POEMMA-Balloon with Radio, towards a space-based Multi-Messenger Observatory

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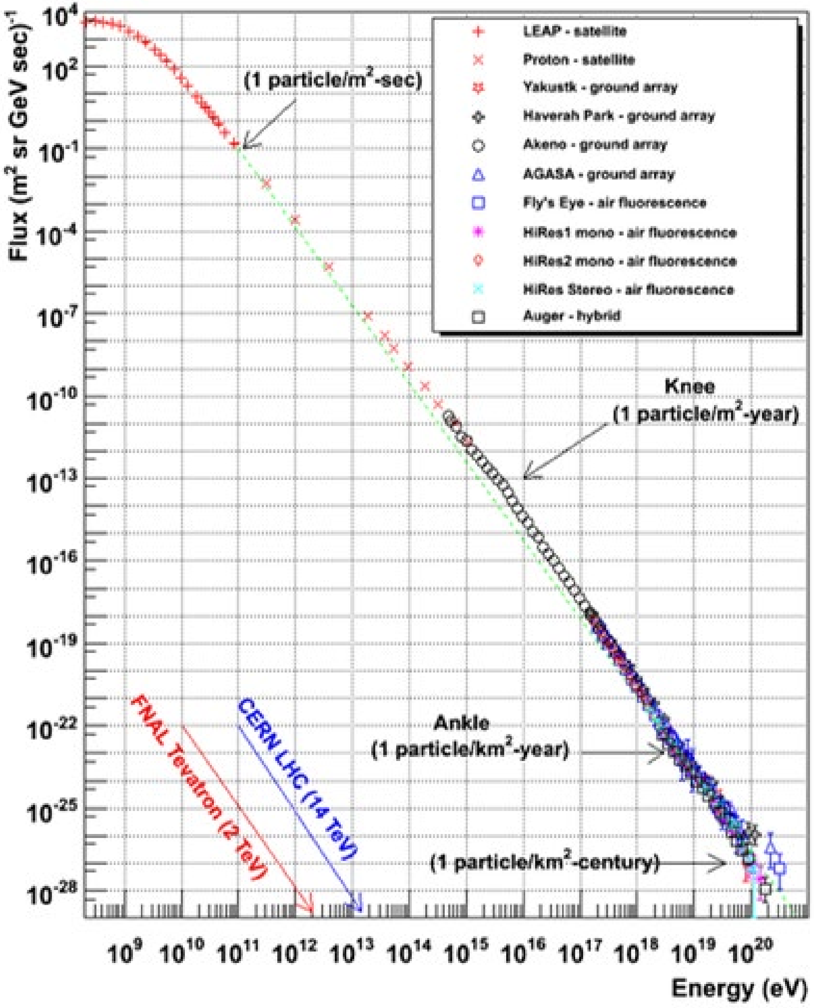
UHECR: Quick Reminder

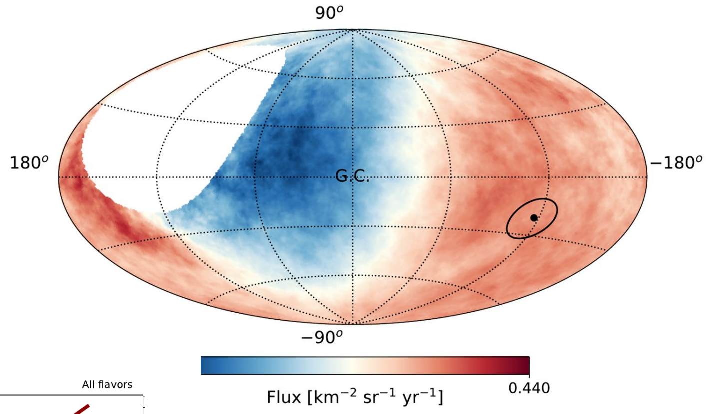
- Flux ranges over 32 orders of magnitude
- Energy ranges 12 orders of magnitude
- Most energetic particle known to exist ($\sim 10^{20}$eV)
- **Ultra-High-Energy Cosmic Rays** (UHECR) or Neutrinos (UHE neutrino) are particles with energies greater than **10^{18} eV** (1 EeV)
- **Very-High-Energy Neutrinos** (VHE neutrino) are particles with energies greater than **10^{15} eV** (1 PeV)

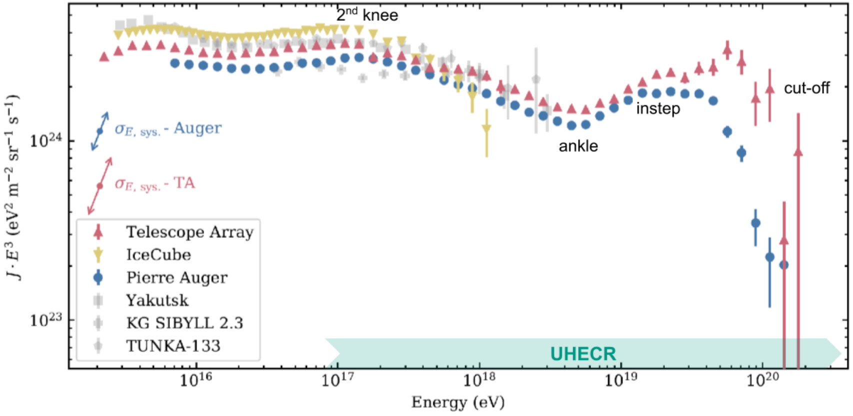


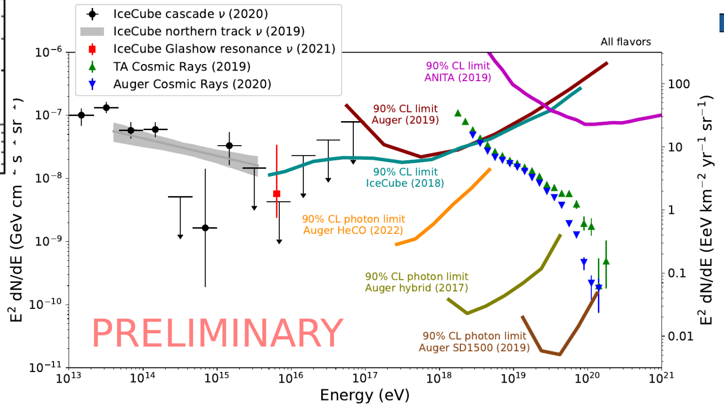
What we know so far

- Well measured energy spectrum
- Measured mass composition of CR primaries
- First indication of anisotropy found (Auger and TA hotspots)
- UHECR Observatories are Multi-Messenger observatories

Driven by ground arrays Auger & TA







Remaining Open Questions

- What is the nature and origin(s) of UHECRs?
- What are the sources and acceleration mechanism of UHECRs?
- What is the nature of the flux suppression at the highest energies?
- To what degree will charged-particle astronomy, the ability to study individual (classes of) sources with cosmic rays, be possible?
- Are there new interactions and phenomena waiting to be discovered at energies past those achievable at the LHC?

Attempt to answer these question by going to Space

➡ **POEMMA**

Community Road-map outlined in AstroPart Vol. 149

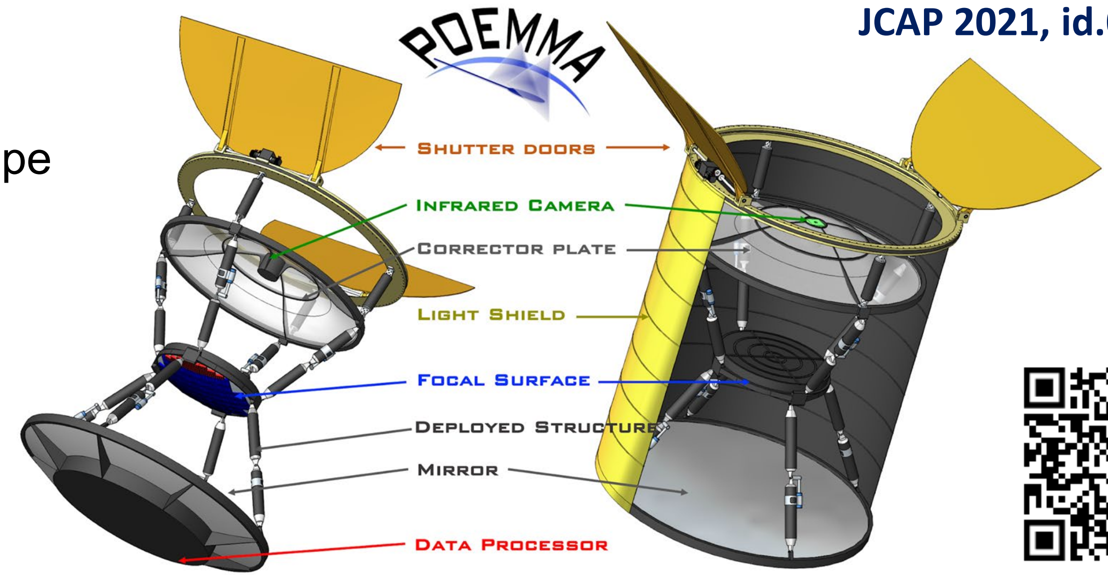
POEMMA's Science Goals

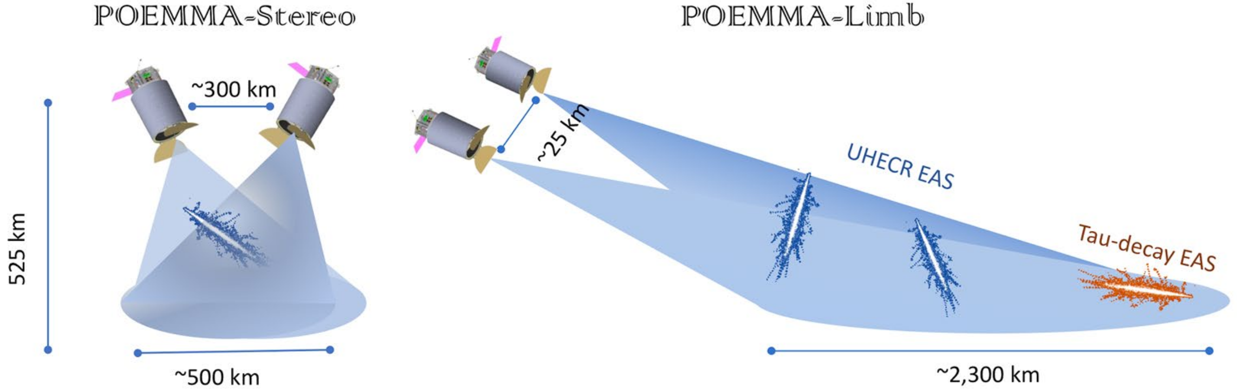
- Discover the origin of Ultra-High Energy Cosmic Rays
  - Measure Spectrum, composition, Sky Distribution at Highest Energies (E_{CR} > 20 EeV)
  - Requires very good angular, energy, and X_{max} resolutions: stereo fluorescence
  - High sensitivity UHE neutrino measurements via stereo fluorescence measurements
- Observe Neutrinos from Transient Astrophysical Events
  - Measure beamed Cherenkov light from upward-moving EAS from τ-leptons source by ν_τ interactions in the Earth (E_ν > 20 PeV)
  - Requires tilted-mode of operation to view limb of the Earth & ~10ns timing
  - Allows for tilted UHECR air fluorescence operation, higher GF but degraded resolutions
- Secondary goals
  - study fundamental physics with the most energetic cosmic particles: CRs and Neutrinos
  - search for super-Heavy Dark Matter: photons and neutrinos
  - study Atmospheric Transient Events, survey Meteor Population, …

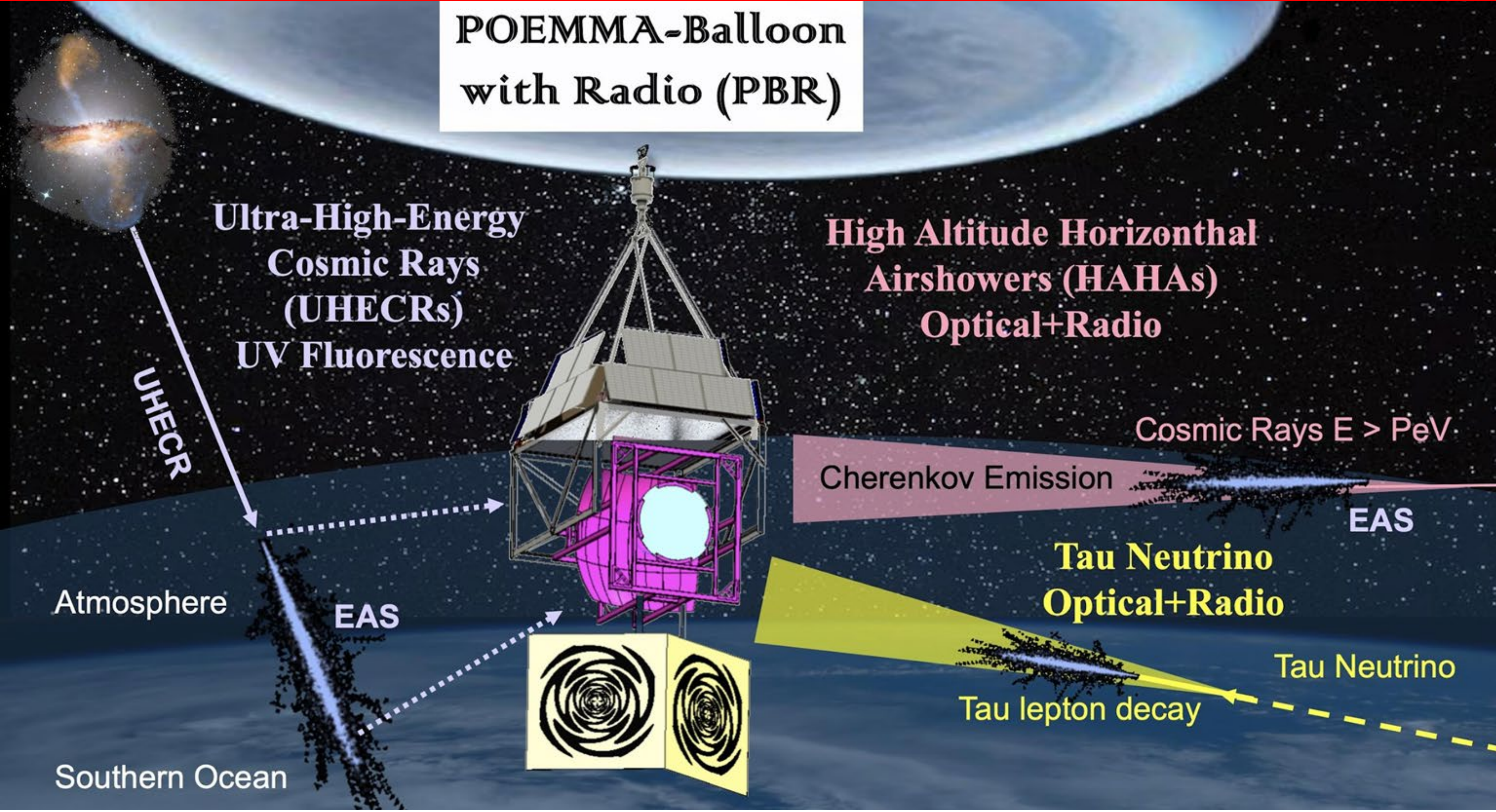
The Telescope & Operation Mode

- 3-5 year dual satellite mission
- Orbit: **525km**, 28.5° inc, Δt:95min
- 3.3m diameter Schmidt optics telescope
  - FoV: **45x45°**
  - Pixel FoV: 0.084°
- **Hybrid** focal surface
  - 126720 MAPMT px (1μs)
  - 15360 SiPM px (10ns)
- Slew rate: **8min/90deg**
- **Two** observation modes
  - **Stereo** for UHECR, separation 300km
  - **Limb** for ToO, separation 25km
  - 300 km → 25 km Satellite Separation
    - Puts both into Cherenkov Light Pool
    - Δt: 3h
    - 8-15 times during mission

