High-energy ν astronomy

Results and Perspectives

October 1, 2020

Christian Spiering, DESY Zeuthen

36 ВСЕРОССИЙСКАЯ КОНФЕРЕНЦИЯ ПО КОСМИЧЕСКИМ ЛУЧАМ

Neutrino Telescopes

Physics Goals

Physics with neutrino telescopes

- Search for the sources of high-energy cosmic rays
- Dark Matter and Exotic Physics
  - WIMPs
  - Magnetic Monopoles and other superheavies
  - Violation of Lorentz invariance
- Neutrino and Particle Physics
  - Neutrino oscillations
  - Charm physics
  - Cross sections at highest energies
- Supernova Collapse Physics
  - MeV neutrinos in bursts $\rightarrow$ early SN phase, neutrino hierarchy, ...
- Cosmic Ray Physics
  - Spectrum, composition and anisotropies, shadows of moon and Sun

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$$p + \text{target} \rightarrow \pi^+ + \;.....$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

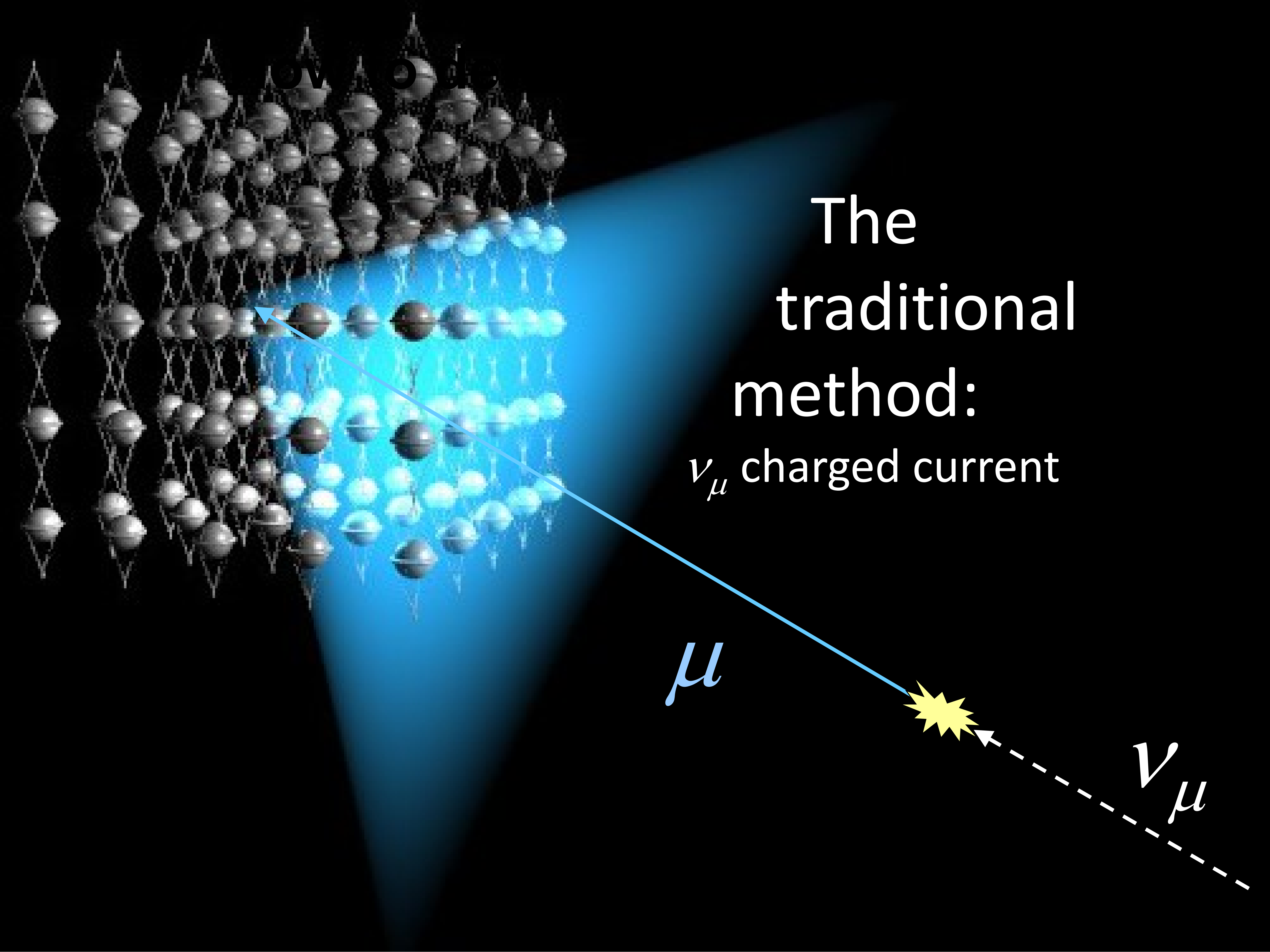
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

at source: $\nu_e : \nu_\mu : \nu_\tau = 1:2:0$

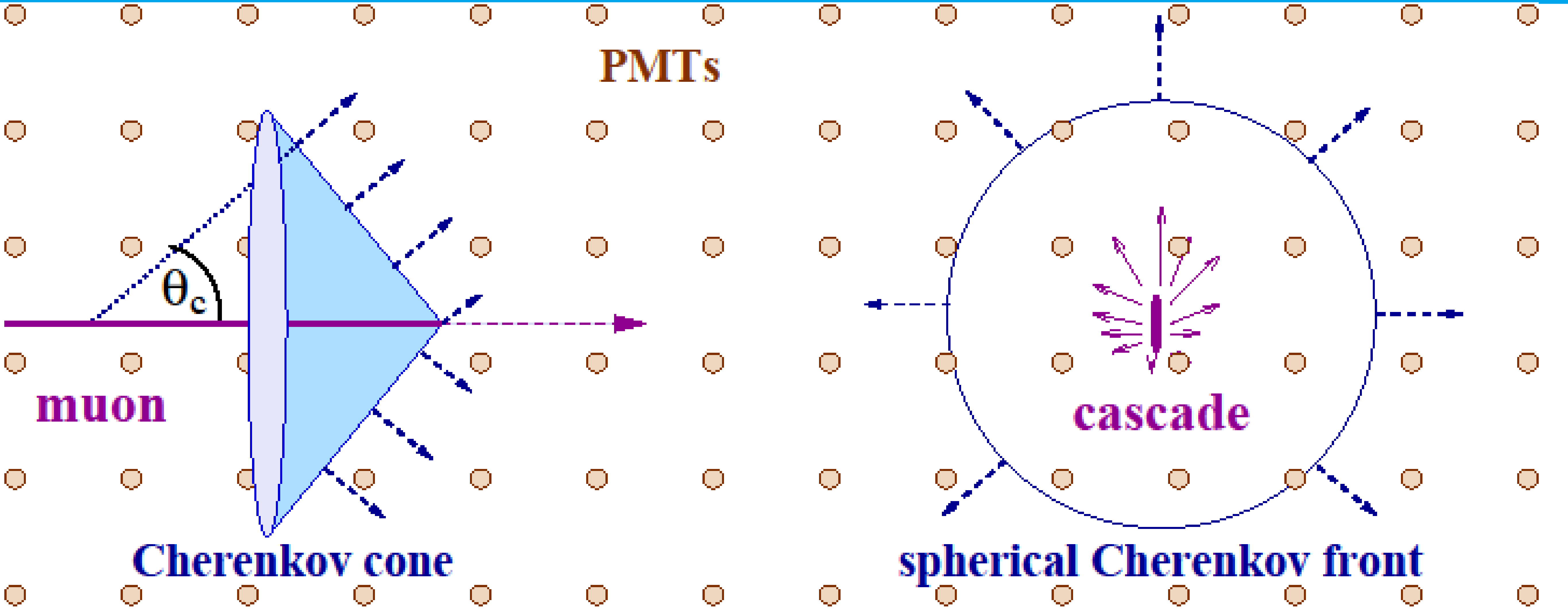
at Earth: $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$

Neutrino Telescopes

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

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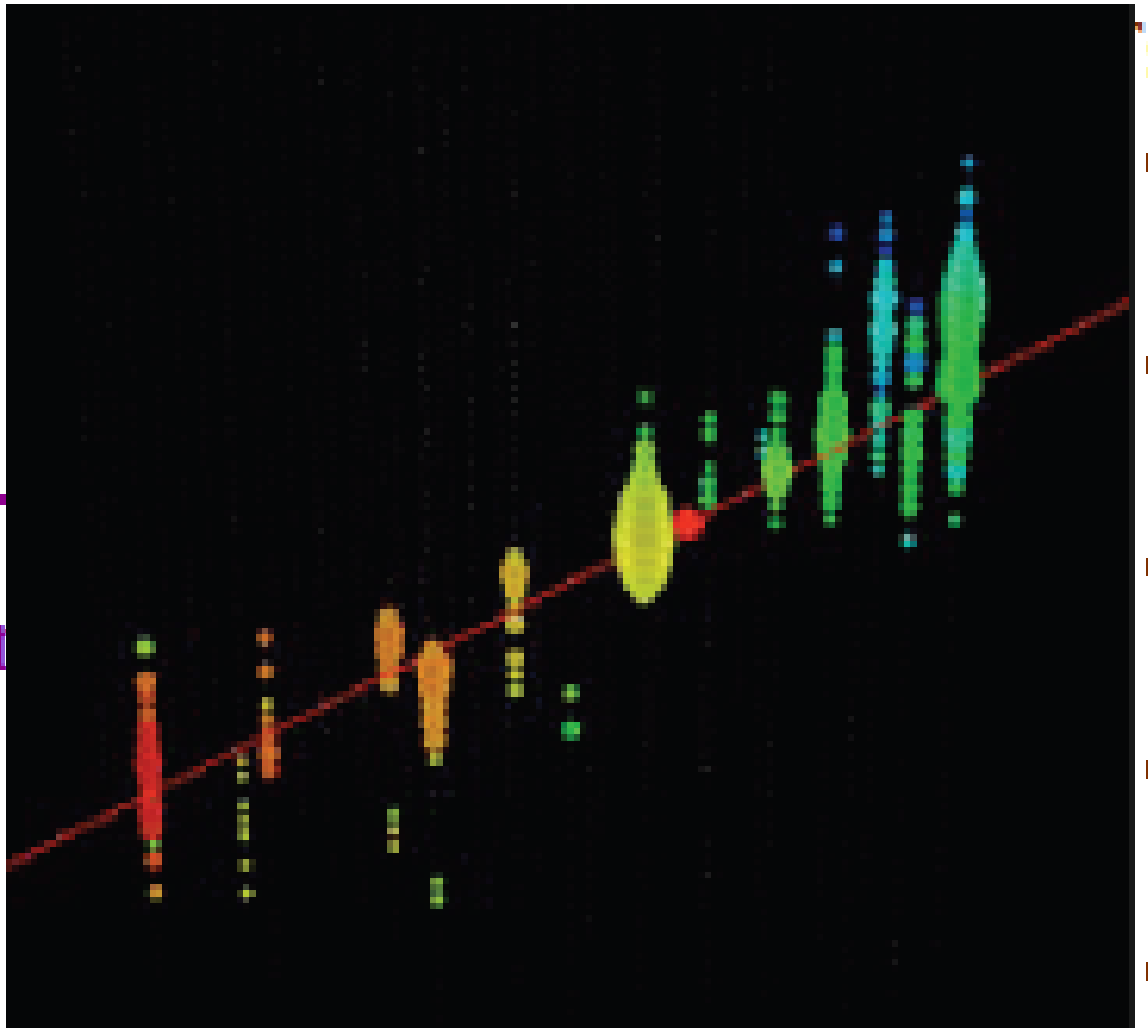

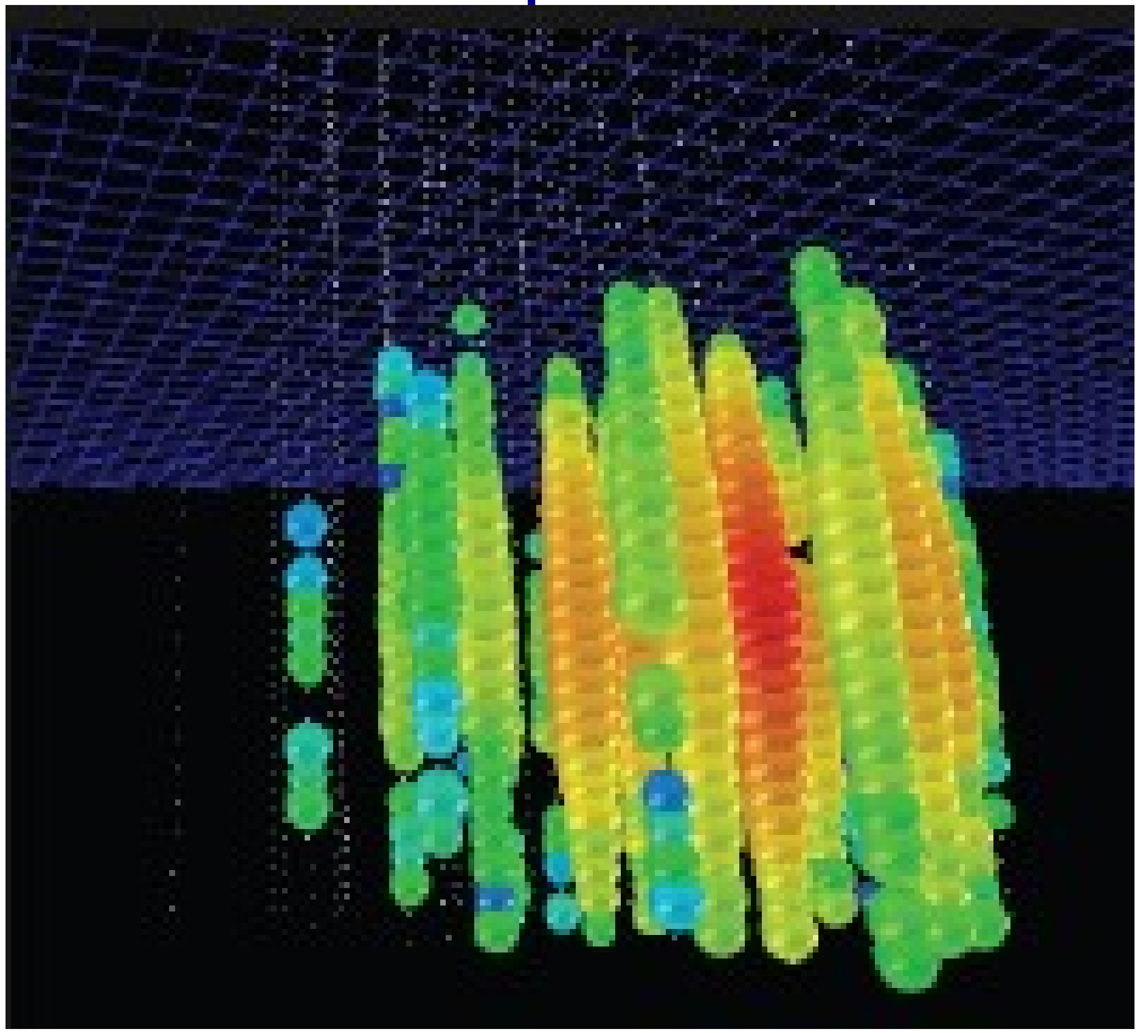

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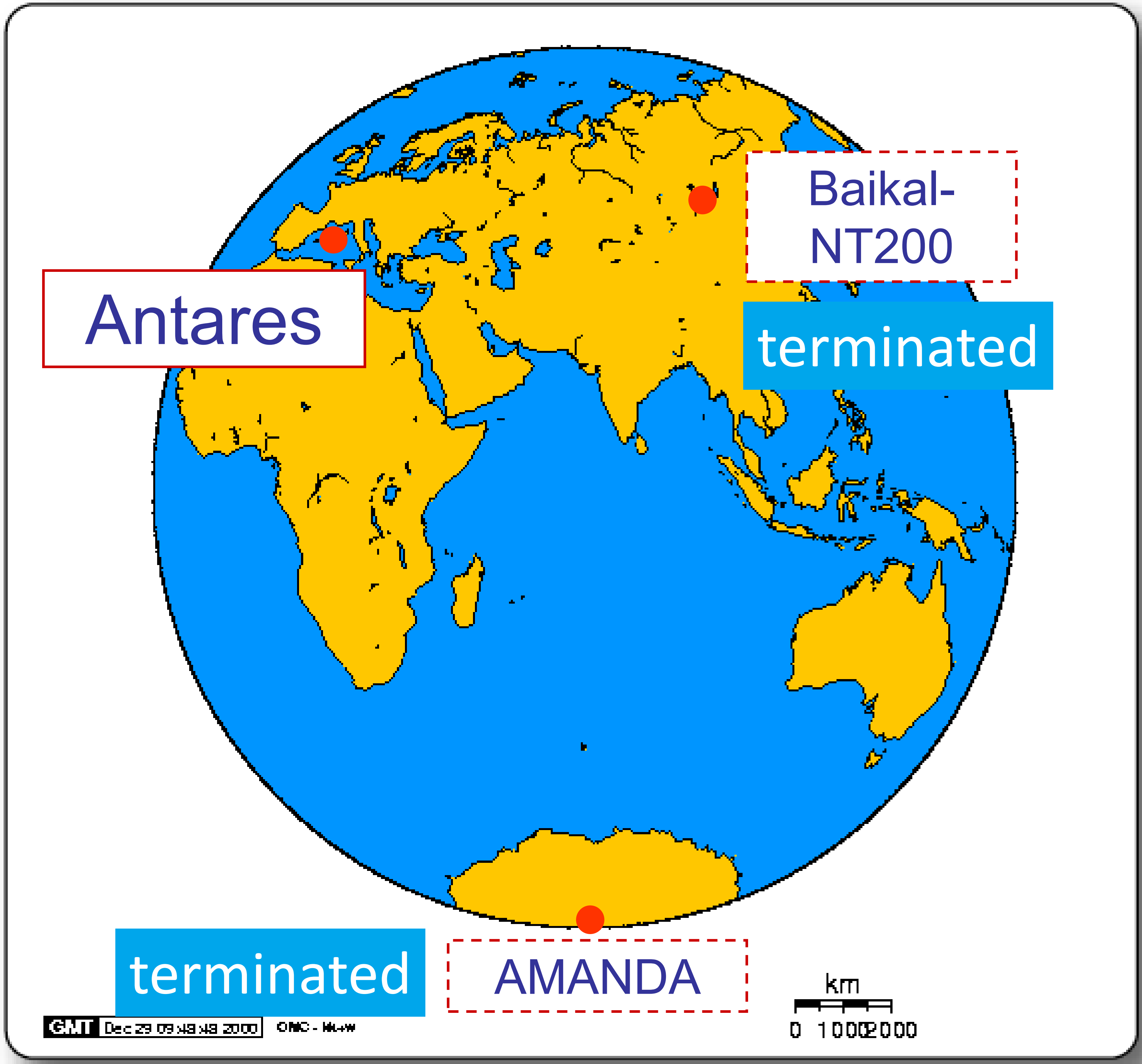
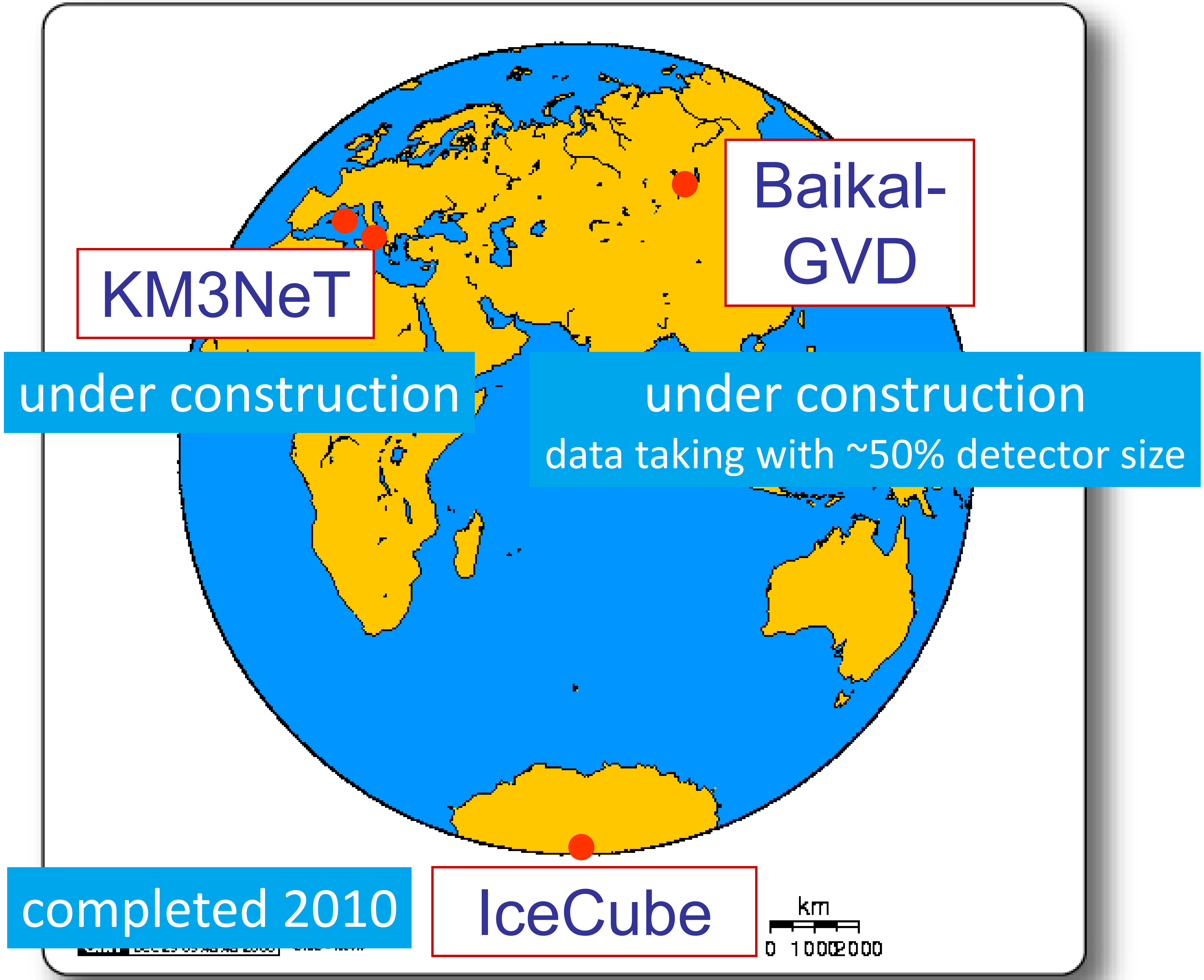
Neutrino Telescopes

The Detectors

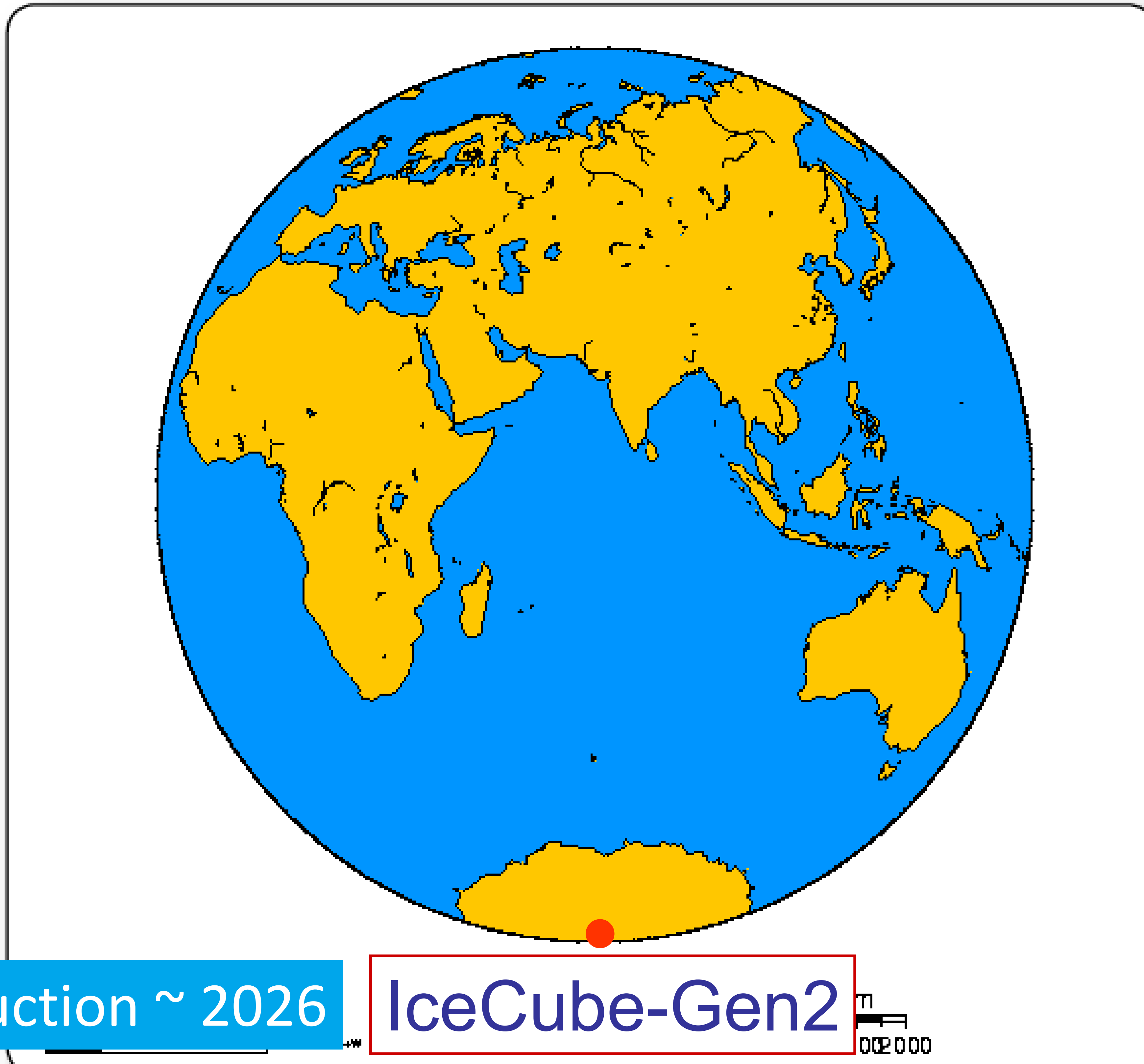
Generation-1 devices (0.002-0.02 km^3)



Generation-2 devices (km^3 scale)

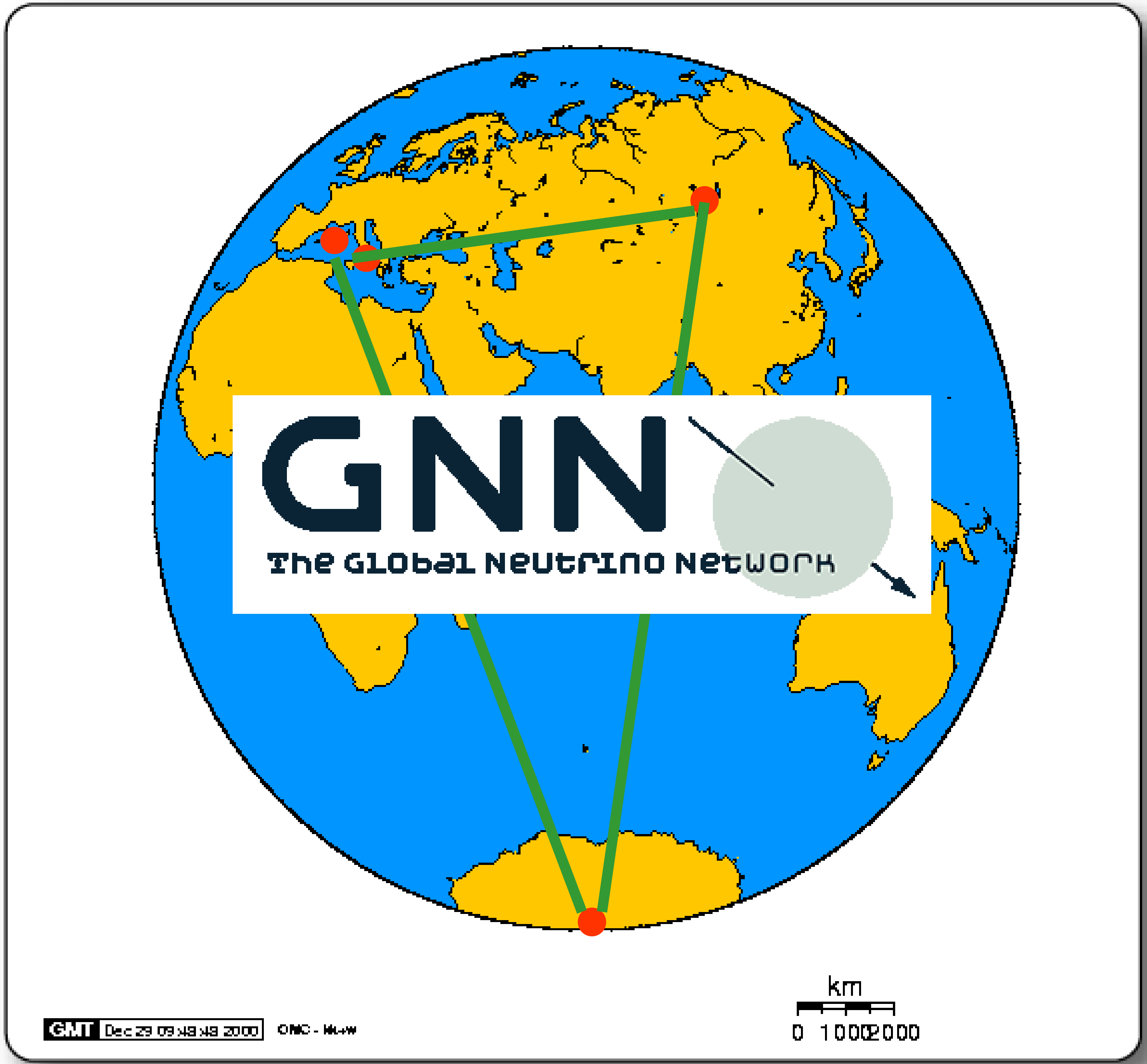


Generation-3 device (10 km^3 scale)



Start construction ~ 2026

Worldwide Common Effort



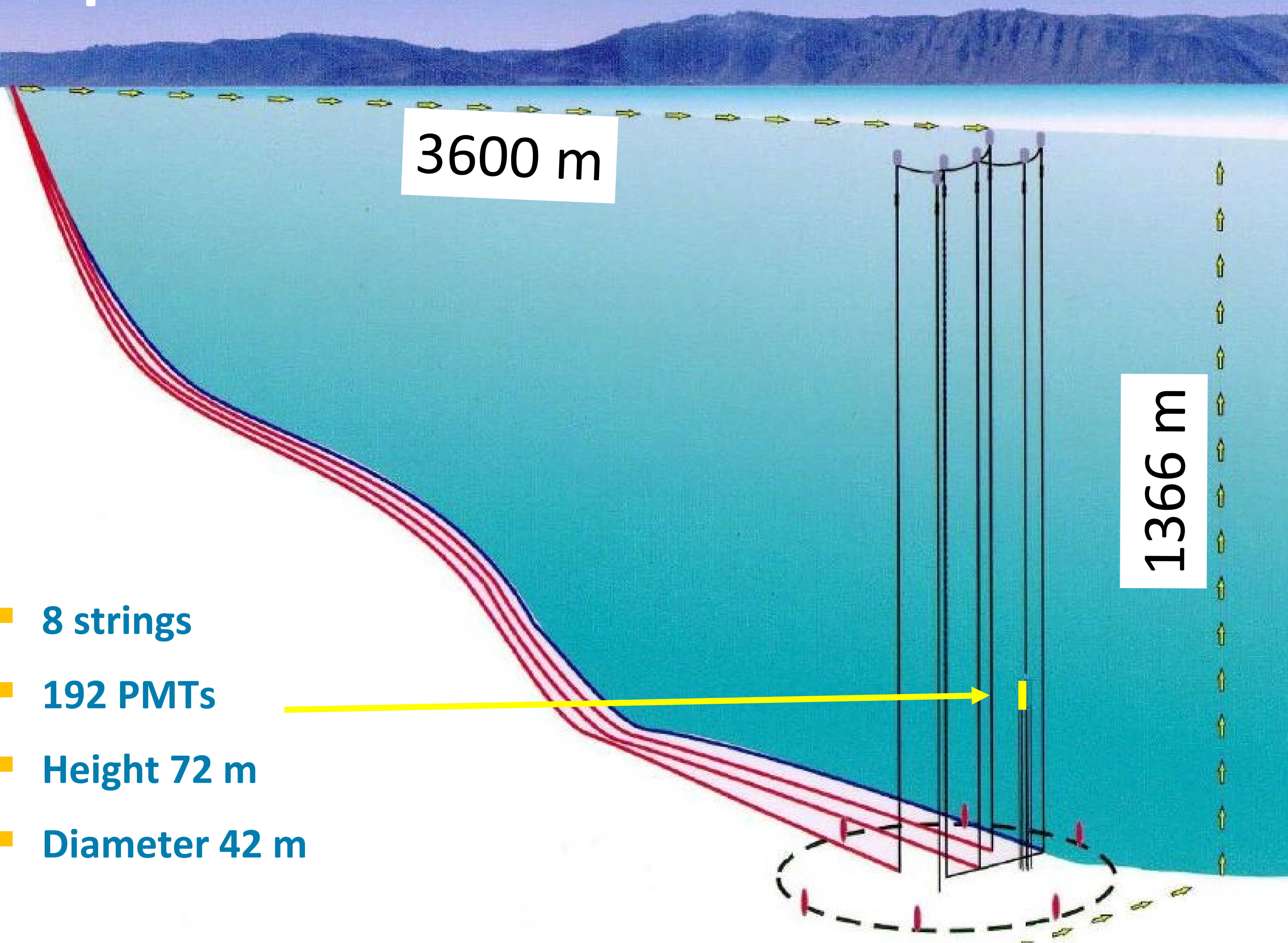
Worldwide Common Effort

GNN

The Global Neutrino Network

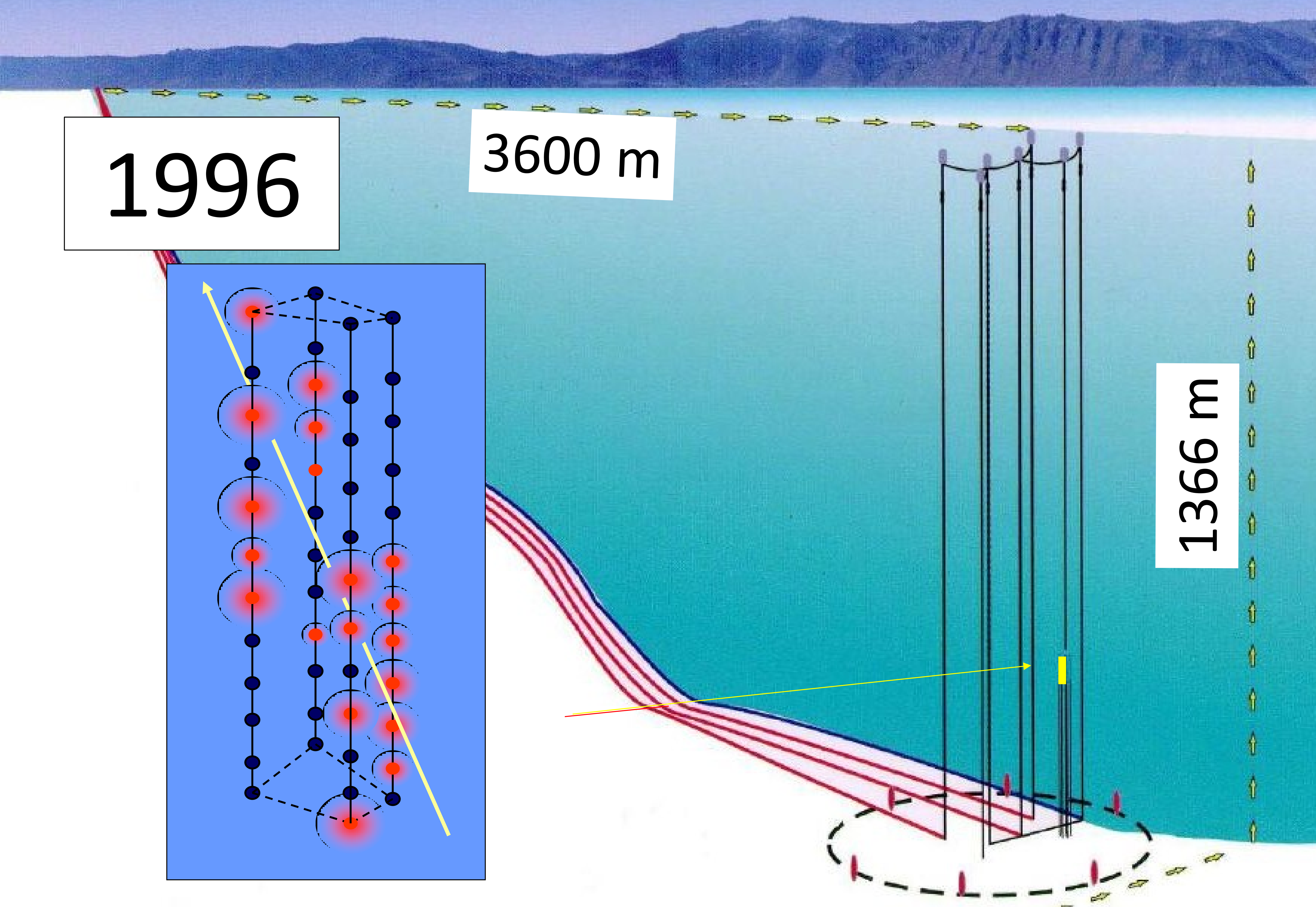
- Exchange knowledge, software, people
- Develop common strategy
- Combine data (skymaps, ..)
- Cross check of results
- Cooperate in multimessenger and alert programs
- Topical Workshops
- Monthly Newsletter

