Ultra-high energy (UHE) neutrinos and recent results from the Askaryan Radio Array (ARA) experiment

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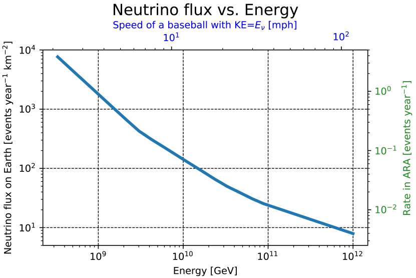
Graduate Student Seminar, 2020

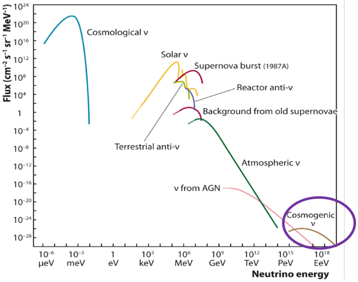
What are UHE-νs

- UHE neutrinos ($E > 10^{17}$eV): cosmogenic (GZK) + astrophysical (from sources).
- GZK-mechanism: Interactions of UHE cosmic rays (UHECRs) and CMB-γ/EBL-γ.
- Flux is $\sim 10^{40}$ times smaller than that of solar neutrinos.
- Need huge experiments: Radio-based in-ice experiments target UHE-νs.

$$p + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow \boxed{n} + \boxed{\pi^{+}}$$
$$\boxed{\pi^{+}} \rightarrow \nu_{\mu} + \boxed{\mu^{+}}$$
$$\boxed{\mu^{+}} \rightarrow e^{+} + \nu_e + \bar{\nu}_{\mu}$$
$$\boxed{n} \rightarrow p + e^{-} + \bar{\nu}_e$$

Each carries ~4% of the proton energy





Katz *et al.*, 2011

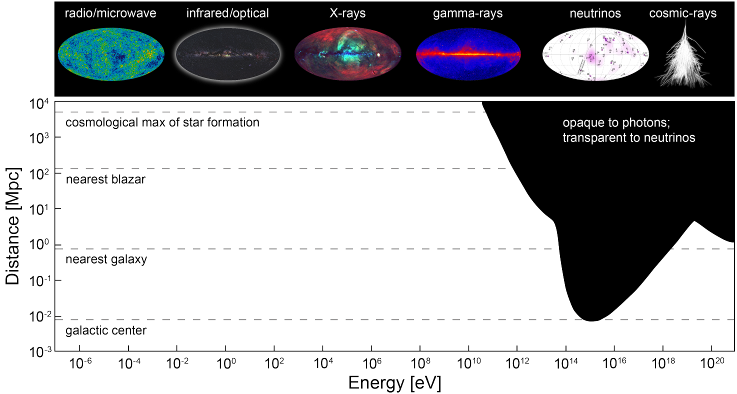
Why to study them?

- Neutrinos are cool
- Neutrino Astronomy.
- Probes of fundamental physics, e.g. ν-nucleon cross section ($\sigma_{\nu-N}$)

Neutrino Astronomy

Neutrino Astronomy

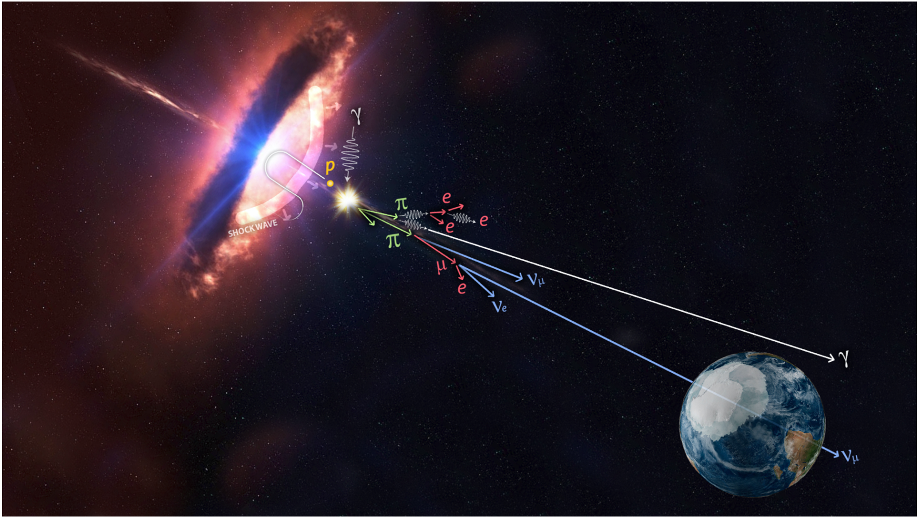
- Exploration of extragalactic high-energy universe ($>$TeV) challenging:
  - Gamma rays highly attenuated by diffuse light sources
  - Cosmic rays (CRs) deflected by magnetic fields and confined to ~ 50 Mpc[1] due to GZK-interactions.



Credits: The IceCube Collaboration

[1] 1 pc≈3.26 ly

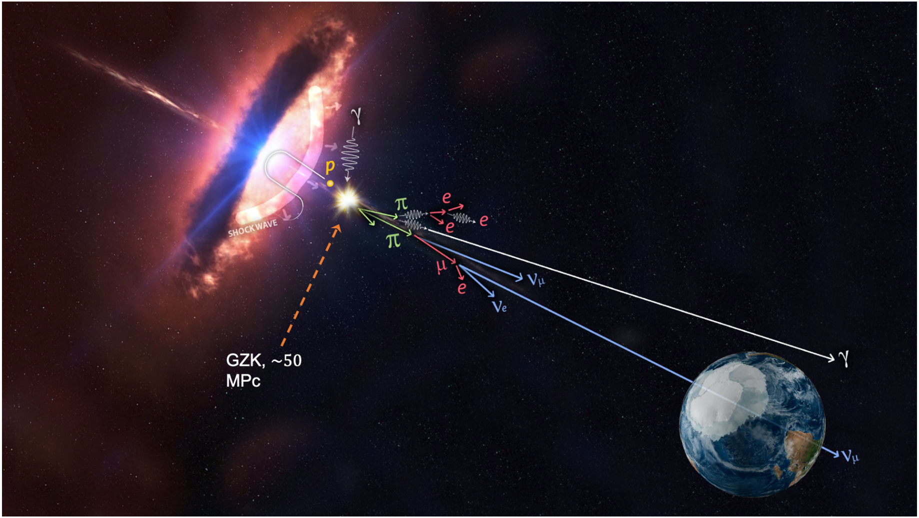
UHE neutrinos



Credits: The IceCube Collaboration

- Mean free path ($\lambda = \frac{1}{n_{\text{CMB}}\sigma_{p\gamma}}$) for cosmic rays is ~50 Mpc

