Particle Astrophysics at Zettavolt Energies with Radio Detectors in Low Lunar Orbit

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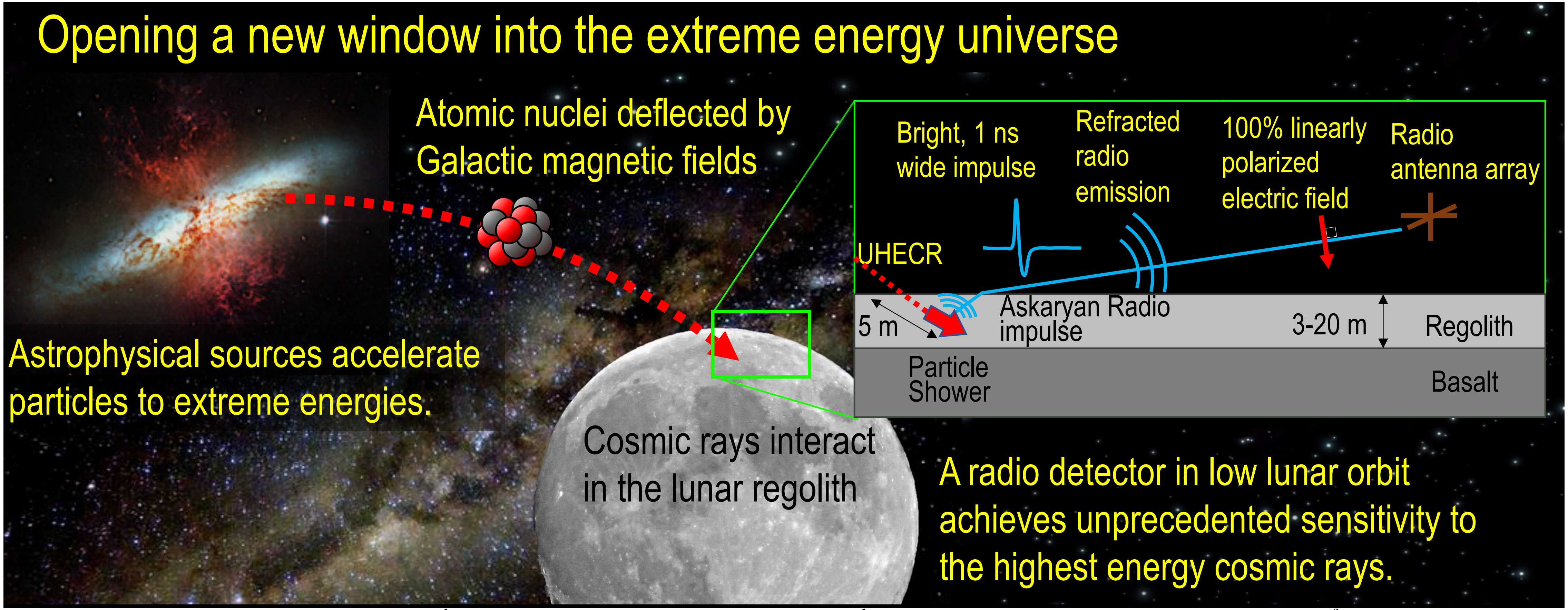
Zettavolt Askaryan Polarimeter ZAP



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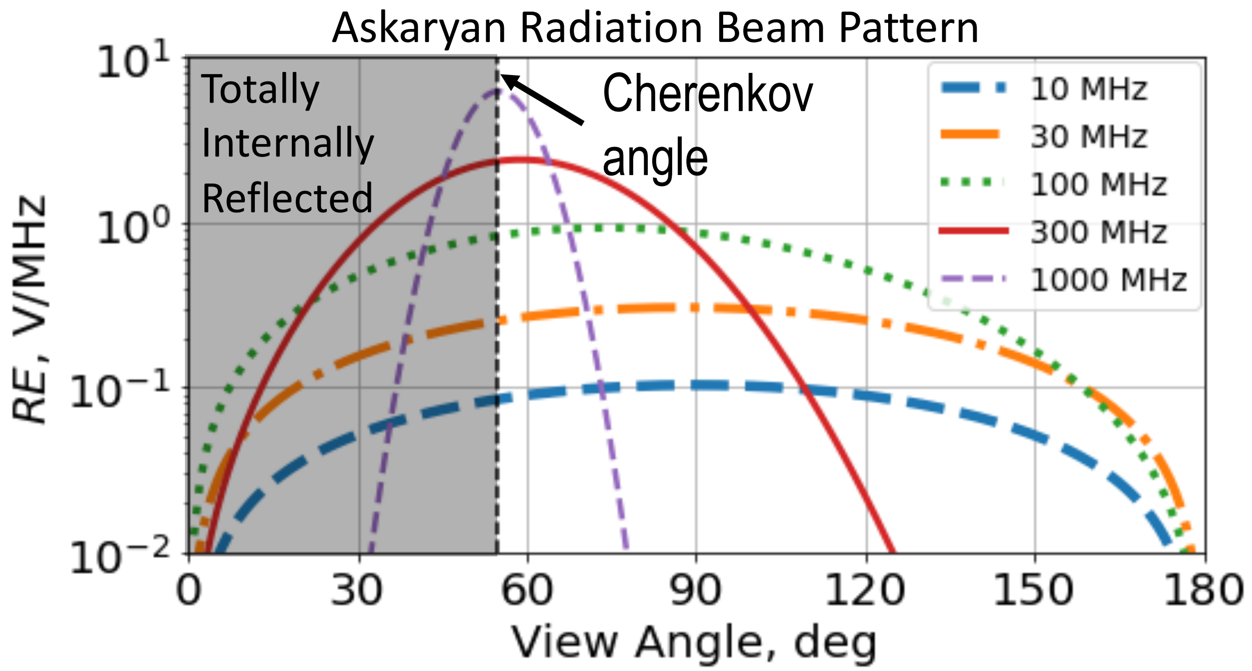
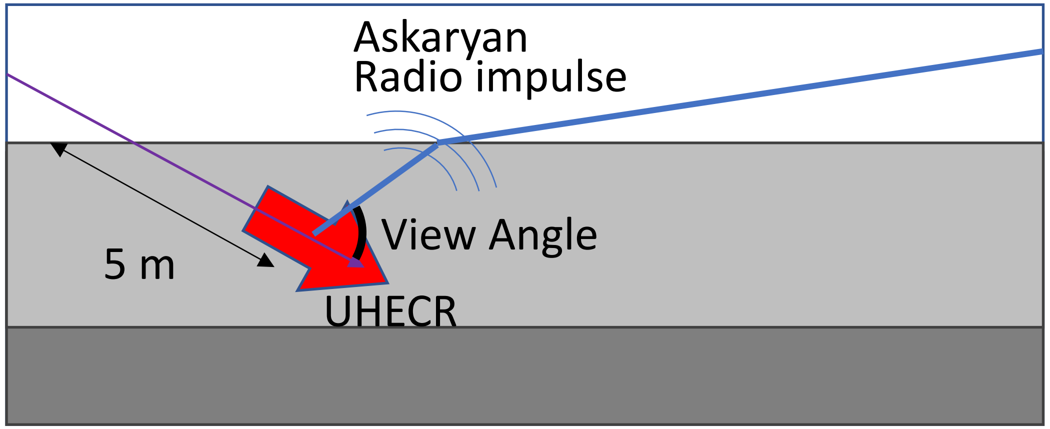
Low Radio Frequencies Provide Access to Higher Energies

