High Energy Neutrino Astronomy *lecture 2*

VII International Pontecorvo School
Prague, August 2017

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  - Scientific context
  - Operation principles
  - The detectors
  - Atmospheric neutrinos
- **Lecture 2**
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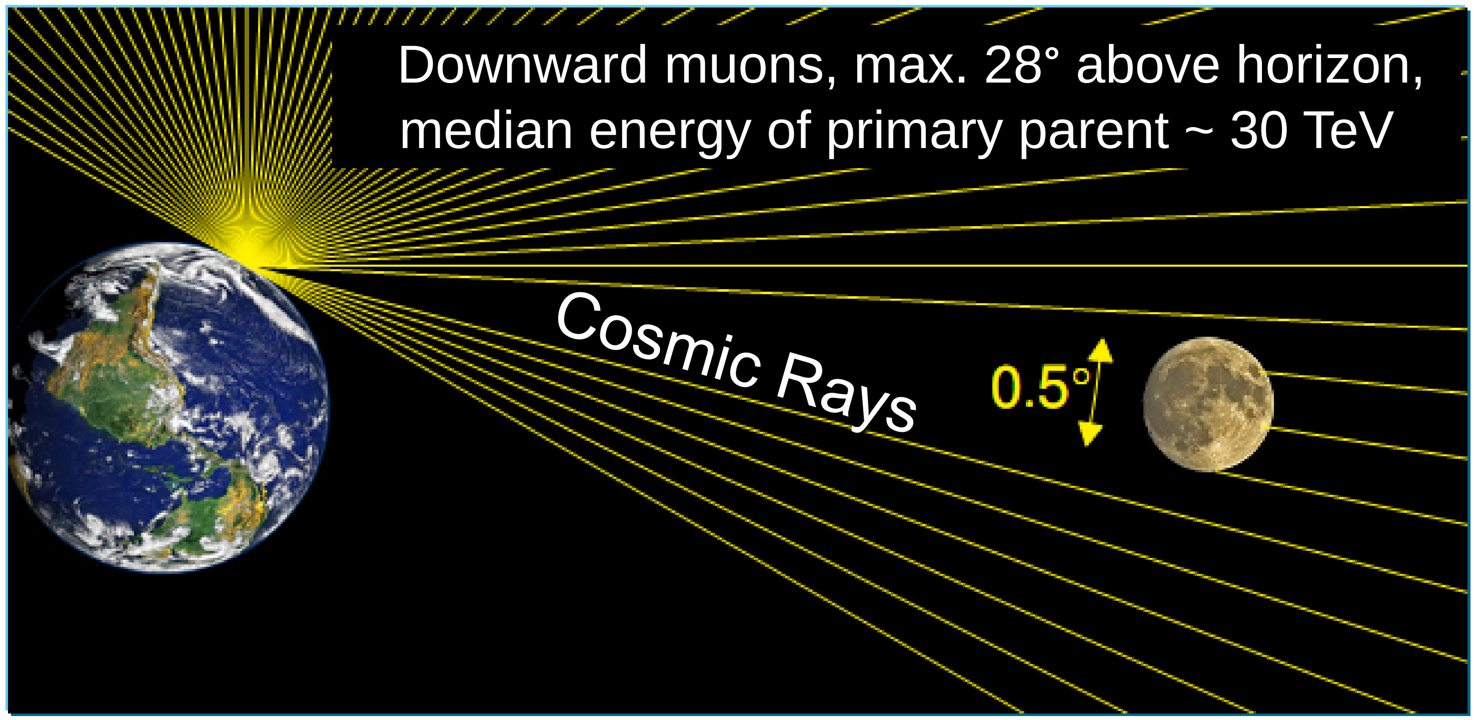
  - Search for transient sources and the multi-messenger concept
  - The diffuse flux of cosmic neutrinos
  - Search for Dark Matter (indirect) and magnetic monopoles
  - A look to the future

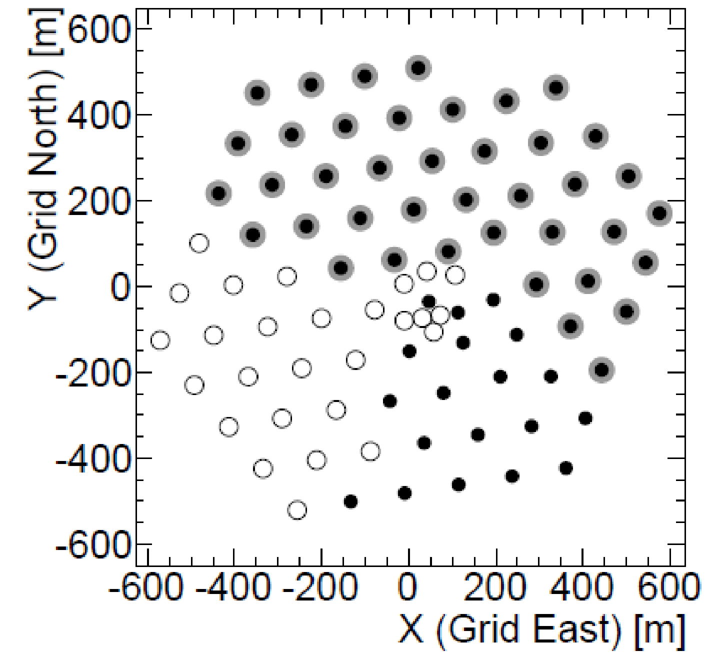
SEARCH FOR STEADY POINT SOURCES

HOW GOOD DO WE POINT ?

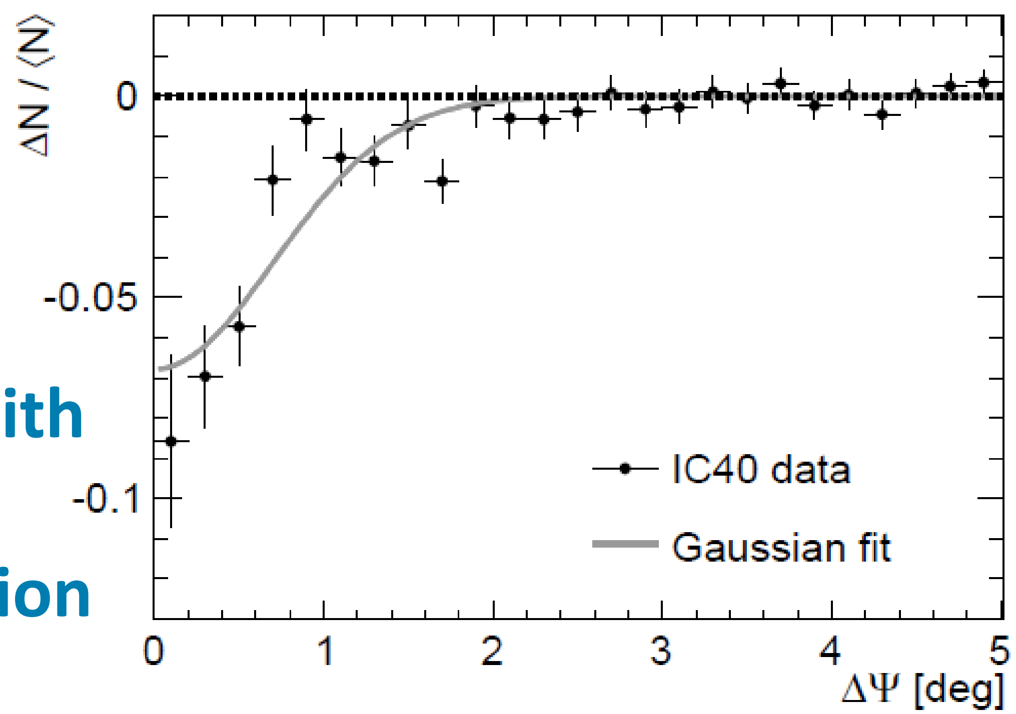
Pointing accuracy: shadow of the moon

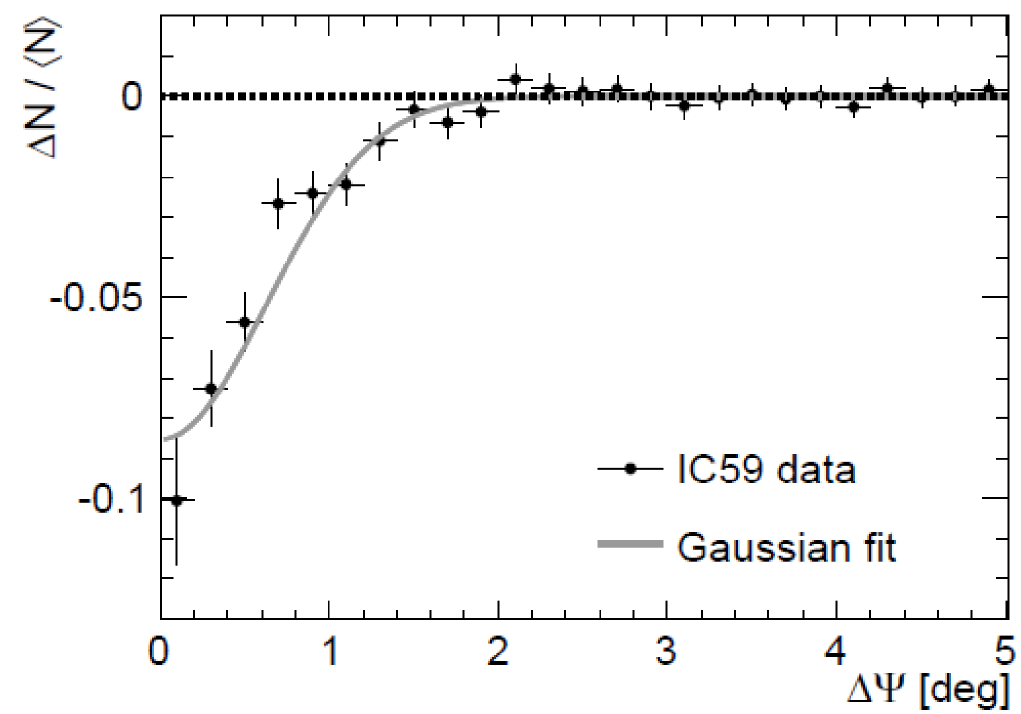
- **Data: IceCube-40, IceCube-59**
  Phys.Rev. D89 (2014) 10, 102004 arXiv:1305.6811



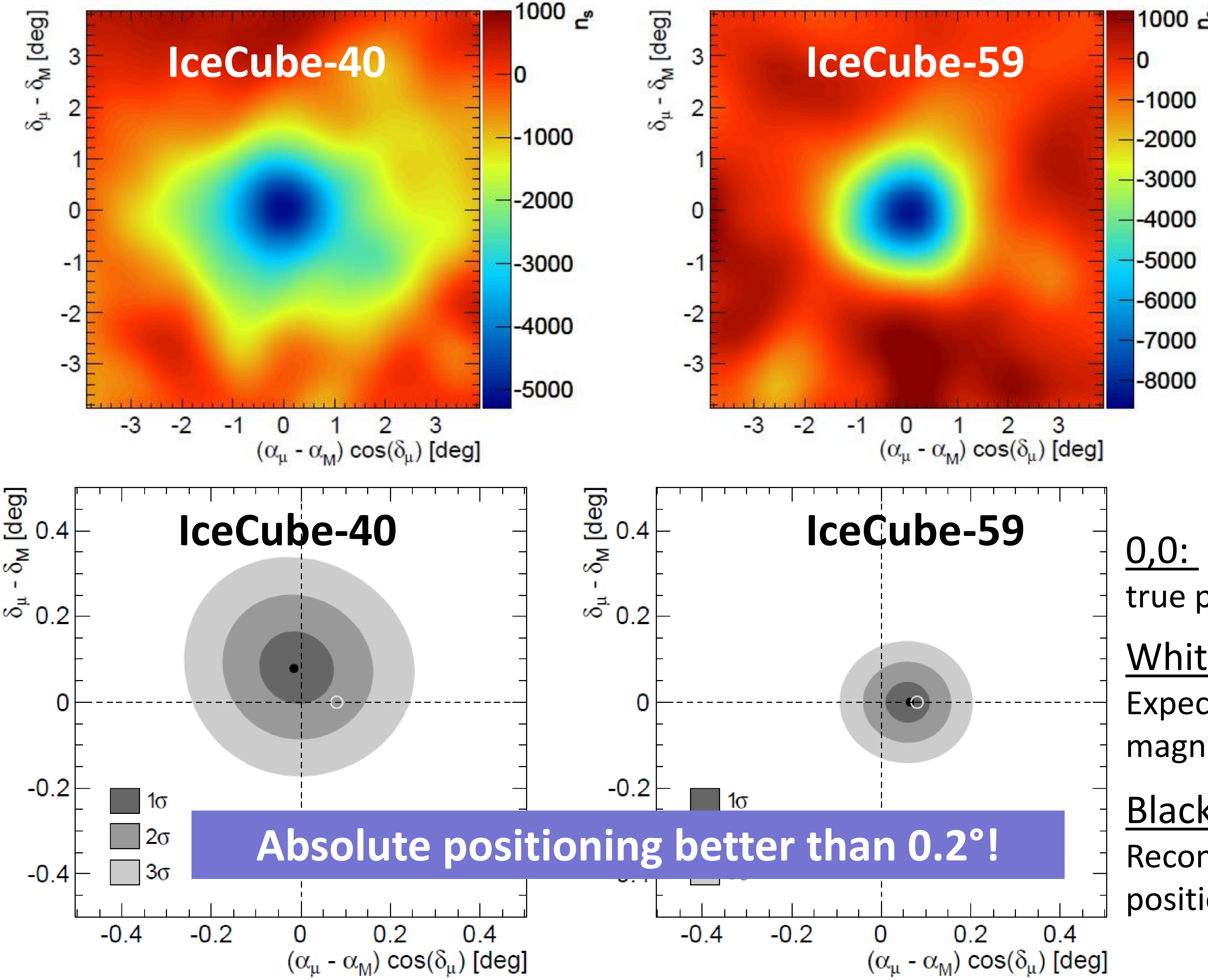


1σ-width 0.7°
in accordance with
MC calculations
(angular resolution
~ 0.5°)





Pointing accuracy: shadow of the moon



Absolute positioning better than 0.2°!

<u>0,0:</u>
true position

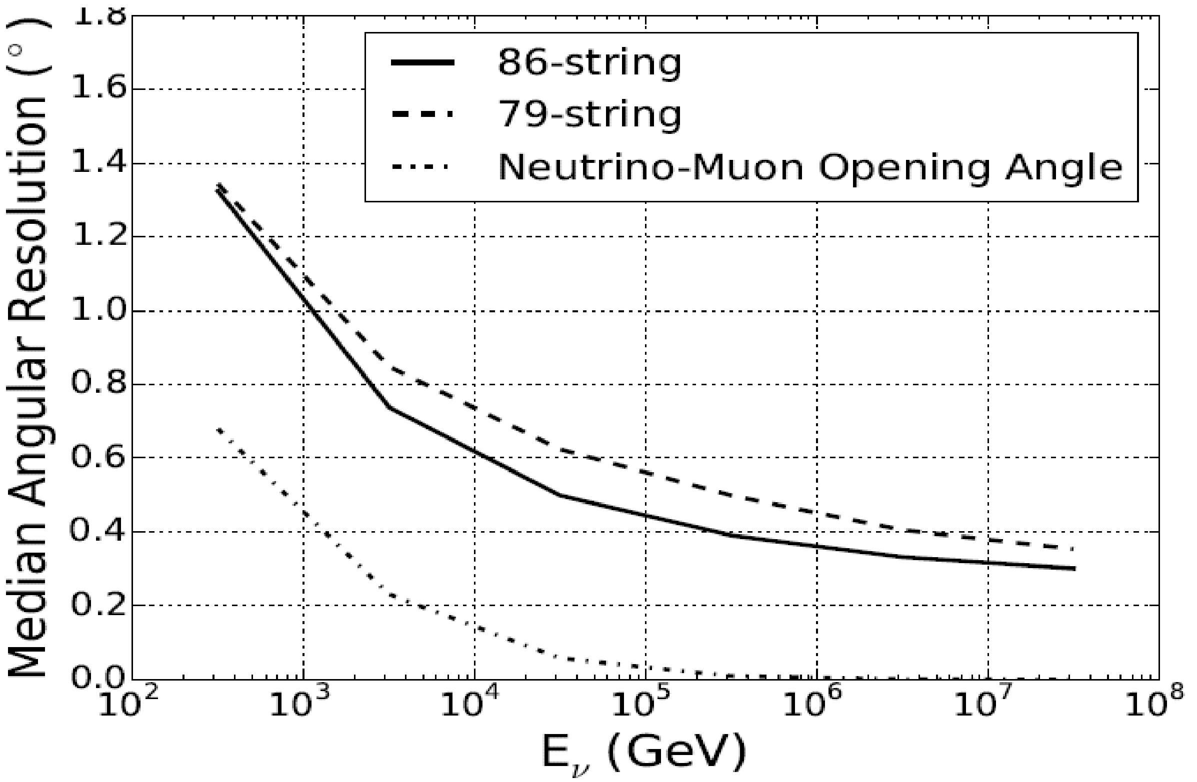
<u>White circle:</u>
Expected after magnetic deflection

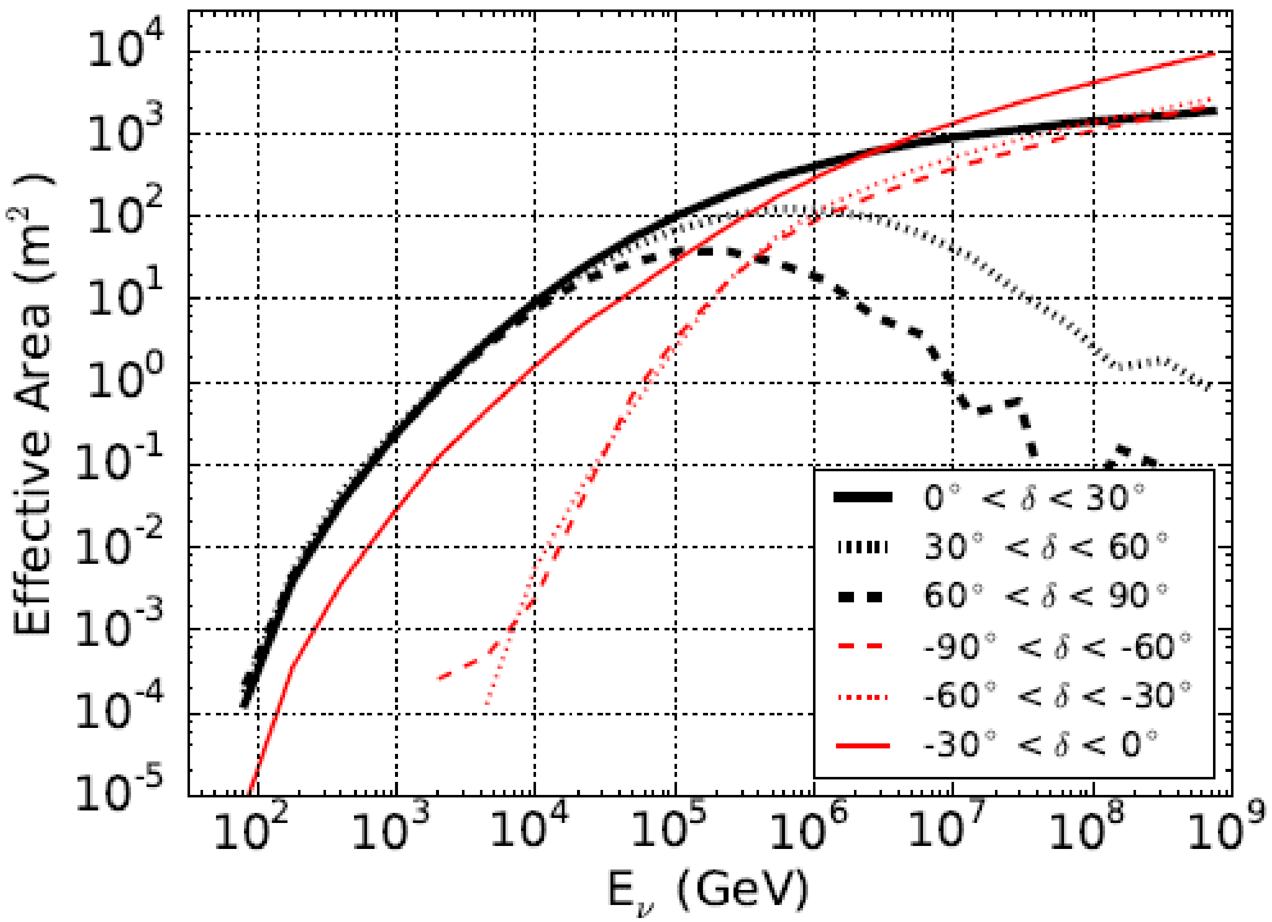
<u>Black dot:</u>
Reconstructed position

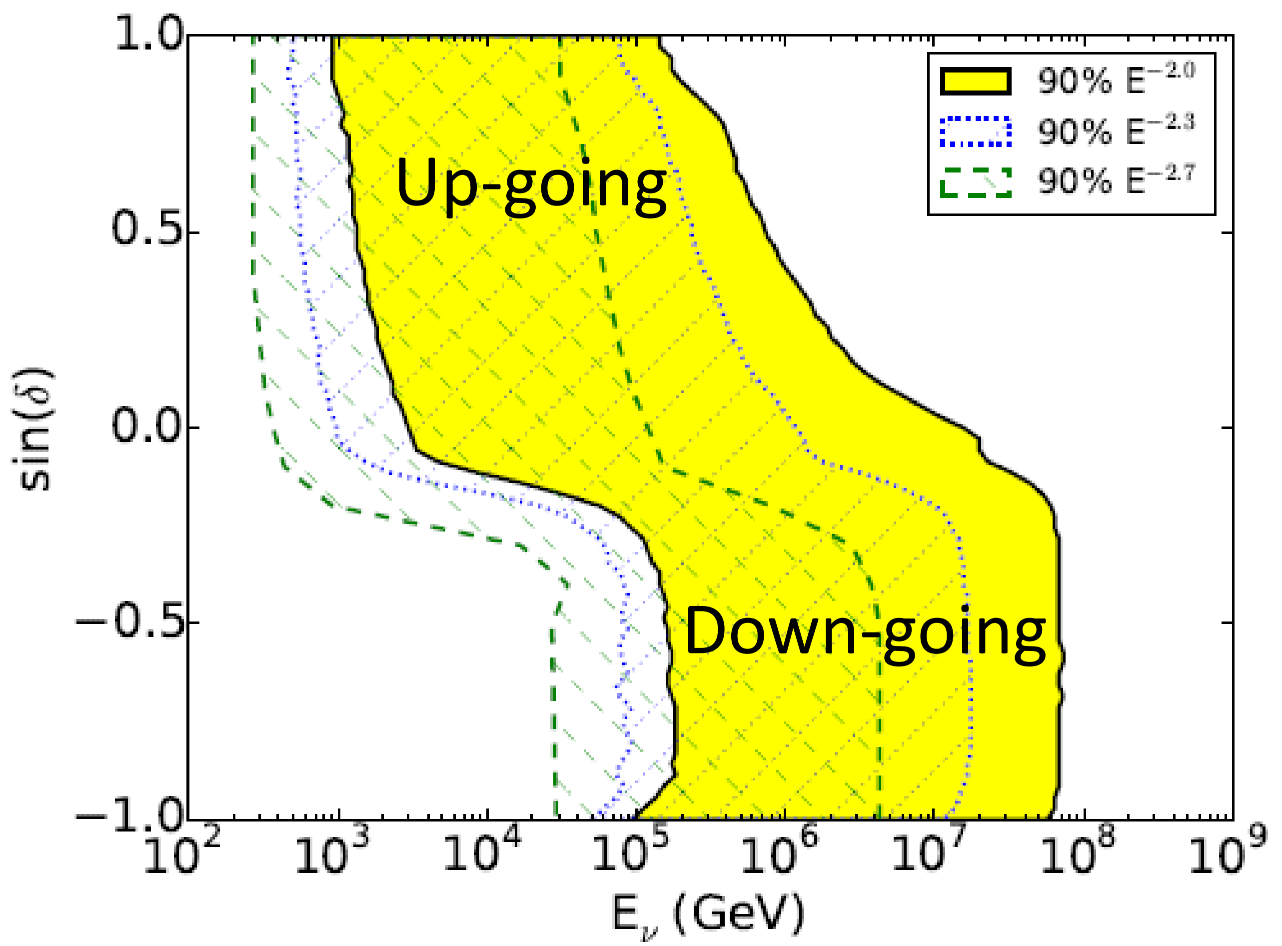
Search for point sources (figures from arXiv:1406.6757, 4 years)

- IceCube Collaboration:
  Searches for Extended and Point-Like Neutrino Sources with Four Years of IceCube Data,
  arXiv:1406.6757

- Figures bottom: Effective neutrino area and central 90% energy/declination region for 3 different spectra



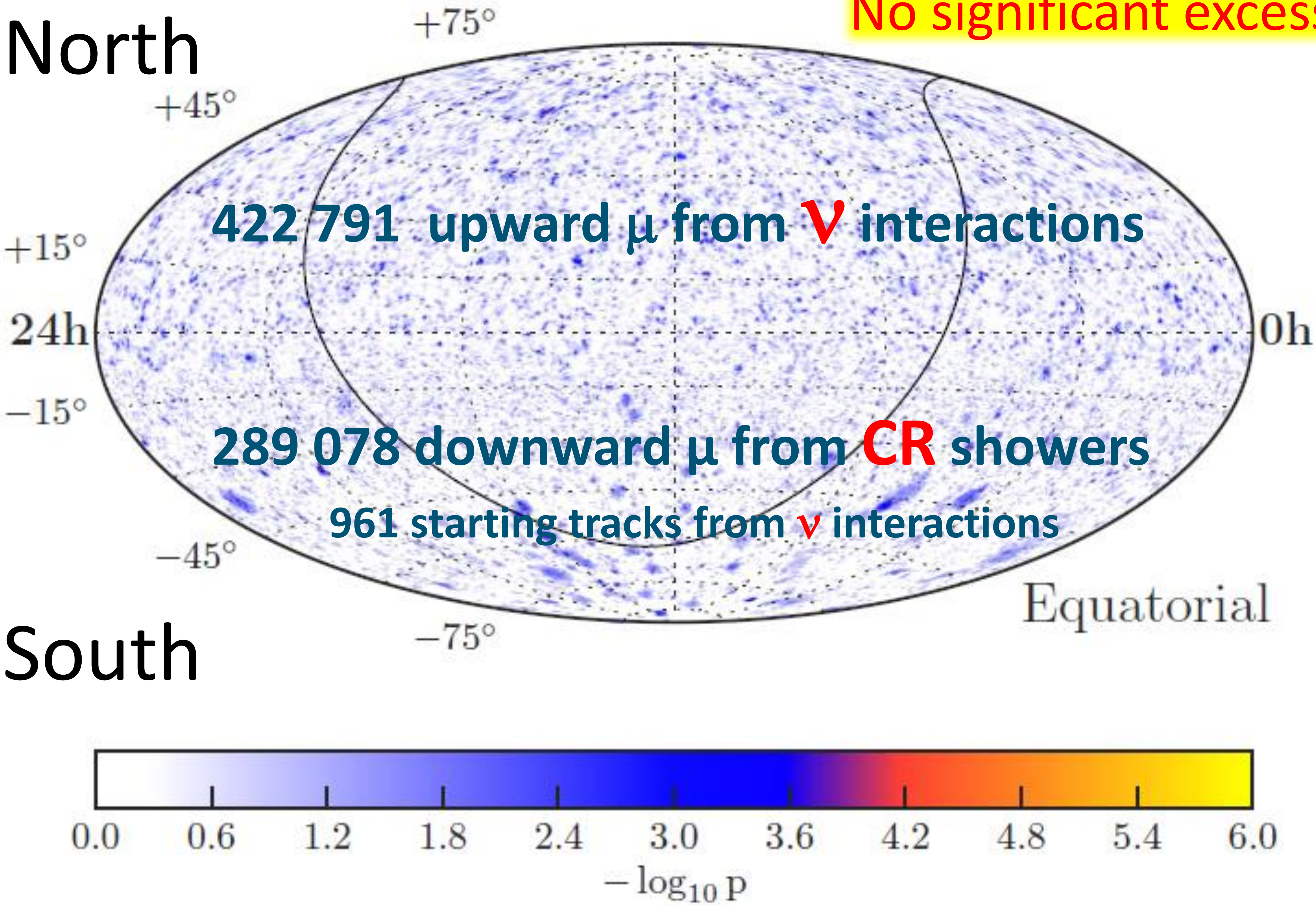




IceCube 7 years

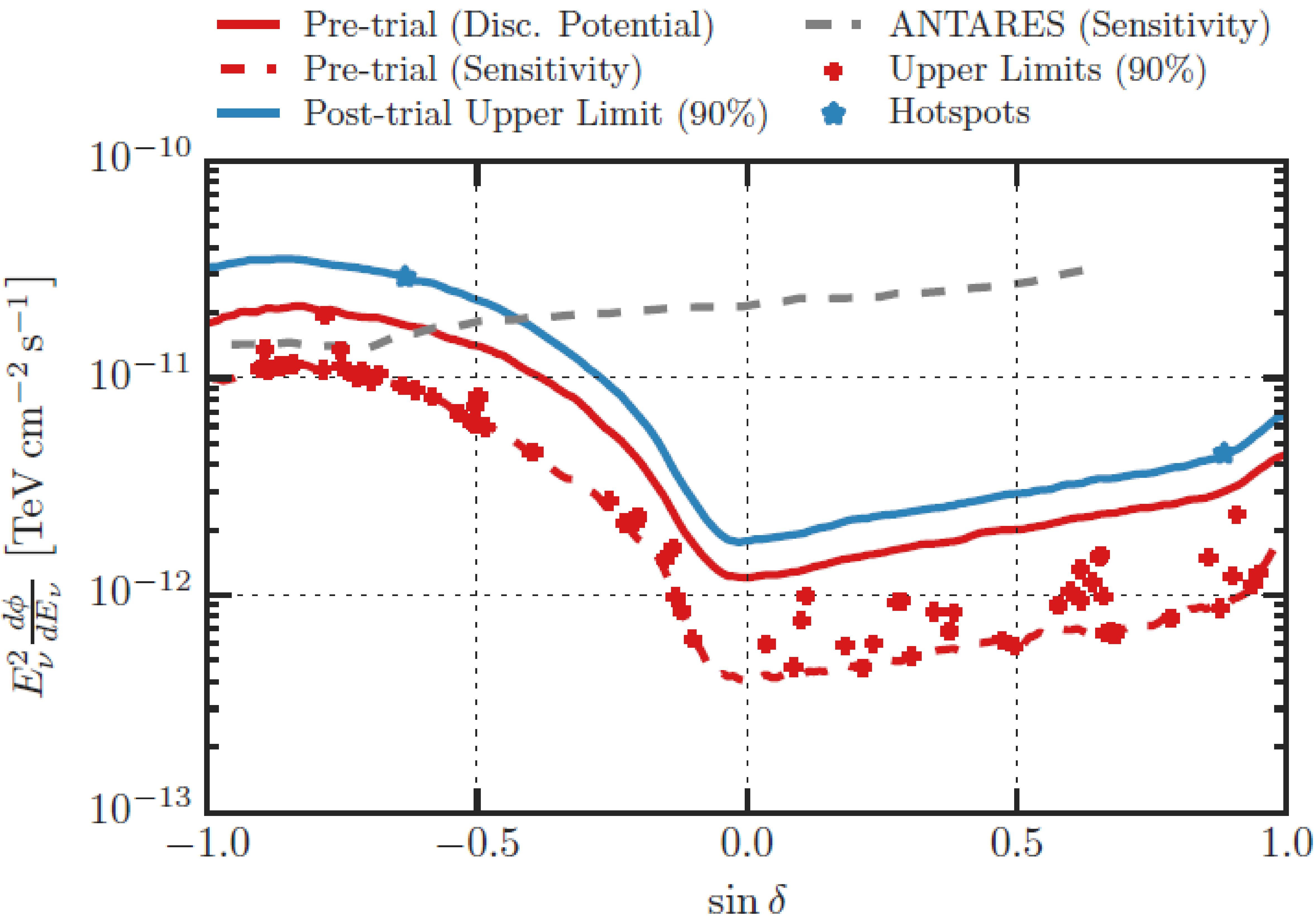
pre-trial significance skymap

No significant excesses



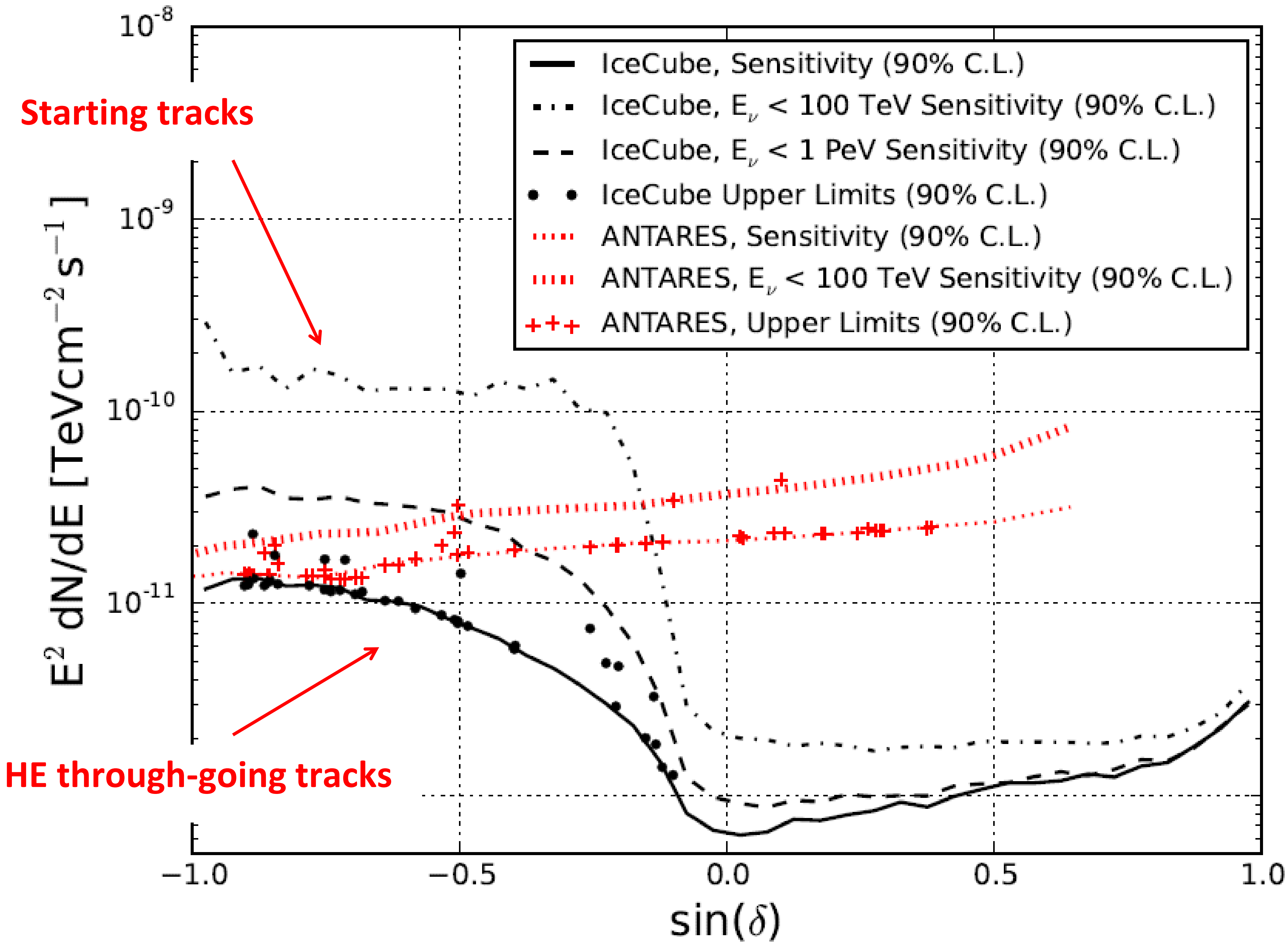
IceCube 7 years

Sensitivities and upper limits



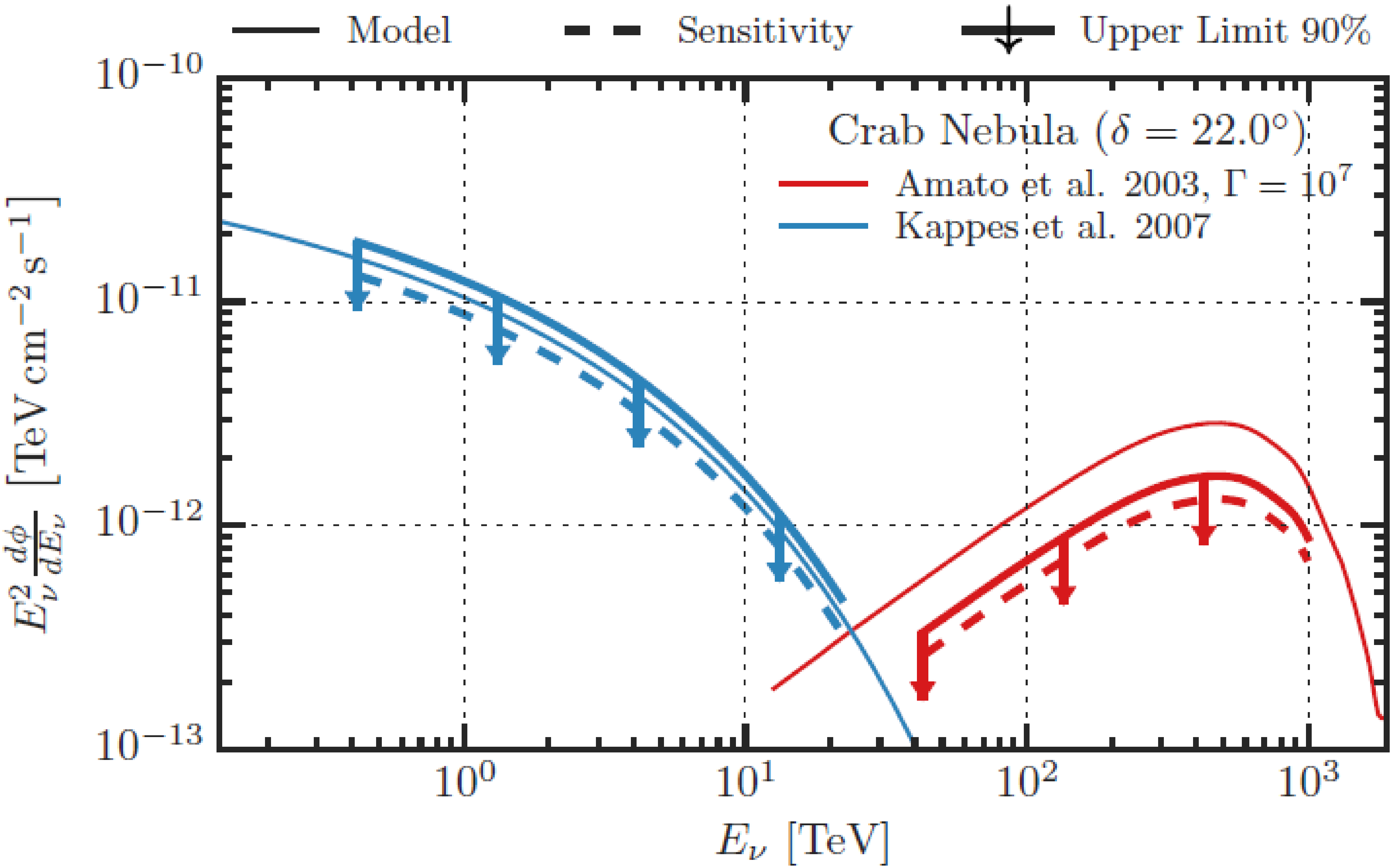
Influence of a cut-off (shown for 4-year sample)

Astrophys. Journal Letters, Vol. 824, Nb.2, L28 (2016)



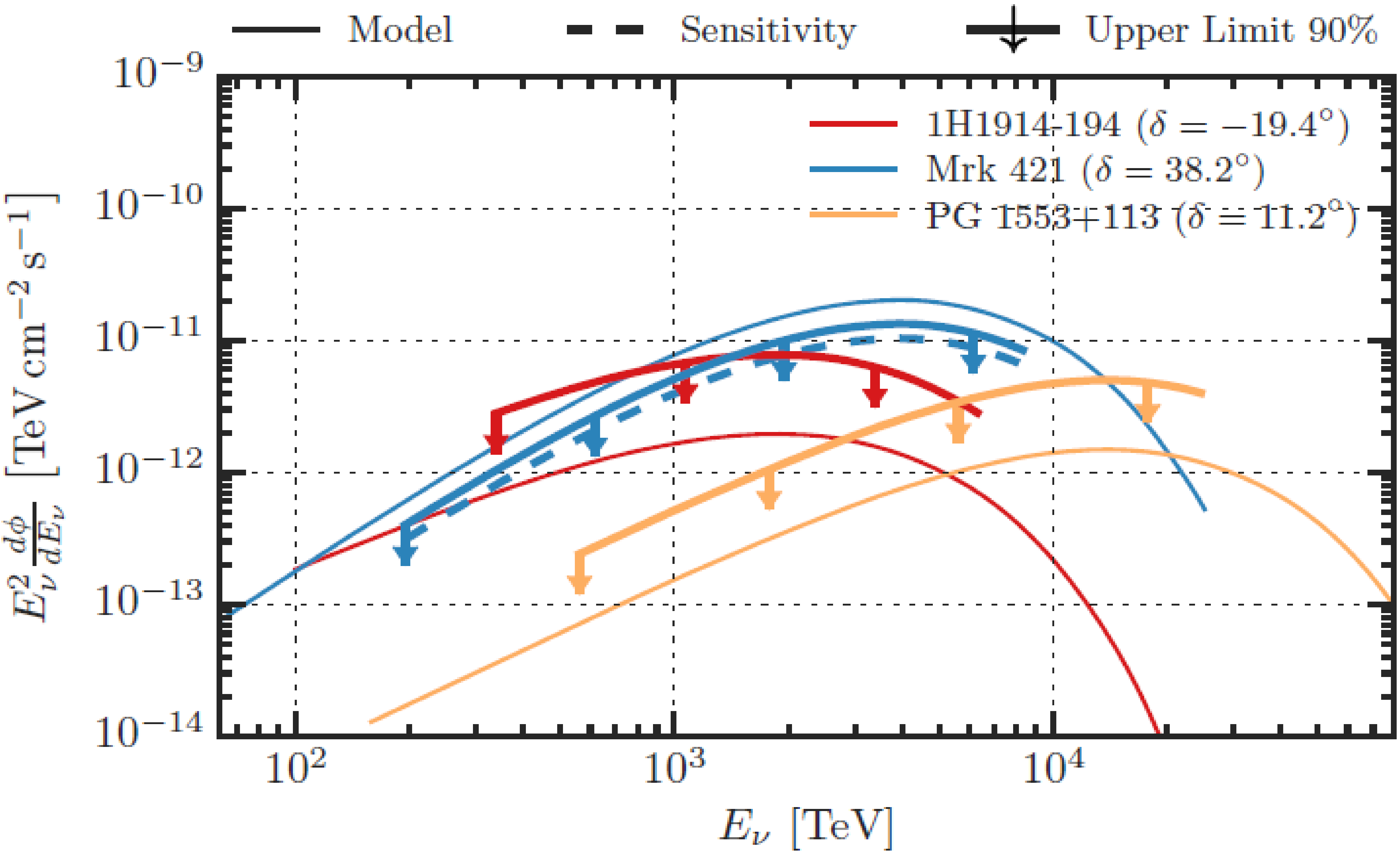
Limits vs. Models for selected sources

Crab Nebula



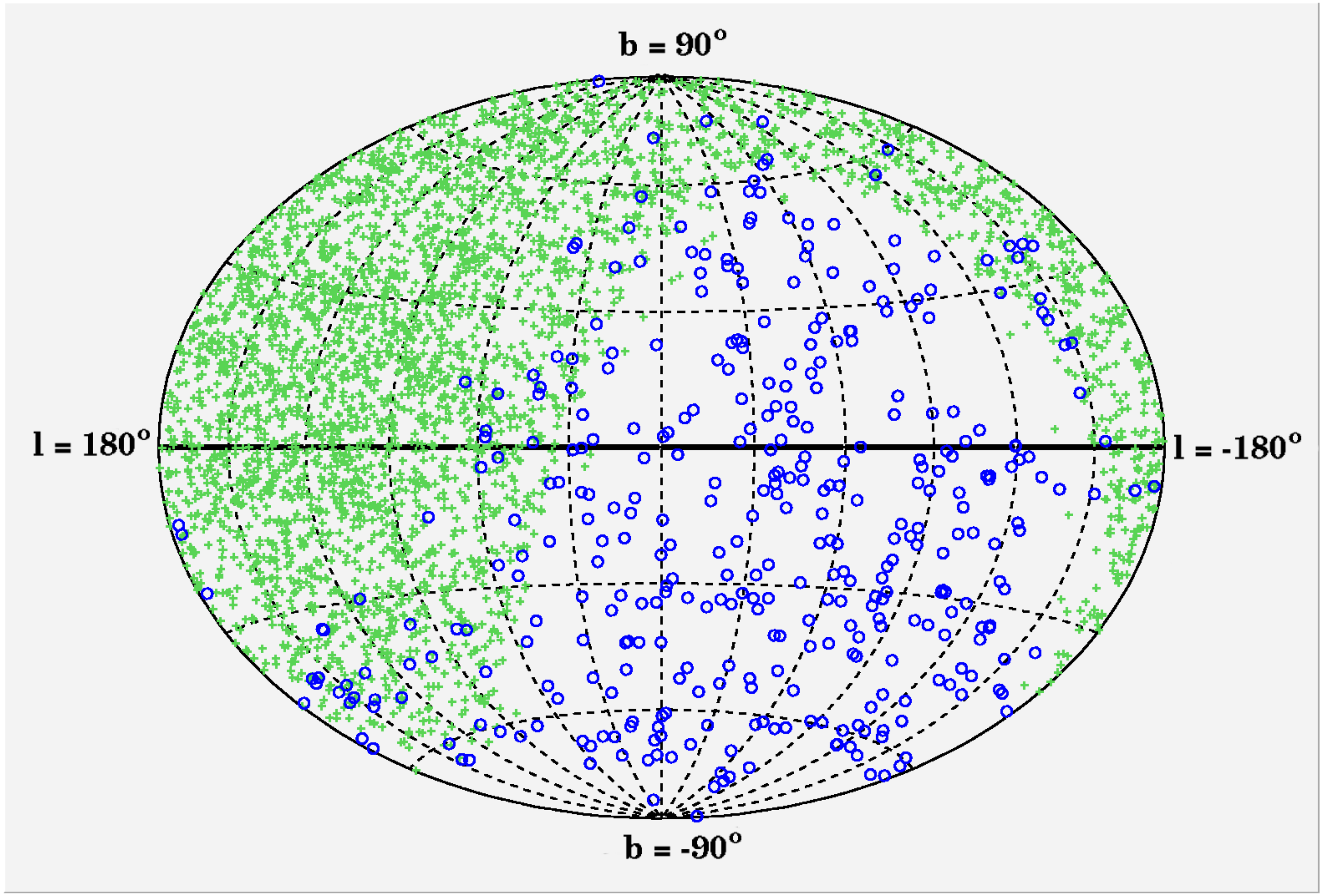
Limits vs. Models for selected sources

Blazars *(Petropolou et al. 2015)*



A reminescence:

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



SEARCH FOR TRANSIENT SOURCES

Gamma Ray Bursts

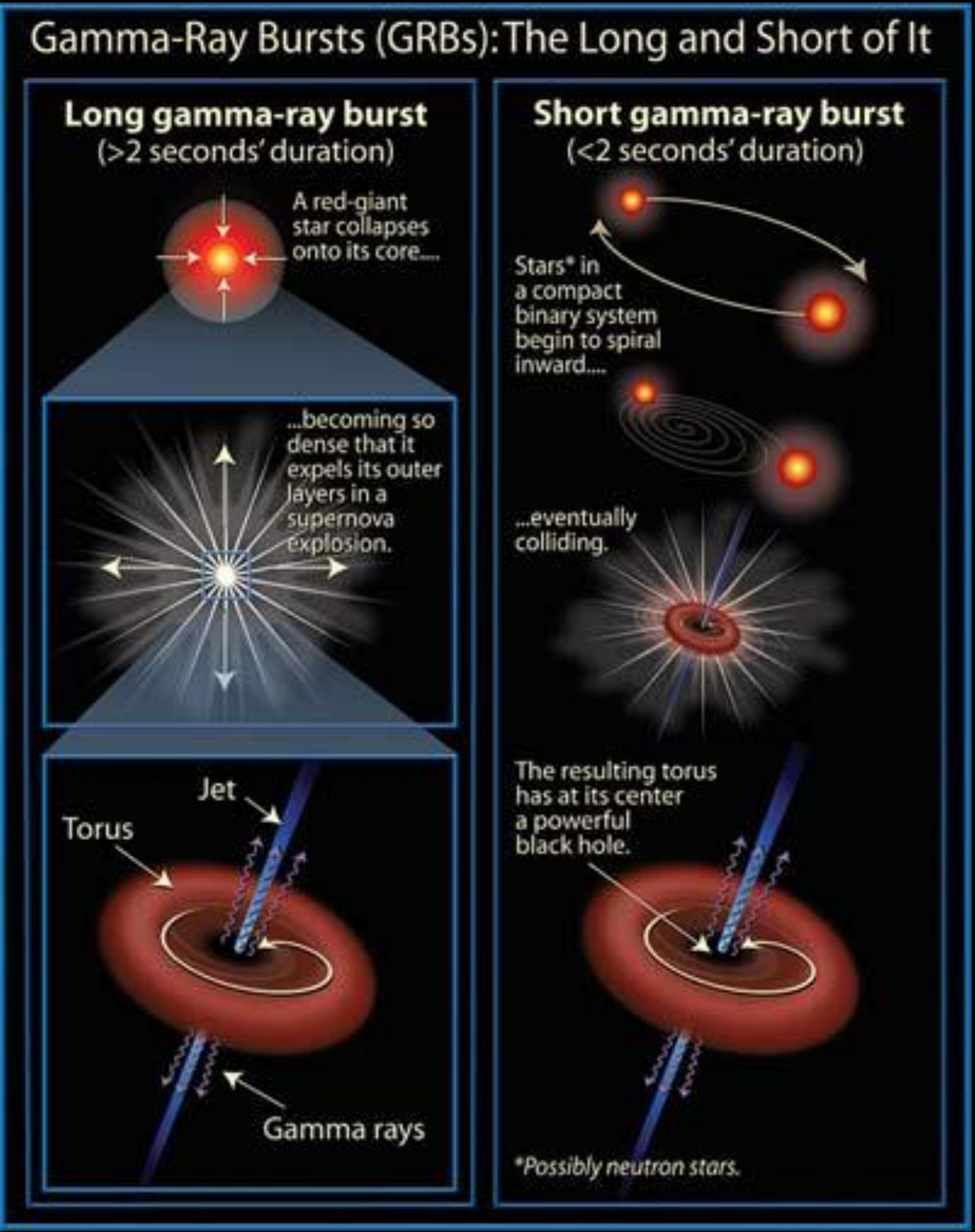
Follow-up Programs

Supernova Trigger

Gamma-Ray Bursts

… from USSR or from the cosmos?

