

Towards IceCube-Gen2

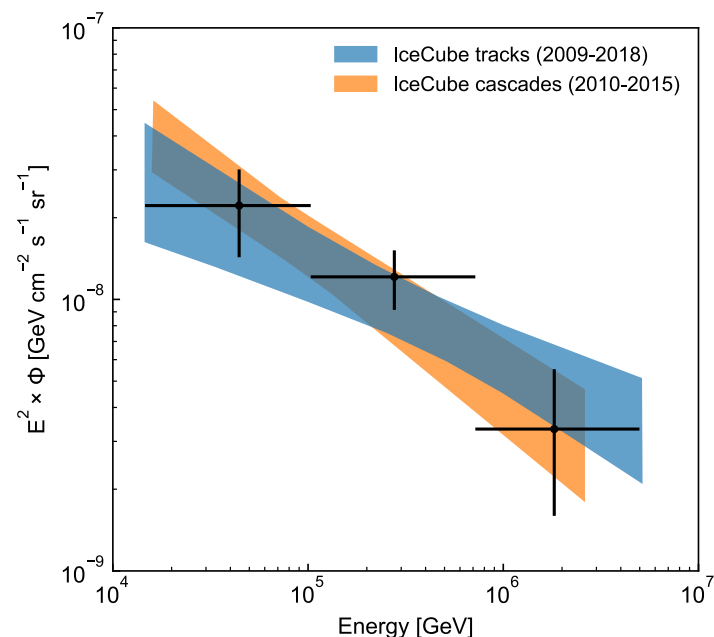
Plans for the in-ice radio array

Anna Nelles for the IceCube-Gen2 Collaboration

Building on the success of IceCube

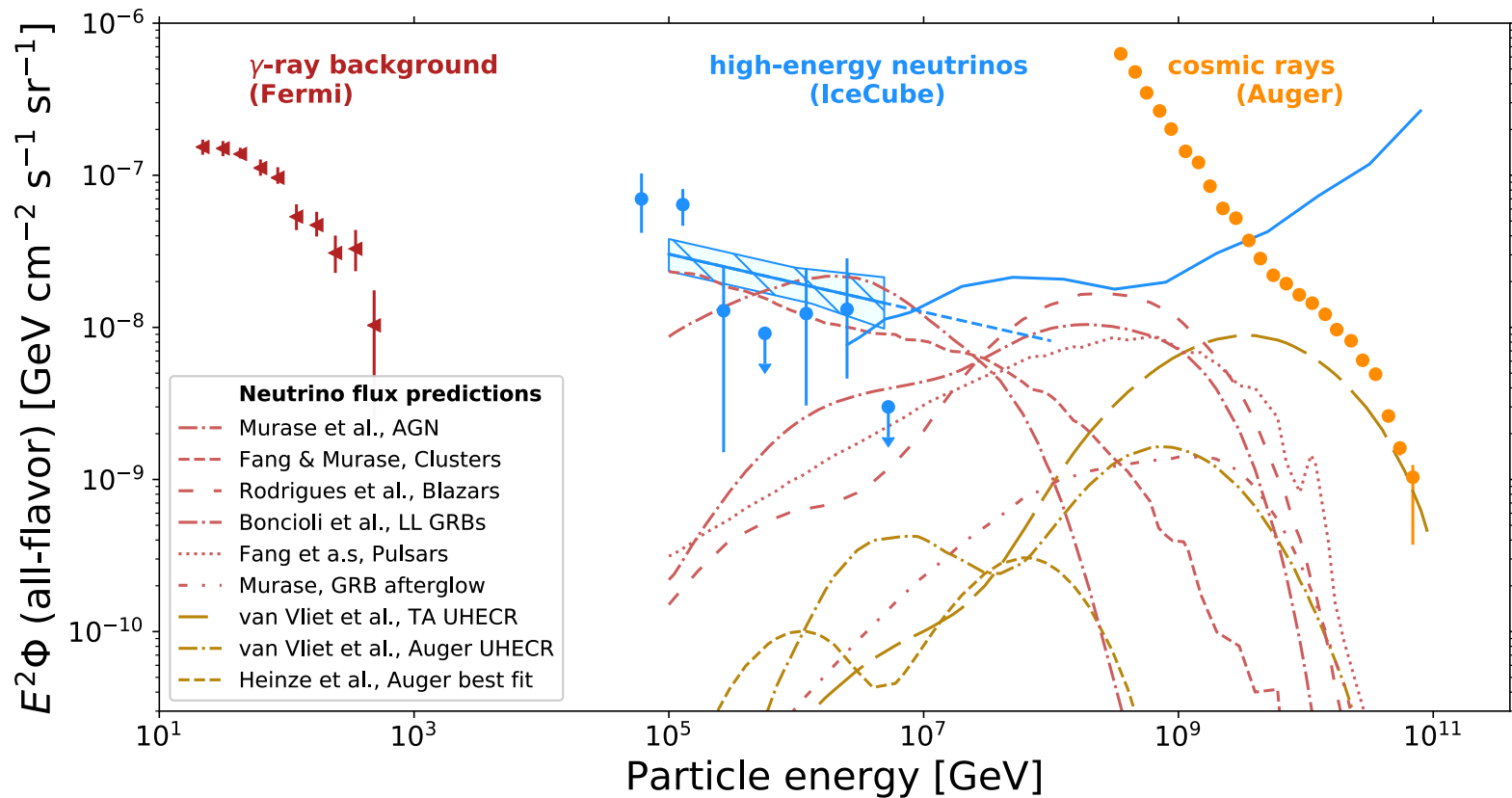
Where is neutrino astronomy at?

- IceCube has discovered astrophysical neutrinos up to at least 10 PeV
- Astrophysical flux is clearly established
- First hints of sources e.g. TXS 0506+056 and other compelling correlations
- Still open questions:
 - **What are the sources of high-energy neutrinos detected by IceCube?**
 - **How are the particles accelerated?**
 - **How do the highest energy particles propagate in the in the Milky Way and beyond?**
 - **Is there new physics in these highest energy particles?**