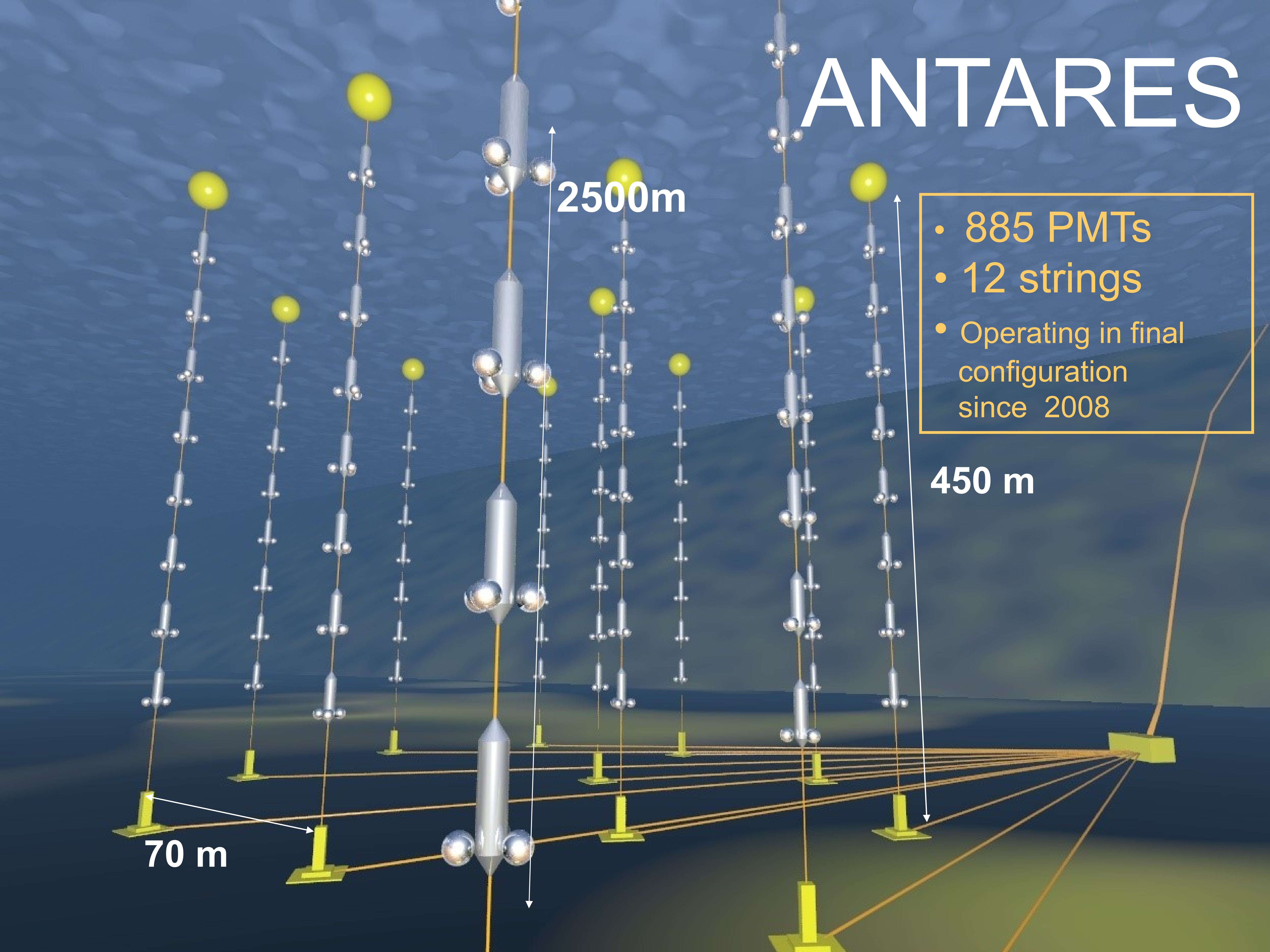
The pioneer: NT200 in Lake Baikal



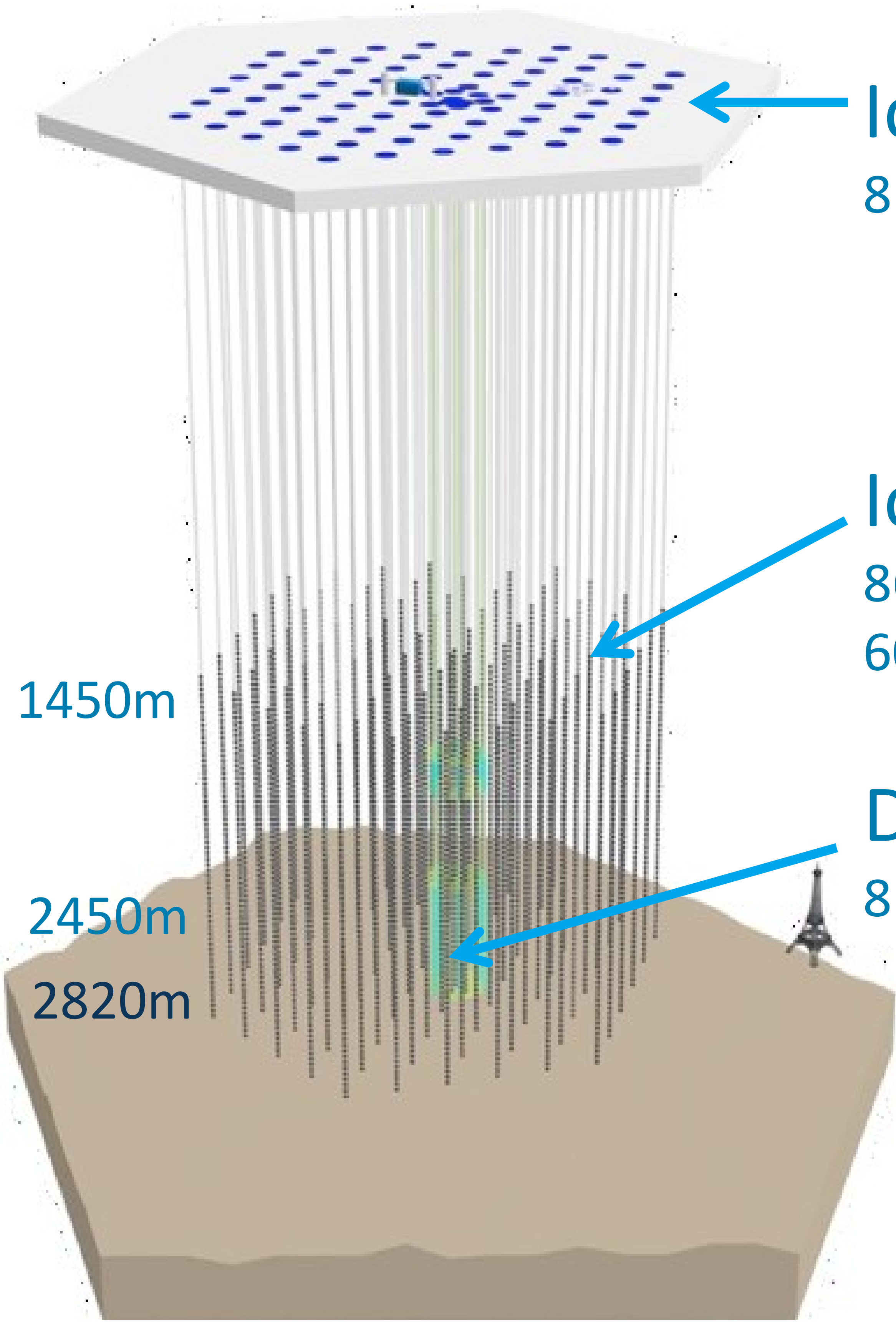
- 8 strings
- 192 PMTs
- Height 72 m
- Diameter 42 m

A textbook underwater neutrino event




ANTARES
2500m
• 885 PMTs
• 12 strings
• Operating in final configuration since 2008
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

Cosmic Rays and Atmospheric Muons

Cosmic Rays and Atmospheric Muons

- **Spectrum of Cosmic Rays** (air showers with IceTop)
- **Spectrum, Composition and Anisotropies of Cosmic Rays** (muons with IceCube, air showers with IceTop)

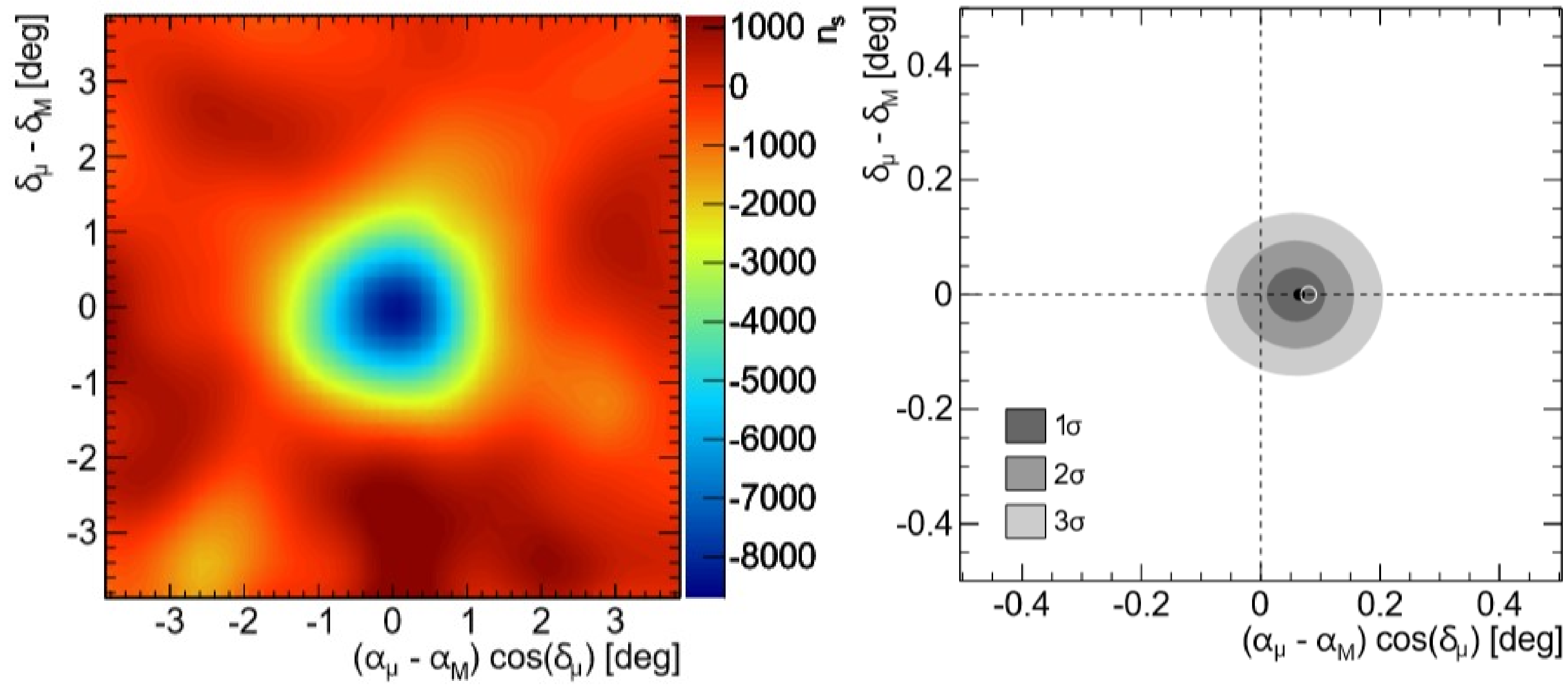
- **Shadow of moon and Sun with muons** (ANTARES and IceCube)

  a) detector calibration
  (angular resolution and absolute pointing)

  b) solar magnetic fields

Shadow of the moon

- **IceCube with the first 59 of the final 86 strings** Phys. Rev. D 89, 102004 (2014)



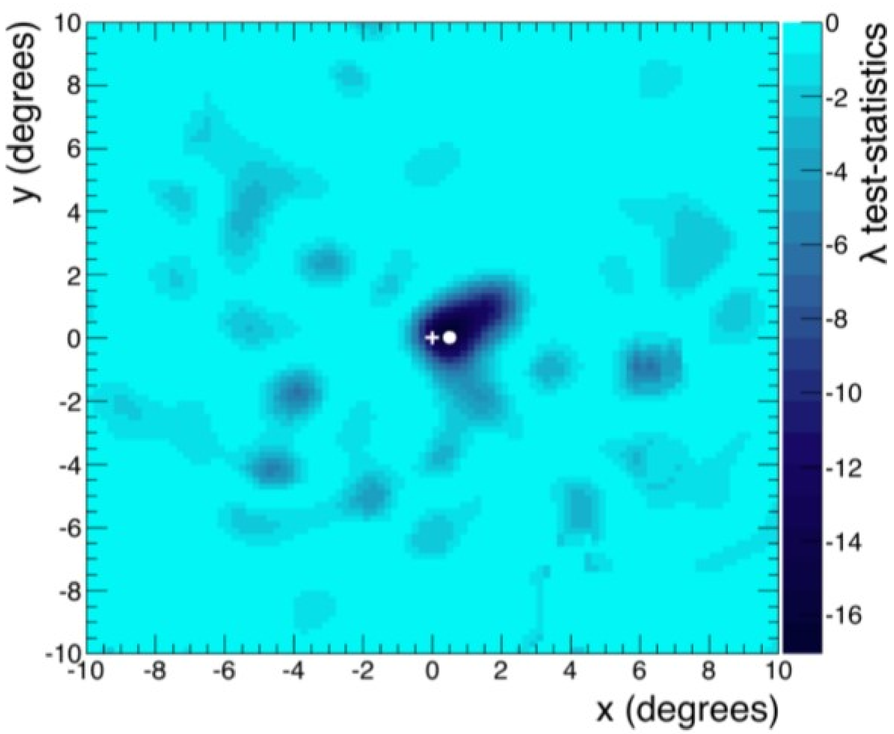
Angular resolution ~ 0.7°

Angular offset < 0.2°

- **ANTARES** Eur. Phys. Journal C 78 1006 (2018)

Angular resolution ~ 0.7°

Angular offset < 0.5°



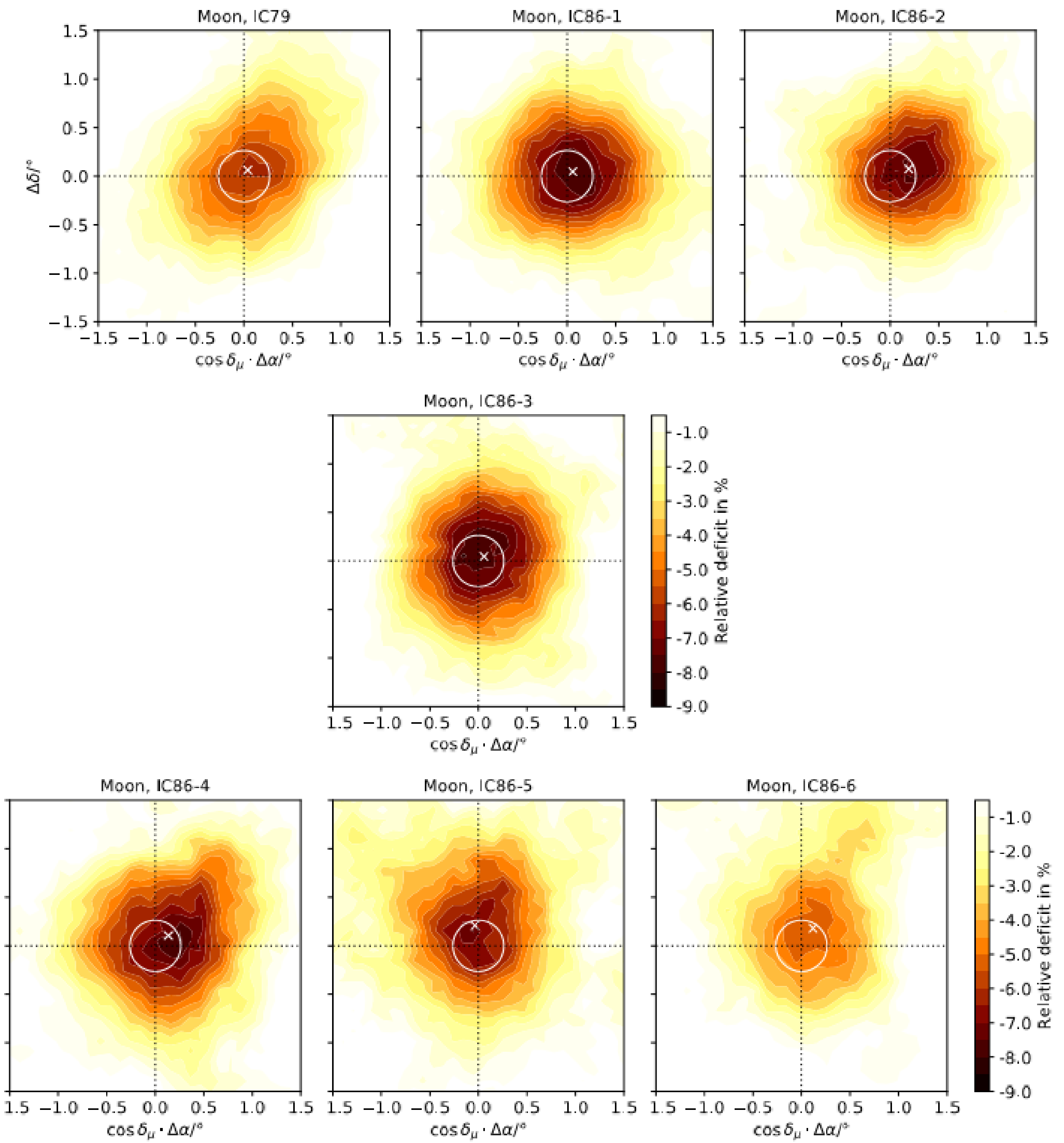
Shadow of the Sun

- **IceCube (2018, 2020) Temporal variation over seven years**

late 2010
- early 2017

ApJ, 872 (2019) 133 and

more recently arXiv:2006.16298



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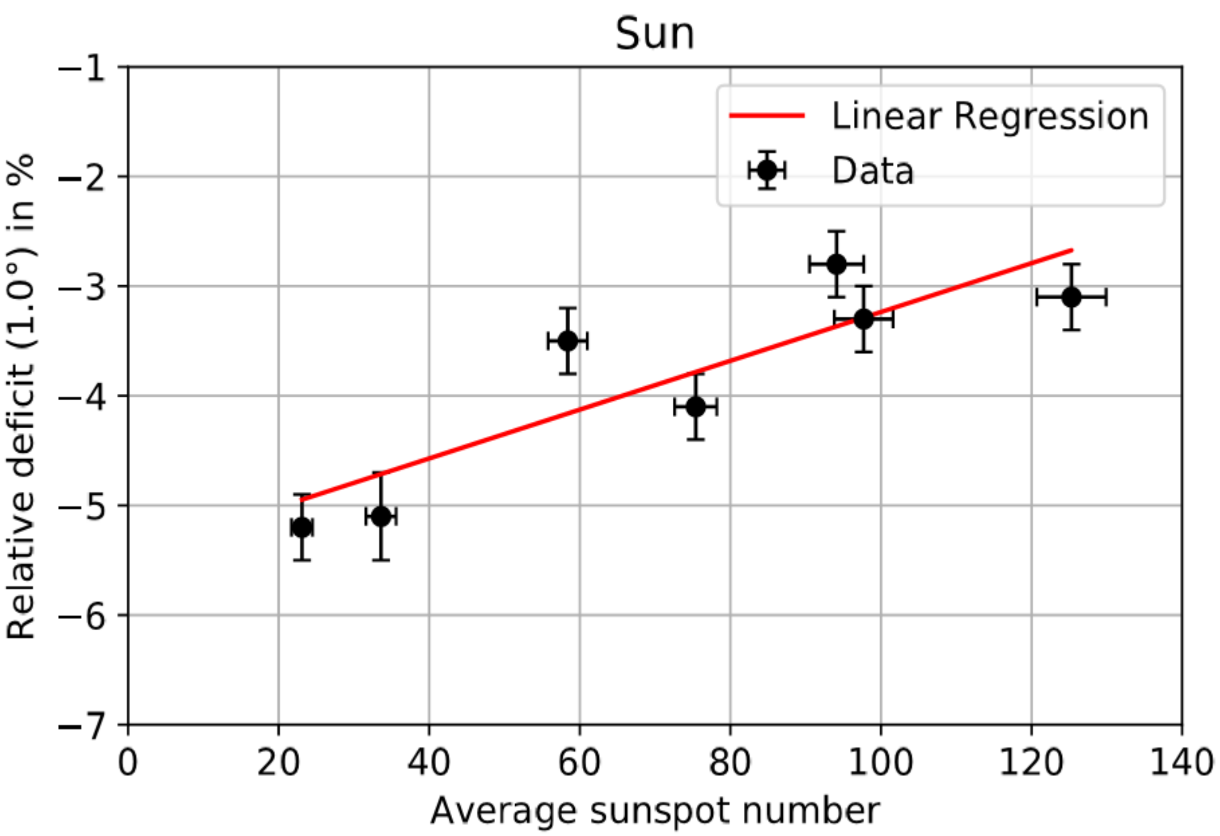
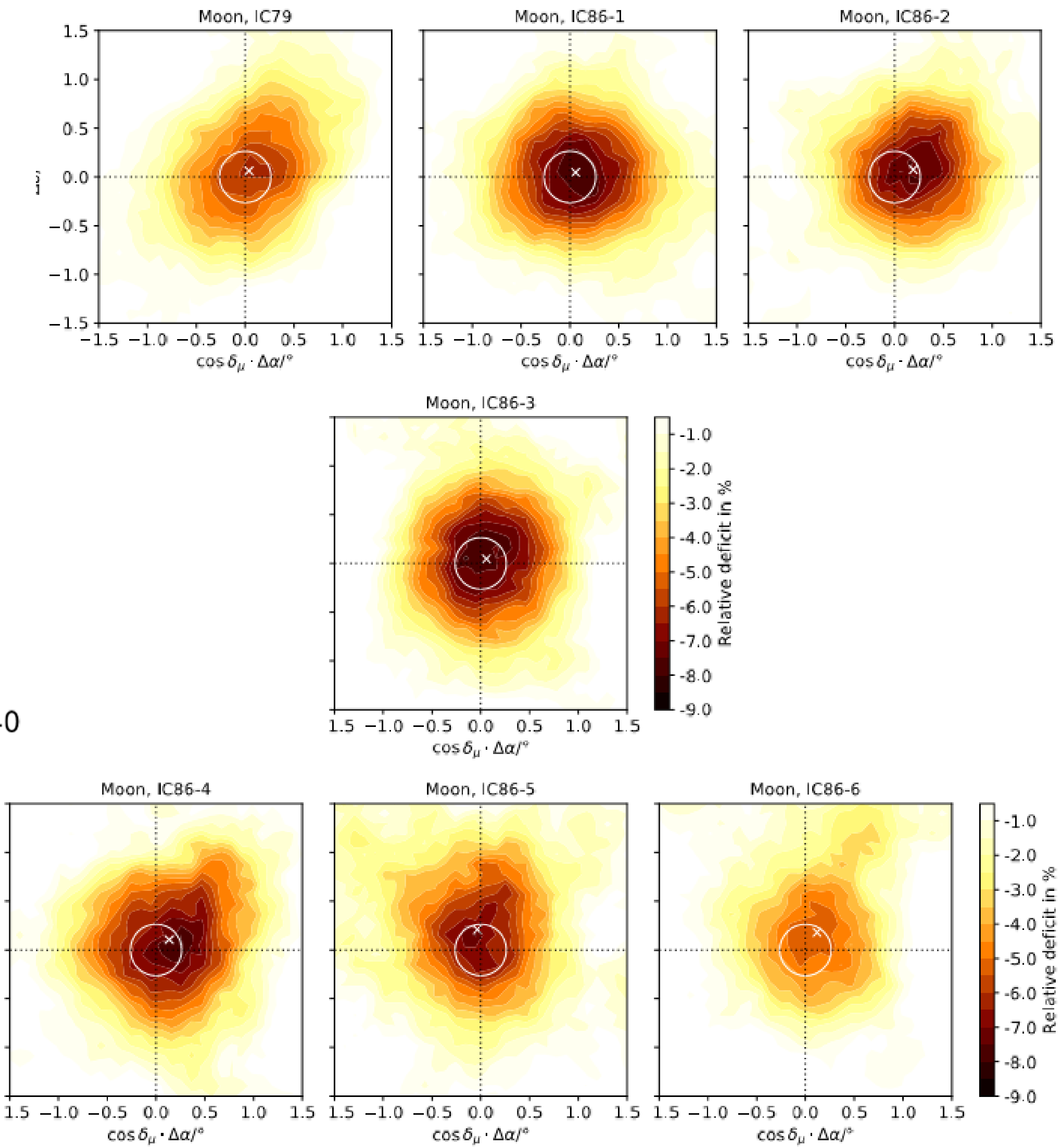
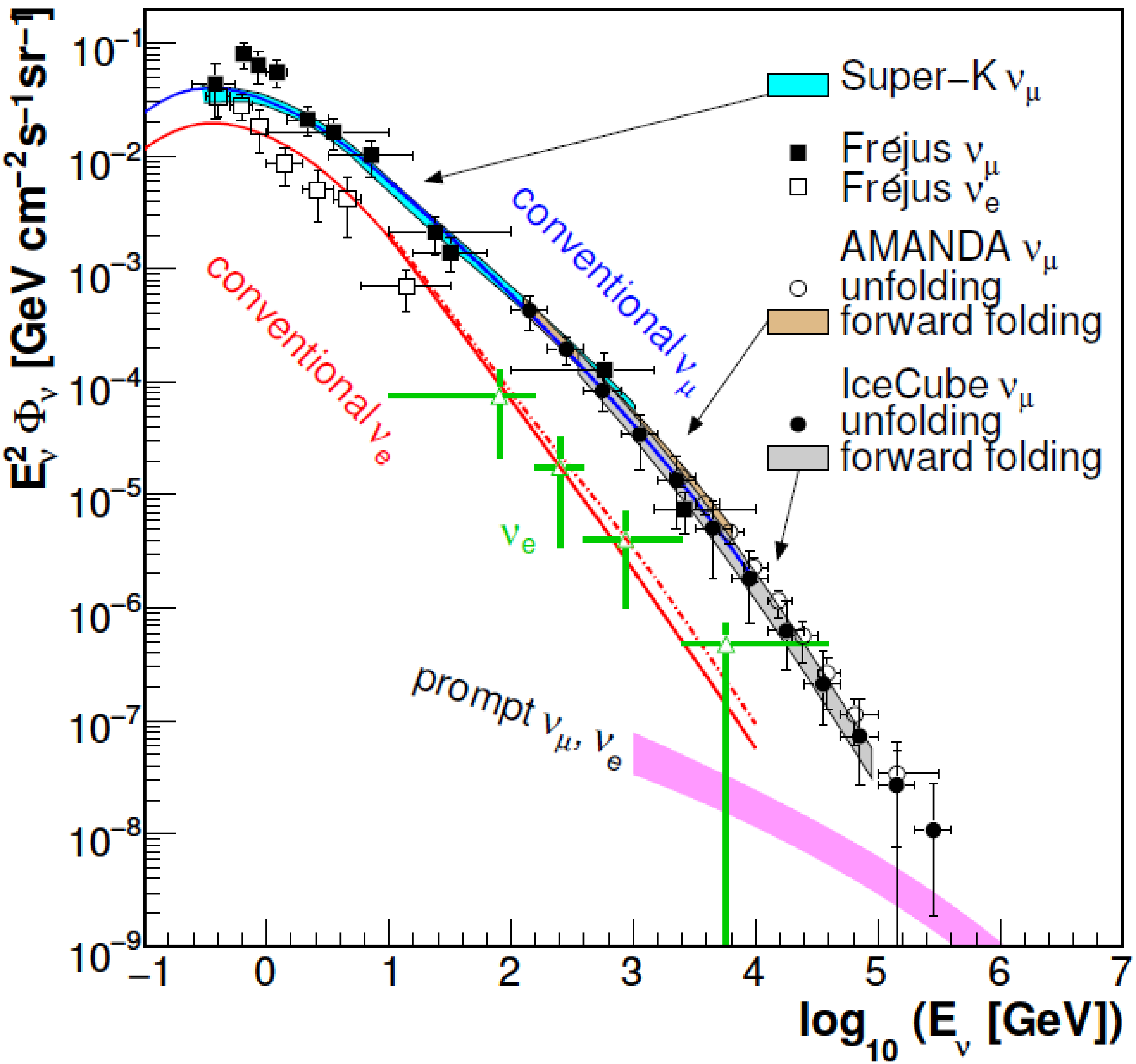
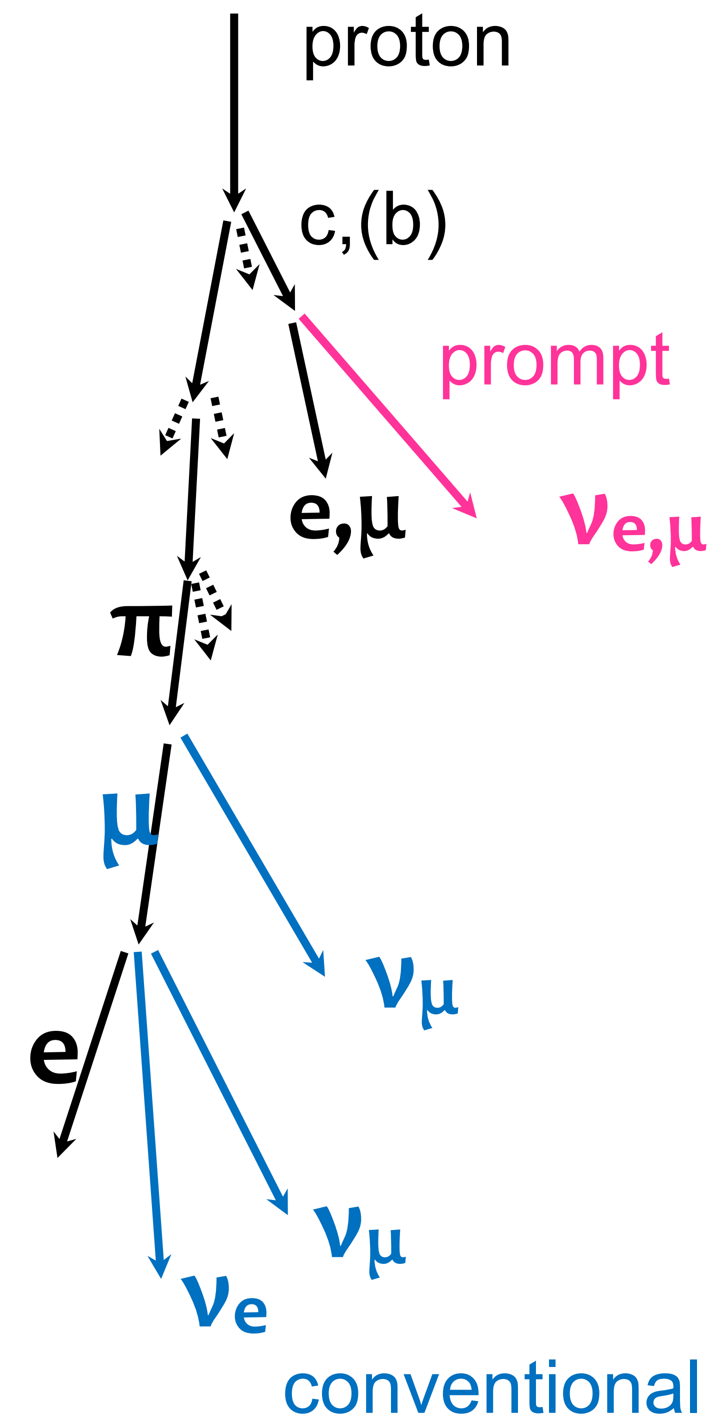




Atmospheric Neutrinos

Atmospheric neutrinos in IceCube (2 years)





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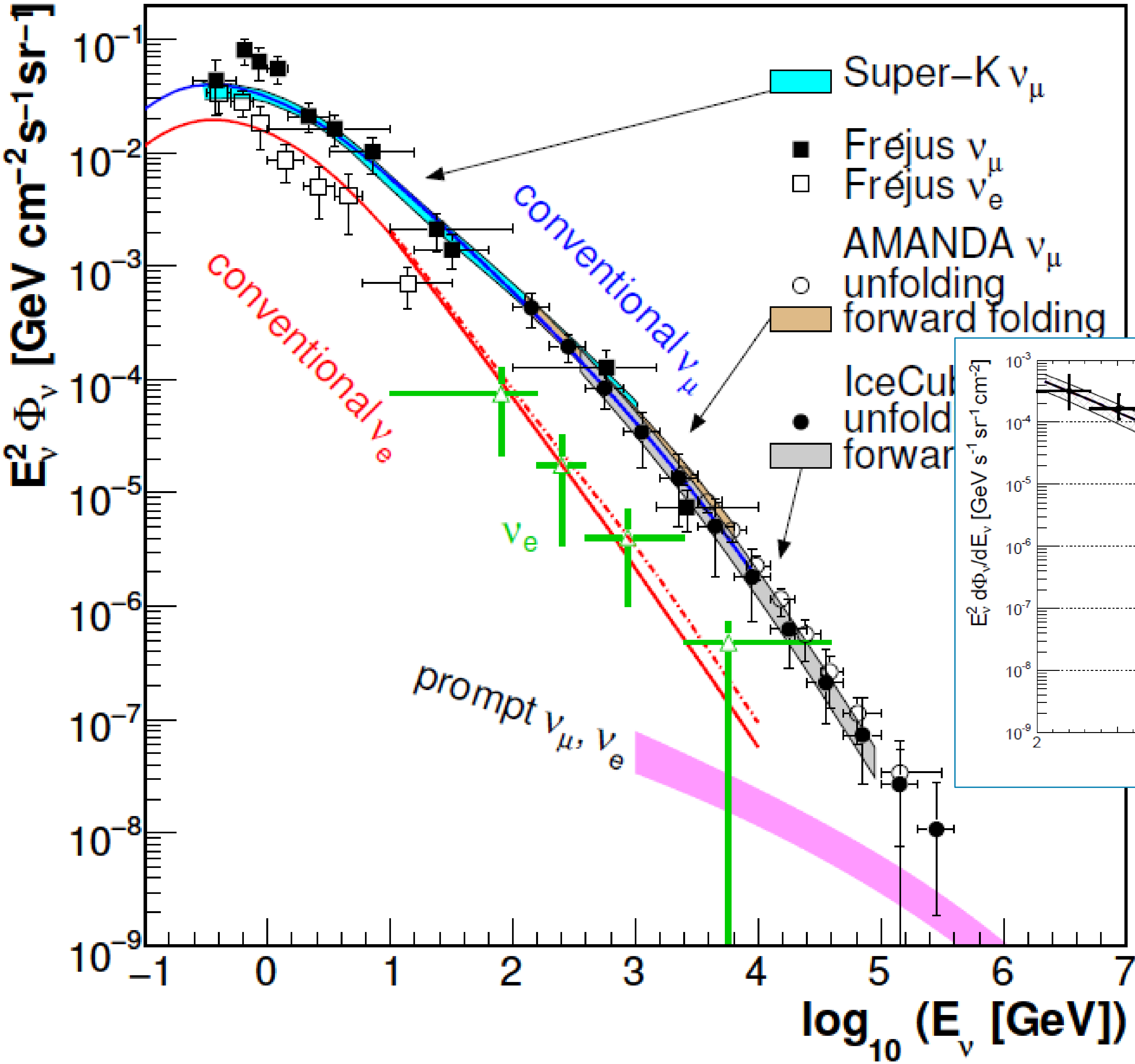
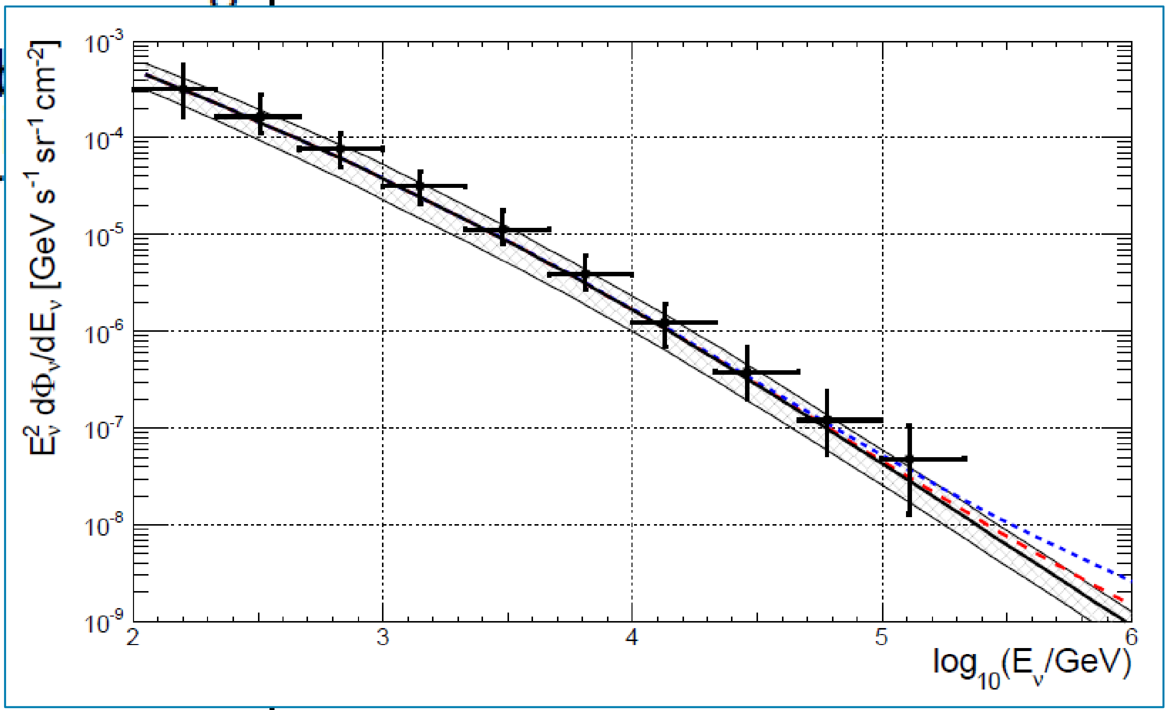


