Radio Detection of Astroparticles at the South Pole

Alan Coleman
for the IceCube Collaboration

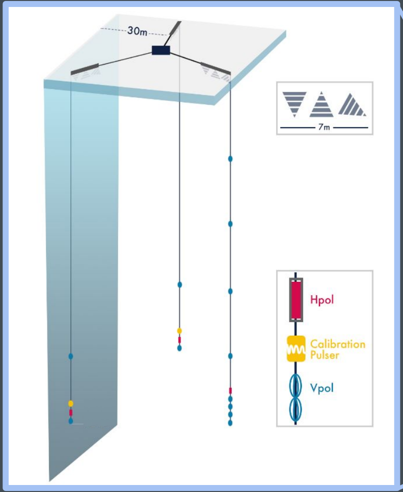
GCOS Workshop
2021.05.20

UNIVERSITY OF DELAWARE
BARTOL RESEARCH INSTITUTE

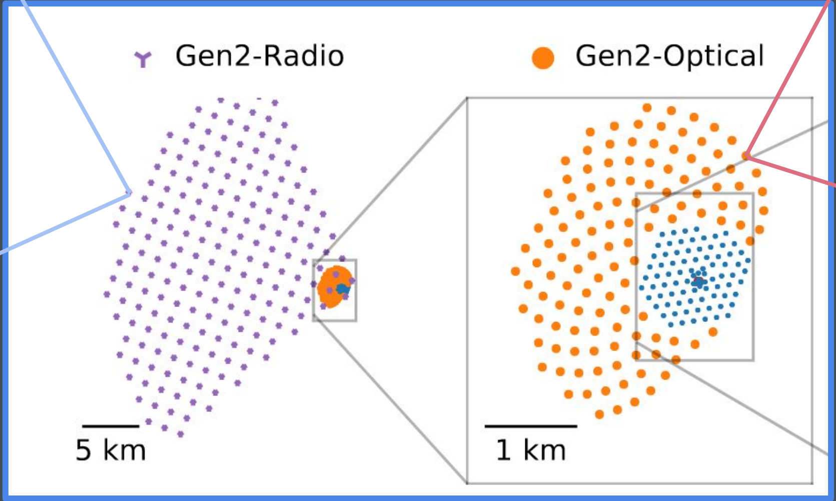
Radio Extensions in Gen2

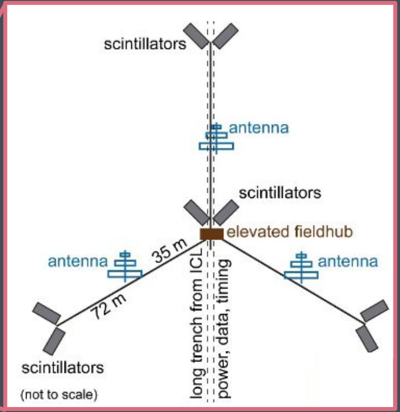
Radio array stations of deep+shallow antennas for cosmogenic neutrino searches and UHECRs

Surface stations with surface antennas for dedicated cosmic ray science studies.



The two efforts are being developed independently up to now





*Not finalized layouts

Cosmic Ray Science by the Surface Array

A surface array is already included as part of an ongoing* addition to the existing IceTop footprint.

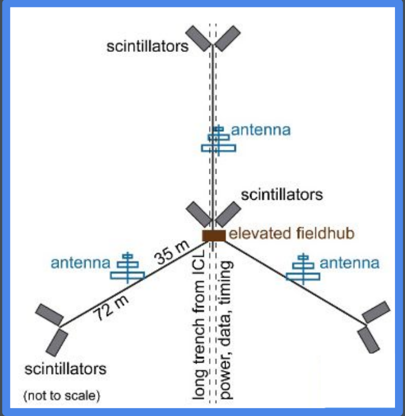
Stations, triggered by 8 scintillator panels, include three SKALAv2 antennas. Both mounted on stilts due to snow build-up concerns.

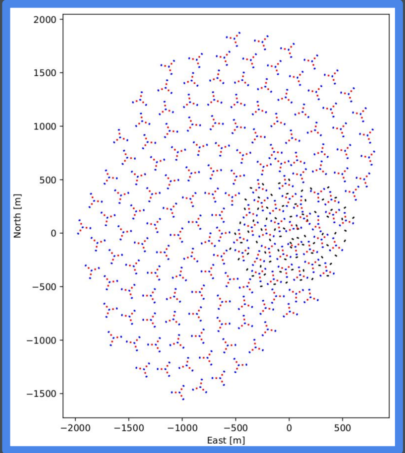
The main CR science goal is to improve measurement accuracy via the separate detection of airshower components muons (IT), low-E muons/EM (scints), EM/X_{max} (radio), and high-E muons (in-ice).

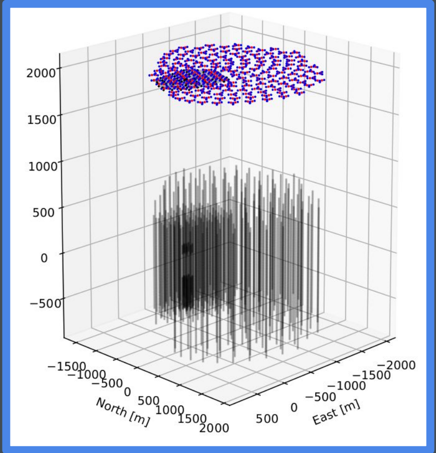
Surface radio targeting energies of the expected (extra-)galactic transition at 100 PeV - EeV

They will also be included in Gen2 with the baseline design. One station above each optical string.