- Frequencies < 300 MHz have wide radio beams with a large range of view angles producing a detectable signal at ultra-high energies.

- Frequencies > 300 MHz are narrowly beamed with a small range of view angles producing a detectable signal.

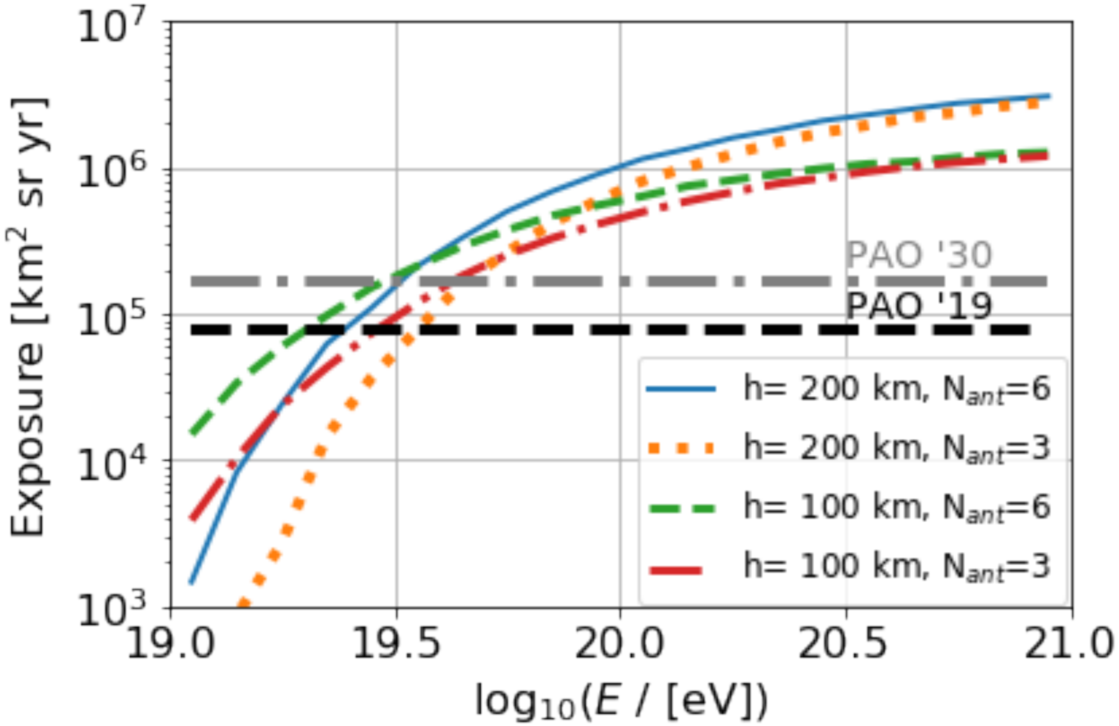




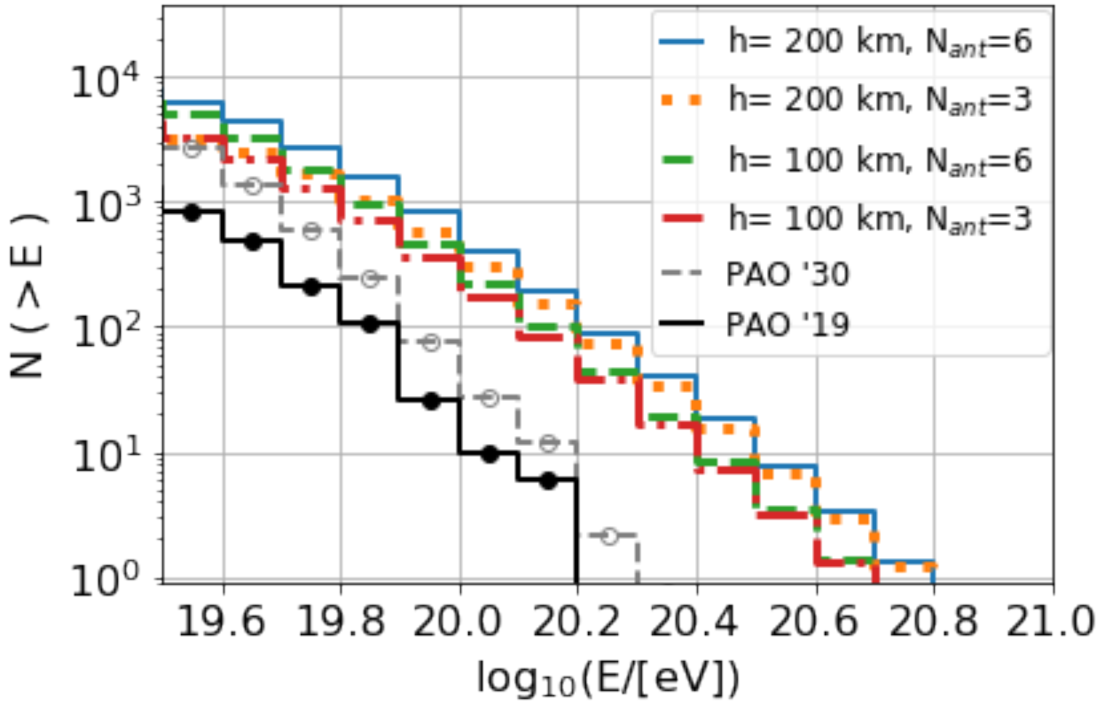
ZAP - prospects

Antenna array in lunar orbit operating for 2 years can increase the statistics by an order of magnitude with full sky coverage.

ZAP Exposure

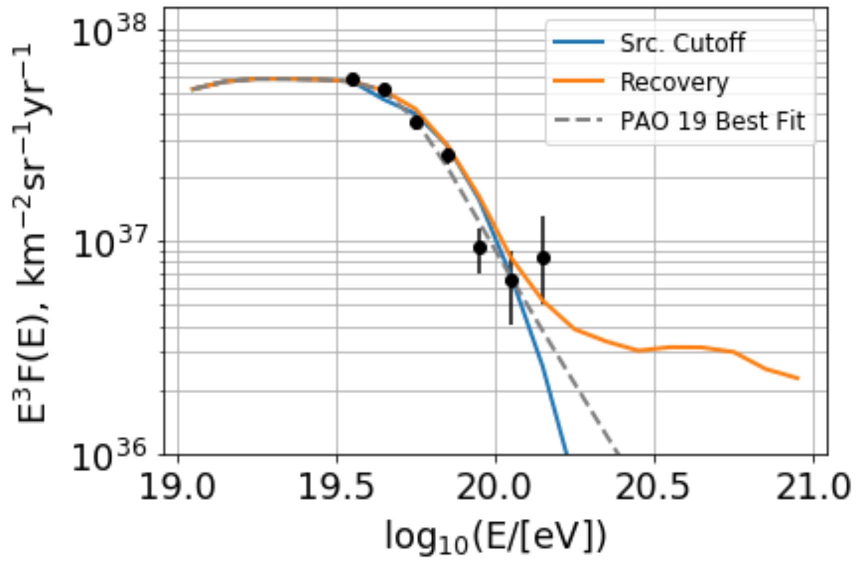


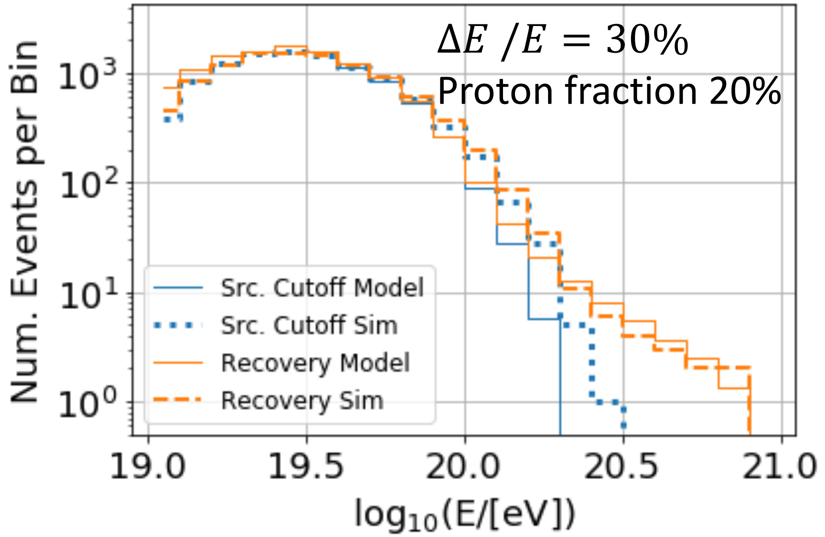
ZAP predicted event counts



ZAP Science – acceleration mechanisms

- Interactions of UHE cosmic rays with photon background (e.g. radio, microwave, IR, optical) result in energy loss during propagation.
- Auger and TA show a clear suppression (20σ significance).
- Increasing mass composition with increasing energy can mean one of two things:
  - Rigidity-dependent maximum energy of nearby sources is limited (running out of steam).
  - Heavier elements are suppressed due to photon fields at the source while lighter elements are not.
    - $E_{max} \propto Z$
    - $\frac{dE}{dx} \propto A$
- Prediction is that the subdominant proton spectrum is recovered for E>$10^{20.2}$ eV.



