High-energy ν astronomy

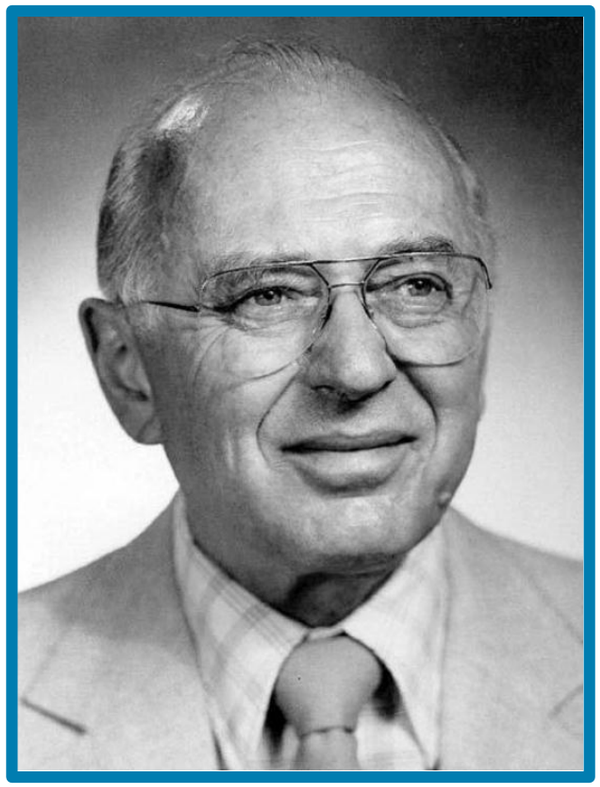
Where do we stand, where do we go ?

Symposium 50 years BNO, June 8, 2016

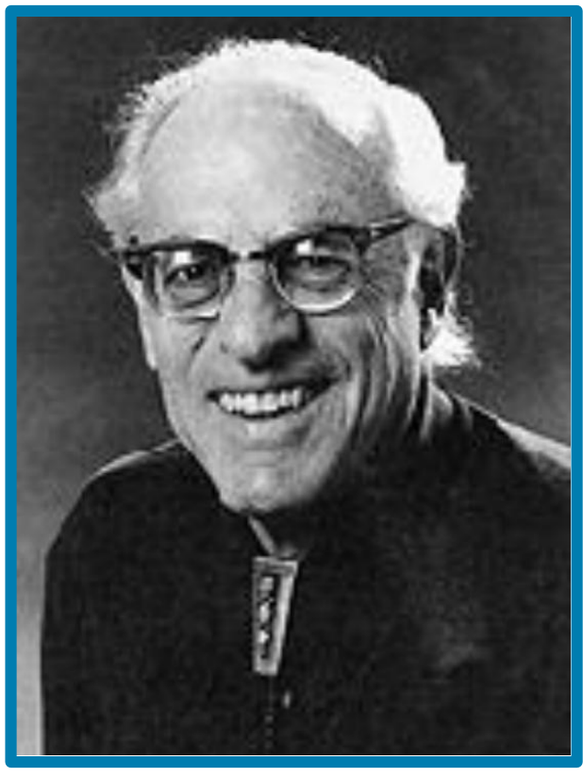
Christian Spiering

First ideas

1960



K. Greisen



F. Reines

M. Markov
(with I. Zheleznykh)

… discuss ways to detect cosmic high-energy neutrinos deep underground or underwater.

M.Markov, **1960**:

„We propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation“ Proc. 1960 ICHEP, Rochester, p. 578.

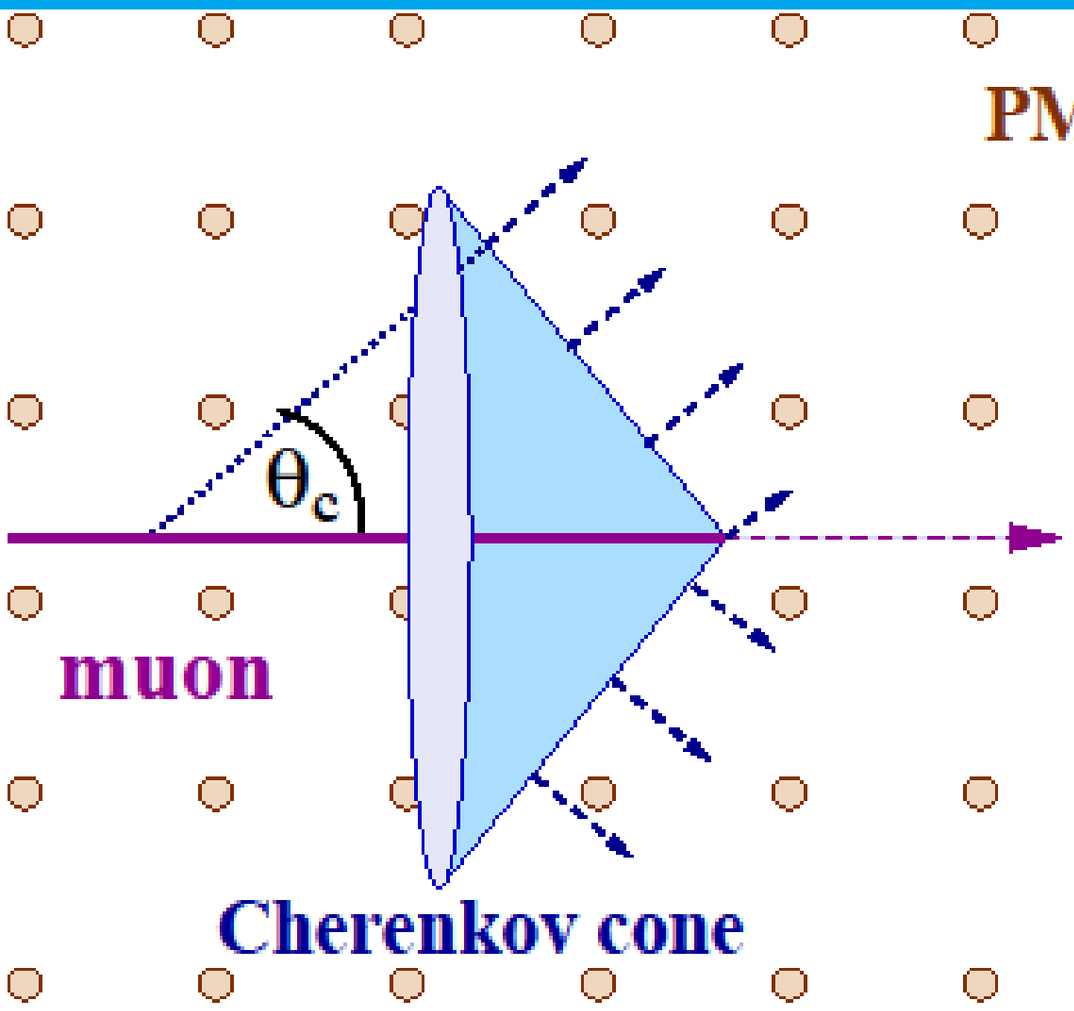
The traditional method:

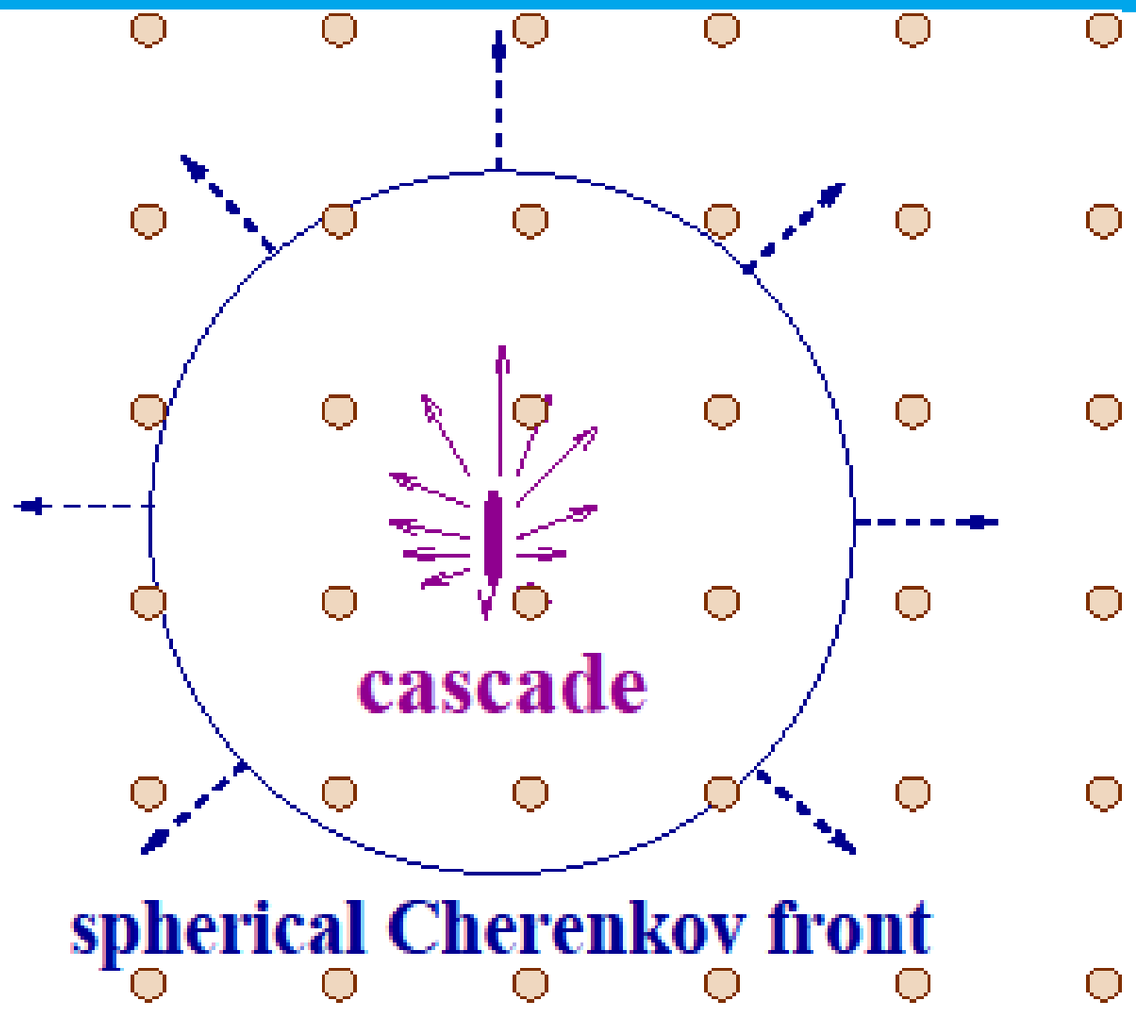
ν_μ charged current

μ

ν_μ

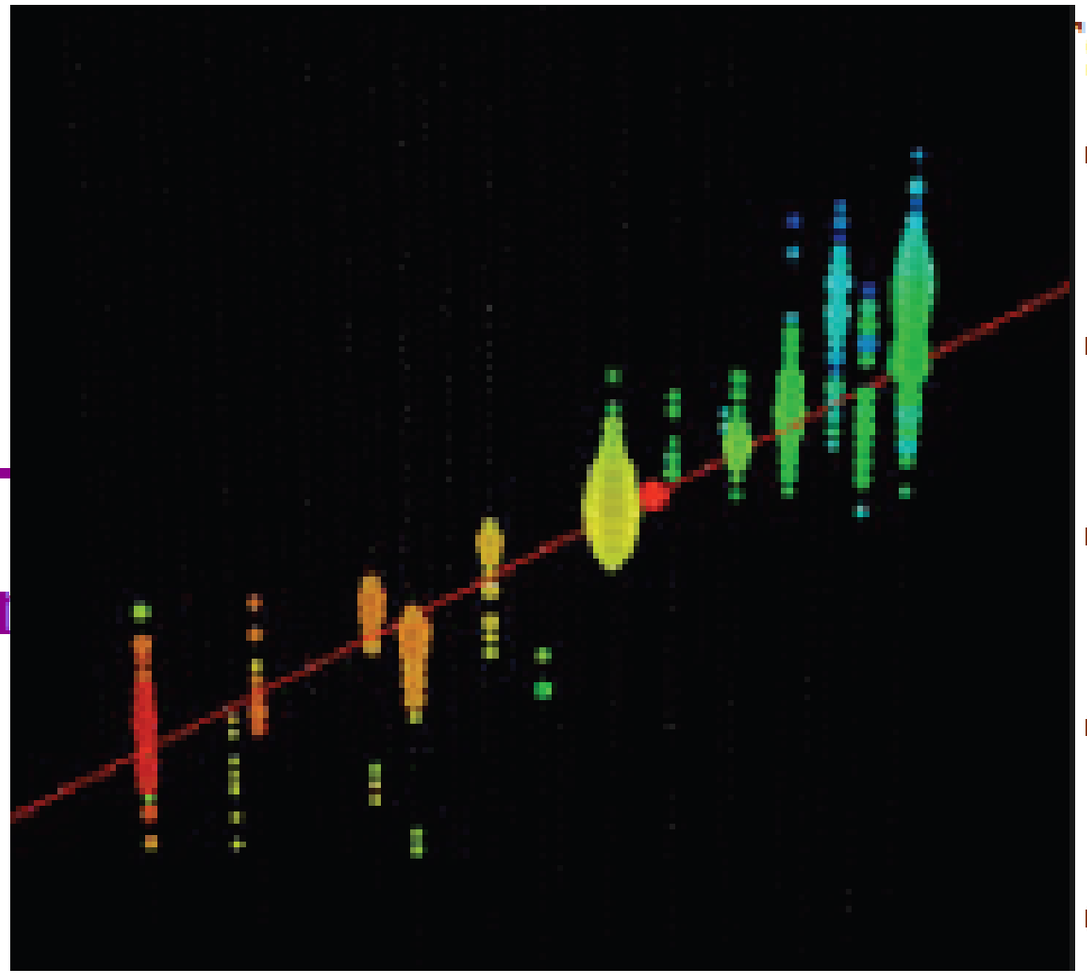
Detection Modes

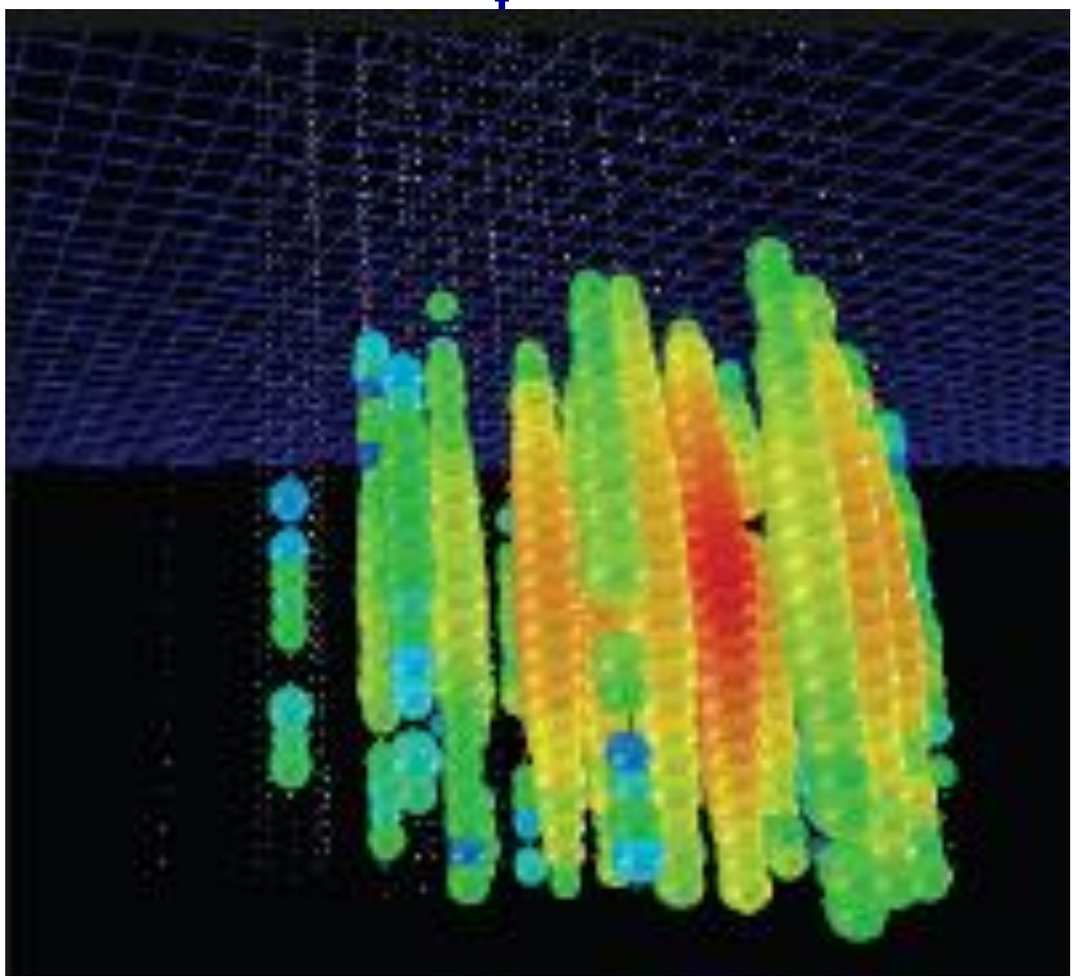




- Muon track from CC muon neutrino interactions
  - Angular resolution 0.1° - 0.5°
  - Energy resolution from dE/dx: factor 2-3
- Cascade from CC electron and NC all flavor interactions
  - Angular resolution 2° - 15 °
  - Energy resolution ~ 15%

Detection Modes





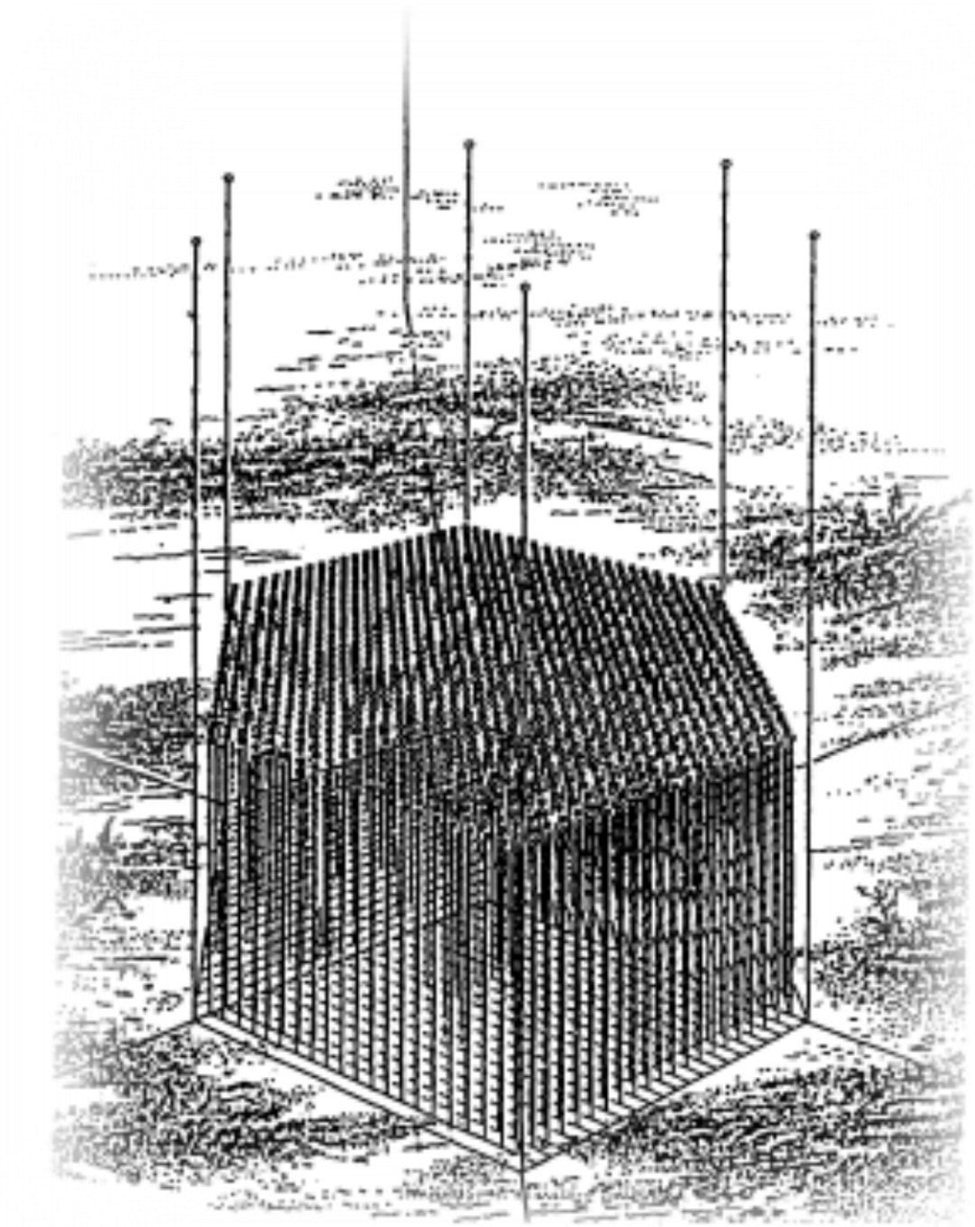
- **Muon track from CC muon neutrino interactions**
  - **Angular resolution 0.1° - 0.5°**
  - **Energy resolution from dE/dx: factor 2-3**
- **Cascade from CC electron and NC all flavor interactions**
  - **Angular resolution 2° - 15 °**
  - **Energy resolution ~ 15%**

THE DETECTORS

DUMAND

- **1973, International Cosmic Ray Conference (ICRC)**

First discussions. F. Reines, J. Learned, H. Davis, P. Kotzer, M. Shapiro (all USA), G. Zatsepin (USSR) and S. Miyake (Japan)

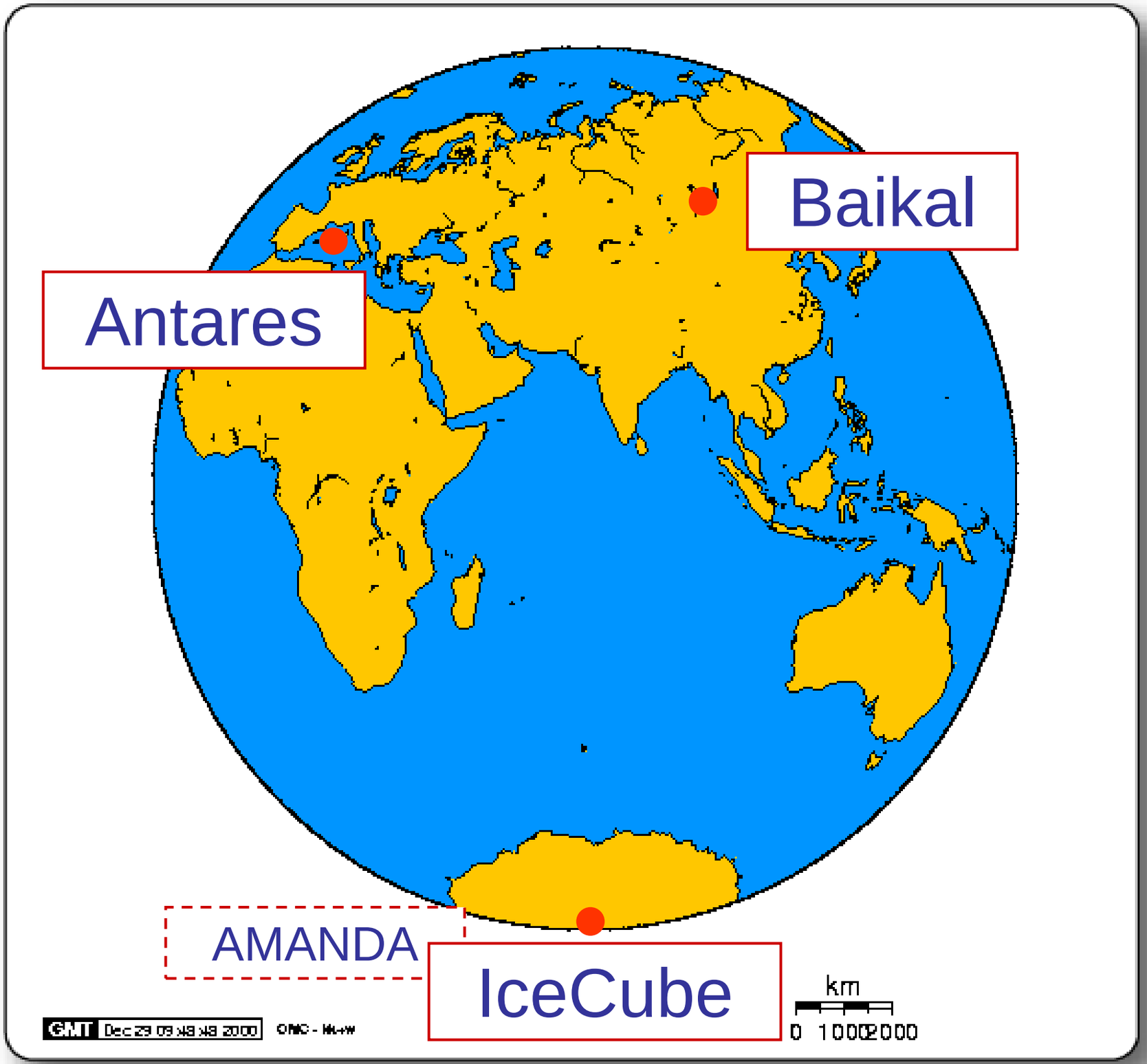


- **1978**

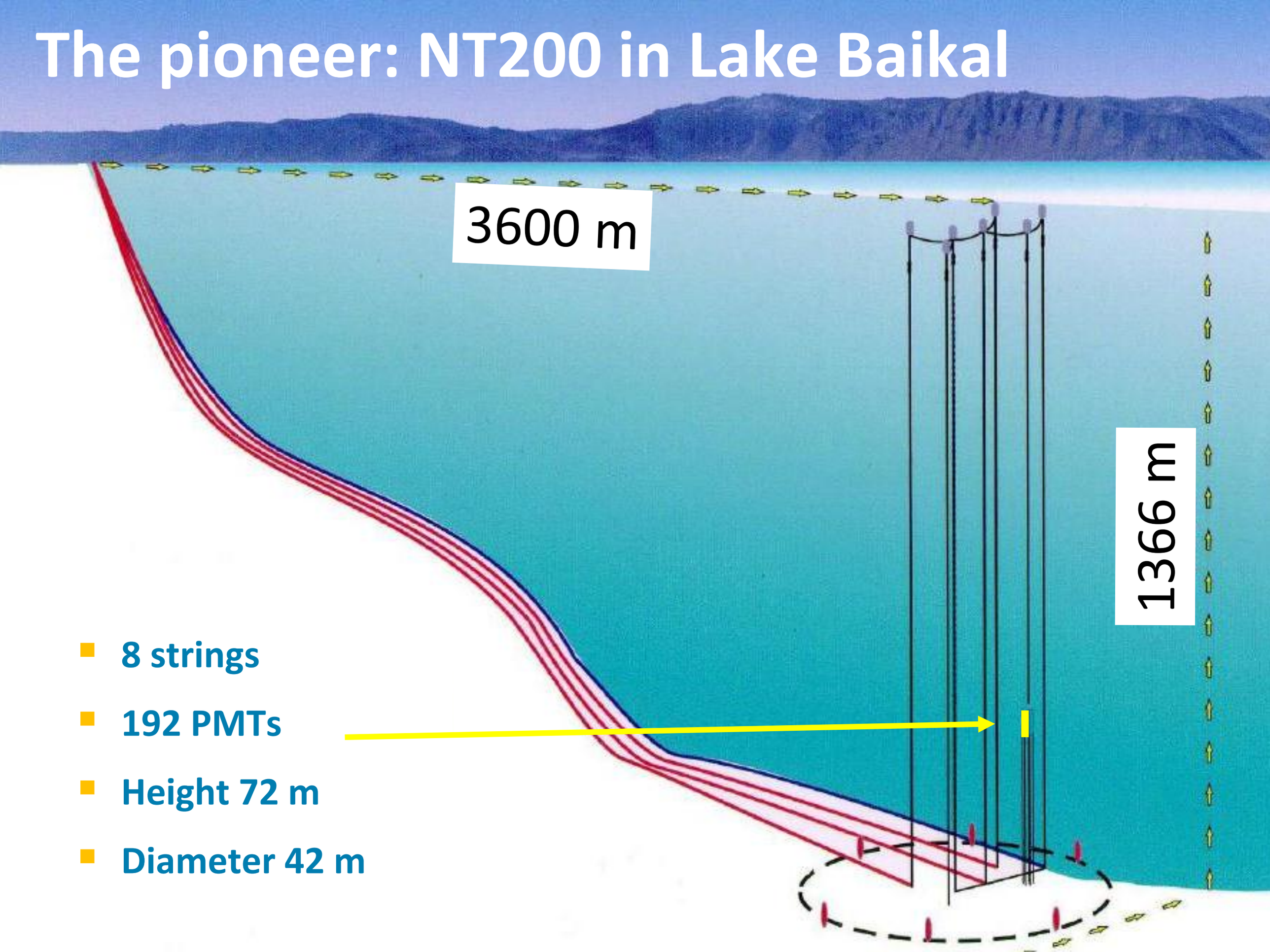
Design of a km³ detector close to Hawaii

- **1995 Termination**

The devices


Baikal
Antares
AMANDA
IceCube
km
0 1000 2000
GMT Dec 29 09:48:48 2000
OMC - MA+W

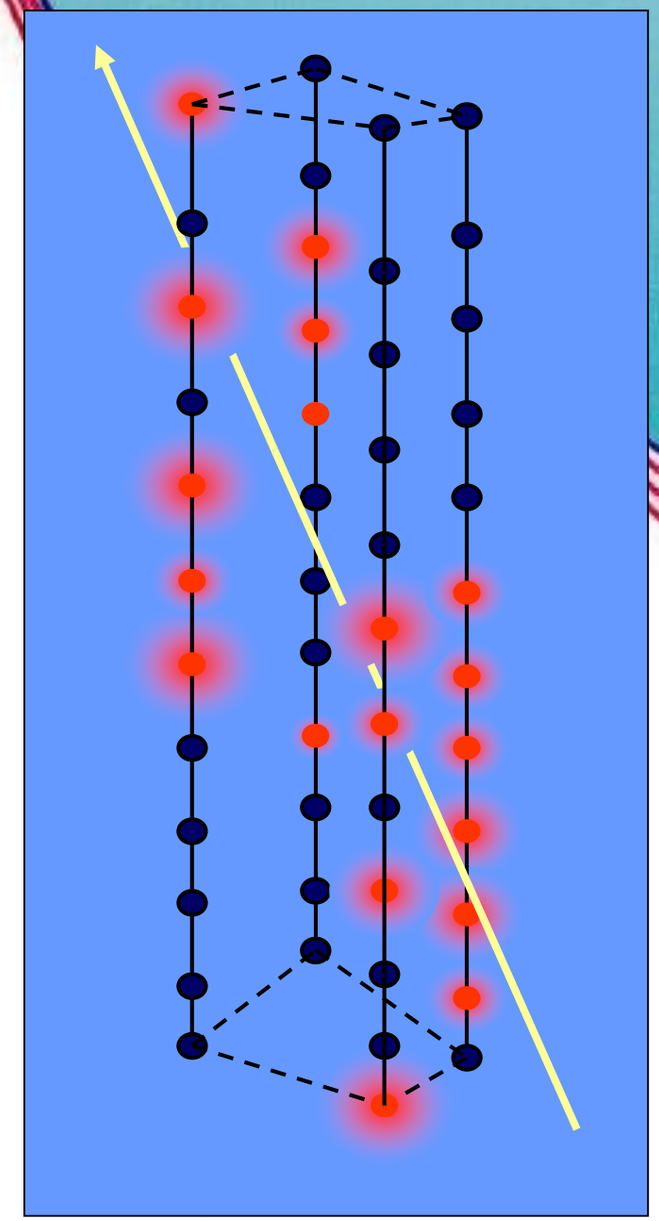
The pioneer: NT200 in Lake Baikal



- 8 strings
- 192 PMTs
- Height 72 m
- Diameter 42 m

A textbook underwater neutrino event

1996



3600 m

1366 m

ANTARES

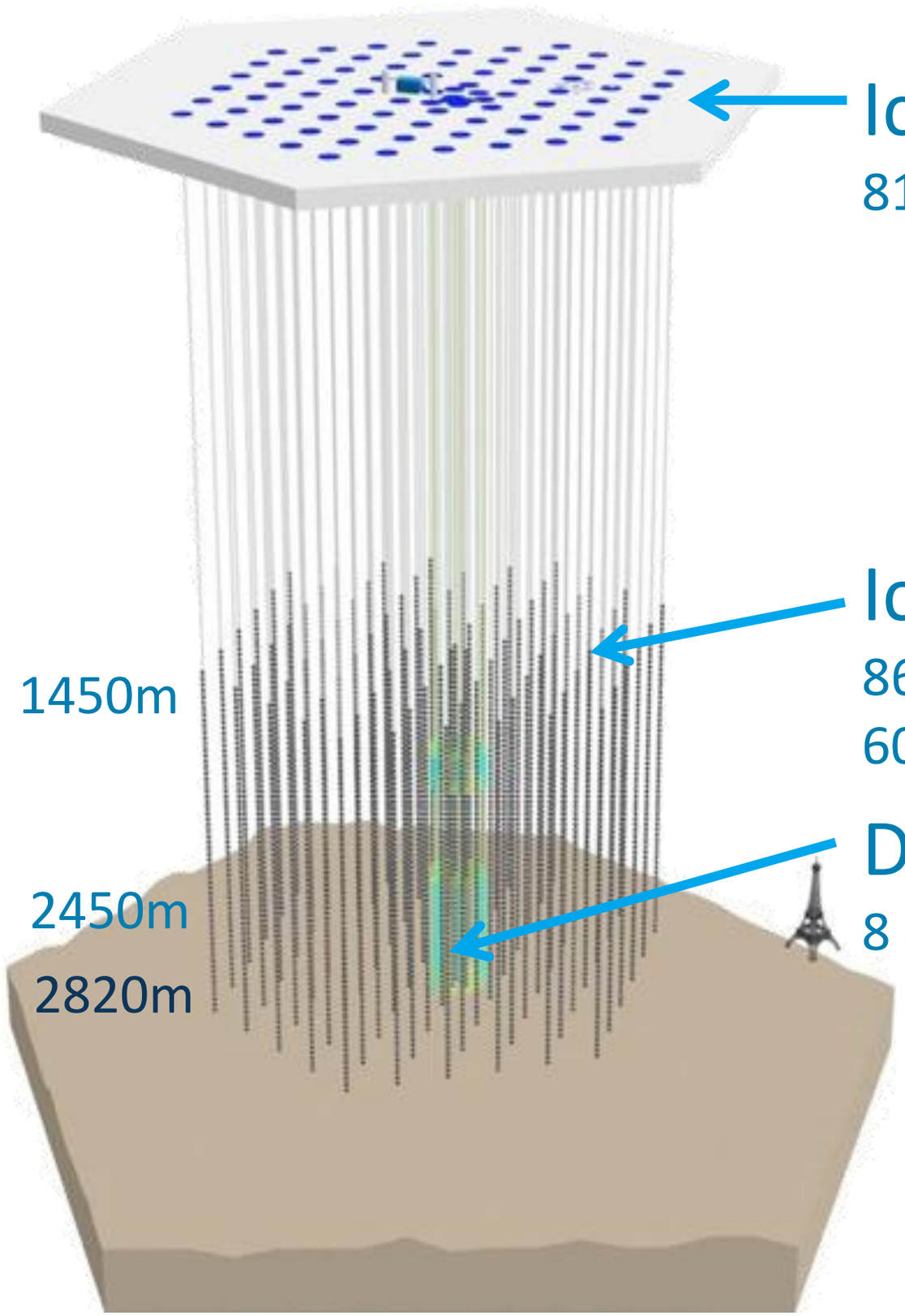
- 885 PMTs
- 12 strings
- Operating in final configuration since 2008

