Cosmic Neutrinos

Experimental Overview

Solvay-Francqui Workshop on Neutrinos
Brussels, May 2015

Christian Spiering, DESY Zeuthen

Content

- Detection principles
- The detectors
- Atmospheric neutrinos
- Search for steady point sources
- Search for transient sources
- Study of the diffuse flux of cosmic neutrinos

DETECTION PRINCIPLES

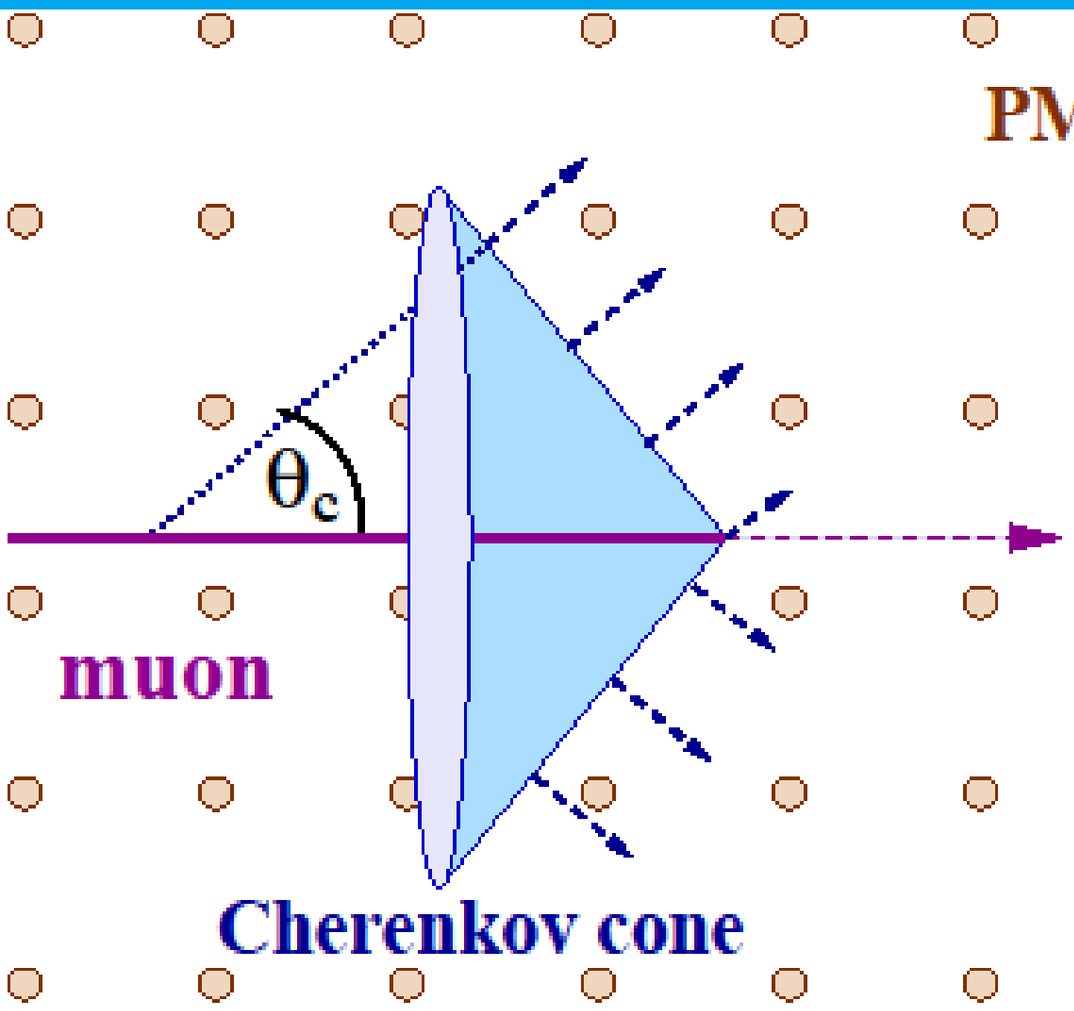
The traditional method:

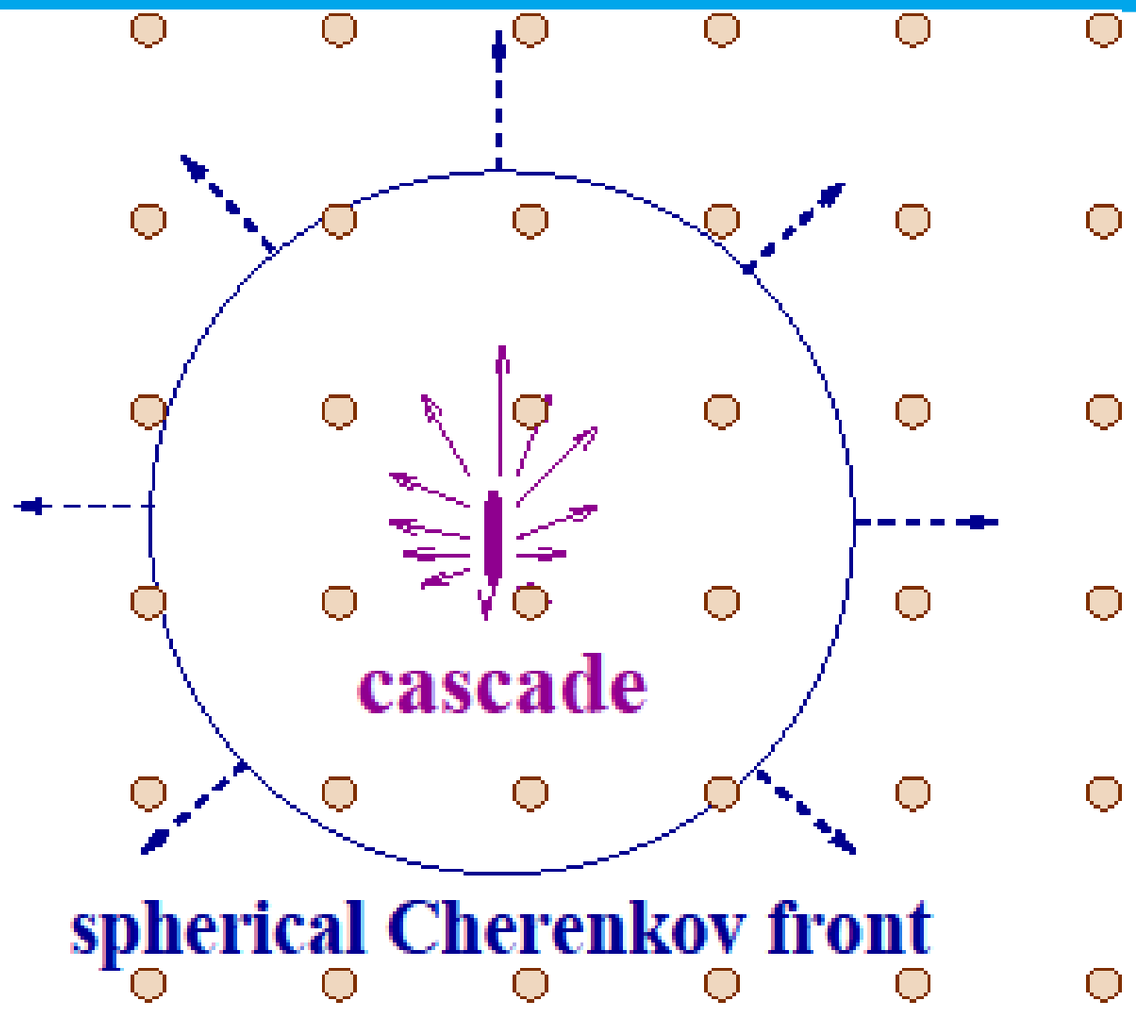
ν_μ charged current

μ

ν_μ

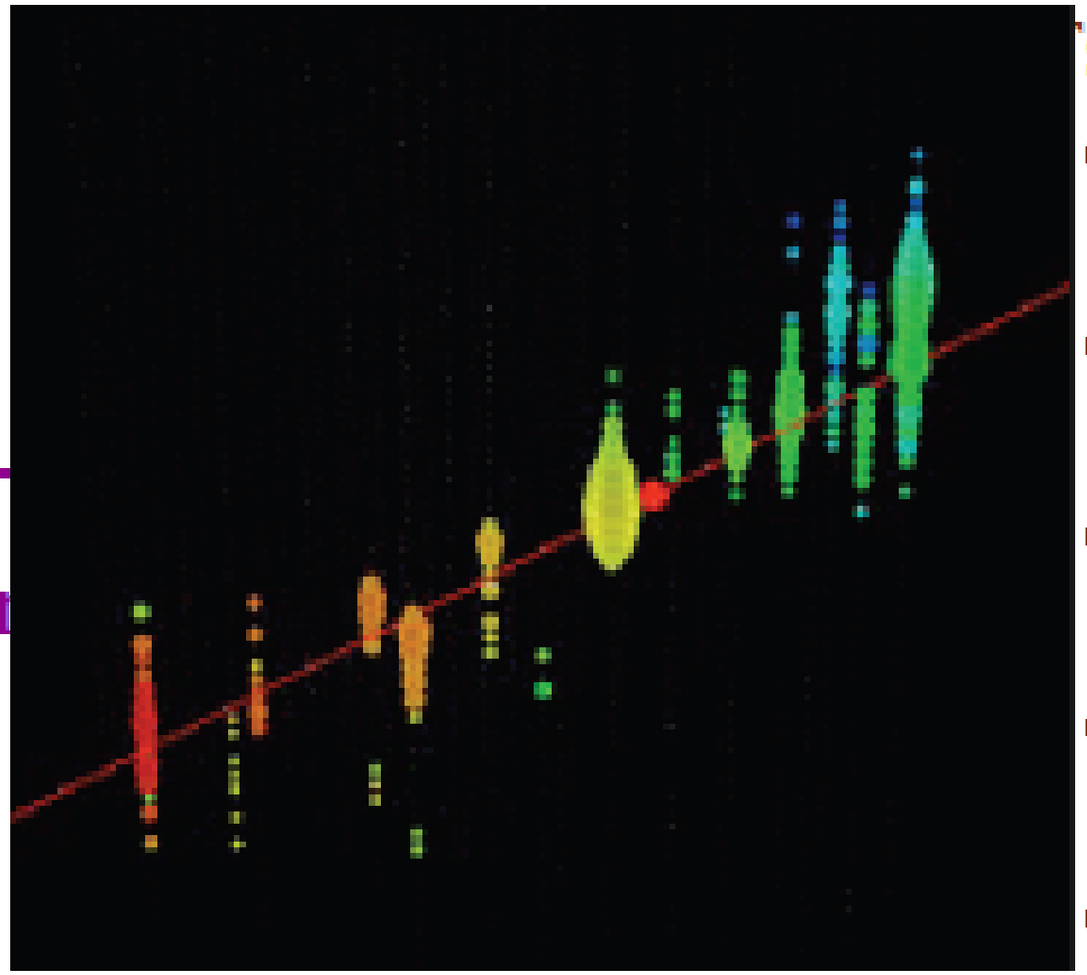
Detection Modes

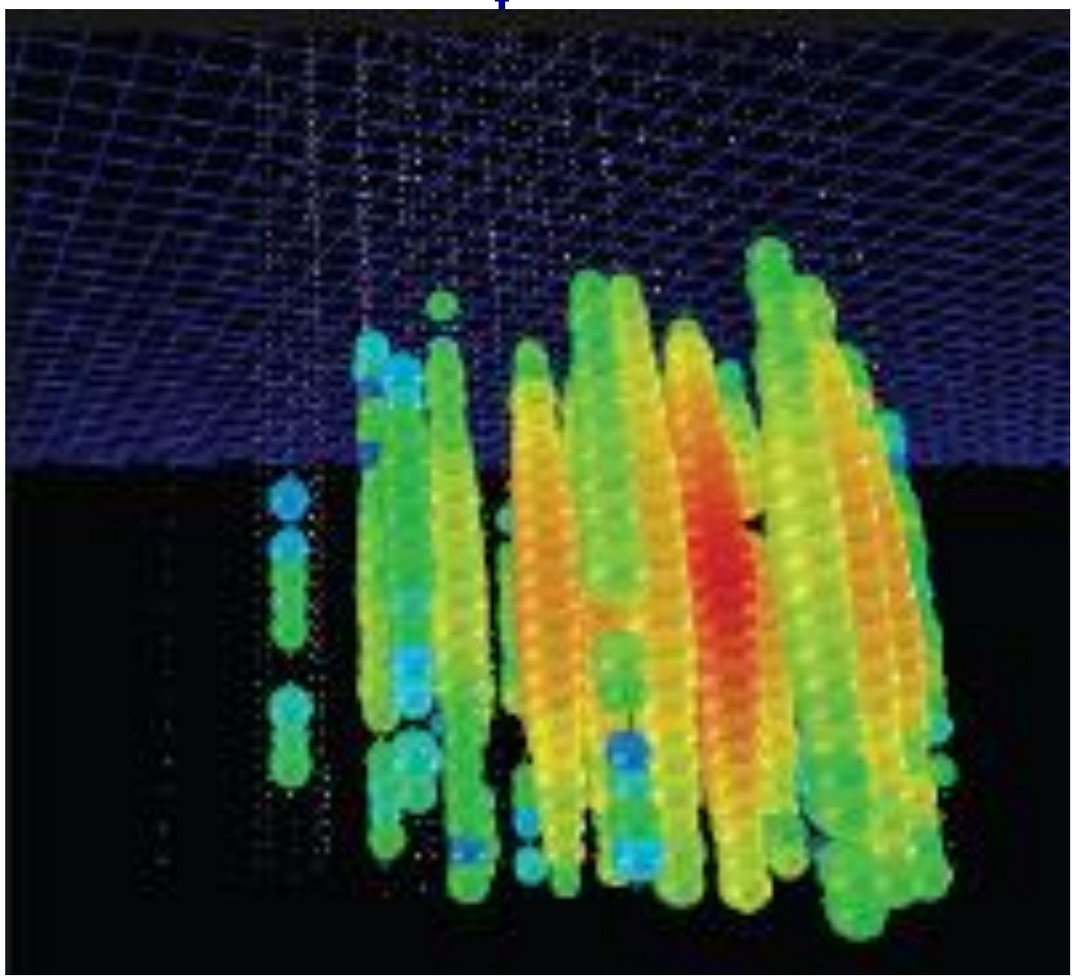




- Muon track from CC muon neutrino interactions
  - Angular resolution 0.1° - 0.5°
  - dE/dx resolution factor 2-3
- Cascade from CC electron and NC all flavor interactions
  - Angular resolution 2° - 15 °
  - Energy resolution ~ 15%

Detection Modes

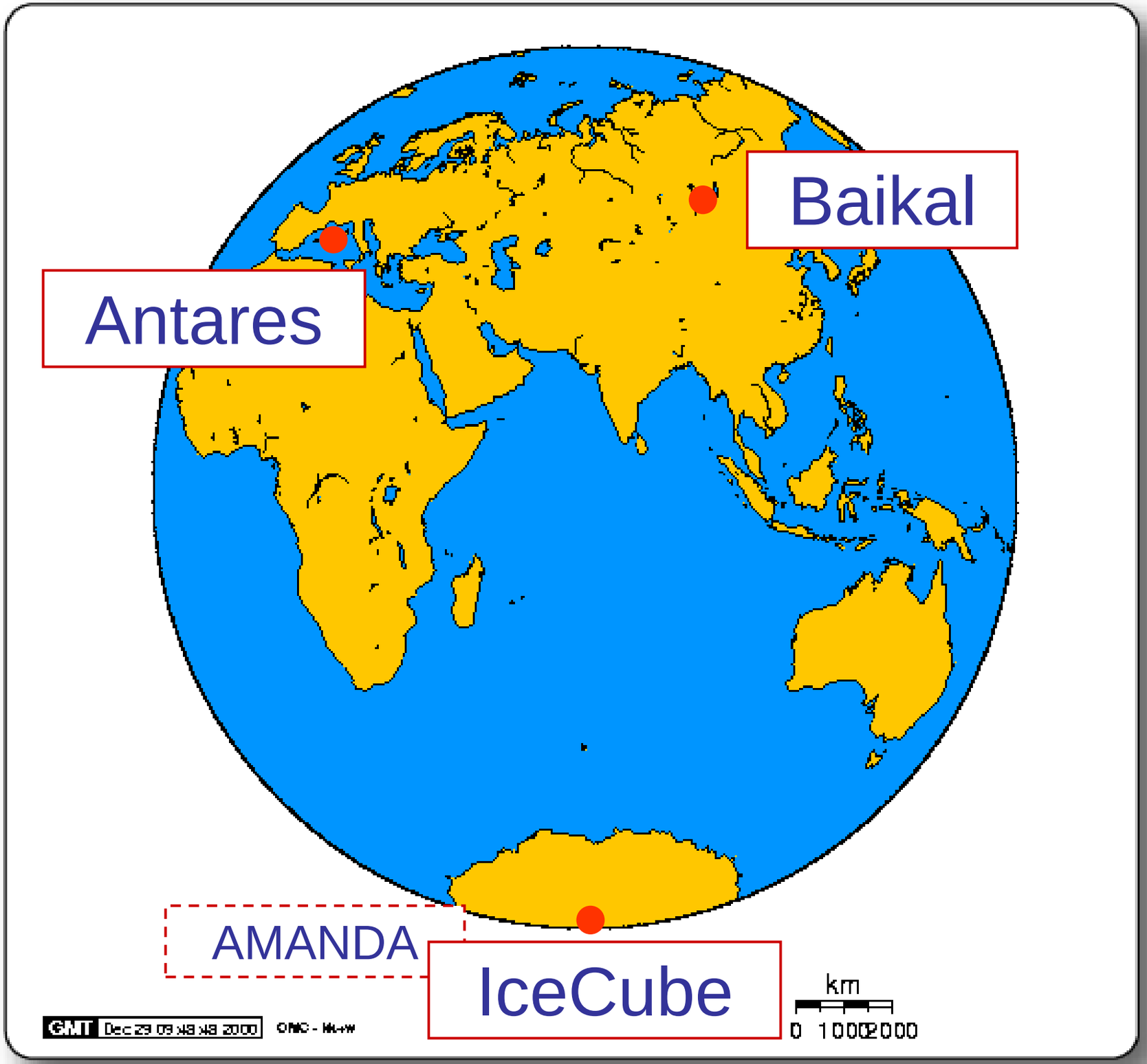




- **Muon track from CC muon neutrino interactions**
  - **Angular resolution 0.1° - 0.5°**
  - **dE/dx resolution factor 2-3**
- **Cascade from CC electron and NC all flavor interactions**
  - **Angular resolution 2° - 15 °**
  - **Energy resolution ~ 15%**

THE DETECTORS

The devices


Baikal
Antares
AMANDA
IceCube
km
0 1000 2000
GMT Dec 29 09:48:48 2000

ANTARES

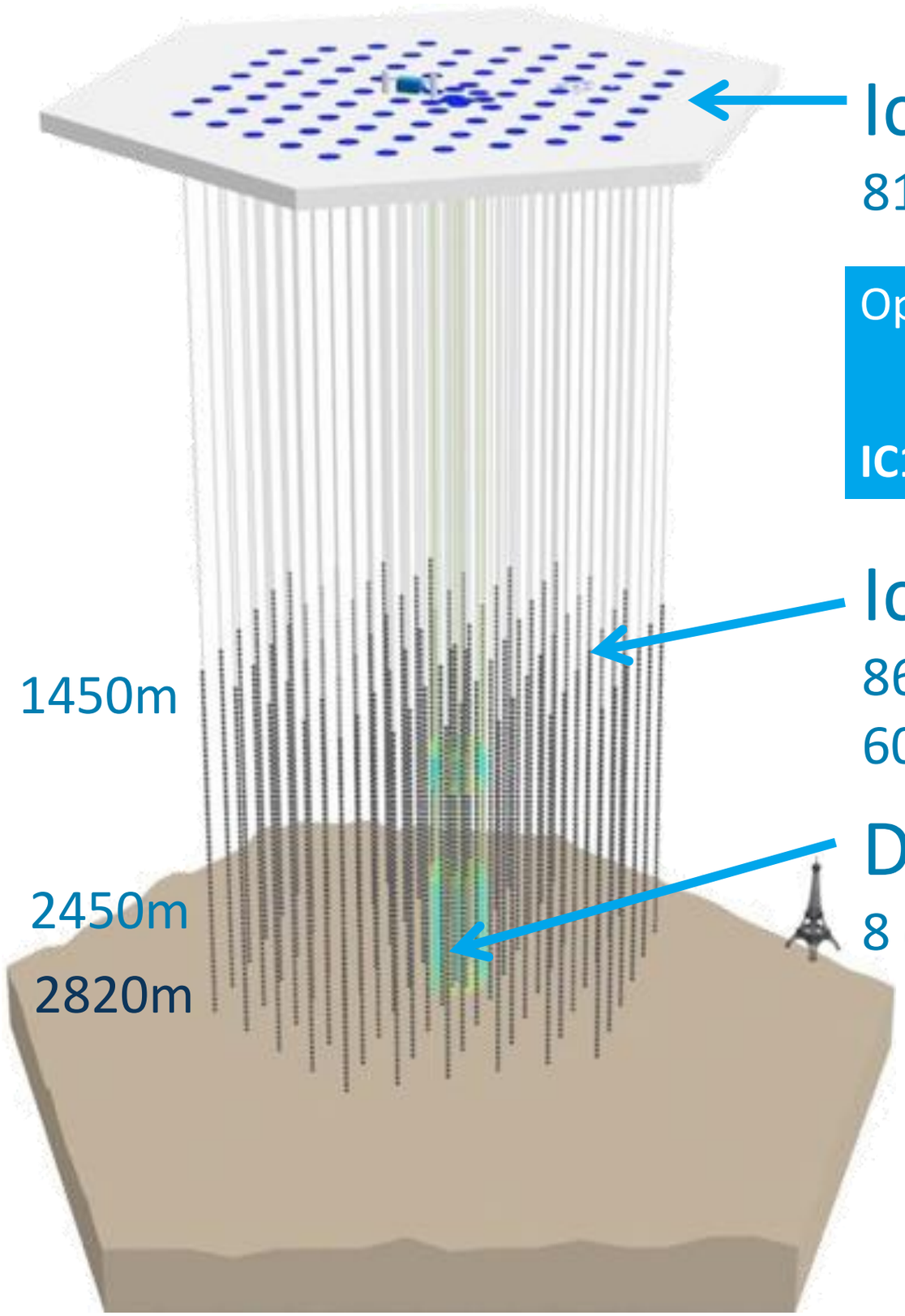
2500m

450 m

70 m

- 885 PMTs
- 12 strings
- Operating in final configuration since 2008

IceCube Neutrino Observatory



IceTop air shower detector

81 pairs of water Cherenkov tanks

Operating in final configuration (IC86) since Dec. 2010

2008 2009 2010 >2010

IC1 → IC9 → IC22 → IC40 → IC59 → IC-79 → IC86

IceCube

86 strings including 8 Deep Core strings

60 PMT per string

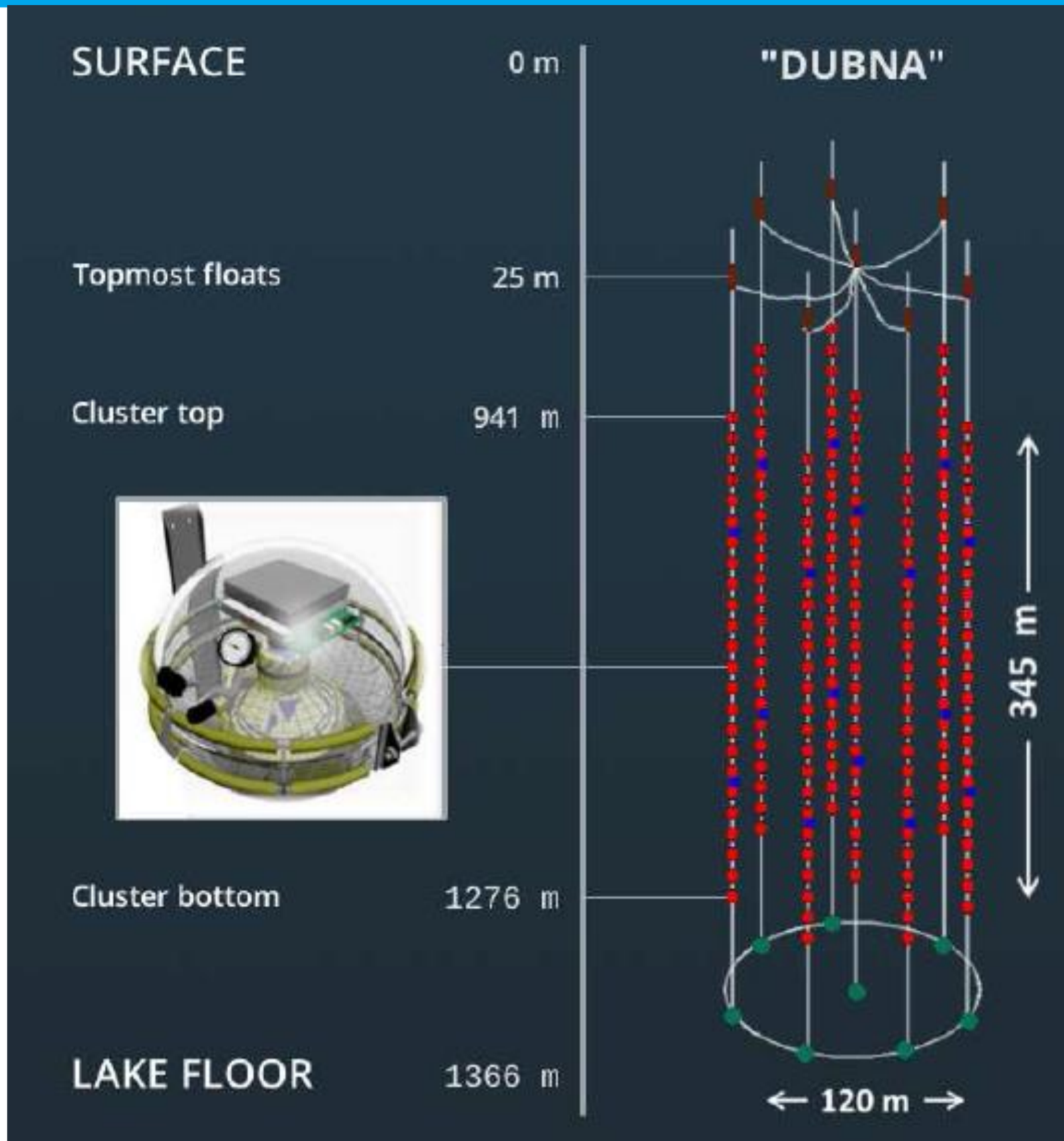
DeepCore

8 closely spaced strings

- ~220 ν/day
- Threshold
  - IceCube ~ 100 GeV
  - DeepCore ~10 GeV

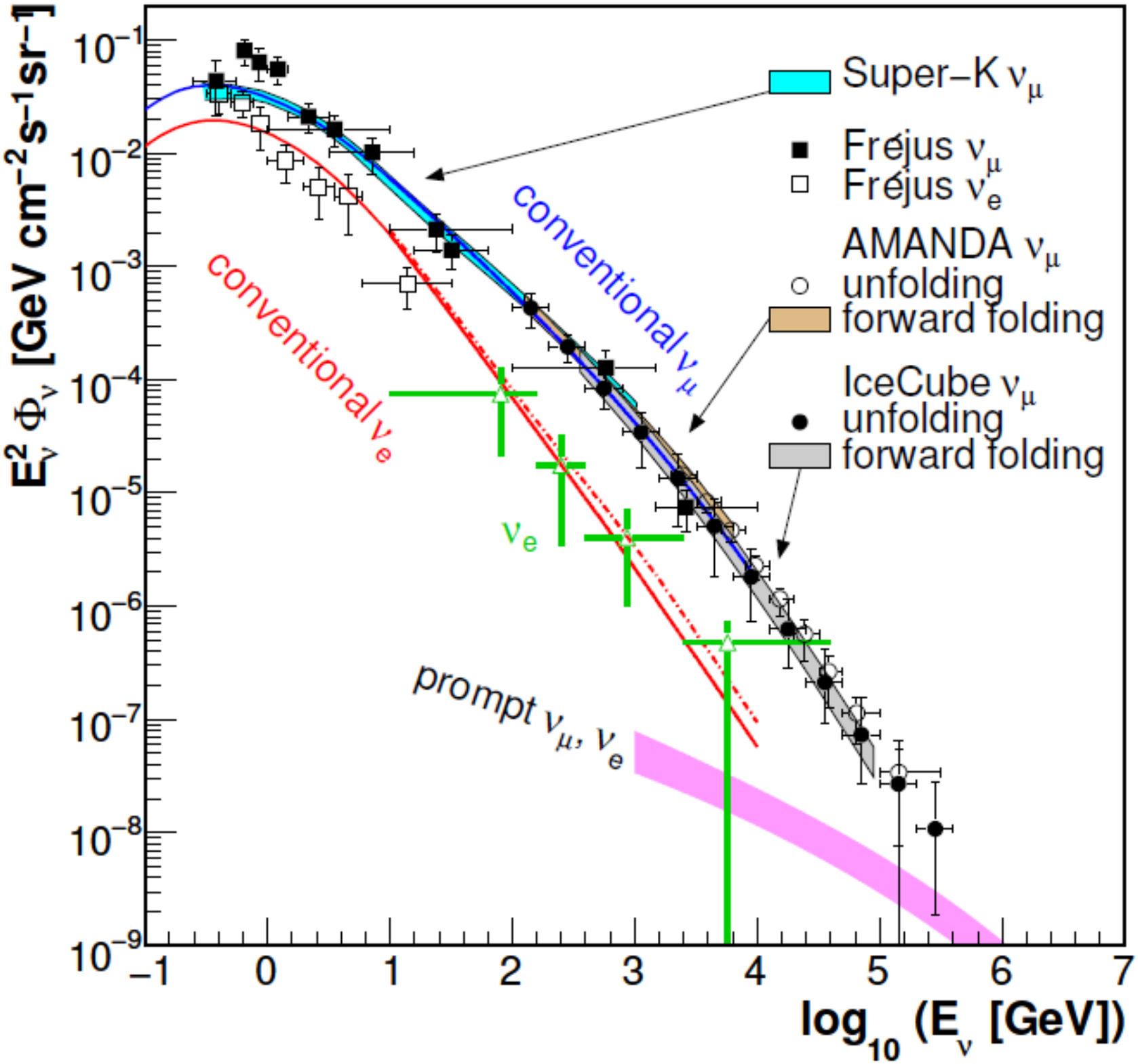
Brand New: Lake Baikal, first cluster of GVD

