Cosmic Neutrinos: Status and Future

Stephanie Wissel
Penn State

NuFact
5 August 2022

Astrophysics

Particle Physics

For Cosmic Neutrinos, the Astrophysics and Particle Physics are inextricably linked

High-Energy and Ultra-High-Energy Neutrinos: A Snowmass White Paper

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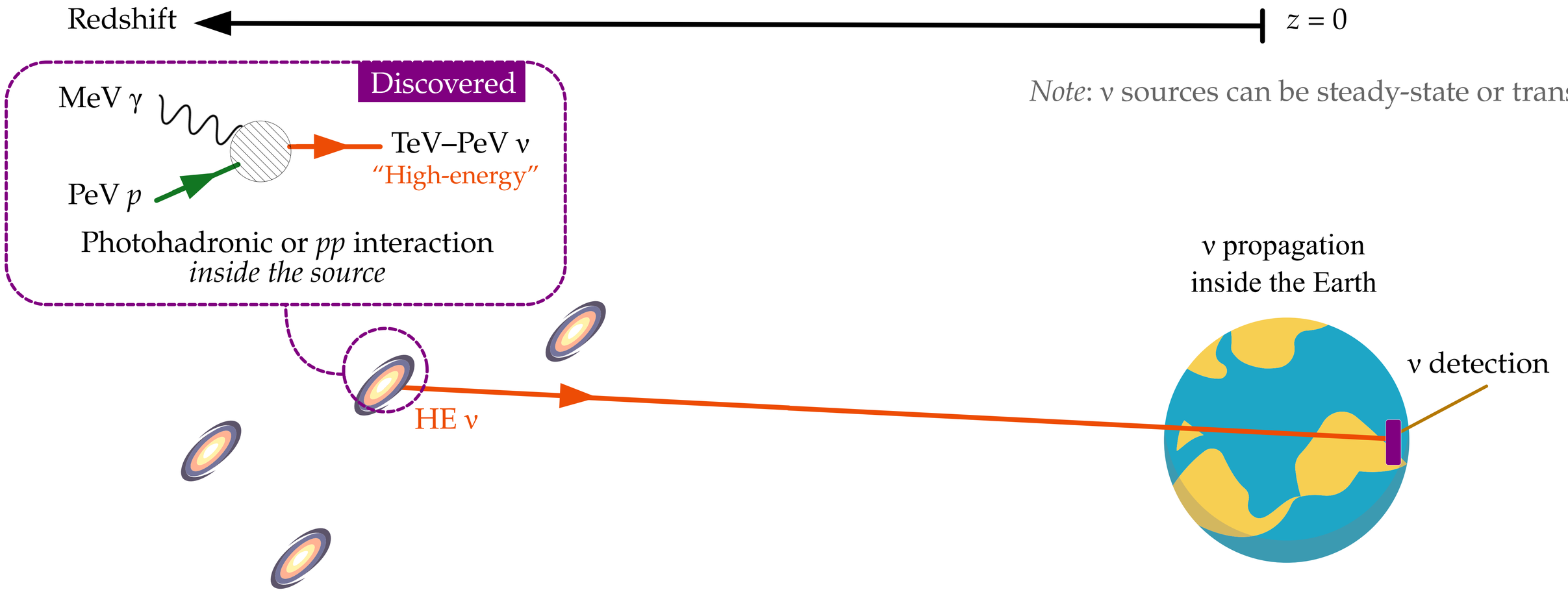
arXiv:2203.08096 accepted JHEAp

Recently summarized in Snowmass whitepaper with ~200 authors + endorsers

- High energy neutrinos: TeV-PeV
    - Discovered, entering the precision era
- Ultra-high energy neutrinos: >100 PeV
    - The next frontier, undiscovered

Redshift ← $z = 0$

Note: ν sources can be steady-state or transient



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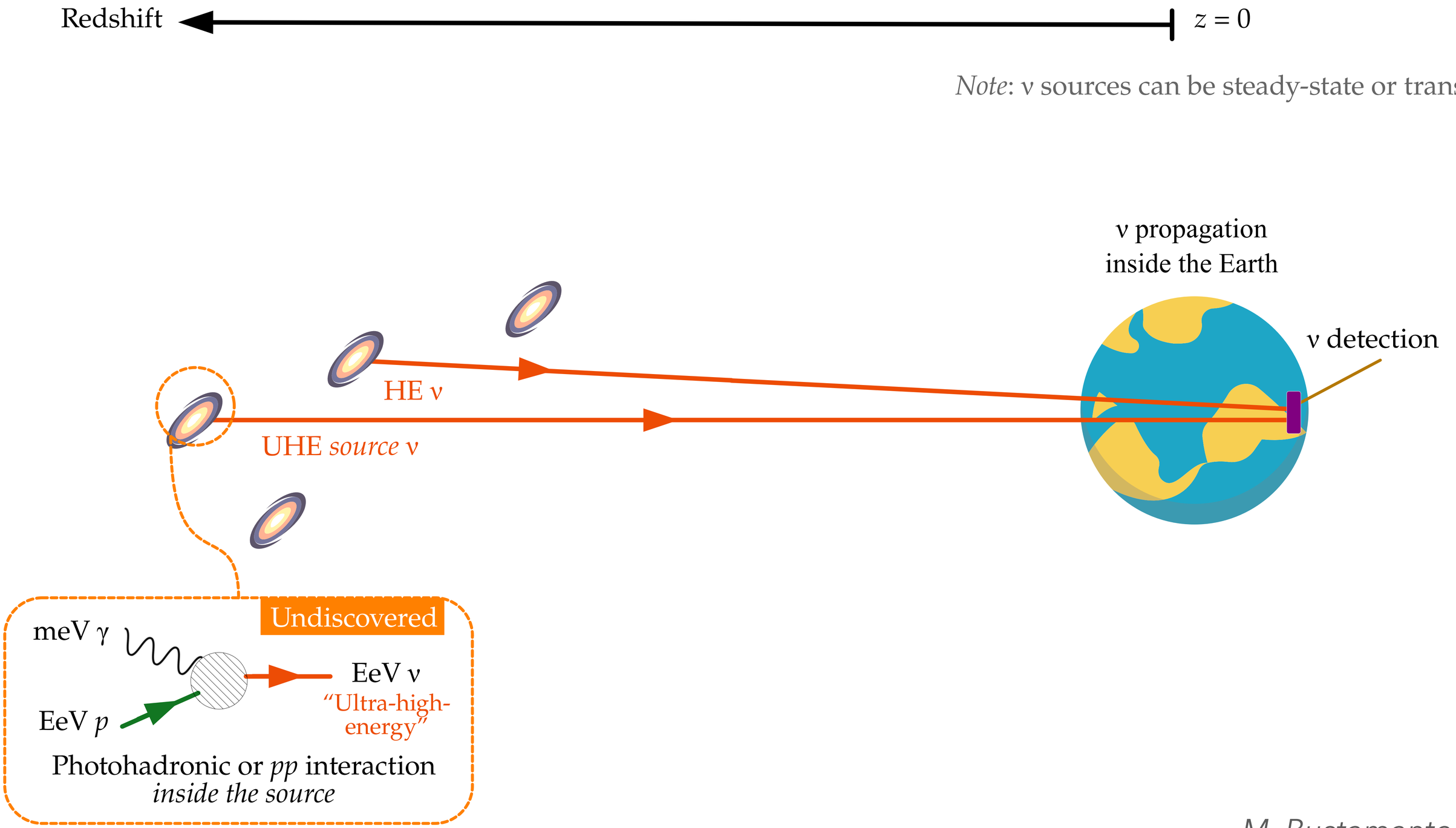
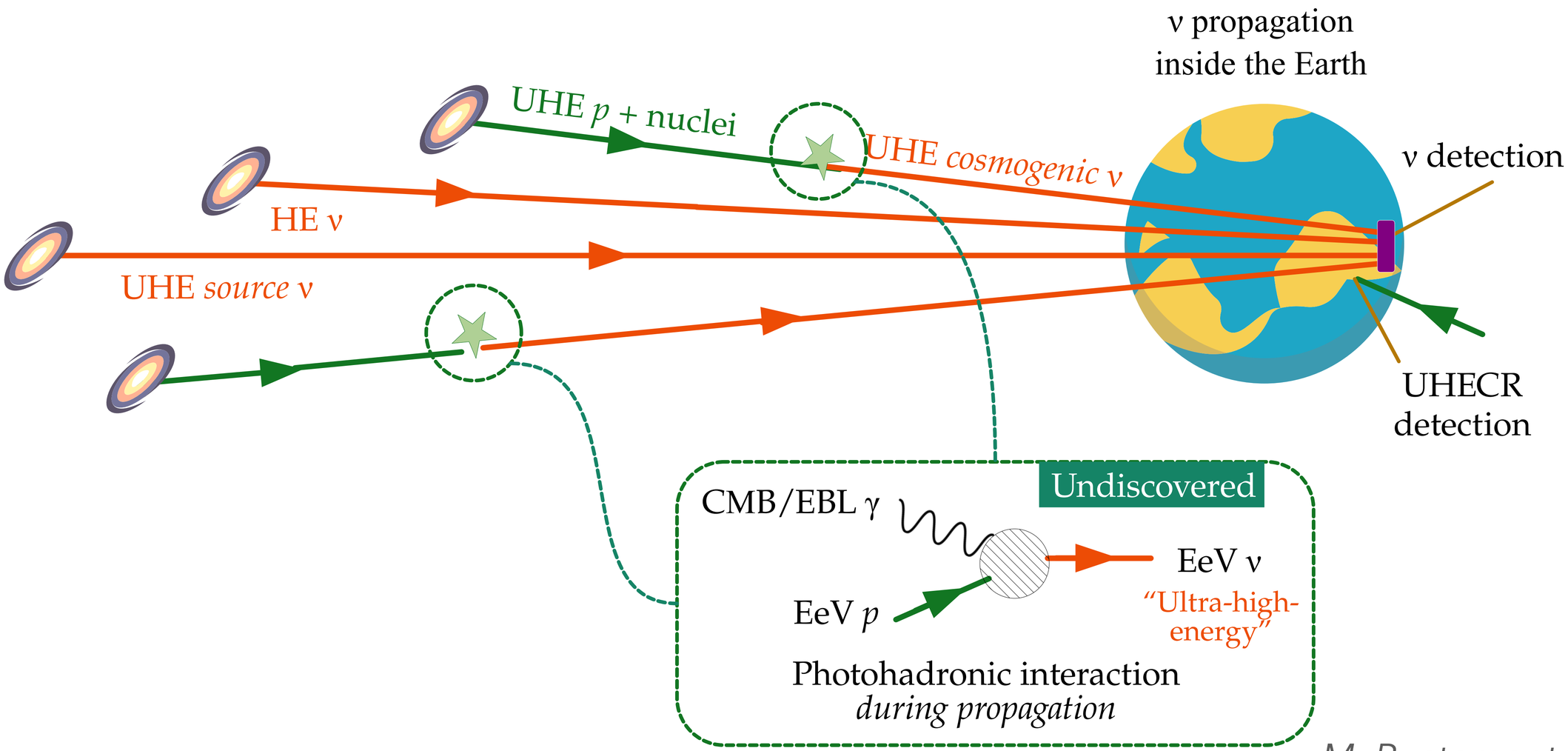
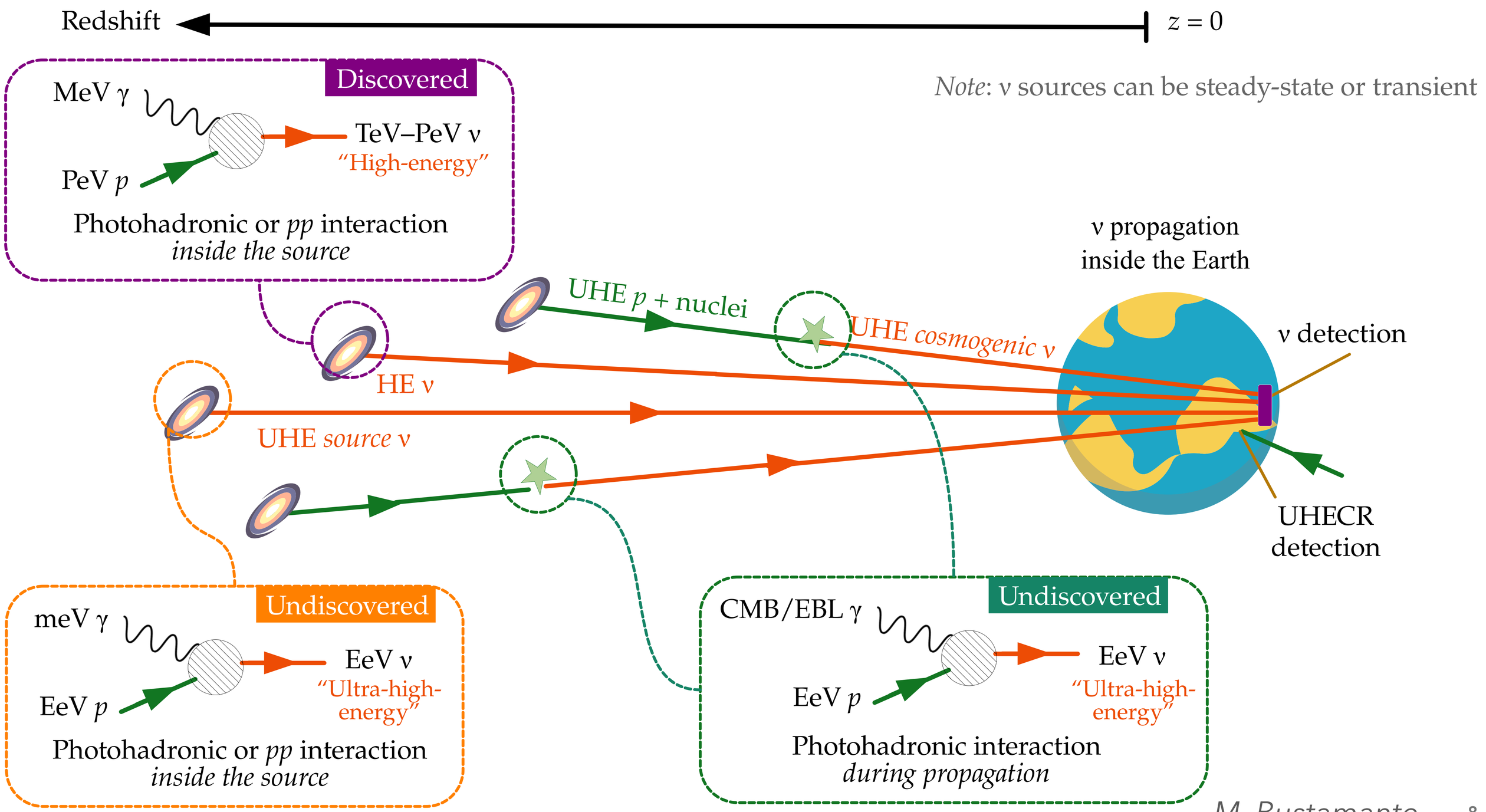

Redshift
z = 0
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν
UHE source ν
Undiscovered
meV γ
EeV ν
"Ultra-high-energy"
EeV p
Photohadronic or pp interaction
inside the source

Redshift ← $z = 0$

Note: ν sources can be steady-state or transient

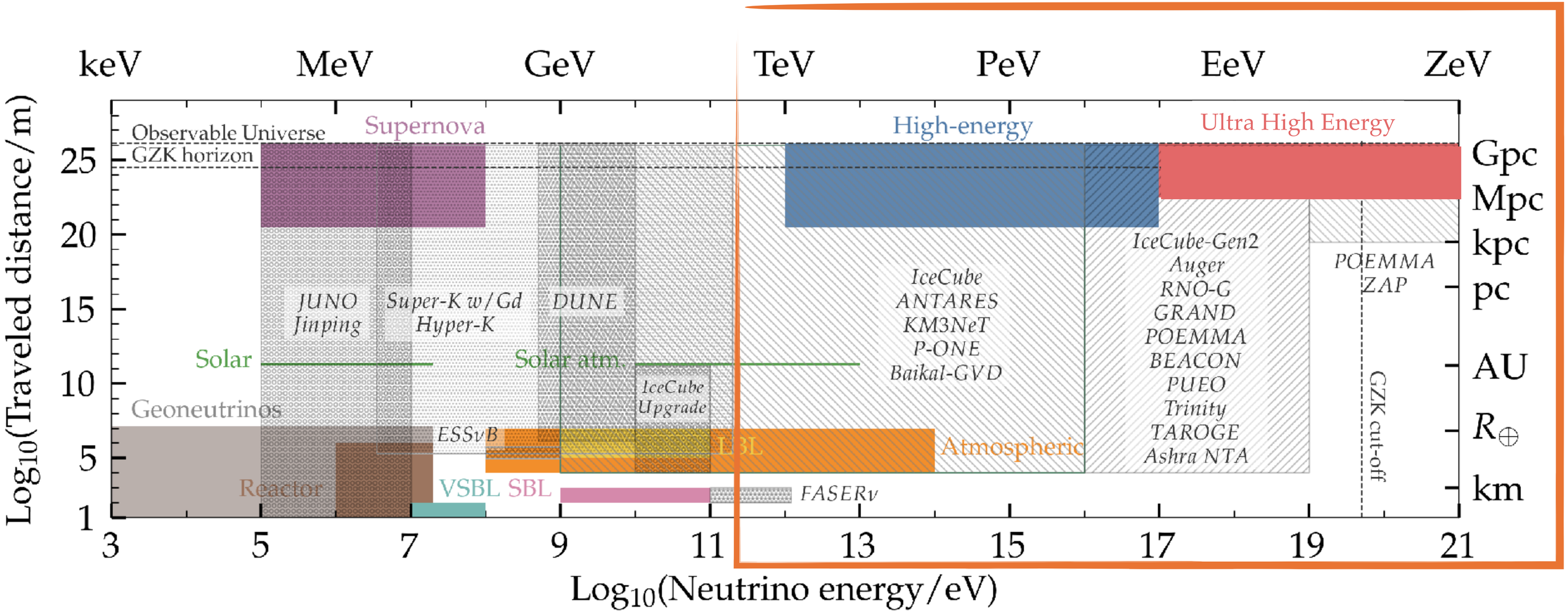




M. Bustamante

Fundamental Physics at the Highest Energies

- Fundamental physics probe at the **highest energy scales (TeV to ZeV)**
- **Longest baselines** (~Gpc) allow even small effects to accumulate over **cosmological distances**



arXiv:2203.08096

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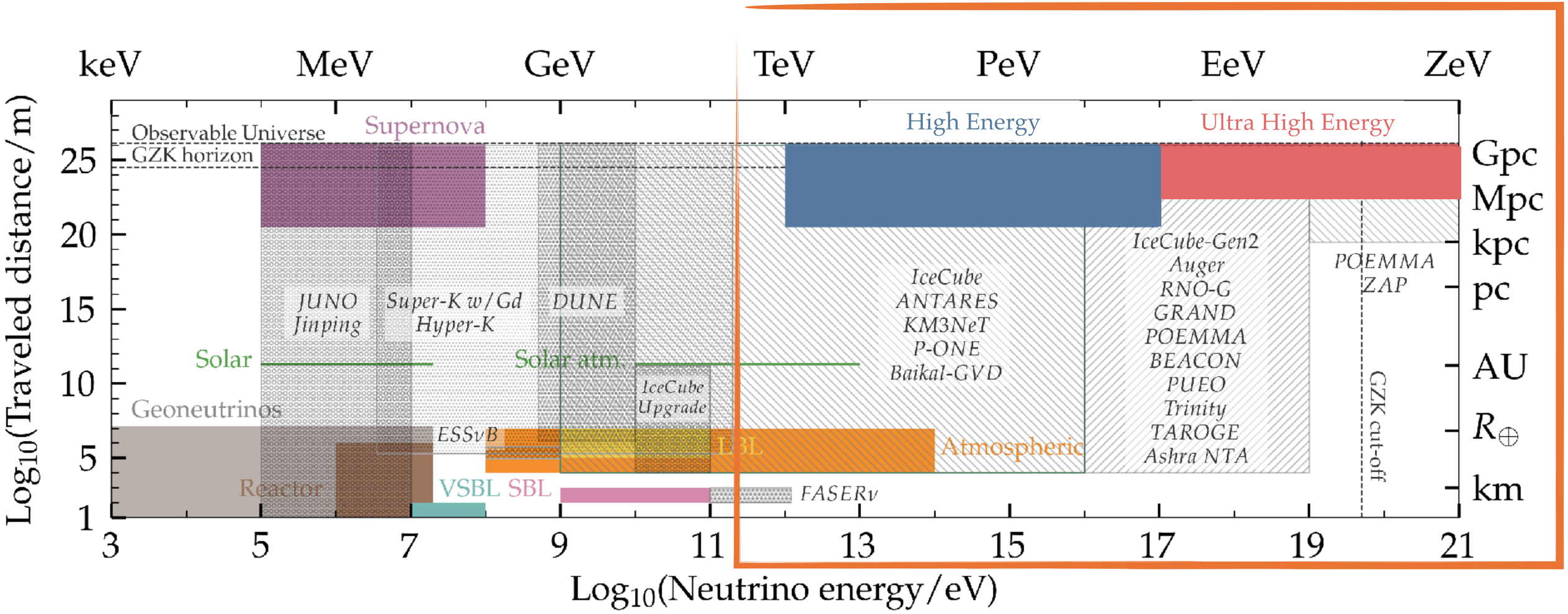

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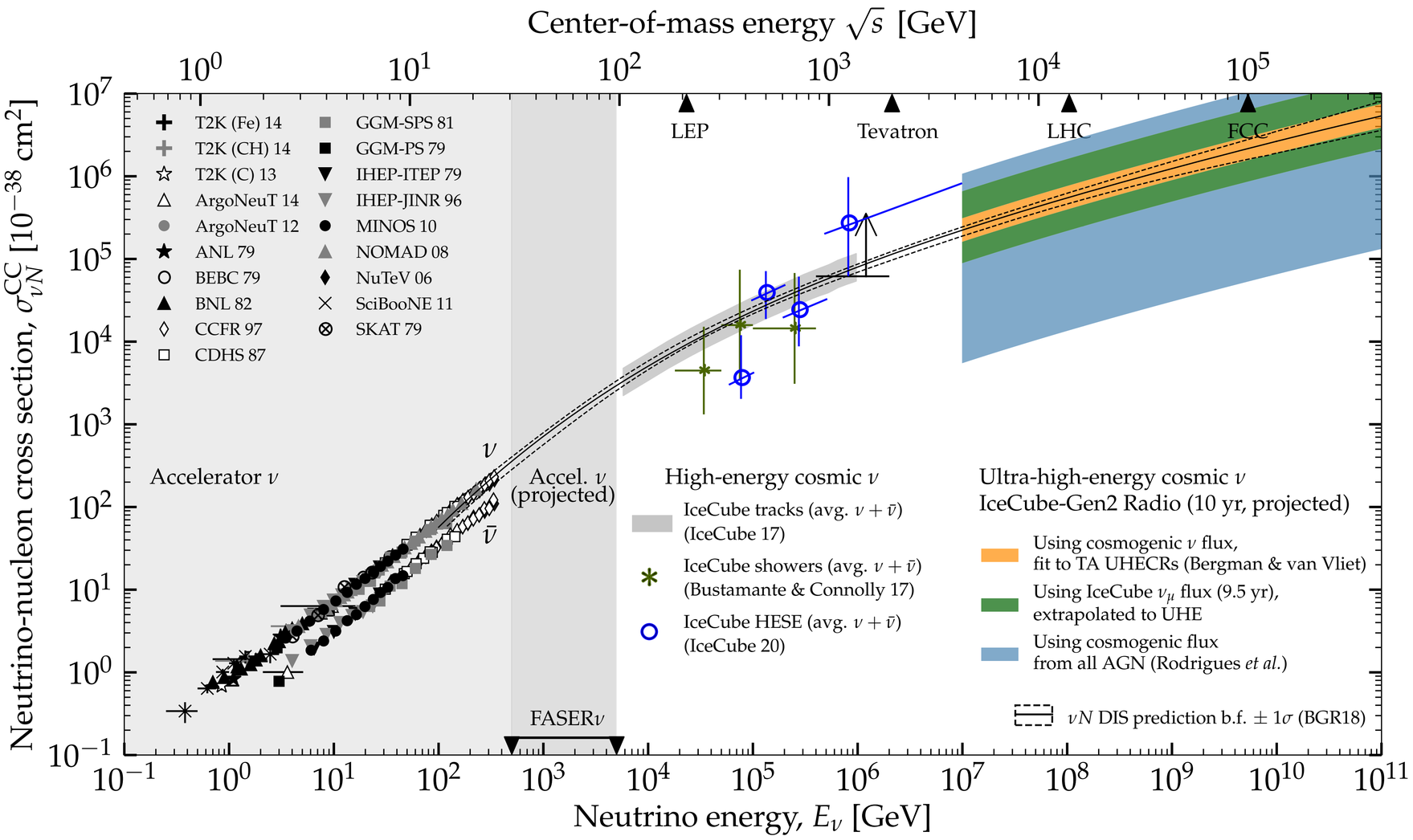
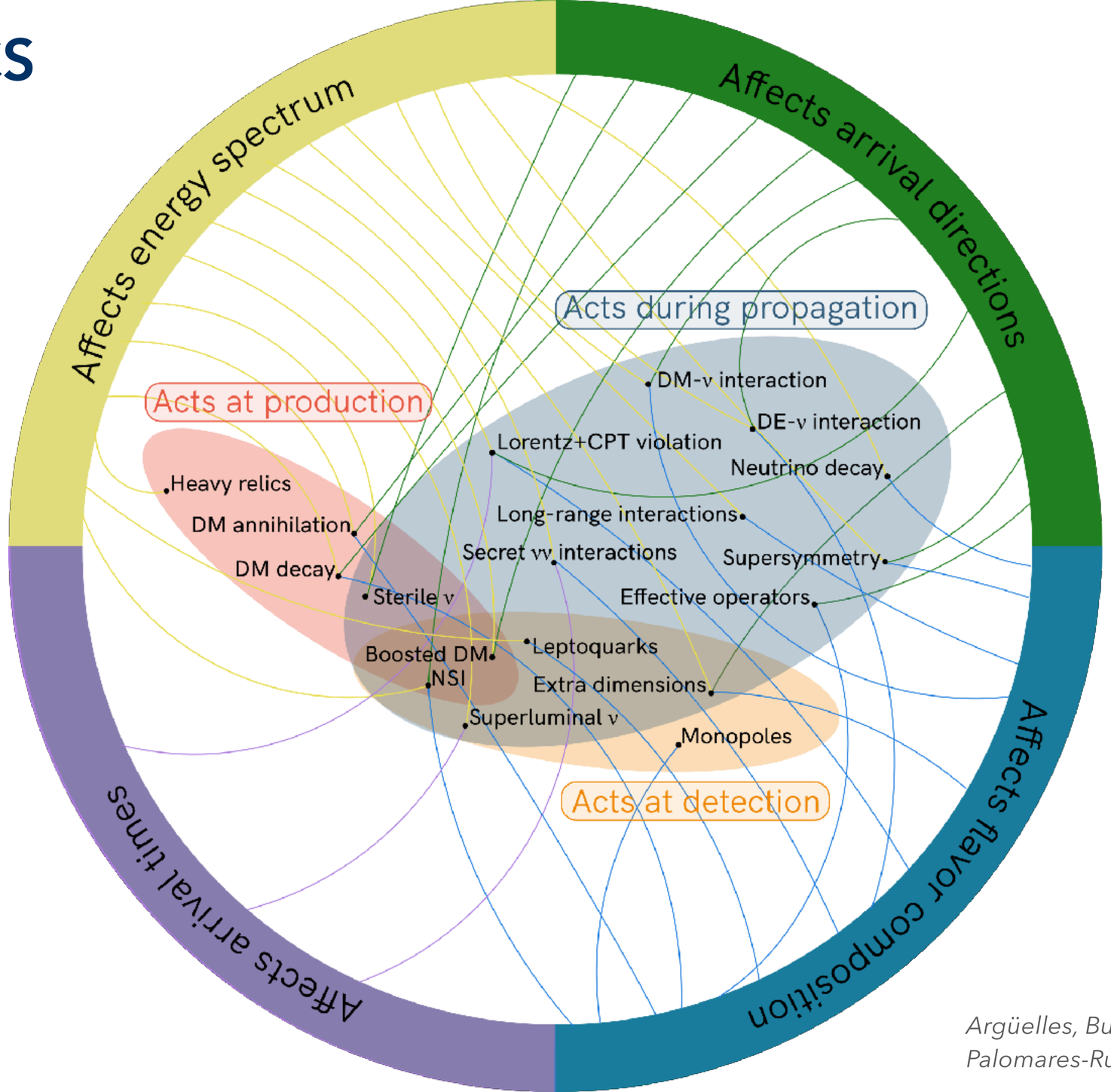
Cross Section

- Current measurements complement accelerator experiments
- UHE (>100 PeV) experiments will probe explore new energy regime ($\sqrt{s} > 30$ TeV)
- Inelasticity y complementary observable



arXiv:2203.08096, Valera, Bustamante, Glaser, arXiv:2204.04237

New Physics Impact on Neutrinos

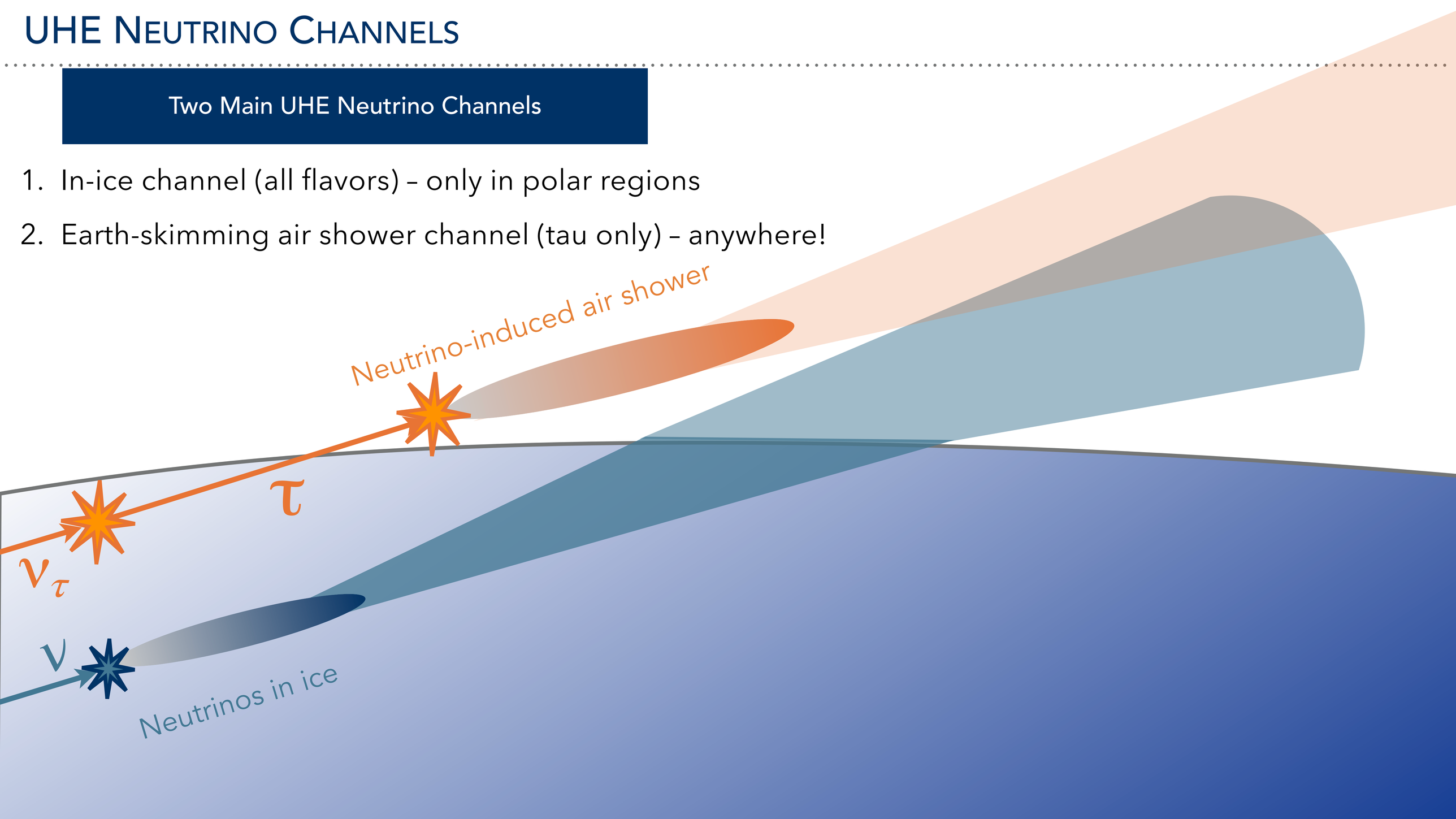


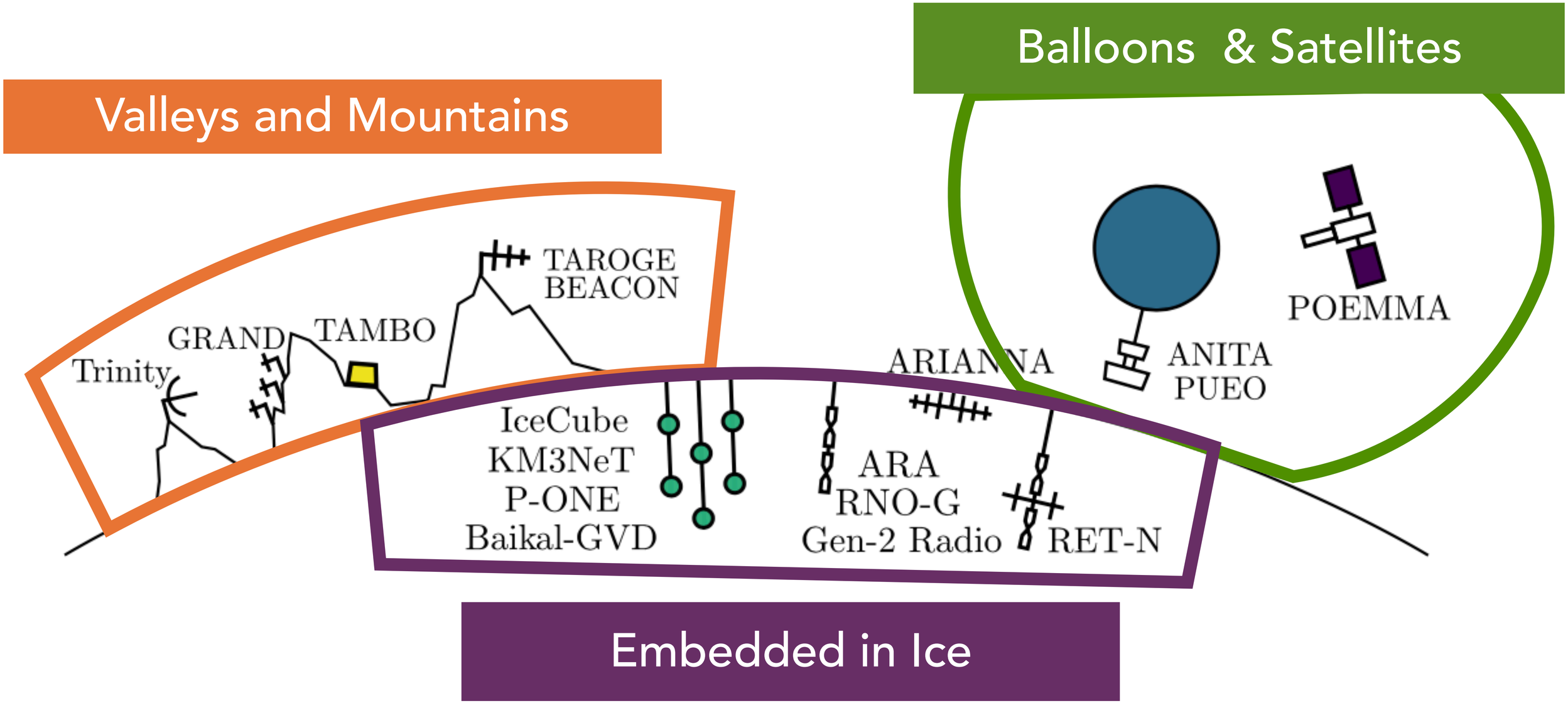
Argüelles, Bustamante, Kheirandish, Palomares-Ruiz, Salvadó arXiv:1907.08690