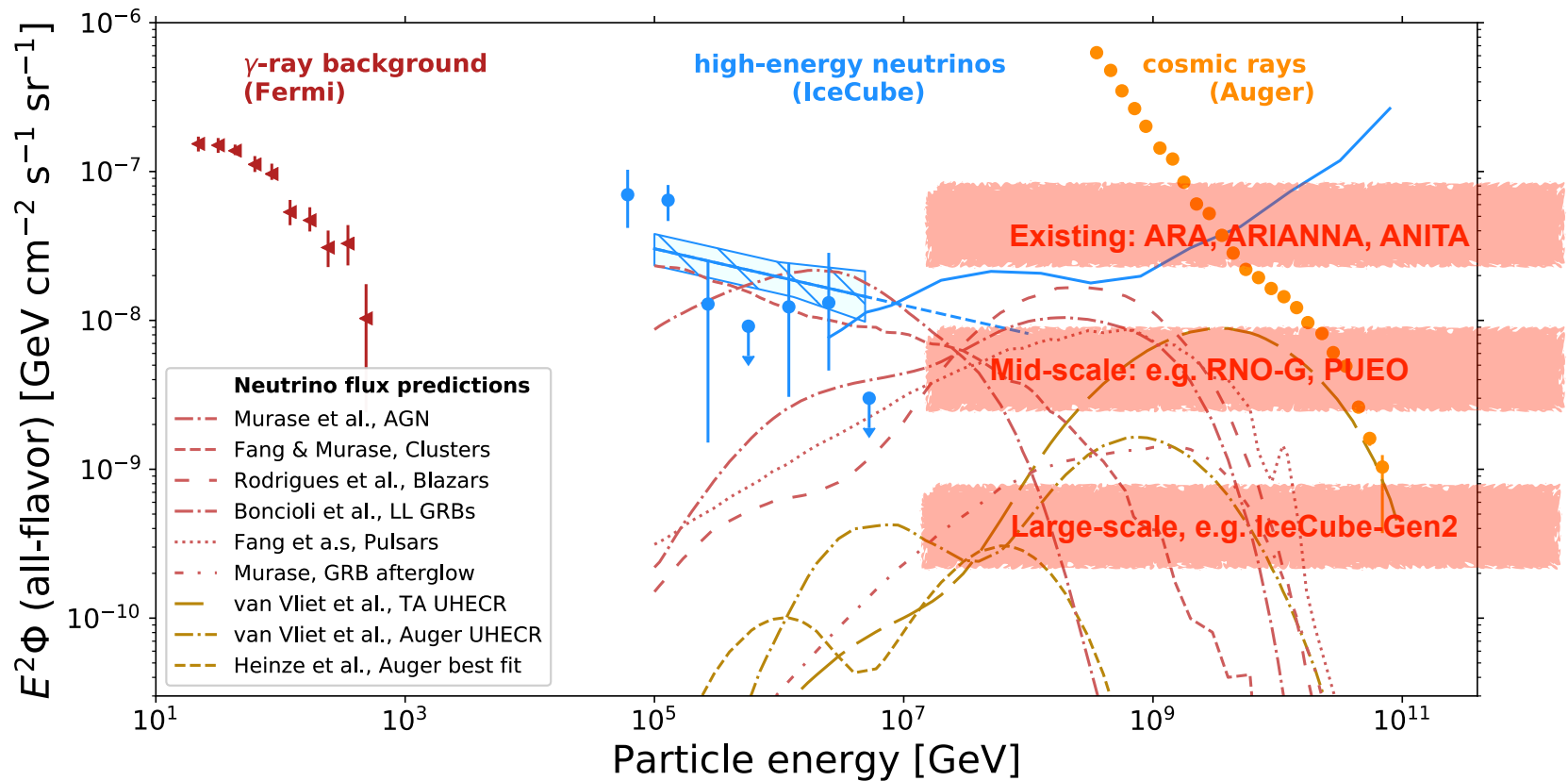
Scientific motivation for the highest energies

The landscape



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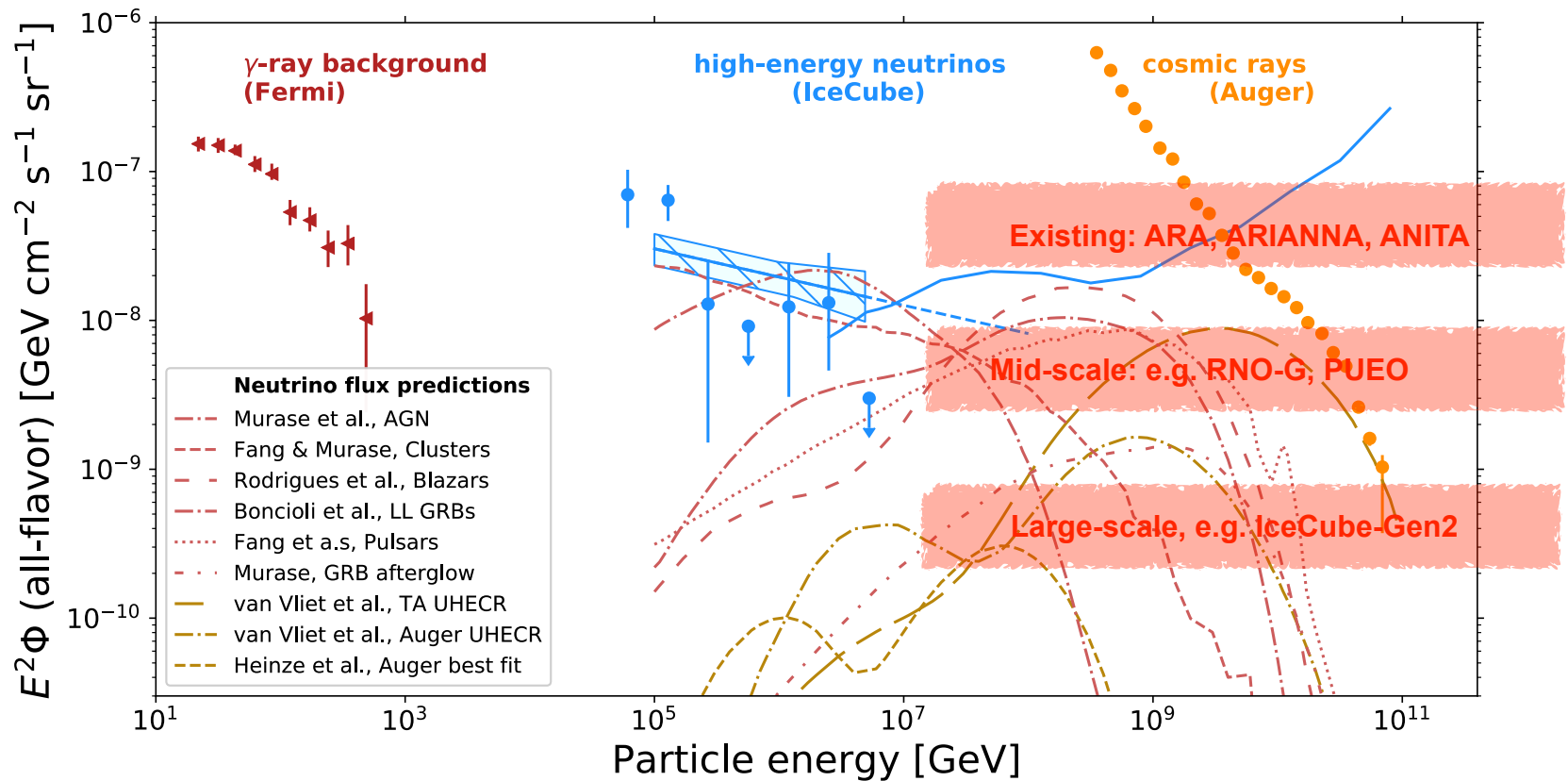
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Scientific motivation for the highest energies