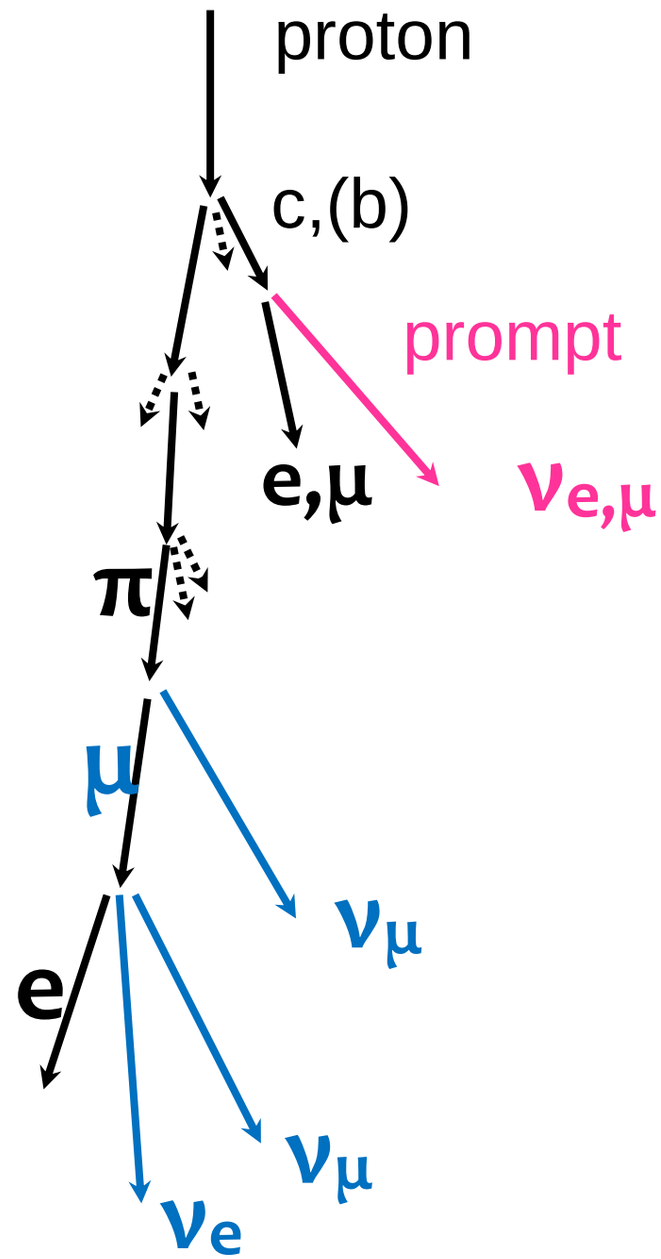
- Old NT200: ~ 0.0001 km³
- DUBNA cluster: 0.004 km³ (Antares 0.015 km³)
- GVD-1:
  12 clusters ~ 0.4 km³ (~2020)
- GVD-2:
  27 clusters ~ 1.5 km³



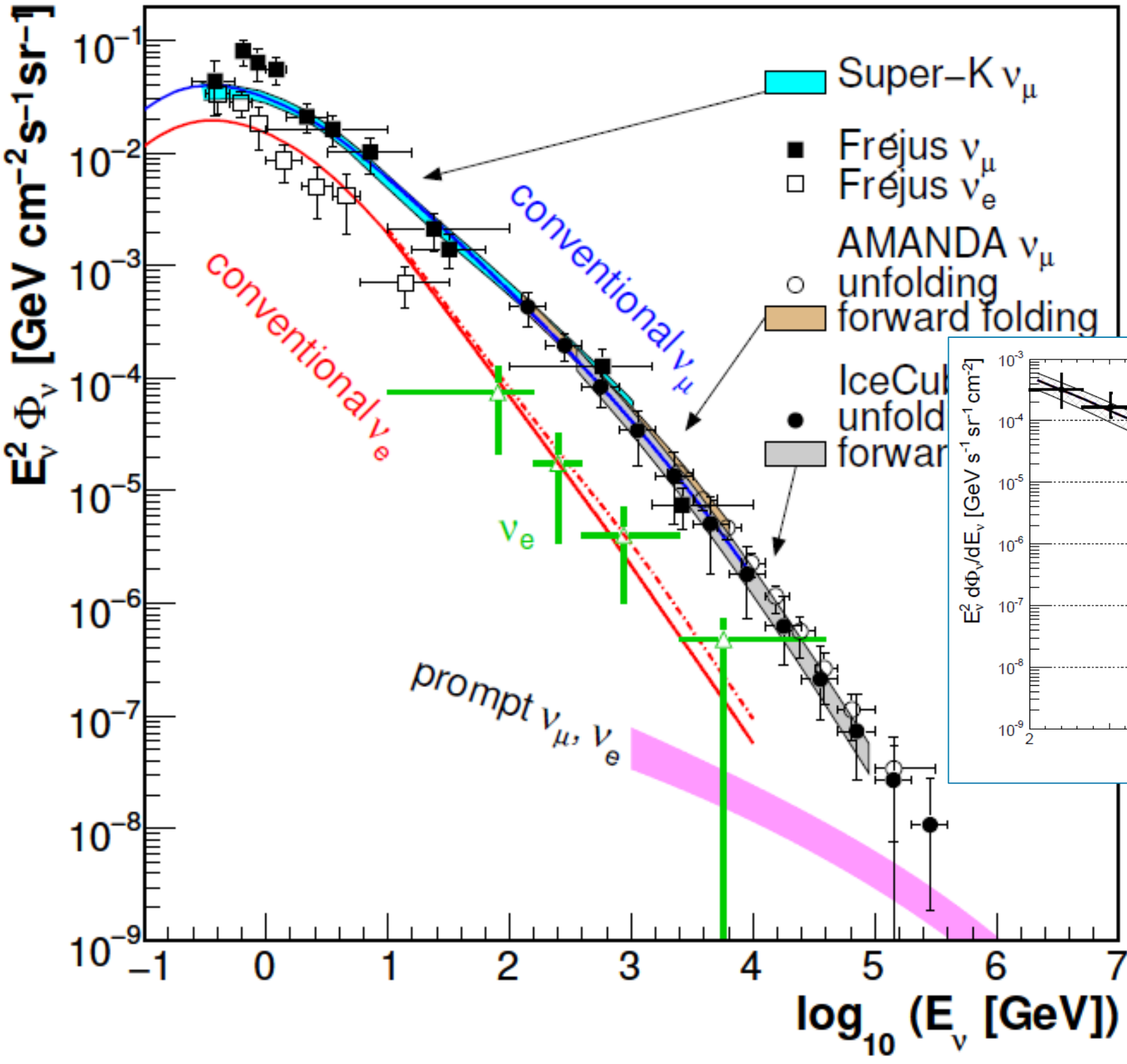
ATMOSPHERIC NEUTRINOS

Atmospheric neutrinos in IceCube

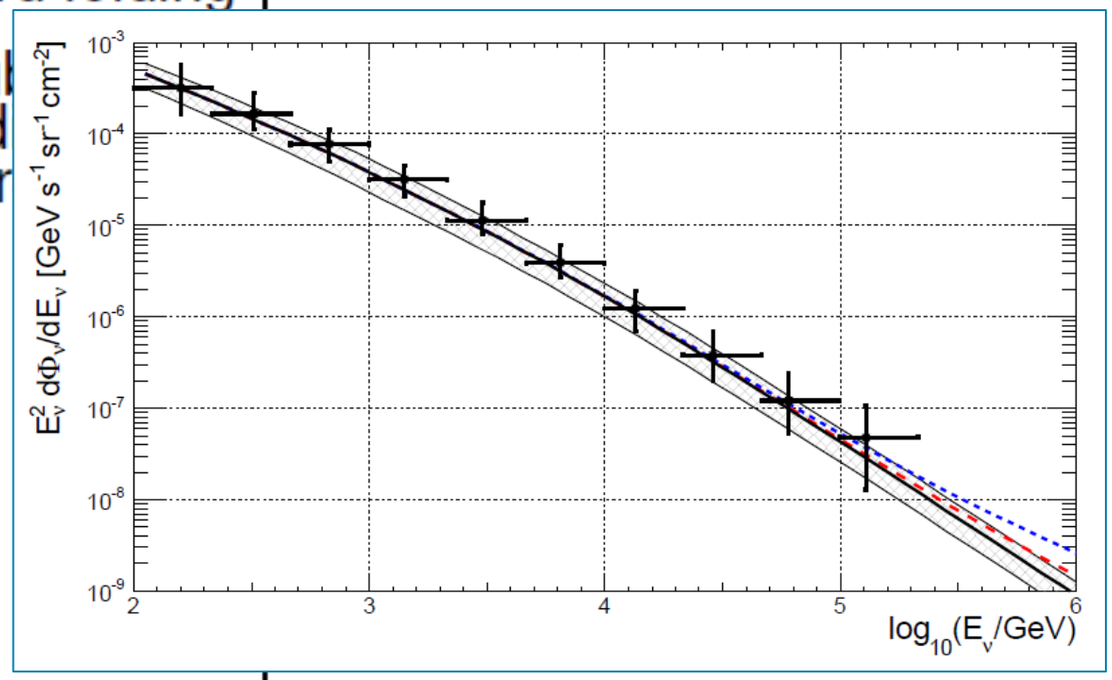




Atmospheric neutrinos in IceCube



.. and ANTARES

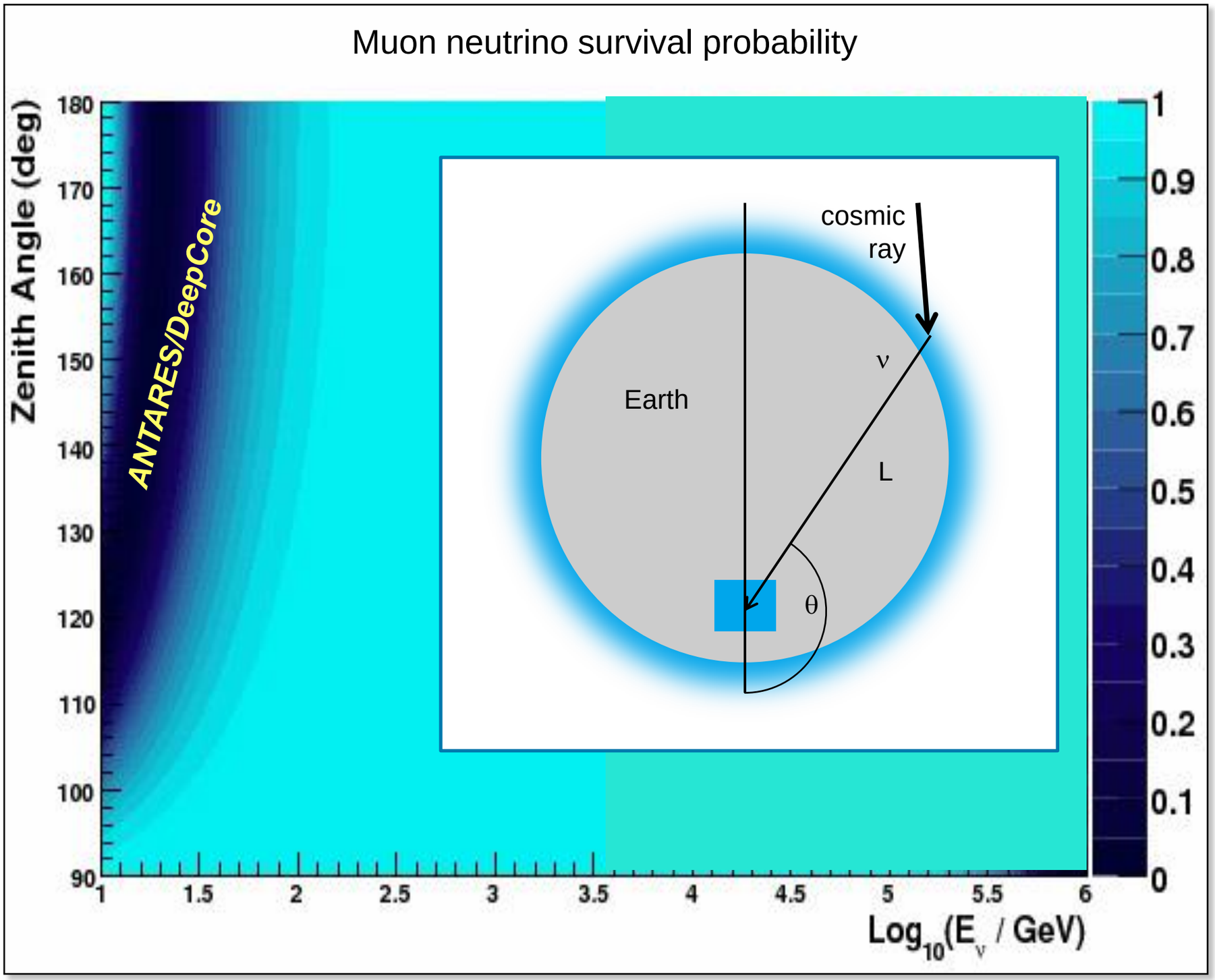


arXiv:1308.1599

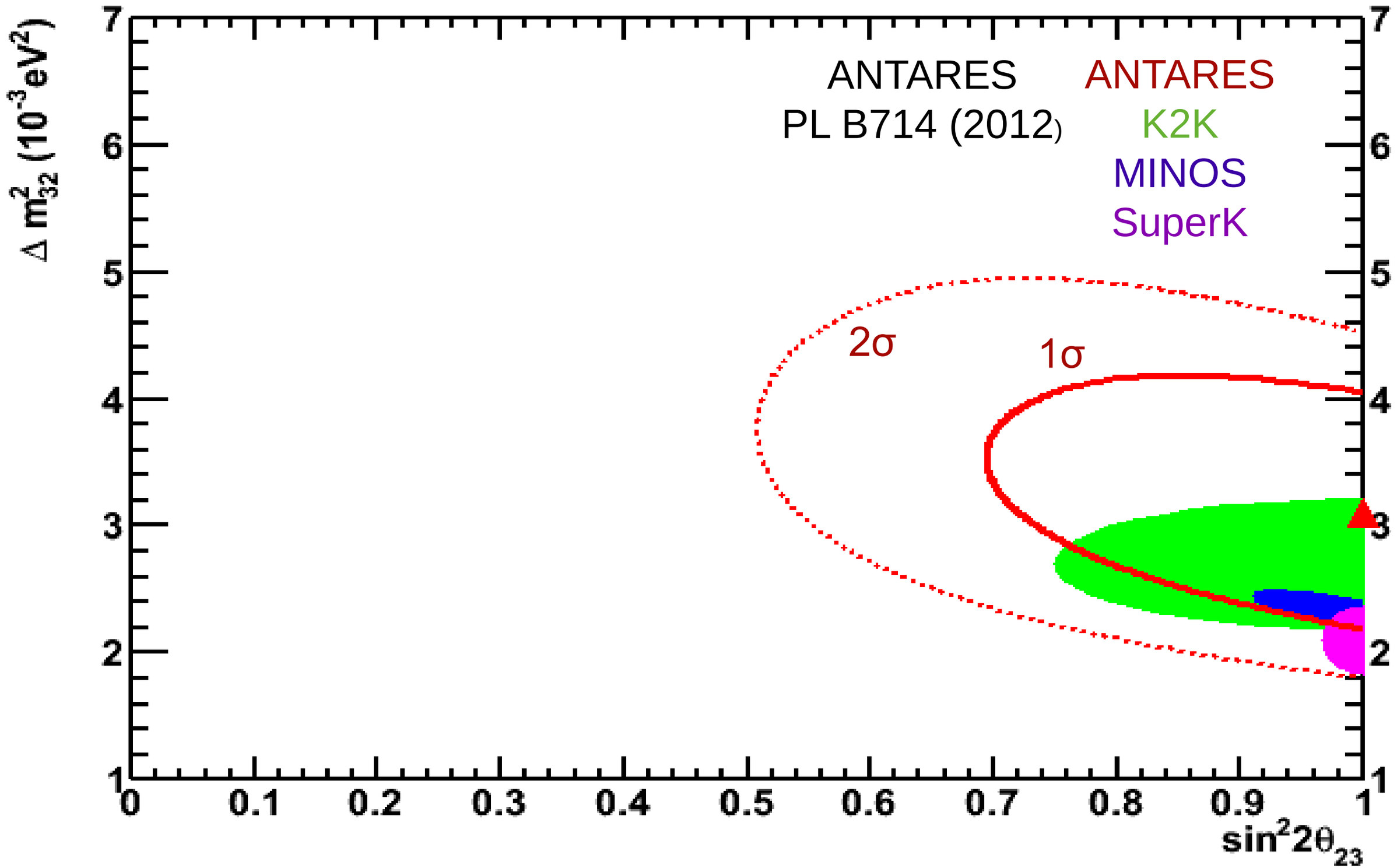
Oscillations of atmospheric neutrinos

Vertically upward

Horizontal

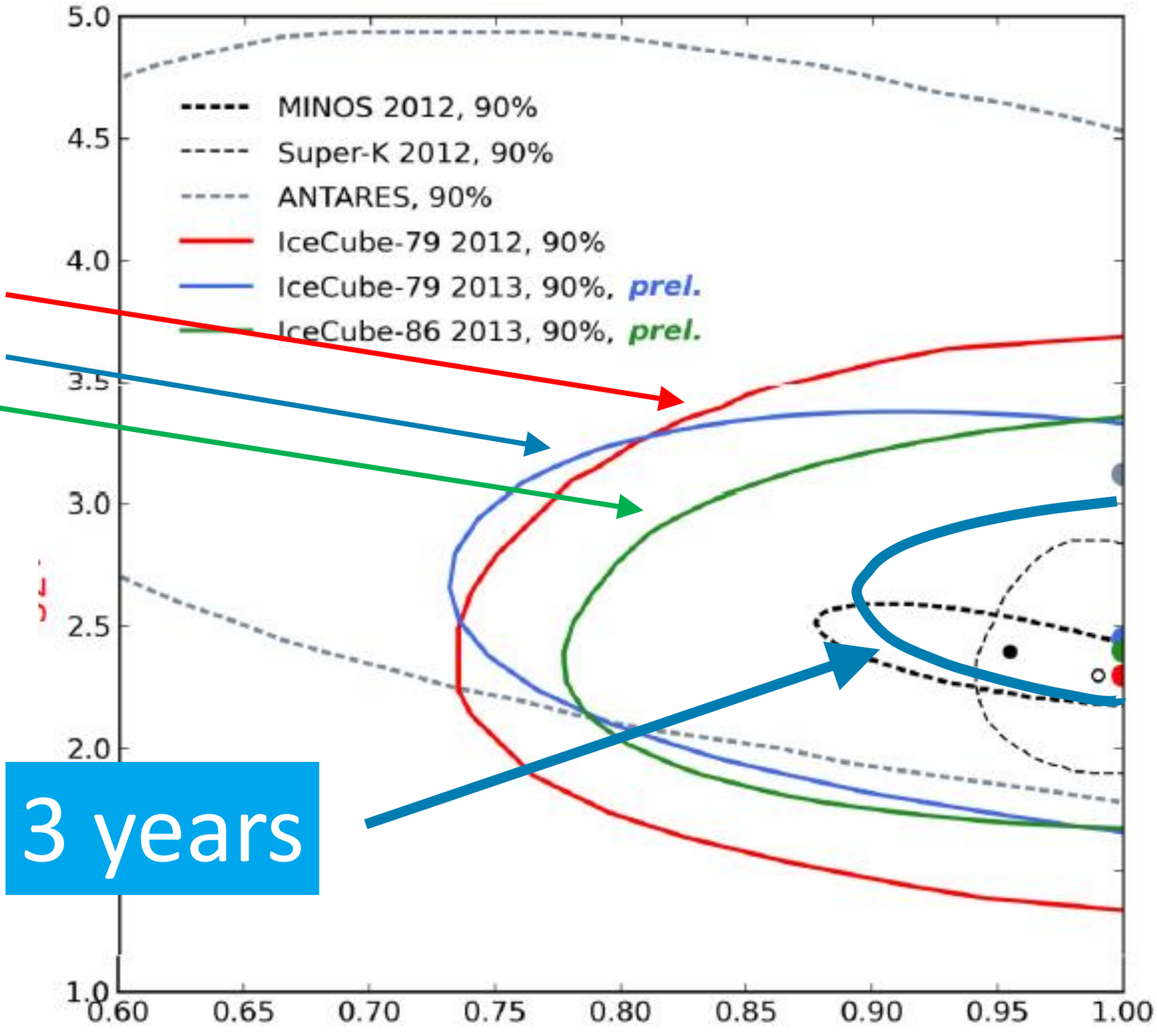


Oscillations underwater and ice: from ANTARES …



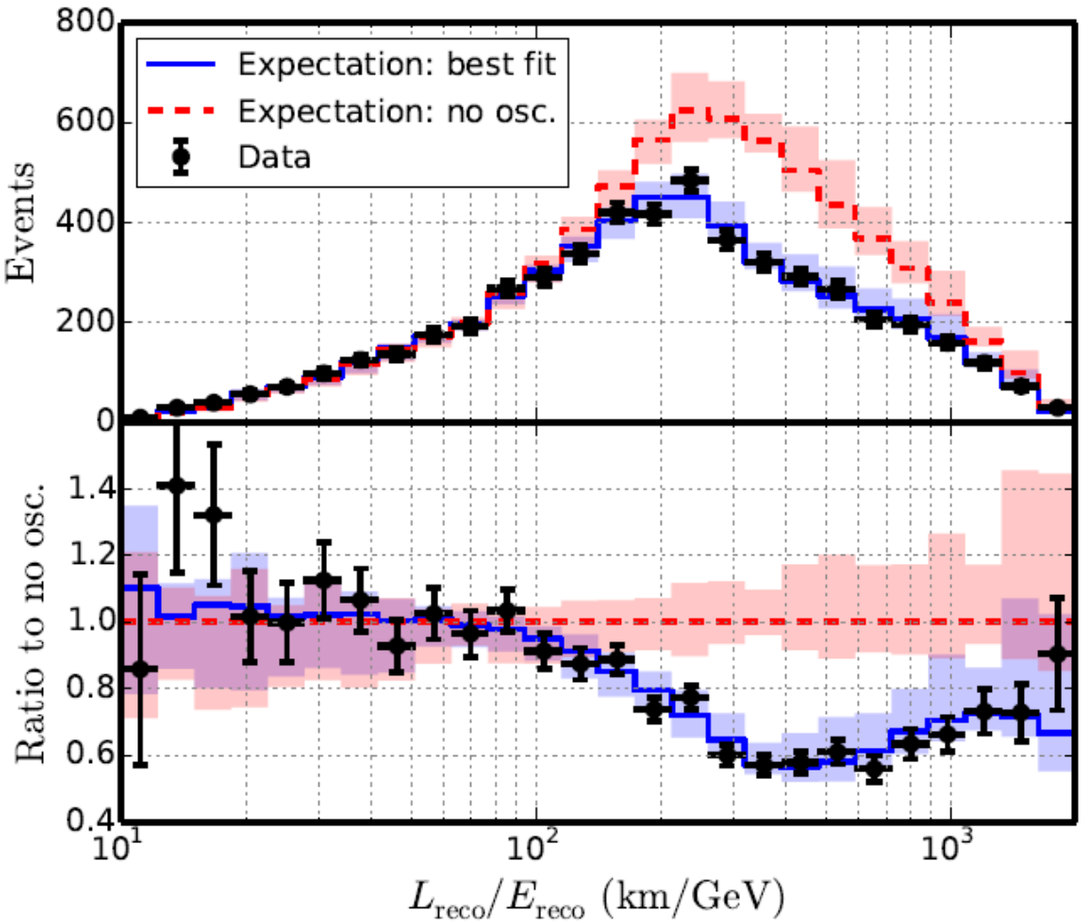
Oscillations underwater and ice: to 3 yrs DeepCore…

1 year
(3 analyses)



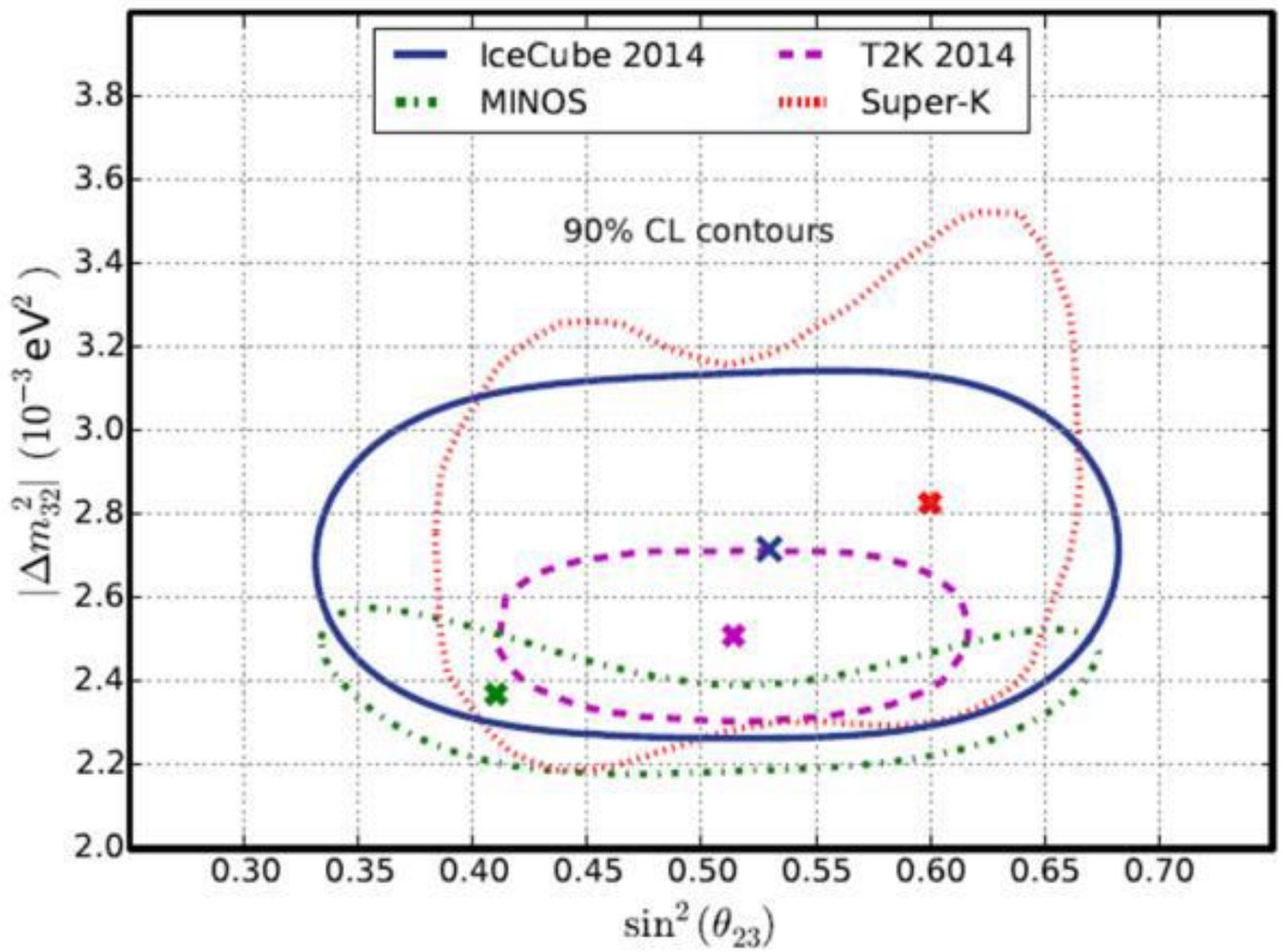
3 years

3 years DeepCore



Determining neutrino oscillation parameters from atmospheric muon neutrino disappearance with three years of IceCube DeepCore data