2500m

450 m

70 m

IceCube Neutrino Observatory



IceTop air shower detector

81 pairs of water Cherenkov tanks

IceCube

86 strings including 8 Deep Core strings

60 PMT per string

DeepCore

8 closely spaced strings

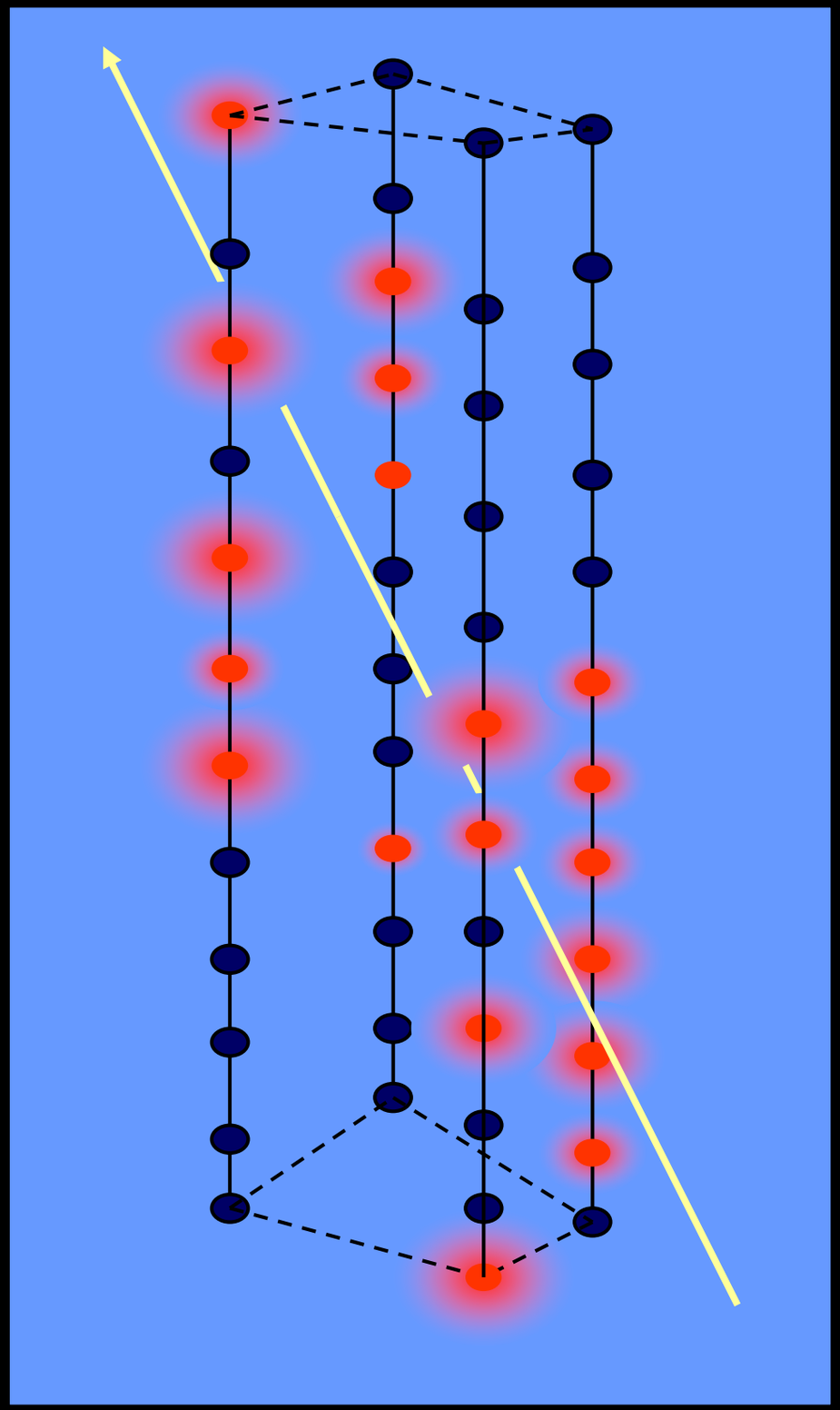
- ~220 ν/day
- Threshold
  - IceCube ~ 100 GeV
  - DeepCore ~10 GeV

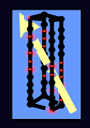
PHYSICS GOALS

Physics with neutrino telescopes

- **Search for the sources of high-energy cosmic rays with neutrinos**
- **Dark Matter and Exotic Physics**
  - **WIMPs**
  - **Magnetic Monopoles and other superheavies**
  - **Violation of Lorentz invariance**
- **Neutrino and Particle Physics**
  - **Neutrino oscillation studies**
  - **Charm physics, cross sections at highest energies, …**
- **Supernova Collapse Physics**
  - **MeV neutrinos in bursts → early SN phase, neutrino hierarchy, ...**
- **Cosmic Ray Physics**
  - **Spectrum, composition and anisotropies**

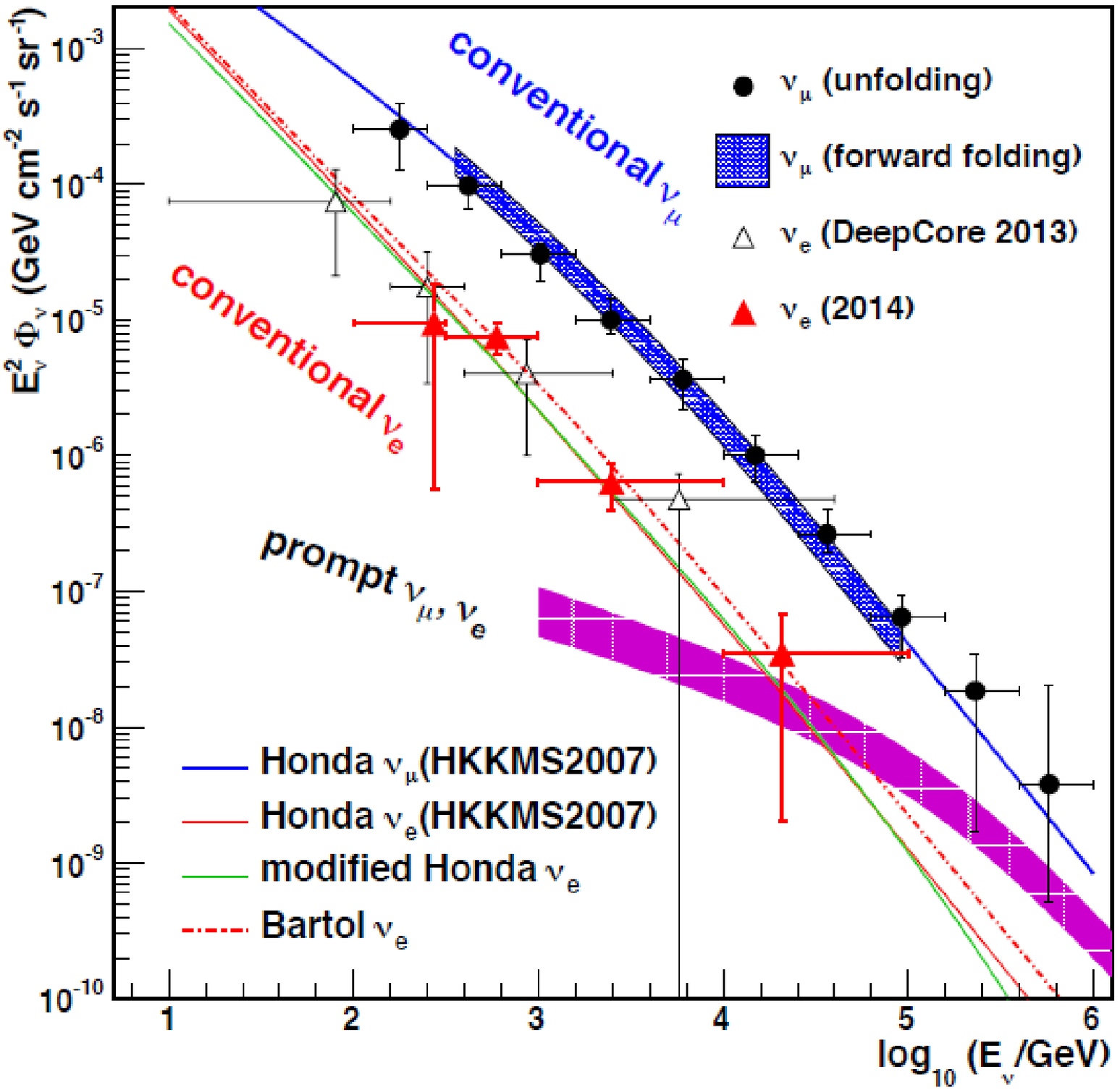
ATMOSPHERIC NEUTRINOS

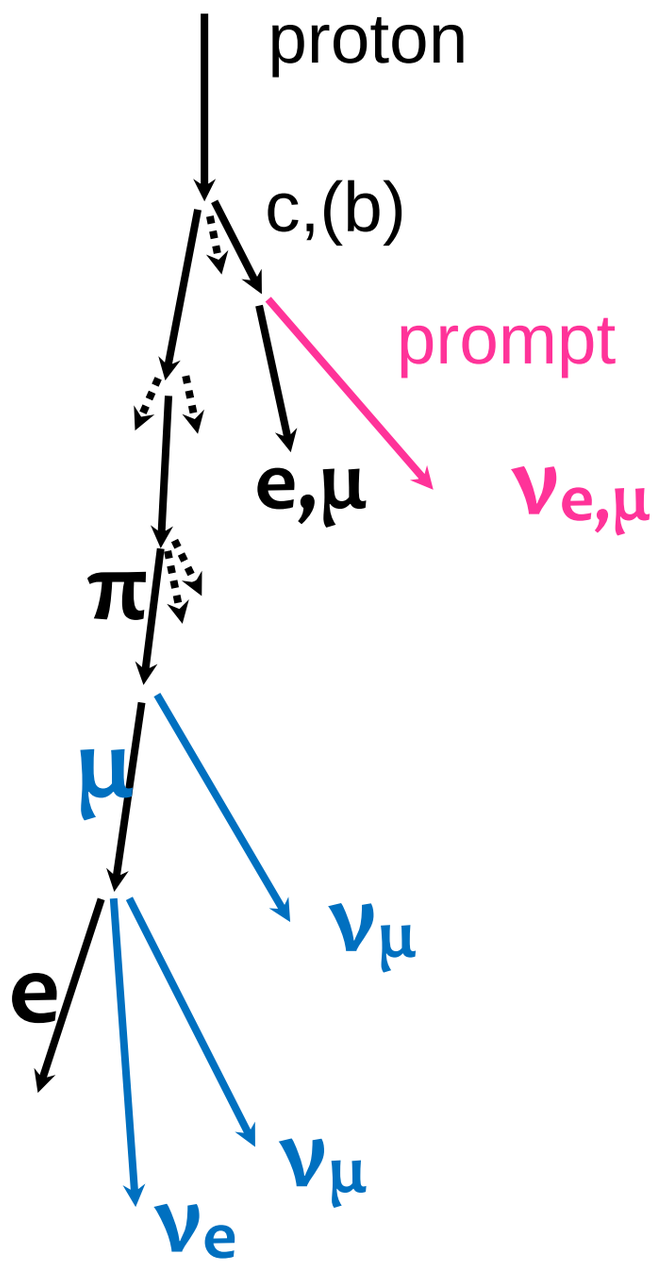




Run 113641 Event 33553254 [6000ns, 9952ns]

IceCube: Spectrum of atmospheric neutrinos

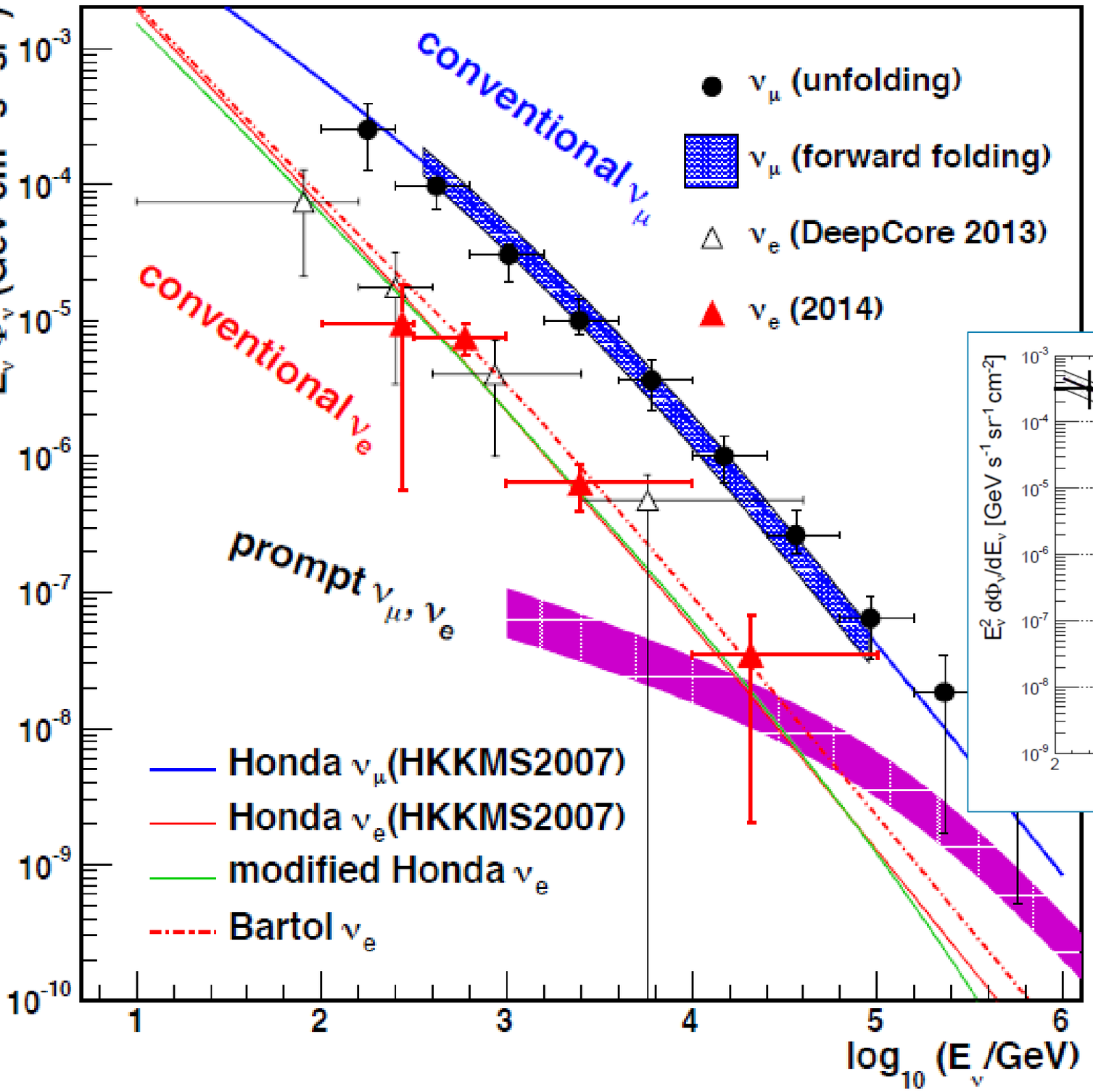




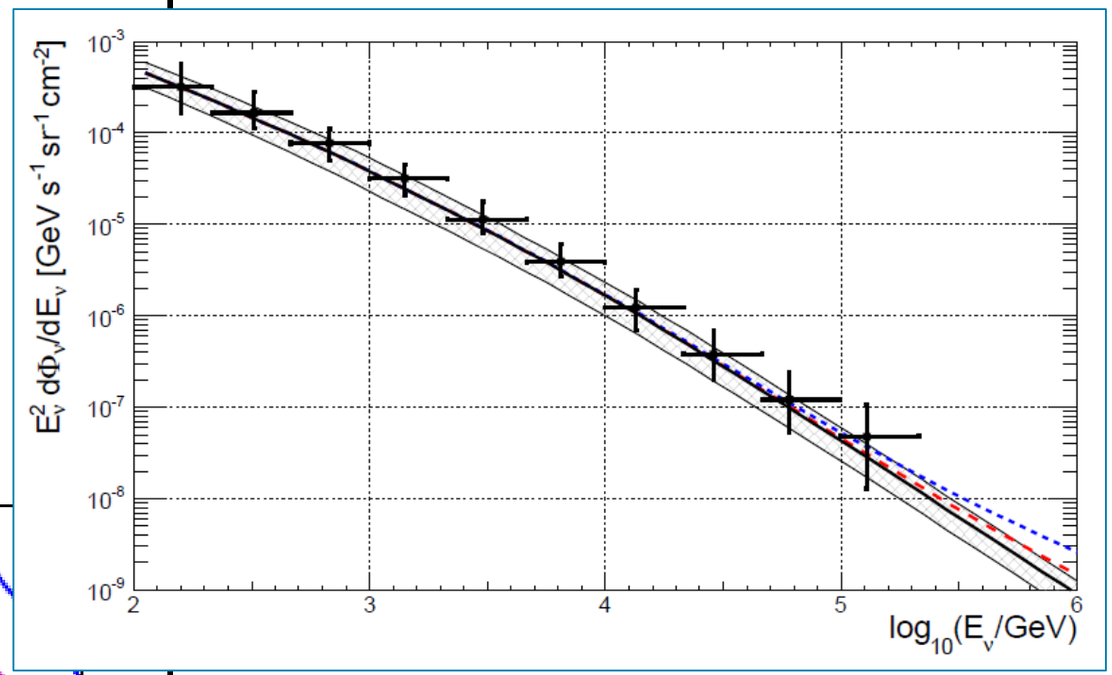
conventional

Phys.Rev. D91 (2015) 122004)

IceCube: Spectrum of atmospheric neutrinos



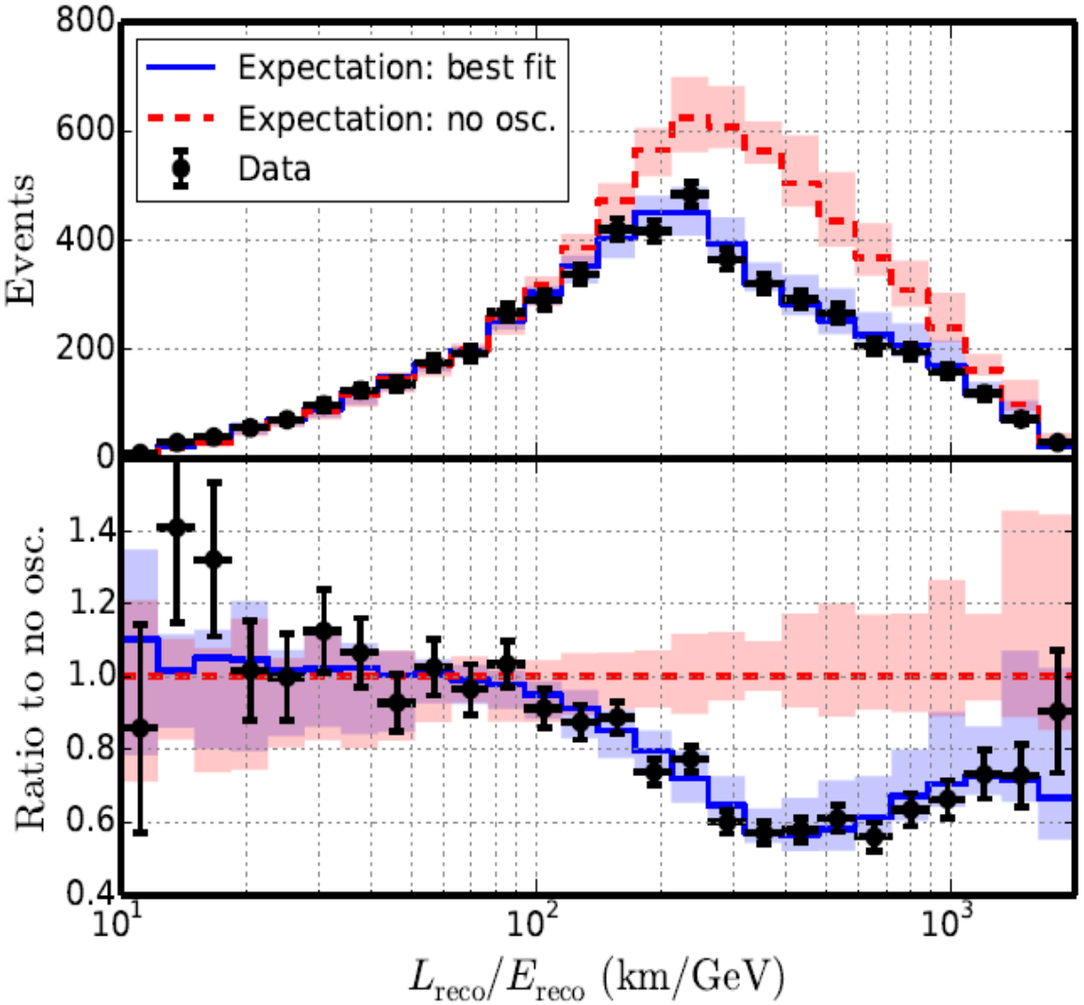
.. and ANTARES

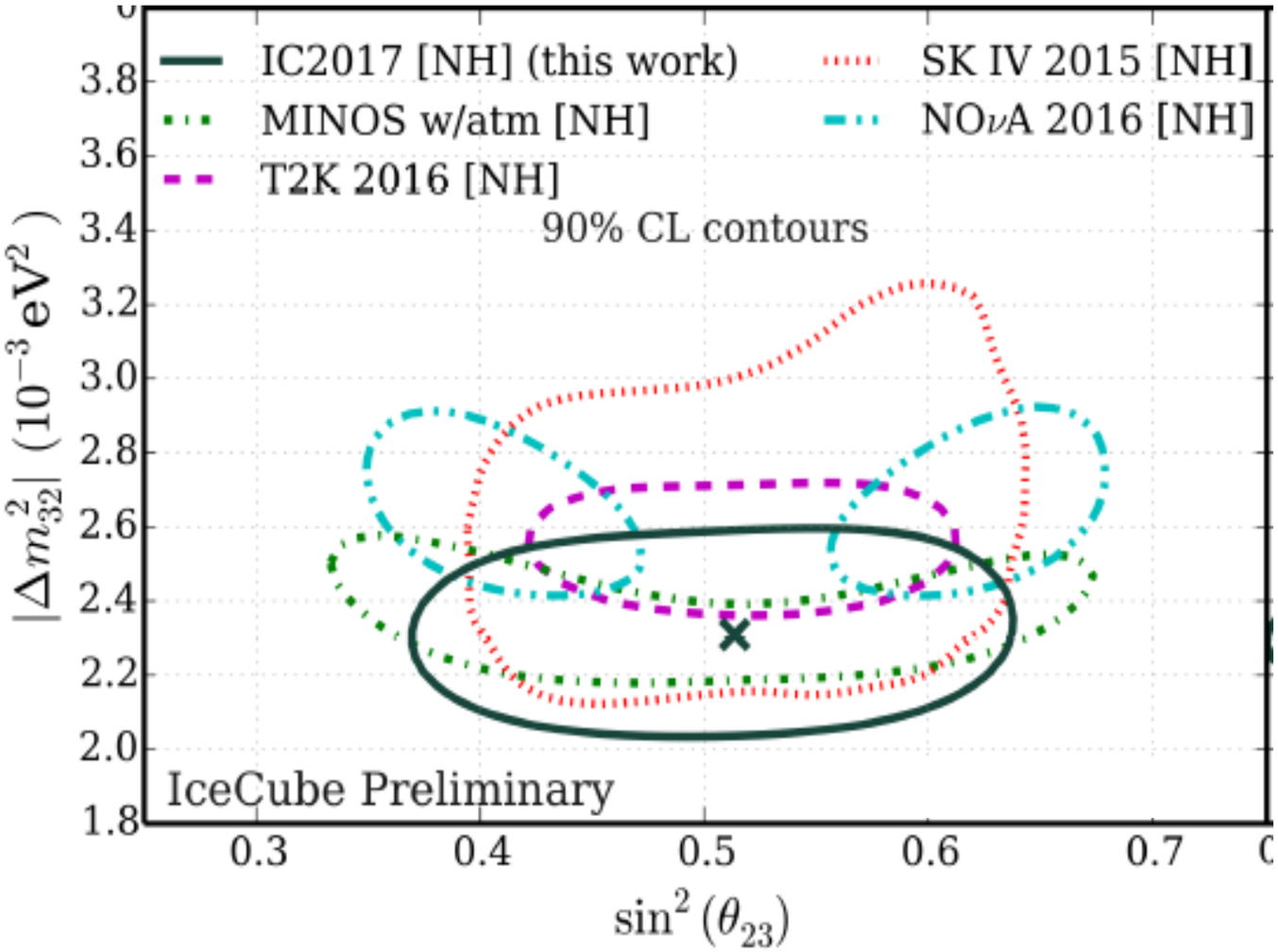


arXiv:1308.1599

Phys.Rev. D91 (2015) 122004)

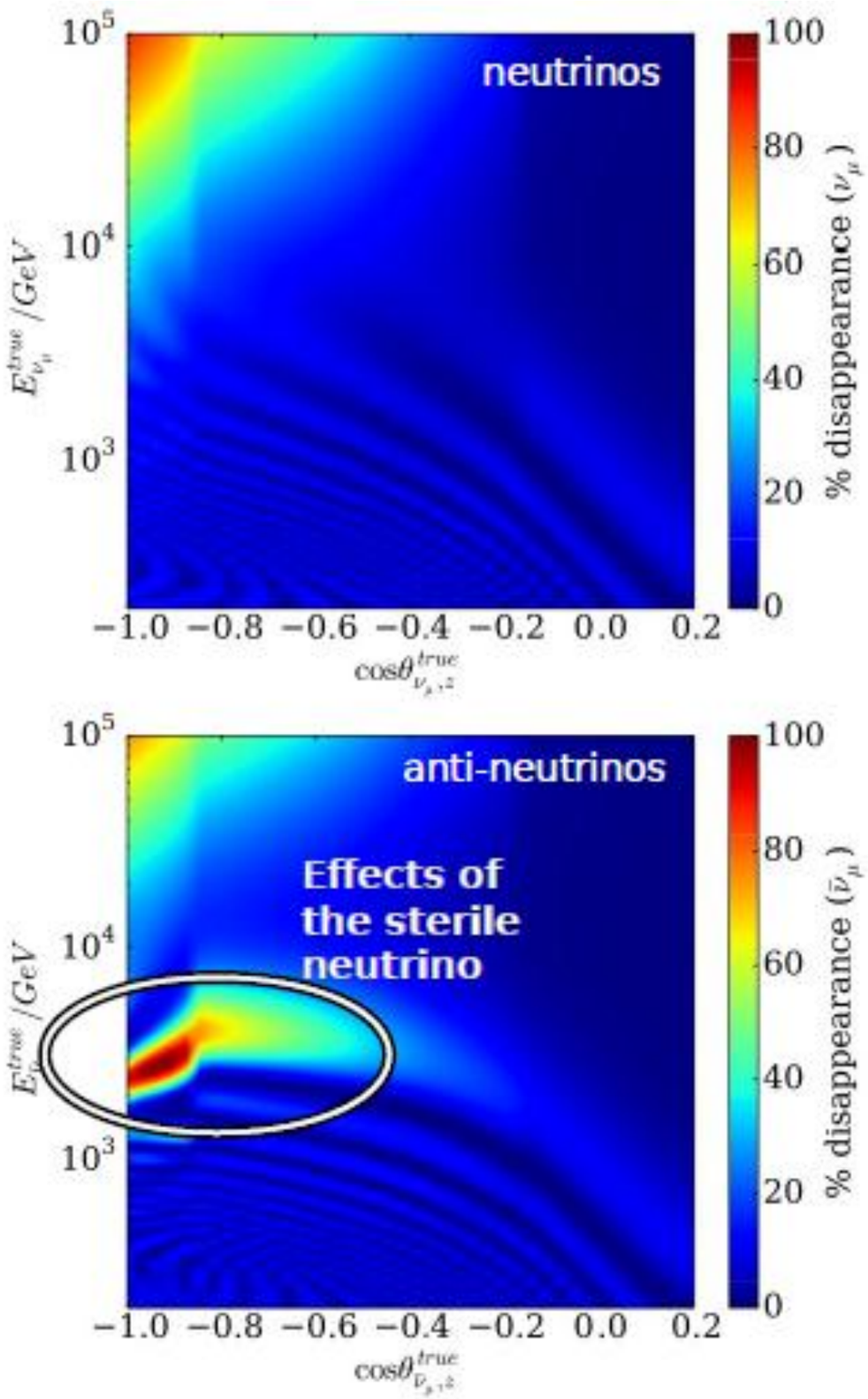
DeepCore: Oscillations for atmospheric neutrinos (E < 30-40 GeV)



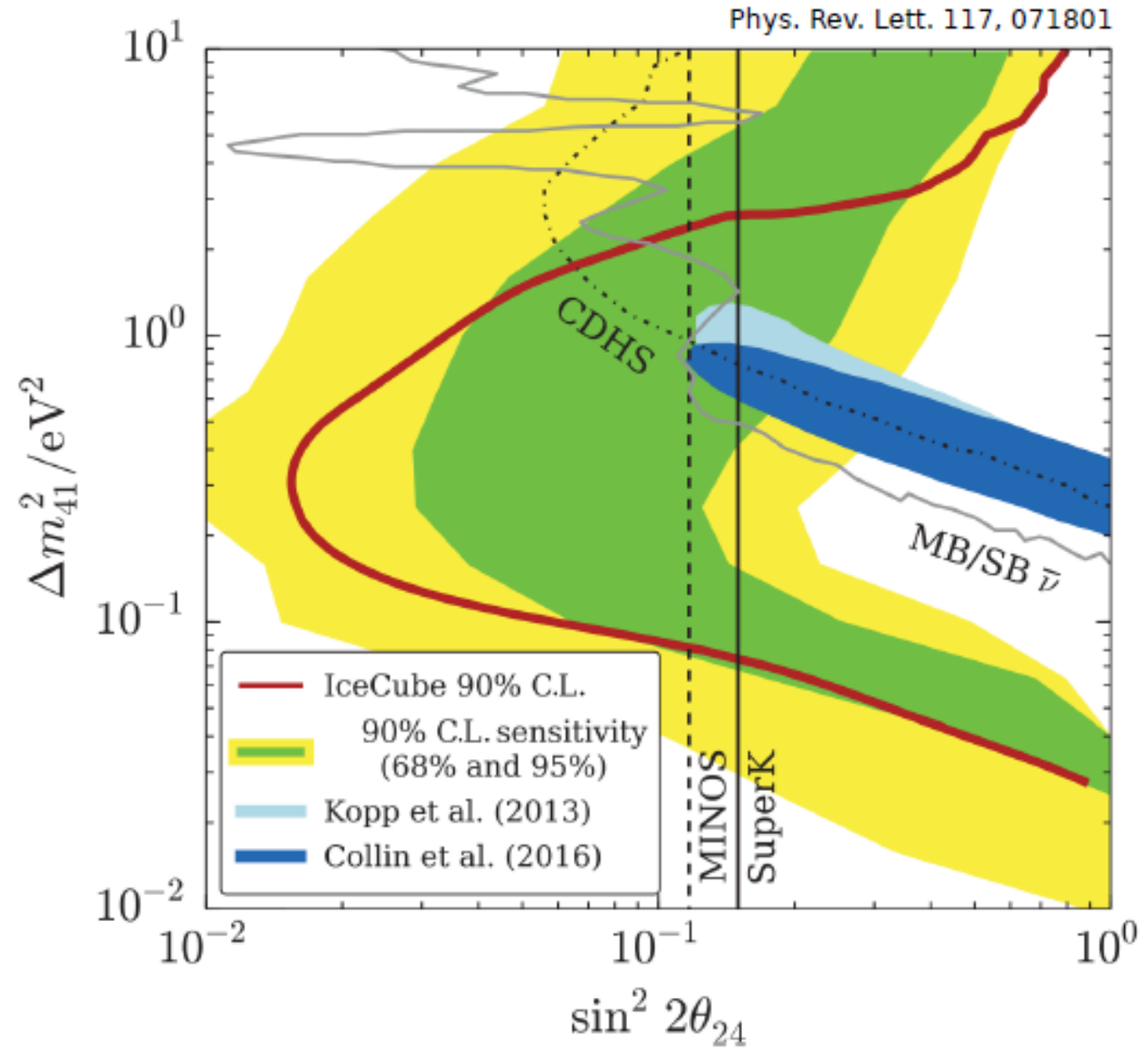


- **Consistent and competitive with accelerator-based measurement**
- **Different energy range and baseline than for accelerator studies!**

IceCube: search for sterile neutrinos (E > 1 TeV)



- **MSW resonance-like transition of atm. ν_μ to ν_s at high energies**
- **Sensitive to mixing angle θ_{24}**

