The Zettavolt Askaryan Polarimeter (ZAP) mission concept: radio detection of ultra-high energy cosmic rays in low lunar orbit.

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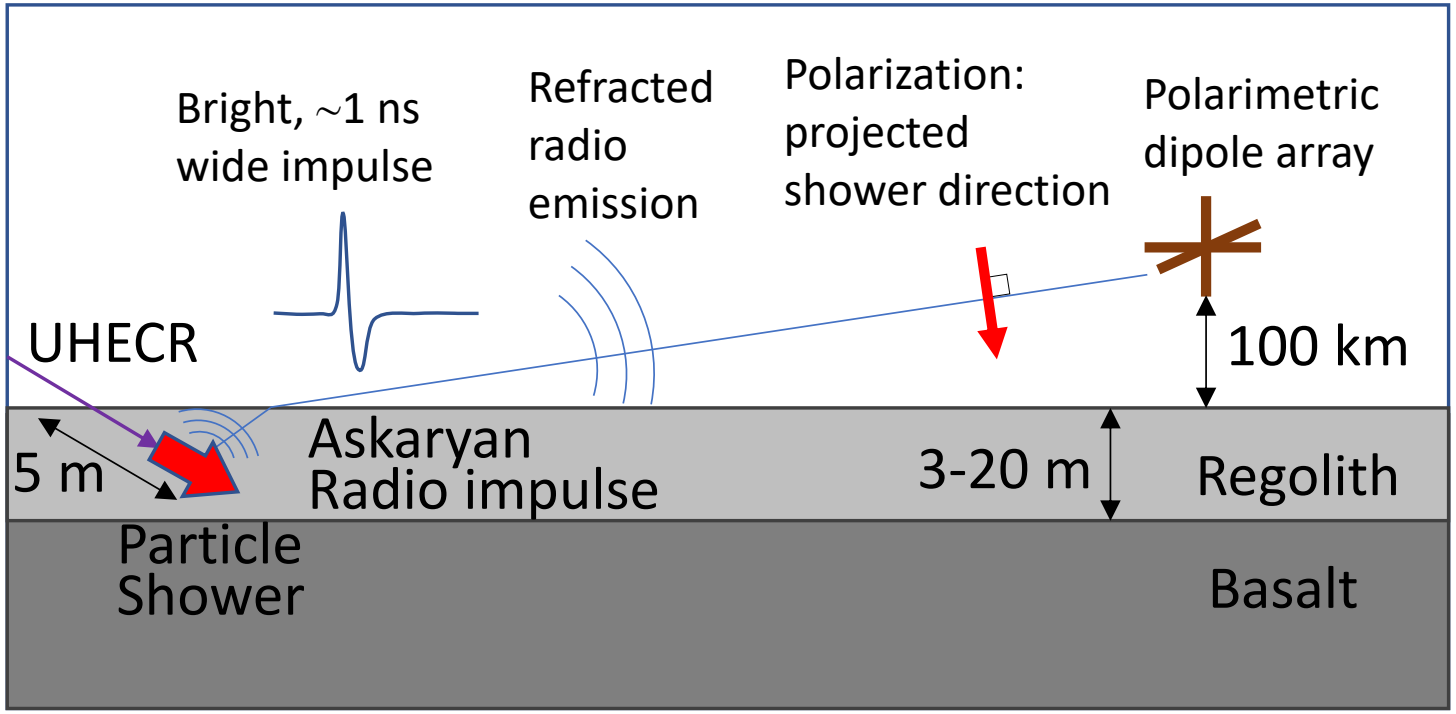
Zettavolt Askaryan Polarimeter