JCAP 2021, id.007






POEMMA-Balloon
with Radio (PBR)
Ultra-High-Energy
Cosmic Rays
(UHECRs)
UV Fluorescence
High Altitude Horizonthal
Airshowers (HAHAs)
Optical+Radio
UHECR
Cosmic Rays E > PeV
Cherenkov Emission
EAS
Tau Neutrino
Optical+Radio
Atmosphere
EAS
Tau Neutrino
Tau lepton decay
Southern Ocean

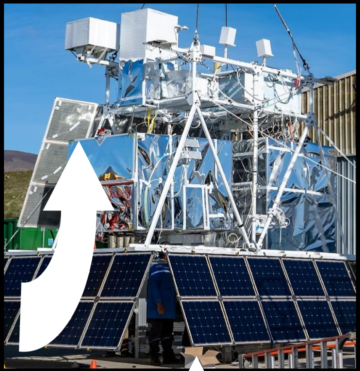
Progression

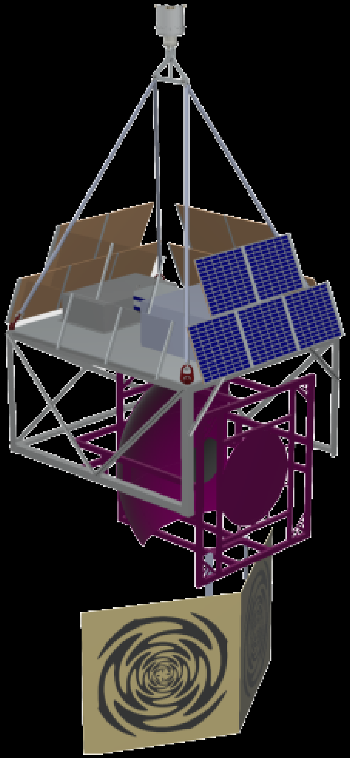
EUSO-Balloon

2014 Timmins

EUSO-SPB1

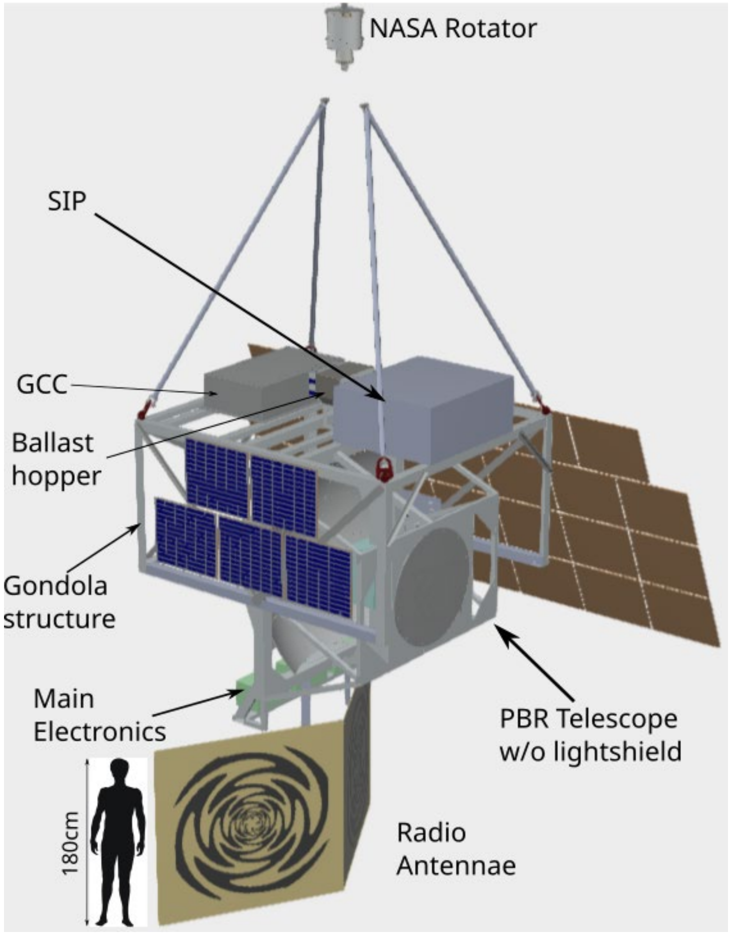
2017 Wanaka





POEMMA

PBR Payload & Mission

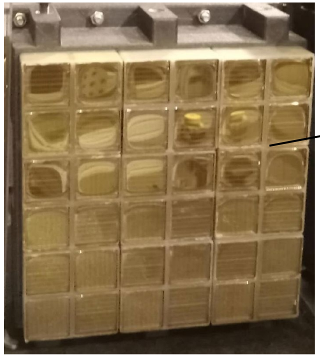


- Payload of NASA **SPB** with launch from Wanaka, NZ
- Target date: Spring, **2027**
- Flight duration: up to **100 days**
- 3000lbs of science
  - 1.1m diameter Schmidt Optic Telescope
  - 2 radio antennas
  - 1 IR Camera
- Pointing:
  - 360° in azimuth via NASA provided rotator
  - Nadir to 10° above horizon in zenith

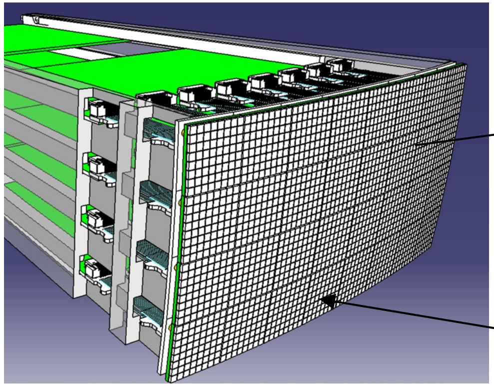
The Hybrid Focal Surface (FS)

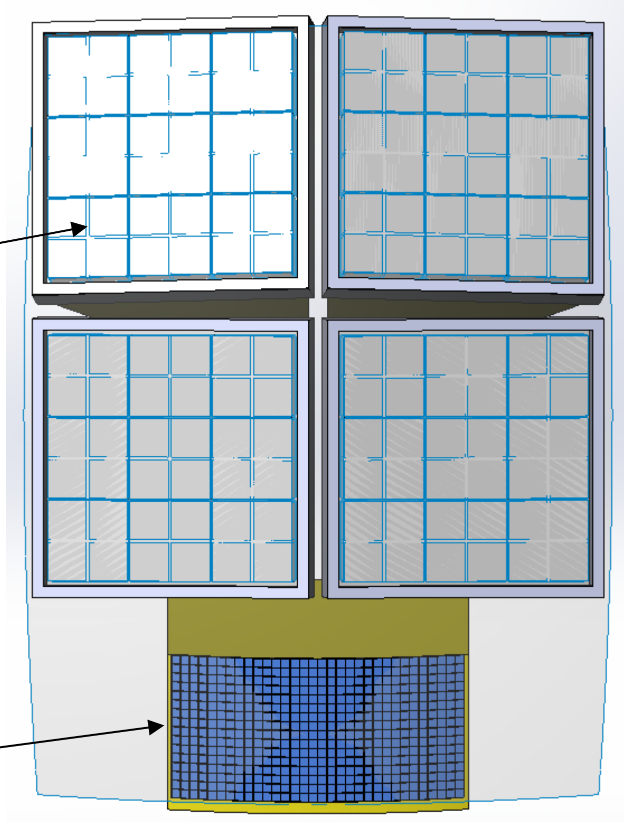
- Fluorescence Camera (FC)
  - Optimized for EAS detection via fluorescence (UHECR)
  - 4 Photo Detection Modules with 2304px each (MAPMTs): **9216px**
  - 24x24deg FoV
  - 290-430nm detection window (BG3 filter)
  - Integration time of **1μs**
- Cherenkov Camera (CC)
  - Optimized for EAS detection via cherenkov (VHEN and CR)
  - 4 rows of SiPM matrices: **2048px**
  - 12x6deg FoV
  - Bi-focal for event selection
  - 320-900 nm detection window
  - Integration time of **10ns**

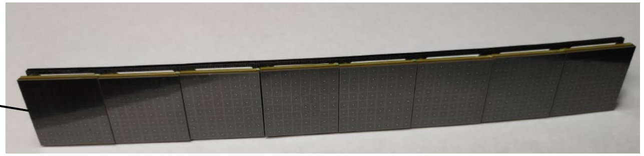
EUSO-SPB2 PDM



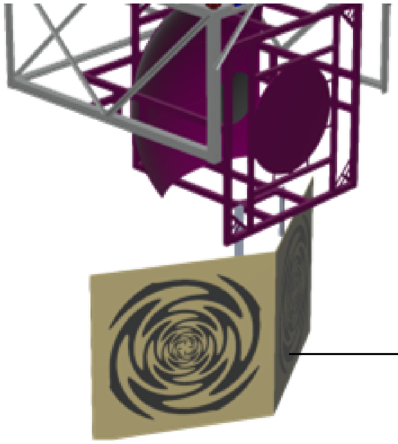
PBR CC Design



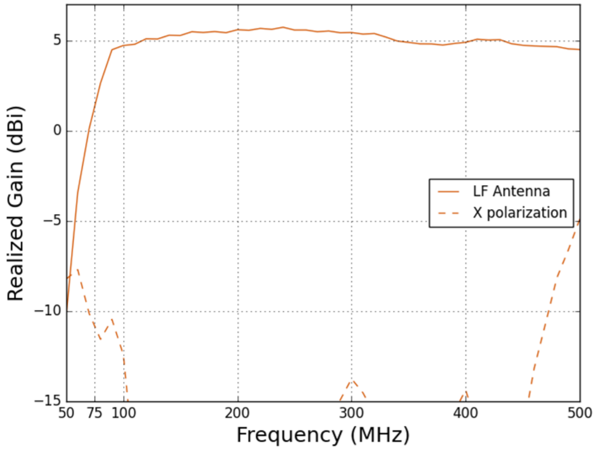




The LF Radio instrument

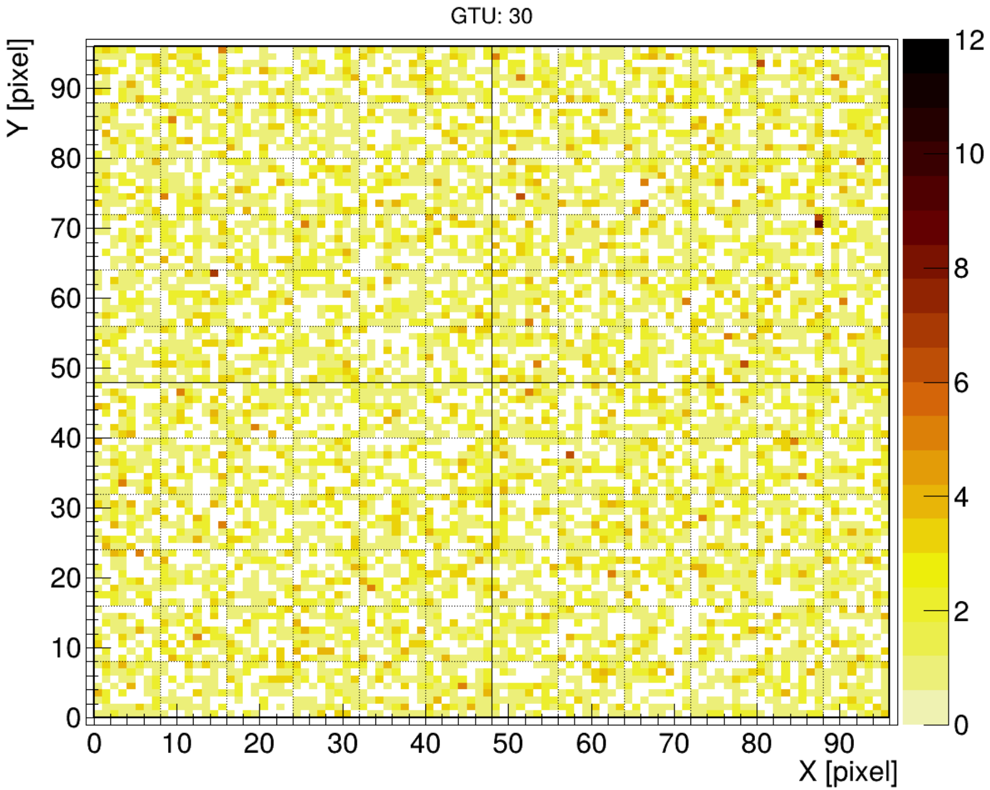


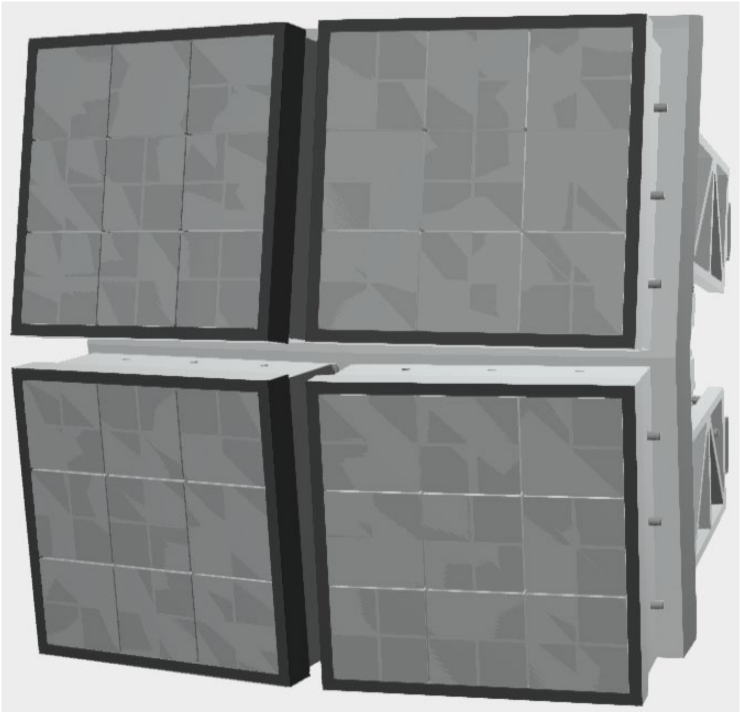
Sinuous antenna design from PUEO



- Two 2 by 2m dual-polarized Sinuous antennas
- Based on PUEO-LF instrument
- Frequency range: 50-500MHz
- 60 x 60deg field of view
- Overlapping with CC
- Canted at 120° from one another
- Expected energy threshold E>10^{18}eV
  - Forced trigger same threshold as CC