*with COVID-related delays last- and this-year







Neutrino Science for In-Ice Radio

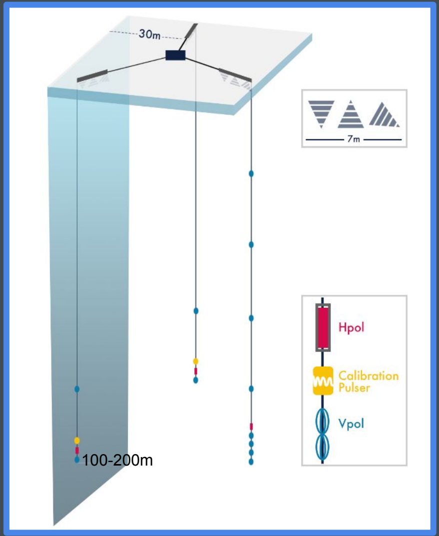
Radio array stations consist of 3 strings. Multiple horizontally and vertically polarized antennas and calibration pulsers

Fit into 20 cm bore holes at a depth of 100 - 200 m to be below the firn, the portion of the snow near the surface where the snow is less compact/ideal

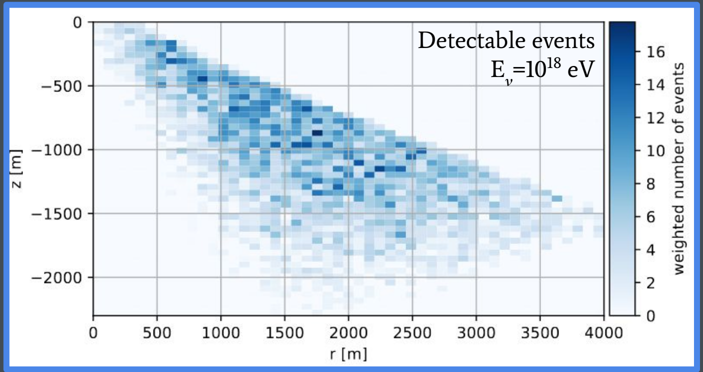
Stations spread out by 1-2 km and are sensitive out to a few km, depending on the neutrino energy.
Would require 200 stations to cover the ~500 km^2 for full design sensitivity

Uses a phased-array trigger to identify events, a design that will be tested at RNO-G

Three, single-pol shallow antennas (a few meters below surface) to help distinguish neutrino-induced cascades from CR-muons undergoing catastrophic losses. Can also perform CR science, exposure ~Telescope Array



One possible station design. The exact dimensions of the stations are still being optimized for V_{eff} and reconstruction accuracy.



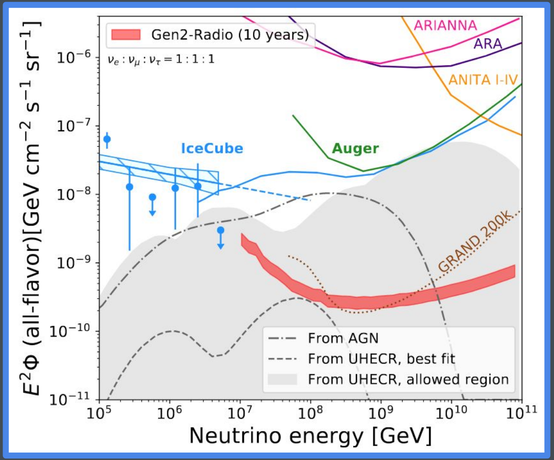
Cosmogenic Flux

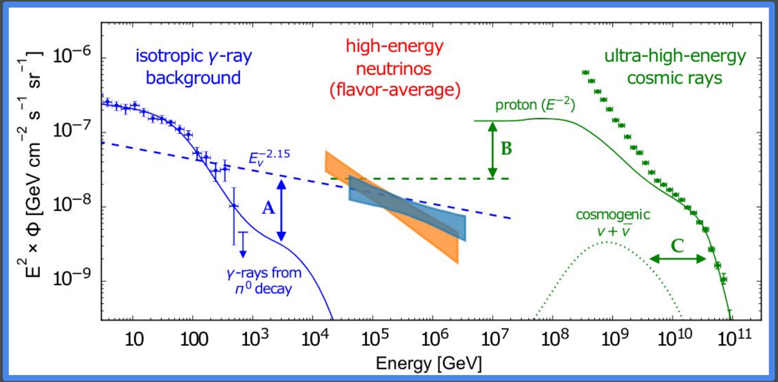
The large effective volume covered by the in-ice radio array targets the highest energy neutrinos

The baseline design of the experiment is sensitive to neutrinos with $E_\nu \gtrsim 10$ PeV.

Will be the main Gen2 component for mapping out the cosmogenic (GZK) ν flux in the energy range of 100 PeV - 10 EeV, a byproduct of the GCOS-targeted CRs interacting with cosmic microwave background.

Observation of, or lack thereof, would have implications on the CR-mass distribution, cosmic evolution, acceleration models, propagation, etc.





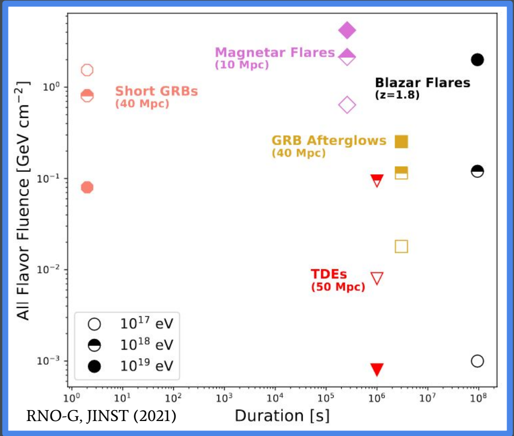
Multi-Messenger Detections

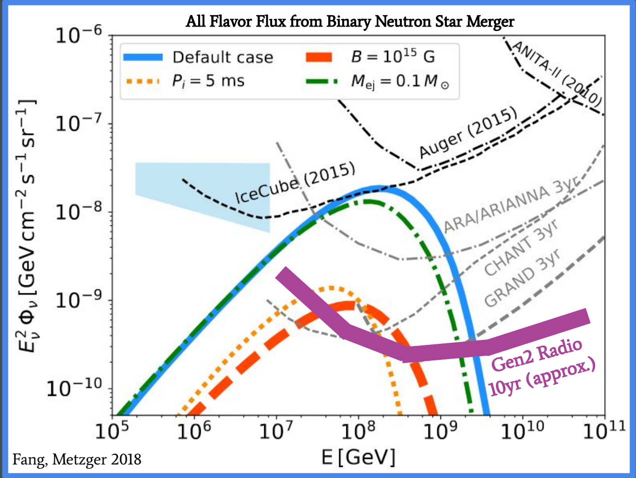
For the highest energy neutrinos, the sources are likely to be beyond the GZK horizon for CRs and are not a likely candidate for multi-messenger studies with GCOS. (See M. Ahlers' talk)

The radio array is more suited for multi-messenger studies of transients such as tidal disruption events, binary neutron star mergers, blazar flaring events, etc. (see talks from Monday)

Based on results from ARIANNA, expected angular resolutions are ≂2° x 10° patches of the sky. Will depend on final antenna design and layout.

