Radio detection techniques

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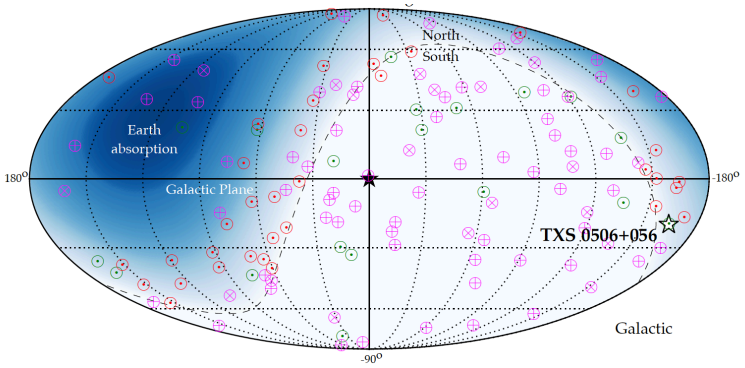
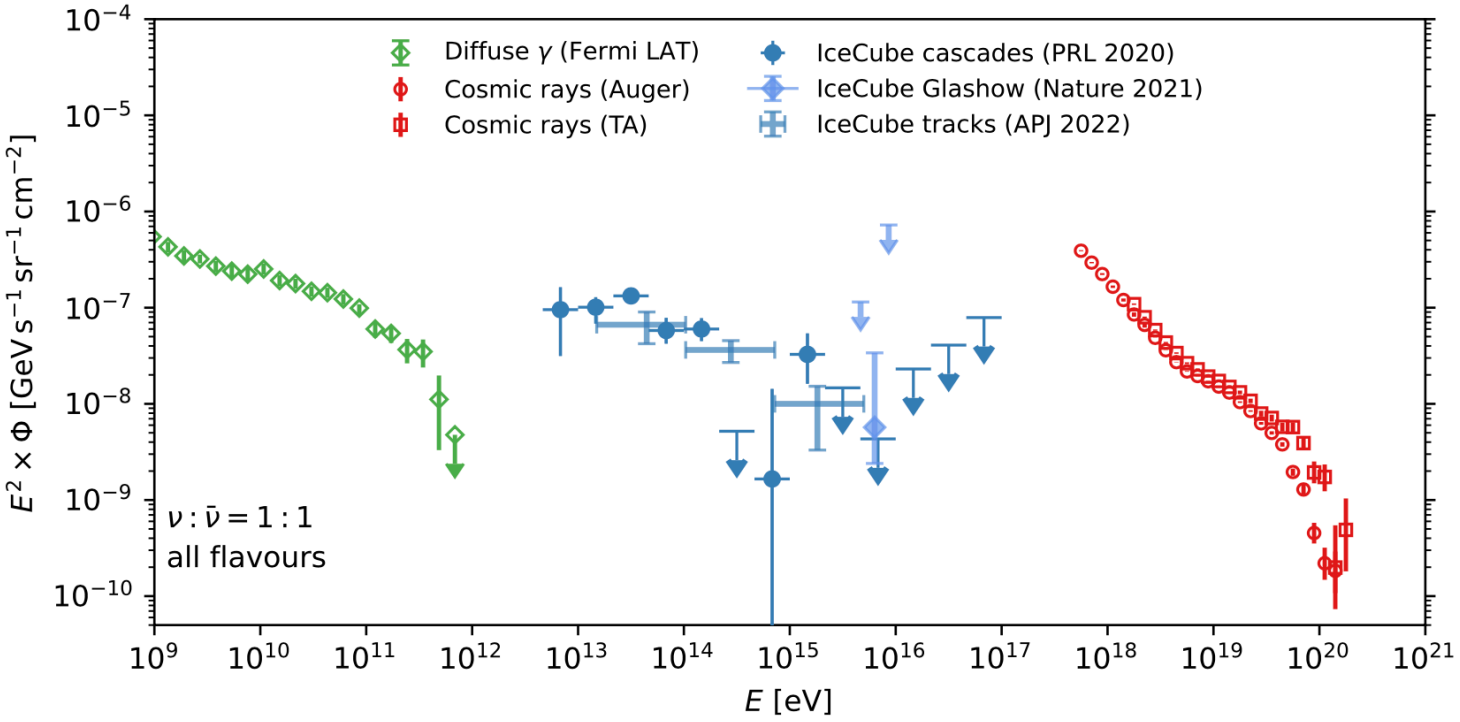
July 23, 2022
Snowmass

10 years of IceCube: The high energy neutrino sky



What are the sources of IceCube's high energy neutrinos?
First evidence: Particle accelerators powered by black holes.



10k astrophysical neutrinos
1 million atmospheric neutrinos:

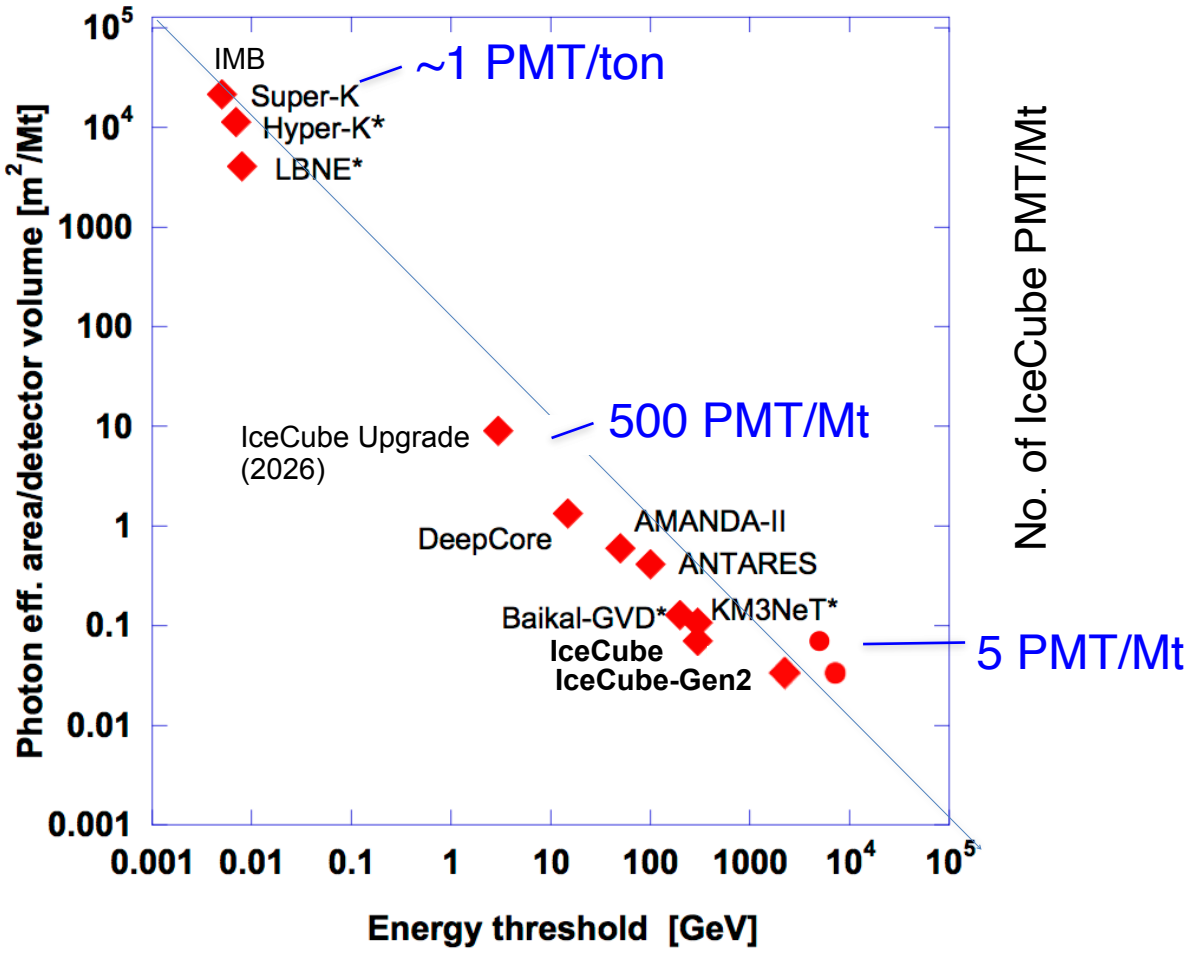
Deep Core: 200k high purity neutrinos above 10 GeV (incl. 7000 nu_taus)

IceCube
Optical Cherenkov

Radio detection

Water Cherenkov detectors: PMT coverage vs energy threshold

New evidence at higher energy → science requirement: focus on higher energy
Deep ice is better then expected
We can reduce the PMT coverage (string density) by increasing the energy threshold.