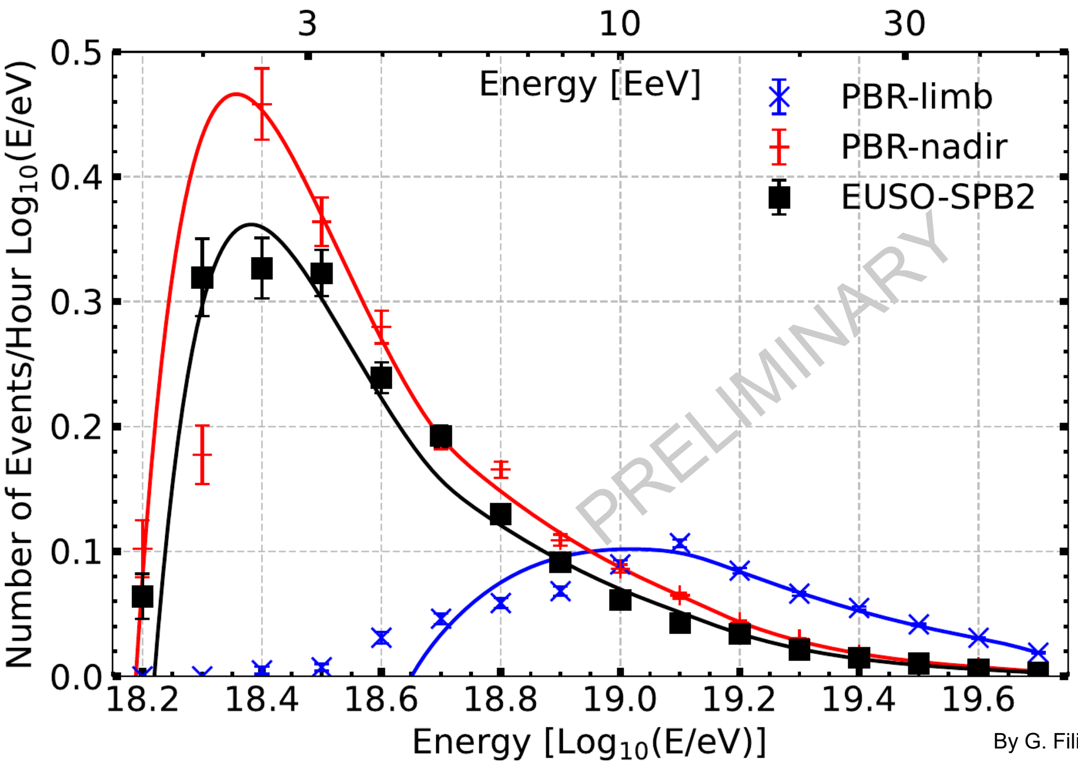
UHECR observation (FC)





- p-shower with energy 20EeV and zenith angle of 57°

UHECR observation (FC)



By G. Filippatos

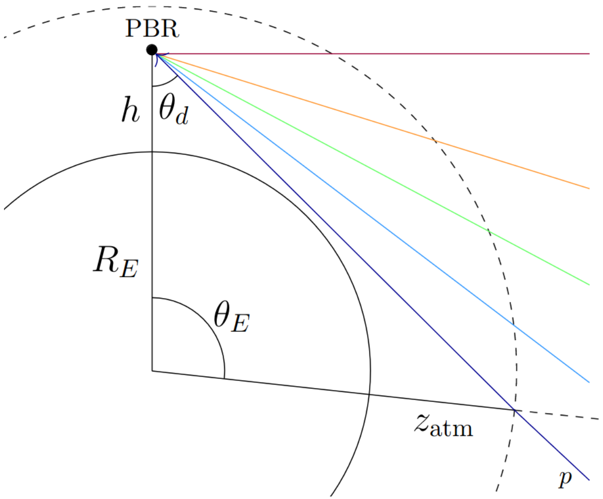
Nadir

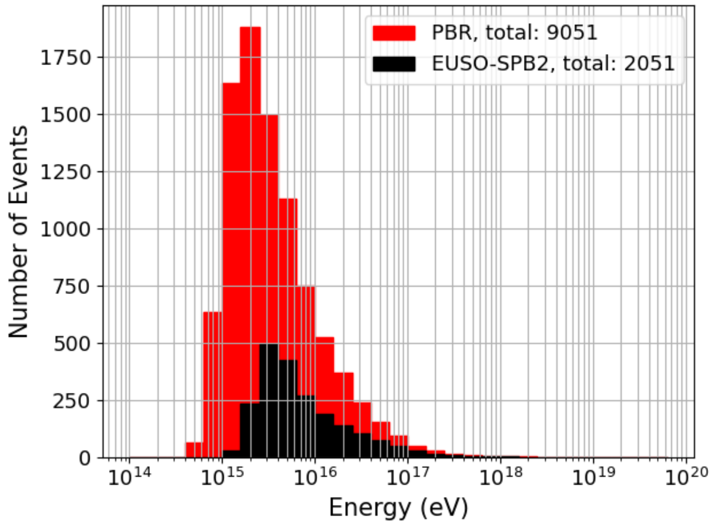
- Event rate: 0.23 evt/h (1.15 per night)
- Energy threshold (Peak): 1.8EeV (2.2EeV)

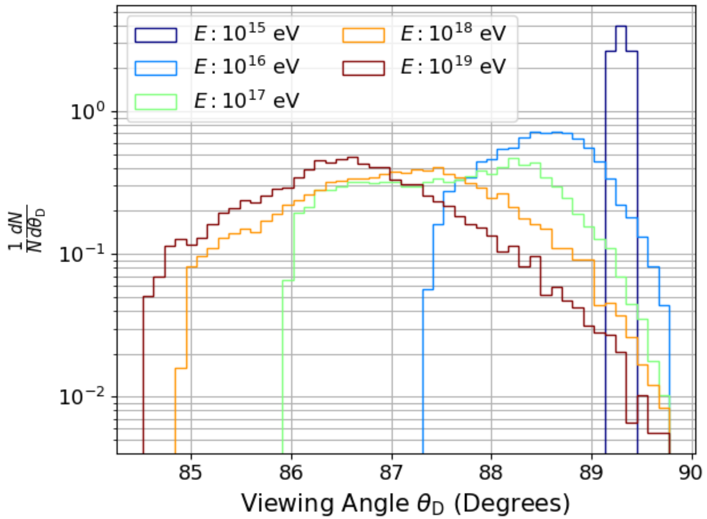
Limb

- Event rate: 0.07 evt/night (0.35 per night)
- Energy threshold (Peak):4EeV (~10EeV)

HAHAs observation (CC)





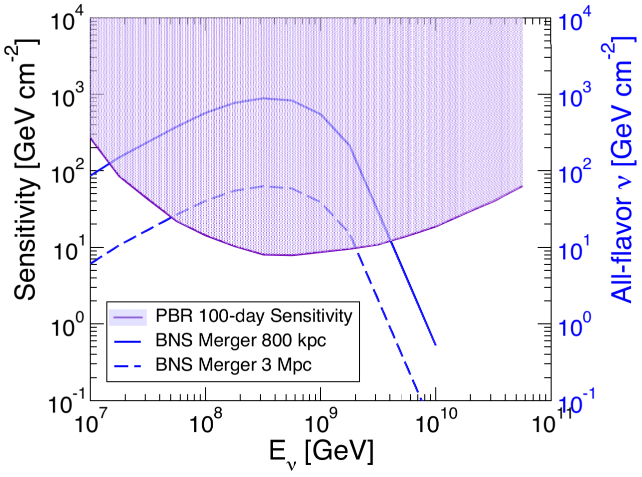


- Guaranteed signal with significant statistics (similar signature to neutrino event)
- Simulation study using EASCherSim*
- Energy threshold of 0.4 PeV (max sensitivity 2PeV) ➡ **~60+ events/h**
- Angular acceptance is energy dependent
  - Geometric energy filter

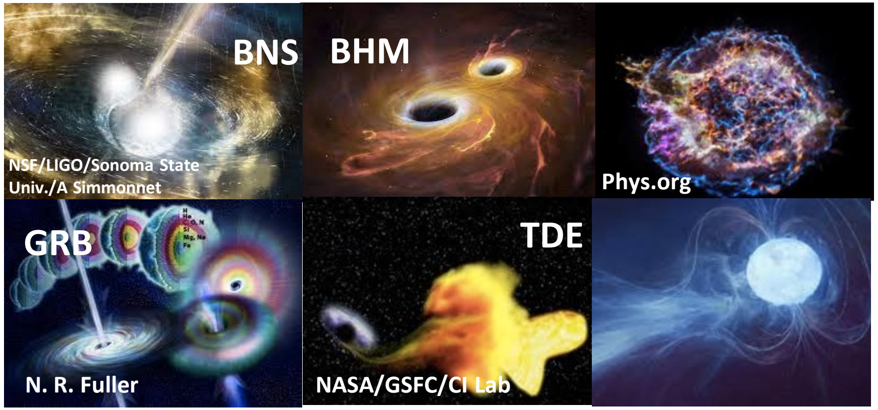
*https://gitlab.com/c4341/easchersim

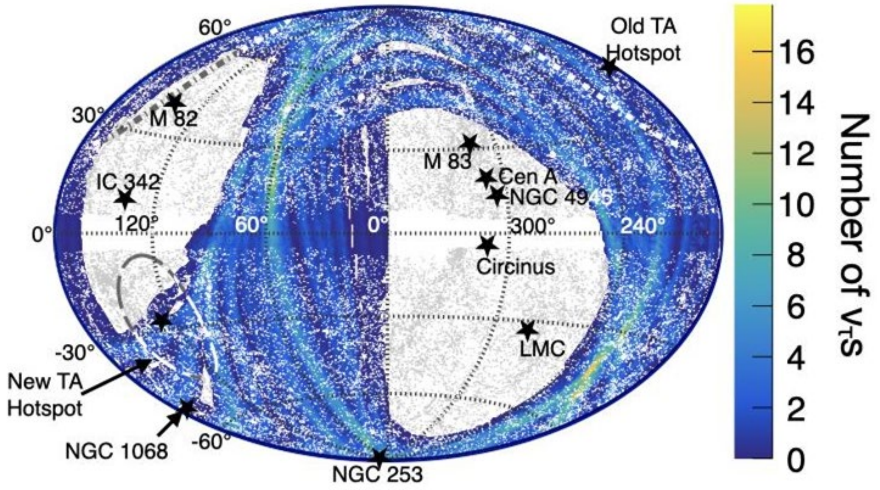
ToO observation (below the limb)

- PBR has very limited sensitivity to diffuse neutrino flux, but can observe transients by pointing (similar to POEMMA and EUSO-SPB2)



- Models are fluences (integrated over time)
- Accounting for Sun/Moon effect but no balloon motion currently
- Flight date of Apr 6 2027 (realistic launch date)





Summary & Conclusion

- POEMMA Balloon is the **successor** of the **EUSO-SPB2** mission and an advanced **precursor** of the dual satellite mission **POEMMA**
- Preparations have started for a launch from Wanaka, NZ in Spring of 2027 as an SPB payload
- Goals:
  - UHECR observation from above
  - Observation of High Altitude Horizontal Air-shower (HAHAs)
  - Neutrino search from Target of opportunity
  - First combined observation of optical Cherenkov and radio signal
  - Raise TLR for POEMMA (first hybrid focal surface)