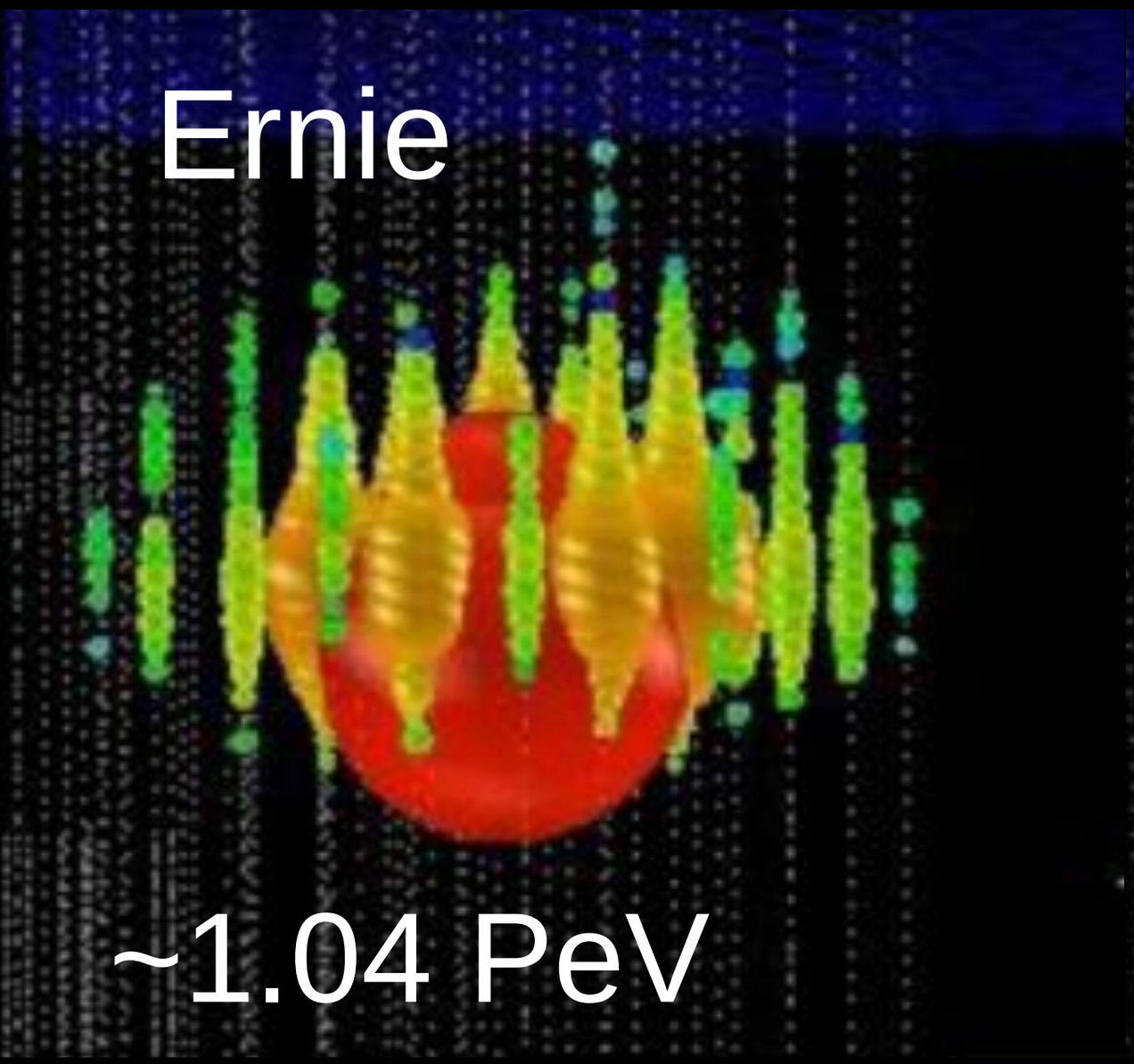


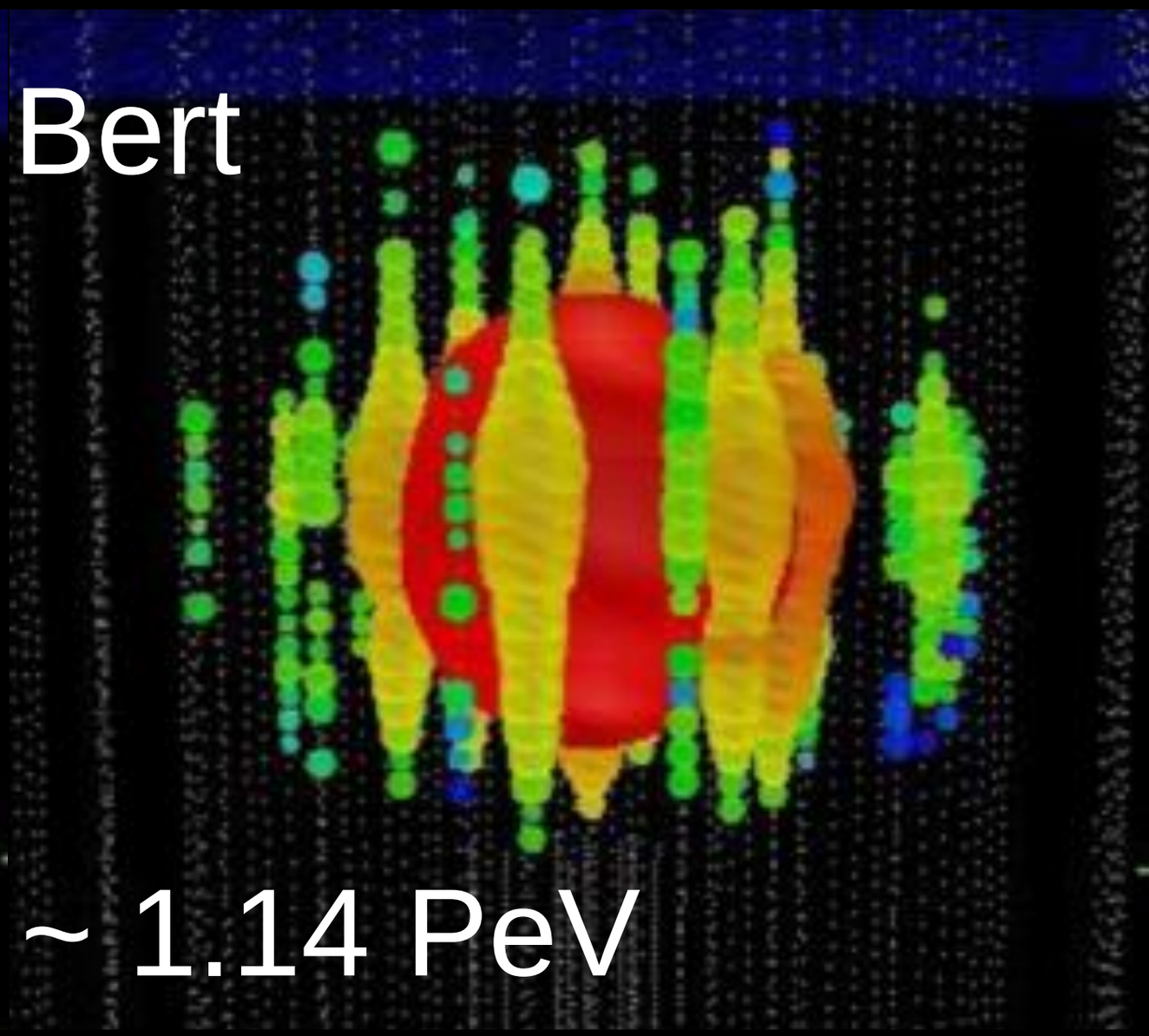
THE DISCOVERY OF A DIFFUSE COSMIC NEUTRINO FLUX

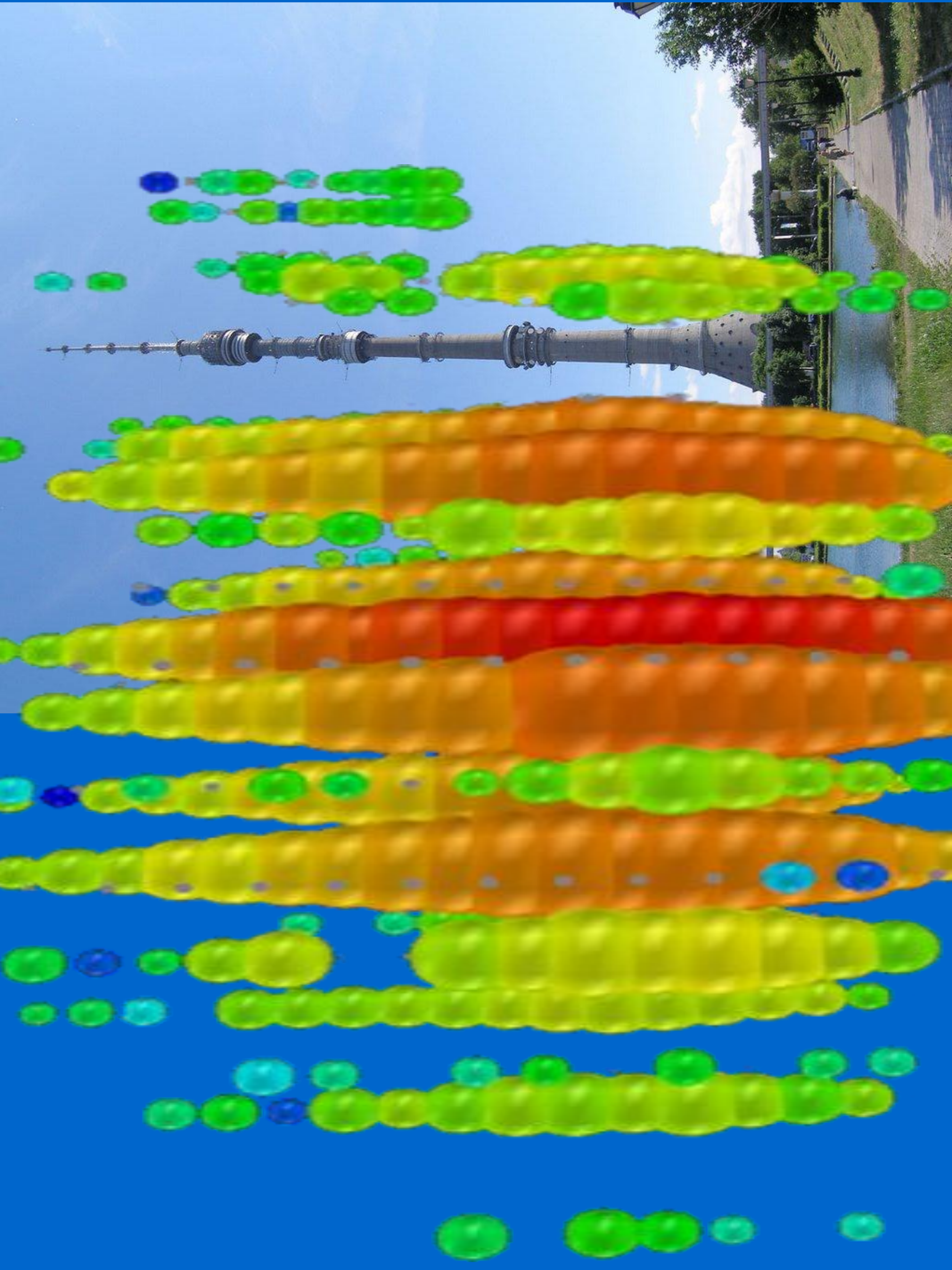
Special search for neutrinos with E_ν > 500 TeV

IC79/IC86

2.8 σ

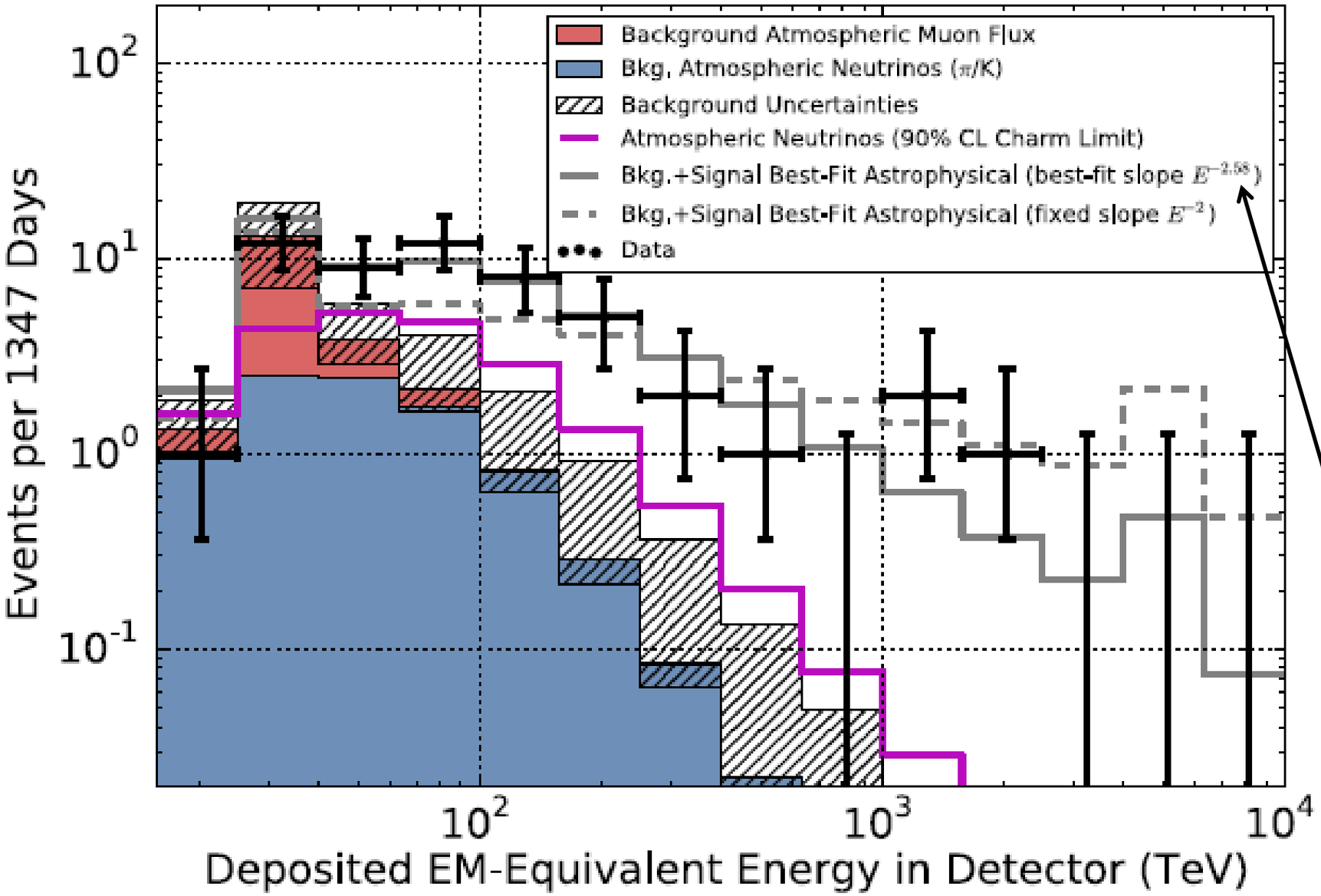






Follow-up Analysis: HESE (High Energy Starting Event)

First evidence for an extra-terrestrial h.e. neutrino flux



2 yrs data, 28 evts 4.1σ
Science 342 (2013)

3 yrs data, 37 evts 5.9σ
Phys.Rev.Lett. 113:101101 (2014)

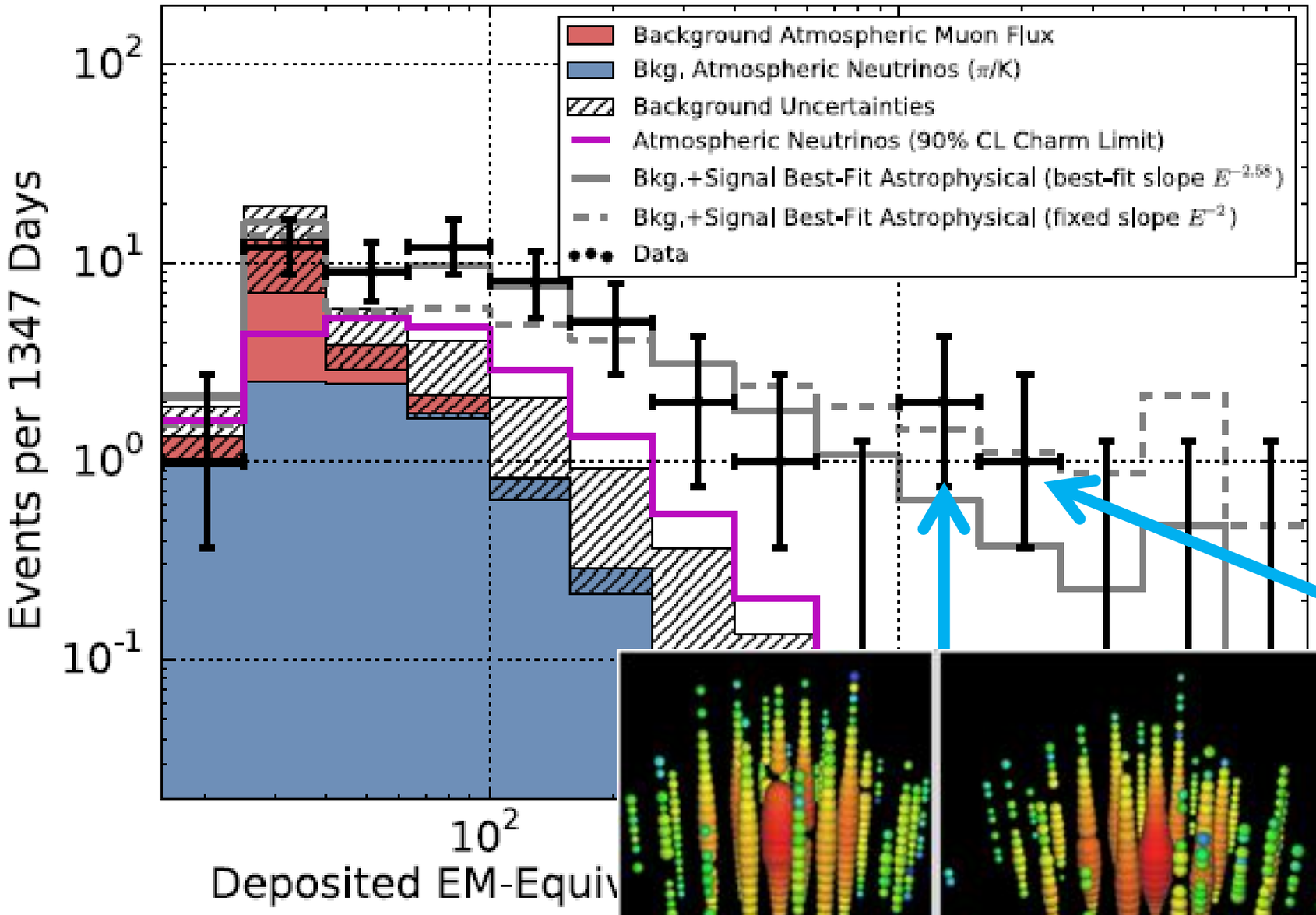
4 yrs data, 54 evts ~ 7σ

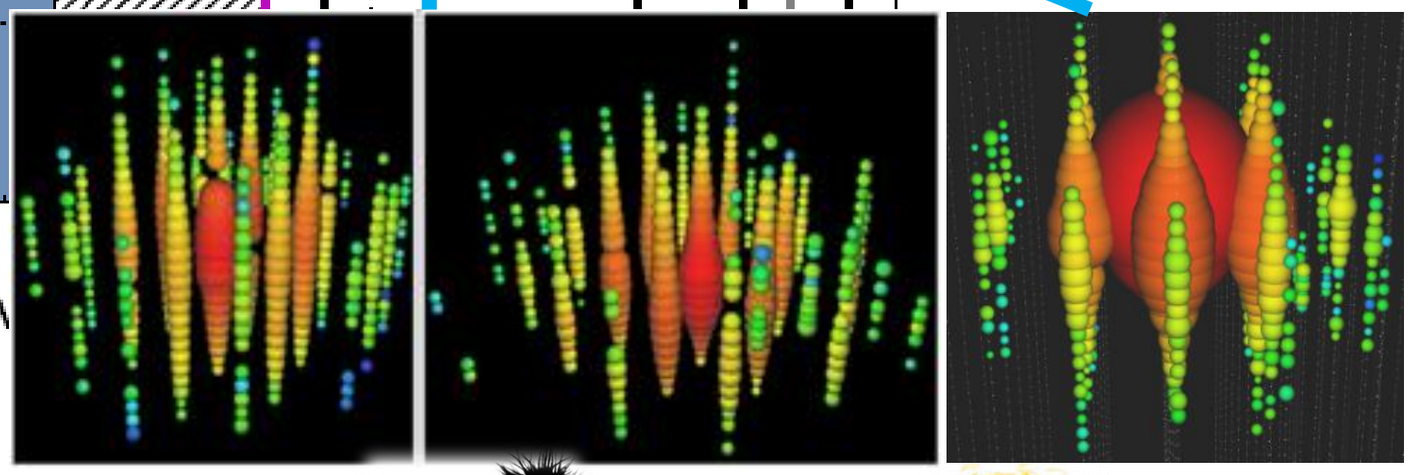
Threshold ~ 30 TeV

Note: relatively soft best-fit spectrum: $dN/dE_\nu \sim E_\nu^{-2.58}$

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

First evidence for an extra-terrestrial h.e. neutrino flux





"Bert"
1.04 PeV
Aug. 2011

"Ernie"
1.14 PeV
Jan. 2012

"Big Bird"
2 PeV
Dec. 2012

2 yrs data, 28 evts 4.1σ
Science 342 (2013)

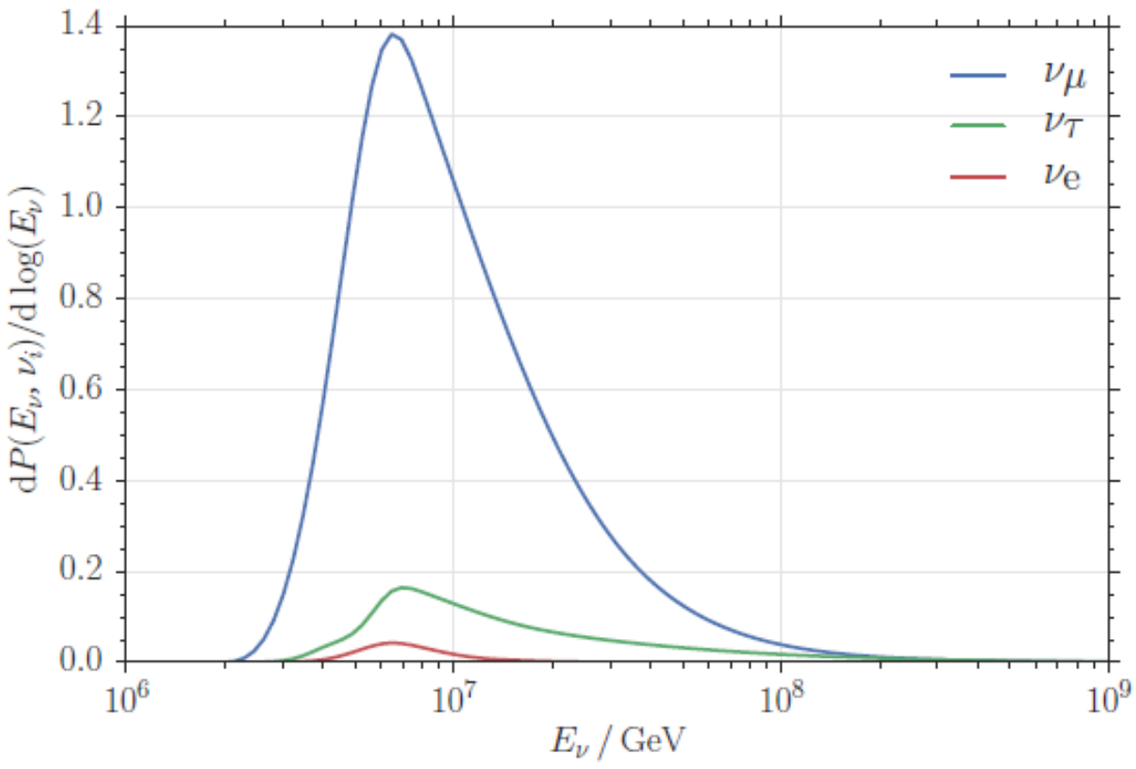
3 yrs data, 37 evts 5.9σ
Phys.Rev.Lett. 113:101101 (2014)

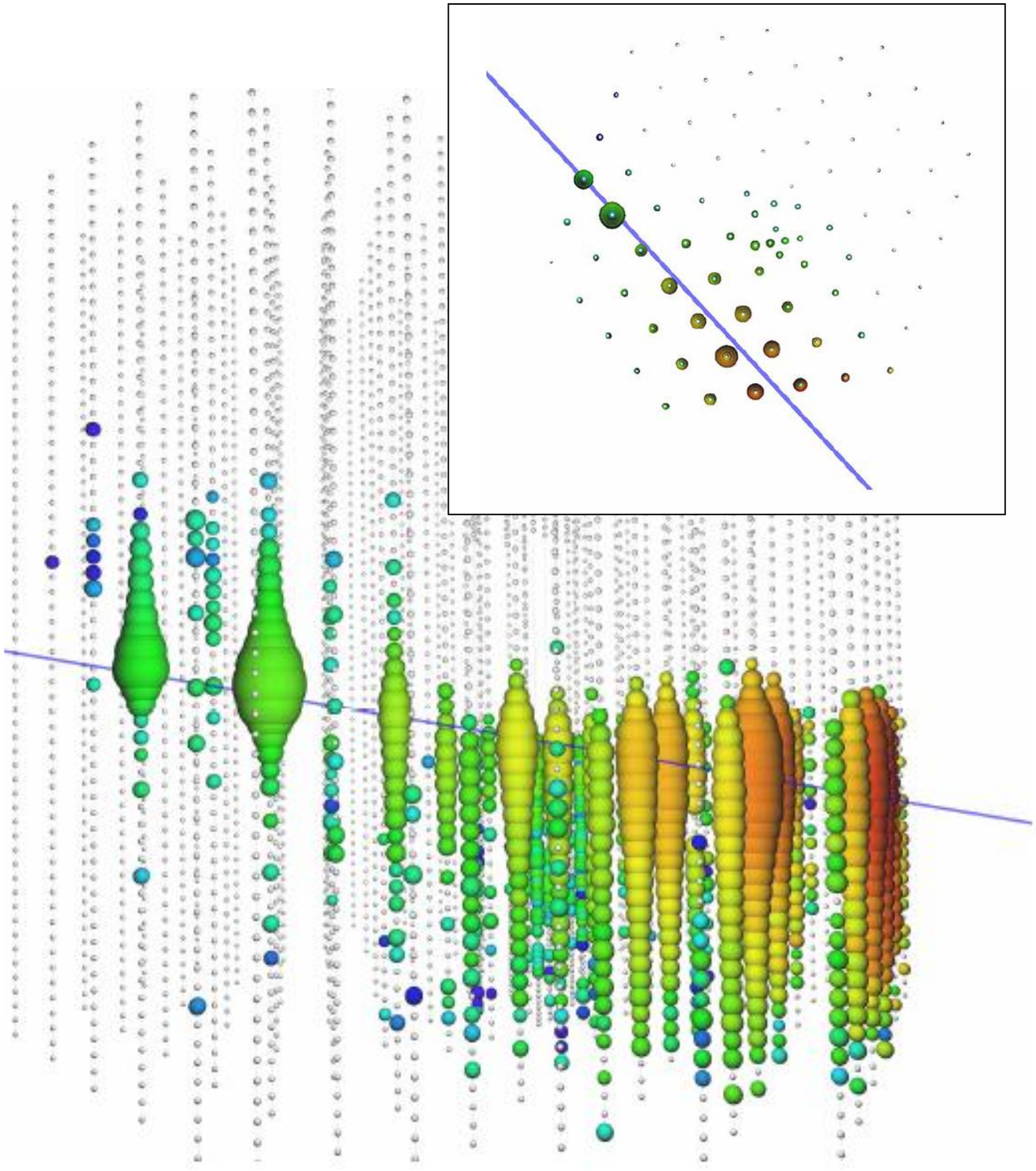
4 yrs data, 54 evts ~ **7σ**

Through-going muons, six years (2009-15)

The highest-energy event

Deposited energy 2.6±0.3 PeV



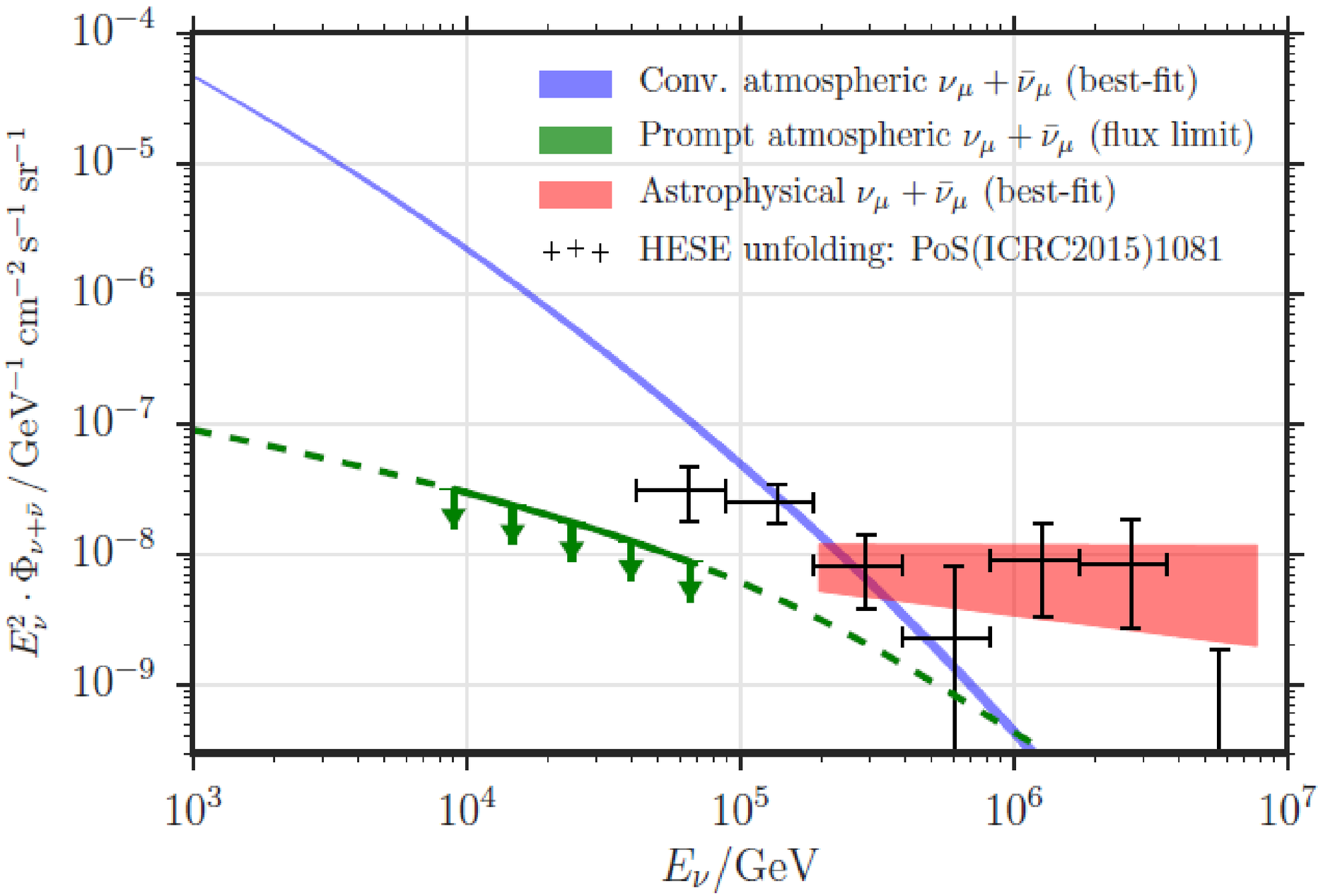


Most probable ν energy ~7 PeV

(for E^{-2} assumption)

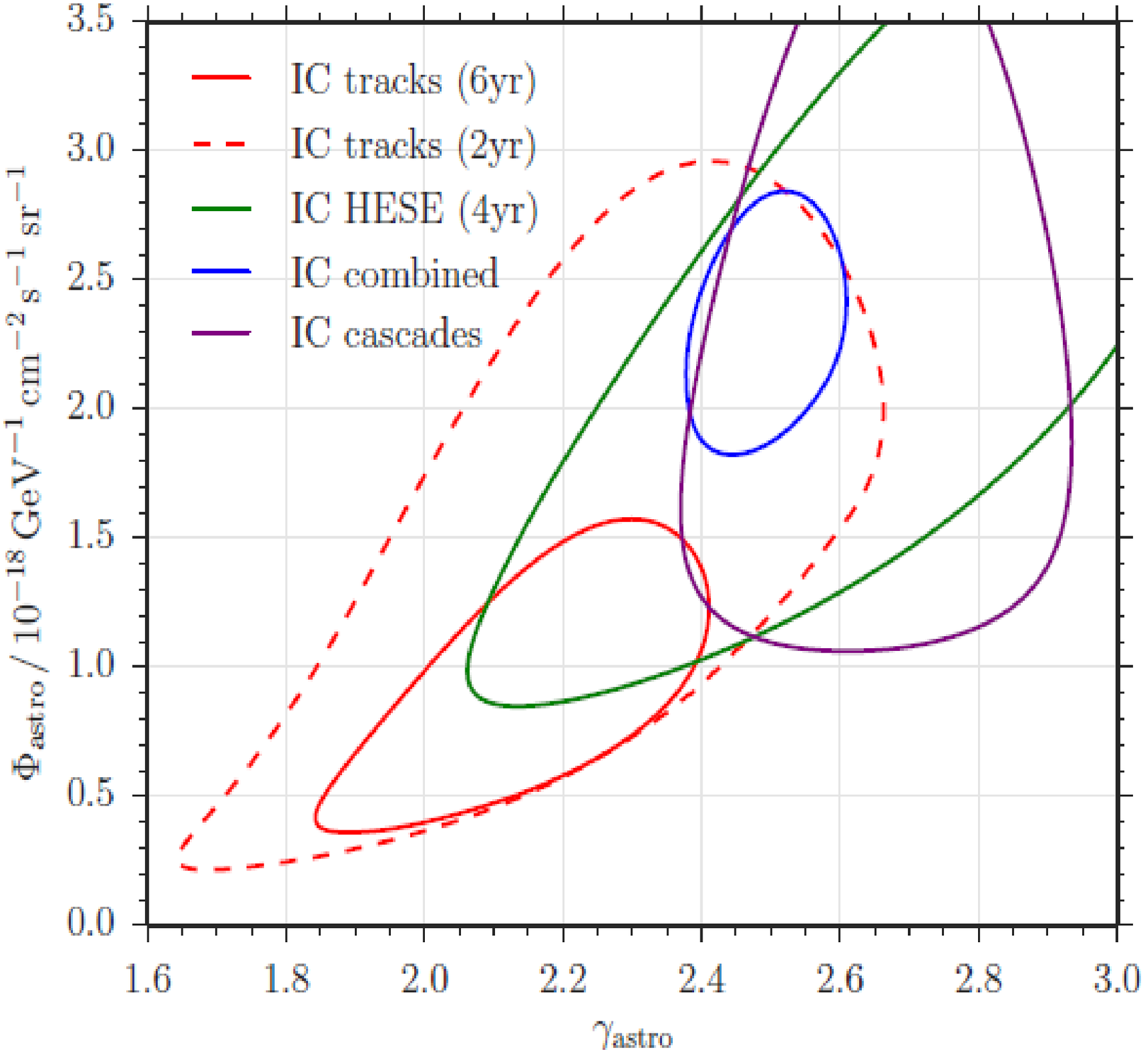
Through-going muons, six years (2009-15)

Spectrum $\Phi_{\nu+\overline{\nu}} = \left(0.90^{+0.30}_{-0.27}\right) \cdot \left(E_\nu / 100\,\mathrm{TeV}\right)^{-(2.13 \pm 0.13)}$

