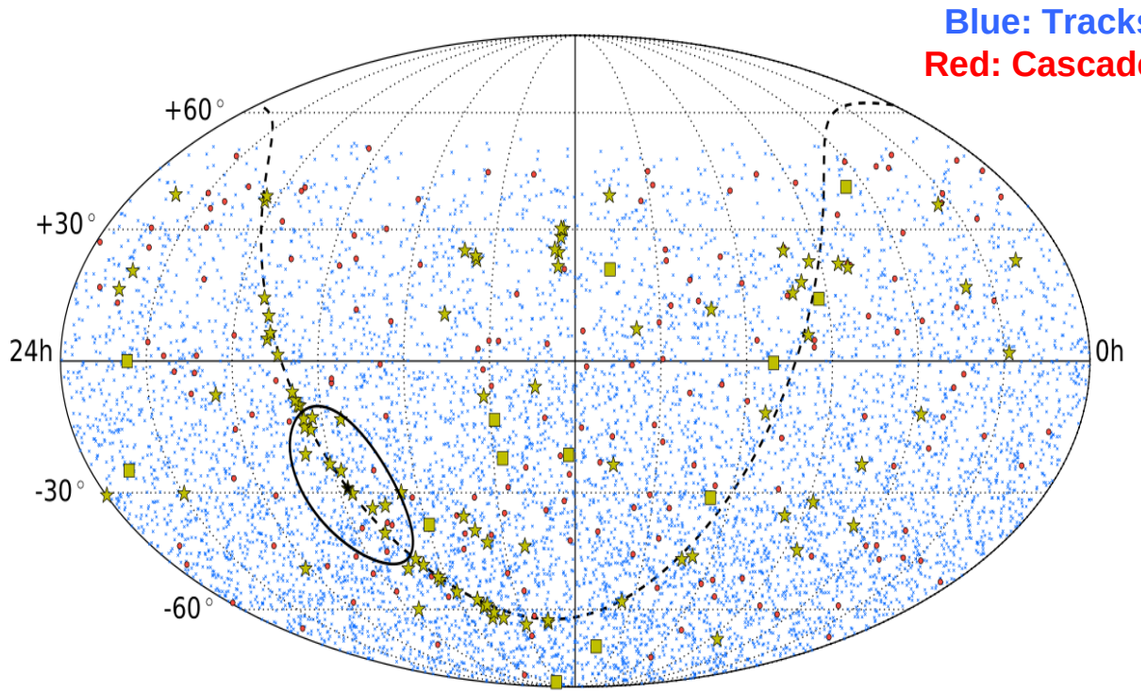
Resolution for ν_e
ANTARES ○
KM3NeT ○

LOOKING FOR POINT-SOURCES

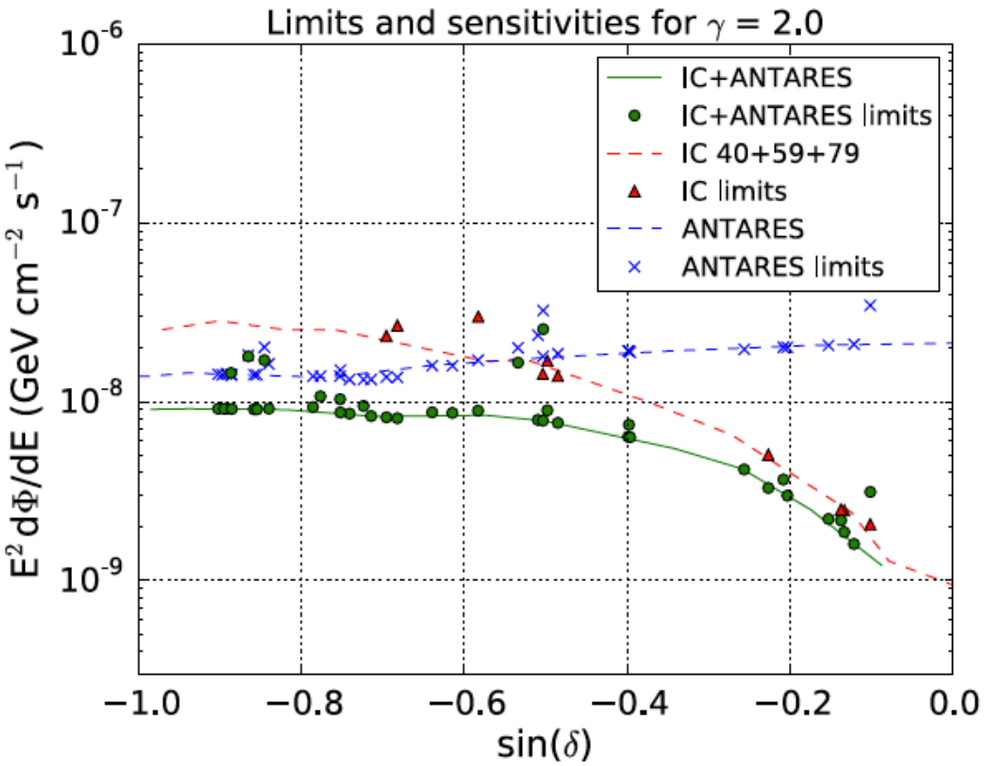
IceCube (7 yrs - tracks)

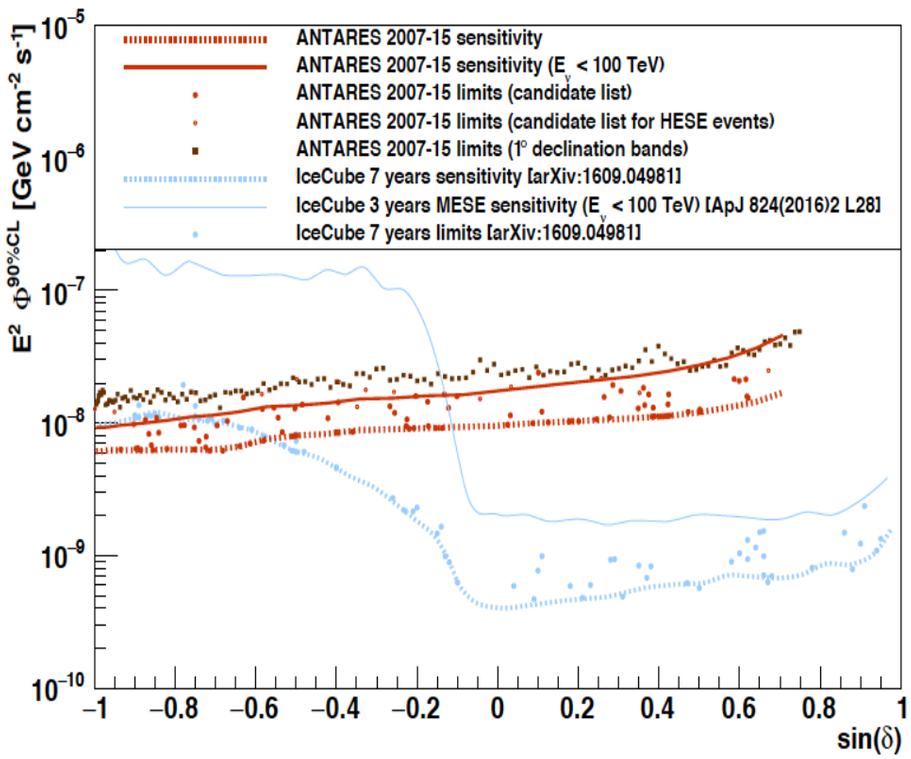


ANTARES (2007-2015)