Reconstruction techniques and methods to improve them are being explored and will be directly tested by the Radio Neutrino Observatory in Greenland (RNO-G) radio array. Currently being deployed, high overlap in person-power.





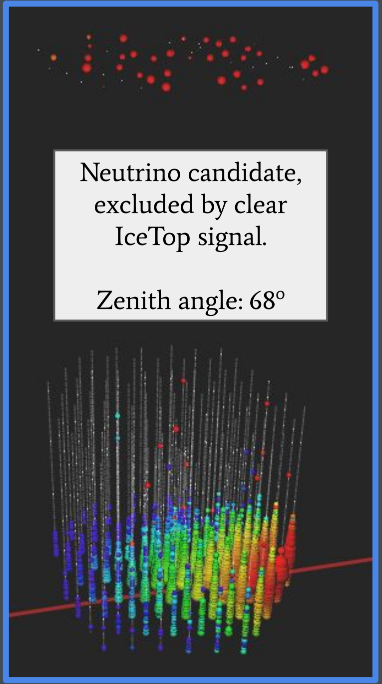
Backgrounds to the Neutrino Science Goals

For neutrino detection, CRs are an intrinsic background.

Optical:
High energy CR-induced (atmospheric) muons that enter the detector are indistinguishable from $\nu_\mu \rightarrow \mu$ outside the detector

Radio:
Prompt muons undergo catastrophic energy losses in the ice and produce showers which look ν-induced radio pulses

Radio emission from CR air showers is refracted into the ice. Distinguishable due to the strong geomagnetic emission/polarization combined with upward-facing shallow antennas near the surface.



Muons: One Person’s Background, Another Person’s Foreground

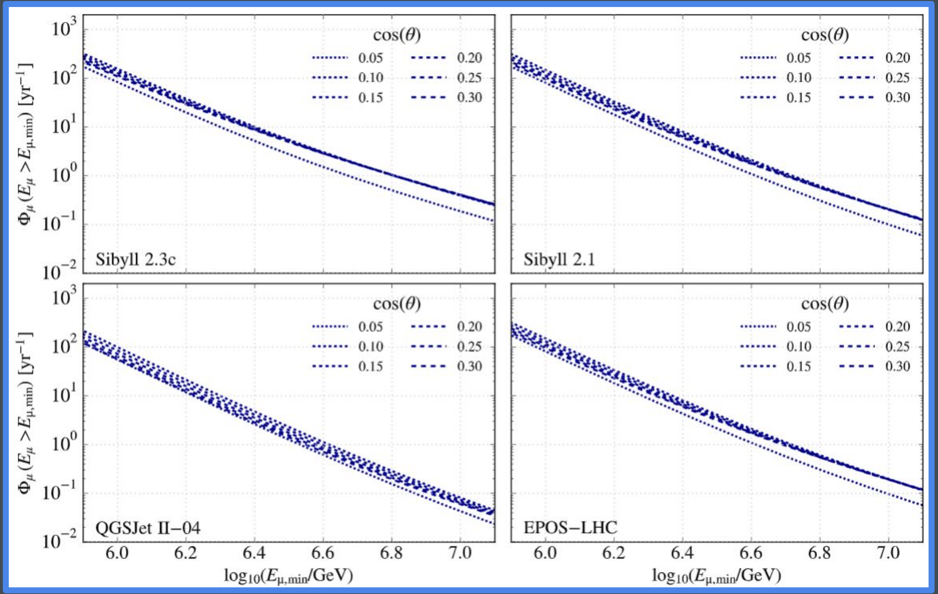
The radio array will be a discovery detector for the cosmogenic flux. Would benefit from a better understanding of of the prompt flux.

Additionally, a better understanding of the hadronic models at these energy scales would simultaneously help the Gen2 (and GCOS) CR science goals.

IceCube can directly measure the (TeV - PeV) muon flux. Relevant for the understanding of, in particular, Auger and GCOS measurements.

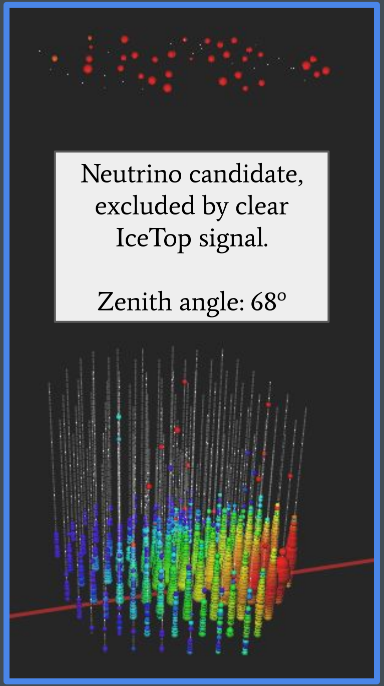
Classifying the CR and neutrino events would benefit the whole astroparticle field. Surface radios are a good candidate.

Inclusive Muon Flux for a Gen2-Scale Optical Detector



D. Soldin - MCEQ, H4a flux model (see his talk)

The Use of Surface Radio to Separate Events



Surface Radio for Event Classification

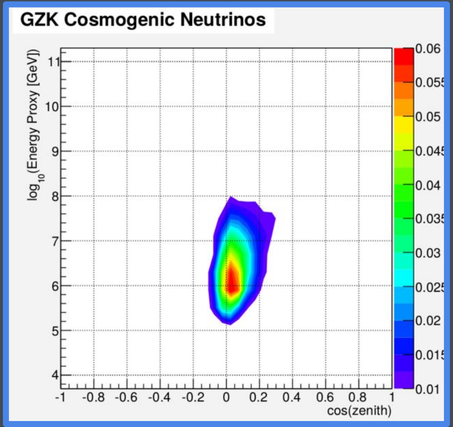
For the highest energy neutrinos seen by the optical detector, the Earth is opaque. Roughly half of all neutrinos will arrive with zenith angles 70 - 90°

Event tagging will reduce systematic uncertainties for determining the cosmogenic neutrino flux

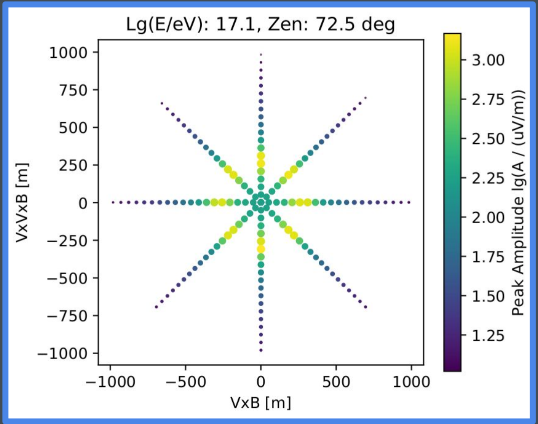
The radio emission from CR air showers at the South Pole results in footprints with large lateral extent.

