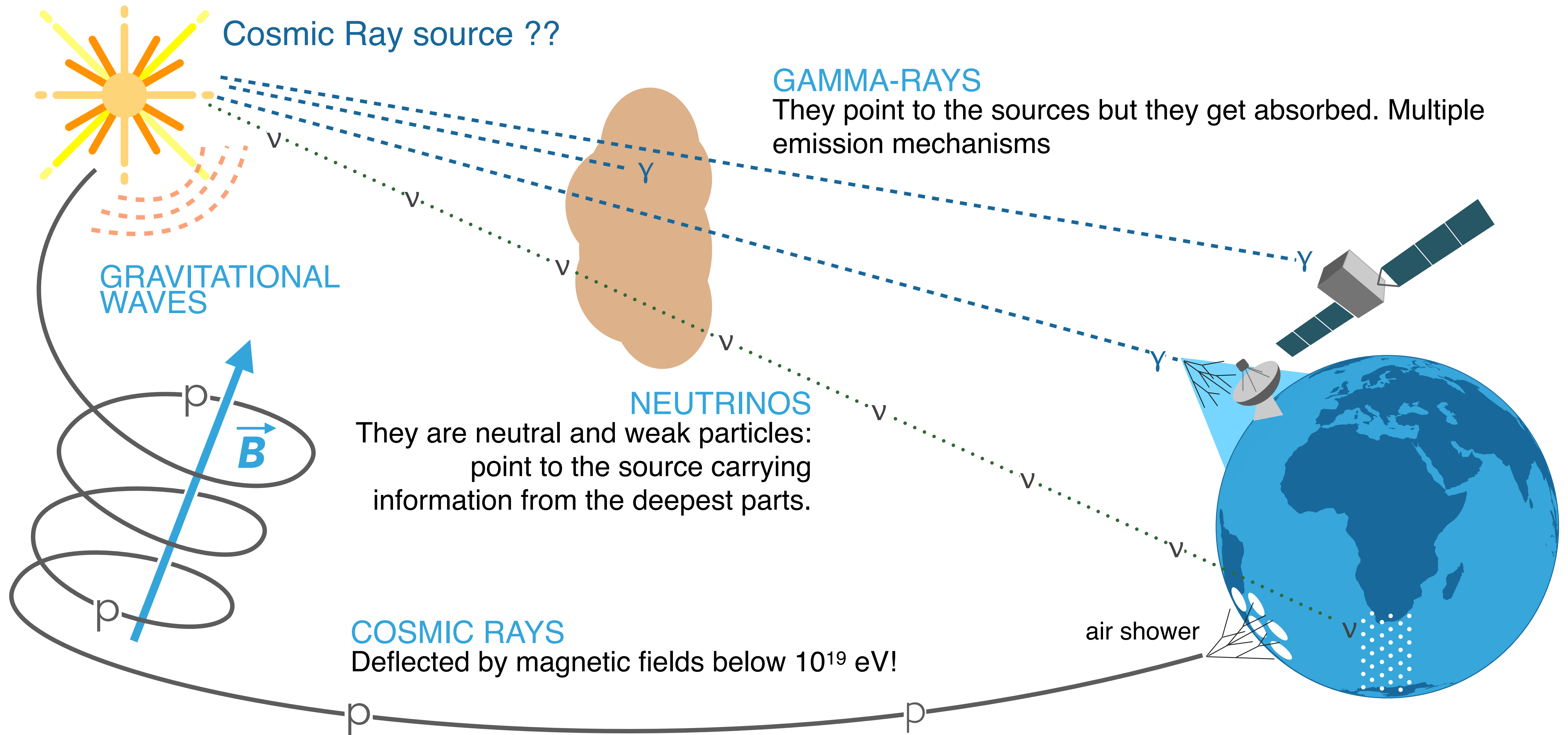




HIGHLIGHTS FROM IceCube

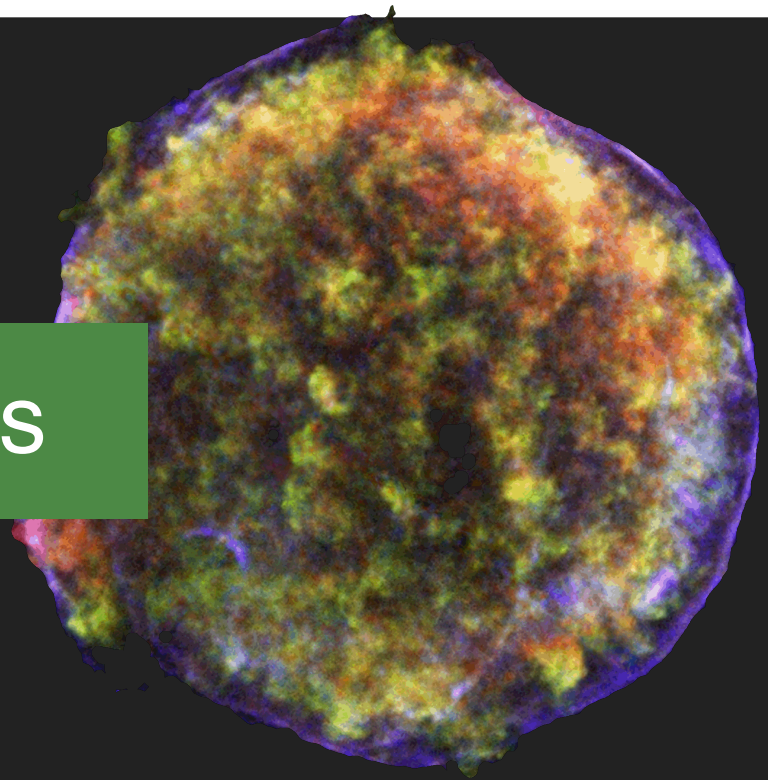
S. Toscano for the IIHE-IceCube group

Why neutrinos?



Neutrino Detectors **Scientific Scope**

SN Neutrinos



Astrophysical



MeV

GeV-TeV

<100 TeV

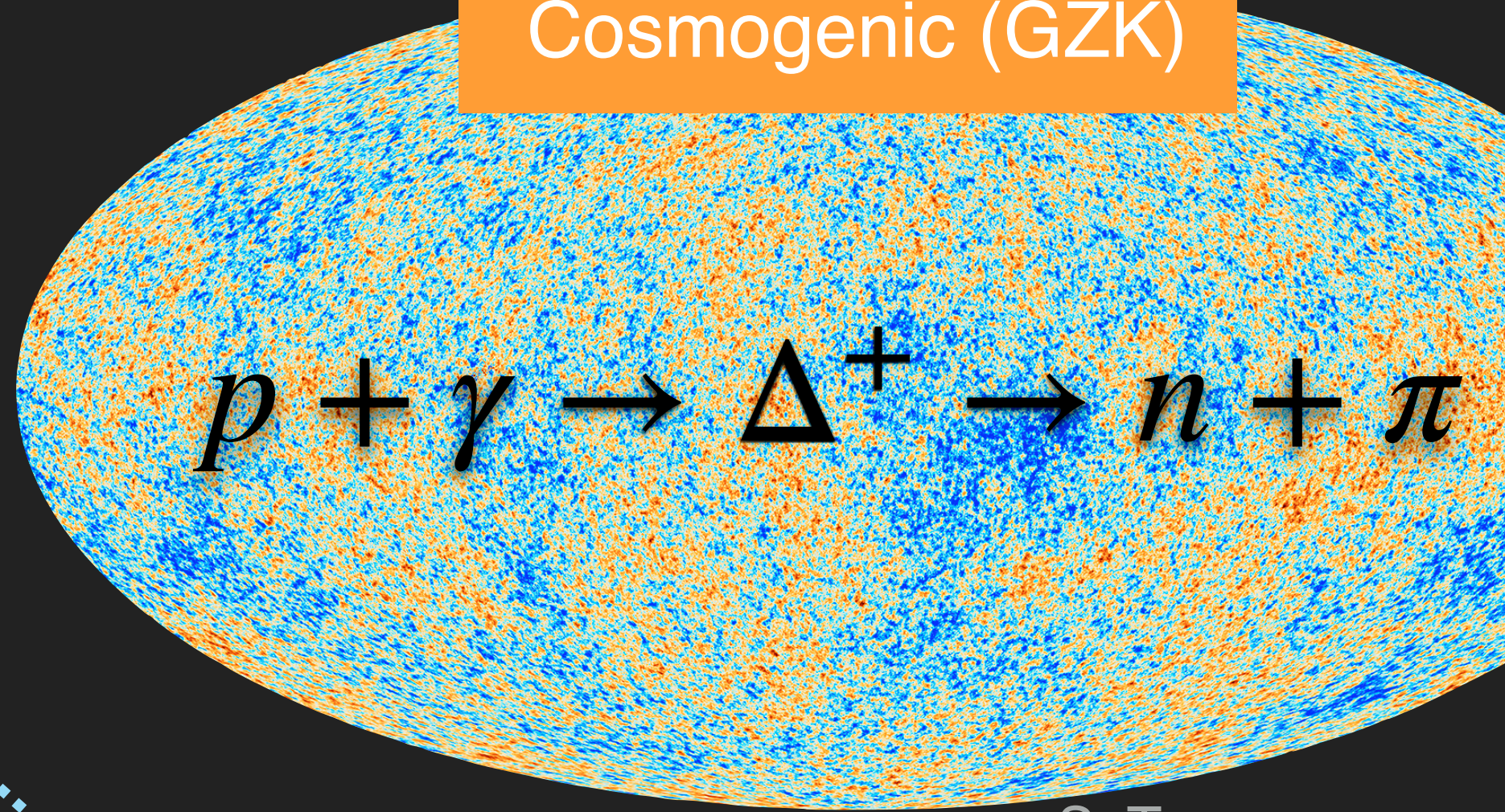
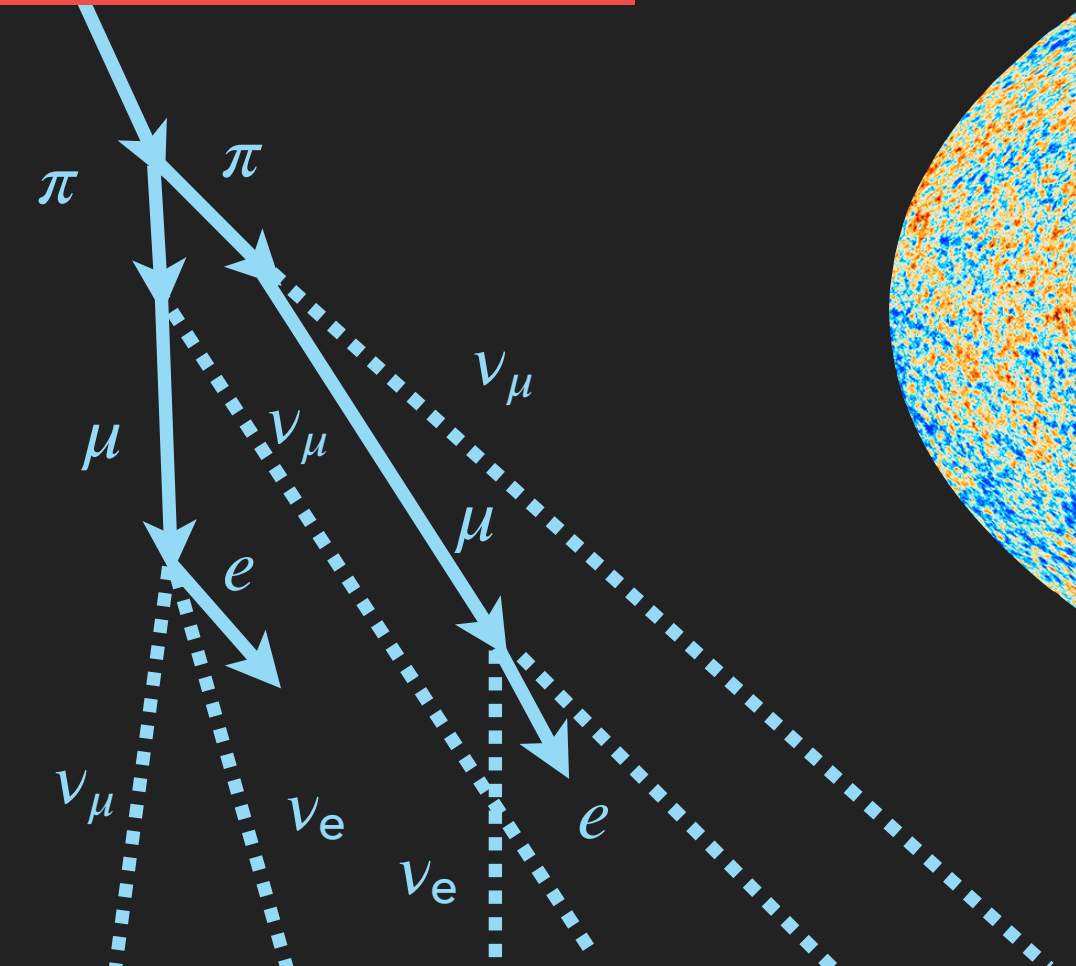
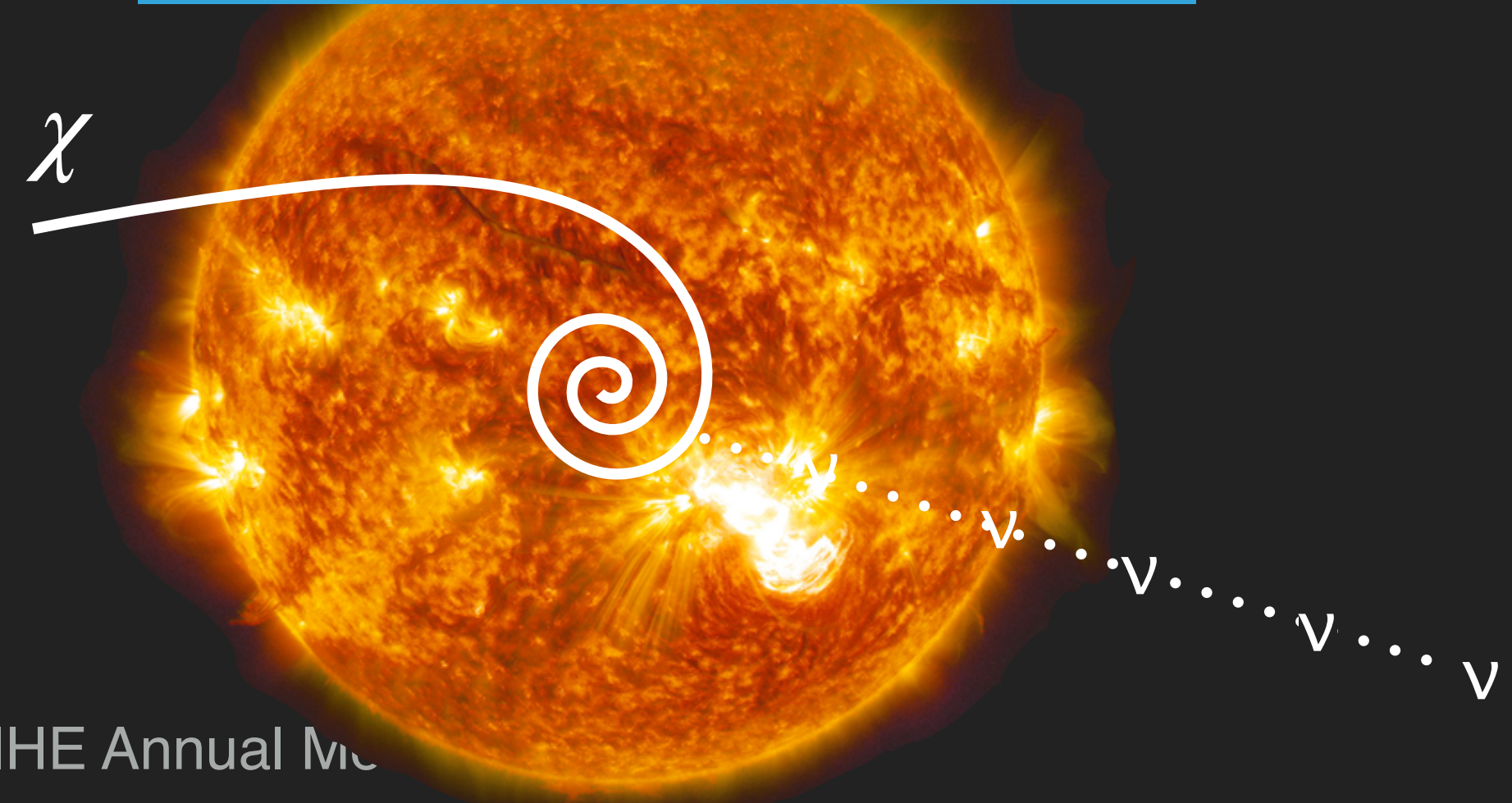
>100 TeV

> 10⁶ TeV

Solar Flares/Dark Matter

Atmos: Oscillations, sterile ν , Prompt

Cosmogenic (GZK)



Admunsen-Scott South Pole Station

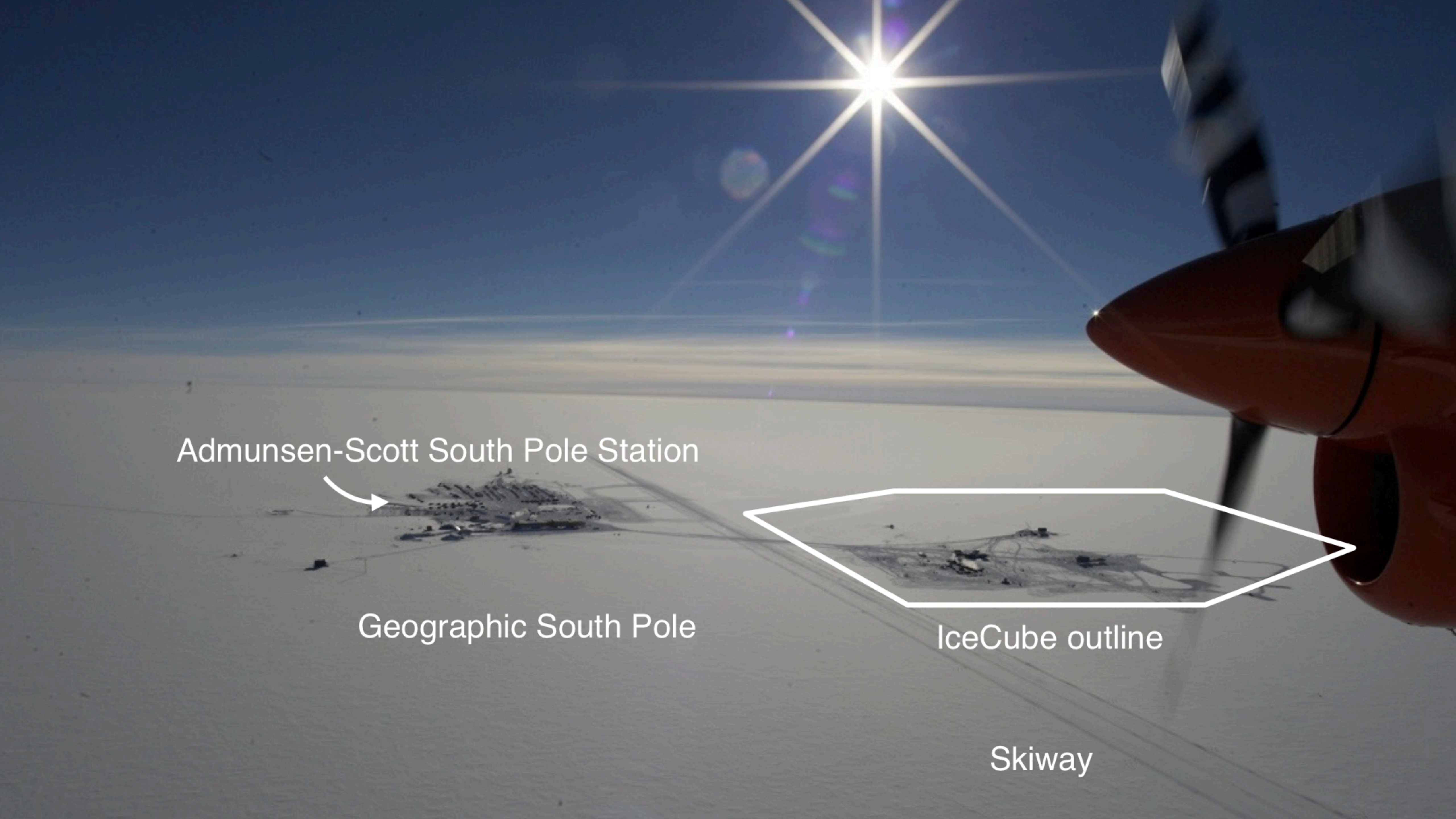


Geographic South Pole

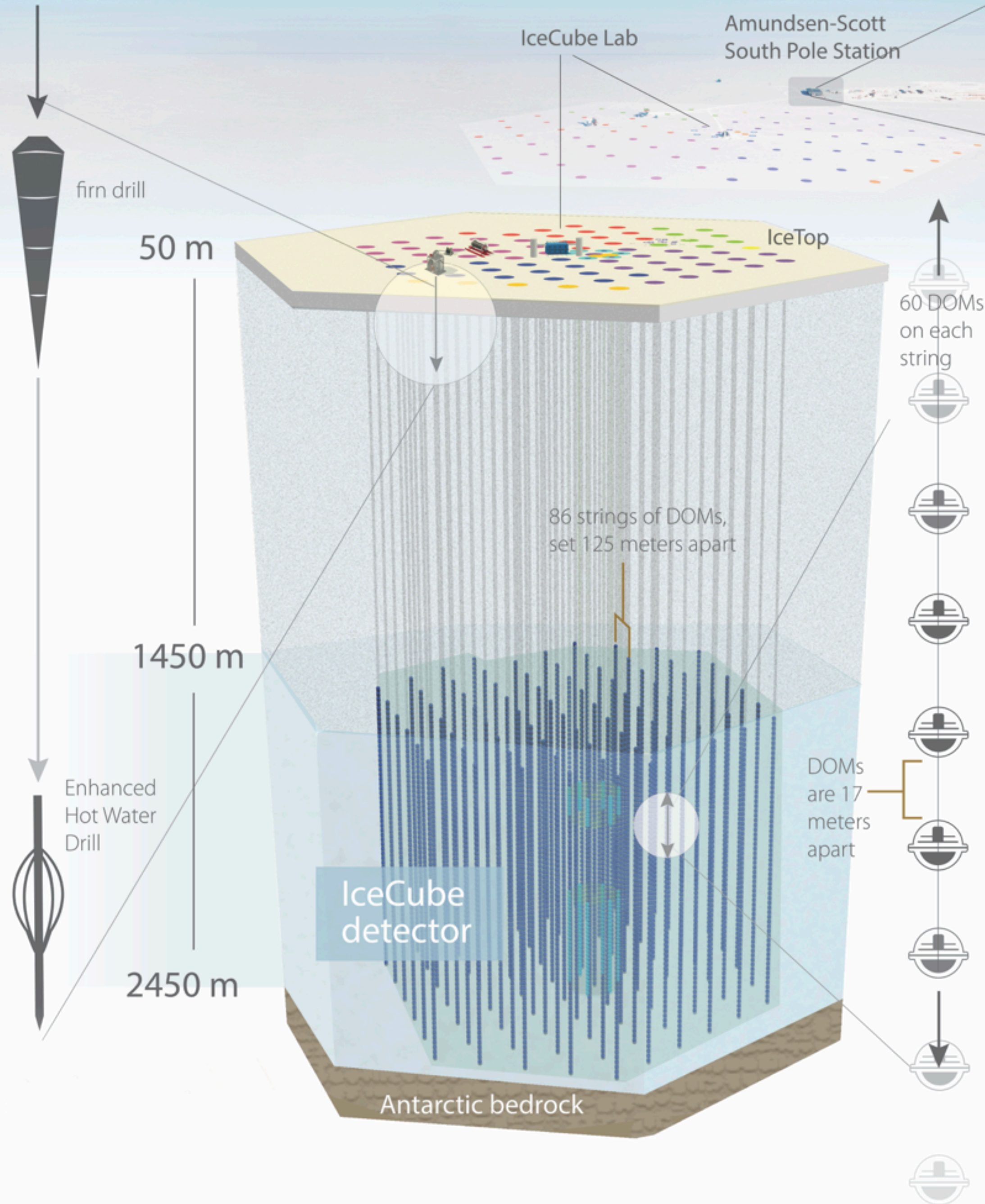


IceCube outline

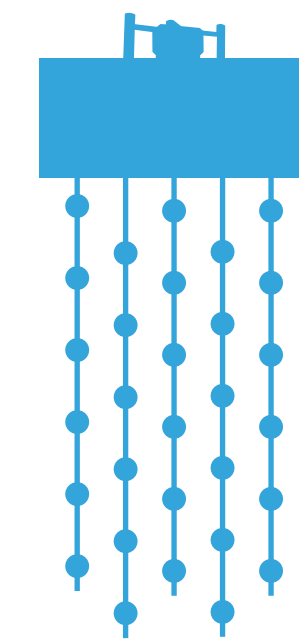
Skiway



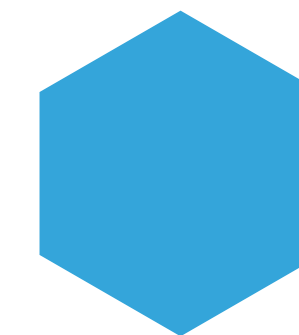
IceCube Neutrino Observatory



5,160 Digital Optical Modules (DOMs)



