

Snowmass Community Planning Meeting

Session 137

High and Ultrahigh Energy Neutrino Experiments

Co-organizers:

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André de Gouvêa (TF11), Abigail Vieregge (IF10)

Oct 7, 2020

Goals

As part of the Snowmass CPM, this session seeks to bring together

- Cosmic Frontier
- Neutrino Frontier
- Theory Frontier
- Instrumentation Frontier

to discuss efforts towards **Future High and Ultrahigh Energy Neutrino Experiments**

- Focus on inter-frontier discussions and establish cross-working-group connections
- Identify gaps and further input needed for planning whitepapers

snowmass2021 slack channel: **#cpm_session_137**

Related LOIs

- <https://docs.google.com/spreadsheets/d/1ROvGxKMgGUKpCC--UxArtrnM1fiSzGoh2vdtaCjigNI/edit?usp=sharing>
- 25 LOIs on the subject of high and ultrahigh energy neutrinos
- 16 focus on current and future experiments, 5 on observational opportunities and strategies, 4 on theory developments

Outline

I. Techniques that may enable future detections

1. Optical detection in ice and water
2. Askaryan radiation detection in ice
3. Radio detection in atmosphere
4. Cherenkov detection in space
5. Air shower detection on the ground

II. Science advances that may be achieved by future observations

1. Neutrino physics
2. Dark matter and dark energy
3. Beyond the standard model
4. Astrophysics

Panel 1: Detection Techniques



- IceCube world's largest NT (2011) → an optical discovery instrument in the TeV - PeV range
 the HE cosmic ν flux now firmly established ~ 100 per year above 10 TeV
 highest energy leptons ever - few above 1 PeV, none yet above 10 PeV
 matching energy density for HE ν , γ -rays and CR → many hadron accelerators in the sky
- Complemented in Northern hemisphere by smaller water-based NT's - Lake Baikal / ANTARES

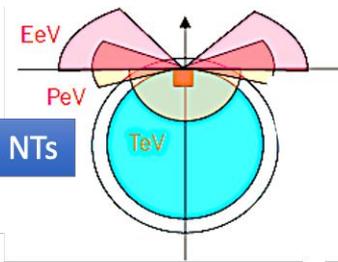
BOTH TECHNIQUES ARE MATURE AND WORK WELL

- require monitoring of huge instrumented volumes of optically transparent media
- deep sites to shield against atm. μ 's: 2500 - 5000 m in water; 1350 - 2650 m in ice
 - Photon transport: less scattering in water → better pointing accuracy
 less absorption in ice → better calor. energy measurement
 - Caveats: noise (^{40}K , bioluminescence), sedimentation in water; ice properties
 - logistics

- QUO VADIS?
- IceCube-Gen2 - 8x volume (+12 000 OMs)
 - KM3NeT and GVD target km^3 size

TO ENSURE STATISTICS & FULL SKY EXPOSURE ABOVE FEW TENS OF TEV NEED A GLOBAL NETWORK OF NTs

- P-ONE - a segmented km^3 array in the Pacific, off the coast of Canada
- Dedicated instruments - TAMBO (array of water tanks for ν_τ at 1-100 PeV)



Earth opaque to ν 's > 50 TeV

2. Askaryan Radio detection in ice

Results from past Decade

Fundamentals of the method and the use of ice are understood!

Enormous progress in instrumentation.

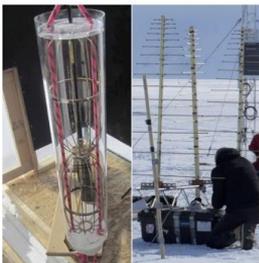
(ANITA, incl. measurements at SLAC.
Air shower experiments: LOFAR, AERA)

Detectors in operation*:

Goals: science and development

ARIANNA:

Location: Antarctica, -79°
+ 1 at Pole
Stations: 7
antennas: log periodic
depth: ~surface (3 m)
(shallow)



ARA:

