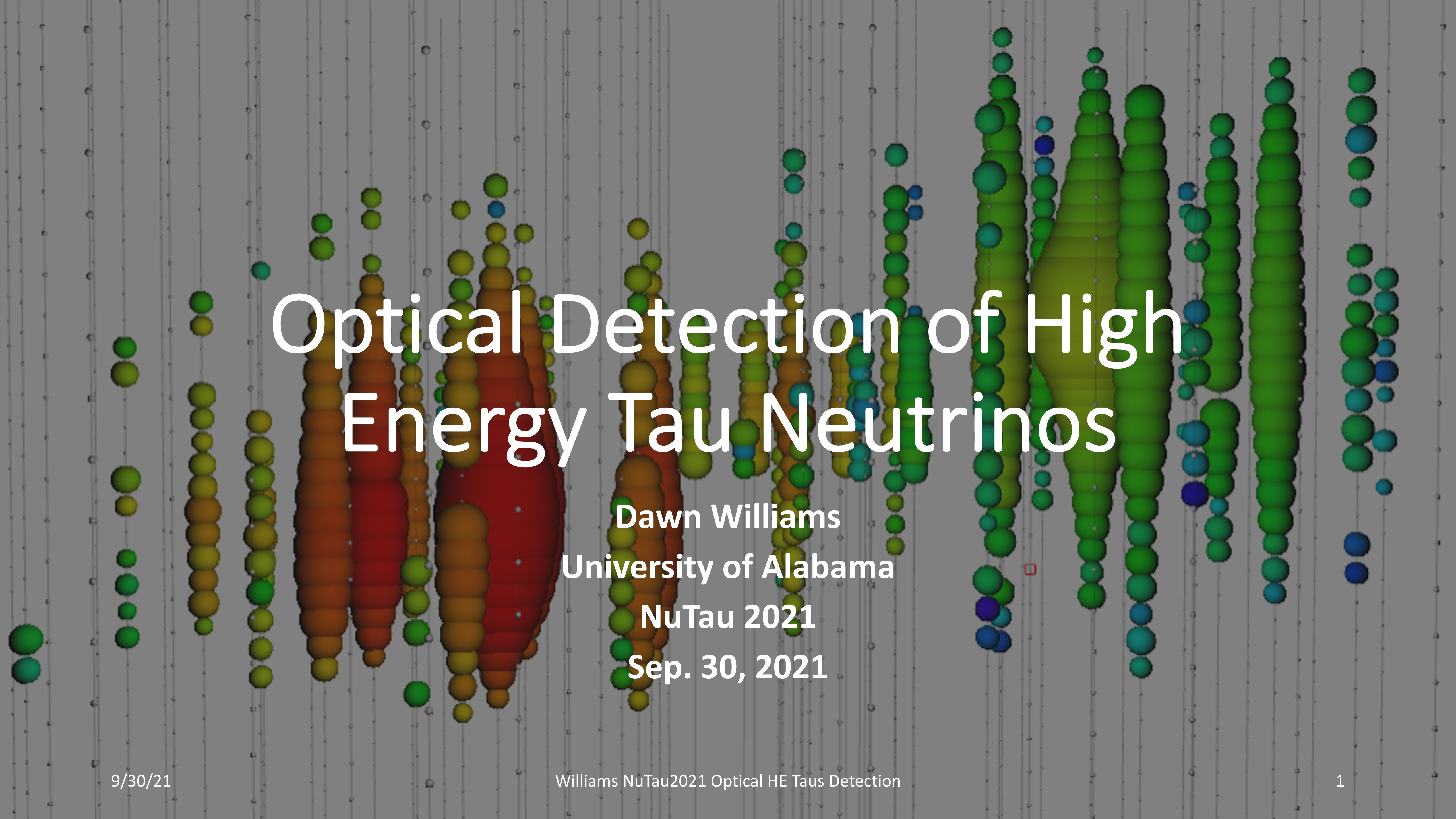


Optical Detection of High Energy Tau Neutrinos

Dawn Williams

University of Alabama

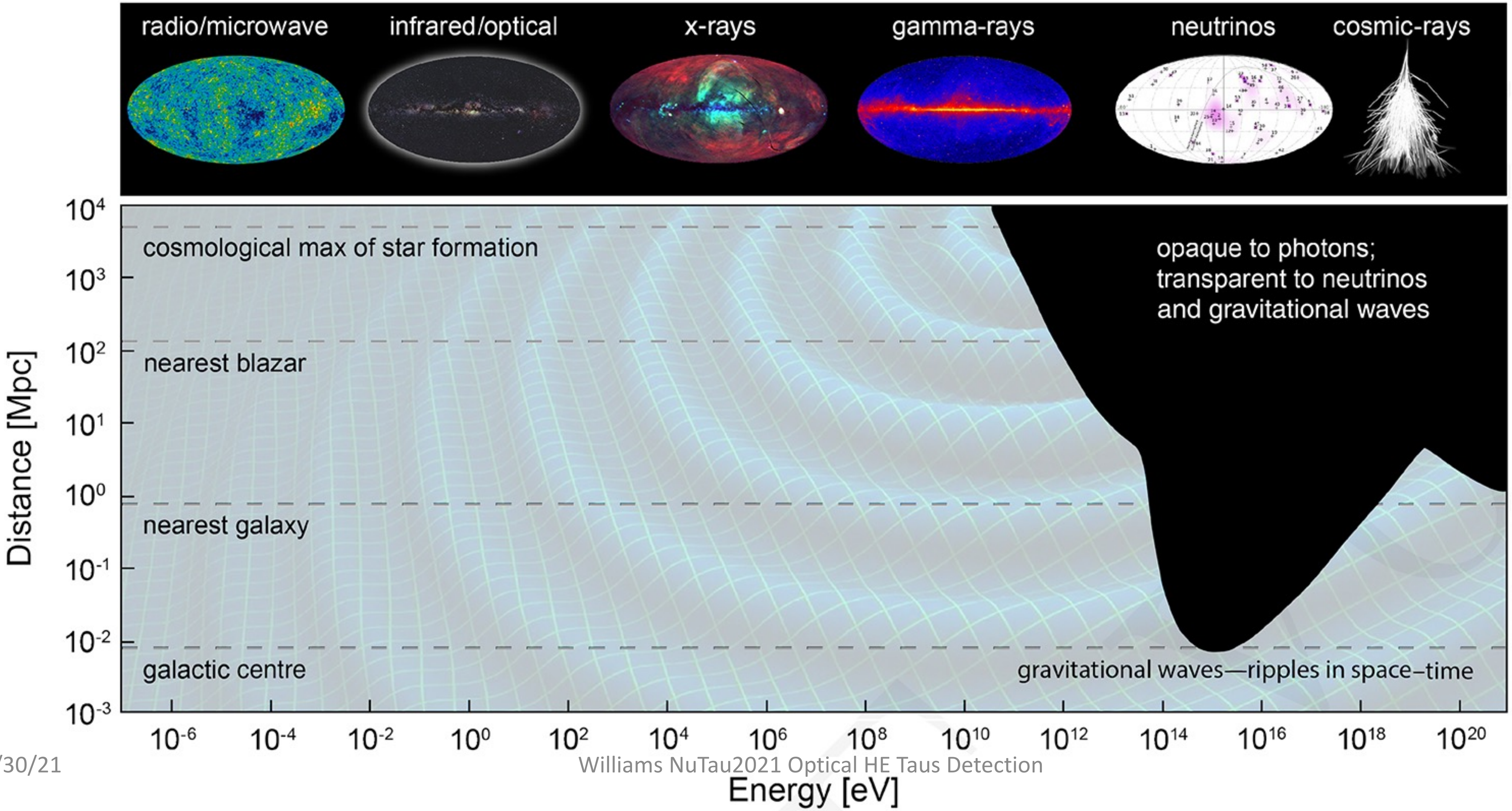
NuTau 2021

Sep. 30, 2021

Overview

- This talk covers optical/UV detectors – see Enrique Zas' talk next for the radio technique
  - Motivation
  - Water/ice Cherenkov
  - Air Cherenkov and particles from air showers
- Thanks to the members of all the experiments whose slides and proceedings are the sources for this talk (especially for VLVNT 2021, ICRC 2021 and Astro 2020)

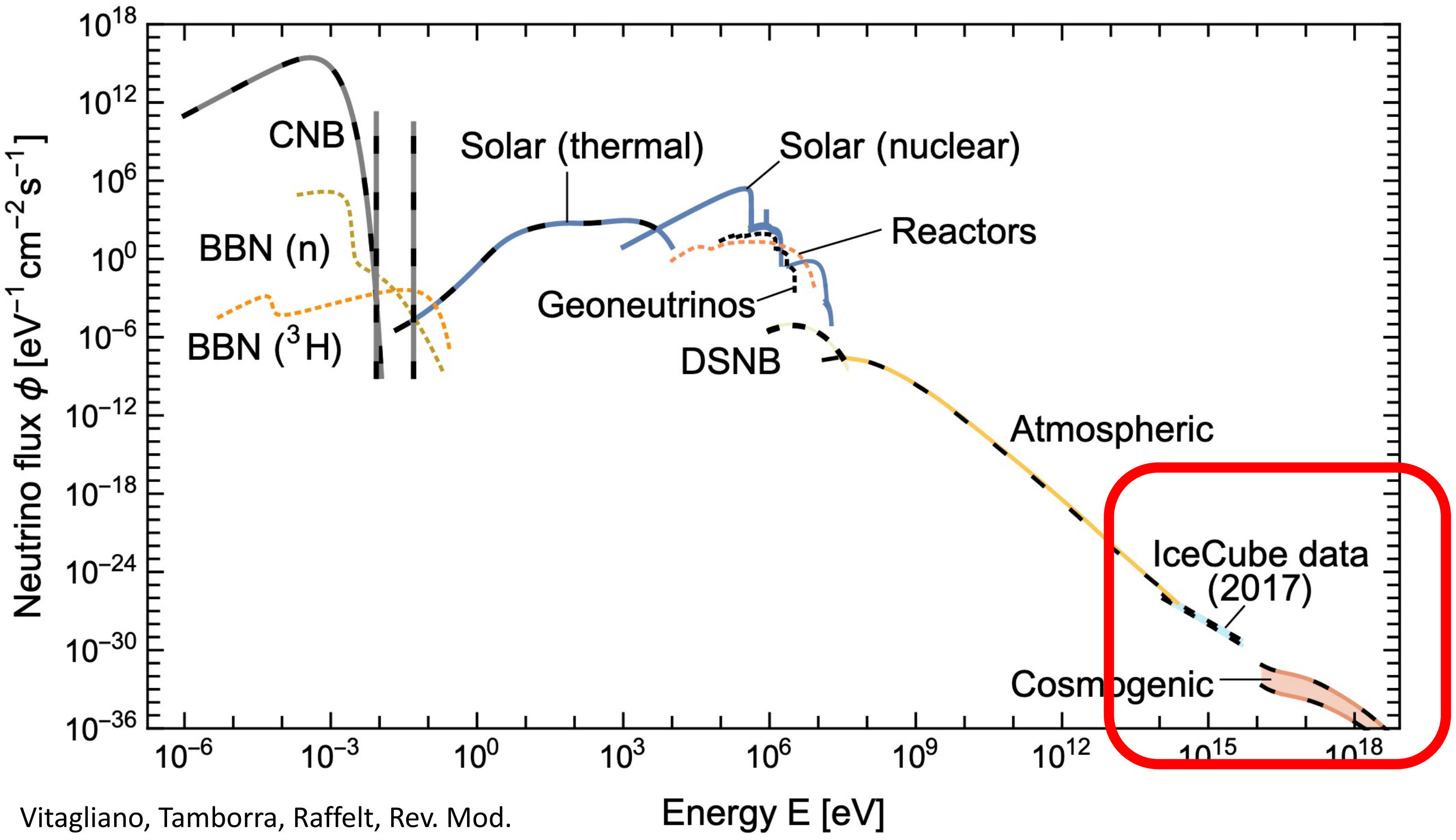
The multi-messenger universe



Motivation for PeV – EeV Tau Neutrino Searches

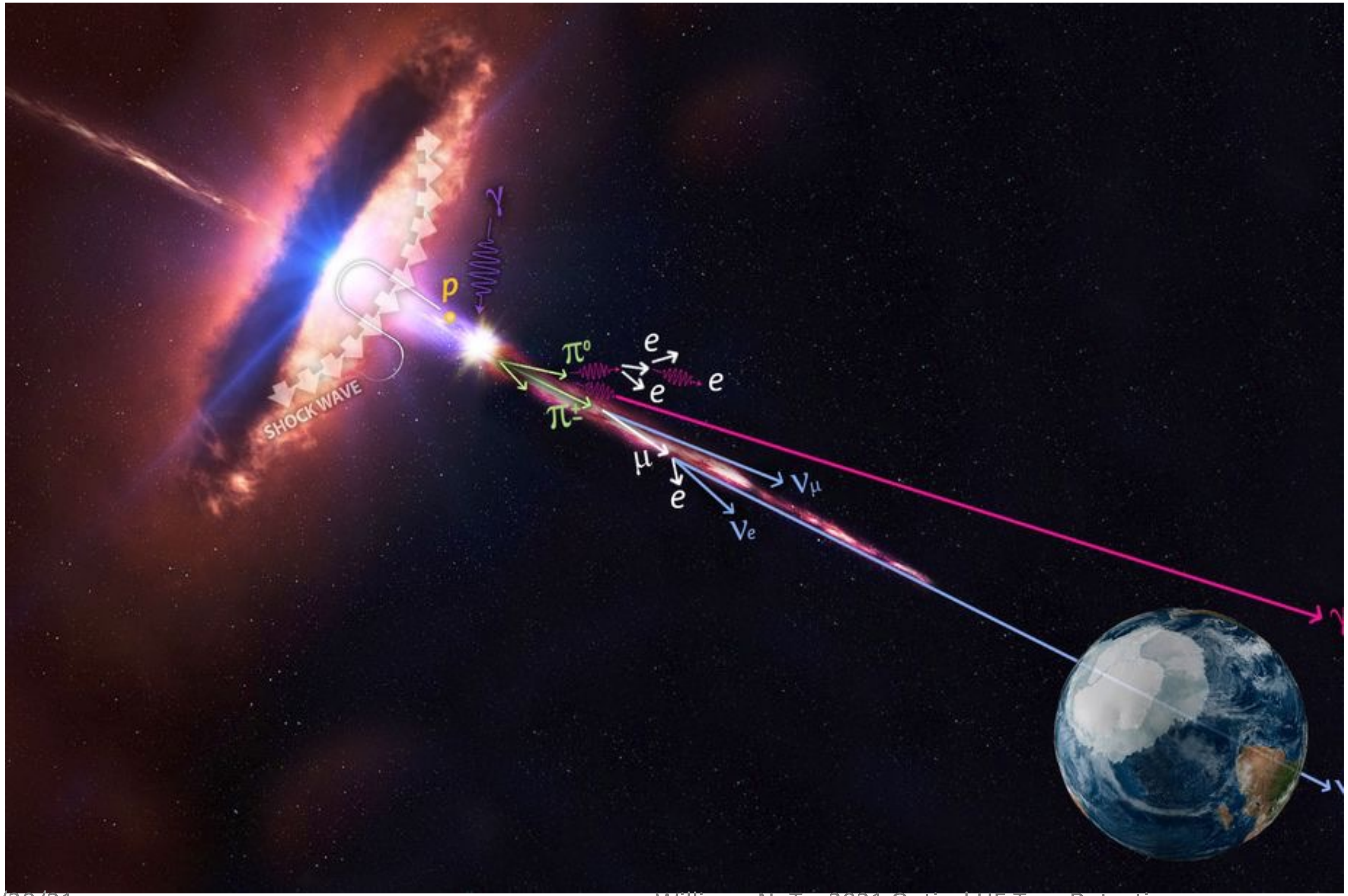
- Background from atmosphere is very low (some taus from decay of charmed mesons) – PeV – EeV taus are almost certainly astrophysical
- Taus are not expected to be produced in large numbers in cosmic sources, but are expected to form a third of the flux at Earth
- Tau regeneration extends the horizon of neutrino telescopes at energies where other flavors are absorbed in the Earth
- Earth-skimming taus form a unique opportunity for neutrino observation by cosmic ray observatories and air Cherenkov telescopes
- The tau sector has a lot of exciting opportunities for BSM physics – see Mauricio Bustamante’s talk tomorrow

PeV – EeV Neutrinos



Vitagliano, Tamborra, Raffelt, Rev. Mod. Phys. 92, 45006 (2020)

Cosmic accelerators



Interactions between accelerated protons and protons or photons lead to production of pions

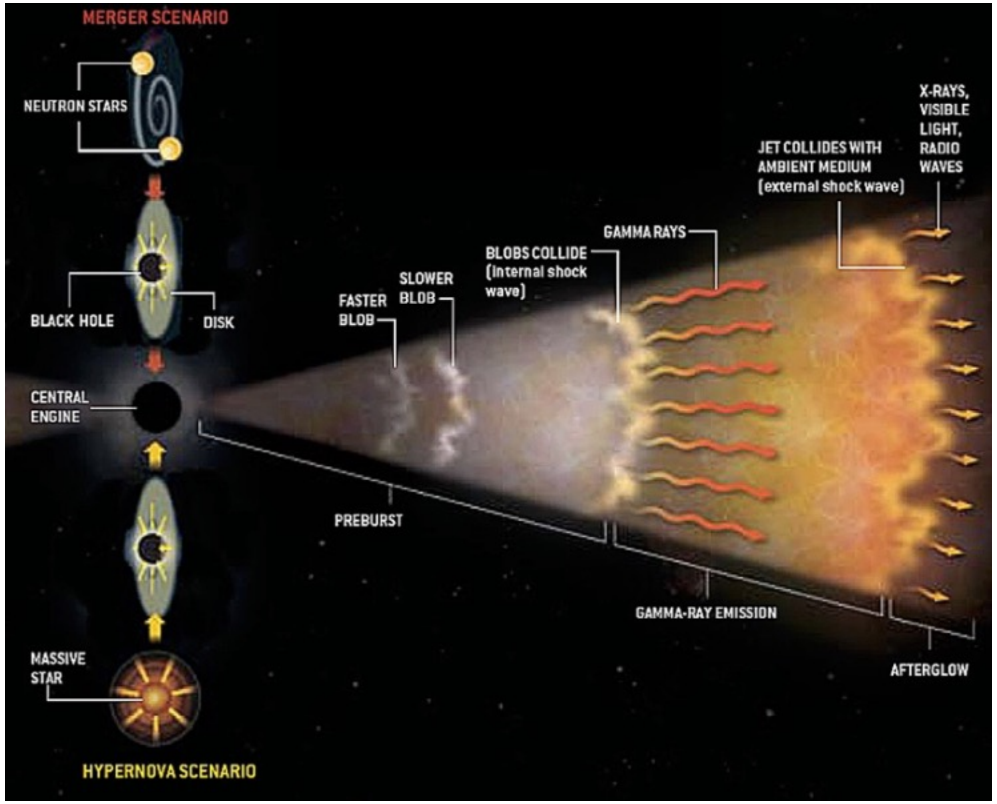
Charged pion decay produces neutrinos, neutral pion decay produces gamma rays : multi-messenger

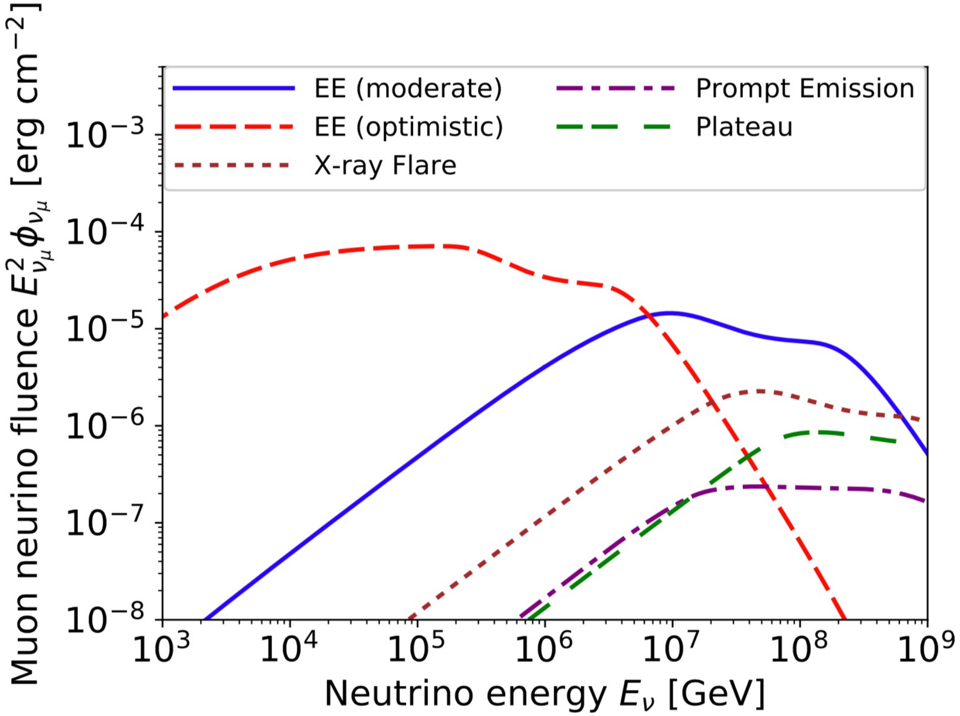
Simple model expects
ν_e: ν_μ: ν_τ = 1:2:0 at source

Flavor change leads to
ν_e: ν_μ: ν_τ = 1:1:1 at Earth

Dominates over atmospheric background above ~100 TeV

Cosmic accelerators and multi-messenger events

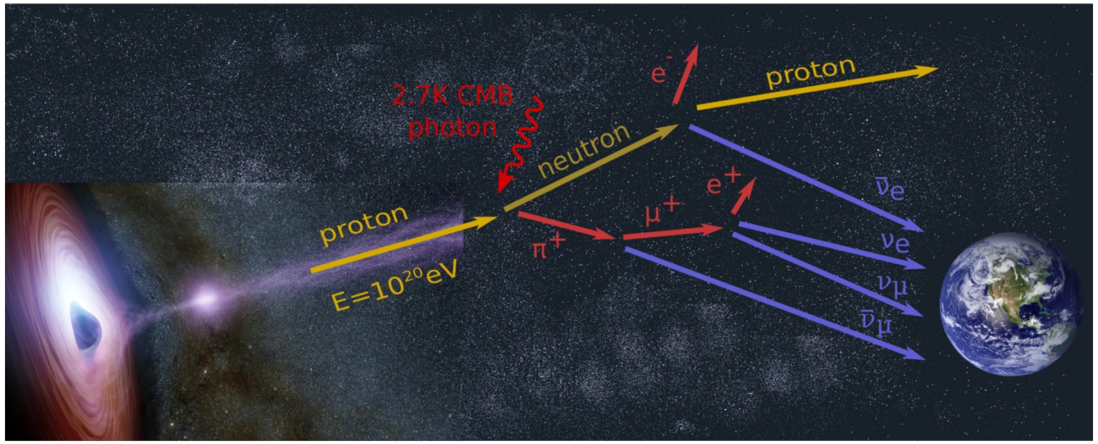




Kimura et al. Astrophys.J. 848 (2017) L4

Cosmogenic neutrinos (EeV)

