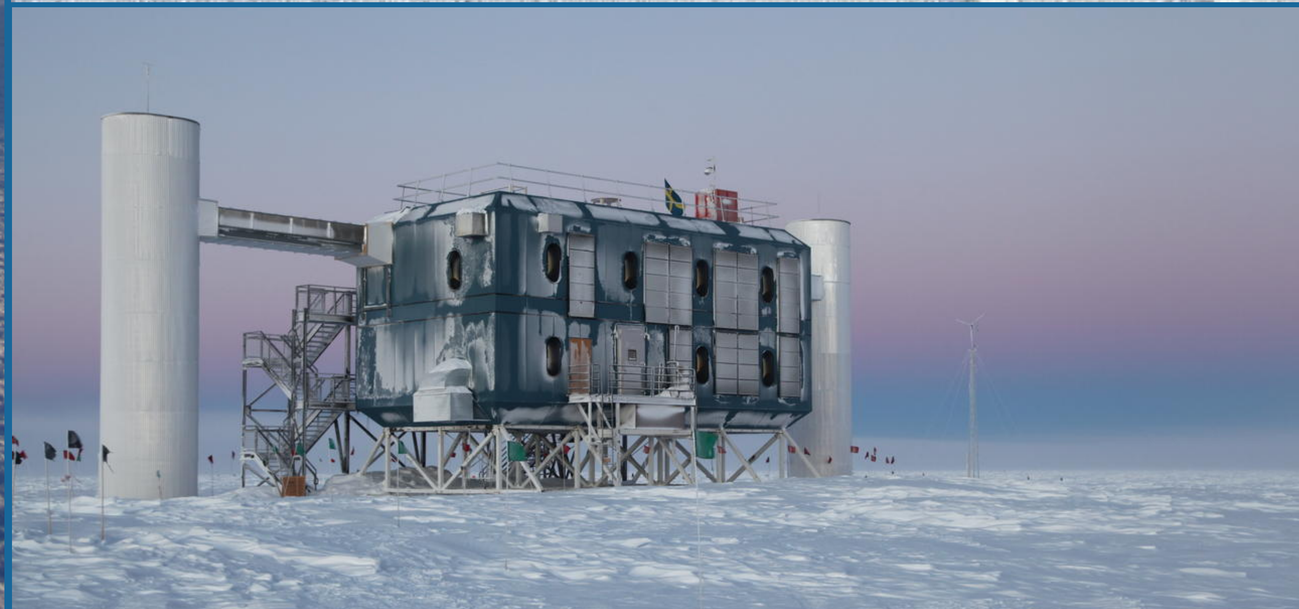
POTENTIAL OF NEXT- GENERATION PEV-ZEV NEUTRINO TELESCOPES

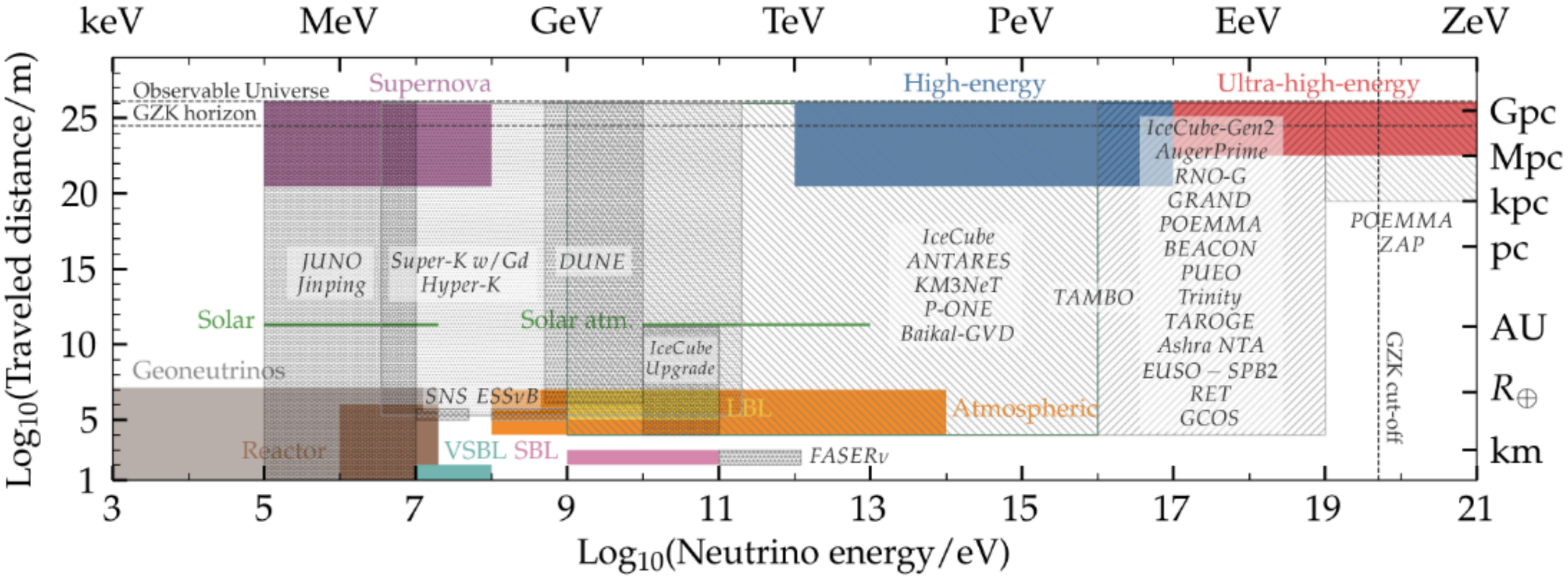


Simona Toscano

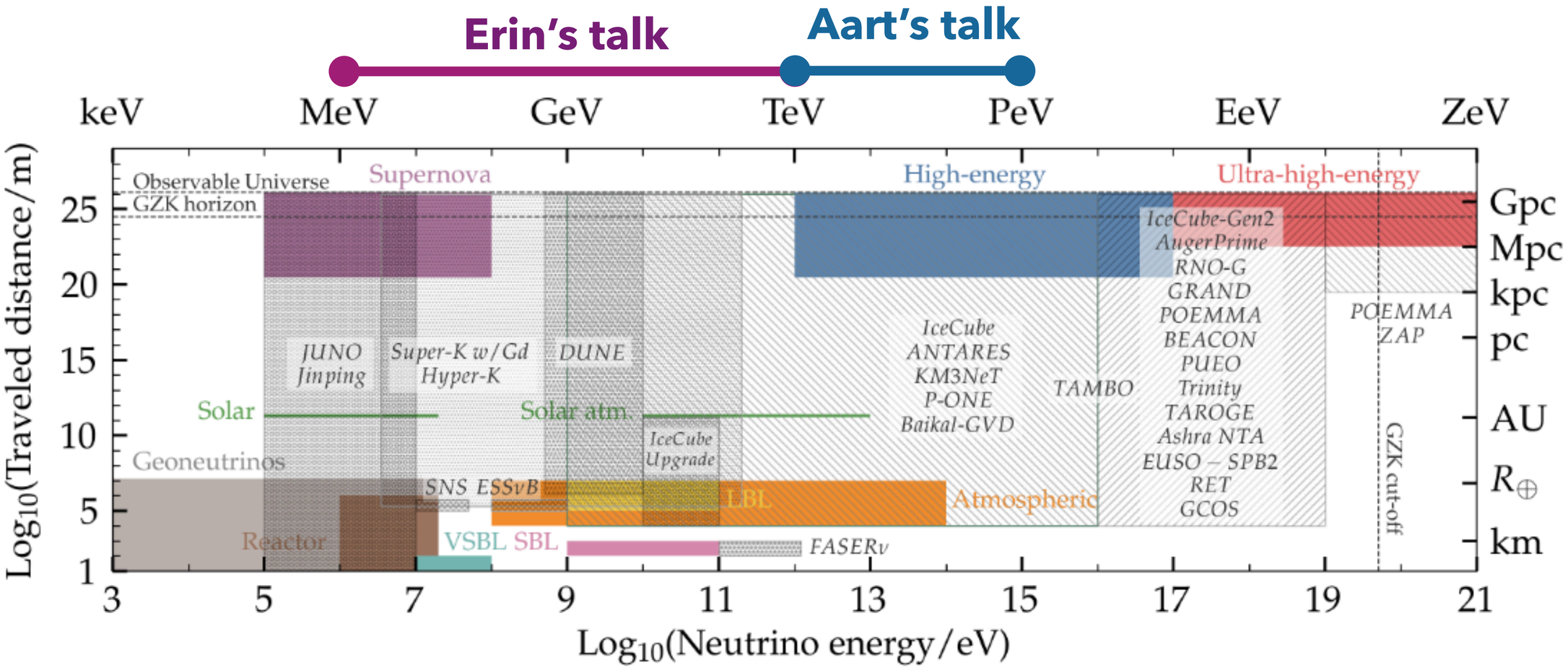
Interuniversity Institute for High Energies (IIHE - ULB)

toscano@icecube.wisc.edu

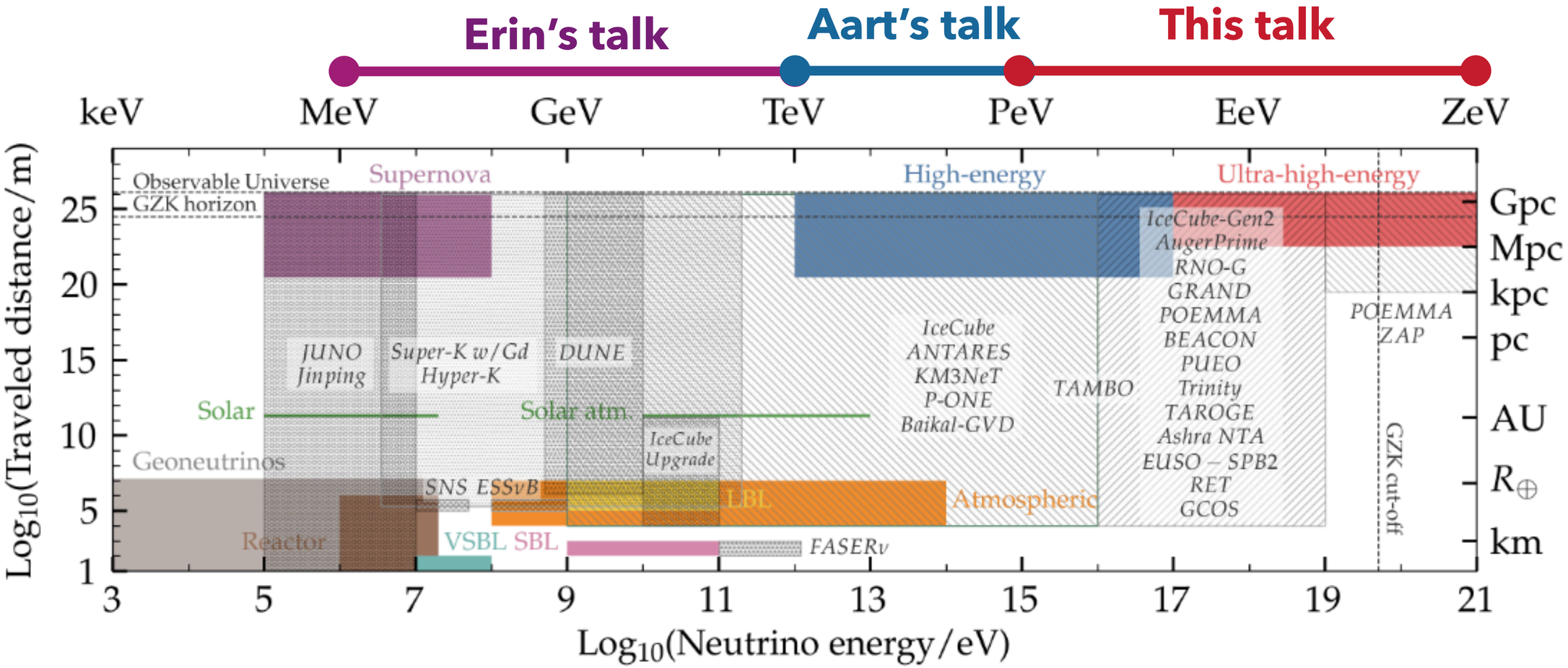
The Neutrino sky: experimental landscape



The Neutrino sky: experimental landscape

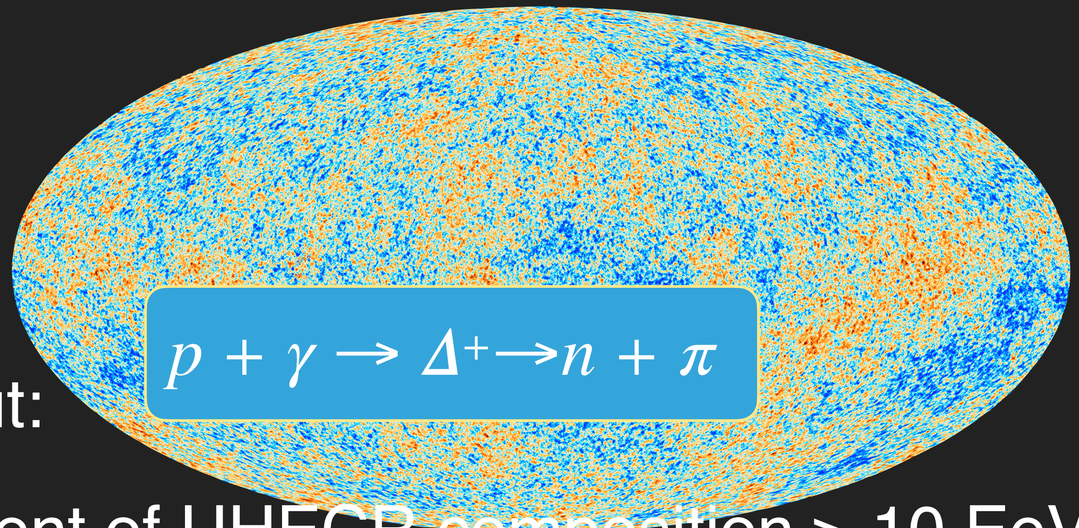


The Neutrino sky: experimental landscape



The neutrino sky: what are we hunting?

Astrophysical > 10 PeV | **Cosmogenic (GZK) > EeV**

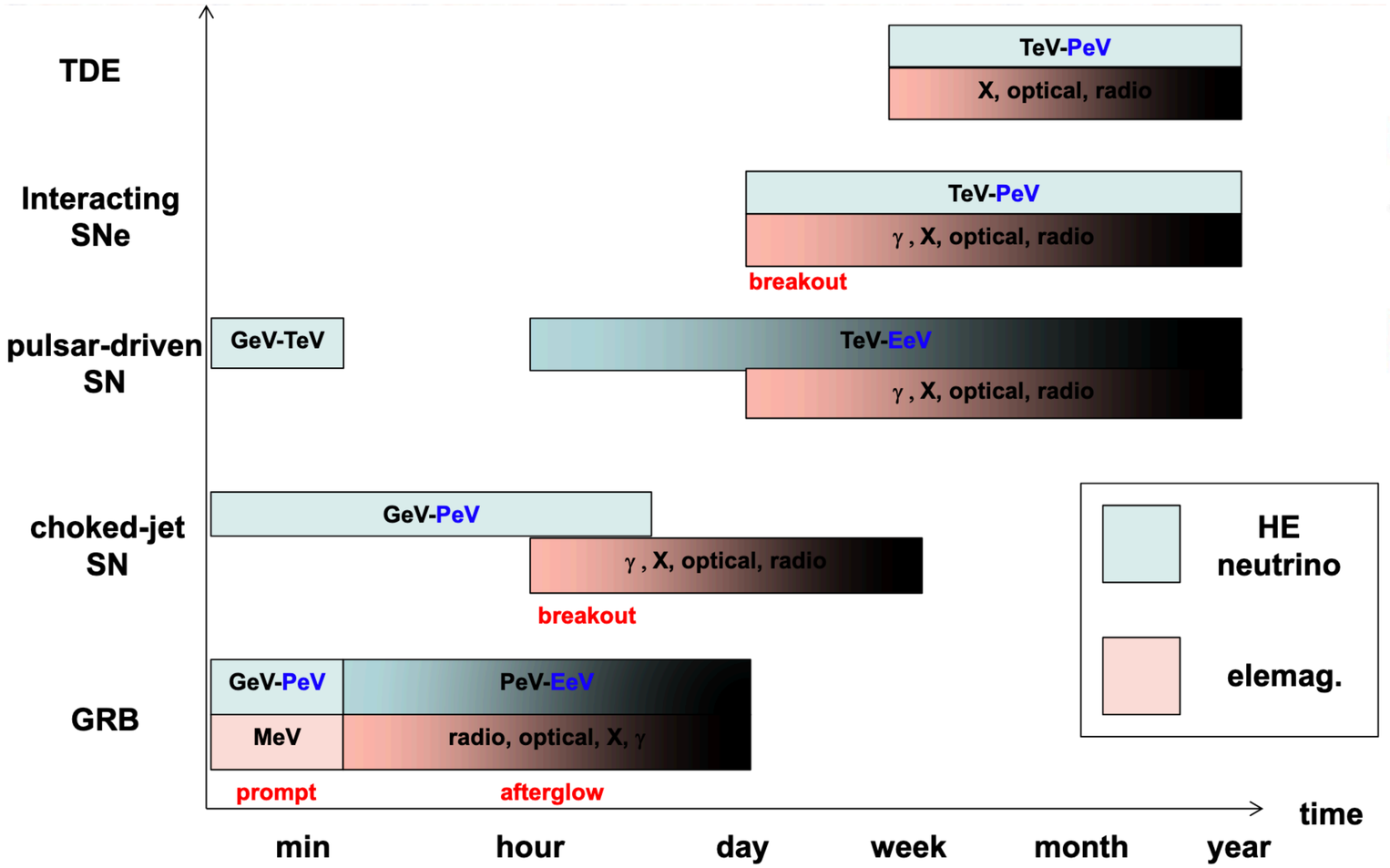


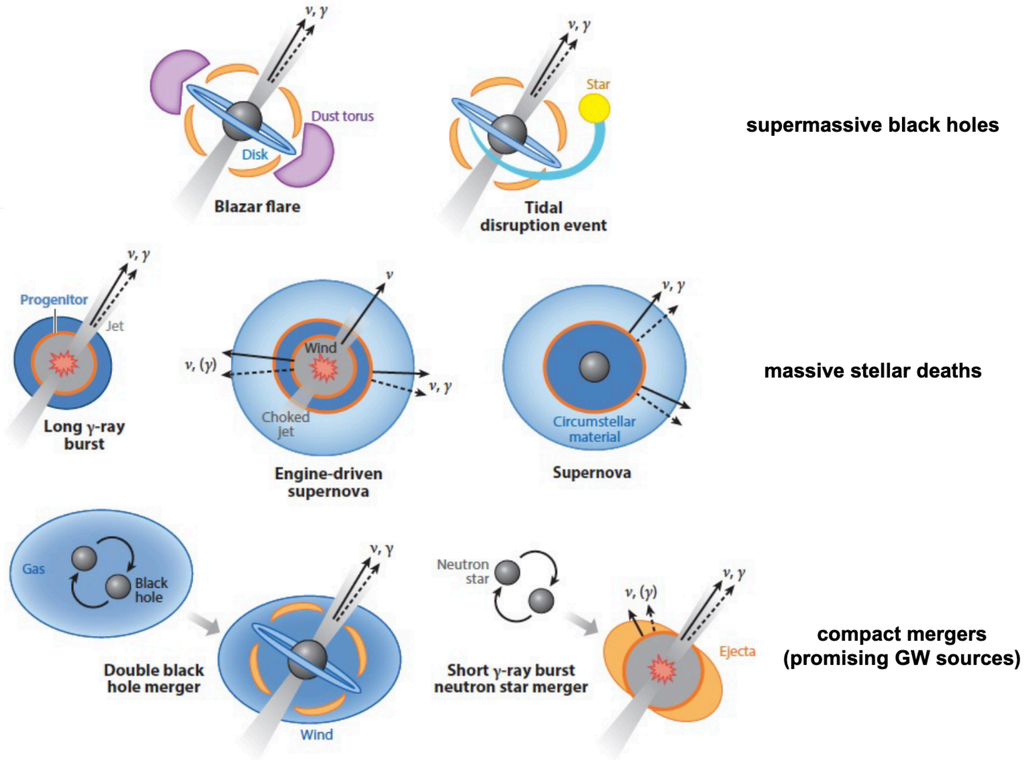
UHE neutrinos can give information about:

- Cosmogenic flux serves as measurement of UHECR composition > 10 EeV. Direct link to highest energy CRs (carry 5% of primary energy)
- Astrophysical neutrino sources (transient multi-messenger astronomy is a powerful tool with low statistics).
- Fundamental physics at energies not accessible at Earth (covered by Mauricio and Carlos this morning)

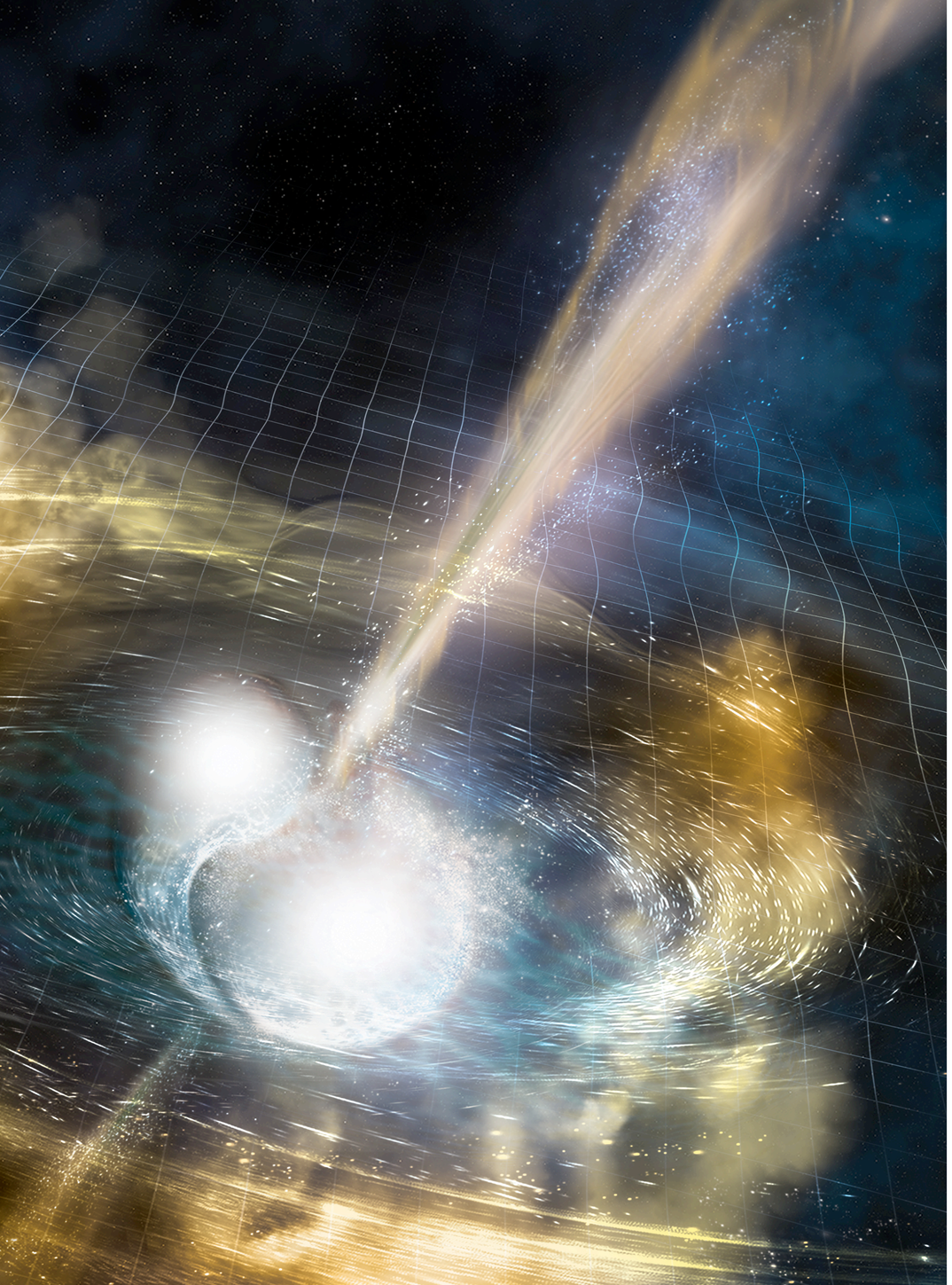
High-energy transients and the neutrino sky

from Kohta's talk on Wednesday





Several sources might emit neutrinos at E >PeV.



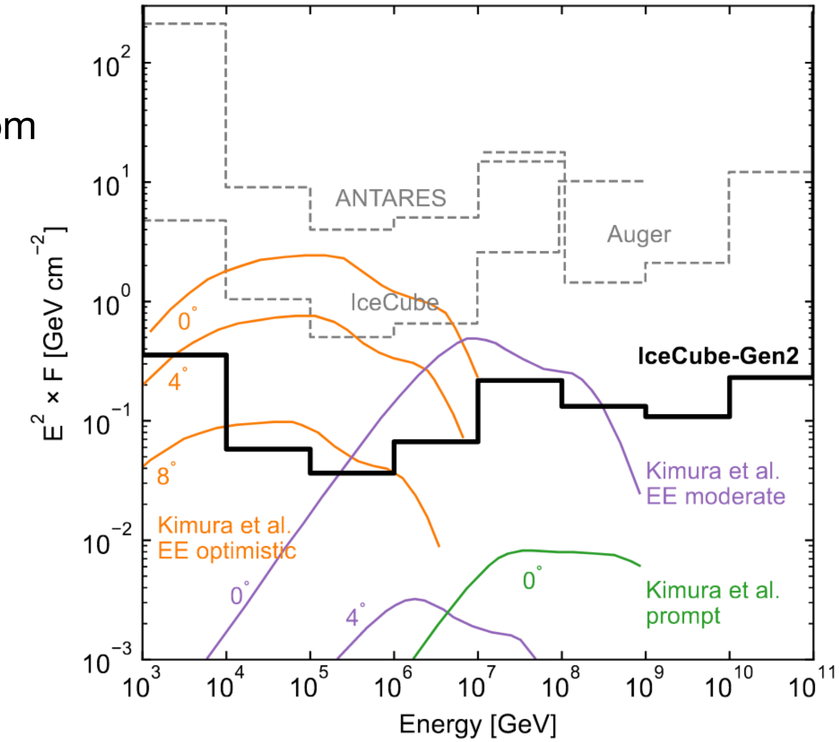
Binary NS mergers: GW170817

Multimessenger discovery of the binary neutron star merger GW170817.

