Ultra High Energy Neutrinos - Experimental Landscape

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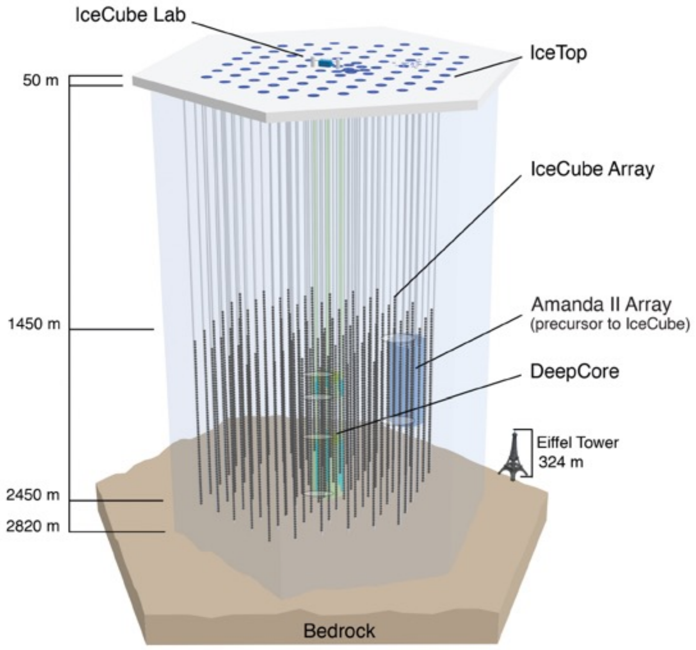
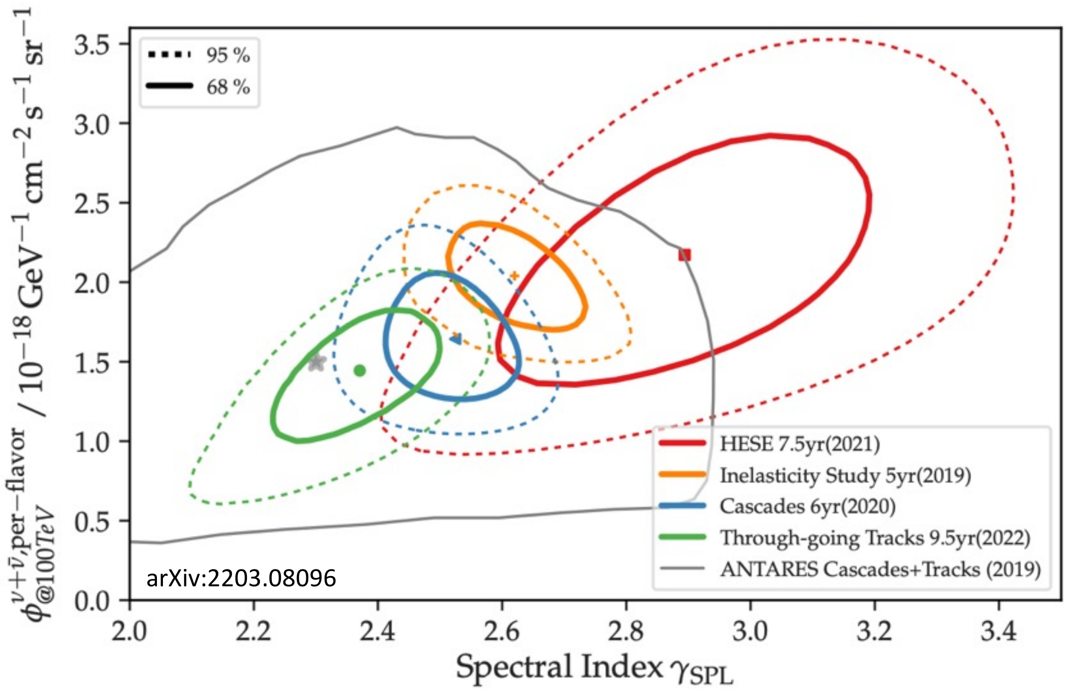
IceCube



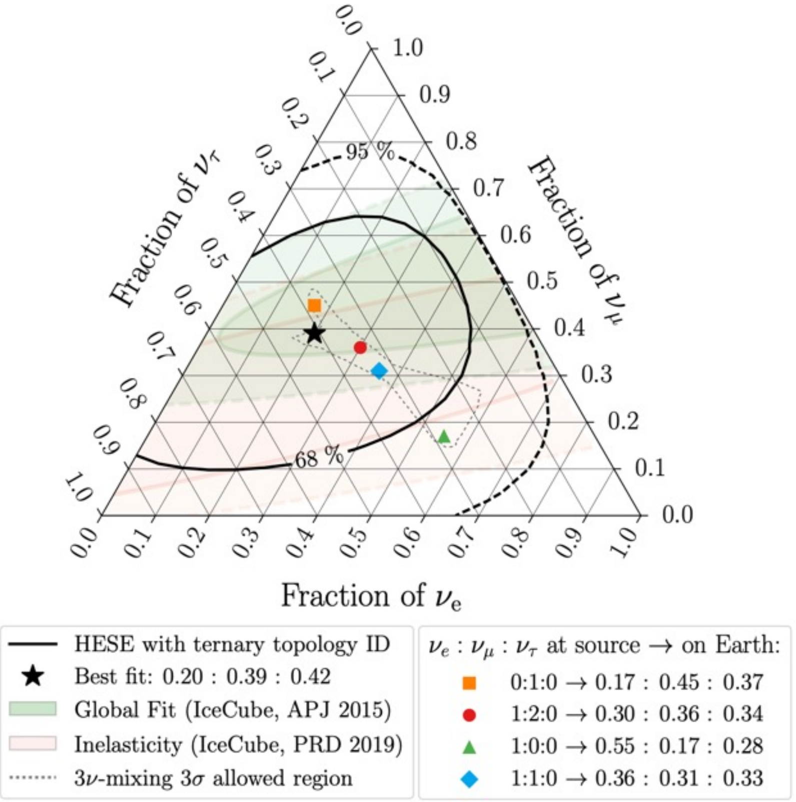
<u>Neutrino Detections</u>

- Discovery of PeV-scale extra-Galactic neutrinos **(> 5σ)**.
- Evidence of neutrino flare TXS 0506+056 in coincidence with neutrino detection **(3.5 σ)**. [IC Collab, Science 361, 147]
- Support for tau neutrinos flux **(2.8 σ)** [IC Collab arXiv:2011.03561]

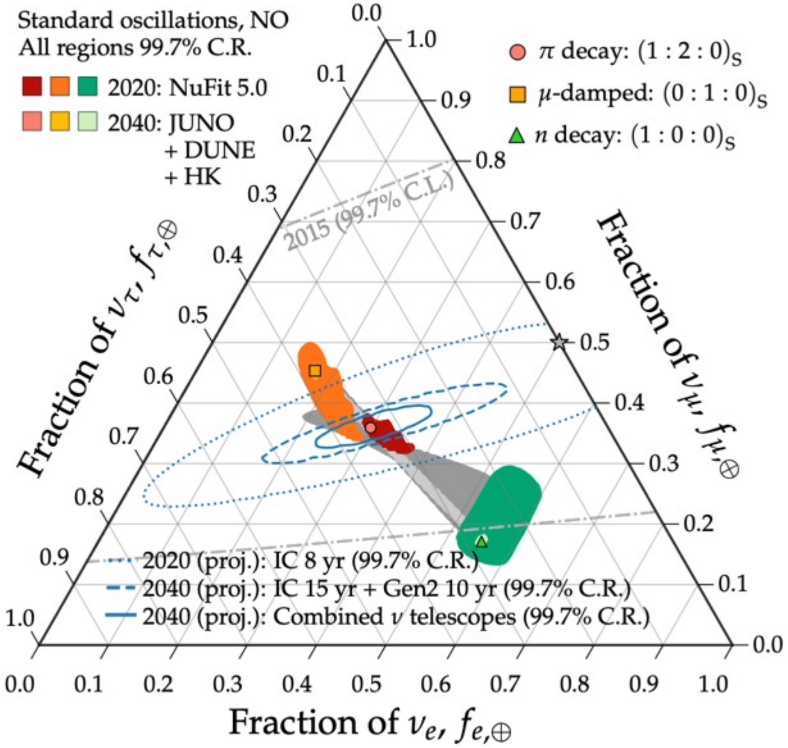


Tau Neutrinos

- A pair of tau neutrino ”double bang” candidates have been identified in IceCube data.
- The significance of the tau detection is 2.8 σ



arXiv:2203.08096



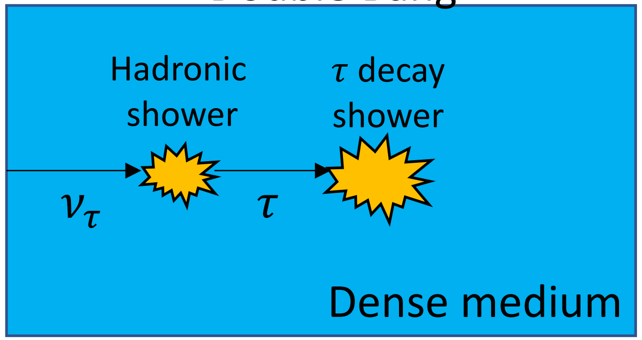
arXiv:2008.04323

Identifiable Tau Interactions

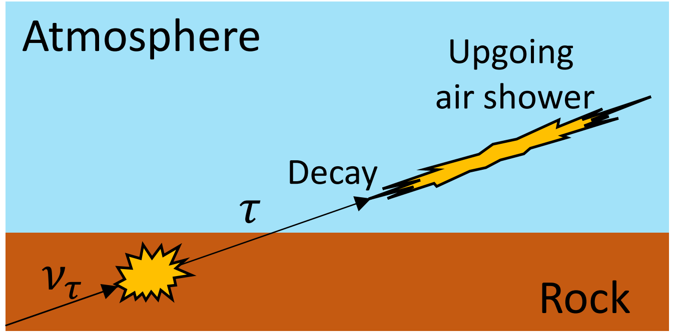
Experiments aiming at identifying tau neutrino interactions rely broadly on two methods:

1. "Double bang" in dense media:
   1. Tau neutrino interacts producing, in some cases, hadronic shower + tau.
   2. Tau propagates $L \sim 49\ \mathrm{m} \times (\mathrm{E/PeV})$ before it decays
   3. Tau decays to produce a second shower.
   4. Detection occurs if two showers with the epected characteristics are observed.
2. "Upgoing" air showers
   1. Tau neutrino interacts in the Earth producing, in some cases, a hadronic shower (not visible to the detector) + tau
   2. Tau propagates $L \sim 49\ \mathrm{m} \times (\mathrm{E/PeV})$ and exits the ground escaping into the atmosphere.
   3. The tau decays in the atmosphere producing an air shower.
   4. Detection occurs if an air shower pointed upwards from the ground is detected.