UHE neutrinos



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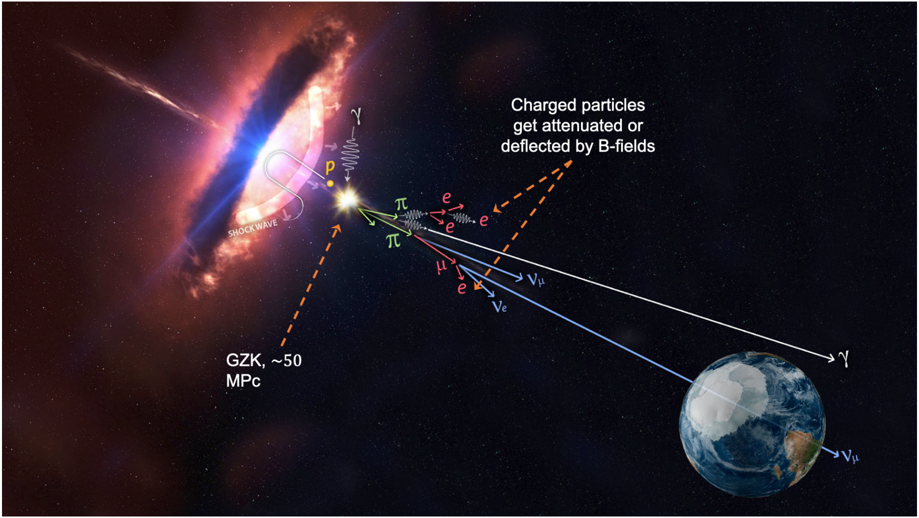

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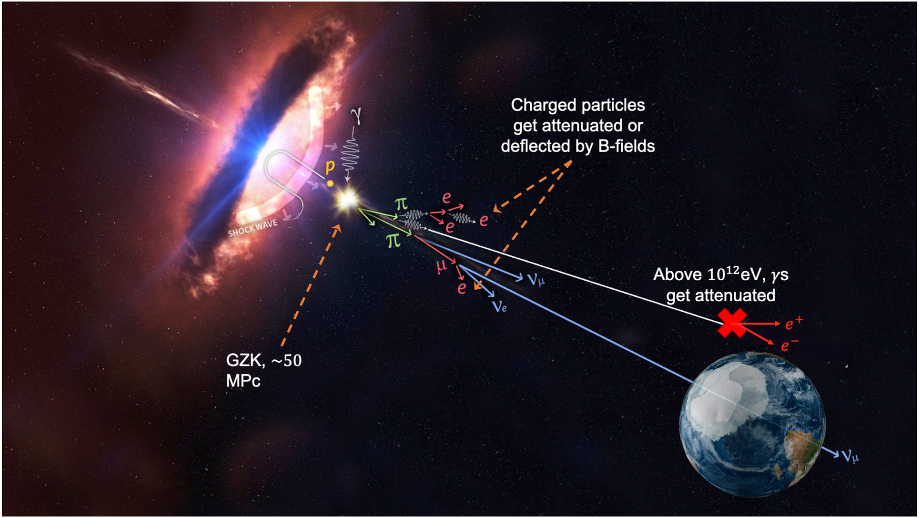
UHE neutrinos



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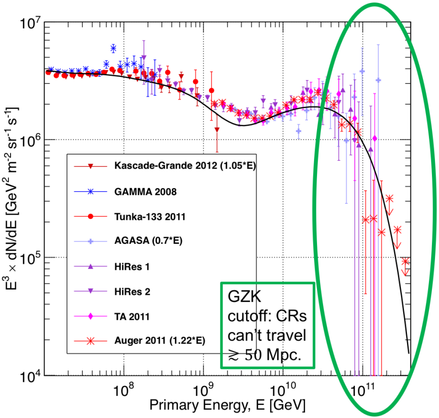
Neutrino Astronomy

- Neutrinos as cosmic messengers: undeflected and almost non-interacting.
- Point back to the source: identification of UHECRs sources.
- Will help with elucidating origin and composition of UHECRs

UHE-Cosmic Rays

- Main ingredient for the GZK-mechanism.
- What we don't know about them:
  - Origin? SNR, AGN, GRB?
  - Composition? Protons, heavy nuclei?
  - Acceleration and emission?
- Constrained to a ~50 Mpc radius.
- Deflected by magnetic fields.
- See talk by Keith McBride in a few weeks.



Gaisser, Stanev, Tilav, 2013.

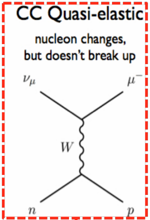
How do UHECRs shape the ν-flux?

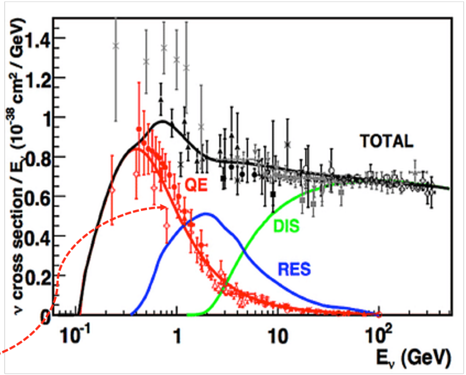
1. Mass composition
   - ◇ photo-hadronic ($p\gamma$) interactions significantly suppressed for heavy-nuclei, also different energy loss mechanisms. Heavier CRs make less ν.
2. Evolution of CR sources
   - ◇ At higher redshifts, $\bar{E}_{\text{CMB}}$ is higher. More sources at high redshift result in more GZK ν.
3. Source's maximum CR energy
   - ◇ More UHECRs produced by the source→ more GZK neutrinos.
4. Other factors.