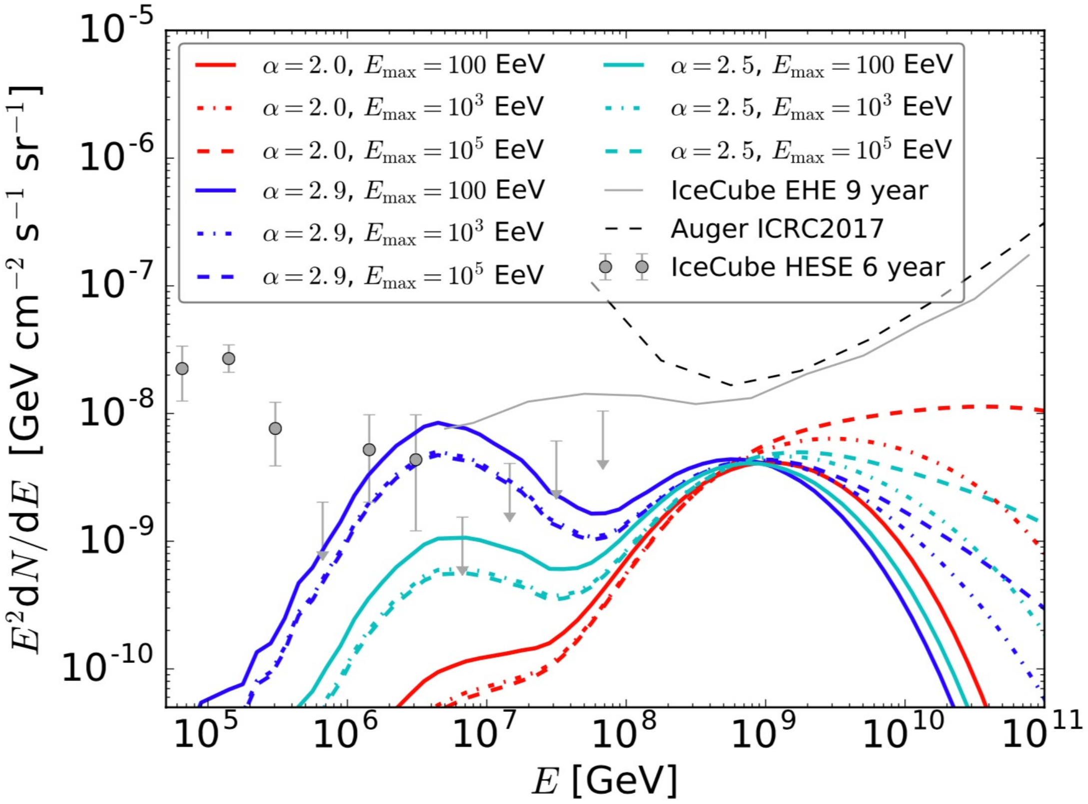
http://trinity.physics.gatech.edu/the-new-umoma-opens-its-doors-2/



UHECR interacting with the CMB produce secondary particles including neutrinos

”Guaranteed” flux… but depends on UHECR composition

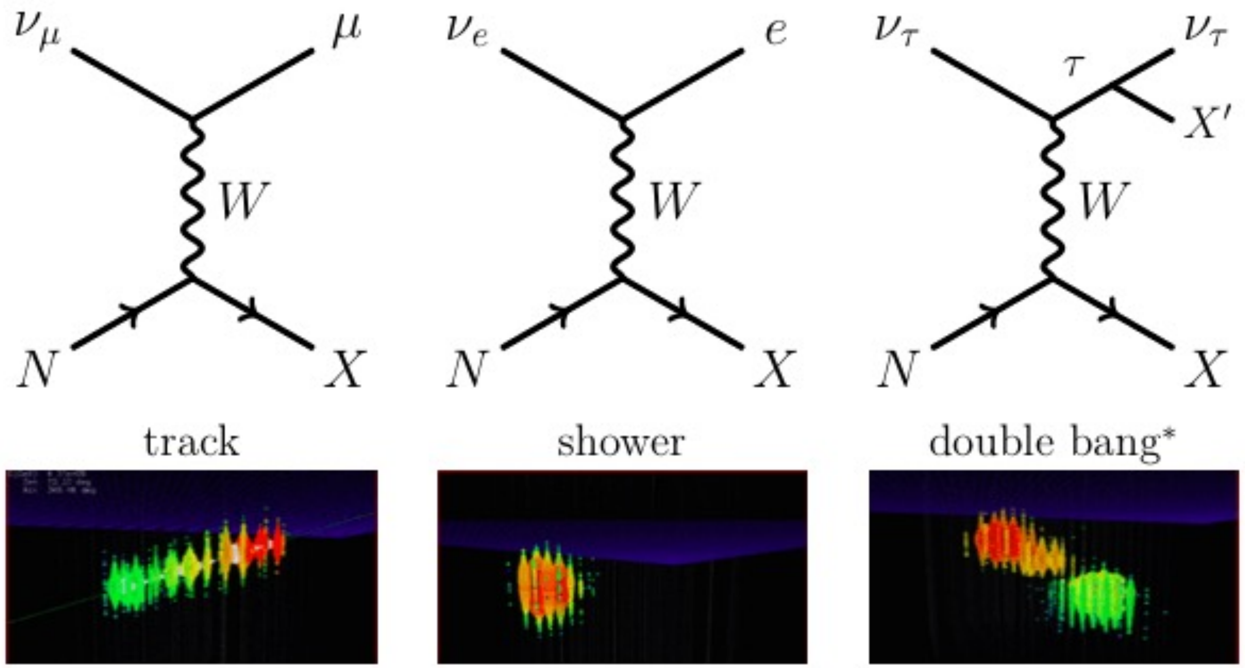
A. Van Vliet, R. A. Batista and J. Hoerandel, Phys. Rev. D 100, 021302 (2019)



Cosmogenic neutrino flux in a pure proton composition scenario

Neutrinos interacting in water and ice

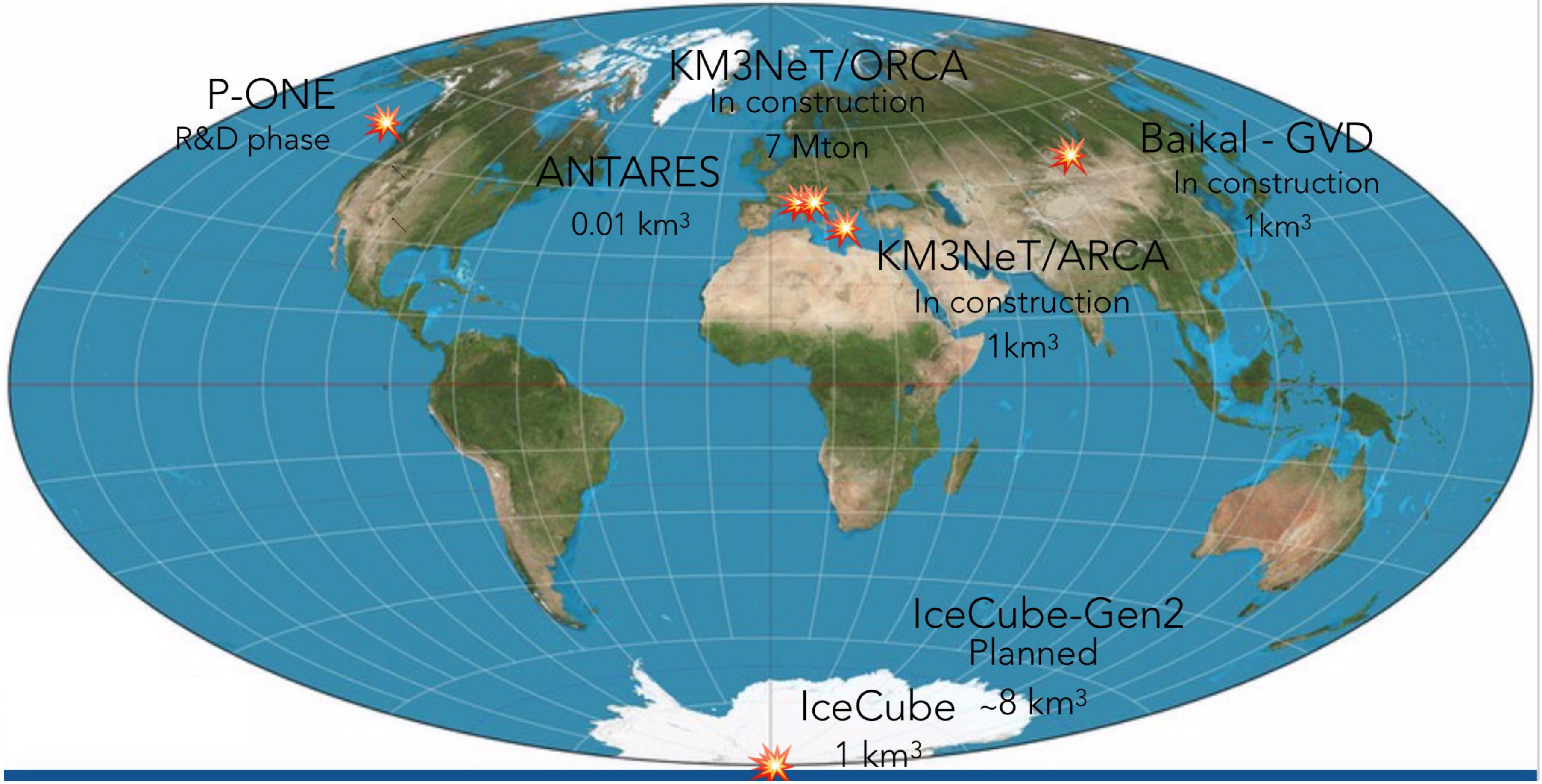
- A km^3 scale (gigaton) detector is necessary to see the fluxes of neutrinos expected from cosmic accelerators
- Deploy optical sensors in water or ice to see light from neutrino interactions
- Ice offers a stable deployment platform, low radioactivity/background, long optical absorption length
- Water offers more suitable sites near land/infrastructure, long optical scattering length



"cascade"

"double cascade"

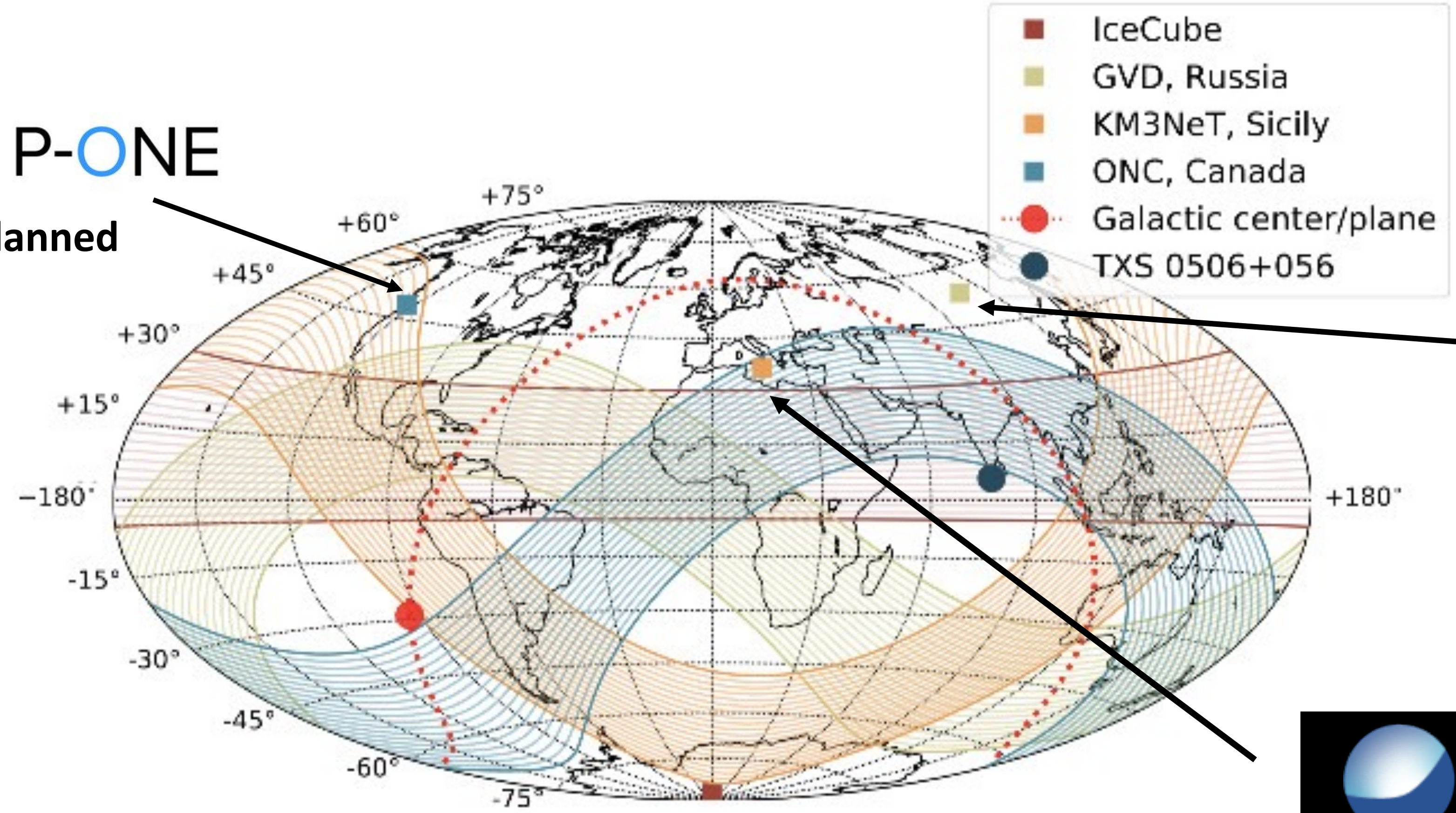
Cosmic Neutrino Detectors in Water and Ice



Cosmic Neutrino Detectors in Water and Ice

P-ONE

Planned



BAIKAL-GVD

Under construction

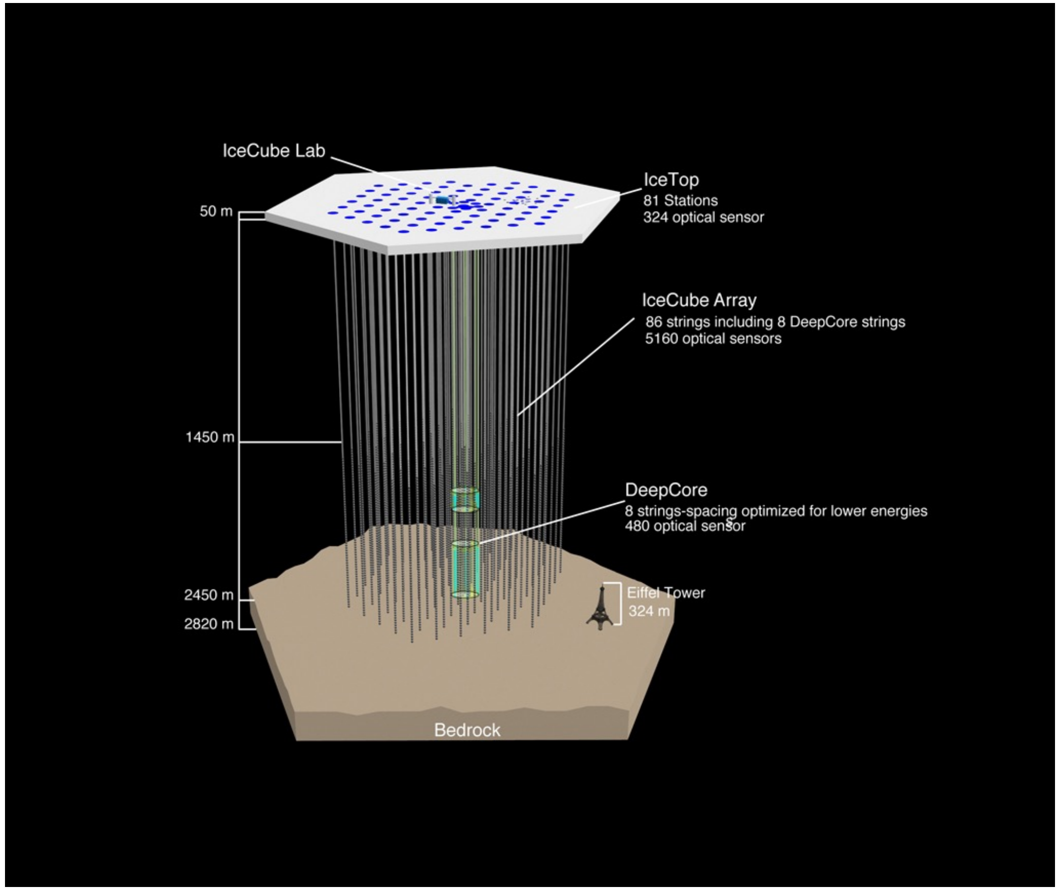
KM3NeT

Under construction

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

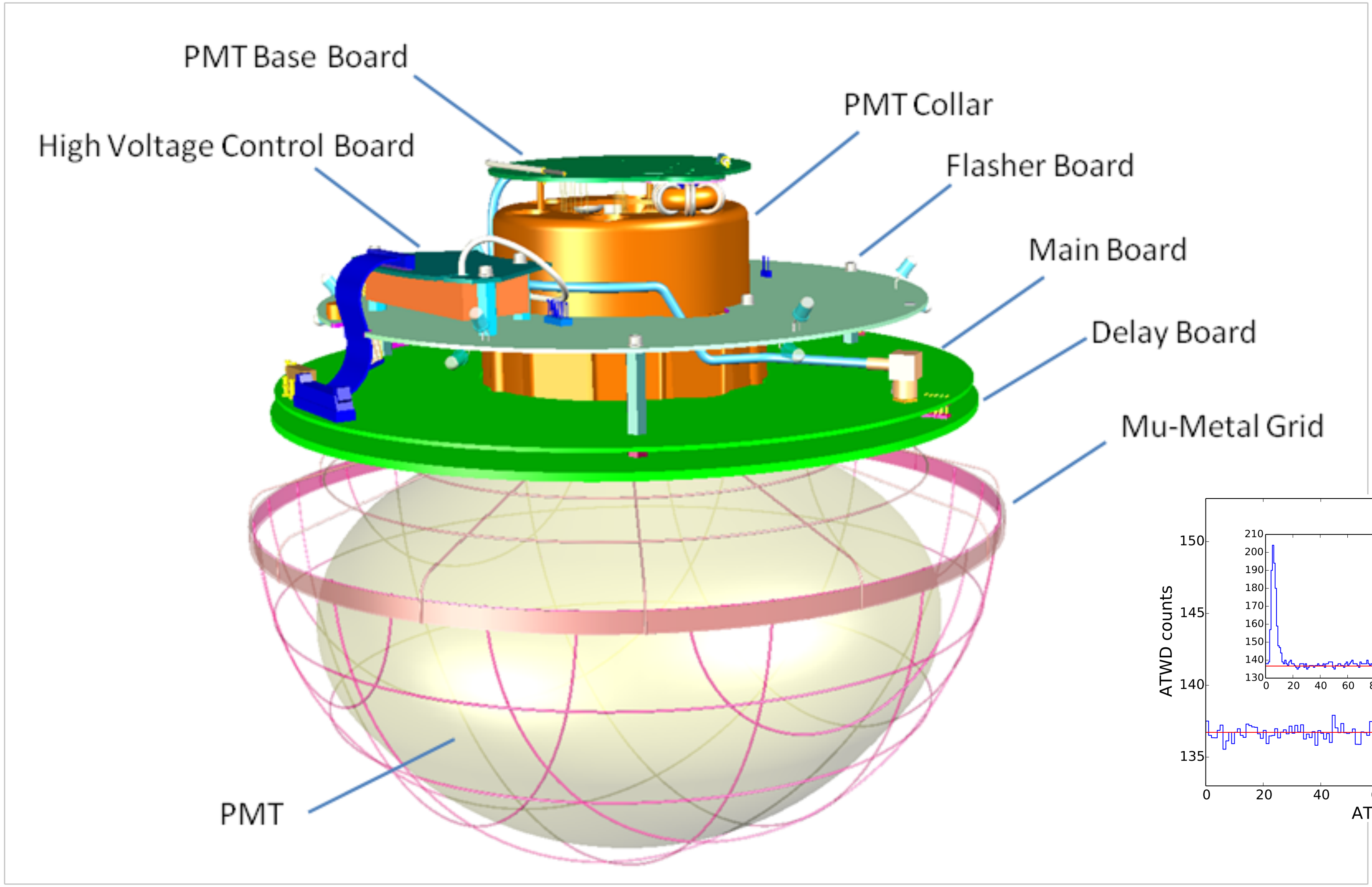
Complete since 2010

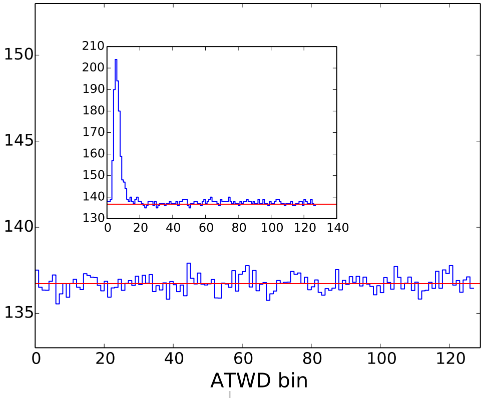
The IceCube Neutrino Observatory



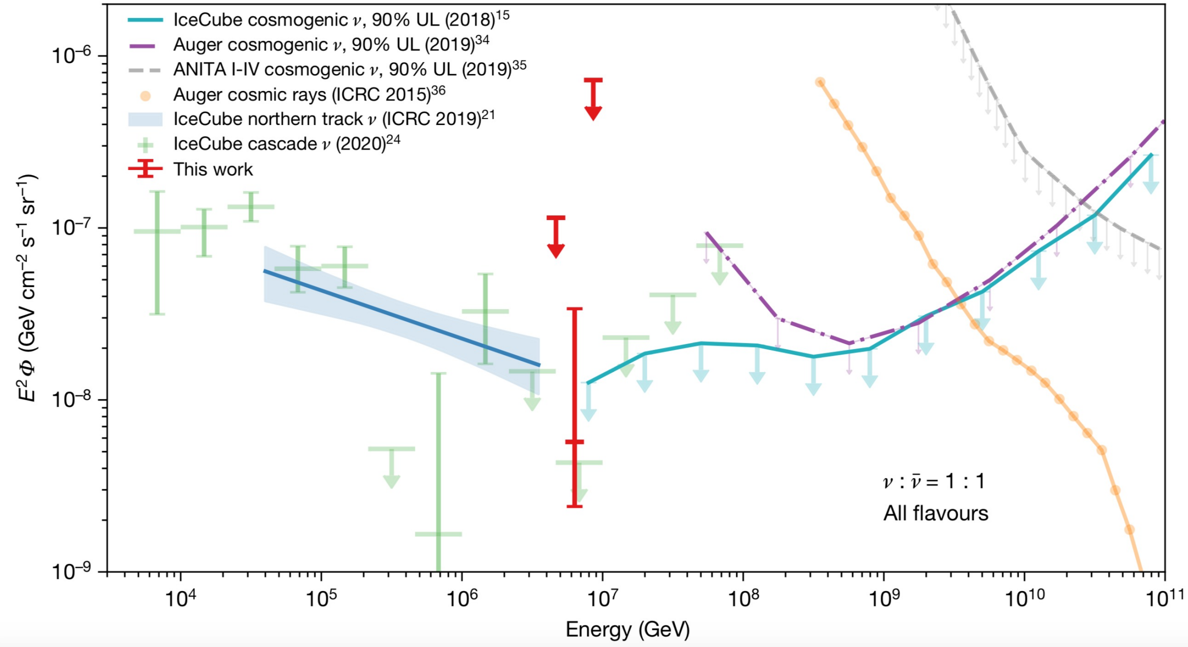
- **Located at the Amundsen-Scott South Pole station near the geographic south pole**
- **Instrumented volume of 1 km^3**
- **86 cables called "strings", each with 60 Digital Optical Modules (DOMs) between 1450 and 2450 m deep**
- **Denser "DeepCore" subarray in the center**
- **81 IceTop surface detectors**
- **Completed in 2010**