Acknowledgments

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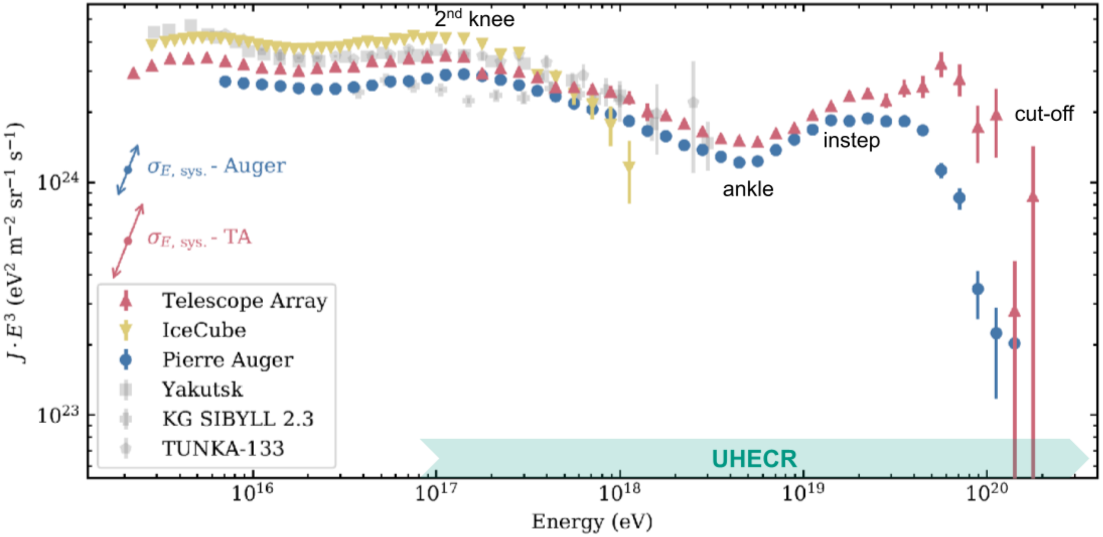
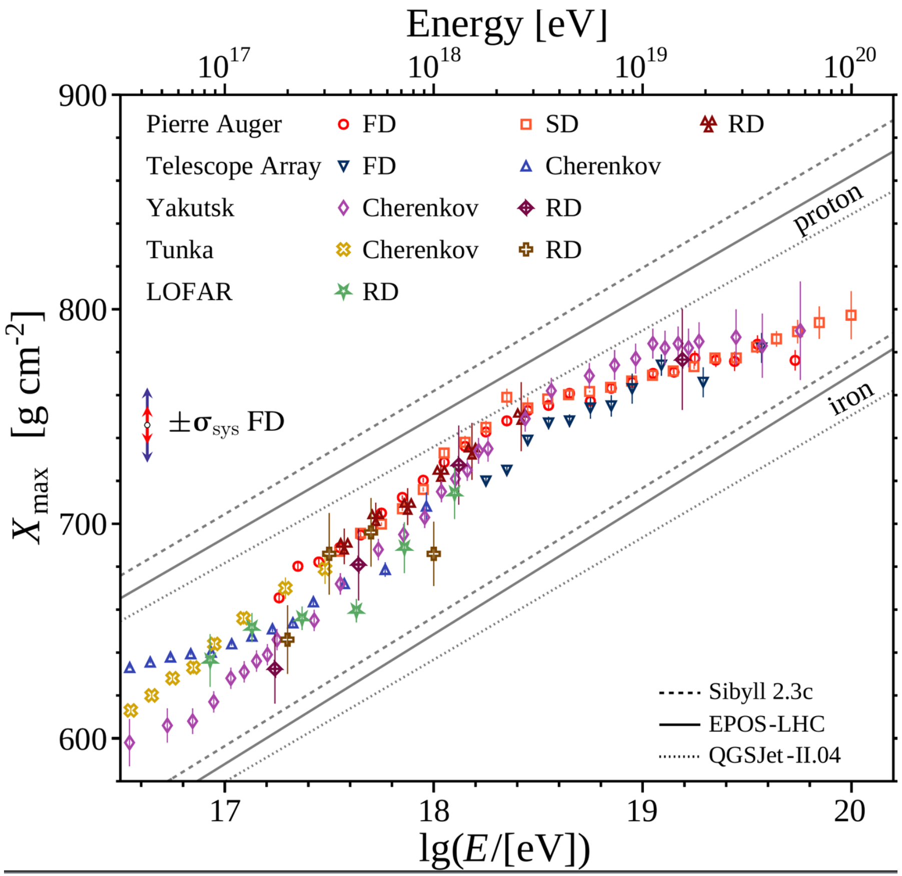
Additional slides

What do we know so far?

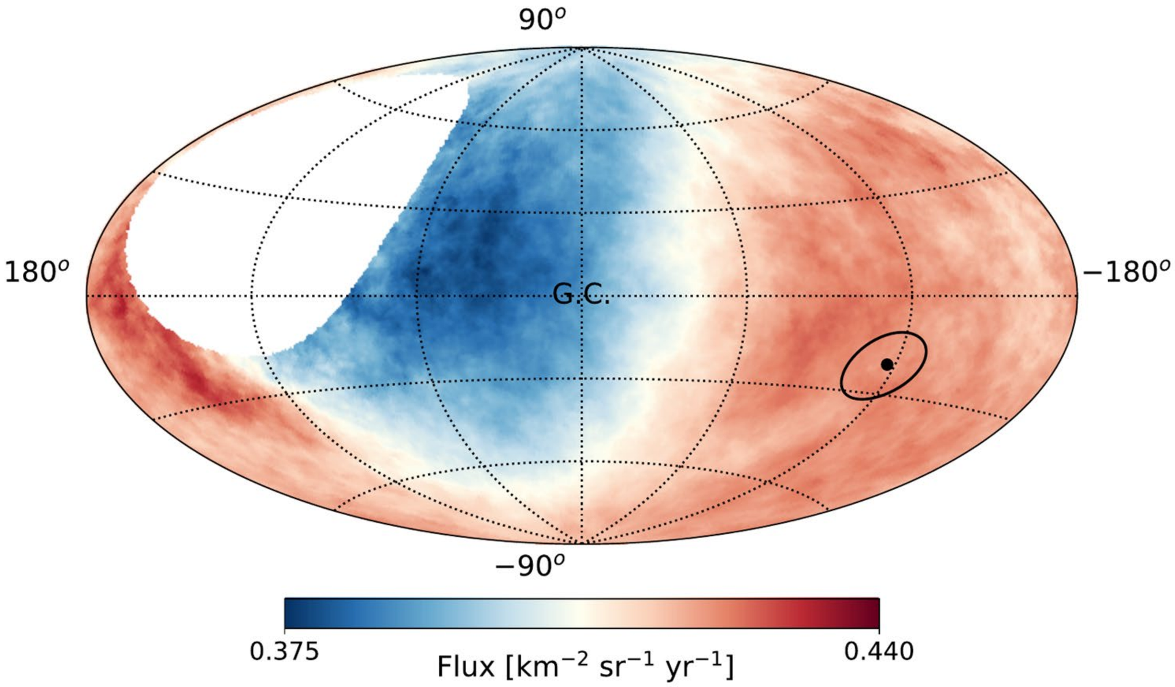
- Progress mainly driven by Pierre Auger observatory and Telescope Array project
- Well measured energy spectrum
- Measured mass composition of CR primaries





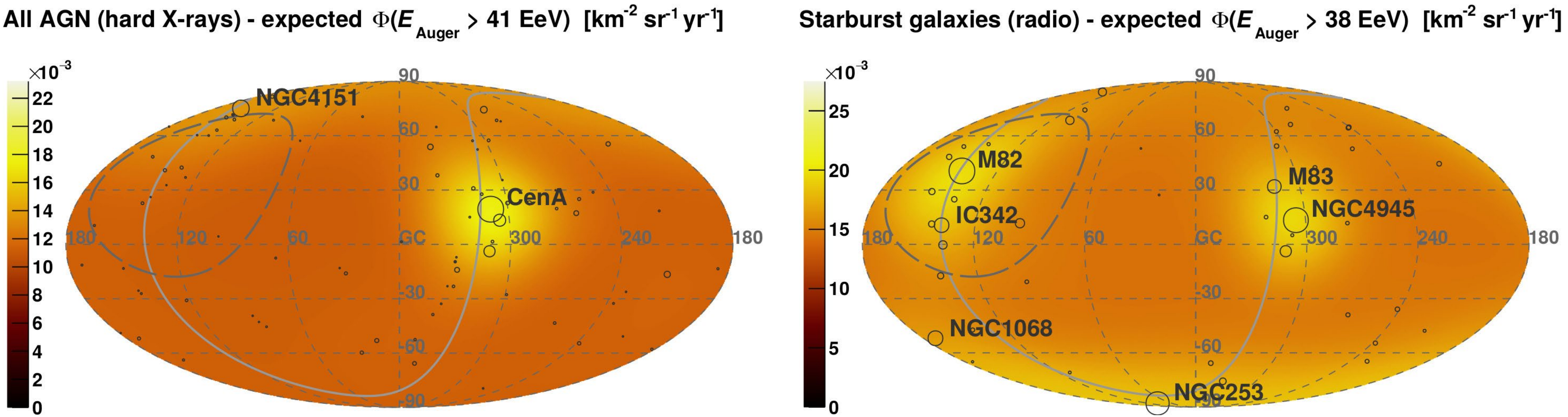
What do we know so far?

- First indication of anisotropy found
  - Auger Dipol for E > 8EeV
  - 115° away from galactic center (extragalactic origin)



What do we know so far?

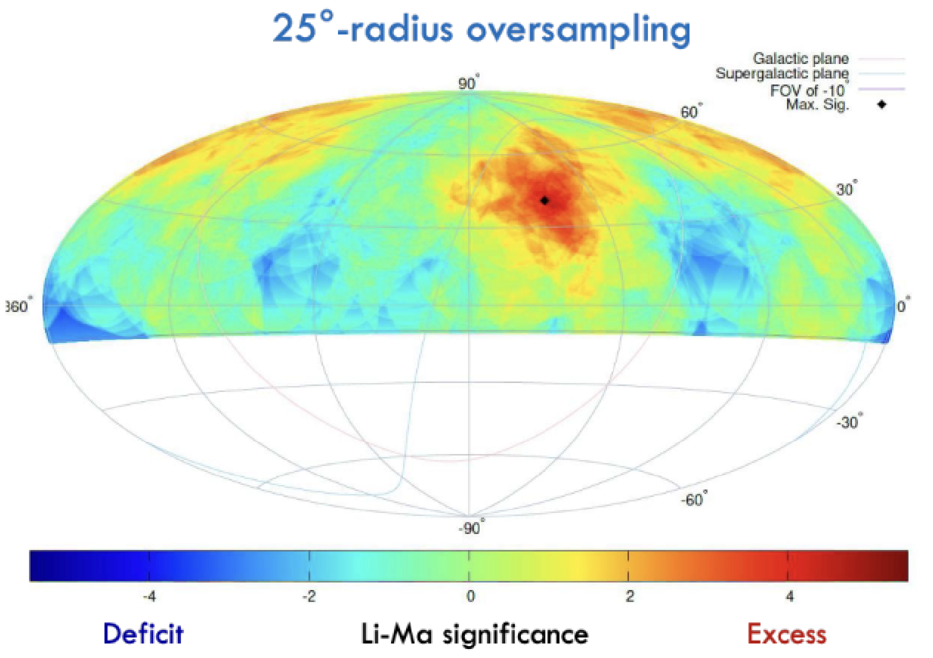
- First indication of anisotropy found
  - Auger's small/medium scale anisotropy, a warm spot

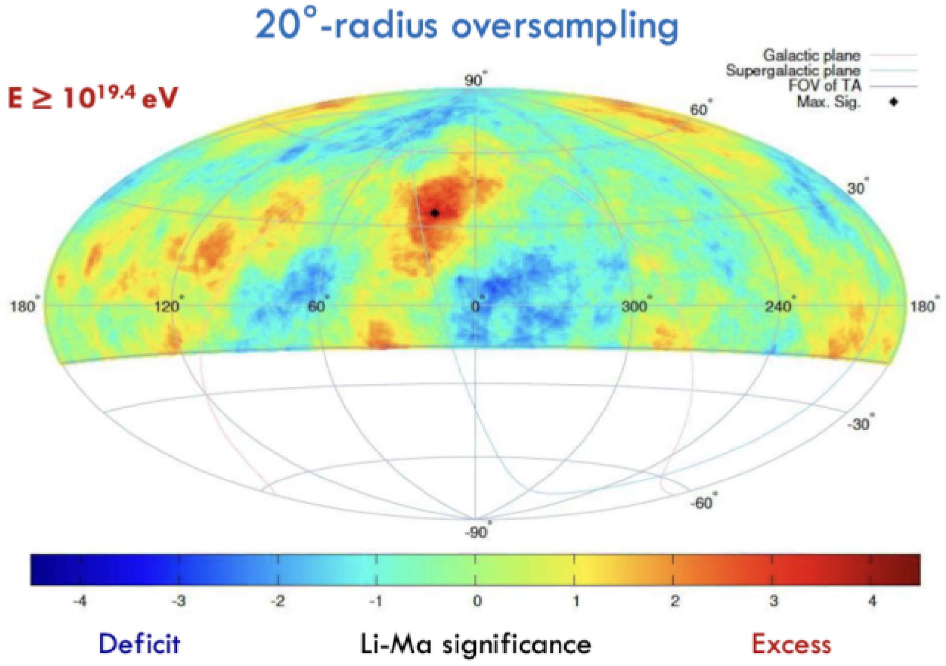


CenA excess 3.9σ

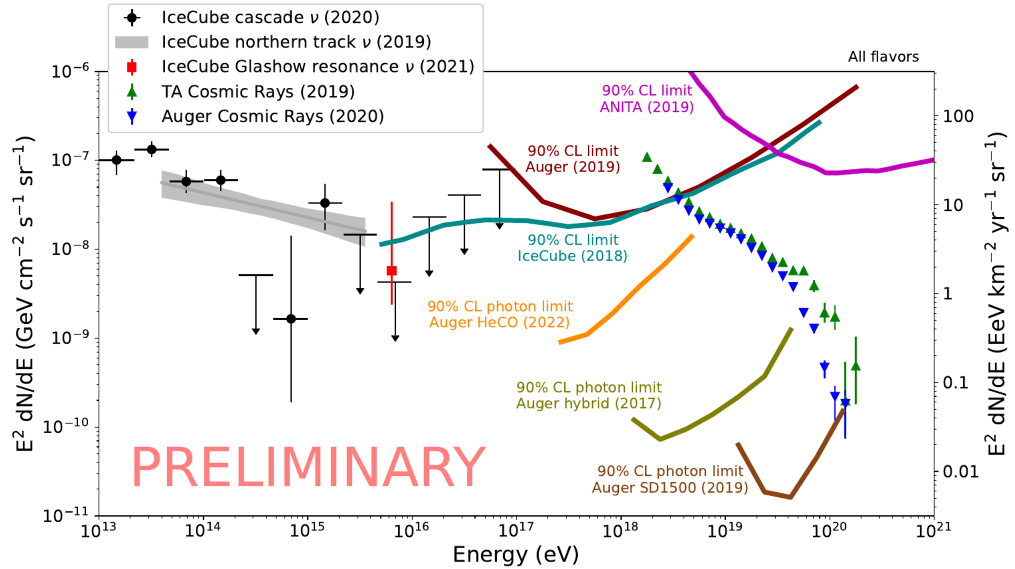
What do we know so far?

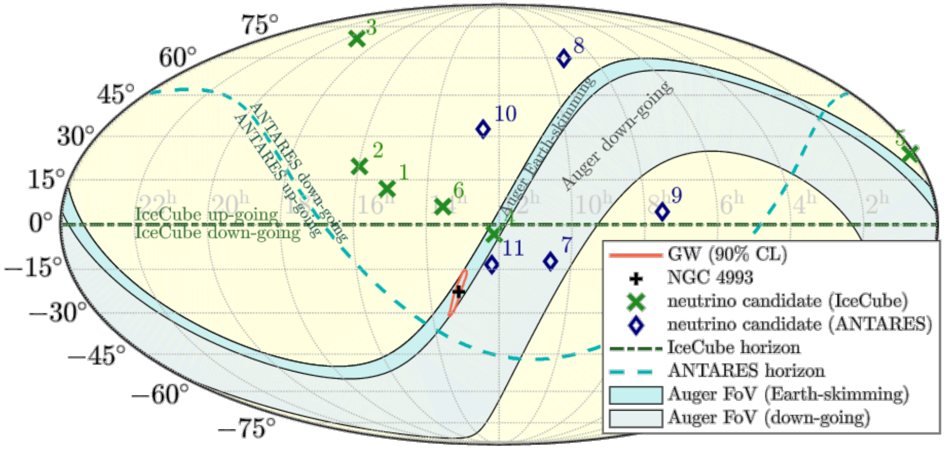
- First indication of anisotropy found
  - TA hotspots





What do we know so far?