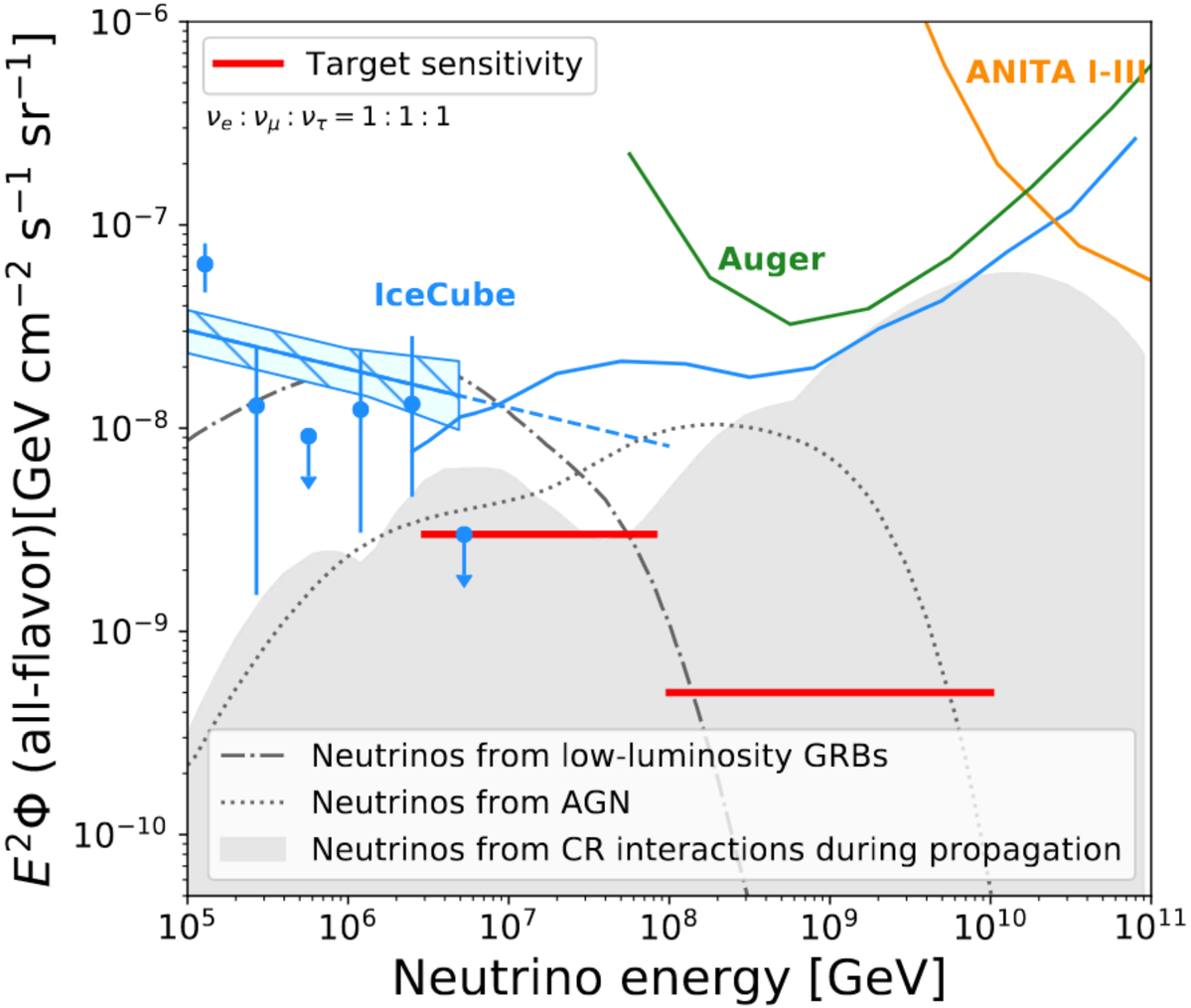
Coincident with observation of sGRB.

No neutrinos but constraints on neutrino emission from 100 GeV to 100 EeV.

on-axis extended emission from optimistic scenarios ruled out



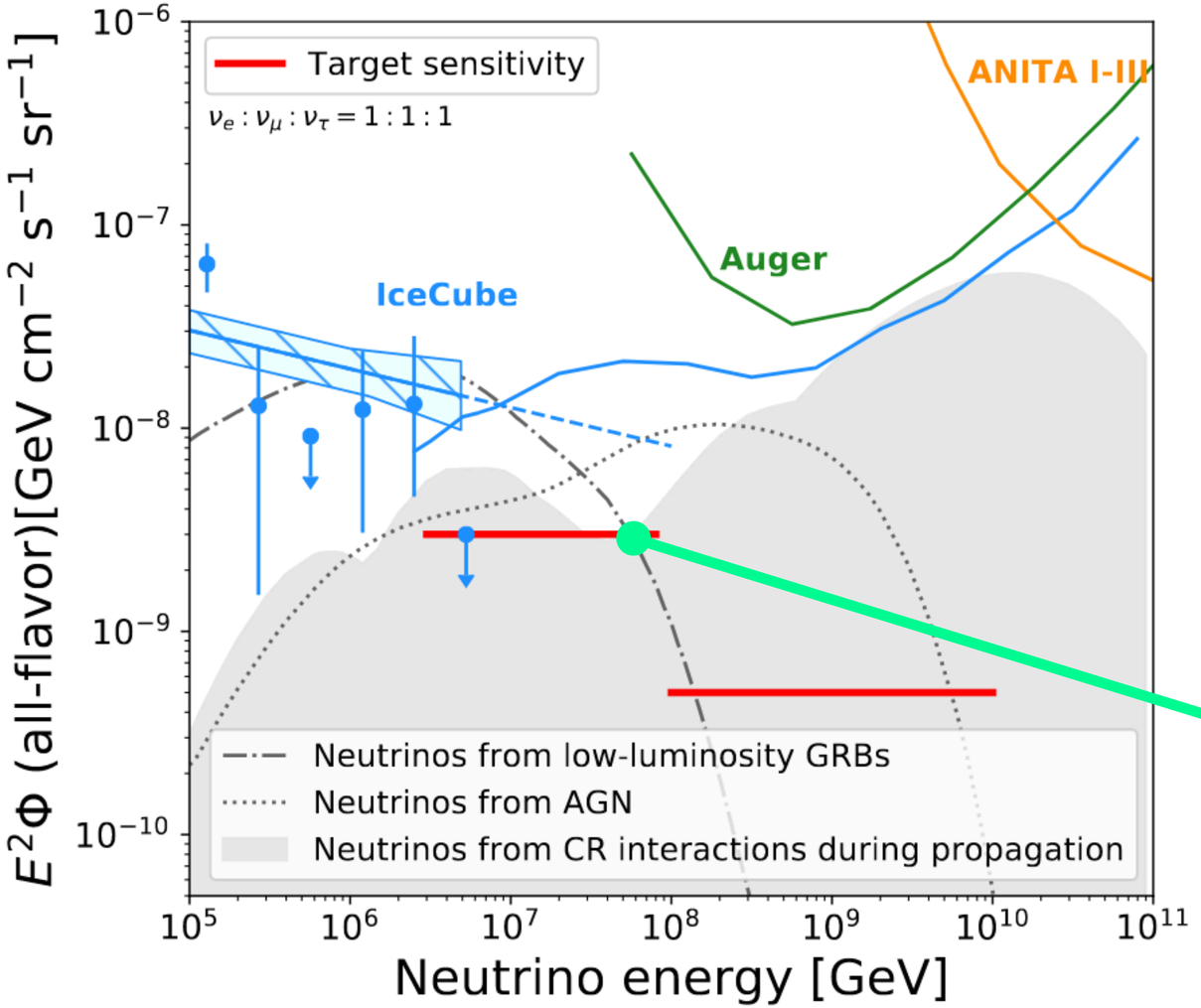
Science goal: target sensitivity of new experiments



- Very large effective volumes (Teraton) needed.
- E > 10 PeV is an uncovered territory.

[Ackerman et al., Astro2020 White Paper, arXiv:1903.04334.pdf]

Science goal: target sensitivity of new experiments

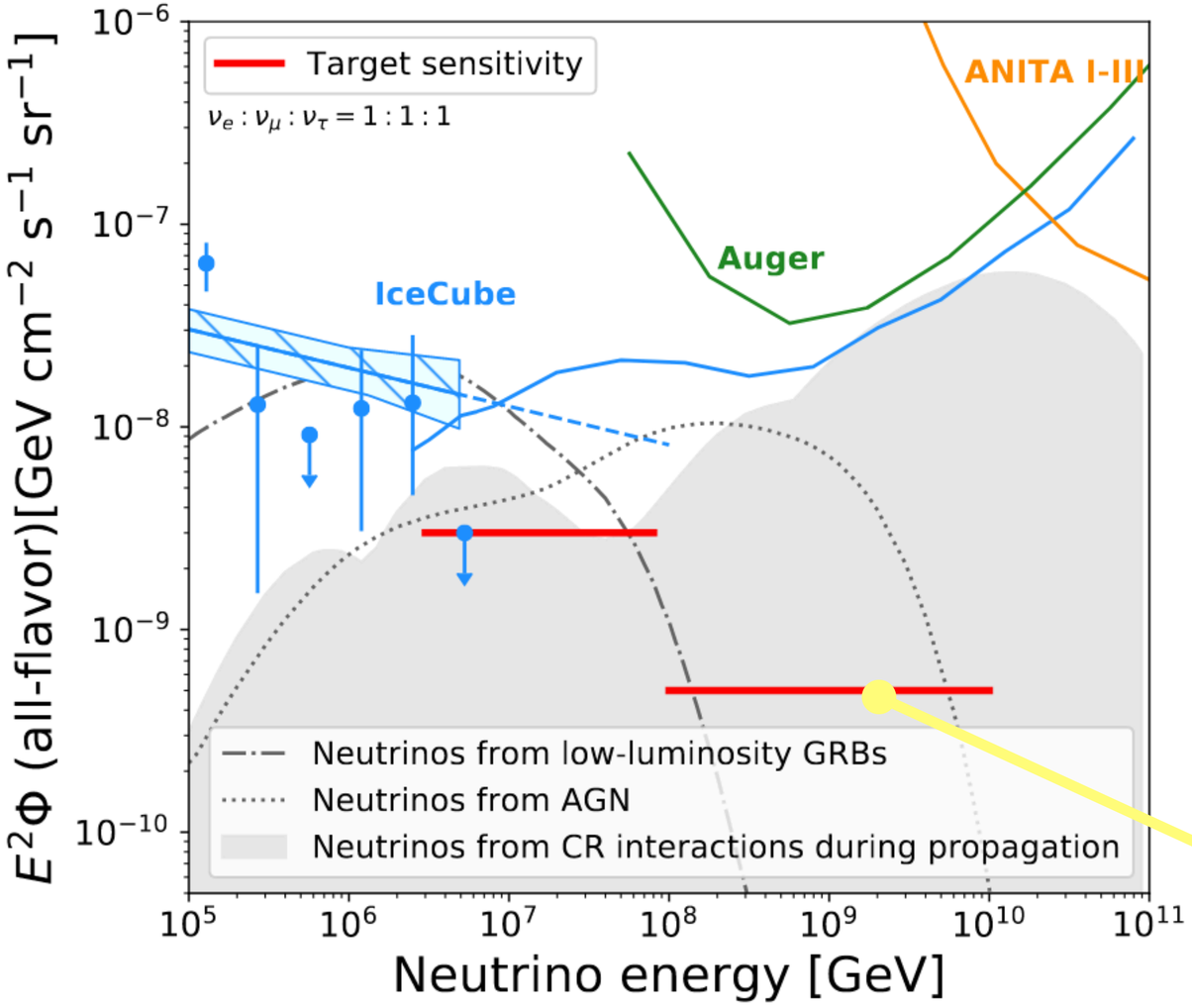


- Very large effective volumes (Teraton) needed.
- E > 10 PeV is an uncovered territory.

Study of the astrophysical flux properties (cutoff, breaks) at higher energies than IceCube requires an order-of-magnitude improvement in sensitivity.

[Ackerman et al., Astro2020 White Paper, arXiv:1903.04334.pdf]

Science goal: target sensitivity of new experiments



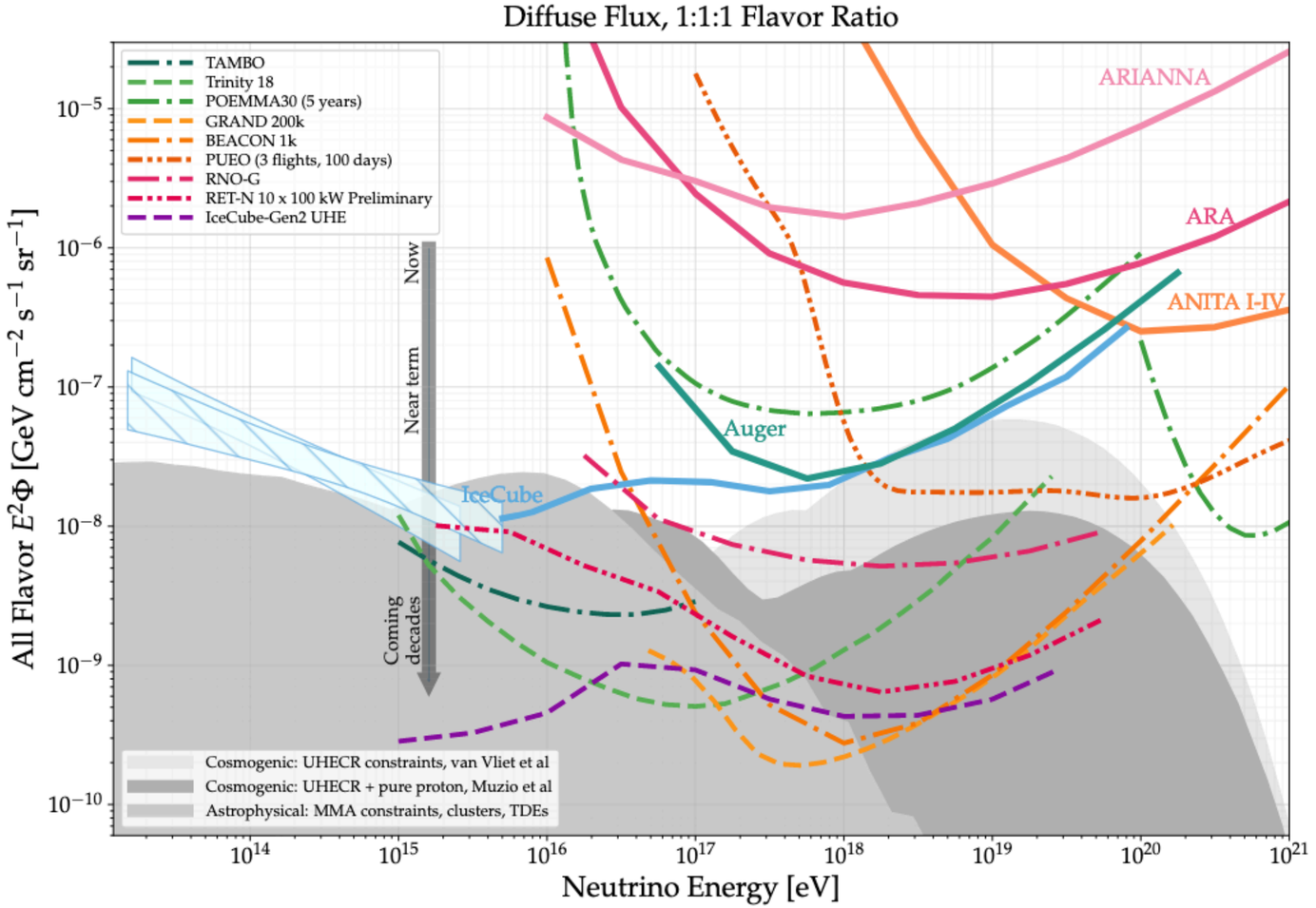
[Ackerman et al., Astro2020 White Paper, arXiv:1903.04334.pdf]

- Very large effective volumes (Teraton) needed.
- E > 10 PeV is an uncovered territory.

Study of the source evolution and propagation mechanism needs ~2 orders of magnitude improvement in sensitivity (to reach more pessimistic scenarios).

The experimental landscape: diffuse neutrino flux

UHE neutrinos Snowmass White Paper: arxiv.org/pdf/2203.08096.pdf



Particle detectors

Optical Cherenkov and fluorescence

Earth-Skimming in-air radio

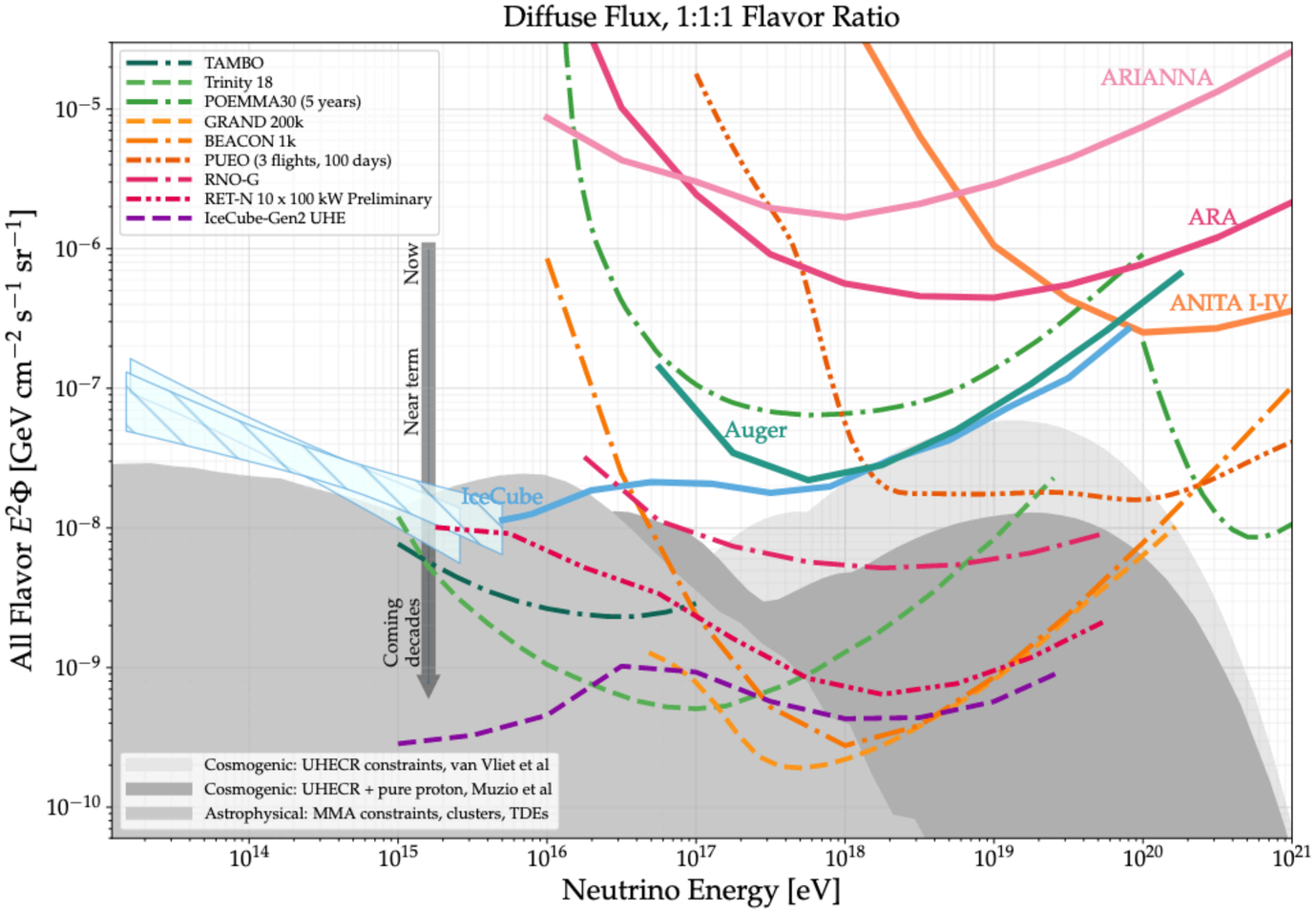
In-ice radio

Optical Cherenkov

IceCube, Auger, and ANITA experiments already constrain the cosmogenic neutrino parameter space.
Major goal for next-generation observatories is detection (reaching pessimistic predictions: flux sensitivity near 10^{-10} GeV cm^{-2} s^{-1} sr^{-1} @ 1 EeV.

The experimental landscape: diffuse neutrino flux

UHE neutrinos Snowmass White Paper: arxiv.org/pdf/2203.08096.pdf



Particle detectors

Optical Cherenkov and fluorescence

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WILL TALK (MOSTLY) ABOUT RADIO DETECTION

The experimental landscape: diffuse neutrino flux

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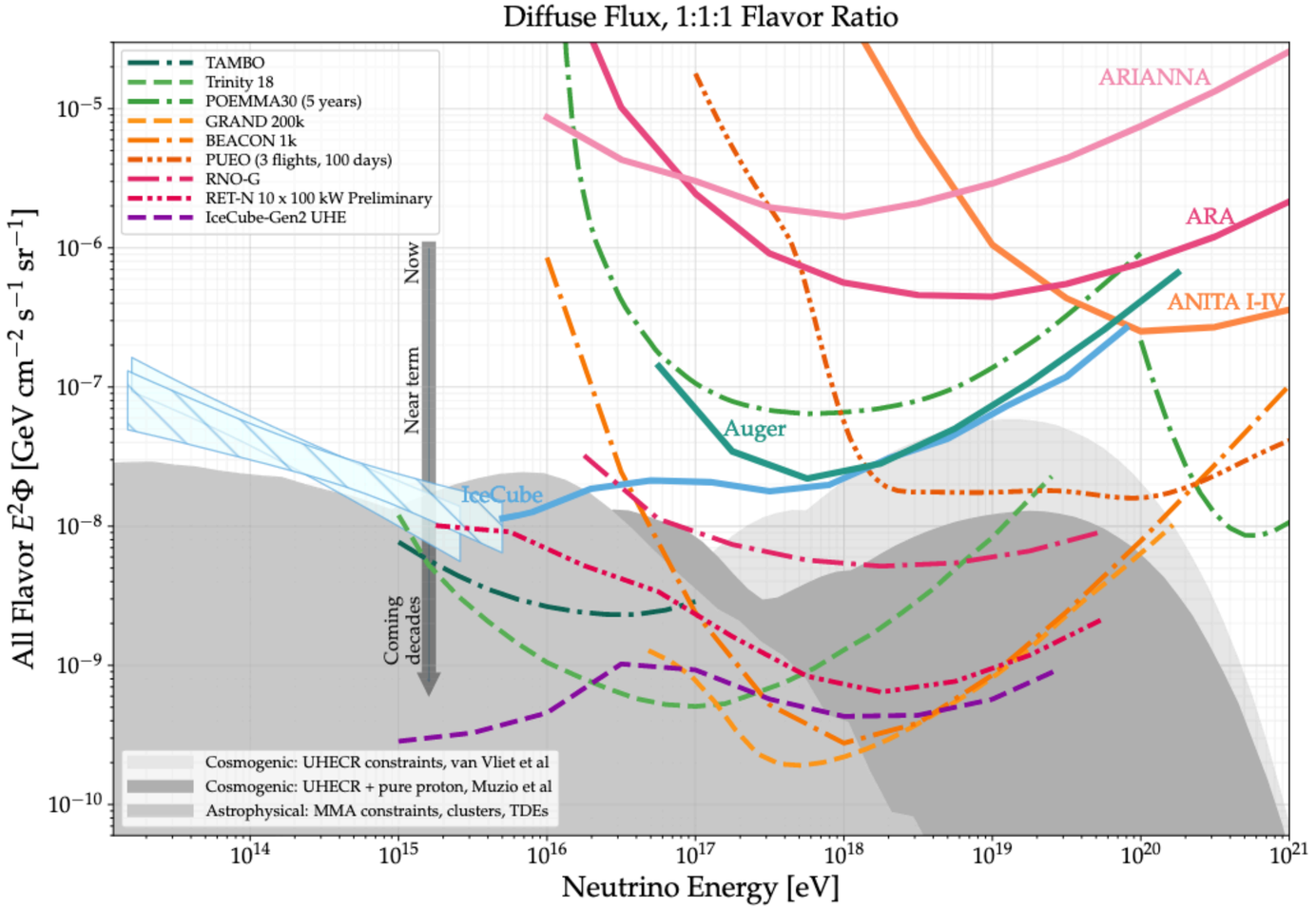

Particle detectors

Optical Cherenkov and fluorescence

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Optical Cherenkov

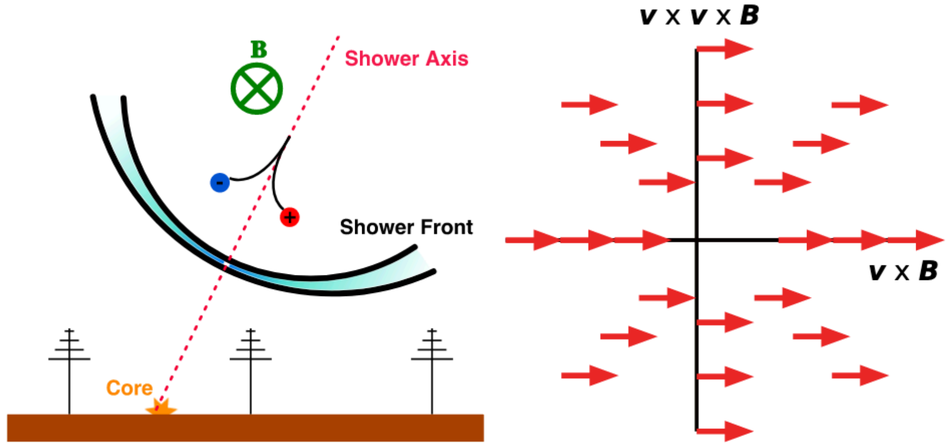
WILL TALK (MOSTLY) ABOUT RADIO DETECTION

