Sensitivity studies for the IceCube-Gen2 radio array

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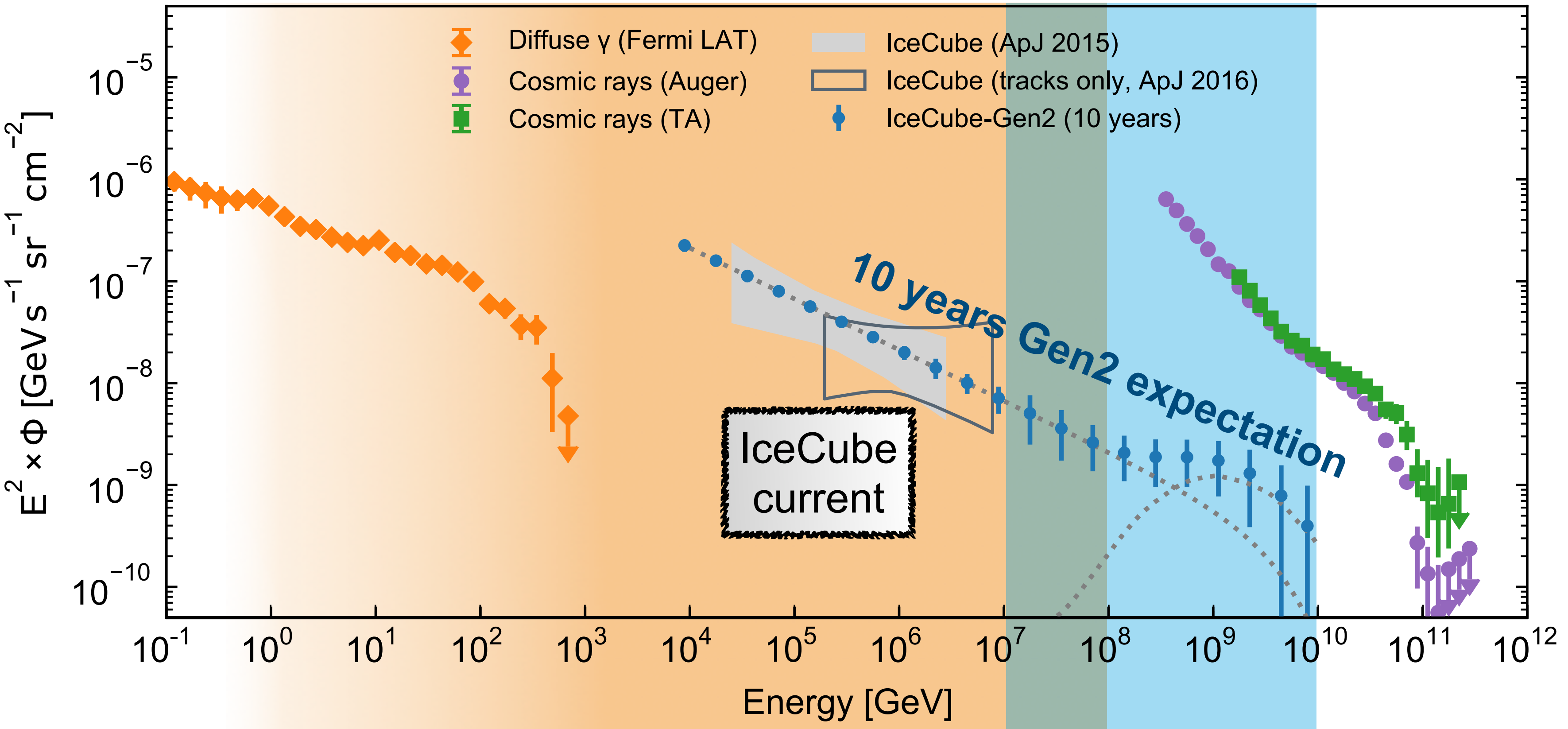
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Next decade facility: IceCube Gen2



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Gen2 **optical**:

- 10× more cosmic neutrinos / year
- sensitive to 5× fainter point-sources

Gen2 **radio**:

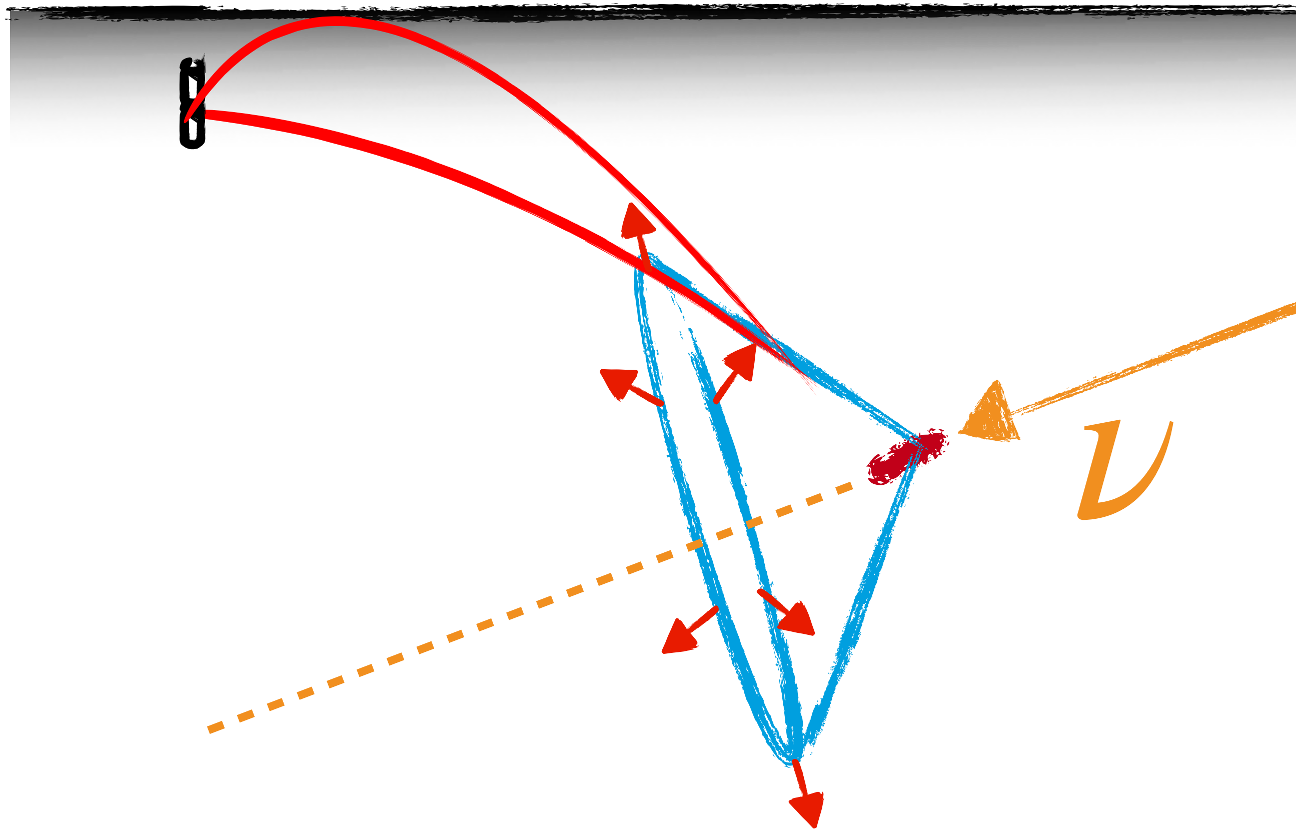
- extend energy range by several orders of magnitude
- measure continuation of astrophysical spectrum
- discover cosmogenic neutrino flux