Double Bang



Upgoing Air Shower



Detection Methods for Tau Neutrino Interactions

- Particle counters
  - Scintillators and water tanks only used for air showers.
- Fluorescence
  - Applied to air showers
  - No known analogous mechanism in dense media.
- Cherenkov Radio
  - Includes geomagnetic for air showers.
  - Double bang requires dielectric media (e.g. ice, salt)
  - Simulations in ice do not show sensitivity to identifying double bangs.
- Cherenkov Optical
  - Double bang requires optically translucent or transparent media (e.g. ice, water)
- Radar
  - Successfully demonstrated in dense media.
  - Tried unsuccessfully on air showers.

	Double Bang	Upgoing
Particle counters	✗	✓
Fluorescence	✗	✓
Cherenkov Radio	✗	✓
Cherenkov Optical	✓	✓
Radar	✓	✗

Current and Proposed Tau Neutrino Experiments

	Double Bang	Upgoing
Particle counters	❌	**Auger**, TAMBO
Fluorescence	❌	**Auger**
Cherenkov Radio	❌	**ANITA/PUEO**, BEACON, TAROGE-M GRAND
Cherenkov Optical	**IceCube,** **KM3NeT** IceCube-Gen2, Baikal-GVD / P-ONE	**EUSO-SPB**, POEMMA, TRINITY
Radar	RET-N	❌

High Energy Tau Neutrino Experimental Landscape

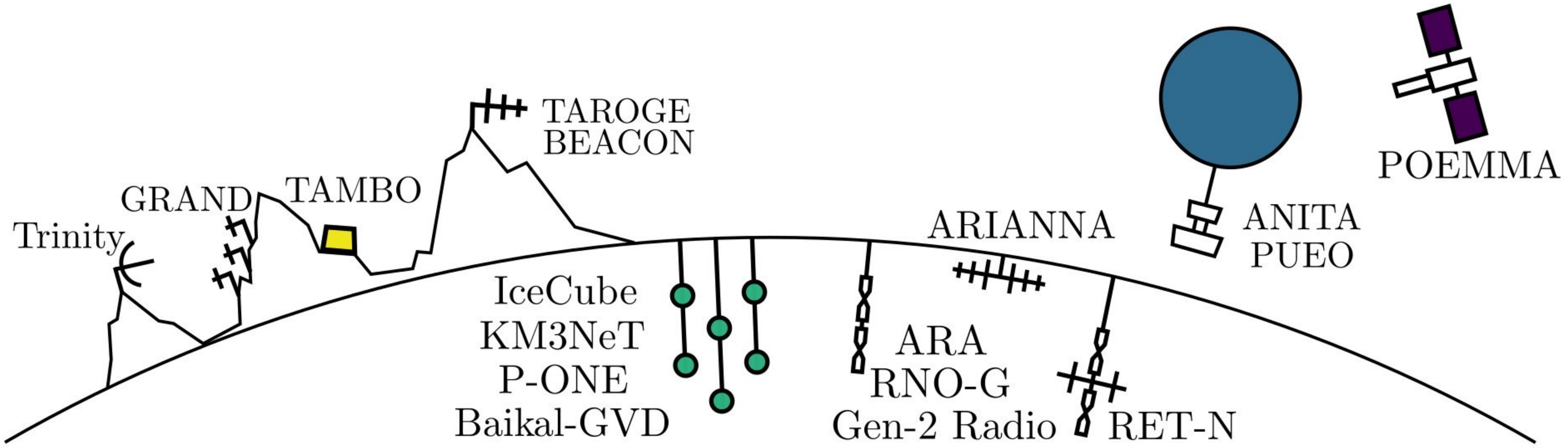
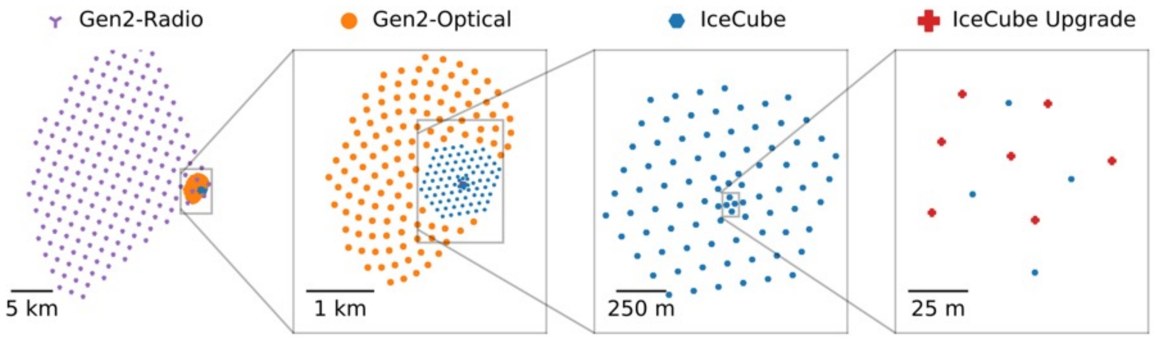


Image credit: Ivan Esteban https://twitter.com/iesteban_ph/status/1528683020932288513/photo/1

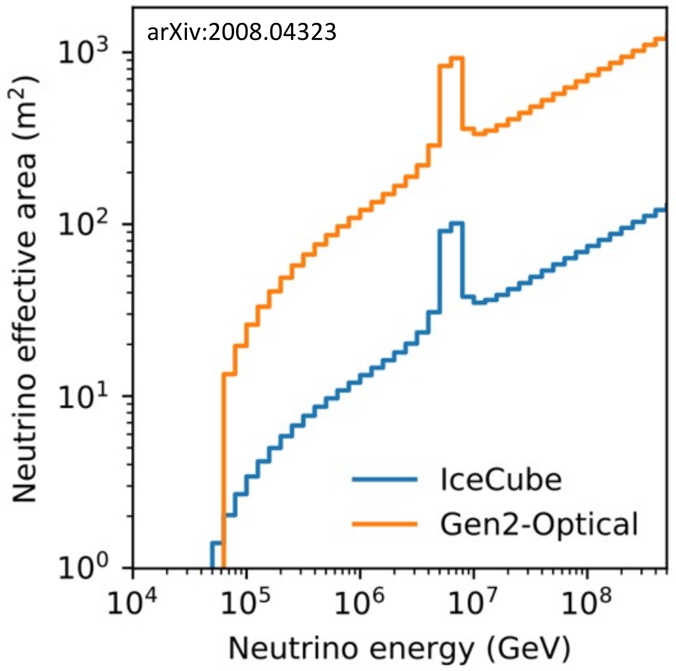
IceCube Gen2

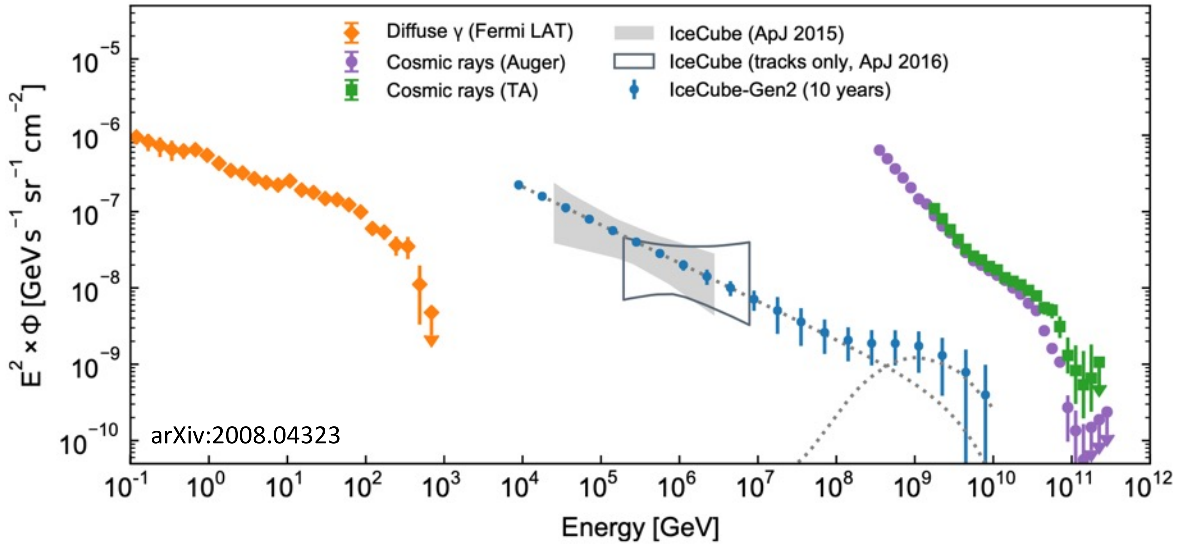
- Expand the optical array to give an order of magnitude increase in effective area.
- Include a large radio array covering to reach the highest energies.



arXiv:2008.04323

Figure 21: Top view of the envisioned IceCube-Gen2 Neutrino Observatory facility at the South Pole station, Antarctica. From left to right: The radio array consisting of 200 stations. IceCube-Gen2 strings in the optical high-energy array. 120 new strings (shown as orange points) are spaced 240 m apart and instrumented with 80 optical modules (mDOMs) each, over a vertical length of 1.25 km. The total instrumented volume in this design is 7.9 times larger than the current IceCube detector array (blue points). On the far right, the layout for the seven IceCube Upgrade strings relative to existing IceCube strings is shown.





IceCube Tau

- ”Double Bangs” as two spatially resolved distributions require higher energies (rare).
- Can detect double pulses in PMT readout at lower energies.
- Double pulse background dominated by ν_μ events.
- Improvement in Gen2:
  - Higher event rate (1 ν_τ / yr or 10 events in 10 years).
  - Calibrations enable higher significance distinction between double pulses.
  - Larger array, higher acceptance will produce spatially resolved double bangs.