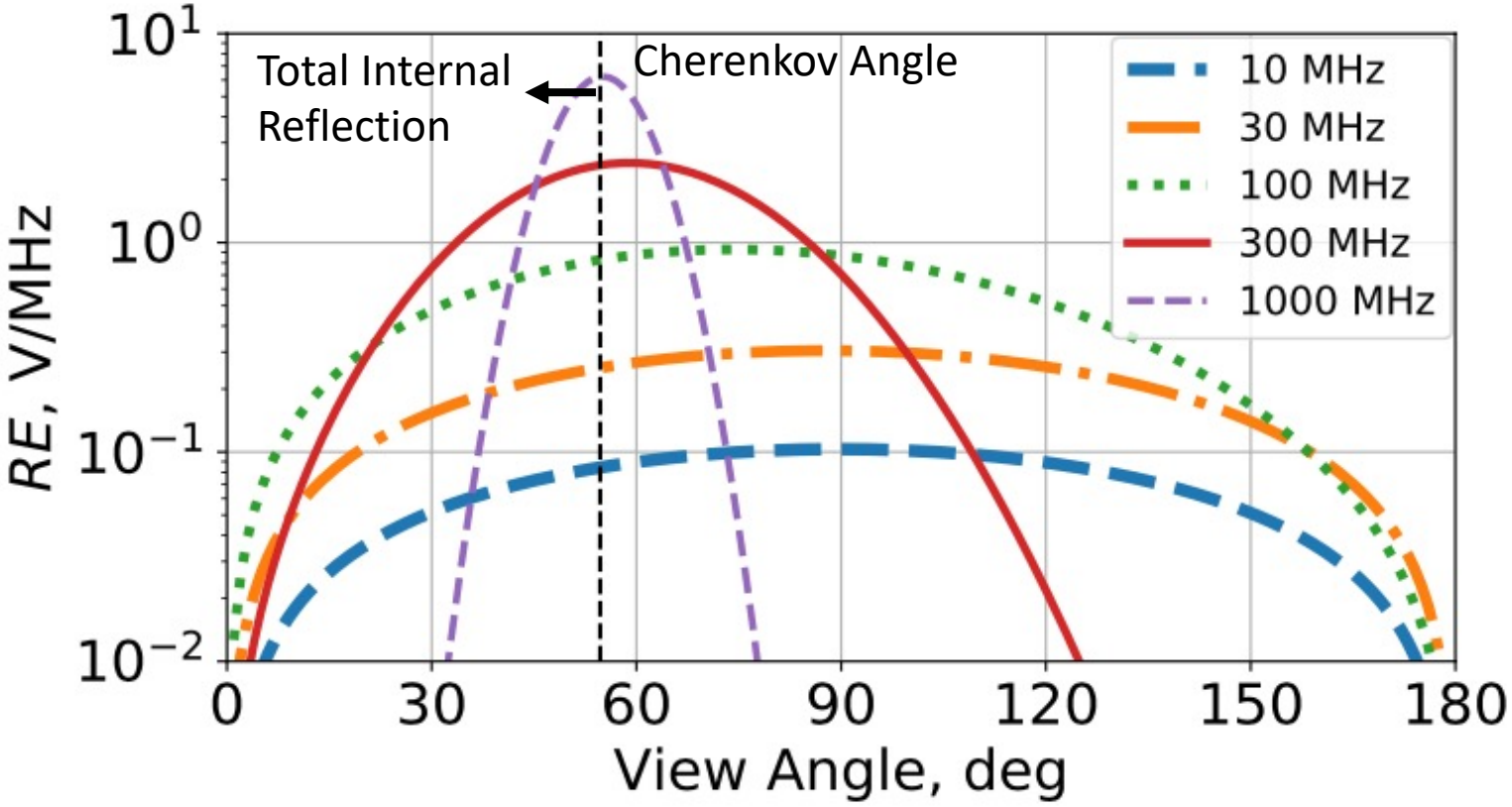
ZAP

- Detection of UHECR radio pulses produced by interactions in the lunar regolith (PI: A. Romero-Wolf, JPL).
- Smallsat with VHF (30-300 MHz) polarimetric antenna array.
- Leverages successful developments of NASA's ANITA suborbital UHE particle observatory.



Low frequencies enable large exposures

- Askaryan radiation at low frequencies has a broad beam pattern.
- Extremely high energy events are visible from a broad range of view angles at low frequencies (<100 MHz).