Thus, measure UHE-ν flux to rule out scenarios...or to find the right one!

Neutrino-Nucleon Cross Section at UHE

Neutrino Cross Section: Current Status





Formaggio and Zeller, 2012.

$\lambda \propto \frac{1}{p_\nu}$: ν probes smaller distances as E increases

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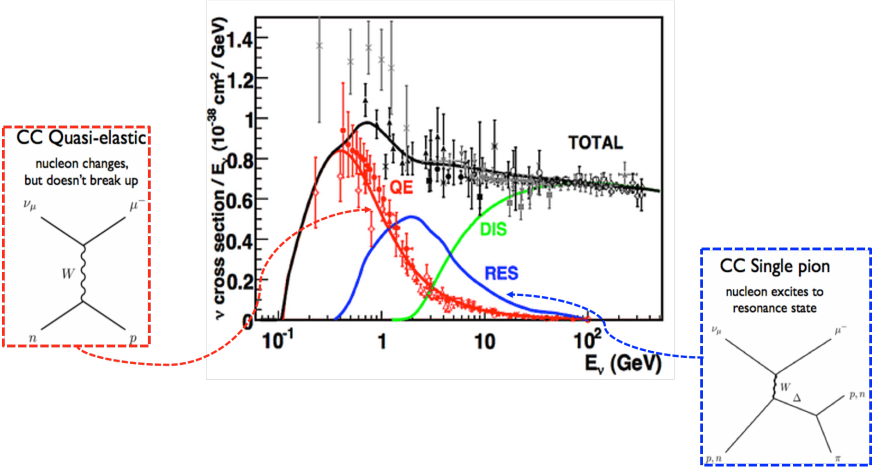

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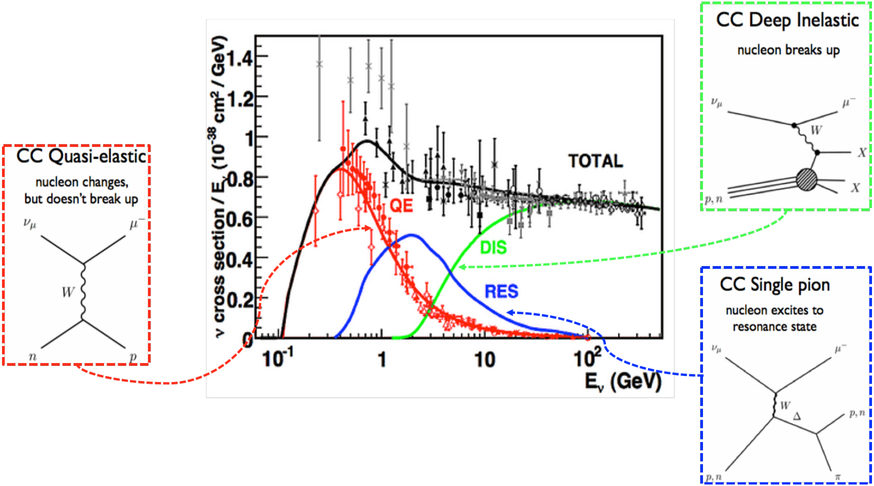

Formaggio and Zeller, 2012.

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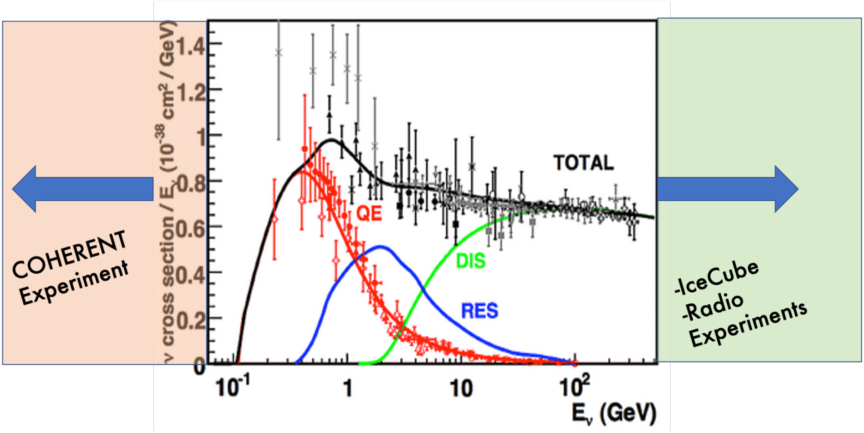


Formaggio and Zeller, 2012.

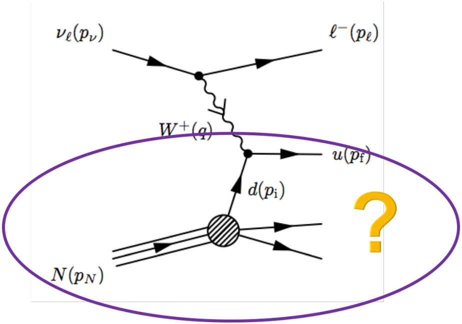
- $E <$ 1 MeV: Not observed.
- 1 MeV-350GeV: Observed. Lots of data.
- $E >$ 350 GeV: Observed up to few PeV.

Neutrino-Nucleon Cross Section ($\sigma_{\nu N}^{CC}$) at UHE

- Small cross section, e.g. @ $\sqrt{s} = 1$ GeV
  - $\sigma_{pp} \sim 10^{-28}$ cm^2
  - $\sigma_{\gamma p} \sim 10^{-29}$ cm^2
  - $\sigma_{\nu p} \sim 10^{-38}$ cm^2
- At very high energies,

$$\sqrt{s} \approx \sqrt{2E_\nu m_p} \approx 45\,\text{TeV}$$

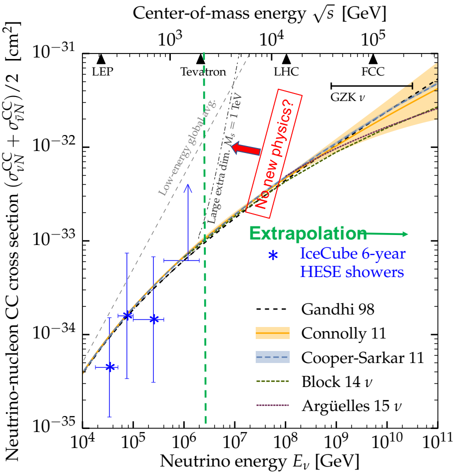
  for $\nu - p$ interaction and $E_\nu = 10^{18}$ eV.
- Higher than the LHC, but...N_{events}?
- Goals:
  - New physics?
  - Test DIS and unprobed nucleon structure ($\lambda \propto \frac{1}{p}$).