- arXiv:1410.7227
- accepted by PRD

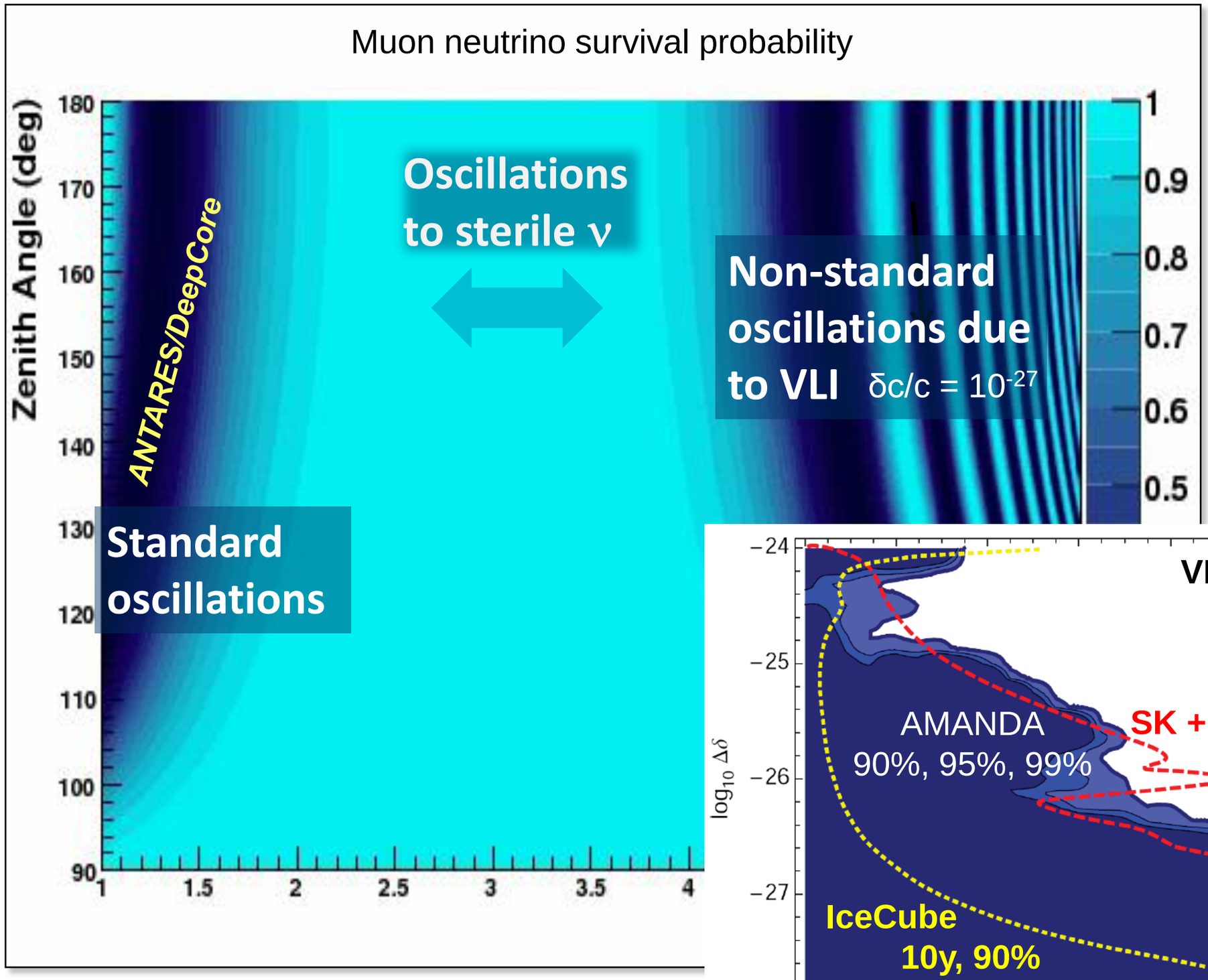


- New results with even better constraints in Summer 2015
- Good basis for P I N G U and O R C A

Oscillations of atmospheric neutrinos

Vertically upward

Horizontal



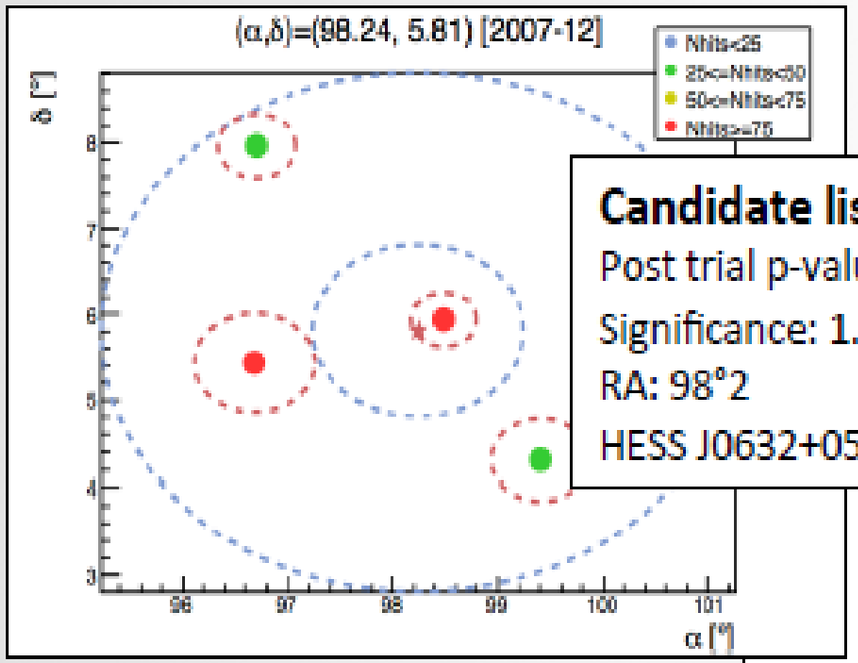
SEARCH FOR POINT SOURCES

Pre-trial significance skymap, IC40+59+79+86 (4 years)

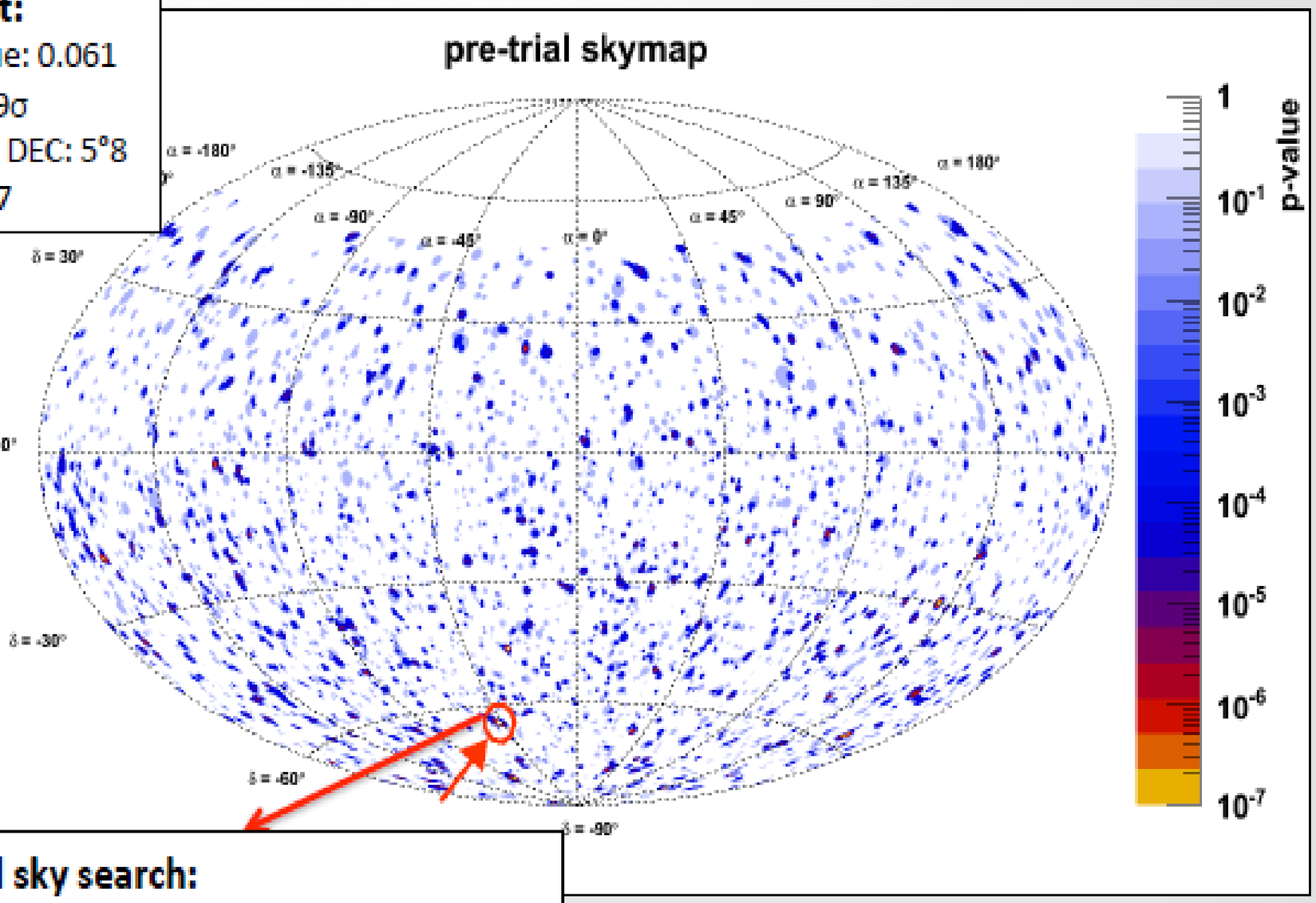
North

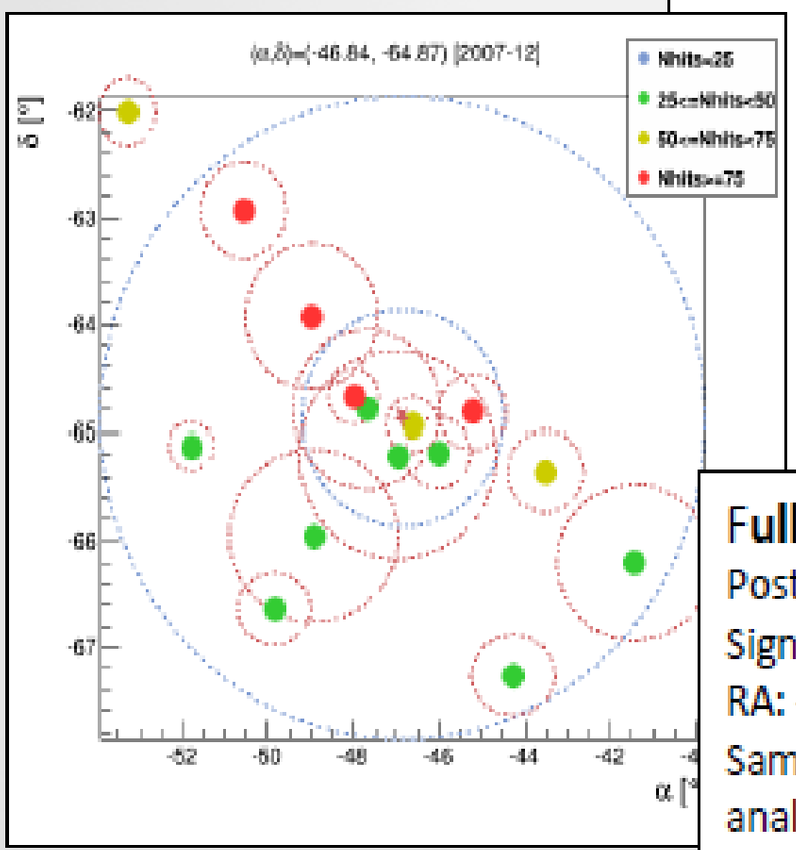
South

ANTARES point source search



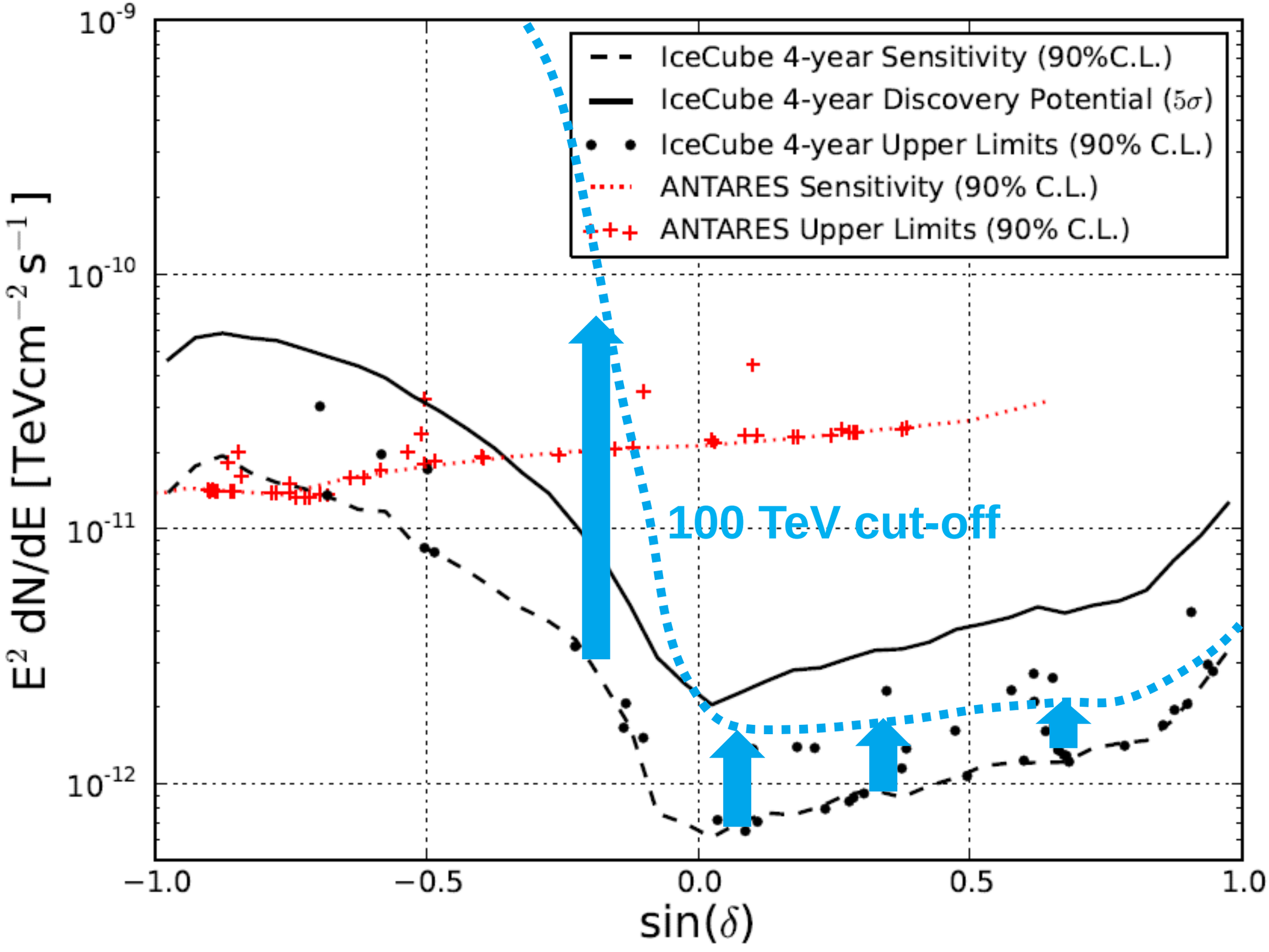
Candidate list:
Post trial p-value: 0.061
Significance: 1.9σ
RA: 98°2 DEC: 5°8
HESS J0632+057





Full sky search:
Post trial p-value: 0.027
Significance: 2.2σ
RA: -46°8 DEC: -64°9
Same cluster than in the 2007-2010 analysis

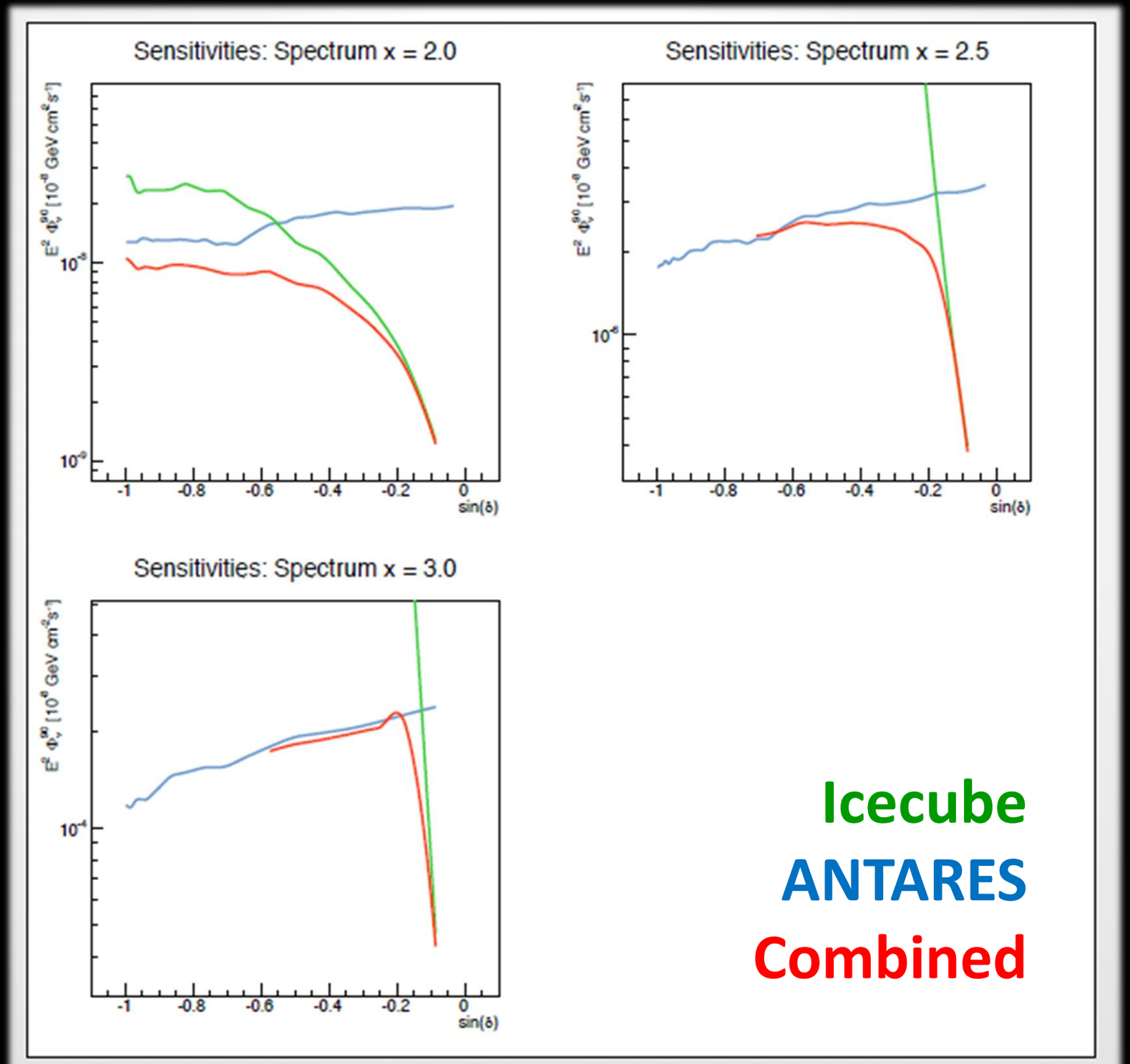
Upper limits and 5σ discovery potential



Combining ANTARES + IC 40/59/79

- For different spectral indices

- For spectral indices > 2.5 small effect of combination



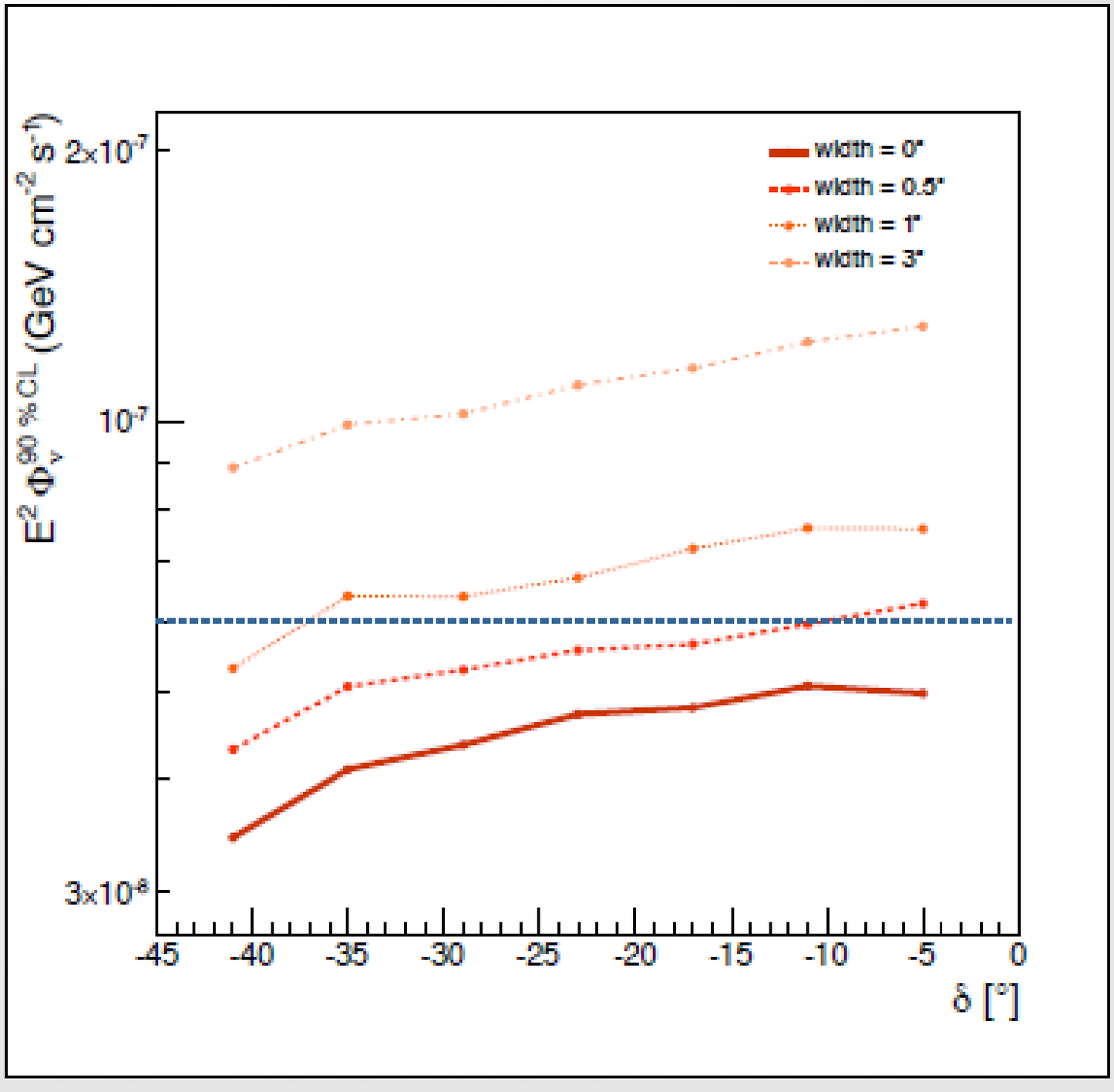
ANTARES scrutinizes IceCube‘s warm spot

Single source with

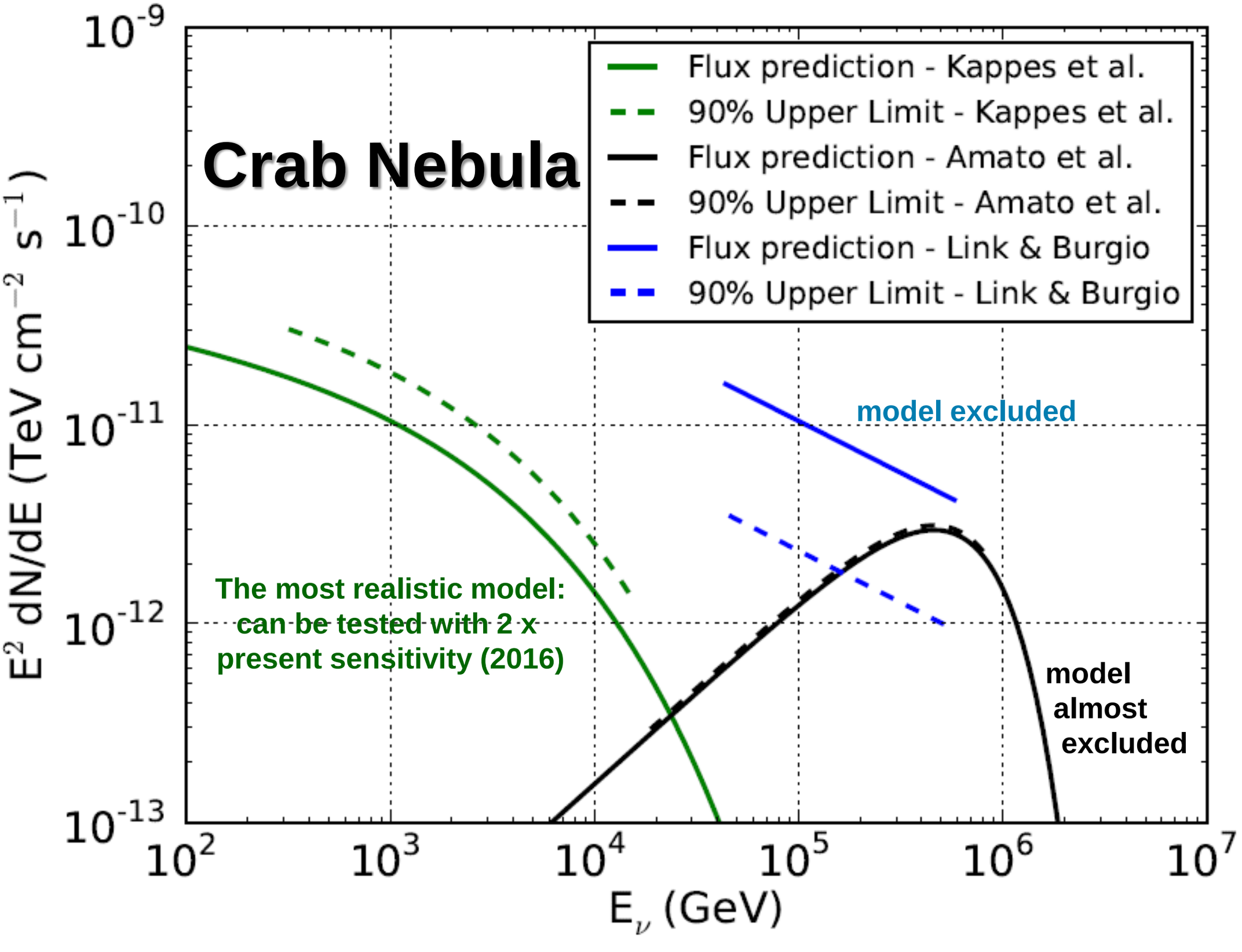
$E^2 \cdot \Phi = 8 \times 10^{-8}$ GeV/(cm²s)

and ***0.5° width***

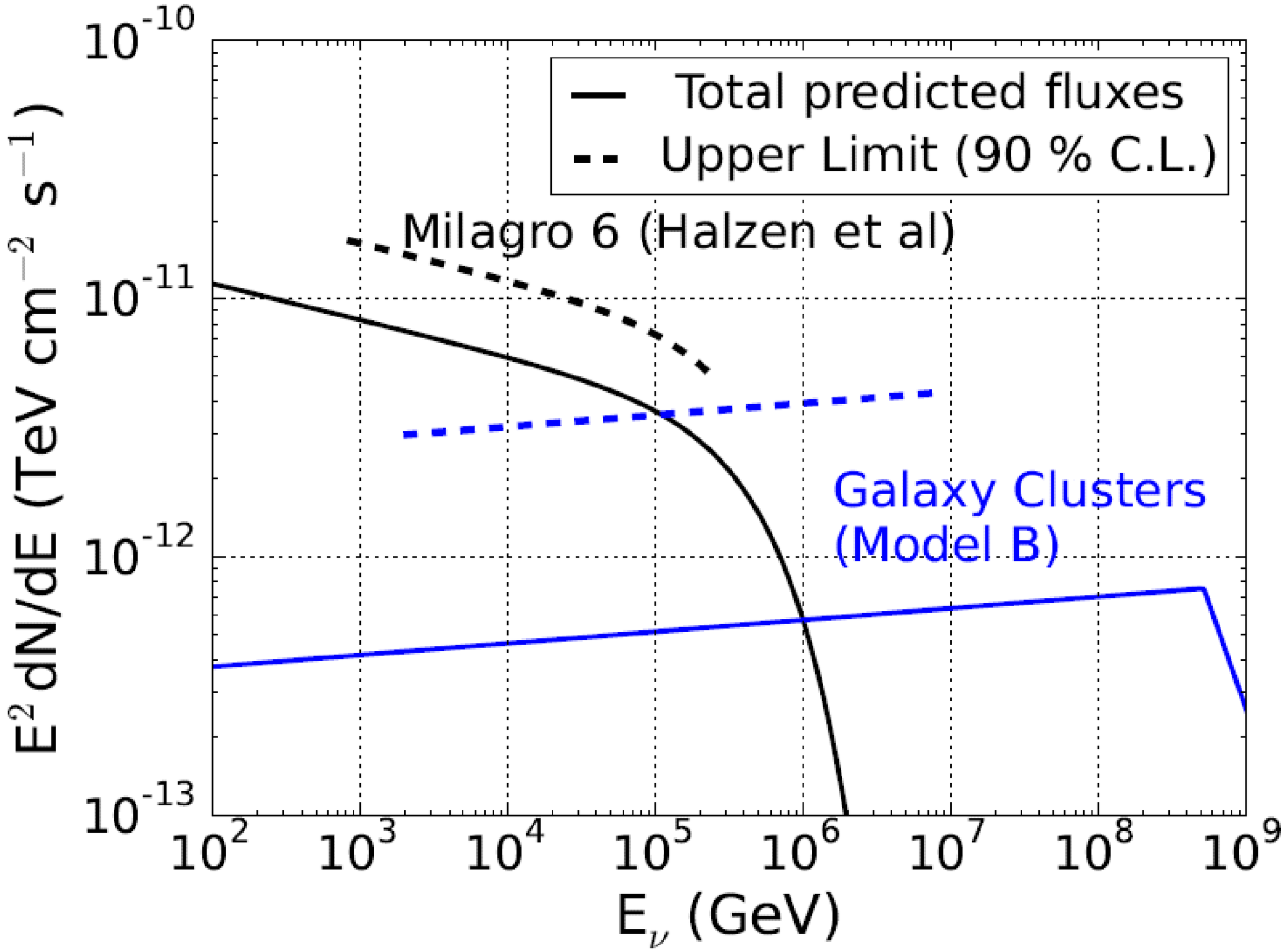
is discarded as reason for IceCube‘s „warm spot“.