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IceCube-Gen2 target: $O(1600)$ km³ at 1 EeV



Boundary conditions

Options, options, options

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- **Balloon-borne:**
 - ANITA: comparatively high energy threshold, but large exposure during a short amount of time.
 - lower threshold: PUEO (see talk from Tuesday)

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 - Any (large) experiment sensitive to horizontal air showers can target tau neutrinos, strong limits from Auger (and expected from AugerPrime)
 - Various proposals for dedicated arrays with various technologies: GRAND, BEACON (see talks from Wednesday), POEMMA, TRINITY, ...

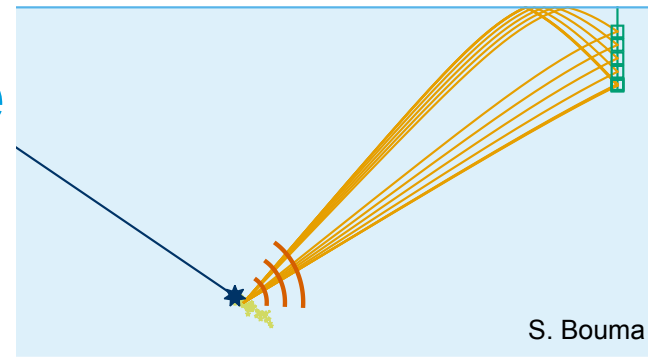
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- **In-ice Arrays** (see many talks from Tuesday):
 - Sensitive to all flavors. Optical technology only technology that has detected $> \text{PeV}$ neutrinos. However expansion to higher energies prohibitively costly.
 - Large scale in-ice radio implementation seems feasible: **IceCube-Gen2**

Experimental strategies: in-ice

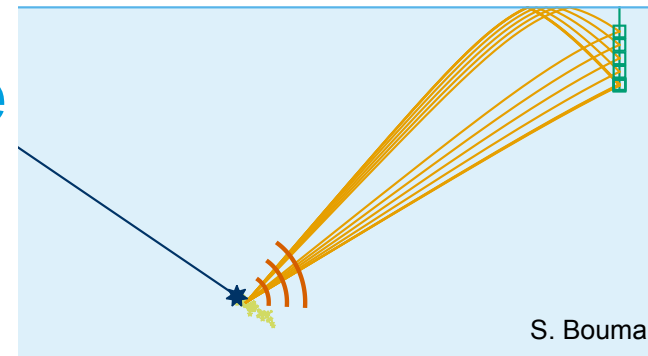
Different approaches in the past



Experimental strategies: in-ice

Different approaches in the past

Deep antennas vs. shallow antennas

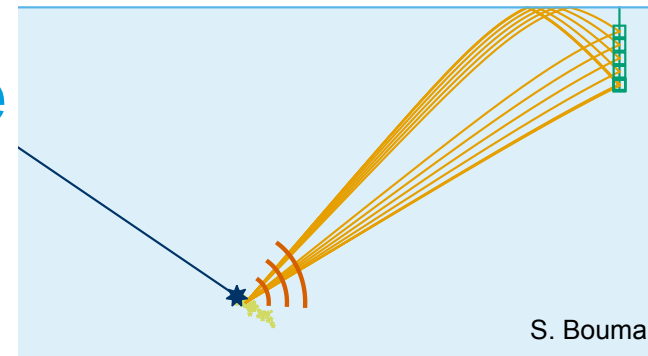


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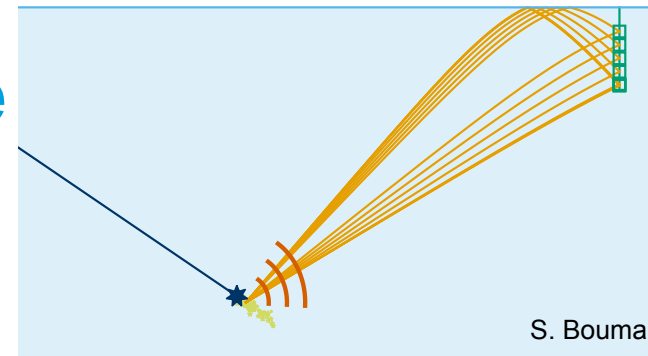


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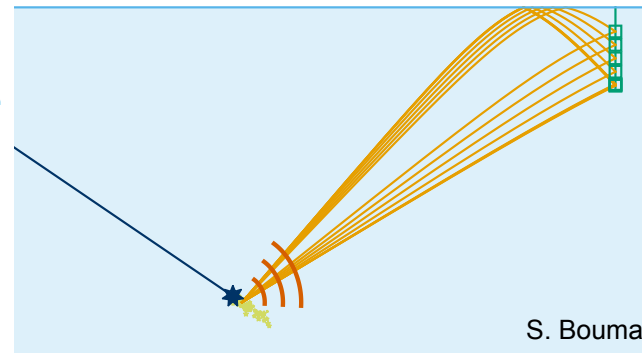


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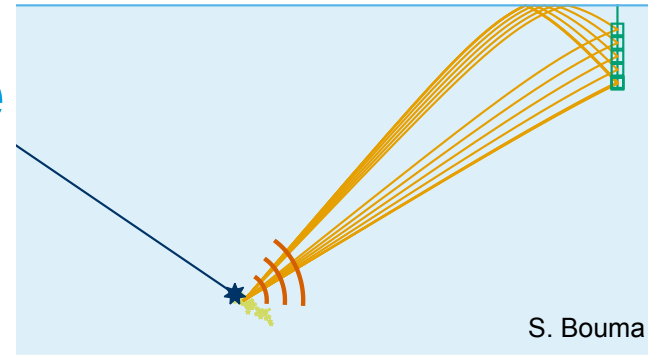
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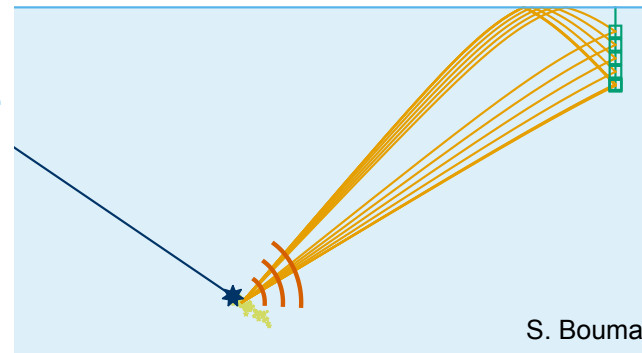


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- **Within (currently large) uncertainties there is a similar sensitivity / cost ratio for both types of approaches.**
- **Strategy for complete array:** Mitigate risks for such a large scale detector (both in installation and different detection mechanisms) and use complimentary advantages: combine deep antennas with shallow antennas.