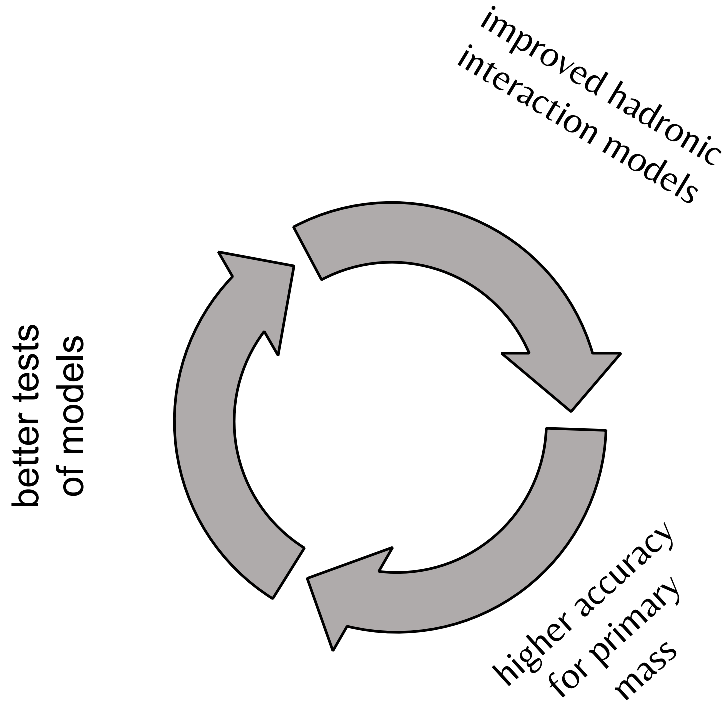


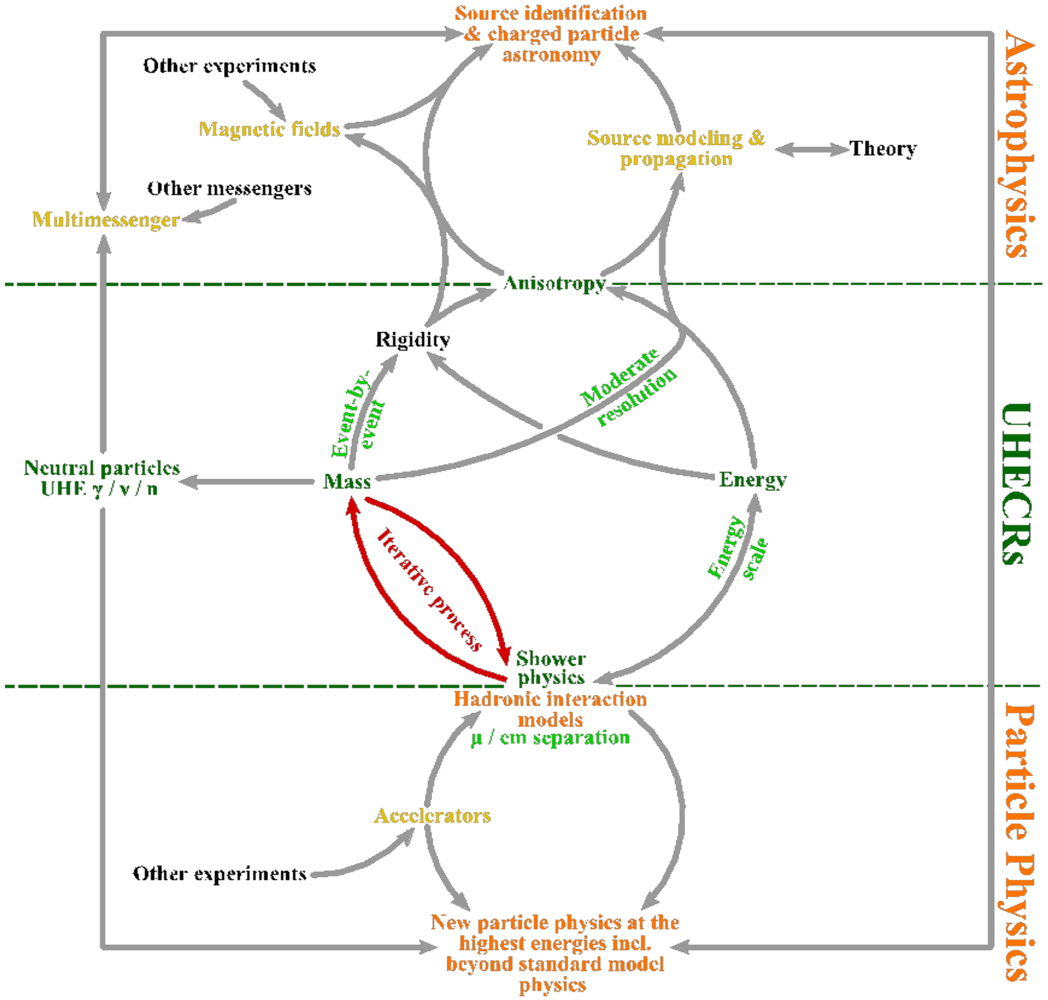


- UHECR Observatories are Multi-Messenger observatories
  - e.g. Auger has limits for VHE neutrinos and UHE photons
- Auger has made highest energy measurement of muon production in hadronic cascades and found significant tension with the muon production expected from accelerator-based hadronic interaction models
- UHECR experiments have provided the highest energy direct measurements of p-air cross section

The Cycle of Progress

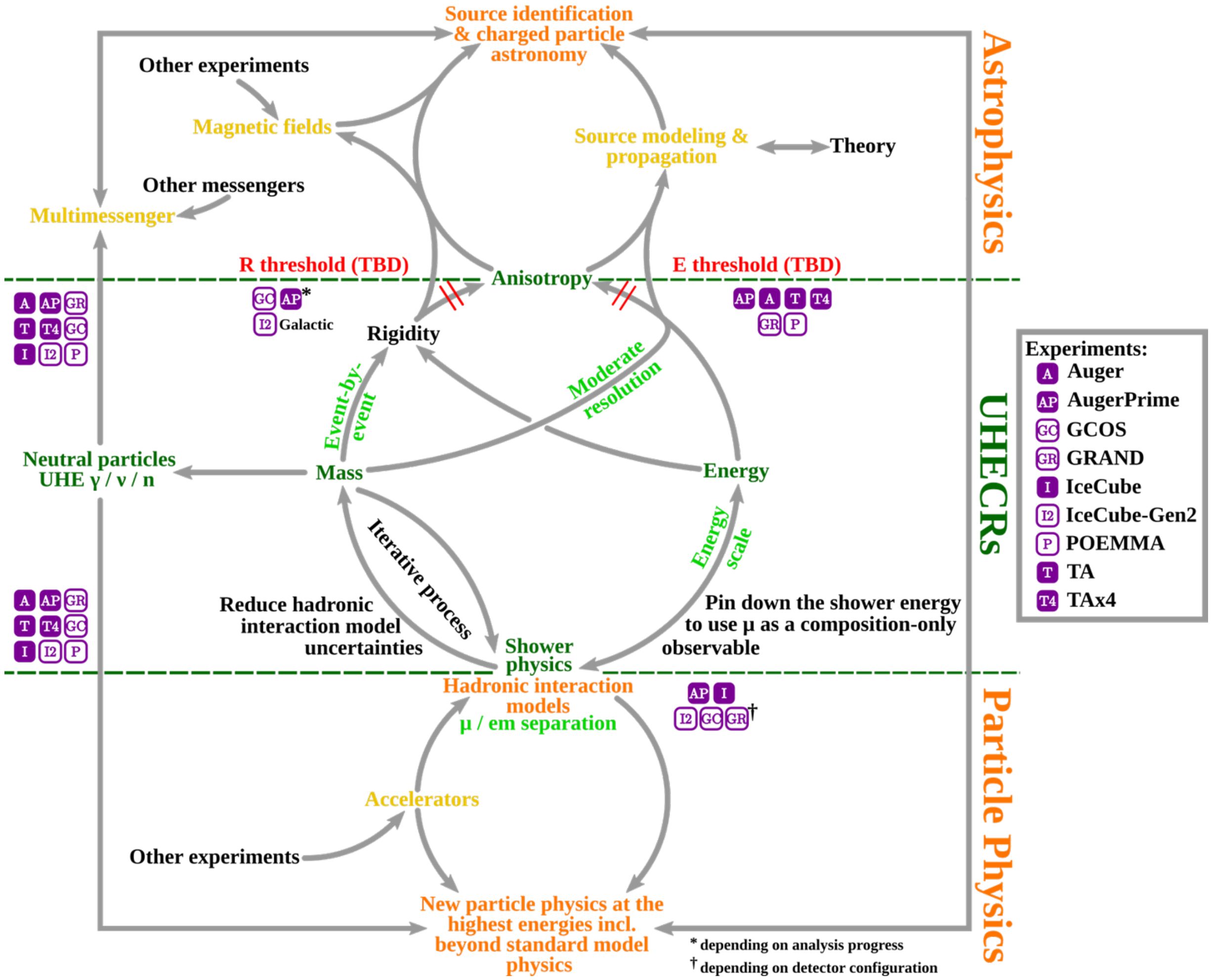
- Mutual benefit of Particle and Cosmic Ray physics



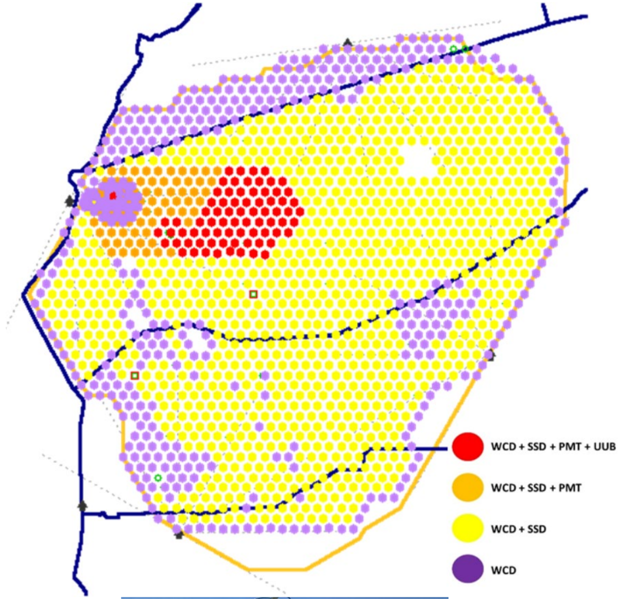


Future Experiments: Types

- Event-by-event Rigidity
  - requires high accuracy for mass and energy of primary particle
  - enables rigidity selection to search for sources in distribution of arrival directions
  - promising if rigidities R > 10 EV stem from mixed composition
- Huge Exposure
  - anisotropy measurements with very high statistics
  - requires only average mass composition for interpretation
  - promising if composition is pure at highest energies, or if ZeV particles could be discovered



Upgraded Detector: Auger Prime

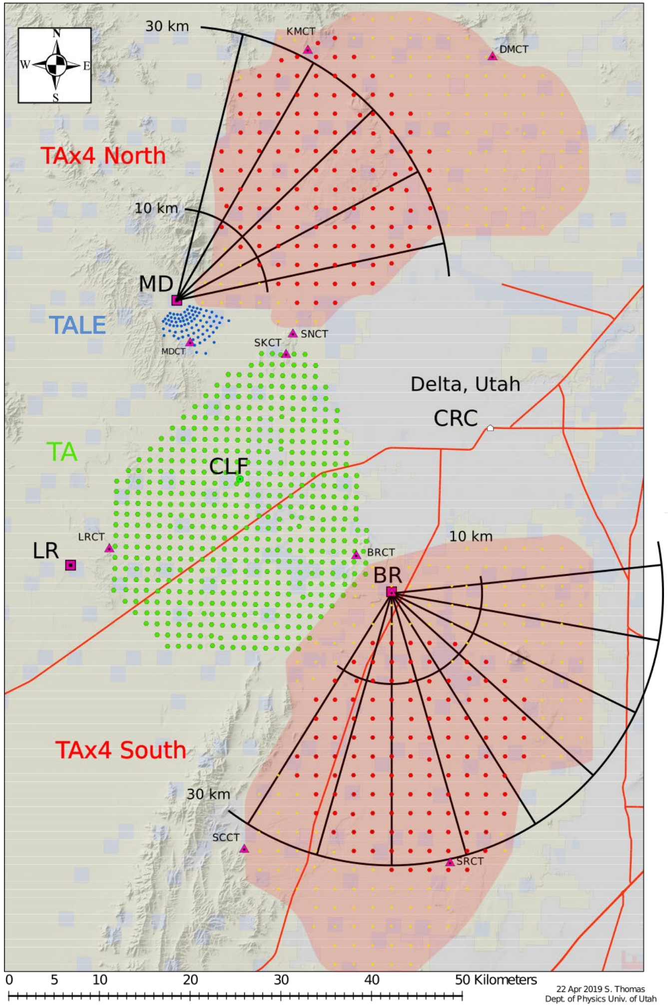


- Scintillation detector (SSD), 3.8m x 1.3m x 1cm positioned atop the water Cherenkov detector (WCD) to better distinguish between muonic and electromagnetic elements in signals from vertical showers.
- Extended dynamic range due to faster electronics and additional 1’’ PMT in the water-Cherenkov tank
- RD antenna: Detects inclined showers with FD-level precision and SD-level operational efficiency."
- Each SD-750 and SD-433 station has an adjacent UMD with three $10m^2$ scintillation detectors at 2.3m deep
- Initial data taking started in 2022 and full operational data taking started in 2023