Define:

Photon effective area =

Number of PMT

x Cathode area

x Quantum efficiency

= equivalent area of 100% photon detection.

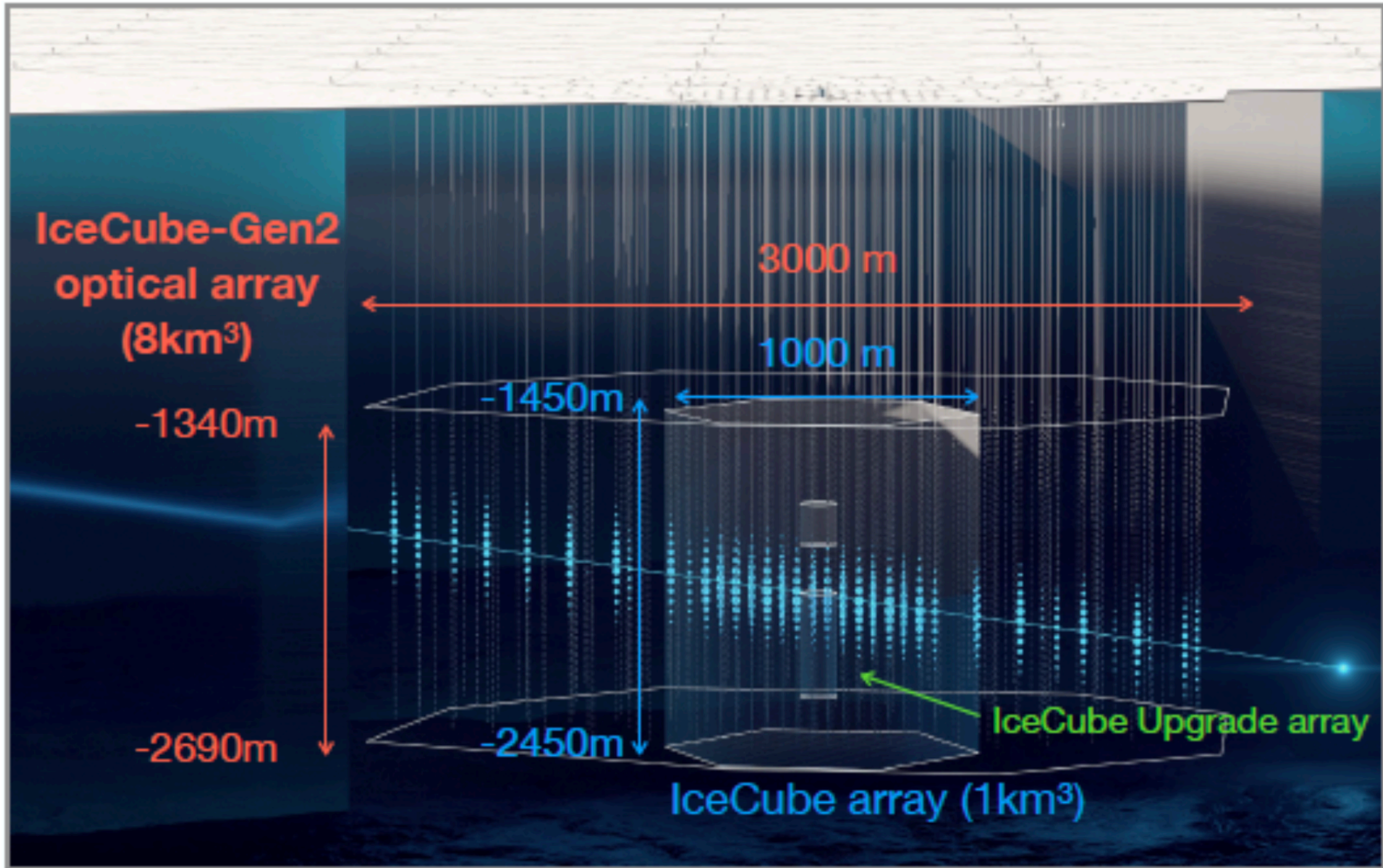
(collection efficiency not included here.)

Photon effective area prop. ~ 1/Energy threshold.

Detector arrangements and optical properties of water and ice are different, yet the PMT density scales well with energy threshold.

IceCube-Gen2

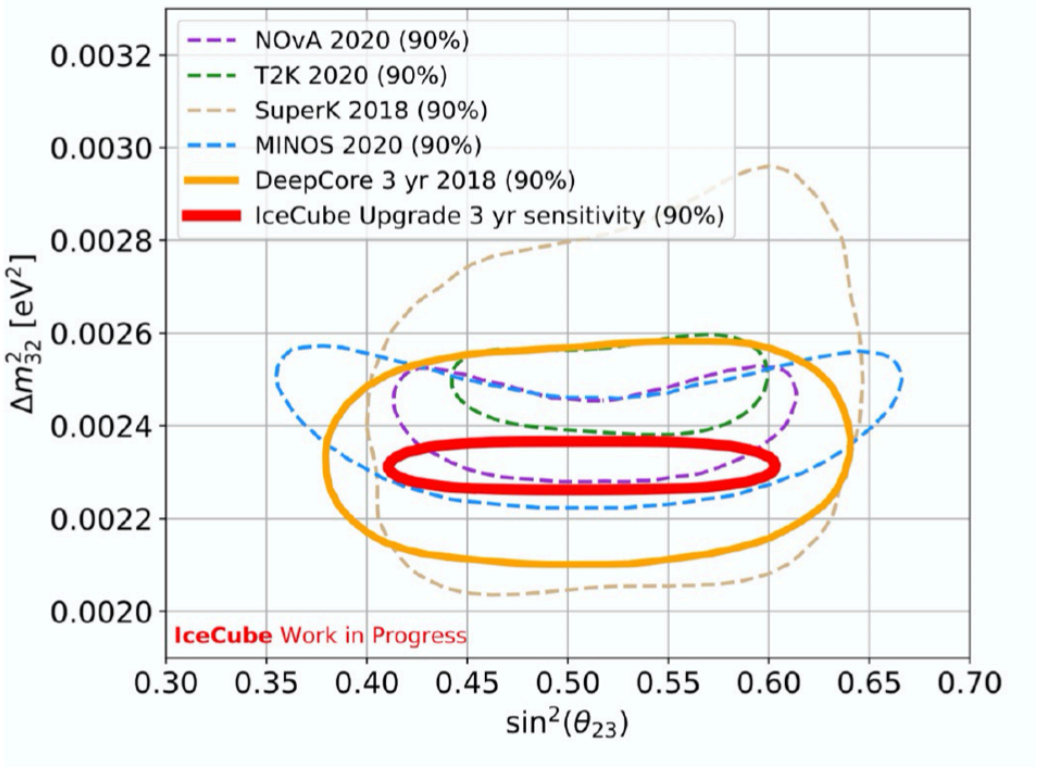
- **IceCube-Gen2 has a reference design** and is preparing a Technical Design document to be released this year and is ready for preliminary design.
  - Optical array, 8 km^3
  - Air shower array on top
  - Radio array, ~500 km^2