ANTARES+IceCube

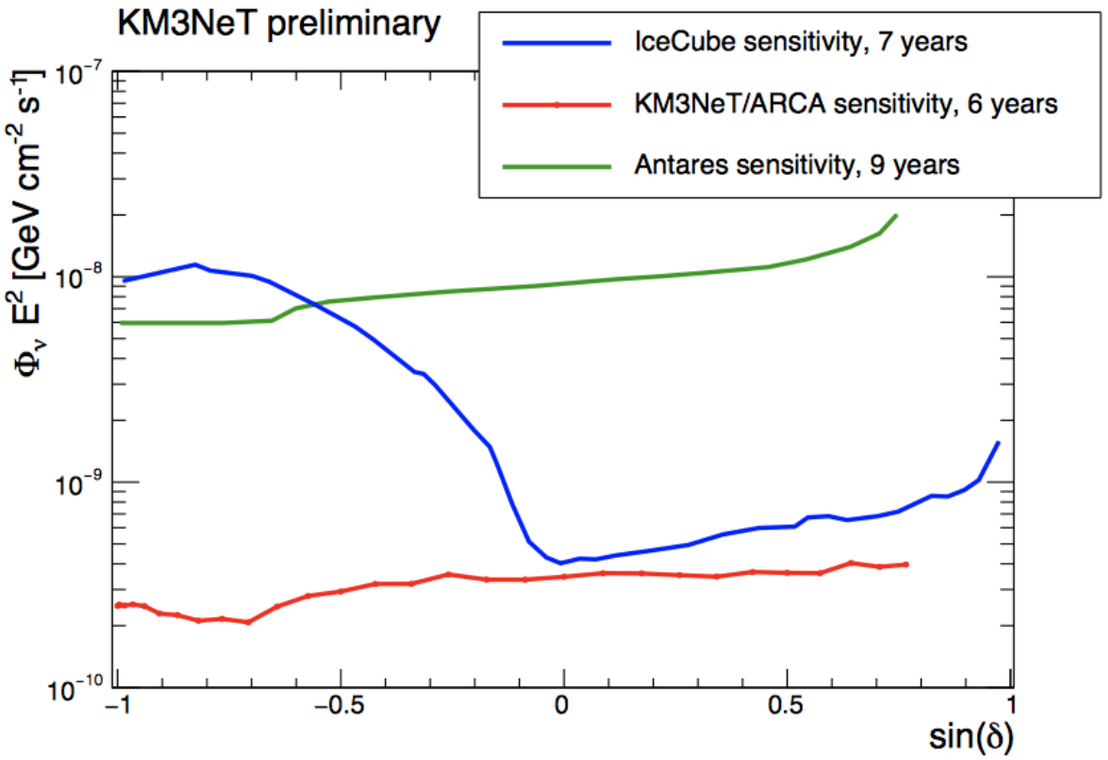


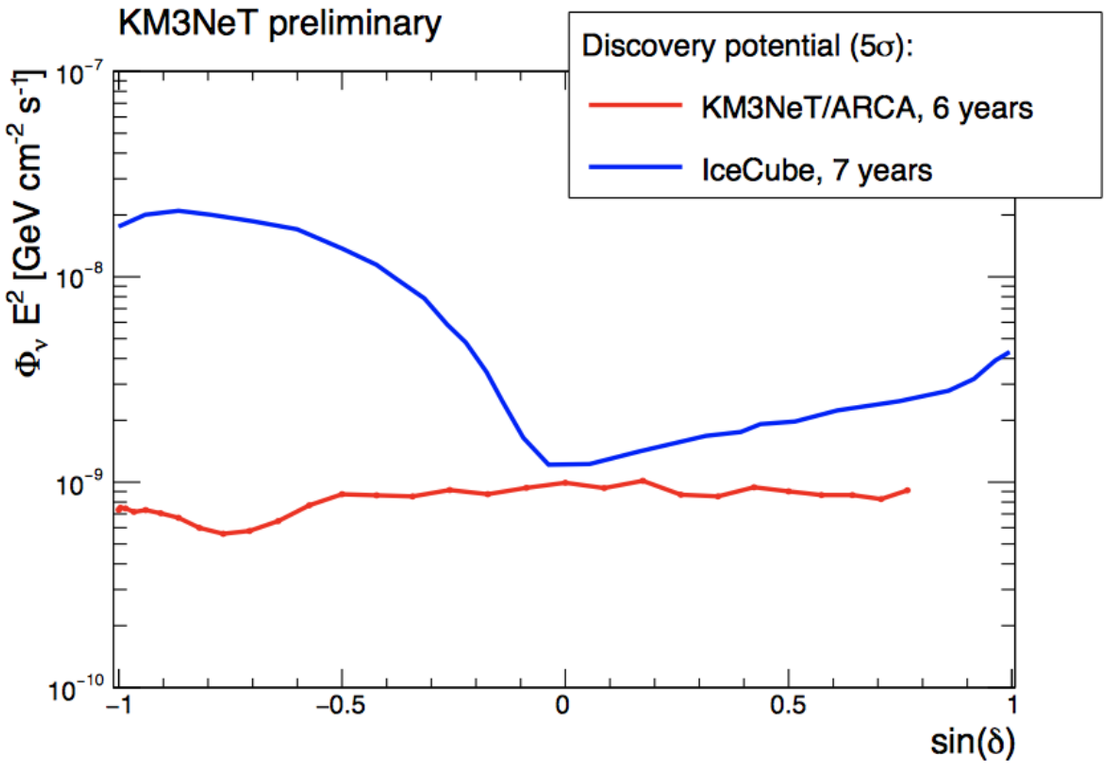


📖 Phys. Rev. D 96, 082001 (2017)