UHE Neutrino Channels

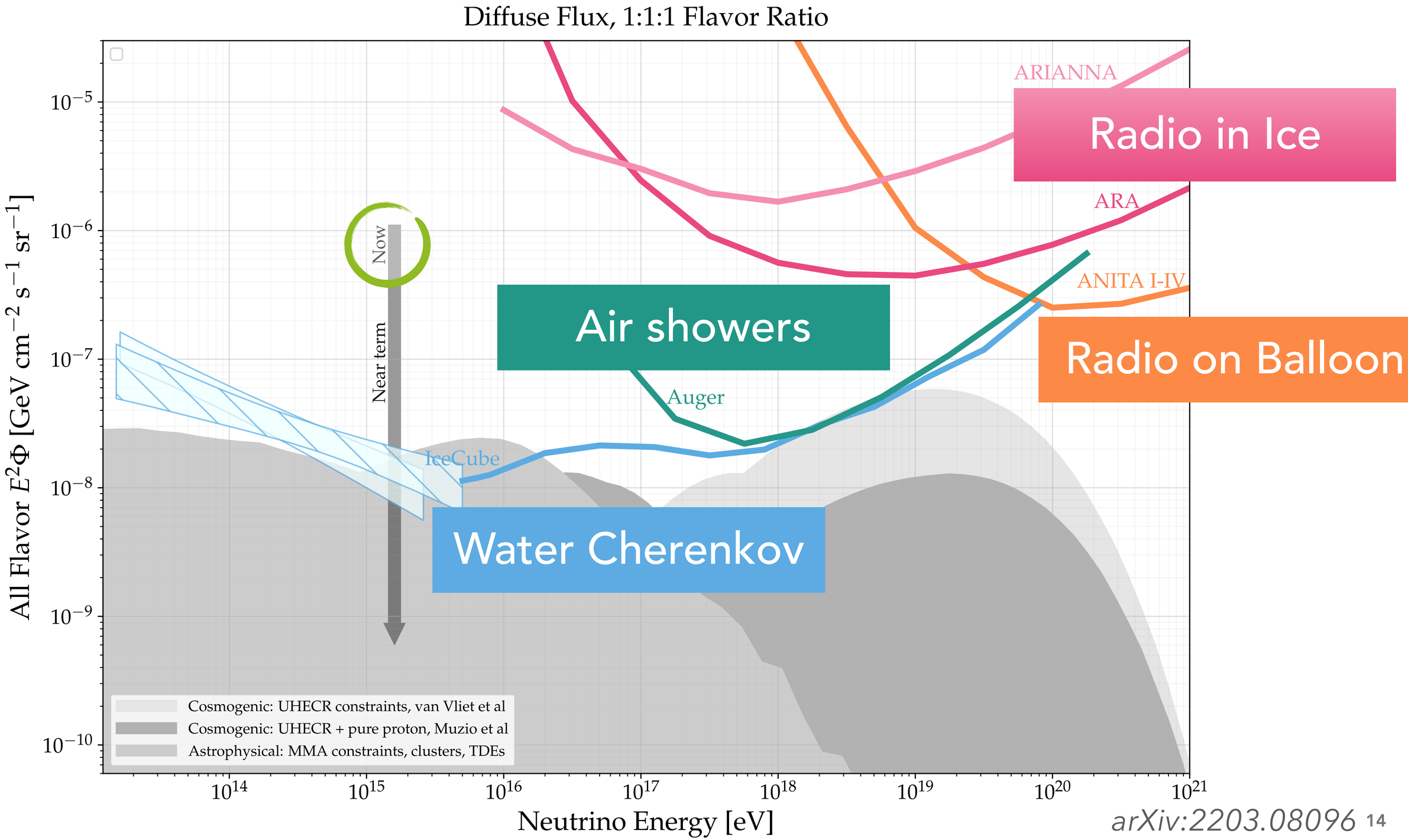
Two Main UHE Neutrino Channels

1. In-ice channel (all flavors) – only in polar regions
2. Earth-skimming air shower channel (tau only) – anywhere!





Estaban, Prohira, Beacom 2022 arXiv:2205.09763



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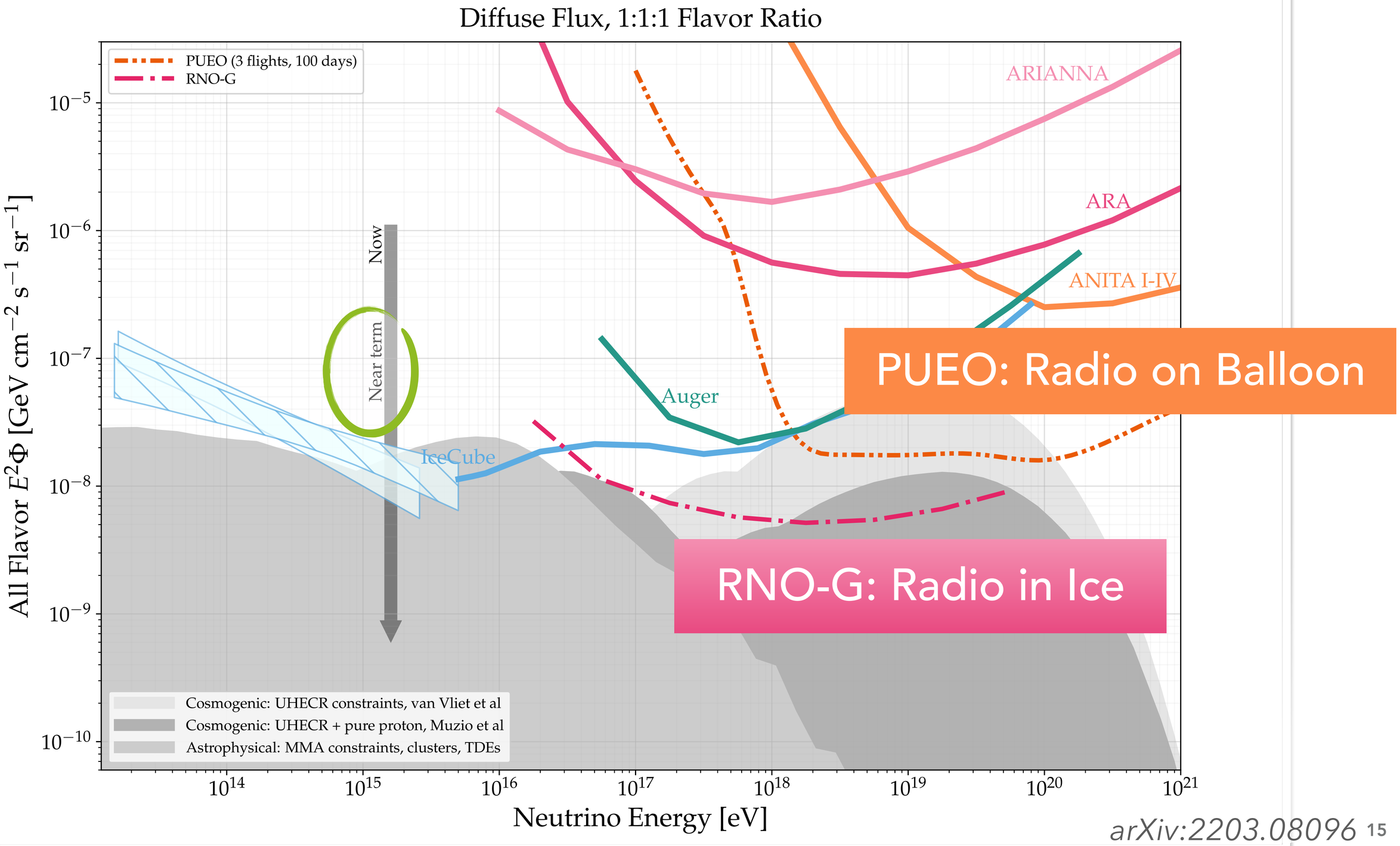

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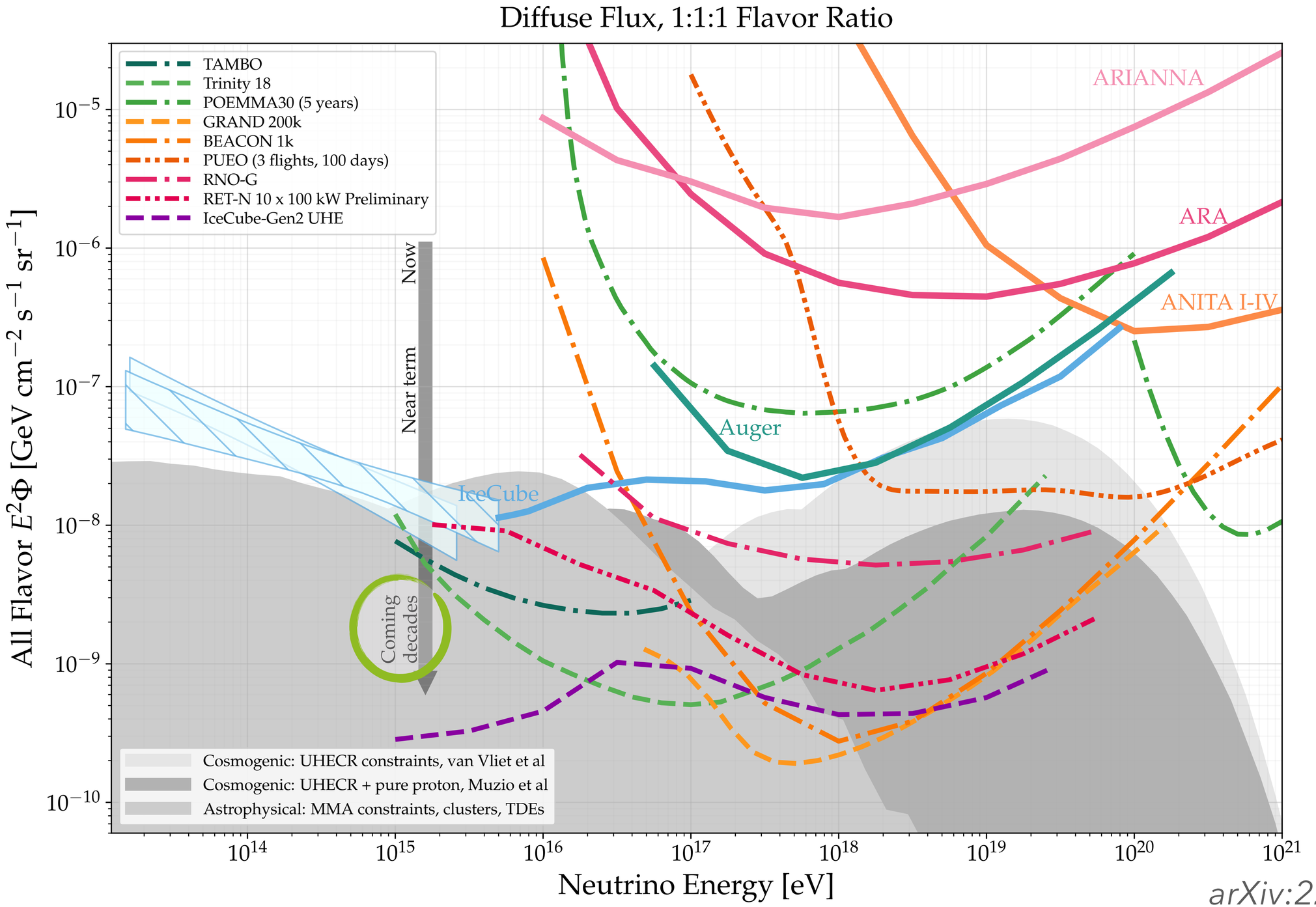

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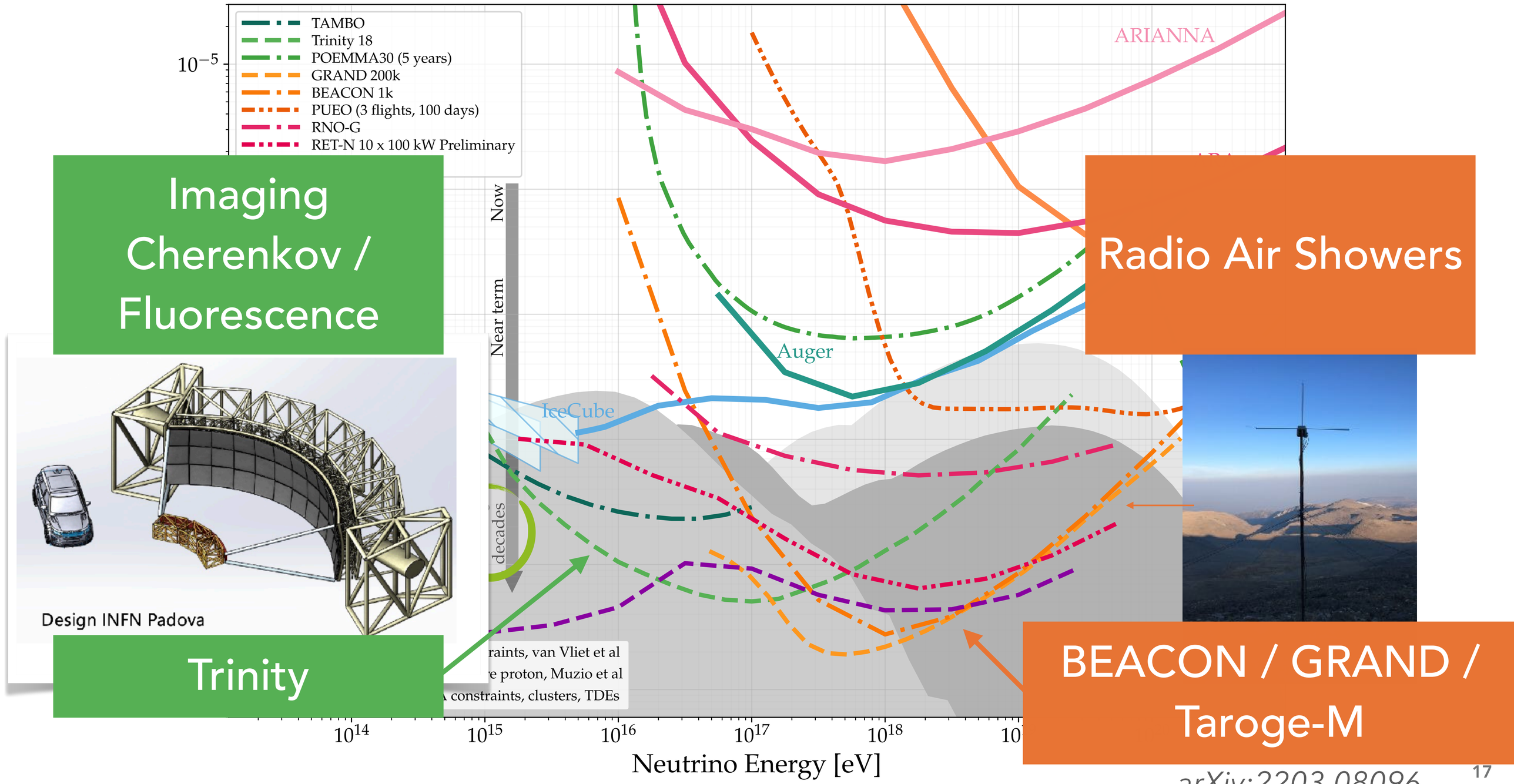
Diffuse Flux, 1:1:1 Flavor Ratio



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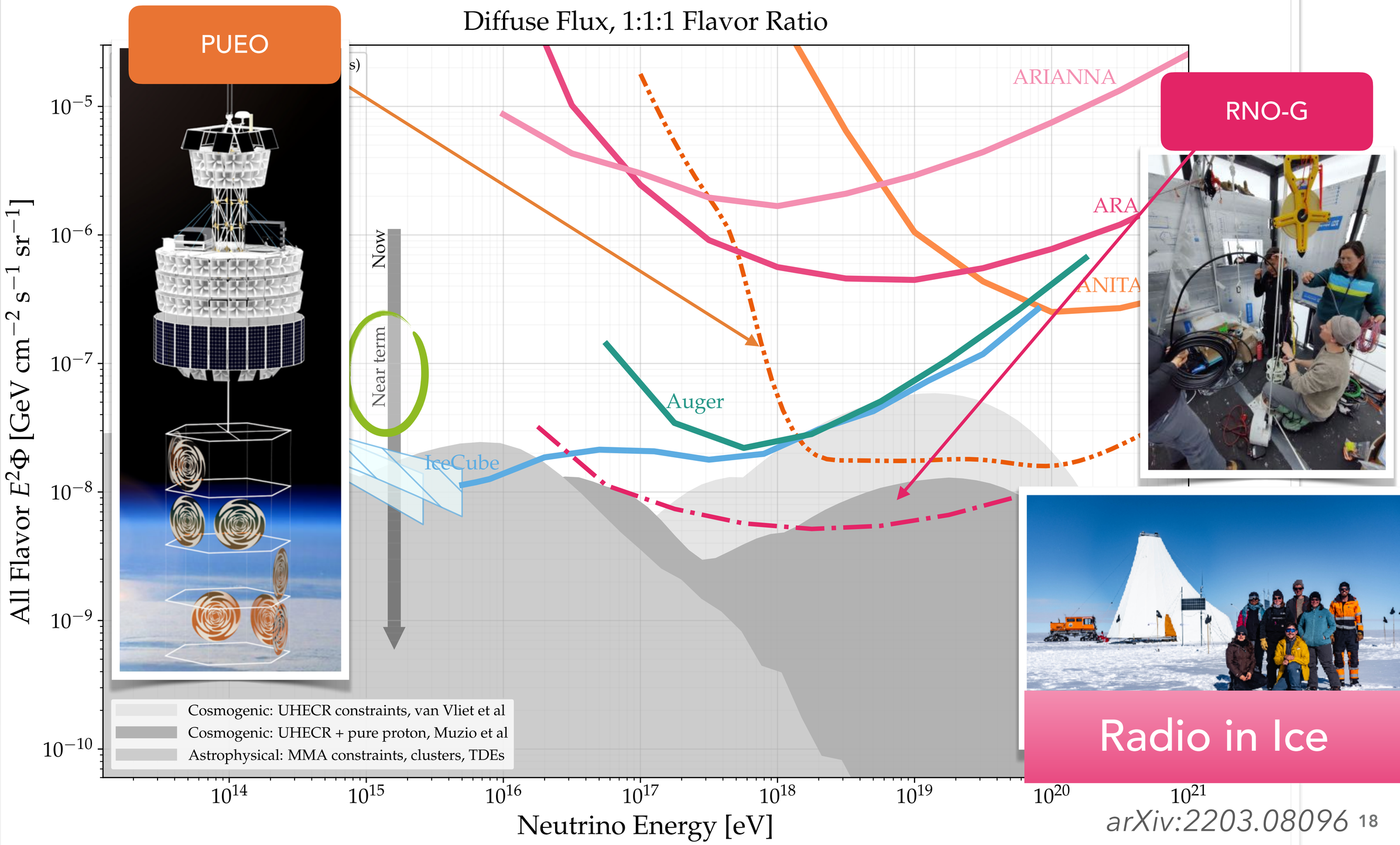

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Why Radio?

- Long propagation lengths – $\mathcal{O}$(1-100's km)
- Low cost instrumentation – $\mathcal{O}$($1k) per channel
- Continuous data collection
- Polar ice and Earth's limb offer large natural neutrino targets

Large Detector with Minimal Instrumentation

In Ice

Balloons

Mountains

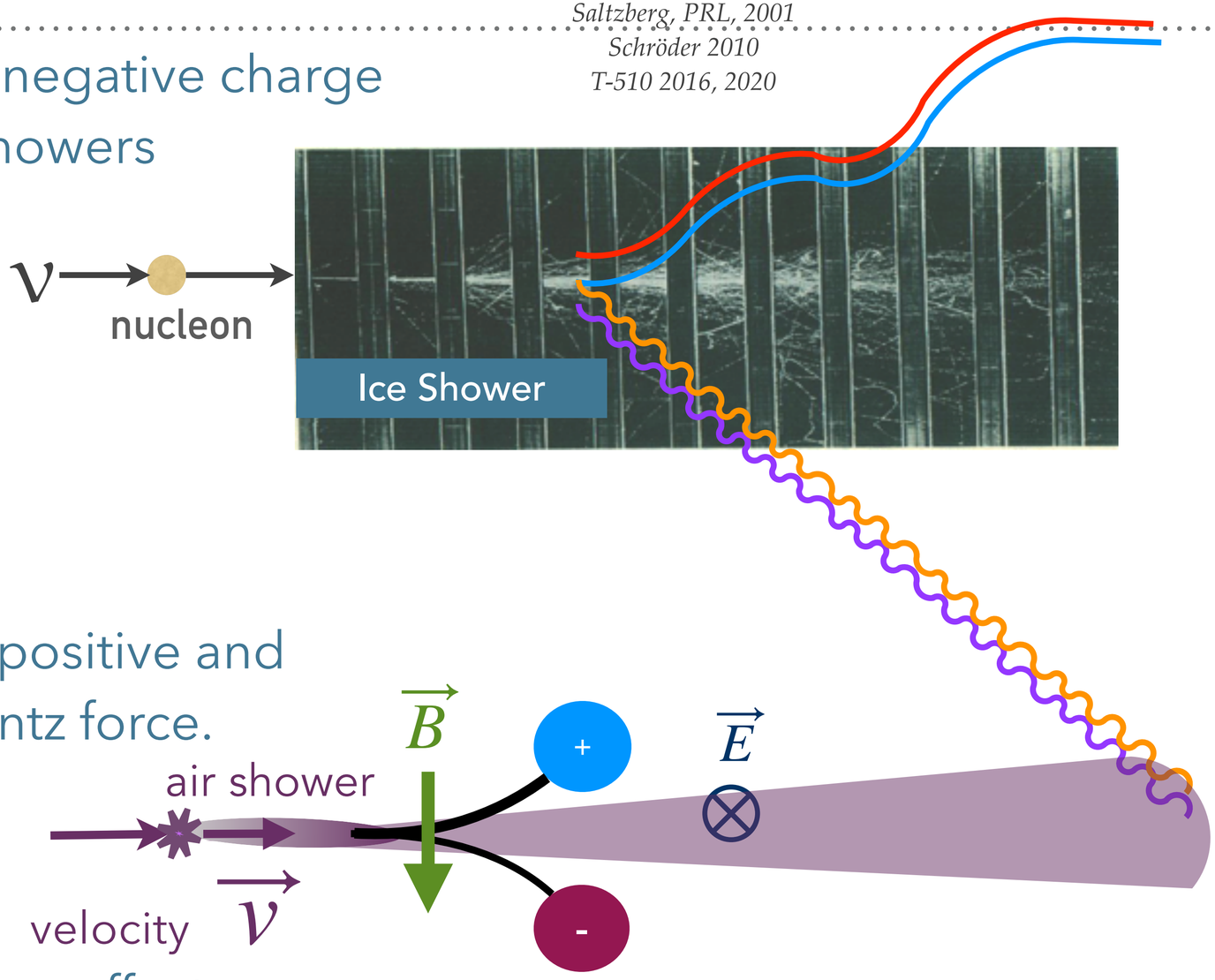
Several Options for Detector Geometries

Radio Emission from Neutrino Interactions

Askaryan 1969,
Saltzberg, PRL, 2001
Schröder 2010
T-510 2016, 2020

- **Askaryan emission**: radiation from net negative charge excess in shower. Dominant for ***in-ice*** showers

λ >> Shower width
Coherent: P ~ E^2
λ << Shower width
Incoherent: P ~ E

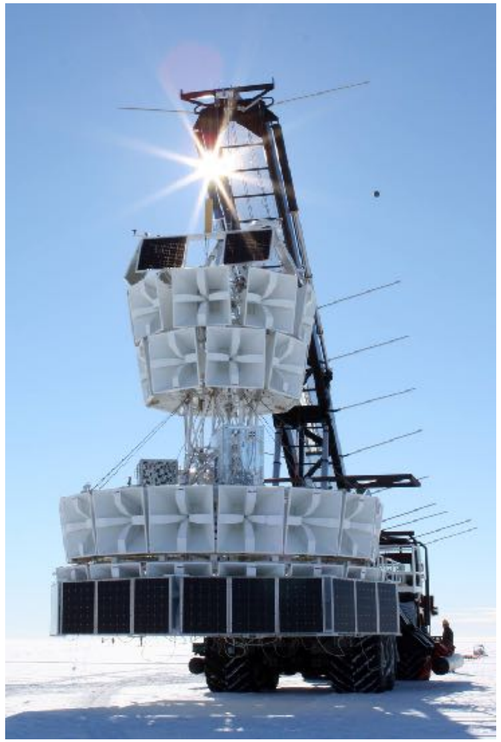


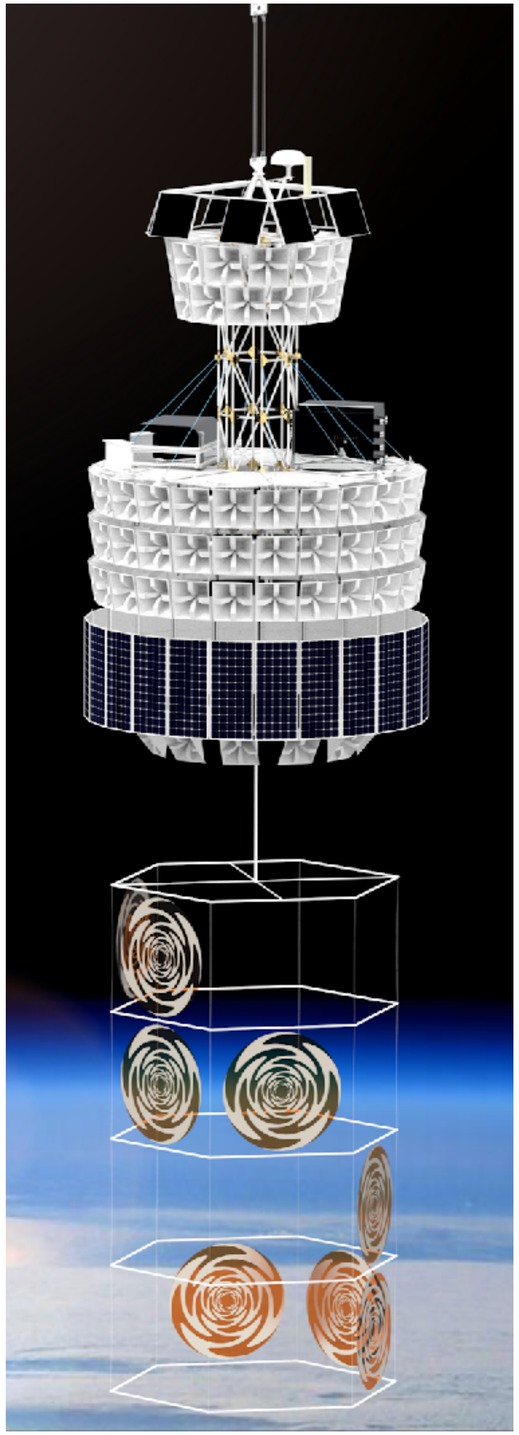
- **Geomagnetic emission:** separation of positive and negative charges in shower due to Lorentz force. Dominant for ***air*** showers

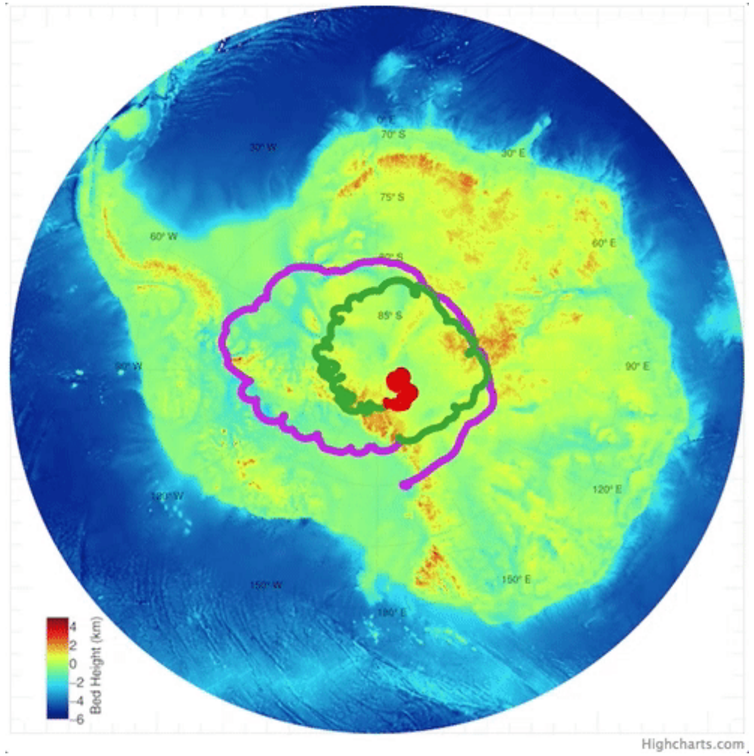
- Both benefit from boost due to coherence effects near the Cherenkov angle

PUEO: Payload for Ultra-High Energies

…and its predecessor ANITA







- Flight in 2024
- Recently funded through NASA's new PIONEERS program

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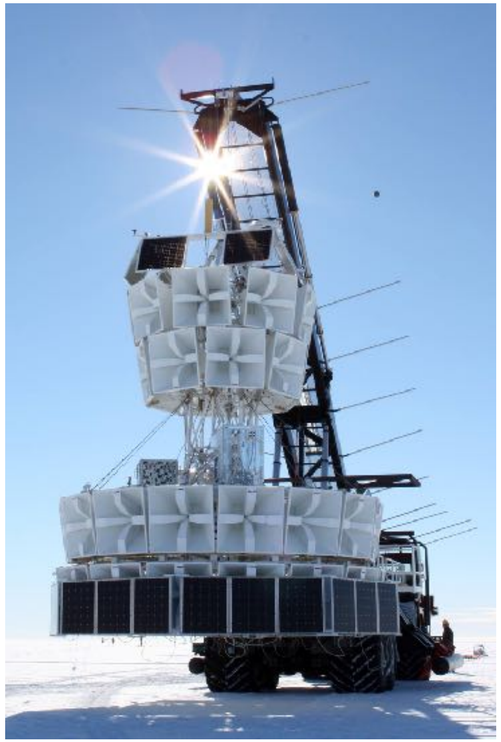

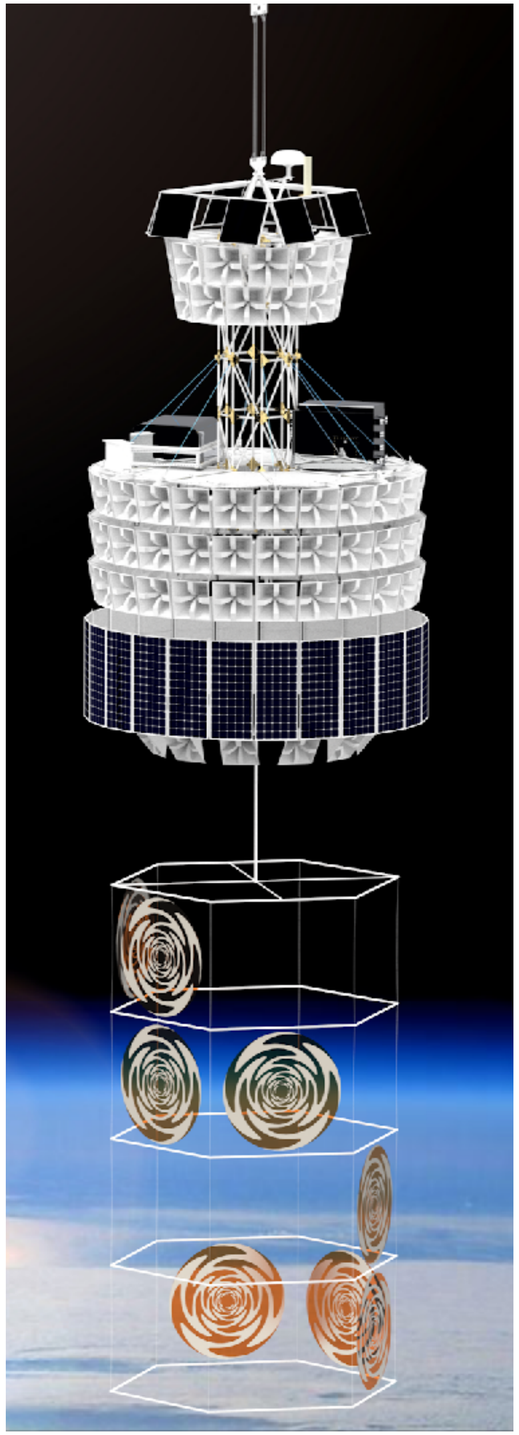

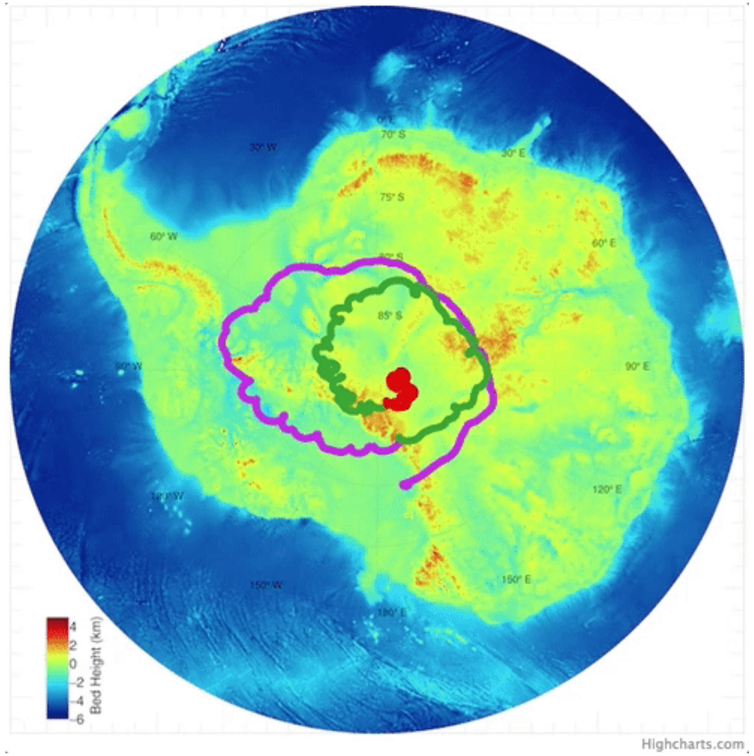

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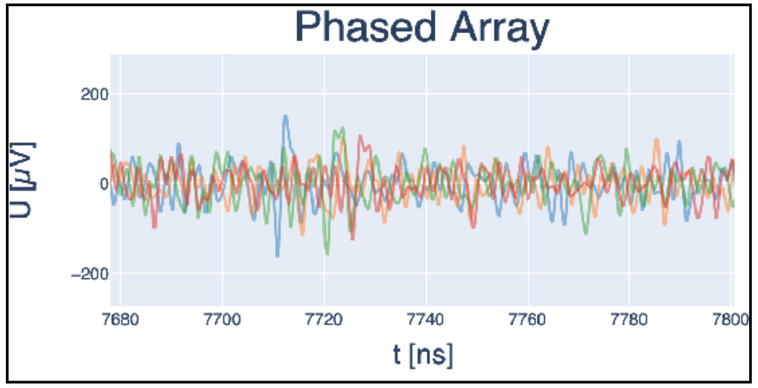
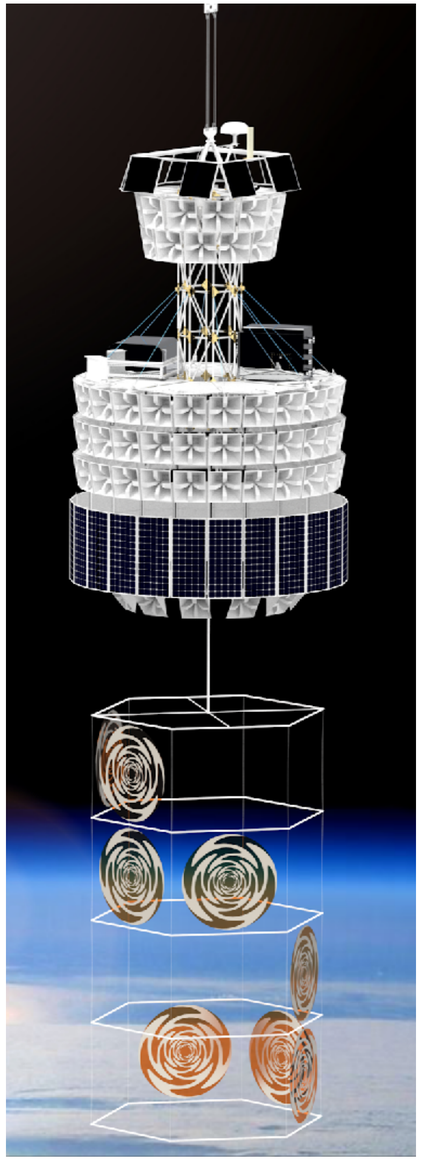
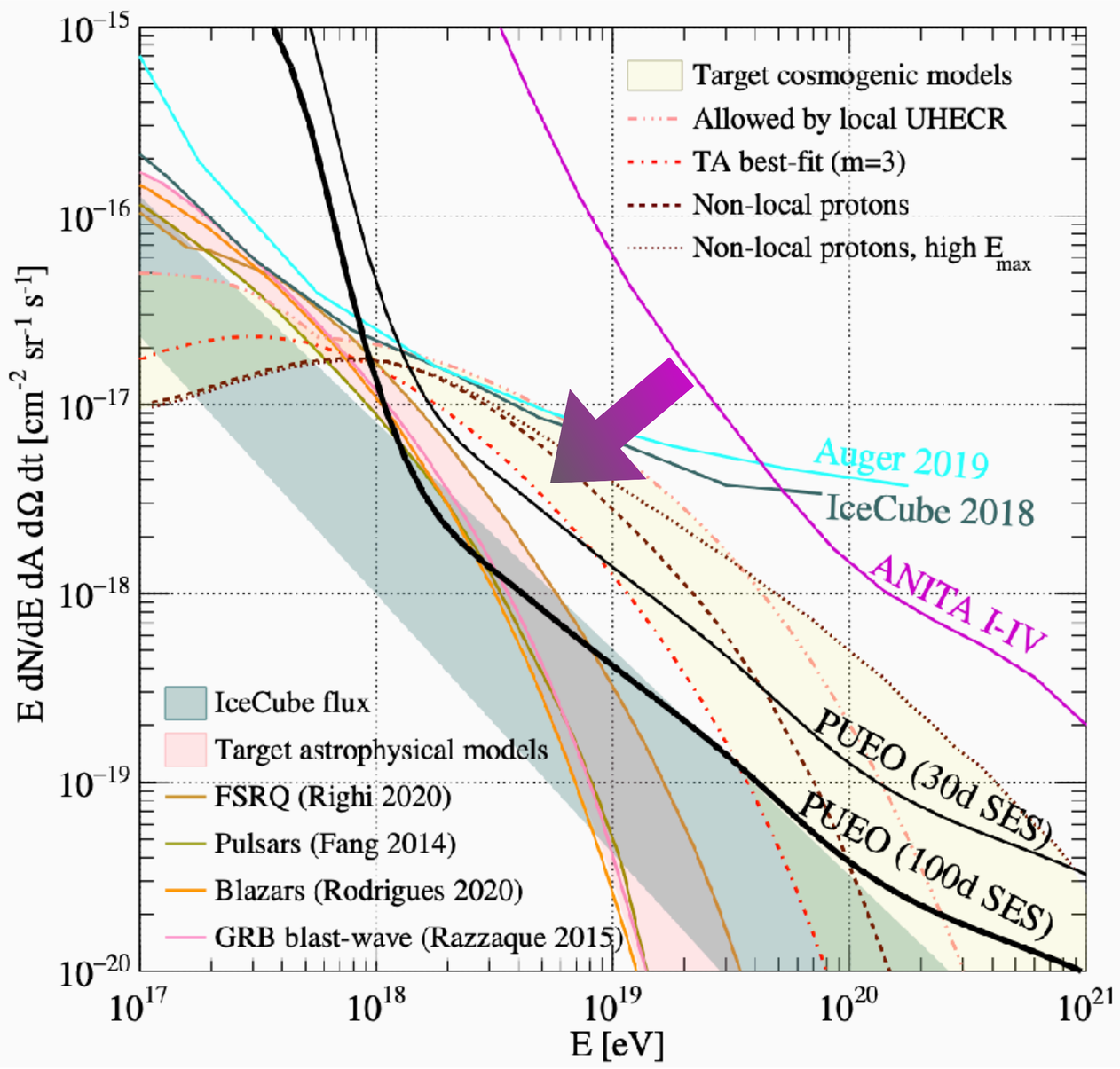
PUEO: Payload for Ultra-High Energy Observations