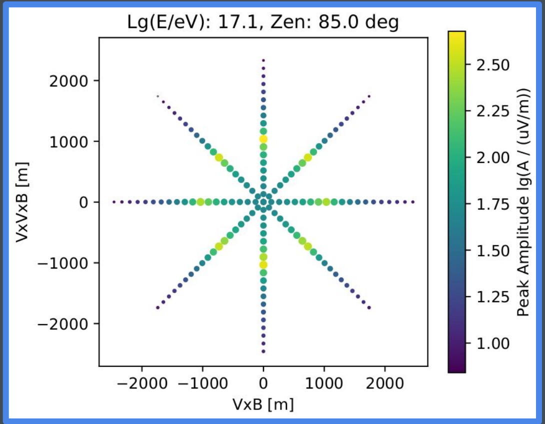
Cherenkov ring 0.2 km - 1.5 km in size for zenith angles >70°. Projected on the ground, the footprints can be 1 - 20 km in length. The near-vertical (17°) magnetic field at the Pole is ideal for detecting CR from all arrival directions near the horizon.

A dedicated surface array with ~km spacing is appropriate for tagging air shower events amongst the cosmogenic flux



Expected rate of GZK neutrinos for IC Gen1
Most events arrive from just above the horizon





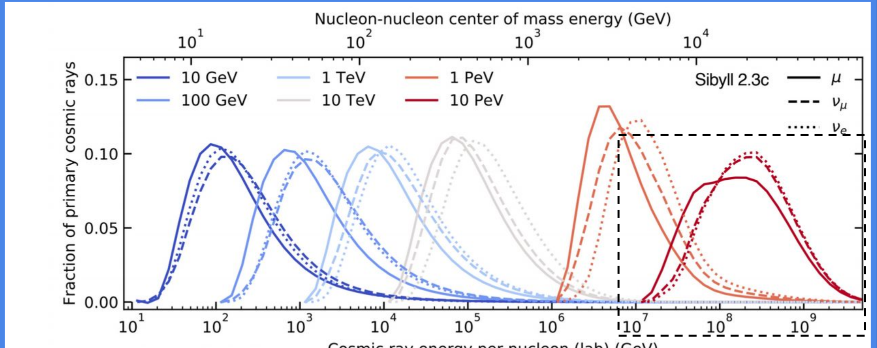
What Needs to be Tagged

The cosmogenic flux expected to be observed at E_ν ~100 PeV ⇒ E_μ~10 PeV

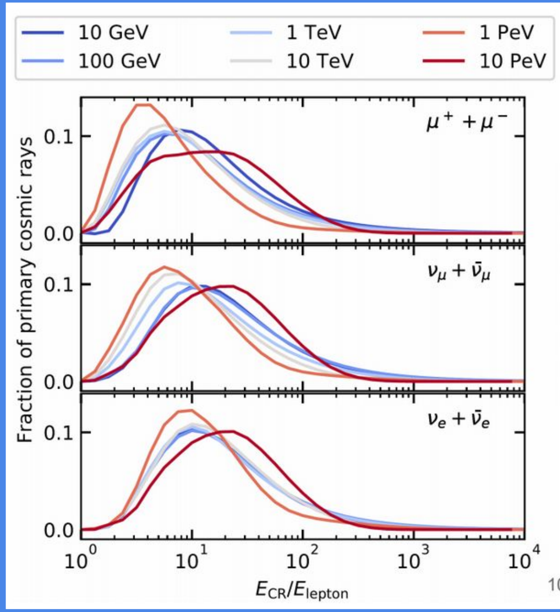
Thus the tagging needs to be sensitive to cosmic rays which produce ≥10 PeV muons.

Primarily created by ≥30 PeV air showers.

Expect on the order of ~1 per year seen by the optical strings assuming a 2.19 spectrum continues above the current IceCube measurements.
The prompt muon background is highly uncertain (flux/hadronic models).



[A. Fedynitch et al., Phys. Rev. D 100 (2019)]



A. Fedynitch et al. PRD 100 (2019) 103018

CR Tagging Study

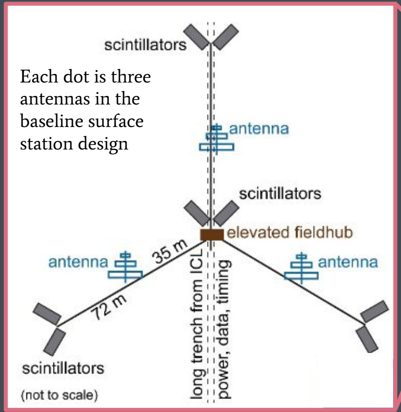
The buried, shallow antennas of the in-ice radio stations have reduced background noise, but are less sensitive to such inclined showers.

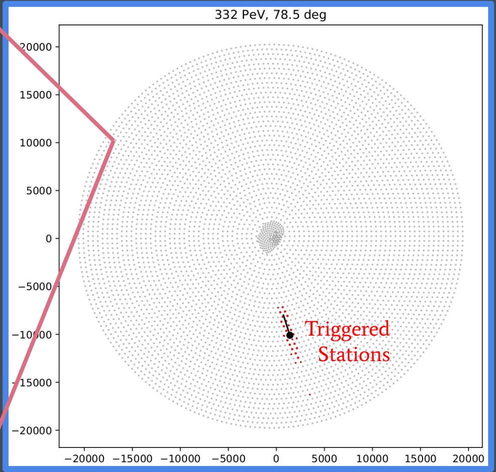
CR-tagging test was performed using baseline surface array design.