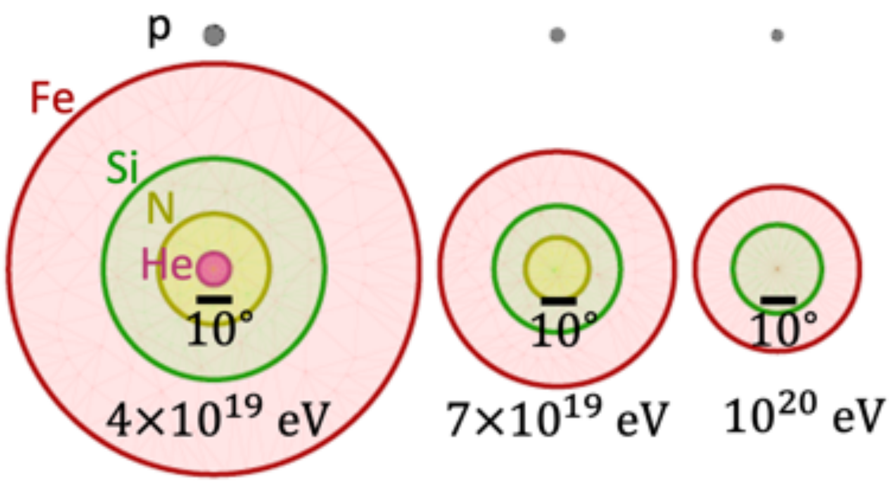


ZAP Science – composition at the highest energies

- ZAP is not sensitive to X_{max} (nuclear composition).
- However, it can test for clustering of hot spots as a function of energy.
- Composition is expected to get heavier with increasing energy.
- Clustering of hotspots as a function of energy could identify clusters could reveal sources of light particles at ultra-high energies expected from energy cutoffs due to photon field.
- This finding would be important for prospects of neutrino astronomy at ultra-high energies.

Scattering due to Galactic magnetic field deflections

$$\theta \sim 1^\circ \, Z \left(\frac{E}{100\ \mathrm{EeV}}\right)^{-1}$$



Adapted from Anchordoqui et al. 2020

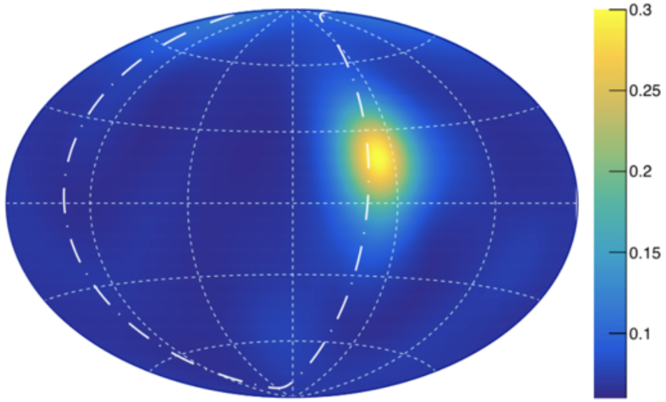
ZAP Science – full sky anisotropy studies

- Independent identification the sources of the highest energy cosmic rays and test the mechanism by which the spectrum cuts off.
- Full sky coverage with $\gtrsim$ 1000 events with $\mathrm{E} \gtrsim 10^{19.6}$ eV

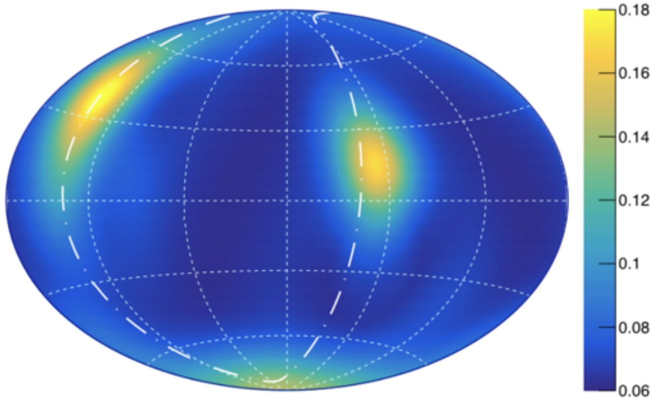
Table 1-1: Anisotropy 5σ requirements.

Parameter		Num. of Events Required		
f_{sig}	**Θ**	AGN	SBG	2MRS
10%	20°	1240	2,060	>5,000
	15°	920	1,910	4,830
15%	20°	680	1,000	2,550
	15°	660	870	2,280
20%	20°	<650	<650	1,520
	15°	<650	<650	1,320

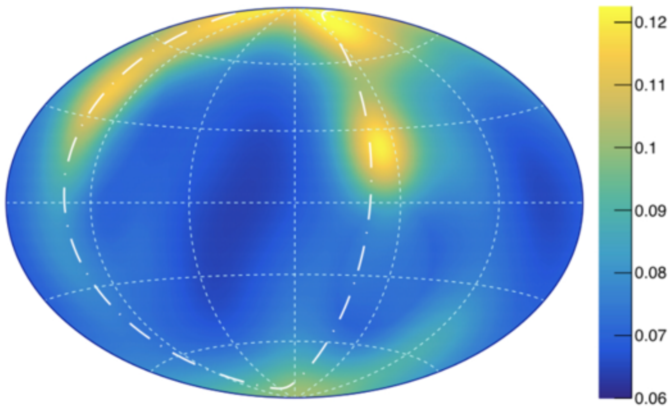
Swift-BAT AGNs



Starburst Galaxies (SBG)



2MRS



ZAP Science – Channels for detection of superheavy dark matter

SHDM identified >ZeV ν's and γ's and directionally correlated with local DM distribution.

