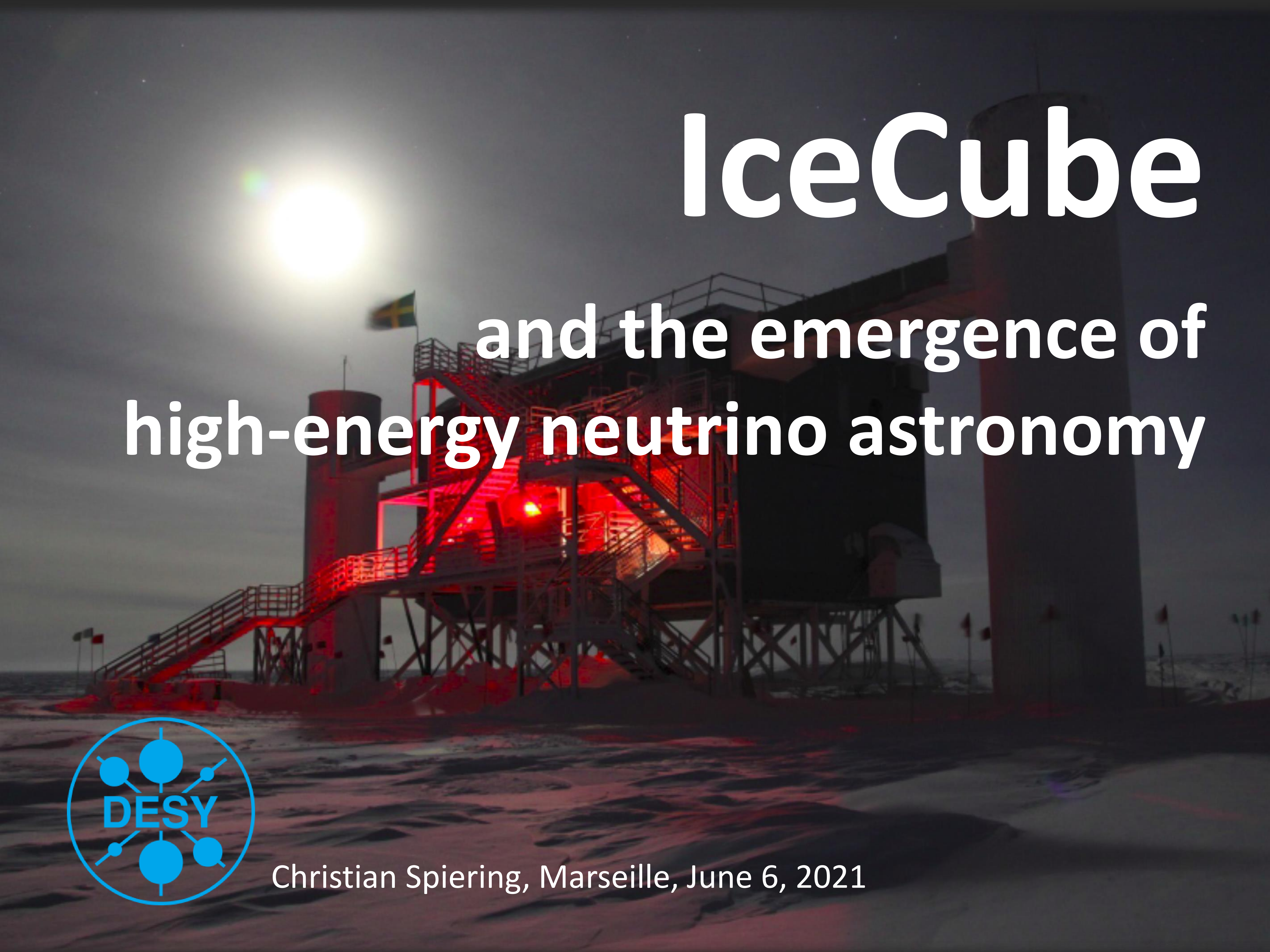


IceCube

and the emergence of high-energy neutrino astronomy

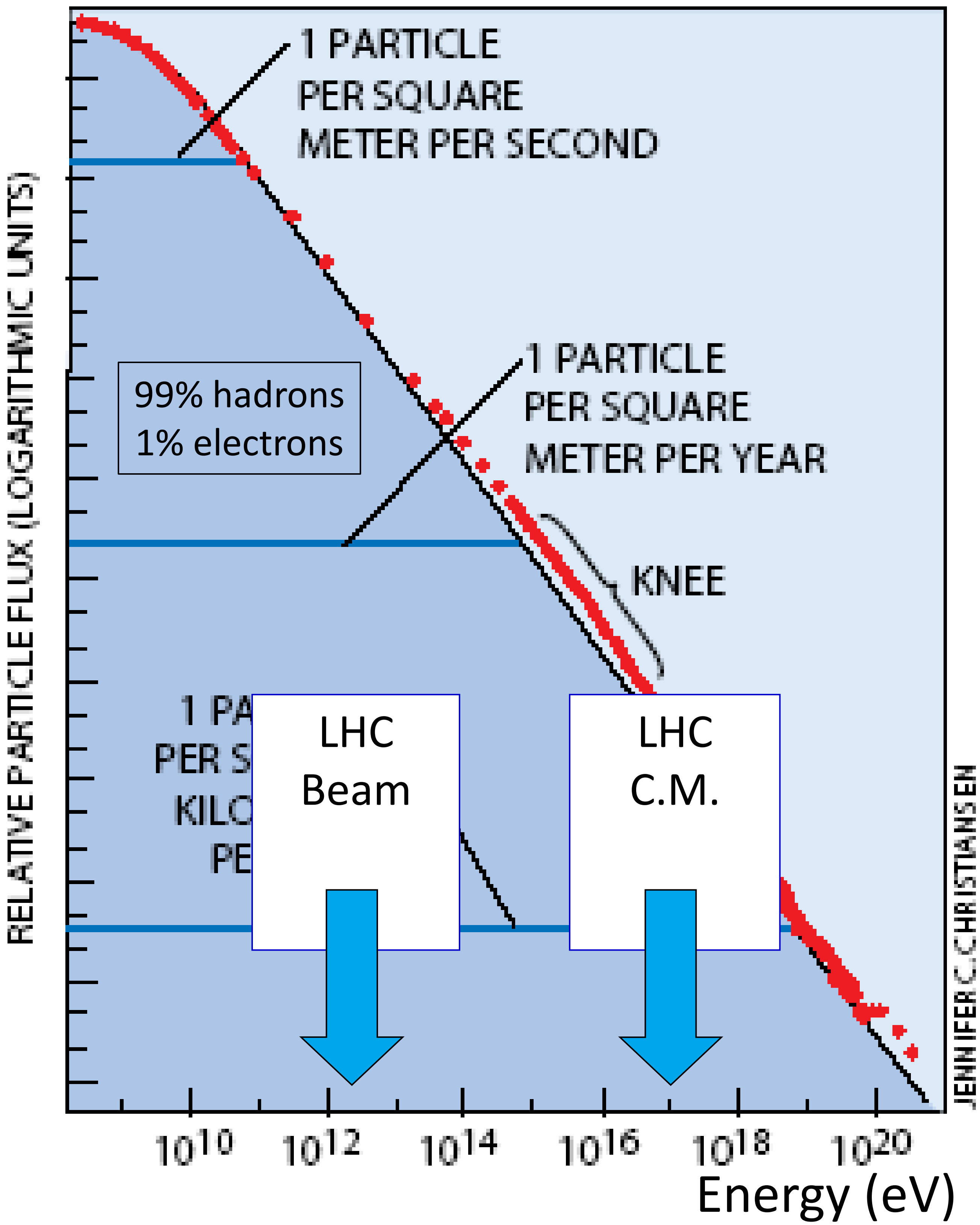
DESY

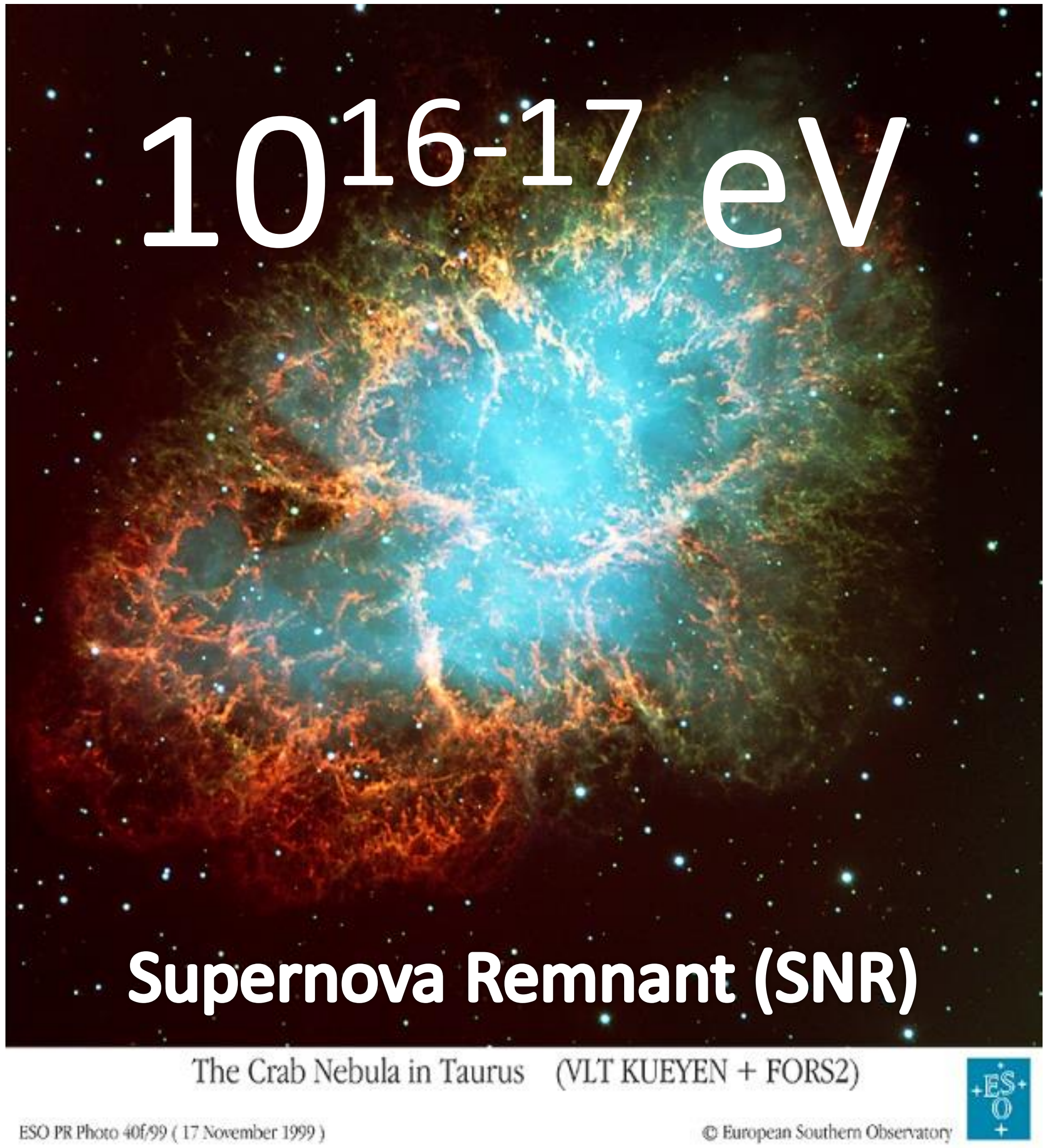
Christian Spiering, Marseille, June 6, 2021

1.

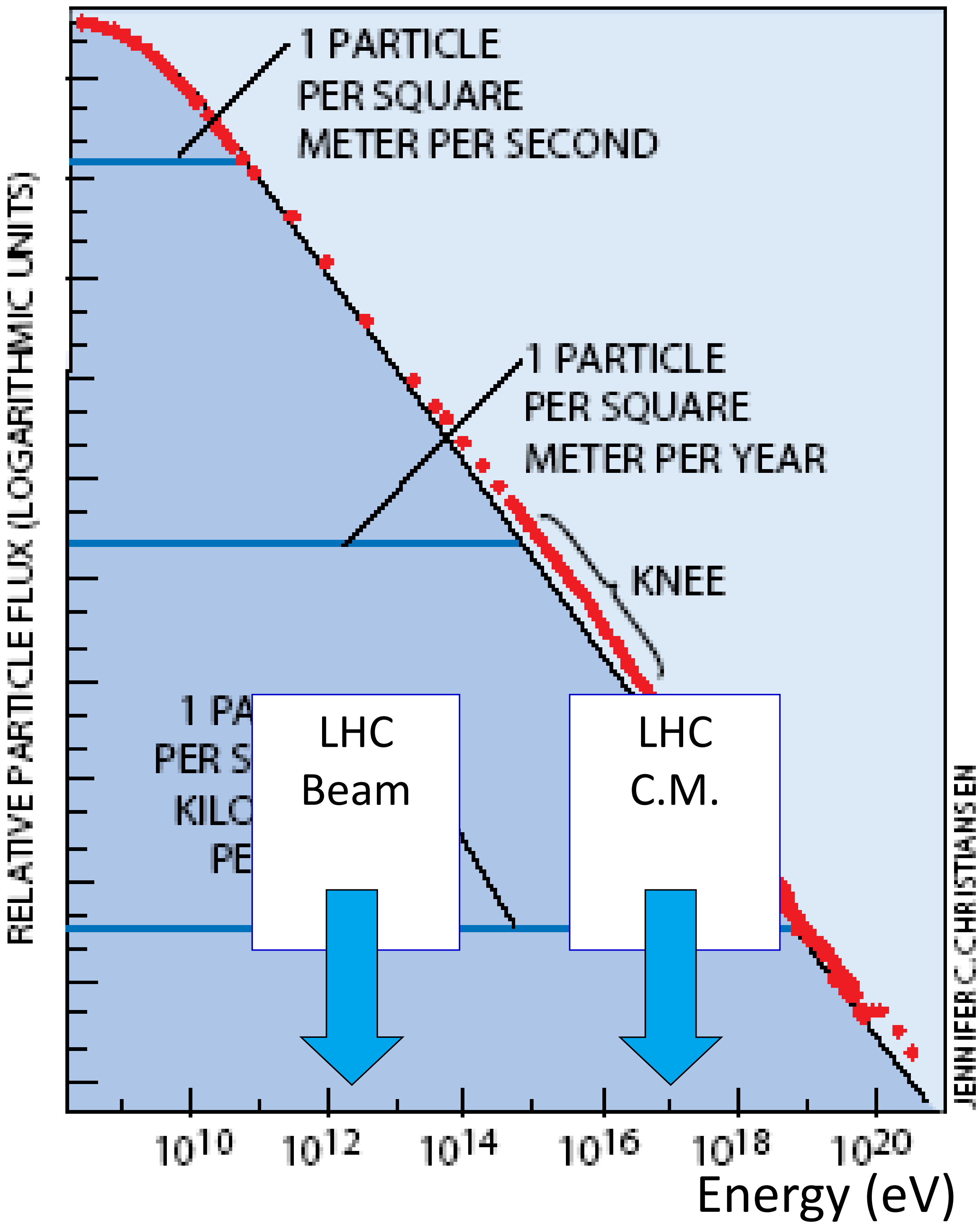
Scientific motivation

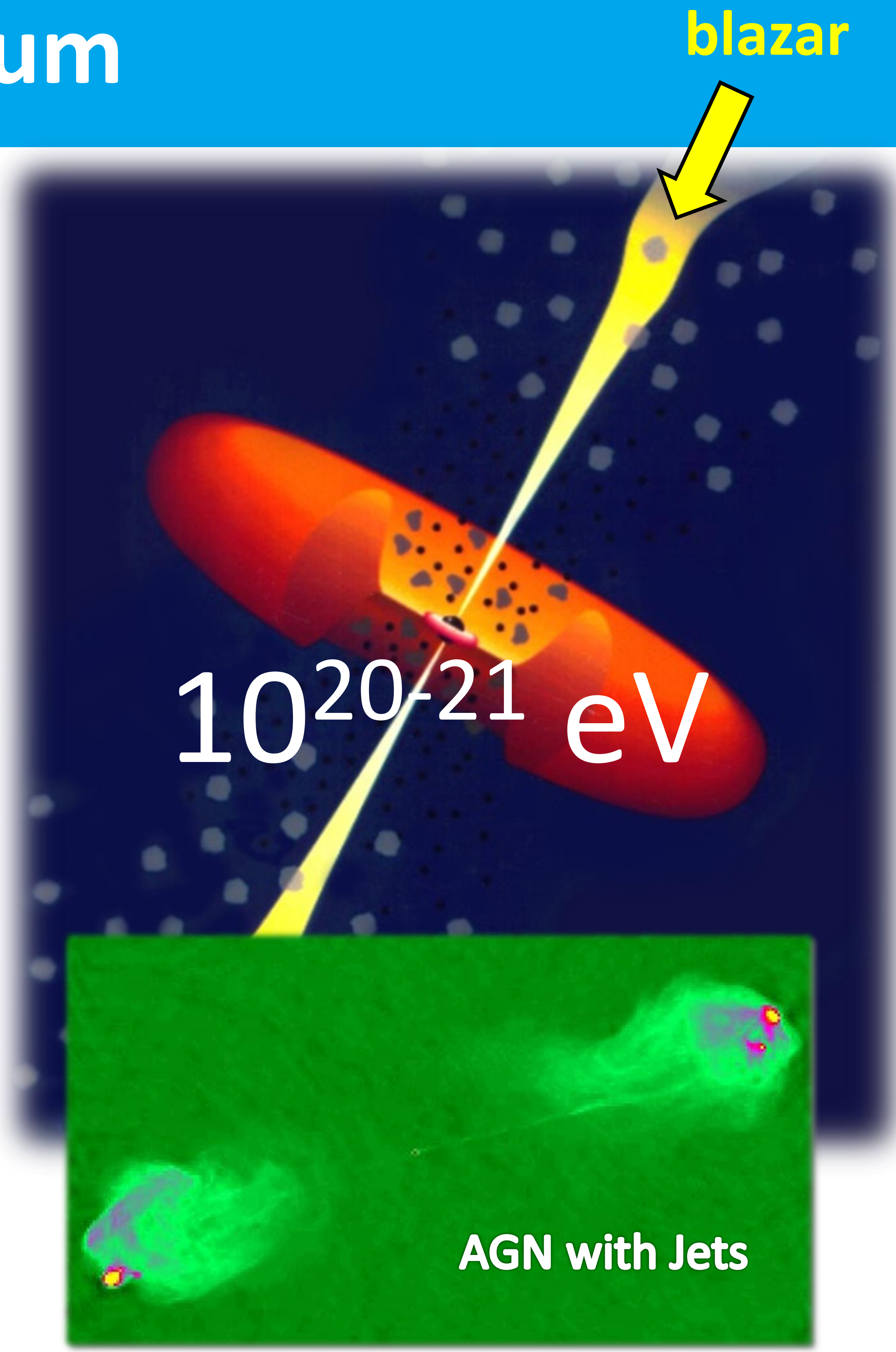
The cosmic ray spectrum



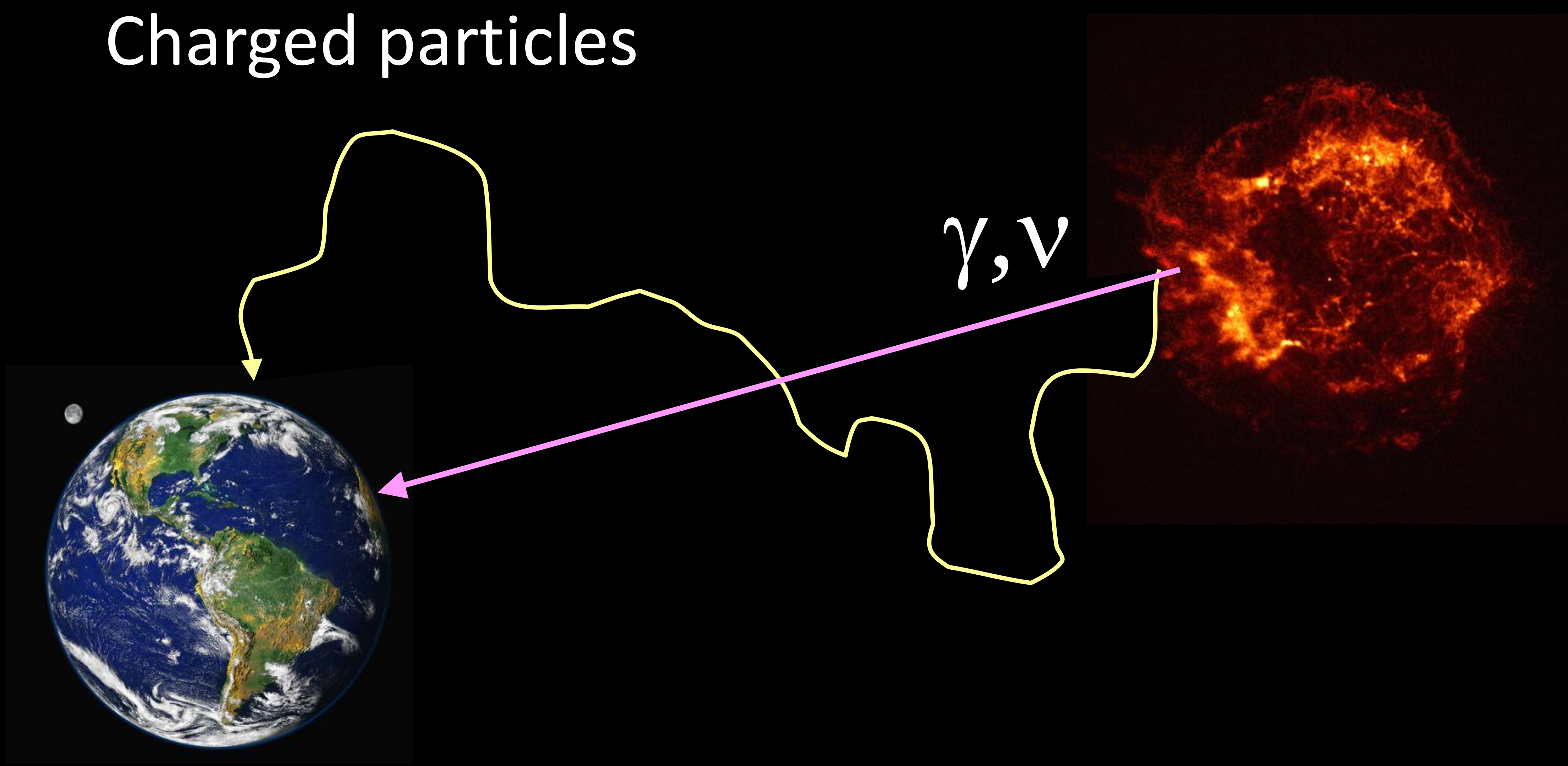


The cosmic ray spectrum





Charged cosmic rays vs. gamma rays vs. neutrinos



Gamma-Ray Generation

$$p + \text{target} \rightarrow \pi^0 + \ldots..$$

$$\rightarrow \gamma + \gamma$$

but also

$$e^- + \gamma_{\text{low energy}} \rightarrow e^- + \gamma_{\text{high energy}}$$

(inverse Compton process)

Neutrino Generation

$$p + \text{target} \rightarrow \pi^+ + \ldots\ldots$$

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

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

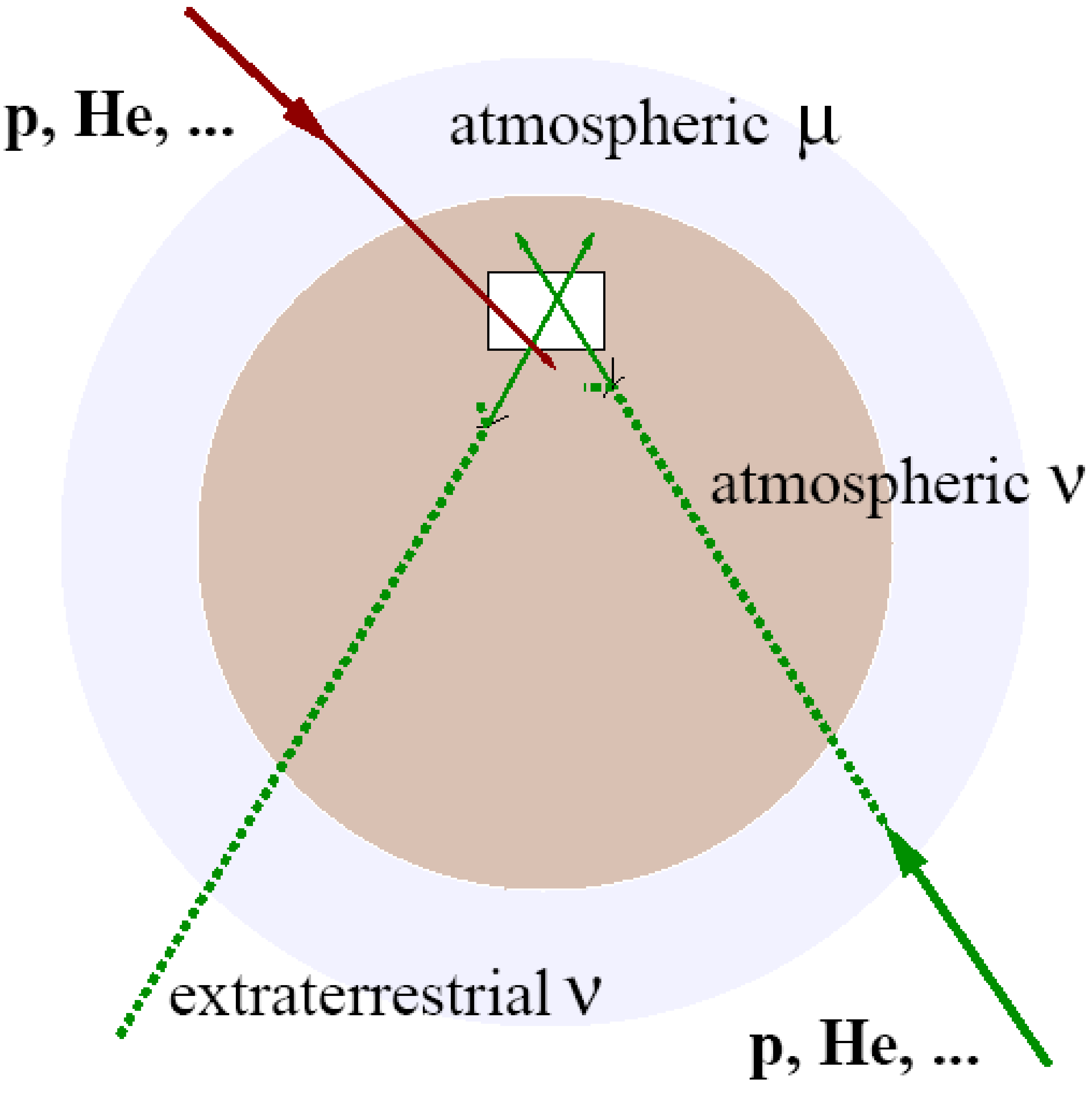
This is the water-tight way to identify hadron accelerators !

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

2. Operational principles

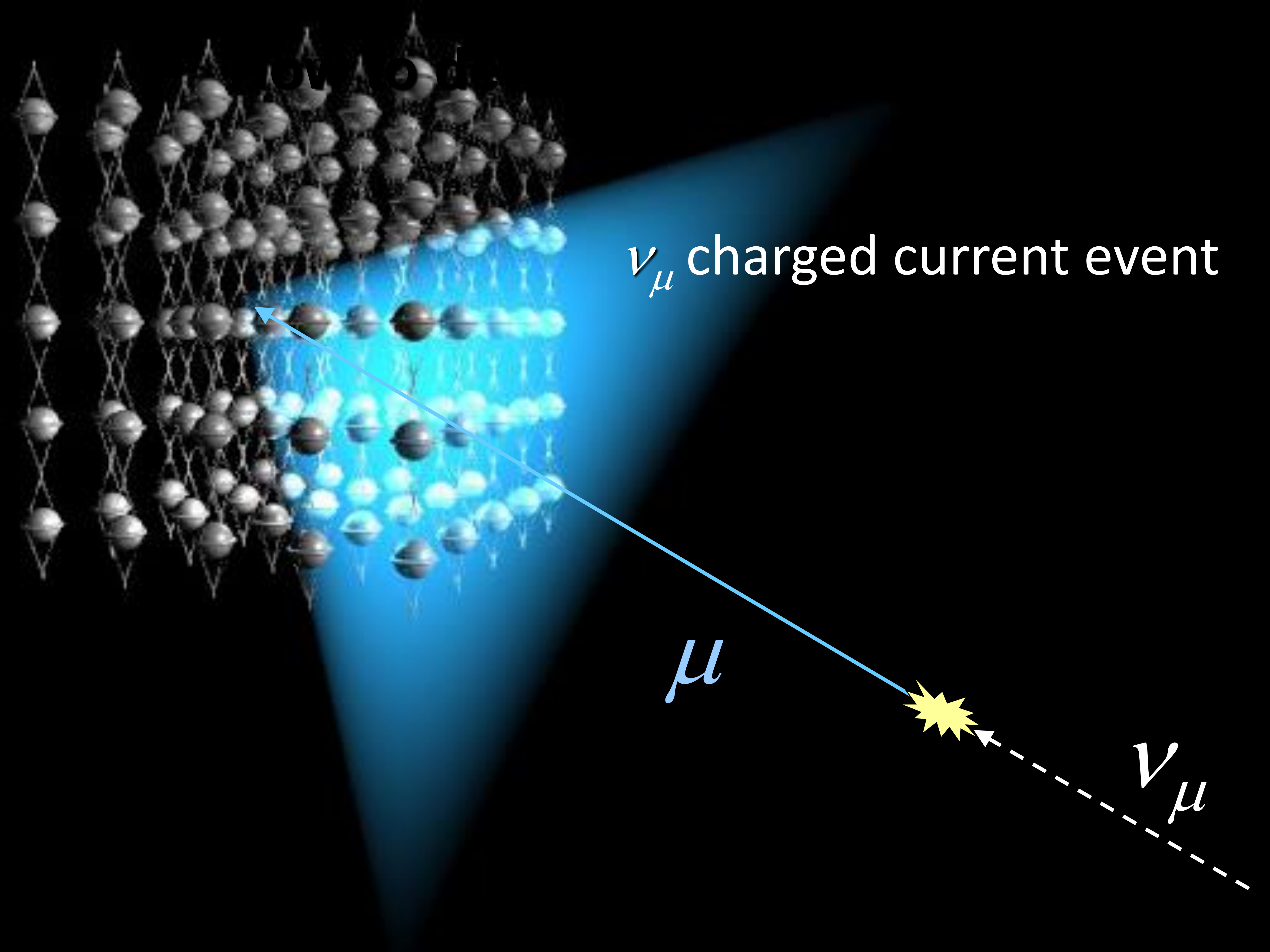
Detection deep under-ground/-water/-ice



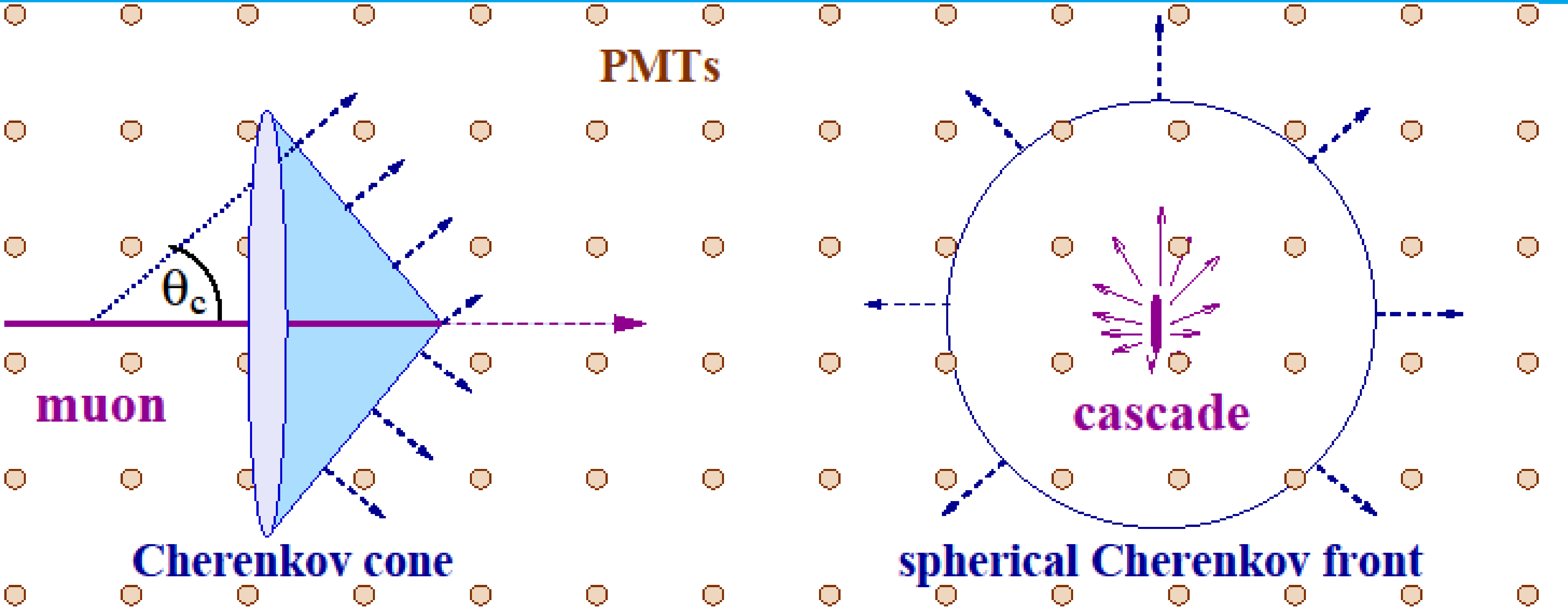
Detection deep underwater

Moisej 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.