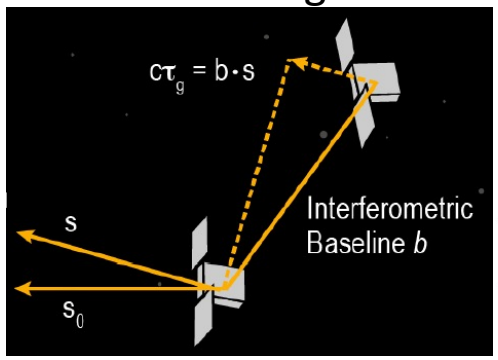
ZAP - Event Reconstruction

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

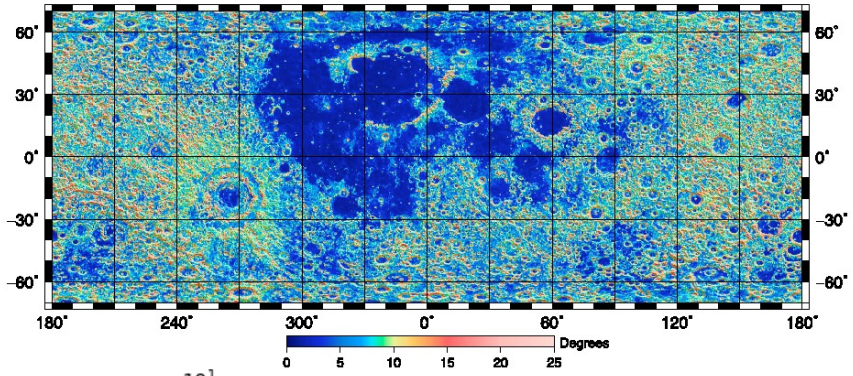
Contribution	Allocation	Depends on…	Controlling parameters
RF Pointing	3°	• Antenna separation. • Signal strength.	• Antenna separation • Sensitivity
Lunar topography	1 – 3°	• RF pointing • Lunar region	• RF pointing (TBD)
In-plane CR tilt angle	5°	• Askaryan signal spectrum	• RF Sensitivity
Out of plane CR tilt angle	8°	• Polarization	• RF Sensitivity

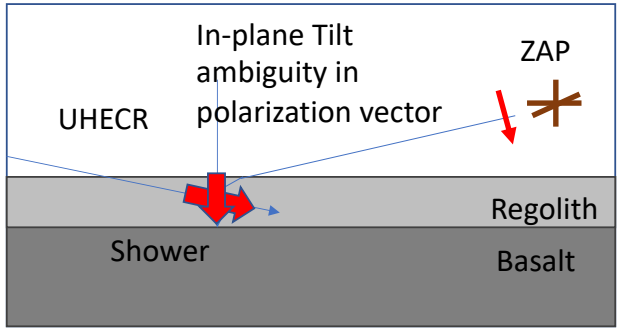
Reconstruction will require 3 or 4 antennas in each polarization (9-12 dipoles total).
Baseline separation > 6 m needed.