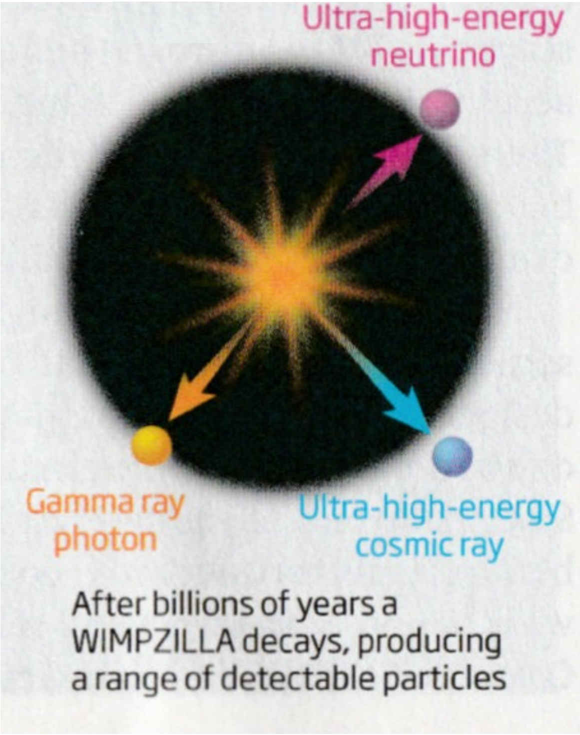
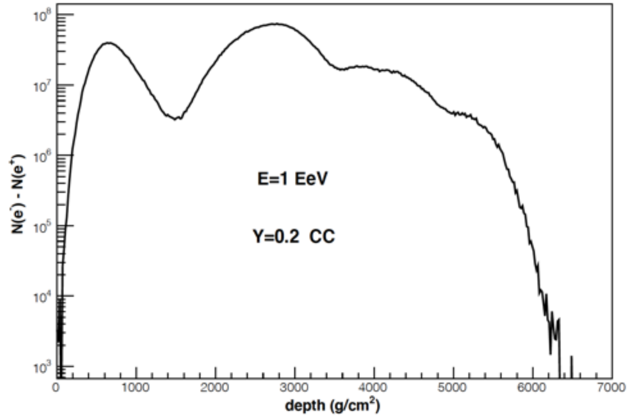
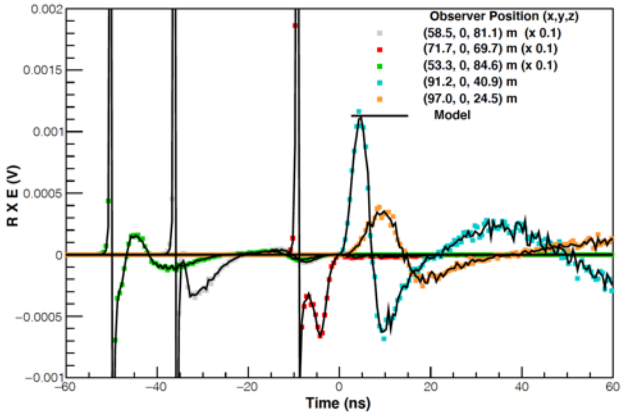


Image credit: new scientist

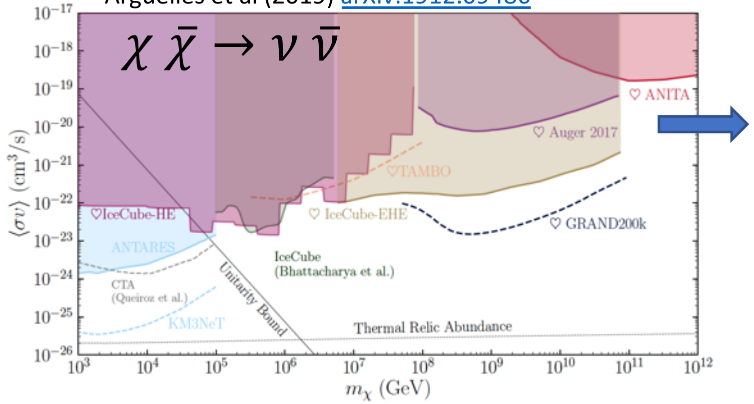
Purely electromagnetic showers can be identified via the LPM effect.



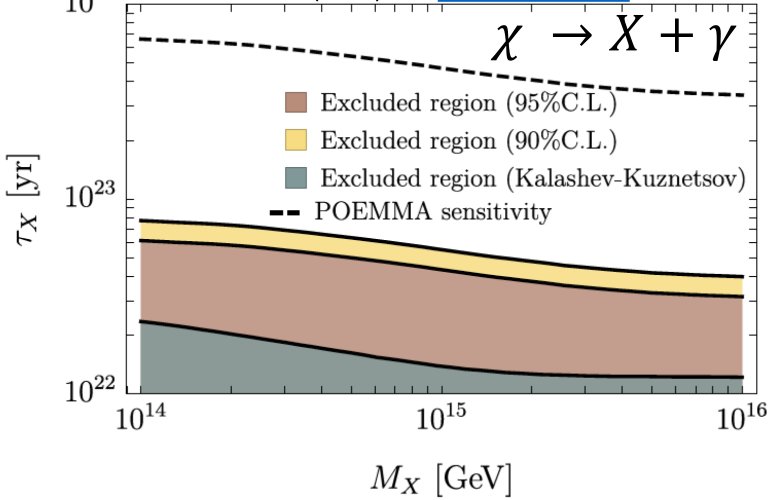


Expected to provide order of magnitude improvements in SHDM constraints.

Argüelles et al (2019) arXiv:1912.09486



Alcantara et al (2019) PRD arXiv:1903.05429



Detector Concept

SmallSat array of short dipoles (~ 1m)