ν_μ charged current event
μ
ν_μ

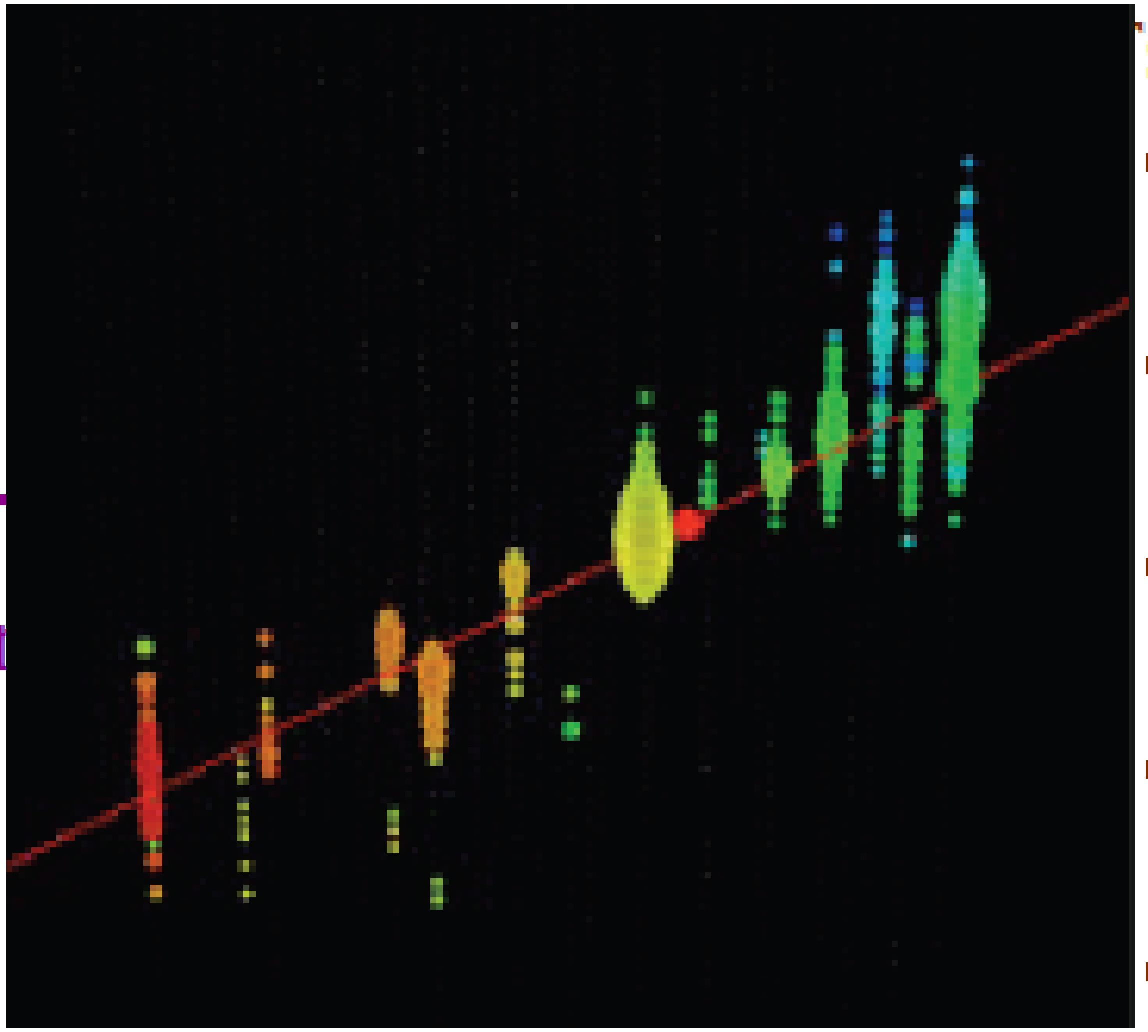
Two Detection Modes: tracks and cascades

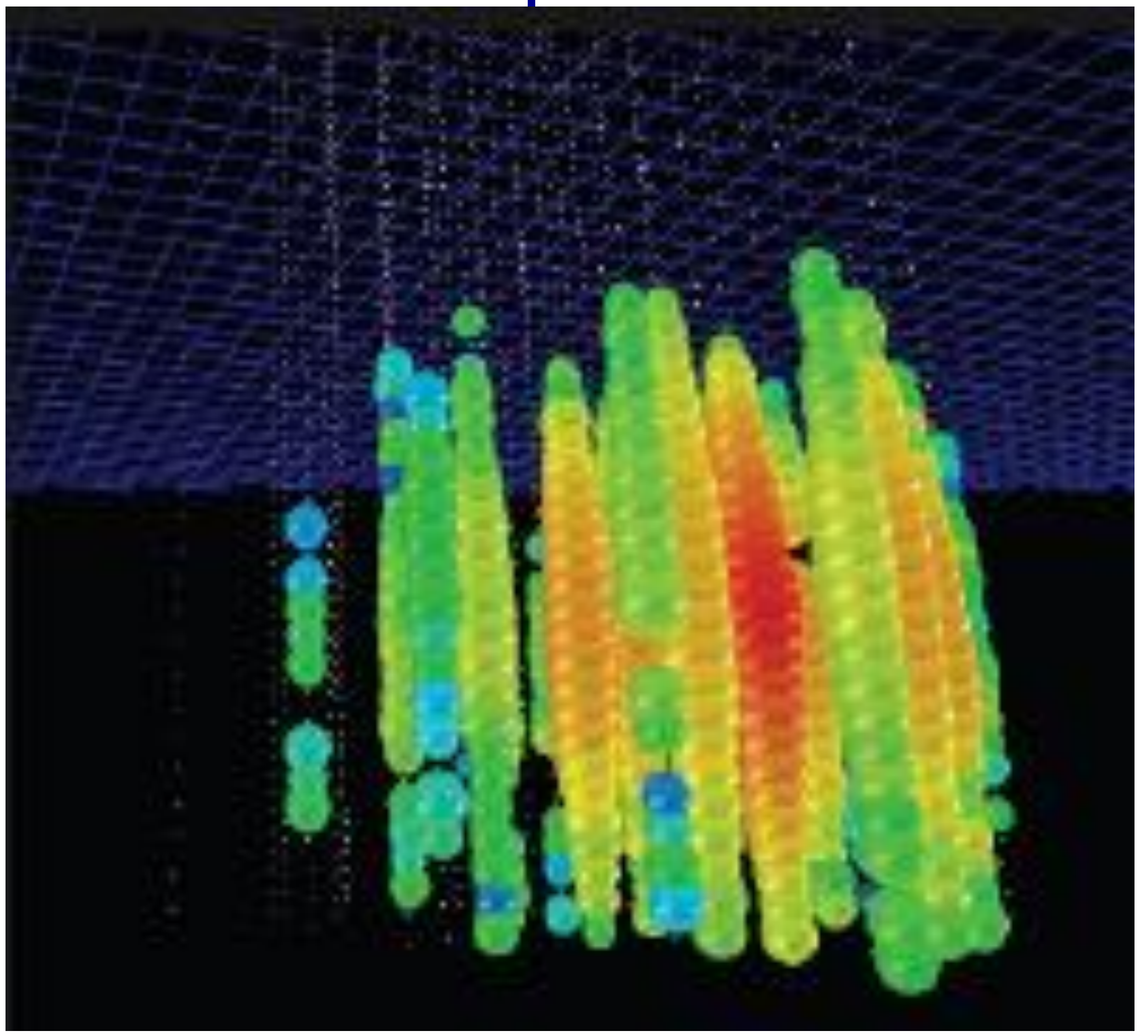


- $\nu_\mu + A \rightarrow \mu + \ldots$
  - Angular resolution < 1°
  - Energy resolution ~ factor 3

- $\nu_{e,\tau} \rightarrow e, \tau + \ldots$
- $\nu_X \rightarrow \nu_X + \ldots$
  - Angular resolution 2° - 10°
  - Energy resolution ~ 15%

Two Detection Modes





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  - Energy resolution ~ 15%

3.

Some history

1978: 1.26 km^3

22,698 OMs

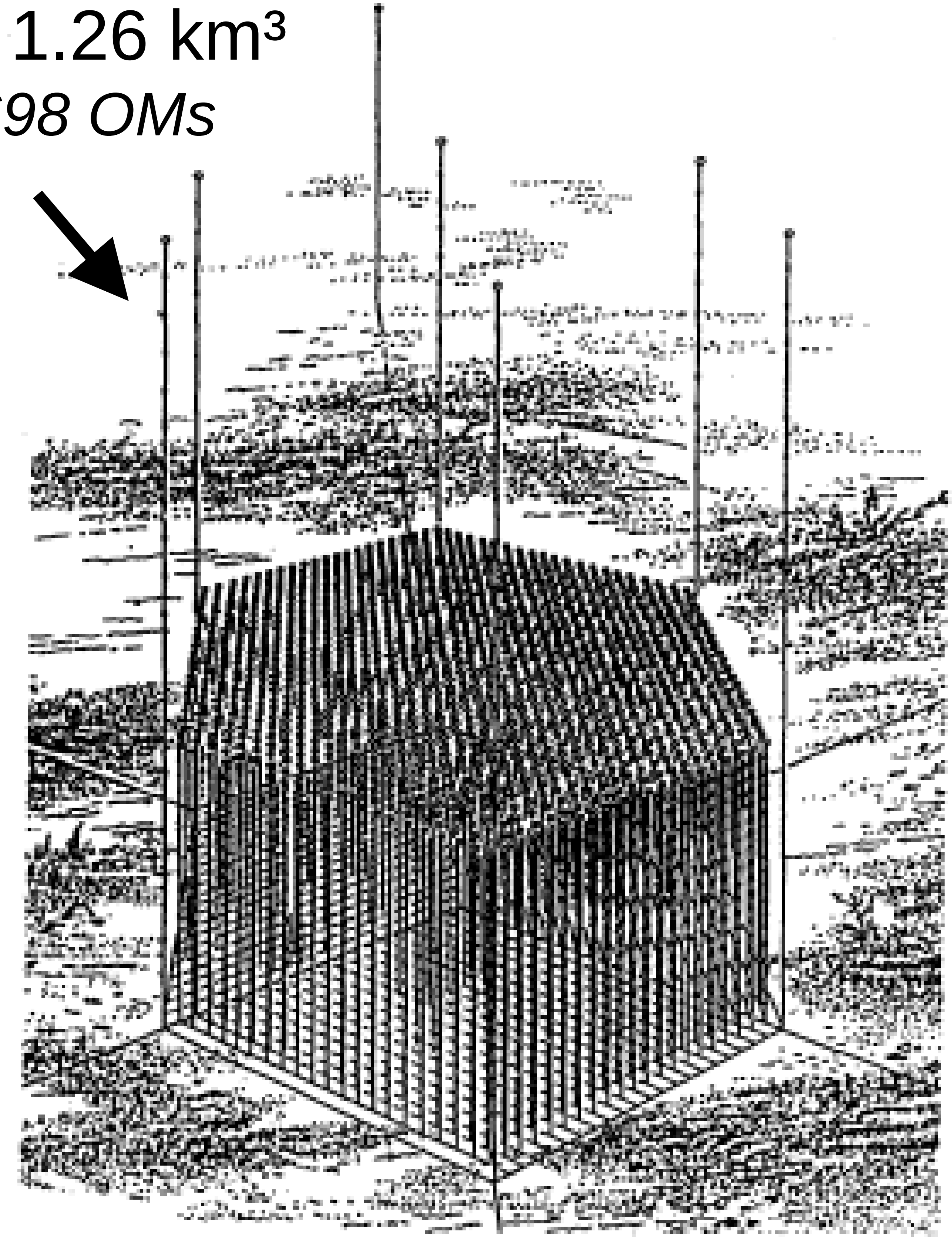


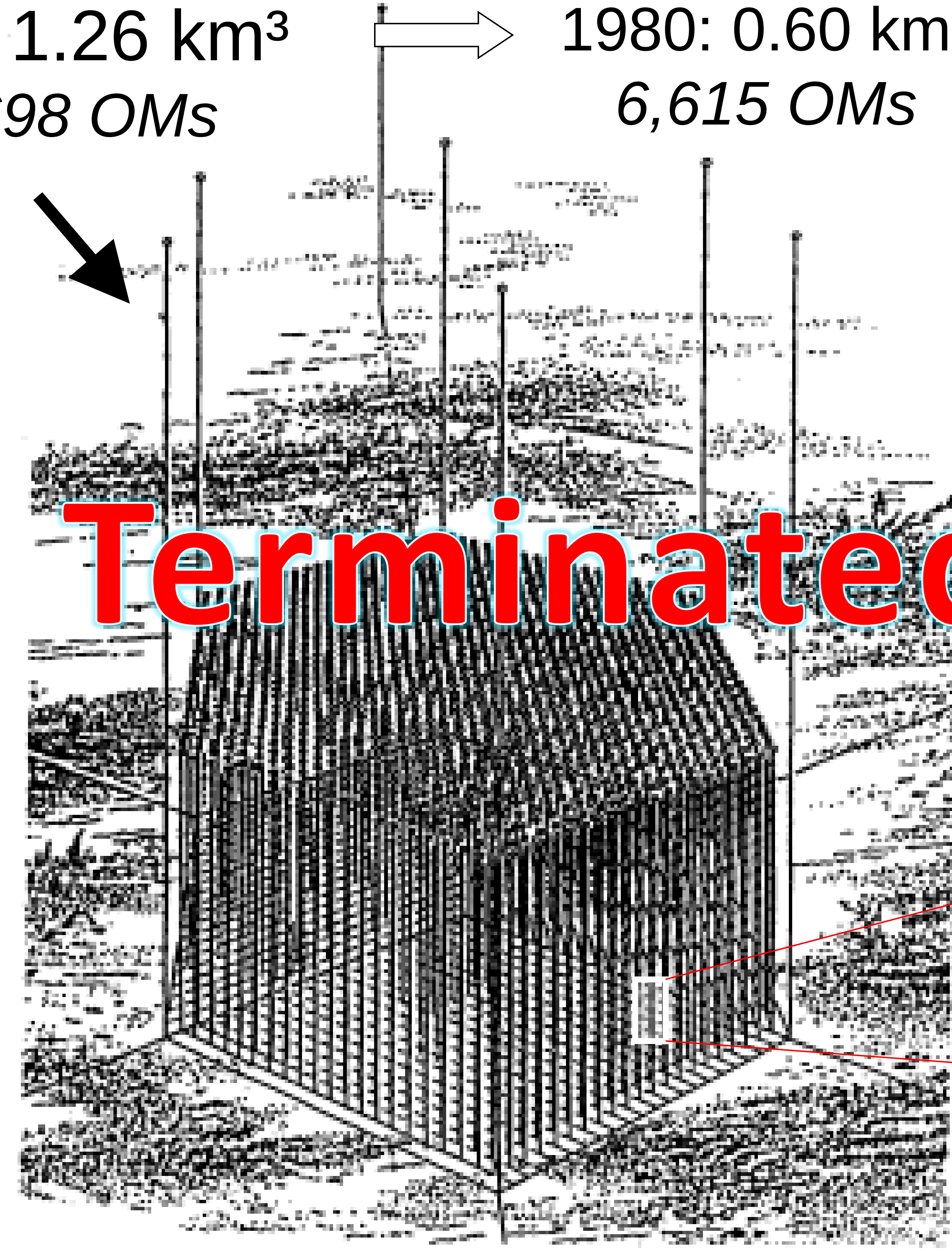
FIG. 9. The first DUMAND array: DUMAND G, the 1978 model. See text for details (Roberts and Wilkins, 1978).

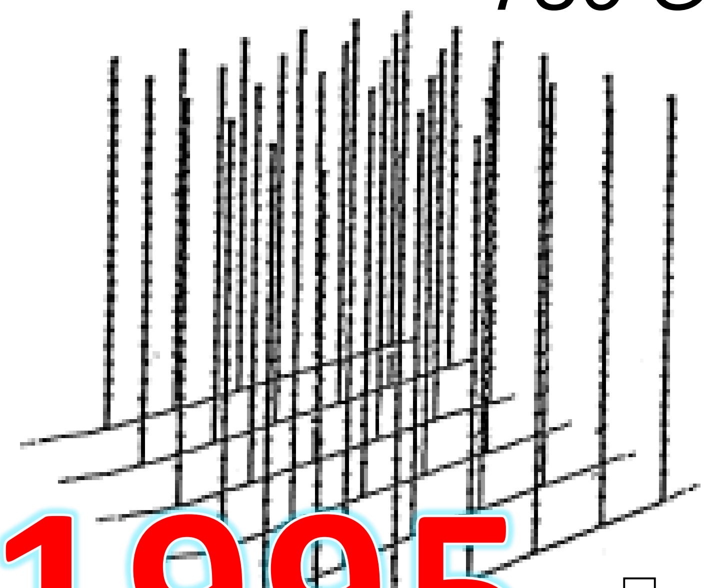
DUMAND

1978: 1.26 km³
22,698 OMs

1980: 0.60 km³
6,615 OMs

1982: 0.015 km³
756 OMs





Terminated 1995

1988:
0.002 km³
216 OMs

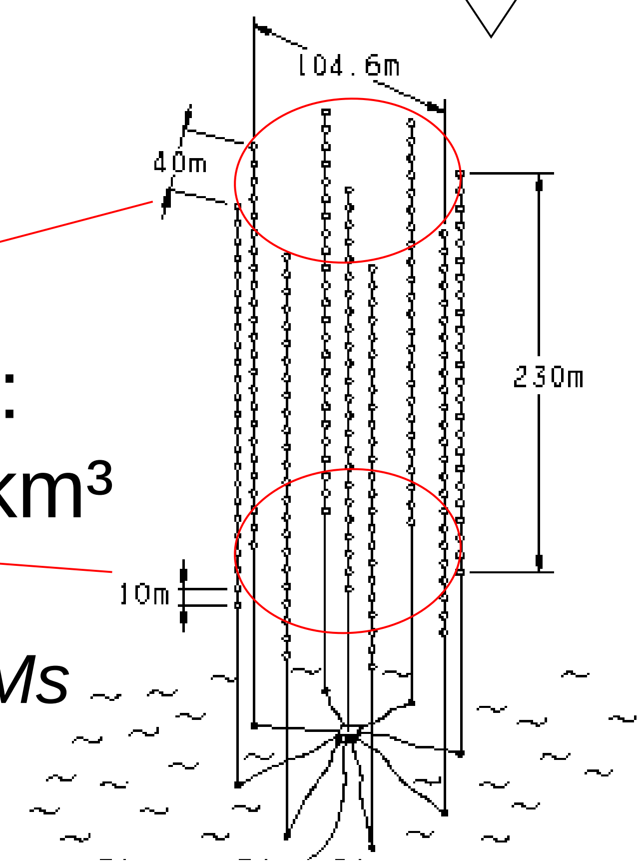
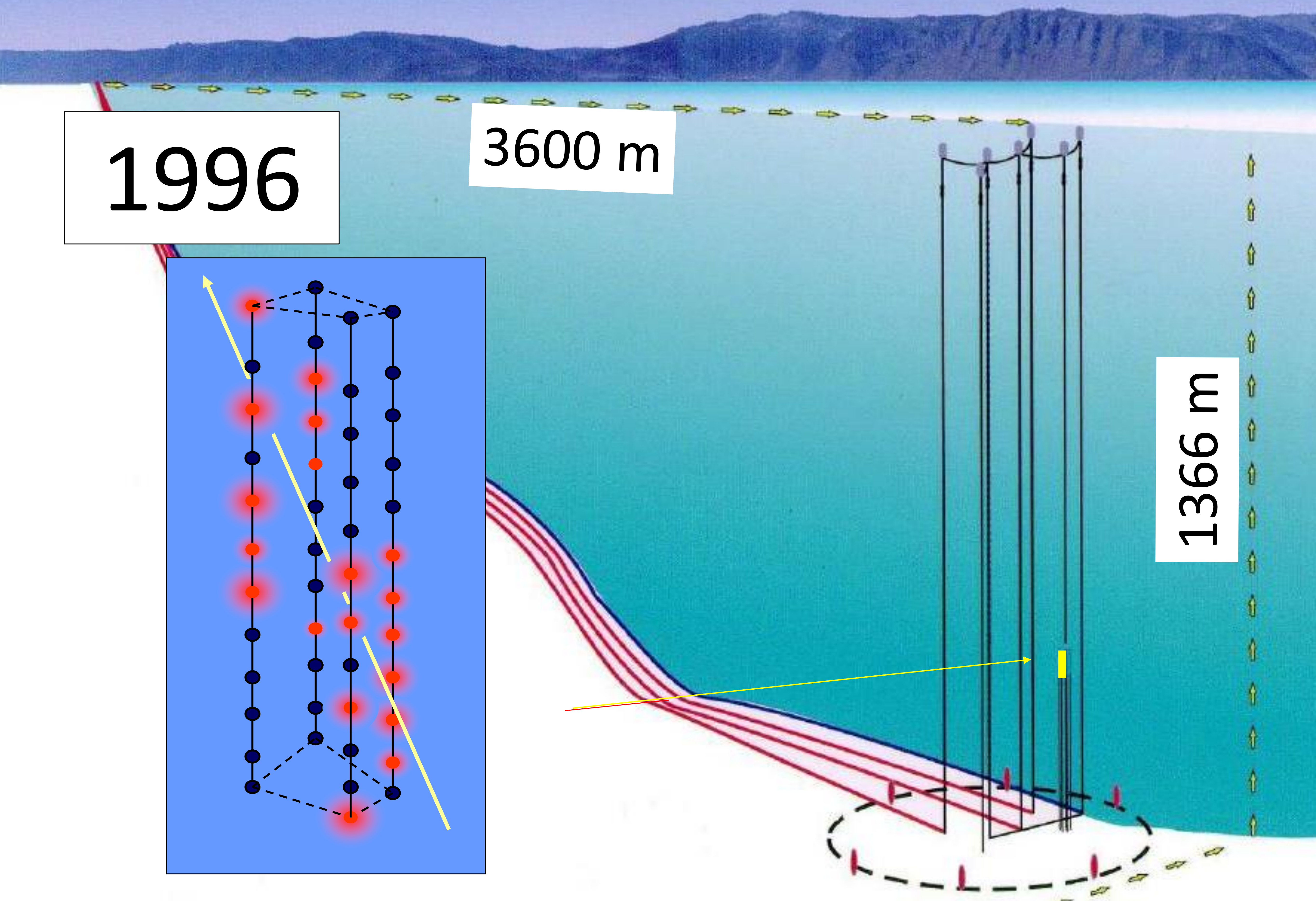


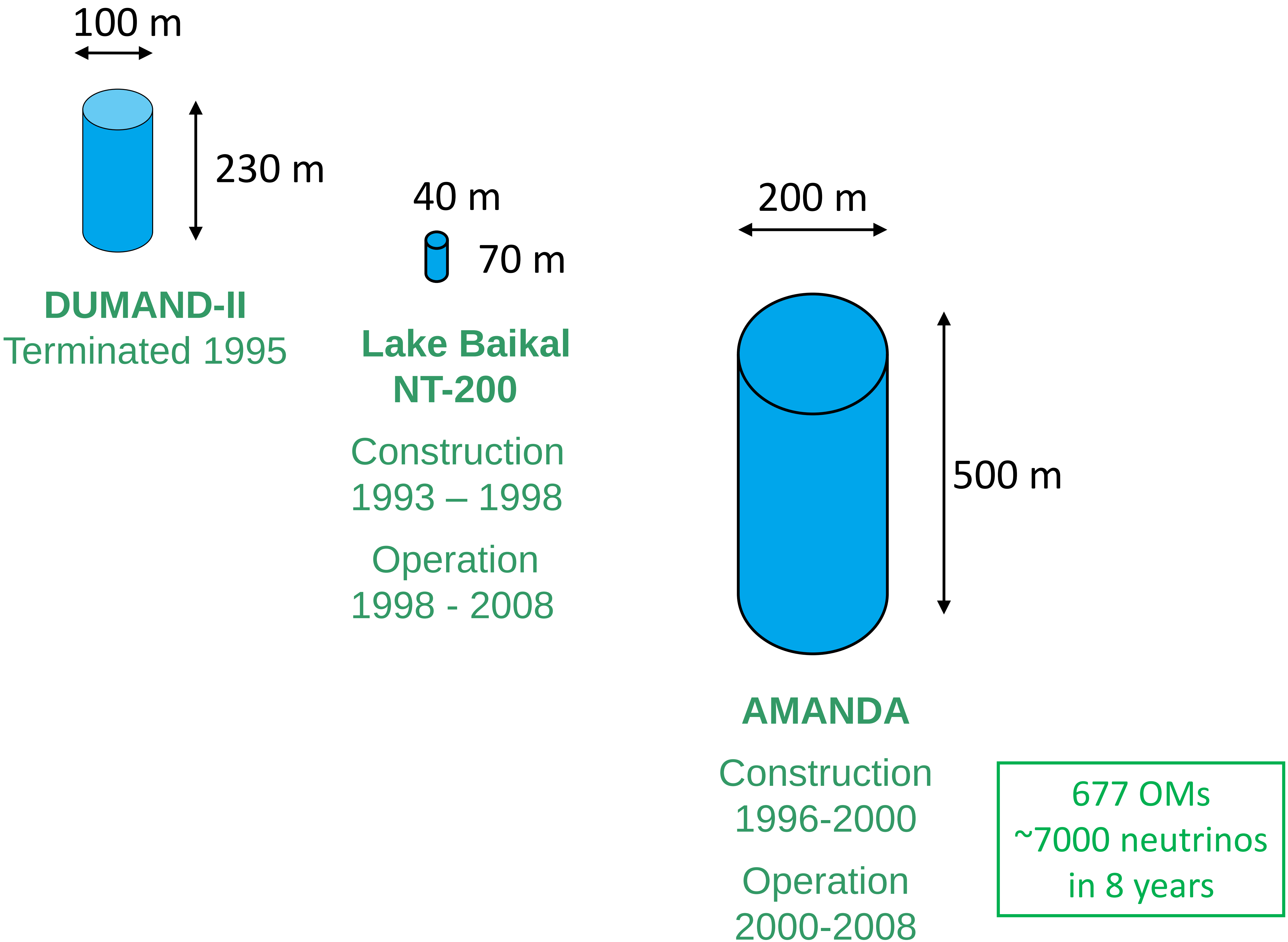
FIG. 9. The first DUMAND array: DUMAND G, the 1978 model. See text for details (Roberts and Wilkins, 1978).

DUMAND-II

Lake Baikal

A first textbook underwater neutrino event

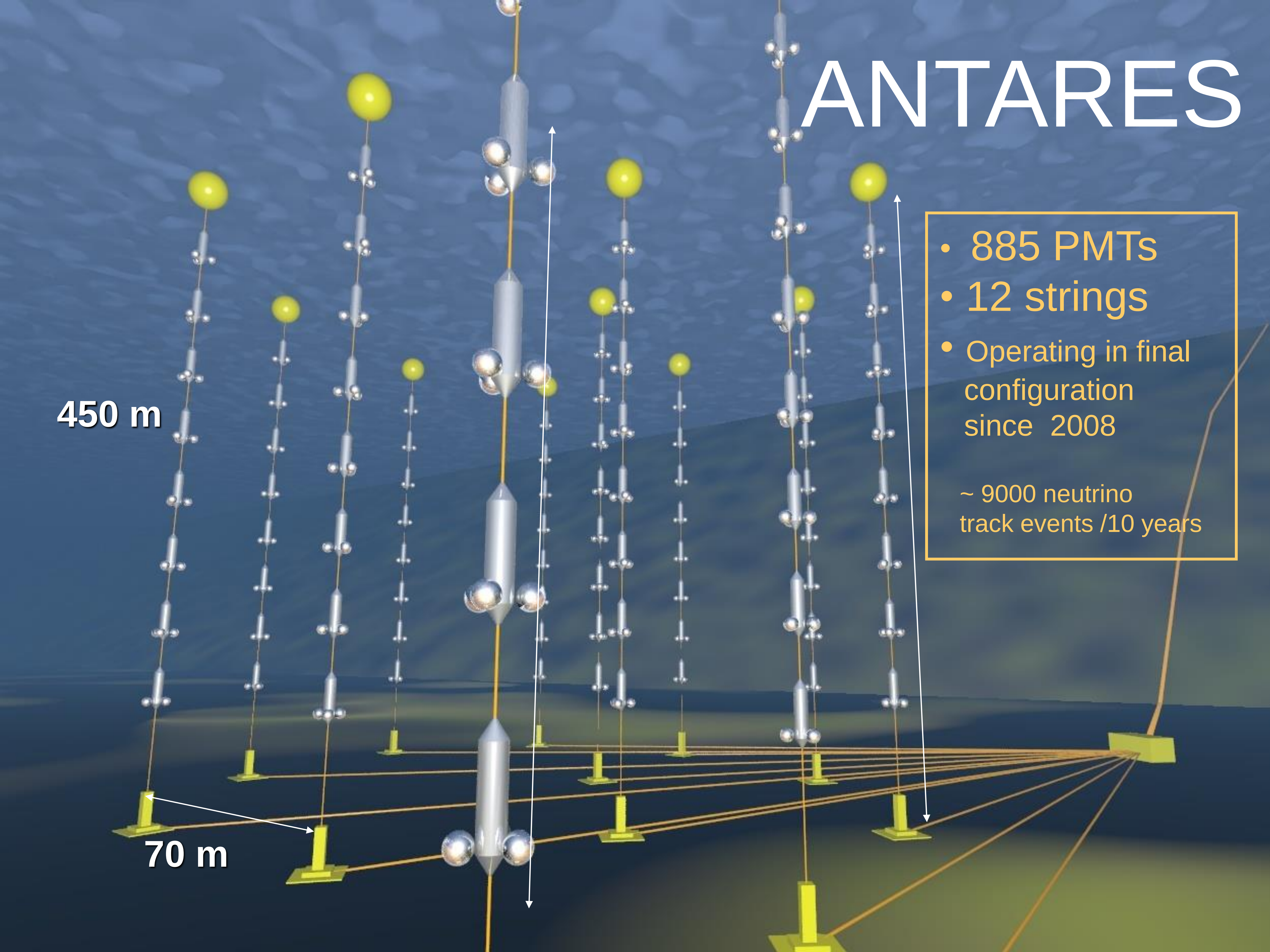



100 m
230 m
DUMAND-II
Terminated 1995
40 m
70 m
Lake Baikal
NT-200
Construction
1993 – 1998
Operation
1998 - 2008
200 m
500 m
AMANDA
Construction
1996-2000
Operation
2000-2008
677 OMs
~7000 neutrinos
in 8 years

ANTARES

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

~ 9000 neutrino track events /10 years

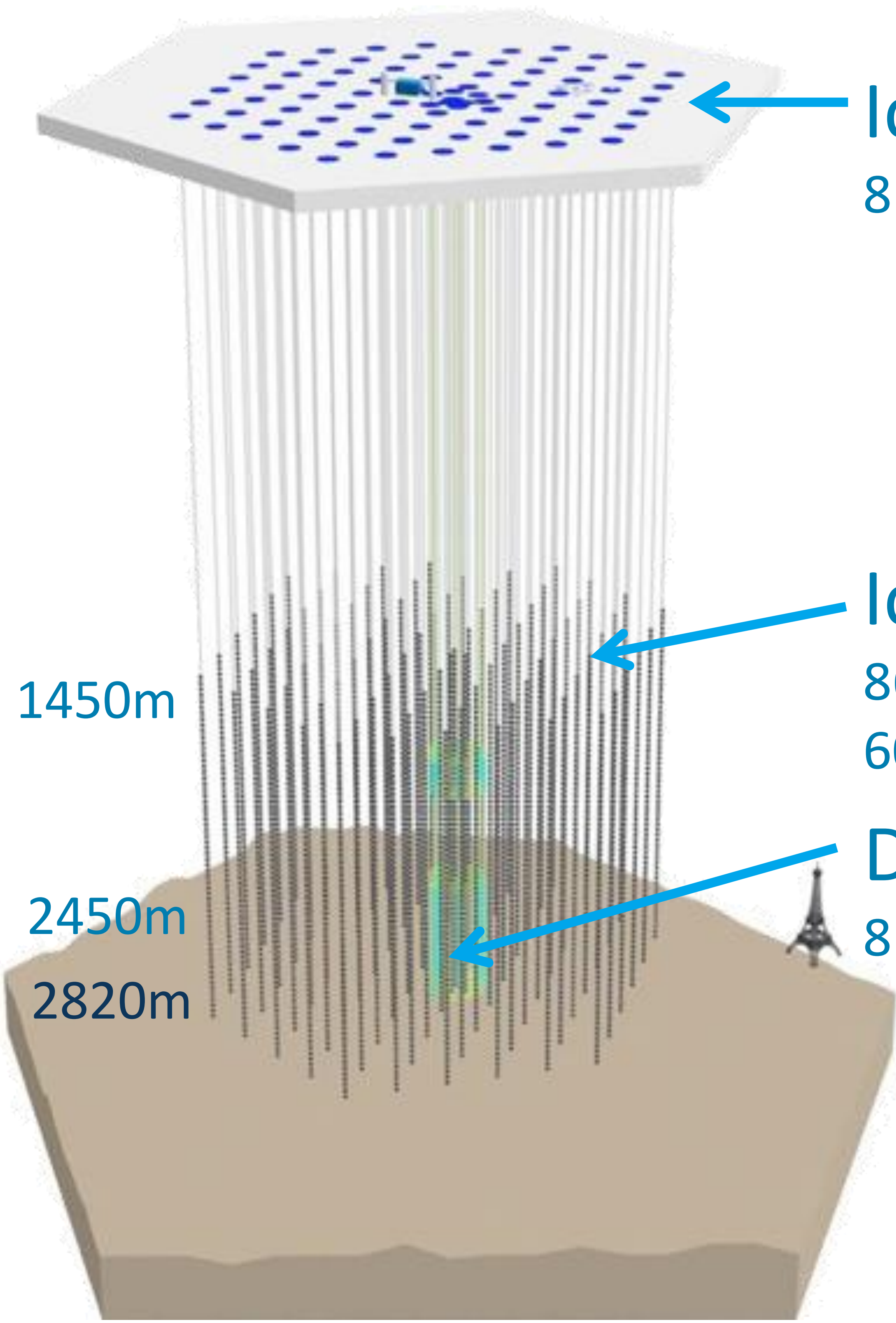


4.