KM3NeT: POINT-SOURCE

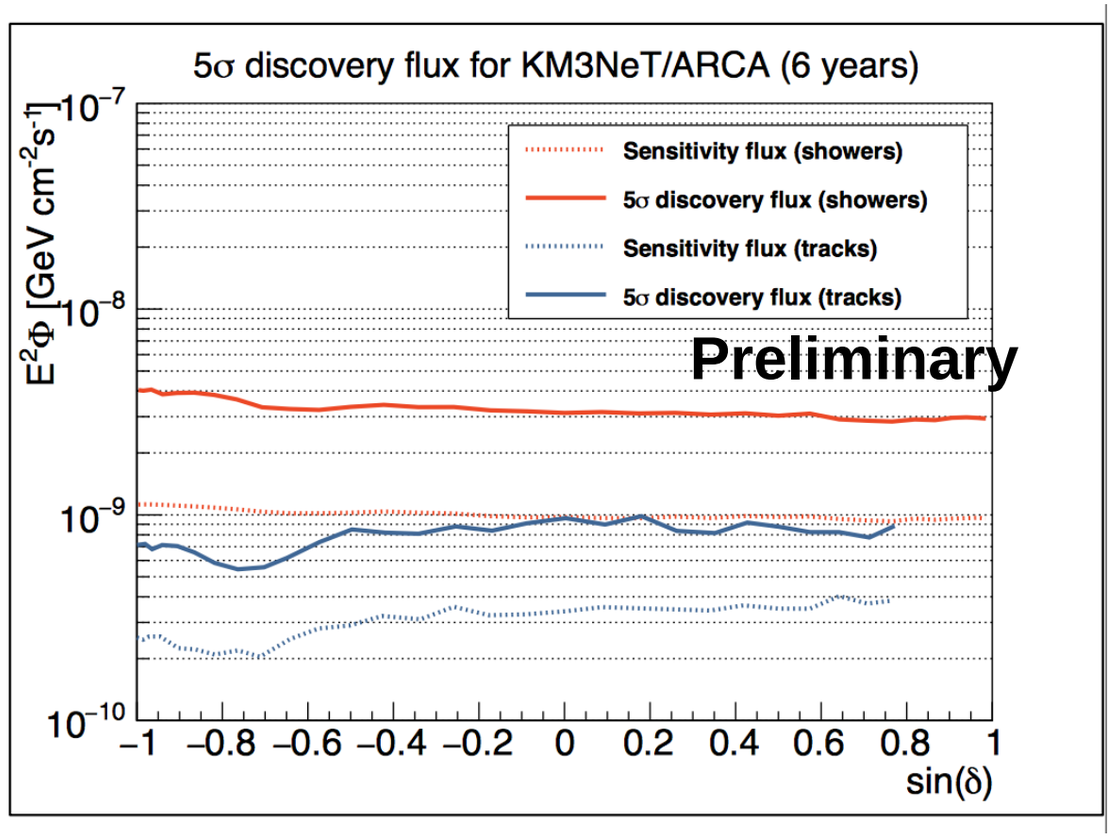
Generic source





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

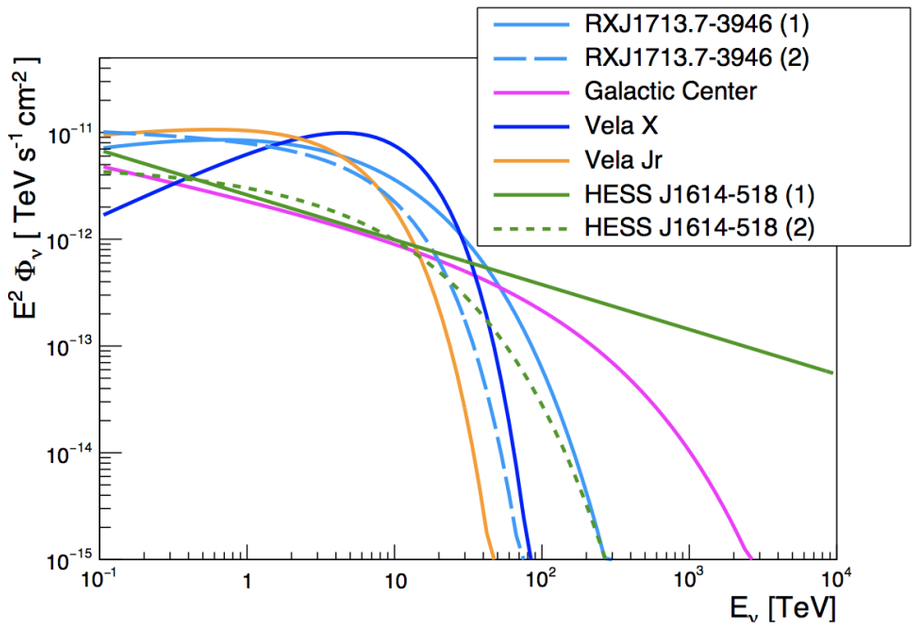
- ➞ Due to the quite good angular resolution for cascade events, the point-source search is also very efficient.
- ➞ Expected better performances for the transient neutrino sources (GRB, AGN…)



KM3NeT: POINT-SOURCE

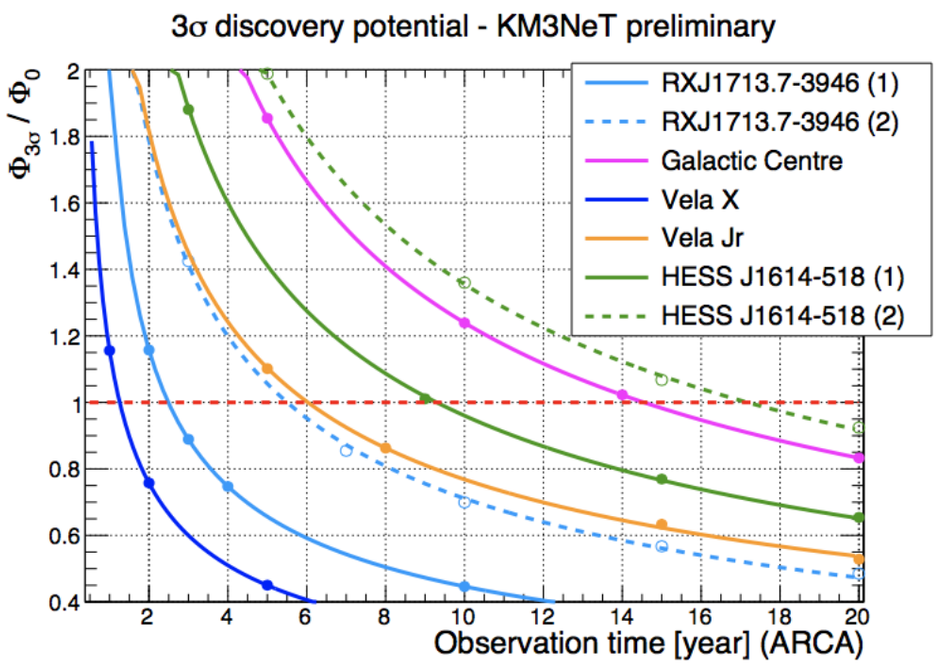
Specific galactic sources

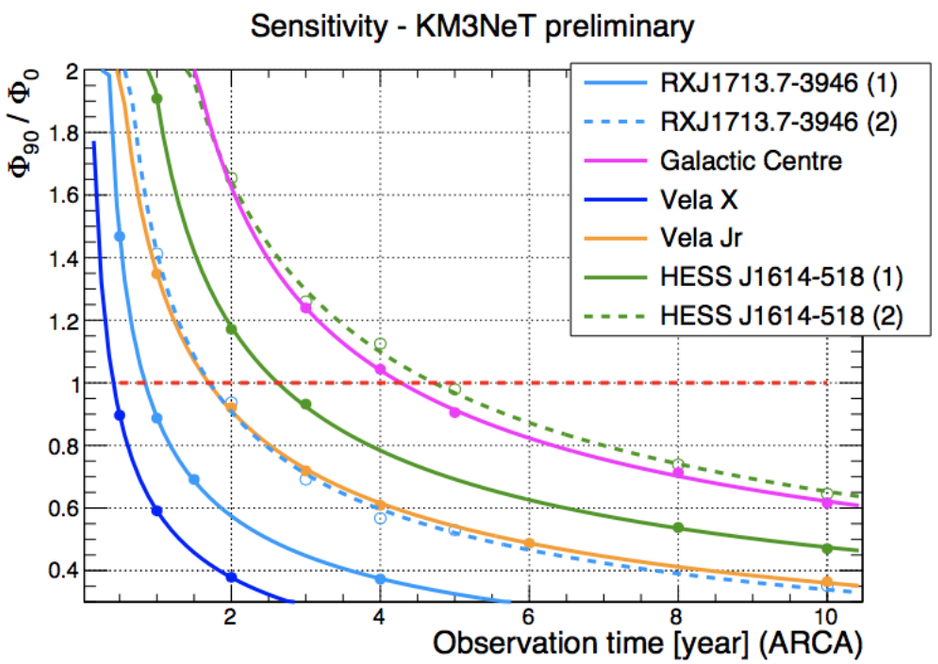
Source	δ	extension	Φ_0	Γ	E_{cut}	β	γ-ray data
RX J1713.7-3946 (1)	-39.77°	0.6°	1.68	1.72	2.1	0.5	[13]
RX J1713.7-3946 (2)	-39.77°	0.6°	0.89	2.06	8.04	1	[14]
Vela X	-45.6°	0.8°	0.72	1.36	7	1	[15]
Vela Jr	-46.36°	1°	1.30	1.87	4.5	1	[16]
HESSJ1614-518 (1)	-51.82°	0.42°	0.26	2.42	-	-	[17]
HESSJ1614-518 (2)	-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.