IceCube Digital Optical Module (DOM)

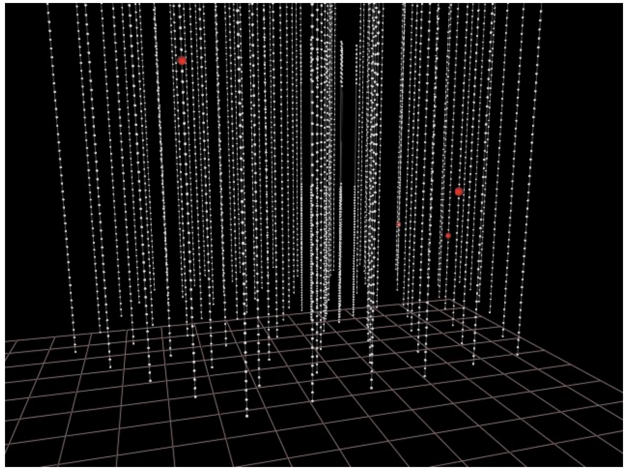


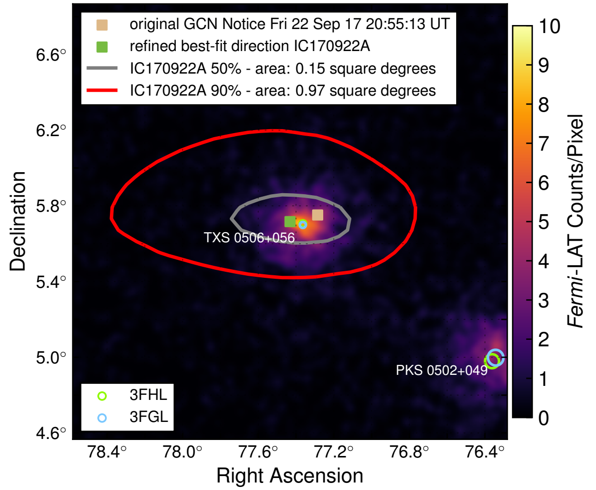


Cosmic Neutrinos Observed by IceCube



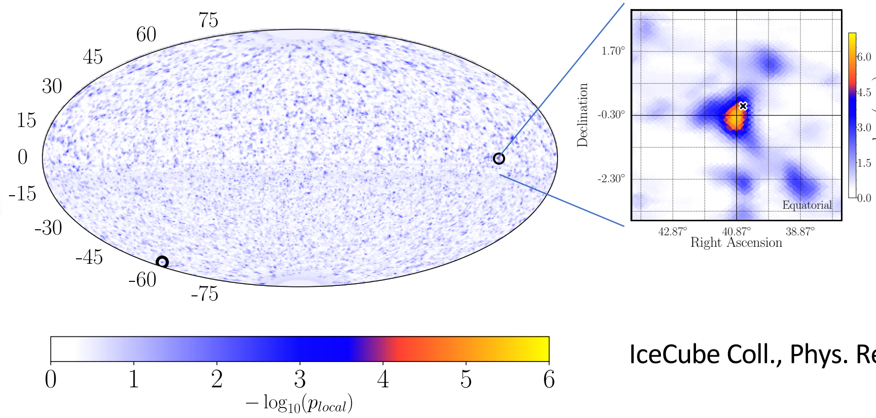
IceCube Coll., *Nature* **volume 591**, pages 220–224 (2021)





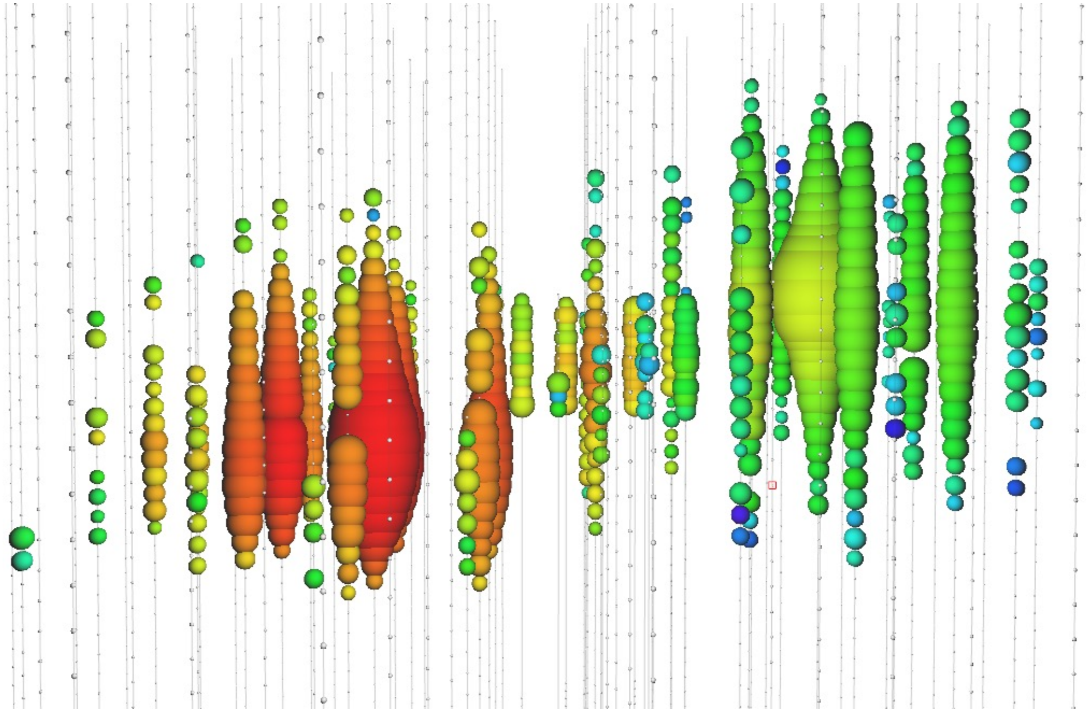
Science 13 Jul 2018: Vol. 361, Issue 6398

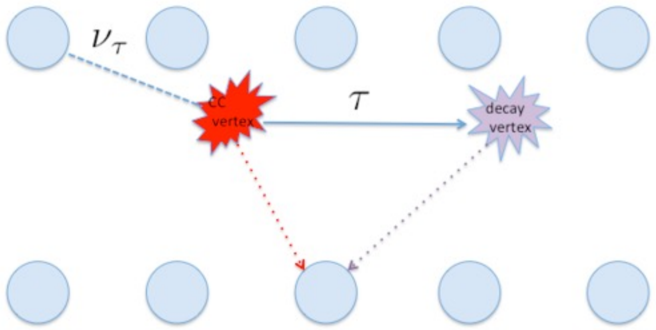
IceCube, Fermi, MAGIC and 13 additional collaborations

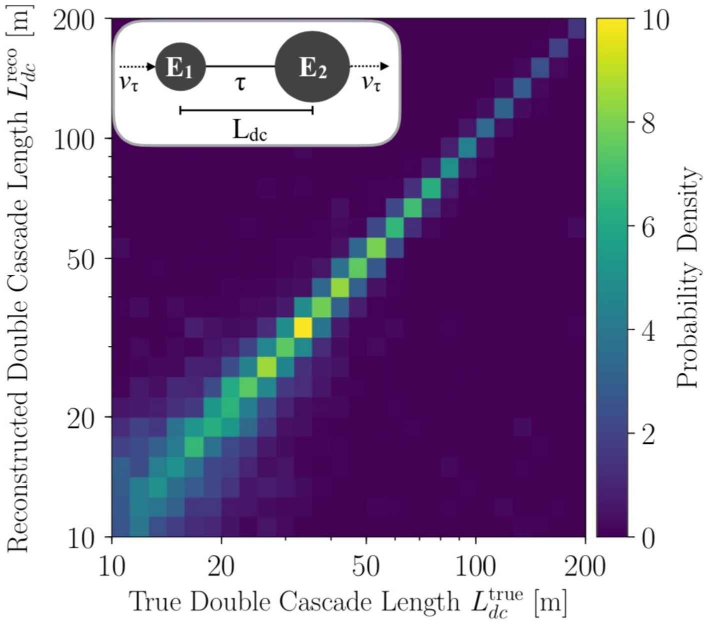


IceCube Coll., Phys. Rev. Lett. 124, 051103 (2020)

Tau neutrinos in IceCube



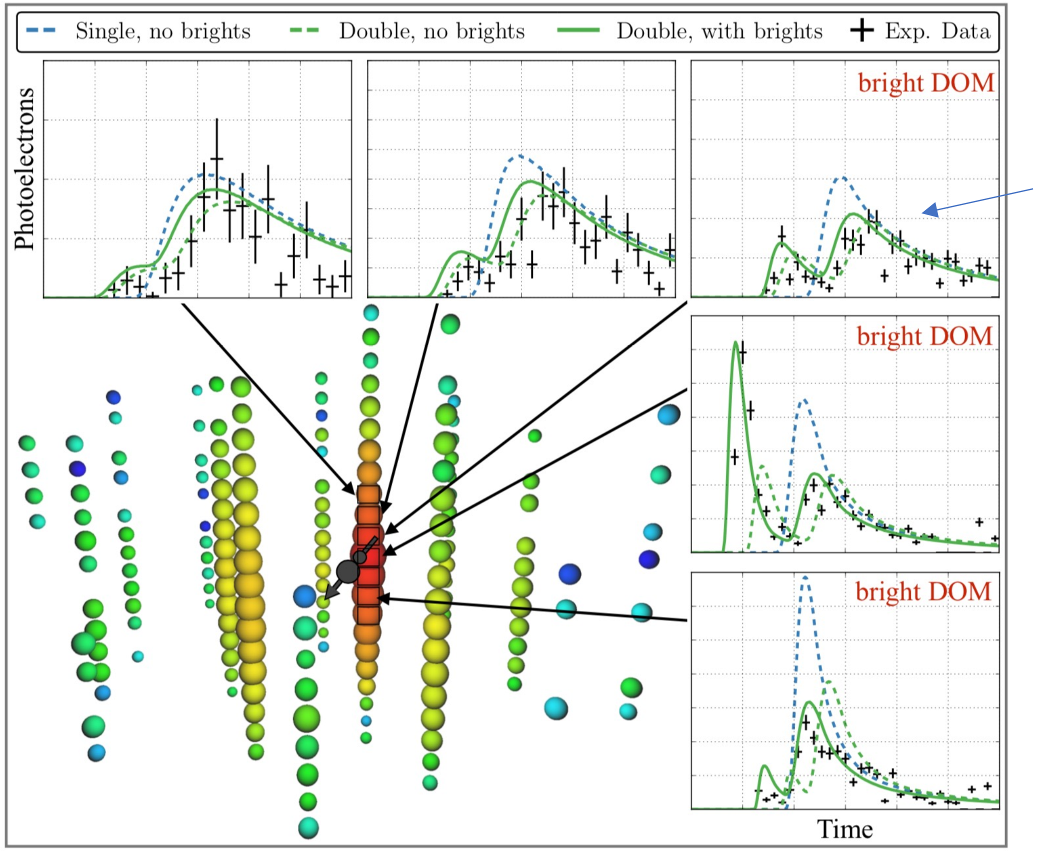




See Juliana Stachurska's talk later today

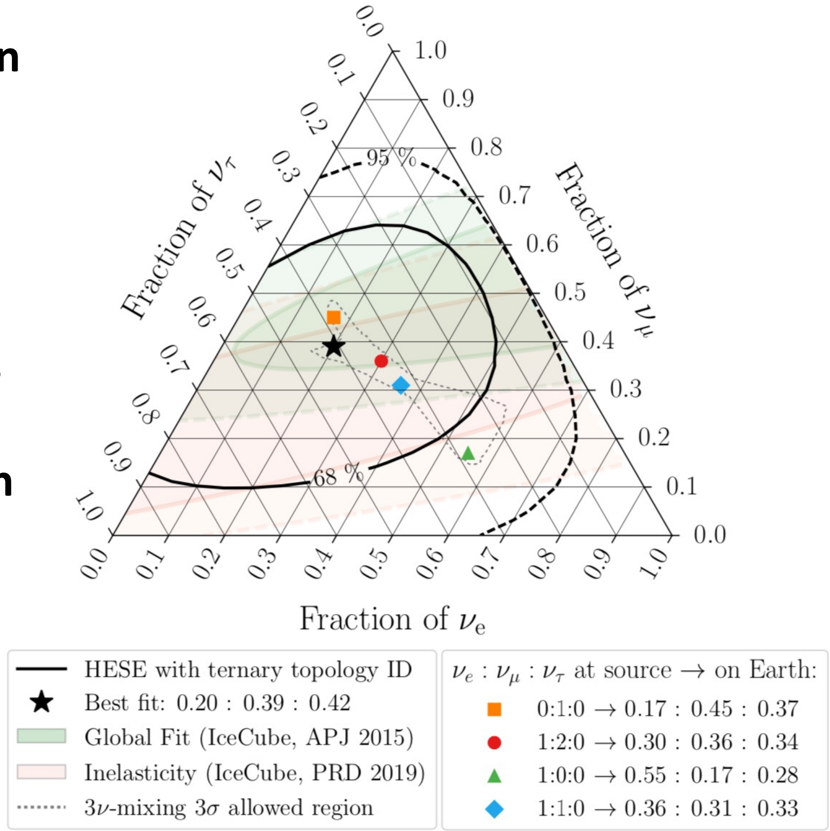
IceCube Coll. arXiv:2011.03561 [hep-ex]

First tau neutrino candidates in IceCube



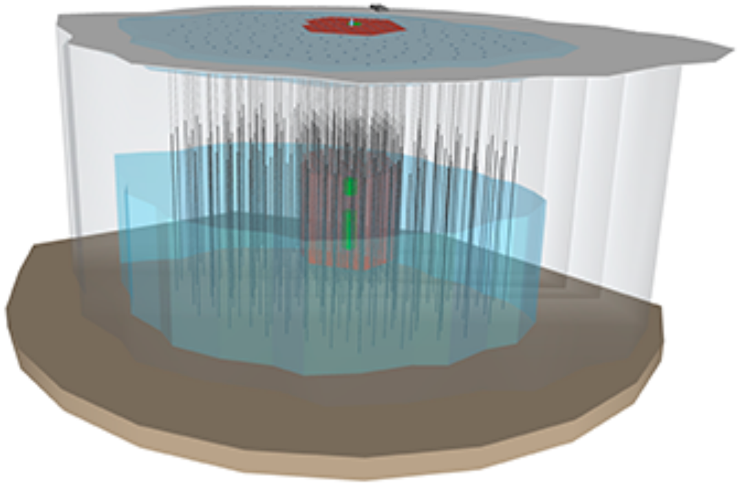
Double pulses in IceCube DOM waveforms

Reconstructs as a double cascade, though not visible by eye

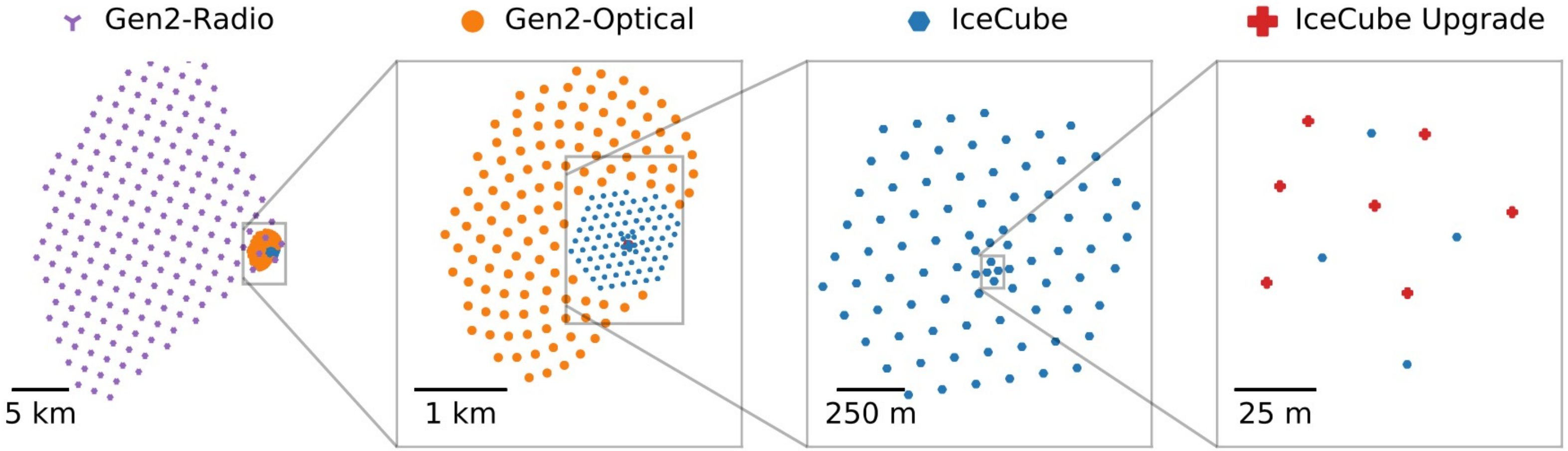


IceCube Coll. arXiv:2011.03561 [hep-ex]

IceCube-Gen2



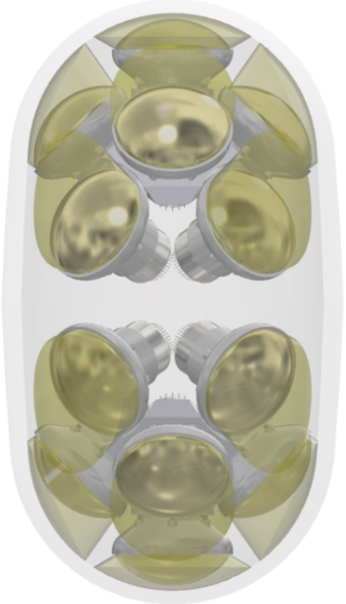
IceCube Gen2 Coll. - J.Phys.G 48 (2021) 6, 060501



Next generation neutrino detector at the South Pole: nearly an order of magnitude increase in detection volume

Sensitivity to 5x fainter sources

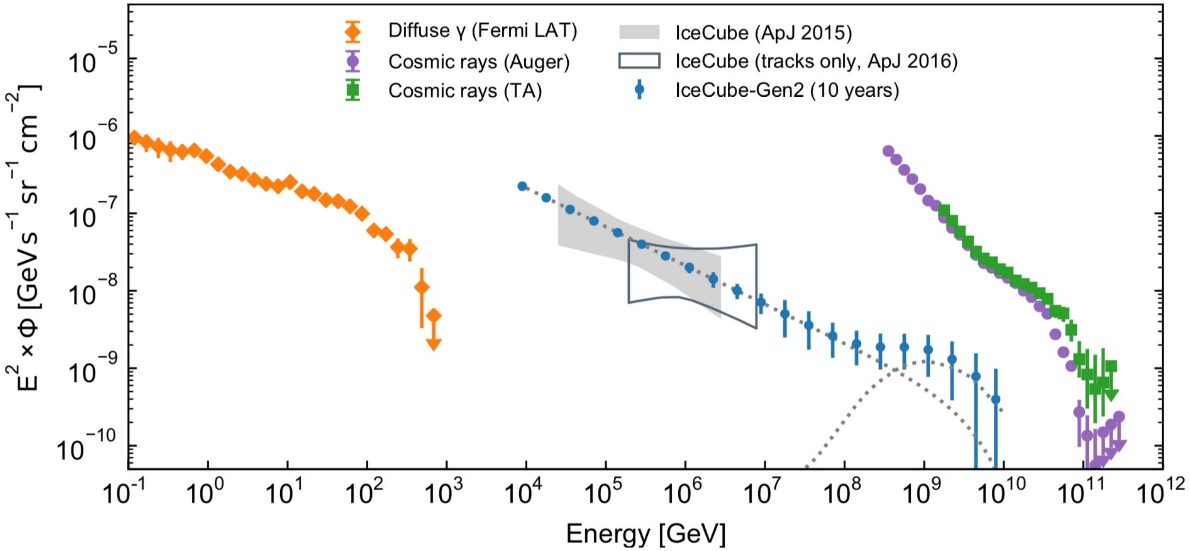
Radio component for detection of cosmogenic neutrinos (from cosmic rays interacting with the CMB), following on current generation radio detectors ARA, ARIANNA, ANITA and RNO-G