Location: Antarctica, -90°
ice: 2.8 km, cold
stations: 5
antennas: Hpol, Vpol
depth: 200 m (deep)

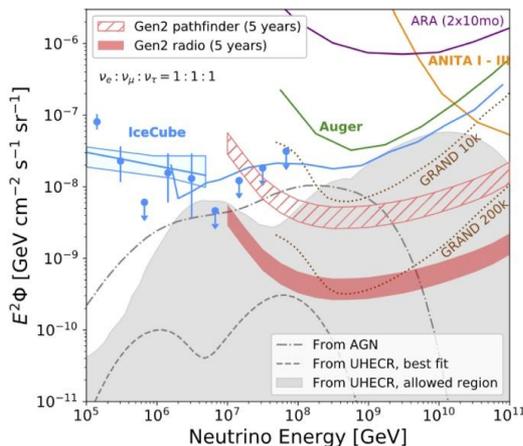
Intermediate scale detector configurations: explored in recent years:

ARIANNA 200 (ARIANNA heritage) [LOI 13]
RNO Greenland (ARA heritage, first construction 2021) [LOI 139]

New Ideas: Radar Echo Telescope [LOI 109]

The Community is ready for a bold move!

- Workshops (Weizmann 2017, OSU RNO 2019, Munich, DESY)
- > Science requirements:
Revealing the sources and propagation of the highest energy particles in the universe.
 - Cosmogenic neutrinos
 - Astrophysical Sources



IceCube-Gen2* Radio

IceCube-Gen2 Radio Working group formed.

Broad community engagement

Detector scope in reference design:
Target area:
Area: 500 km²
Viewable ice target: ~1000 km²
Reference design: 200 stations

Complements IceCube-Gen2 optical.
Adopted as detector component by IceCube collaboration.

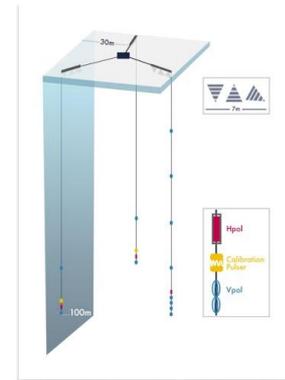
Station design and geometry (and with it number of stations) currently under review in the IceCube-Gen2 radio working group.

Maturity of design elements

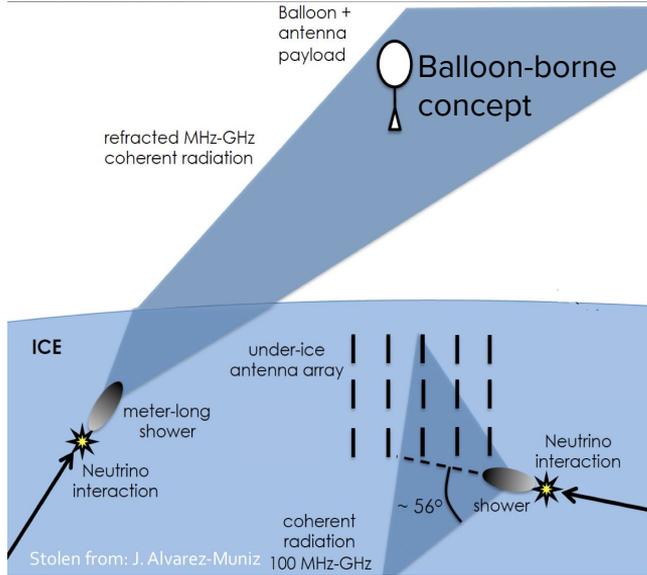
- Interferometric trigger = Phased Array ✓
- Autonomous operation at Pole is a challenge (ARA runs on cables, Arianna has made progress on autonomous. RNO-G will test fully autonomous in 2021) ✓
- Electronics ✓
- Antennas ✓
- Drilling and deployment ✓
- Operational experience ✓

At a point to plan a large array.