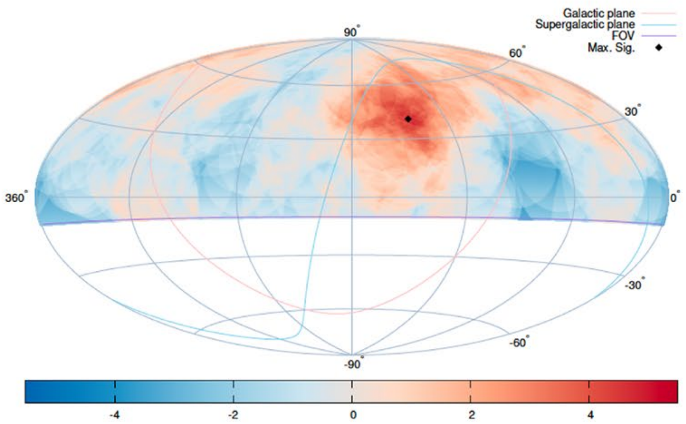
Upgraded Detector: Auger Prime

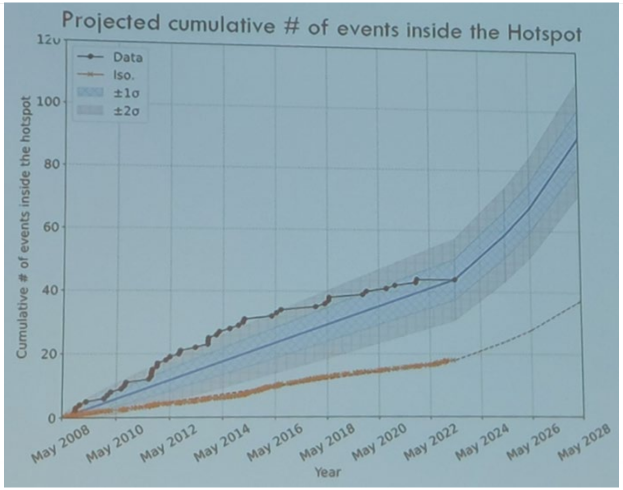
- Absolute energy calibration through radio with ~ 10% systematic uncertainty
- Muonic content of air showers can be reconstructed combining data from the WCDs and SSDs
  - key observable for estimating primary masses on an event-by-event basis
  - distinguish between protons and iron showers with merit factors ranging from around 1.2 to 2.1
  - within five years of operation a proton fraction as low as 10% could be detected at the highest energies
  - able to study mass-dependent features in the distribution of UHECR arrival directions
- Separation of e/m and muonic components by combining the data from different detectors is of vital importance for probing hadronic interaction models beyond the energy regions of accelerators

Upgraded Detector: TA x4



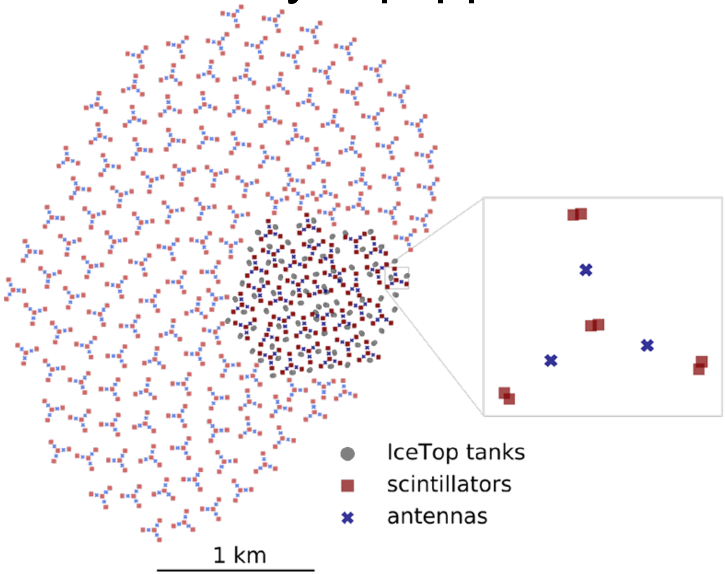
- Extension of original TA by factor of 4 to 3000m^2
  - Adding 500 new surface stations
  - Adding 12 telescopes over looking new sites
- more precisely observe anisotropy features, the energy spectra, and mass composition in the northern hemisphere
- TA×4 data will allow hybrid composition measurements up to ~ $10^{19.6}$ eV

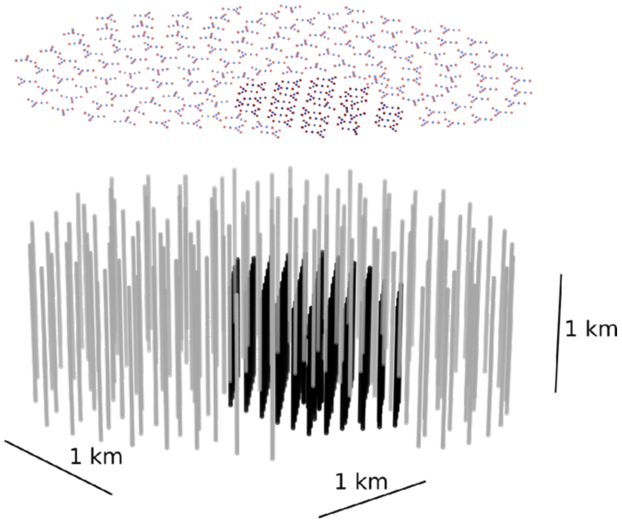




Next generation: IceCube Gen2

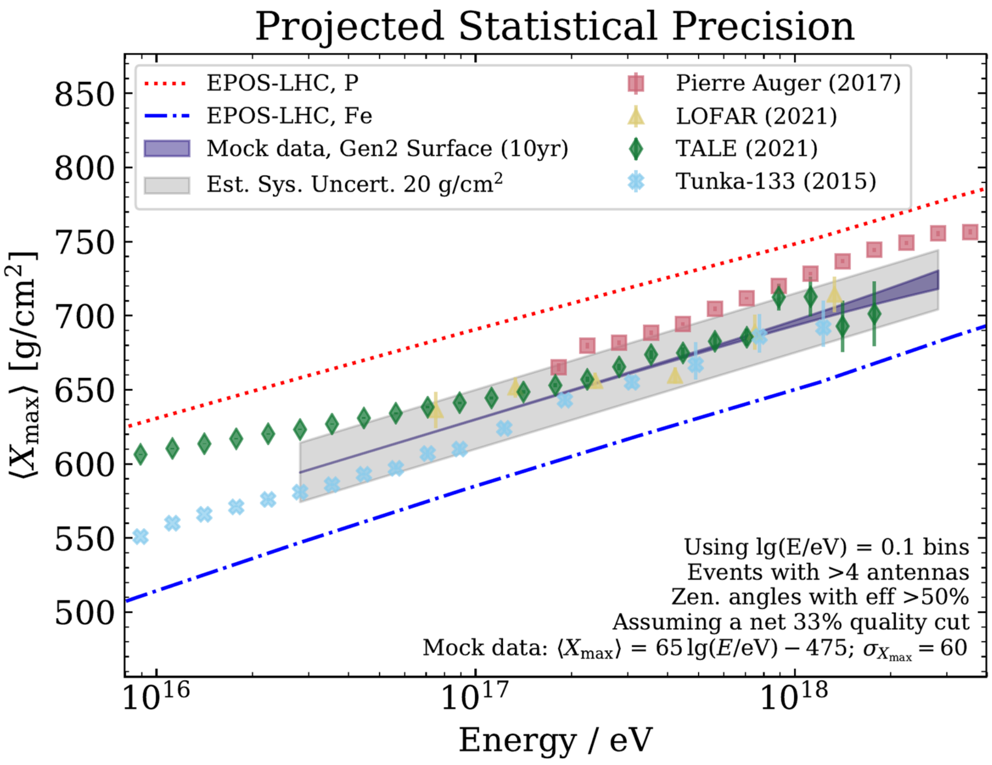
- Planned Extension of IceCube
  - Start of deployment in 2025 in stages and fully operational by 2035
  - 8km^3 in ice optical array for PeV neutrino astronomy
  - 500km^2 radio array for EeV neutrino detection
  - 6km^2 surface array equipped with scintillators and radio antennas

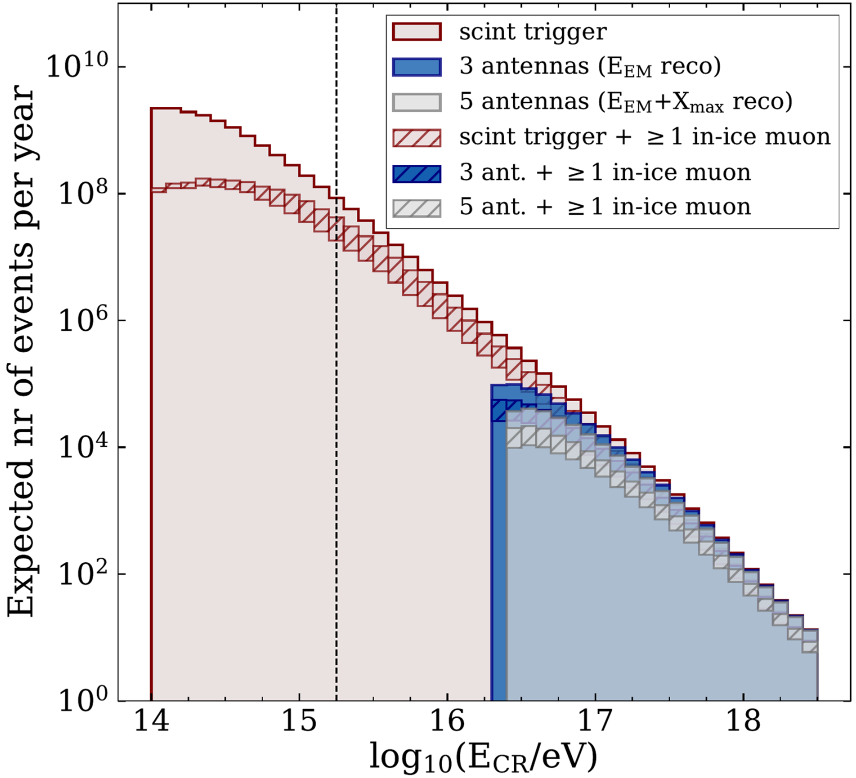


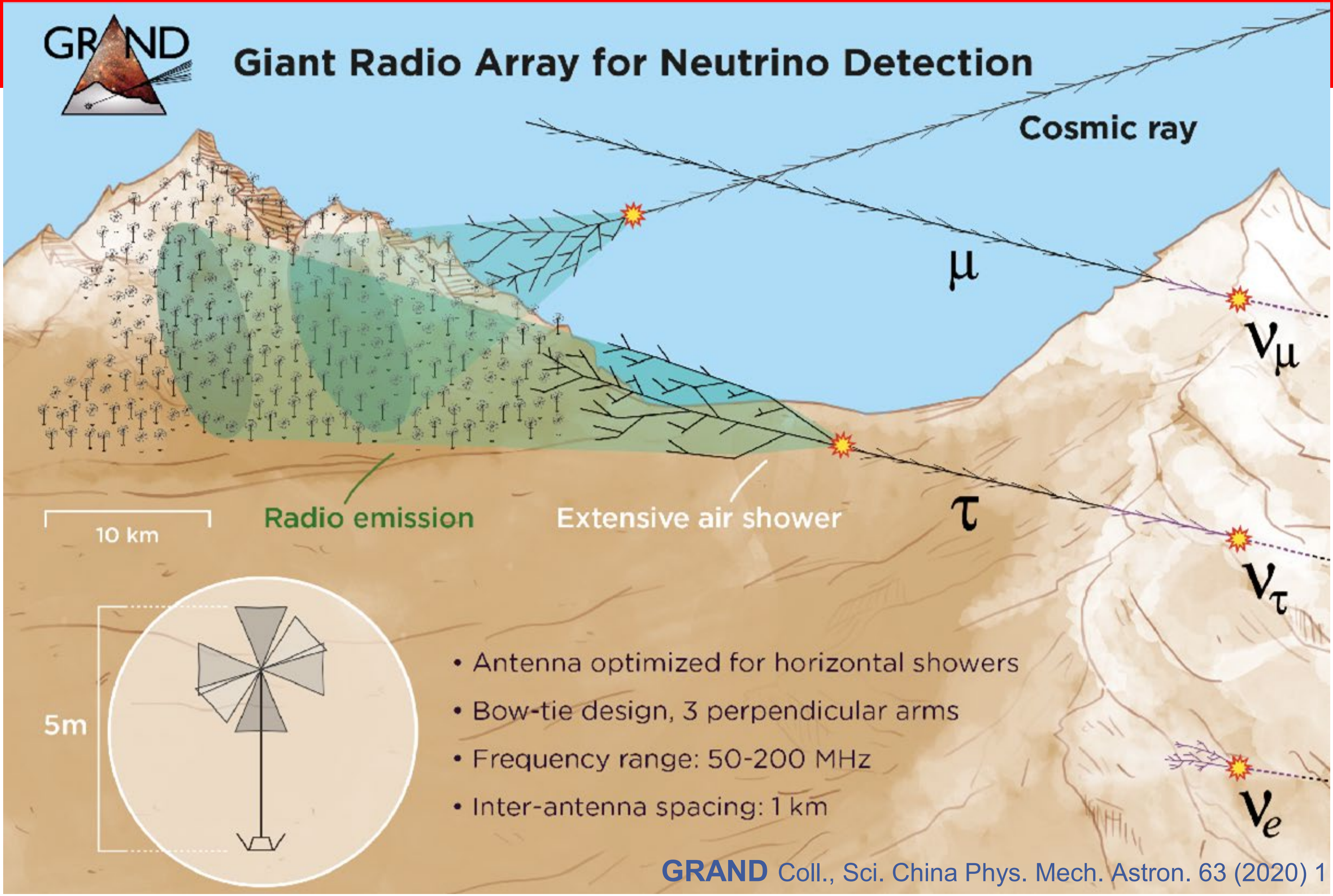


IceCube Gen2: UHECRs

- Accurate energy and X_{max} measurement at energies around and above the second knee







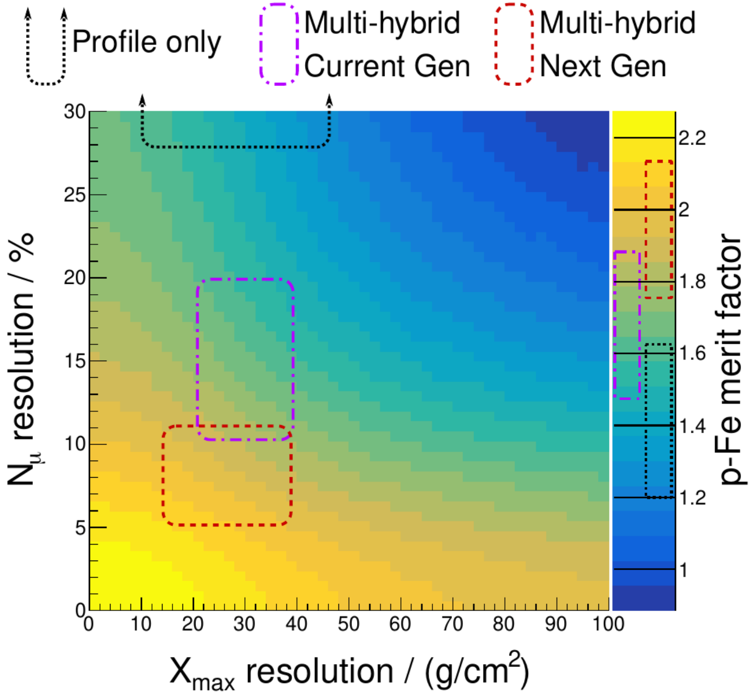
GRAND Coll., Sci. China Phys. Mech. Astron. 63 (2020) 1