IceCube Neutrino Observatory

The IceCube Collaboration

IceCube Neutrino Observatory



IceTop air shower detector

81 pairs of water Cherenkov tanks

IceCube

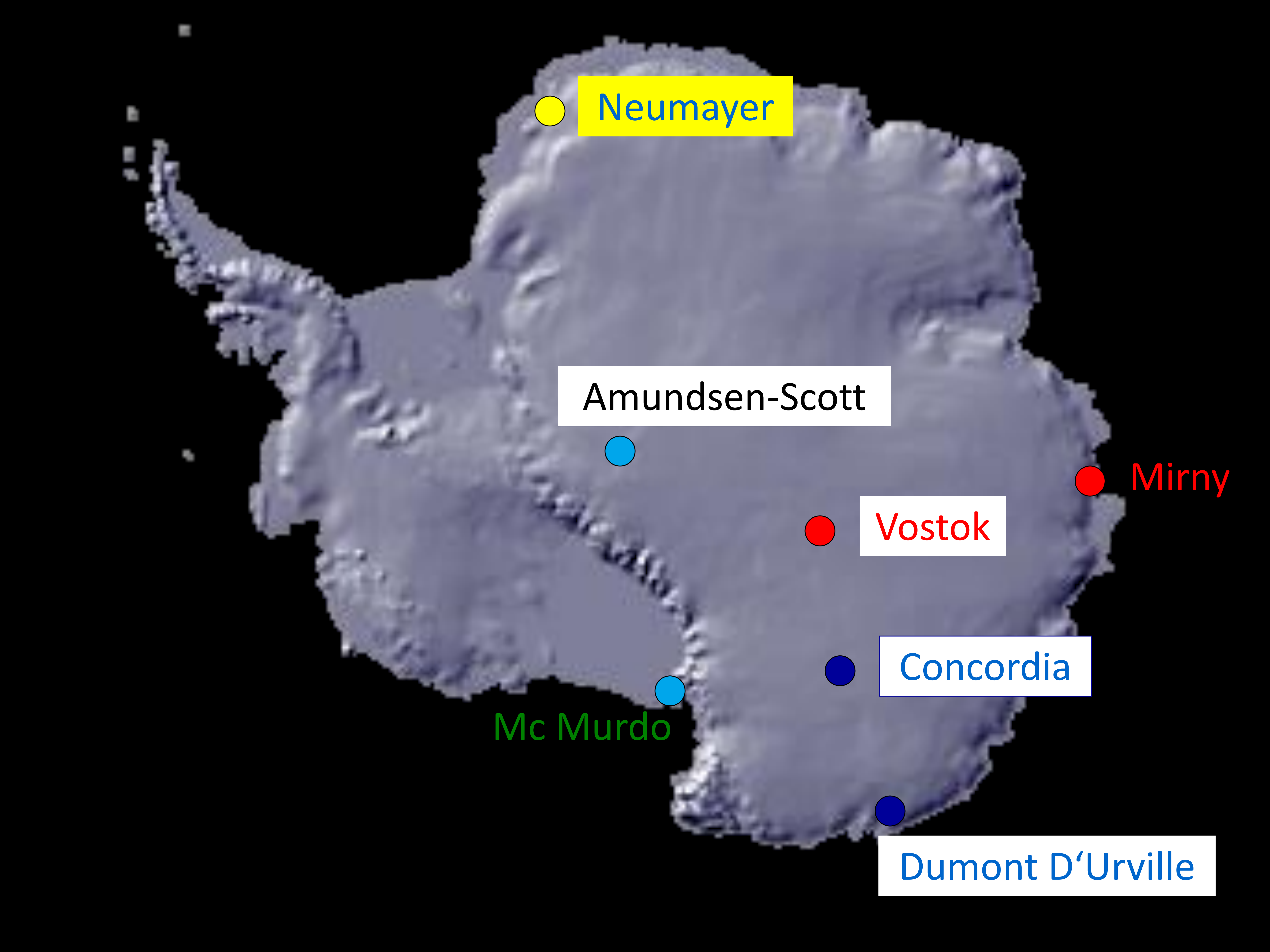
86 strings including 8 Deep Core strings
60 PMT per string

DeepCore

8 closely spaced strings

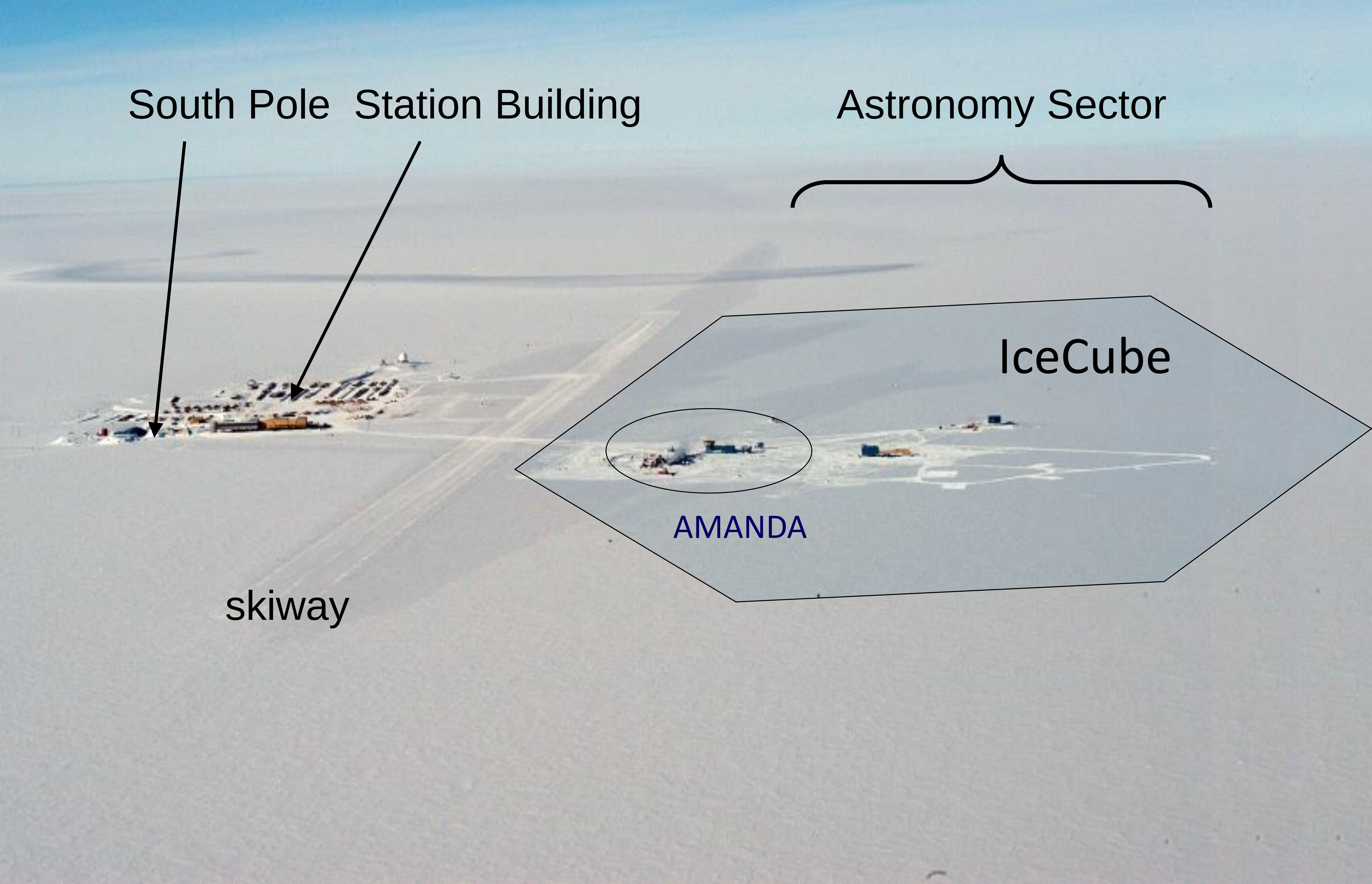
Threshold: **IceCube** **~ 100 GeV**
DeepCore **~10 GeV**

PHOTO BY CHARLIE KAMINSKI SOUTH POLE DEC 2, 2000

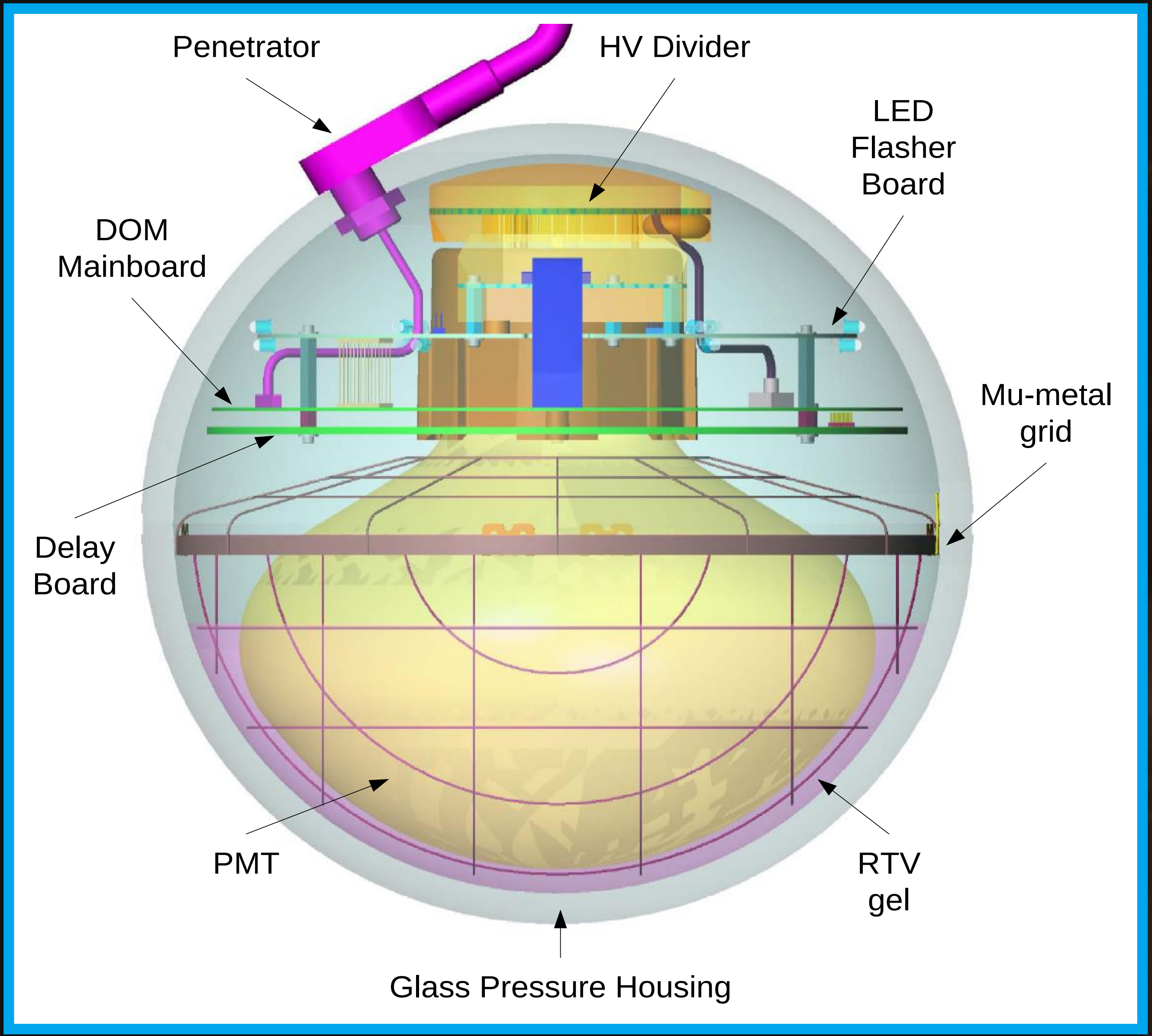


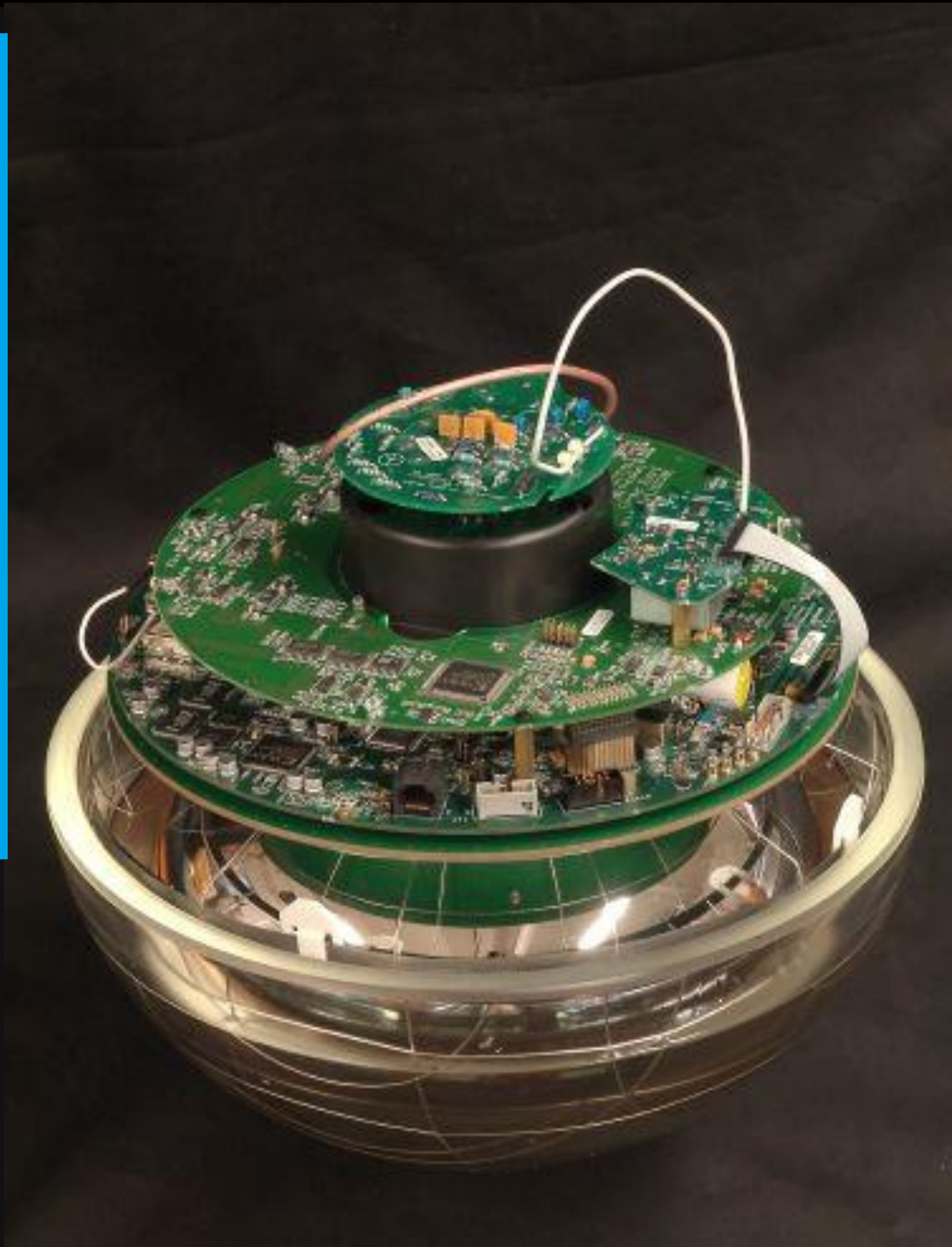
Neumayer
Amundsen-Scott
Mirny
Vostok
Concordia
Mc Murdo
Dumont D'Urville

The Amundsen-Scott Station



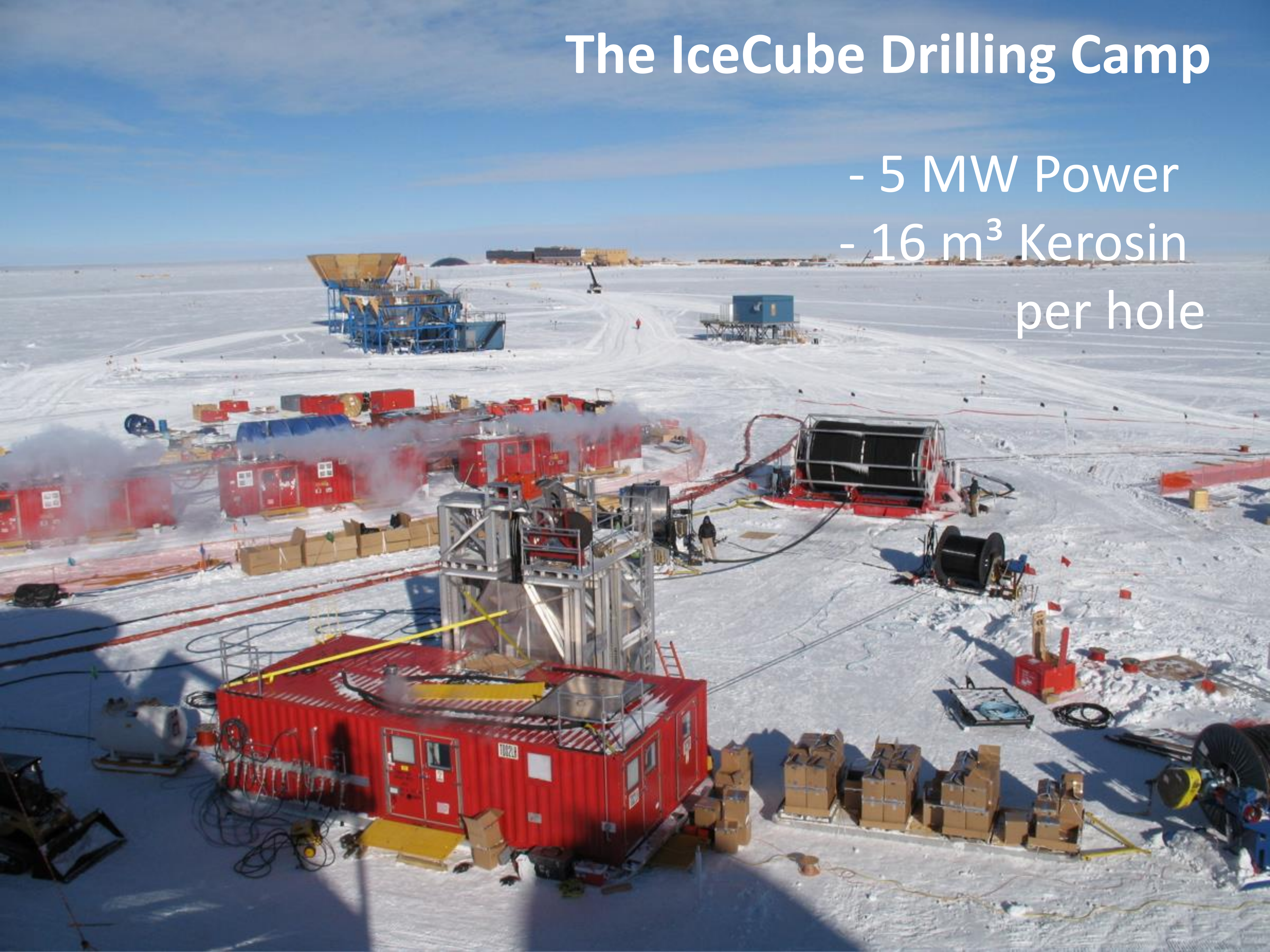
The Digital Optical Module (DOM)





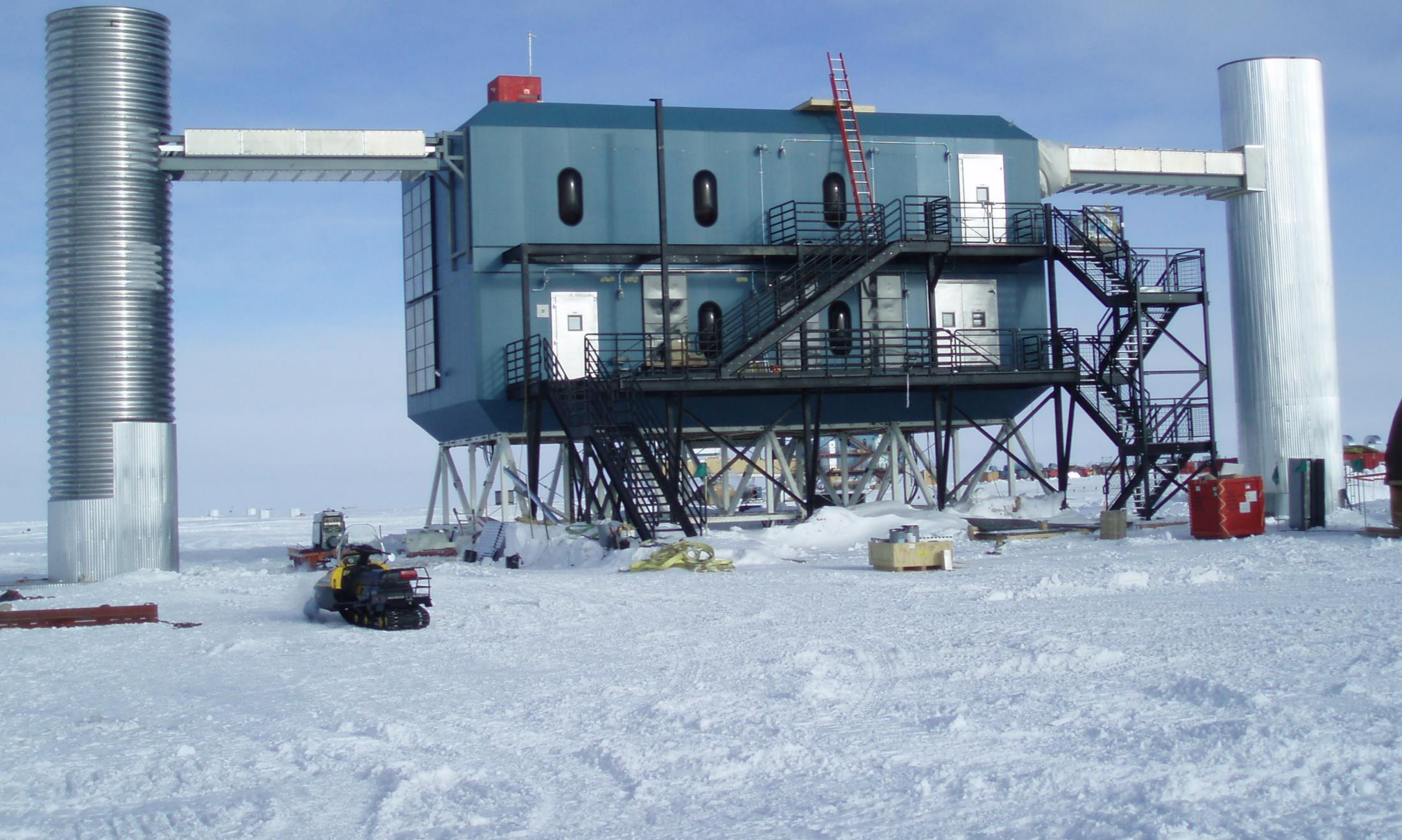
Failure rate ~1 DOM/year

(out of 5160 !)

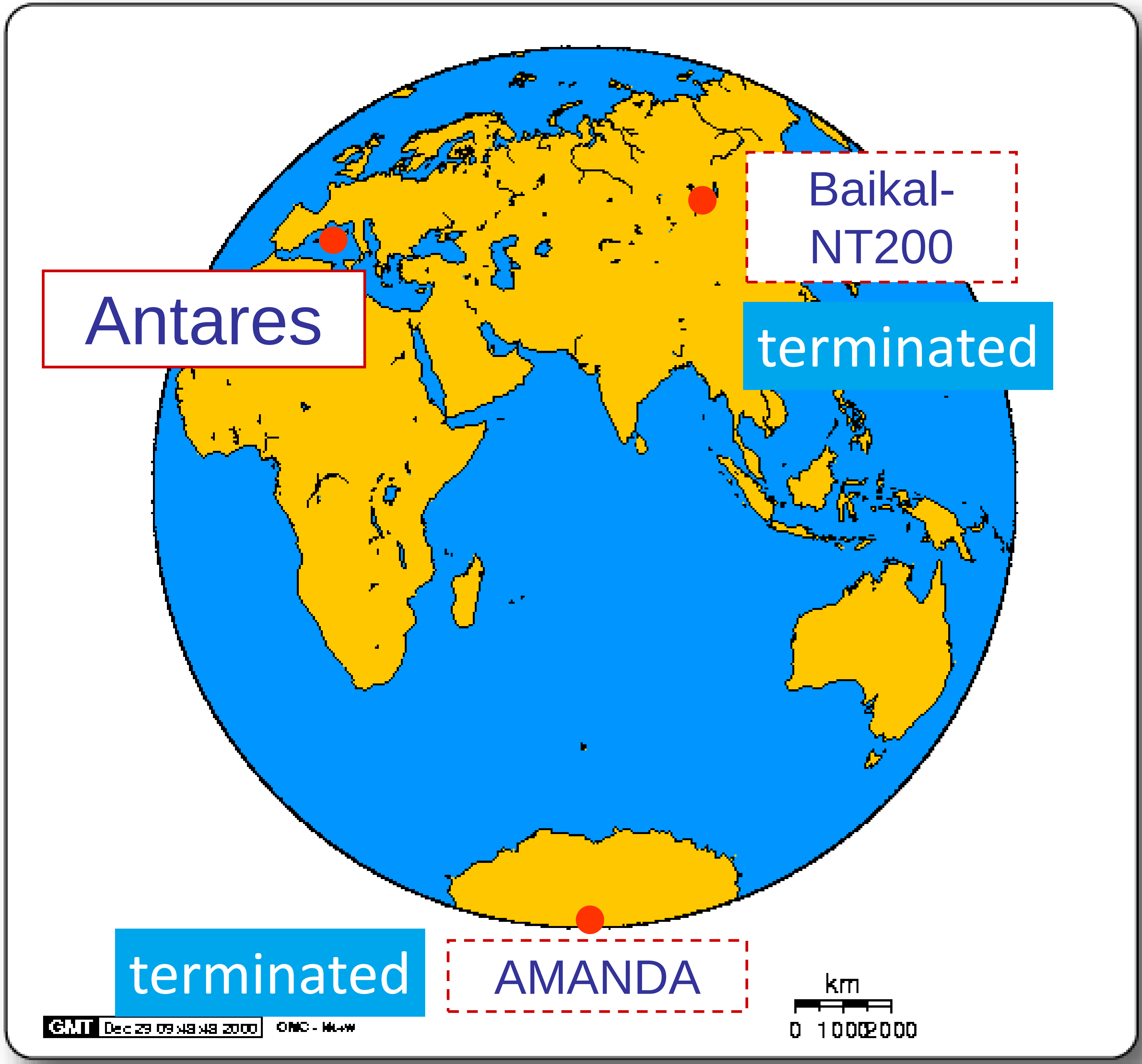

The IceCube Drilling Camp
- 5 MW Power
- 16 m³ Kerosin
per hole

18.Dec. 2010: the last string

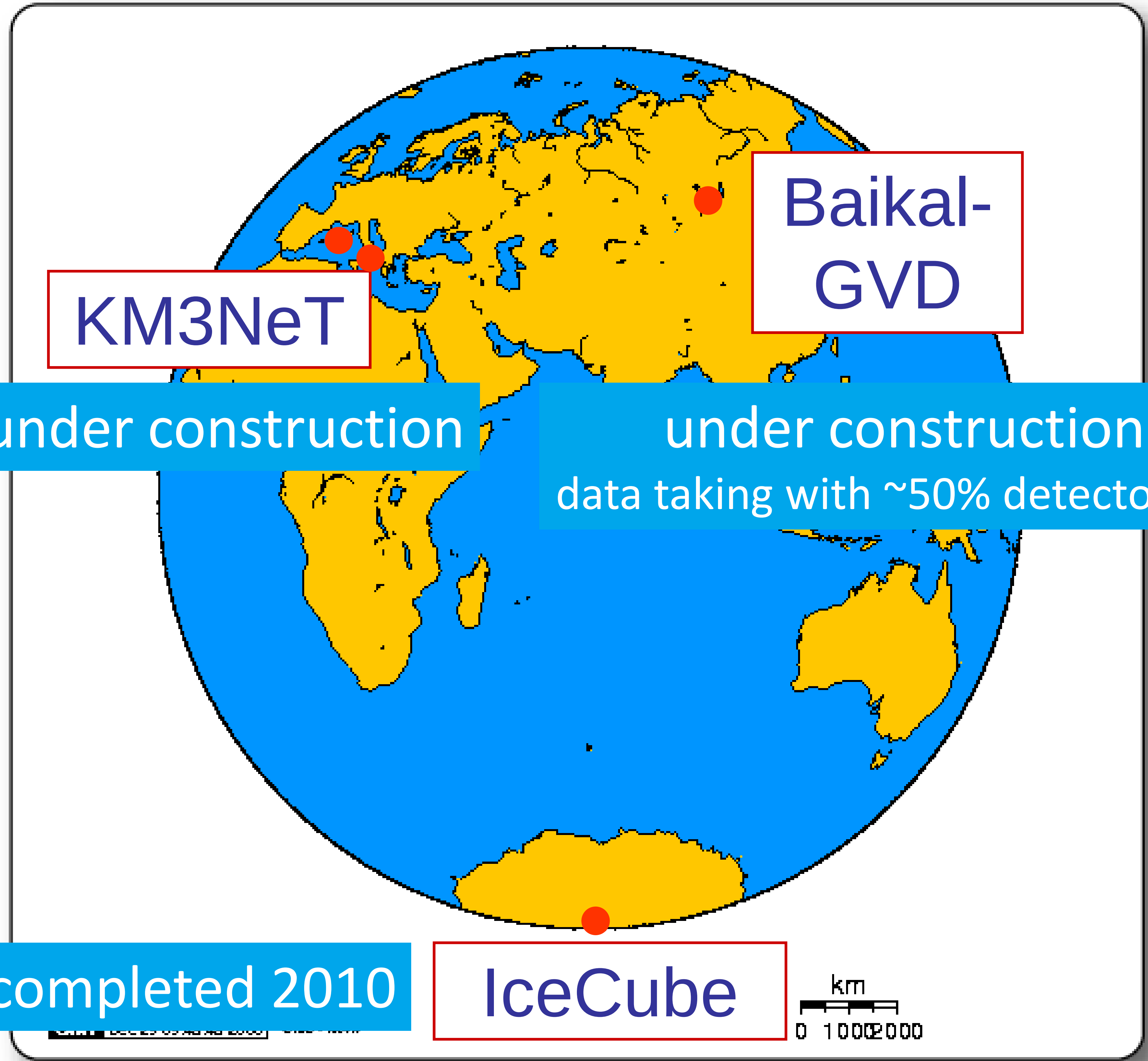
IceCube Laboratory and Data Center



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



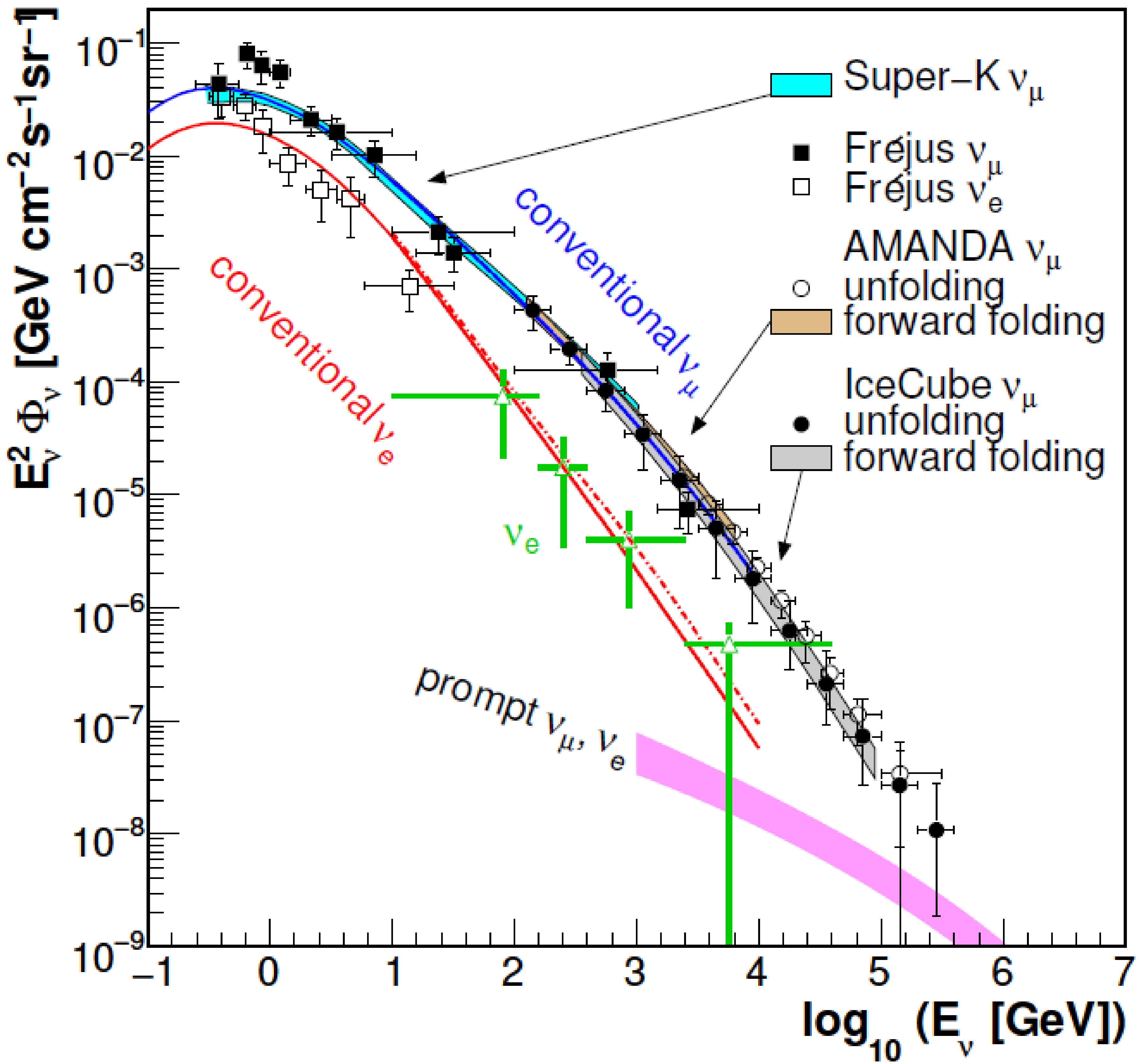
Generation-2 devices (km^3 scale)

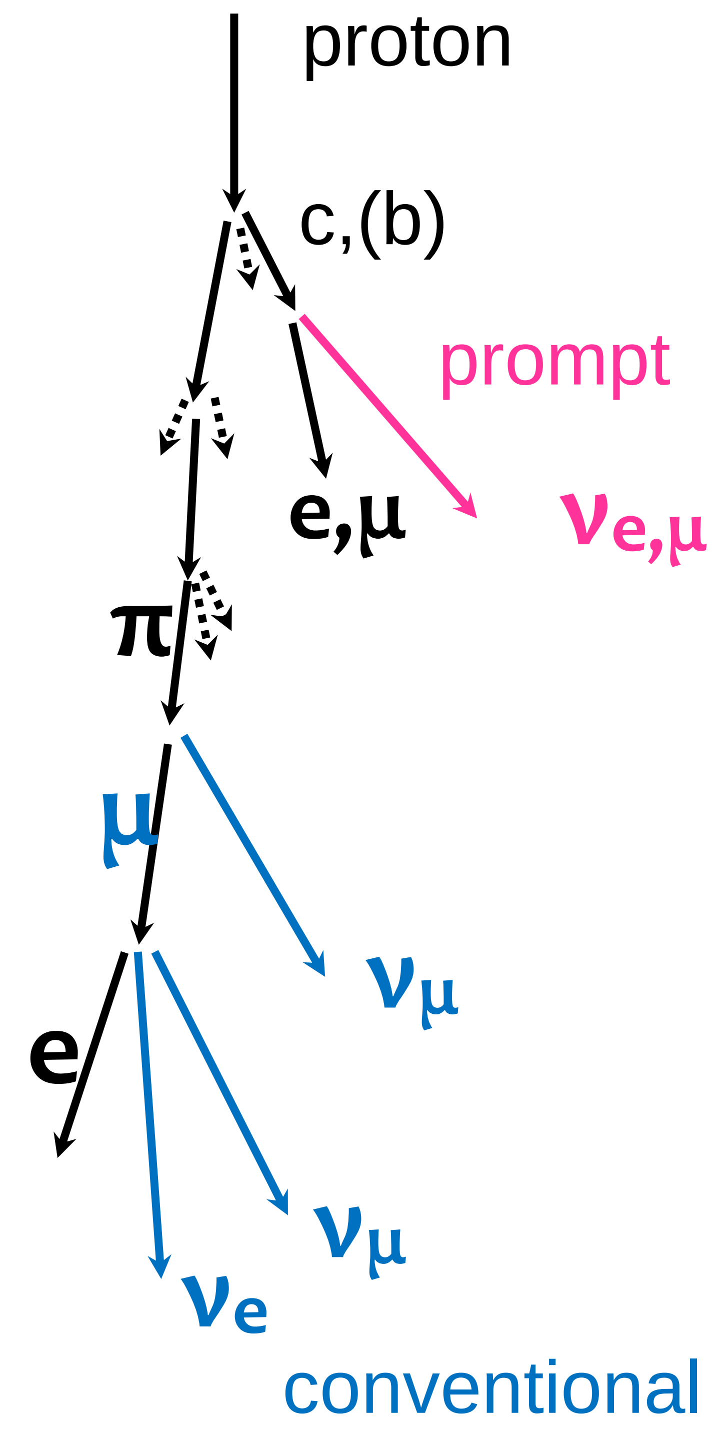


5.