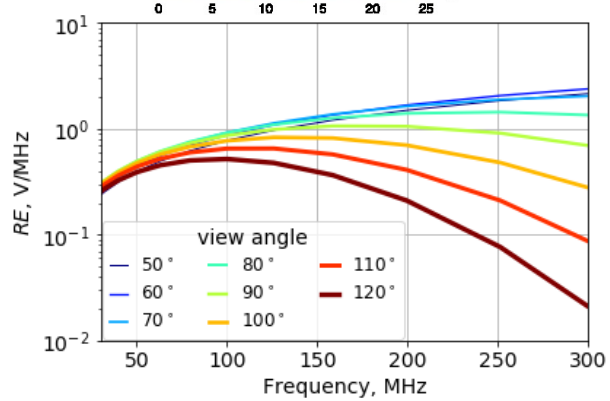
RF Pointing

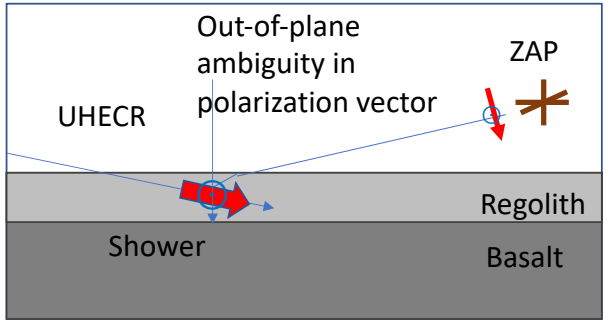


Lunar Topography







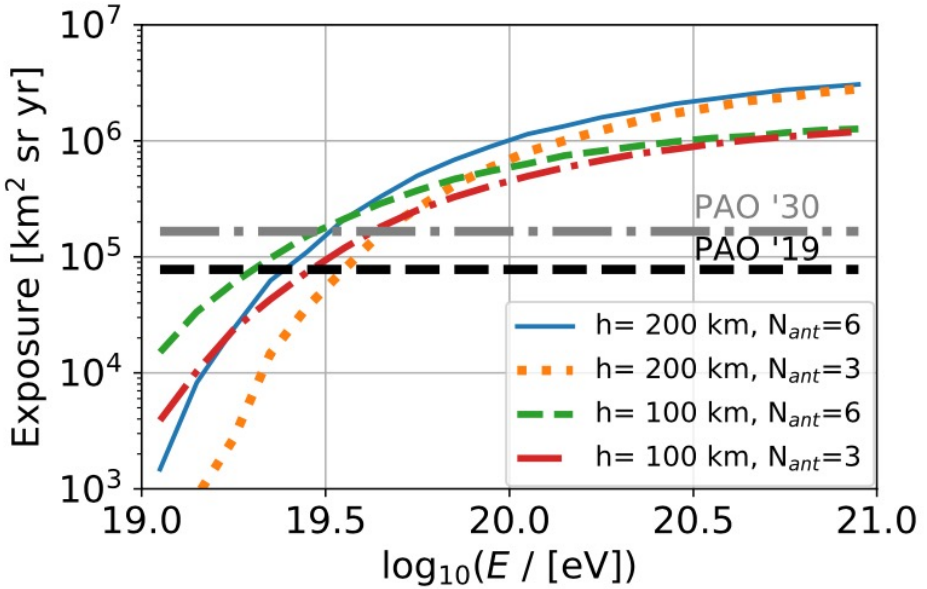


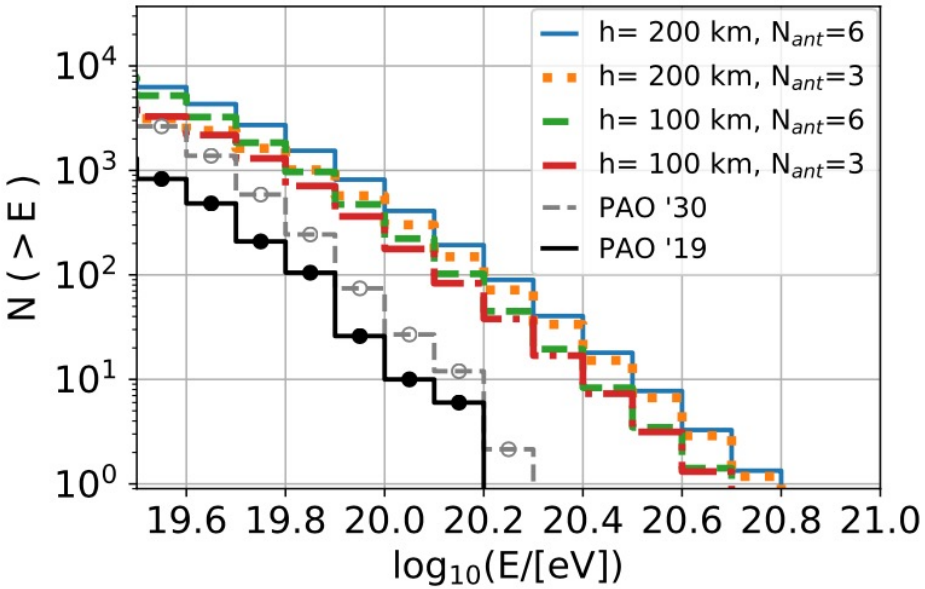
Polarization angle resolution

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

ZAP - prospects

Single smallsat in low lunar orbit operating for 2 years can achive >2,000 events with full sky coverage.

