

IceCube

and the emergence of high-energy neutrino astronomy

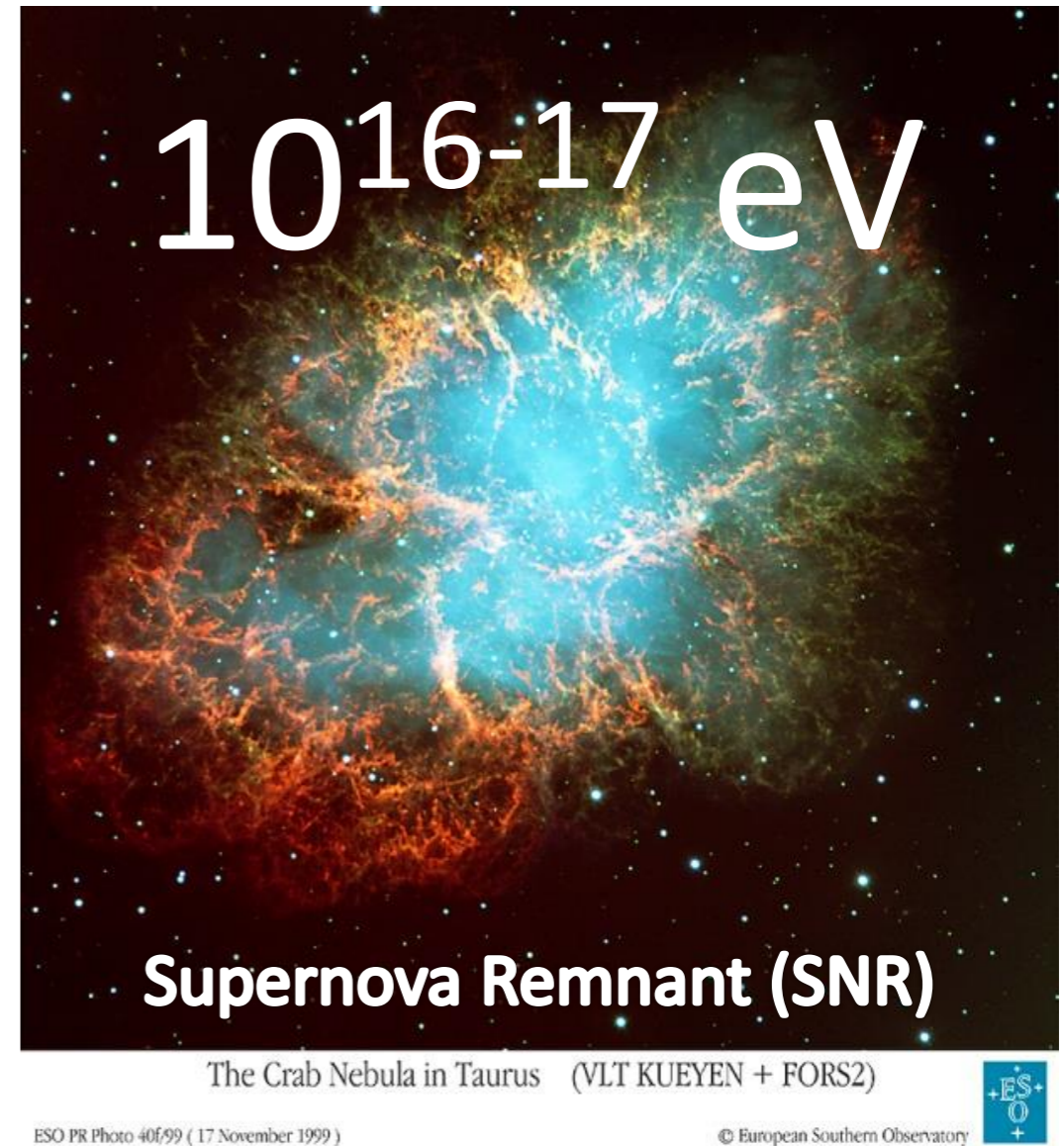
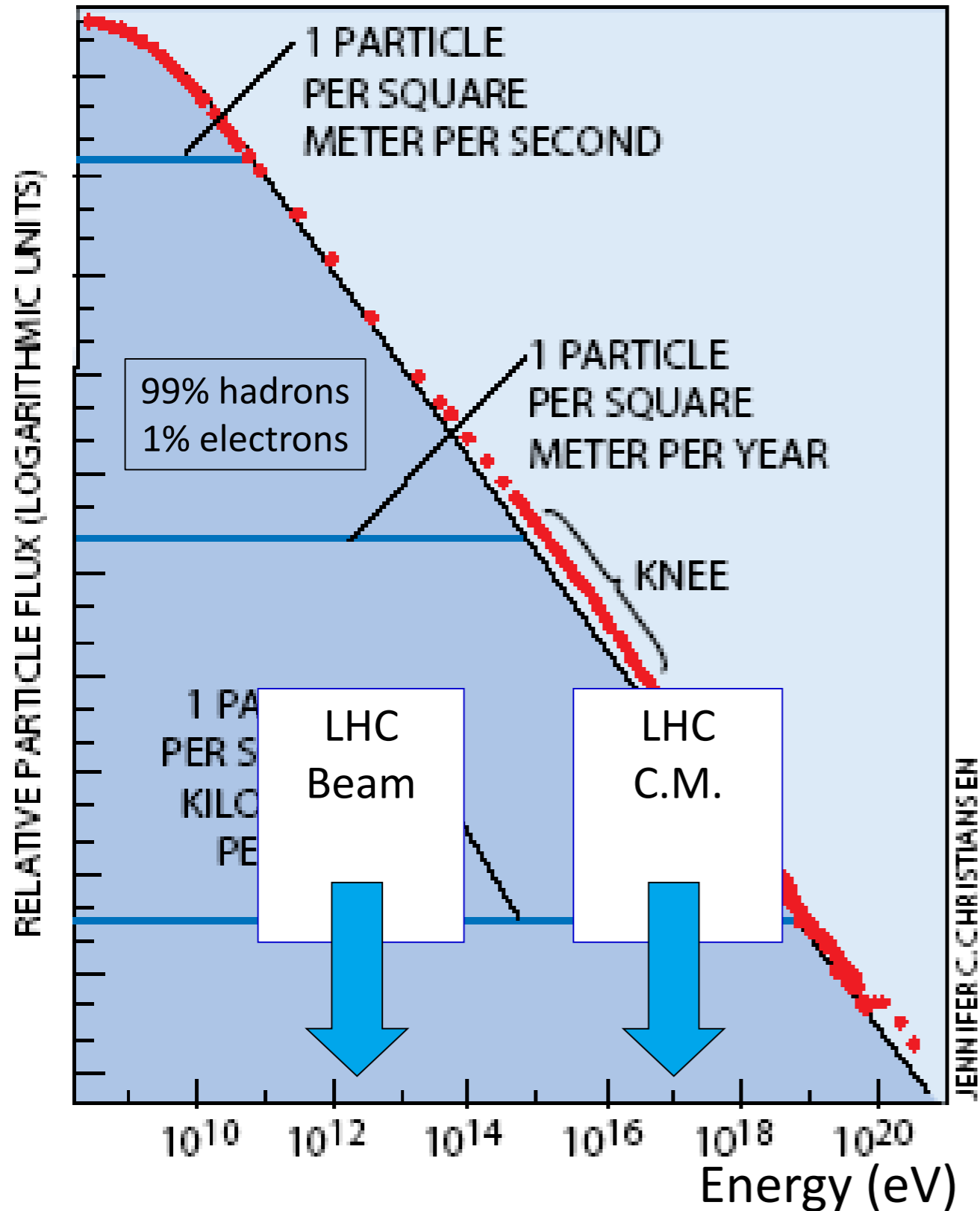


Christian Spiering, Marseille, June 6, 2021

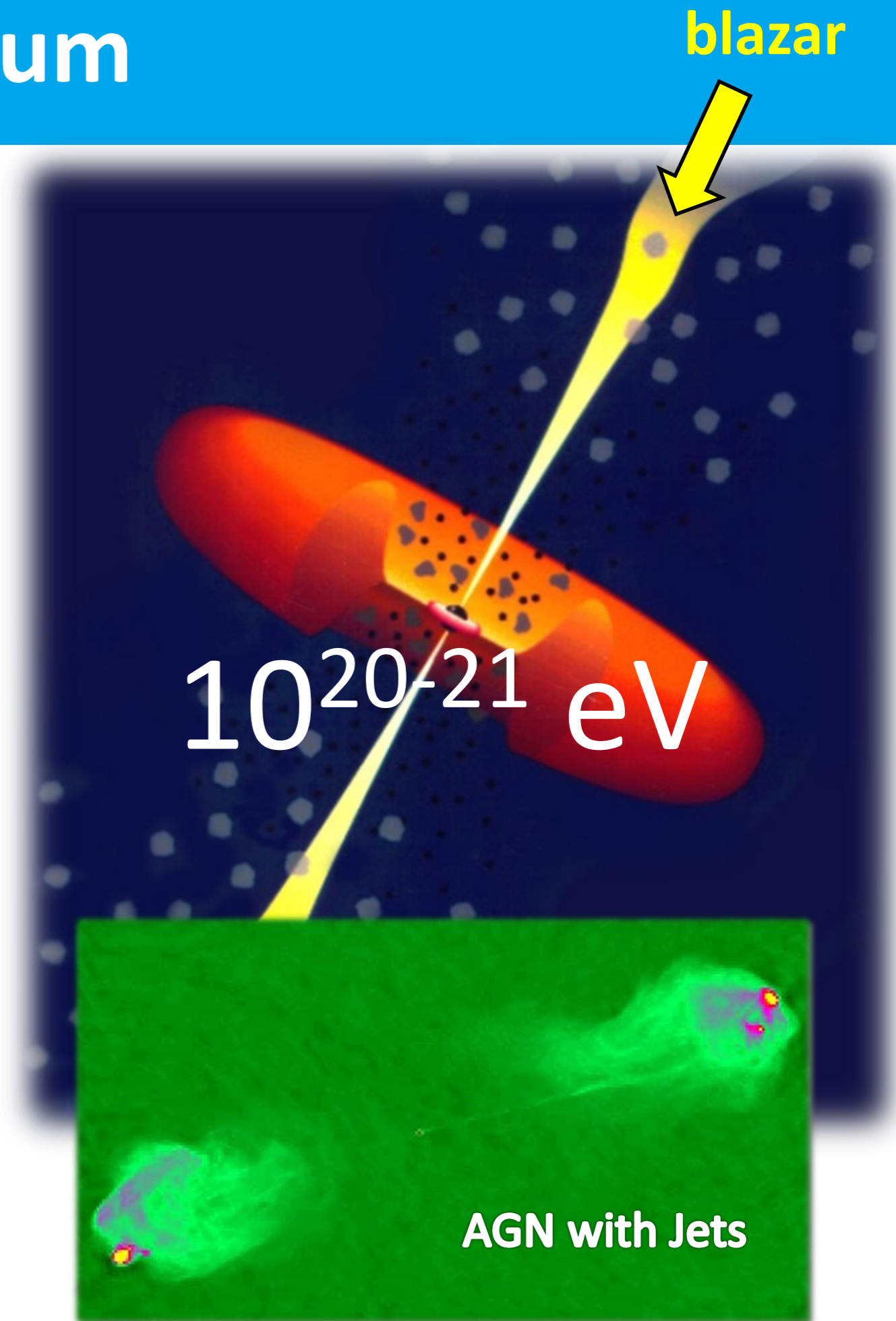
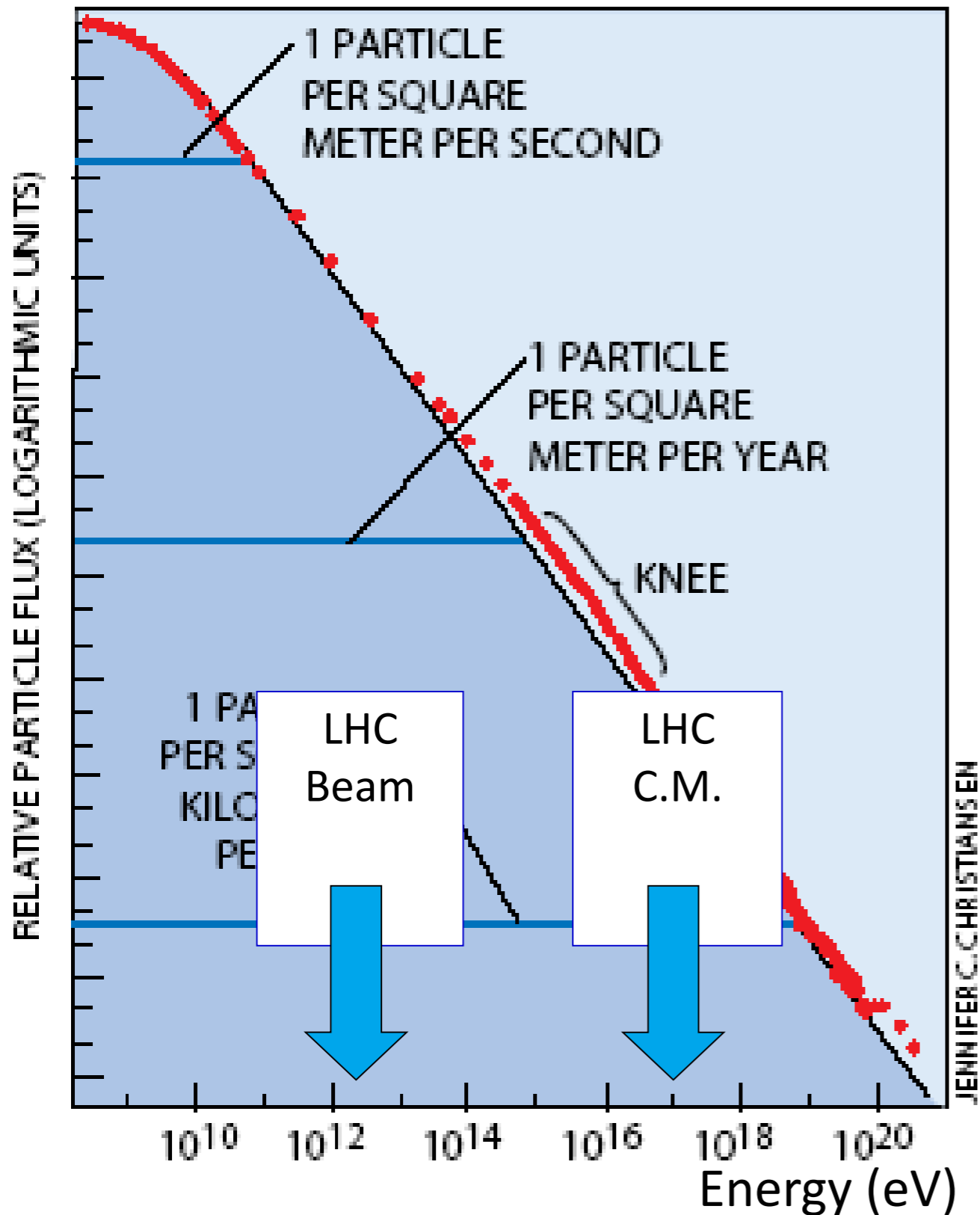
1.

Scientific motivation

The cosmic ray spectrum

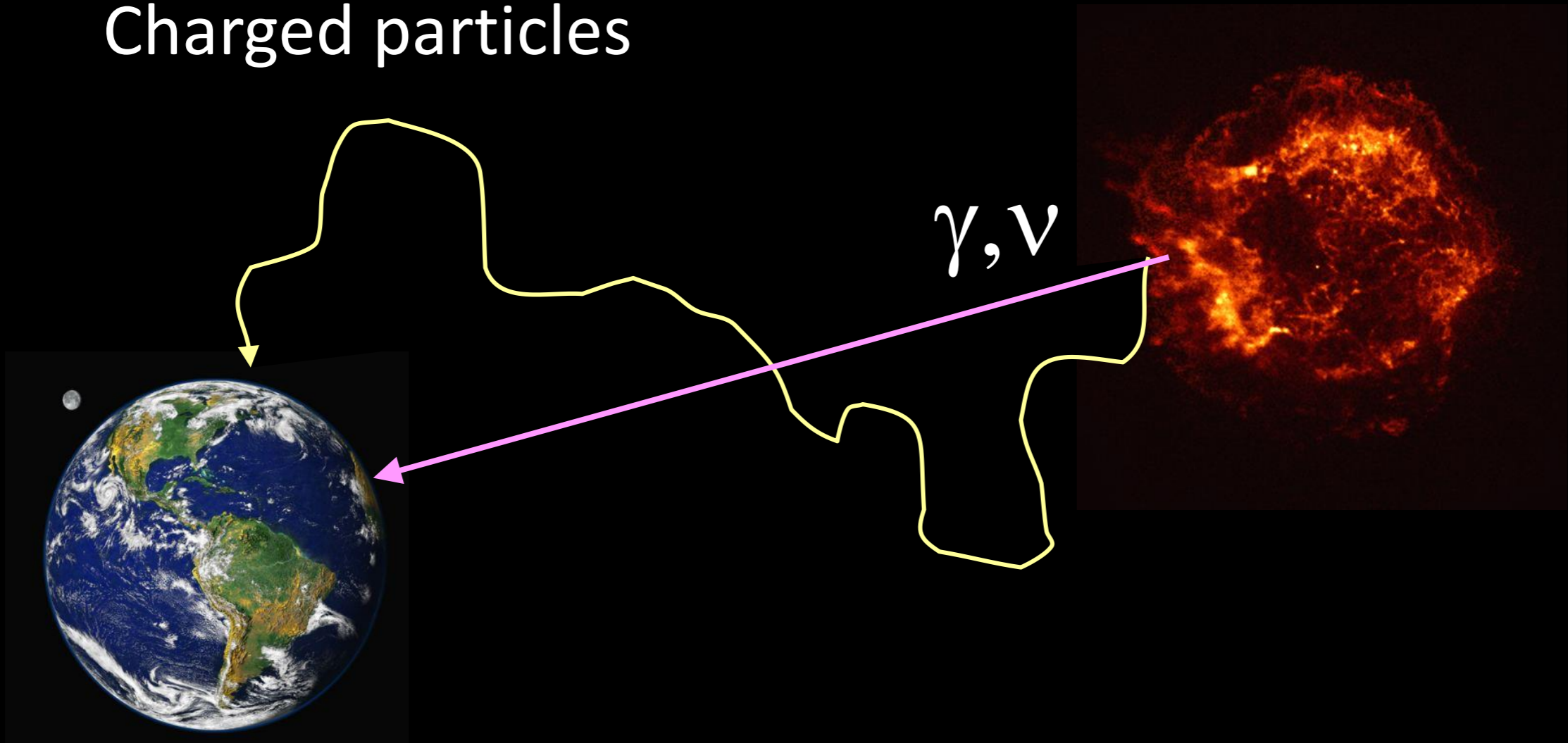


The cosmic ray spectrum



Charged cosmic rays vs. gamma rays vs. neutrinos

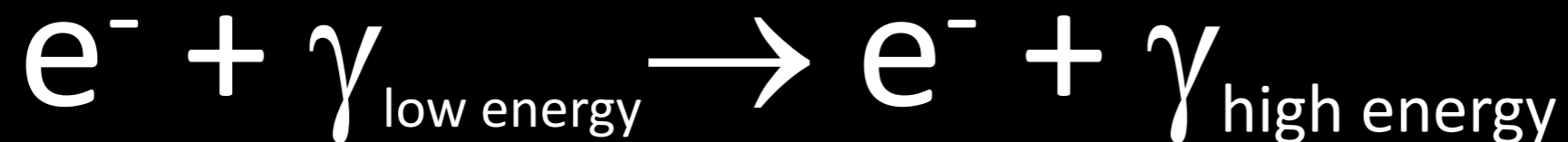
Charged particles



Gamma-Ray Generation



but also



(inverse Compton process)

Neutrino Generation

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

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

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

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

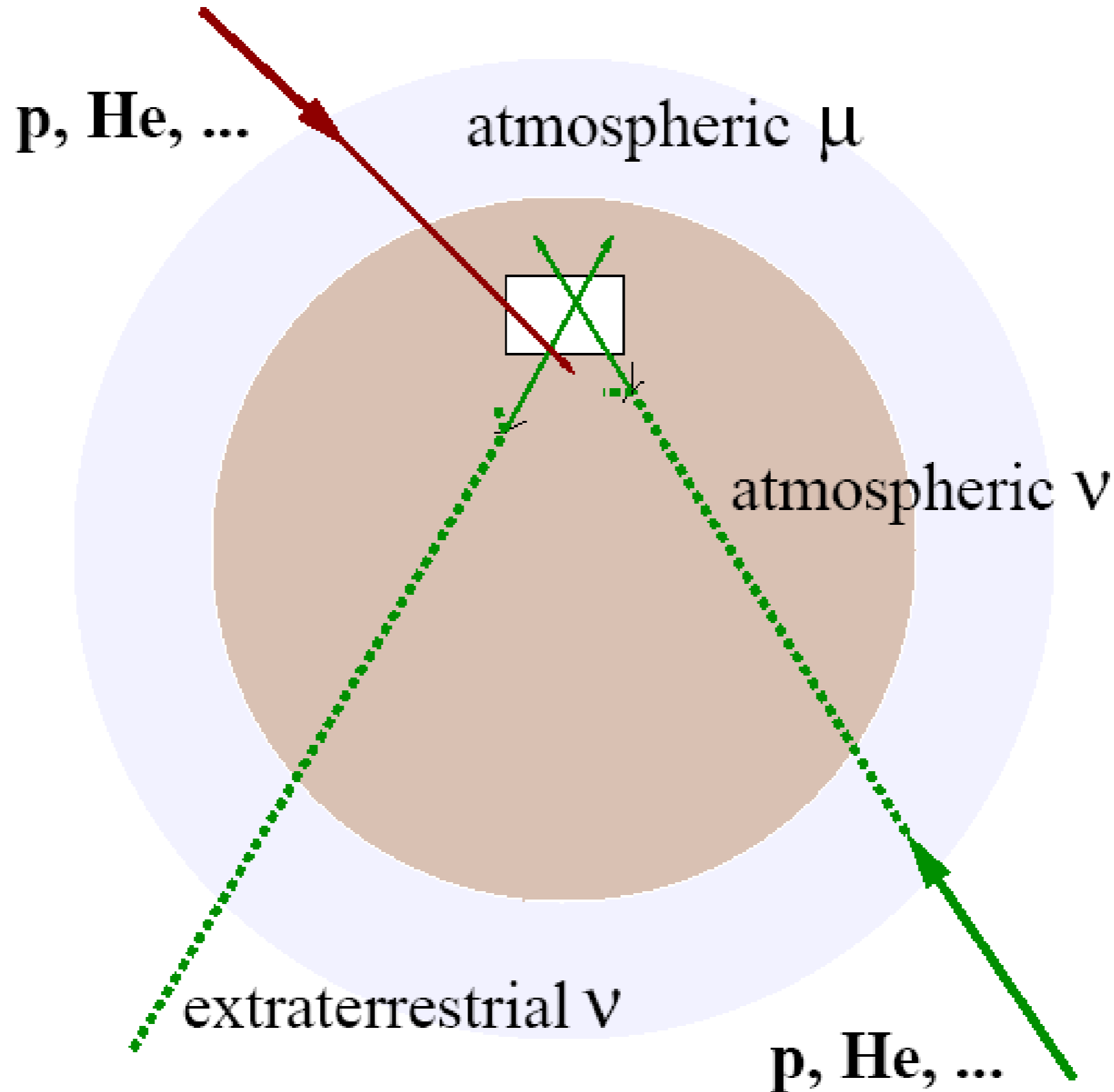
Physics with neutrino telescopes

- **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 → early SN phase, neutrino hierarchy, ...
- Cosmic Ray Physics
 - Spectrum, composition and anisotropies

2.

Operational principles

Detection deep under-ground/-water/-ice

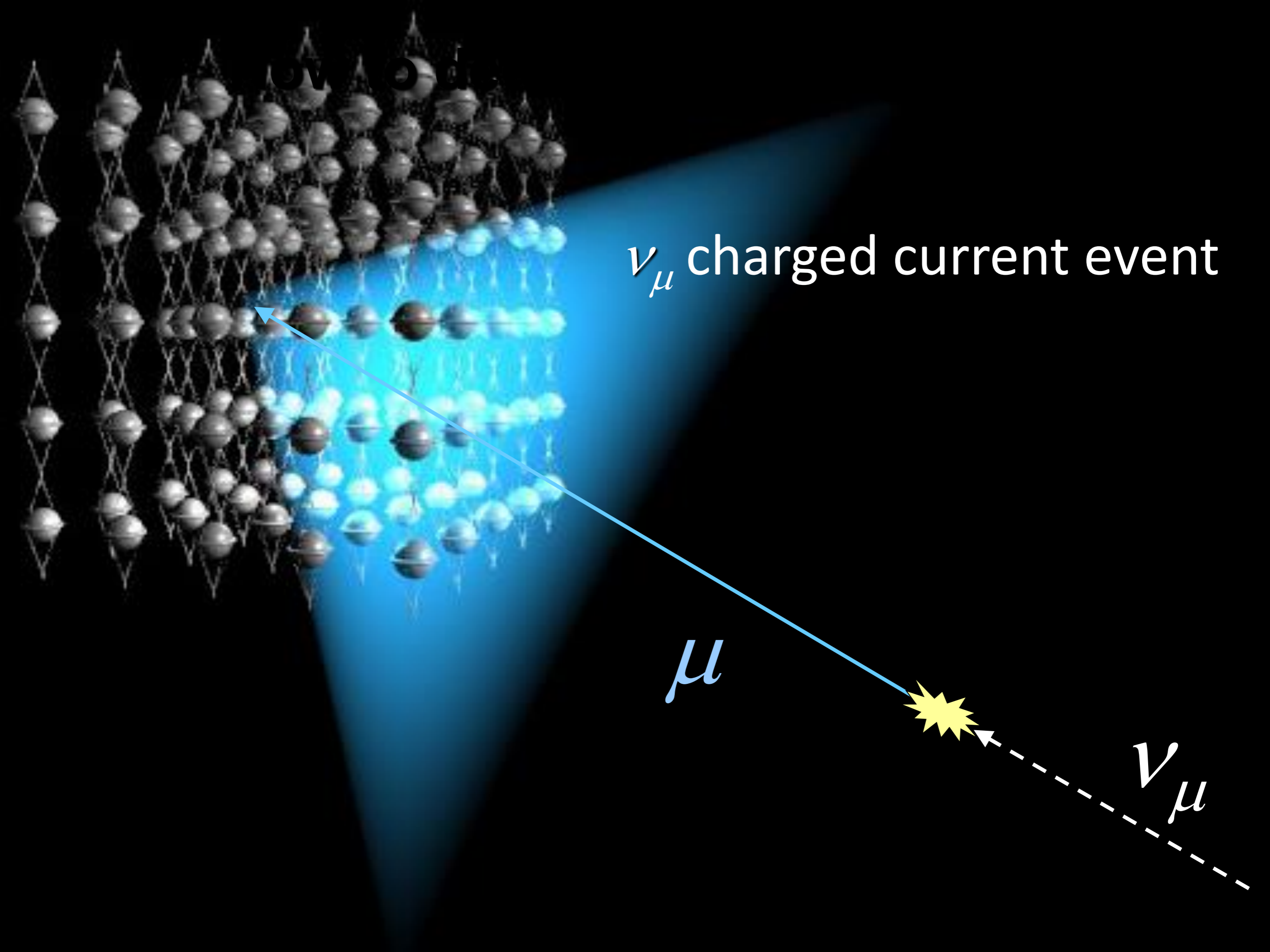


Detection deep underwater



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.

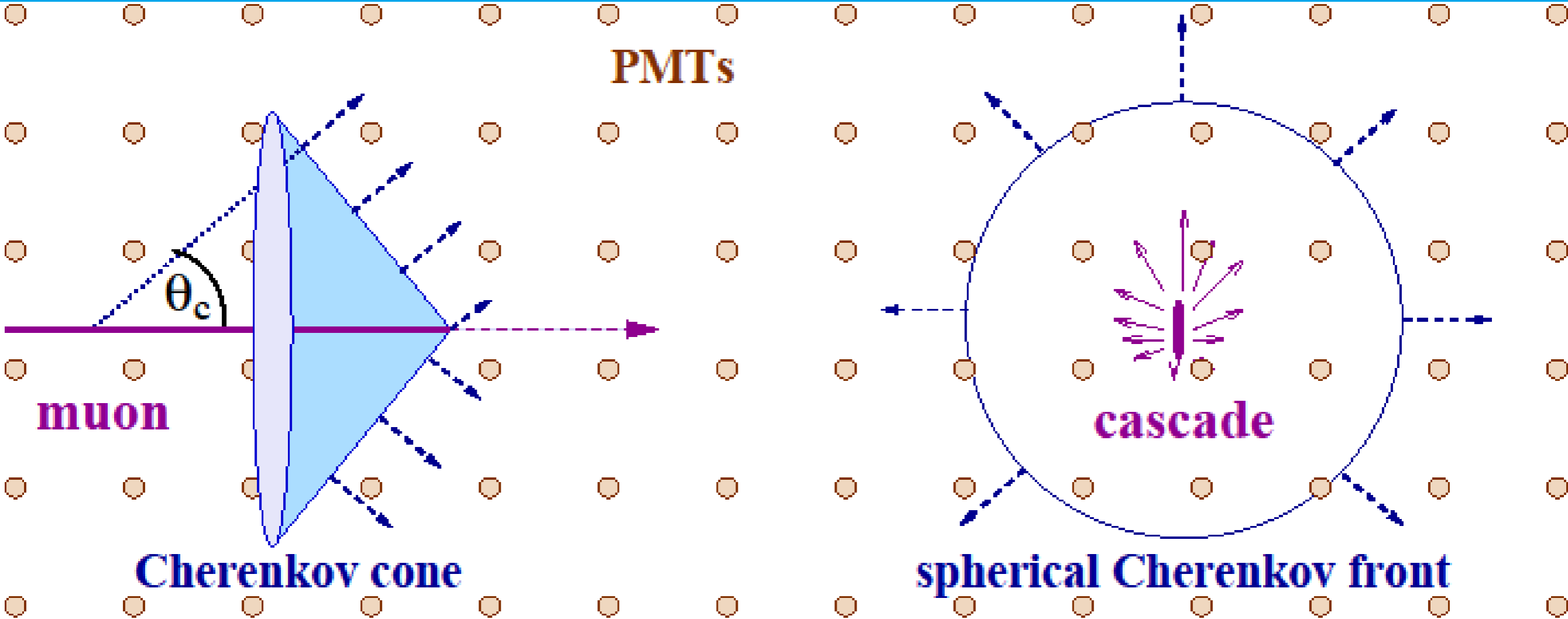


ν_μ charged current event

μ

ν_μ

Two Detection Modes: tracks and cascades



- $\nu_\mu + A \rightarrow \mu + \dots$

- Angular resolution $< 1^\circ$

- Energy resolution \sim factor 3

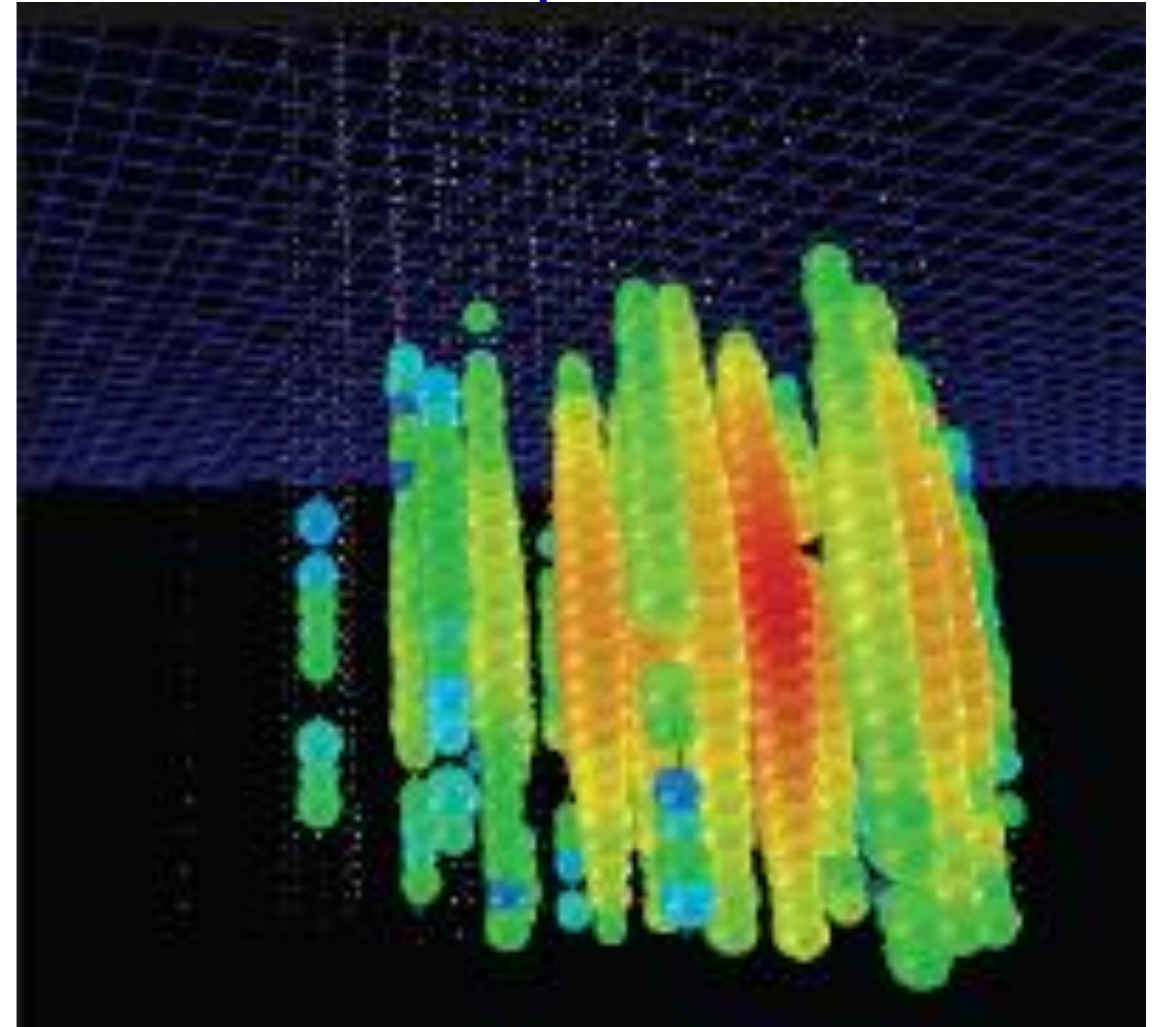
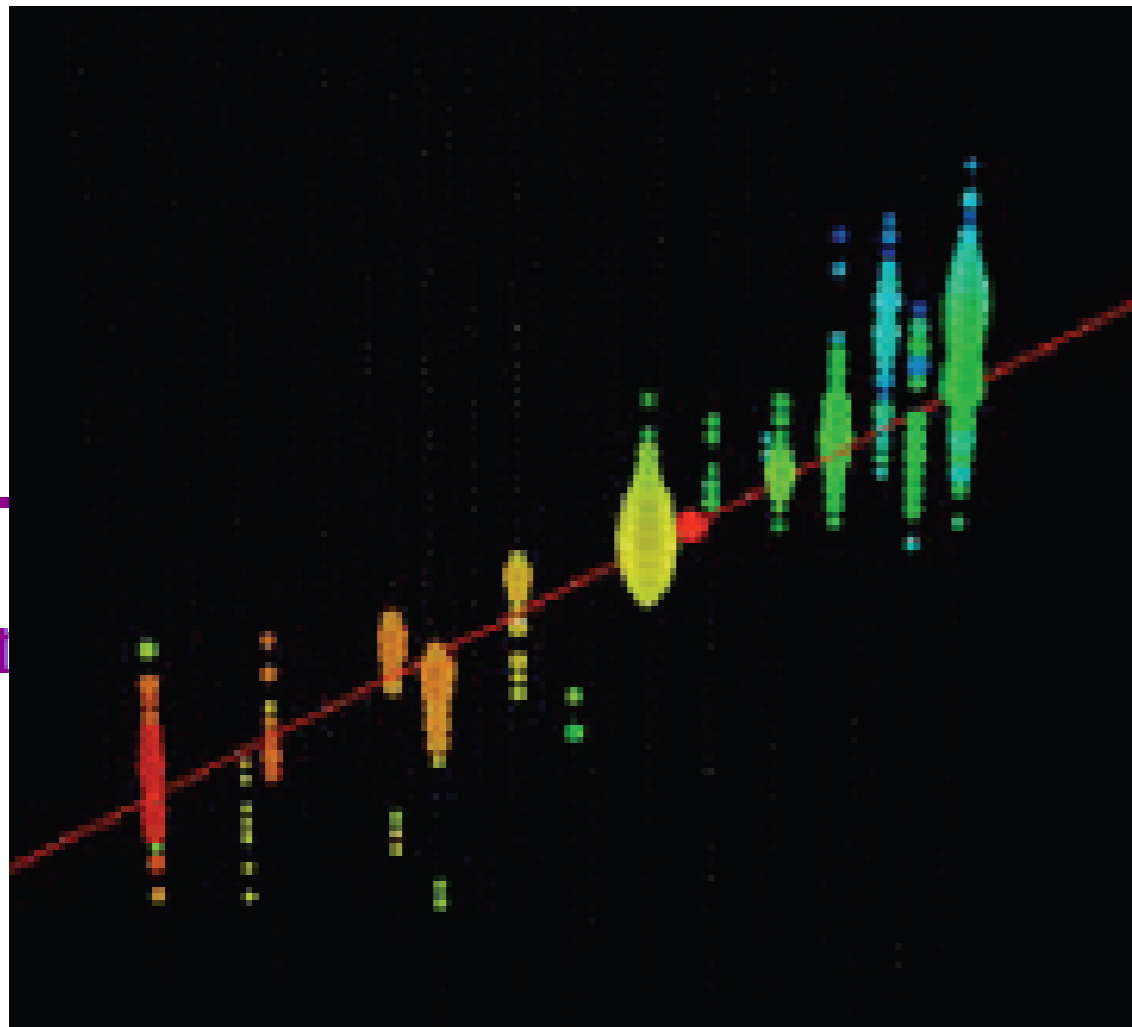
- $\nu_{e,\tau} \rightarrow e, \tau + \dots$

- $\nu_\chi \rightarrow \nu_\chi + \dots$

- Angular resolution $2^\circ - 10^\circ$

- Energy resolution $\sim 15\%$

Two Detection Modes



- Angular resolution $< 1^{\circ}$
- Energy resolution \sim factor 3



- Angular resolution $2^{\circ} - 10^{\circ}$
- Energy resolution $\sim 15\%$

3.