Coming to a reference design for IceCube-Gen2

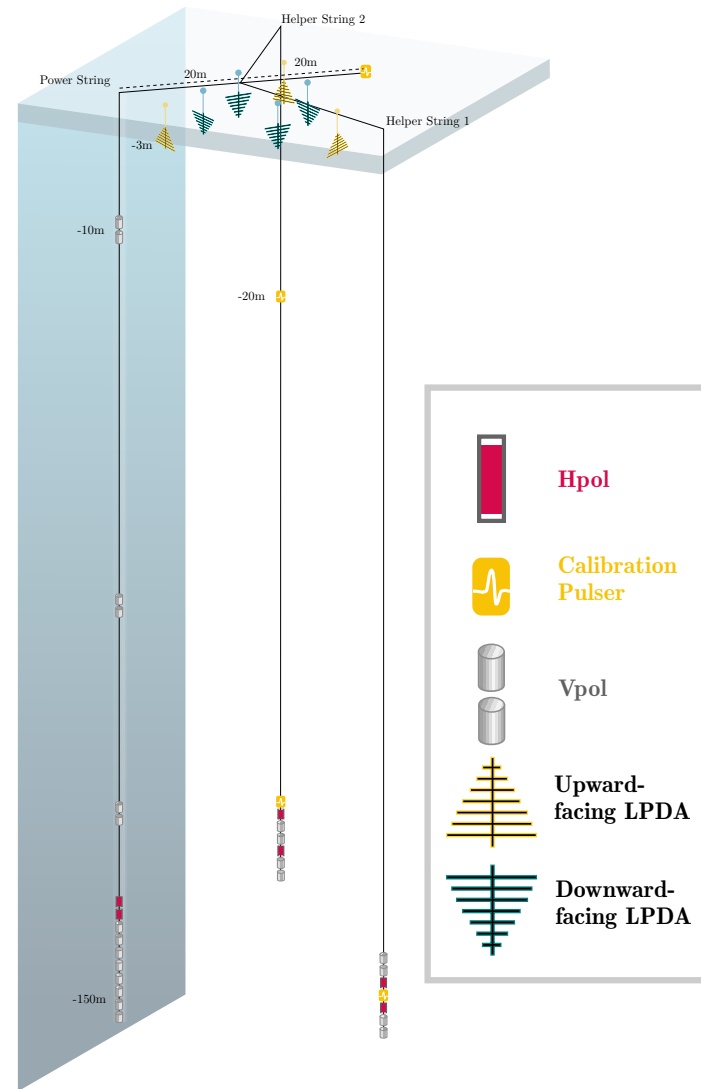
Rationale for radio stations

- Chose combination of shallow stations and hybrid stations
 - 150 meter depth: larger firn at South Pole (= useful to go deeper than RNO-G)
 - Revised shallow antenna positions as compared to RNO-G & ARIANNA
 - Additional calibration pulsers

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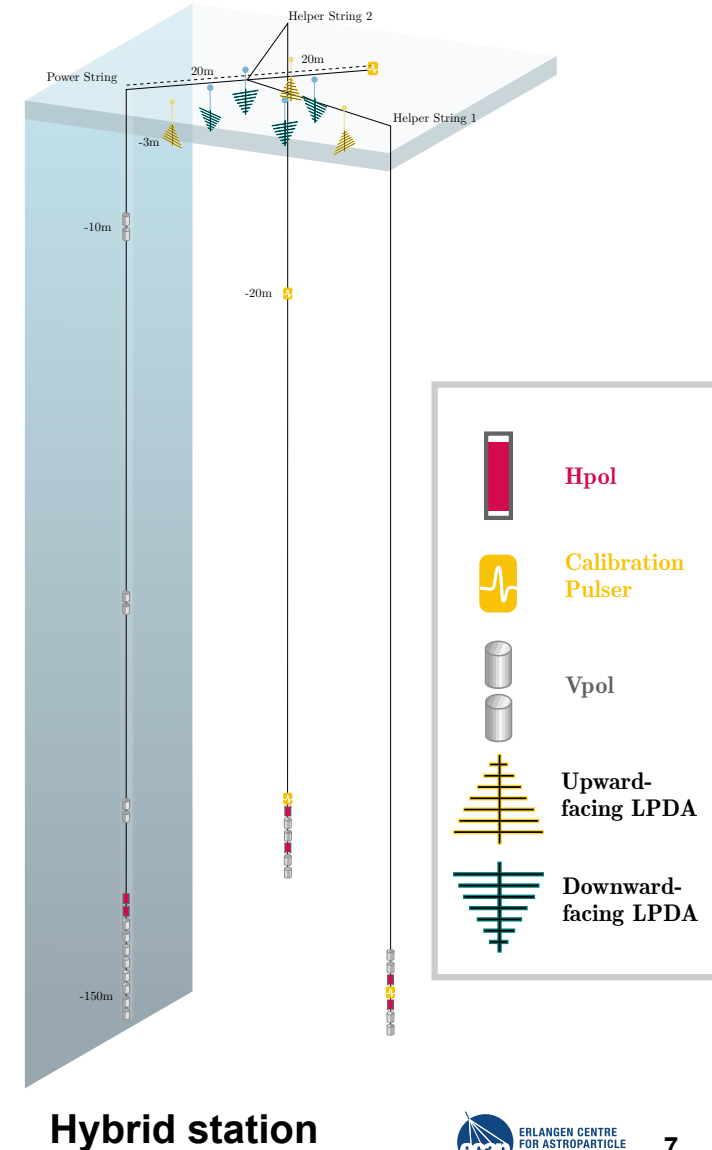
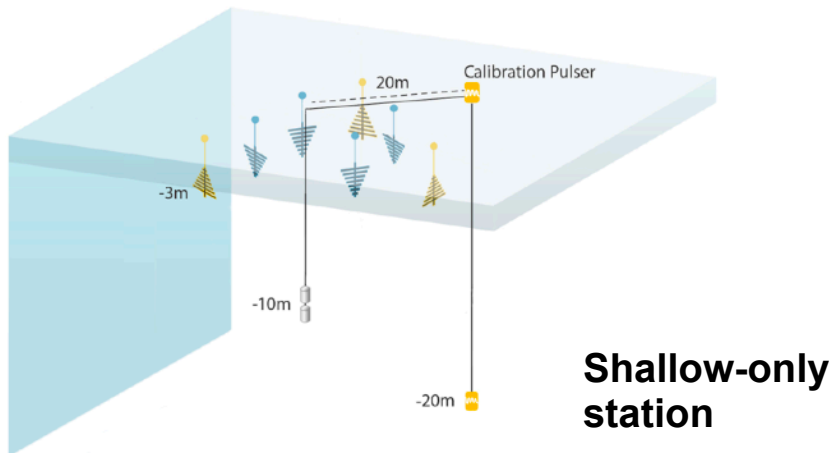
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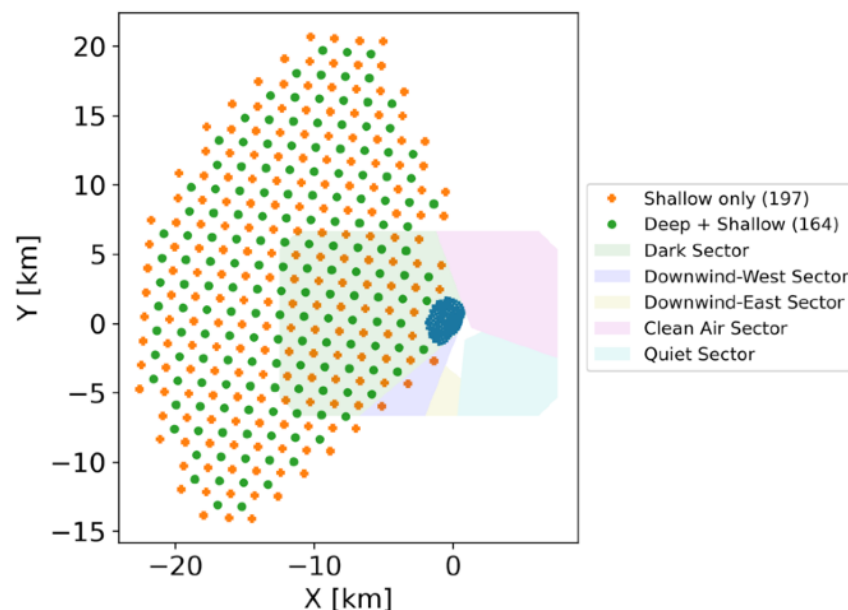
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Rationale for radio array