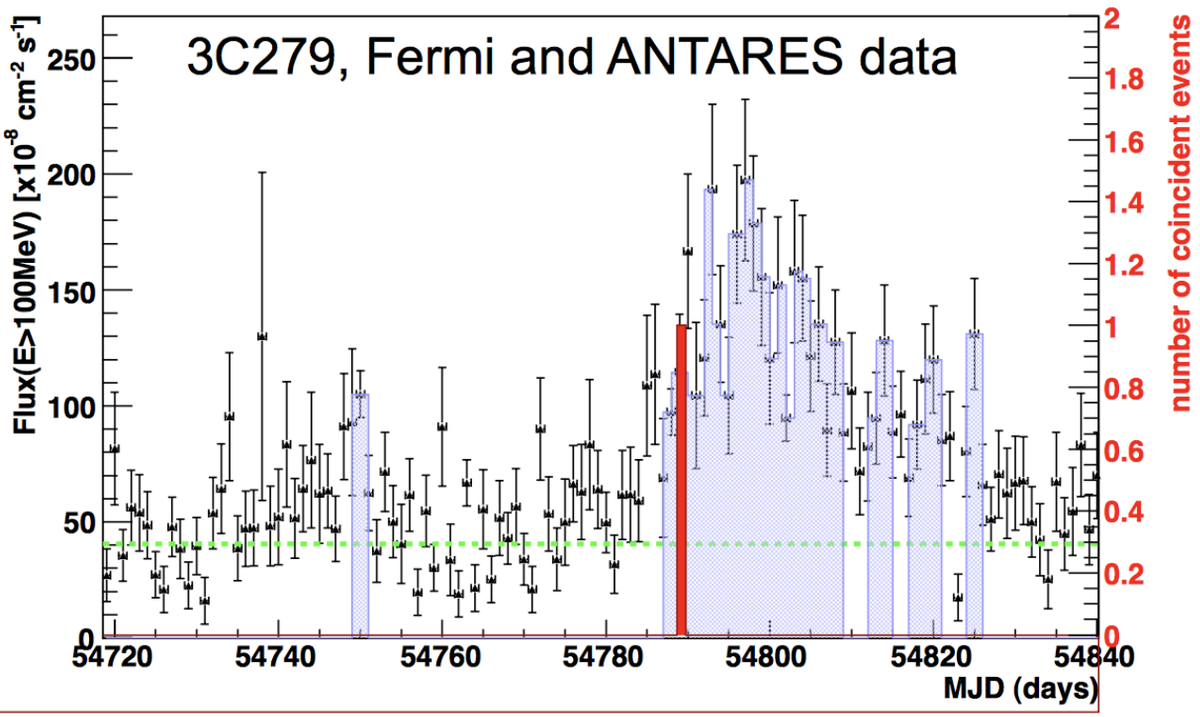




With reasonable 100% hadronic models, large probabilities to observe individual neutrino sources in the Galactic Plane