COMMON FEATURE: INSTRUMENTING HUGE EFFECTIVE VOLUMES TO REACH EXTREMELY LOW FLUX

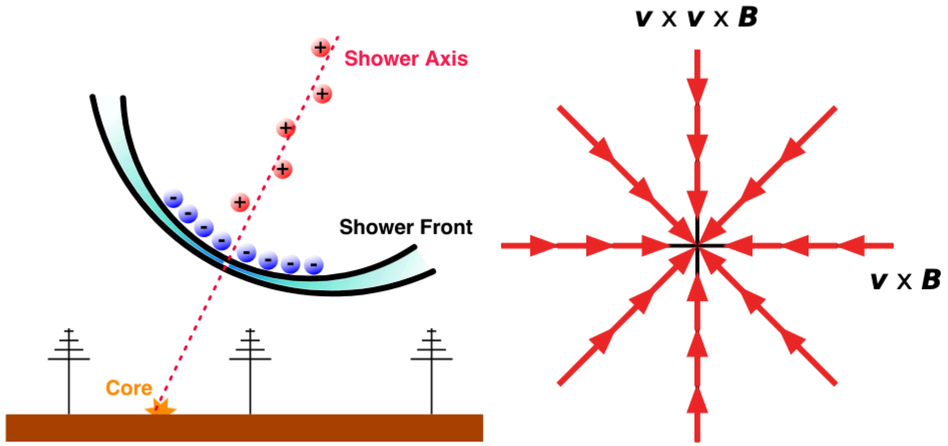
Shower radio detection: emission mechanism

Three effects explain the radio emission: Magnetic field, charge imbalance, index of refraction

Geomagnetic effect: charge separation. Lorentz-force, polarization orthogonal to shower axis and magnetic field

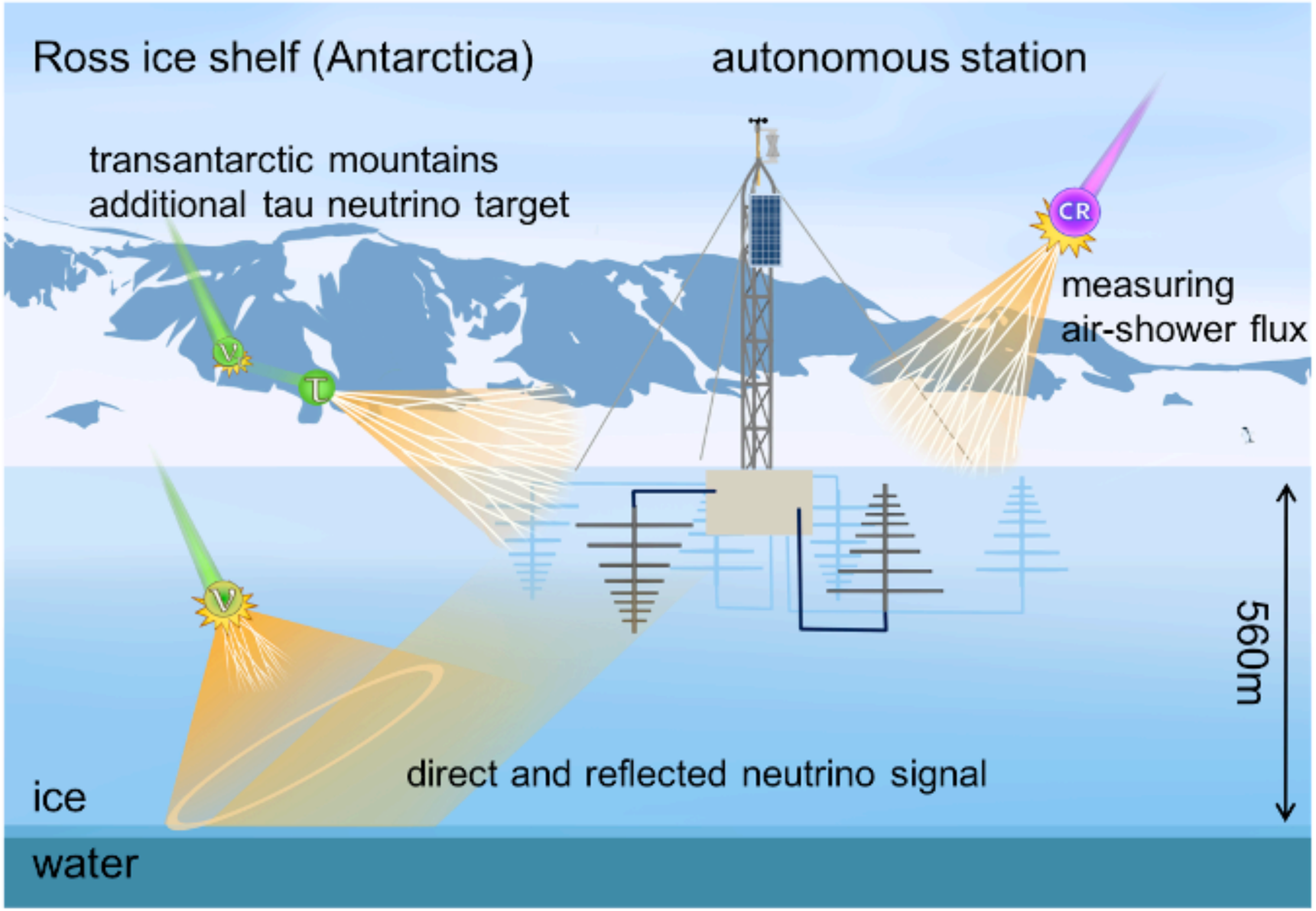


Charge excess: Polarization points towards shower axis.



T. Huege and D. Besson, Prog. Theor. Exp. Phys. 12 (2017) 12A106.

(Radio) detection of neutrinos



Neutrinos interactions generate electro-magnetic cascades (radio emission).

1 - air-showers from tau decay (Earth-Skimming tau neutrinos)

2 - in-ice showers following a neutrino interaction (CC, NC all flavor)

All experiments make use of negligible radio attenuation in air and kilometer-scale attenuation length in ice.

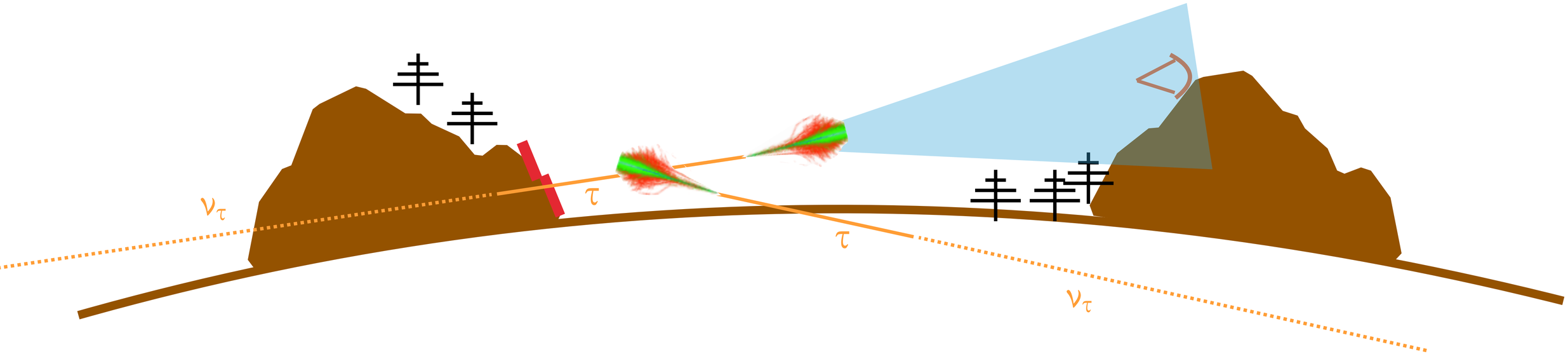
Air-shower radio detection: Earth-Skimming neutrinos

Looking at air-showers generated from tau leptons emerging from Earth

Exploiting the mountain-valley shape (neutrinos interact and tau showers)

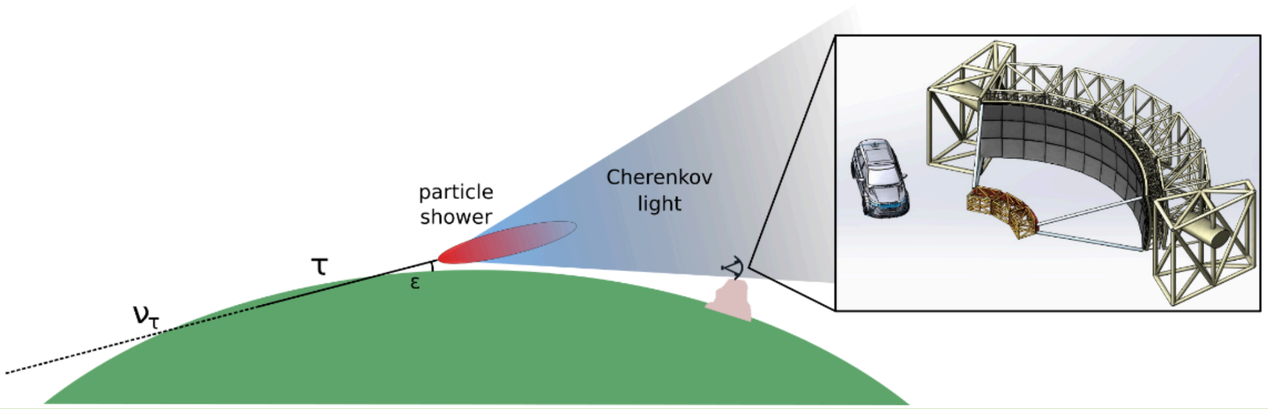
Several experiments running and proposed/prototyping: GRAND, BEACON (radio), Auger, TAMBO (water-Cherenkov), Trinity (air-Cherenkov).

Particle and optical detectors sensitive to > 10 PeV energies (filling energy gap).



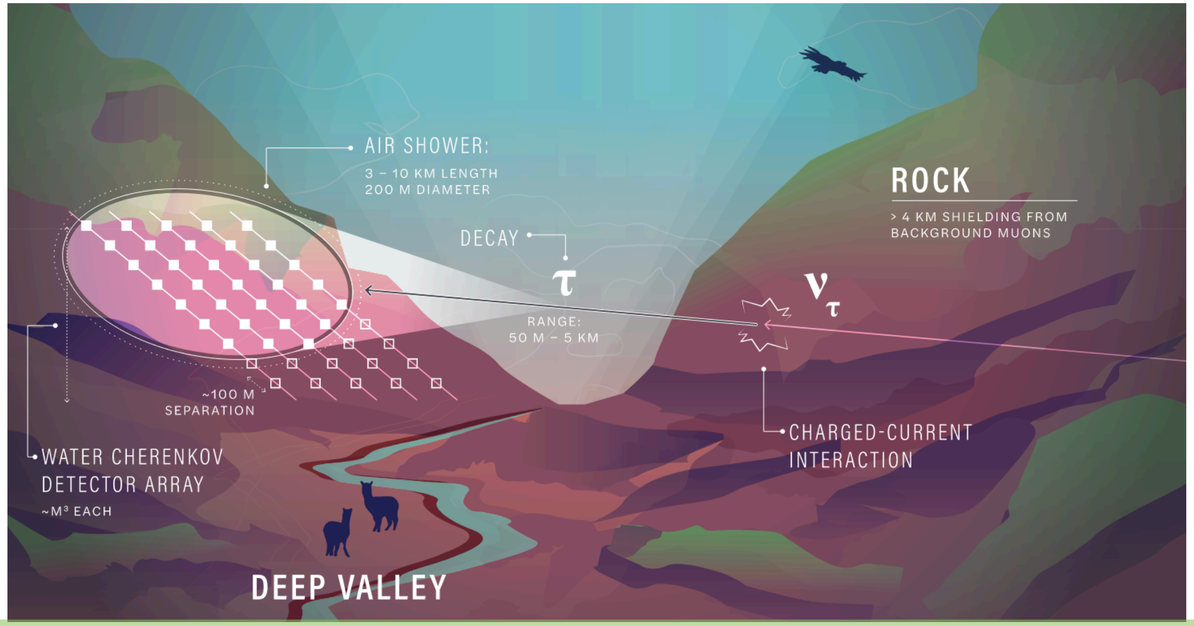
Trinity

- 8 air-shower Cherenkov telescopes optimized for detecting Earth-Skimming neutrinos in 10-1000 PeV range.
- Wide-FoV (60deg)
- Located at 2-3 km altitude
- 20% duty cycle compensated by detection of very distant showers (as far as 200 km)



TAMBO

- 22k water tanks deployed in slope
- characterization of astrophysical neutrino flux in 1-10 PeV range (ν_τ component)
- small tank separation: low-energy threshold



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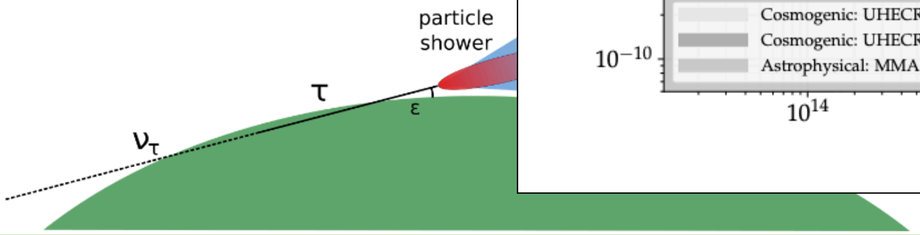

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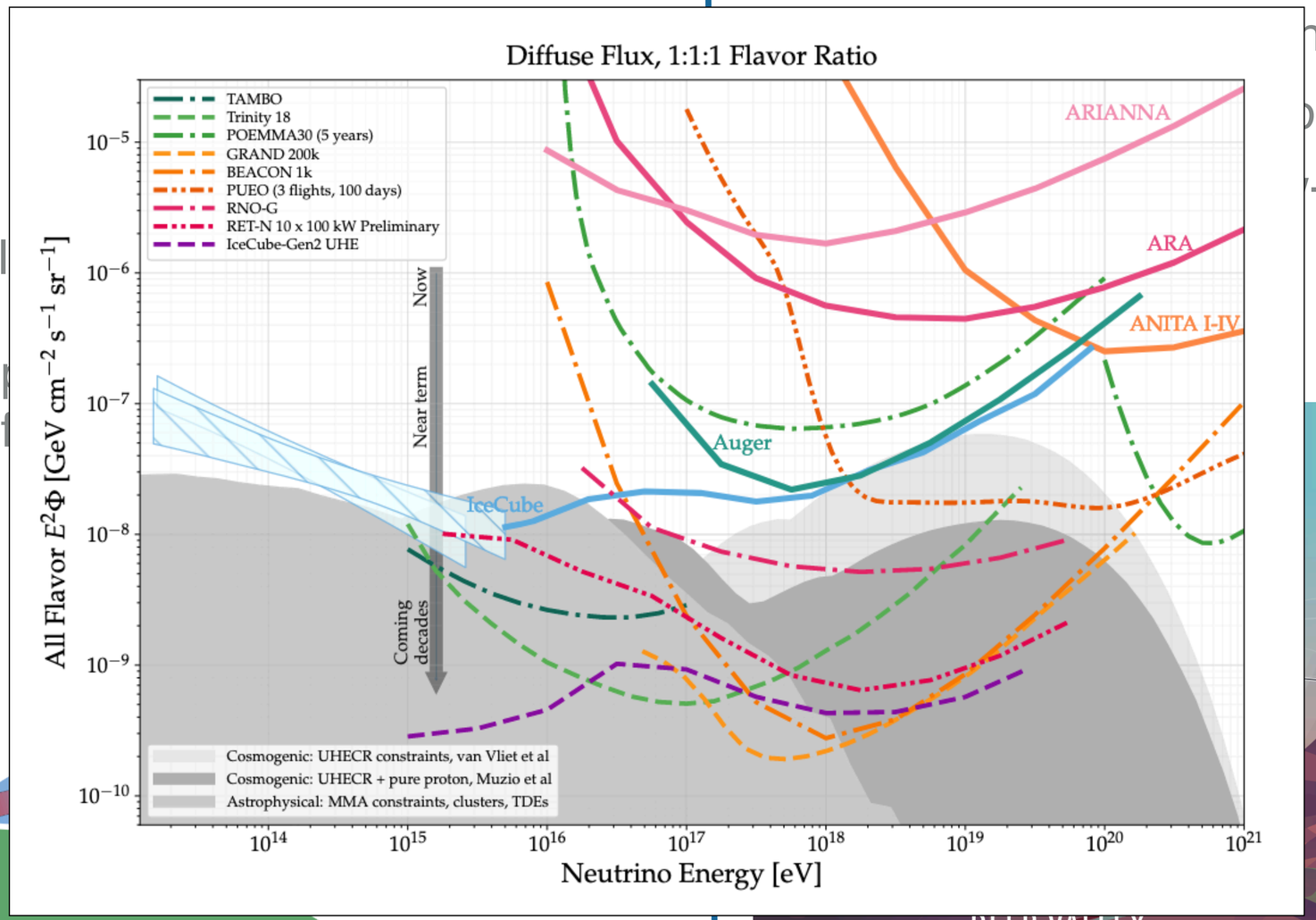
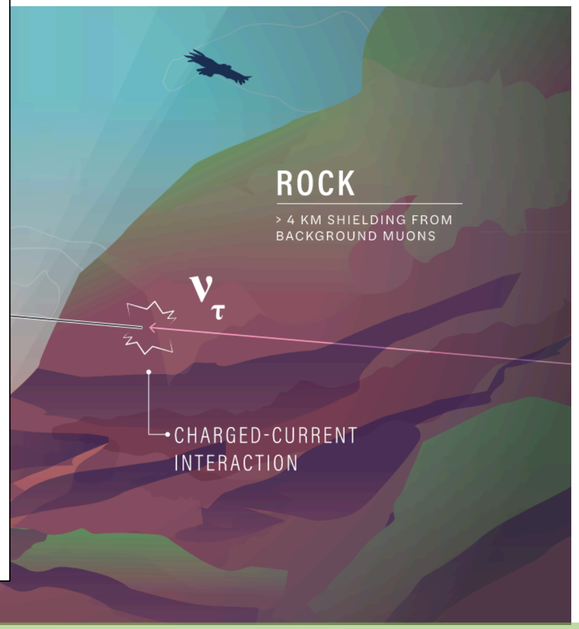
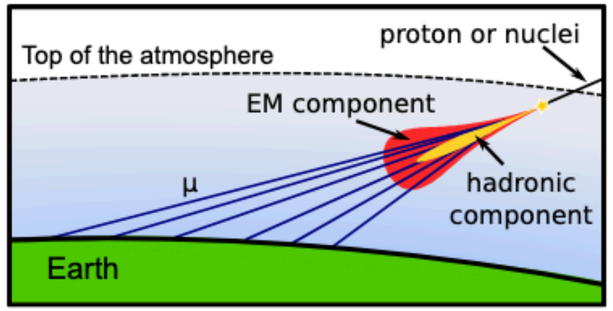
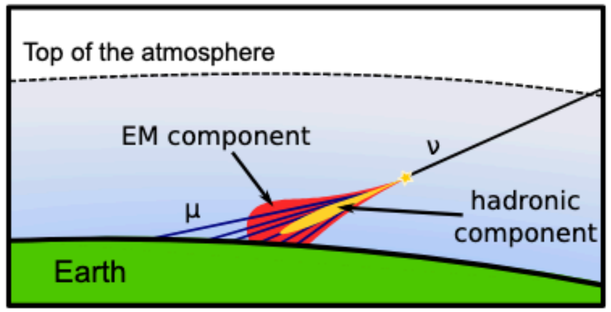
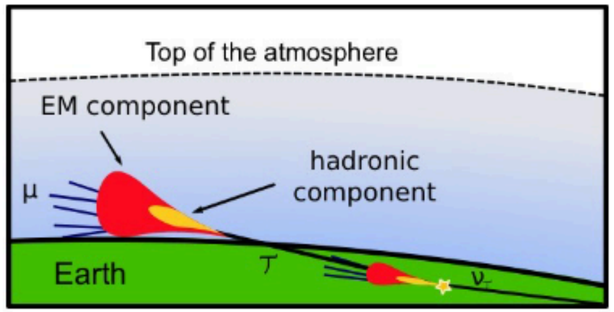




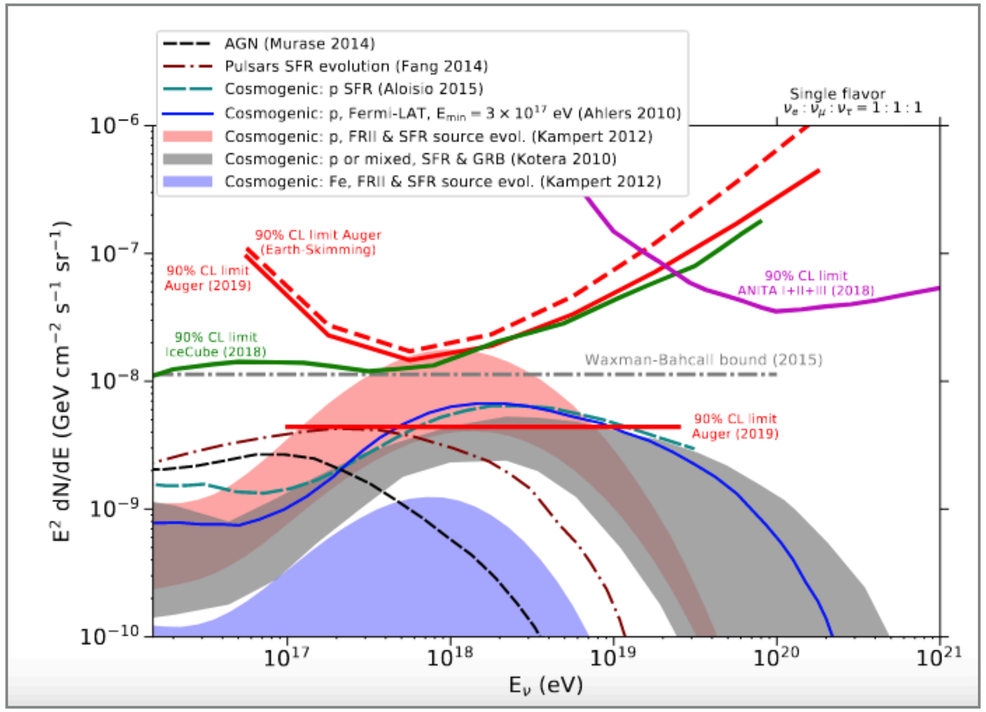
Neutrino detection at the Pierre Auger Observatory



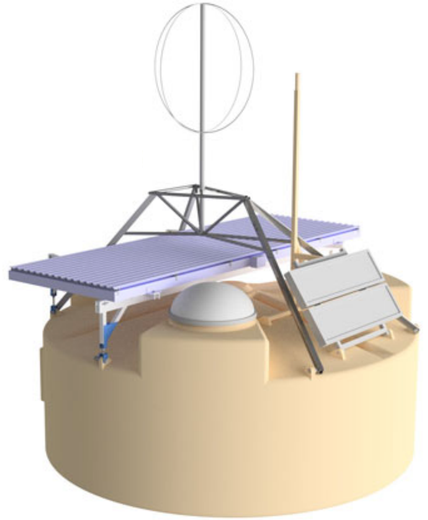




- Mostly Earth-skimming but also very inclined down-going (dominated)
- Looking for young showers (rich in electromagnetic component).
- Strong limits constraining already several cosmogenic and astrophysical scenarios.