IceCube 4 years: upper limits and predictions

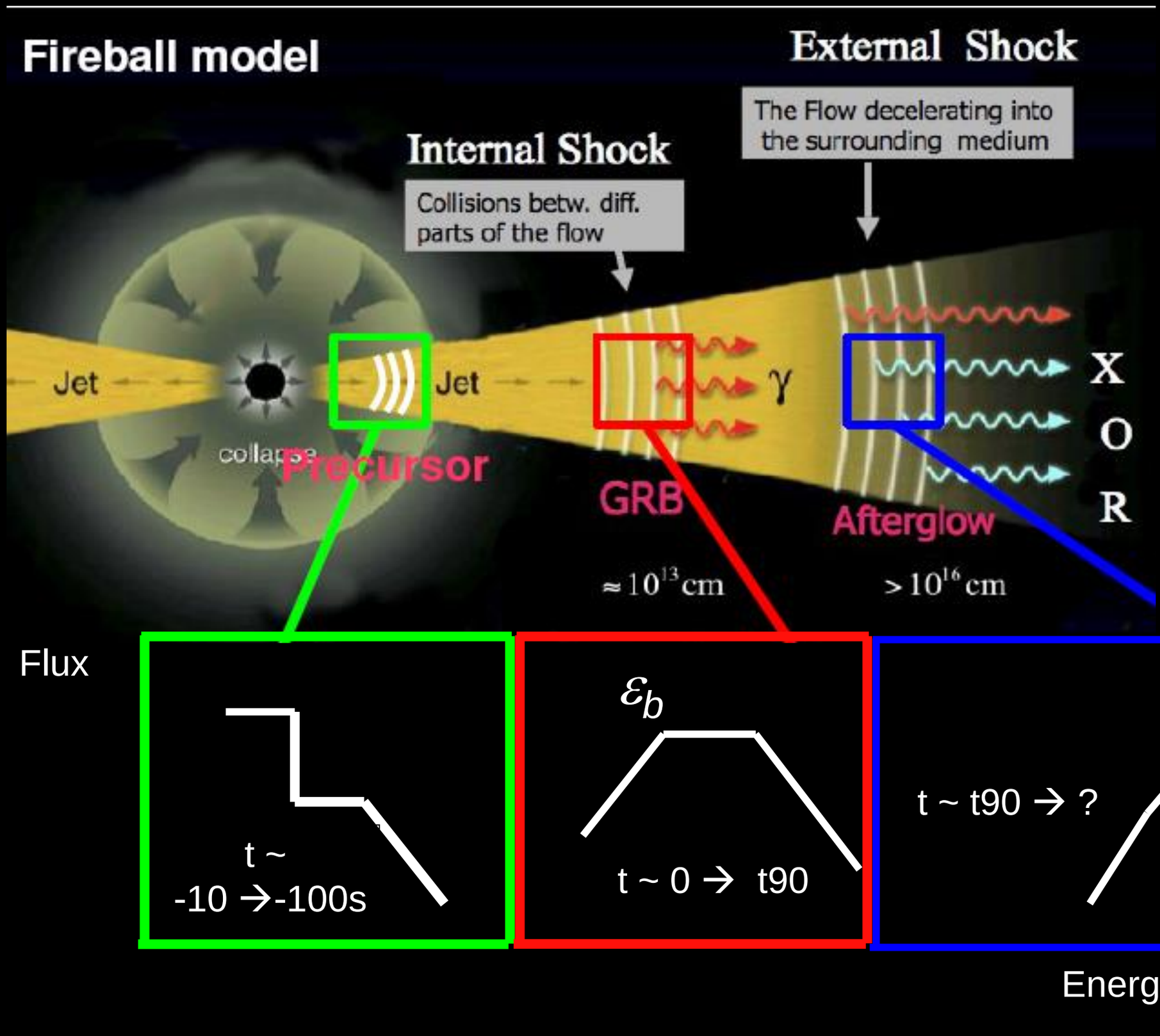


2 examples for stacked-source limits

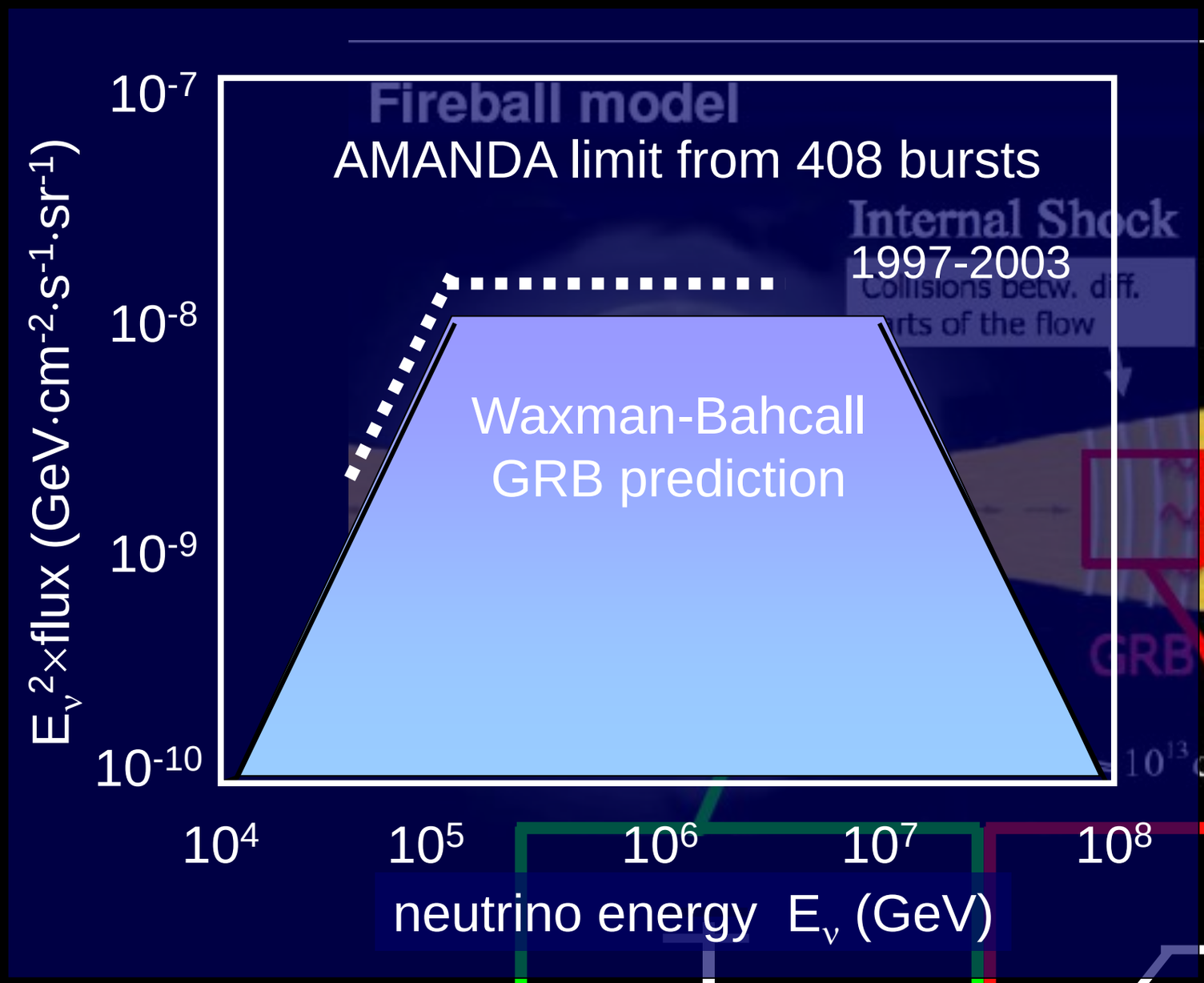


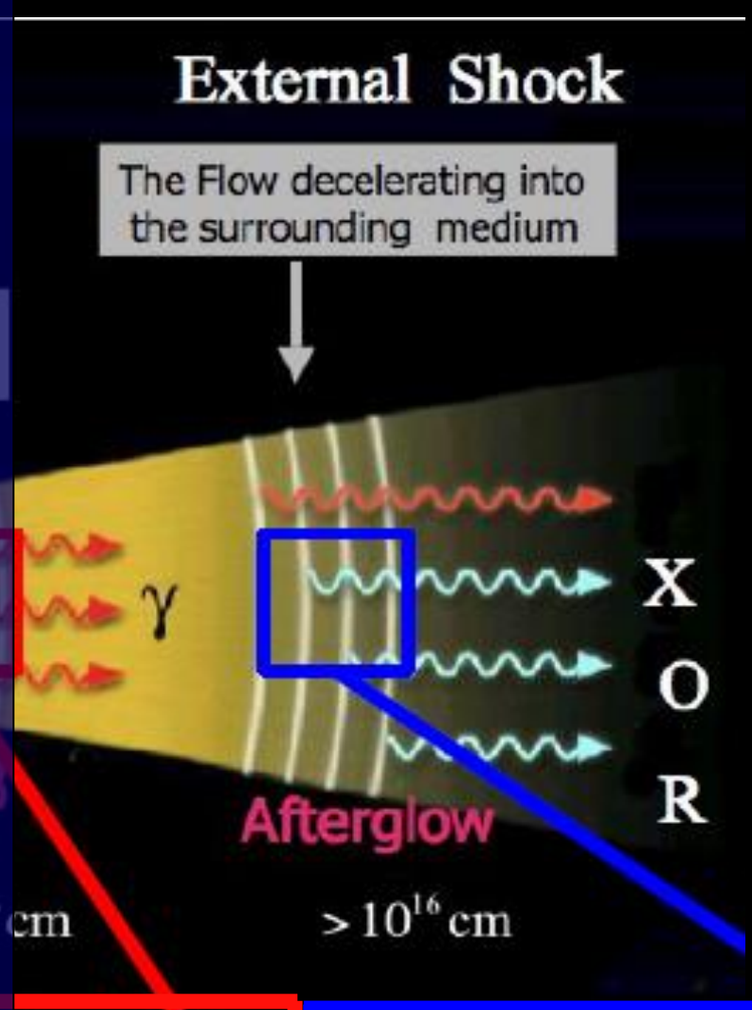
SEARCH FOR TRANSIENT SOURCES

Neutrinos from GRB



Neutrinos from GRB





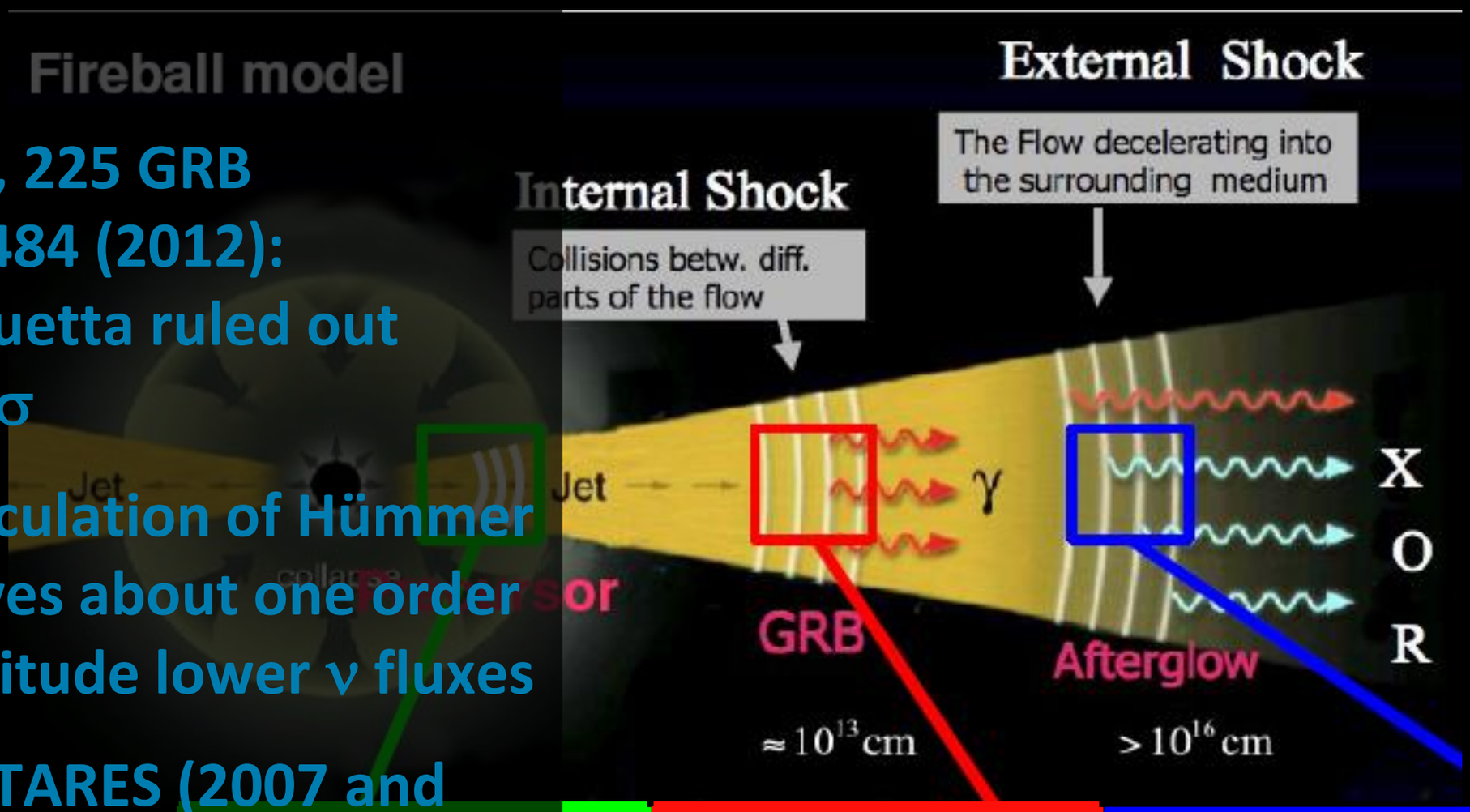
t ~
-10 → -100s

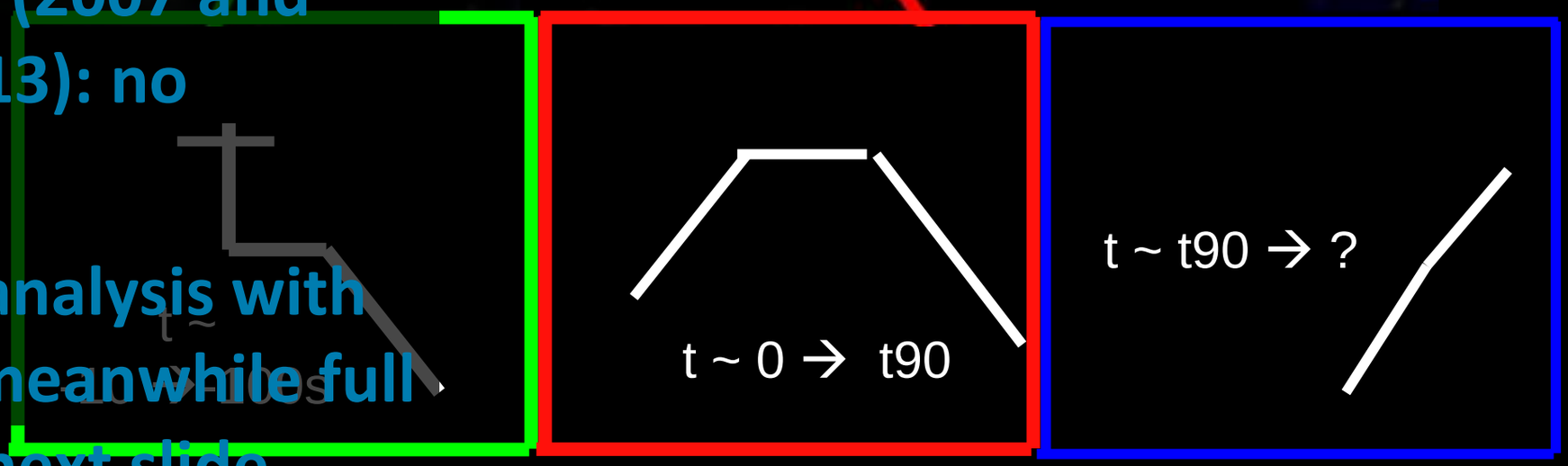
t ~ 0 → t90

t ~ t90 → ?

Neutrinos from GRB

- IceCube, 225 GRB Nature 484 (2012): WB & Guetta ruled out with > 3σ
- New calculation of Hümmer et al. gives about one order of magnitude lower ν fluxes
- Also ANTARES (2007 and 2013, A&A 2013): no coincidence
- New IceCube analysis with 506 GRB and meanwhile full detector: see next slide





Neutrinos from GRB

arXiv:1412:6510

- 506 GRB
- One single low-significance coincidence, consistent with atmospheric background
- IceCube has ruled out neutron escape models

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

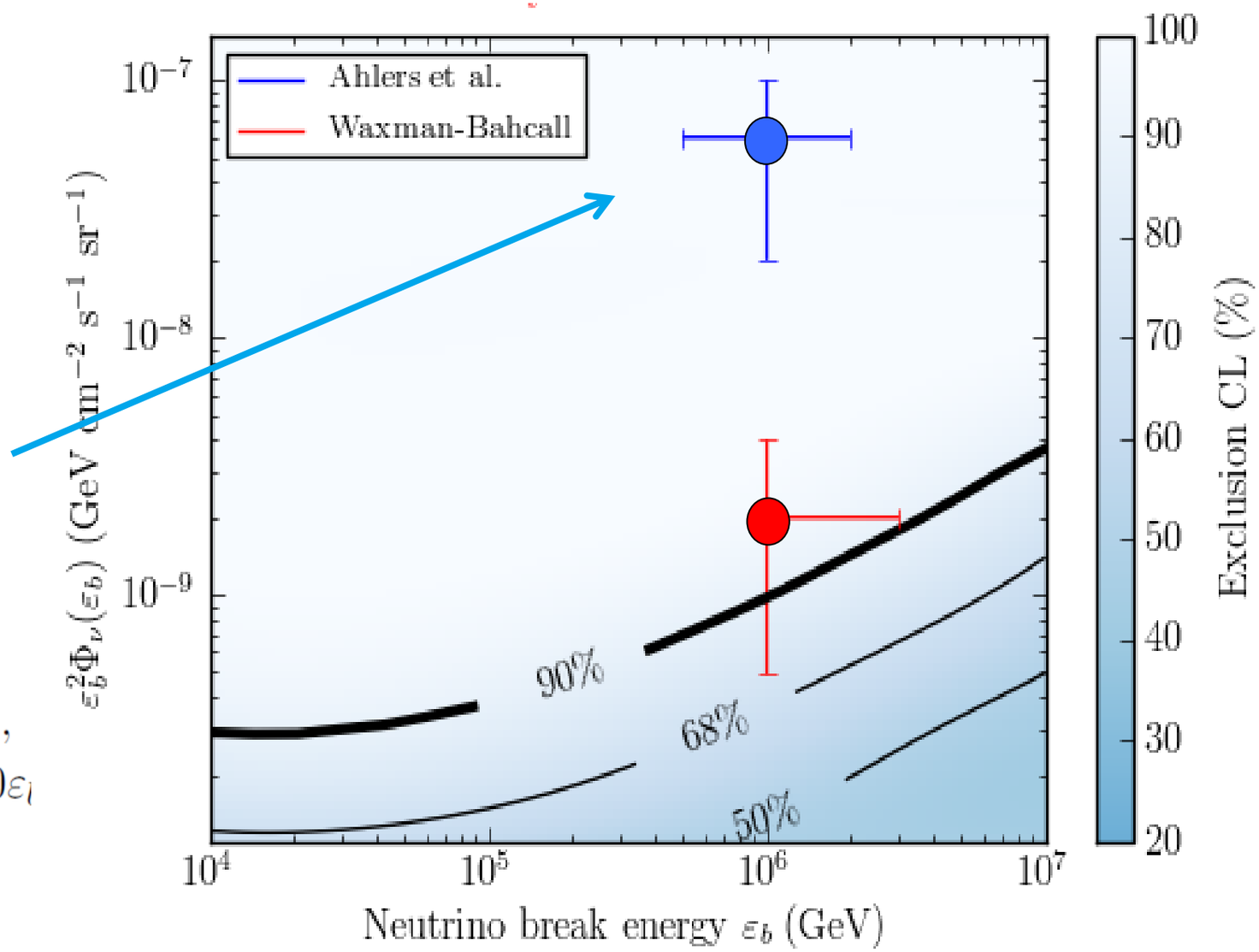
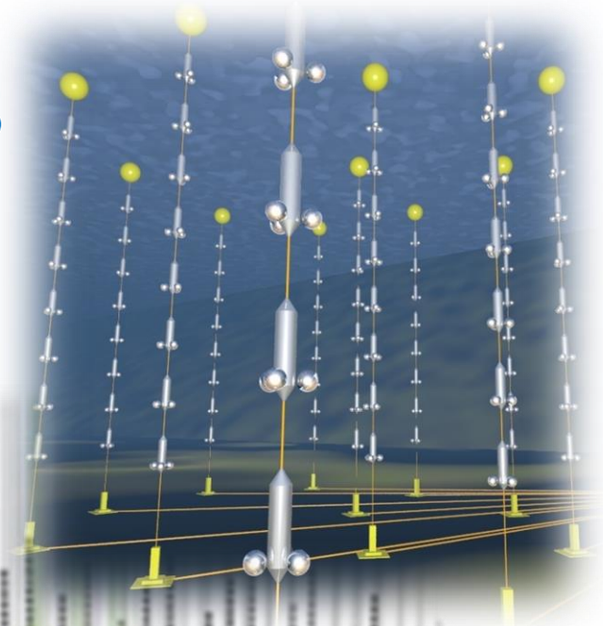


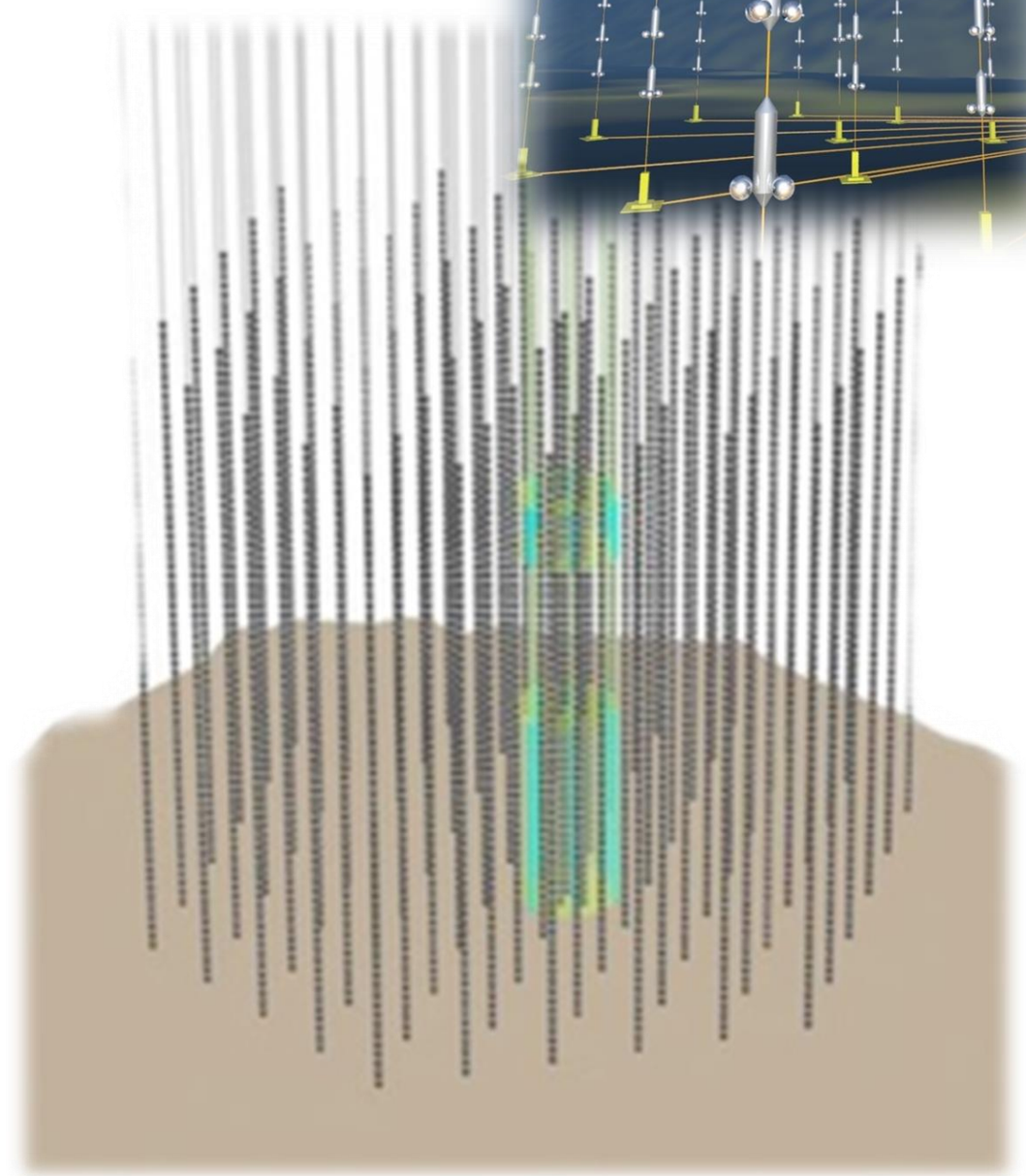
Fig. 1.— Constraint on generic doubly-broken power law neutrino flux models as a function of first break energy ε_b and normalization Φ_0. The model by Ahlers et al. (2011) assumes that only neutrons escape from the GRB fireball to contribute to the UHECR flux. The Waxman-Bahcall model (1997), which allows all protons to escape the fireball, has been updated to account for more recent measurements of the UHECR flux (Katz et al. 2009) and typical gamma break energy (Goldstein et al. 2012).