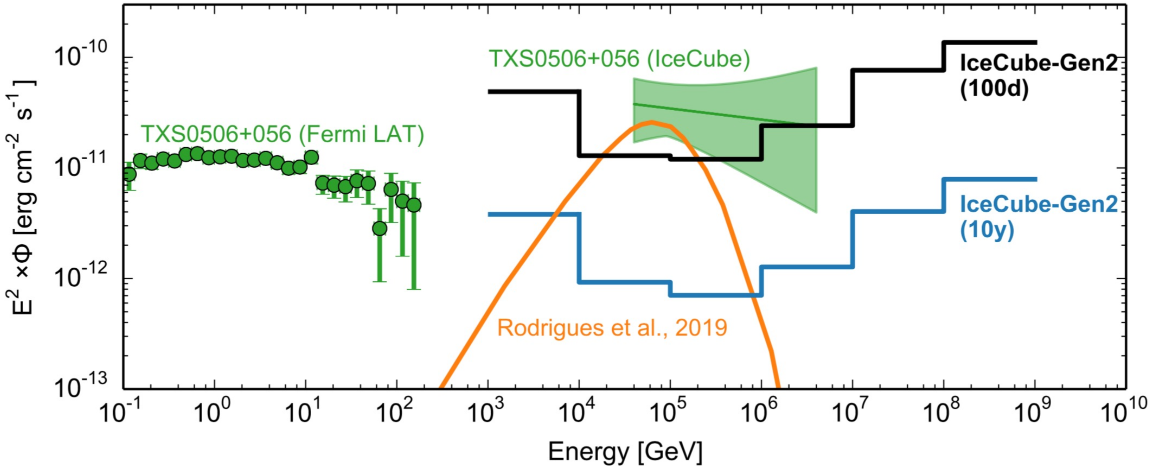


Long Optical Module (LOM) design concept

Gentoo penguin

Cosmic Neutrinos in IceCube-Gen2

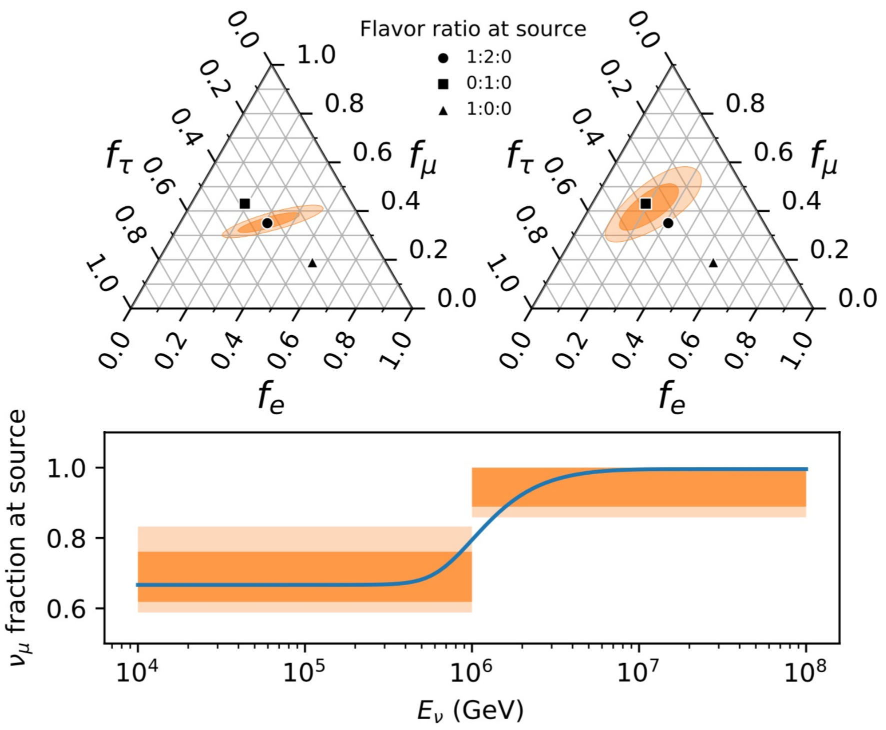




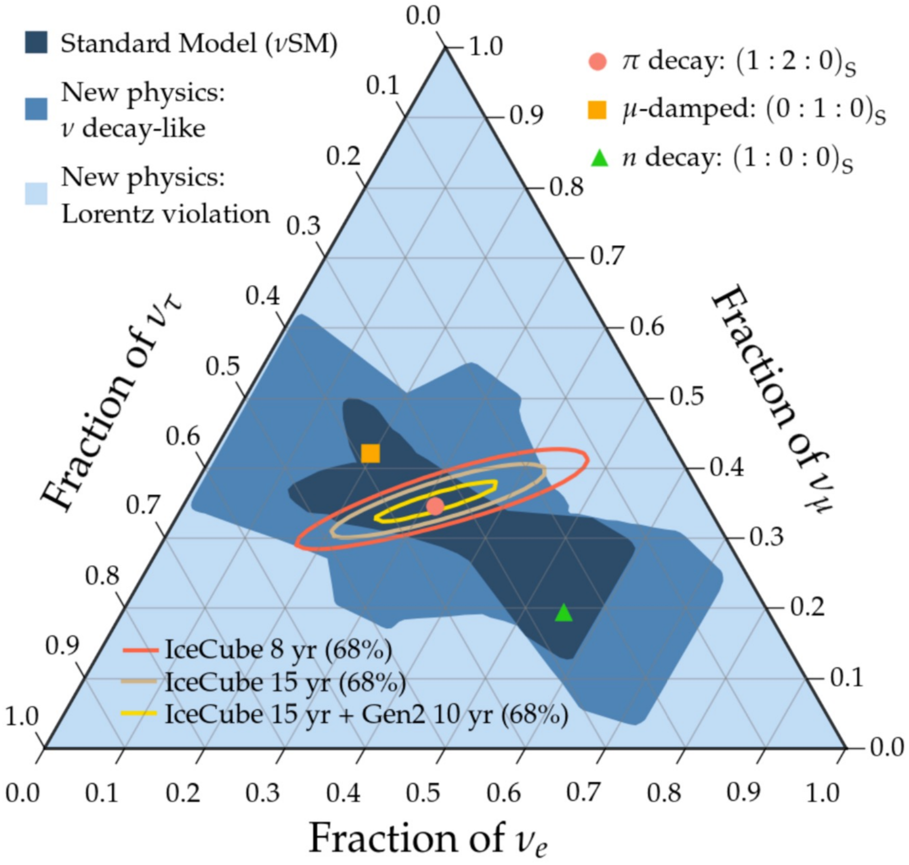
IceCube Gen2 Coll. - J.Phys.G 48 (2021) 6, 060501

Tau Neutrinos in IceCube-Gen2

5x more tau neutrinos per year expected in IceCube-Gen2 compared to current detector



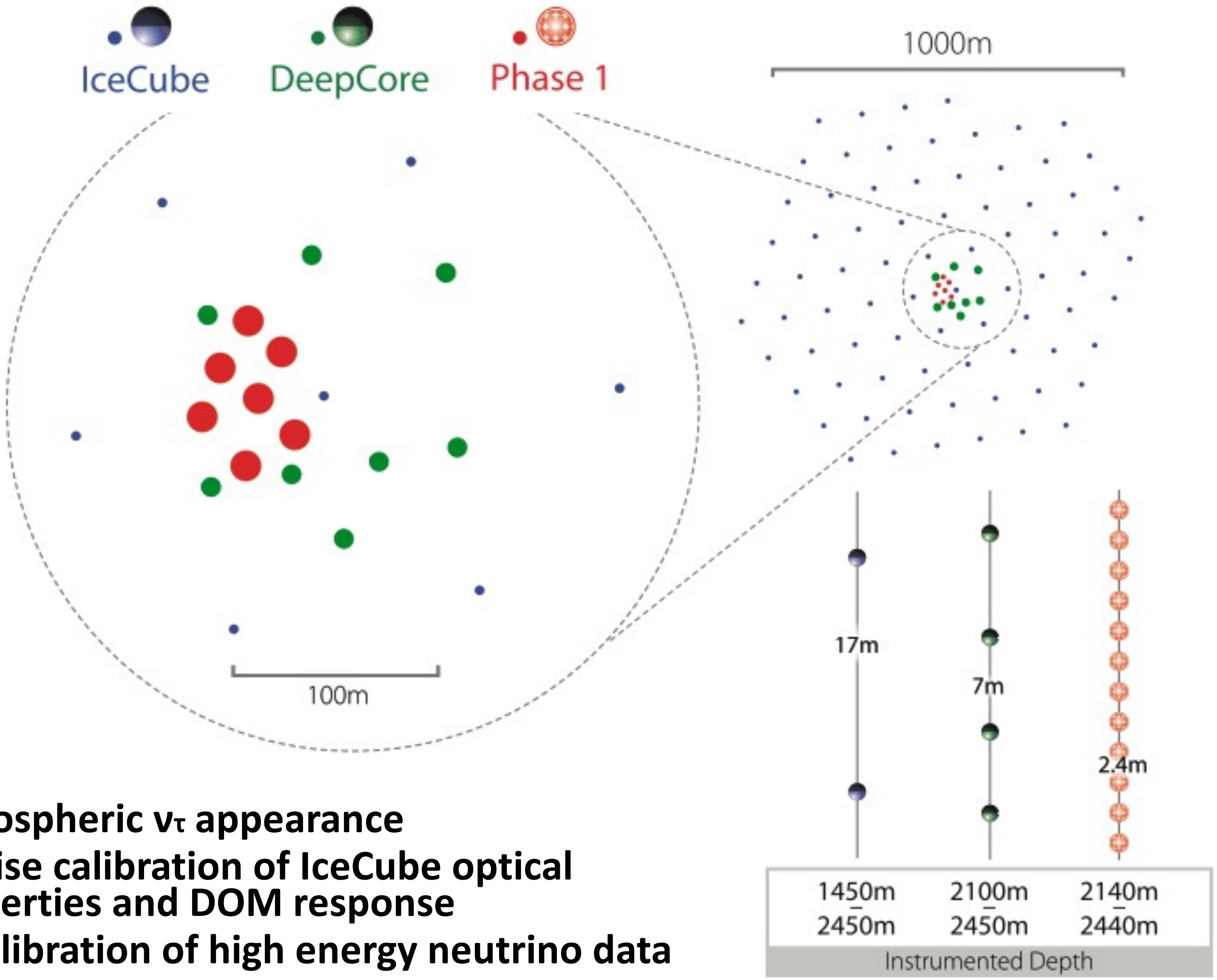
IceCube Gen2 Coll. - J.Phys.G 48 (2021) 6, 060501

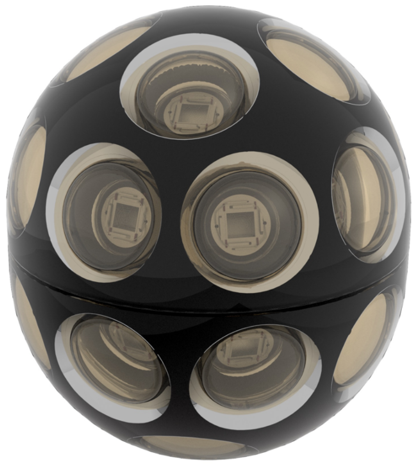


The first phase: IceCube Upgrade

7 new strings scheduled for deployment in 2022/23

Currently schedule is under review due to impact of COVID

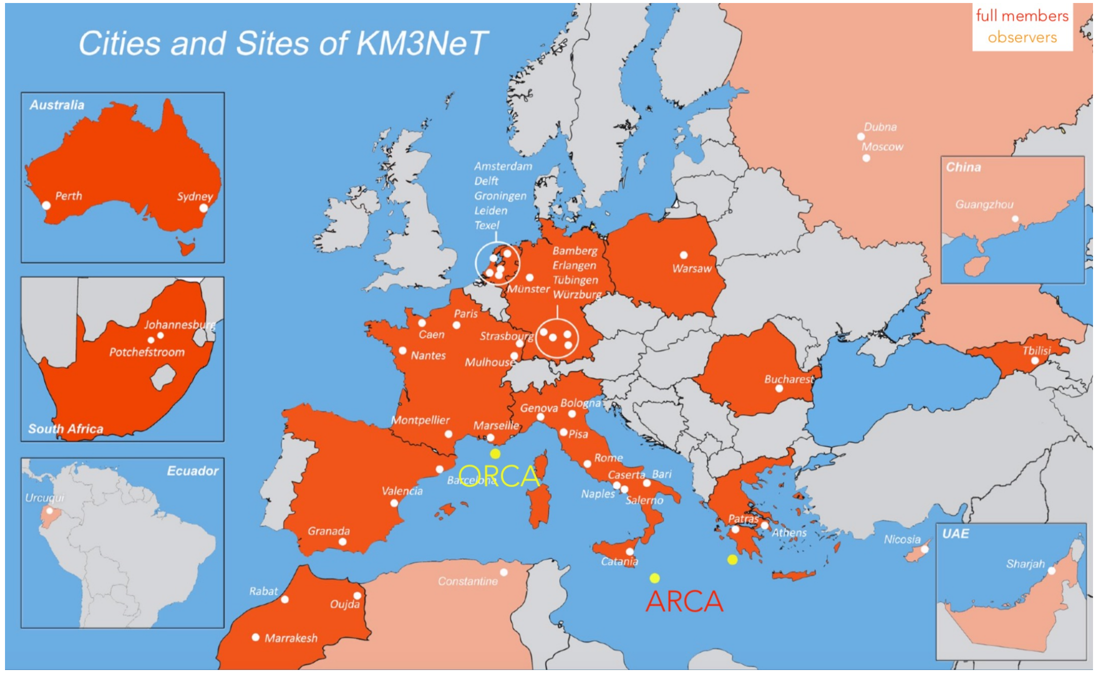




Upgraded sensor designs

- **Atmospheric ν_τ appearance**
- **Precise calibration of IceCube optical properties and DOM response**
- **Recalibration of high energy neutrino data**

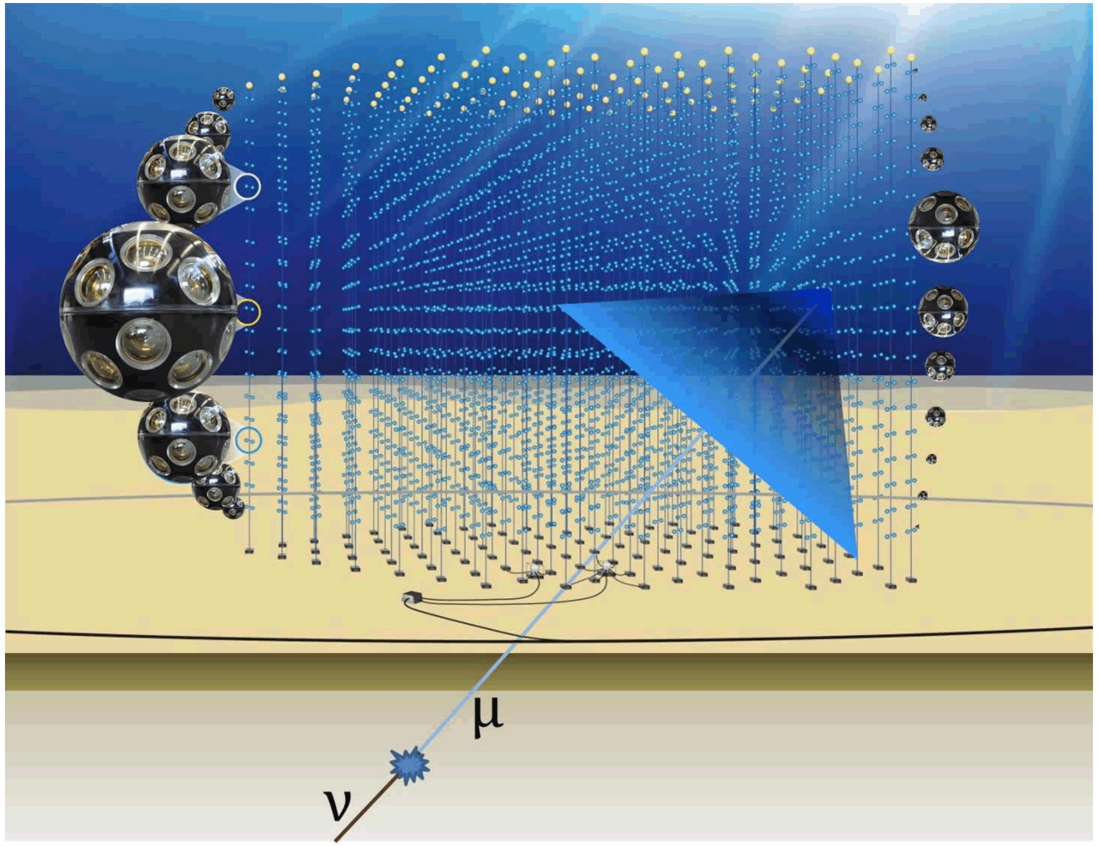
KM3NET

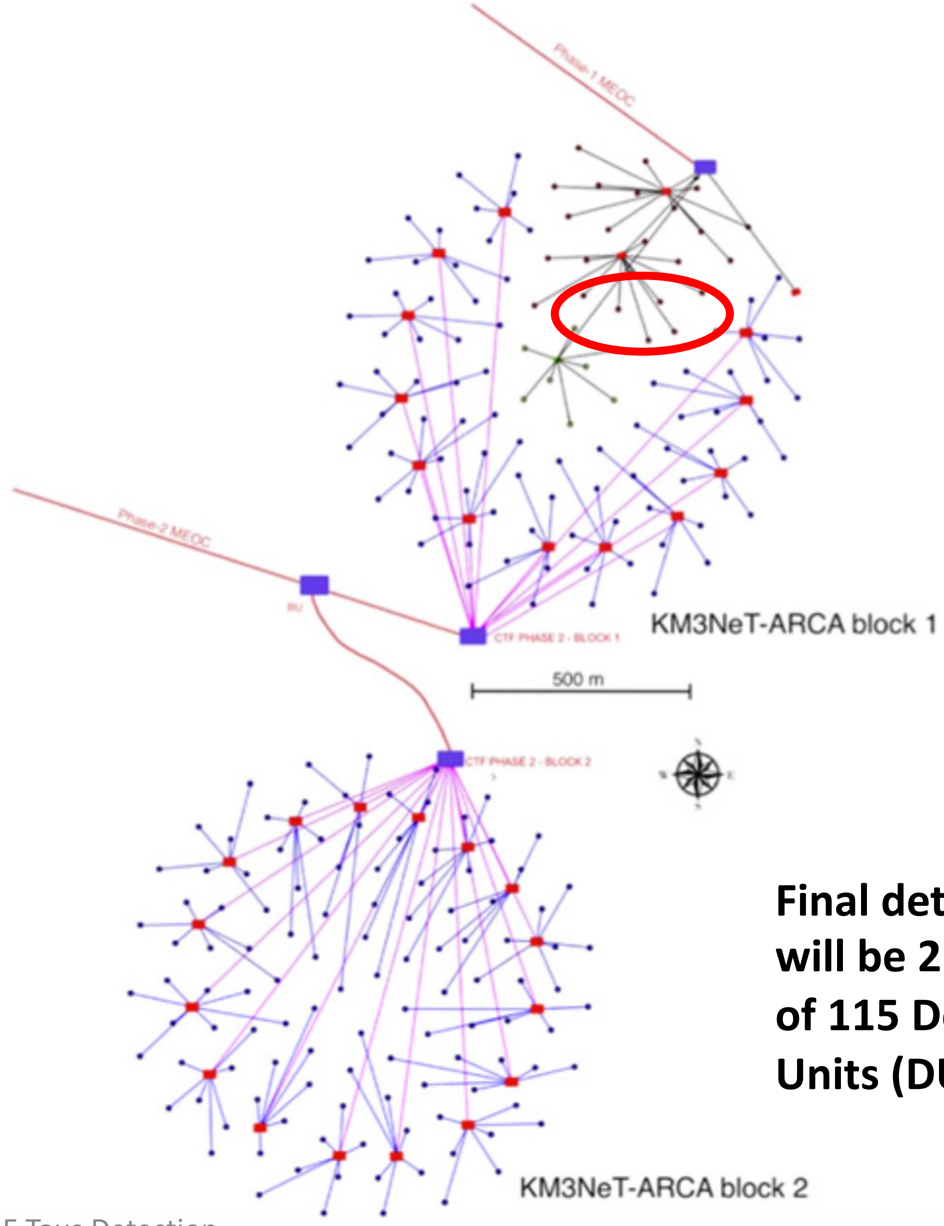


R. Coniglione, VLVNT 2021

- ORCA: Oscillation Research with Cosmics in the Abyss
  - 7 Mton atmospheric neutrino science detector
  - Located off the coast of France
- ARCA: Astroparticle Research with Cosmics in the Abyss
  - 1 km^3 cosmic neutrino detector
  - Located off the coast of Italy