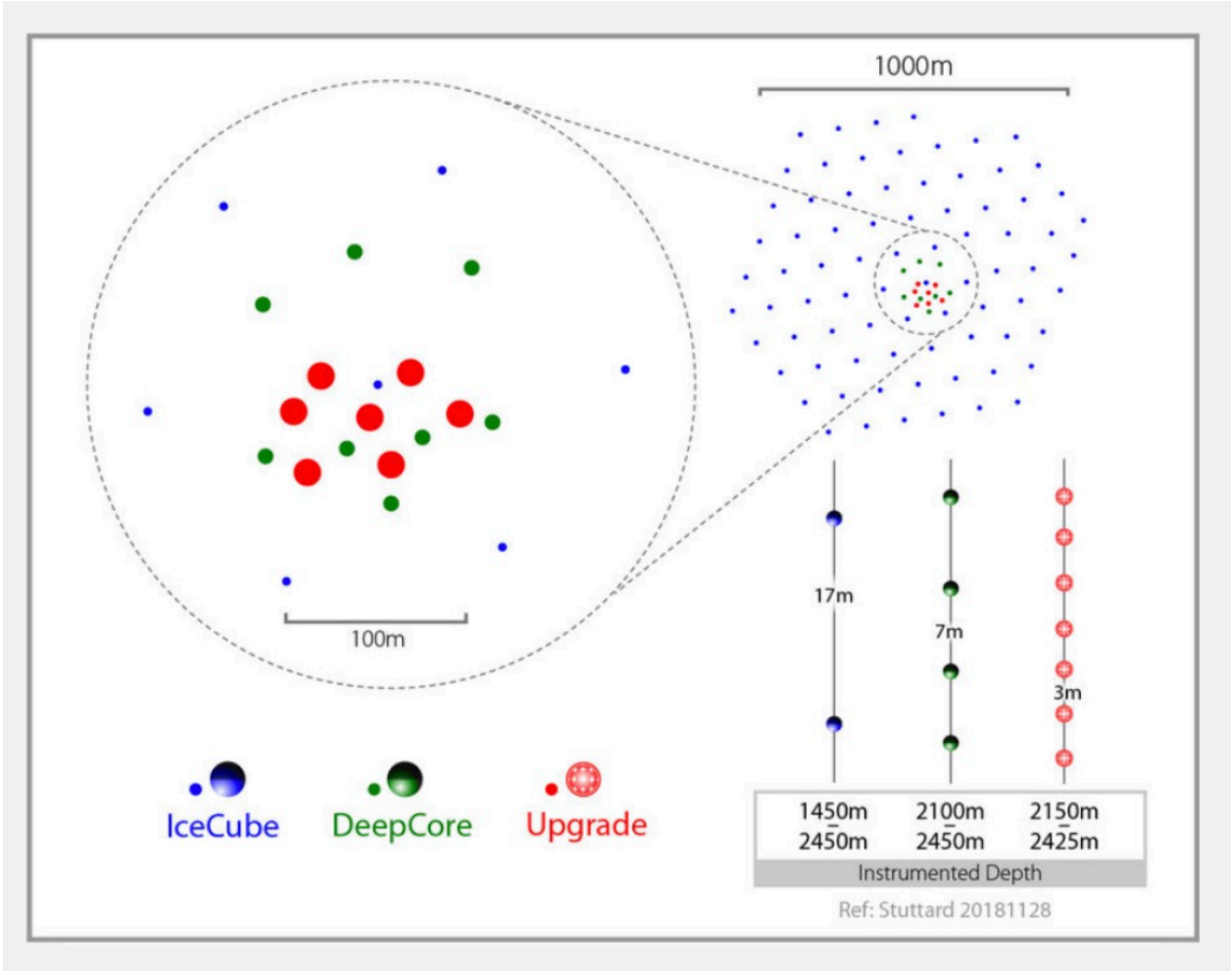


IceCube Upgrade: 7 dense strings infill

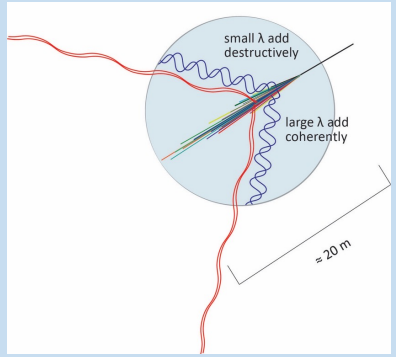
Run start: 2/2026

Projected 3yr sensitivity





RF emission from showers (Askaryan)



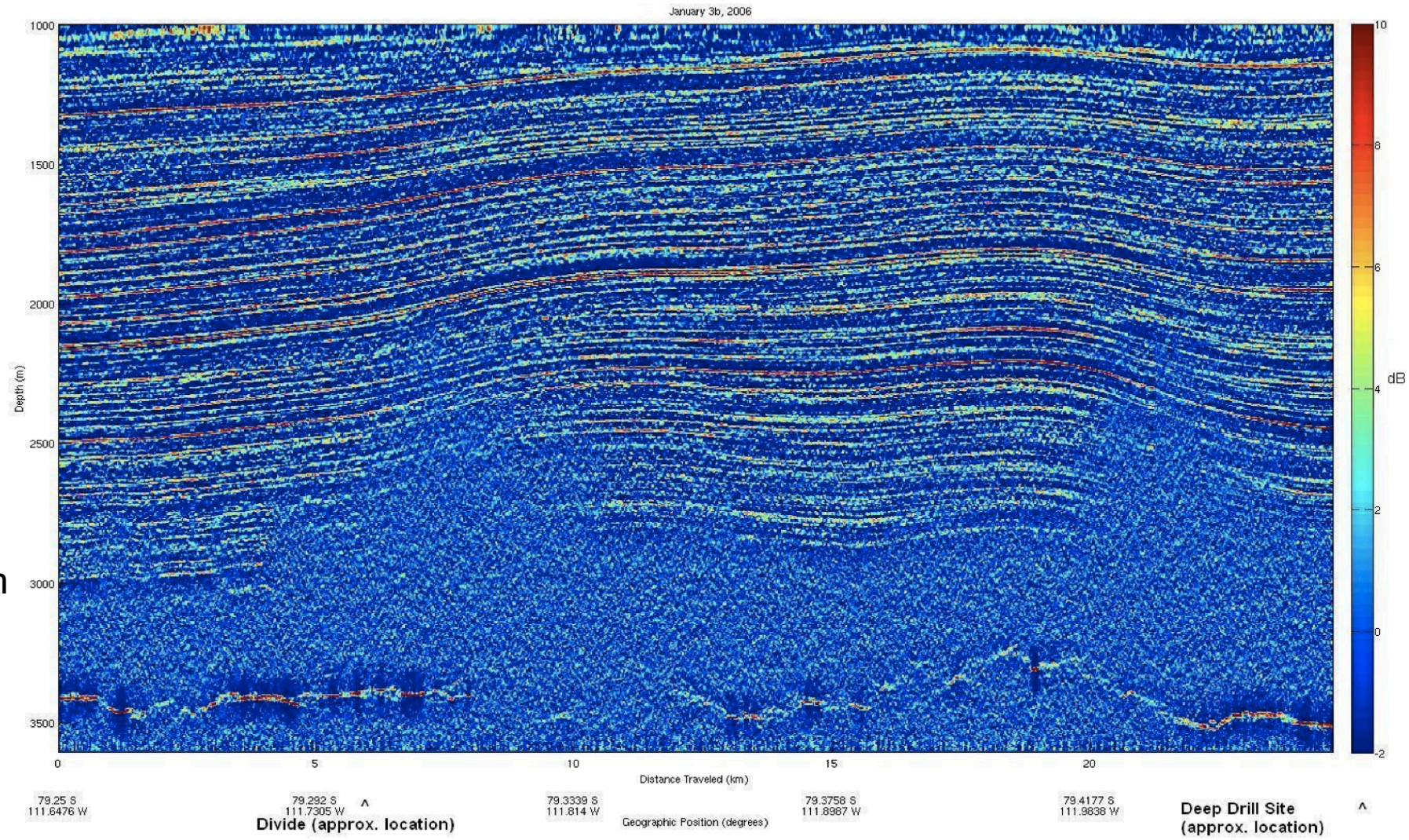
High energy showers produce coherent radio waves in dense dielectric media.