Some history

1978: 1.26 km³
22,698 OMs

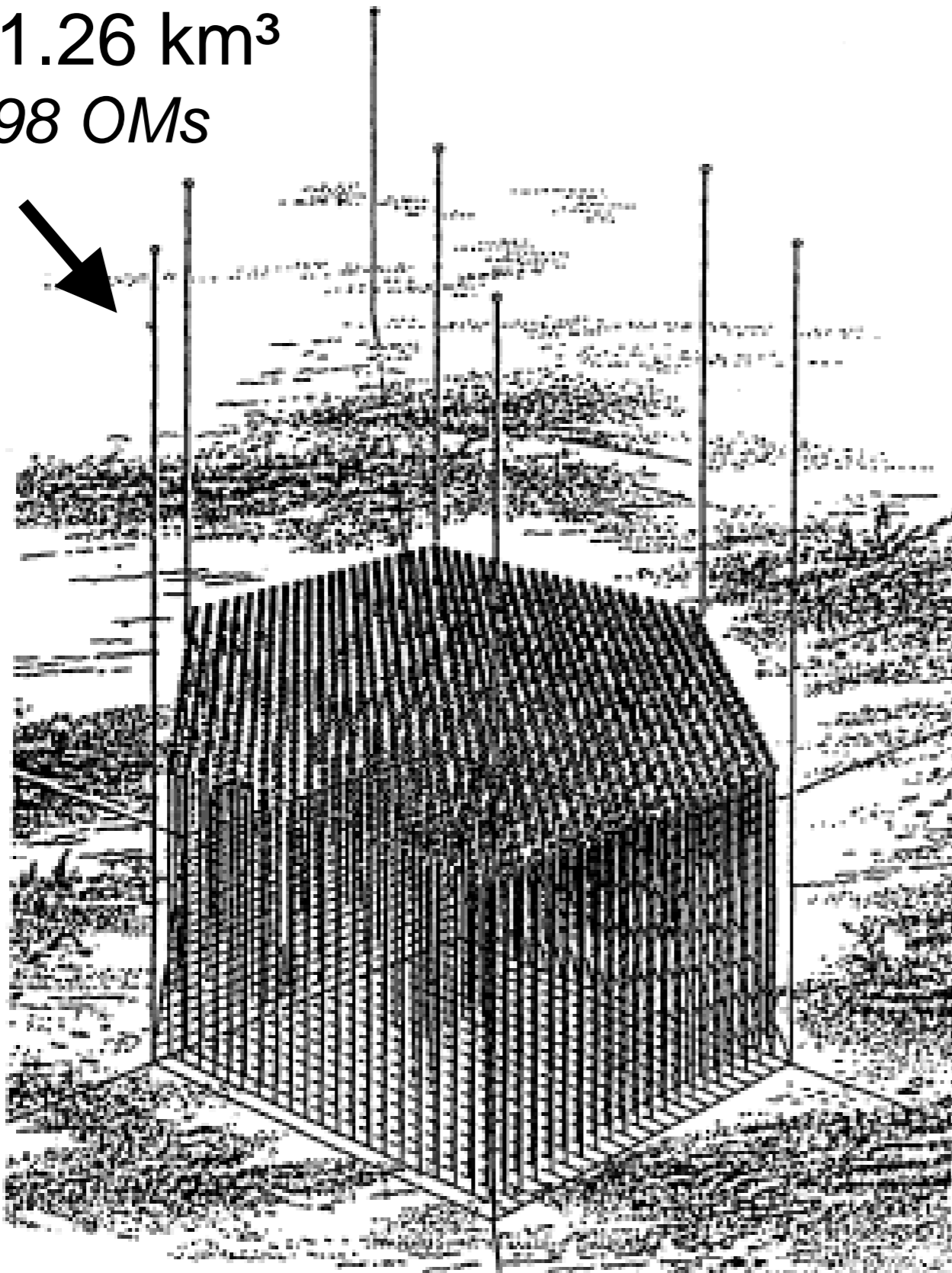
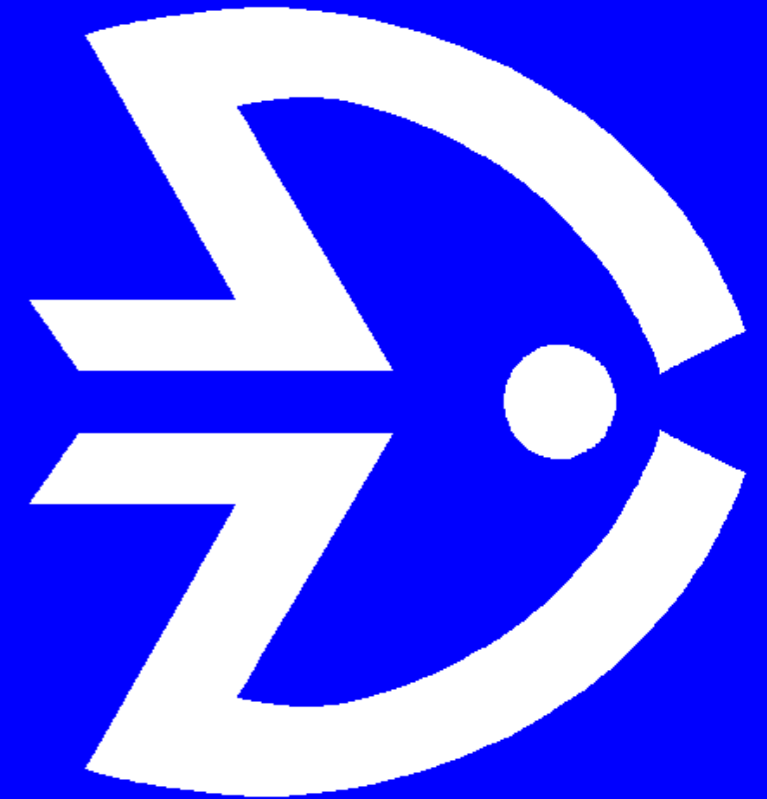


FIG. 9. The first DUMAND array: DUMAND G, the 1978 model. See text for details (Roberts and Wilkins, 1978).

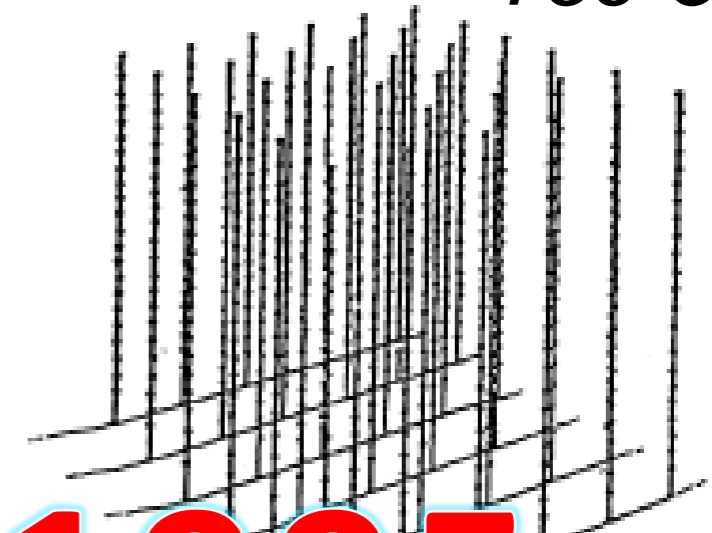
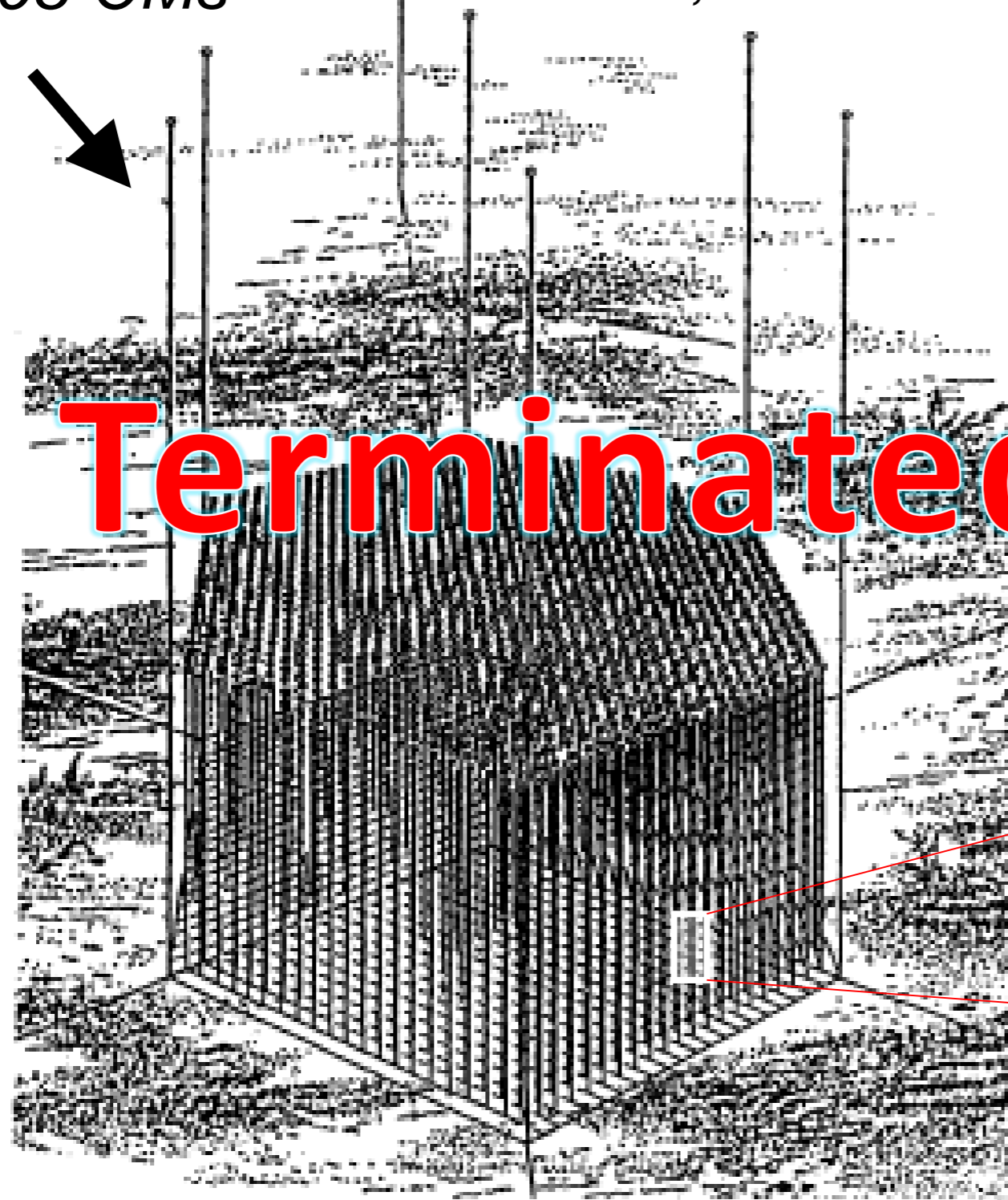
DUMAND



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

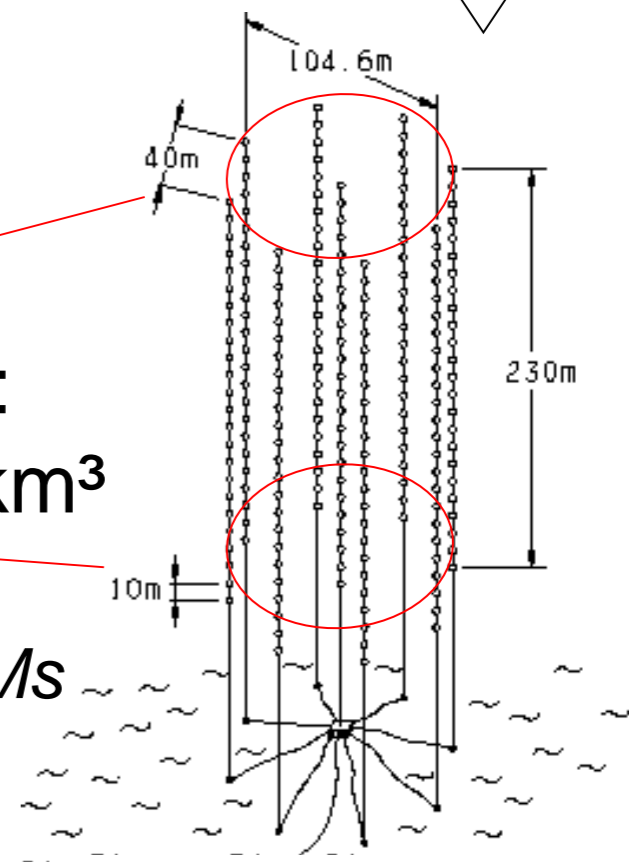


FIG. 9. The first DUMAND array: DUMAND G, the 1978 model. See text for details (Roberts and Wilkins, 1978).

DUMAND-II

Lake Baikal

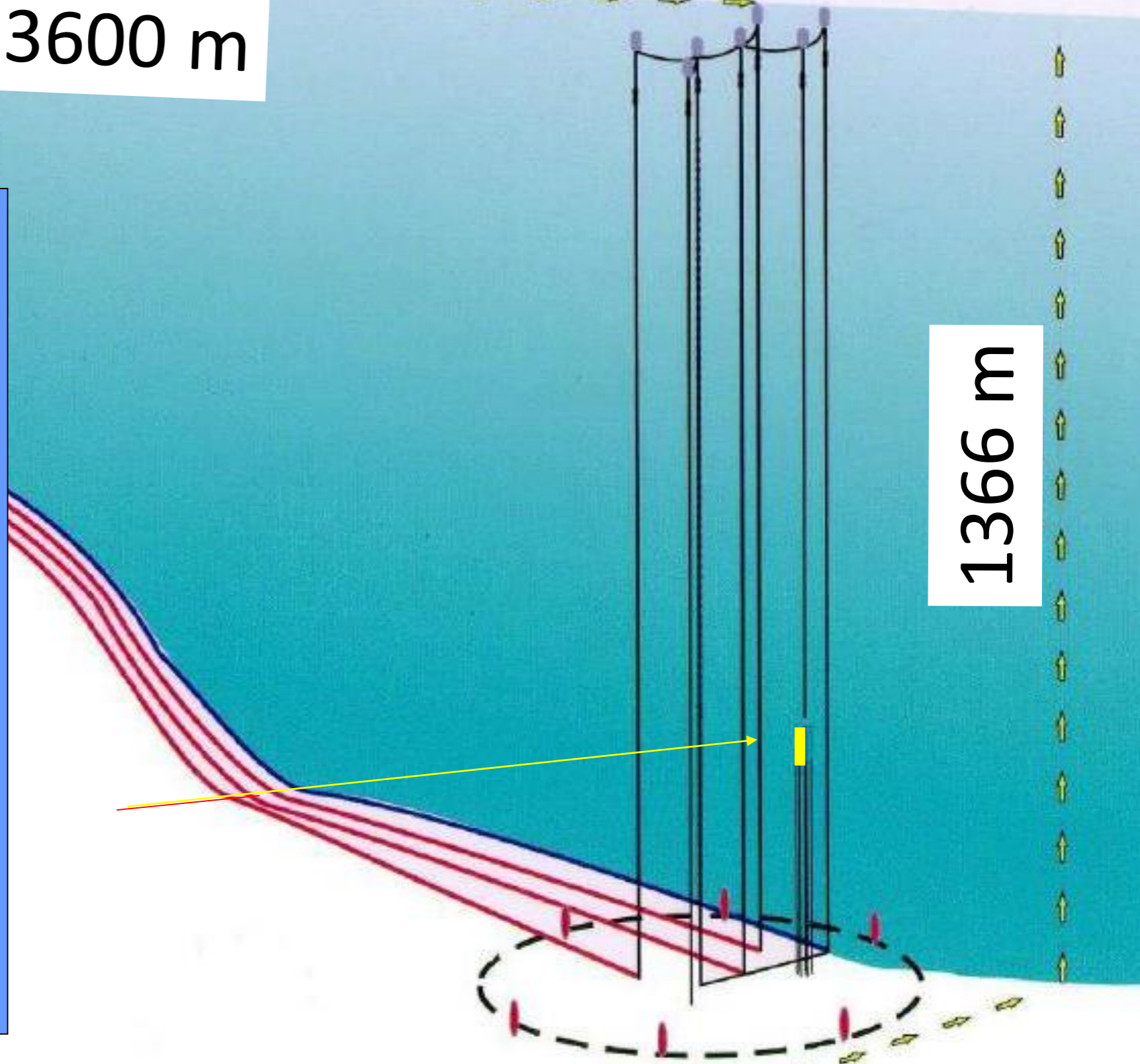
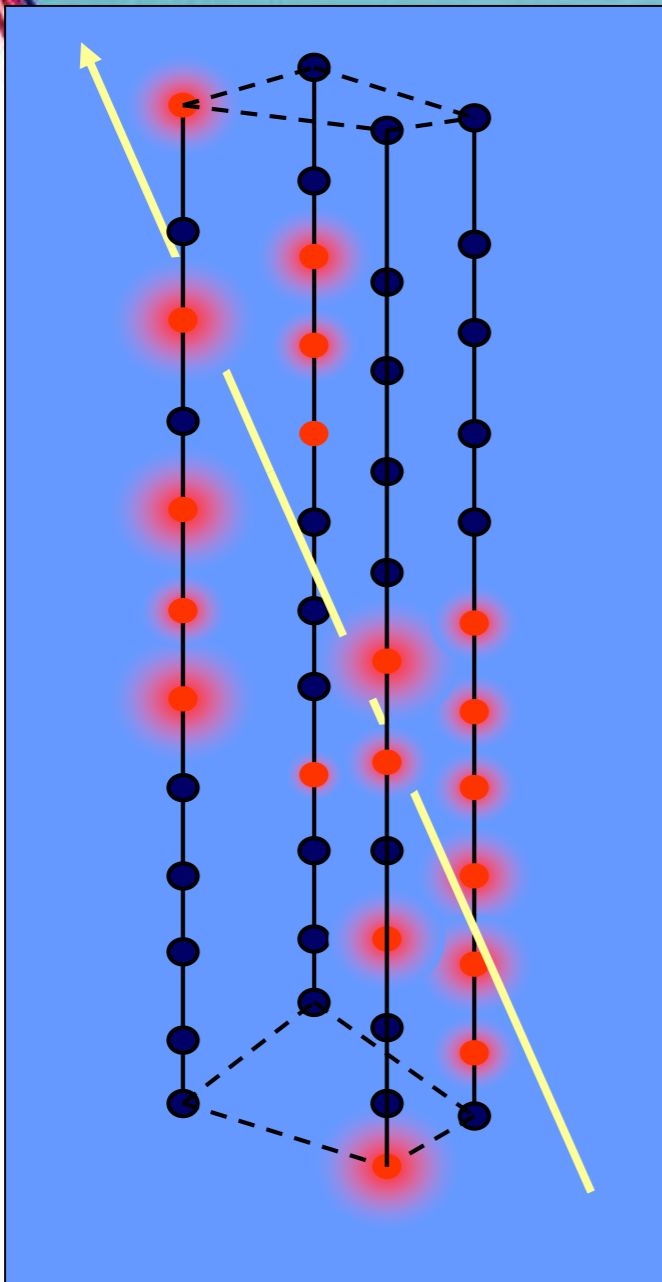


A first textbook underwater neutrino event

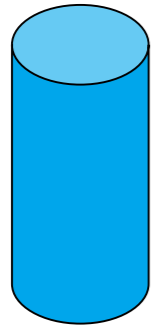
1996

3600 m

1366 m



100 m



230 m

DUMAND-II
Terminated 1995

40 m



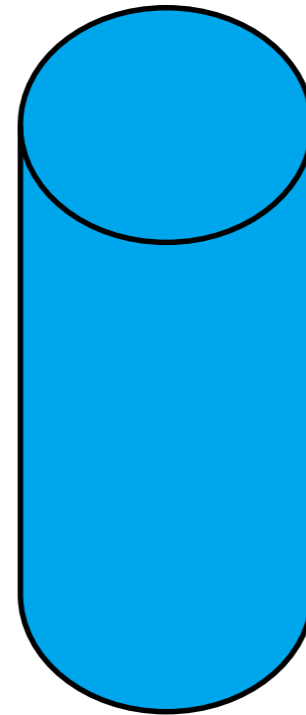
70 m

**Lake Baikal
NT-200**

Construction
1993 – 1998

Operation
1998 - 2008

200 m



500 m

AMANDA

Construction
1996-2000

Operation
2000-2008

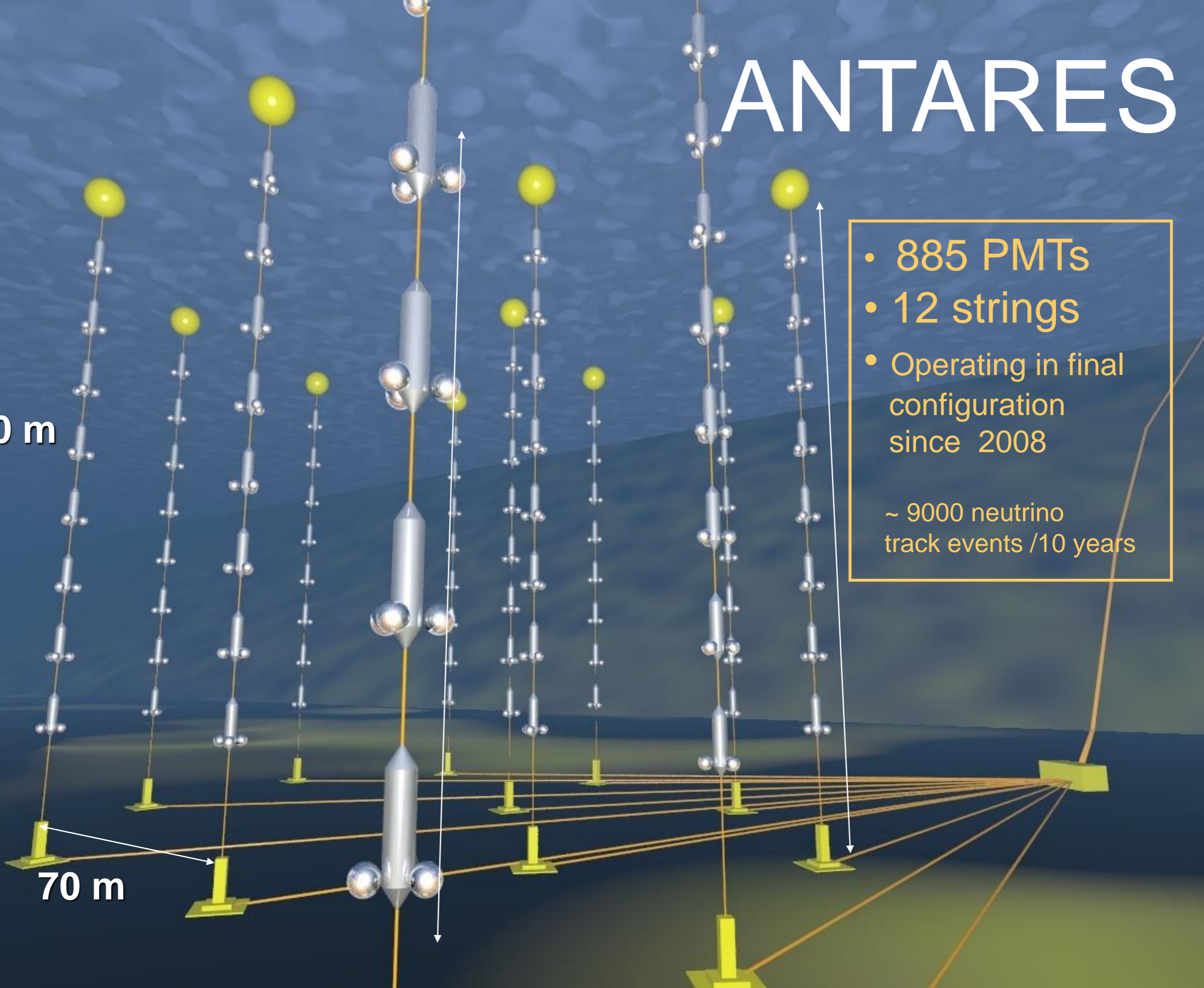
677 OMs
~7000 neutrinos
in 8 years

ANTARES

450 m

70 m

- 885 PMTs
 - 12 strings
 - Operating in final configuration since 2008
- ~ 9000 neutrino track events /10 years



4.