[LOI 101, IceCube-Gen2]



3. Radio Detection in Atmosphere



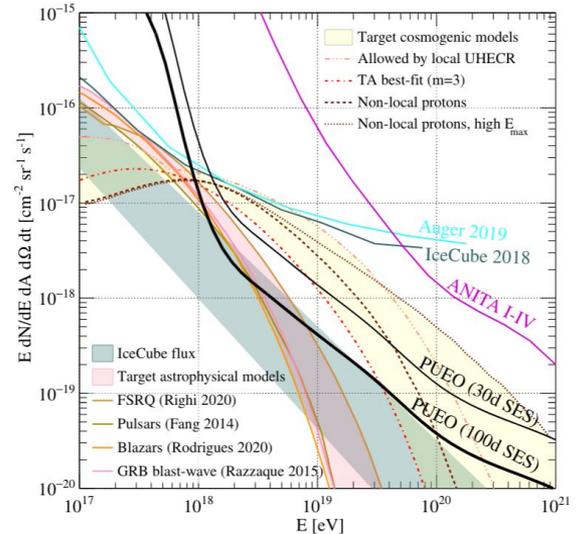
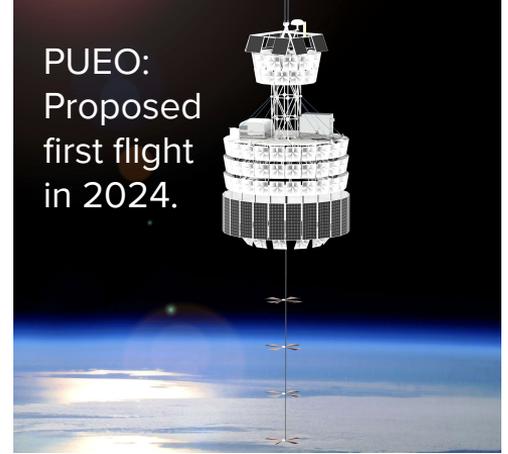
Two radio detection channels are accessible from a balloon platform

- 1) Askaryan emission from neutrinos interacting in ice
- 2) Geomagnetic emission from air showers induced by tau leptons generated in tau neutrino interactions in the Earth.

ANITA has not detected neutrinos via the Askaryan channel. ANITA has seen some “mystery events” that look like upward-going air showers

PUEO leverages new technology (a phased array trigger implemented with RFSocS) and a payload re-design to dramatically improve sensitivity.

Abby Viereg, UChicago



Cherenkov + Fluorescence from Space



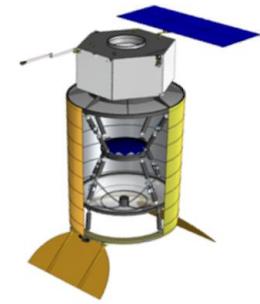
POEMMA (Probe Of Extreme Multi Messenger Astrophysics)

Astro 2020 NASA Probe Class (<1B\$) design = 2 observatories Fluorescence and Cherenkov hybrid camera

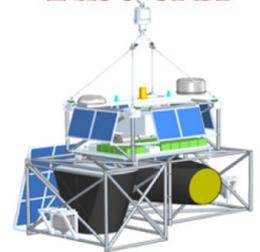
Fluorescence: UHE Cosmic Rays stereo and **UHE all flavor neutrinos $E > 20$ EeV**
(see M Bustamante and PhysRevD.101.023012)

Cherenkov Earth's Limb: *tau neutrino/tau decay showers*
 $E > 20$ PeV below current radio technique
Target of Opportunity (TDE, NS-NS, BH-BH, sGRB)
Full sky coverage for long transients
For short transients: fast reaction time (mins)
(see T Venters, M.H. Reno and arxiv.1906.07209)