Cause: charge separation leads to a momentary local current.

In atmospher, also synchrotron emission in geomagnetic field.

(Power ~ sqr(El. Field), in that direction)

Ground penetrating radar (350MHz) image of Antarctic ice sheet
Cold Ice attenuation length: 1.5 km



1000m

2000m

3000m

0 5 10 15 20

[km]

Figure:
WAIS GPR map at 150MH
~4km deep, 25km wide

Ref: WAIS 2006 CReSIS Radar Da
Summary

With (mostly) LOFAR & Auger we established cosmic-ray radio detection

Slide: Sijbrand de Jong

State-of-the-art resolution for

- Direction 0.1^o – 0.5^o
- Energy 20 – 30 %
- Particle type X_{max} 20 – 40 g/cm²

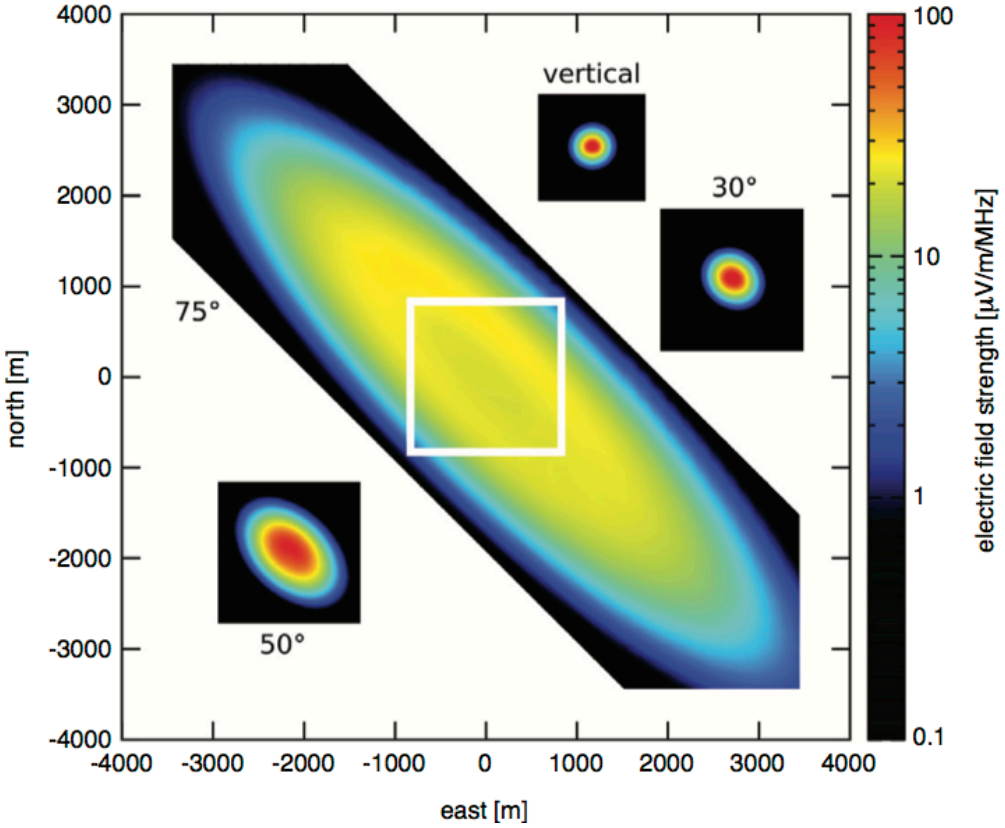
AERA: 17 km² 150 stations

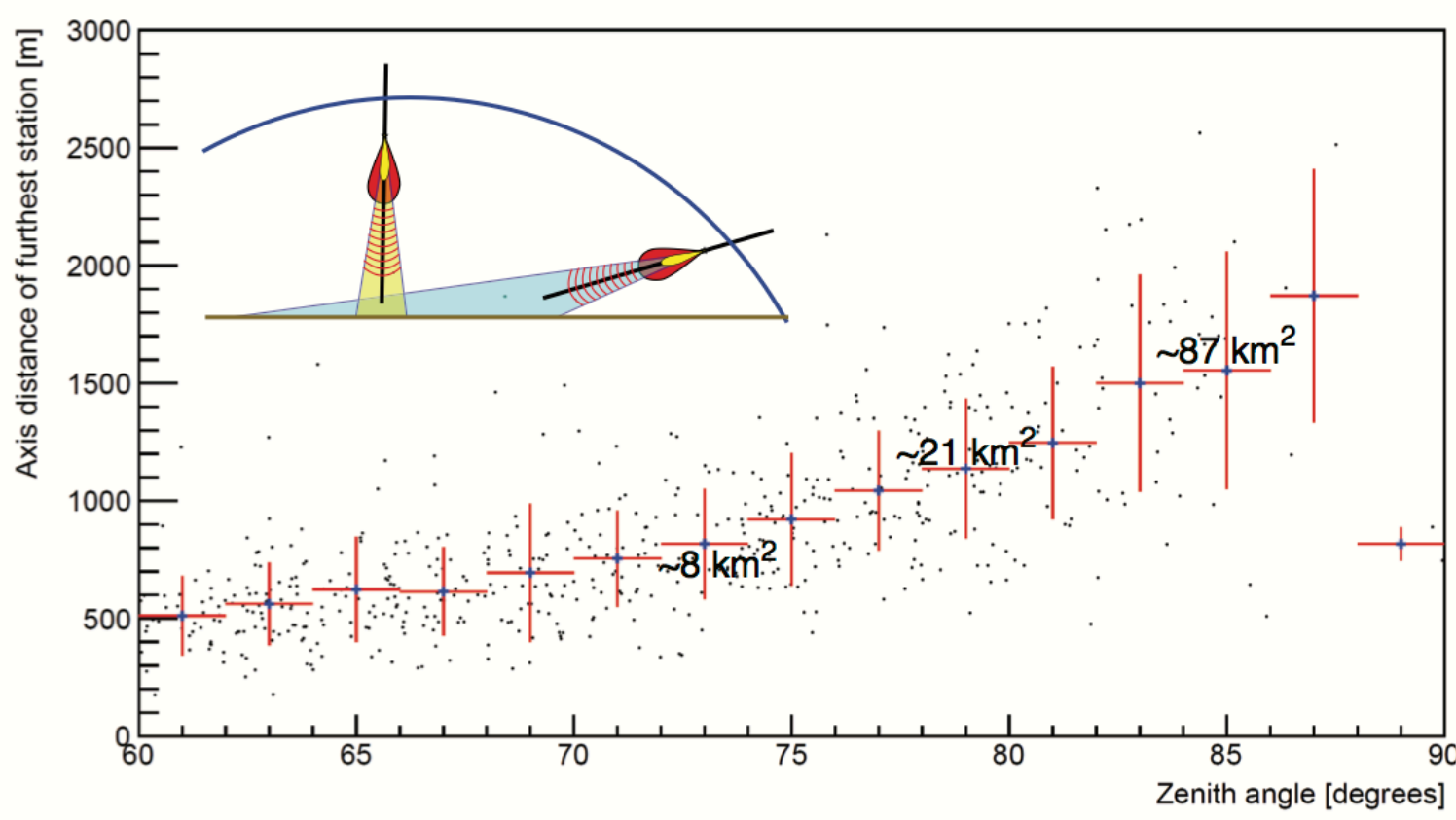
LOFAR: 5 km² >2000 stations

Horizontal air showers

Large footprint of radio signals

Slide: Sijbrand de Jong





Radio detectors for neutrinos

Target
Location (elevation)