KM3NET-ARCA

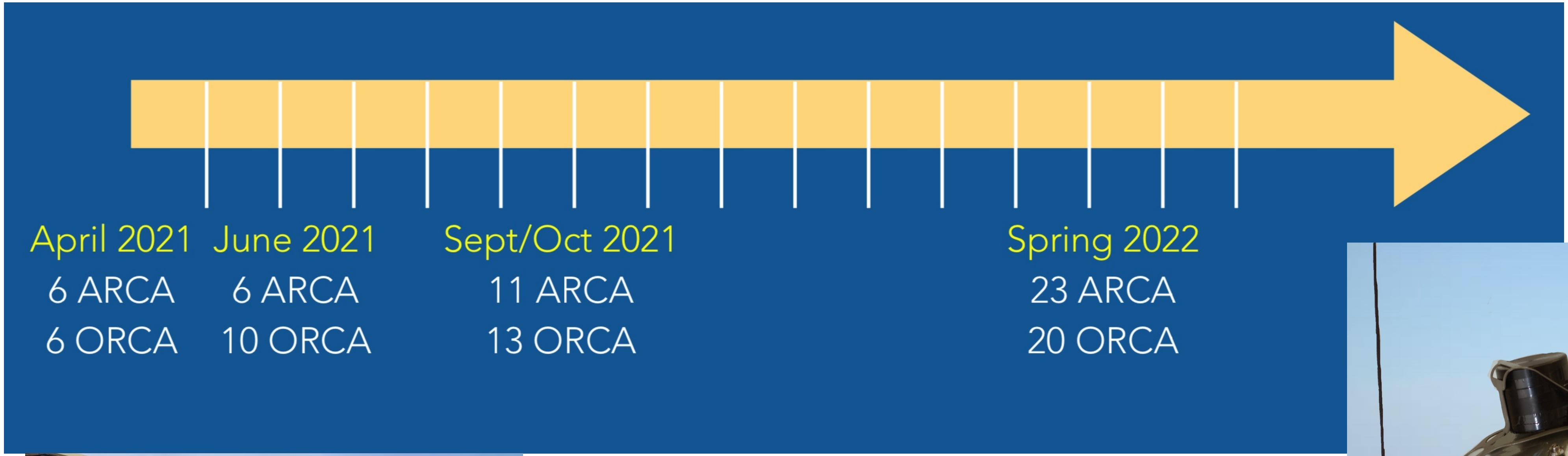




Final detector will be 2 blocks of 115 Detector Units (DUs) each

R. Coniglione, VLVNT 2021

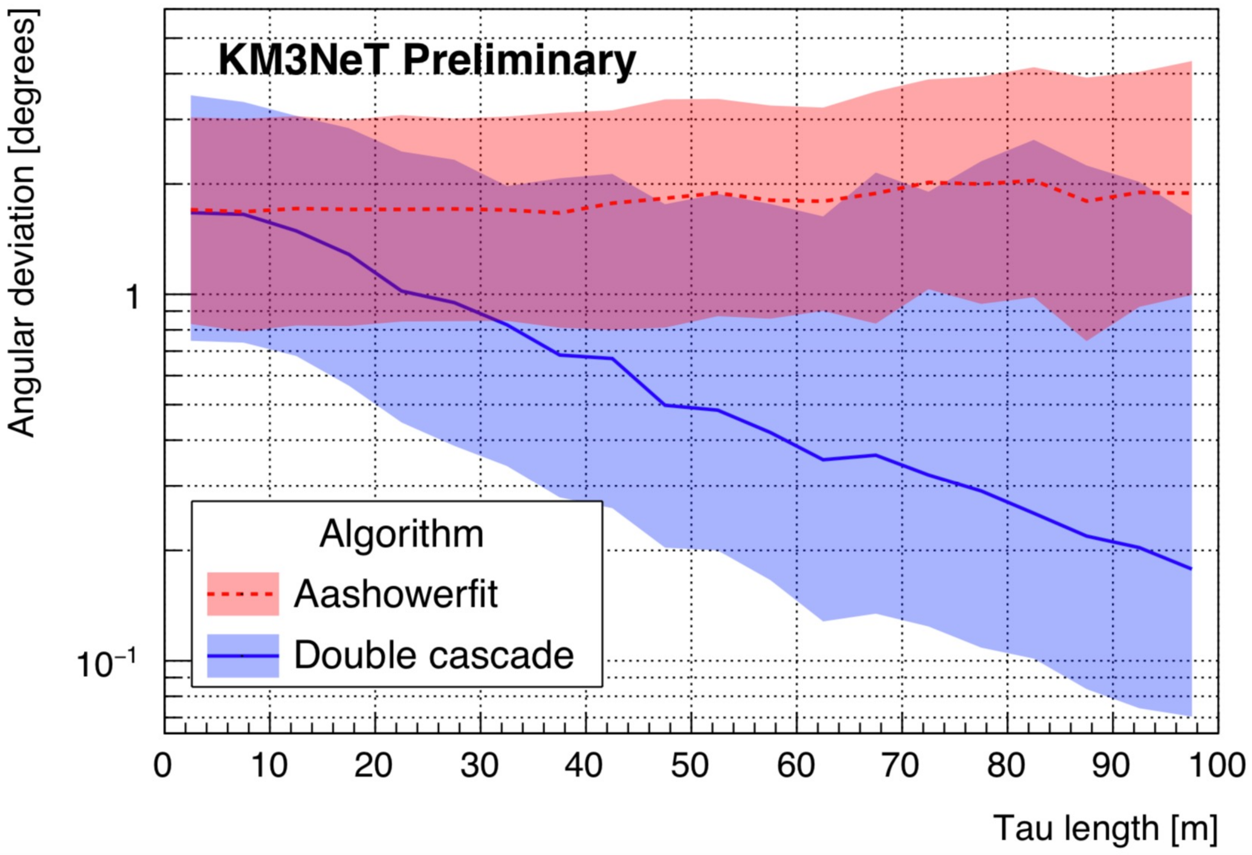
KM3NET ARCA Status

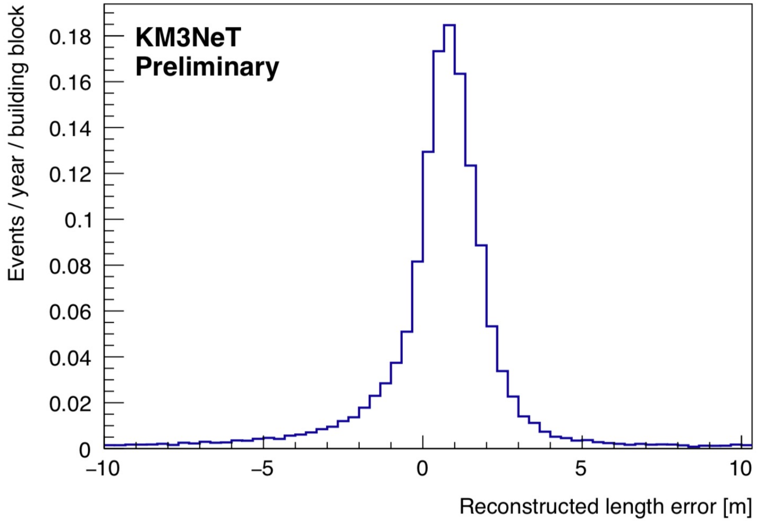


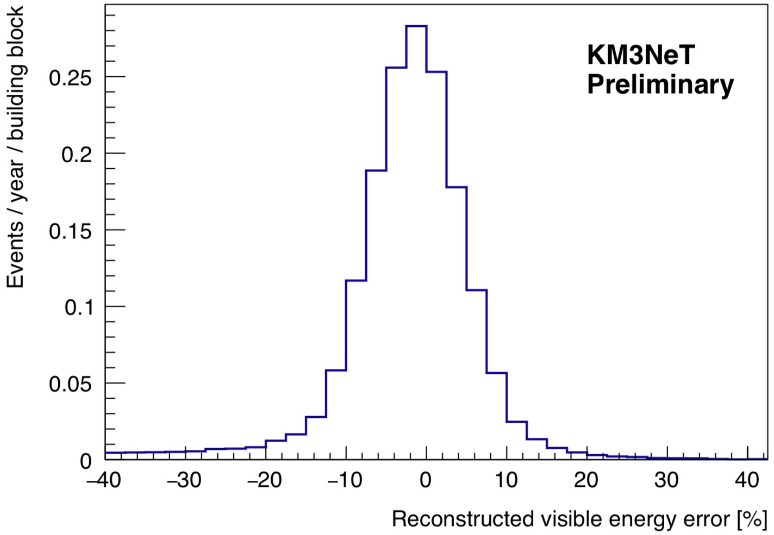
3 new DUs deployed in ARCA in September 2021 (2 more stayed on the ship due to technical issues) – 9 DUs now operating in ARCA

R. Coniglione, VLVNT 2021

Tau neutrinos in KM3NET

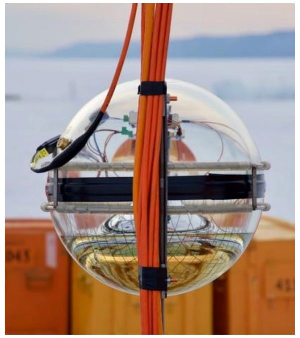


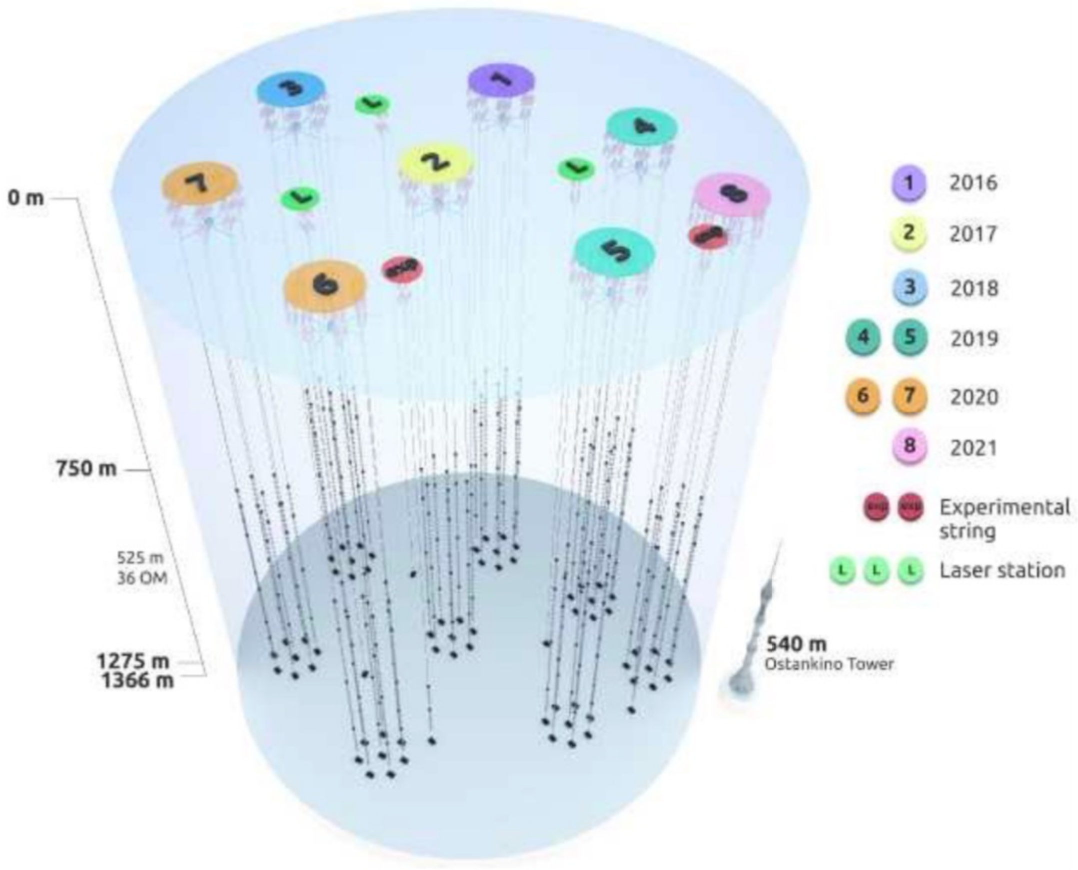


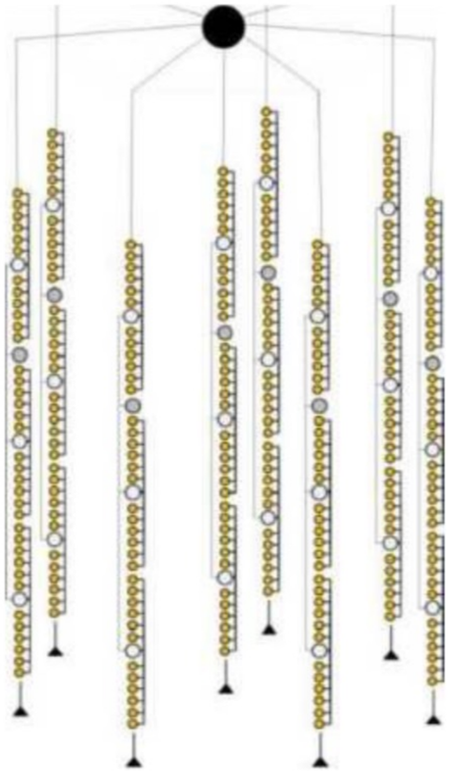


van Eeden, Seneca and Heijboer for KM3NET Coll. , ICRC 2021, PoS(ICRC2021)1089

Baikal-GVD
(Gigaton Volume Detector)







Deployment schedule

Year	Number of clusters	Number of OMs
2016	1	288
2017	2	576
2018	3	864
2019	5	1440
2020	7	2016
2021	8	2304
2022	10	2880
2023	12	3456
2024	14	4032

8 clusters of 8 strings deployed as of 2021

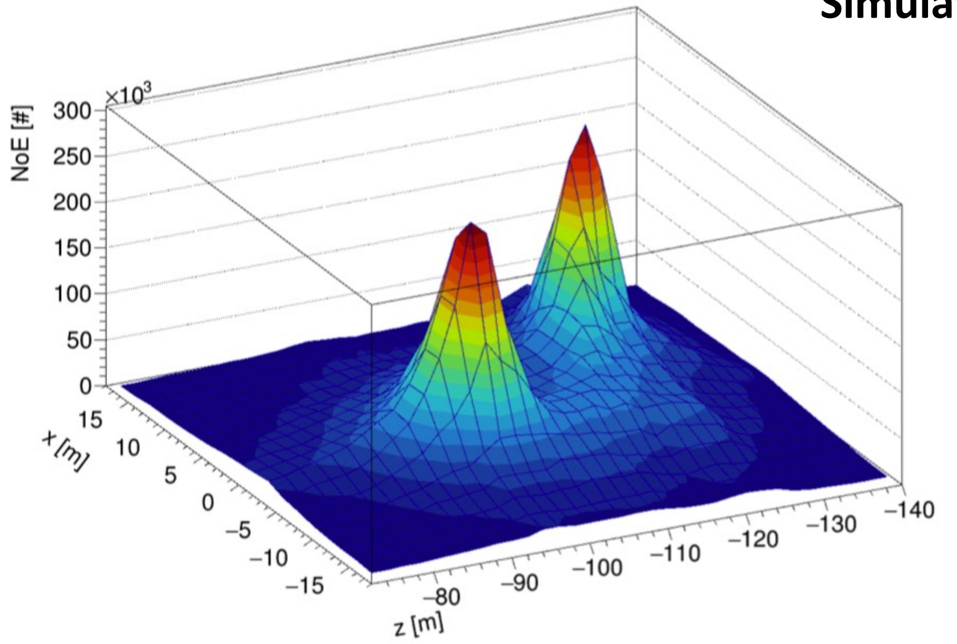
V. Aynutdinov, VLVNT 2021

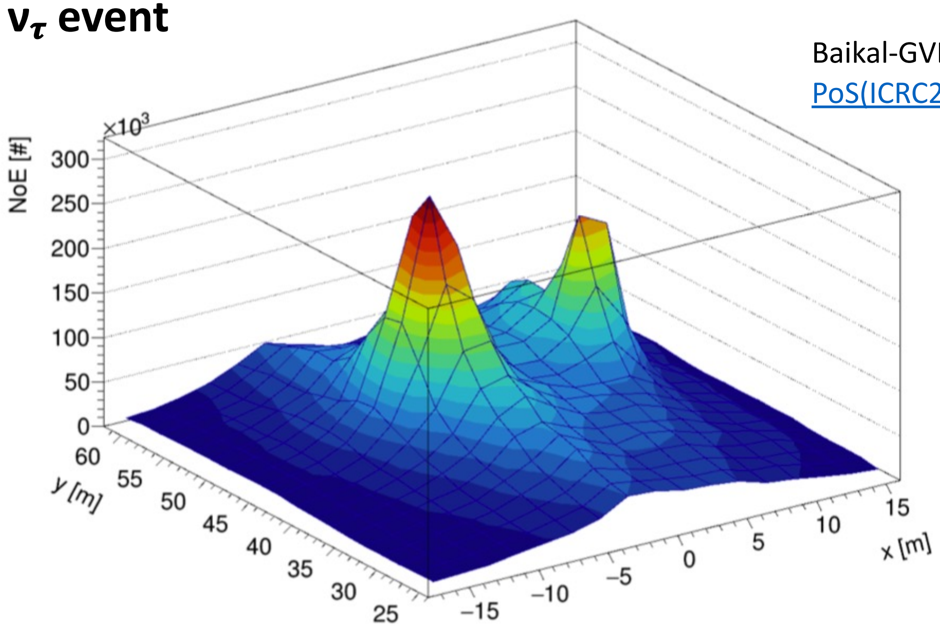
Current volume 0.4 km^3 (2021)

Tau Neutrinos in Baikal-GVD

Simulated ν_τ event

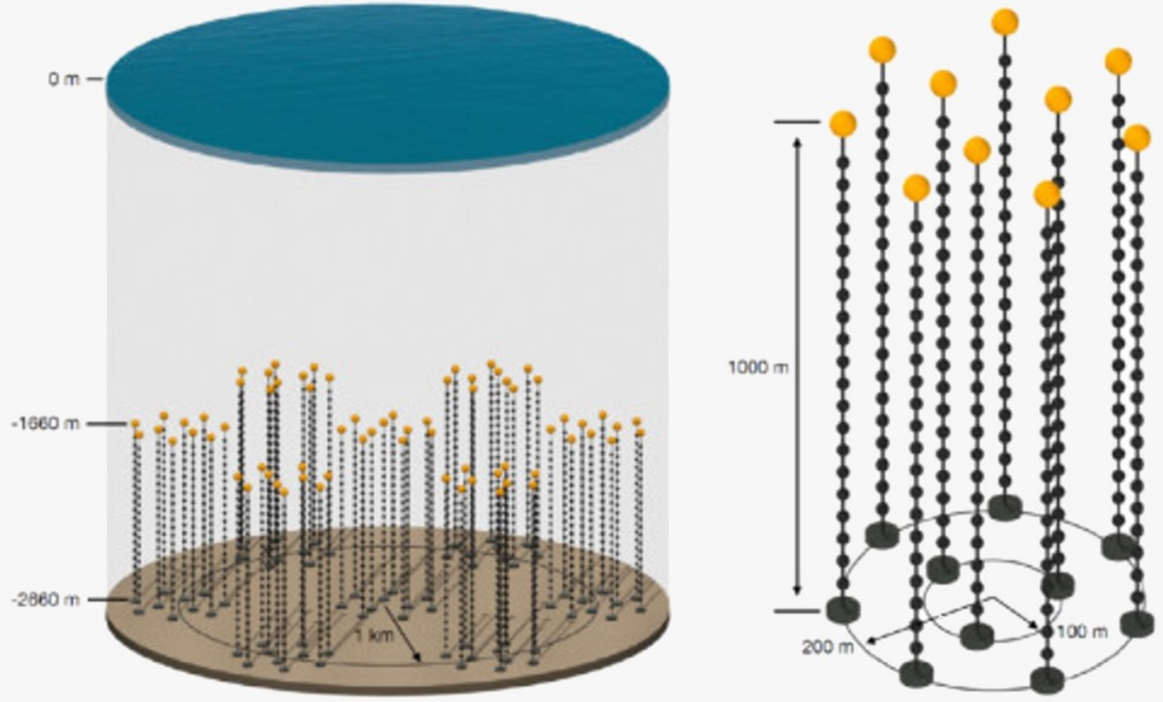
Baikal-GVD Coll., ICRC 2021, [PoS(ICRC2021)1167]()

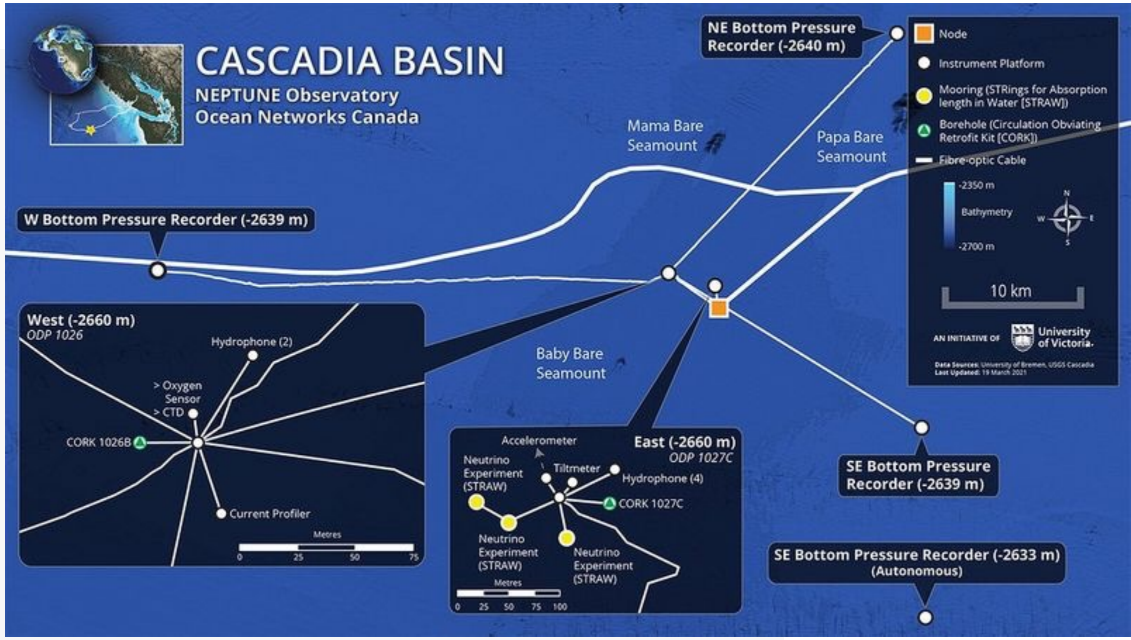




Double pulse and double cascade reconstruction methods are under investigation, a double cascade search of 2019 data yielded one event but tau origin is strongly ruled out due to low energy/long distance between cascades

Pacific Ocean Neutrino Experiment (P-ONE)

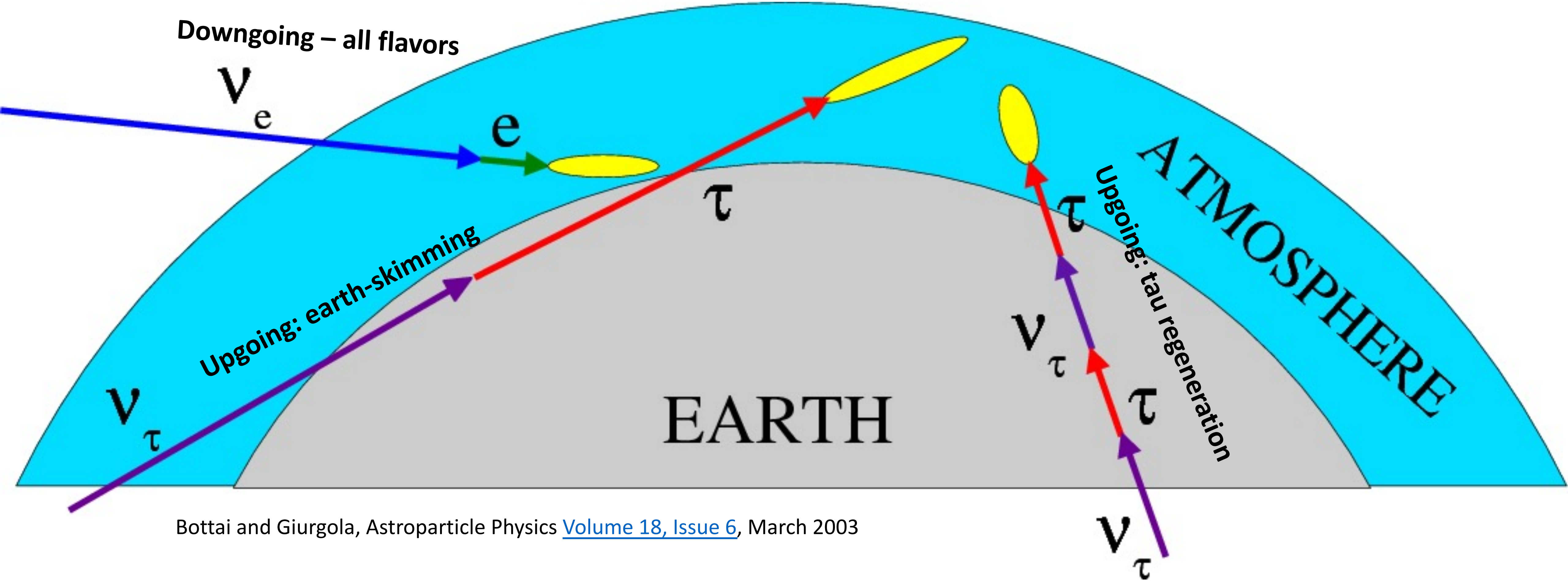




https://www.pacific-neutrino.org/

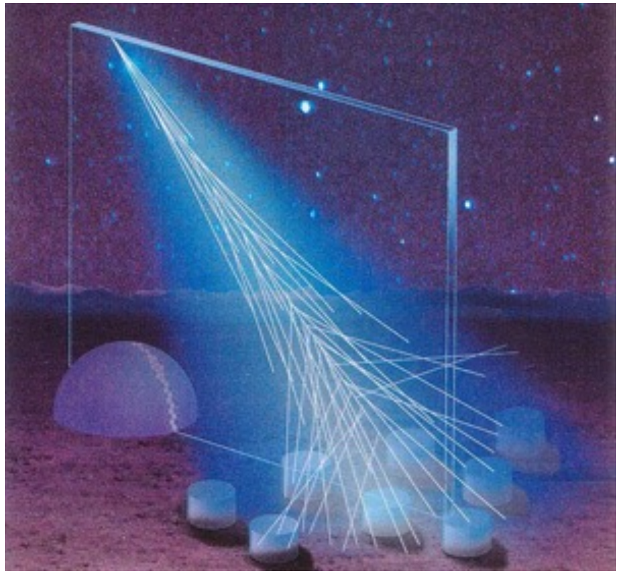
STRAW-a (2018) measured optical attenuation length in Cascadia Basin
STRAW-b (2020) to completely characterize optical properties of site
Prototype line under construction