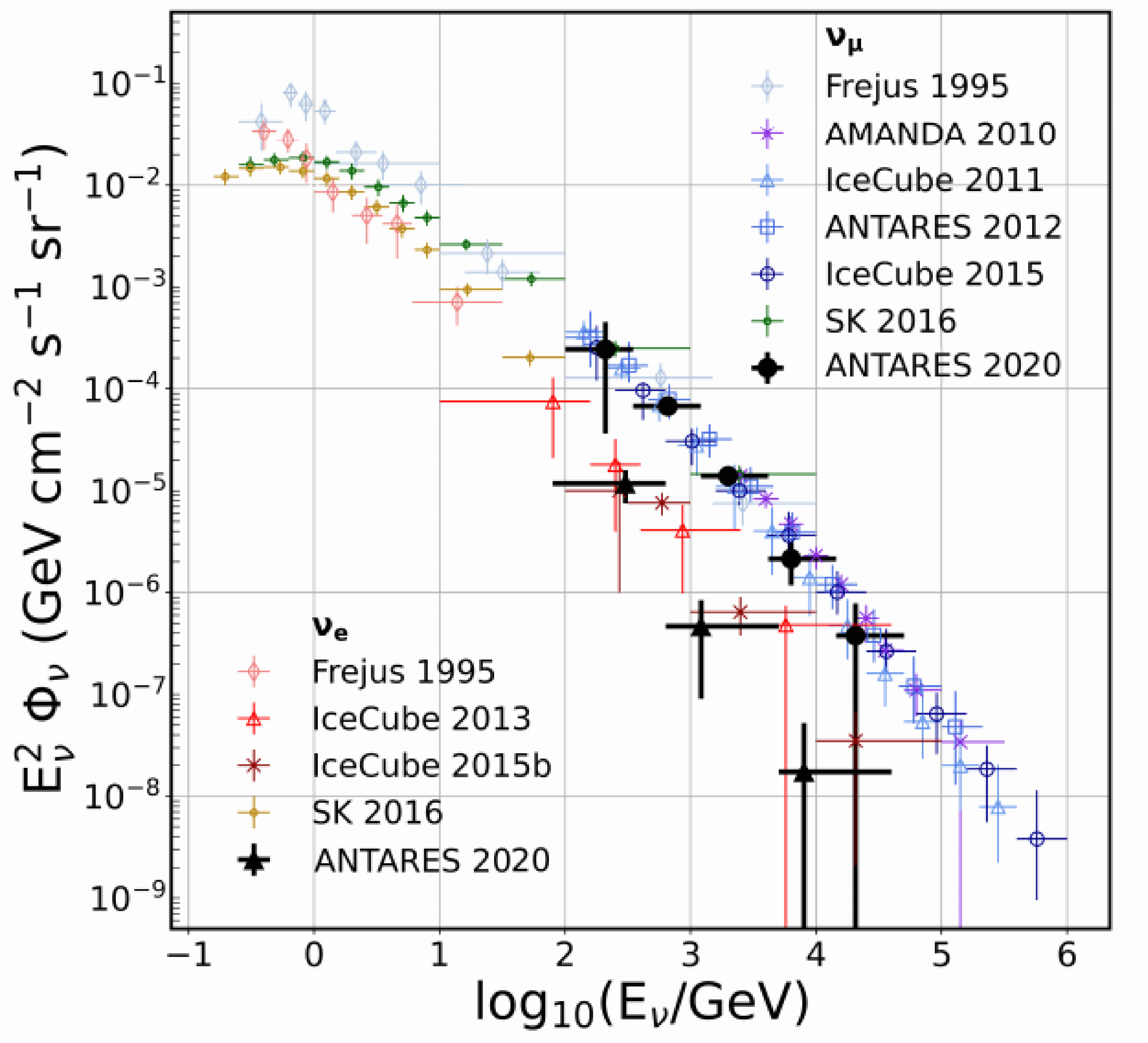
Atmospheric neutrinos

Atmospheric neutrinos in IceCube (2 years)





Atmospheric neutrinos, IceCube + ANTARES



6.

Cosmic neutrinos

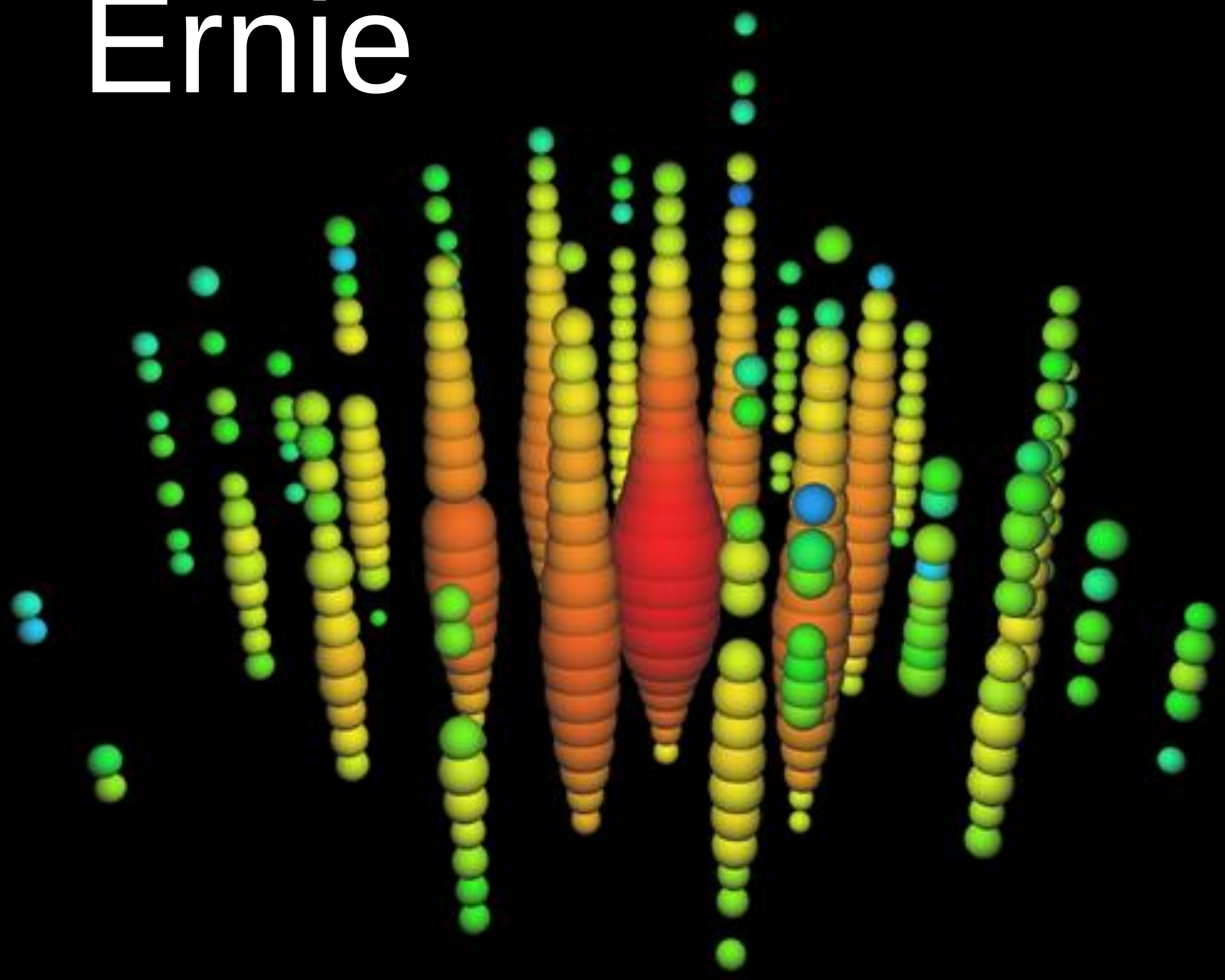
The Discovery of a Diffuse Cosmic Neutrino Flux

Special search for neutrinos with E_ν > 500 TeV

IC79/IC86

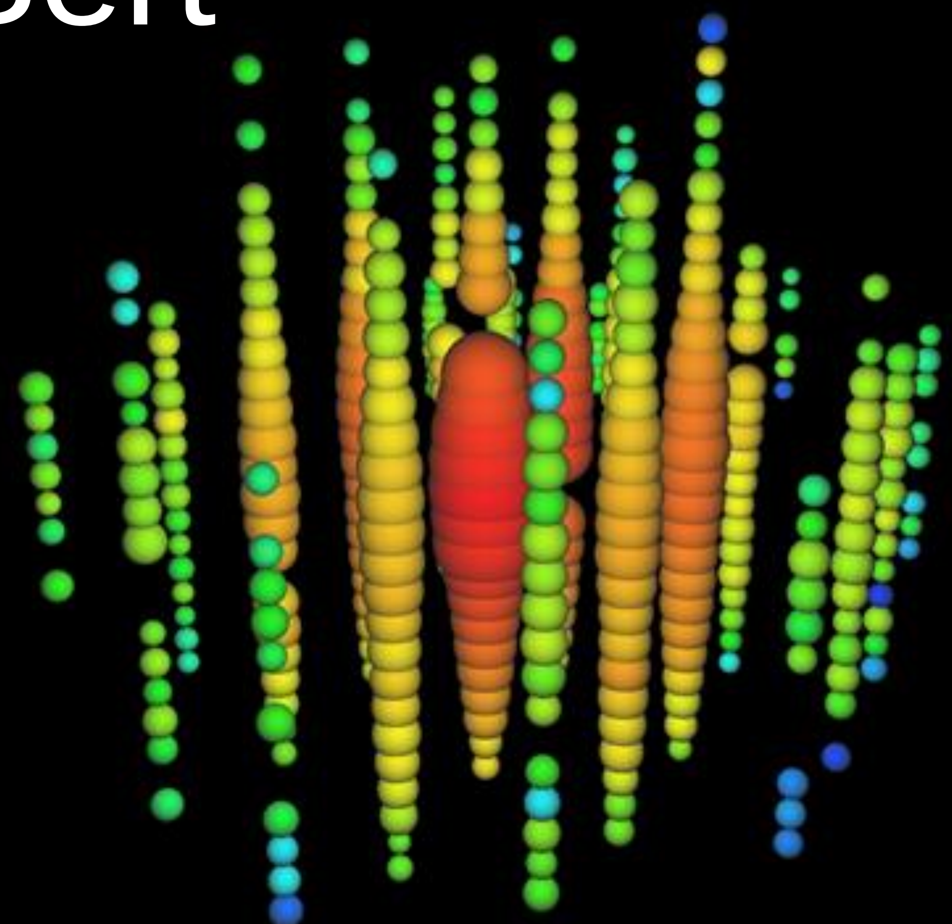
2.8 σ

Ernie



~1.04 PeV

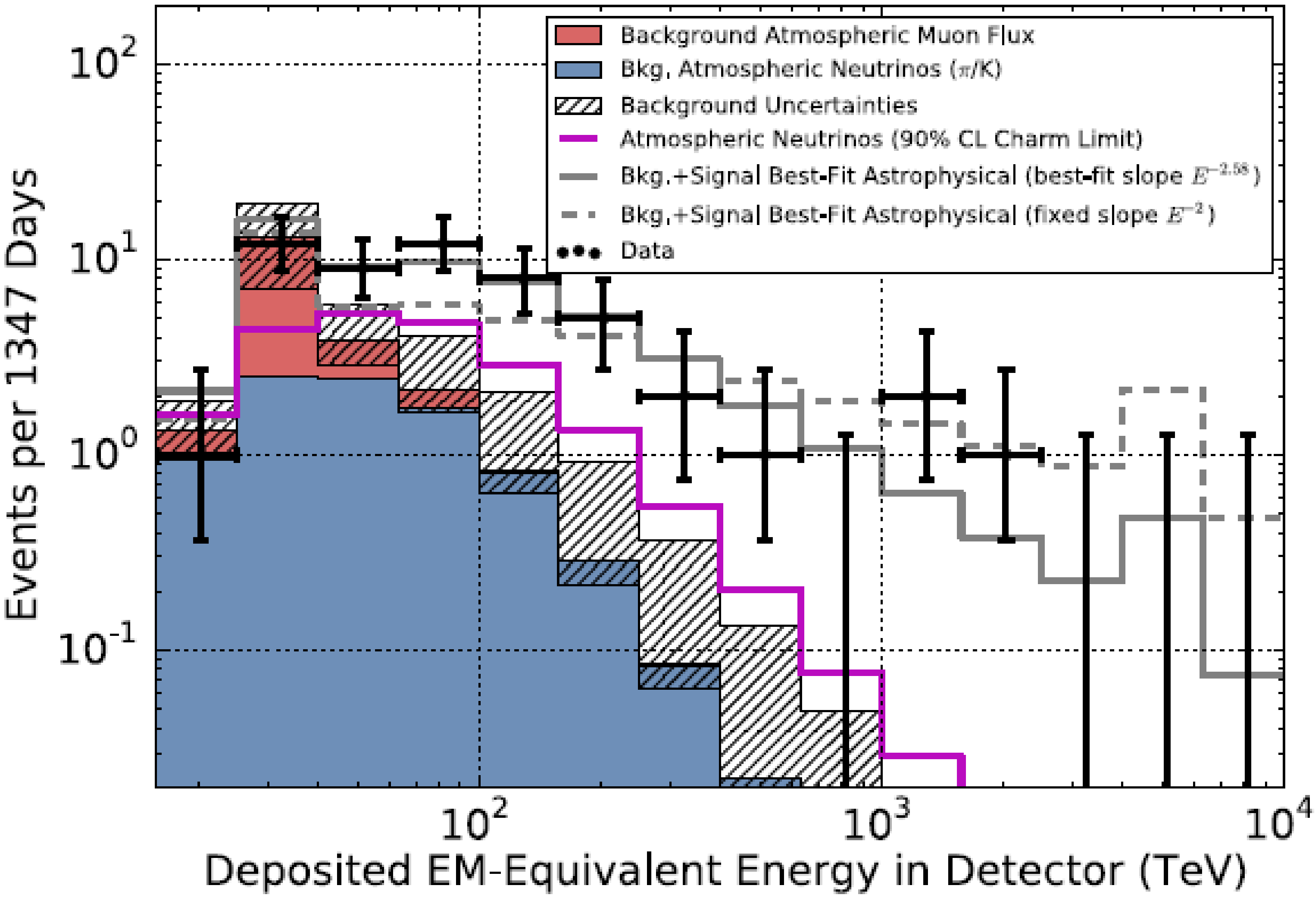
Bert



~ 1.14 PeV

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)

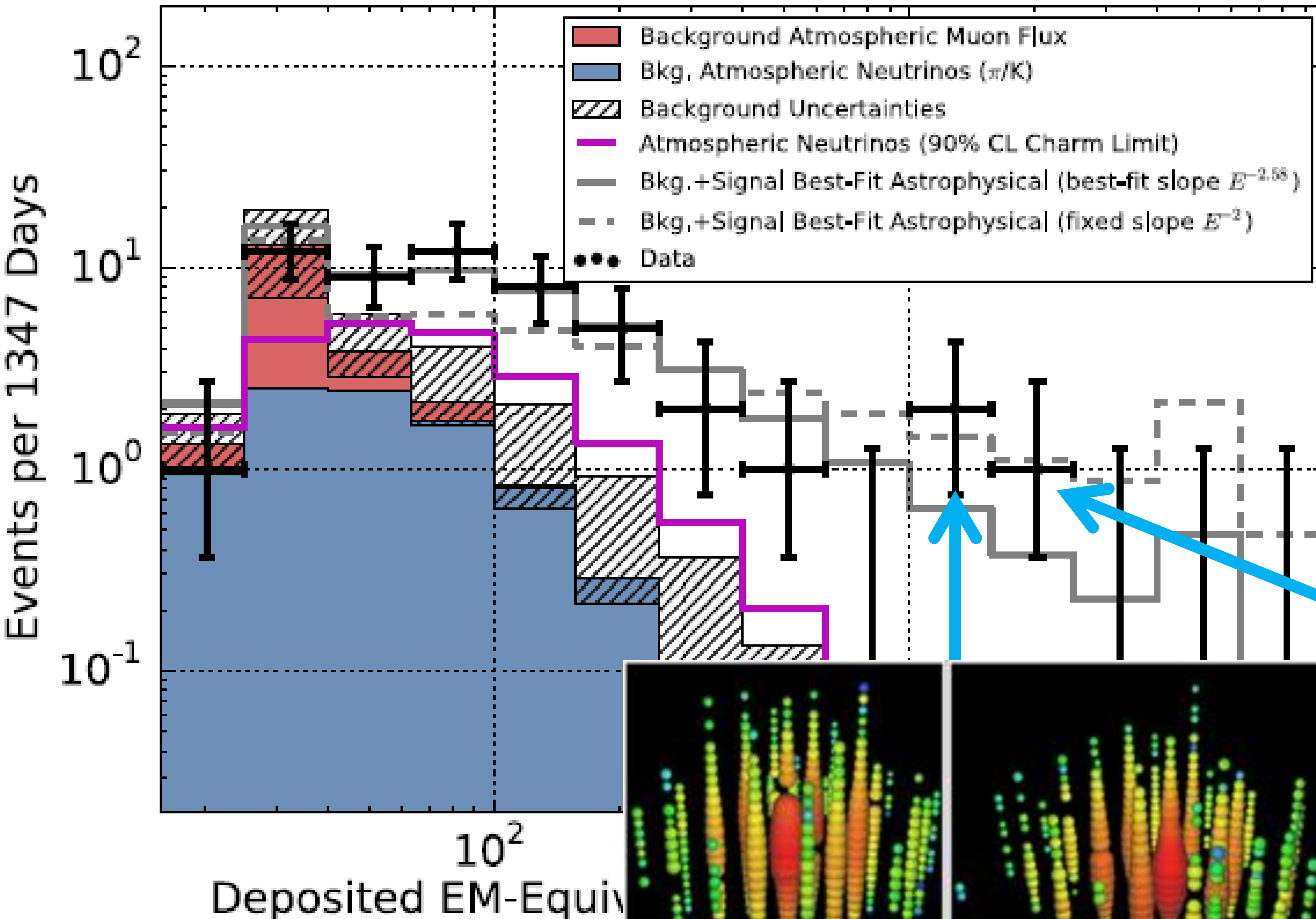
3 yrs data, 37 evts 5.9σ
Phys.Rev.Lett. 113:101101 (2014)

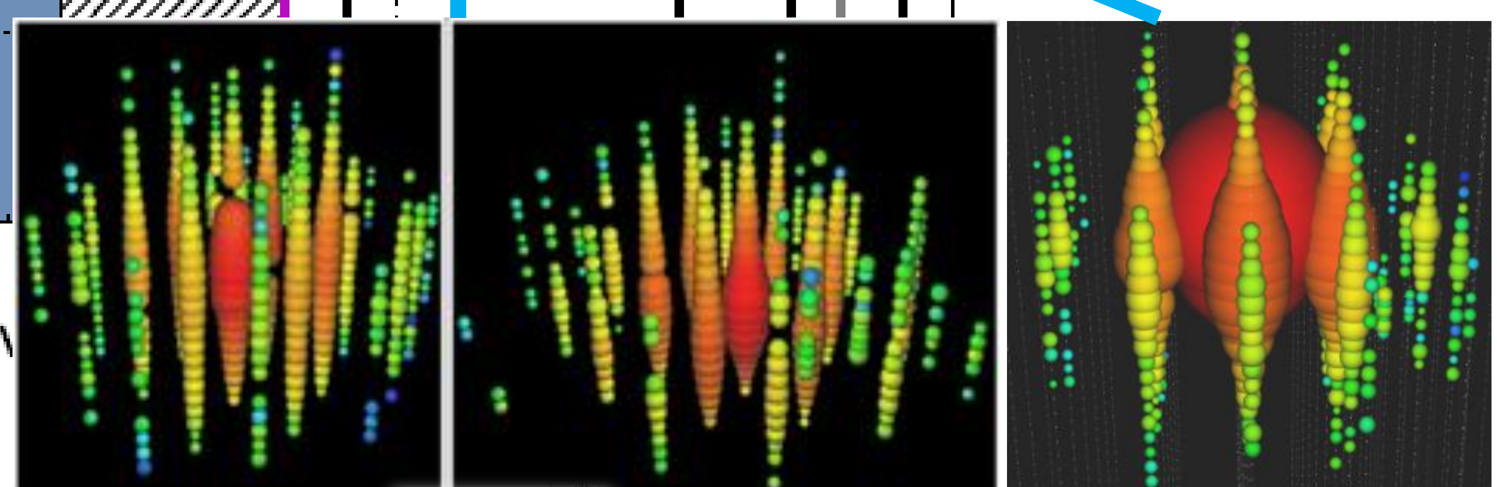
4 yrs data, 54 evts ~ 7σ

Threshold ~ 30 TeV

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

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





"Bert"
1.04 PeV
Aug. 2011

"Ernie"
1.14 PeV
Jan. 2012

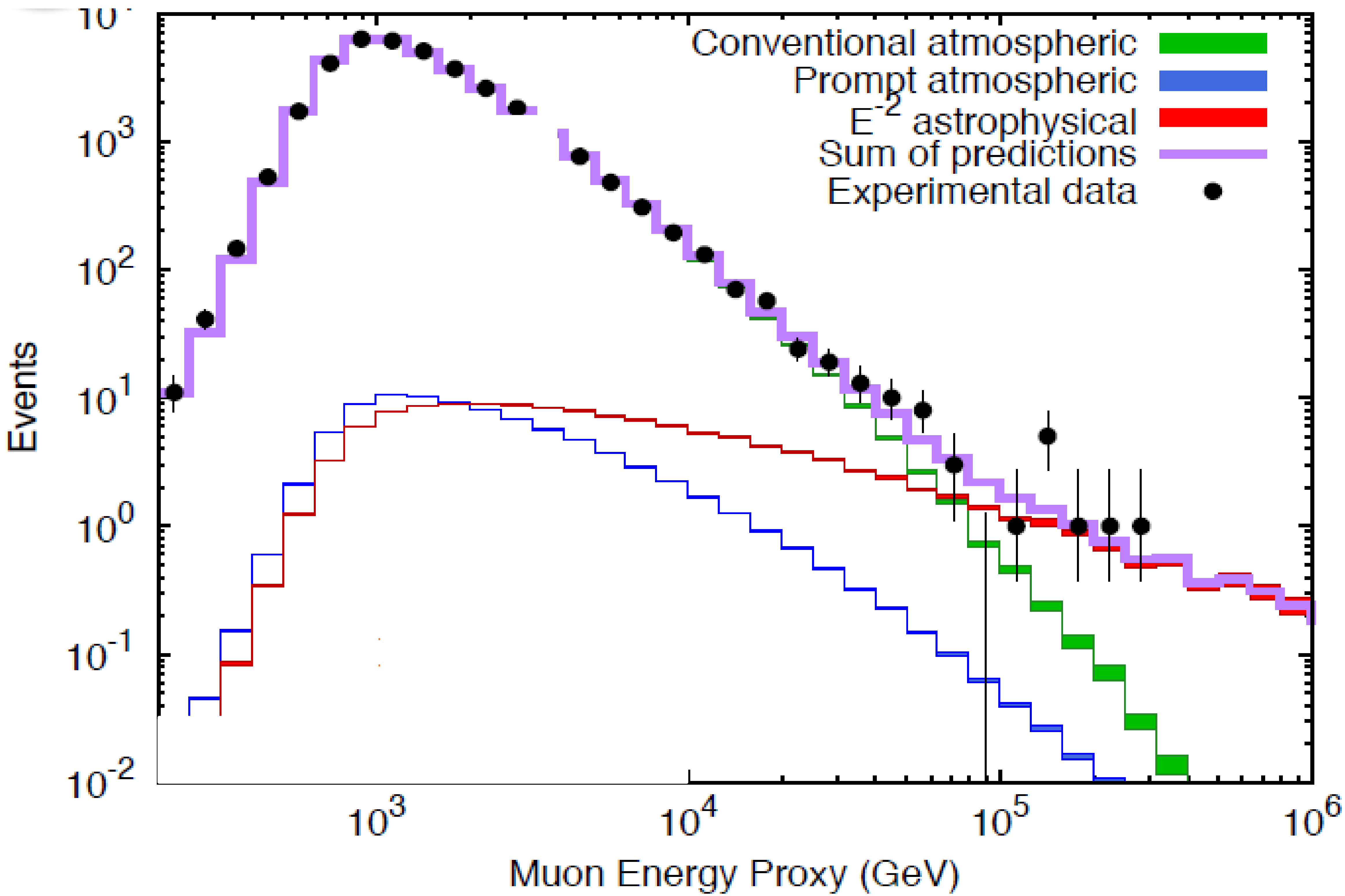
"Big Bird"
2 PeV
Dec. 2012

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

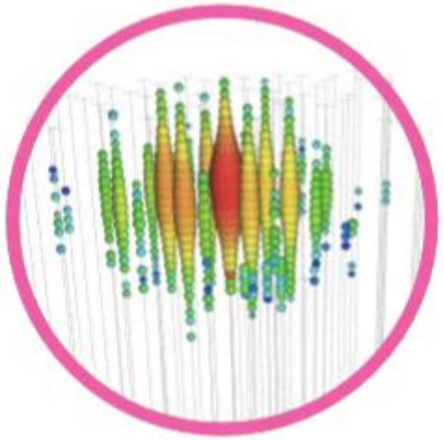
3 yrs data, 37 evts 5.9σ
Phys.Rev.Lett. 113:101101 (2014)

4 yrs data, 54 evts ~ **<u>7σ</u>**

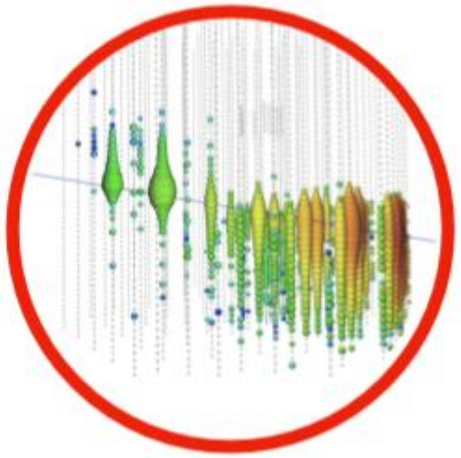
Through-going muons, IC-79/86



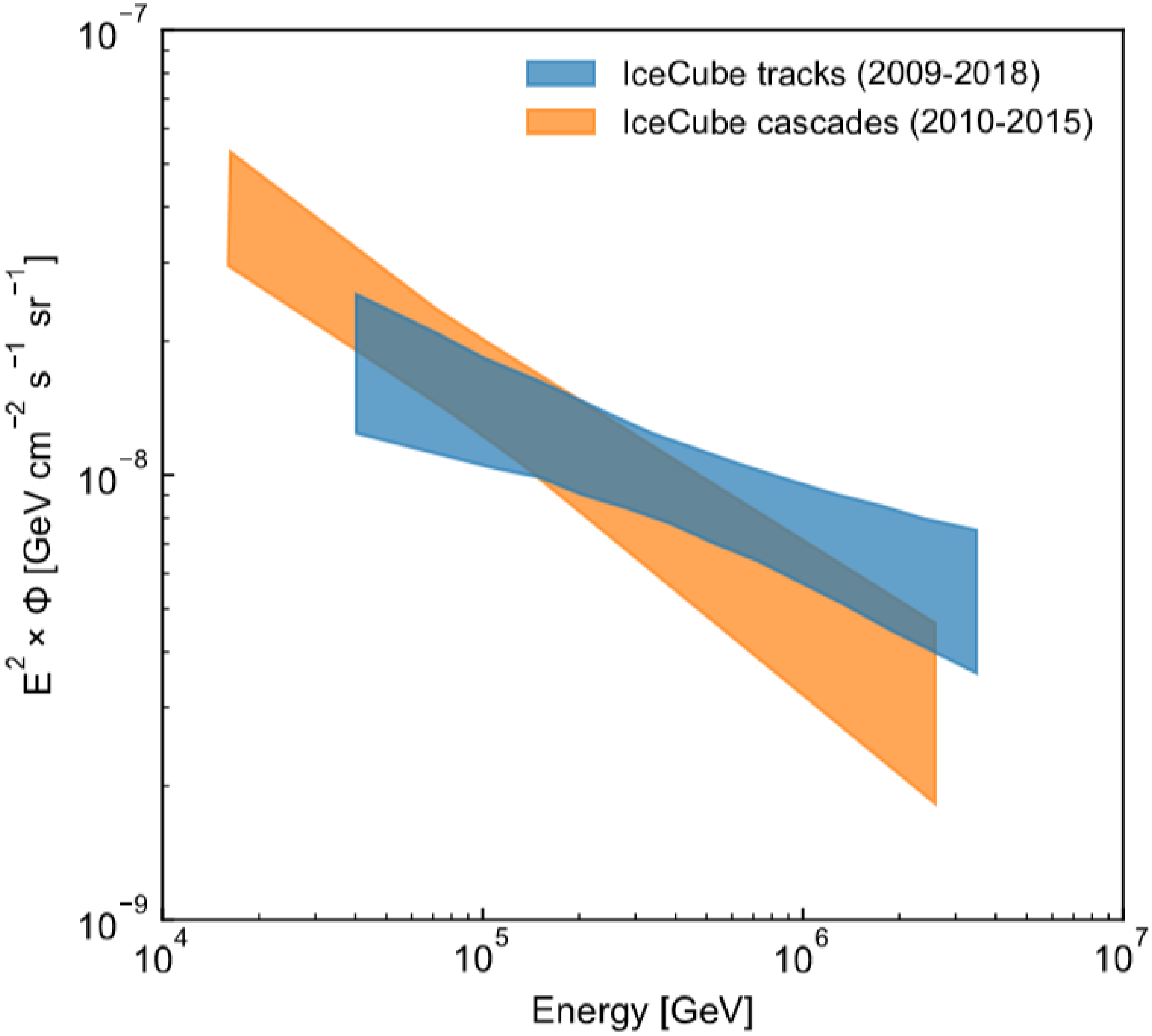
The Astrophysical Neutrino Flux



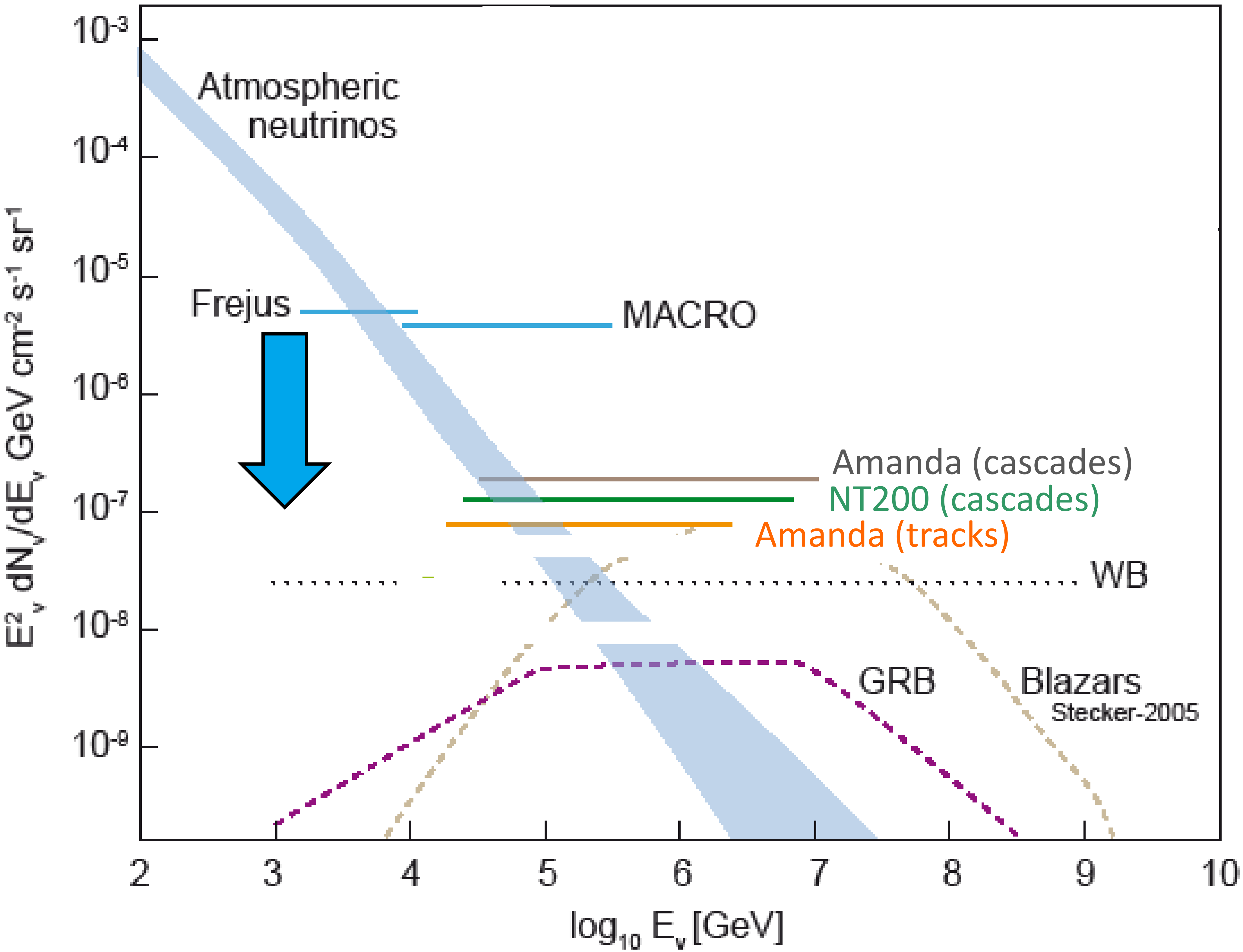
High-energy starting events (HESE)
Interaction vertex in the detector
All flavor, all sky