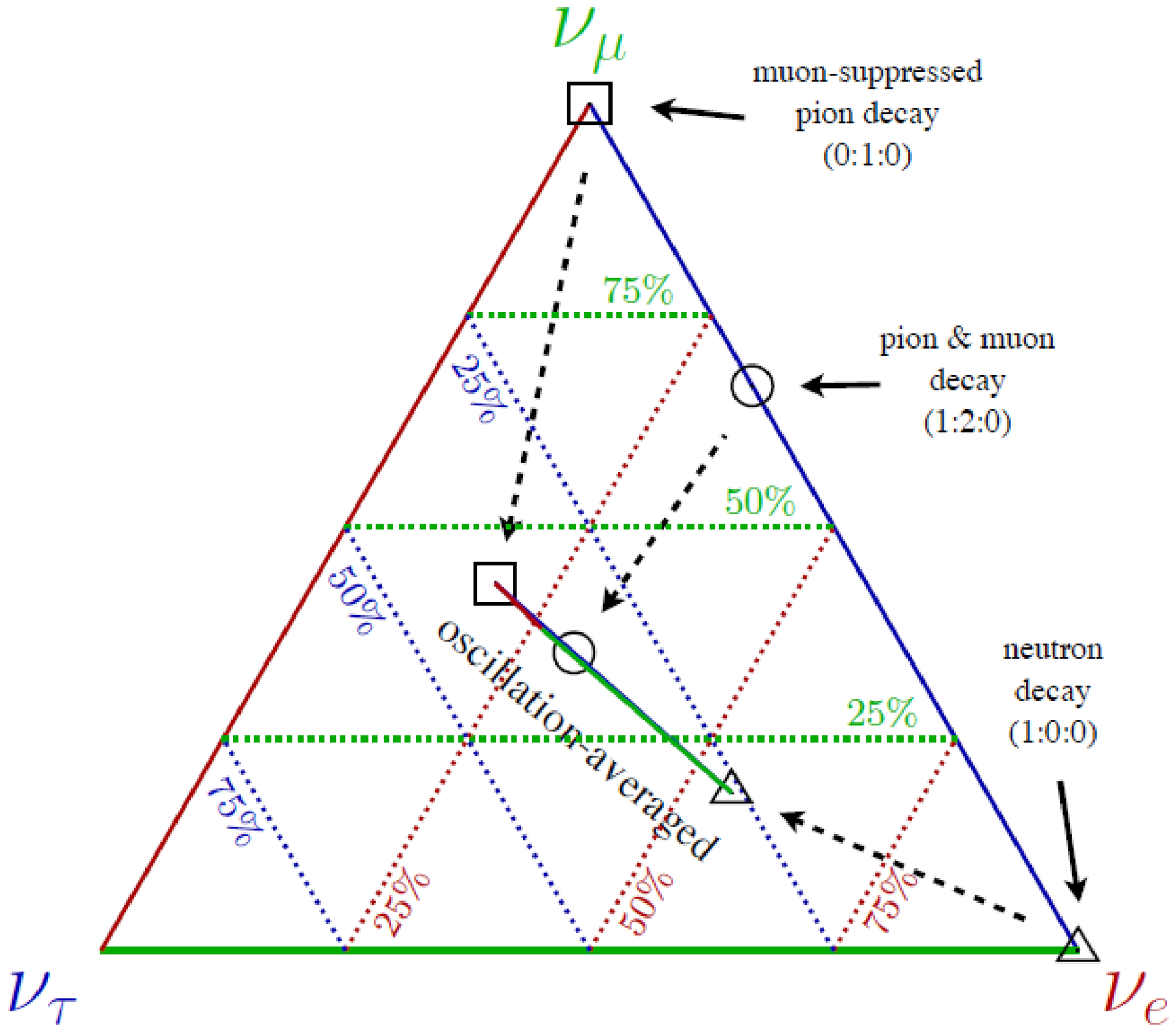


Broken Spectrum?

$$\Phi = \Phi_0 \times E_\nu^{\gamma}$$

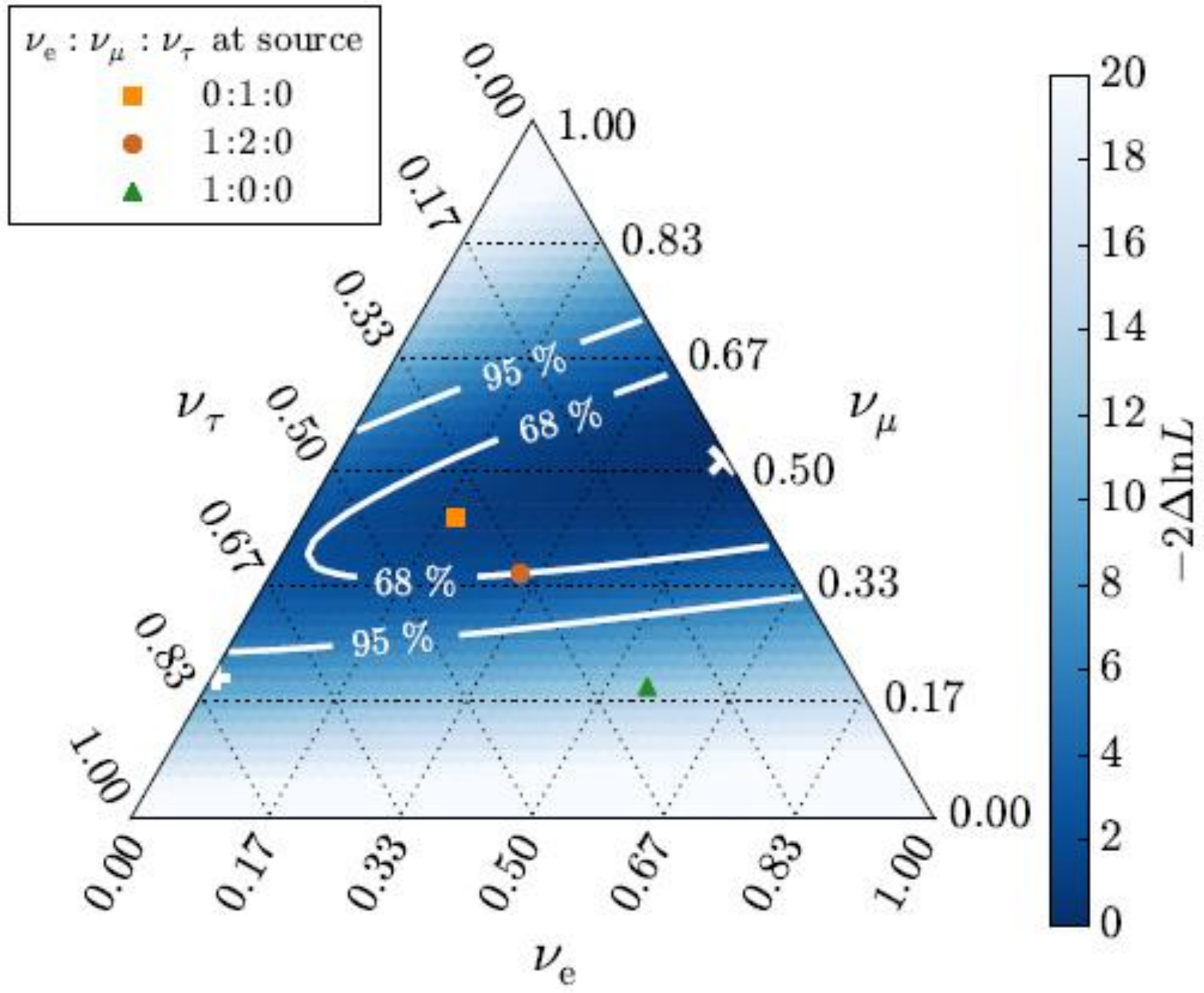


Flavor composition: what do we expect?



Flavor composition: what do we measure?

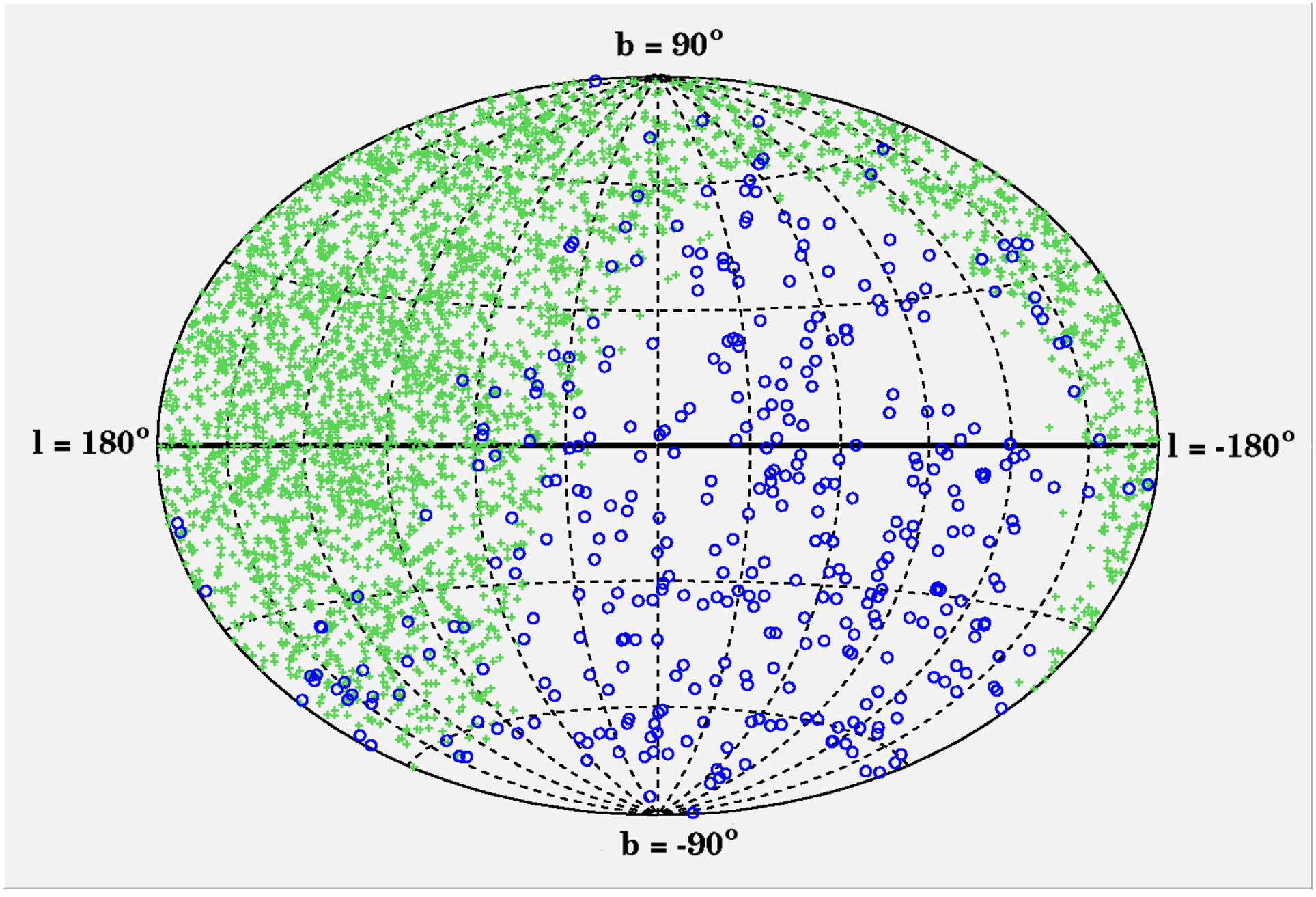
the best fit flavor composition disfavors 1:0:0 at source at 3.6 σ



SEARCH FOR POINT SOURCES

A reminescence:

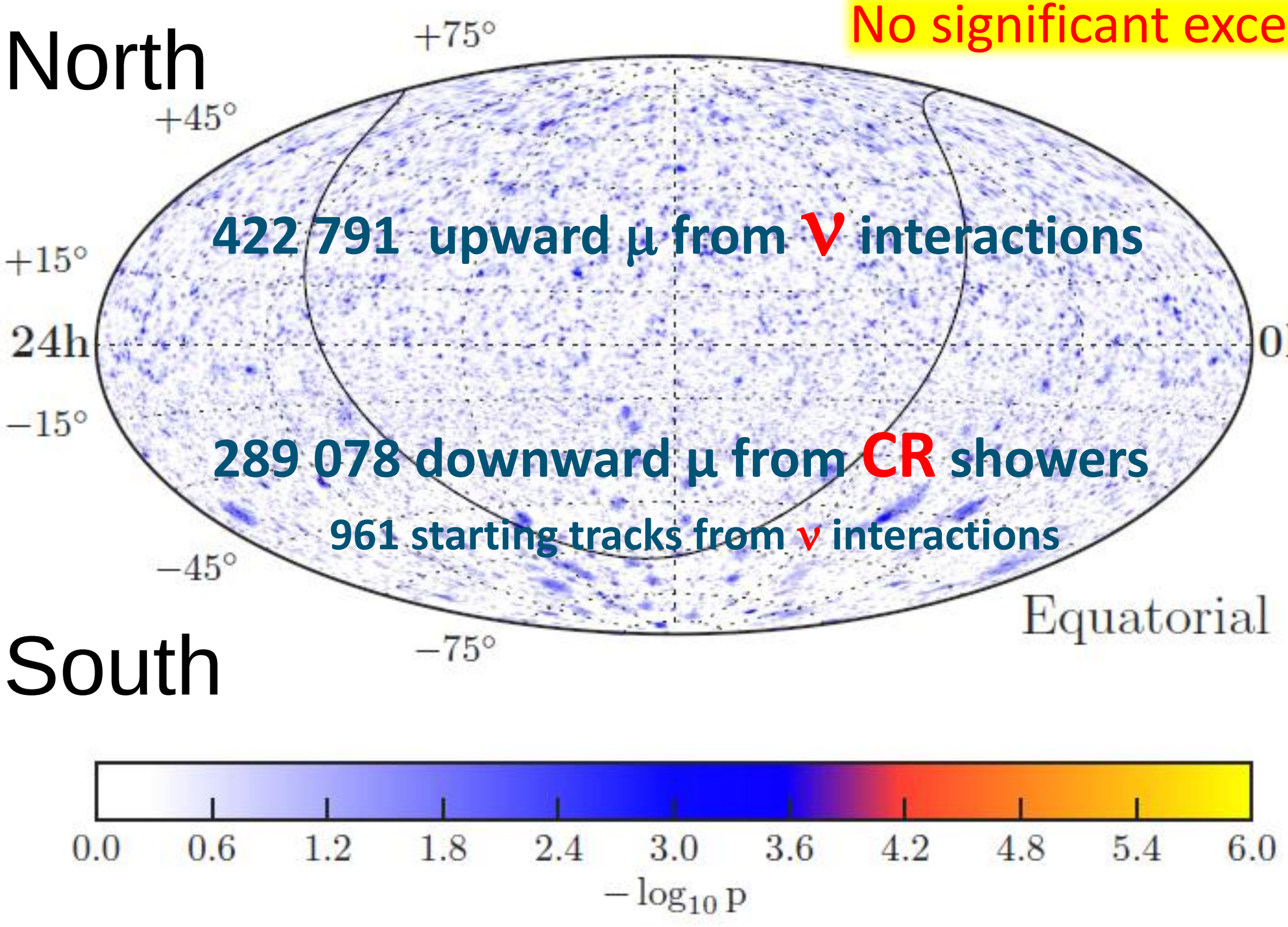
The first combined skymap Amanda + Baikal NT200, ~ 15 years ago



IceCube 7 years

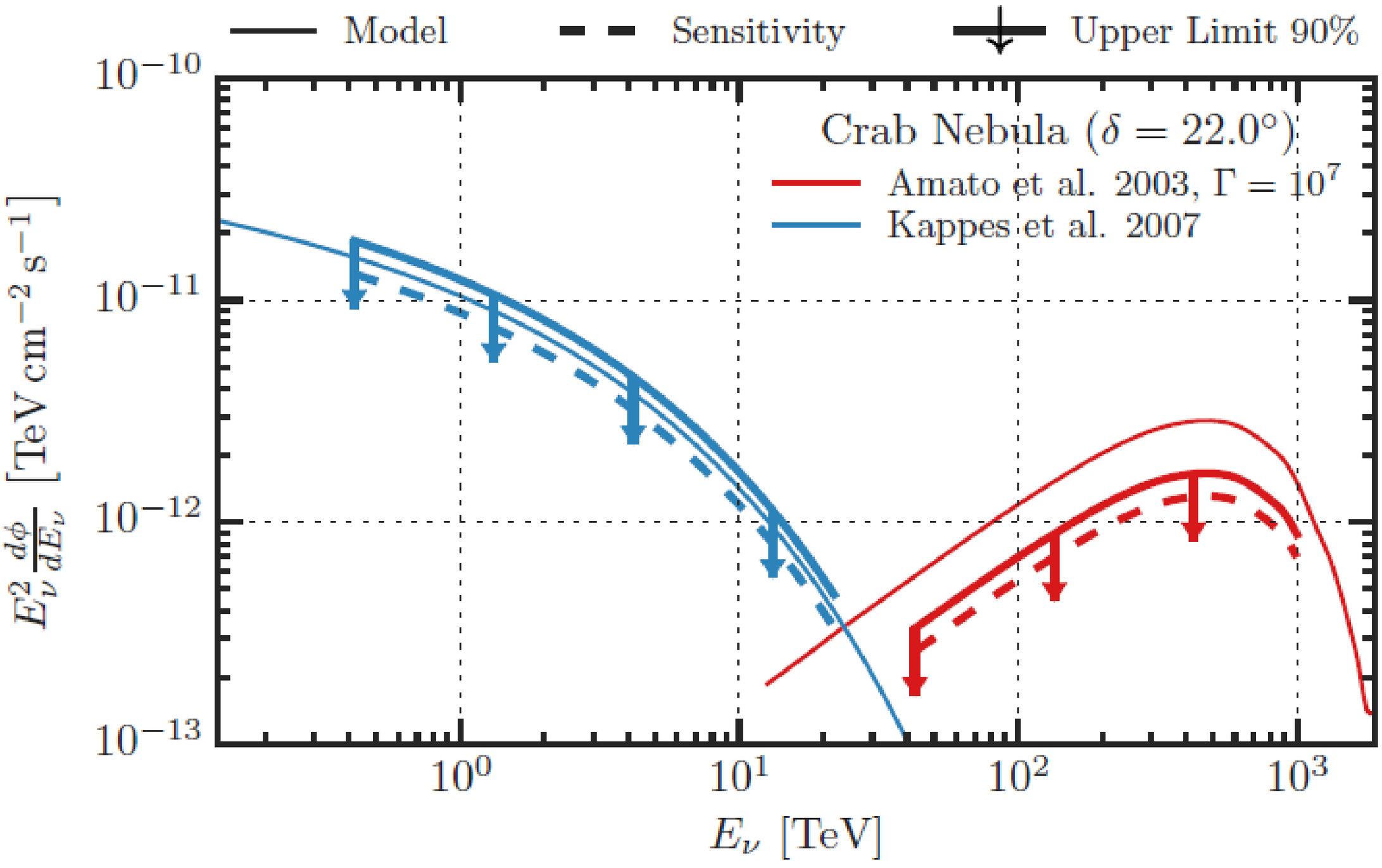
pre-trial significance skymap

No significant excesses



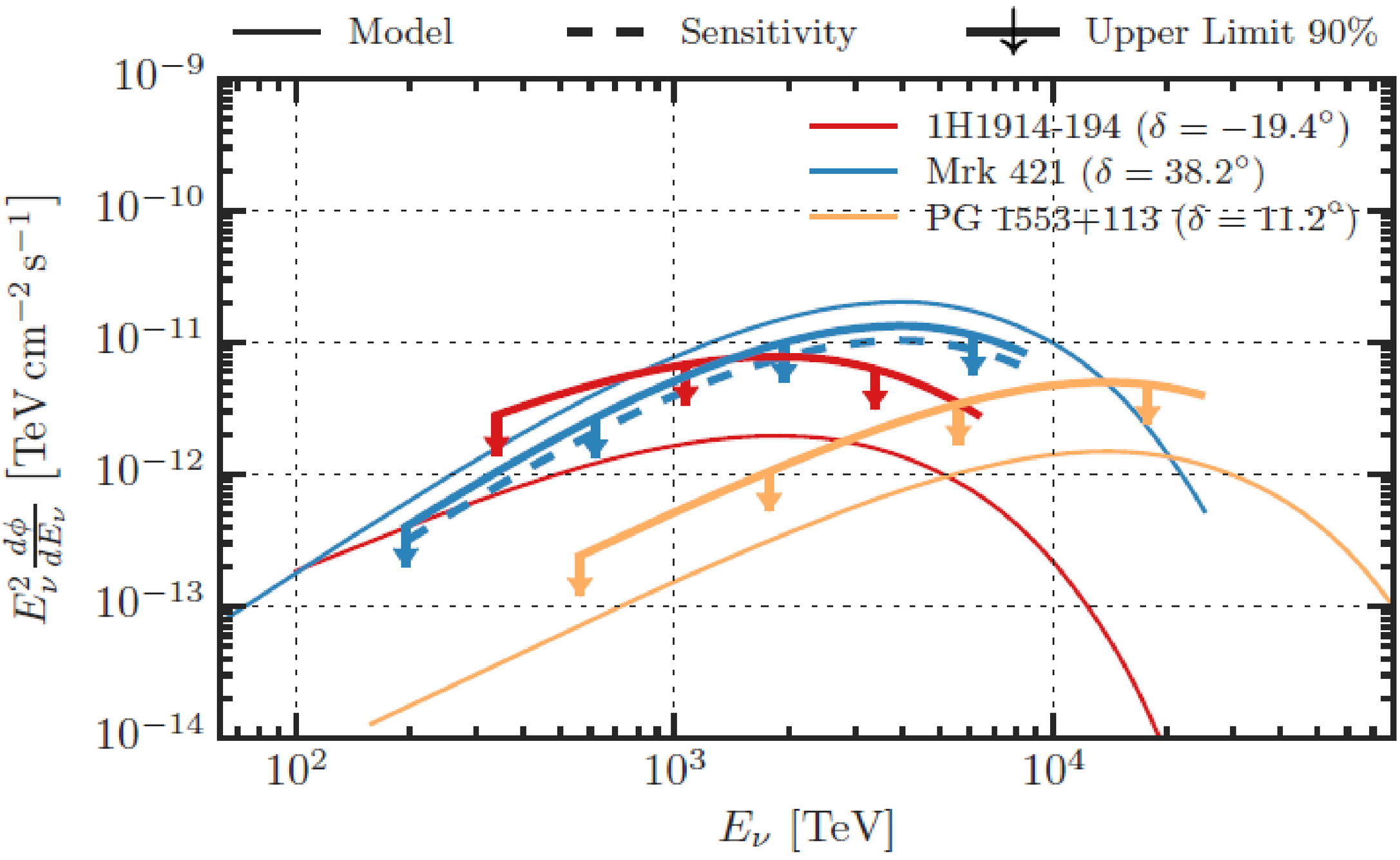
Limits vs. Models for selected sources

Crab Nebula

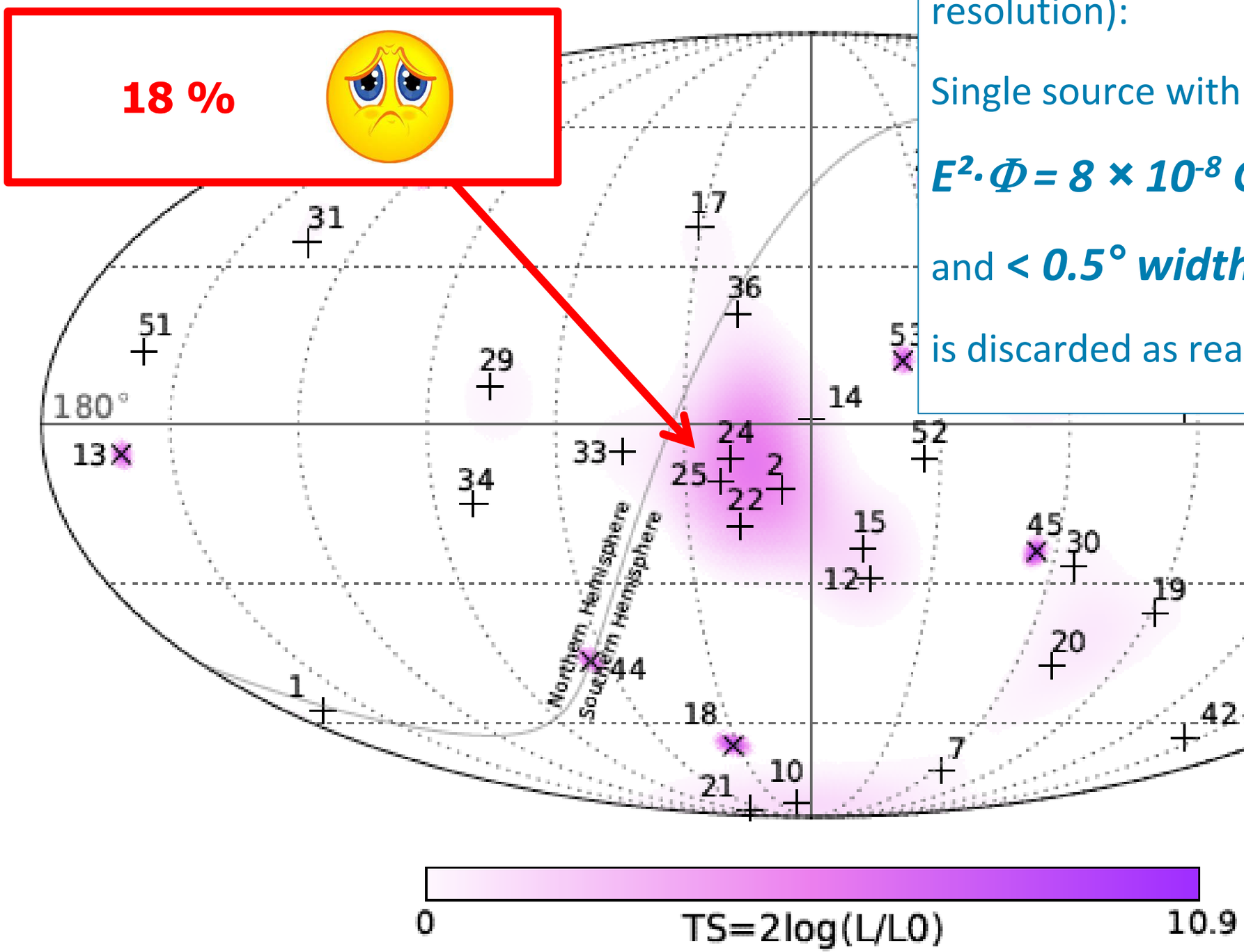


Limits vs. Models for selected sources

Blazars *(Petropolou et al. 2015)*



Also no source in HESE skyplot (4 years)



ANTARES (looking from the North at lower energies and with better angular resolution):

Single source with

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

and **< 0.5° width**

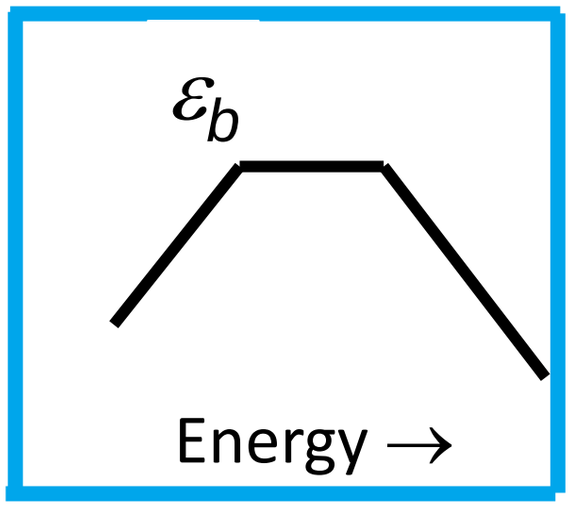
is discarded as reason for this „hot spot“.

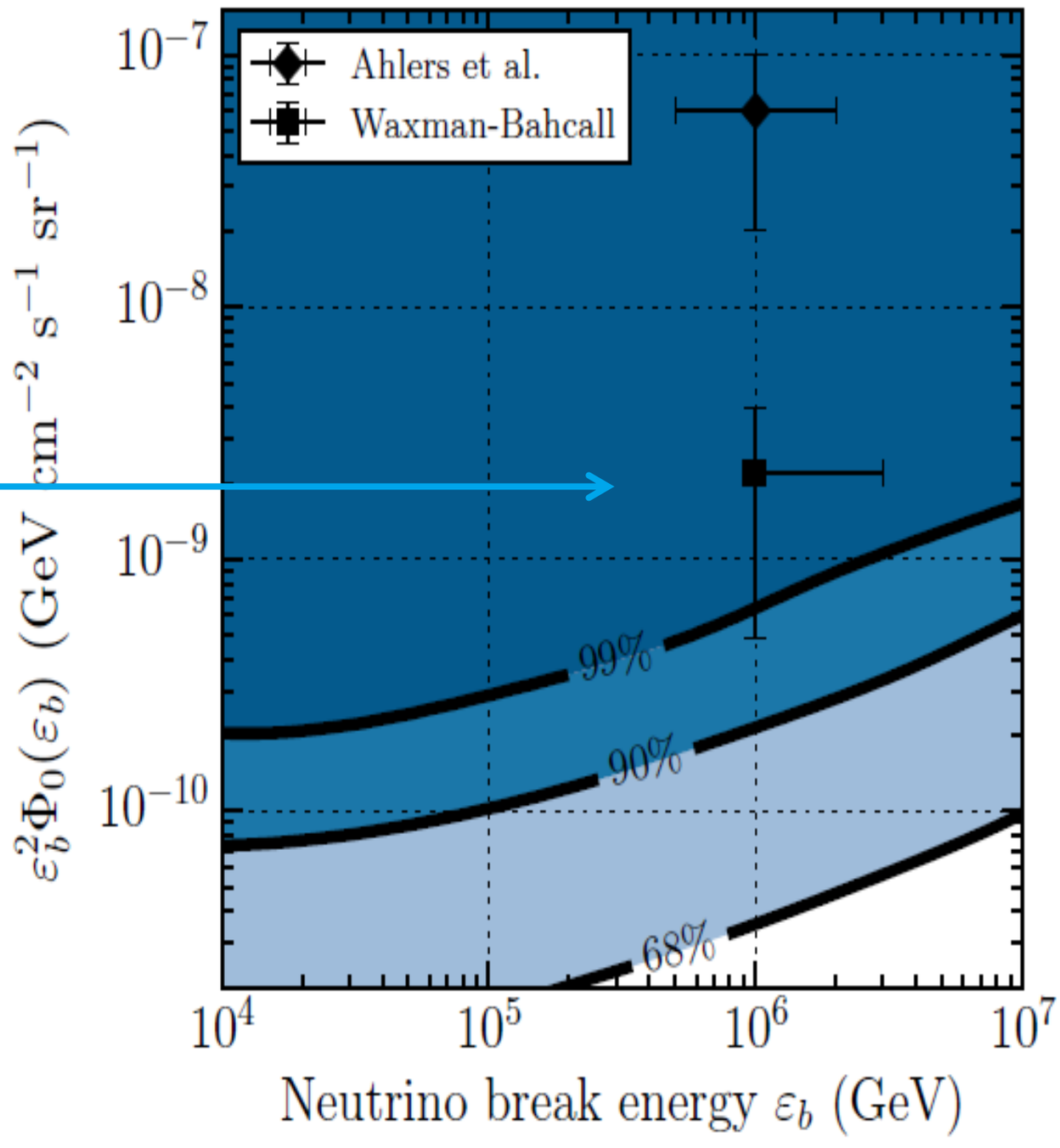
Transient sources: example GRB

Steadily improving limits from Baikal, AMANDA, ANTARES, IceCube

Latest IceCube result (2017):

- 1172 GRB
- Neutron escape models à la Ahlers ruled out.
- Waxman Bahcall model almost ruled out.