IceCube Neutrino Observatory

The IceCube Collaboration

 **AUSTRALIA**
University of Adelaide

 **BELGIUM**
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

 **CANADA**
SNOLAB
University of Alberta-Edmonton


 **DENMARK**
University of Copenhagen


 **GERMANY**
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt-Universität zu Berlin
Karlsruhe Institute of Technology
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
Westfälische Wilhelms-Universität
Münster


 **JAPAN**
Chiba University

 **NEW ZEALAND**
University of Canterbury

 **REPUBLIC OF KOREA**
Sungkyunkwan University

 **SWEDEN**
Stockholms universitet
Uppsala universitet

 **SWITZERLAND**
Université de Genève

 **UNITED KINGDOM**
University of Oxford

 **UNITED STATES**
Clark Atlanta University
Drexel University
Georgia Institute of Technology
Harvard University
Lawrence Berkeley National Lab
Loyola University Chicago
Marquette University
Massachusetts Institute of Technology
Mercer University
Michigan State University
Ohio State University
Pennsylvania State University

South Dakota School of Mines
and Technology
Southern University
and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of California, Los Angeles
University of Delaware
University of Kansas

University of Maryland
University of Rochester
University of Texas at Arlington
University of Wisconsin-Madison
University of Wisconsin-River Falls
Yale University

THE ICECUBE COLLABORATION

FUNDING AGENCIES

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen
(FWO-Vlaanderen)

Federal Ministry of Education and Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)

Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat

The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)



icecube.wisc.edu

IceCube Neutrino Observatory

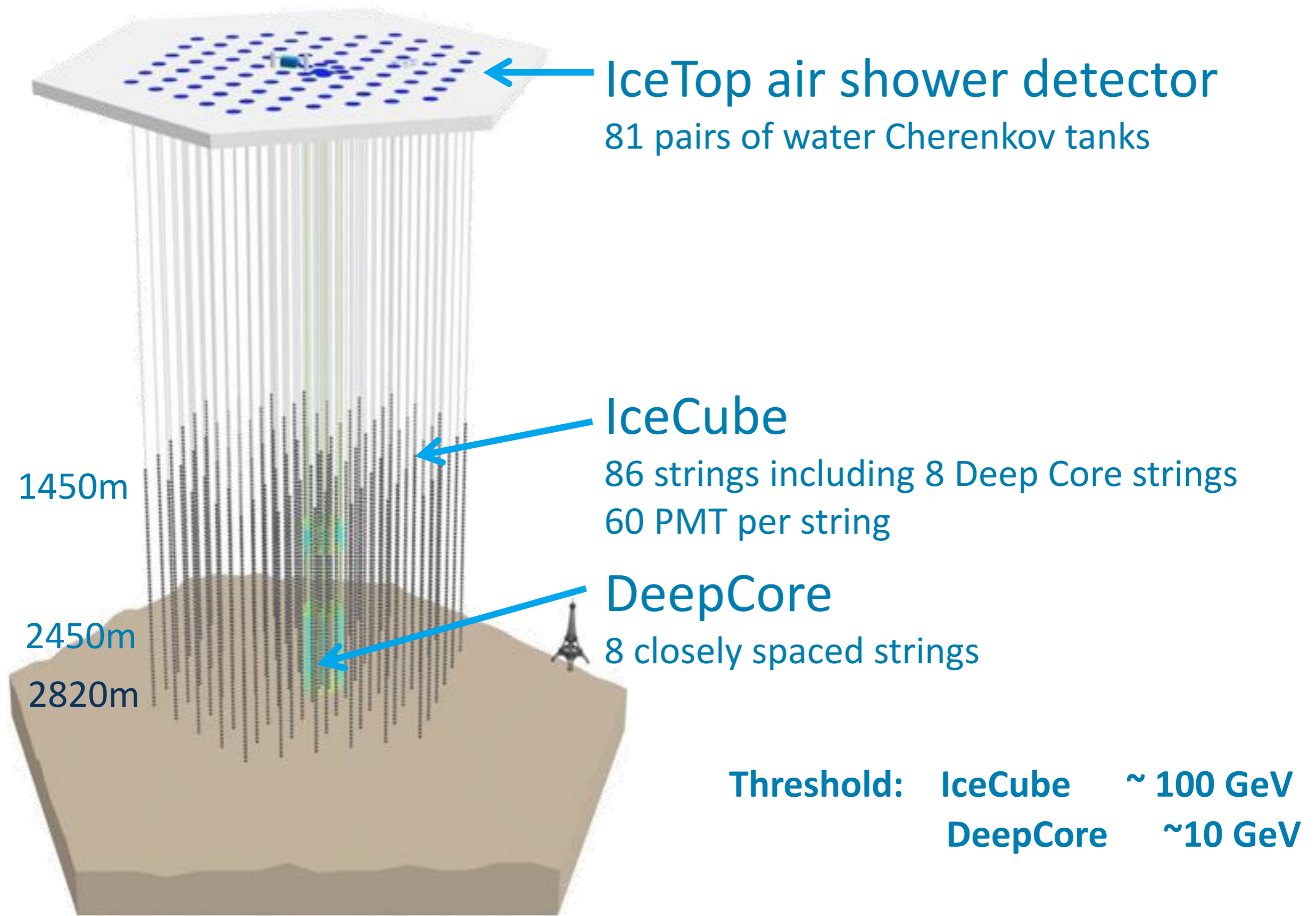
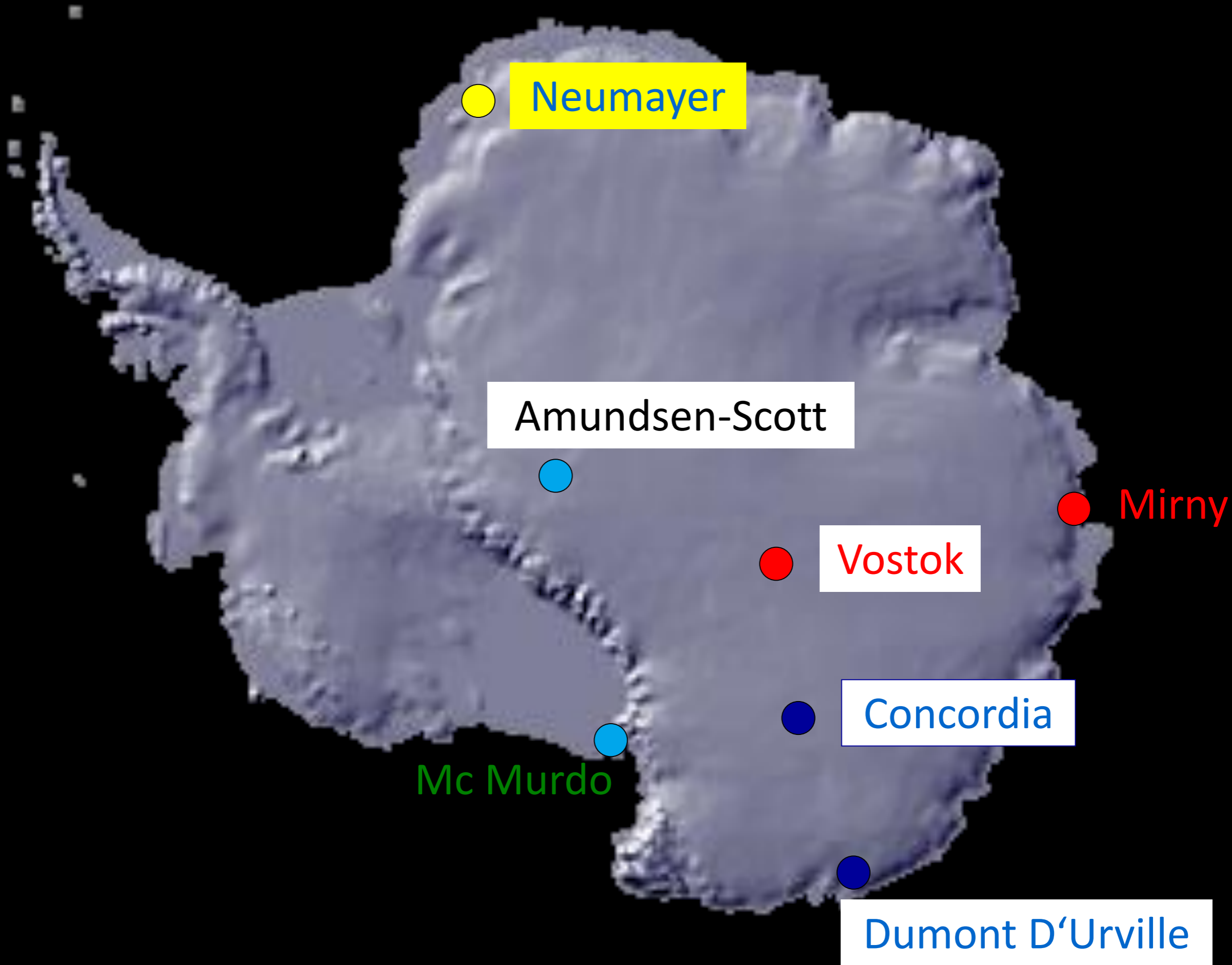




PHOTO BY CHARLIE KAMINSKI

SOUTH POLE DEC 2, 2000



The Amundsen-Scott Station

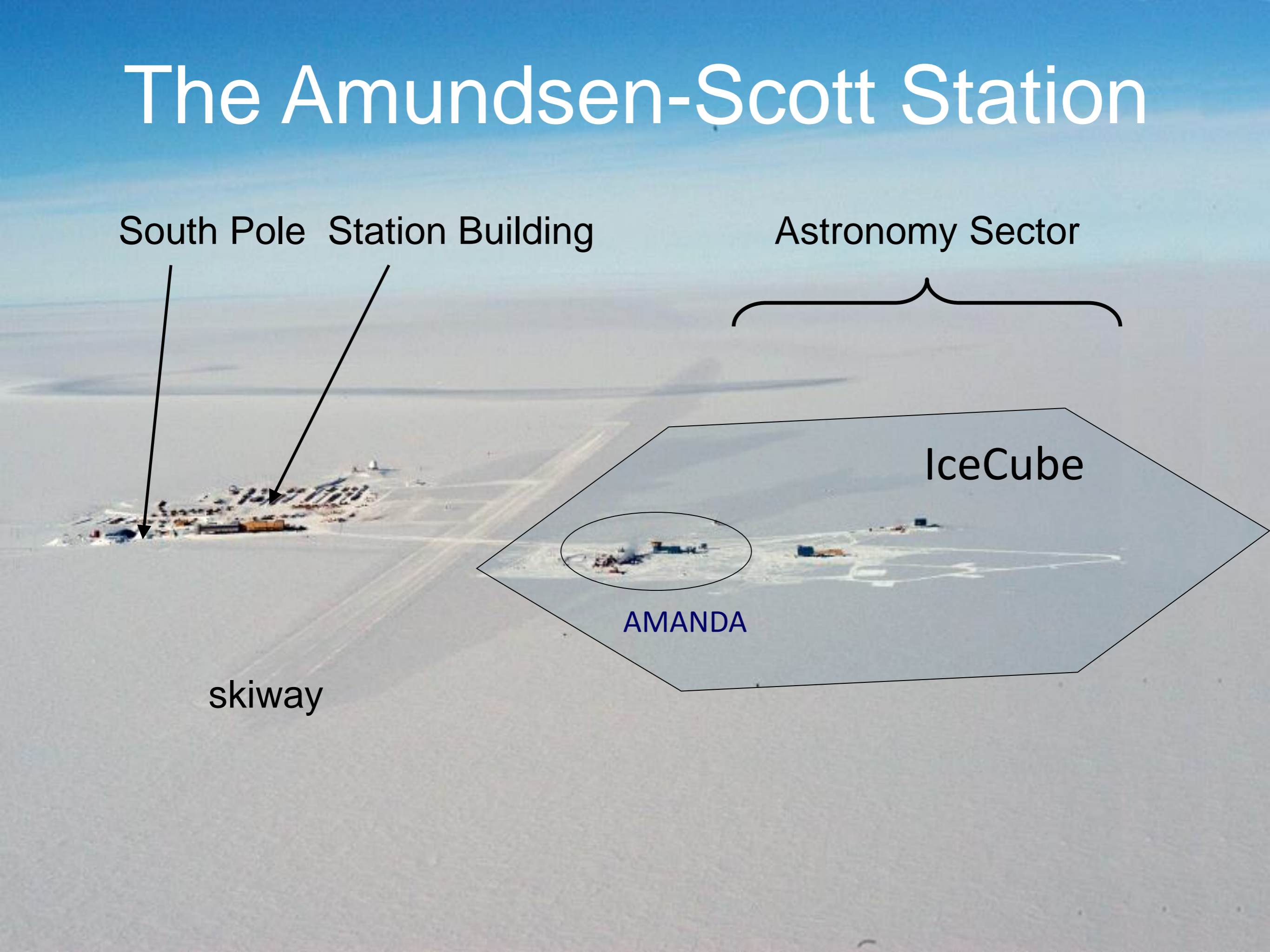
South Pole Station Building

Astronomy Sector

IceCube

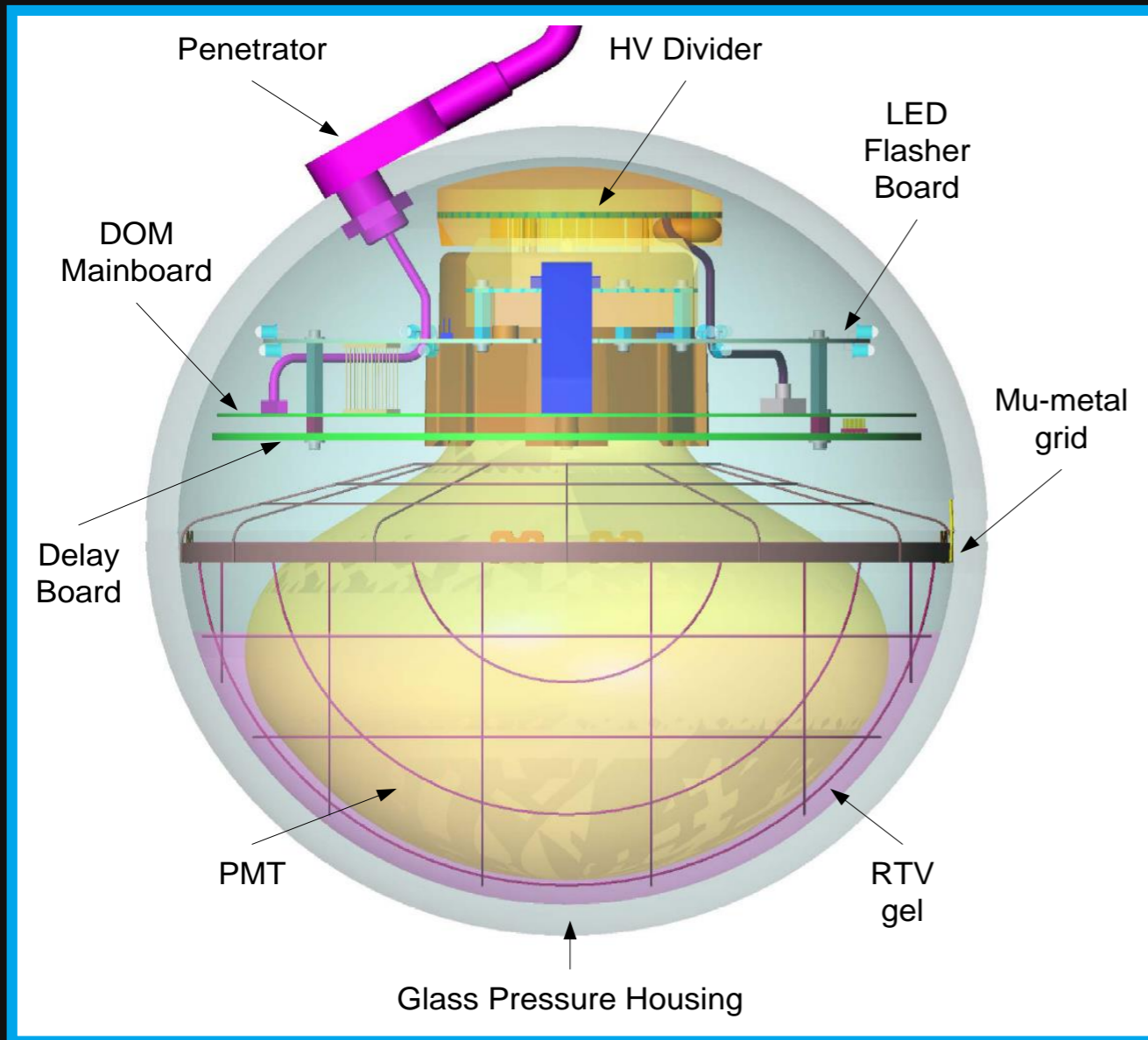
AMANDA

skiway





The Digital Optical Module (DOM)

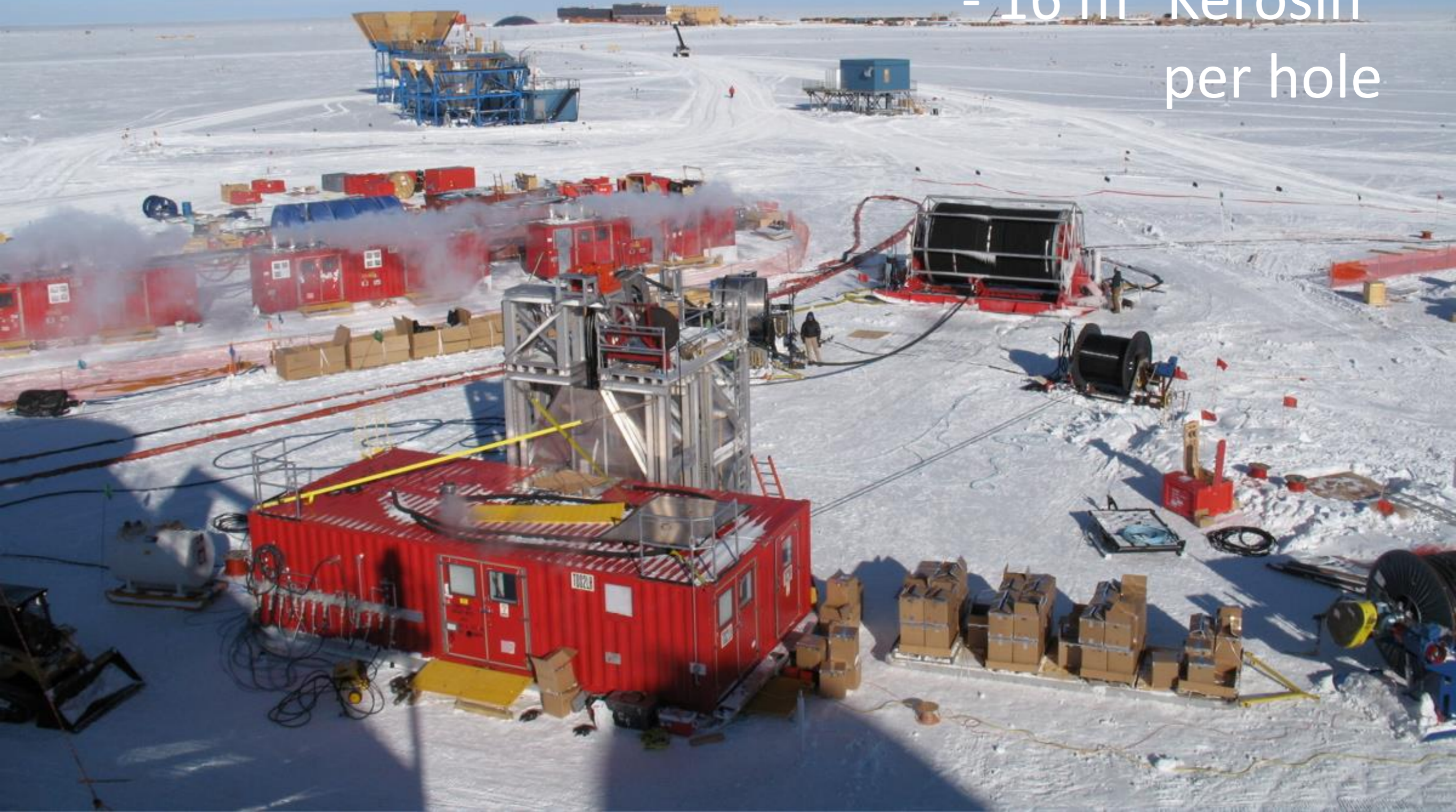


Failure rate ~ 1 DOM/year

(out of 5160 !)

The IceCube Drilling Camp

- 5 MW Power
- 16 m³ Kerosin per hole

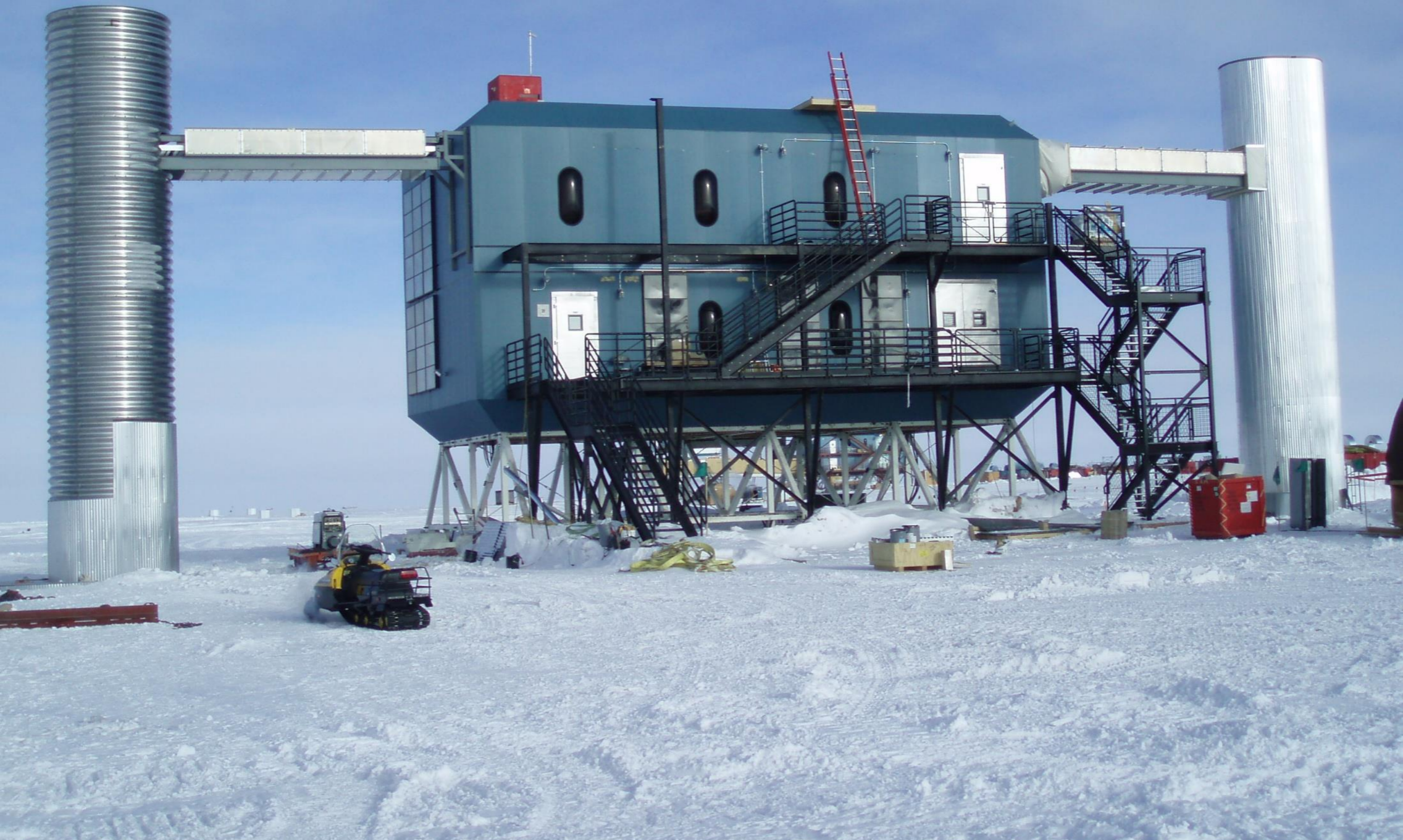




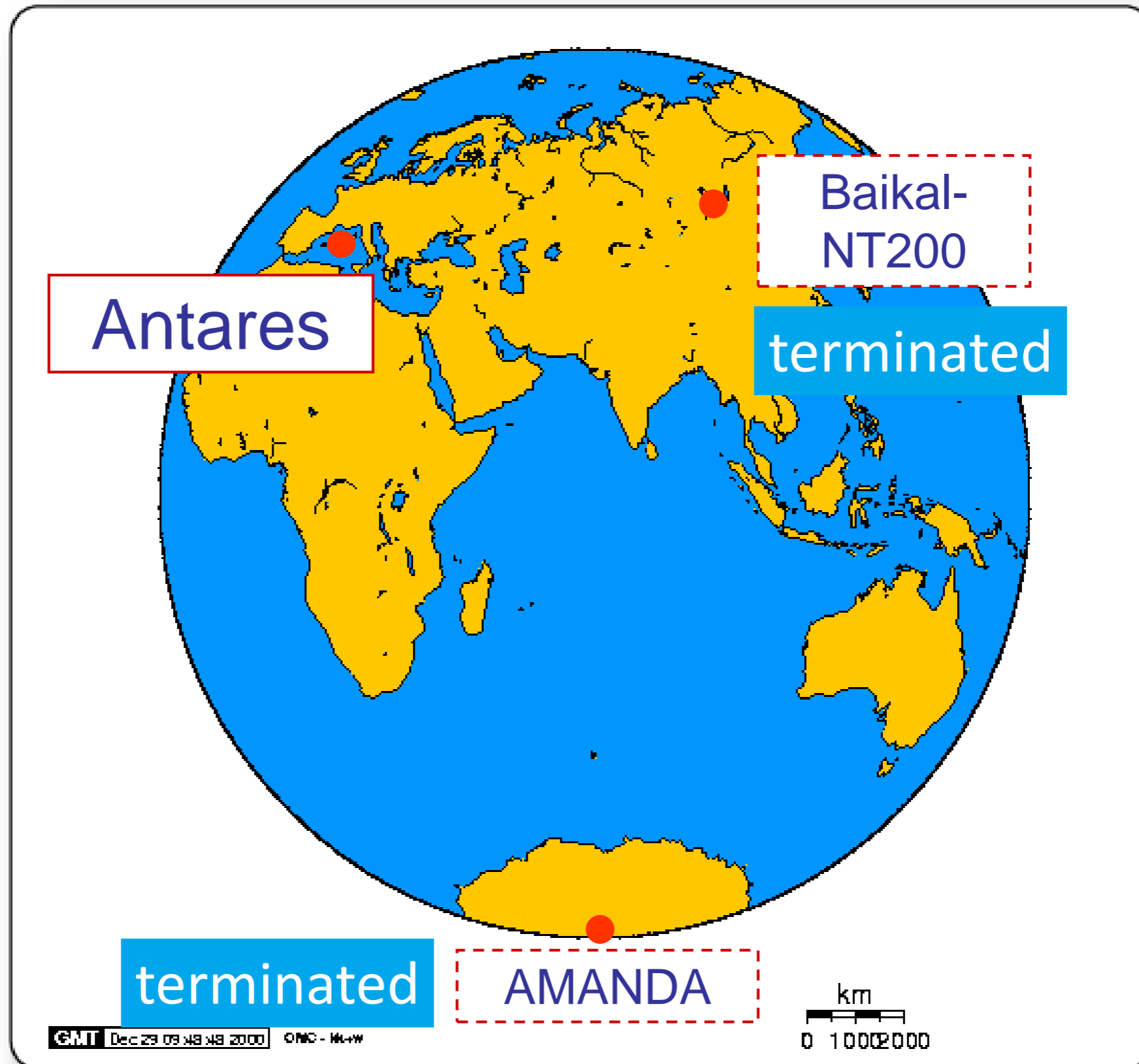


18.Dec. 2010: the last string

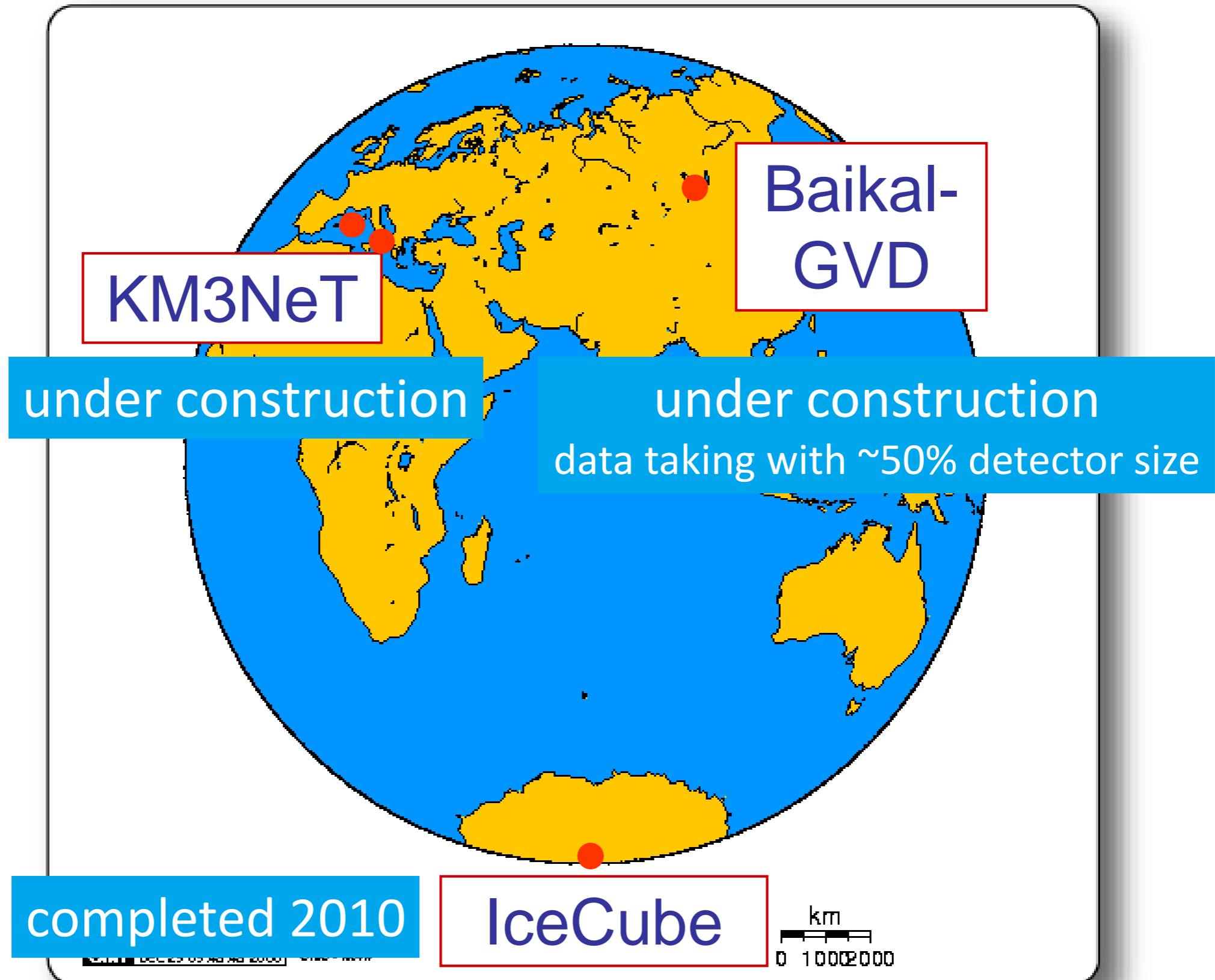
IceCube Laboratory and Data Center



Generation-1 devices (0.002-0.02 km³)



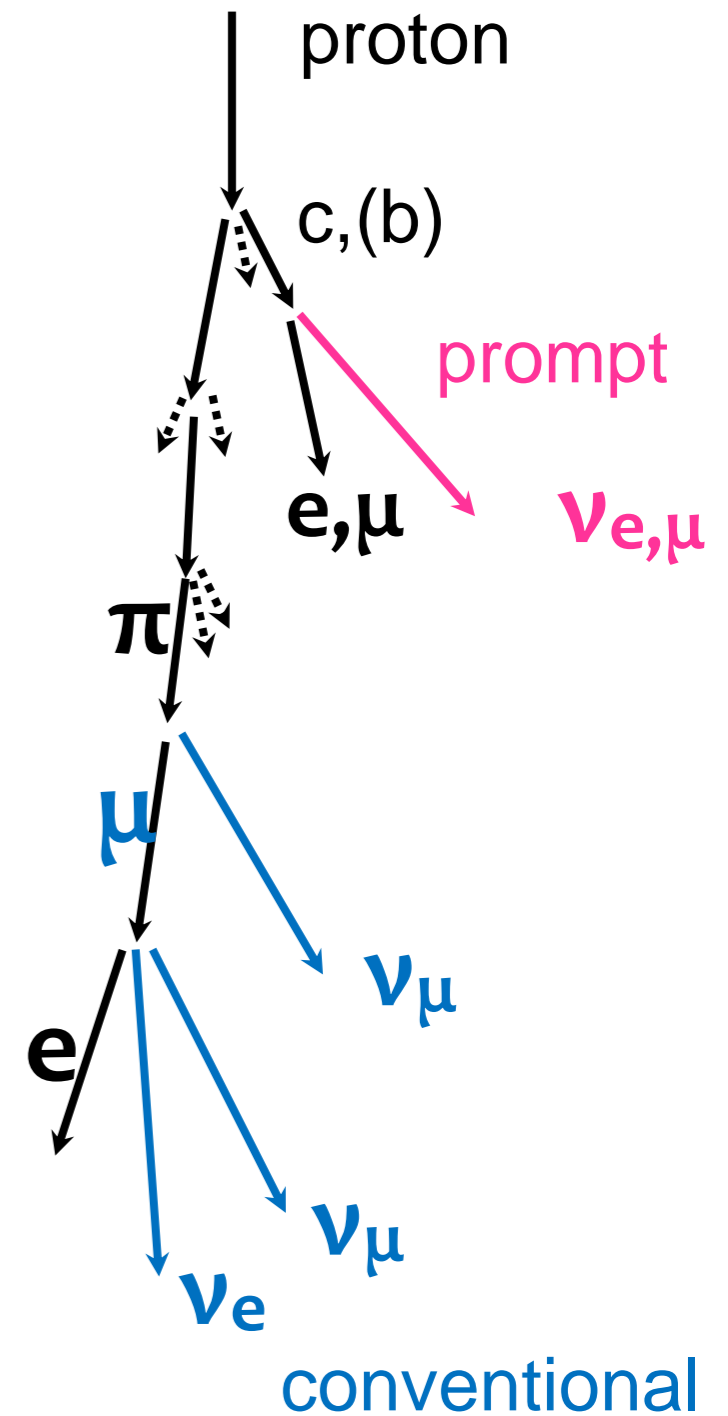
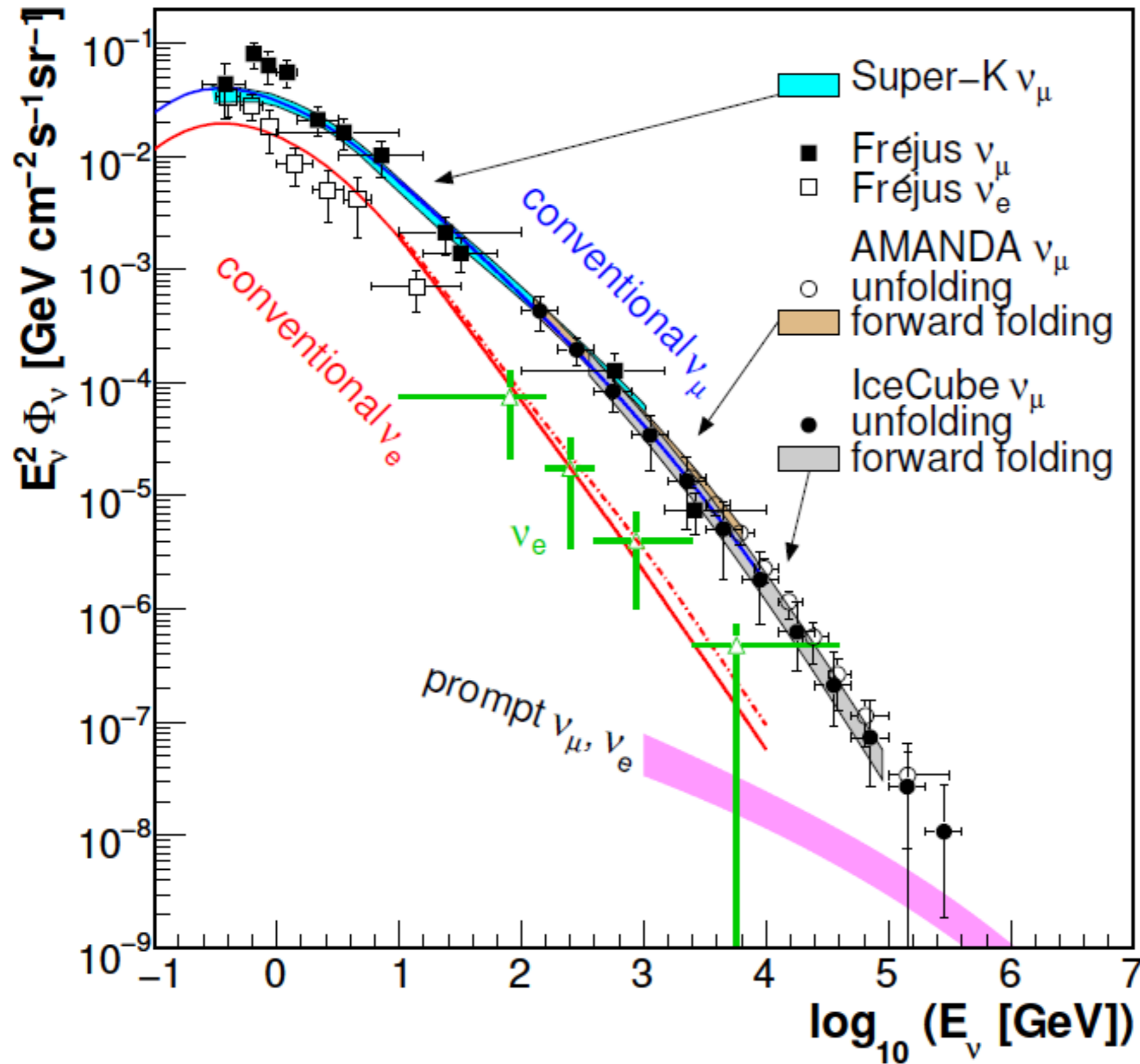
Generation-2 devices (km³ scale)



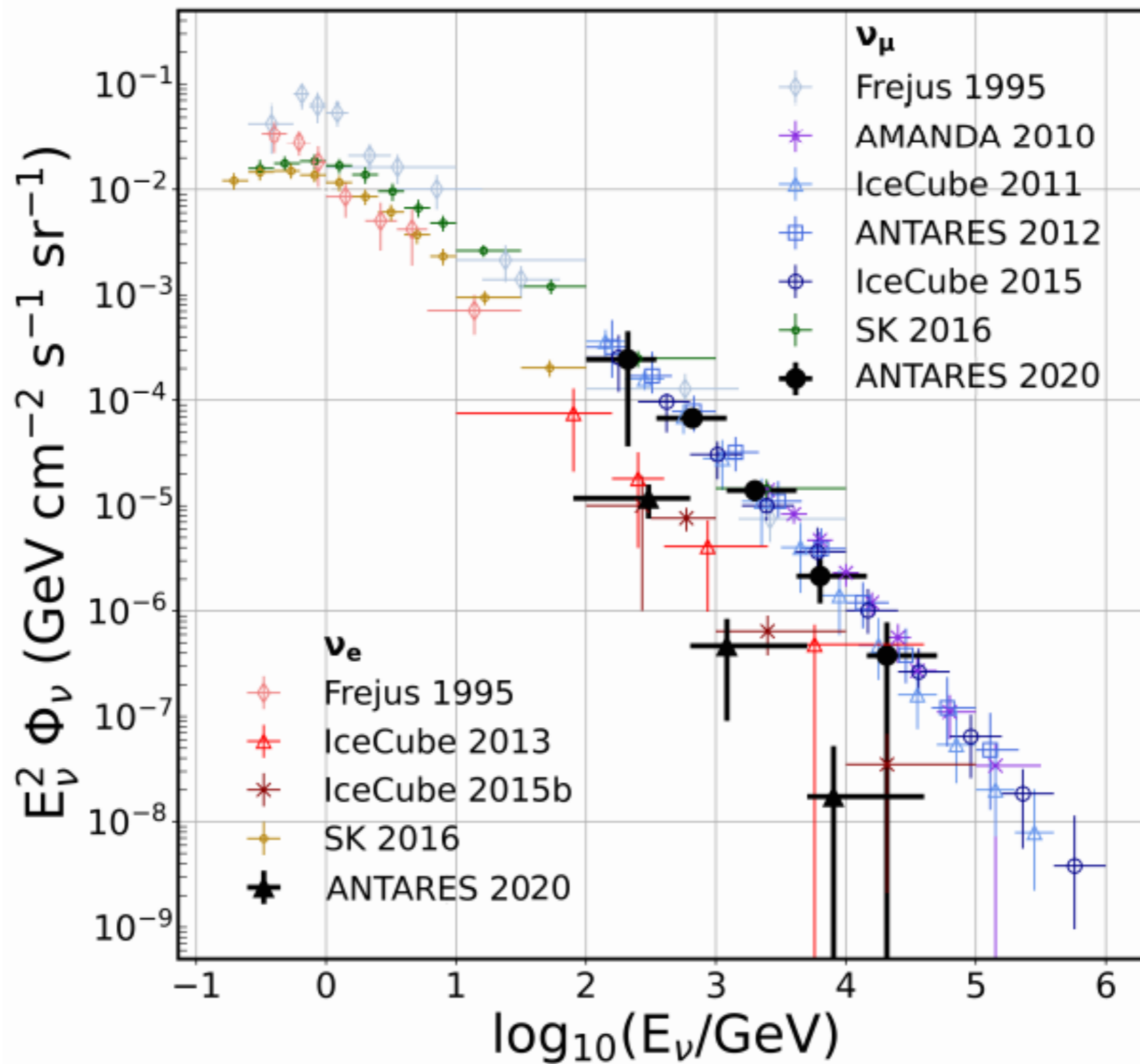
5.