AugerPrime
completed in ~2023

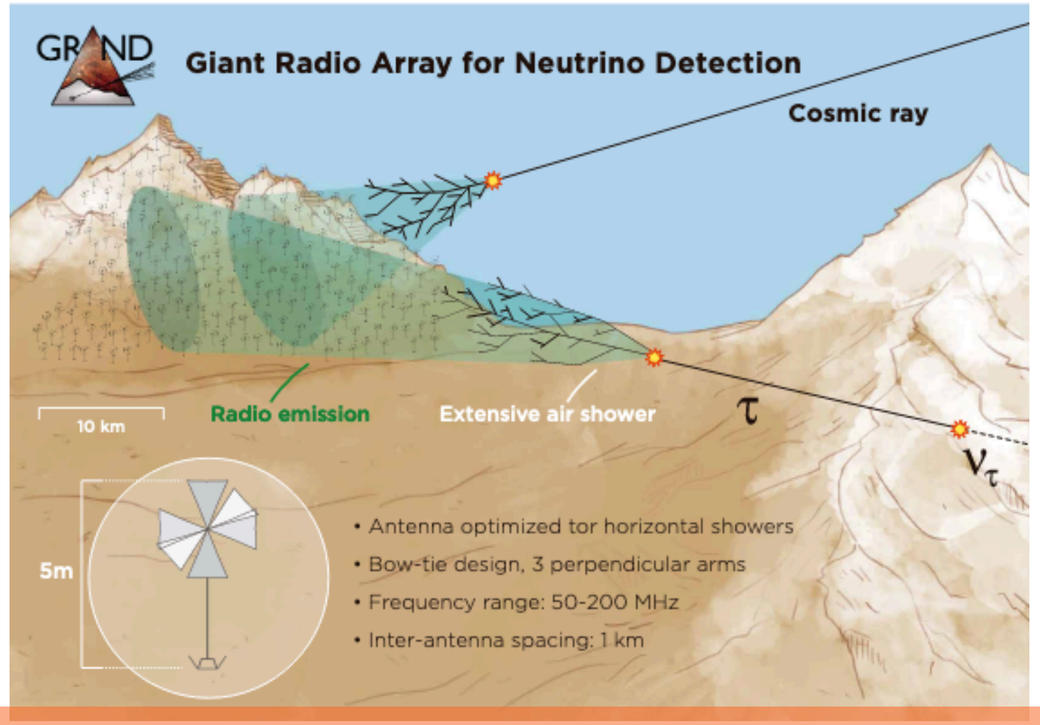


Impression of the upgraded SD

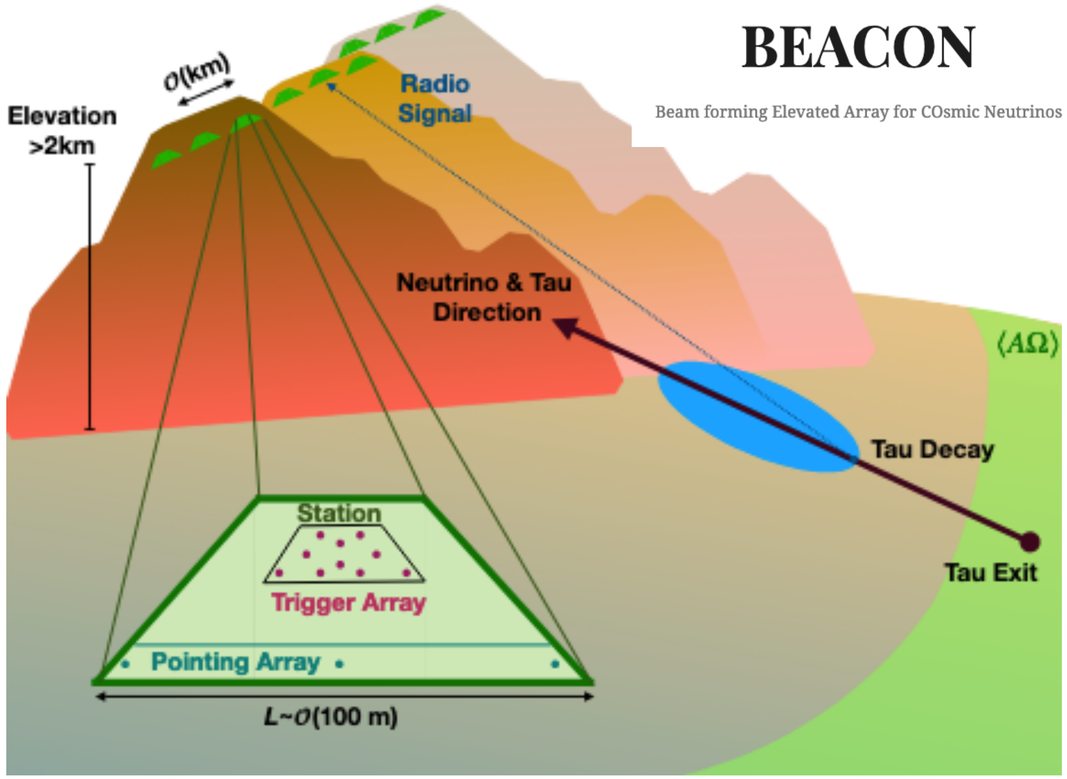
Air-shower radio detection: Earth-Skimming neutrinos

- 200k radio antennas over 200k km^2 : ~ 20 hotspots of 10k antennas at various favorable sites around the world

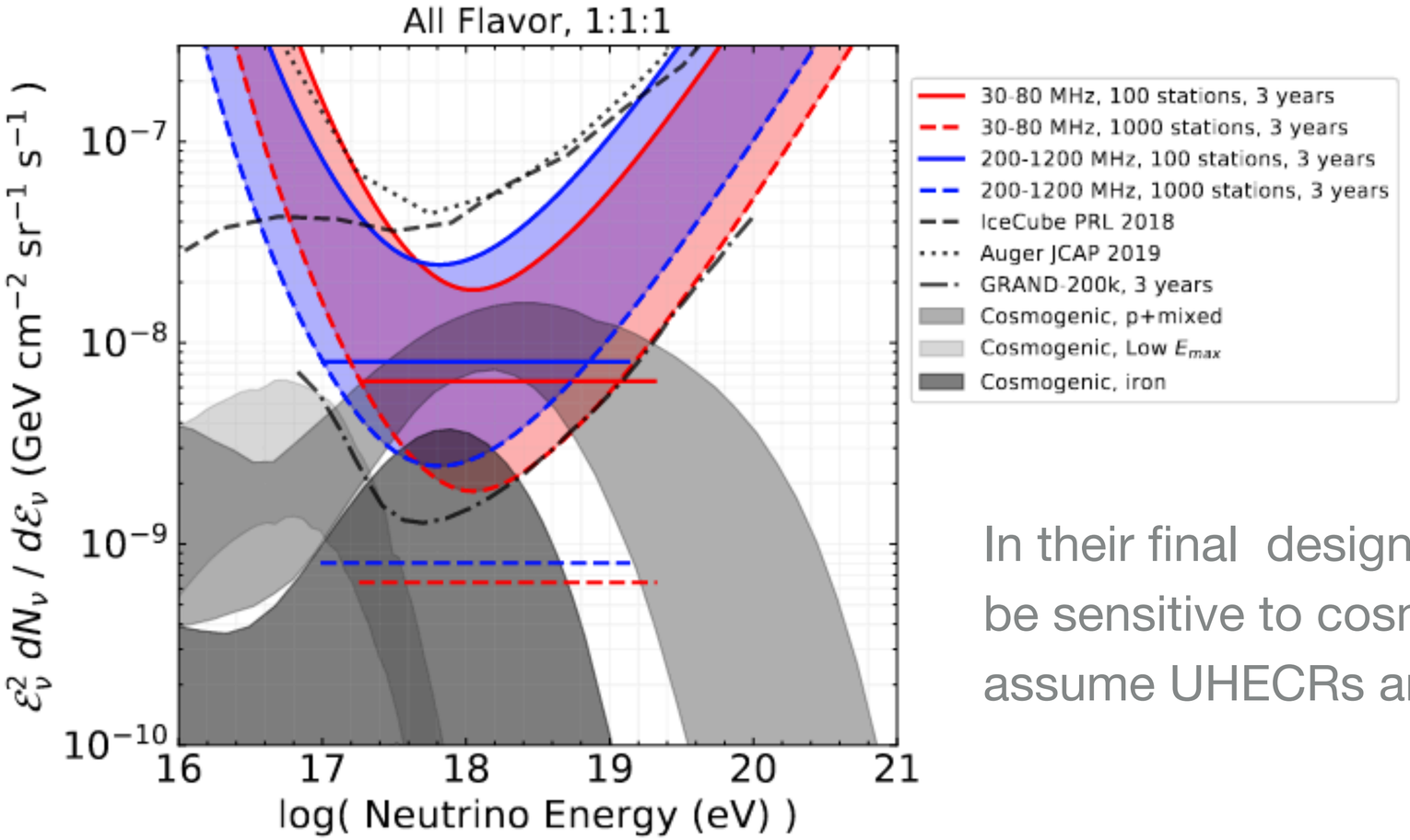
- Phased approach:
  - prototype GRANDProto300 - hardware developed, but site search delayed (COVID)
- GRAND 10k (> 2025) - 1 sub-array
- GRAND 200k (> 203x) - 20 sub-arrays



- 100-1000 stations with ~10 antennas each, viewing shower from top of mountain.
- Interferometer concept: clustered phased-array for triggering, and long-baselines for pointing.
- Prototype: 4 dual-polarized dipole already searching for CR signals (California).



Air-shower radio detection: Earth-Skimming neutrinos



[S. Wissel et al. JCAP 11 (2020) 065]

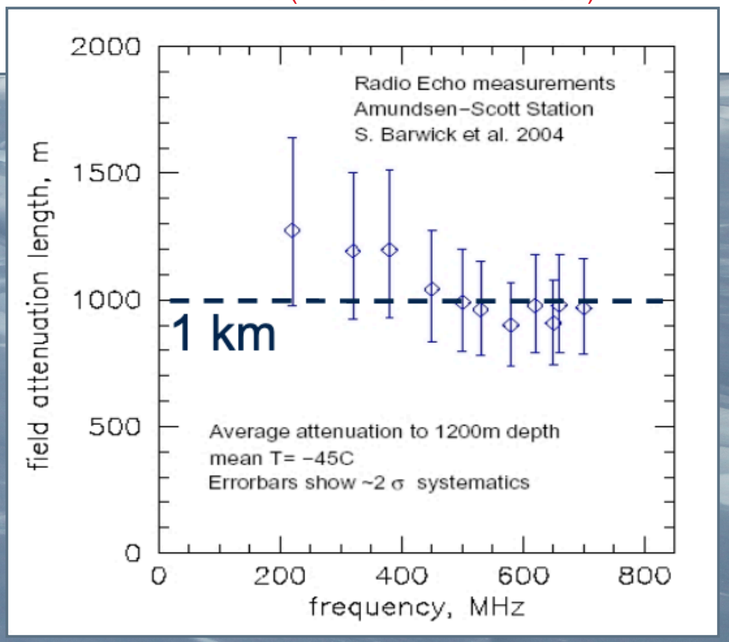
In their final designs BEACON and GRAND will be sensitive to cosmogenic neutrino models which assume UHECRs are iron only

IN-ICE RADIO DETECTION OF NEUTRINOS

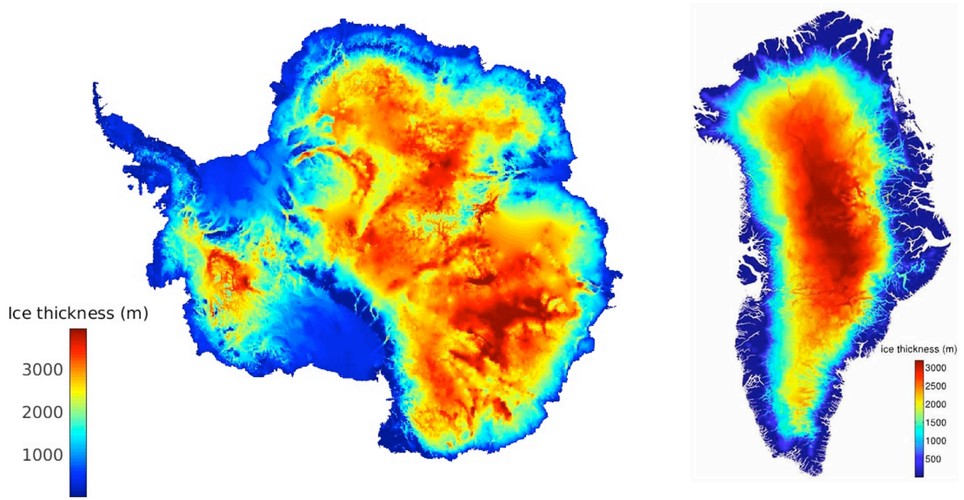
BIG EFFECTIVE VOLUME WITH SMALL NUMBER OF DETECTION UNIT (λ_{att} ~1 km)

CHEAPEST OPTION (BOTH IN HARDWARE AND DEPLOYMENT)

One radio station can typically monitor
1 km^3 of ice (= the size of IceCube)



IN-ICE RADIO DETECTION OF NEUTRINOS

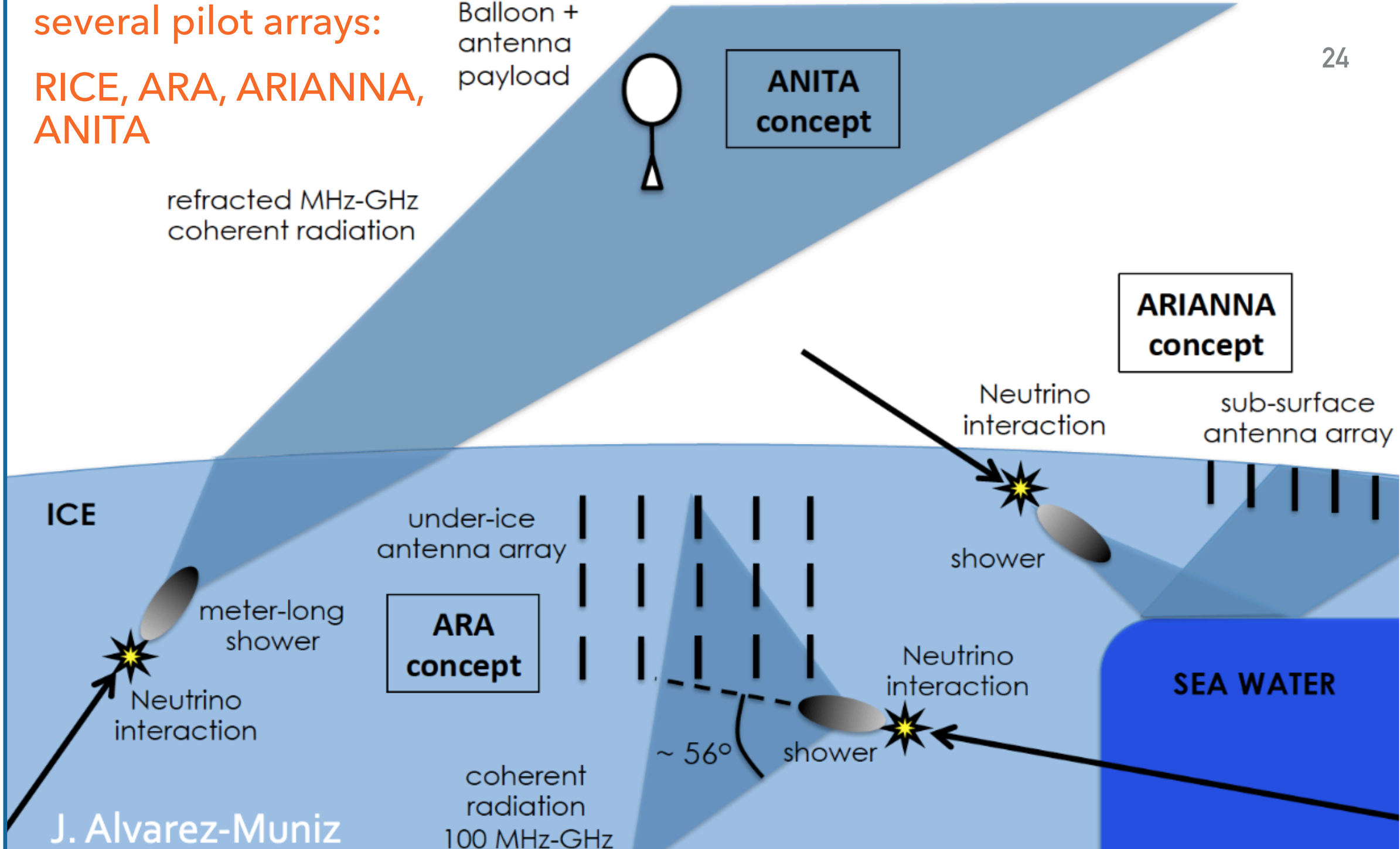


REMOTE LOCATIONS

- ✓ big target volume: ~3 km thick ice sheet.
- ✓ Low thermal noise.
- ✓ Relatively little human activity.

several pilot arrays:

RICE, ARA, ARIANNA, ANITA

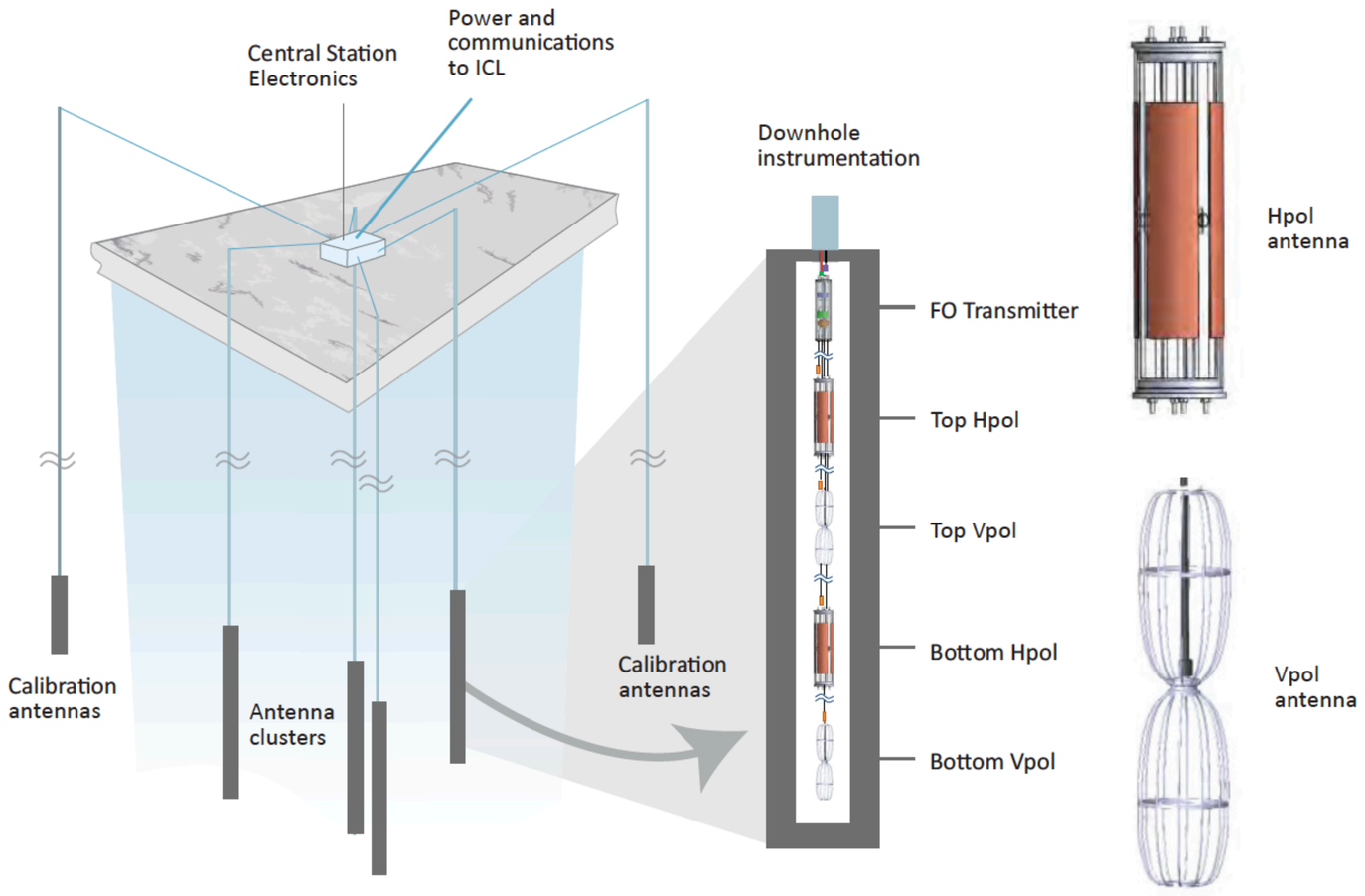


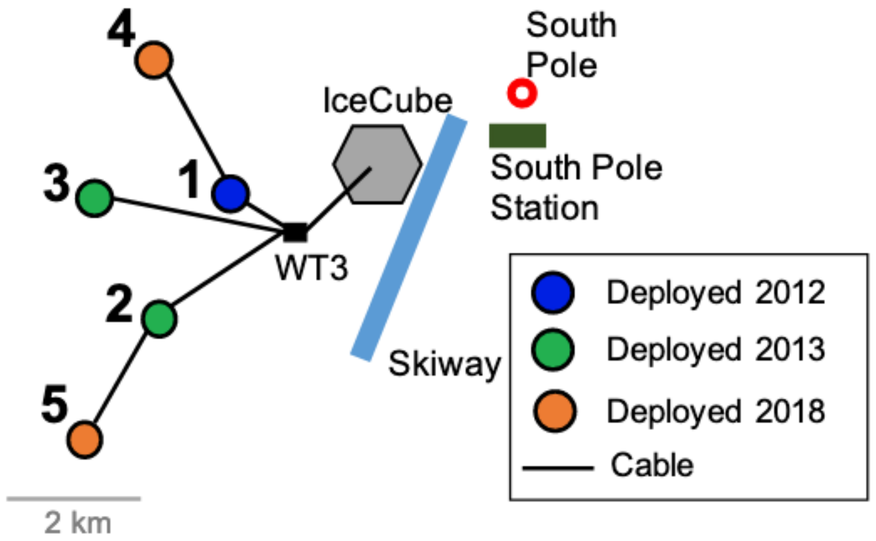
IN-ICE RADIO DETECTION OF NEUTRINOS

WHAT'S DONE SO FAR…

- Experiments have demonstrated the feasibility of in-ice radio detection (efforts in improving simulations and reconstruction)
- CR signals detected with surface antennas from ARIANNA
- Solar flare detected with ARA deep antennas
- Current limits still far away from predicted flux.

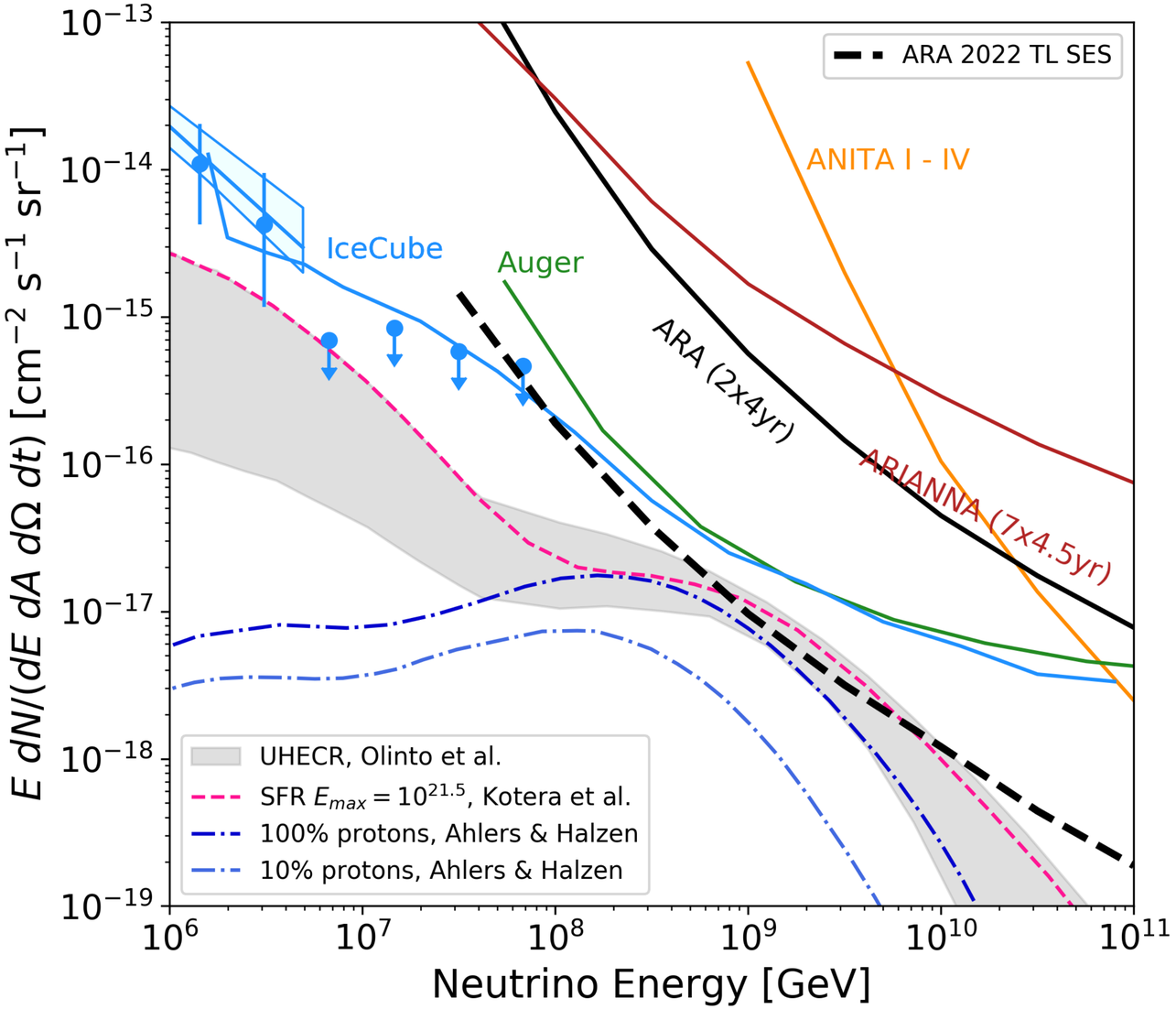
The Askaryan Radio Array (ARA): detector layout





- Running since 2012.
- max 200 meters deep in ice.
- Powered by South Pole station (100% uptime).
- A5 equipped with phased array to lower trigger threshold.

The Askaryan Radio Array (ARA): results and prospects



- ARA 90% confidence-level upper limit on the all-flavor diffuse neutrino flux is the best limit from an in-ice radio detector above 100 PeV.