86 string with 60 DOMs each
6 denser strings called DeepCore



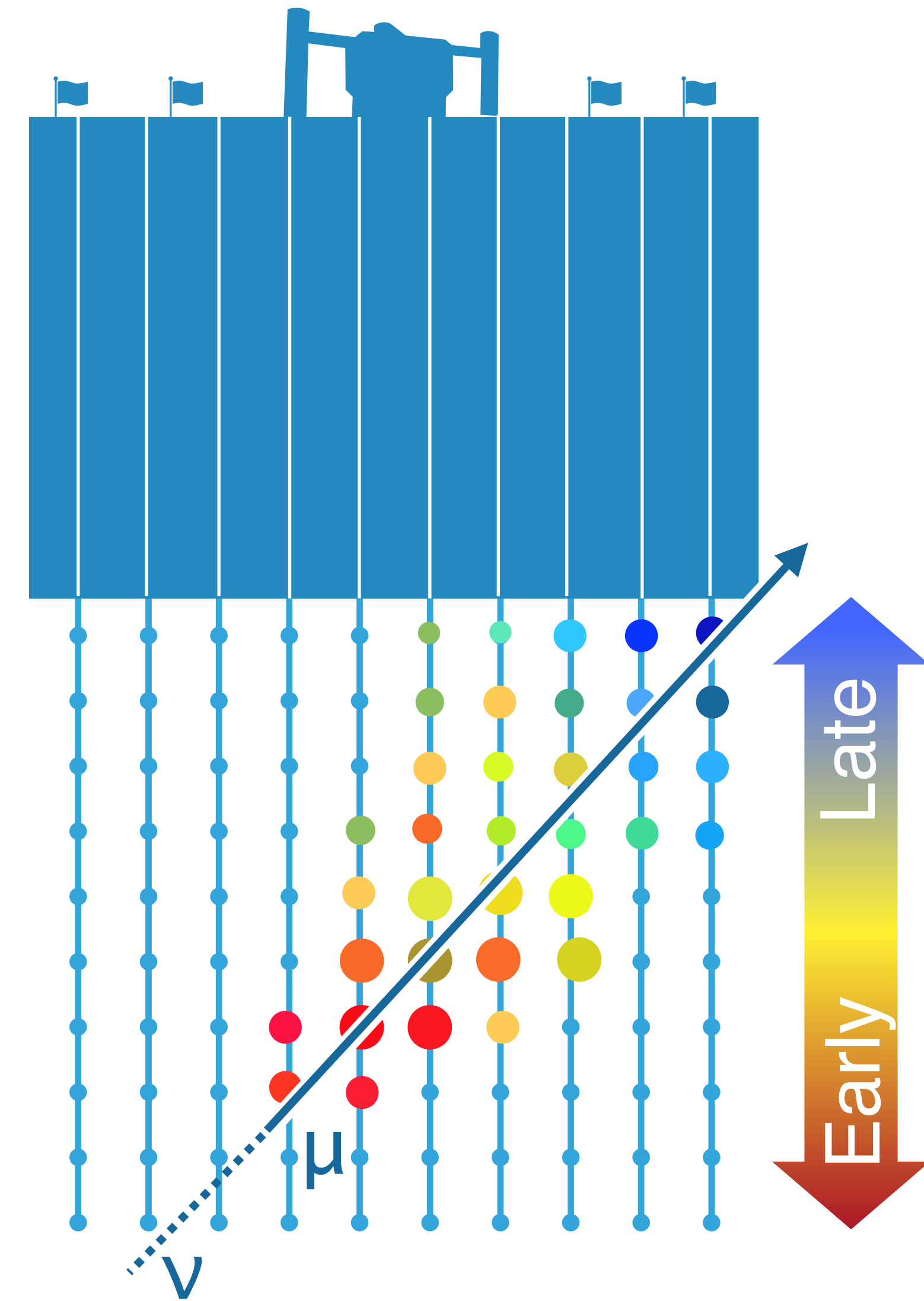
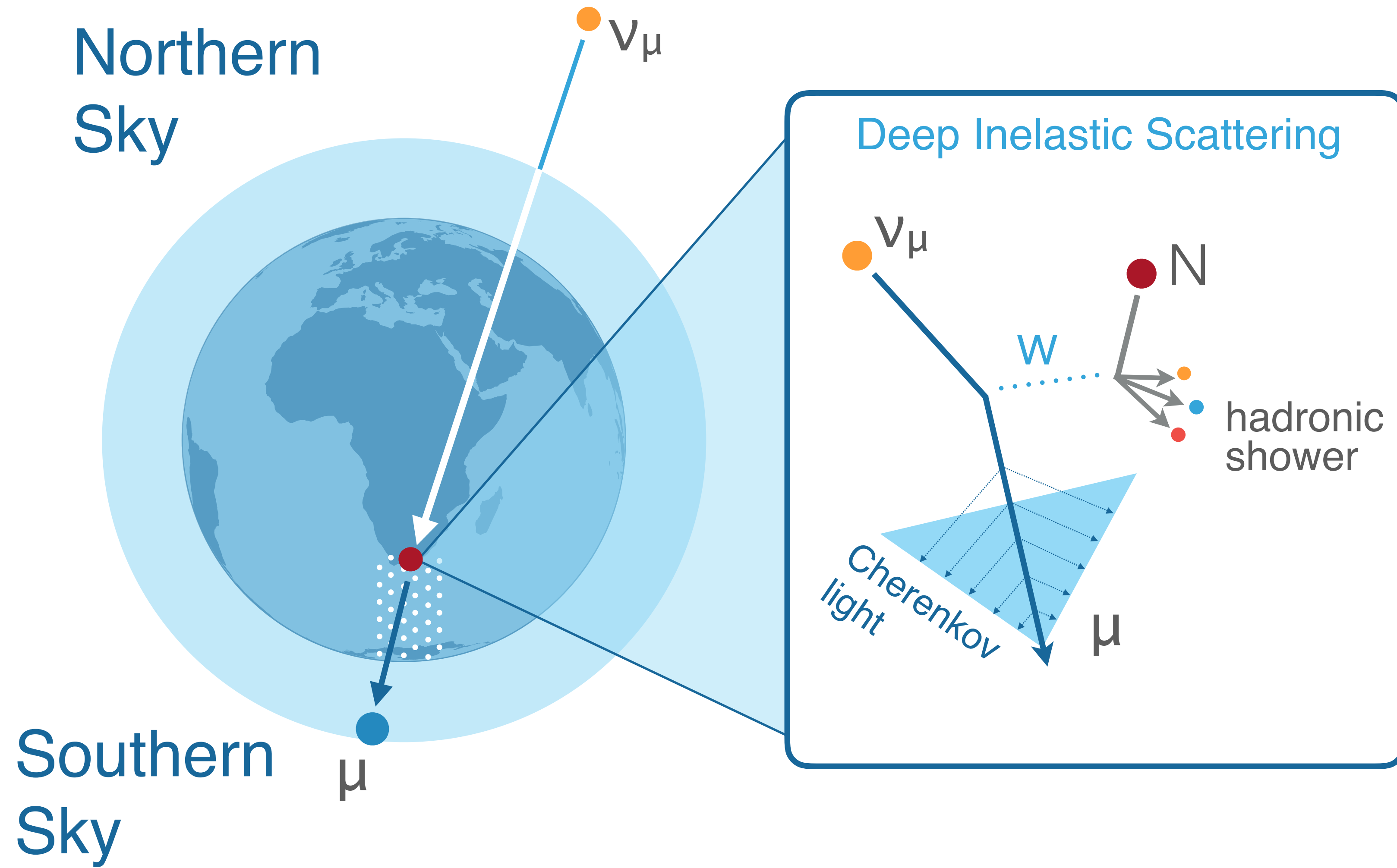
1 km² surface array with 324 DOMs: IceTop



Completion in December 2010



Detection principle

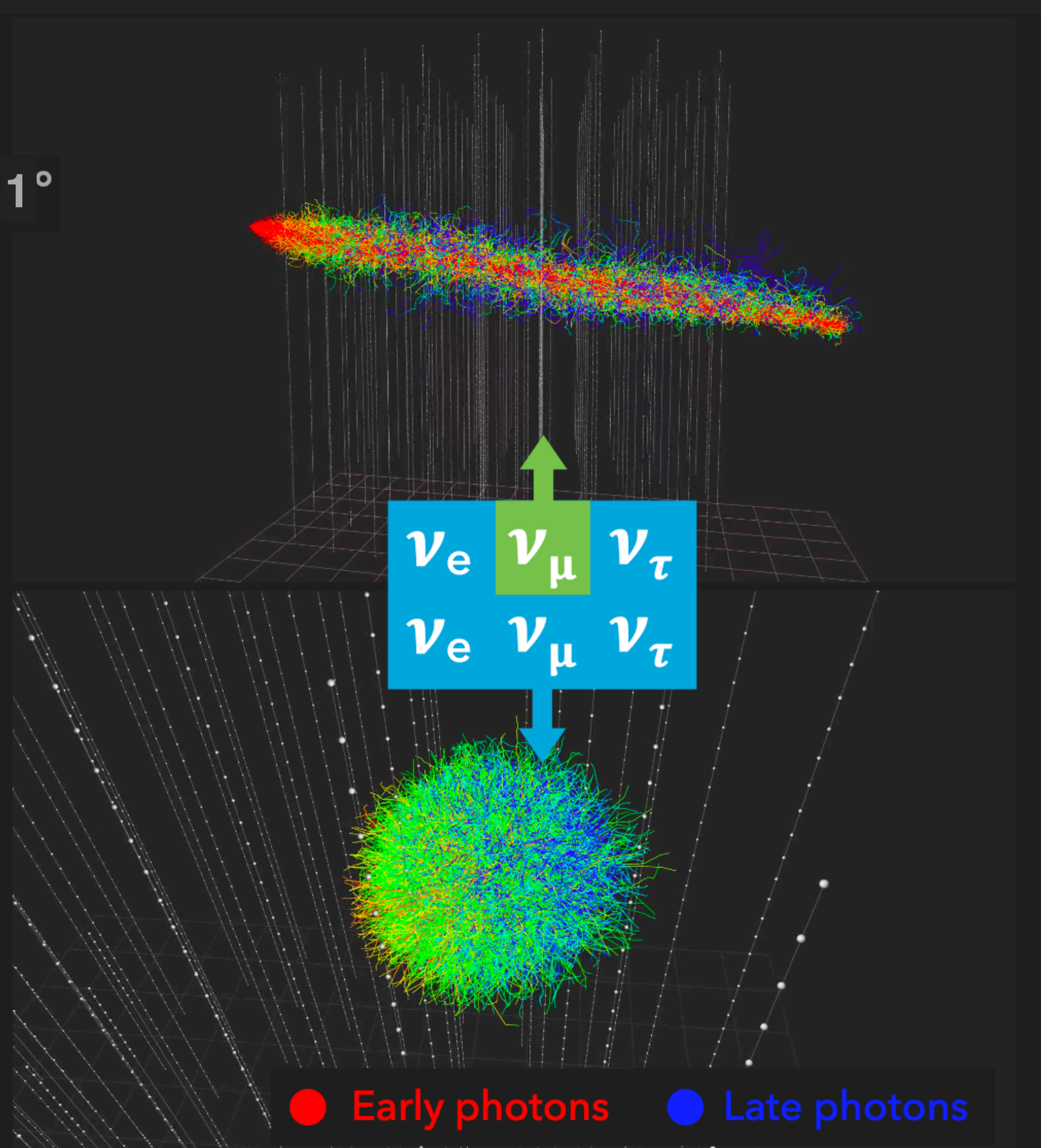


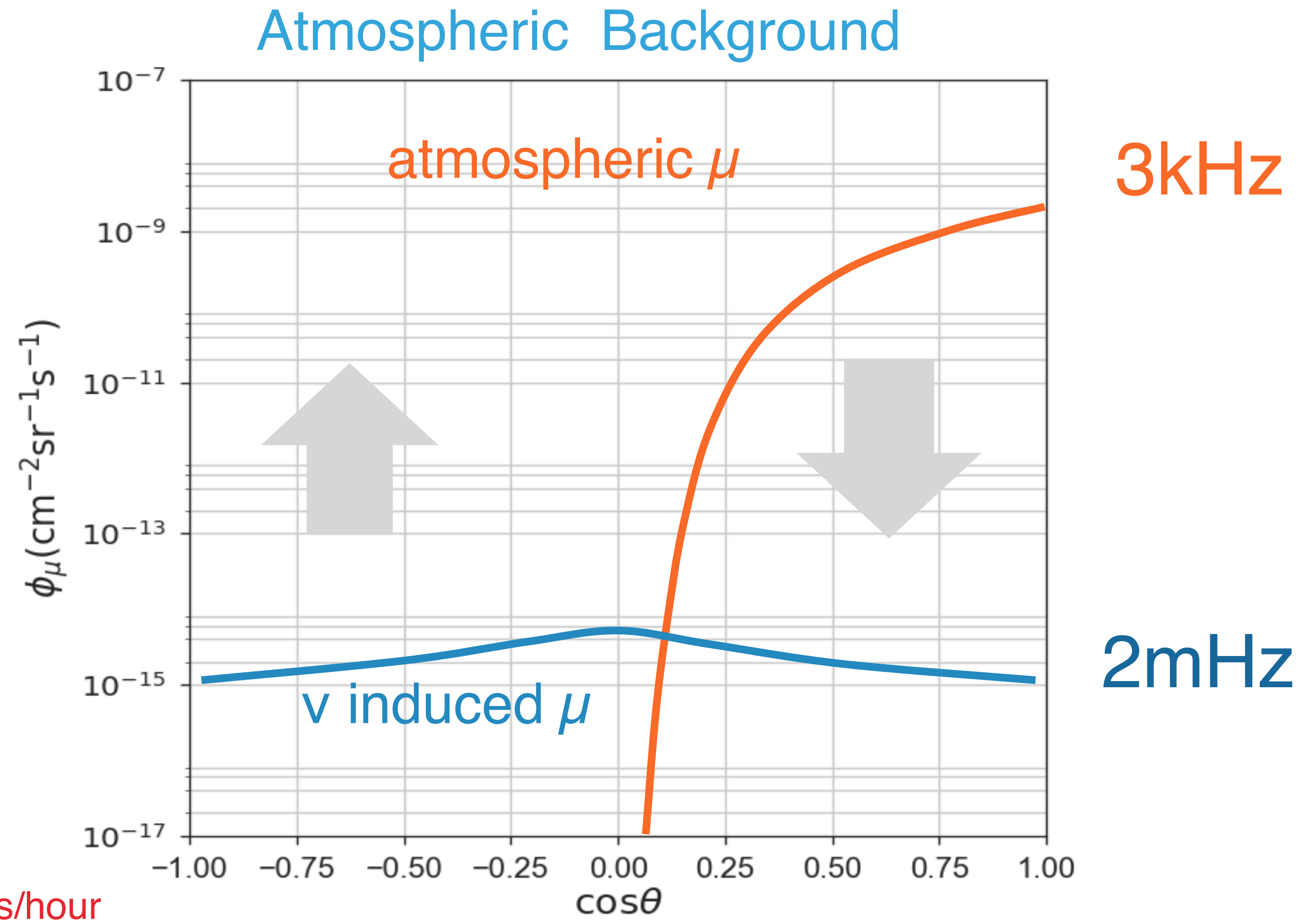
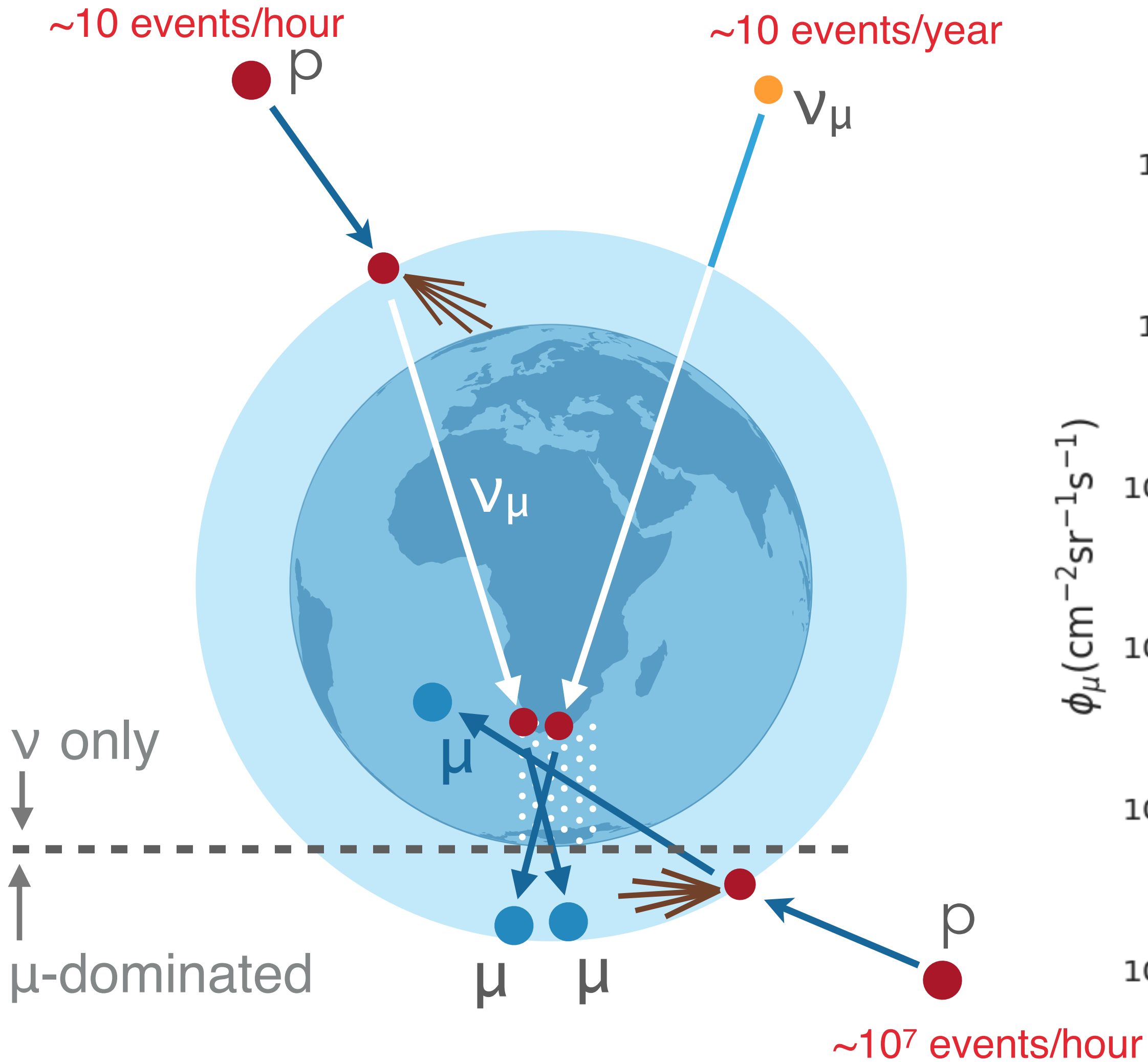
Track topology

- ▶ Good angular resolution $0.2^\circ - 1^\circ$
→ Neutrino Astronomy
- ▶ Vertex can be outside the detector → Increased effective volume

Cascade topology

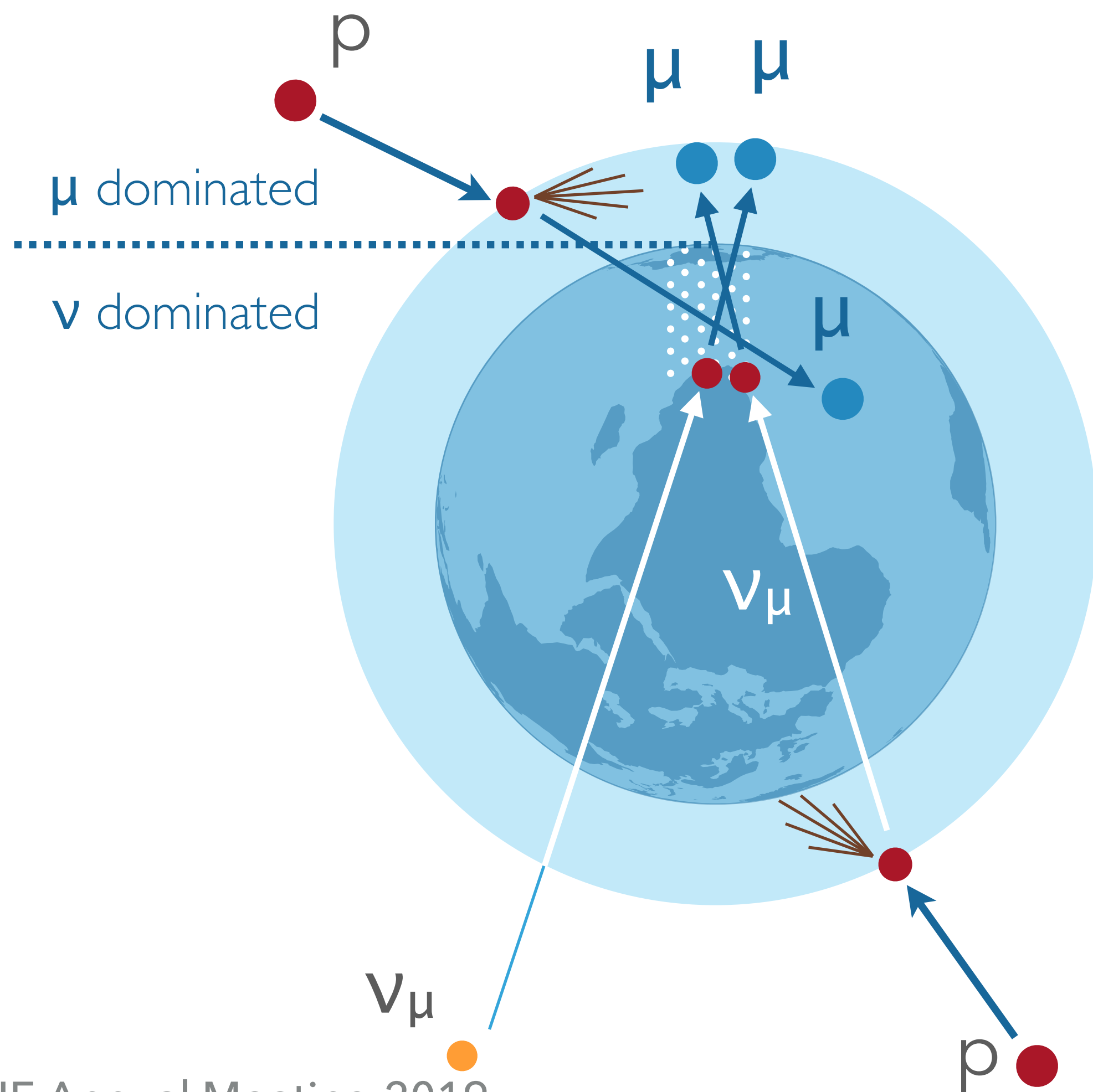
- ▶ All flavors
- ▶ Fully active calorimeter → Good energy resolution $\pm 15\%$ deposited energy
- ▶ Angular reconstruction possible → $\sim 10^\circ > 100 \text{ TeV}$