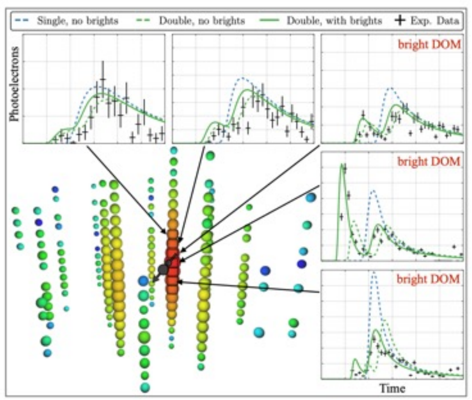


FIG. 3. Double cascade event #2 (2014). The reconstructed double cascade vertex positions are indicated as grey circles, the direction indicated with a grey arrow. The size of the circles illustrates the relative deposited energy, the color encodes relative time (from red to blue). Bright DOMs are excluded from this analysis.

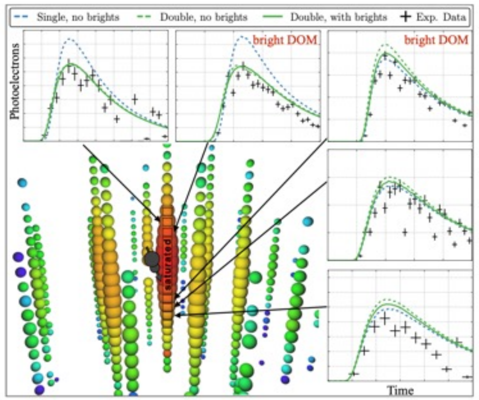
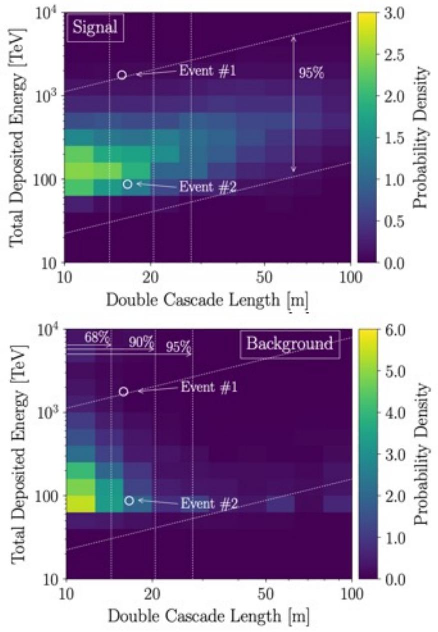
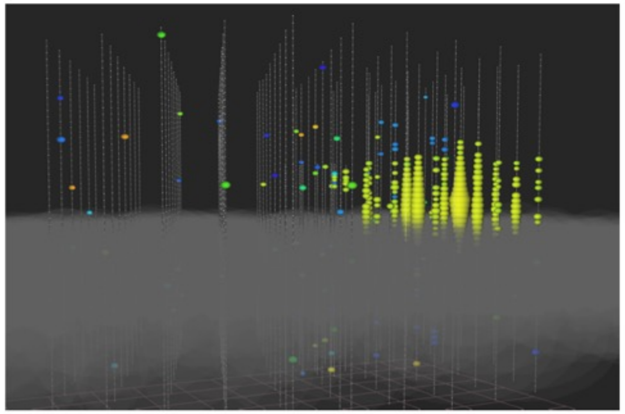


FIG. 5. Double cascade event#1 (2012). The reconstructed double cascade vertex positions are indicated as grey circles, the direction indicated with a grey arrow. The size of the circles illustrates the relative deposited energy, the color encodes relative time (from red to blue). Bright and saturated DOMs are excluded from this analysis.

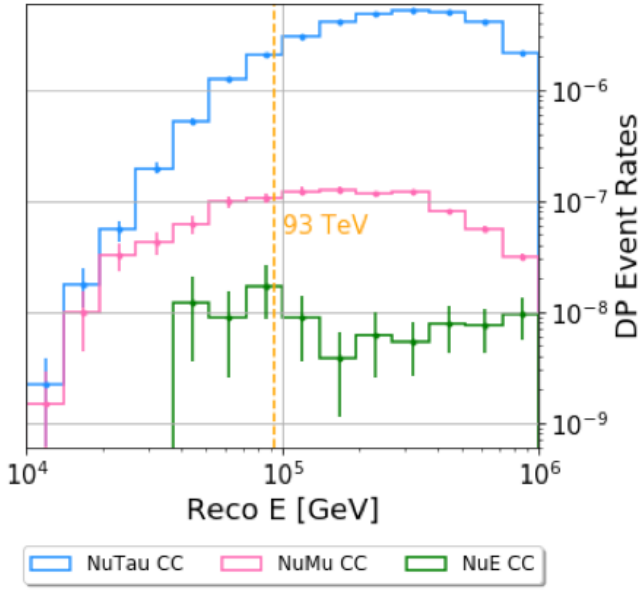


arXiv:2011.0356

PoS(ICRC2021)1146



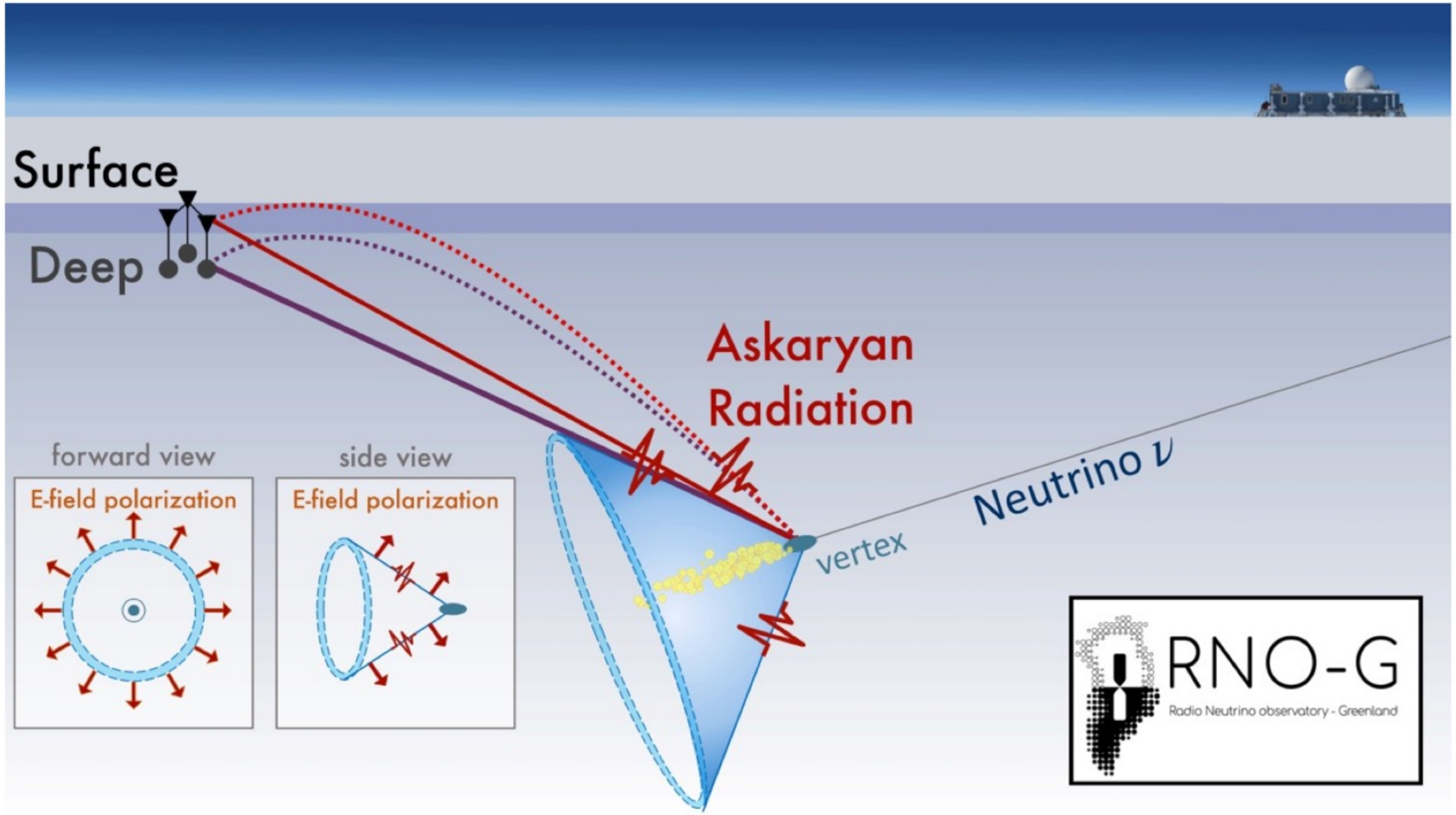
(a) 2014 event visualisation.



Radio Detection in Ice (Askaryan)

Principle behind
- ARA
- RNO-G
- ARIANNA
- IC-Gen2 Radio

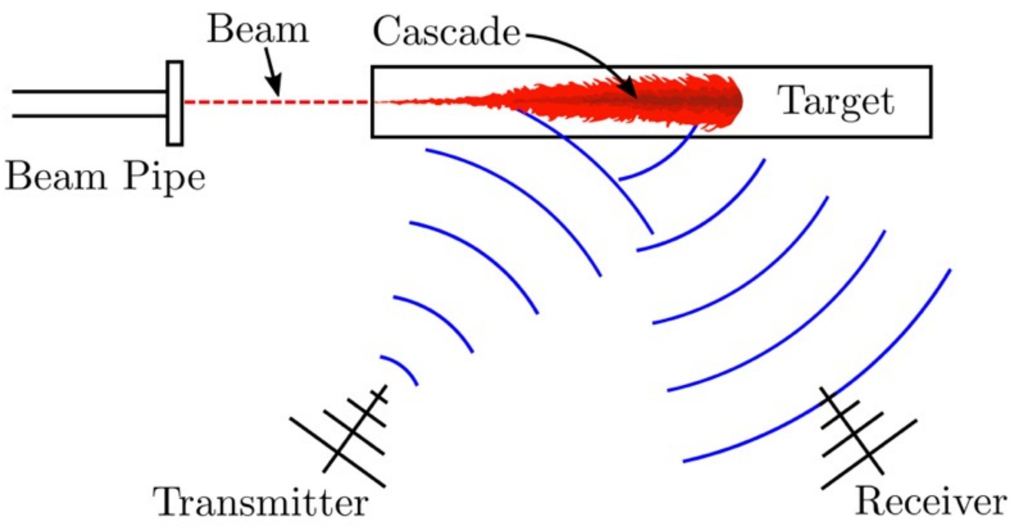
Currently not expecting to be able to identify double bang events due to the narrowness of the cone and the density of receiver detection would require.