POEMMA Prototype: EUSO-SPB2 to fly 2023



EUSO-SPB2

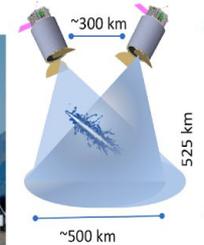


EUSO-SPB1

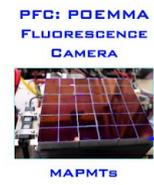
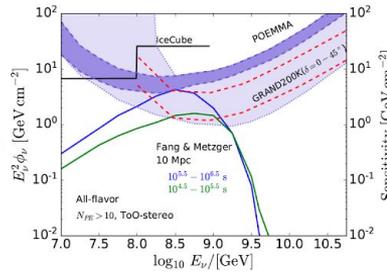
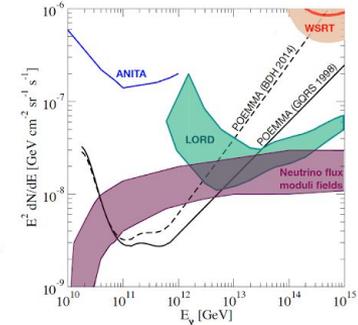
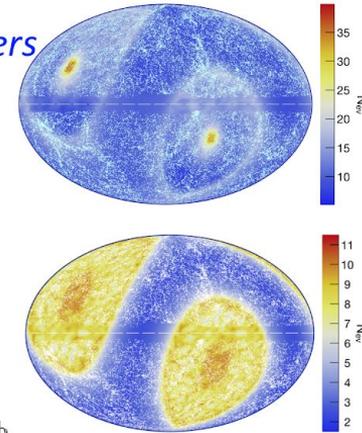
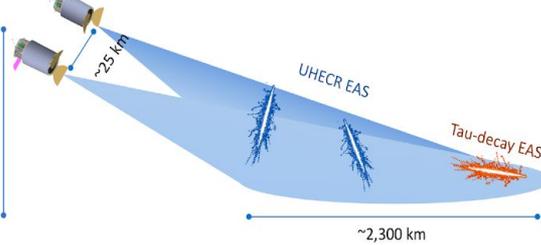
mini-EUSO



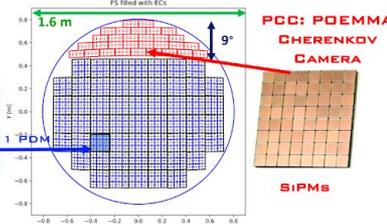
POEMMA-Stereo



POEMMA-Limb



PFC: POEMMA FLUORESCENCE CAMERA
MAPMTs



PCC: POEMMA CHERENKOV CAMERA
SiPMs

5. Air Shower Detection On the Ground

Stephanie Wissel, PSU

Upgoing tau neutrinos: $\nu_{\tau} \rightarrow \tau \rightarrow \text{decay} \rightarrow \text{inclined air showers}$

Cherenkov/fluorescence detection:

ASHRA-NTA, Auger, Trinity

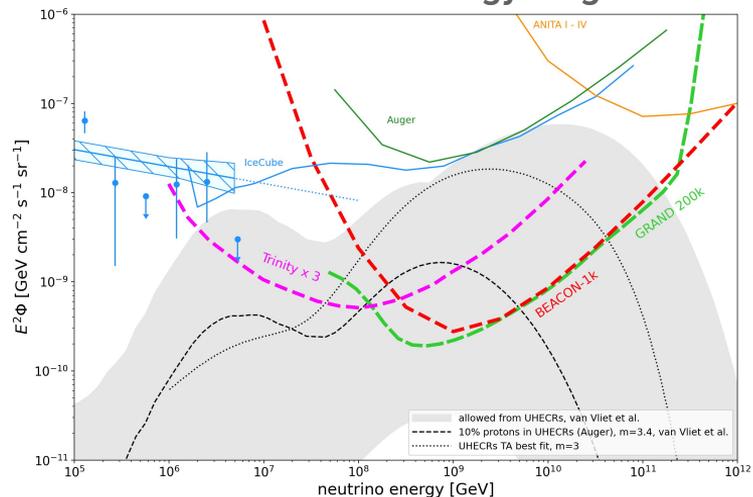
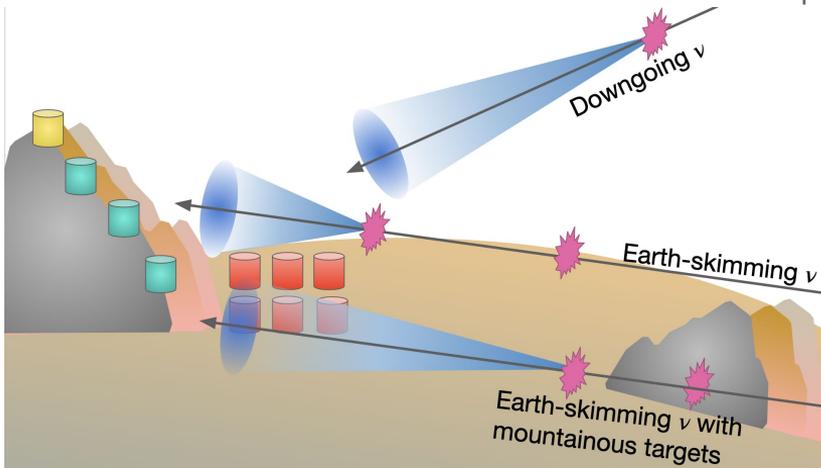
Particle counters:

TAMBO, Giant Radio Array, Auger

Radio detection:

GRAND, TAROGE, BEACON, Auger

- Common advantages include a **purely tau neutrino filter & broad sky coverage**.
- Techniques based on cosmic-ray air shower detection, matured over decades, \rightarrow Cherenkov/fluorescence/particle counter techniques longest legacy
- Radio detection is newer, but can allow detection of highly inclined showers over large sparse arrays with high duty cycle (+ heritage from several CR experiments)
- We as a community can coordinate the instruments, sites, etc. to maximize science output across a **broad tau neutrino energy range**



All flavor limits (-)

Some projected limits over 10 years (-)

Full decade bins

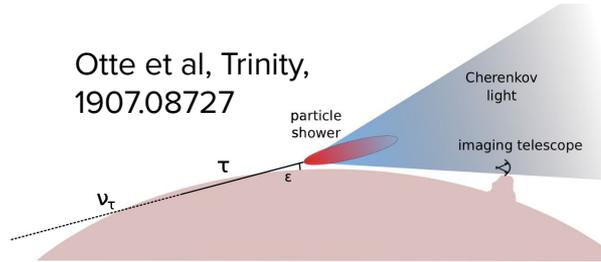
LOIs: [044](#), [088](#), [117](#), [140](#), [195](#), [202](#)

Questions

- How mature is the technique?
- What would be a unique advantage of the technique?
- How should we, as a community, plan the development of experiments for the maximum science return?
- Other questions from the audience?

Panel 2: Future Observations and Science Discoveries

1. Neutrino Physics



Tau neutrino showers play a big role in some detection methods: on surface or on balloons/satellite.

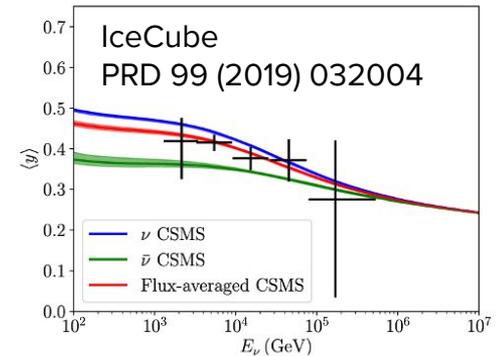
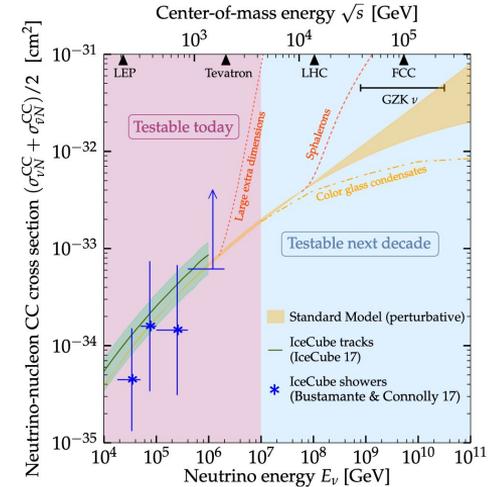
Higher energies mean trajectories that are more skimming. Angular resolution and limb effects important.