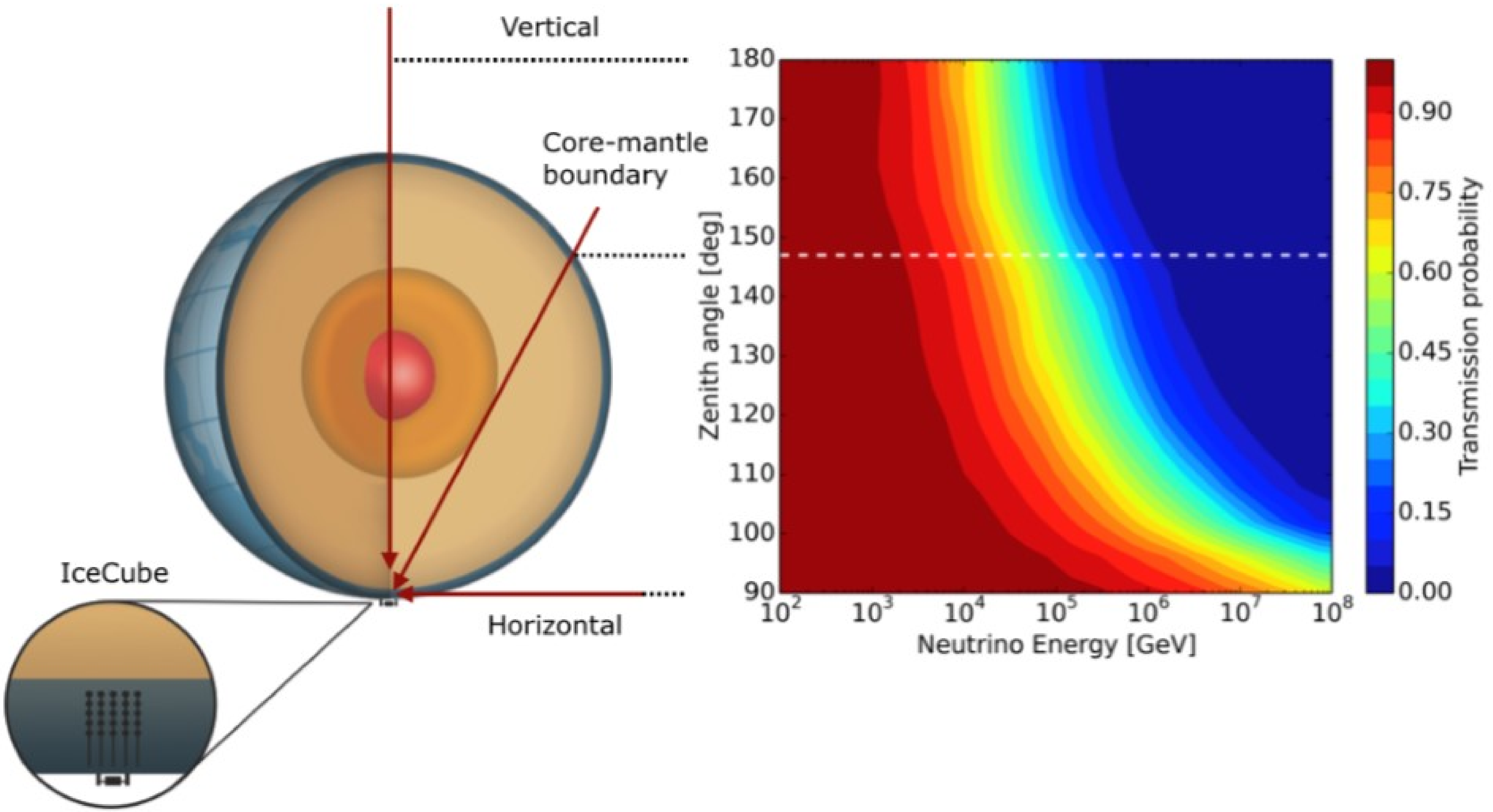
.. and ANTARES



arXiv:1308.1599

Using atmospheric neutrinos to measure σ_ν at > TeV

IceCube Coll.: Measurement of the multi-TeV neutrino cross section with IceCube using Earth absorption Nature 551 (2017) 596 and arXiv:1711.08119



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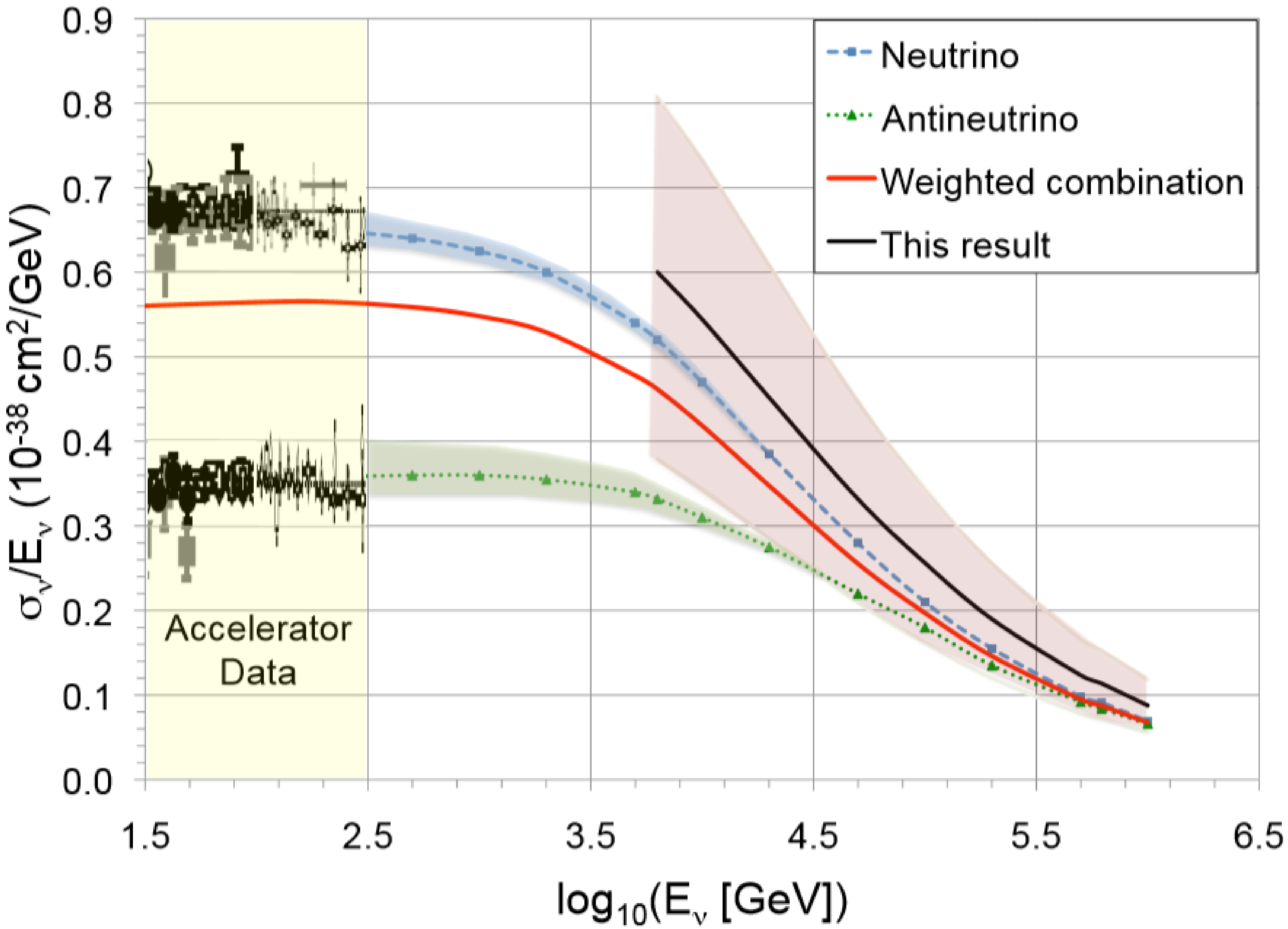
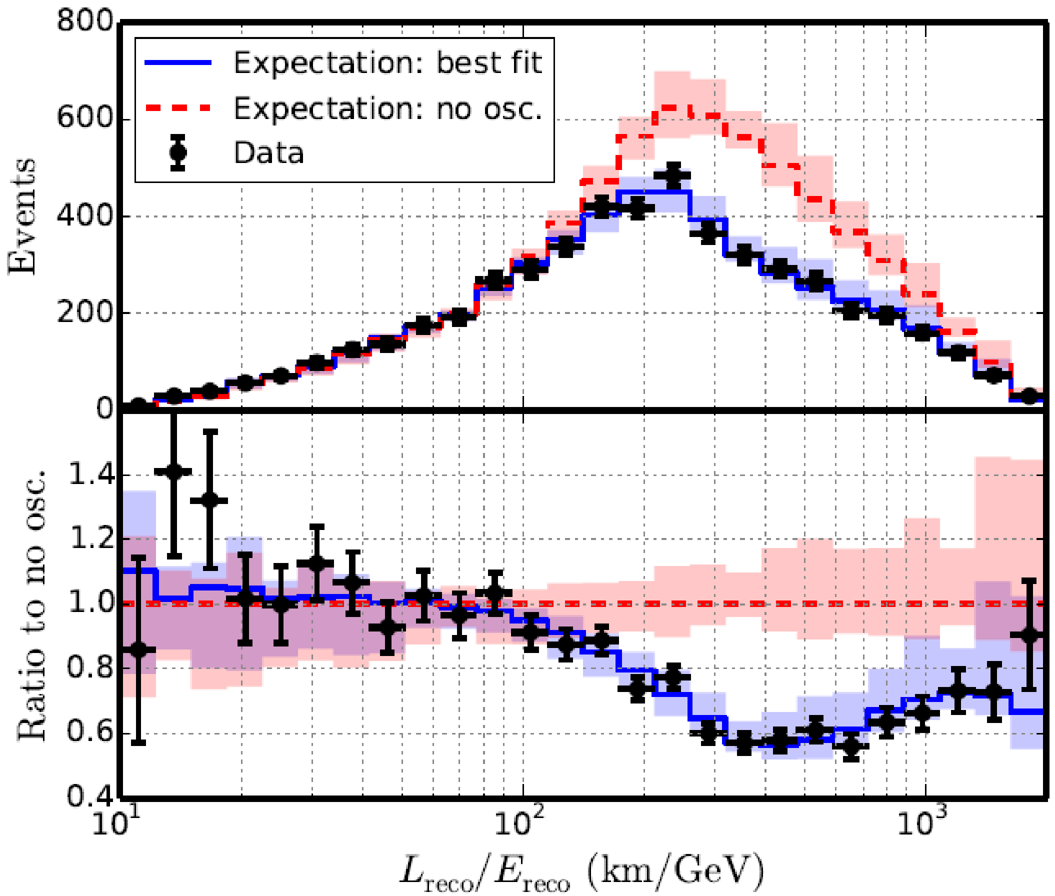
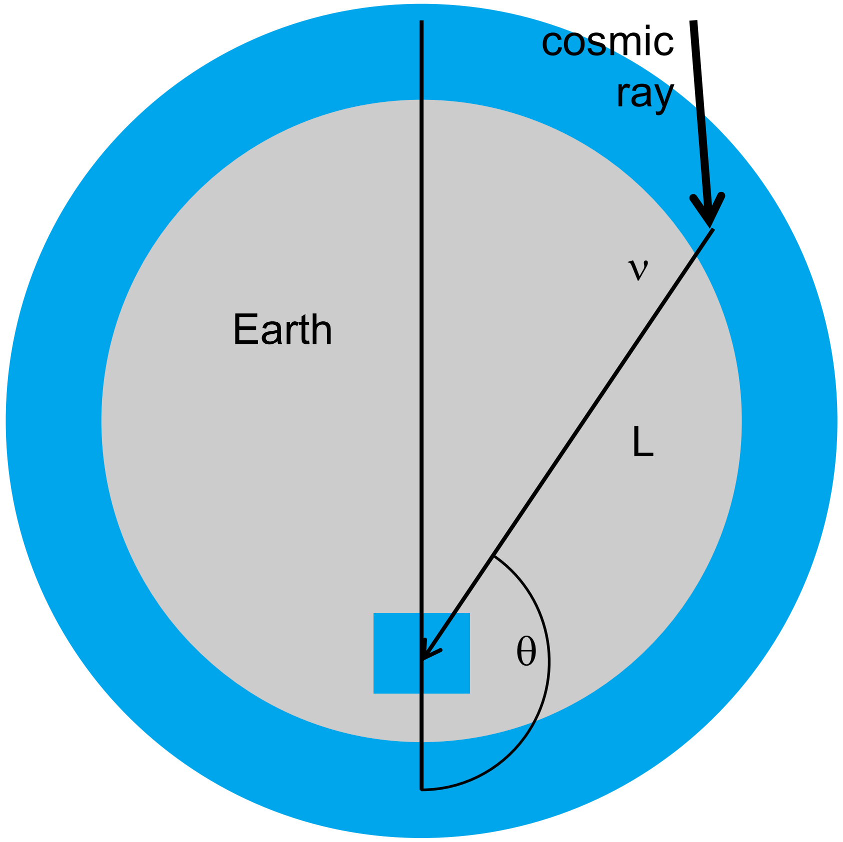


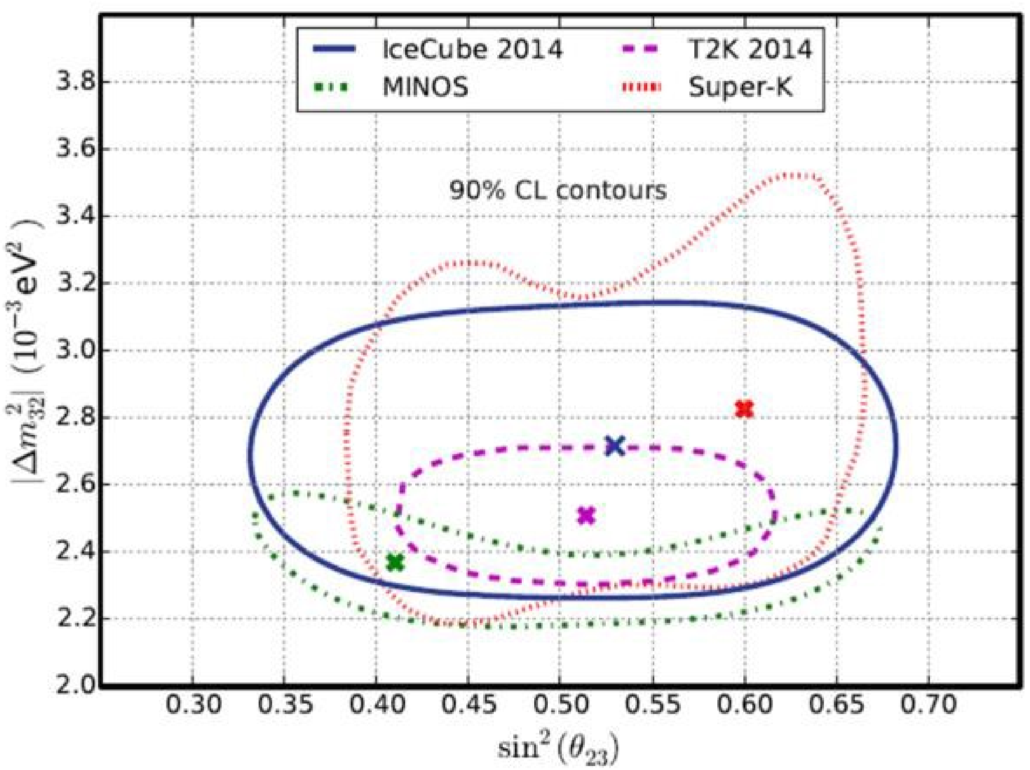
DeepCore: Oscillations for atmospheric neutrinos (E < 30-40 GeV)



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

Phys. Rev. D91, 072004 (2015)





$$P\left(\nu_\mu \rightarrow \nu_x\right) = \sin^2 2\theta \cdot \sin^2(2.5\,\Delta m^2 \cdot L/E_\nu)$$

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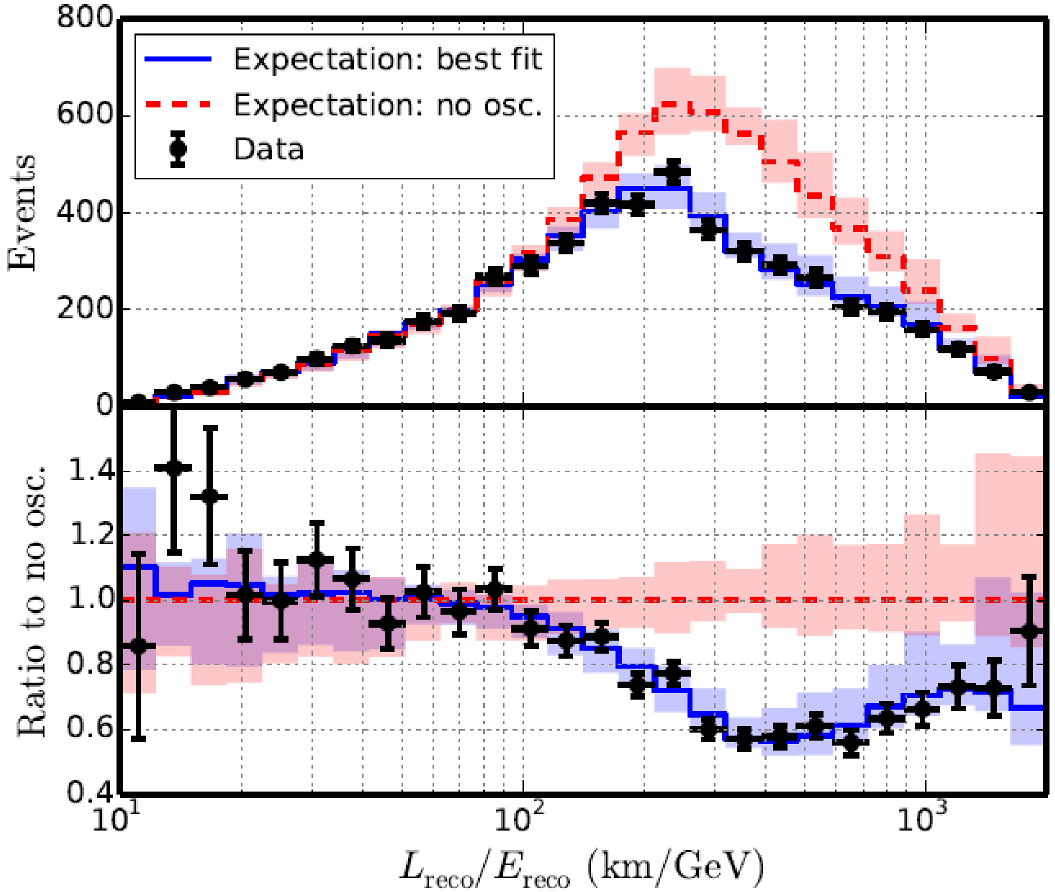

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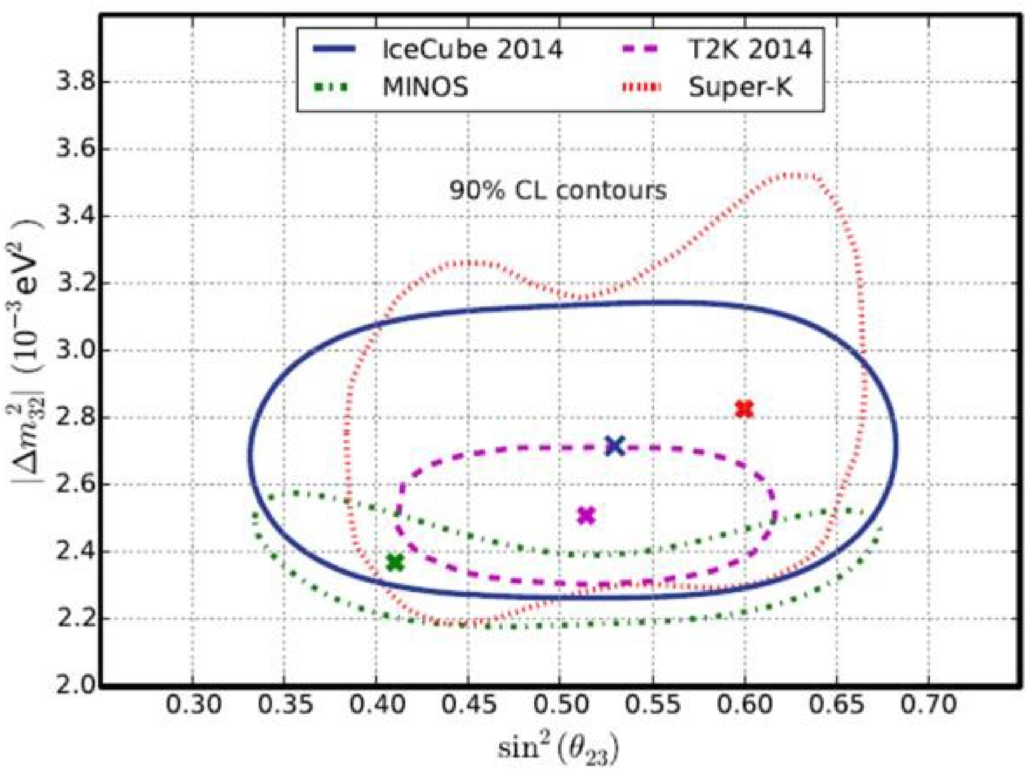
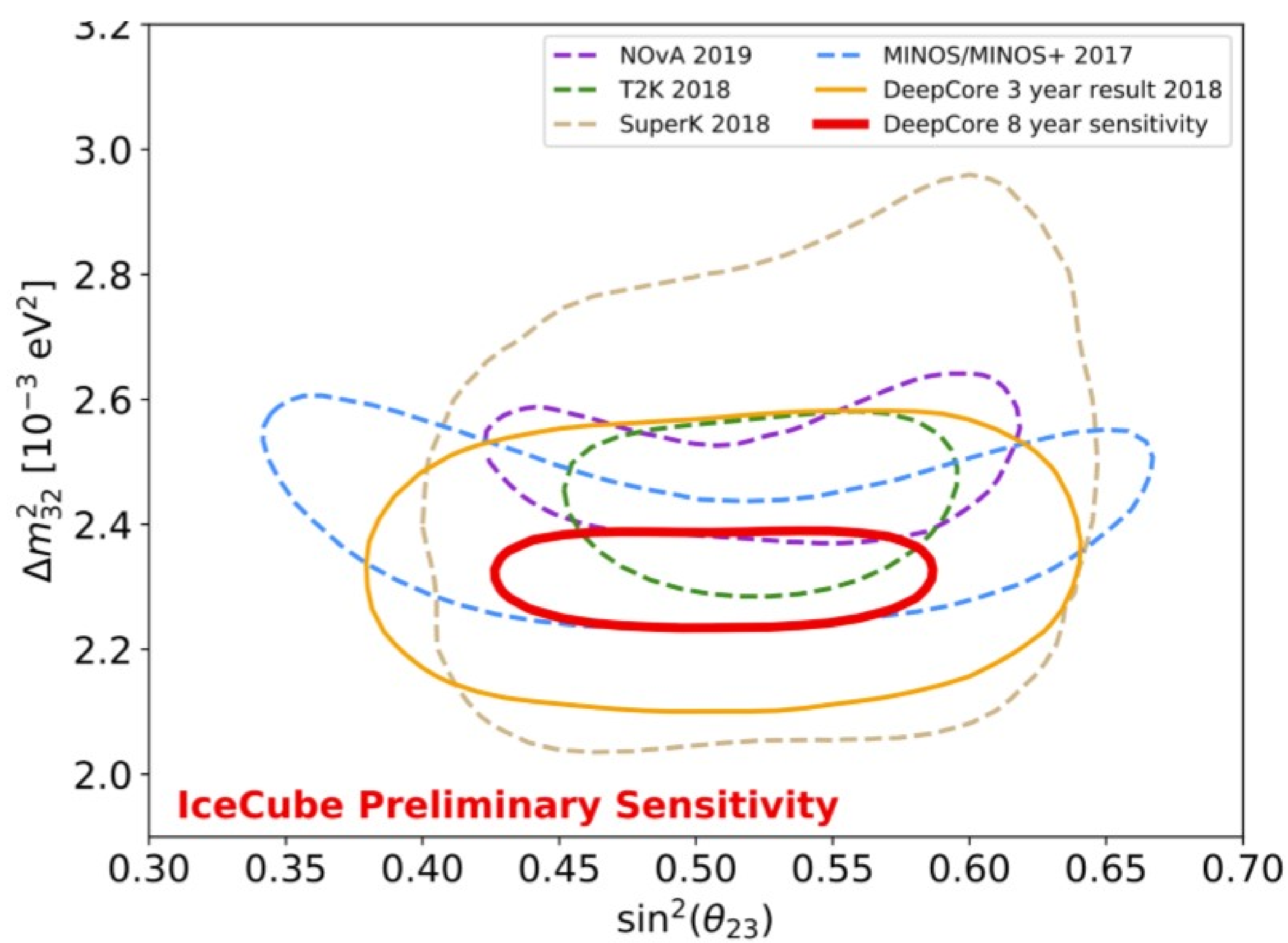


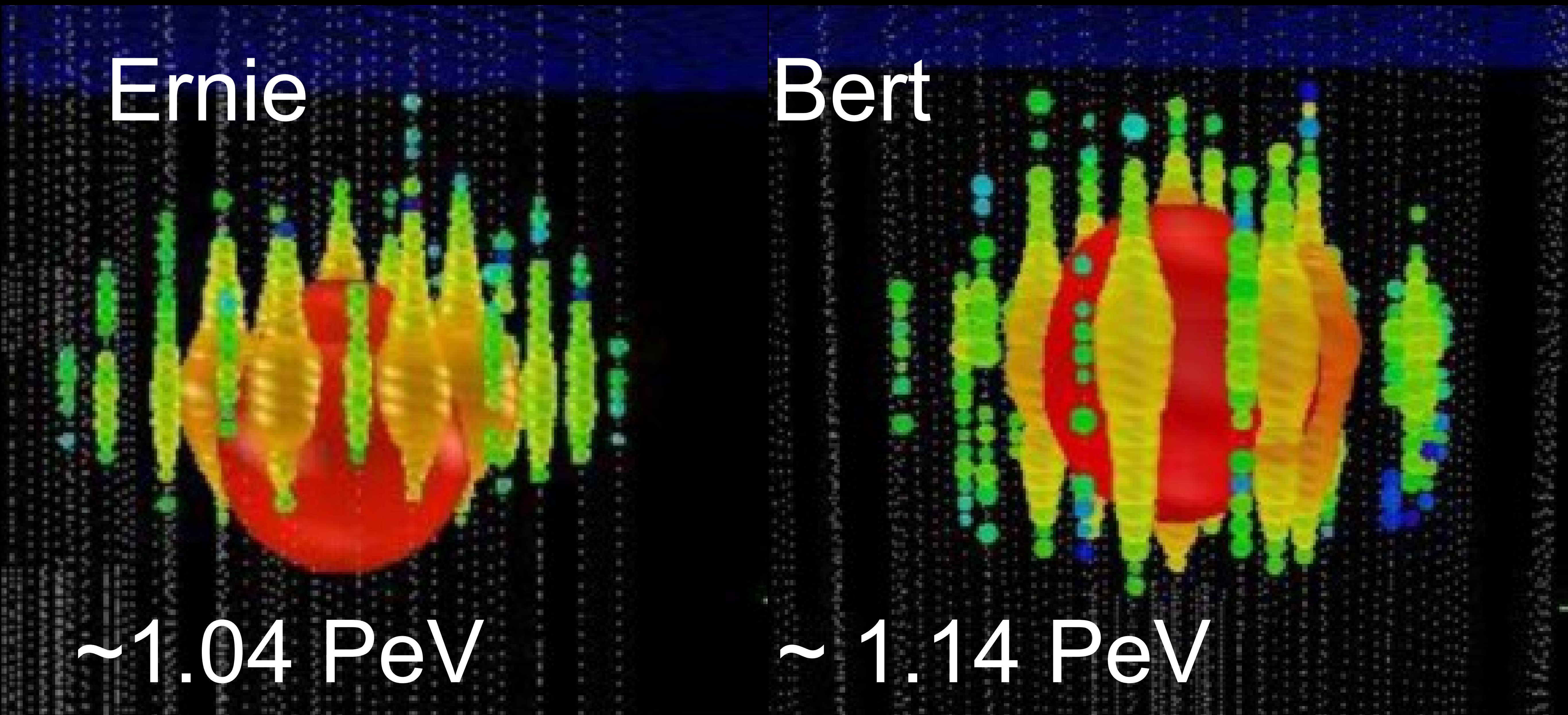
Neutrino Conference 2020



The Discovery of a Diffuse Cosmic Neutrino Flux

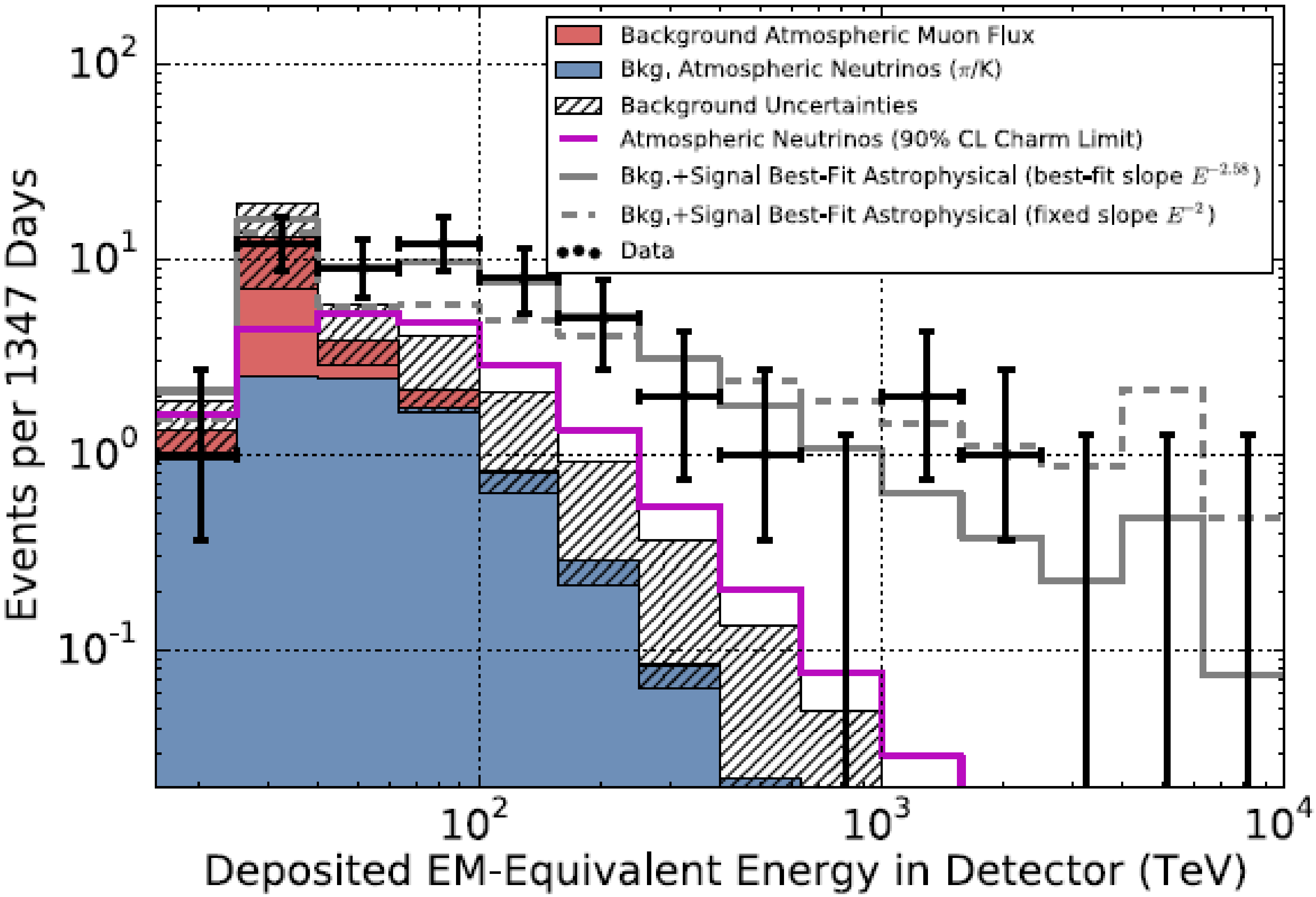
Special search for neutrinos with E_ν > 500 TeV

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

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

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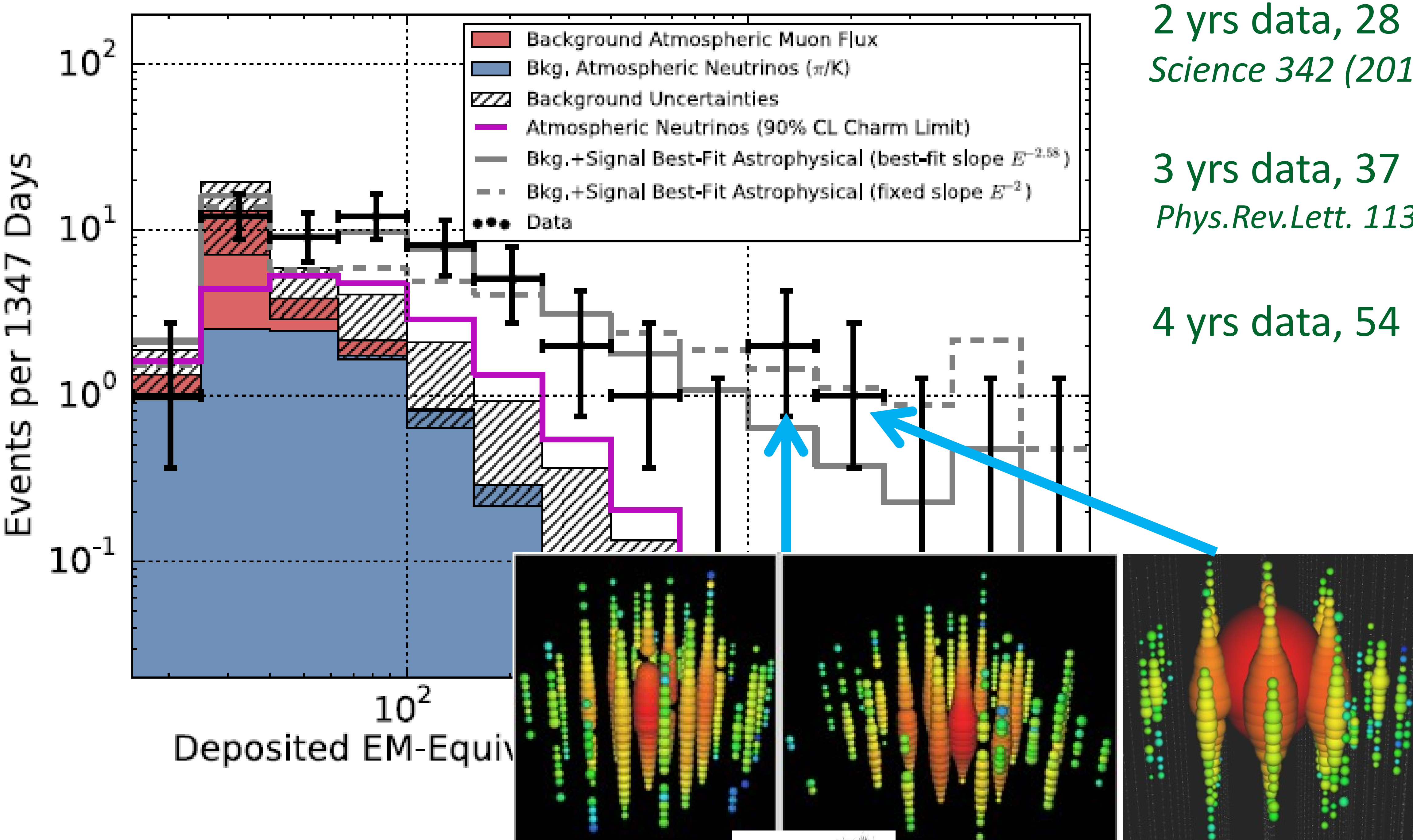