Deep Inelastic Scattering (DIS). Giunti and Kim, Fundamentals of Neutrino Physics and Astrophysics.

Measuring $\sigma_{\nu N}^{CC}$ at UHE (multi-TeV)

- $\sigma_{\nu N}^{CC}$ increases with increasing E_ν.
- Neutrinos with $E_\nu > 40$ TeV expected to be absorbed as they pass through Earth.
- $\sigma_{\nu N}^{CC}$ determined by observing the change in angular distribution of Earth-transiting neutrinos with increasing neutrino energy.



Bustamante and Connolly, 2017

Mid-talk summary

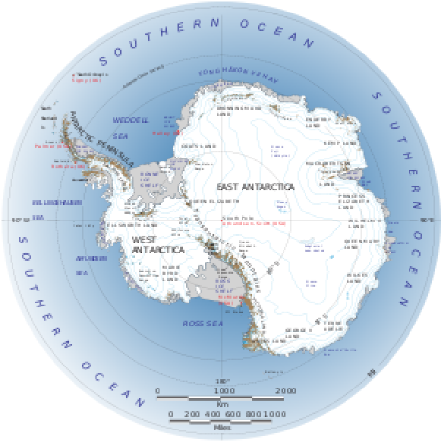
1. UHE-neutrinos have energies above 10^{17} eV.
2. Flux very small: expect $\mathcal{O}(0.1\,\mathrm{y}^{-1}\,\mathrm{km}^{-2})$
3. We don't know where these neutrinos come from.
4. UHE-neutrinos are important for astrophysics and particle physics:
   - Neutrino astronomy, origin of UHECRs.
   - $\nu - N$ cross sections at high energies, others.

The physics behind radio detection of UHE-ν

Radio Detection of UHE-ν

Where?

Antarctica...as of now.



Radio Detection of UHE-ν

Why?

- Great detection effective volume. Need > 100 km^3 to detect few (~ 1) neutrinos per year!
- Ice is transparent to radio (~ 100 MHz) waves: $\lambda_{\text{att,radio}} \approx 1000$ m, $\lambda_{\text{att,visible light}} \leq 100$ m[a]
- Radio quiet environment in Antarctica.

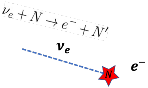
[a] λ_{att} is the distance at which the intensity of the wave dropped by 63%

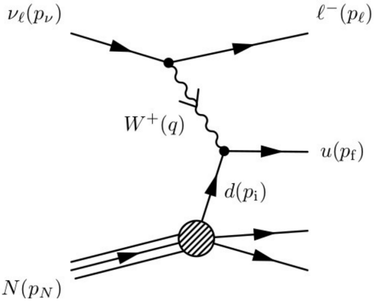
Radio Detection of UHE-ν (particle-level)

How?

Using antennas to detect Askaryan radiation

- ν – N CC interaction



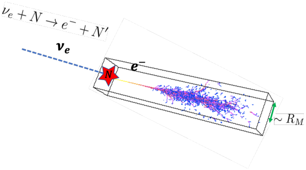


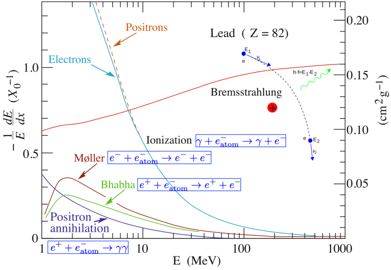
Radio Detection of UHE-ν (particle-level)

How?

Using antennas to detect Askaryan radiation

- $\nu - N$ CC interaction → EM shower in ice $(\gamma + e^+/e^-)$



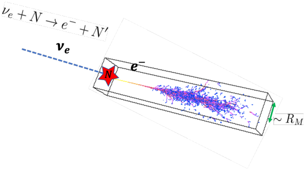


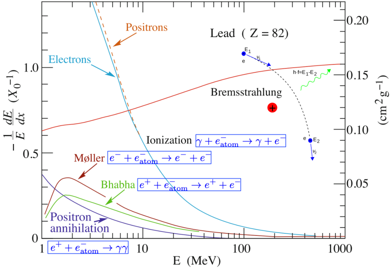
Radio Detection of UHE-ν (particle-level)

How?

Using antennas to detect Askaryan radiation

- $\nu - N$ CC interaction → EM shower in ice ($\gamma + e^+/e^-$) → negative charge asymmetry



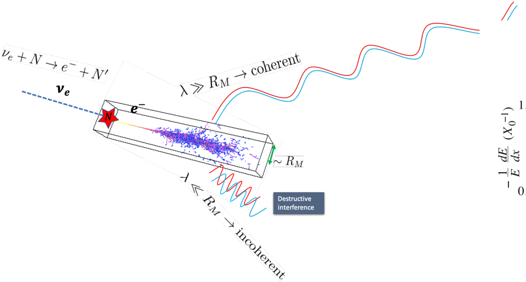


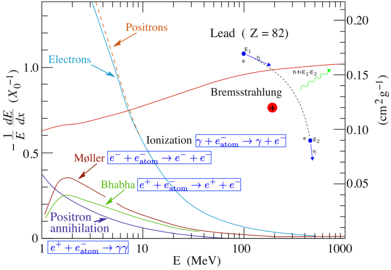
Radio Detection of UHE-ν (particle-level)

How?

Using antennas to detect Askaryan radiation

- $\nu - N$ CC interaction → EM shower in ice ($\gamma + e^+/e^-$) → negative charge asymmetry → charge moving faster than light = radiation!





Radio Detection of UHE-ν (observer-level)

How?