As a preliminary study of the layout, simulated guard rings of stations surrounding the optical footprint. Trajectories go through optical detector. Surface stations, separated by 0.5 km along a ring.

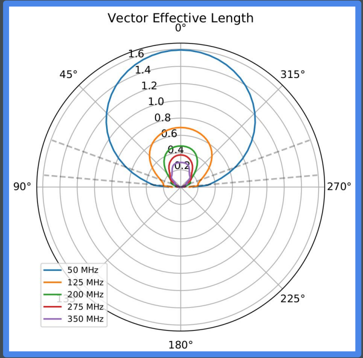
Focused on the most inclined showers, 70° - 85° where the neutrino sensitivity is peaked

Considered Guard Rings

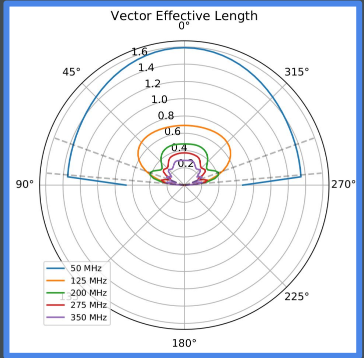




Azi = 0°



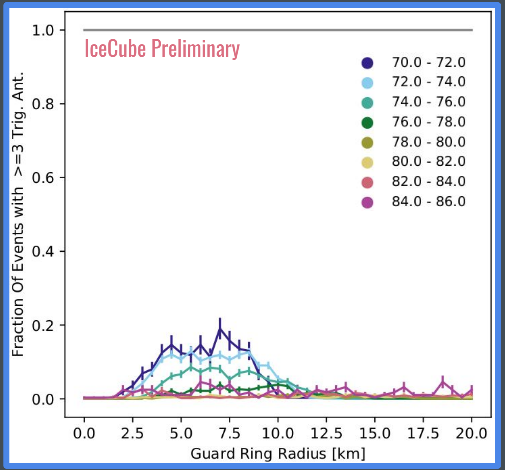
Azi = 180°



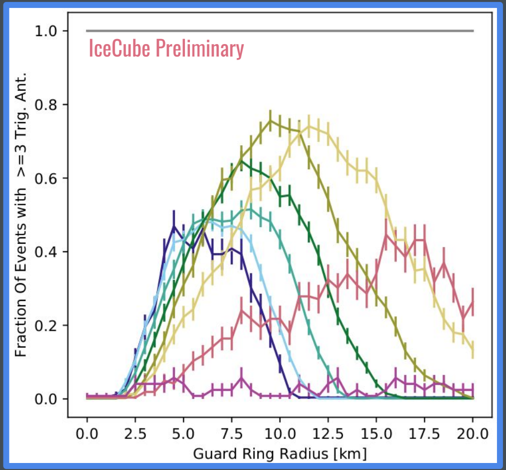
Using a Single Ring

Only partial veto possible, regardless of the ring radius
High angles are more easily seen at large radii due to larger footprint
Challenge: Low signal-to-noise at 100 PeV in this simple study → can be overcome with more dedicated hard/software

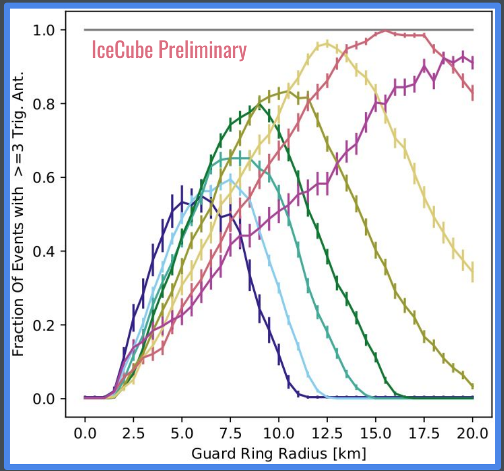
100 PeV P/Fe



300 PeV P/Fe



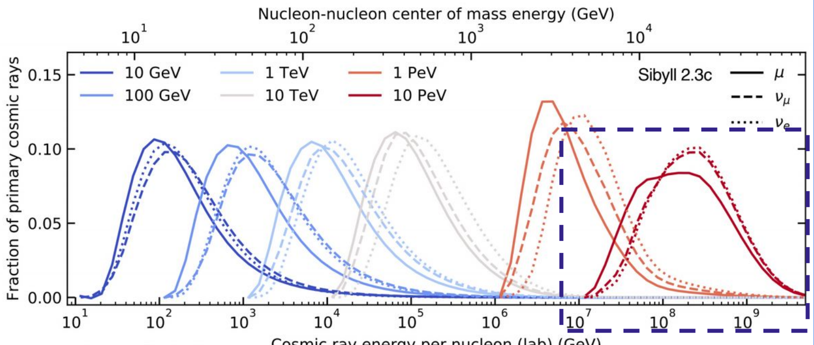
1 EeV P/Fe



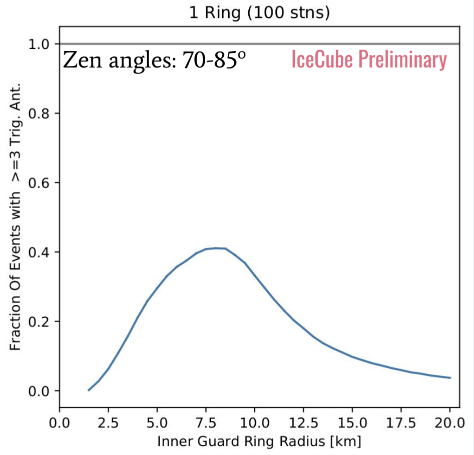
Using Additional Rings

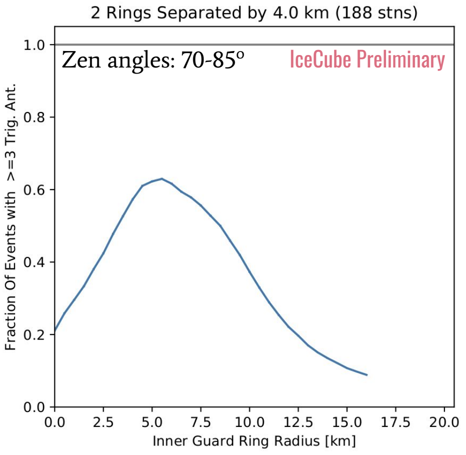
Folded with the flux of PeV muons, picture is unchanged: a partial veto could be built using 100 stations on the surface