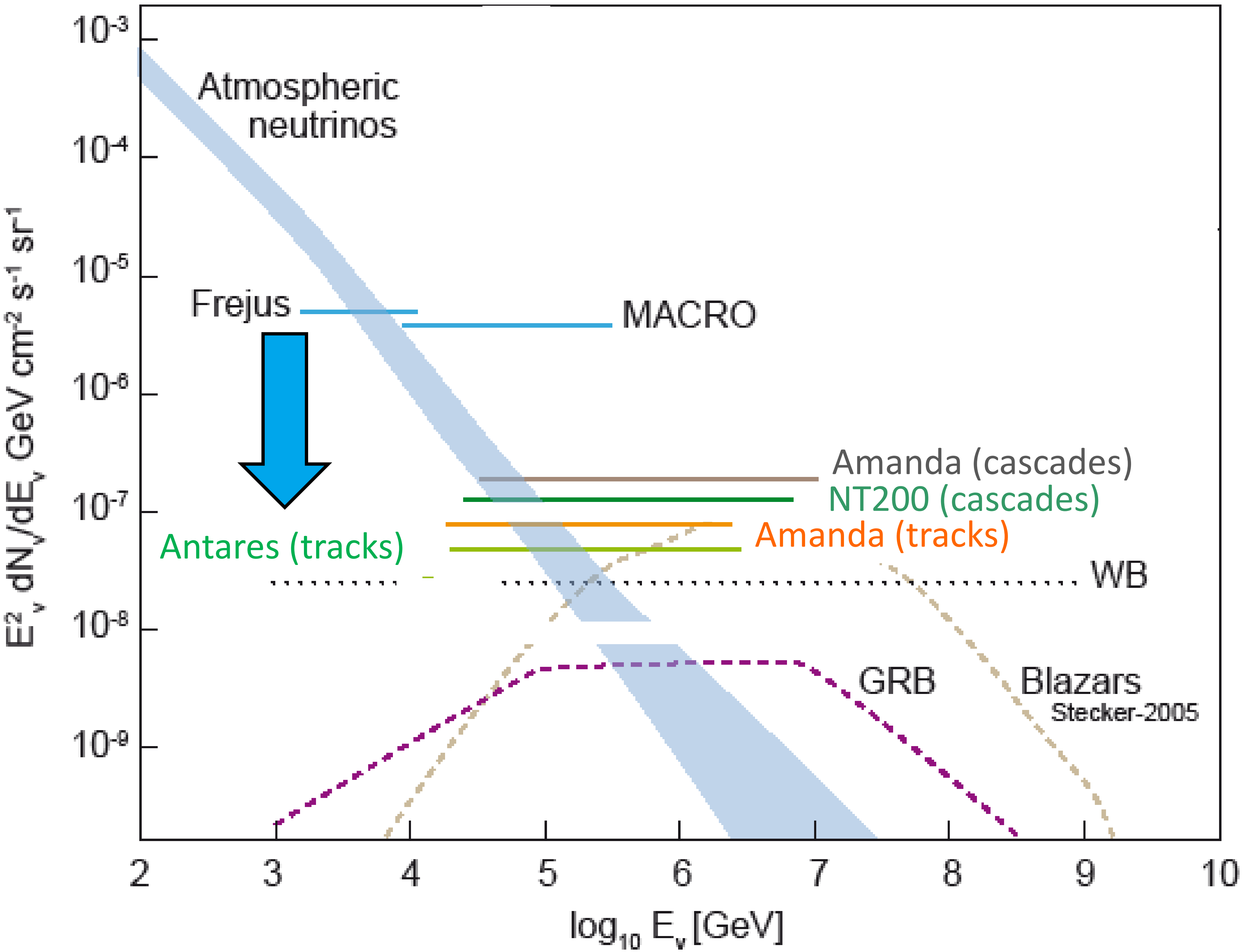
Up-going tracks
Muon-dominated
Northern sky



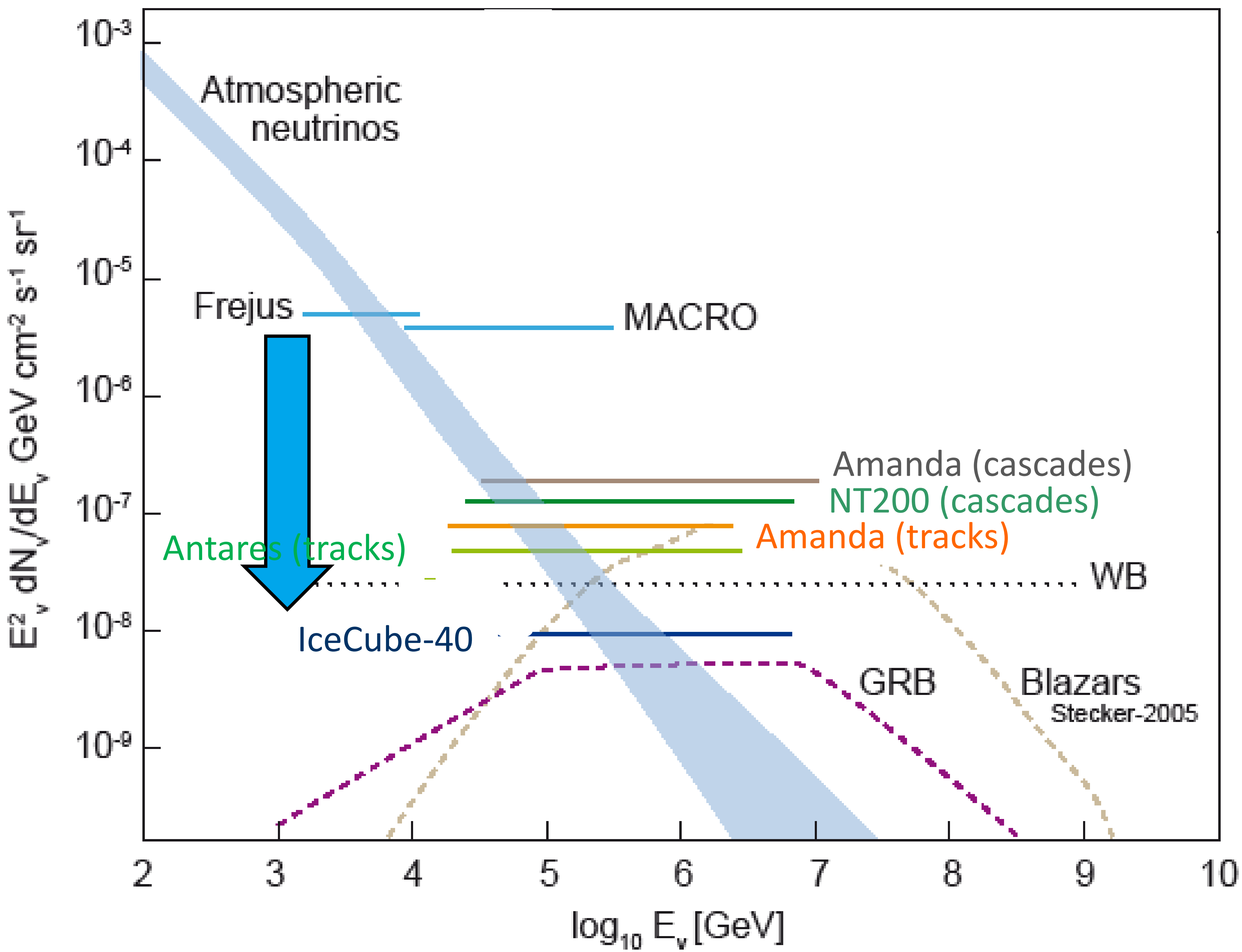
Limits on the diffuse flux (2003)



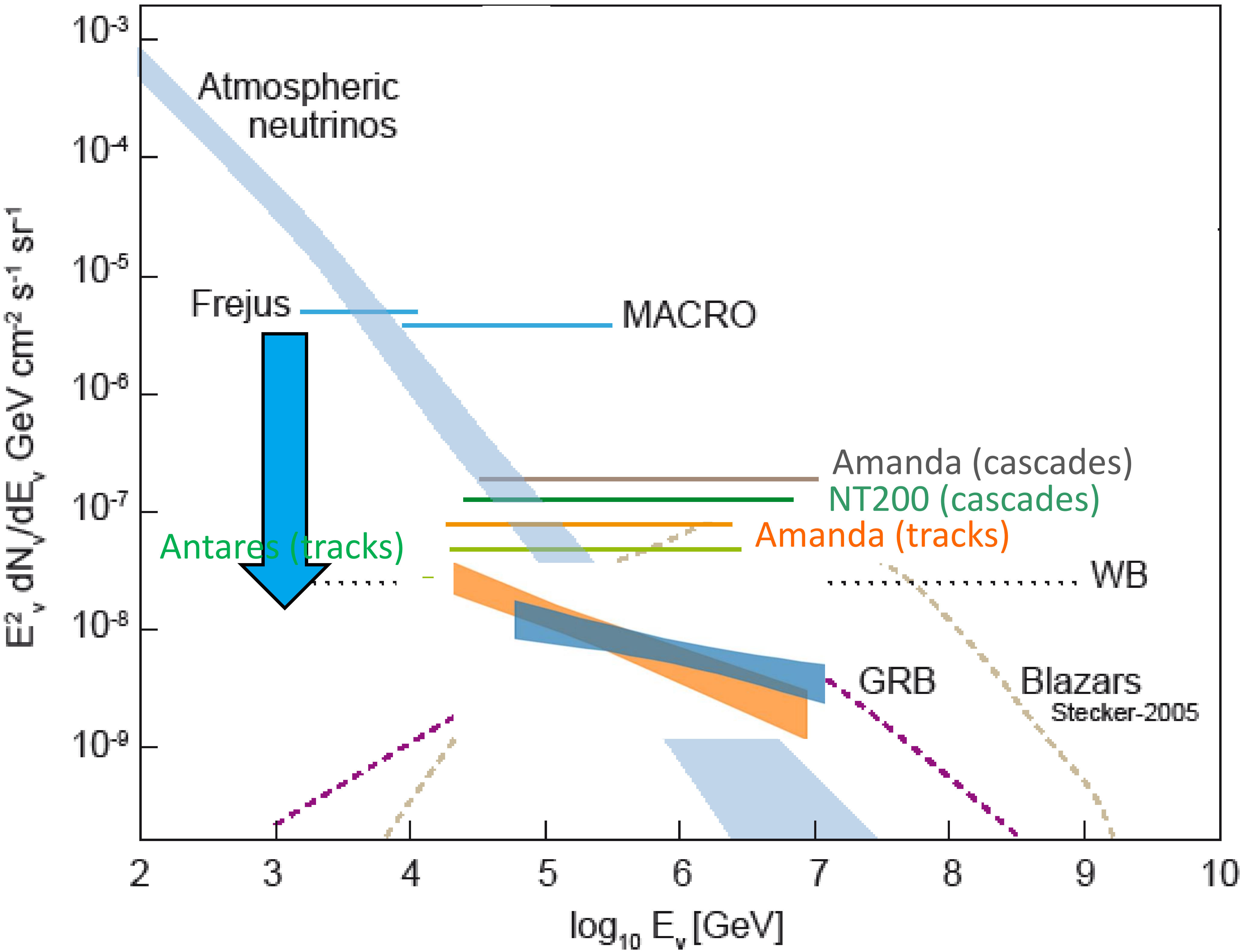
Limits on the diffuse flux (2007)



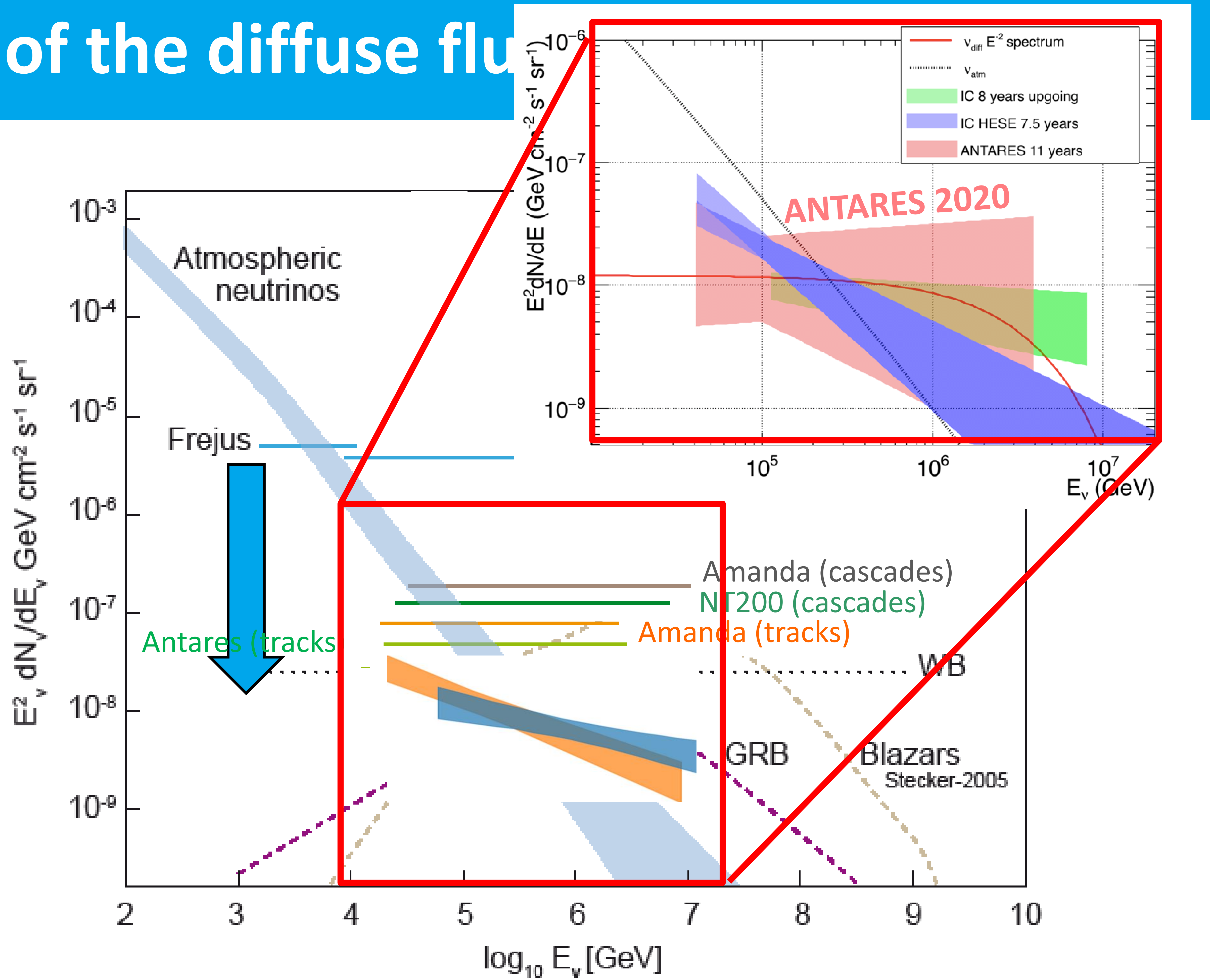
Limits on the diffuse flux (2008)



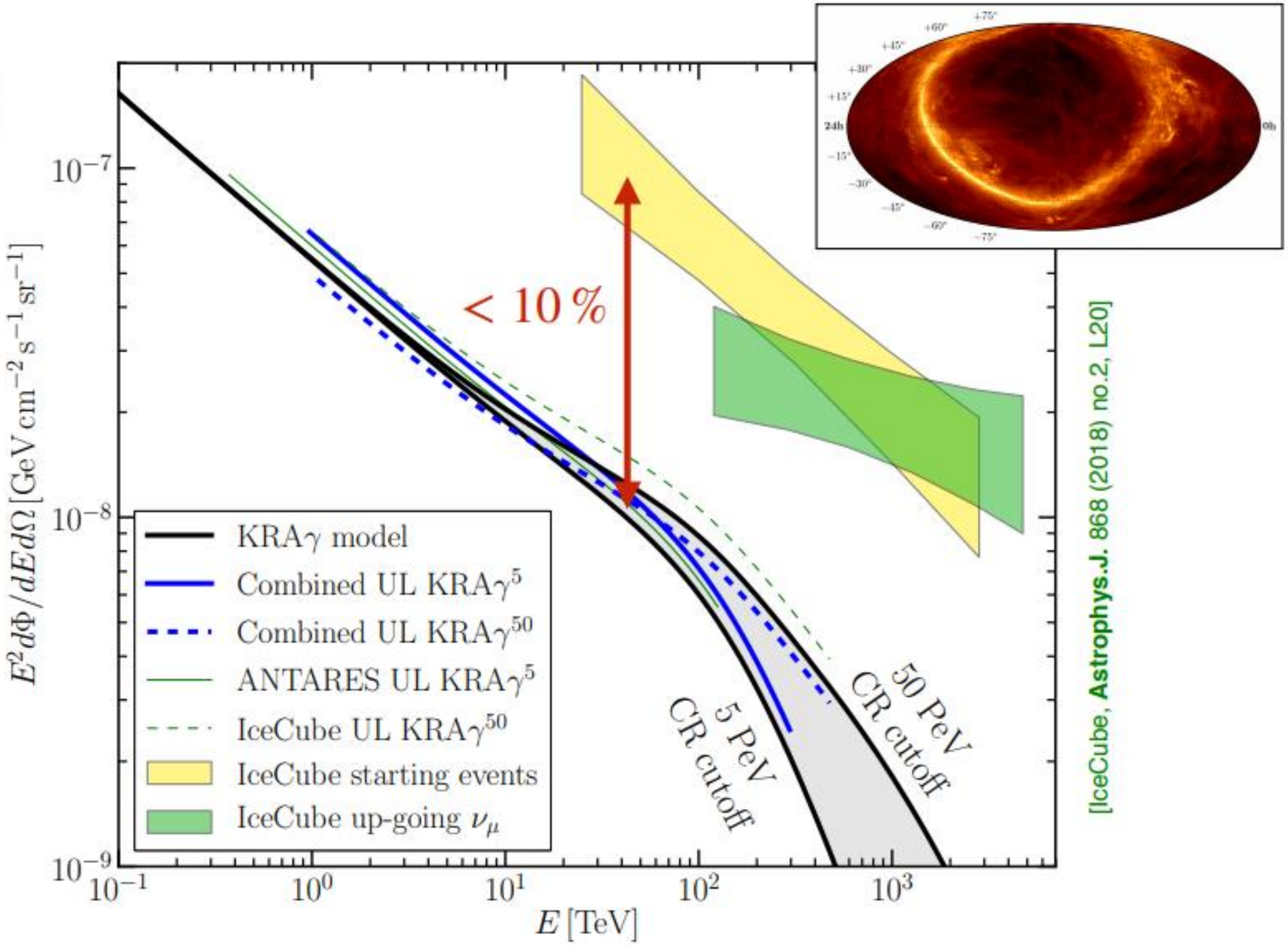
Size of the diffuse flux (2013-18)



Size of the diffuse flu



Galactic Neutrino Emission (quasi-diffuse)

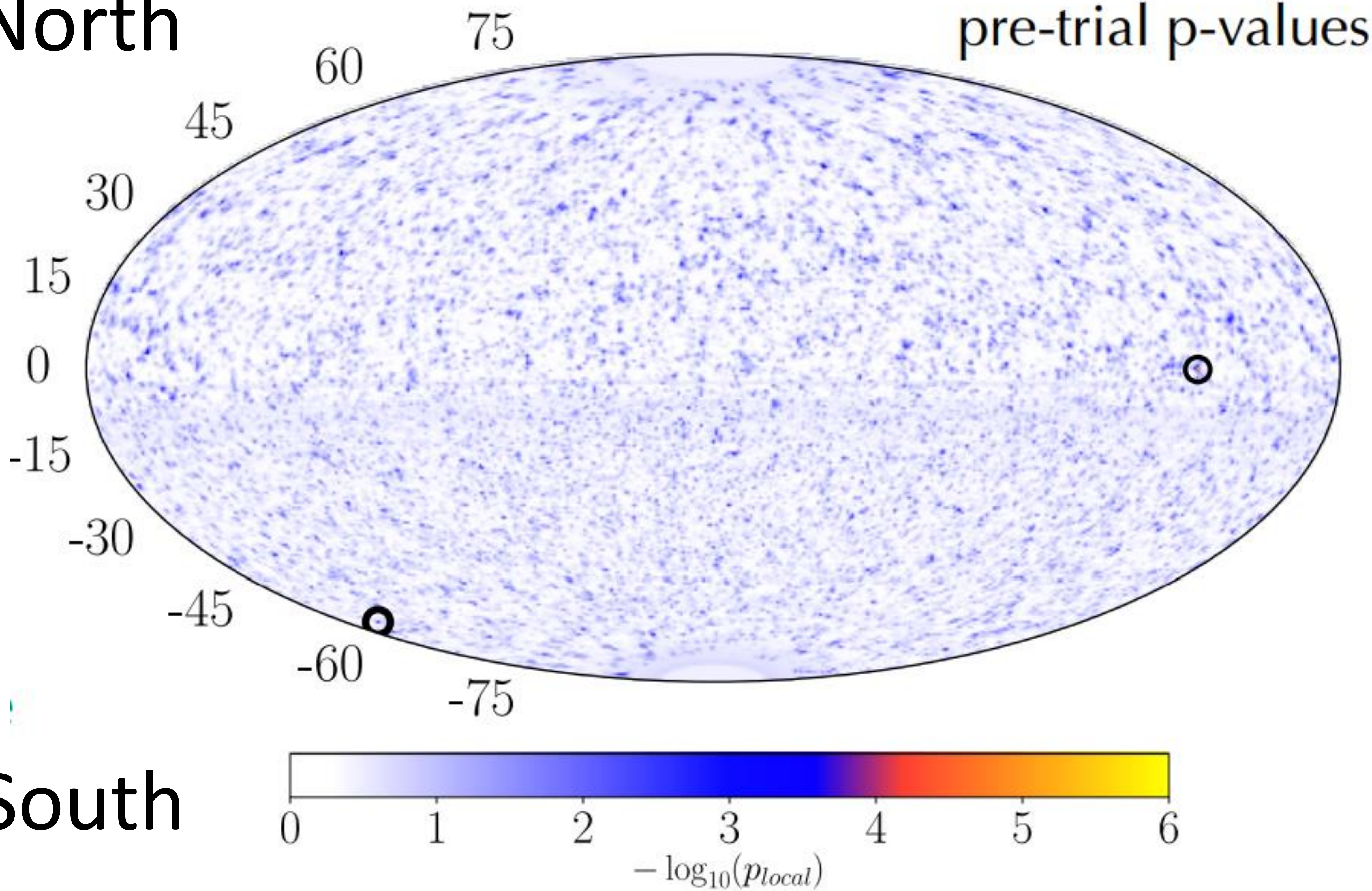


Contribution of Galactic diffuse emission at 10TeV-PeV is subdominant.

Individual Sources and Source Classes

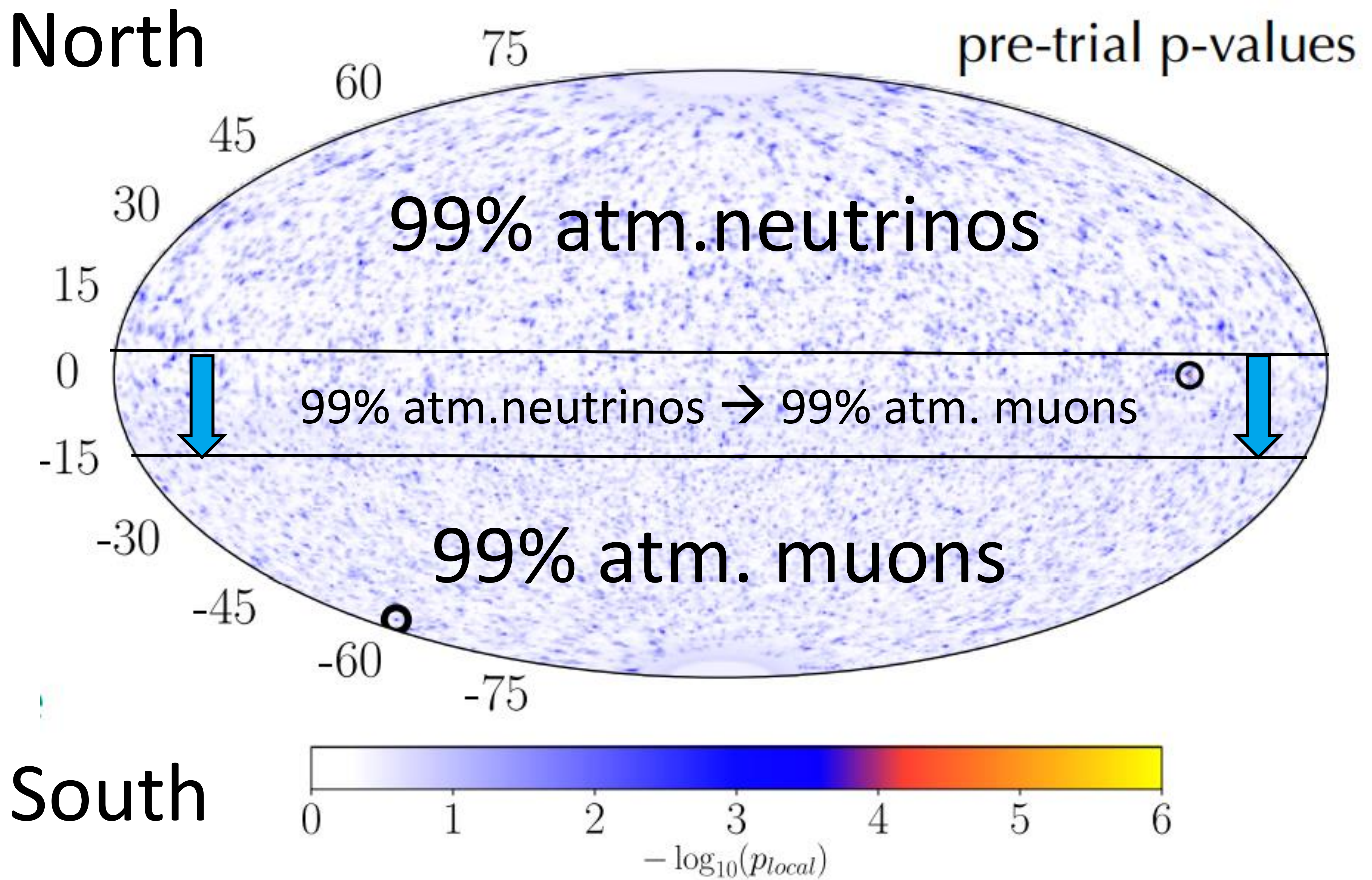
Skymap: significance map of ν (North) and μ (South)

North



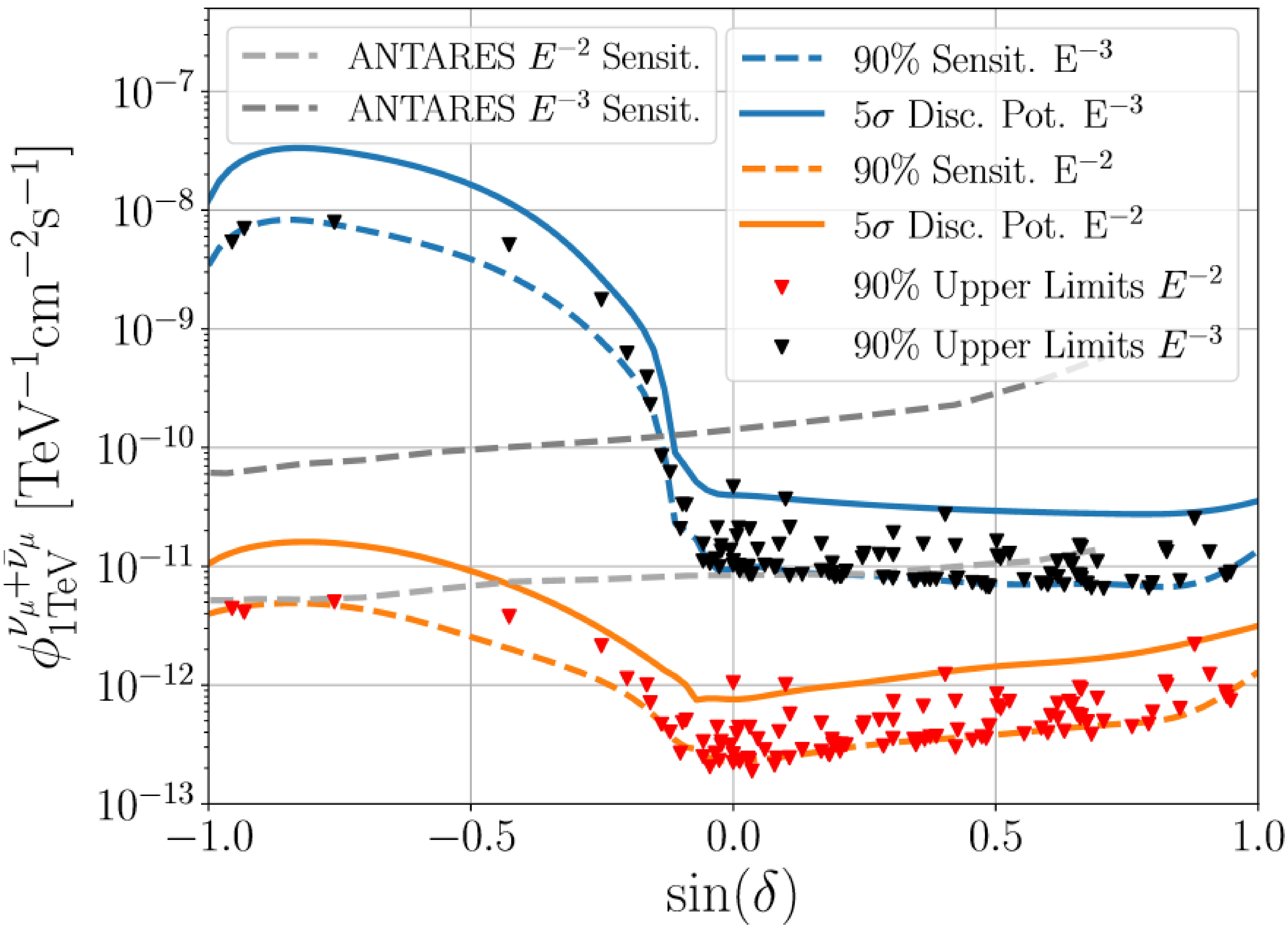
South

Skymap: significance map of ν (North) and μ (South)



IceCube, 10 years

PRL 124, 051103 (2020), arXiv:1910.08488



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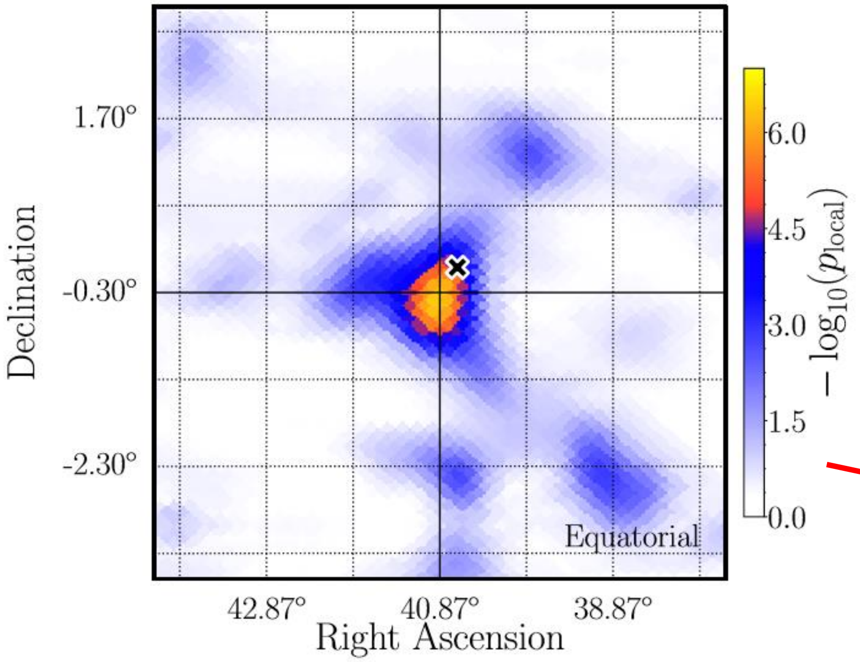
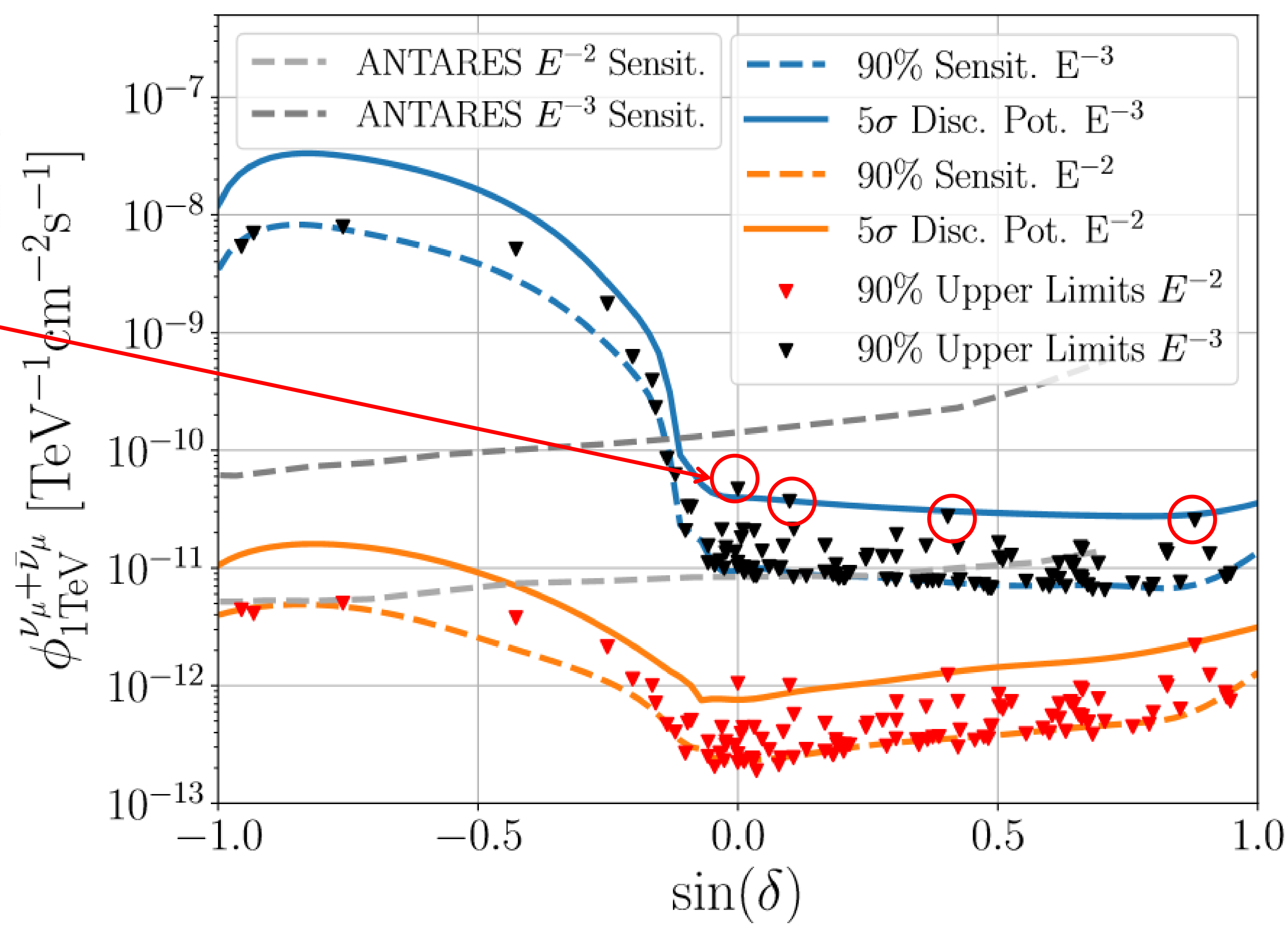
Some evidence for non-uniform skymap in 10 years of IceCube data (3.3σ). Mostly resulting from 4 extragalactic source candidates.

No indications for galactic sources.