"Bert"
1.04 PeV
Aug. 2011

"Ernie"
1.14 PeV
Jan. 2012

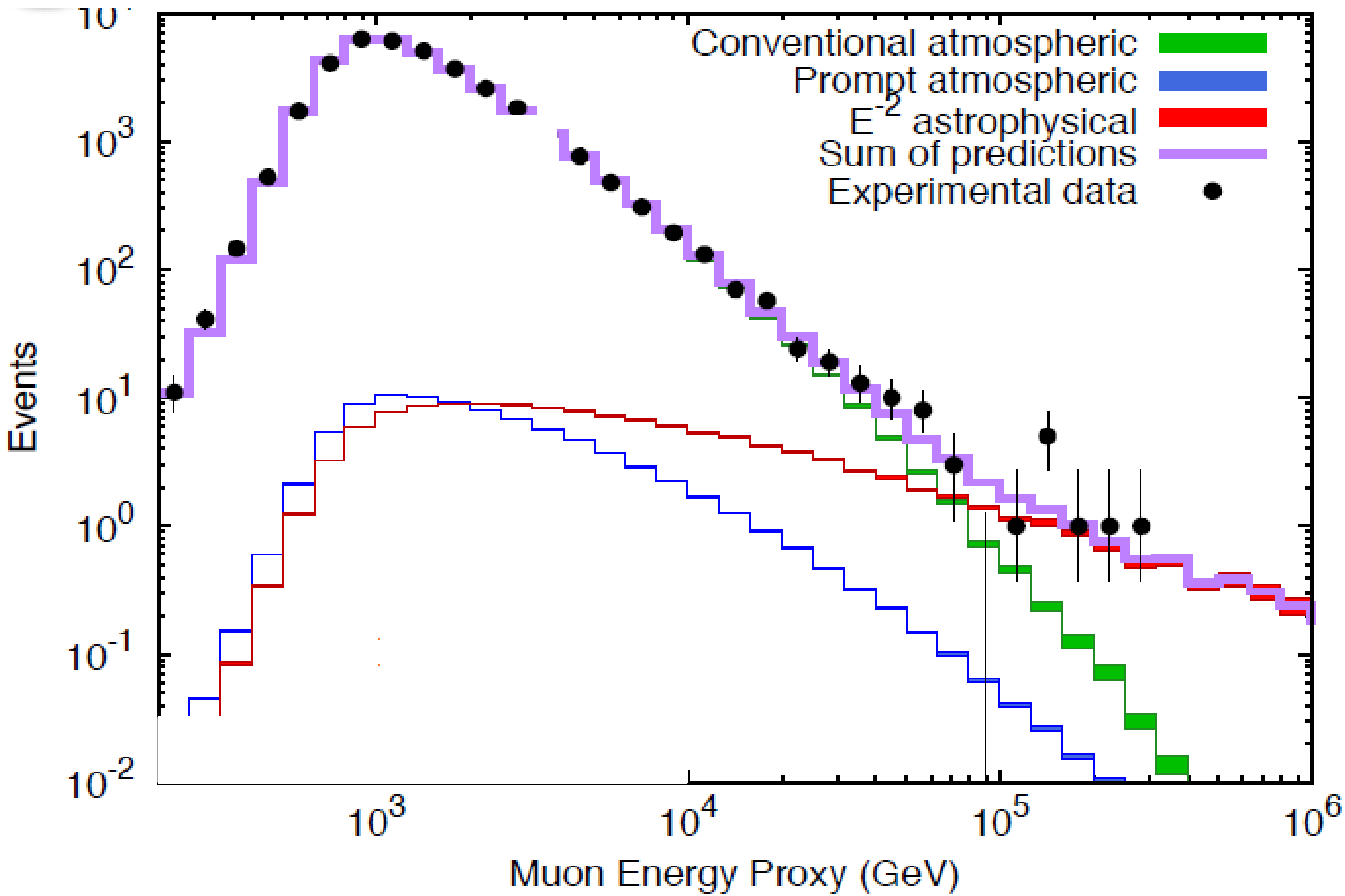
"Big Bird"
2 PeV
Dec. 2012

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

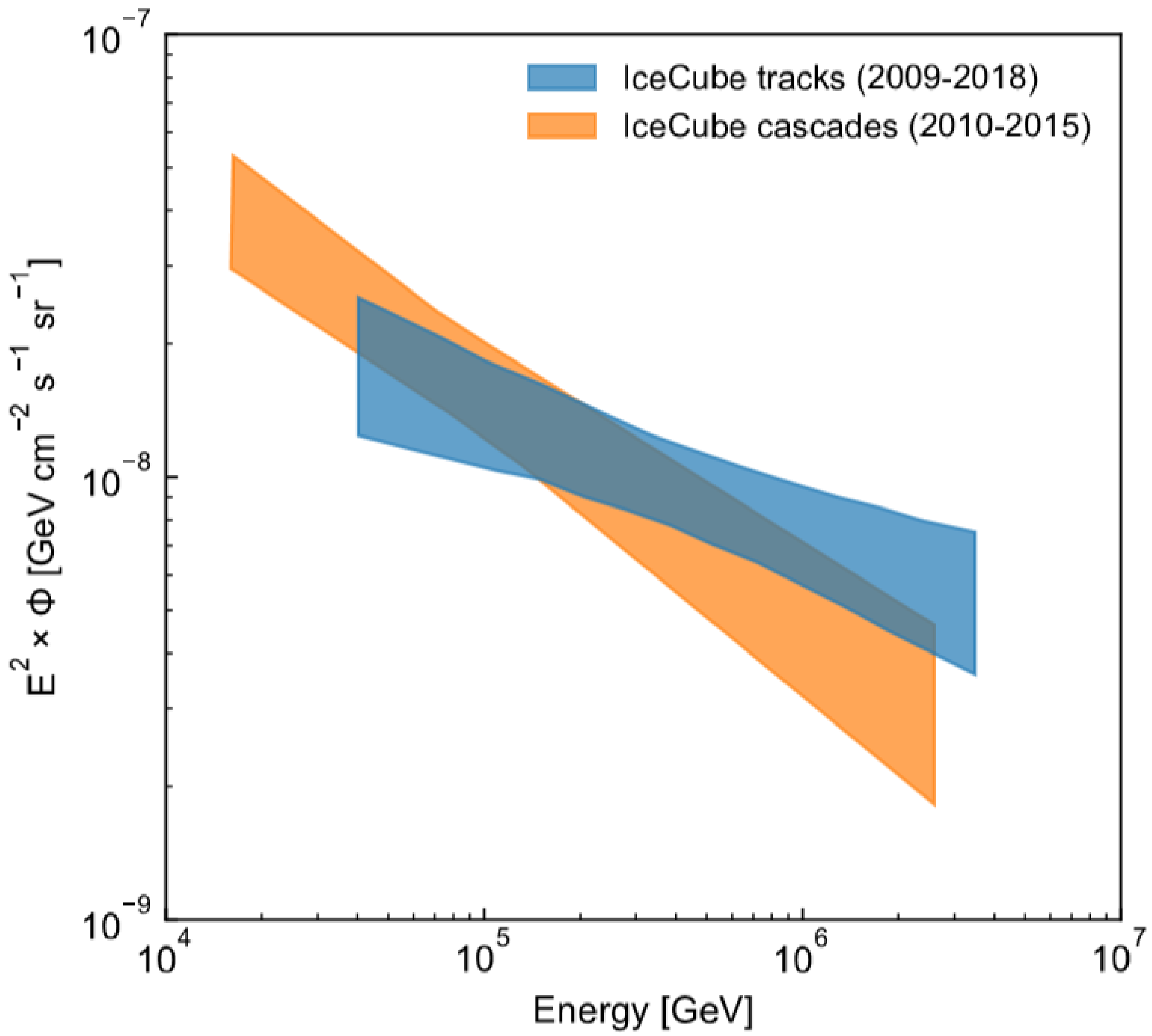
3 yrs data, 37 evts 5.9σ
Phys.Rev.Lett. 113:101101 (2014)

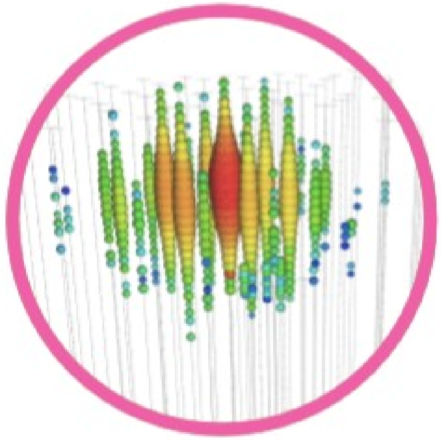
4 yrs data, 54 evts ~ **<u>7σ</u>**

Through-going muons, IC-79/86

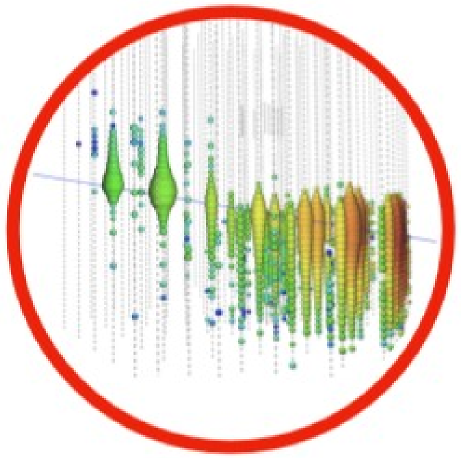


The Astrophysical Neutrino Flux



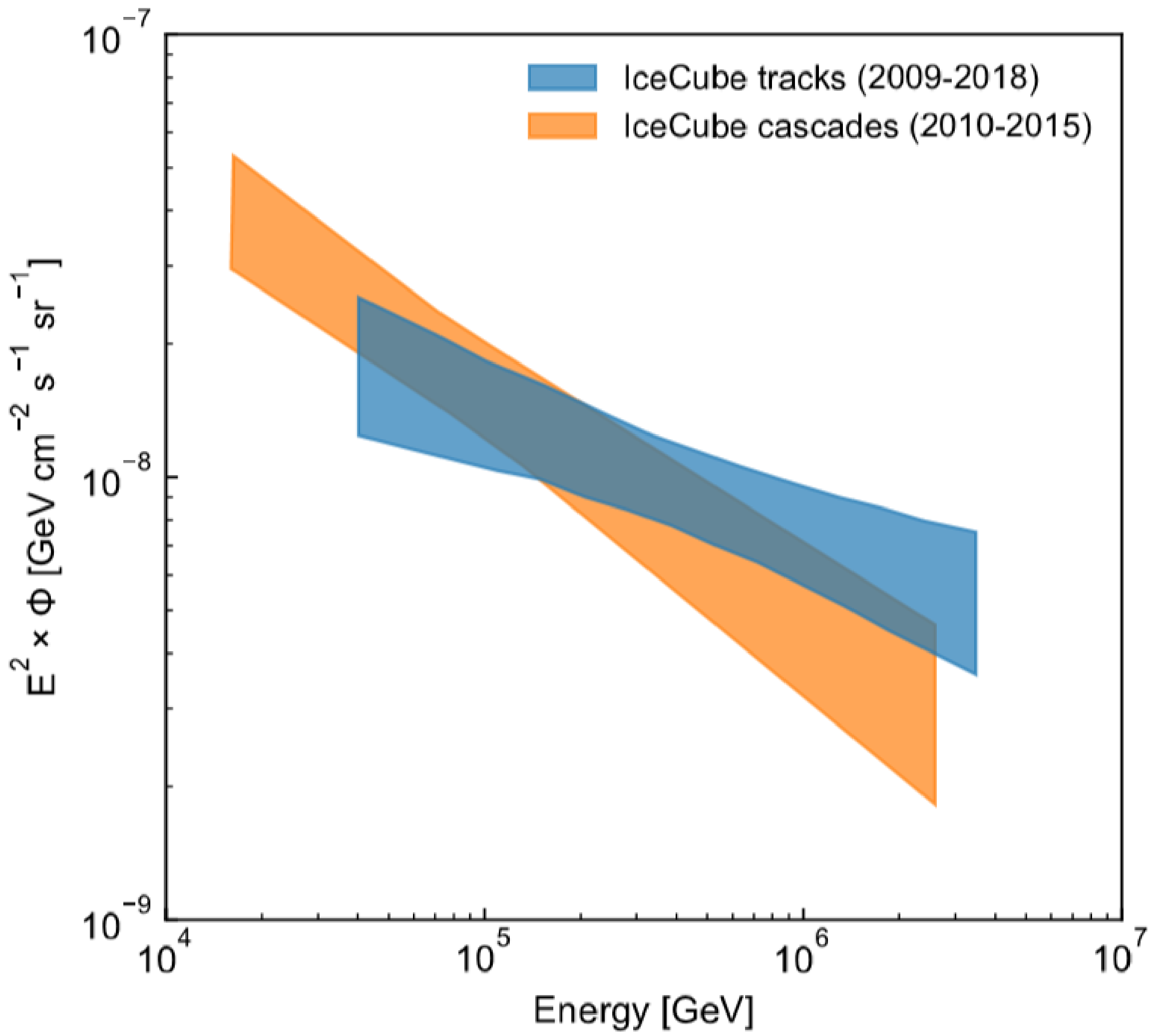


High-energy starting events (HESE)
Interaction vertex in the detector
All flavor, all sky



Up-going tracks
Muon-dominated
Northern sky

The Astrophysical Neutrino Flux



Adding ANTARES

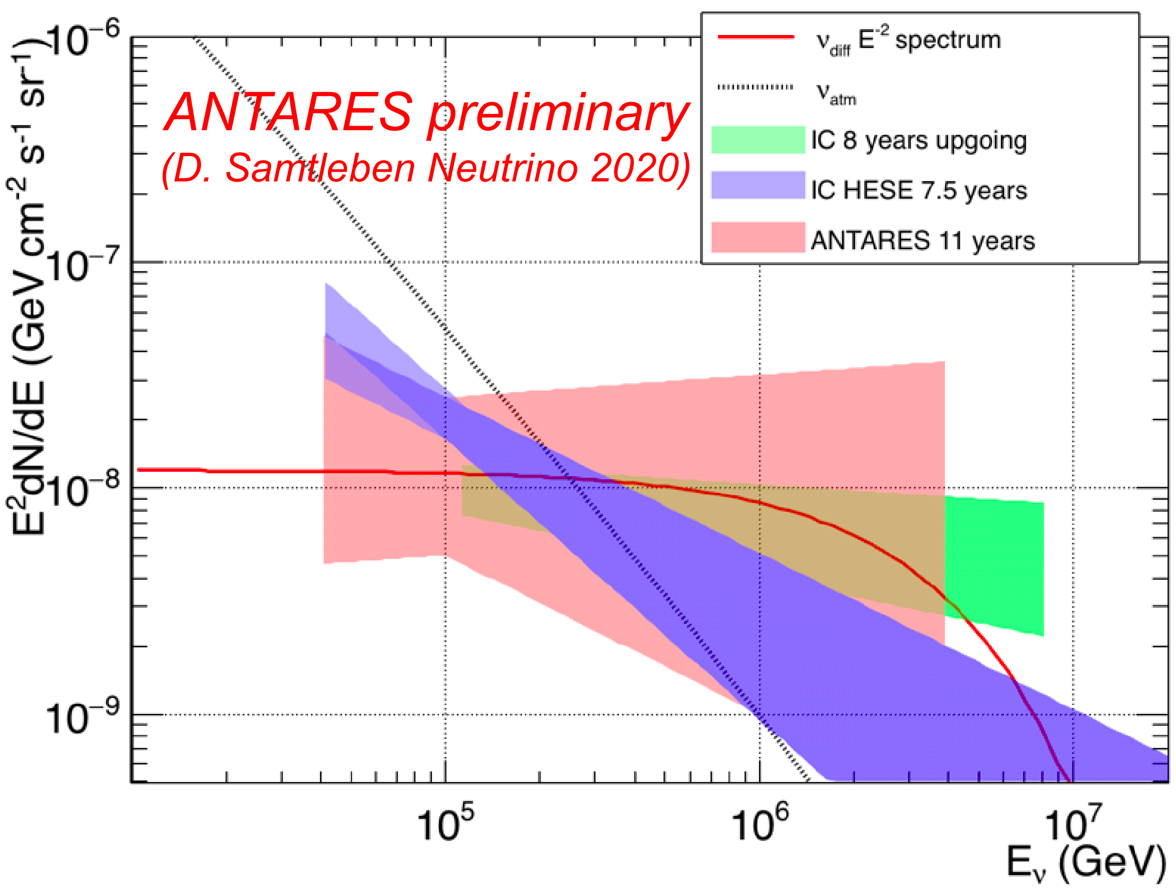
Total: 50 events, Simulation: 36.1 ± 8.7

Best fit $\Phi = 1.5 \pm 1 \; 10^{-8}$ GeV^{-1} cm^{-2} sr^{-1} s^{-1}

$\gamma = 2.3 \pm 0.4$

1.8 σ excess

ApJ 853 (2018) L7
arXiv:1711.07212



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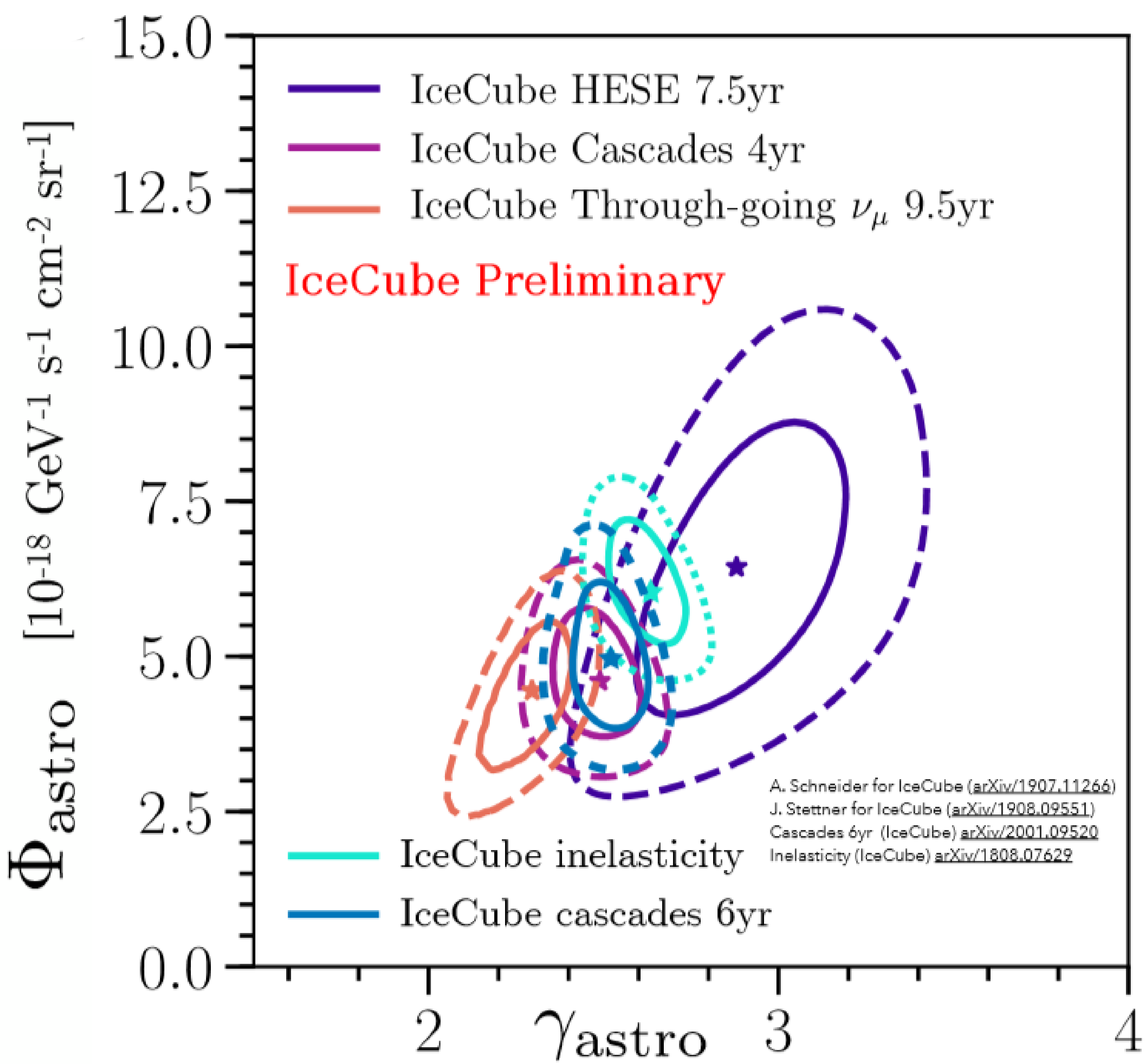


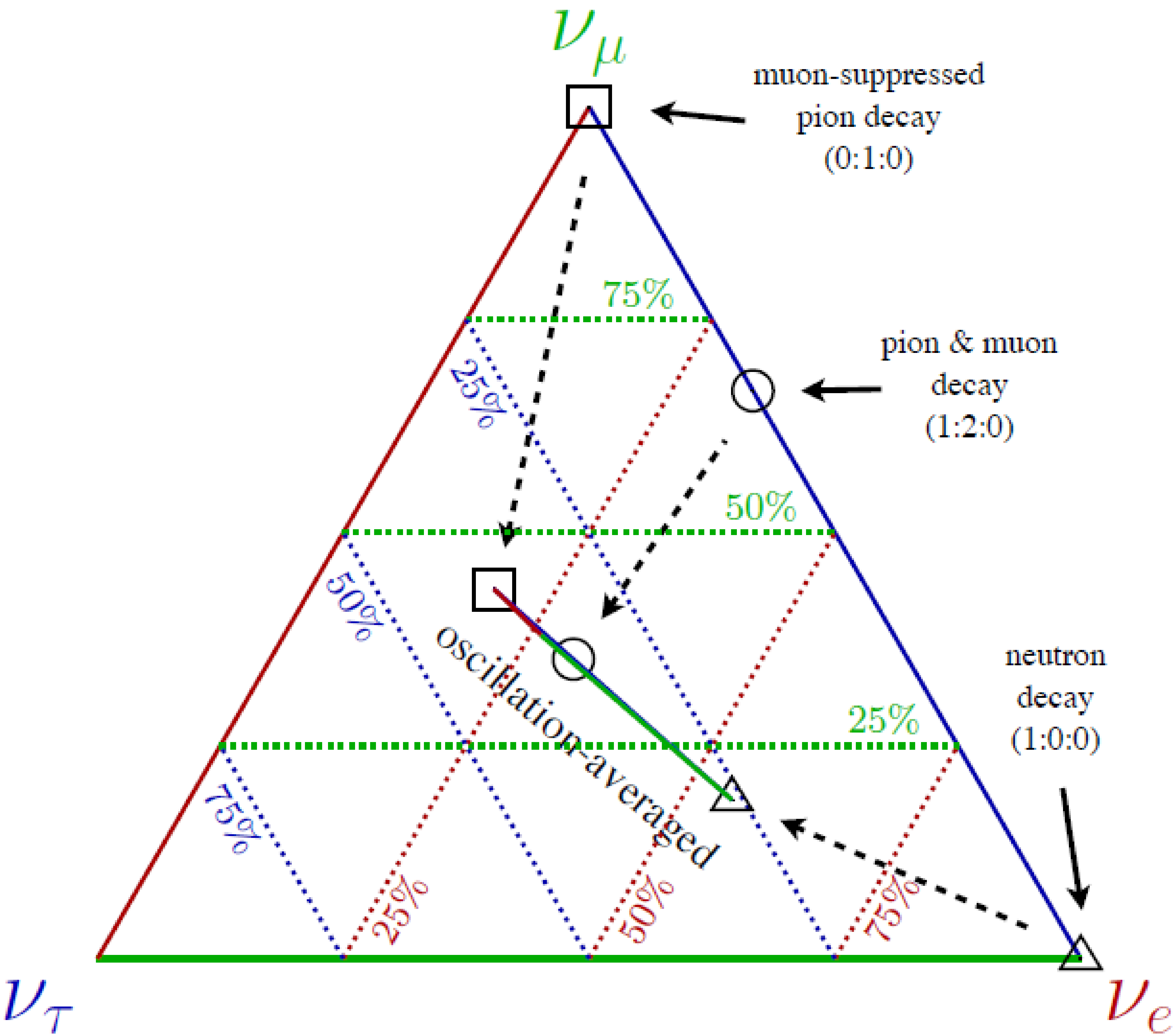
M. Santander, talk at Neutrino 2020

- Flux modeled with simple power law:

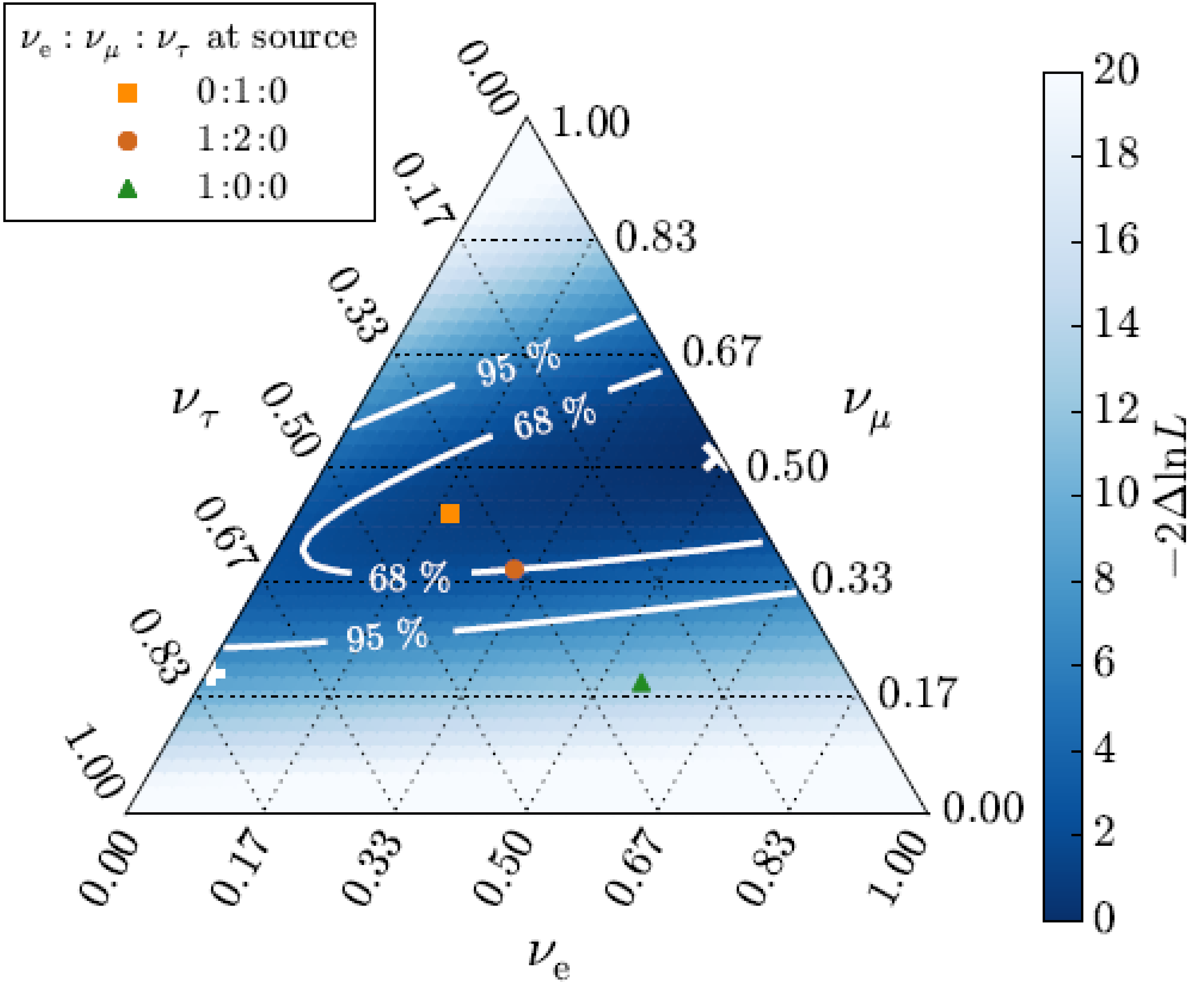
$$\Phi(E_\nu) = \Phi_{\mathrm{astro}} \left(\frac{E_\nu}{100\ \mathrm{TeV}} \right)^{-\gamma_{\mathrm{astro}}}$$

- Different events samples (energy, topology, sky hemisphere) favor slightly different indices and normalisations.
- Broken spectrum?
- **→ Need independent measurements with different systematics: KM3NeT, GVD !**

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

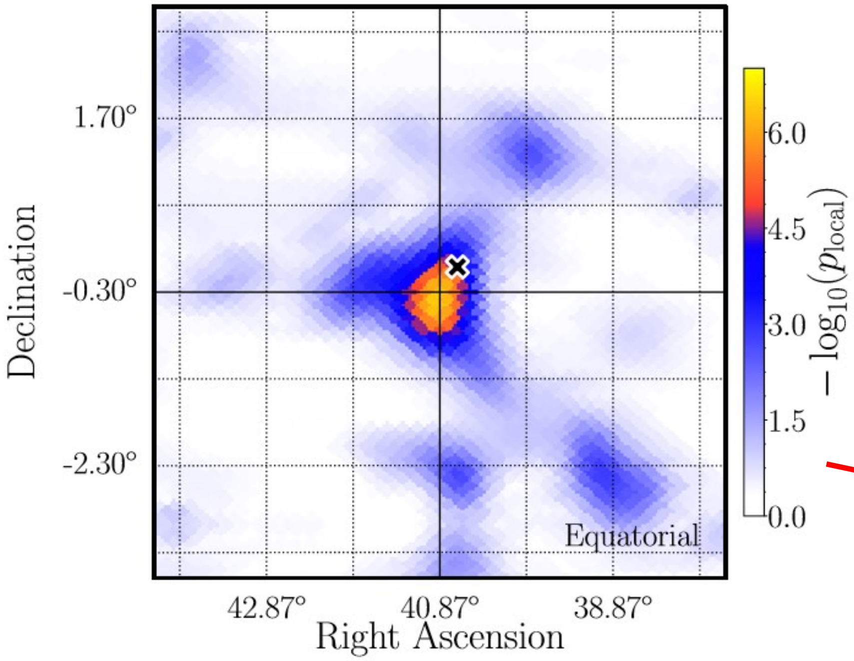
Individual Sources and Source Classes

IceCube, 10 years

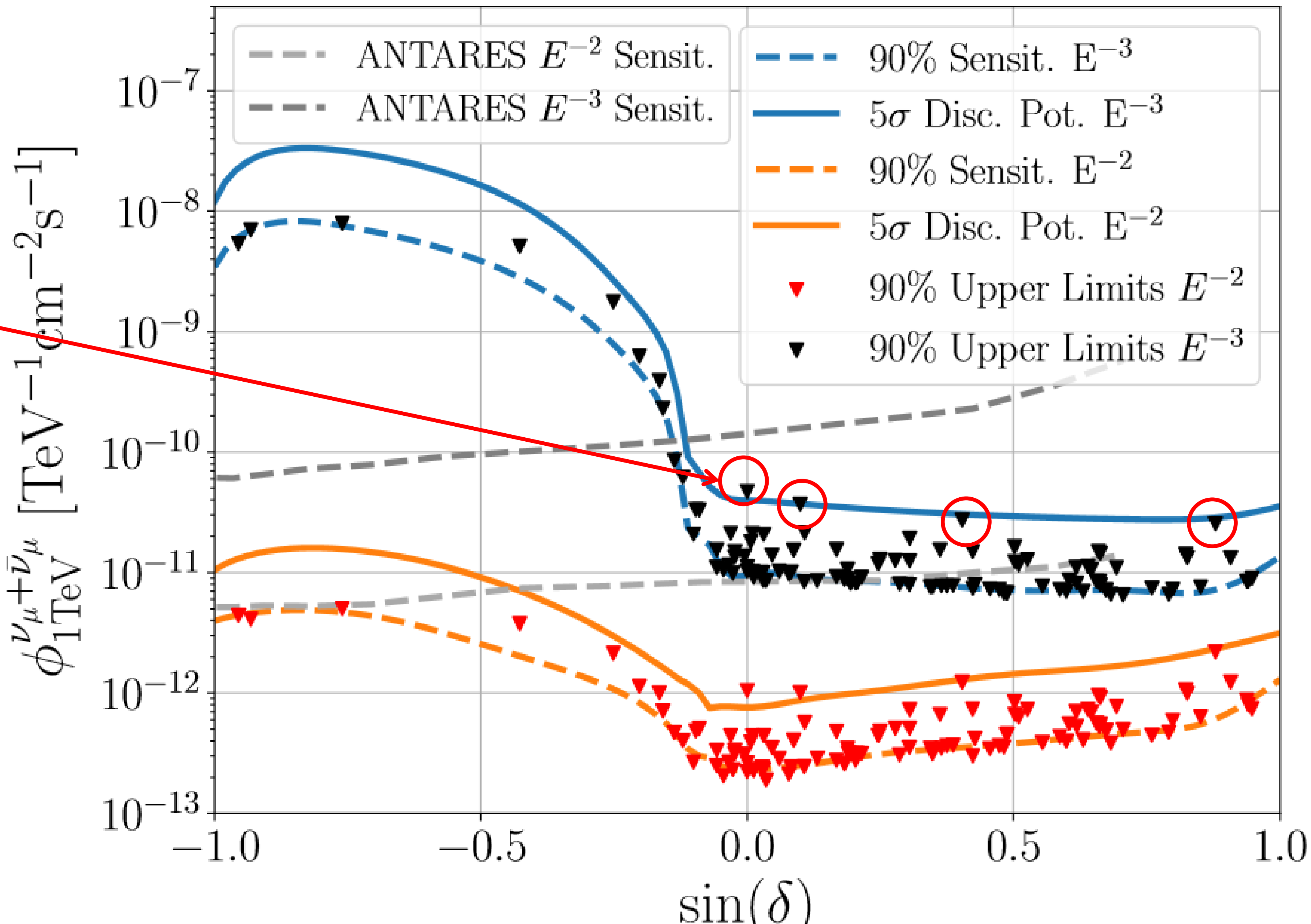
PRL 124, 051103 (2020), arXiv:1910.08488

Some evidence for non-uniform skymap in 10 years of IceCube data (3.3σ). Mostly resulting from 4 extragalactic source candidates.

No indications for galactic sources.

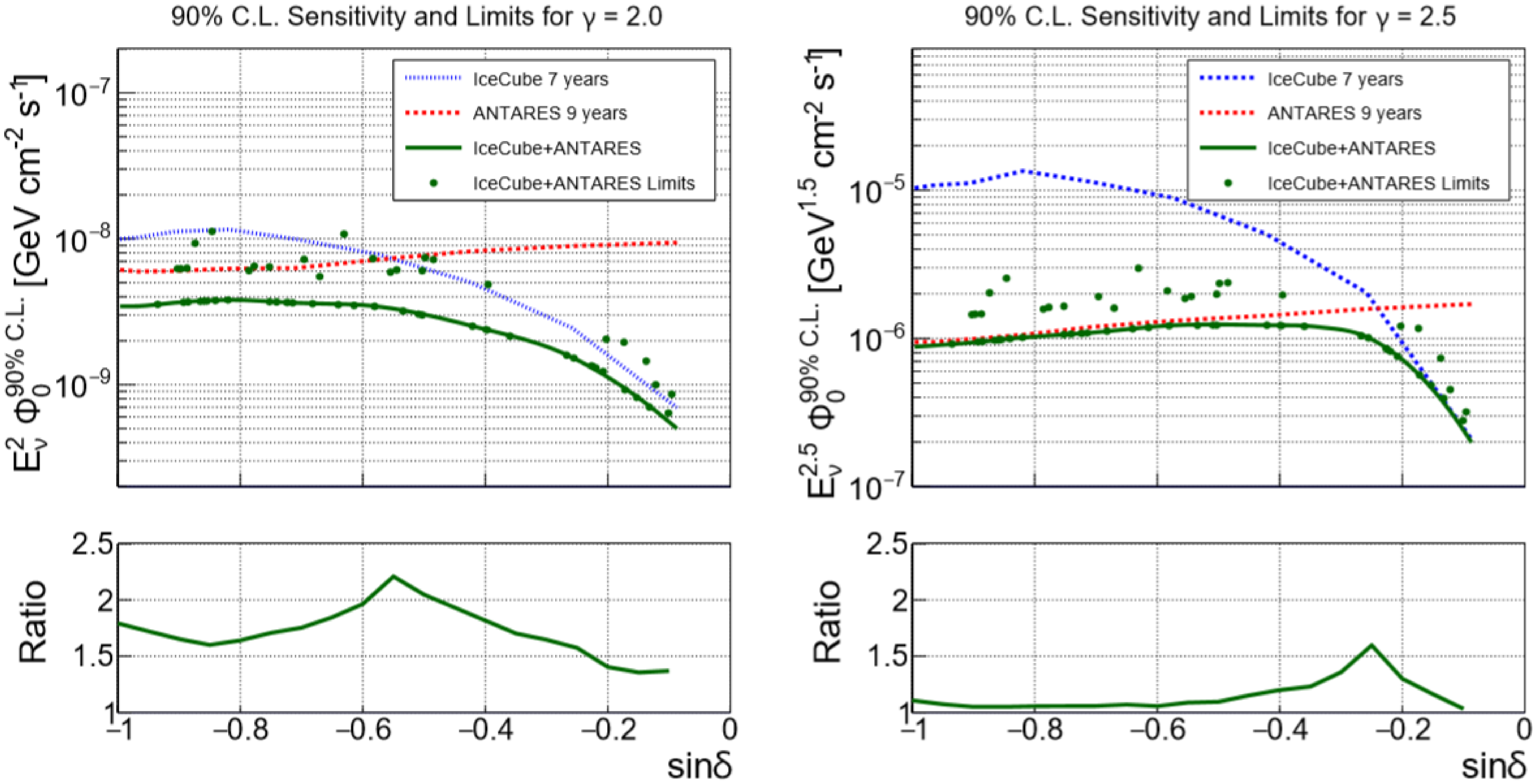


Strongest excess (2.6 σ post trial) close to galaxy NGC 1068 (cross)



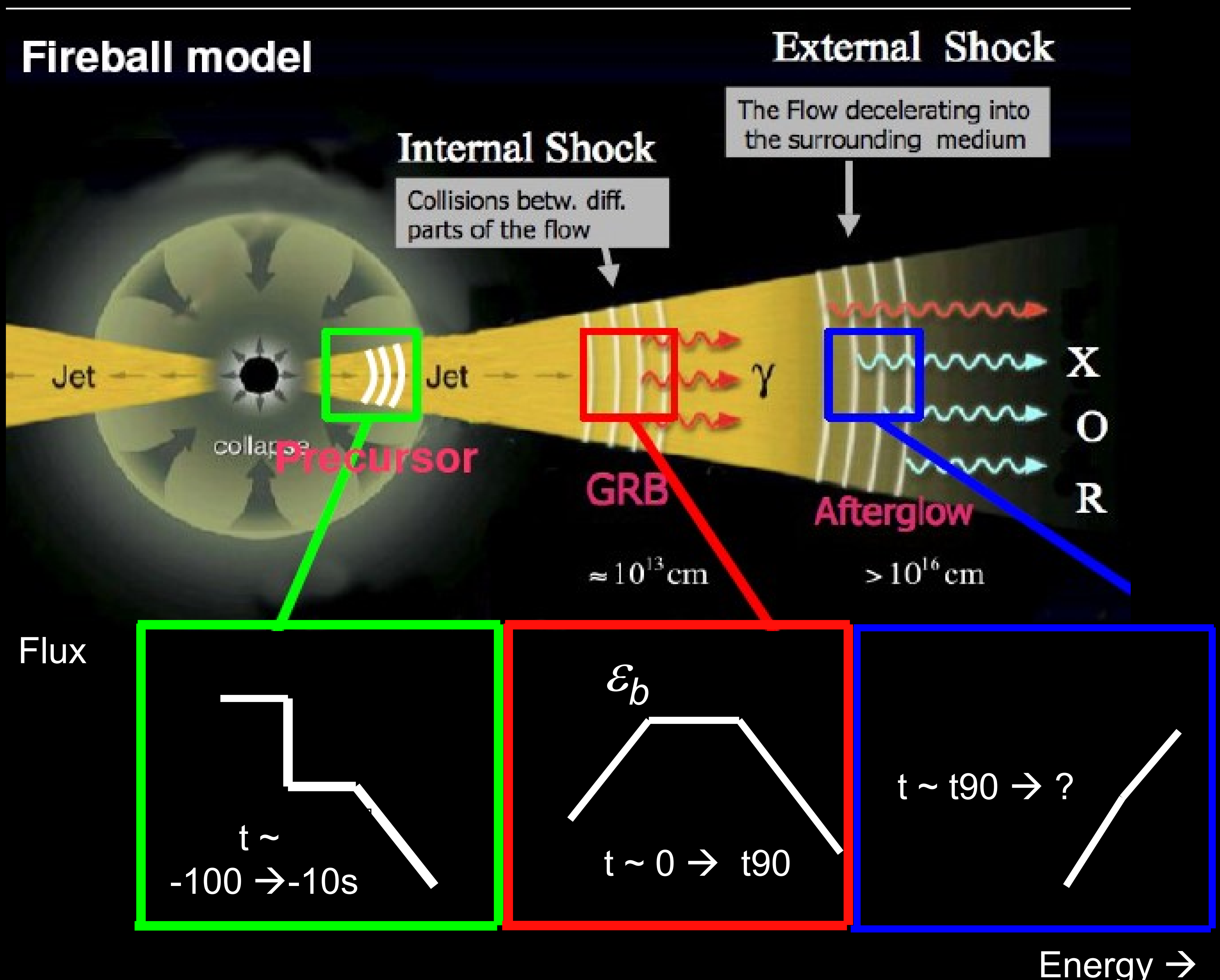
Combining ANTARES and IceCube data

Here: *ANTARES and IceCube Combined Search for Neutrino Point-like and Extended Sources in the Southern Sky* Astrophys. J. 892 (2020) 92