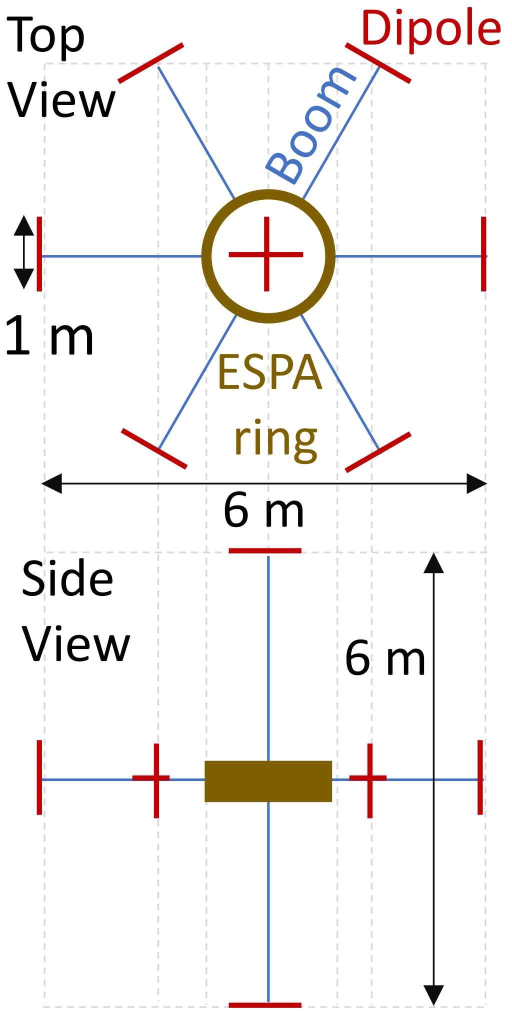
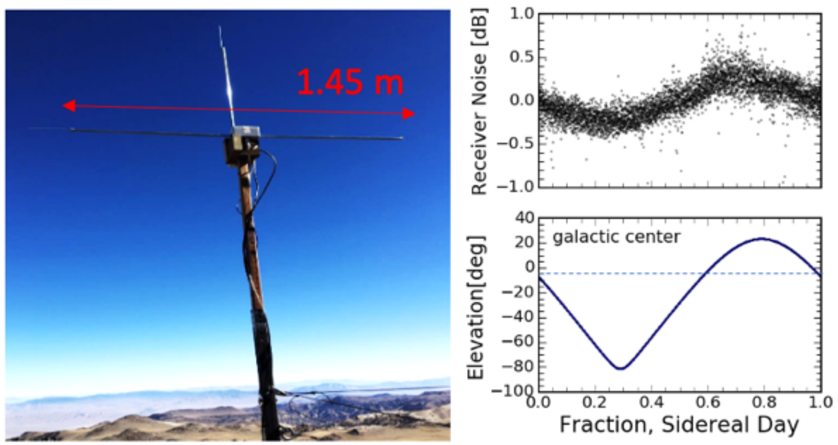
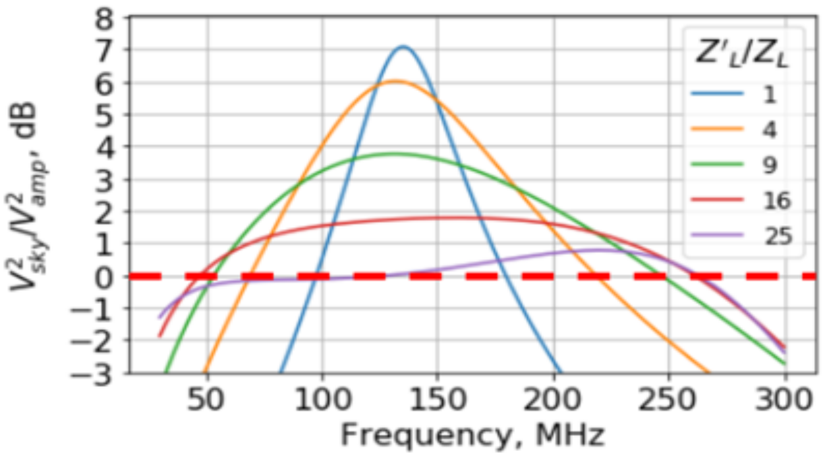


Image credit: E. Oberla



BEACON short dipoles demonstrated Galactic noise limited sensitivity 30 – 80 MHz band.



Sky noise-limited sensitivity of 1 m dipole with impedance transformer.

ANITA heritage of low power digitizers and triggering electronics.

Image credit: ANITA Collaboration

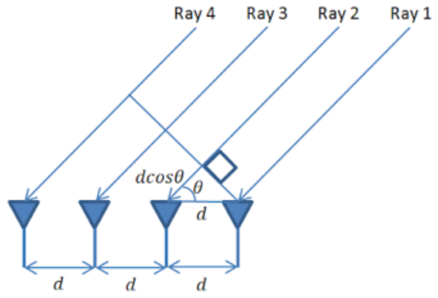
ZAP - Event Reconstruction

Pointing resolution ~10° is achievable
It is possible to drive it down further with more channels.

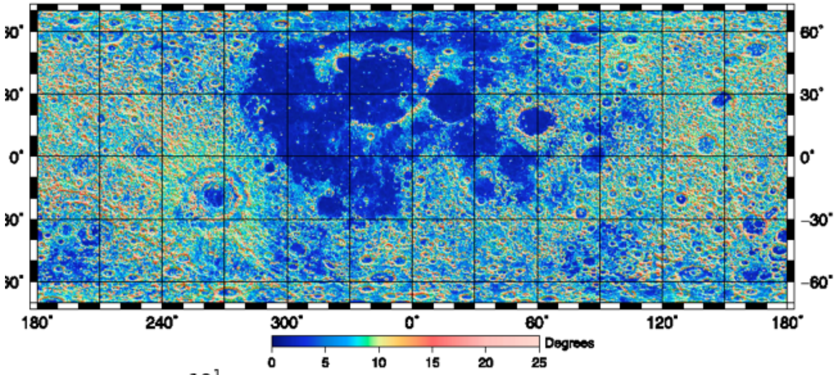
Contribution	Allocation	Depends on…	Controlling parameters
RF Pointing	3°	• Antenna separation. • Signal strength.	• Antenna separation • Sensitivity
Lunar topography	$2-8°$	• RF pointing • Lunar region	• RF pointing (TBD)
In-plane CR tilt angle	5°	• Askaryan signal spectrum	• RF Sensitivity
Out of plane CR tilt angle	8°	• Polarization	• RF Sensitivity