Atmospheric neutrinos

Atmospheric neutrinos in IceCube (2 years)



Atmospheric neutrinos, IceCube + ANTARES



6.

Cosmic neutrinos

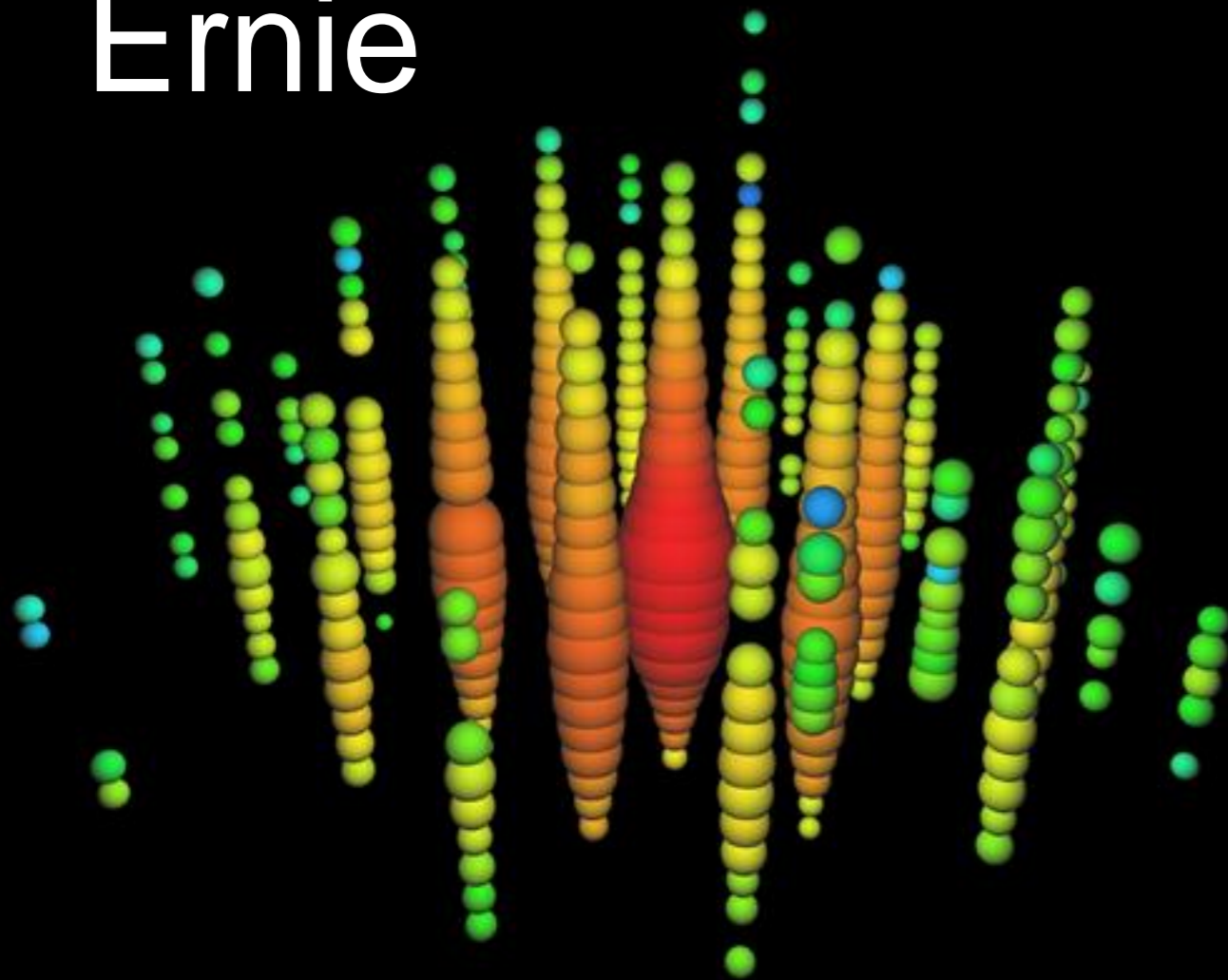
The Discovery of a Diffuse Cosmic Neutrino Flux

Special search for neutrinos with $E_\nu > 500$ TeV

IC79/IC86

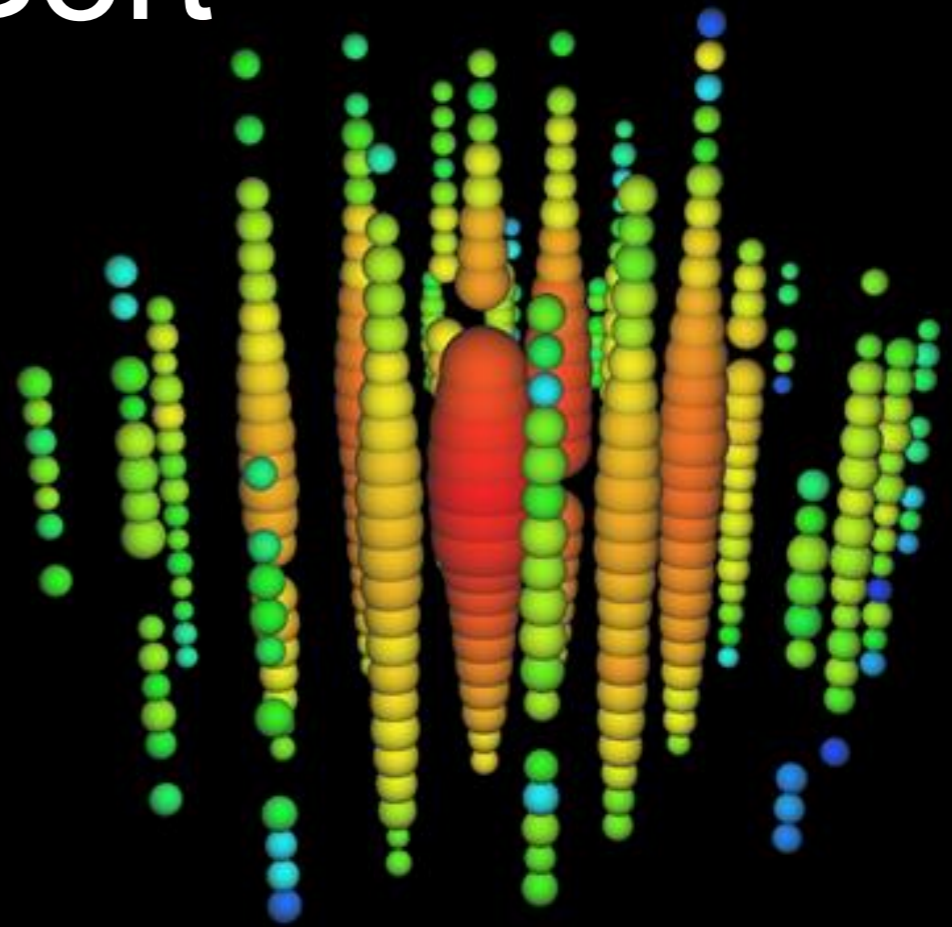
2.8 σ

Ernie



~ 1.04 PeV

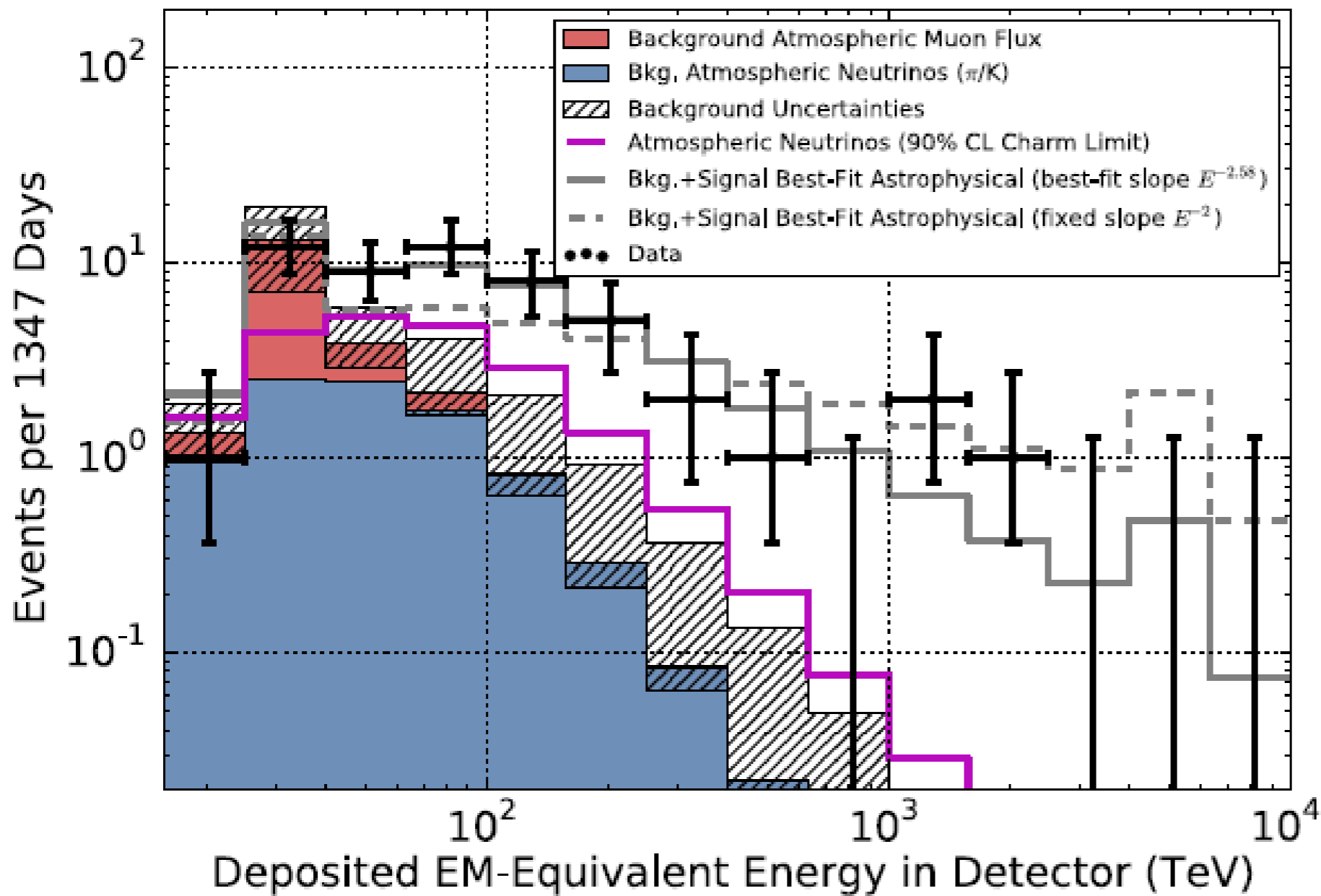
Bert



~ 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)

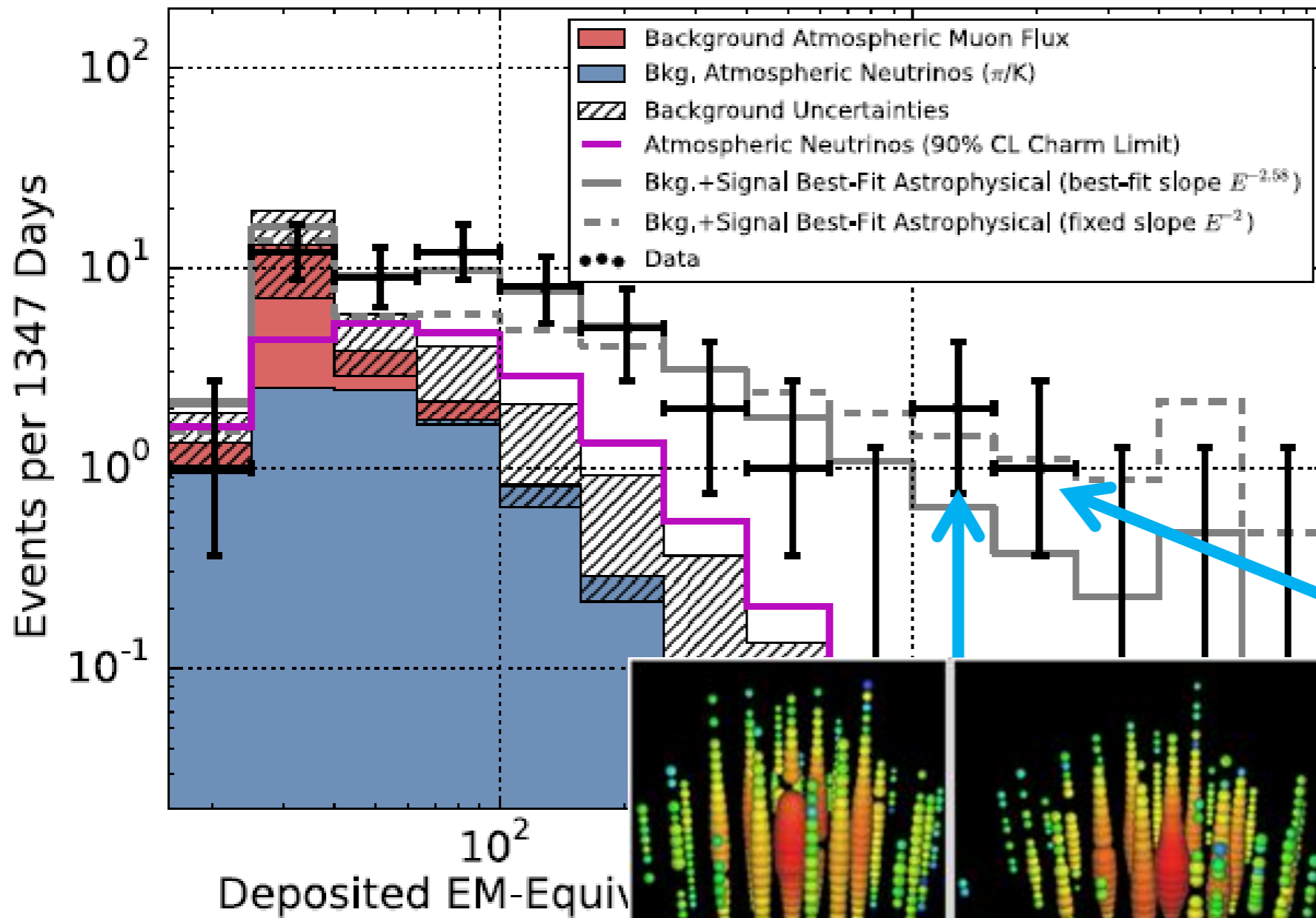
3 yrs data, 37 evts 5.9σ
Phys.Rev.Lett. 113:101101 (2014)

4 yrs data, 54 evts $\sim 7\sigma$

Threshold ~ 30 TeV

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

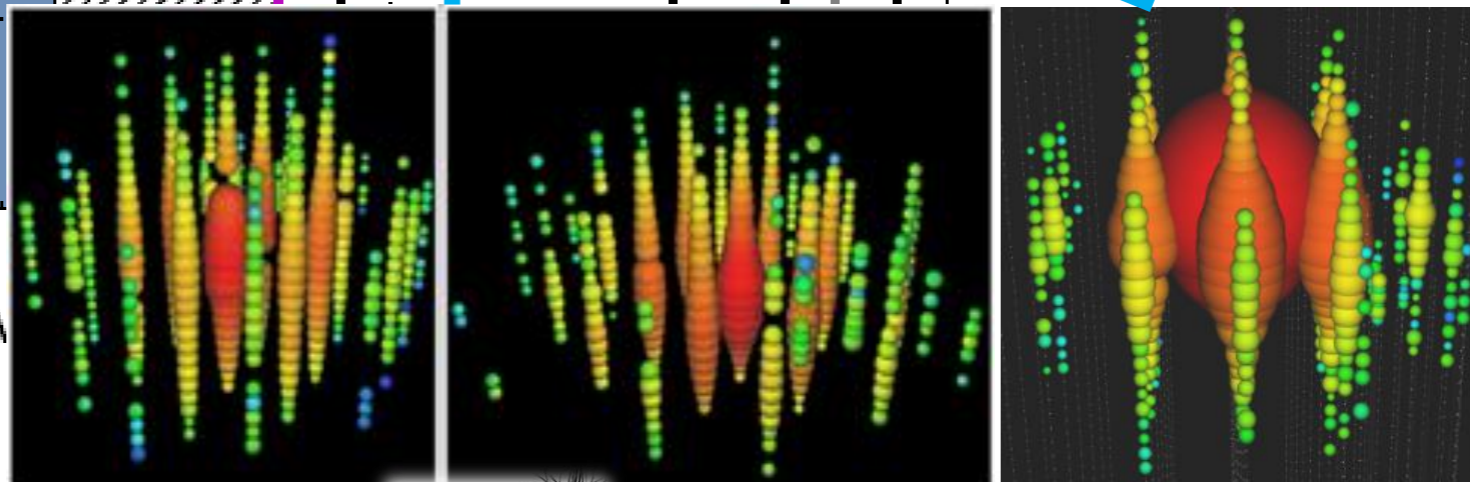
First evidence for an extra-terrestrial h.e. neutrino flux



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 $\sim \underline{7\sigma}$



"Bert"
1.04 PeV
Aug. 2011

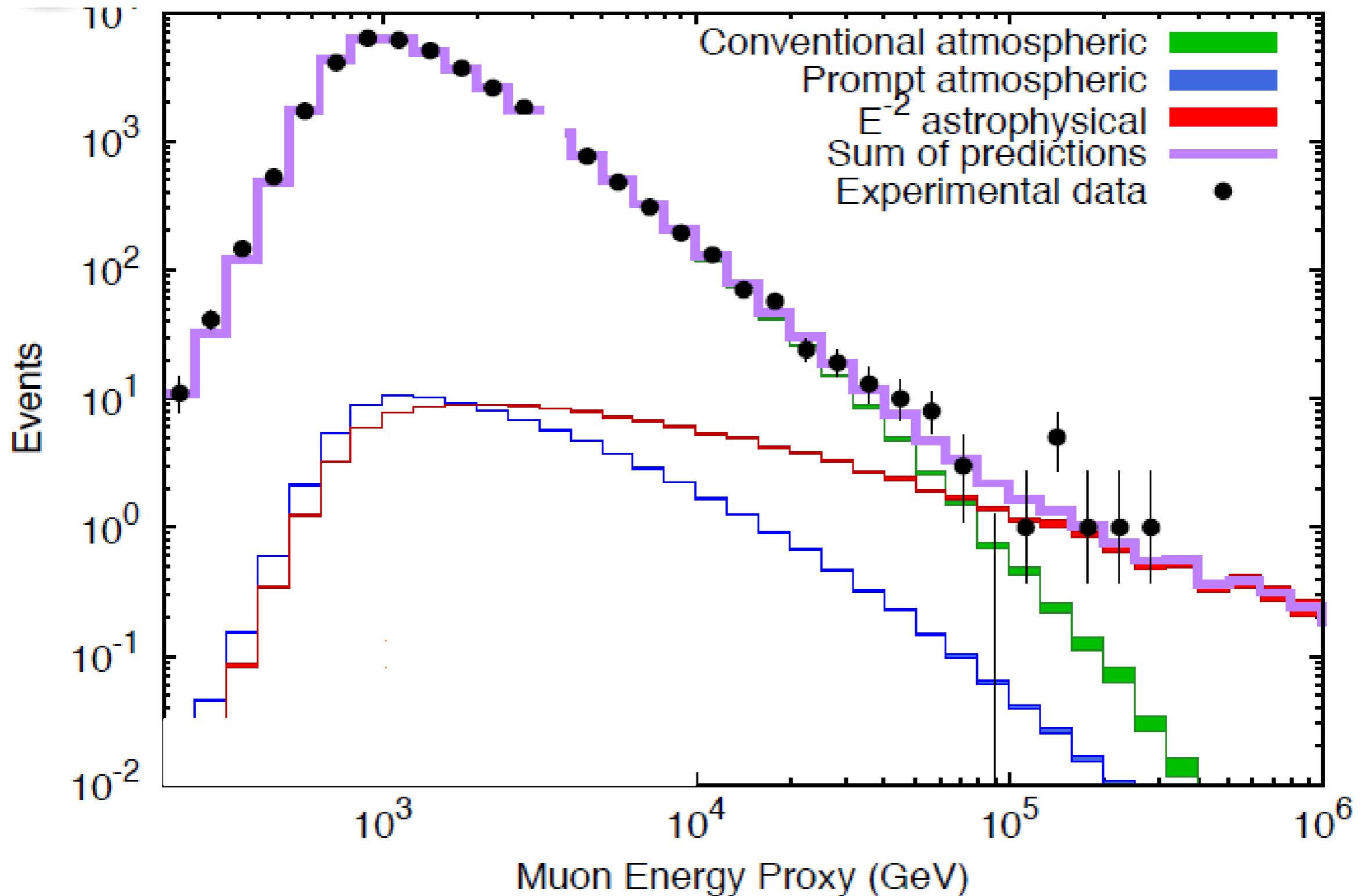


"Ernie"
1.14 PeV
Jan. 2012

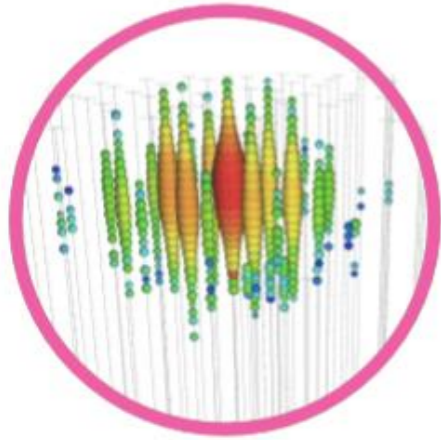


"Big Bird"
2 PeV
Dec. 2012

Through-going muons, IC-79/86

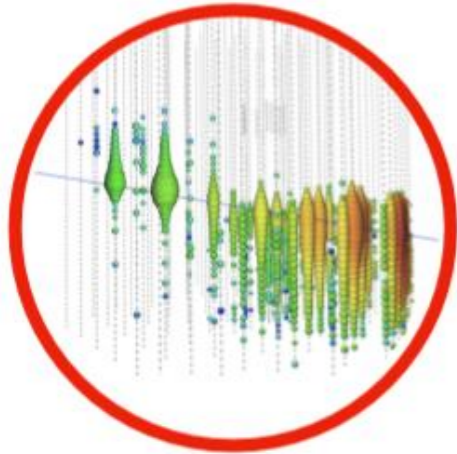


The Astrophysical Neutrino Flux



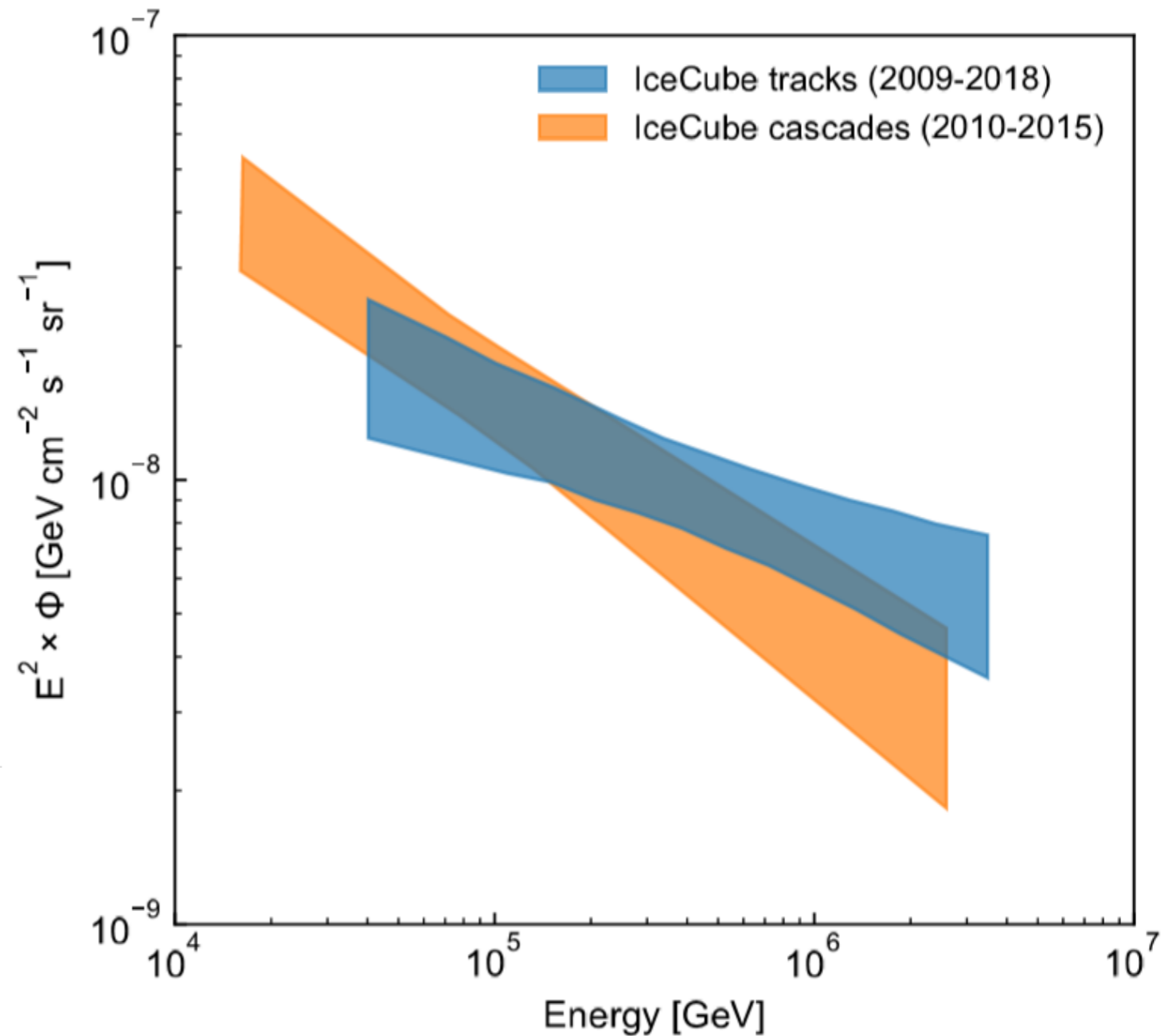
High-energy starting events (HESE)

