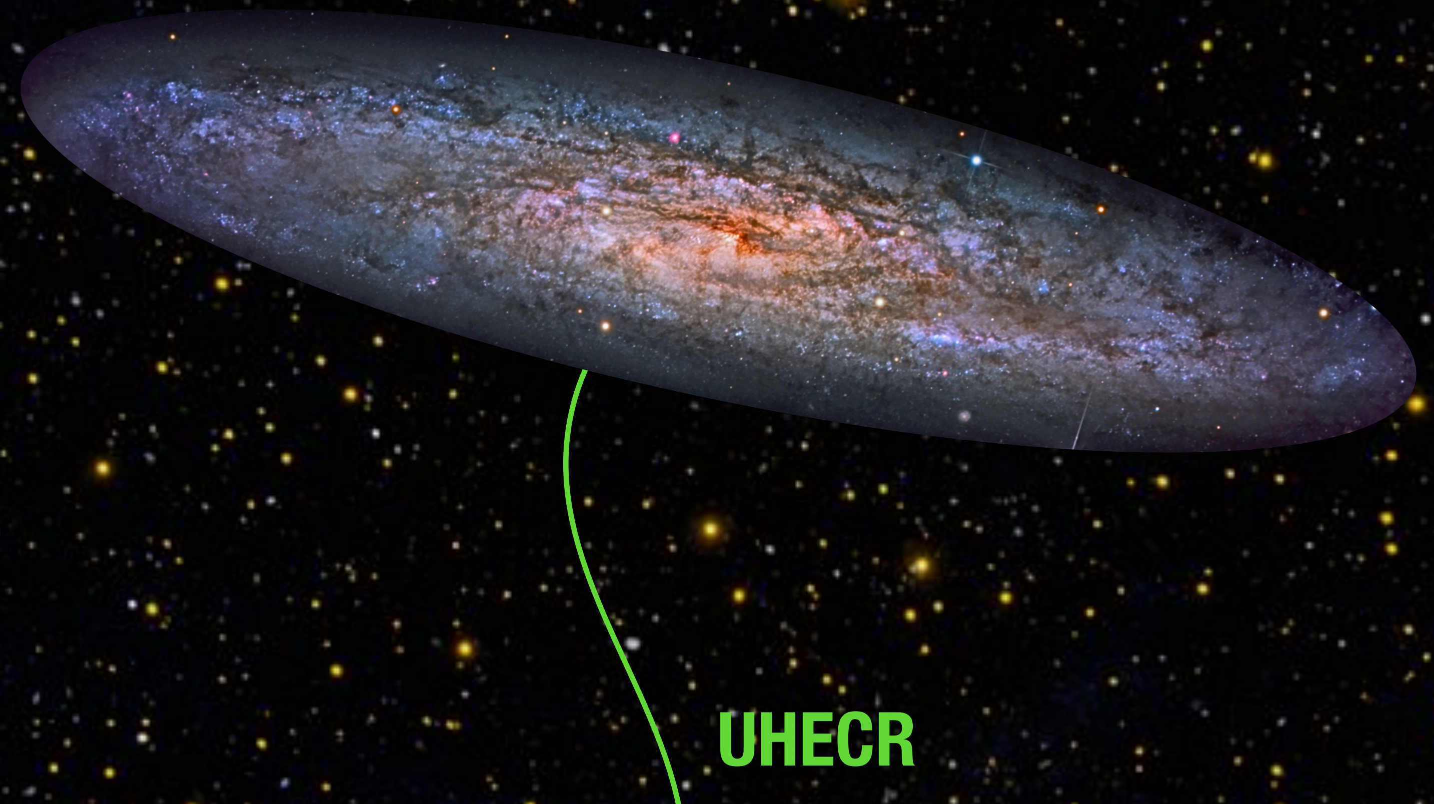

Prospects for Cross-correlations of UHECR Events with Astrophysical Sources with Space-based Experiments