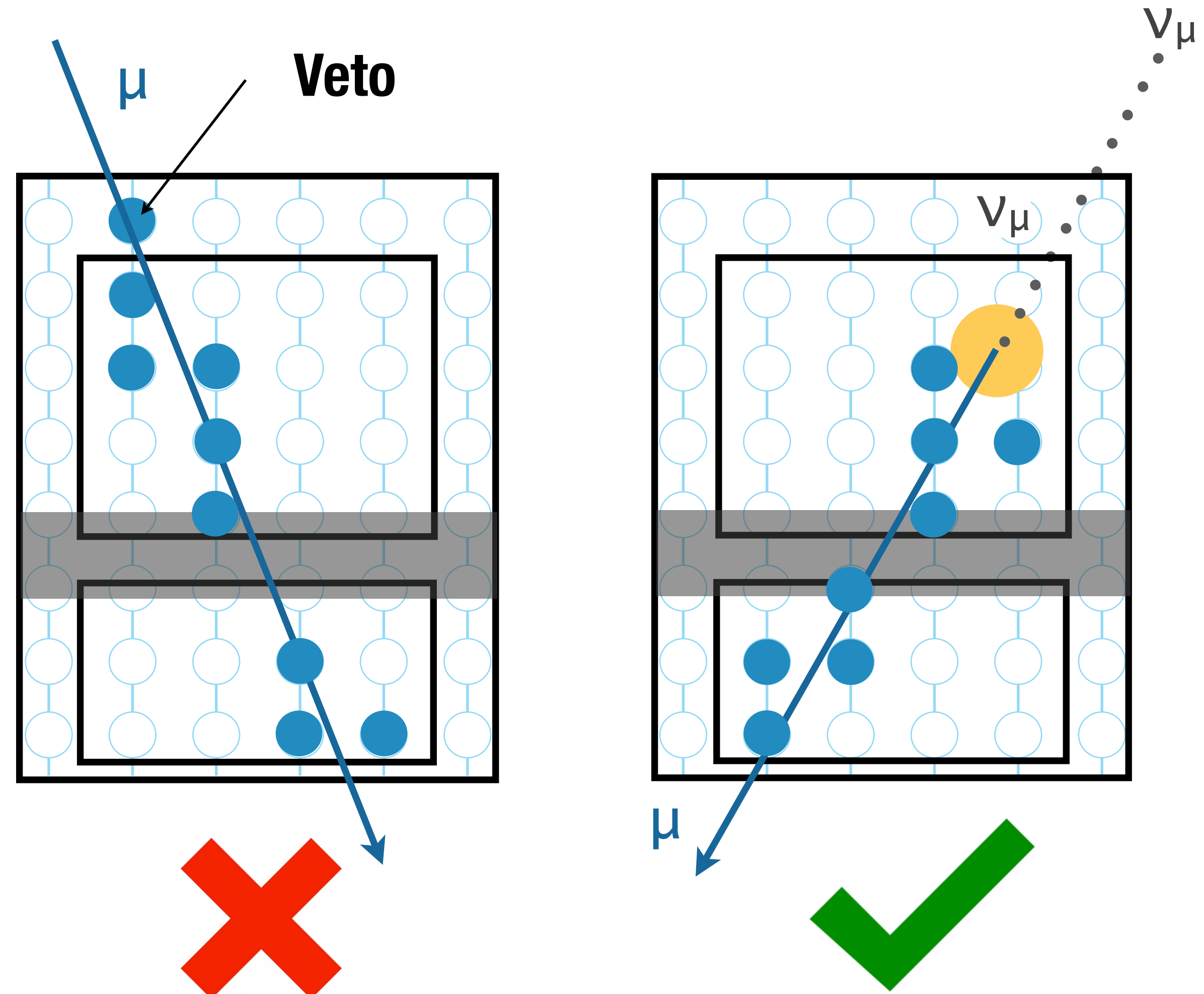


Rejecting the Background

1 Using up-going **through-going muon** events using Earth as a shield against atmospheric muons.

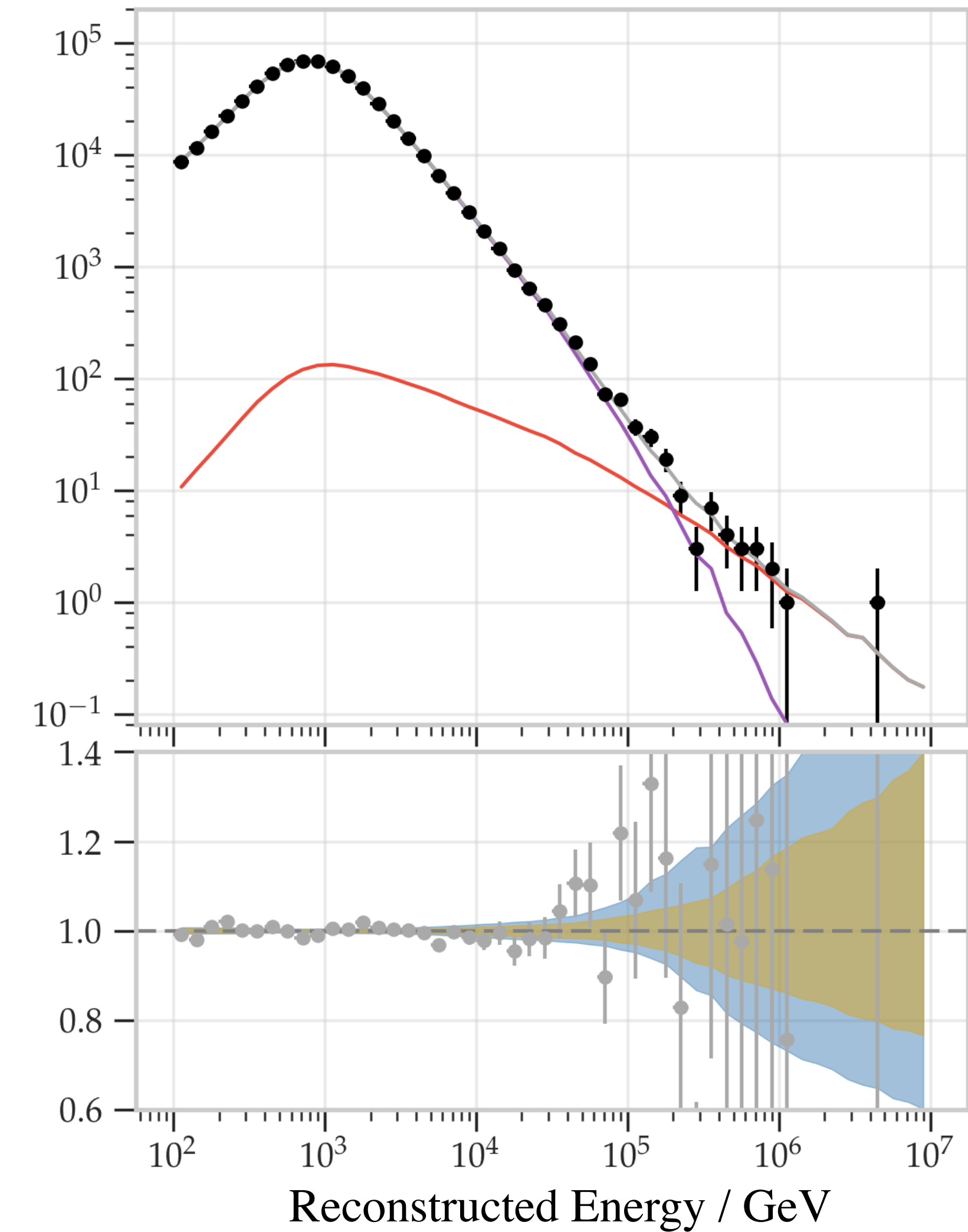
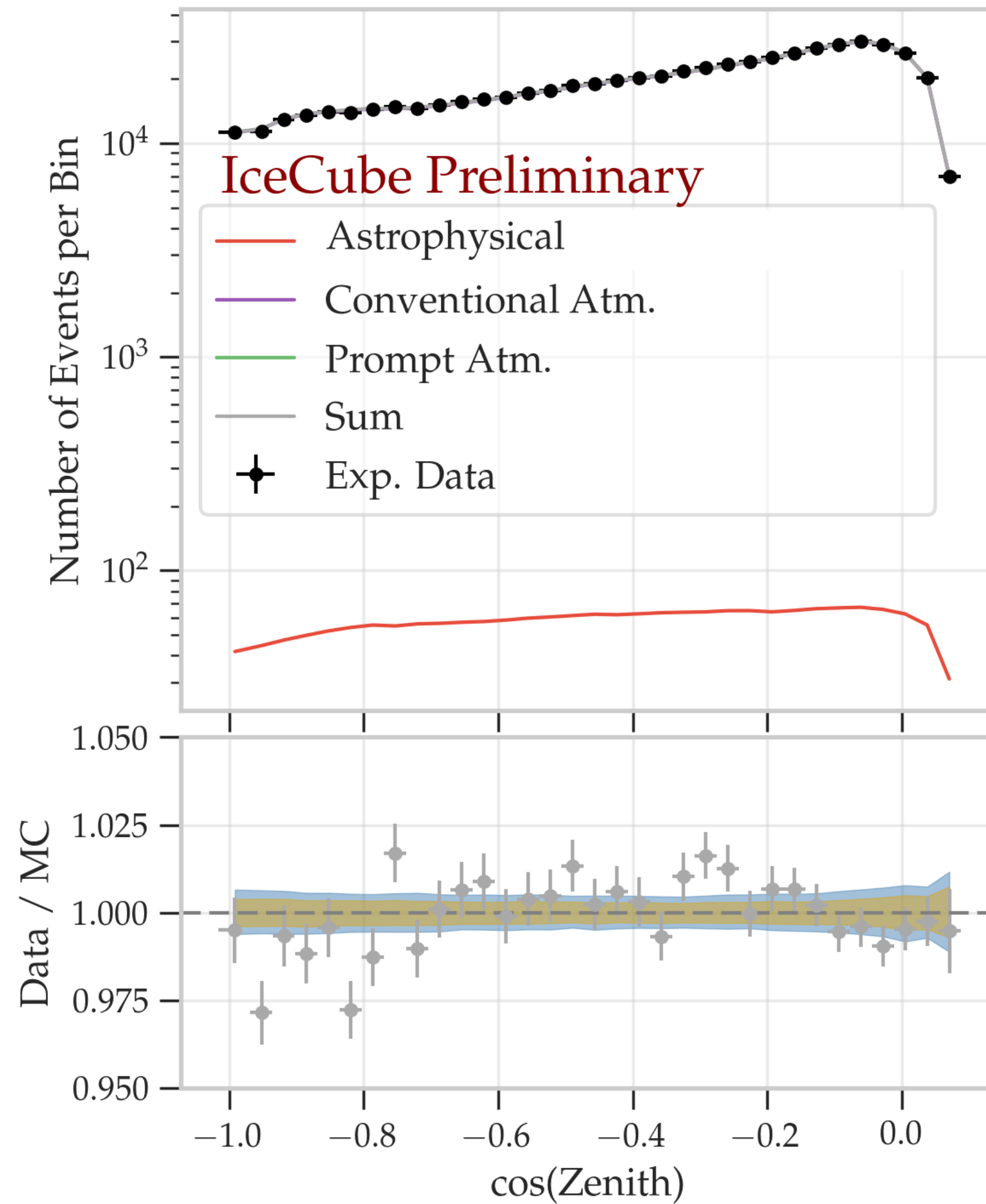


2 Using the outer layers as an active veto to select **starting events**.



Updated calibration, updated background modeling and systematics.

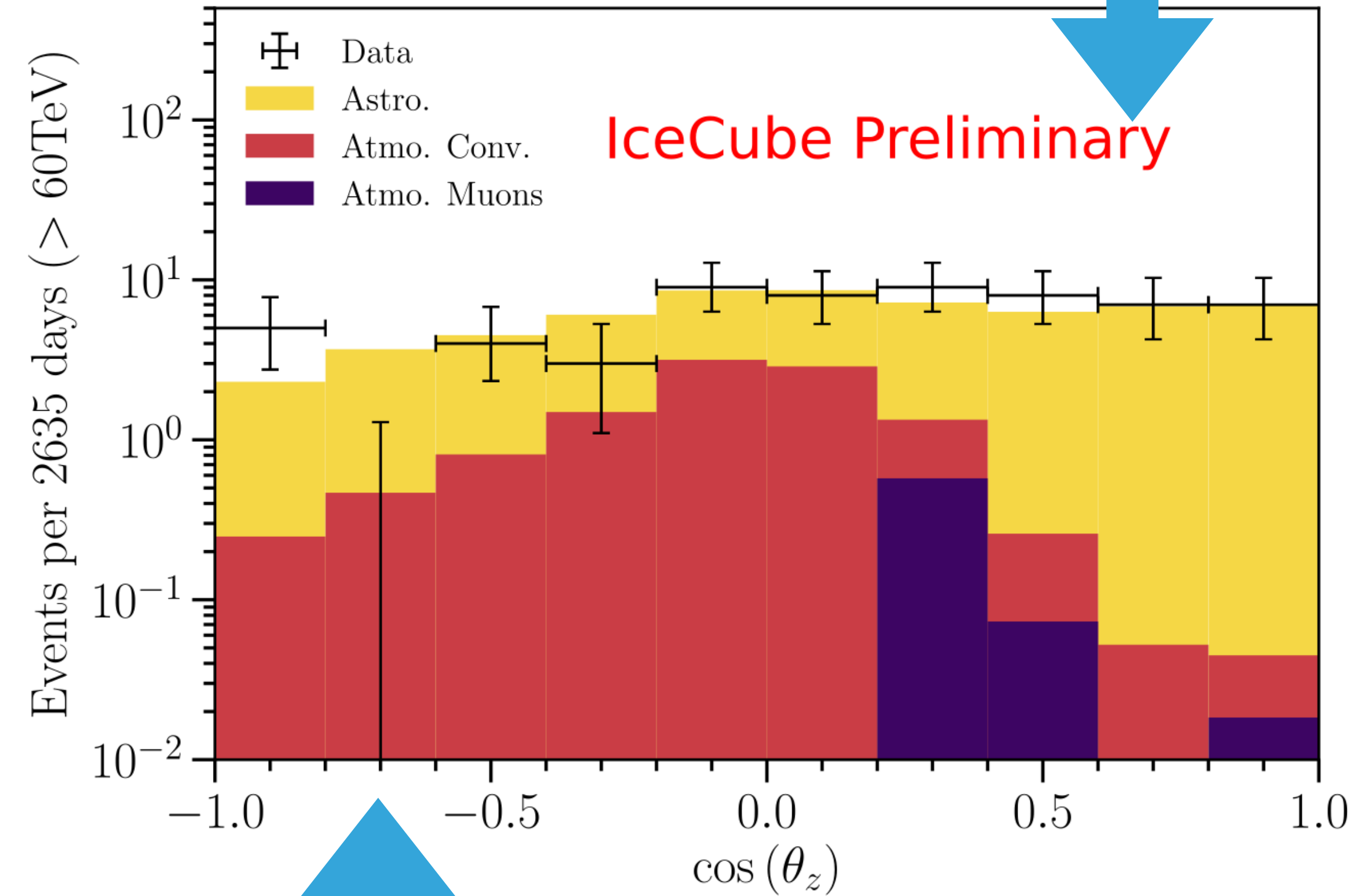
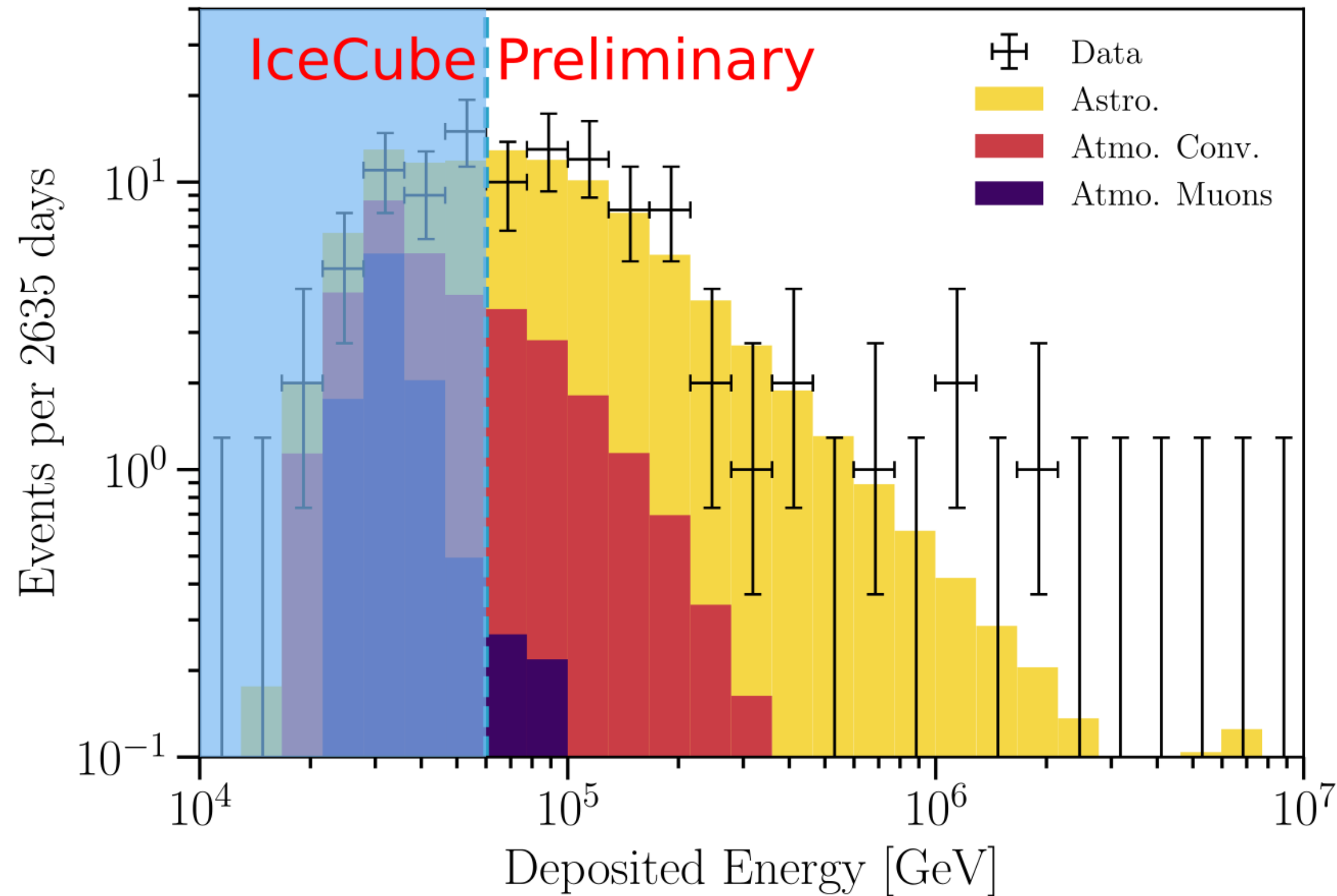
[IceCube Collaboration, PoS (ICRC2019) 1017]



CLEAR EXCESS > 100 TEV (57 EVENTS)
HIGH STAT. ~650,000 EVENTS (~1000-2000 ASTROPHYSICAL)
HARD SPECTRUM ($\gamma \sim 2.28$), SLIGHTLY SOFTER THAN PREVIOUS 8YR RESULTS ($\gamma \sim 2.19$) MOSTLY CAUSED BY A BETTER TREATMENT OF THE PRIMARY COSMIC-RAY FLUX

Updated calibration, updated background modeling and systematics, new double cascade identifier.

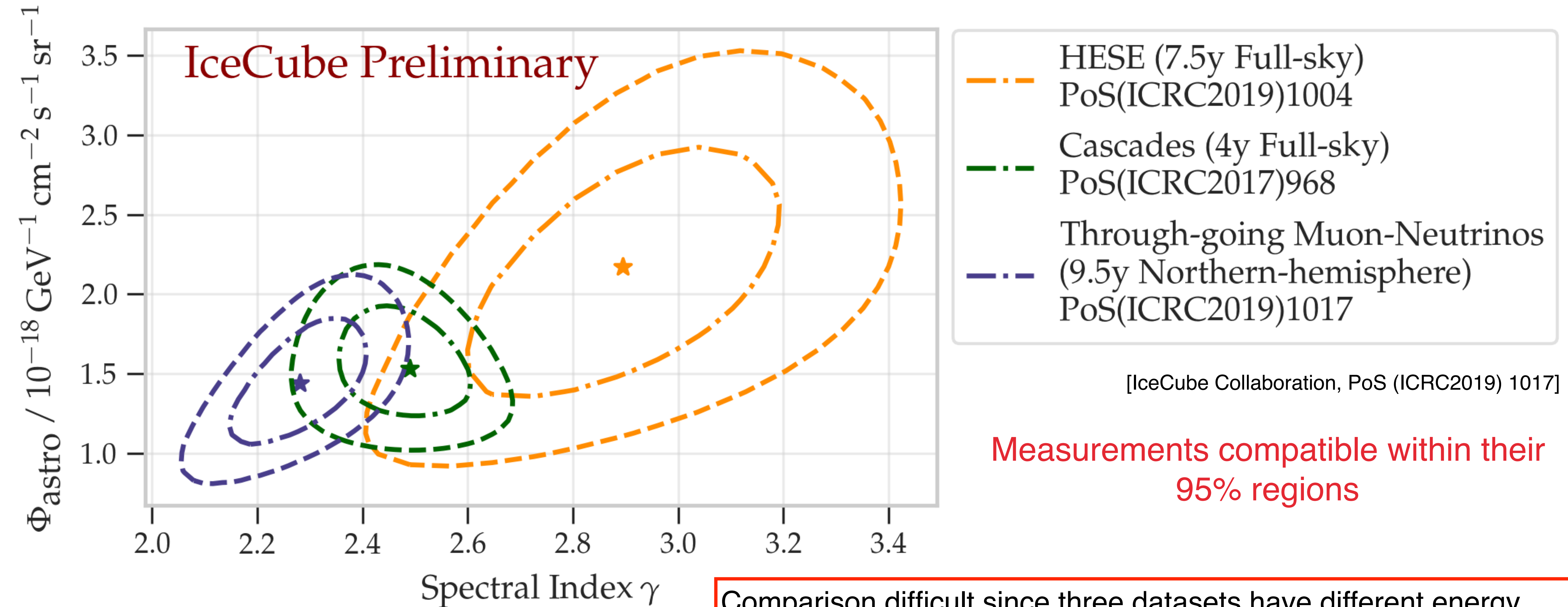
Southern Sky



Northern Sky

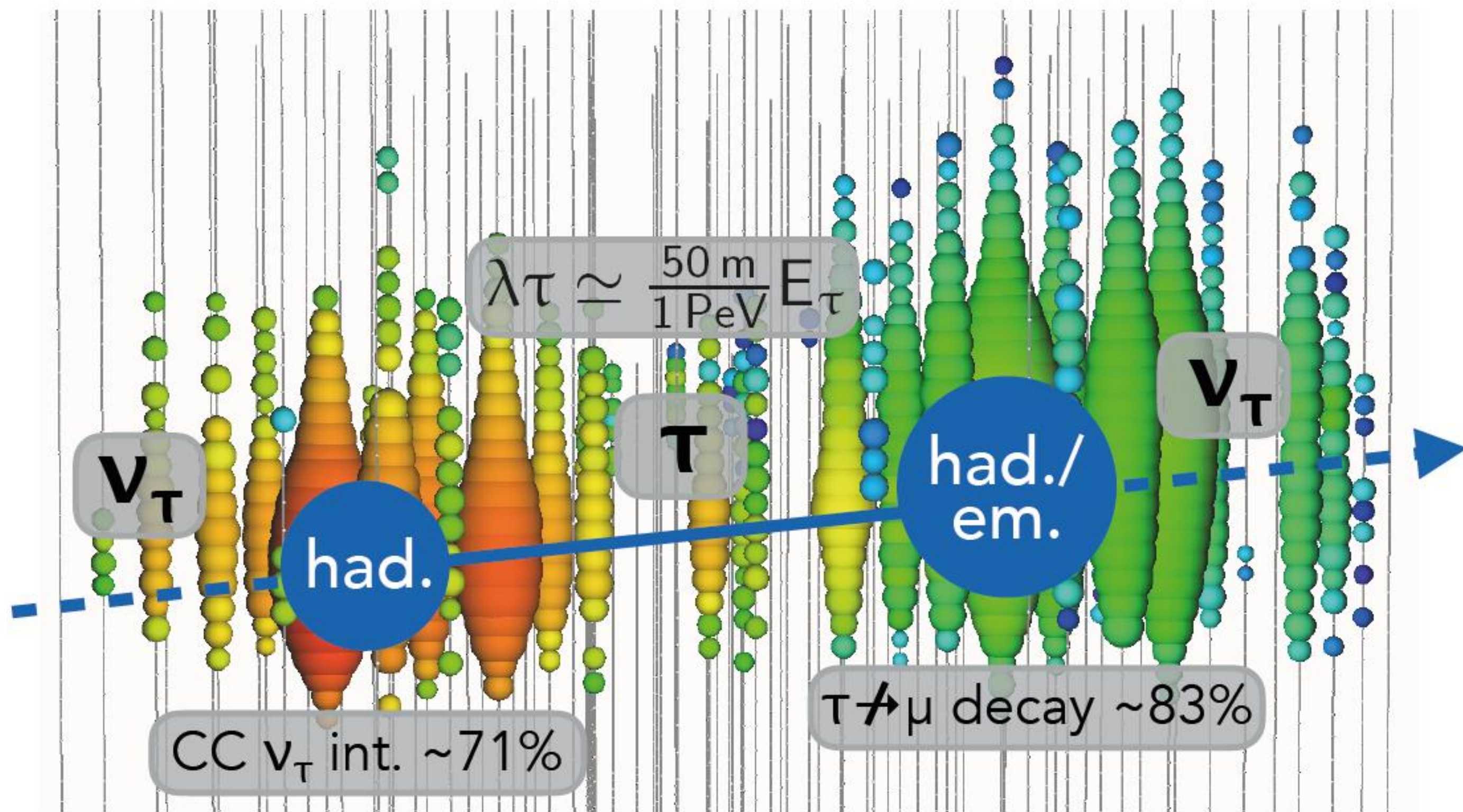
CLEAR EXCESS ABOVE ATMOSPHERIC BACKGROUND $> 60\text{ TeV}$
 SOFT SPECTRUM ($\gamma \sim 2.9$)
 NO PeV EVENTS OBSERVED SINCE 2013

Single power law astrophysical neutrino spectrum (no break preferred)



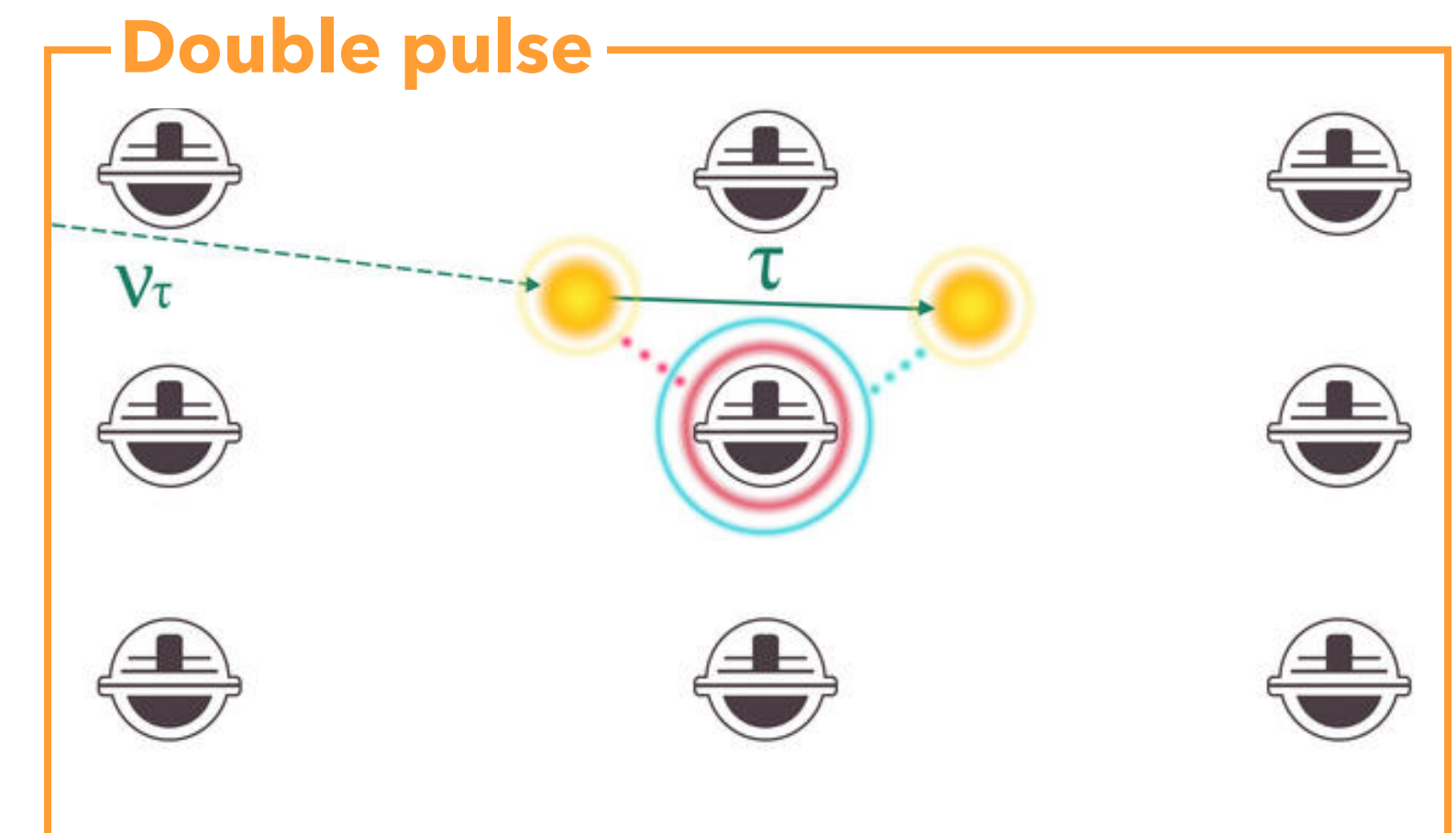
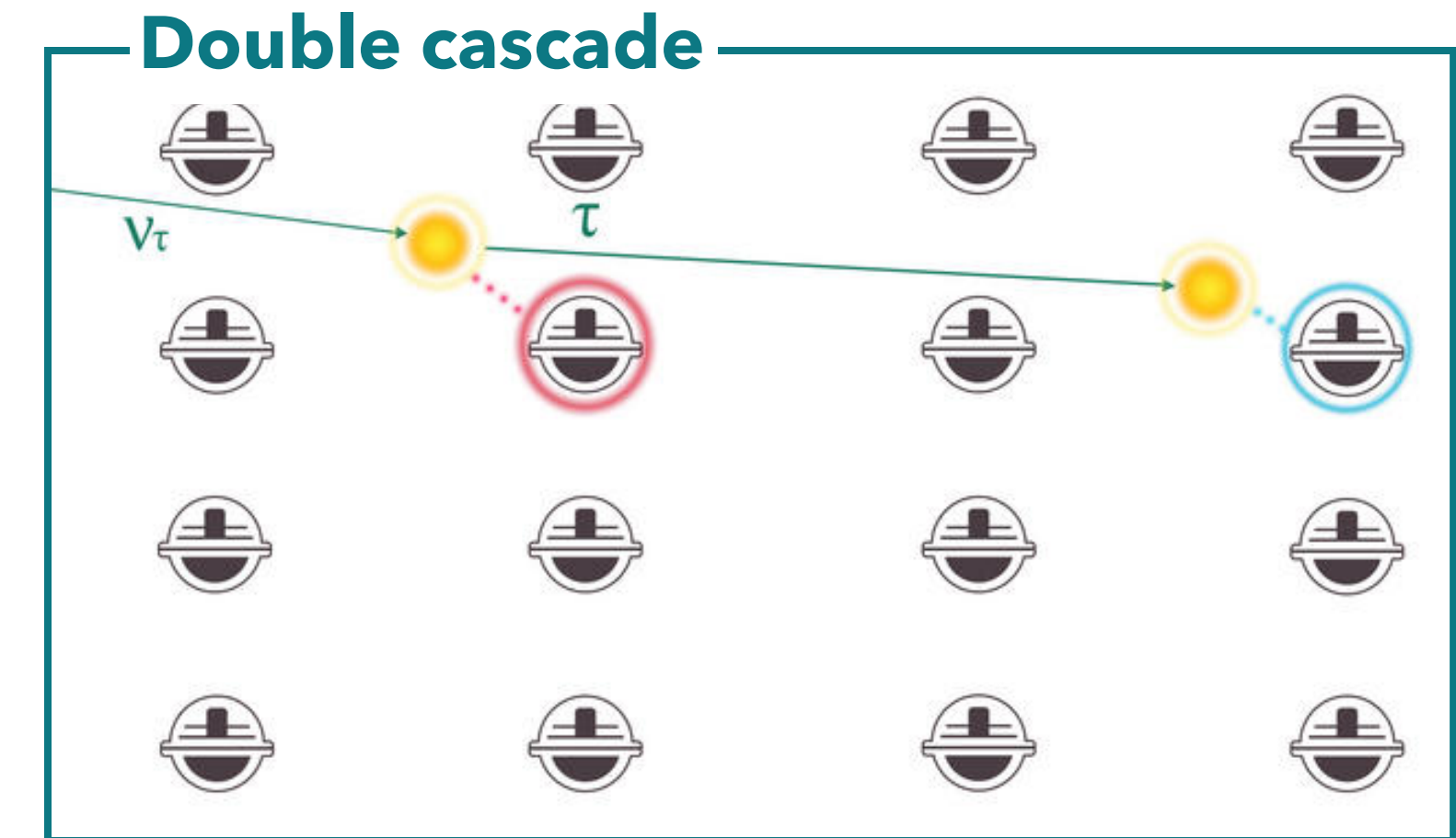
Comparison difficult since three datasets have different energy cuts and select different morphologies -> Working on a global fit