balloon borne

air shower

ground based
look up

in ice detector

shower
in ice

Radio echo detection - a new strategy

Successful test in beam

PHYSICAL REVIEW LETTERS 124, 091101 (2020)

Editors' Suggestion | Featured in Physics

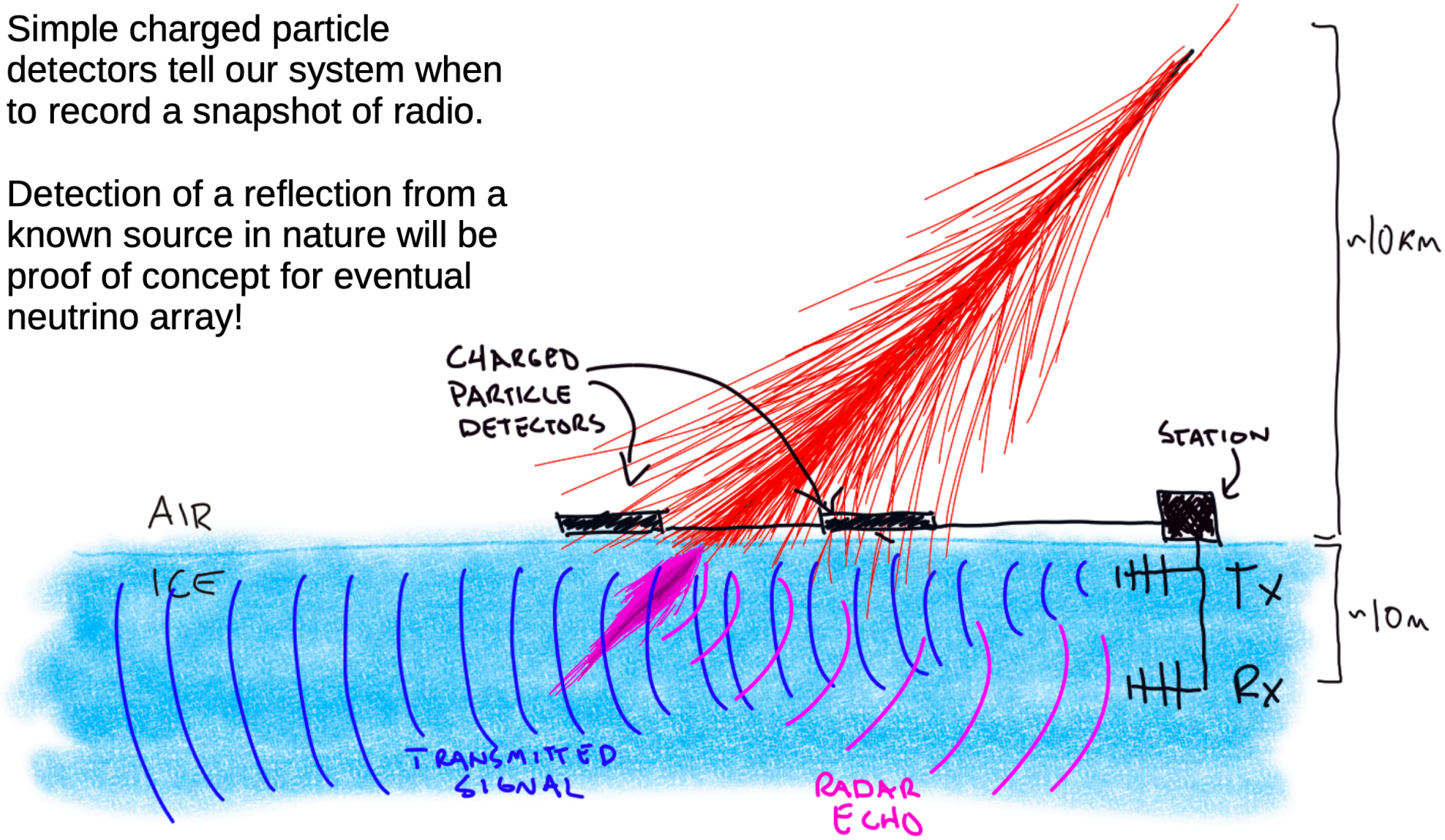
Observation of Radar Echoes from High-Energy Particle Cascades

S. Prohira,[1,*] K. D. de Vries,[2] P. Allison,[1] J. Beatty,[1] D. Besson,[3,4] A. Connolly,[1] N. van Eijndhoven,[2] C. Hast,[5] C.-Y. Kuo,[6] U. A. Latif,[3] T. Meures,[7] J. Nam,[6] A. Nozdrina,[3] J. P. Ralston,[3] Z. Riesen,[8] C. Sbrocco,[1] J. Torres,[1] and S. Wissel[8]

KU THE UNIVERSITY OF KANSAS

Simple charged particle detectors tell our system when to record a snapshot of radio.

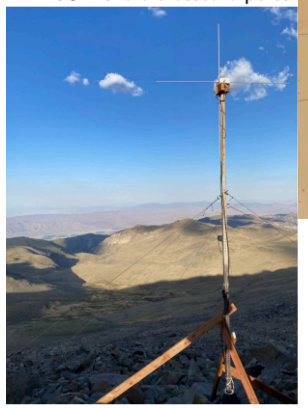
Detection of a reflection from a known source in nature will be proof of concept for eventual neutrino array!

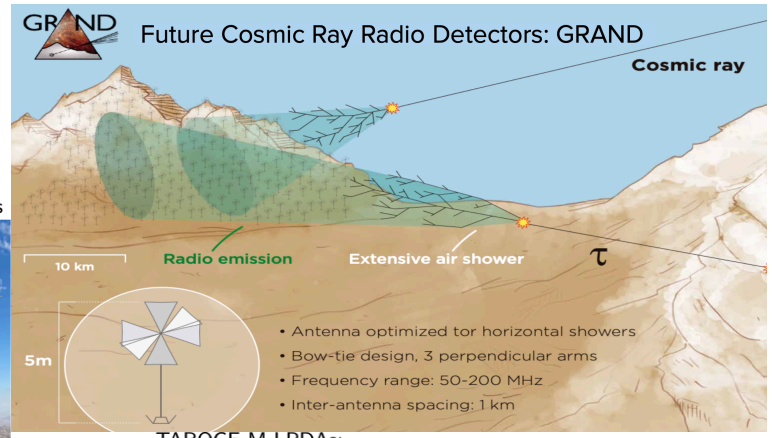


Radio detectors (in construction and proposed):

PUEO, including low-frequency dropdowns:

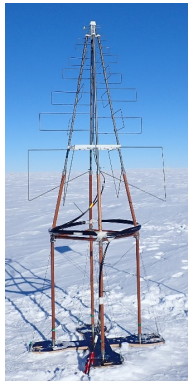
BEACON short crossed-dipoles





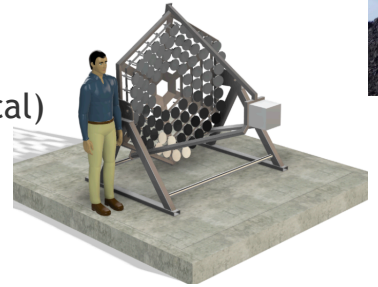
GRAND

TAROGE-M LPDAs:

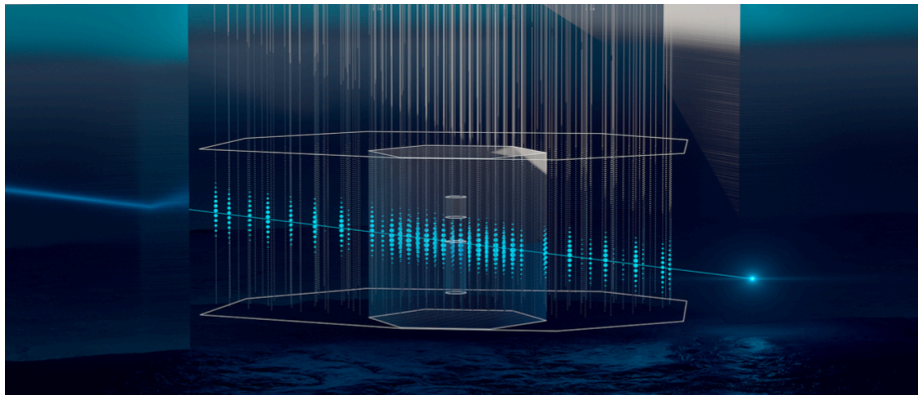


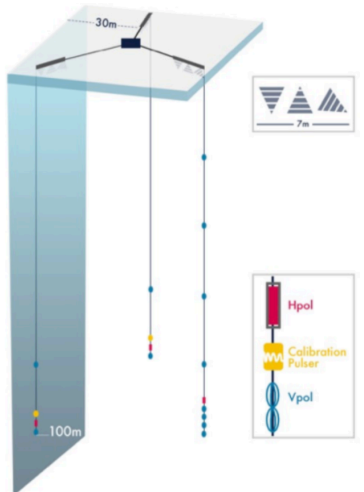
ARA, RNO-G
IceCube-Gen2

Trinity
(proto, optical)



IceCube-Gen2

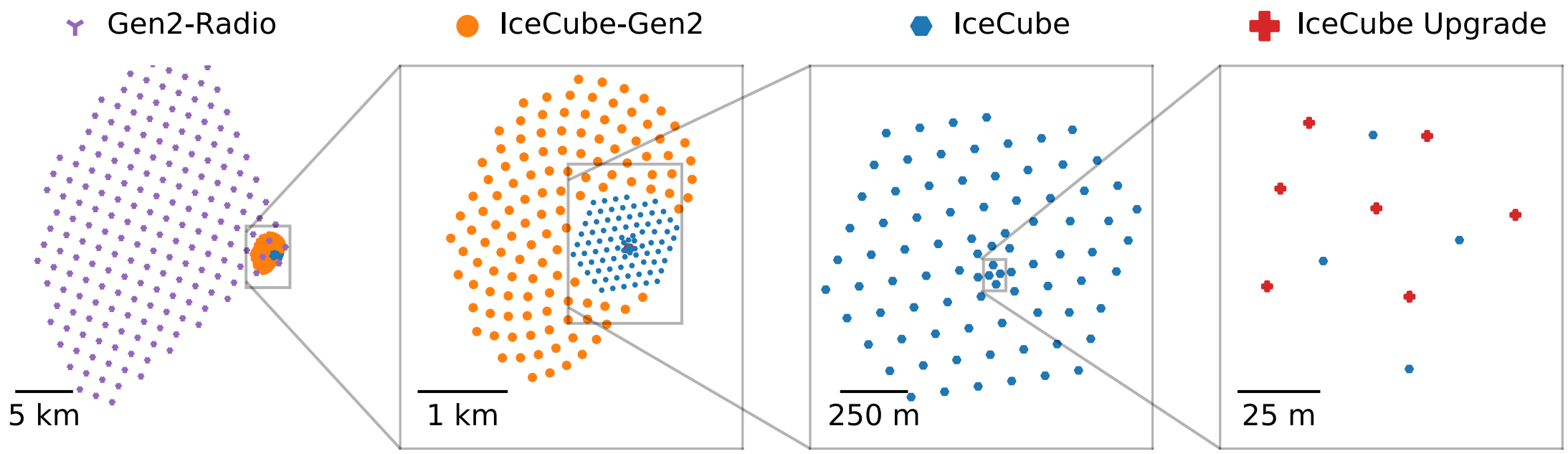




IceCube-Gen2: optical + radio

IceCube and Gen2 on different scales reflecting different energies

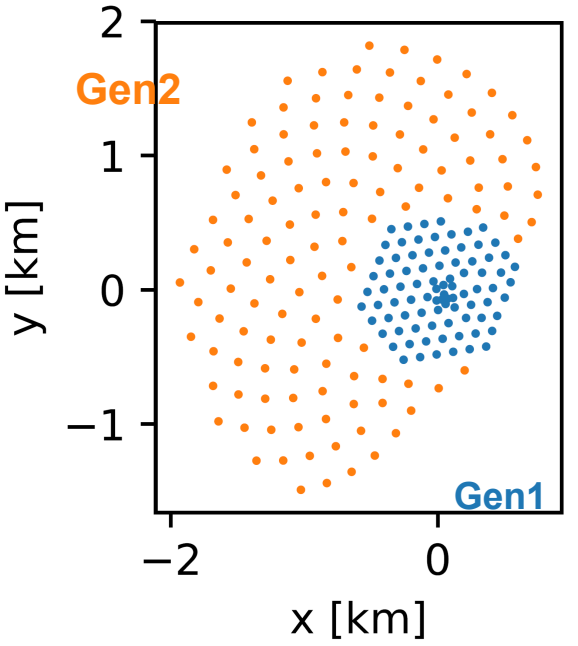
- **IceCube-Gen2 reference design:**
  - Optical array (8km^3)
  - Air shower array on top
  - Radio array (150m, 500km2)



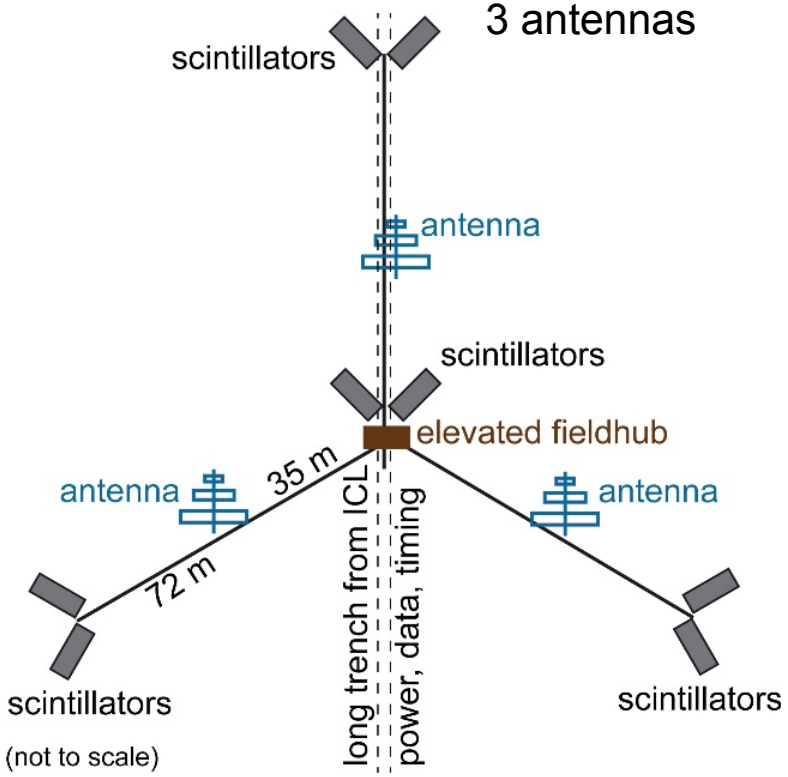
100 PeV	10 TeV	1 TeV	few GeV
~1000 km^3	~8 km^3	1 km^3	~10 Mt