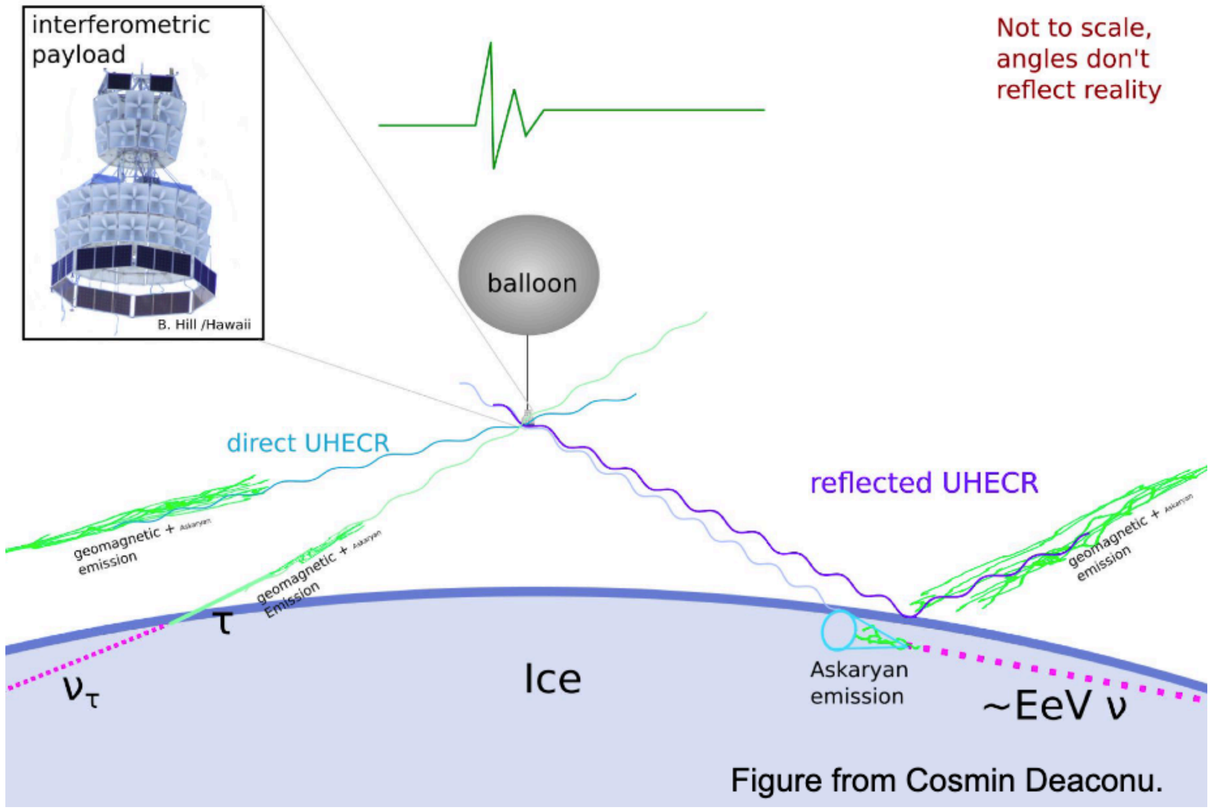
- 25 station-years of data recently calibrated and under analysis will provide more stringent constraints with a real chance for a first discovery

IN-ICE RADIO DETECTION OF NEUTRINOS

WHAT'S DONE SO FAR…

Interesting results from **ANITA**:

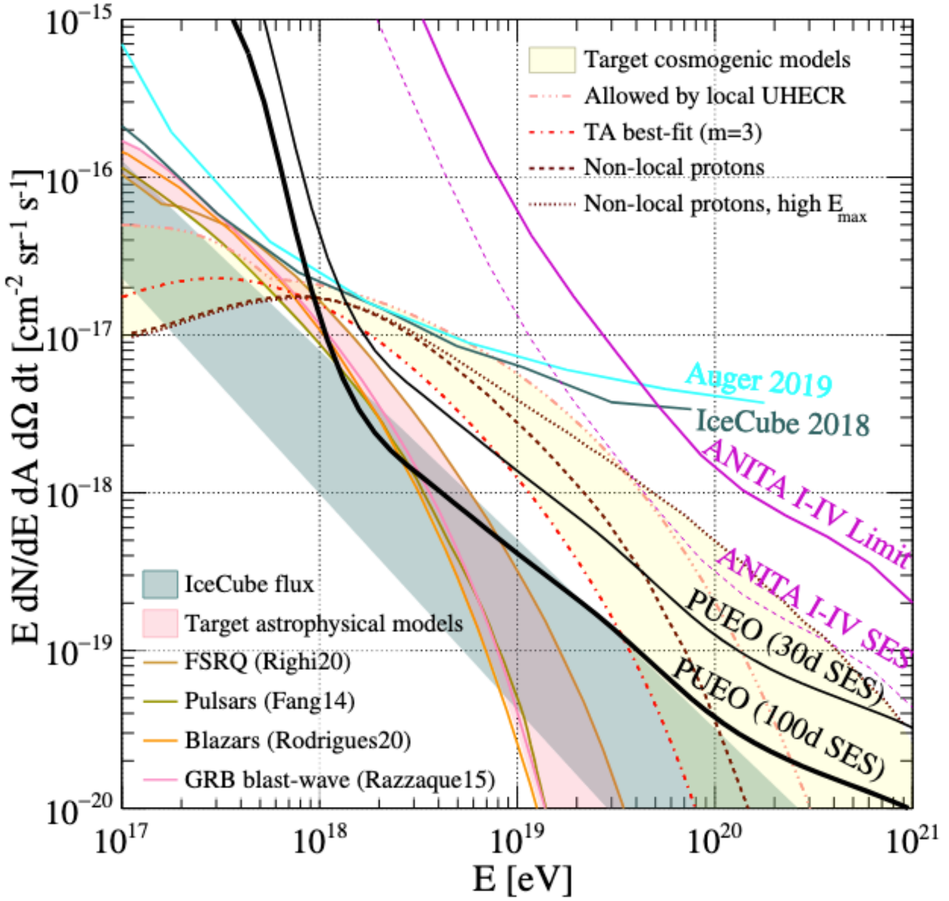
- 2 "mystery" events (ANITA I-III) - behave like reflected CRs from ground but show polarity/polarization as from neutrinos.
- If neutrinos: BSM and in tension with IceCube results (arxiv.org/abs/2001.01737)
- Other explanations possible: coherent transition radiation, snow effect (surface roughness)



- 4 additional anomalous events found in ANITA IV: more horizontal -> less tension with Standard Model scenarios. (analysis on-going)

From ANITA to PUEO

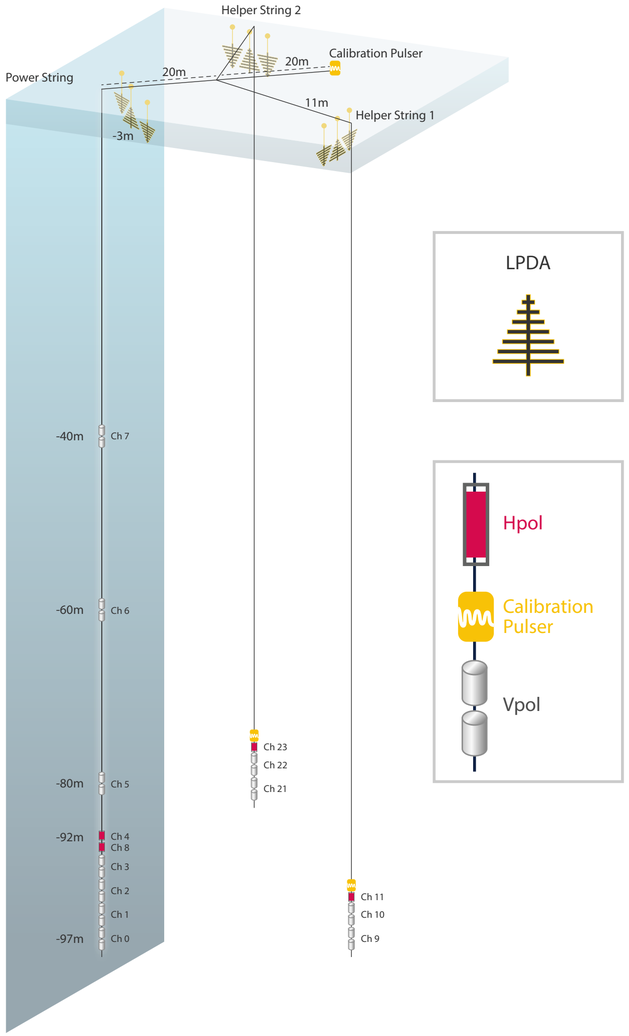
Launch from McMurdo in December 2024, expected 30 day flight



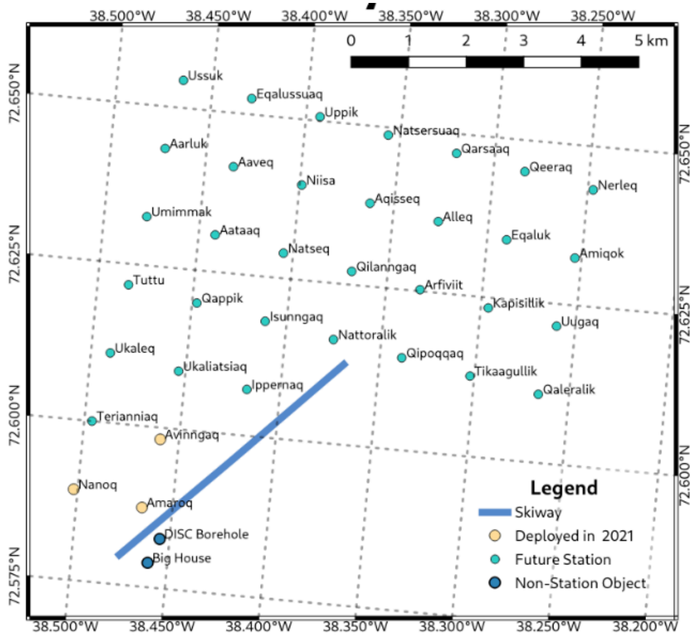
PUEO White Paper: JINST 16 (2021) 08, P08035

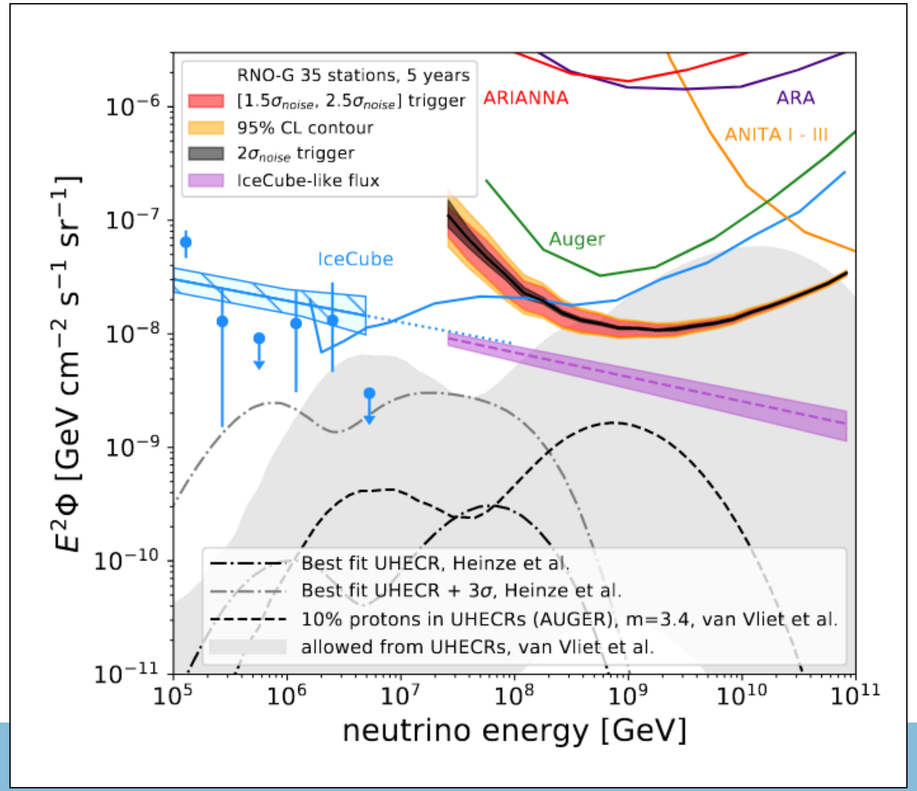
The Radio Neutrino Observatory in Greenland (RNO-G)

2 Posters: F. Schlüter, B. Oeyen



- 7/35 stations in ice and powered with solar panels (wind turbines testing)
- When completed (by 2026) will be the most sensitive UHE Askaryan neutrino detector in 100 PeV - 10 EeV range.
- Unique location in the North
- Scalable design: towards next-generation (IceCube-Gen2 Radio)

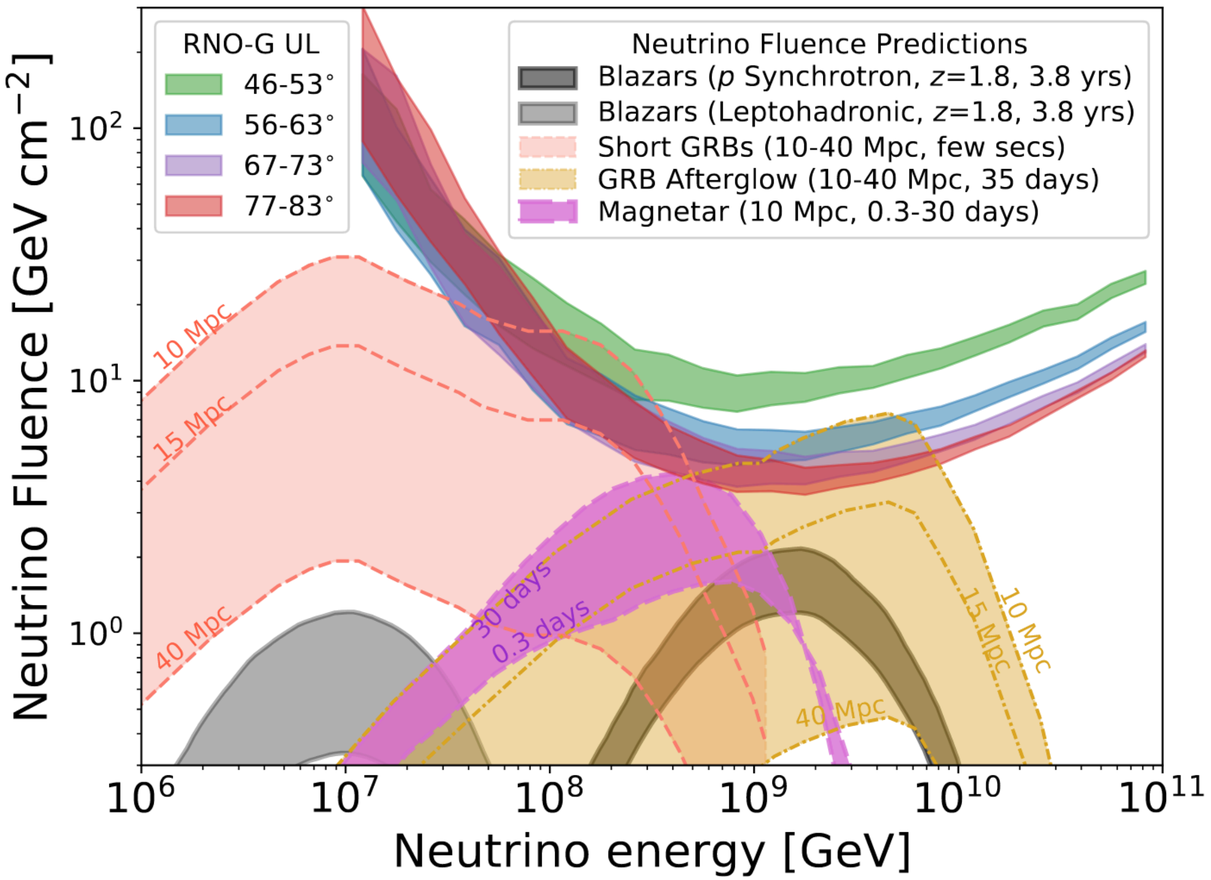




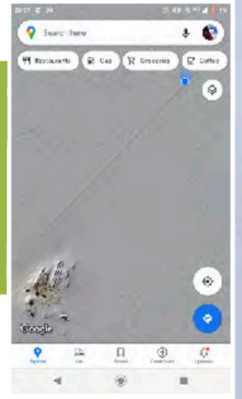
RNO-G: sensitivity to transient sources

- Unique capabilities to processing alerts in nearly real time.
- Sensitive to nearby and/or transient events.

J. Aguilar et al, (RNO-G Collaboration),JINST 16 P03025 2021



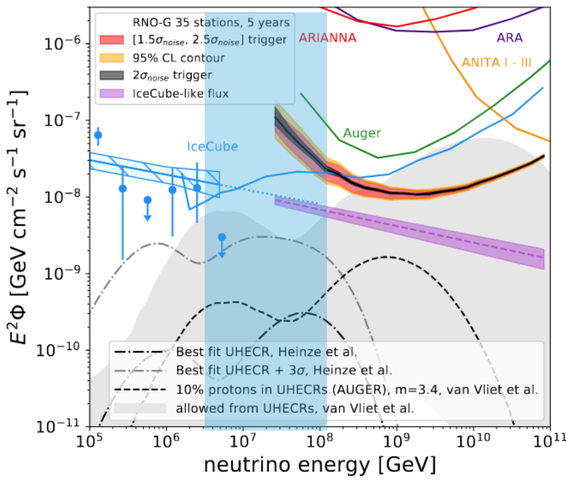
Multi-messenger follow-up enabled with continuous satellite coverage, beam-forming and LTE cellular comms networking



C. Deaconu with LTE coverage at furthest station site (Nerleq), 10 km away

Filling the energy gap: the Radar Echo Telescope

3 Posters: R. Stanley, E. Huesca, S. De Kockere

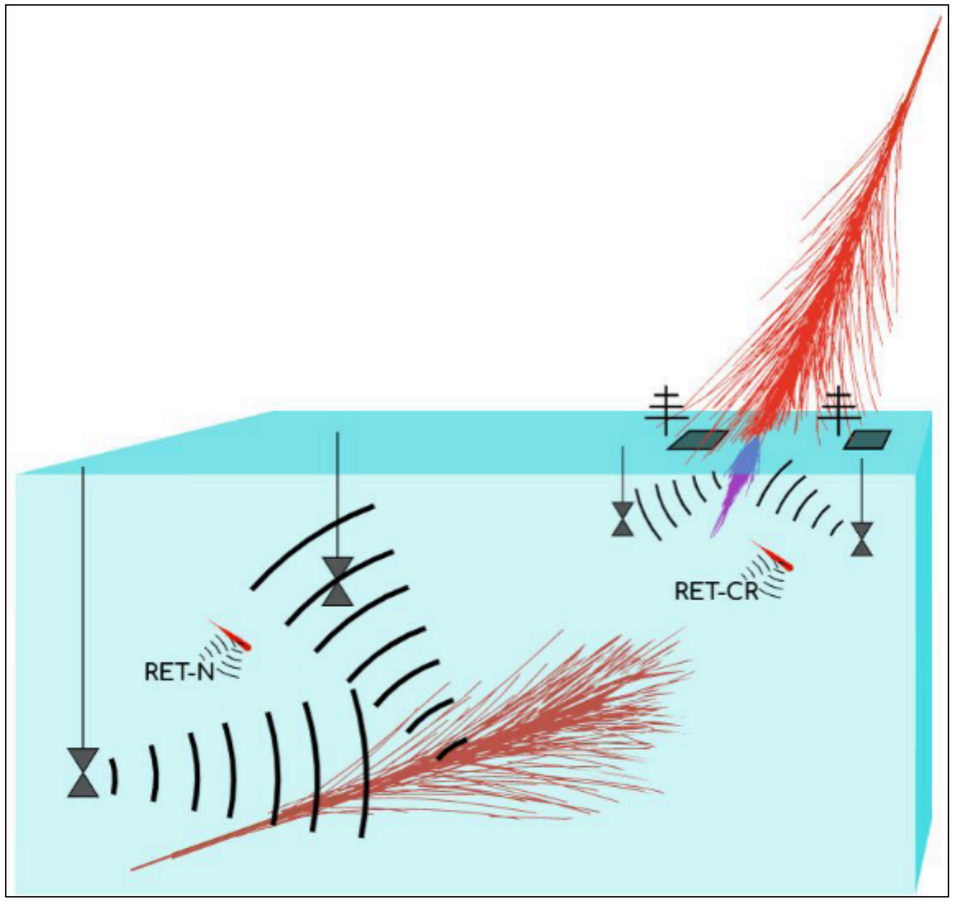


In-ice Neutrino interactions generate a dense in-ice cascade.

Active method of neutrino detection using radio

- Bridge the gap between Cherenkov and Askaryan detection
- Complementary method to Askaryan detection
- Not restricted to the Cherenkov cone

R. Stanley, ARENA 2022



Filling the energy gap: the Radar Echo Telescope

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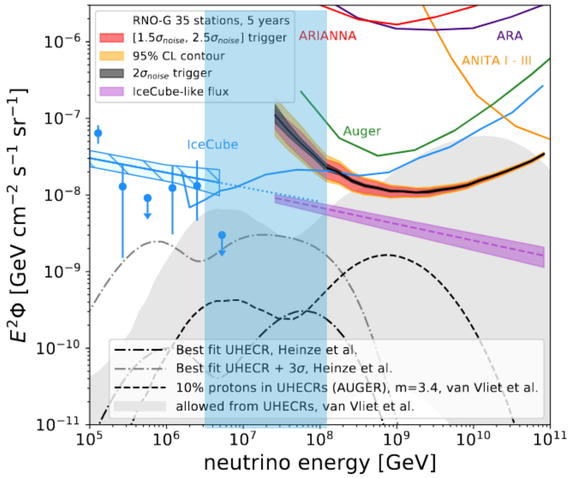

In-ice Neutrino interactions generate a dense in-ice cascade.

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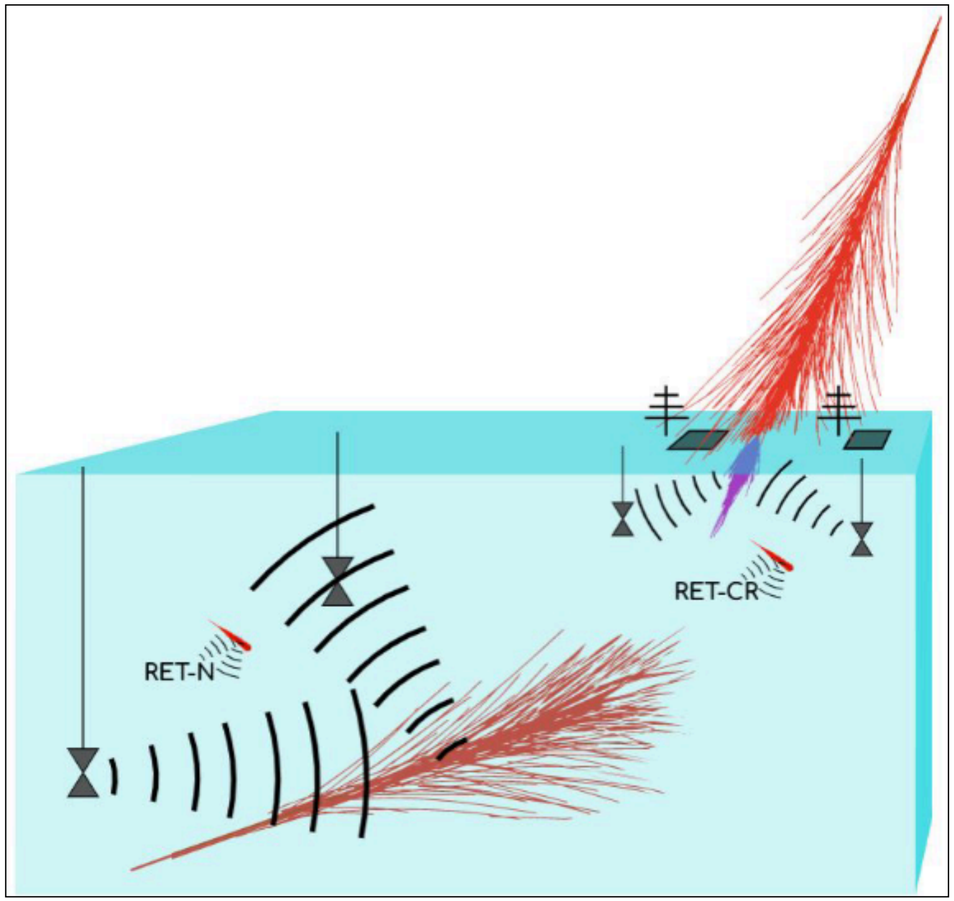
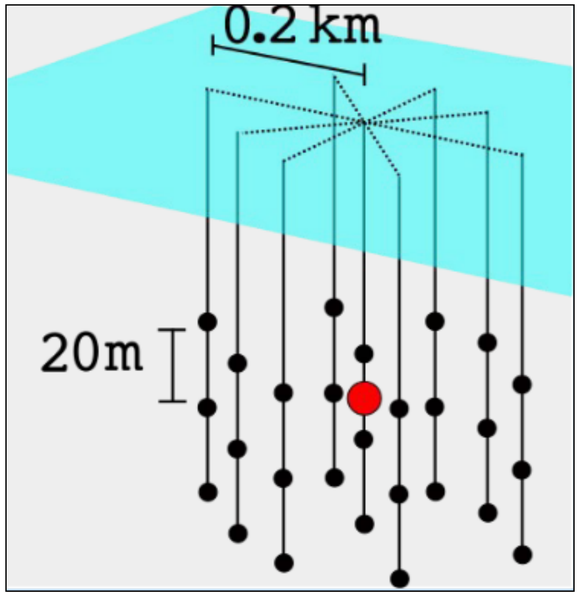
R. Stanley, ARENA 2022



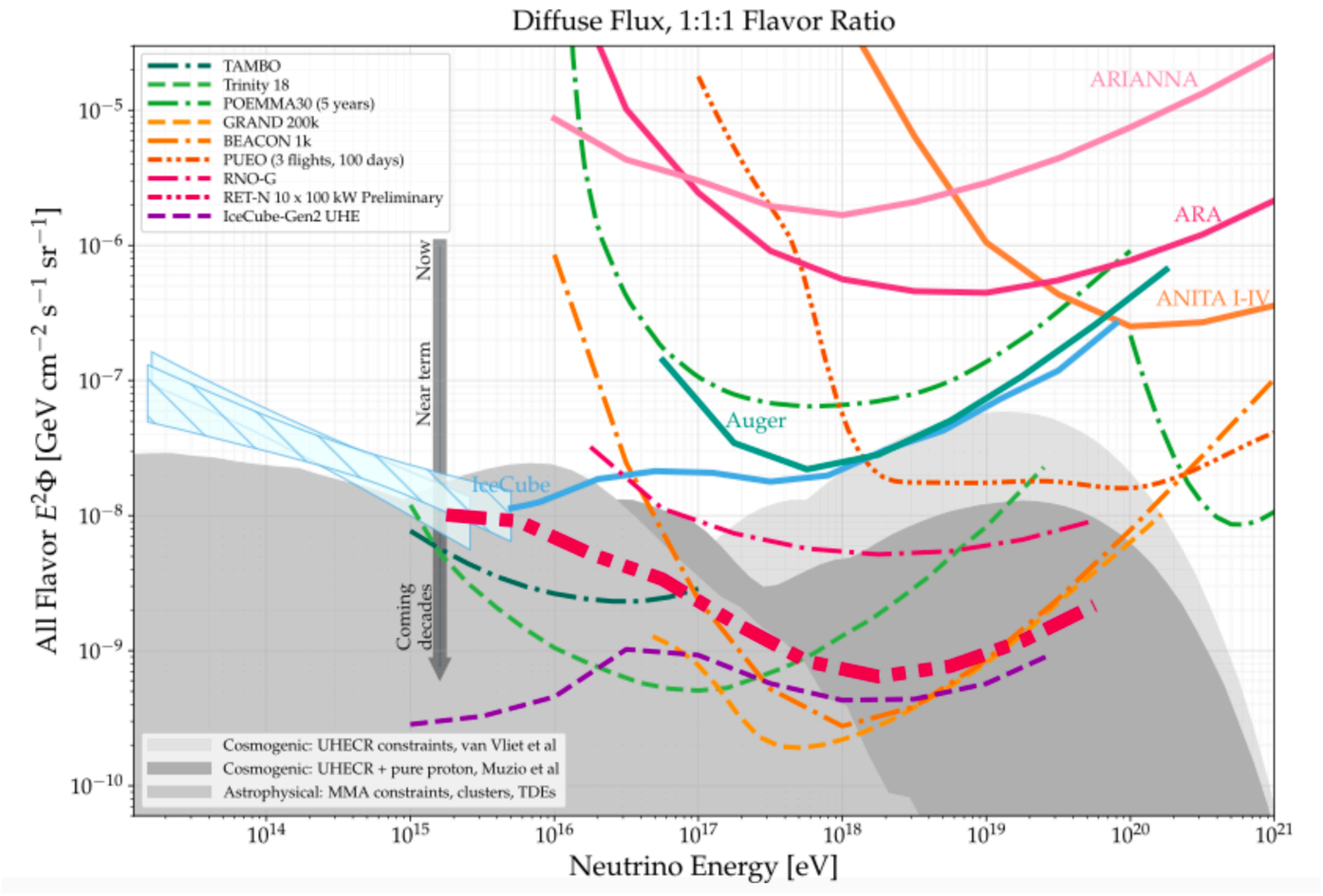
- Layout optimization in progress
- RET-CR (in-nature demonstrator) is funded and be deployed soon (2023-24) [S. Prohira et al., Phys. Rev. D 104, 102006]