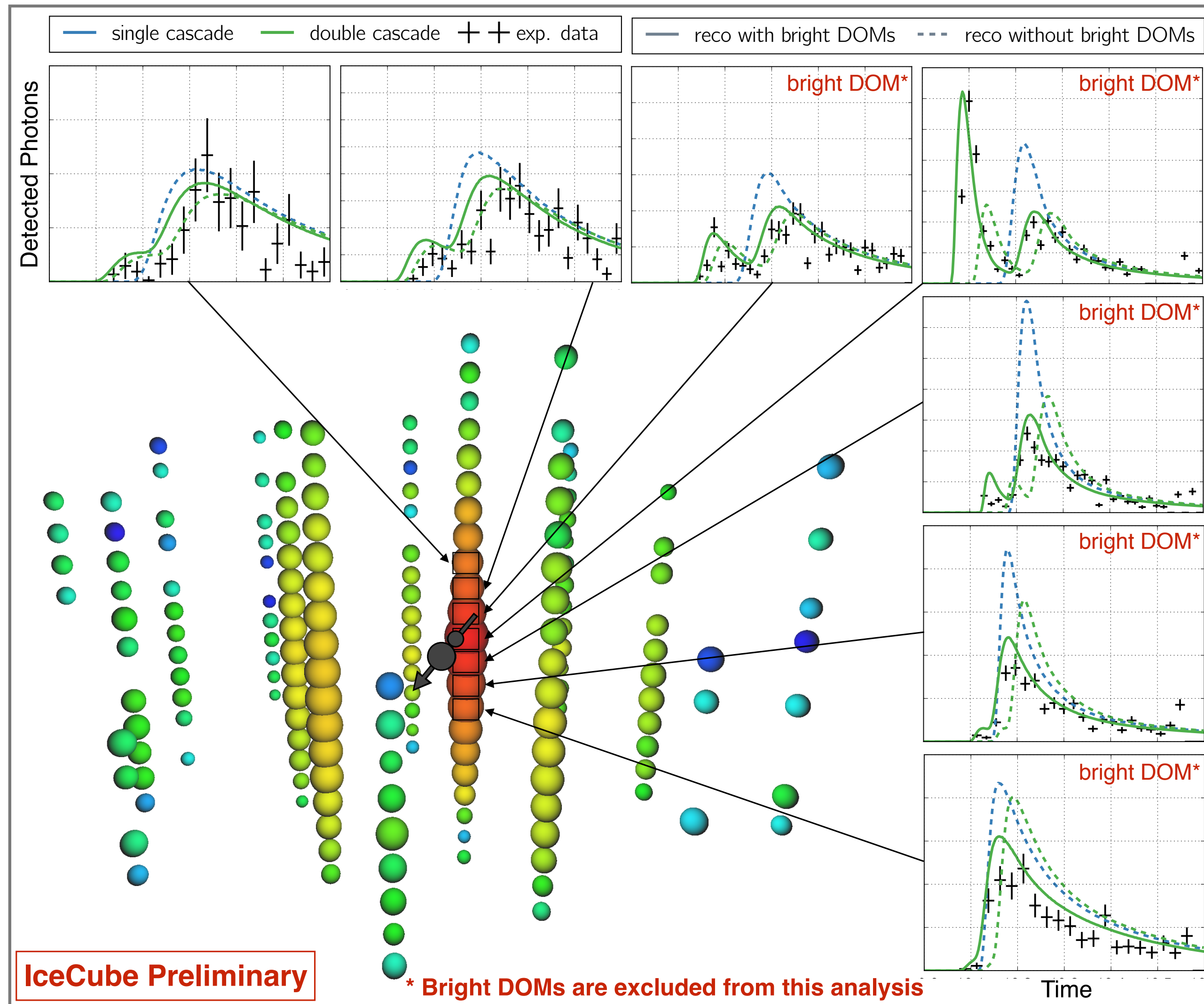
Standard neutrino oscillation predicts full mixing at Earth: $\sim 1/3$ of astrophysical neutrinos should be ν_τ



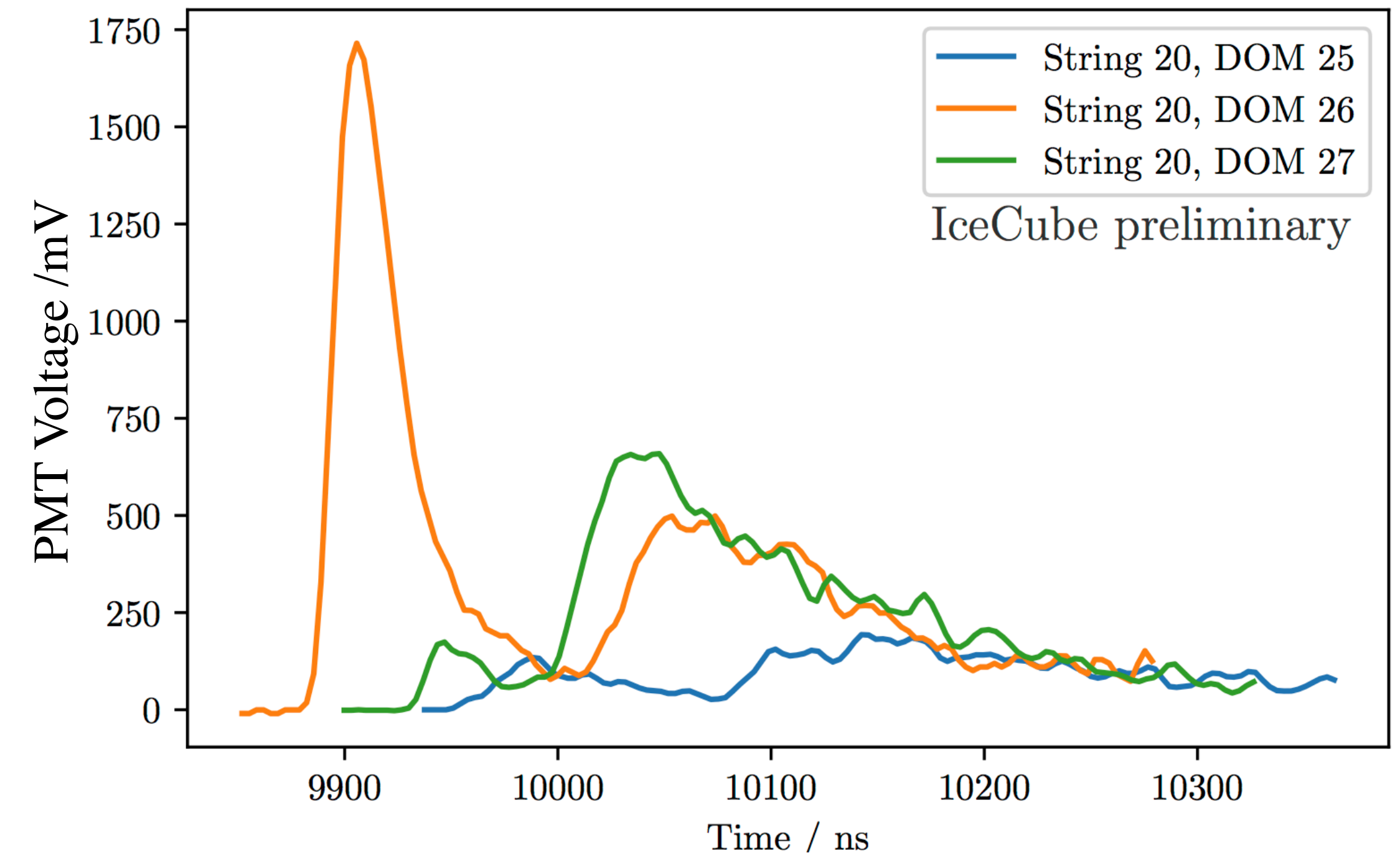
simulated double bang event with ~ 10 PeV neutrino energy

- ▶ (Almost) no atmospheric background
- ▶ Good energy resolution
- ▶ Good angular resolution





It is the only event passing both the double cascade search and double pulse waveform criteria from two independent searches.

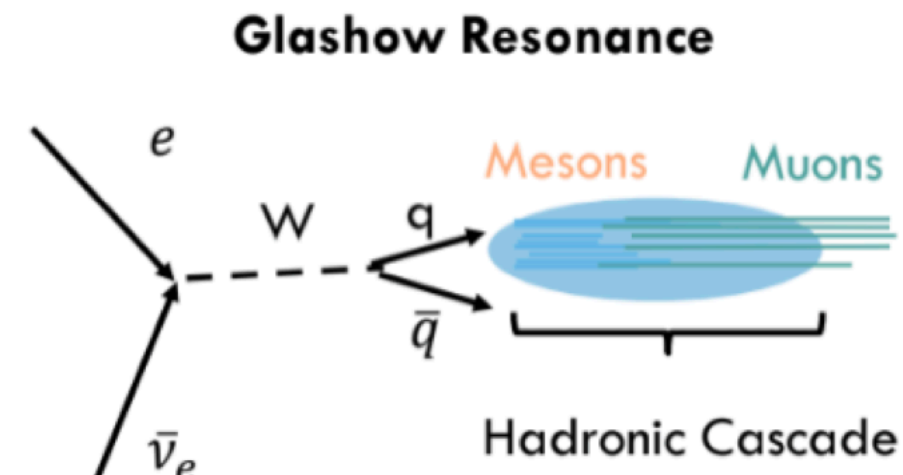
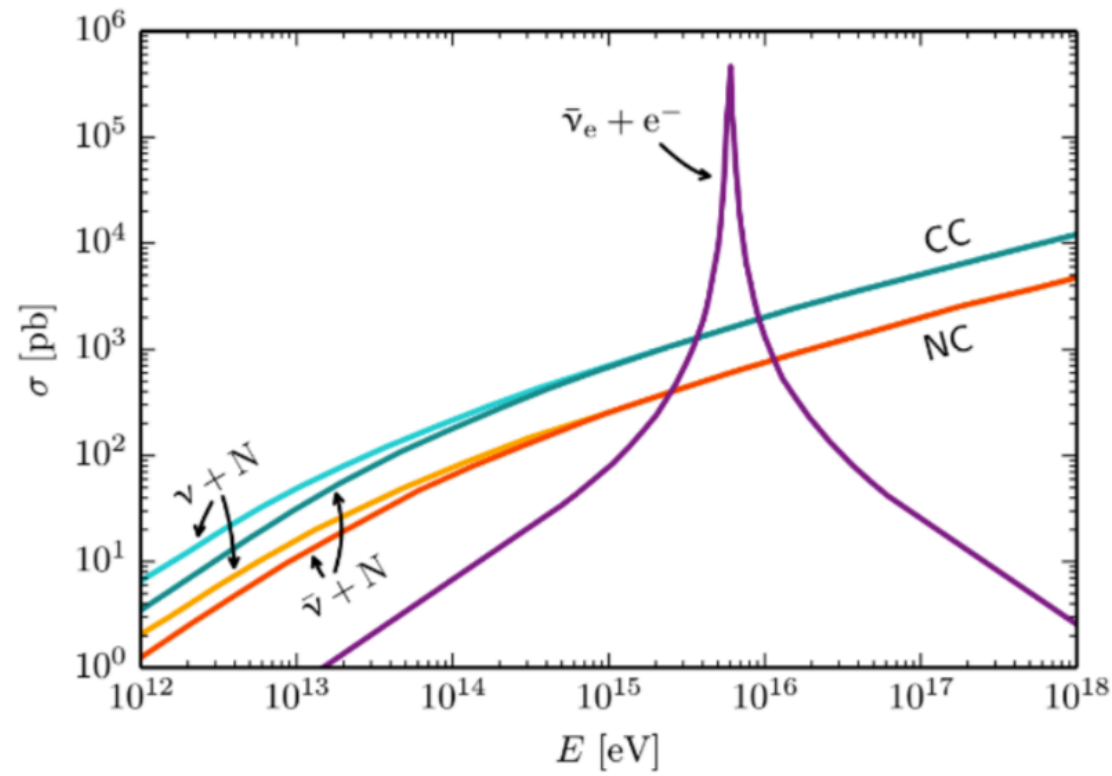


[IceCube Collaboration, PoS (ICRC2019) 1036]

[IceCube Collaboration, PoS (ICRC2019) 960]

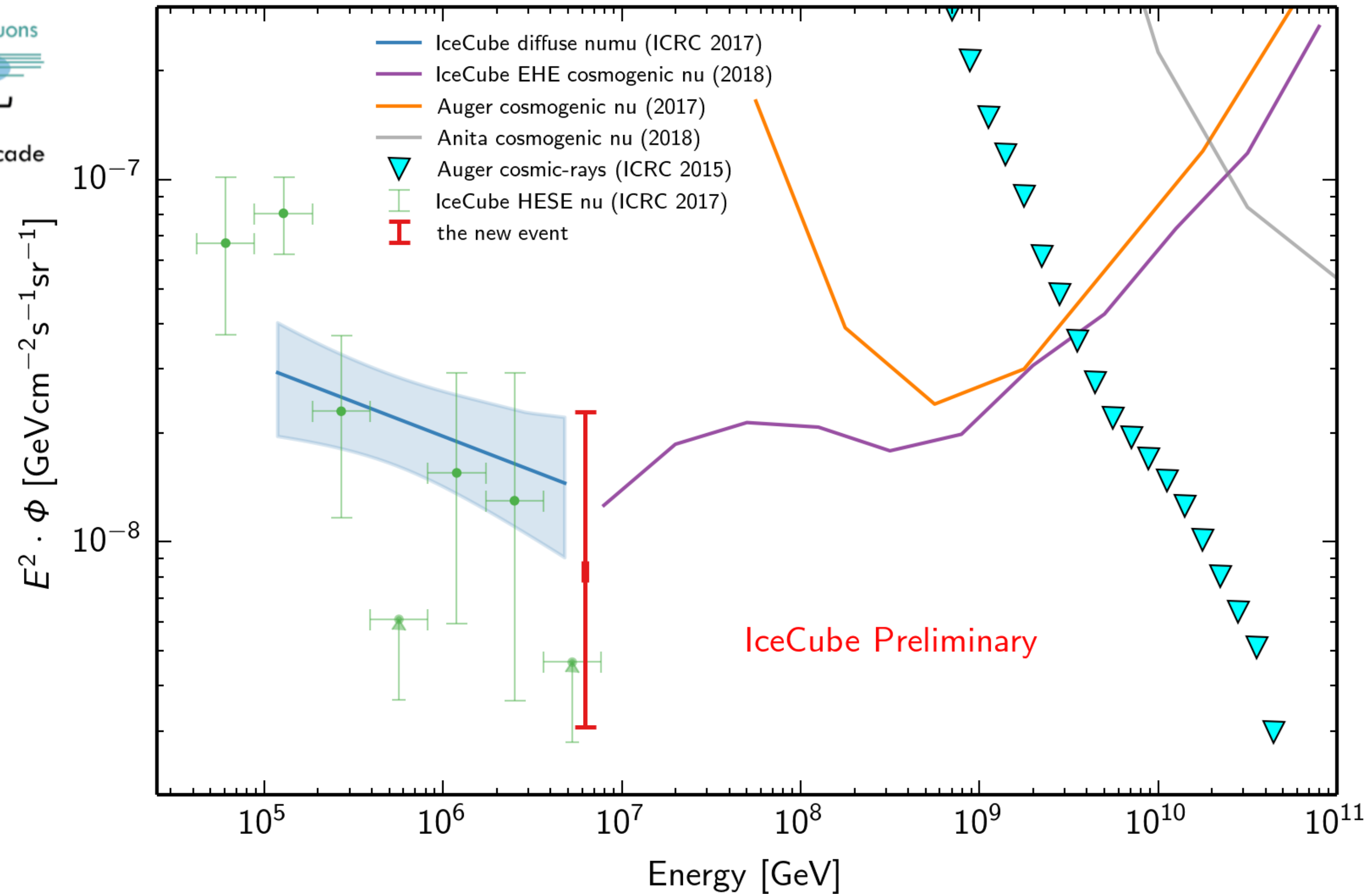
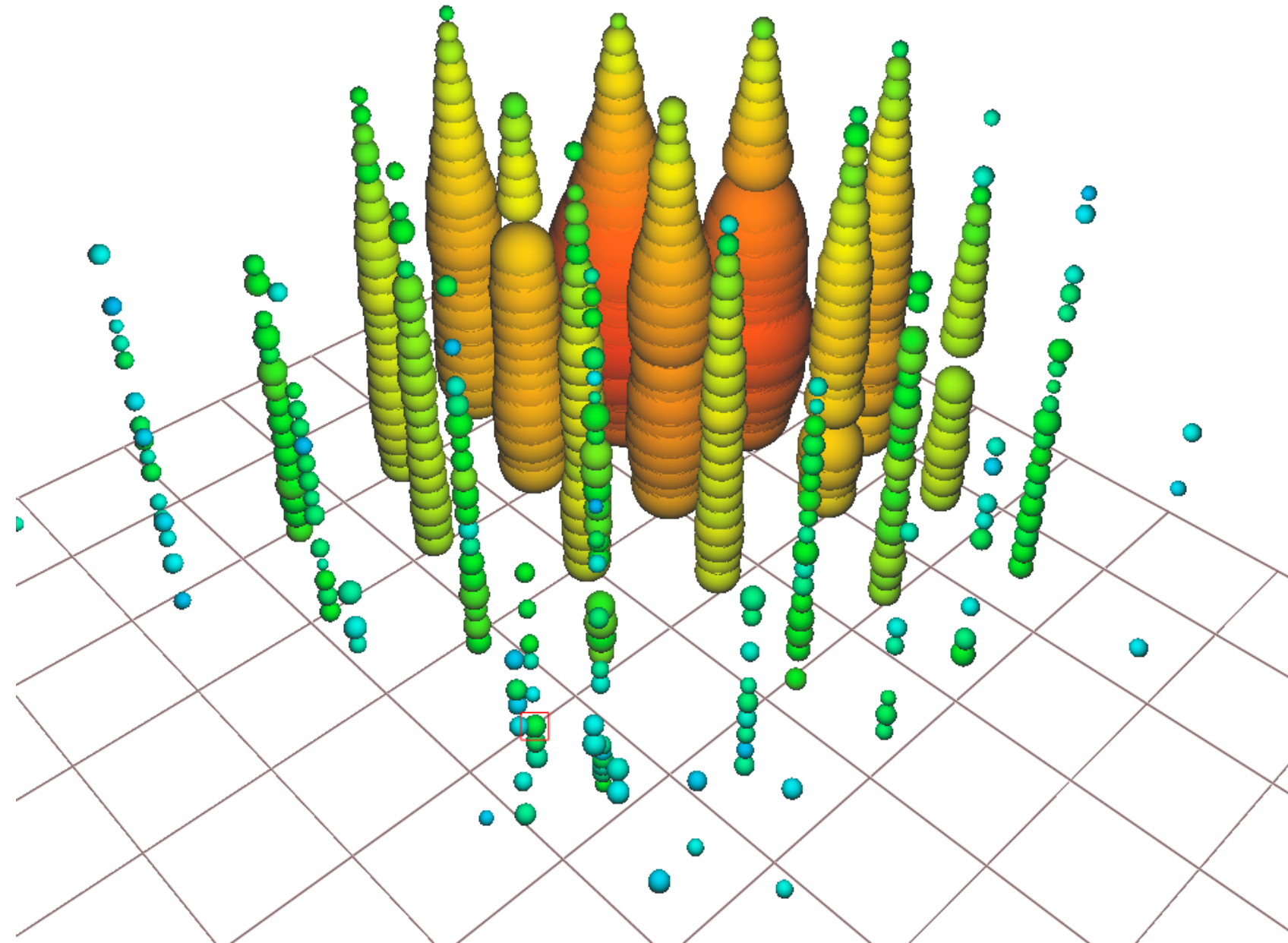
Partially contained cascades: the first Glashow event candidate

S. L. Glashow, Phys. Rev. 118 (1960) 316-317.



[Lu Lu (IceCube coll.), UHECR 2018, pub. in prep.]

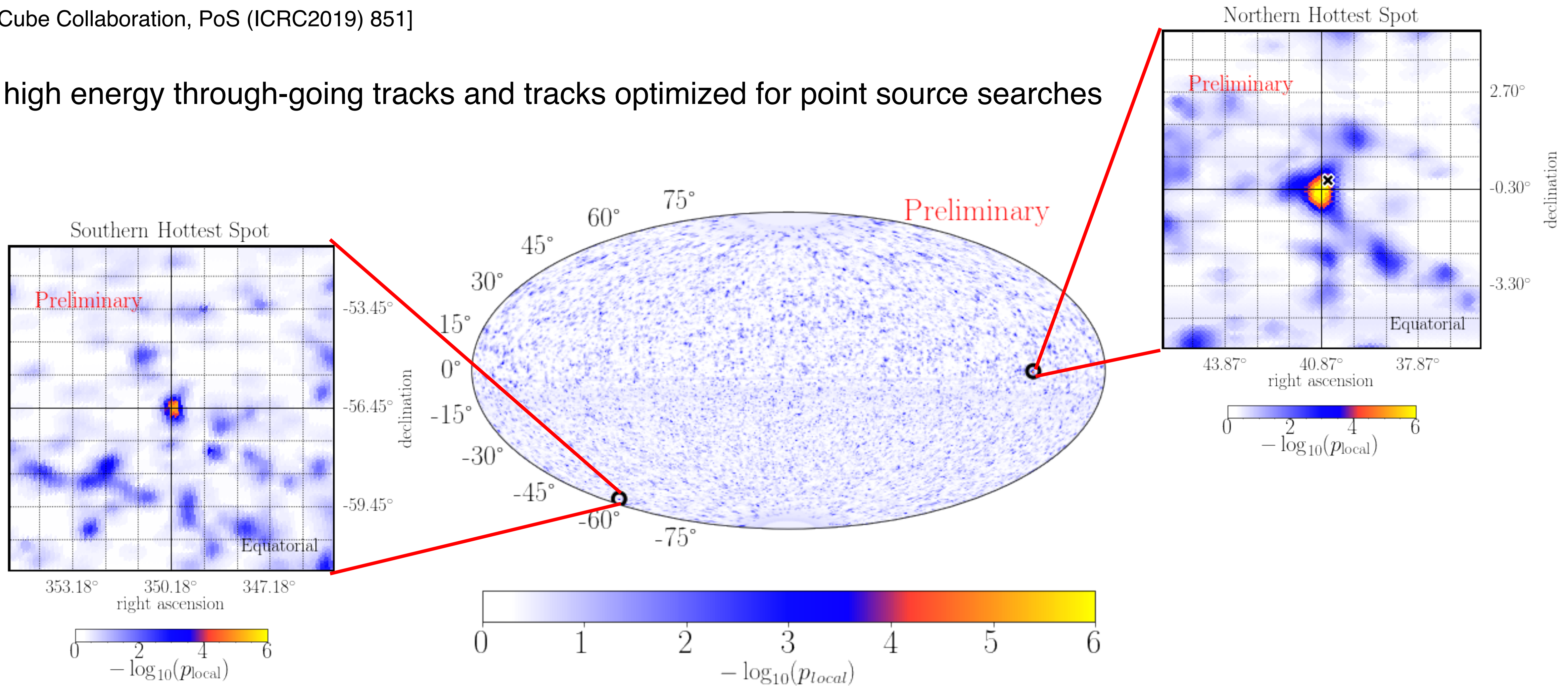
Resonance: $E_\nu = 6.3$ PeV
 Typical visible energy is 93%