Interaction vertex in the detector
All flavor, all sky

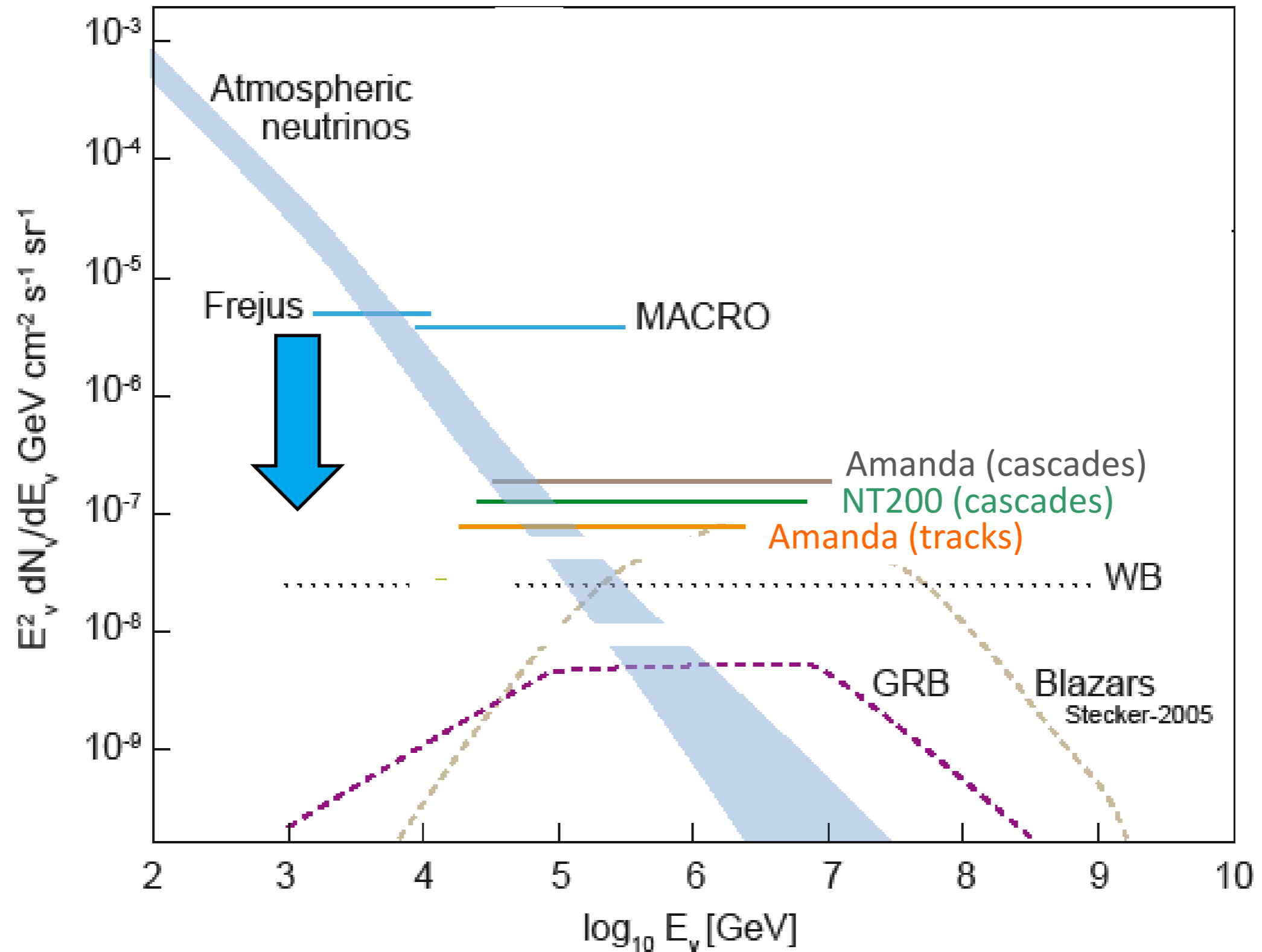


Up-going tracks

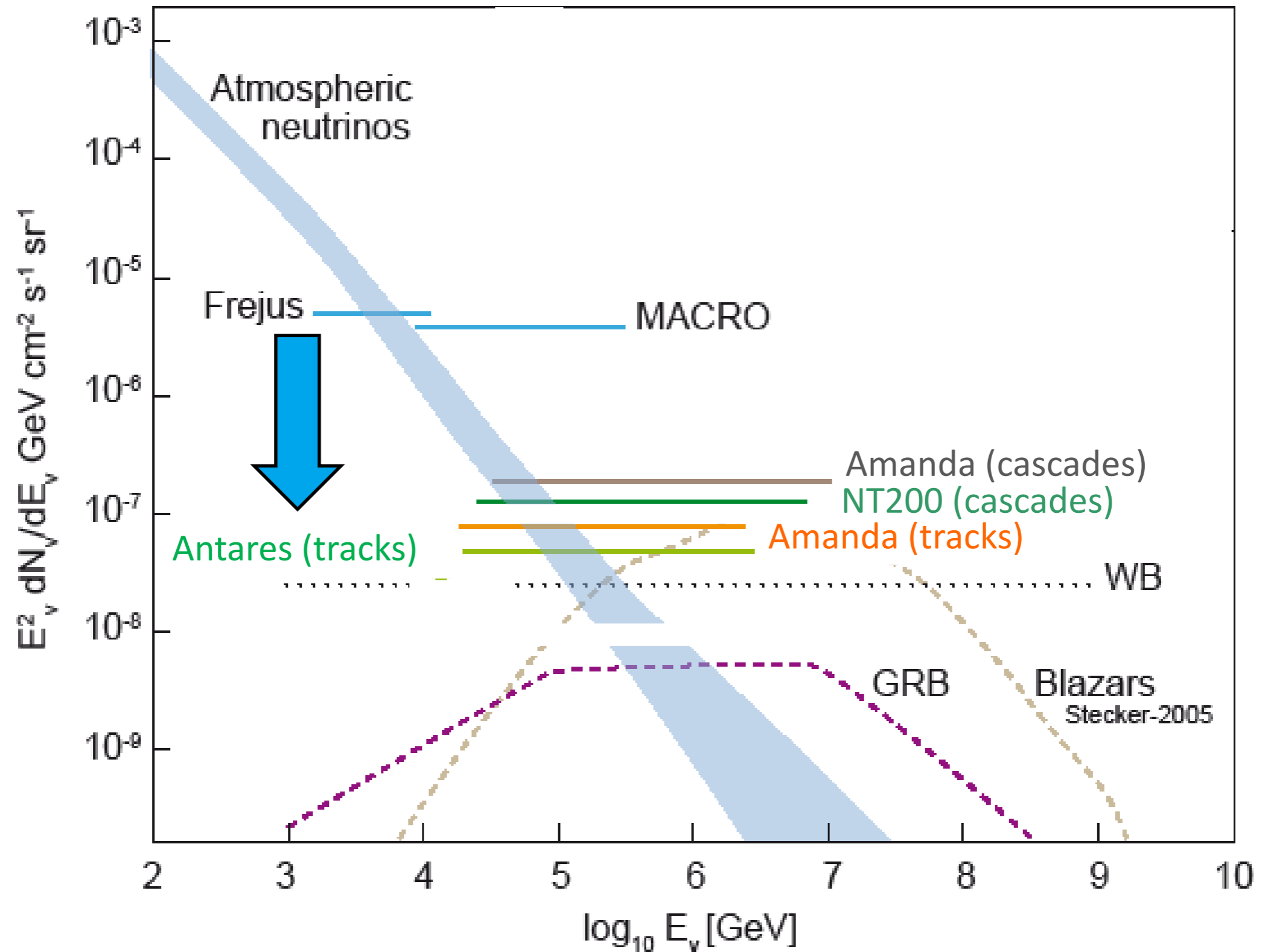
Muon-dominated
Northern sky



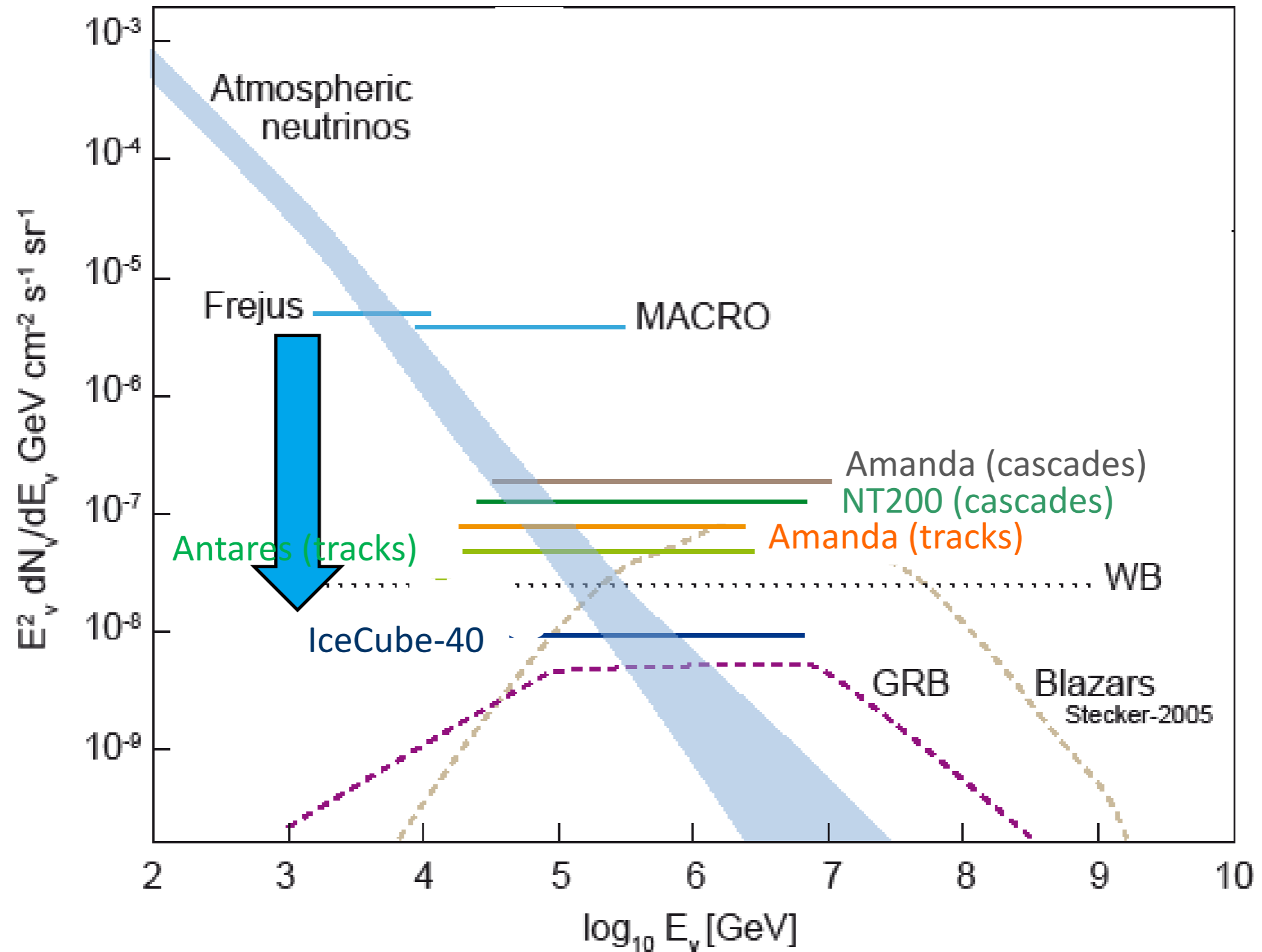
Limits on the diffuse flux (2003)



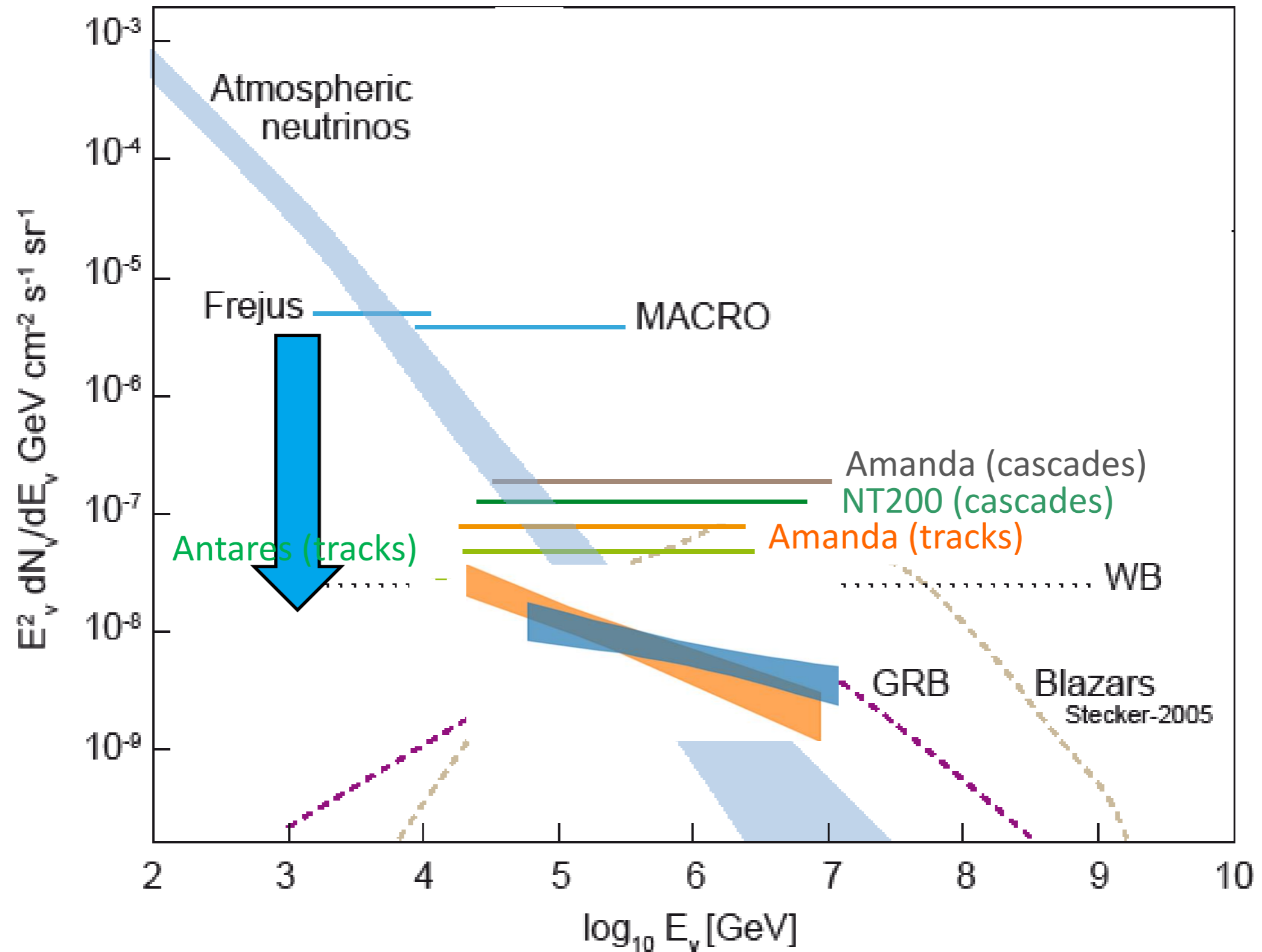
Limits on the diffuse flux (2007)



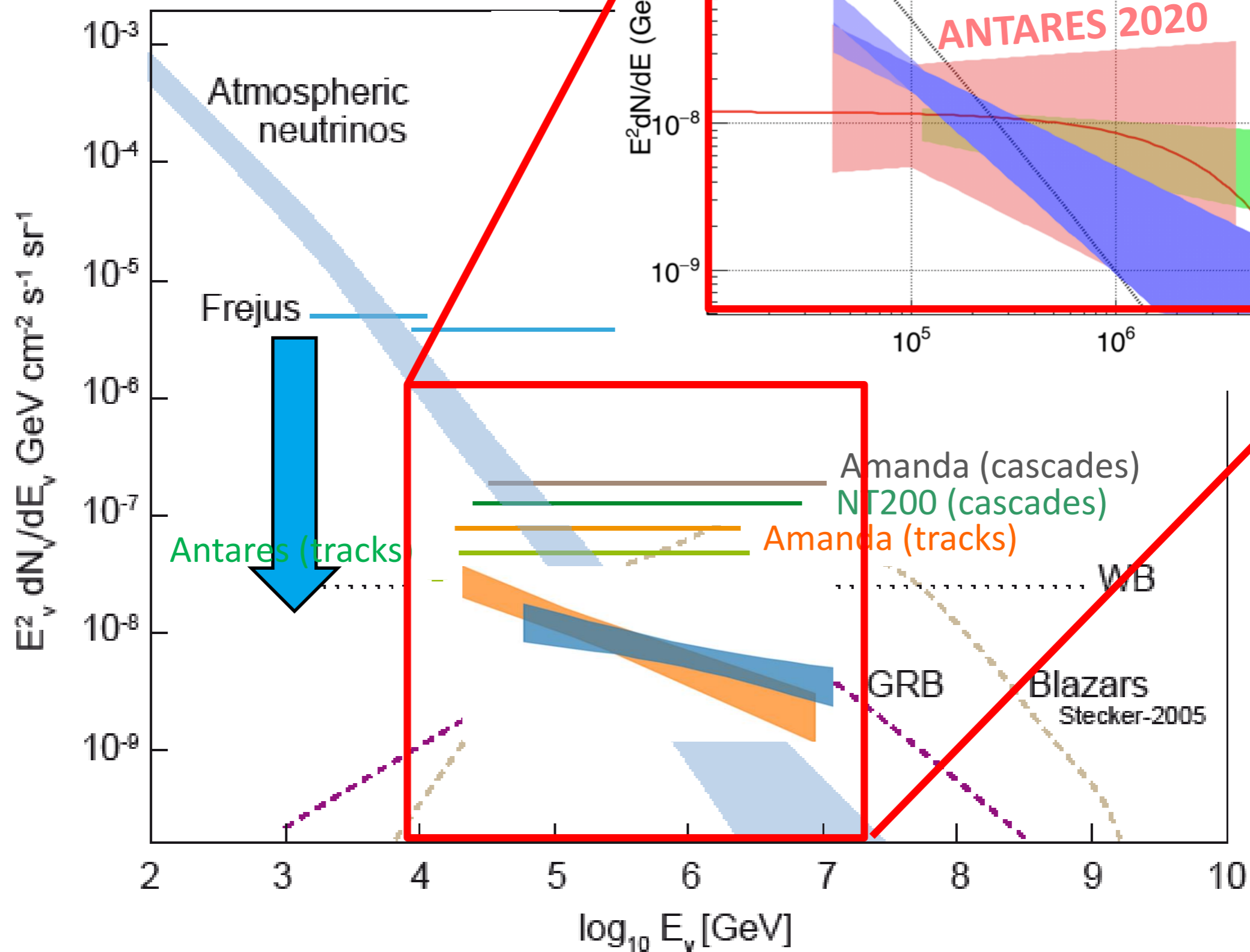
Limits on the diffuse flux (2008)



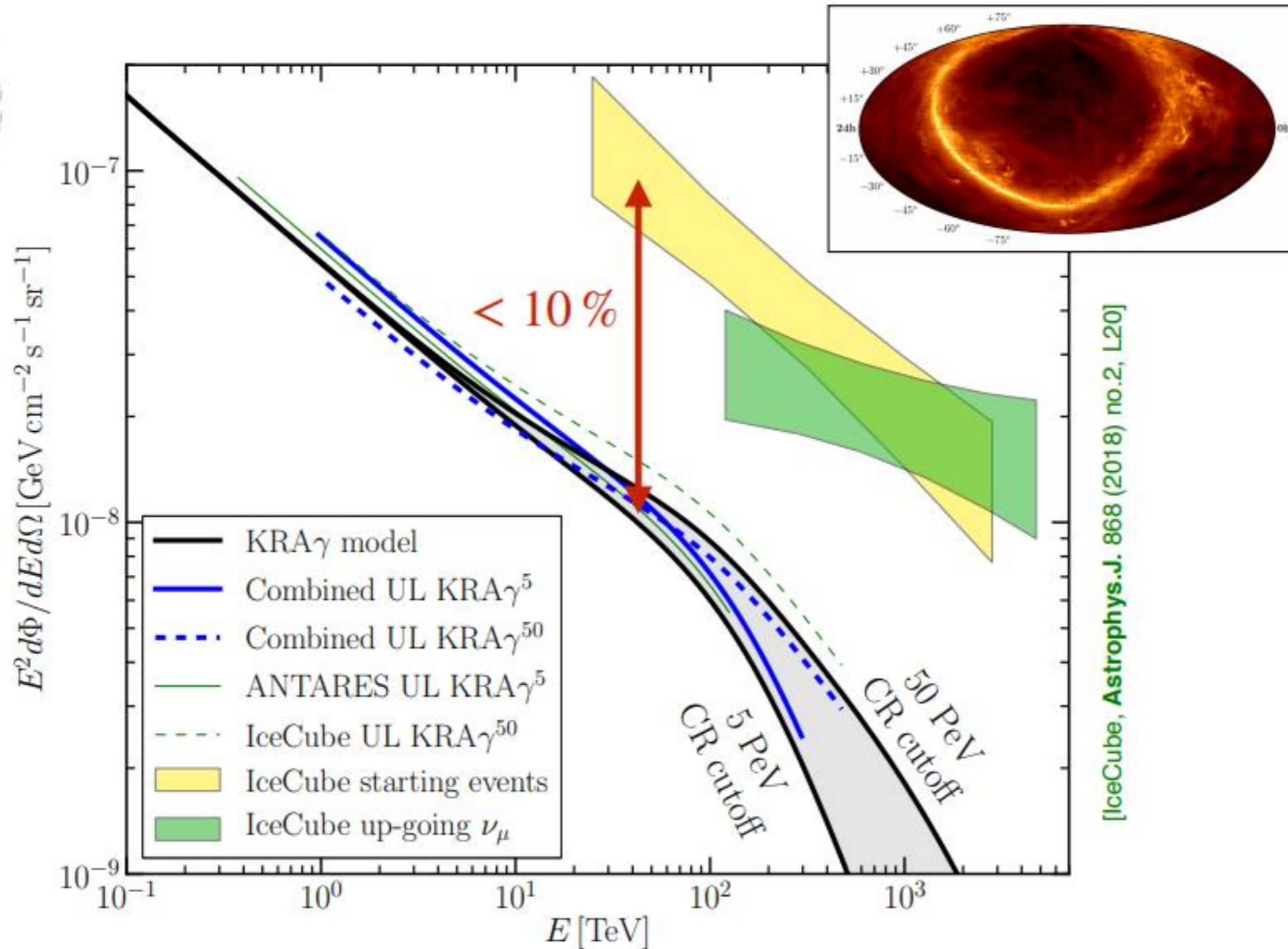
Size of the diffuse flux (2013-18)



Size of the diffuse flux



Galactic Neutrino Emission (quasi-diffuse)

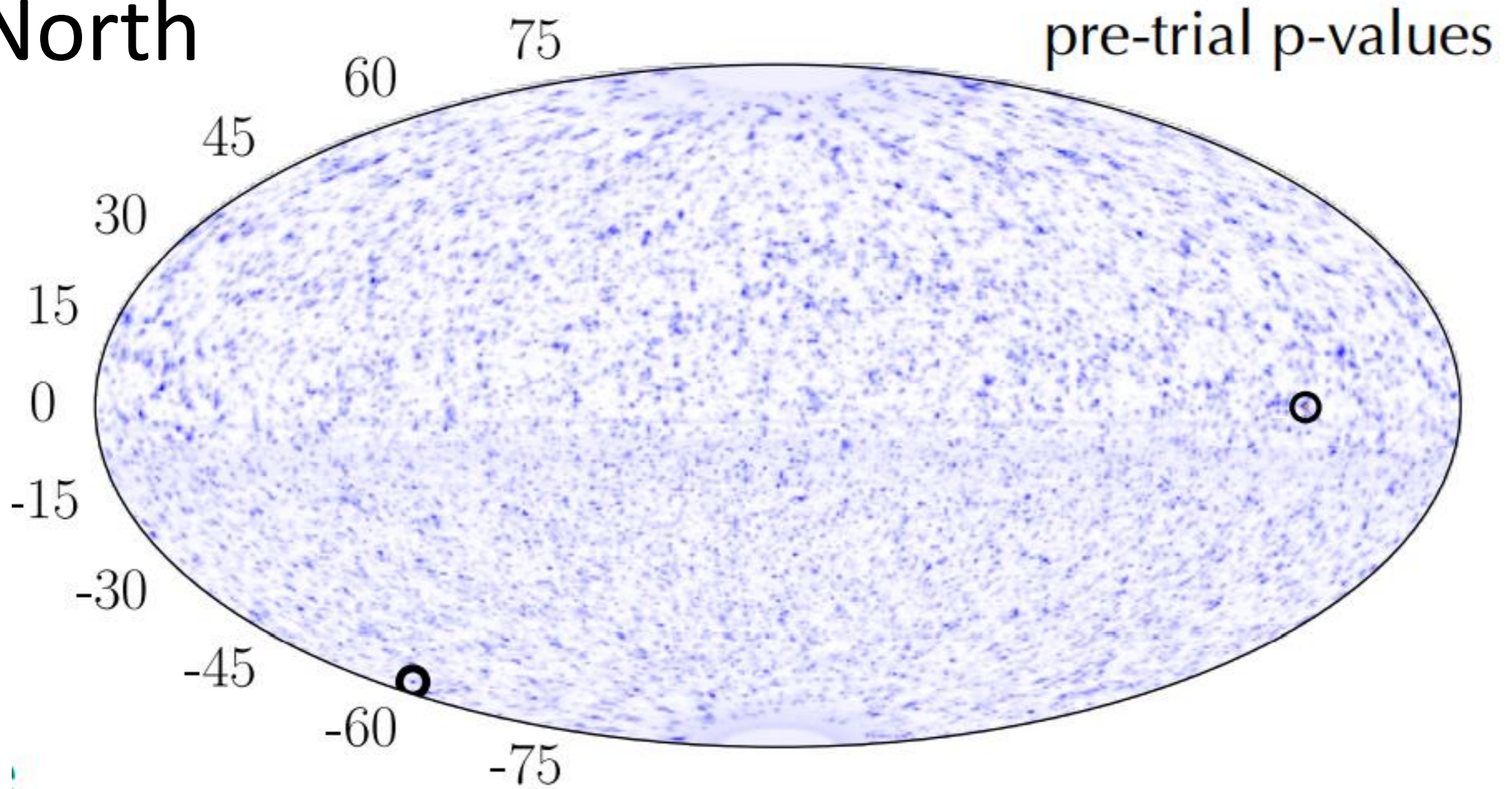


Contribution of Galactic diffuse emission at 10TeV-PeV is subdominant.

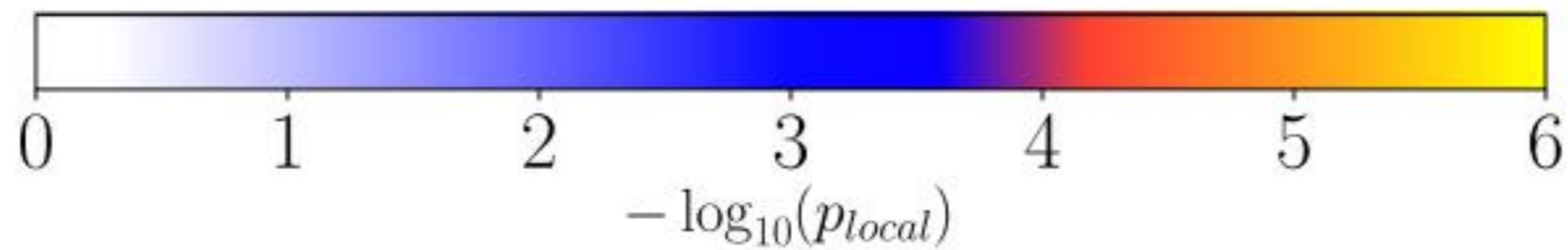
Individual Sources and Source Classes

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

North

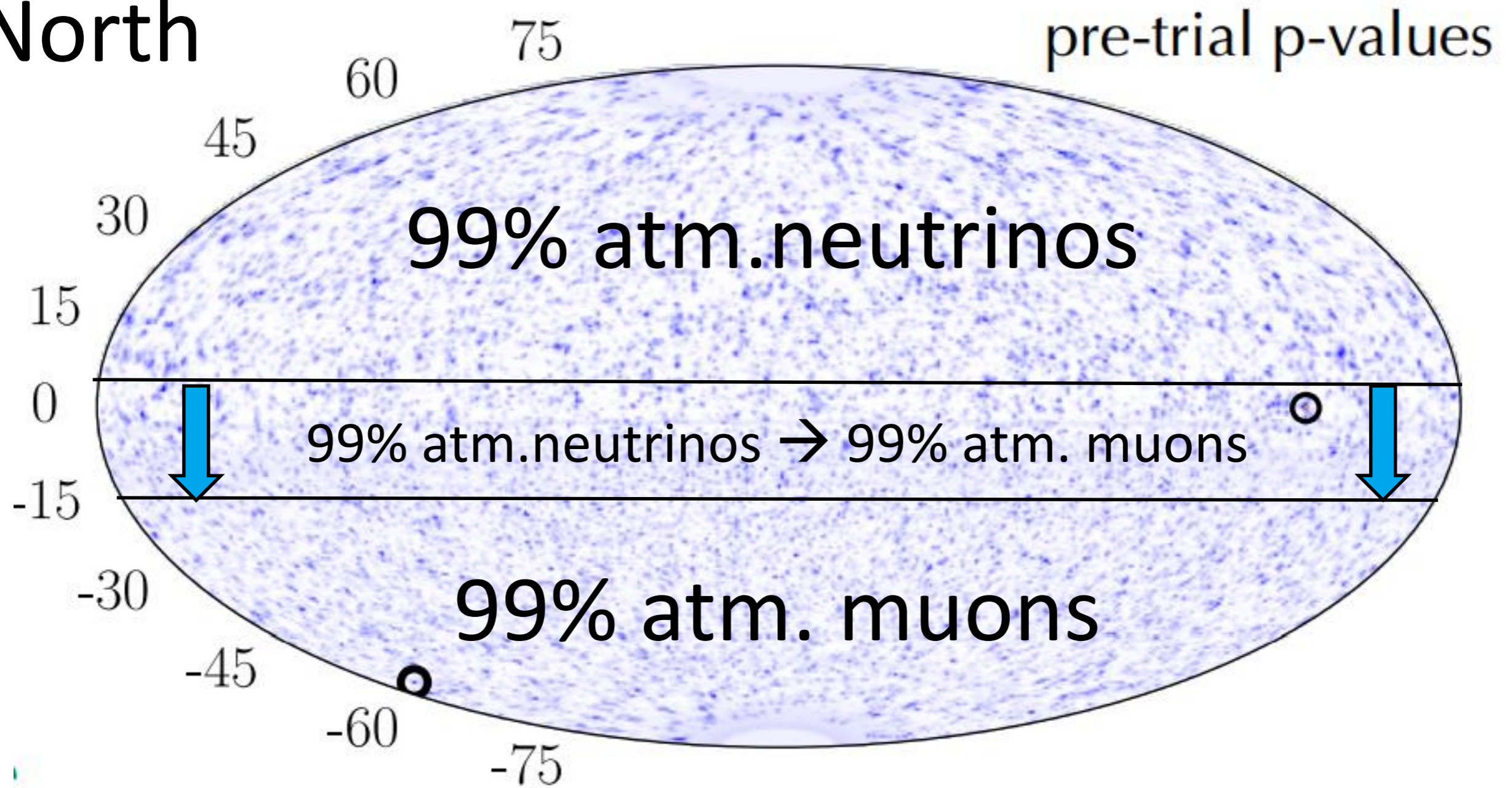


South

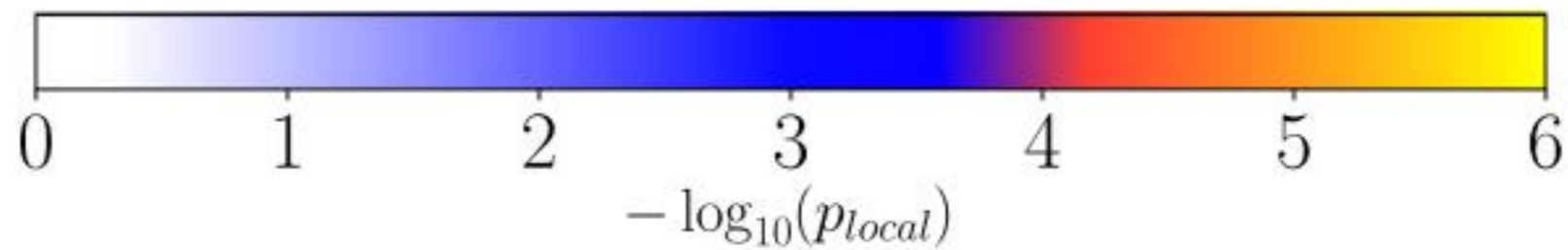


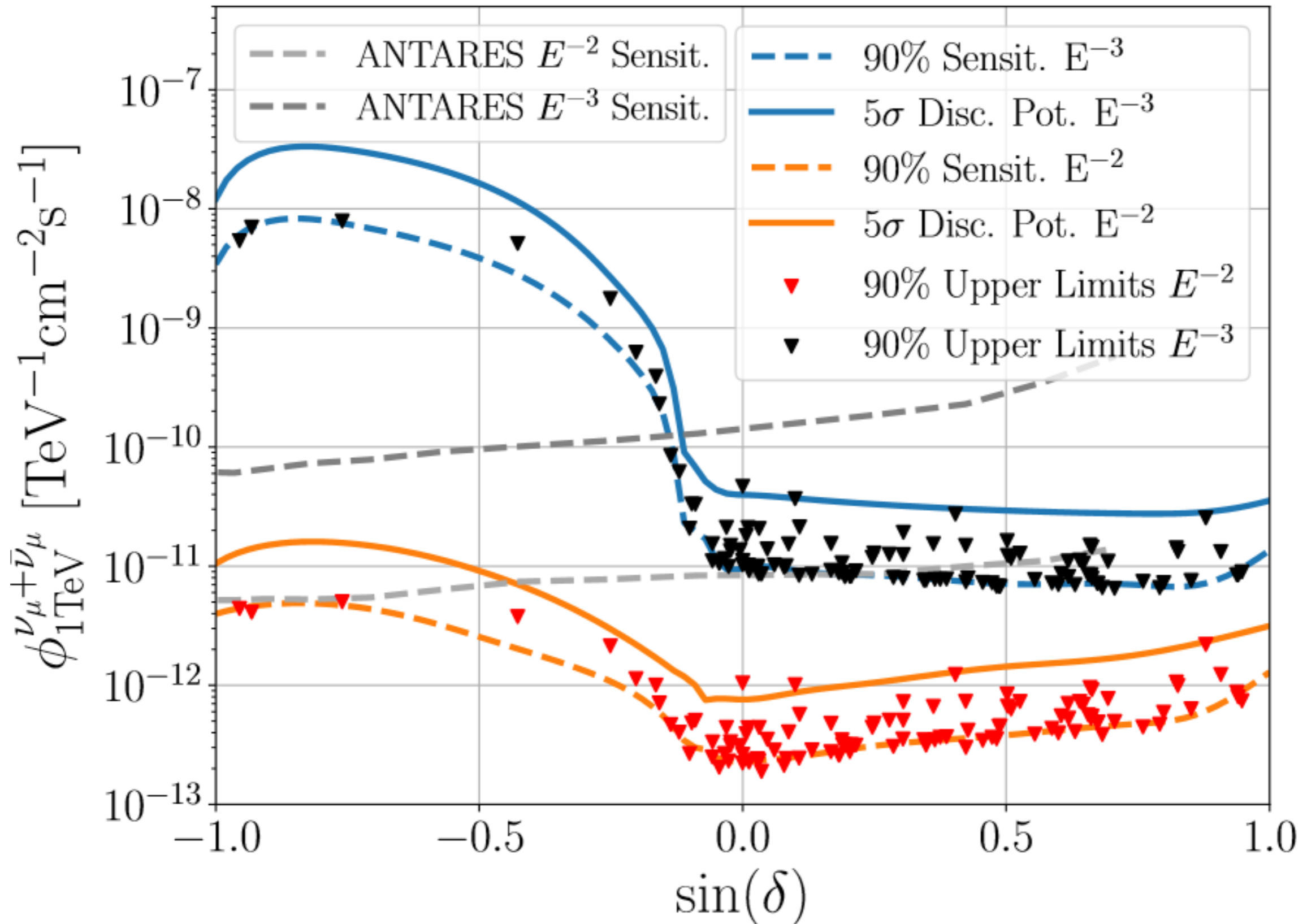
Skymap: significance map of ν (North) and μ (South)

North



South



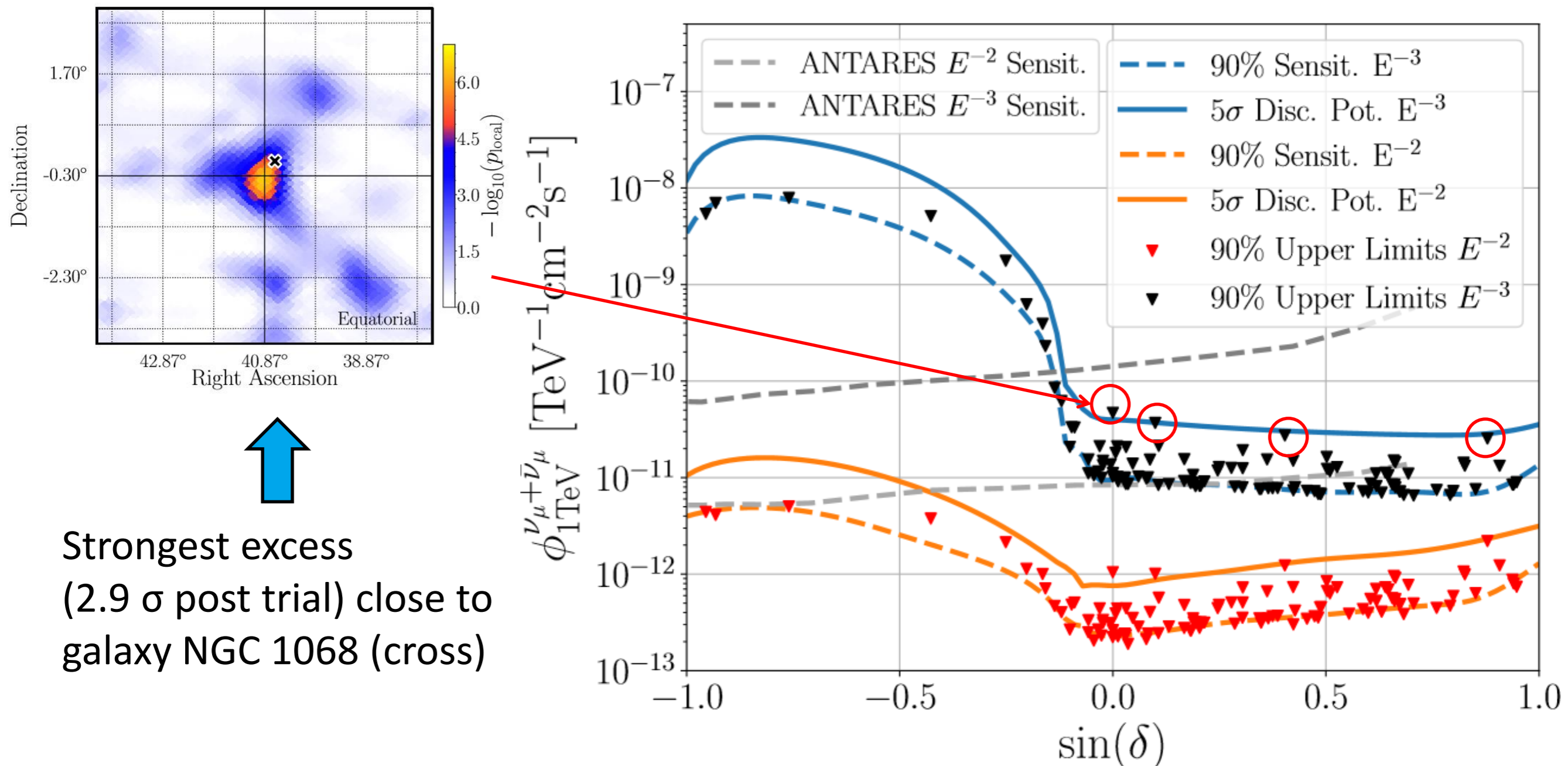


IceCube, 10 years

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.