1 transmitter: 1.5 km depth, 100 kW effective transmit power
- 27 receivers: 200 m spokes, 20 m vertical spacing

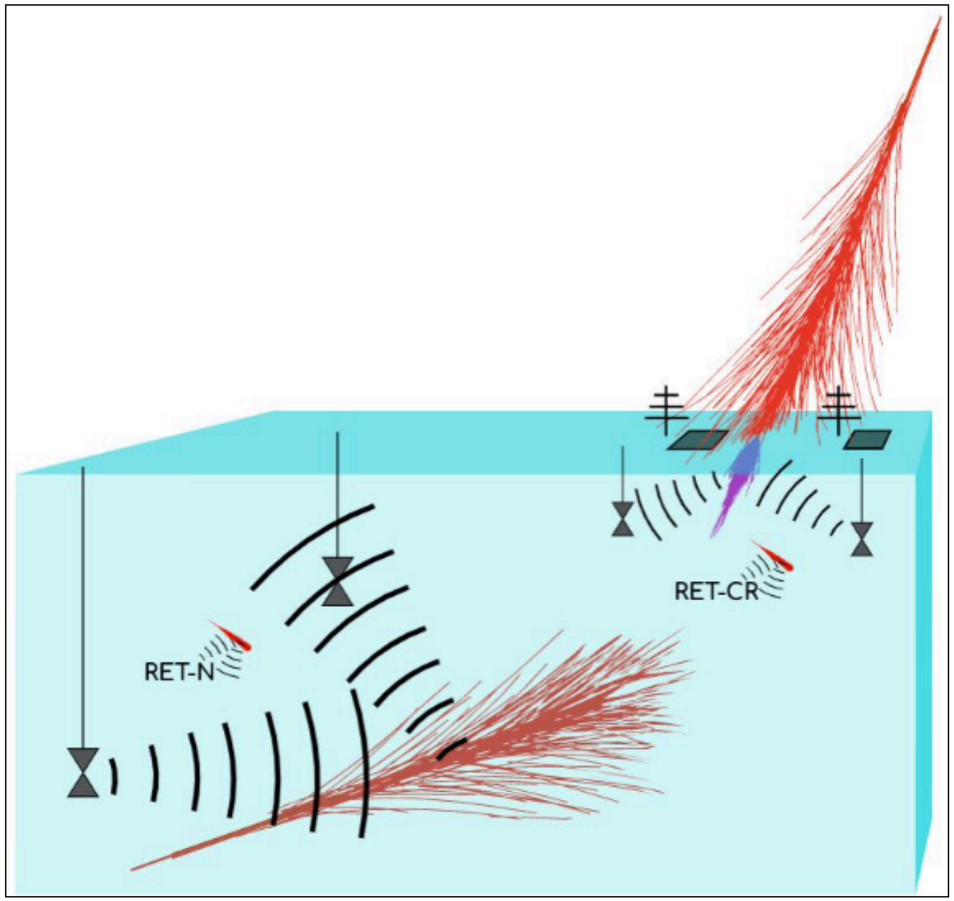
Filling the energy gap: the Radar Echo Telescope

3 Posters: R. Stanley, E. Huesca, S. De Kockere

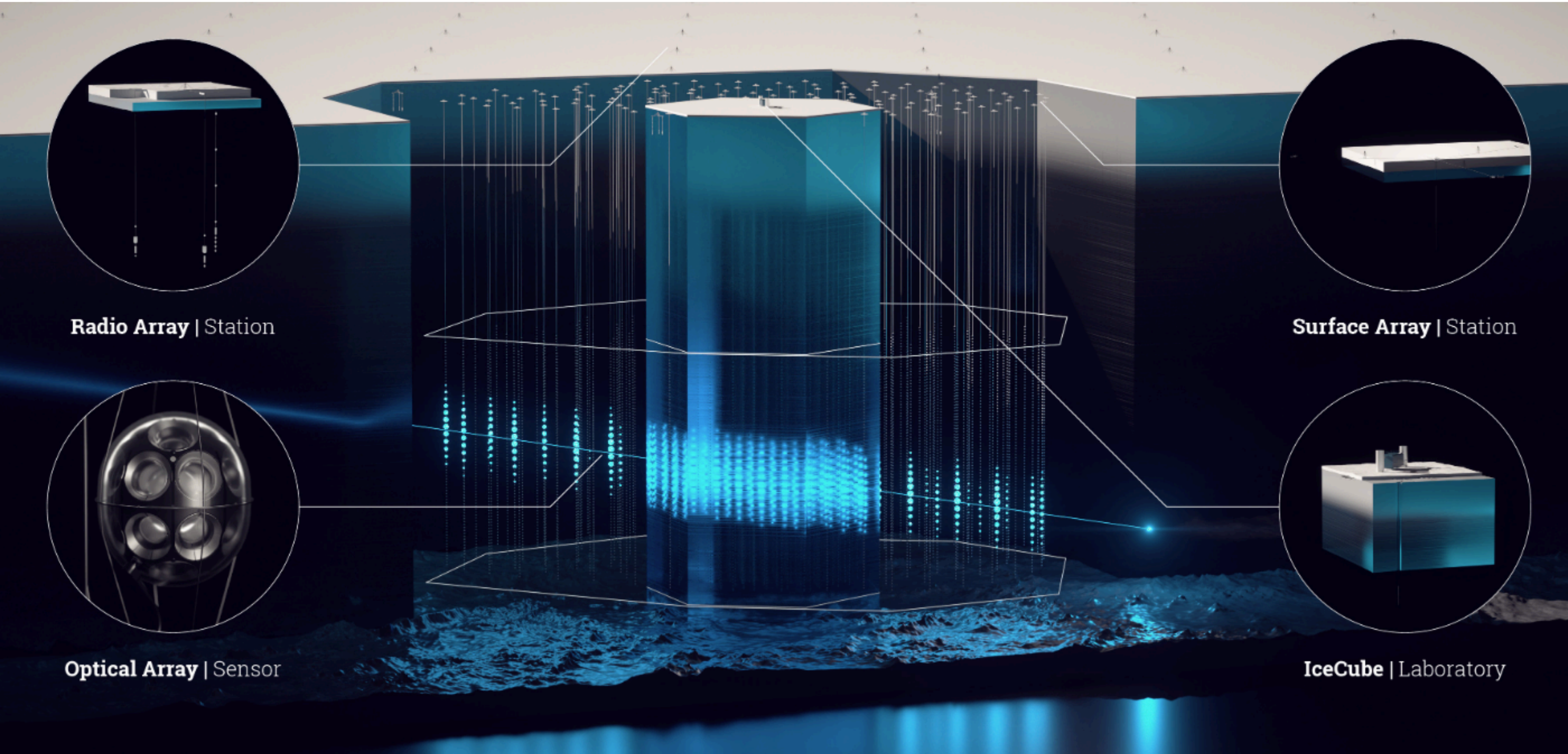


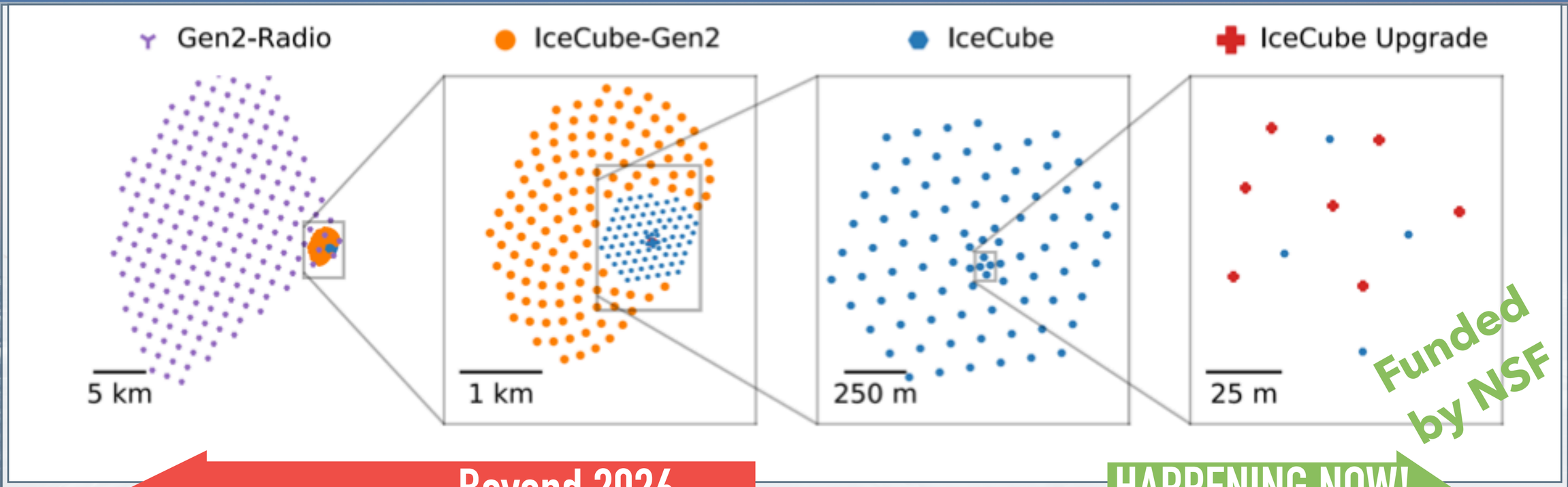
UHE neutrinos Snowmass White Paper: arxiv.org/pdf/2203.08096.pdf

R. Stanley, ARENA 2022

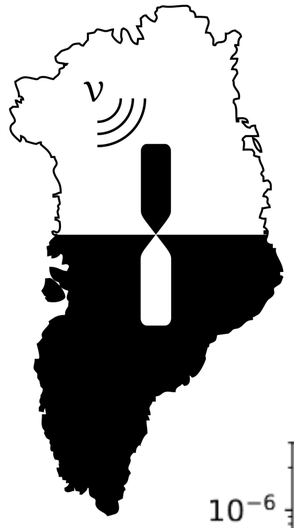


The future IceCube-Gen2 Observatory





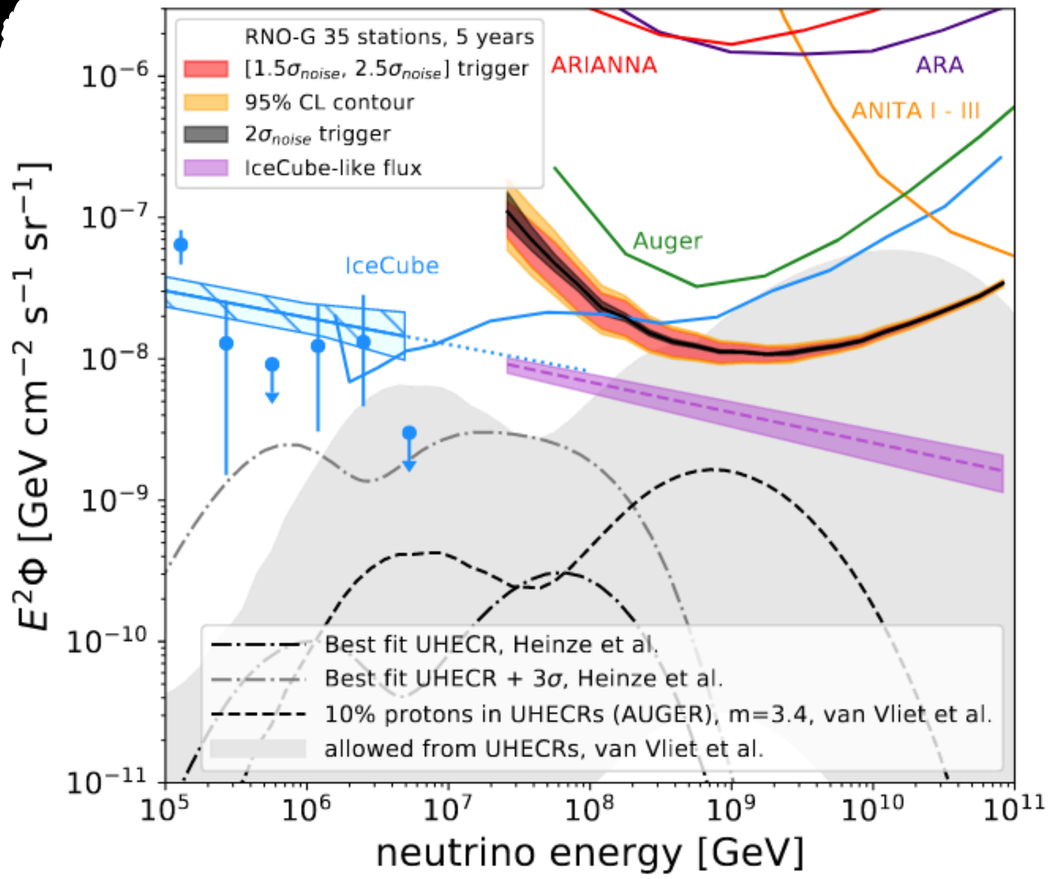
Radio community is working together towards a viable and scalable design.



RNO-G

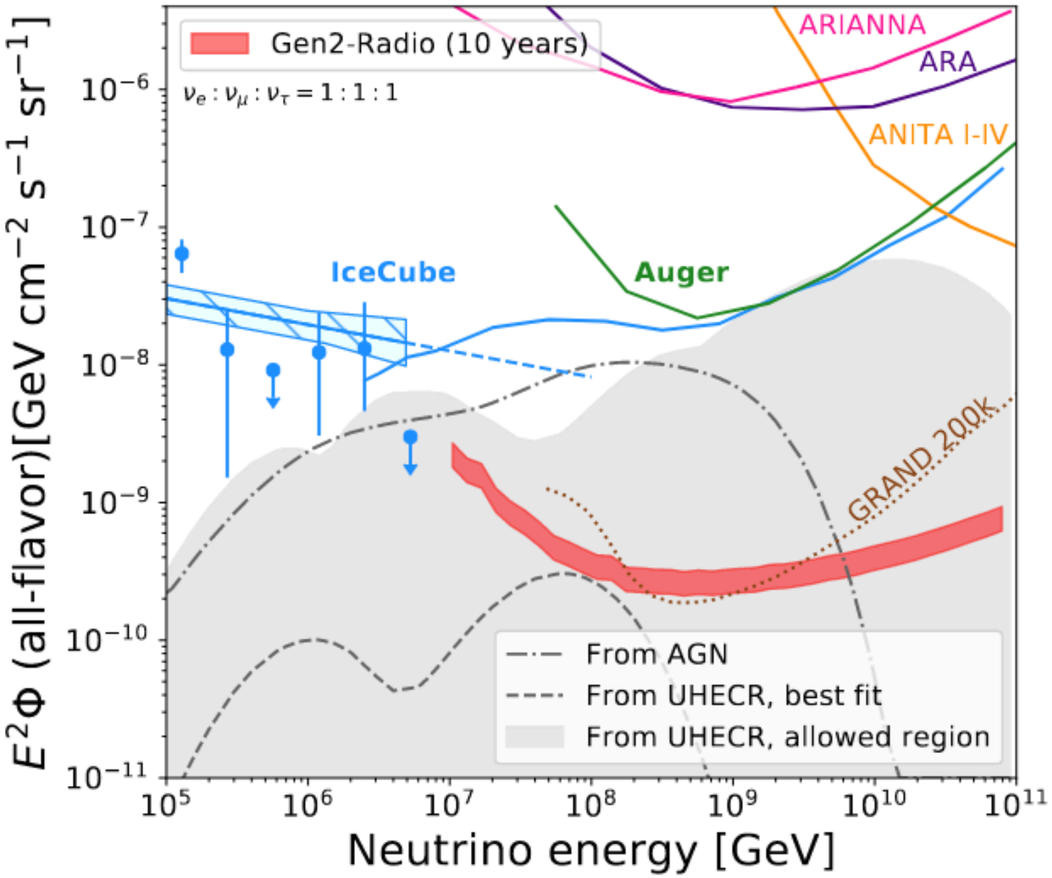
Radio Neutrino Observatory - Greenland

J. Aguilar et al, (RNO-G Collaboration),JINST 16 P03025 2021



IceCube GEN2 Radio

Aartsen et al., (IceCubee-Gen2 Collaboration), arXiv:2008.04323



SUMMARY

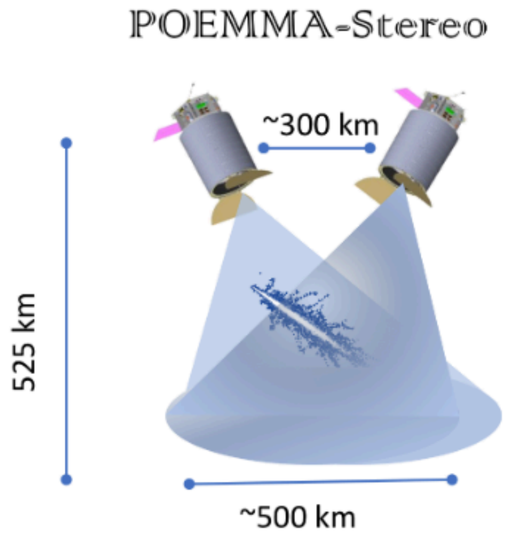
- >10 years of IceCube has led to the discovery of first sources but not enough to study them (or detect more).
- Interest in going to higher energies (study of the astrophysical flux and cosmogenic) to connect to UHECRs.
- Existing experiments starting to constrain models but better sensitivities are needed.
- Several coming online now and in the horizon.
- Transients are probably the best bet. We need full and instantaneous sky coverage.
- Exiting time for HE neutrino (and UHECR) astronomy.

THANK YOU

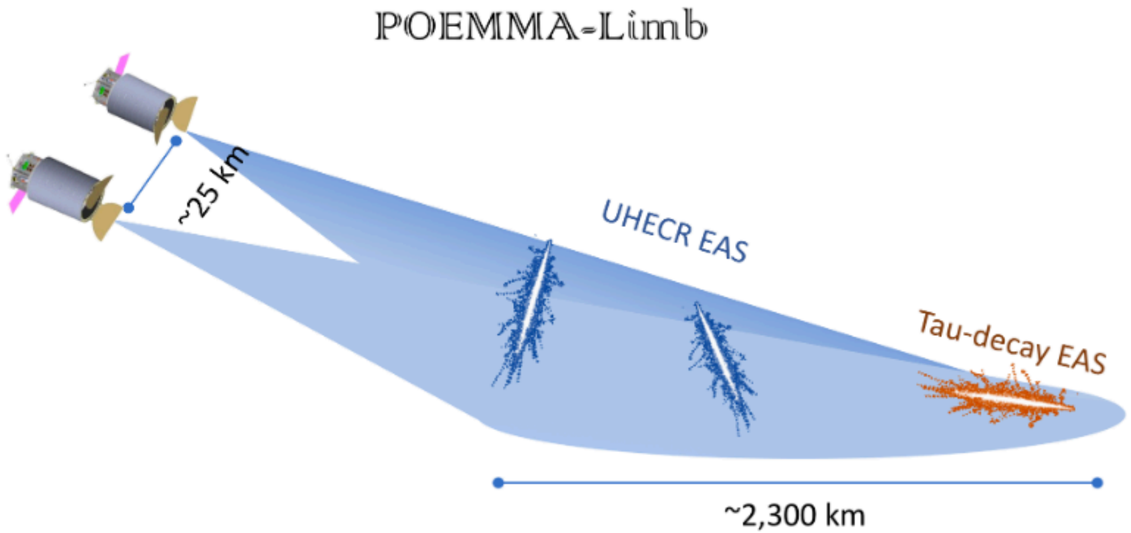
Credit: SPT/Aman Chokshi

Probe Of Extreme Multi-Messenger Astrophysics (POEMMA)

Two wide (45˚) FOV Schmidt optical telescopes flying in a low Earth orbit



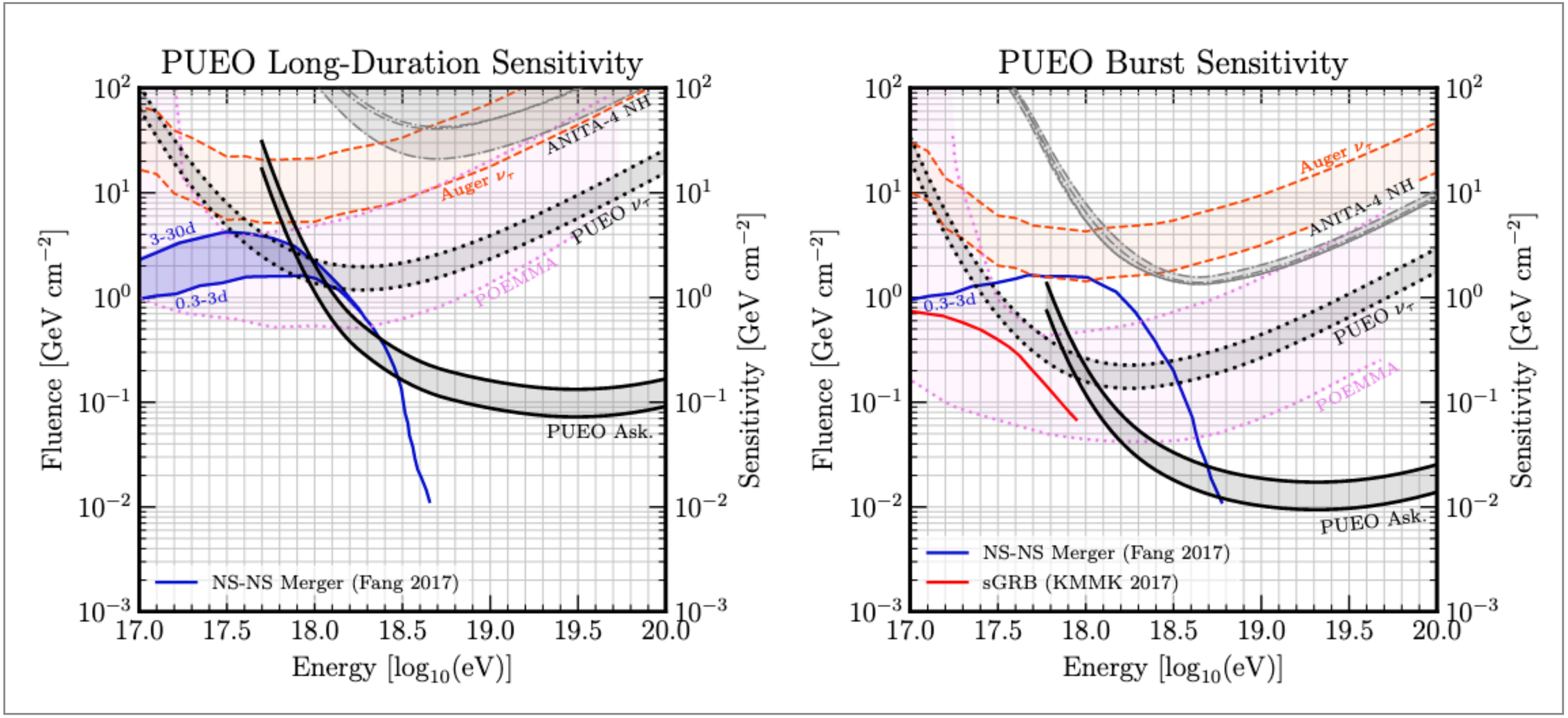
Fluorescence from UHE cosmic rays and neutrinos in stereo (E_{th} = 20 EeV).