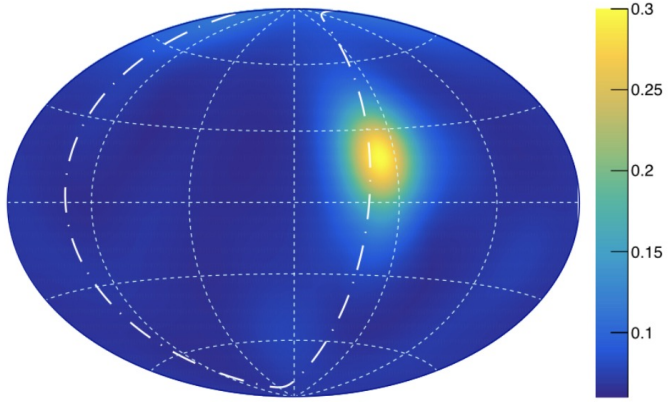




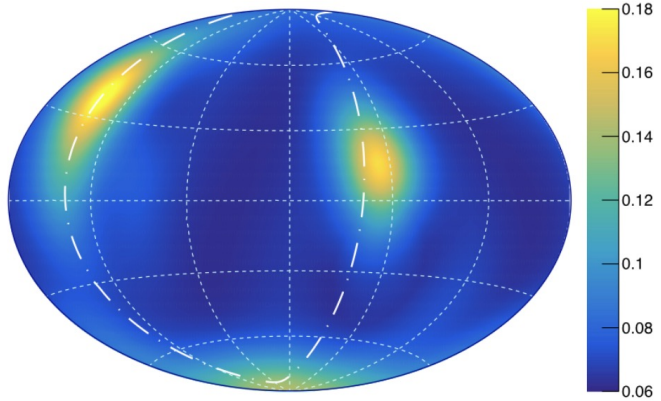
ZAP Science – full sky anisotropy studies

- 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

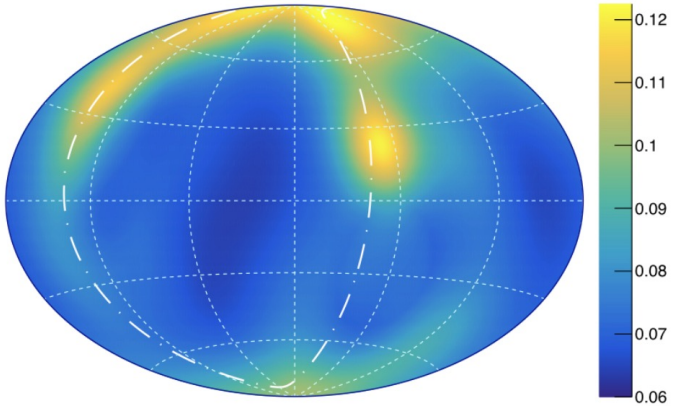
Swift-BAT AGNs



Starburst Galaxies (SBG)