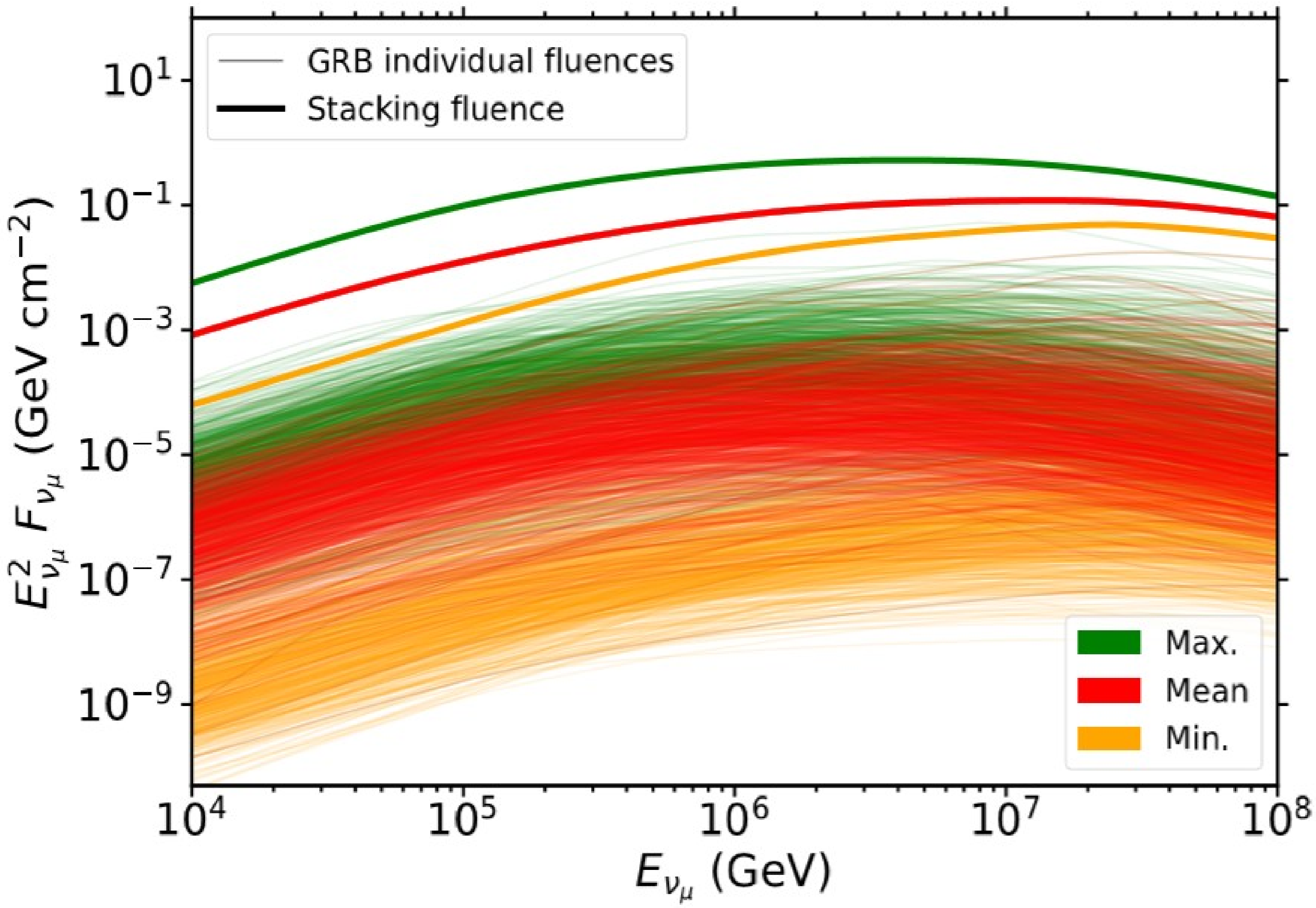


Similar combined searches exist for galactic diffuse emission and galactic dark matter

Neutrinos from GRB



Constraints on the contribution to the diffuse flux

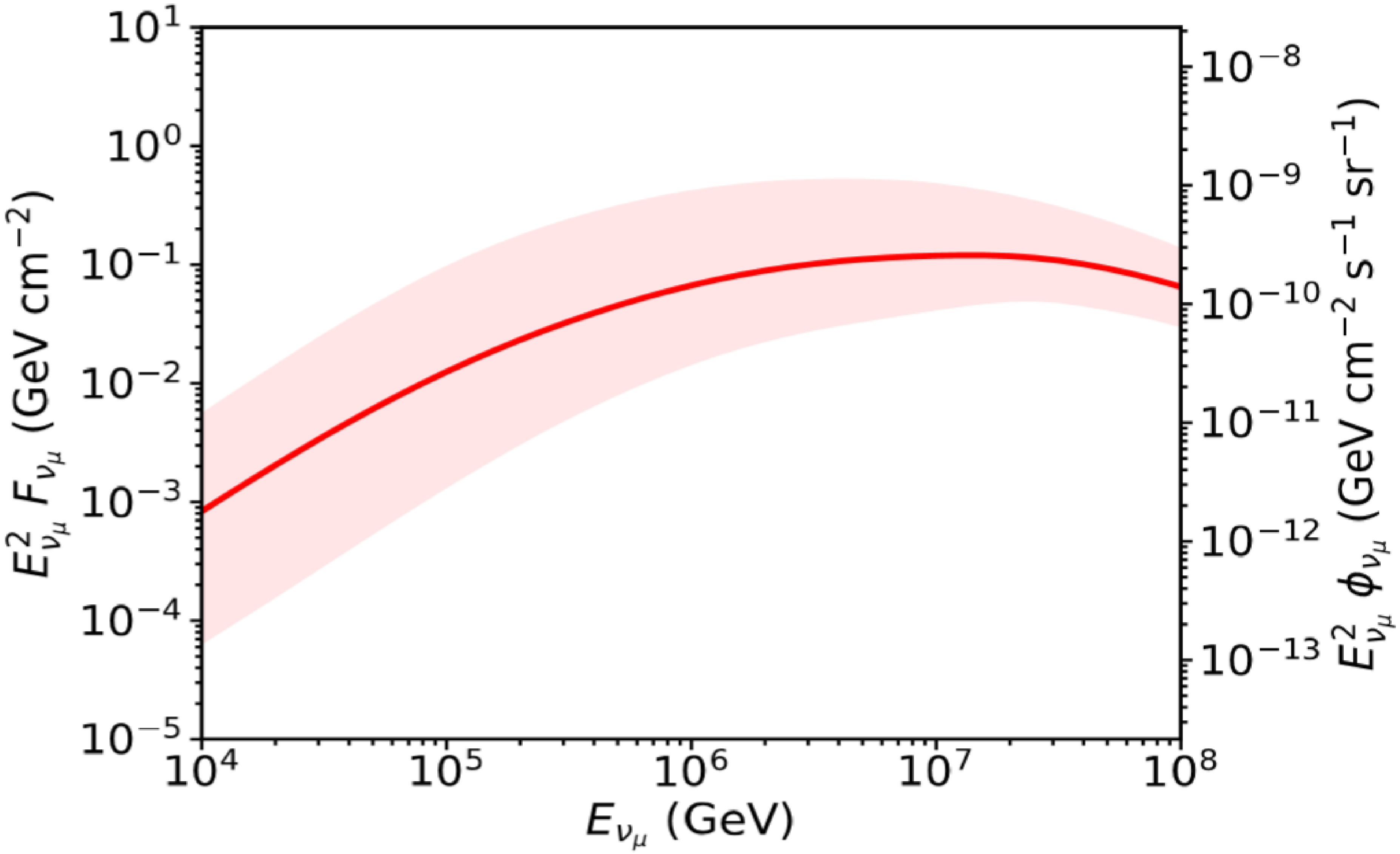


Constraining the contribution of Gamma-Ray Bursts to the high energy diffuse neutrino flux with 10 years of ANTARES data
https://arxiv.org/pdf/2008.02127.pdf

Individual fluences calculated for each of the 784 GRBs (thin lines) and the corresponding stacked fluence (thick line)

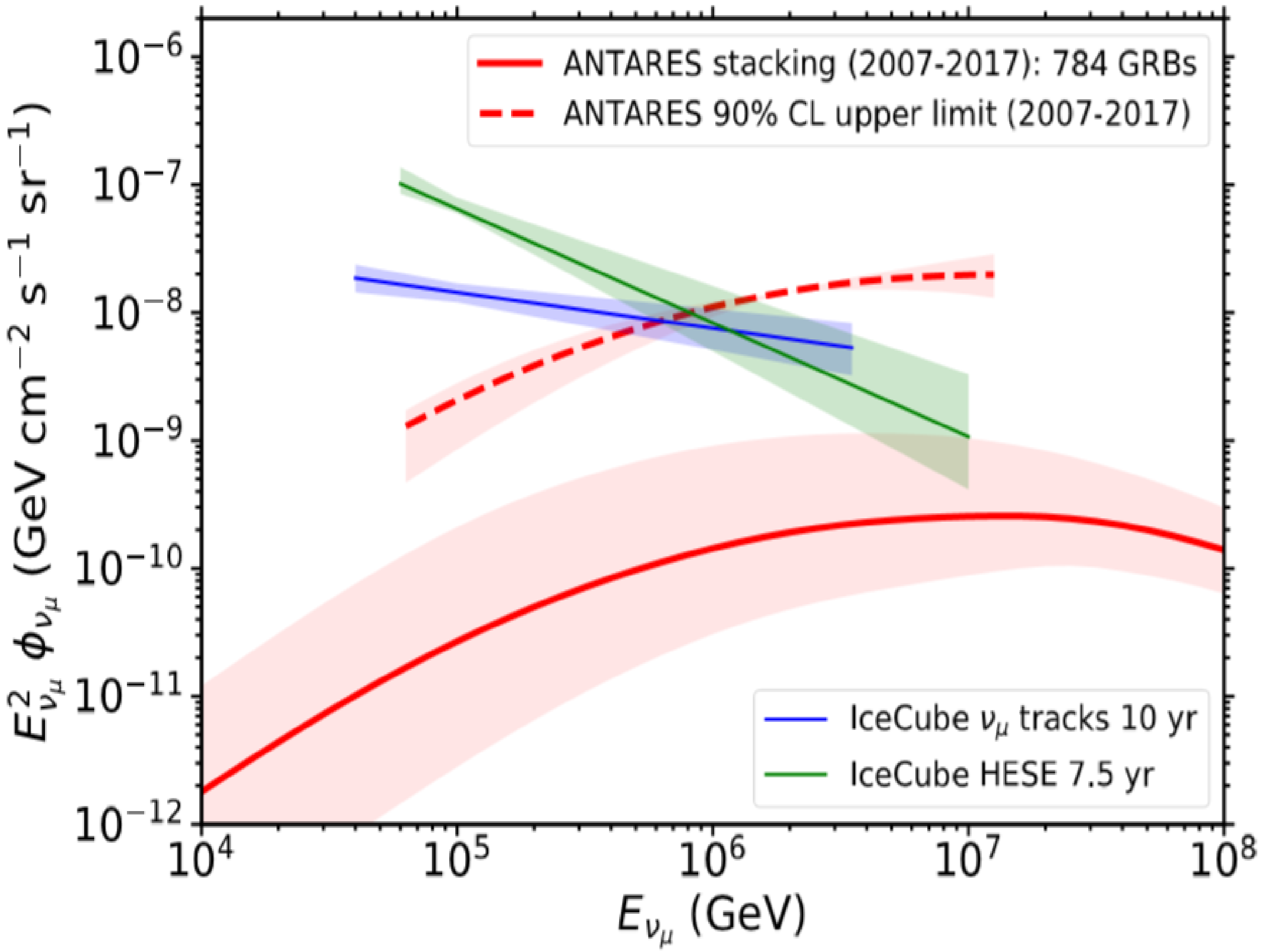
Example:
recent ANTARES result
(10 times less sensitive than IceCube limit !)

Constraints on the contribution to the diffuse flux



Translation of the stacked fluence to the corresponding quasi-diffuse neutrino flux (colored band: min.-to-max. range)

Constraints on the contribution to the diffuse flux



Quasi-diffuse flux for 784 GRBs:

model: red solid line ANTARES 90% CL upper limit: dashed red line.

IceCube best fits for νμ tracks and HESE events: blue and green

GRB cannot contribute more than 10% (ANTARES) / 1% (IceCube) to the IceCube diffuse flux at 100 TeV.

Other stacking searches

Similar stacking searches have been performed for

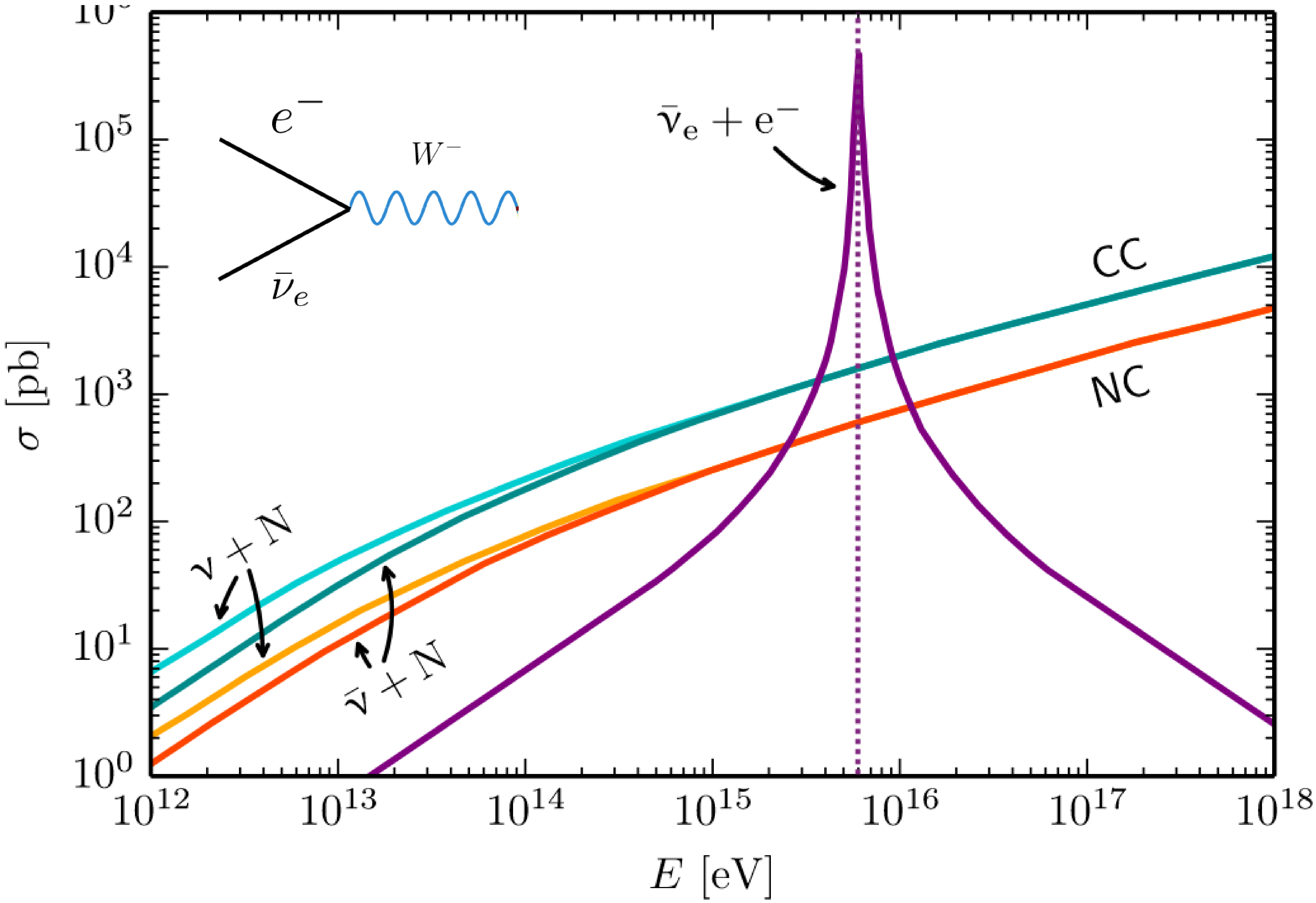
- **Gamma-loud blazars**
- **Flat spectrum radio quasars (FSRQs)**
- **…**

with all IceCube searches resulting in upper limits

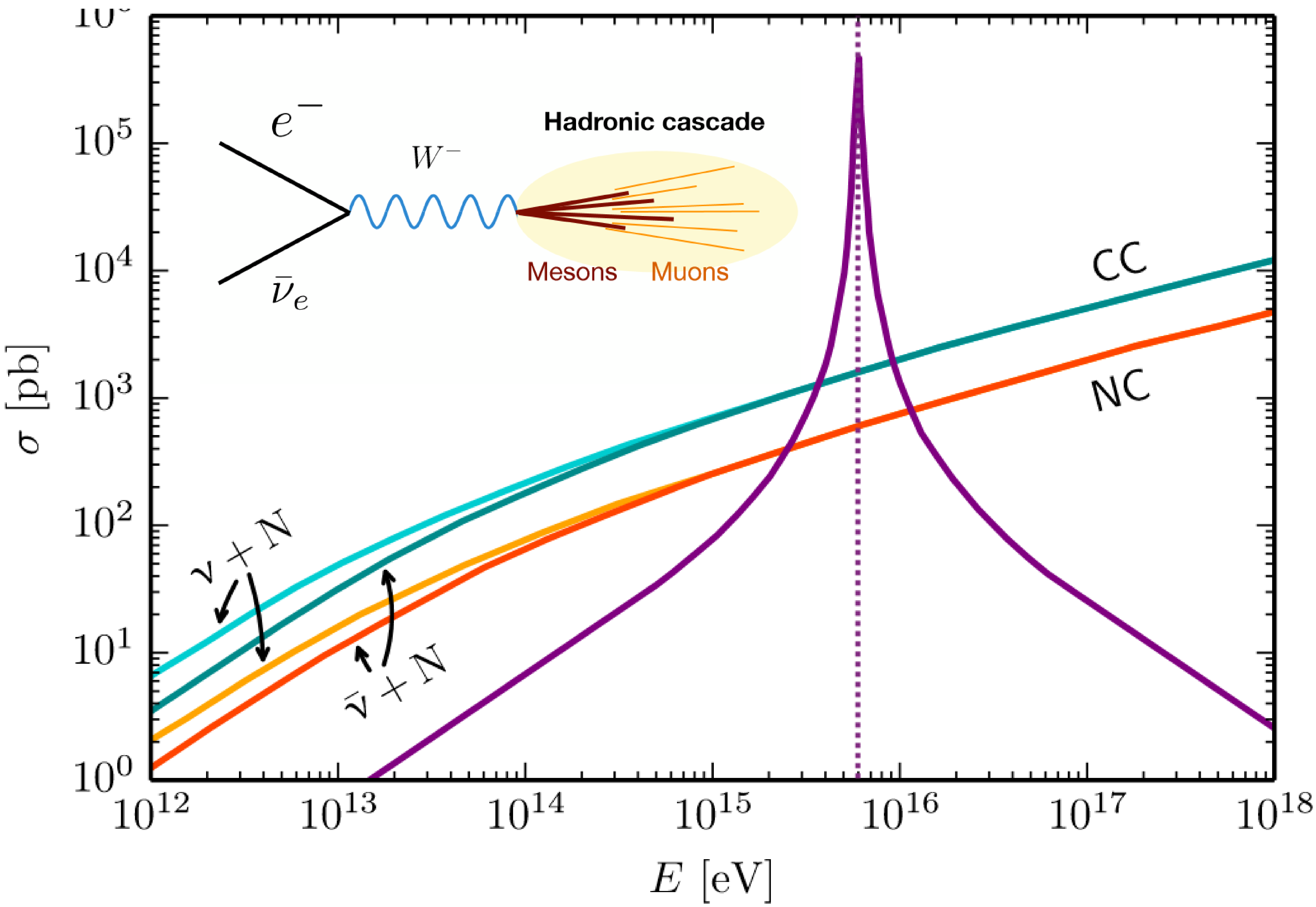
- See, however, A. Plavin, Y. Kovalev, Yu. Kovalev, S. Troitsky: **Directional association of TeV to PeV astrophysical neutrinos with active galaxies hosting compact radio jets,** arXiv:2009.08914, subm. to ApJ, and yesterday talk of A. Plavin

Two Very Special Events

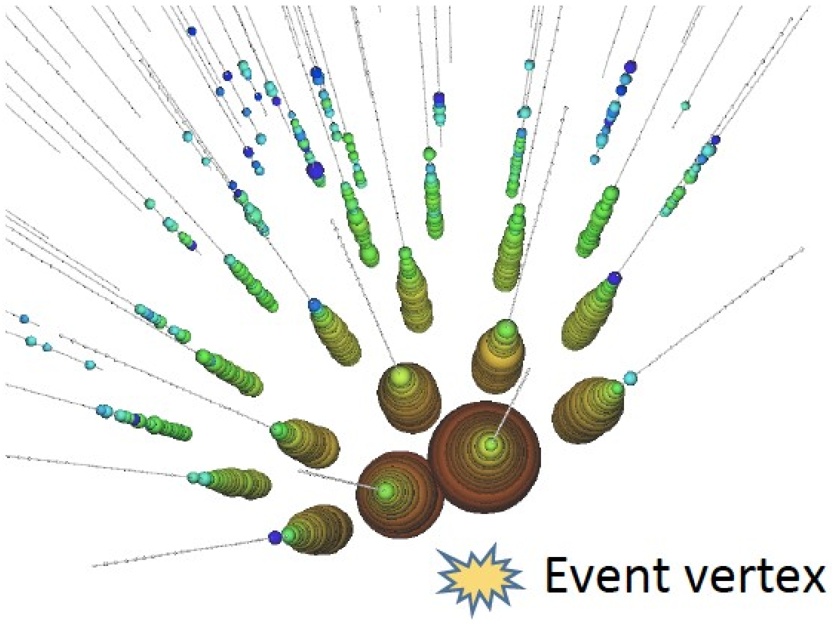
The first candidate for the Glashow resonance

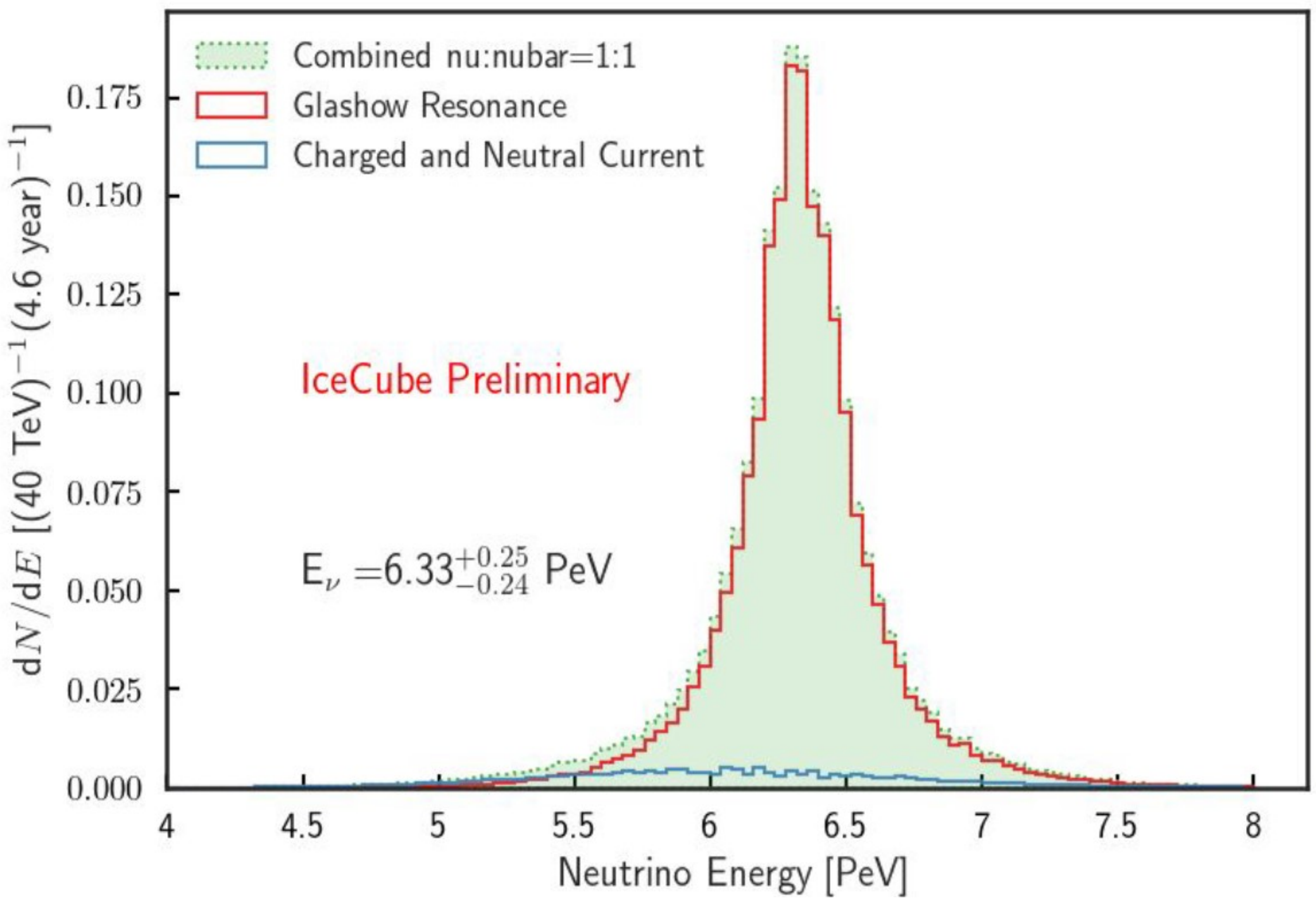


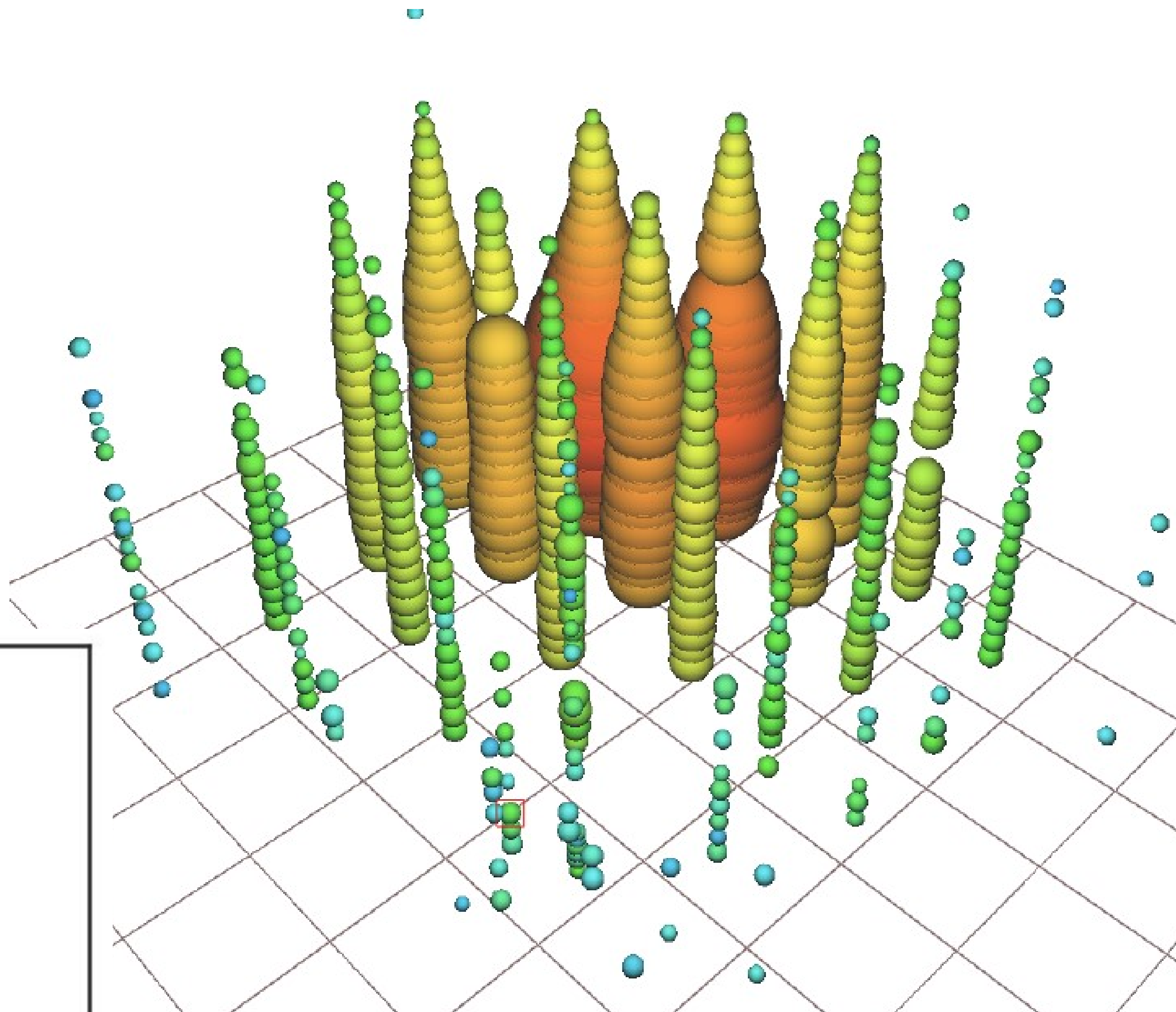
The first candidate for the Glashow resonance



Partially contained event with E = 6.3 PeV





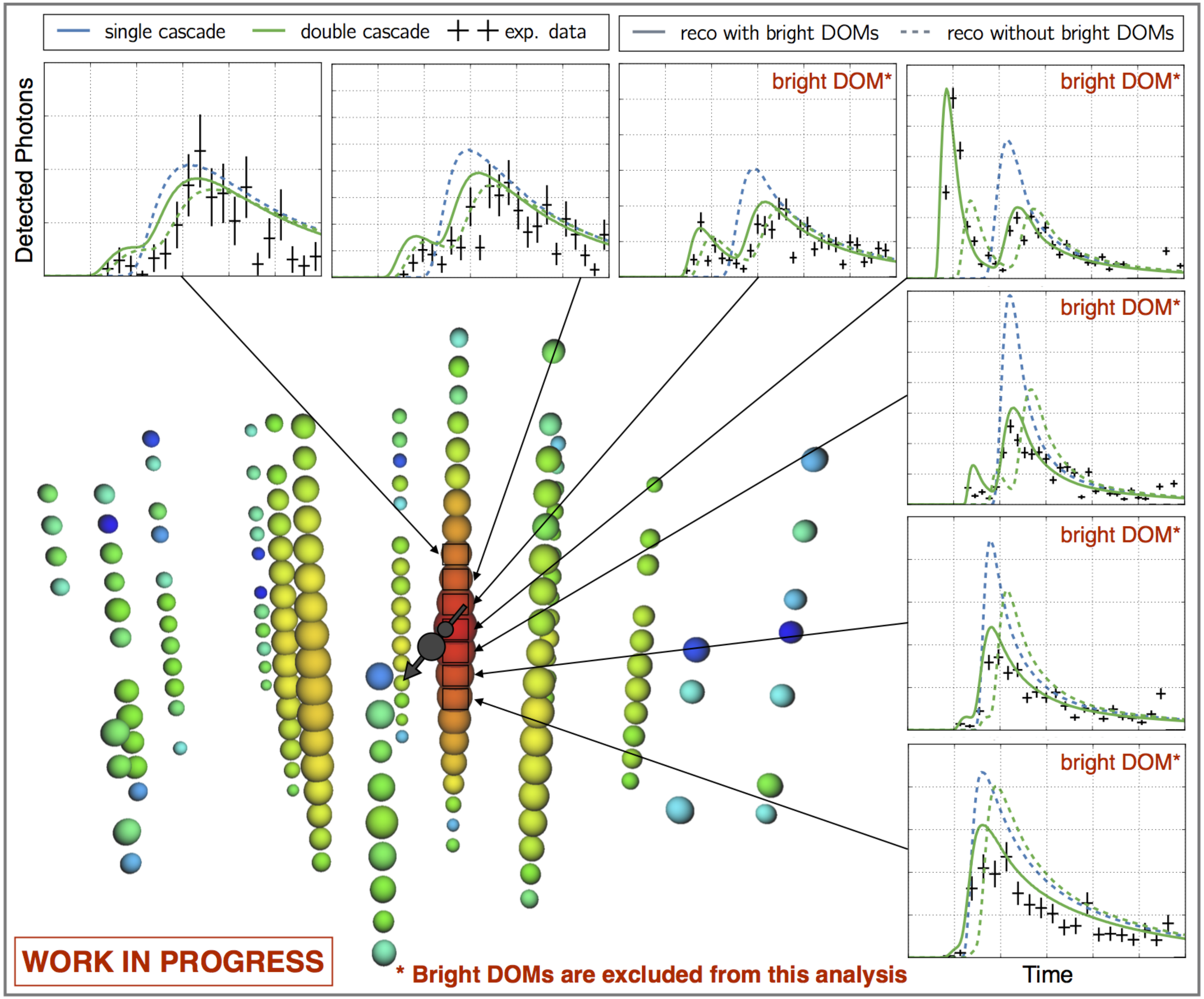


First identification of a clear candidate for an anti-electronneutrino in an underwater detector !