Astrophysical neutrinos: 10 years all sky point sources

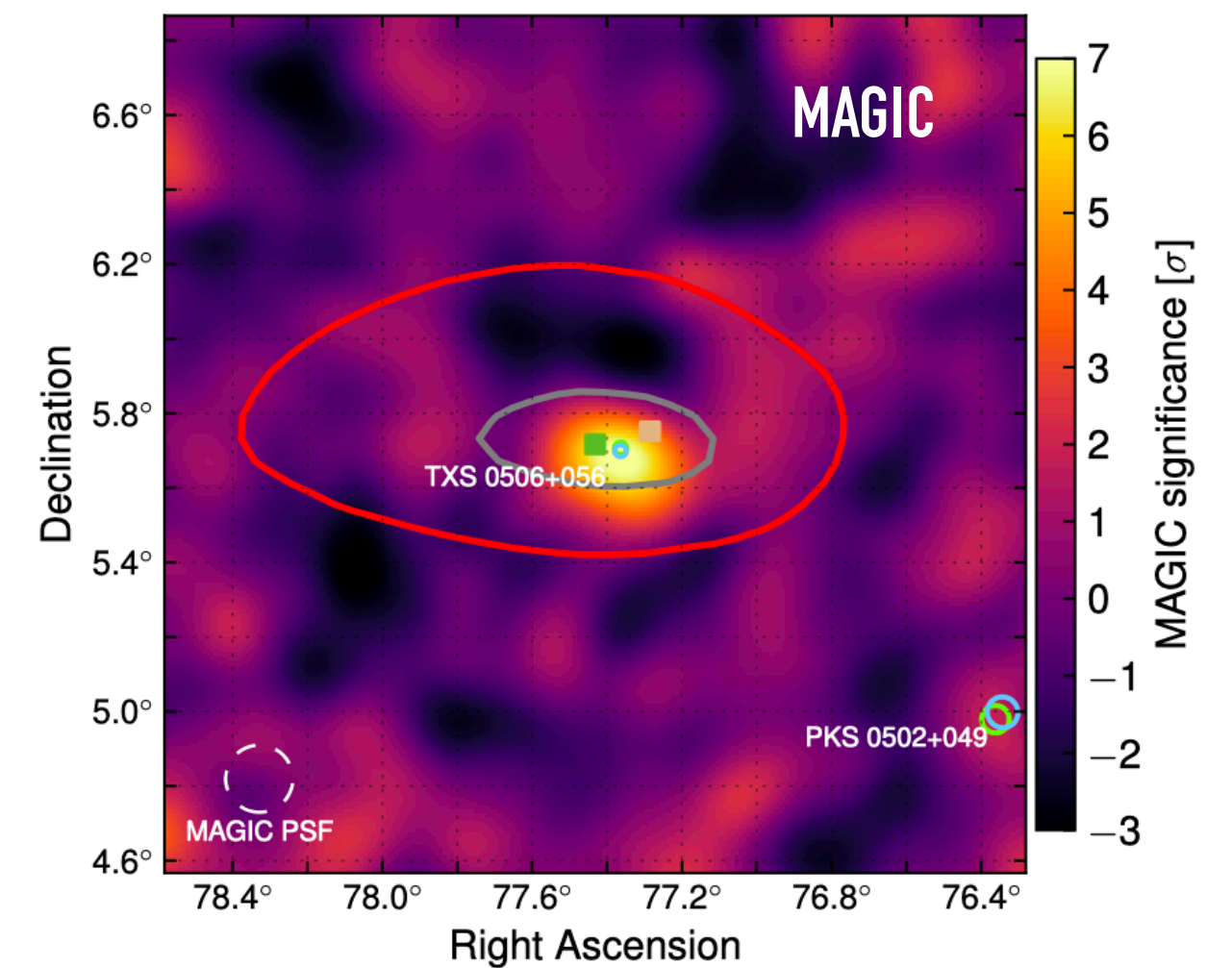
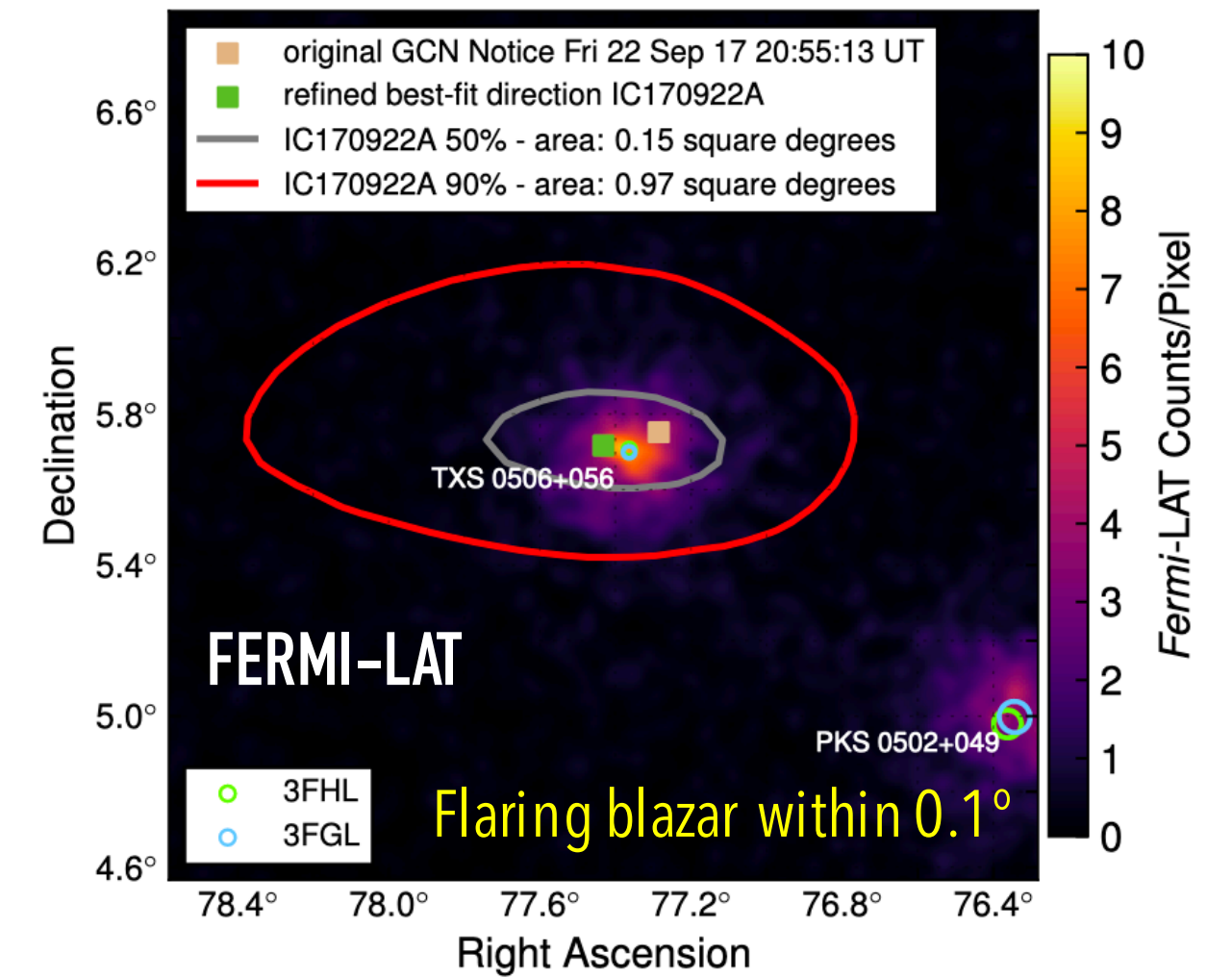
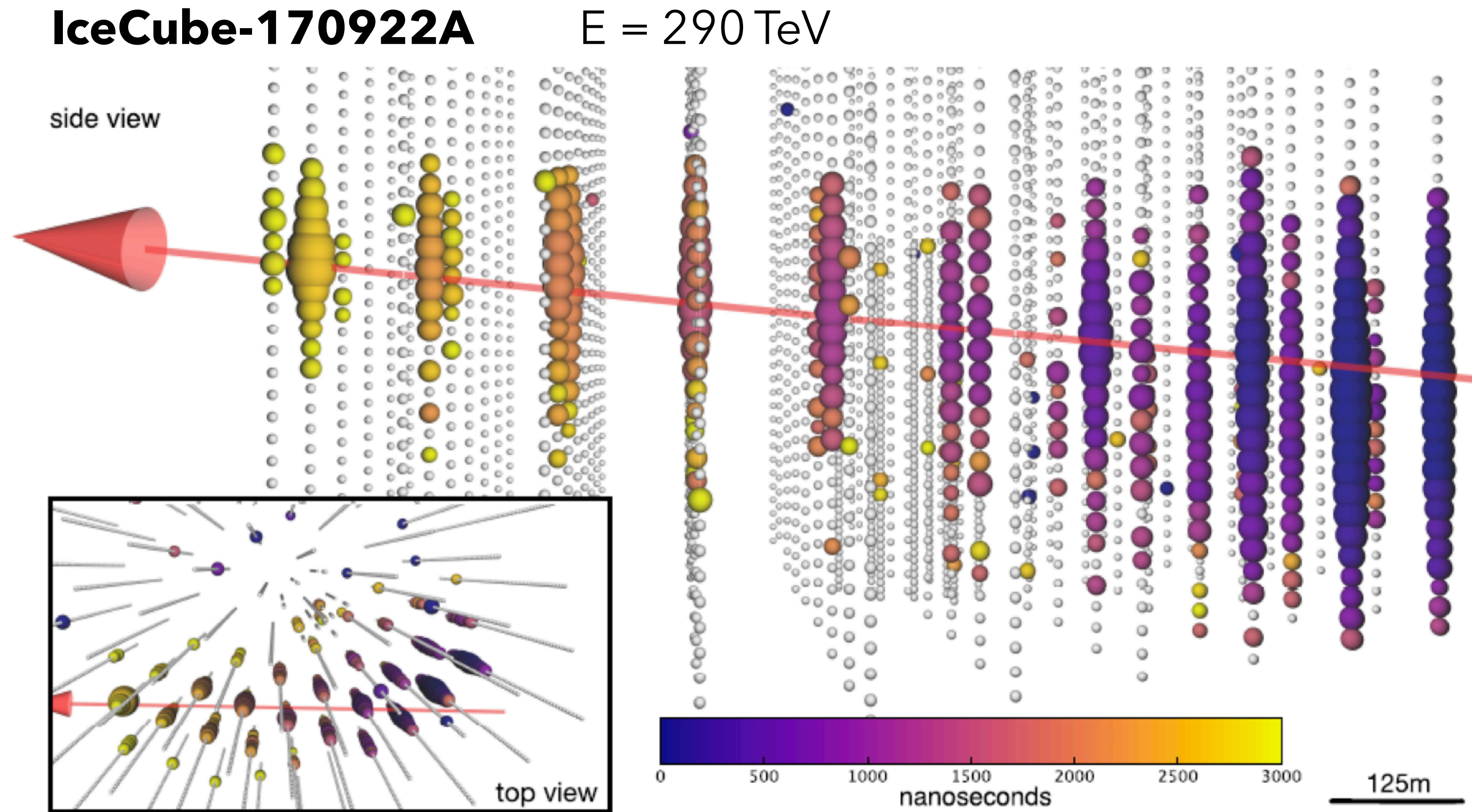
[IceCube Collaboration, PoS (ICRC2019) 851]

Using high energy through-going tracks and tracks optimized for point source searches

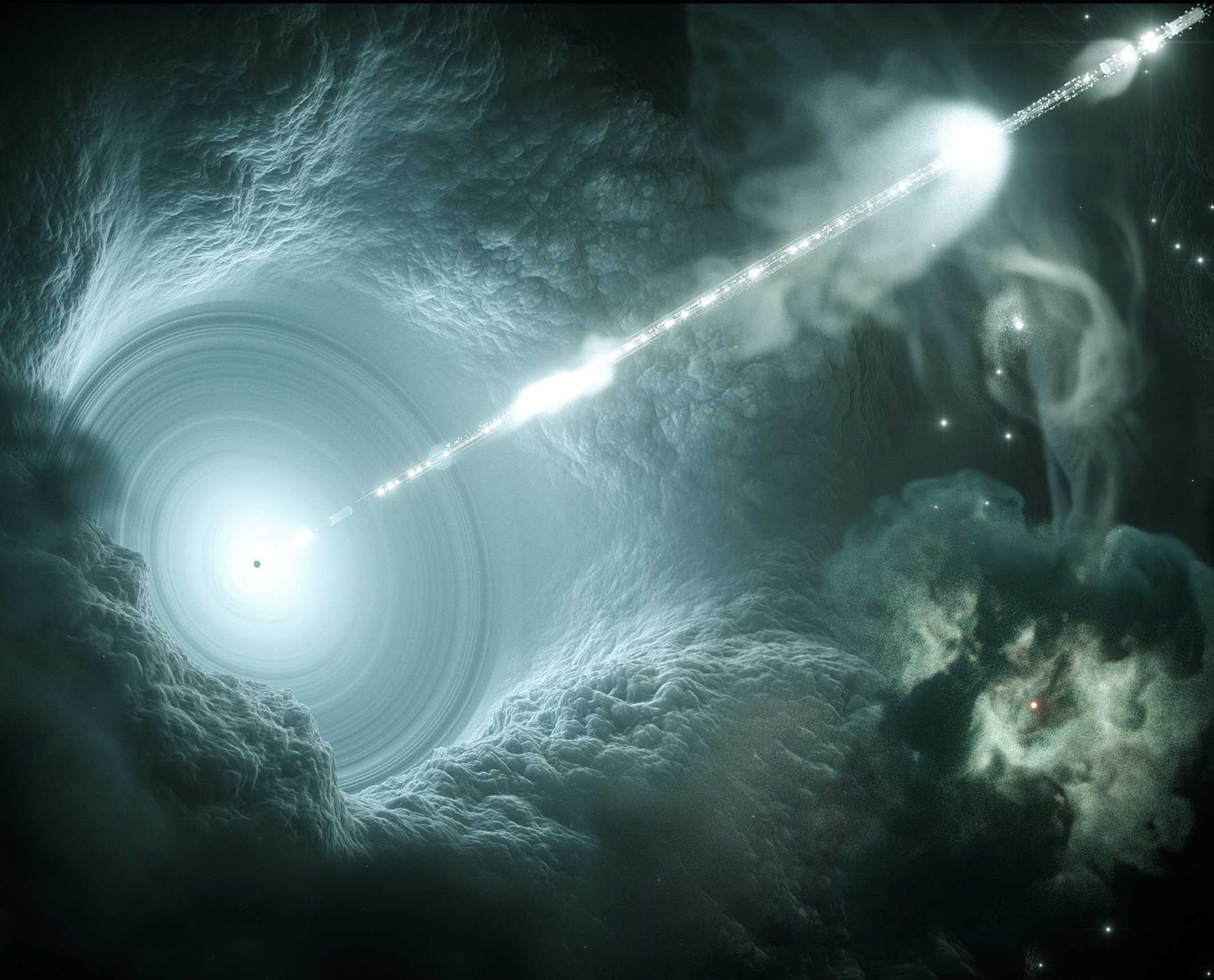


**NEW SOURCE LIST OF 110 GALACTIC AND EXTRAGALACTIC OBJECTS.
HOTTEST SPOT IN THE NORTHERN HEMISPHERE IS A 2.9σ EXCESS AT THE POSITION OF THE SEYFERT GALAXY NGC 1068 (M77)
SOURCE LIST SEARCH IS INCOMPATIBLE WITH BACKGROUND AT 3.3σ (2.25σ WITHOUT TXS 0506)**

What are the sources of cosmic neutrinos?



Several searches for different classes: energy, spatial, timing information as well as multimessenger campaigns can be used.

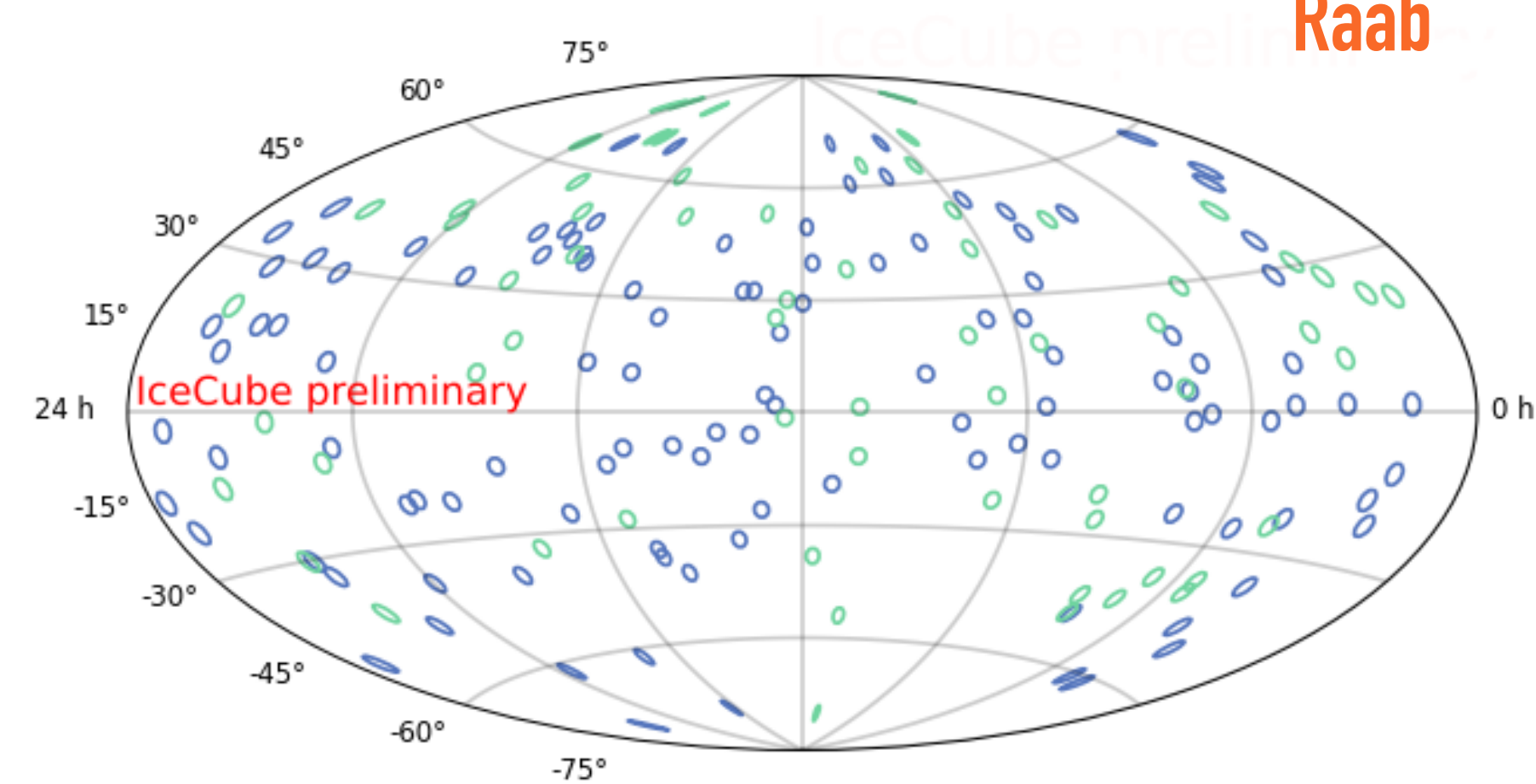
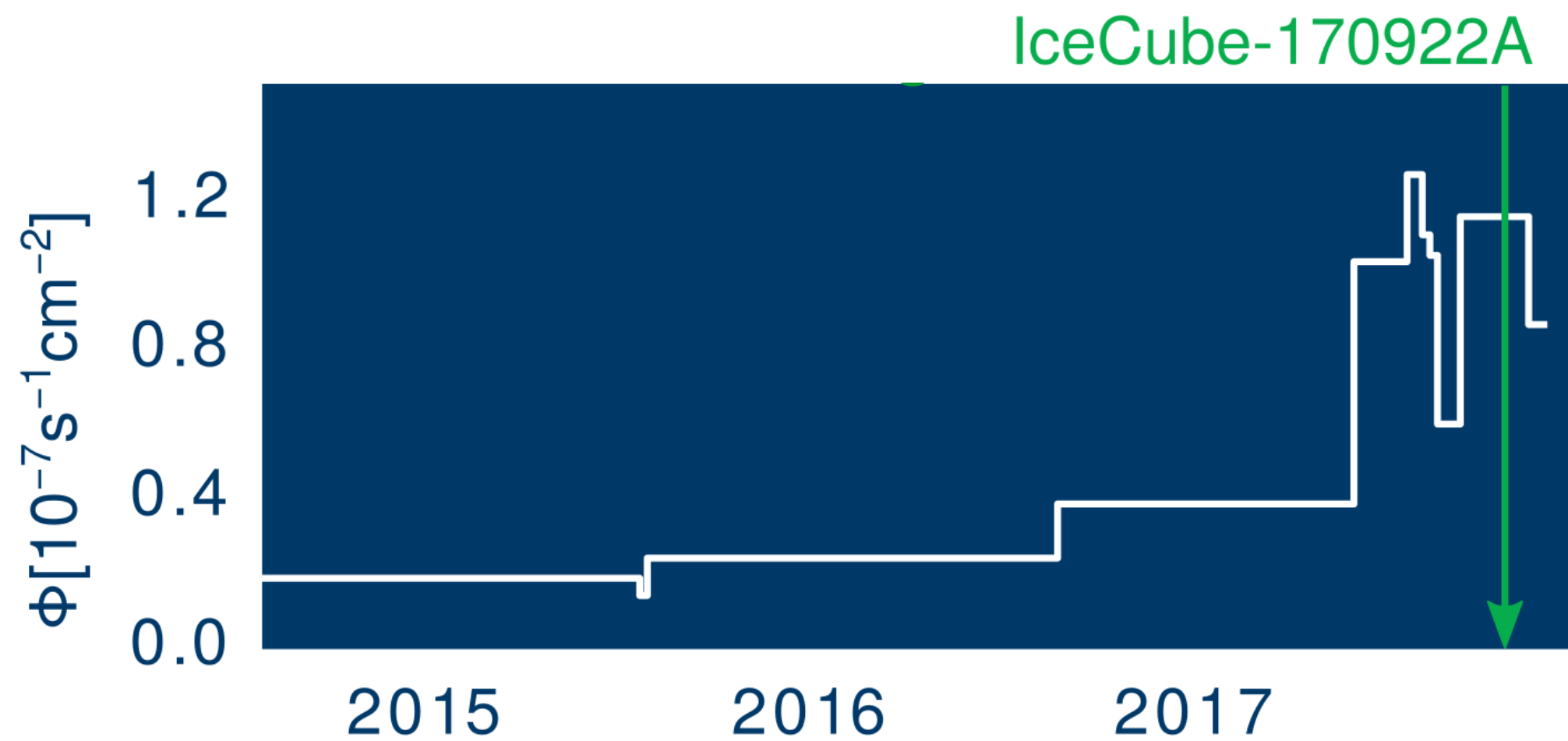


- Galaxies with a center that outshines the rest of the galaxy are called **Active Galactic Nuclei** (AGNs). Power comes from material falling towards a supermassive black hole.
- We call them **blazars** when their jets point to us. They are extremely variable sources!



Christoph Raab

- Multimessenger searches for neutrinos \propto GeV γ -ray lightcurves



- Blazar “TXS 0506+056” in Orion

- **Unblinded February 2018**

→ Nothing apart from 170922A
(or 3.2σ with 170922A)

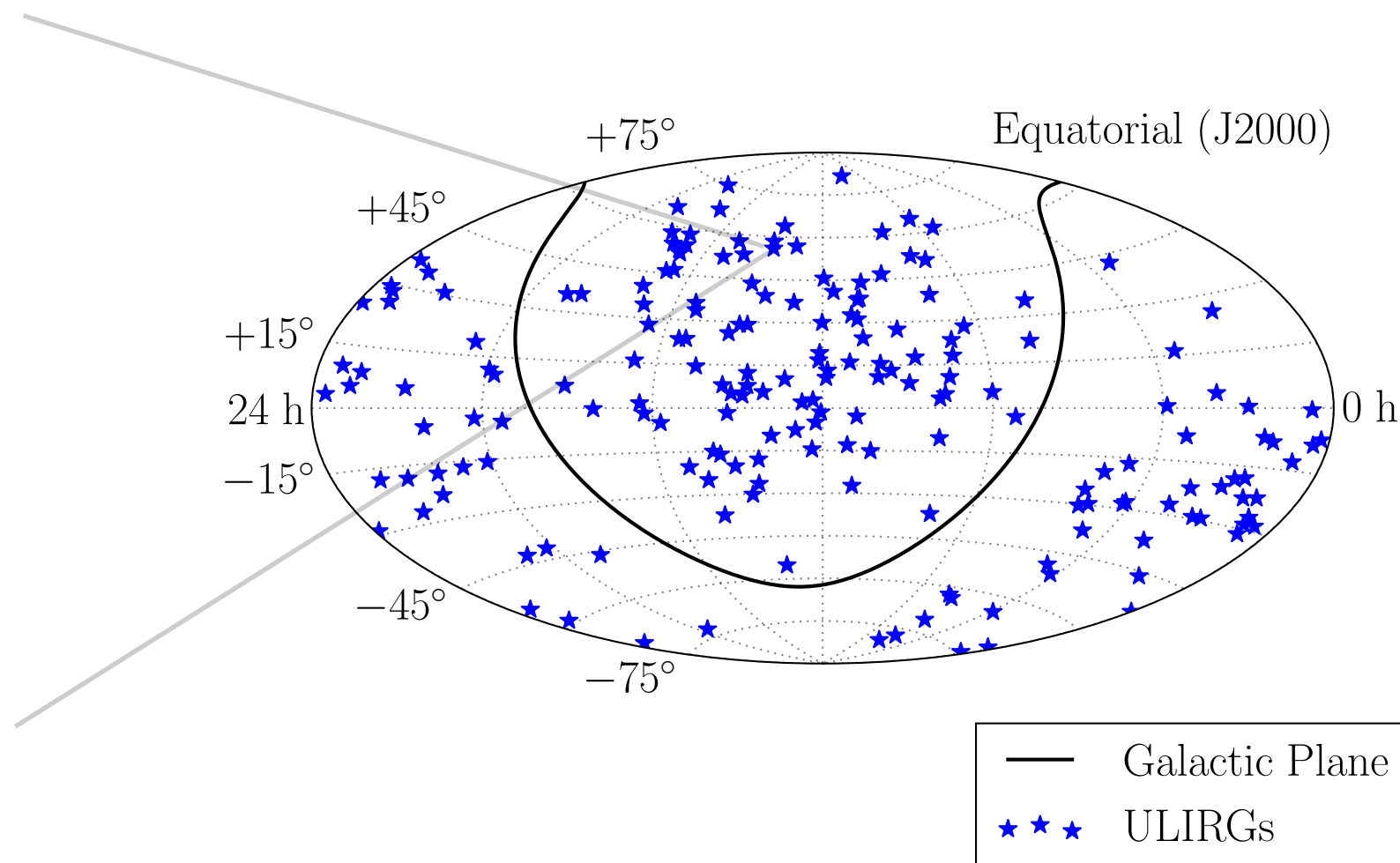
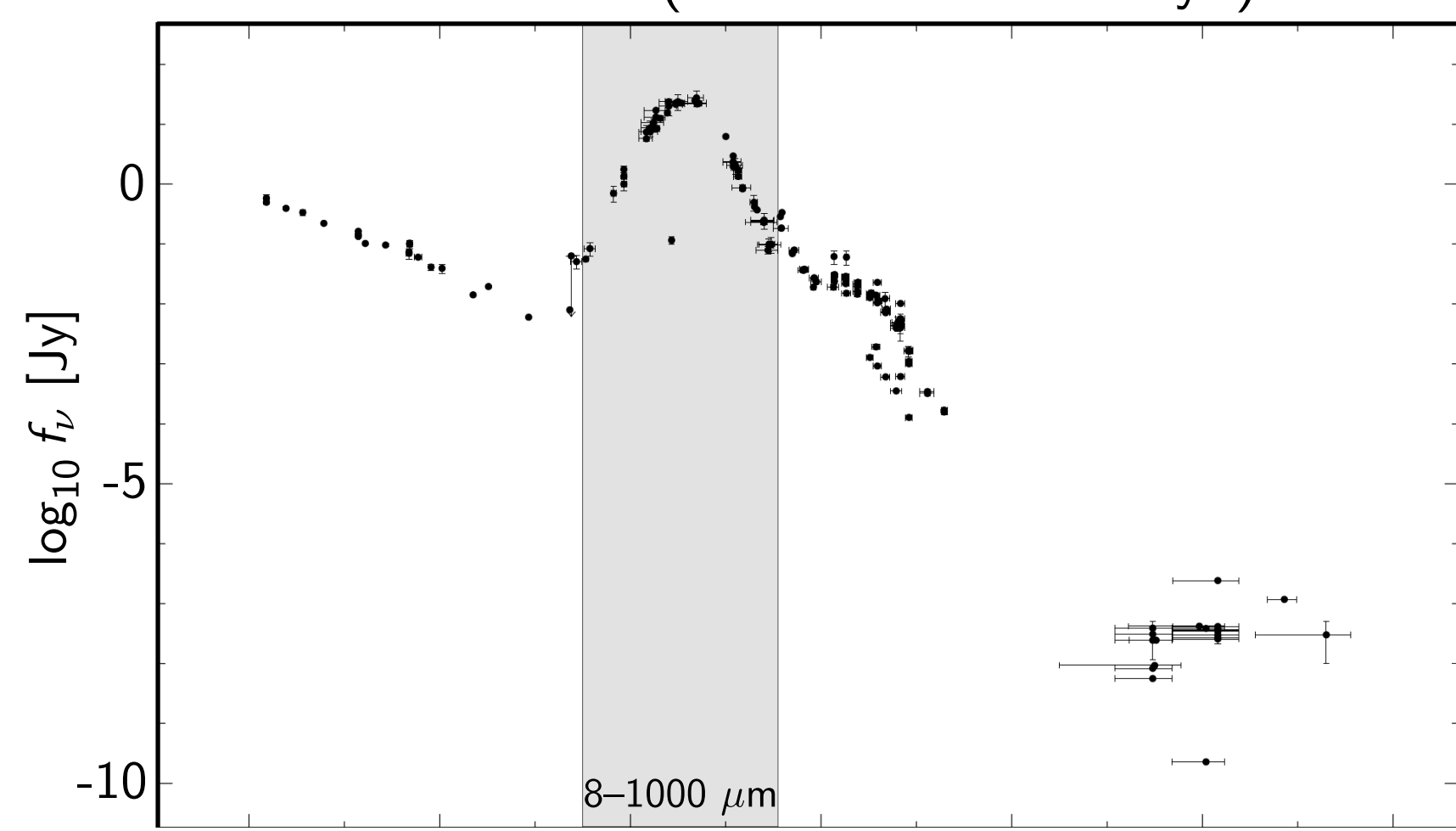
- 179 blazars combined in “stacking”