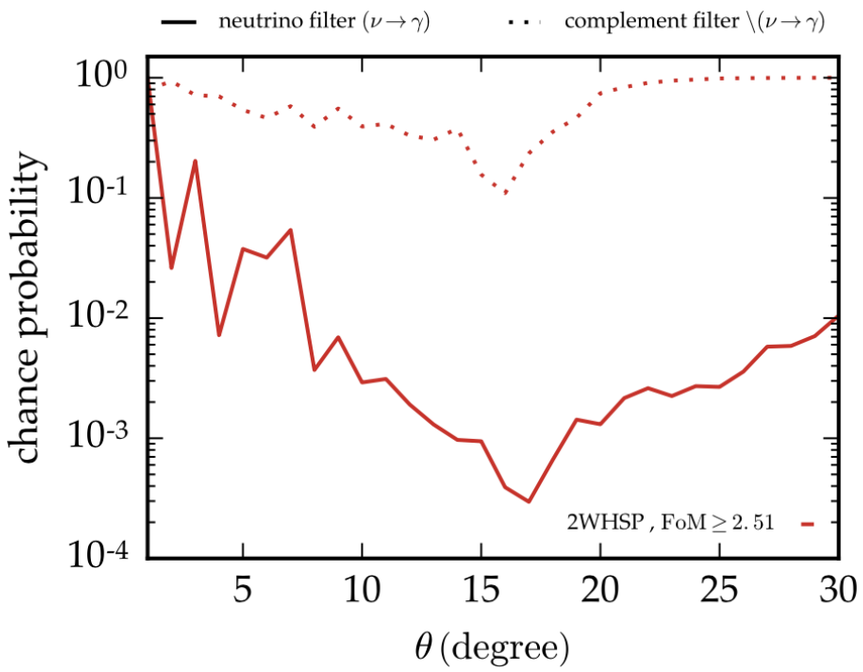
LOOKING FOR VARIABLE SOURCES

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

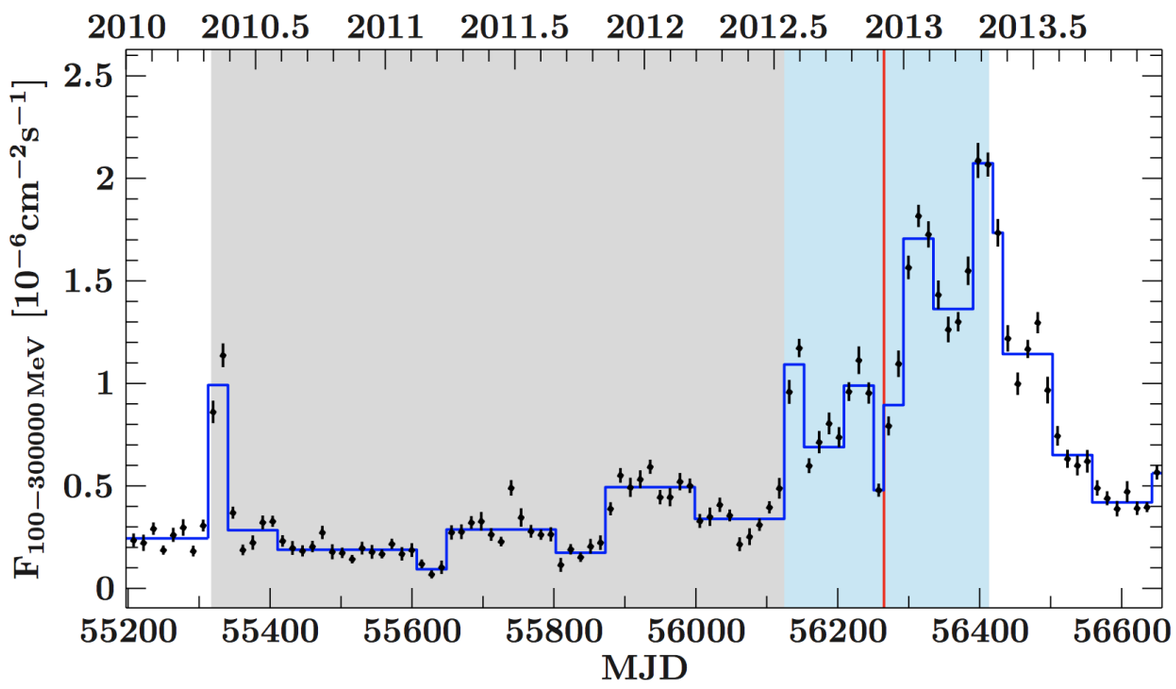


Connection ν-γ-UHECR

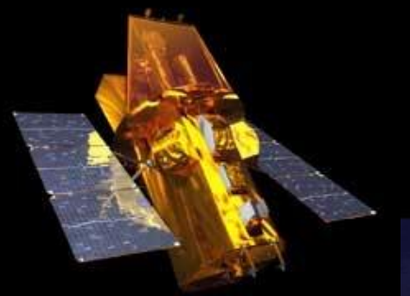
Resconi et al 2017, 2.9 sigma correlation with sub-sample of HBLs, IC nu and Auger UHECR



IceCube- Big Bird PKS B1424-418



Multi-λ observatories linked to ANTARES for the real-time analysis



SWIFT

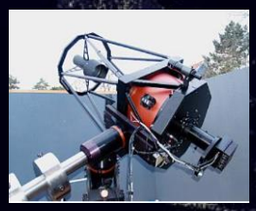
INTEGRAL

MASTER

ANTARES

HAWC

SVOM
GWAC



TAROT

HESS

MWA

ZADKO

ROTSE

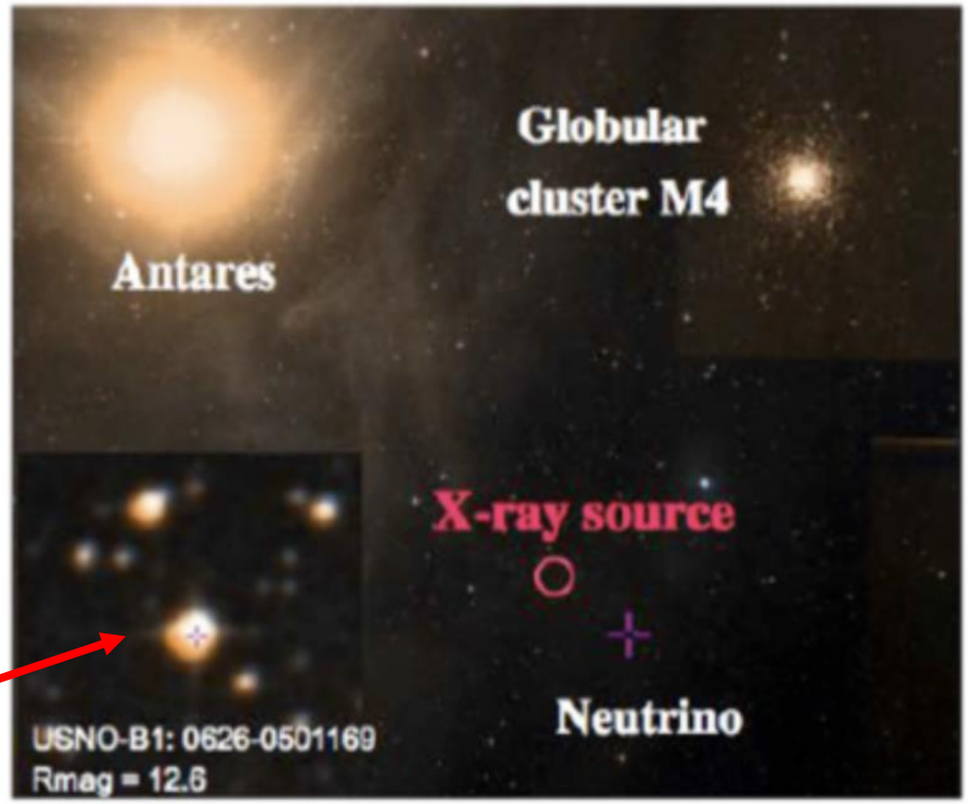
- + **GW alerts from LIGO/VIRGO**
- + **UHECR/UHEν with Auger/TA**
- + **Neutrino alerts from IceCube**
- + **AMON**

(Update 01/2018)