Next generation: GRAND

- Mainly a neiutrino observatory but UHECR is second science case
- Mature technique (AERA, LOFAR, Tunka-Rex...)
- Multiple sites planned worldwide (antennas: cheap, robust, scalable)
  - 200,000km^2
    - Inclined showers only (spacing)
    - 100,000km^{2}sr aperture
- **High statistics**
- Limited mass resolution
  - X_{max} possible but no muon number
- Common sites with other instruments possible to increase performance (i.e. GCOS)

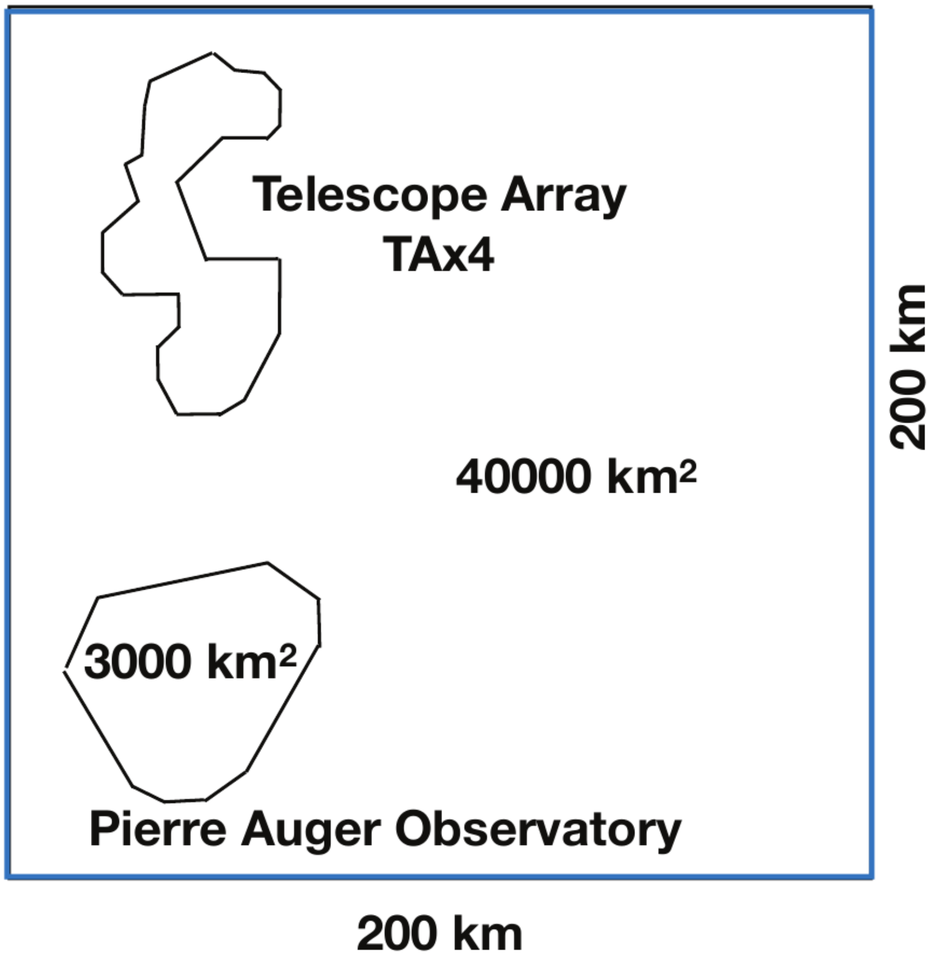
Future Detetcors: Expectations

- *“At least one next-generation experiment needs to be able to make high-precision measurements to explore new particle physics and measure particle rigidity on an event-by-event basis. Of the planned next-generation experiments, GCOS is th* … *this recommendation.”*

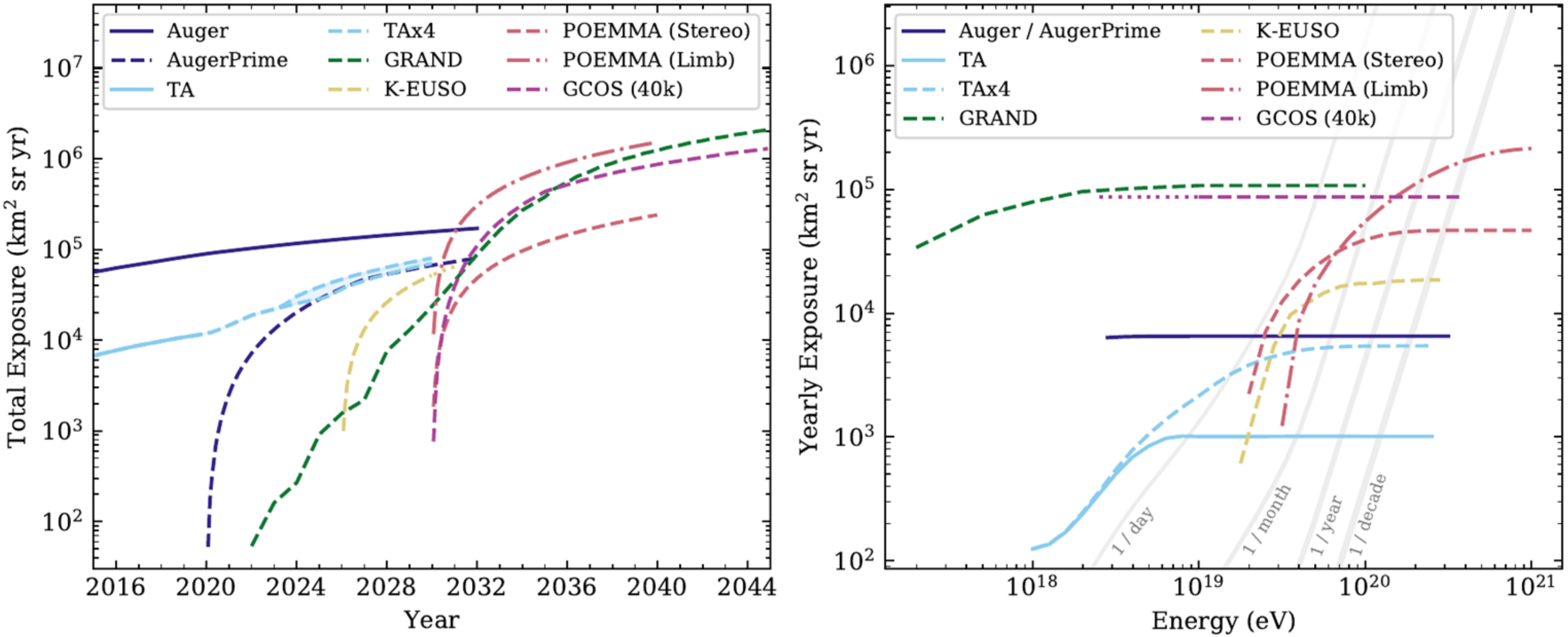


Next generation: GCOS

- Global Cosmic Ray Observatory is dedicated for UHECR science
- GCOS design with the aim for most accurate mass and energy measurements
  - Event-by-event rigidity
- Multiple site design would allow for full sky coverage
  - Co-locating with existing or other new generation detectors
- Currently in very early design phase



Future Detetcors: Expectations



Future Detetcors: Timeline

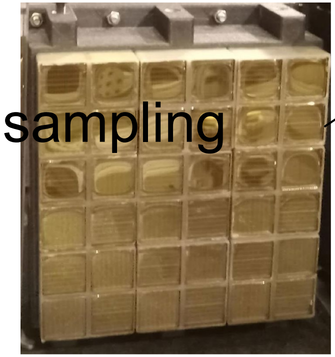
Experiment	Feature	Cosmic Ray Science*	Timeline
Pierre Auger Observatory	Hybrid array: fluorescence, surface e/μ + radio, 3000 km^2	Hadronic interactions, search for BSM, UHECR source populations, $\sigma_{\text{p-Air}}$	AugerPrime upgrade
Telescope Array (TA)	Hybrid array: fluorescence, surface scintillators, up to 3000 km^2	UHECR source populations proton-air cross section ($\sigma_{\text{p-Air}}$)	TAx4 upgrade
IceCube / IceCube-Gen2	Hybrid array: surface + deep, up to 6 km^2	Hadronic interactions, prompt decays, Galactic to extragalactic transition	Upgrade + surface enhancement → IceCube-Gen2 deployment → IceCube-Gen2 operation
GRAND	Radio array for inclined events, up to 200,000 km^2	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	GRANDProto 300 → GRAND 10k → GRAND 200k multiple sites, step by step
POEMMA	Space fluorescence and Cherenkov detector	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	EUSO program → POEMMA
GCOS	Hybrid array with $X_{\max}$ + e/μ over 40,000 km^2	UHECR sources via event-by-event rigidity, forward particle physics, search for BSM, $\sigma_{\text{p-Air}}$	GCOS R&D + first site → GCOS further sites

Timeline: 2025 2030 2035 2040

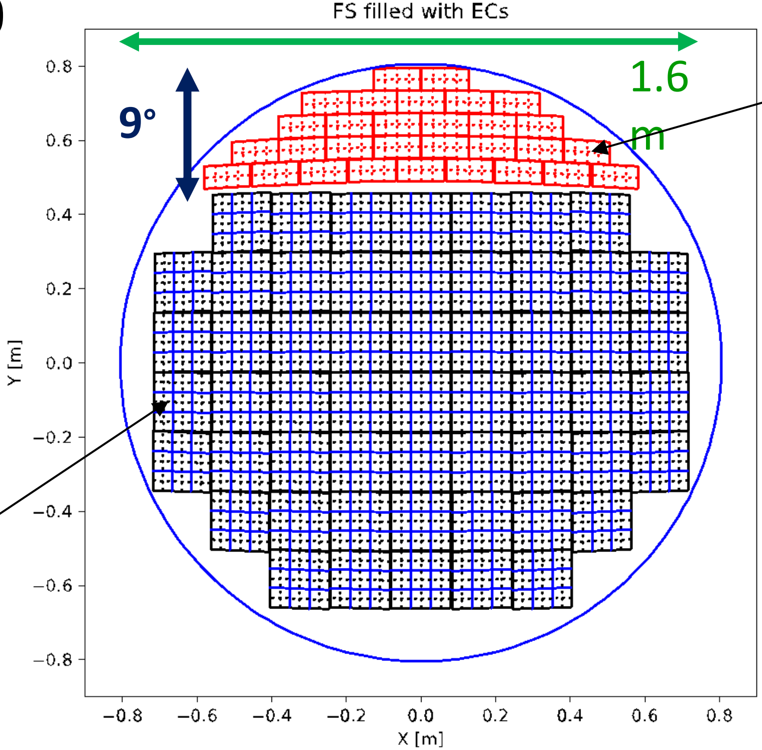
*All experiments contribute to multi-messenger astrophysics also by searches for UHE neutrinos and photons; several experiments (IceCube, GRAND, POEMMA) have astrophysical neutrinos as primary science case.

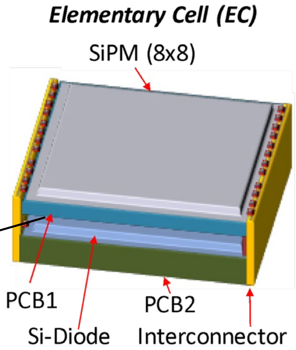
POEMMA's Focal Surface

- Fluorescence Optimized Detection
  - 55 PDMs = 126,720 pixels (JEM-EUSO design)
  - 2304 MAPMT px/PDM
  - BG3 filter (300-500 nm)
  - 1μs sampling