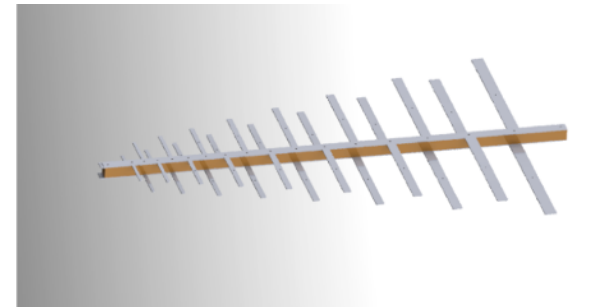
- Spacing is defined by a desired ratio of 10% coincidences at EeV energies
- Depth of 150m + South Pole attenuation length = larger spacing of hybrid-array (RNO-G: 1.25 km \rightarrow 1.75 km at South Pole)
- Natural spacing of shallow-only stations smaller
- Thus, array of hybrid stations can be interspersed with shallow-only stations
 - No loss of combined effective volume
 - Better air shower detection capabilities with smaller array spacing
 - Compact array advantageous for installation
 - Cross-check of systematics



A couple of technical details

It is taking shape what we want to build

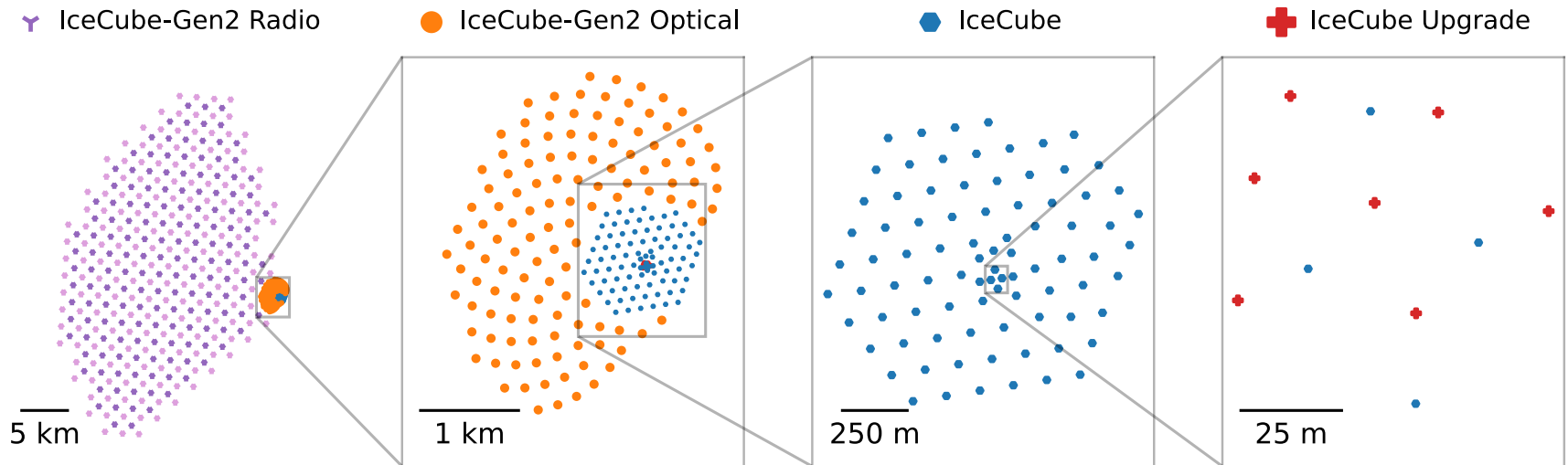
- Building on experience of ARIANNA and ARA
- Reference technology will lean heavily on RNO-G
 - Same drill(ing technology)
 - Next generation of the same electronics, amplifiers, Vpol antennas, RF over fibre, phased array trigger, ...
- RNO-G site may be used to test elements that are made dedicatedly for IceCube-Gen2
 - Likely mass production LPDAs (stream-line costs and construction time)
 - Possibly dedicated ASIC (under development at U Chicago)
- Infrastructure will be different, current plan A: Cabled power and communications



The process, where are we?