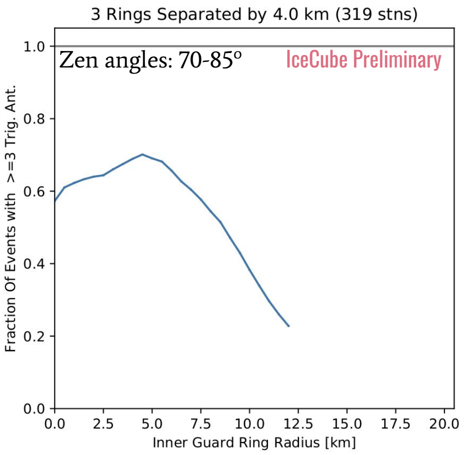
Would certainly be able to tag events to study the prompt muon flux and the remove from the sample of cosmogenic neutrinos, reducing uncertainty.



[A. Fedynitch et al., Phys. Rev. D 100 (2019)]







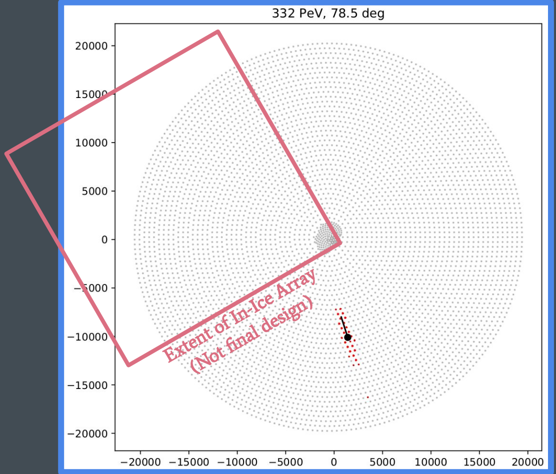
Further Optimizations

Some of this phase space will already be covered by the Gen2 in-ice stations, which include just-below-surface stations Currently exploring the science impact of moving them to the surface.

A more dedicated antenna design would help. Beamed towards the horizon rather than upwards.

For all events that need tagging, the trajectory of the potential CR can be determined from in-ice reconstructions radio and/or optical. Using beamforming, can better reduce the background and improve surface-detection thresholds ~sqrt(N).

If a full ring is created, should they be only surface or also include in-ice radio?



Conclusions

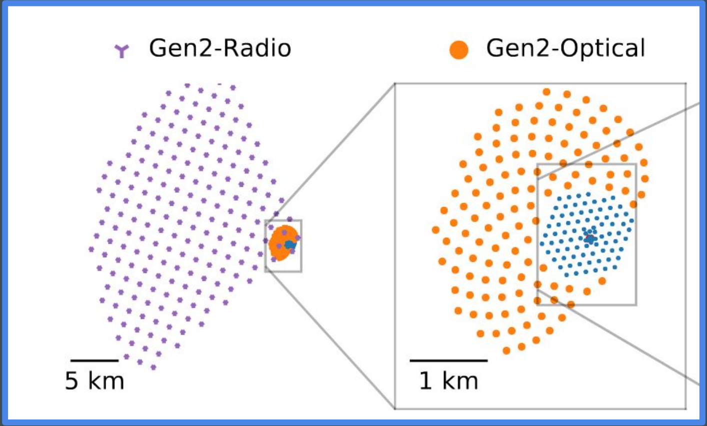
The radio array is designed to observed the first cosmogenic neutrinos.

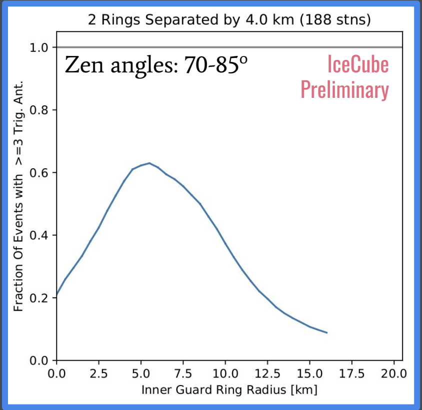
The detection of this flux will be important for understanding mass, propagation, and acceleration models for the CRs that GCOS will measure.

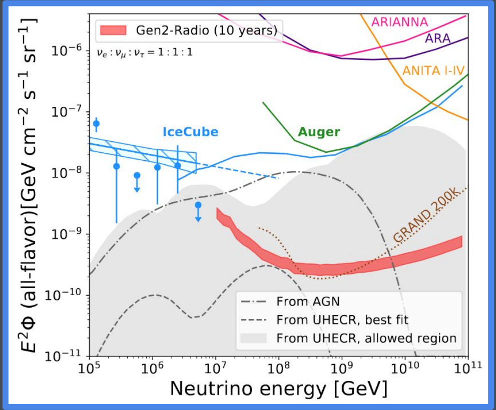
For multi-messenger studies, the radio array will provide ≈2° x 10° resolution at the highest energies

The prompt muon flux at the relevant energies is both uncertain and an intrinsic background to determining this flux. It is also intrinsically important for GCOS-scale hadronic interactions.