Measurements of the neutrino cross section, inelasticity distribution, flavor composition, particle/antiparticle of neutrino sources up to the highest energies.

Clear picture of the SM required to constrain/measure BSM physics, e.g., “unusual neutrinos.”

Incident neutrino flux needs to be well understood. For atmospheric neutrinos, this means understanding hadronic interactions of cosmic rays in the atmosphere: surface detectors, MC simulations.

Lol's of Klein, Seckel, Bustamante, Alvarez-Muniz and numerous detector contributions.



3. Beyond the Standard Model

Testing BSM:

- Vast BSM-testing potential due to high energies (TeV–EeV) & cosmological-scale distances
- BSM may affect energy spectrum, flavor composition, arrival directions, arrival times
- Lorentz & CPT violation, ν **self-interactions** (see *plots*), ν decay, non-standard mixing, heavy neutral leptons, sterile ν , NSI, BSM νN cross section, tests via flavor composition, exotic non- ν particles

Lols: [Álvarez-Muñiz](#), [Anchordoqui](#), [Archidiacono](#), [Blinov](#), [Bustamante](#), [Denton](#), [Hostert](#), [Jones](#), [Katori](#), [Klein](#), [Lehnert](#), [Pollmann](#), [Taboada](#)

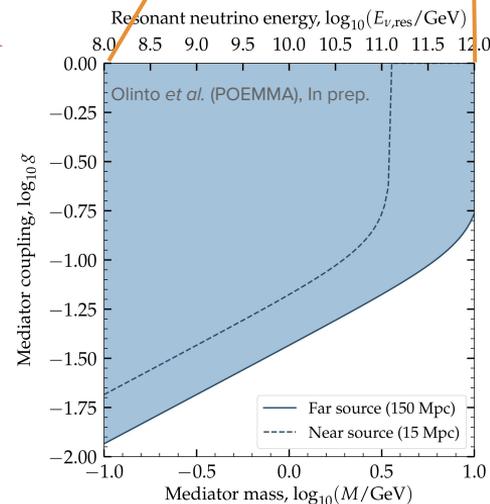
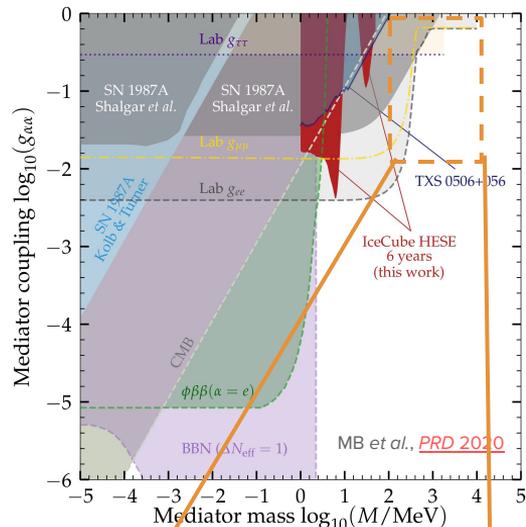
See also: Ackermann *et al.*, *Fundamental Physics with High-Energy Cosmic Neutrinos*, [1903.04333](#), white paper for the Astro2020 Decadal Survey

TeV–PeV ν (today):