Cherenkov emission of tau showers from ν_τ interactions in the Earth from below the limb. (Followup ToO transient alerts)

Transient UHE ν sensitivity

Very large instantaneous aperture makes it well-suited to measuring UHE neutrino fluence from transient astrophysical sources in FoV



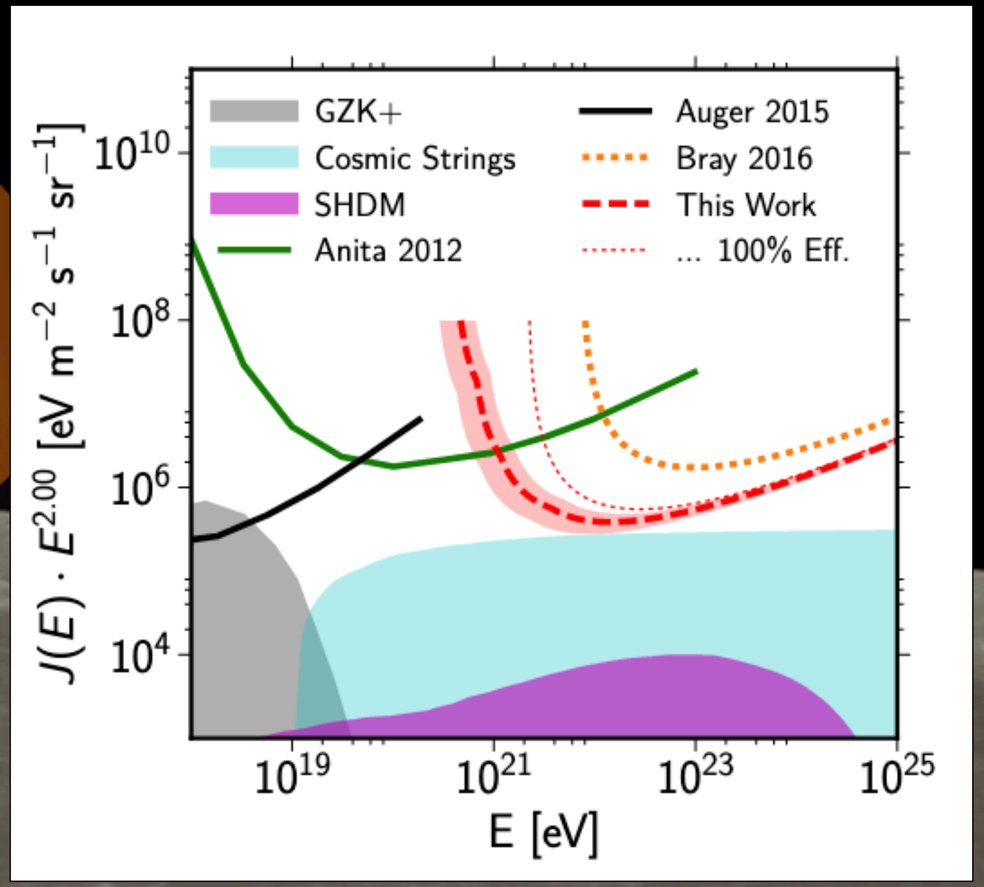
PUEO White Paper: JINST 16 (2021) 08, P08035

Exploring the highest energies: the NuMoon project

Radio emission from neutrino interactions in the lunar regolith

10^{20} - $10^{??}$ eV: Moon = 10^{7} km^2 detector area

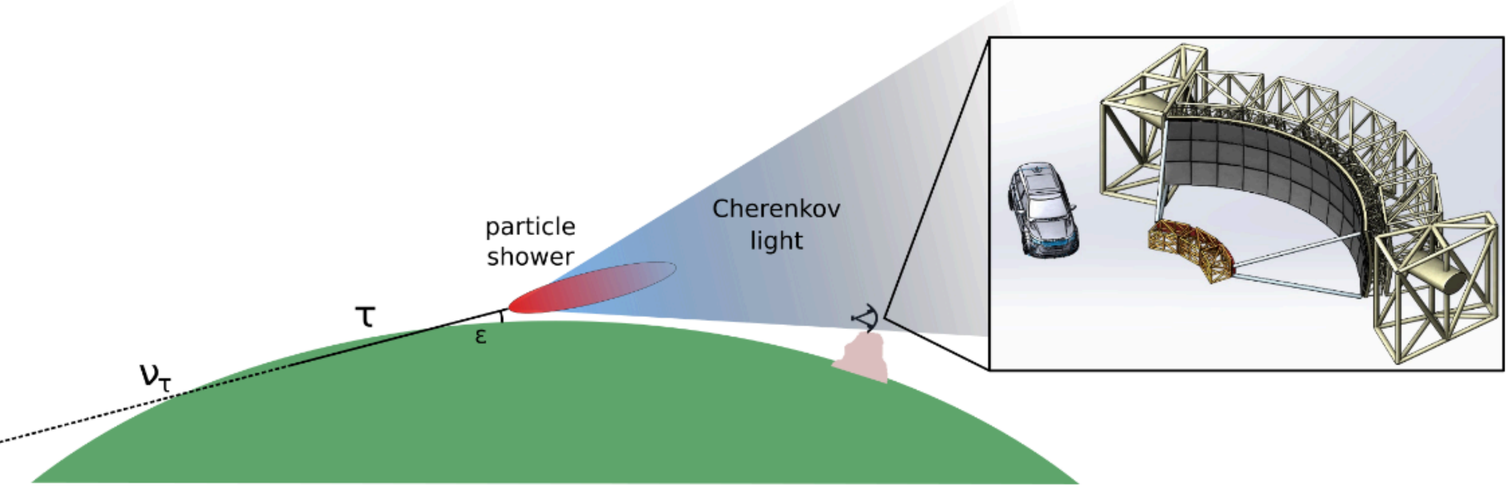
Latest results from G. K. Krampah, ARENA 2022

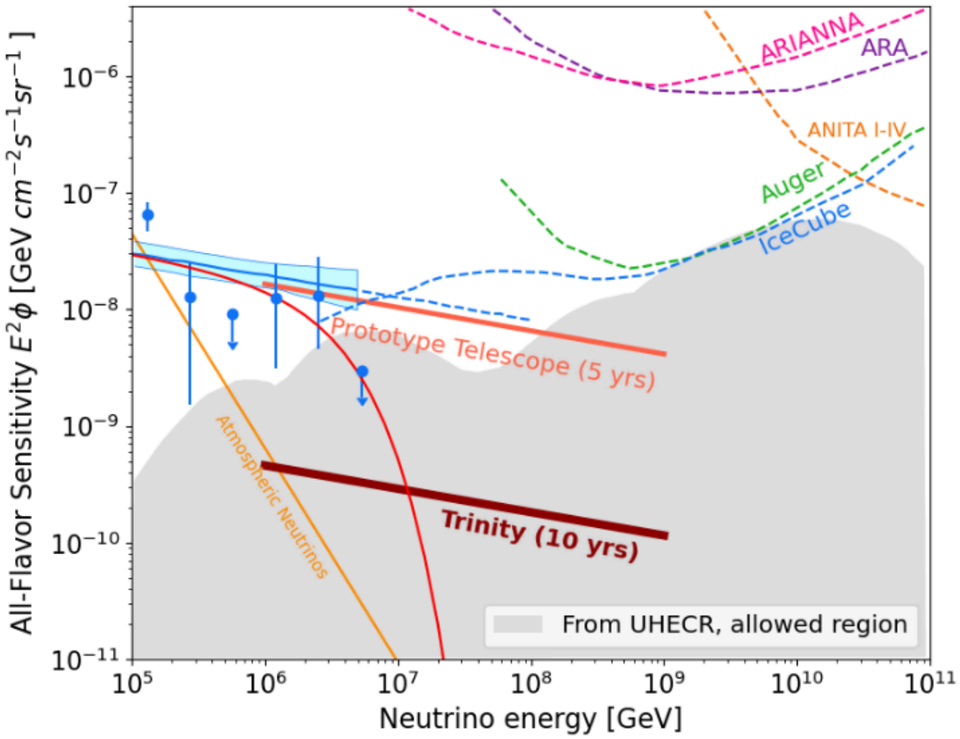


Original idea: Dagkesamanskii & Zheleznykh (1989)

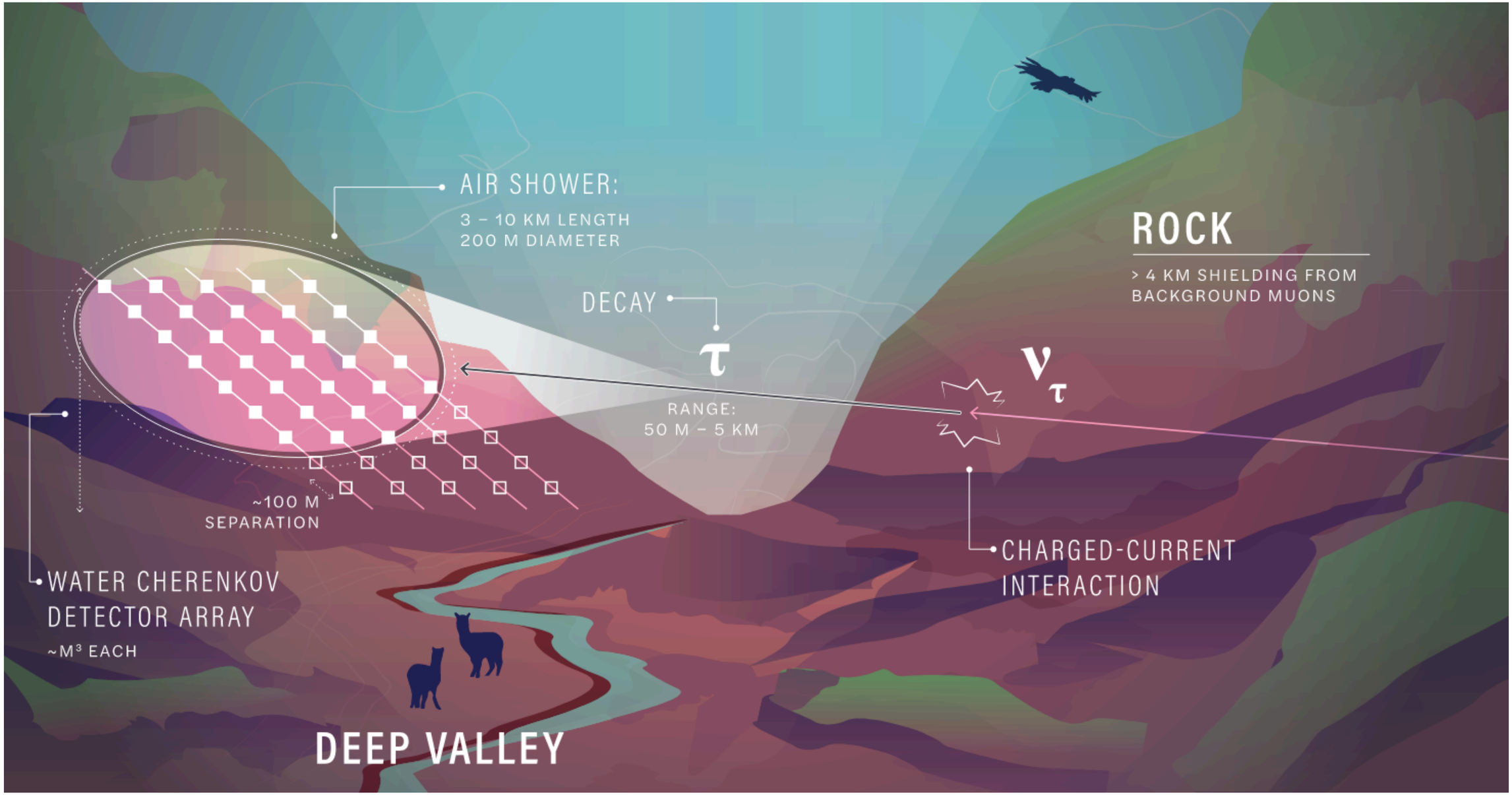
Trinity

- 8 air-shower Cherenkov telescopes optimized for detecting Earth-Skimming neutrinos with energies between 10 PeV and 1000 PeV.
- Wide-FoV (60deg)
- Located at 2-3 km altitude
- 20% duty cycle compensated by detection of very distant showers (as far as 200 km)

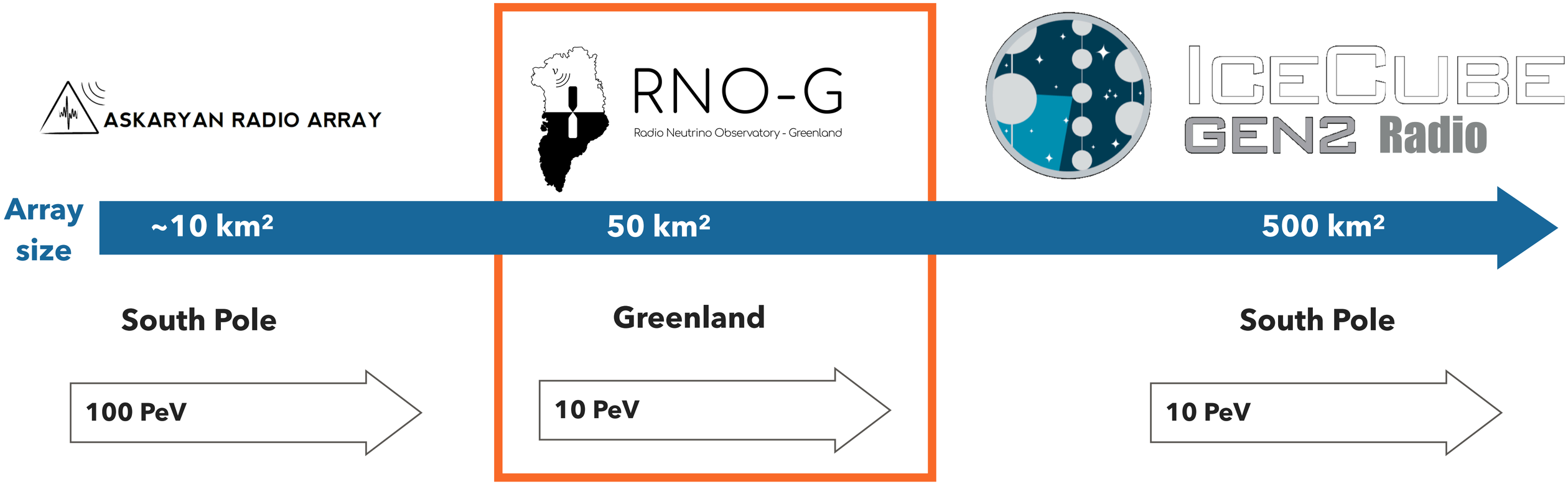




Tau Air-Shower Mountain-Based Observatory (TAMBO)

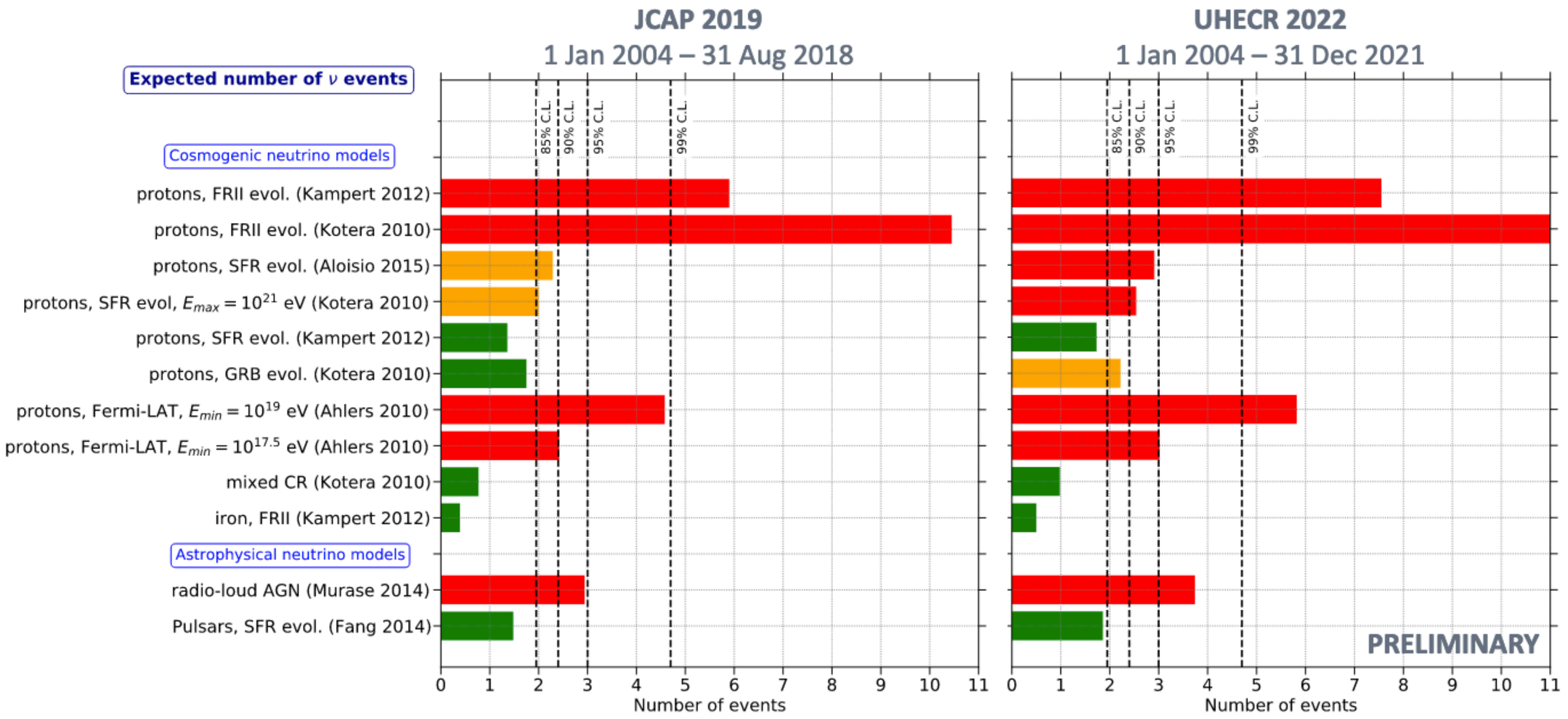


RNO-G: the road towards Gen2-Radio



- RNO-G is a middle-scale **discovery** instrument
- RNO-G **design will inform** IceCube-Gen2 Radio design (now preparing for TDR).

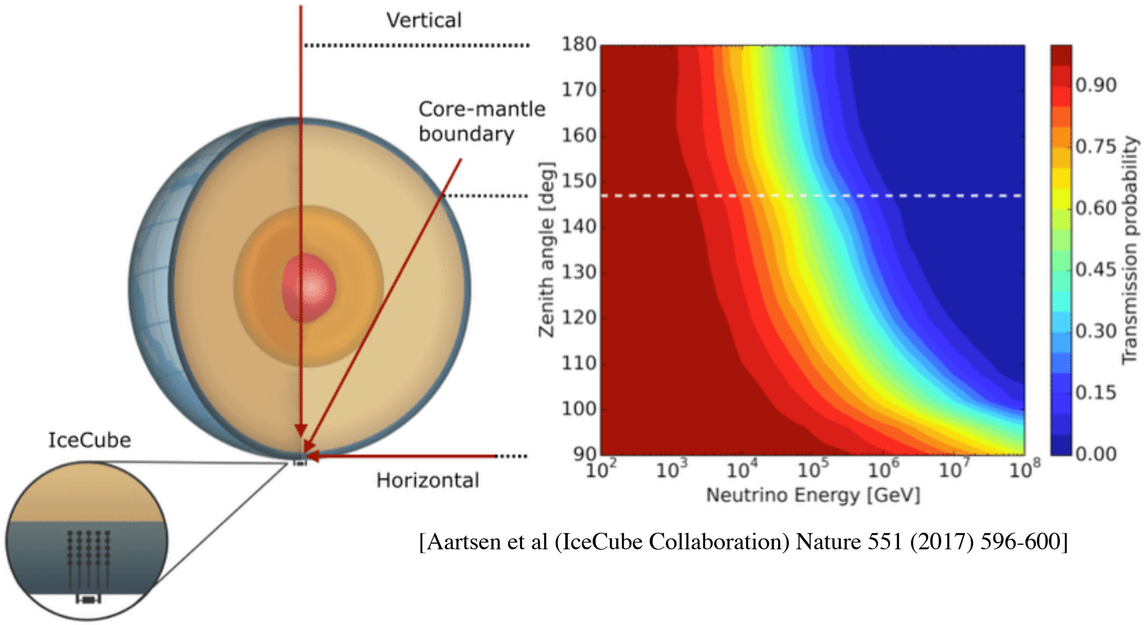
Auger neutrino search: Expected ecent rates for selected models



The experimental landscape

Because of the increasing cross section with energy Earth is opaque to HE neutrinos.

Experiments loose the 4π angular coverage and look at interactions in atmosphere or ice/rock surrounding the detector volume.



[Aartsen et al (IceCube Collaboration) Nature 551 (2017) 596-600]

ν_e ν_μ ν_τ

In-ice Optical Cherenkov: IceCube, IceCube-Gen2

In-ice radio: ARA, ARIANNA, RNO-G, RET-N, PUEO, IceCube-Gen2

ν_τ

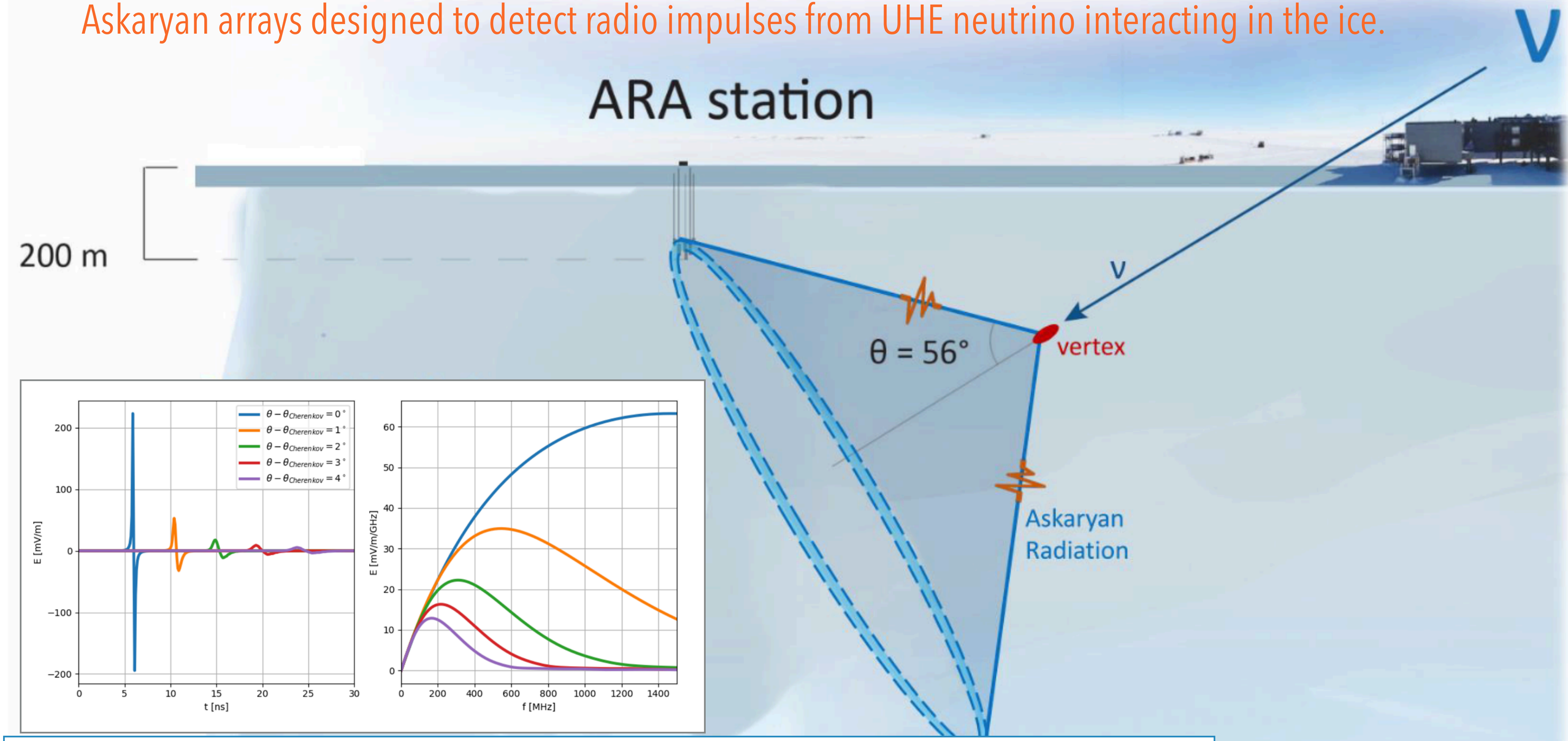
Earth-skimming radio: GRAND, BEACON, PUEO, AugerPrime

Earth-skimming optical Cherenkov (Trinity) and fluorescence (POEMMA)

Particle detectors: TAMBO, Auger

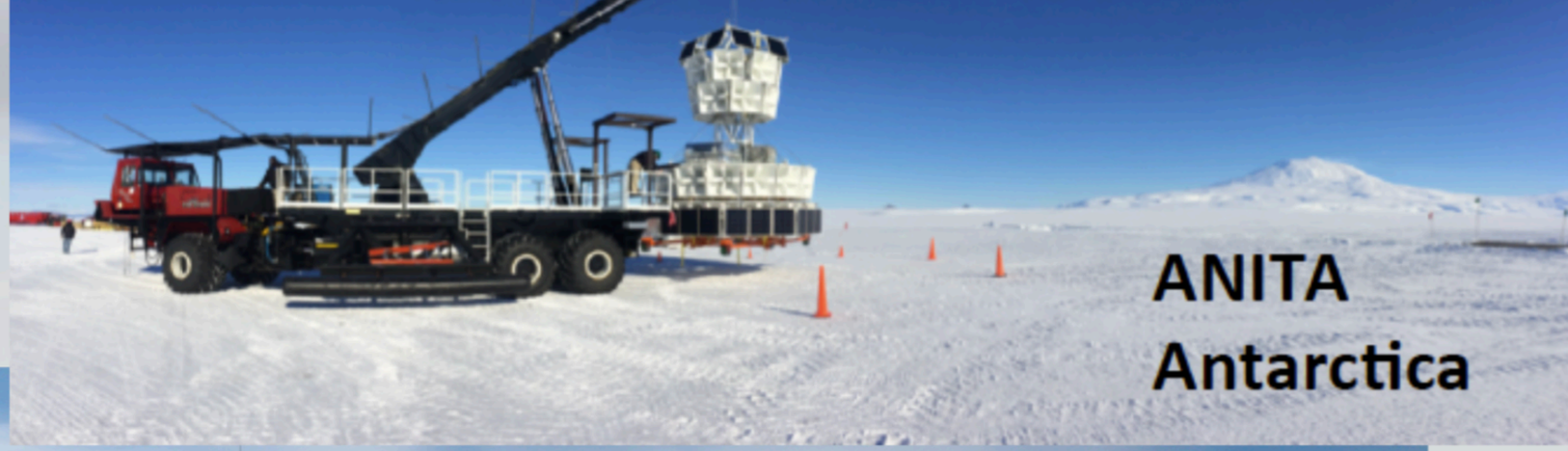
Radio detection in dense media: the Askaryan effect

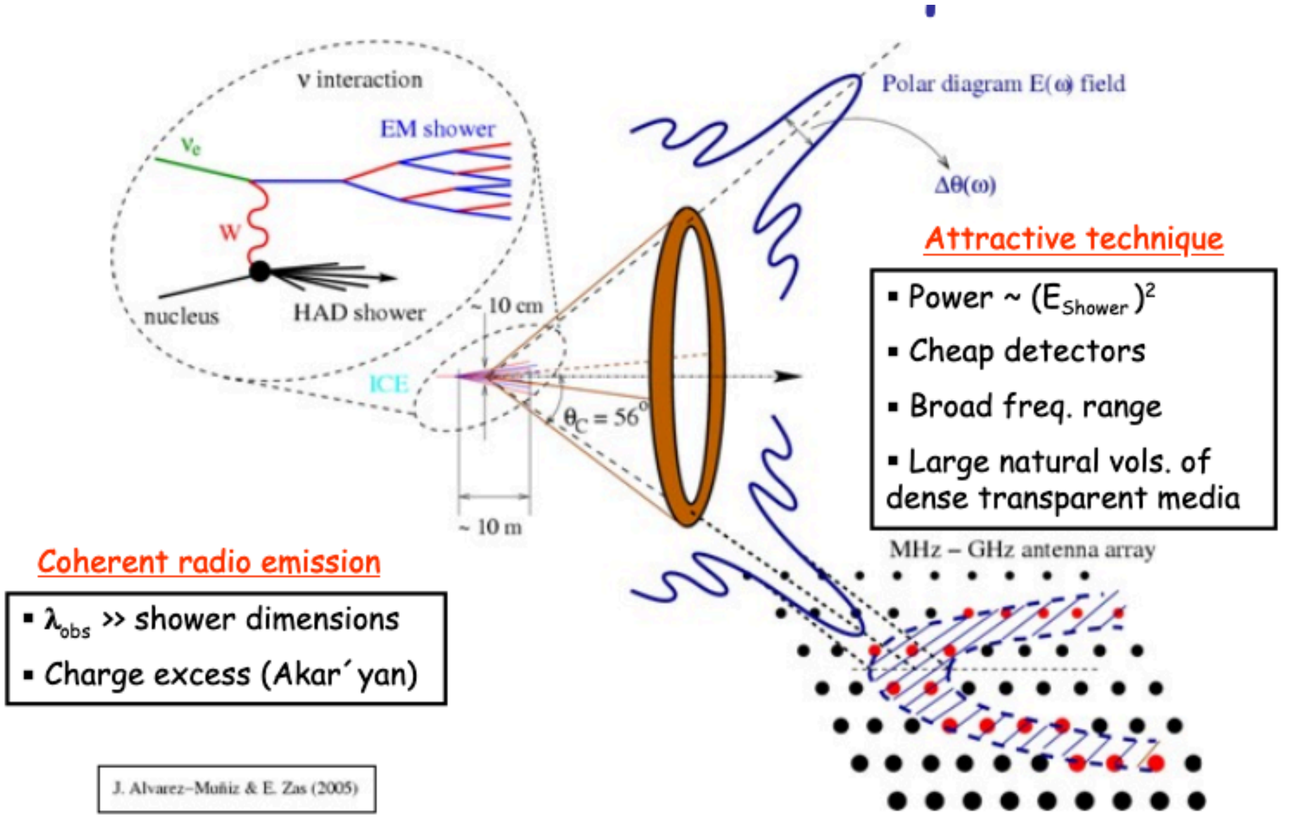
Askaryan arrays designed to detect radio impulses from UHE neutrino interacting in the ice.