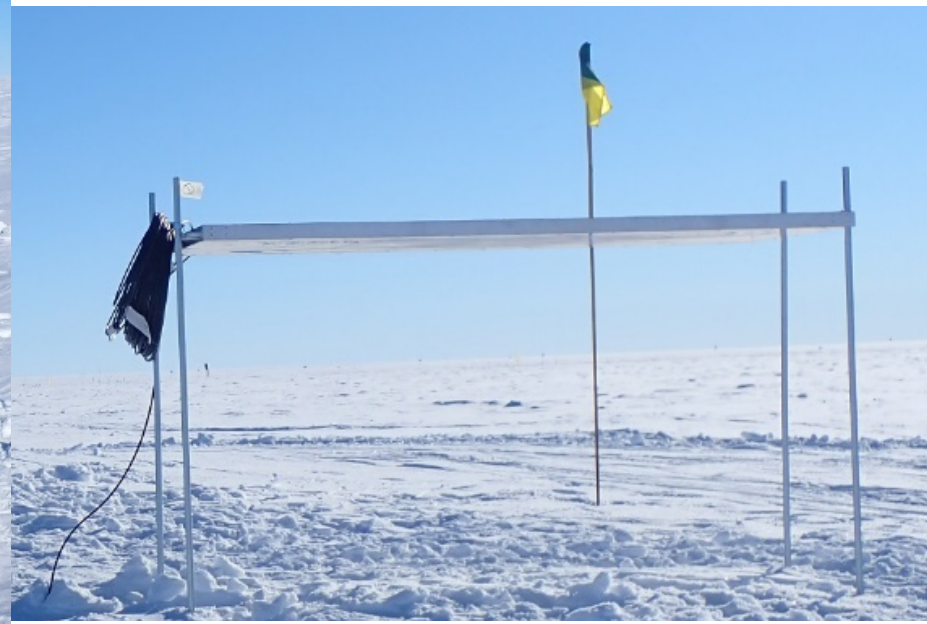
Gen2 Surface Array

Baseline design extends the planned IceTop enhancement to footprint of the IceCube-Gen2 optical array

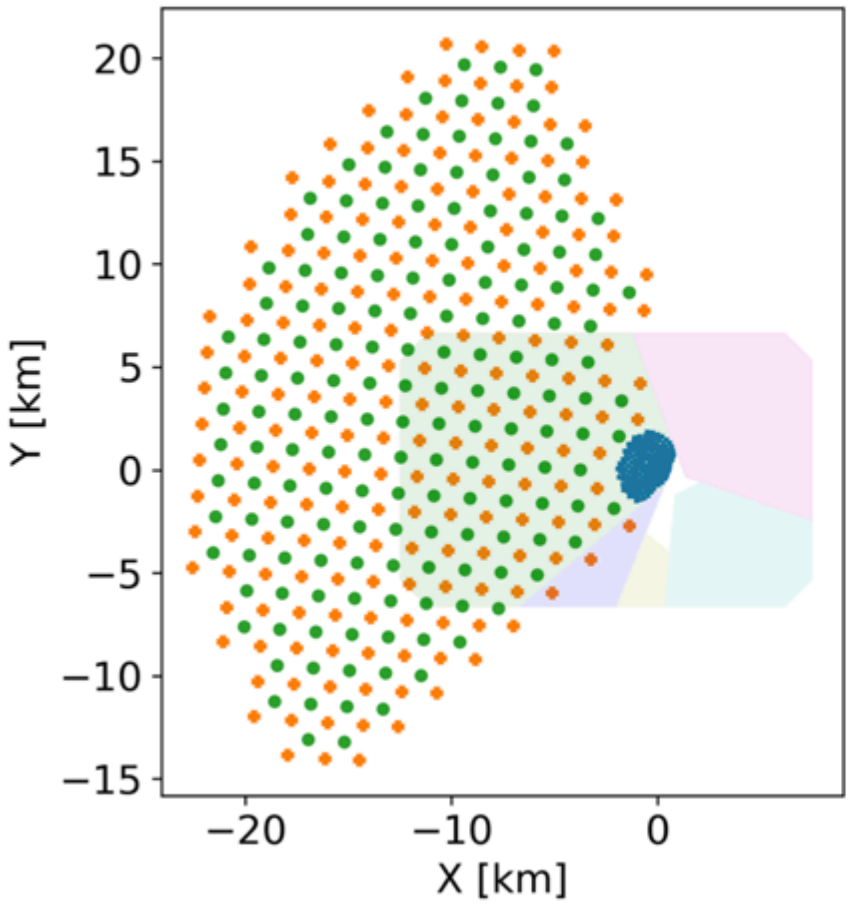


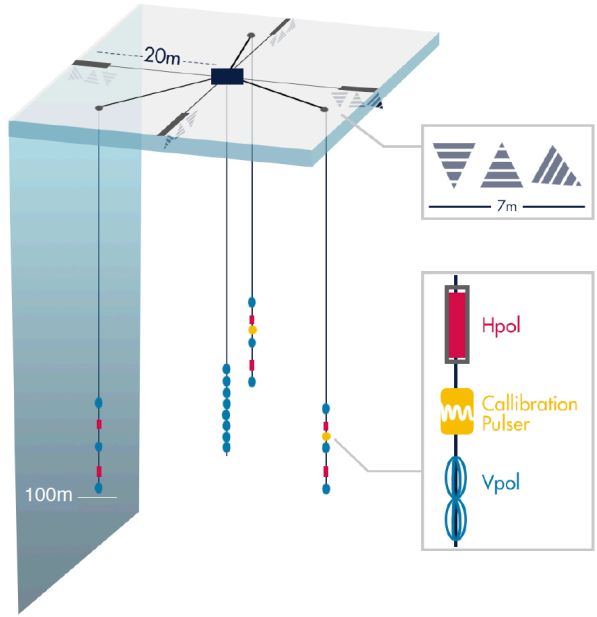
Station Design:
4 pairs of scintillators
3 antennas