IceCube-Gen2: An idea, but work in progress

- IceCube-Gen2 is envisioned as combination of **extension of optical array**, **surface air shower array** and **in-ice radio neutrino array**
- Project costs similar to IceCube, radio array 10% of total costs
- Technical Design Report in progress
- First milestone: favorably reviewed in Astro 2020 US Decadal Survey

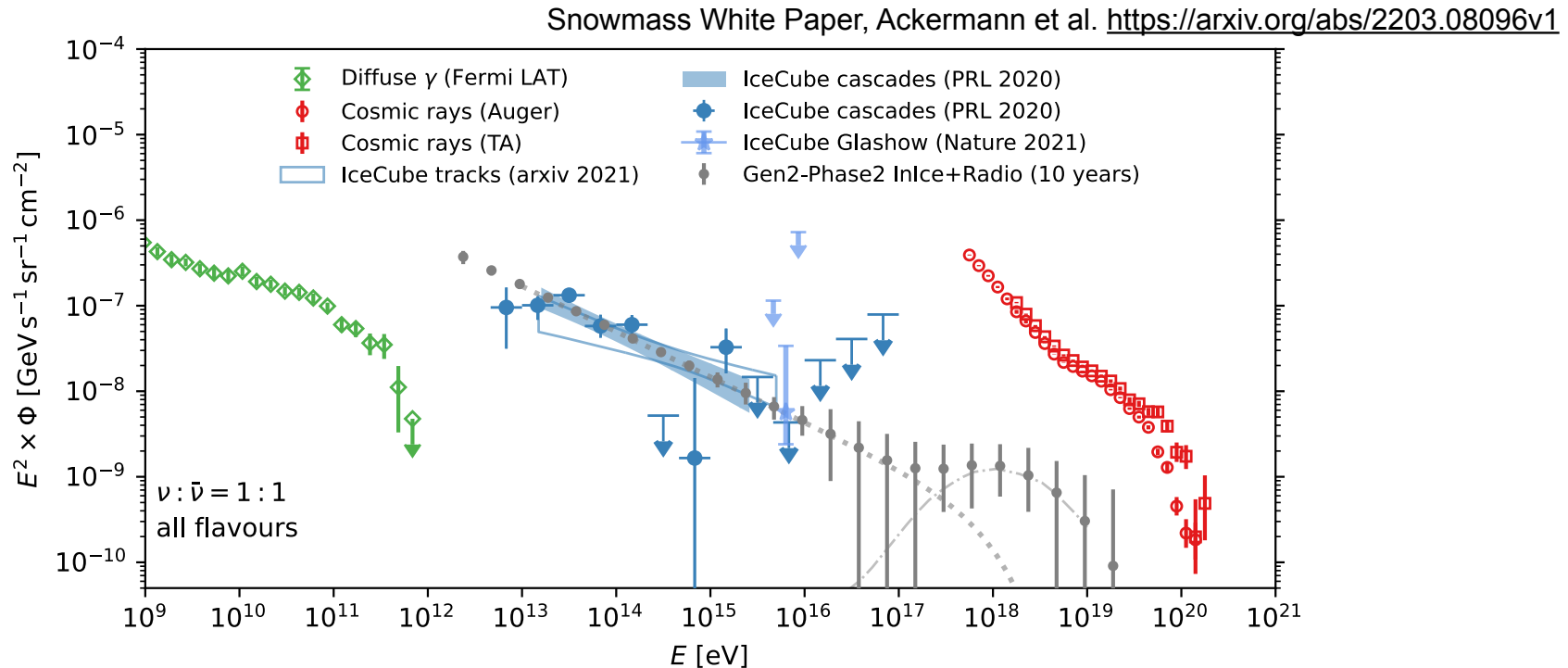


Radio detection of neutrinos

IceCube-Gen2

“IceCube-Gen2 will play an essential role in shaping the new era of multi-messenger astronomy, fundamentally advancing our knowledge of the high-energy universe.”

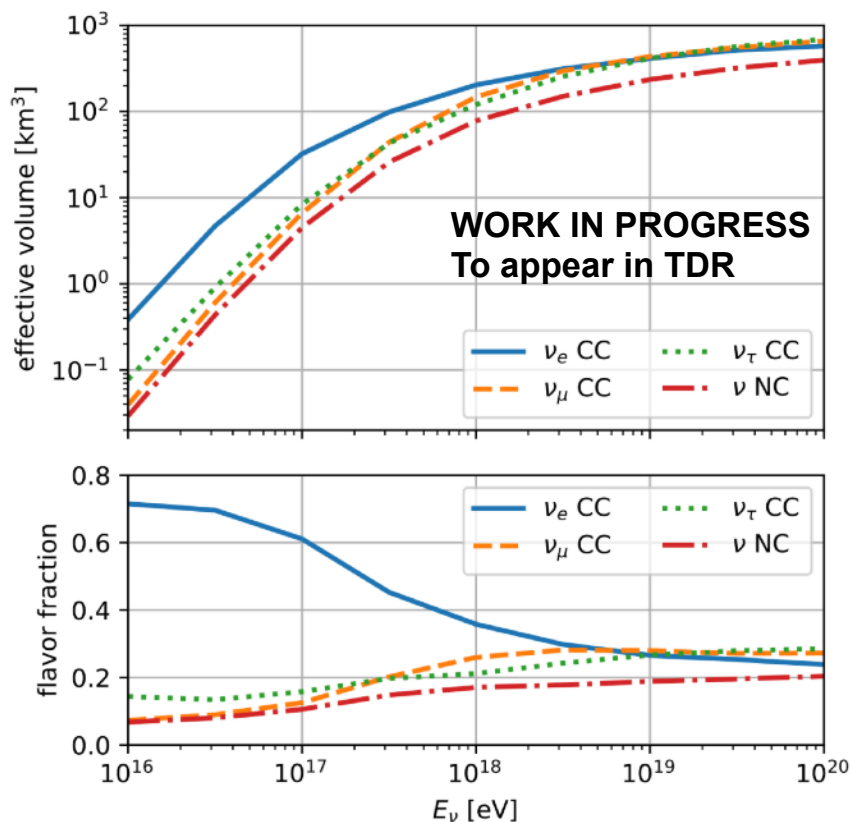
IceCube-Gen2: The Window to the Extreme Universe ,
<https://arxiv.org/abs/2008.04323>, *J.Phys.G* 48 (2021) 6, 060501