Askaryan radio signal

- energy threshold: ~ 30 PeV
- detection in frequency range between 100 MHz and 1 GHz
- attenuation length: ~ 1 km (vs. ~100 m for optical Cherenkov)

Unique signal properties:

- viewing angle wrt. Cherenkov cone
- 'DnR' signature (time delay between direct + reflected / refracted ray)
- polarization perpendicular to shower axis



Gen2 builts on experience from current Askaryan detectors

Operational

ARA: vertically/horizontally polarized (Vpol, Hpol) dipole antennas, ~ 200 m deep (South Pole)

ARIANNA: high-gain log-periodic dipole antennas (LPDAs), in shallow firn (Ross Ice Shelf & South Pole)

ANITA: balloon based (Antarctica)

Construction of mid-scale array in Greenland has started

RNO-G: combination of 100m deep Vpols/Hpols and shallow LPDAs, 35 stations covering ~50km^2

Credits: RNO-G deployment team, C. Deaconu

Gen2 radio array

Simulated detector setup in this work

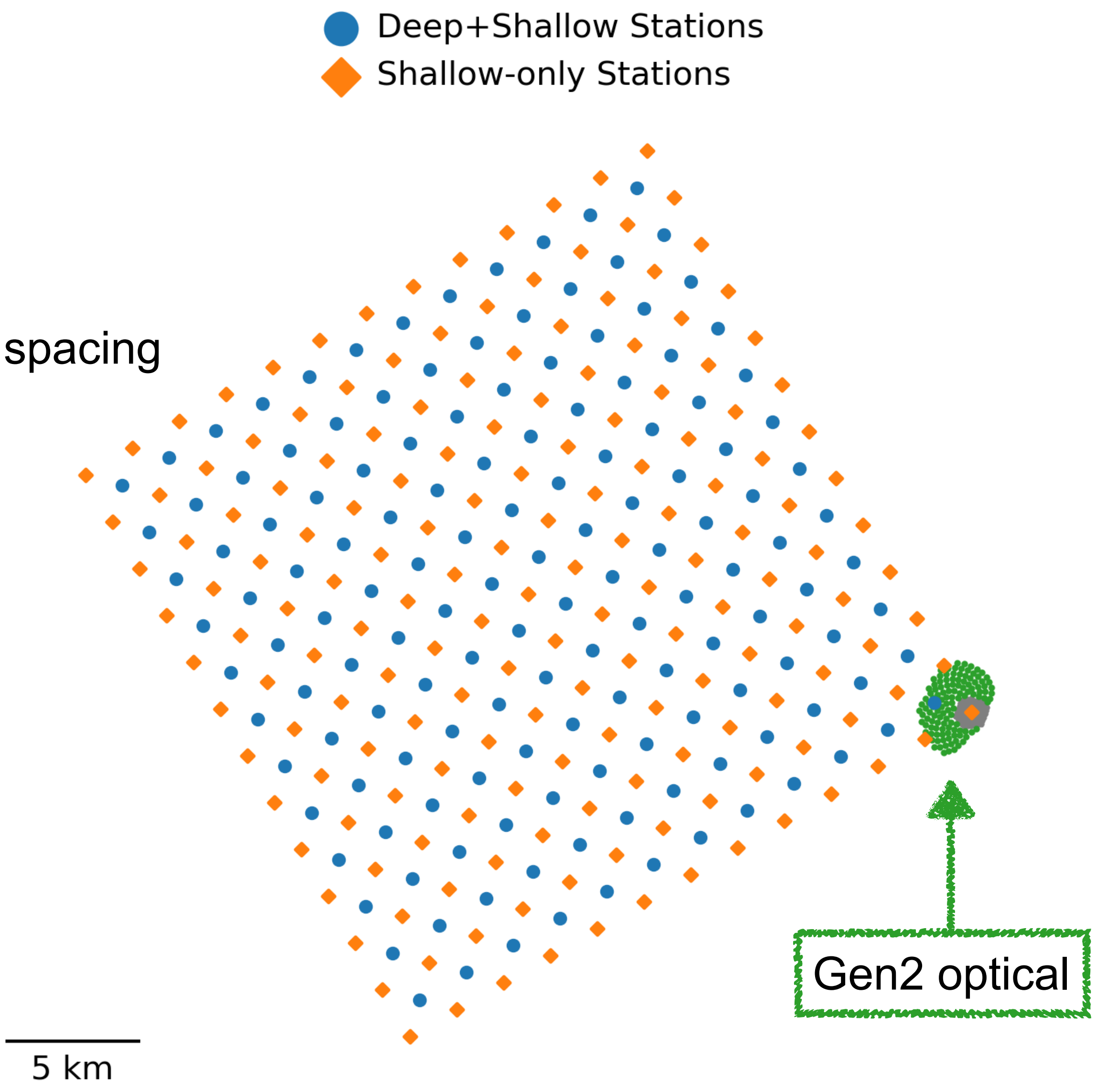
~500 km² area covered by

144 hybrid (deep + shallow) stations , 2 km station spacing

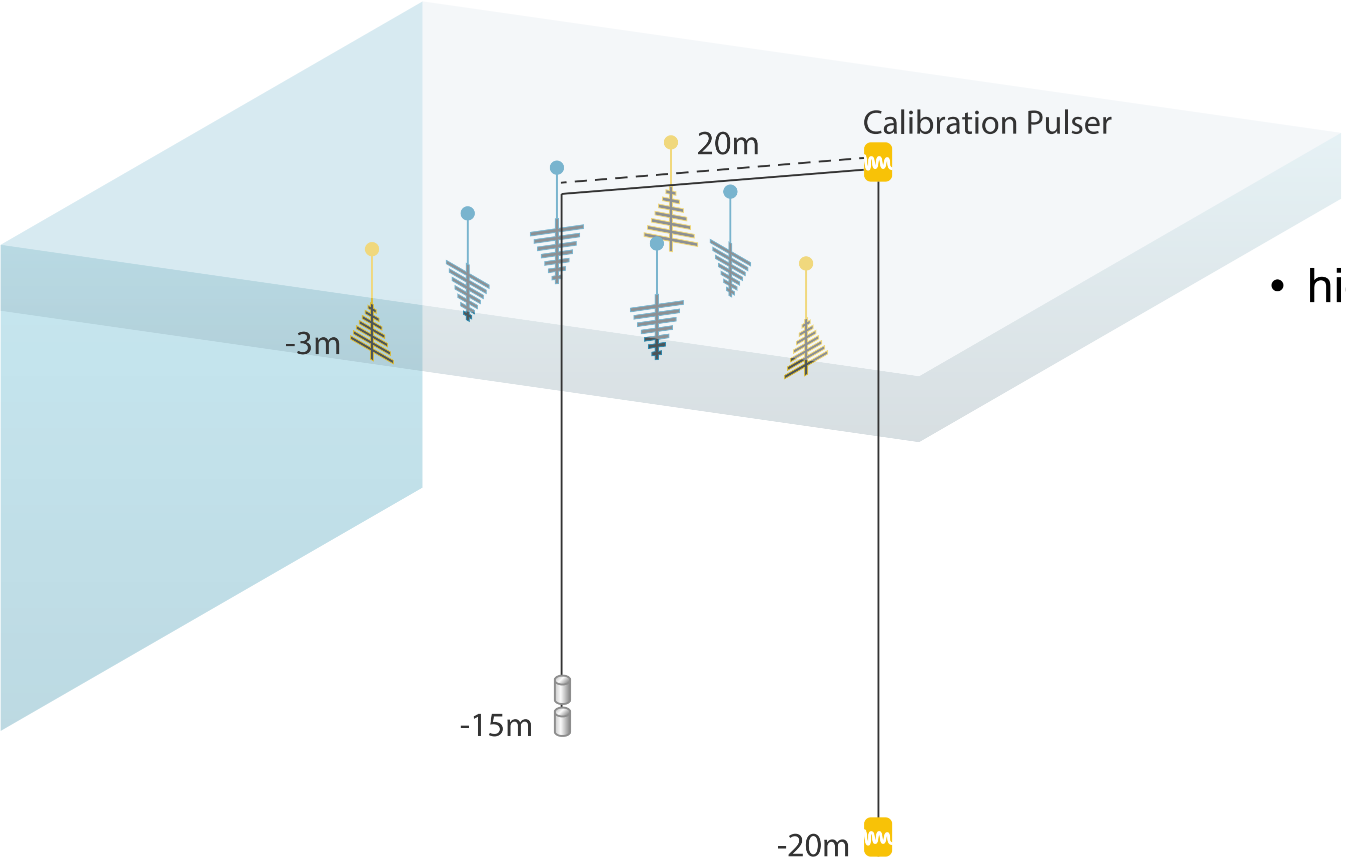
+

169 shallow-only stations

for increased instrumentation density at the surface



Shallow-only stations



- high-gain log-periodic dipole antennas (LPDAs):
  - 3 LPDAs facing upwards:

    sensitivity to cosmic-ray air showers

    rejection of anthropogenic noise
  - 4 LPDAs facing downwards:

    sensitivity to in-ice showers
    signal arrival direction, and polarization information
    from perpendicularly aligned pairs
- 15m deep vertically polarized (Vpol) dipole antenna:

  improved vertex localization from ‘**DnR**’ signal

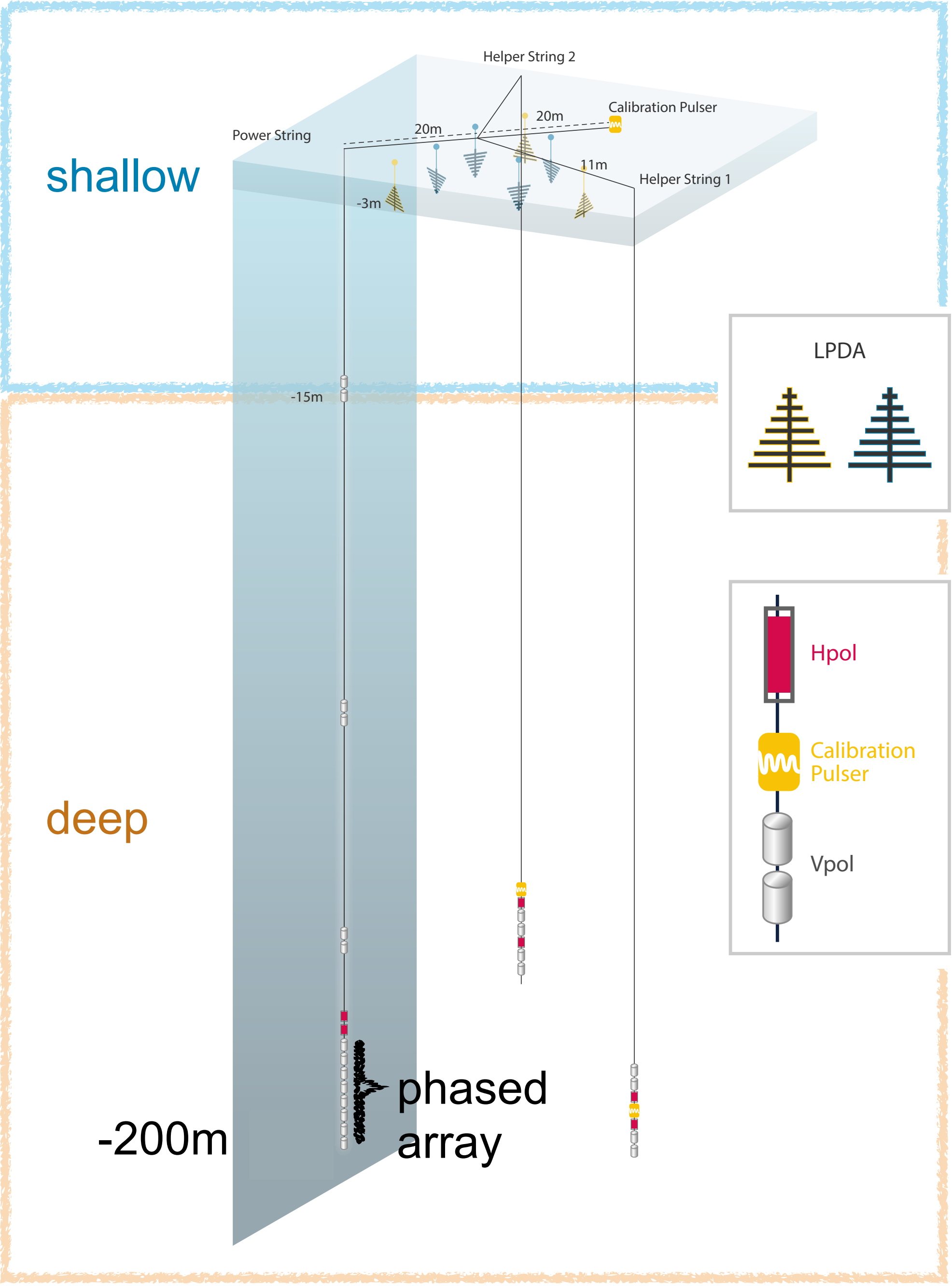
Hybrid (deep + shallow) stations

shallow component in the firn identical to shallow-only stations

+

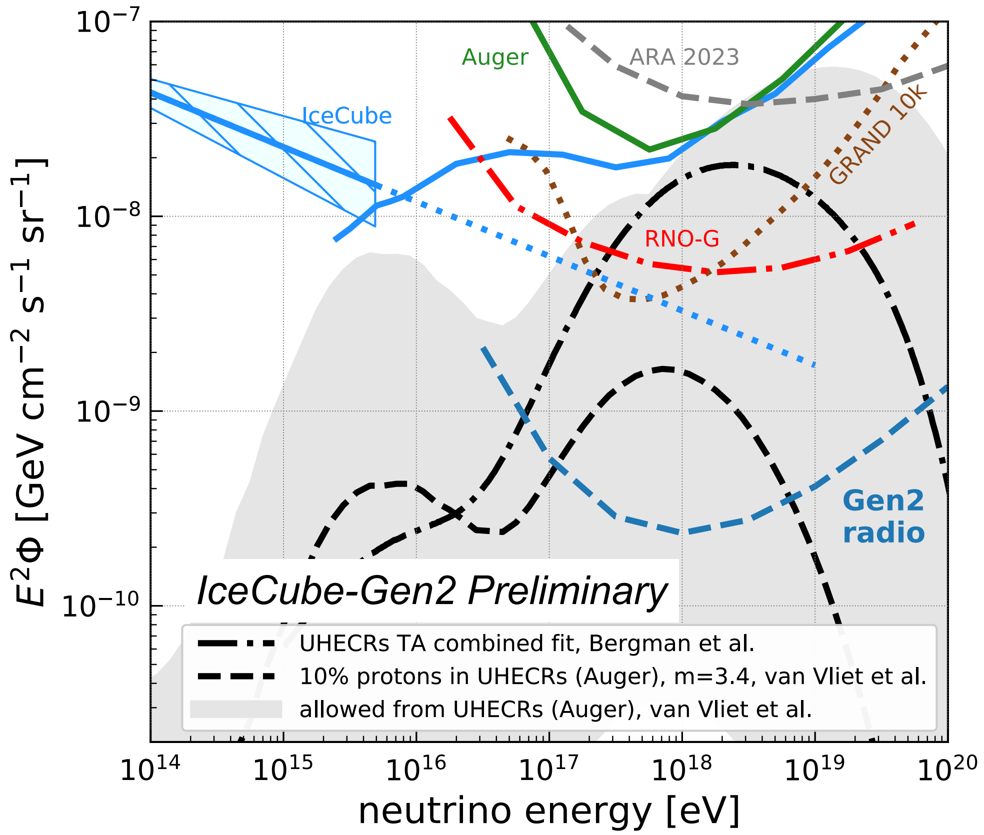
Deep component

- three 200m deep strings provide large effective area
- **phased array** of 4 Vpol antennas for triggering
  → beamforming reduces threshold by $\sqrt{4}$ (in signal-to-noise ratio)
  → phased array technology also used in ARA and RNO-G
- additional antennas to aid event reconstruction
  → vertex, energy, and viewing angle reconstruction (3×2 Vpols in addition to phased array)
  → polarization sensitivity for accurate pointing (3×2 Hpols)