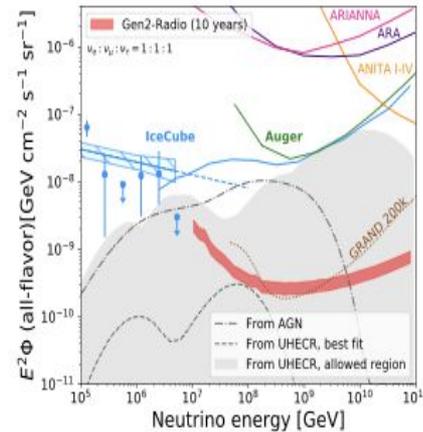
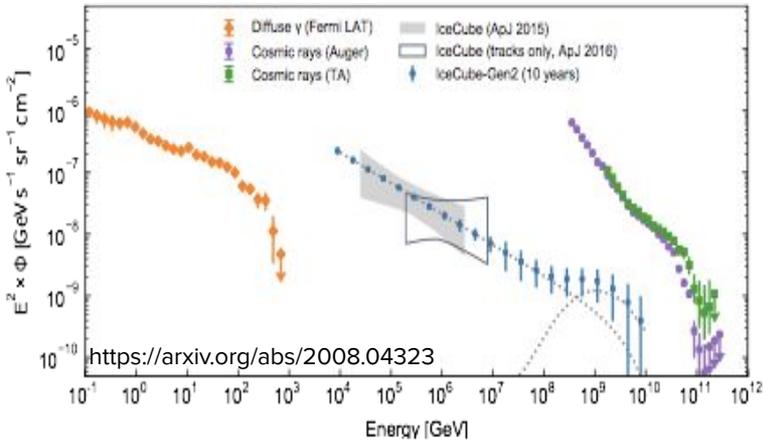
- Post-discovery, growing-statistics stage
- Already used to look for BSM
- Main avenues for progress (ongoing!):
 - Increase statistics: larger detectors (IC-Gen2) + global telescope network (PLE ν M)
 - Improve flavor measurements
 - Factor in astrophysical unknowns

EeV ν (next 10–20 years):

- Pre-discovery stage now
- Cosmogenic ν flux may be very low
- We may only have a handful of EeV neutrinos; *what BSM tests can we perform with them?*
- Need to improve BSM predictions as capabilities of next-gen detectors are fine-tuned
- Measure flavor with non-optical detectors?



4. Astrophysics

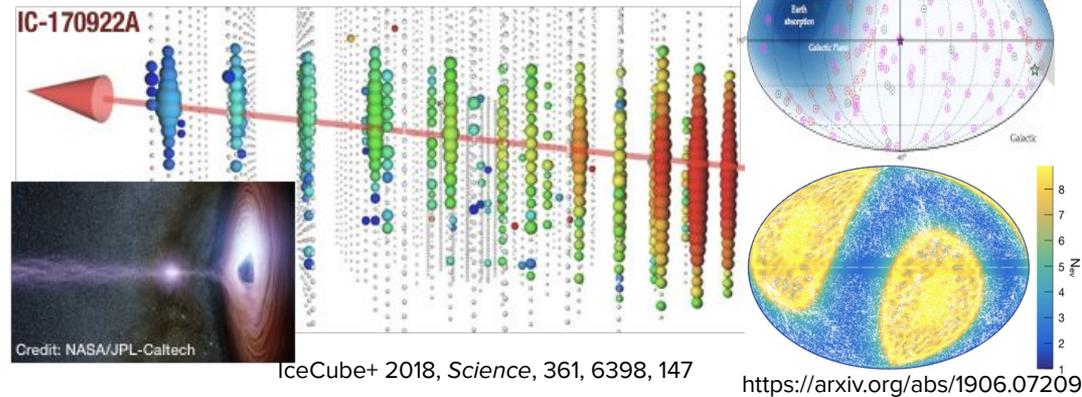


Diffuse Astrophysical ν Flux

- Measure density and evolution of ν sources/CR accelerators
- Test common origin(s) of EGB, diffuse ν , and UHECR flux
 - ➡ In-source γ and CR opacity
- Measure cosmogenic ν flux
 - ➡ UHECR spectrum, composition, source density and evolution