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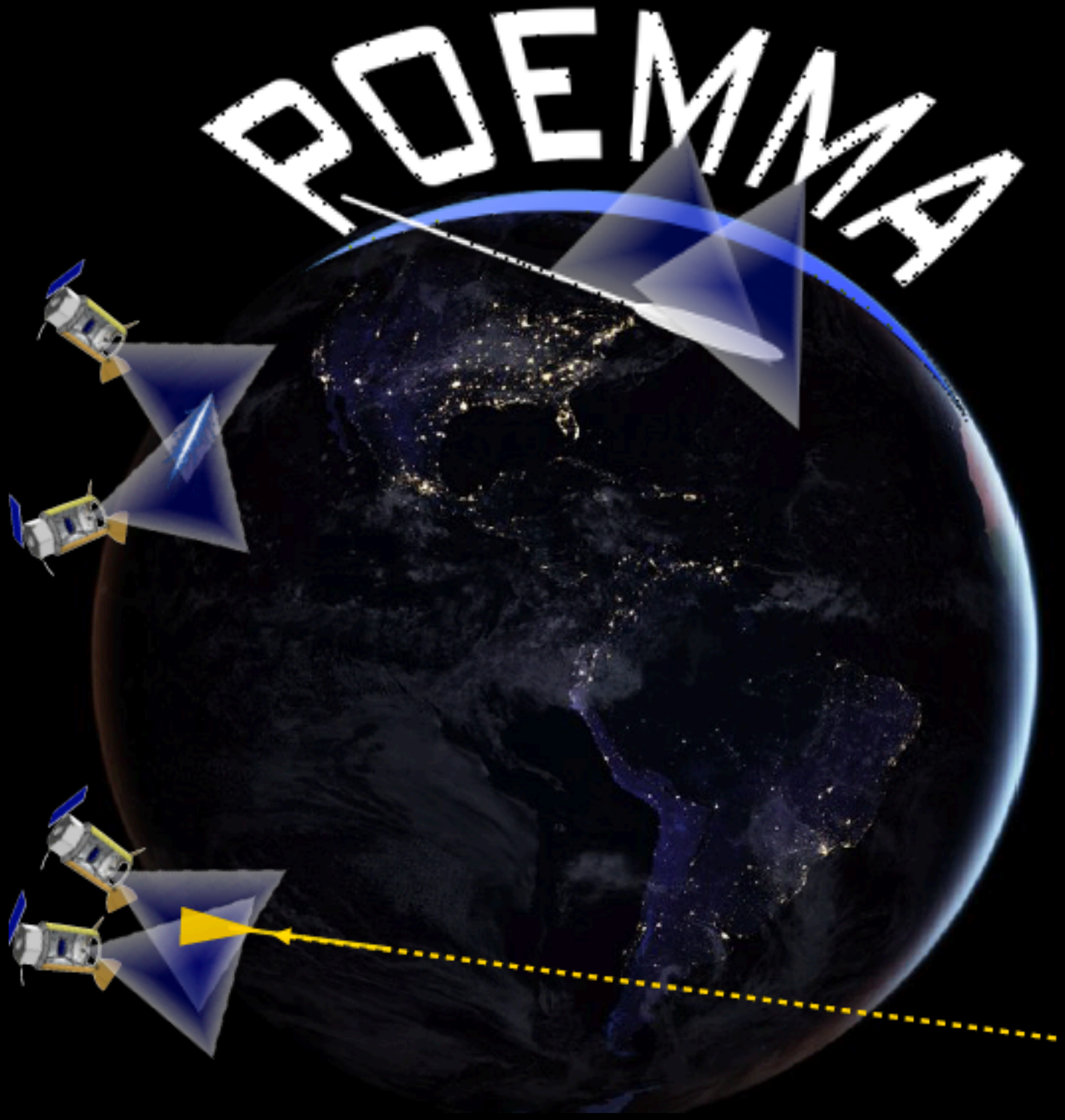
for the POEMMA and ZAP Collaborations
[1]NASA Goddard Space Flight Center, [2]Jet Propulsion Laboratory/Caltech

Image Credits:
M31: GALEX, JPL-Caltech, NASA
NGC 253: Star Shadows Remote Observatory, PROMPT/CTIO(Mazlin, Harvey, Gilbert, & Verschatse)