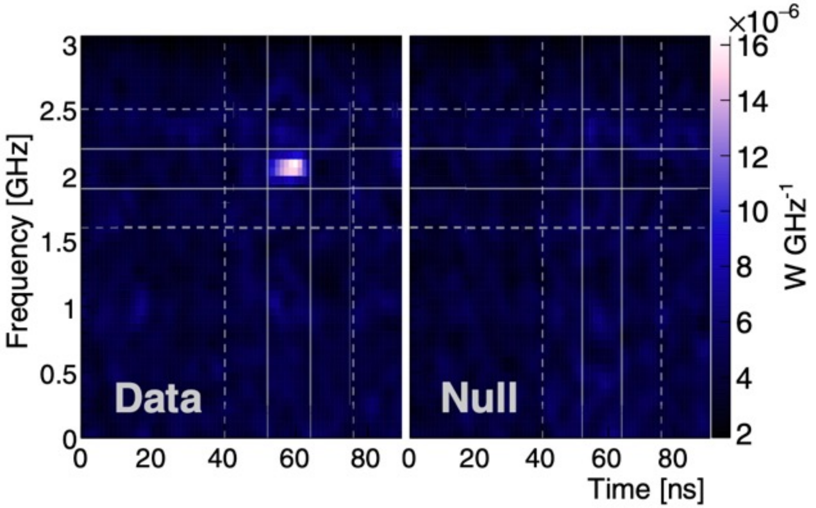


Radar Echo Telescope

- Radio transmitter reflects off ionized traces form particle cascade.
- Reflection detected by radio receiver.
- Main advantage: shower can be detected over wide range of angles (not just the ~1 deg Askaryan cone).
- Prototype to demonstrate CRs in ice being built.
- Method can resolve "double bangs" but detailed simulations are ongoing.

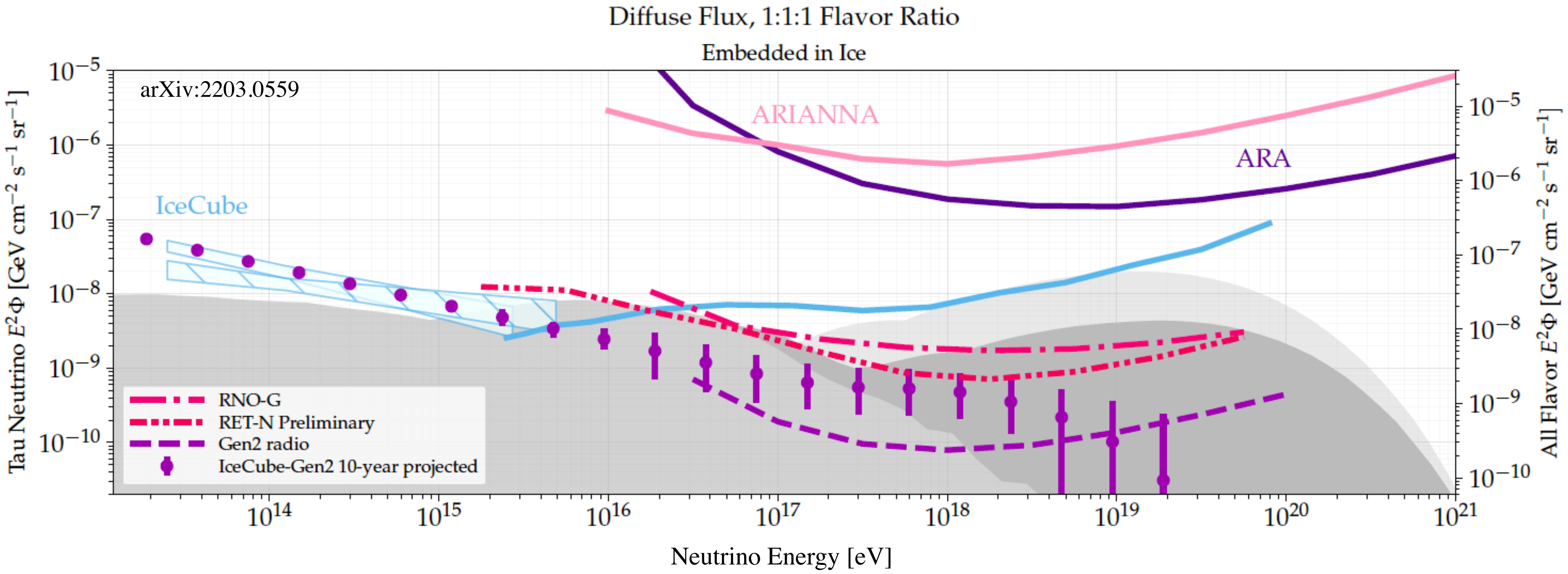
Prohira et al., PRL 2020





Double Bang Prospects

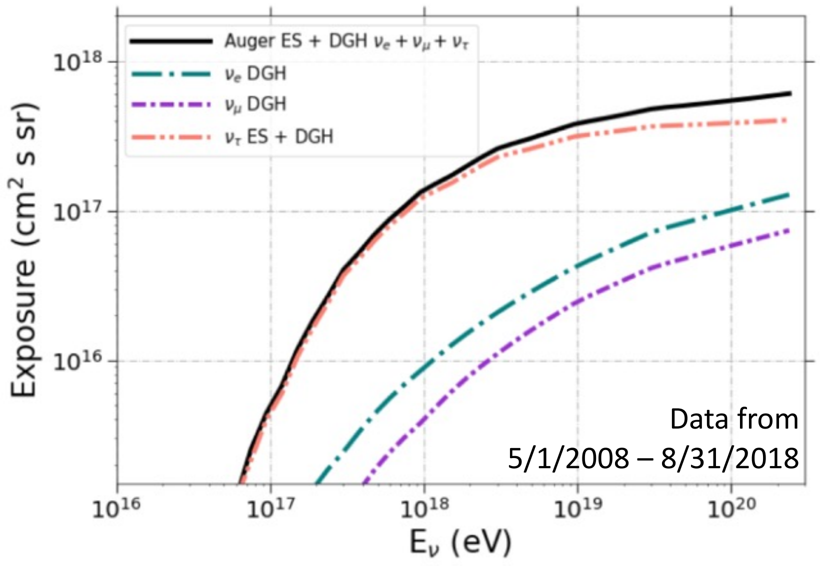
- **Gen2**: ~10 “double bang” events in 10 yrs with a tentative 20:1 signal to background ratio.
- **Water (KM3NeT / Baikal / P-One):** longer photon scattering length helps but event rates are not competitive w/ Gen-2.
- **RET-N**: could be sensitive “double bang” events but expected event rate remains to be determined.
- **Askaryan in-ice detectors**: not yet identified a way to detect double bangs with current designs & analysis techniques.



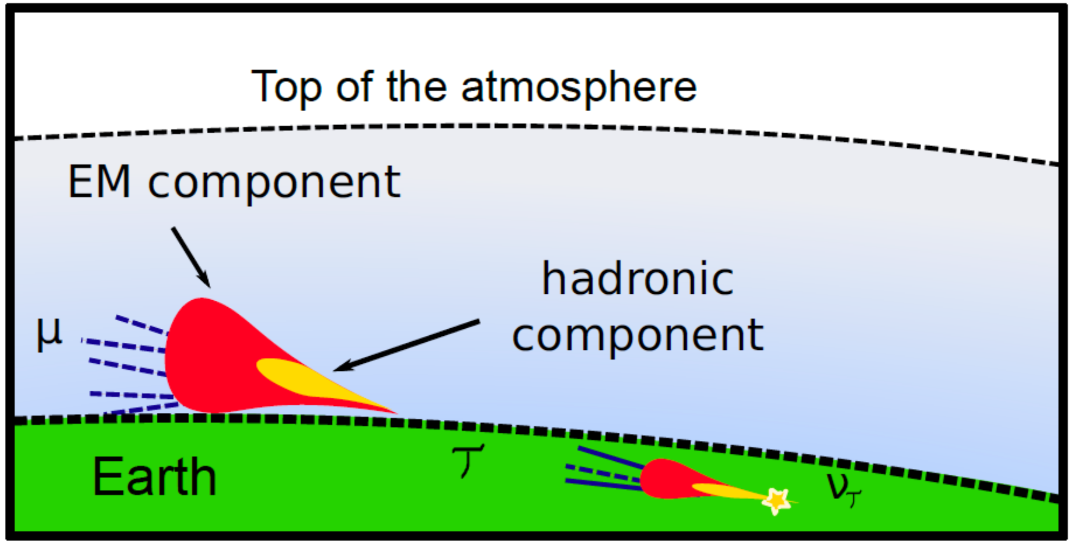
Auger (Surface Detector)

- Auger predominantly sensitive to skimming air showers (tau).
- All-flavor limits at EeV and greater energies comparable to IceCube extreme energy event searches.
- No events above background found.