Vela Satellite 1969



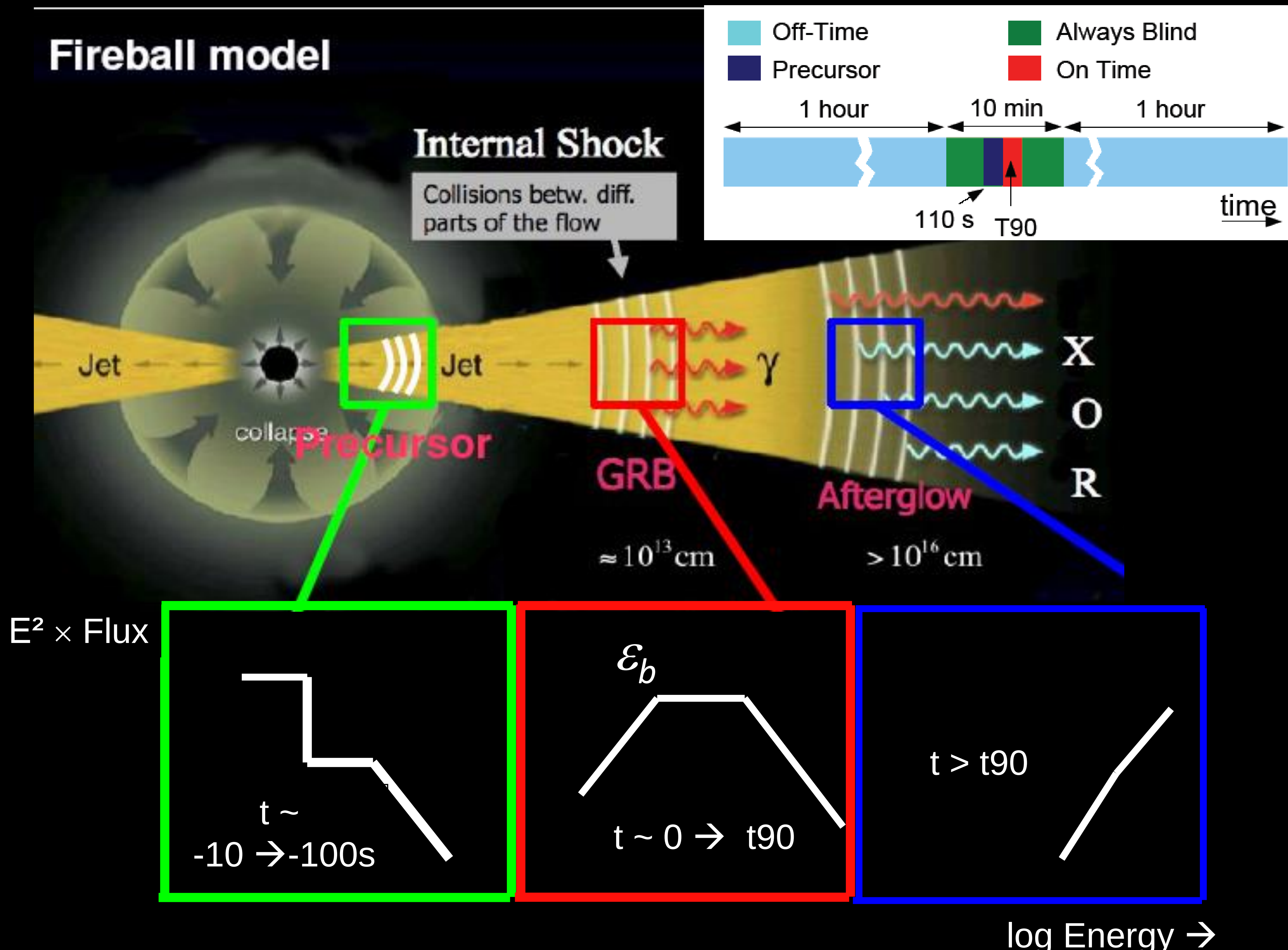
Long and Short GRB

Waxman/Bahcall:

GRB are the sources of highest energy cosmic rays

→ **Expect neutrinos from GRB**

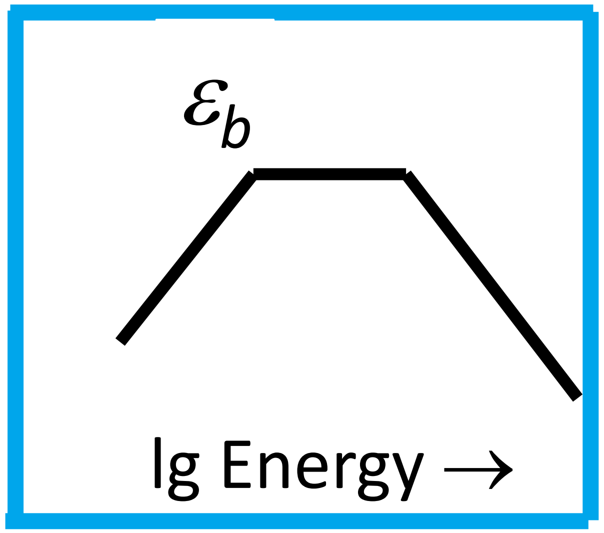
Neutrinos from GRB



Neutrinos from GRB

Astrophys. J. 805, L5 (2015) & arXiv:1412:6510

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



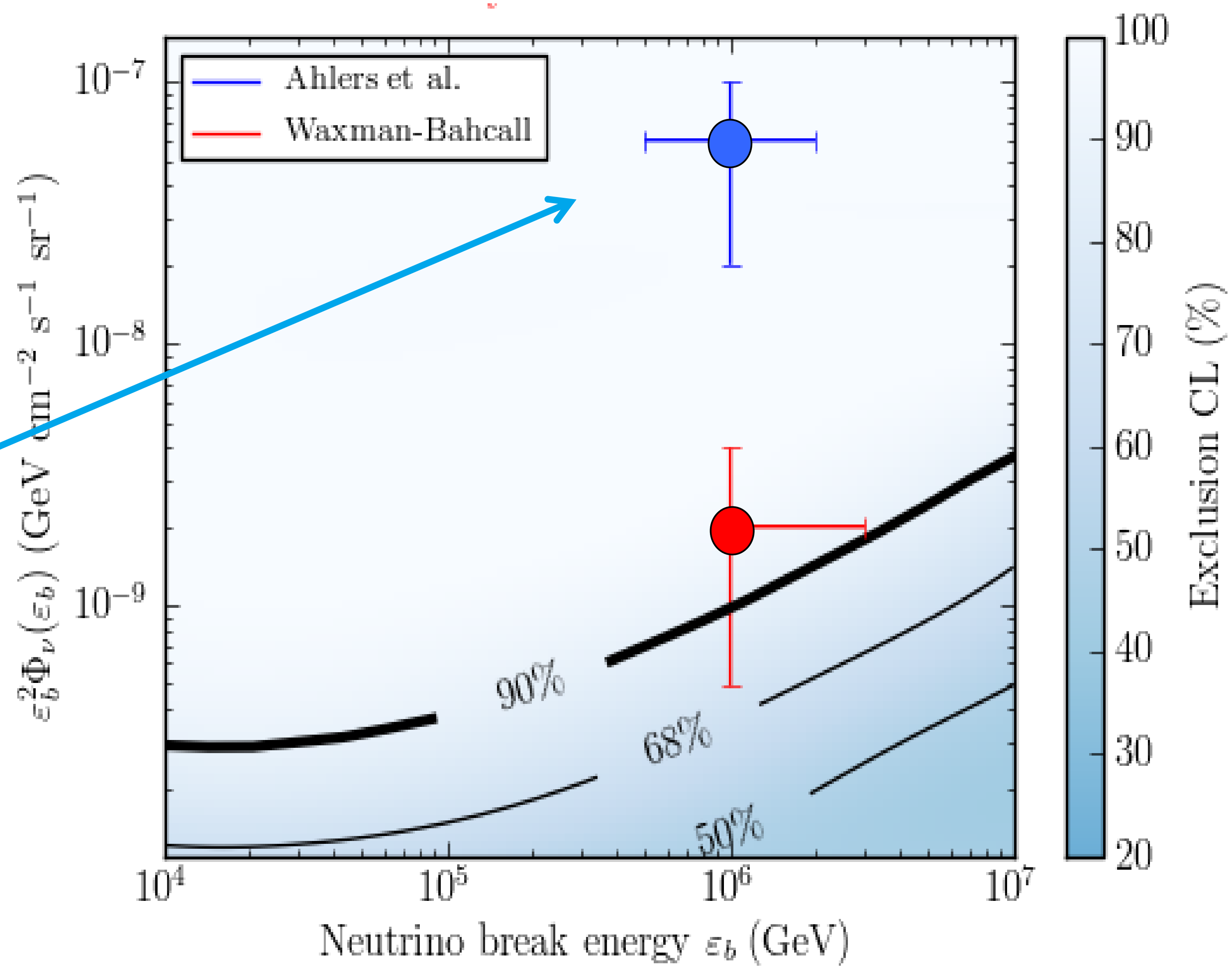
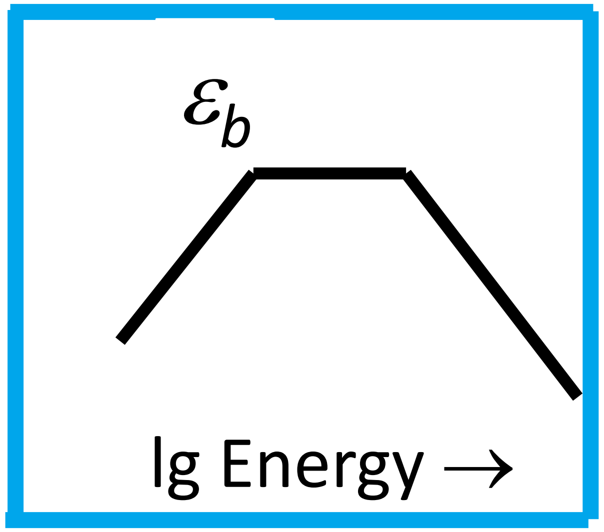
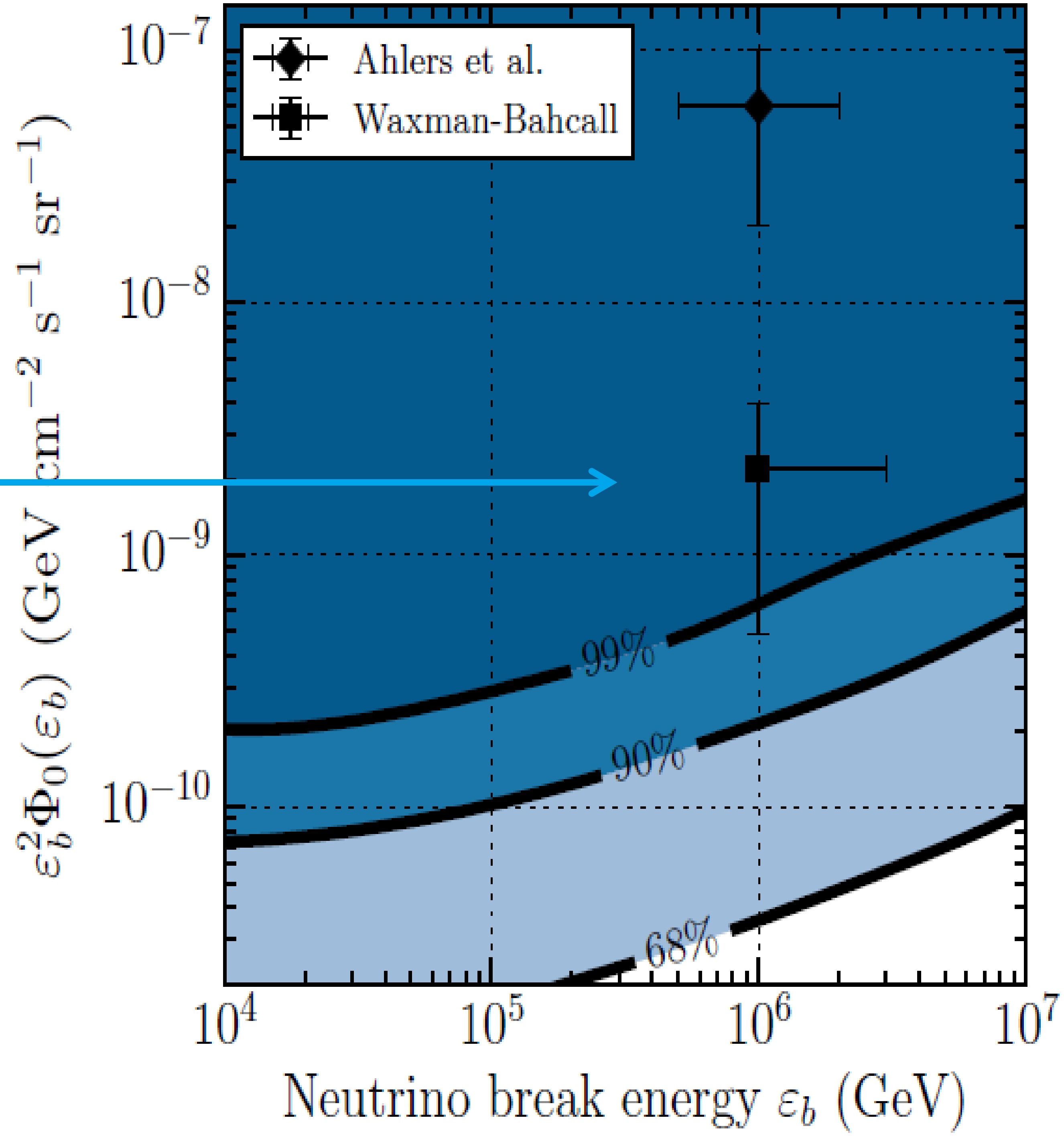


Fig. 1.— Constraint on generic doubly-broken power law neutrino flux models as a function of first break energy ε_b and normalization Φ_0. The model by Ahlers et al. (2011) assumes that only neutrons escape from the GRB fireball to contribute to the UHECR flux. The Waxman-Bahcall model (1997), which 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).

Neutrinos from GRB subm. to ApJ & arXiv:1702:6510

- **1172 GRB**
- **Neutron escape models à la Ahlers ruled out.**
- **WB model almost ruled out.**



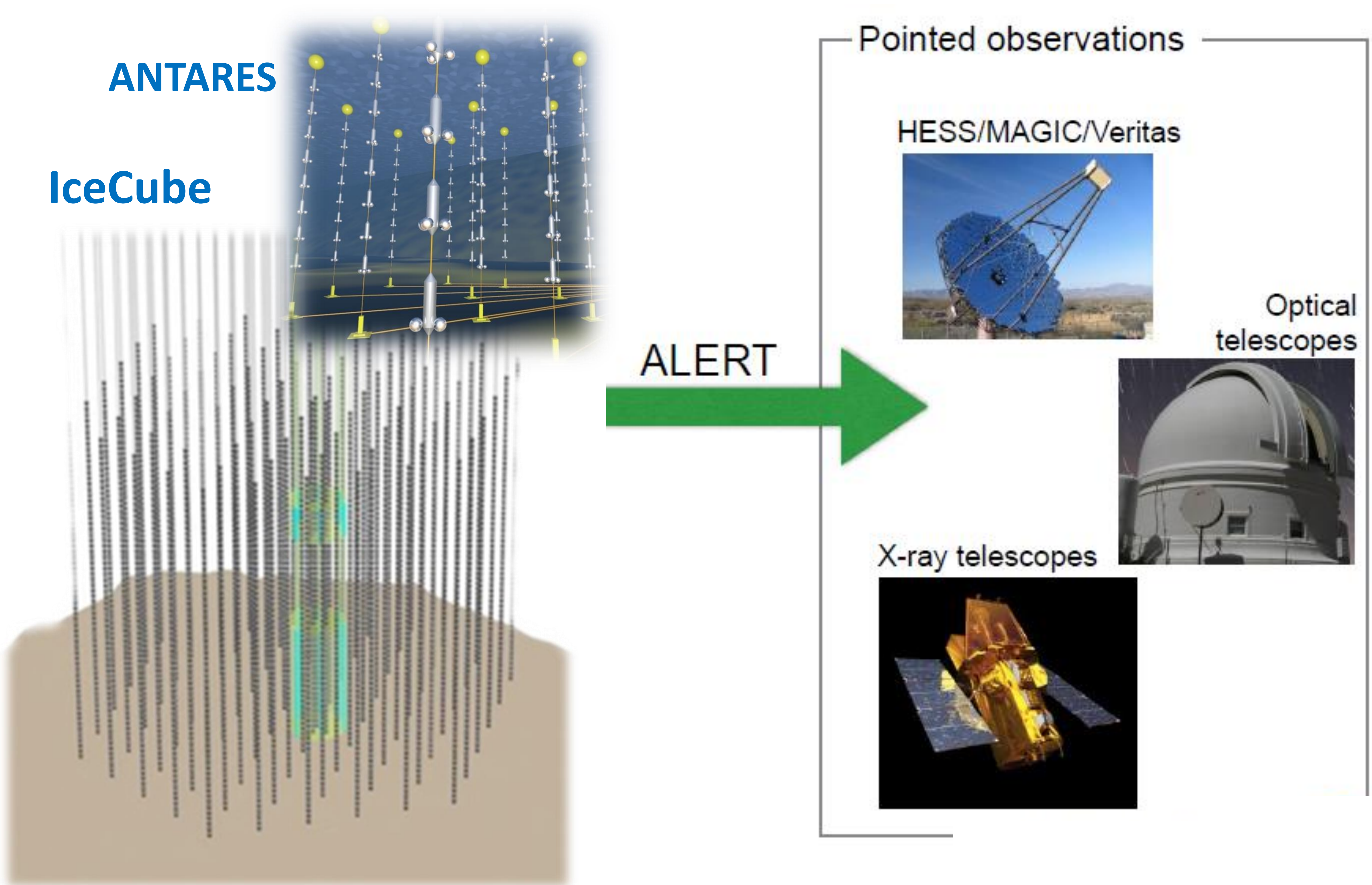


Note that we assume roughly uniform production across all GRB. Should a rare subclass of GRB produce a significant neutrino signal, it may still be discoverable by IceCube and with MWL observations!

FOLLOW-UP PROGRAMS

… with just one recent example

Follow-up observations all-sky devices → pointing devices



Rationale of the follow-up programs

Impact on the significance of a possible ν signal by observations of flares/bursts in el.-magnetic waves

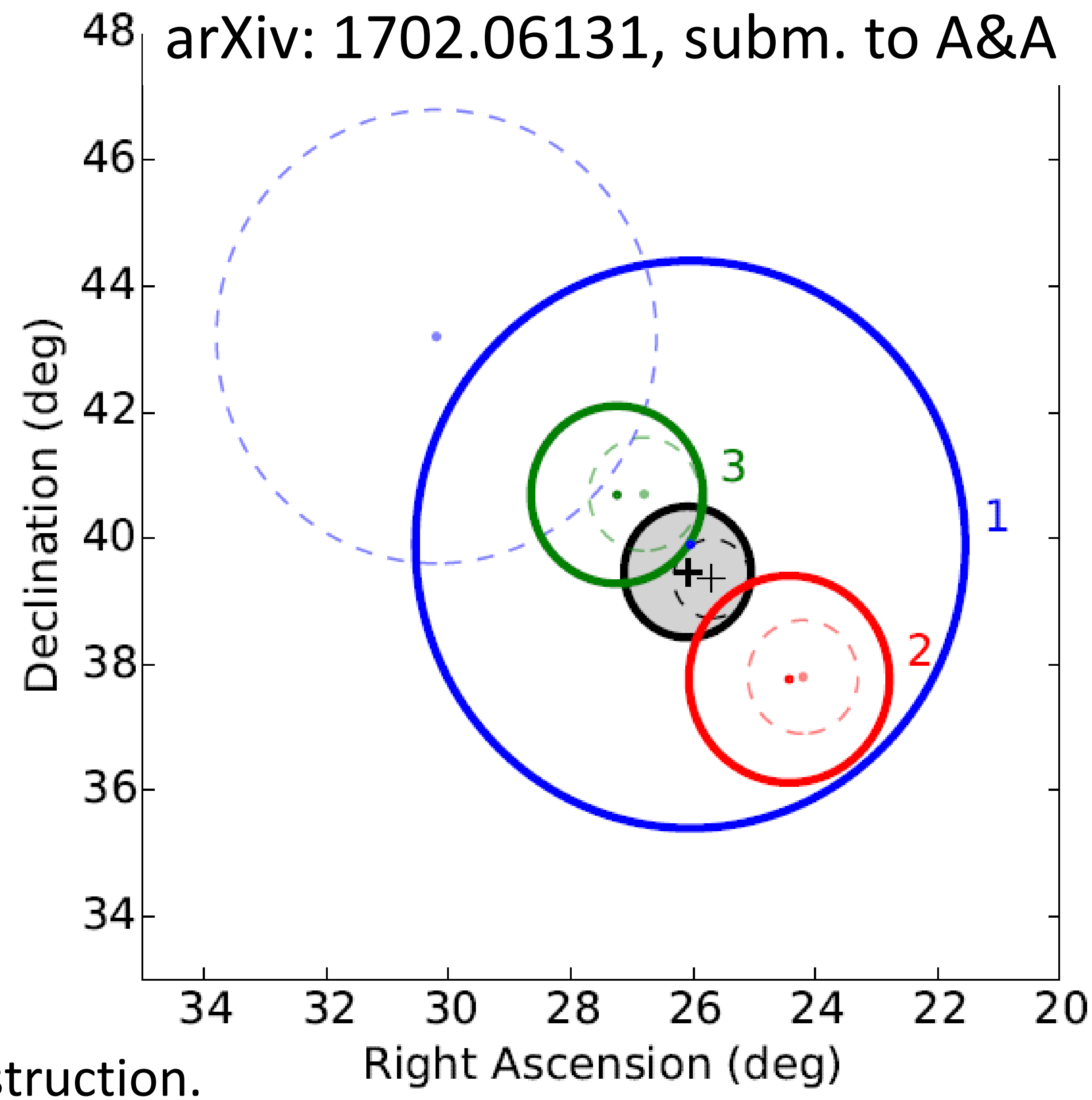
Neutrino alerts have the potential to observe otherwise un-noticed flares/bursts in el.-magnetic waves

Getting the full picture

of a source by combining information from different messengers

Multi-wavelength follow-up of a rare ν multiplet

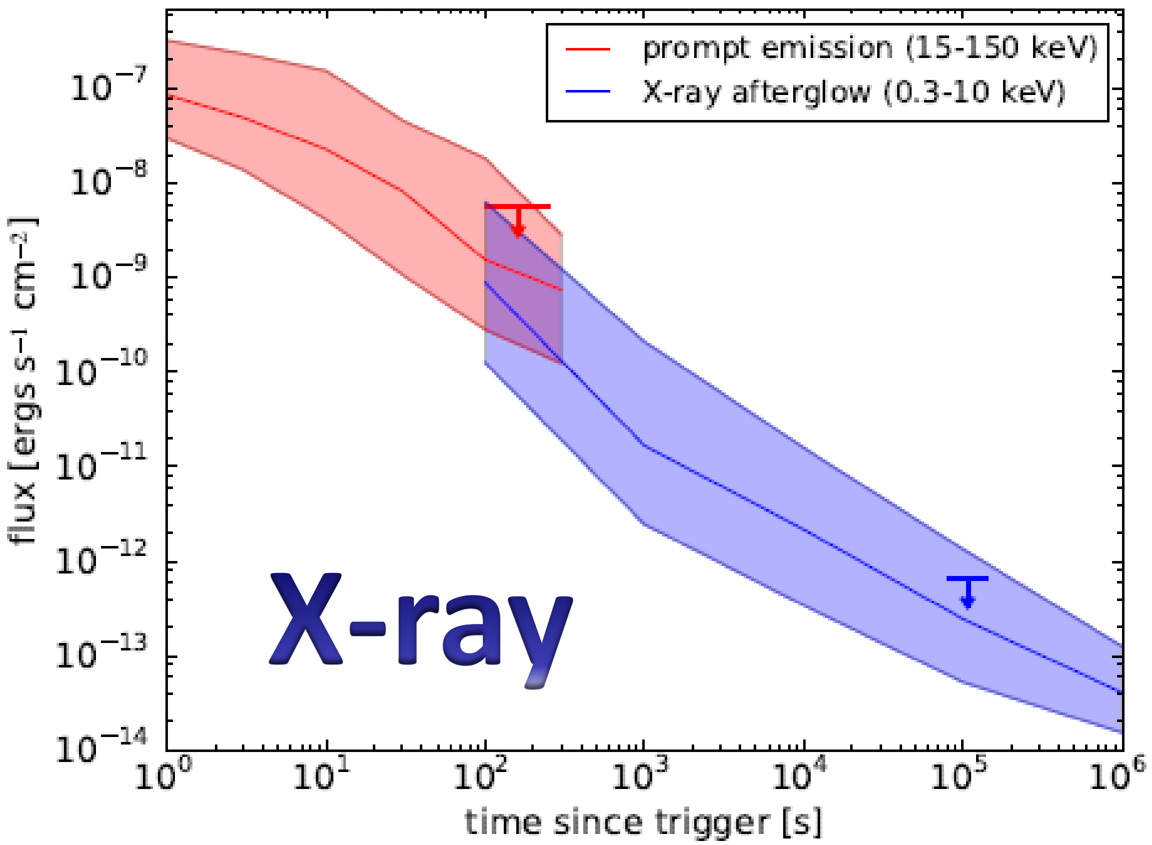
- **2/17, 2016: 3 ν-induced tracks within 100 s, consistent with point source.**
- **Expected once every 13.7 years as random coincidence of BG events.**
  → Detection of 0.38 BG events was expected at the time of the alert.



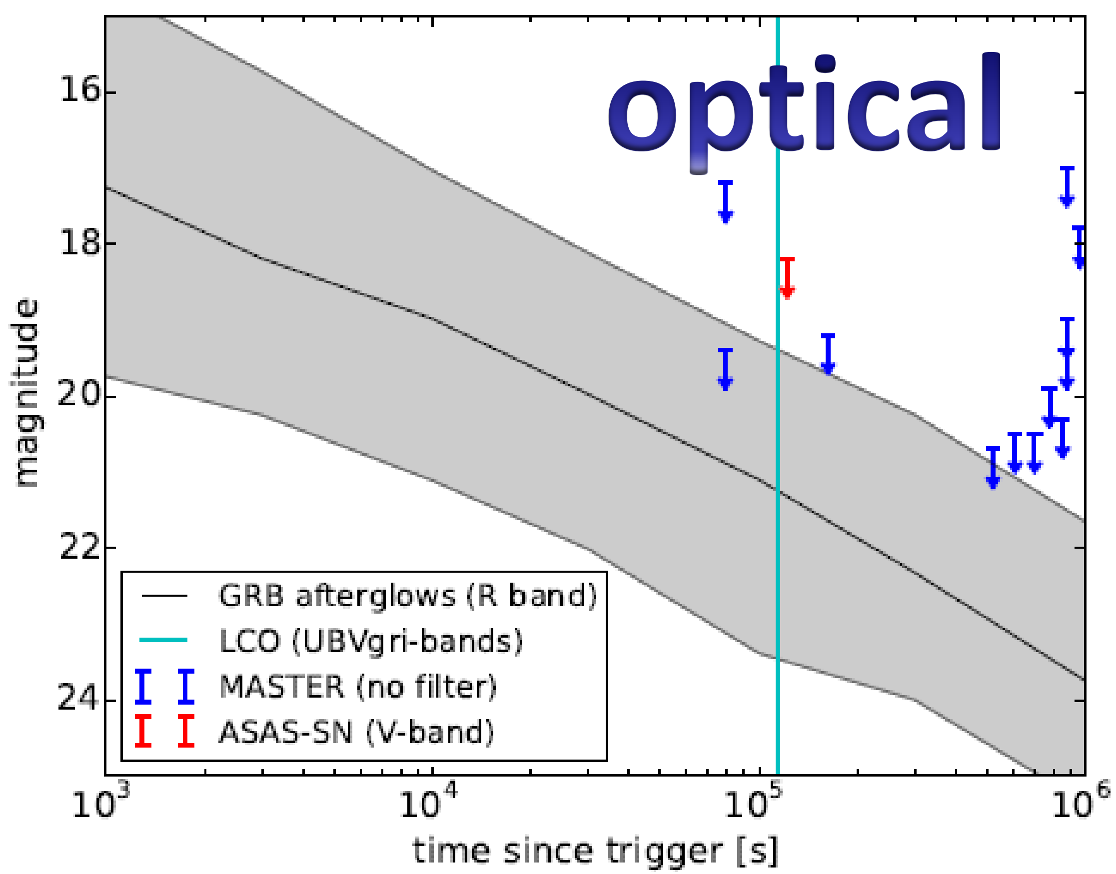
Location of the 3 events with their 50% error circles.
+ is combined direction, the shaded circle :combined 50% error circle. Solid and dashed circles : results of the standard (solid) and an alternative (dashed) reconstruction.

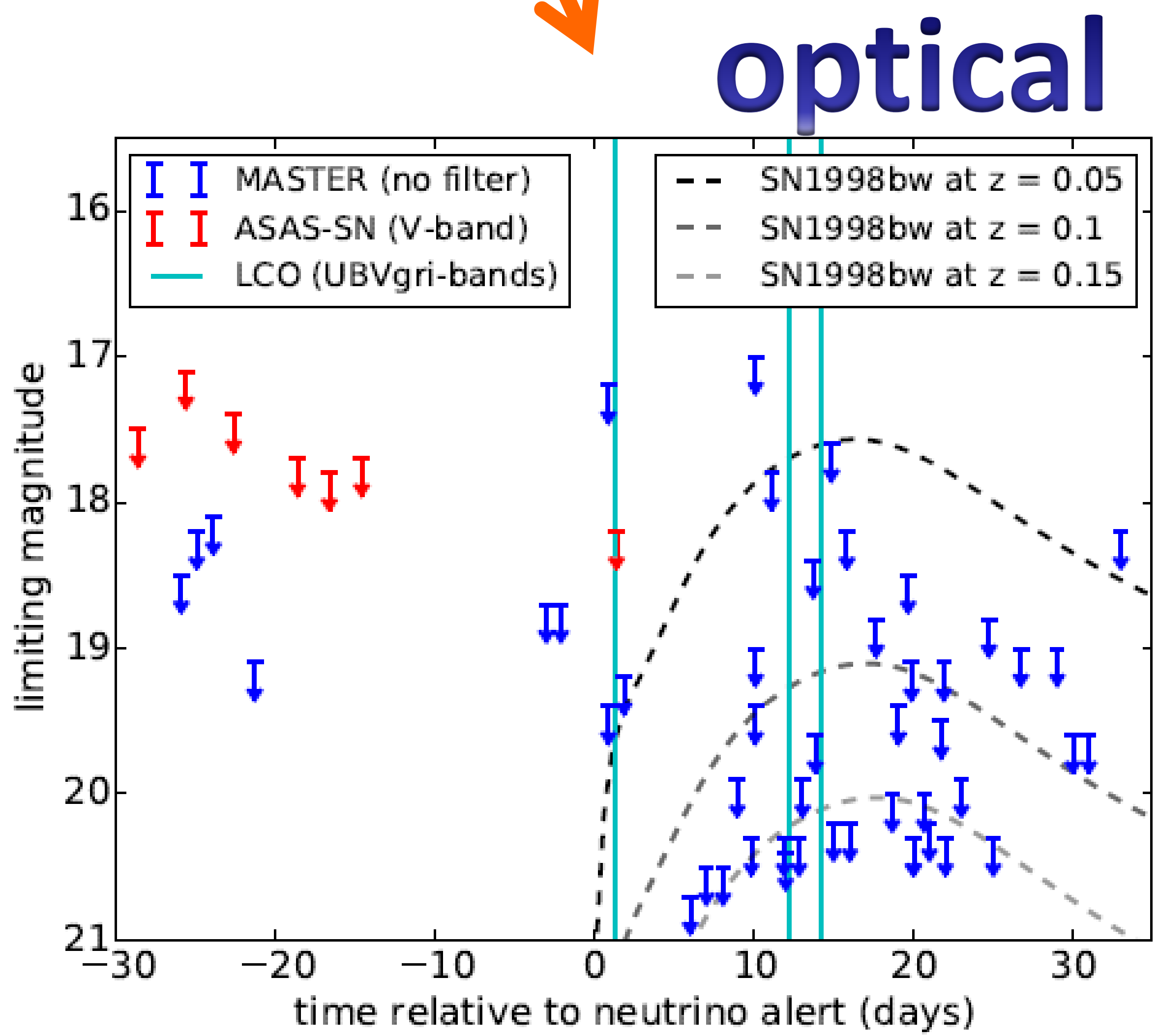
- **Follow-up observations by Swift's X-ray telescope, by ASAS-SN, LCO and MASTER at optical wavelengths, and by VERITAS in the very high energy gamma-ray regime, plus analysis of Fermi LAT and HAWC.**

Multi-wavelength follow-up of a rare ν multiplet



No likely electromagnetic counter-part detected, setting constraints on candidate ν sources such as GRB, core-collapse SN and AGN flares.





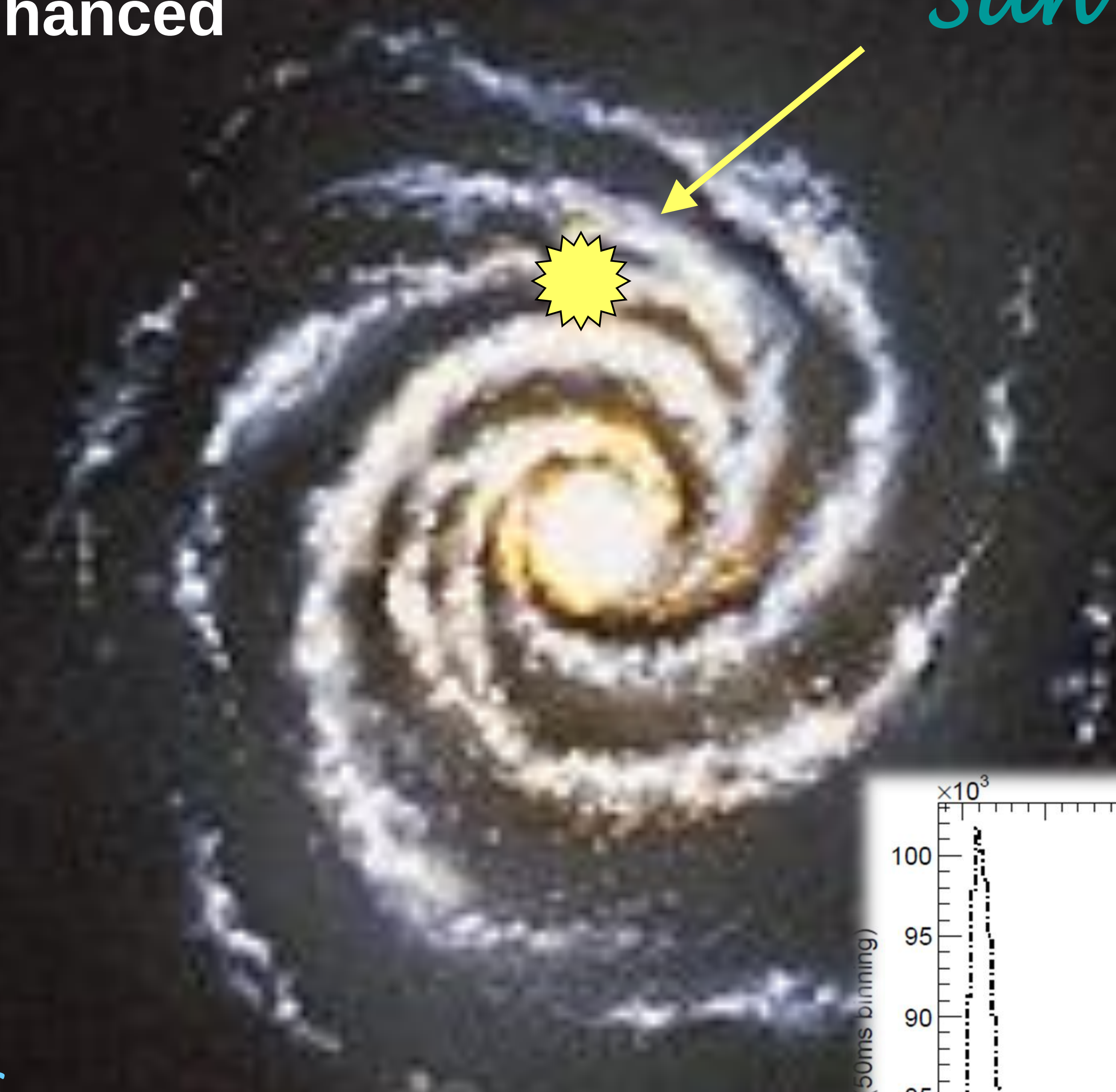
30 years SN 1987A

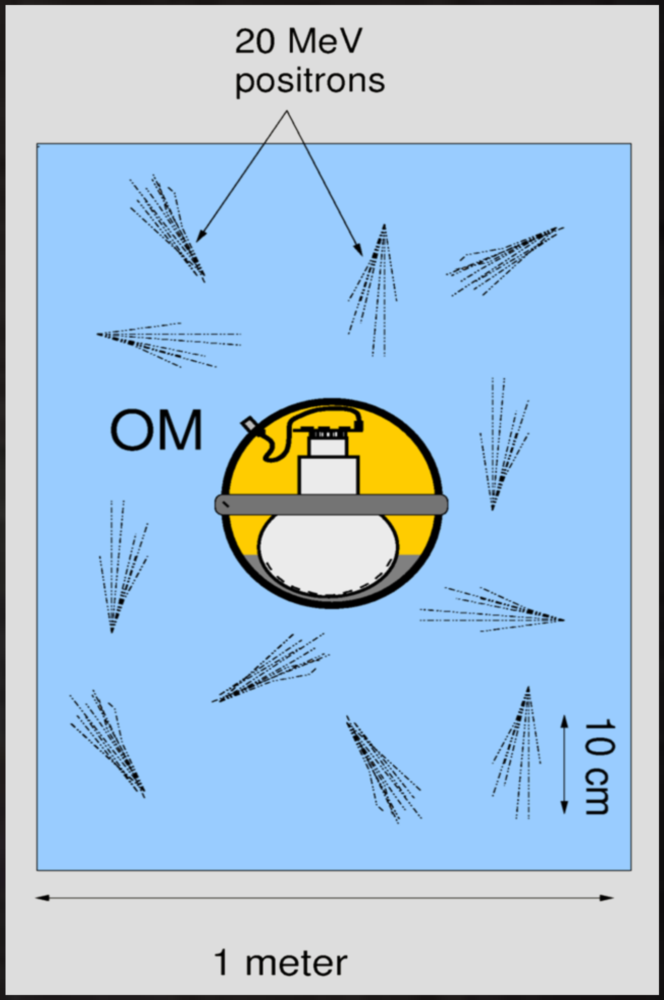
SUPERNOVA BURST MONITORING

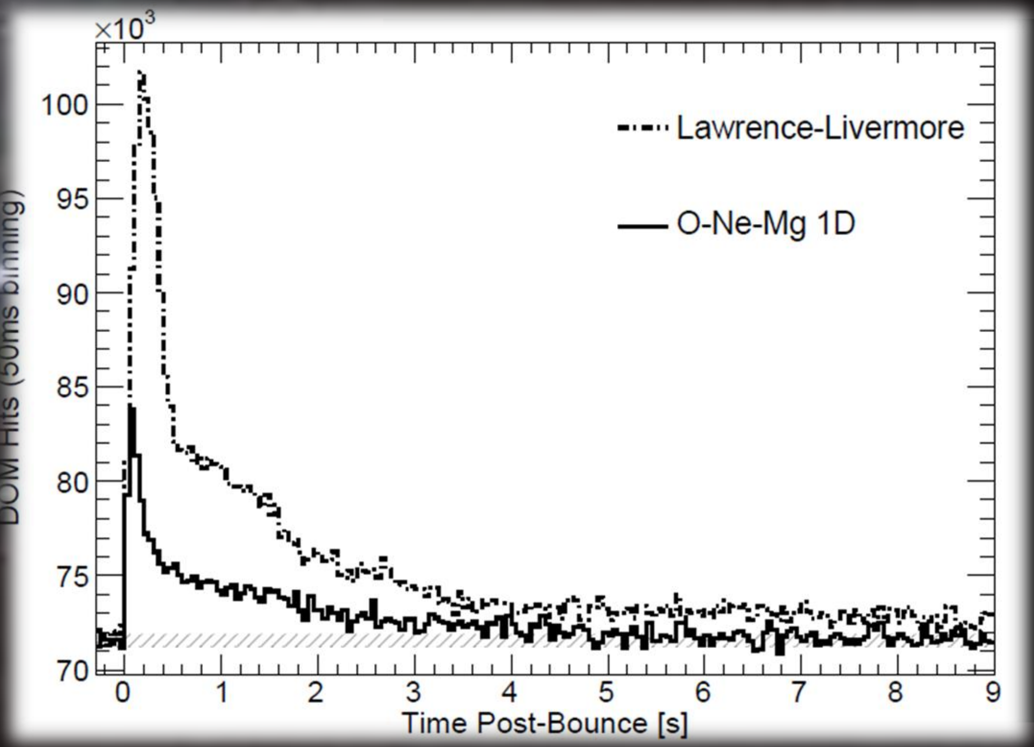
Supernova detection in IceCube

Detection via enhanced PMT noise rates

Dark noise (1PE) in IceCube photomultipliers only ~ 320 Hz !