First tau-neutrino candidate

Looking for double-bang events
(Tau decay length is ~ 50 m at 1 PeV)

Two candidate events in 7.5 years of data

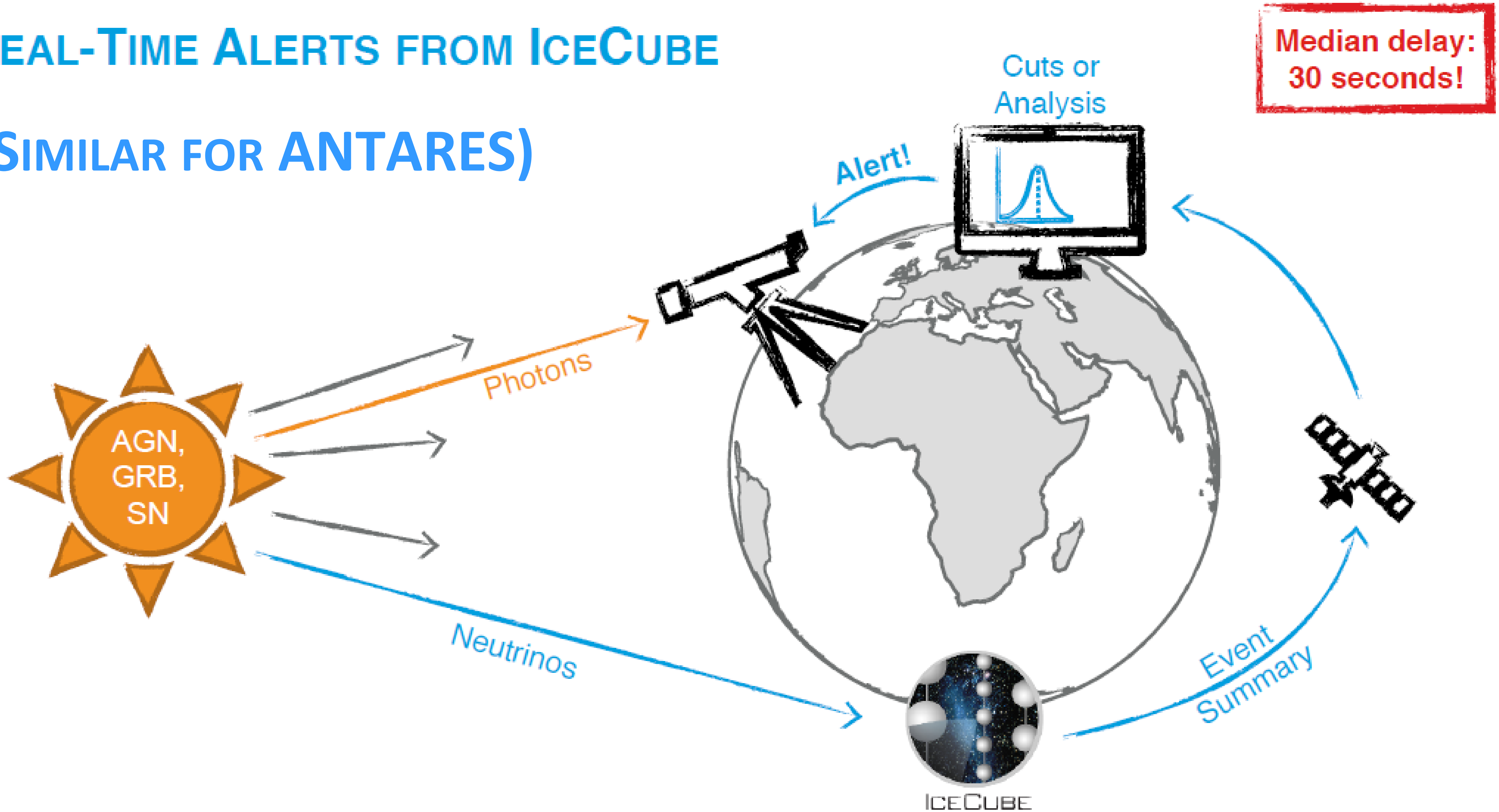


Multi-Messenger Results

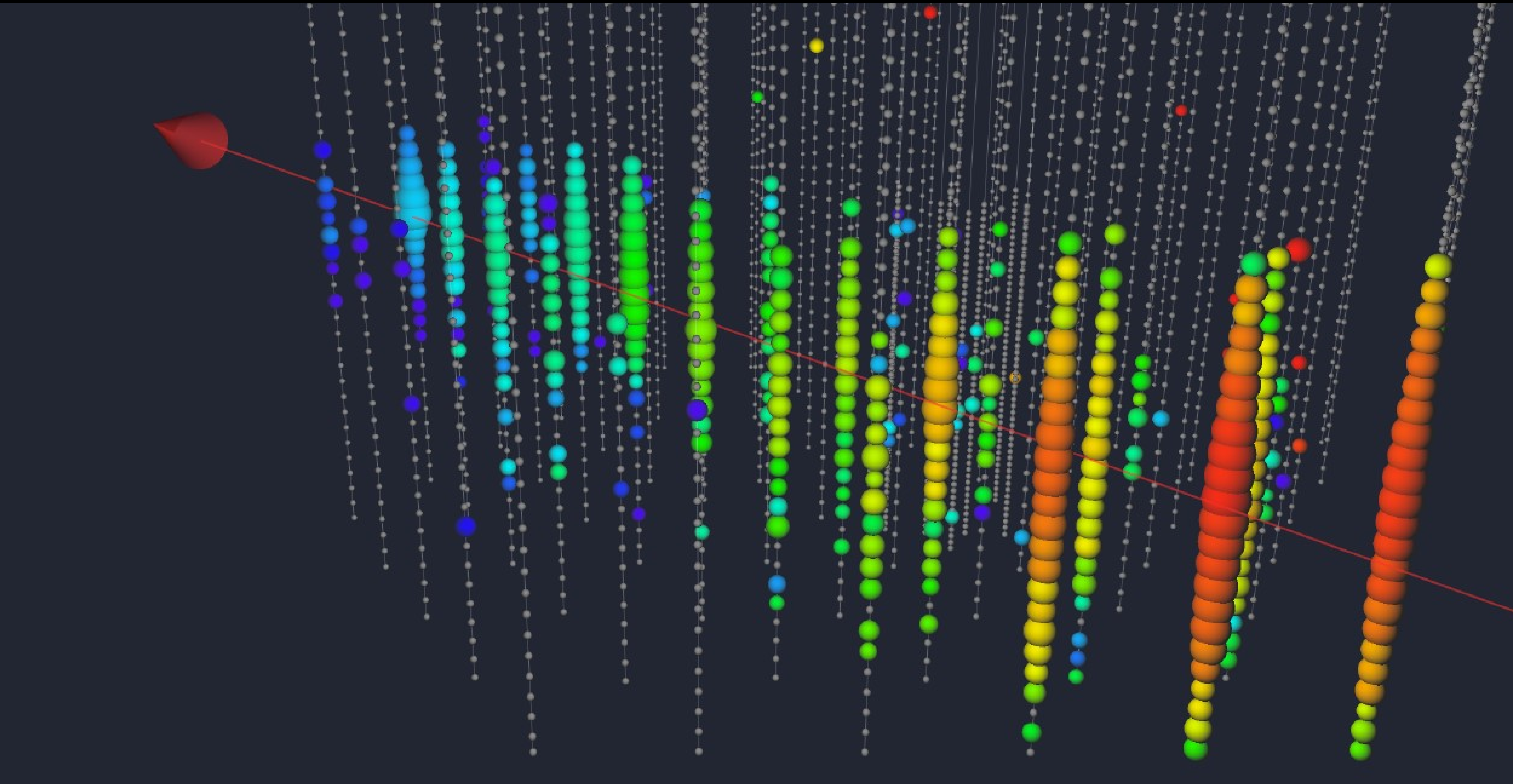
Alerts to optical, radio and gamma-ray telescopes and to x-ray detectors on satellites

REAL-TIME ALERTS FROM ICECUBE

(SIMILAR FOR ANTARES)



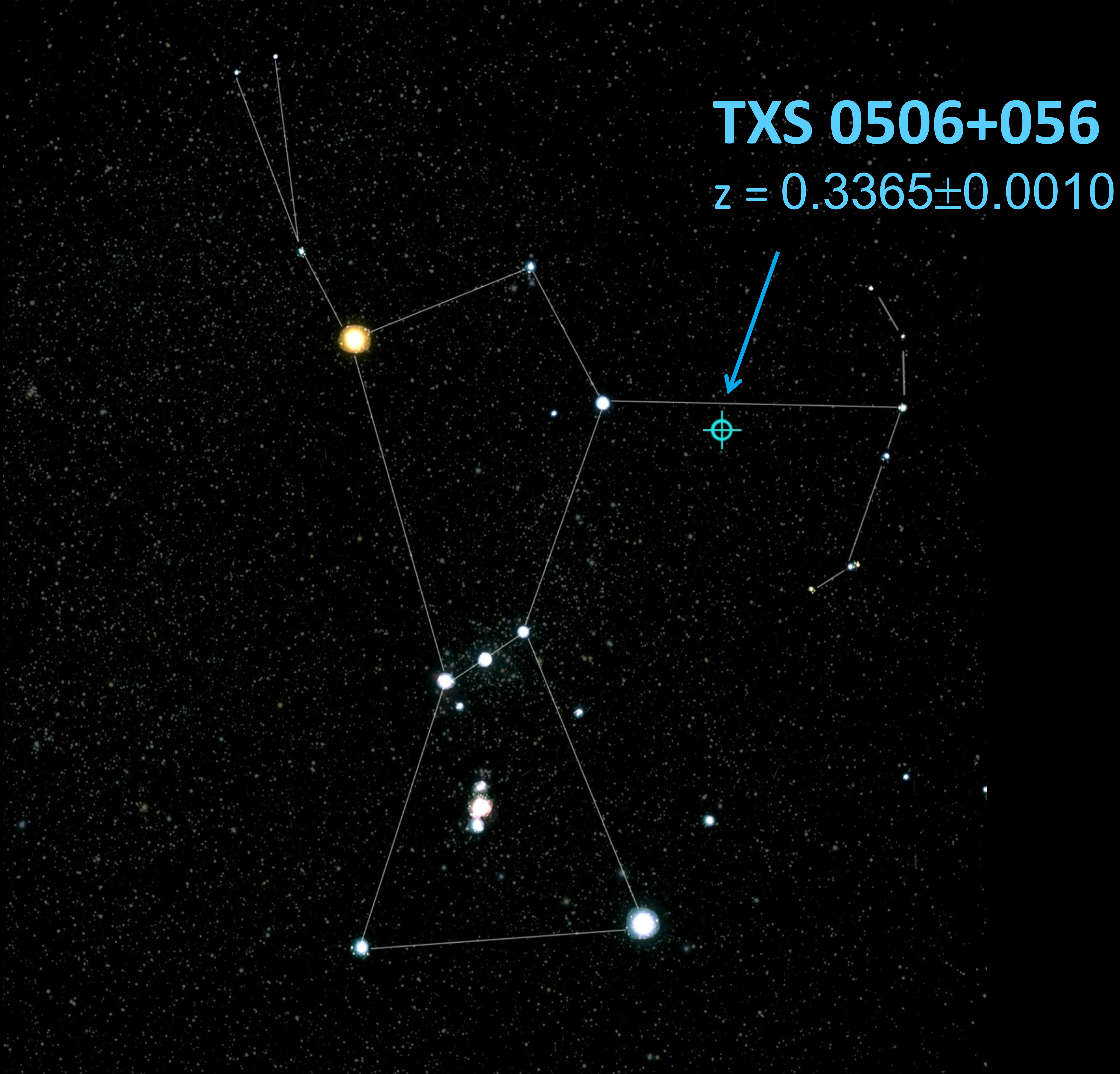
The first point source candidate



22. September 2017, 20:54 UTC

The first point source candidate

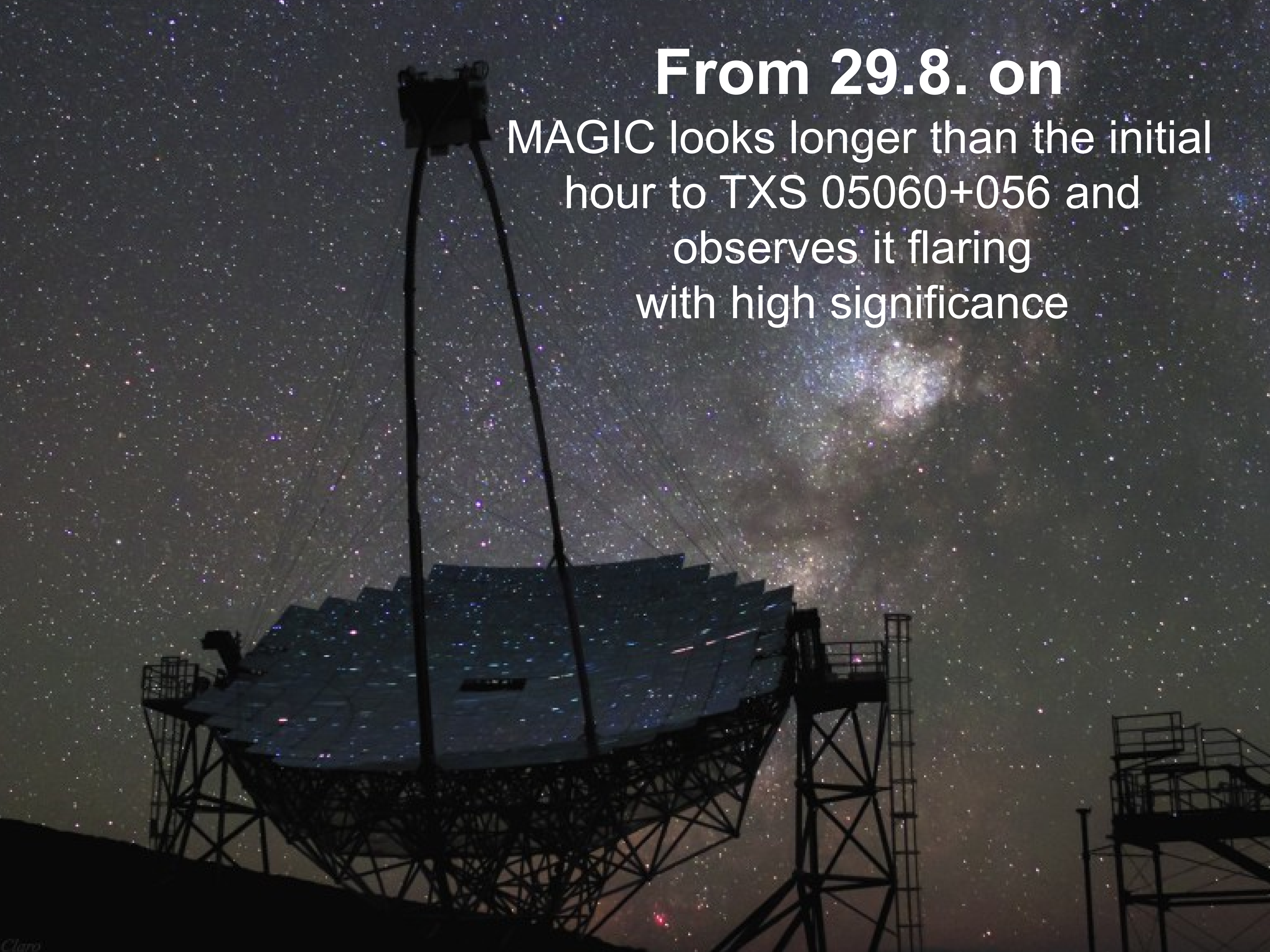
- 43 seconds later: first alarm with preliminary direction
- Sequence of refined reconstruction algorithms
- ~ 4 hours later: GCN Circular issued
- Only 0.1° off the position of the known γ-ray blazar TXS 0506+056.
- Most probable energy of the neutrino ~290 TeV.
- Broad multi-wavelength campaign



TXS 0506+056
z = 0.3365±0.0010

28. 9. Fermi-Satellite:

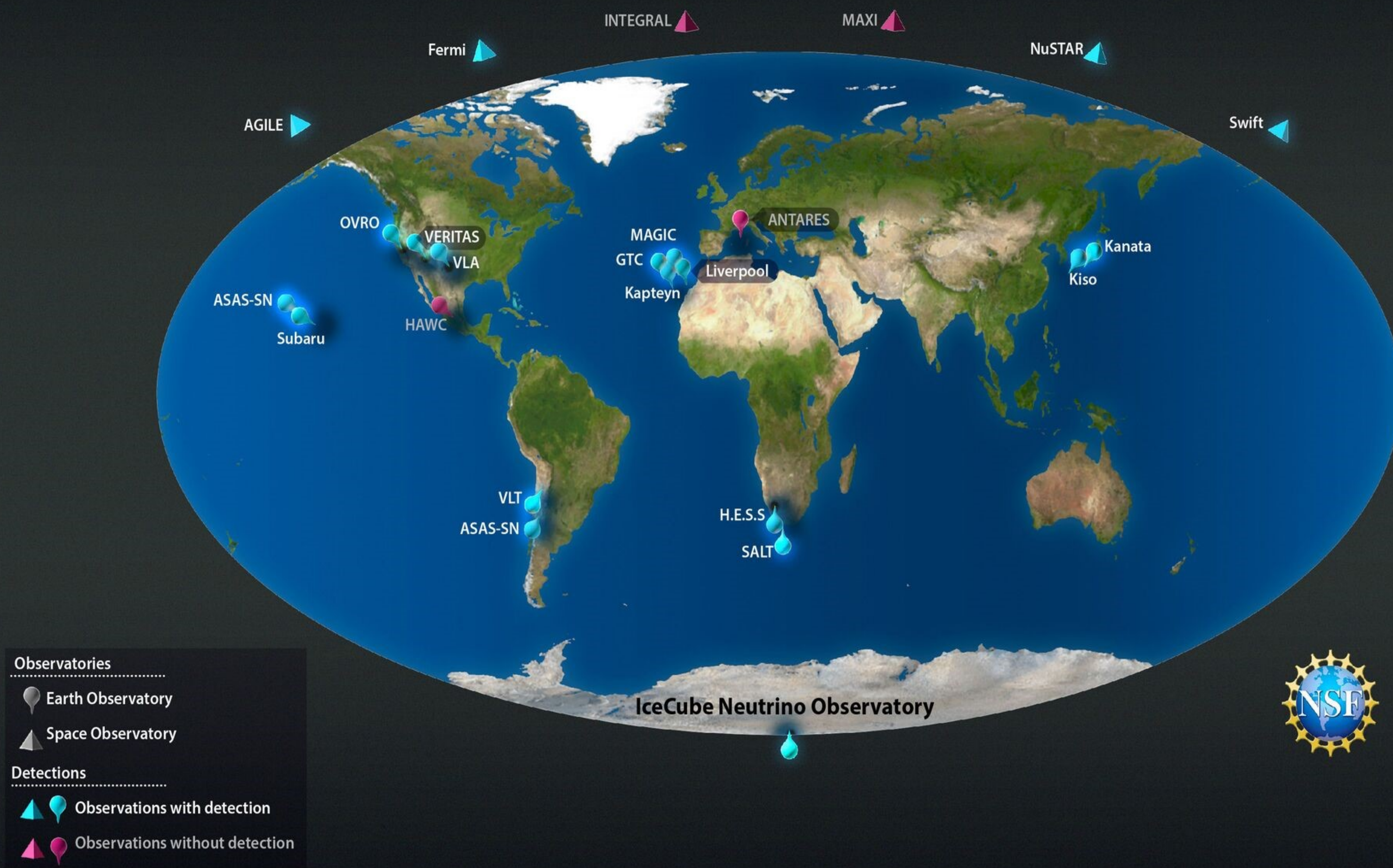
- Source: Active Galaxy TXS 0505+056, which is in a flaring state



From 29.8. on

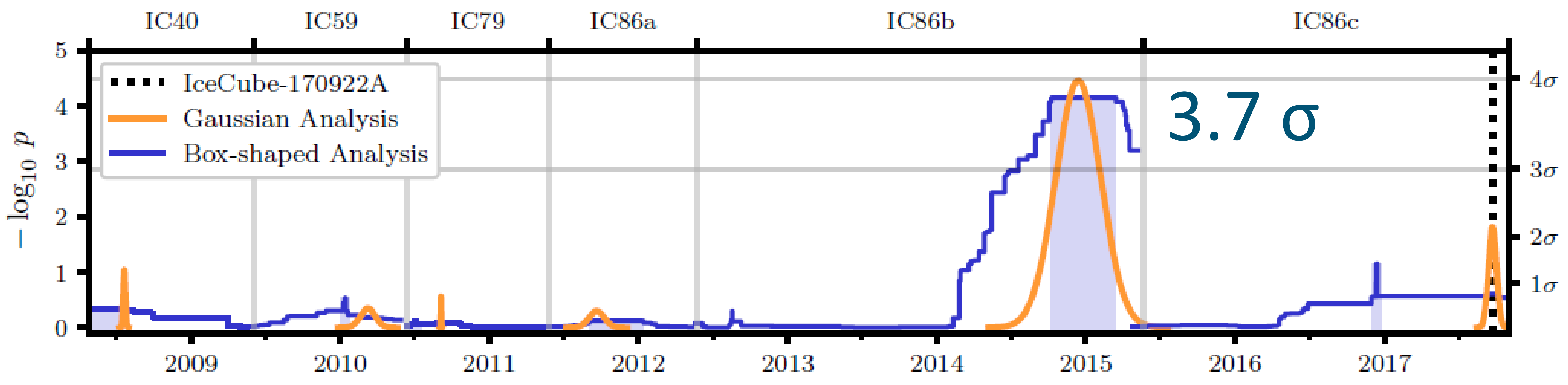
MAGIC looks longer than the initial hour to TXS 05060+056 and observes it flaring with high significance

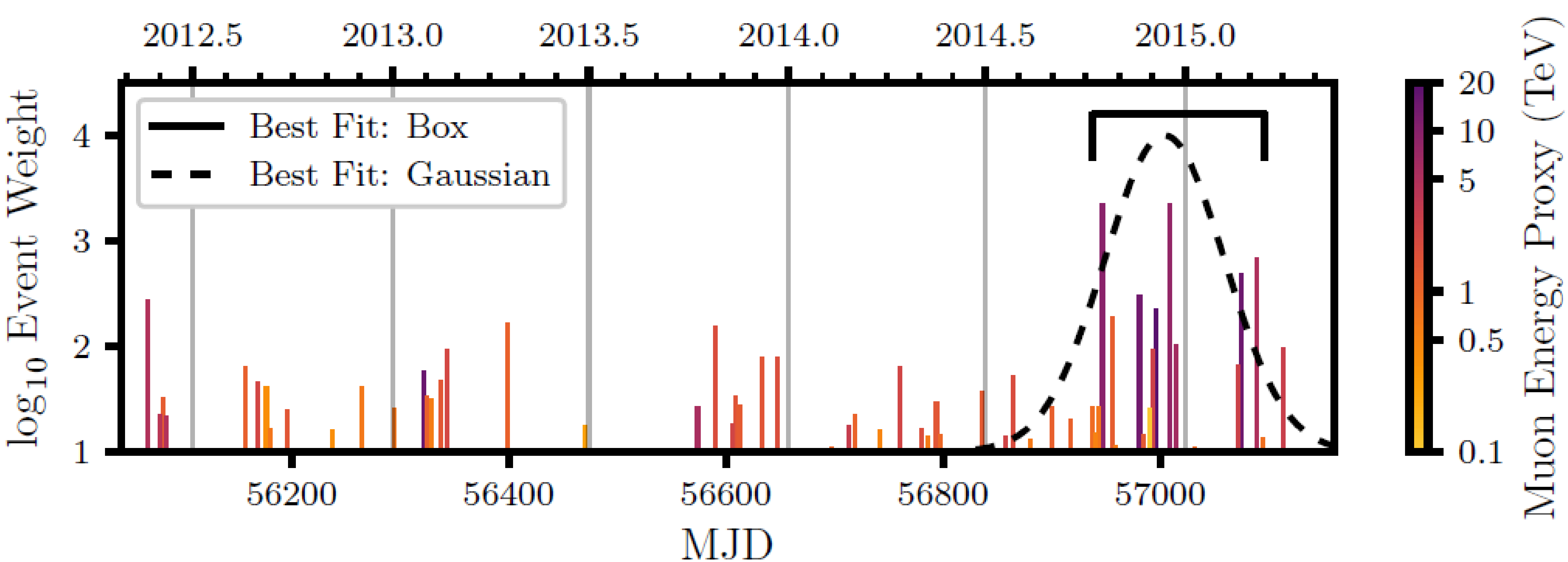
Follow-up Observations of IceCube Alert IC170922



Looking back to archival data

Science 361 (2018) 147





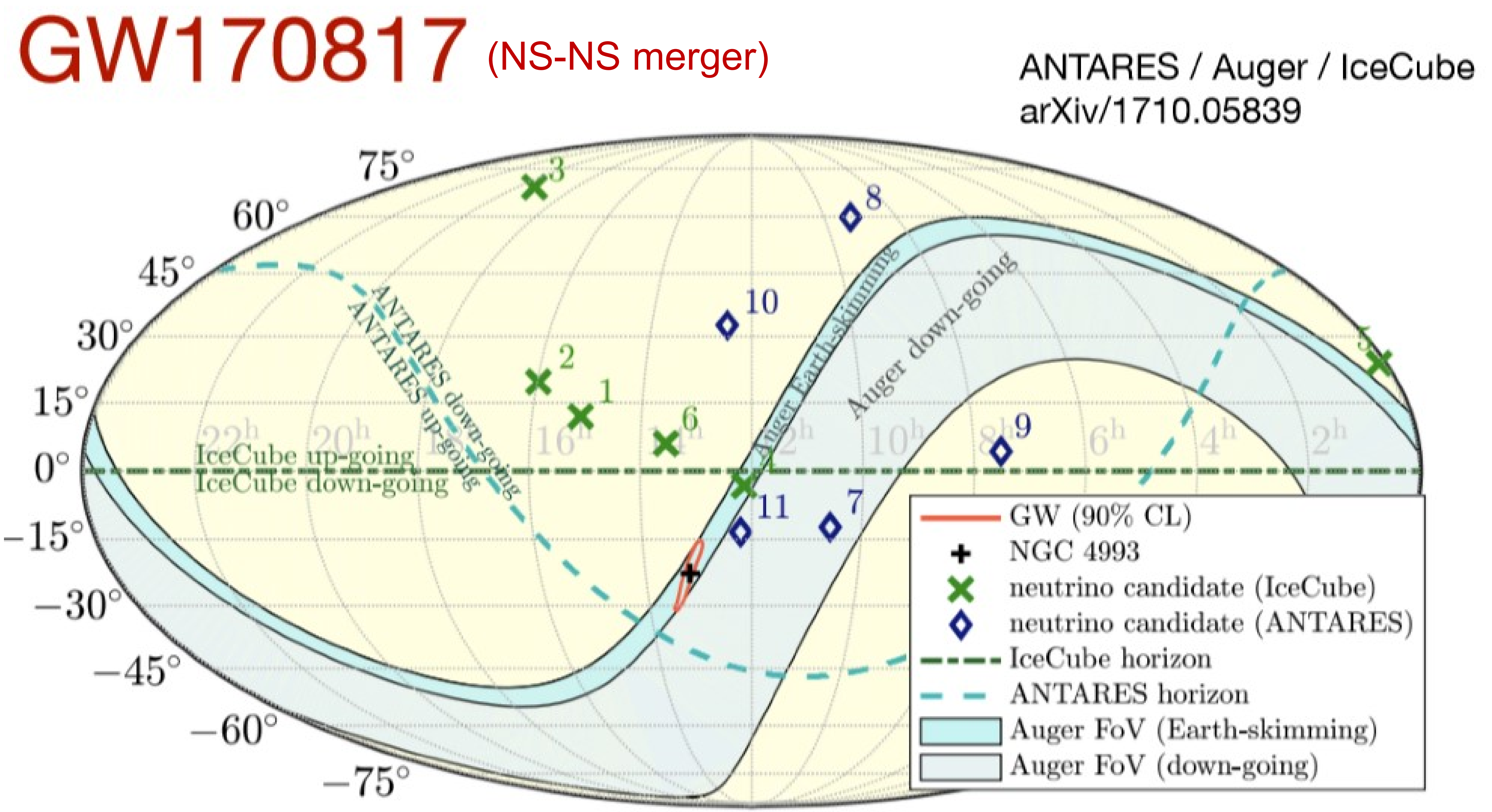
Conclusions on TXS 0506+056

- Strong evidence (but not yet an undisputable discovery, i.e. an effect of 5 standard deviations), that blazars, especially TXS 0506+056, belong to the sites of very-high-energy cosmic ray acceleration.

Fantastic demonstration of the potential of multi-messenger observations !

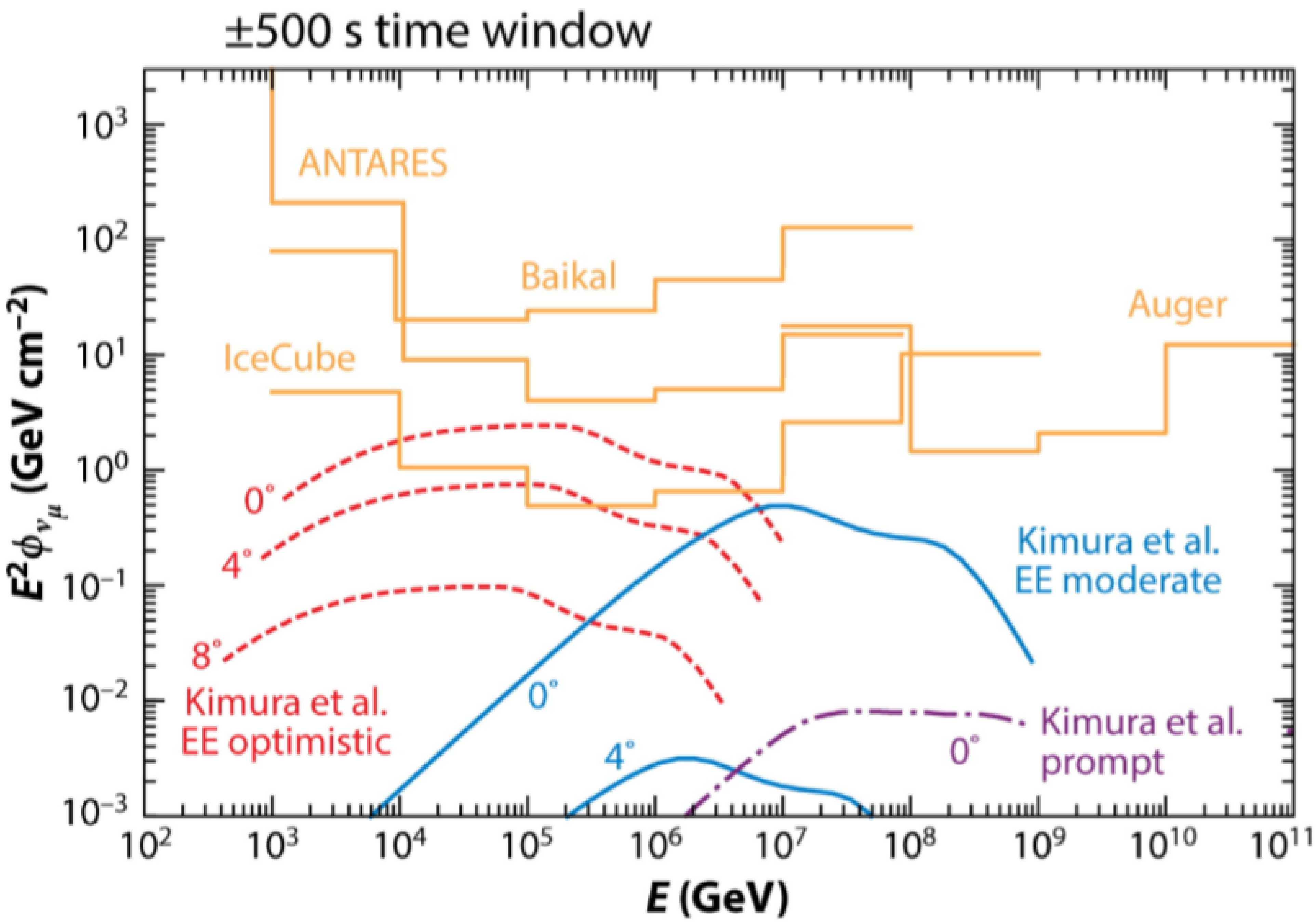
Search for neutrinos from GW170817

See “SEARCH FOR HIGH-ENERGY NEUTRINOS FROM BINARY NEUTRON STAR MERGER GW170817 WITH ANTARES, ICECUBE, AND THE PIERRE AUGER OBSERVATORY”



Search for neutrinos from GW170817

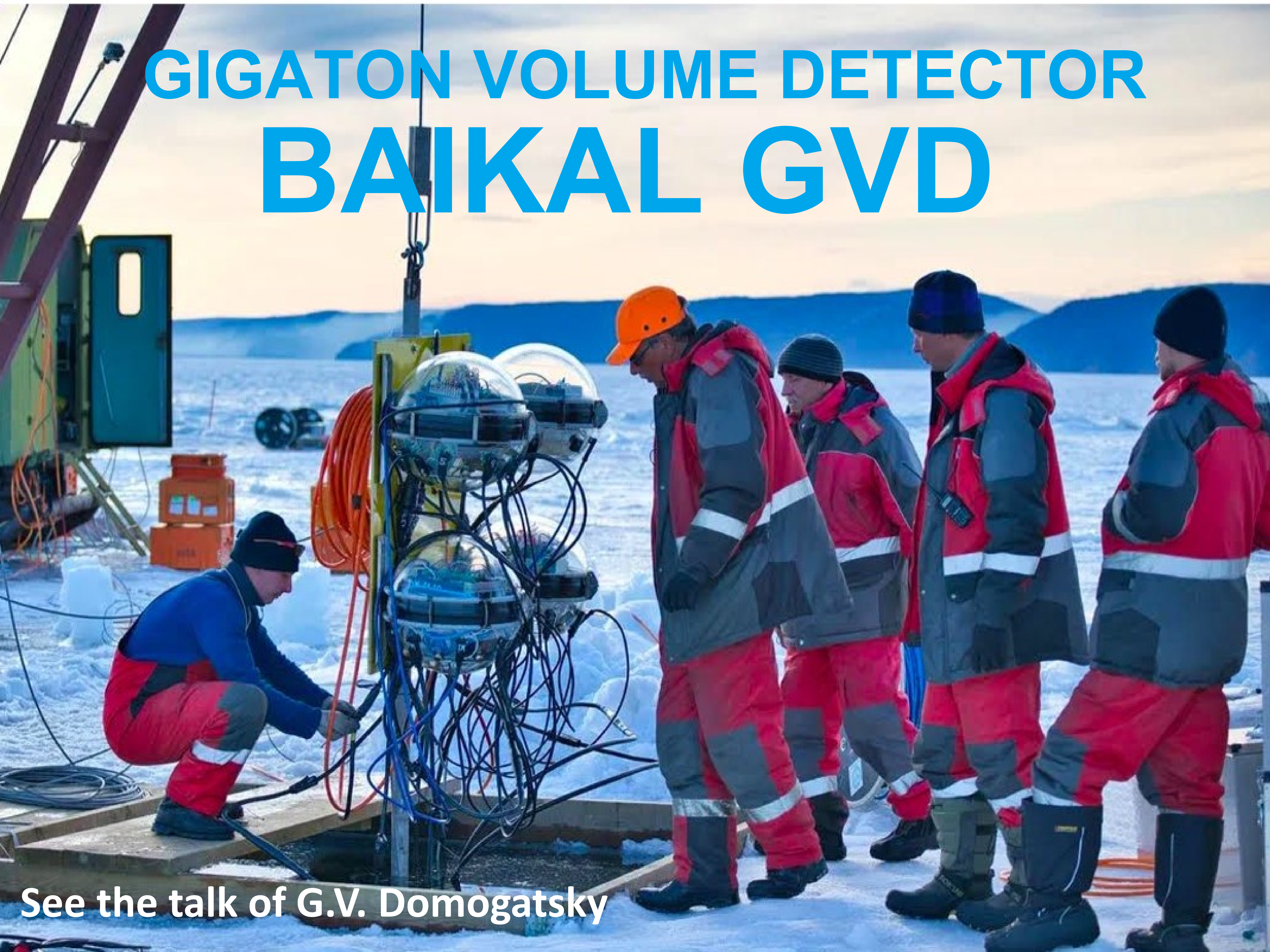
Figure from "SEARCH FOR HIGH-ENERGY NEUTRINOS FROM BINARY NEUTRON STAR MERGER GW170817 WITH ANTARES, ICECUBE, AND THE PIERRE AUGER OBSERVATORY", Figure taken from K. Murase, I. Bartos, *Ann.Rev.Nucl.Part Sci*. 69, 477. Baikal results: JETP Letters, 108, 12

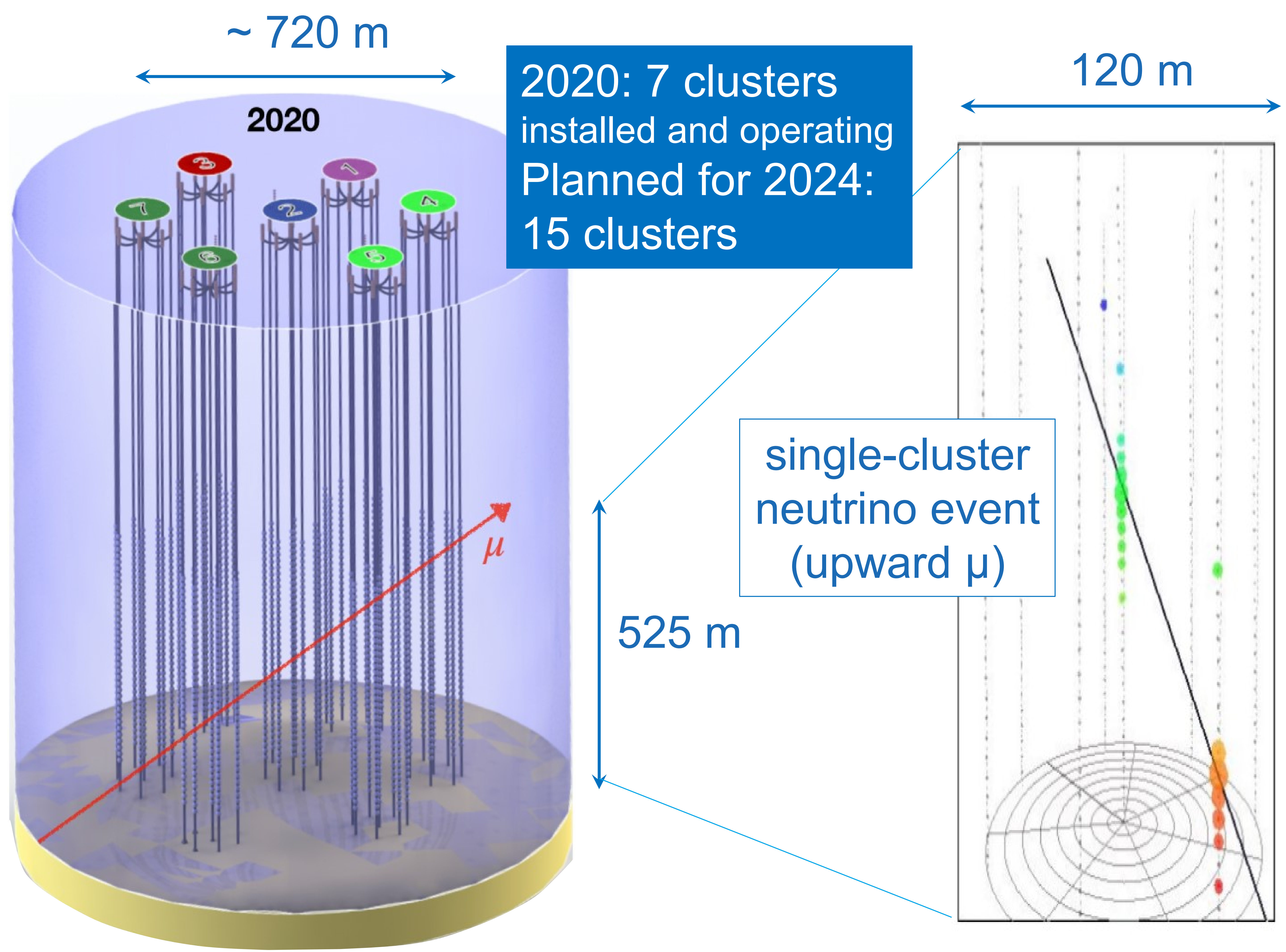


Summary of where we stand

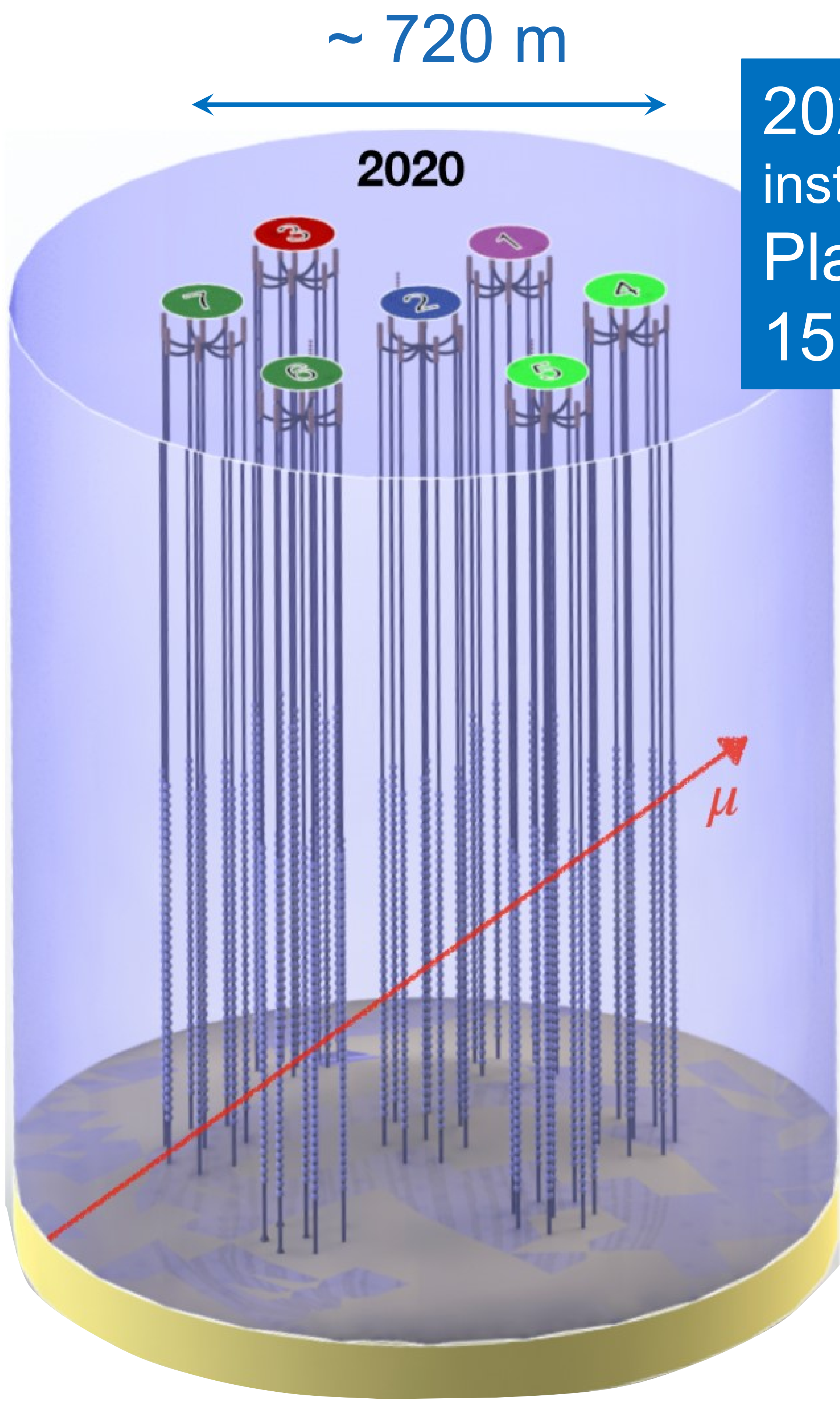
- **Cosmic high-energy ν discovered**
- **Opened new window, but landscape not yet charted: no steady point sources identified up to now**
- **Also: remaining uncertainties on spectrum and flavor composition**
- **Some individual sources in reach!**
- **Excluded GRB, Blazars, …. as sole source of HESE events**

Where do we go?