Diffuse flux sensitivity

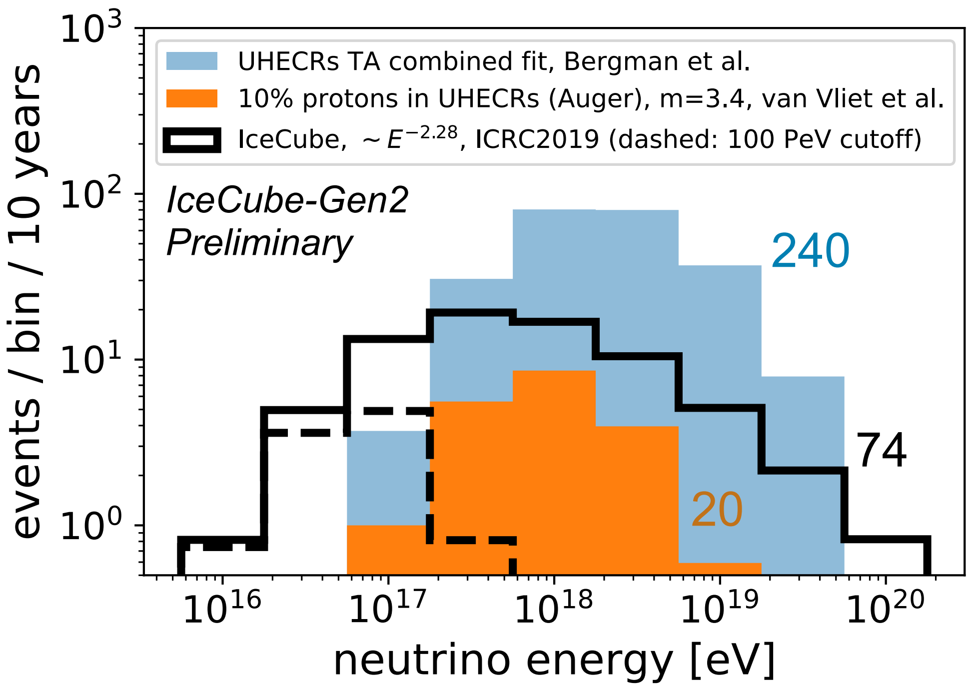
for the simulated array



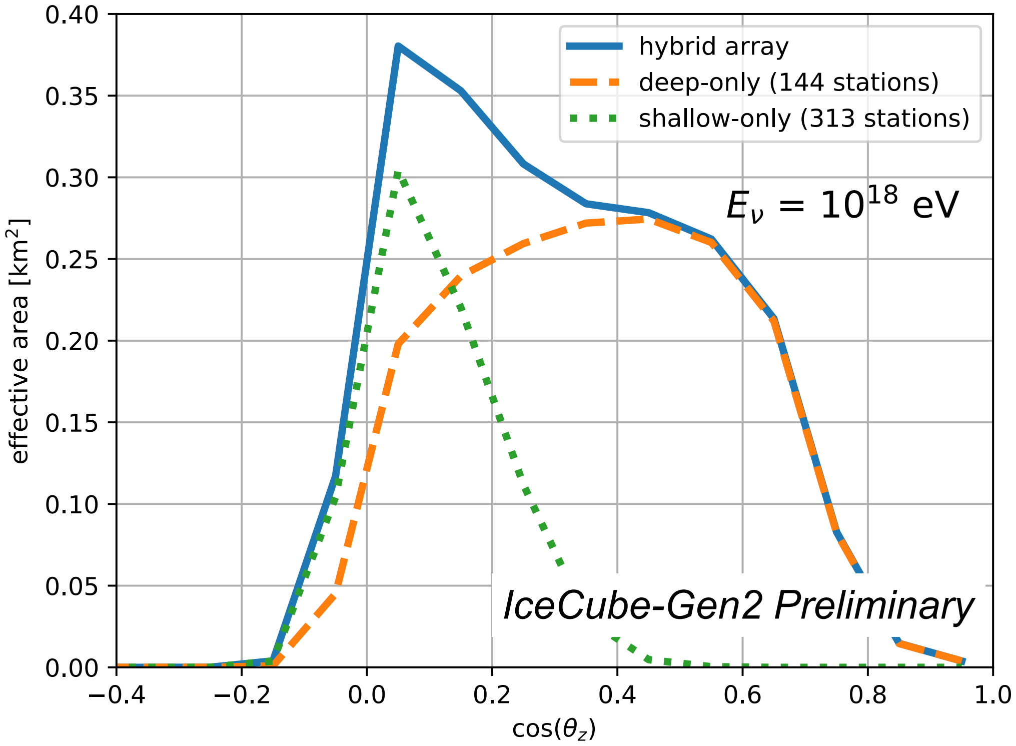
- trigger-level sensitivity @ 90% CL for 10 years of uptime
- 10× better sensitivity compared to future mid-scale arrays
- 100× better sensitivity compared to currently collected data

event numbers strongly depend on

- cosmic ray spectrum and proton fraction at the highest energies for cosmogenic neutrinos
- continuation of the fitted IceCube spectrum for astrophysical neutrinos at ultra-high E



Effective area



- enlarged field of view by combination of shallow and deep components
  - sensitive in declination band $-42^\circ < \delta < 2^\circ$
  - Earth absorption below horizon

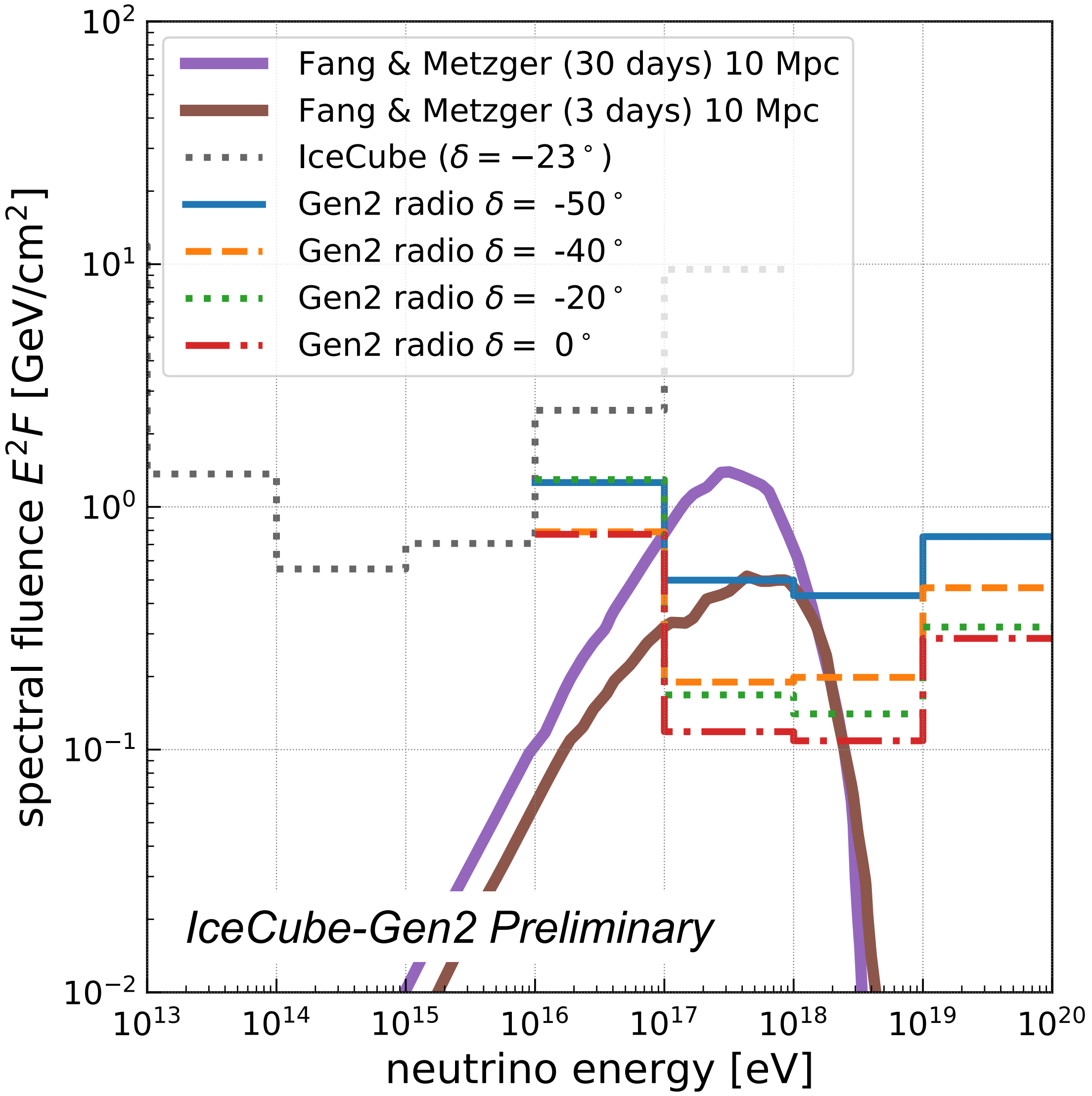
- different systematics (antenna / signal propagation in deep ice and firn)