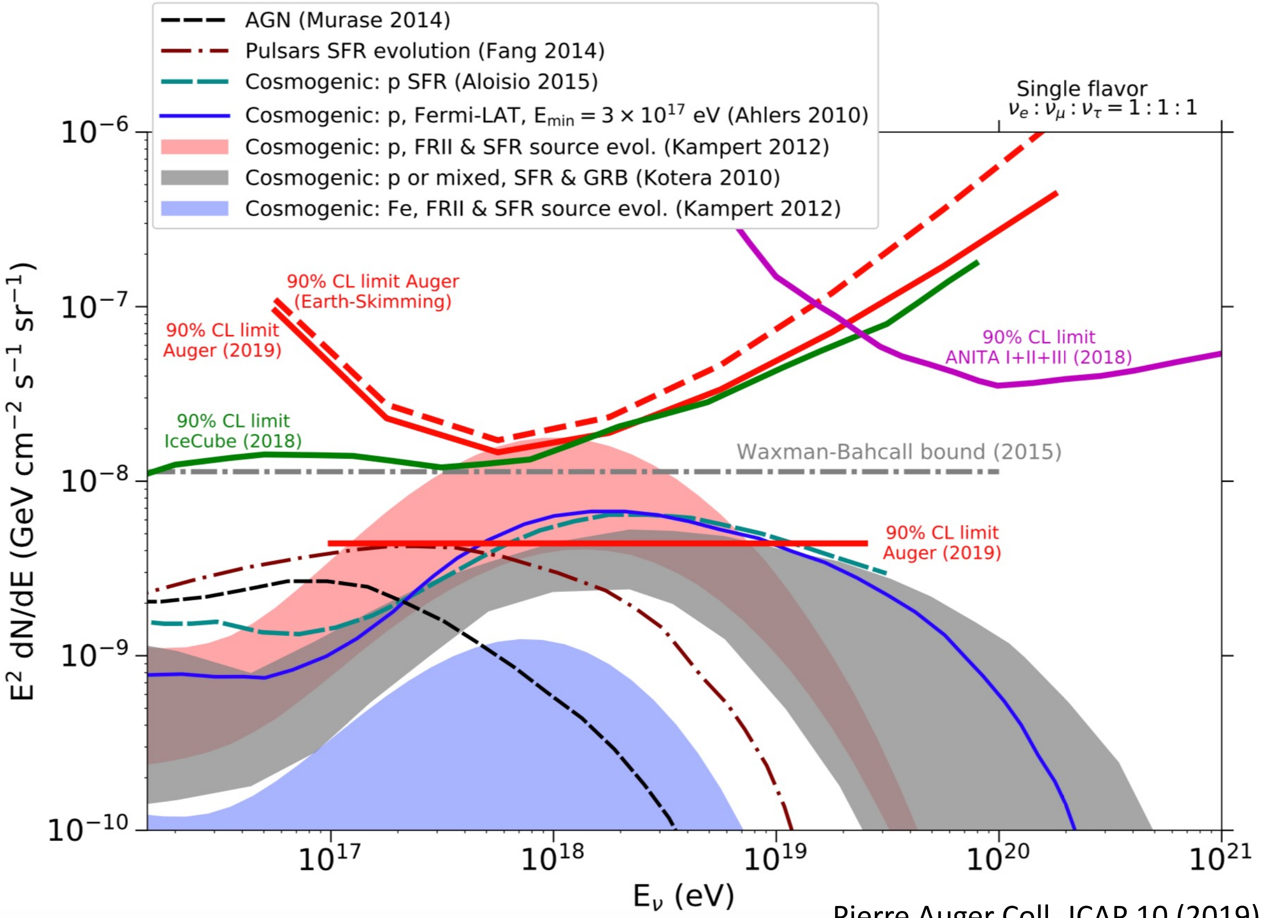
Air showers from neutrinos



Bottai and Giurgola, Astroparticle Physics Volume 18, Issue 6, March 2003

Pierre Auger Observatory sensitivity to neutrinos



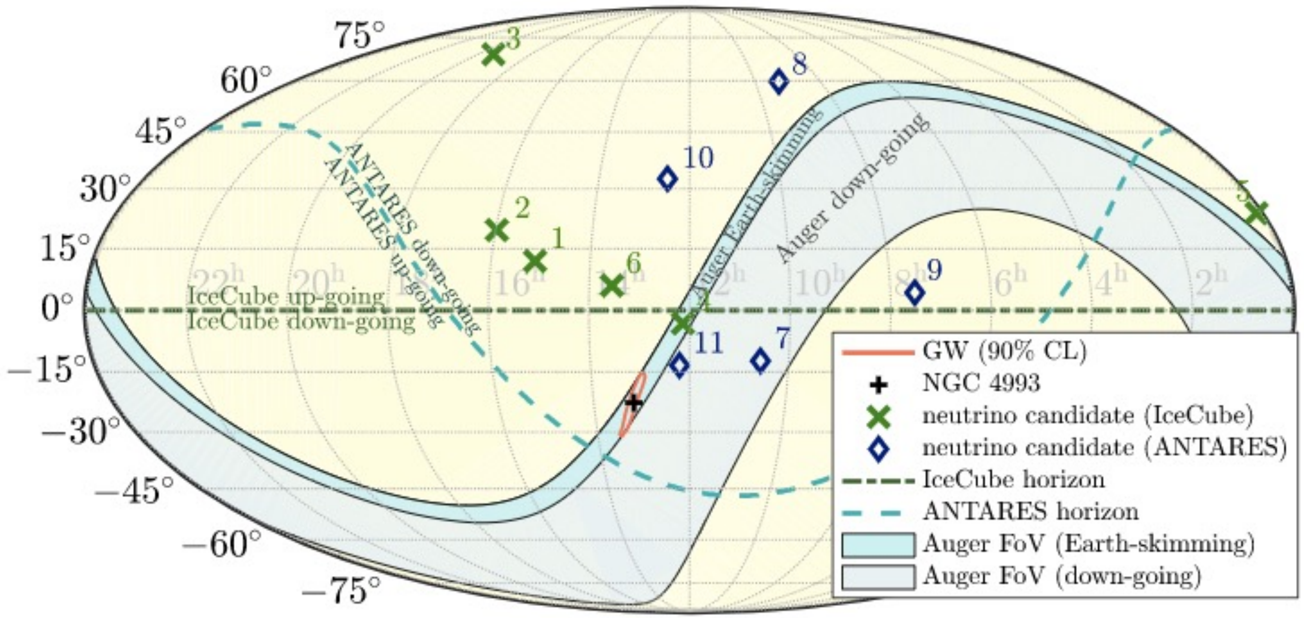


Pierre Auger Coll. JCAP 10 (2019) 022

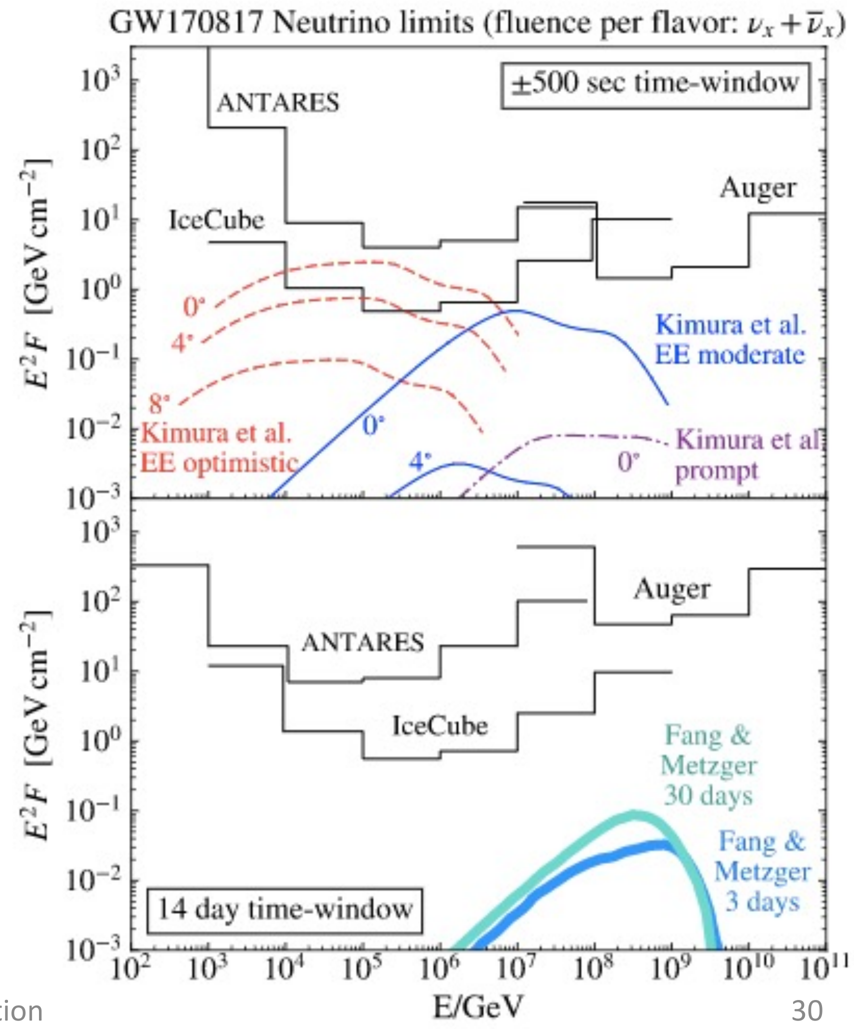
Auger Prime upgrade is ongoing, will include more sensitive triggers for neutrino-induced showers

A major goal is to improve CR mass composition measurements, which will impact predictions for cosmogenic neutrino flux

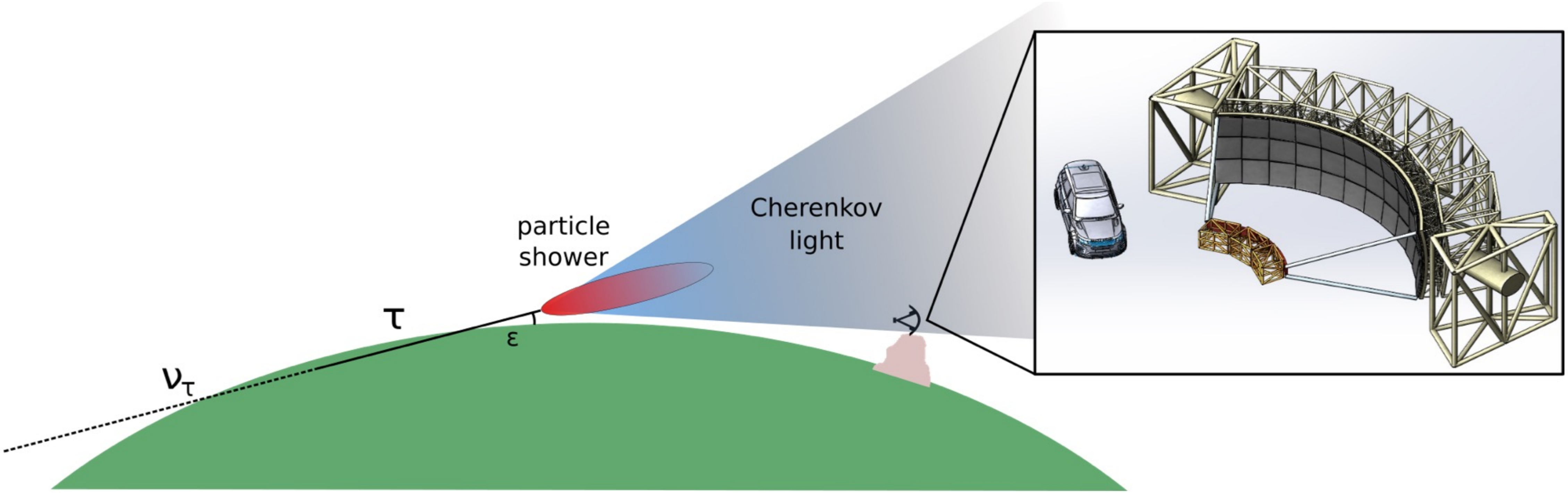
GW170817 with Auger, IceCube and ANTARES



ANTARES, IceCube and Pierre Auger Observatory Collaborations, ApJ Letters Volume 850, No. 2 (2017)

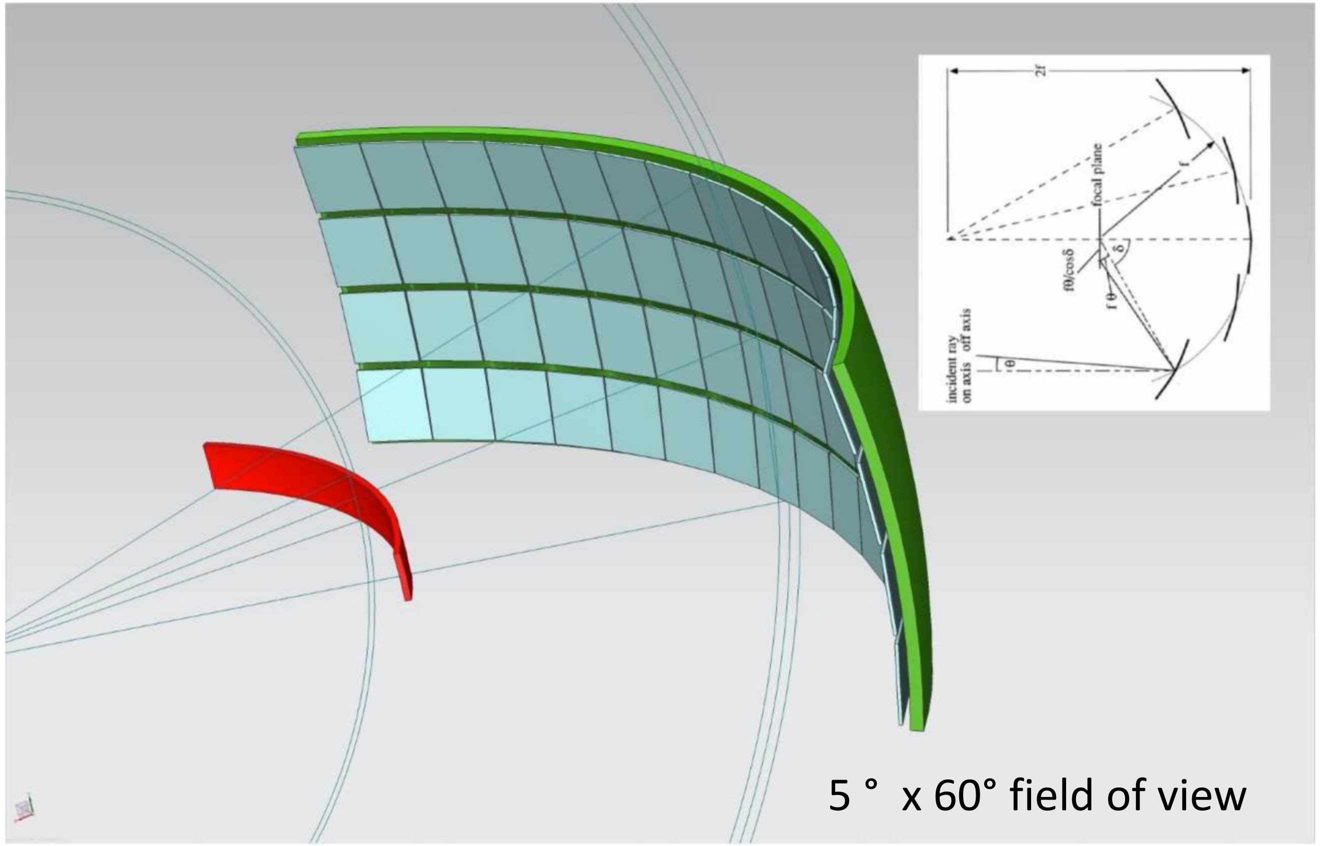


The Trinity Tau Neutrino Observatory



http://trinity.physics.gatech.edu/

Trinity telescope design



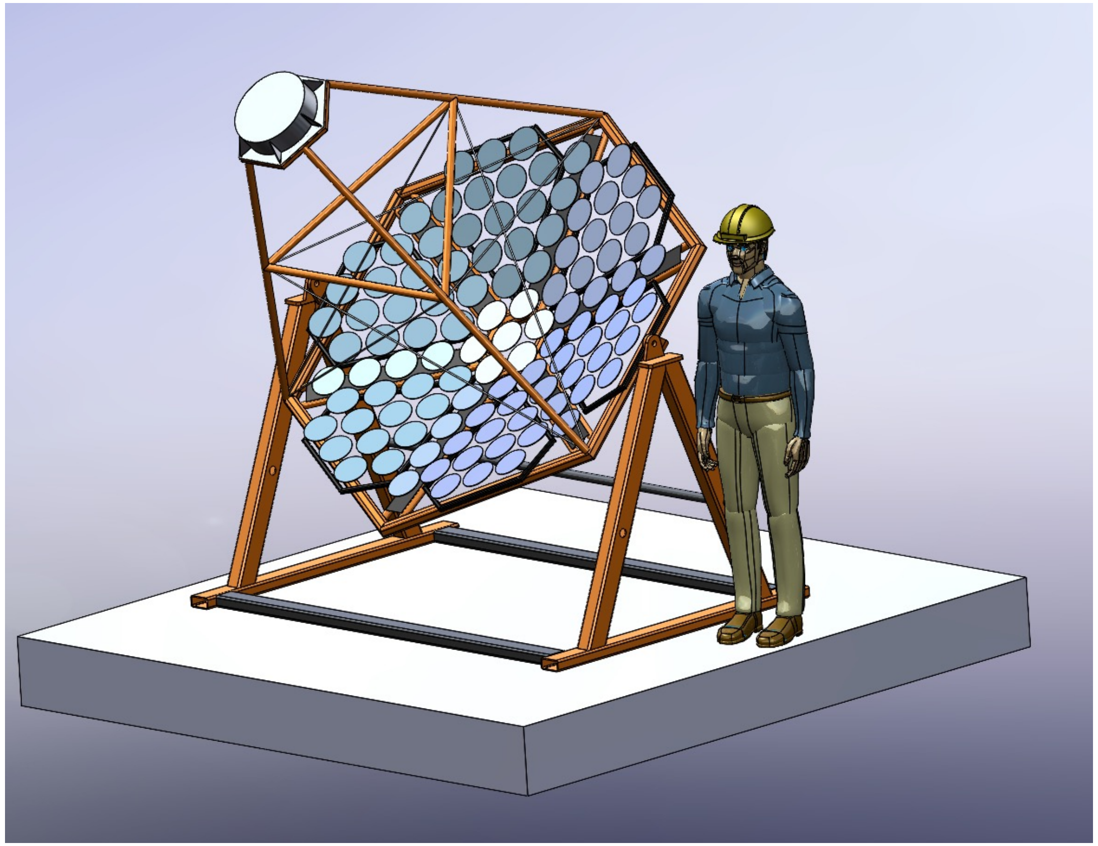
N. Otte et al., arXiv:1907.08727 [astro-ph.IM], Astro2020 APC White paper

Baseline Trinity array design is 6 telescopes pointed at the horizon, at an altitude of 2-3 km

Designed to be run remotely to reduce operating costs

Parameter	Value
Duty cycle	20% (1800 hours per year)
Effective light collection surface	$> 10\,\mathrm{m}^2$
Vertical field of view	5°
Azimuthal field of view	360°
Pixel size	0.3°
Sensitive wavelength range	340 nm - 900 nm
Readout sampling speed	100 mega-samples per second
Readout amplitude resolution	1 photoelectron
Dynamic Range	1000 photoelectrons