Follow-up observations all-sky devices → pointing devices

ANTARES



IceCube

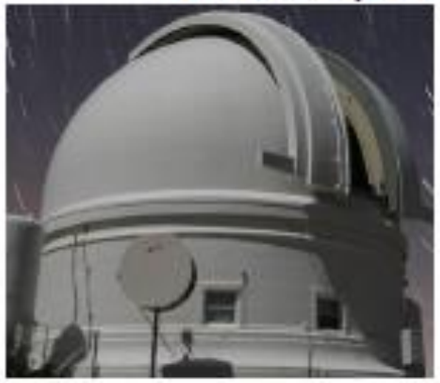


ALERT

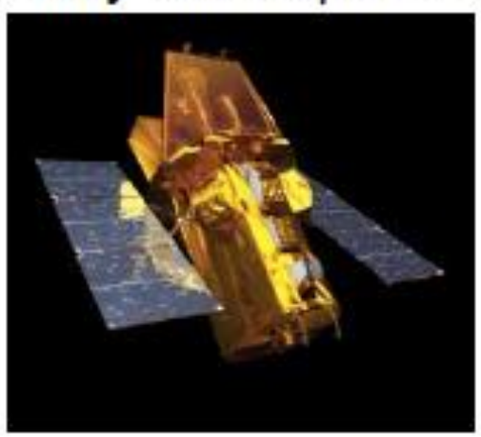
Pointed observations

HESS/MAGIC/Veritas

Optical telescopes

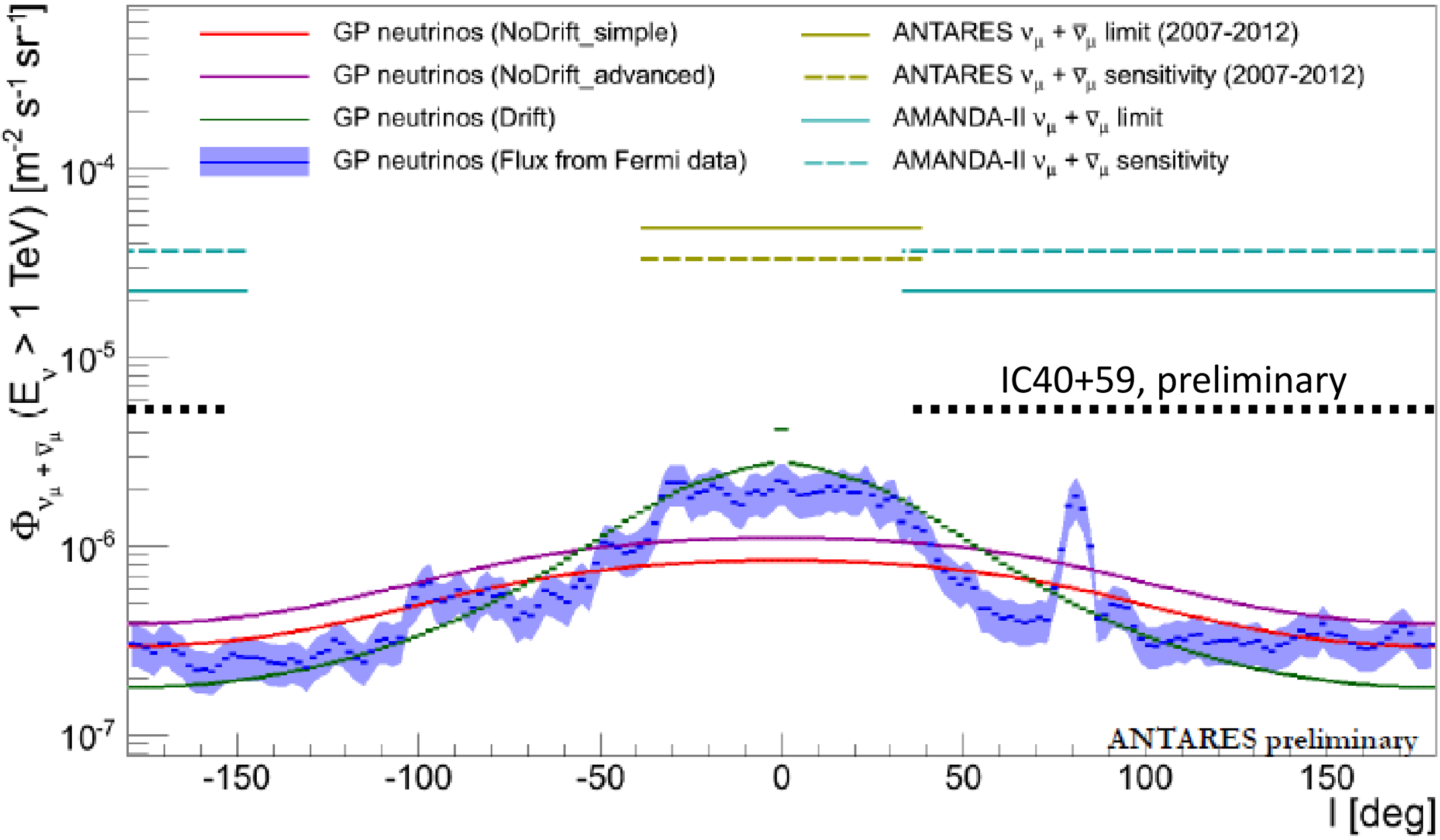


X-ray telescopes



GALACTIC PLANE

Galactic plane

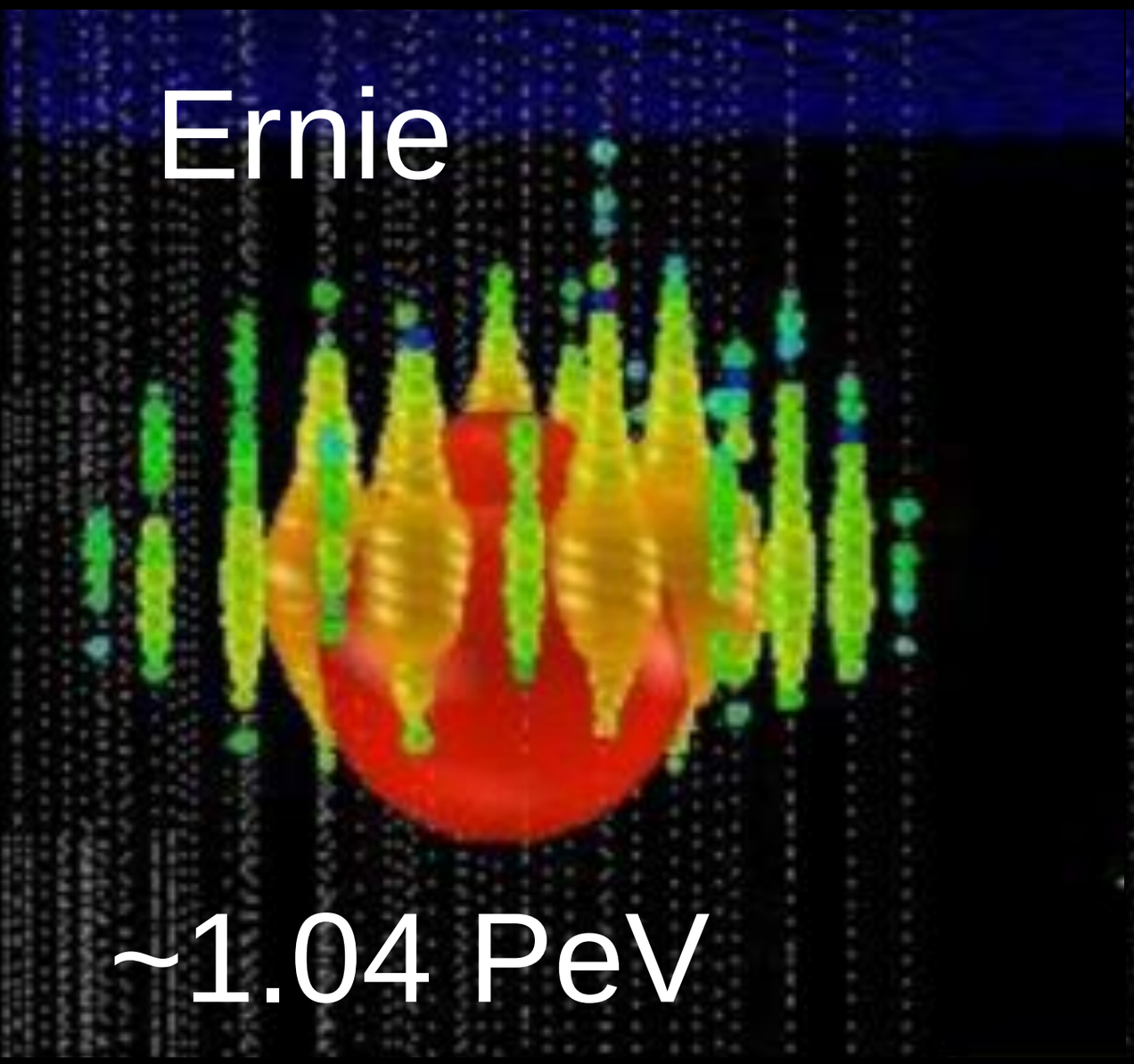


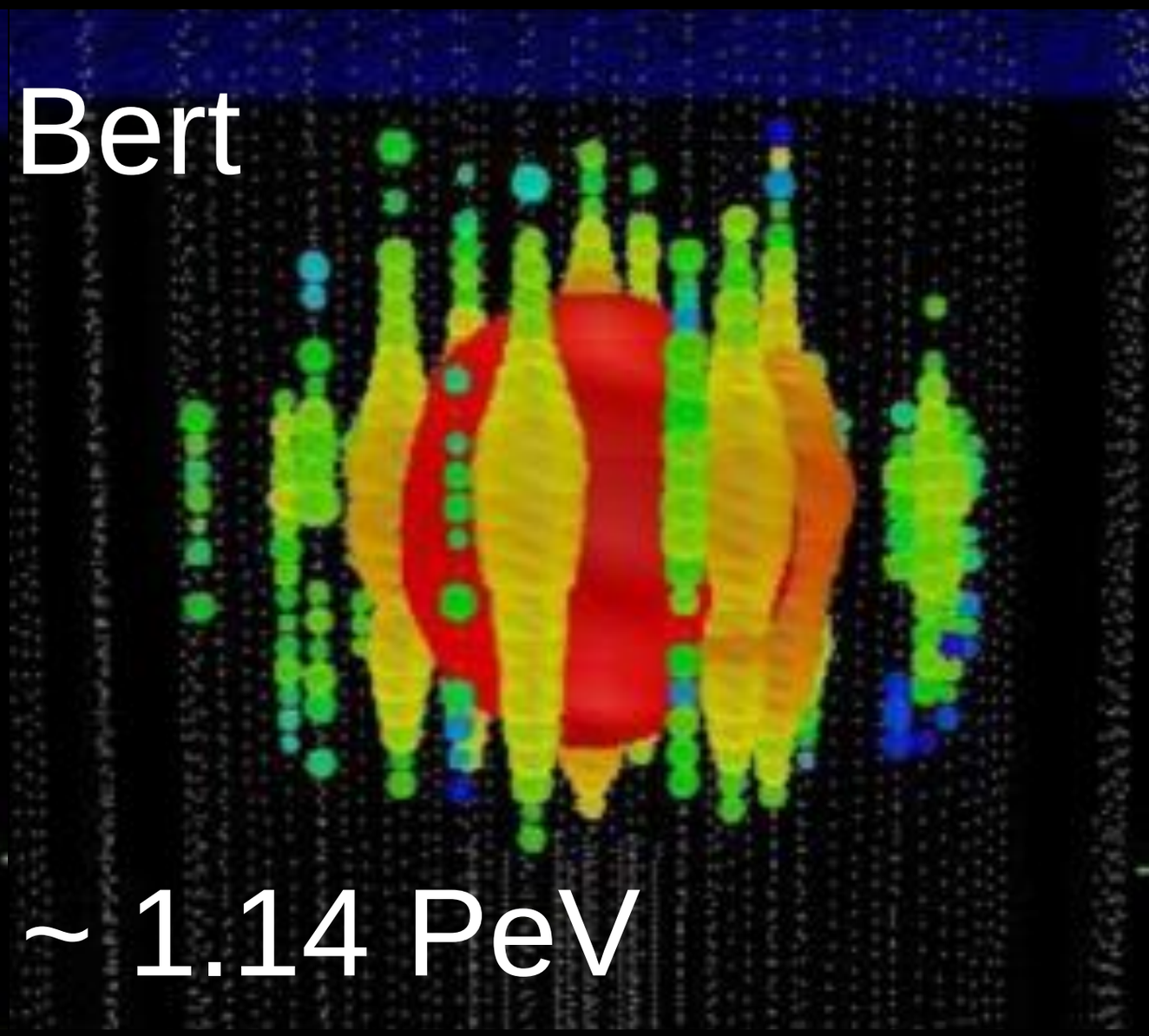
STUDY OF A DIFFUSE COSMIC NEUTRINO FLUX

Special search for neutrinos with E_ν > 500 TeV

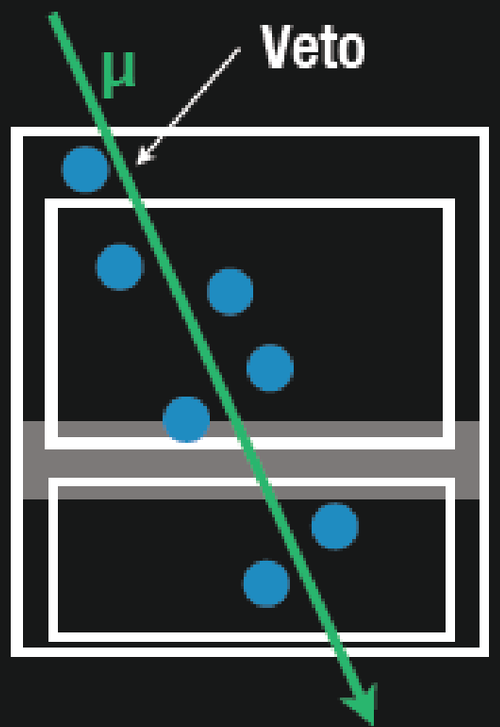
IC79/IC86

2.8 σ

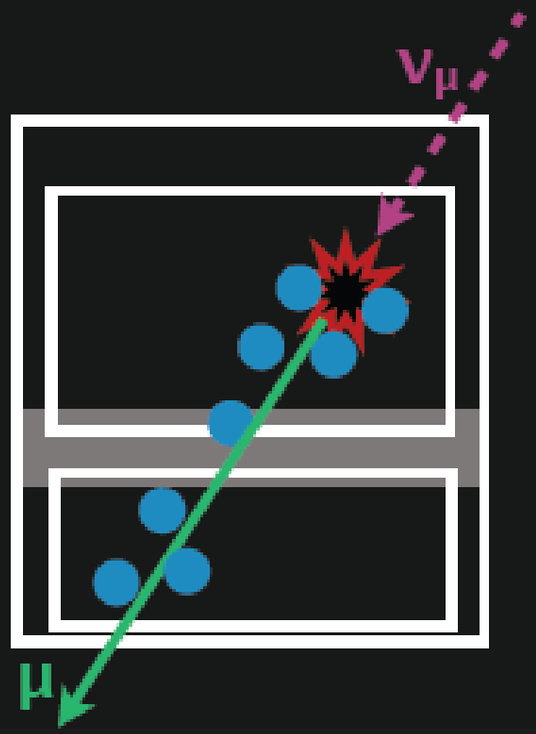




Follow-up Analysis: HESE (High Energy Starting Event)



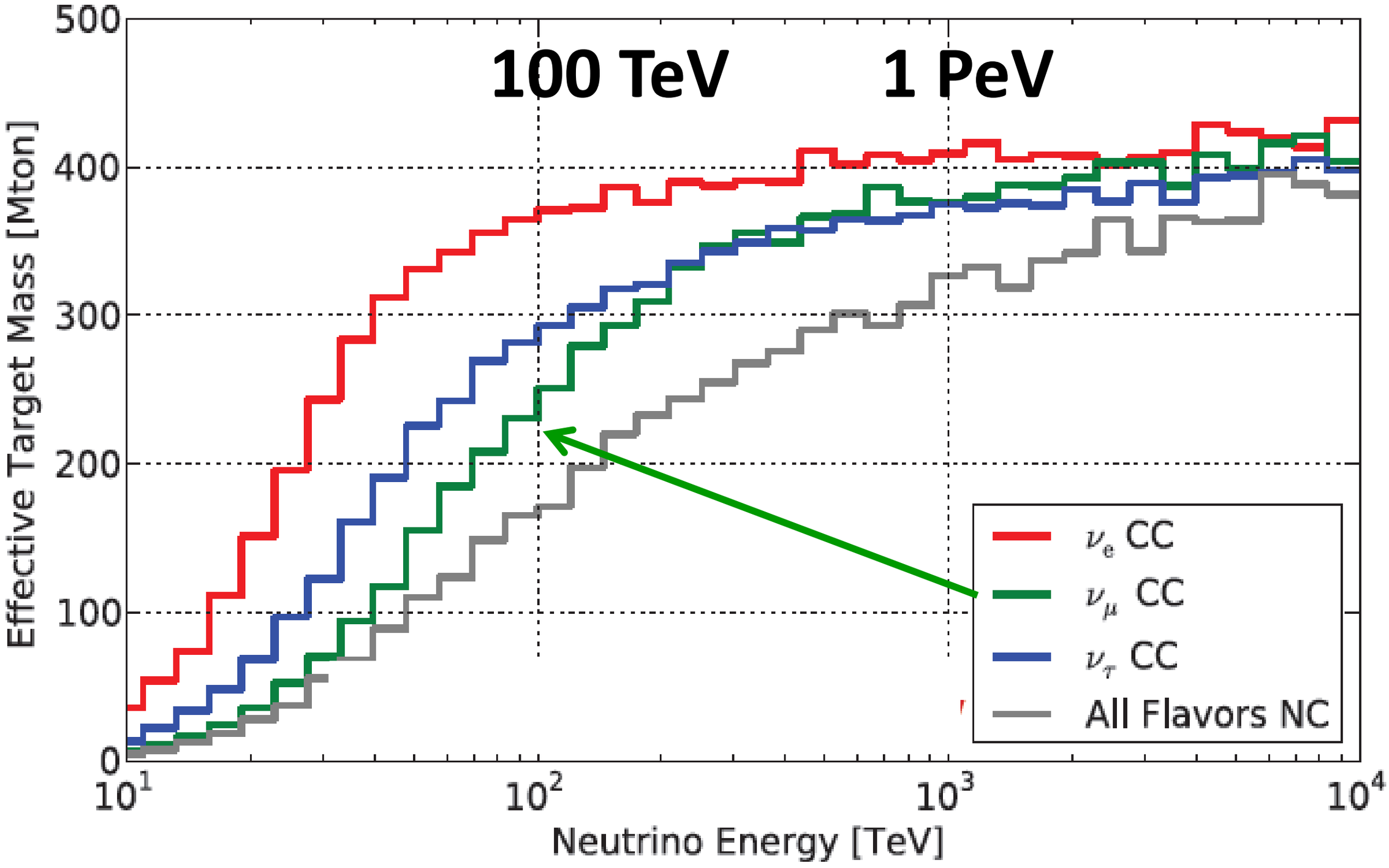
- Muon Veto
- Q_{tot} > 6000 photoelectrons



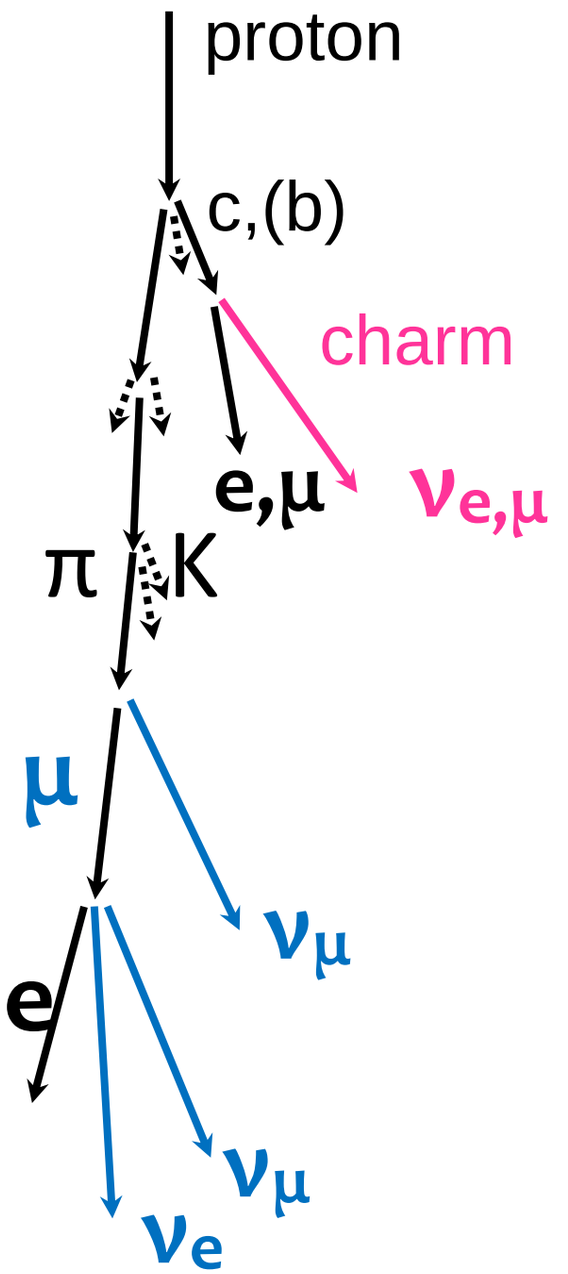
→ 400 Mton eff. Volume

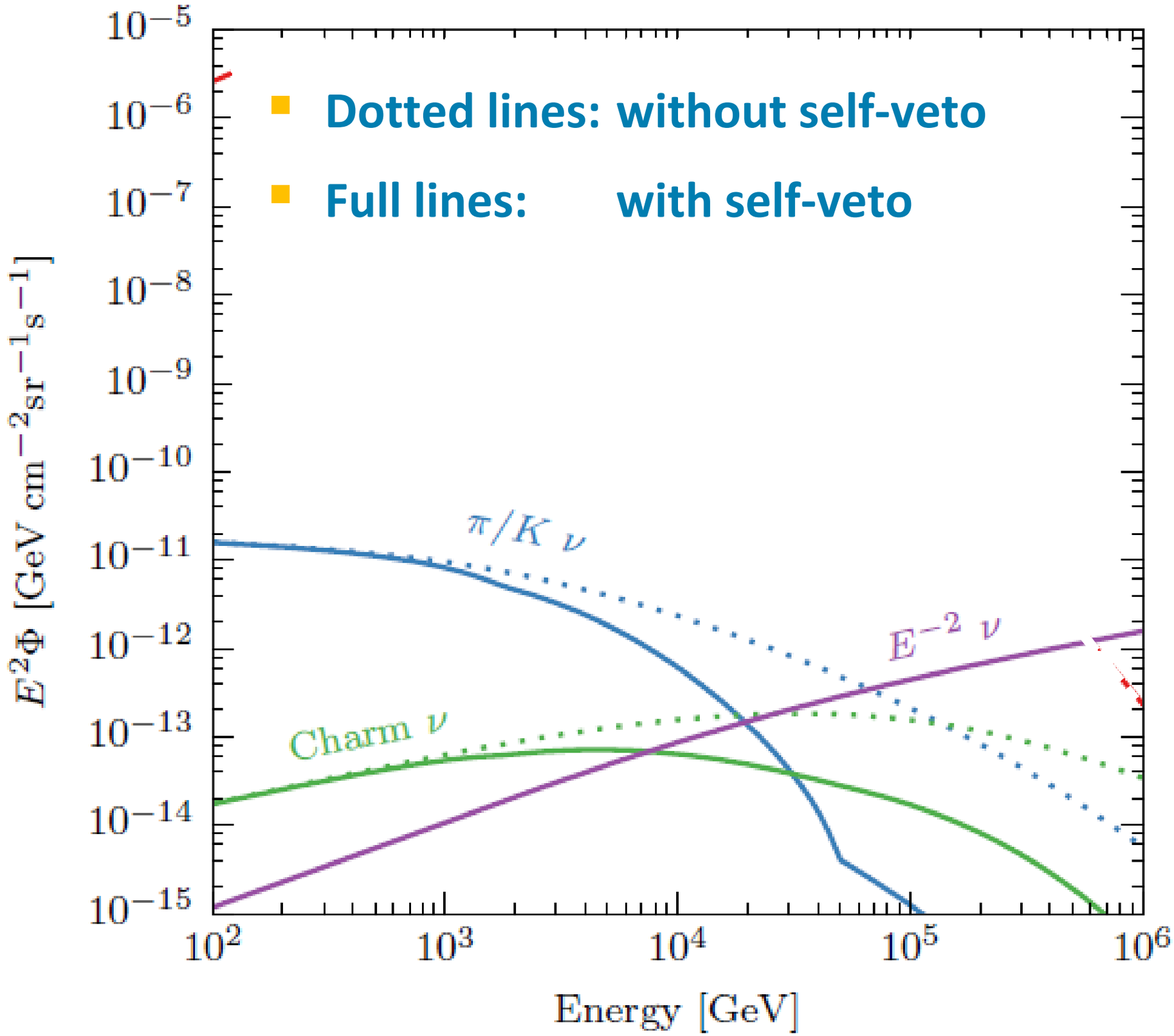
HESE analysis

- **Effective target mass for various interactions**

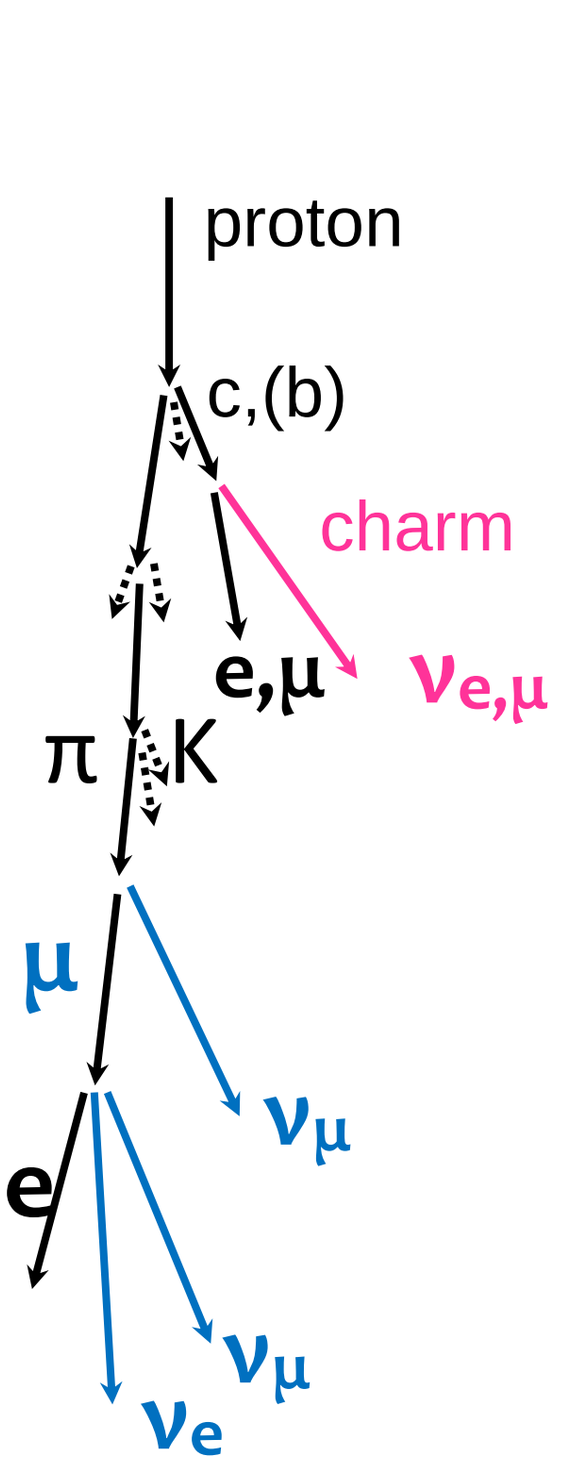


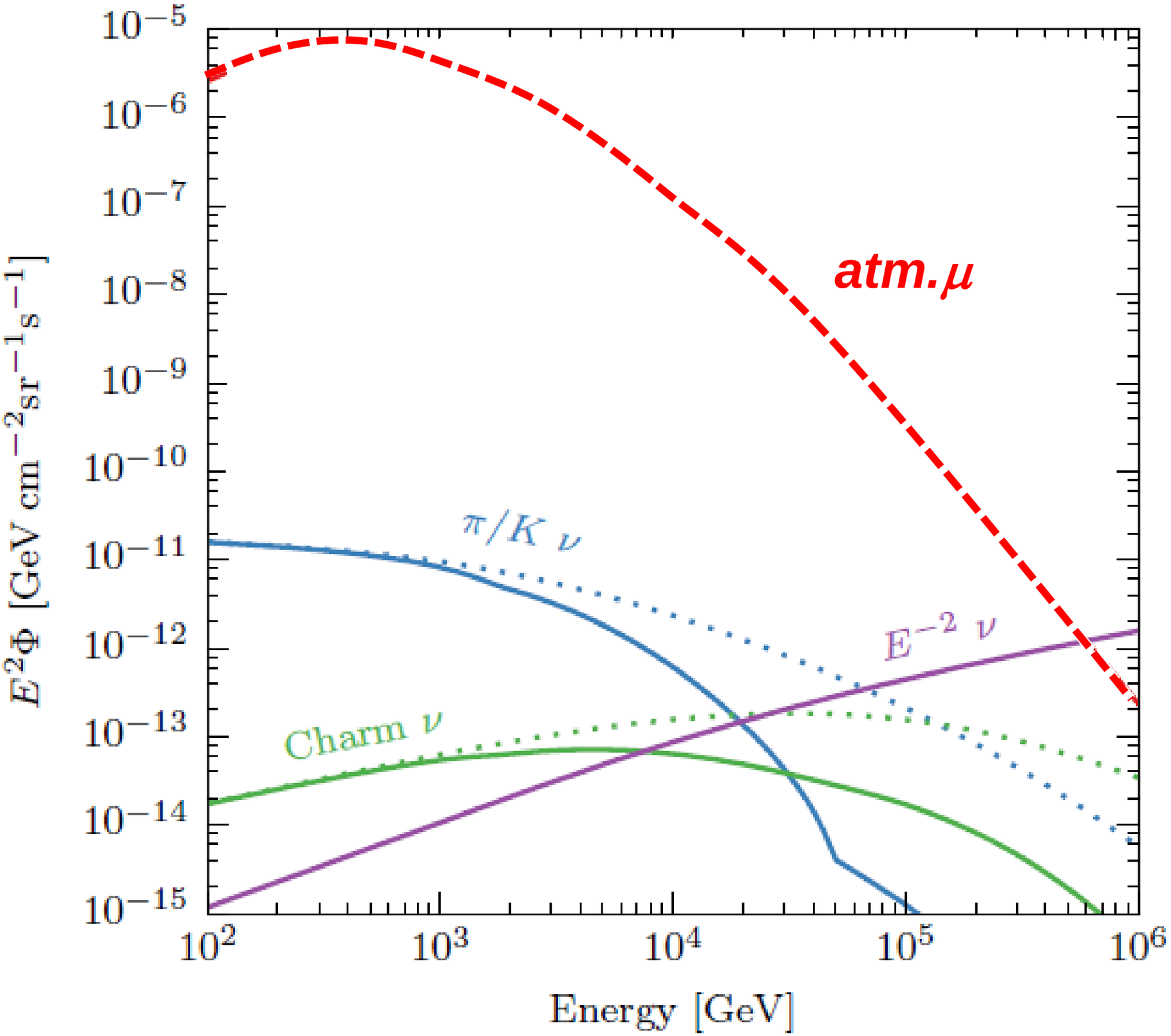
Rejection of atmospheric μ and ν by „selfveto“