Features

1. PUEO targets the **Maximum Energy** from astrophysical sources
2. Improved sensitivity over ANITA by **with novel trigger, more antennas,** & **RFSoCs**
3. Sensitive to both **in-ice neutrinos** and **Earth-skimming tau neutrinos**







PUEO Whitepaper arXiv:2010.02892

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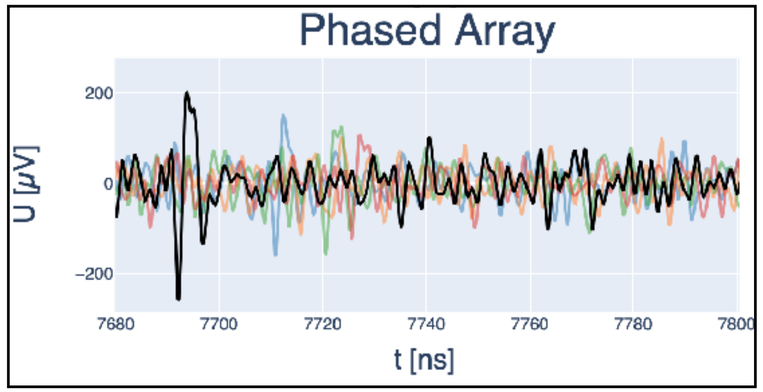

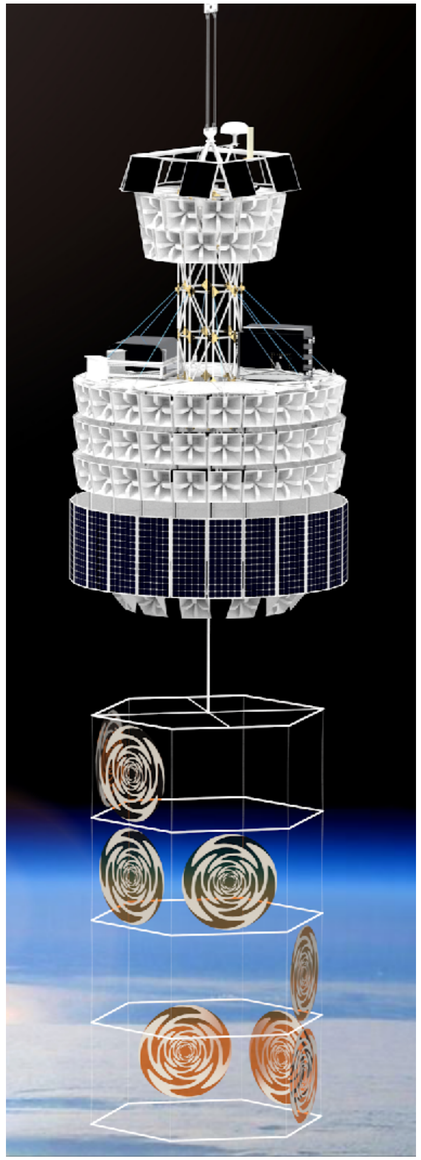

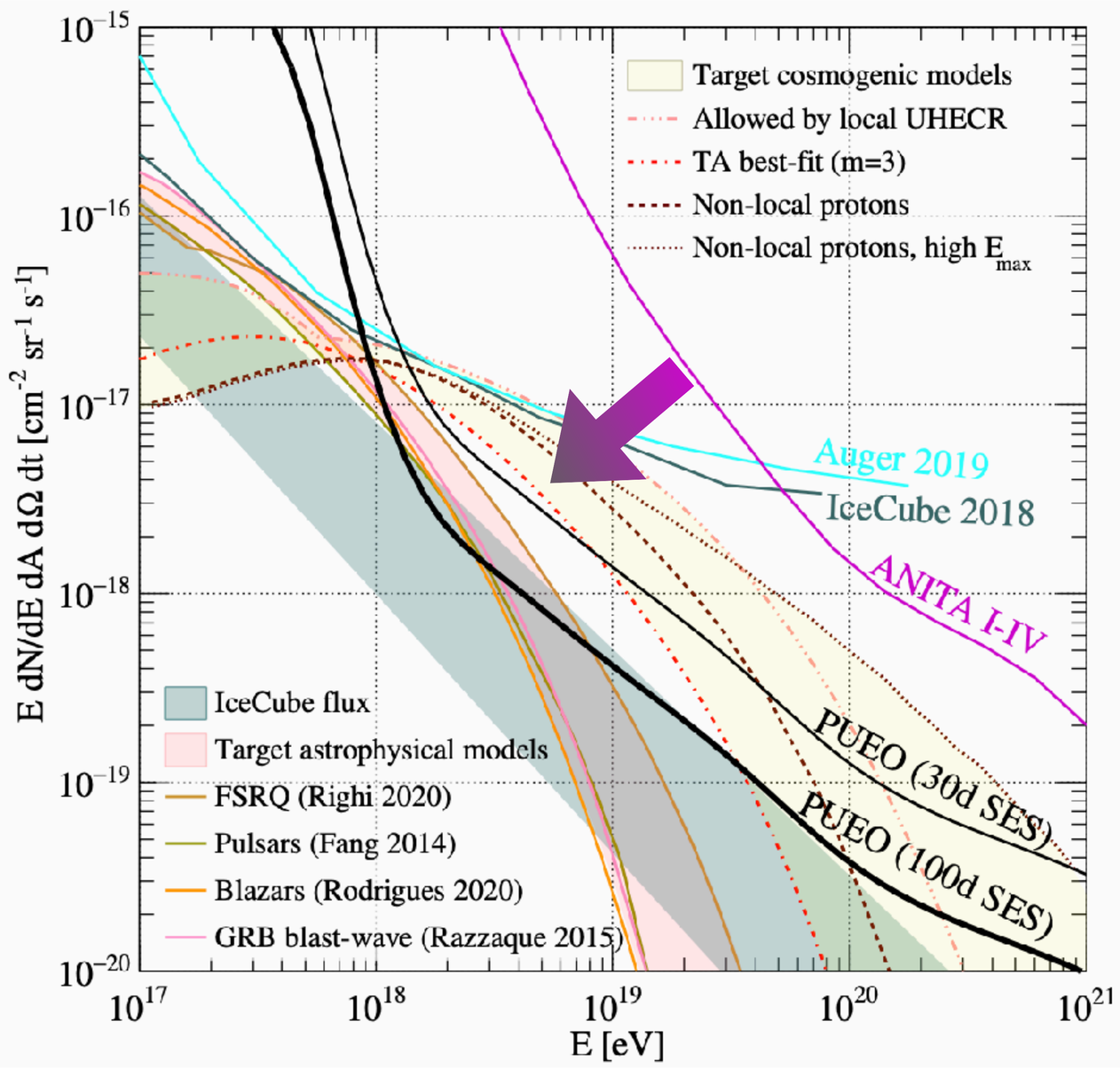

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TRANSIENTS WITH PUEO

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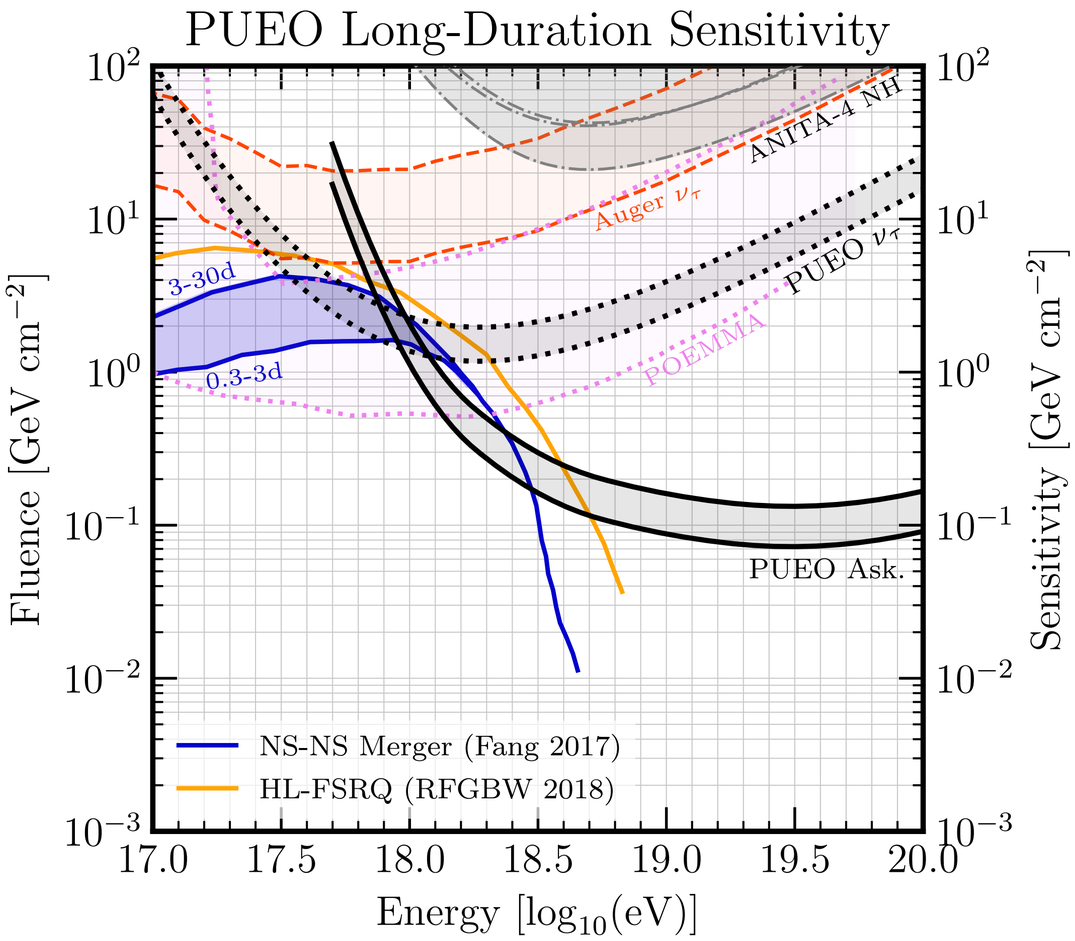
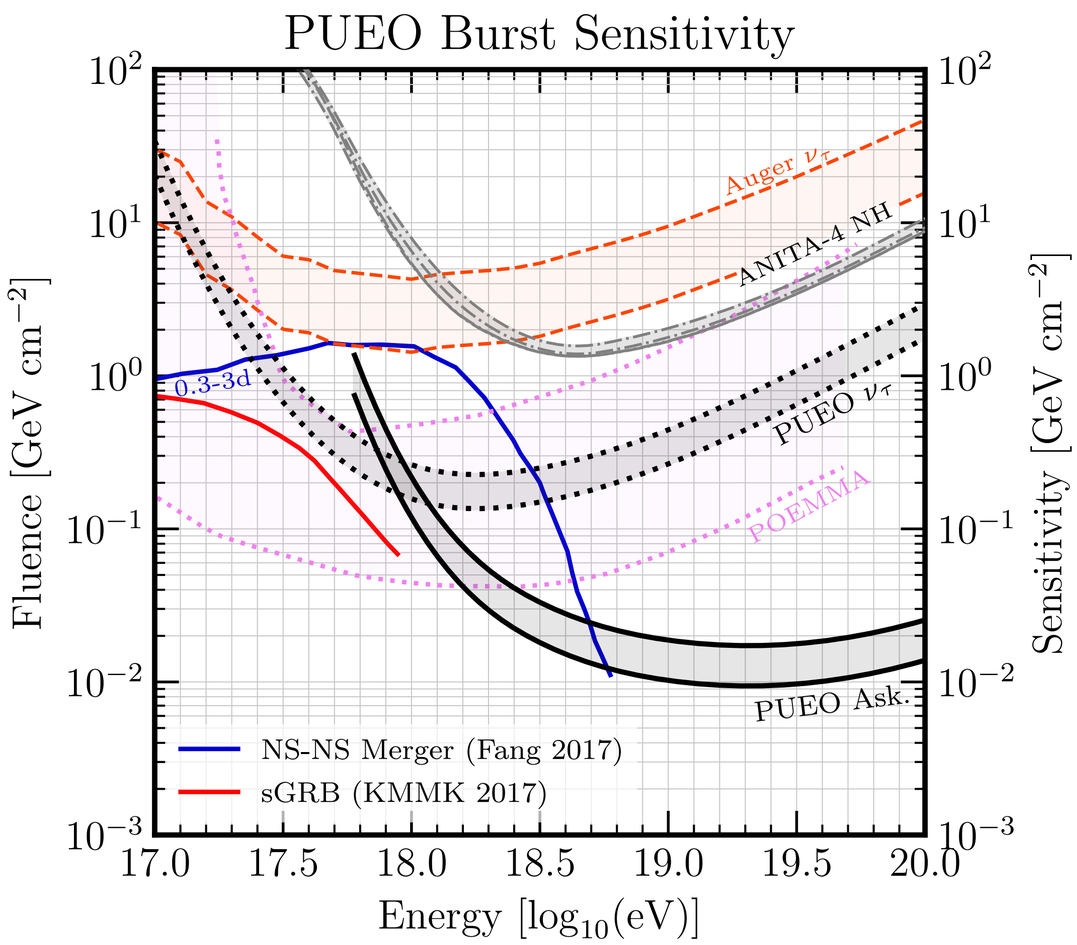
➤ Tau channel extends to lower energies and has ~ sub-degree scale pointing





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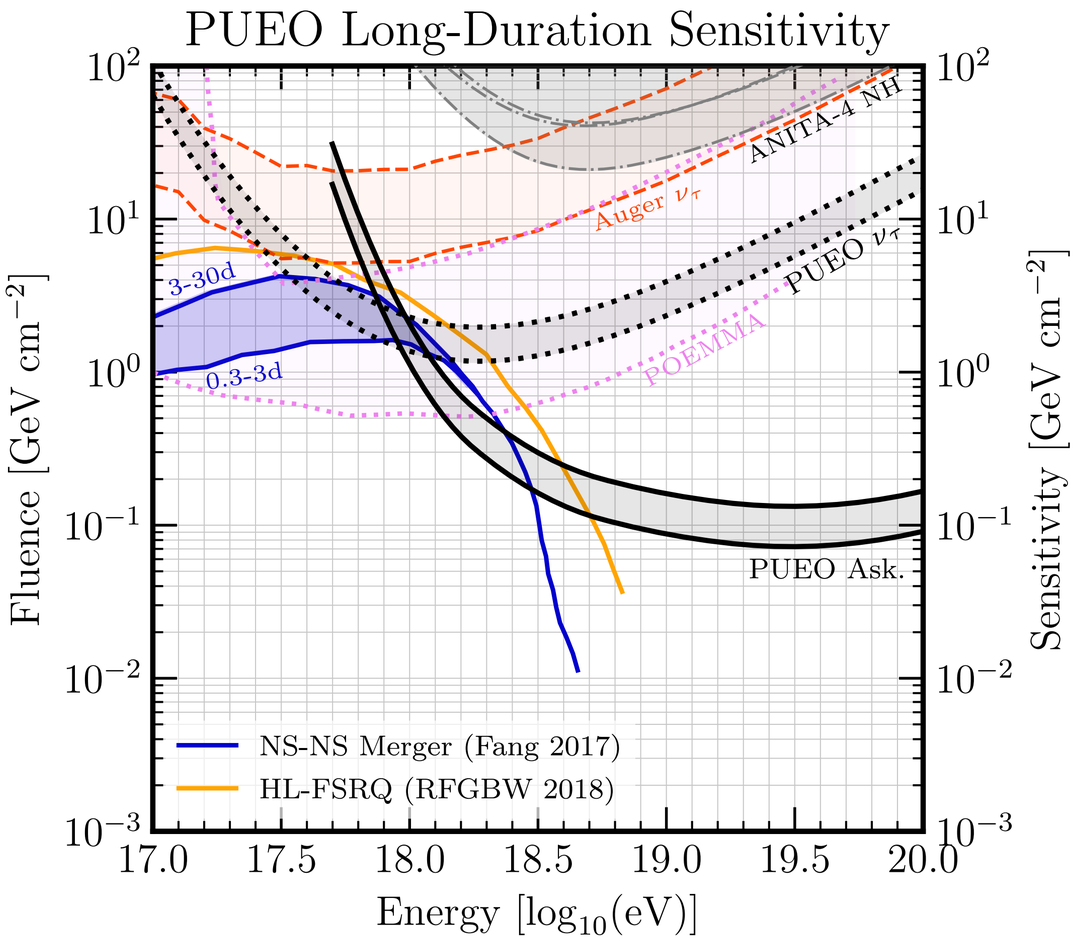
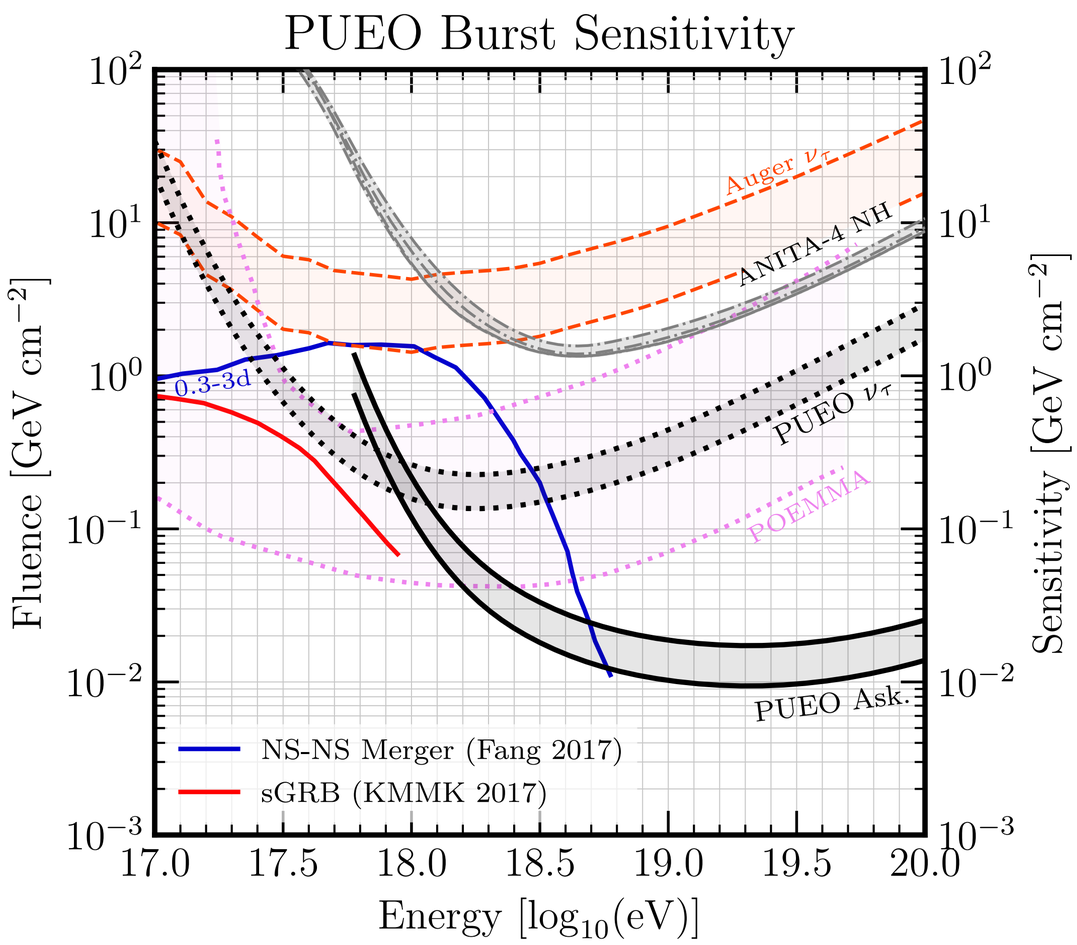


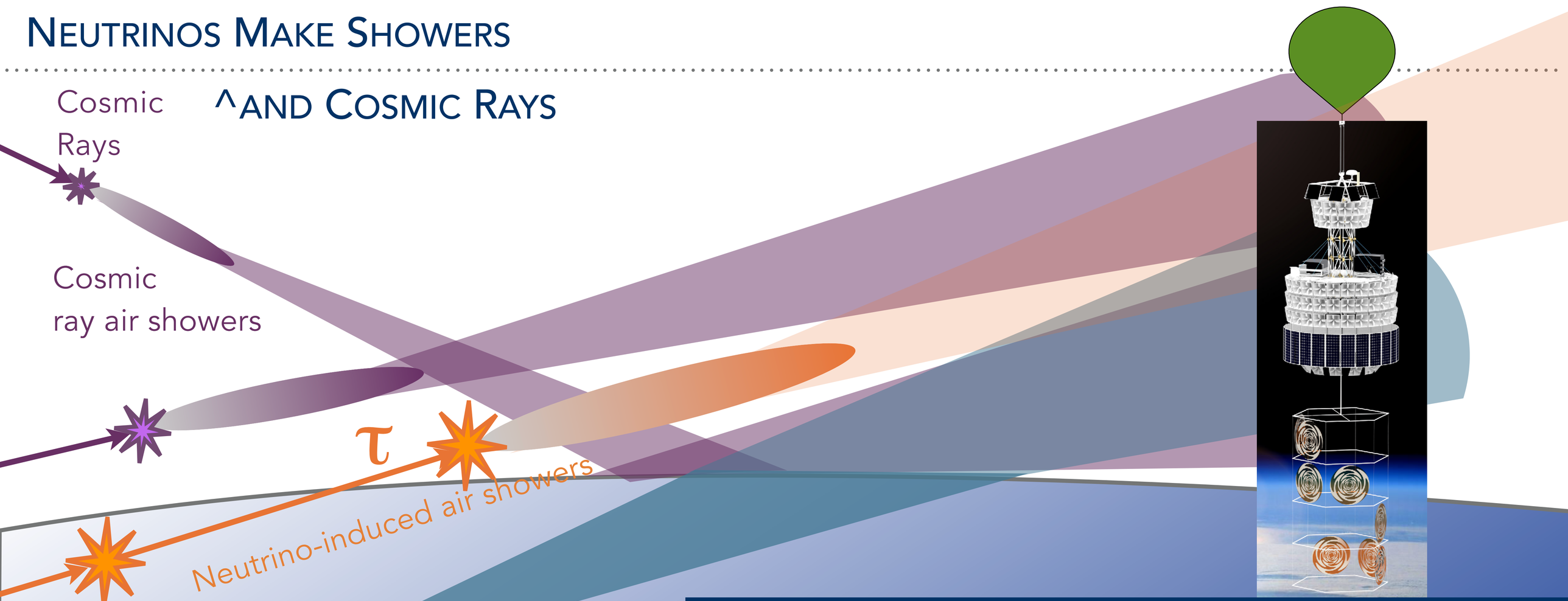


- Air shower channel also sensitive to cosmic rays (validation)

- Anomalous air shower events in ANITA unexplained, but consistent with air showers reconstructing **below** the horizon → **PUEO will address**

Neutrinos Make Showers

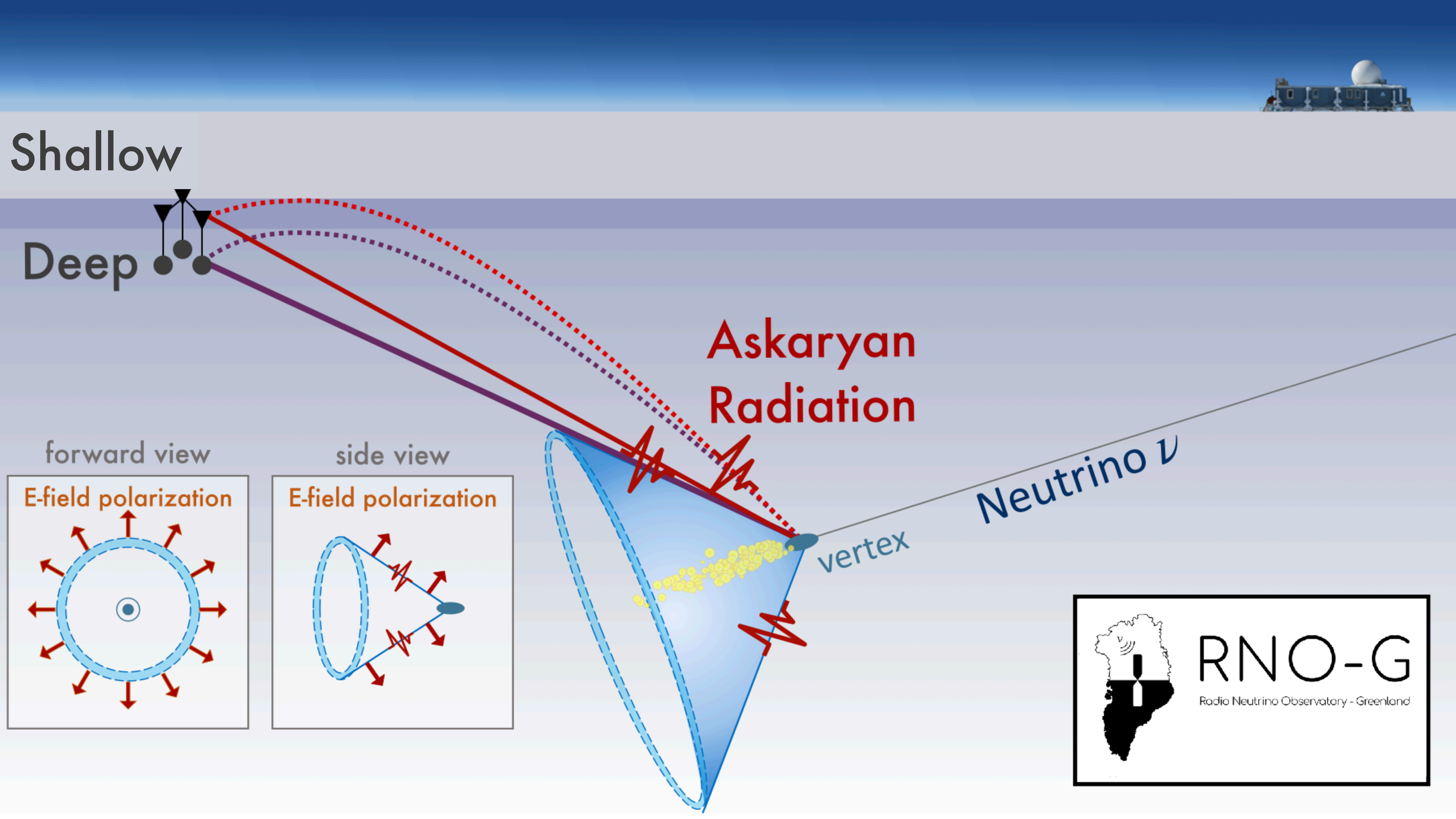
^and Cosmic Rays



Air Shower Discrimination in PUEO

1. *Broad spectrum observation from 50 MHz to 1 GHz*
2. *Joint polarity and polarization observation in two frequency ranges*

RNO-G
Radio in Greenlandic Ice


Shallow
Deep
Askaryan Radiation
Neutrino ν
vertex
forward view
E-field polarization
side view
E-field polarization
RNO-G
Radio Neutrino Observatory - Greenland

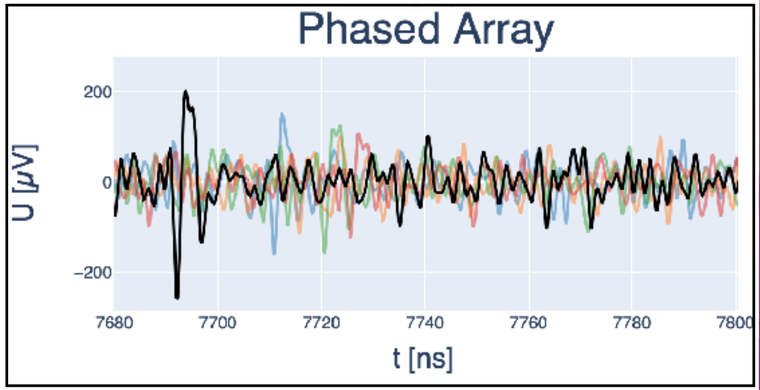
RNO-G Station Concept

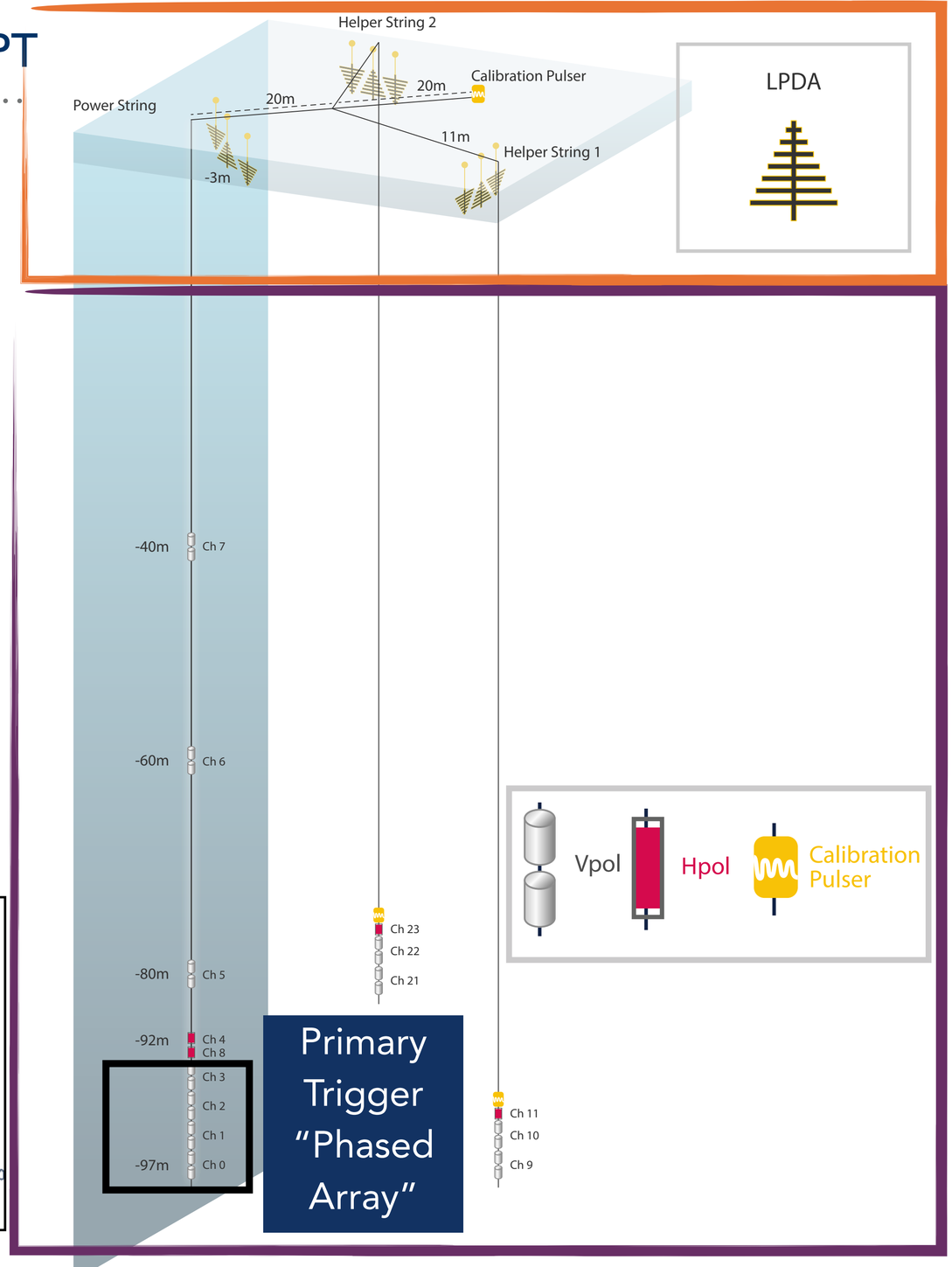
Deep component:

Effective Volume

Low Threshold (2σ) trigger with compact phased array

Outrigger antennas enable reconstruction





Shallow component:

Cosmic rays

Veto

Additional channels for reconstruction

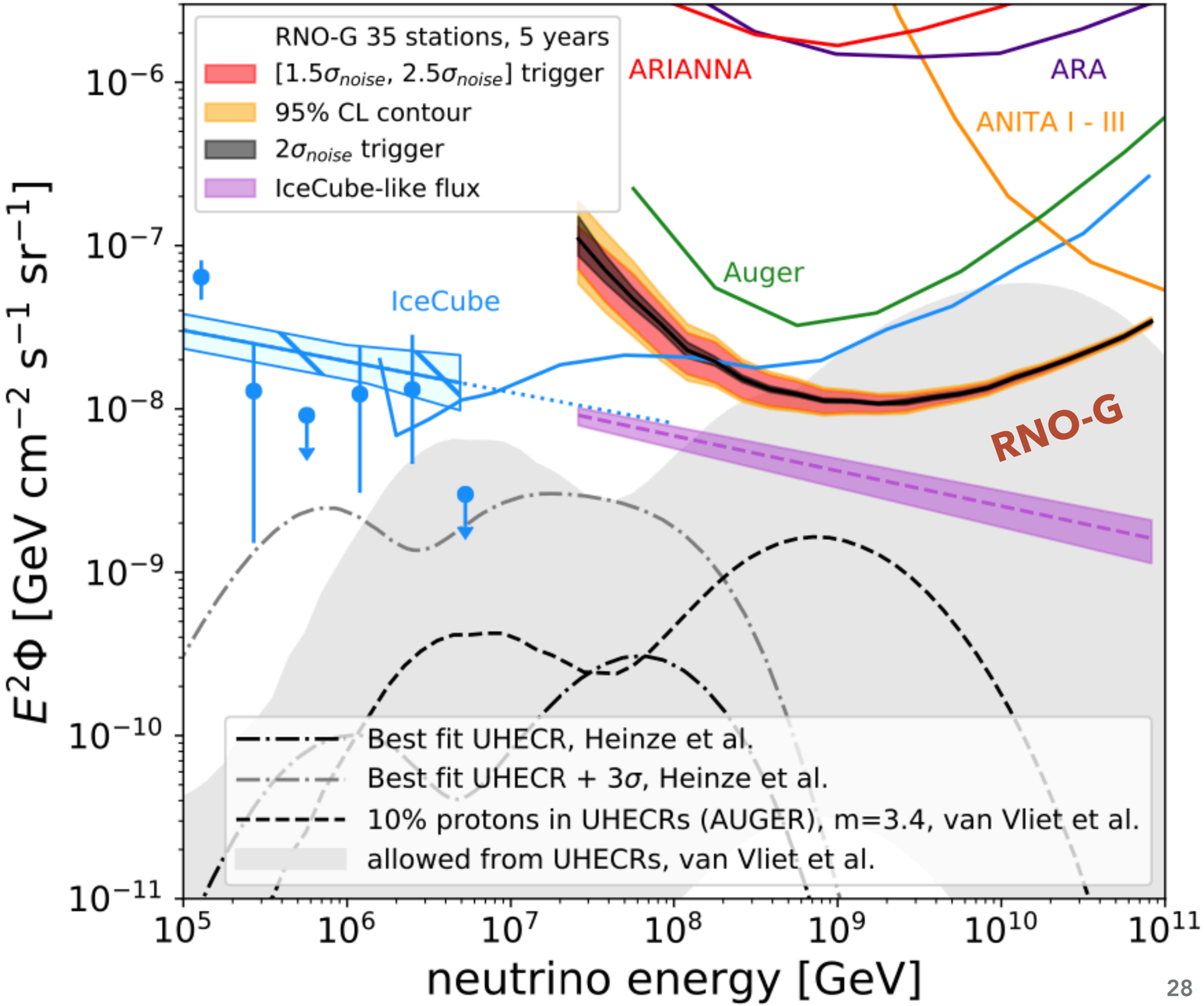
Independent trigger

RNO-G in a Nutshell

All-flavor

Scale up from current arrays

- Hybrid design combines advantages of ARA (deep) & ARIANNA (shallow)
  - Large effective volume
  - Cosmic ray veto
- Highly scalable