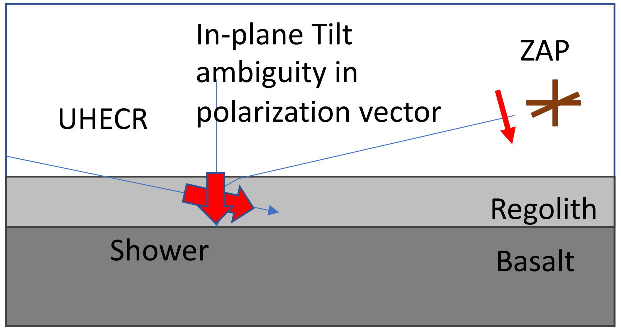
Reconstruction will require 3 or 4 antennas in each polarization (9-12 dipoles total).
Baseline separation > 5m needed.

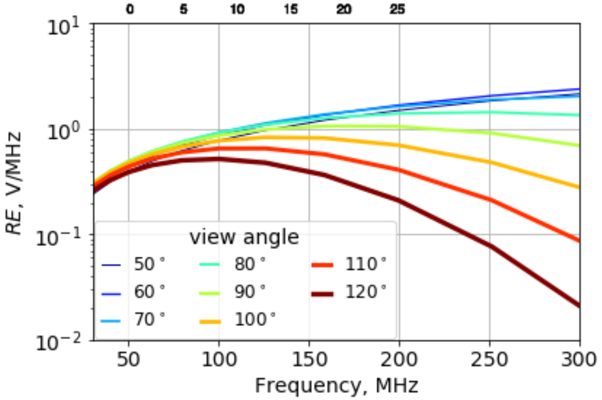
RF Pointing by beamforming

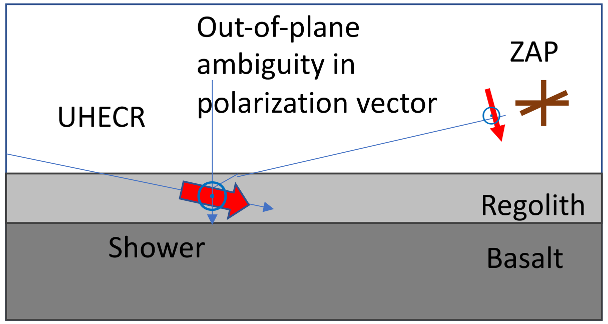


Lunar Topography









Polarization angle resolution

$$\delta\theta \simeq \frac{1}{SNR}$$

Planetary Science Application: Detecting Ice in the Permanently Shadowed Regions of Airless Bodies

- Evidence of relatively pure extensive ice deposits in Mercury's Permanently Shadowed Regions (PSRs).
- Only traces of water ice have been found on the surface of lunar PSRs.
- The Moon could host extensive ice deposits at > 1 m depths.
- UHECRs illuminate subsurface ice!

Mercury

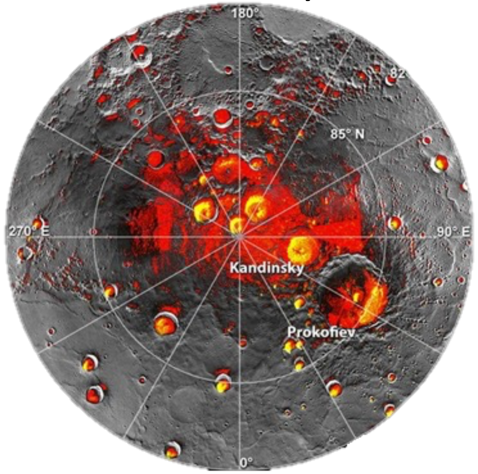


Image Credit: *NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington/National Astronomy and Ionosphere Center, Arecibo Observatory*