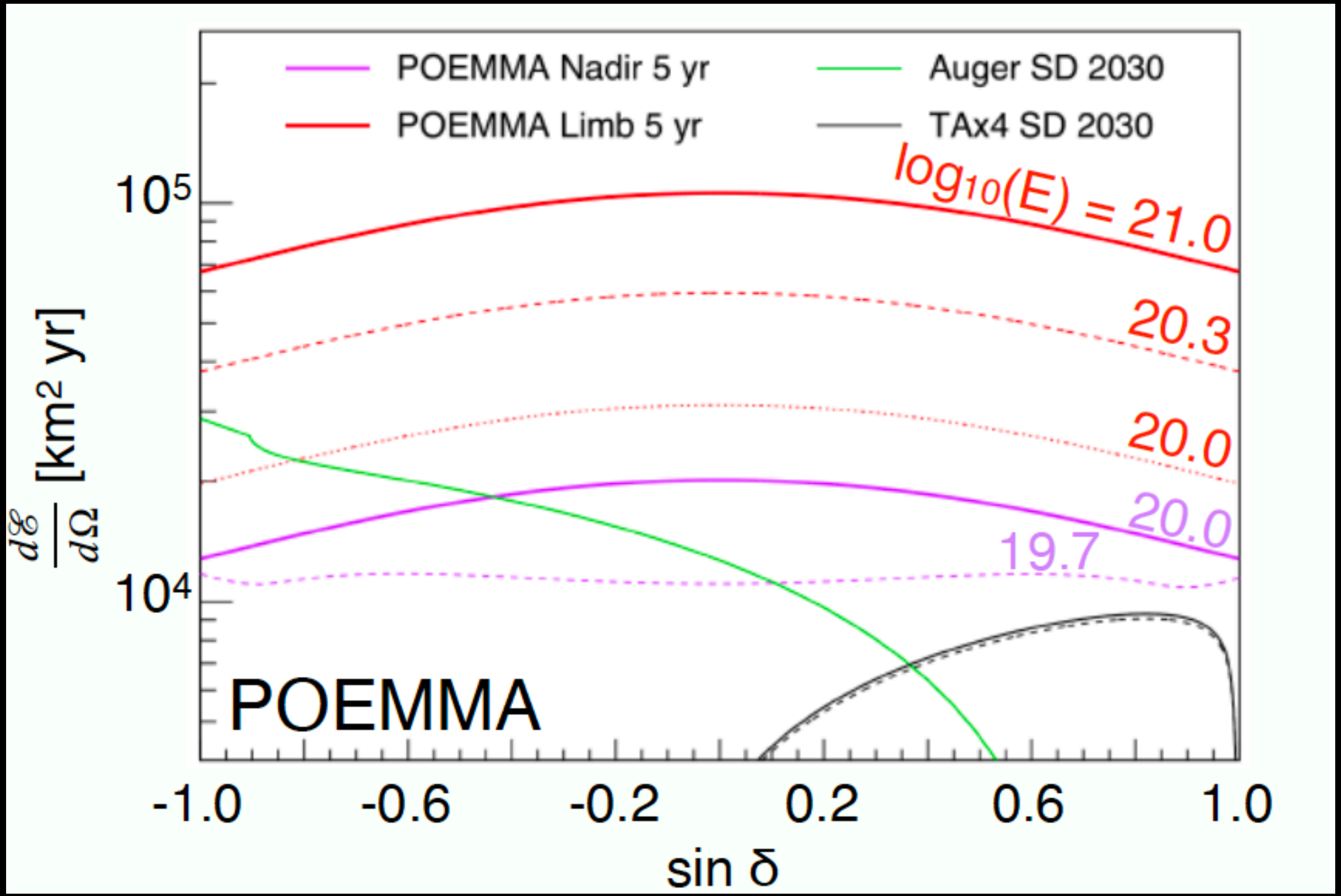


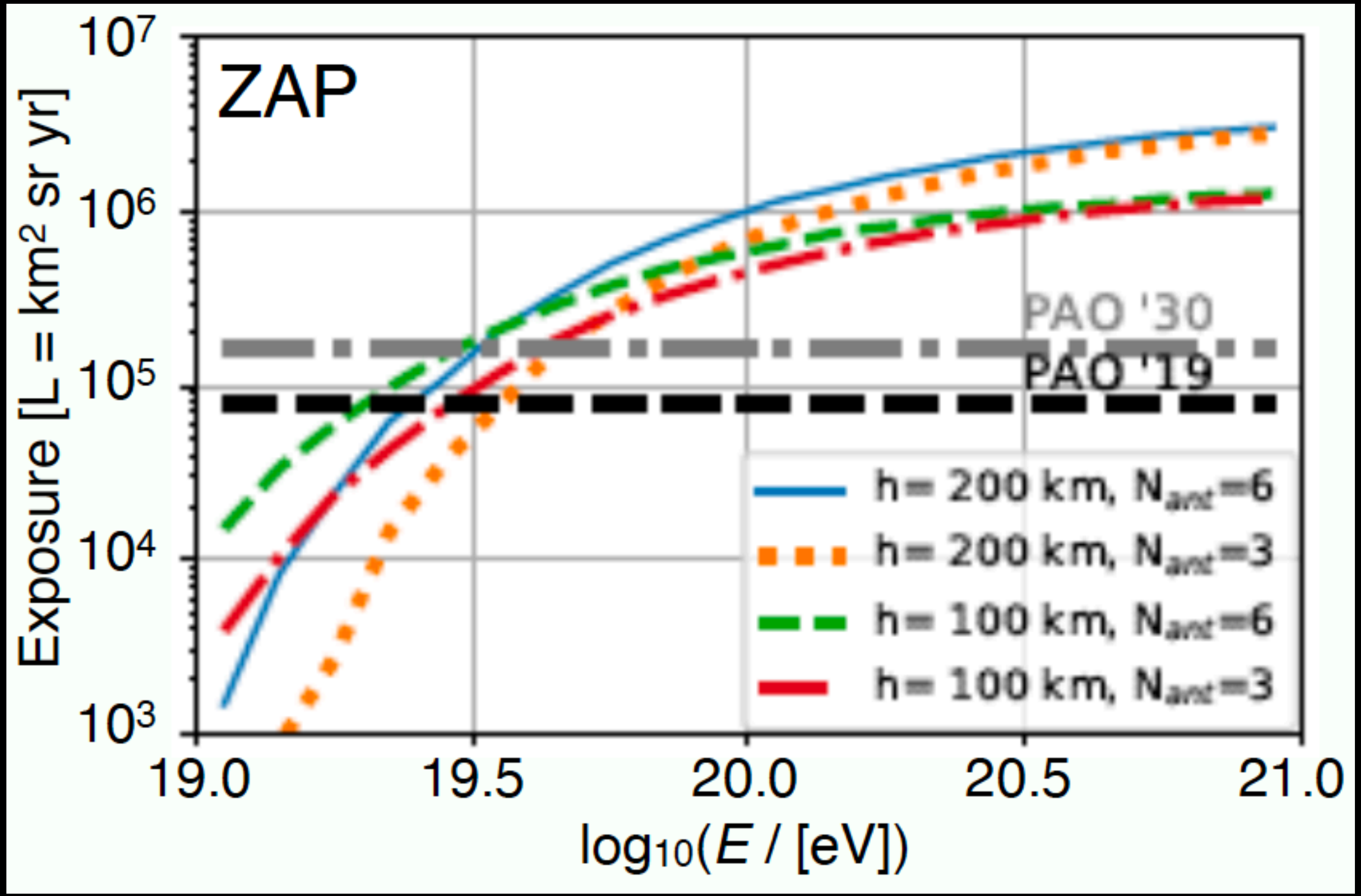
Probe of Extreme
Multi-Messenger Astrophysics