Strongest excess (2.9 σ post trial) close to galaxy NGC 1068 (cross)



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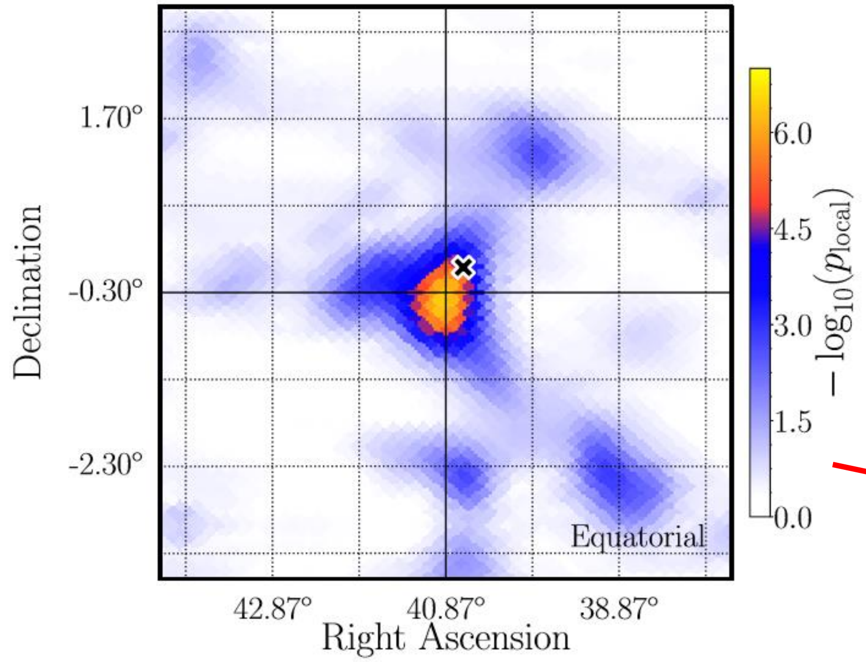
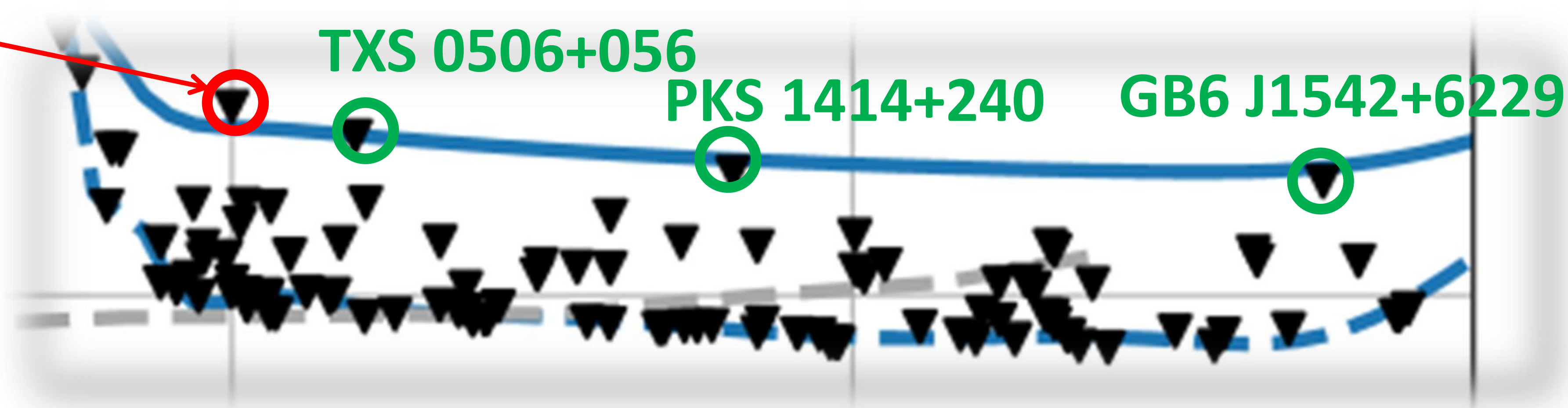


Seyfert Galaxy

Blazars



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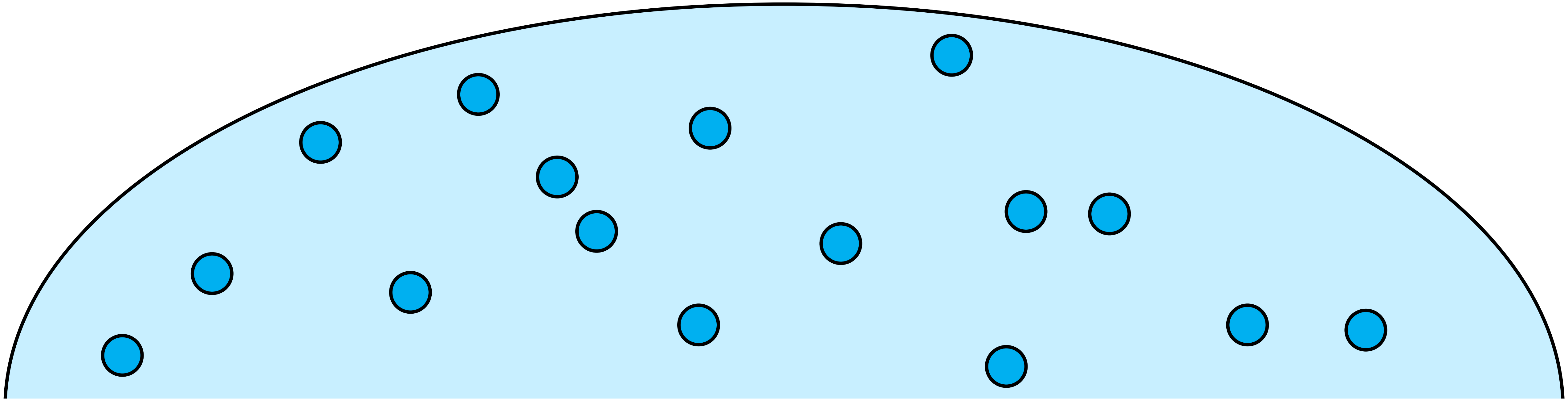
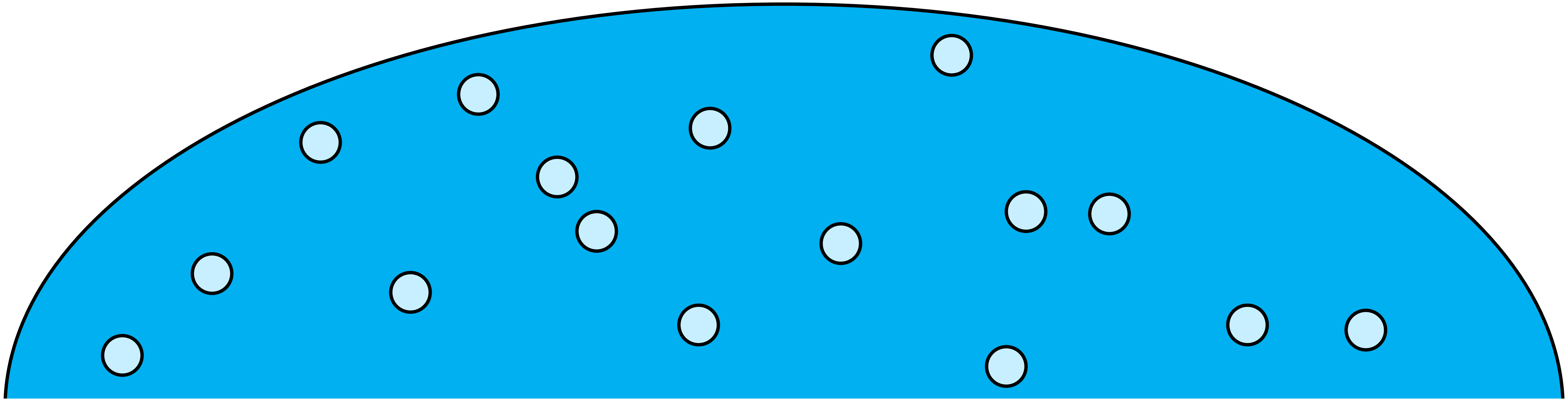
Source Classes: stacking searches



Source Classes: stacking searches

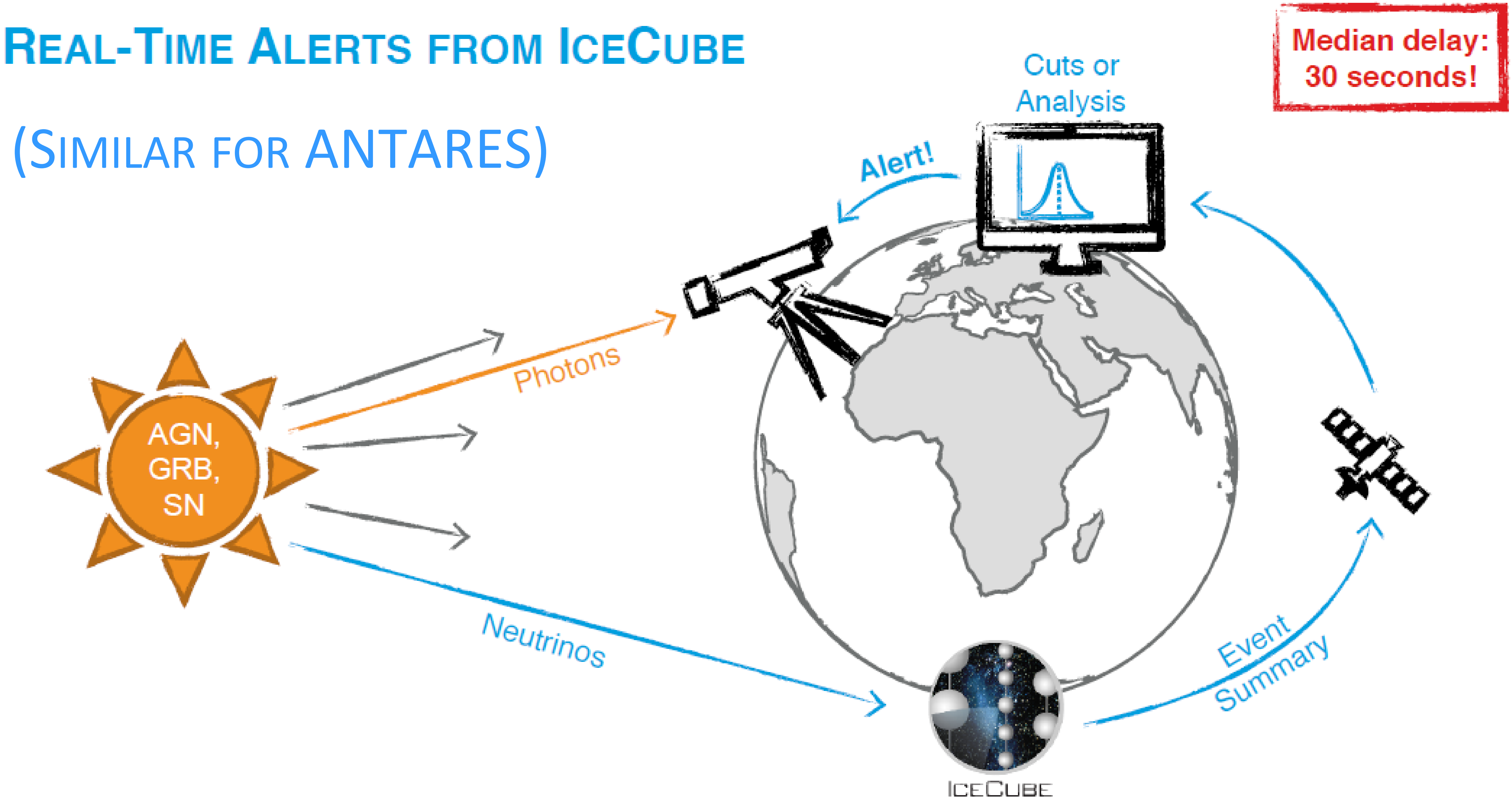


Source Classes: stacking searches

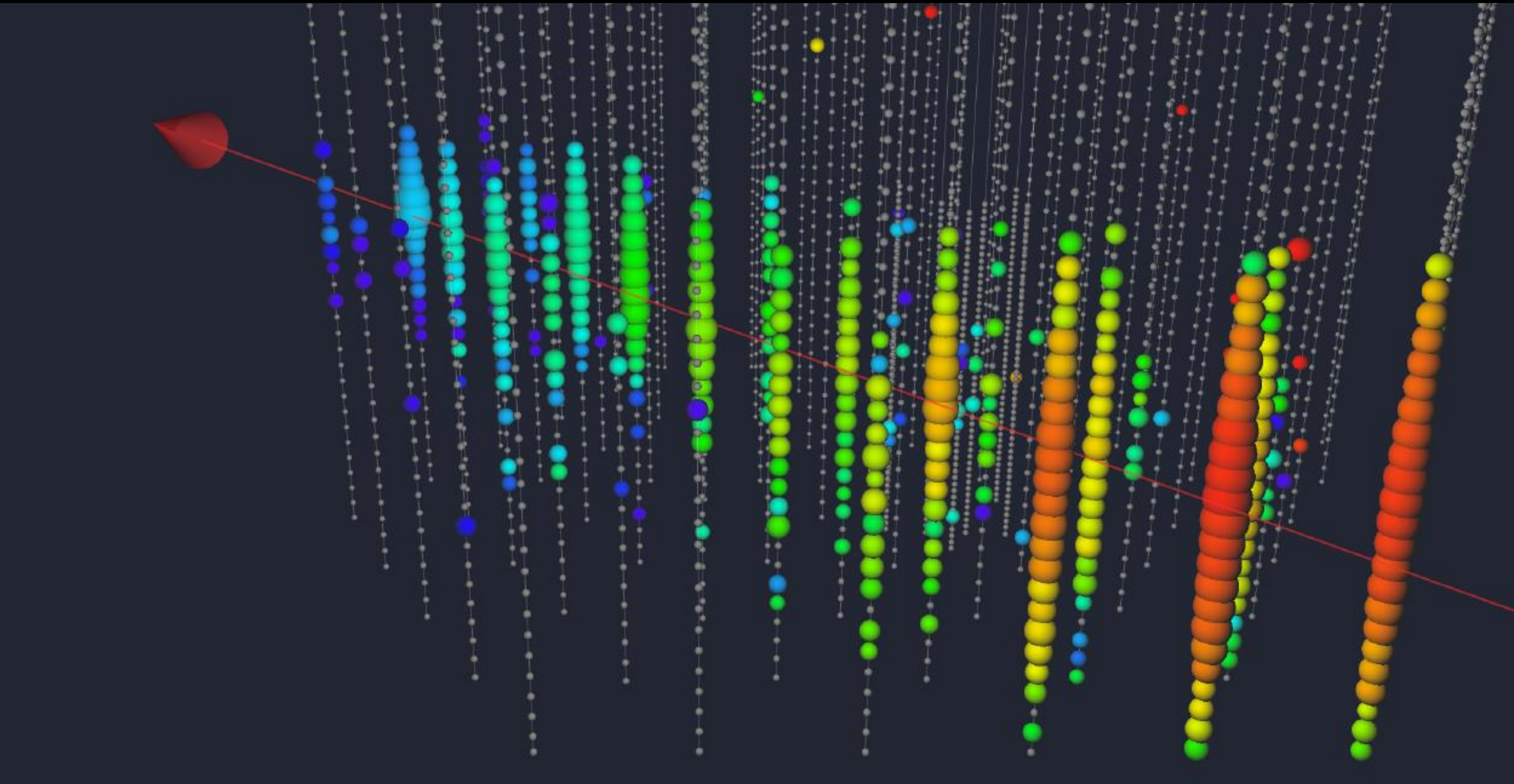
- Blazars → Cannot contribute with more than ~15 % to the diffuse flux (but: 3 promising candidates!)
- Radio-loud Blazars → some (controversial) indications
- Gamma-loud Blazars → upper limits
- Flat spectrum radio quasars (FSRQs) → upper limits
- X-ray Active Galaxies → upper limits
- Gamma Ray Bursts → upper limits strongly constraining models
- ....

Multi-Messenger Results

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



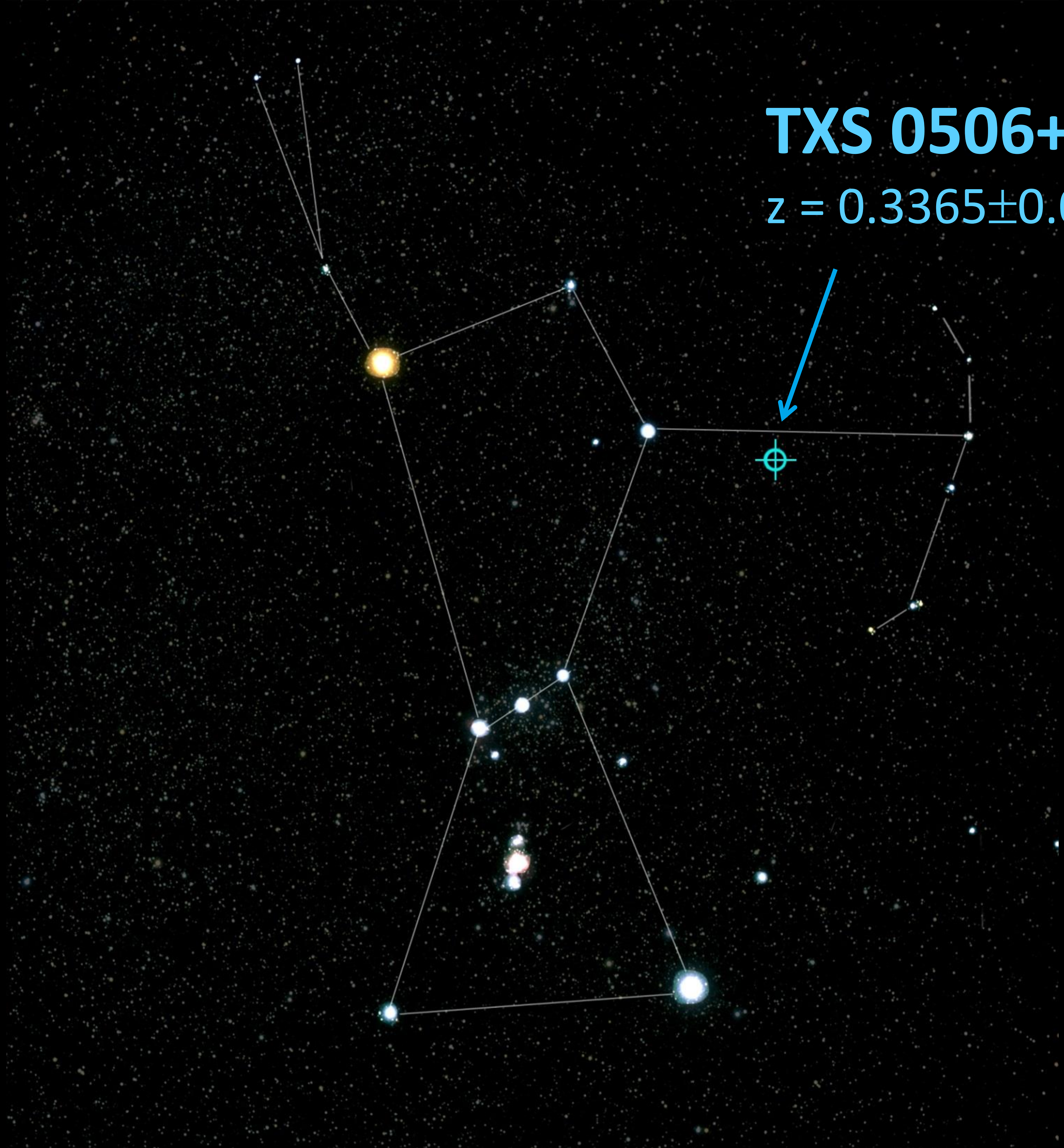
The first point source candidate



22. September 2017, 20:54 UTC

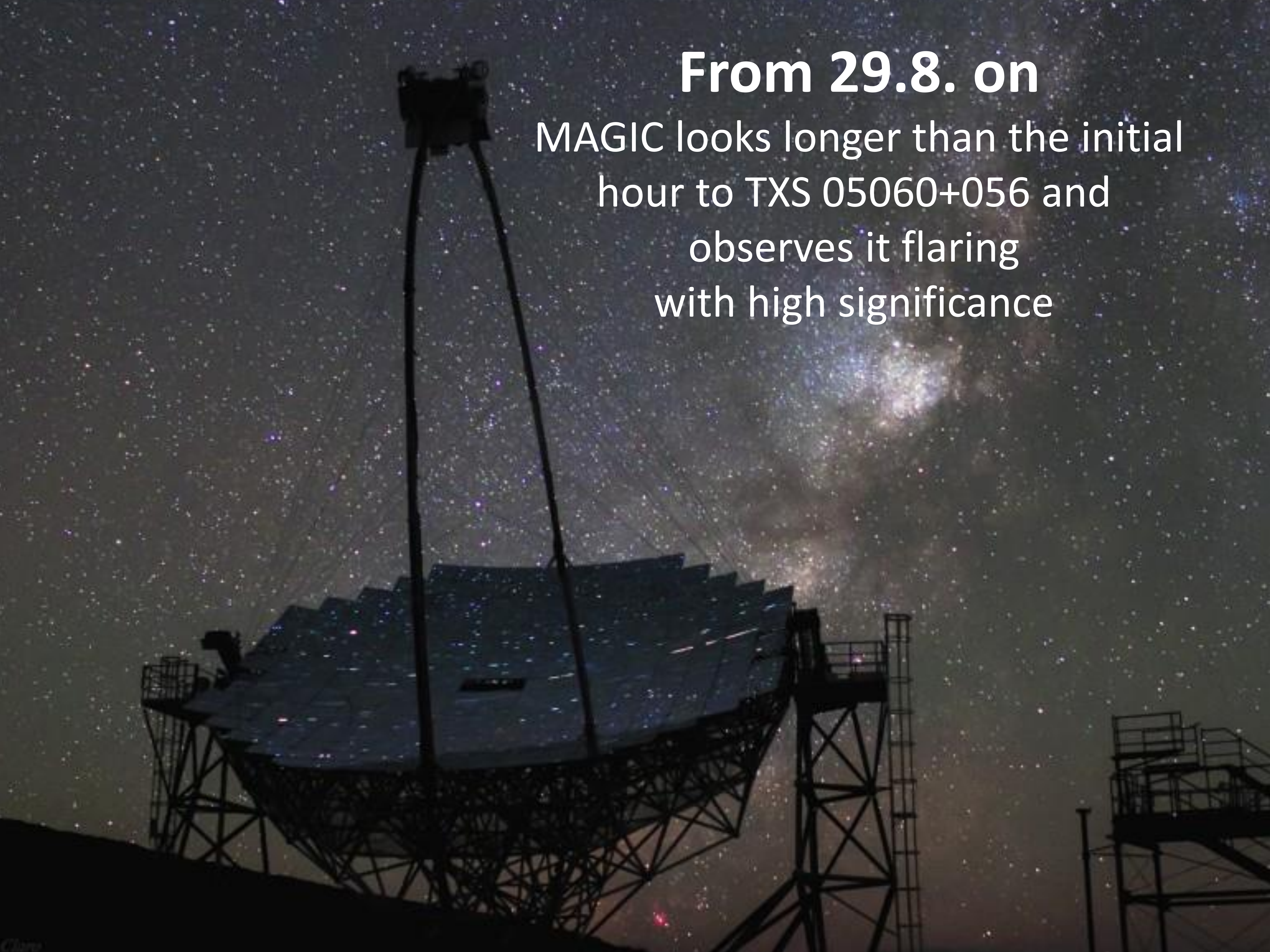
The first point source candidate

- 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:

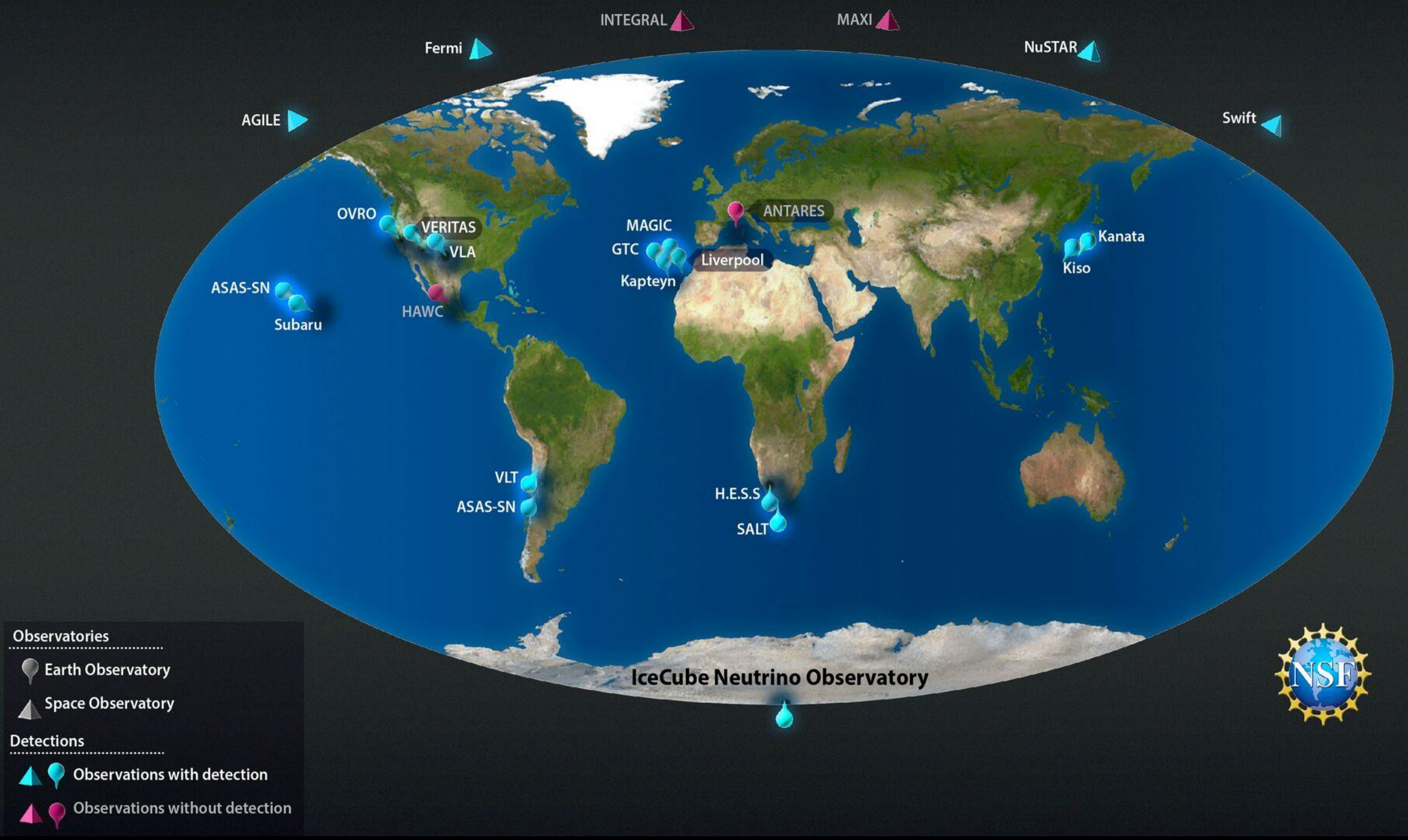
- Source: Active Galaxy TXS 0505+056, which is in a flaring state



From 29.8. on

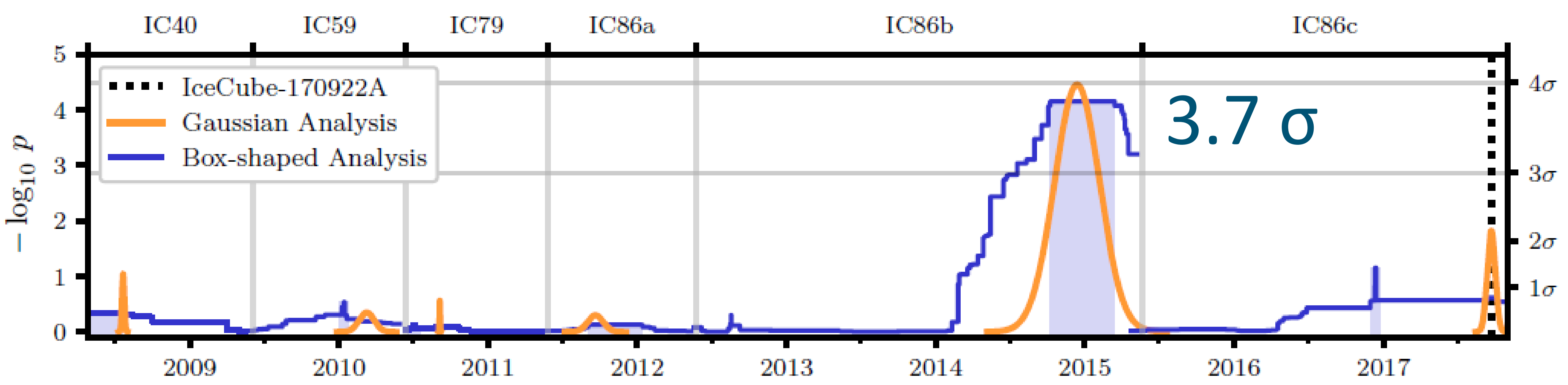
MAGIC looks longer than the initial hour to TXS 05060+056 and observes it flaring with high significance

Follow-up Observations of IceCube Alert IC170922



Looking back to archival data

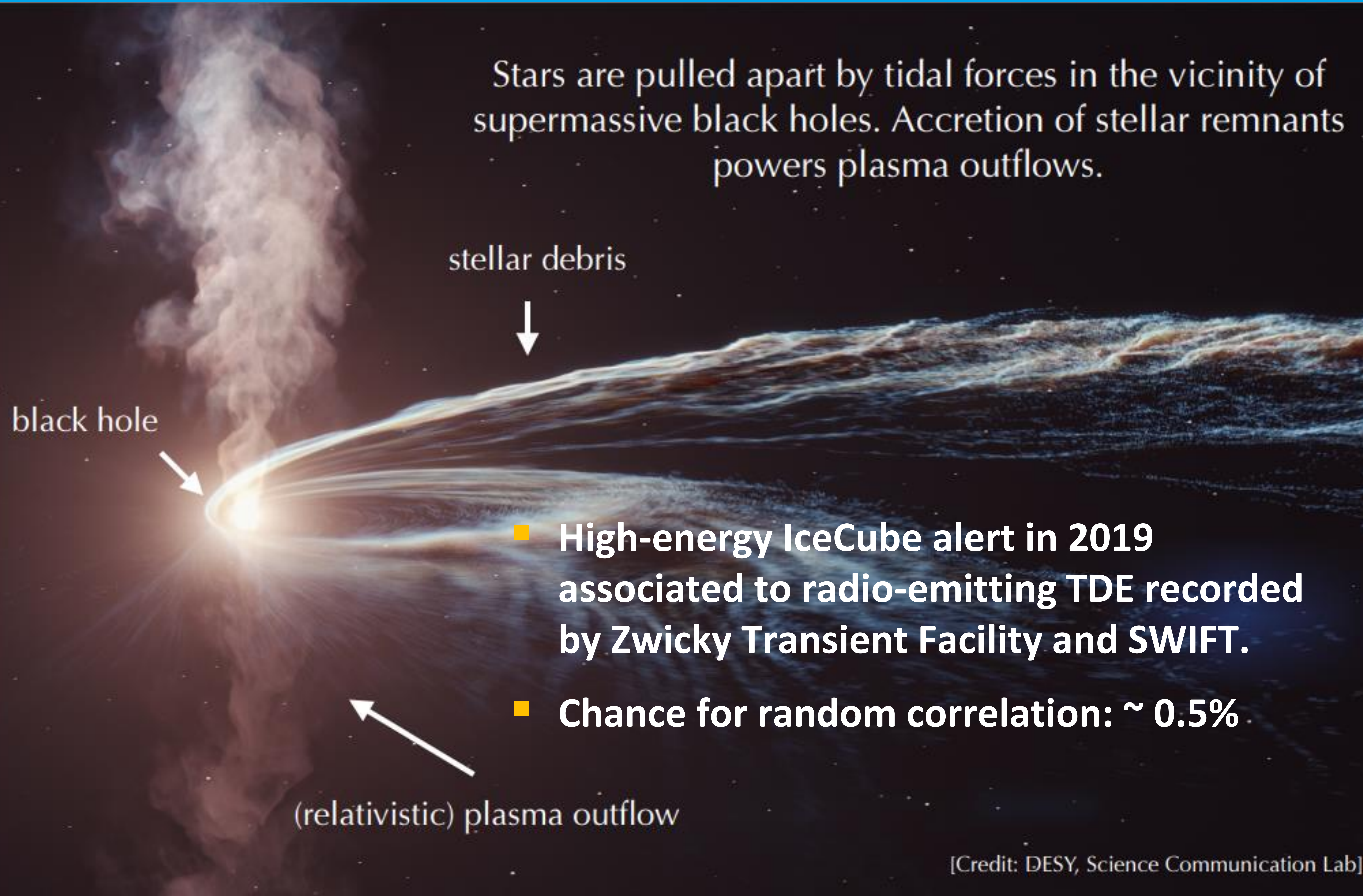
Science 361 (2018) 147



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.

Impressive demonstration of the potential of multi-messenger observations

A Tidal Disruption Event



- **High-energy IceCube alert in 2019 associated to radio-emitting TDE recorded by Zwicky Transient Facility and SWIFT.**
- **Chance for random correlation: ~ 0.5%**

7.

Where do we stand and where do we go?

Summary of where we stand

- Cosmic high-energy ν discovered
  - Remaining uncertainties on spectrum and flavor composition
  - Opened new window, but landscape not yet charted:
    no undisputable steady point sources identified up to now.
  - Several interesting associations between IceCube neutrinos and astronomical sources. Need more data to turn „evidences“ to „discoveries“.