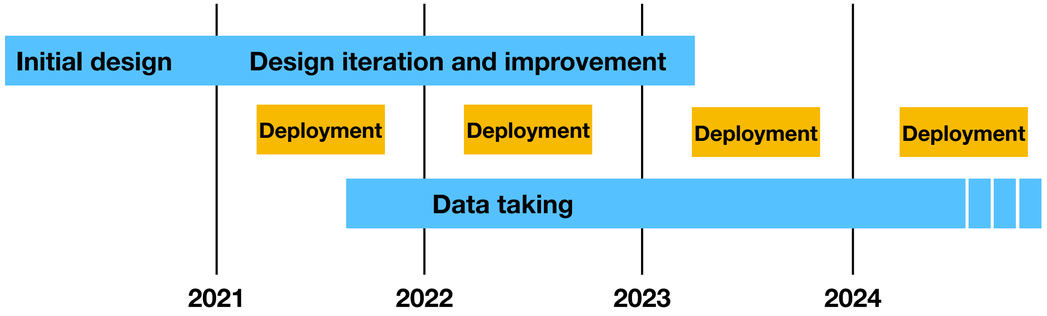
Projected limits assume 5 year livetime, trigger level sensitivities, 95% FC UL

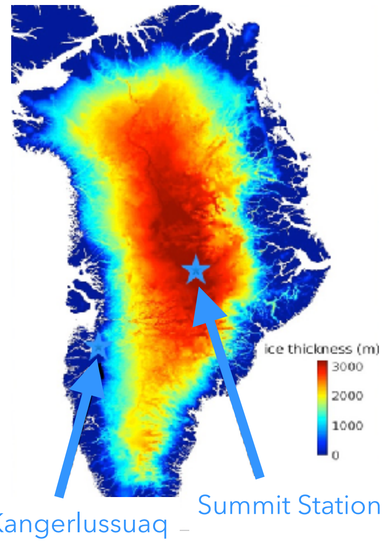
RNO-G Whitepaper arXiv:2010.12279

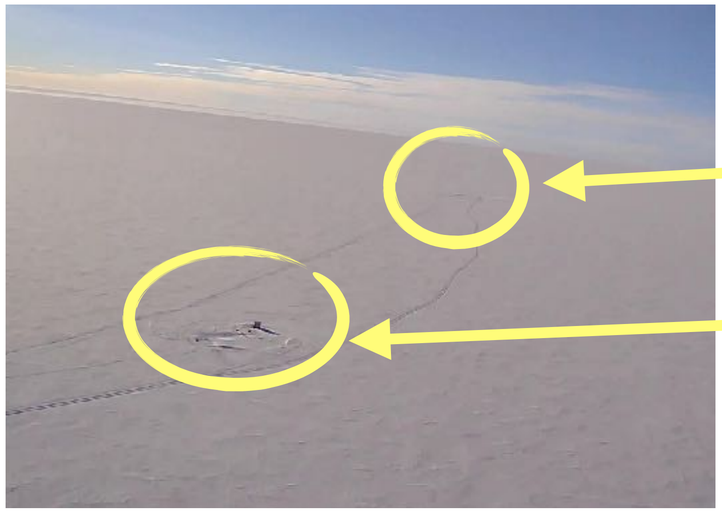
RNO-G Map

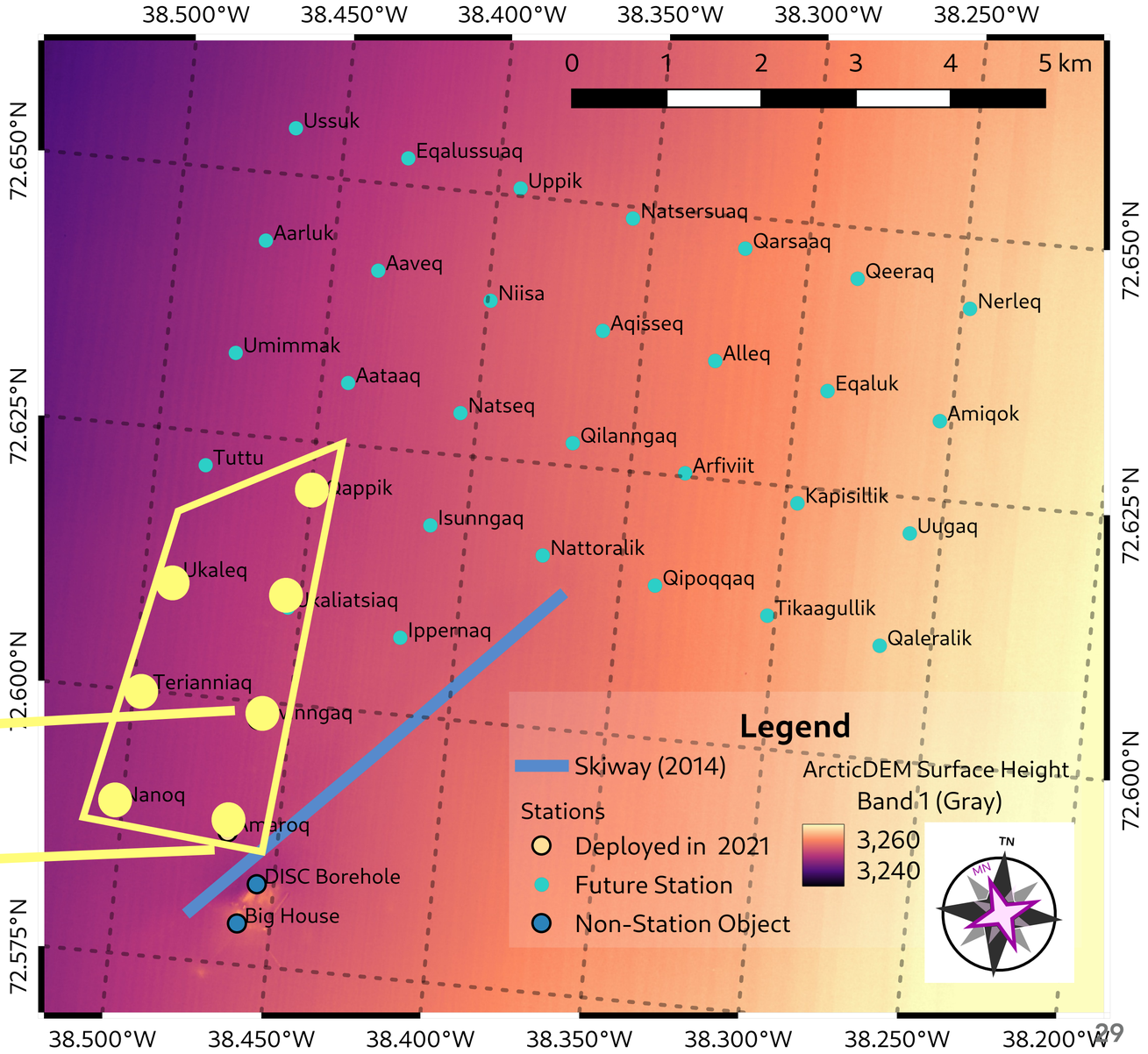
See https://rno-g.github.io/station-map/

- 35 stations, 1.25 km spacing, 50 km²
- Summit Station, Greenland
- Seven completed stations as of this season









Station Deployment

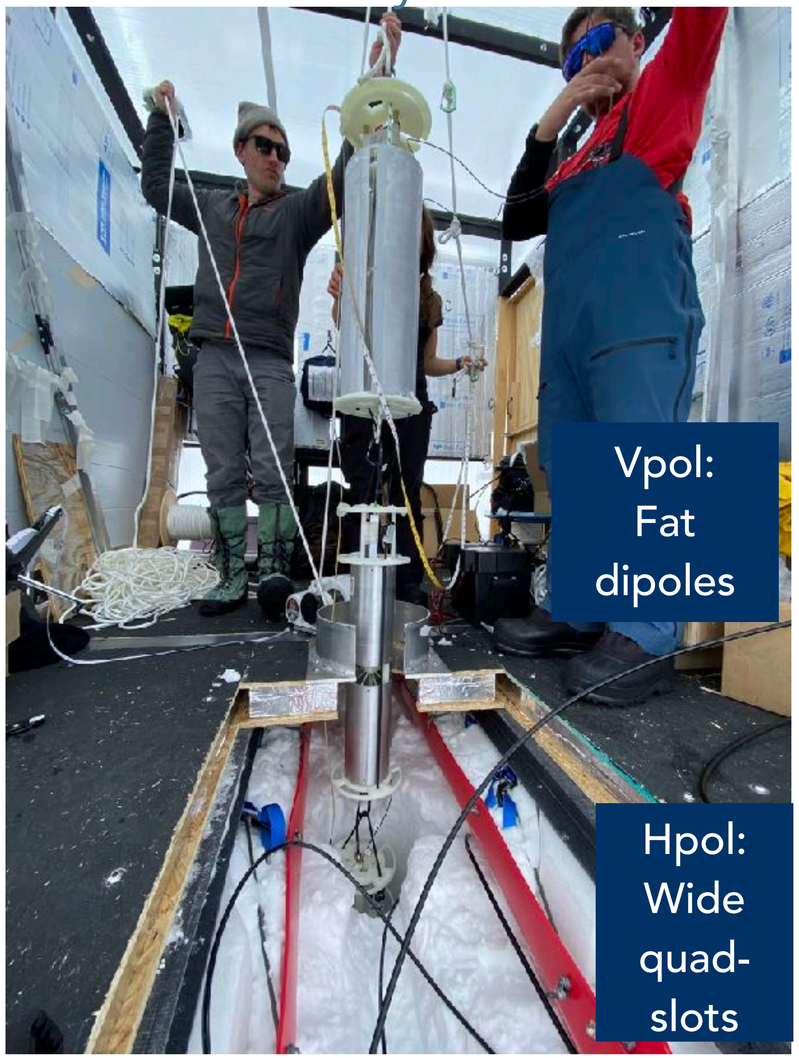
BigRAID Drill

11-inch holes, 100 m

Warm deployment sled movable by snowmobile

Shallow antennas deployed in trenches

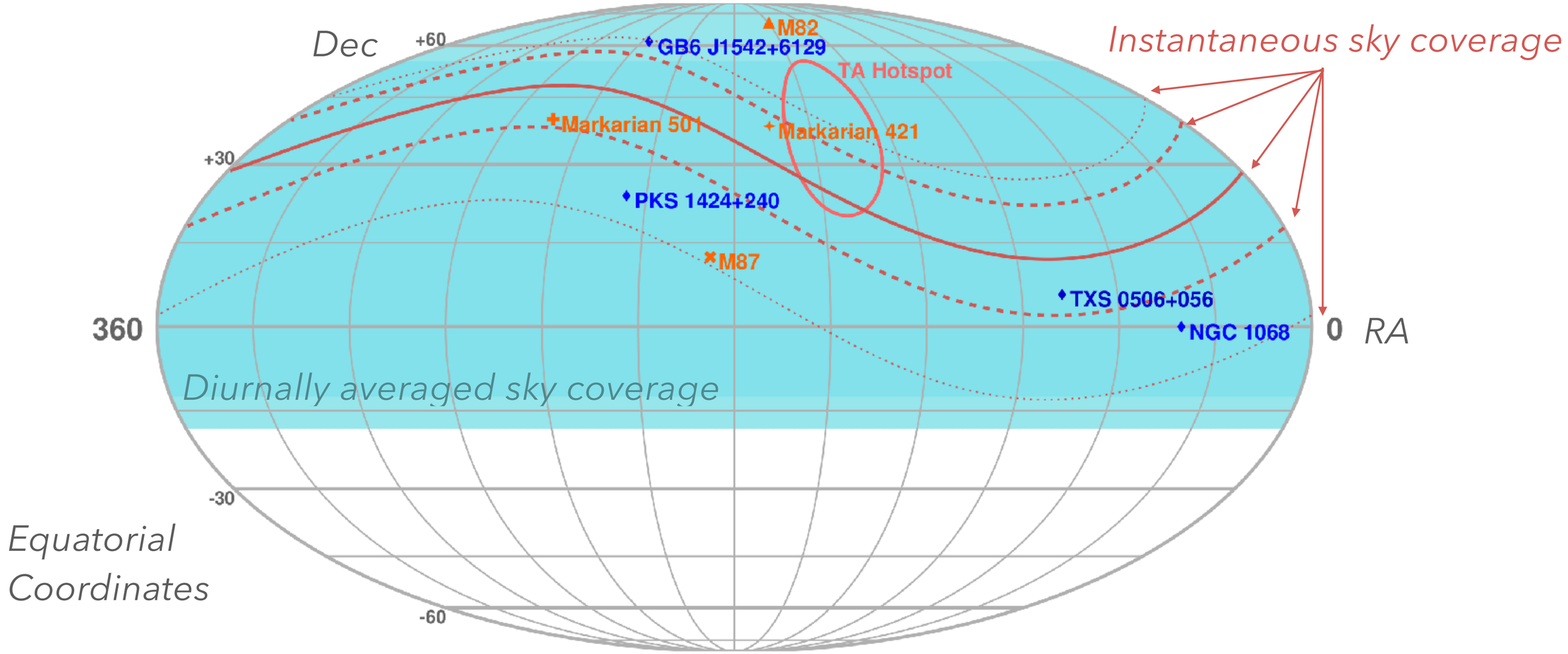
Deep channels lowered by hand



Northern Sky Coverage

RNO-G Whitepaper arXiv:2010.12279

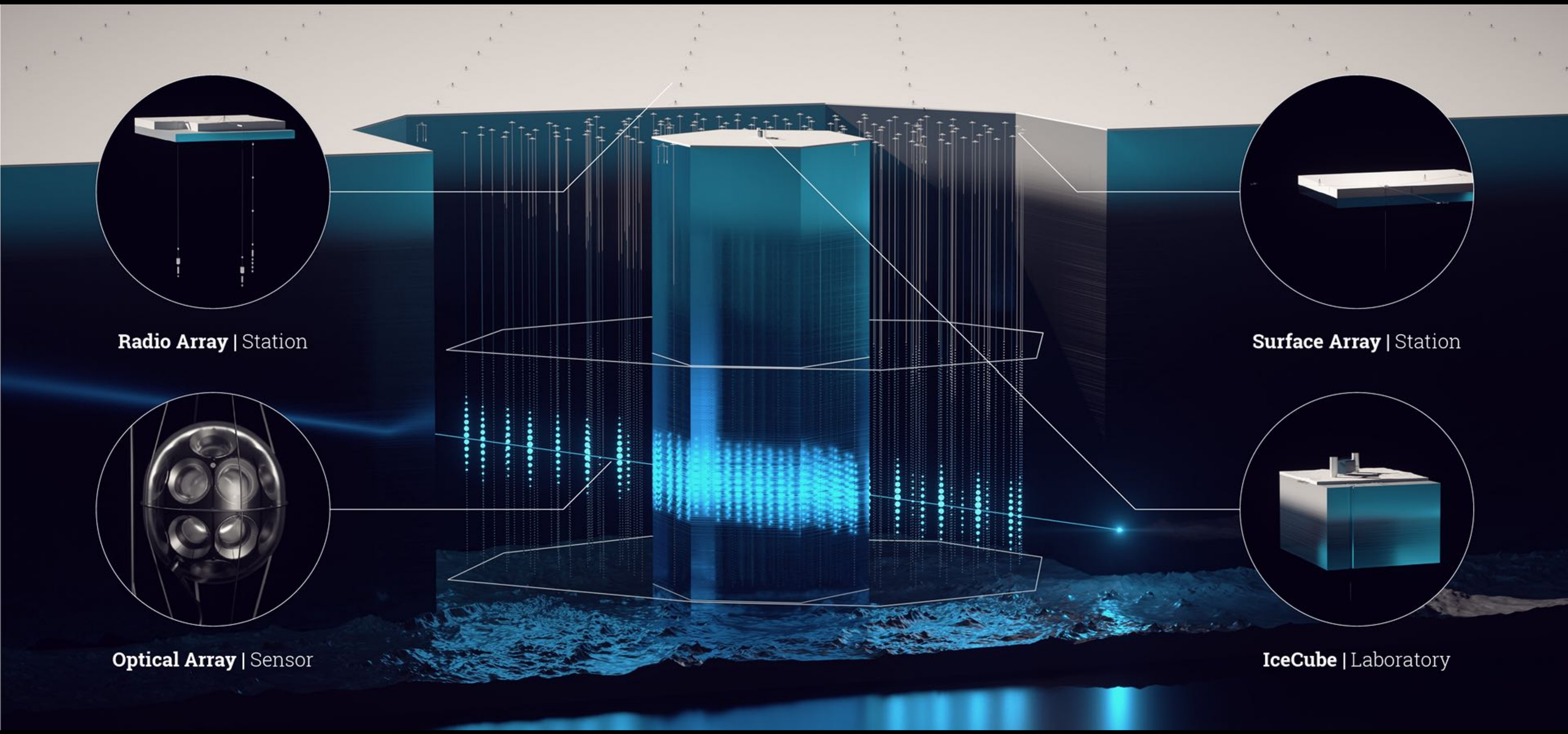
➤ At UHE energies, primarily sensitive to down-going or Earth-skimming neutrinos



➤Arrival direction reconstruction expected to be few degree scale, with improvements as more baselines added

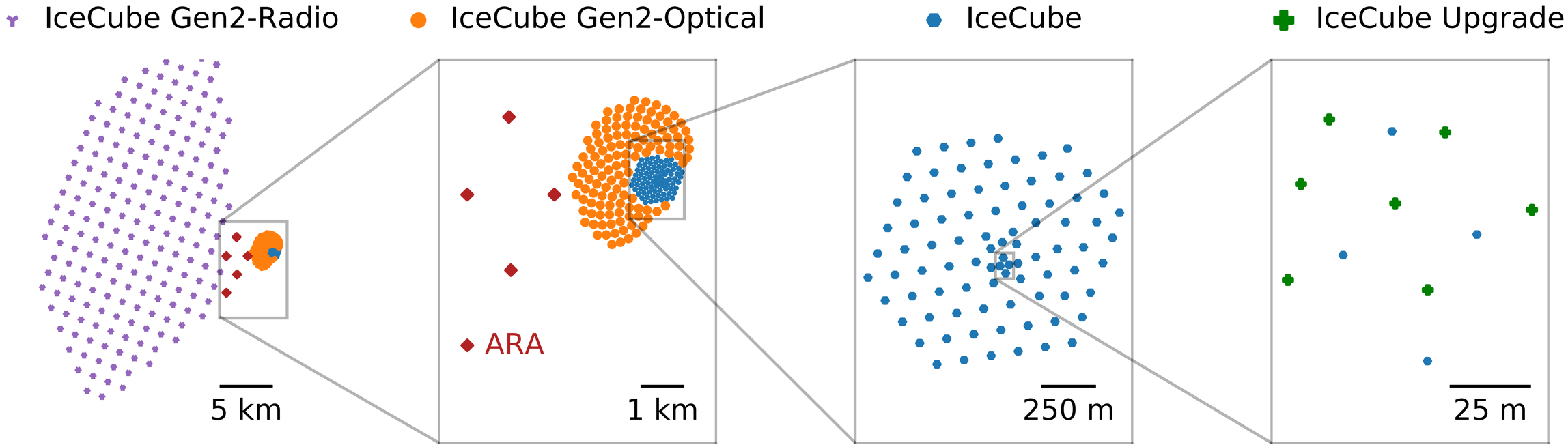
➤Beamformed trigger allows multi-messenger followup

➤Continuous LTE networking + on-station computing permits connections to real-time alerts


Radio Array | Station
Surface Array | Station
Optical Array | Sensor
IceCube | Laboratory

Connection between RNO-G and IceCube-Gen2 Radio

- Gen2 radio goal: improve sensitivity by 100x in EeV range
  - …by expanding footprint by hundreds of km^2
    - …by using radio (1 km attenuation length)
- Planned combination of deep and shallow stations



- RNO-G allows us to **explore new technology with $\mathcal{O}(10\%)$ stations**

Take Aways

RNO-G
Radio Neutrino Observatory - Greenland

BEACON

PUEO

AMON
Astrophysical Multimessenger Observatory Network

SOUTH POLE
ASKARYAN RADIO ARRAY

ICECUBE
GEN2

Take Aways

- Entering the precision era of neutrino astroparticle physics in the TeV-PeV energy range
- Several upcoming experiments target the PeV-EeV energy range with complementary techniques, energy ranges, and flavor sensitivity
  - Near term: RNO-G, PUEO promising experiments ***currently*** being ***built***.

RNO-G Radio Neutrino Observatory - Greenland
BEACON
PUEO
AMON Astrophysical Multimessenger Observatory Network
South Pole Askaryan Radio Array
IceCube Gen2

Take Aways

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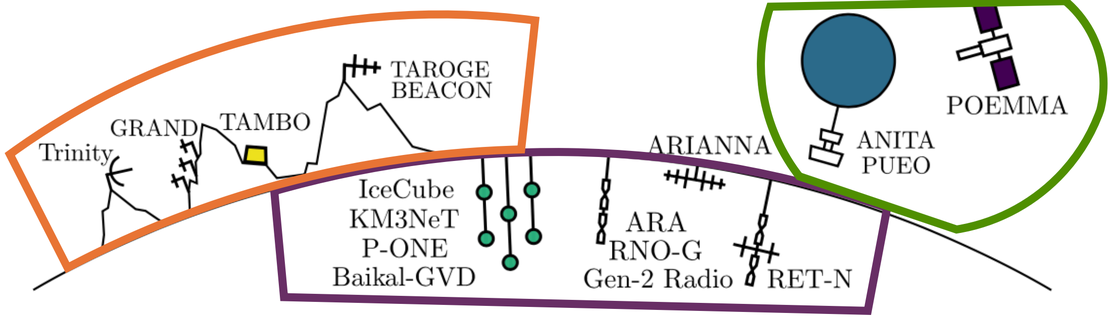
- Several upcoming experiments target the PeV-EeV energy range with complementary techniques, energy ranges, and flavor sensitivity
  - Near term: RNO-G, PUEO promising experiments ***currently*** being ***built***.
  - Soon: Prototypes with Earth-skimming techniques (BEACON, e.g.)
  - Ultimately: Full scale detectors reveal UHE neutrinos

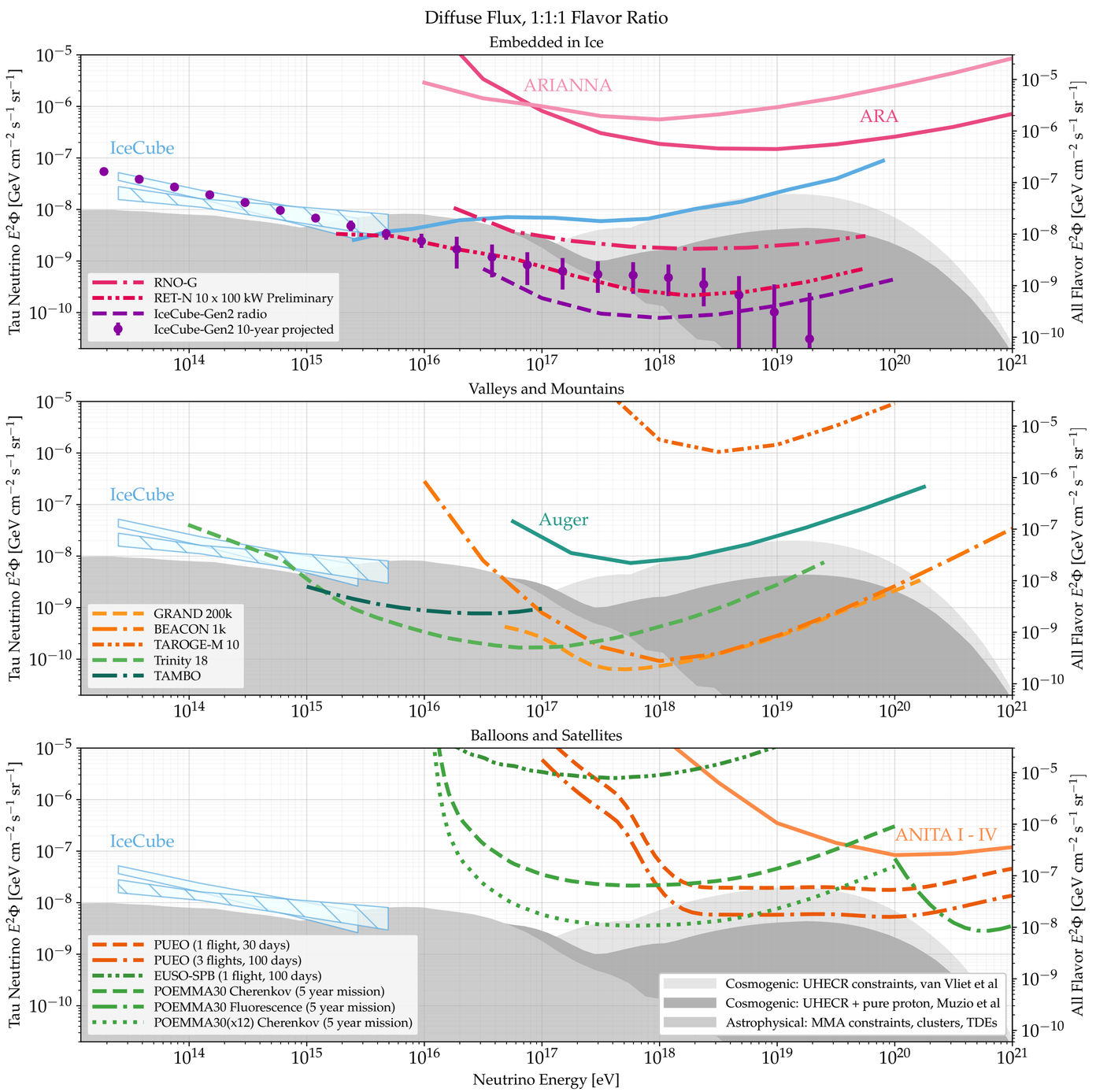
Bonus Slides



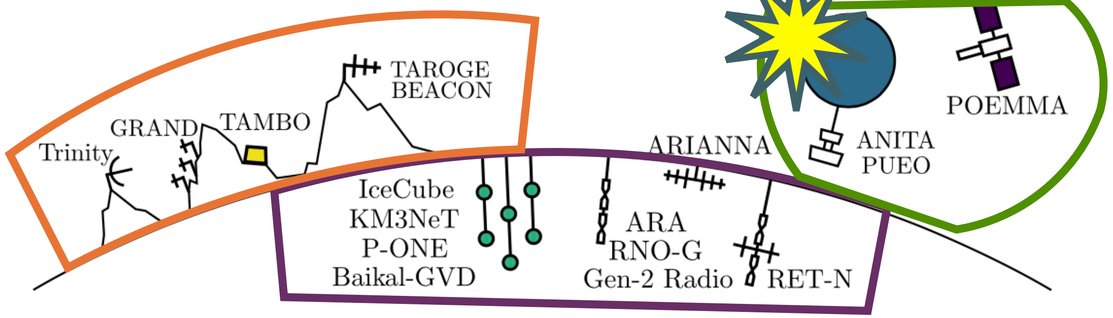
Embedded in Ice

Valleys and Mountains

Balloons & Satellites



SAW et al NuTau Snowmass Whitepaper 2022, Estaban, Prohira, Beacom 2022



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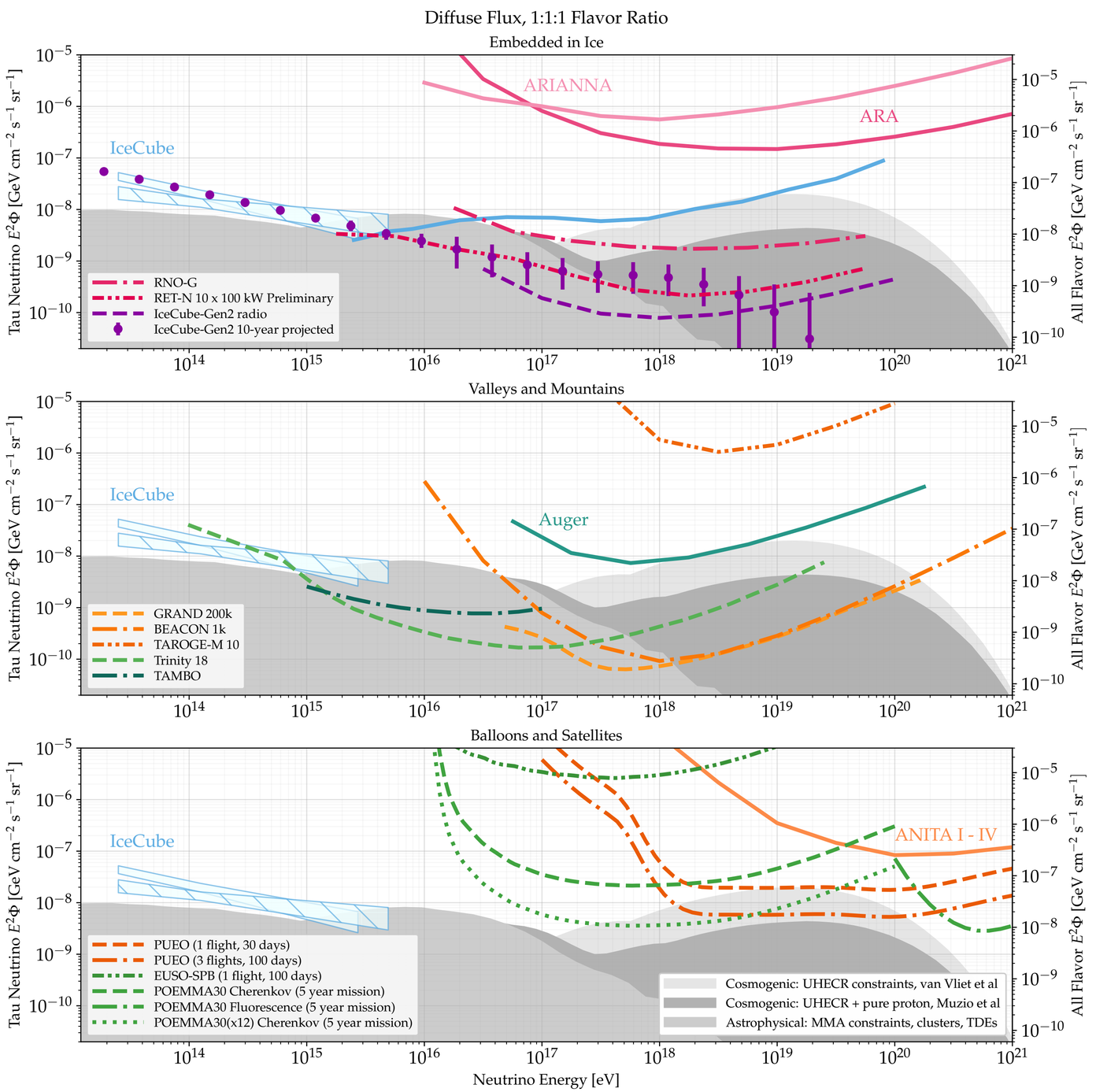

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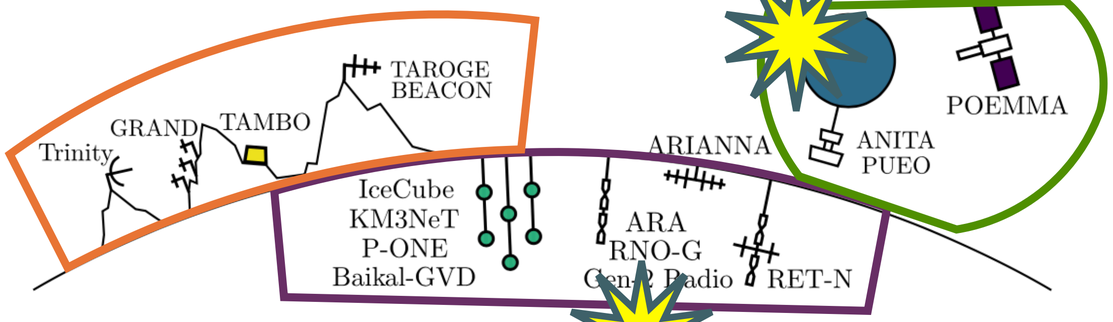

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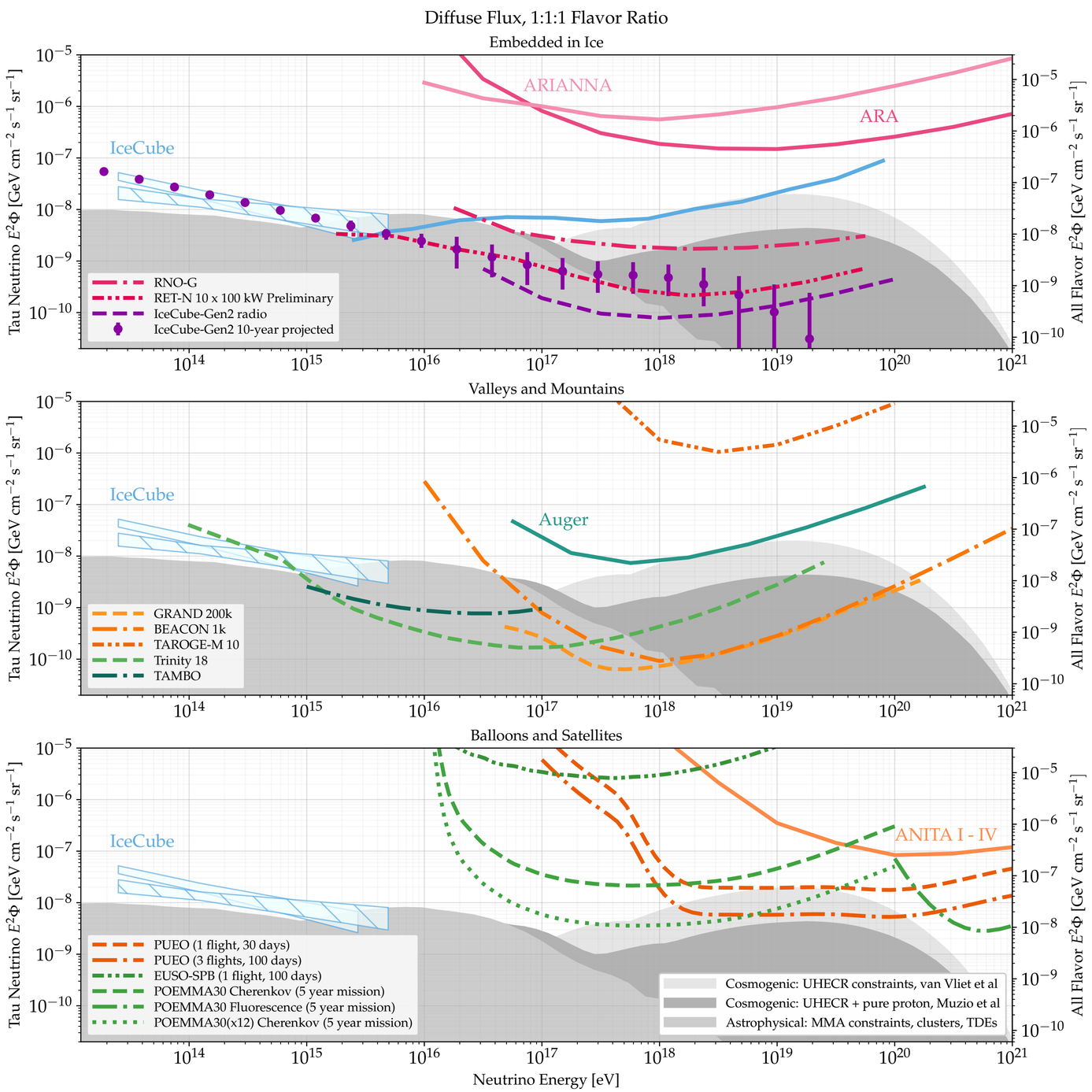

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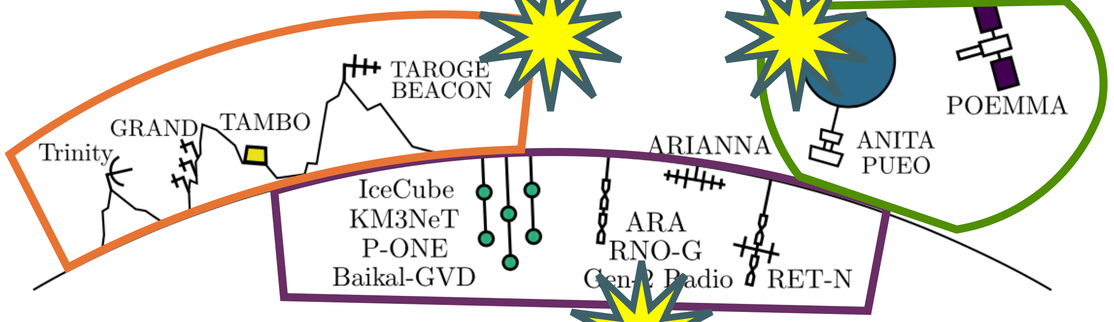