Moon

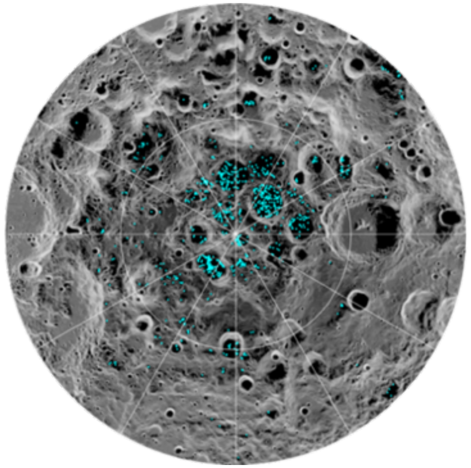


Image Credit: *Li et al. PNAS 2018*

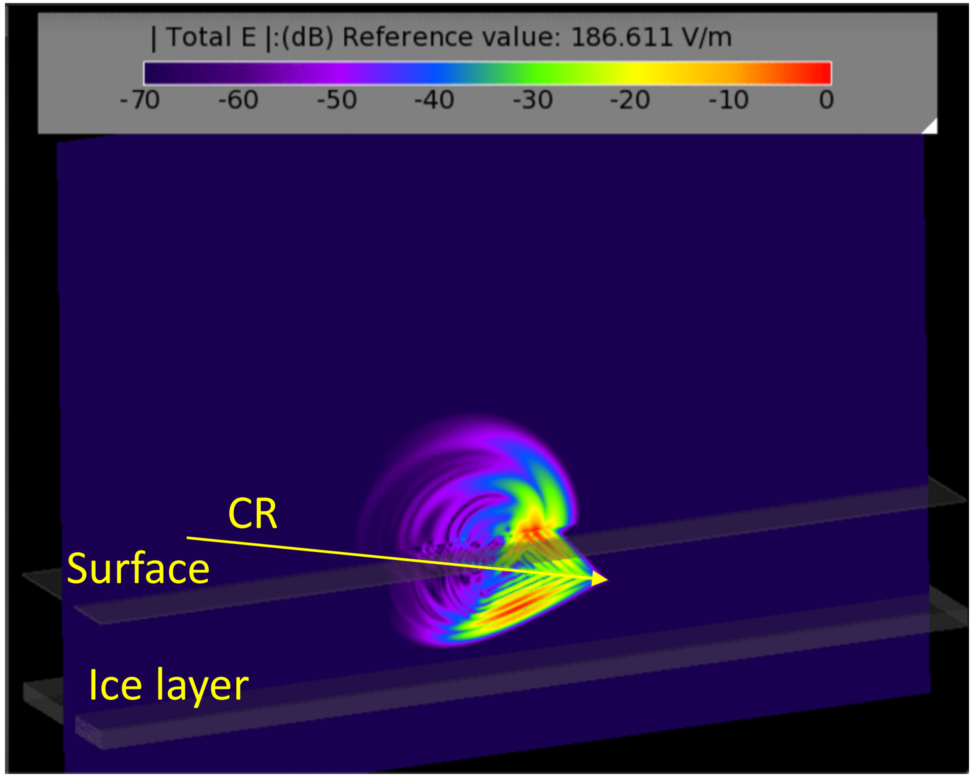


Image credit: P. Gorham w/ Remcom XFDTD

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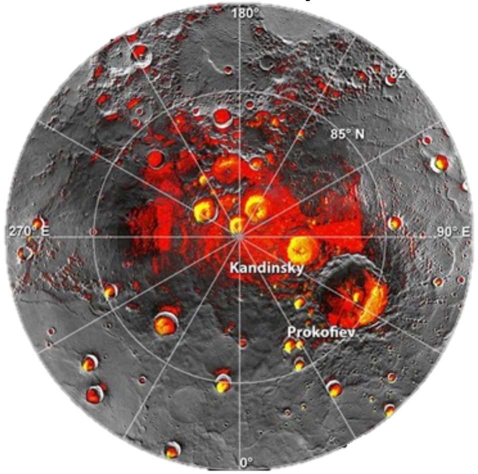
Mercury



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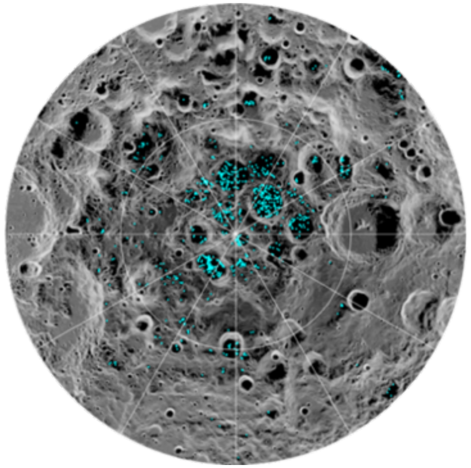

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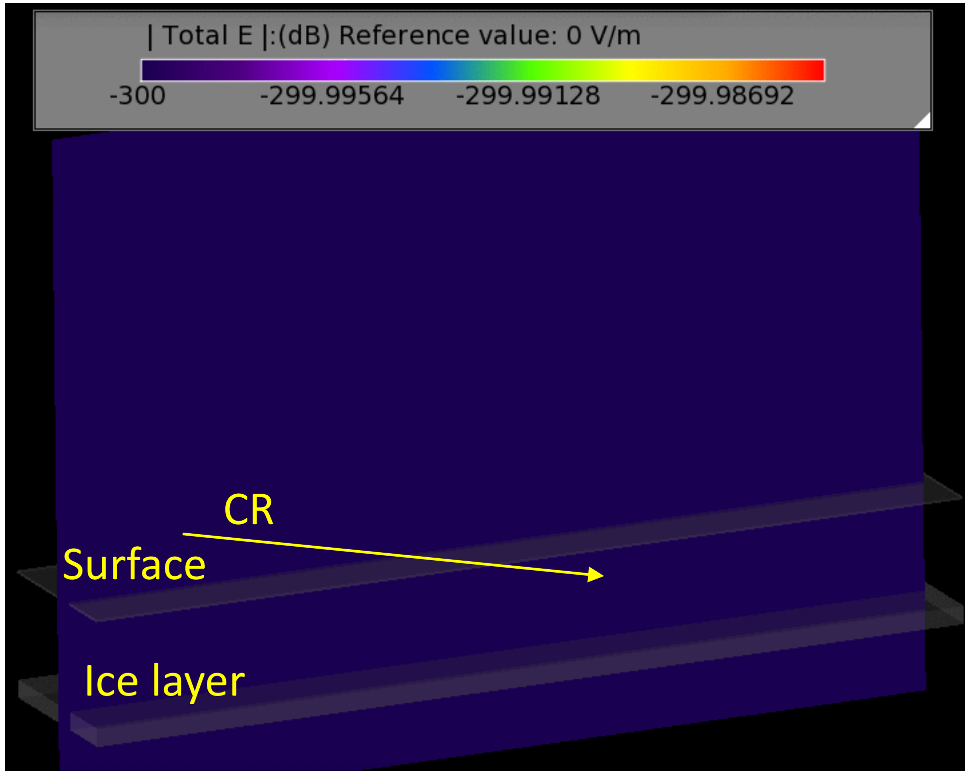

Image credit: P. Gorham w/ Remcom XFDTD

Outlook and Conclusions

- Lunar detector concept under development.
  - Event clustering simulations at the highest energies.
  - Particle and radio emission propagation models for the Moon.
  - Development of ultra-wide band electrically short dipole.
  - Sensitivity to extensive ice deposits.
- Initial estimates of a low-frequency antenna array in lunar orbit show promising prospects for extremely high energy particles not available to ground arrays.
- ZAP offers a low cost way to search for extensive ice deposits in the permanently shadowed regions of airless bodies.