Summary of where we go

- **Cosmic high-energy ν discovered**
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  - Several interesting associations between IceCube neutrinos and astronomical sources. Need more data to turn „evidences“ to „discoveries“.
  - Need detectors .... on the northern hemisphere (galactic center!)
    .... with better angular resolution
    .... with different systematics
    .... of larger size

Summary of where we go

Cosmic high-energy ν discovered

- Remaining uncertainties on spectrum and flavor composition
- Opened new window, but landscape not yet charted:
  no undisputable steady point sources identified up to now.
- Several interesting associations between IceCube neutrinos and astronomical sources. Need more data to turn „evidences“ to „discoveries“.
- Work together:

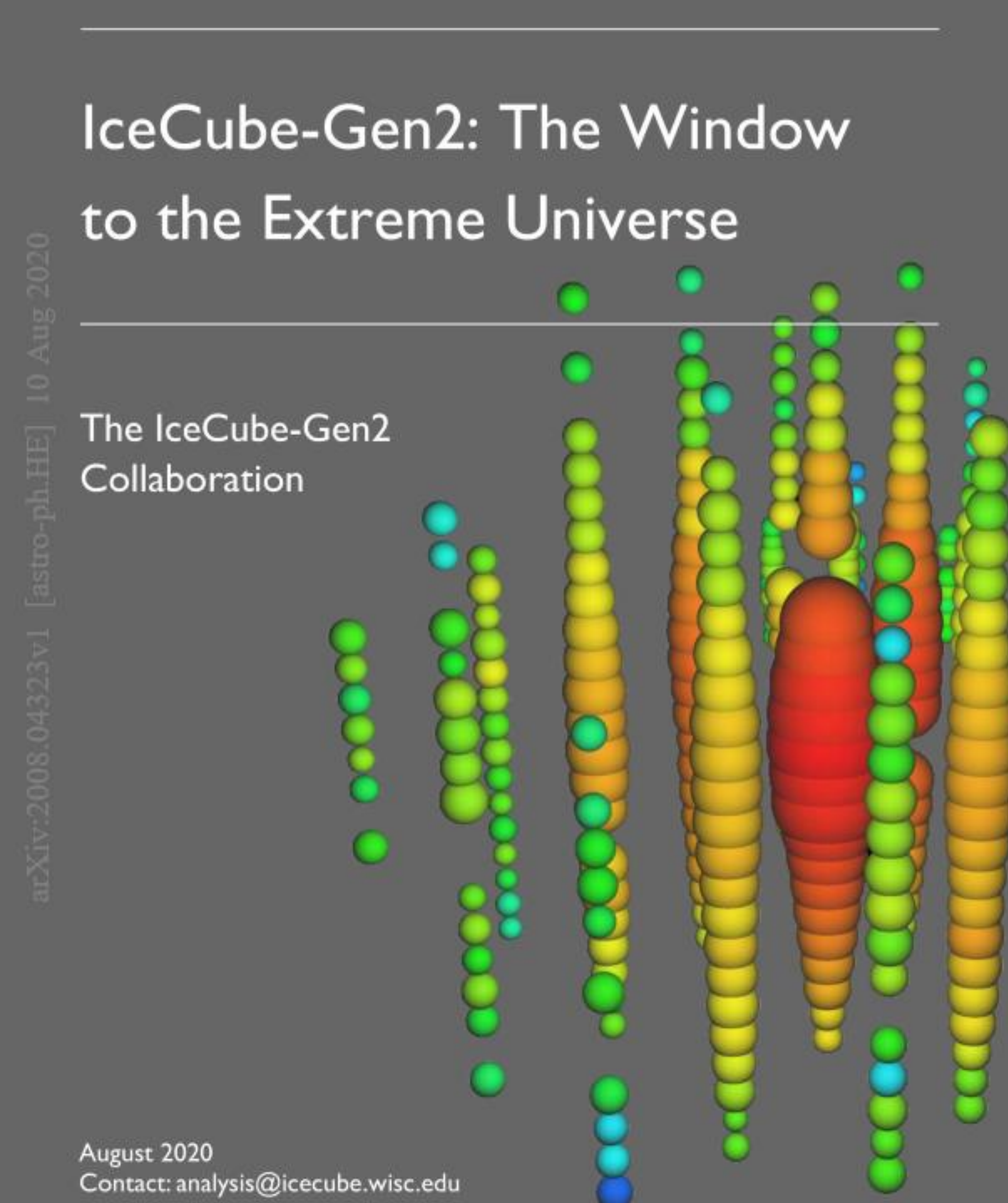
GNN
The Global Neutrino Network


GIGATON VOLUME DETECTOR
BAIKAL GVD
0.5 – 1.0 km³

KM3NET

ARCA: $2 \times 0.6\ km^3$

ORCA: 3.7 Mtons


IceCube-Gen2: The Window to the Extreme Universe

The IceCube-Gen2 Collaboration

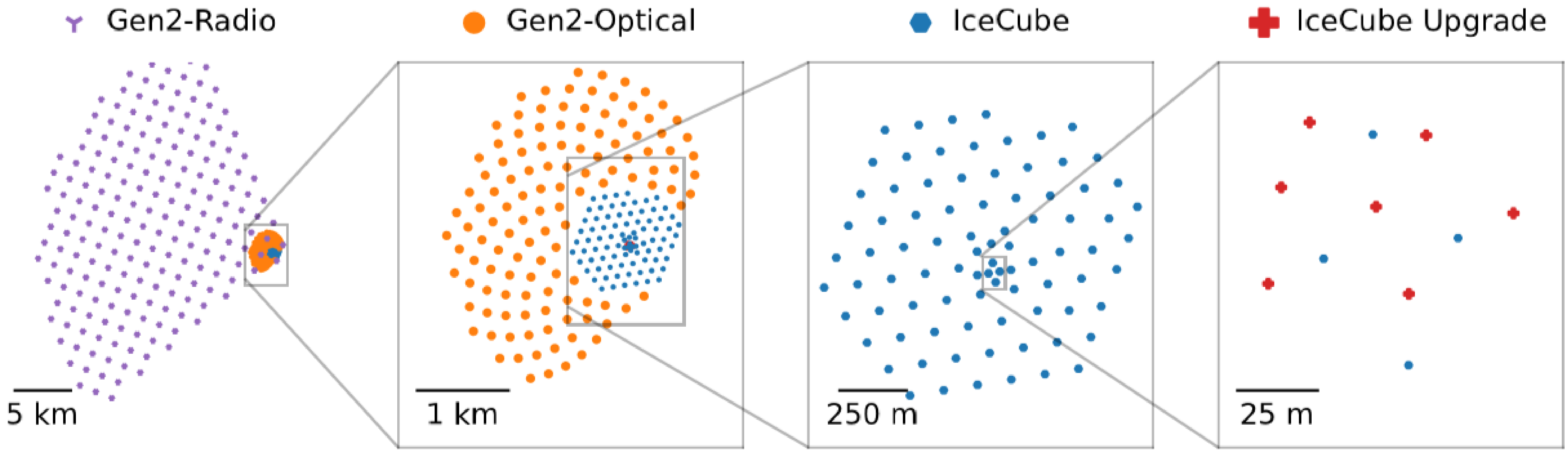
August 2020
Contact: analysis@icecube.wisc.edu

~ 8 km^3

+ 100 km^2 radio array

arXiv:2008.04323

IceCube Gen2: from GeV to EeV



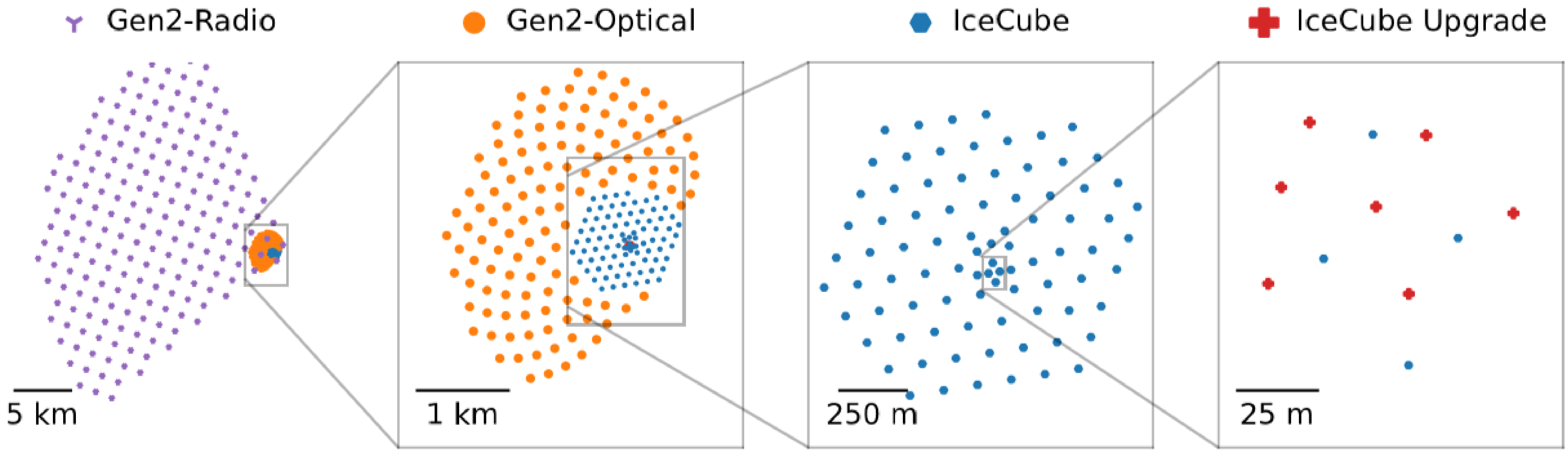
10 PeV to >10 EeV

10 TeV – 50 PeV

100 GeV – 5 PeV

improves DeepCore performance at < 10 GeV

IceCube Gen2: from GeV to EeV



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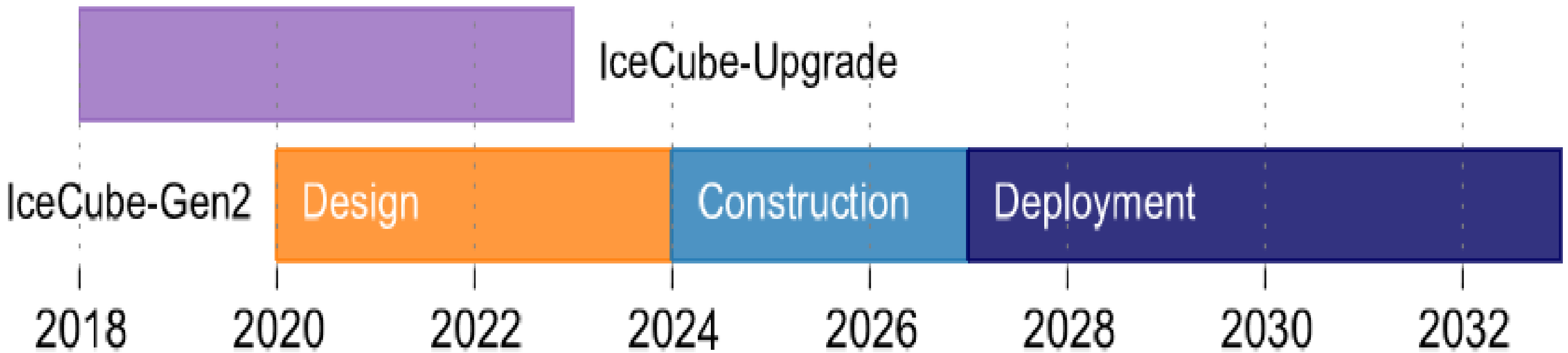
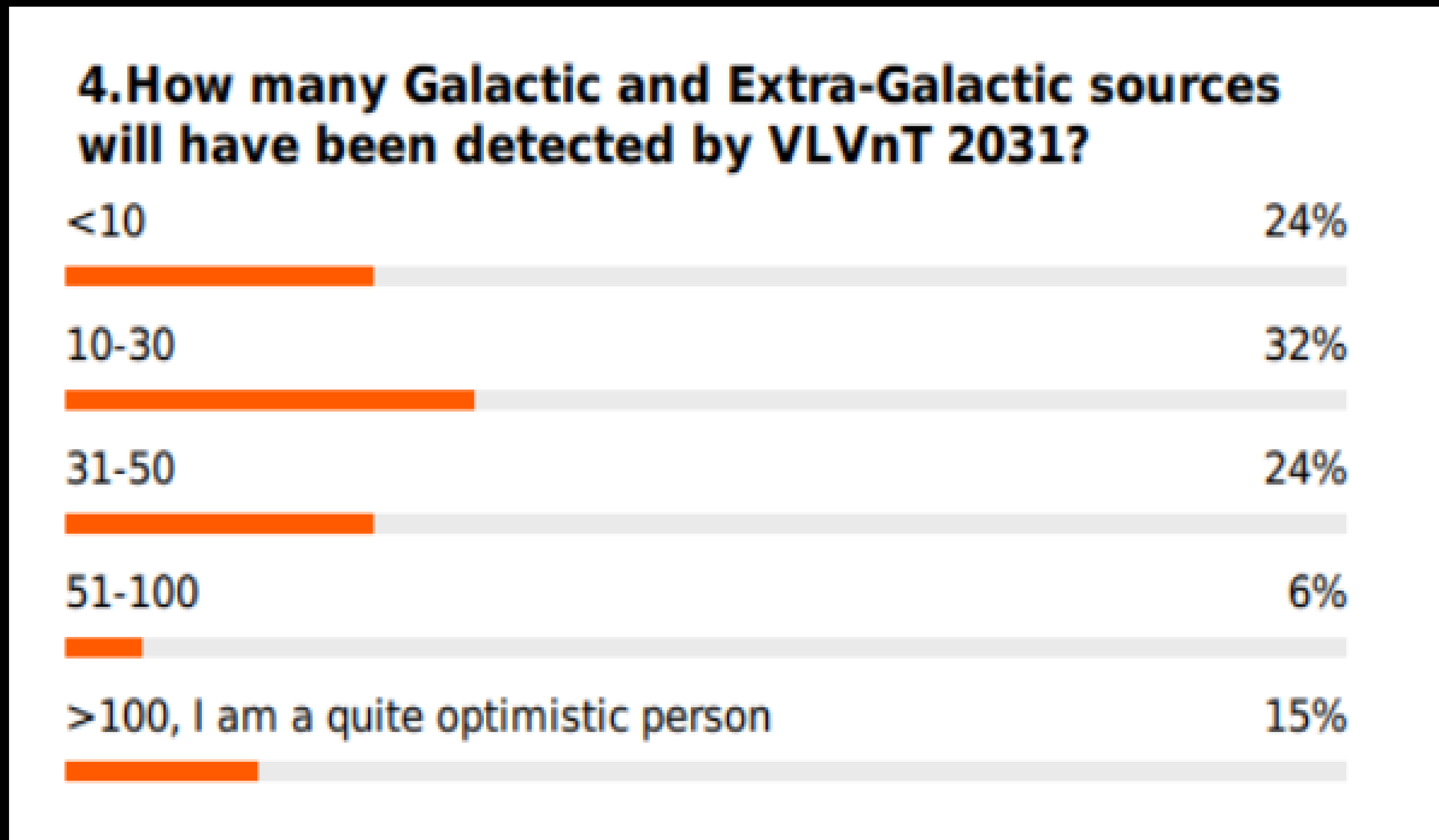


Conclusions

- High-energy neutrino window is opened
- Extremely dynamical field
- Northern hemisphere:
  towards cubic kilometer detectors.
  Baikal-GVD, KM3NeT-ARCA, ….
- 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 ! (?)

VLVνT May 2021: *A bet*



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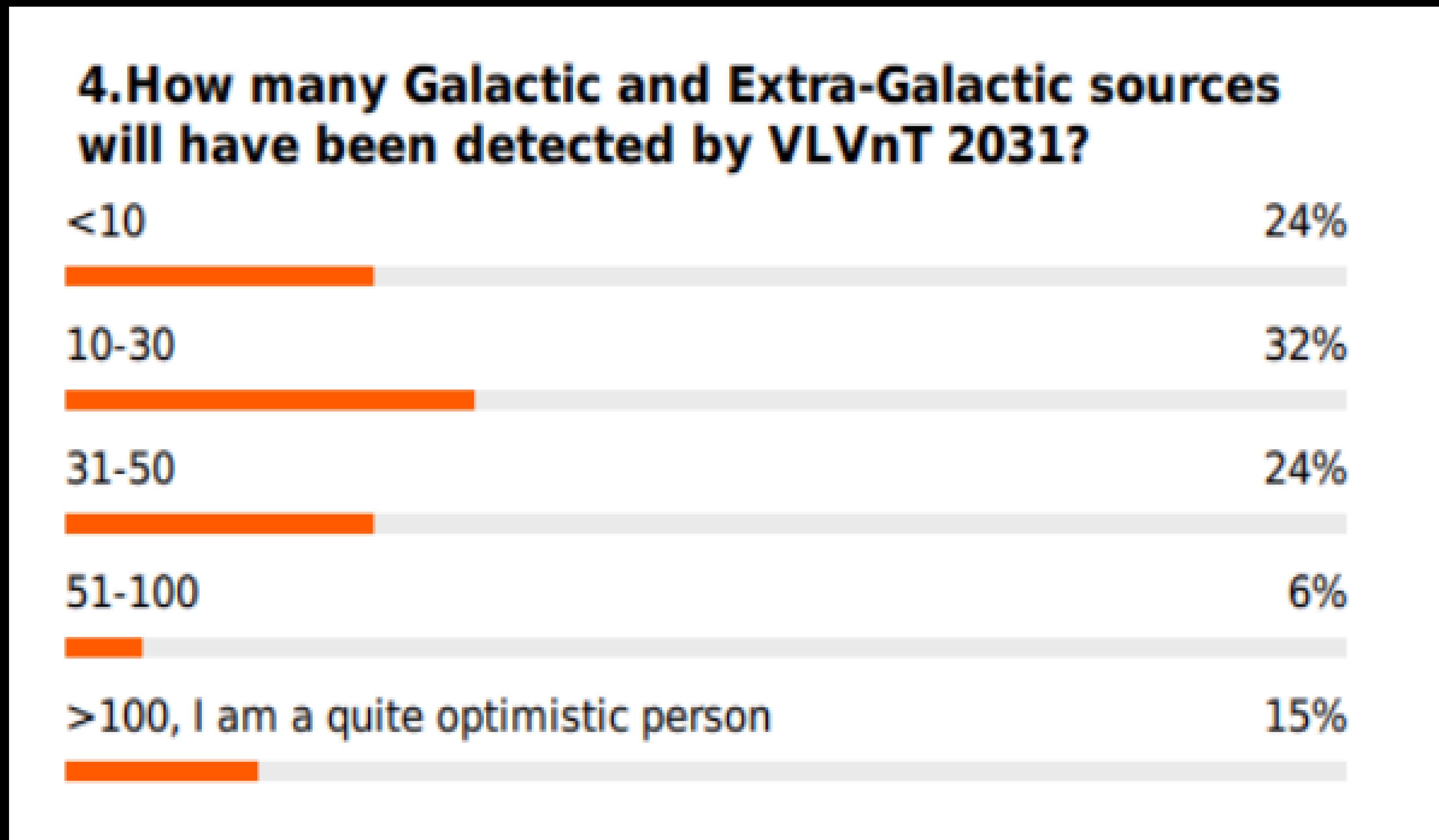
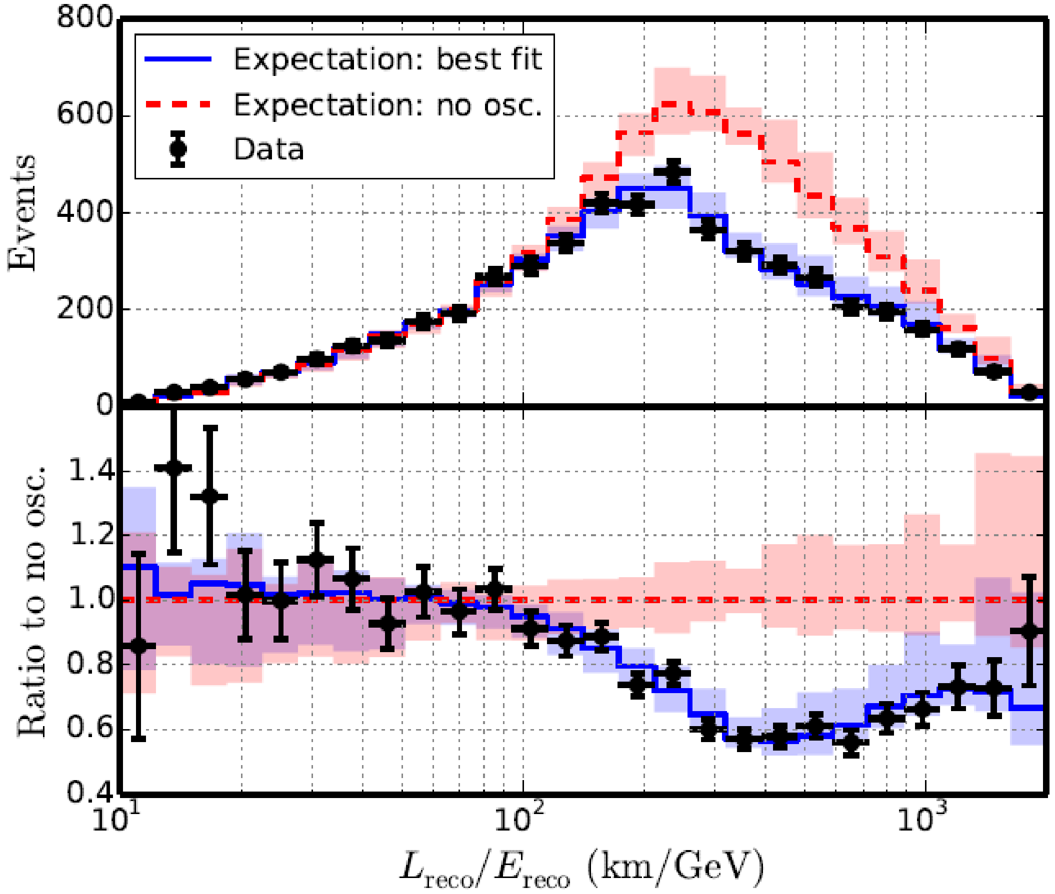


Thank you for your attention!

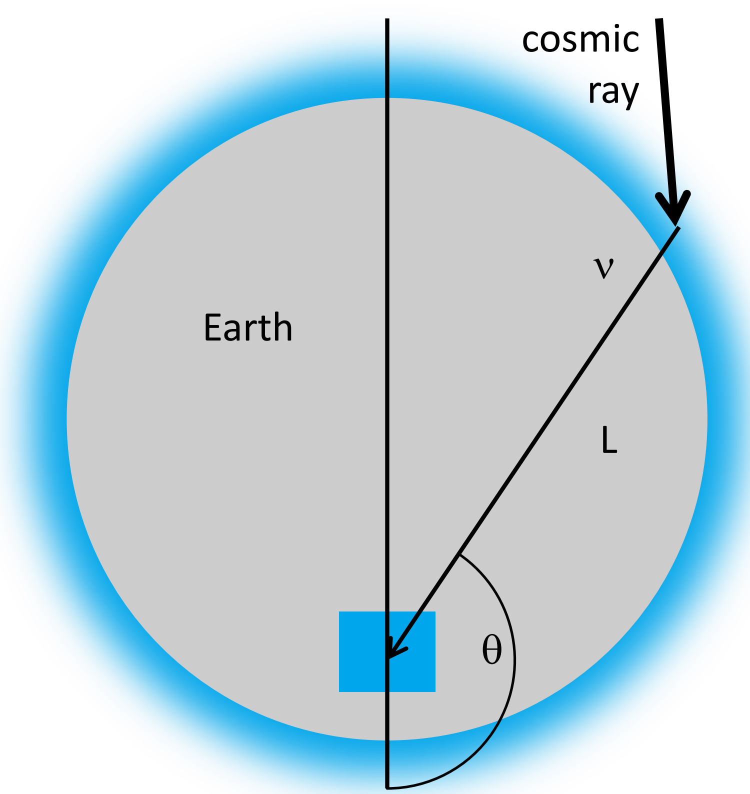
Backups

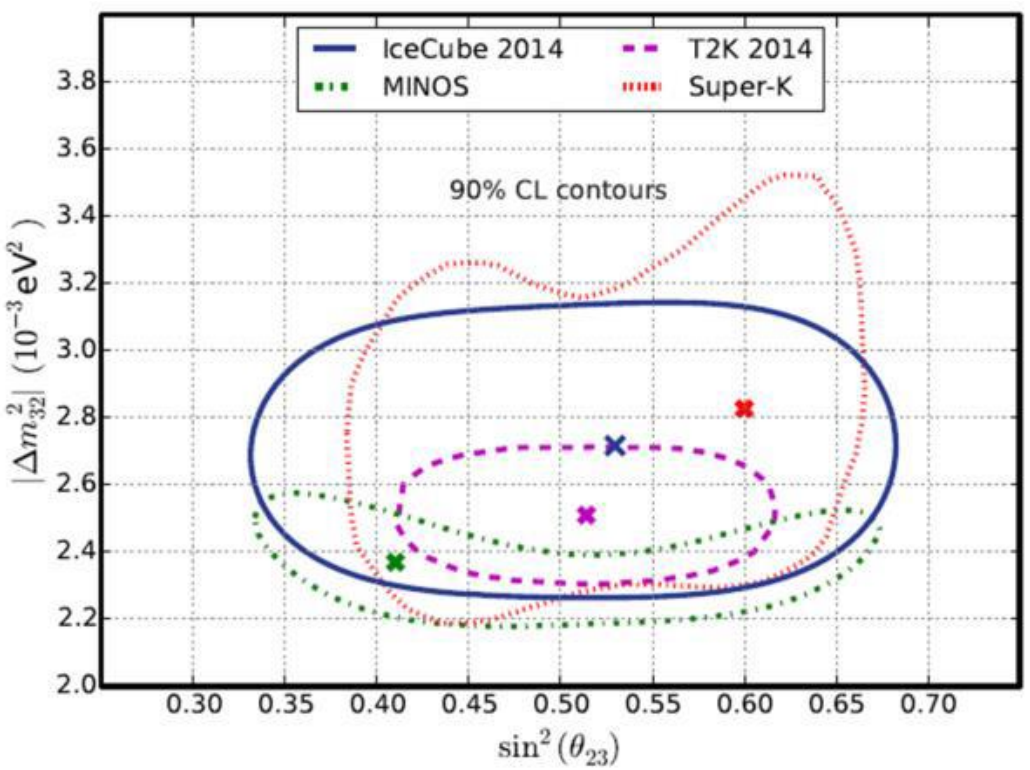
DeepCore: Oscillations for atmospheric neutrinos (E < 30-40 GeV)



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

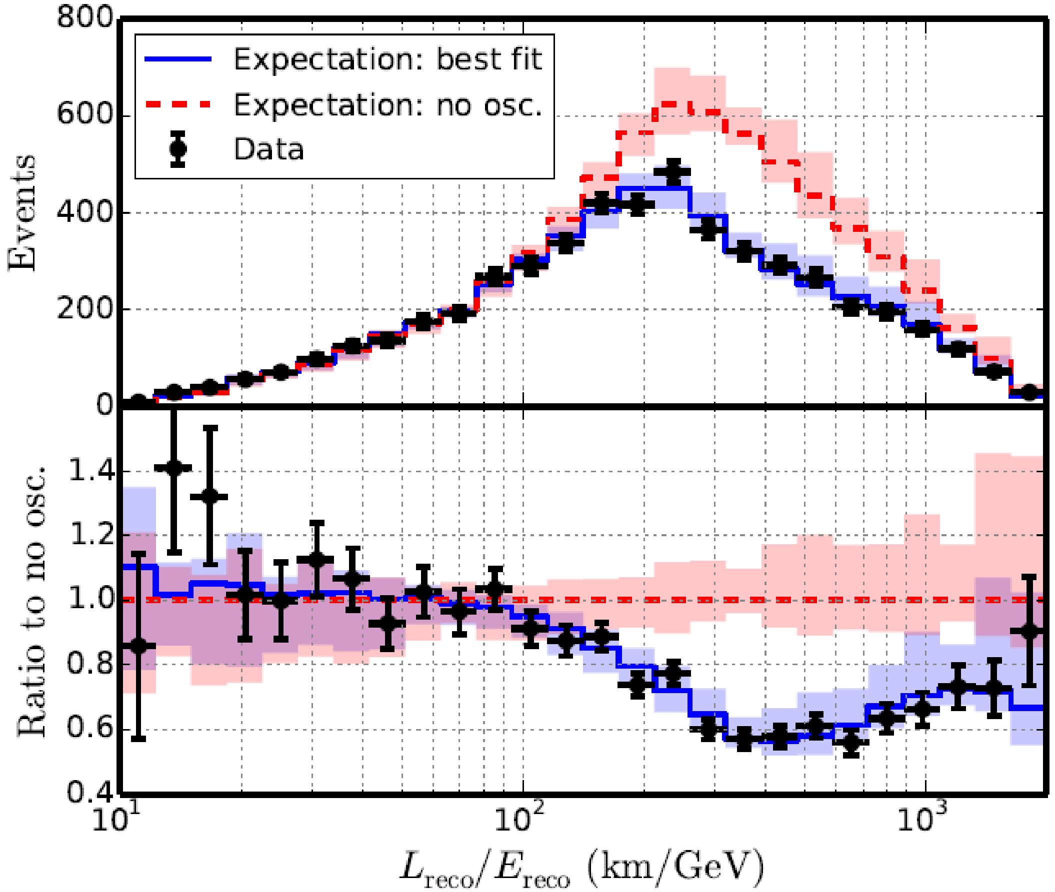
Phys. Rev. D91, 072004 (2015)





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

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



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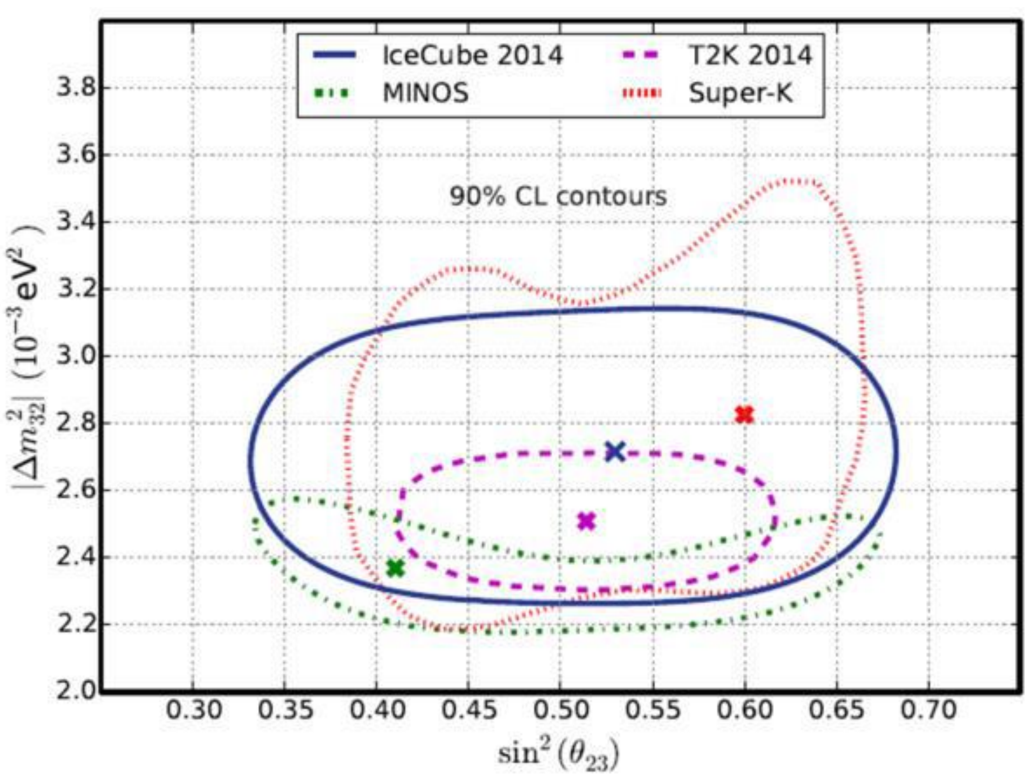
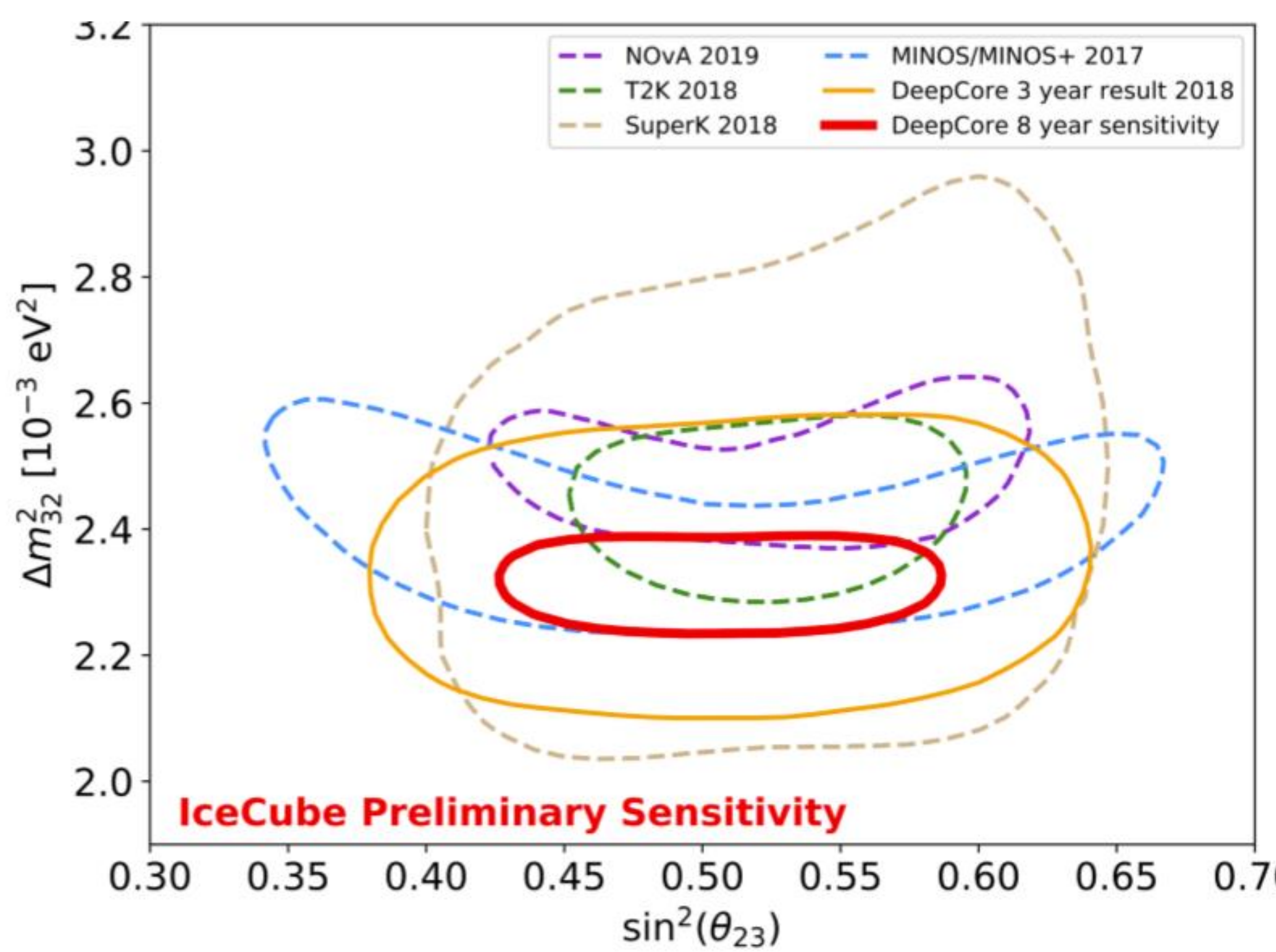
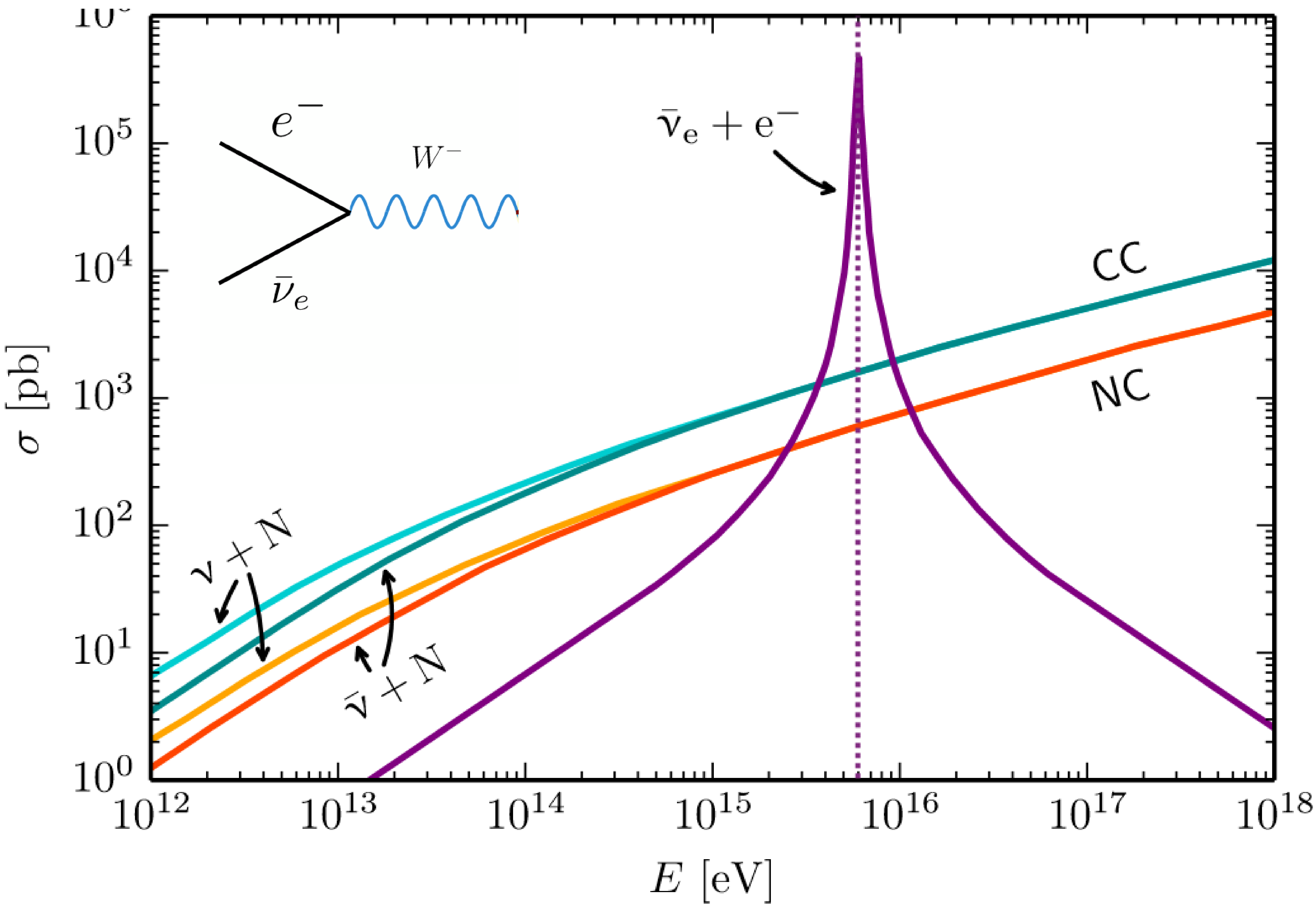