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Valleys and Mountains

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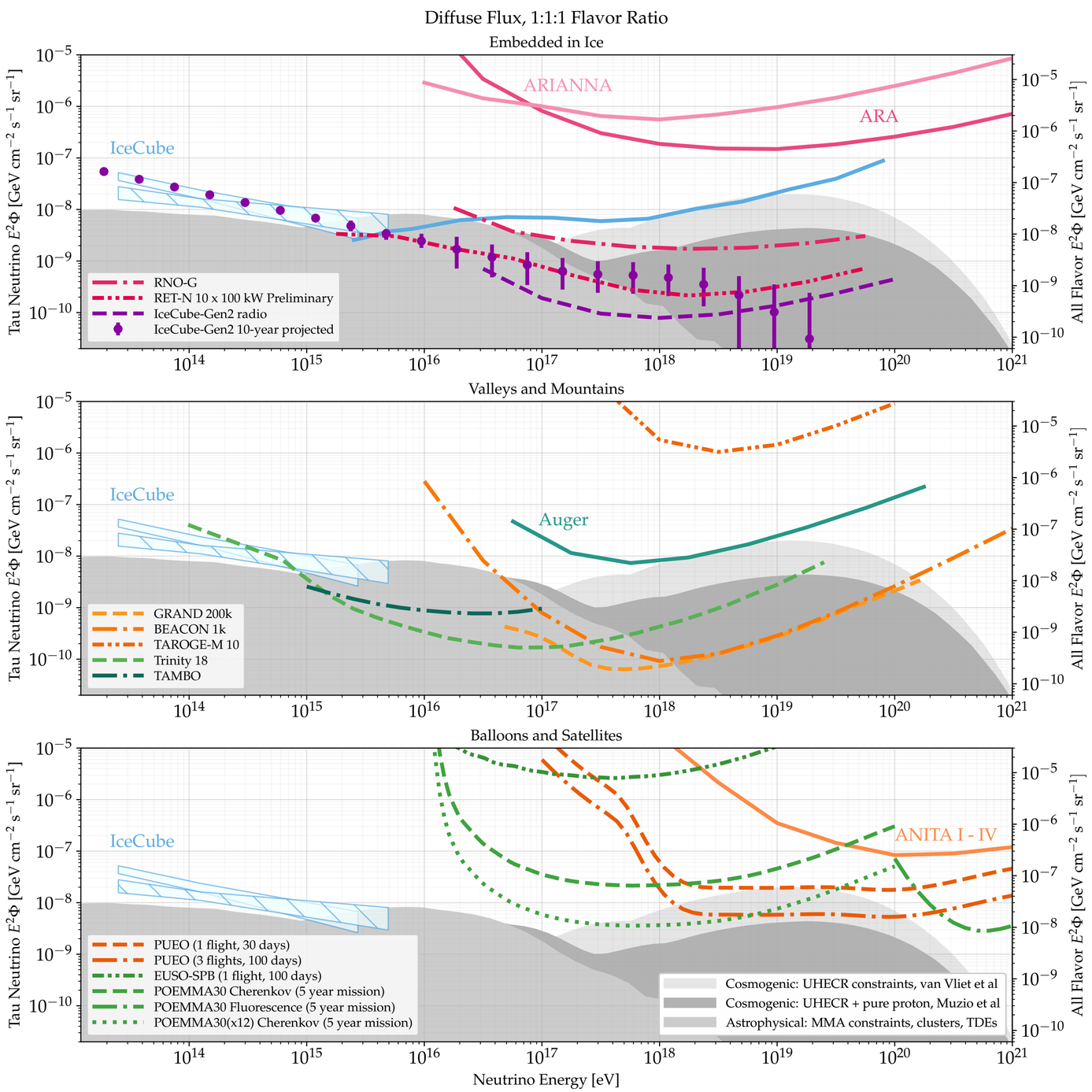

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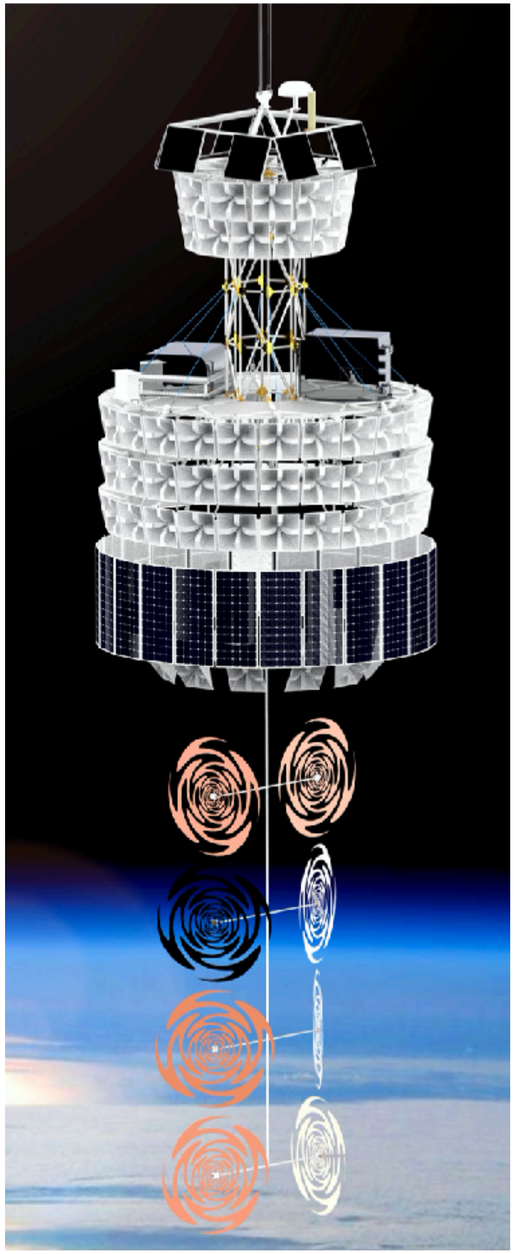
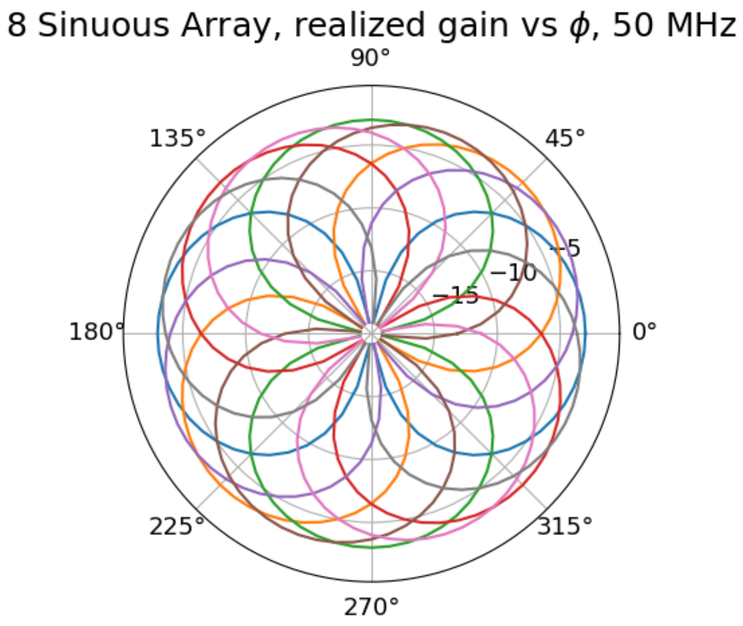
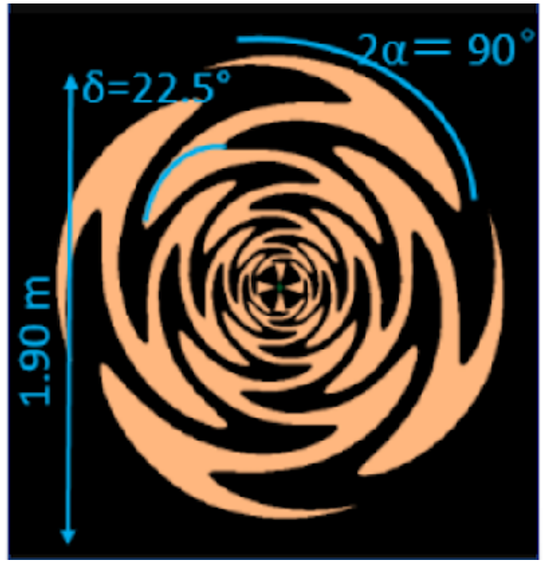


Two Reasons for the LF Instrument

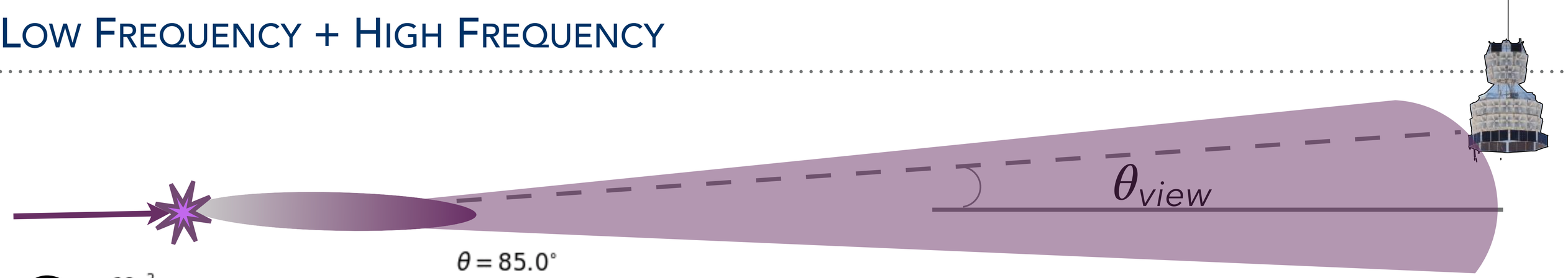
1. Tau neutrino sensitivity

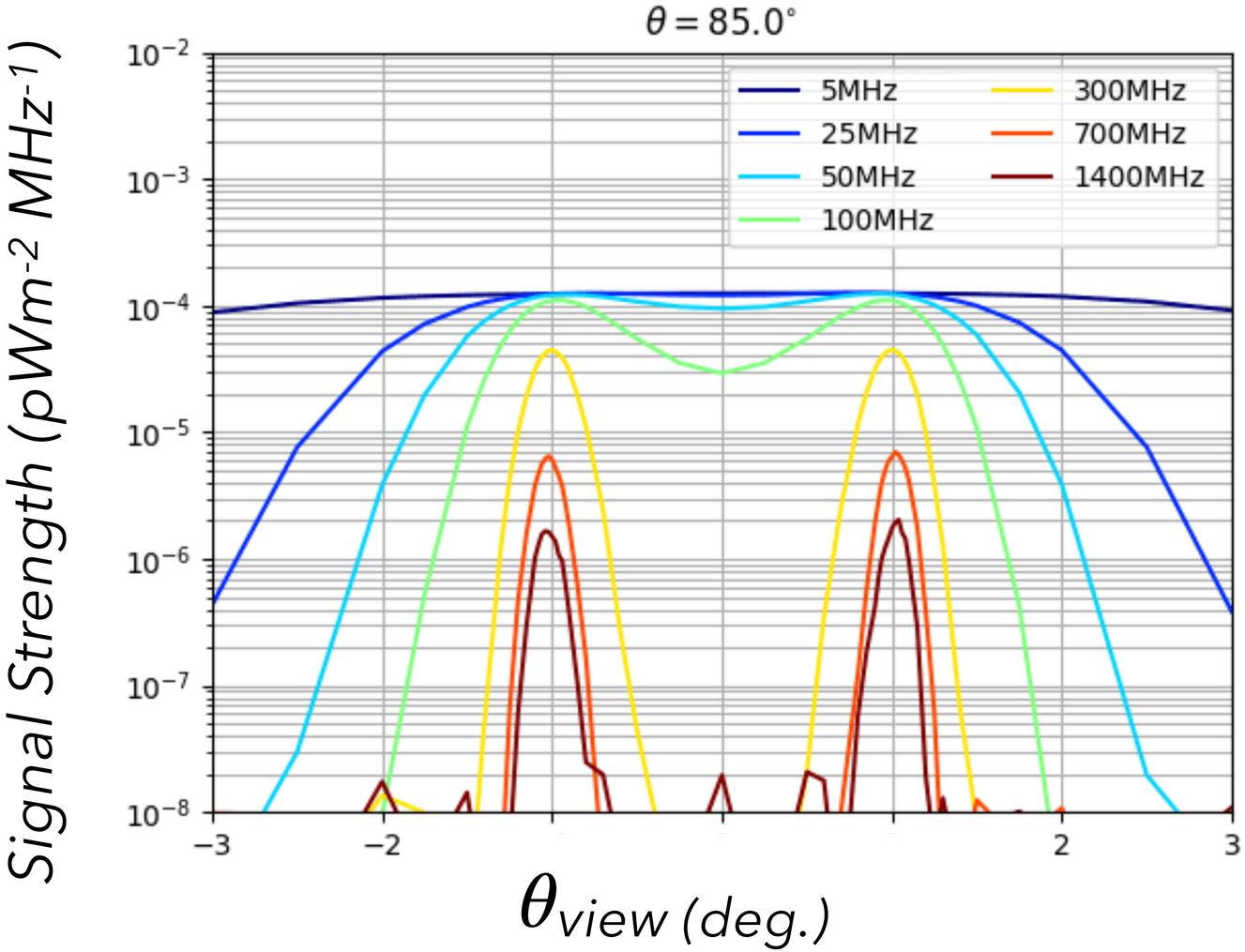
2. Background identification





Low Frequency + High Frequency





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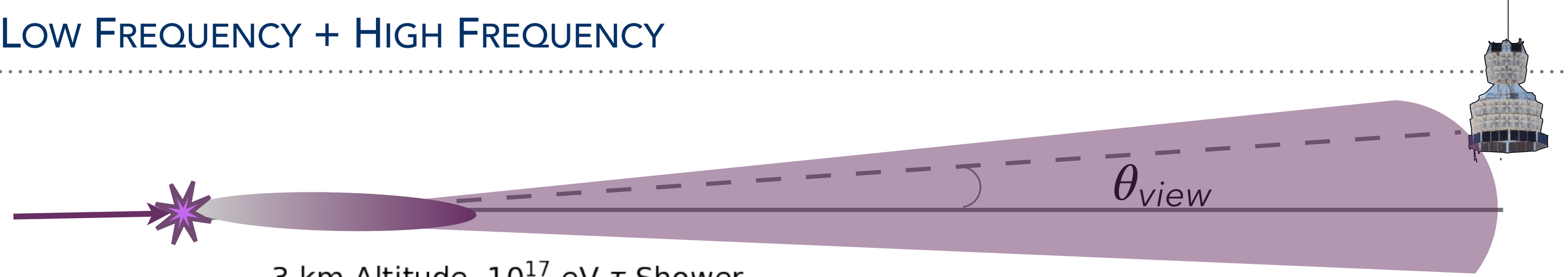

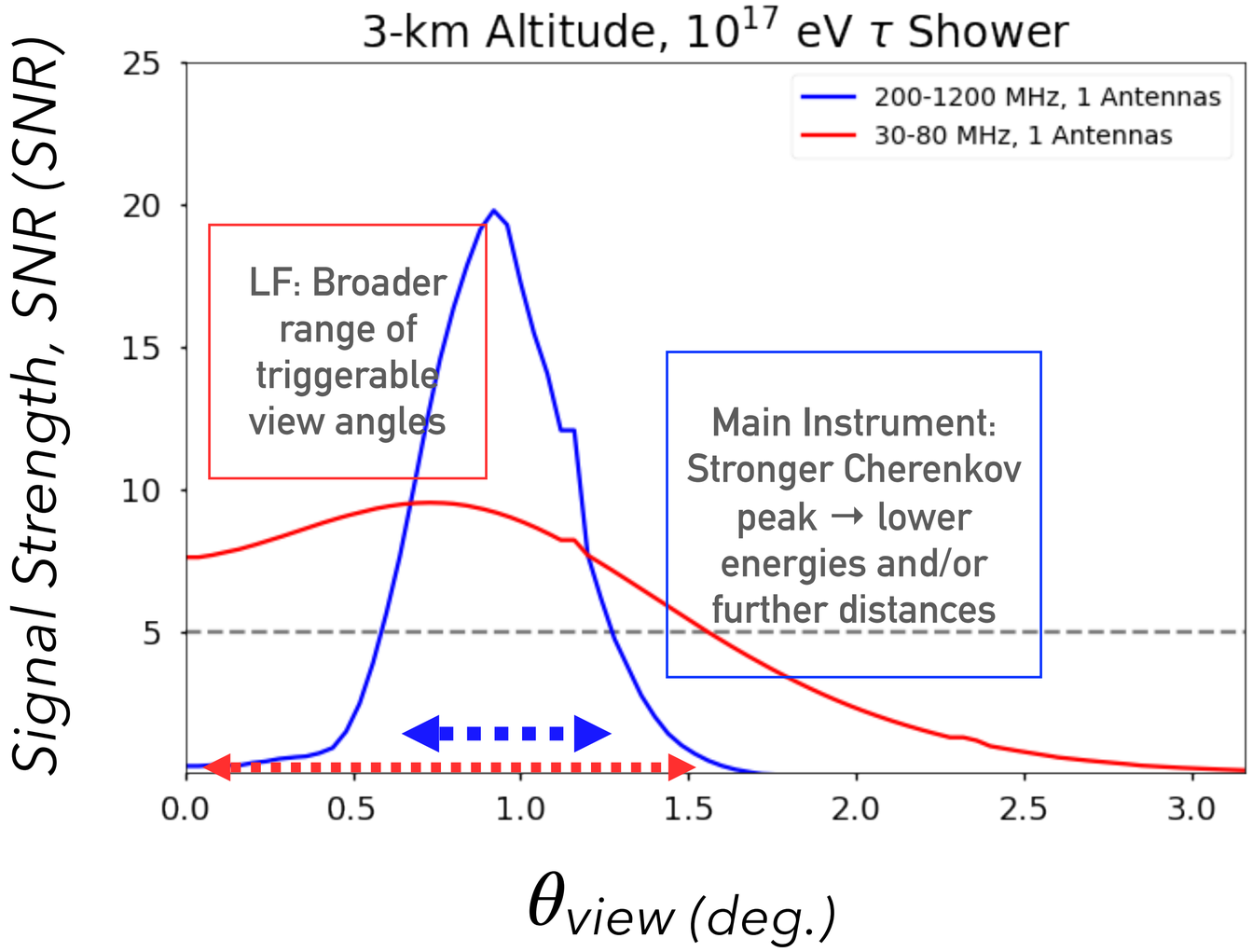

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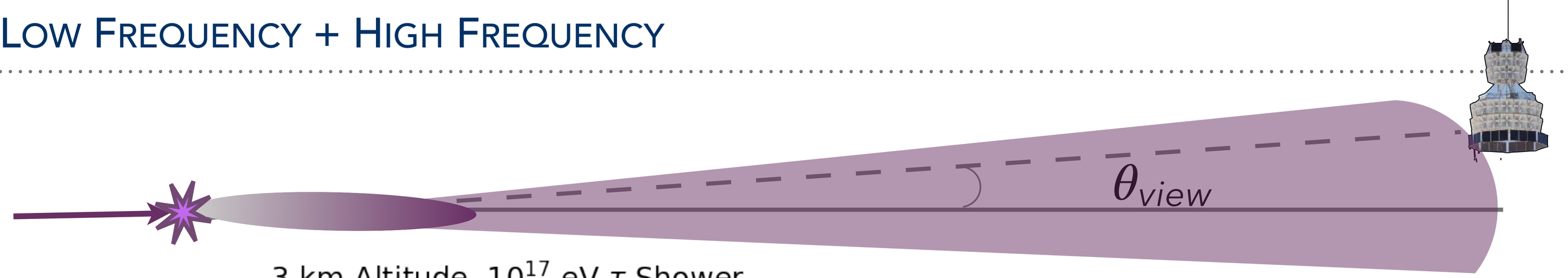

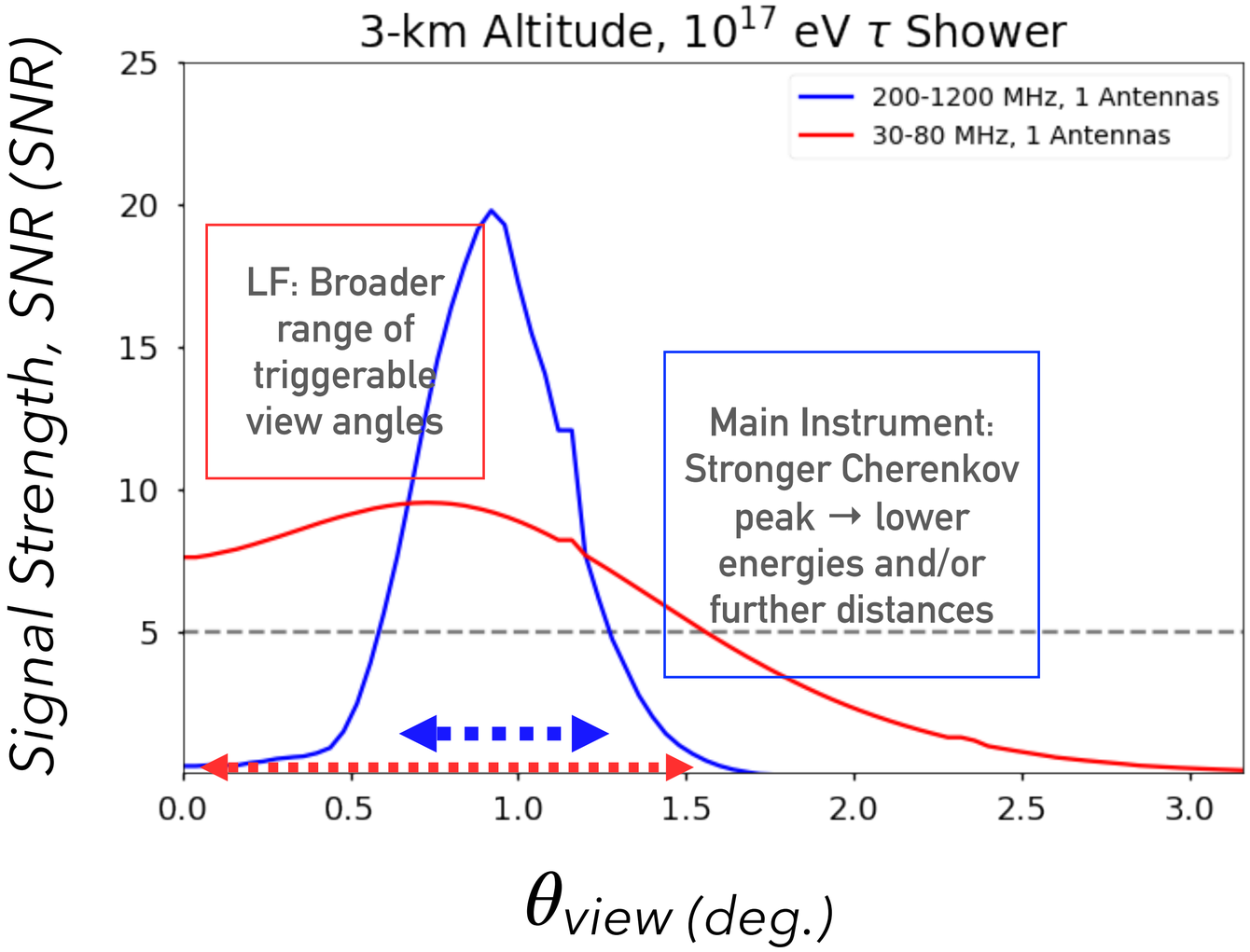

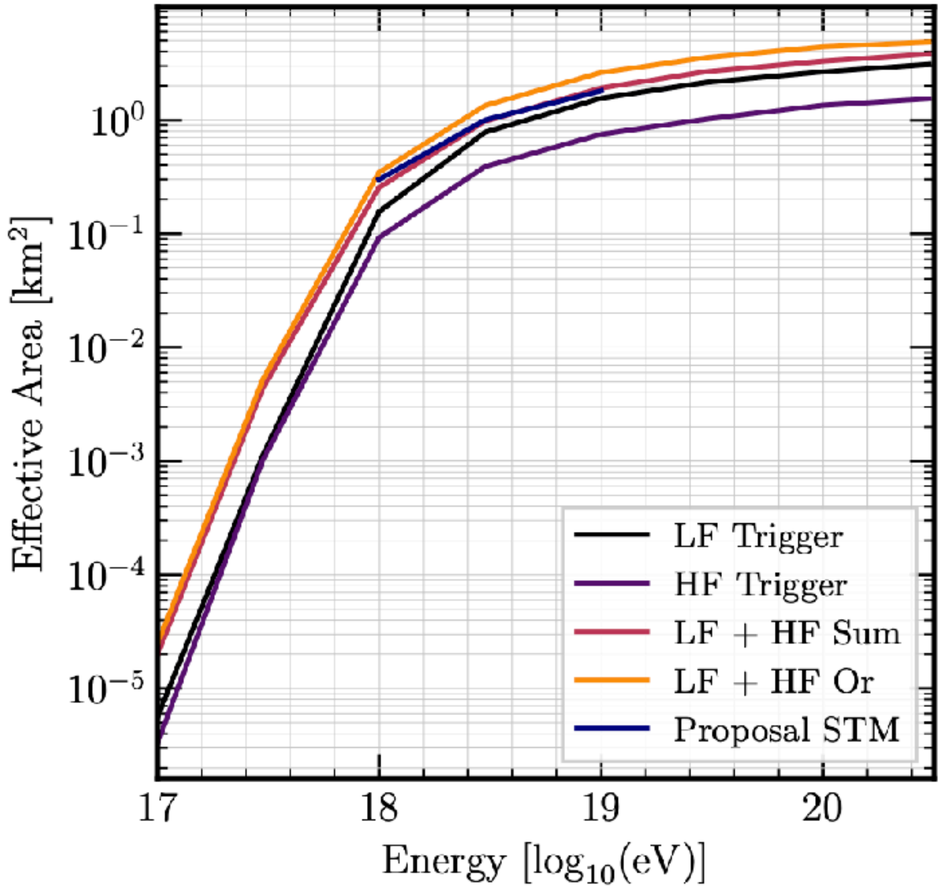

Cosmic Ray Air Showers in PUEO and ANITA

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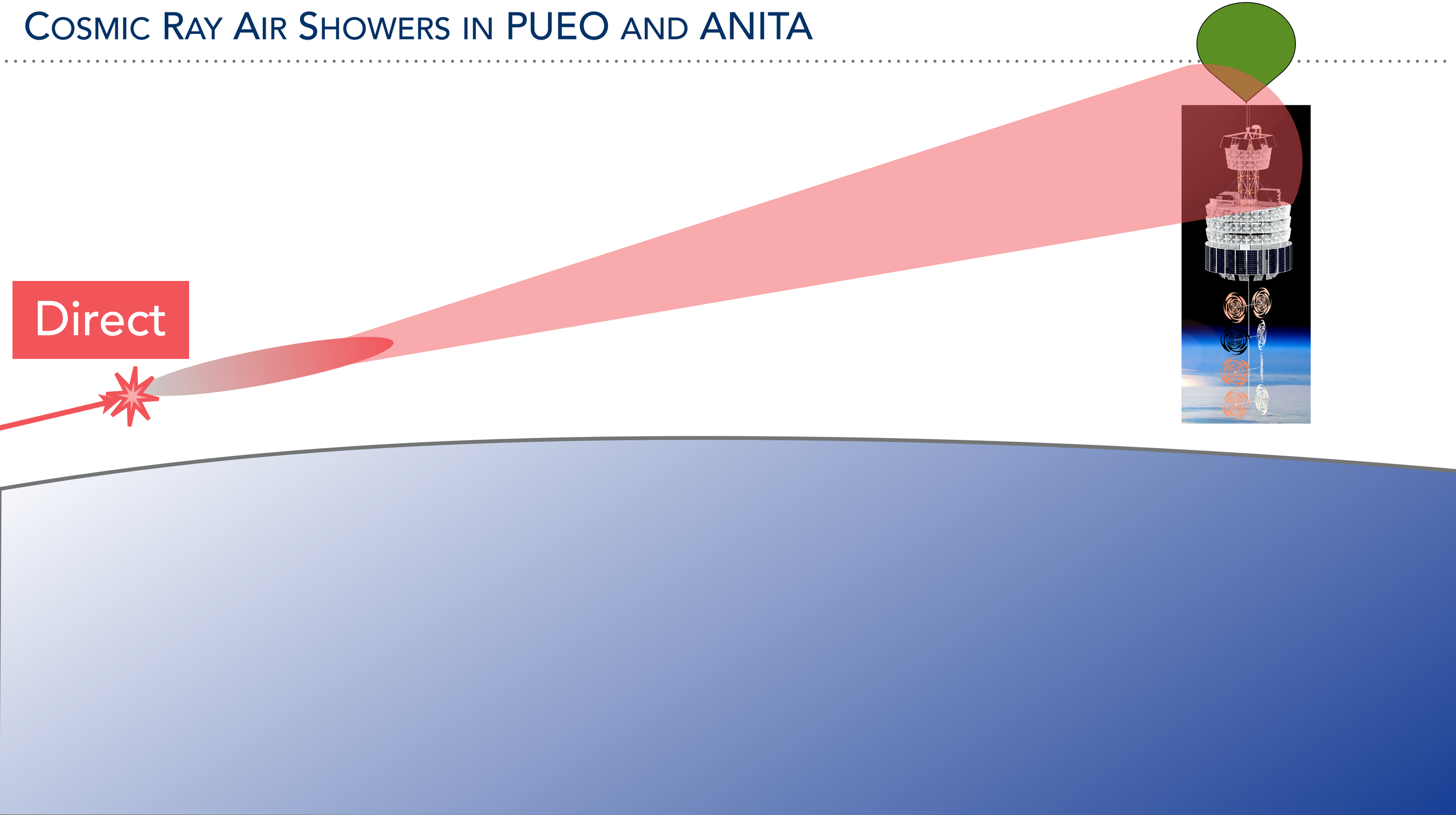

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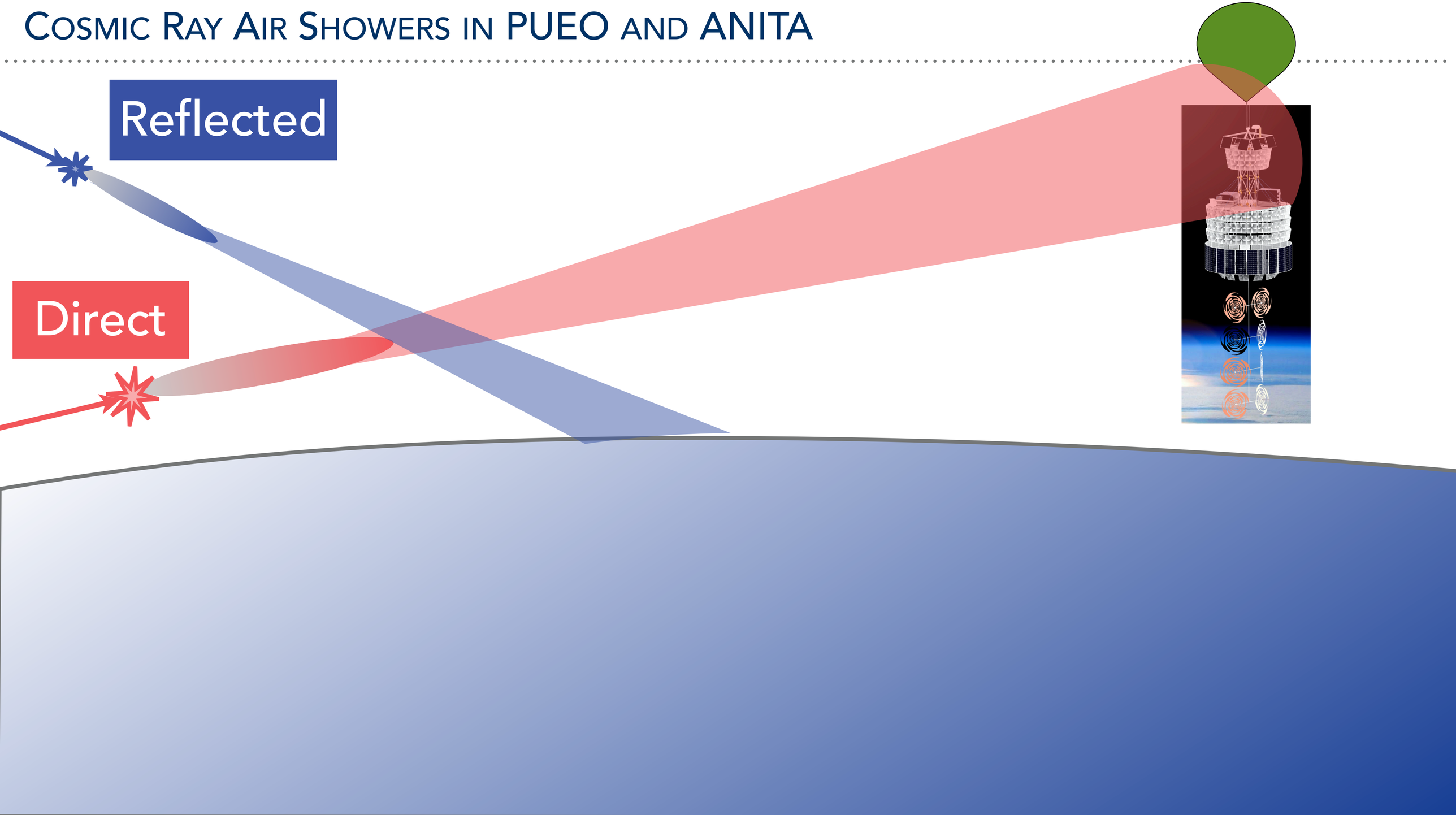

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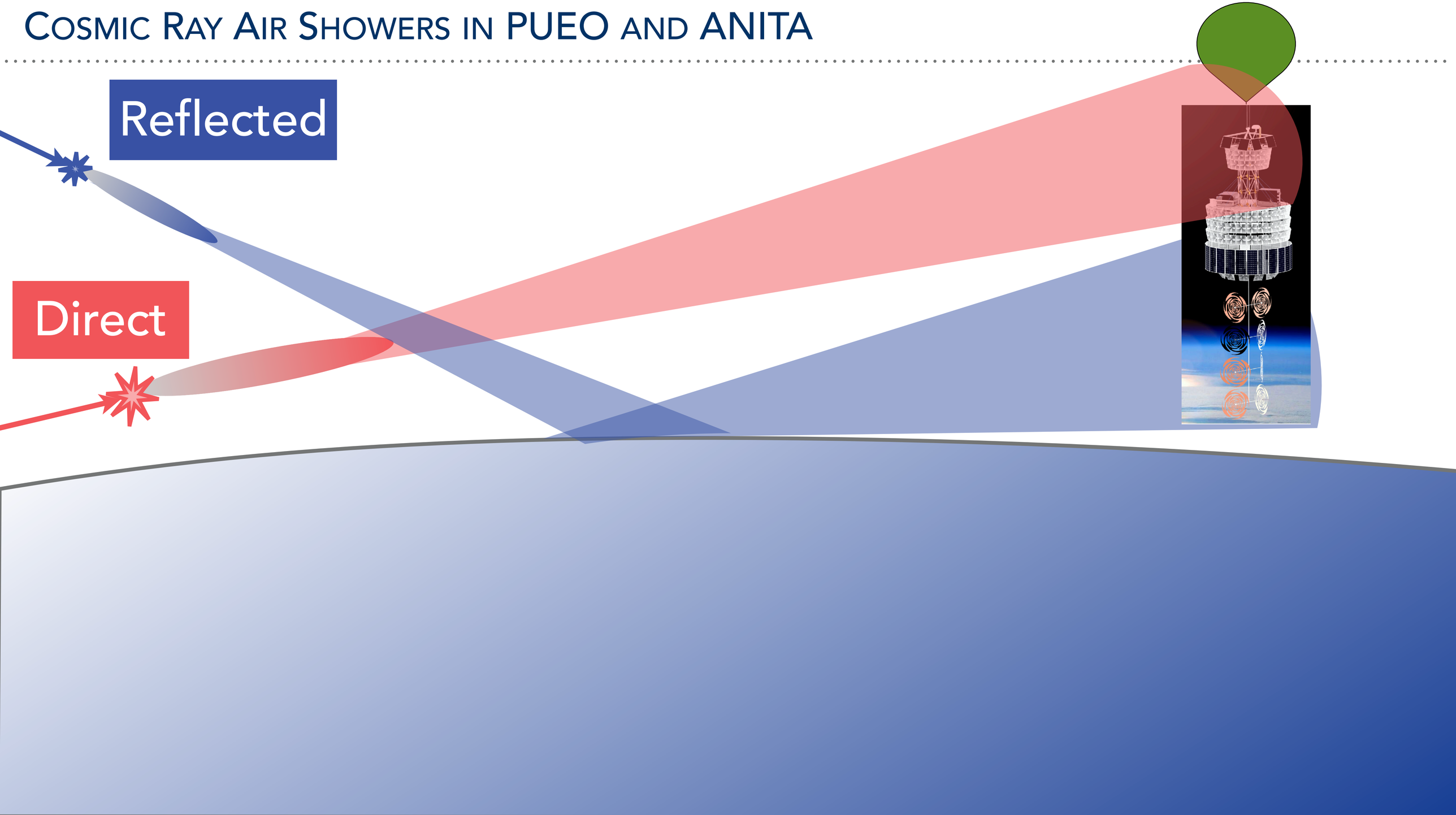