Performance of the radio array of IceCube-Gen2

Still learning based on RNO-G, ARA and ARIANNA

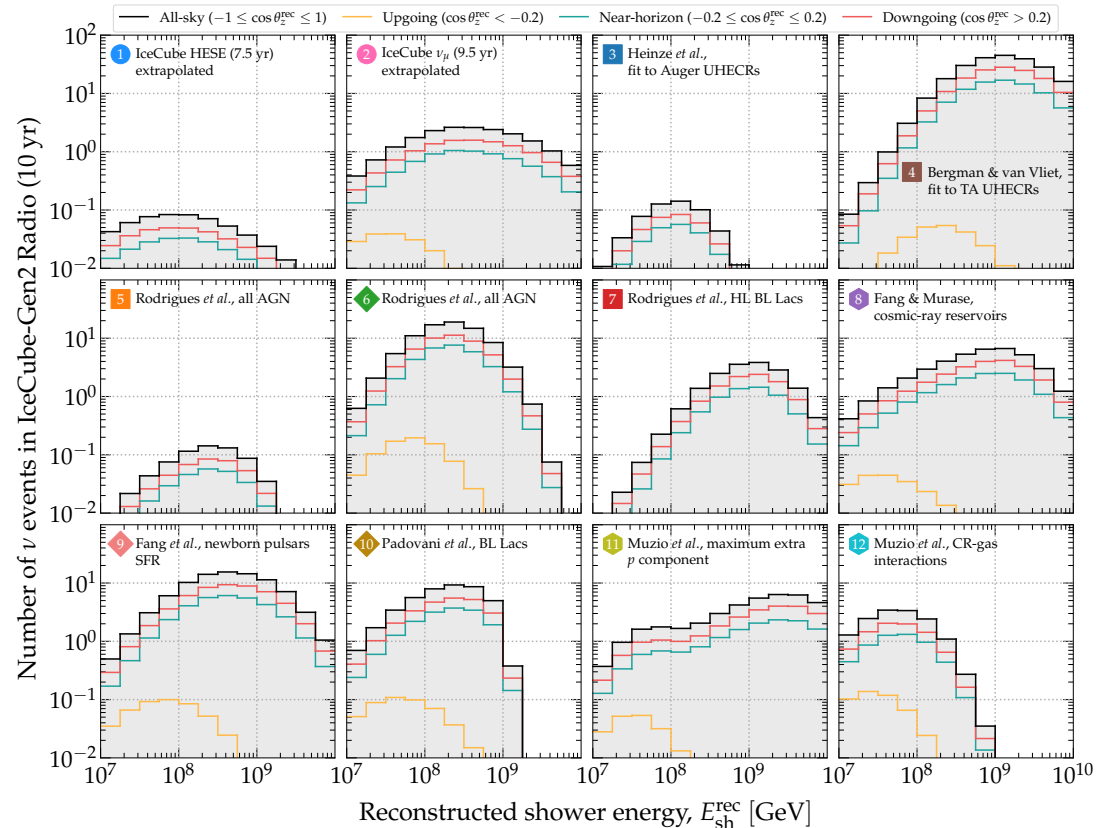
- In-ice radio detection is sensitive to all flavors
- The expected ratio of flavor sensitivity is energy dependent
 - LPM suppression of detectable EM showers
 - Increasing probability of stochastical energy losses of muons and taus
- Effective area close to threshold very dependent on ice properties and exact detector configuration and trigger settings



Performance of the radio array of IceCube-Gen2

Still learning based on RNO-G, ARA and ARIANNA

- Neutrino flux predictions at $> \text{PeV}$ energies are all over the map
- Ranging from less than 1 neutrino to several 100 neutrinos in 10 years
- Array has to be designed for worst-case scenario (priority on effective volume), but also better scenarios (excellent reconstruction capabilities)

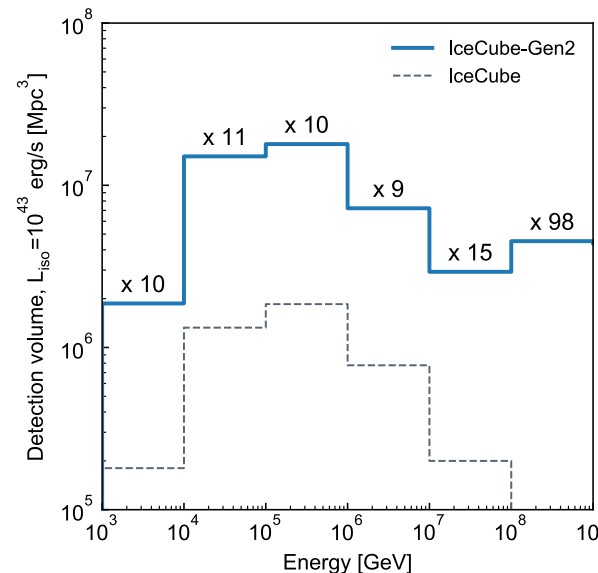
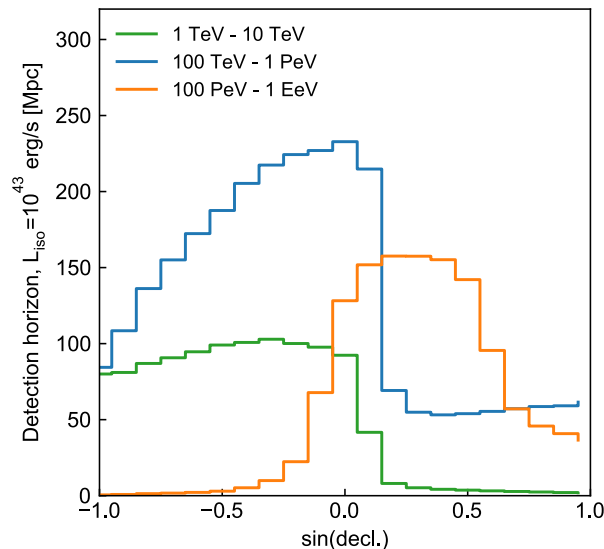


M. Bustamante, et al, in prep
Update to appear in TDR

Science with IceCube-Gen2

More to come in the Technical Design Report

- Radio array complements the high energy capabilities of the optical array of IceCube-Gen2, delivers much improved flux detection capabilities at high energies
- Combined analyses will provide full energy spectrum coverage, although different angular coverage