Zettvolt Askaryan Polarimeter

Charged Particle Astronomy from the Earth to the Moon

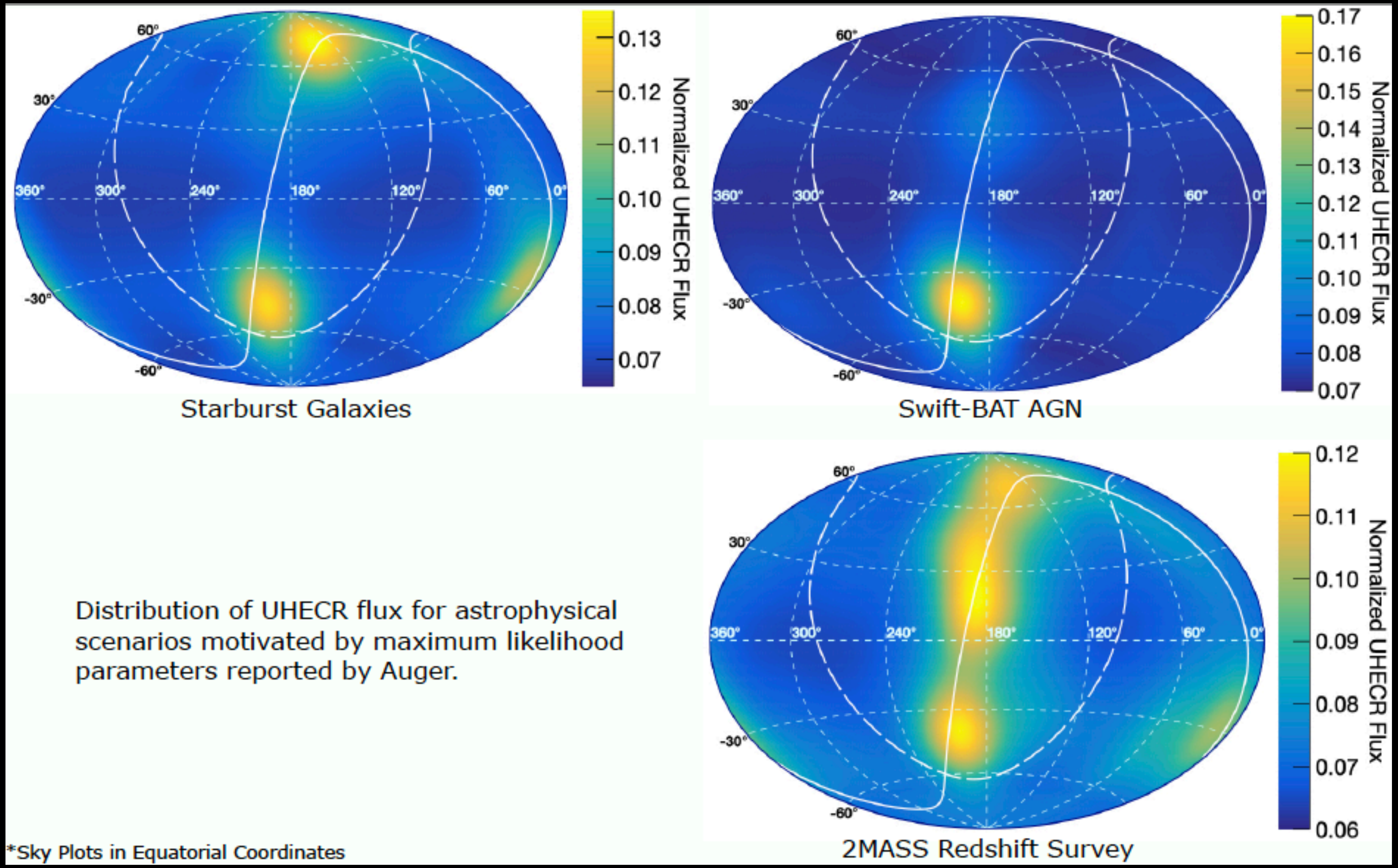
Benefits of Going to Space





- Vast increase in exposure
- Full-sky coverage

Prospects for Discovery Reach



Distribution of UHECR flux for astrophysical scenarios motivated by maximum likelihood parameters reported by Auger.

Catalog	f_{sig}	TS	σ
SBG	5%	6.2	2.0
	10%	24.7	4.6
	15%	54.2	7.1
	20%	92.9	9.4
2MRS	5%	2.4	1.0
	10%	8.7	2.5
	15%	20.0	4.1
	20%	35.2	5.6
Swift-BAT AGN	5%	10.4	2.8
	10%	39.6	6.0
	15%	82.4	8.8
	20%	139.3	11.6

TS and σ values for astrophysical scenarios w/ Θ = 15° and N_{ev} = 1400 (5 yrs. of POEMMA Stereo-precision)

Parameter		N_{ev} Required		
f_{sig}	Θ	AGN	SBG	2MRS
10%	20°	1240	2060	>5000
	15°	920	1910	4830
15%	20°	680	1000	2550
	15°	660	870	2280
20%	20°	<650	<650	1520
	15°	<650	<650	1320

Number of events required for 5σ detection.

Likelihood Tests for Cross-correlations with Astrophysical Catalogs

Potential and requirements for 5σ detection.

Prospects for Cross-correlations of UHECR Events with Astrophysical Sources with Upcoming Space-based Experiments

T. M. Venters[1] and A. Romero-Wolf[2] on behalf of the POEMMA and ZAP Collaborations

Background

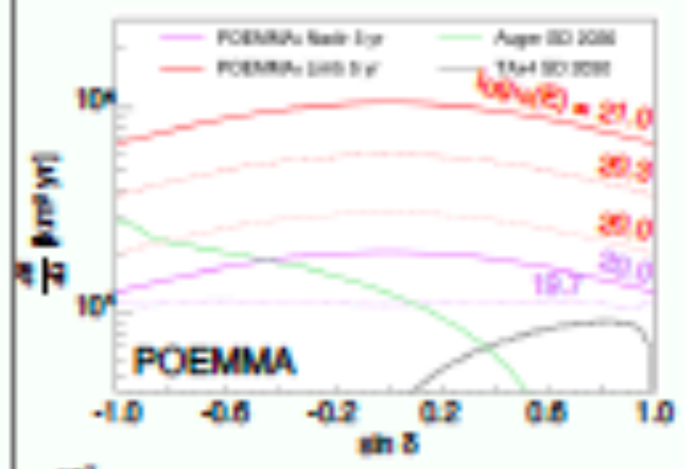
- Sources of ultra-high energy cosmic rays (UHECRs) remain elusive
- Magnetic fields that deflect UHECRs remain poorly understood, though expect weaker deflection at the highest energies
- Expect UHECR sky distribution to exhibit anisotropy suggestive of underlying source population and possibly even hotspots
- A common test for UHECR anisotropy cross-correlates UHECR arrival directions with astrophysical catalogs
  - ε 4.5σ correlation above ~40 EeV with nearby starburst galaxies reported by Auger
- POEMMA and ZAP will monitor large target volumes from space in order to detect UHECR showers:
  - ➢ *Unprecedented UHECR exposures with full-sky coverage*
  - ➢ *5σ discovery reach for many astrophysical scenarios*