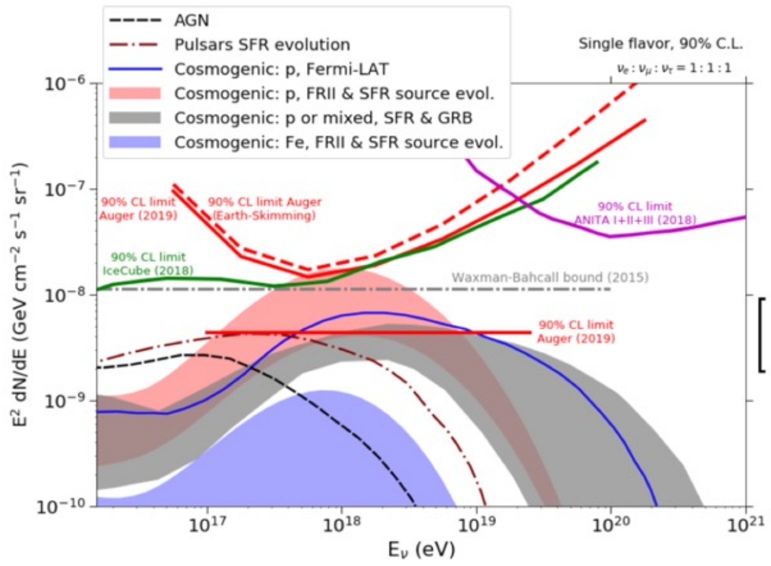
Parente et al., 2021



Data from 5/1/2008 – 8/31/2018

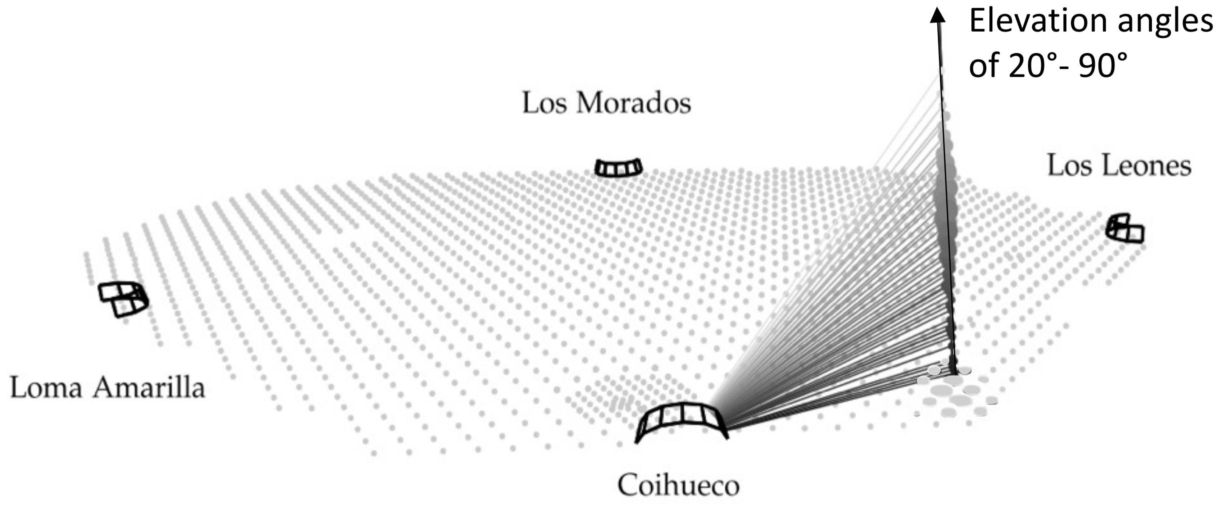


Guardincerri 2013 Thesis



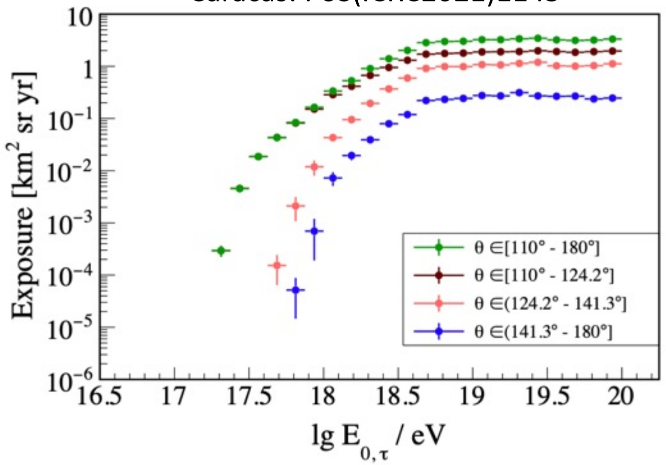
Auger (Fluorescence Detector)

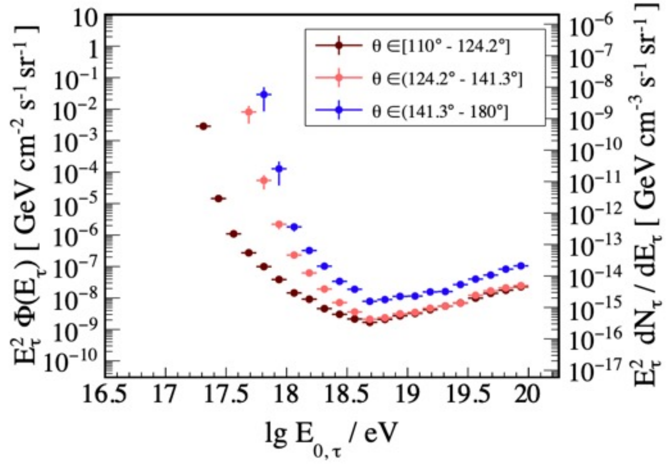
- Recent upgoing event searches with Auger fluorescence detector (motivated by ANITA-1 and ANITA-3 steeply upgoing tau candidates).
- Mastrodicasa PoS(ICRC2021)1140: 14 year dataset, expected background of 0.45 events, found 1 event.
- No events above background found.



Adapted from Albrecht et al 2022

Caracas: PoS(ICRC2021)1145



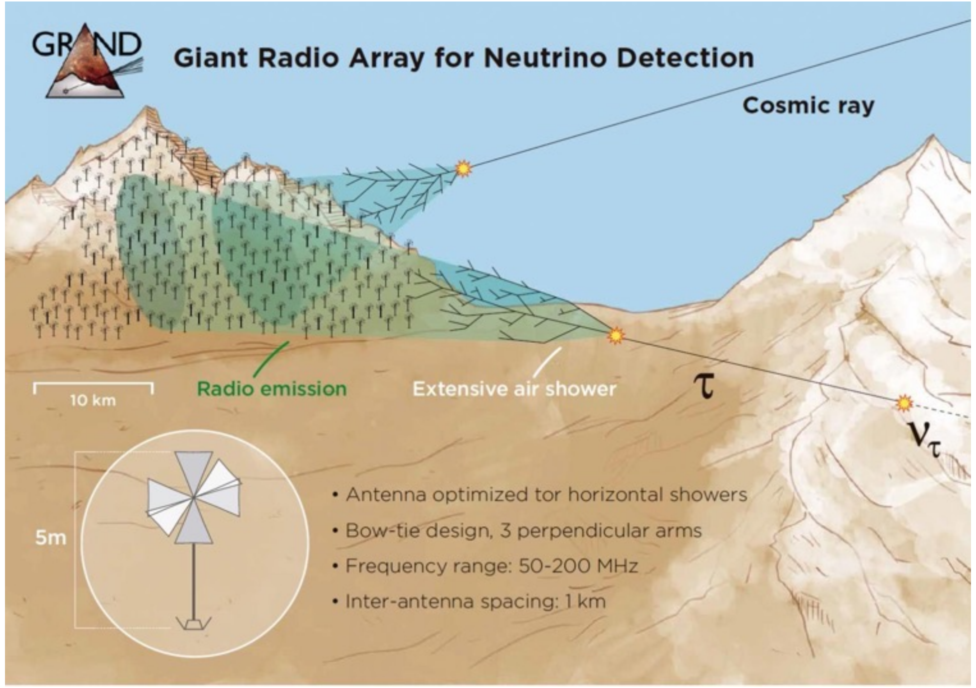


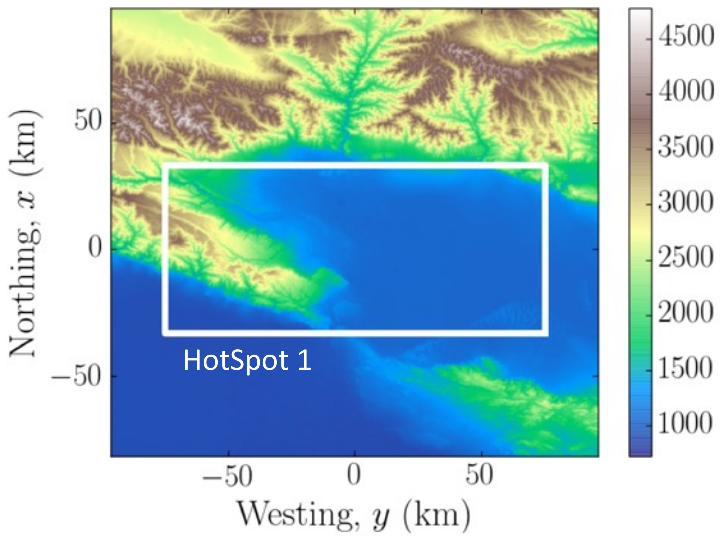
(b) $\Phi_\tau \propto E_0^{-2}$

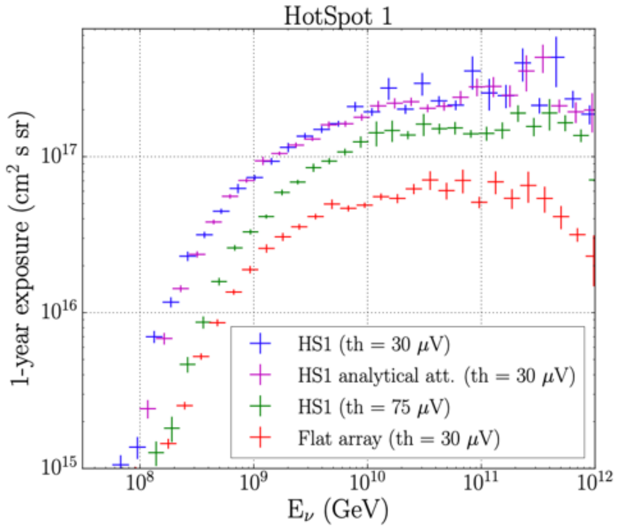
NB: 10^{18} cm^2 sr s ~ 3.2 km^2 sr yr arXiv: 1810.09994

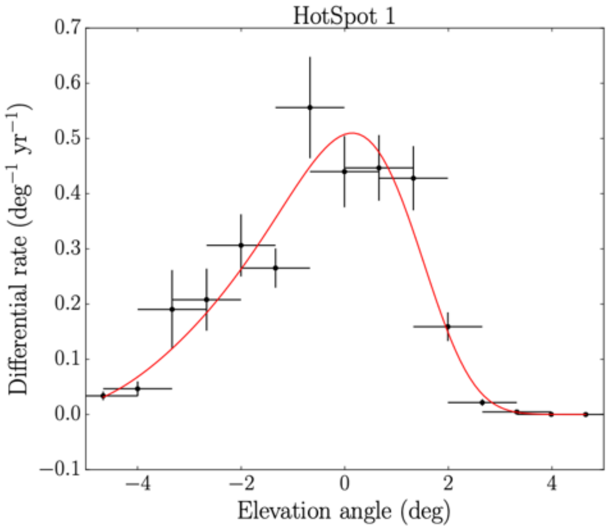
GRAND

- Large radio array (200,000 km^2).
- 50-200 MHz band.
- Skimming tau air showers produce a radio footprint detected by 1-km spaced antennas.
- 200,000 antennas triggering independently.
- Planned to distribute world-wide (20 clusters of 20,000 antennas each.
- Self-triggered individual antennas, requiring clustering and coincidence.