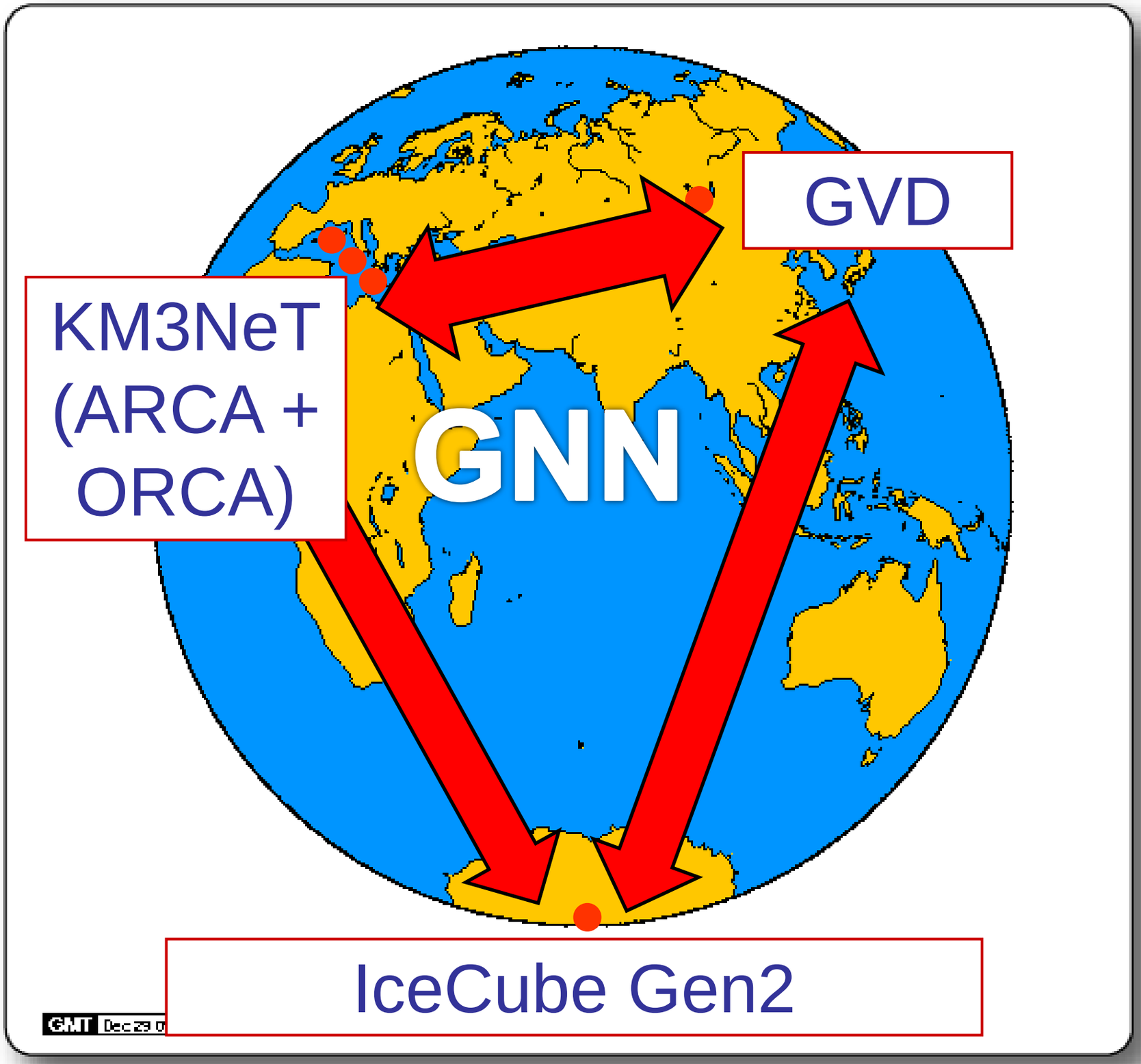
Summary of where we stand:

- **Cosmic high-energy ν discovered**
  - **New window opened, but landscape not yet charted: no point sources identified up to now**
  - **Remaining uncertainties on spectrum and flavor composition**
  - **Excluded GRB, Blazars, …. as sole source of HESE events**
  - **But: some individual sources seem to be in reach**
  - ***Don‘t forget: fascinating results on oscillation physics!***

We need detectors …

- … with different systematics
- … with better angular resolution
- … in North and South
- … larger area

Baikal, Mediterranean Sea, South Pole

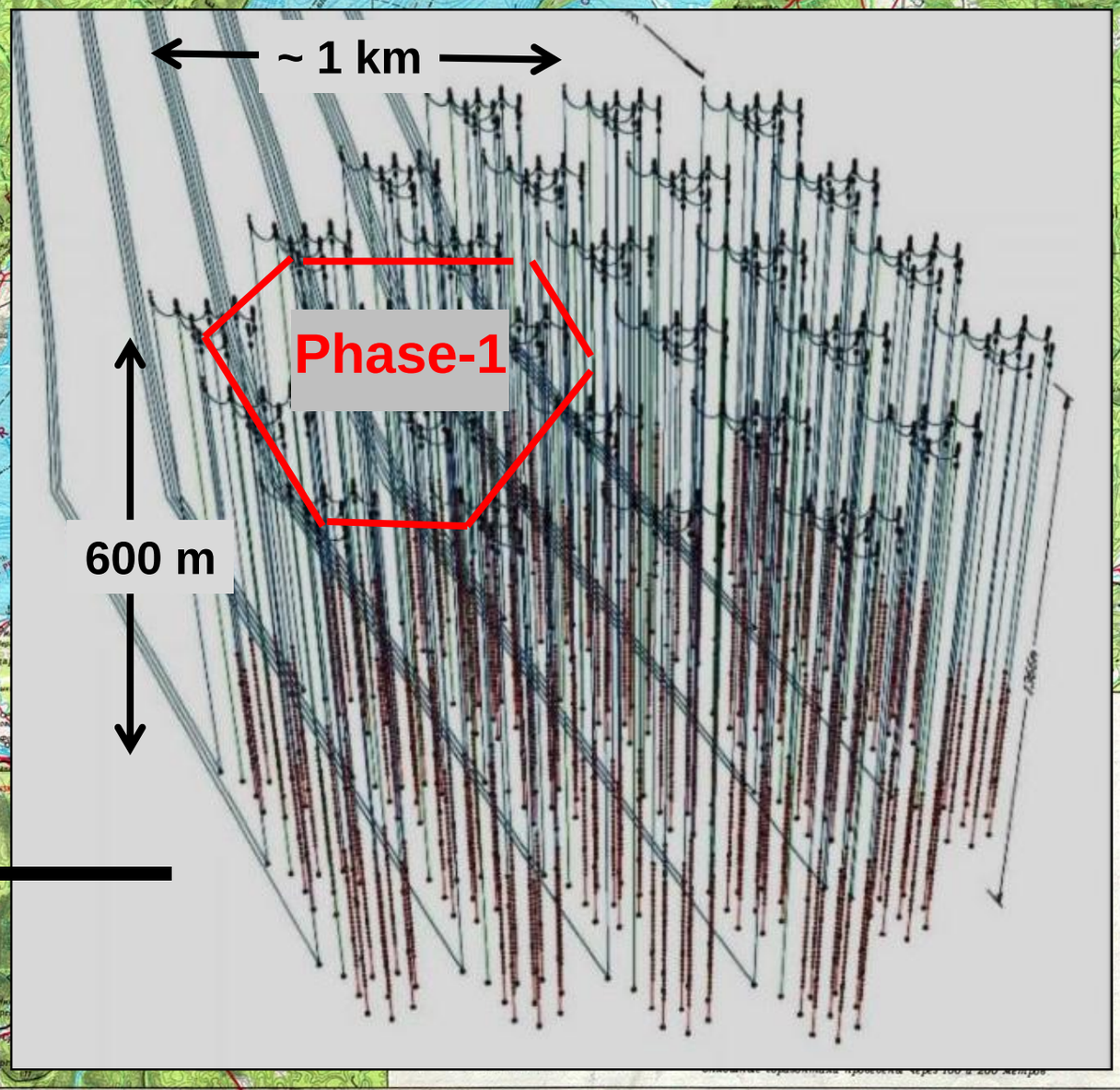


GIGATON VOLUME DETECTOR

BAIKAL GVD

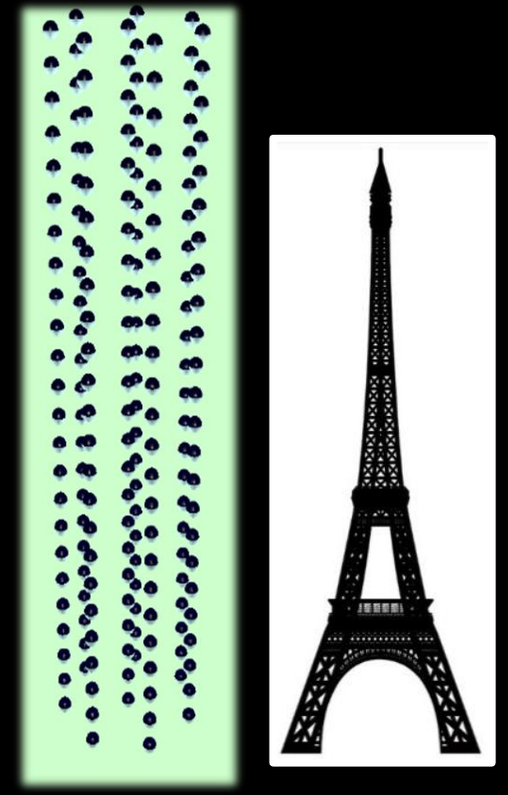
~ 60 authors

6 Russian, 1 Czech, 1 Slovakian and 1 Polish institution
(lead Institutions: INR Moscow and JINR Dubna)


~ 1 km
Phase-1
600 m

After 5 years of prototype tests:

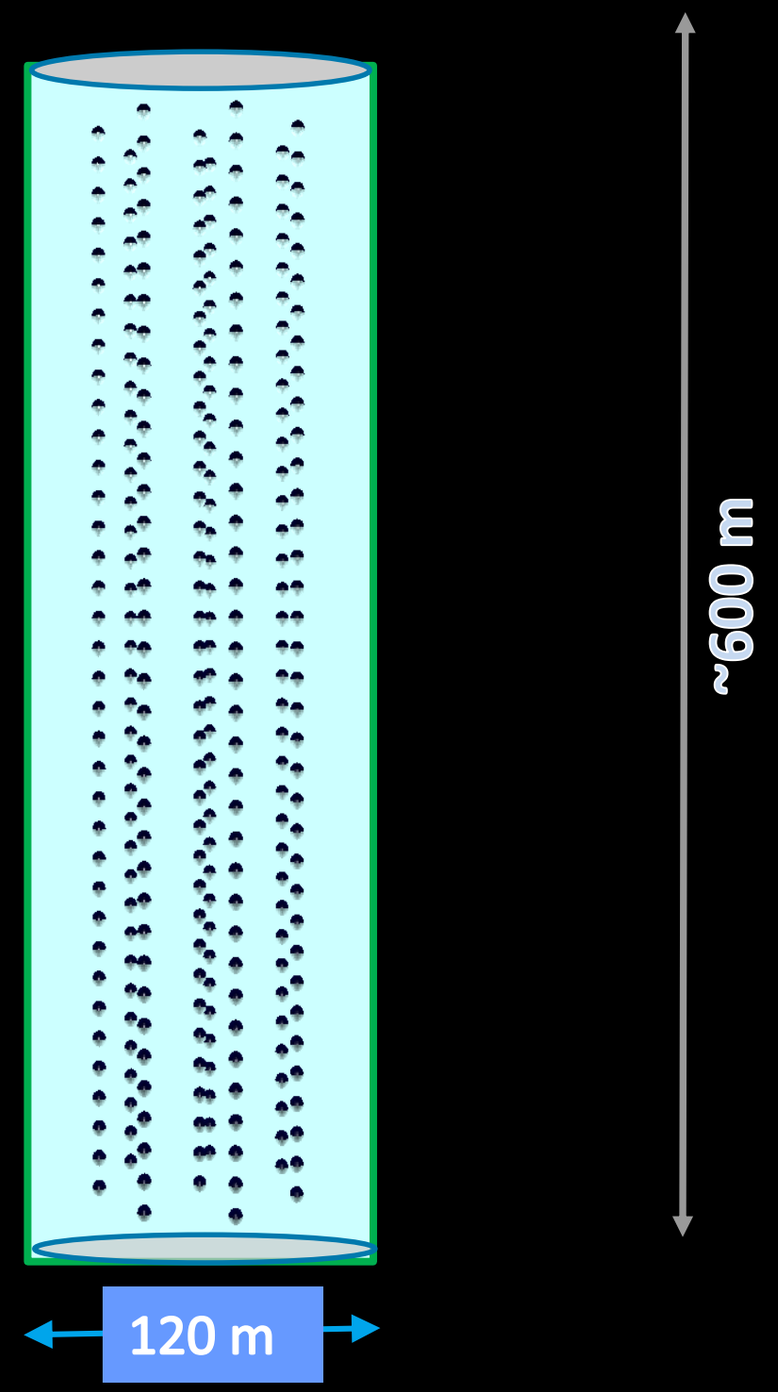
“Dubna”
Demonstration
cluster
April 2015



Old NT200:
volume ~ 0.0001 km³

GVD cluster:
0.006 km³
(Antares 0.015 km³)

Full scale cluster April 2016

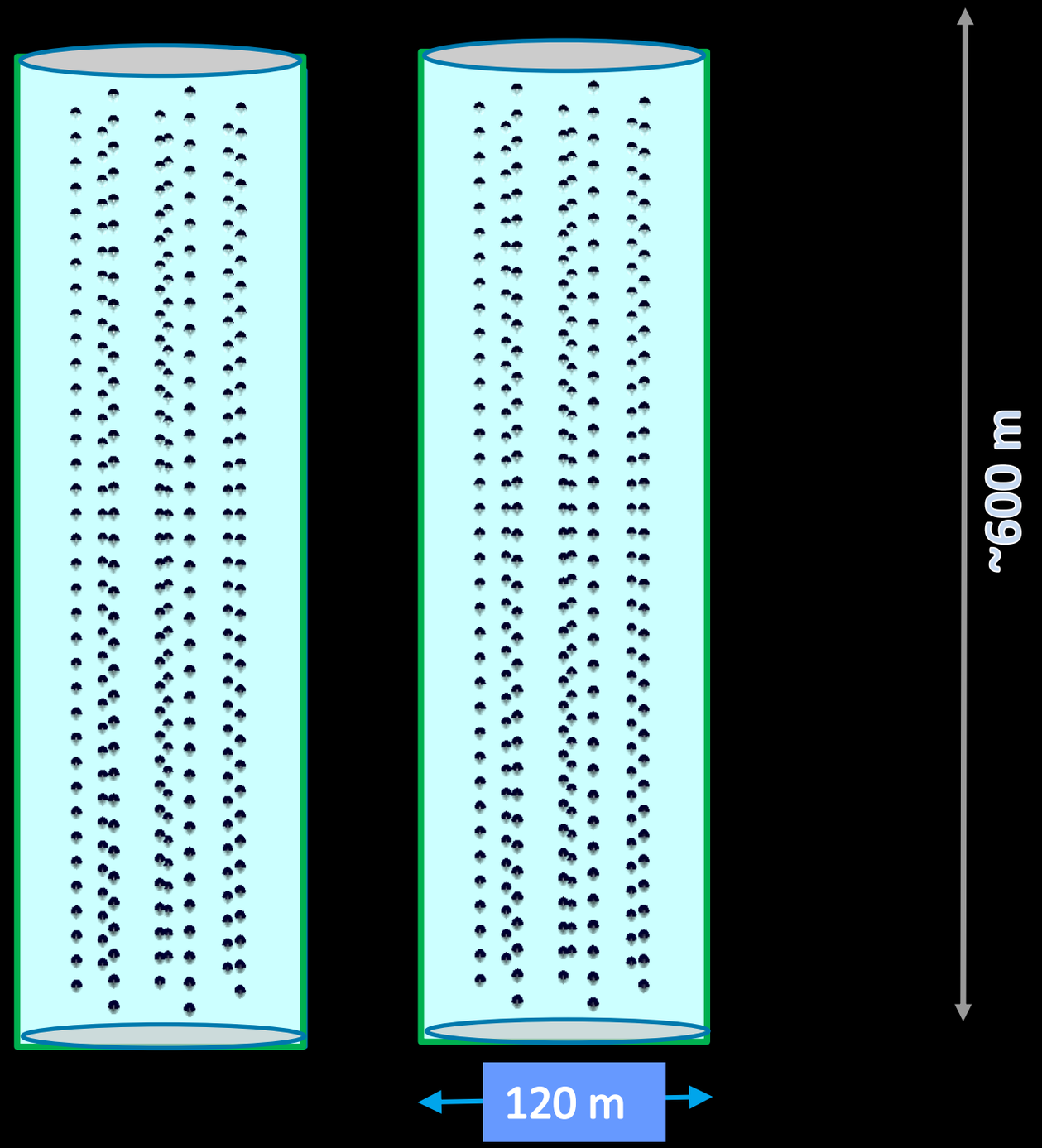


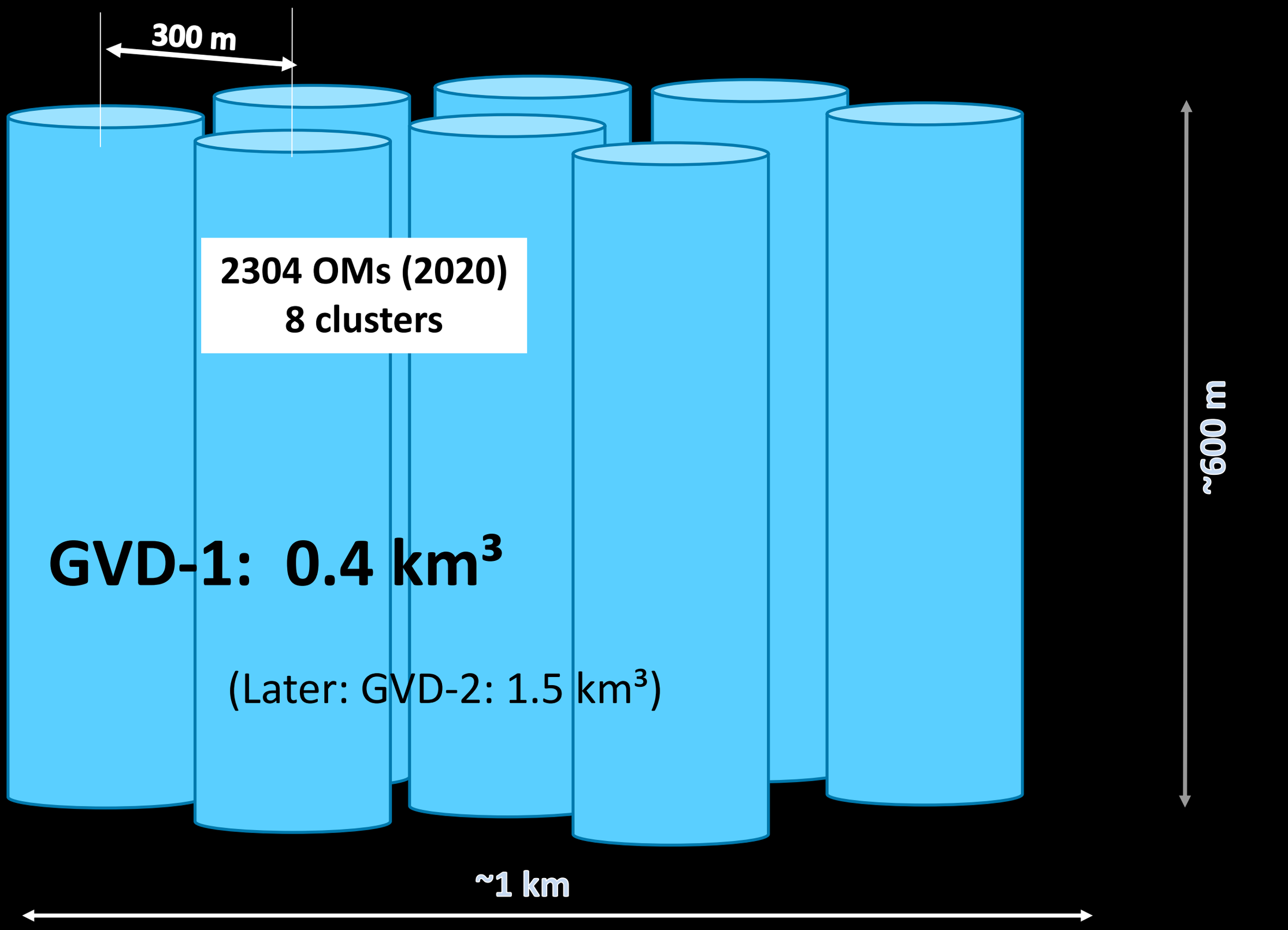
Old NT200:
volume ~ 0.0001 km³

GVD cluster:
0.006 km³
(Antares 0.015 km³)

2 GVD Clusters
0.012 – 0.04 km³

Second cluster April 2017
Both clusters taking data

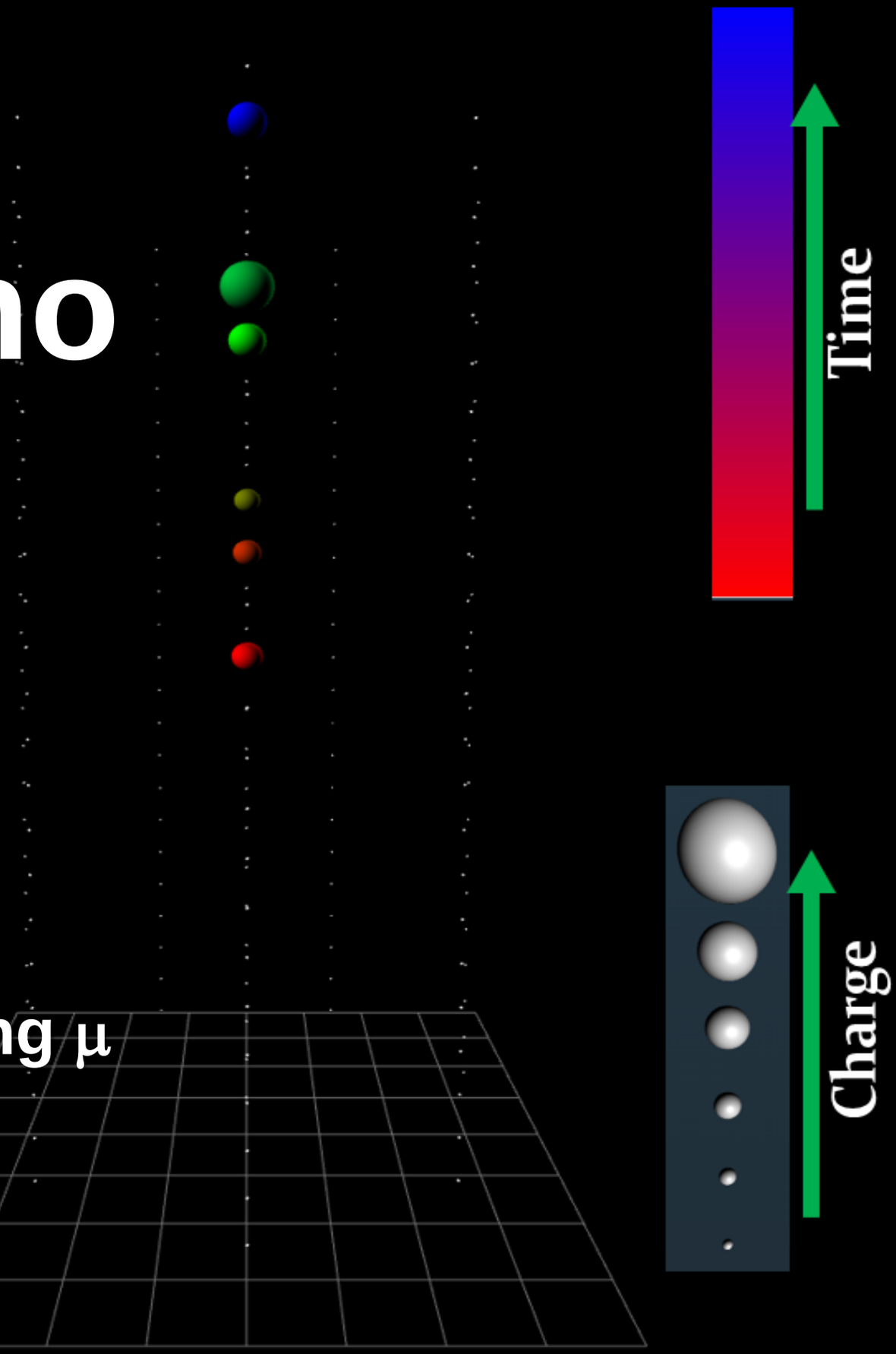



300 m
2304 OMs (2020)
8 clusters
GVD-1: 0.4 km³
(Later: GVD-2: 1.5 km³)
~600 m
~1 km

A clear muon neutrino candidate

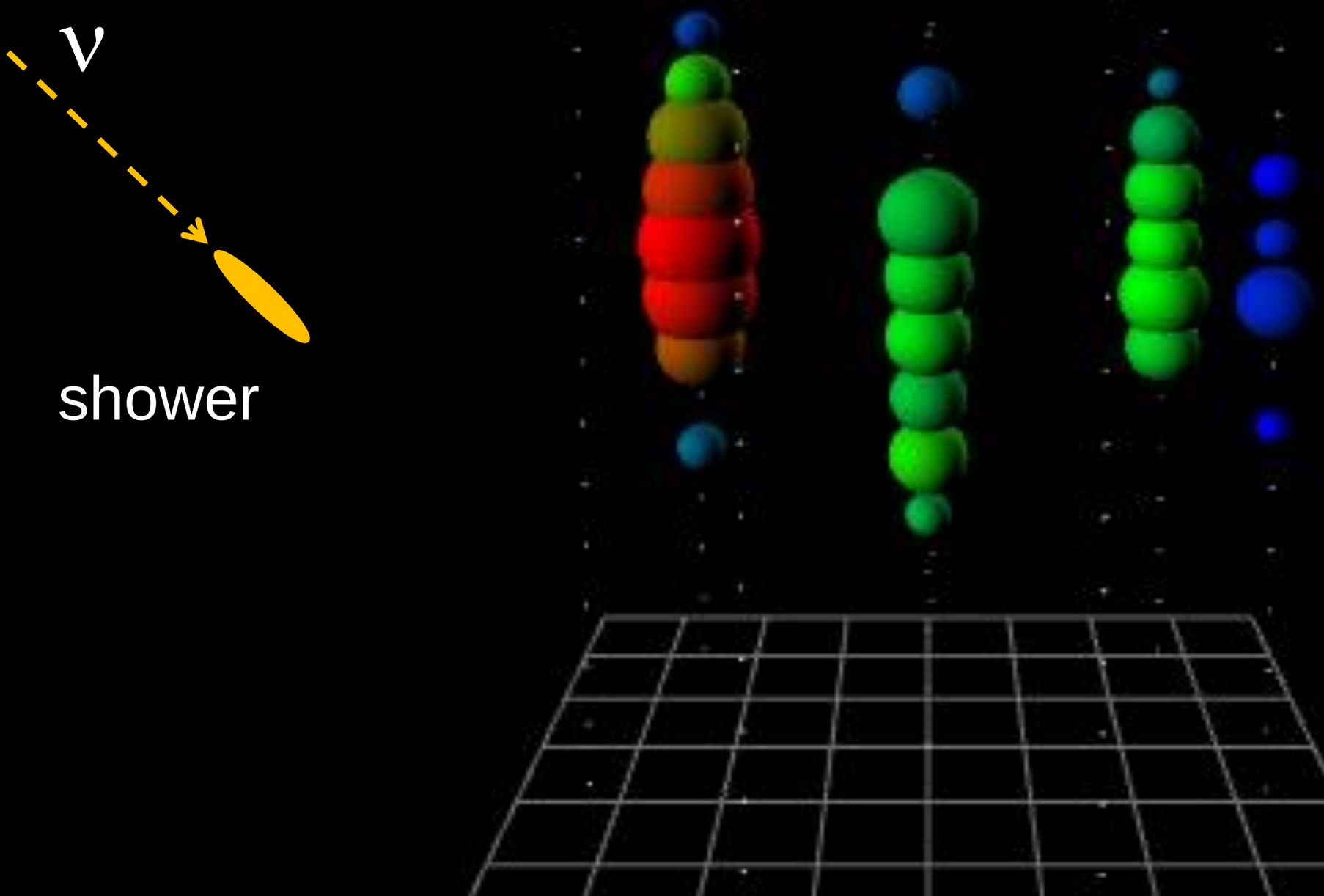
(Dubna cluster)

Single string. Upward moving μ



An interesting cascade event

E = 158 TeV, θ = 59°, ρ = 73 m (radius of *Dubna* cluster = 40 m)



GVD-1 timeline

Cumulative number of clusters vs. year

Year	2016	2017	2018	2019	2020
Nb. of clusters	*1*	*2*	*4*	*6*	*8*
Nb. of OMs	*288*	*576*	*1152*	*1728*	*2304*

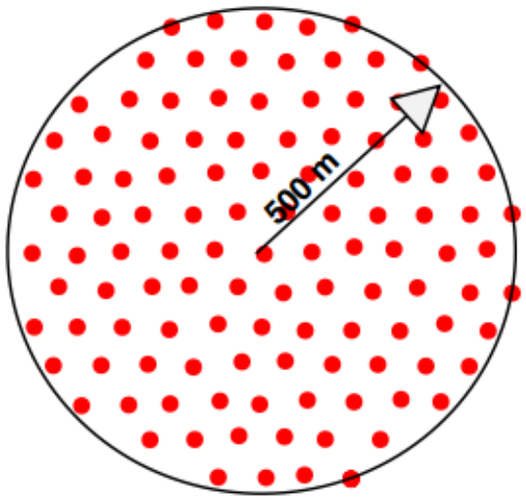
Effective volume GVD-1 for cascades ~ 0.4 km^3

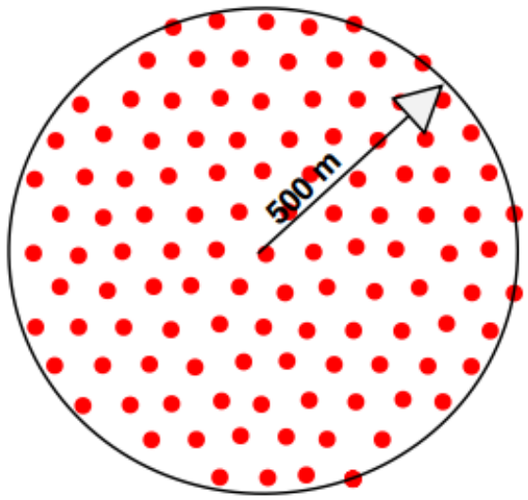
KM3NET

~ 400 authors

50 institutions in 15 countries
(lead Countries: Italy, France, The Netherlands)

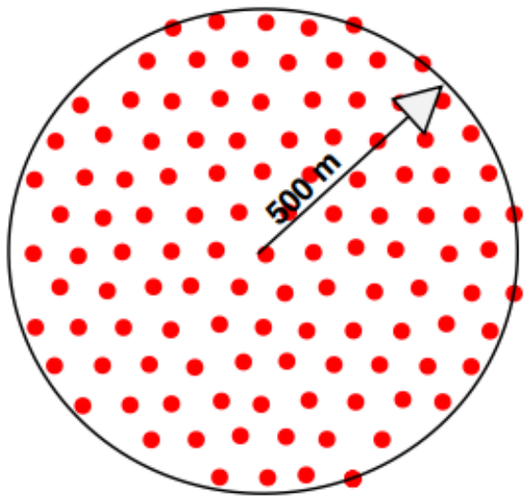
Original idea: 6 blocks at 3 locations: 6 x 0.6 km³

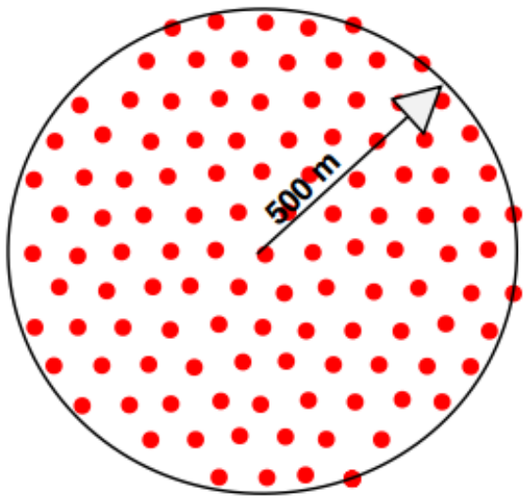




France

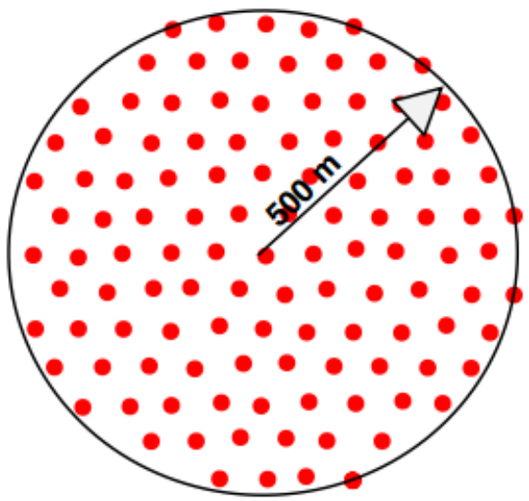
115 strings per block
18 DOMs per string
31 PMTs per DOM

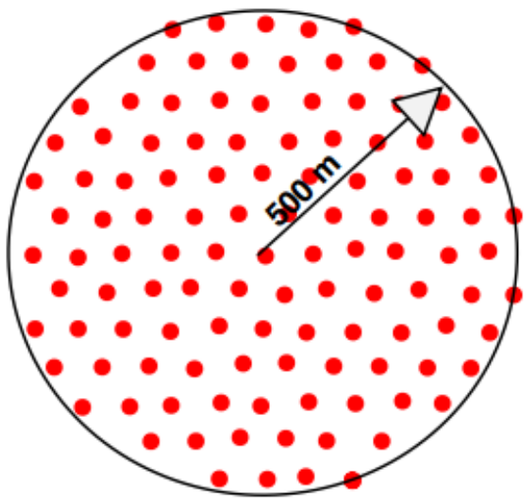




Italy

Greece

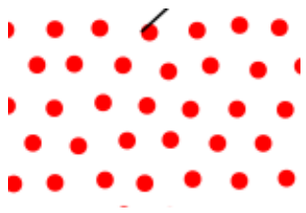




KM3NeT Phase 1: Prototype (2018)

France

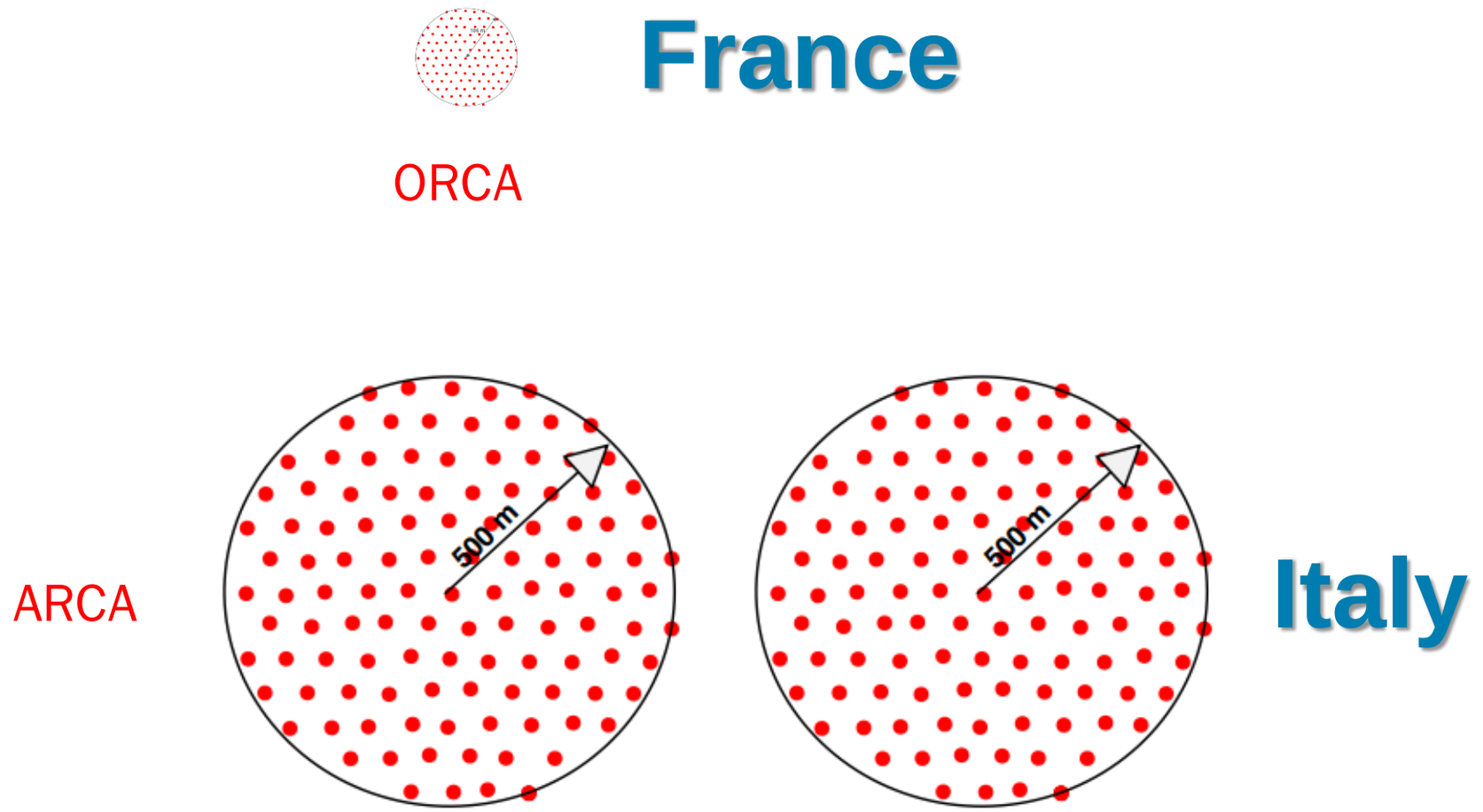
7 strings, small spacing
- Feasibility test for ORCA



Italy

24 strings, 124 m spacing
- Demonstrate principle
- Physics on the 3-4 times Antares scale