Using antennas to detect radio-Cherenkov radiation (a.k.a. Askaryan radiation): broadband pulse

- In ice: coherent radiation → radiation power (measurable) $\propto$ (energy of shower)$^2 \propto E_\nu^2$
- Measure E-field of signal with an antenna. Interferometry to locate source.

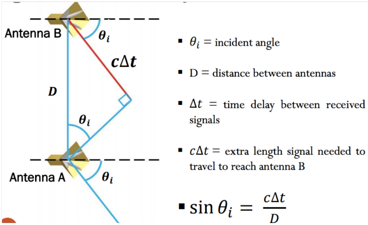


Image by O. Banerjee

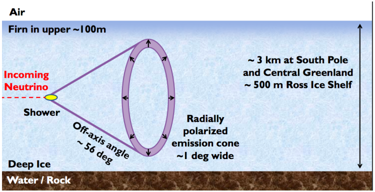


Image by Keith Bechtol

Radio-Experiments: General Specifications

1. Observe great volume.
   - Due to the small flux and small cross section.
   - Cover as much sky as possible
2. Small influence from external factors.
   - Low temperatures shouldn't affect behavior
3. Sensitive to highly linearly-polarized RF pulses (Askaryan).
   - Askaryan radiation: 1 ns wide pulse, broadband
4. Sensitive to distant and close sources.
5. Ability to constraint neutrino direction with sub-degree accuracy.
6. Cheap.

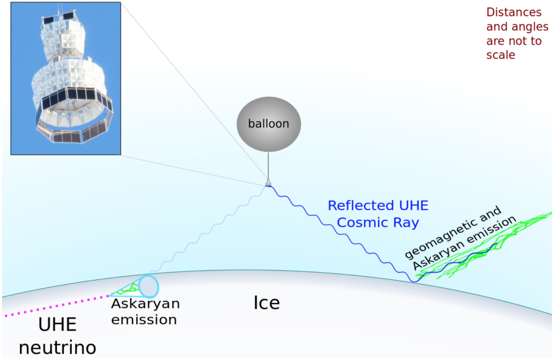
Radio Detection of UHE-ν

Who?

- ANITA (Antarctic Impulsive Transient Antenna)
- ARIANNA (Antarctic Ross Ice-Shelf Antenna Neutrino Array)
- ARA (Askaryan Radio Array)

ANITA

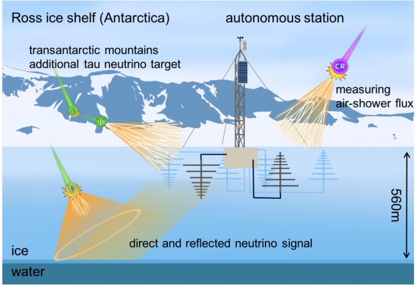
- Balloon-borne experiment. Carries 64 antennas.
- Flies at ~ 30 km over Antarctica, for about 30 days.
- 4 campaigns so far. Last one in 2016.
- Energy range [eV]: $10^{18} - 10^{21}$.
- Best constraints on the end of the neutrino spectrum.



Credits: The ANITA collaboration

ARIANNA

- Detection of down-going neutrinos via reflections off ice-water interface.
- Stations comprised of 4 in-ice antennas (few meters deep).
- ~1000 planned surface stations over 30 km x 30 km.
- 3 stations currently taking data.
- Energy range [eV]: $10^{17} – 10^{19}$.

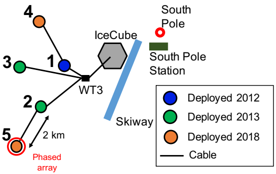


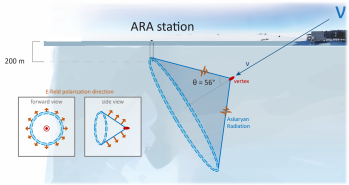
Credits: The ARIANNA collaboration

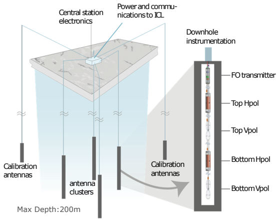
Latest results from the ARA experiment (based on arXiv:1912.00987)

The Askaryan Radio Array (ARA)

- Located in Antarctica, it is designed to detect radio impulses from UHE neutrino-ice interactions.
- 16 antennas per station deployed at 200 m depth under the ice.
  - 8 Vpol
  - 8 Hpol
- Five stations and a phased array deployed so far.







The ARA collaboration

Figure credit: C. Pfendner

USA

Cal Poly	University of Delaware
Denison University	University of Kansas
Michigan State University	University of Maryland
Penn State University	University of Nebraska
The Ohio State University	University of Wisconsin-Madison
University of Chicago	Whittier College

International Collaborators

Chiba University

Moscow Engineering Physics Institute

National Taiwan University

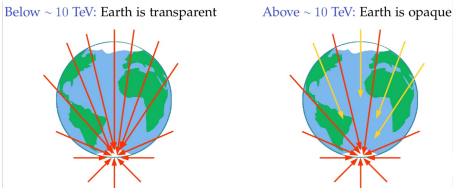
University College London

Vrije Universiteit Brussel

Weizmann Institute of Science

Neutrino diffuse search

- Looking for GZK neutrinos everywhere ARA can see.
- Due to neutrino absorption + detector sensitivity, ARA doesn't completely see the whole sky.



Credits: M. Bustamante

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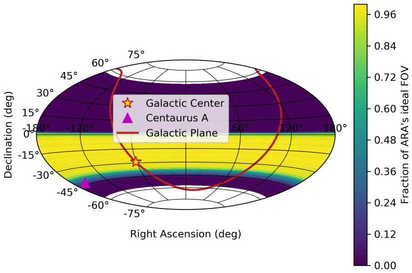
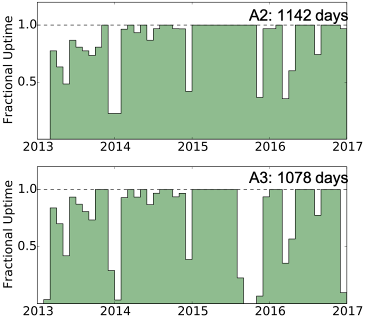


ARA field-of-view

Neutrino diffuse search (cont.)