- **Unblinded October 2018**

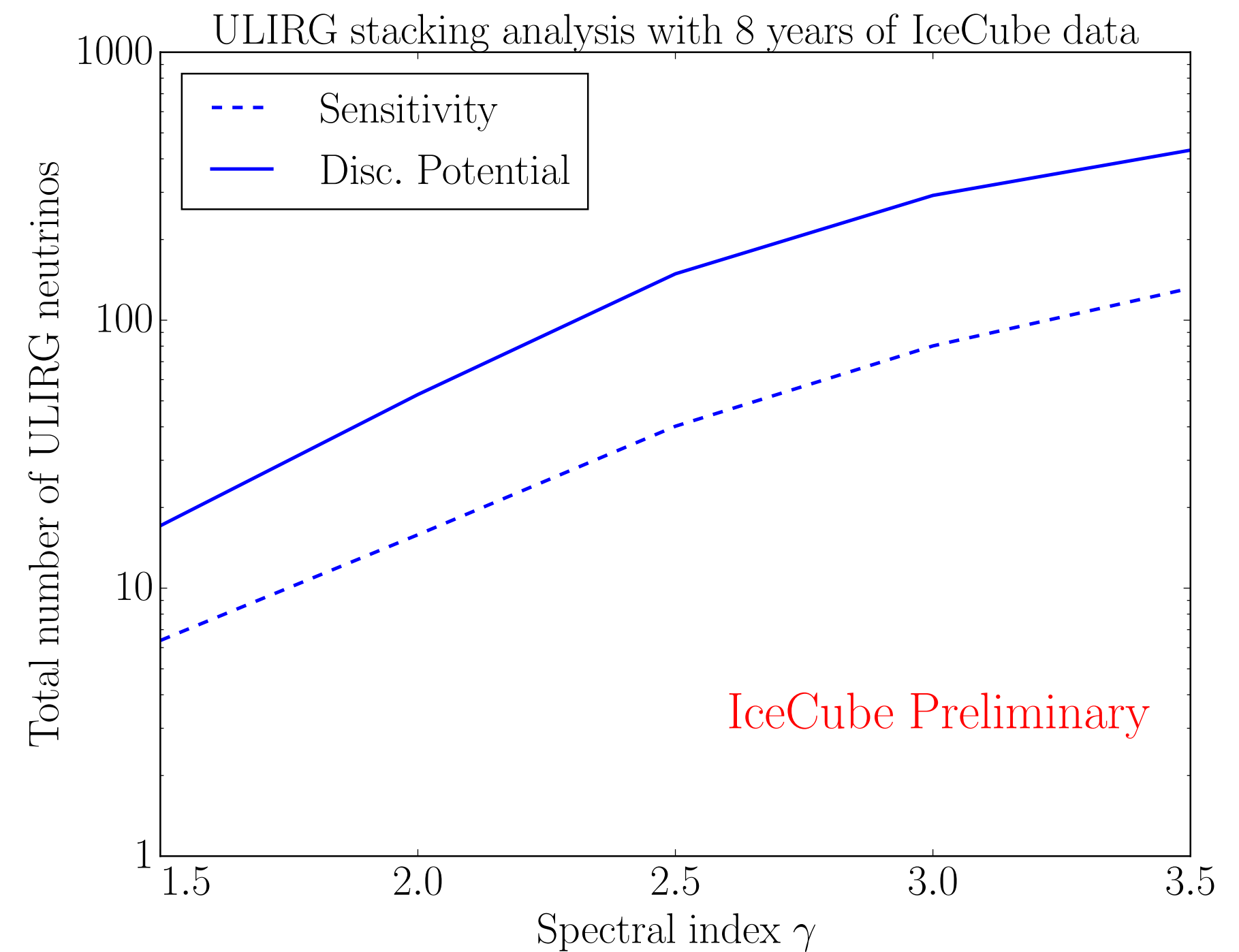
→ $p=78\%$ without TXS
 $p=1.6-1.9\sigma$ with TXS

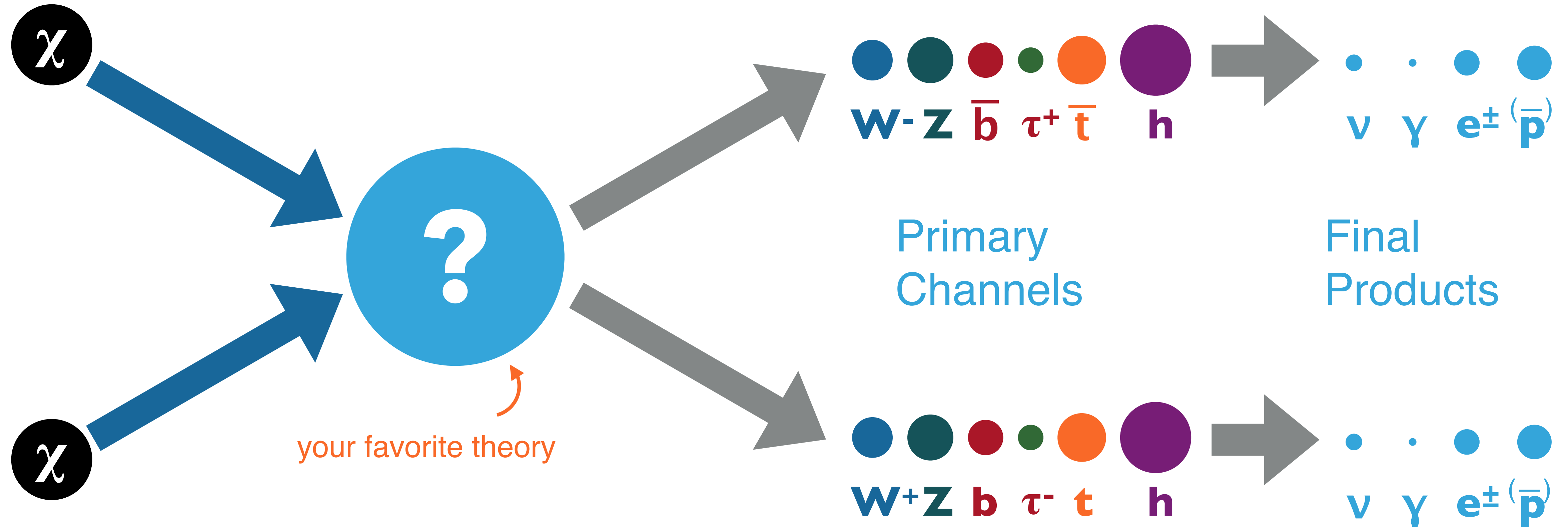


MRK 273 ("Toothbrush Galaxy")



- Most luminous objects in the IR sky: $L_{IR} \geq 10^{12} L_{\odot}$ → very **dusty**
- Candidate neutrino sources that could be **obscured** in gamma rays
- 189 ULIRGs selected for **stacking analysis** with 8 years of IceCube data

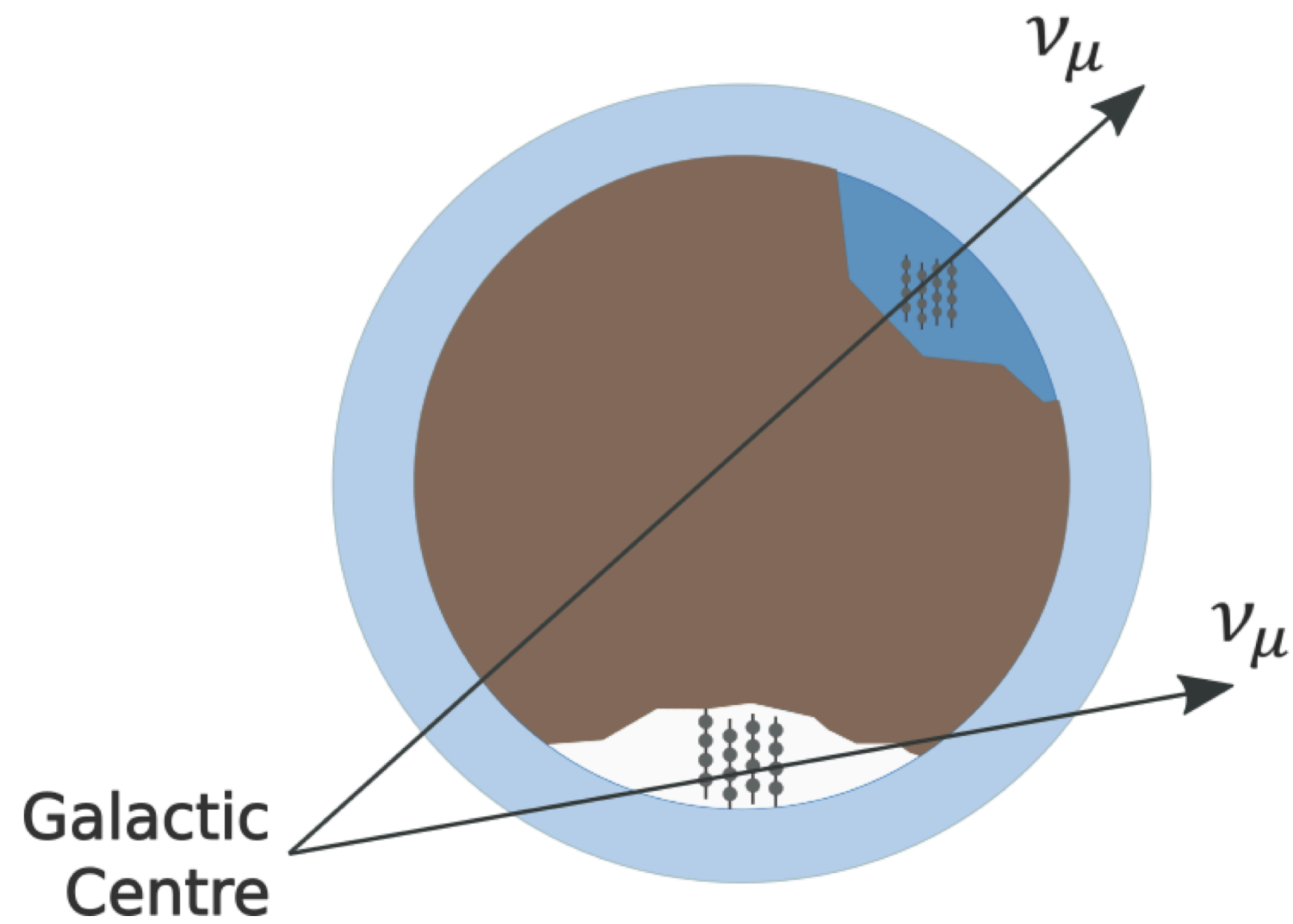




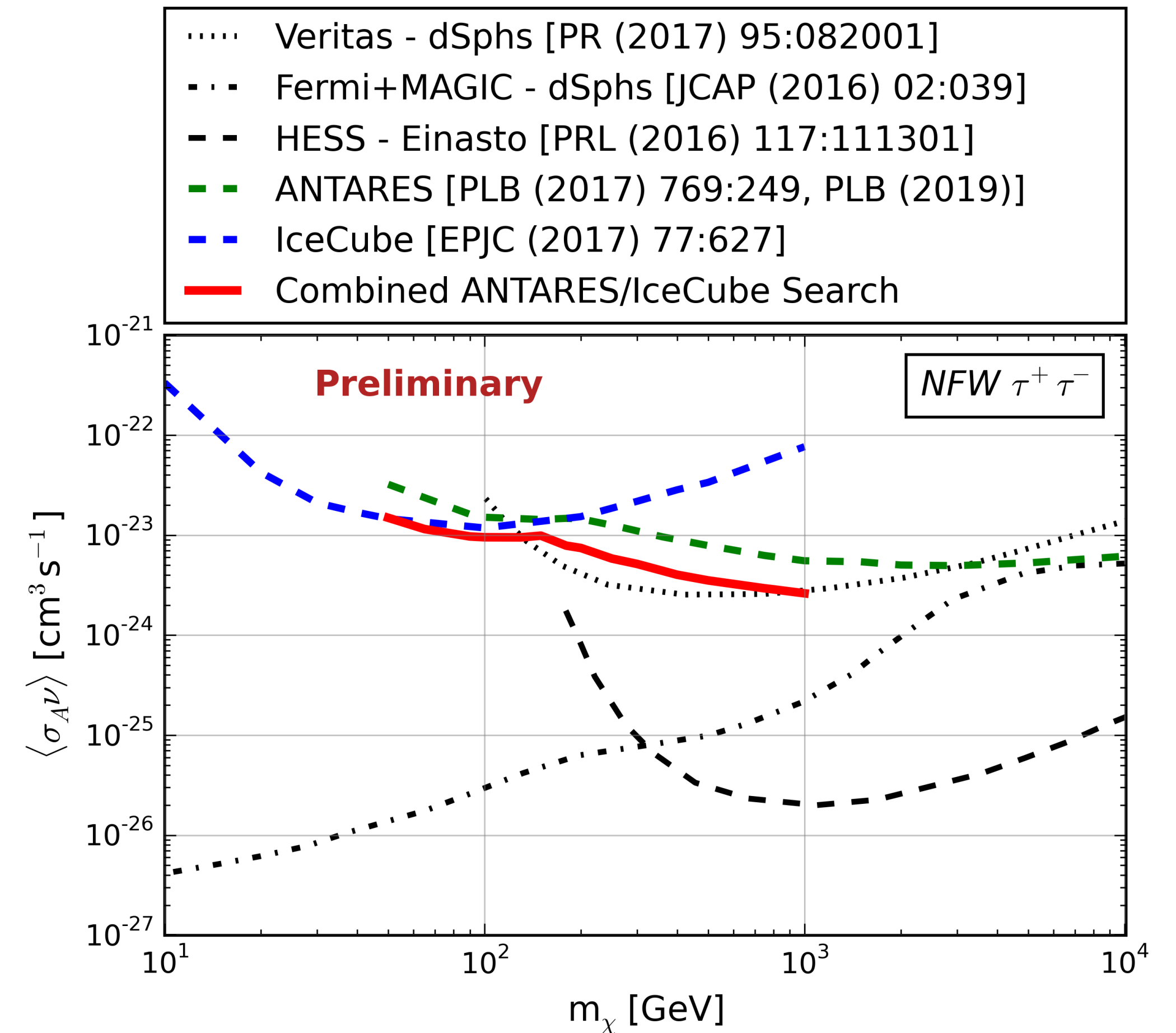
- No need of specialized detectors: **Gamma-ray telescopes, neutrino detectors, CR-experiments**
- Search for products of dark matter annihilation processes: **Focus on large reservoirs of dark matter**

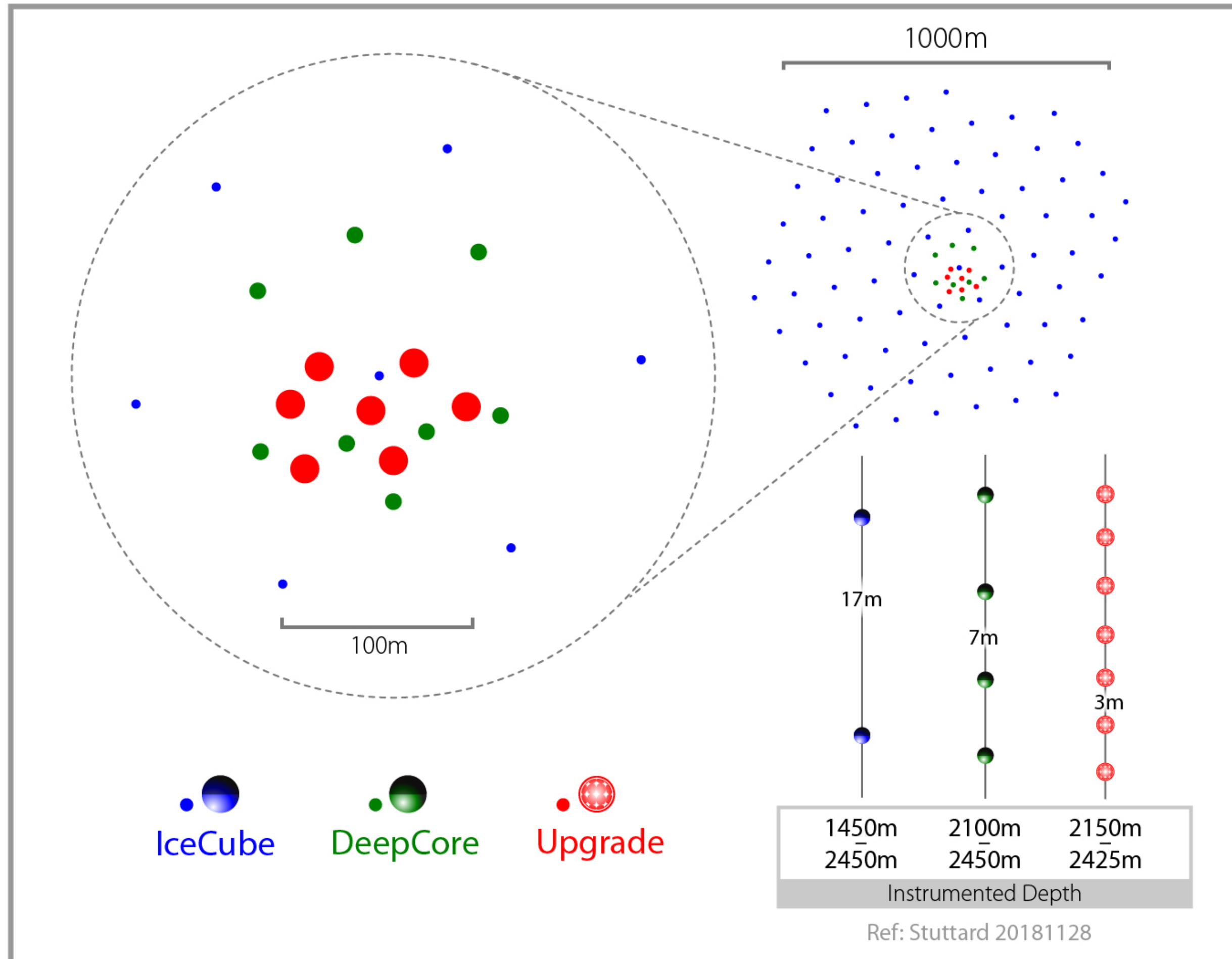


Nadège Iovine



- Combination of 3 years of IceCube data and 9 years of ANTARES data
- Improvement compared to the individual limits
- **Outlook:** Update IceCube only results with more years of data

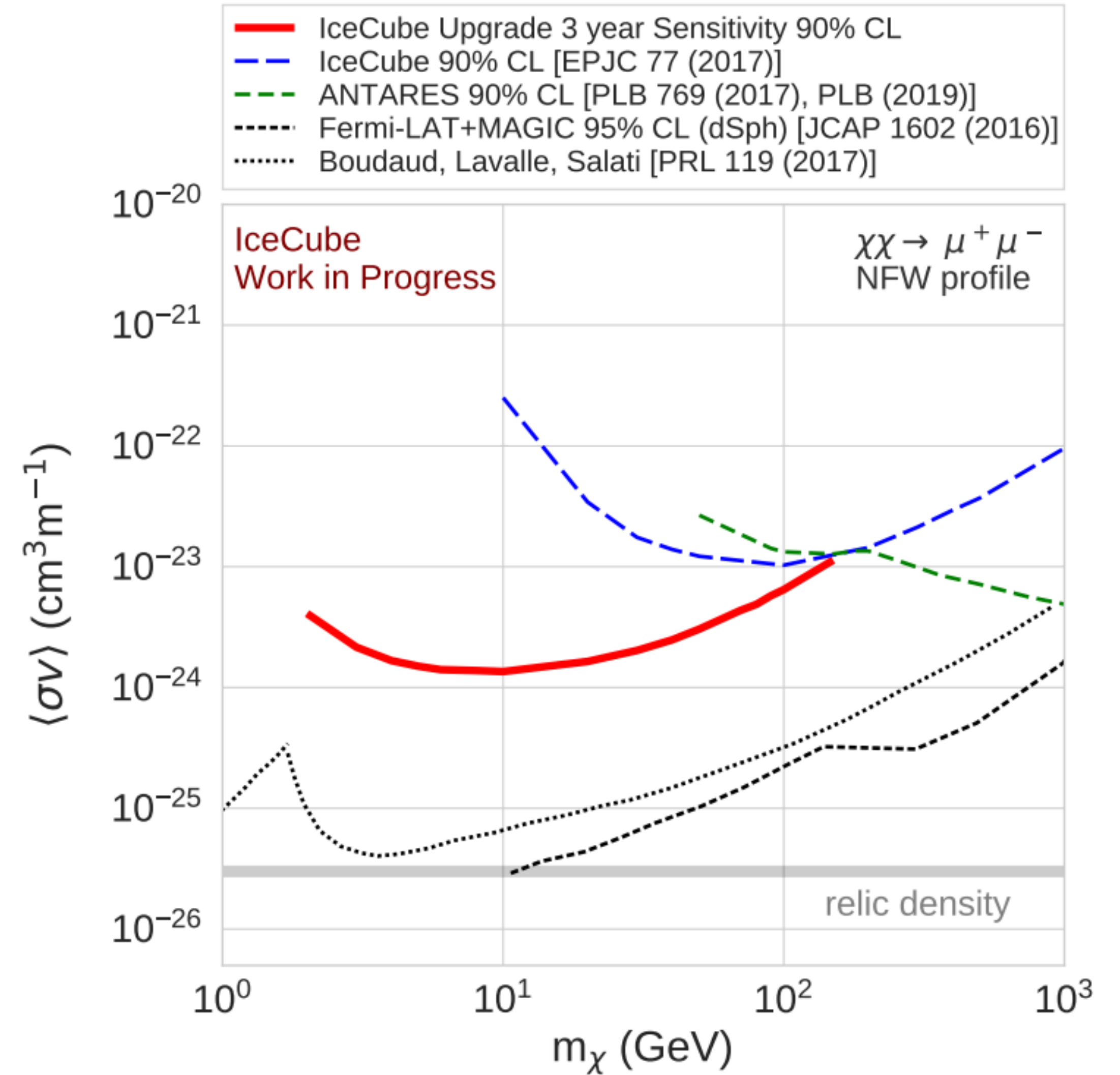
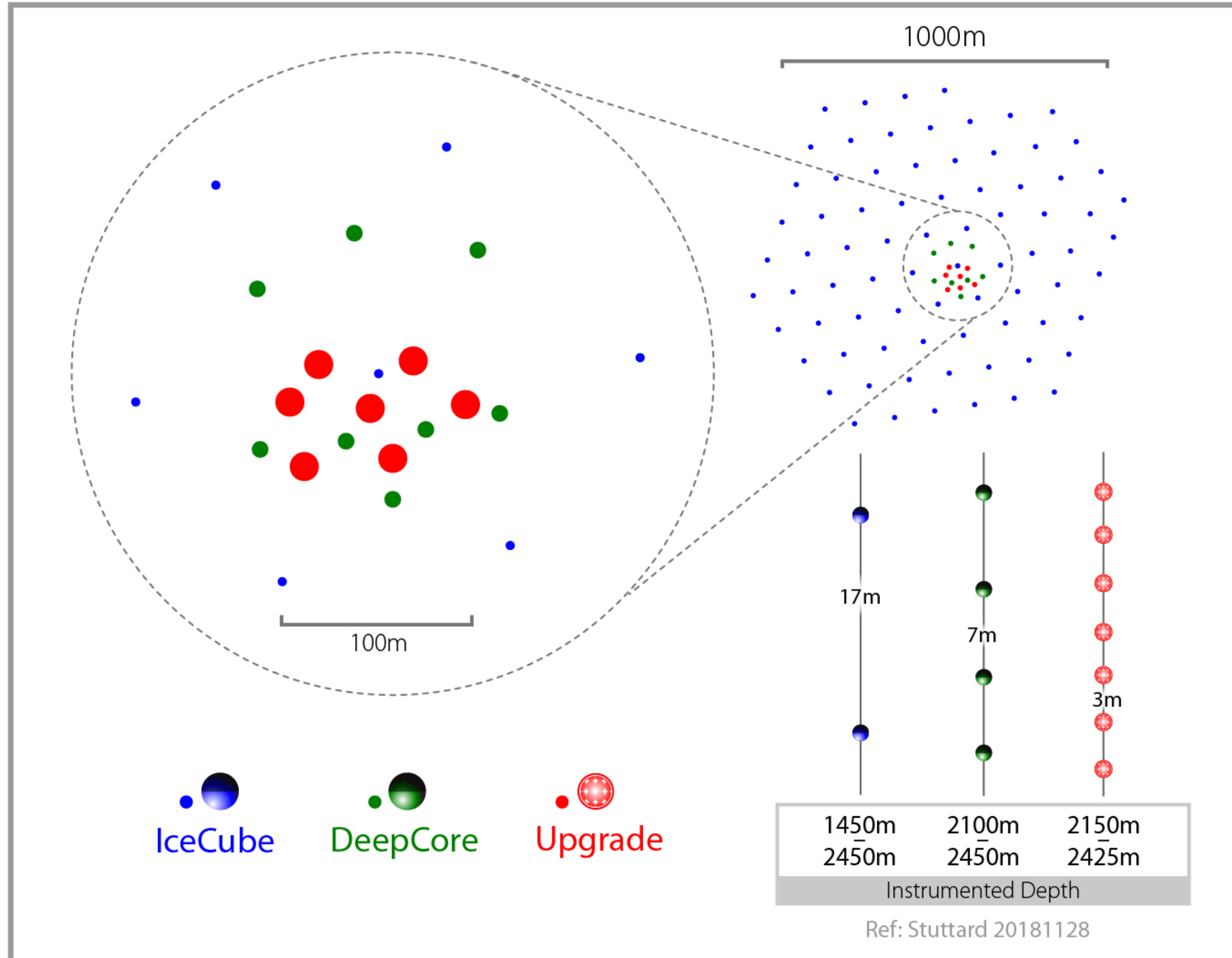




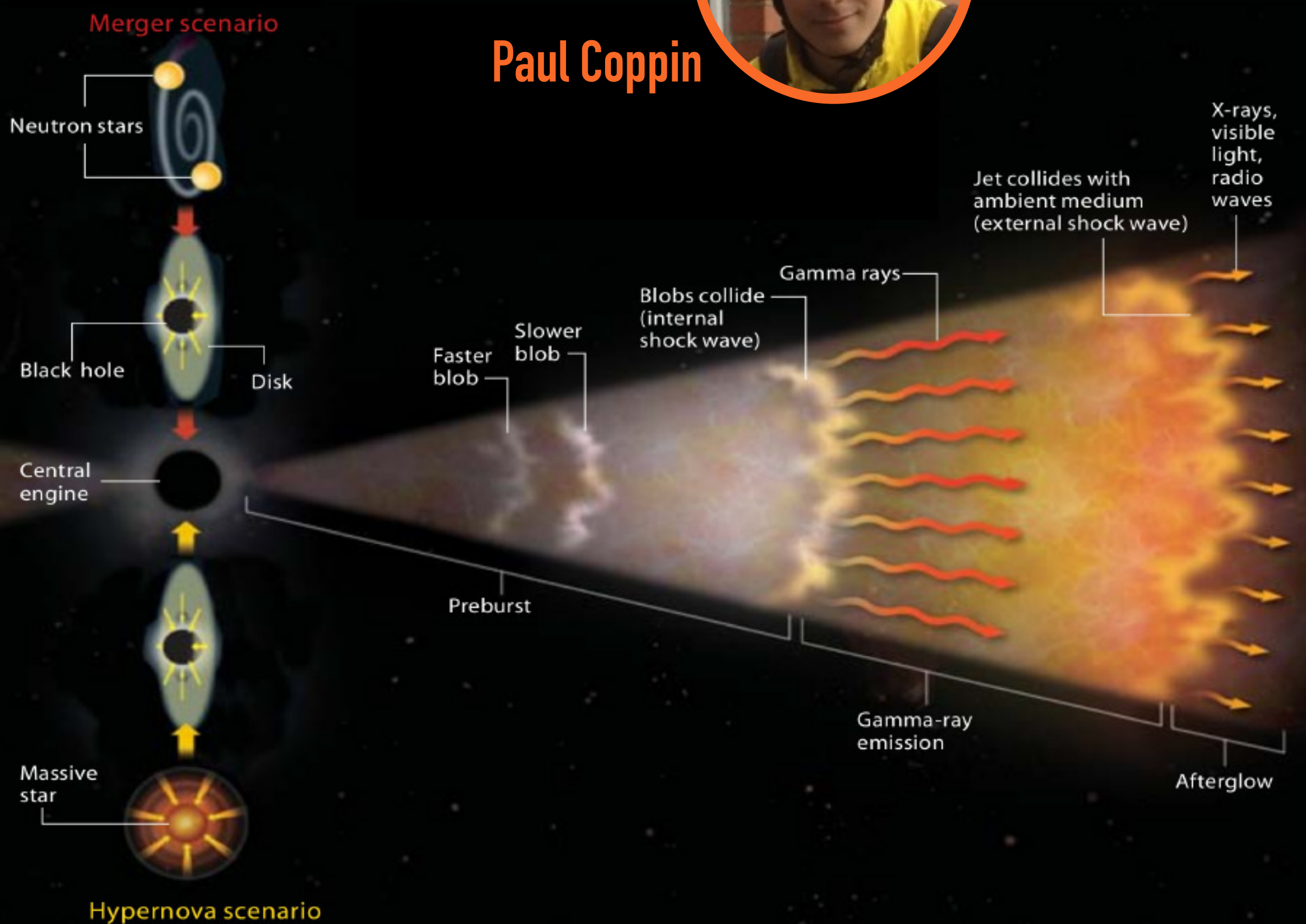
- DEEP CORE INFILL (7 NEW STRINGS) IN 2022-2023.
- NEUTRINO OSCILLATION.
- R&D FOR GEN2: DRILLING, NEW SENSORS.
- IMPROVED CALIBRATION OF ARCHIVAL DATA.