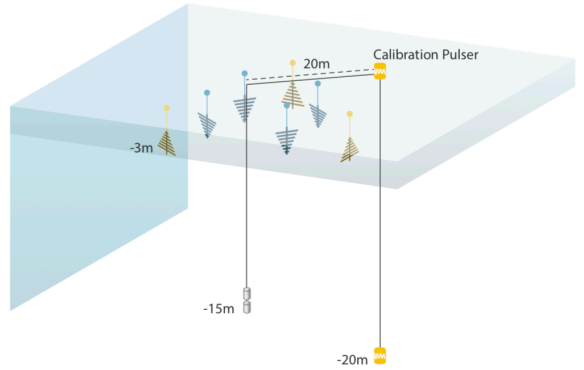




IceCube-Gen2 radio array conceptual design







Area: 500 km^2

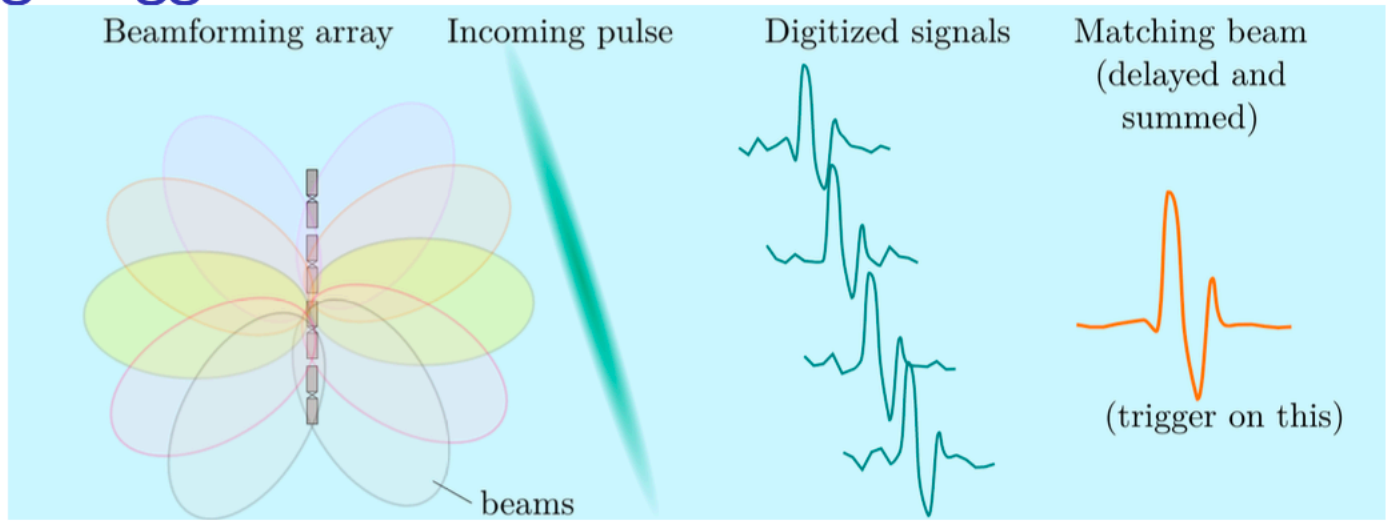
300 stations

1000 km^3 of ice volume

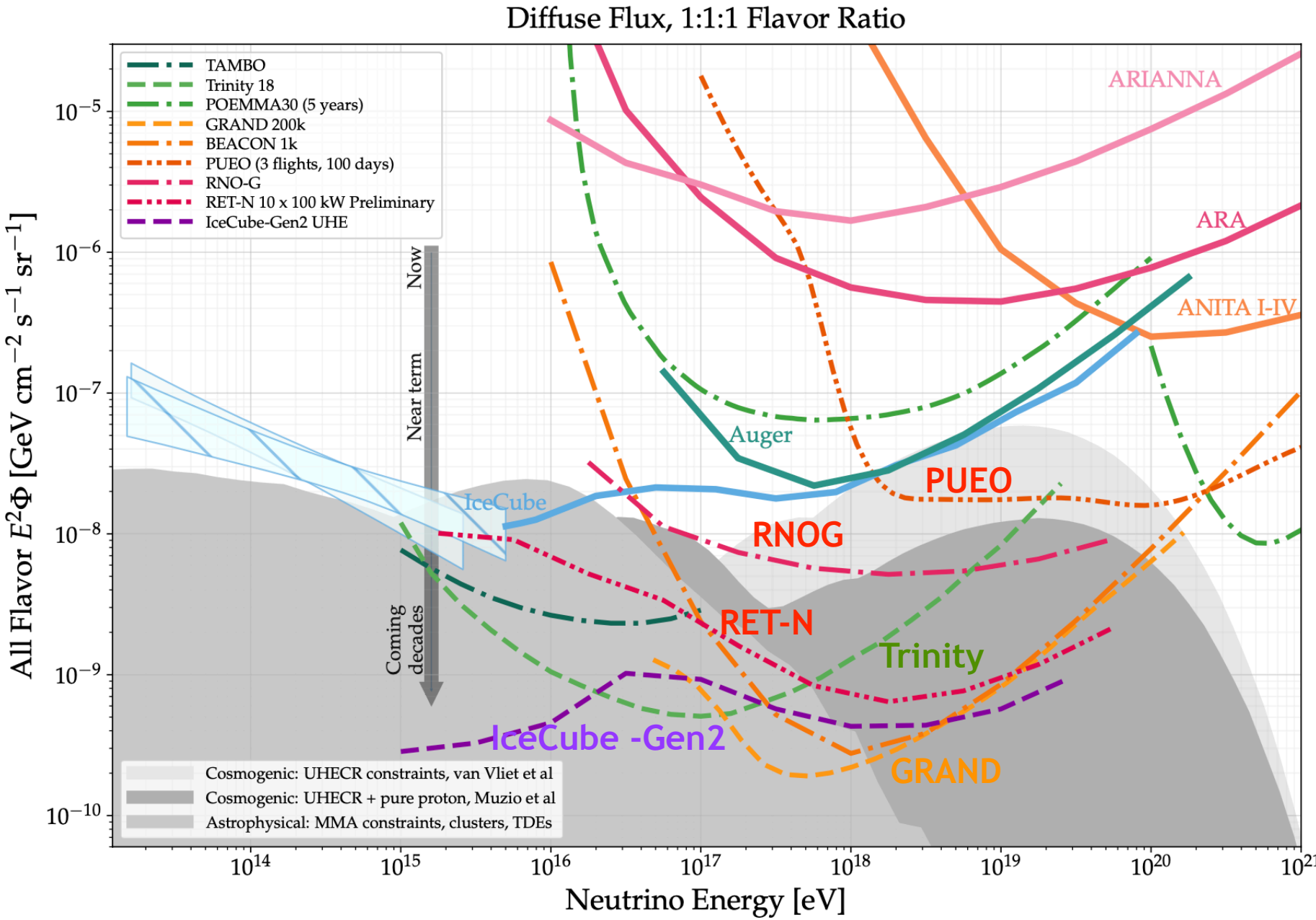
IceCube GEN2

Phased arrays of antennas - beam forming trigger

Beamforming Trigger



- With digital trigger, can synthesize multiple high-gain "beams" from low-gain antennas
- Take multiple antennas and combine signals with time delays to enhance certain directions (beams), then trigger on the beam
  - Technique demonstrated at South Pole with Askaryan Radio Array (see arXiv:1809.04573, arXiv:2202.07080)
  - Used in BEACON (including RFI masking)
  - Will be used in PUEO with RFSoCs
  - Will be used with subset of antennas (bottom 4) in RNO-G, Gen2Radio



Solid lines are actual limits.

dotted lines are sensitivities

Takeaways

Thriving program of astroparticle experiments, cosmic rays and neutrinos.

Radio Technology is ready for science class facility.

IceCube-Gen2: integrated approach, optical + radio, over wide energy range.
Reference design to be released Technical Design Report this fall.

Great opportunities for students getting involved in instrumentation.

At lower energies: Neutrino properties - atmospheric

Use 200,000 atmospheric neutrinos, 7000 nu_taus atmospheric neutrinos (10 yrs IceCube) to measure neutrino properties with extreme statistics,
incl. nonstandard interaction.

IceCube Upgrade sensitivity (run start: 2026)