  → both components individually sensitive to detect neutrinos, together they will allow Gen2 to make a convincing discovery of cosmogenic neutrinos

Point source sensitivity

- continuous ~35% sky coverage

- 90% CL fluence senstitivity @ trigger level
- sensitive to point sources such as nearby binary neutron star mergers



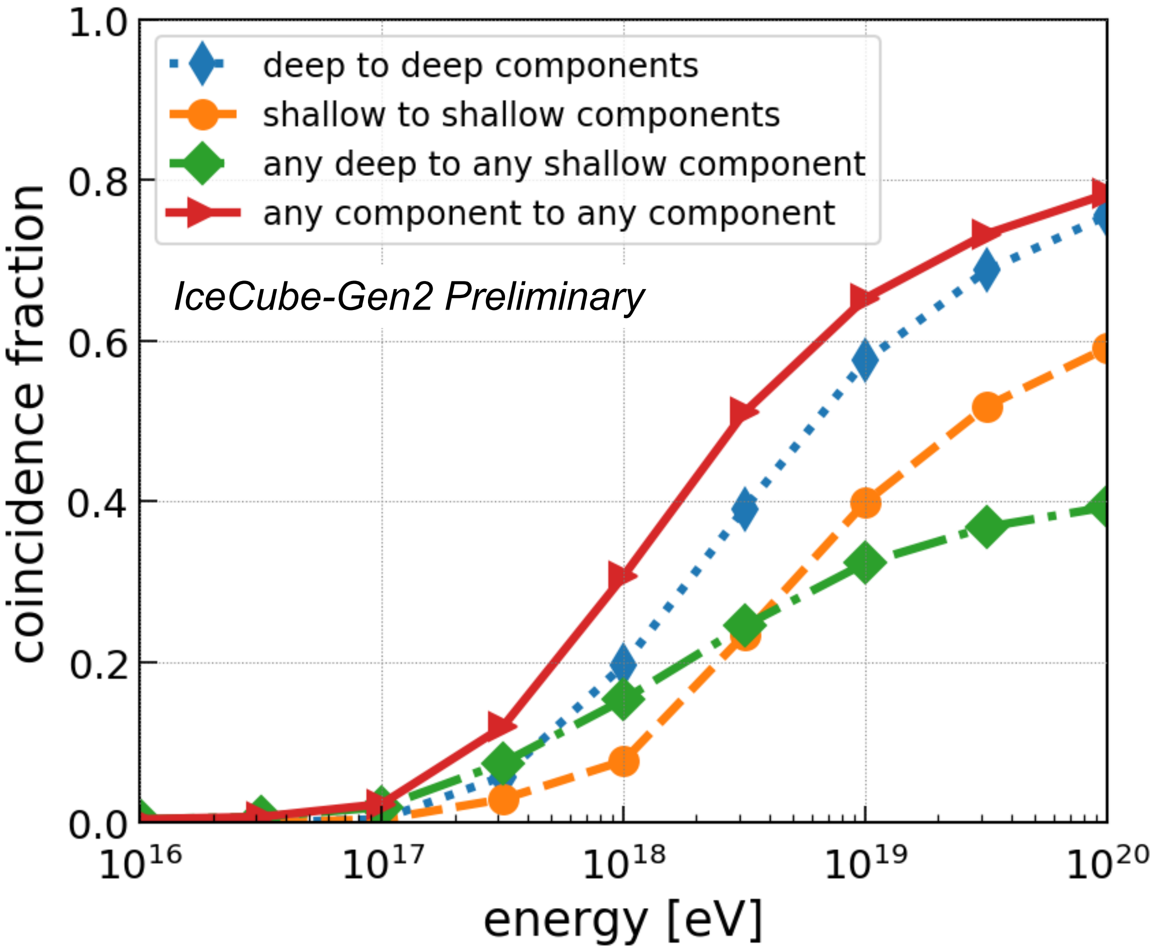
Station spacing

- 2 km (1.4 km) spacing between deep (shallow) components

- stations designed to operate & trigger autonomously
  → event reconstruction (primarily) on single-station level