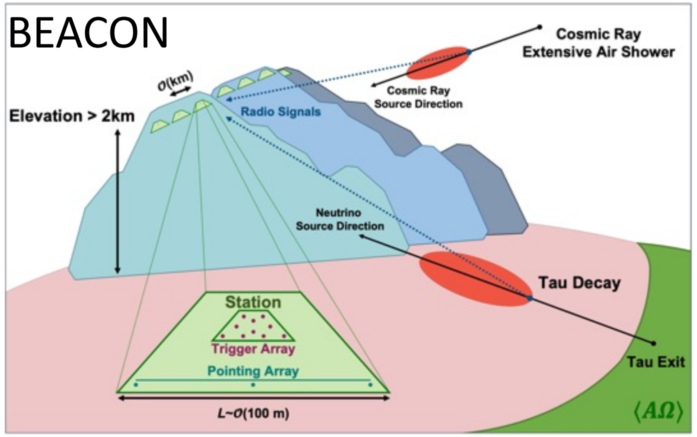


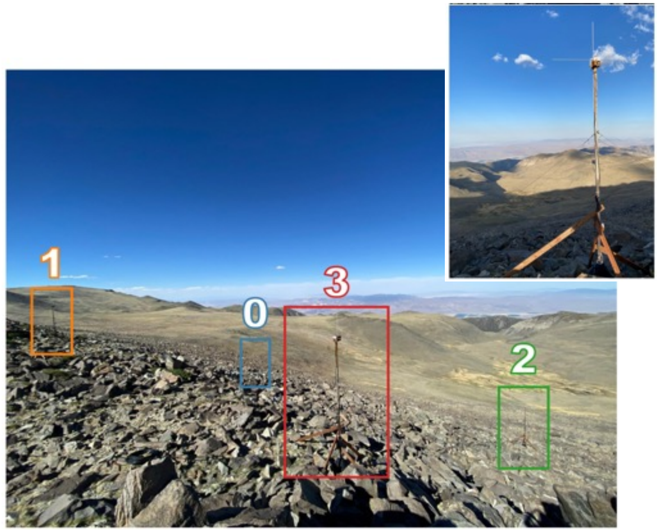


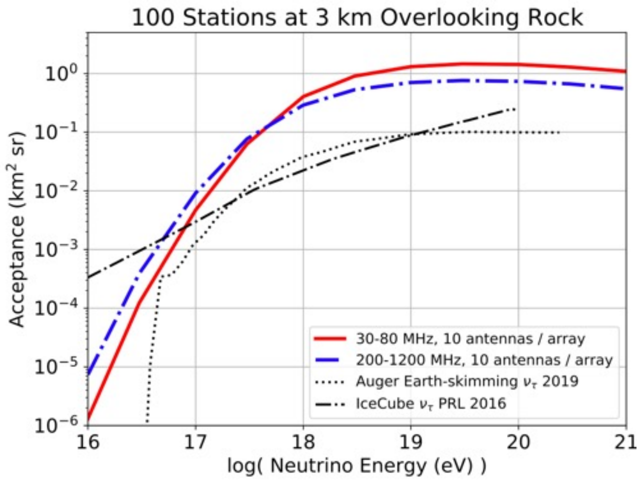


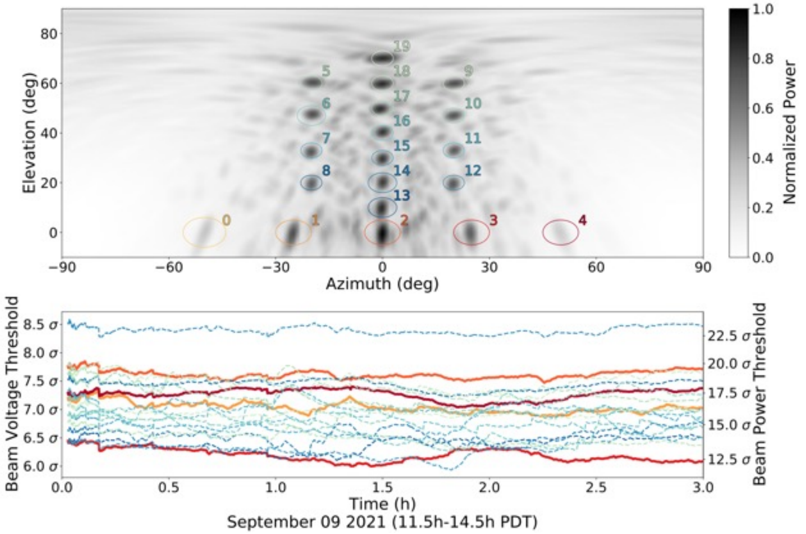
BEACON

- BEACON concept leverage:
  - Geometry: mountain view has improved geometric factor.
  - Interferometry: multiple trigger beams to manage RFI.
- Trigger array is compact.
- Pointing array has extended baselines for spatial resolution.
- Can operate in VHF (30-80 MHz) or UHF (200-1200 MHz) bands with similar sensitivity to help mitigate local RFI.
- Relatively compact self-contained stations help to eventually deploy it as a worldwide series of mountain-based stations.





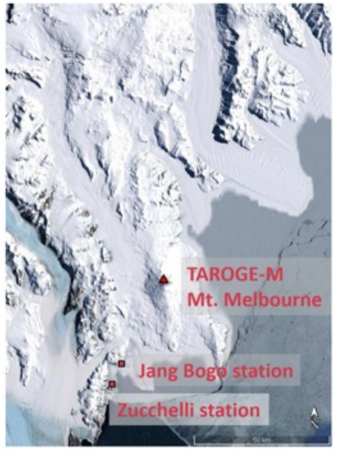


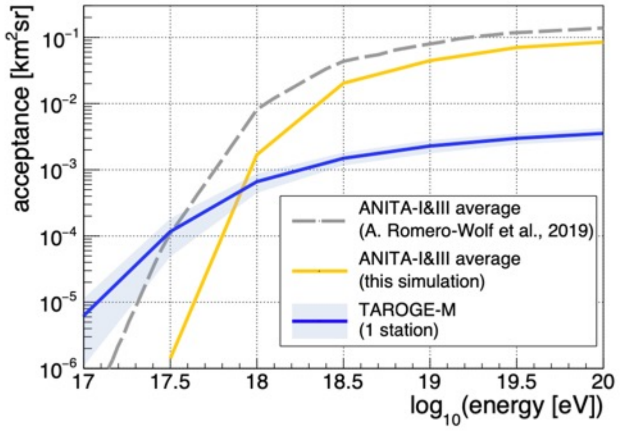


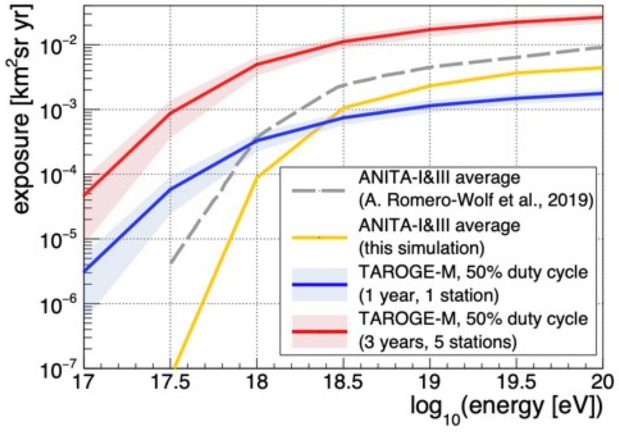
TAROGE-M

arXiv:2207.10616

- Mountain-side radio detector array in Antarctica
- 180-450 MHz LPDA antennas.
- Motivated by ANITA upgoing air showers.
- Has successfully detected cosmic ray air showers.
- Demonstrated radio-quiet site. Trigger methods are more like ANITA (threshold crossing coincidence).
- Not currently proposing to expand to a large tau detector array but there is a lot in common with BEACON.