- Two complementary data analyses performed for four years of data for two stations: A2 and A3.
- These two stations have collected data since Feb 2013. Previous analysis published for 10 months[1].
- Analysis workflow:
  1. Data is divided into two sets:
     - ★ 10% set: used to tune cuts
     - ★ 90% set: used to set limit
  2. Data is cleaned:
     - ★ glitches (0.001%)
     - ★ calibration runs (< 2%)
  3. Perform analysis in 10% set and then in 90% set
  4. Set neutrino flux limit.



[1] P. Allison *et. al.* PRD 93, 082003 (2016)

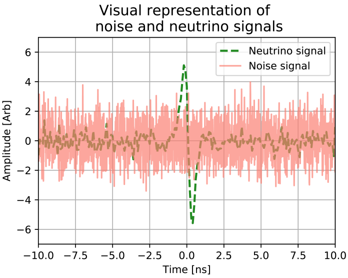
Data analysis: reducing the dataset

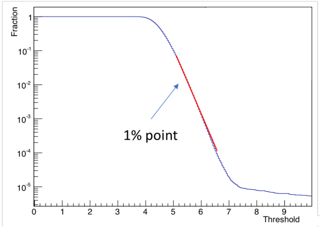
- ARA records at ~ 5 Hz (10^8 events/year), and $> 99.9999\%$ of data is thermal noise.
- In order to quickly/cheaply reject noise events, an SNR filter is applied first. An event passes the filter if in at least three channels

$$SNR \equiv \frac{V_{peak}}{\sigma_{noise}} \geq N_{thresh},$$

where V_{peak} is the peak voltage and σ_{noise} is the noise rms.

- N_{thresh} is chosen such that 1% of thermal noise passes the filter.

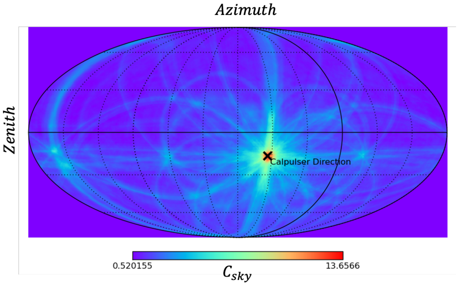




Noise passing rate as a function of N_{thresh} Figure by Ming-Yuan Lu (UW)

Data analysis: reconstruction cut

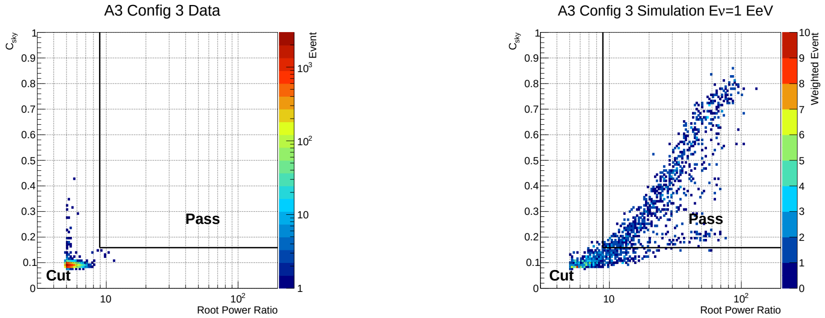
- Due to its computationally expensive nature, we perform interferometric reconstructions only on events that pass the filter.
- This technique relies on the signal arrival times among antennas, and assigns a correlation value (C_{sky}) to each direction.
- Highest C_{sky} position is assumed to be the source.
- This allows us to remove:
  - Events above surface
  - Events reconstructing to known anthropogenic noise sources (SP, and others)
  - Events in the direction of the calibration pulser.



A correlation map for a calibration pulser event is shown. The × shows the true pulser position. Figure by Ming-Yuan Lu (UW)

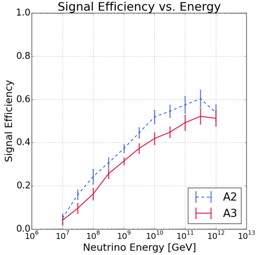
Data analysis: the final cut

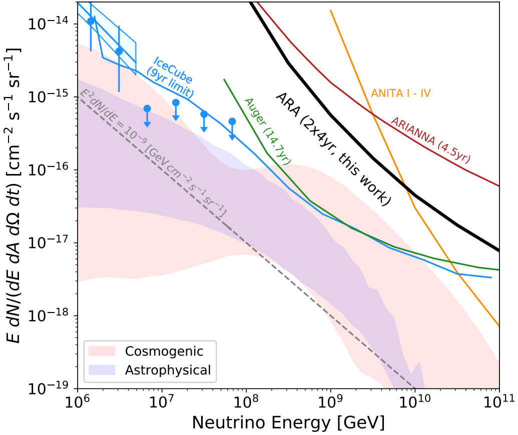
- Neutrinos are expected to have higher signal strength than noise and to reconstruct well.
- We use a cut in the peak cross-correlation (C_{sky}) vs signal strength plane to separate noise from potential neutrino signals.
- The cut is set such that $\lesssim 0.01$ background events pass all the cuts, a result of optimizing for the best limit.



Results

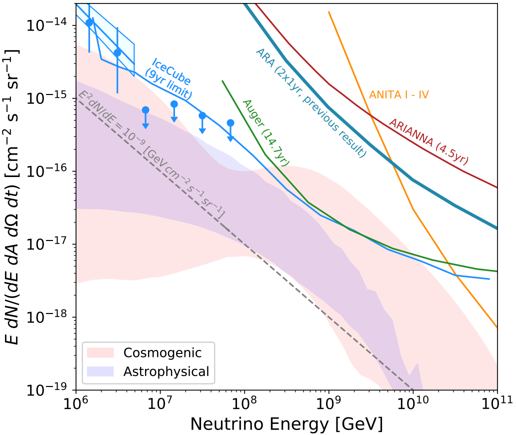
- No statistically significant excess of events is observed.
- In the absence of events we estimate the 90% confidence level (CL) upper limit on the diffuse flux of UHE neutrinos.





Summary and outlook for ARA

- Analysis performed for two stations for four years of data. Improvement of a factor of ~ 3 in the limit compared to previous result.