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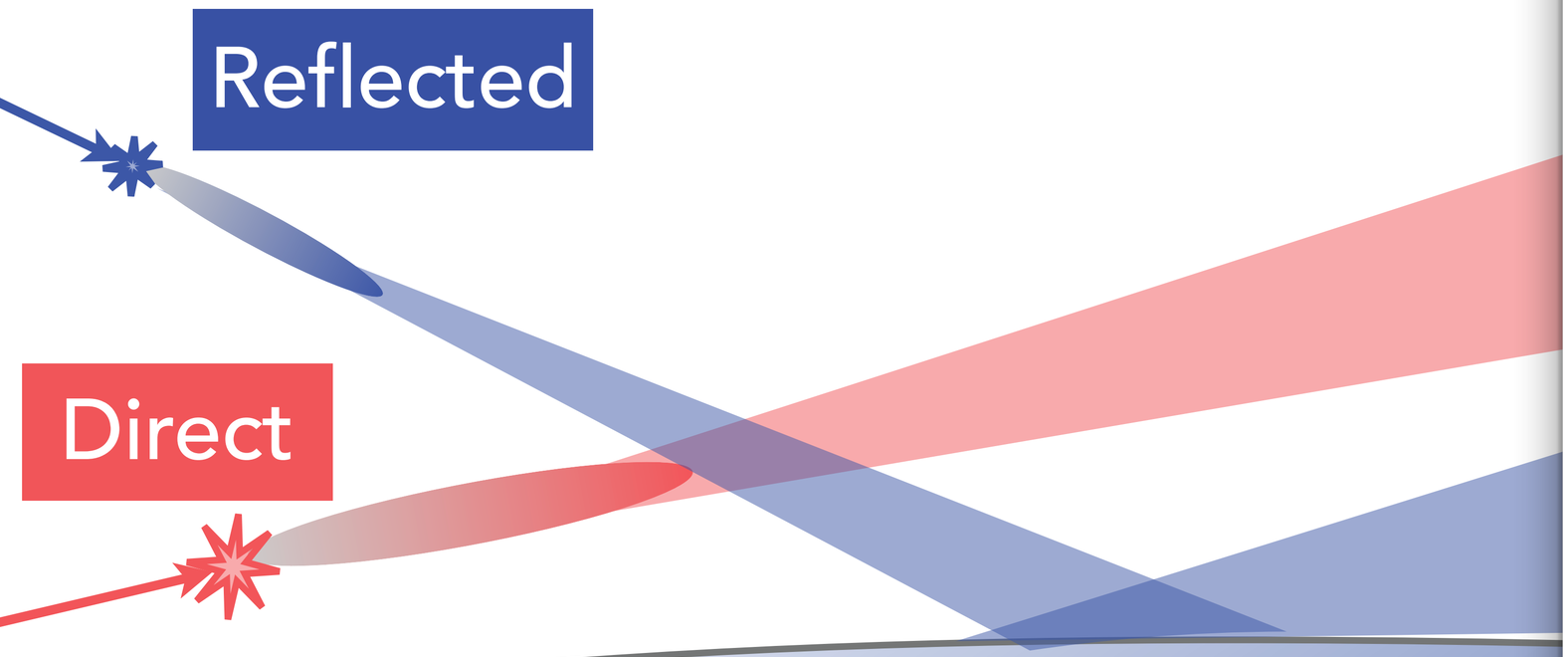
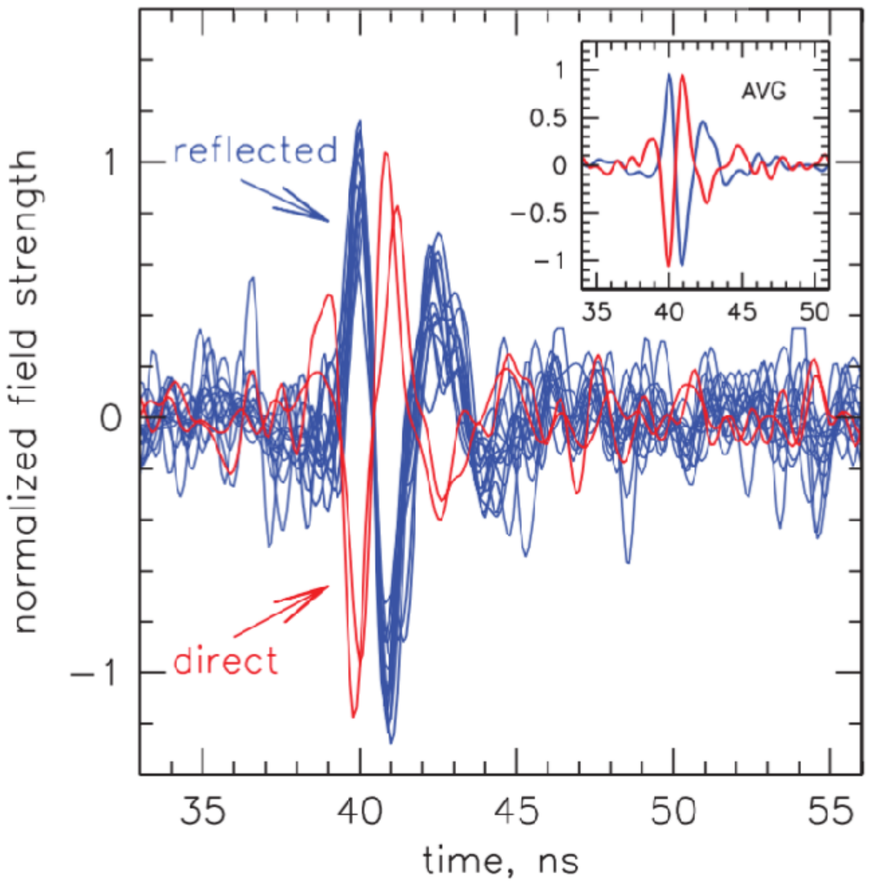


ANITA PRL 105:151101,2010



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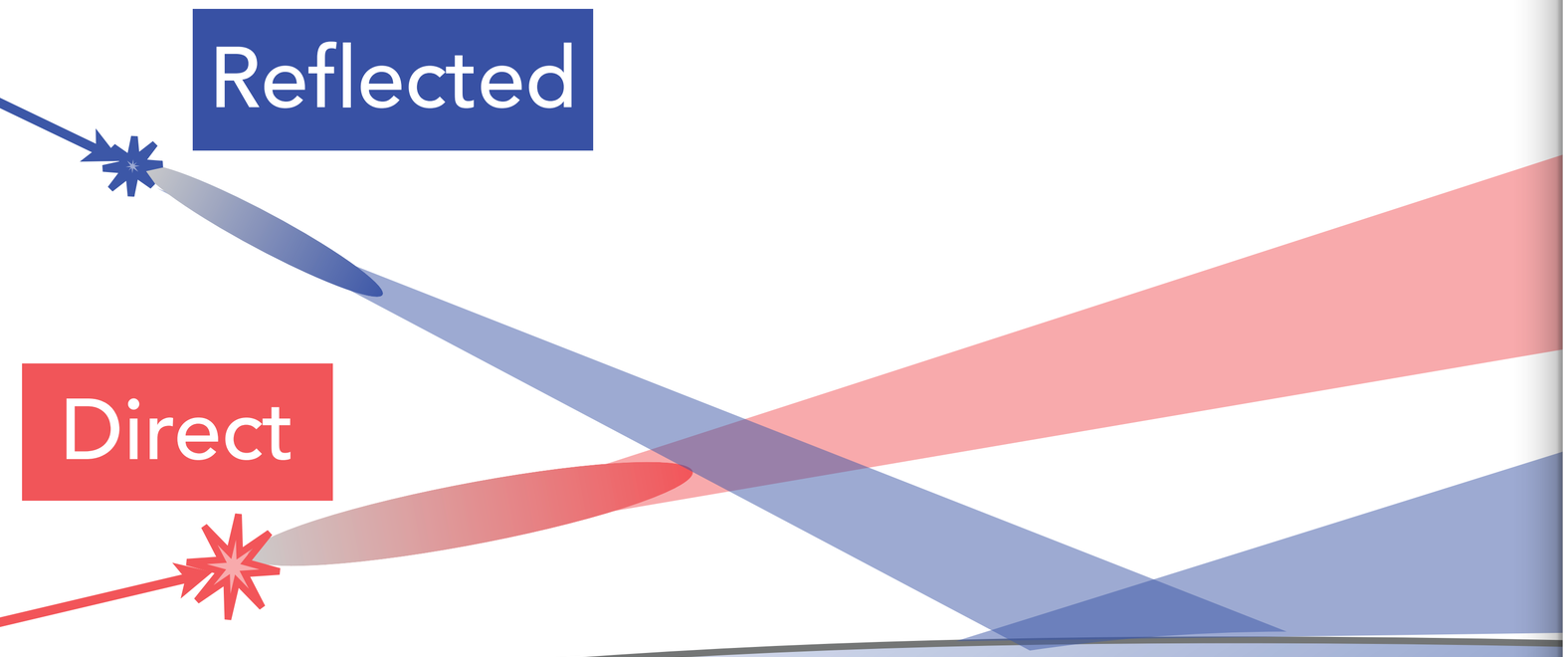

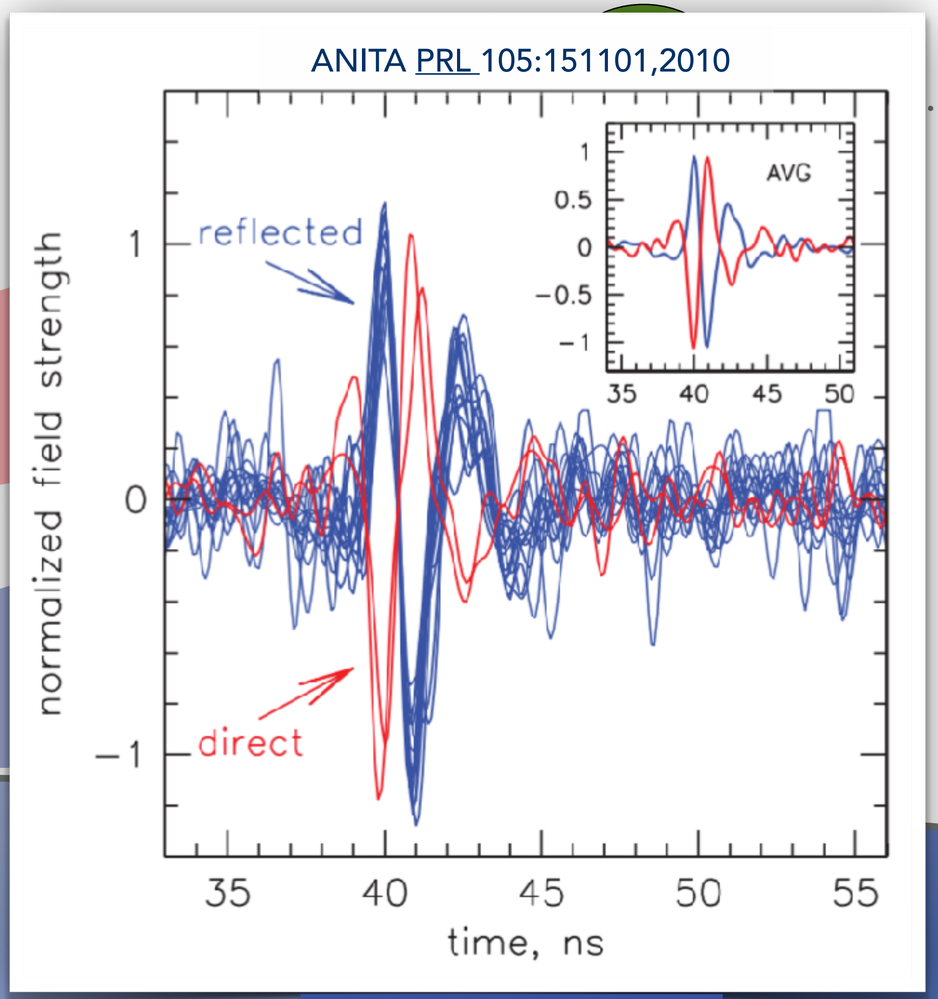

- Polarity* (phase) and arrival direction indicate whether Direct or Reflected

*Polarization determined by $\vec{v} \times \vec{B} \rightarrow$ predominately Hpol

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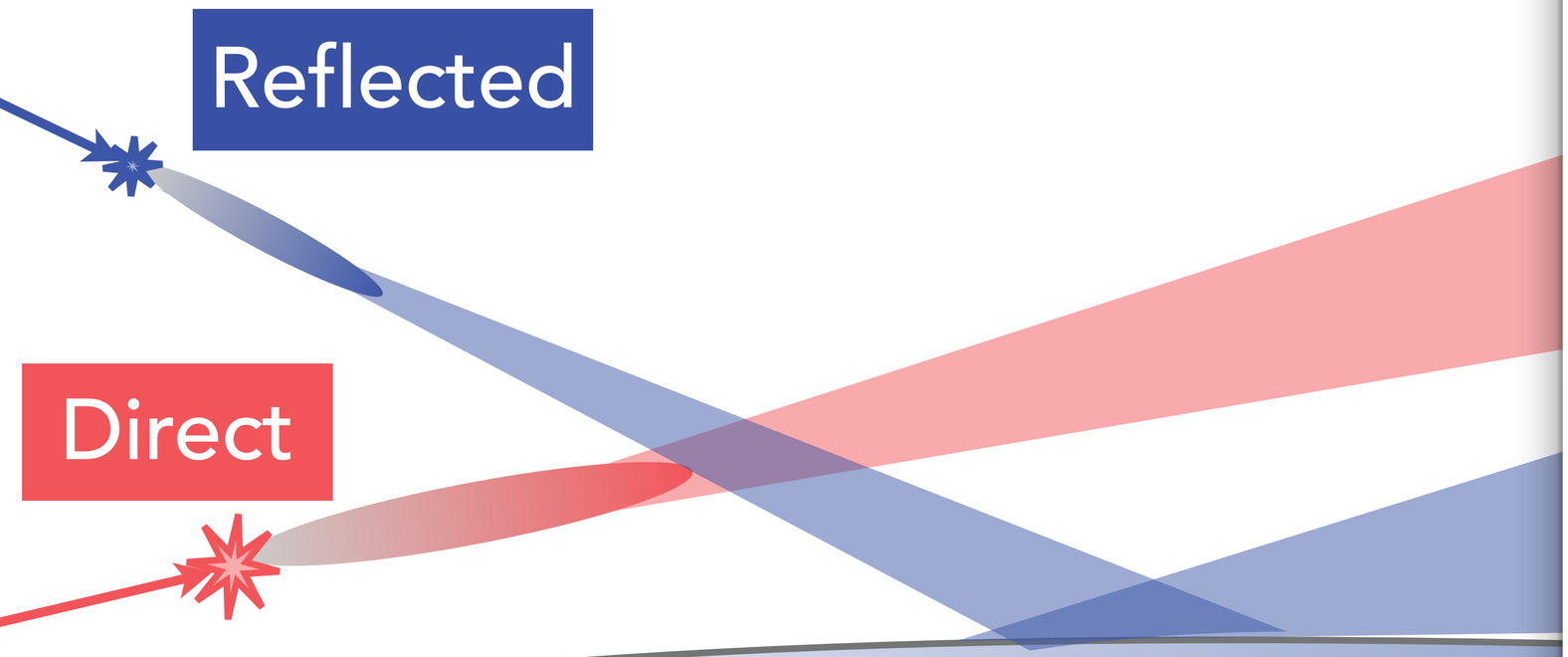
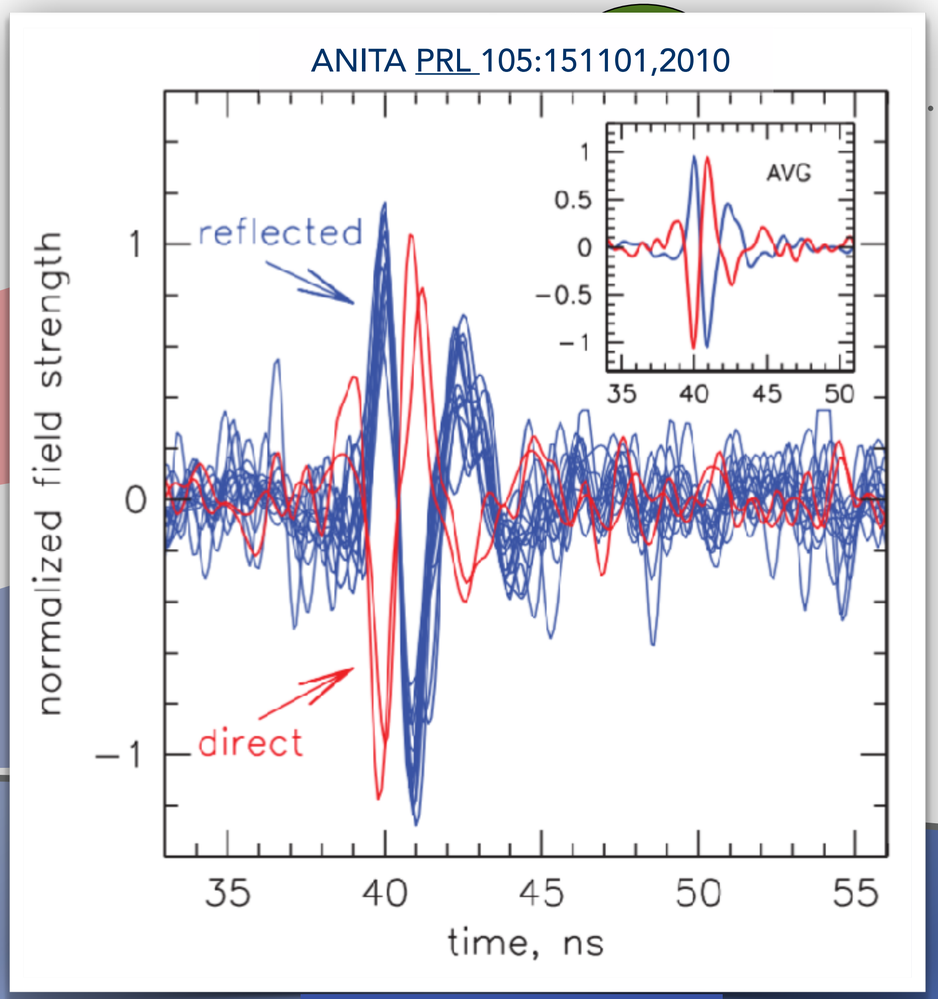
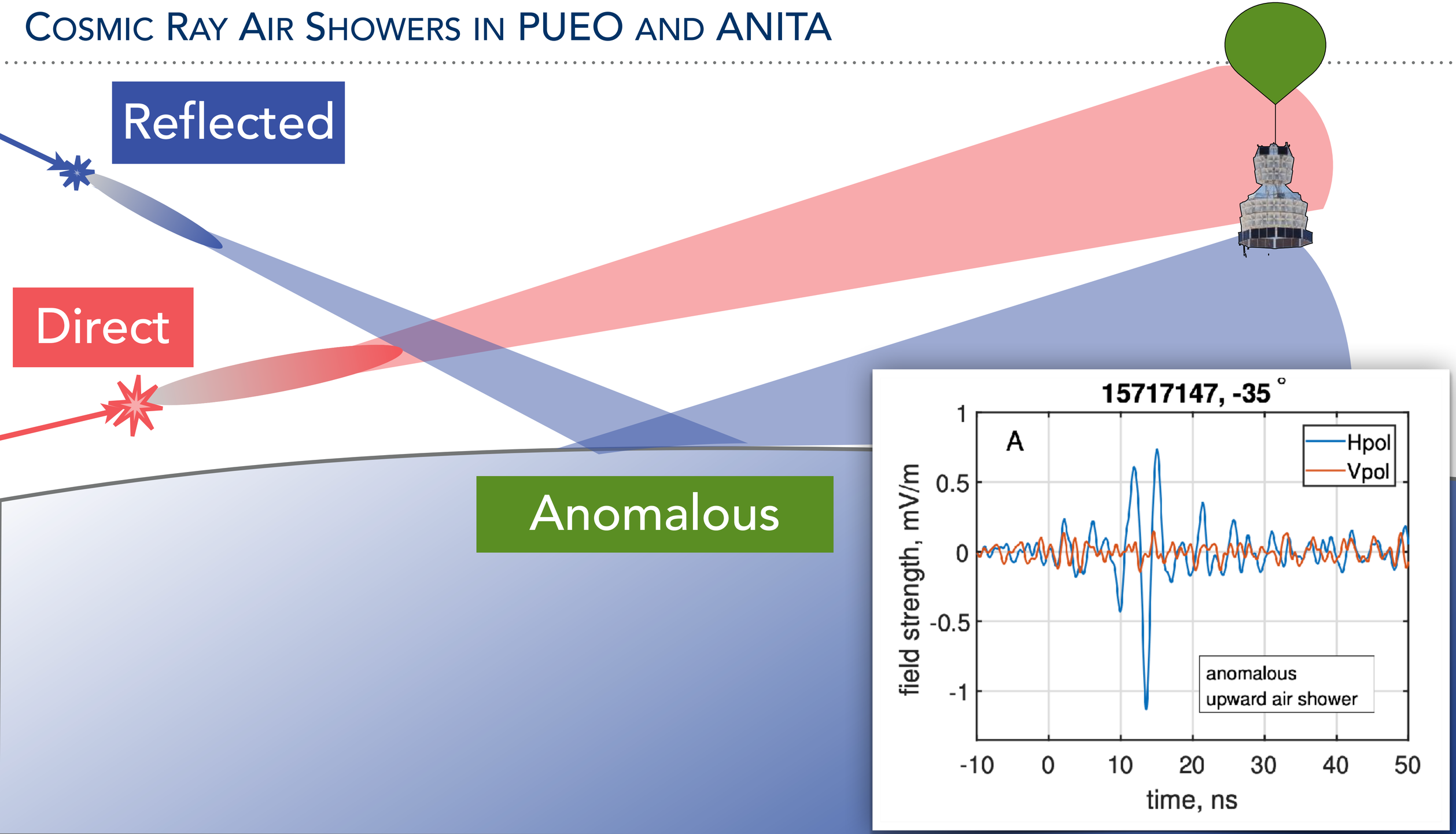




- Polarity* (phase) and arrival direction indicate whether Direct or Reflected
- **Tau neutrinos** would reconstruct below the horizon, but have the same polarity as Direct

*Polarization determined by $\vec{v} \times \vec{B}$ → predominately Hpol

Cosmic Ray Air Showers in PUEO and ANITA



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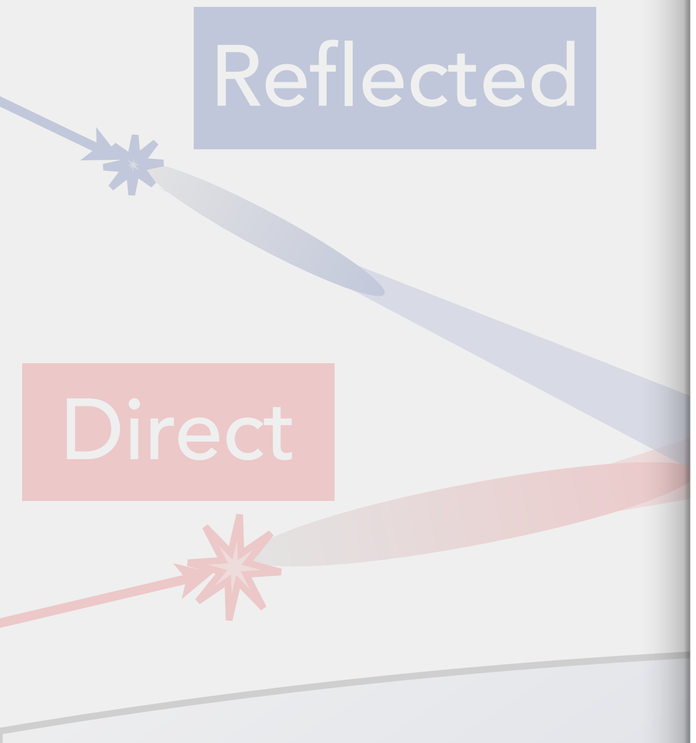

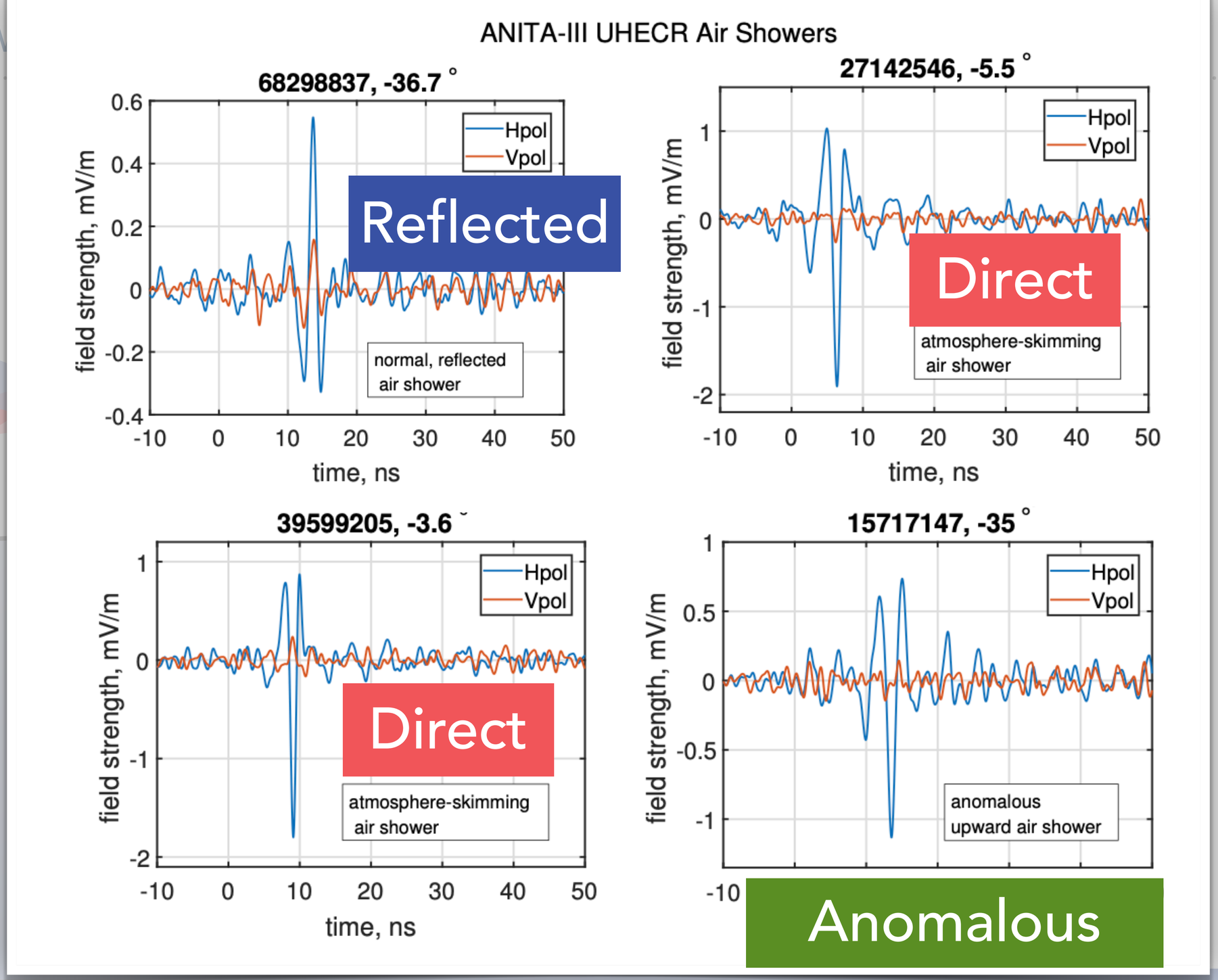

ANITA Anomalous Events

- Two sets which are **direct air shower events** from **below the horizon** (challenging to explain as cosmic rays)
  - **ANITA-1&3 Anomalous Events:** ANITA PRL 2018, ANITA PRL 2016
    - One steep (~30° below horizon) in each flight
  - **ANITA-4 Anomalous Events:** ANITA PRL 2021
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Romero-Wolf, SAW, ANITA, et al PRD 2019
IceCube ApJ 2020
Prechelt, SAW, Romero-Wolf, ANITA PRD 2022

EXPLANATIONS?

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ARW, SAW, ANITA, et al PRD 2019

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IceCube ApJ 2020
Prechelt, SAW, Romero-Wolf, ANITA PRD 2022

Other Possibilities?

- Air Shower with some other polarity non- or double inversion?
  - Transition Radiation?

Motloch, et al PRD 95 4 2017
de Vries & Prohira PRL 091102 2019

  - Sub-surface reflections, mirages?

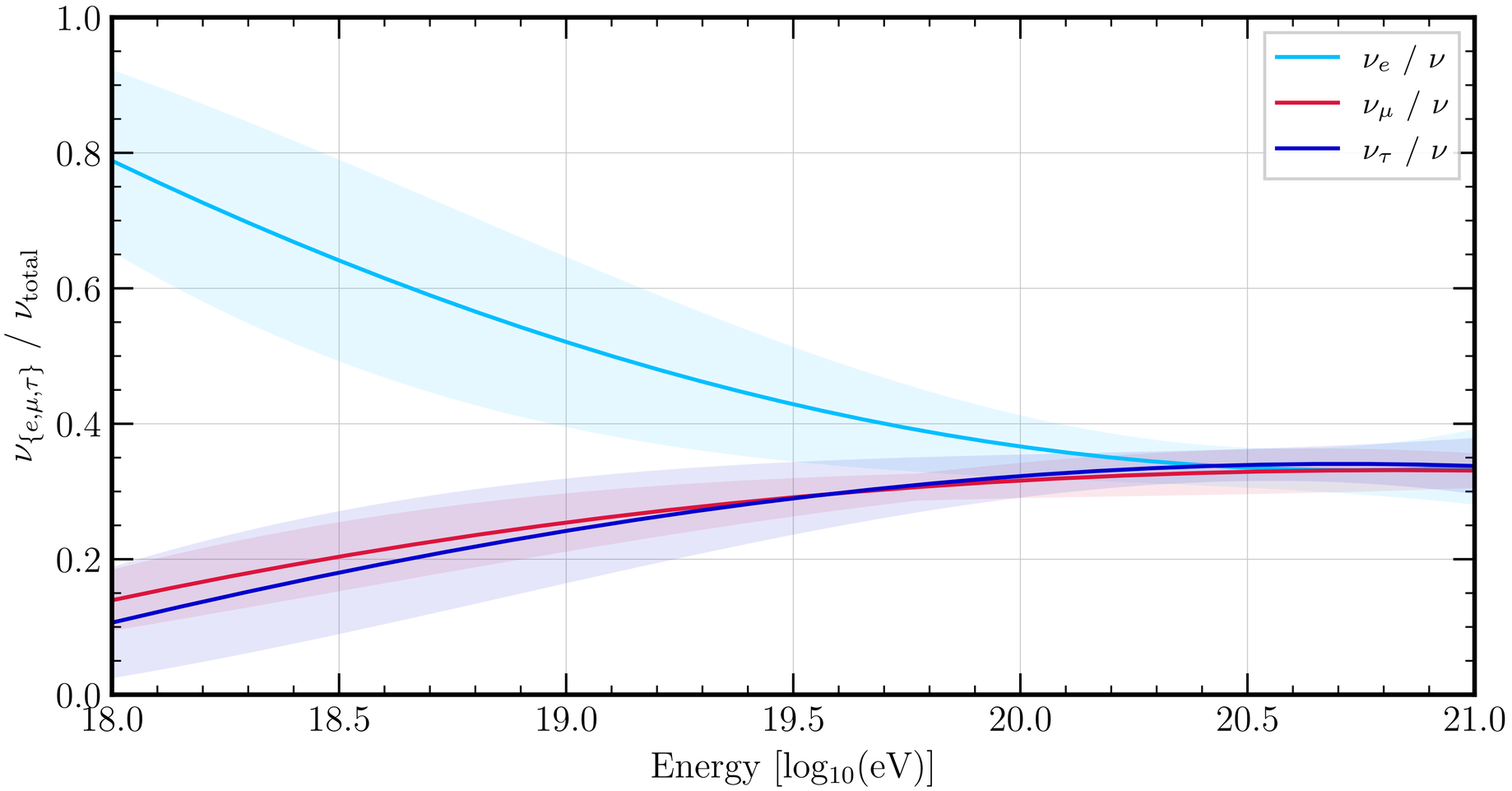
Shoemaker et al Annal. Glac. 2020
ANITA arXiv:2009.13010

- Beyond the standard model (sterile neutrinos, dark matter decay, supersymmetry, axions…)

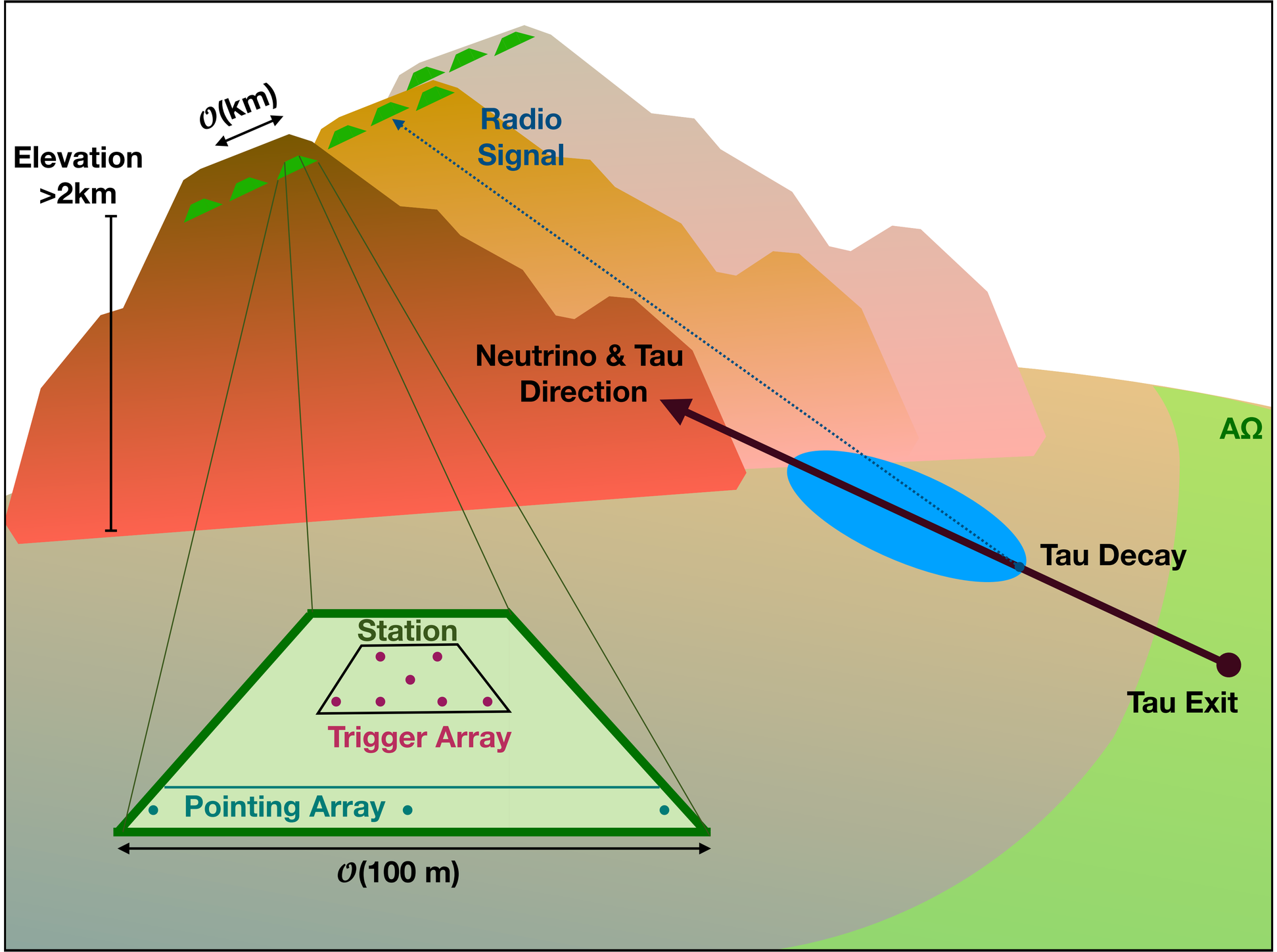
arXiv:1802.01611, arXiv:1803.11554, arXiv:1804.05362, arXiv:1805.07342, arXiv:1807.08892, arXiv:1809.09615, arXiv:1810.08479, arXiv: 1812.00919, arXiv:1812.01520 arXiv:1905.10372, arXiv:1907.06308, arXiv:2003.08738 2003.02846, arXiv:2006.03325, 2004.09464, 2002.12910,

PUEO May be able to Measure Flavor Ratios

- Tau channel is a high-purity flavor filter
- Askaryan channel dominated by electron showers at 10^{18} eV

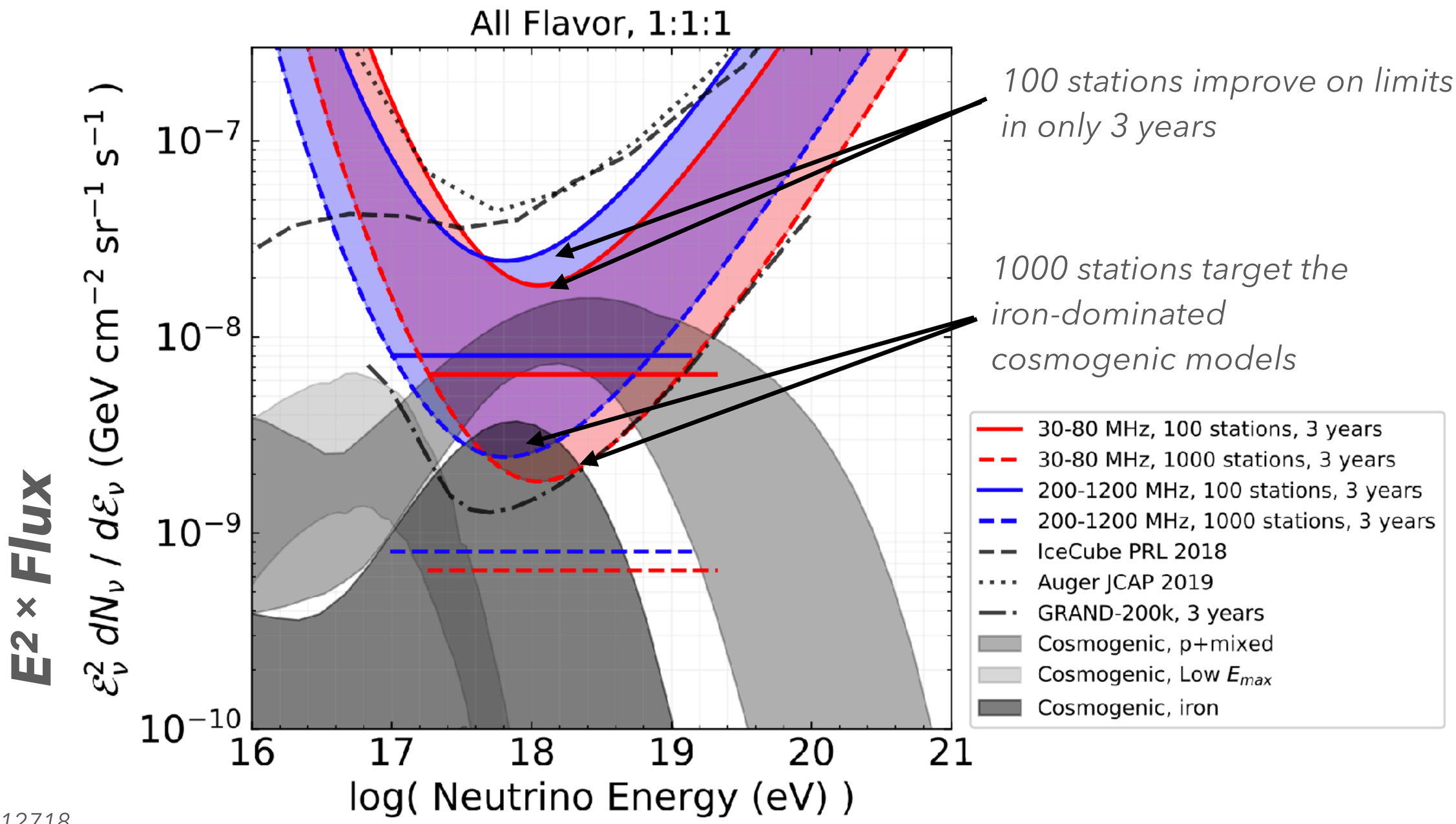


PUEO Whitepaper 2021 arXiv:2010.02892



Wissel
JCAP 2020
arXiv:2004:12718

BEACON is an Efficient Design



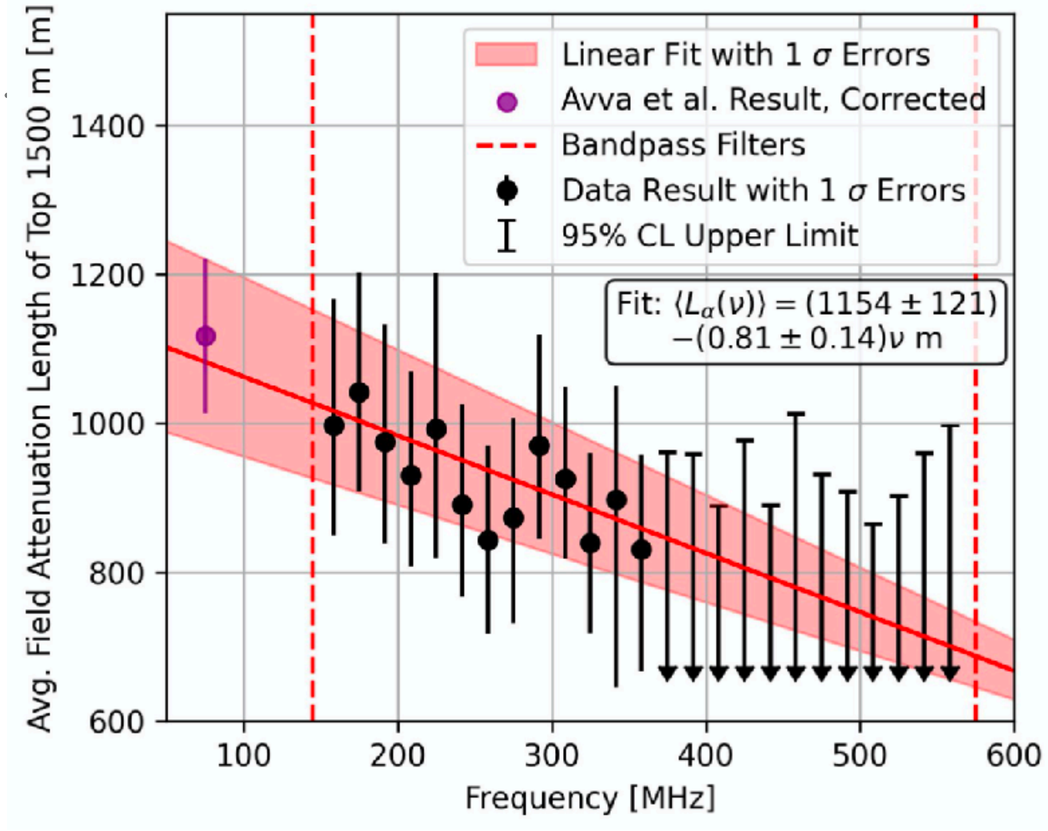
100 stations improve on limits in only 3 years

1000 stations target the iron-dominated cosmogenic models

Wissel
JCAP 2020
arXiv:2004:12718

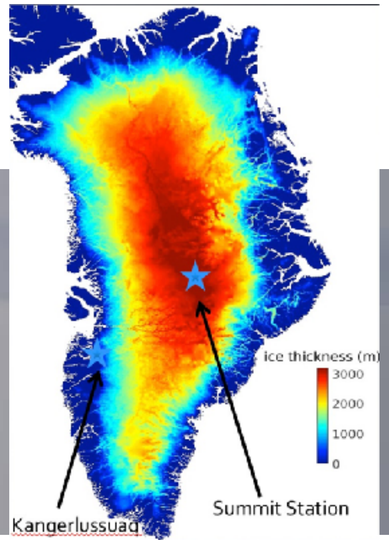
Why Greenland?