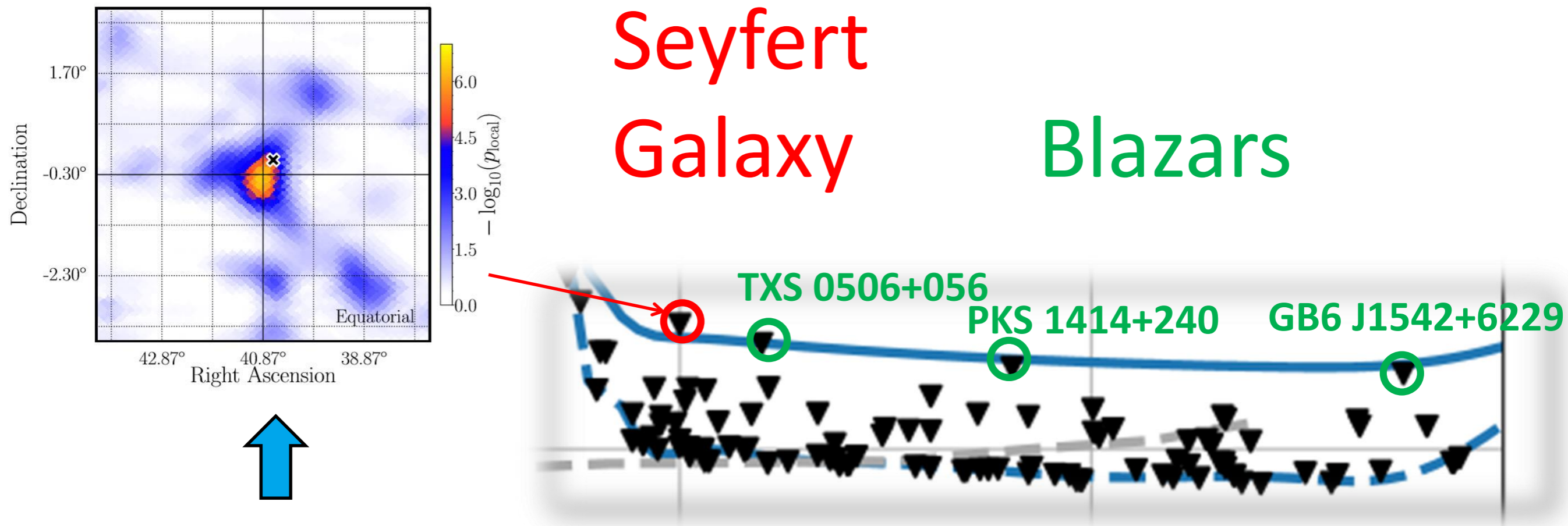


IceCube, 10 years

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.



Seyfert
Galaxy

Blazars

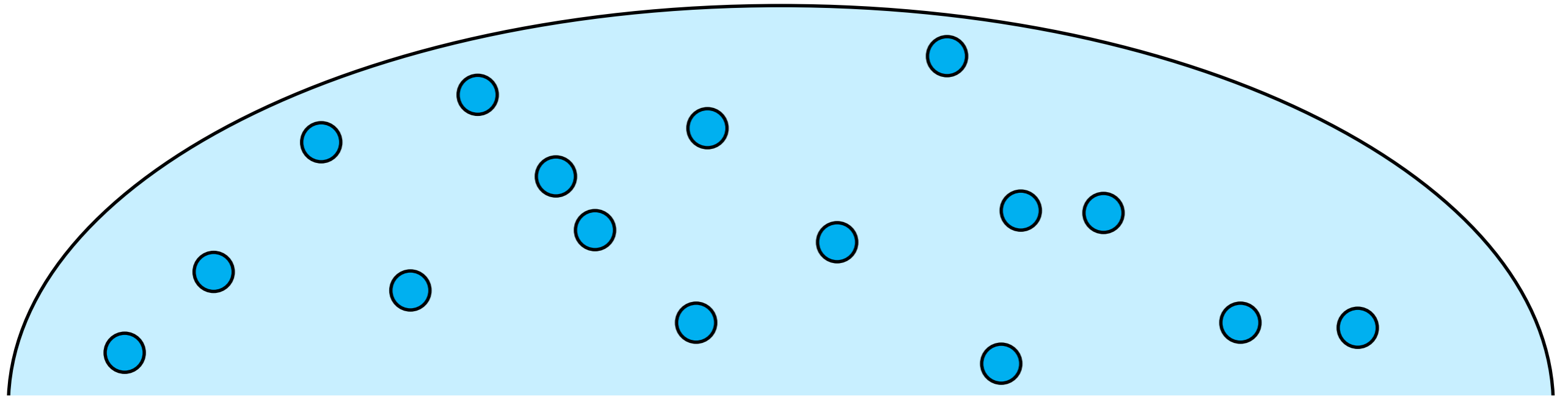
TXS 0506+056

PKS 1414+240

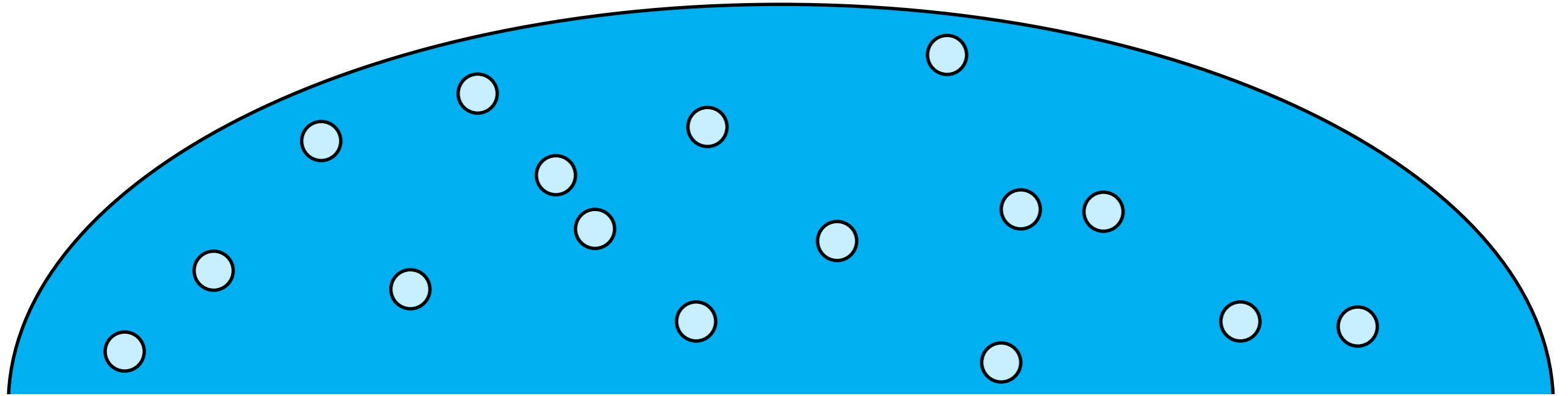
GB6 J1542+6229

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

Source Classes: stacking searches



Source Classes: stacking searches



Source Classes: stacking searches

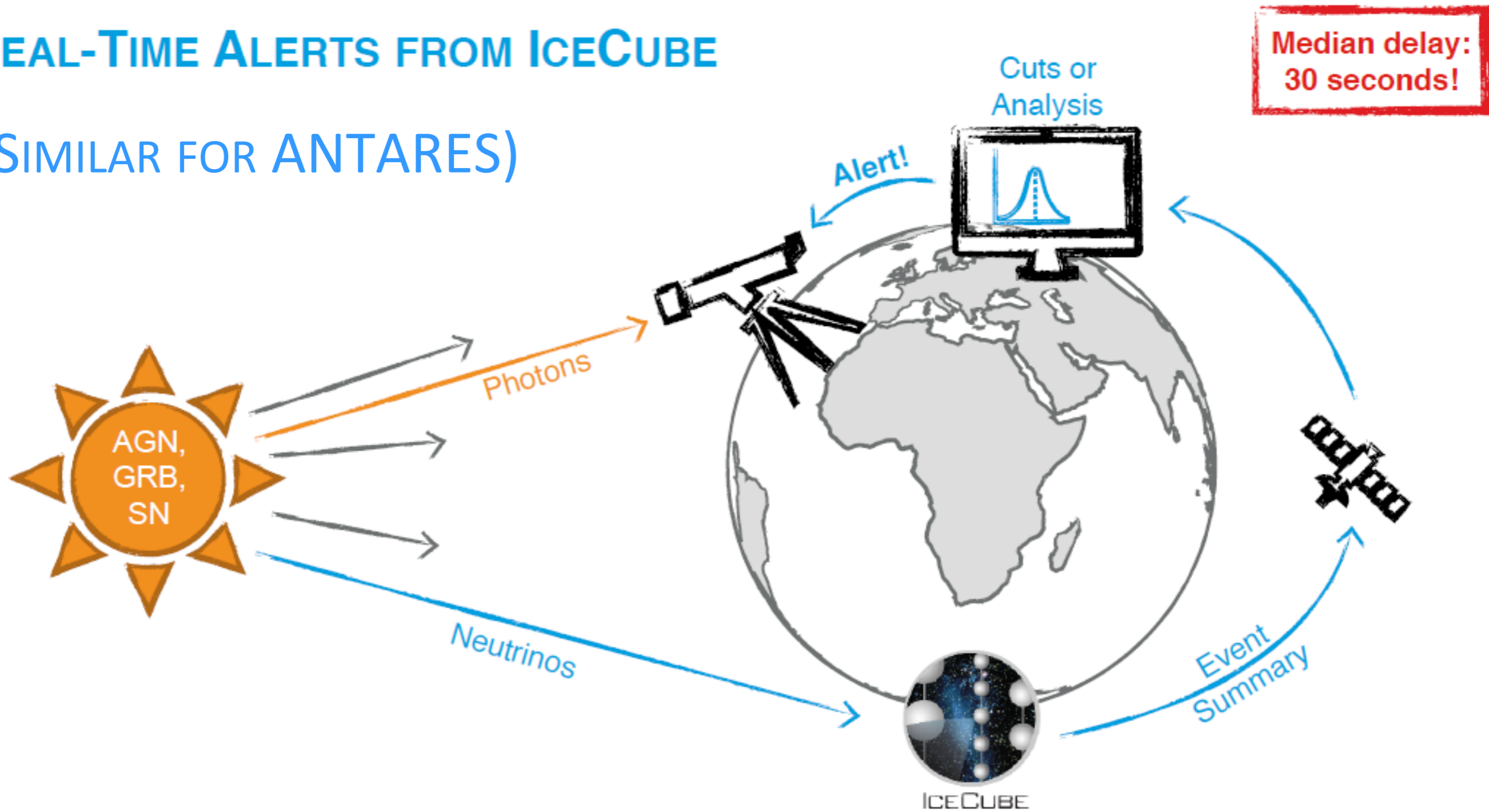
- Blazars → Cannot contribute with more than ~15 % to the diffuse flux (but: 3 promising candidates!)
- Radio-loud Blazars → some (controversial) indications
- Gamma-loud Blazars → upper limits
- Flat spectrum radio quasars (FSRQs) → upper limits
- X-ray Active Galaxies → upper limits
- Gamma Ray Bursts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

Multi-Messenger Results

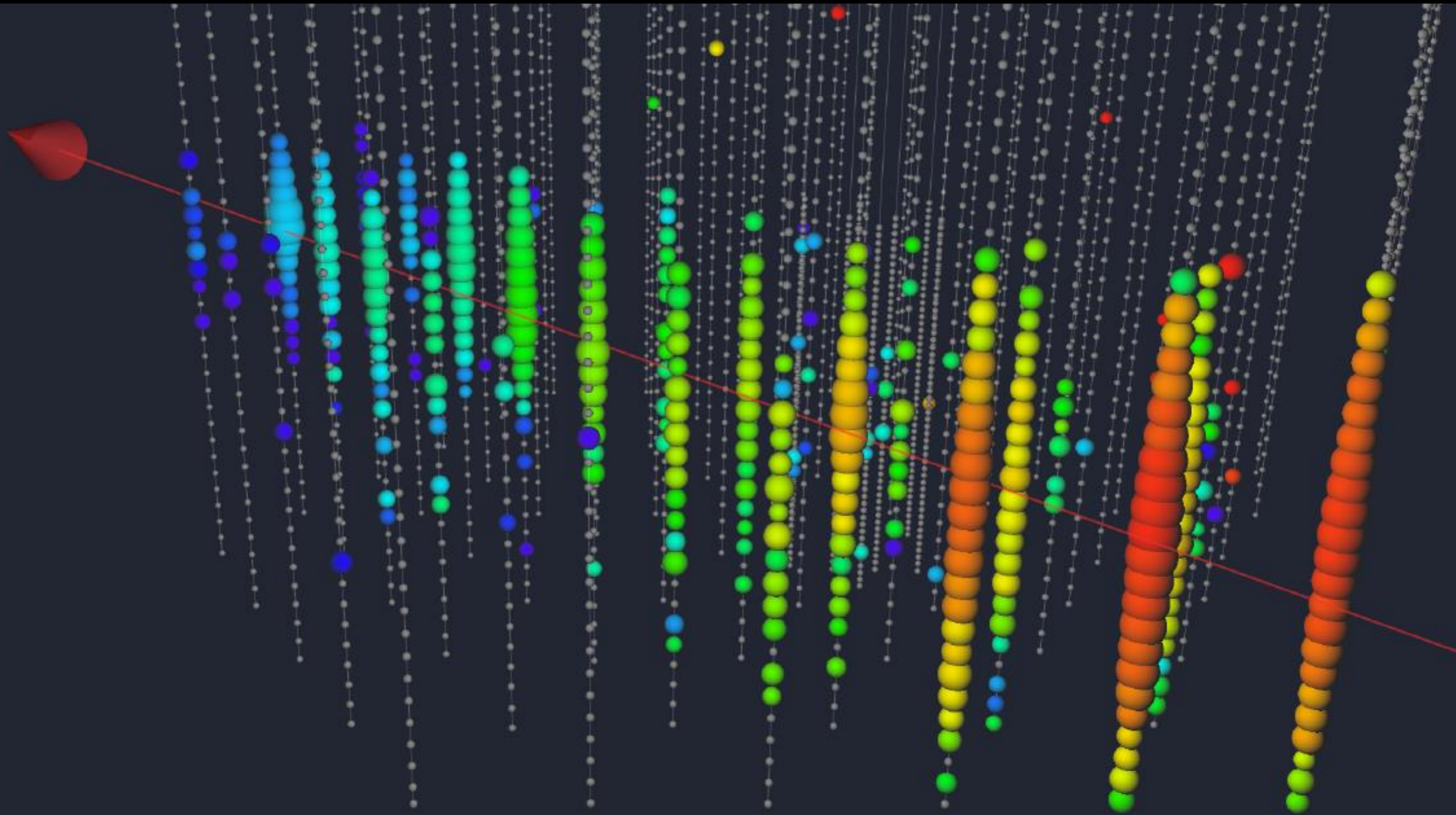
Alerts to optical, radio and gamma-ray telescopes and to x-ray detectors on satellites

REAL-TIME ALERTS FROM ICECUBE

(SIMILAR FOR ANTARES)



The first point source candidate



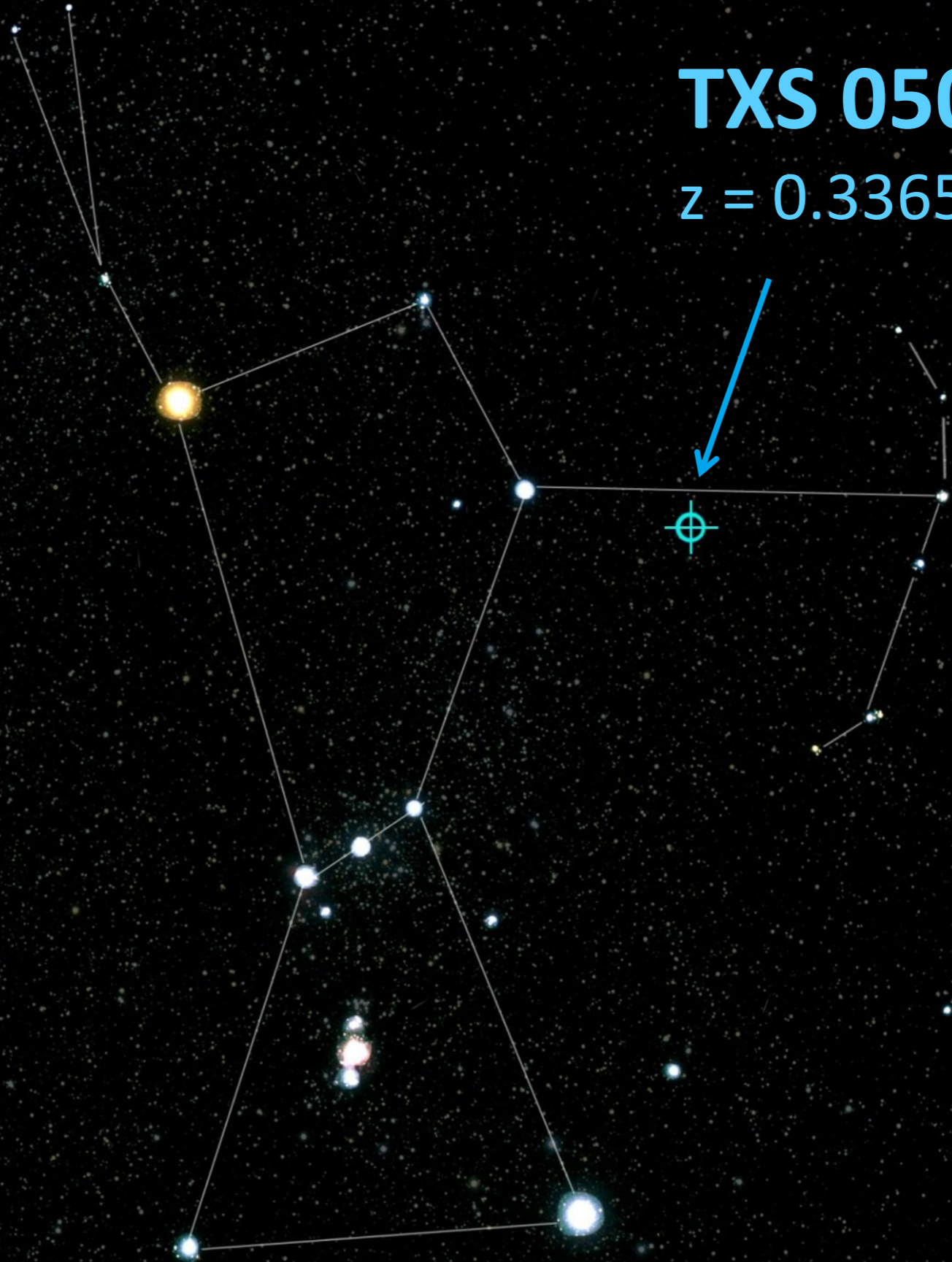
22. September 2017, 20:54 UTC

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

$z = 0.3365 \pm 0.0010$



28. 9. Fermi-Satellite:

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

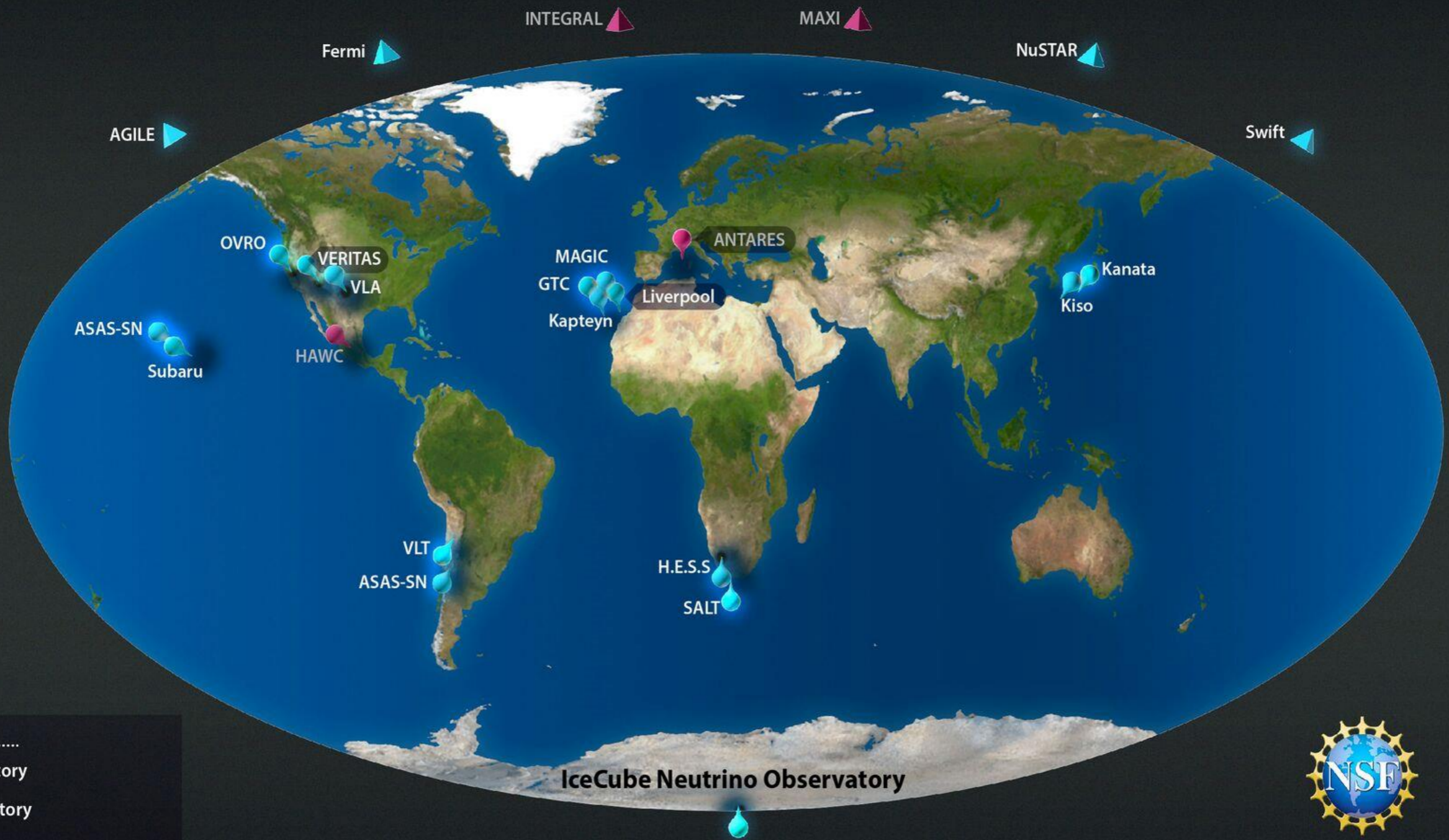


From 29.8. on

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



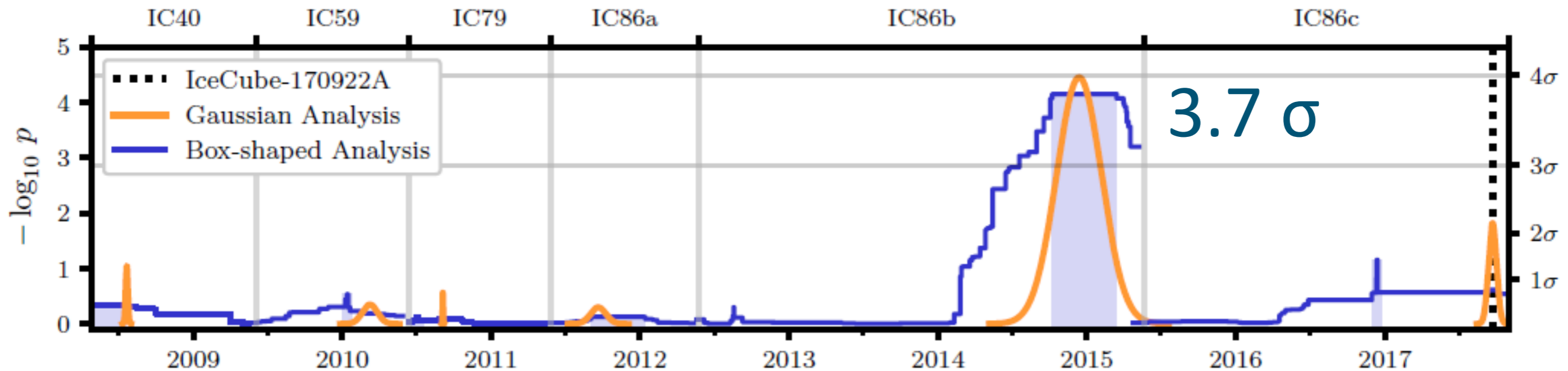
Observatories

- Earth Observatory
- Space Observatory

Detections

- Observations with detection
- Observations without detection





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

Stars are pulled apart by tidal forces in the vicinity of supermassive black holes. Accretion of stellar remnants powers plasma outflows.

stellar debris



black hole



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

(relativistic) plasma outflow



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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- **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:**




GIGATON VOLUME DETECTOR BAIKAL GVD

0.5 – 1.0 km³

A photograph showing a team of scientists in winter gear working on a detector on an ice floe. The detector consists of several large, clear spherical modules stacked vertically, connected by a complex network of cables. One scientist is crouching and working on the base of the detector, while others stand nearby observing. The background shows a vast, flat expanse of ice under a pale sky.

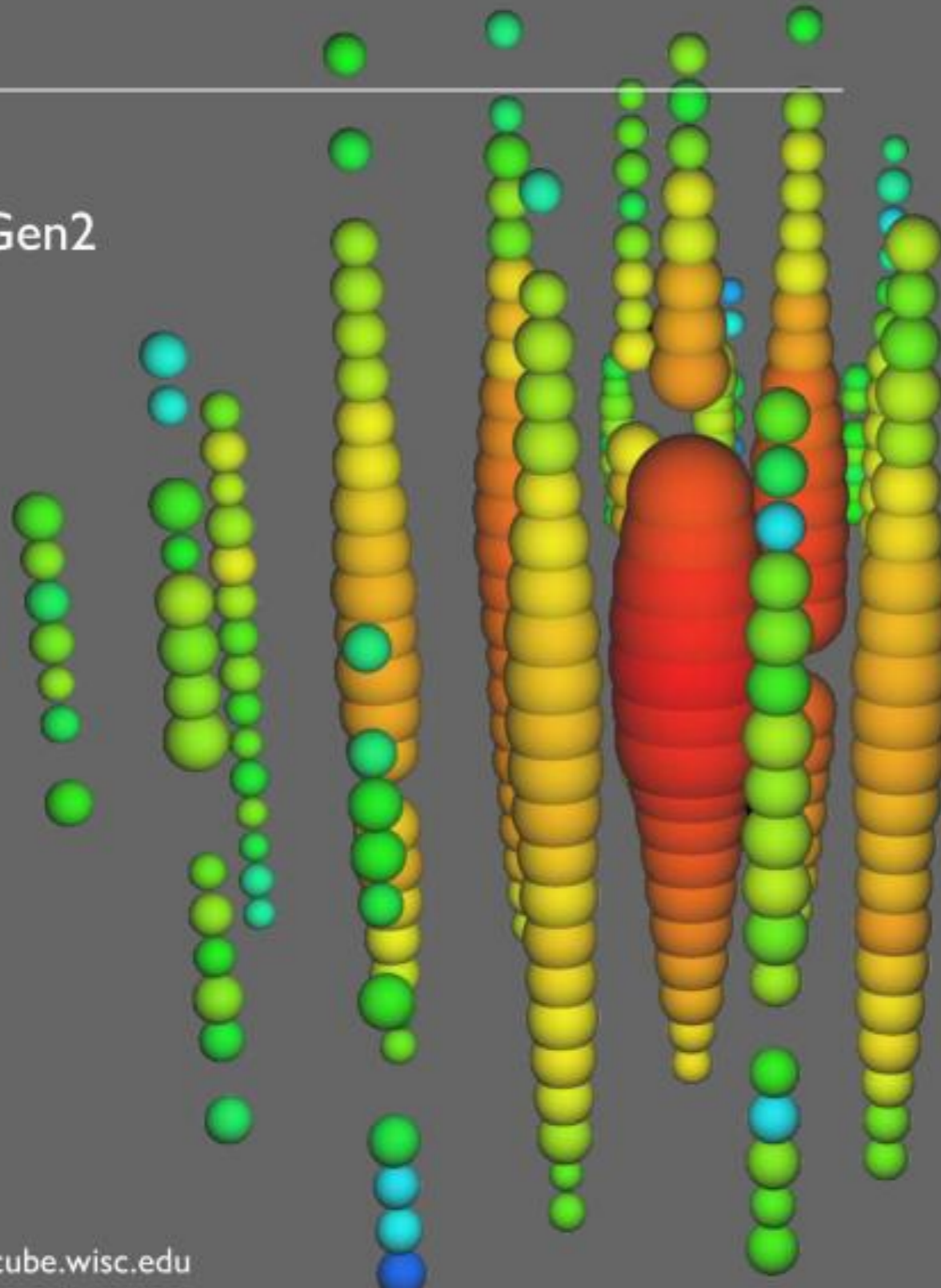
KM3NET



ARCA: $2 \times 0.6 \text{ km}^3$
ORCA: 3.7 Mtons

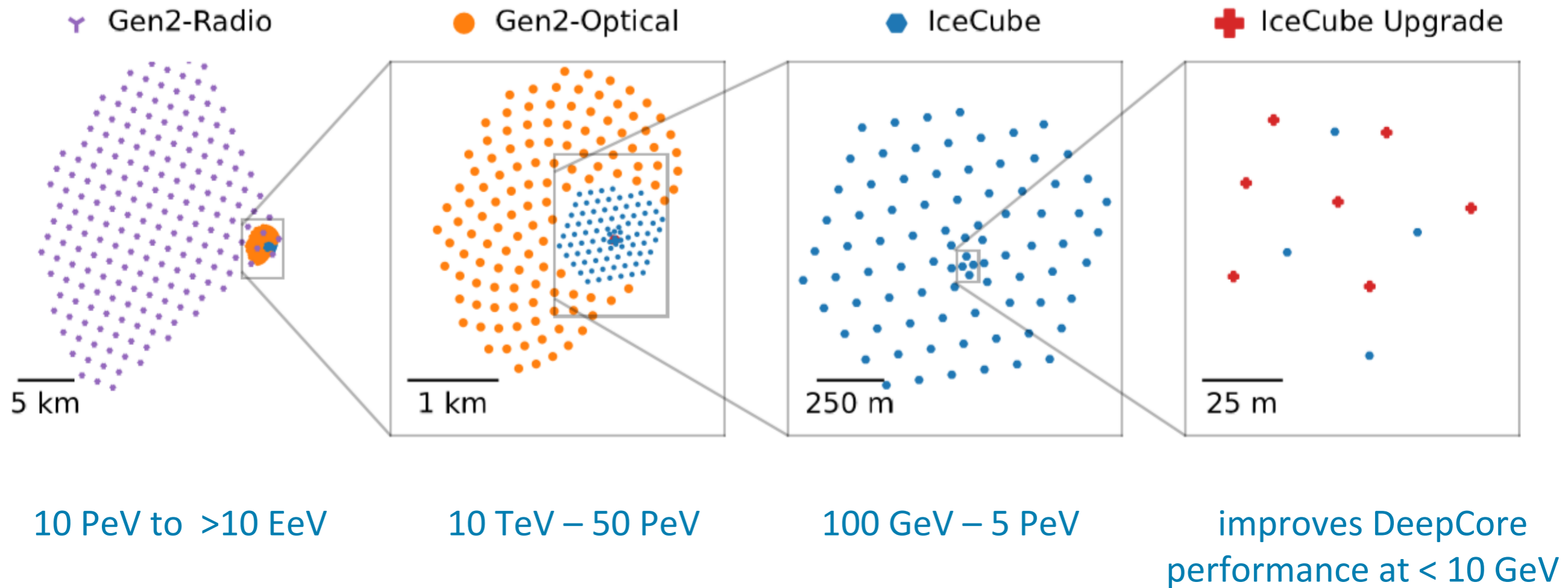
IceCube-Gen2: The Window to the Extreme Universe