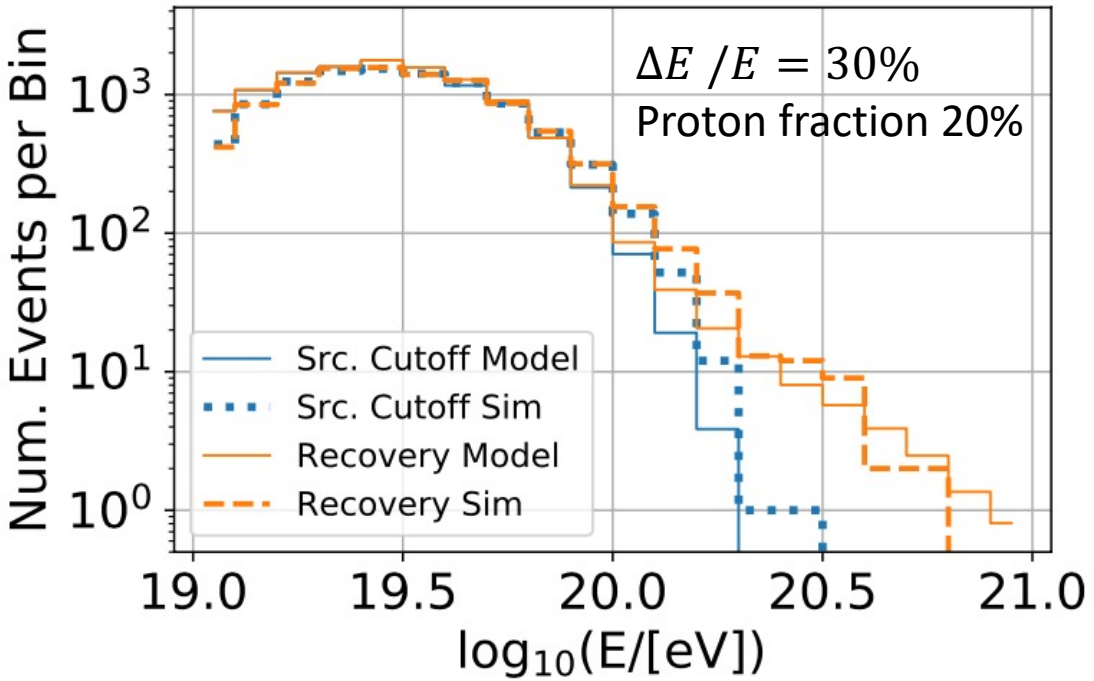


2MRS



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:
  - The acceleration potential 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.

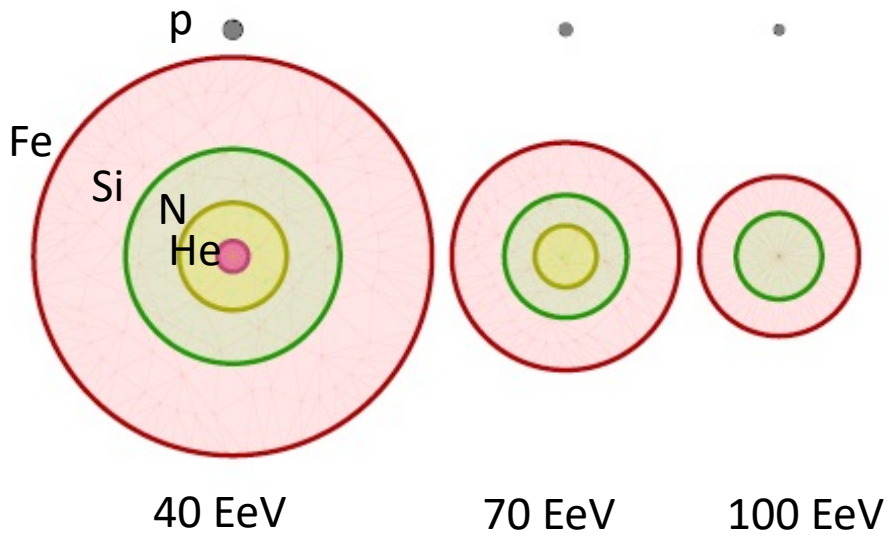


ZAP Science – composition at the highest energies

- ZAP is not sensitive to Xmax.
- 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.

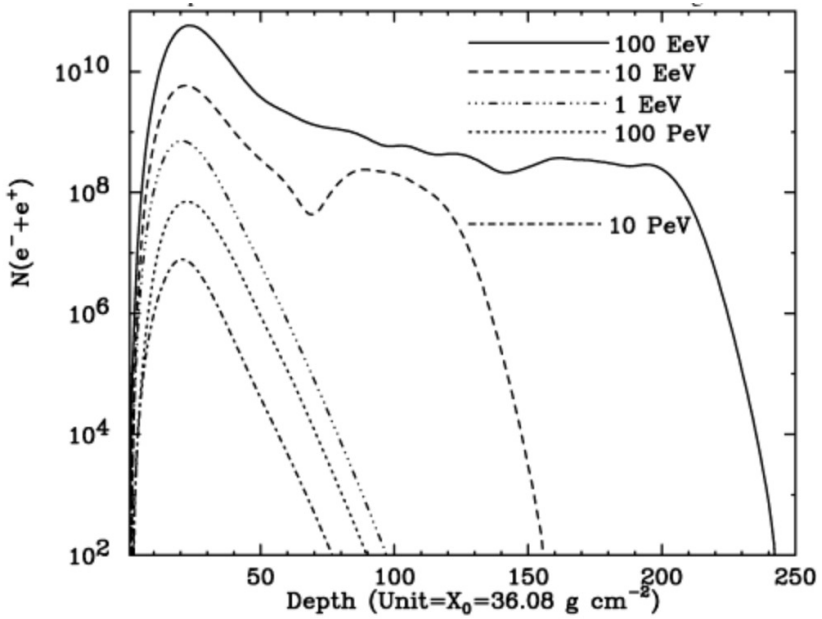
Scattering due to Galactic magnetic field deflections