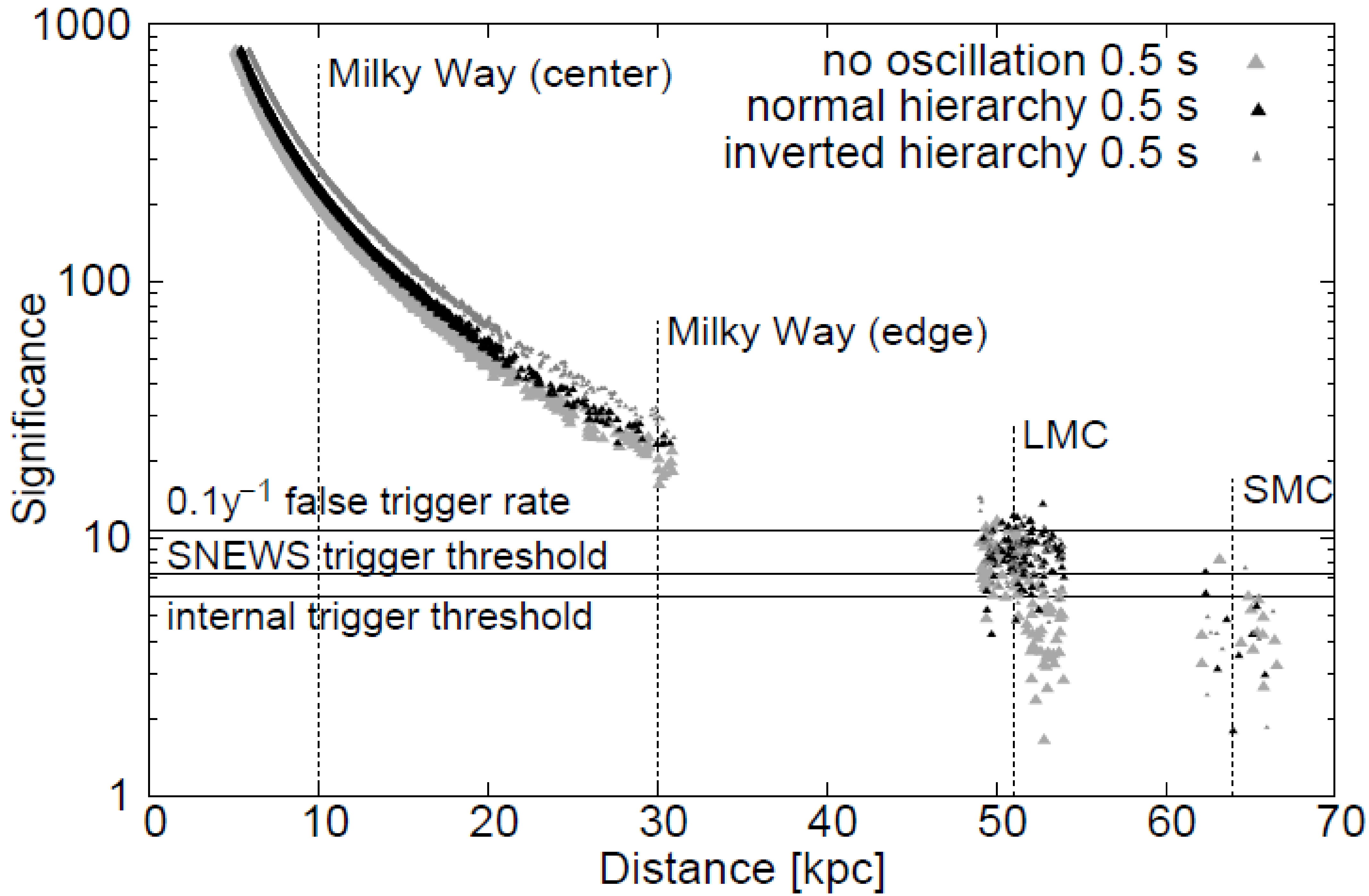


Signal for SN in GC, 10^6 counts

Significance as function of the distance

IceCube Sensitivity for Low-Energy Neutrinos from Nearby Supernovae

IceCube Coll. A&A, Sept 2011

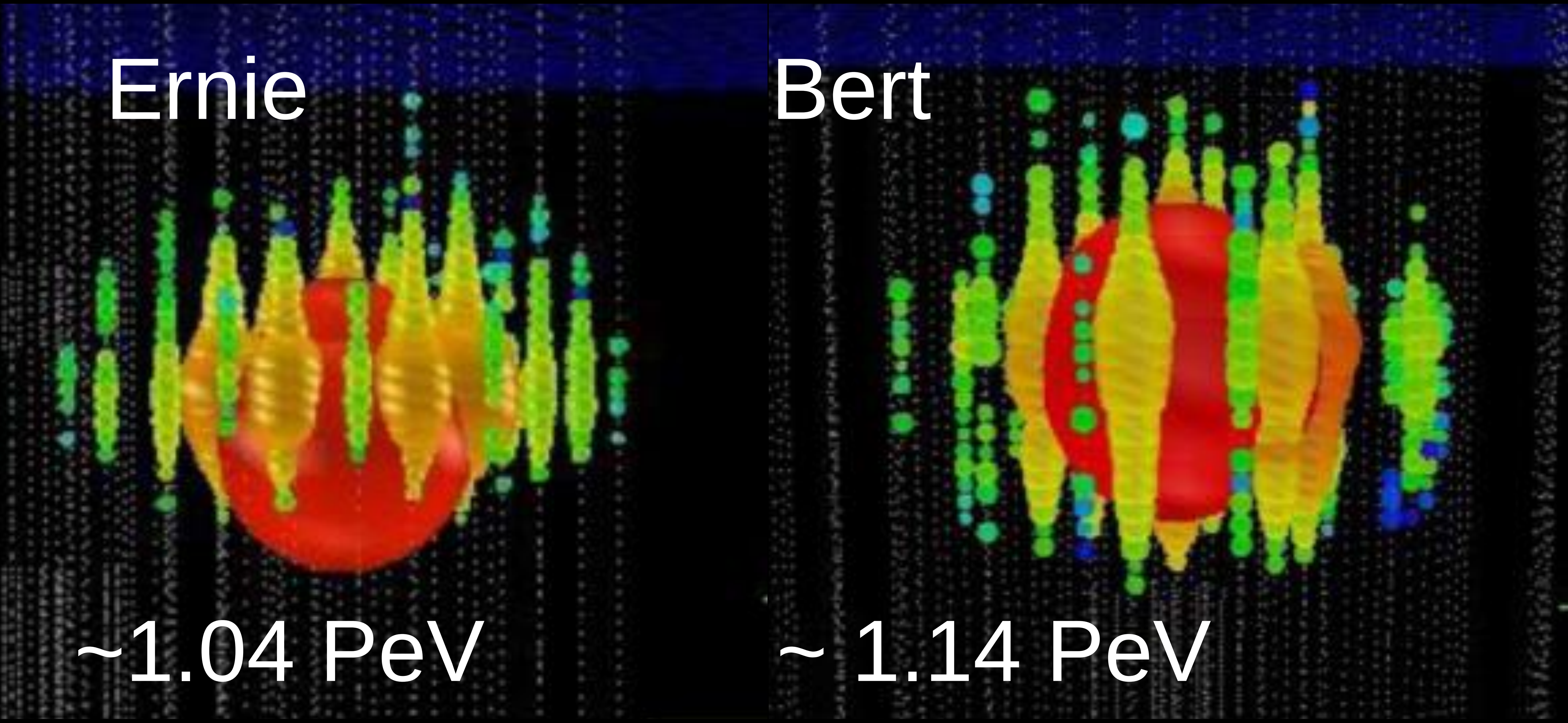


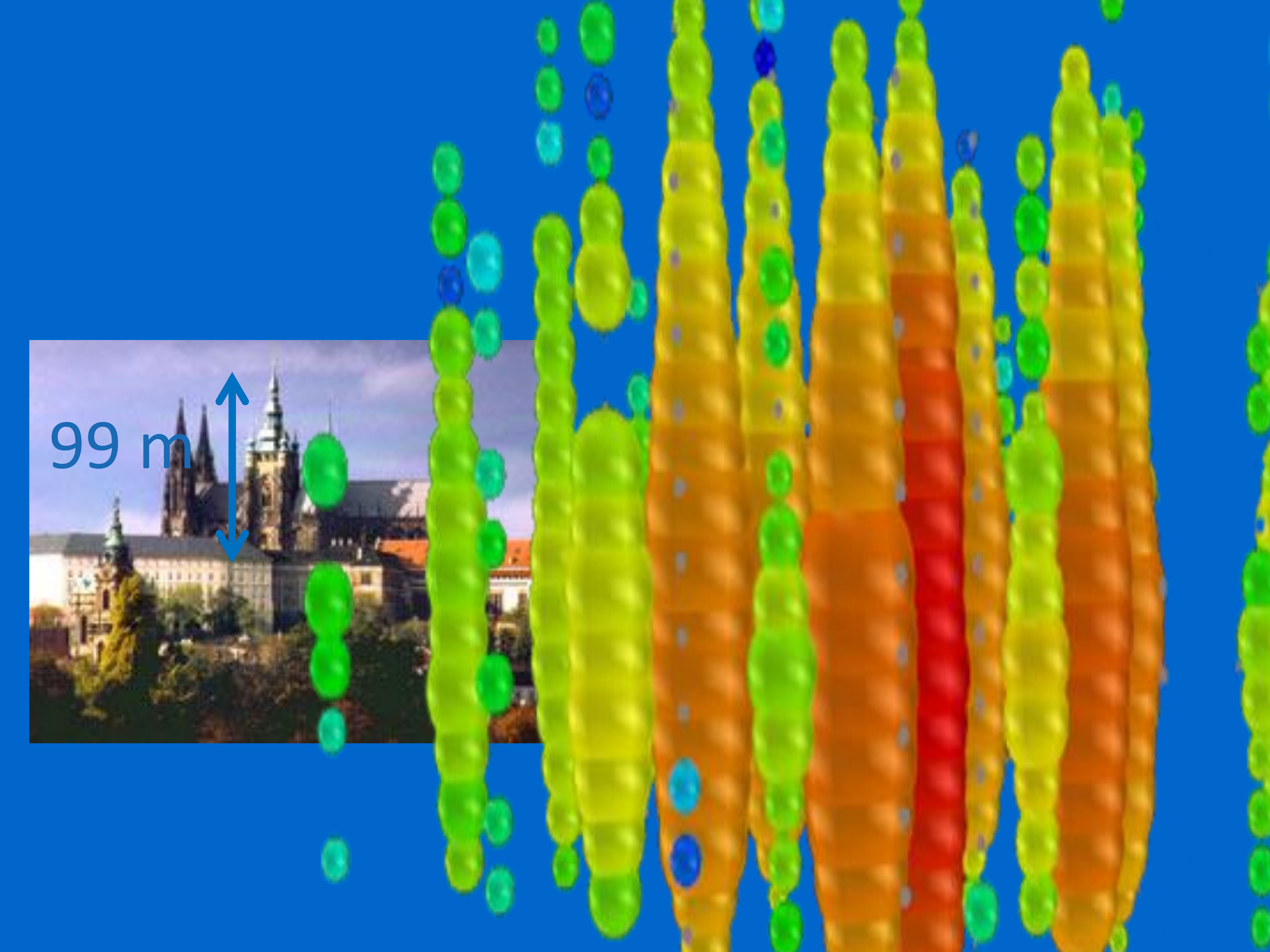
THE DISCOVERY OF A

DIFFUSE COSMIC NEUTRINO FLUX

Special search for neutrinos with E_ν > 500 TeV

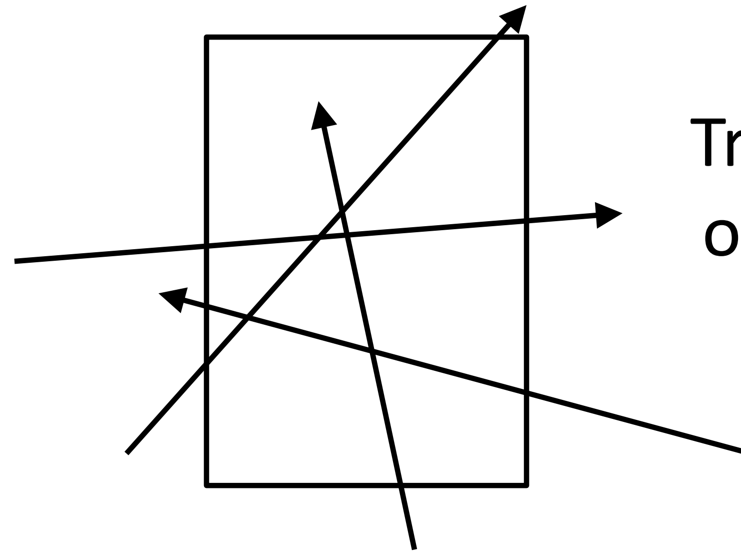
IC79/IC86 **2.8 σ**




99 m

4 different approaches (note the overlap of the event samples!)

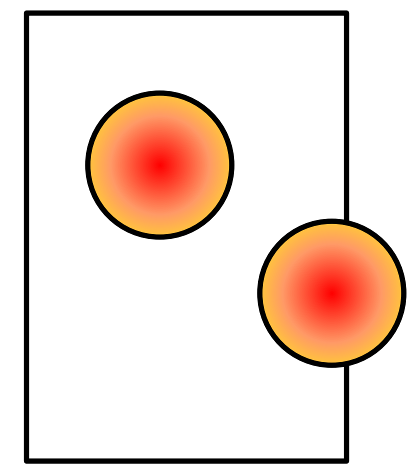
- **Through-going muons**



Tracks from below
or around horizon

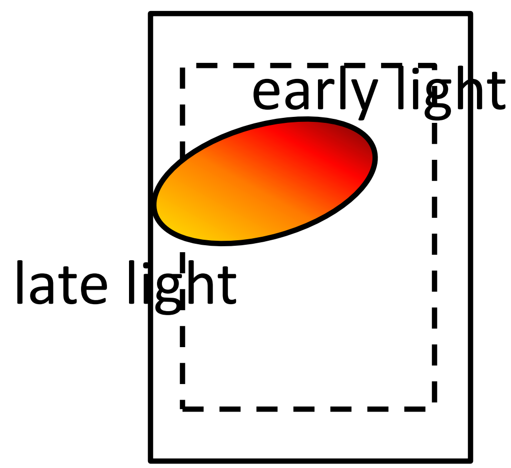
- **Cascades**

  Spherical light propagation



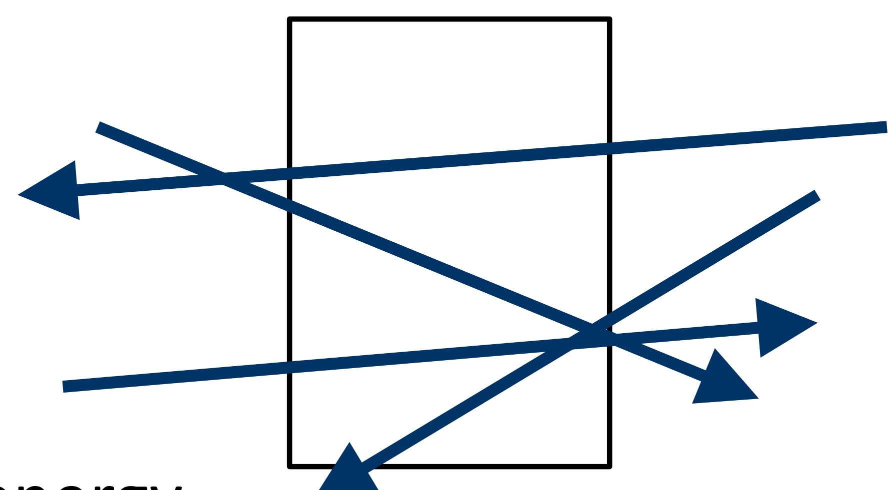
- **High-energy starting events (HESE)**

  E > 30 TeV, meanwhile lowered)



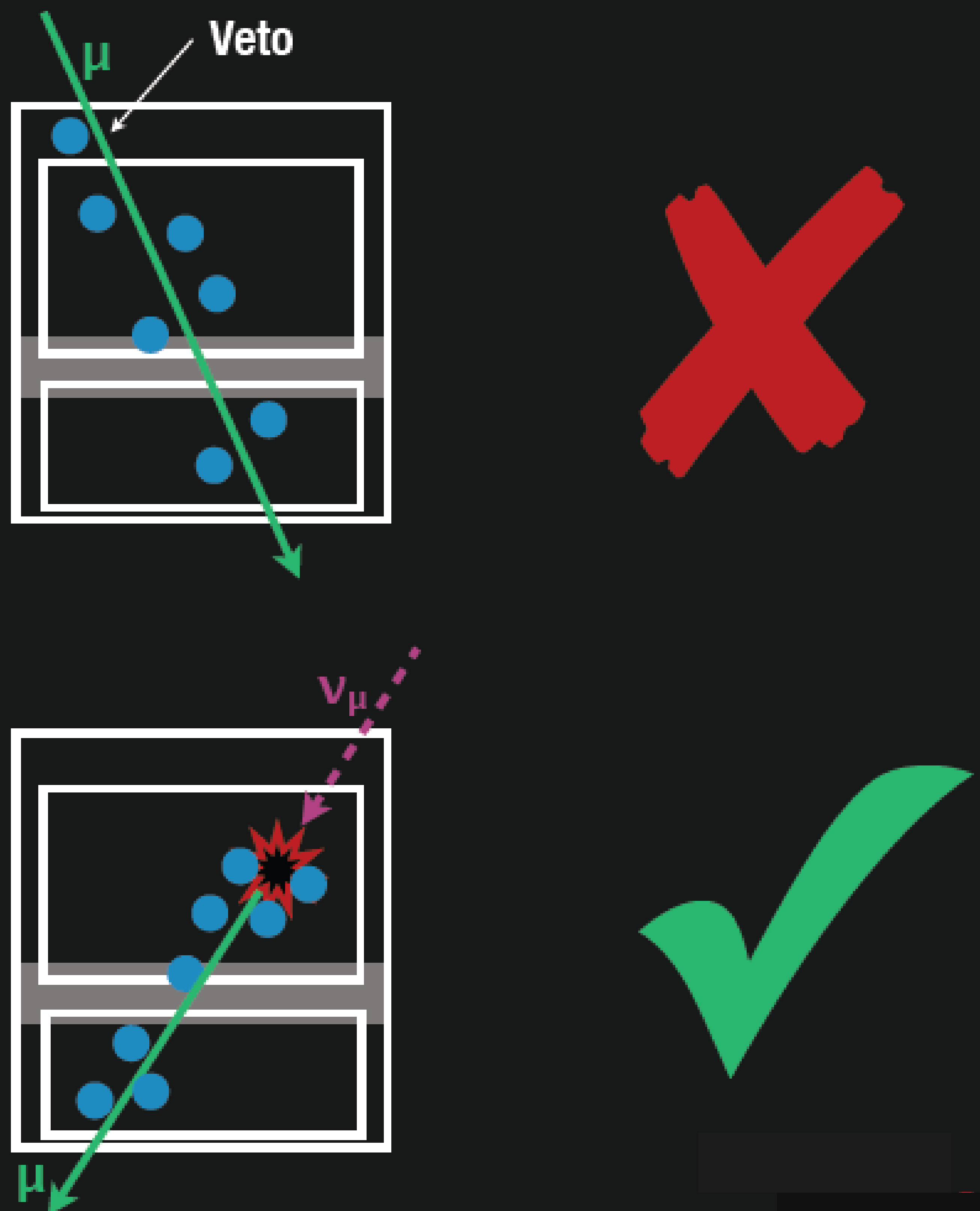
Events start inside,
not in veto region

- **Extremely high energy events (EHE)**



> 10 PeV events, mostly
from horizon or above.
Discrimation against atm μ: energy

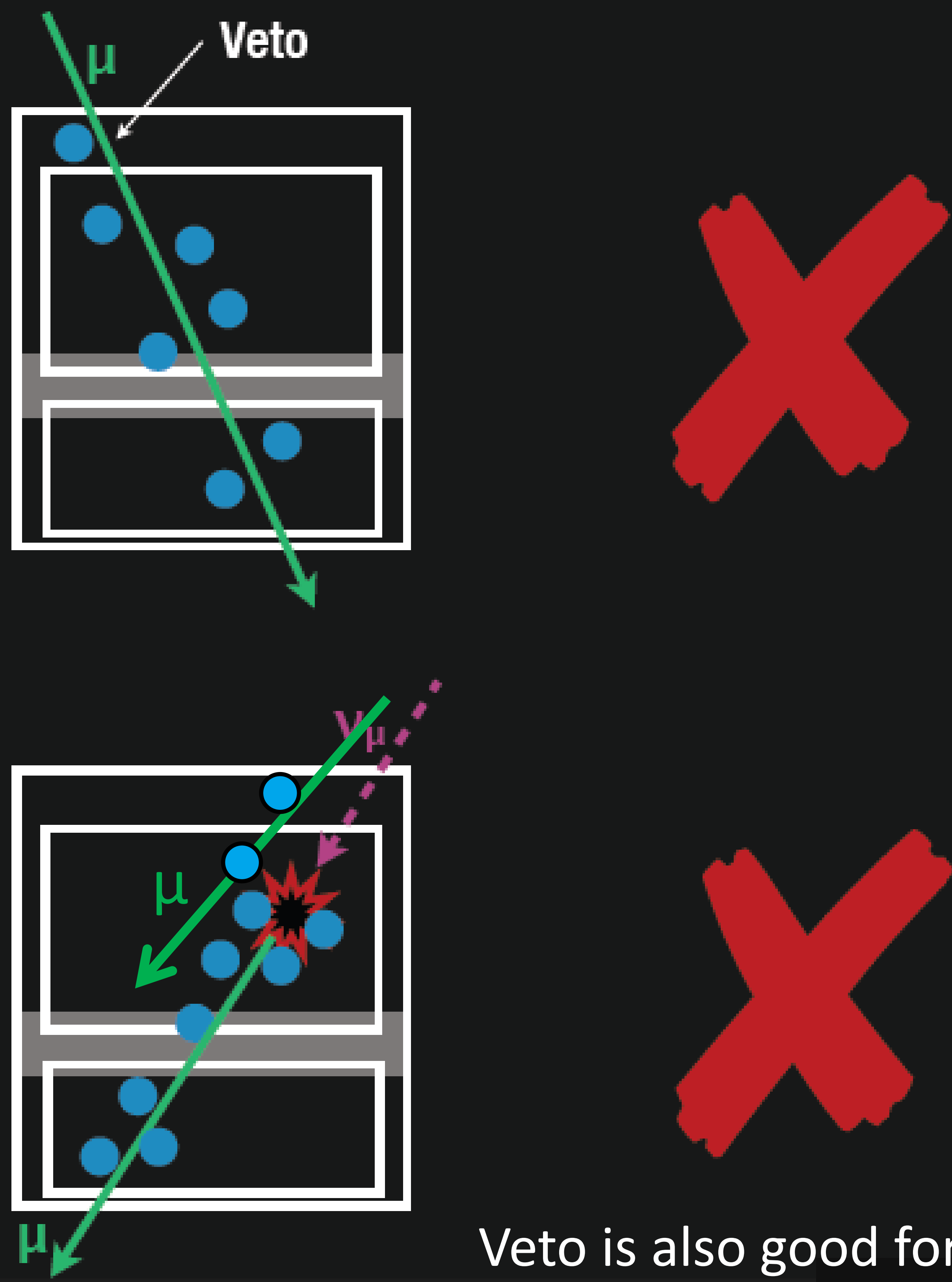
HESE analysis



- **Muon Veto**
- **Q_{tot} > 6000 photoelectrons**

→ 400 Mton eff. Volume

HESE analysis



- Muon Veto
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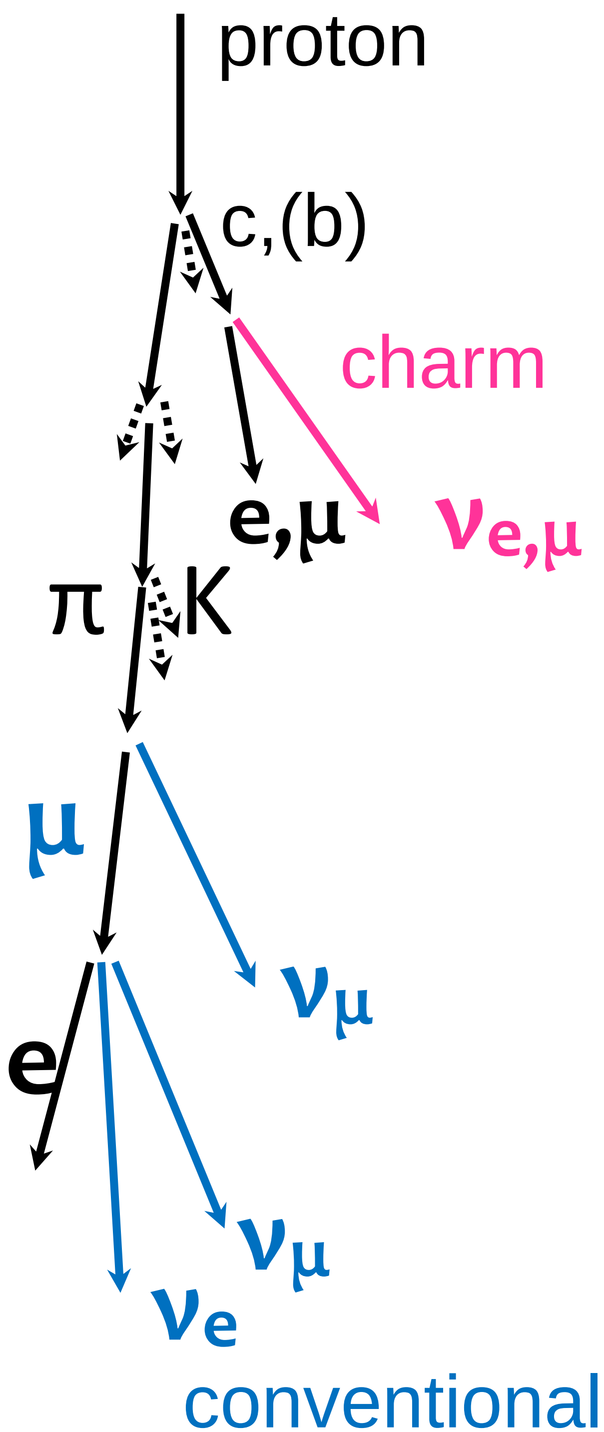
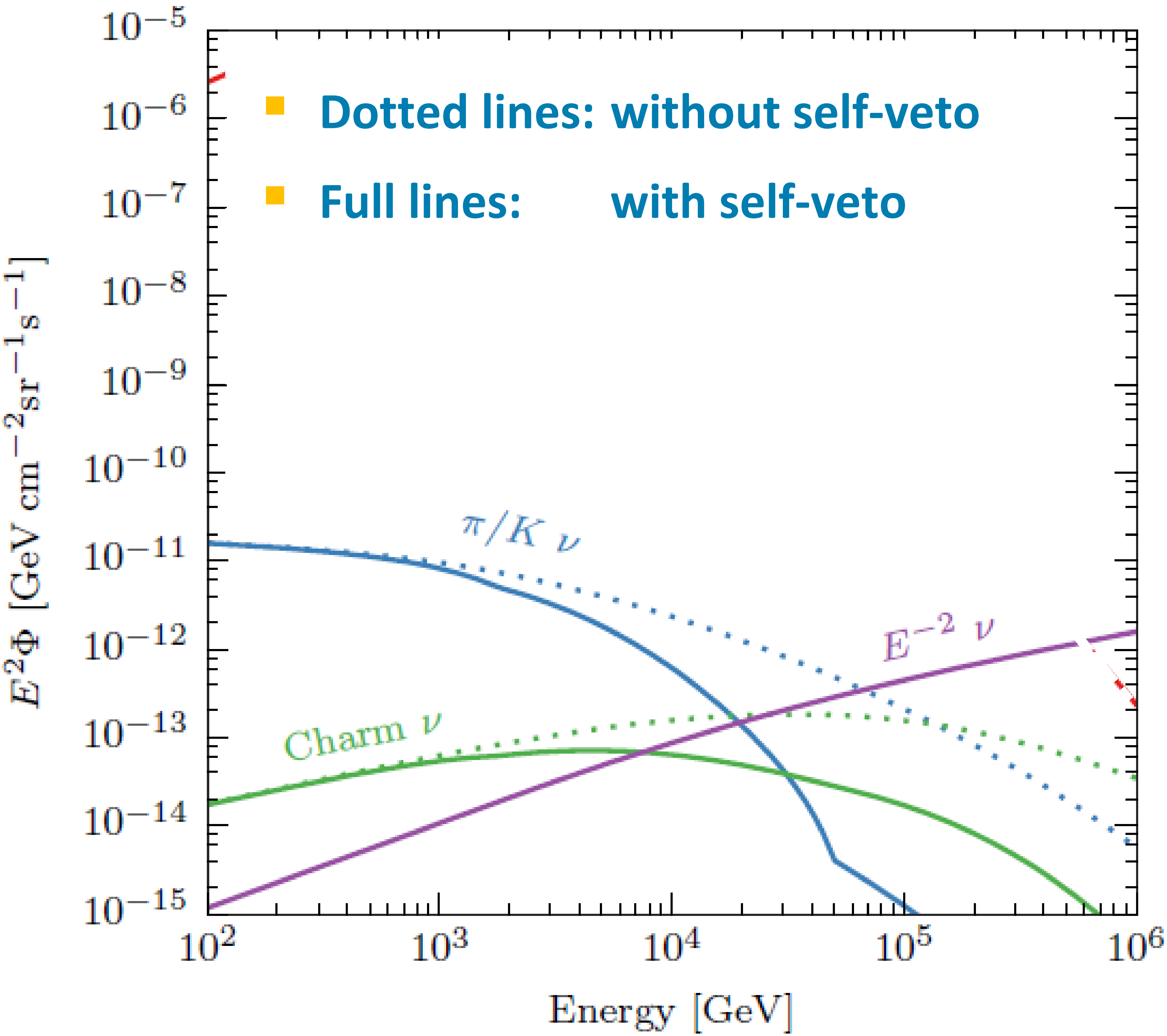
→ 400 Mton eff. Volume

Veto is also good for rejecting large part of atmospheric ν !!

Rejection of atmospheric μ and ν by „selfveto“





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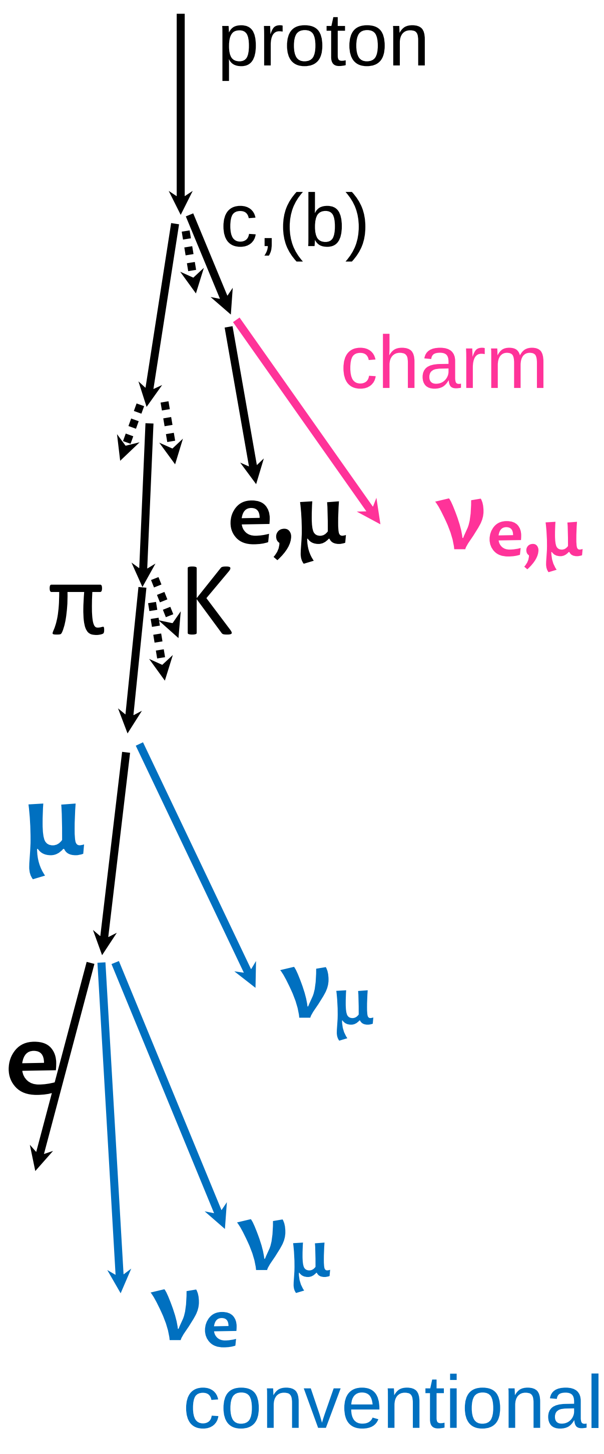
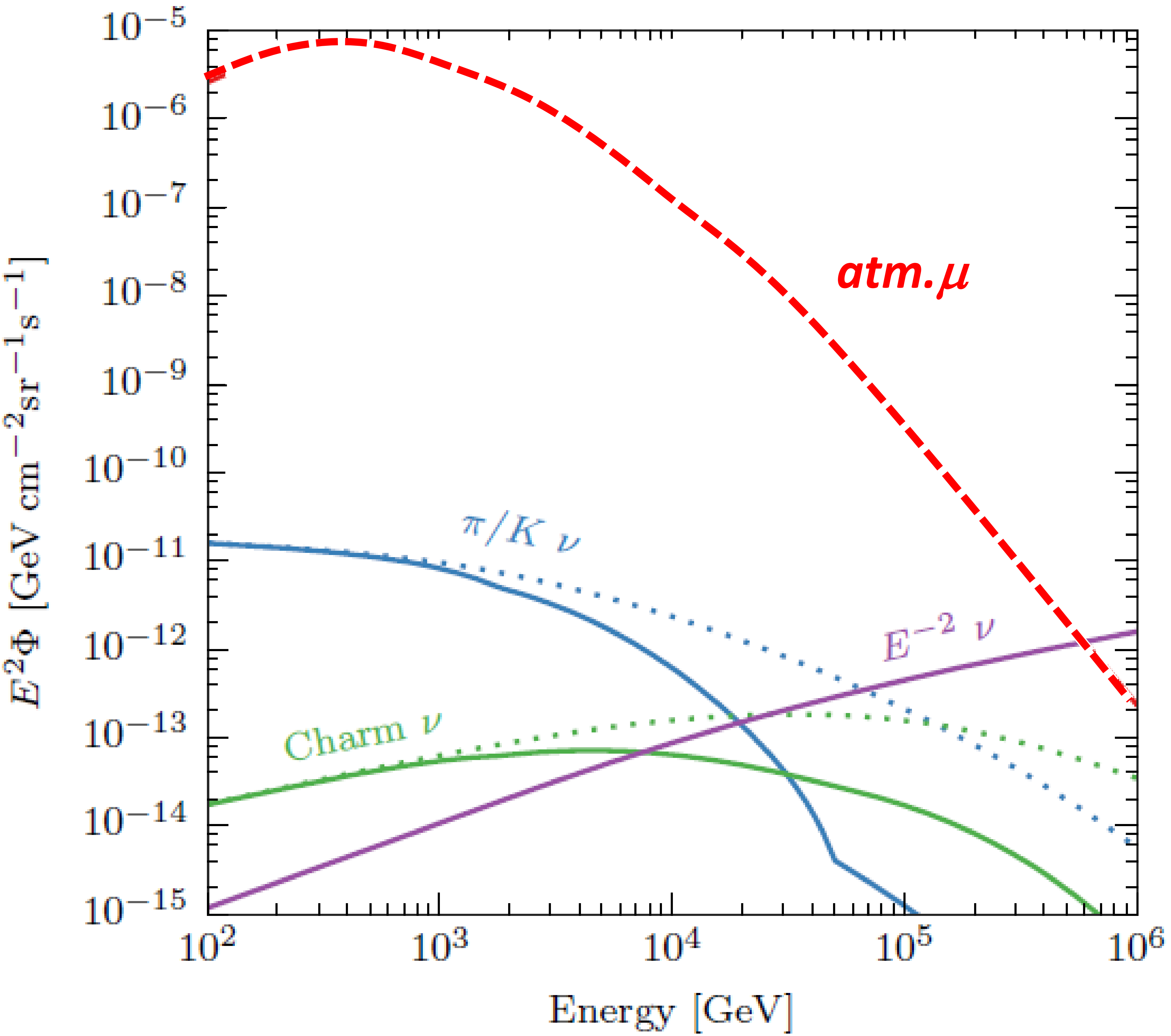
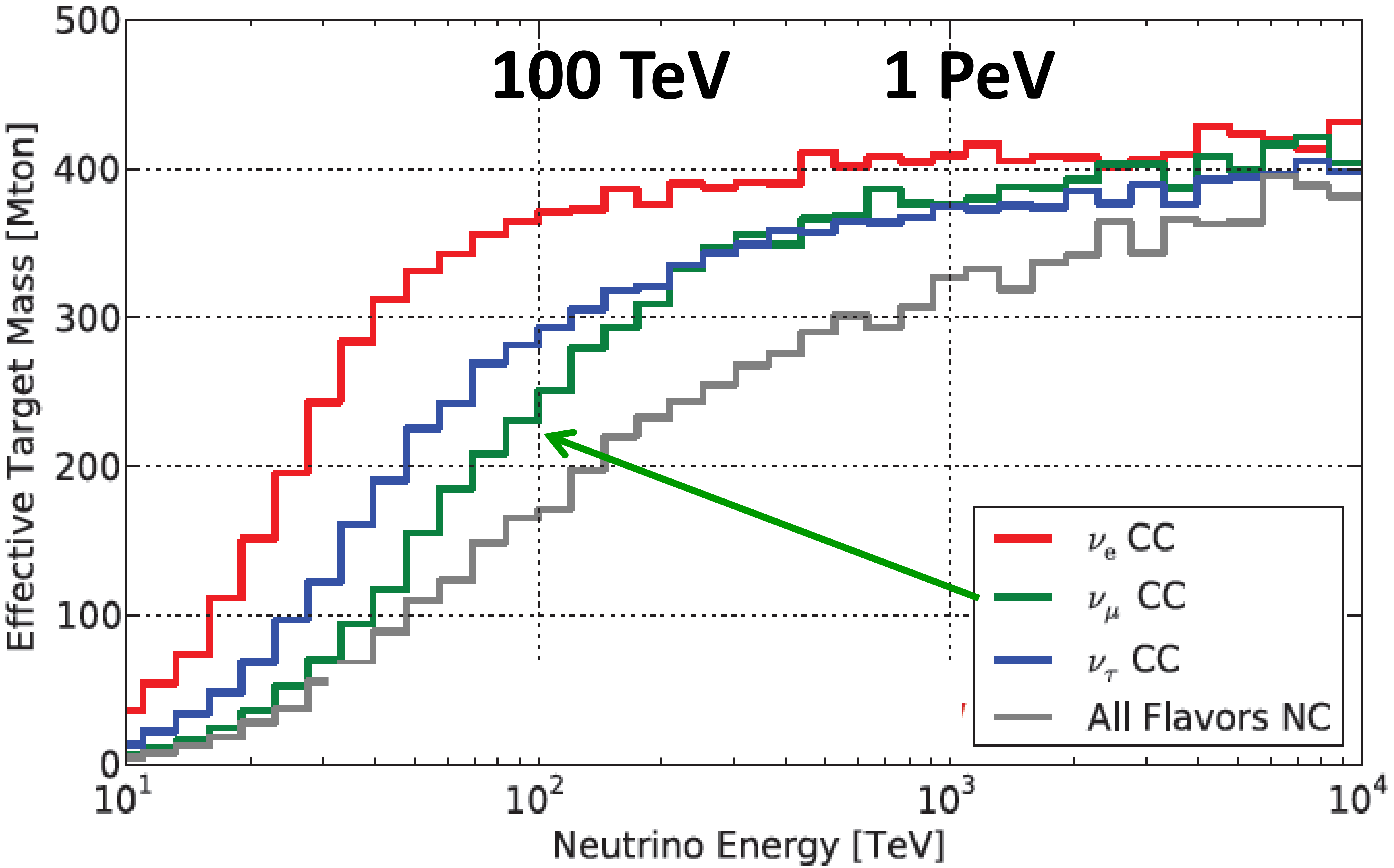




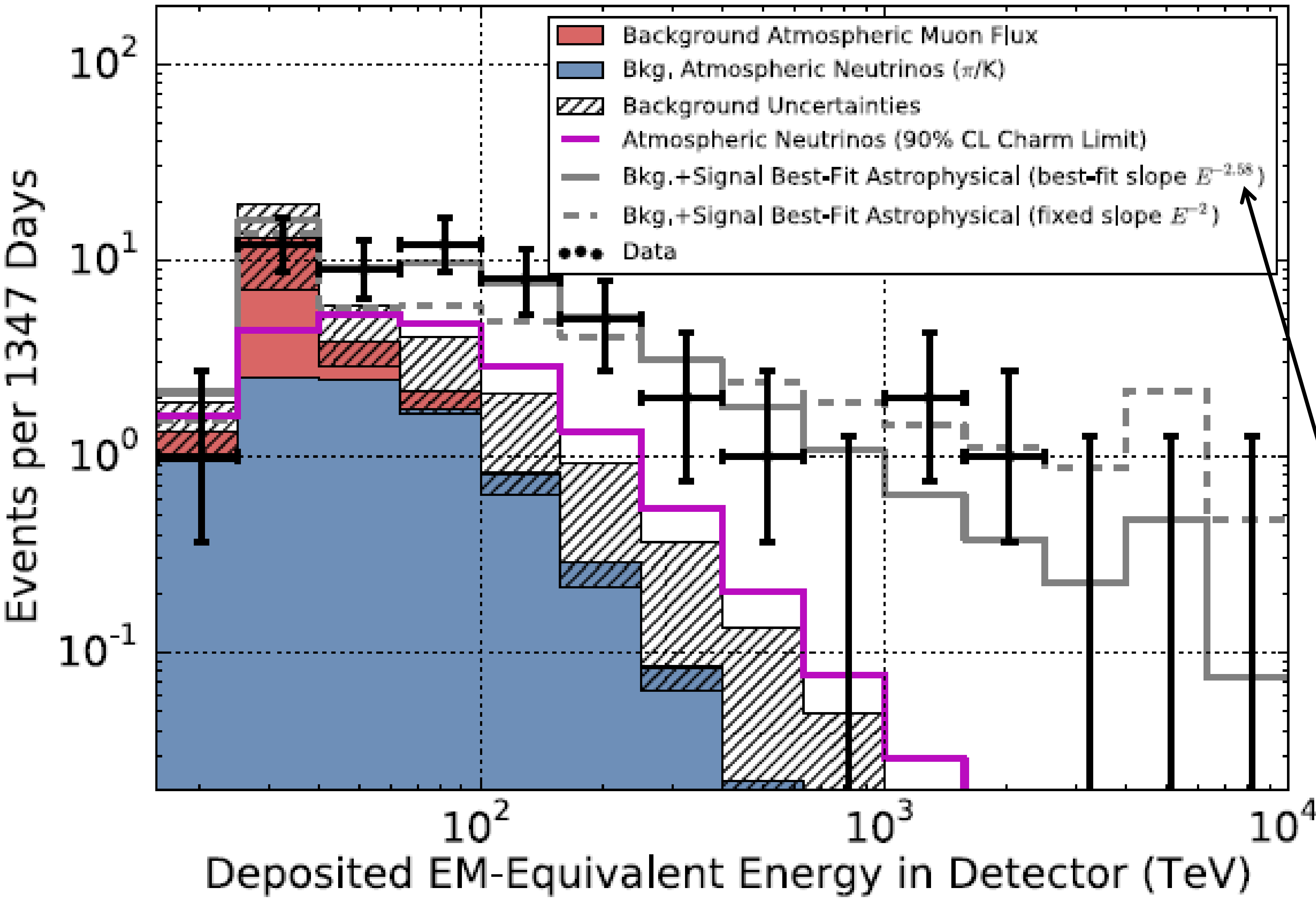
HESE analysis

- **Effective target mass for various interactions**



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: $dN/dE_\nu \sim E_\nu^{-2.58}$

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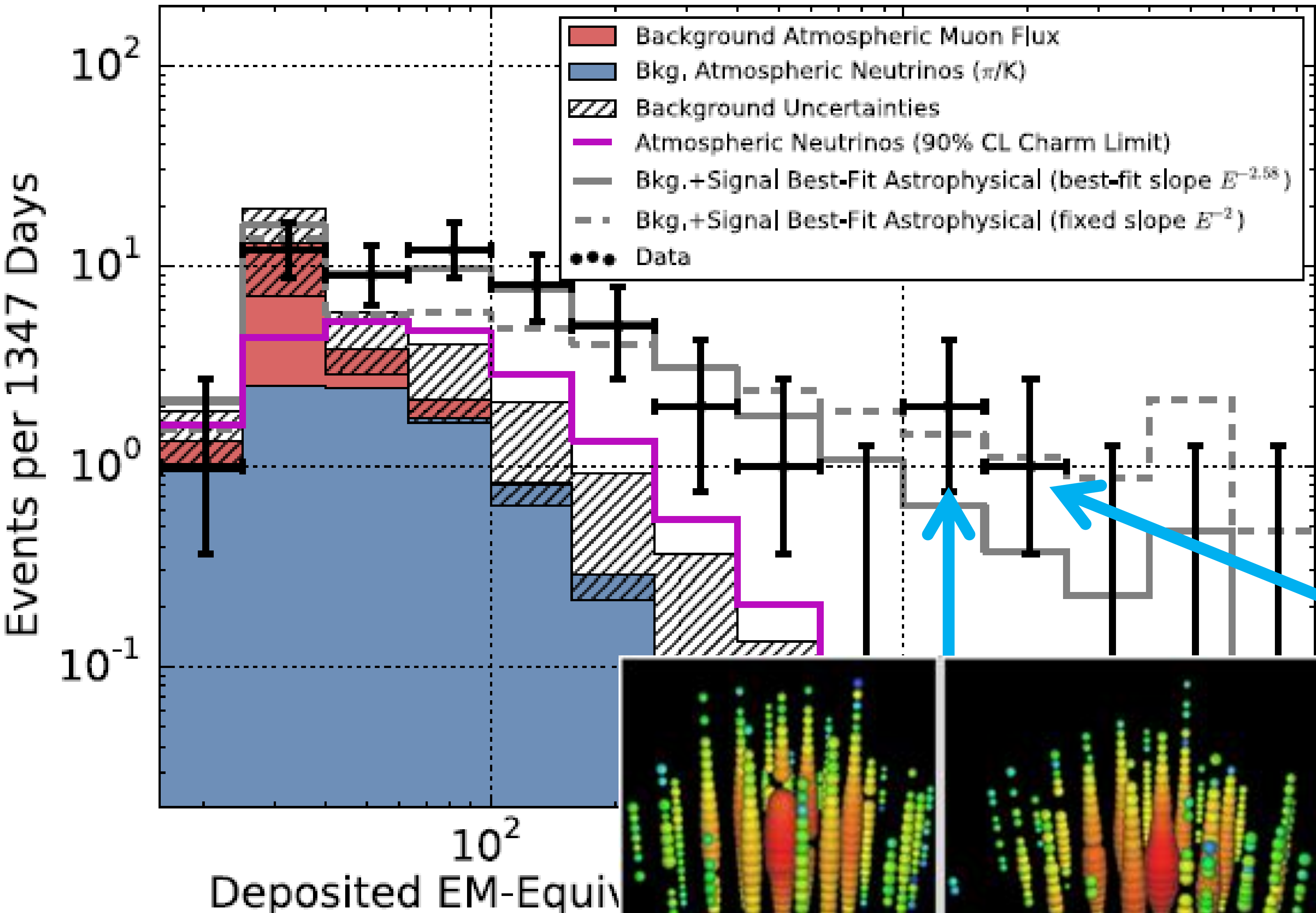