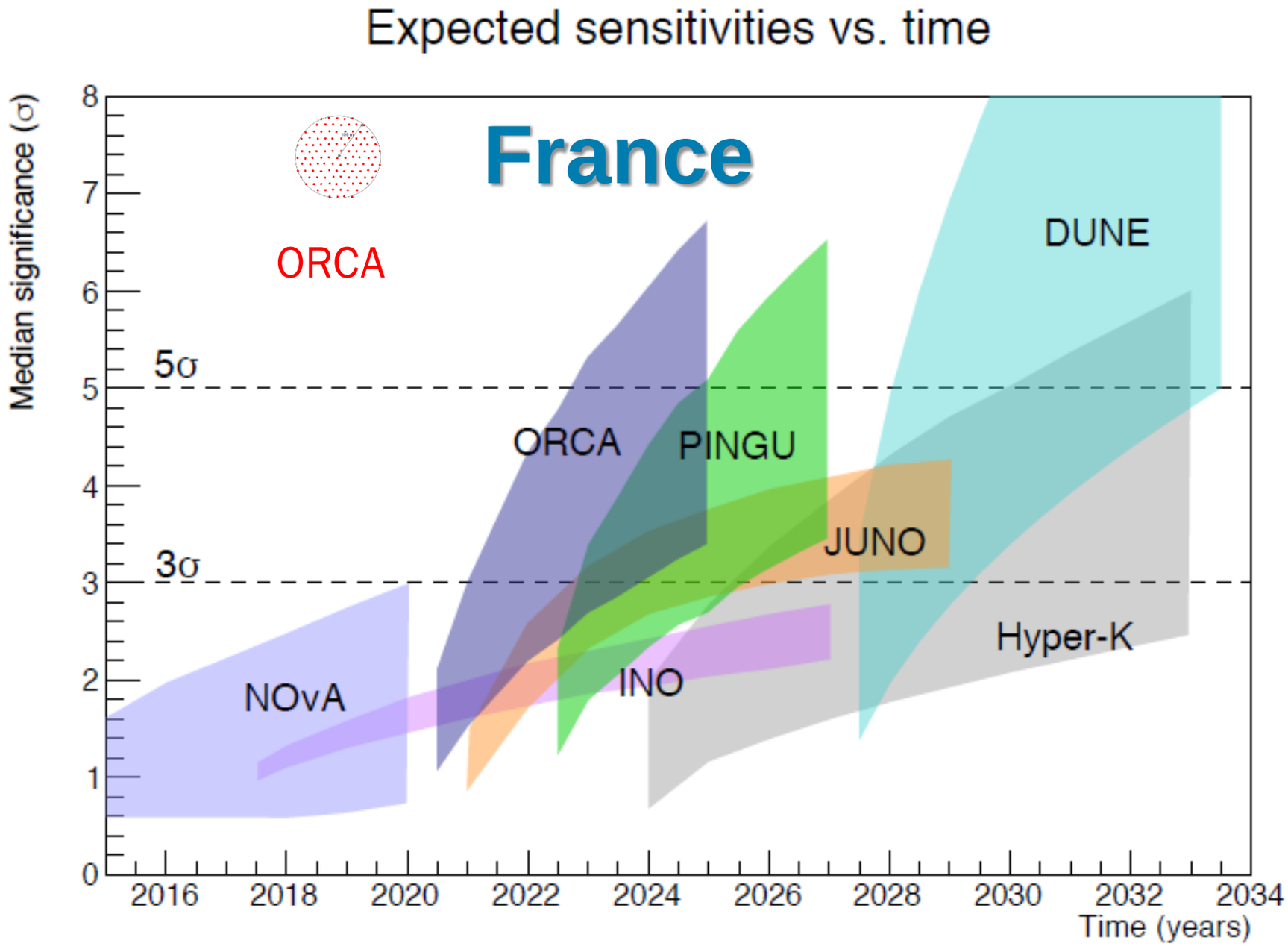
KM3NeT Phase 2: ORCA and ARCA (2021)



ORCA: determination of the Neutrino Mass Hierarchy (NMH)

ARCA: IceCube physics, but with better angular resolution and from the Northern hemisphere

KM3NeT Phase 2: ORCA



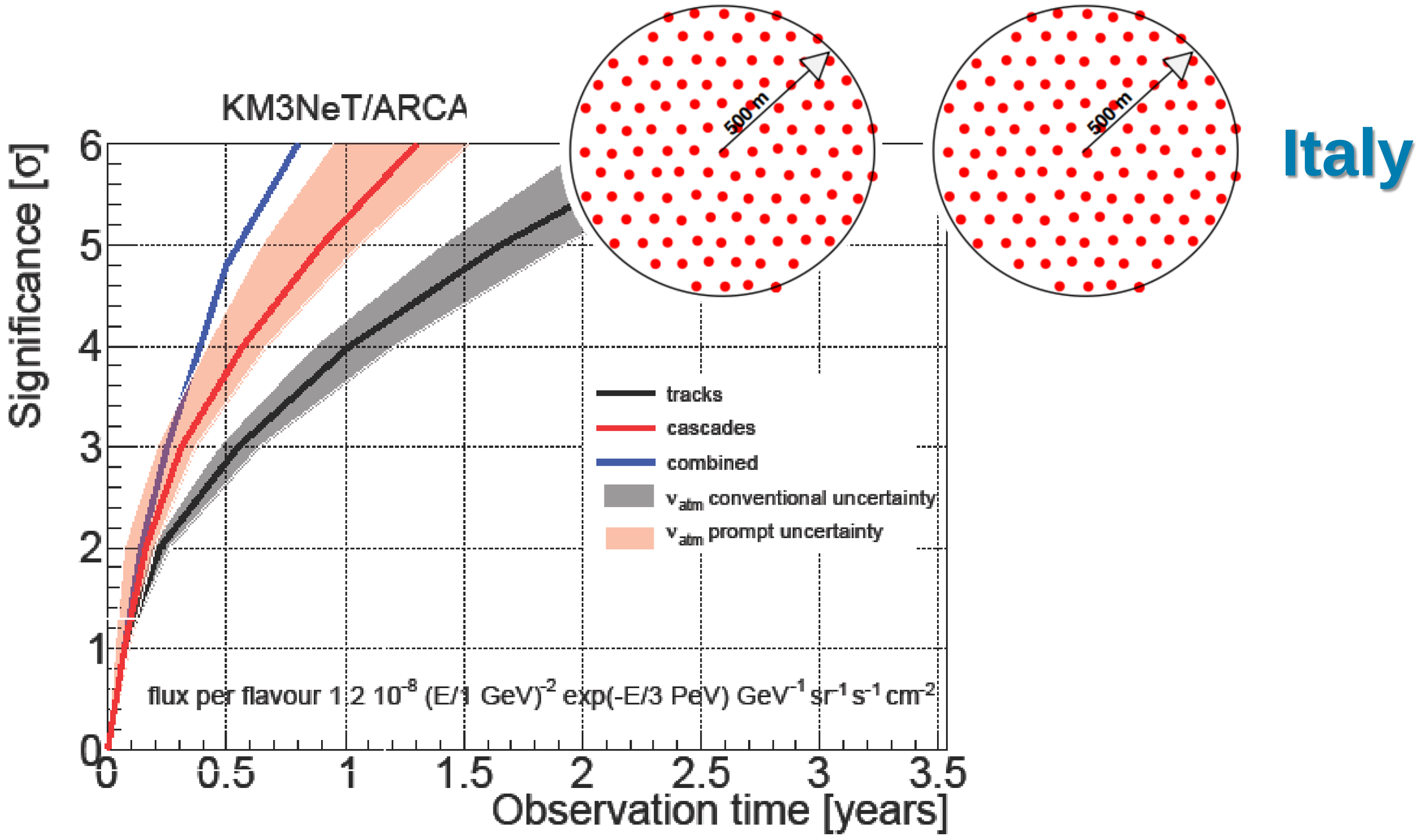
ORCA: determination of the Neutrino Mass Hierarchy (NMH)

Time schedules have to be taken with a grain of salt!

NMH sensitivity of ORCA/PINGU depends on the octant of θ_{23} (lower values for 1st octant), that of JUNO on energy resolution (lower values for 3.5%, upper for 3%), that for DUNE on the δ_{CP} value.

Compilation by p.Coyle, based on the original one of Blennow et al.

KM3NeT Phase 2: ARCA



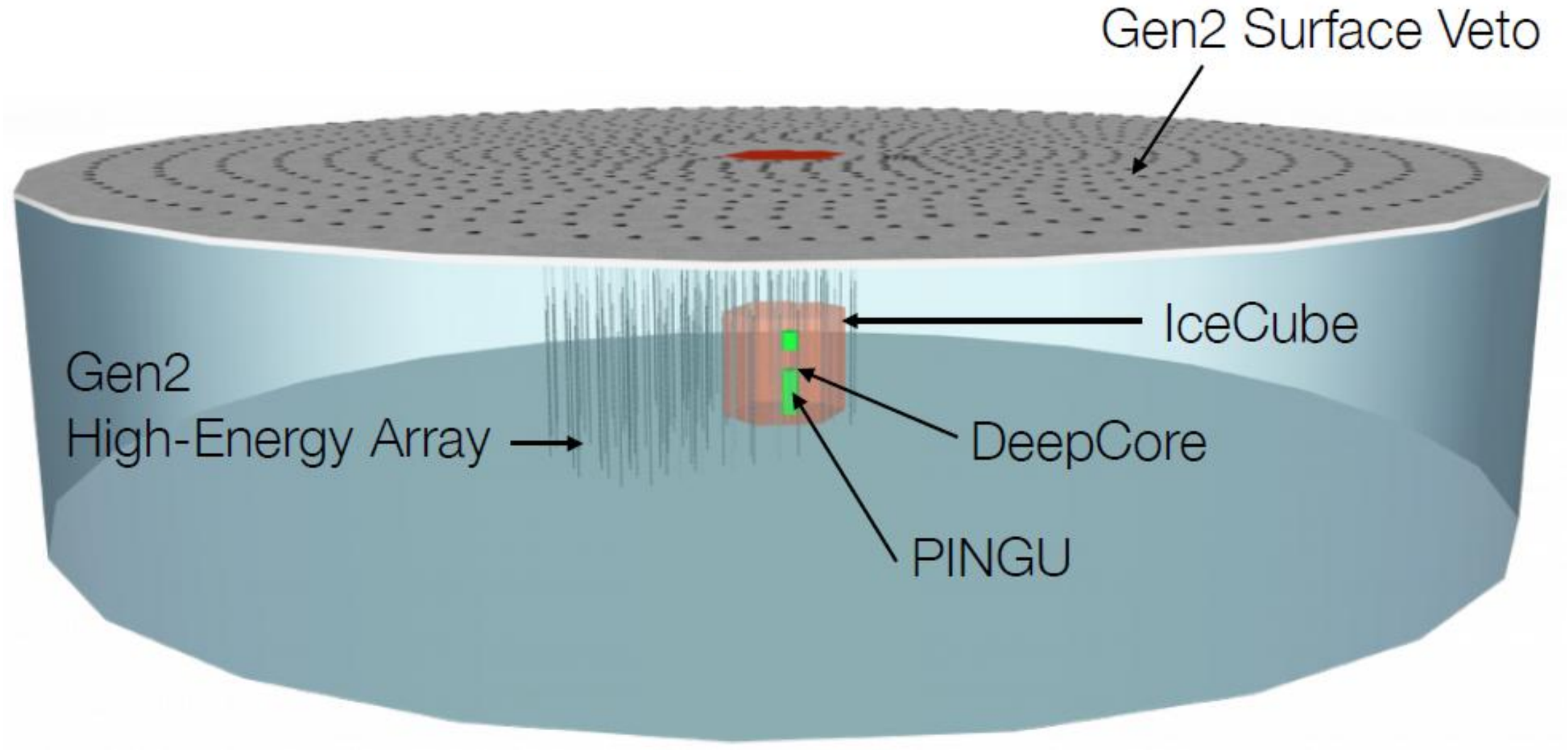
ARCA: IceCube physics, but with better angular resolution and from the Northern hemisphere

ICECUBE GEN2

~ 400 scientists

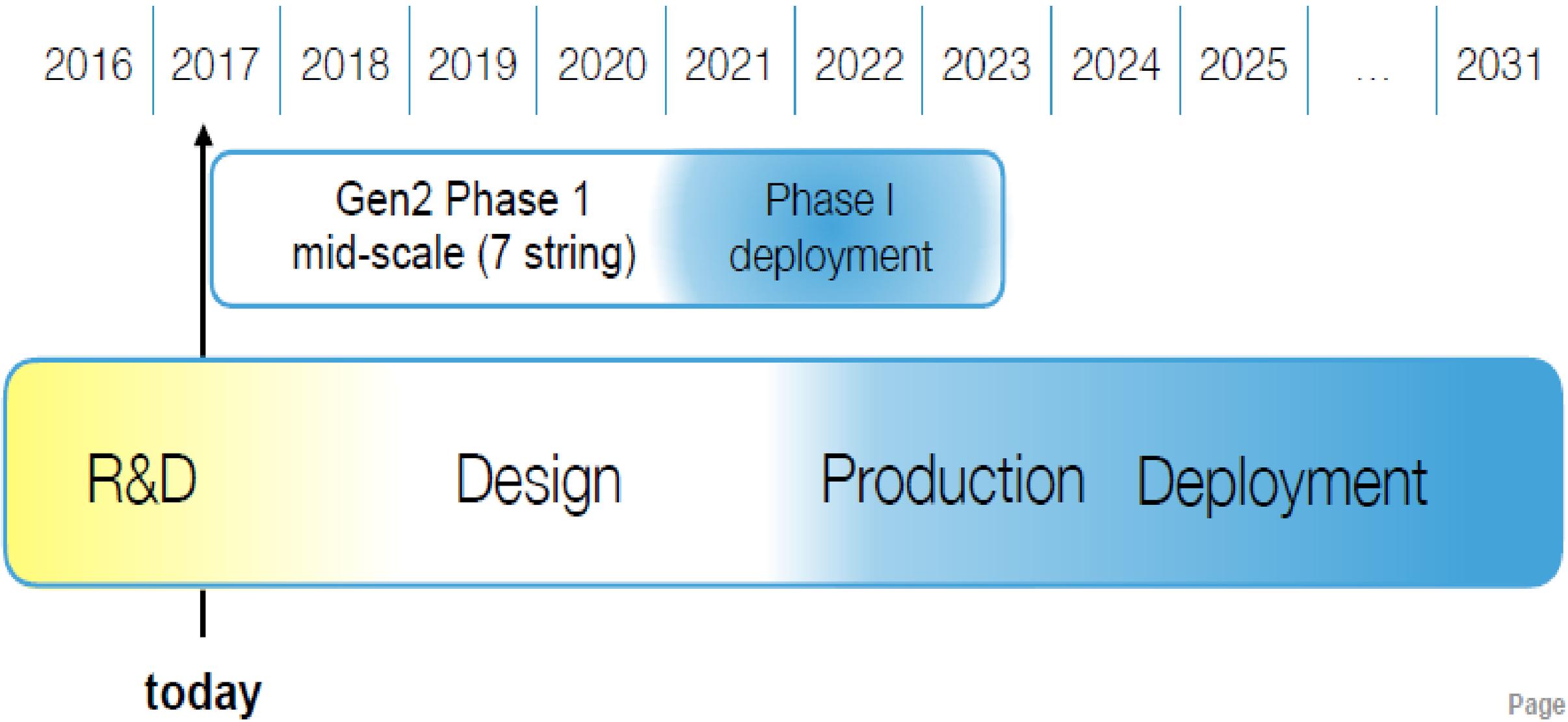
~50 institutions in 12 countries
(lead Institutions U. Wisconsin, DESY)

IceCube Gen2

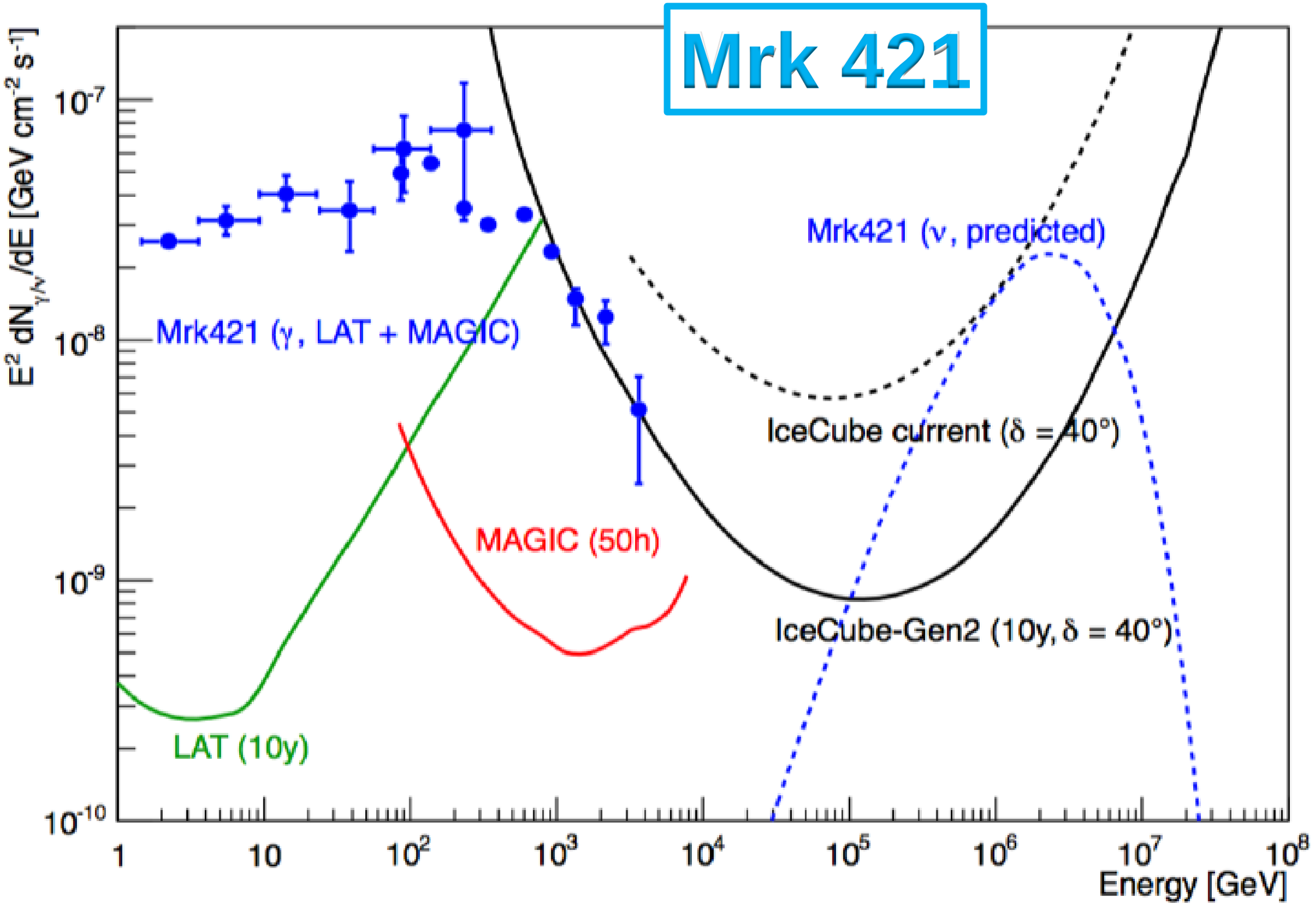


- **PINGU :** GeV scale, ν mass hierarchy
- **High Energy Array:** PeV scale , ν astronomy
- **Surface array:** Veto array for HEA , cosmic ray physics
- **Radio Array:** > 100 PeV, BZ (GZK) neutrinos

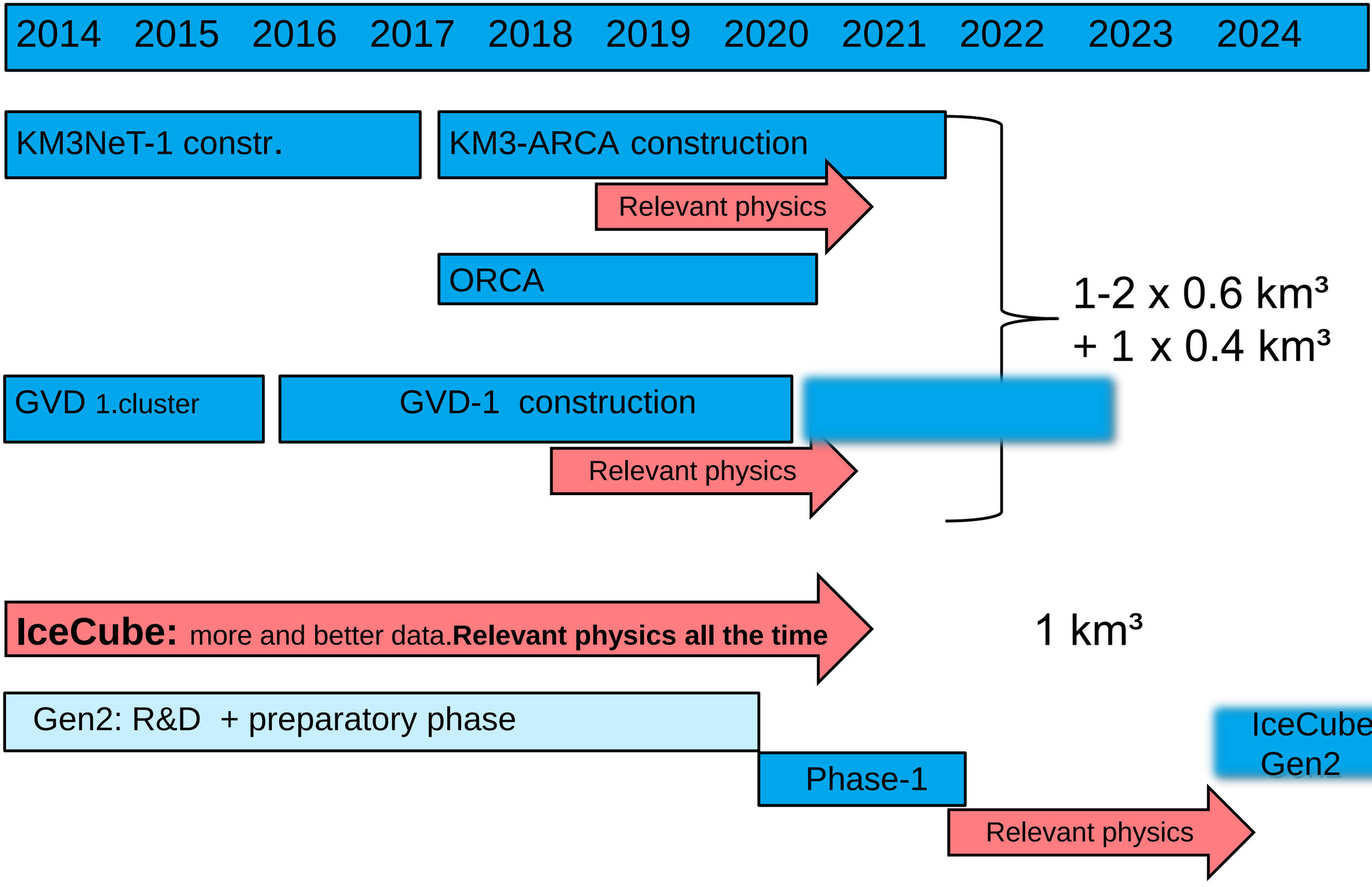
Gen2: Tentative time scale



Gen2: Example for point source sensitivity



Global timeline



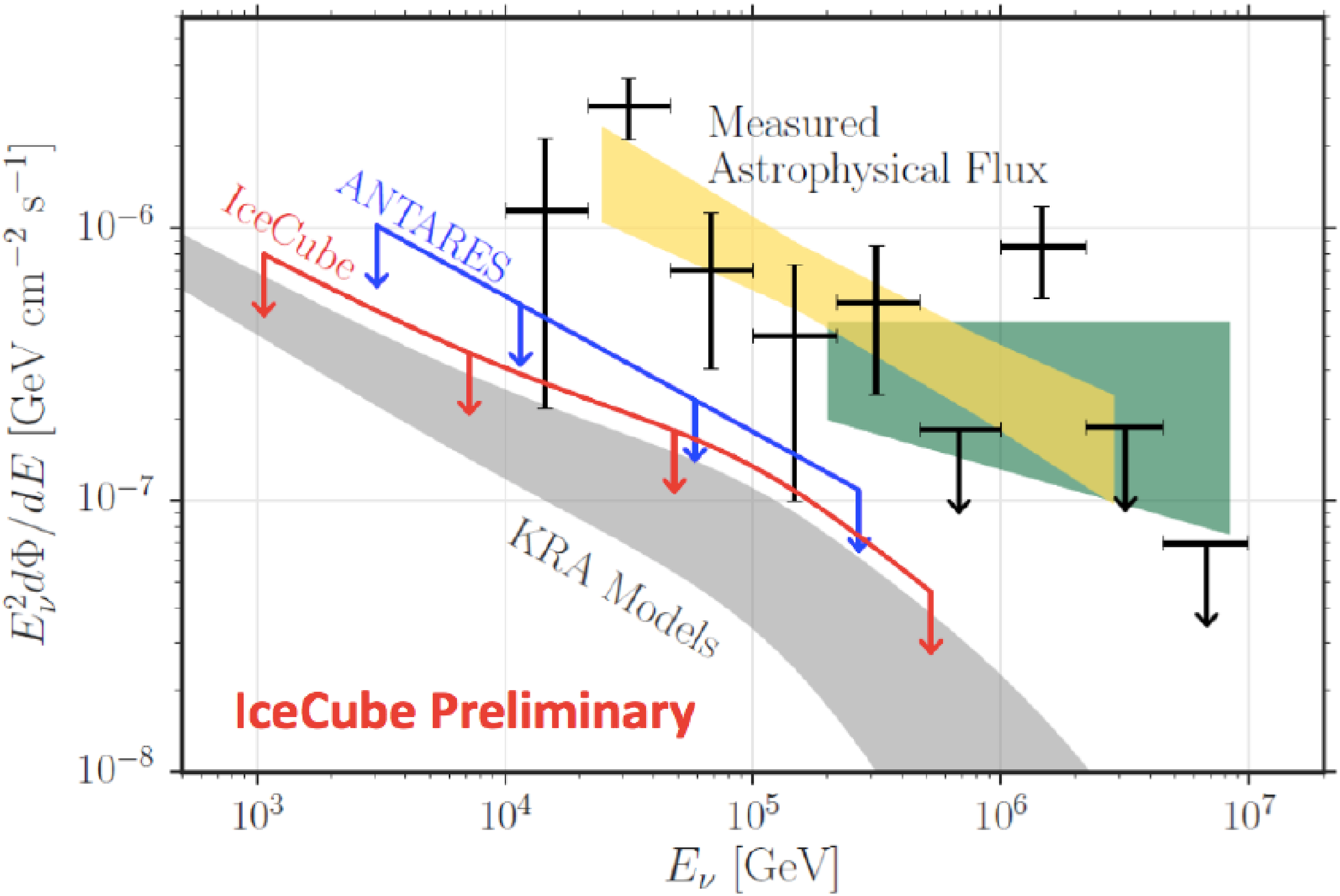
Summary of where we go

- ≥ 2020:
  Baikal GVD-1 and KM3NeT-ARCA will scrutinize IceCube results on diffuse fluxes with different systematics.

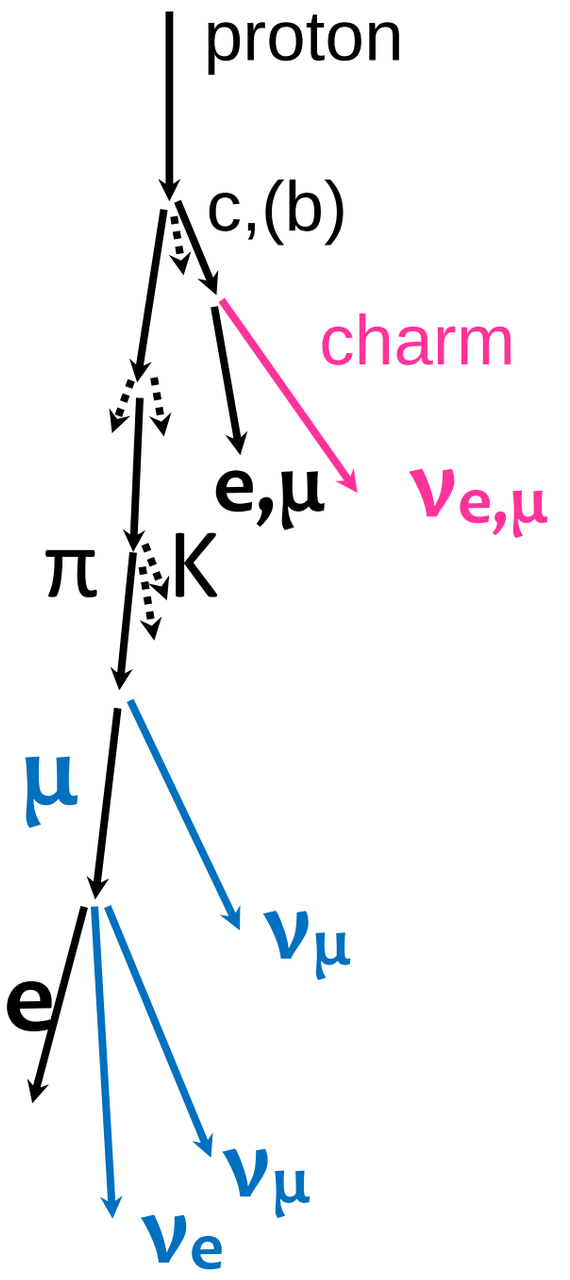
  IceCube with more statistics, and GVD-1, ARCA will measure the ν flux from the Galactic plane and *very likely* identify individual sources.
- End of the 2020s:
  Hope to have 5-7 km^3 in the North (GVD-2 and full ARCA) and 7-10 km^3 in the South (IceCube Gen2)
- Start full ν astronomy (individual sources, spectra)
- *And don‘t forget: particle physics (oscillation physics, ...) !*

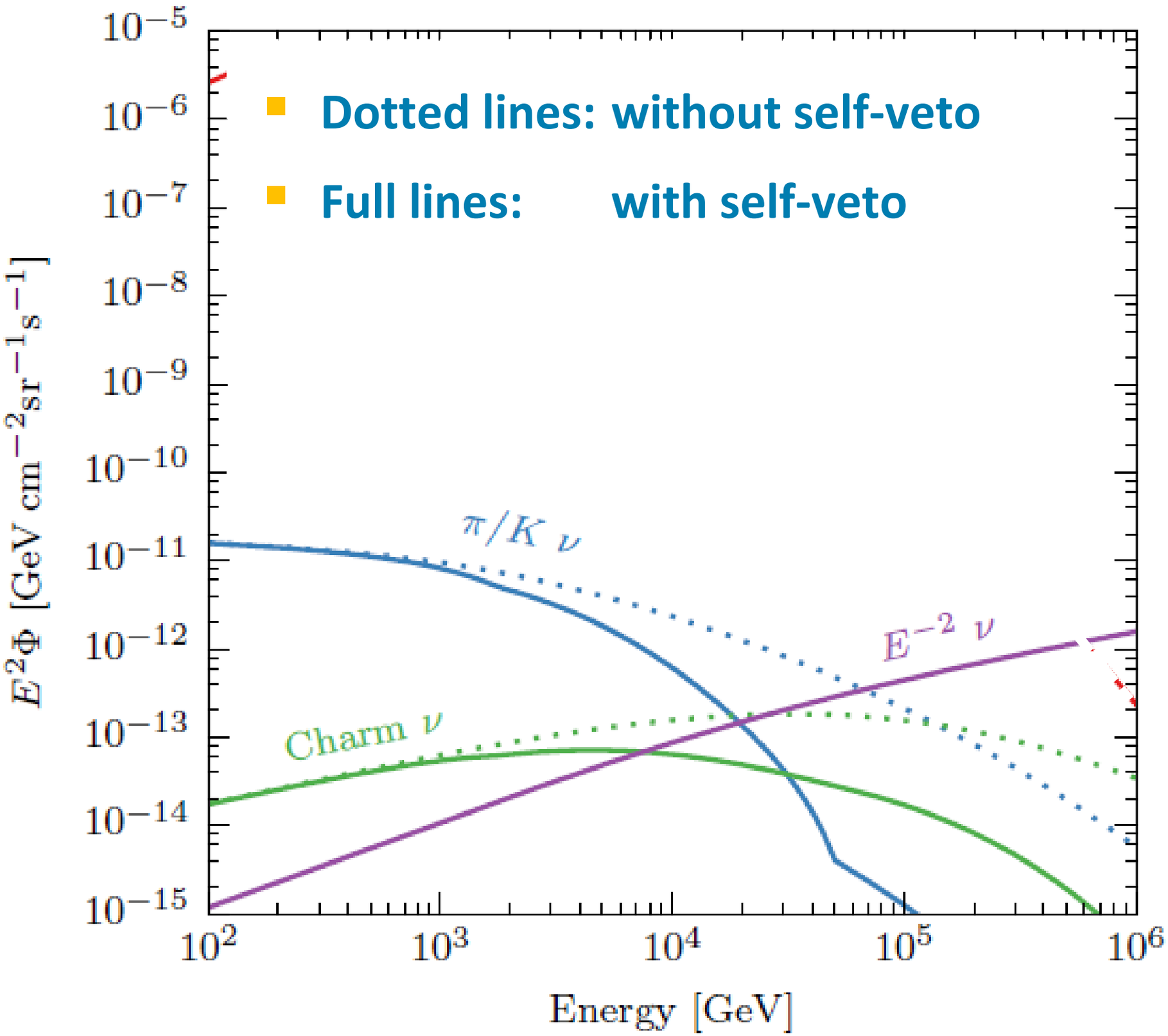
THANK YOU FOR YOUR ATTENTION

Galactic Plane emission (from CR interactions with dust)