Sebastian Baur

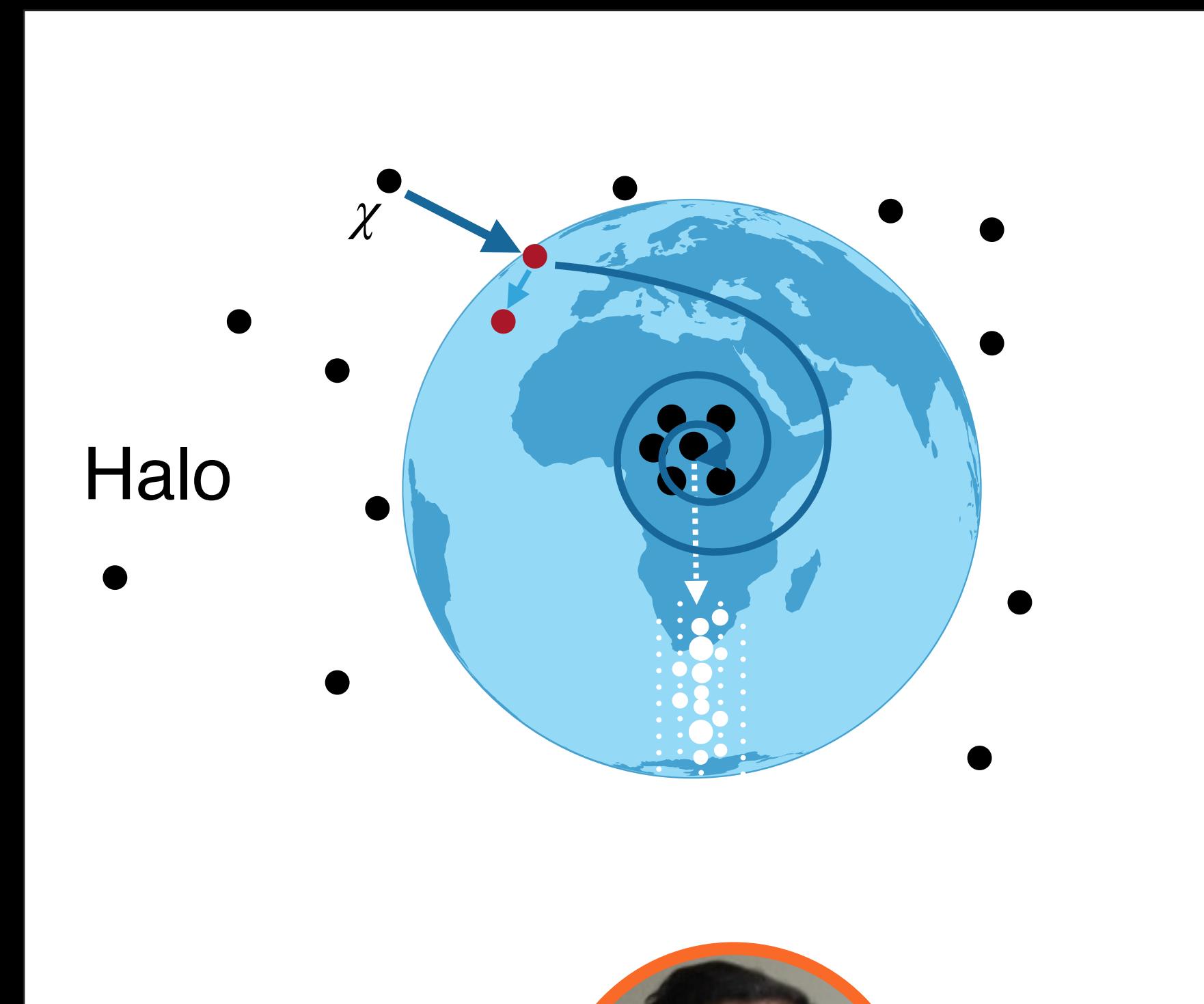


Paul Coppin



Identification of GRB precursors

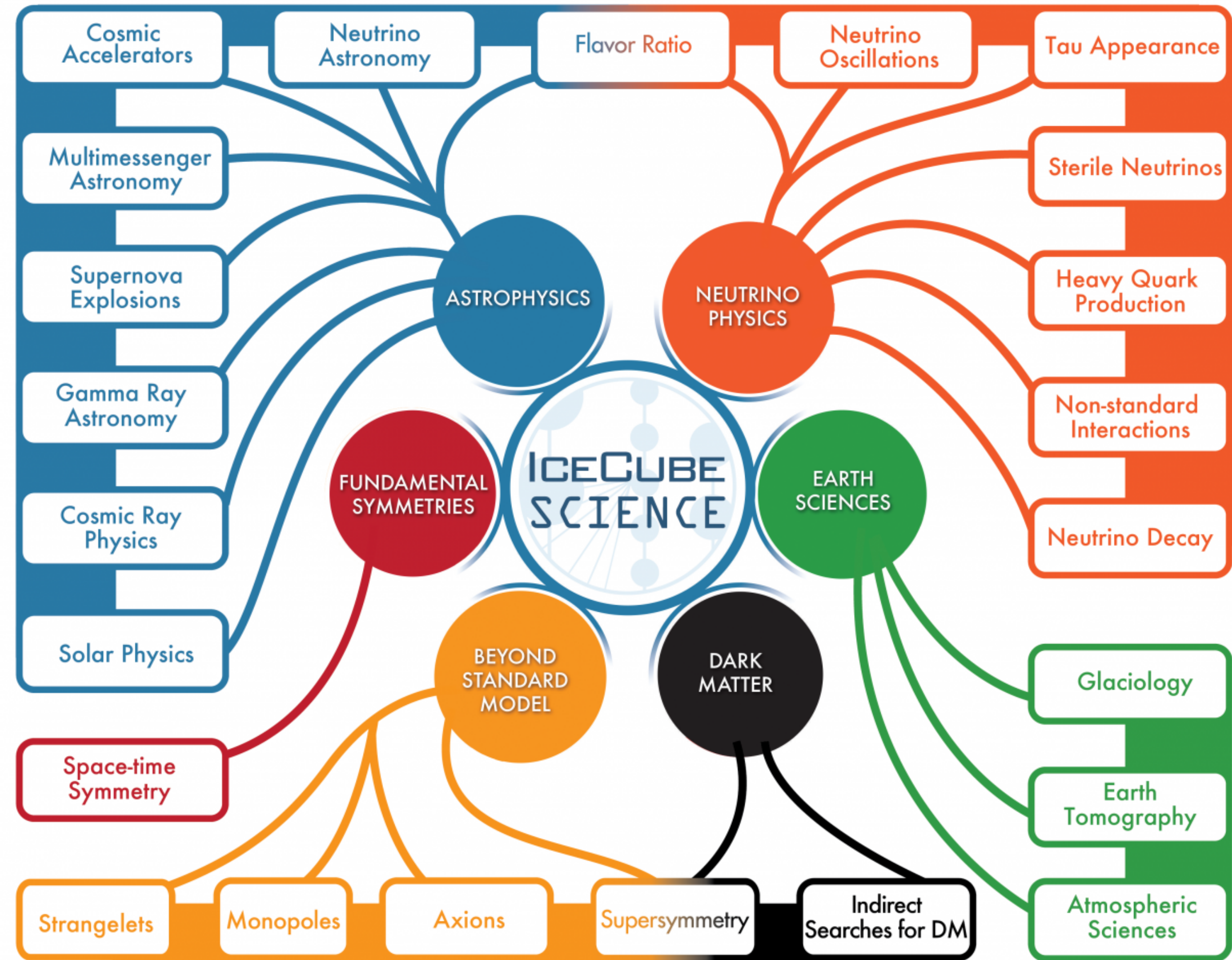
IceCube search for DM at the center of the Earth



Giovanni Renzi



- IceCube has a broad portfolio of scientific results.
- Multi-messenger astronomy is the key to study the highest energy phenomena in the Universe.
- Competitive results for dark matter searches.
- Interesting results on flavor ratio and first Glashow.

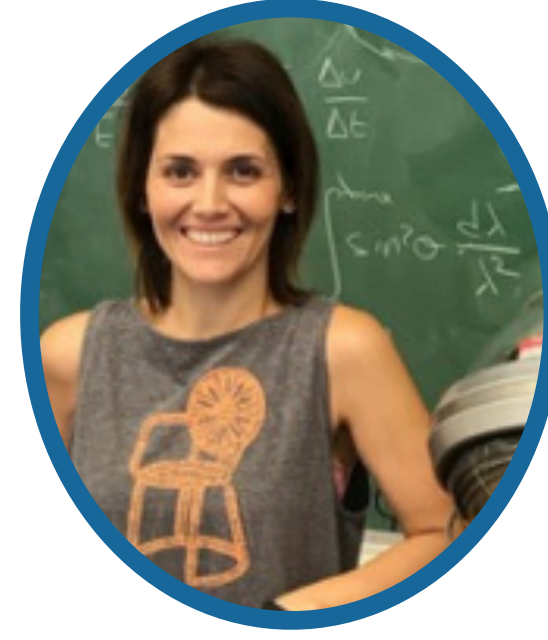




Juanan



Ioana



Simona



Nick



Krijn



Catherine



Sebastian



Daniela



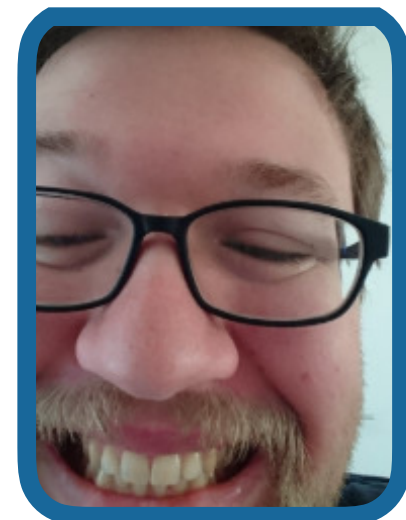
Pablo



Paul



Simon



Chris
(leaving soon)



Giovanni



Nadège



Rose




Enrique




THE ICECUBE COLLABORATION

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University of Adelaide

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

 **CANADA**
SNOLAB
University of Alberta–Edmonton

 **DENMARK**
University of Copenhagen

 **GERMANY**
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ECAP, Universität Erlangen-Nürnberg
Humboldt-Universität zu Berlin
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
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Technology

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and A&M College
Stony Brook University
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University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
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

FUNDING AGENCIES

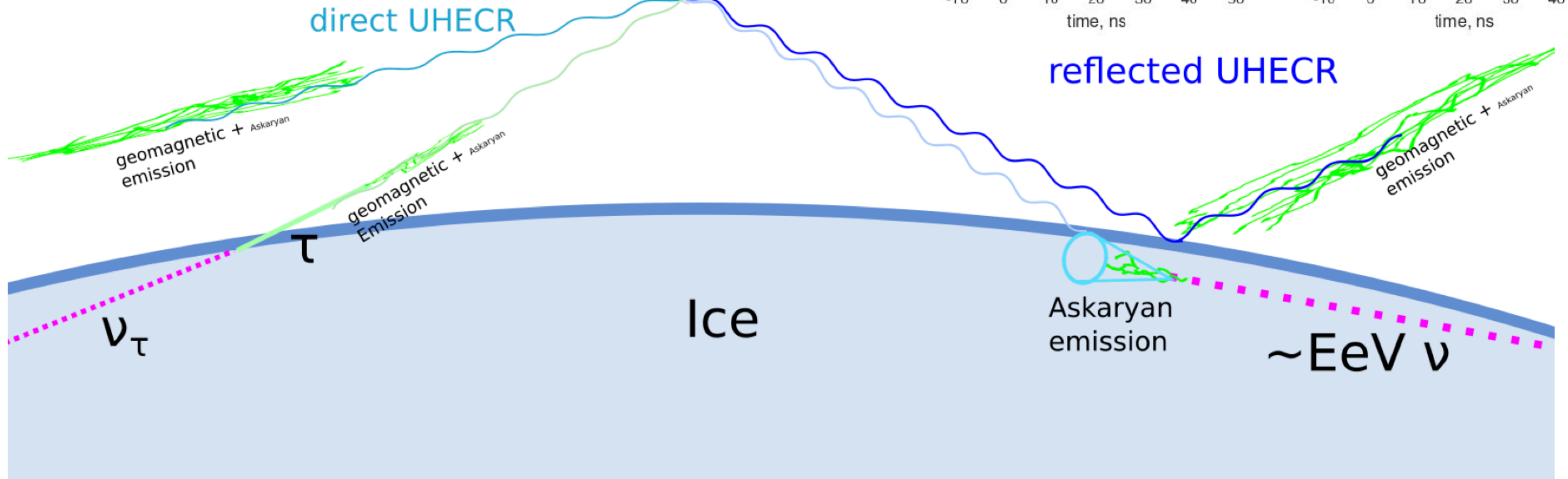
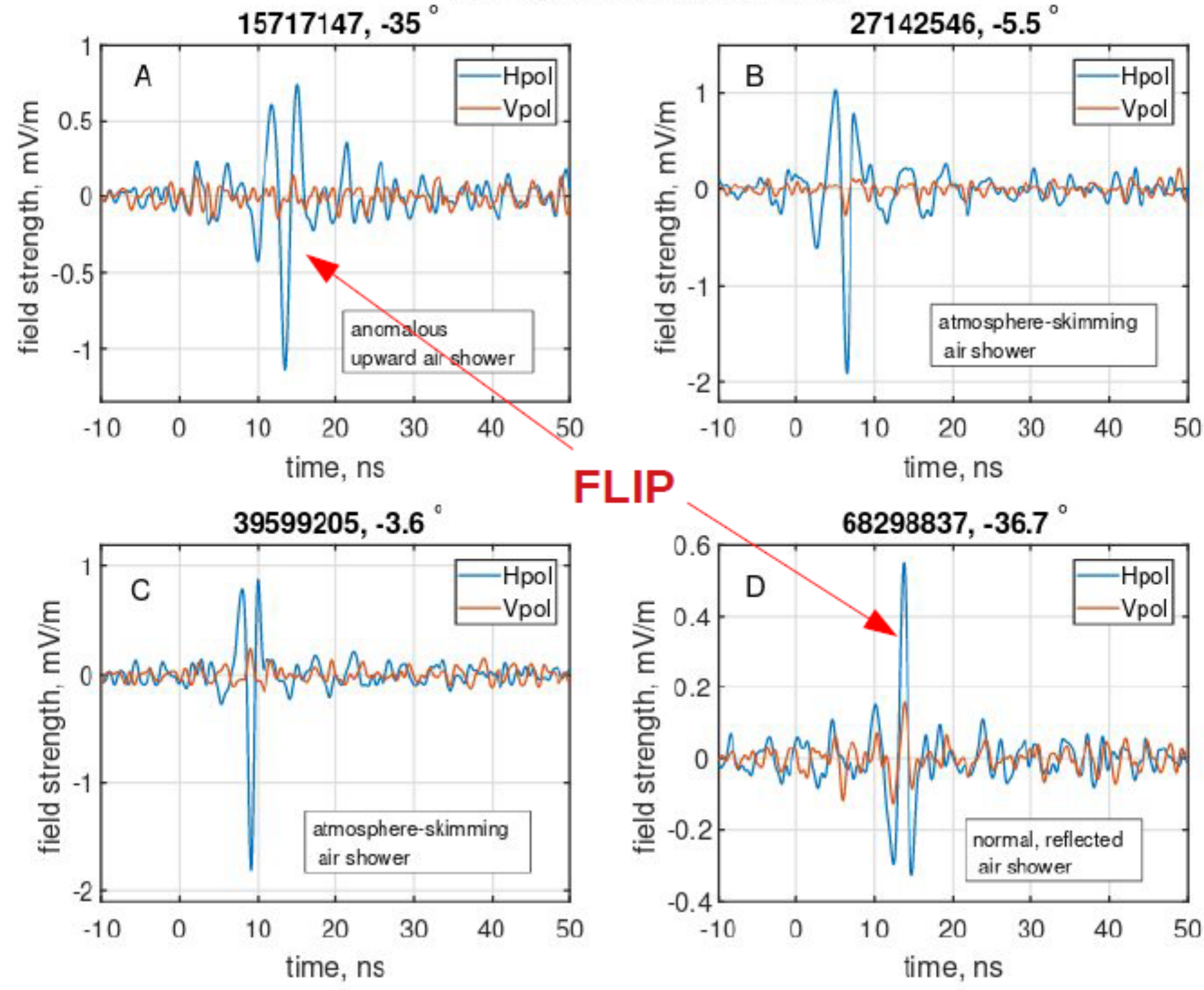
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen
(FWO-Vlaanderen)