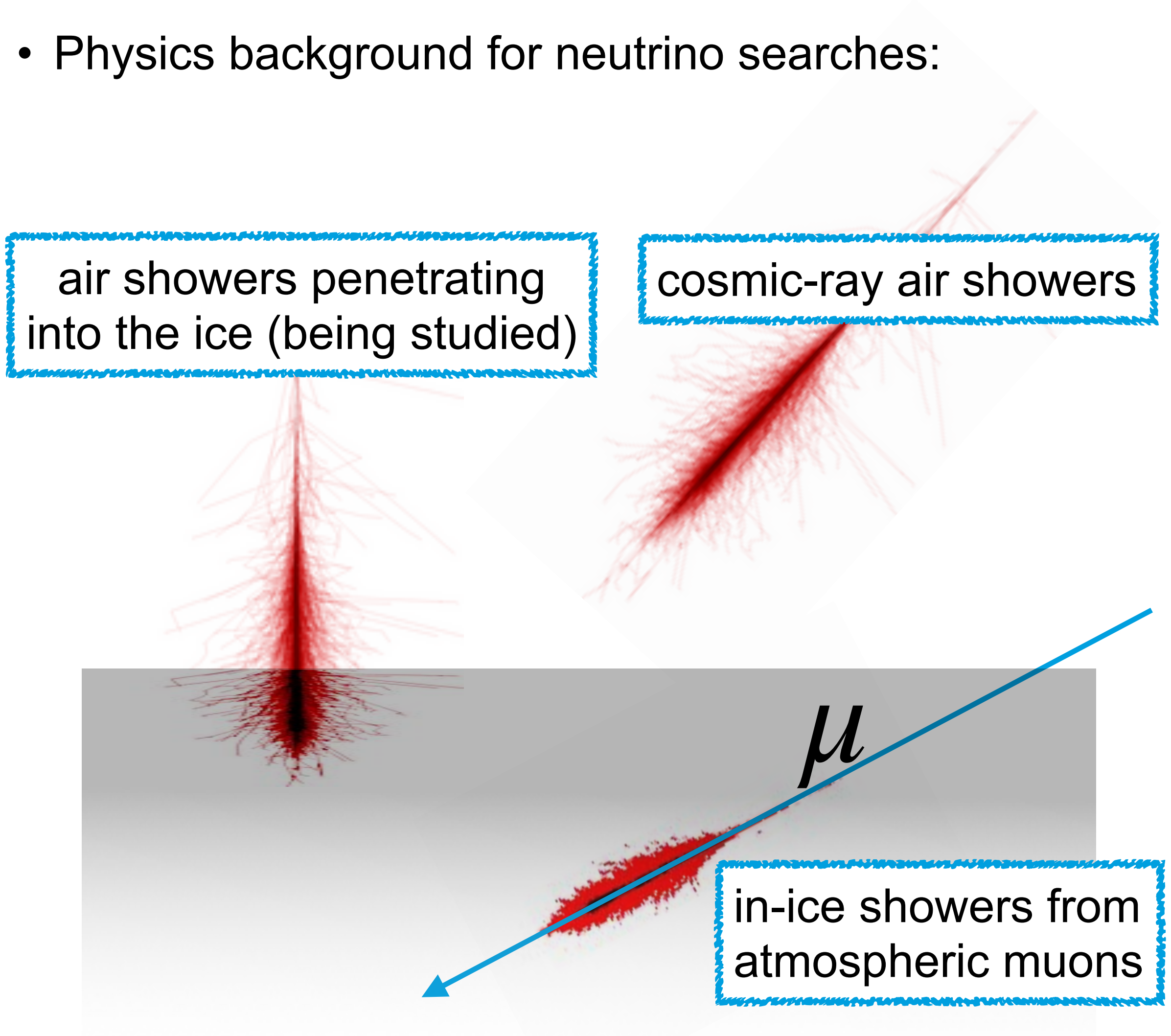
Coincident triggers

- ~30% events seen in multiple stations at EeV energies
  → large effective volume
  → 500 km² still close enough to deploy & operate
  → set of 'golden events' seen in coincidence



Cosmic-ray air showers

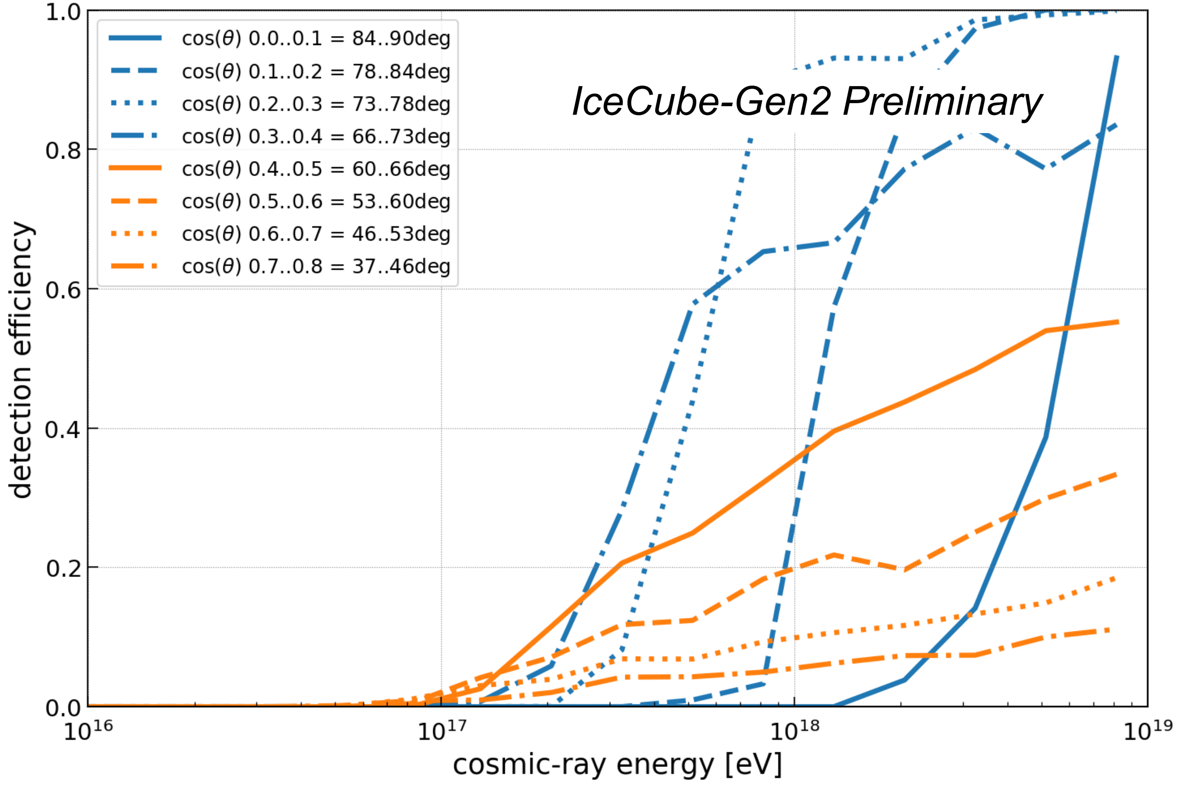
- Physics background for neutrino searches:



$\mathcal{O}$(0.4/array/year) [*], but strongly dependent on cosmic-ray flux and interaction model

Cosmic-ray tagging

- shallow station spacing is being further optimised with focus on background control
- fully efficient air shower tagging for inclined showers (>70°) at EeV energies



[*] using GSF cosmic-ray flux + Sibyll 2.3c interaction model

Background suppression

Thermal, wind-related, and anthropogenic backgrounds

- for **shallow LPDAs**:
  ARIANNA has shown, that all non-physics backgrounds can be suppressed while retaining ~79% signal efficiency at Moore's Bay (A. Anker *et al.* JCAP **03**(2020) 053)