Hybrid Focal Surface 100,000+ channels

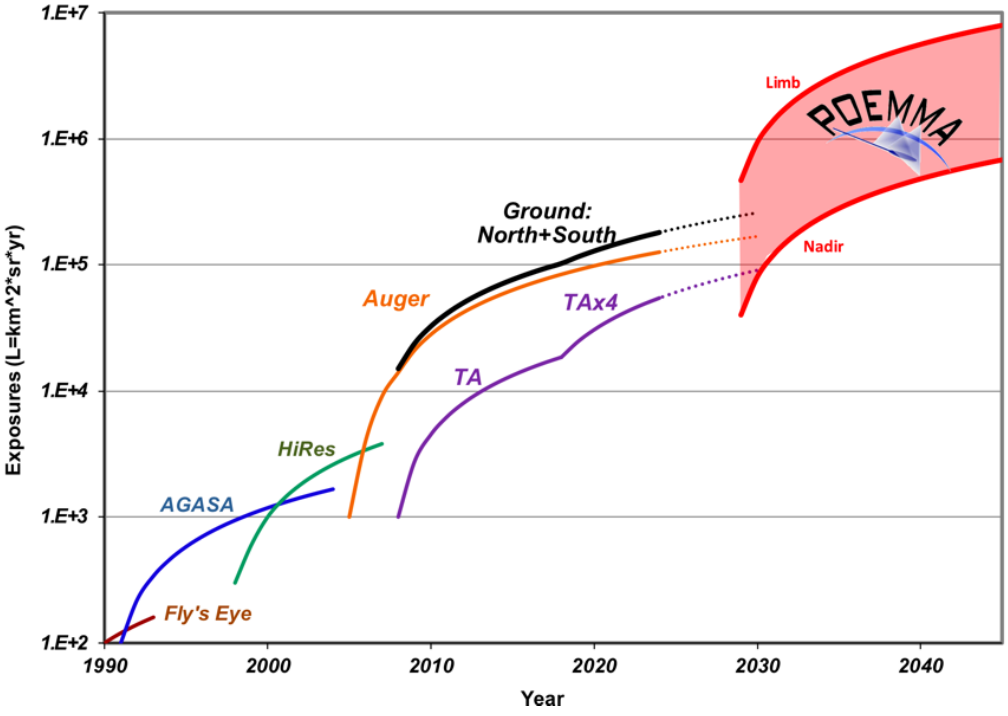


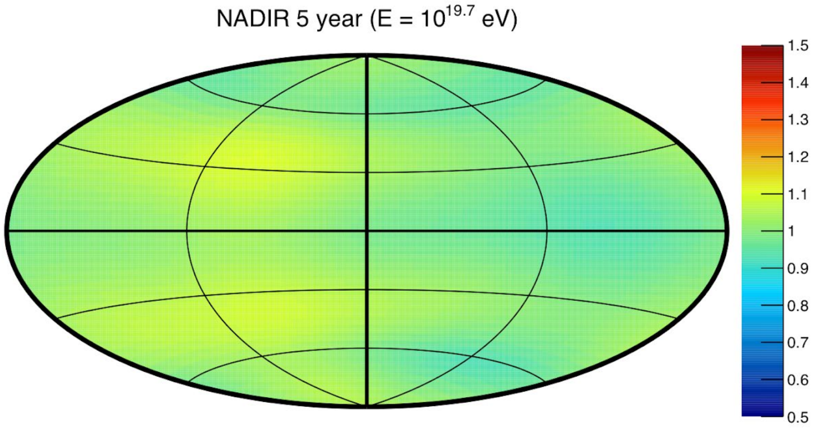


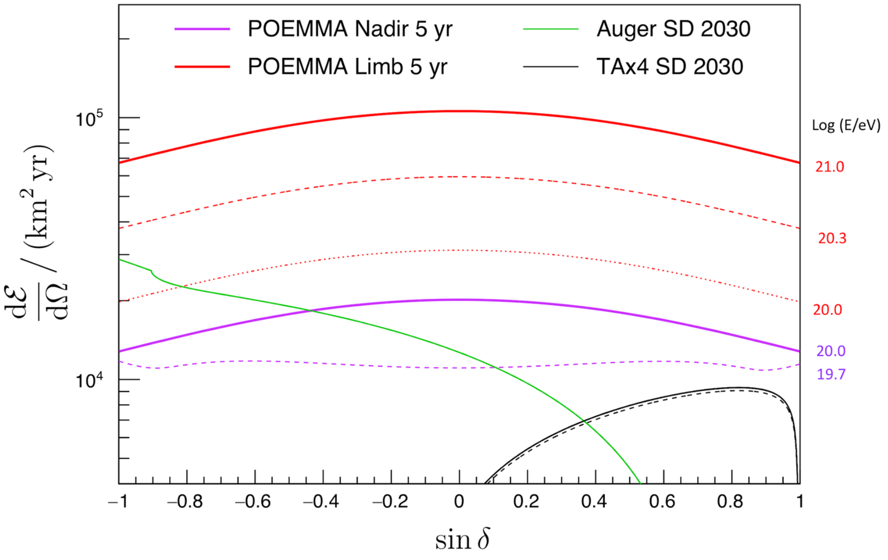
- Cherenkov Optimized Detection
  - 30 SiPM FSU = 15360 pixels
  - 512 pixels/FSU (64x4x2); 300-1000nm
  - 10ns sampling
  - **Updated design based on PBR development**

UHECR Observation Perfromance

- Significant increase in exposure with full sky coverage (by 1 detector)

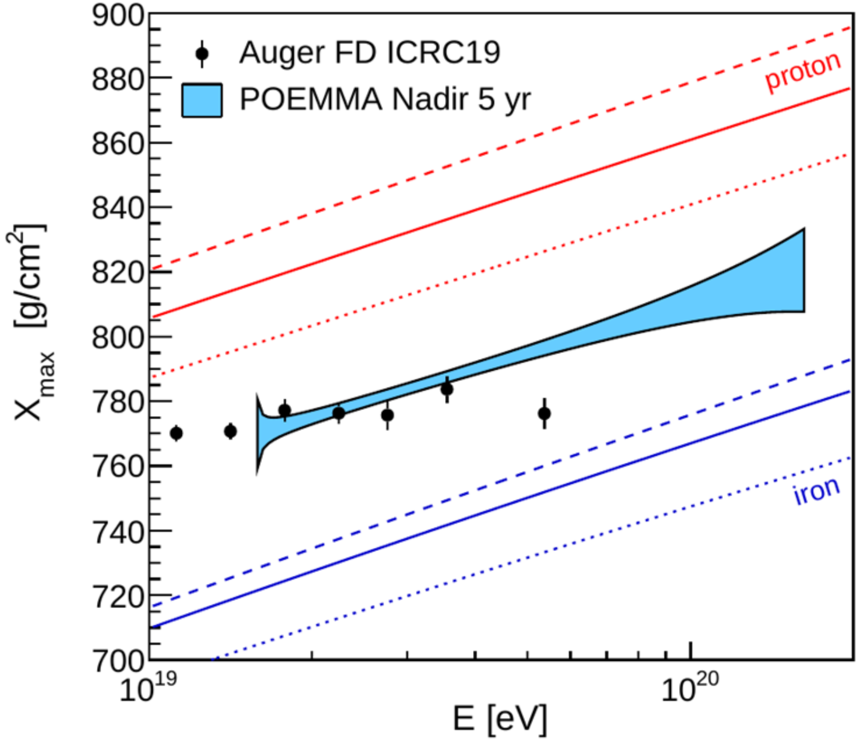


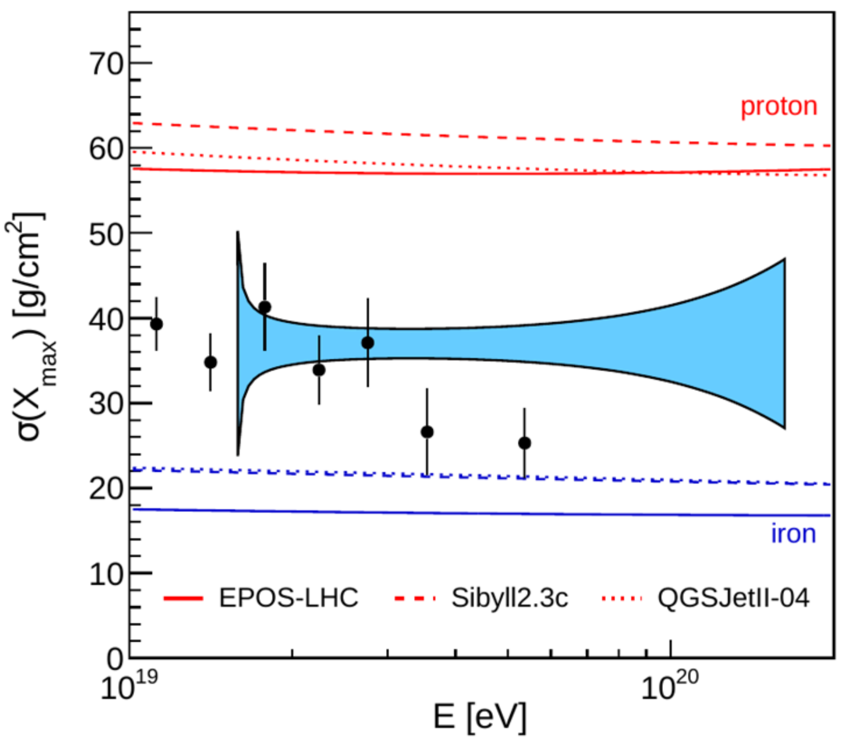




UHECR Observation Perfromance

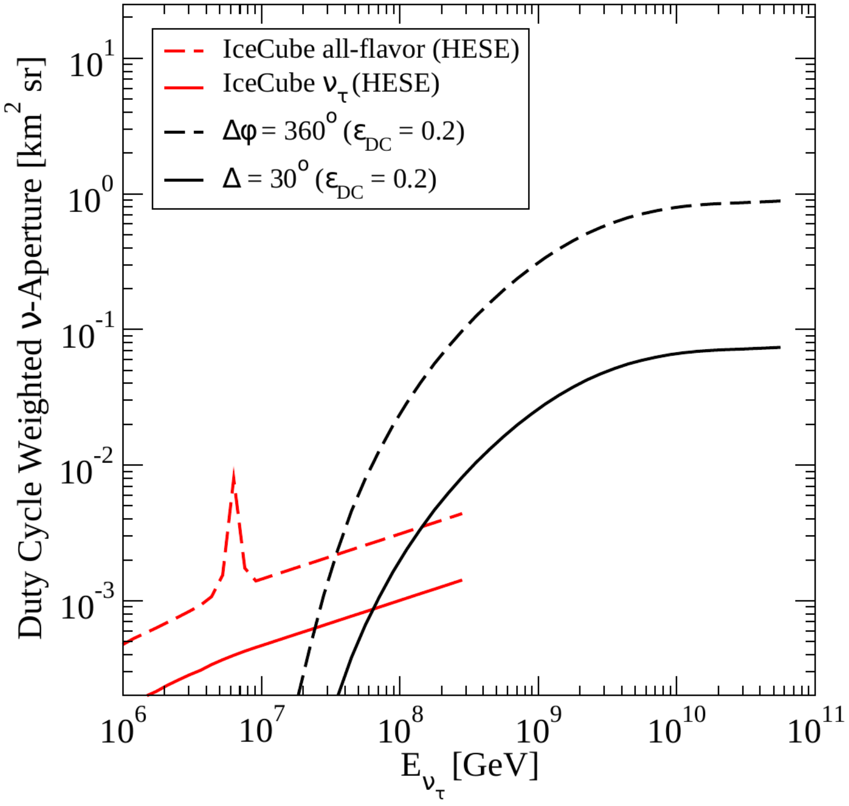
- Spectrum, Composition, Anisotropy: E_{CR} > 20 EeV
  - Very good energy (<20%) angular (<1.2°), composition (σ_{Xmax} <30g/cm2) resolutions





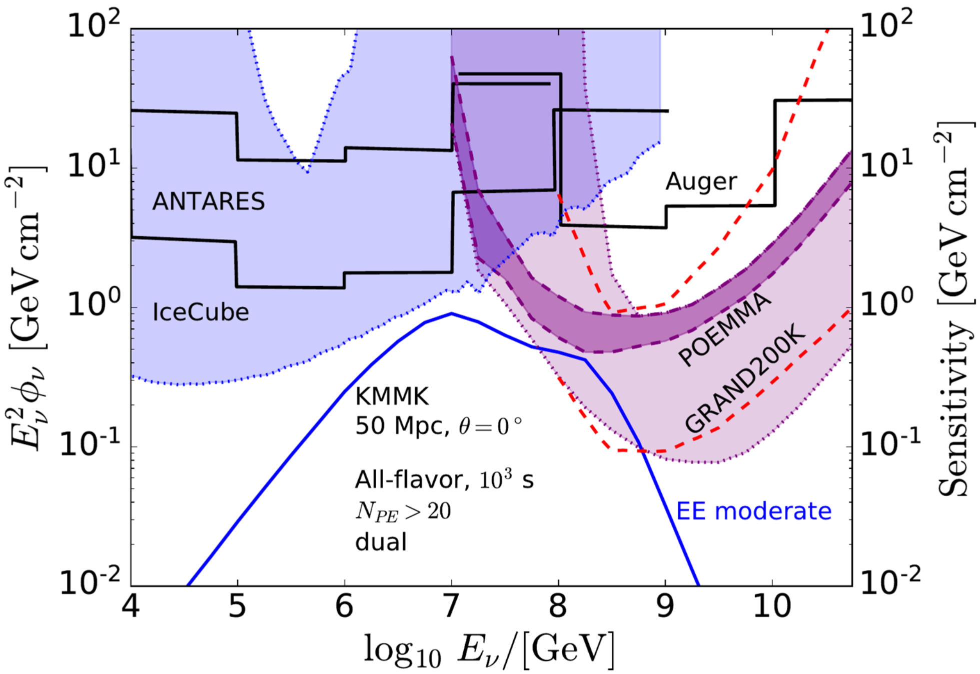
ToO Observation Performance

- No competitive sensitivity to diffuse ν-flux
- Observe Neutrinos from Transient Astrophysical Events
  - τ-lepton EAS from ν_τ interactions in the Earth (E_ν > 20 PeV)

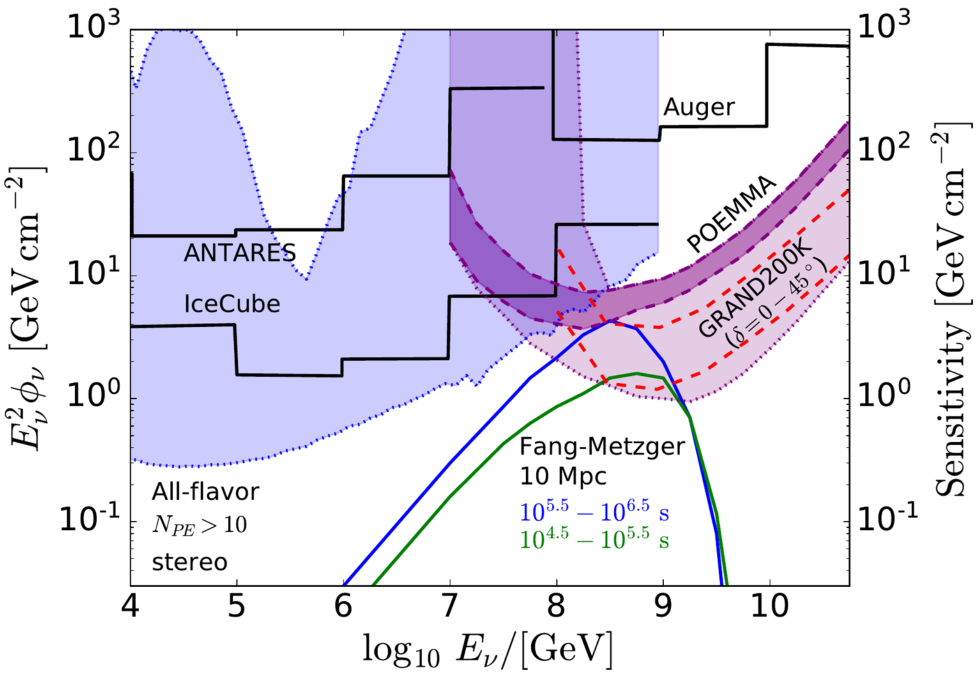


ToO Observation Performance

Short Burst (1000 s)



Long Burst (>10^5s)



- Ideal source location (500s to slew after alert)
- ➡ Two independent Cherenkov measurements
- 20 PE threshold:

- 3 to 24+hr to move Satellite Sep to 50 km
- Simultaneous Cherenkov measurements
- ➡ 10 PE threshold (time coincidence):
  - AirGlowBack < 10^{-3}/year