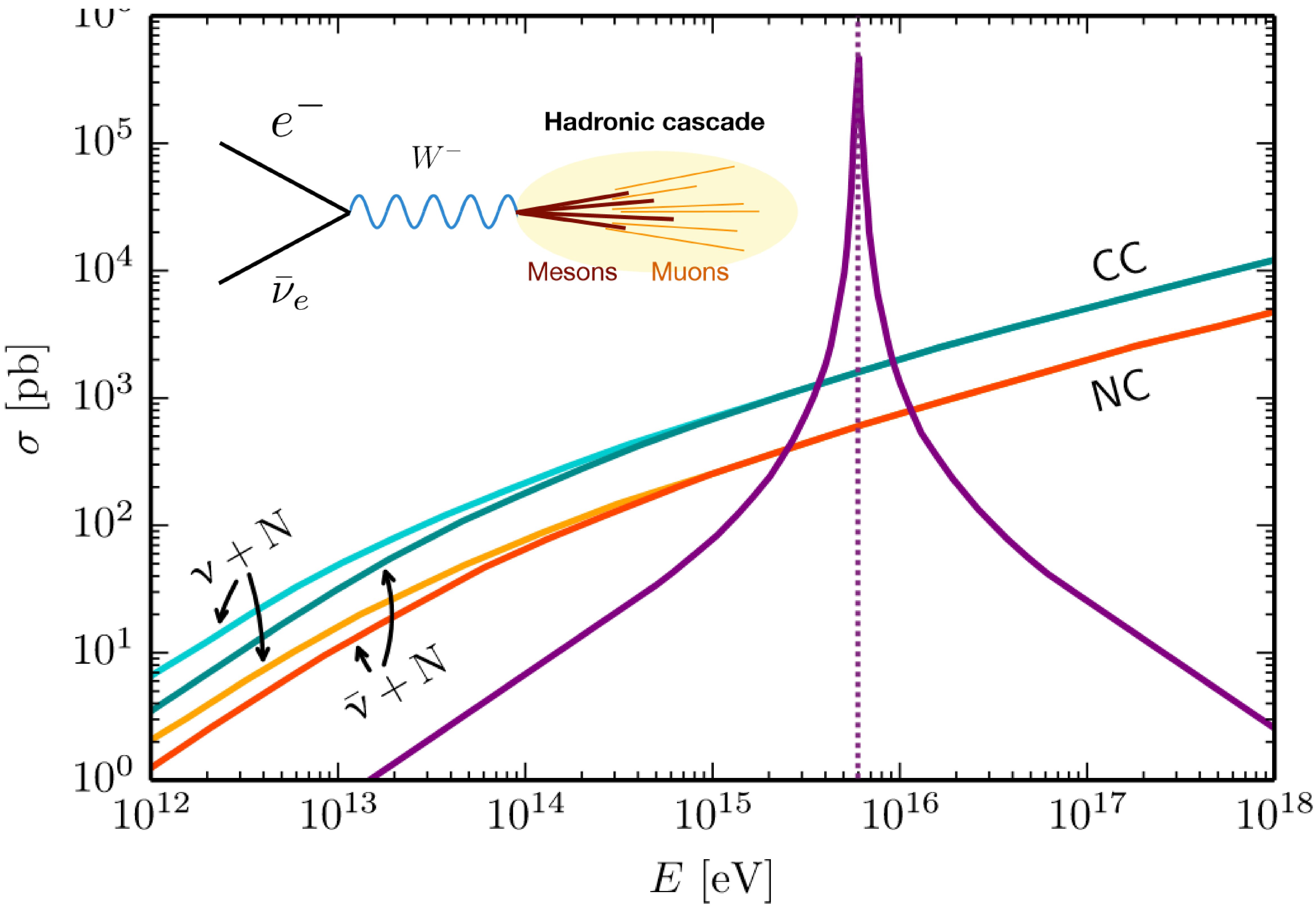
Neutrino Conference 2020



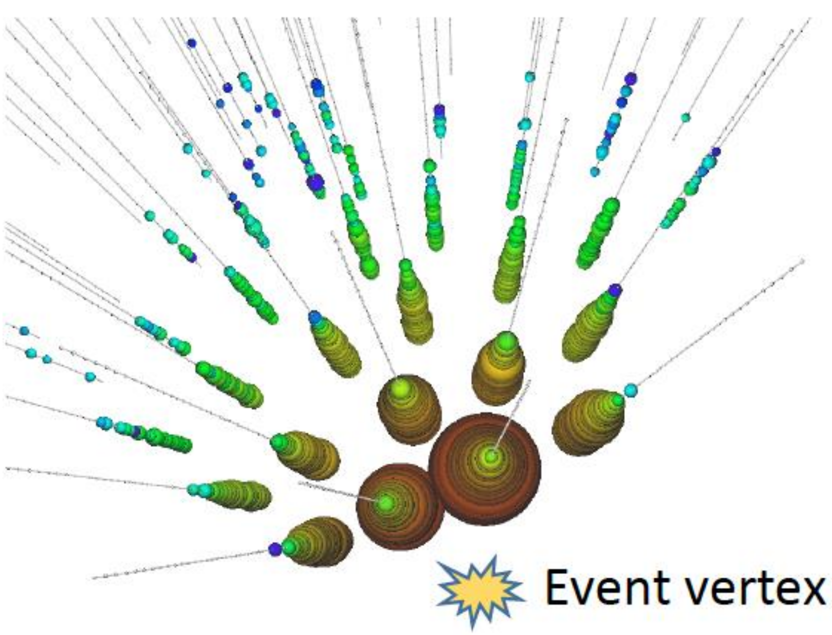
The first candidate for the Glashow resonance

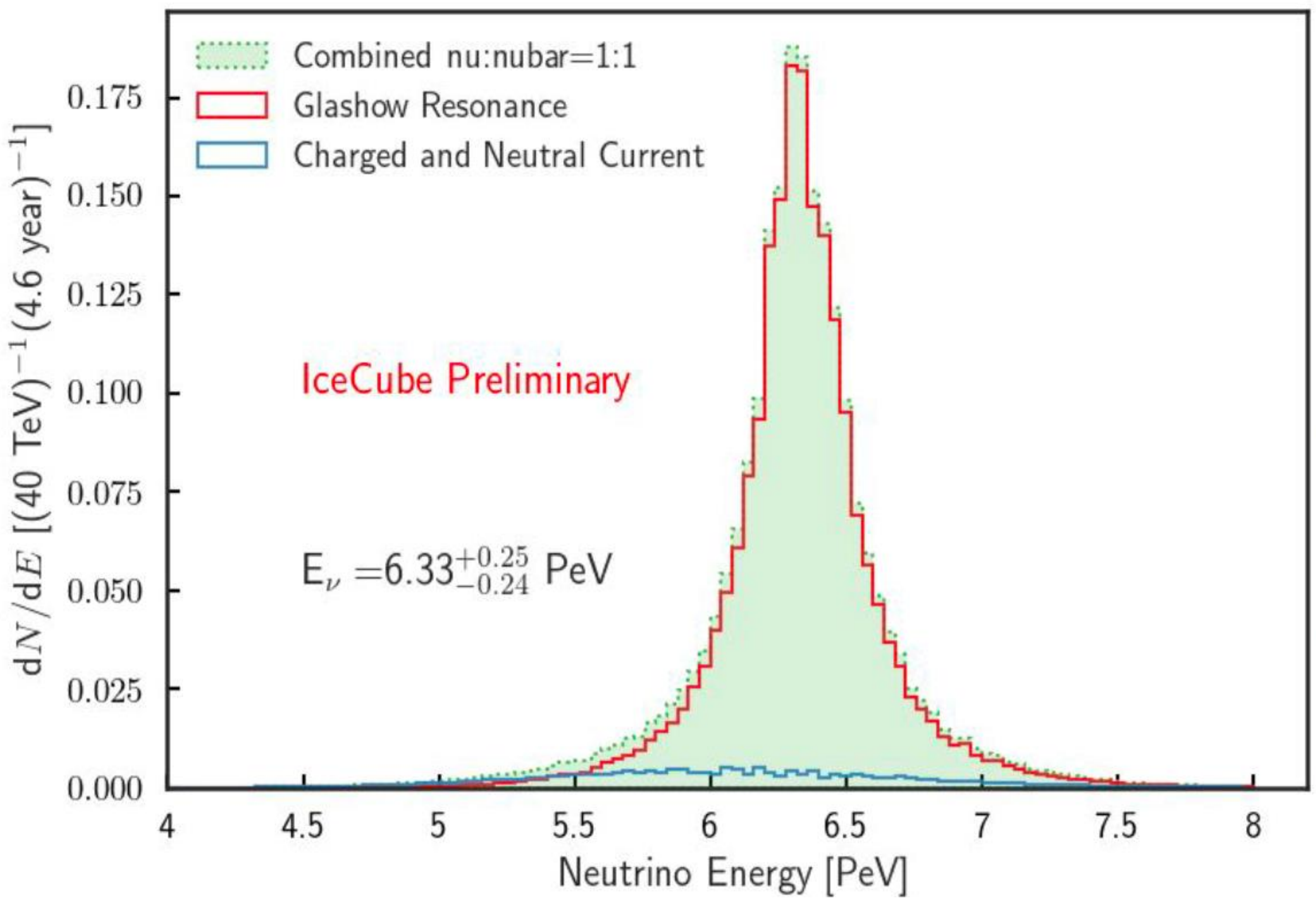


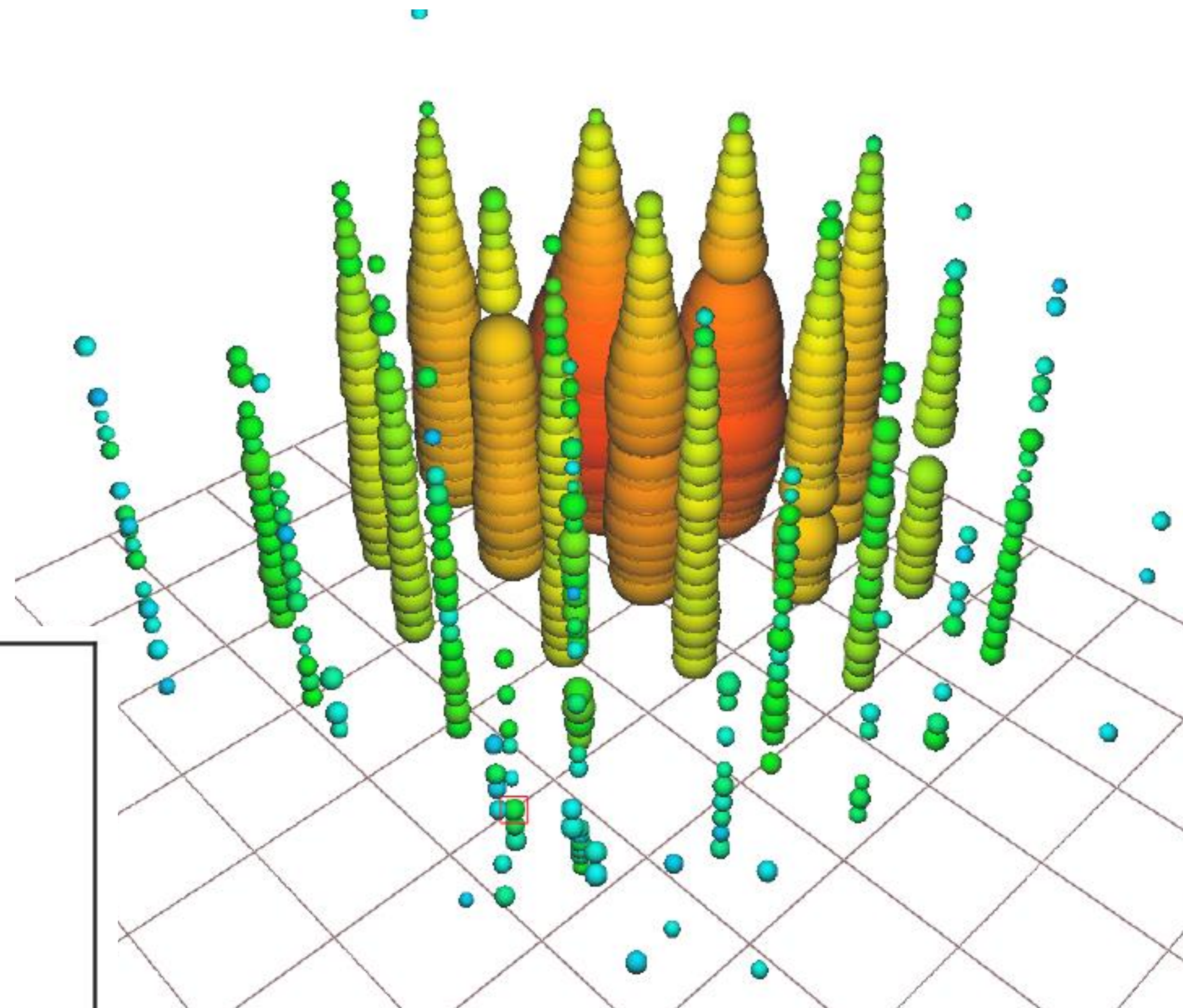
The first candidate for the Glashow resonance



Partially contained event with E = 6.3 PeV







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

Flavor composition $\nu_e : \nu_\mu : \nu_\tau$

$$p + \text{target} \rightarrow \pi^+ + \ldots$$
$$\rightarrow \mu^+ + \nu_\mu$$
$$\rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

1 : 2 : 0

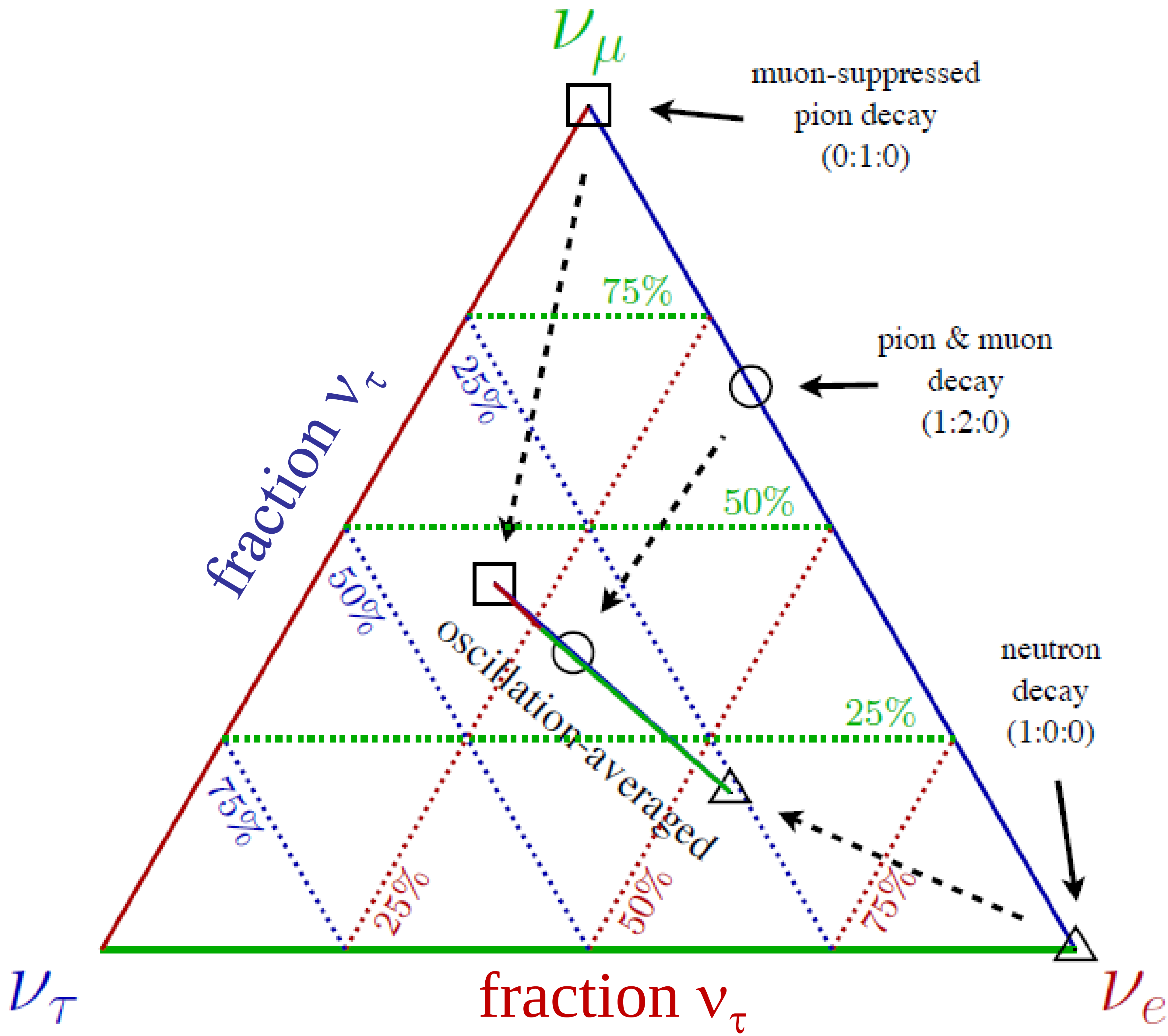
$$p + \text{target} \rightarrow \pi^+ + \ldots$$
$$\rightarrow \mu^+ + \nu_\mu$$

0 : 1 : 0

$$n \rightarrow p + e^- + \bar{\nu}_e$$

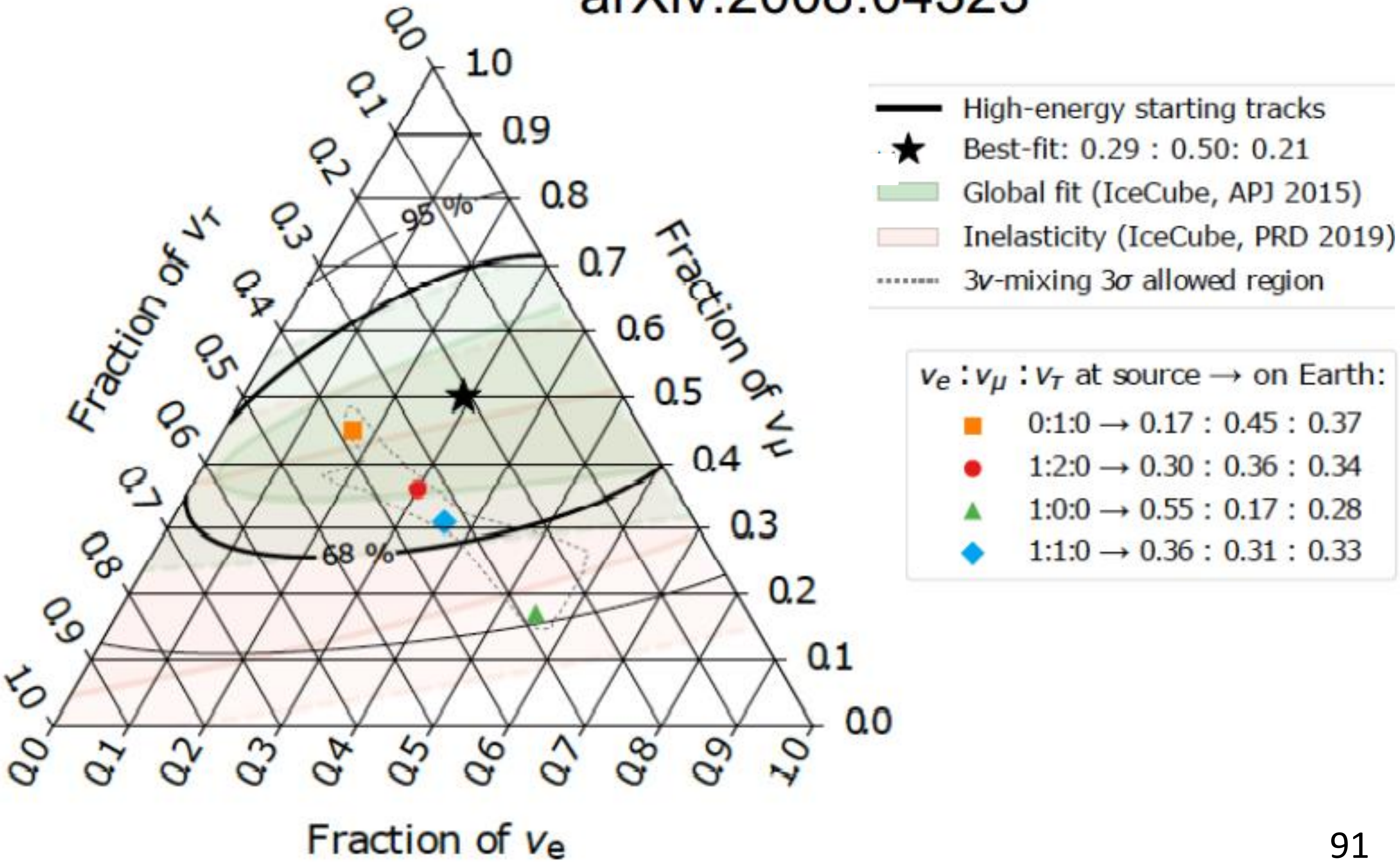
1 : 0 : 0

Flavor composition



Flavor composition

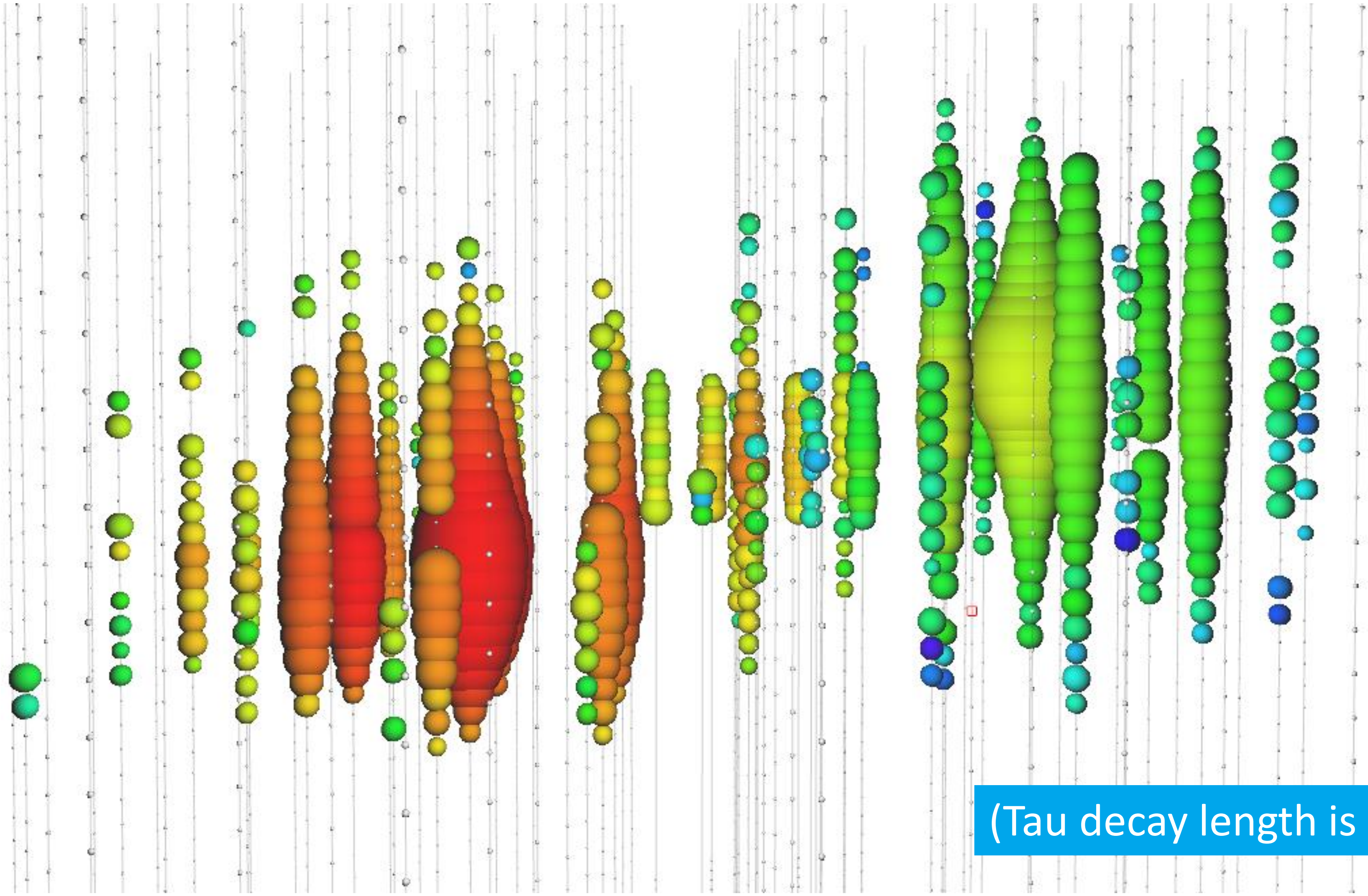
arXiv:2008.04323



Double bang events from tau decays

Monte Carlo event: $\nu_\tau + X \rightarrow \tau$ + cascade

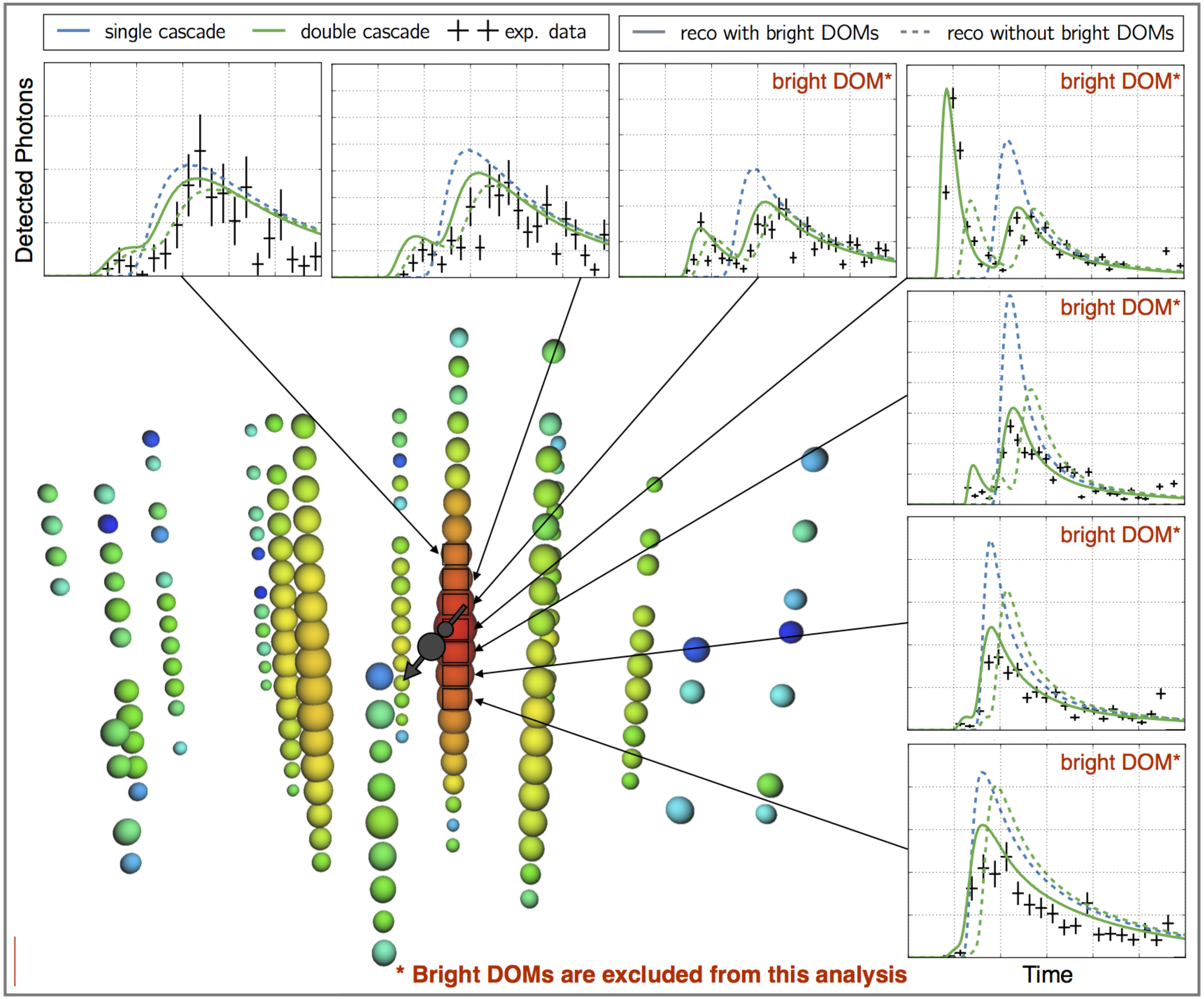
$\tau \rightarrow$ cascade



(Tau decay length is ~ 50 m at 1 PeV)

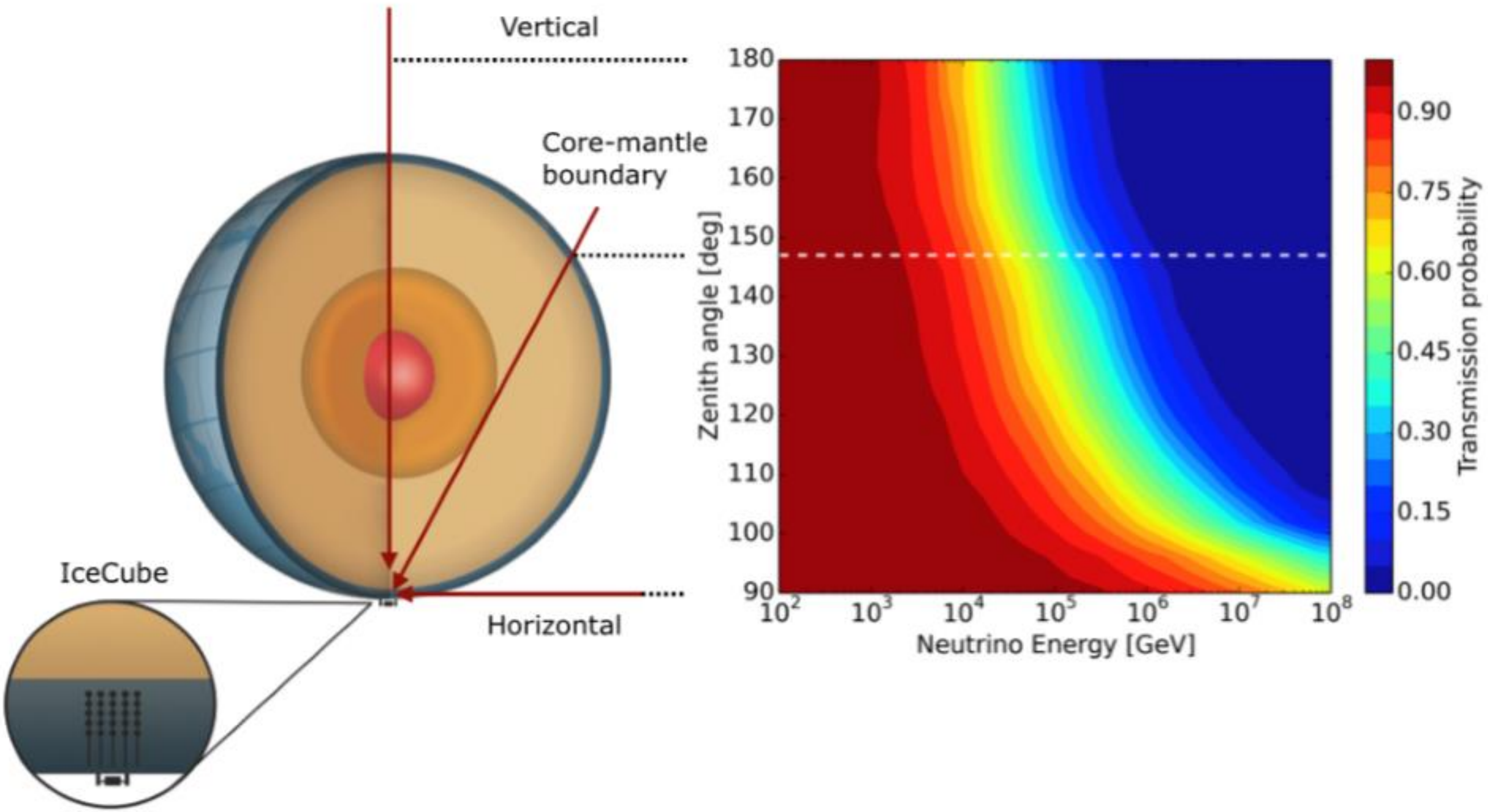
First tau-neutrino candidate

Two candidate events in 7.5 years of data



Using 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



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