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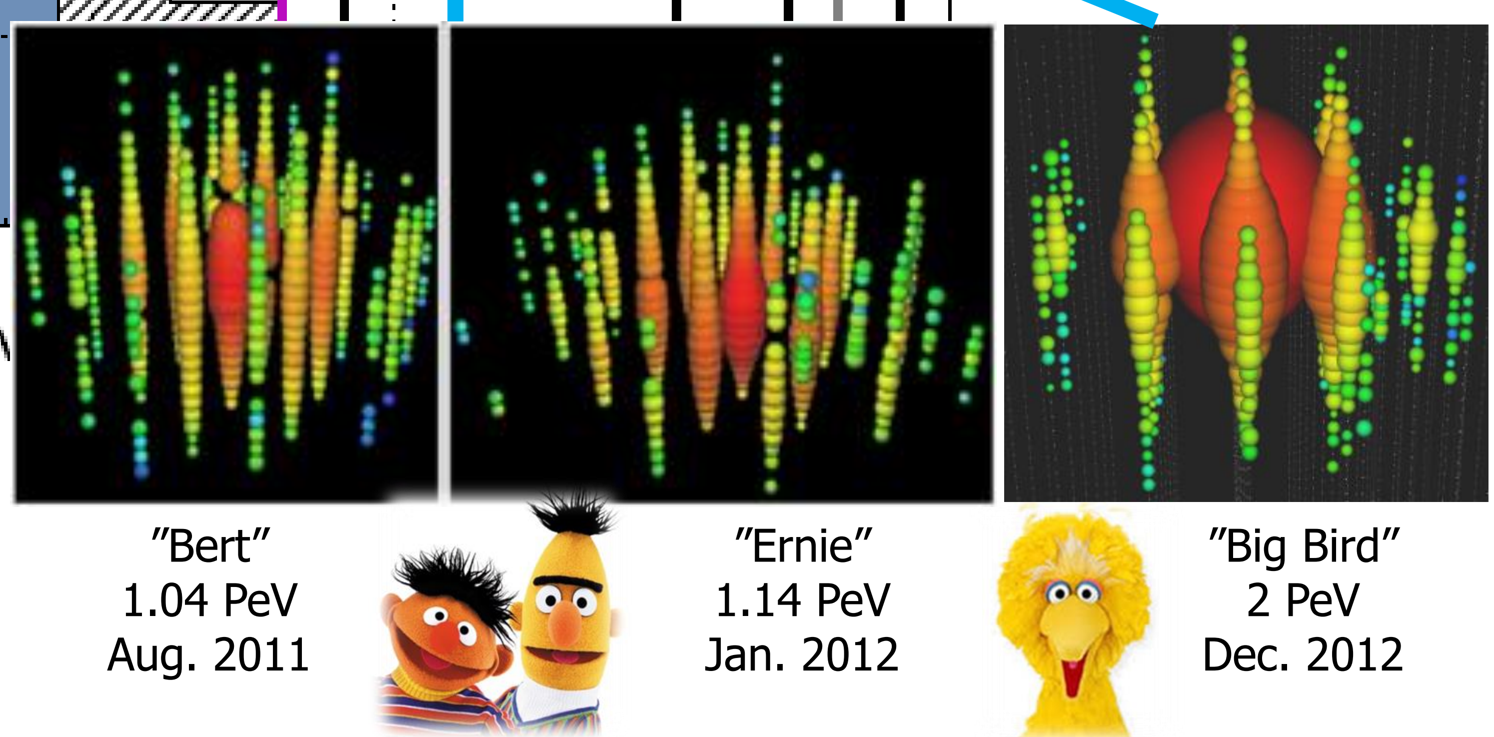
4 yrs data, 54 evts ~ **<u>7σ</u>**



"Bert"
1.04 PeV
Aug. 2011

"Ernie"
1.14 PeV
Jan. 2012

"Big Bird"
2 PeV
Dec. 2012

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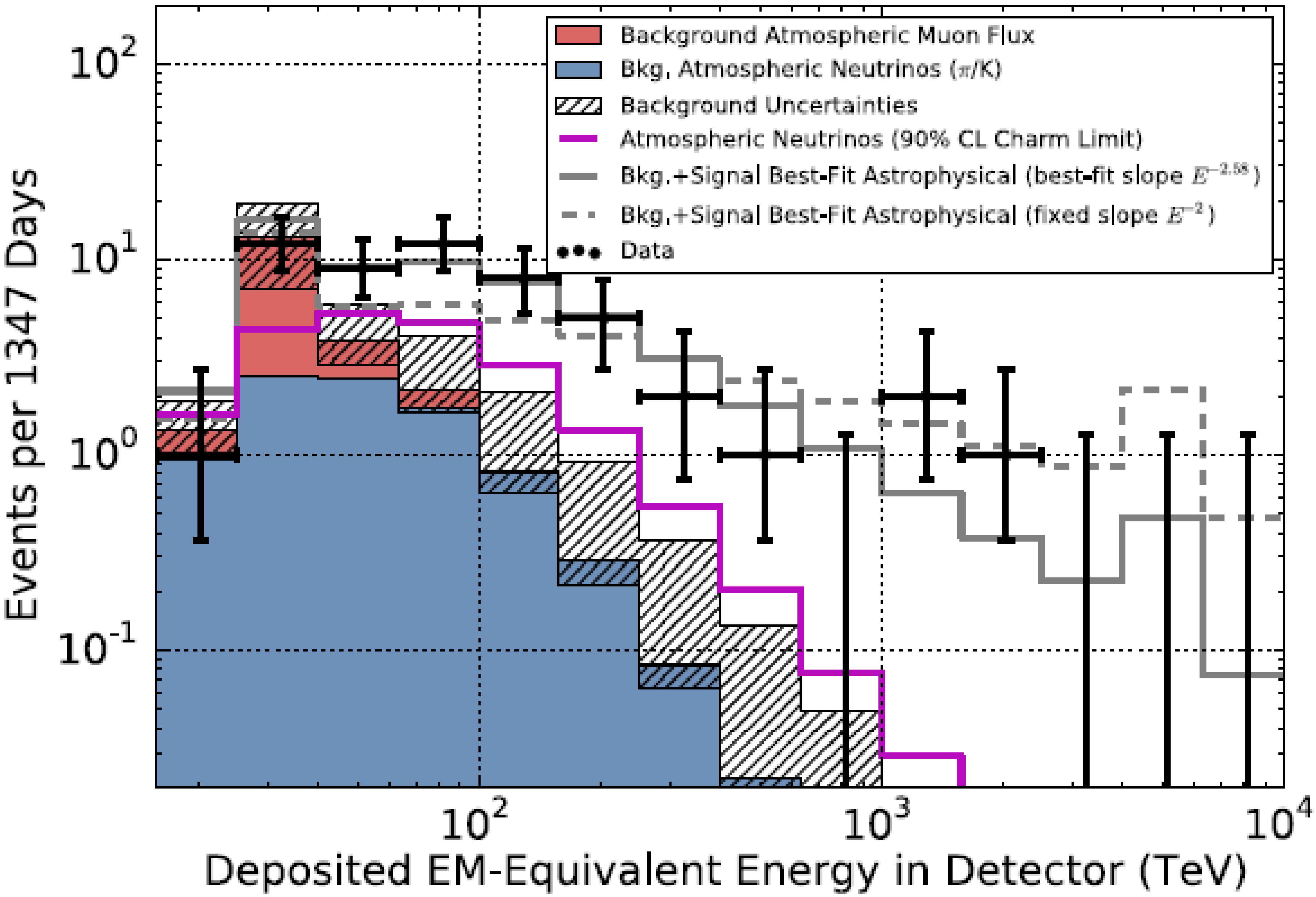
First evidence for an extra-terrestrial h.e. neutrino flux



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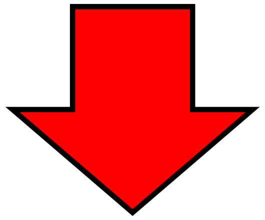
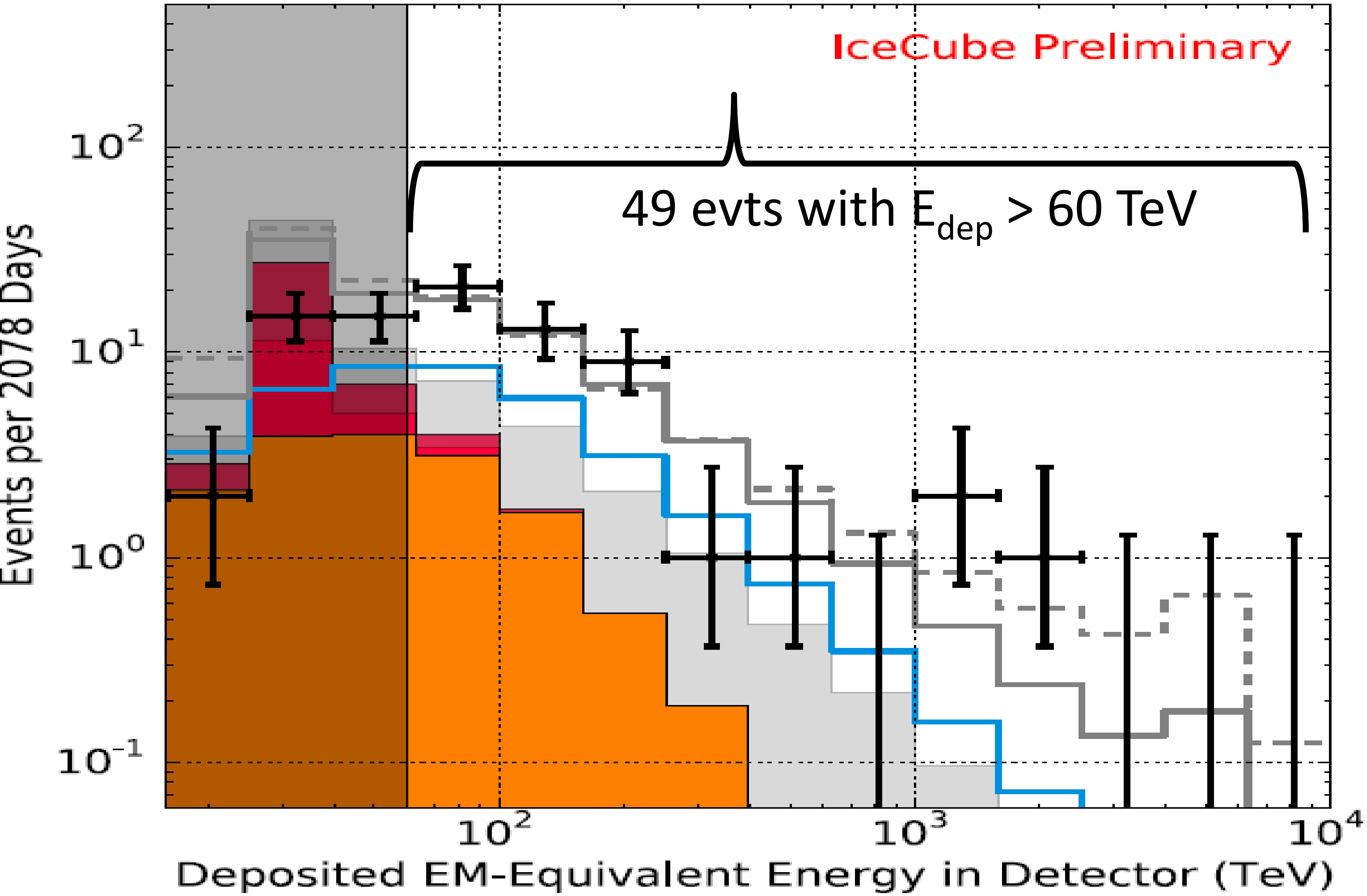


Analysis has been extended down to ~ 10TeV threshold: Phys.Rev. D91 (2015) 022001

Results from a 6-year sample released at ICRC 2017

HESE (High Energy Starting Event)



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Science 342 (2013)

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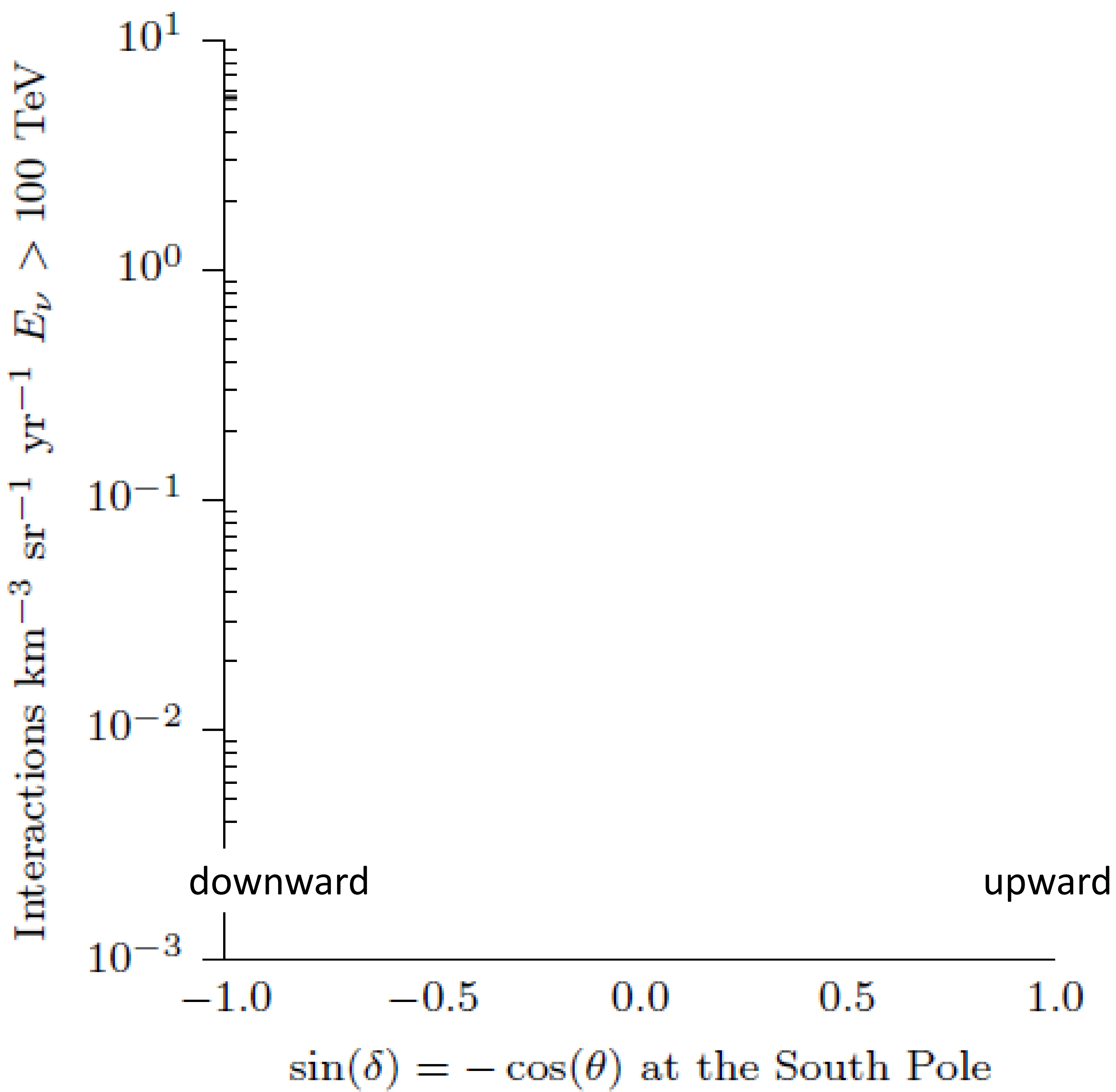
Phys.Rev.Lett. 113:101101 (2014)

4 yrs data, 54 evts ~ **7σ**

6 yrs data, 80 evts. ~ 8σ

Results from a 6-year sample released at ICRC 2017

Atmospheric neutrino self-veto



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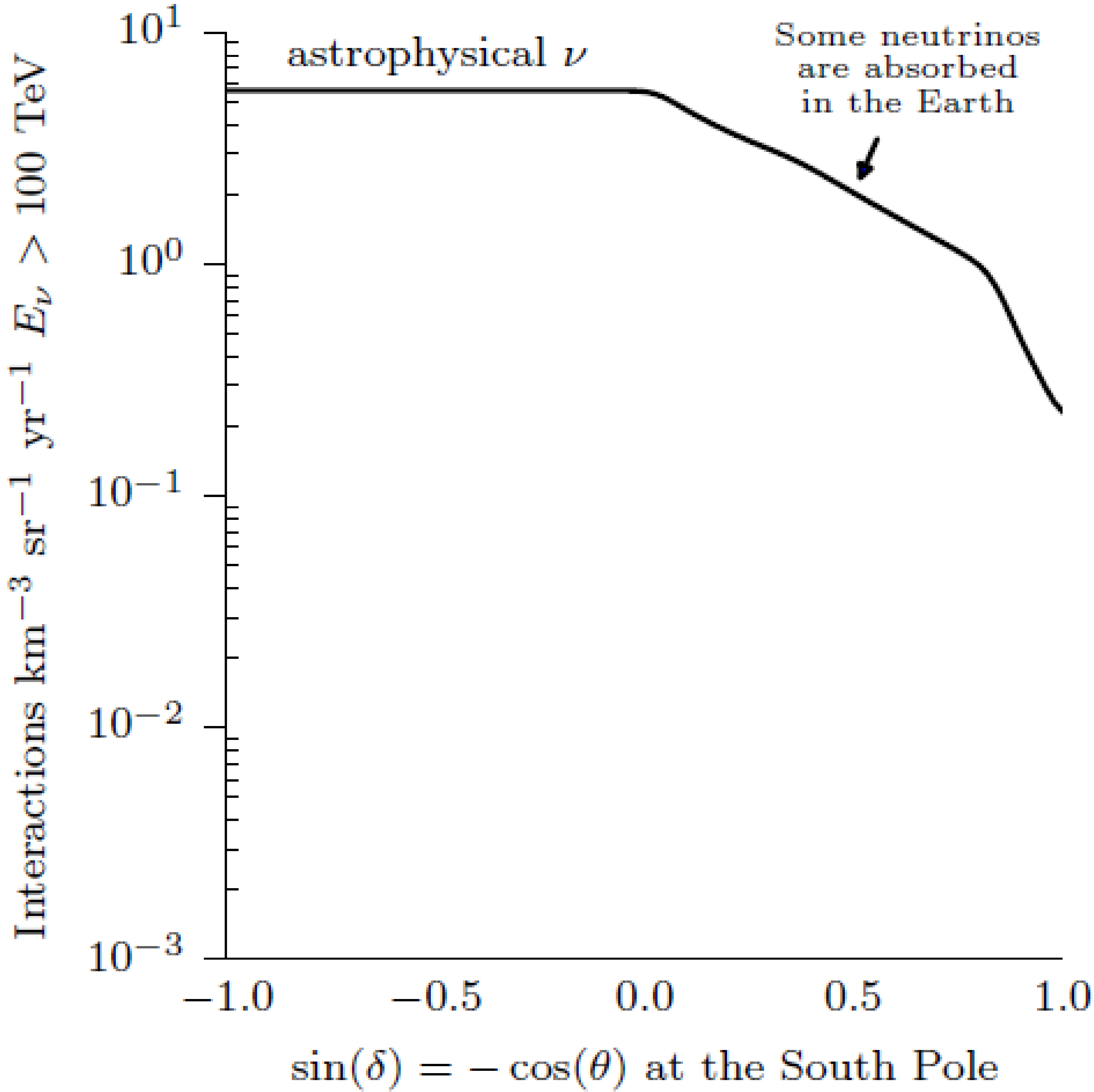

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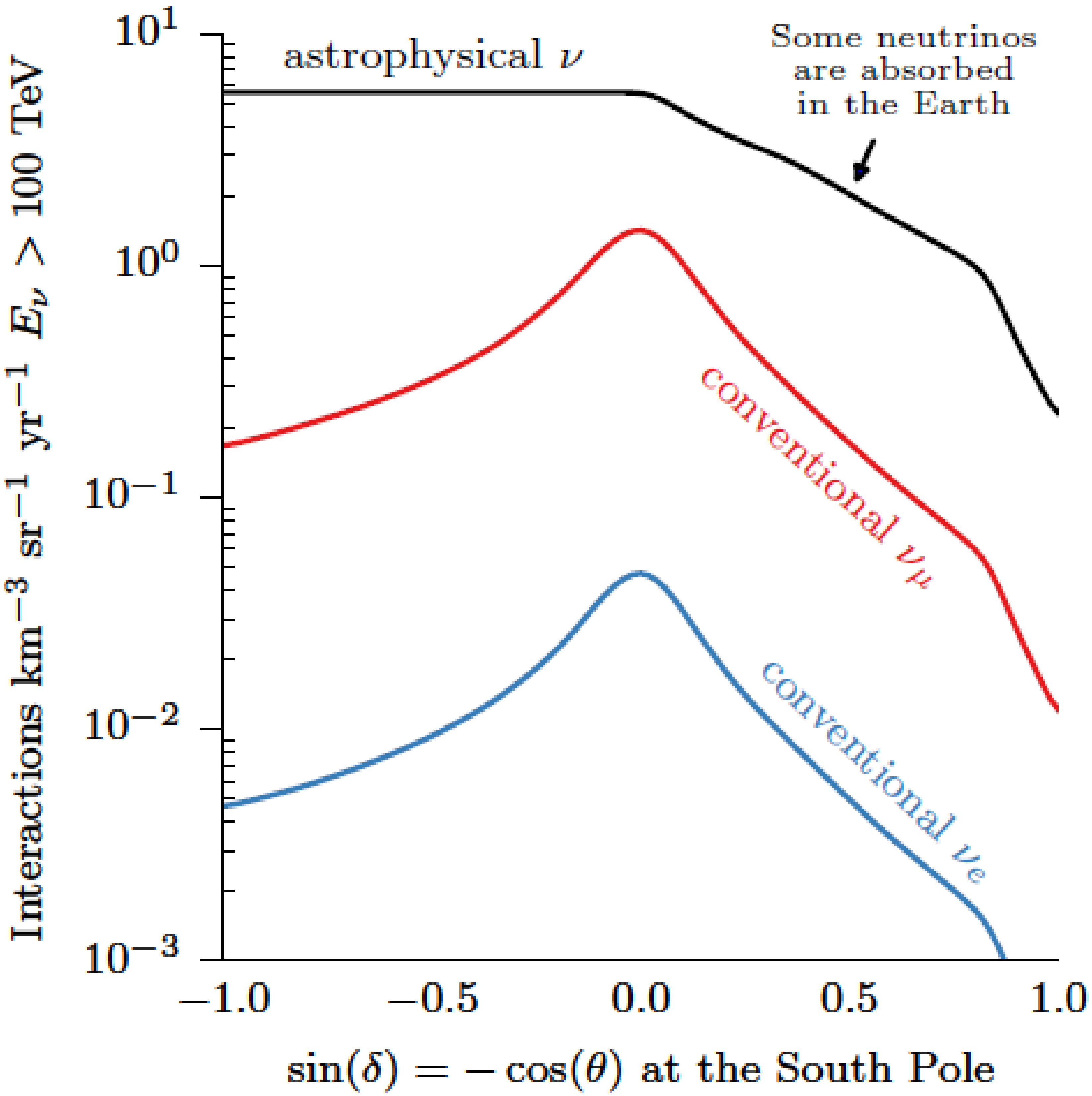

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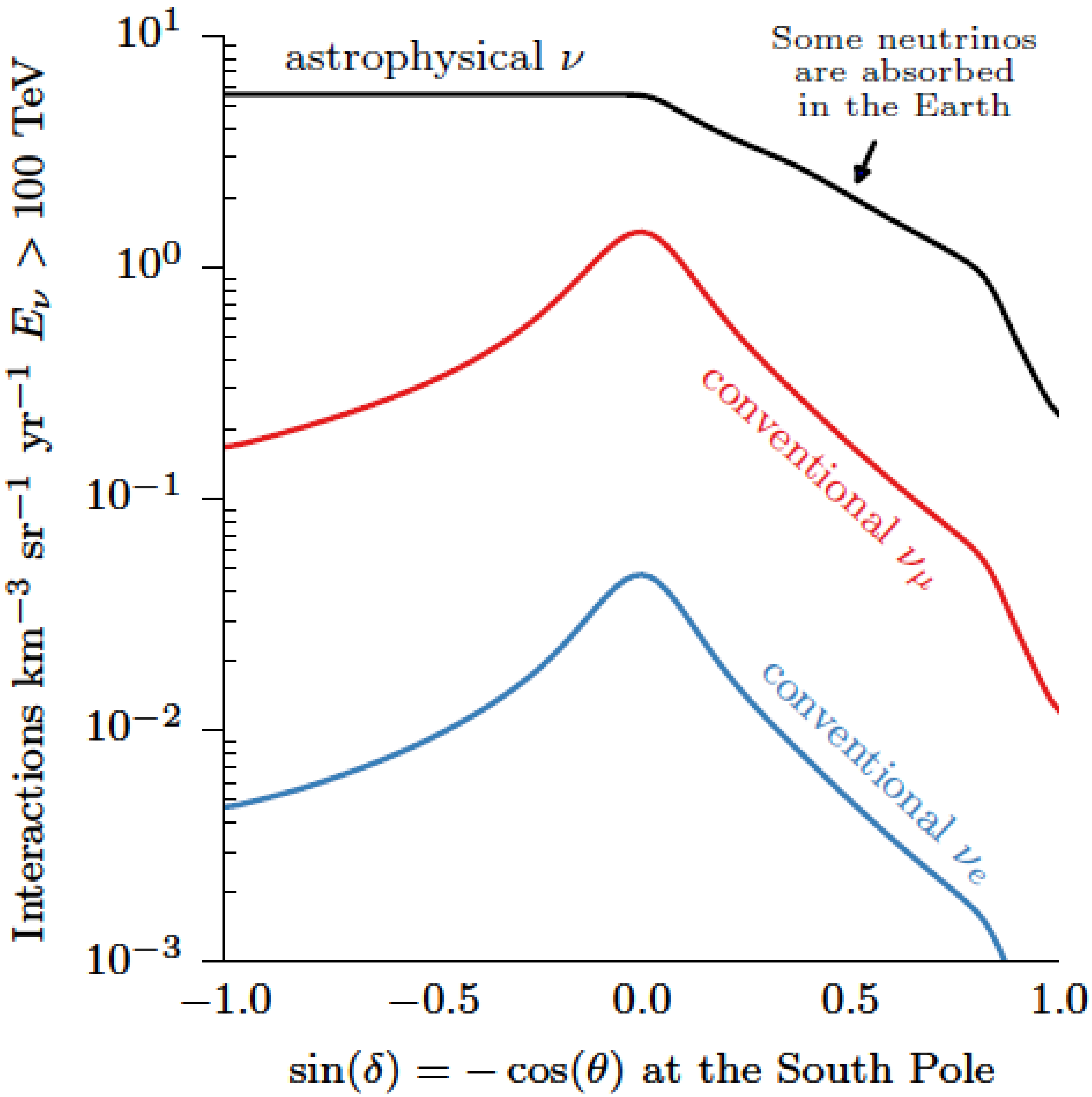

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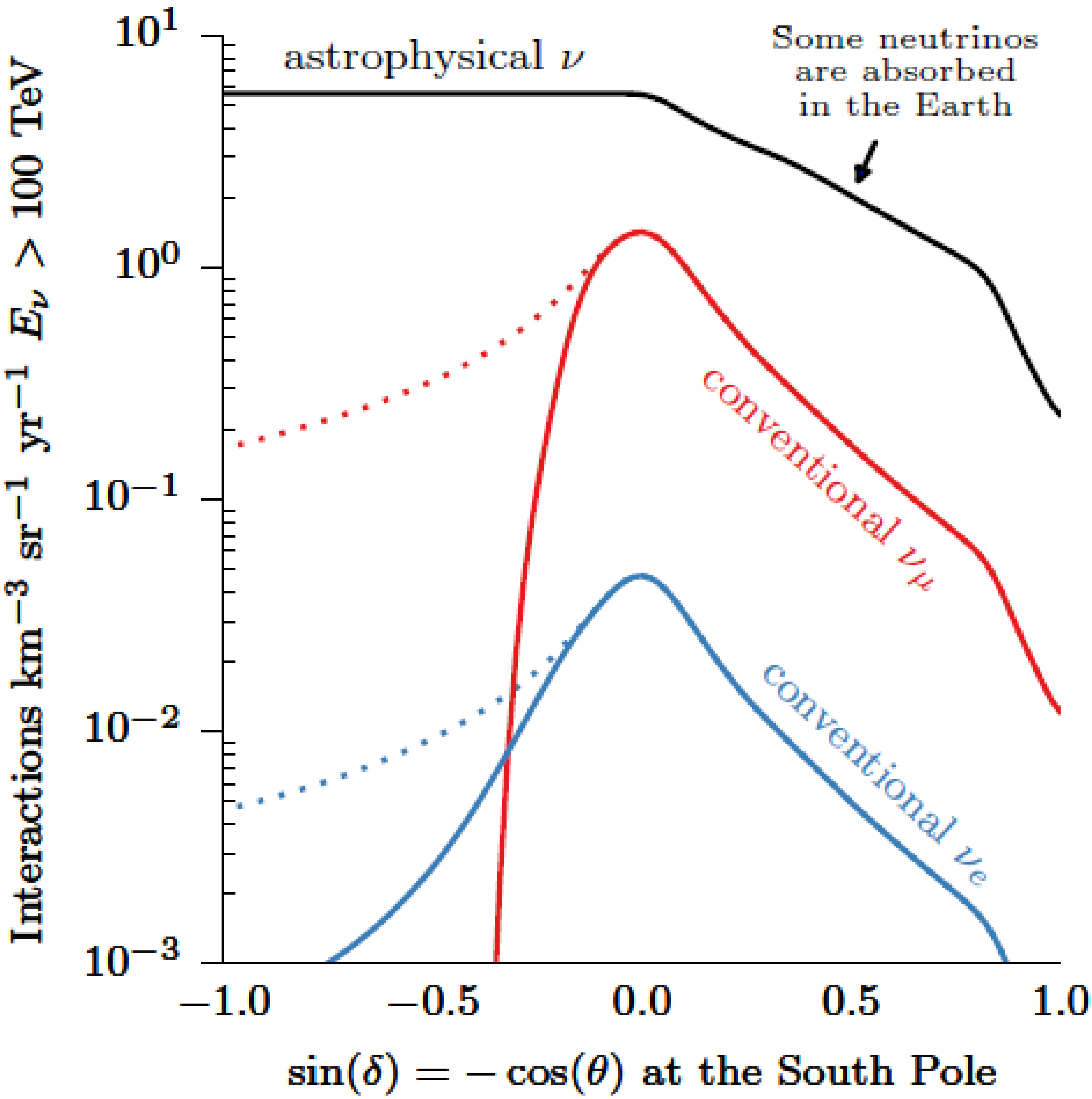

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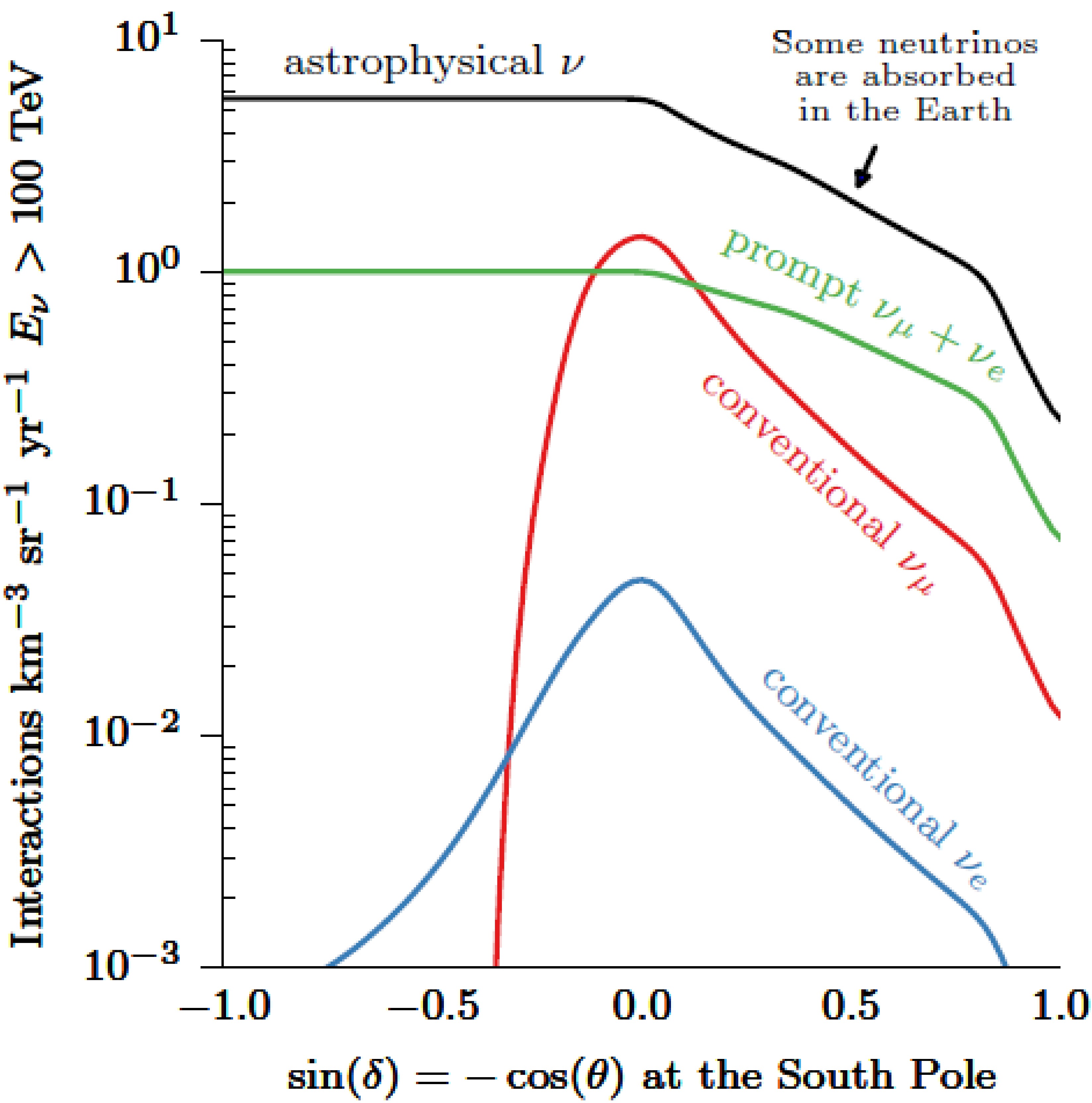

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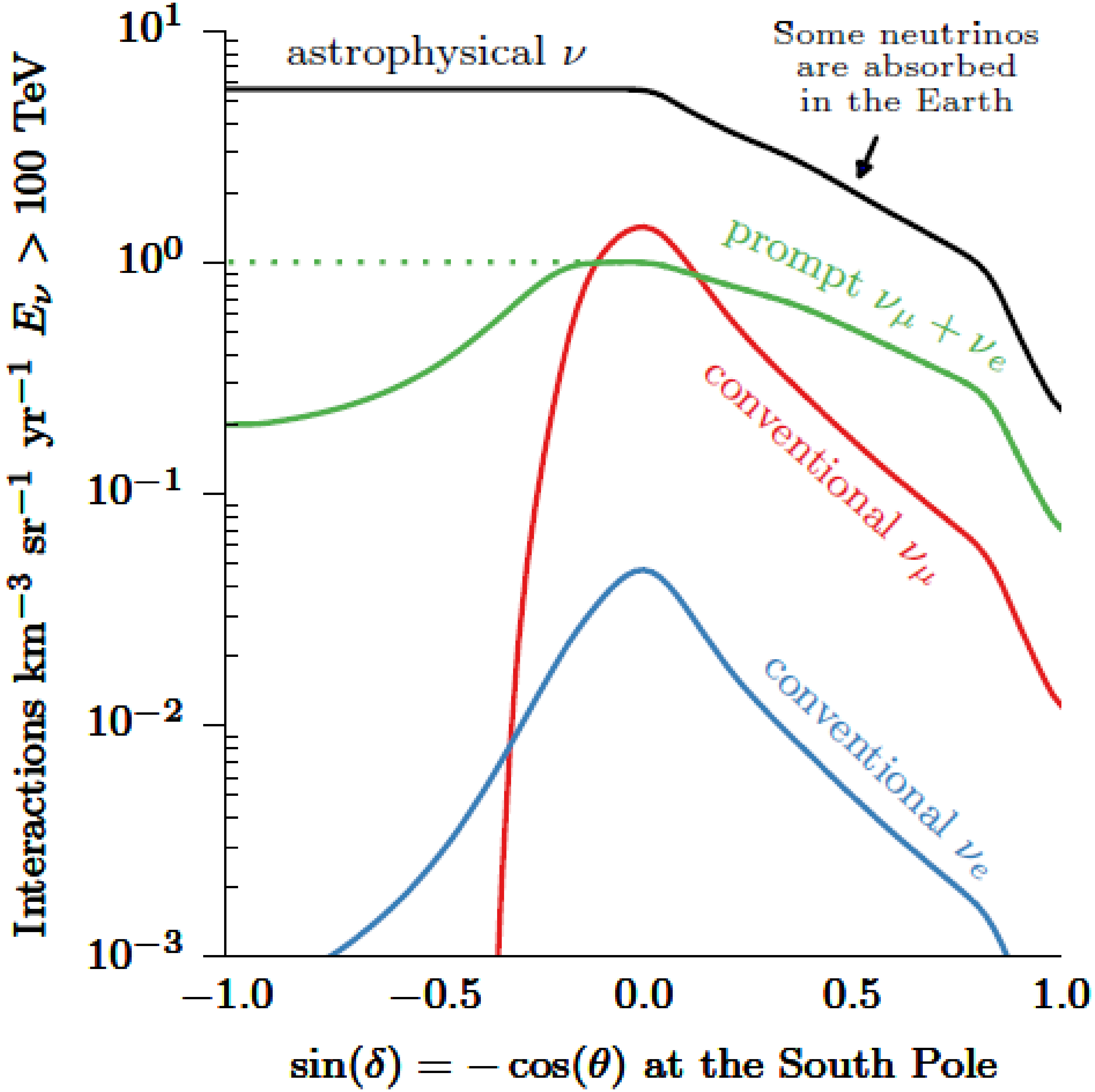

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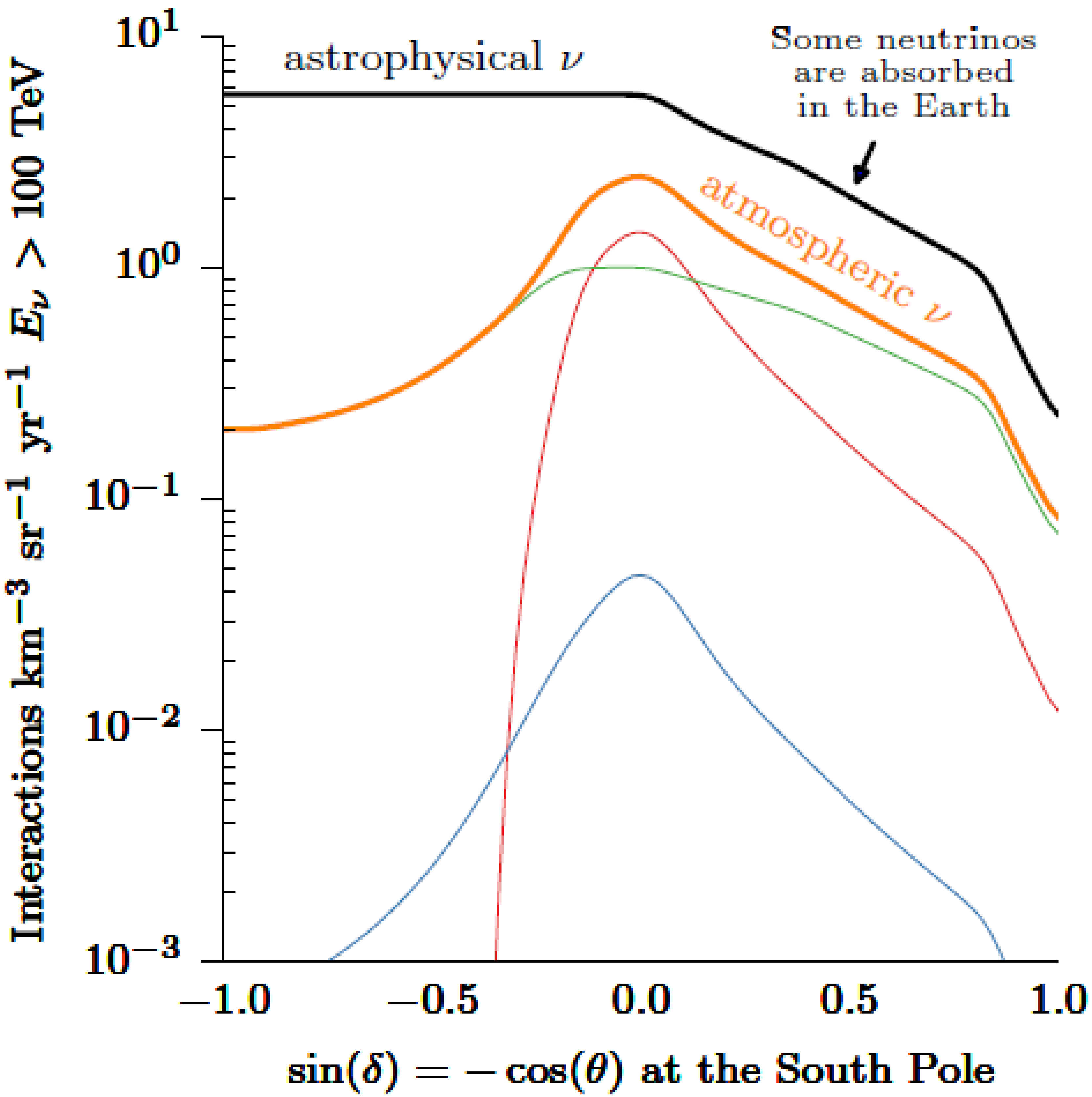
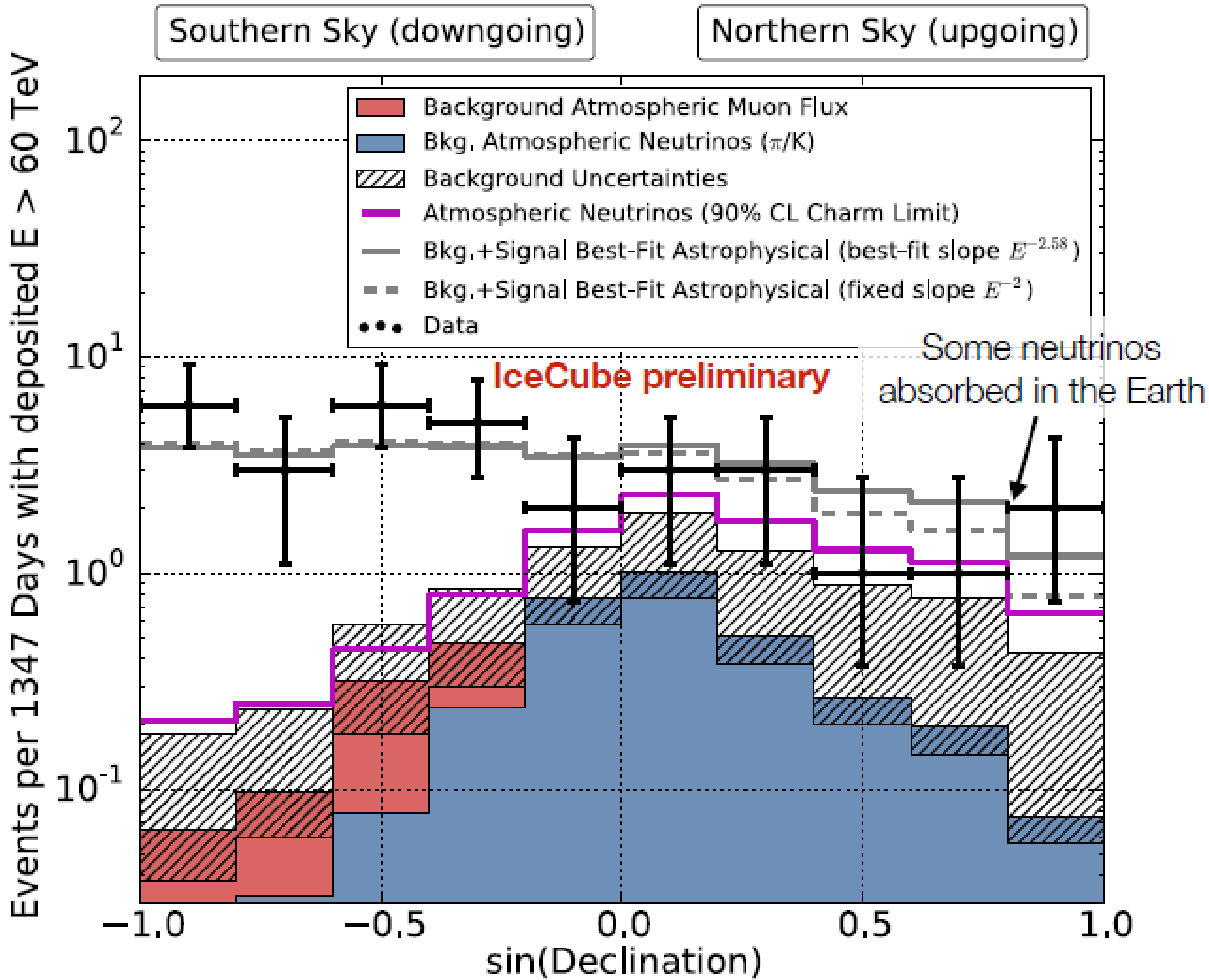


The zenith distributions of high-energy astrophysical and atmospheric neutrinos are fundamentally different.