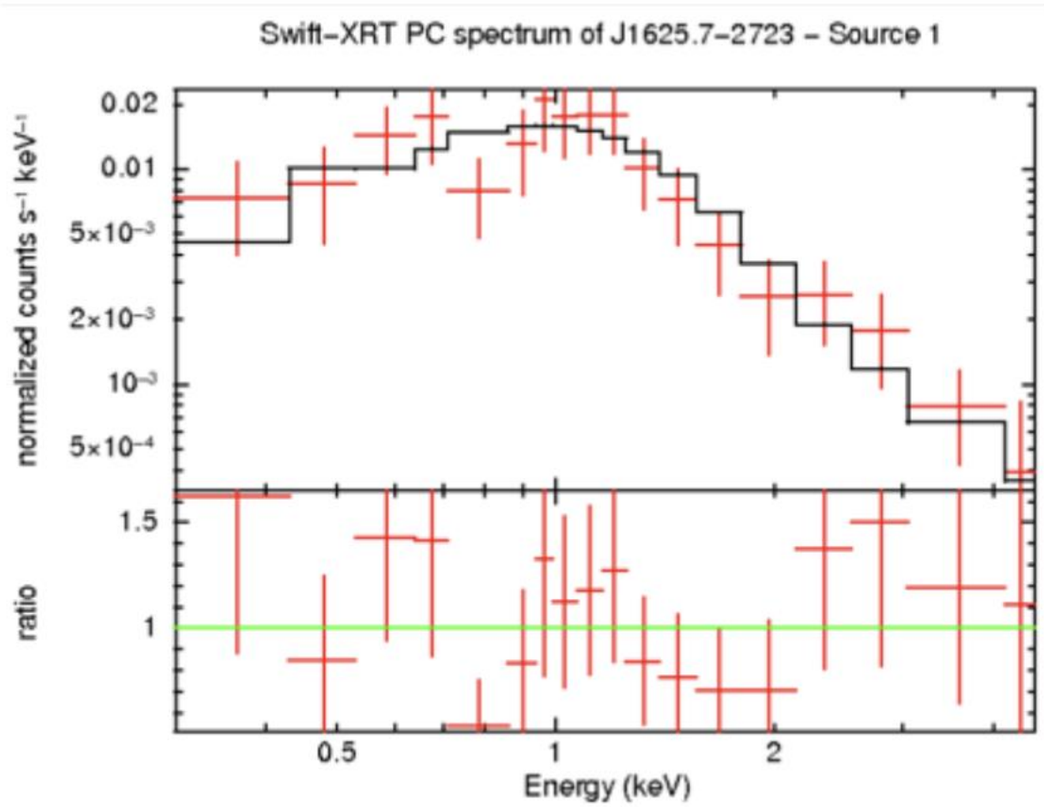
TAToO, one exemple: ANT150901A

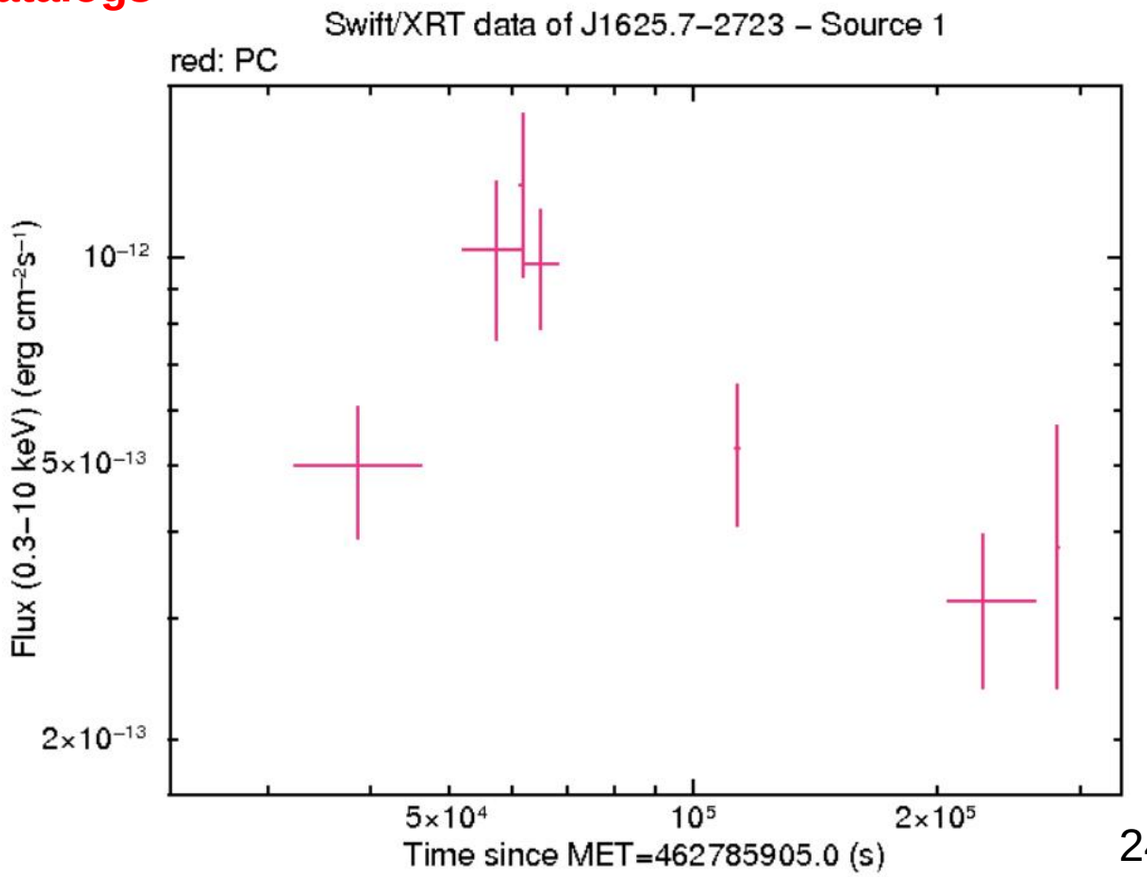
TATOO: ANT150109A ALERT

- E ~50-100 TeV
- Error box=18 arcmin
- Sent in 10s to Swift and Master
- Swift obs: +9h
- Master obs: +10h



Conclusion multi-λ IR+Radio → young variable star not in catalogs





TAToO, one exemple: ANT150901A

- Neutrinos
  - IceCube: ATel 8097
- Optical
  - Pan-STARRS: ATel 7992, 8027
  - SALT: ATel 7993
  - NOT: ATel 7994 GCN18236
  - WiFeS: ATel 7996
  - CAHA: ATel 7998, GCN18241
  - MASTER: ATel 8000 GCN18240
  - LSGT: ATel 8002
  - NIC: ATel 8006
  - ANU: GCN18242
  - GCM: GCN18239
  - VLT/X-shooter
- X-rays
  - Integral: ATel 7995
  - MAXI: ATel 8003
  - Swift: ATel 8124, GCN18231
- Radio
  - Jansky VLA: ATel 7999, 8034
- Gamma-rays
  - MAGIC: ATel 8203
  - Fermi-GBM: GCN18352
  - HAWC
  - HESS

Great interest by astro-community

25

TAToO ⟹ GWAC@SVOM

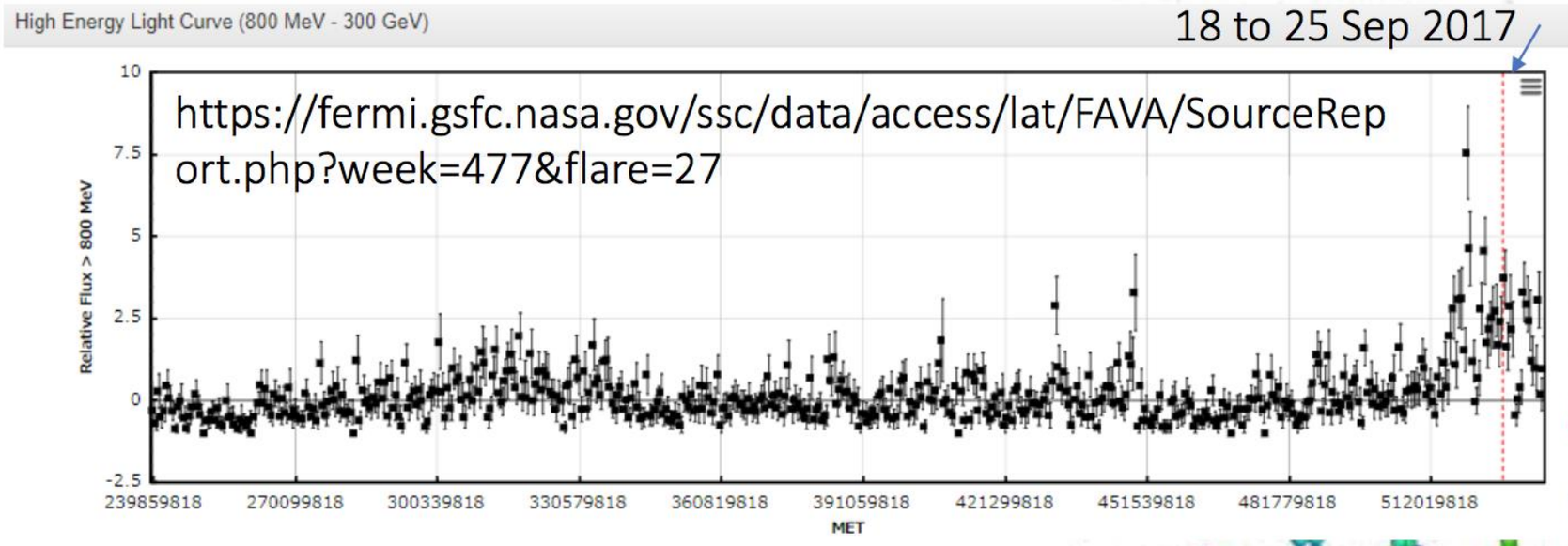
- MoU between ANTARES-SVOM signed summer 2017