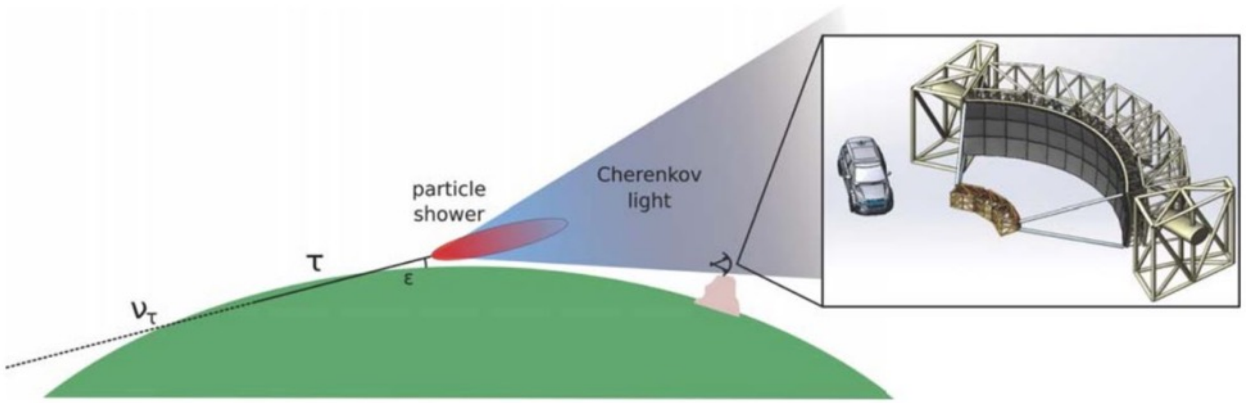


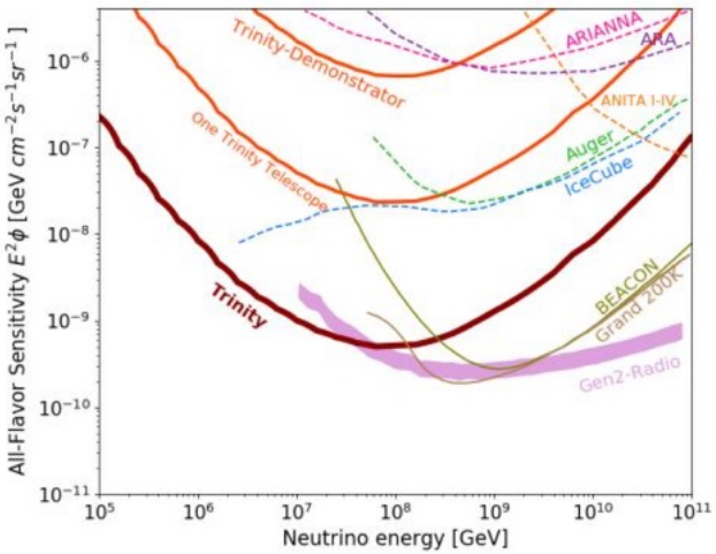


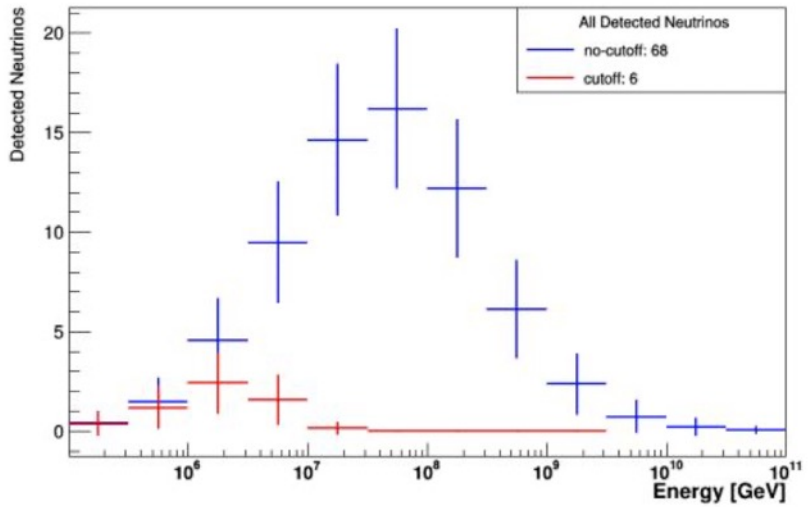
TRINITY

ICRC 2021

- Mountain-side optical detector using optical Cherenkov radiation.
- Also leveraging high-elevation geometric factor.
- Sensitive to PeV tau neutrinos and above.
- Proposed array of 18 stations.
- Funded as NSF MRI for one station.

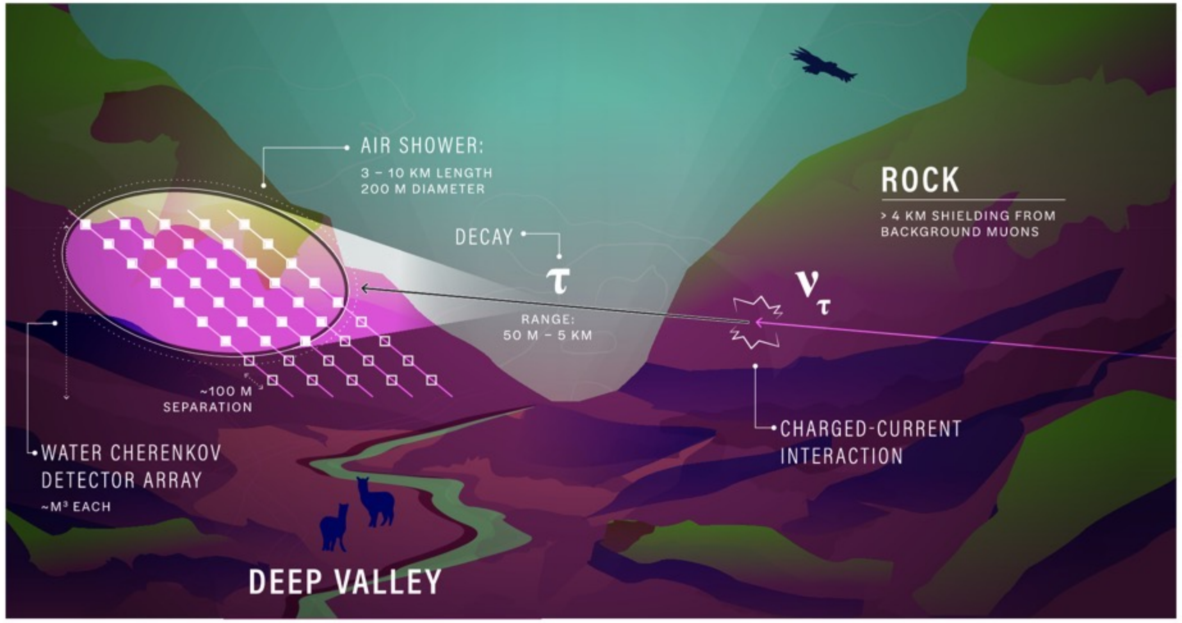




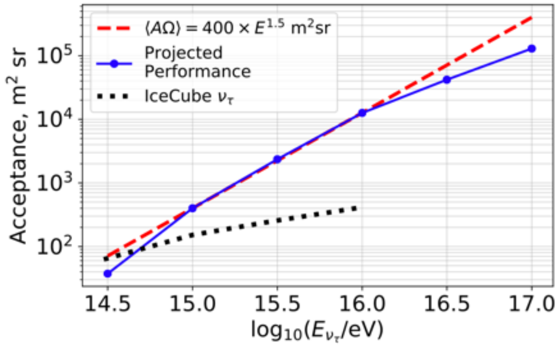


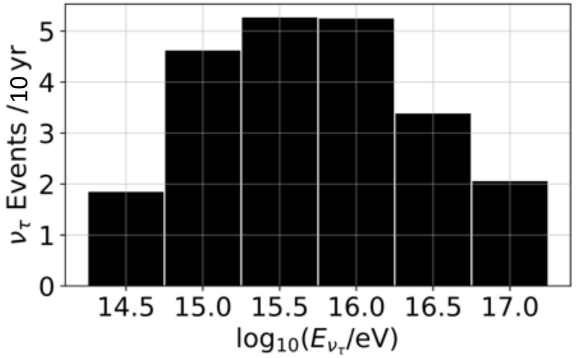
TAMBO

- Air shower array in a deep valley leveraging geometric factor and shielding from backgrounds.
- Leverages the use of particle counters (open trade of water Cherenkov detectors or vertical scintillator paddles).
- Access is possible in the Colca Valley of Peru with existing infrastructure and water present rivers at bottom of valley.
- Leveraging developments in SWGO, which may also be hosted in Peru.



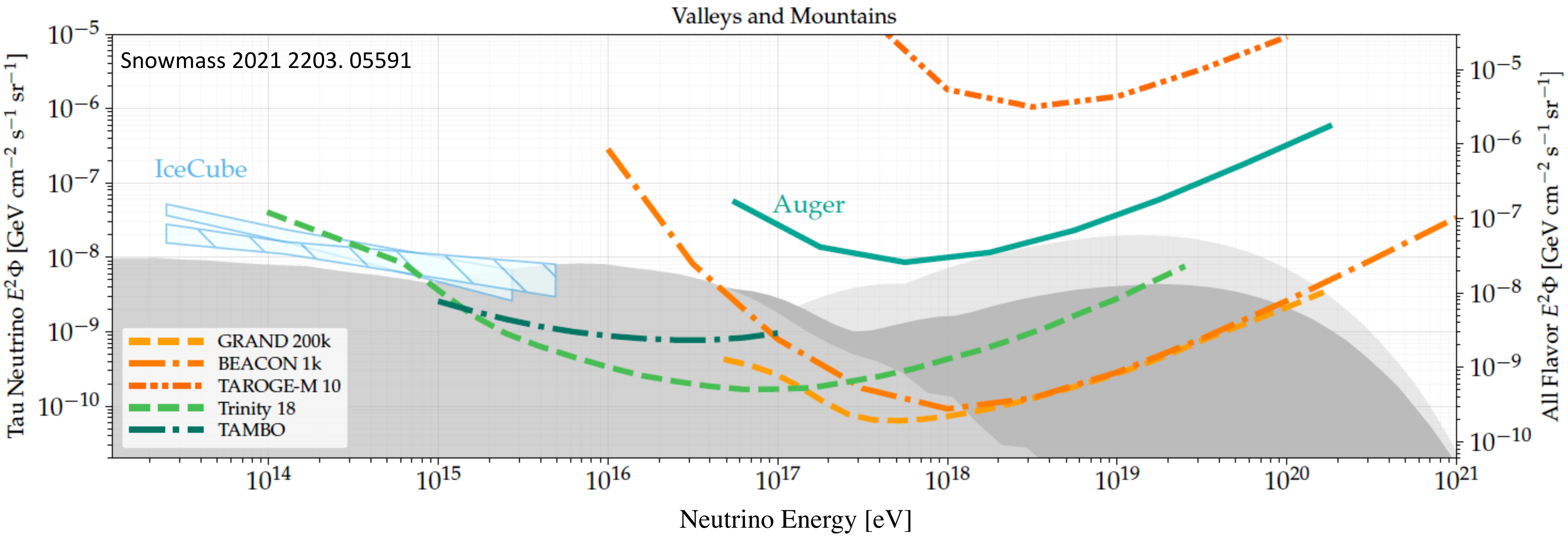
TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) · COLCA VALLEY, PERU





Ground Based Upgoing Shower Summary

- A number of options for upgoing tau air showers from PeV to 100 EeV.
- Multiple techniques have pros and cons. No obvious winner at this point.
- Could envision hybrid detection concepts (particle / optical / radio).



Orbital & Sub-Orbital

- High altitudes provide access to very large effective areas.
- Distance from air showers result in a high energy threshold.