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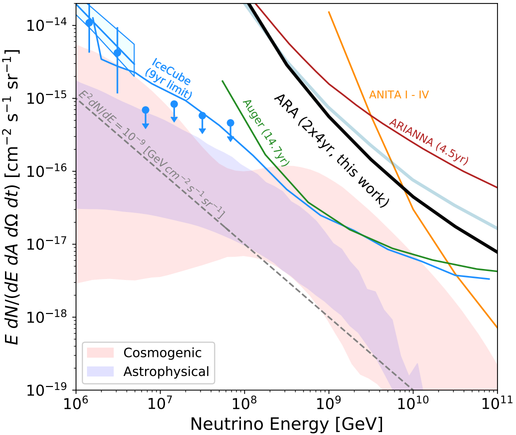

Summary and outlook for ARA

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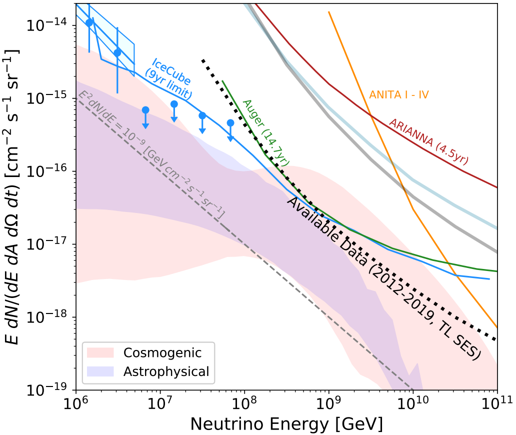
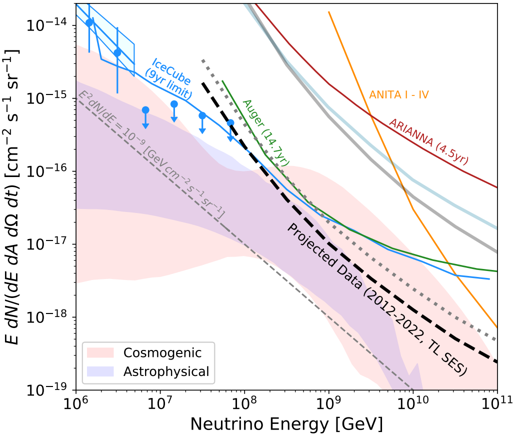
- ARA has the **strongest limit** on the UHE neutrino flux among all in-ice radio experiments above 10^8 GeV.
- Analysis of accumulated and projected data (5 station, trigger level) shows ARA could be a **world-leading** neutrino detector above 10^8 GeV by 2022.



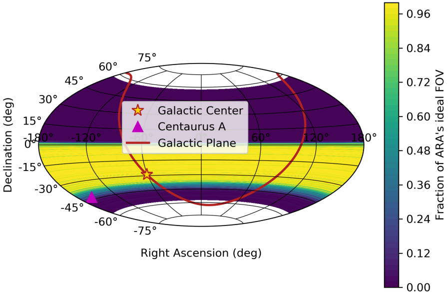
Summary and outlook for ARA

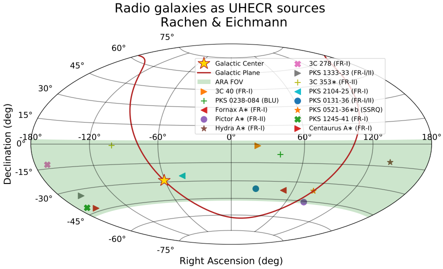
- Analysis performed for two stations for four years of data. Improvement of a factor of ~ 3 in the limit compared to previous result.
- ARA has the **strongest limit** on the UHE neutrino flux among all in-ice radio experiments above 10^8 GeV.
- Analysis of accumulated and projected data (5 station, trigger level) shows ARA could be a **world-leading** neutrino detector above 10^8 GeV by 2022.



In the near future: source searches with ARA

- ARA monitors about 30% of the southern sky.
- Centaurus A (Cen A) falls in ARA's field of view (FOV):
  - UHE neutrino emission is expected [e.g. Cuoco+ , Kachelriess+]
  - Auger sees a spatial correlation with a handful of UHECRs [Auger 2007, Science Vol. 318, Issue 5852]
  - Bright in gamma rays [HESS 2009, ApJ 695:L40–L44]
- Work in progress to see how well ARA can test Cen A neutrino emission models.
- Can easily be extended to other sources.





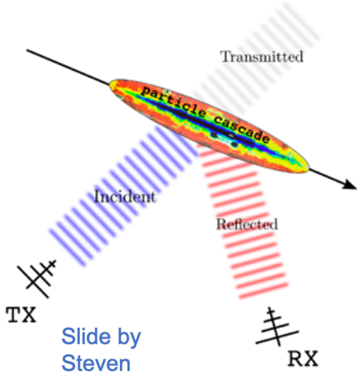
Quo vadis? The future of radio detection

Current experiments

- Several radio experiments have accumulated a significant amount of data, with discovery potential (recall $\sim 1\ \nu$ every 10 years):
  - ARA has been running for almost 9 years.
  - ARIANNA has been running for almost 10 years.
  - ANITA has had four campaigns.
- Data are there, but need to be analyzed
- Additionally, lessons have been learned, and developments have been made.

New techniques: RADAR

- Project lead by S. Prohira (CCAPP fellow)



- A transmitter (TX) illuminates a volume with radio (Incident)
- if a particle cascade occurs within the illuminated volume, this incident signal will be reflected to a remote receiver (RX), monitoring the same volume
- can instrument a large (10's-100's km³) volume with minimal apparatus