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

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

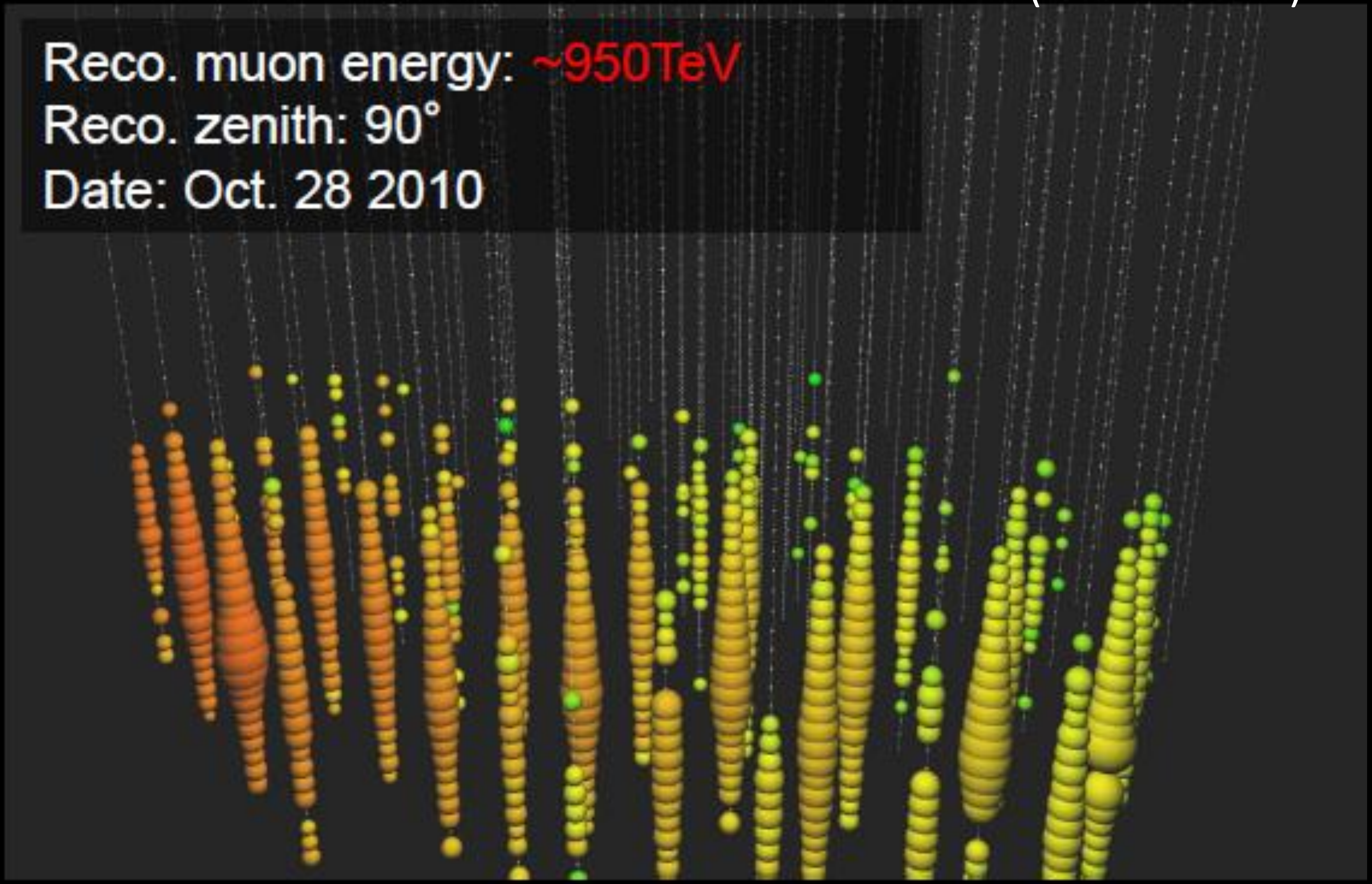
Model-independent proof of astrophysical origin:



Through-going muons

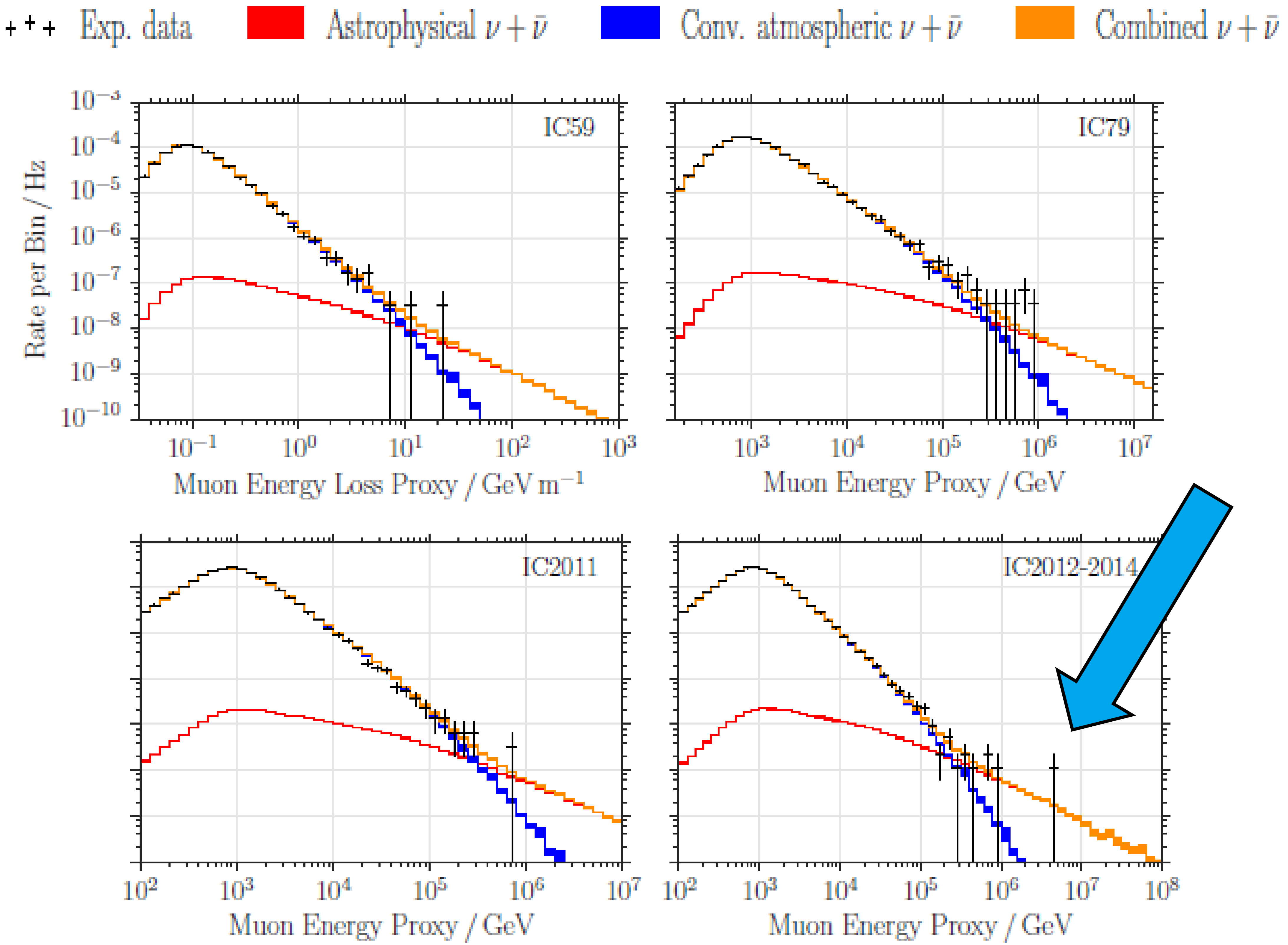
Highest energy muon in 2009-12

(IC 59+79+86)



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

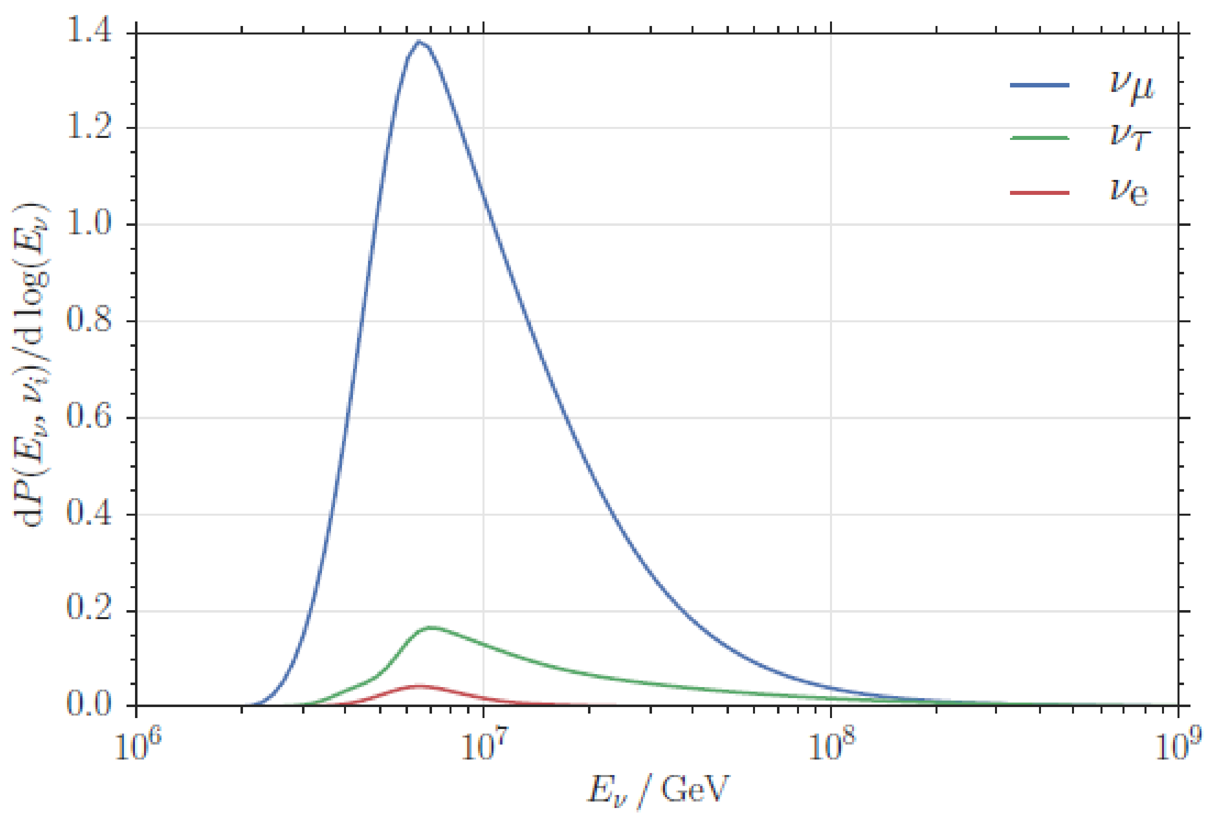
Astrophys. J. 833 (2016) 3

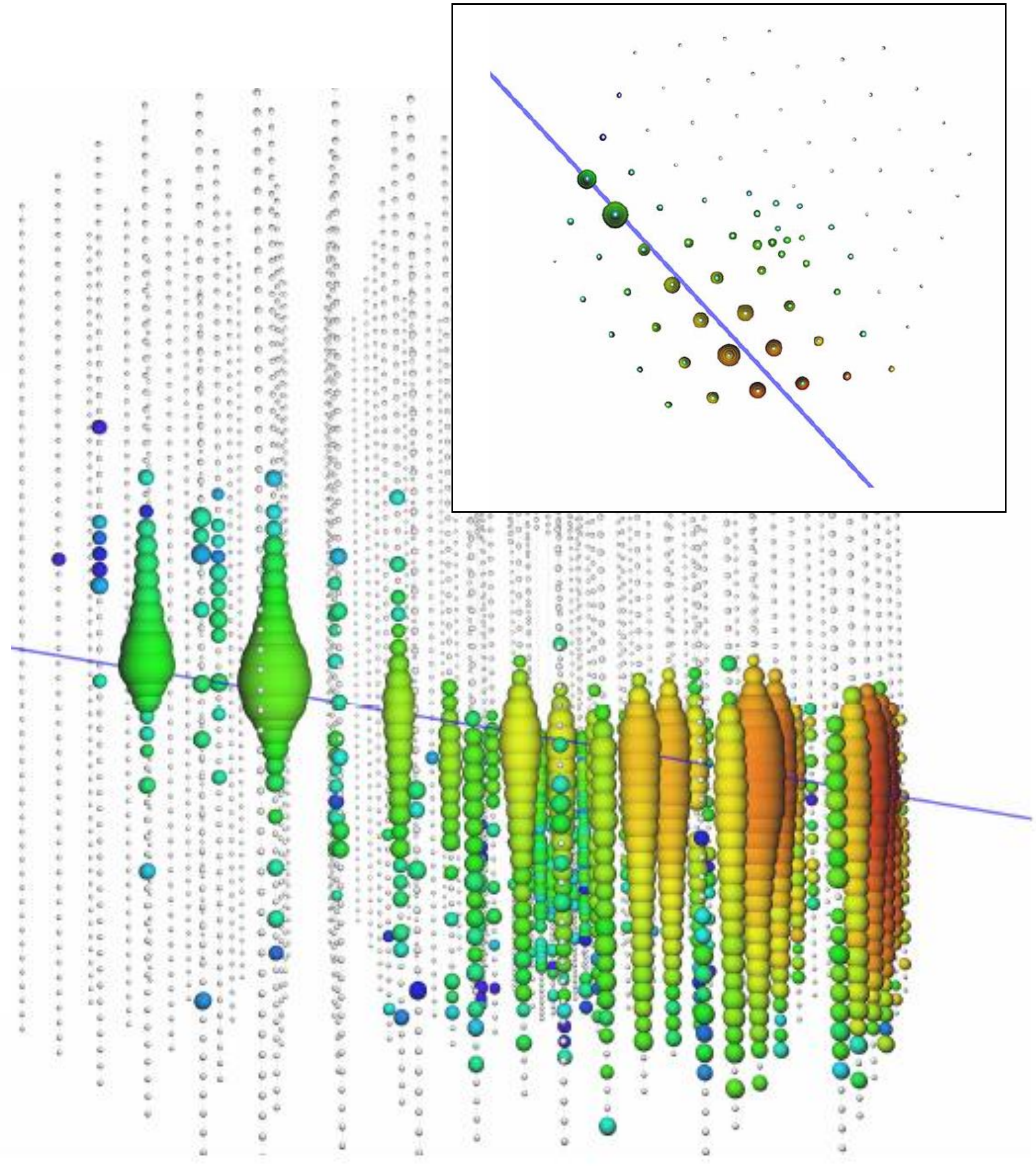


Through-going muons, six years (2009-15)

The highest-energy event

Deposited energy 2.6±0.3 PeV





Most probable ν energy ~7 PeV

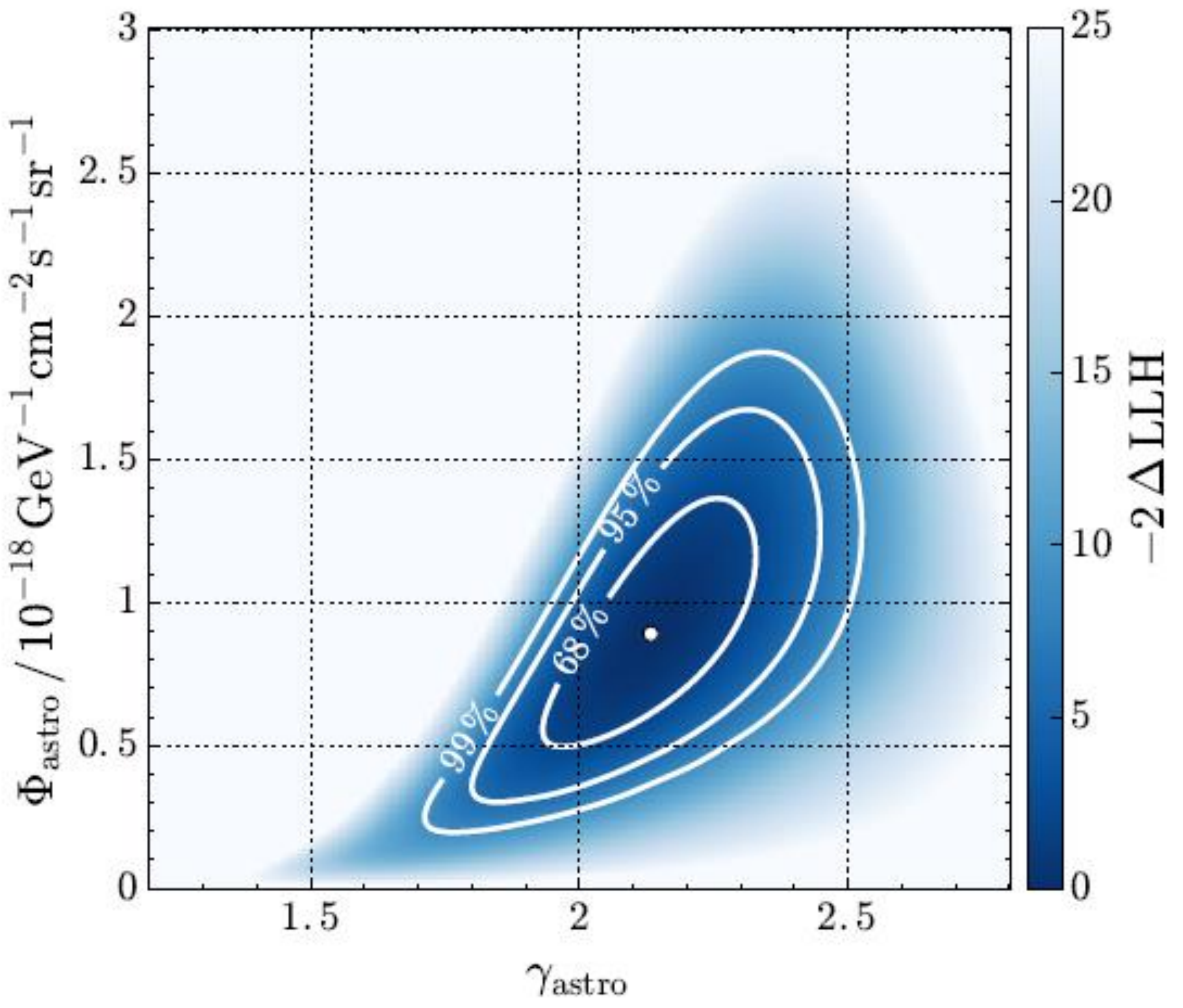
(for E^{-2} assumption)

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

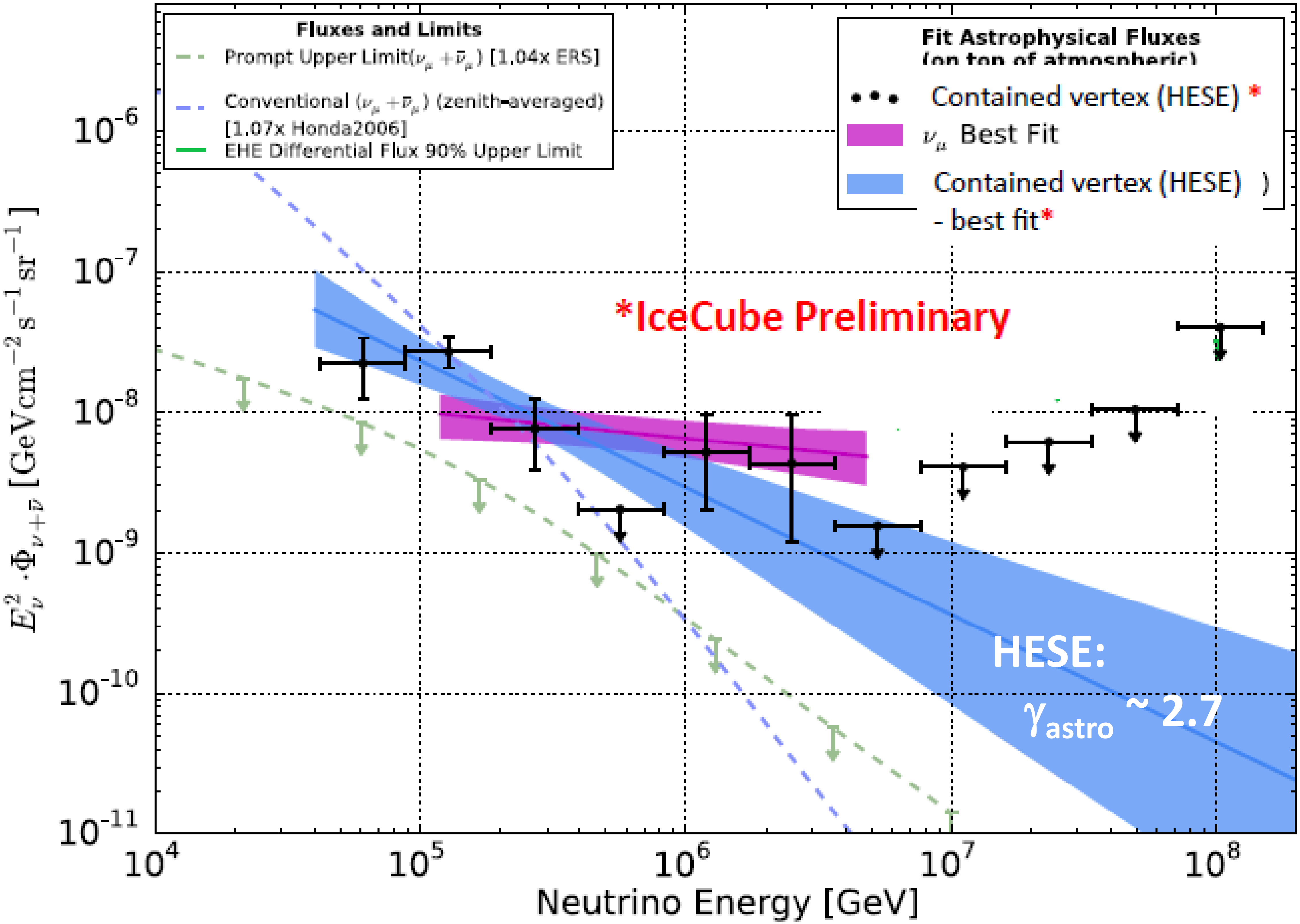
Spectrum: $\Phi_{\nu+\overline{\nu}} = \left(0.90^{+0.30}_{-0.27}\right) \cdot (E_\nu / 100\,\mathrm{TeV})^{-(2.13 \pm 0.13)}$

Fit parameters:

Parameter	Best-Fit	68% C.L.
Φ_{astro}	0.90	0.62 – 1.20
γ_{astro}	2.13	2.00 – 2.26
Φ_{prompt}	0.00	0.00 – 0.19

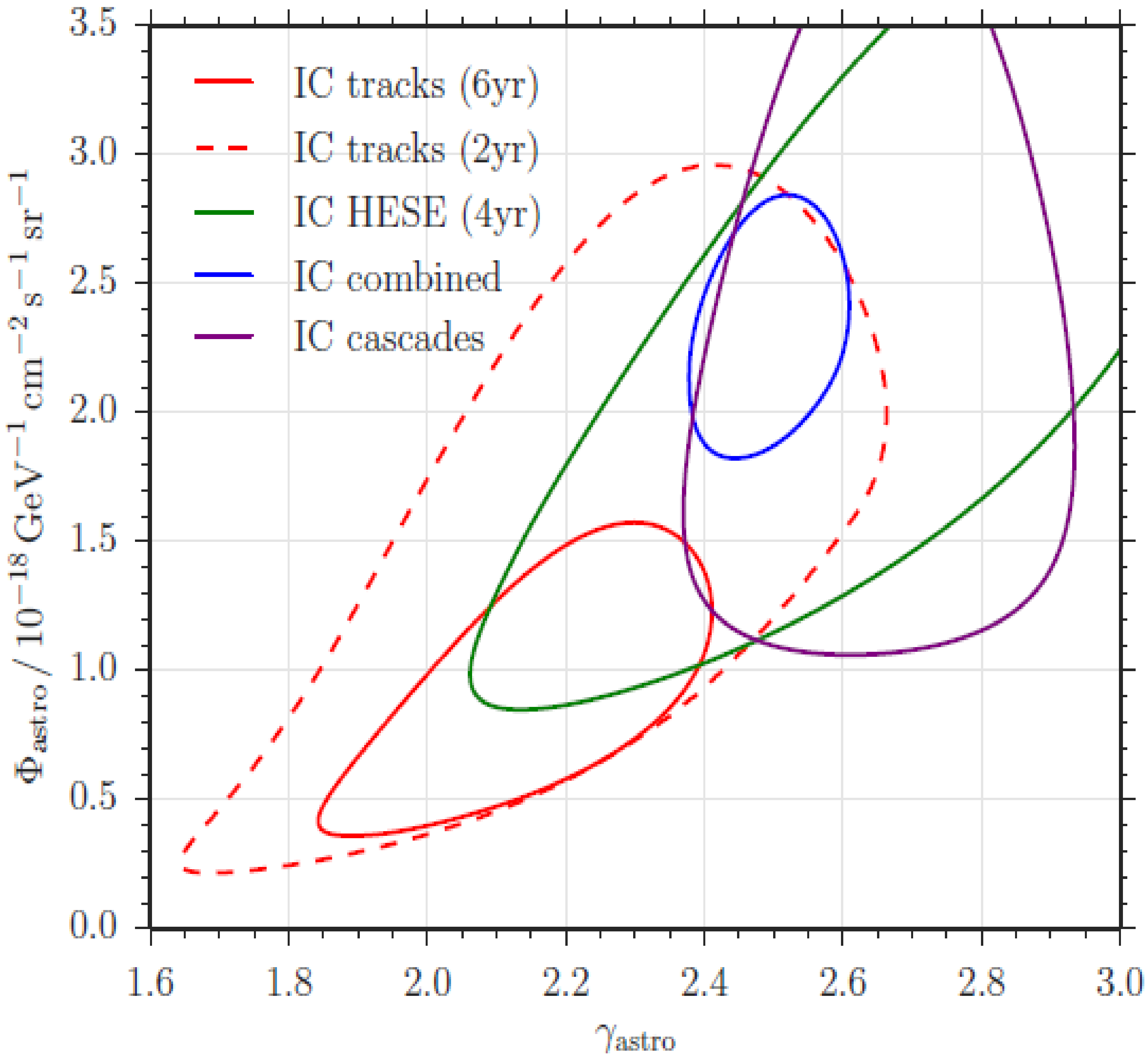


Spectrum: throughgoing muons vs HESE

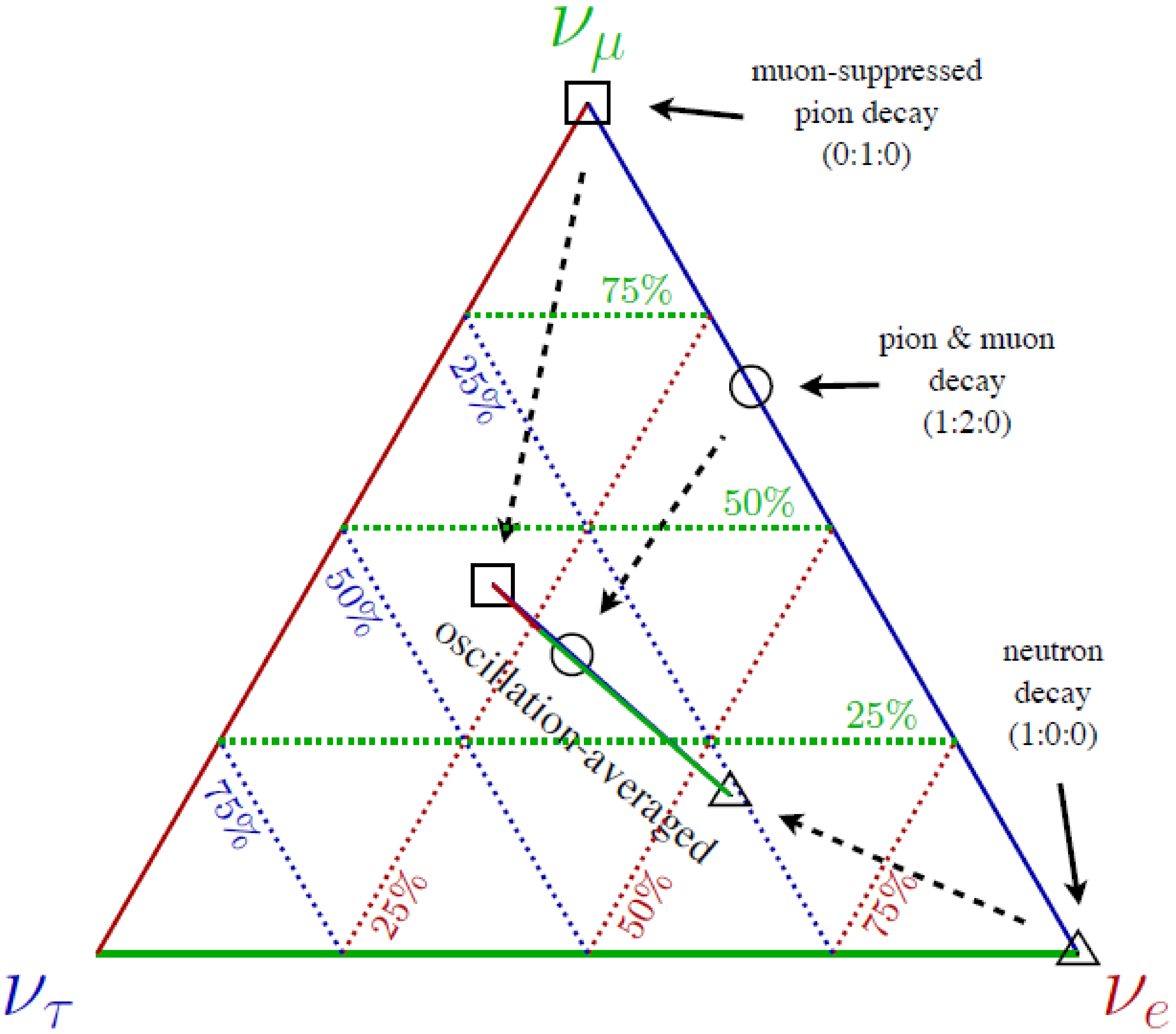


Broken Spectrum?

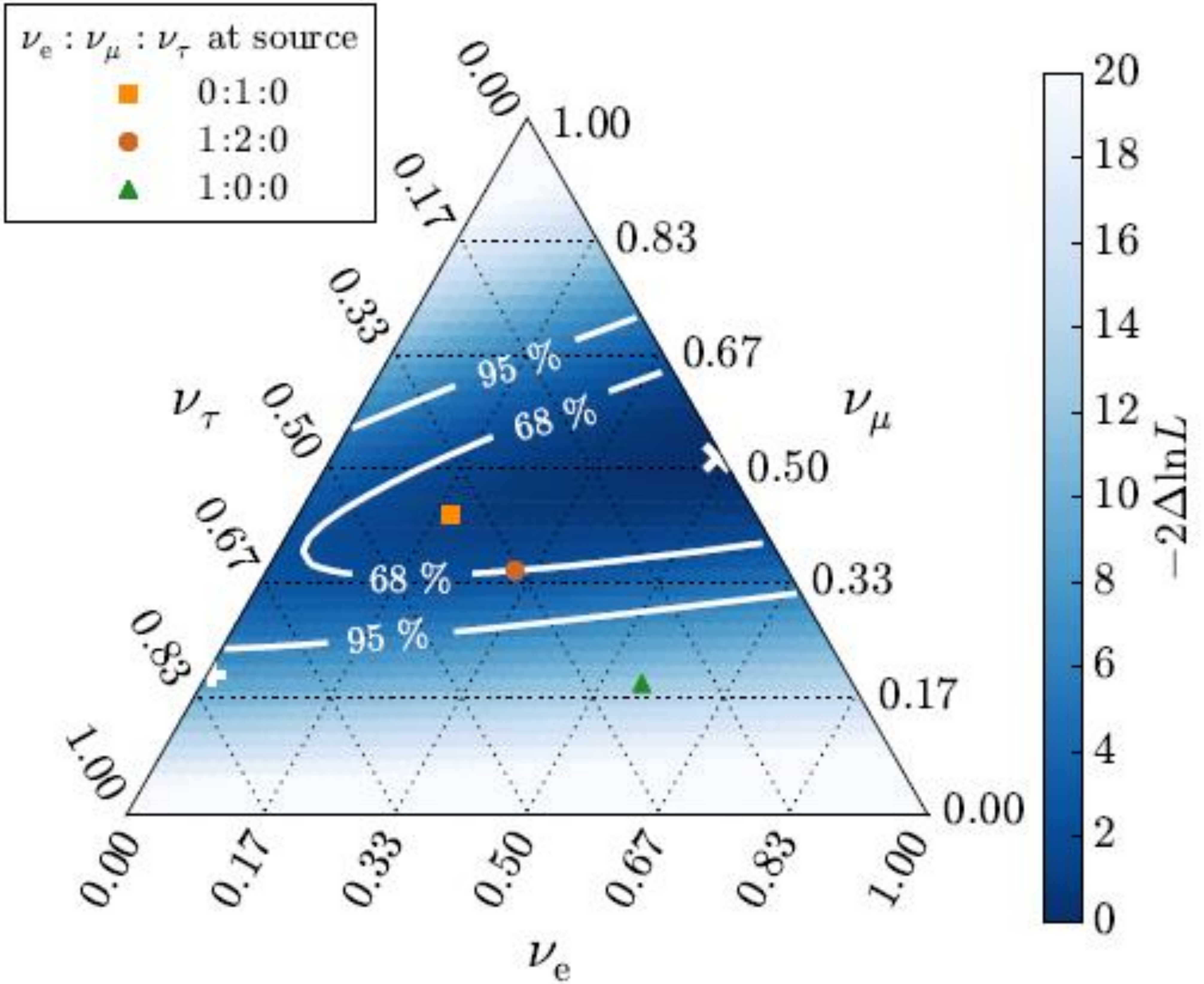
$\Phi = \Phi_0 \times E_\nu^{\gamma}$



Flavor composition: what do we expect?



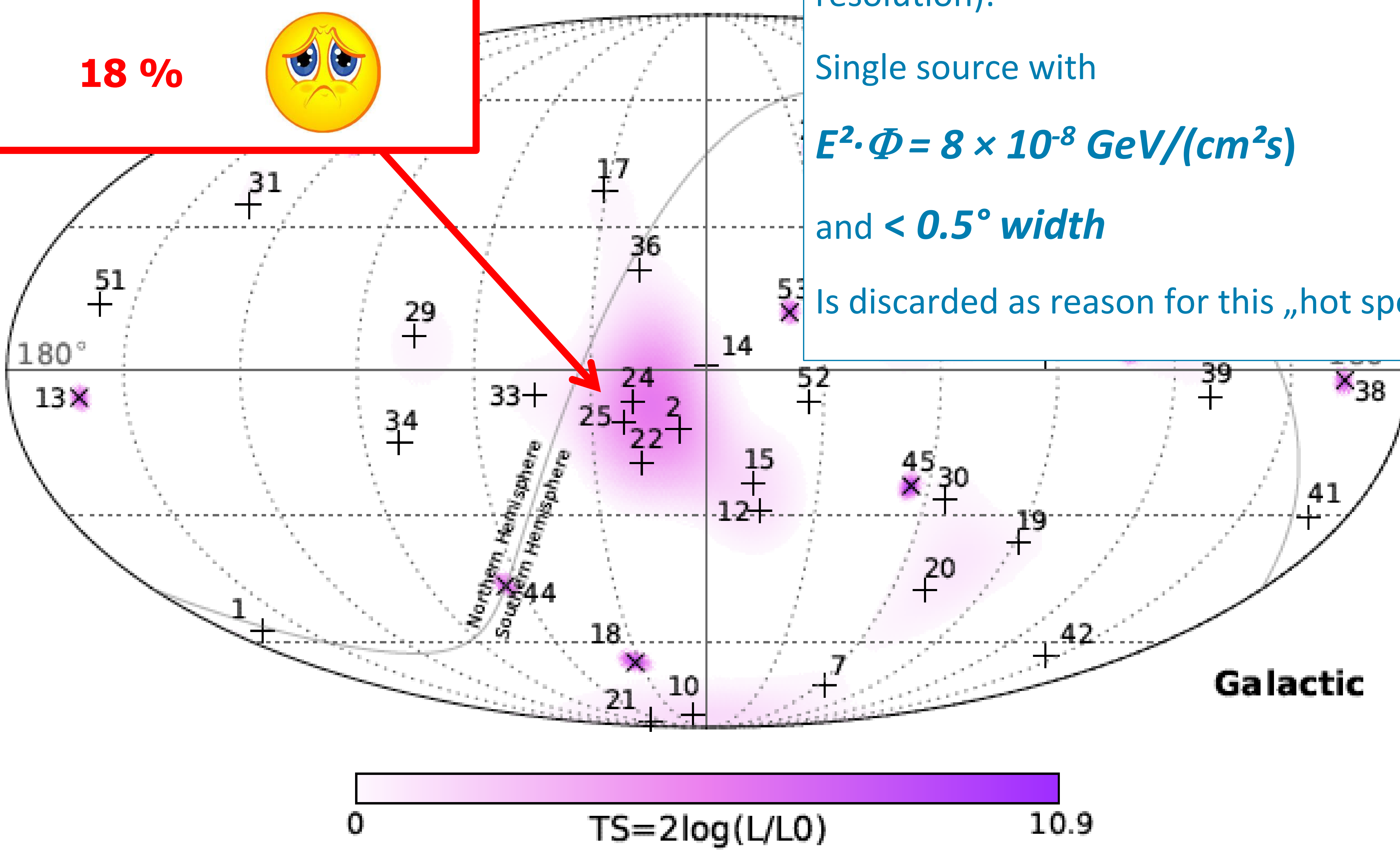
Flavor composition: what do we measure?



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

Sources of HESE events? 4 year skyplot

18 %



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

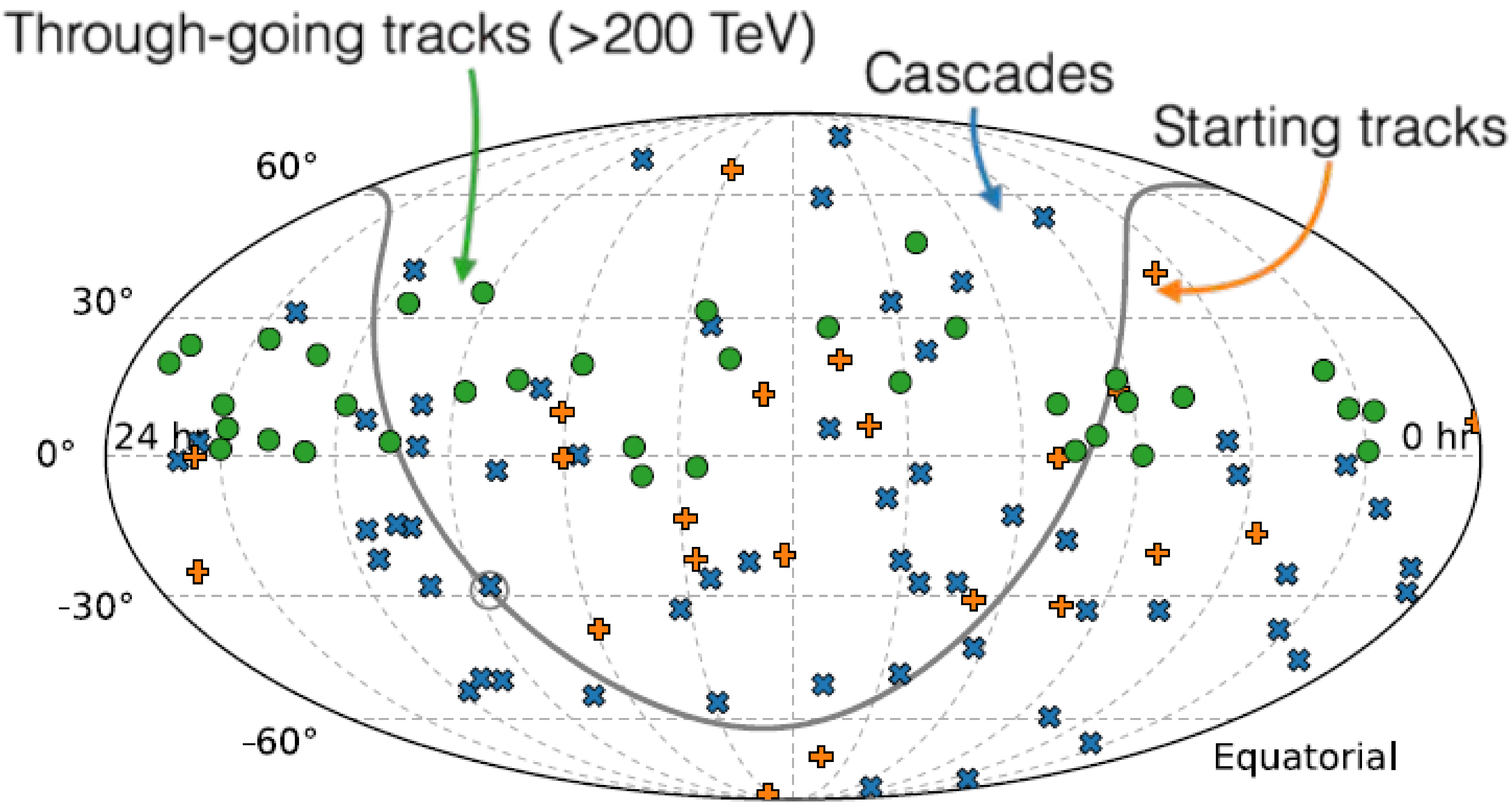
Single source with

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

and ***< 0.5° width***

Is discarded as reason for this „hot spot“.