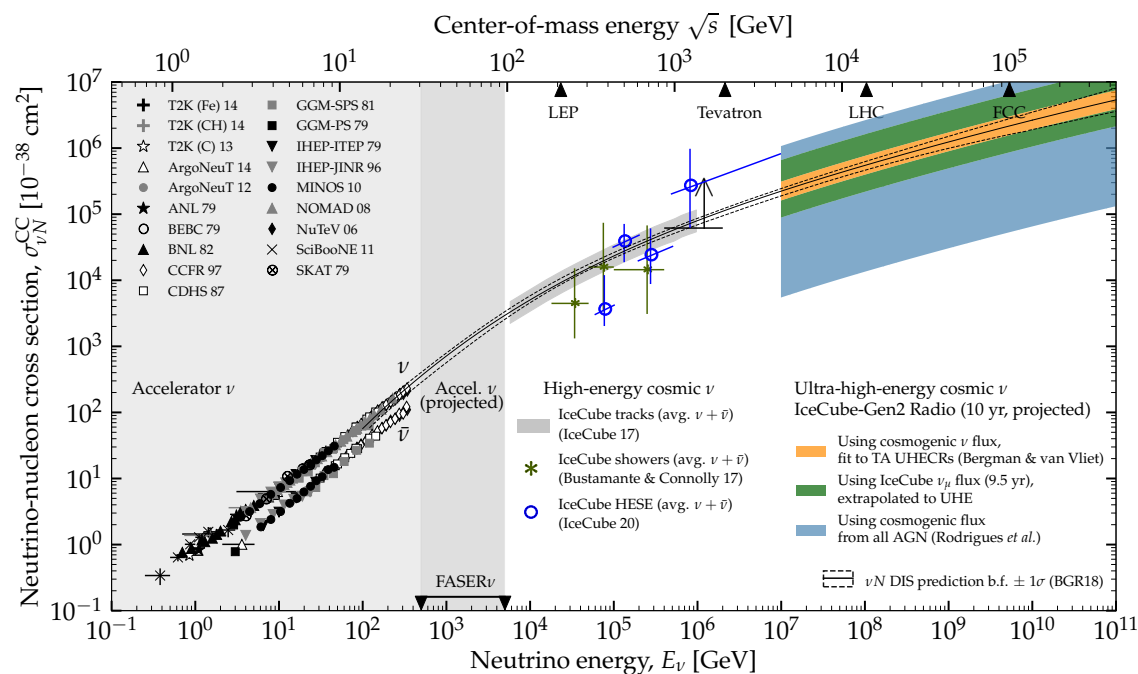


**IceCube-Gen2,
Technical
Design
Report,
WORK IN
PROGRESS**

Science with IceCube-Gen2

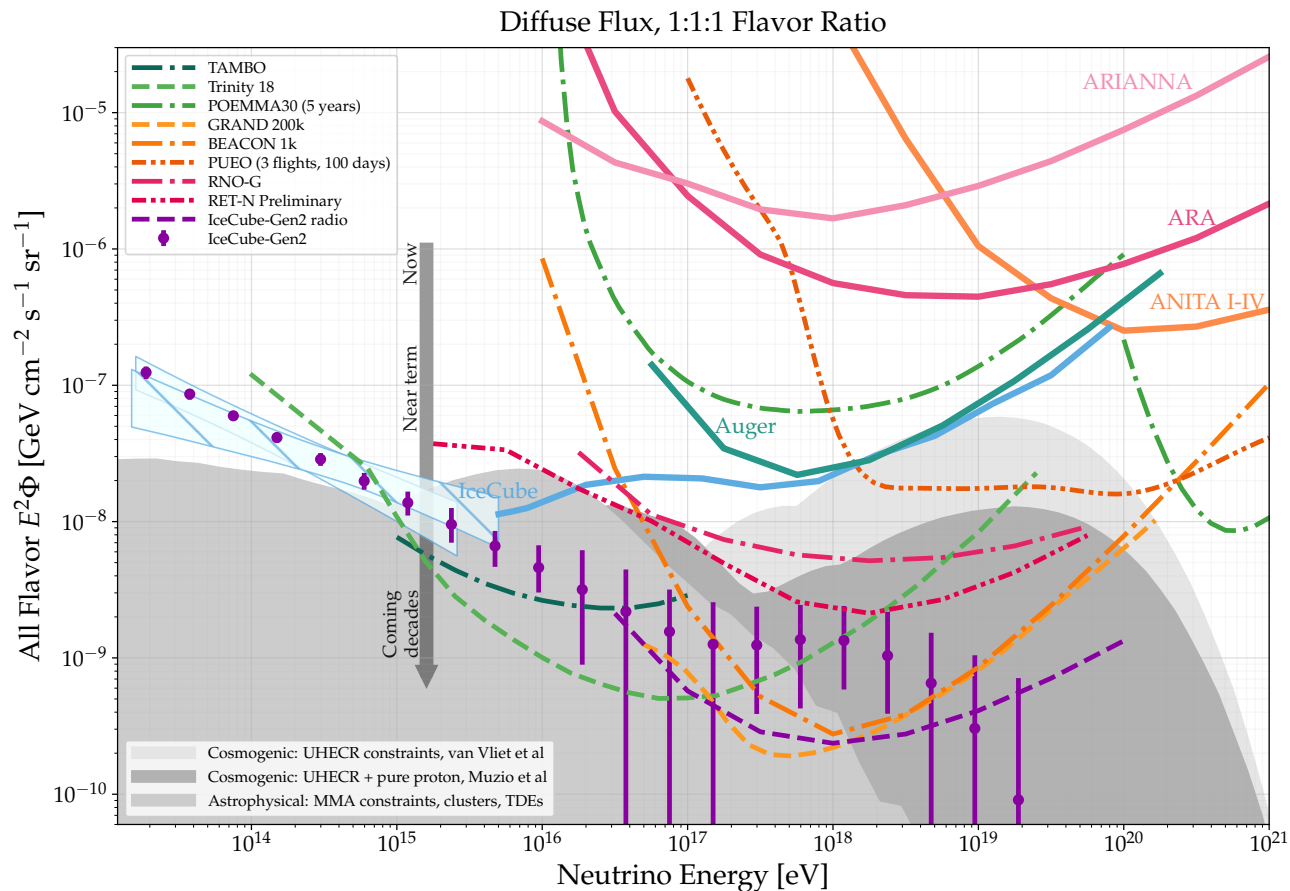
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- Discovery of neutrinos at EeV energy highest priority, unless detected prior by for example RNO-G or PUEO
- After the discovery will come disentangling of spectrum and origin of the flux
- Interesting aspect for highest energies will be a cross-section measurement at the highest energies



Science with IceCube-Gen2

In the experimental landscape



Snowmass White Paper, Ackermann et al. <https://arxiv.org/abs/2203.08096v1>

Towards IceCube-Gen2

Stay tuned, things are moving