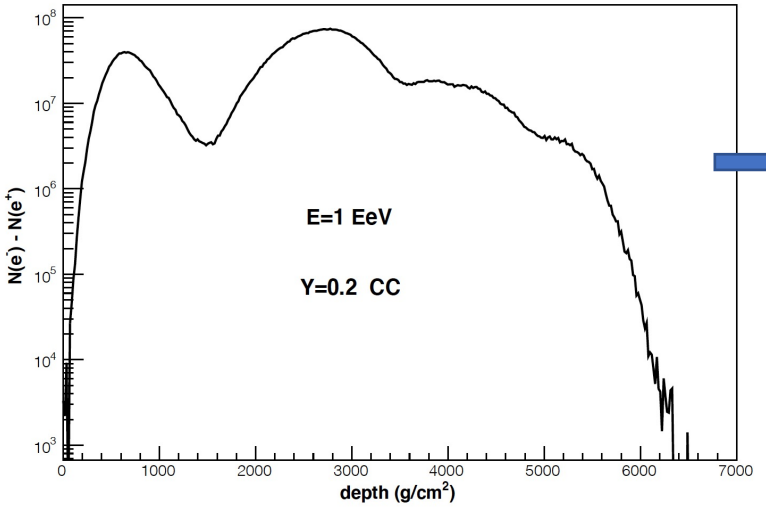
$$\theta \sim 1^\circ \, Z \left(\frac{E}{100 \text{ EeV}}\right)^{-1}$$

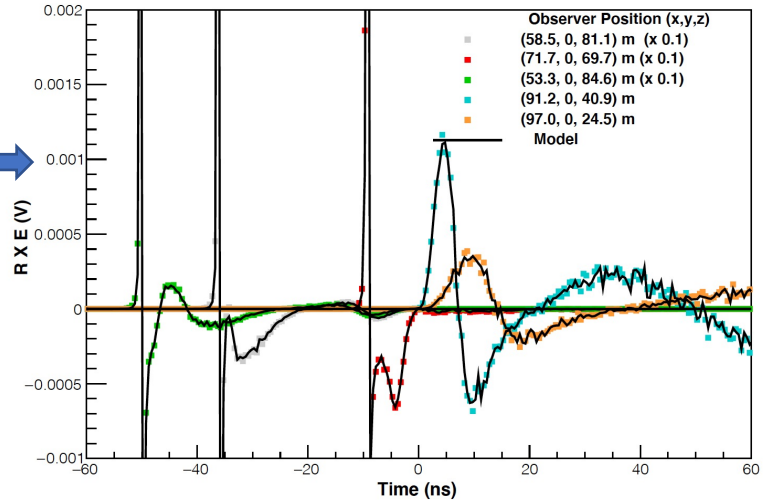


ZAP Science: Superheavy Dark Matter via the LPM Effect

- LPM effect is a suppression of the cross-section of electromagnetic particles at UHE.
- It results in multiple shower trains that results in structure in the Askaryan radio pulse.