- 29% of the ANTARES neutrino triggers visible at Xinglong, 20% have been followed with mini-GWAC + 30 cm telescope [in agreement with the location of the telescopes in Xinglong and the weather constrains]
  ⇒ Delay: [0, 50min] for mini-GWAC (auto), [0h40, 1h40] for 30cm (manual)
  ⇒ **No counterpart identified [mag<12 for mini-GWAC, mag<≈18 for 30cm]**

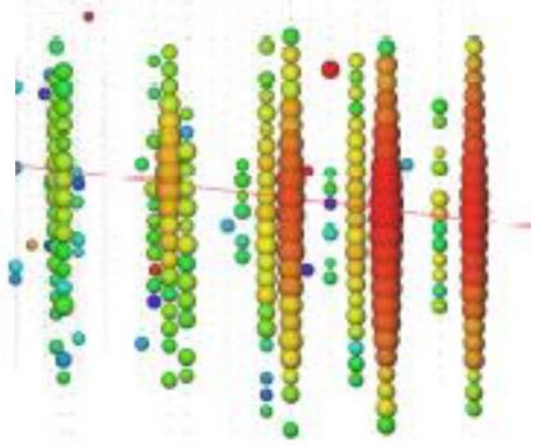
- **Use large FoV of (mini)GWAC and the fact that the optical transients detected in the images are stored to look for offline follow-up of ANTARES cascade events**

IC170922 / Blazar 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

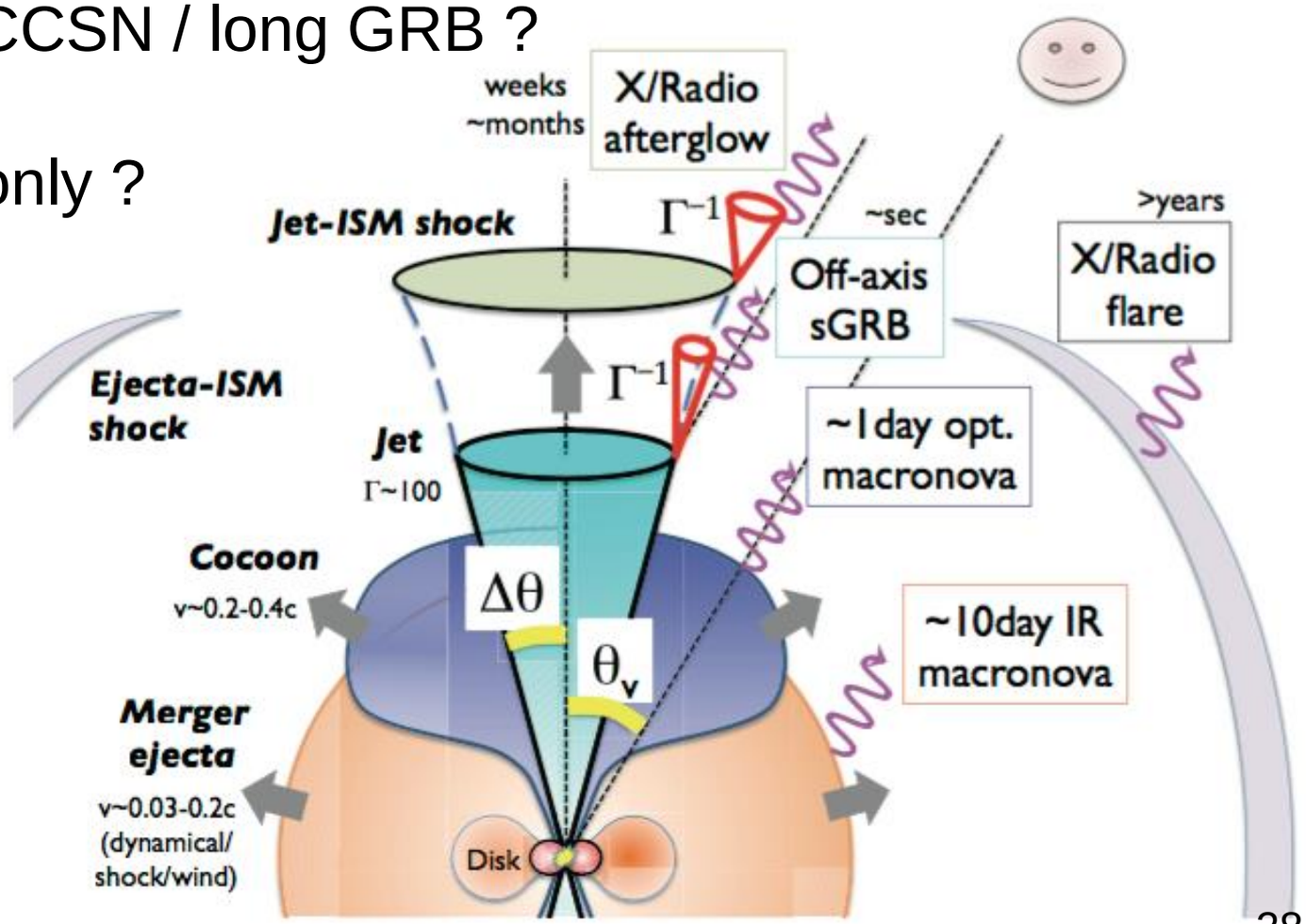
ANTARES offline analysis of this blazar under progress…