- Why not?
- Most ice volume of a reasonable site
  - 3 km thick ice at Summit Station
  - Attenuation measurements 2021 and 2013
    $< L_\alpha > = 1154 \pm 121 - (0.81 \pm 0.14)\nu$ m
  - Sunlight 10 months / year → solar power
- Northern Sky observatory
- NSF-operated year-round

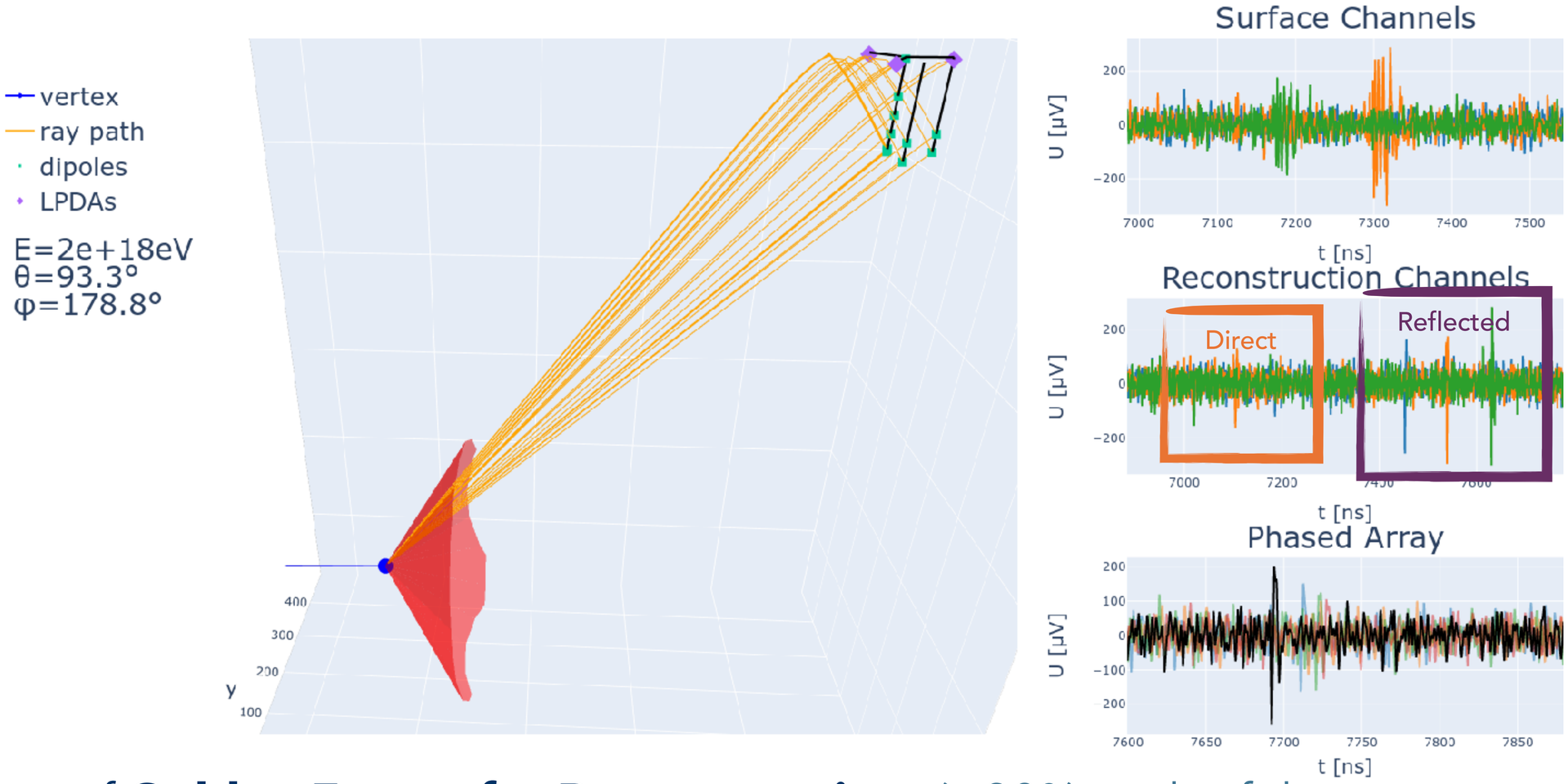


arXiv:2201.07846

arXiv:1409.5413



RNO-G Events



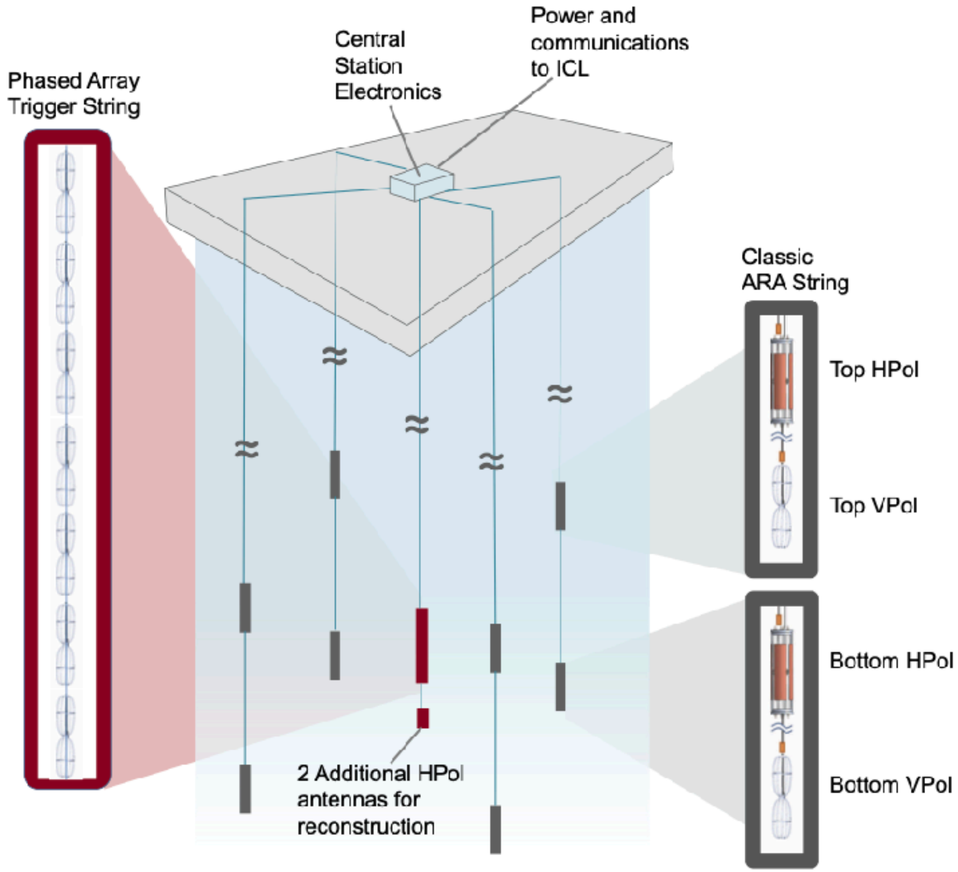
Two Types of **Golden Events for Reconstruction:** (~20% each of the events at 10^{18} eV)

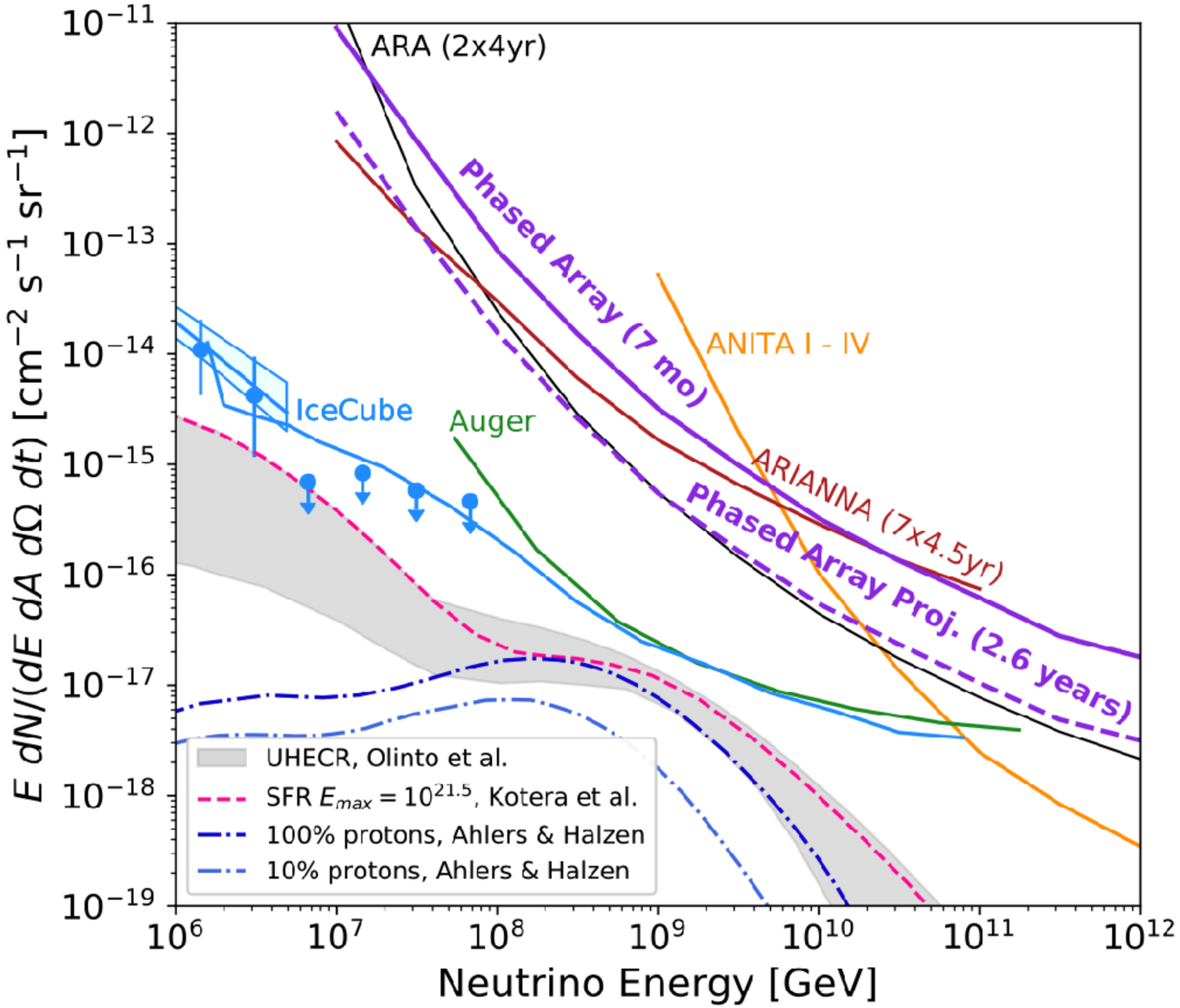
1. **Direct** *and* **reflected** signals on the downhole antennas
2. **Surface-Deep Coincident** Events

This event has both.

Neutrino Search in ARA's Phased Array

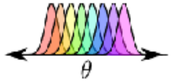
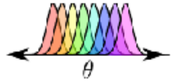
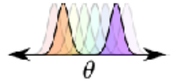
- Search in 7 months of single phased array string on ARA
- Low SNR events seen in phased array reconstructed with > 80% analysis efficiency → ***promising***





RNO-G Multi-Messenger Capabilities

- Beamforming and online event reconstruction

Mode	RNO-G Baseline	Proposed Normal	Proposed Burst Mode existing HW / new HW
Total Trigger Rate (Hz)	1	10-20	30-40 / 500-1000
Effective No. of beams	8 	8 	~2 
Trigger rate / beam (Hz)	0.1	1-2	15-20 /250-500
Data to Summit Station	1 Hz average	1 Hz average	1 Hz average + burst data
Trigger Threshold (σ)	2.0	1.9	1.8 / 1.5
Data to satellite	5 GB / day (random)	5 GB / day (prioritized)	5 GB/ day (prioritized)

PRELIMINARY

RNO-G Multi-Messenger Capabilities

➤ Beamforming and online event reconstruction

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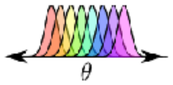
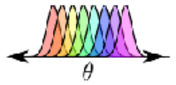
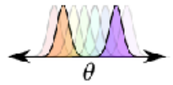
Effective No. of beams	8 	8 	~2 
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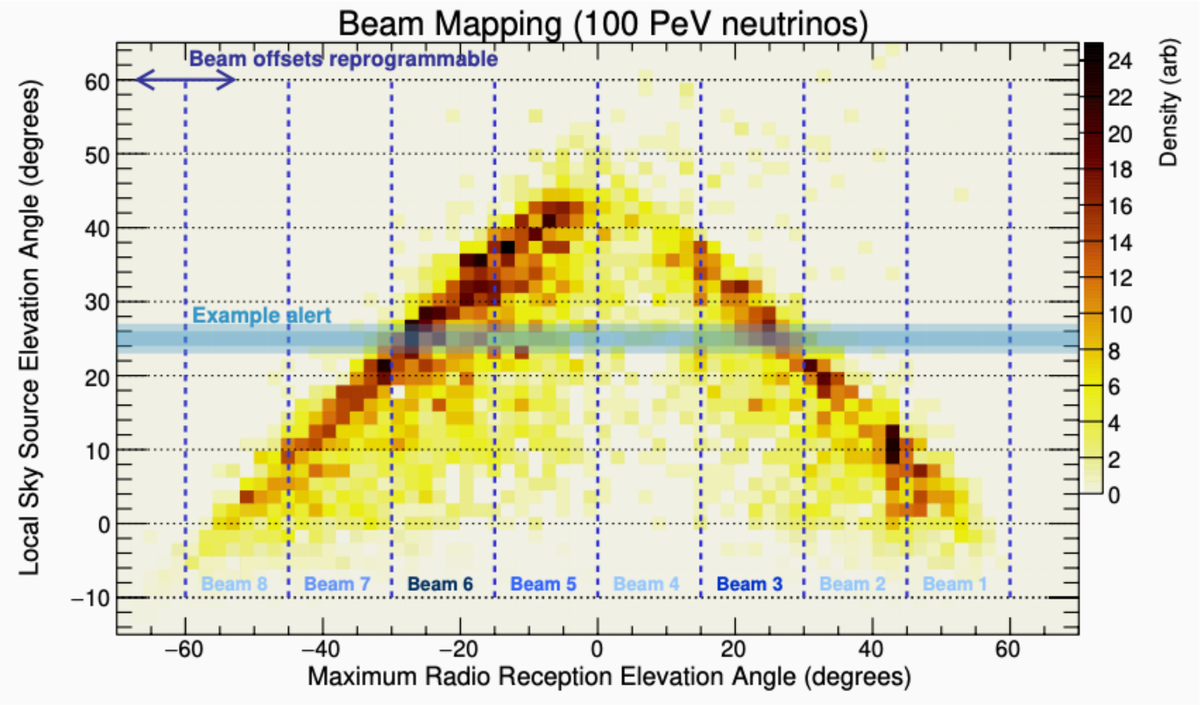

PRELIMINARY

RNO-G Multi-Messenger Capabilities

➤ Beamforming and online event reconstruction

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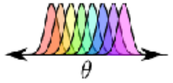
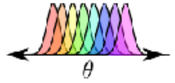
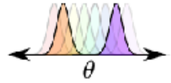
Effective No. of beams	8 	8 	~2 
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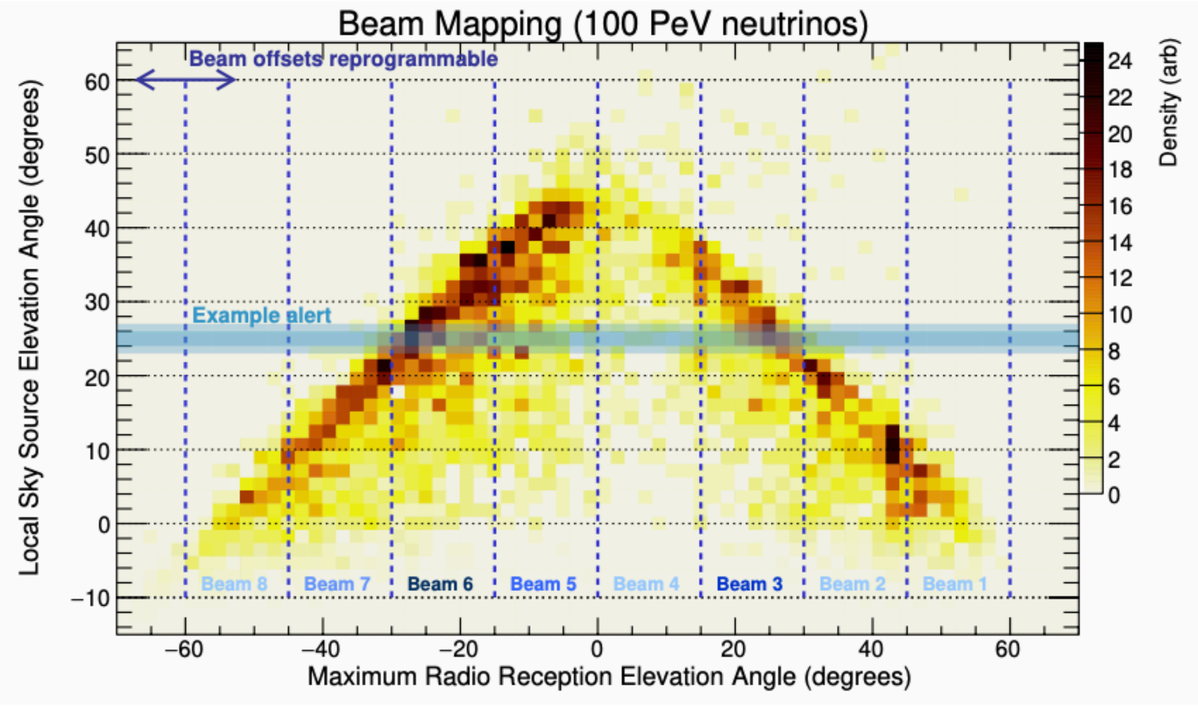

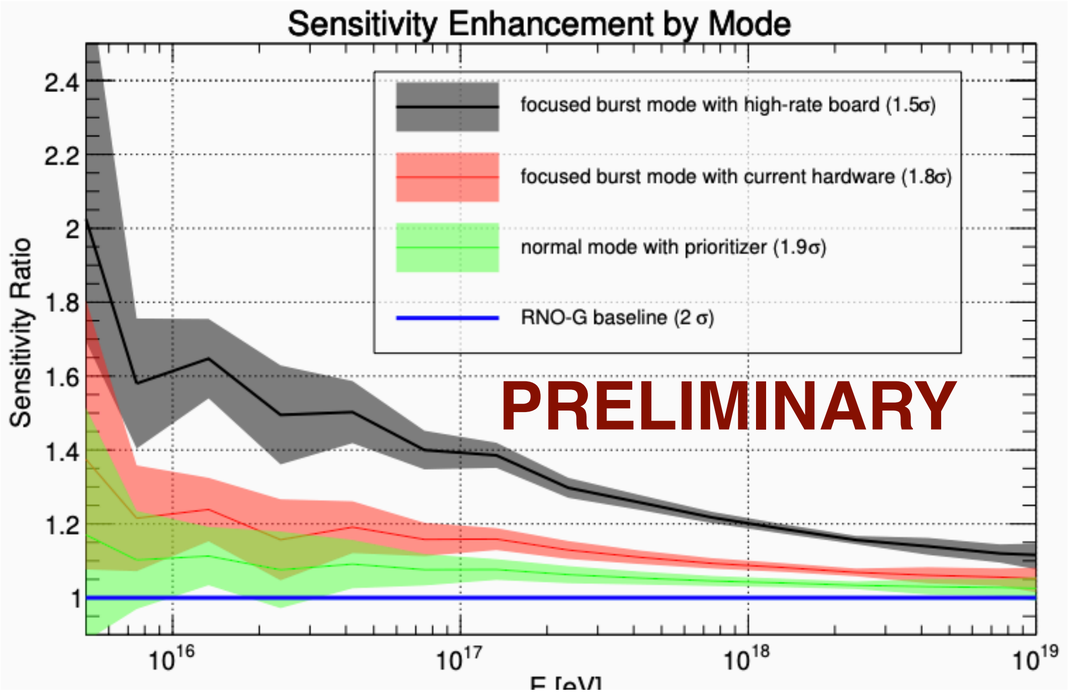

RNO-G Multi-Messenger Capabilities

- Beamforming and online event reconstruction

Mode	RNO-G Baseline	Proposed Normal	Proposed Burst Mode existing HW / new HW
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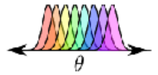
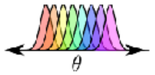
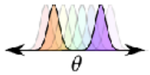
Effective No. of beams	8 	8 	~2 
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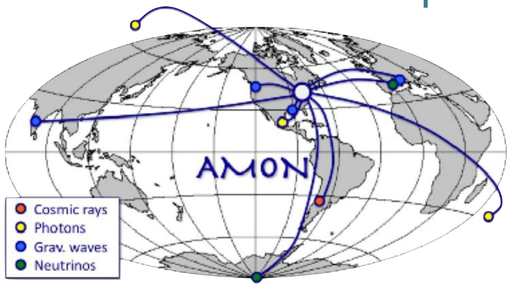
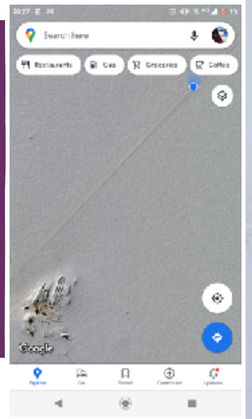
Data to satellite	5 GB / day (random)	5 GB / day (prioritized)	5 GB/ day (prioritized)

- Multi-messenger follow-up enabled with continuous satellite coverage & LTE cellular comms networking

- Plans to run AMON / SCiMMA client and respond to alerts

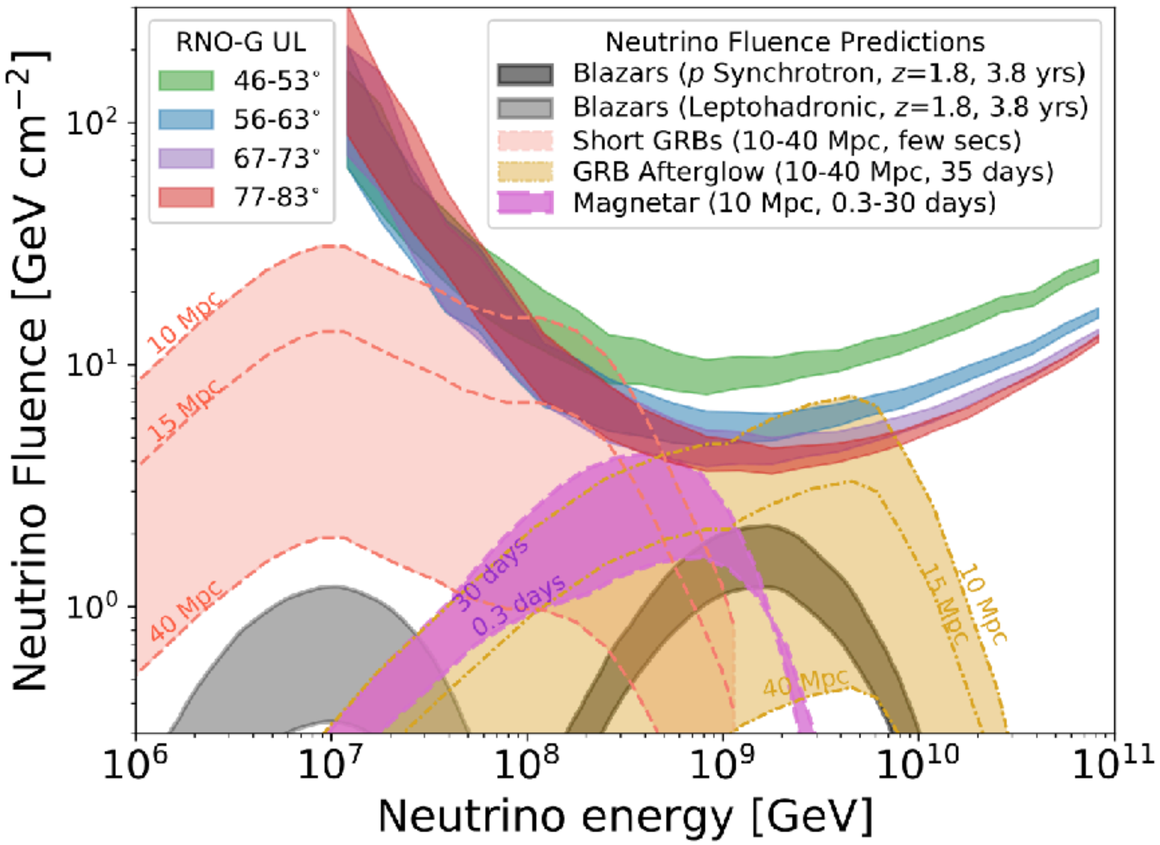


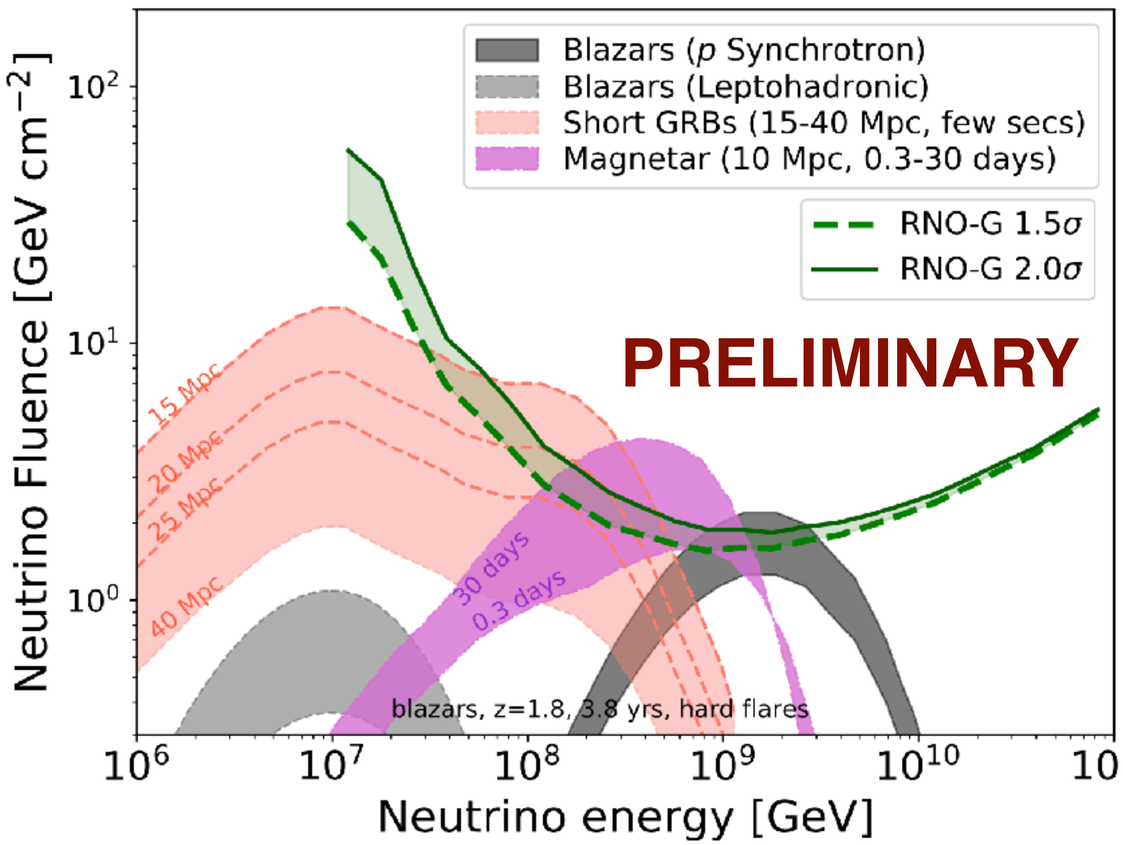
C. Deaconu with LTE coverage at furthest station site (Nerleq), 10 km away



Neutrino Fluence Sensitivity

- Sensitive to nearby and/or bright transient events

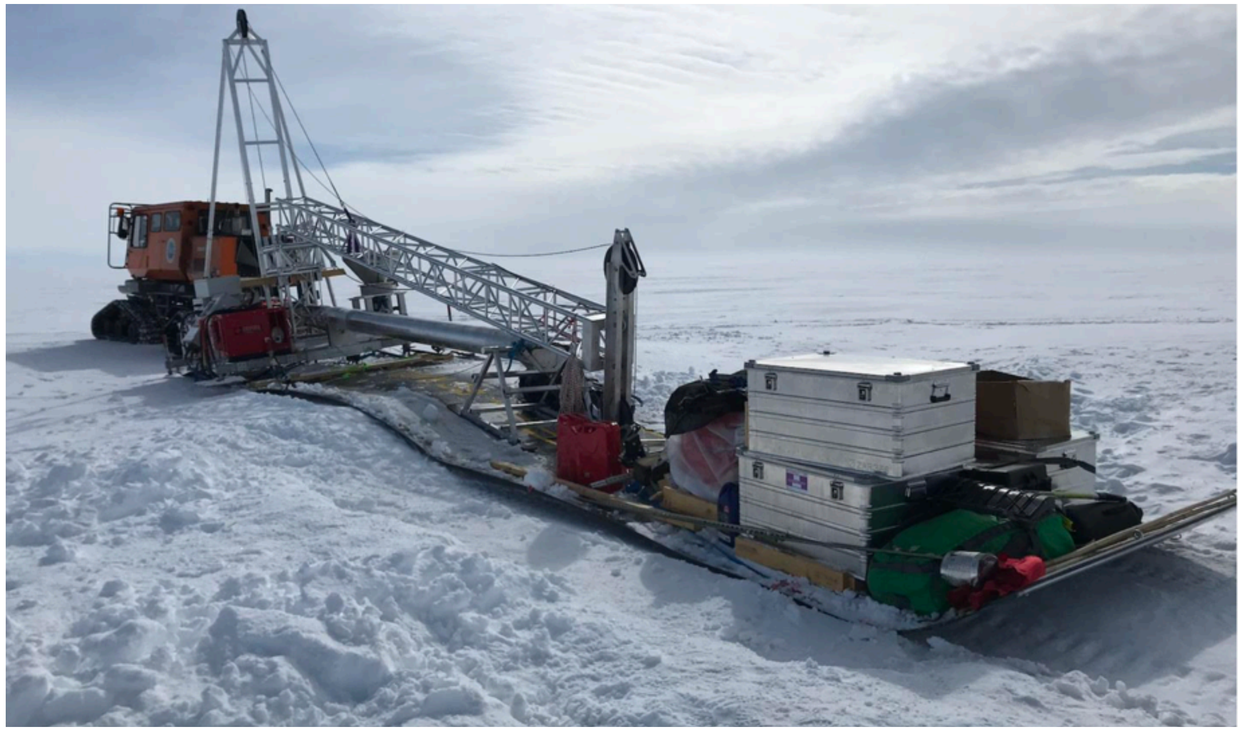


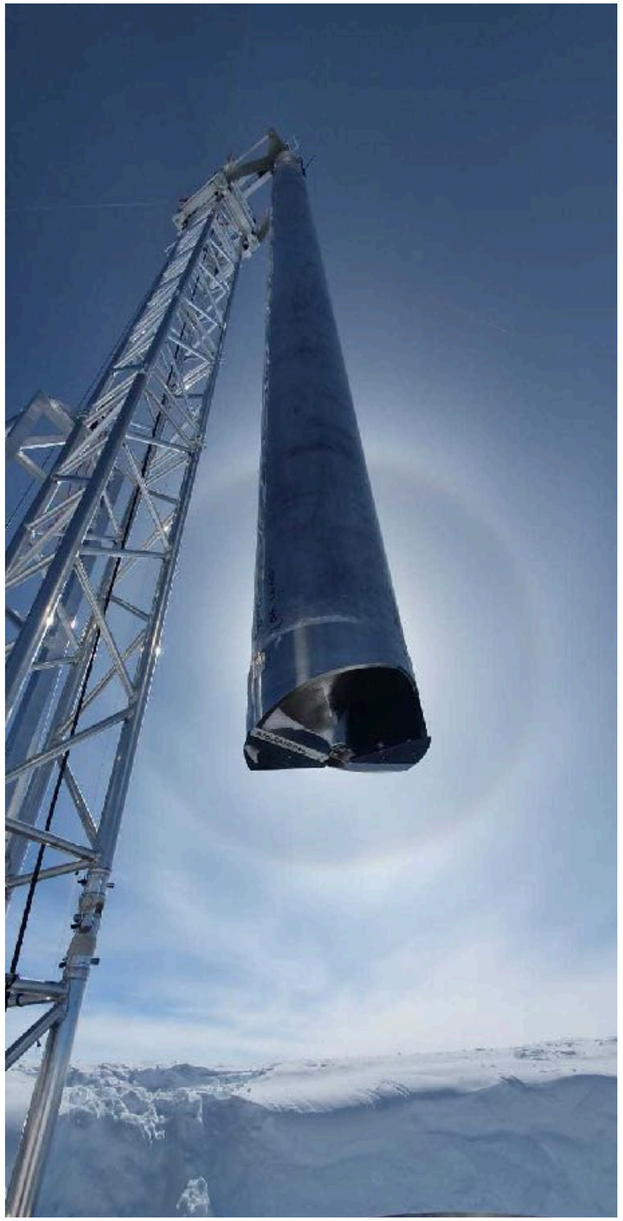


RNO-G Whitepaper arXiv:2010.12279

RNO-G Drill

- **BAS BigRAID Drill**
  Custom auger drill developed for RNO-G by the British Antarctic Survey
- 11-inch diameter holes
- Most holes drilled this season are 2 shifts / hole