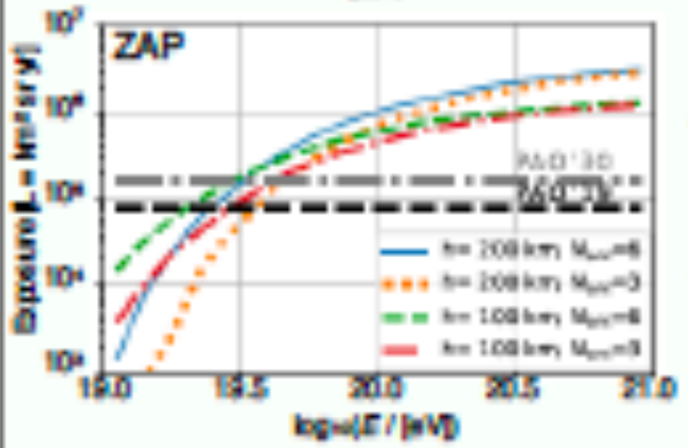
Method

Objectives

- Objective 1: For a given number of UHER events and a given astrophysical scenario, determine average significance of cross-correlation with astrophysical catalog.
- Objective 2: For a given astrophysical scenario, determine the number of events needed to guarantee a 5σ detection of the cross-correlation.

Likelihood Test for Cross-correlations





- Construct mock UHECR datasets w/ params.(N_{ev}, f^{*}_{aniso}, Θ*):
  - N_{ev} from exposure or left free
  - f^{*}_{aniso} fraction of aniso. events
  - Θ* smearing angle
- Construct astrophys. hypothesis maps, $\mathcal{F}_{sky}$, w/ params. (f_{sig}, Θ):

$$\mathcal{F}_{sky}(\hat{n}) = \frac{\omega(\hat{n})}{\mathscr{E}}\left[(1-f_{sig})\frac{1}{4\pi} + f_{sig}\mathcal{F}_{src}(\hat{n})\right]$$

(exposure; normalization; UHECR flux from sources)

- Compute TS for each (f_{sig}, Θ):

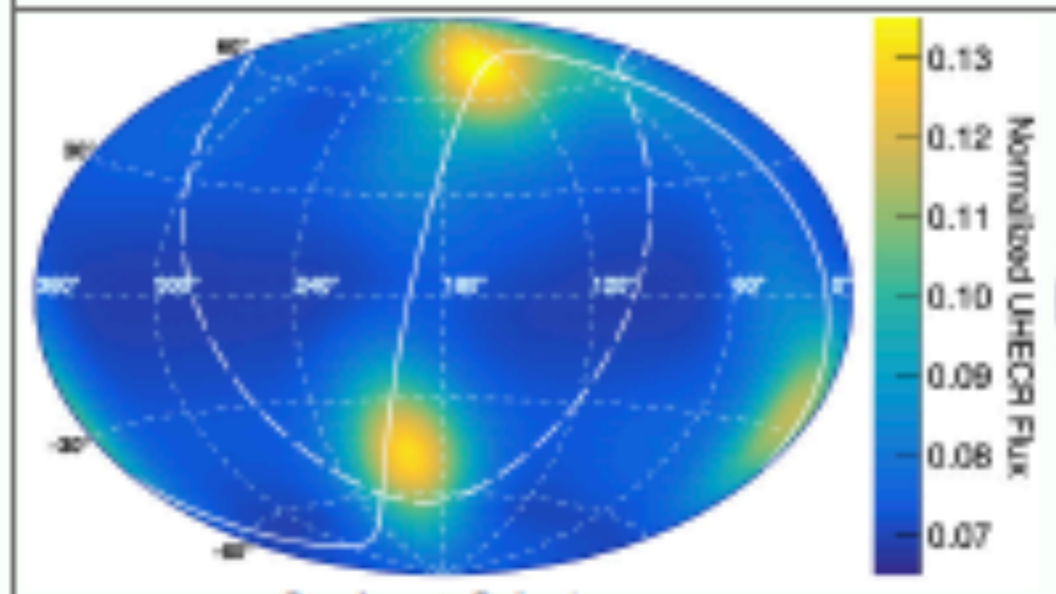
$$TS = 2\ln\left(\frac{L(\mathcal{F}_{sky})}{L(\mathcal{F}_{iso})}\right)$$

(likelihood)