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

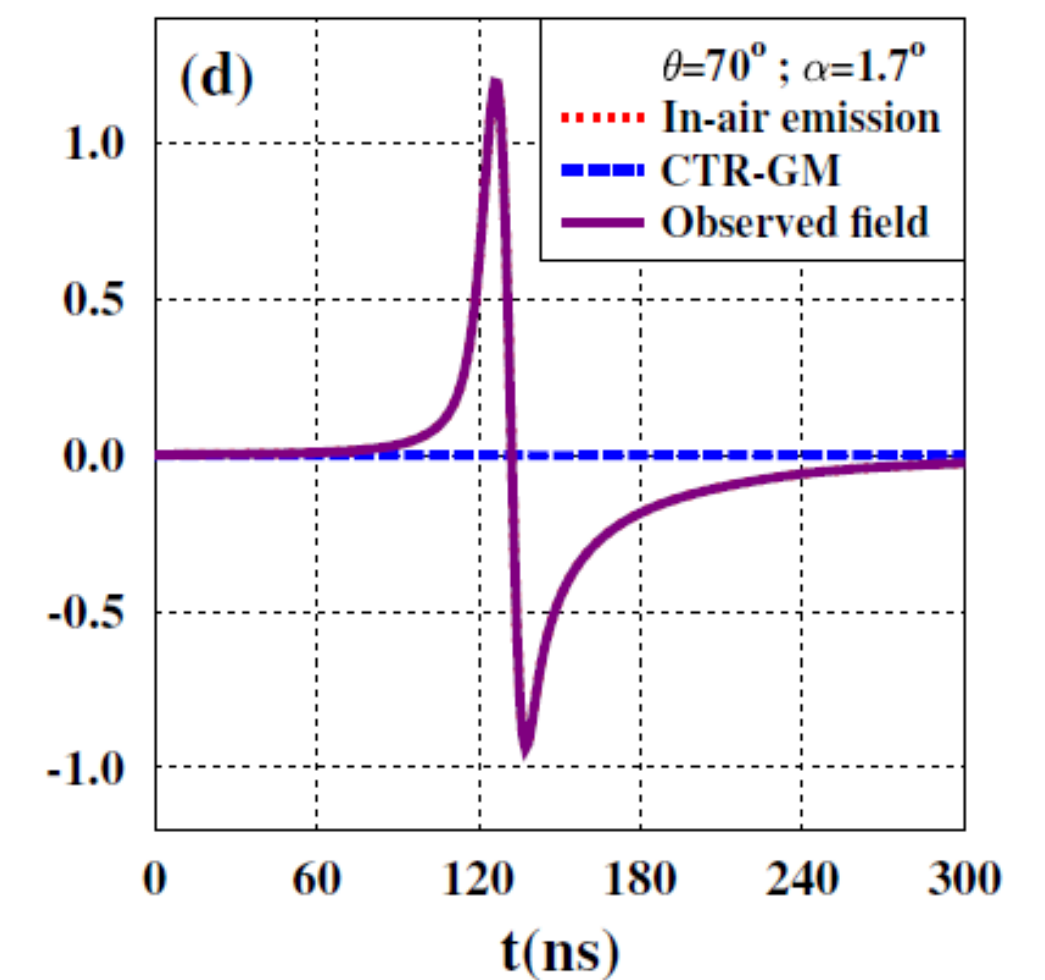
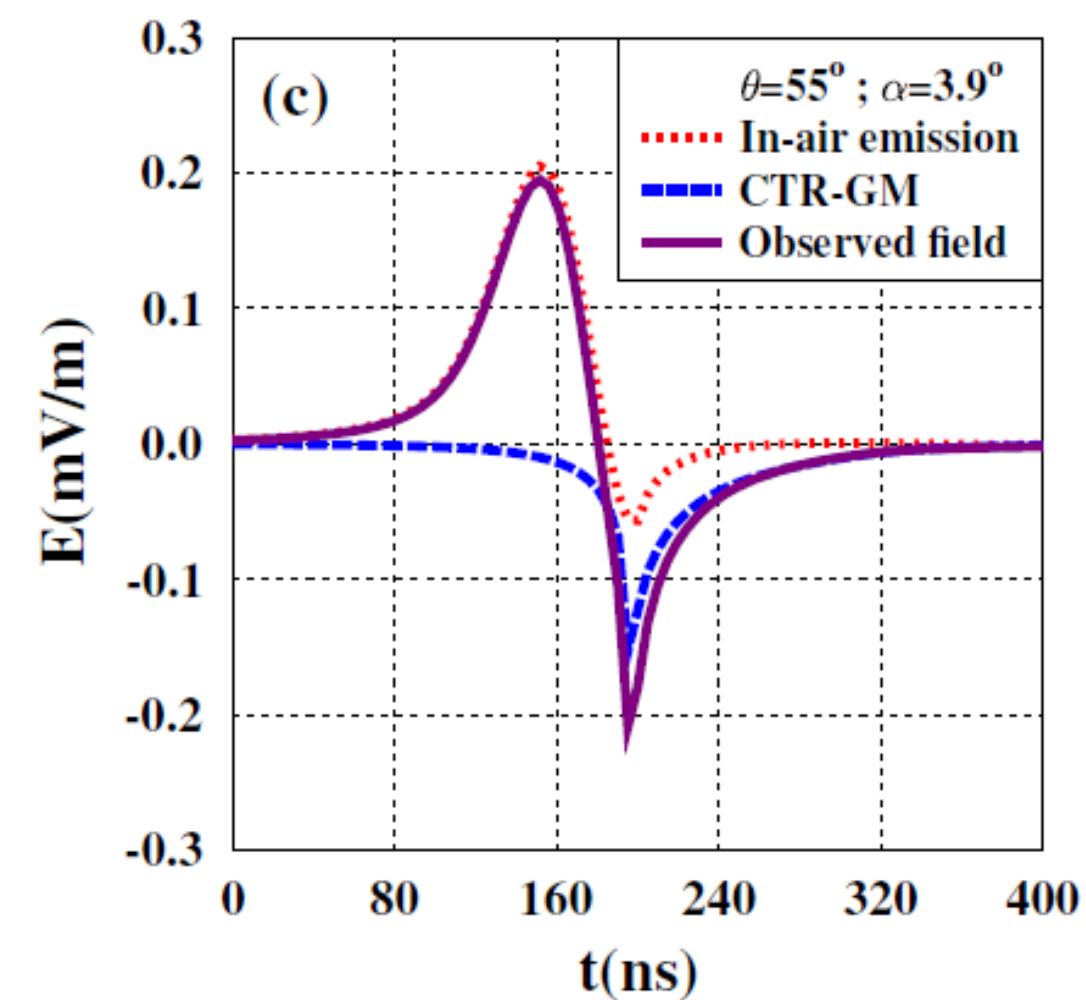
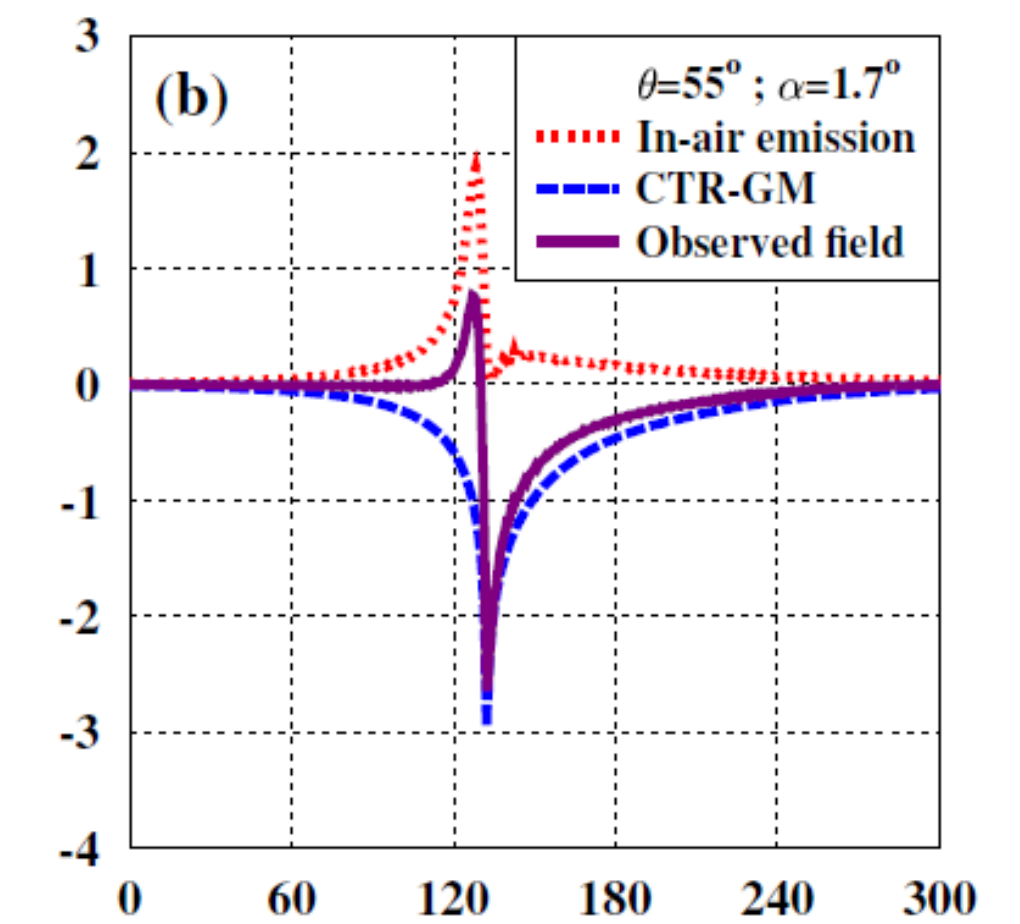
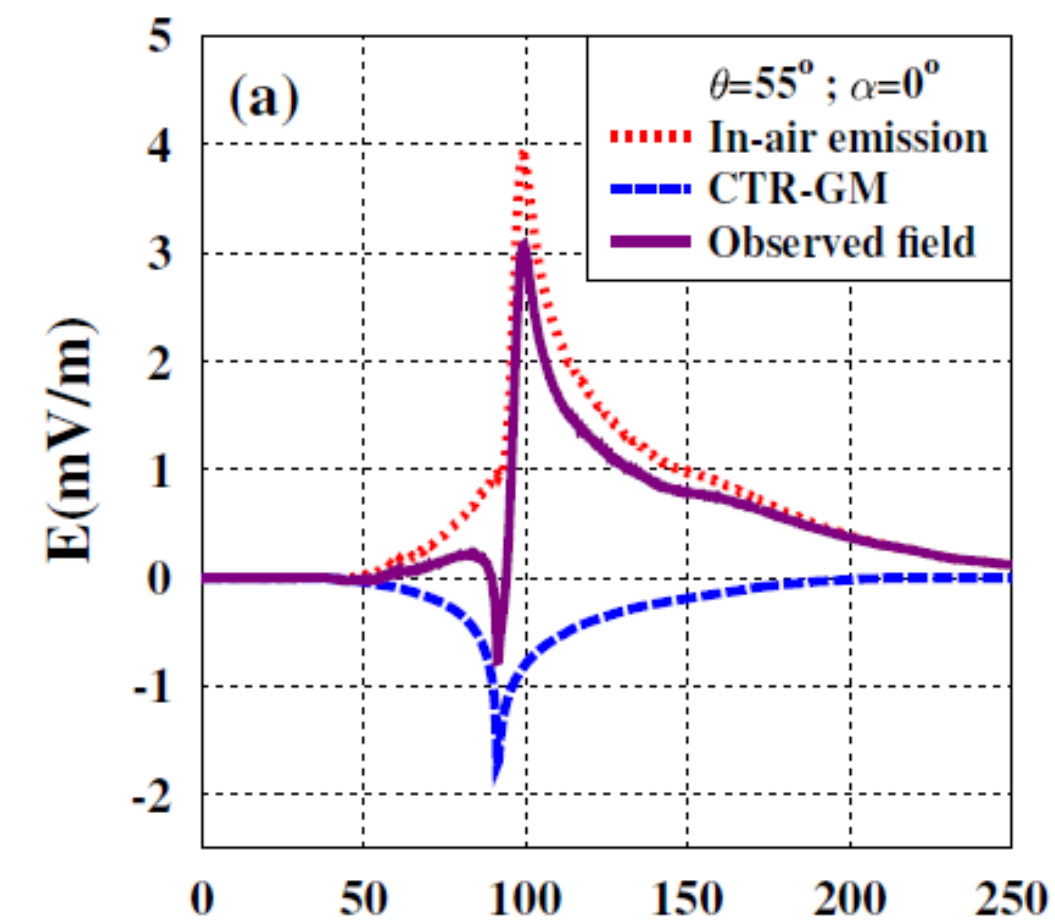
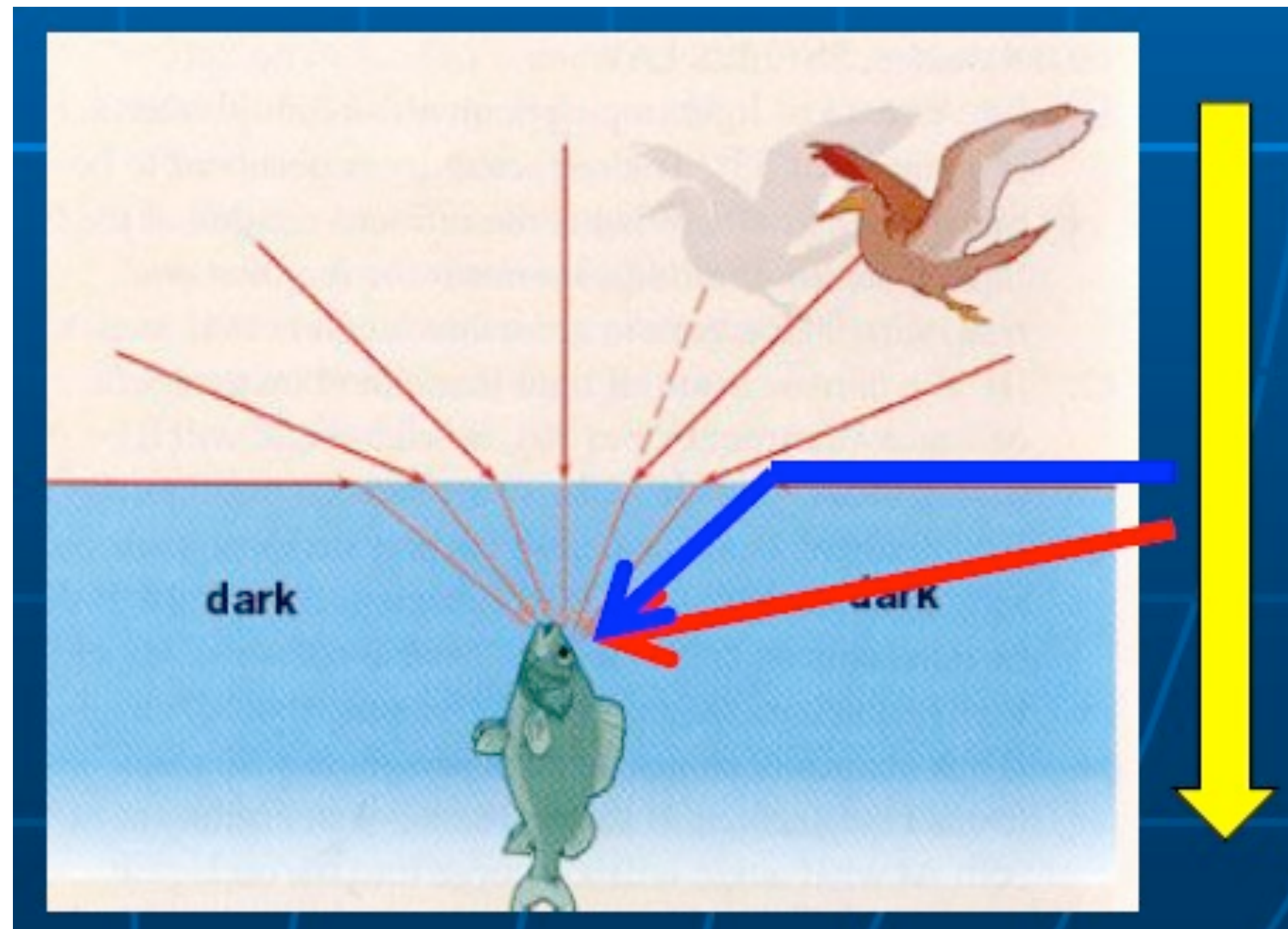
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)



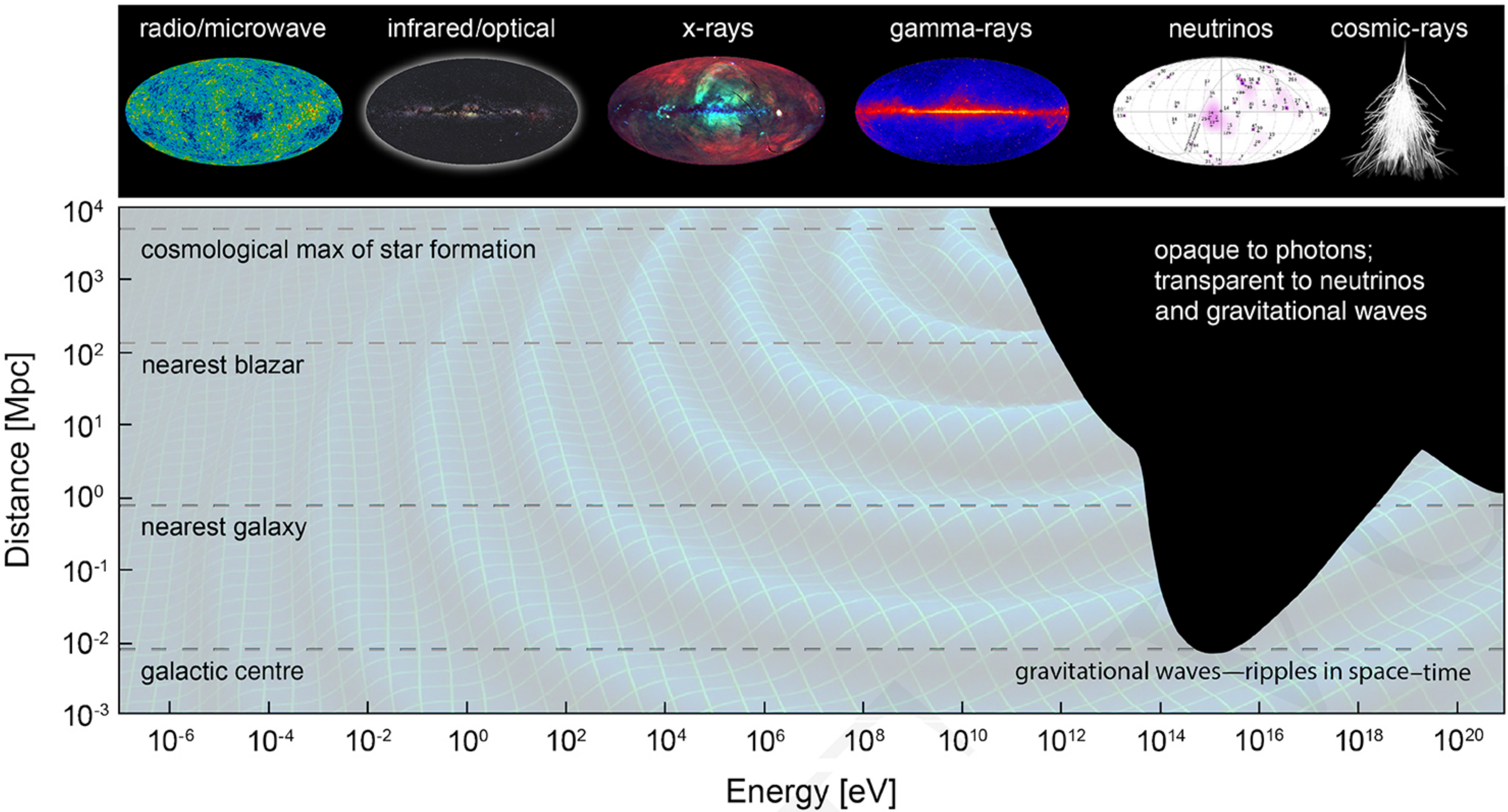


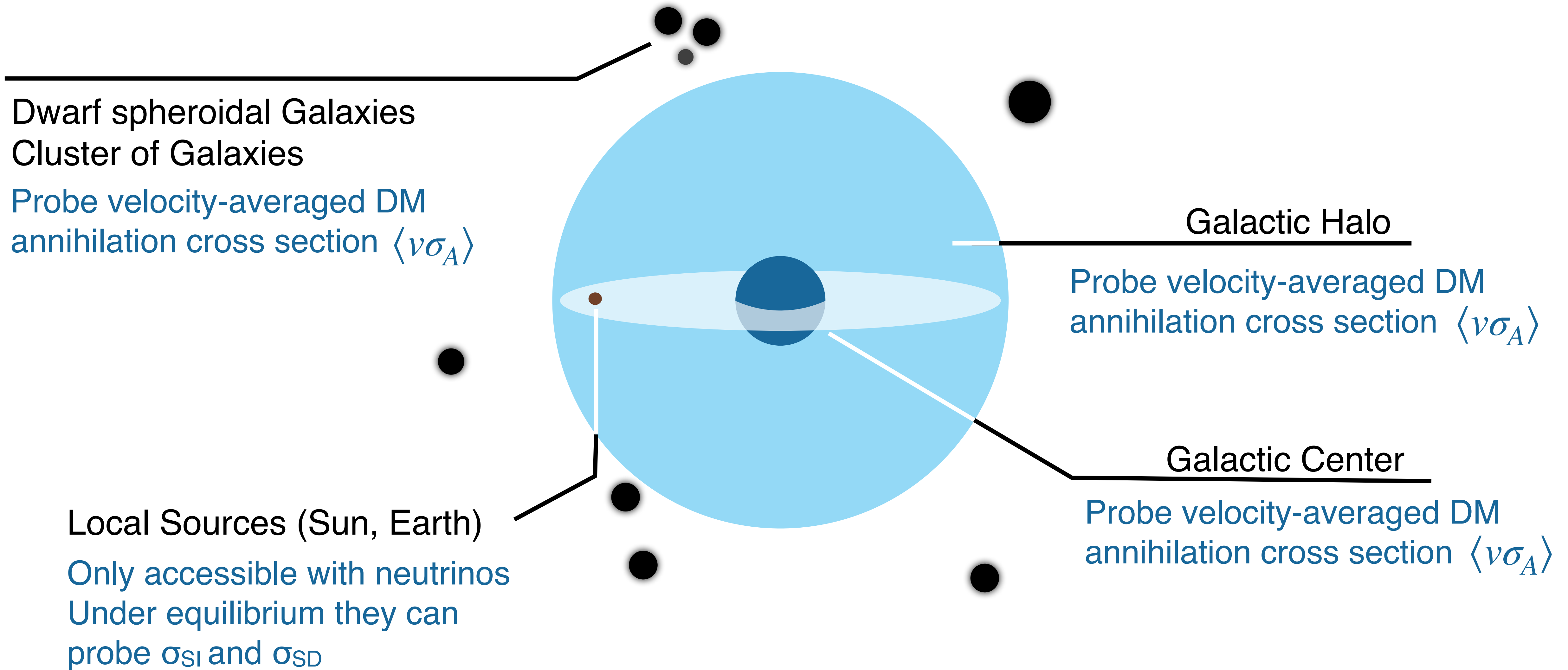


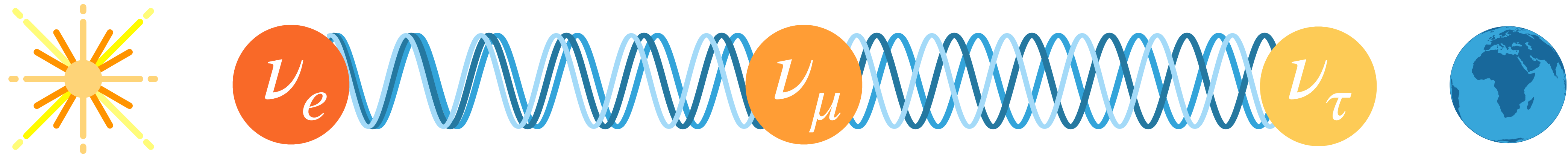
Coherent transition radiation from the geomagnetically-induced current in cosmic-ray air showers



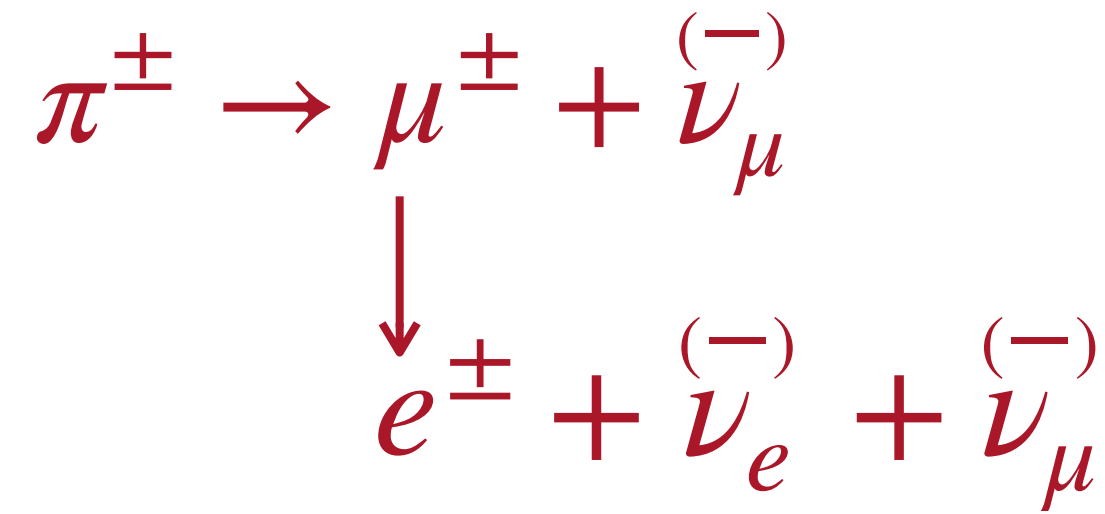
arXiv:1903.08750, PRL accepted







pion production



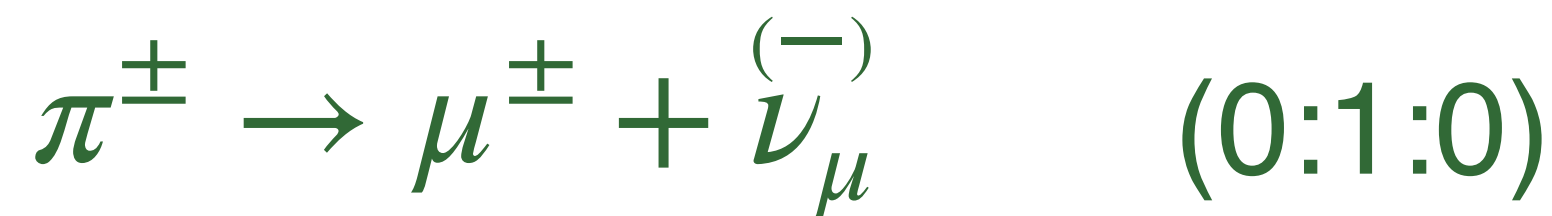
(1:2:0)

neutron decay

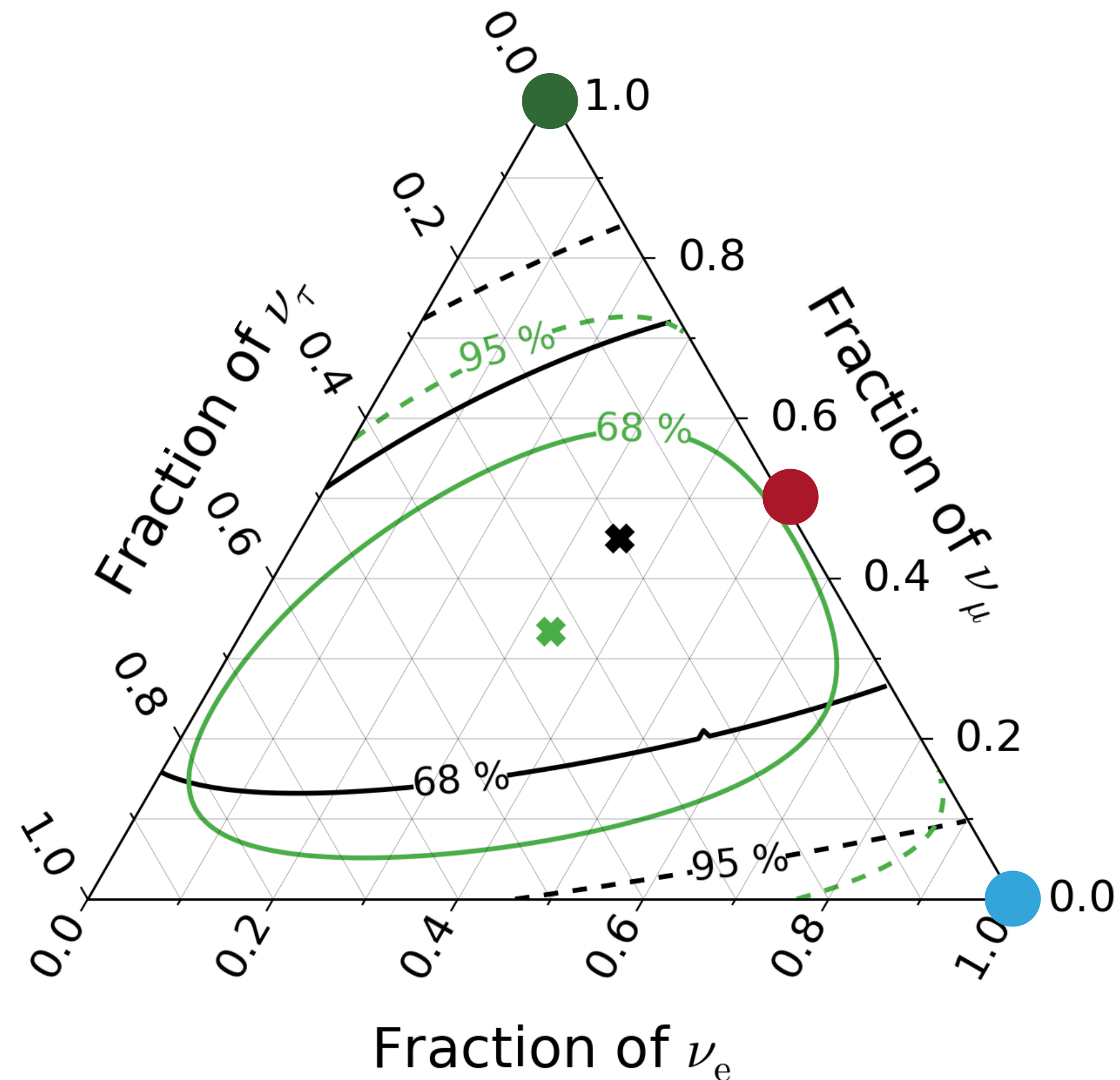


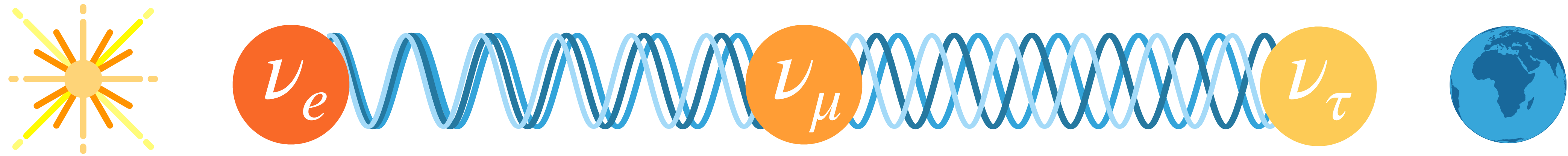
(1:0:0)

muon dumped

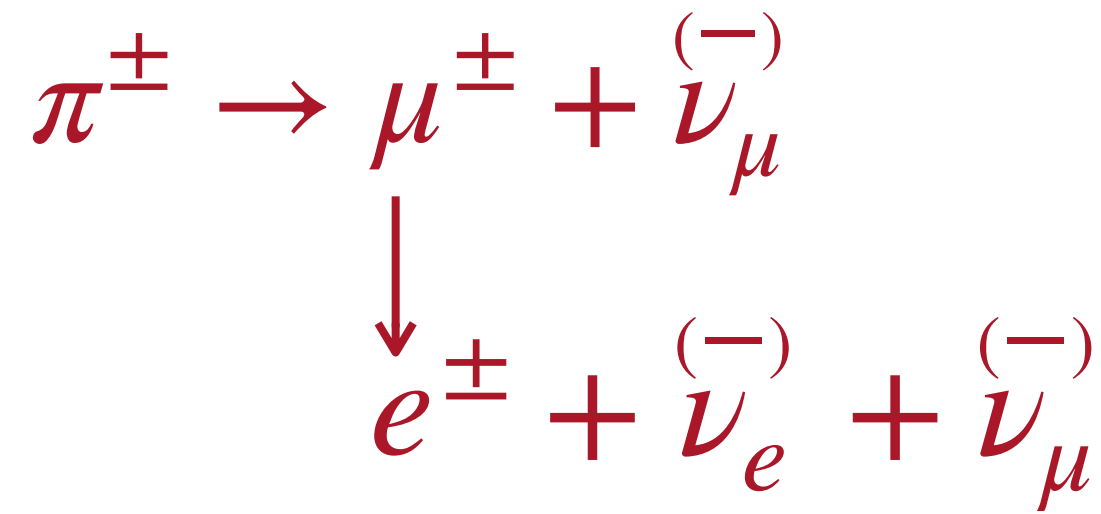


(0:1:0)





pion production



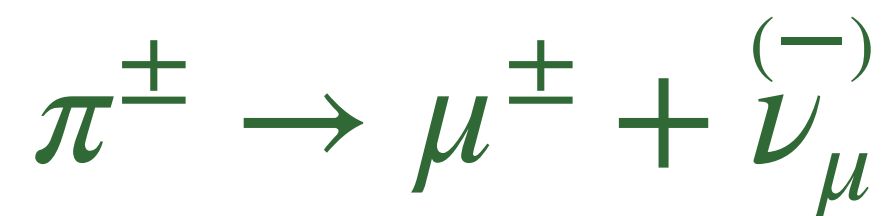
(1:2:0)

neutron decay



(1:0:0)

muon dumped



(0:1:0)