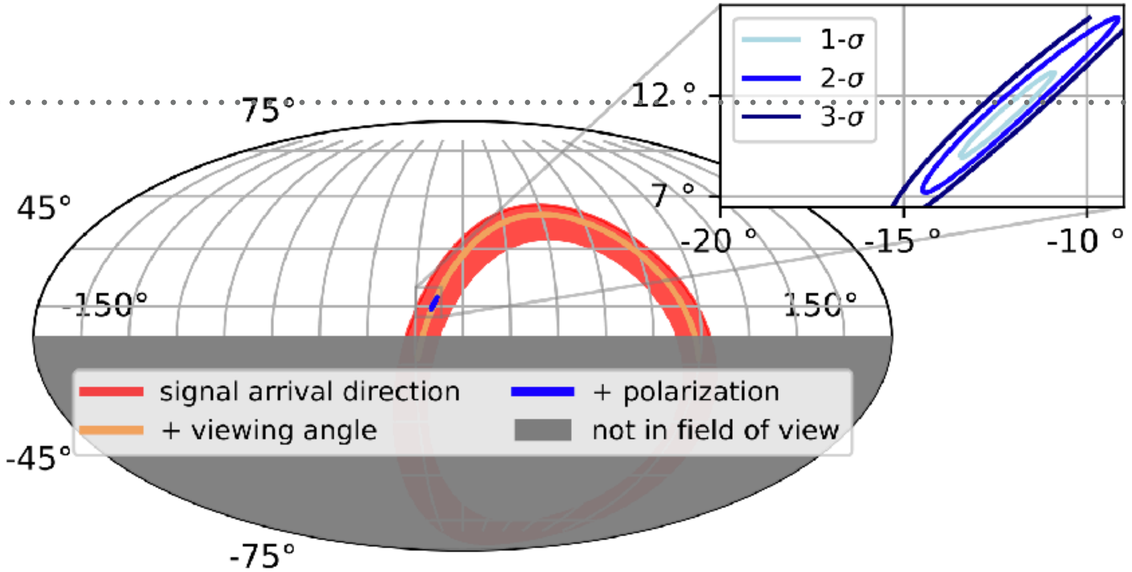


ANTENNAS

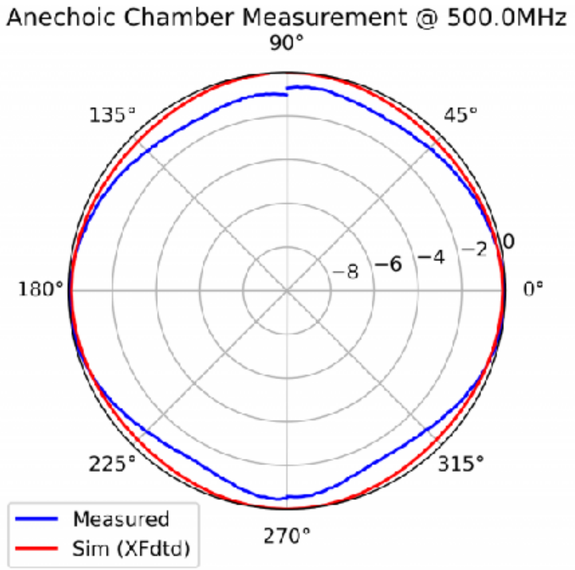
	Downhole Vpol	Downhole Hpol	Surface
Antenna type	Fat Dipole	Slotted antenna (no ferrites)	Log periodic dipole antenna
Design stage	Updated design based on RICE, GNO dipoles to make lower cost & easier to manufacture	**Under R&D at PSU**. Without ferrites expect antennas to be lightweight, easier to model and manufacture	Commercial off-the-shelf
Cost per antenna	$300-400	$300-400	$1000

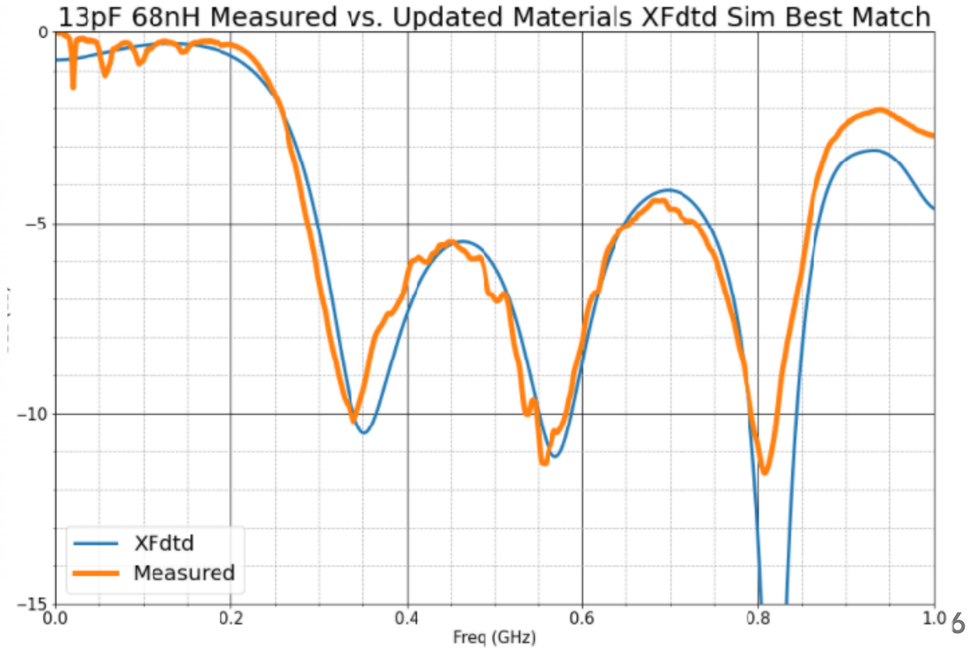
Horizontally Polarized Antennas

- Hpol antennas are particularly important for reconstructing polarization
- Challenging to design a horizontally polarized antenna that fits down a narrow borehole
- Also exploring novel antenna designs (Alford Loop, Box antennas)

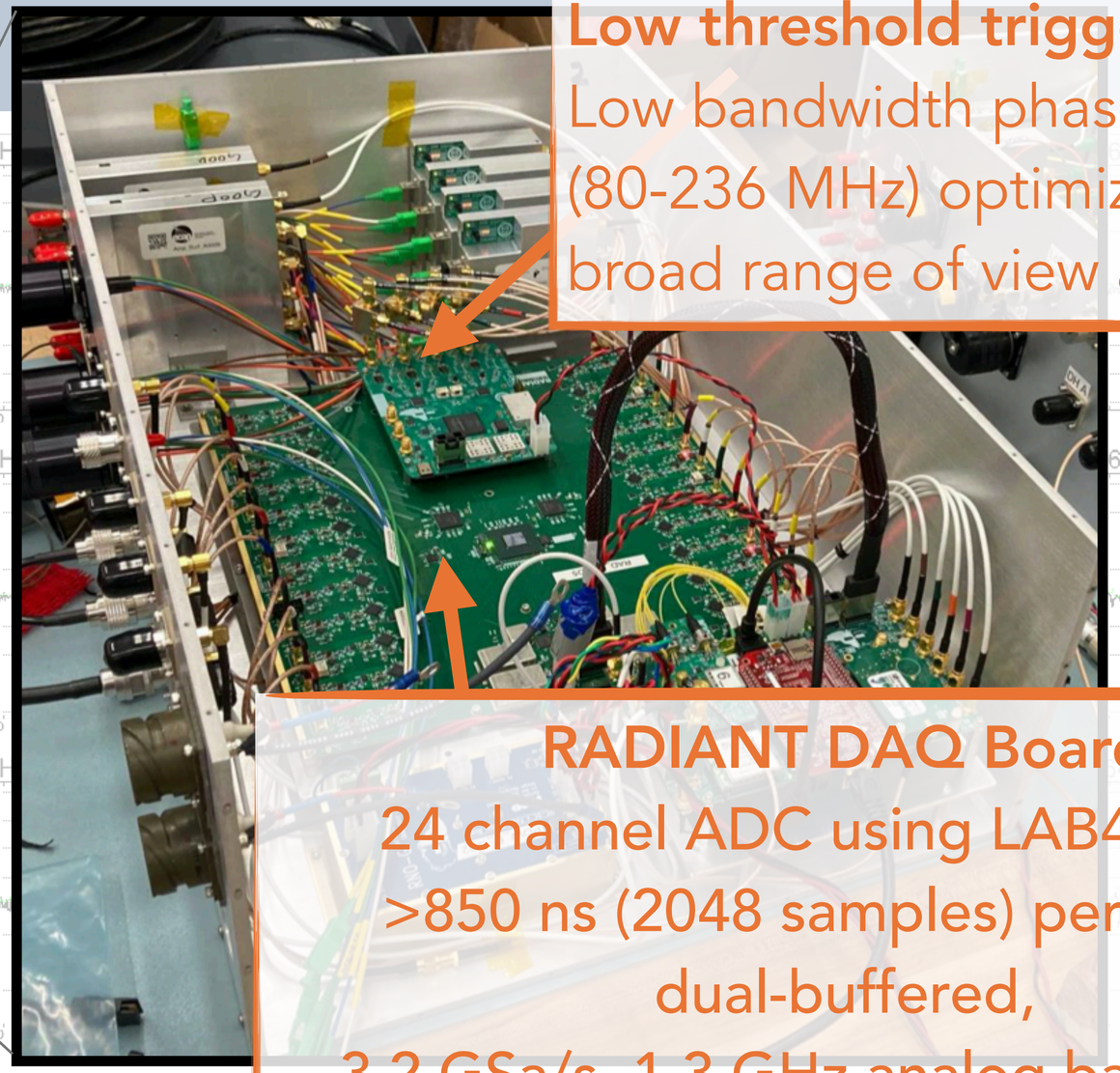


Hpols match Sims within 12% in voltage





First Deep Events - Hardware



Low threshold trigger board

Low bandwidth phased trigger (80-236 MHz) optimized for broad range of view angles

RADIANT DAQ Board

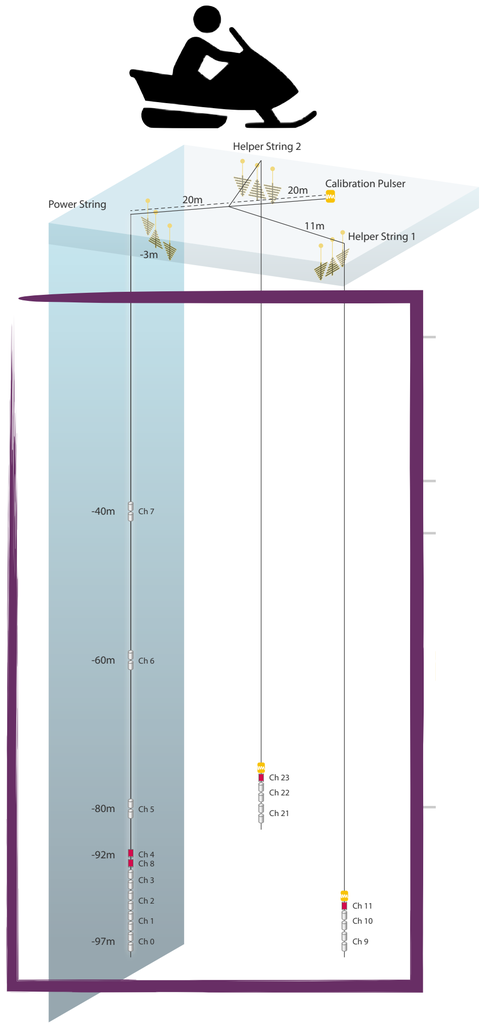
24 channel ADC using LAB4D SCA

>850 ns (2048 samples) per event, dual-buffered,

3.2 GSa/s, 1.3 GHz analog bandwidth

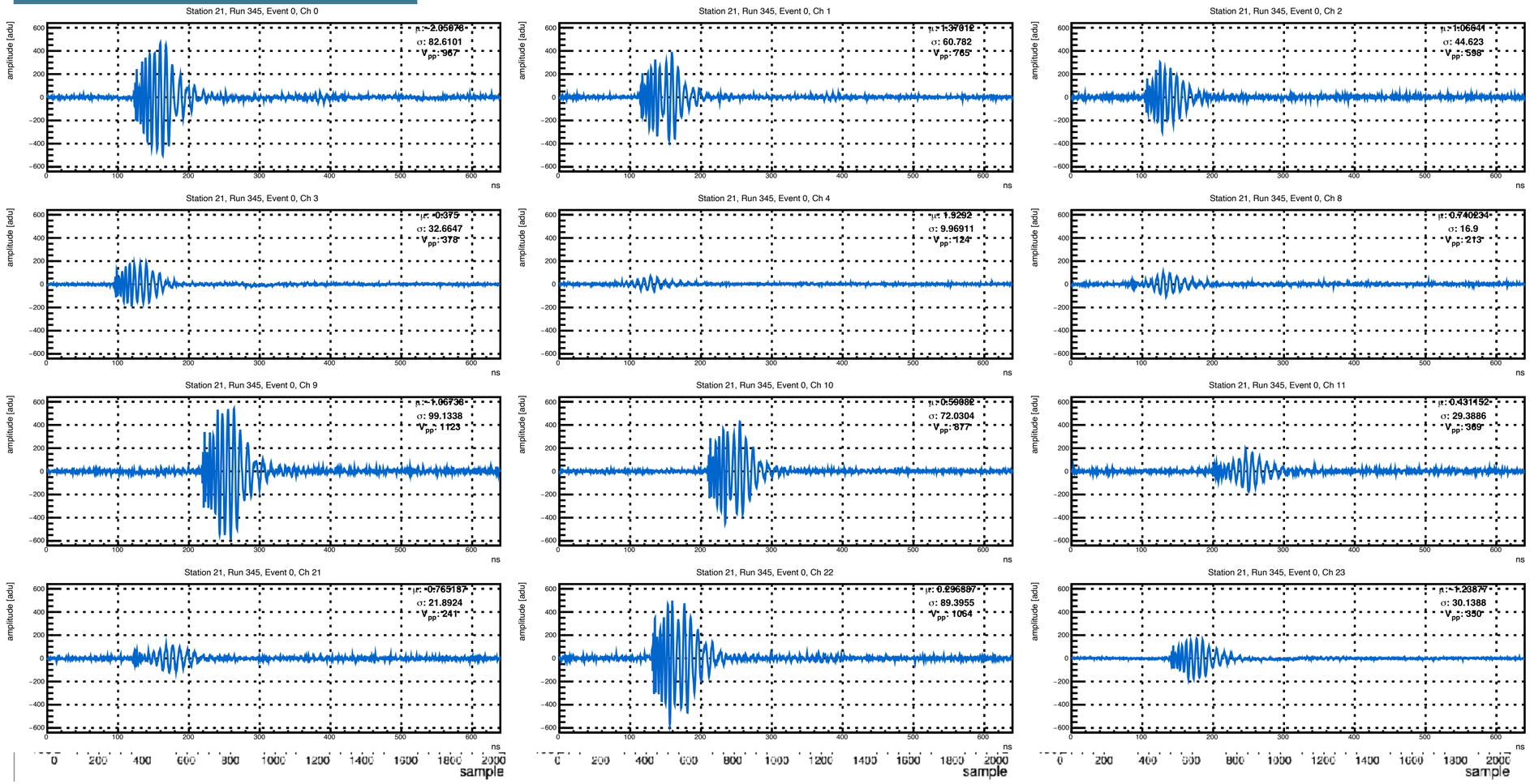
Low power envelope trigger

First Deep Events



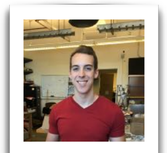
Snowmobile lights up the deep channels

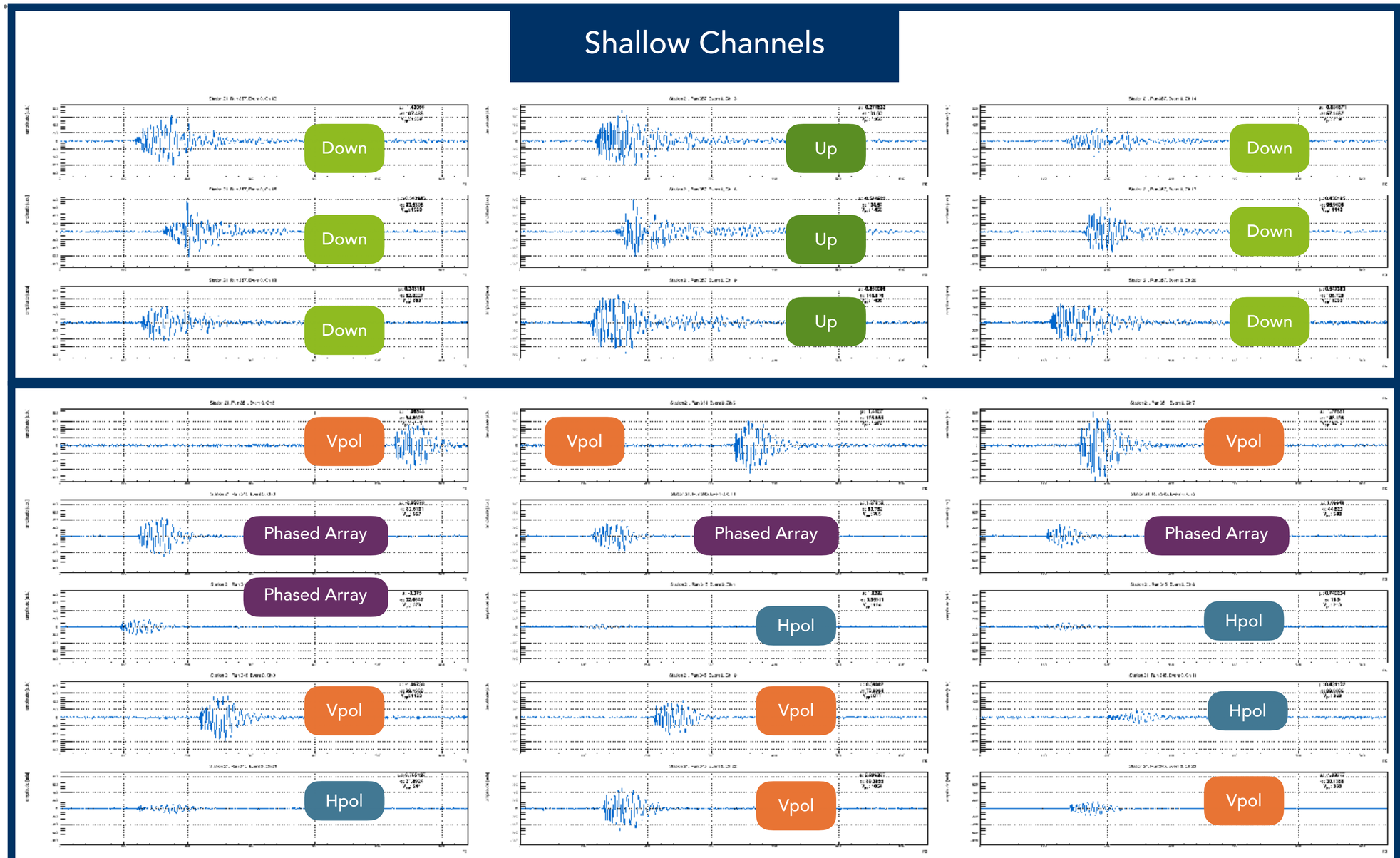
Deep Vpol Channels



Bermtop Calibration Pulsing

Increasing depth





Stations are designed for **scalability**

- Low Power ~ 25 W / station
- Autonomous:
  - Solar power ~ expect 60-70% uptime
  - LTE / LoRaWAN communications
- Plan to use wind turbines in later seasons to extend livetime

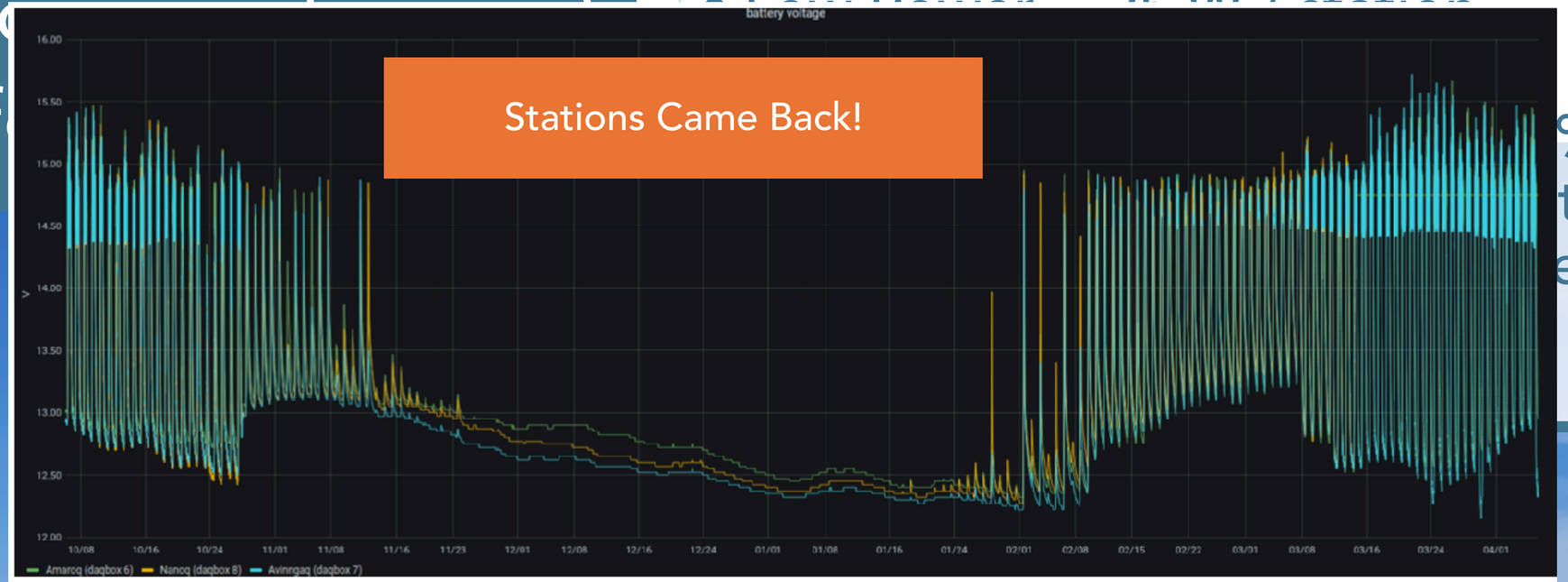
Stati

f

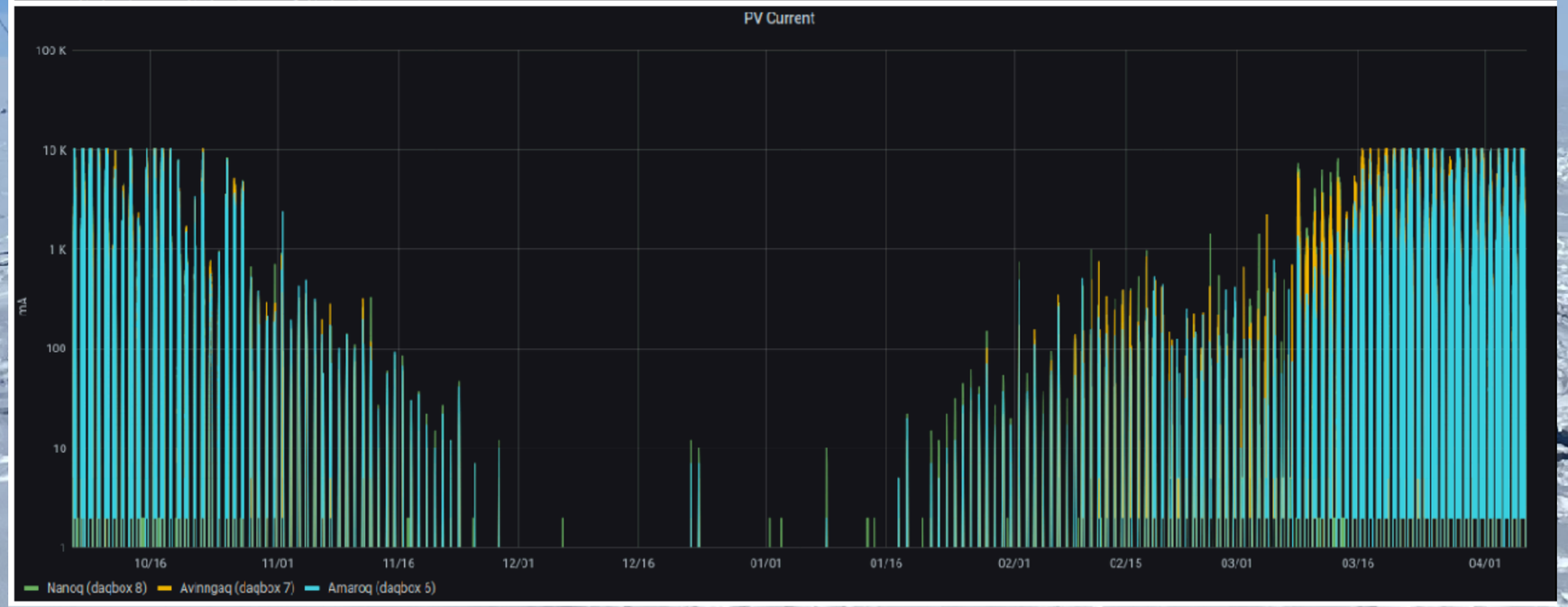
% uptime

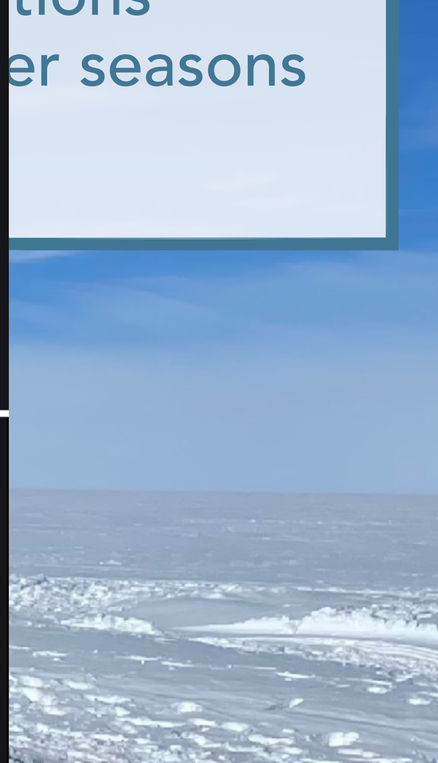
tions

er seasons

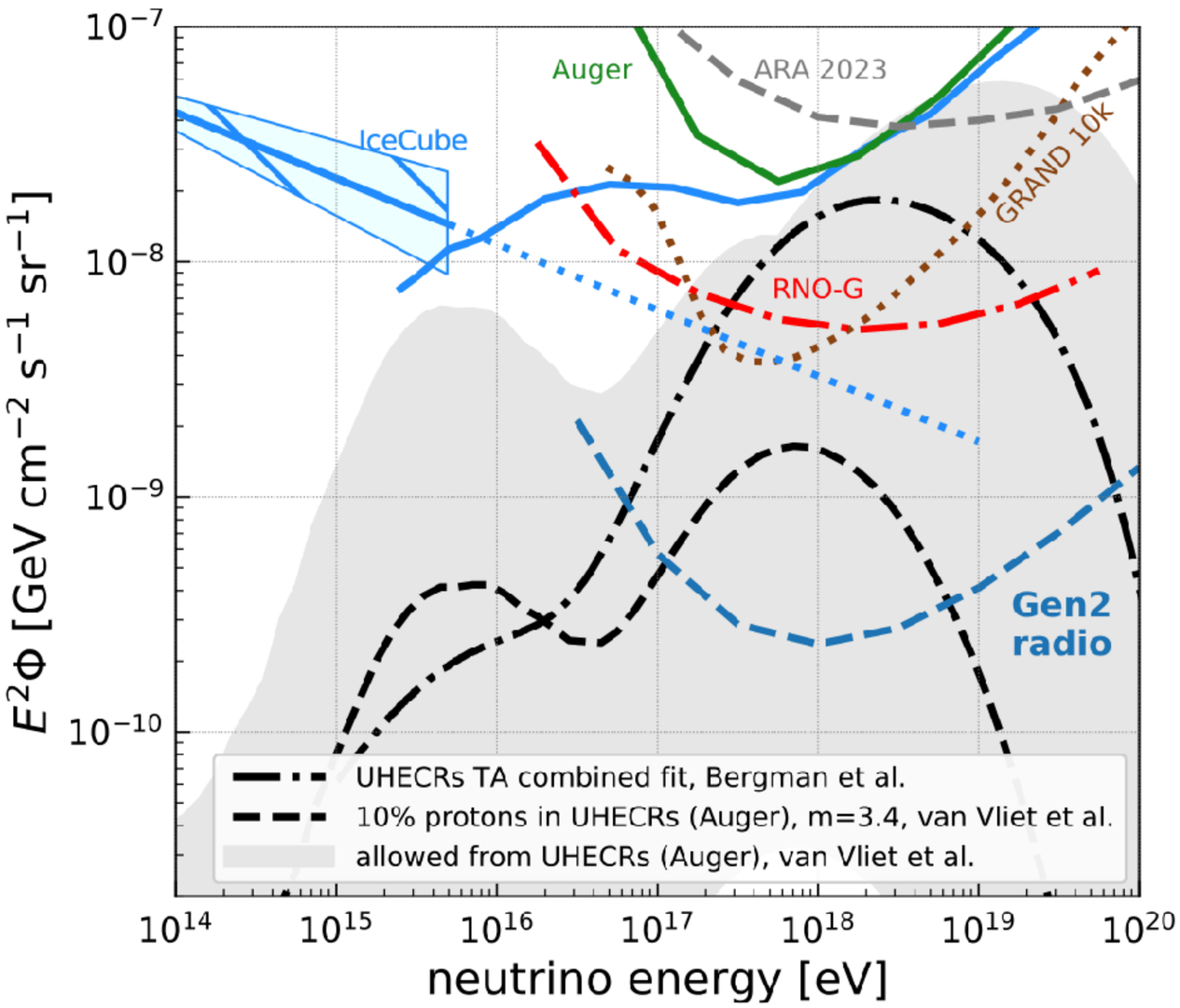


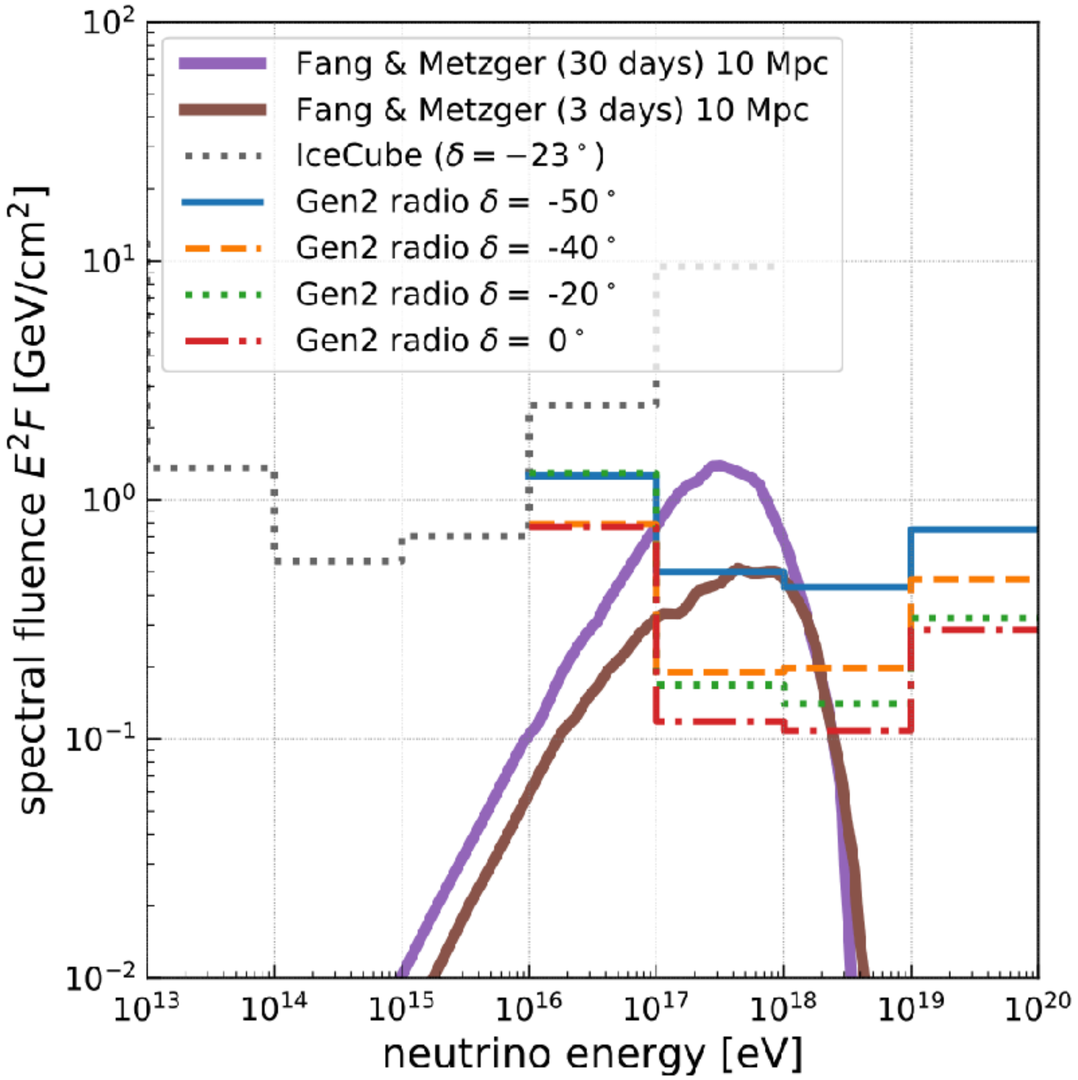
Stations Came Back!

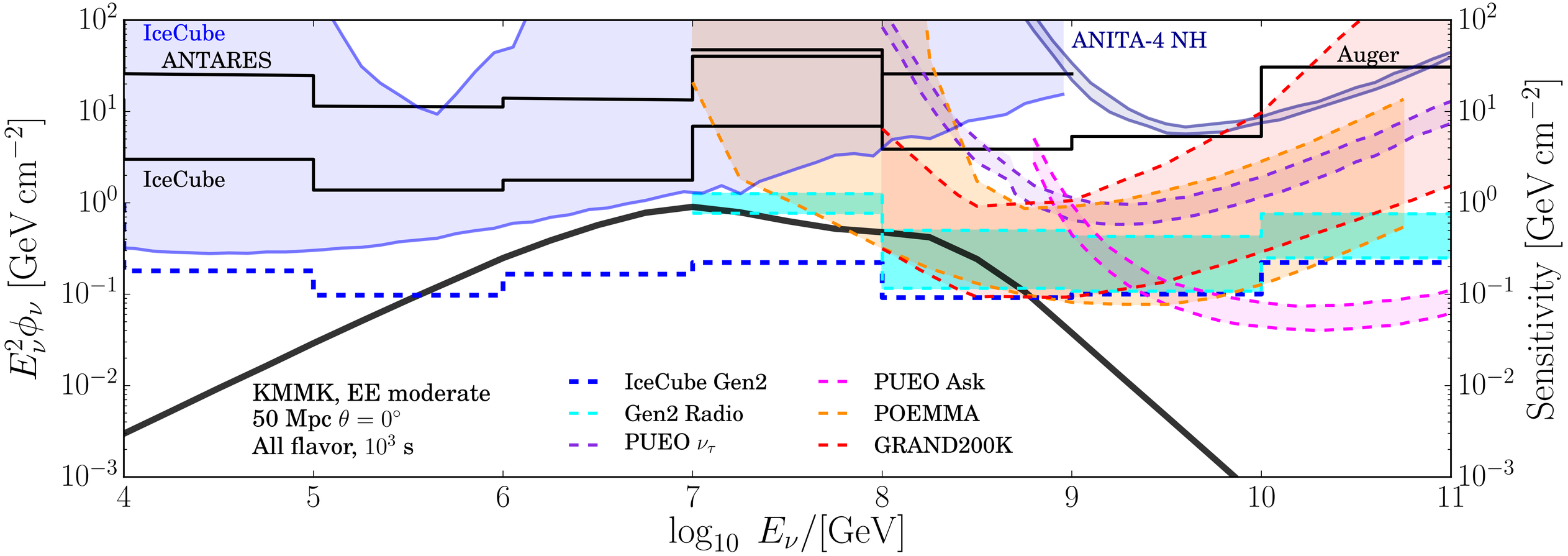




Radio Array Sensitivity Studies





Steffen Hallman for Gen2 ICRC 2021 395, 1183

Targeting Bursts of Neutrinos