The IceCube-Gen2
Collaboration

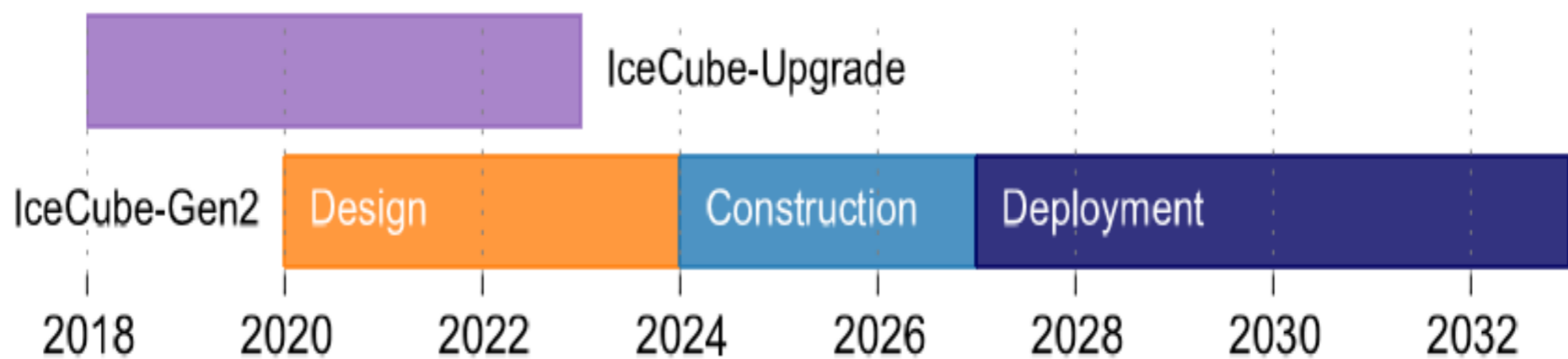
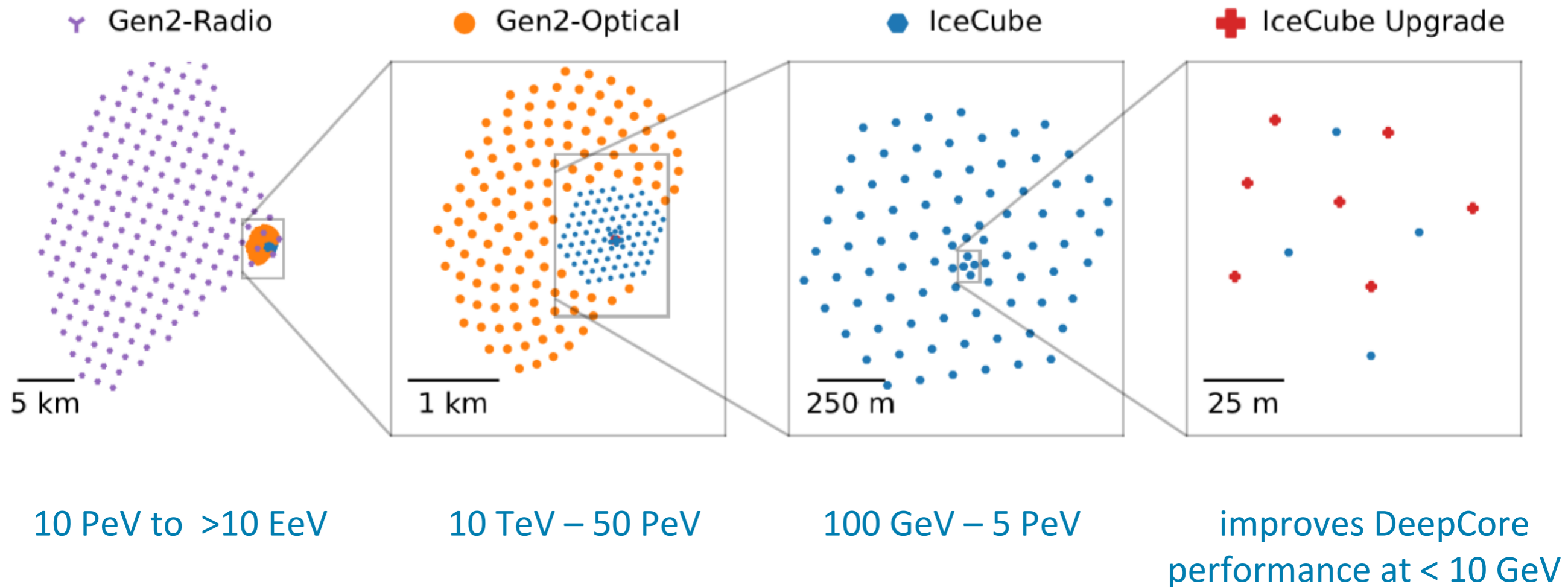


$\sim 8 \text{ km}^3$
+ 100 km² radio array

IceCube Gen2: from GeV to EeV



IceCube Gen2: from GeV to EeV

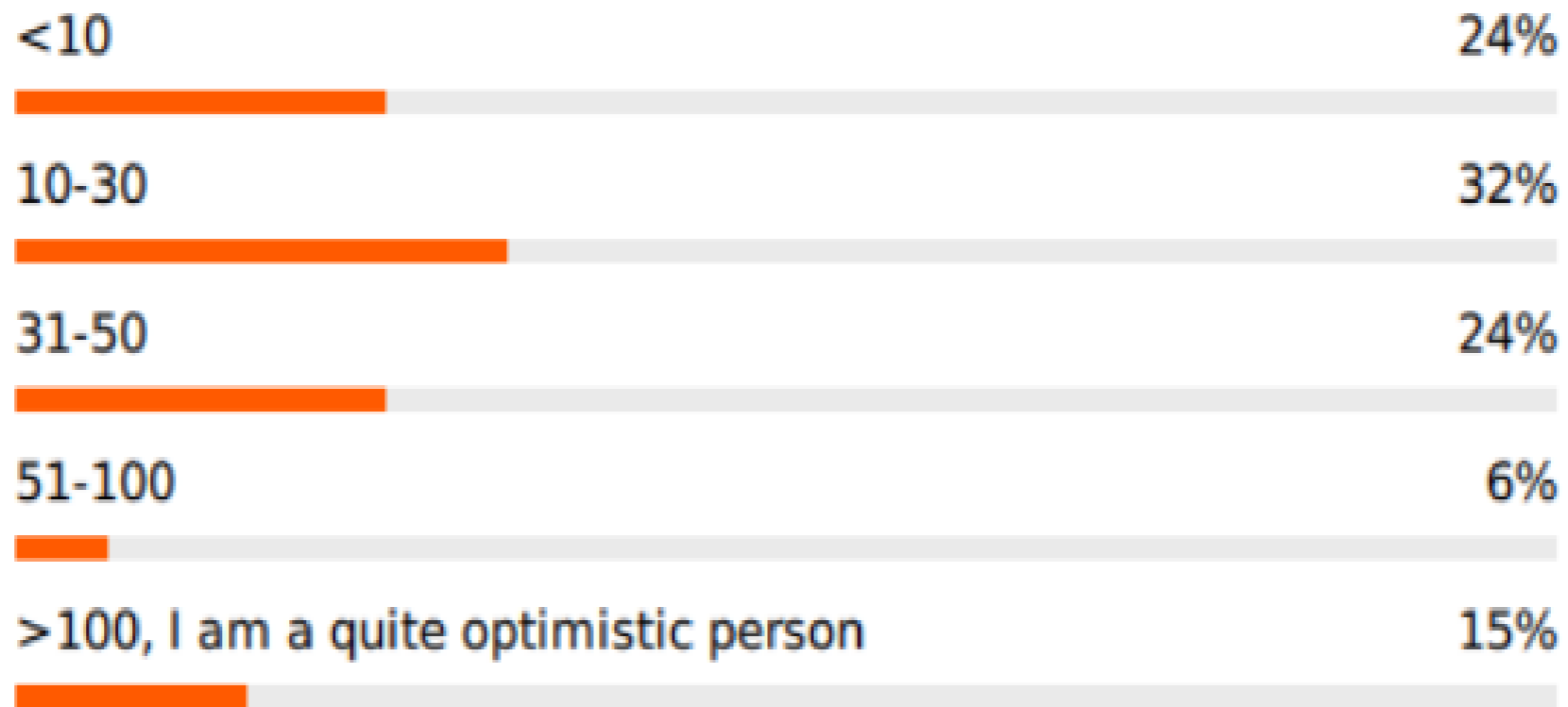


Conclusions

- 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 ! (?)

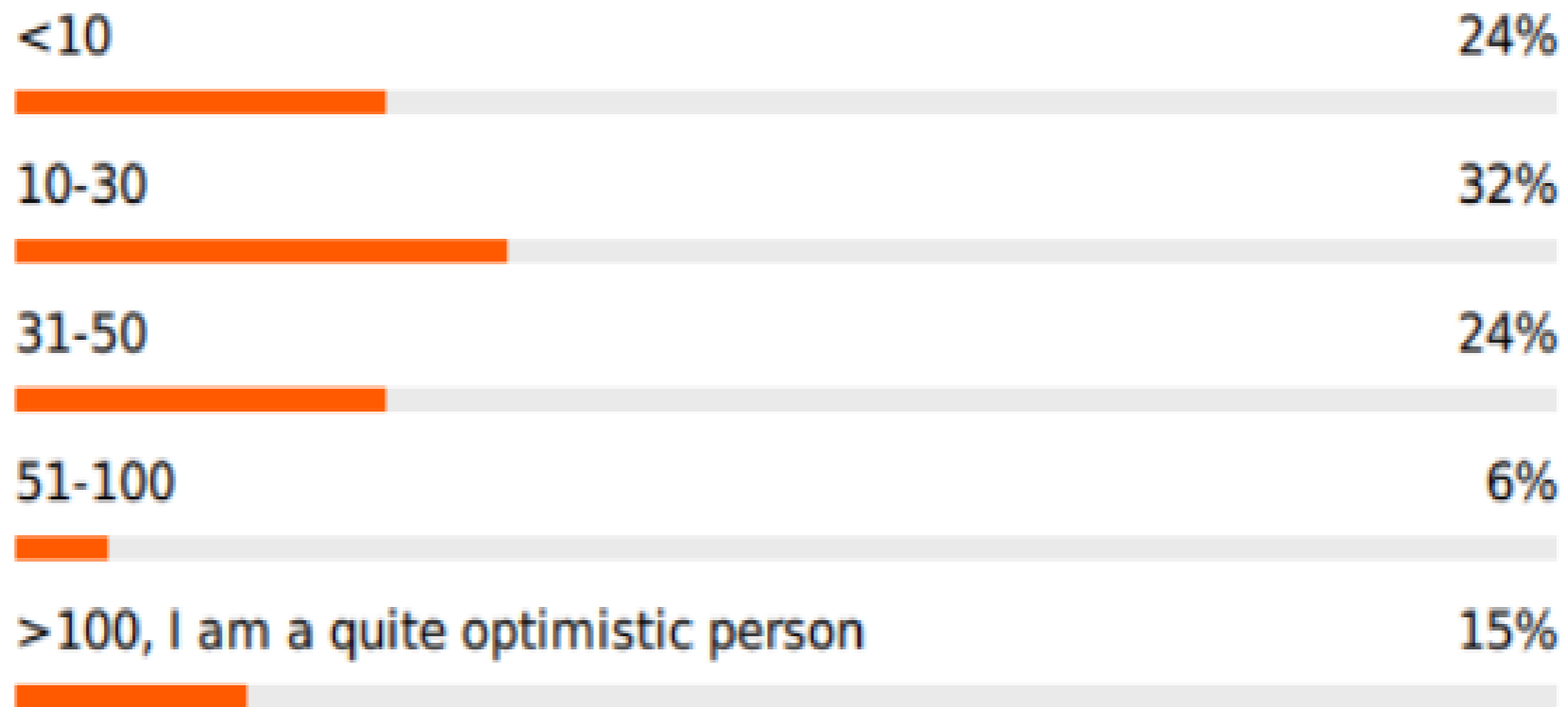
VLV ν T May 2021: *A bet*

4. How many Galactic and Extra-Galactic sources will have been detected by VLV ν T 2031?



- Mid 2020s and later:
fill landscape of ν sources with more and more entries. Close-in on cosmic ray sources ! (?)

4. How many Galactic and Extra-Galactic sources will have been detected by VLVT 2031?



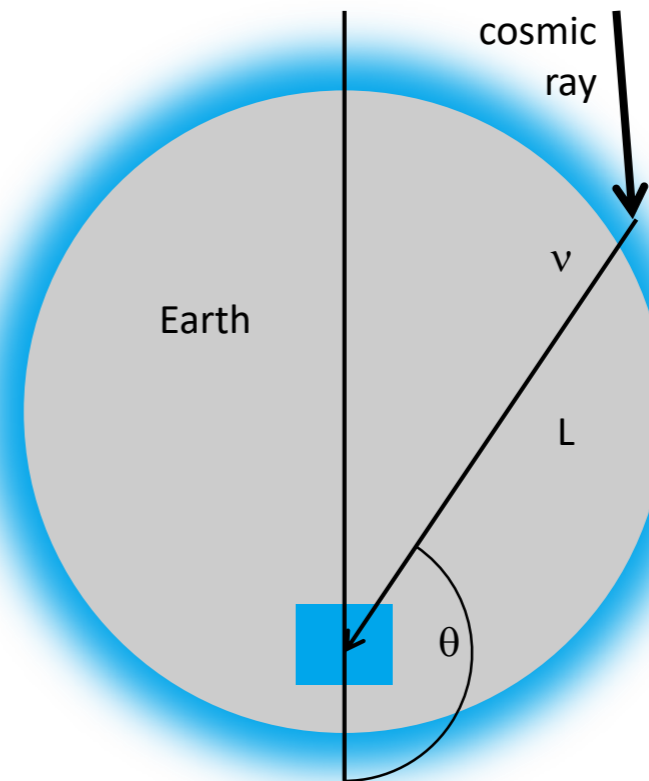
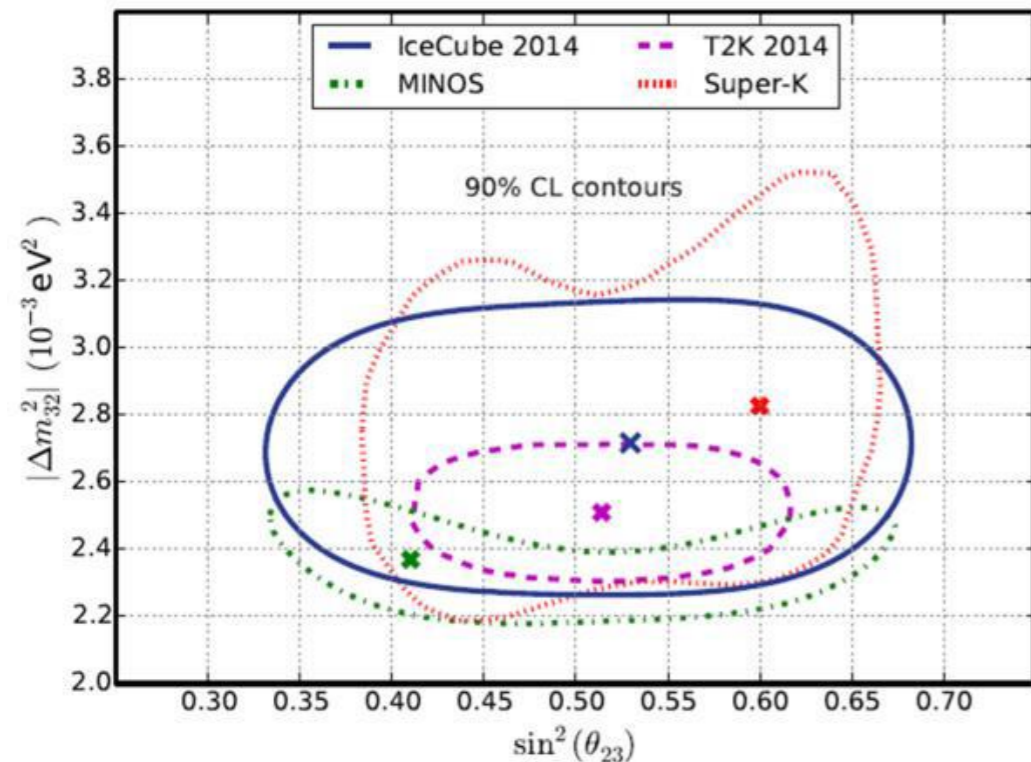
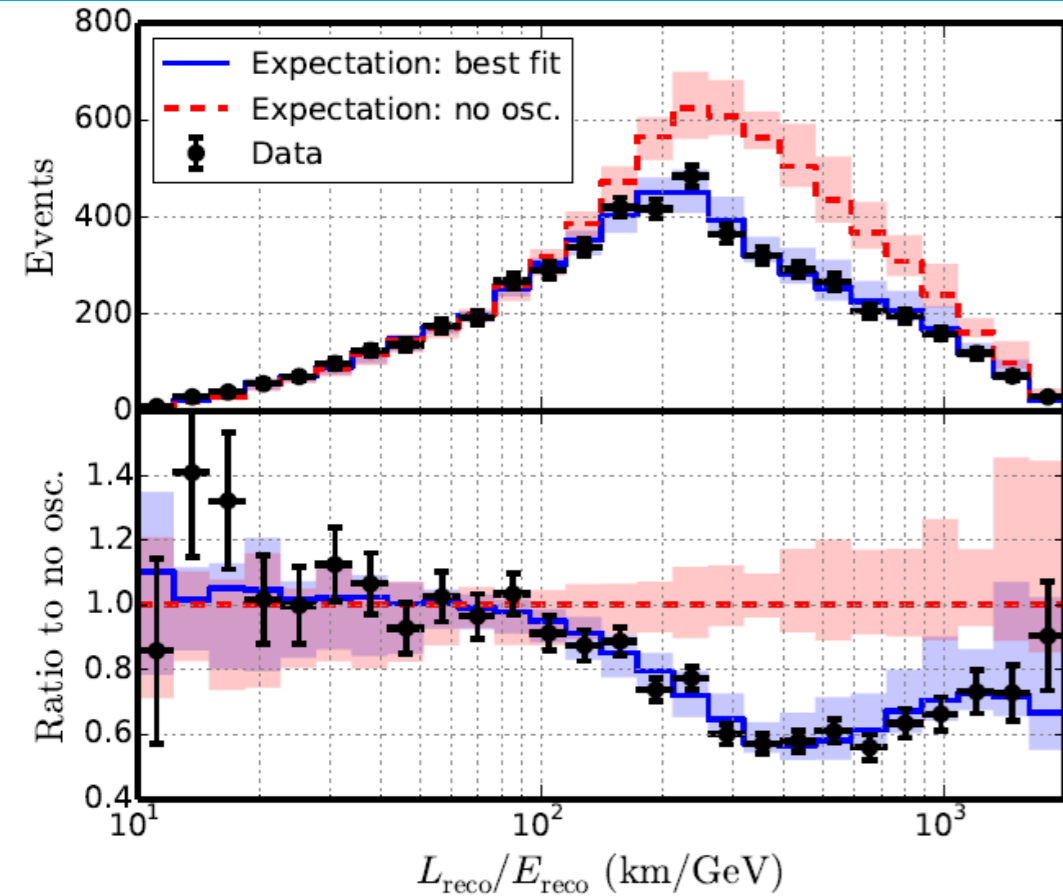
Thank you for your attention!

Backups

DeepCore: oscillations for atmospheric neutrinos ($E < 30\text{-}40$ GeV)

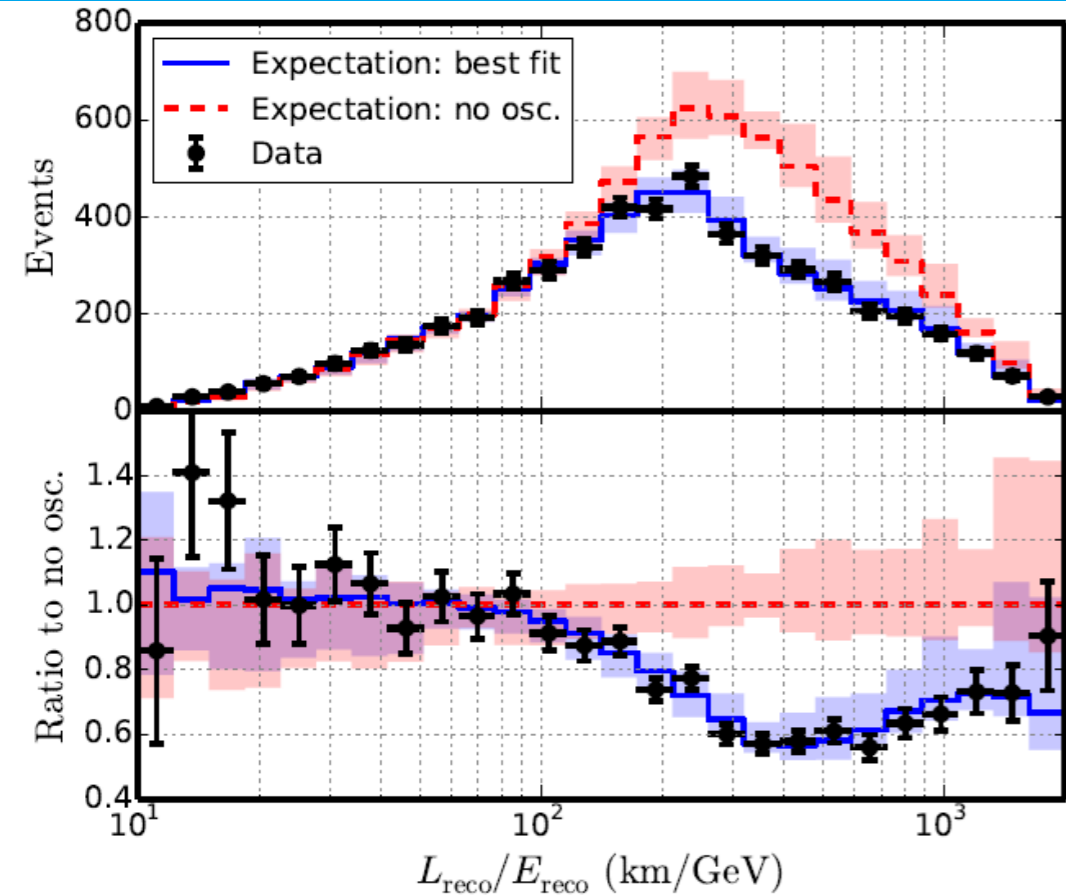
Determining neutrino oscillation parameters from atmospheric muon neutrino disappearance with three years of IceCube DeepCore data

Phys. Rev. D91, 072004 (2015)



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

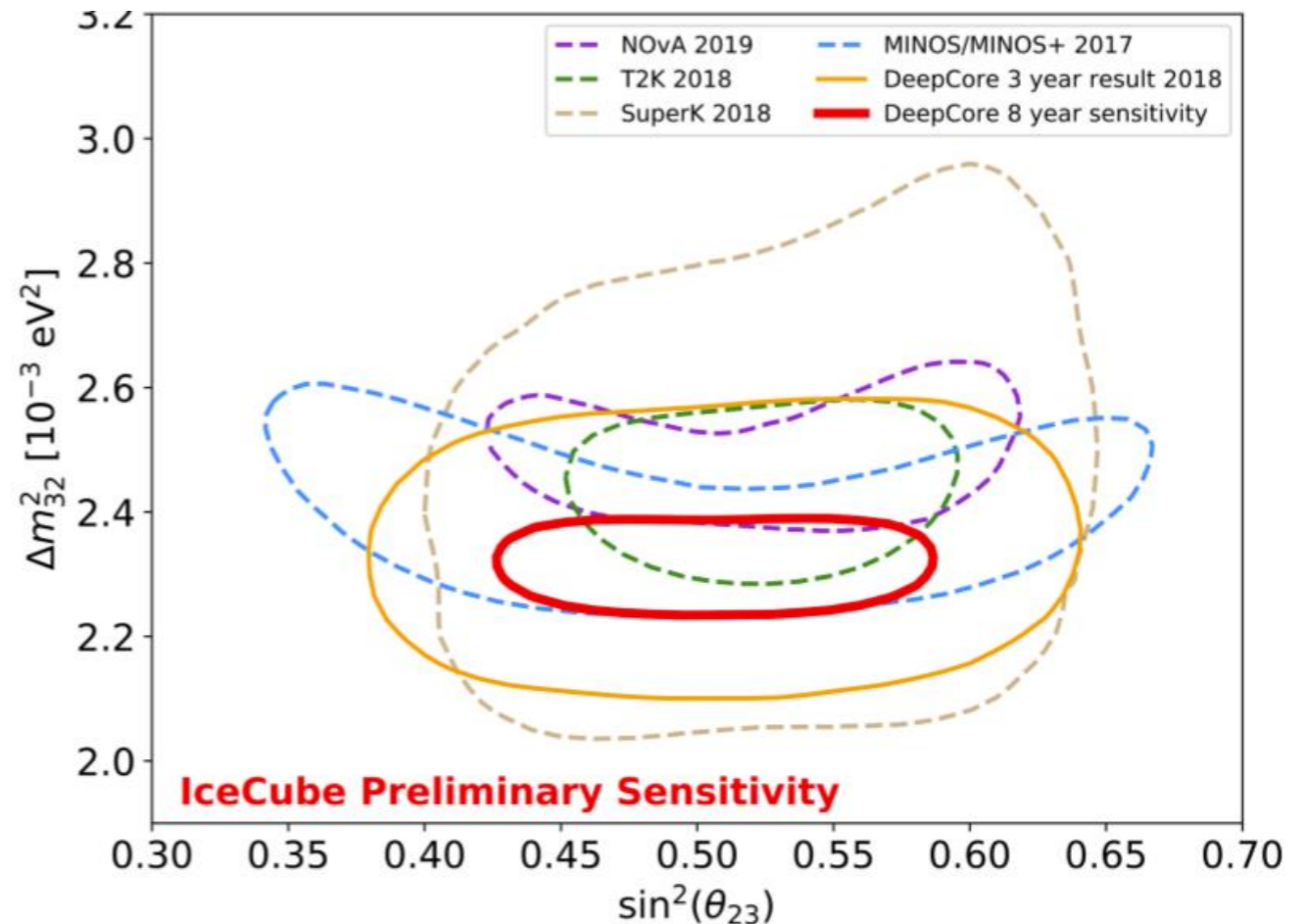
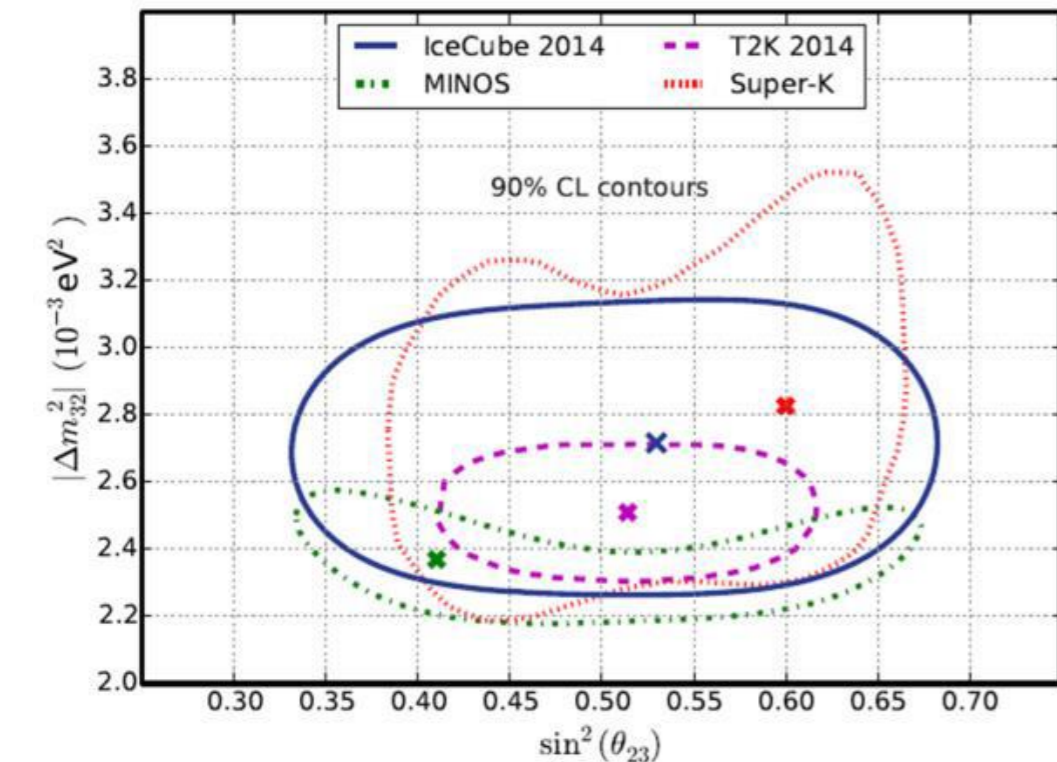
DeepCore: oscillations for atmospheric neutrinos ($E < 30\text{-}40\text{ GeV}$)



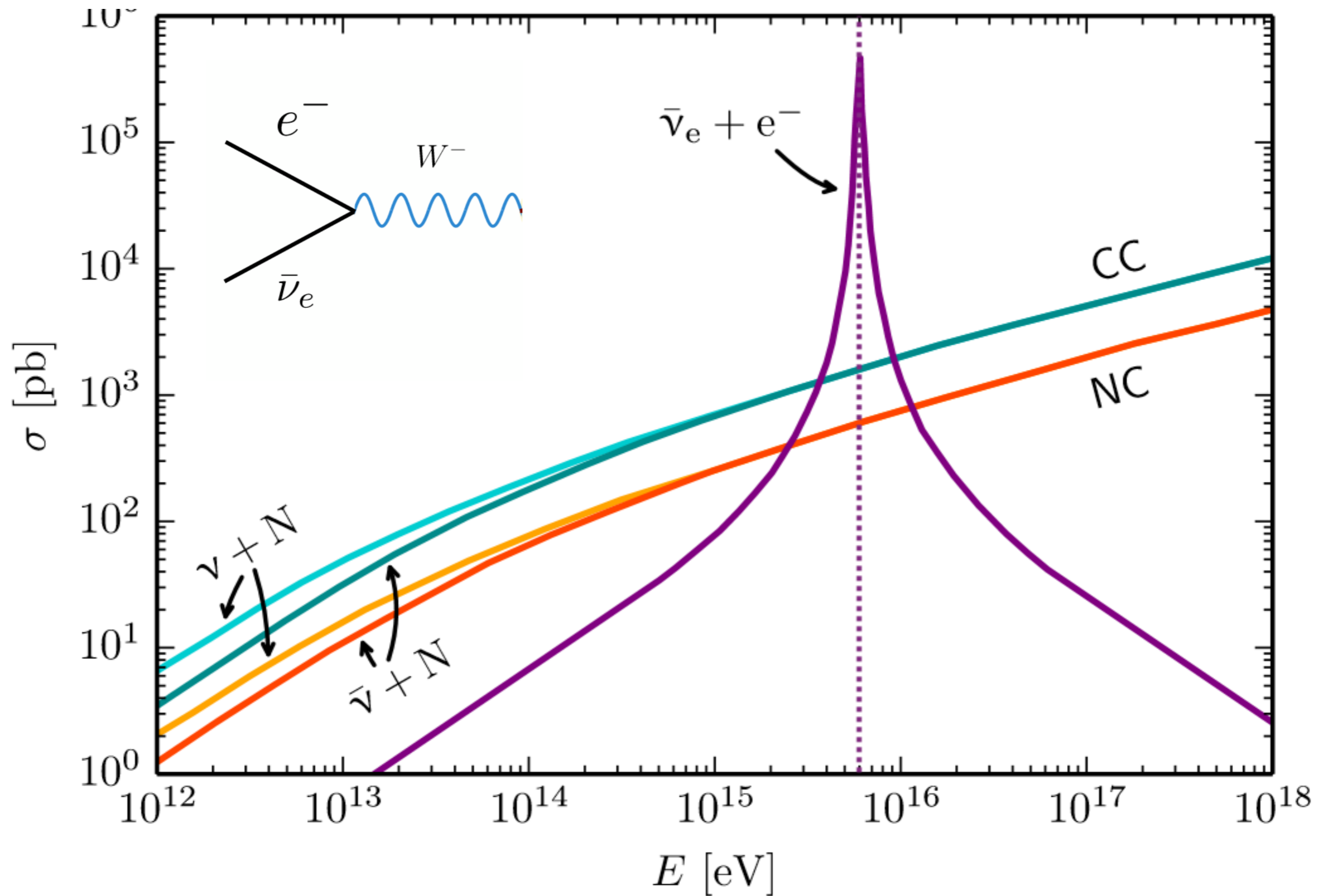
Determining neutrino oscillation parameters from atmospheric muon neutrino disappearance with three years of IceCube DeepCore data

Phys. Rev. D91, 072004 (2015)