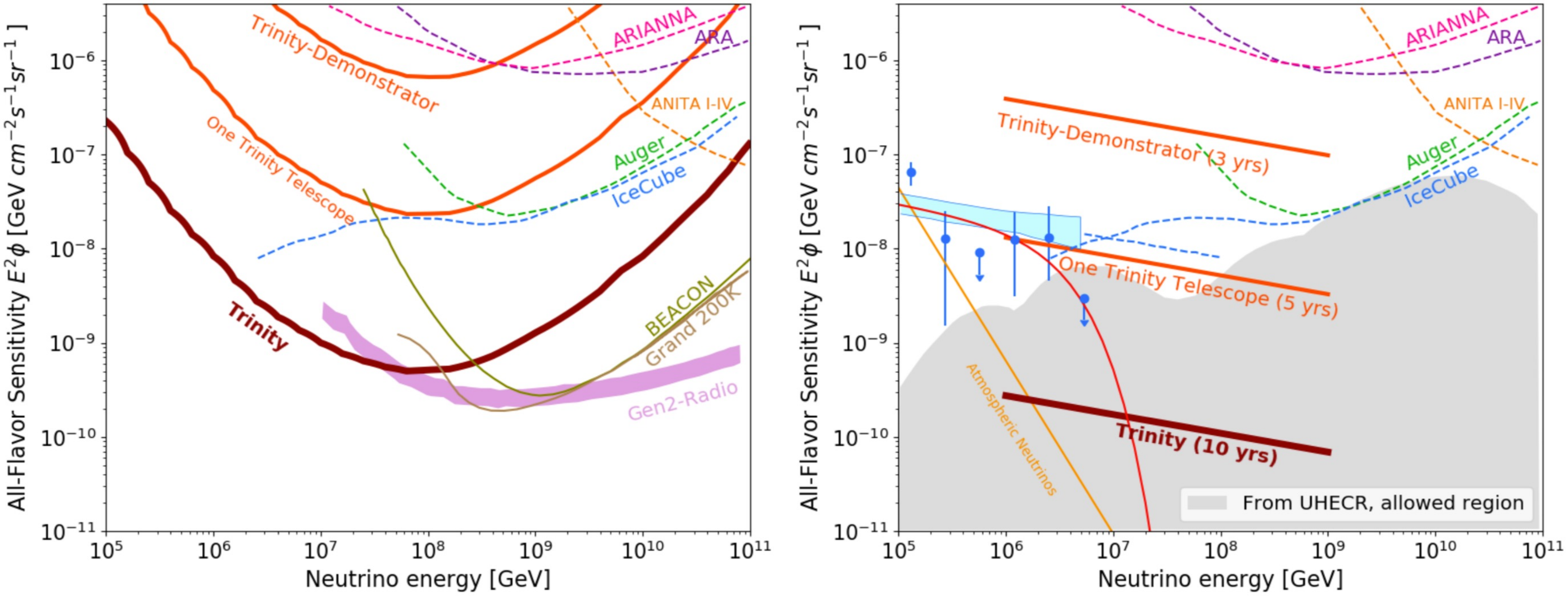
Trinity Demonstrator



http://trinity.physics.gatech.edu/

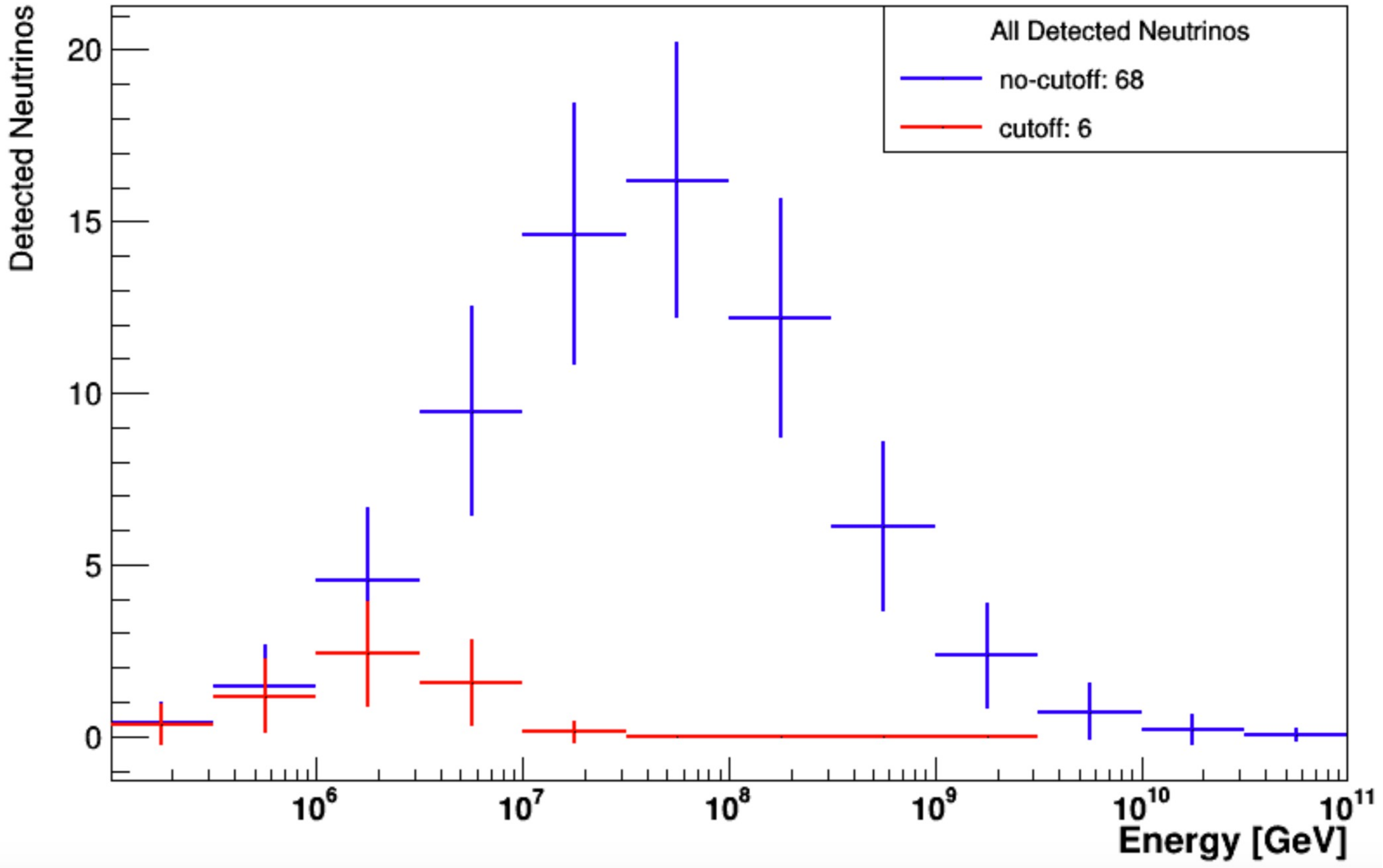
1.5 m^2 telescope funded by NSF to study potential sources of background, prove remote operation, demonstrate technological readiness. First light expected in 2022

Trinity sensitivity



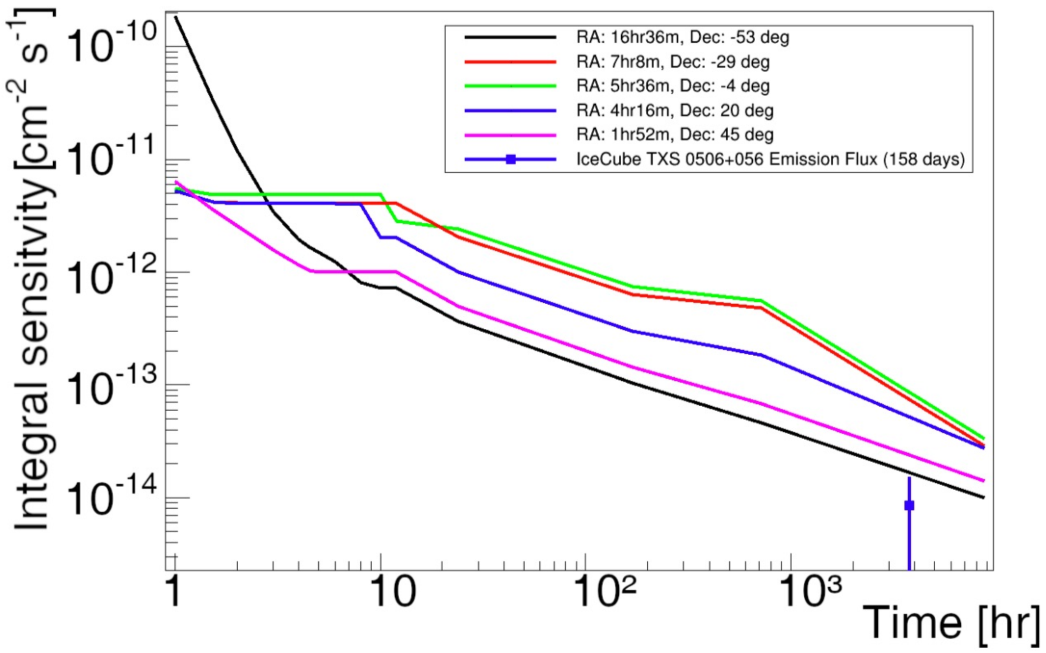
Wang et al. ICRC 2021, PoS(ICRC2021)1234

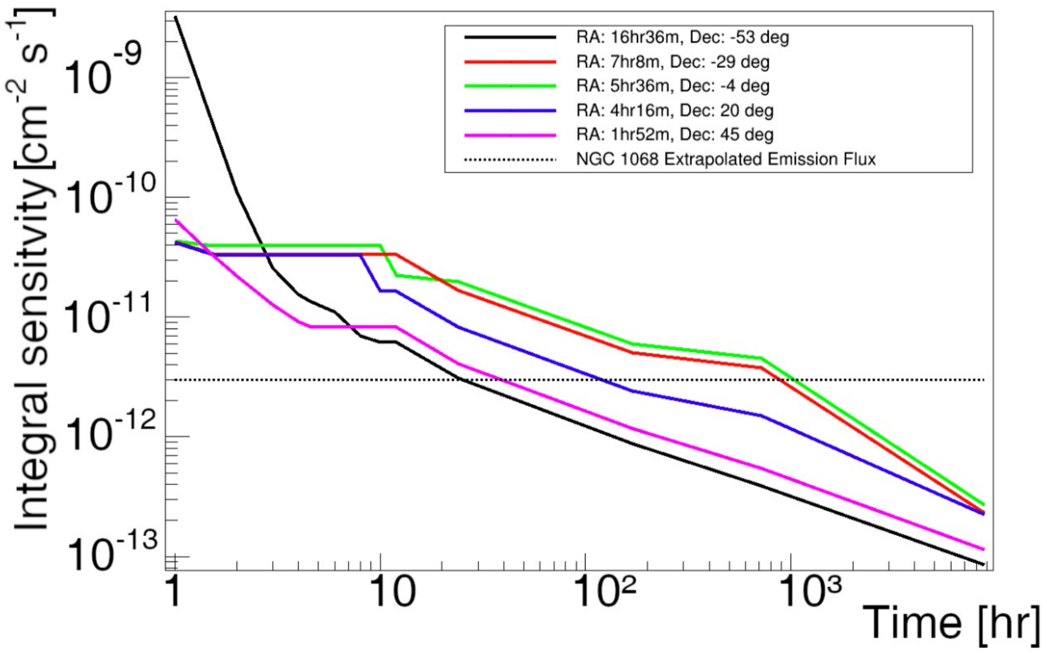
Trinity sensitivity to IceCube diffuse flux (10 years)



Wang et al. ICRC 2021, PoS(ICRC2021)1234

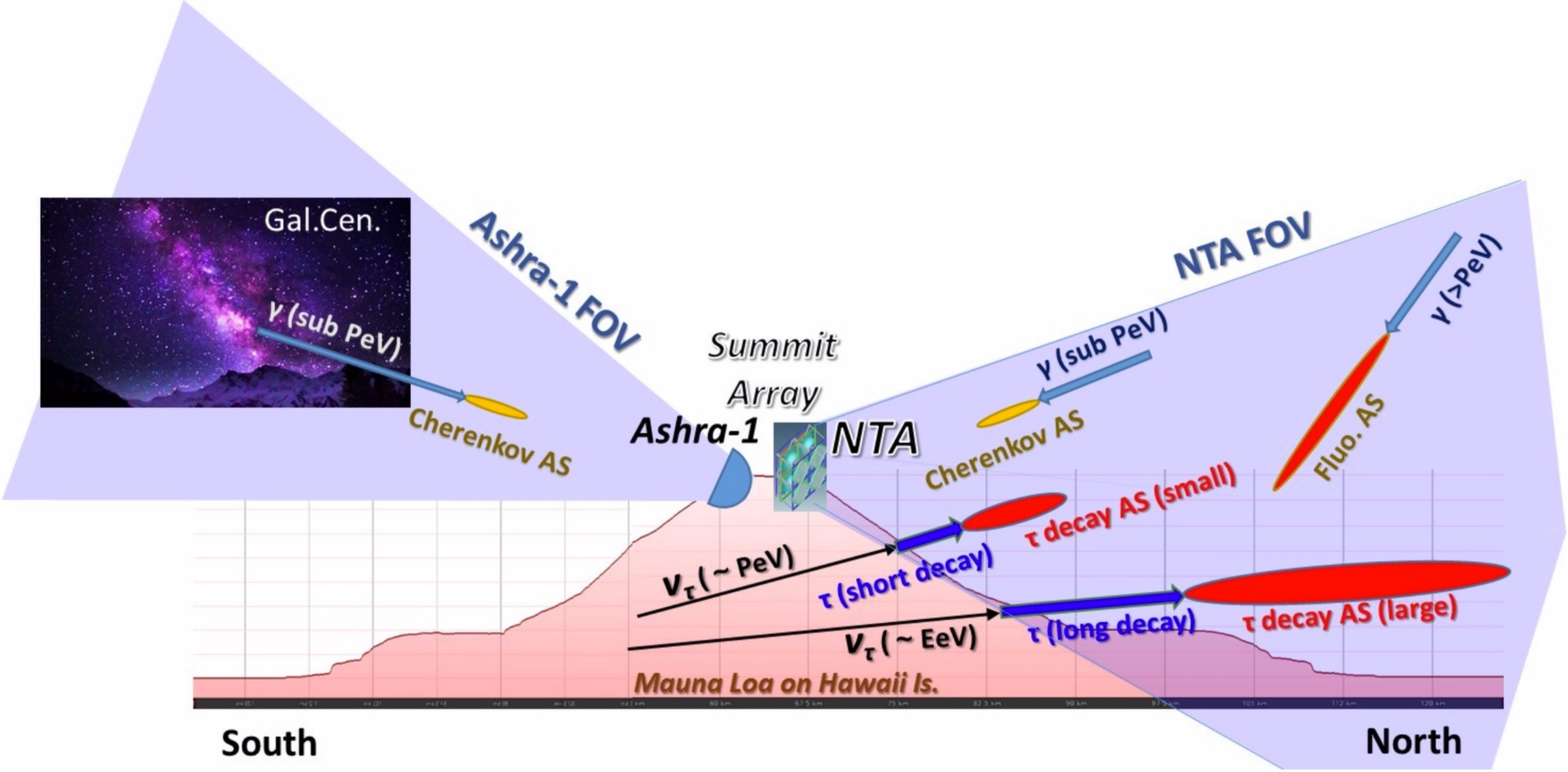
Trinity sensitivity to point sources





Wang et al. ICRC 2021, [PoS(ICRC2021)1234]

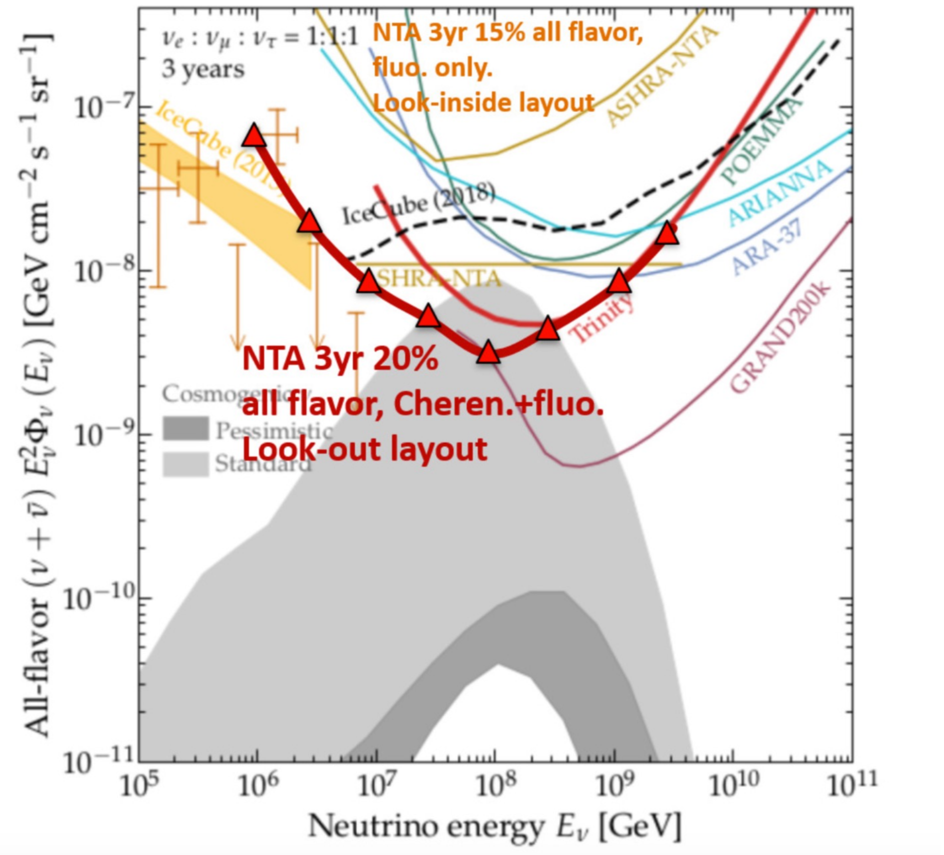
Ashra-1 and Neutrino Telescope Array (NTA)

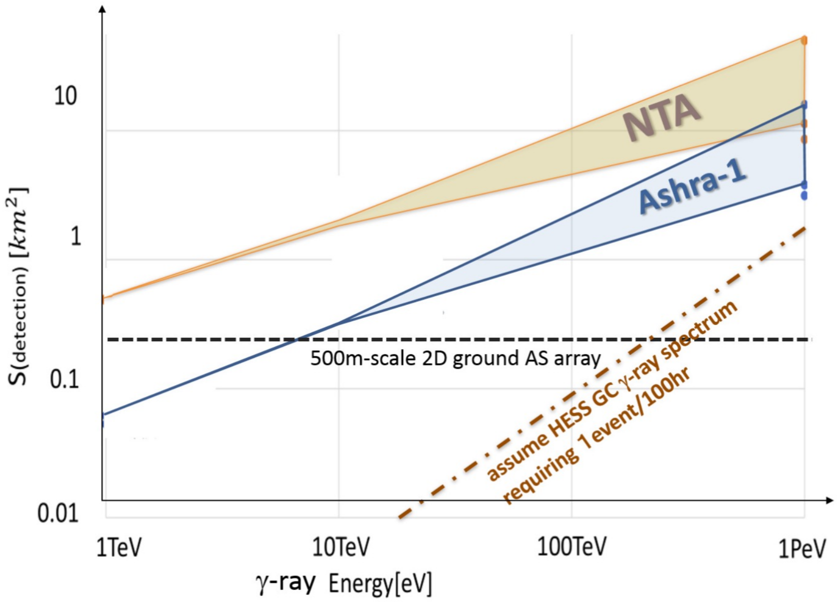


Ogawa and Sasaki, ICRC 2021 [PoS(ICRC2021)970]

Planned array of 4 stations on Mauna Loa, Hawaii to look for earth-skimming tau neutrinos based on existing Ashra-1 detector operating since 2008

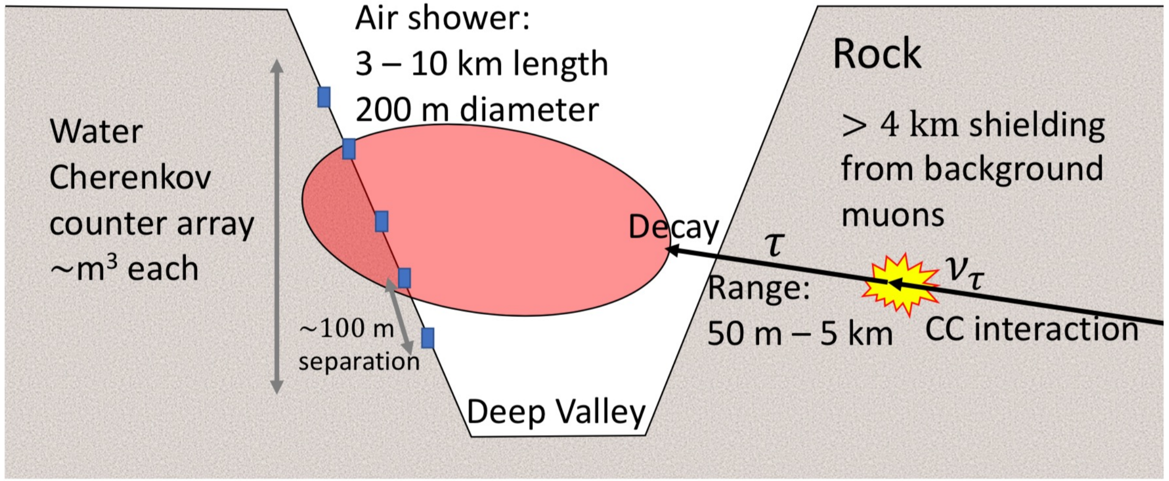
NTA sensitivity





Ogawa and Sasaki, ICRC 2021 PoS(ICRC2021)970

Tau Air shower Mountain Based Observatory: TAMBO

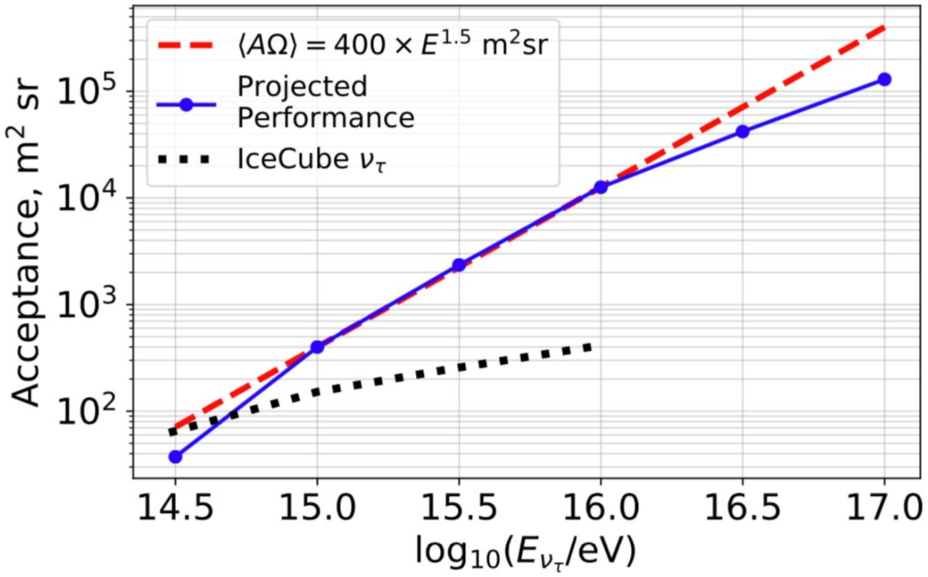


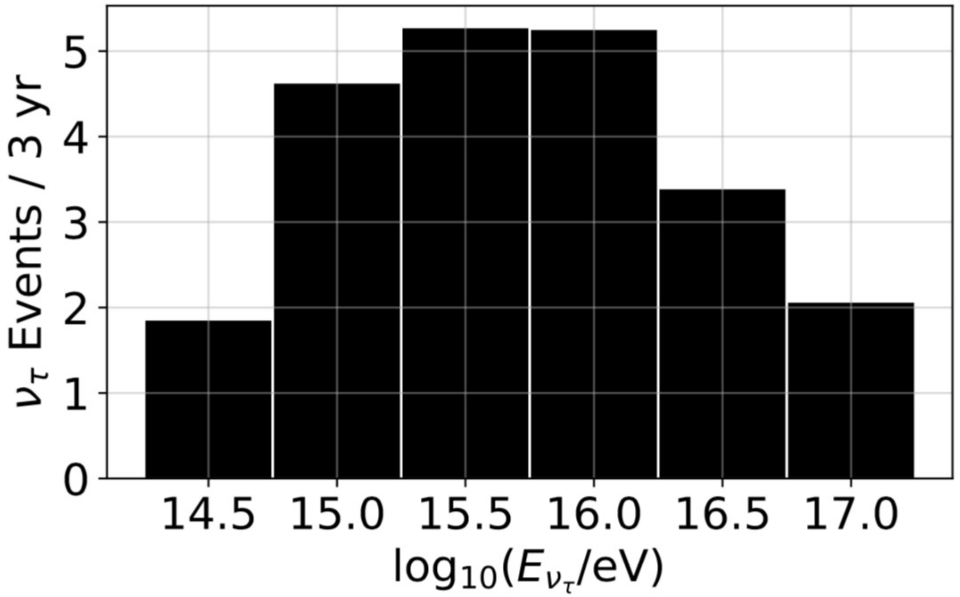
Proposed experiment in Colca Valley, Peru
Deep valley improves geometric acceptance
Water Cherenkov counters have high duty cycle

Objective	Physical Parameters	Observatory Requirements
(O1) Determine whether high-energy neutrino sources continue to accelerate particles above 10 PeV.	Sensitivity of $\geq 5\sigma$ to the τ component of the flux extrapolated from IceCube data for energies 1 - 100 PeV	Diffuse τ neutrino flux acceptance $\langle A\Omega\rangle \geq 400\ \mathrm{m}^2\ \mathrm{sr} \times E_{\mathrm{PeV}}^{3/2}$ between 1-10 PeV and > 10 times IceCube between 10-100 PeV. Integrated sky coverage > 0.5 sr. Energy resolution: neutrino $\Delta E/E \leq 1.0$, air shower $\Delta E/E \leq 0.8$ (both 1σ) Tau air-shower direction resolution $\leq 1°$. Tau neutrino flavor identification >95% confidence per event. Point source effective area $\langle A\rangle \geq 300\ \mathrm{m}^2 \times E_{\mathrm{PeV}}^{3/2}$ (peak) with instantaneous sky coverage > 0.1 sr.
(O2) Characterize the astrophysical sources of the neutrino flux between 1-10 PeV by measuring the τ component.	Sensitivity to the diffuse τ neutrino flux at energies between 1-10 PeV with efficient flavor identification.	
(O3) Constrain the particle acceleration potential of point source transients observed with multi-messenger probes.	Point source flux of τ neutrinos as a function of energy.	