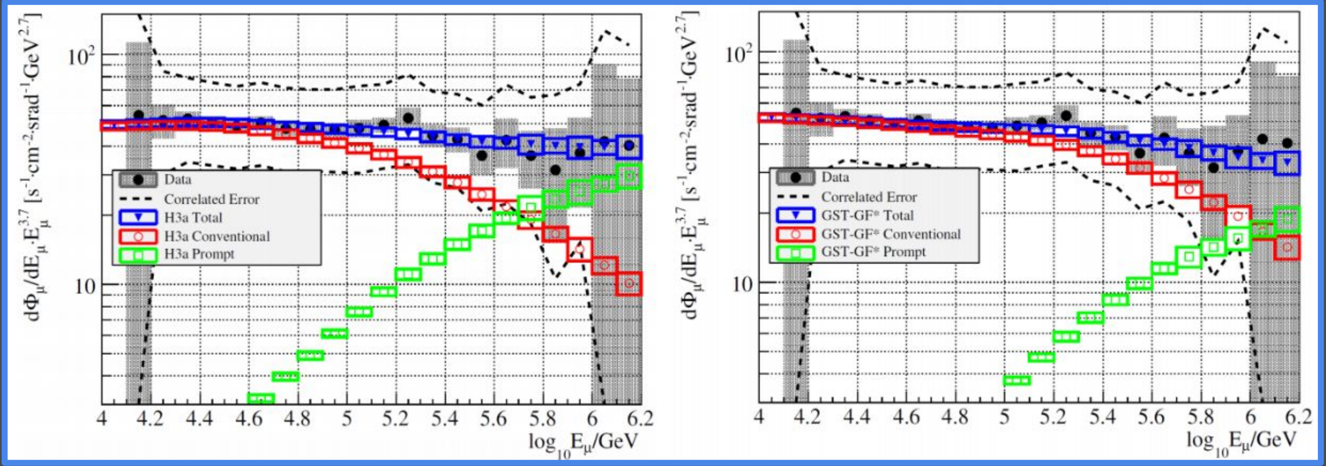
As an extension of the proposed Gen2 in-ice radio, exploring the possibility to include a design for CR tagging for the optical detectors using antennas above the surface. Optimizations ongoing.







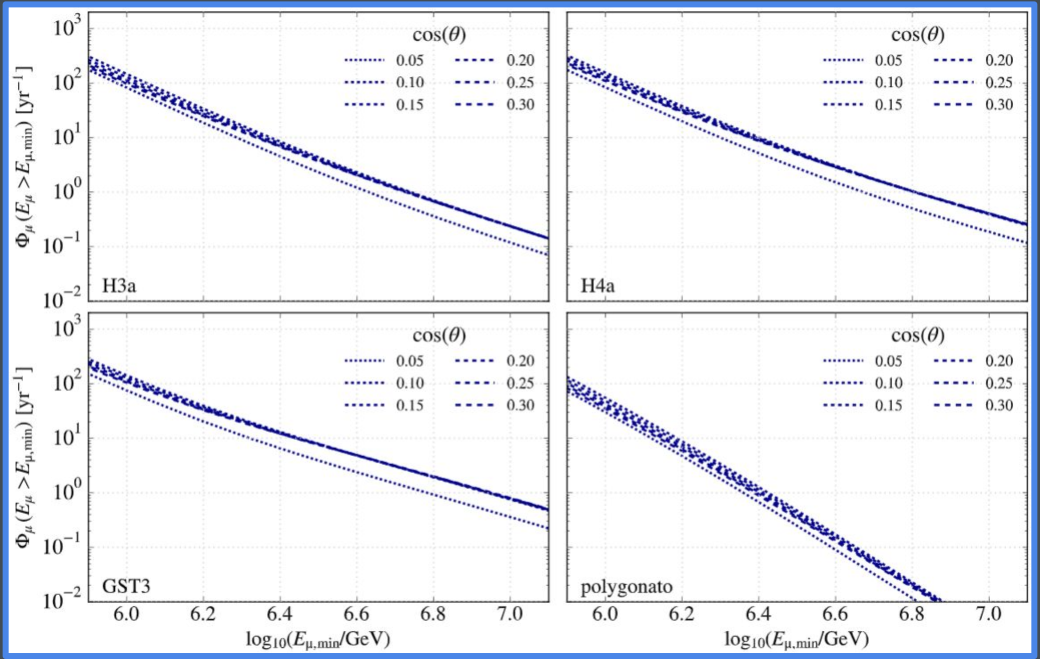
Prompt Muon Flux



IceCube, Astropart. Phys. 78 (2016) 1-27

Prompt Flux from CR Flux

Inclusive Muon Flux for a Gen2-Scale Optical Detector



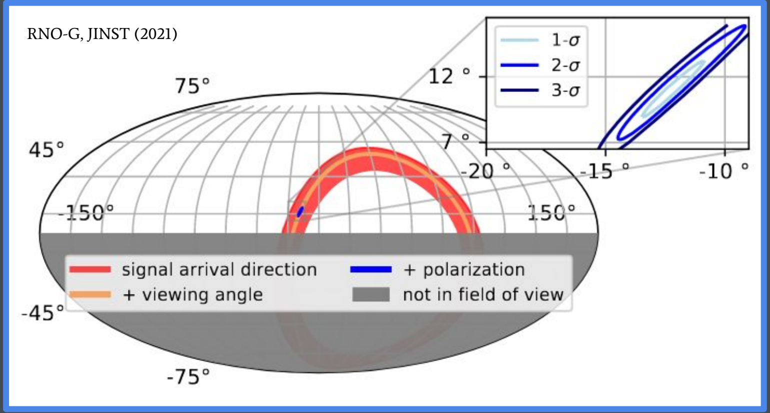
D. Soldin - MCEQ, Sibyll2.3c (see his talk)

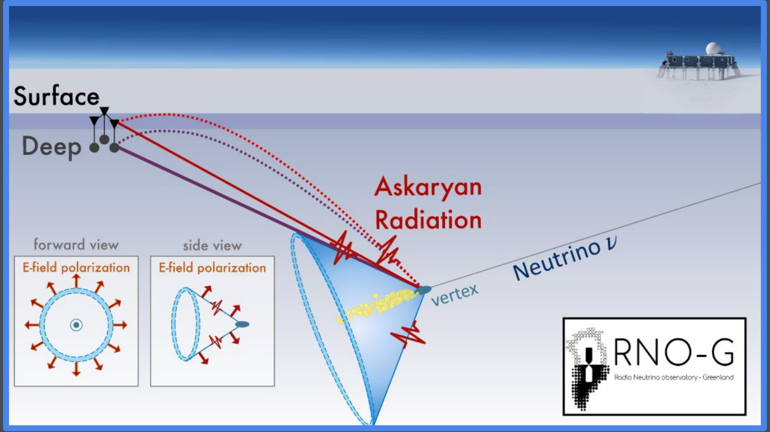
Angular Resolution of In-Ice

Based on timing alone, the in-ice radio reconstruction results in a ring on the sky

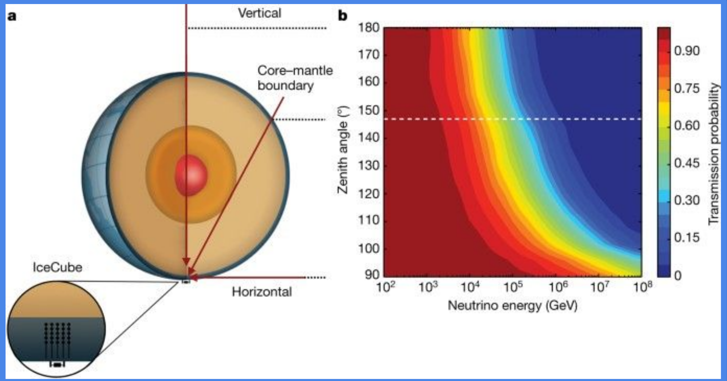
The width of the ring is given by the width of the Cherenkov cone which can be determined to ~2° using the spectral slope. The position on the ring is limited using measurements of the polarization of the radio waves. Shown to be determined to about 10°.