Radio

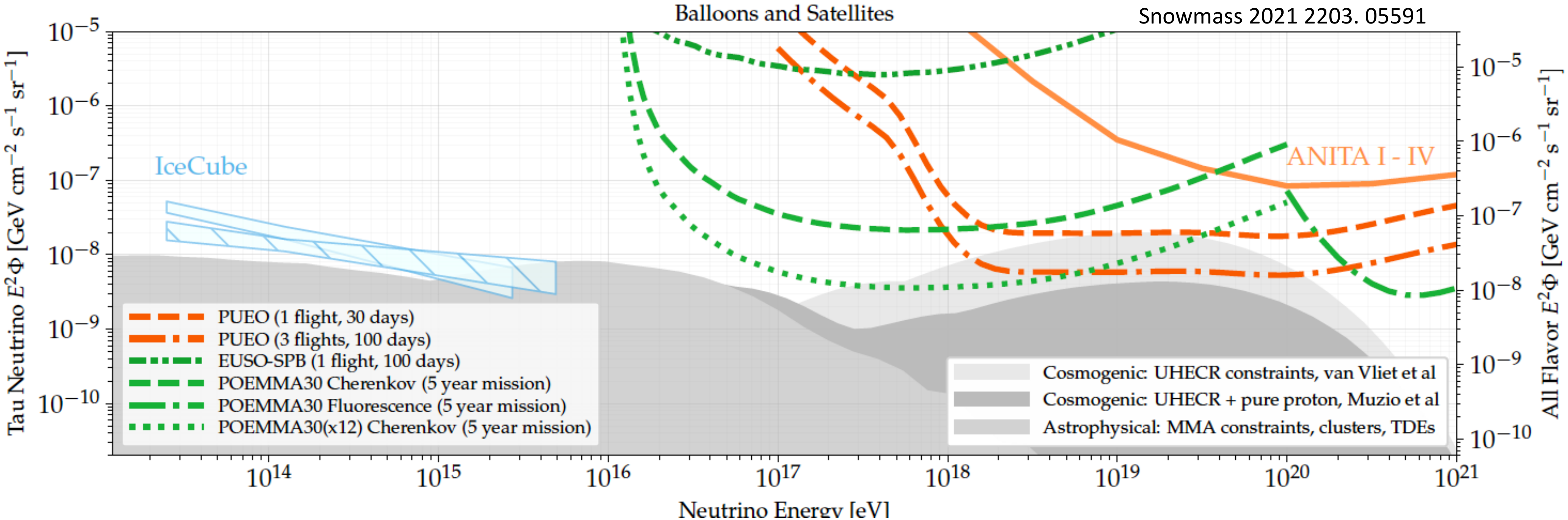
Optical

Suborbital

Orbital

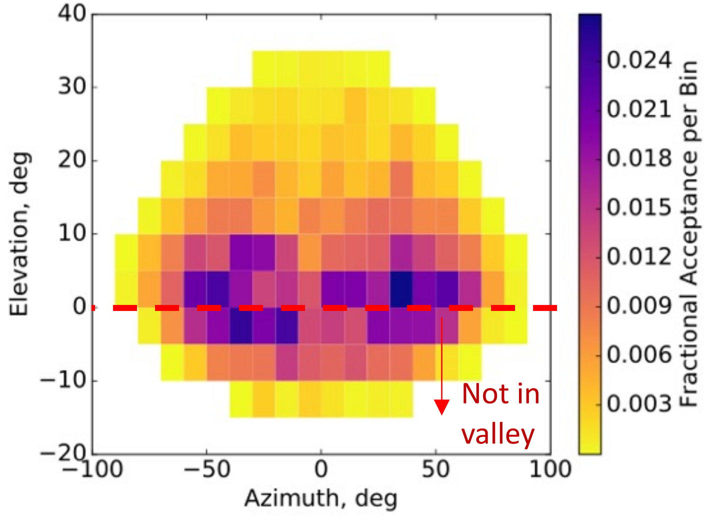
Potential radio instrument for hybrid optical detector.

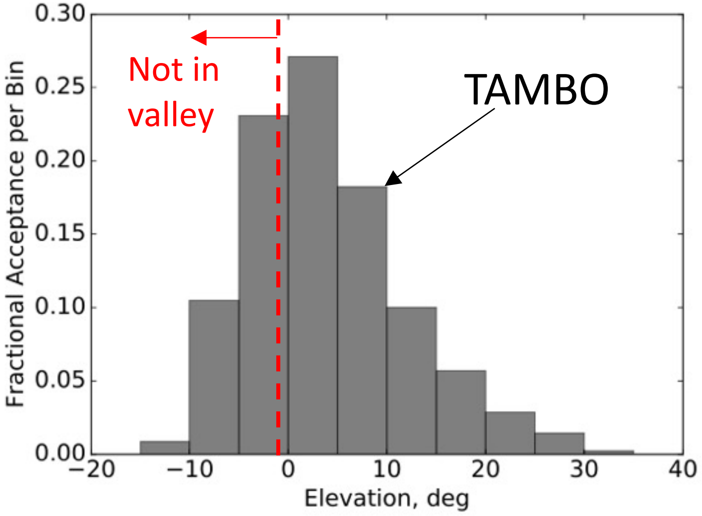
Summary of Upgoing Orbital & Suborbital Detectors



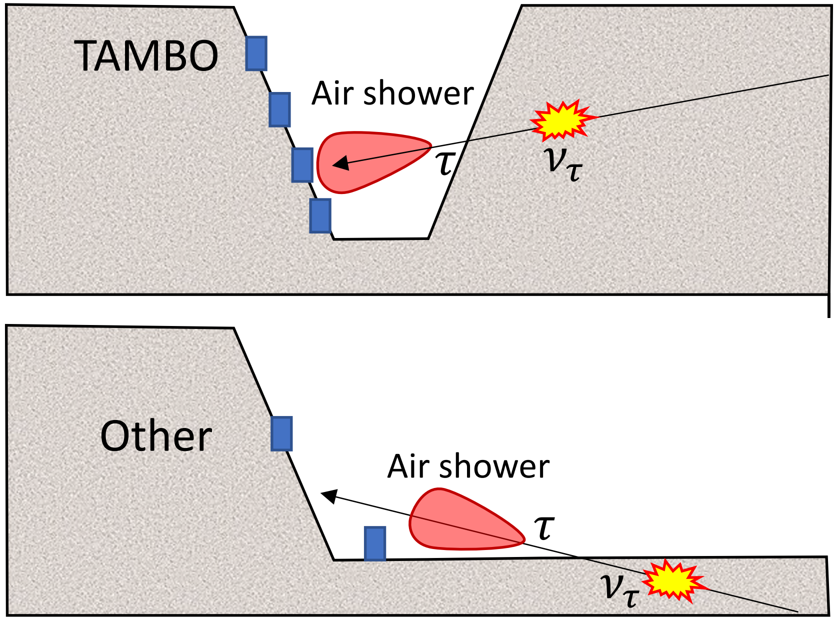
TDAMM Considerations

- Time Domain & Multimessenger Astronomy presents other drivers:
  - Point source sensitivity comparisons.
  - Instantaneous sky coverage.
- Deep valley detectors enable a larger sky view.





Deep valley enables larger sky view



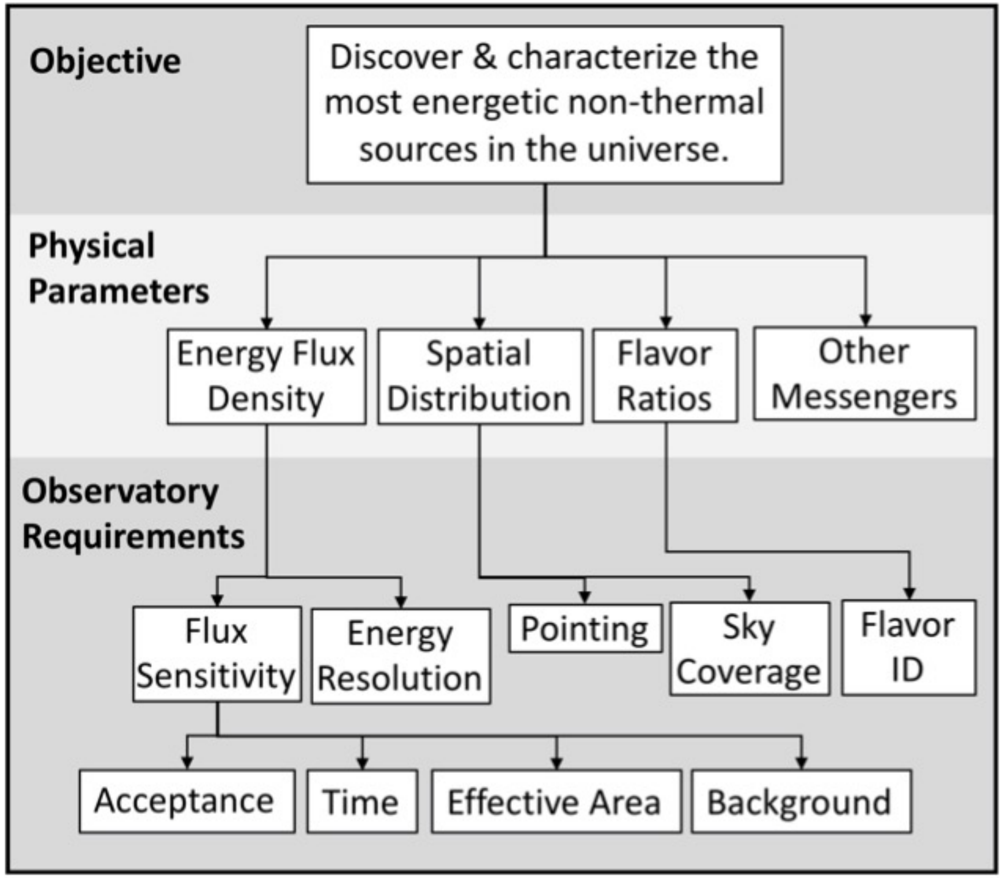
Where does TAMBO stand out?

- **Strengths**
  - Well tested detector techniques.
  - Backgrounds are not anthropogenic (unlike upgoing radio & optical).
  - Candidate sites have infrastructure to work with (road access, power, water source).
  - View of the Galactic center, wider instantaneous field of view. TDAMM is a hot topic.
- **Weaknesses**
  - A large array is required (though not unique in this regard).
  - Construction challenges are currently unknown (can be addressed with a prototype).
- **Opportunities**
  - Possible to leverage developments of optical and radio for hybrid detection.
  - Optical detection may not be as sensitive as currently envisioned.
- **Threats**
  - Funding is competitive and there is a lot of competition.

Backup

What drives neutrino observatory requirements?

Experimental Drivers	Driving Observatory Requirements
Discovery	1. Exposure 2. Background Discrimination
Features in the flux vs energy spectrum	1. Exposure 2. Background Discrimination 3. Energy resolution
Flavor Ratios	1. Exposure 2. Background Discrimination 3. Energy resolution 4. Flavor discrimination
Astrophysical Source Characterization	1. Exposure 2. Background Discrimination 3. Energy resolution 4. Flavor discrimination 5. Pointing Resolution
Multimessenger Astronomy	1. Point Source Sensitivity 2. Sky Coverage 3. Pointing Resolution 4. Background Discrimination 5. Energy Resolution 6. Flavor discrimination



From ASTRO 2020 white paper on astrophysics with neutrinos