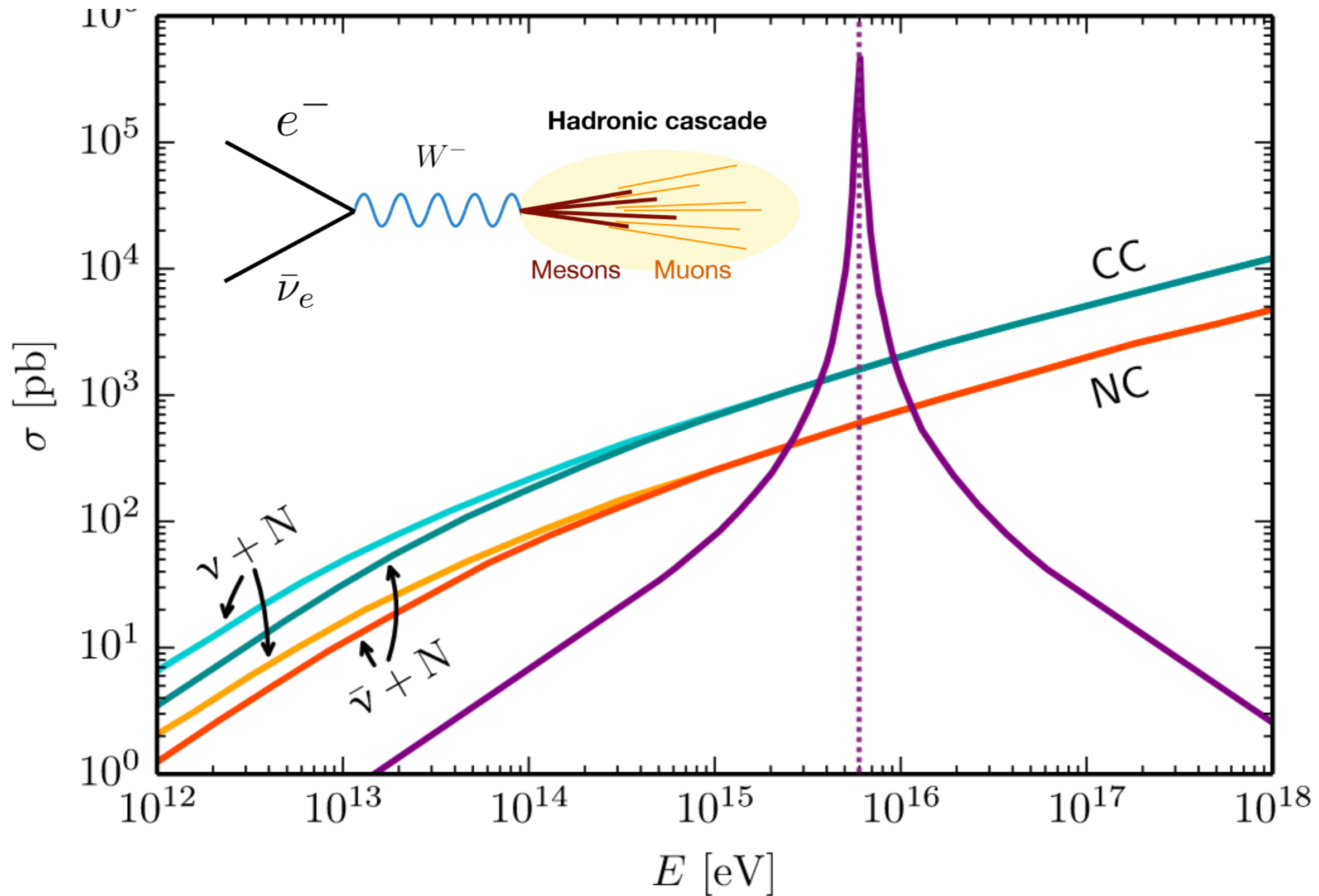
Neutrino Conference 2020



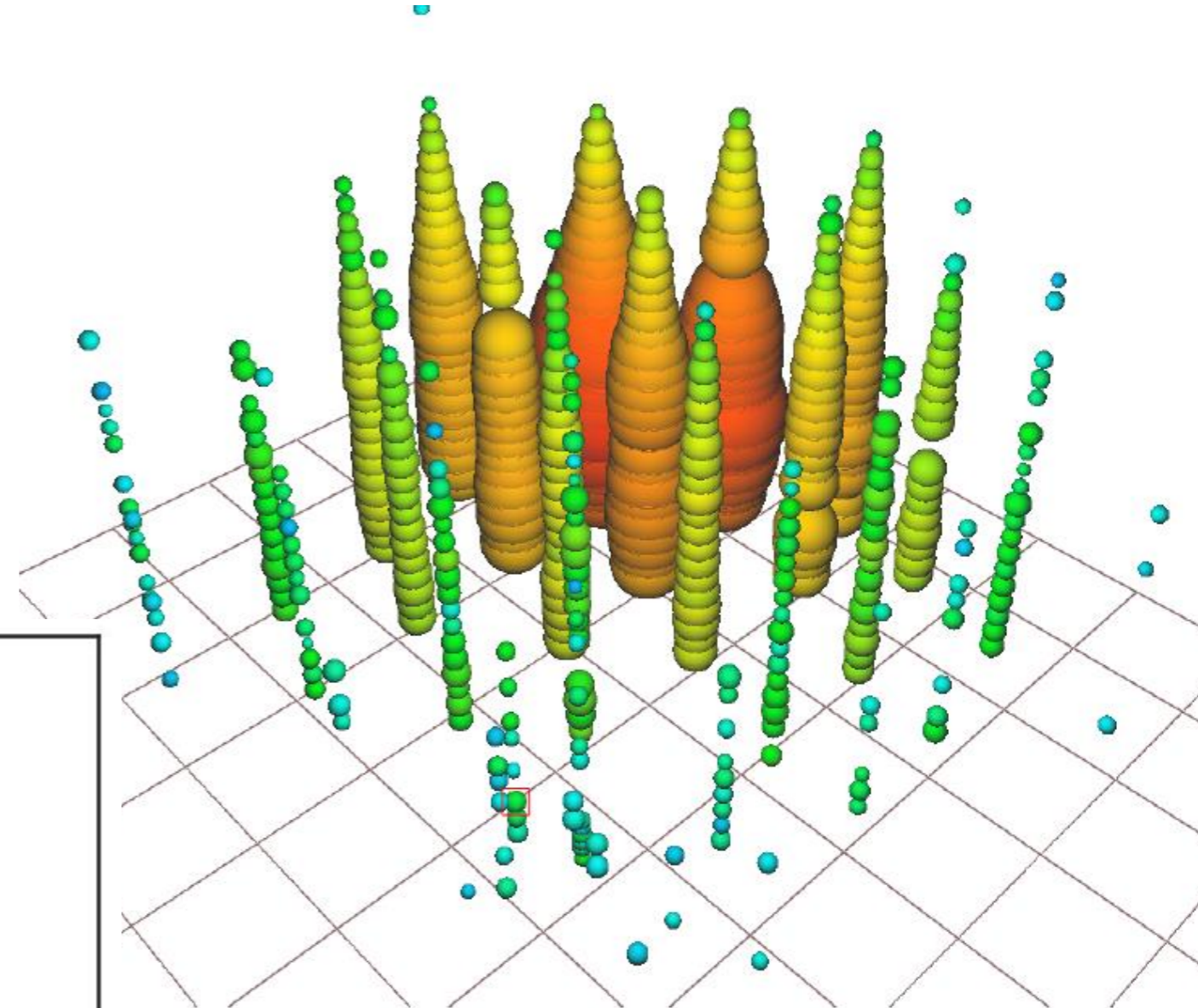
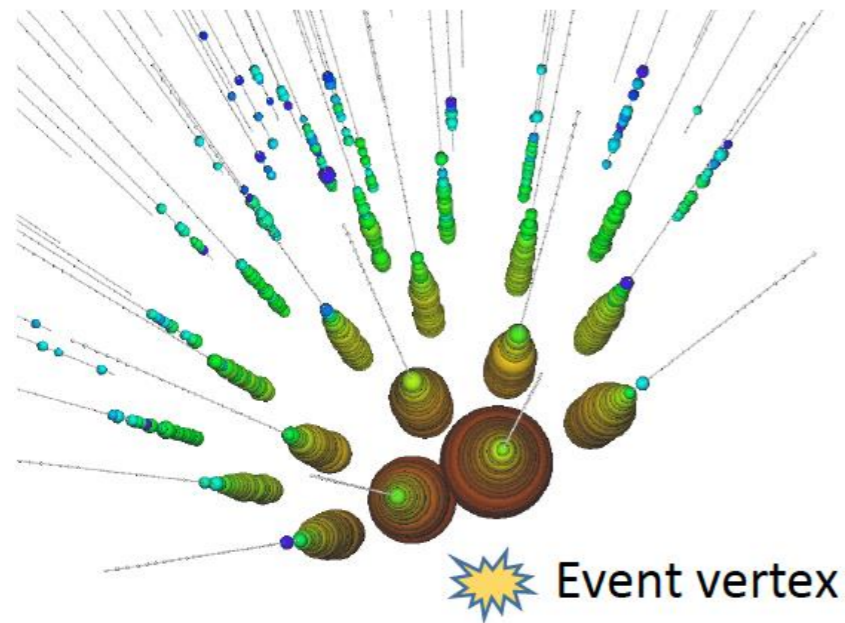
The first candidate for the Glashow resonance



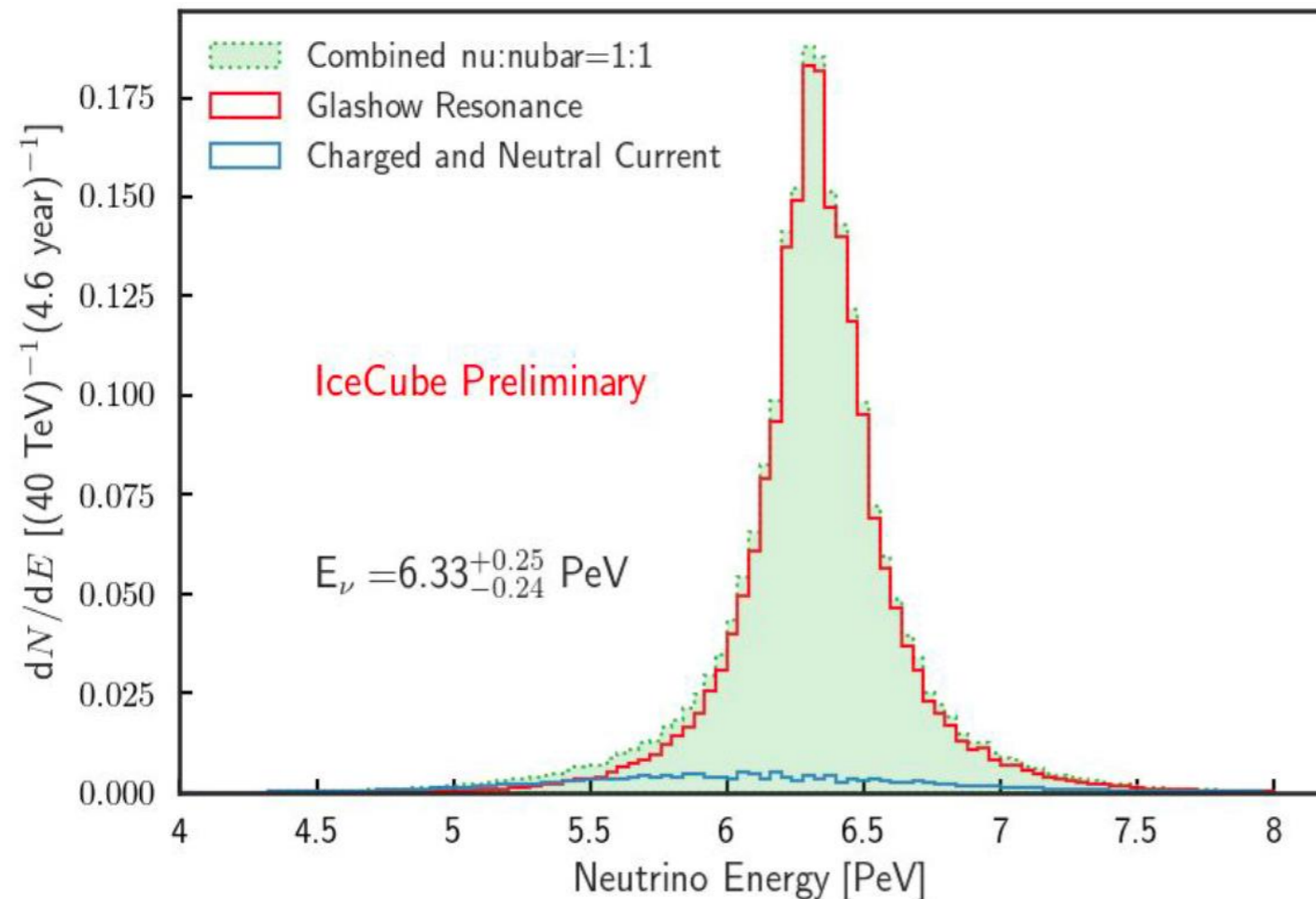
The first candidate for the Glashow resonance



Partially contained event with $E = 6.3$ PeV

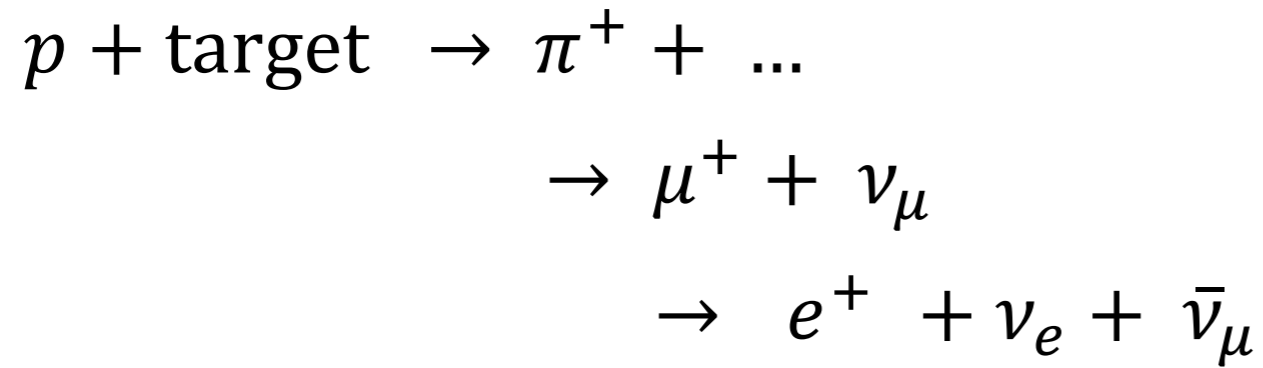


First identification of a clear candidate for an anti-electron neutrino in an underwater detector !

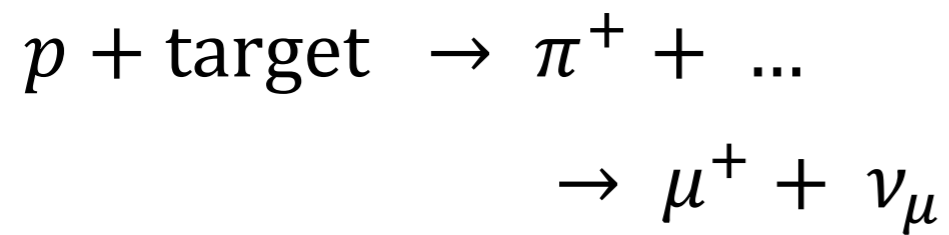


Flavor composition

$\nu_e : \nu_\mu : \nu_\tau$



1 : 2 : 0

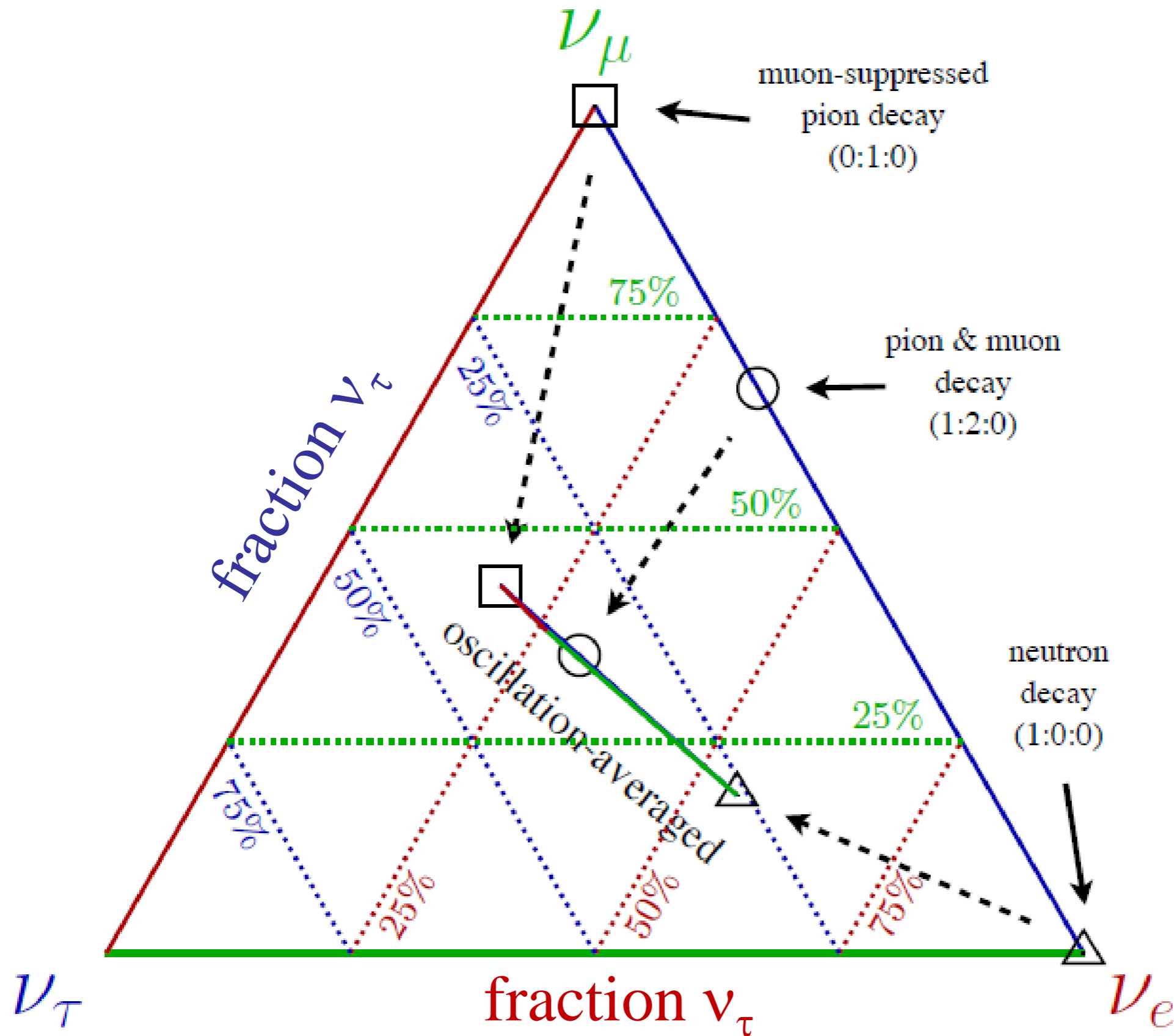


0 : 1 : 0



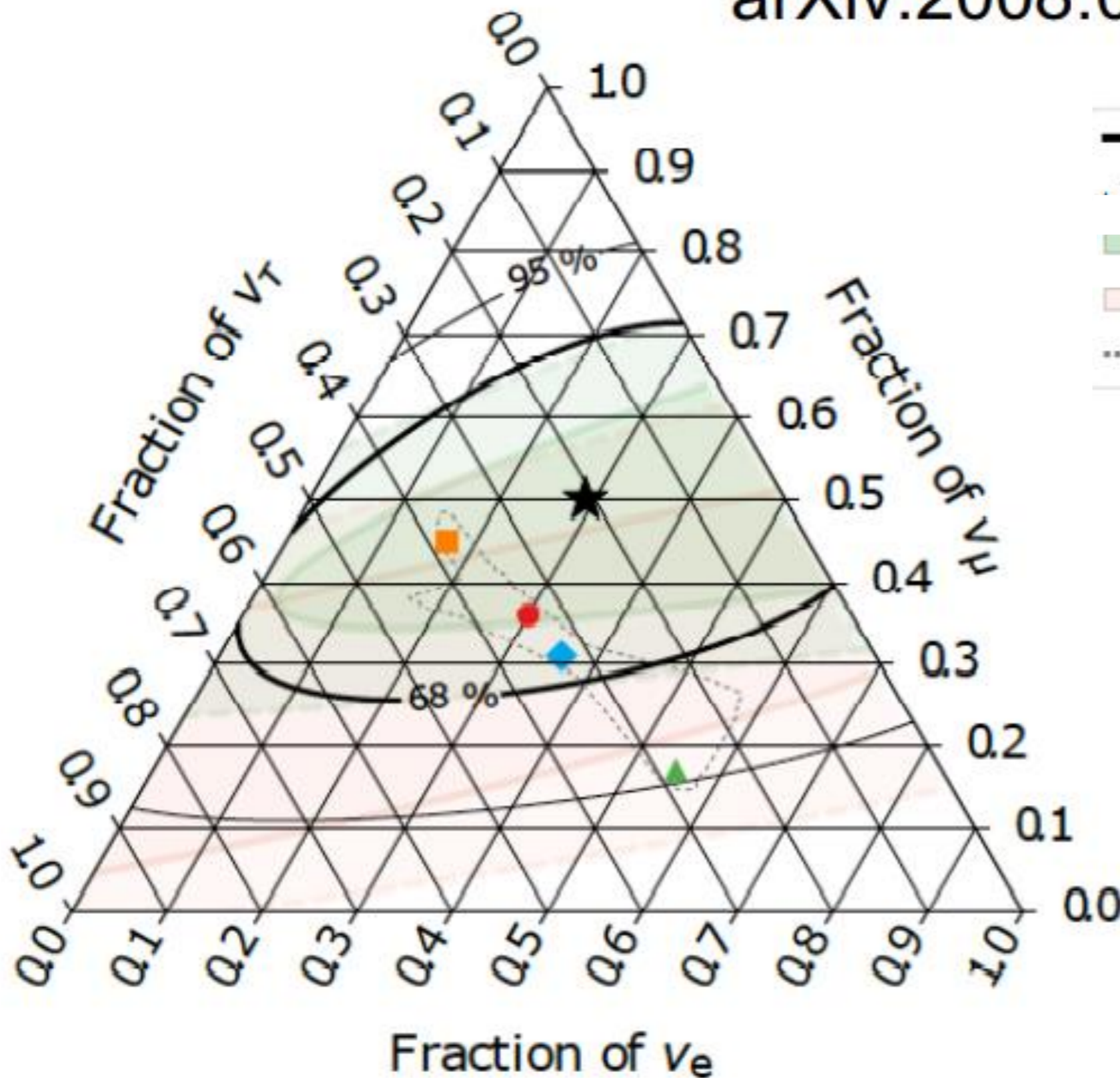
1 : 0 : 0






Flavor composition







Flavor composition

arXiv:2008.04323



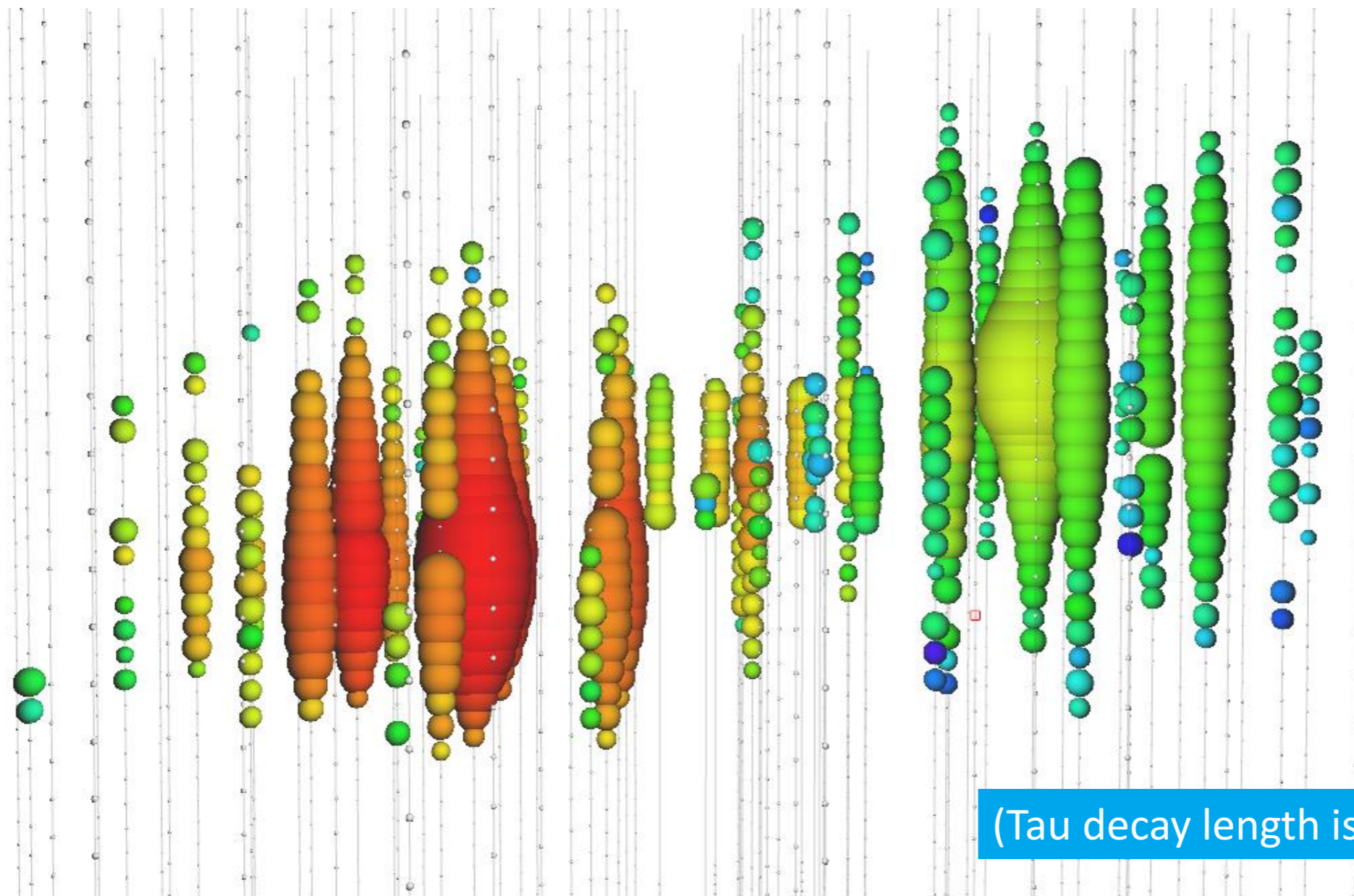
-  High-energy starting tracks
-  Best-fit: 0.29 : 0.50 : 0.21
-  Global fit (IceCube, APJ 2015)
-  Inelasticity (IceCube, PRD 2019)
-  3ν -mixing 3σ allowed region

$\nu_e : \nu_\mu : \nu_\tau$ at source \rightarrow on Earth:

-  0:1:0 \rightarrow 0.17 : 0.45 : 0.37
-  1:2:0 \rightarrow 0.30 : 0.36 : 0.34
-  1:0:0 \rightarrow 0.55 : 0.17 : 0.28
-  1:1:0 \rightarrow 0.36 : 0.31 : 0.33

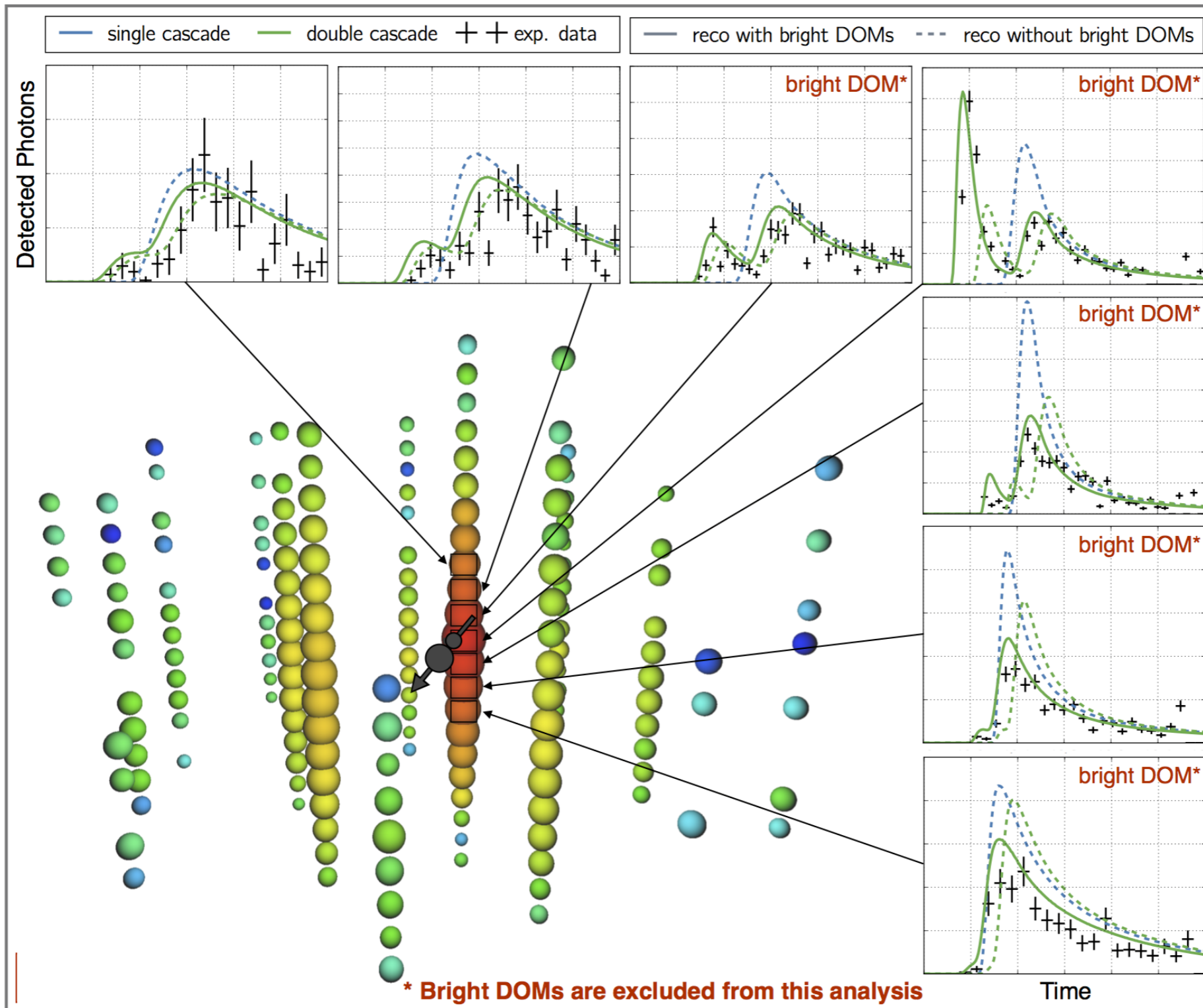
Double bang events from tau decays

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



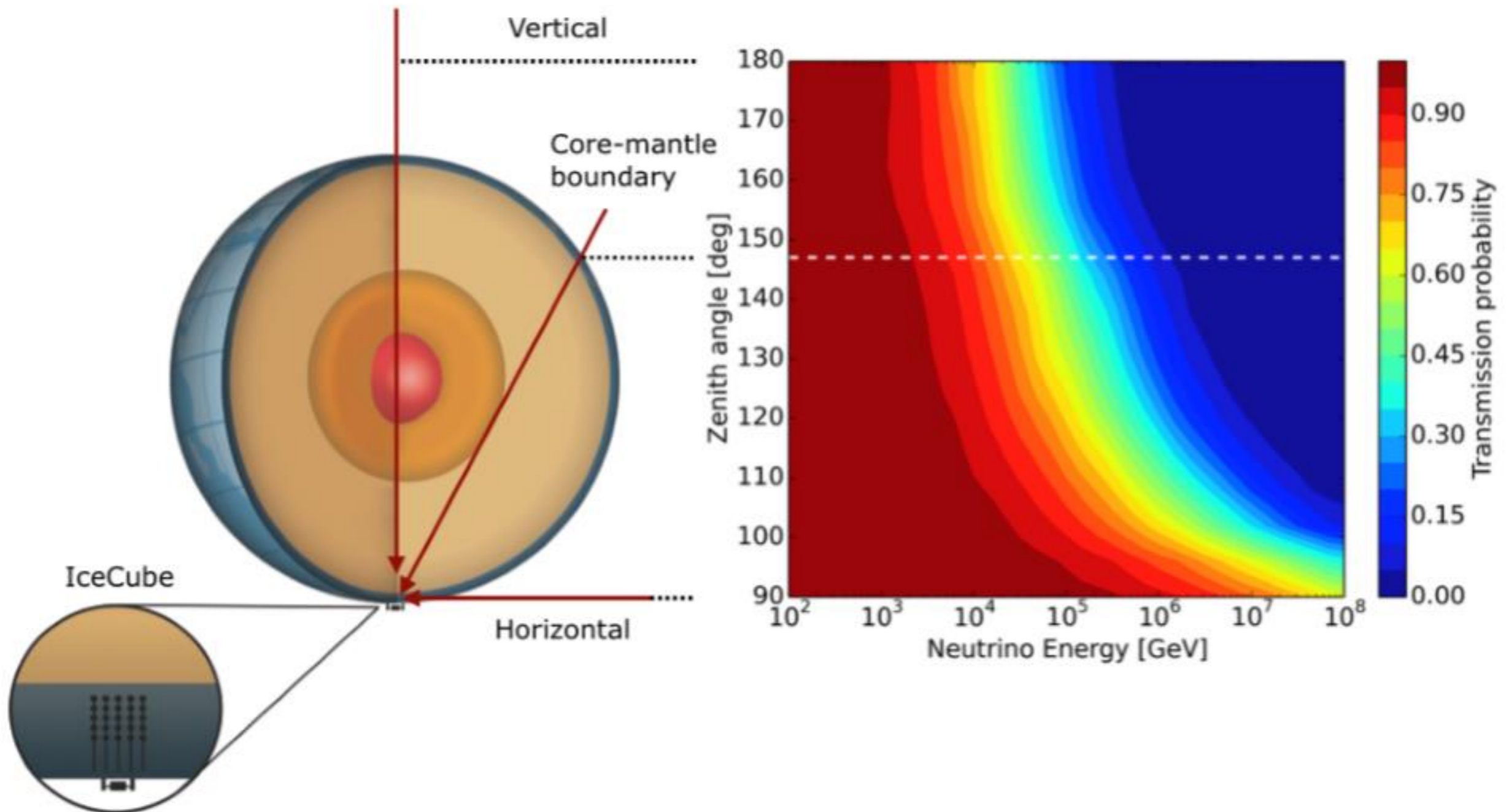
First tau-neutrino candidate

Two candidate events in 7.5 years of data



Using neutrinos to measure σ_ν at $> \text{TeV}$

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 $> \text{TeV}$

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