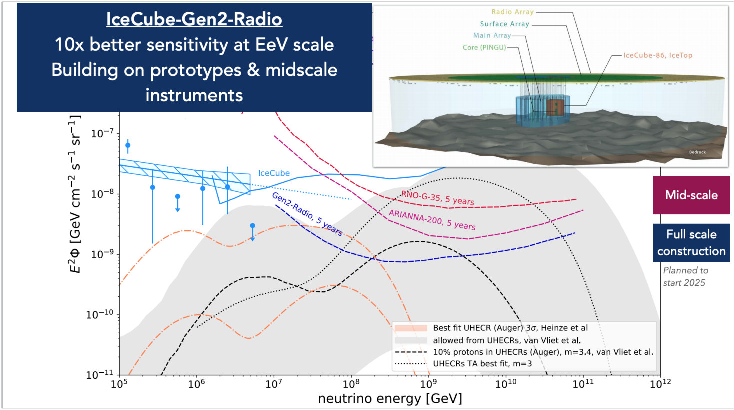
Slide by Steven Prohira

Observation of Radar Echoes from High-Energy Particle Cascades

S. Prohira, K. D. de Vries, P. Allison, J. Beatty, D. Besson, A. Connolly, N. van Eijndhoven, C. Hast, C.-Y. Kuo, U. A. Latif, T. Meures, J. Nam, A. Nozdrina, J. P. Ralston, Z. Riesen, C. Sbrocco, J. Torres, and S. Wissel
Phys. Rev. Lett. **124**, 091101 – Published 6 March 2020

Next generation of experiments: (RNO-G, ARIANNA-200)→ IceCube-Gen2

- Synergy between current experiments and newly developed techniques



Slide by S. Wissel (Nu 2020)

Summary

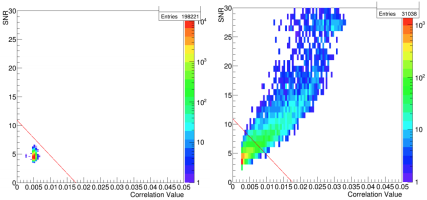
It is an exciting time in the search for UHE neutrinos!

Backup Slides

Explanation of background estimation and slanted cut

- For the final cut, an event will pass if

$$SNR \geq C_{sky} \times m + d \tag{1}$$



(a) A2 config 1 data. (b) A2 config 1 simulated Kotera neutrinos

Fig. by B. Clark

- We optimize the cut to set strongest possible upper limit on ν-flux, since we don't expect to see any events.

Explanation of background estimation and slanted cut (cont.)

1. Generate data driven model of background: fit exponential of the form $e^{\beta_1 \times SNR + \beta_2}$ to tail of differential distribution.

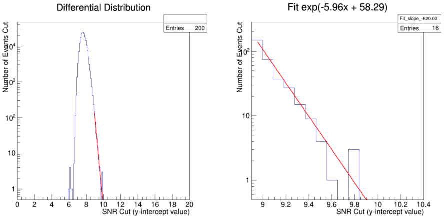


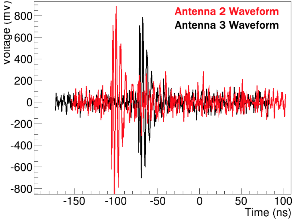
Fig. by B. Clark

2. A value d for the y-intercept and slope m are chosen such that they give the best flux limit.
3. For a select value of y-intercept d, the number of bkg events b that will pass the cuts is:

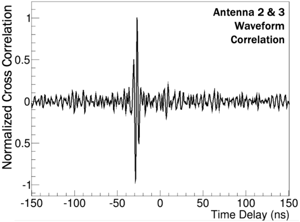
$$b = \int_{d}^{\infty} e^{\beta_1 \times x + \beta_2} dx \tag{2}$$

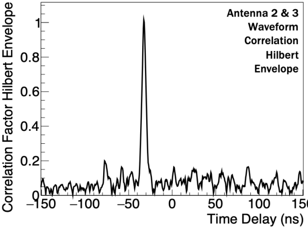
Details on interferometric reconstruction

- Interferometry based reconstruction:
  - Putative source angle ⟶ Time Delay between antennas ⟶ Correlation Value
  - Take Hilbert envelope to interpret as power



2. P. Allison *et. al.* j.astropartphys.2015.04.006
3. P. Allison *et. al.* j.astropartphys.2016.12.003

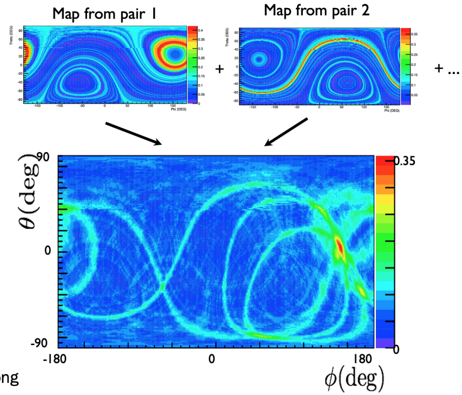




Slide by B. Clark

Details on interferometric reconstruction (cont.)

- For pair of antennas, compute time delays and correlation values for all points on the sky
  - Propose a source distance, θ, and ϕ
  - Trace ray from source to array center
- Sum up correlation value for many pairs of antennas
- **Interpret peak in map as source direction**

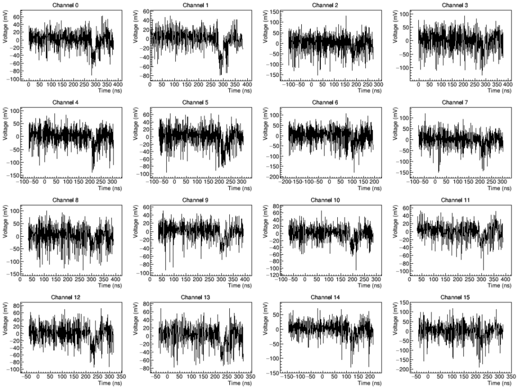


1. P. Allison *et. al.* j.astropartphys.2015.04.006
2. P. Allison *et. al.* j.astropartphys.2016.12.003

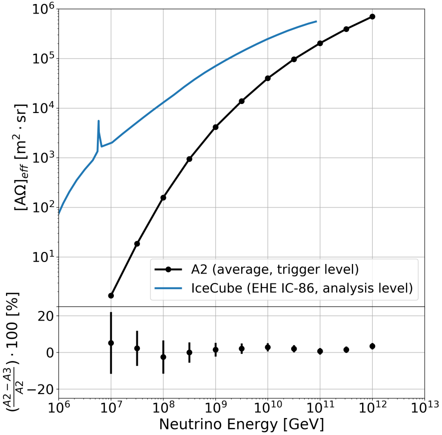
maps by E. Hong

Slide by B. Clark

Glitches and digitizer errors



Effective volume



ARA field of view