Rejection of atmospheric μ and ν by „selfveto“





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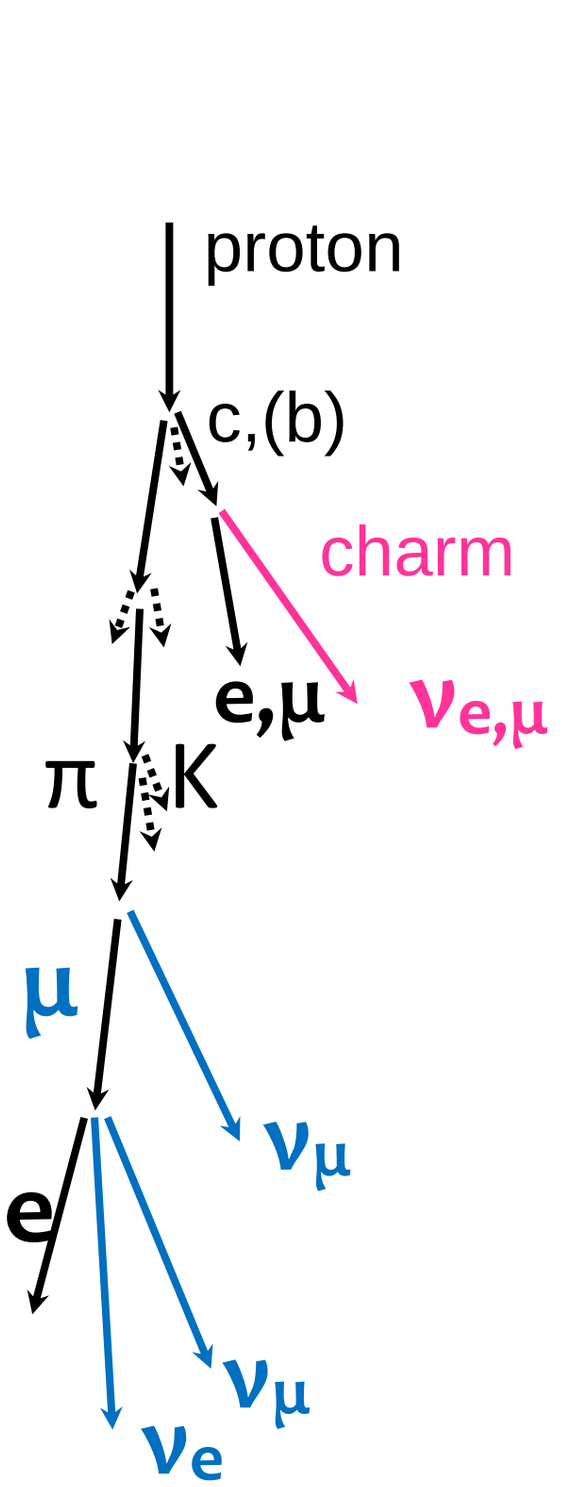
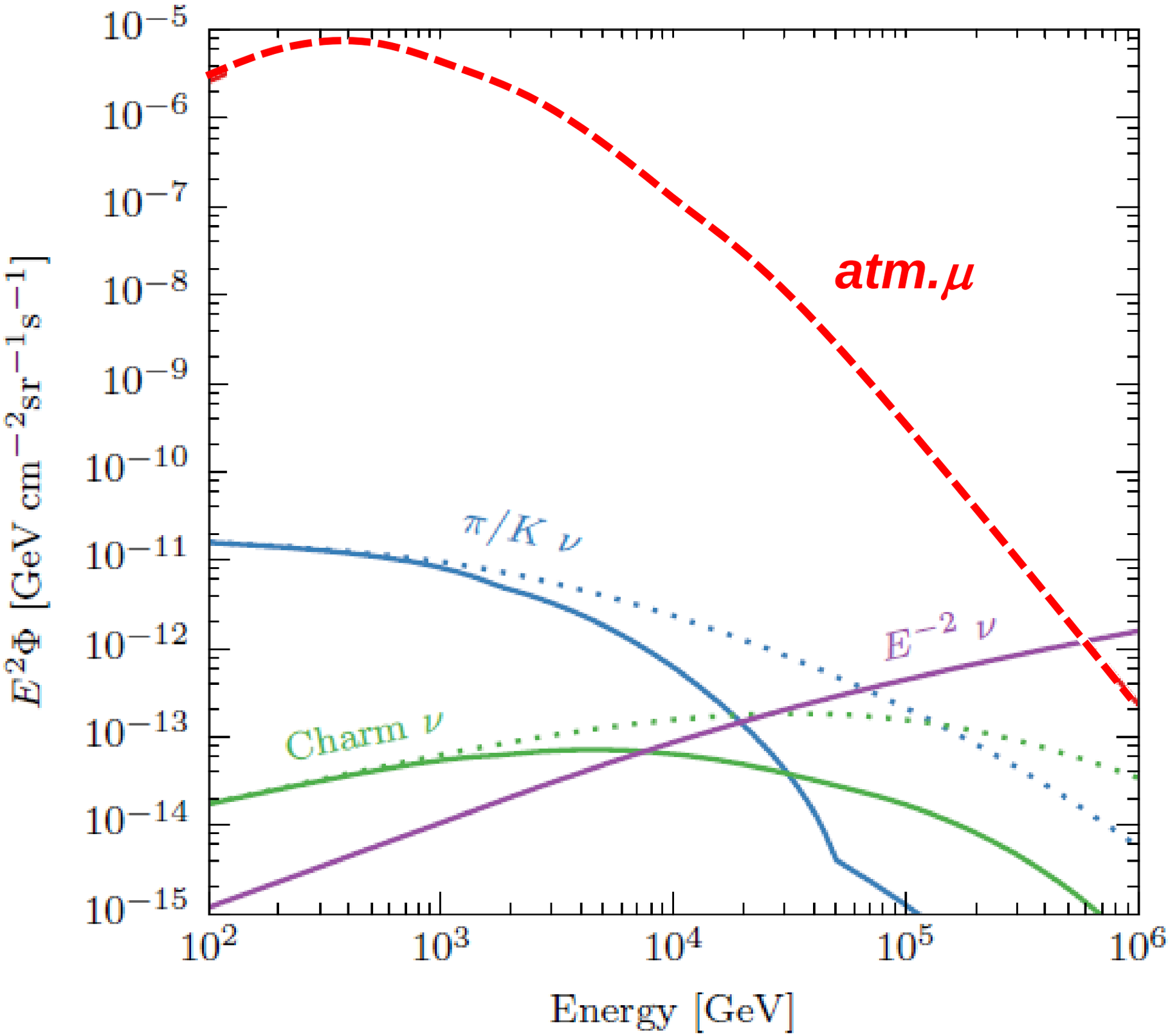
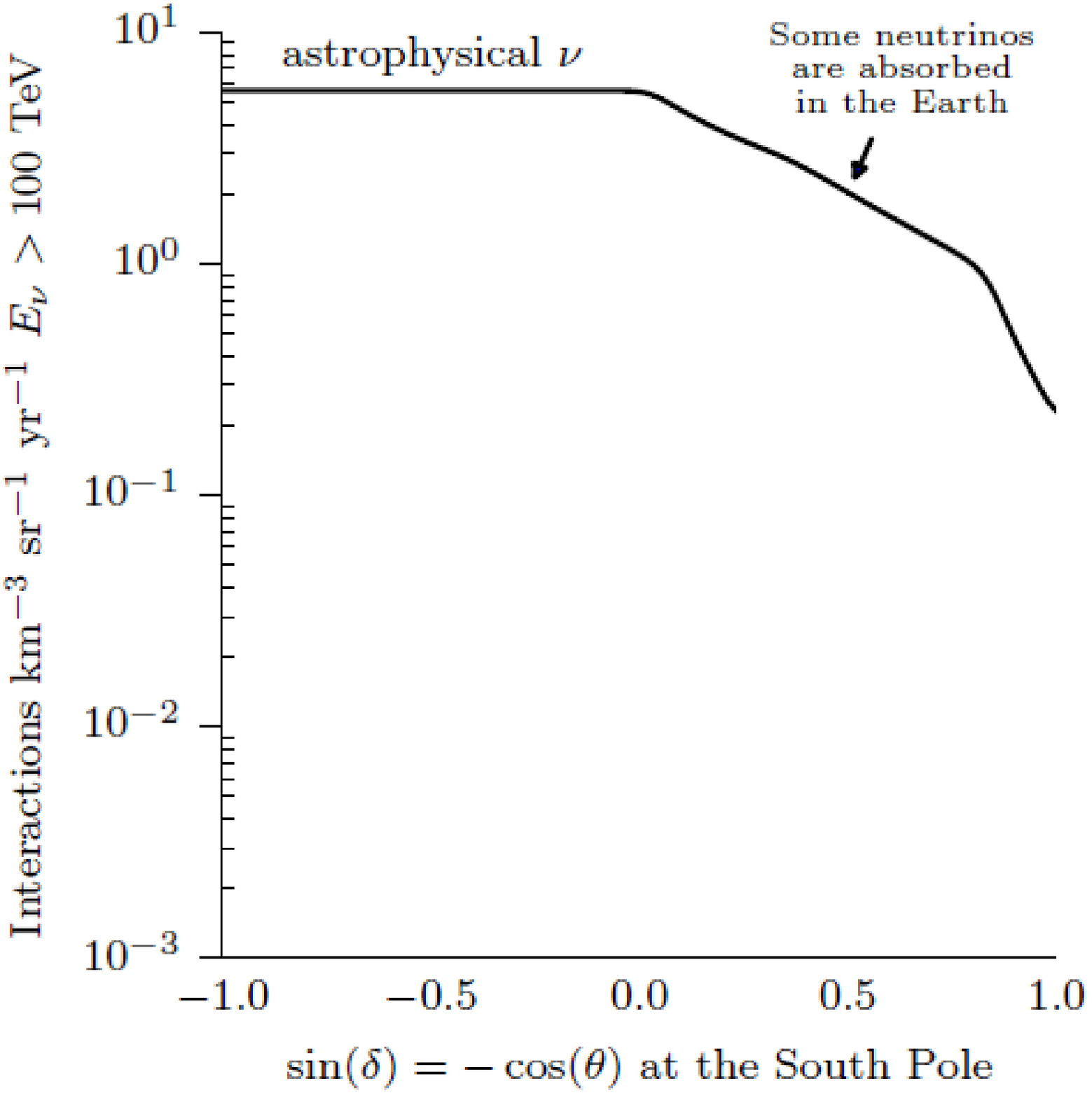
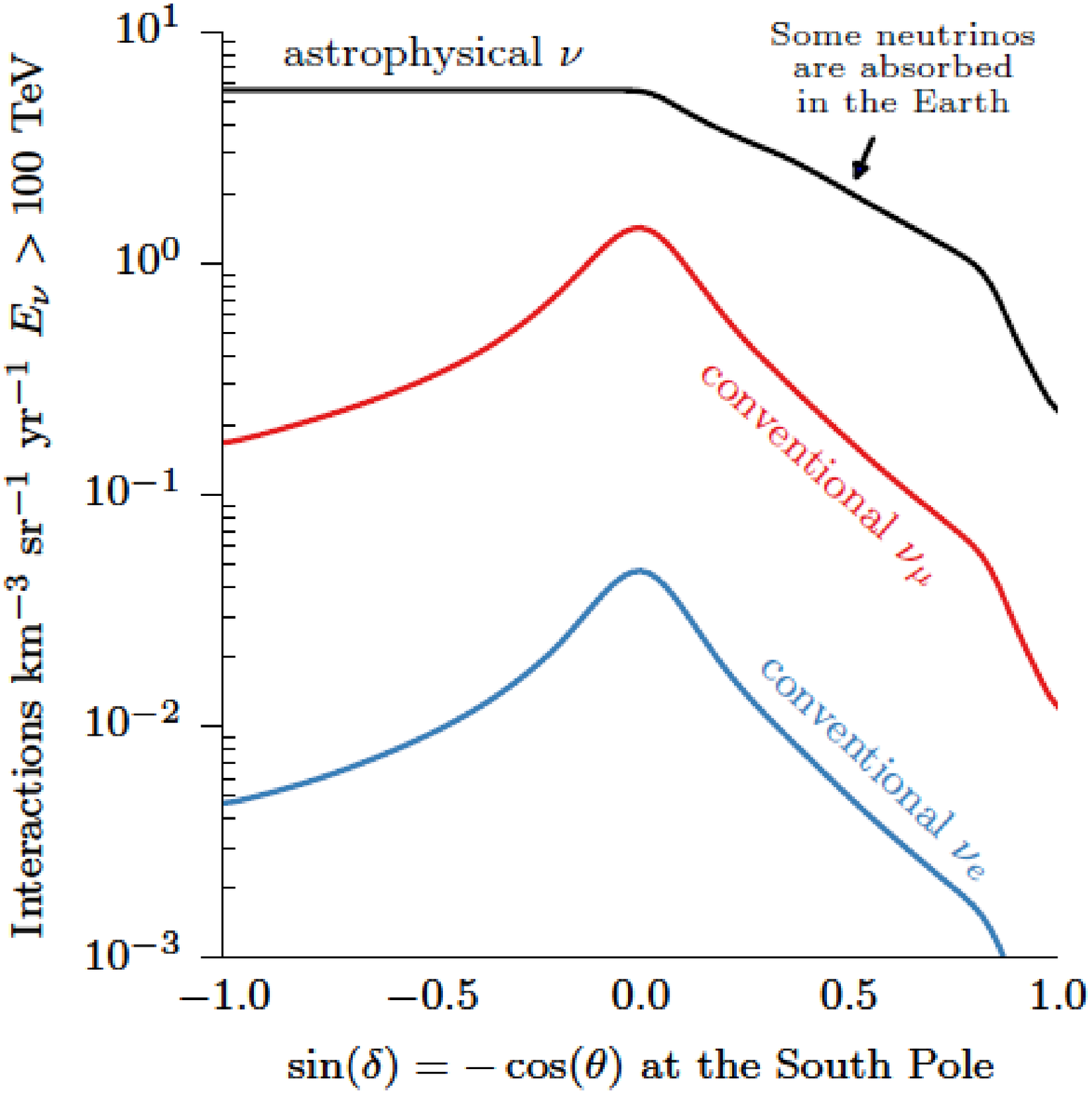




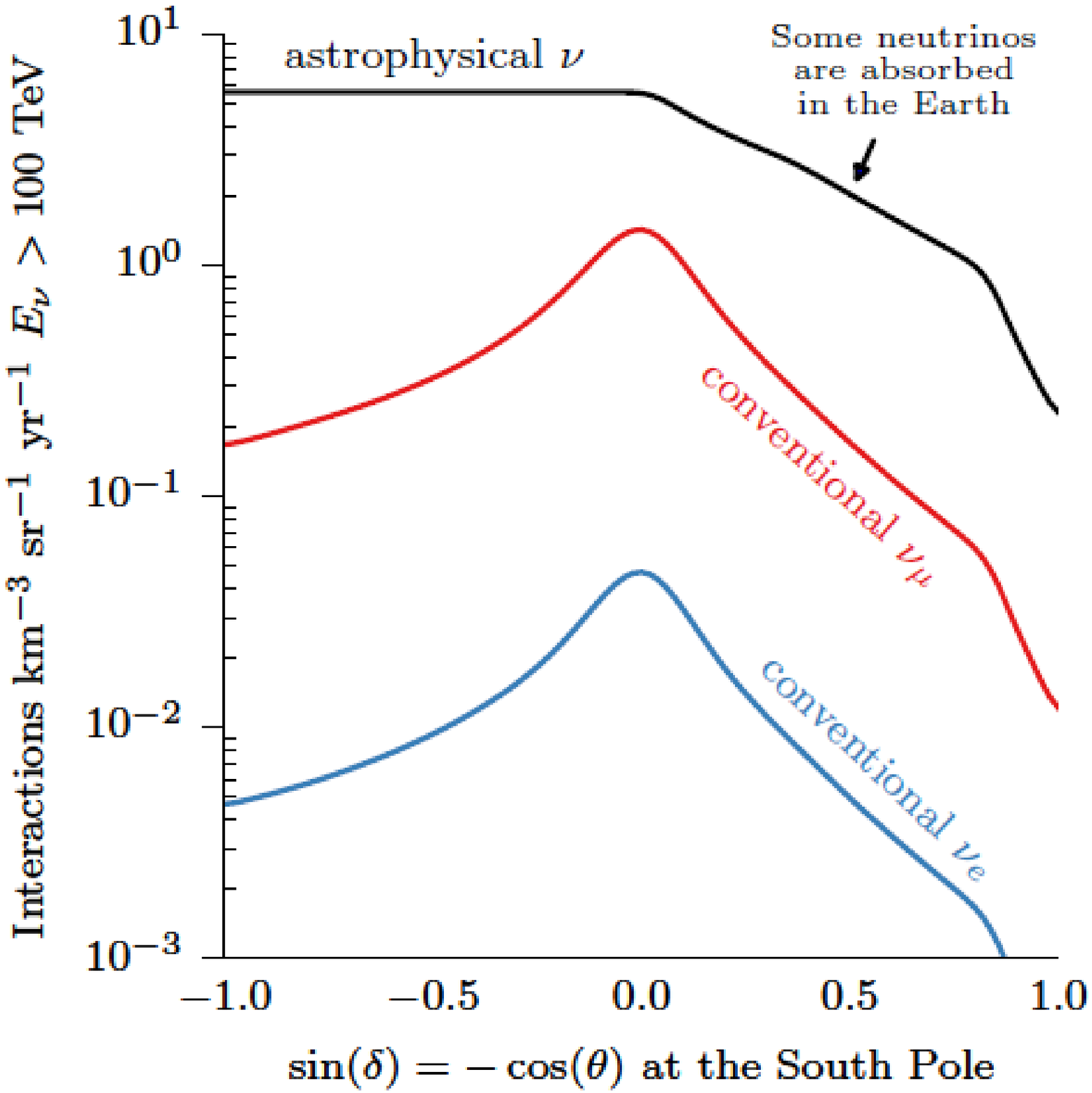
Atmospheric neutrino self-veto



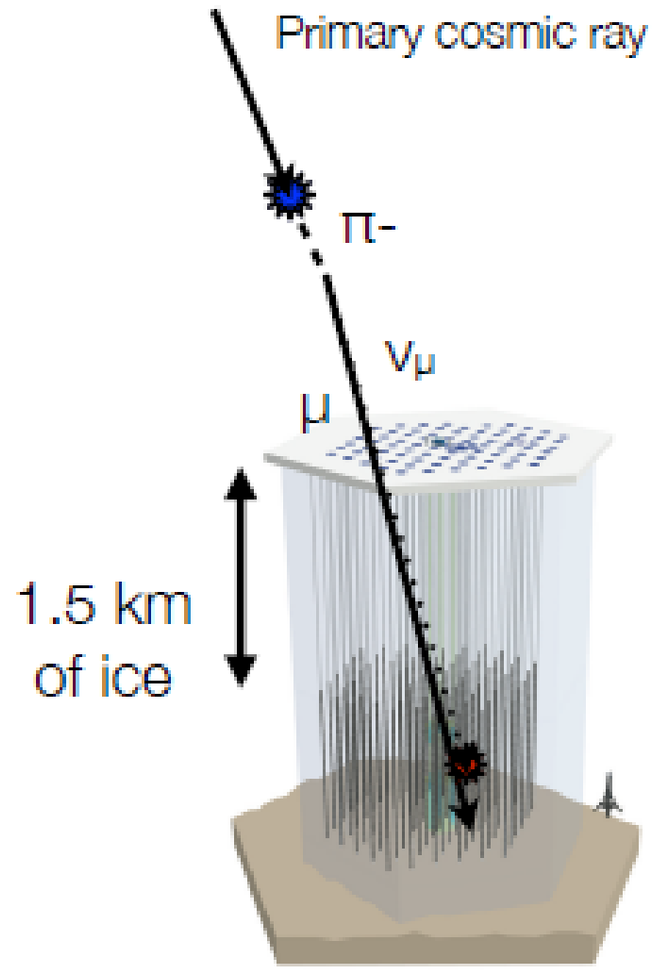
Atmospheric neutrino self-veto



Atmospheric neutrino self-veto



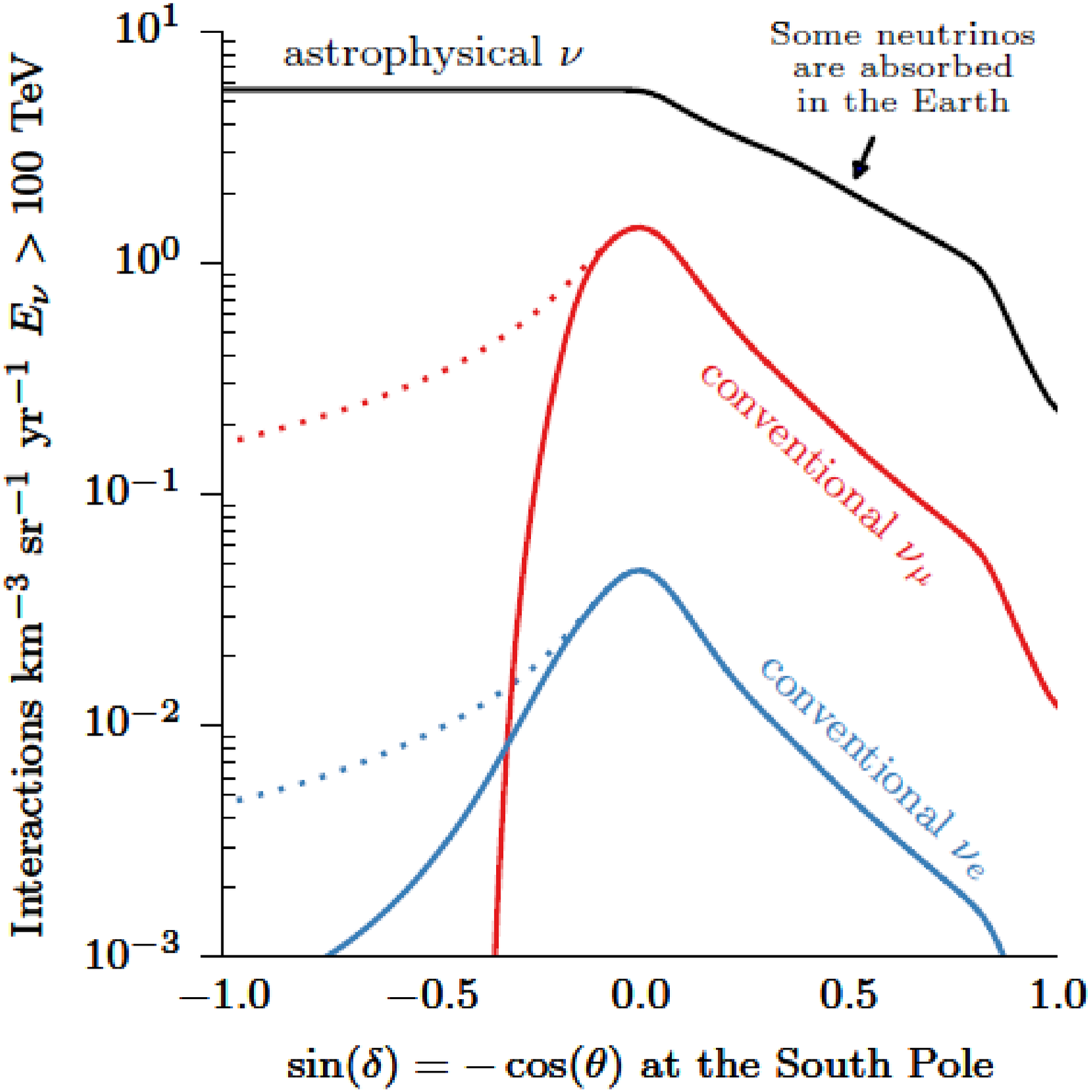
An active muon veto removes down-going atmospheric neutrinos.



Schönert, Gaisser, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

Atmospheric neutrino self-veto



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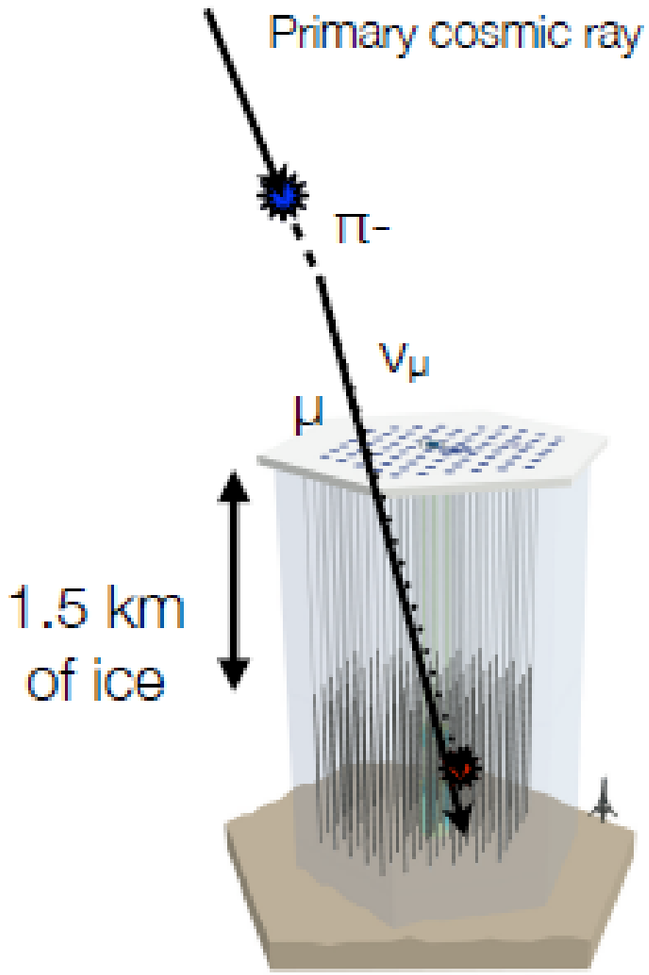

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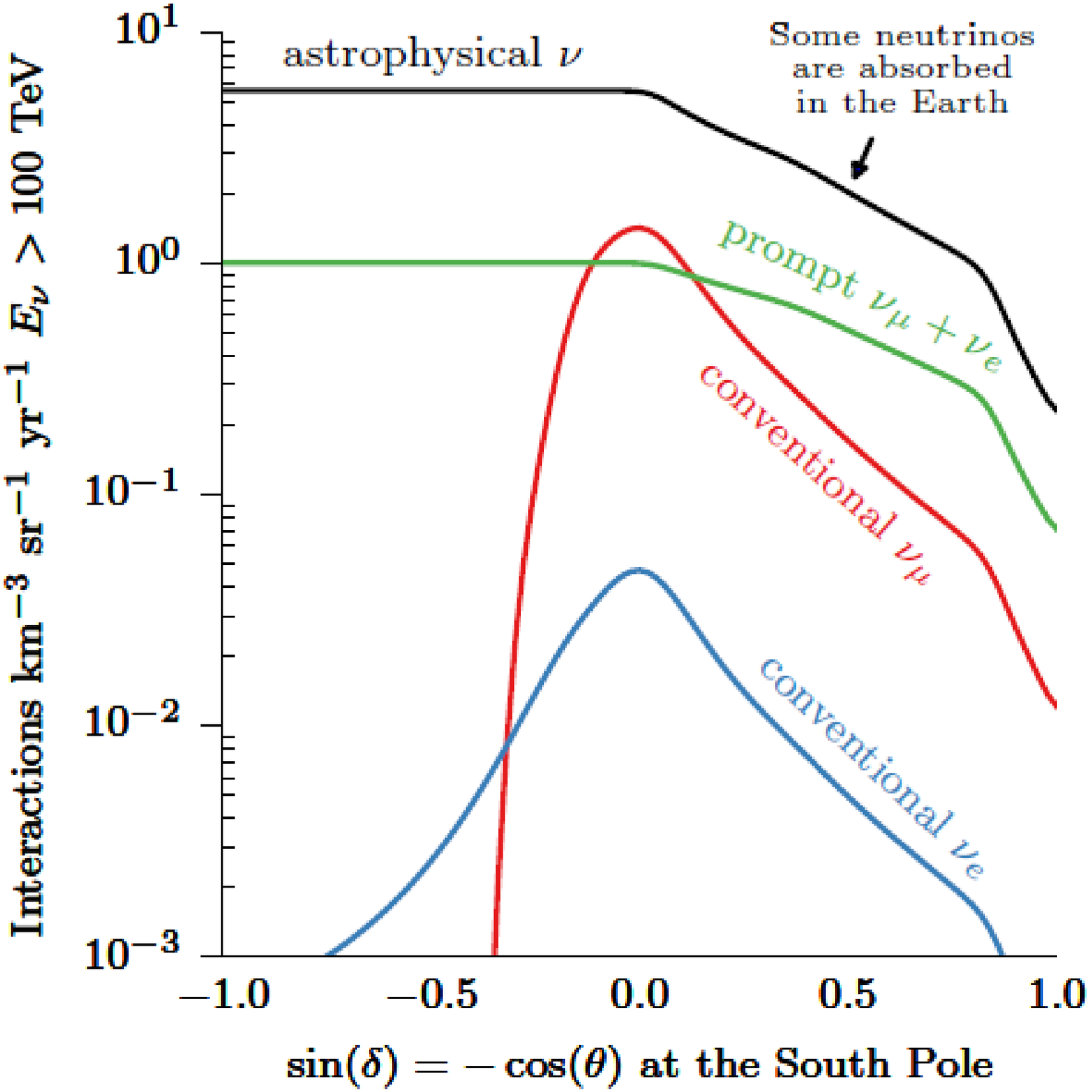

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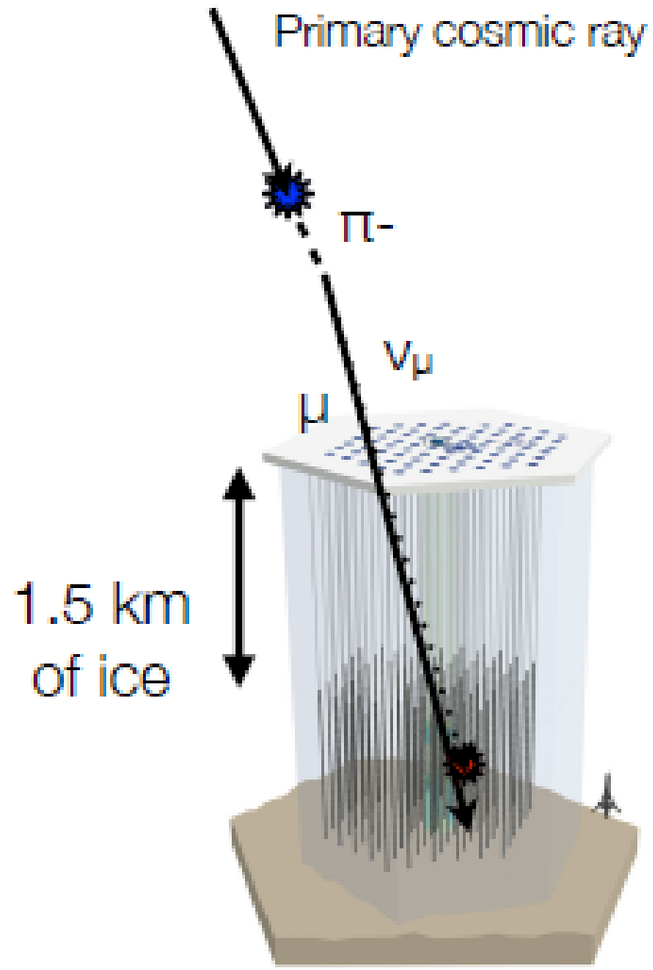
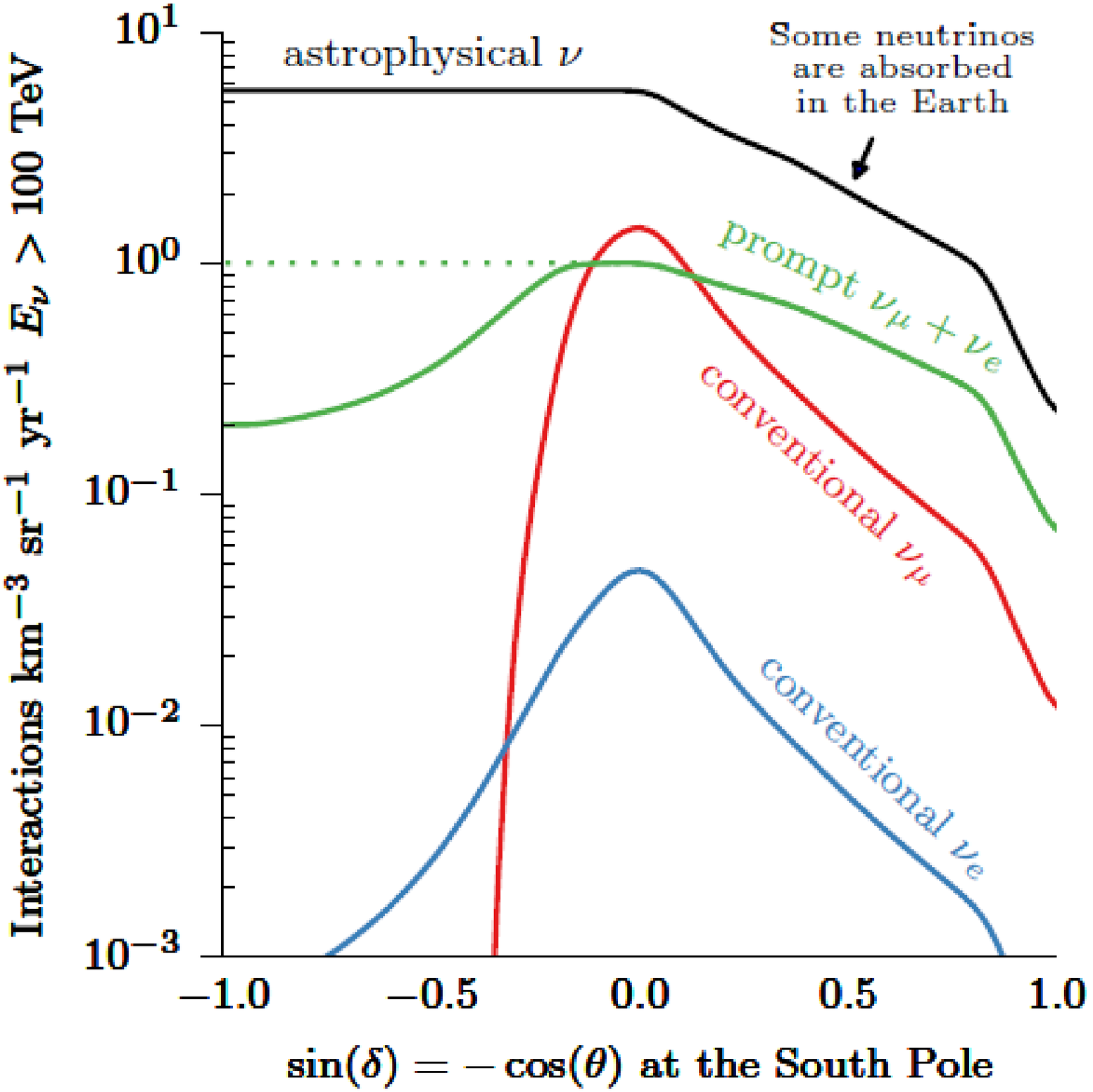


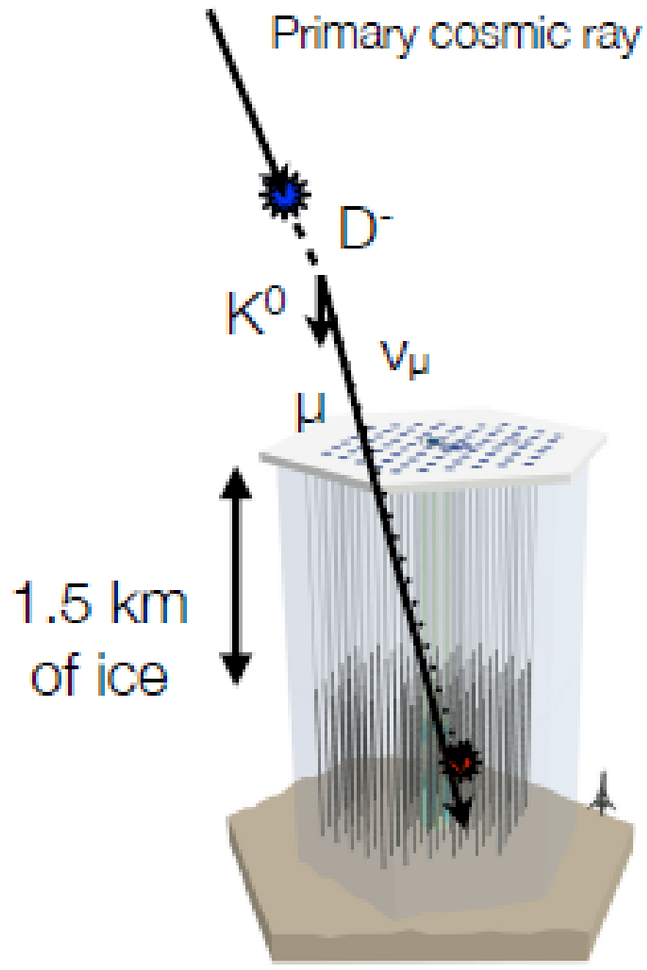
Schönert, Gaisser, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

Atmospheric neutrino self-veto



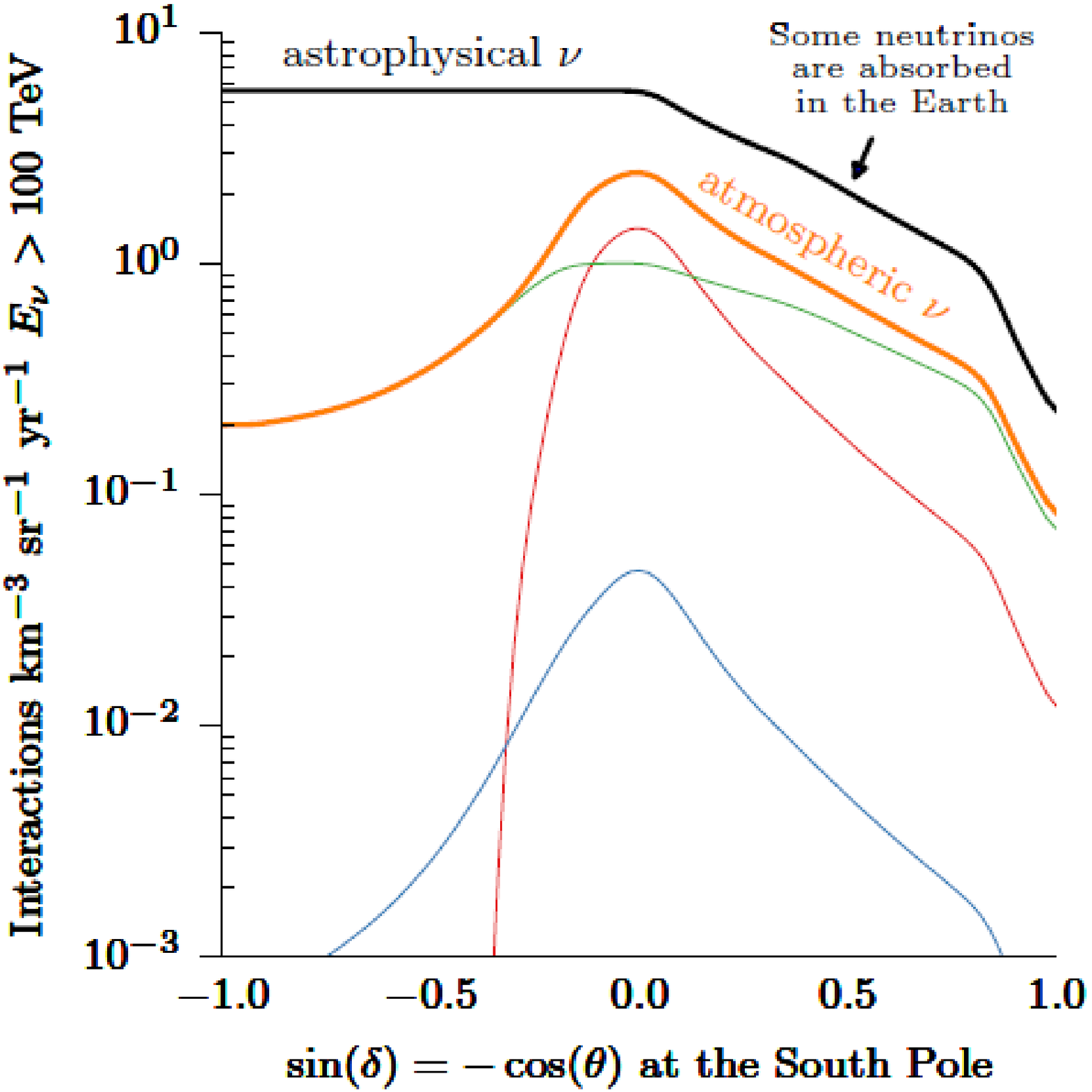
Prompt atmospheric neutrinos are vetoed, too.