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

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

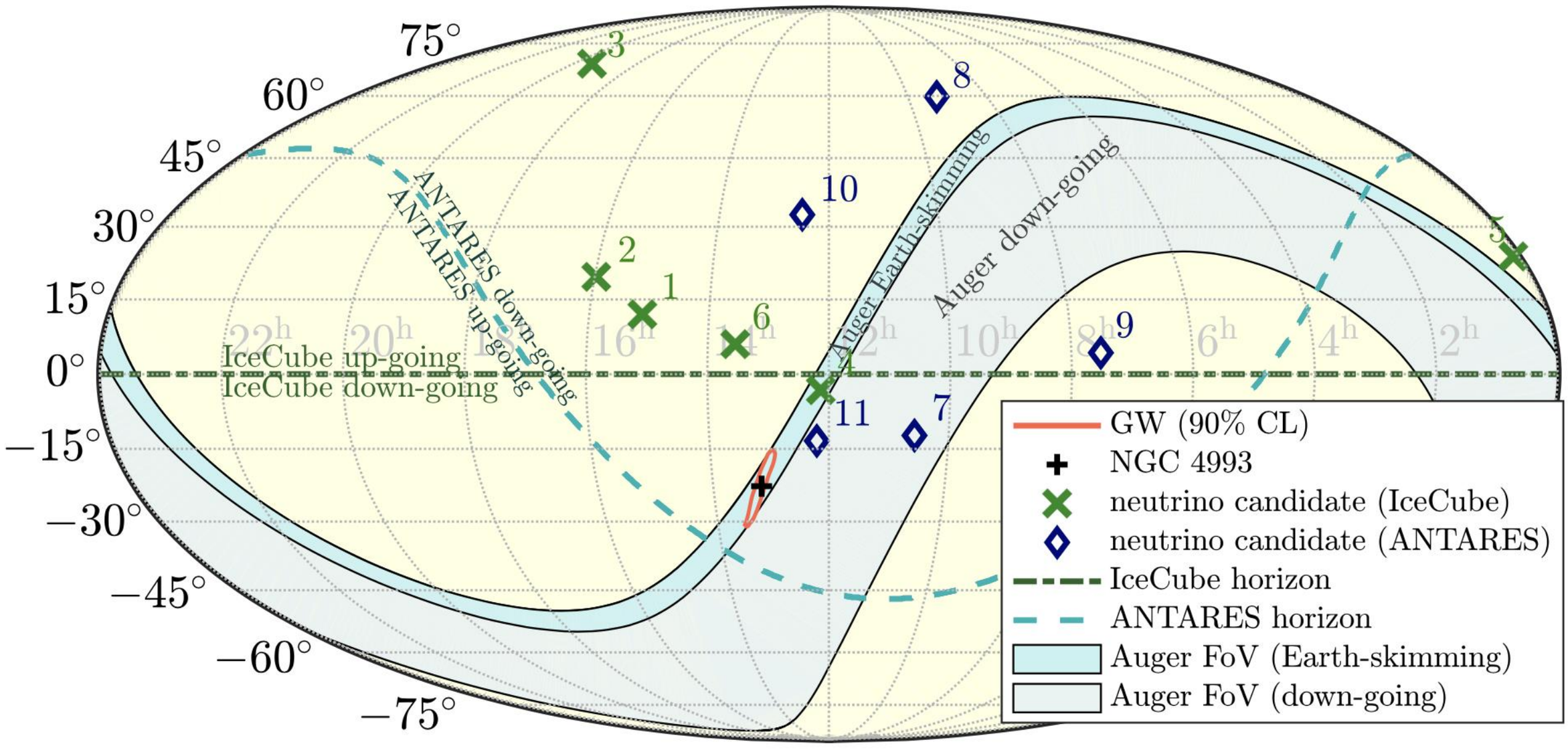
GW + neutrinos

- **Coincident neutrino observation could constrain the source position** (LIGO/Virgo 90% contour ~30°^{2} vs ANTARES/KM3NeT: ~0.5°)
- Low level of background for transients → a few neutrino enough to have significant implications for GRB physics.
- Would confirm hadronic content of relativistic jets + dissipation processes.
- Chocked jets and unified picture CCSN / long GRB ?
- Dark bursts observed in nu+GW only ?
- **Relativistic jet formation/dynamics (hadronic component)**
  - ✴ on-axis / off-axis
  - ✴ jet aperture
  - ✴ shape of the outflow (cocoon / chocked jet ?)
  - ✴ lower energy neutrinos with ORCA (~10 - 100 GeV)



NEUTRINO FROM GRB170817/GW170817 ?

Joint analysis of all HE-UHE neutrino experiments: ANTARES + IceCube + Auger + LVC

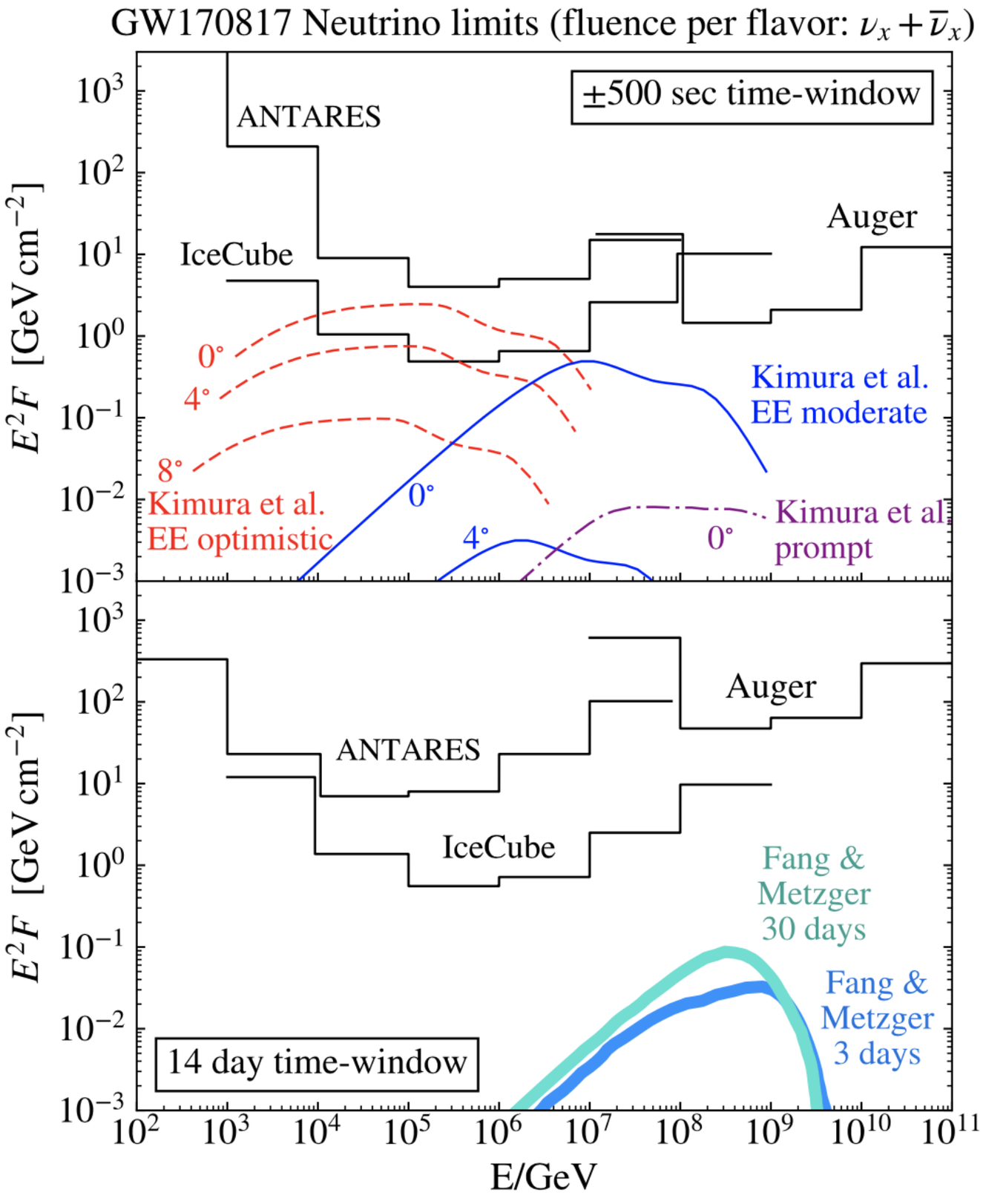


⟹ **Bad luck localisation for ANTARES/IC, very very lucky for Auger**

⟹ **No neutrino in space & time coincidence (± 500s)**

ApJL 850 L35 (2017)

NEUTRINO FROM GRB170817/GW170817 ?



⇒ **Limited upper-limits from ANTARES/IC** (very high background contaminations)

⇒ **Comparison with hadronic model predictions (prompt emission from off-axis GRB or extended emission)**

ApJL 850 L35 (2017)

Summary

Multi-Messenger astronomy era ! (EM + 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 data policy:

- ➞ KM3NeT neutrino data are proprietary but become public after a latency of 2 years after the data taking.
- ➞ However, significant events might trigger alerts that will be distributed publicly to the astro community using standard VO event format within ~10s after the neutrino detection [Open Public Alerts]
- ➞ Sub-threshold alerts and multiplets will be distributed though private channel to observing teams upon MoU agreements.