GIGATON VOLUME DETECTOR
BAIKAL GVD
See the talk of G.V. Domogatsky



~ 720 m
2020
2020: 7 clusters
installed and operating
Planned for 2024:
15 clusters
120 m
μ
single-cluster
neutrino event
(upward μ)
525 m



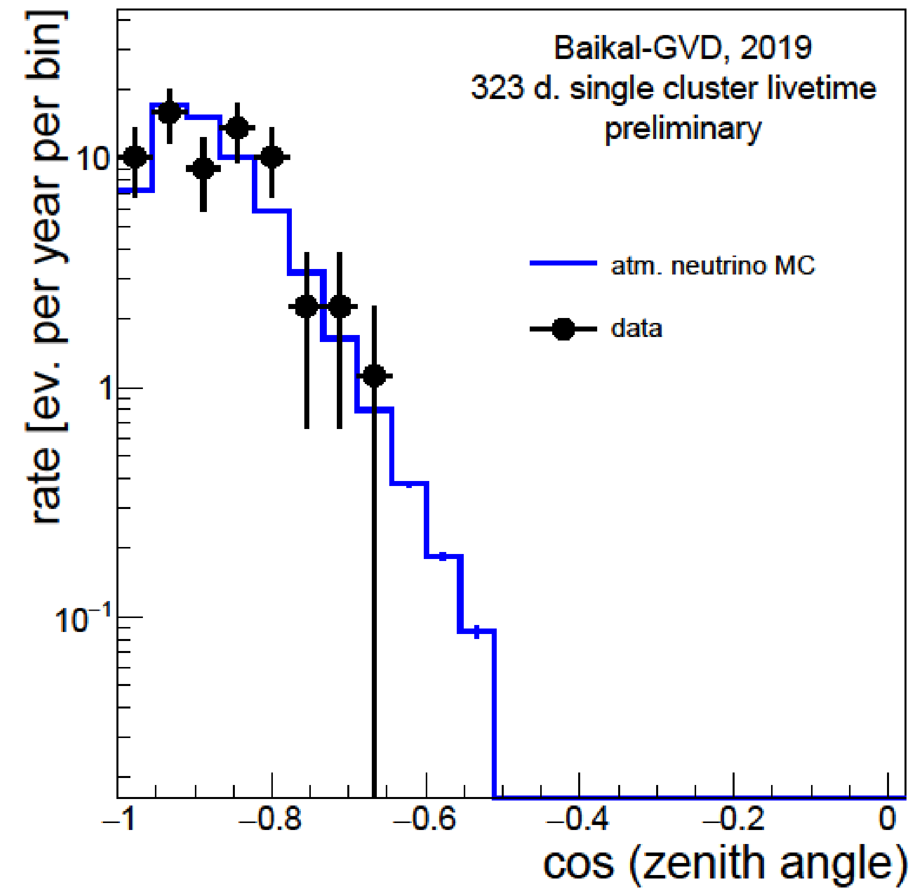
2020: 7 clusters
installed and operating
Planned for 2024:
15 clusters

Year	Total number of clusters	Total number of strings	Number of OMs
2016	1	8	288
2017	2	16	576
2018	3	24	864
2019	5	40	1440
2020	**7**	**56**	**2016**
2021	9	72	2592
2022	11	88	3168
2023	13	104	3744
2024	15	120	4320

Baikal GVD: examples of first results

- **Upward going muons from neutrino interactions (single cluster events)**

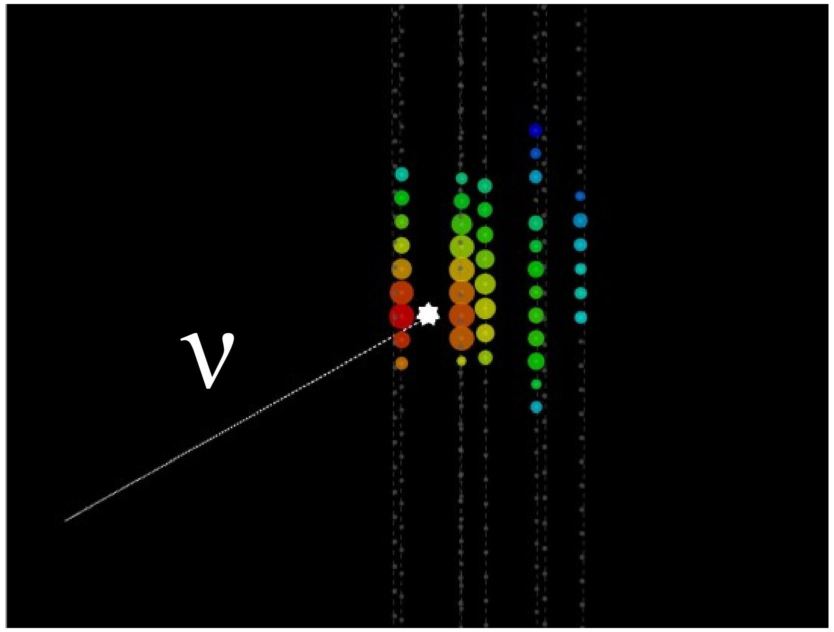
Taken from G. Domogatsky's talk from yesterday



- **High energy cascades**

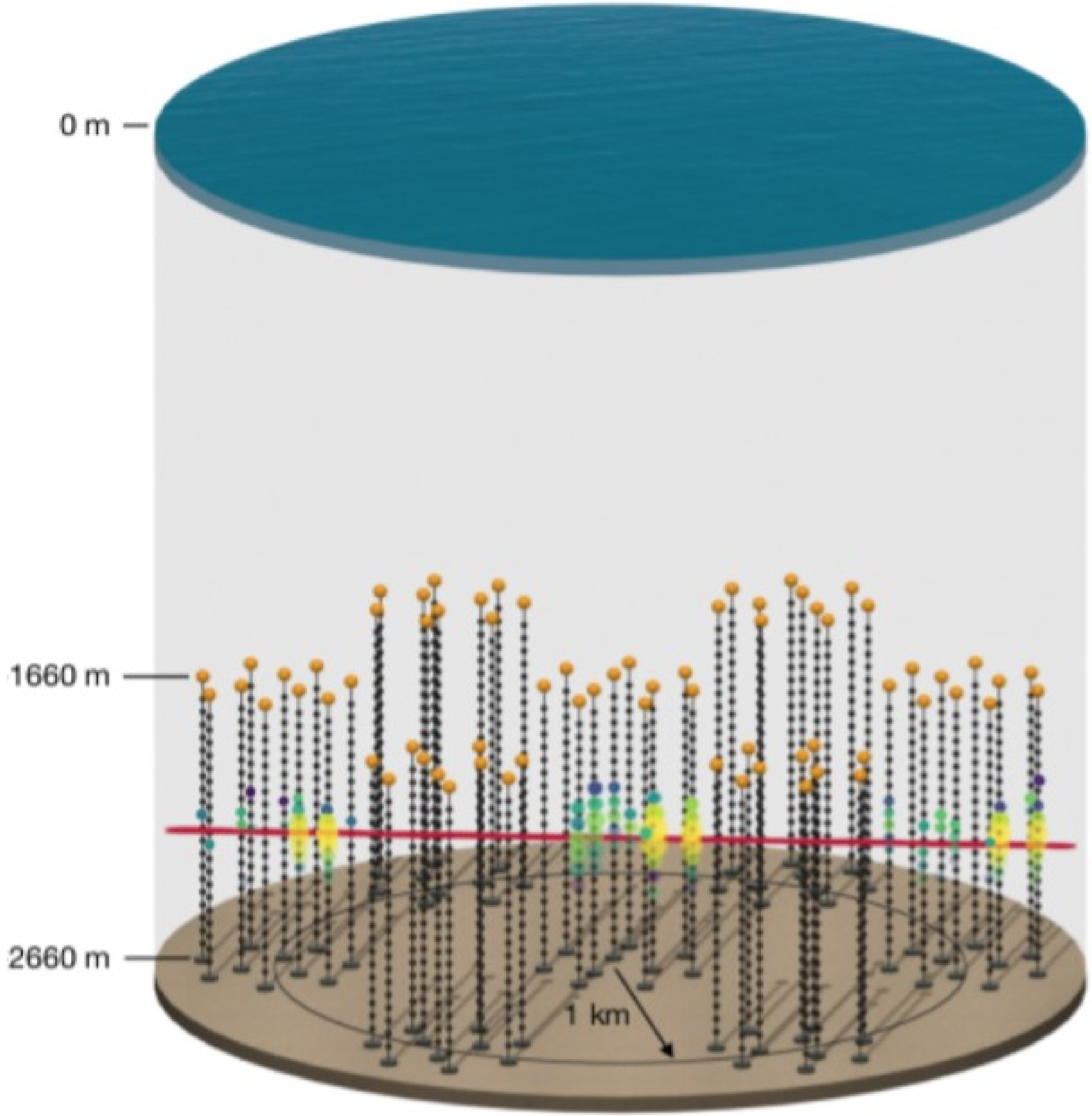
Livetime 4.36 years × cluster:

12 candidates with E ≥ 100 TeV and > 19 hits, plus 2 upward going events with 93.3 TeV (35 hits) and 22.9 TeV (23 hits)



- **Limits on neutrinos from GW 170817**
  (see previous slides on multi-messenger results)

The Pacific Ocean Neutrino Experiment



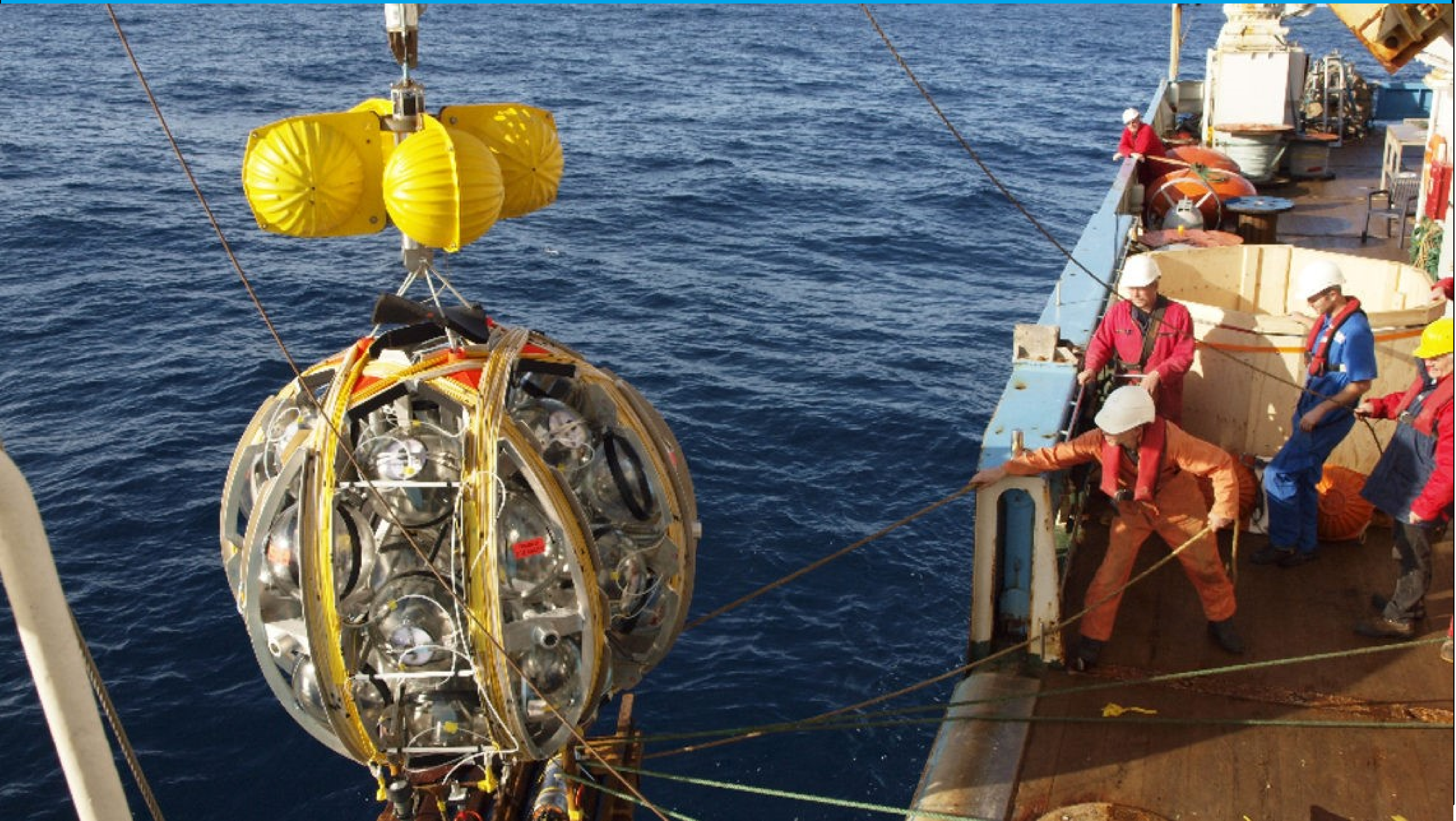
Prototyping for a multi-cluster array at the km³ scale (Canadian Pacific coast)

Makes use of existing infrastructure of oceanographers

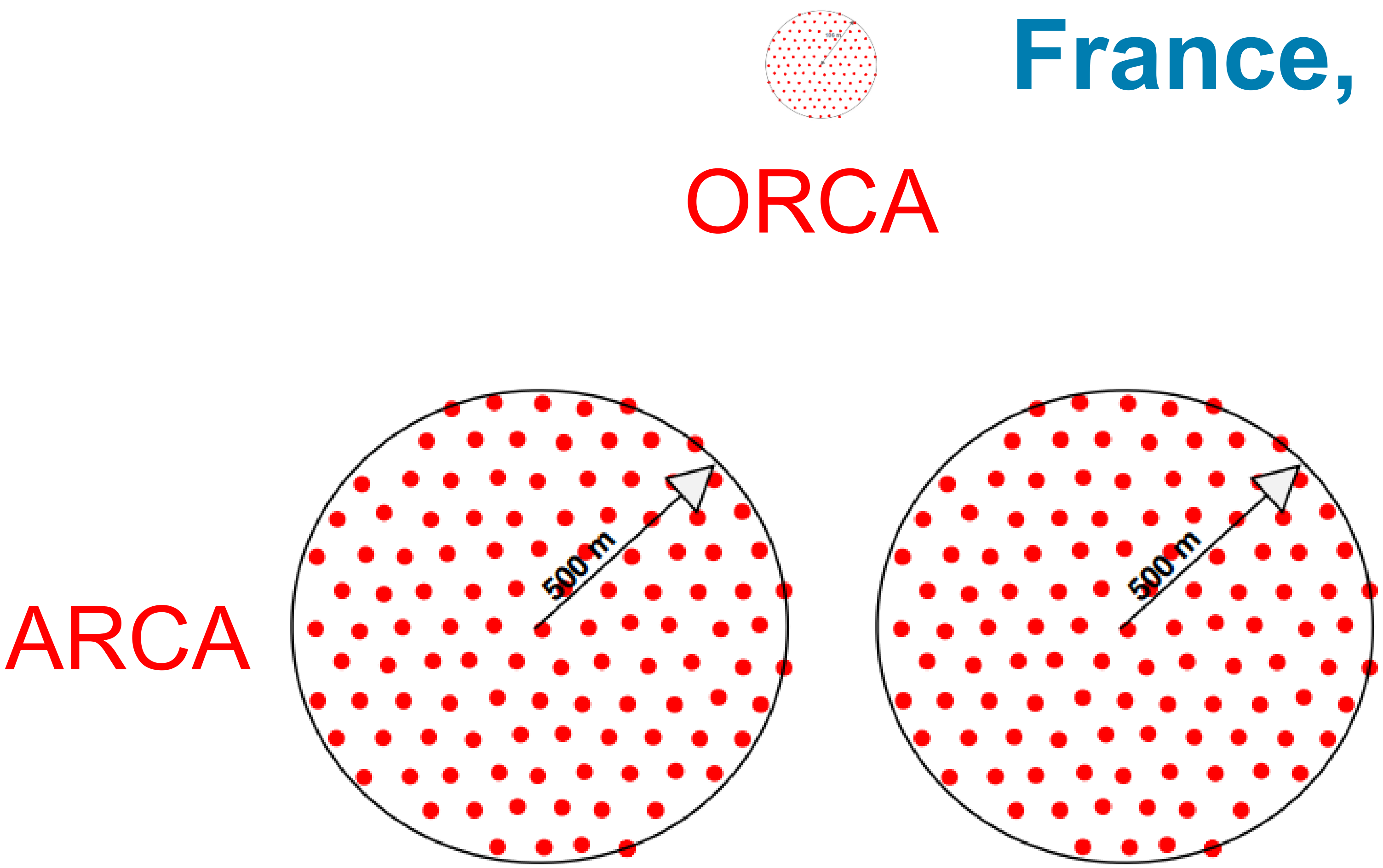
Until now still rather small collaboration

Would add observation power at the Northern Hemisphere

KM3NET



KM3NeT: ORCA and ARCA



France, 40 km from Toulon

Italy,
100 km from Sicily

ORCA: determination of the Neutrino Mass Hierarchy, precision oscillation physics

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

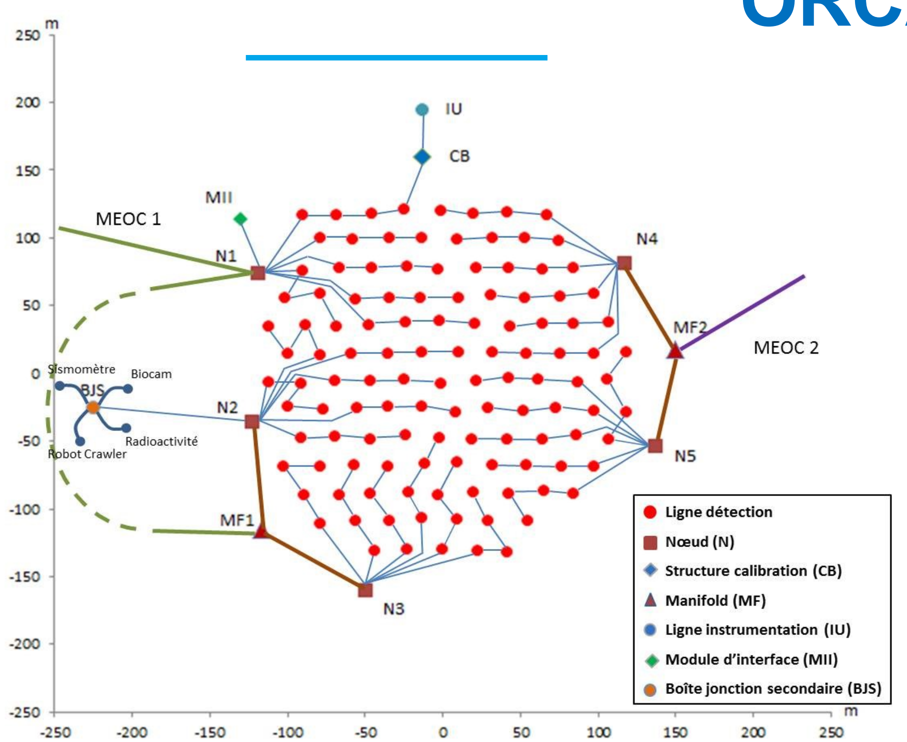
KM3NeT: ORCA and ARCA

DOM

- 31 PMTs in one sphere
- ~3 times cathode area of ANTARES Optical Module
- Directional information

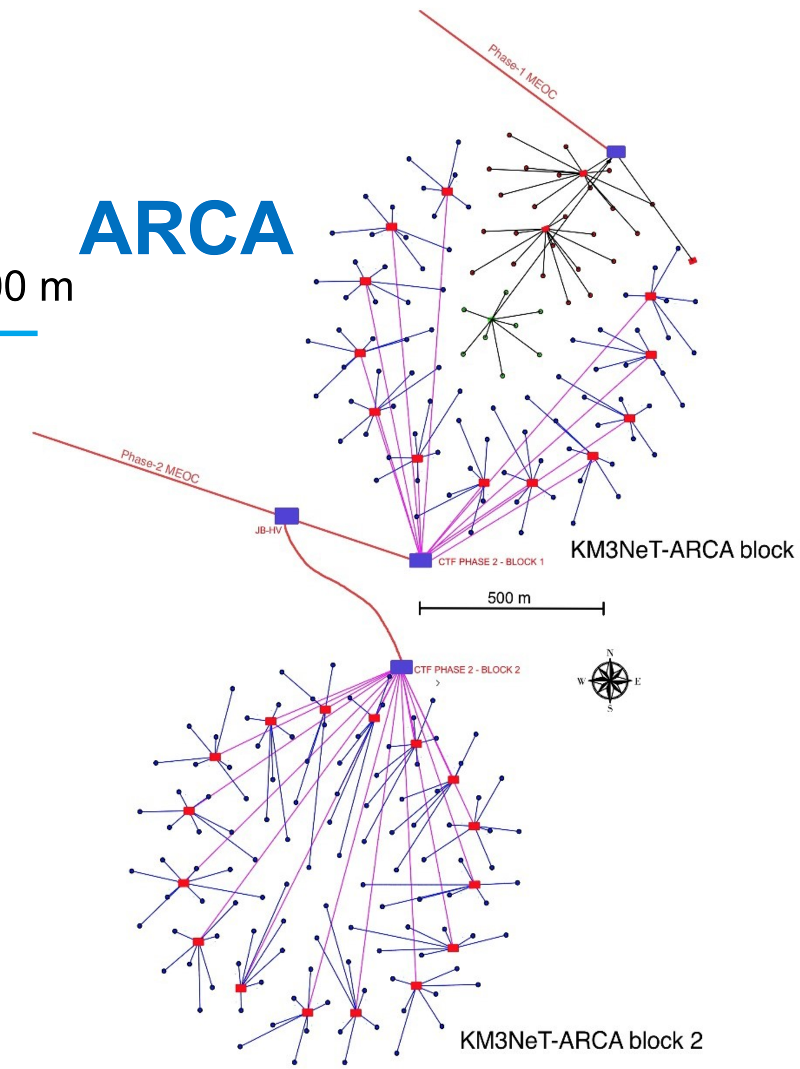
200 m

ORCA



ARCA

200 m



Completion planned for 2024

Completion planned for 2026

Each block has 115 strings with 18 Digital Optical Modules (DOMs)

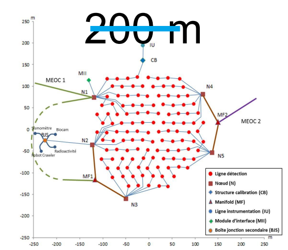
Taken from Dorothea Samtleben, talk at Neutrino 2020

KM3NeT: Measured depth-intensity curve

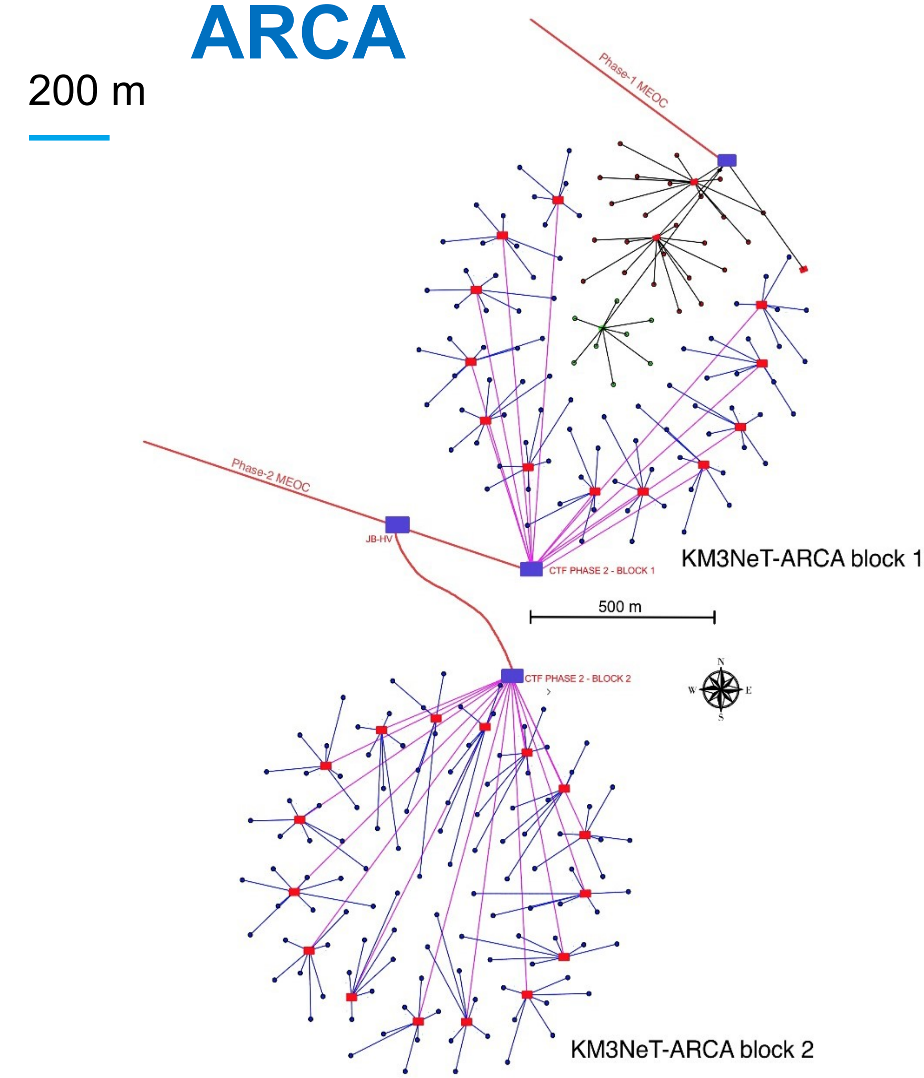
ORCA

6 strings operating

(planned 115)

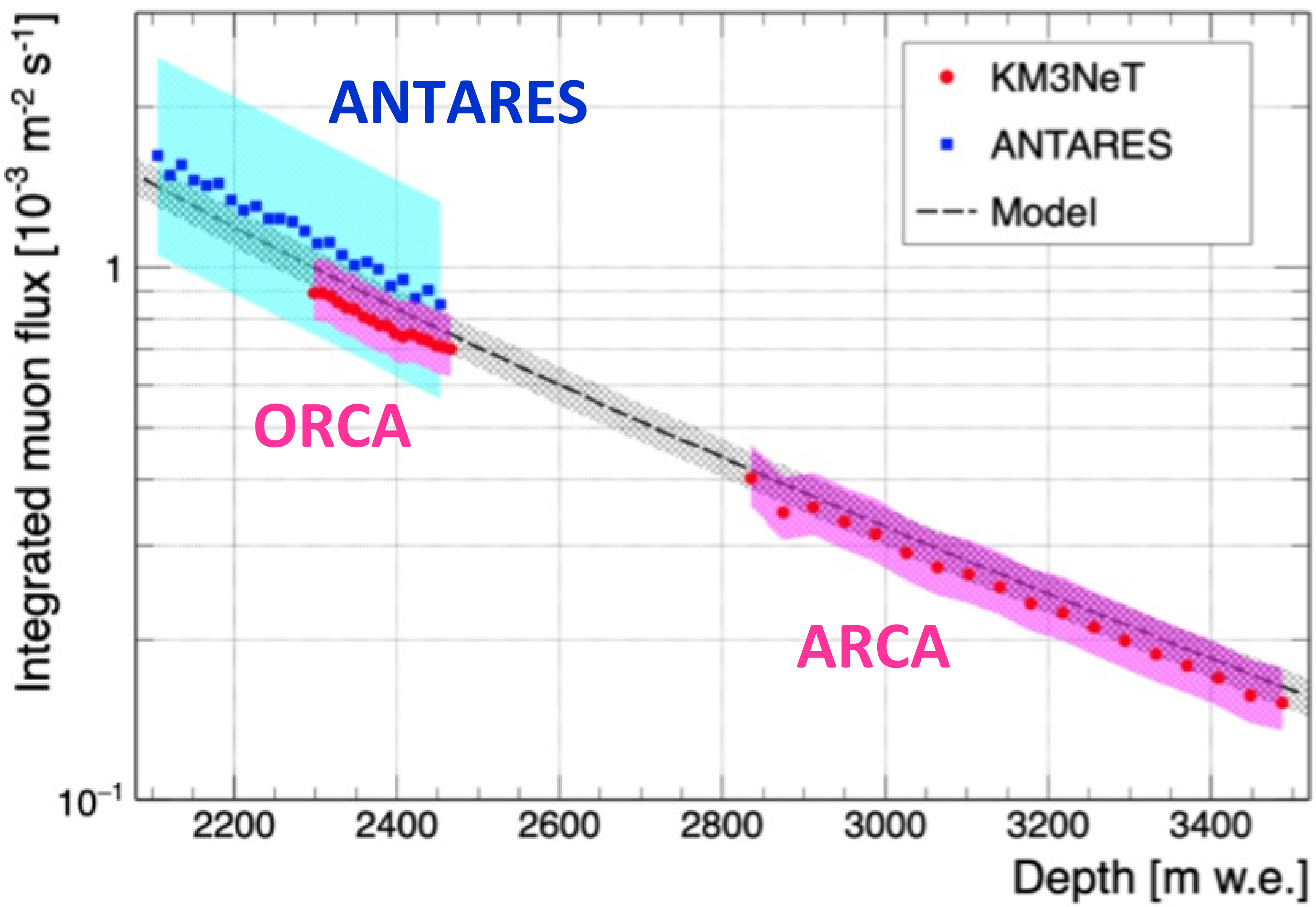


ARCA



1 string operating

(planned 2 x 115)



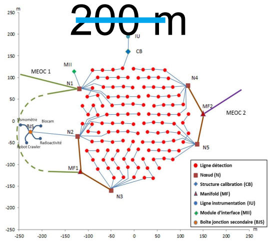
ORCA: Zenith Distribution of atm. ν

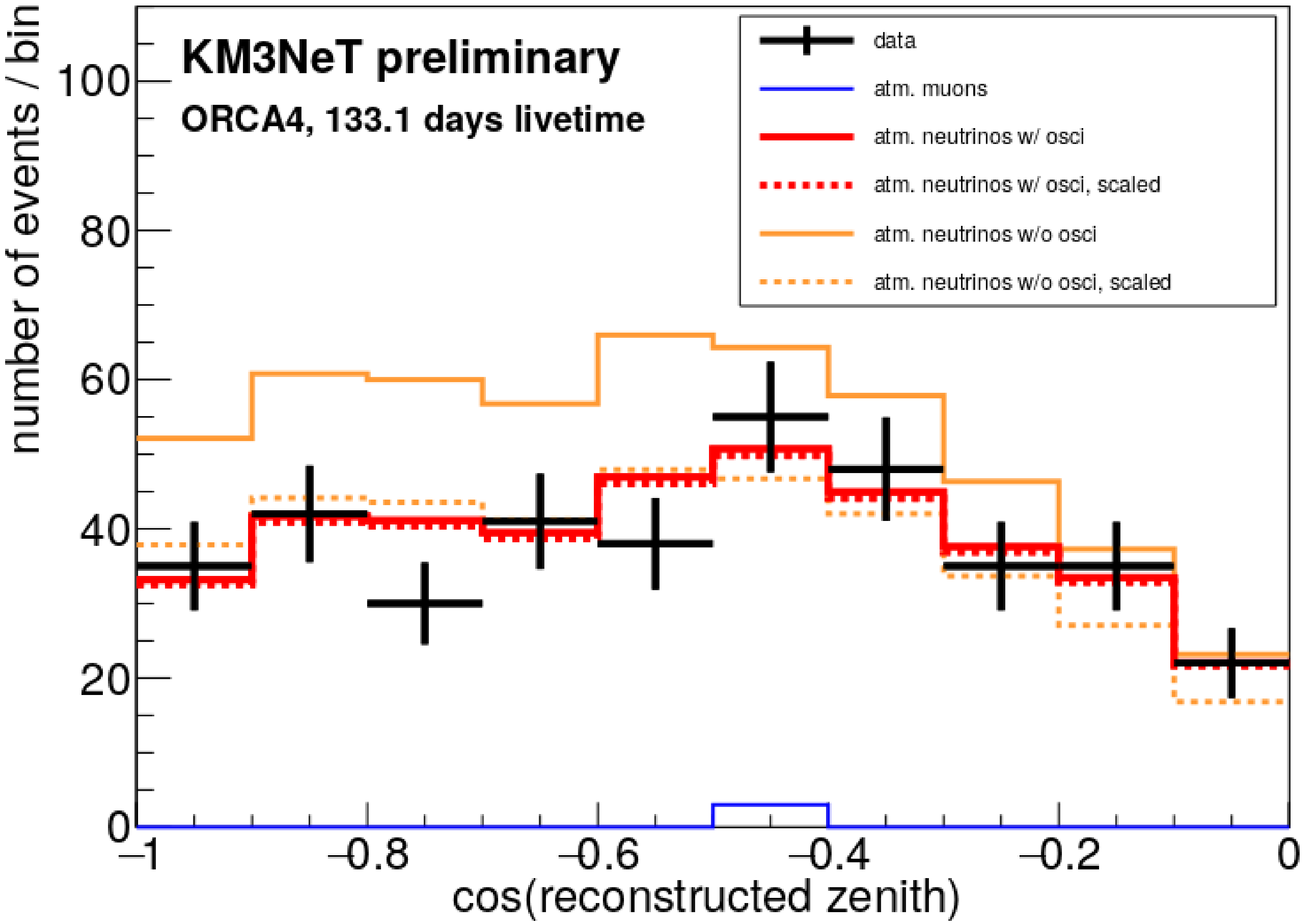
ORCA

200 m

6 strings operating

(planned 115)