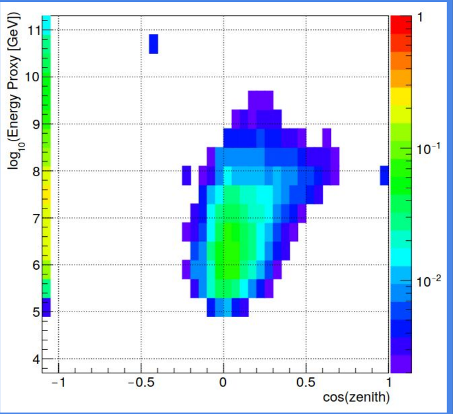
Thus the resolution on the sky is a 2° x 10° annulus segment on the sky.



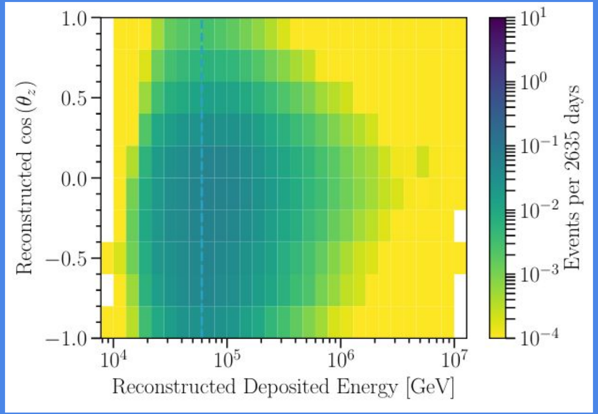


Arrival Directions of High E Muons

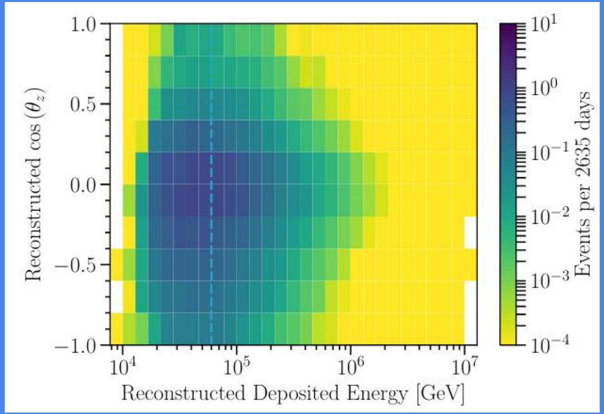




Simulated distribution of cosmogenic neutrinos in Gen1
IC Collab. PRD (2018)



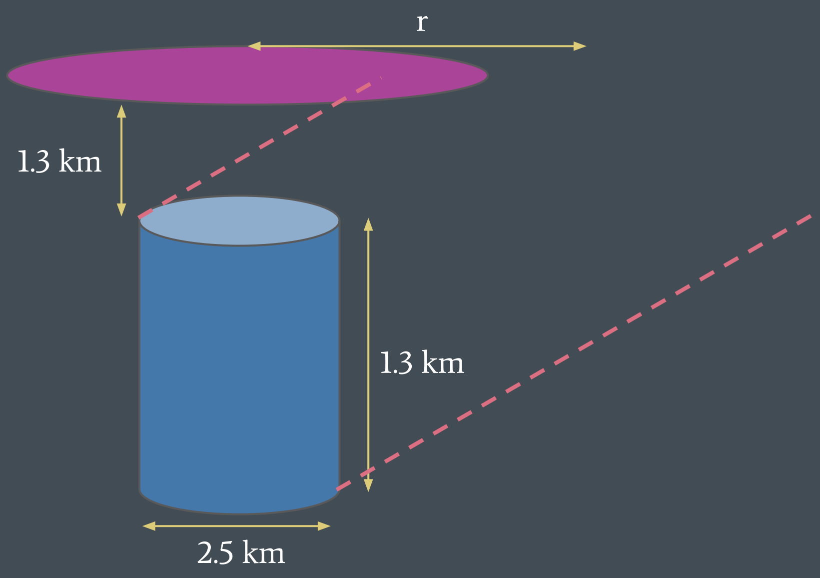
Expected neutrino rate from charmed hadrons, Gen1
IC Collab, arXiv:2011.03545

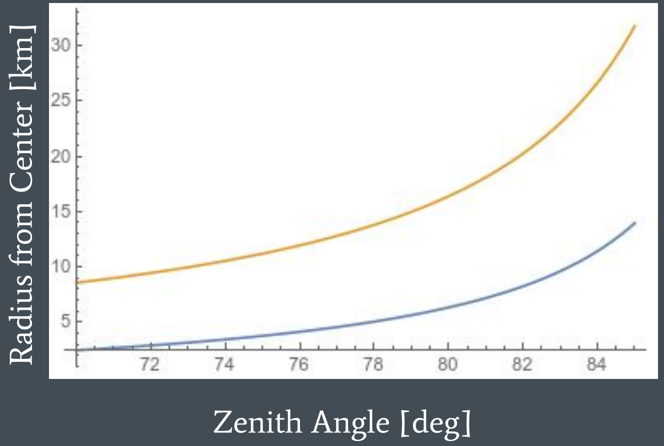


Expected neutrino rate from pions+kaons, Gen1
IC Collab, arXiv:2011.03545

Possible Core Locations

The spread of the locations of cores for 70 - 85^0 zenith angle showers that go through the optical volume





The Plan for the Future of Gen2

The deployment plan is still not completely set, but is approximately…