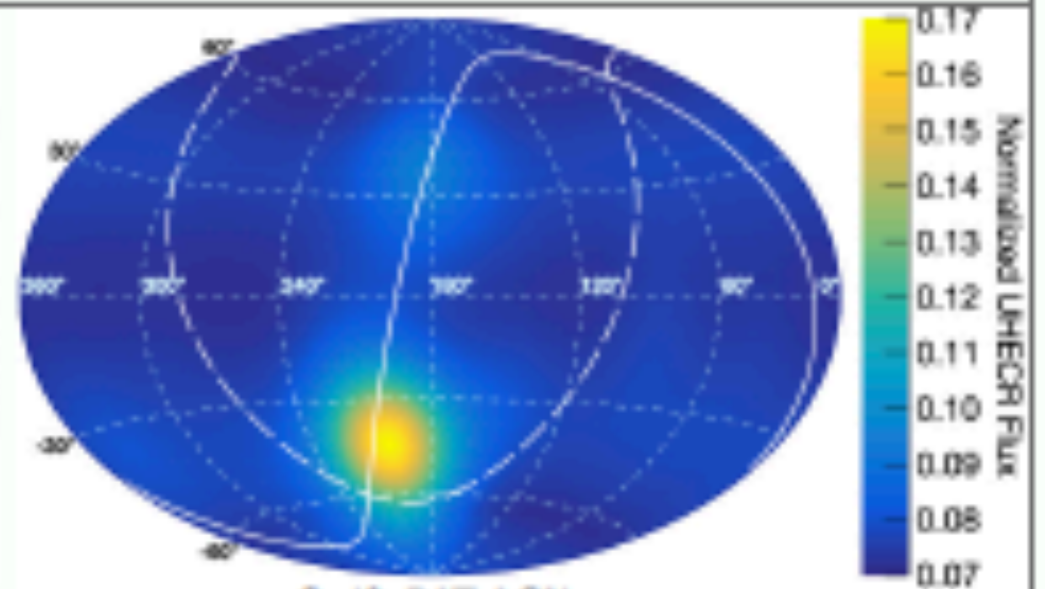
- Obj. 1: Compute average TS values, find maximum, compute significance
- Obj. 2: Construct TS distributions for mock and isotropic datasets; compute req. N_{ev} to distinguish at level of 5σ

Results

*UHECR Flux Sky Plots**



Starburst Galaxies



Swift-BAT AGN

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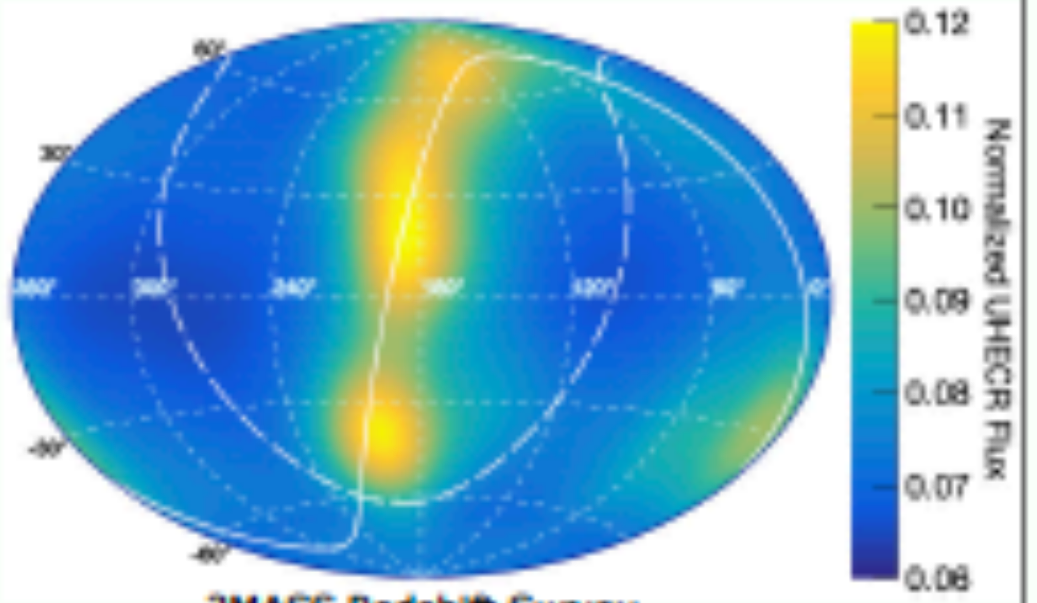
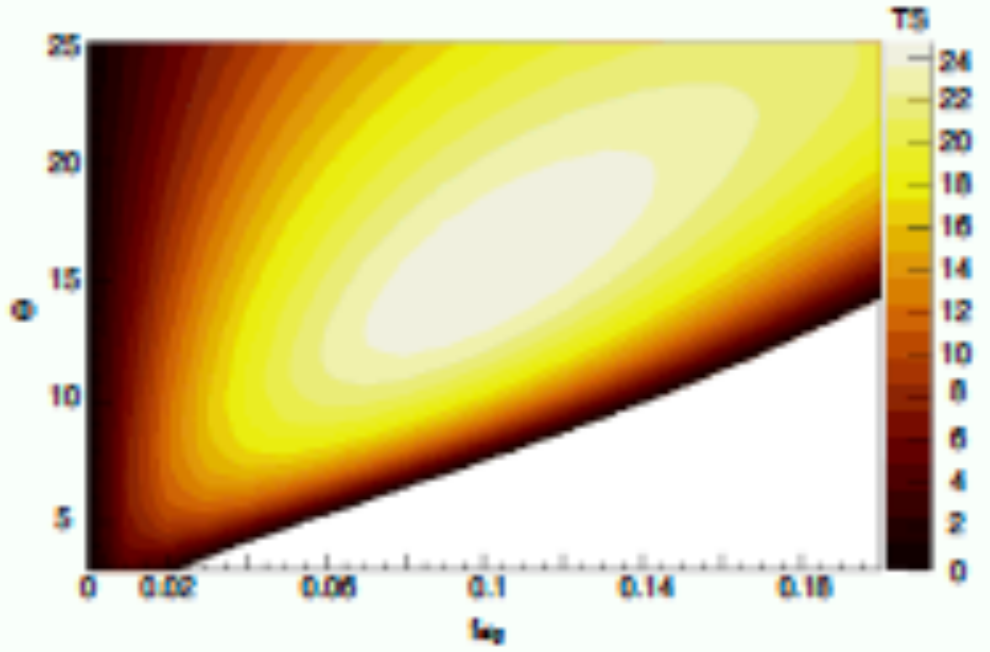