We are looking for impulsive **nanosecond-scale** broadband (**150 MHz — 1 GHz**) signal

CURRENT DETECTORS:
pilot radio arrays





Attractive technique

- Power ~ $(E_{Shower})^2$
- Cheap detectors
- Broad freq. range
- Large natural vols. of dense transparent media

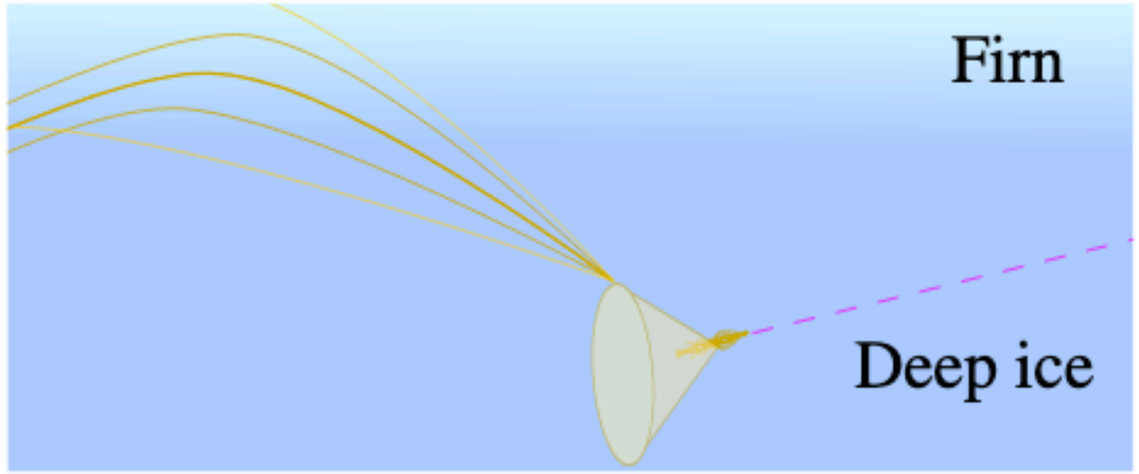
Coherent radio emission

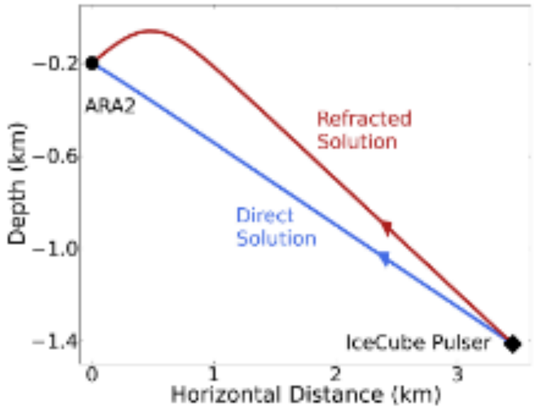
- λ_{obs} >> shower dimensions
- Charge excess (Akar´yan)

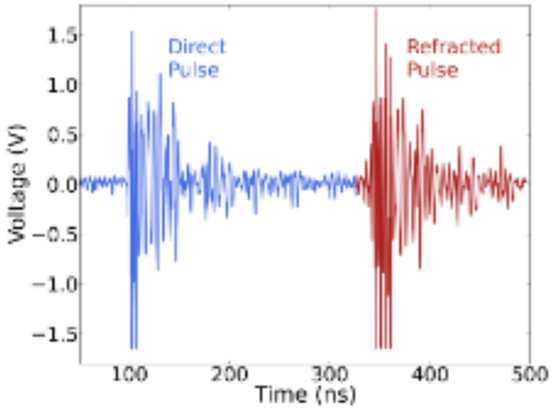
J. Alvarez–Muñiz & E. Zas (2005)

Ice considerations: surface versus deep

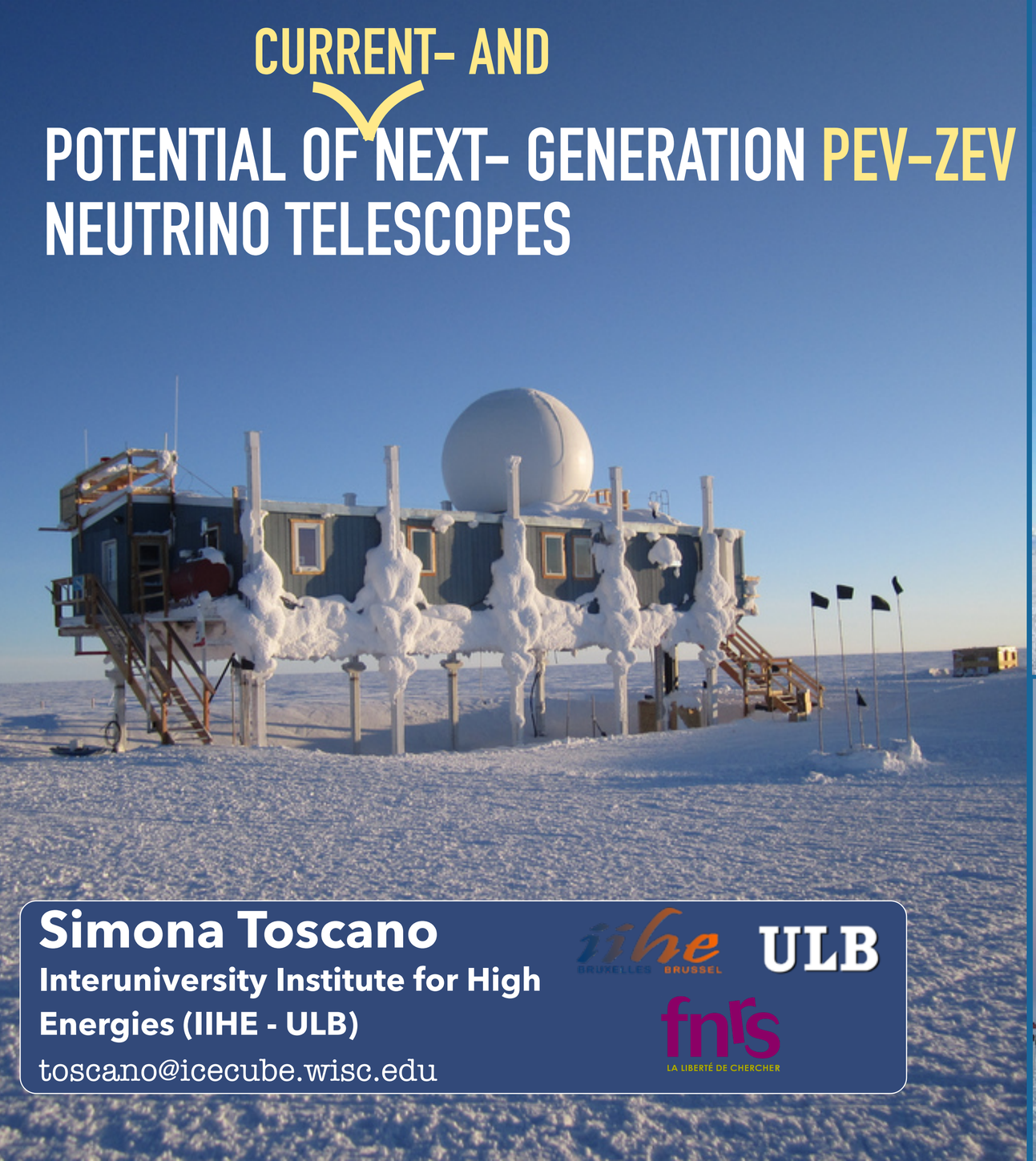
- Near-surface antennas are easier to deploy, and more flexible (can use higher gain antennas, same antenna for all polarizations.)
- But top layer of ice ("firn") has density gradient → index of refraction gradient so not all signals reach surface
- Deep antennas see more volume, but drilling adds to cost and antenna options limited by borehole size
- Another consequence of firn is existence of with multiple paths ("direct" and "refracted") which allow for more precise vertexing

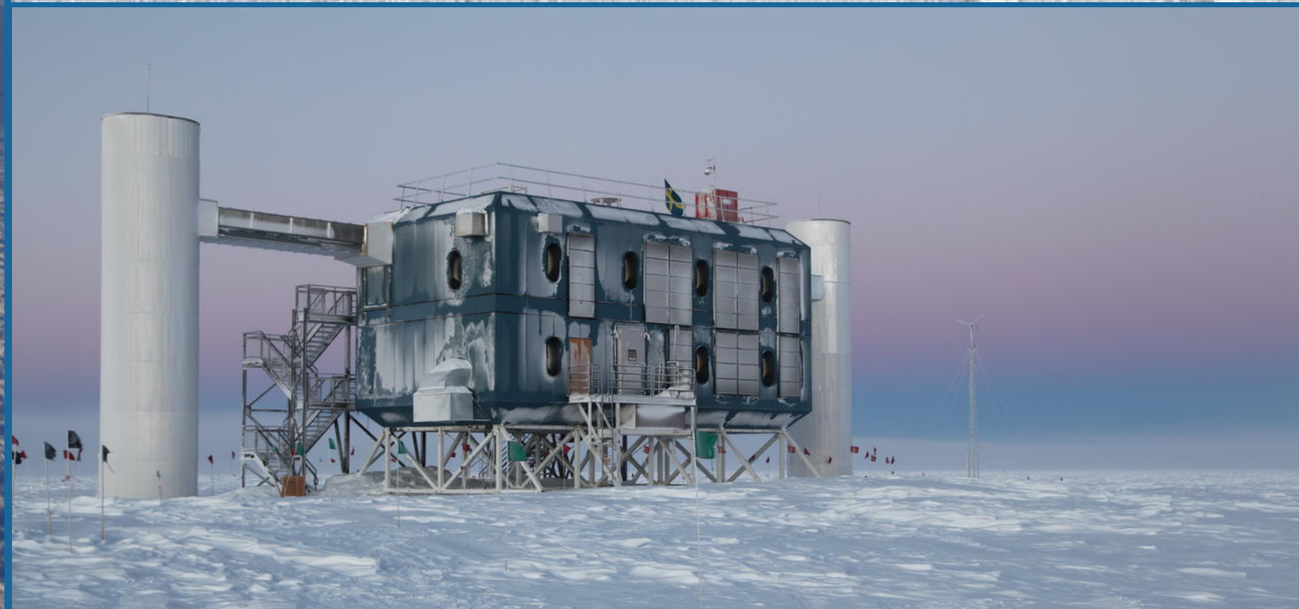






CURRENT- AND POTENTIAL OF NEXT- GENERATION PEV-ZEV NEUTRINO TELESCOPES



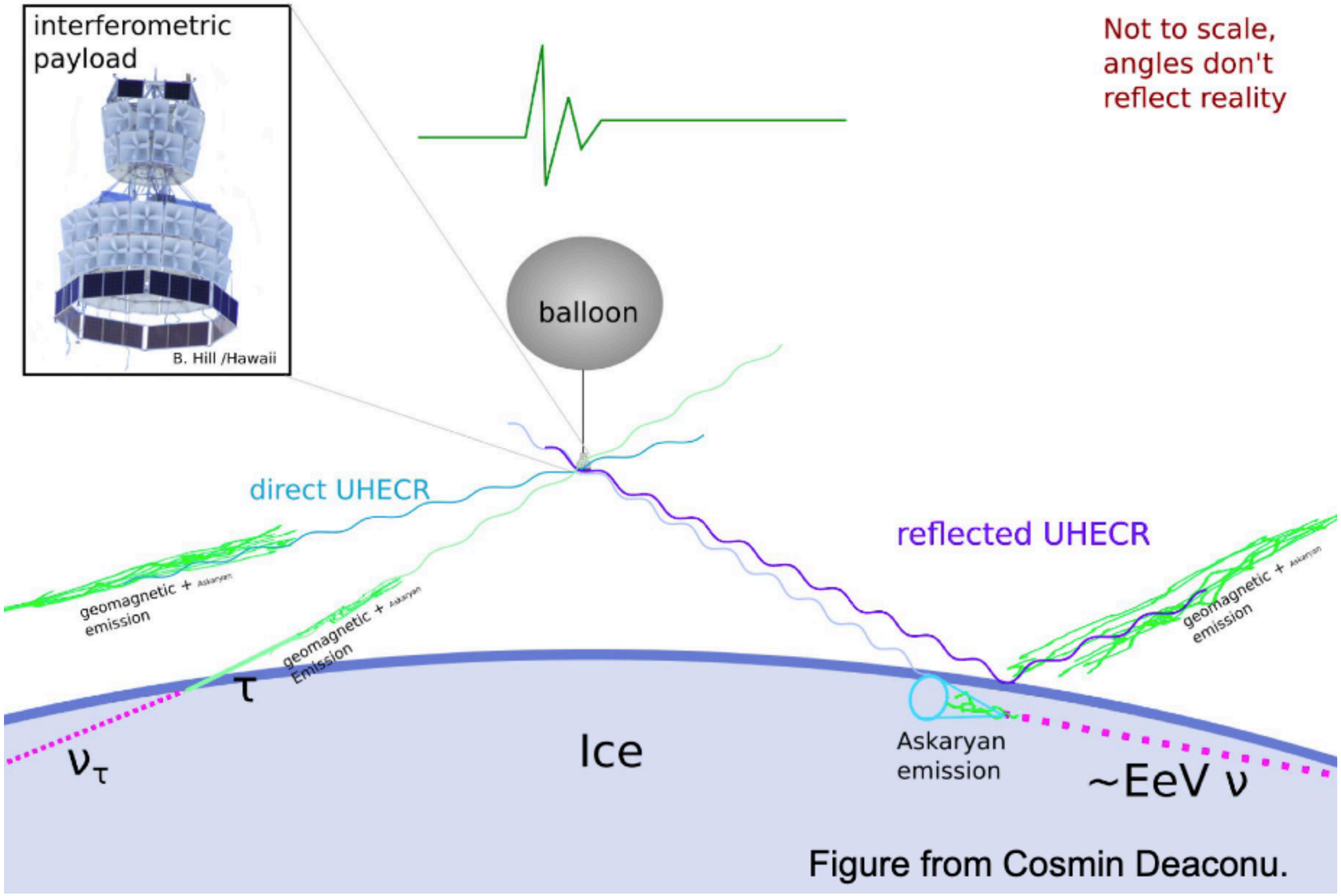


Simona Toscano

Interuniversity Institute for High Energies (IIHE - ULB)

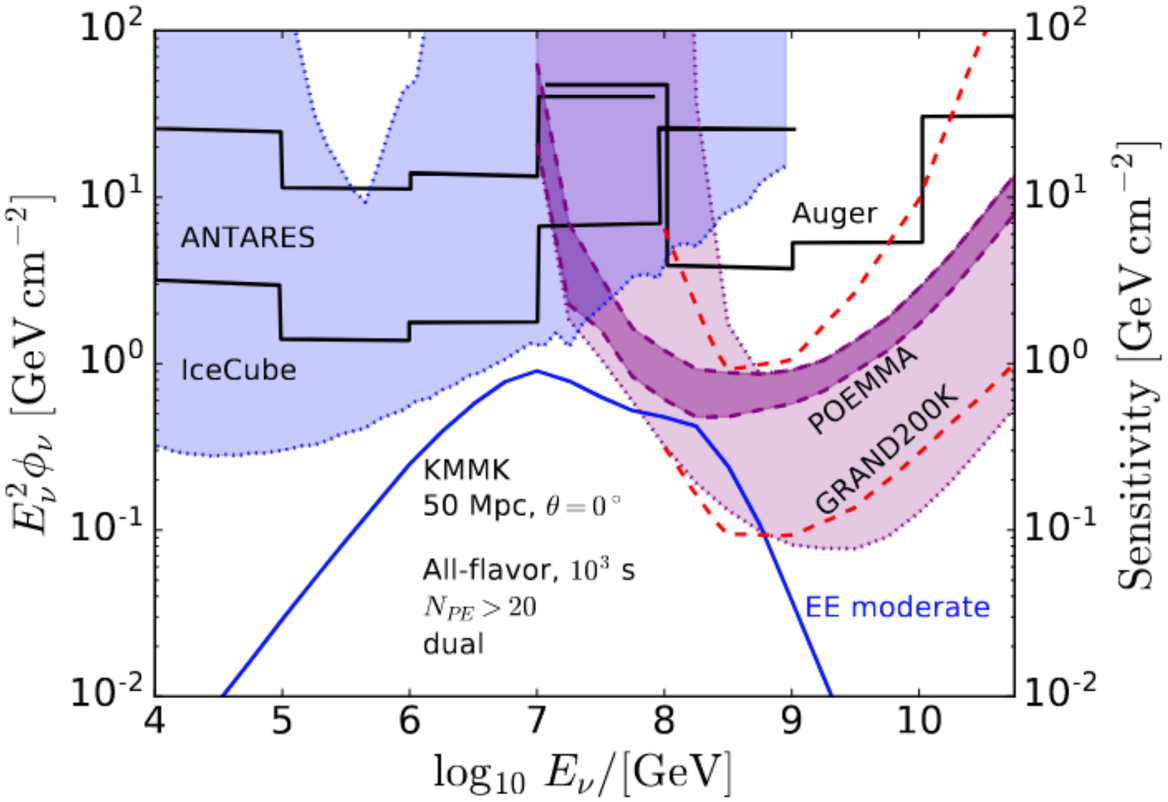
toscano@icecube.wisc.edu

Pilot projects: The ANtarctic Impulsive Transient Antenna

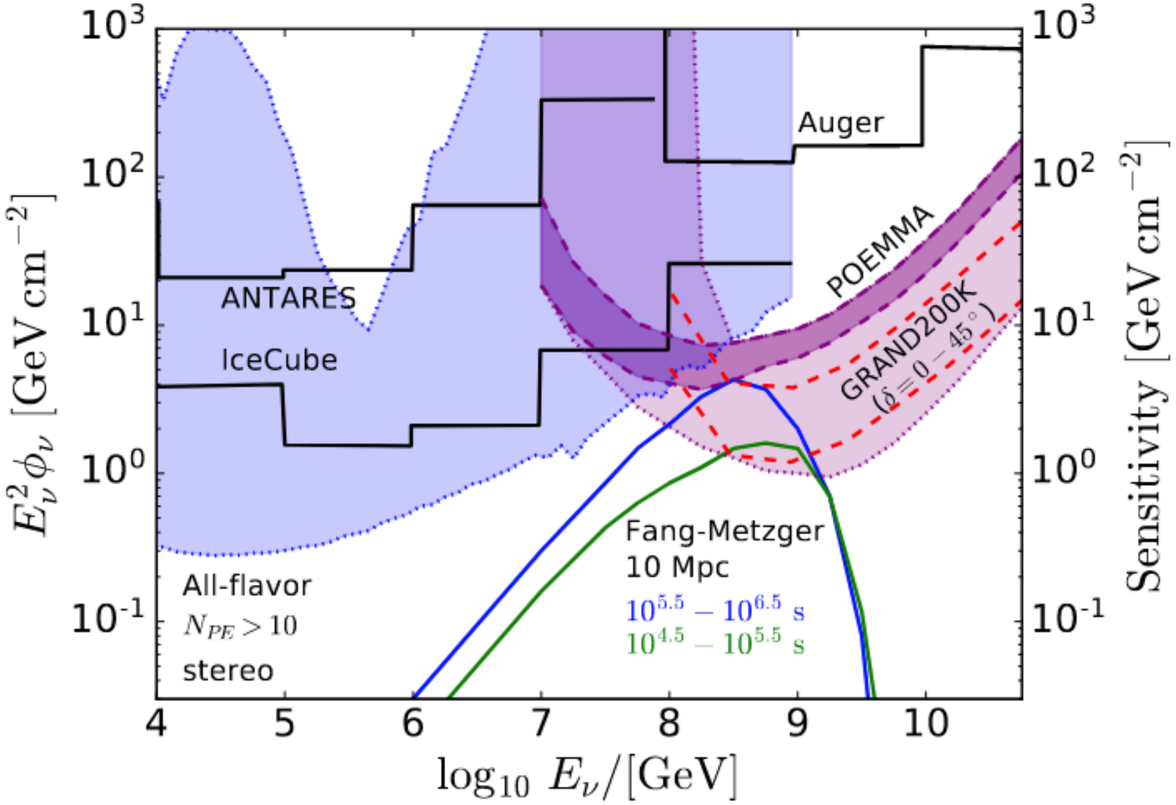


Probe Of Extreme Multi-Messenger Astrophysics (POEMMA)

ToO sensitivity to a short, 1000s burst



ToO sensitivity to a long, 1000s burst



Science goals

We know the story…

Neutrinos represent a UNIQUE window into the deep extragalactic Universe and opaque sources.

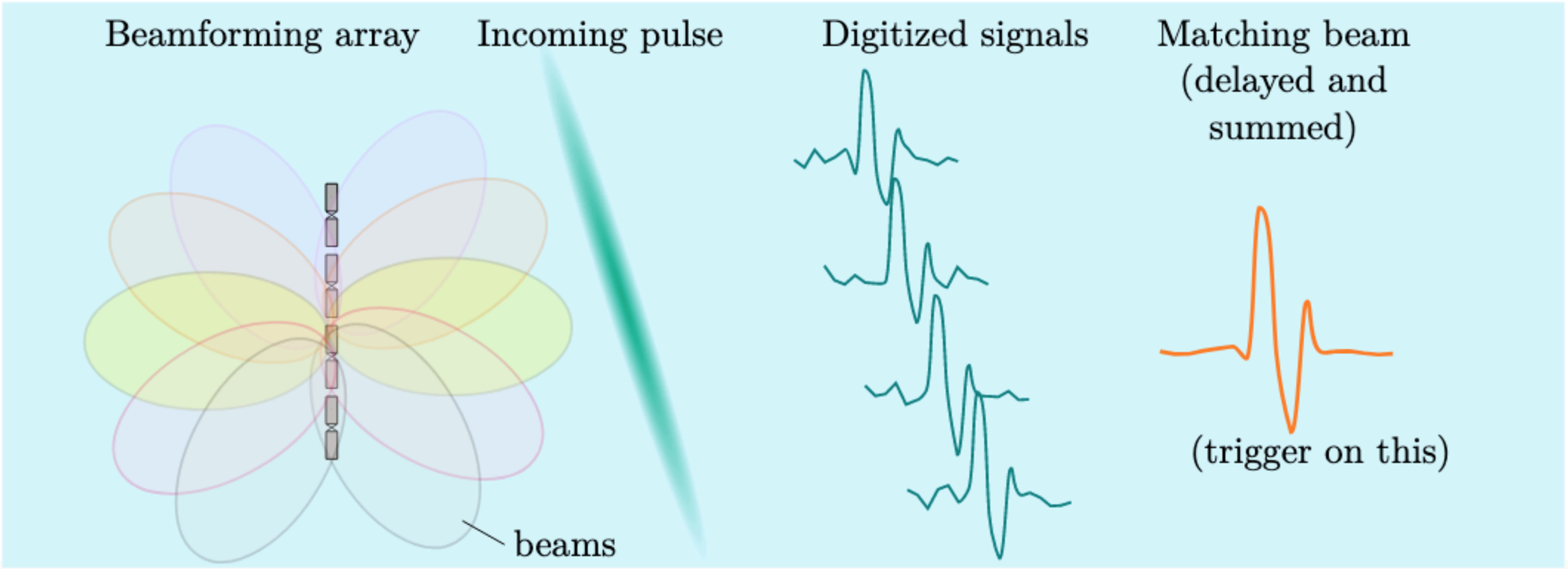
Sources of IceCube cosmic neutrinos *might not* be the same of (Auger/TA) UHECR sources.

UHE neutrinos can give information about:

- Astrophysical neutrino sources (transient multi-messenger astronomy)
- UHECRs composition and source evolution (direct link to the highest CR energies).

The RNO-G Phased Array Trigger

- We can't fit high-gain antennas down a borehole :(
- But we can synthesize multiple high gain antennas from several low-gain antennas
- Phased array trigger: 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)
- In RNO-G, the 4 VPols will serve as the primary trigger



slide from C. Deaconu, PPC22

HE and UHE neutrinos: possible sources

Secondaries take up 5-10% of parent cosmic-ray energy

$E_\nu \sim 5\%\ E_{CR}$ $E_\gamma \sim 10\%\ E_{CR}$

$E_{CR} > 10^{18}$ eV

$E_\nu > 10^{16}$ eV

Clean probe of the Universe
- $E > 10^{17}$eV neutrinos is uncharted territory
- Direct link to highest energy CRs (5%/A of primary energy)
- Transient multimessenger astronomy