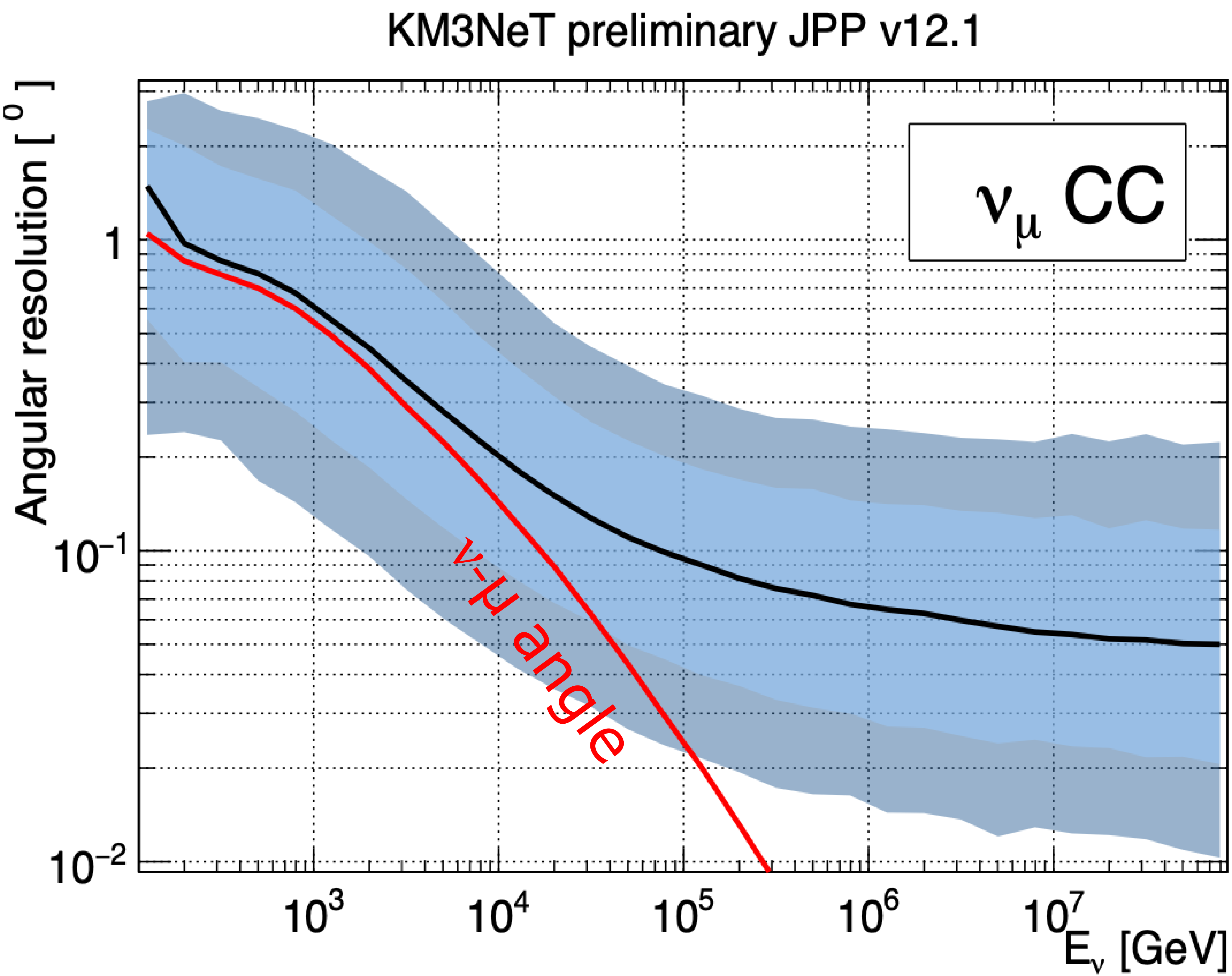


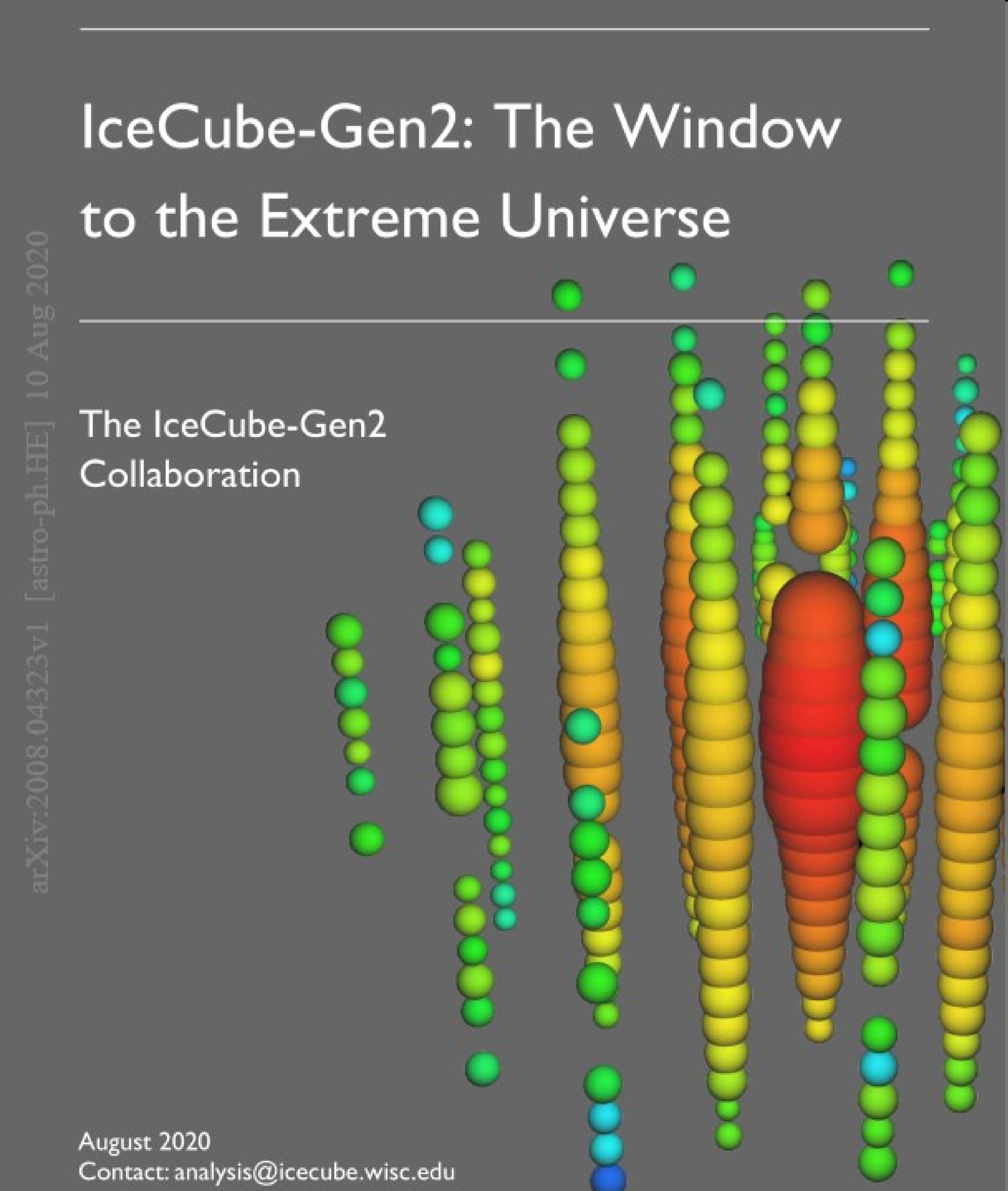


Mild evidence for oscillations

taken from D. Samtleben's talk at Neutrino 2020

Important for point sources: Angular resolution



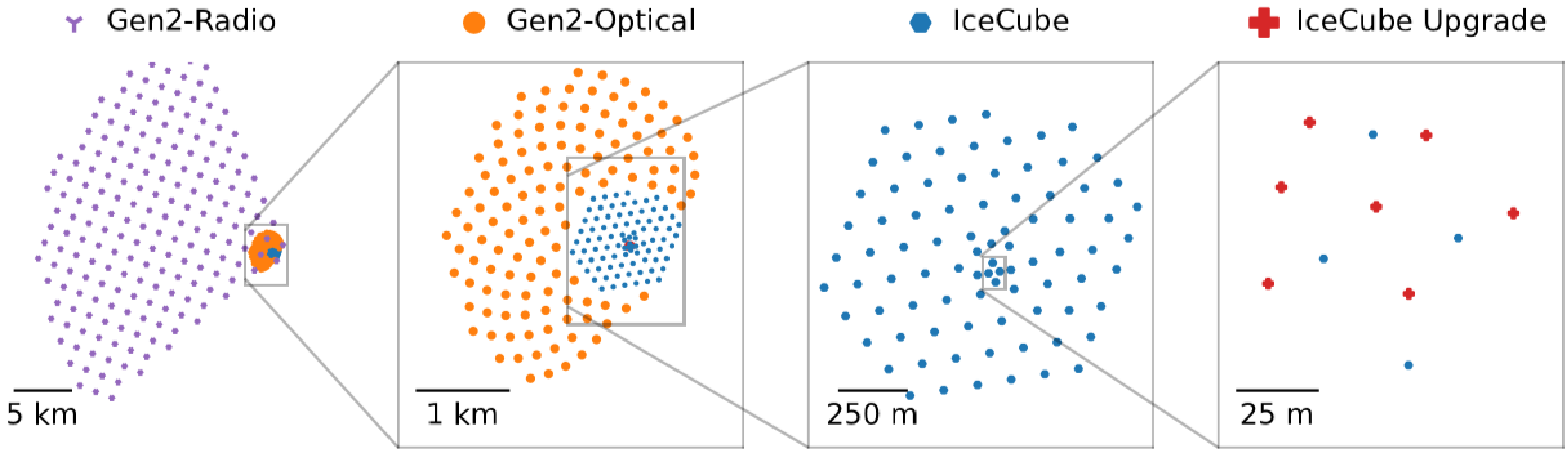

IceCube-Gen2: The Window to the Extreme Universe

The IceCube-Gen2 Collaboration

August 2020
Contact: analysis@icecube.wisc.edu

arXiv:2008.04323

IceCube Gen2: from GeV to EeV



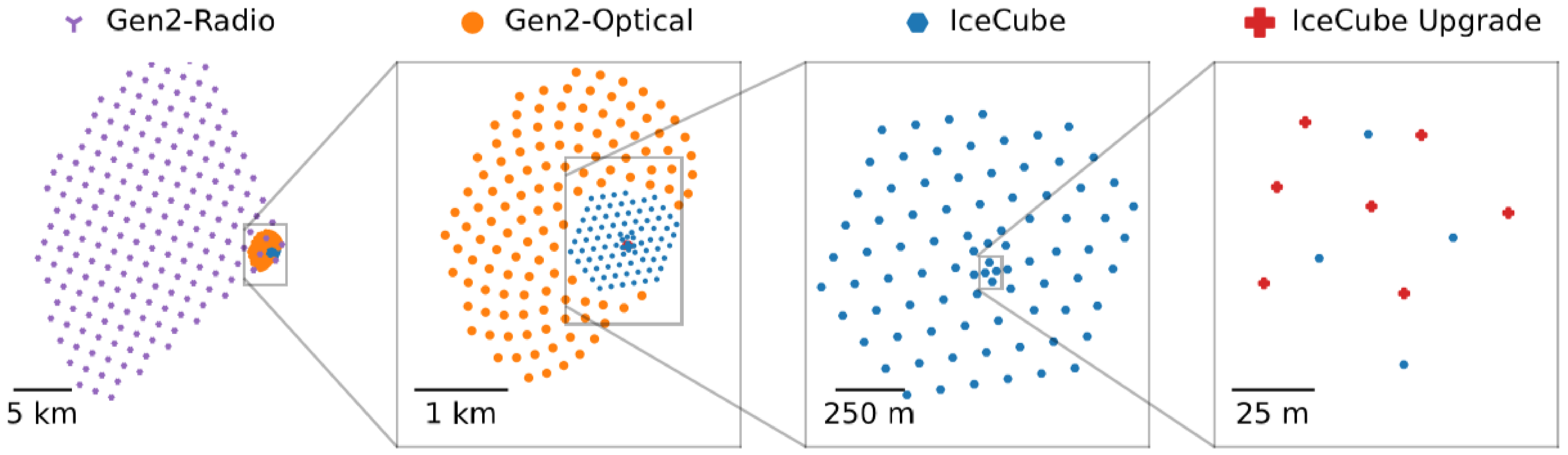
10 PeV to >10 EeV

10 TeV – 50 PeV

100 GeV – 5 PeV

improves DeepCore performance at < 10 GeV

IceCube Gen2: from GeV to EeV



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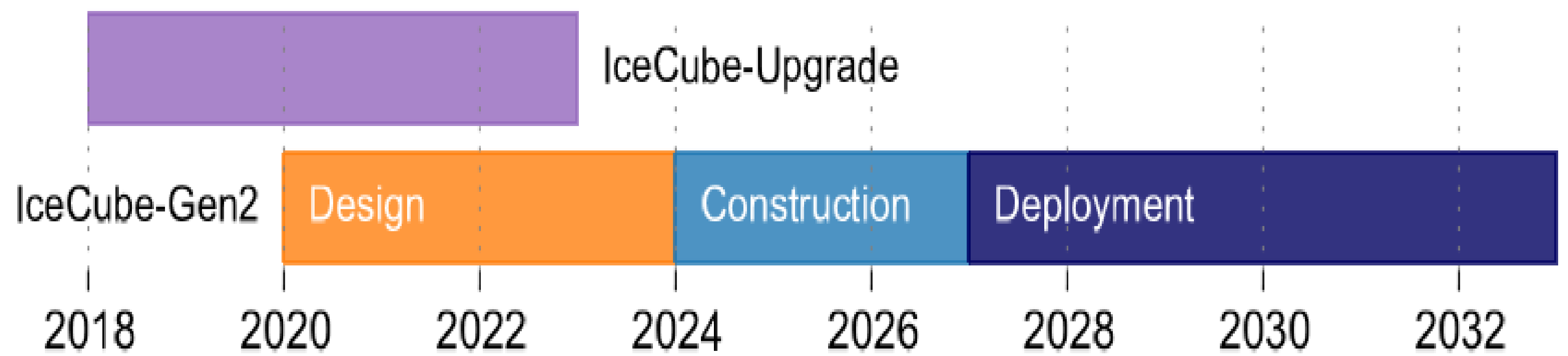
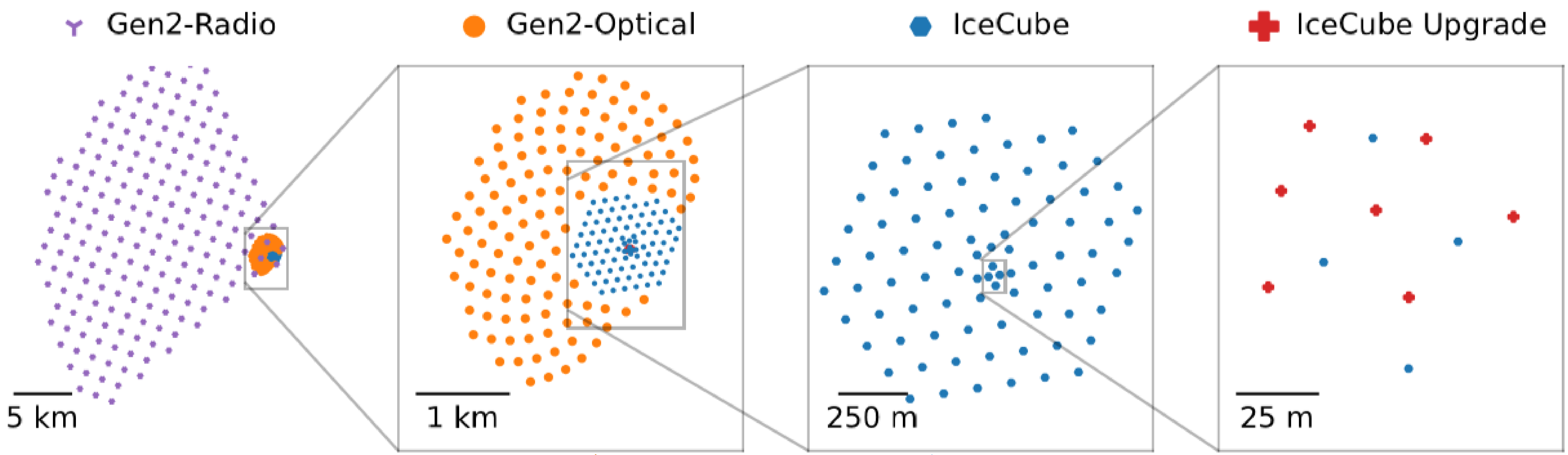
improves DeepCore performance at < 10 GeV



IceCube Gen2: from GeV to EeV

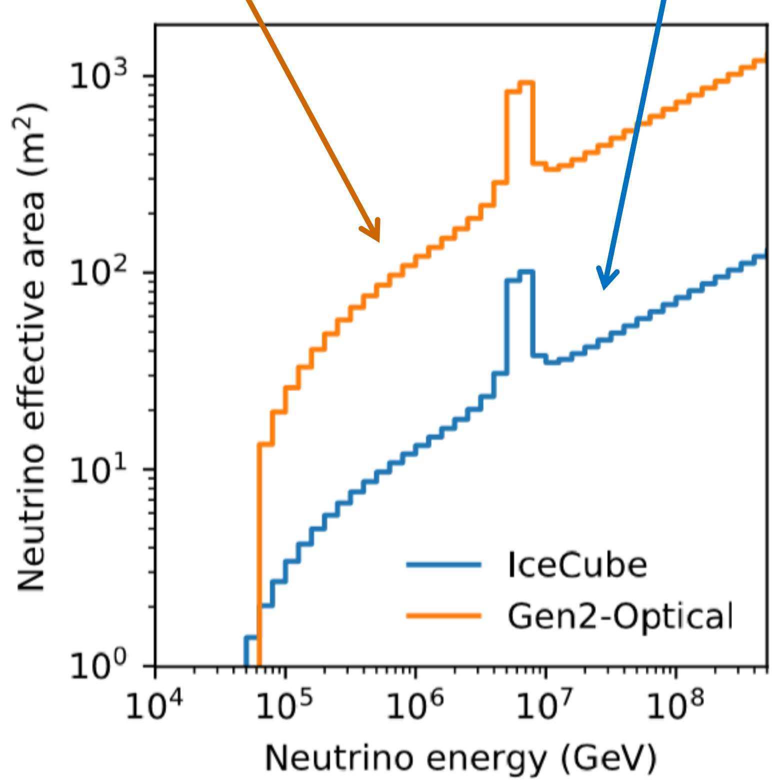


10 PeV to >10 EeV

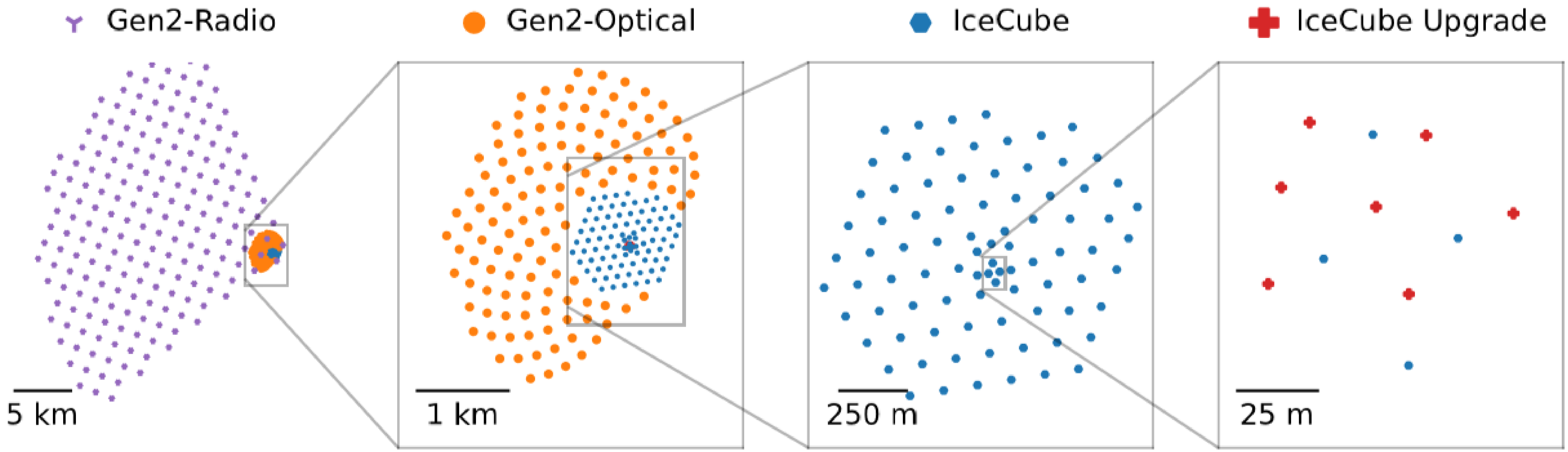
improves DeepCore performance at < 10 GeV

Neutrino effective area:

Gen2 -Optical vs. IceCube



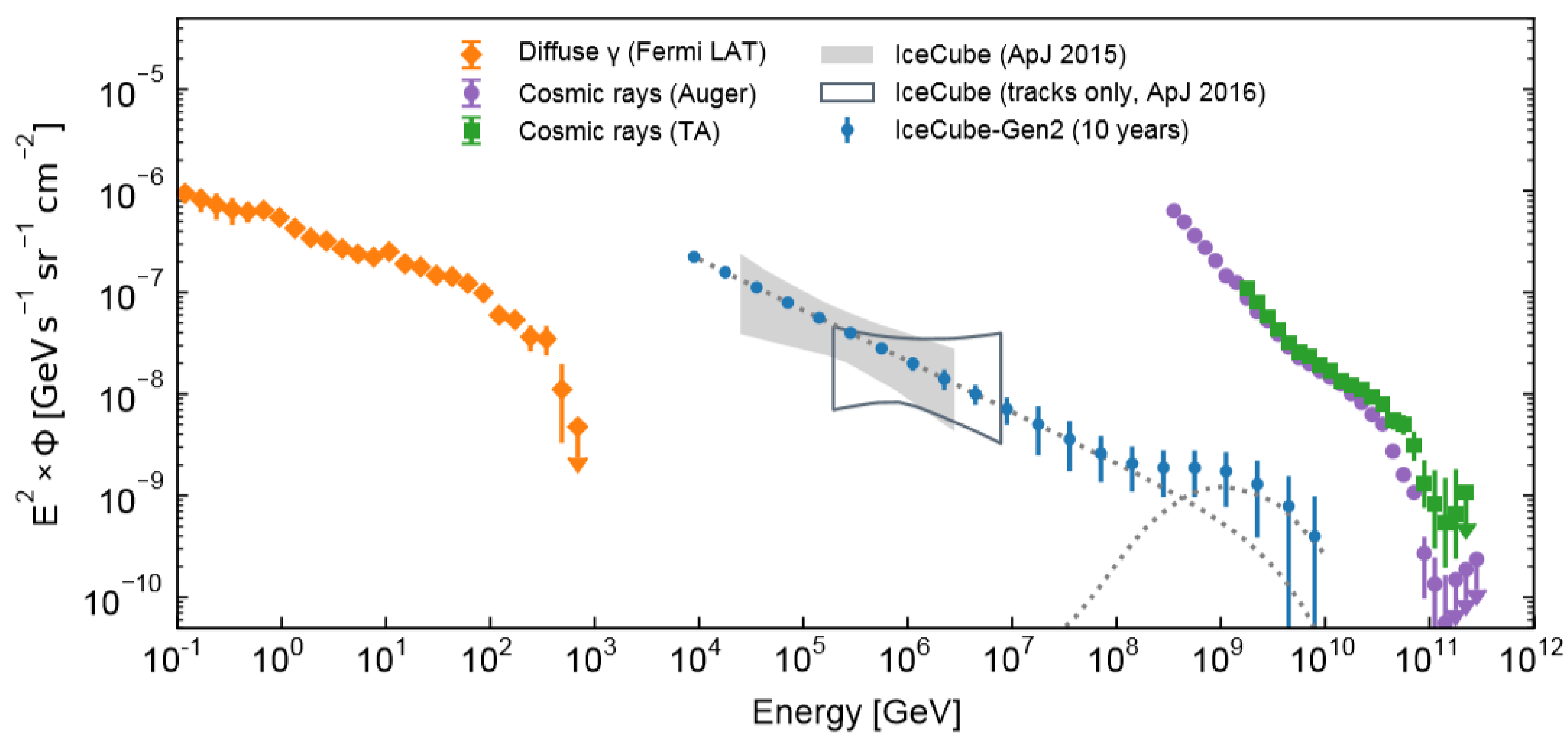
IceCube Gen2: from GeV to EeV



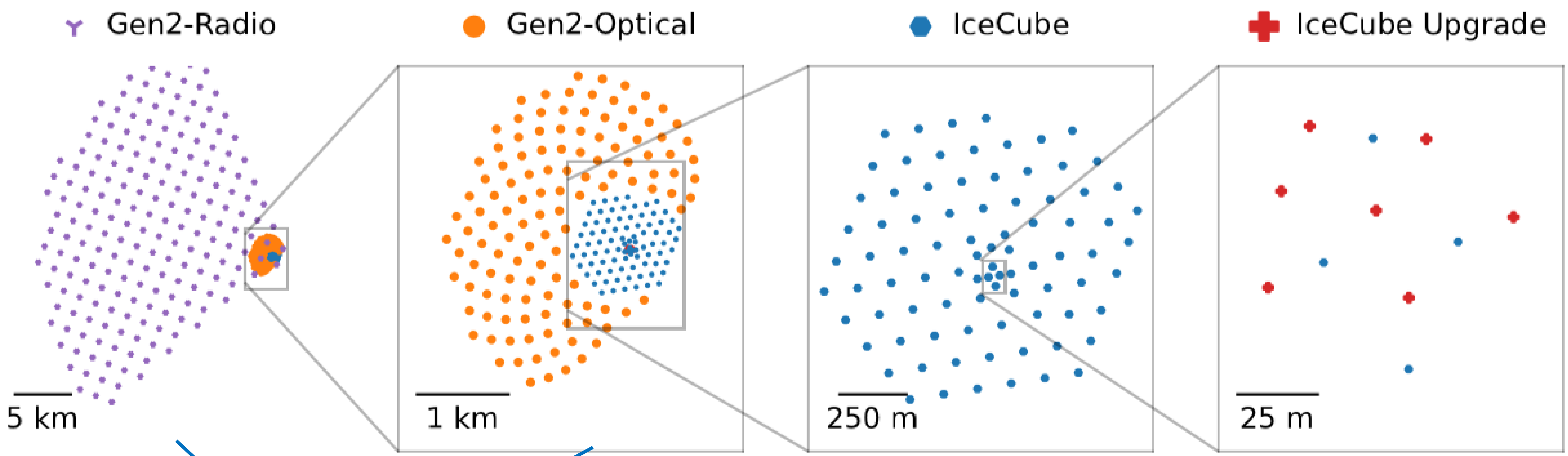
10 PeV to >10 EeV

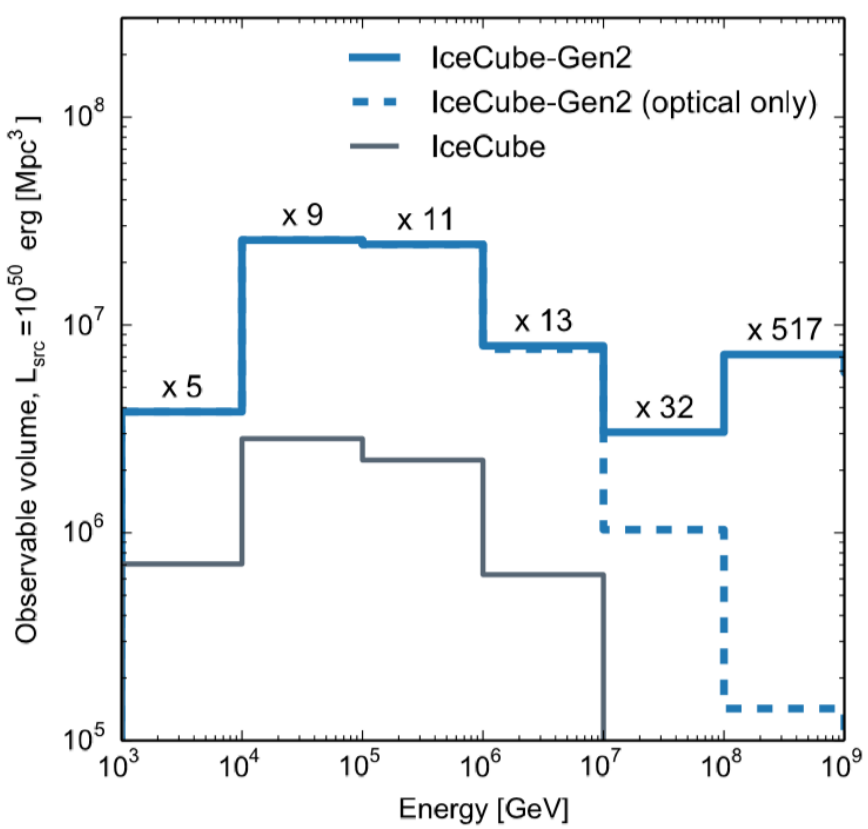
Spectrum of diffuse flux

(Gen2 optical and radio)



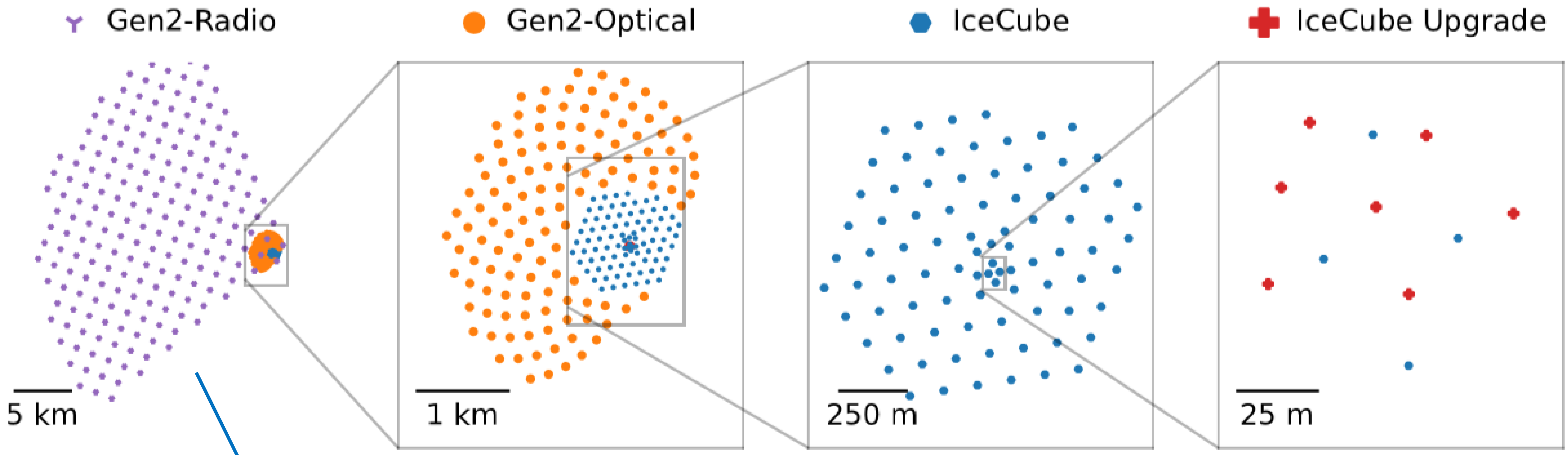
IceCube Gen2: from GeV to EeV

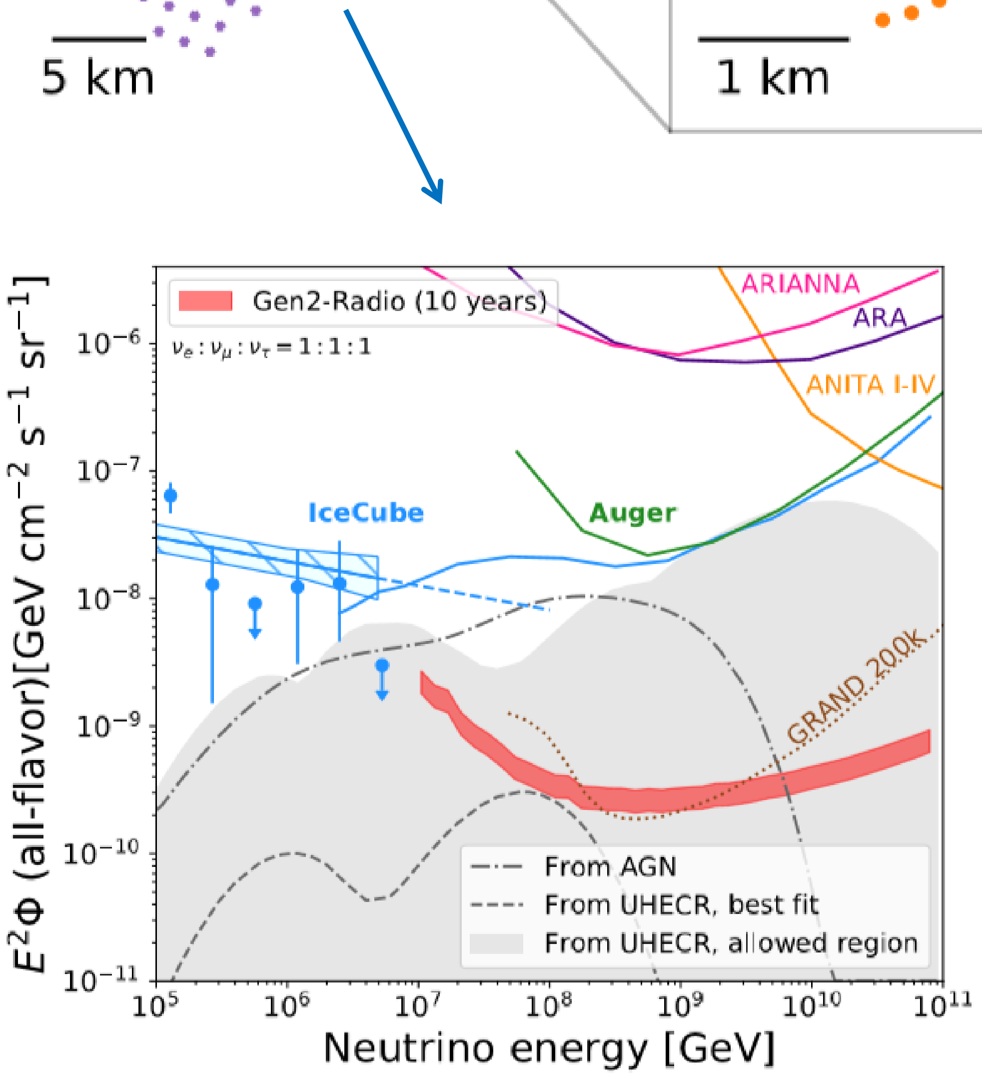




Observable volume of IceCube and IceCube-Gen2 for a generic 100 s burst with equivalent isotropic emission of 10^{50} erg in neutrinos.

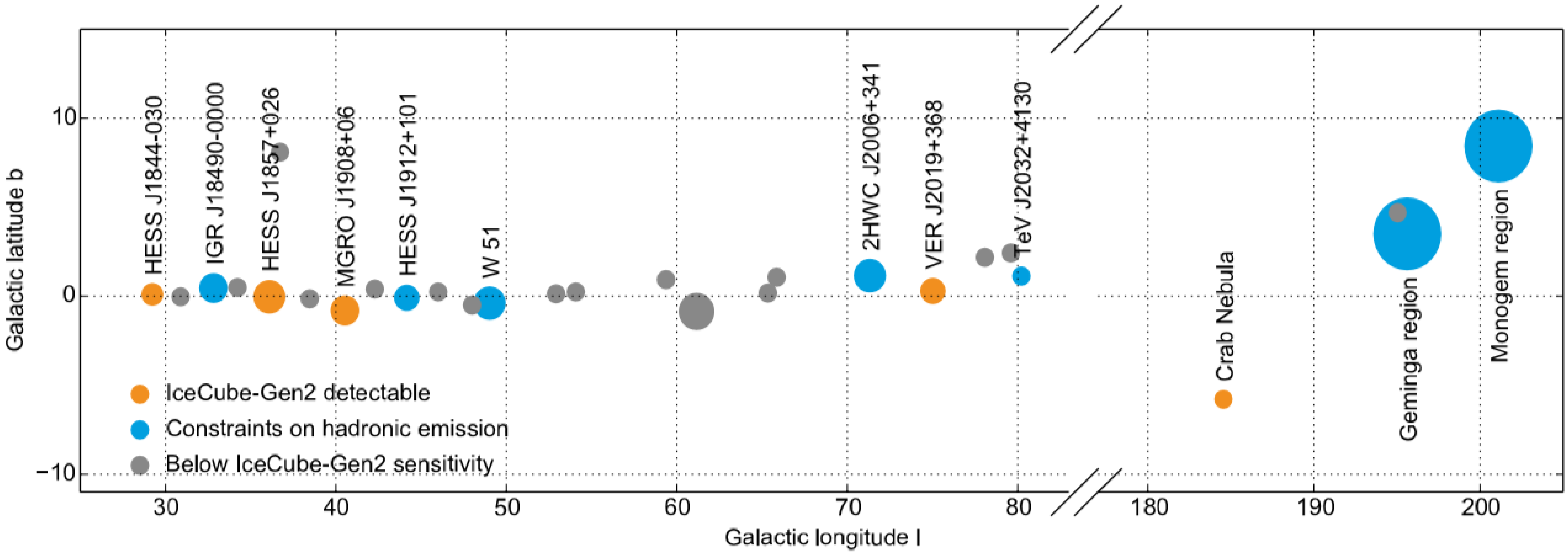
IceCube Gen2: from GeV to EeV



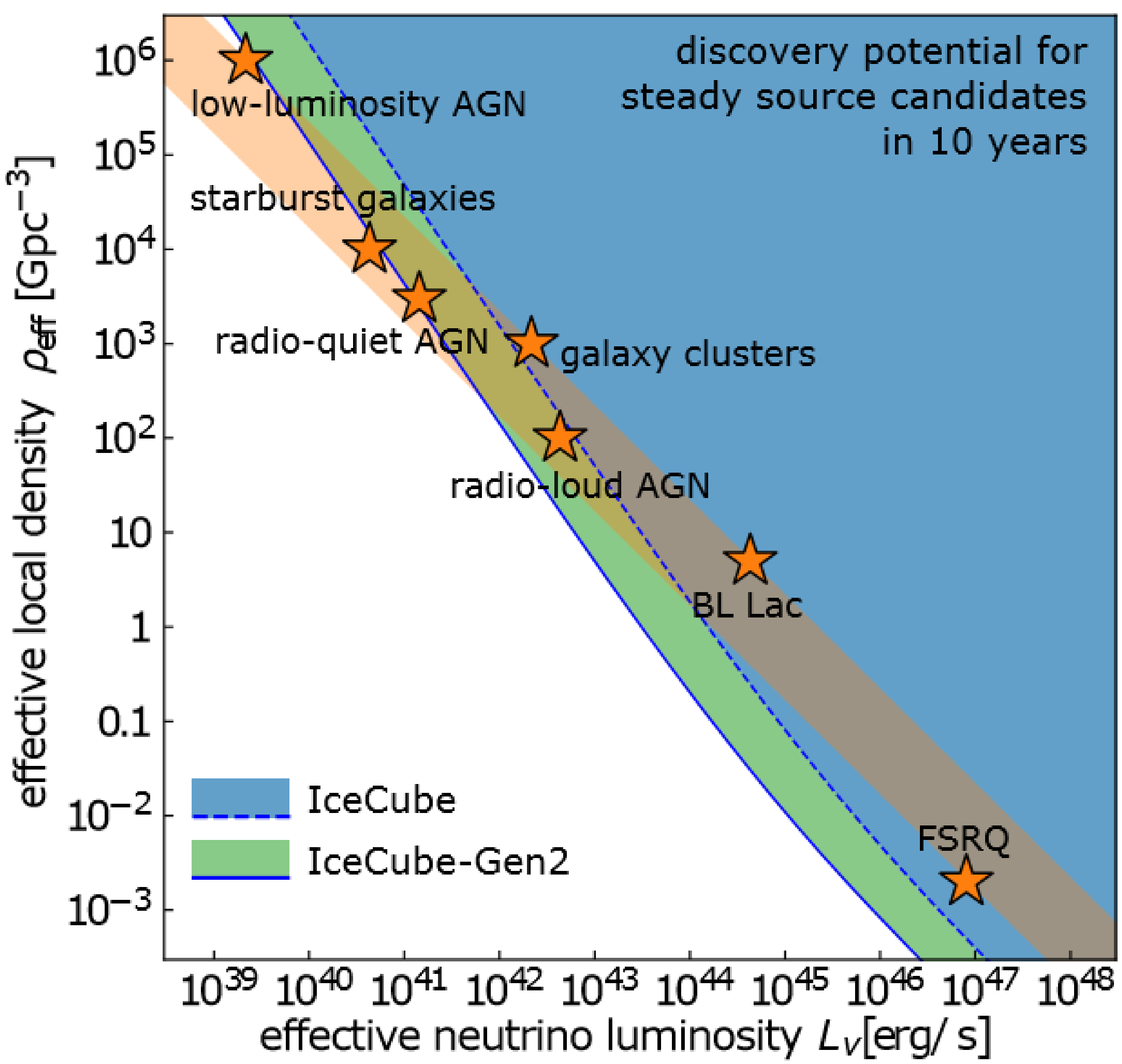


Sensitivity of the IceCube-Gen2 radio array in comparison to models, existing upper limits, and the 10 year sensitivity of the proposed GRAND array of 200,000 antennas.

Galactic sources with IceCube-Gen2



Discovery potential



Comparison of local density and luminosity of extragalactic neutrino source populations to the discovery potential of IceCube and IceCube-Gen2.

Several candidate populations are marked by the required neutrino luminosity to account for the full diffuse flux .

Orange band: luminosity / density range that is compatible with the total observed diffuse neutrino flux. Lower (upper) edge of the band: rapid (no) redshift evolution.

Shaded regions IceCube's (blue, dashed line) and IceCube-Gen2's (green, solid line) ability to discover one or more sources of the population.

Conclusions

- **High-energy neutrino window is opened**
- **Extremely dynamical field**
- **Northern hemisphere:**
  towards cubic kilometer detectors.
  Baikal-GVD, KM3NeT-ARCA, (PON)
- **Soon later IceCube towards 10 km^3**
- **Mid 2020s and later:**
  fill landscape of ν sources with more and more entries. Close-in on cosmic ray sources ! (?)

СПАСИБО ЗА ВАШЕ ВНИМАНИЕ