Schönert, Gaisser, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

Atmospheric neutrino self-veto

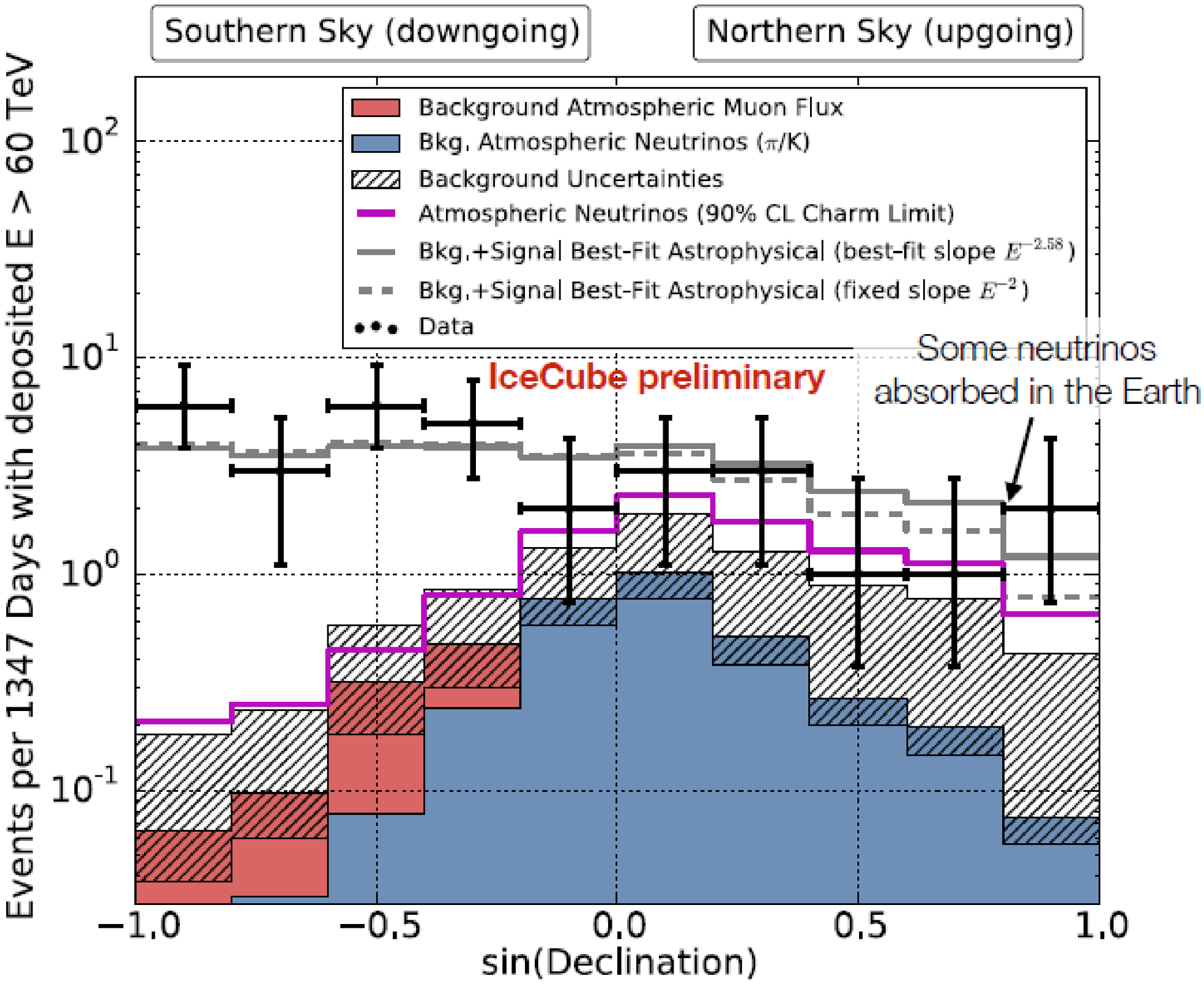


The zenith distributions of high-energy astrophysical and atmospheric neutrinos are fundamentally different.

Schönert, Gaisser, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

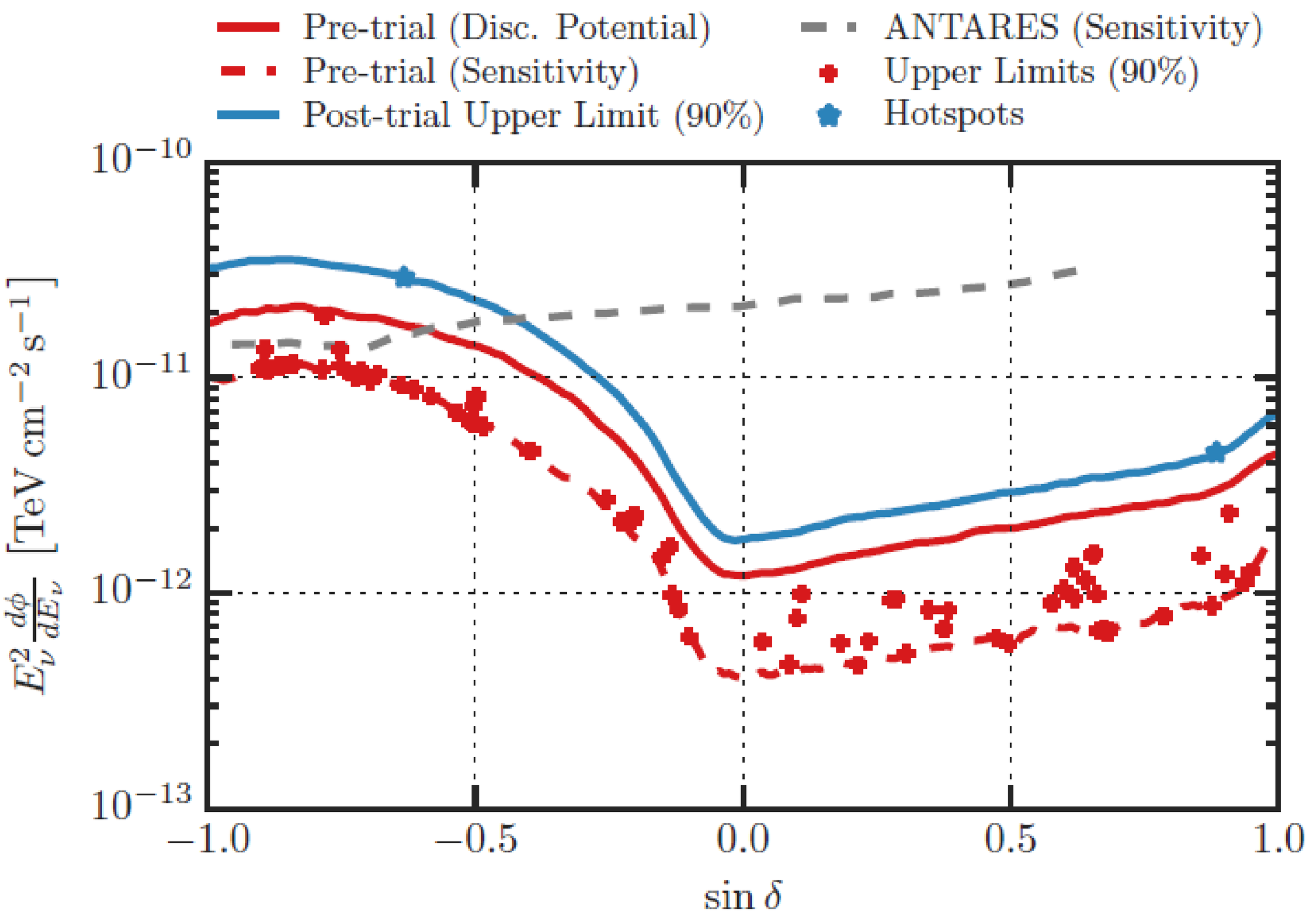
Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

Model-independent proof of astrophysical origin:



IceCube 7 years

Sensitivities and upper limits

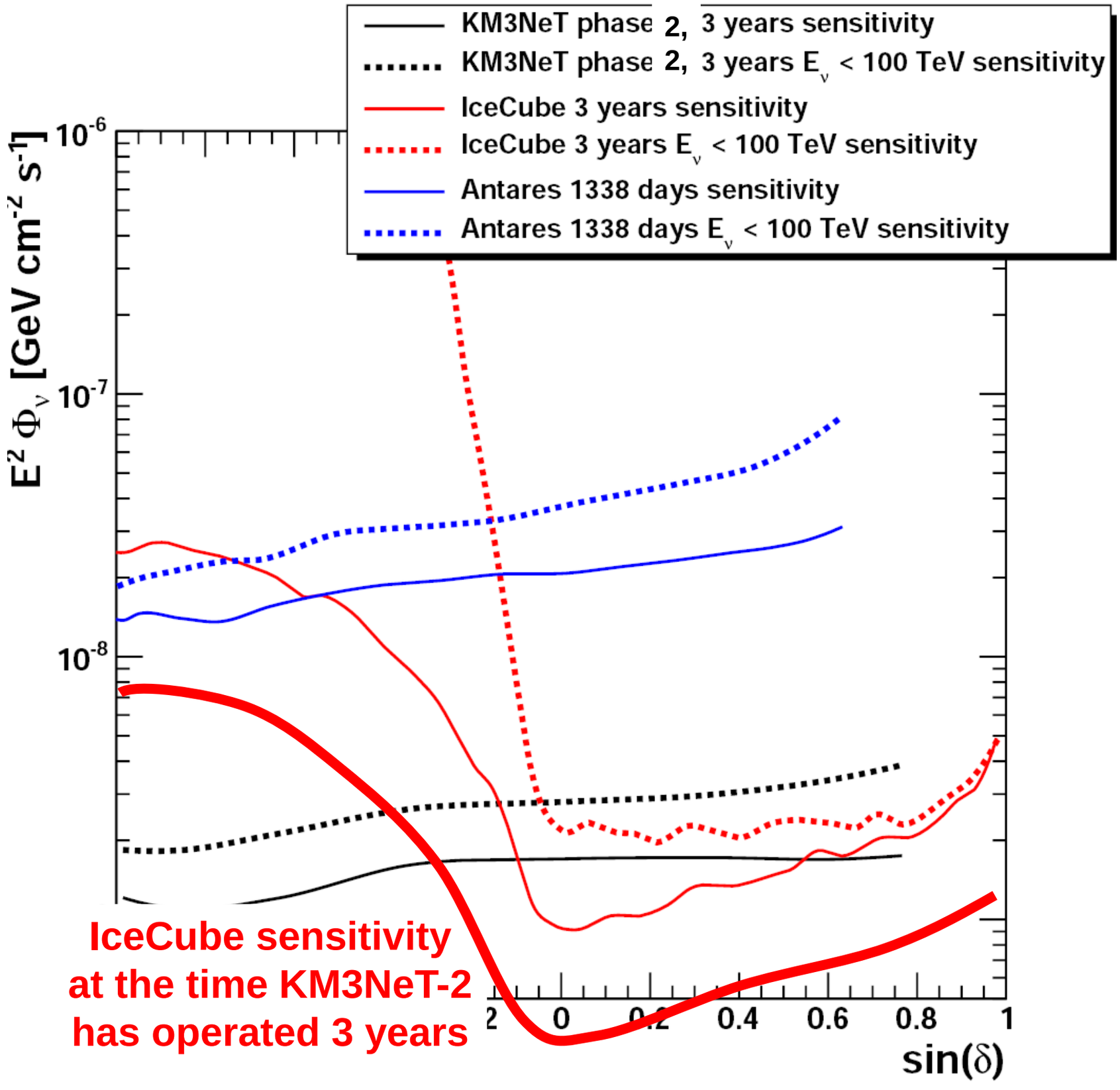


KM3NeT Phase 2: point source sensitivity

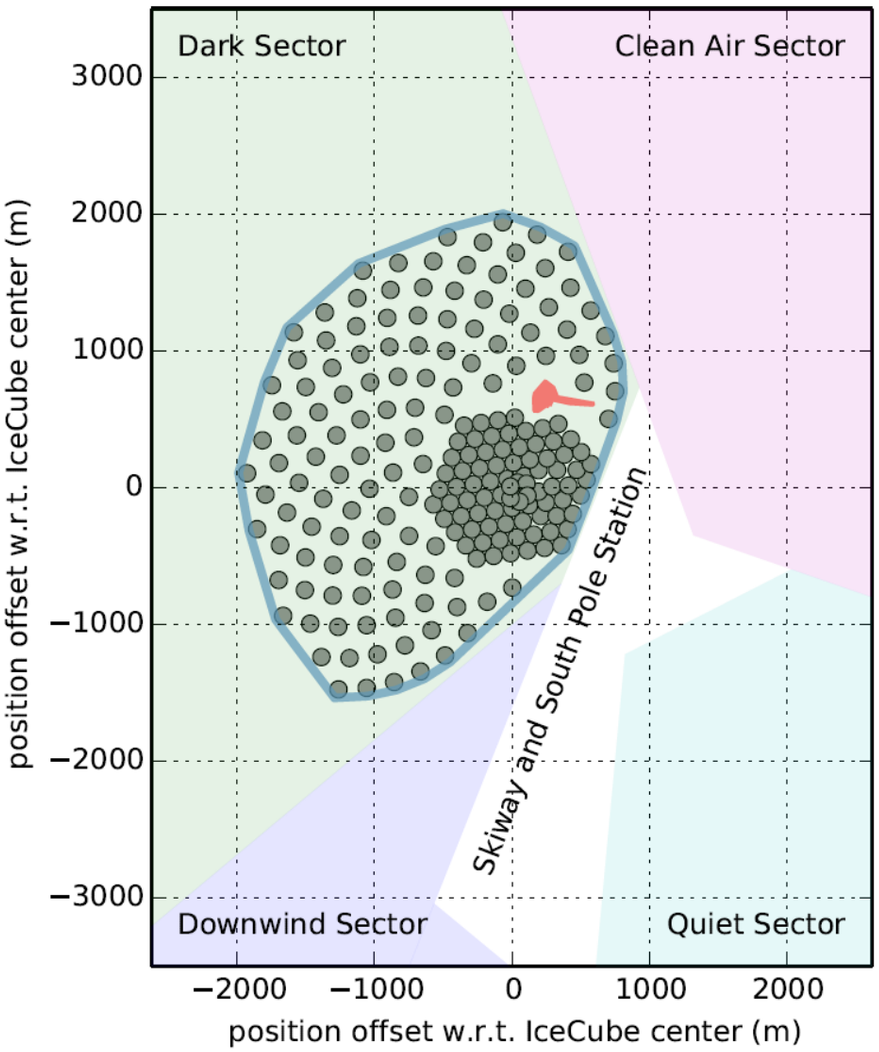
For specific flux assumptions for Supernova Remnants (modeled using γ-ray results)

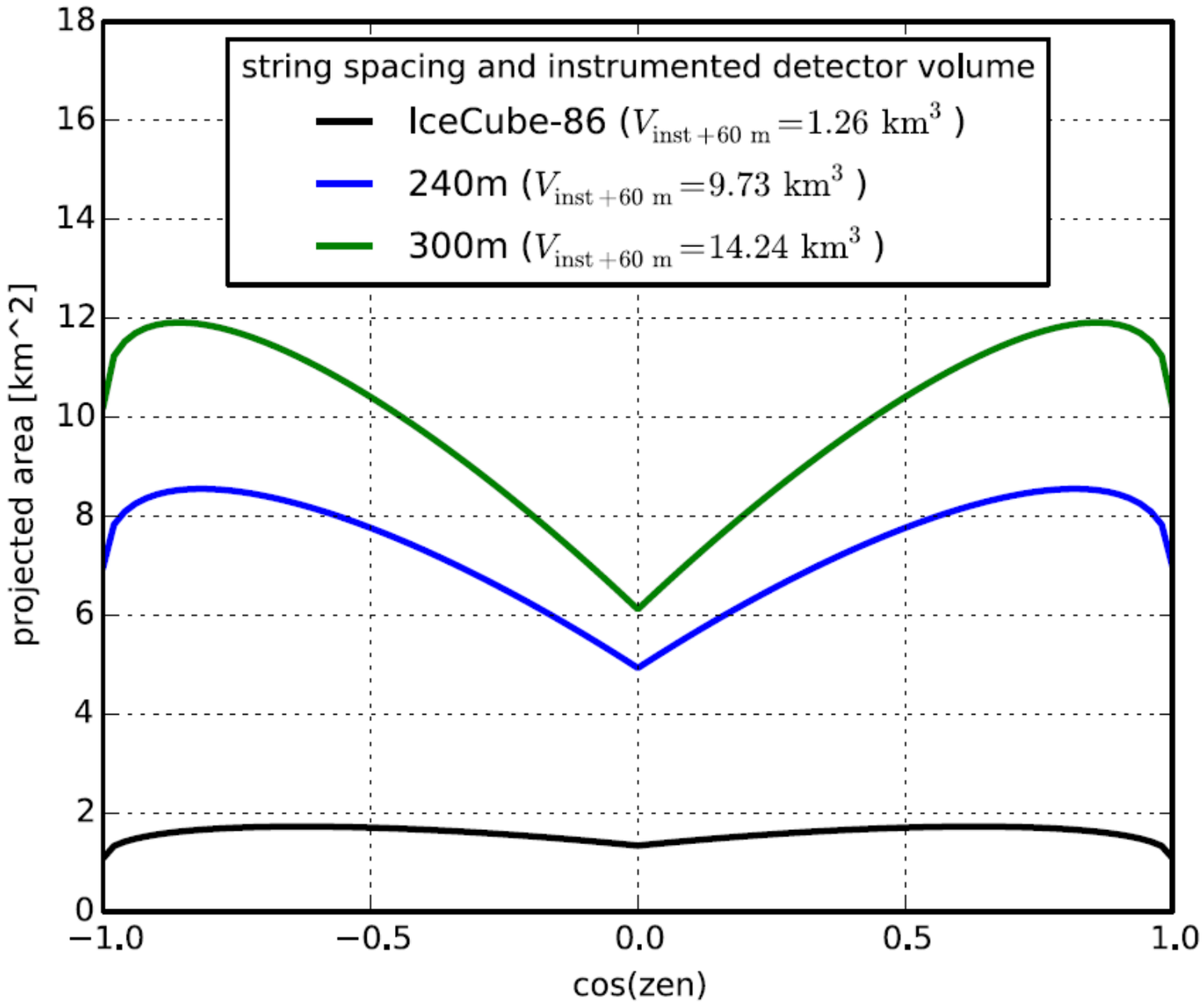
Kelner et al., Phys.Rev. D74 (2006) 034018

→ 3σ detection in ~5 years



Gen2/HEA



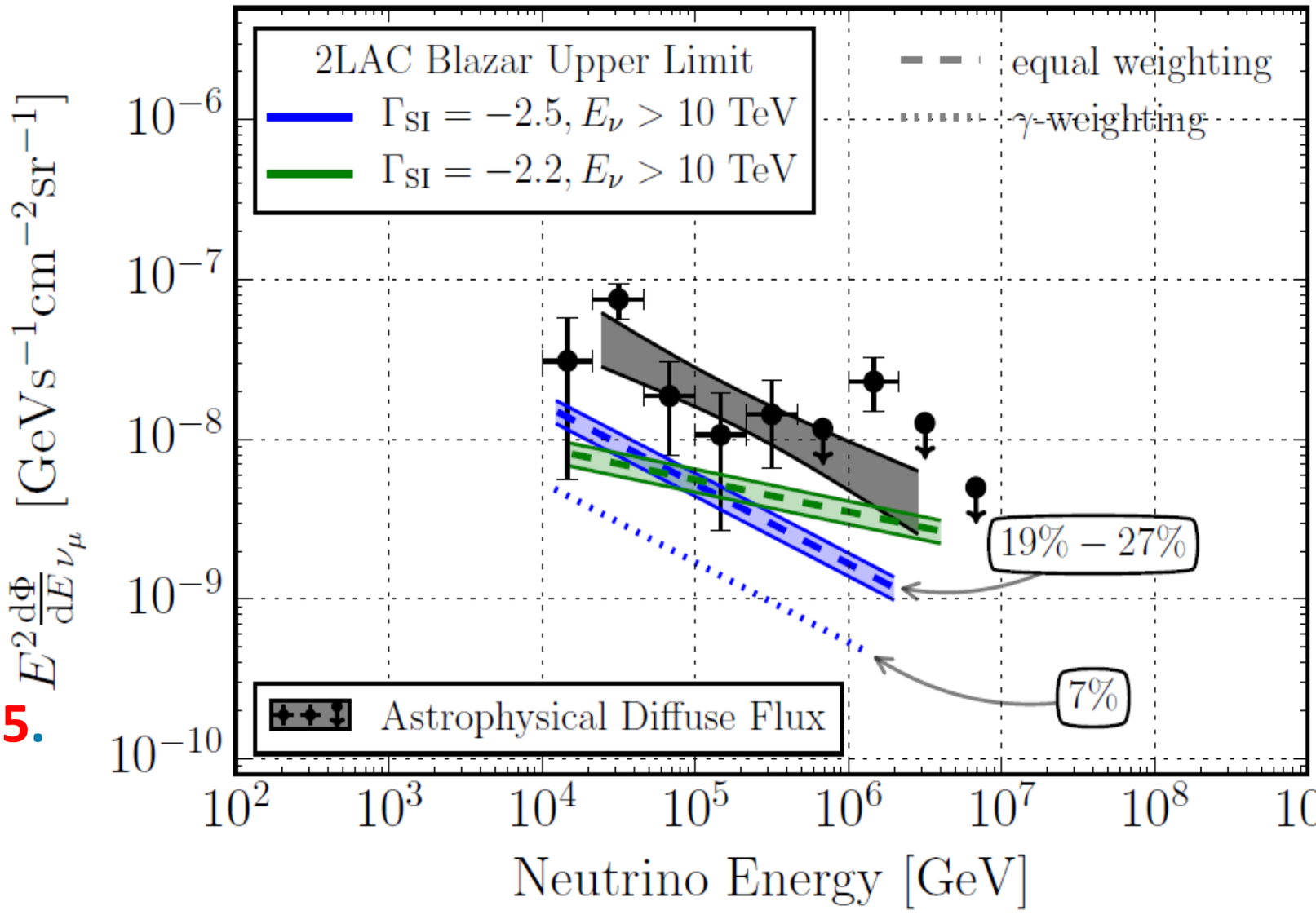


# Strings	120
DOMs / String	80
String Length	1.3 km

Contribution of Fermi-2Lac Blazars to the diffuse TeV-PeV flux

ApJ vol. 835, no. 1, p. 45 (2017)

- **Search for cumulative neutrino emission from blazars in the 2nd Fermi-LAT AGN catalogue (862 blazars)**
- **Data from 2009-2012**
- **No significant excess**
- **Contribution of 2LAC blazars to IceCube's astrophysical ν flux ≤ 27% (0.01- 2 PeV), for equipartition of flavors at Earth and spectral index 2.5.**
- **< 50% for spectral index 2.2**



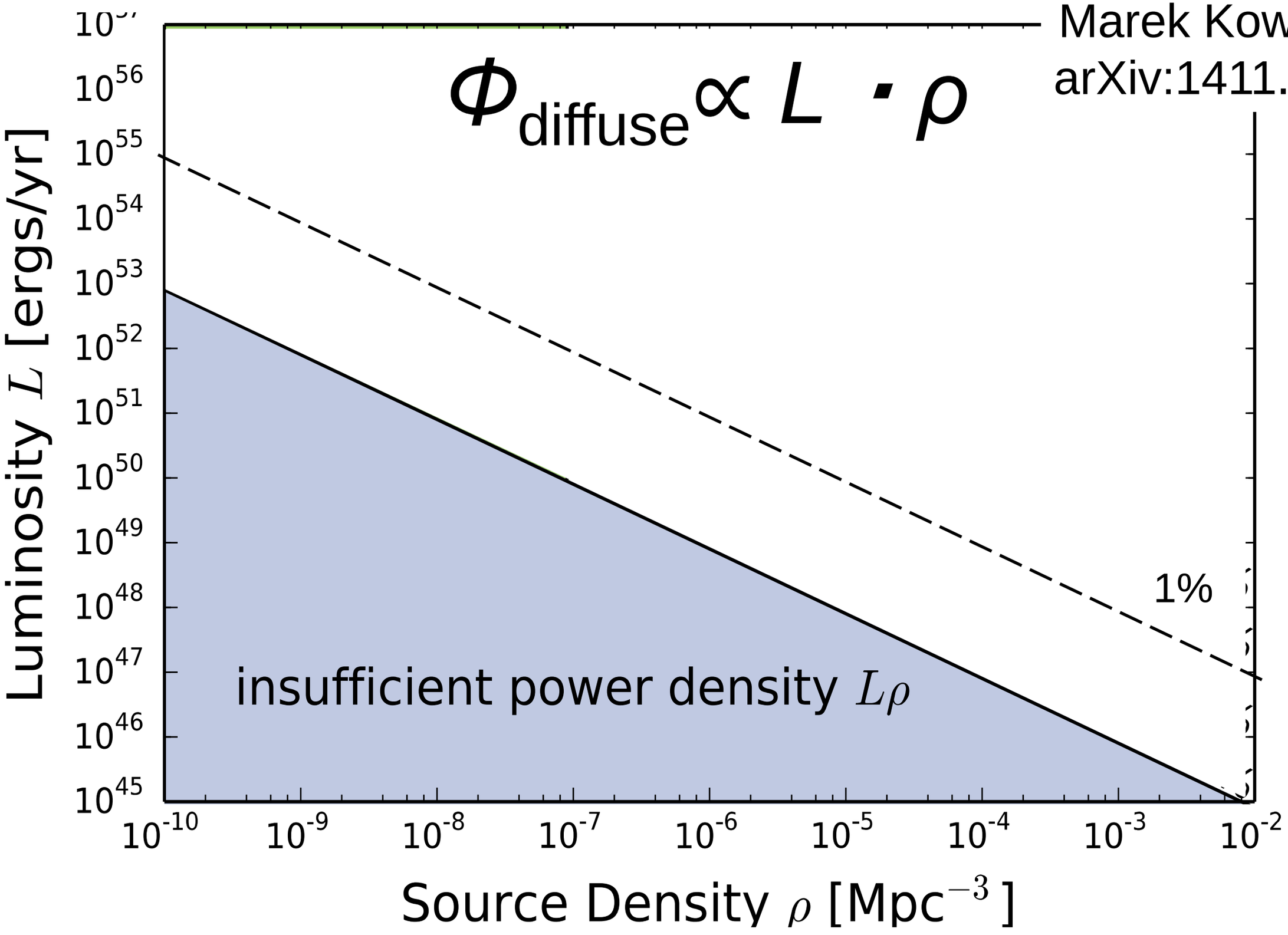
- **Constrains recent models for neutrino emission by blazars**

REMAINING SOURCE CANDIDATES TO EXPLAIN THE *HESE* FLUX

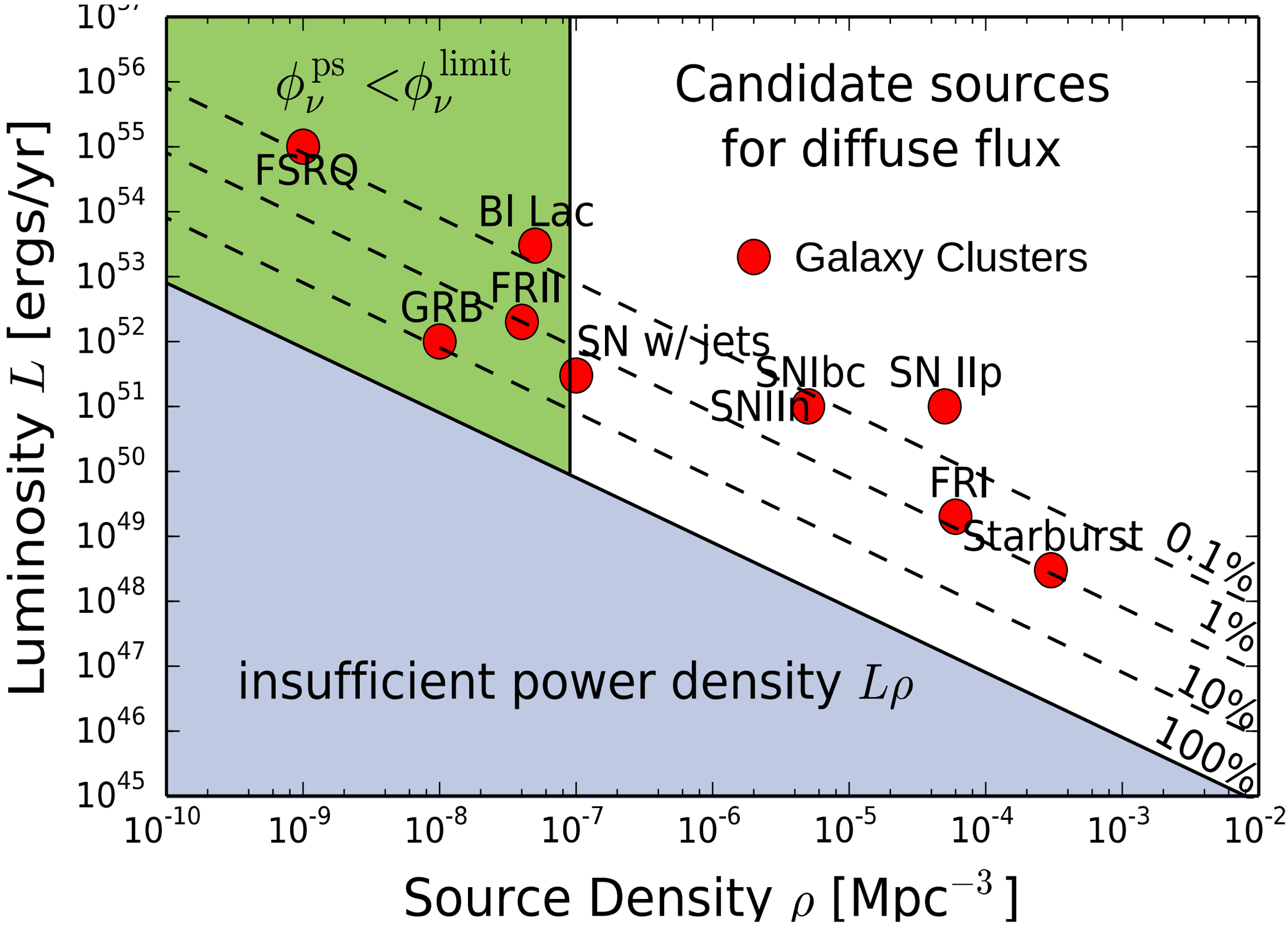
Resolving the sources of the diffuse flux

Marek Kowalski
arXiv:1411.4385

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



Resolving the sources of the diffuse flux



IceCube Gen2: Top View