A. Romero-Wolf et al., arXiv:2002.06475 [astro-ph.IM]

TAMBO sensitivity to tau neutrinos

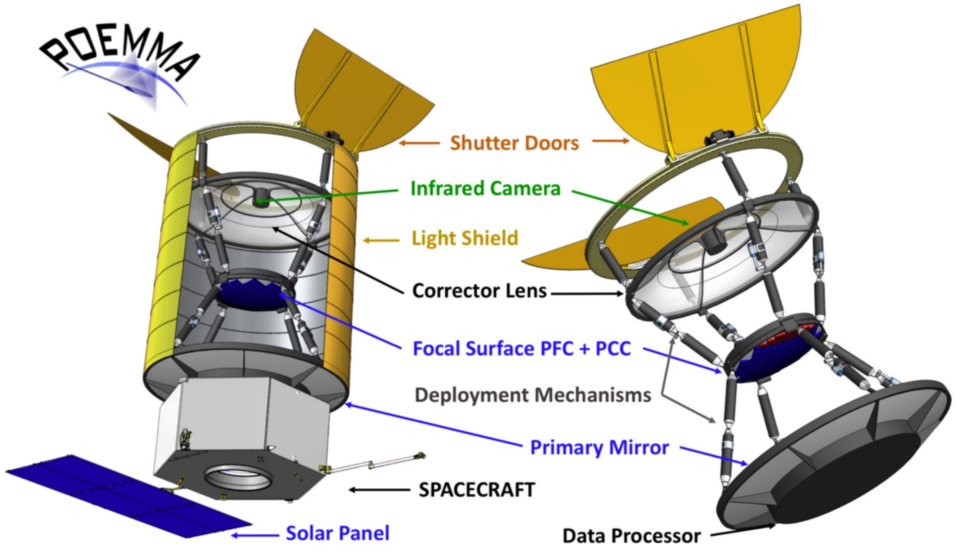




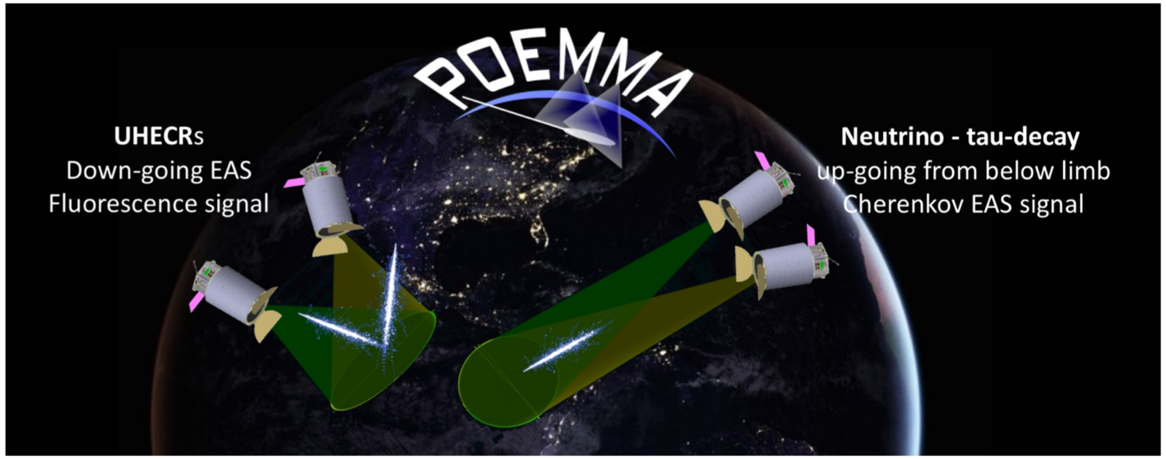
A. Romero-Wolf et al., arXiv:2002.06475 [astro-ph.IM]

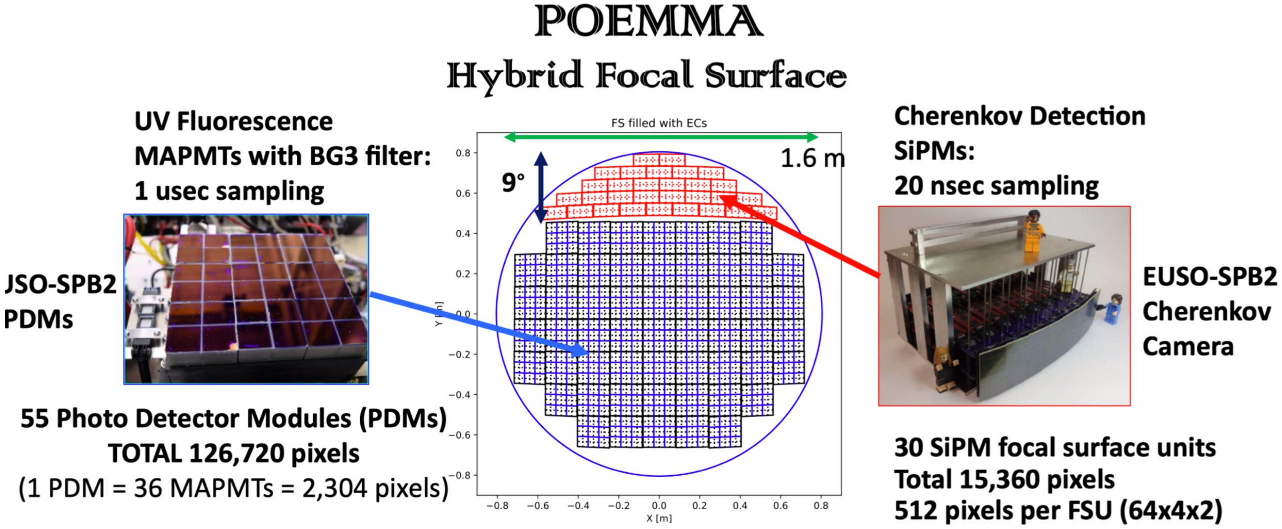
Probe Of Extreme Multi-Messenger Astrophysics (POEMMA)

See John Krizmanic's talk tomorrow



- Selected as a conceptual study funded by NASA in preparation for the Astro2020 decadal survey
- Mission concept follows on from previous work on OWL, CHANT, JEM-EUSO and EUSO-SPB



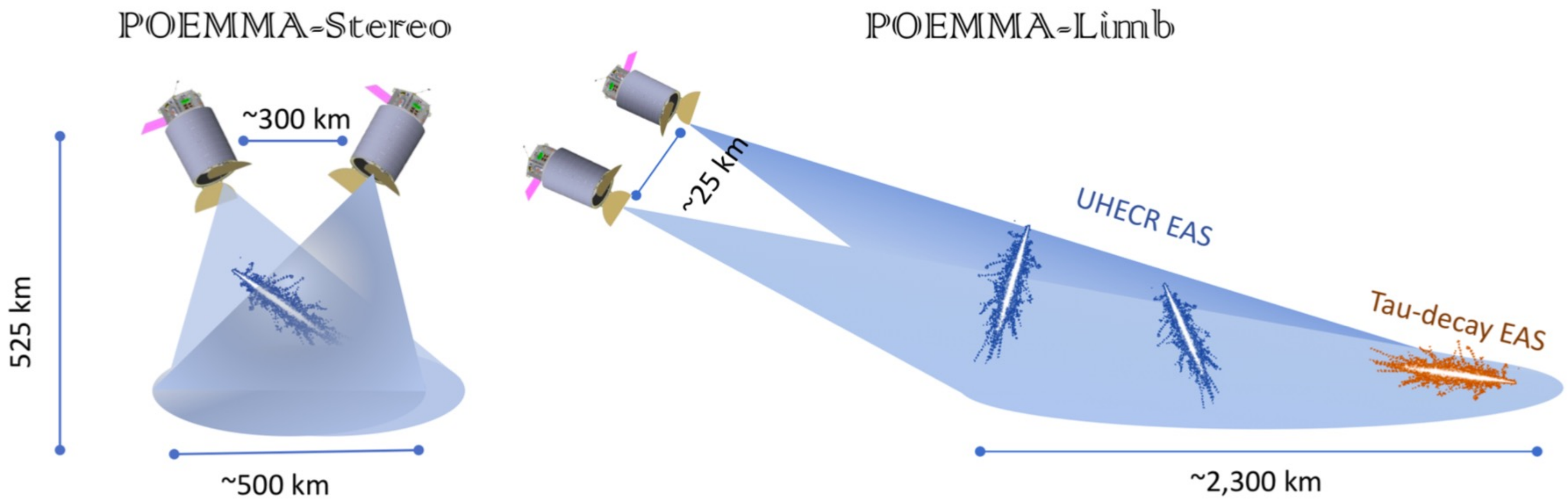


Olinto et al., arXiv:1907.06217 [astro-ph.HE], Astro 2020

POEMMA viewing modes

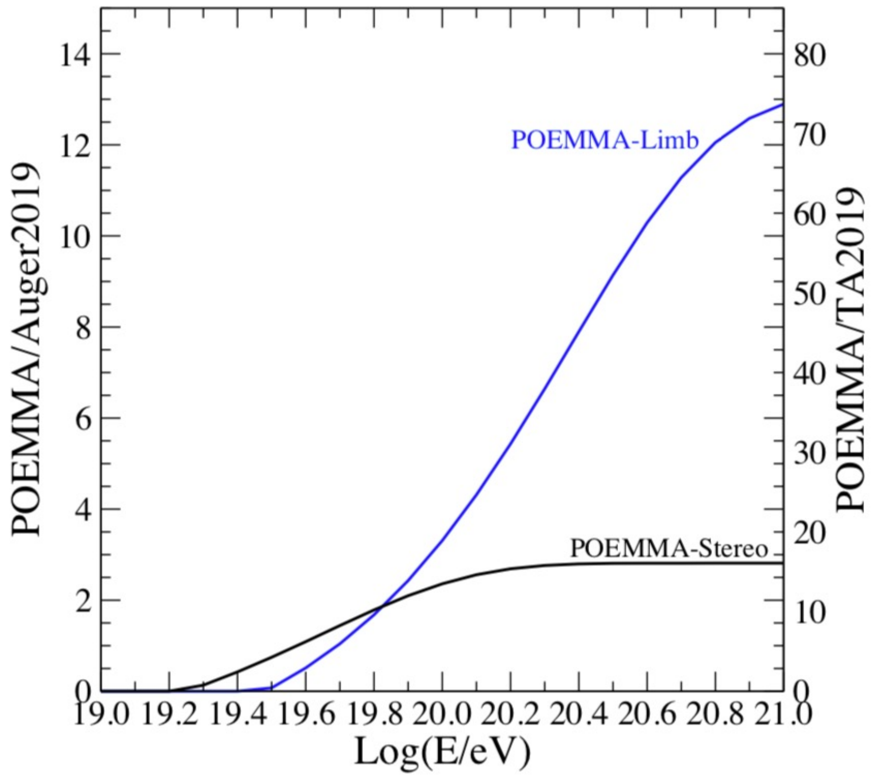
Stereo mode is sensitive to fluorescence from UHECR air showers

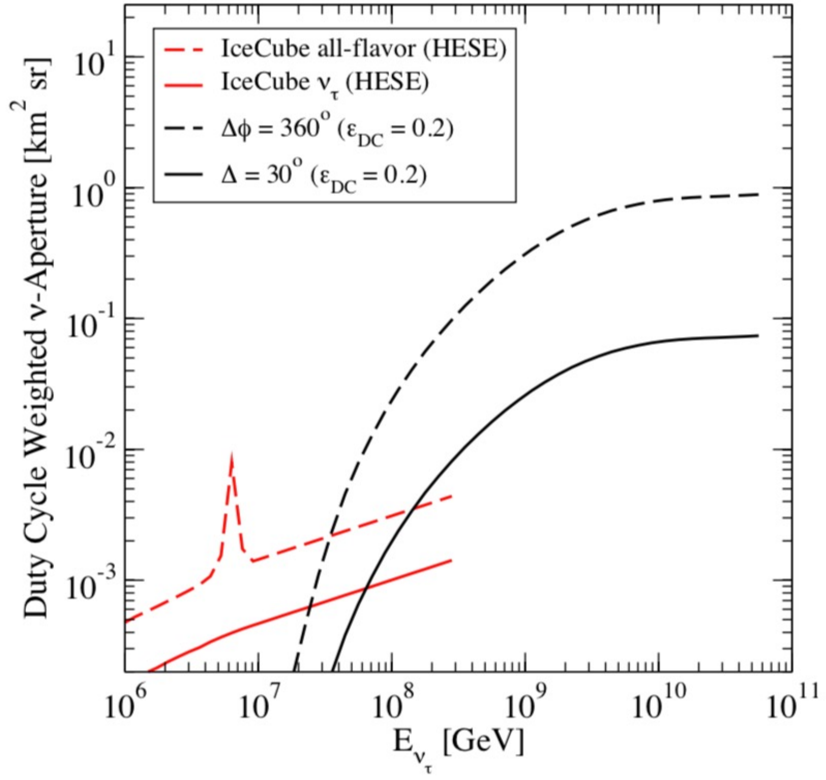
Limb viewing mode is sensitive to Cherenkov from tau-induced air showers, as well as fluorescence from UHECR air showers



Olinto et al., arXiv:2012.07945 [astro-ph.IM]

POEMMA sensitivity

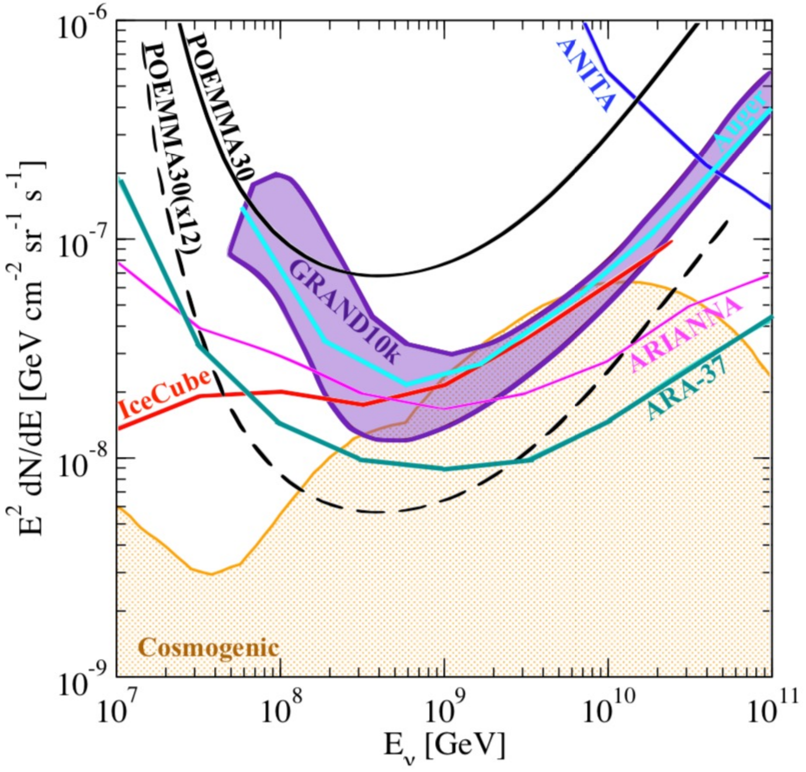




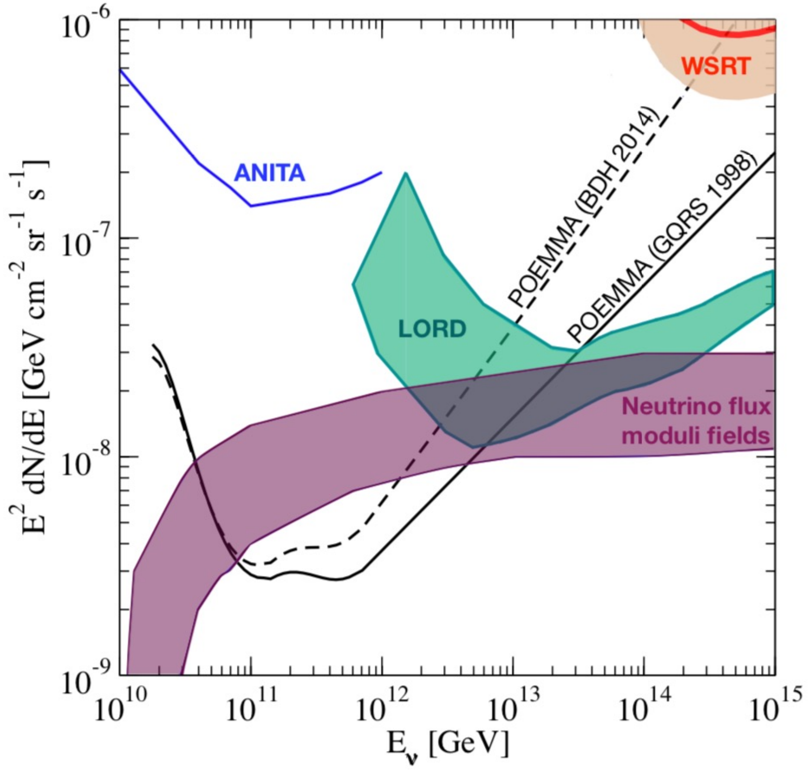
Olinto et al., arXiv:2012.07945 [astro-ph.IM]

POEMMA sensitivity (5 years)

Tau-induced showers

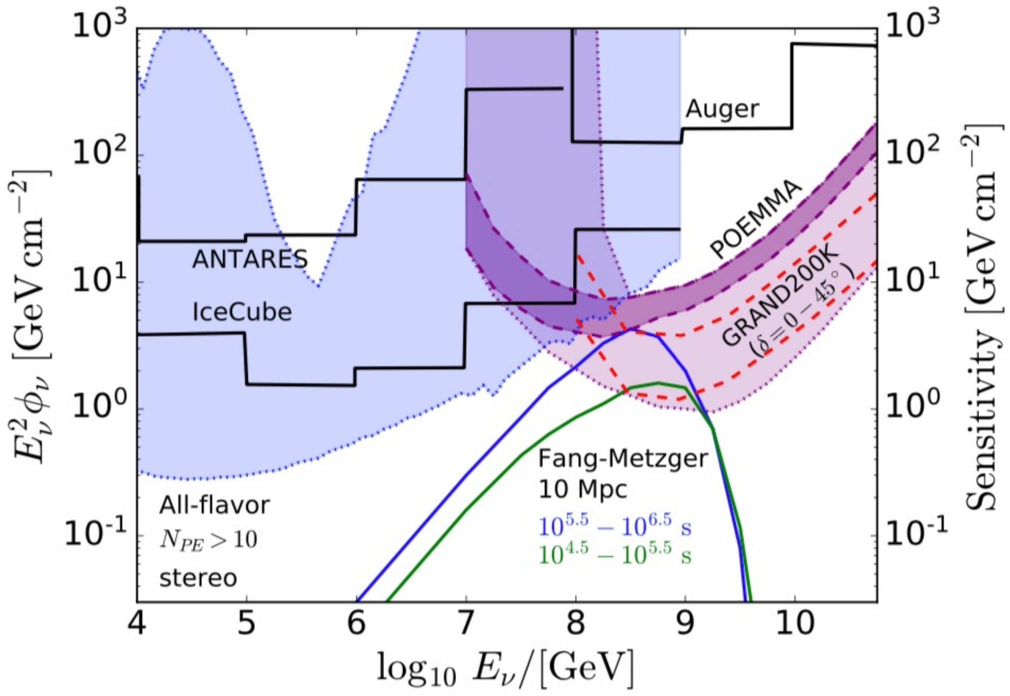


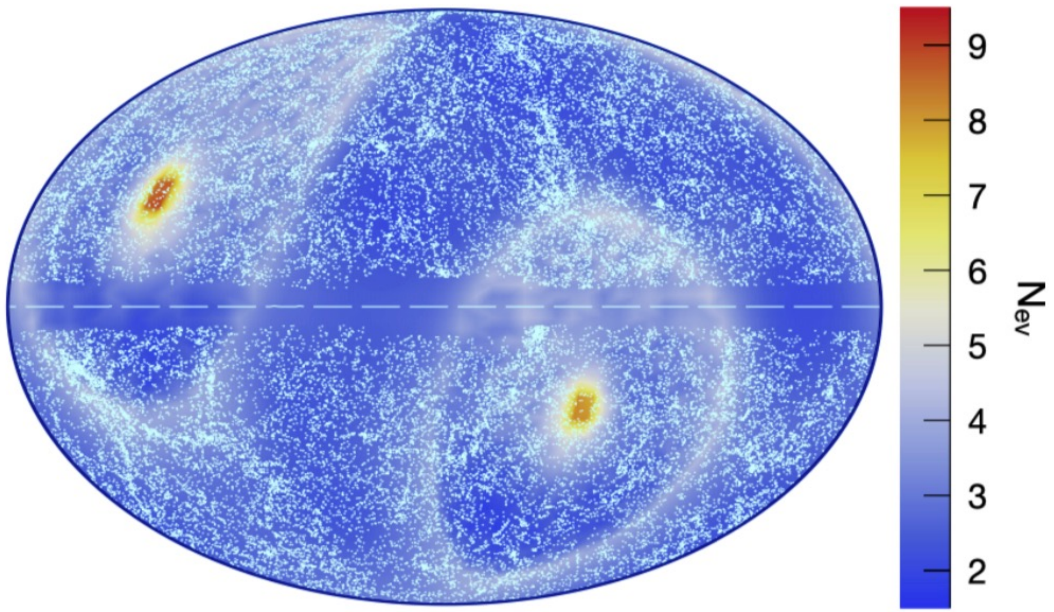
All-flavor showers



Olinto et al., arXiv:2012.07945 [astro-ph.IM]

POEMMA Target of Opportunity (ToO)





Olinto et al., arXiv:2012.07945 [astro-ph.IM]

POEMMA will be able to slew 90° within 500 s to observe transient events triggered by other observatories

Summary

- IceCube has established the existence of the cosmic neutrino flux and begins to see associations with sources
- IceCube has seen the first cosmic tau neutrino events
- This is a very busy time for neutrino telescopes with the IceCube Upgrade funded and Baikal-GVD and KM3Net under construction
- Planning for IceCube-Gen2 is underway
- The earth-skimming tau neutrino technique has great promise and multiple efforts are underway on the ground and in space