Latest skyplot for E > 100 TeV (> 50% are cosmic)

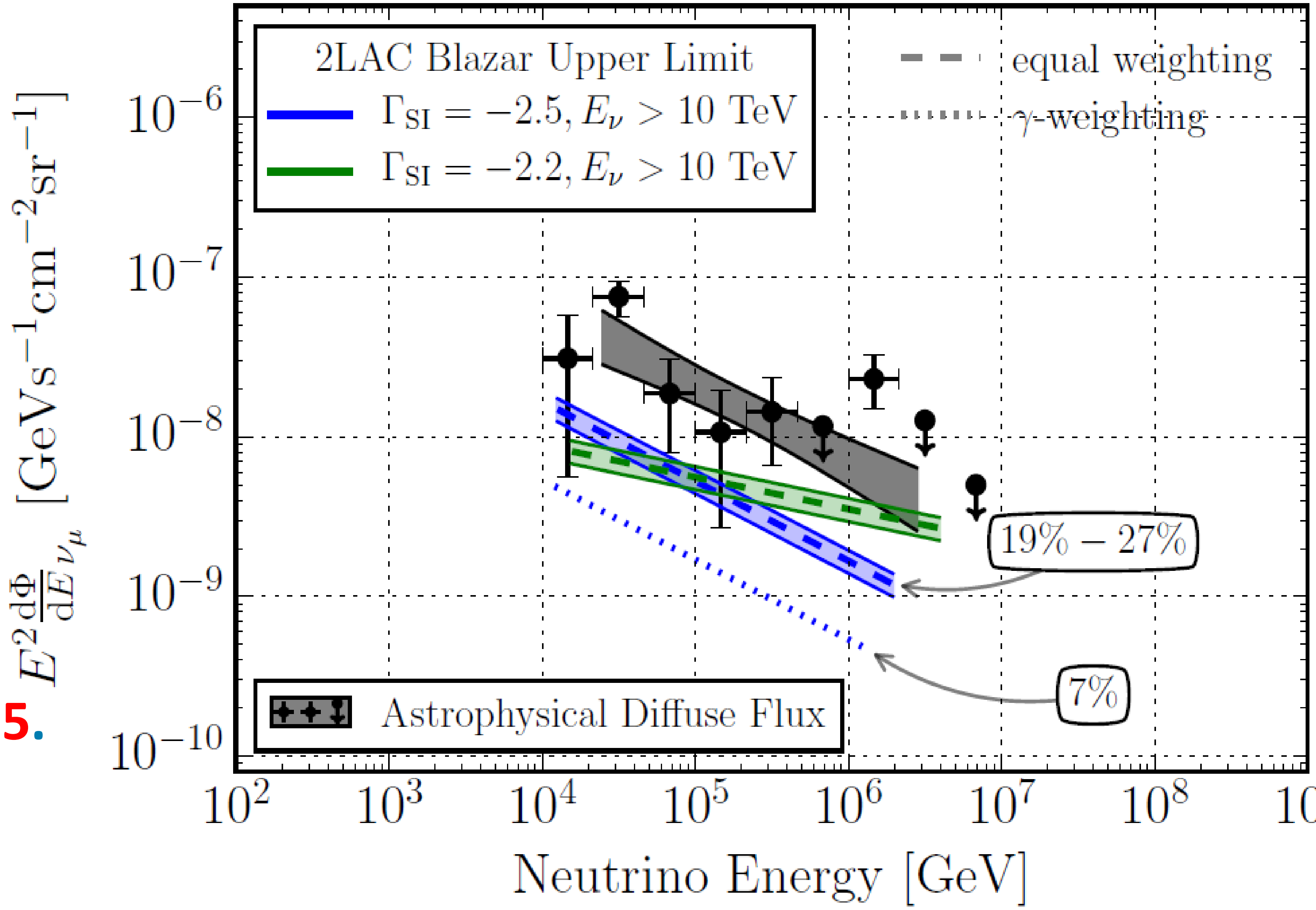


Alas! No hints to clustering…

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

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

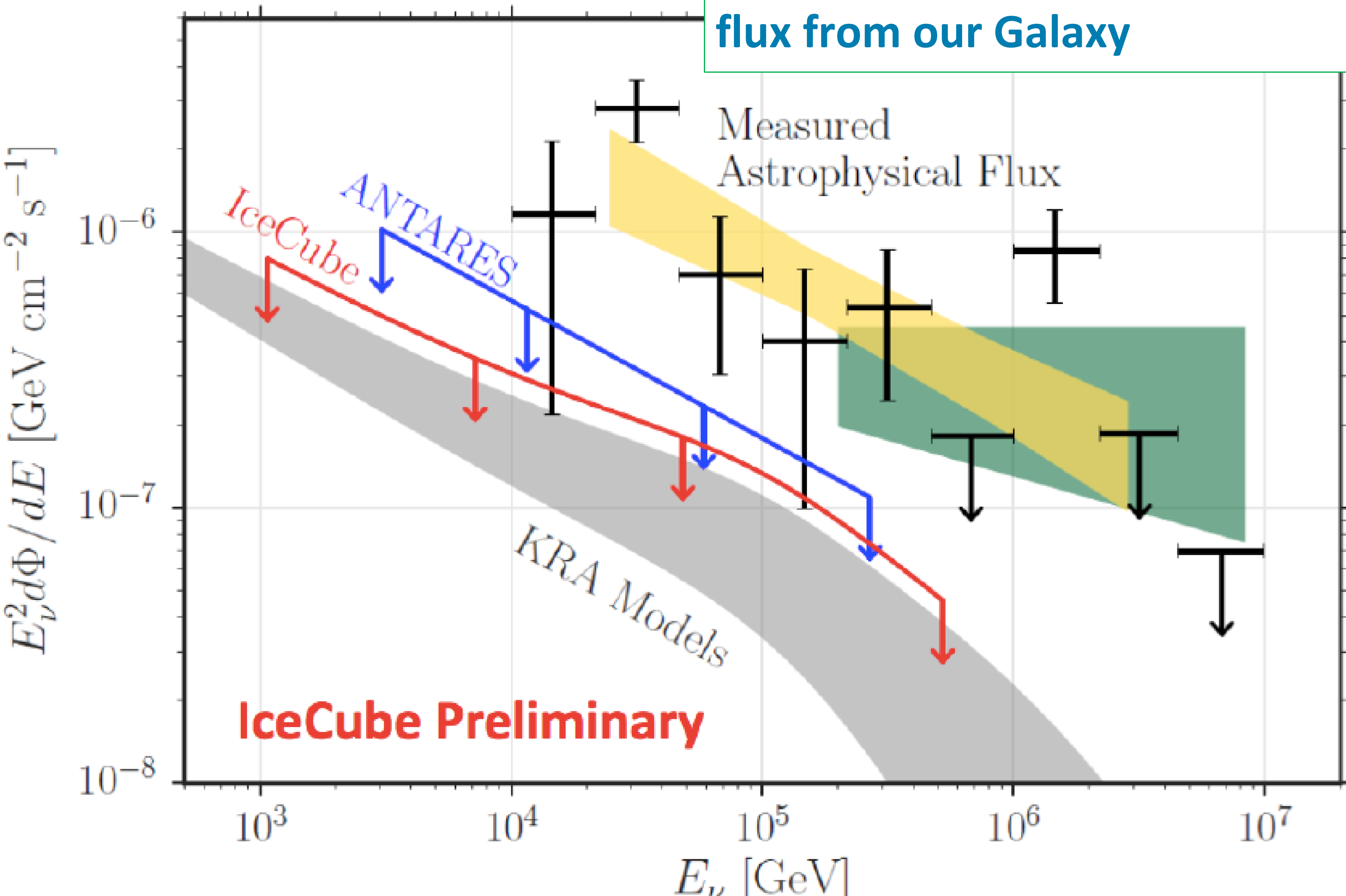
- **Search for cumulative neutrino emission from blazars in the 2nd Fermi-LAT AGN catalogue (862 blazars)**
- **Data from 2009-2012**
- **No significant excess**
- **Contribution of 2LAC blazars to IceCube's astrophysical ν flux ≤ 27% (0.01- 2 PeV), for equipartition of flavors at Earth and spectral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



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

Galactic Plane emission (from CR interactions with dust)

max. 16% of measured astrophys. flux from our Galaxy



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!***

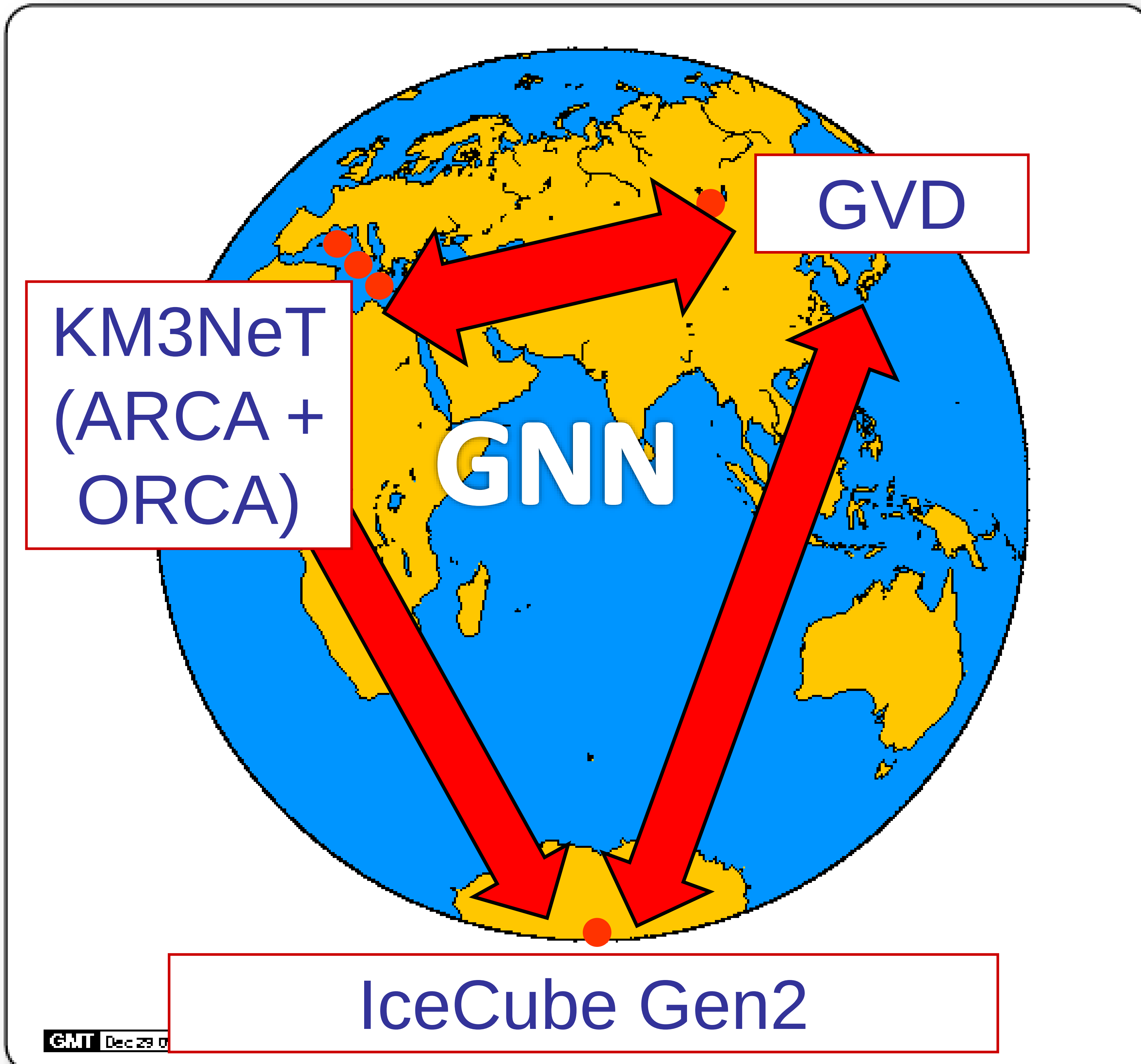
We need detectors ...

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

GNN

The Global Neutrino Network

Baikal, Mediterranean Sea, South Pole

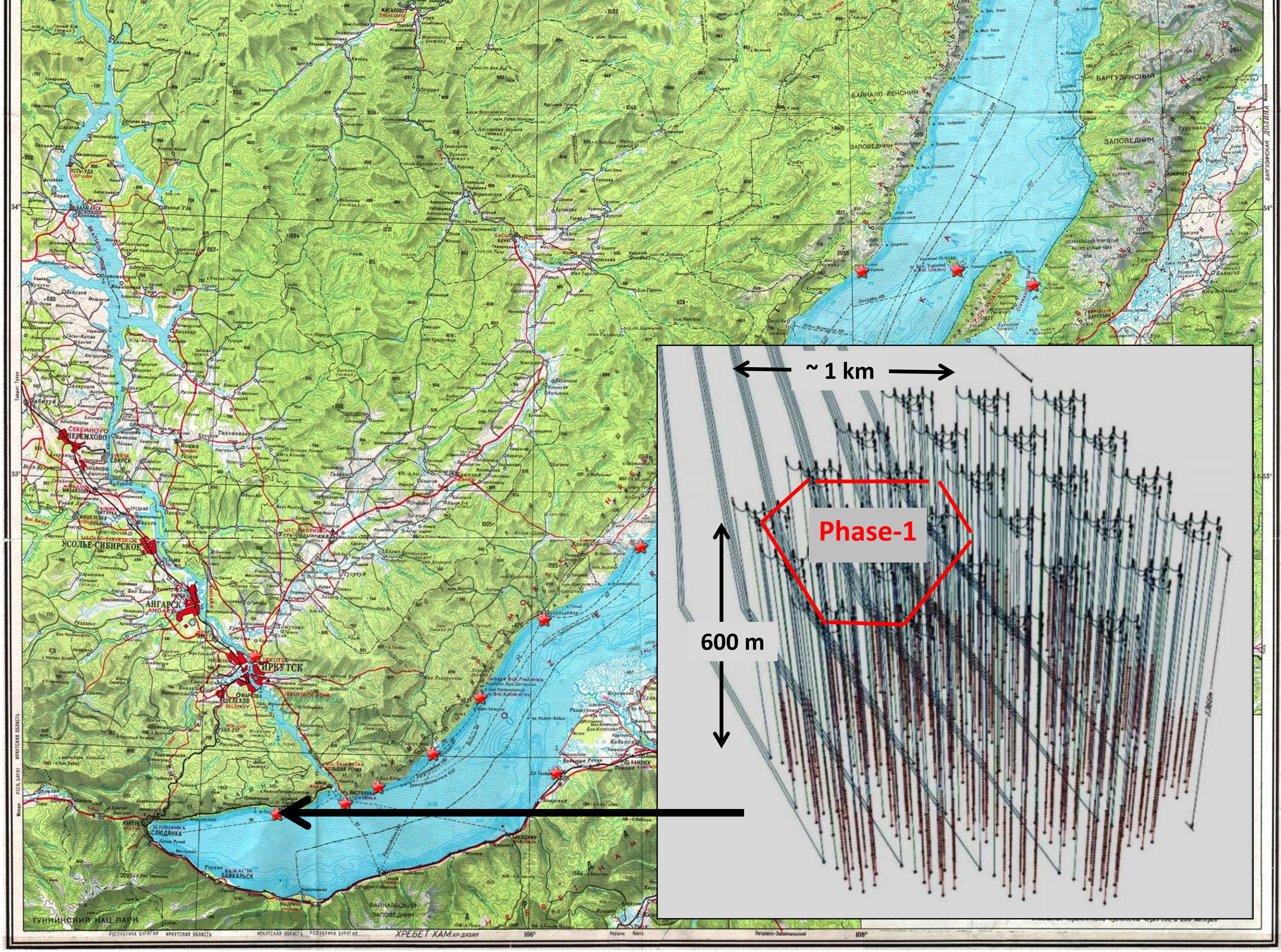


GIGATON VOLUME DETECTOR

BAIKAL GVD

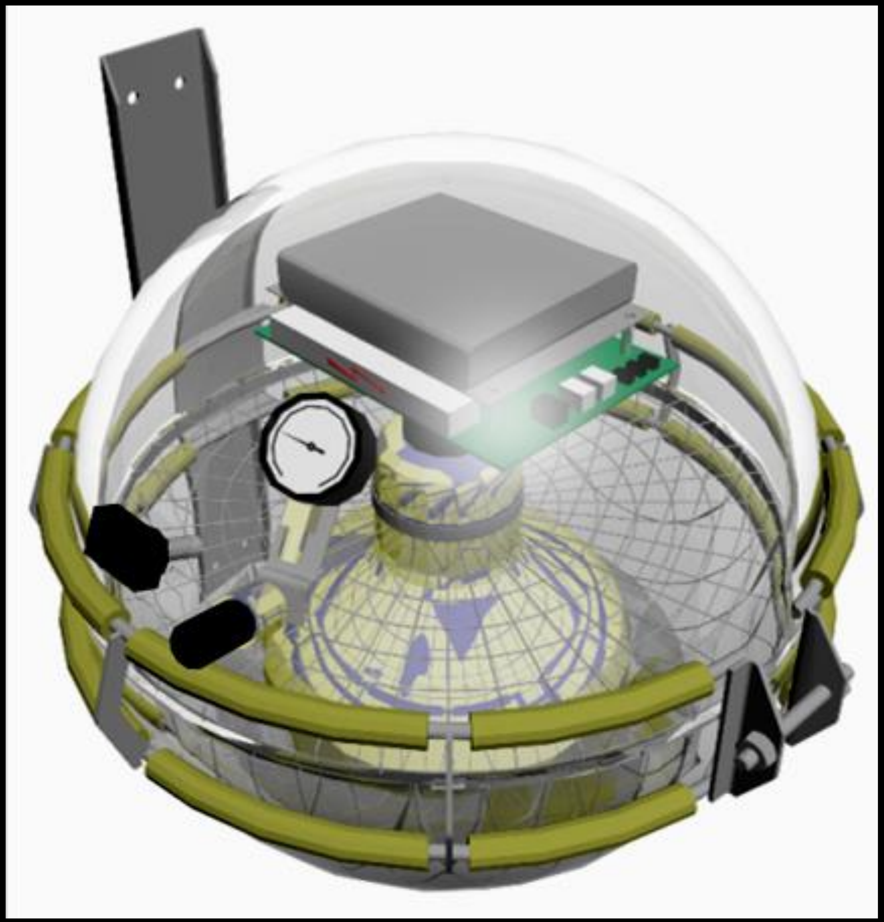
~ 60 authors

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

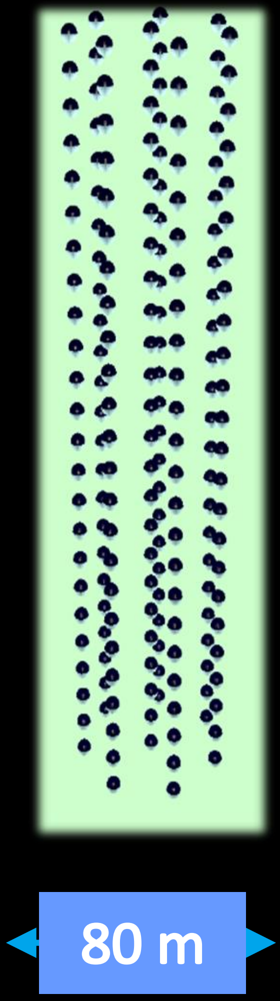


~ 1 km
Phase-1
600 m

After 5 years of prototype tests:

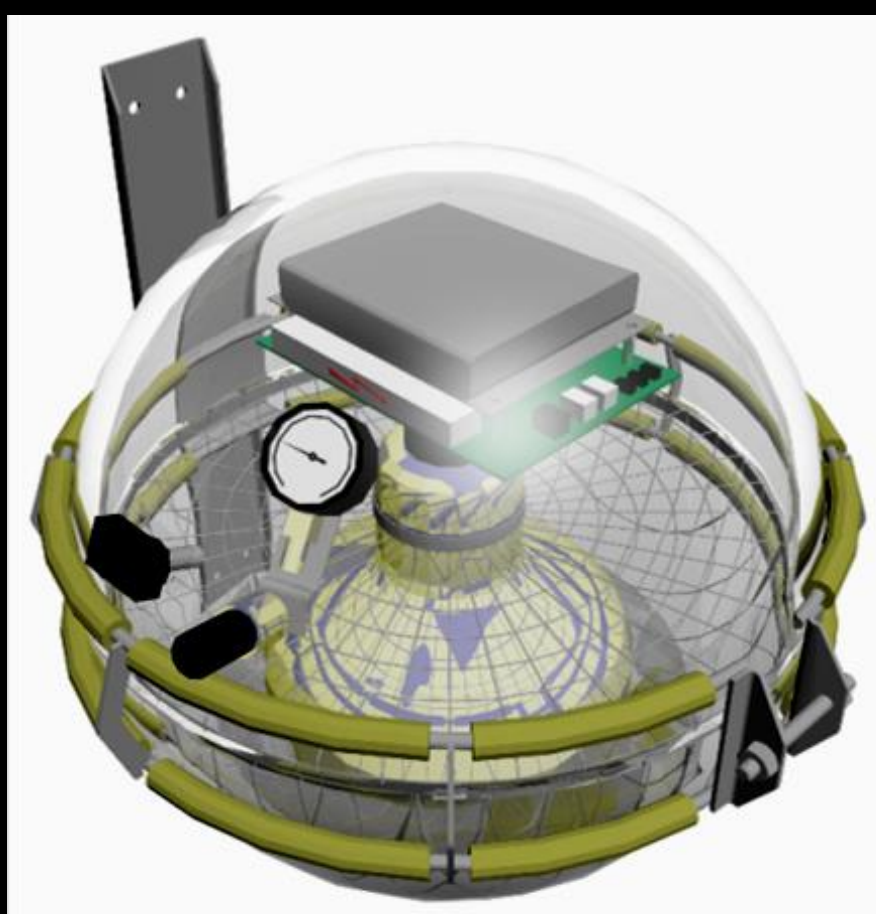


“Dubna”
Demonstration
cluster
April 2015

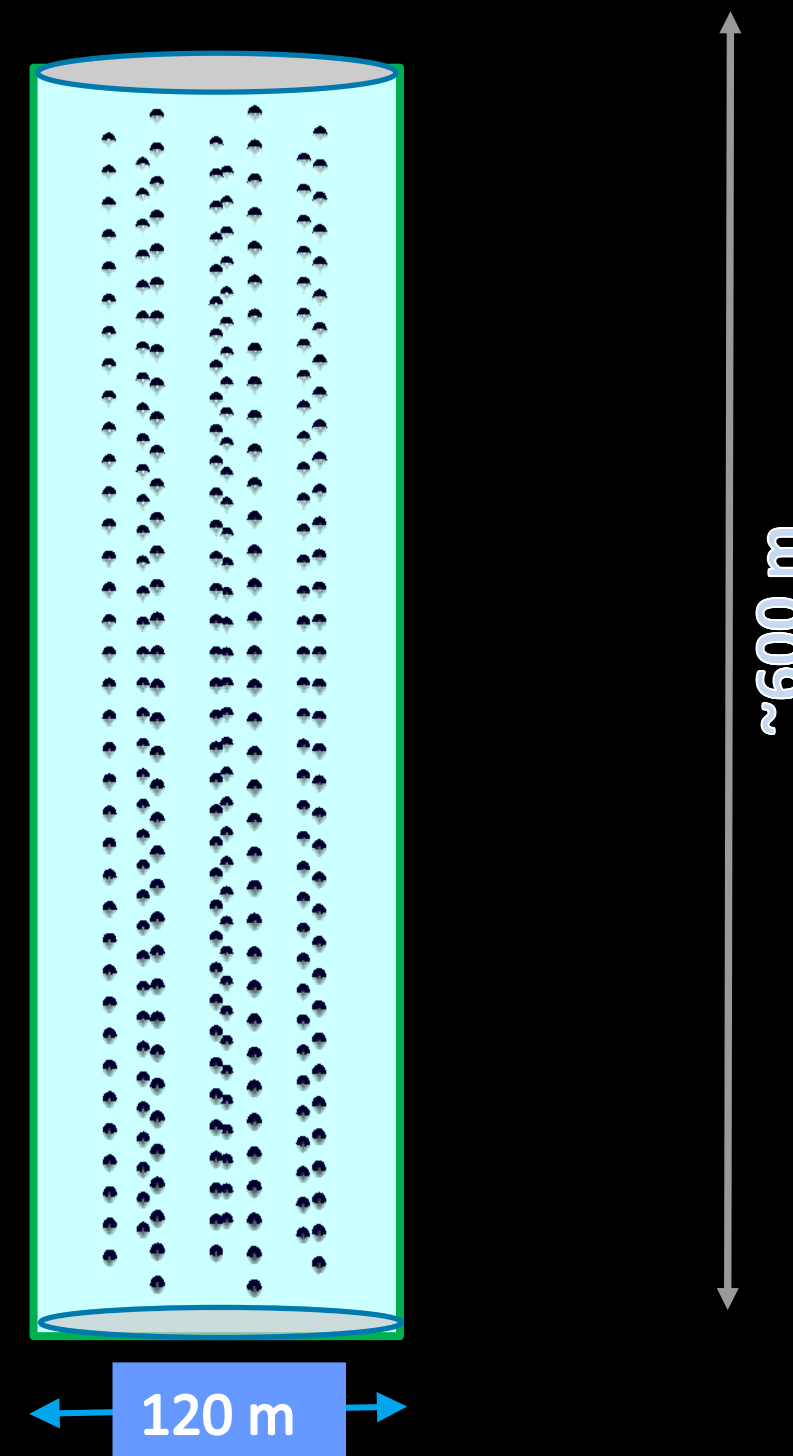


Old NT200:
volume ~ 0.0001 km³

GVD cluster:
0.006 km³
(Antares 0.015 km³)



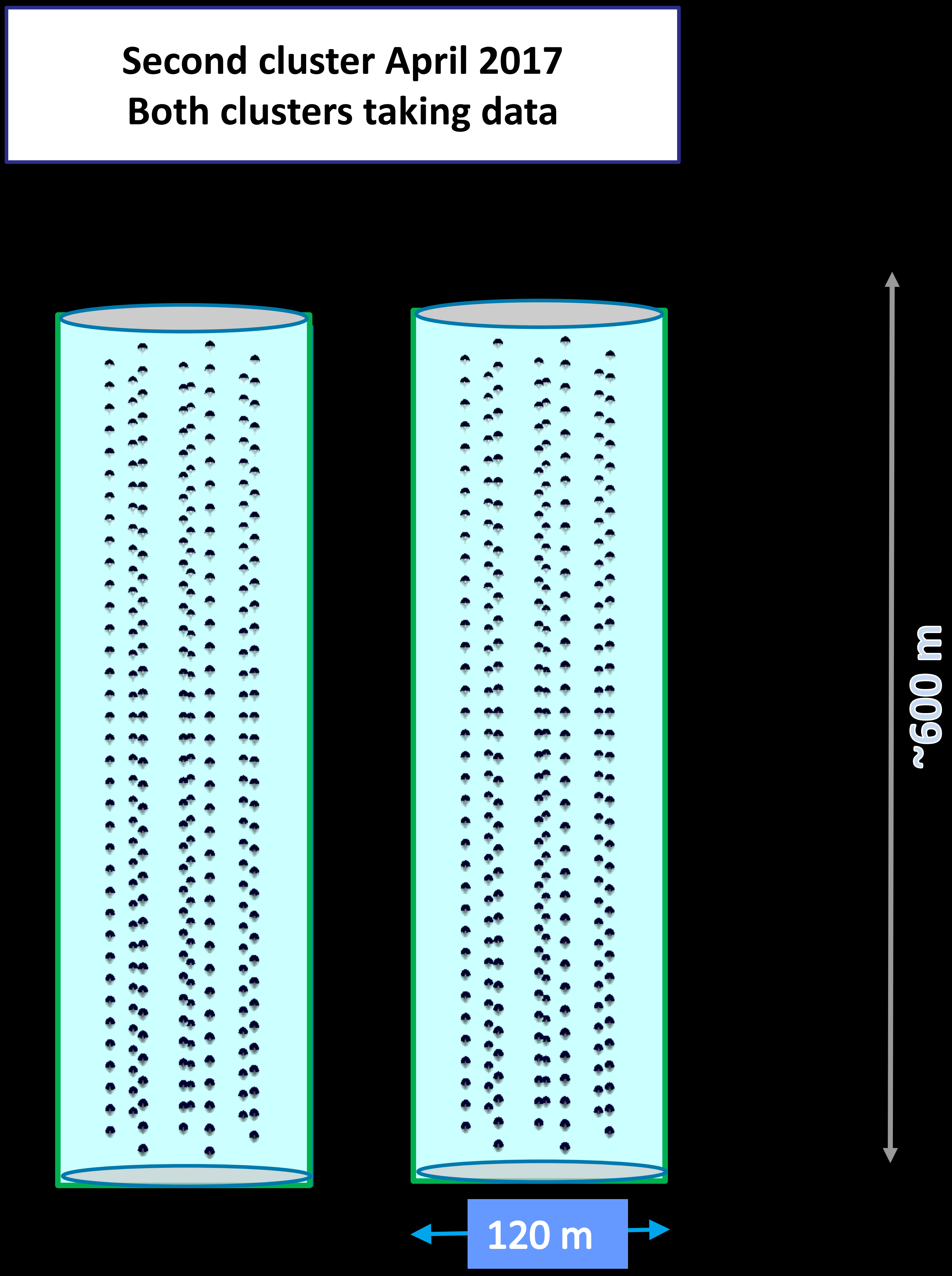
Full scale cluster April 2016

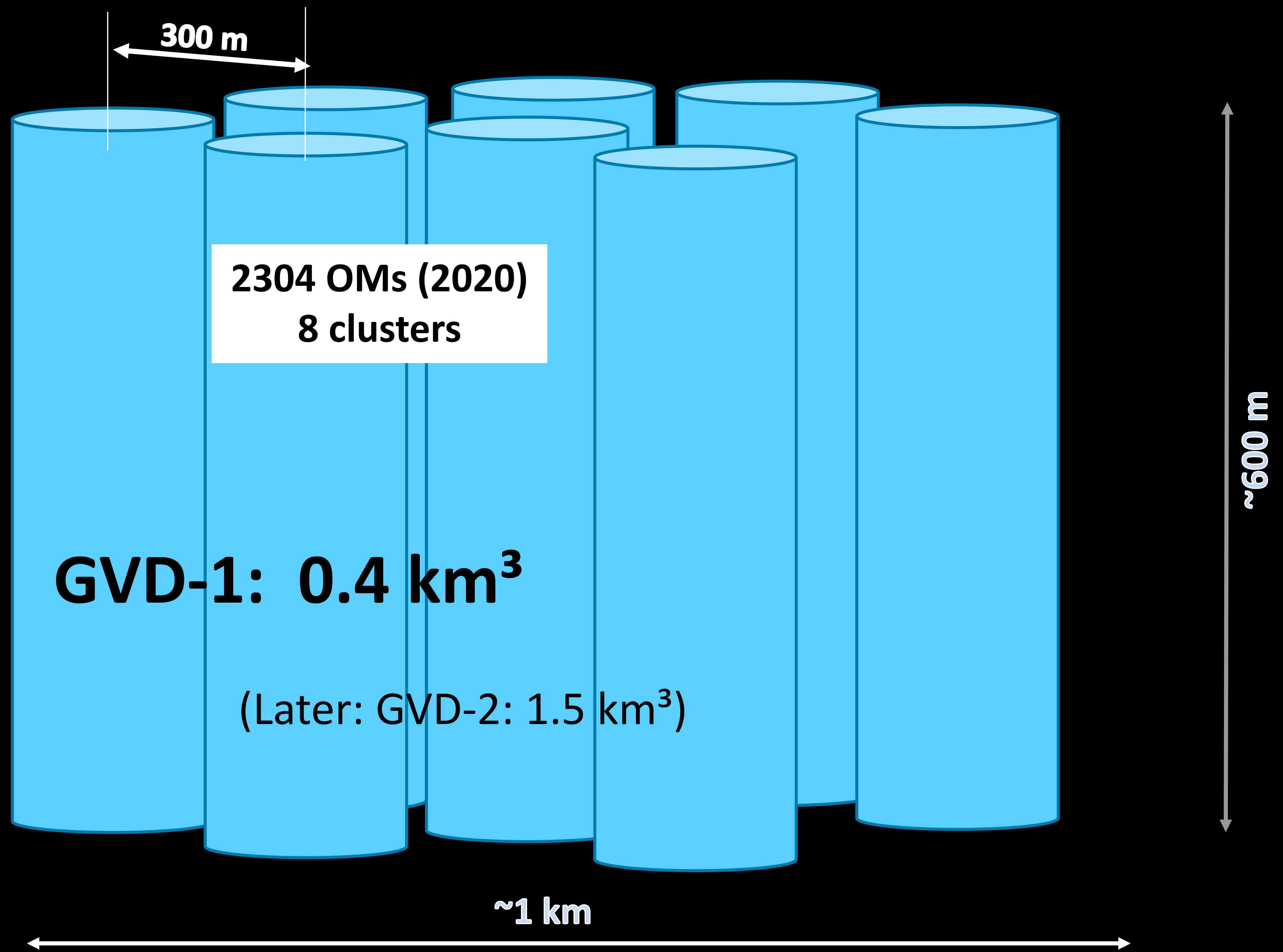


Old NT200:
volume ~ 0.0001 km³

GVD cluster:
0.006 km³
(Antares 0.015 km³)

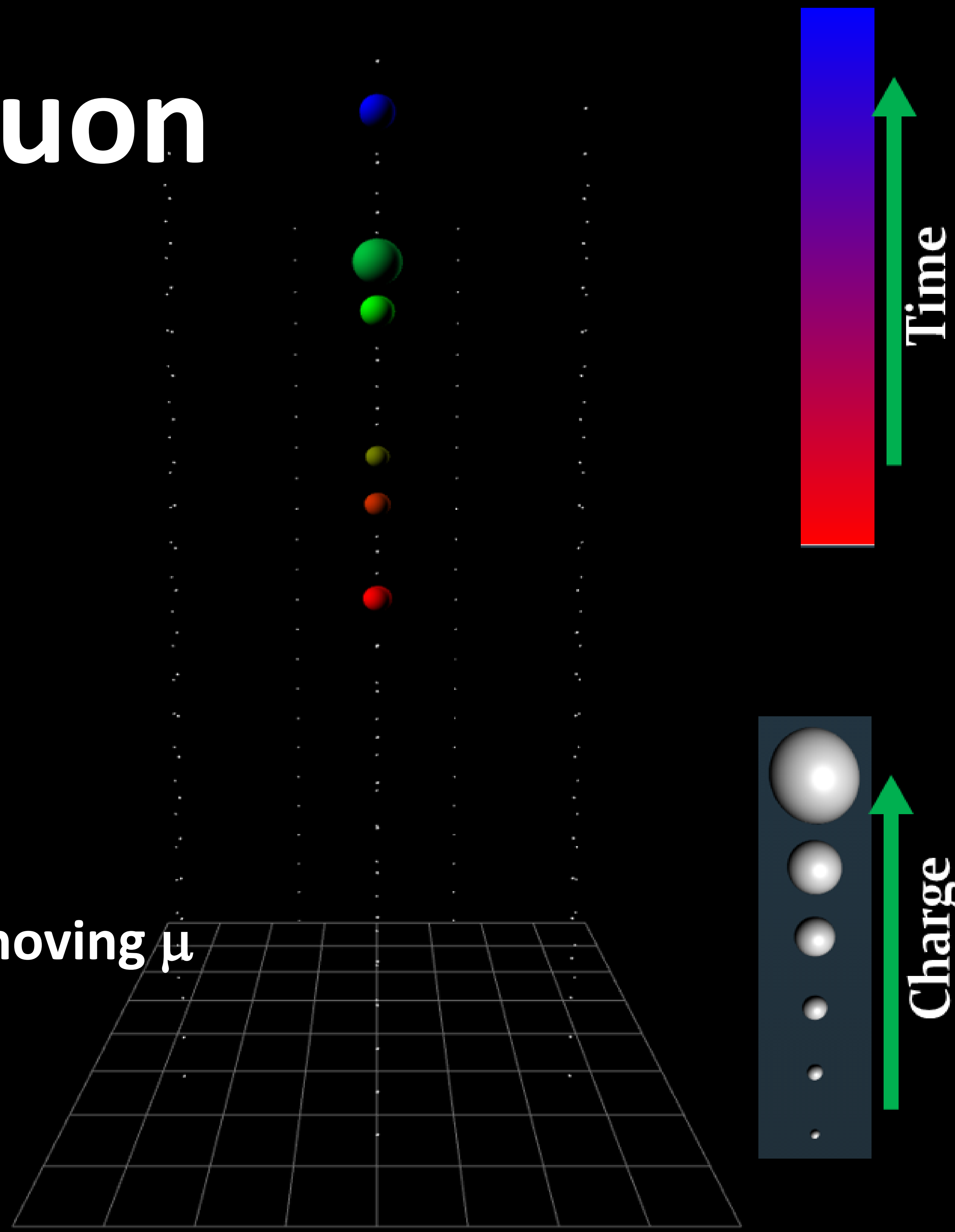
2 GVD Clusters
0.012 – 0.04 km³




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

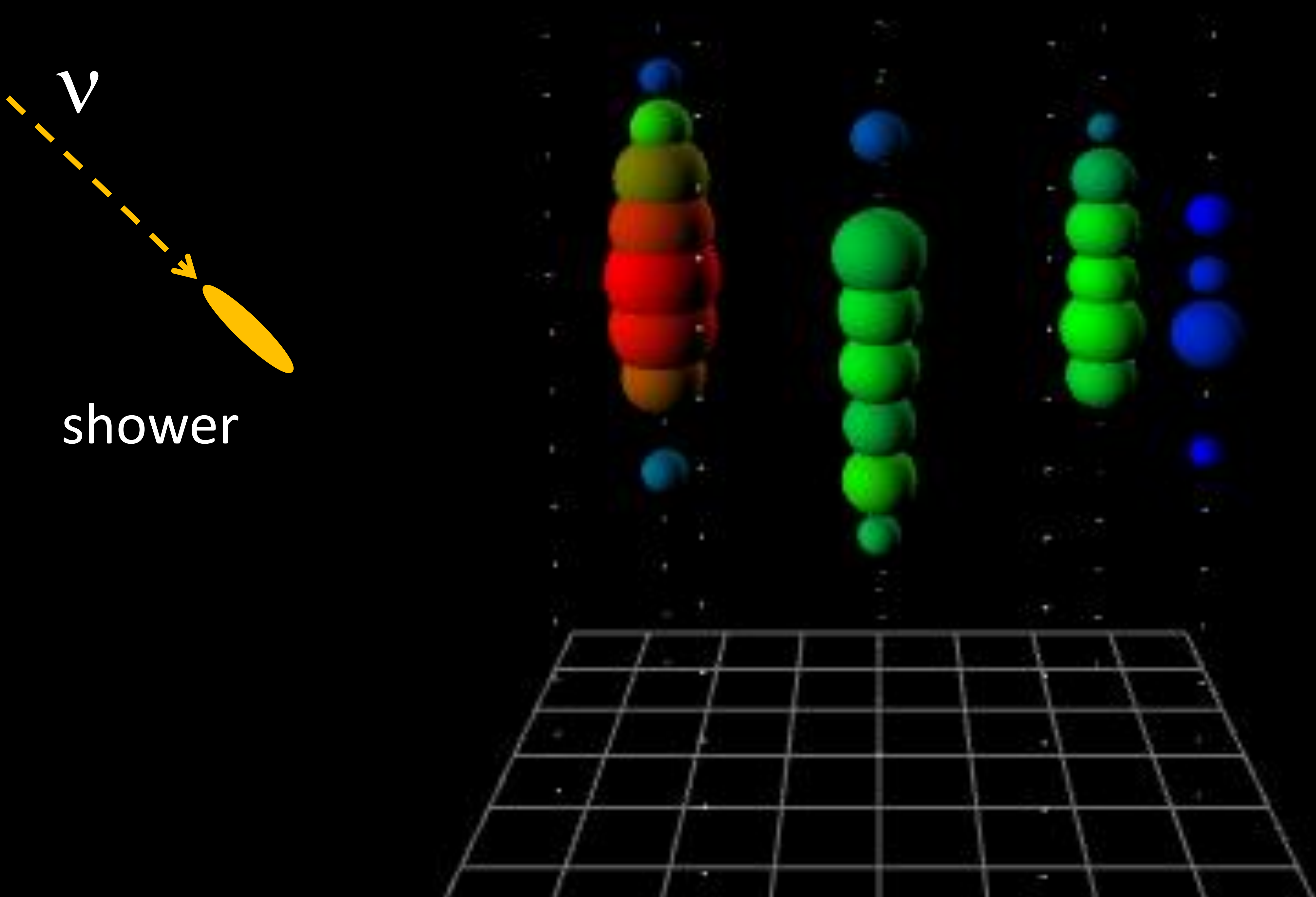
(Dubna cluster)



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***

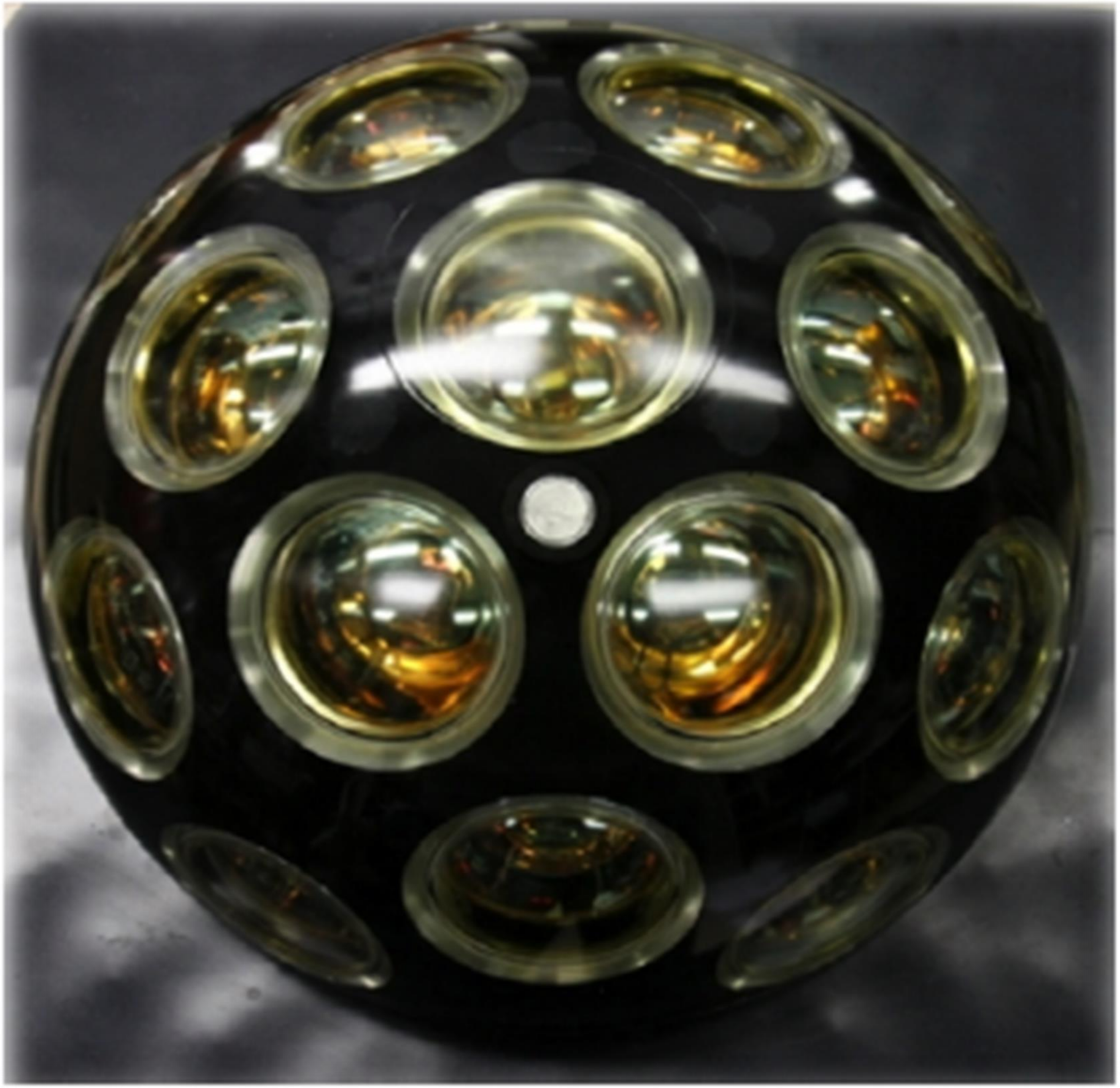
Effective volume GVD-1 for cascades ~ 0.4 km^3

KM3NET

~ 400 authors

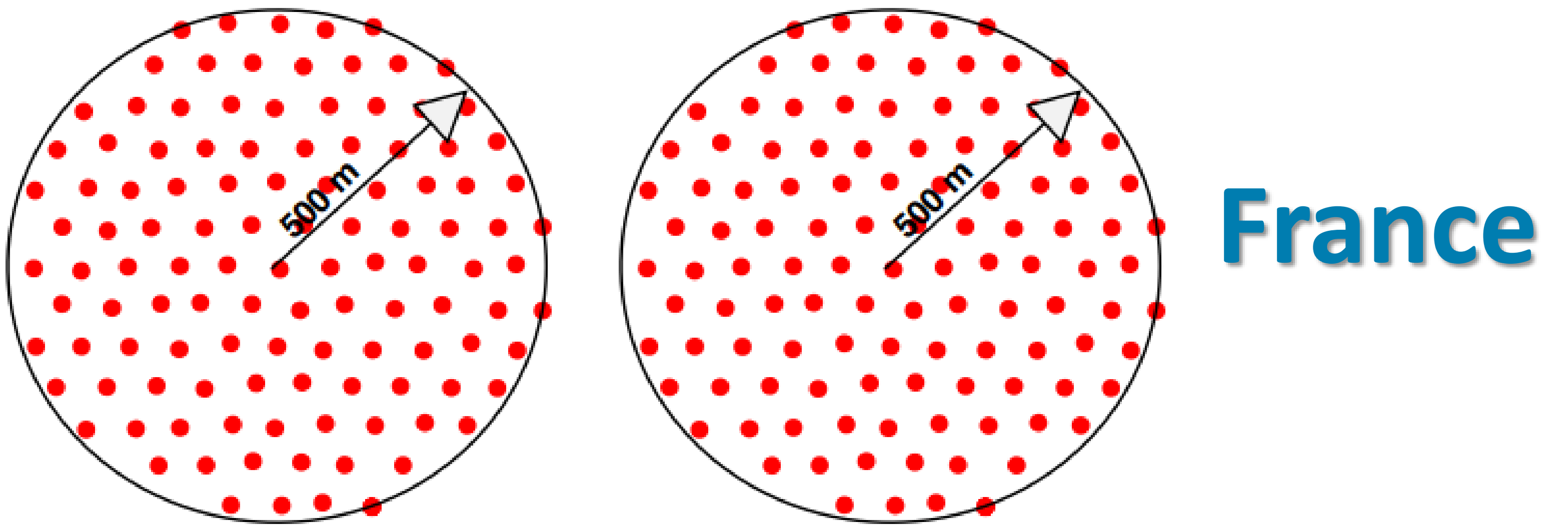
50 institutions in 15 countries
(lead Countries: Italy, France, The Netherlands)

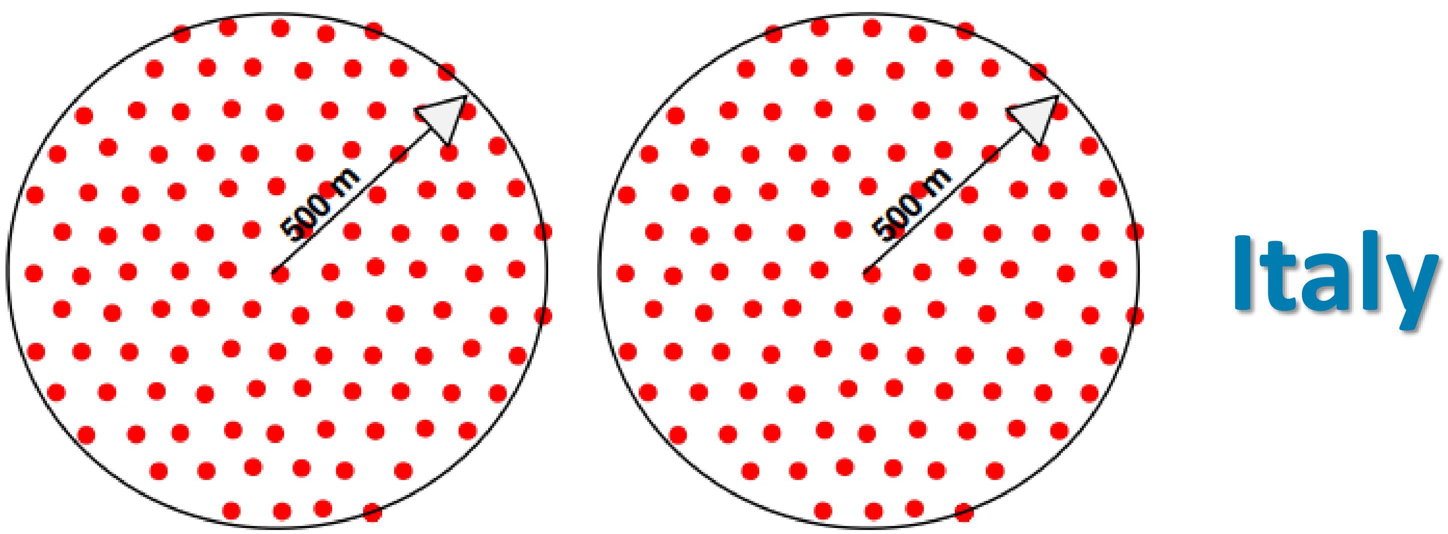
The KM3NeT Optical Module

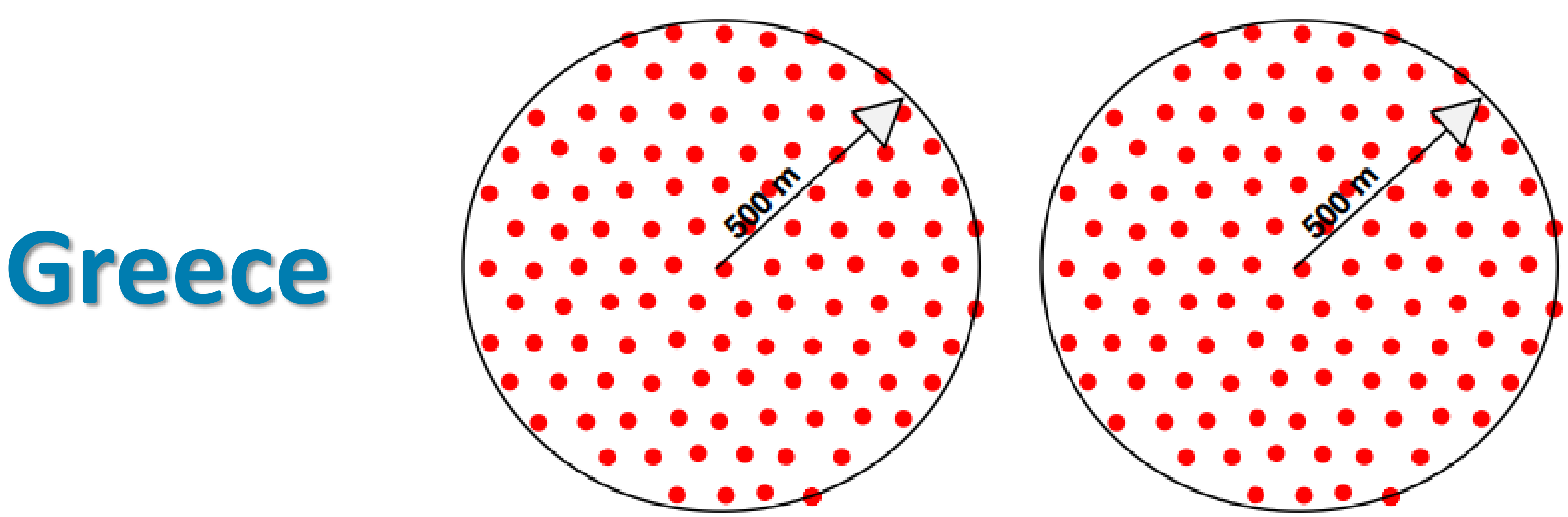


Original idea: 6 blocks at 3 locations: 6 x 0.6 km^3

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



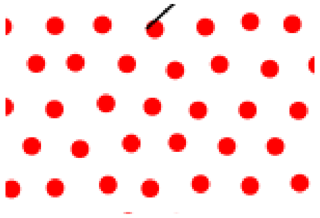




KM3NeT Phase 1: Prototype (2018)