Rejection of atmospheric μ and ν by „selfveto“



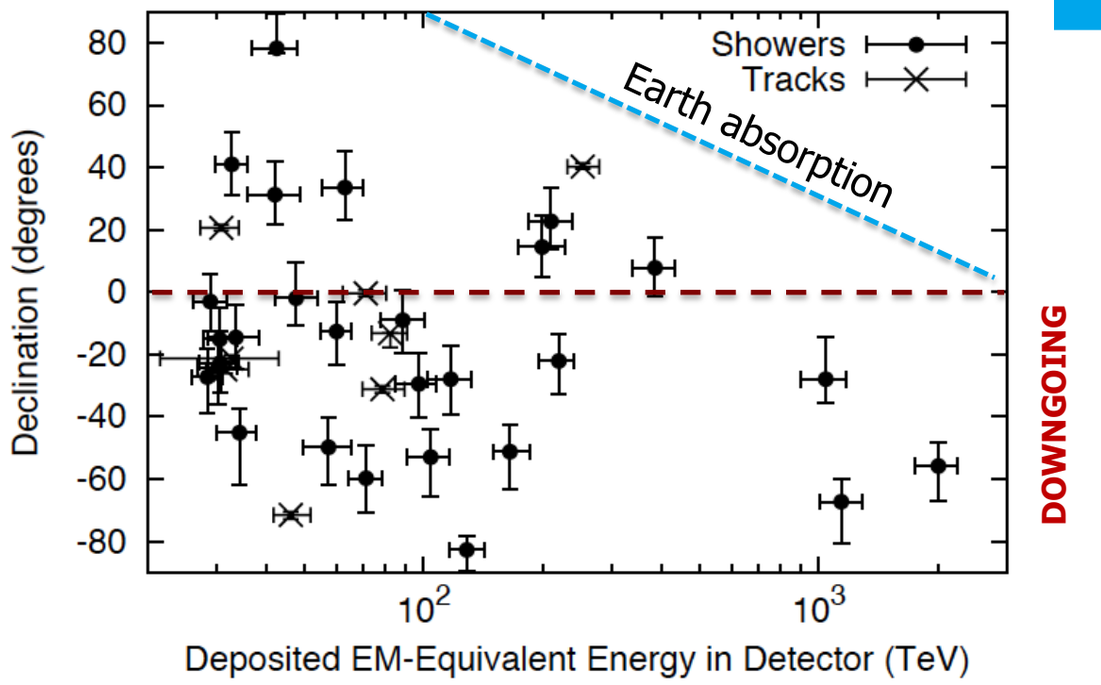


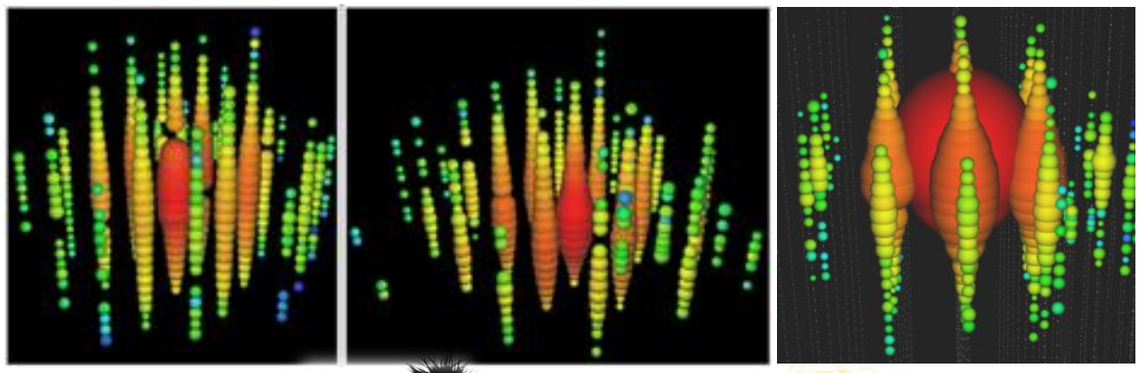
first evidence for an extra-terrestrial flux shown at IPA2013 [*IceCube, Science 342 (2013)*]

[*IceCube, Phys.Rev.Lett. 113:101101 (2014)*] **5.7σ**

- 3 yrs: 37 events in 988 days
- bkg. 8.4±4.2 atm. μ and 6.6+5.9 atm.ν

mostly ν_e CC and NC cascades



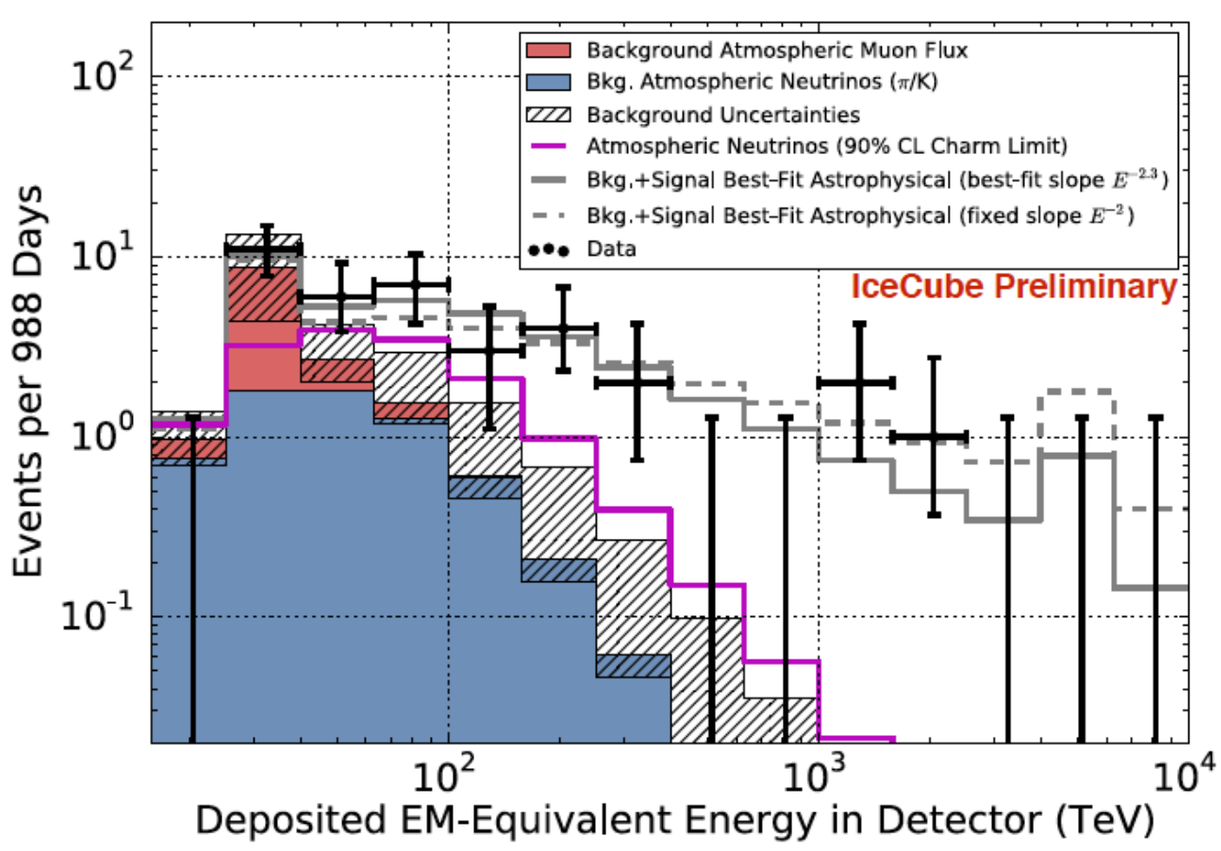


"Bert"
1.04 PeV
Aug. 2011

"Ernie"
1.14 PeV
Jan. 2012

"Big Bird"
2 PeV
Dec. 2012

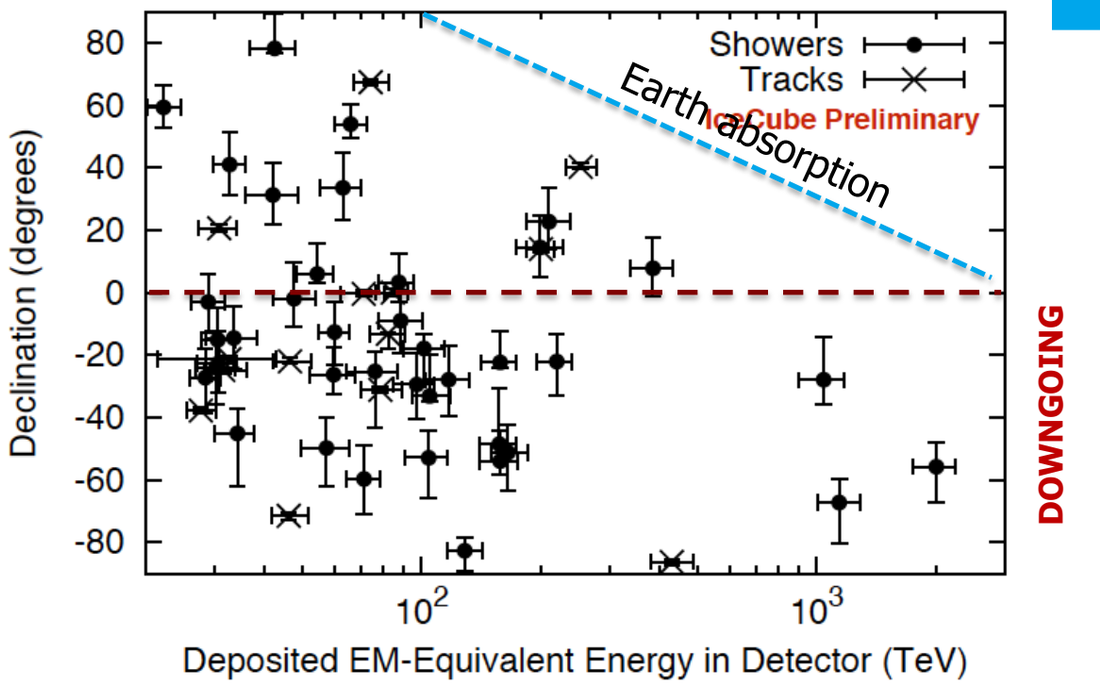
- zenith distrib. ~ isotropic astrophysical flux

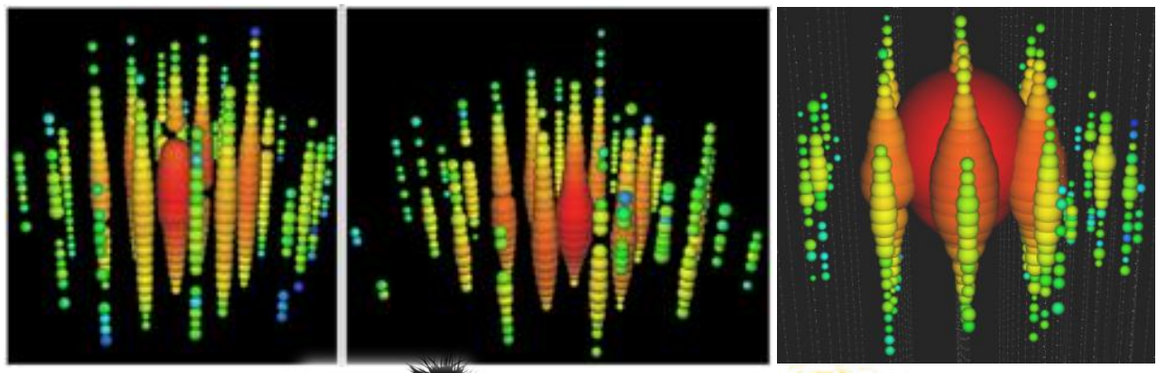


first evidence for an extra-terrestrial flux shown at IPA2013 [*IceCube, Science 342 (2013)*]

[*IceCube, Phys.Rev.Lett. 113:101101 (2014)*] **5.7σ**

- 3 yrs: 37 events in 988 days
- bkg. 8.4±4.2 atm. μ and 6.6+5.9 atm. ν
- **4 years: 54 events** **≈7σ**
  mostly ν_e CC and NC cascades



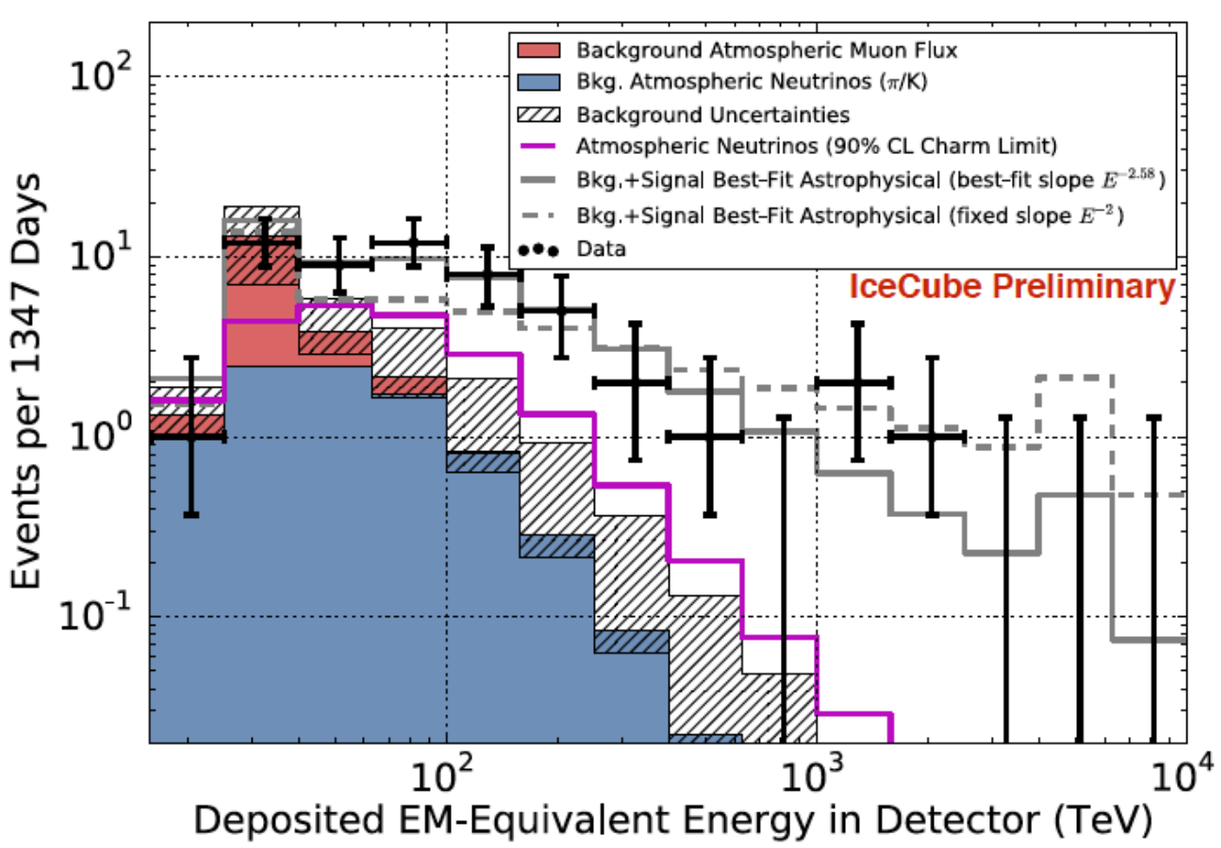


"Bert"
1.04 PeV
Aug. 2011

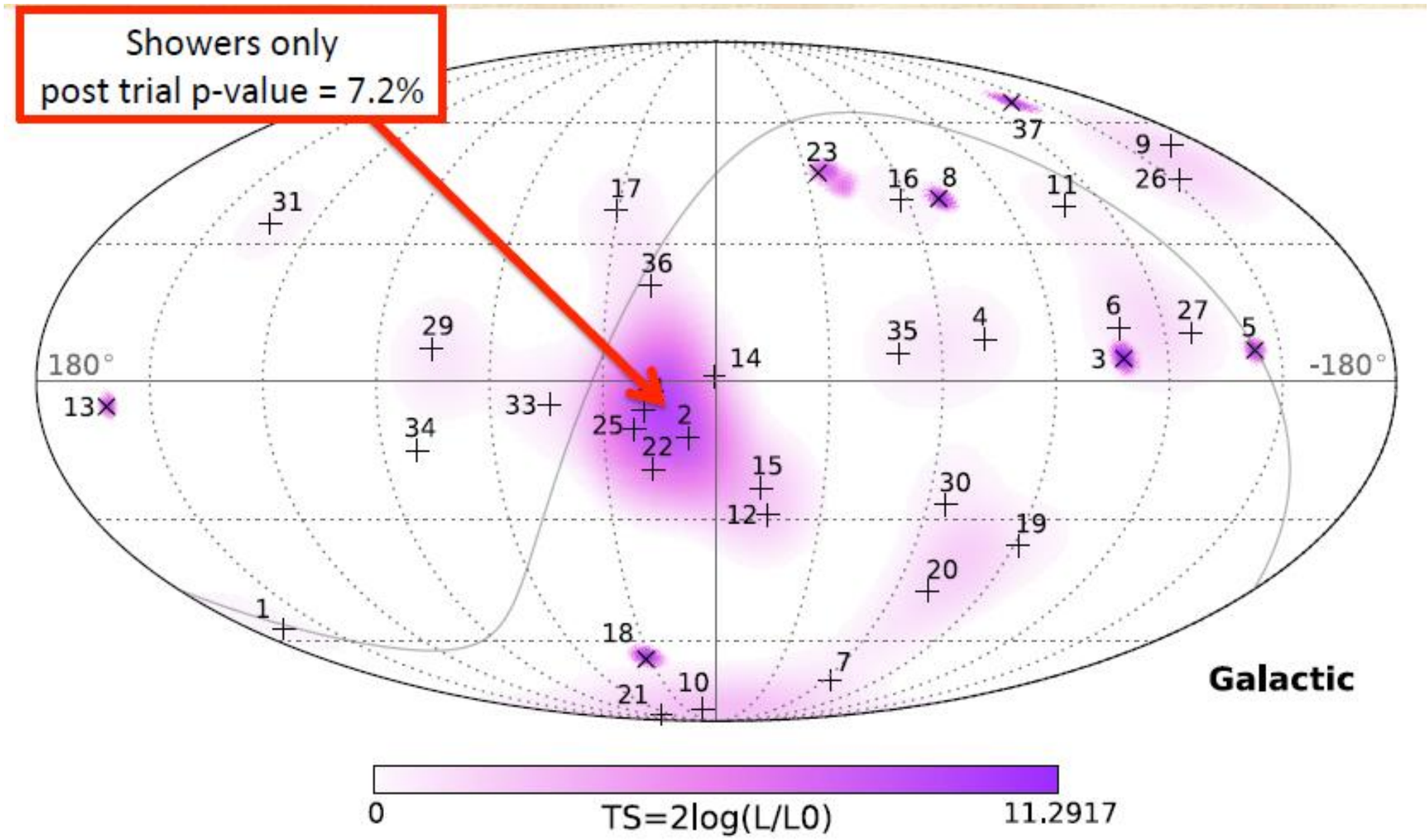
"Ernie"
1.14 PeV
Jan. 2012

"Big Bird"
2 PeV
Dec. 2012

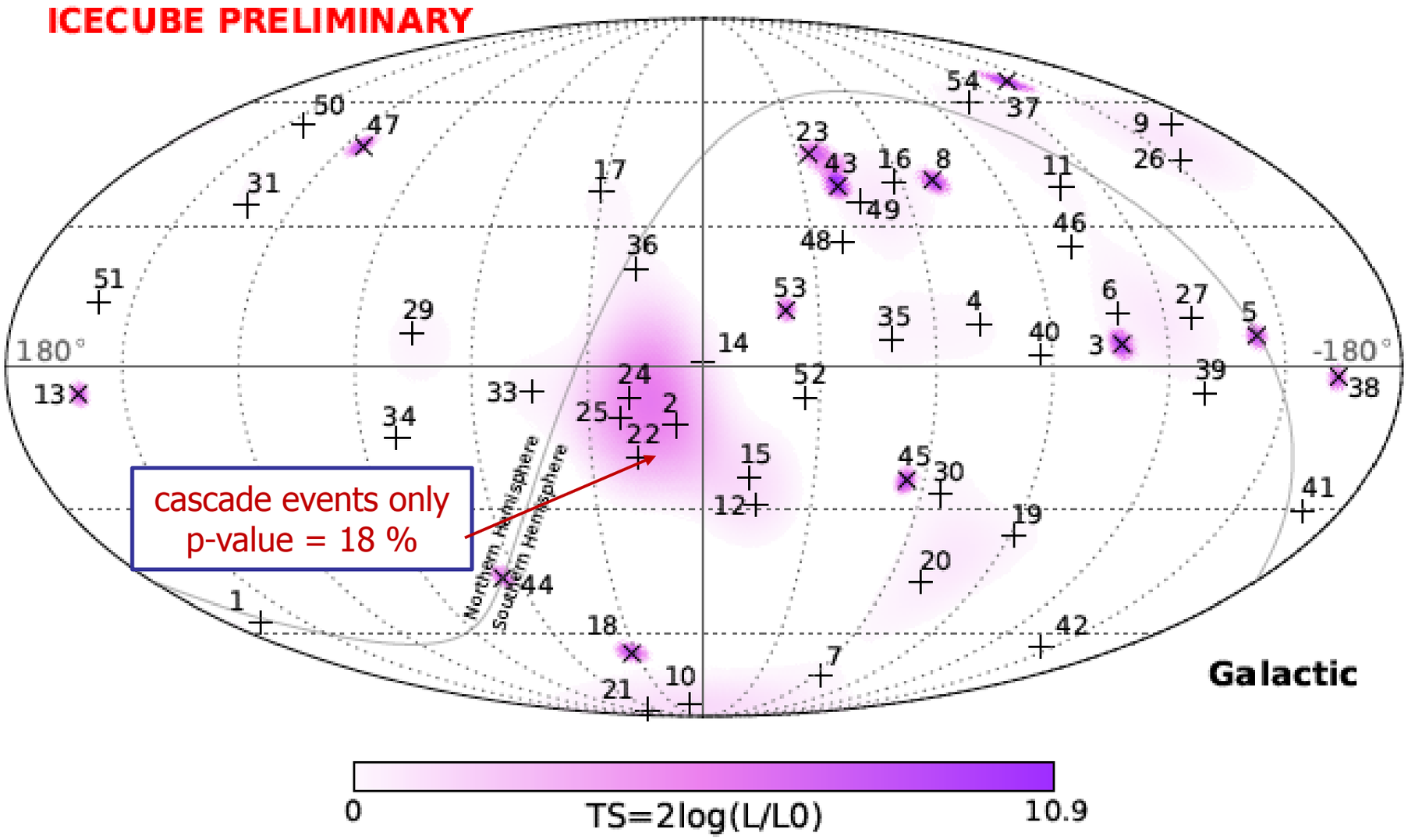
- zenith distrib. ~ isotropic astrophysical flux



HESE skyplot, 3 years



HESE skyplot 4 years



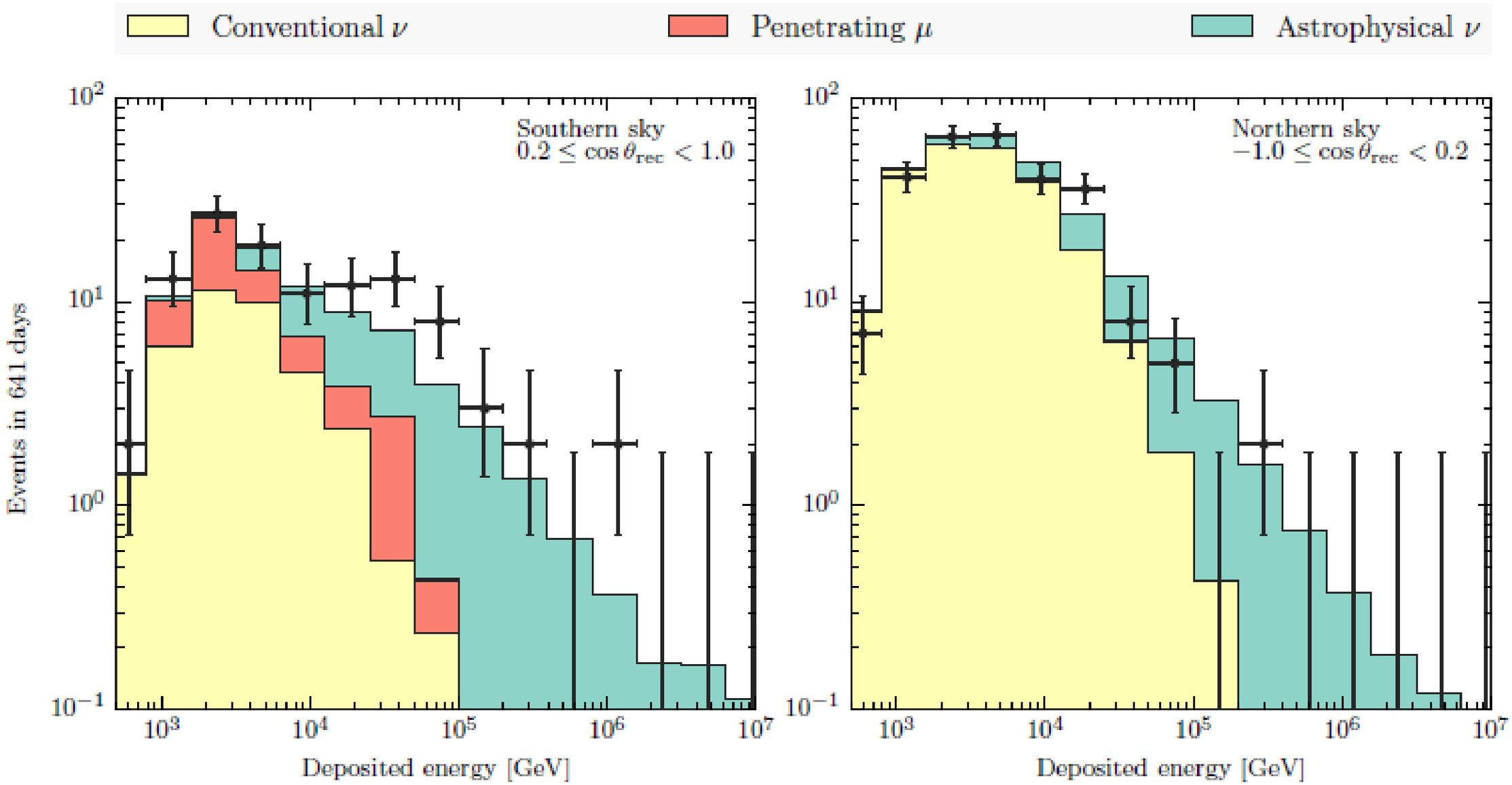
- Significance of the warm spot has decreased (p-value from 7% to 18%)
- No significant correlation to know sources, neither spatial nor temporal
- Need more events to irdentify sources

MESE (Medium Energy Starting Events)