Individual Source Diagnostics

- Measure ν source spectra
 - ➡ CR acceleration efficiency/CR collisions
- Measure ν flavor ratios at Earth
 - ➡ Sensitive to ν production at source
- ToO follow-up observations
 - ➡ Identify hadronic processes assoc. w/ transient phenomena
 - ➡ Fidelity for low-stat. obs. (fainter sources)
- Observe evolution of neutrino fluence with time



Questions

- Is there any unique discovery in this area that can only be made by high and ultrahigh energy neutrino observations?
- What detector sensitivity and which energy band are needed to achieve the discovery?
- Do the studies require any specific observation strategies, such as all-flavor detection and large field-of-view?
- Other questions from the audience?

Discussion



Cosmic Frontier

Snowmass 2013 CF report

What would be a good strategy to describe our subject to the general physics community?

Chapter 4: Cosmic Frontier
Conveners: J. L. Feng and S. Ritz

[Working Group Summary \(arXiv:1401.6085\)](#)

Subgroup Reports:

- | | | |
|-----|--|---------------------------|
| 24. | WIMP Dark Matter Direct Detection | 1310.8327 |
| 25. | WIMP Dark Matter Indirect Detection | 1310.7040 |
| 26. | Non-WIMP Dark Matter | 1310.8642 |
| 27. | Dark Matter Complementarity | 1310.8621 |
| 28. | Dark Energy and CMB | 1309.5386 |
| 29. | Cosmic Probes of Fundamental Physics | 1310.5662 |

Contributed Papers:

General:

- | | | | |
|-----|-----------------------------------|---|---------------------------------|
| 023 | M.W. Cahill-Rowley, <i>et al.</i> | pMSSM Benchmark Models for Snowmass 2013 | 1305.2419 (PDF) |
| 040 | Pierre Auger Collaboration | The Next Frontier in UHECR Research with an Upgraded Pierre Auger Observatory | 1307.0226 (PDF) |
| 093 | L.A. Anchordoqui, <i>et al.</i> | Roadmap for Ultra-High Energy Cosmic Ray Physics and Astronomy | 1307.5312 (PDF) |

Cosmic Probes of Physics:

- | | | | |
|-----|-----------------------------|--|---------------------------------|
| 004 | S. R. Klein, <i>et al.</i> | Neutrino Absorption in the Earth, Neutrino Cross-Sections, and New Physics | 1304.4891 (PDF) |
| 007 | VERITAS Collaboration | VERITAS contributions to CF6-A: Cosmic Rays, Gamma Rays and Neutrinos | 1304.6764 (PDF) |
| 009 | F. Krennrich, <i>et al.</i> | The Extragalactic Background Light (EBL): A Probe of Fundamental Physics and a Record of Structure Formation in the Universe | 1304.8057 (PDF) |
| 010 | A. Weinstein, <i>et al.</i> | The impact of astrophysical particle acceleration on searches for beyond-the-Standard-Model physics | 1305.0082 (PDF) |
| 011 | J. Dumm, <i>et al.</i> | Gamma-ray Signatures of Ultra High Energy Cosmic Ray Line-of-sight | 1305.0253 (PDF) |
| 015 | N. Otte, <i>et al.</i> | Tests of Lorentz Invariance Violation with Gamma Rays to probe Quantum Gravity | 1305.0264 (PDF) |
| 116 | E. G. Adelberger | Torsion-balance probes of fundamental physics | 1308.3213 (PDF) |
| 117 | F. Halzen, <i>et al.</i> | IceCube: Neutrino Physics from GeV - PeV | 1308.3171 (PDF) |

Upcoming Events and Deadlines

- Topical group meetings <https://indico.fnal.gov/category/1098/>
- Community meeting at APS April Meeting 2021
- Community Summer Study July 11-20, 2021
- Contributed papers, due July 31, 2021
<https://snowmass21.org/submissions/start>