2MASS Redshift Survey

*Sky Plots in Equatorial Coordinates

Cross-Correlation Significances



Example TS Map

Catalog	f_{sig}	TS	σ
SBG	5%	6.2	2.0
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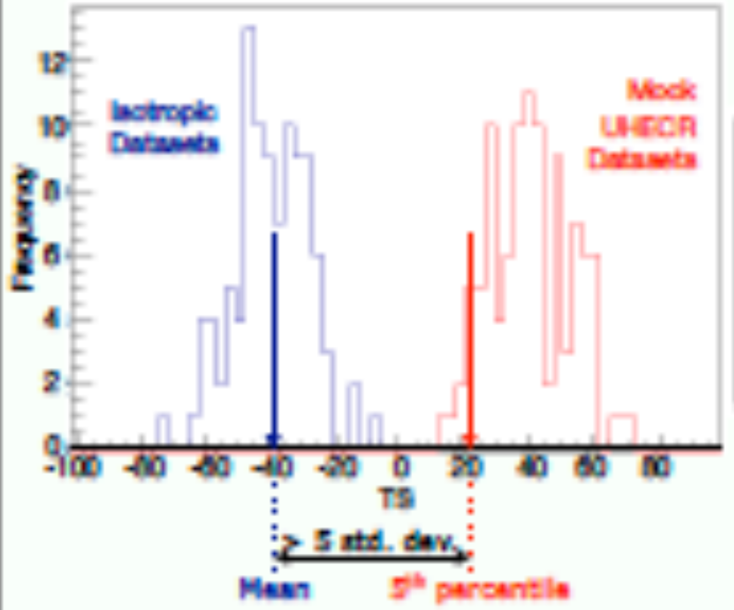
TS and σ values for astrophysical scenarios w/ Θ = 15° and N_{ev} = 1400 (5 yrs. of POEMMA Stereo-precision)

Results (cont.)

Events Requirement



Parameter		N_{ev} Required		
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20%	20°	<650	<650	1520
	15°	<650	<650	1320

Determine N_{ev} such that 5th percentile of mock dataset separated by more than 5 std. devs. from mean of isotropic datasets.

	POEMMA	ZAP
Energy Resolution	≲ 15% above 50 EeV	< 30%
Angular Resolution	< 1.5° above 40 EeV	1° – 4°

Parameter values represent astrophysical scenarios convolved with detector characteristics, such as ang. resolution and energy resolution. Different experiments can expect different parameter values, leading to different requirements for the number of events.

Conclusions

- POEMMA and ZAP will achieve unprecedented UHECR exposures in ~ few years.
- Both will have full-sky coverage, providing them access to regions of the sky that are inaccessible for ground-based expts.
- Both will achieve 5σ discovery reach for many plausible astrophysical scenarios.

References

[1] The POEMMA Collab., 2021, JCAP, 06, 007
[2] Romero-Wolf, A., et al., 2021, PoS (ICRC2021), 403
[3] Anchordoqui, L. A., et al., 2020, PRD, 101, 023012
[4] Pierre Auger Collab., 2018, ApJL, 853, 29
[5] Telescope Array Collab., 2018, ApJL, 867, 27
[6] Cacciariga, L., et al., 2019, PoS (ICRC2019), 206
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