- **Reduce threshold by further cuts down to ~ 1 TeV**

Atmospheric and Astrophysical Neutrinos above 1 TeV Interacting in IceCube

- arXiv:1410.1749



Throughgoing muons, IC-79/86

Highest energy event

0.5 PeV muon

~1 PeV neutrino

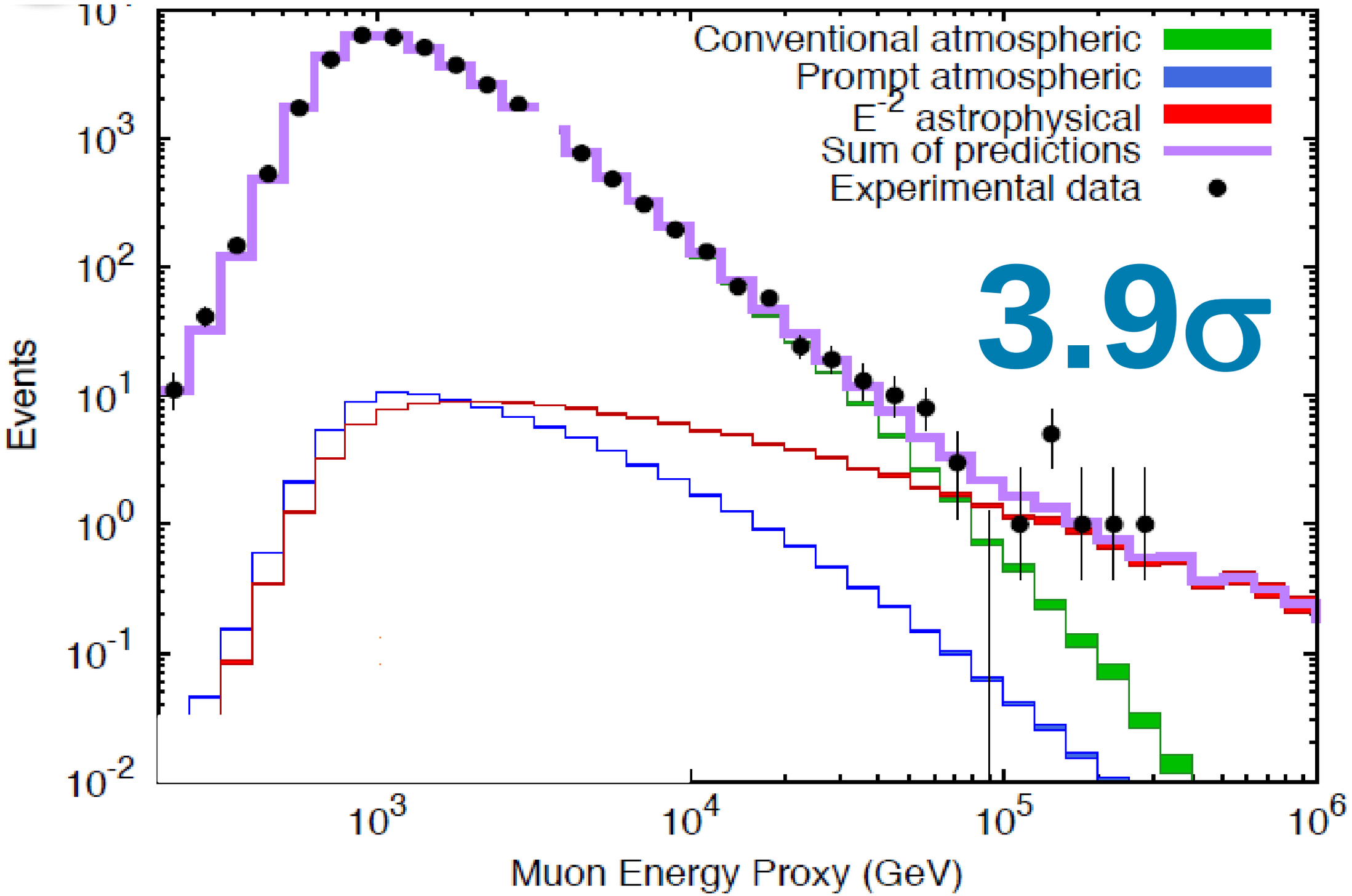
Also found in HESE

Examples of muons found in IC79/86 upgoing diffuse analysis

More muons, IC-79/86

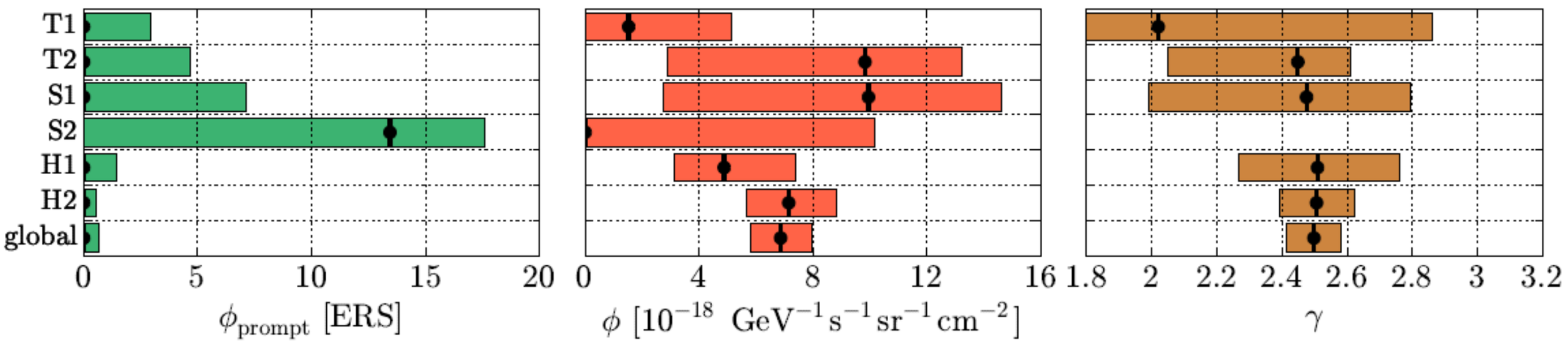
Hi

Through-going muons, IC-79/86



Putting (all) together: Global fit

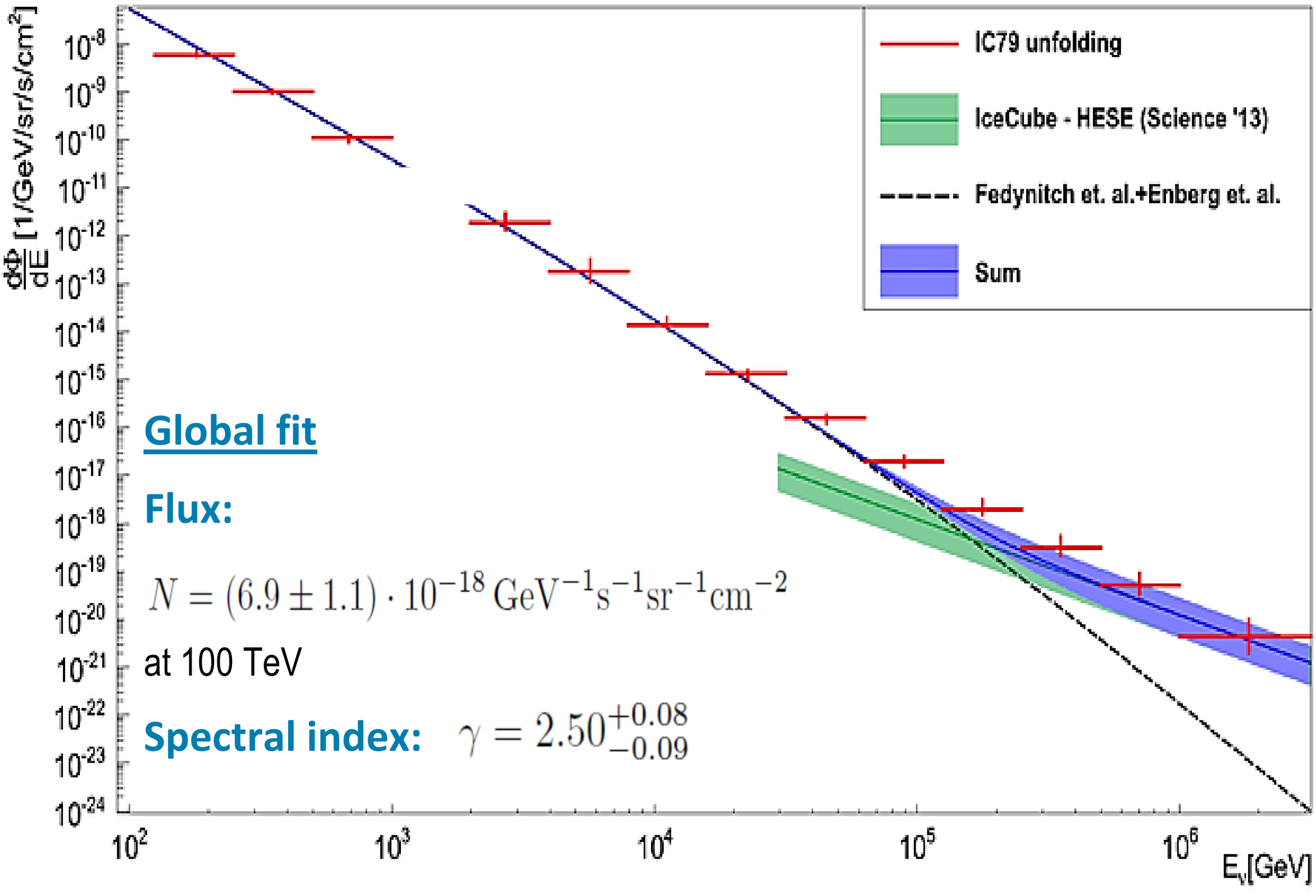
ID	Topology	Containment	Energy range (TeV)	Zenith range (deg)	Data taking period	Observables
T1	tracks	no	> 100	$90 - 180$	2009-2010	energy, zenith
T2	tracks	no	> 100	$85 - 180$	2010-2012	energy, zenith
S1	showers	yes	> 100	$0 - 180$	2008-2009	energy
S2	showers	yes	> 10	$0 - 180$	2009-2010	energy
H1	showers, tracks	yes	> 50	$0 - 180$	2010-2013	energy, zenith
H2	showers, tracks	yes	> 1	$0 - 180$	2010-2012	energy, zenith, topology



T1 = tracks (IC59) T2 = tracks (IC79), S1 = showers (IC40), S2 = showers (IC59)

H1 = HESE (IC79/86/86) H2 = MESE (IC79/86)

Putting all together



Global fit

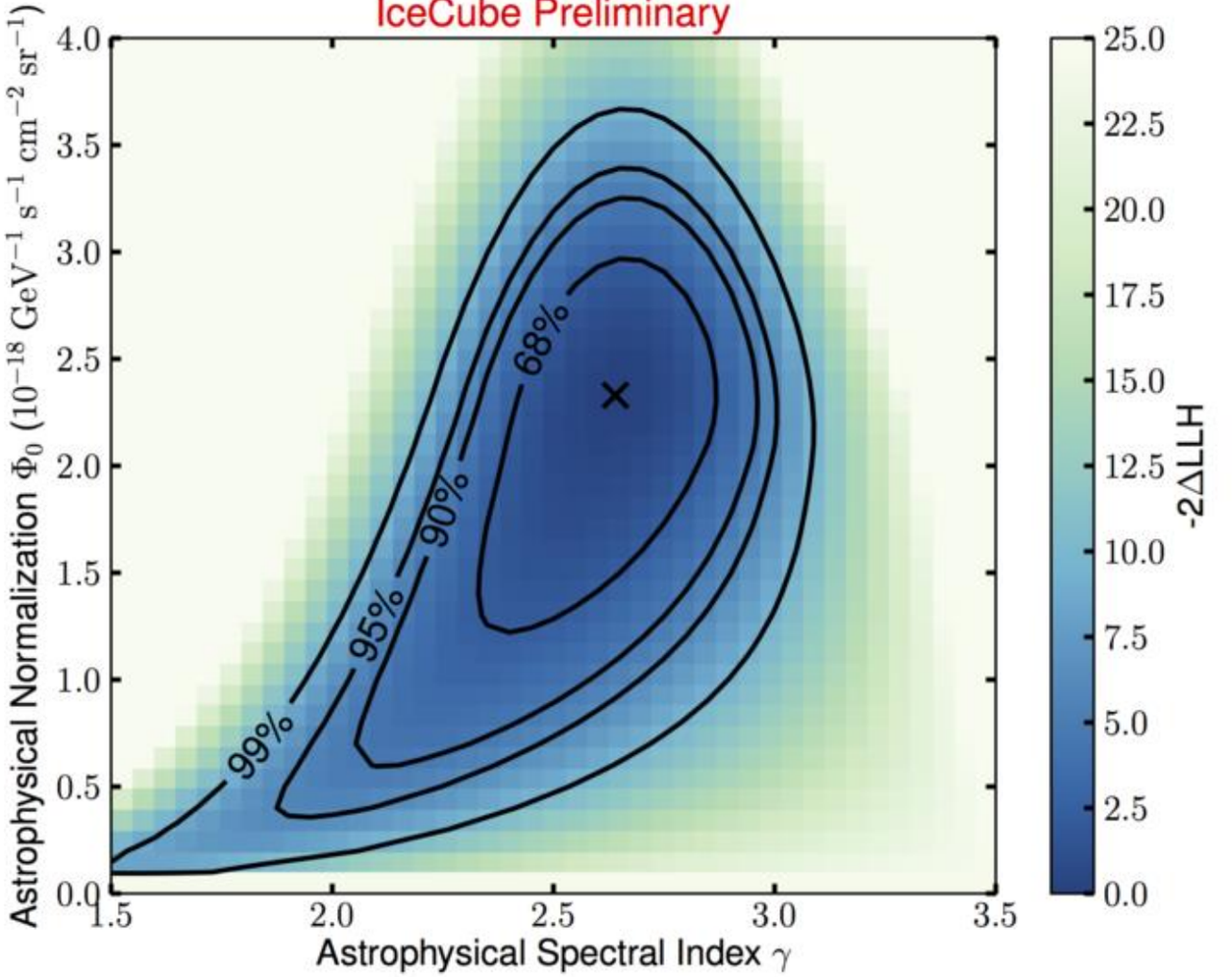
Flux:

$$N = (6.9 \pm 1.1) \cdot 10^{-18}\,\mathrm{GeV}^{-1}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{cm}^{-2}$$

at 100 TeV

Spectral index: $\gamma = 2.50^{+0.08}_{-0.09}$

Putting all together



Global fit

Flux:

$$N = (6.9 \pm 1.1) \cdot 10^{-18}\,\mathrm{GeV}^{-1}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{cm}^{-2}$$

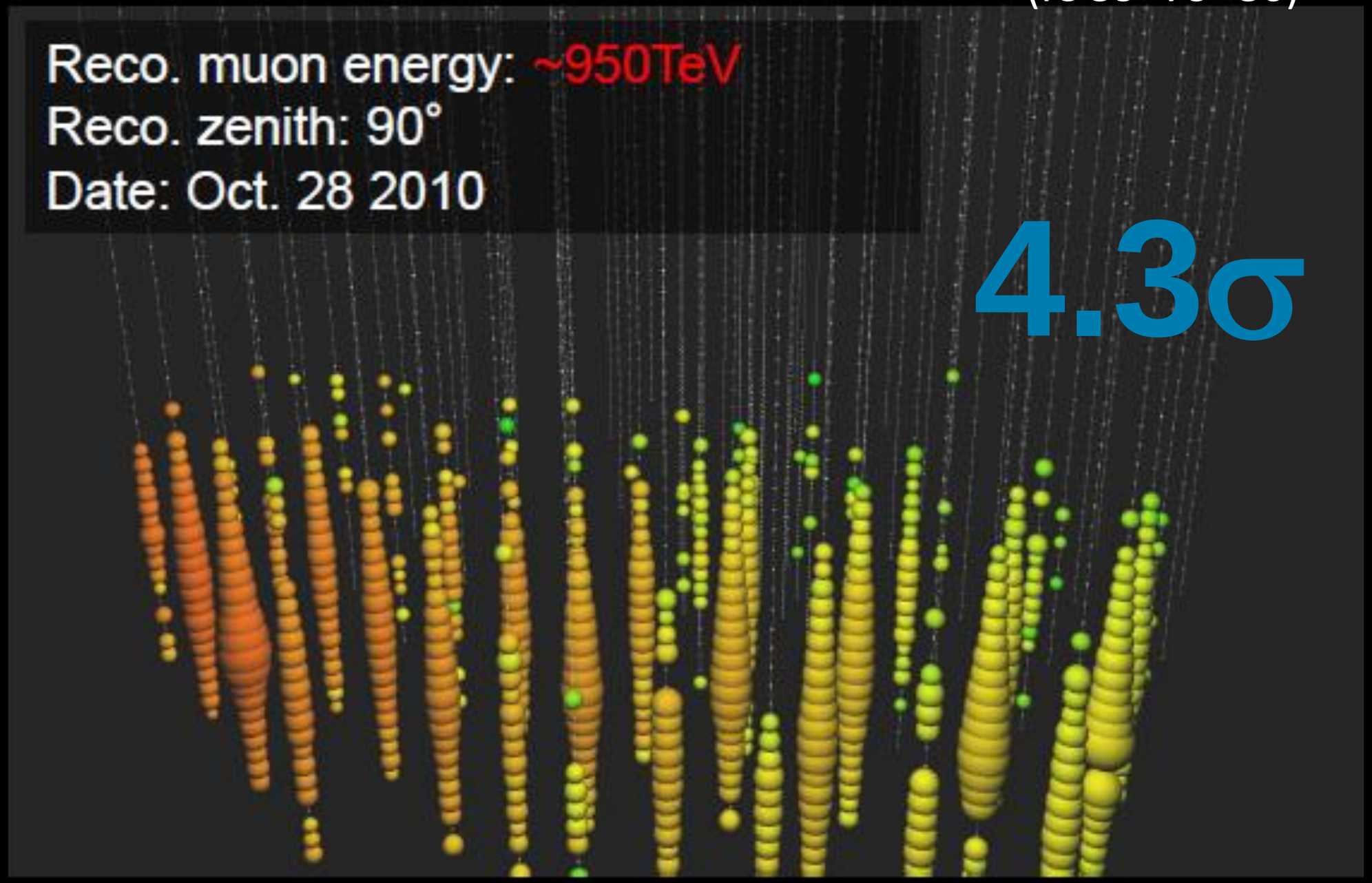
at 100 TeV

Spectral index: $\gamma = 2.50^{+0.08}_{-0.09}$

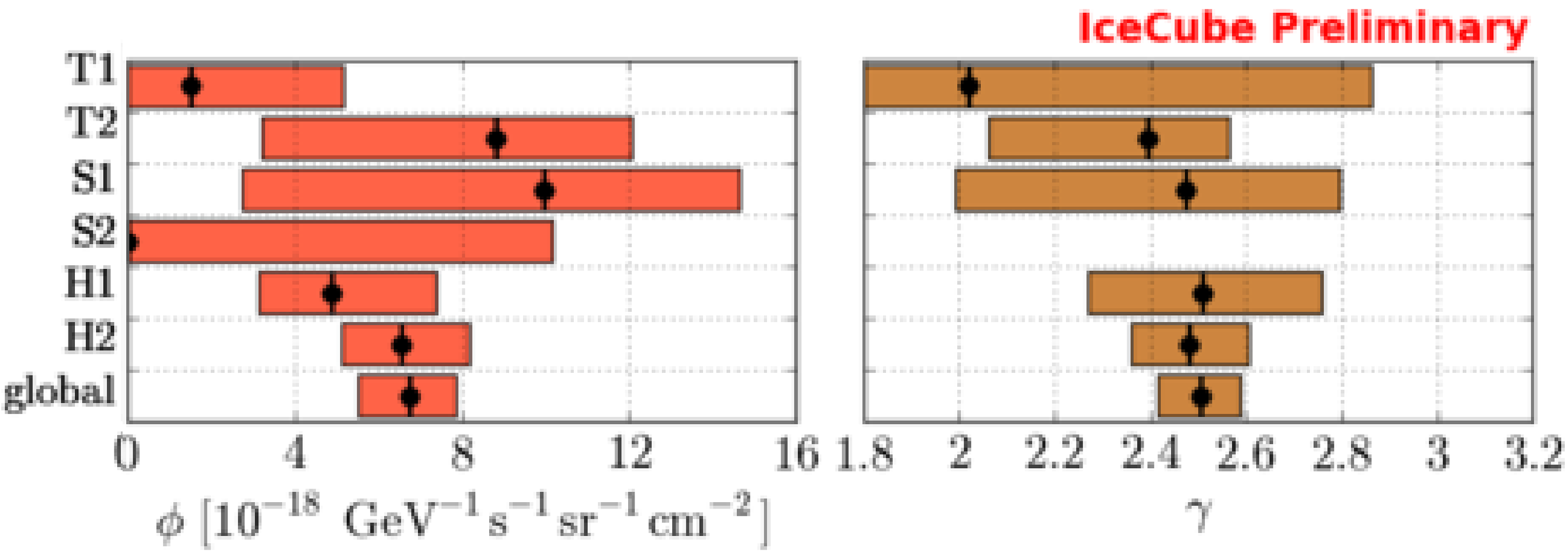
New: 3 years through-going muons

The highest energy muon in 2009-12

(IC 59+79+86)