  + the additional shallow Vpol will allow to improve on this significantly
  (better signal identification by exploiting DnR signatures seen for almost all in-ice showers)

- for **deep component**: estimates based on ARA with phased array trigger show (K. Hughes, ARA, #1153 this ICRC)
  efficient suppression of thermal backgrounds while retaining ~70%–80% of events @ 10^{17} eV–10^{18} eV

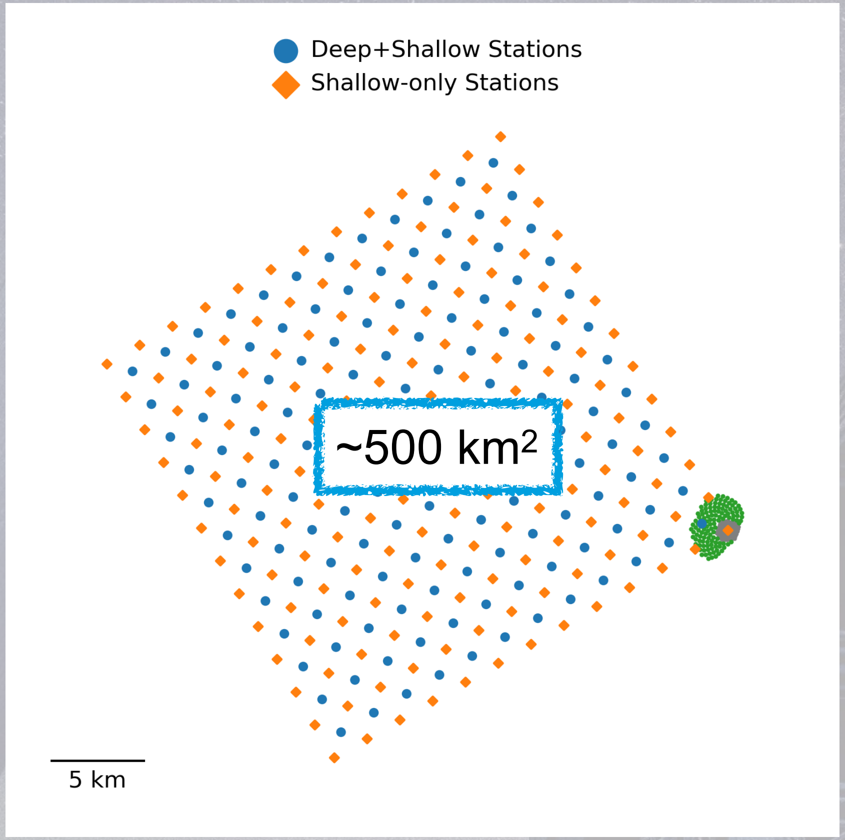
  + likely improvement by O(20%) possible from gains in analysis + help of shallow antennas

Detector resolution

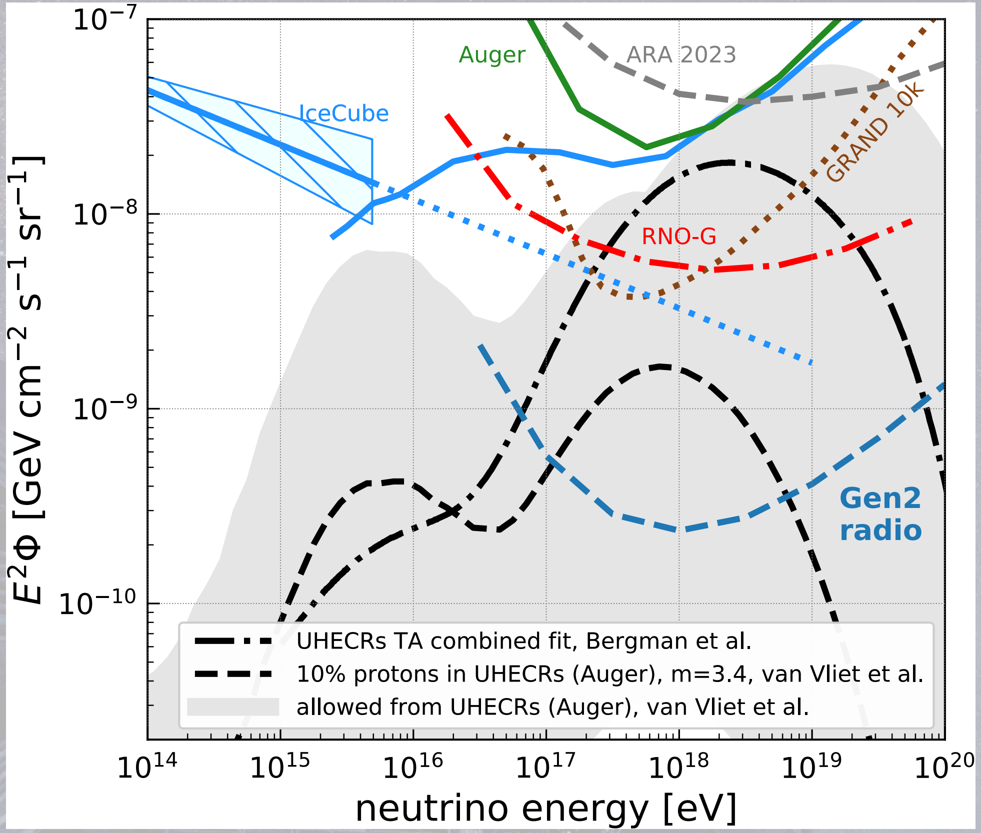
- **Shallow stations:**
  - ~3° angular resolution on all triggered events possible (S. Barwick, ARIANNA, #1151 this ICRC)
  - 0.37° resolution on (pulser) signal direction and 2.7° on polarization measured in in-situ (ARIANNA, JINST **15** no.09 (2020) P09039)

    +
  - DnR signature: energy resolution better than factor ~2 (intrinsic uncertainty from inelasticity) (A. Anker *et al.* JCAP **11**(2019) 030)
- **Deep components:**
  - shown in-situ: signal direction can be triangulated to within 1° (ARA, Astropart. Phys. 108 (2019) 63-79)
  - RNO-G, simulation based
    - energy resolution better than factor ~2 (C. Welling, RNO-G, #1033 this ICRC)
    - angular resolution more challenging due to less sensitive Hpols, but few degrees for subset of events possible (I. Plaisir, RNO-G, #1026 this ICRC)

Conclusion.



10 year diffuse sensitivity @ 90% CL.



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