France

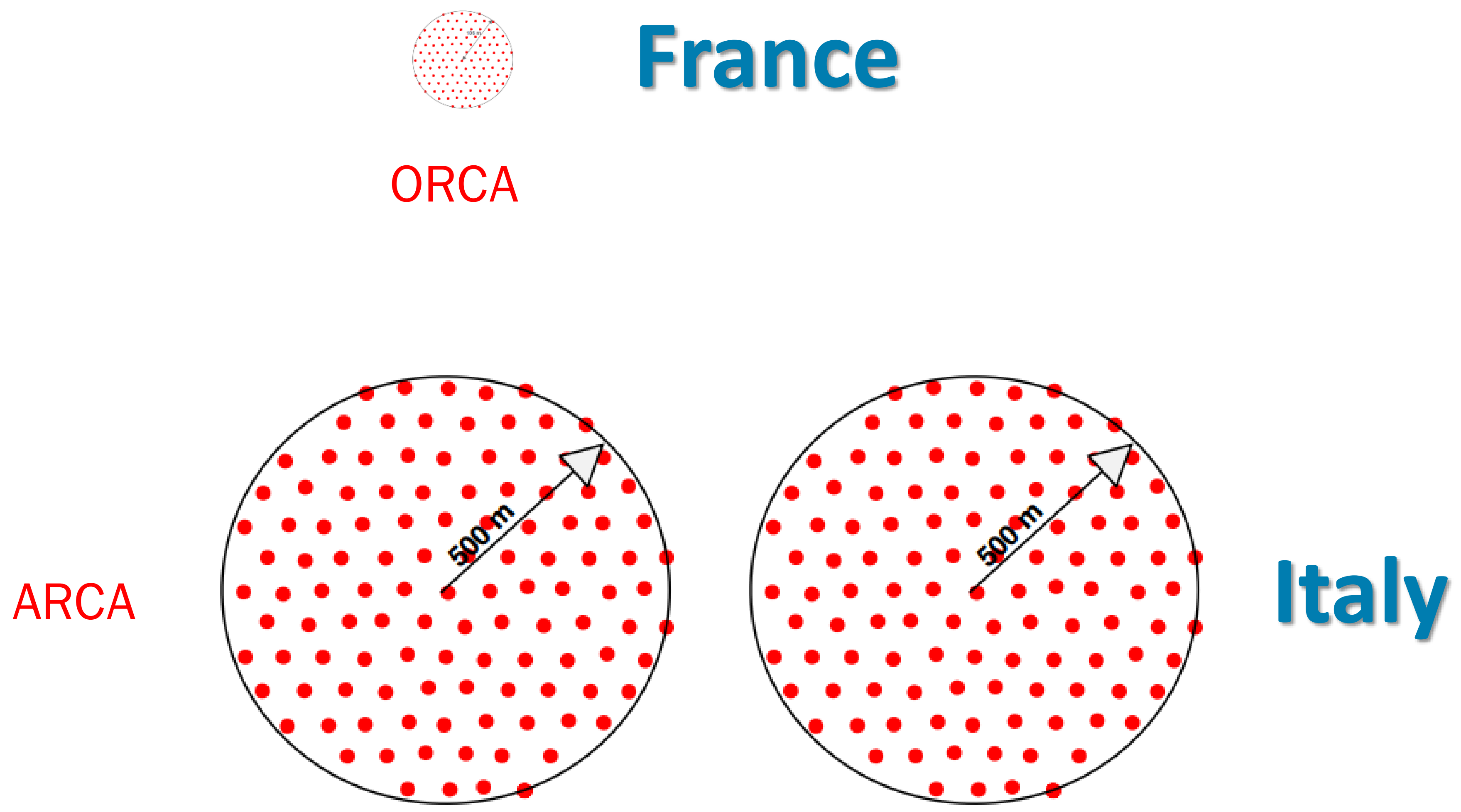
7 strings, small spacing
- Feasibility test for ORCA



Italy

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

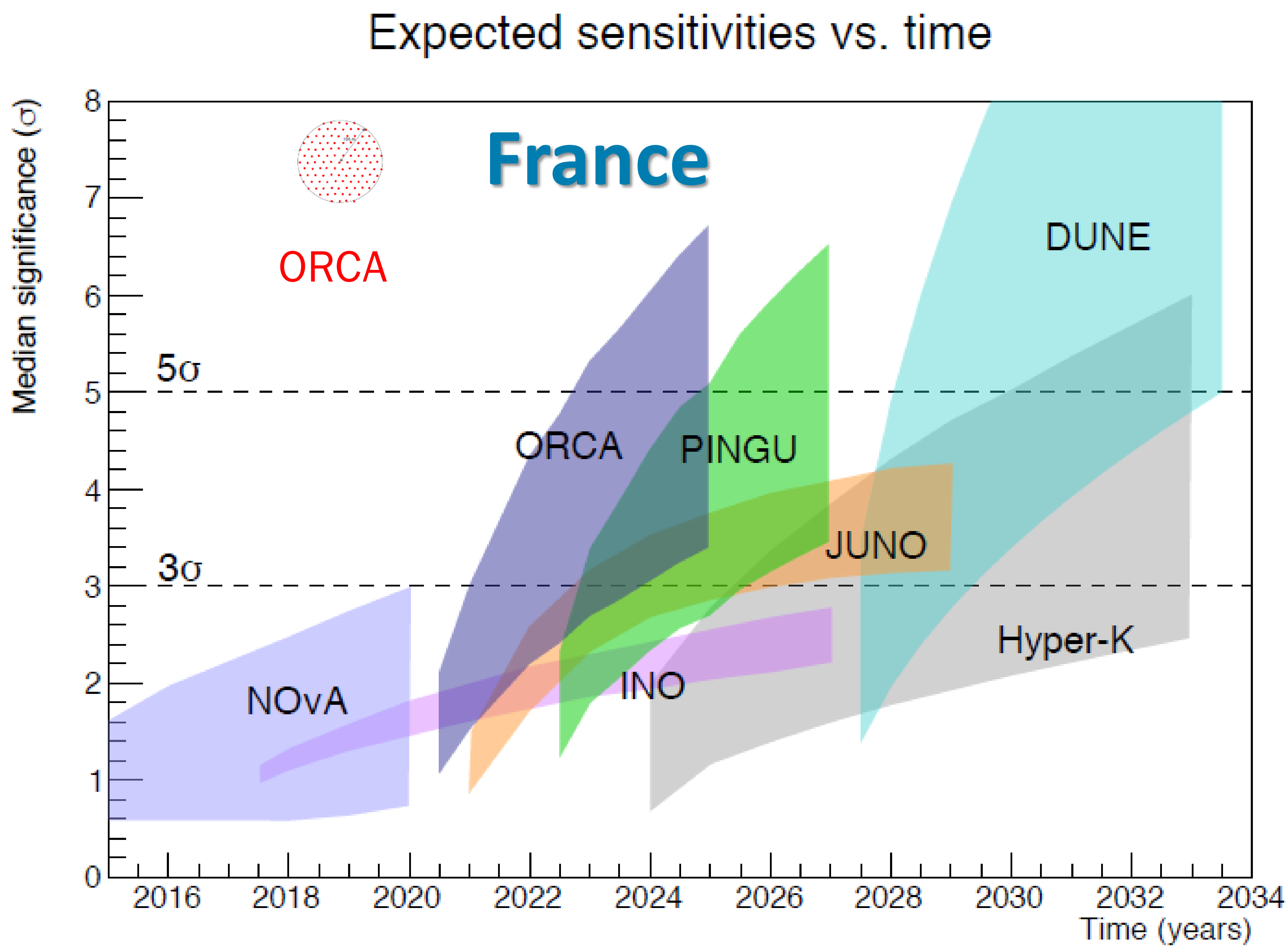
KM3NeT Phase 2: ORCA and ARCA (2021)



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

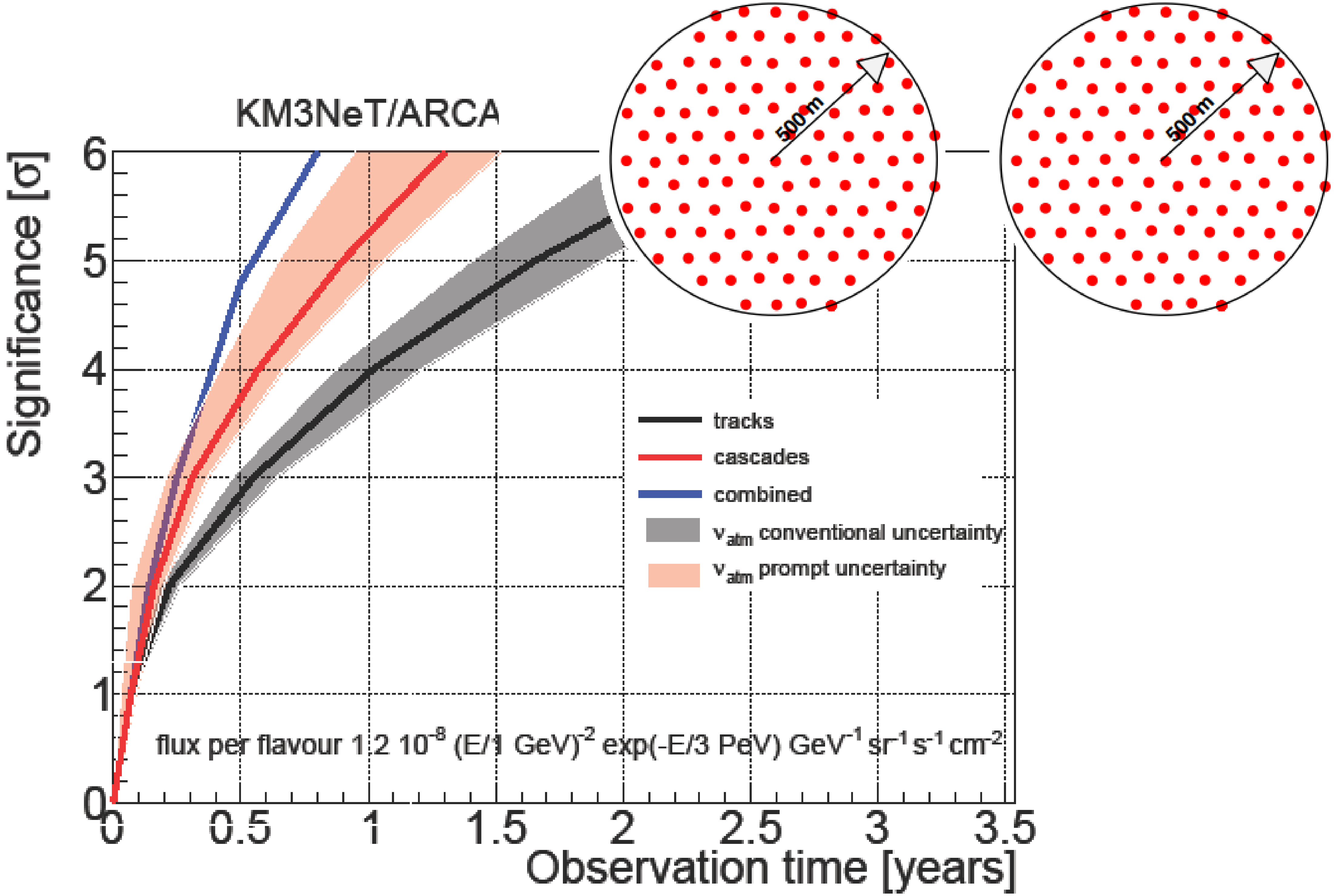


ORCA: determination of the Neutrino Mass Hierarchy (NMH)

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



Italy

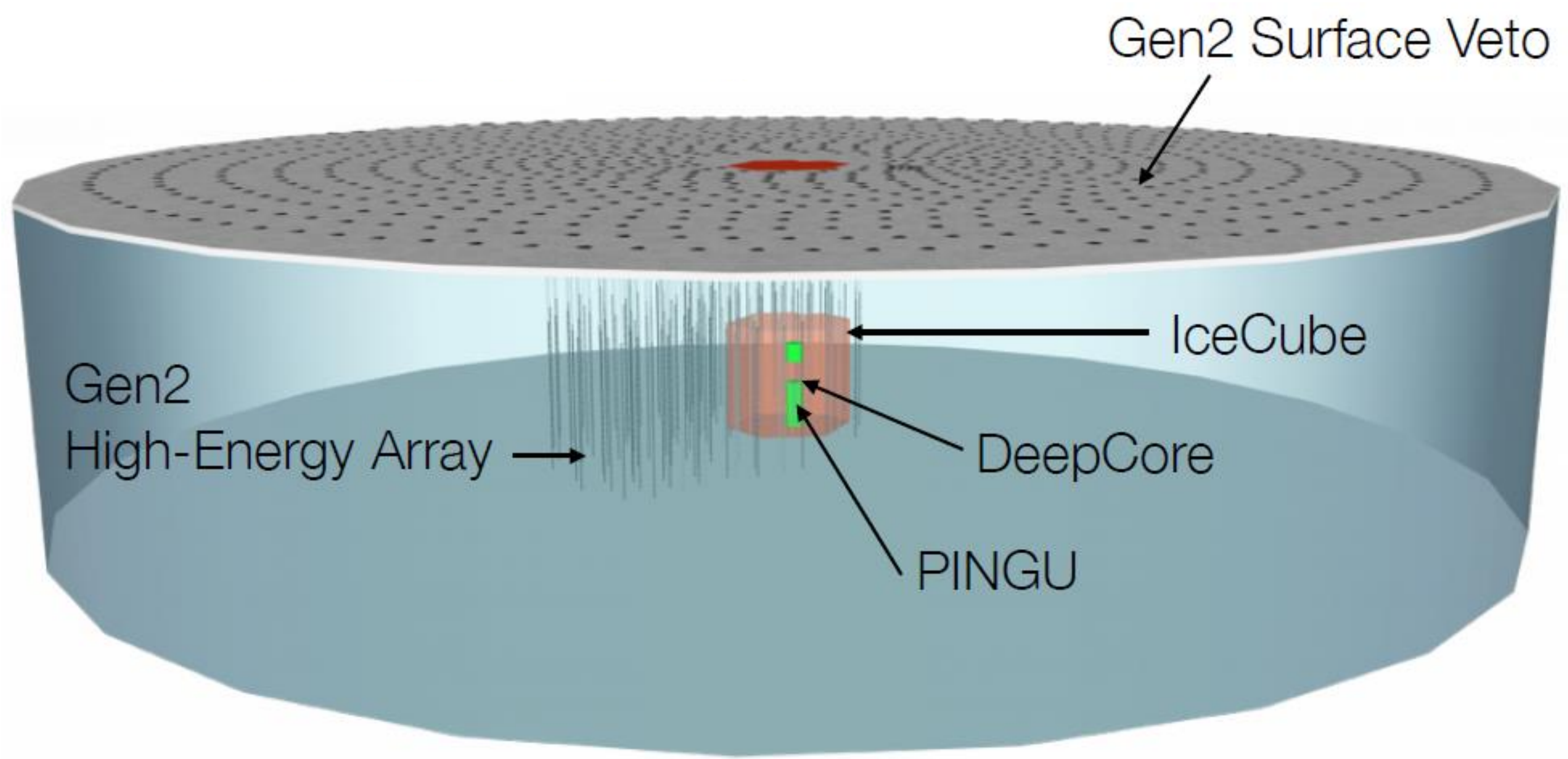
ARCA: IceCube physics, but with better angular resolution and from the Northern hemisphere

ICECUBE GEN2

~ 400 scientists

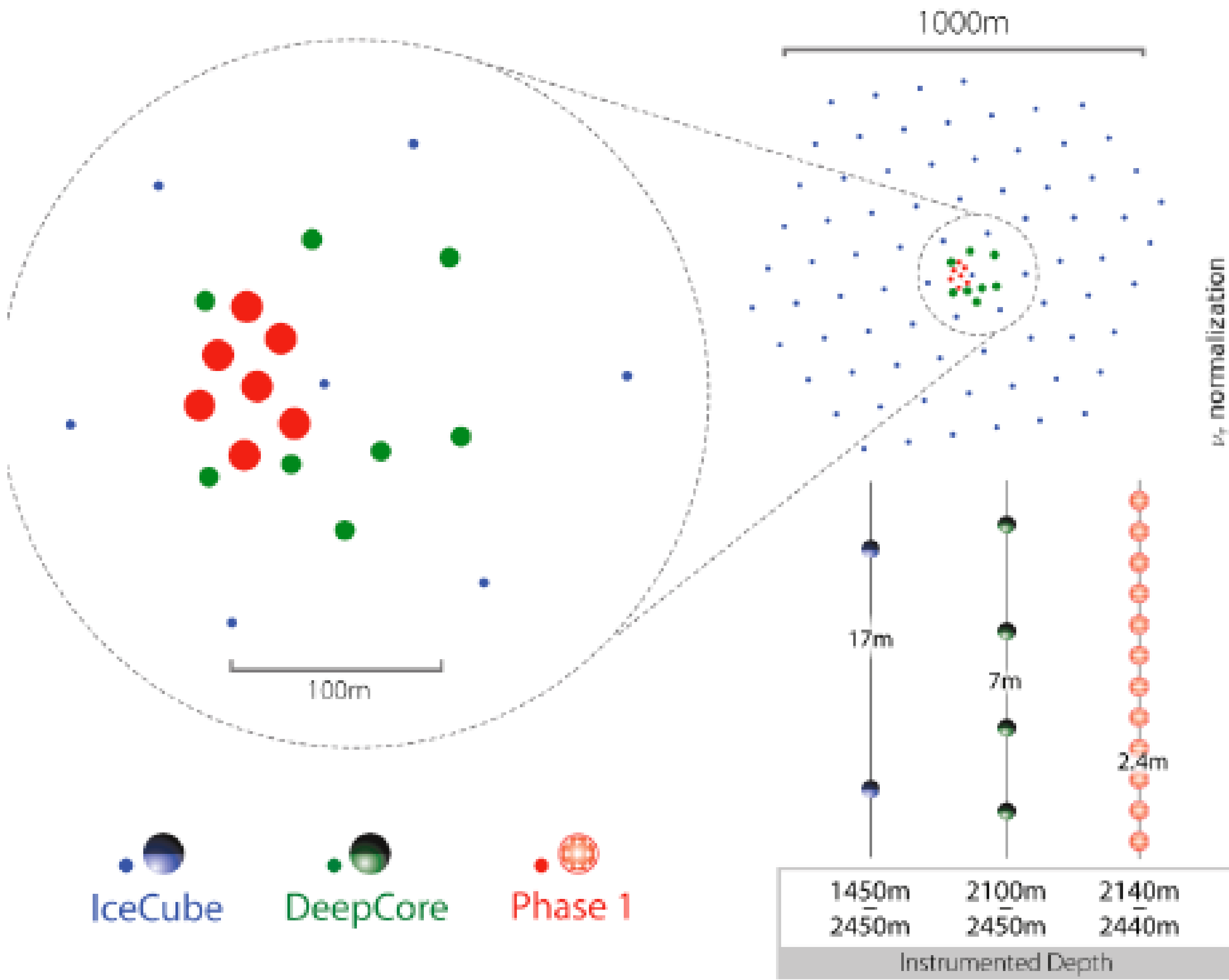
~50 institutions in 12 countries
(lead Institutions U. Wisconsin, DESY)

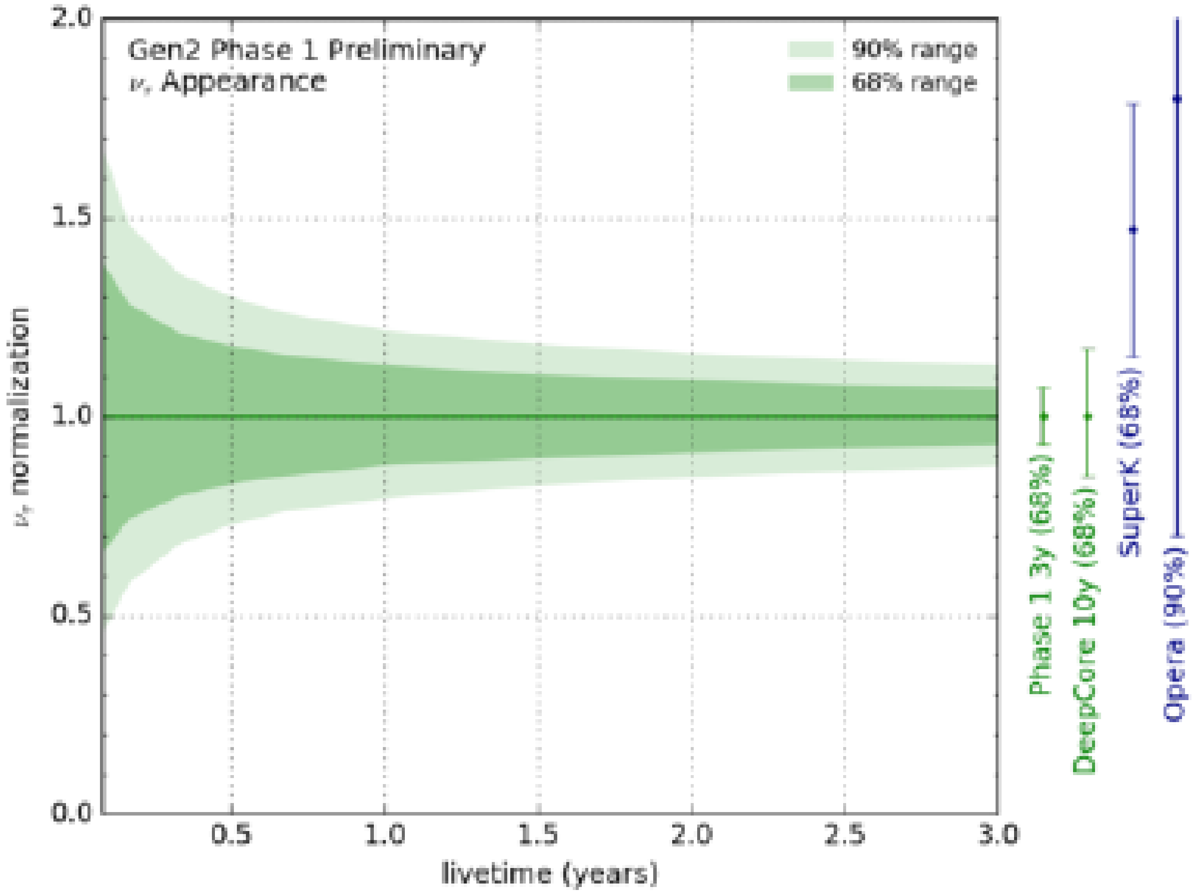
IceCube Gen2

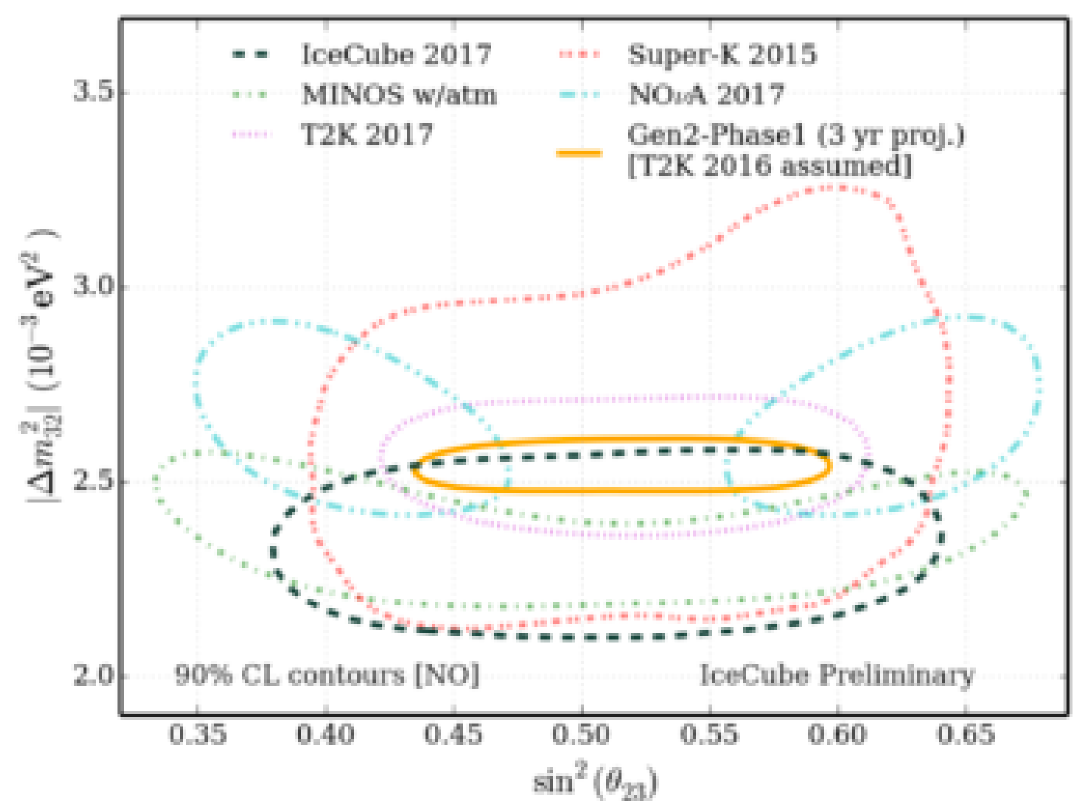


- **PINGU :** GeV scale, ν mass hierarchy
- **High Energy Array:** PeV scale , ν astronomy
- **Surface array:** Veto array for HEA , cosmic ray physics
- **Radio Array:** > 100 PeV, BZ (GZK) neutrinos

Next step: IceCube-Gen2 Phase1





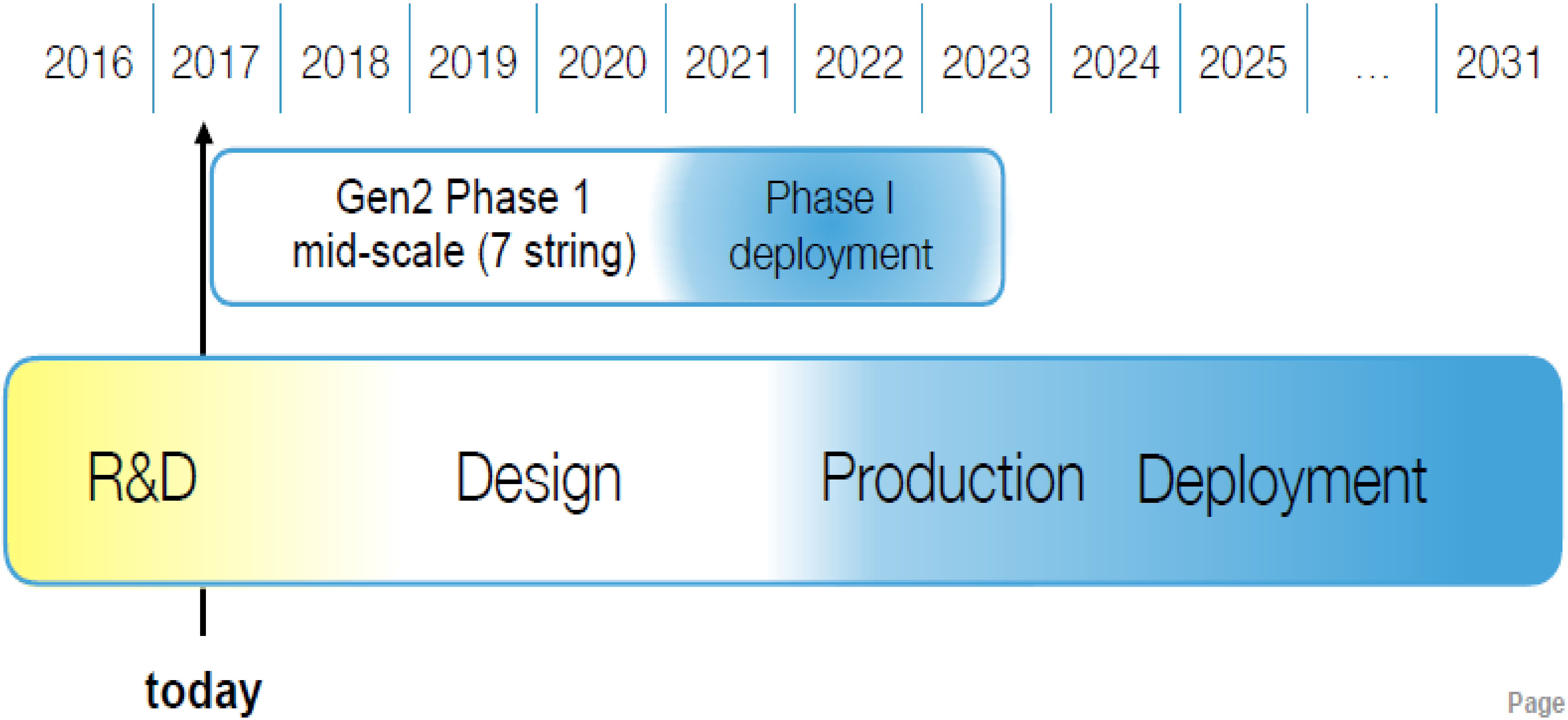


- 7 new strings in the DeepCore footprint.
- Proposed to NSF and international funding agencies.
- Newly deployed calibration devices will also improve reconstruction of high-energy events.

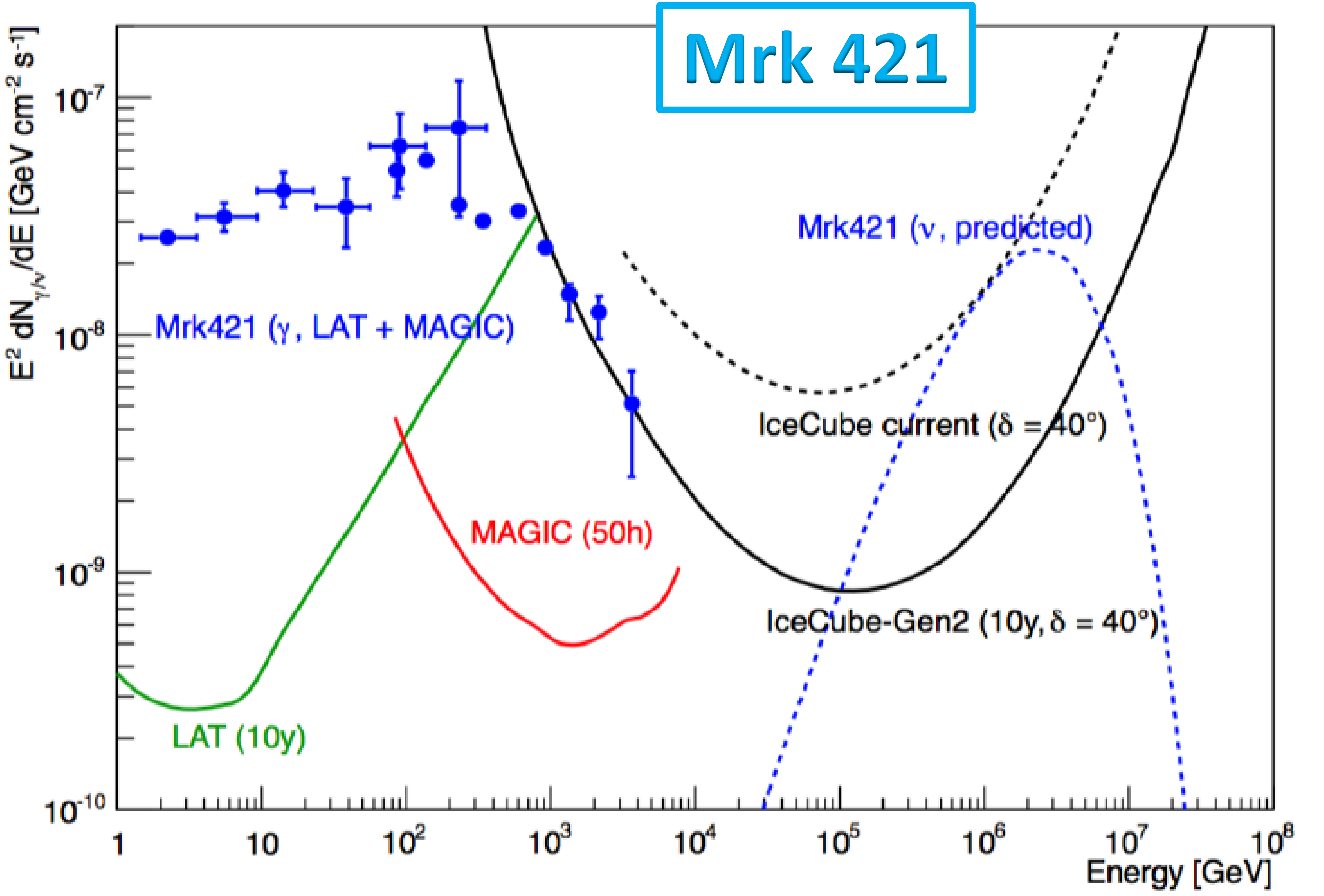
Optical sensors: R&D along various concepts

- P-DOM
- M-DOM
- D-EGG
- WOM
- Brusselsprout OM

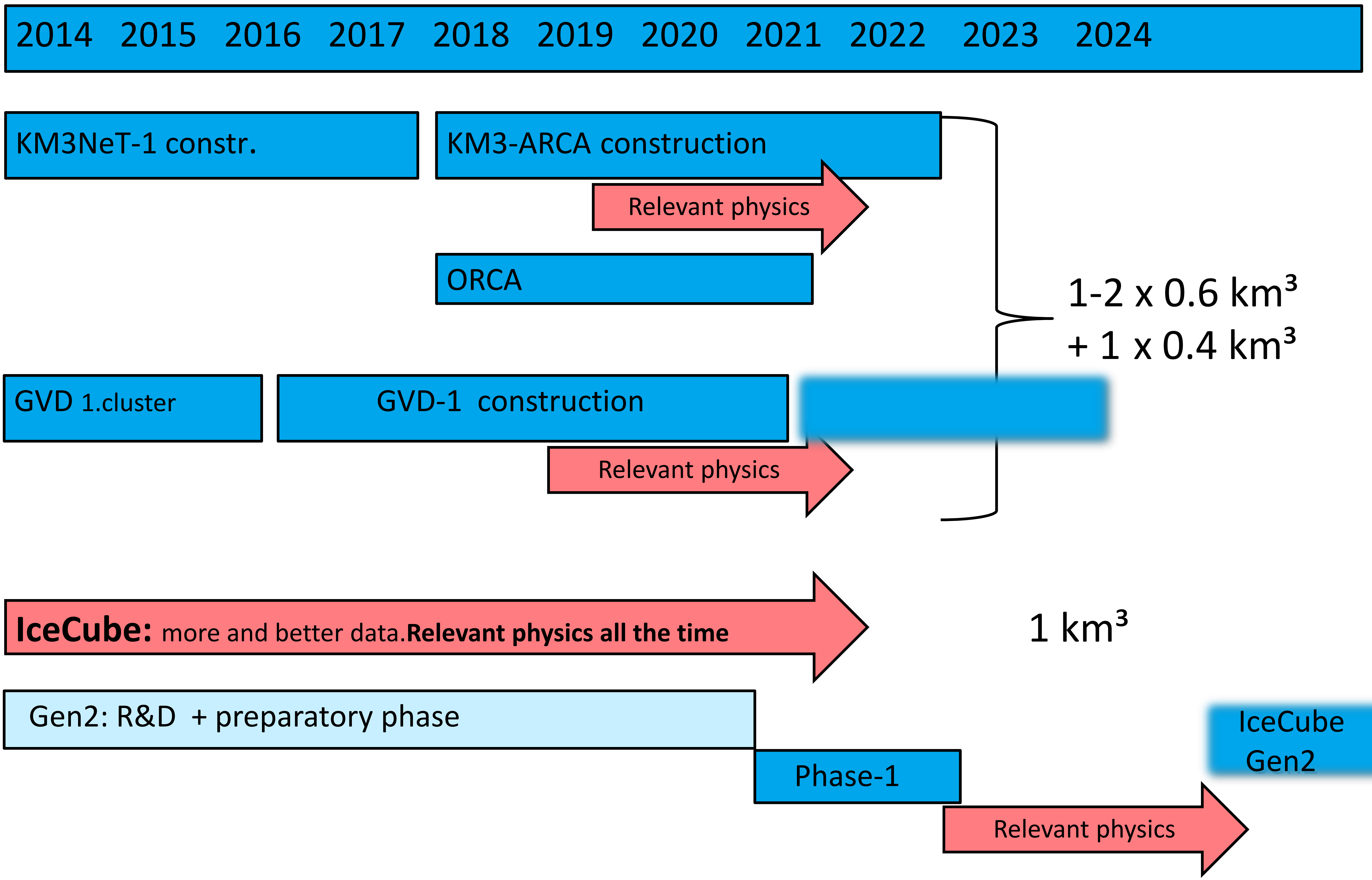
Gen2: Tentative time scale



Gen2: Example for point source sensitivity



Global timeline



Summary of where we go

- $\geq$ 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)

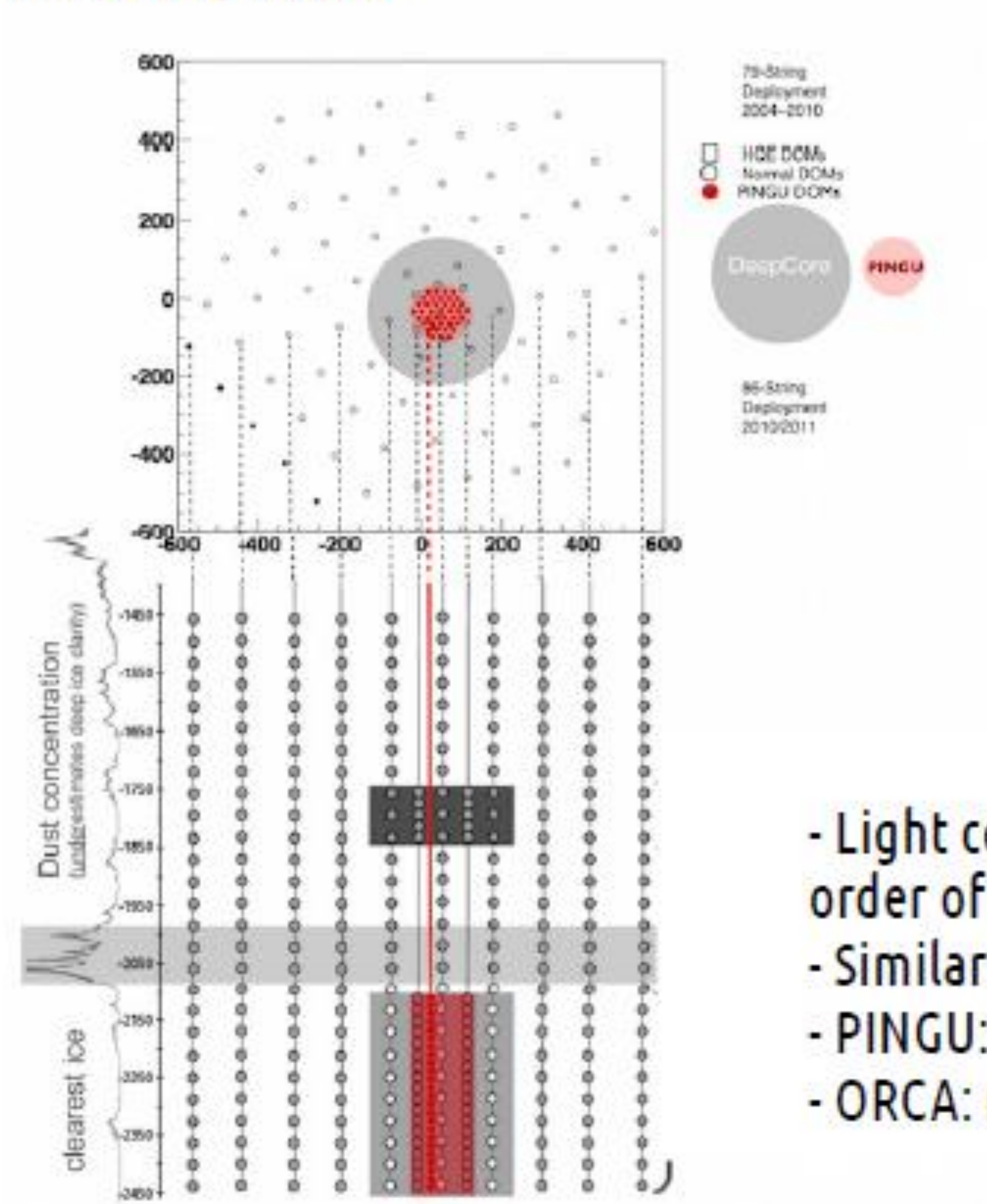
- *And don't forget: particle physics (oscillation physics, ...) !*

END

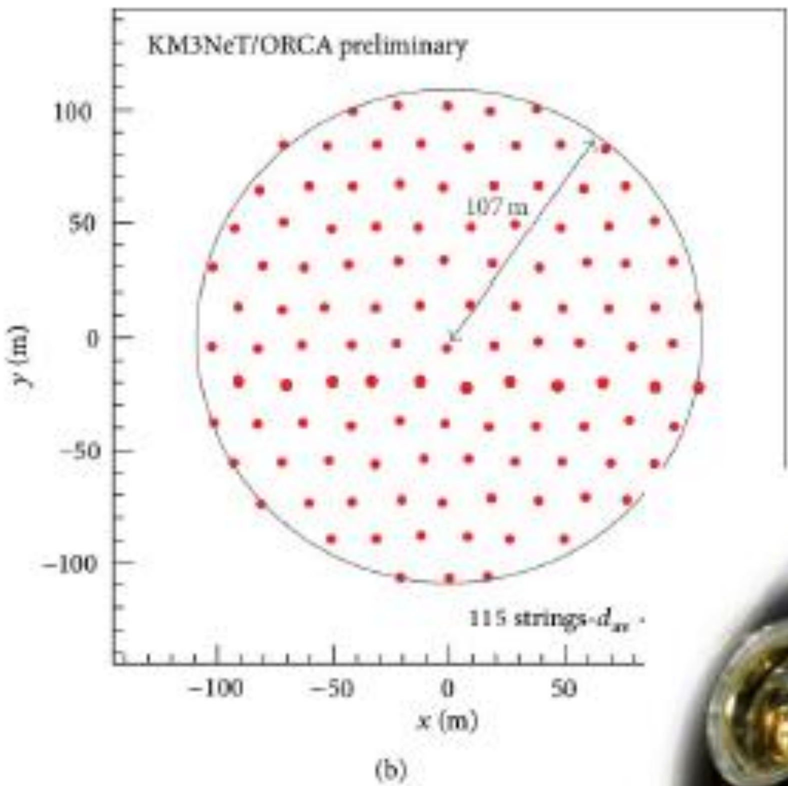
DESY

PINGU and ORCA

- Precision IceCube Next Generation Upgrade (PINGU – IceCube Gen2)
  - Deploy additional 40x96 DOMs
  - Spacing 20x3m

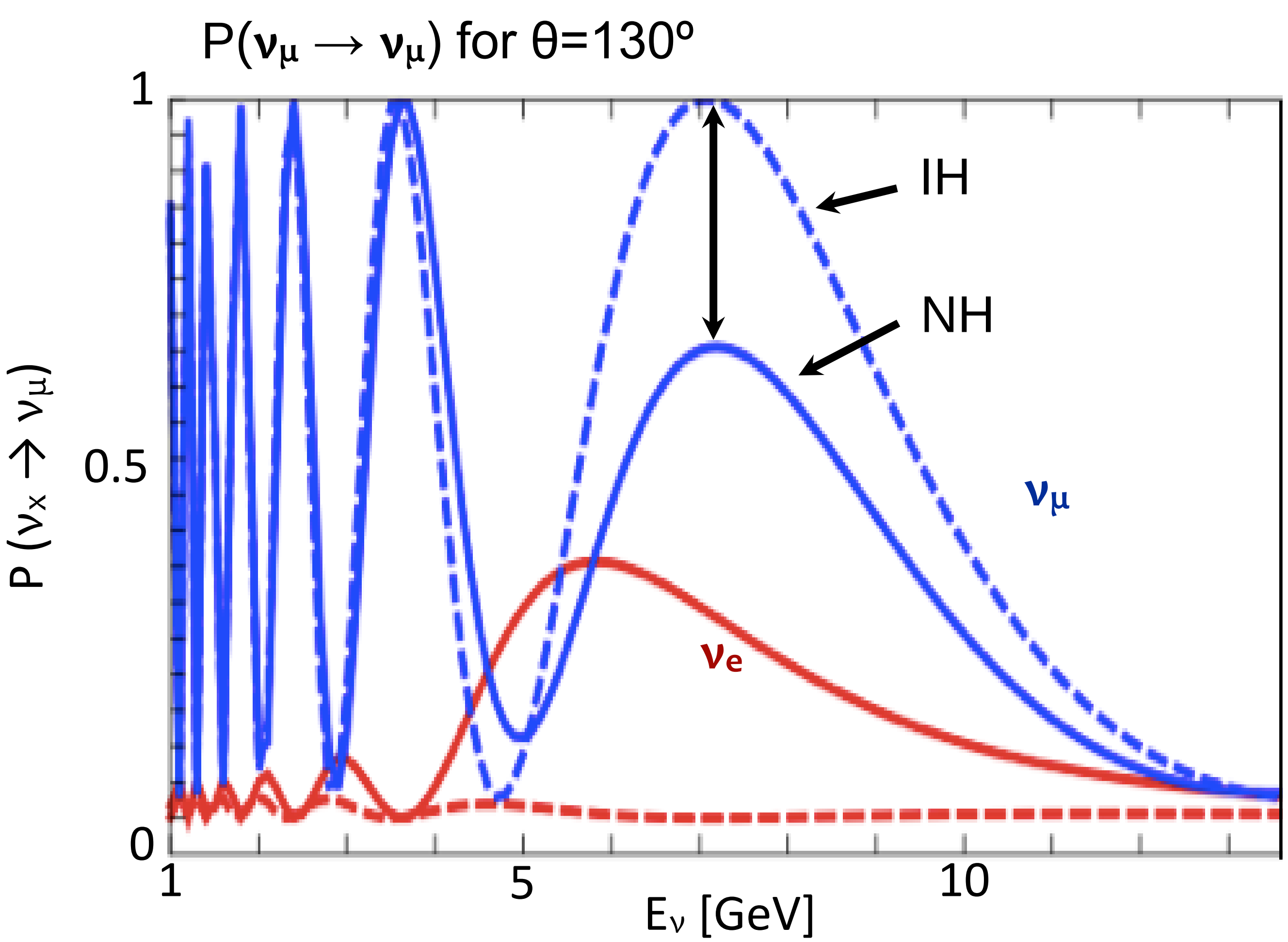


- Oscillations Research with Cosmics in the Abyss (ORCA – Km3NeT)
  - Deploy new 115x18 multiOMs
  - Spacing 20x6m