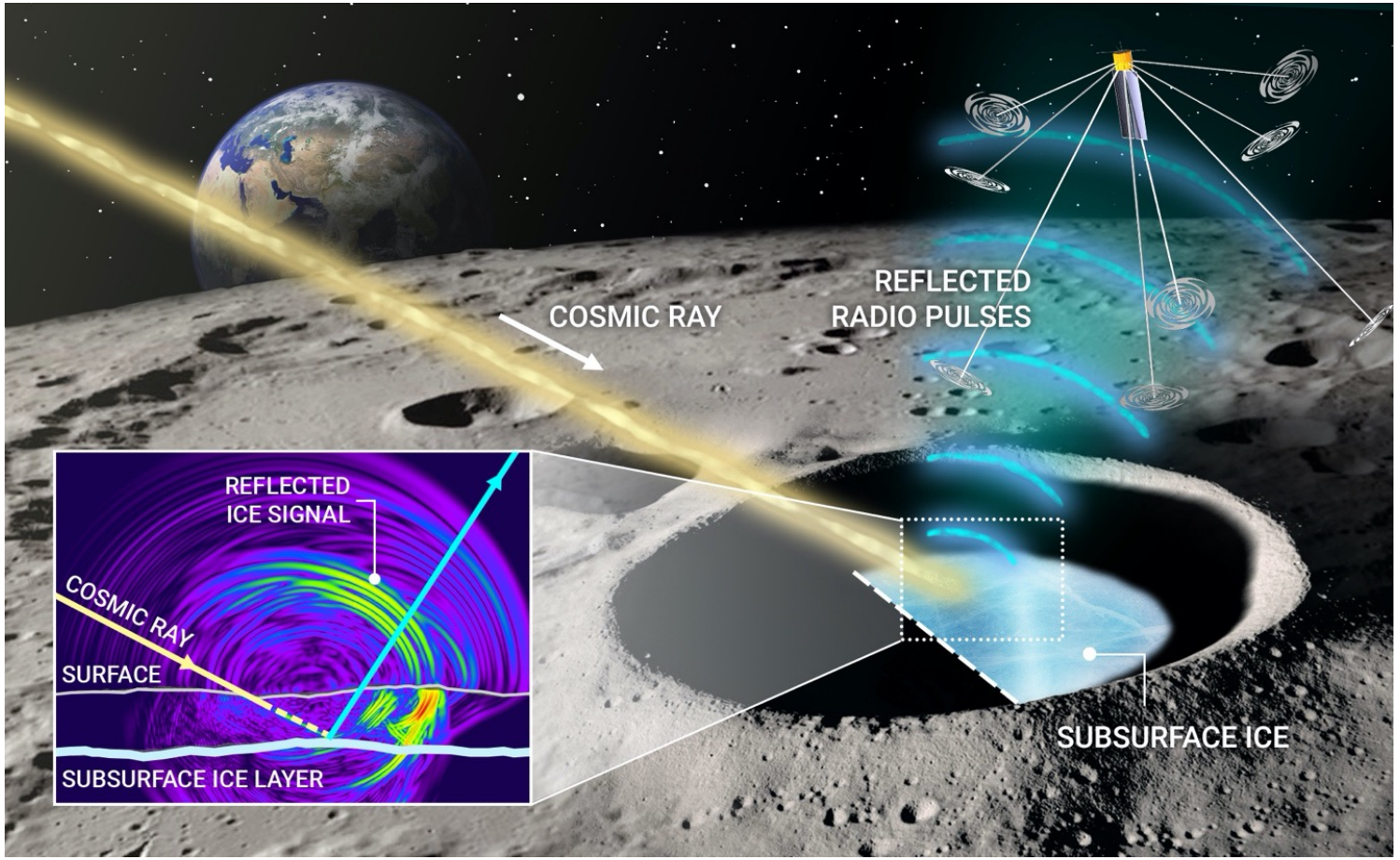






ZAP has a planetary science capability

Search for extensive ice deposits in the permanently shadowed regions of Solar System airless bodies.



Full Authors List: ZAP Collaboration

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Conclusions

Exciting prospects for cosmic rays astrophysics

- The next decade of ground arrays will bring exciting new results in ultra-high energy cosmic rays
  - Anisotropy and source identification.
  - Improvements in composition.
  - Understanding the proton fraction.
- ZAP could provide unprecedented sensitivity at energies $\gtrsim 10^{20}$ eV.
  - Anisotropy at higher energies.
  - Constraining the acceleration source mechanism and prospects for neutrino astronomy at ultra-high energies.
  - A probe of superheavy dark matter.

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