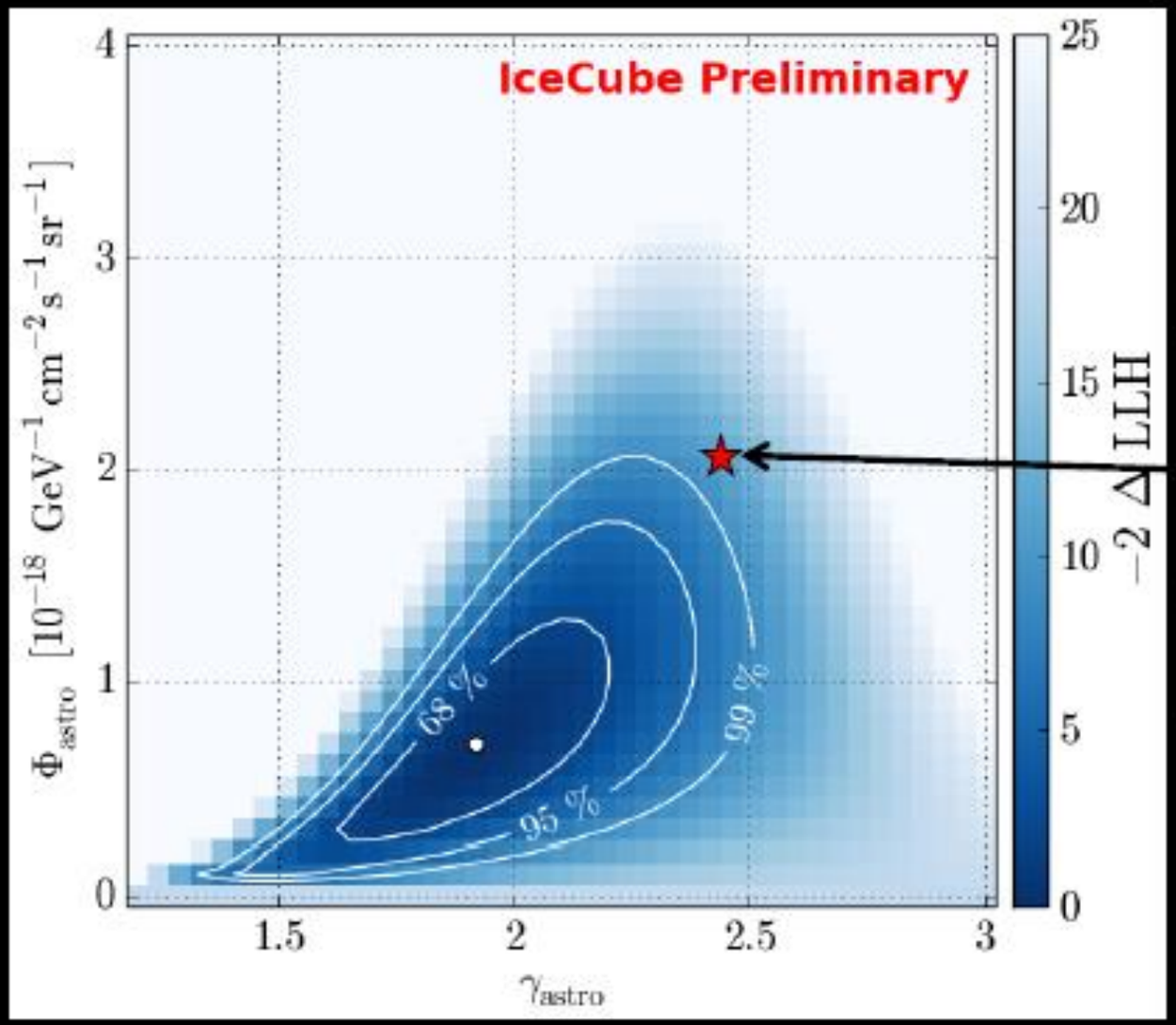


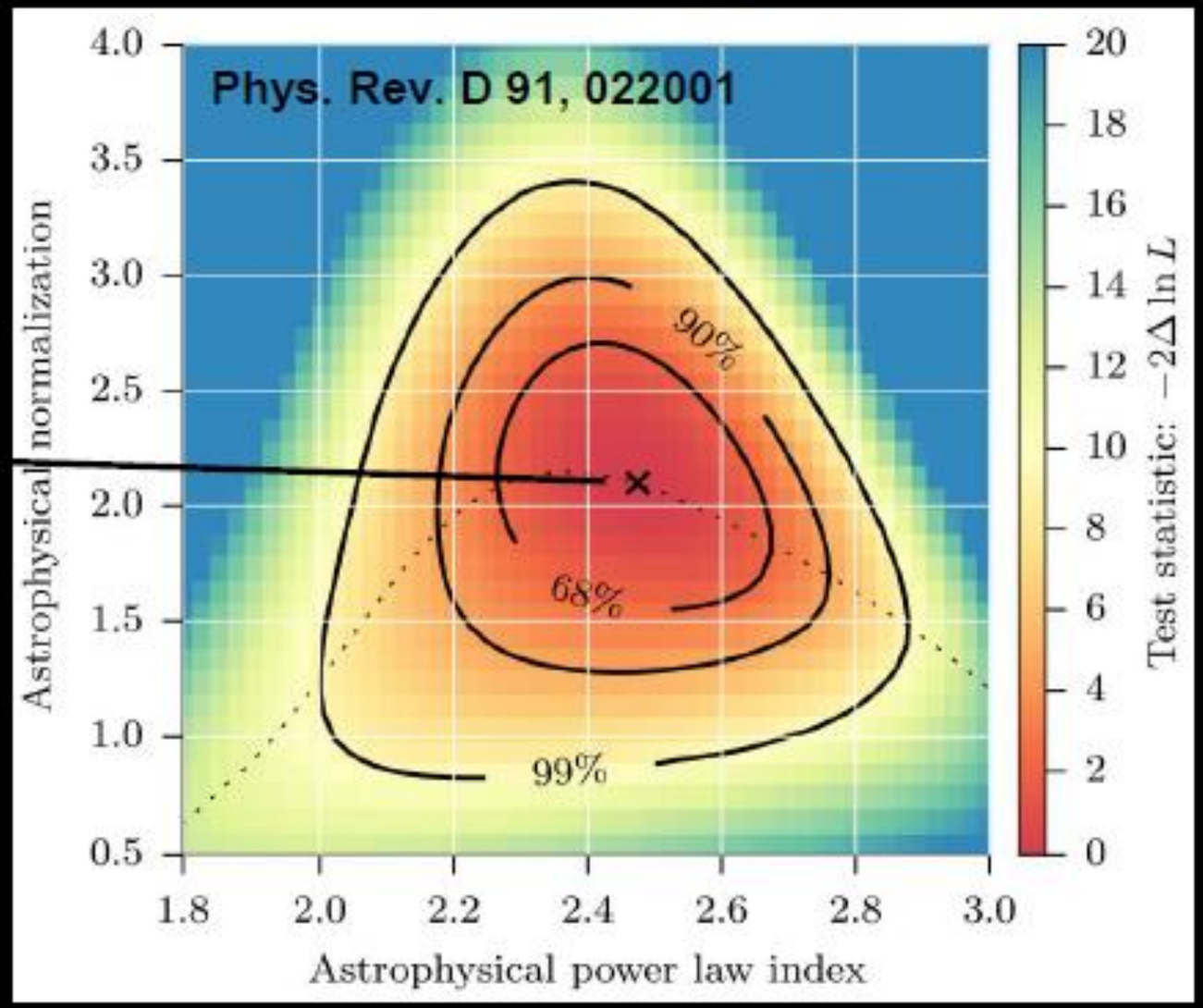
Putting *all* together



T3

Comparison to analysis dominated by shower-like events



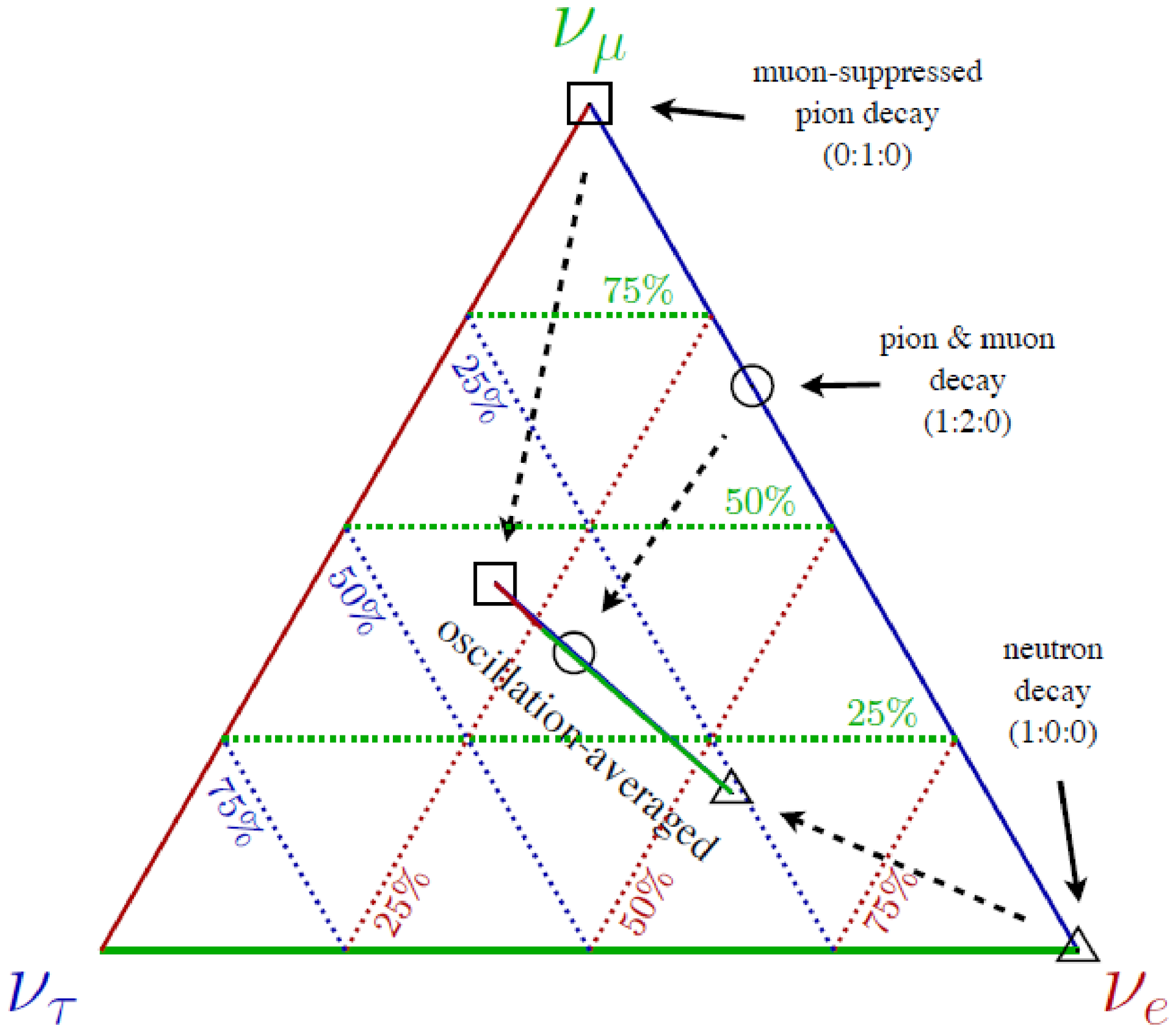


- Right: IceCube result reported in Phys. Rev. D 91, 022001

CCμ 3 years

HESE

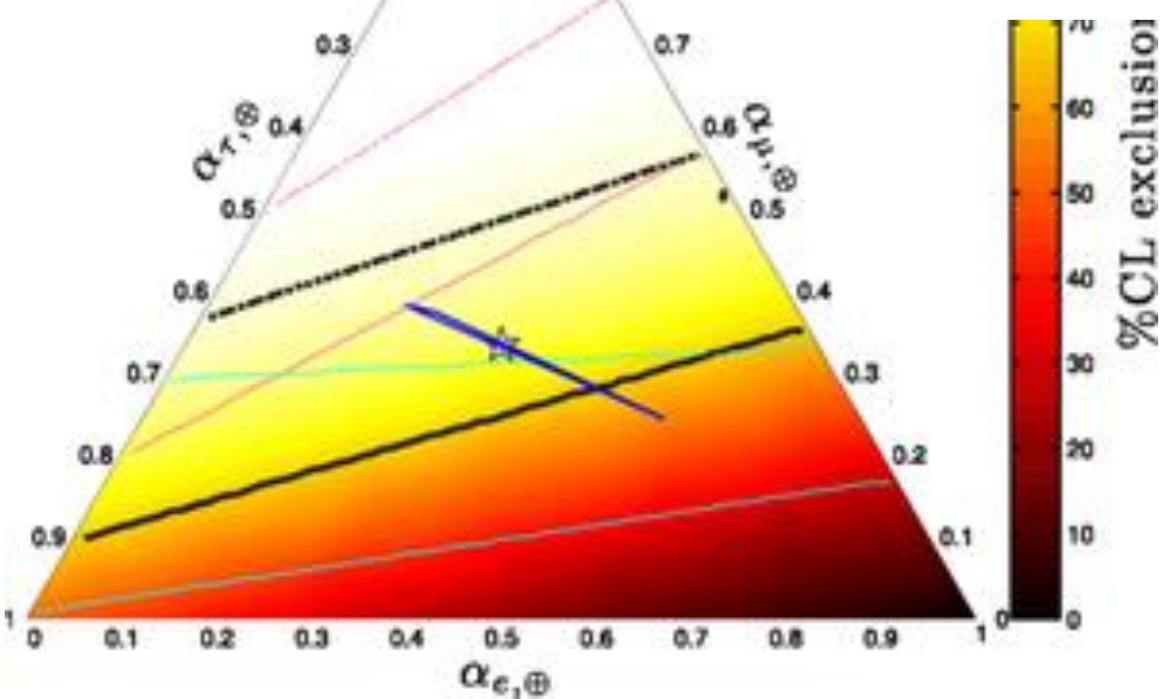
Flavor composition

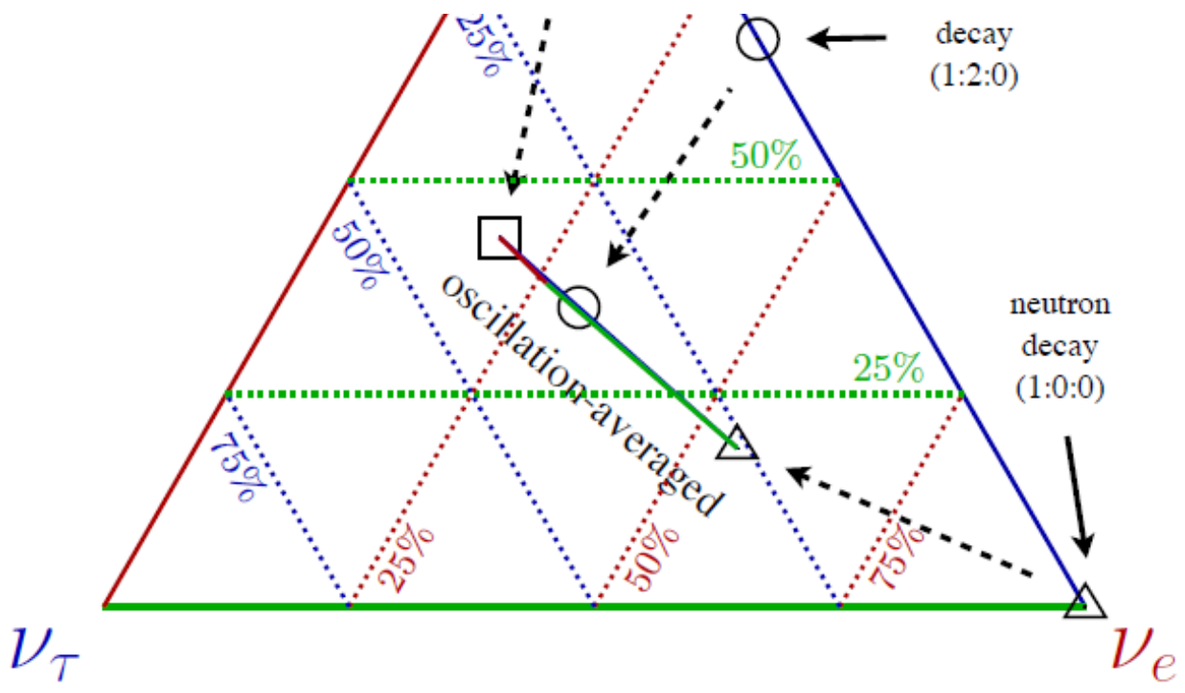


Flavor composition: a complicated issue

- **O. Mena, S. Palomares-Ruiz, A. Vincent, Composition of the High-Energy Neutrino Events in IceCube Phys. Rev. Lett. 113 (2014) 091103**

The IceCube experiment has recently released 3 years of data of the first ever detected high-energy ($\gtrsim$ 30 TeV) neutrinos, which are consistent with an extraterrestrial origin. In this talk, we compute the compatibility of the observed track-to-shower ratio with possible combinations of neutrino flavors with relative proportion $(\alpha_e : \alpha_\mu : \alpha_\tau)_\oplus$. Although this observation is naively favored for the canonical $(1 : 1 : 1)_\oplus$ at Earth, once we consider the IceCube expectations for the atmospheric muon and neutrino backgrounds, this flavor combination presents some tension with data. We find that, for an astrophysical neutrino E_ν^{-2} energy spectrum, $(1 : 1 : 1)_\oplus$ at Earth is currently disfavored at 92% C.L. We discuss the trend of this result by comparing the results with the 2-year and 3-year data. We obtain the best-fit for $(1 : 0 : 0)_\oplus$ at Earth, which cannot be achieved from any flavor ratio at sources with averaged oscillations during propagation. Although it is not statistically significant at present, if confirmed, this result would suggest either a misunderstanding of the expected background events, or a misidentification of tracks as showers, or even more compellingly, some exotic physics which deviates from the standard scenario.

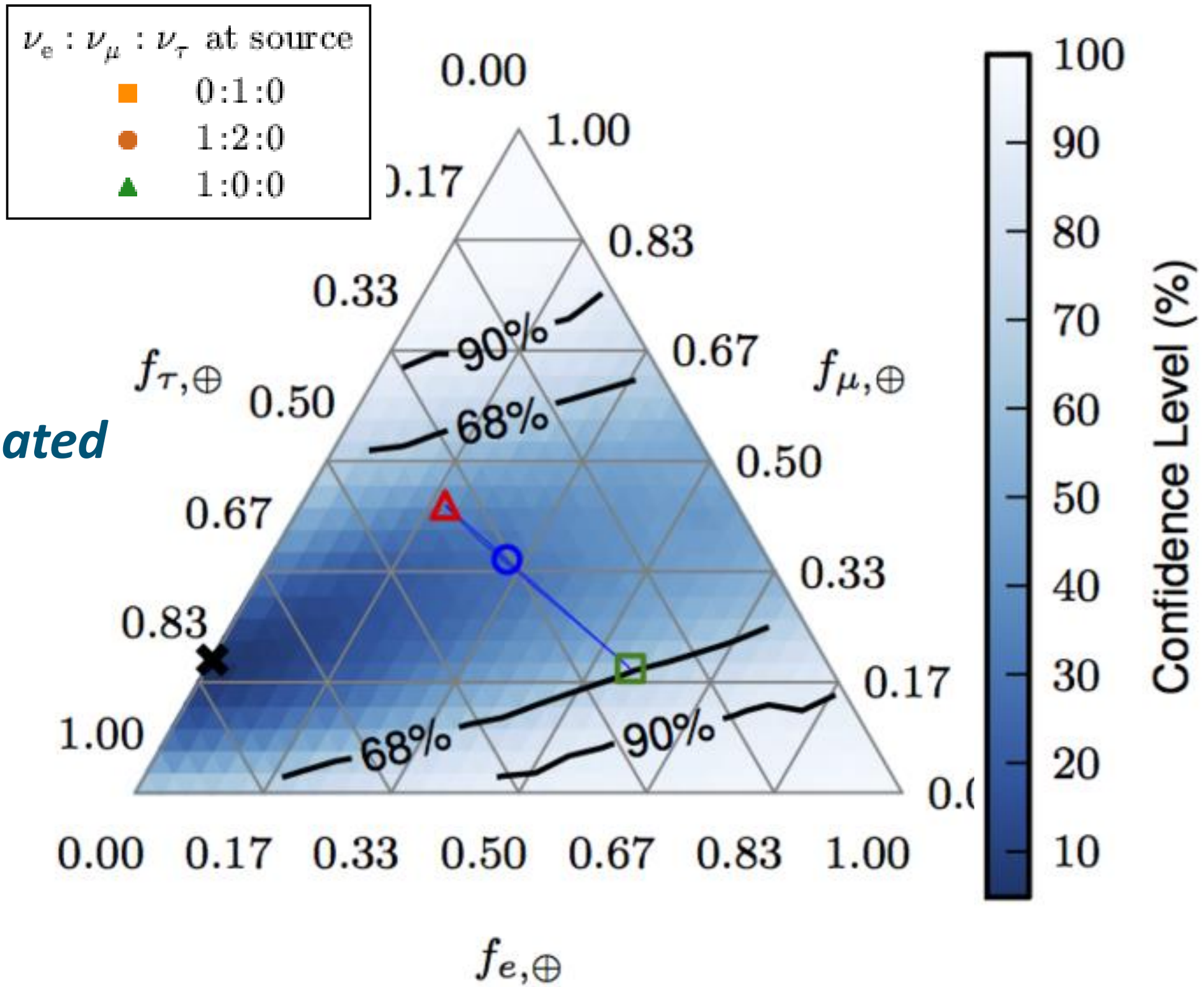




Flavor composition: own IceCube analyses

1)

cascade-dominated sample

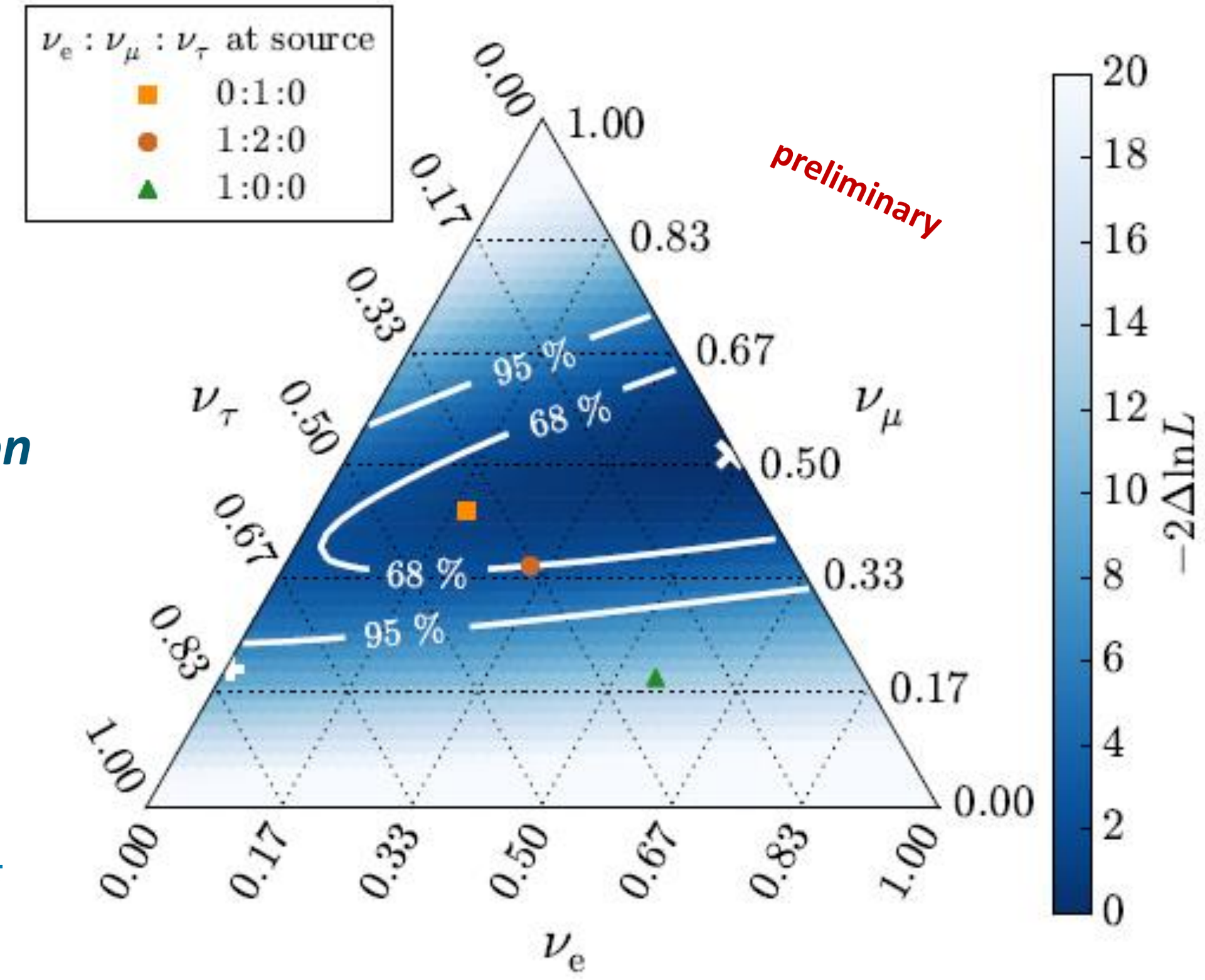


Flavor composition: own IceCube analyses

2)

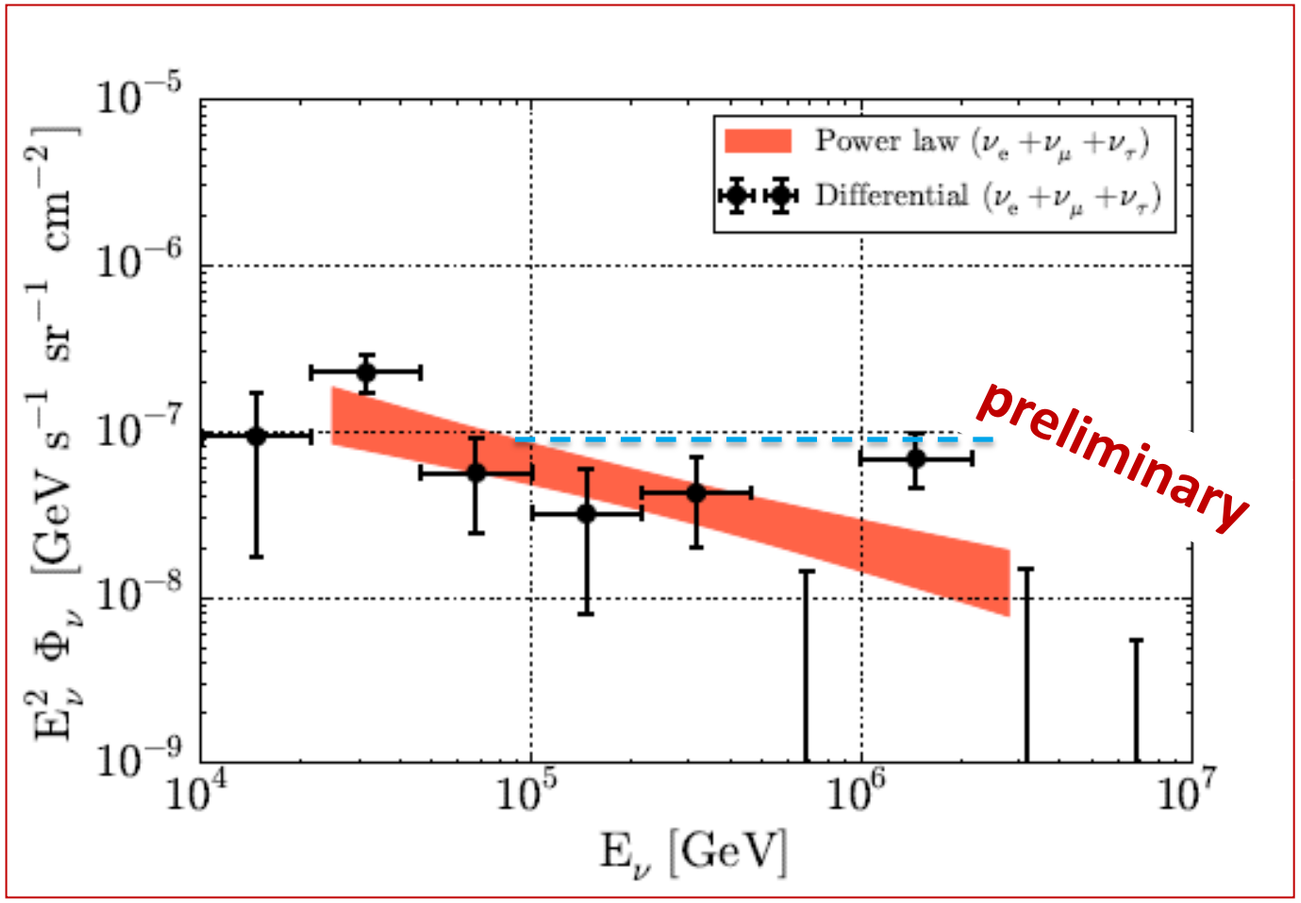
Including muon Sample („global fit“)

the best fit flavor composition
disfavors 1:0:0
at source at 3.6 σ



…and once more the spectrum

- 6 different data samples based on data from 2008 – 2012
- different strategies to suppress the atm. muon background
- Large samples of track-like and cascade-like events



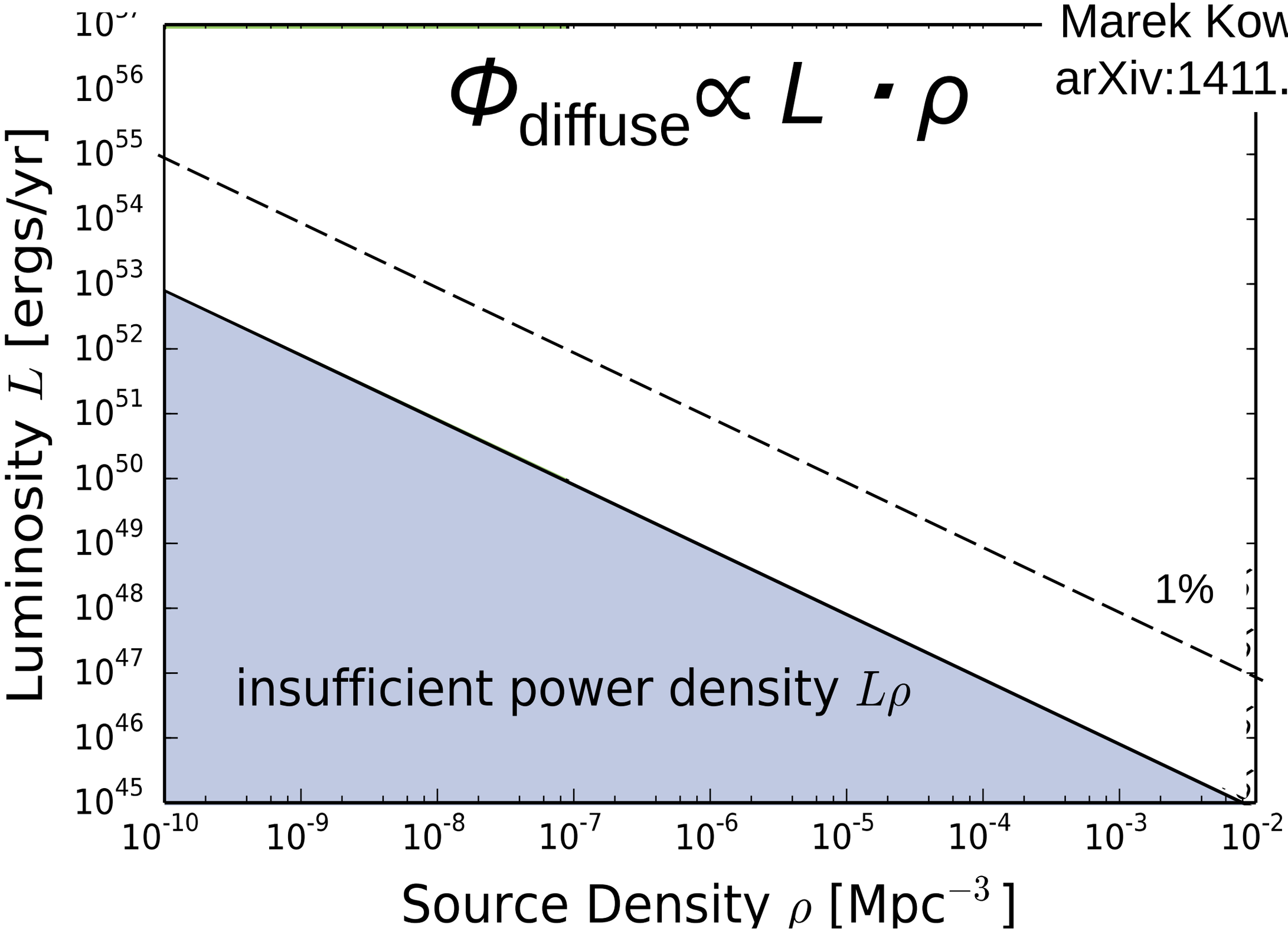
- assume isotropic astrophysical flux and $\nu_e : \nu_\mu : \nu_\tau$ = 1:1:1 at Earth **, then**
  - ***can fit with unbroken power-law between 25 TeV and 2.8 PeV***
  - ***spectral index -2.5 ± 0.09 (-2.0 disfavoured at 3.8σ)***
  - ***flux at 100 TeV $(6.7 \pm 1.2) \times 10^{-18}$ (GeV $\cdot$ cm^2 $\cdot$ s $\cdot$ sr)$^{-1}$***

REMAINING SOURCE CANDIDATES

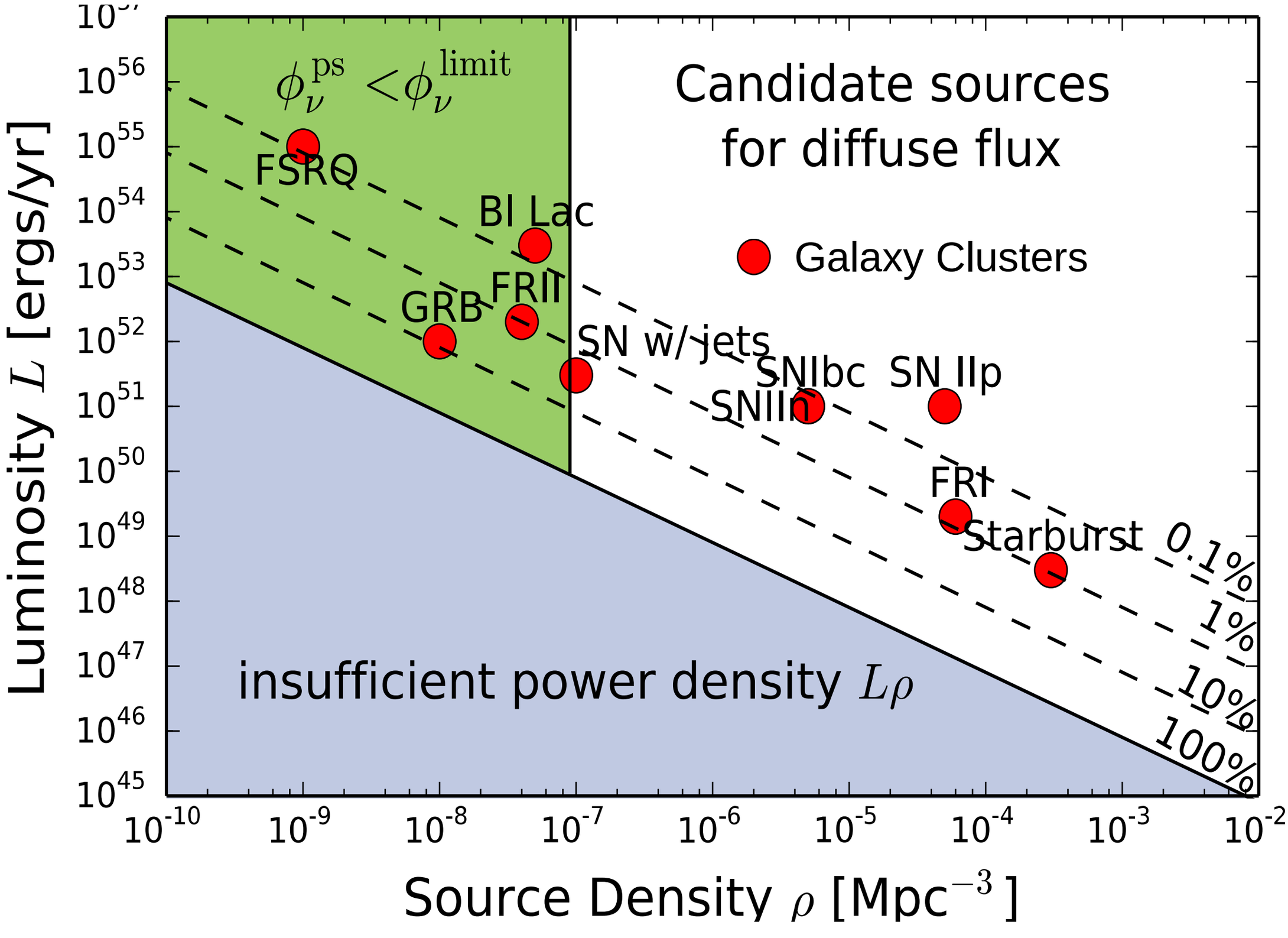
Resolving the sources of the diffuse flux

Marek Kowalski
arXiv:1411.4385

$$\Phi_{\text{diffuse}} \propto L \cdot \rho$$



Resolving the sources of the diffuse flux



END