- Light collection increased by an order of magnitude
- Similar instrumented volume
- PINGU: relying on IC veto
- ORCA: not using a veto

NMH via Matter Oscillations in the Earth

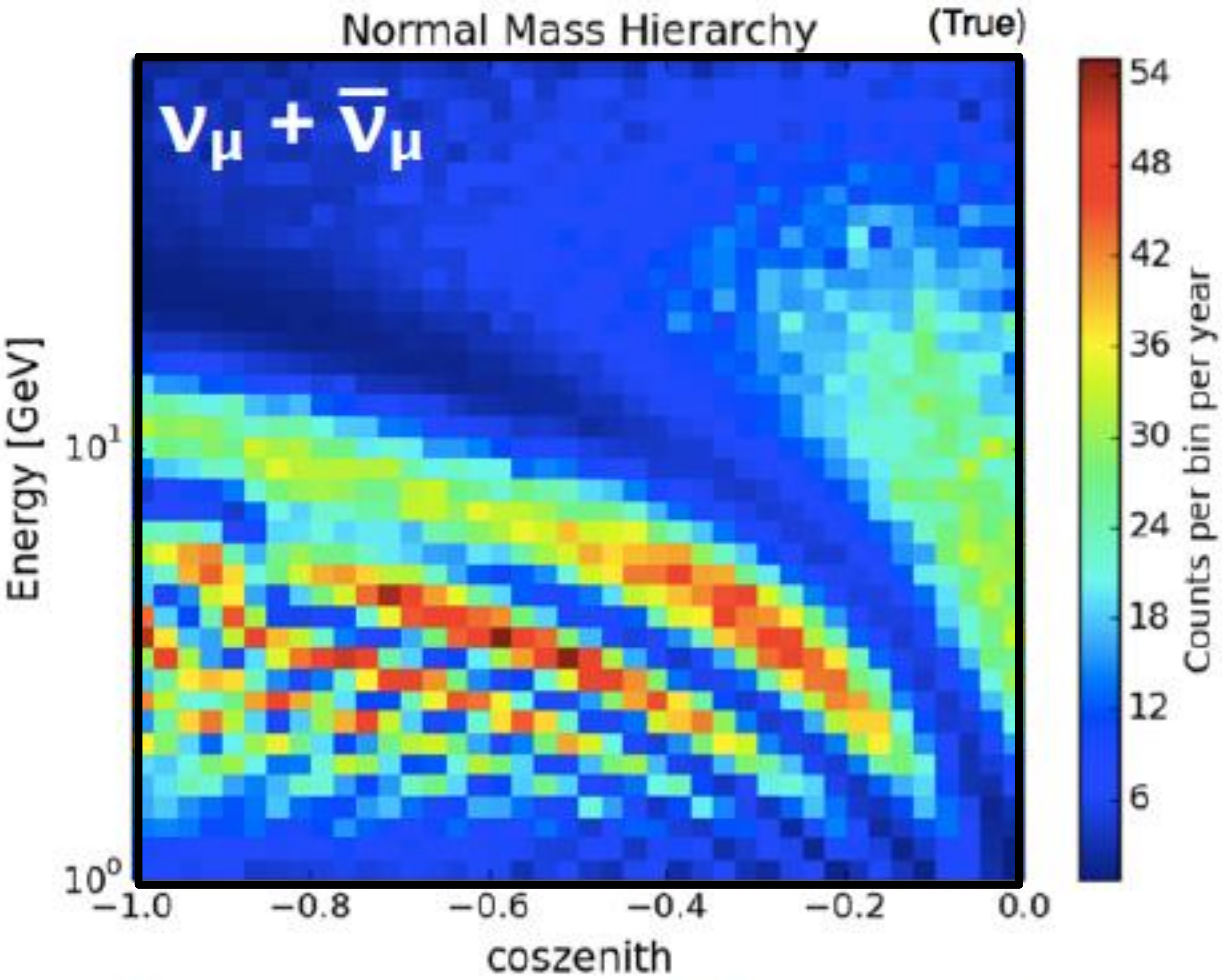


Akhmedov et al., arXiv:1205.7071

- Maximum difference NH ↔ IH for $\theta = 130°$ at 7 GeV
- For anti-ν, NH and IH are approximately swapped → effect cancels if ν and anti-ν have equal fluxes and cross sections and if the detector cannot distinguish μ^+ and μ^-
- However: flux of atm.ν ~ 1.3 × flux of atm. anti -ν

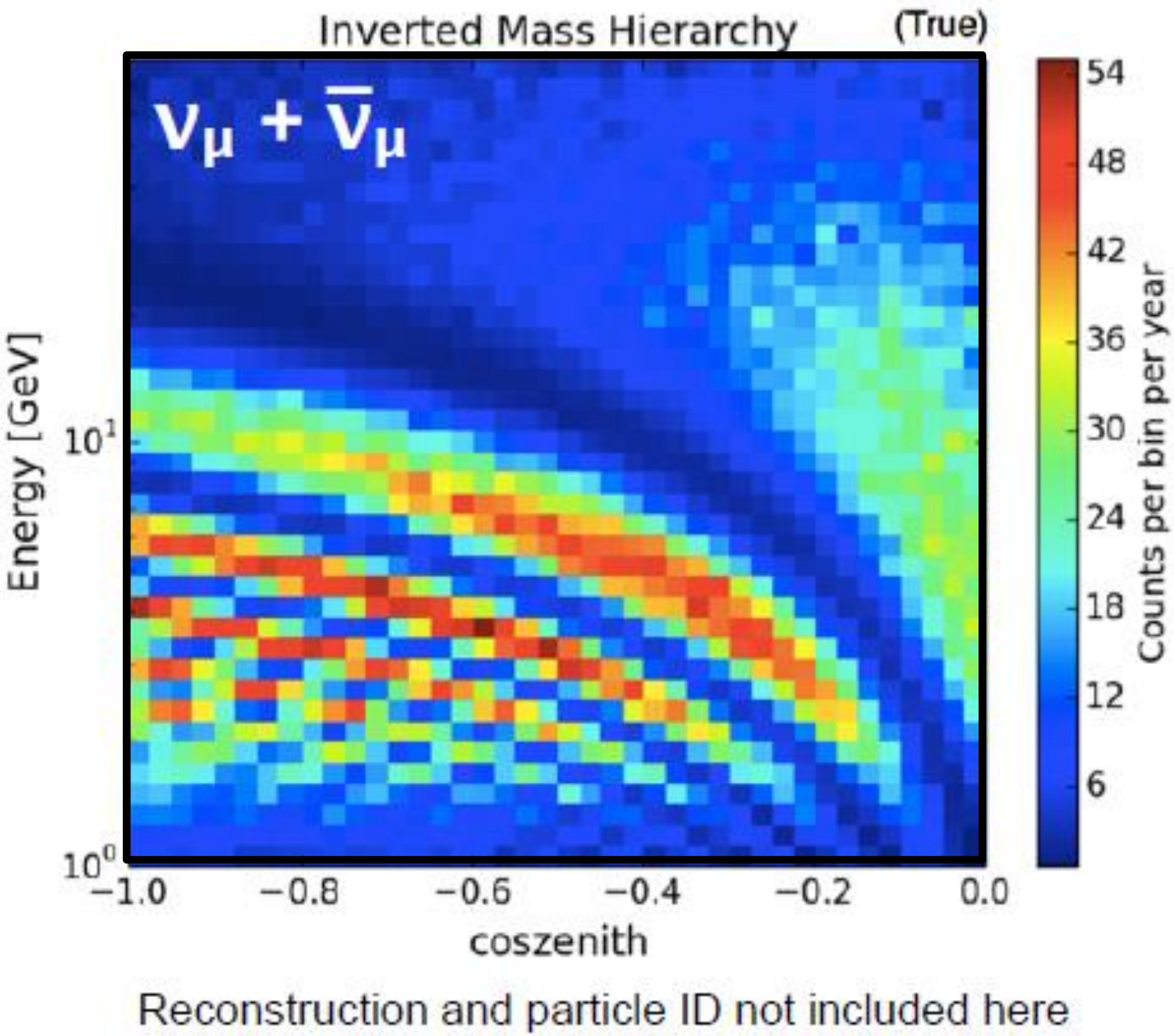
  and $\sigma(\nu)$ ~ 2 × σ(anti-ν) at low energies
- **→ Count $N_\mu(\theta, E)$ from ν_μ + N →μ + X and compare with NH/IH predictions**

NMH via Matter Oscillations in the Earth

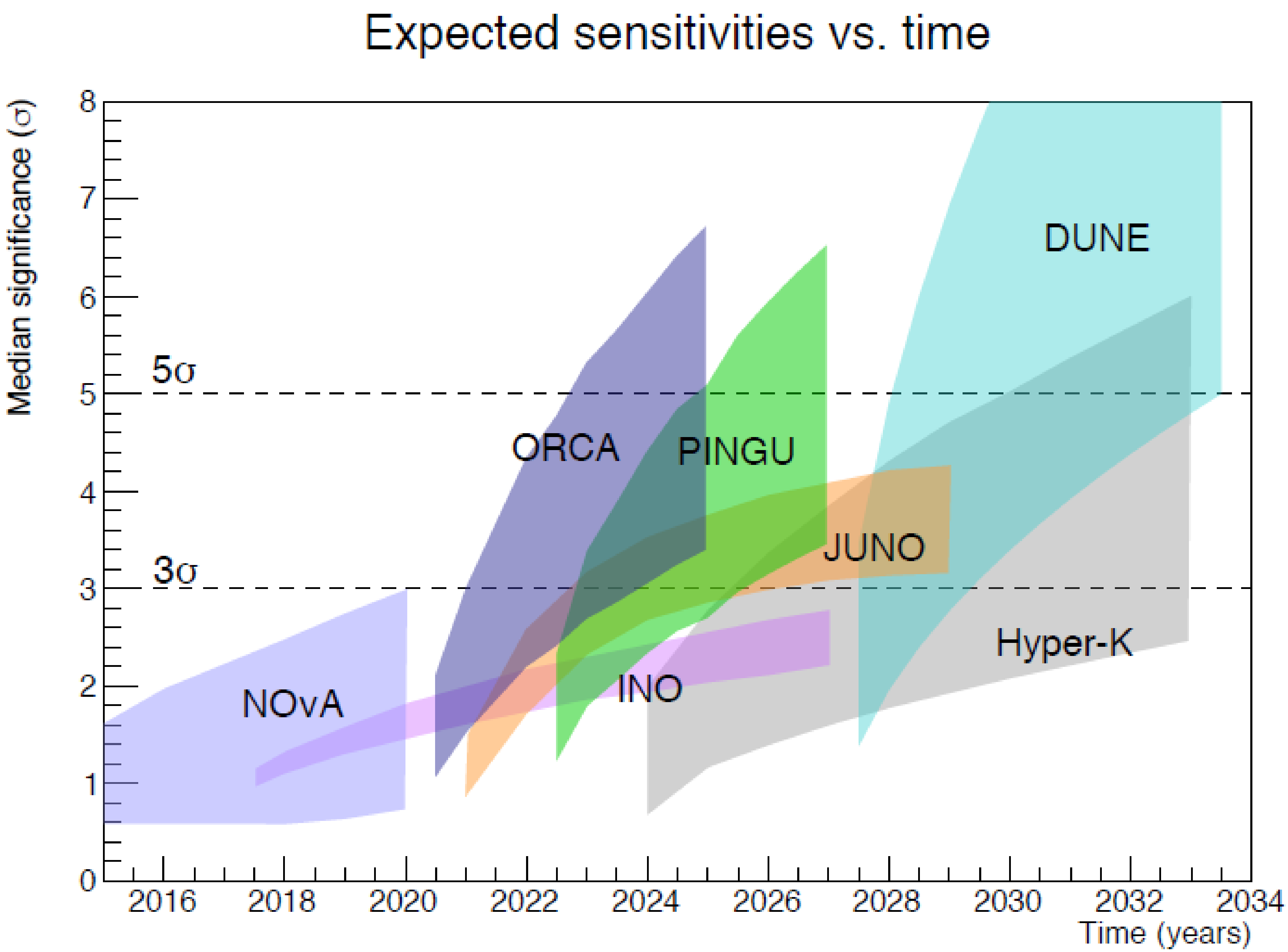


Reconstruction and particle ID not included here

NMH via Matter Oscillations in the Earth



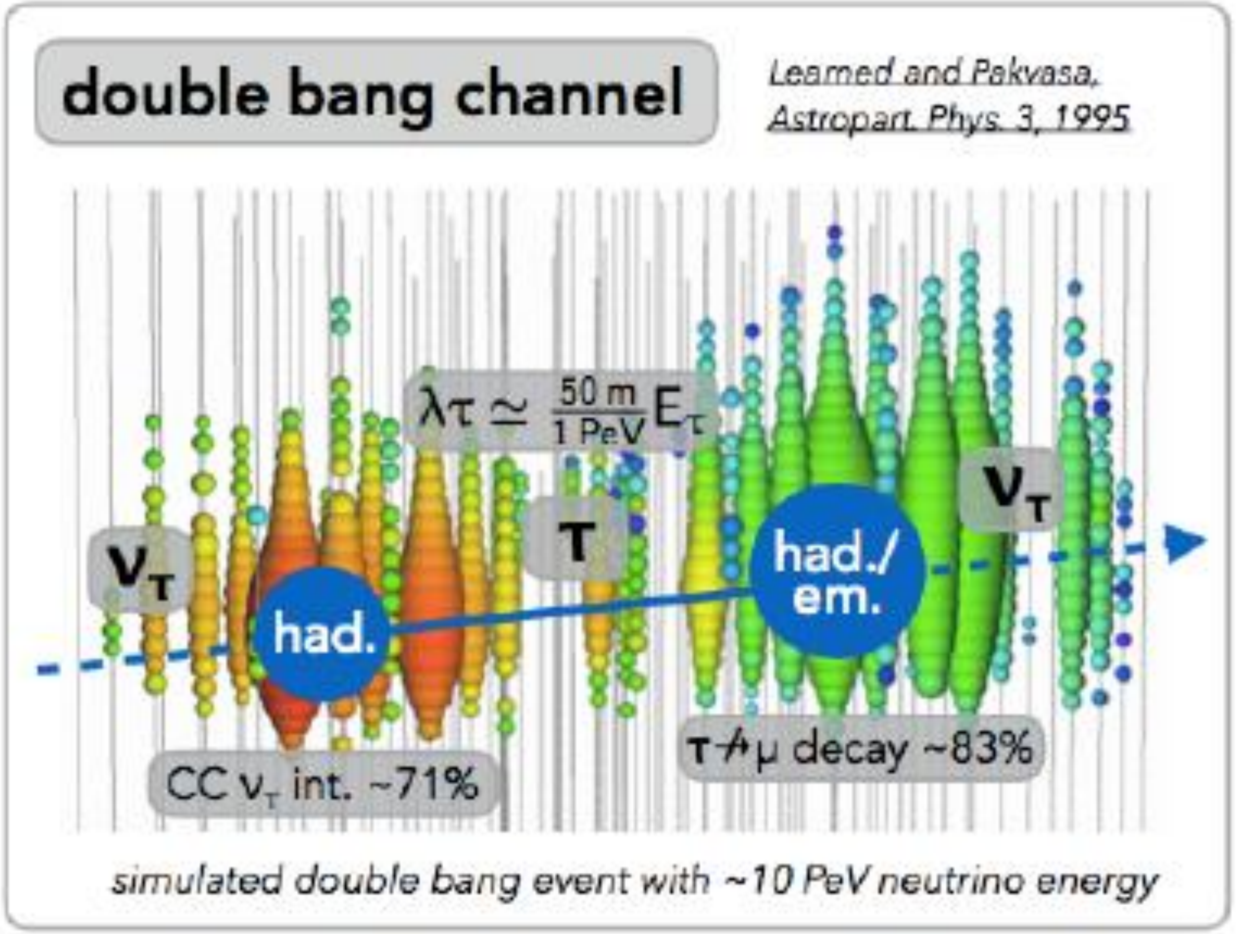
NMH by different experiments

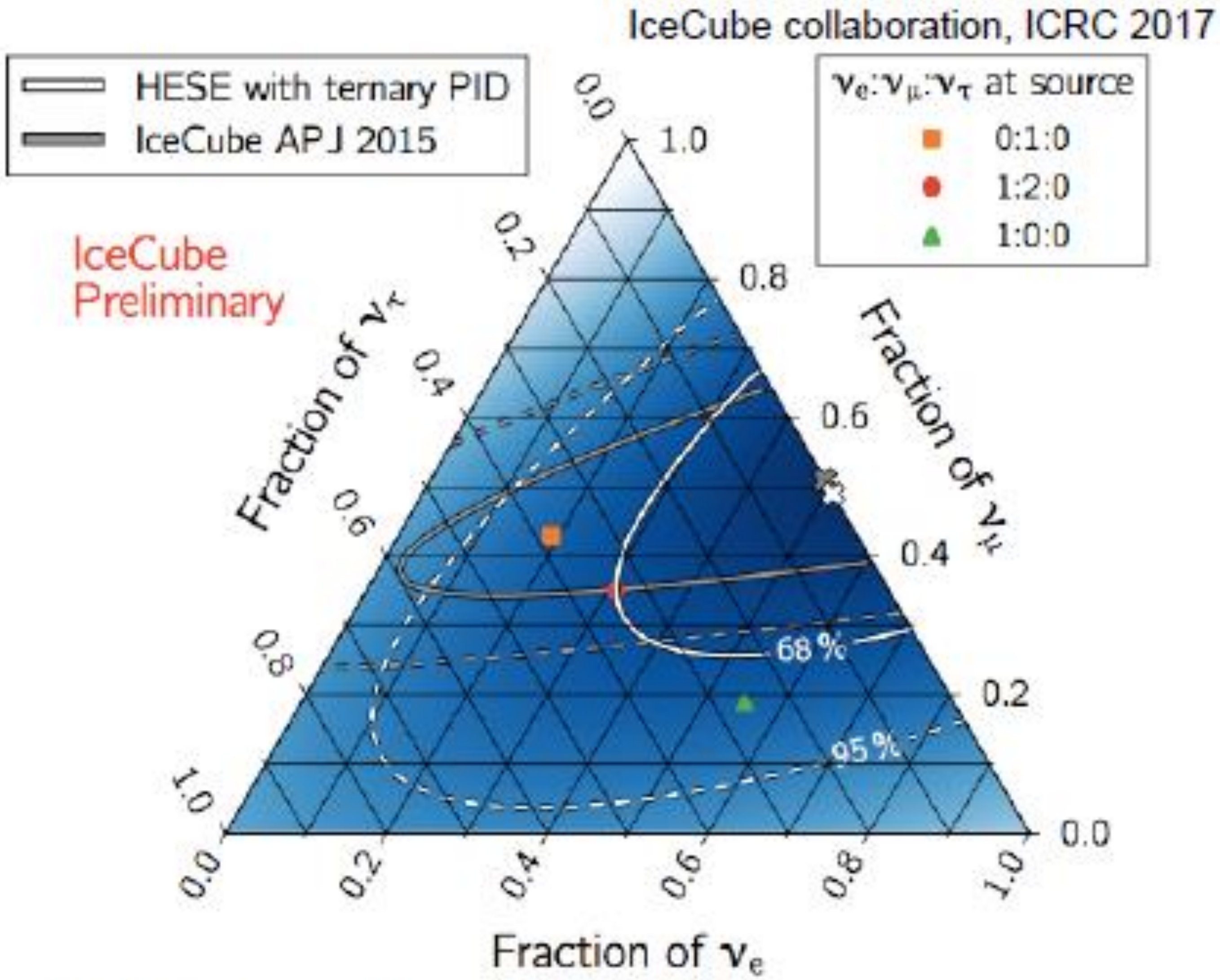


NMH sensitivity of ORCA/PINGU depends on the octant of θ_{23} (lower values for 1st octant), that of JUNO on energy resolution (lower values for 3.5%, upper for 3%), that for DUNE on the δ_{CP} value.

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

Search for astrophysical tau neutrinos





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

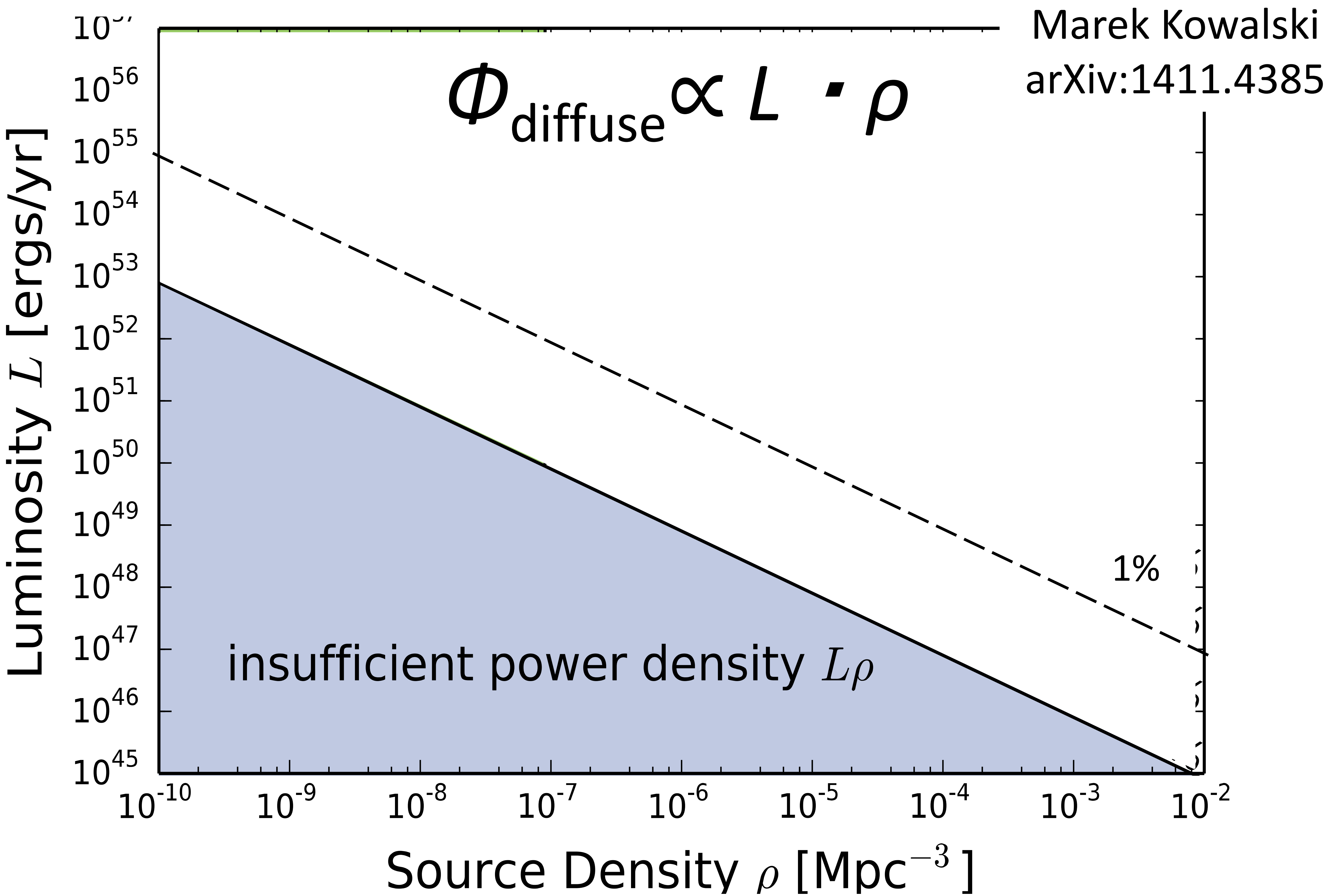
Φ(E) diff. unfolding

$N_{sig} = 1.441^{+0.024}_{-0.018}$

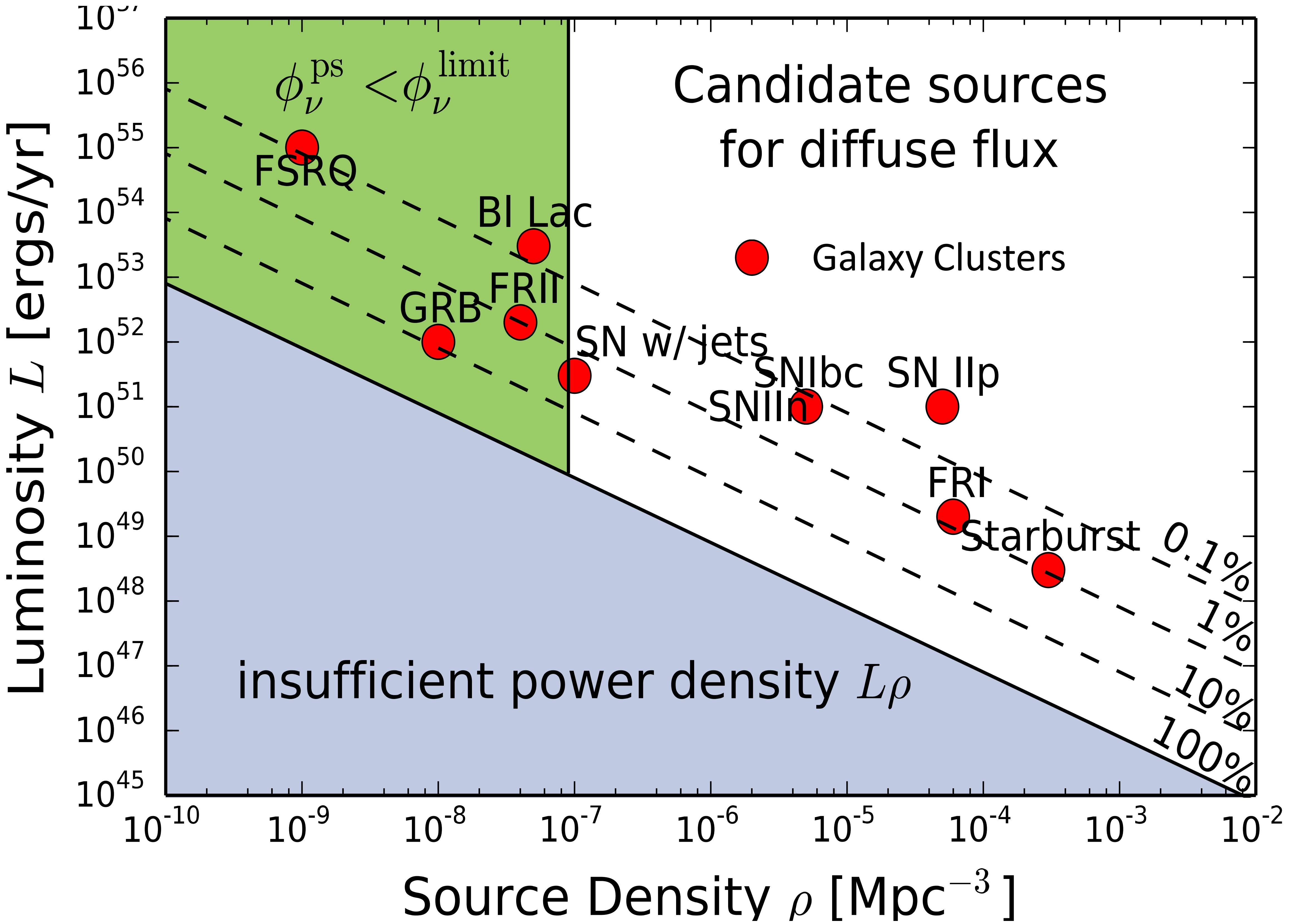
$N_{bg} = 0.938^{+0.219}_{-0.092}$

- Search for characteristic ν_τ signature
- Sensitive to ν_τ with E > 100 TeV
- No tau neutrino candidate found in starting event sample. Consistent with fluctuation.
- Future analysis will be extended to other data samples: up to 50% more expected ν_τ candidates

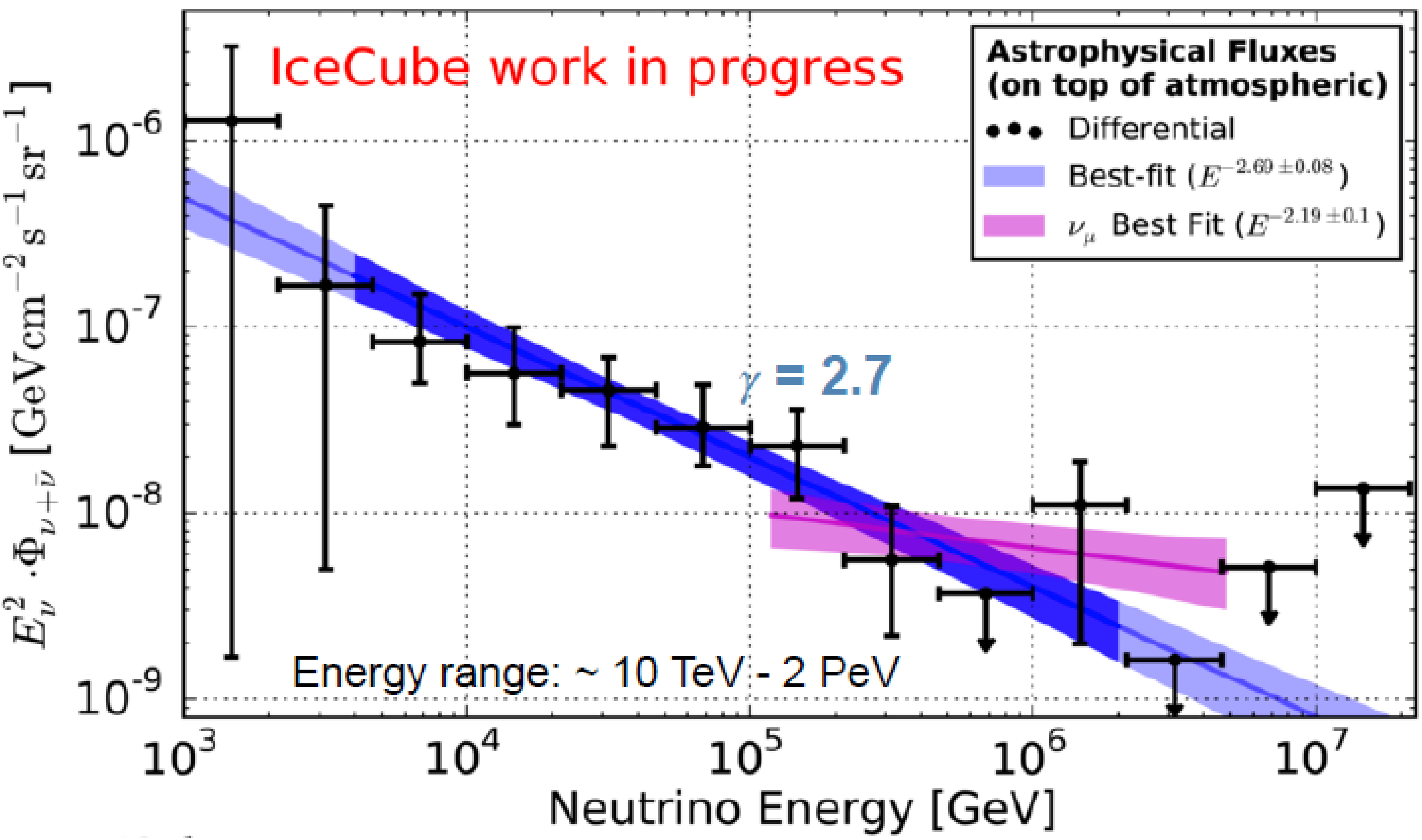
Resolving the sources of the diffuse flux



Resolving the sources of the diffuse flux

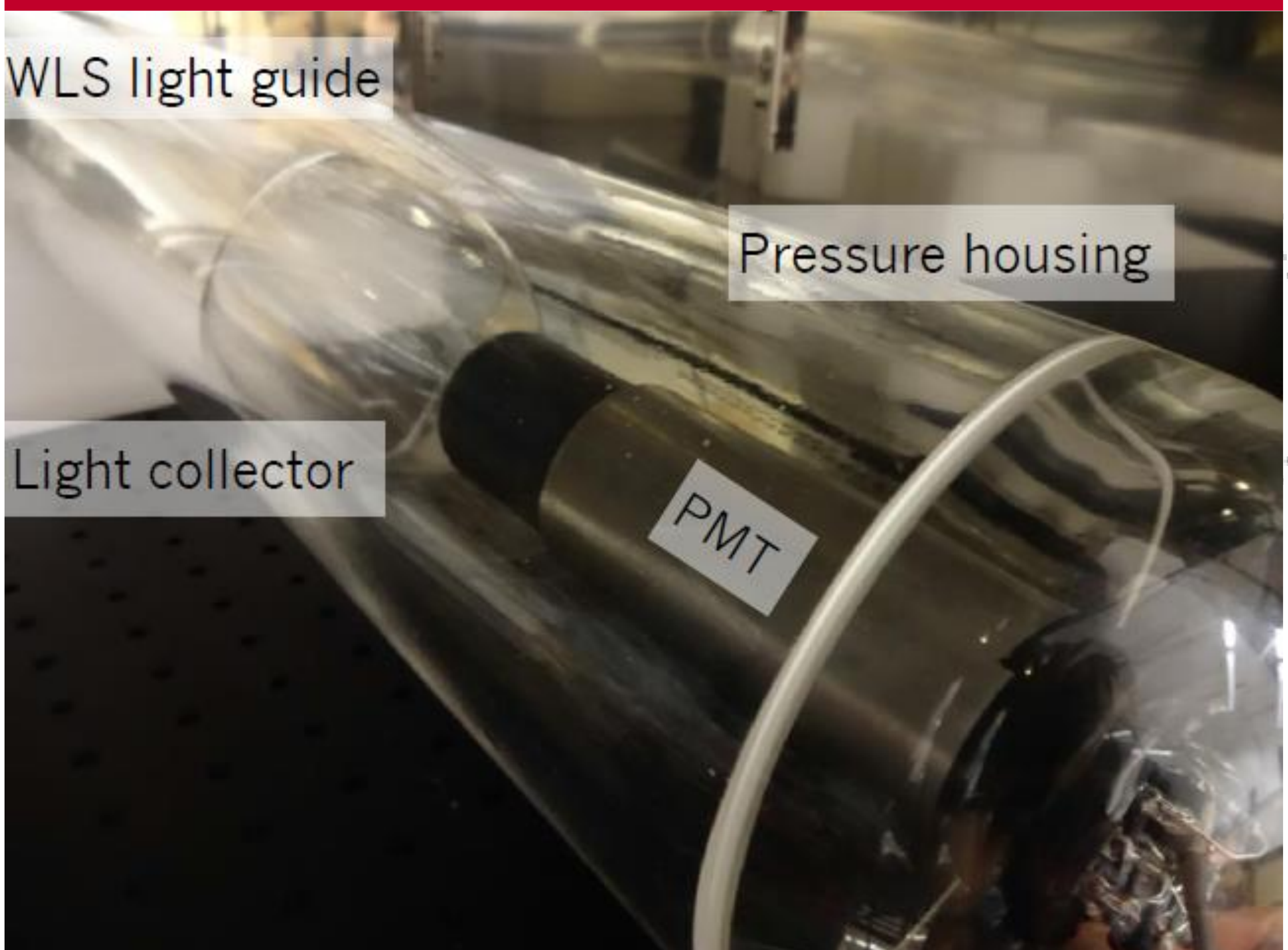


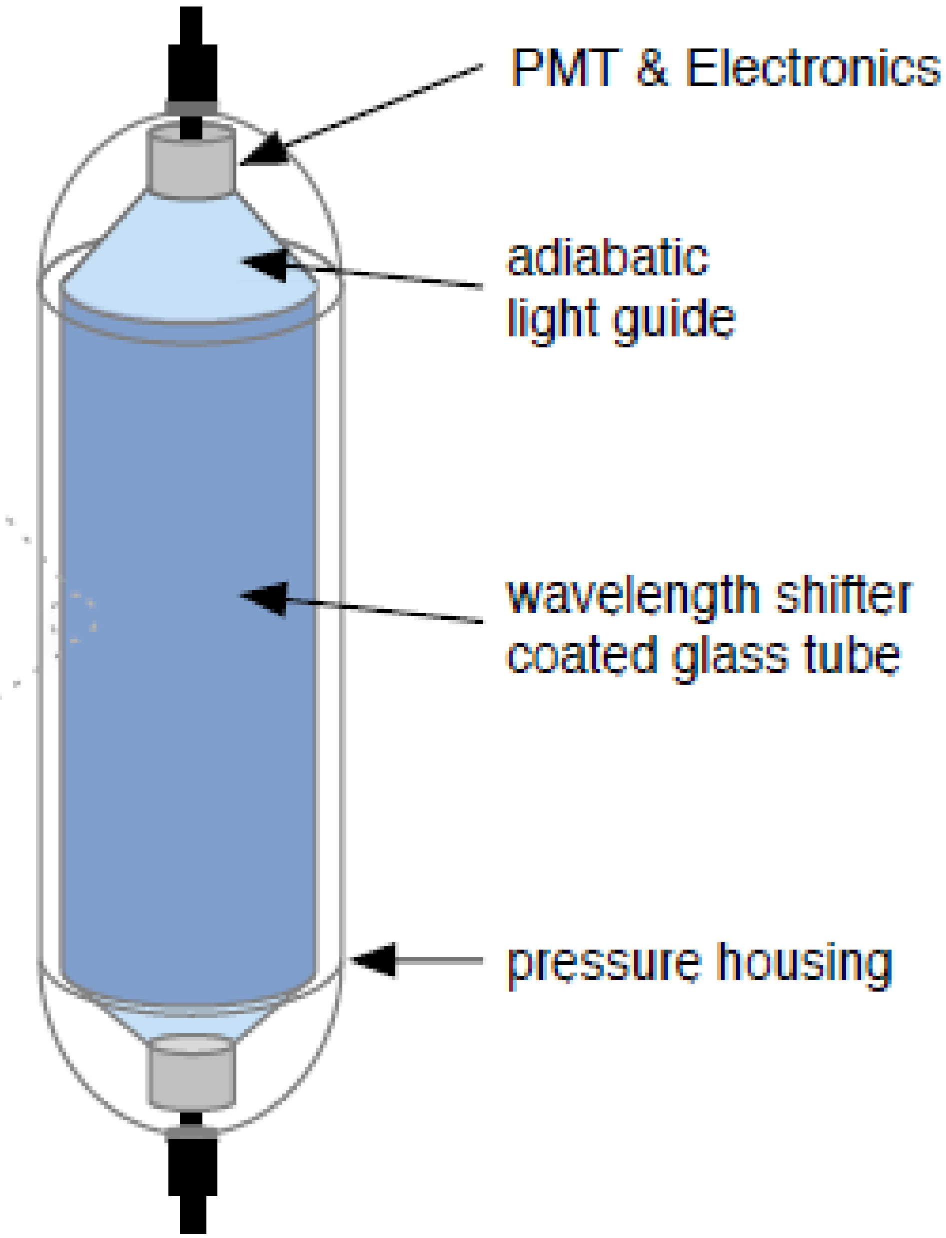
Spectrum: throughgoing muons starting events, HESE



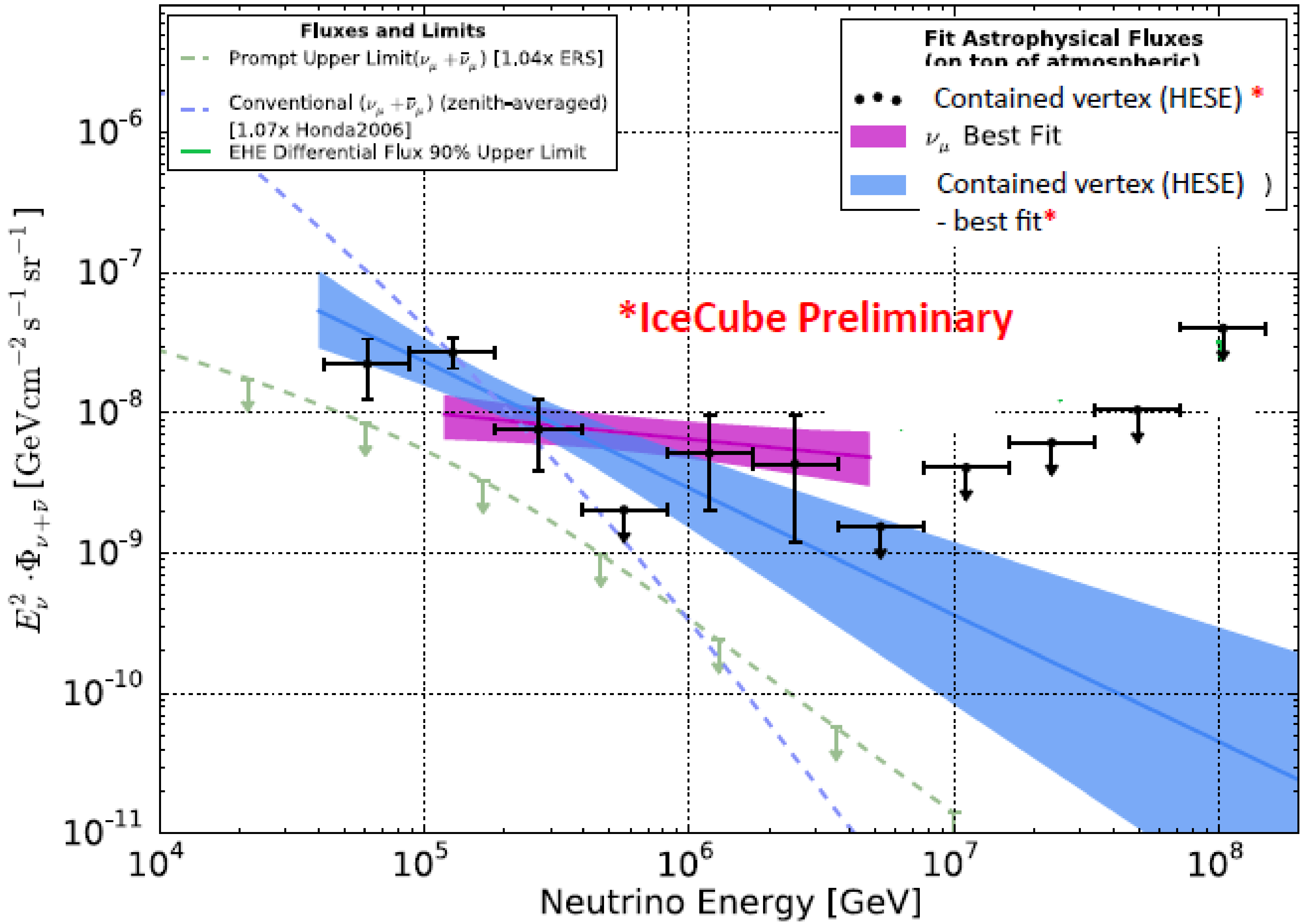
Optical Modules (4): The WOM

Wavelength-shifting Optical Module (WOM)

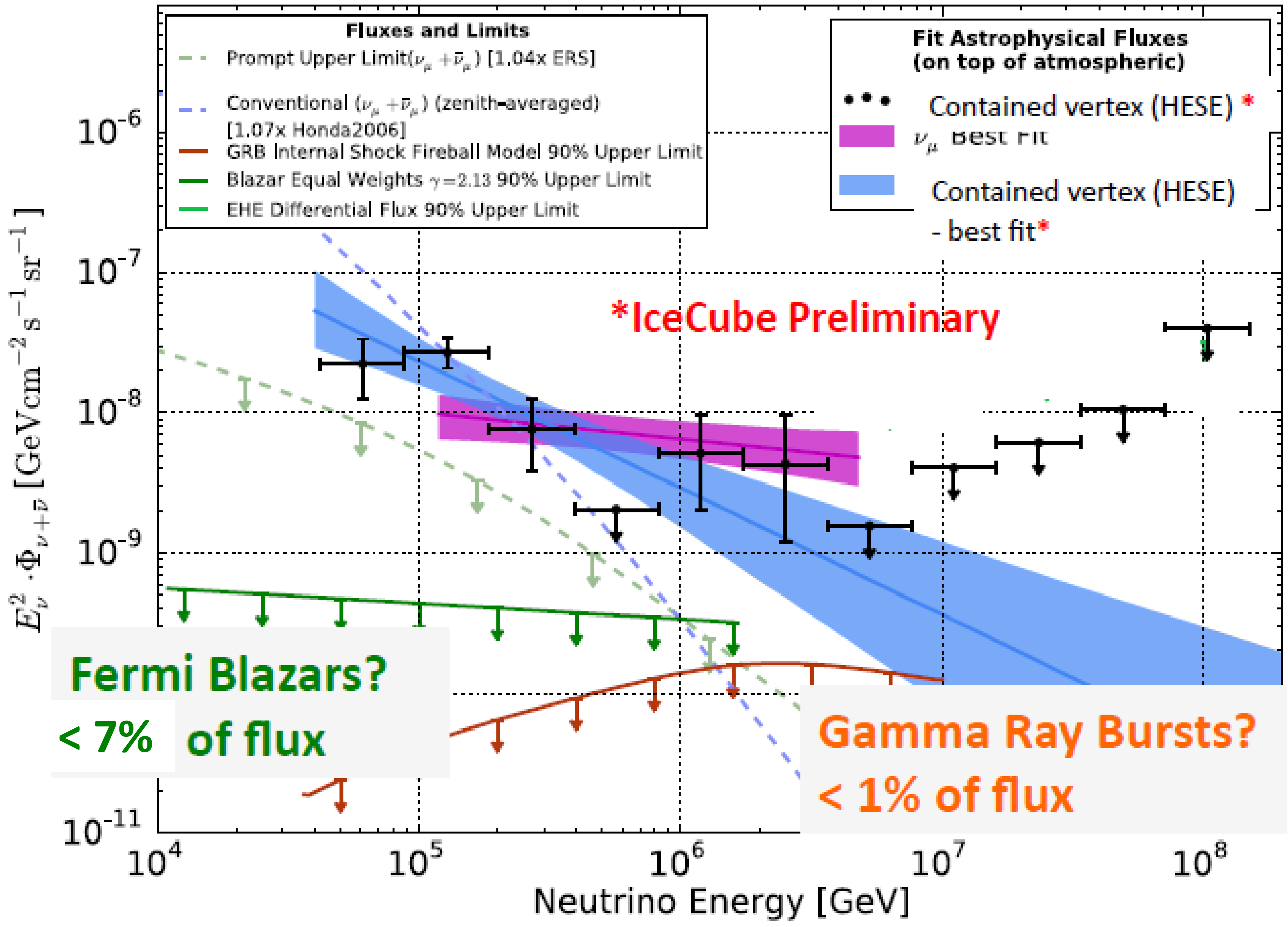




Resolving the sources of the diffuse flux



Resolving the sources of the diffuse flux



IceCube 7 years

Sensitivities and upper limits

Point-source equivalent flux, if the diffuse astrophysical flux (see later) came from: