Poetry in Orbit: Cosmic Ray and Neutrino MultiMessenger Astrophysics with the Probe Of Extreme Multi-Messenger Astrophysics (POEMMA)

NASA Partner

PERFORMANCE AND SCIENCE REACH OF THE PROBE OF … PHYS. REV. D **101**, 023012 (2020)

UHECRs: E > 20 EeV

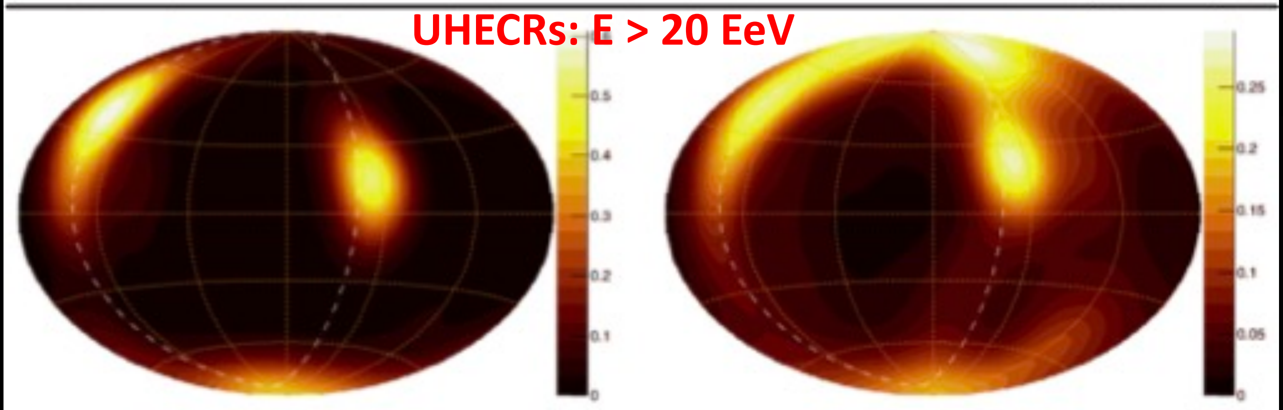


FIG. 23. Left: Skymap of nearby starburst galaxies from Refs. [35,103] weighted by radio flux at 1.4 GHz, the attenuation factor accounting for energy losses incurred by UHECRs through propagation, and the exposure of POEMMA. The map has been smoothed using a von Miser-Fisher distribution with concentration parameter corresponding to a search radius of 15.0° as found in Ref. [35]. The color scale indicates $\mathcal{F}_{src}$, the probability density of the source sky map, as a function of position on the sky. The white dot-dashed line indicates the supergalactic plane. Right: Same as at left for nearby galaxies from the 2MRS catalog [105] and weighting by K-band flux corrected for Galactic extinction.

TONIA M. VENTERS *et al.* PHYS. REV. D **102**, 123013 (2020)

ToO Neutrinos: E > 20 PeV

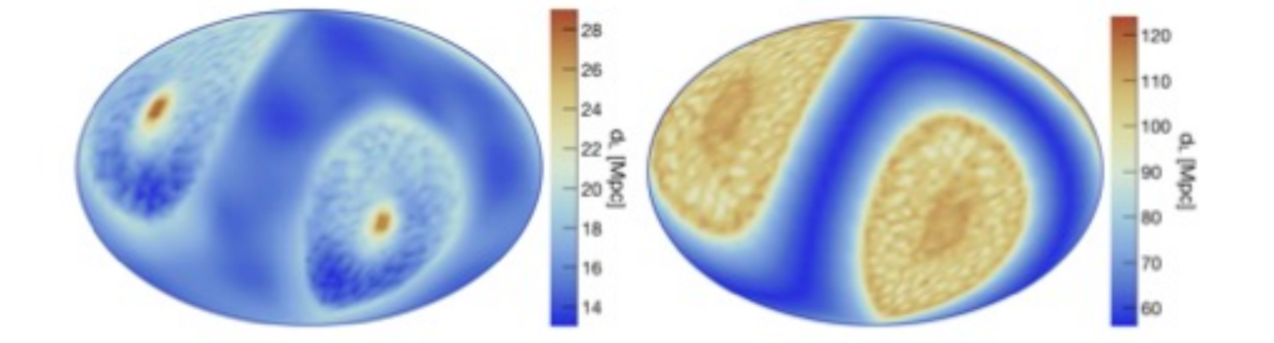
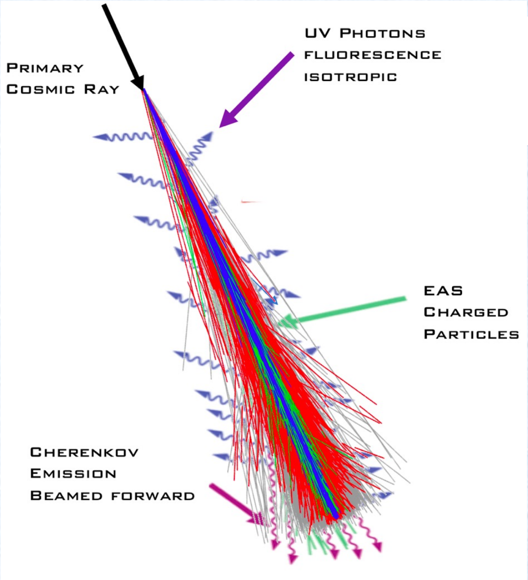
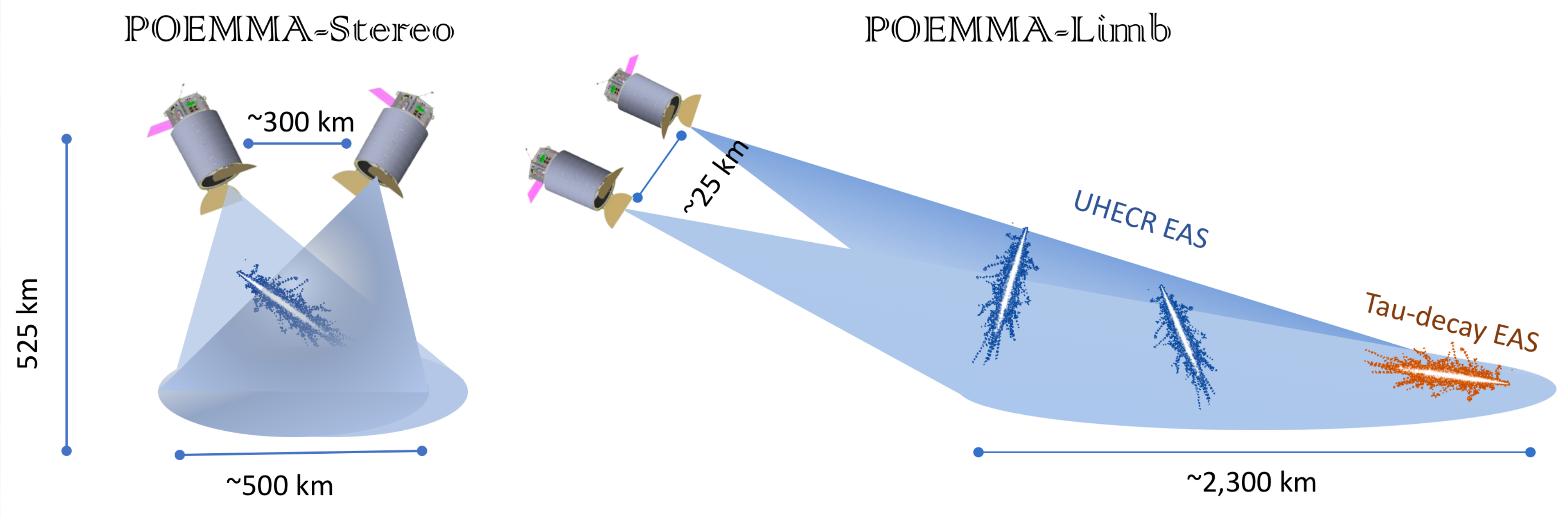


FIG. 18. Left: sky plot of the neutrino horizon for the BNS merger model of Ref. [22]. Right: same as at left for the sGRB EE neutrino model of Ref. [17].

John Krizmanic
UMBC/CRESST/NASA/GSFC
for the POEMMA Collaboration

Outline





1. **Scientific and Experimental Motivation.**
2. **POEMMA & Mission Description:** ***JCAP, Vol 2021, 06, id.007***
3. **POEMMA UHECR & UHE Neutrino Performance via air fluorescence measurements.**
   - ***Summary of results presented in PhysRevD.101.023012 and PhysRevD.103.043017***
4. **POEMMA VHE Neutrino Performance via optical Cherenkov measurements.**
   - ***Summary of results presented in PhysRevD.100.063010 and PhysRevD.102.123013***
5. **POEMMA-inspired Space-based Research and Development … moving forward**
   - **νSpaceSim NASA-funded end-to-end cosmic neutrino simulation development (PoS(ICRC2019)936)**
   - **EUSO-SPB2 ULDB flight in spring 2023**
6. **Summary & Comments**

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POEMMA Collaboration

70+ scientists from 21+ institutions (US 10+)
OWL, JEM-EUSO, Auger, TA, Veritas, CTA, Fermi, Theory

POEMMA

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

The POEMMA (Probe of Extreme Multi-Messenger Astrophysics) observatory

POEMMA collaboration

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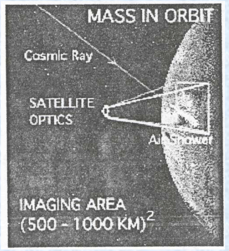
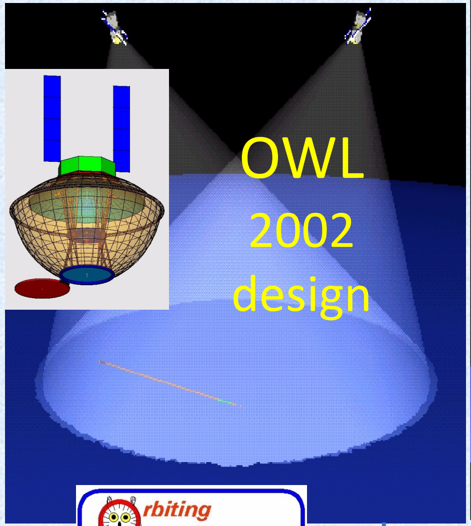
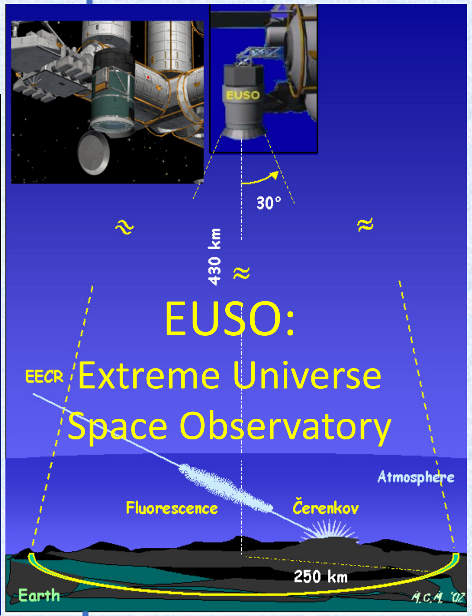
POEMMA Heritage

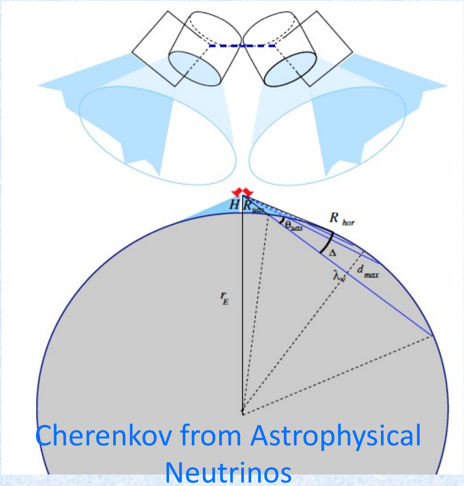
Based on OWL 2002 study, JEM-EUSO, EUSO balloon experience, and CHANT proposal







CHANT



Cherenkov from Astrophysical Neutrinos Telescope

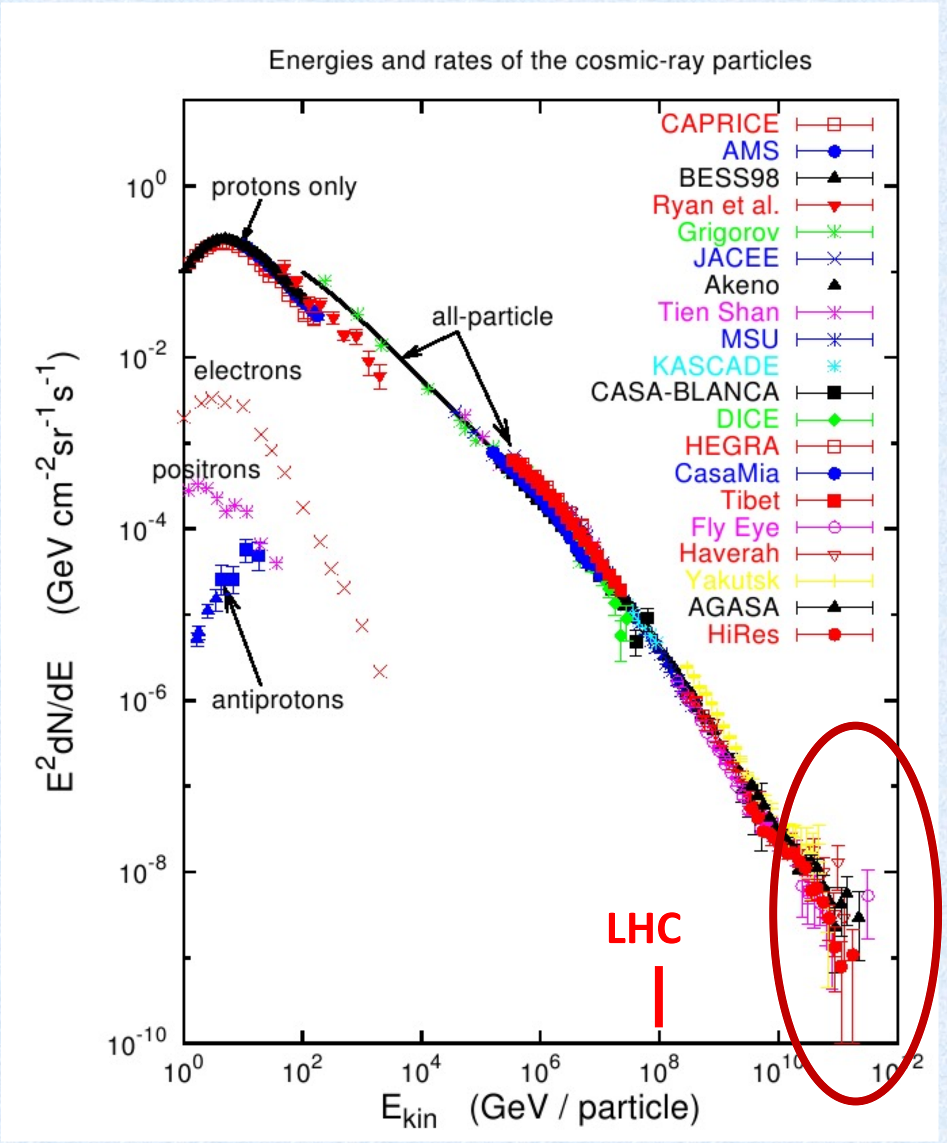
TUS, KLYPVE-EUSO

nueBACH

EUSO-Balloon
EUSO@TA
Mini-EUSO

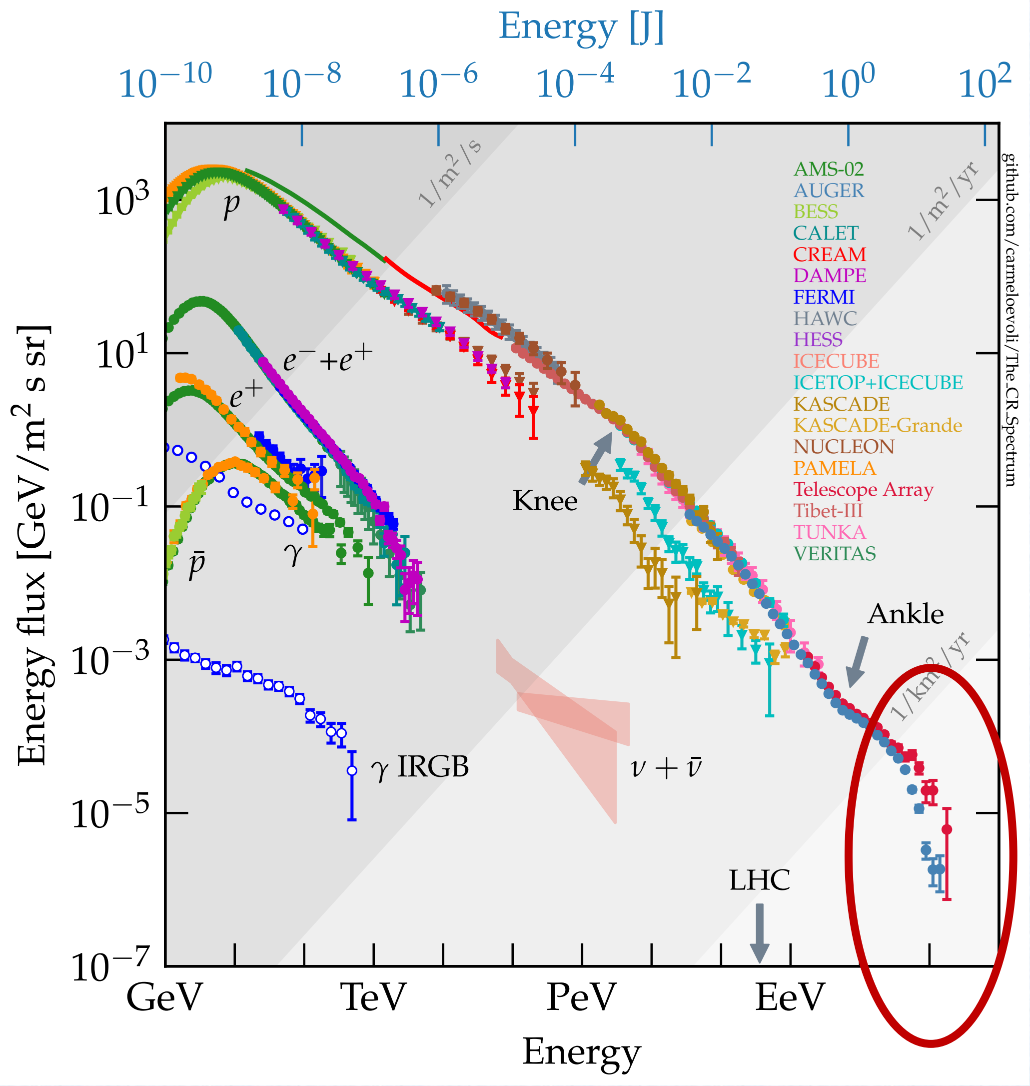
EUSO-SPB2

The Cosmic Ray Spectrum



Key Features:

1. Knee: ~ $10^{6.5}$ GeV
   Consistent with galactic sources changing via Peters cycle, Z-dependent acceleration (lighter going to heavier).
2. Ankle: ~$10^{9.5}$ GeV
   a. Funky composition evolution.
   b. Galactic to extragalactic transition?
   c. Due to proton interactions with evolving CMB (disfavored)
   d. Composition effect?
3. Foot/Toes/Bunions: ~$10^{10.7}$ GeV



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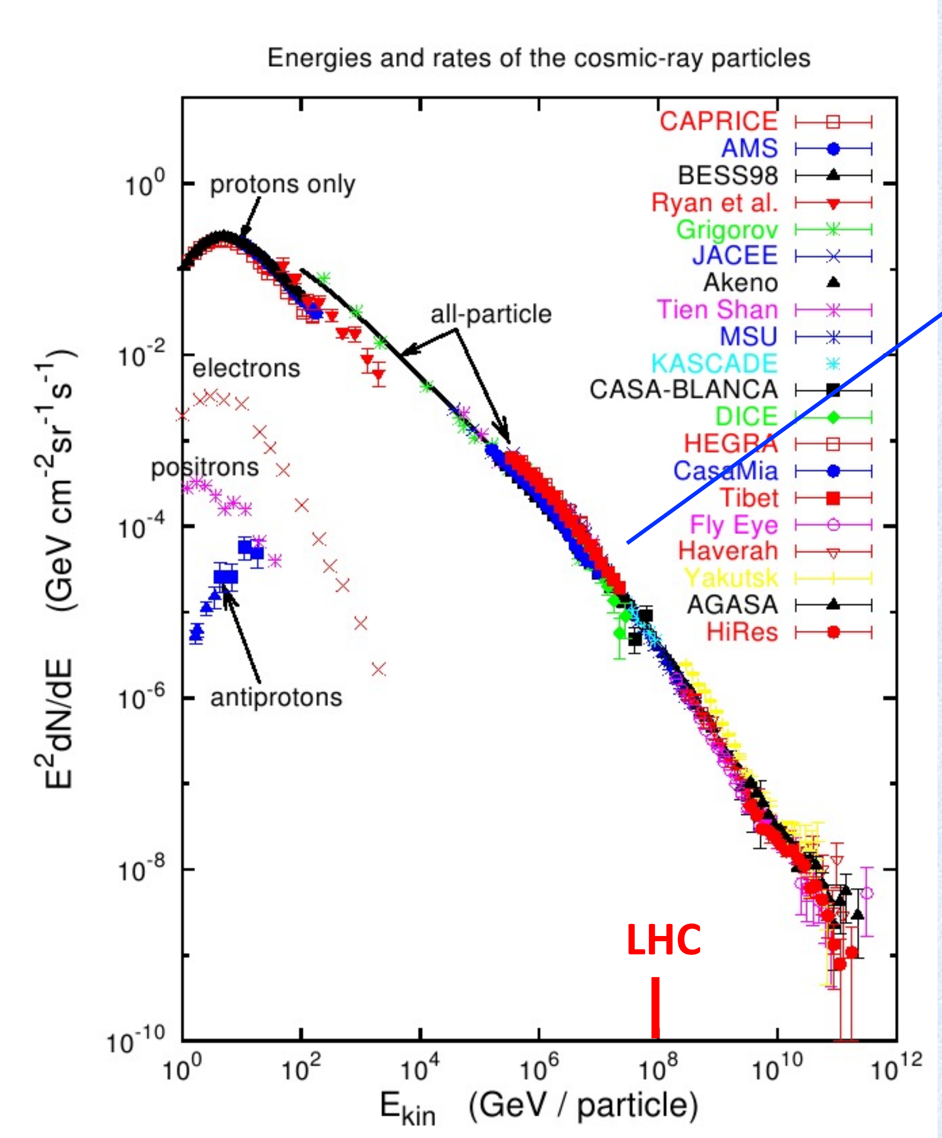
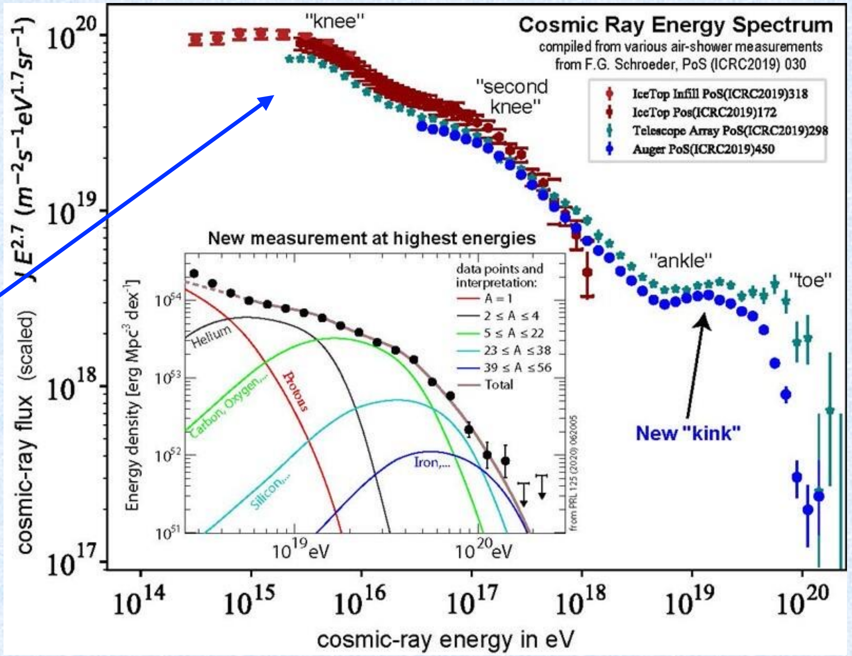
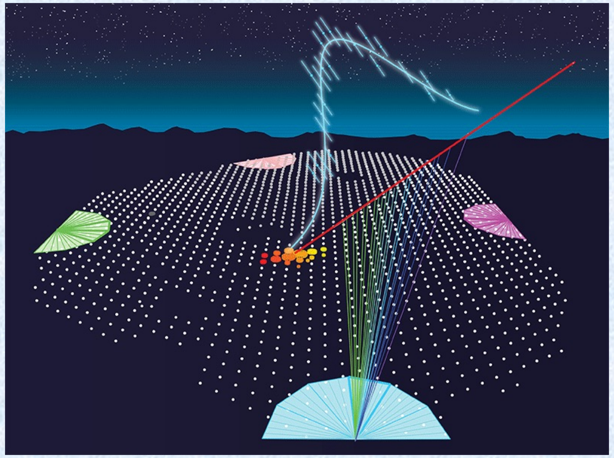
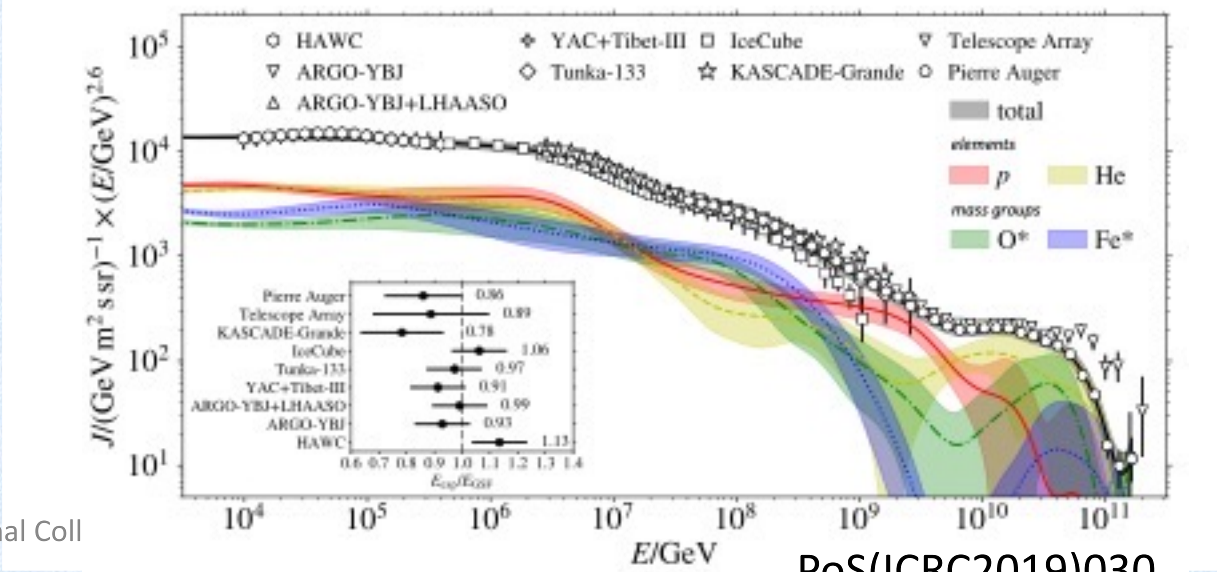
The Cosmic Ray Spectrum: Structure in VHE & UHECR energy range









PoS(ICRC2019)030

UHECR Gound-based Measurement Status

TA HotSpot: PoS(ICRC2019)310

Origin UHECRs still unknown

Giant ground Observatories: Auger & TA

- TA Hotspot: intermediate-scale anisotropy
- sources are extragalactic: Auger dipole > 8 EeV
- spectral features: discrepancies E > 50 EeV
- UHECR Composition: unclear E > 50 EeV
- source anisotropy Hints E > 50 EeV

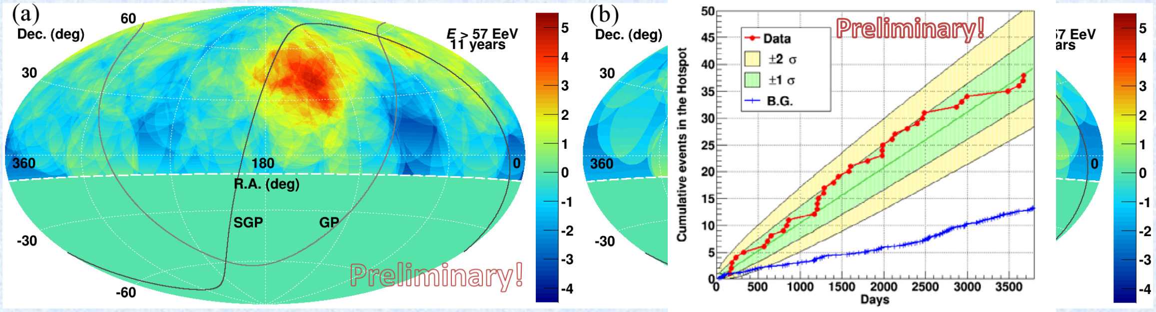


Figure 1: (a) A significance map of the UHECR events with $E > 57$ EeV for 11 years of TA data (May 2008 - May 2019) in the equatorial coordinates. Events are smoothed by 25° oversampling radius circle, which is defined in this paper. (b) A significance map of the UHECR events with $E > 57$ EeV for events observed in the 1st 5 years of TA data (May 2008 - May 2013). Events are smoothed by 20° oversampling radius circle according to our original paper [4]. The solid curves indicate supergalactic plane (SGP) and the galactic plane (GP).

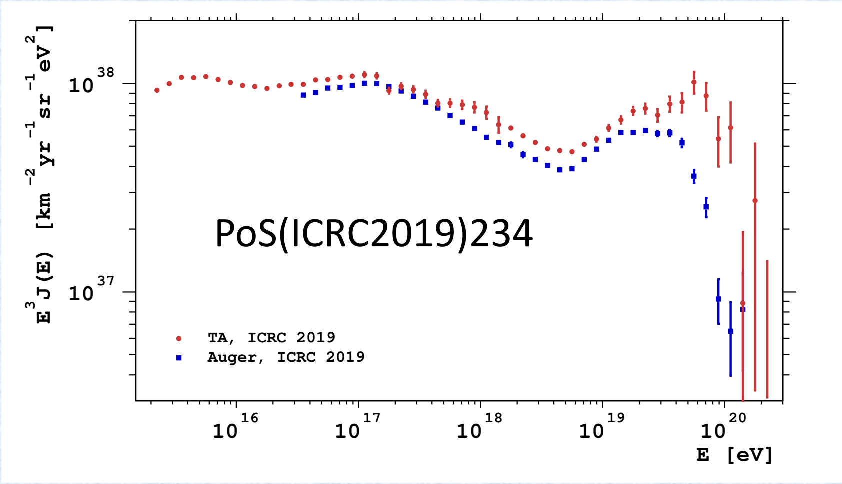


Figure 1: ICRC 2019 energy spectra of the Pierre Auger Observatory and the Telescope Array scaled by E^3. In each experiment, data of different detection techniques are combined to obtain the spectrum over a wide energy range.

Auger Highlights Antonella Castellina

PAO Dipole: ArXiv:1909.10791

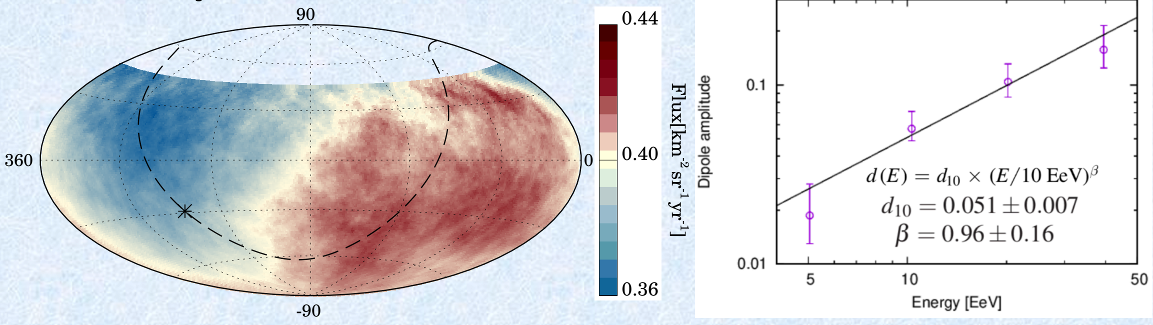
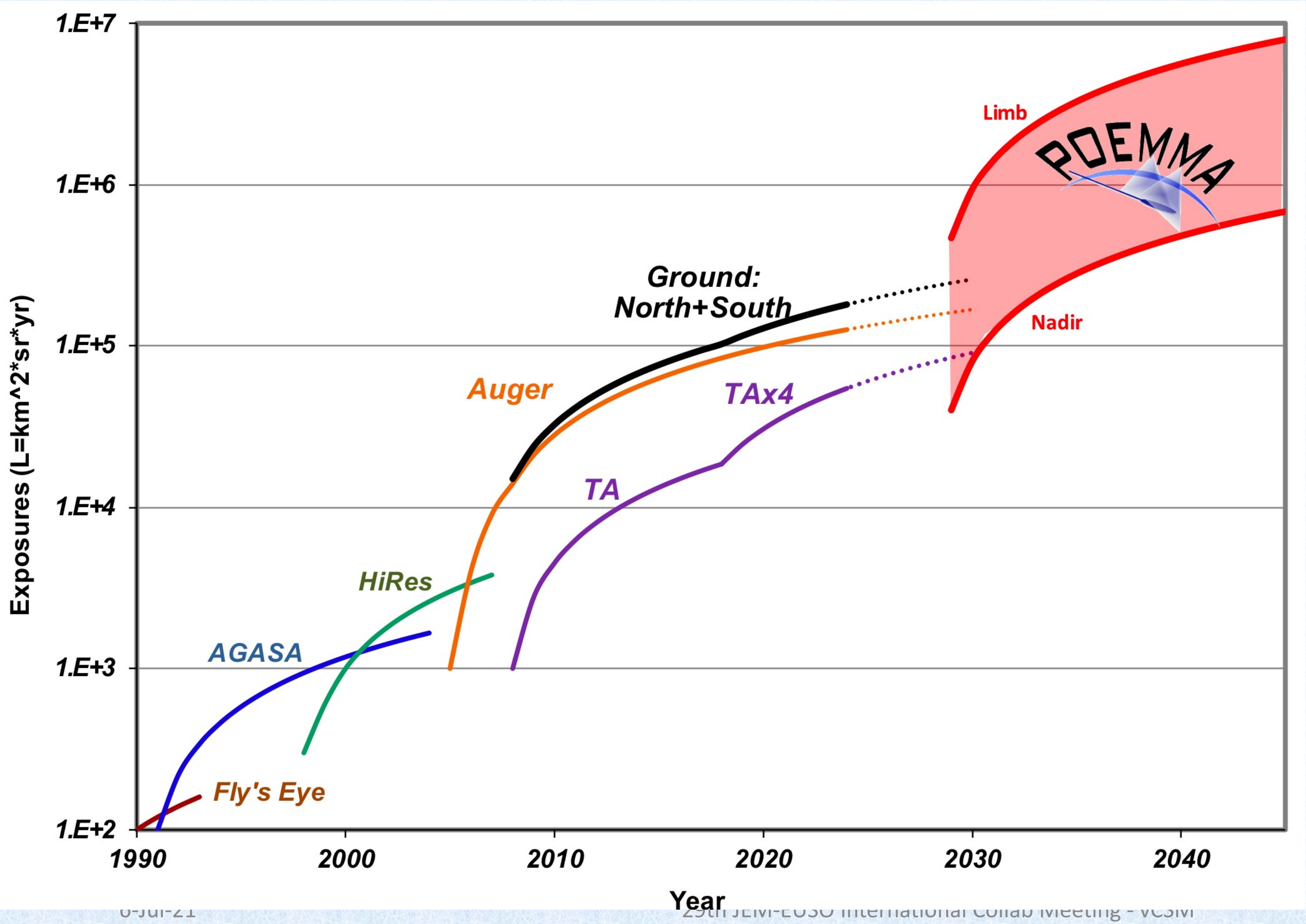
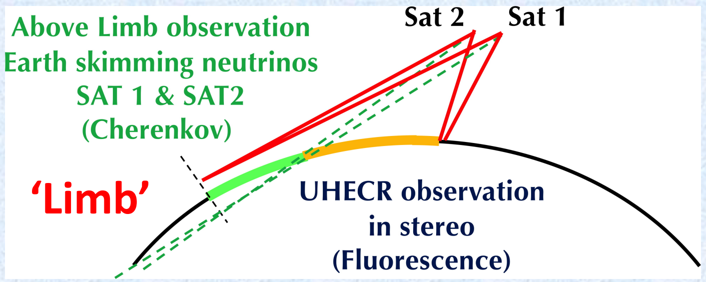
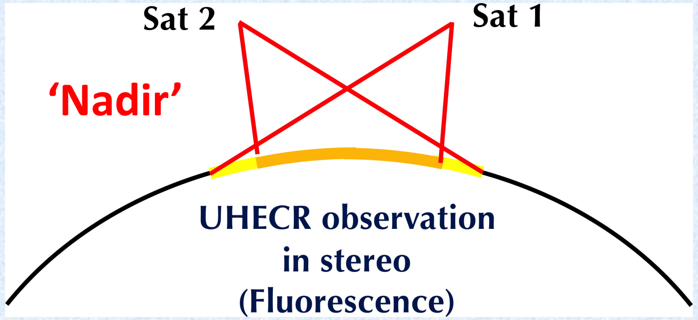


Figure 9: Left: The CR flux above 8 EeV, averaged on top-hat windows of 45° radius (equatorial coordinates). The Galactic plane and the Galactic center are indicated by a dashed line and a star respectively. Right: Energy dependence of the dipolar amplitude measured in four energy bins above 4 EeV.

POEMMA: UHECR Exposure History







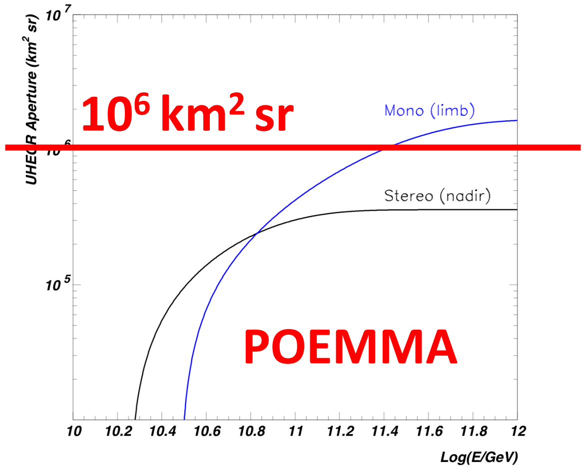


FIG. 10: The simulated UHECR aperture after event reconstruction for POEMMA for stereo mode and tilted mode.

POEMMA: Science Goals

POEMMA Science goals:

primary

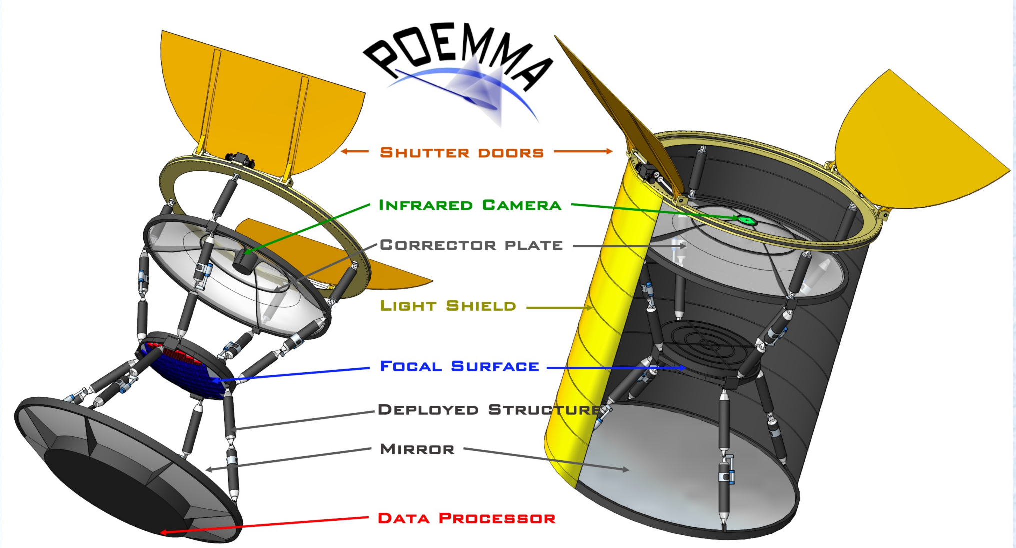
- **Discover the origin of Ultra-High Energy Cosmic Rays**
  Measure Spectrum, composition, Sky Distribution at Highest Energies (E_{CR} > 20 EeV)
  Requires very good angular, energy, and X_{max} resolutions: *stereo fluorescence*
  High sensitivity UHE neutrino measurements via stereo fluorescence 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 & ~10 ns timing
  Allows for tilted UHECR air fluorescence operation, higher GF but degraded resolutions

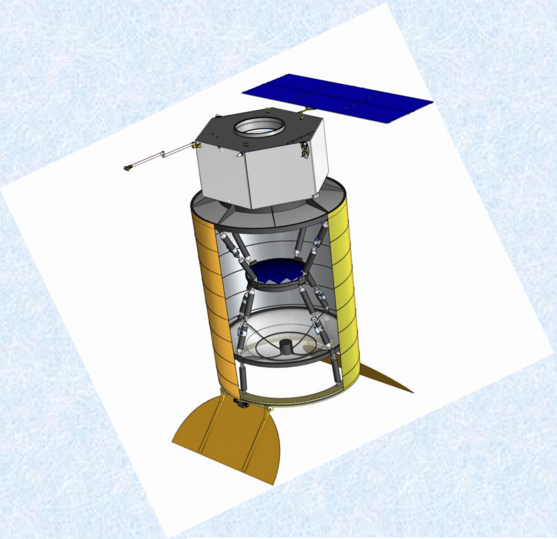
secondary

$\sqrt{s} \approx$ 450 TeV @ 100 EeV

- 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

POEMMA: Instruments defined by weeklong IDL run at GSFC





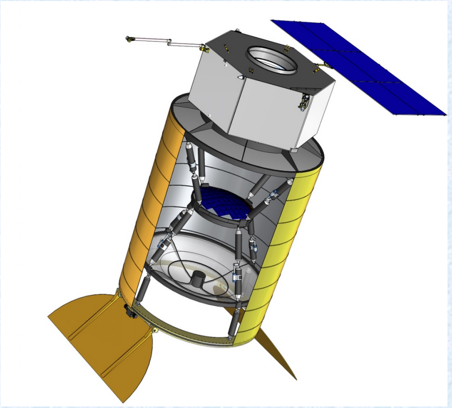
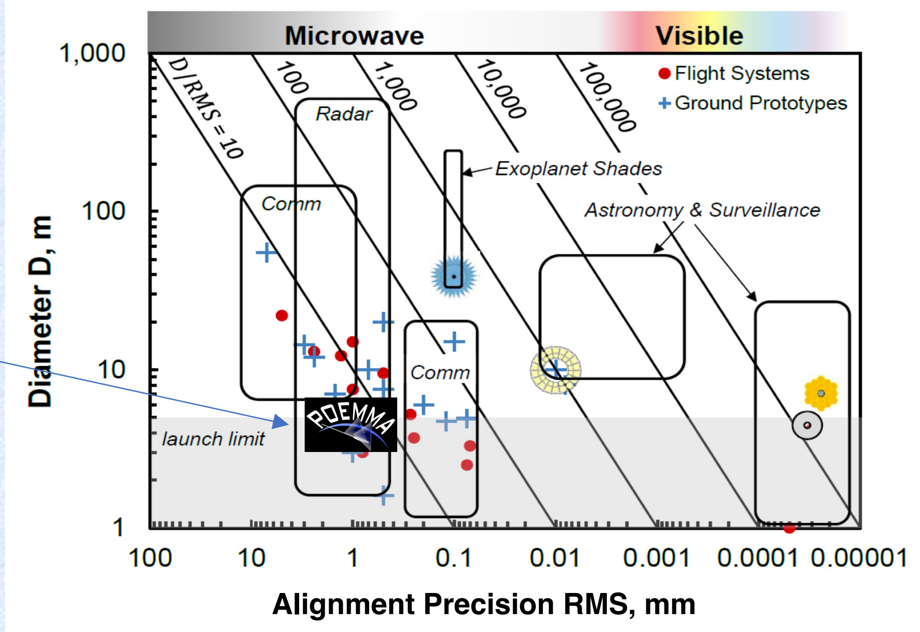


TABLE I: POEMMA Specifications:

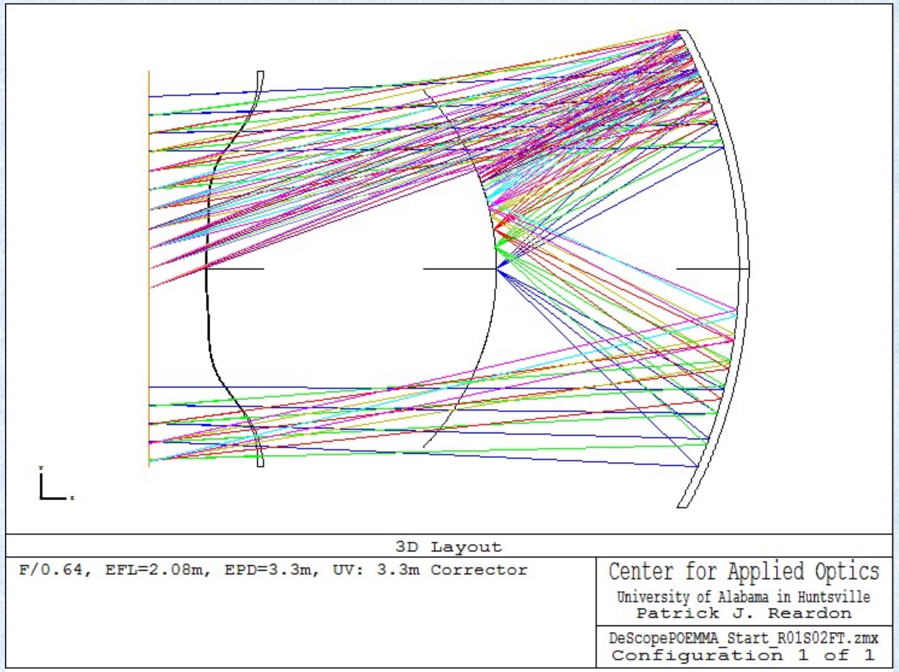
Photometer	Components		Spacecraft	
Optics	Schmidt	45° full FoV	Slew rate	90° in 8 min
	Primary Mirror	4 m diam.	Pointing Res.	0.1°
	Corrector Lens	3.3 m diam.	Pointing Know.	0.01°
	Focal Surface	1.6 m diam.	Clock synch.	10 nsec
	Pixel Size	3×3 mm^2	Data Storage	7 days
	Pixel FoV	0.084°	Communication	S-band
PFC	MAPMT (1μs)	126,720 pixels	Wet Mass	3,450 kg
PCC	SiPM (20 ns)	15,360 pixels	Power (w/cont)	550 W
Photometer	(One)		Mission	(2 Observatories)
	Mass	1,550 kg	Lifetime	3 year (5 year goal)
	Power (w/cont)	700 W	Orbit	525 km, 28.5° Inc
	Data	< 1 GB/day	Orbit Period	95 min
			Observatory Sep.	~25 - 1000+ km

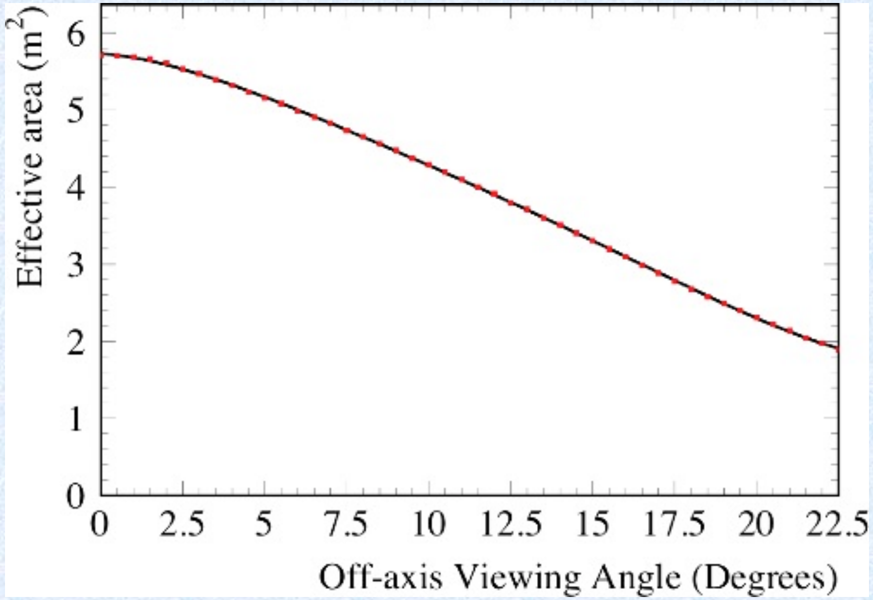
Each Observatory = Photometer + Spacecraft; POEMMA Mission = 2 Observatories



Imaging ~10^4 away from diffraction limit

POEMMA: Schmidt Telescope details





Two 4 meter F/0.64 Schmidt telescopes: 45° FoV

Primary Mirror: **4 meter diameter**

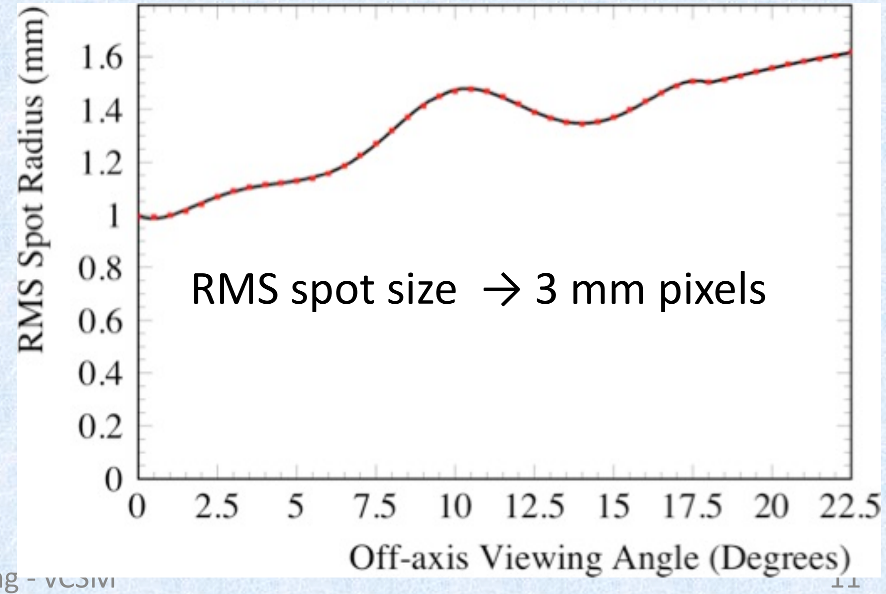
Corrector Lens: **3.3 meter diameter**

Focal Surface: **1.6 meter diameter**

Optical Area$_{EFF}$: **~6 to 2 m^2**

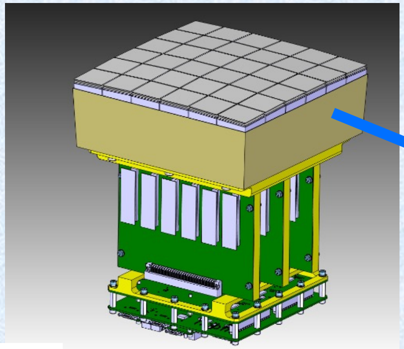
Hybrid focal surface (MAPMTs and SiPM)

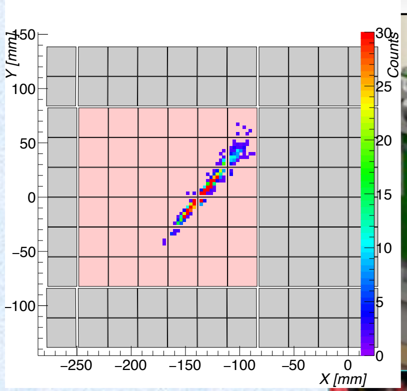
3 mm linear pixel size: 0.084 ° FoV

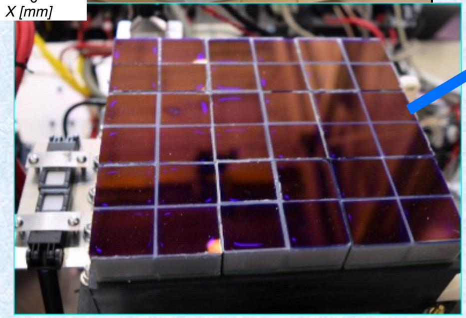


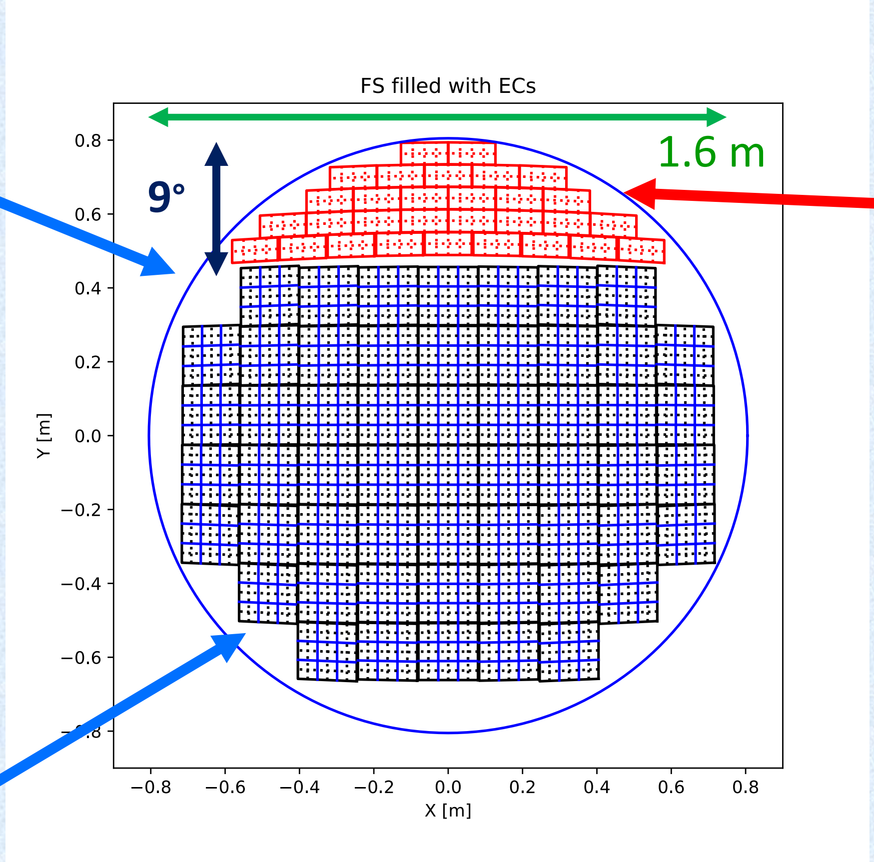
POEMMA: Hybrid Focal Plane

UV Fluorescence Detection using MAPMTs with BG3 filter (300 – 500 nm) developed by JEM-EUSO: 1 usec sampling





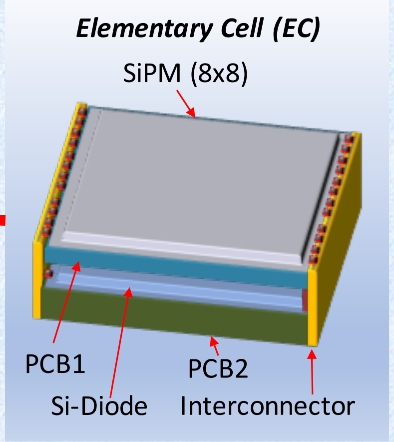




55 Photo Detector Modules (PDMs)= 126,720 pixels

1 PDM = 36 MAPMTs = 2,304 pixels

Cherenkov Detection with SiPMs (300 – 1000 nm): 20 nsec sampling



30 SiPM focal surface units

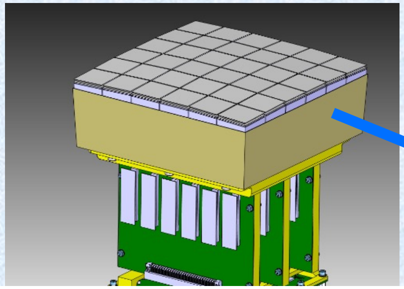
Total 15,360 pixels

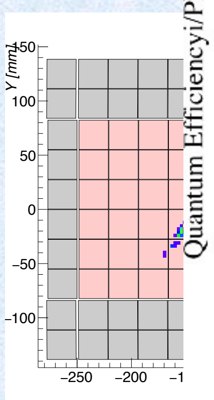
512 pixels per FSU (64x4x2)

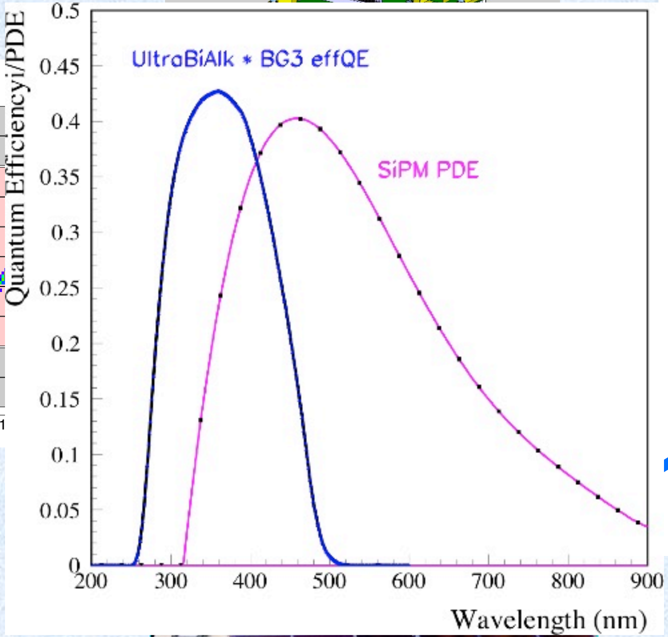
Si-Diode for LEO radiation backgrounds rejection

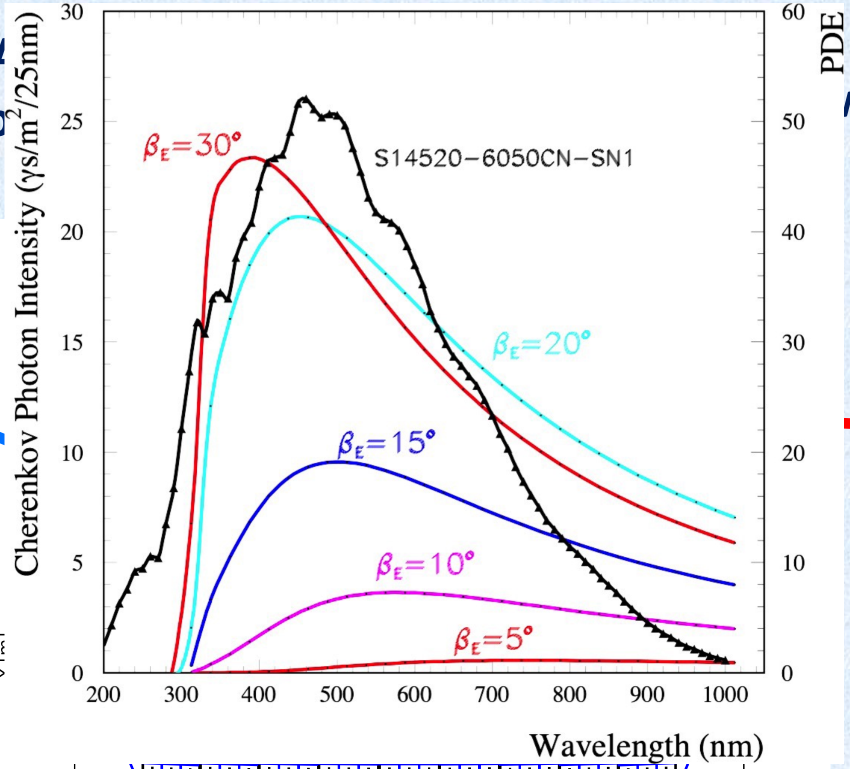
POEMMA: Hybrid Focal Plane

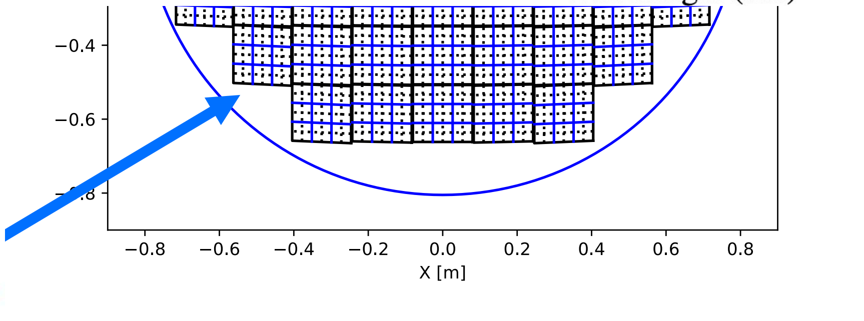
UV Fluorescence Detection using MA
with BG3 filter (300 – 500 nm) develo
JEM-EUSO: 1 usec sampling



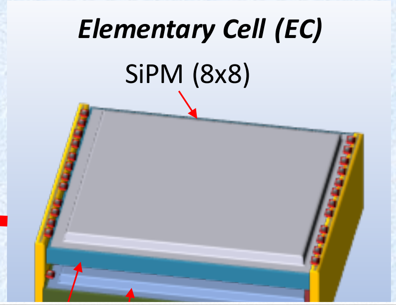


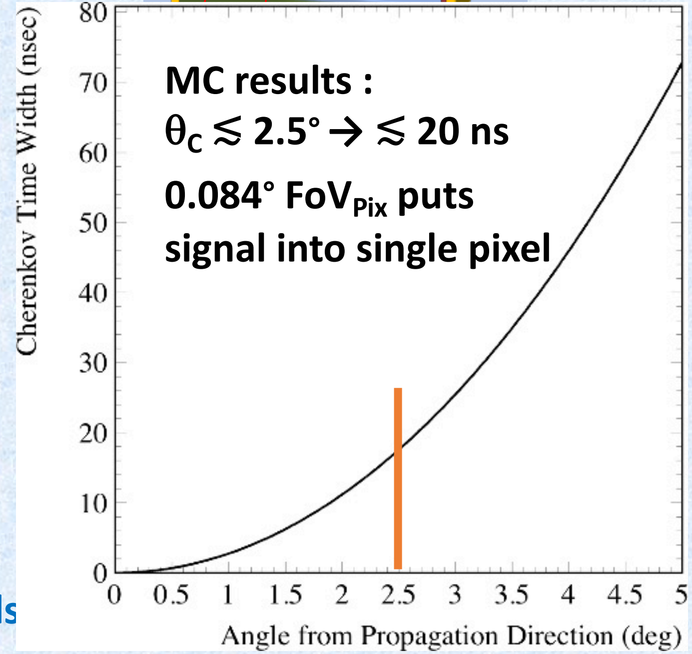






Cherenkov Detection
with SiPMs (300 – 1000 nm):
20 nsec sampling





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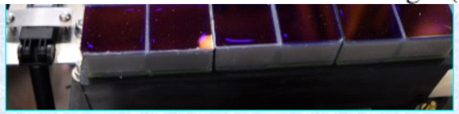
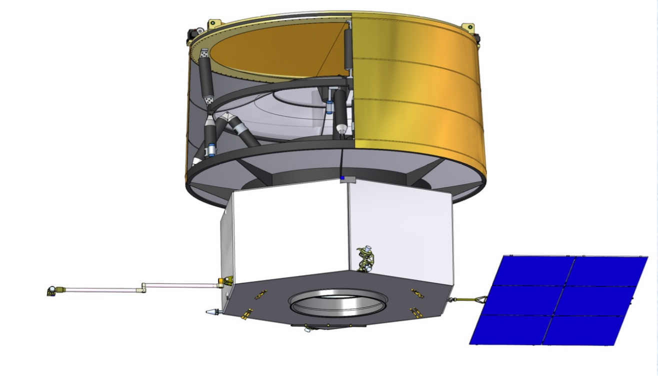


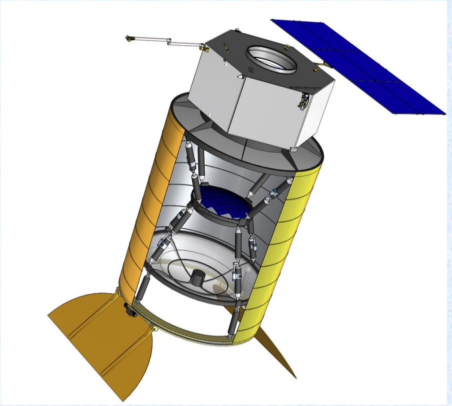
POEMMA: Mission (Class B) defined by weeklong MDL run at GSFC

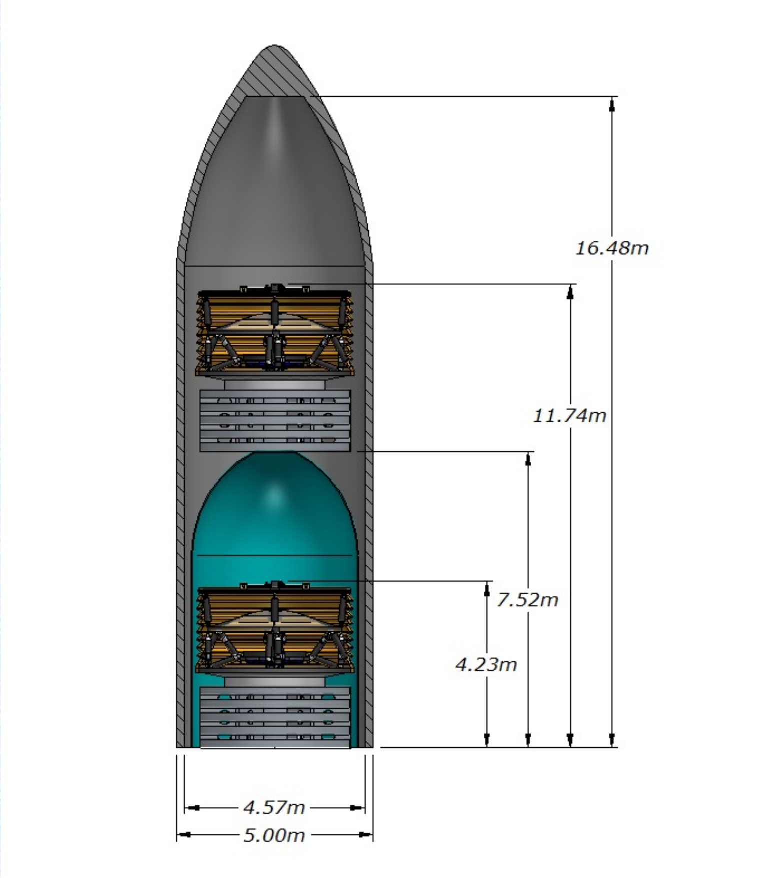
NASA Partner

Mission Lifetime: 3 years (5 year goal)
Orbits: 525 km, 28.5° Inc
Orbit Period: 95 min
Satellite Separation: ~25 km – 1000+ km
Satellite Position: 1 m (knowledge)
Pointing Resolution: 0.1°
Pointing Knowledge: 0.01°
Slew Rate: 8 min for 90°
Satellite Wet Mass: 3860 kg
Power: 1250 W (w/contig)
Data: < 1 GB/day
Data Storage: 7 days
Communication: S-band
Clock synch (timing): 10 nsec

Flight Dynamics/Propulsion:
- 300 km ⟹ 25 km SatSep
  - Puts both in CherLight Pool
- Δt = 3 hr: 8 – 15 times
- Δt = 24 hr: 90 times





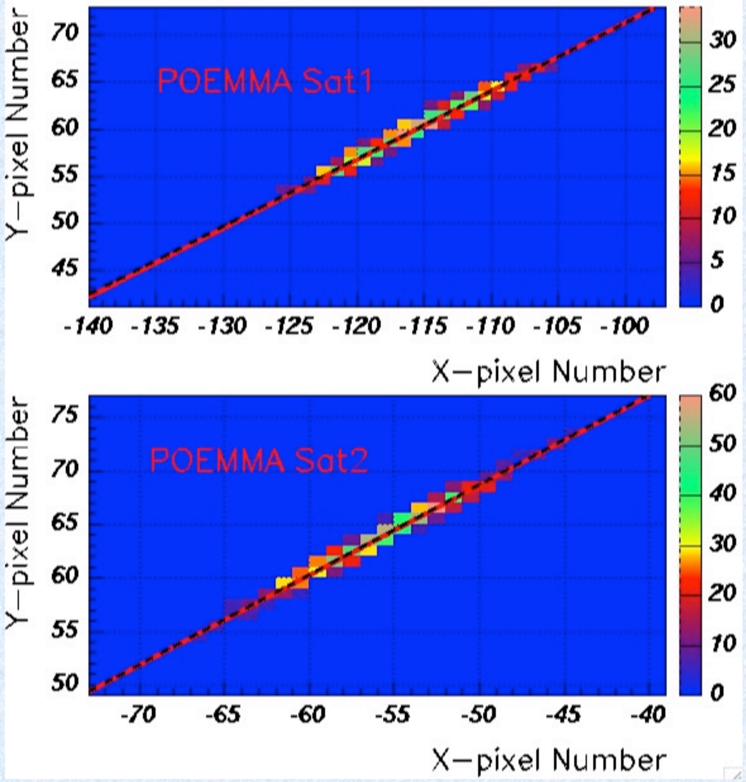


Dual Manifest Atlas V

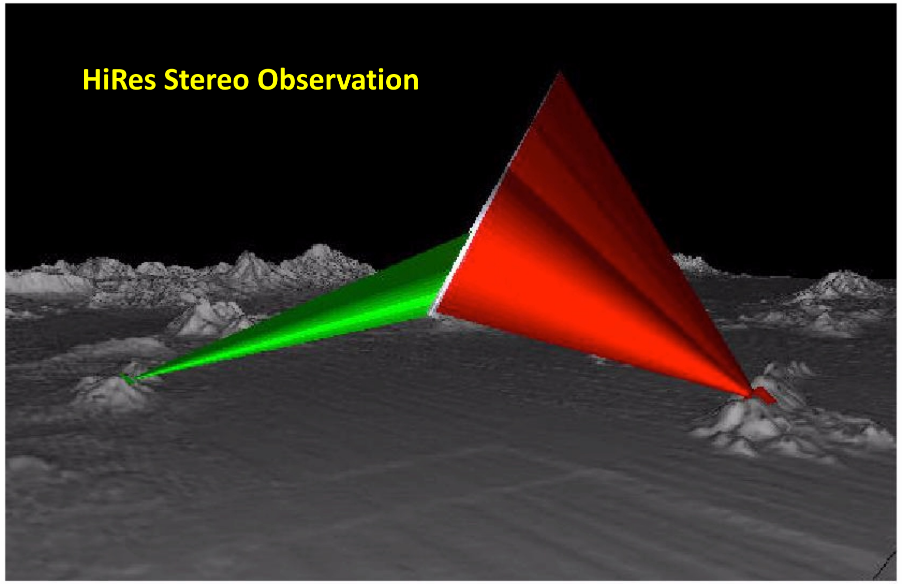
Operations:
- Each satellite collects data autonomously
- Coincidences analyzed on the ground
- View the Earth at near-moonless nights, charge in day and telemeter data to ground
- ToO Mode: dedicated com uplink to re-orient satellites if desired

POEMMA UHECR Performance: Stereo Reconstructed Angular Resolution

Partner

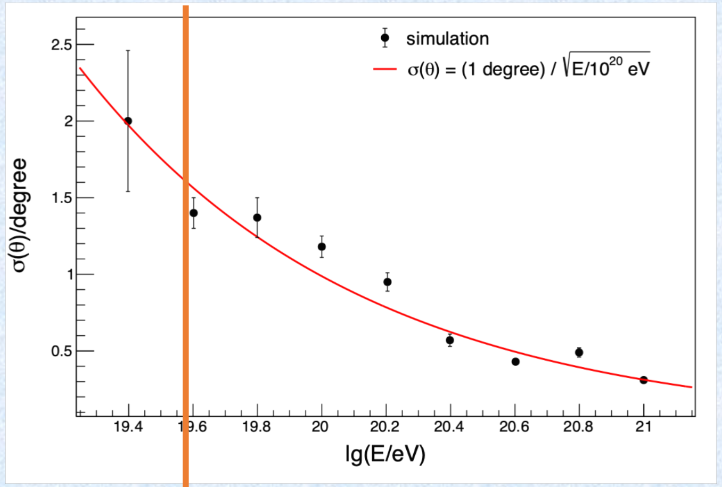


50 EeV simulated event

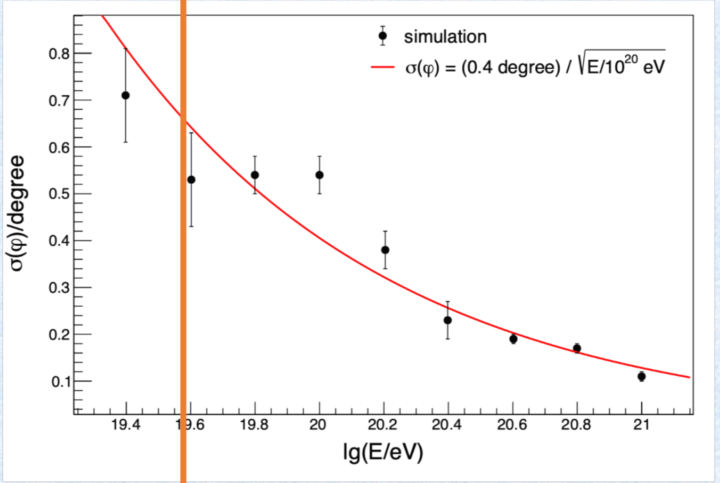


Stereo Geometric Reconstruction

- **Intersection of EAS-detector planes accurately defines the EAS trajectory**
- Requires minimum opening angle between planes ≳ 5°
- With track selection → 80% reconstruction efficiency
- **FoV_{PIX} = 0.084° coupled with small RMS spot size allows for precise determination**



Stereo Reconstructed Zenith Angle Resolution



Stereo Reconstructed Azimuth Angle Resolution

40 EeV

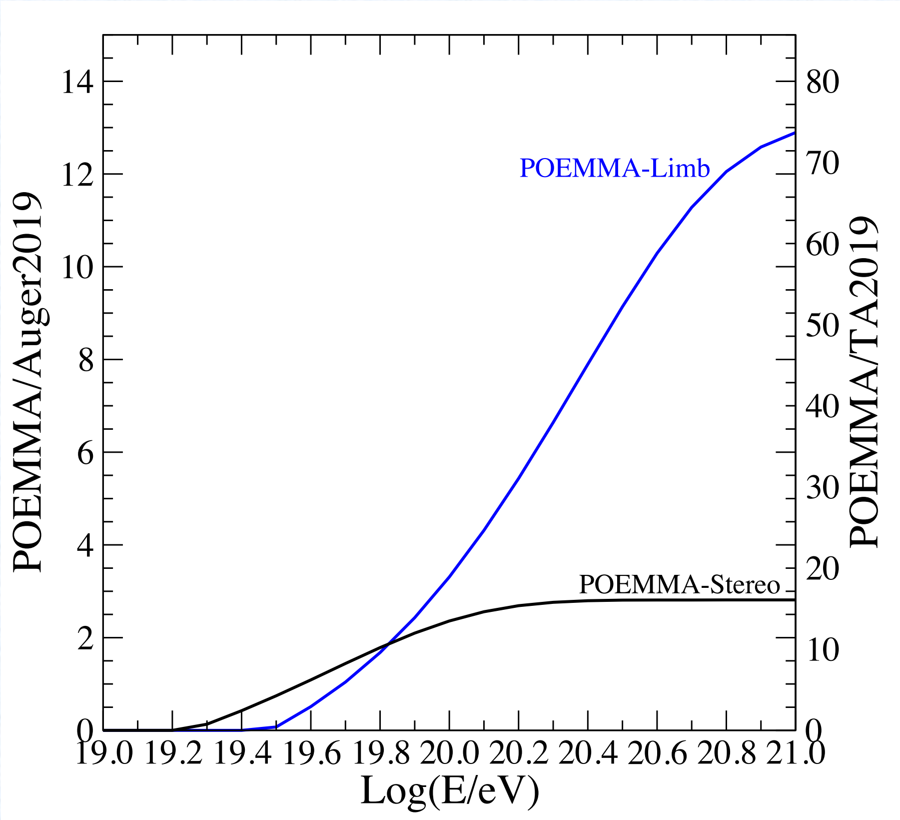
POEMMA: UHECR Performance: *see PhysRevD.101.023012*

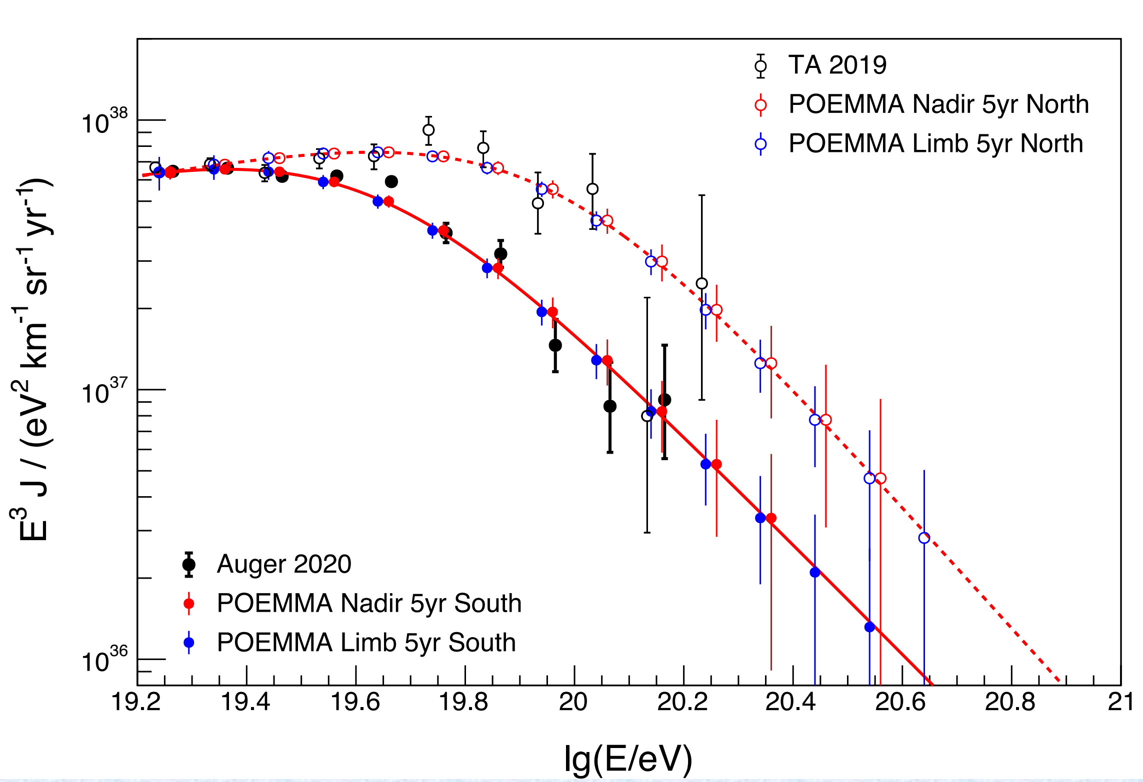
Significant increase in exposure with all-sky coverage

Uniform sky coverage to *guarantee the discovery of UHECR sources*

Spectrum, Composition, Anisotropy: $\mathbf{E_{CR} > 20}$ **EeV**

Very good energy (< 20%), angular ($\lesssim$ 1.2°), and composition ($\sigma_{Xmax} \lesssim 30$ g/cm^2) resolutions



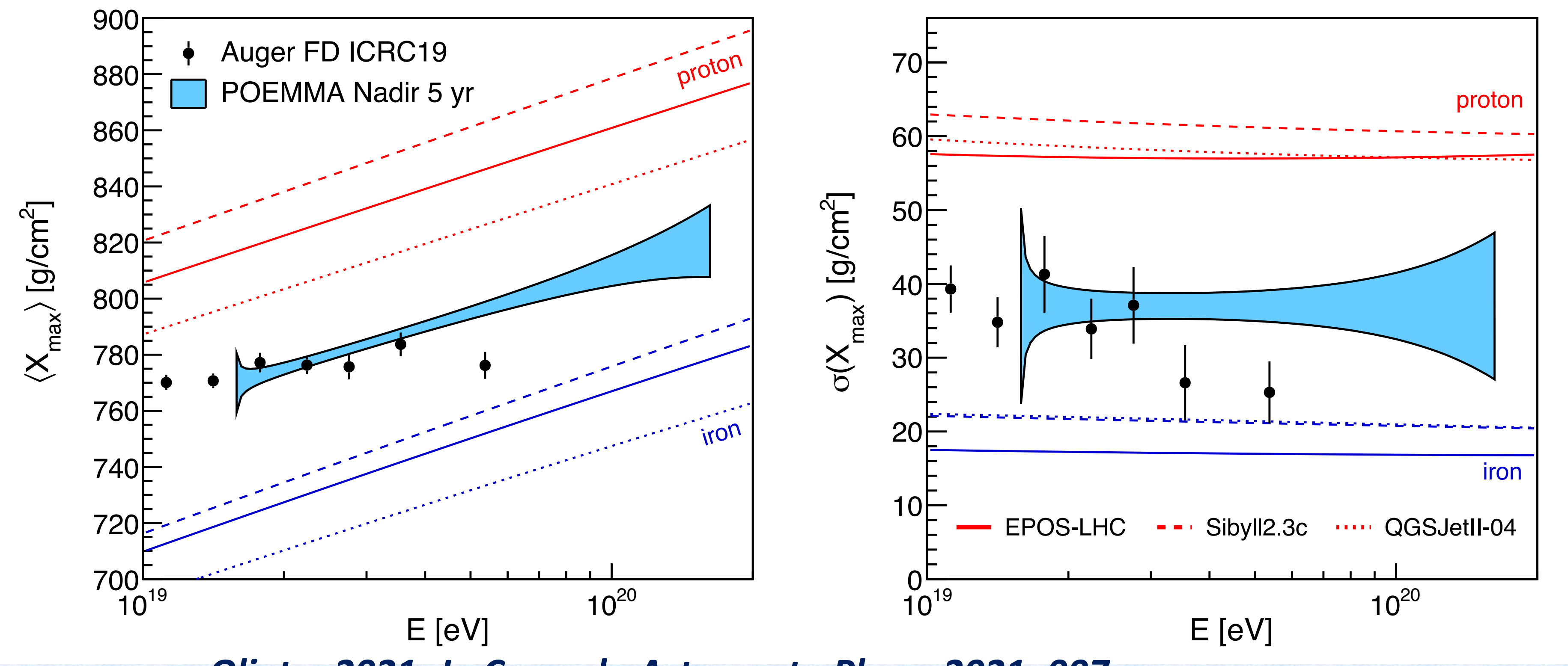


Olinto_2021_J._Cosmol._Astropart._Phys._2021_007

POEMMA: UHECR Composition

Spectrum, Composition, Anisotropy: **E_{CR} > 20 EeV**

Very good energy (< 20%), angular (≲ 1.2°), and composition (σ_{Xmax} ≲ 30 g/cm^2) resolutions



Olinto_2021_J._Cosmol._Astropart._Phys._2021_007

Michael Unger Work:

- Based on *ad hoc* model extrapolating Auger measurements below 40 EeV.
- Around 100 EeV, POEMMA X_{max} uncertainty 0.1 – 0.2 p-Fe separation → several energy points above 40 EeV by POEMMA will determine composition evolution.

JCAP Referee: it is advertised that different scenarios/models can be distinguished}, it would be good to illustrate the prediction of such models in Fig 7. This will allows the reader to judge the discrimination power of PEOMMA, given experimental uncertainties, indicated by the blue band.

POEMMA: UHECR Sky Coverage (isotropic UHECR flux)

Significant increase in exposure with all-sky coverage

Uniform sky coverage to *guarantee the discovery of UHECR sources*

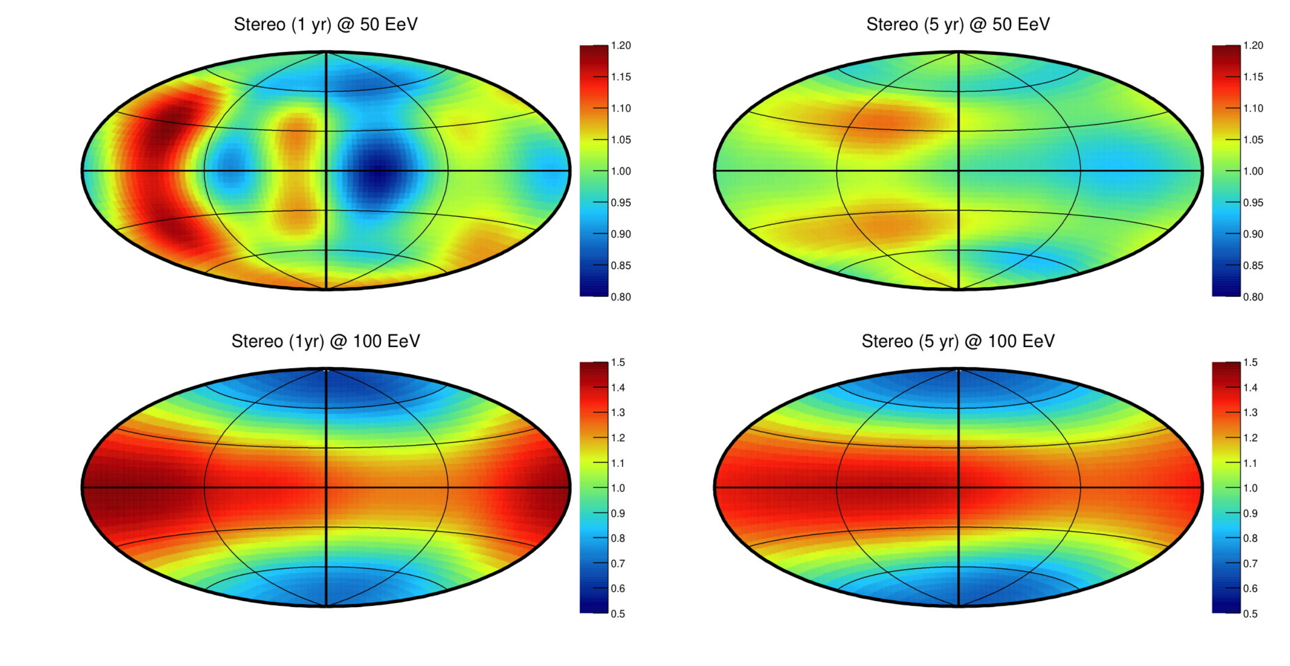
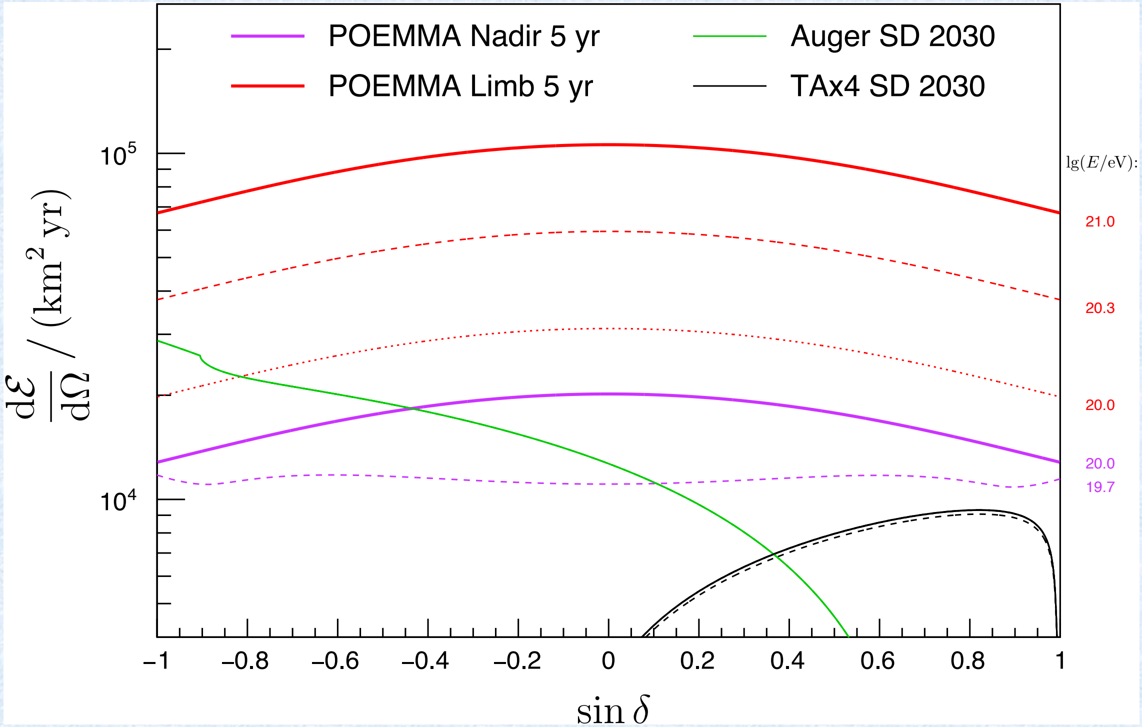


FIG. 13: POEMMA's UHECR sky exposures in declination versus right ascension. The color scale denoting the exposure variations in terms of the mean response taking into account the positions of the sun and the moon during the observation cycle.



POEMMA: UHECR Anisotropy Analysis *see PhysRevD.101.023012*

Partner

15° Angular Spread, 10% StarBurst Fraction

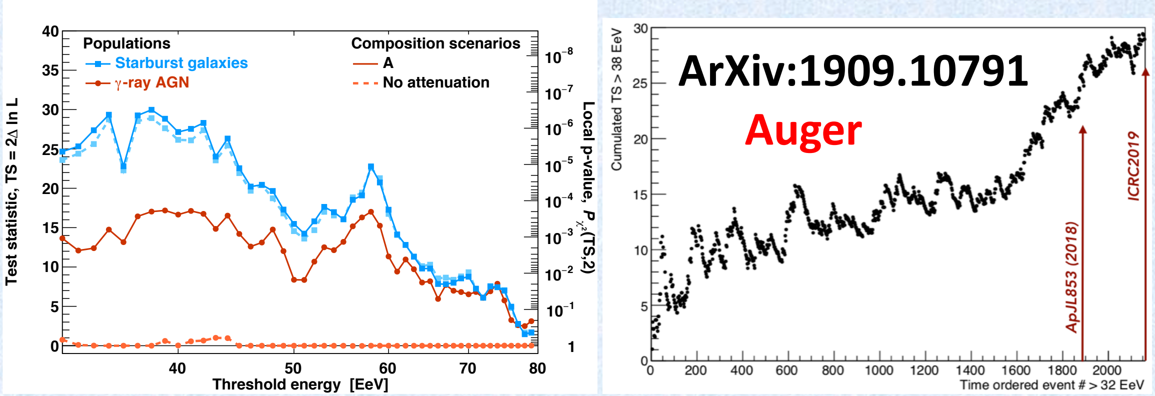


Figure 11: Left: Maximum likelihood-ratio as a function of energy threshold for the models based on SBGs and γAGNs. The results are shown in the attenuation (full line) and no-attenuation (dashed line) scenarios. Right: Cumulated test statistics for $E_{\mathrm{thr}} = 38$ EeV as a function of the time ordered number of events (for the SBG-only model). The number of events at the time of [39] and of this conference are indicated by the red arrows.

TABLE II. TS values for scenarios with $\Theta = 15°$.

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

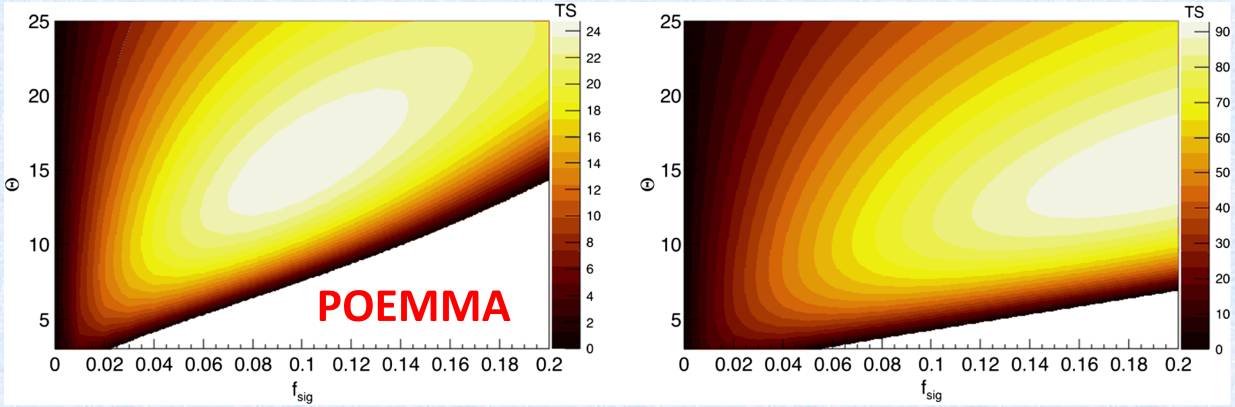


FIG. 24. TS profile for 1400 events for a particular scenario using the starburst source sky map in Fig. 23. In the scenario pictured here, the fraction of events drawn from the source sky map is $f = 10\%$ (left) and 20% (right), and the angular spread is $\Theta = 15°$.

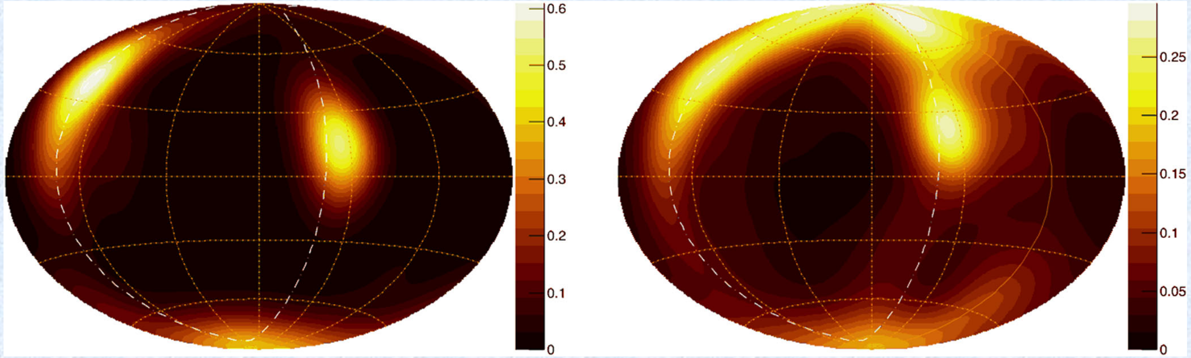
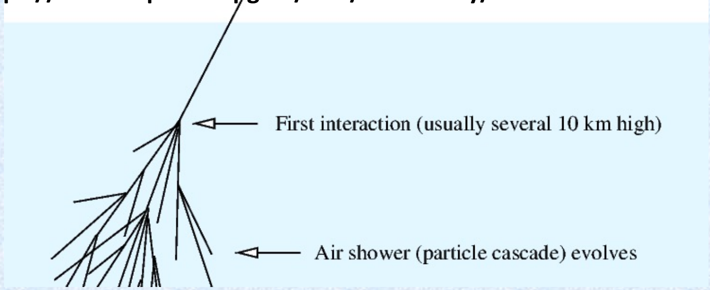


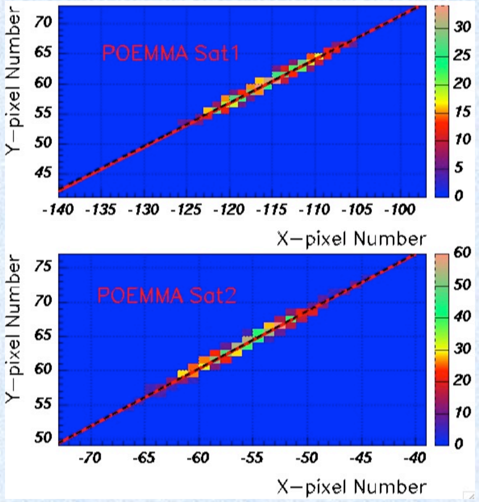
FIG. 23. Left: Skymap of nearby starburst galaxies from Refs. [35,103] weighted by radio flux at 1.4 GHz, the attenuation factor accounting for energy losses incurred by UHECRs through propagation, and the exposure of POEMMA. The map has been smoothed using a von Miser-Fisher distribution with concentration parameter corresponding to a search radius of 15.0° as found in Ref. [35]. The color scale indicates $\mathcal{F}_{\mathrm{src}}$, the probability density of the source sky map, as a function of position on the sky. The white dot-dashed line indicates the supergalactic plane. Right: Same as at left for nearby galaxies from the 2MRS catalog [105] and weighting by K-band flux corrected for Galactic extinction.

POEMMA: Air fluorescence Neutrino Sensitivity

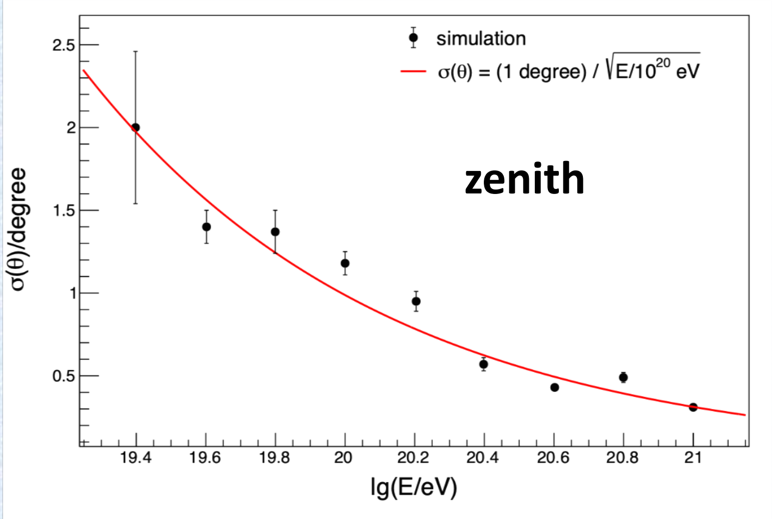
Excellent angular resolution → accurate determination of slant depth of EAS starting point

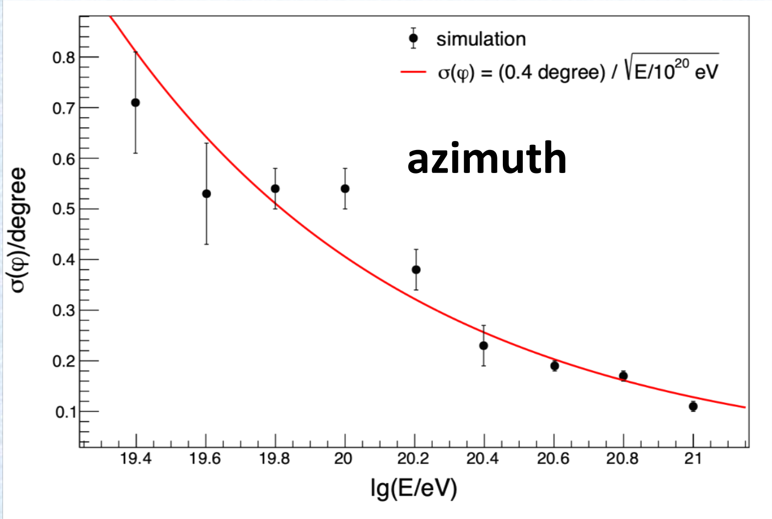
https://www.mpi-hd.mpg.de/hfm/CosmicRay/ShowerDetection.html

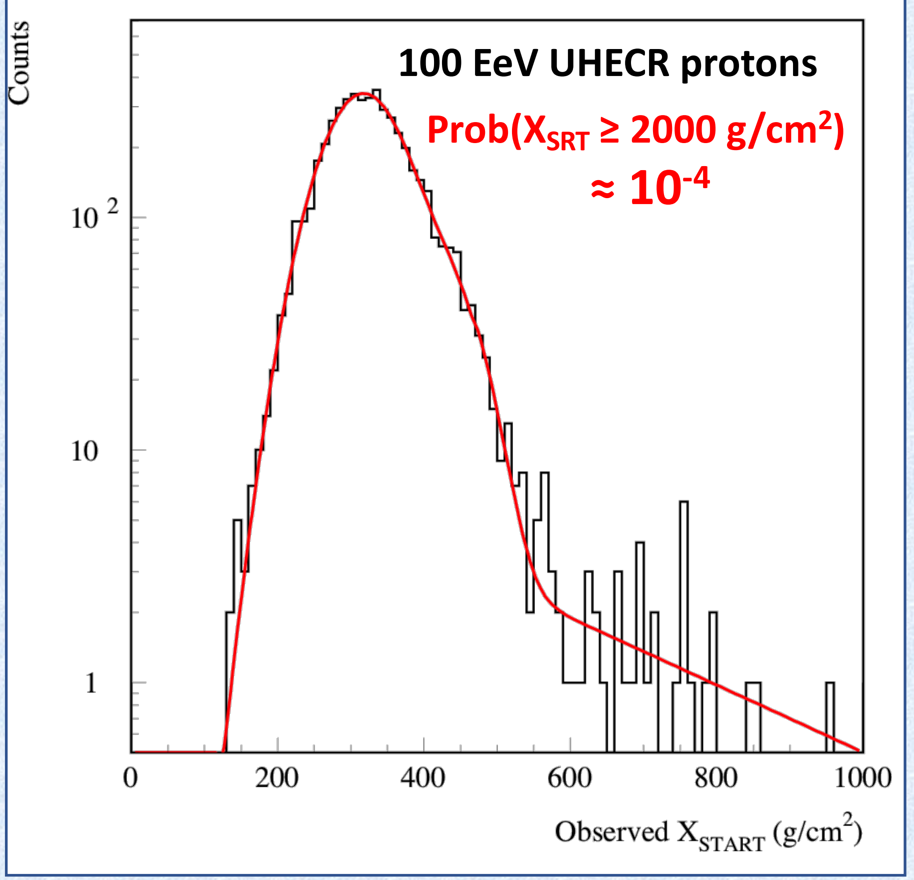




50 EeV simulated event







Prob($X_{SRT} \geq 2000$ g/cm^2) $\approx 10^{-4}$

UHECR 100% proton assumption most conservative

POEMMA: Air fluorescence Neutrino Sensitivity: *see PhysRevD.101.023012*

Effectively comes for free in stereo UHECR mode

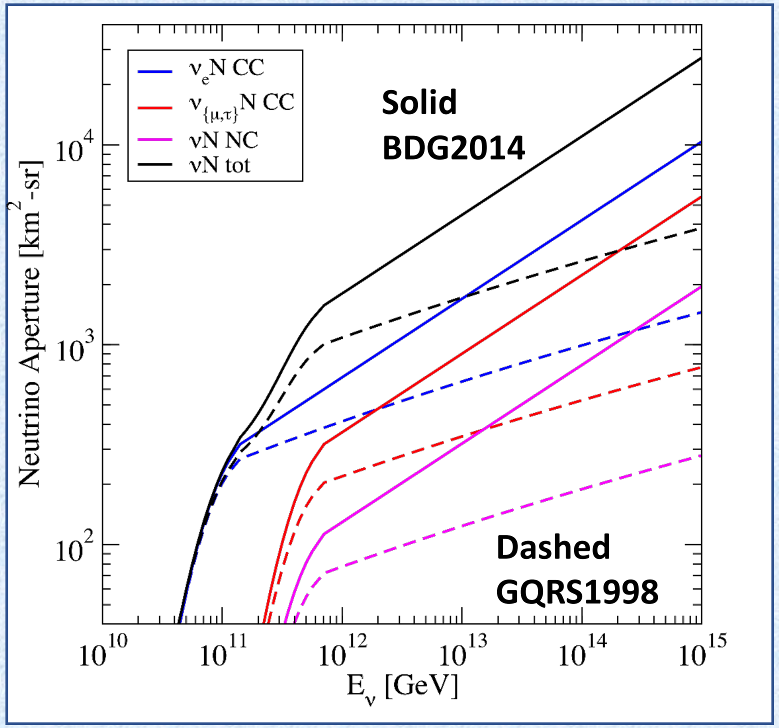
For $E_\nu \gtrsim$ 1 PeV, σ_{CC} & σ_{NC} virtually identical for ν & νbar

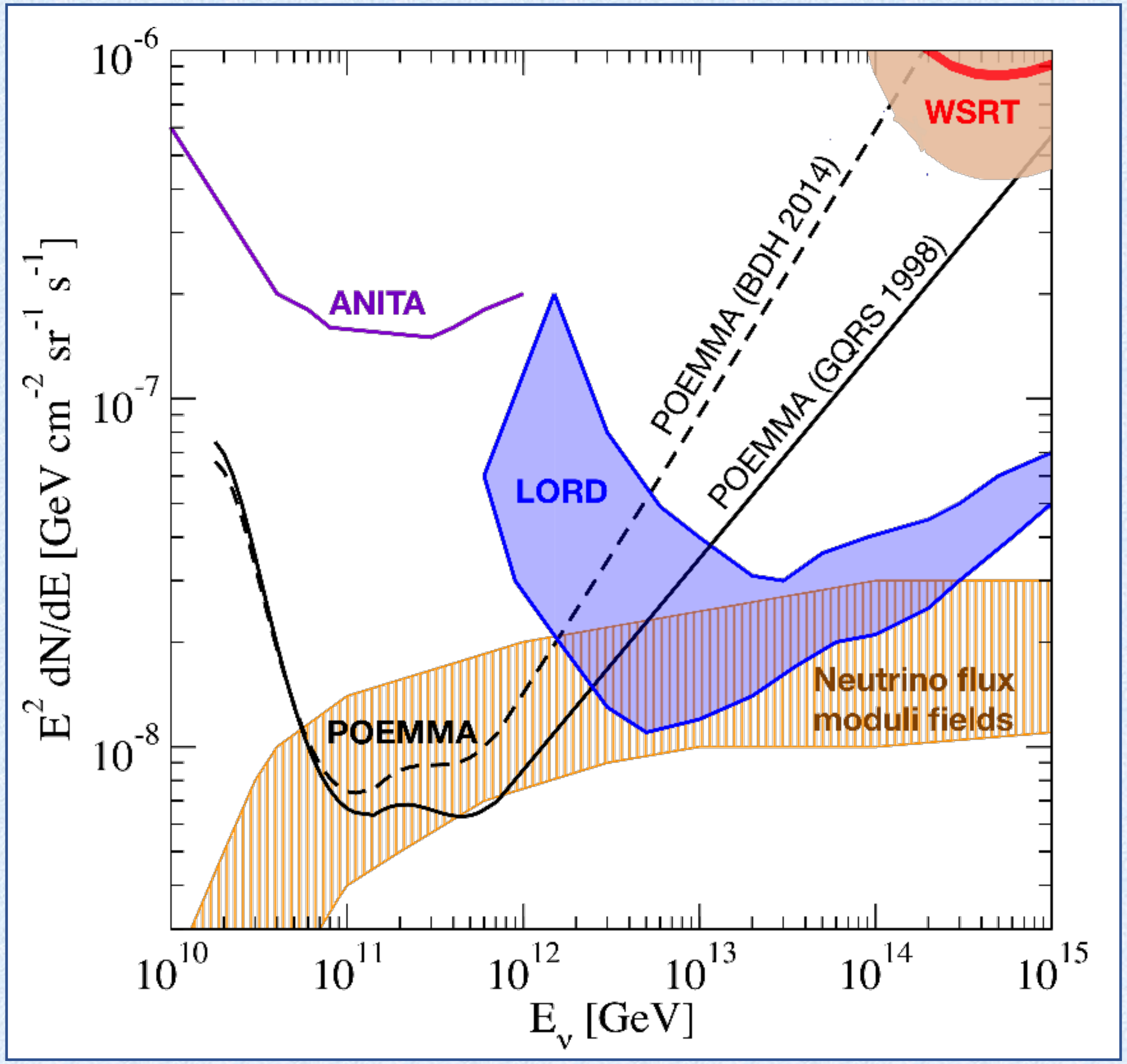
Assumptions:

- CC ν_e : 100% E_ν in EAS
- CC ν_μ & ν_τ : 20% E_ν in EAS ($\gamma c \tau_\tau \approx$ 5000 km)
- NC ν_e & ν_μ & ν_τ : 20% E_ν in EAS

UHECR Background Probabilities (1 event in 5 years):

- Auger Spectrum (100% H): < 1%
- TA Spectrum (100% H): ≈ 4%

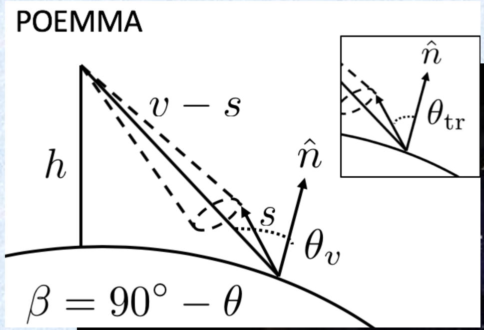


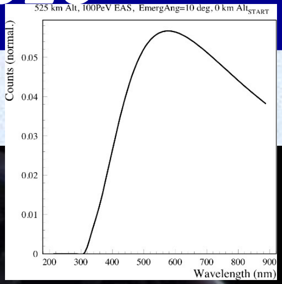


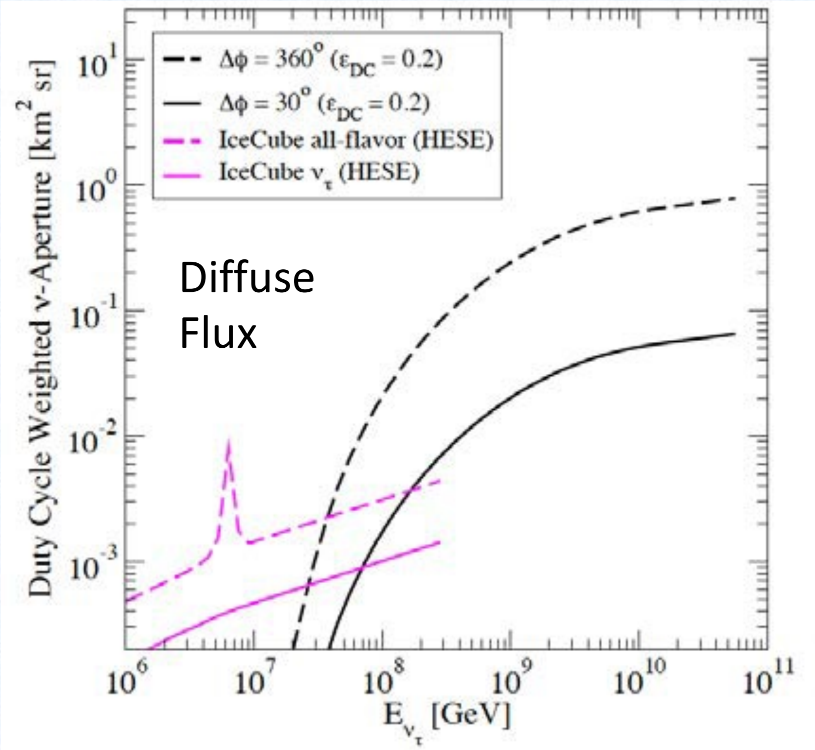
POEMMA Tau Neutrino Detection: *see PhysRevD.100.063010*

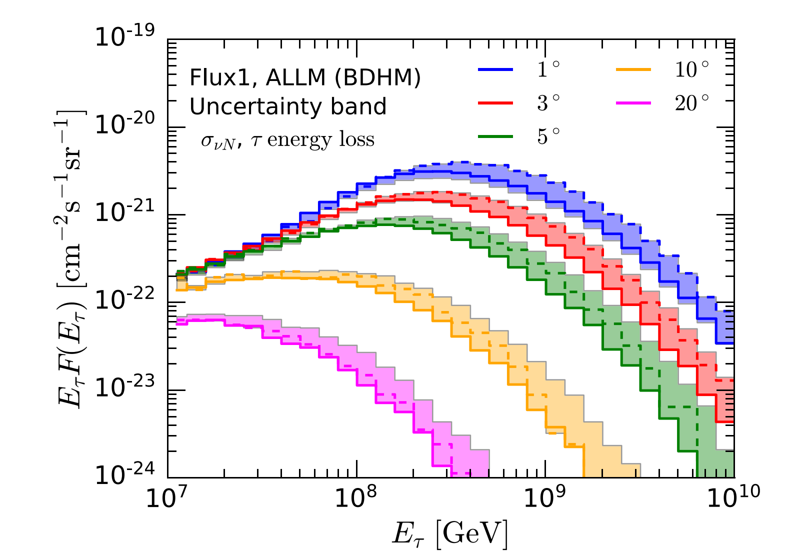
High-Energy Astrophysical Events generates neutrinos (ν_e,ν_μ) and 3 neutrino flavors reach Earth via neutrino oscillations.

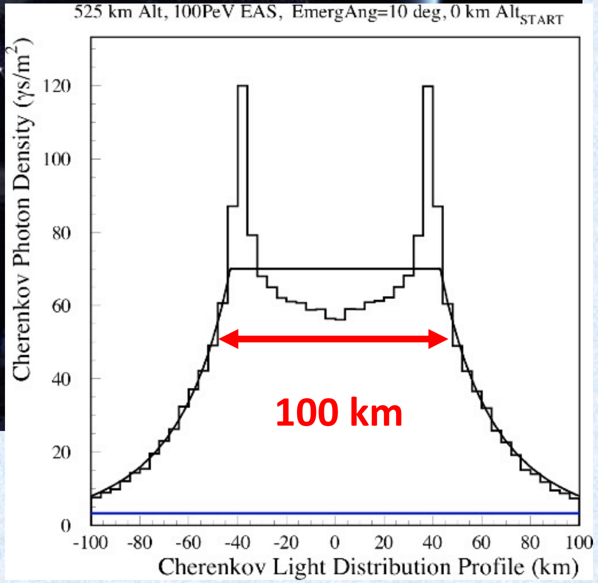
POEMMA designed to observe neutrinos with E > 20 PeV through Cherenkov signal of EASs from Earth-emerging tau decays.





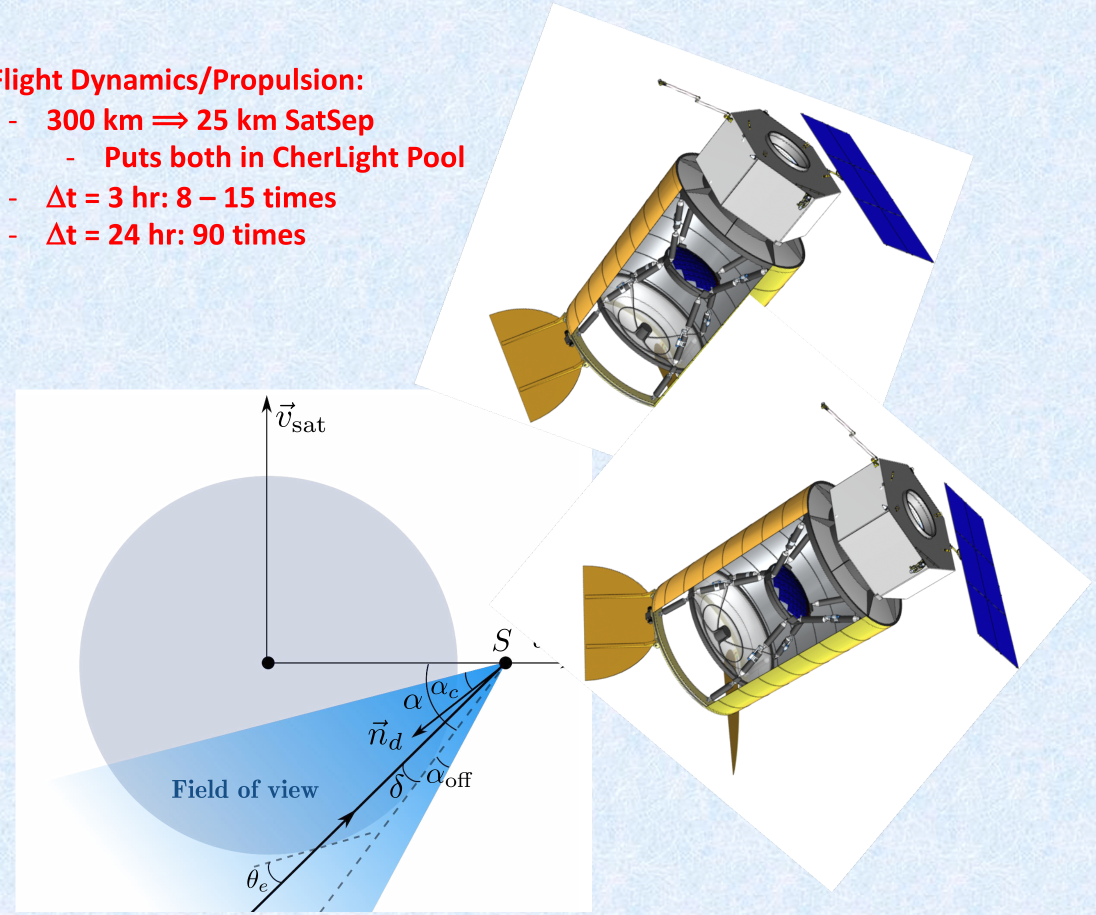




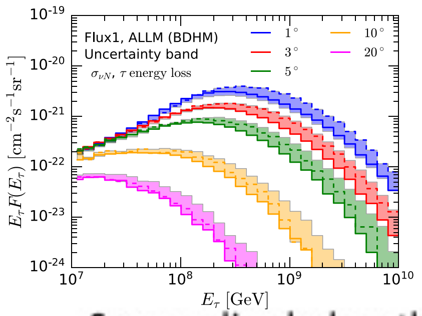


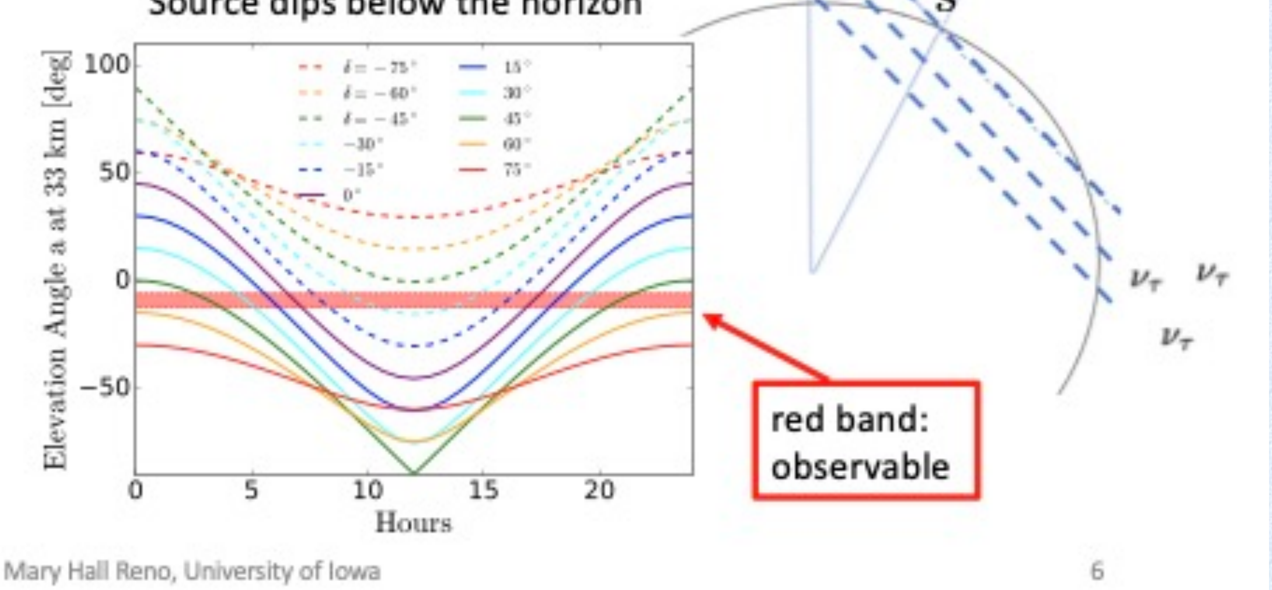
POEMMA Transient Neutrino Detection

Flight Dynamics/Propulsion:
- 300 km ⟹ 25 km SatSep
    - Puts both in CherLight Pool
- Δt = 3 hr: 8 – 15 times
- Δt = 24 hr: 90 times



EUSO-SPB2 Work by M.H Reno, T. Venters, and JFK (see ICRC21 presentations)





Avionics on each POEMMA satellite allow for slewing : 90° in 500 sec

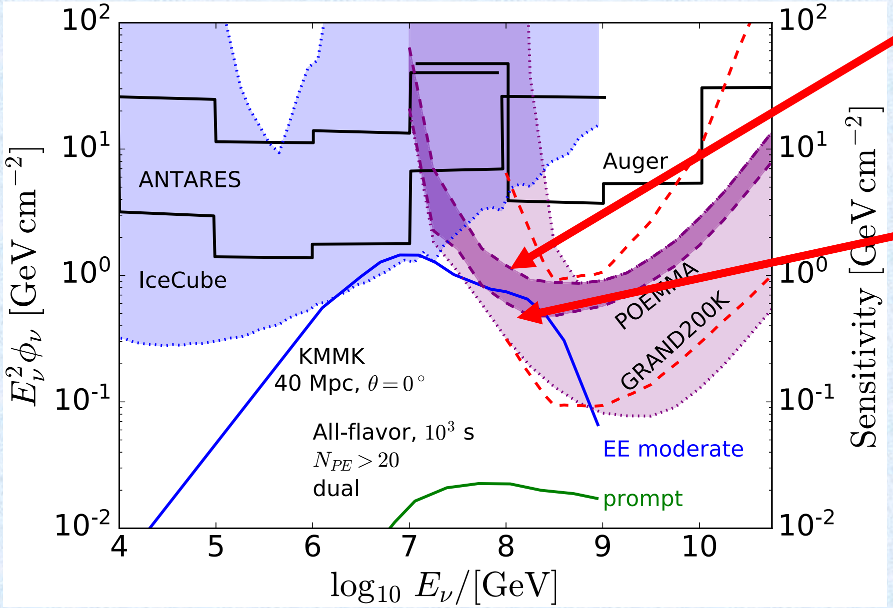
POEMMA ToO Neutrino Sensitivity: *see PhysRevD.102.123013*

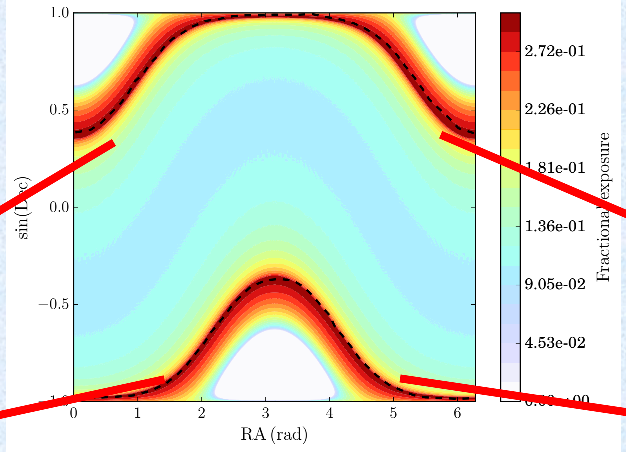
17% hit for ignoring $\tau \rightarrow \mu$ channel

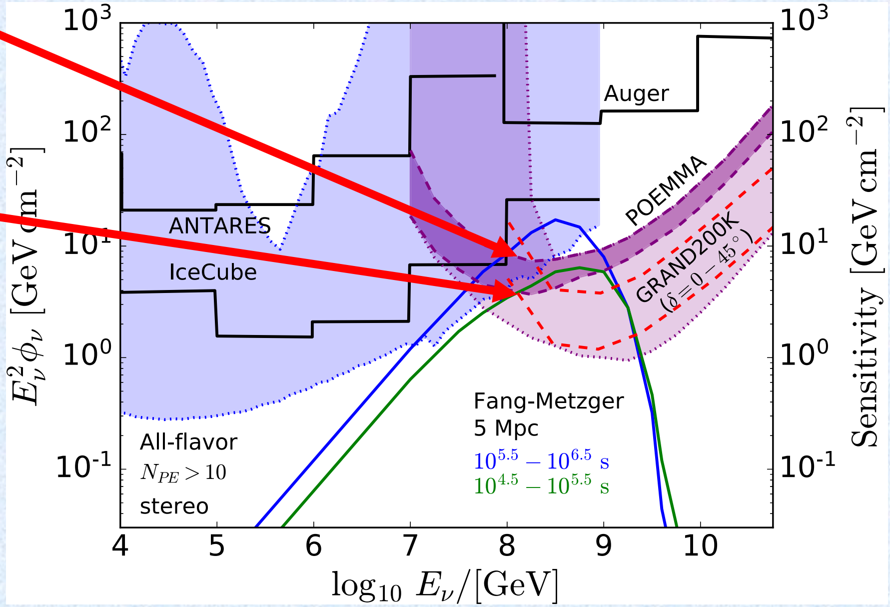
Short Bursts:
- 500 s to slew to source after alert
- 1000 s burst duration
- Source celestial location optimal
- Two independent Cher measurements
  - 300 km SatSep
- 20 PE threshold:
  - AirGlowBack < 10^{-3}/year

One orbit sky exposure assuming slewing to source position

Long Bursts:
- 3 to 24+hr to move SatSep to 50 km
- Burst duration $\gtrsim 10^5$ s (models in plot)
- Average Sun and moon effects
- Simultaneous Cher measurements
  - 50 km SatSep
- 10 PE threshold (time coincidence):
  - AirGlowBack < 10^{-3}/year







IceCube, ANTARES, Auger Limits for NS-NS merger GW170817

Kimura, Murase, Mészáros, Kiuchi

POEMMA ToO Neutrino Sensitivity: *see PhysRevD.102.123013*

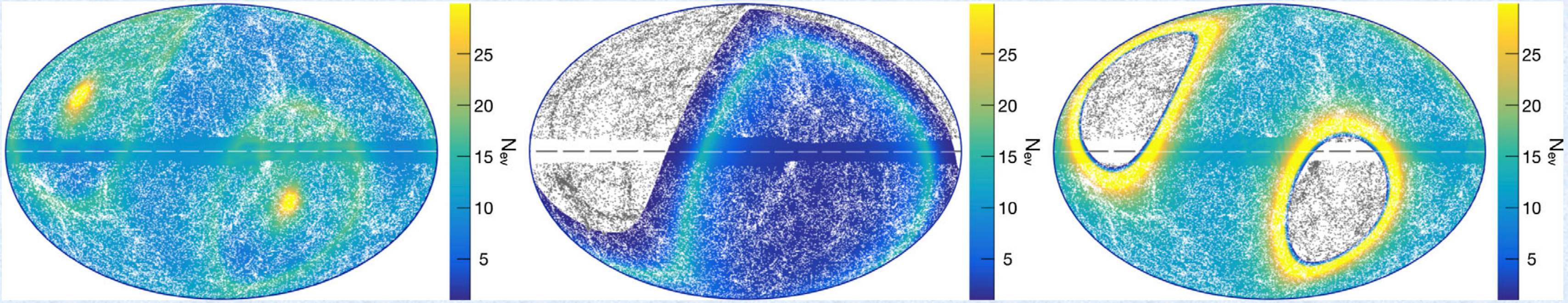


FIG. 7. Left: sky plot of the expected number of neutrino events as a function of galactic coordinates for POEMMA in the long-burst scenario of a BNS merger, as in the Fang and Metzger model [22], and placing the source at 5 Mpc. Point sources are galaxies from the 2MRS catalog [78]. Middle: same as at left for IceCube for muon neutrinos. Right: same as at left for GRAND200k. Areas with gray point sources are regions for which the experiment is expected to detect less than one neutrino.

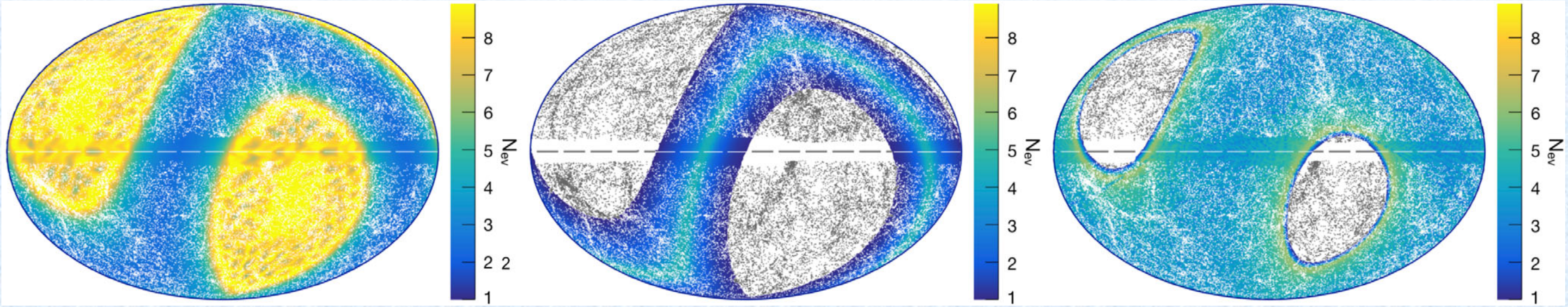


FIG. 8. Left: sky plot of the expected number of neutrino events as a function of galactic coordinates for POEMMA in the best-case short-burst scenario of an sGRB with moderate EE, as in the KMMK model [17], and placing the source at 40 Mpc. Point sources are galaxies from the 2MRS catalog [78]. Middle: same as at left for IceCube for muon neutrinos. Right: same as at left for GRAND200k. Areas with gray point sources are regions for which the experiment is expected to detect less than one neutrino.

POEMMA ToO Rate of Detection: *see PhysRevD.102.123013*

Partner

TONIA M. VENTERS *et al.* PHYS. REV. D **102,** 123013 (2020)

TABLE IV. Average expected numbers of neutrino events above $E_\nu > 10^7$ GeV detectable by POEMMA for several models of transient source classes assuming source locations at the GC and at 3 Mpc. The horizon distance for detecting 1.0 neutrino per ToO event is also provided. Source classes with observed durations $>10^3$ s are classified as long bursts. Those with observed durations $\lesssim 10^3$ s are classified as short bursts. Models in boldface type are those models for which POEMMA has $\gtrsim$10% chance of observing a ToO during the proposed mission lifetime of 3–5 years. Models in italics are the same but for a mission lifetime of 10 years.

Long bursts

Source class	No. of ν's at GC	No. of ν's at 3 Mpc	Largest distance for 1.0ν per event	Model reference
TDEs	1.4×10^5	0.9	3 Mpc	Dai and Fang [18] average
TDEs	6.8×10^5	4.7	7 Mpc	Dai and Fang [18] bright
TDEs	$\mathbf{2.7 \times 10^8}$	$\mathbf{1.7 \times 10^3}$	**128 Mpc**	**Lunardini and Winter [19] $M_{SMBH} = 5 \times 10^6\ M_\odot$ Lumi scaling model**
TDEs	7.7×10^7	*489*	*69 Mpc*	*Lunardini and Winter [19] Base scenario*
Blazar flares	NA[a]	NA[a]	47 Mpc	RFGBW [20]—FSRQ proton-dominated advective escape model
lGRB reverse shock (ISM)	1.2×10^5	0.8	3 Mpc	Murase [16]
lGRB reverse shock (wind)	2.5×10^7	174	41 Mpc	Murase [16]
BBH merger	$\mathbf{2.8 \times 10^7}$	**195**	**43 Mpc**	**Kotera and Silk [21] (rescaled) Low fluence**
BBH merger	$\mathbf{2.9 \times 10^8}$	$\mathbf{2.0 \times 10^3}$	**137 Mpc**	**Kotera and Silk [21] (rescaled) High fluence**
BNS merger	$\mathbf{4.3 \times 10^6}$	**30**	**16 Mpc**	**Fang and Metzger [22]**
BWD merger	25	0	38 kpc	XMMD [23]
Newly born Crablike pulsars (p)	190	0	109 kpc	Fang [24]
Newly born magnetars (p)	2.5×10^4	0.2	1 Mpc	Fang [24]
Newly born magnetars (Fe)	5.0×10^4	0.3	2 Mpc	Fang [24]

Short bursts

Source class	No. of ν's at GC	No. of ν's at 3 Mpc	Largest distance for 1.0ν per event	Model reference
sGRB extended emission (moderate)	1.1×10^8	800	90 Mpc	KMMK [17]

[a]Not applicable due to a lack of known blazars within 100 Mpc.

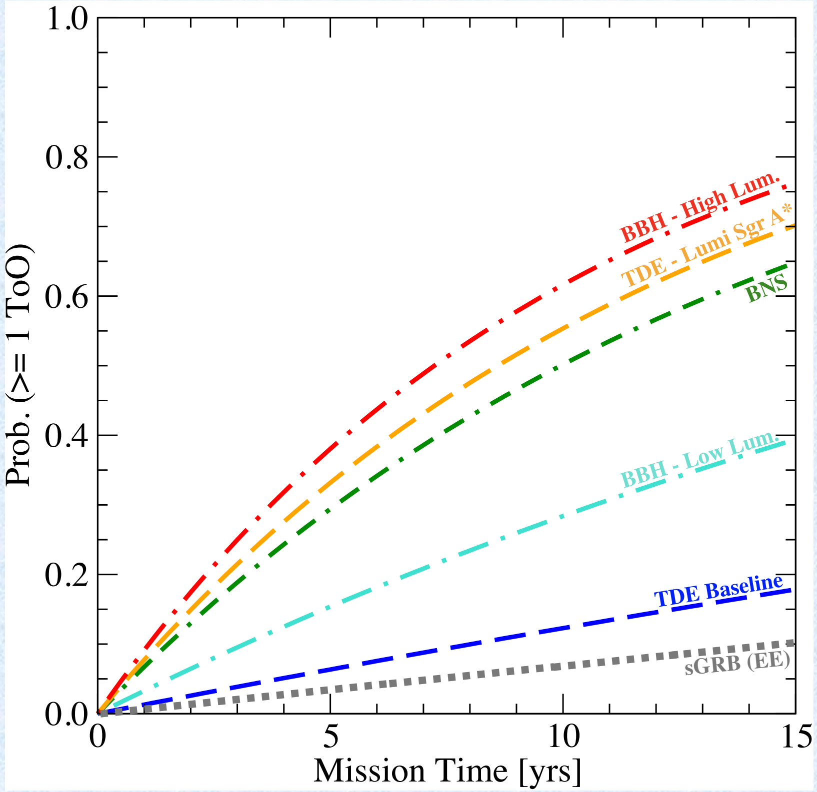


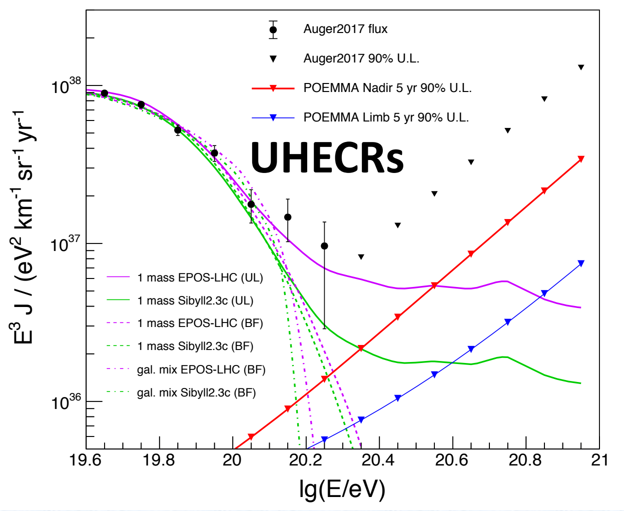
FIG. 9. The Poisson probability of POEMMA observing at least one ToO versus mission operation time for several modeled source classes. Featured source models are TDEs from Lunardini and Winter [19], BNS mergers from Fang and Metzger [22], BBH mergers from Kotera and Silk [21], and sGRBs with moderate EE from KMMK [17].

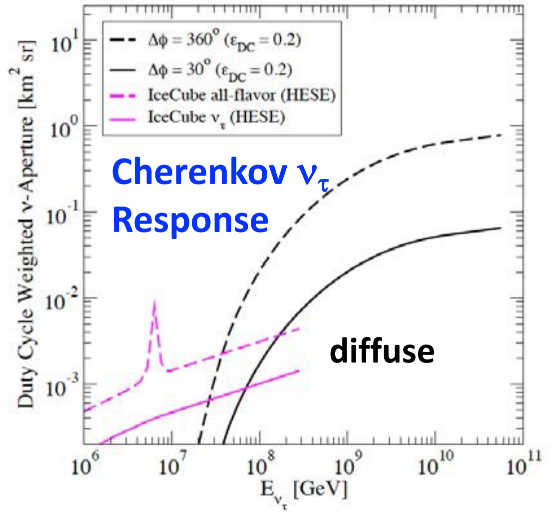
Partner

POEMMA Summary

POEMMA is designed to open two new Cosmic Windows:

- **UHECRS (> 20 EeV), to identify the source(s) of these extreme energy messengers**
  - All-sky coverage with significant increase in exposure
  - Stereo UHECR measurements of Spectrum, Composition, Anisotropy $E_{CR} \geq 50$ EeV
    - Remarkable energy (< 20%), angular ($\lesssim 1.2^{\circ}$), and composition ($\sigma_{Xmax} \lesssim 30$ g/cm^2) resolutions
  - **Leads to high sensitivity to UHE neutrinos (> 20 EeV) via stereo air fluorescence measurements**
- **Neutrinos from astrophysical Transients (> 20 PeV)**
  - **Unique sensitivity to short- & long-lived transient events with 'full-sky' coverage**
  - **Highlights the low energy neutrino threshold nature of space-based optical Cherenkov method, even with duty cycle of order ~20%**
- **POEMMA sensitivity to SHDM → ν's in 20+ PeV (Cherenkov) and 20+ EeV (fluorescence) energy bands**
  - **C. Guepin et al.: arXiv:2106.04446)**

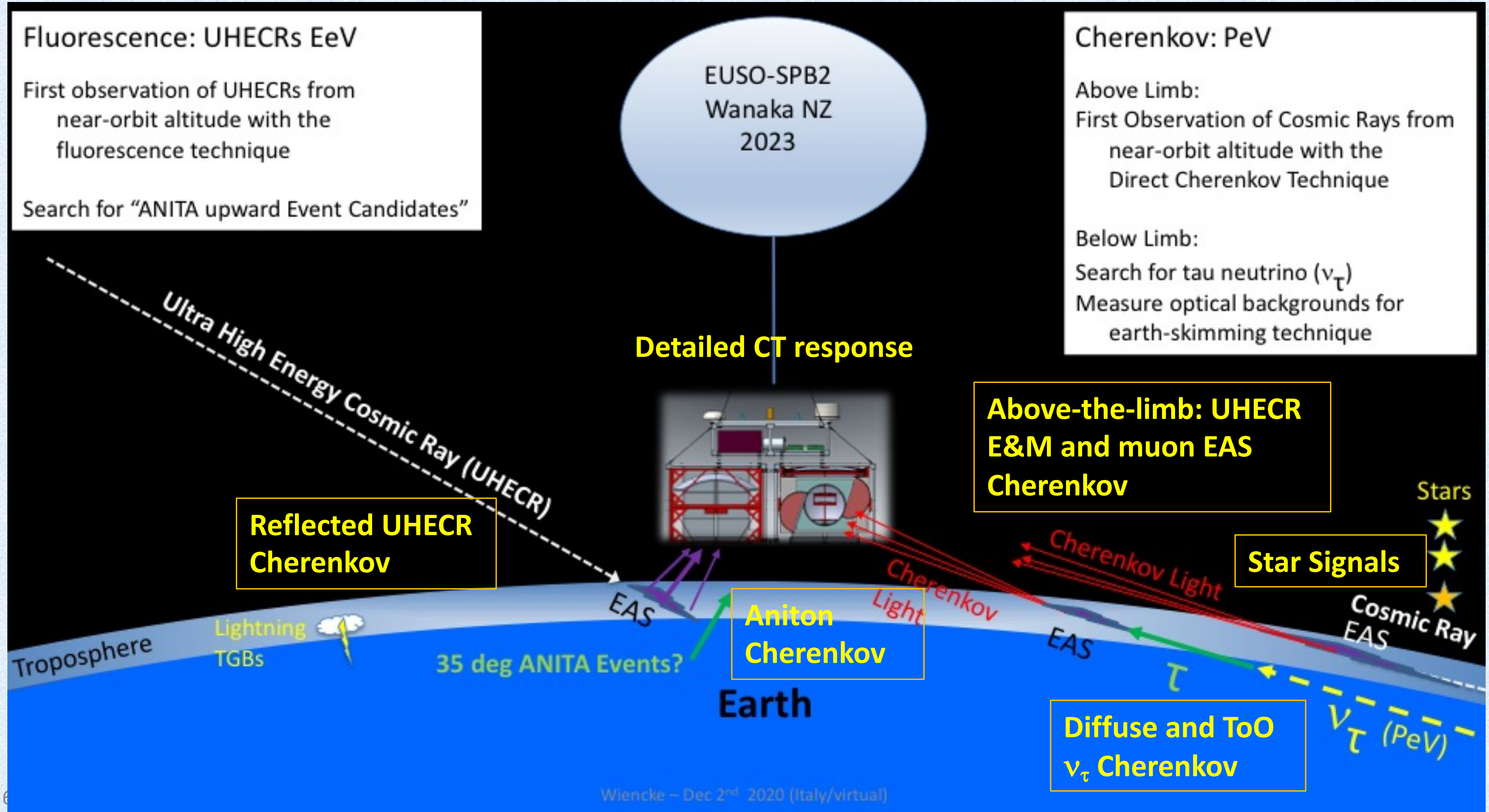




Work in Progress:

- **Awaiting Results from Astro2020 regarding NASA Probe recommendation and NASA implementation.**
- **Group is building upon POEMMA neutrino studies investigating focused neutrino missions**
- **νSpaceSim: Neutrino Simulation work continue under funded NASA-APRA grant:** Goal to develop *robust* end-to-end neutrino simulation package for space-based and sub-orbital experiment: ***optical Cherenkov and radio signals.***
- **EUSO-SPB2 (with Cherenkov Camera) under development to ULDB fly in 2023.**

EUSO-SPB2: Sources of Cherenkov Signals



BackUps

POEMMA: proton-Air Cross Section Measurements

Partner

LUIS A. ANCHORDOQUI *et al.* PHYS. REV. D **101,** 023012 (2020)

Assuming 1400 UHECRs for $E_{CR} \geq 40$ EeV

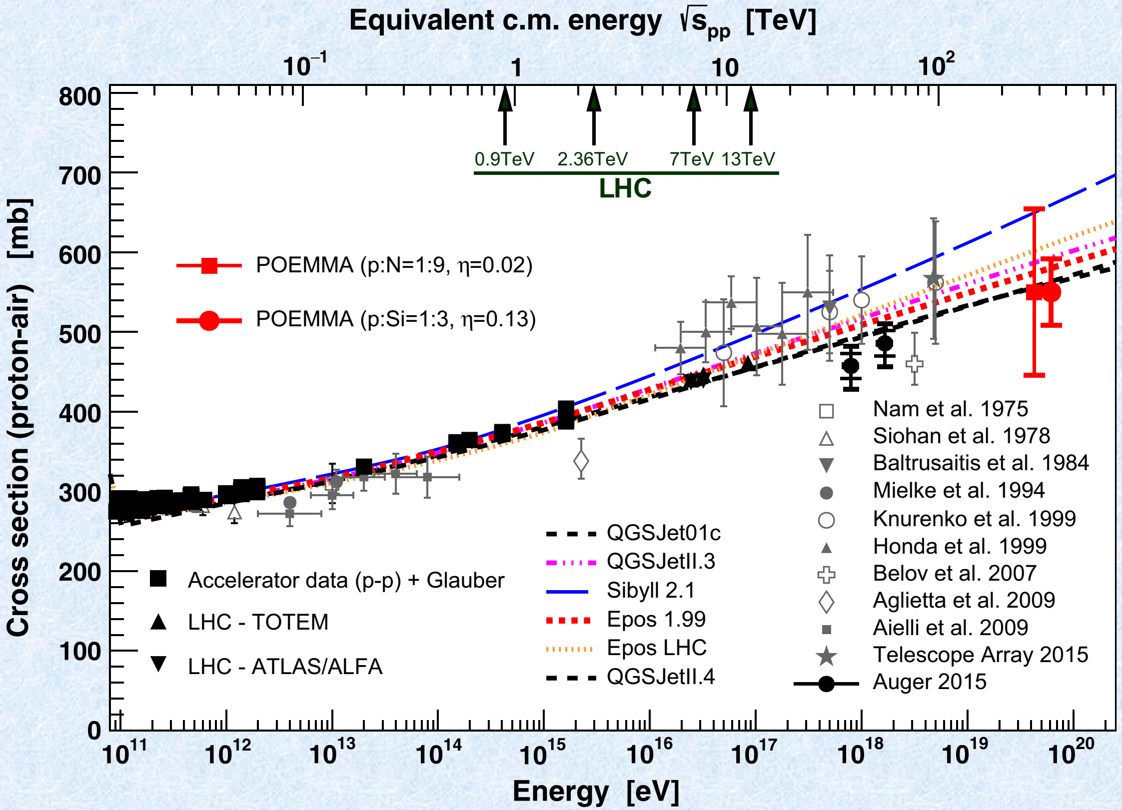


FIG. 26. Potential of a measurement of the UHE proton-air cross section with POEMMA. Shown are also current model predictions and a complete compilation of accelerator data converted to a proton-air cross section using the Glauber formalism. The expected uncertainties for two composition scenarios (left, $p:N = 1:9$; right, $p:Si = 1:3$) are shown as red markers with error bars. The two points are slightly displaced in energy for better visibility.

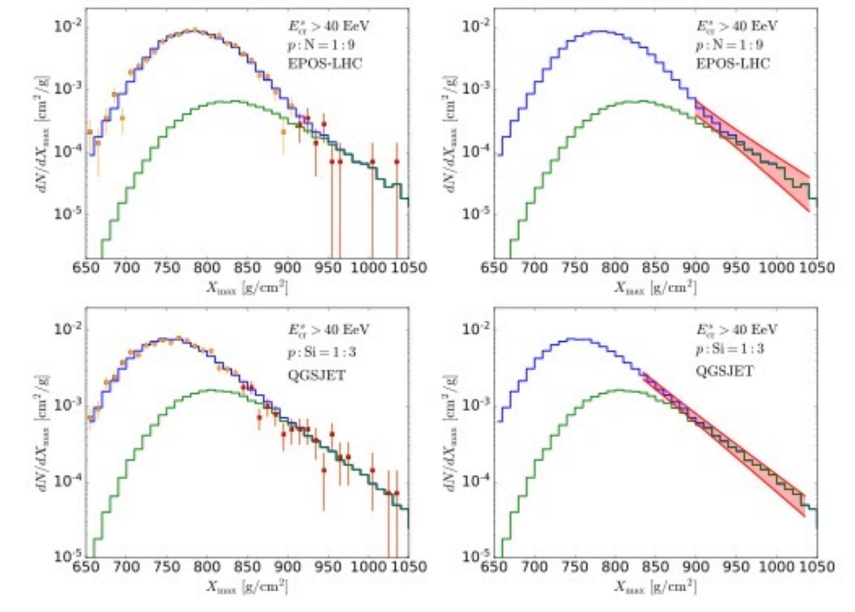
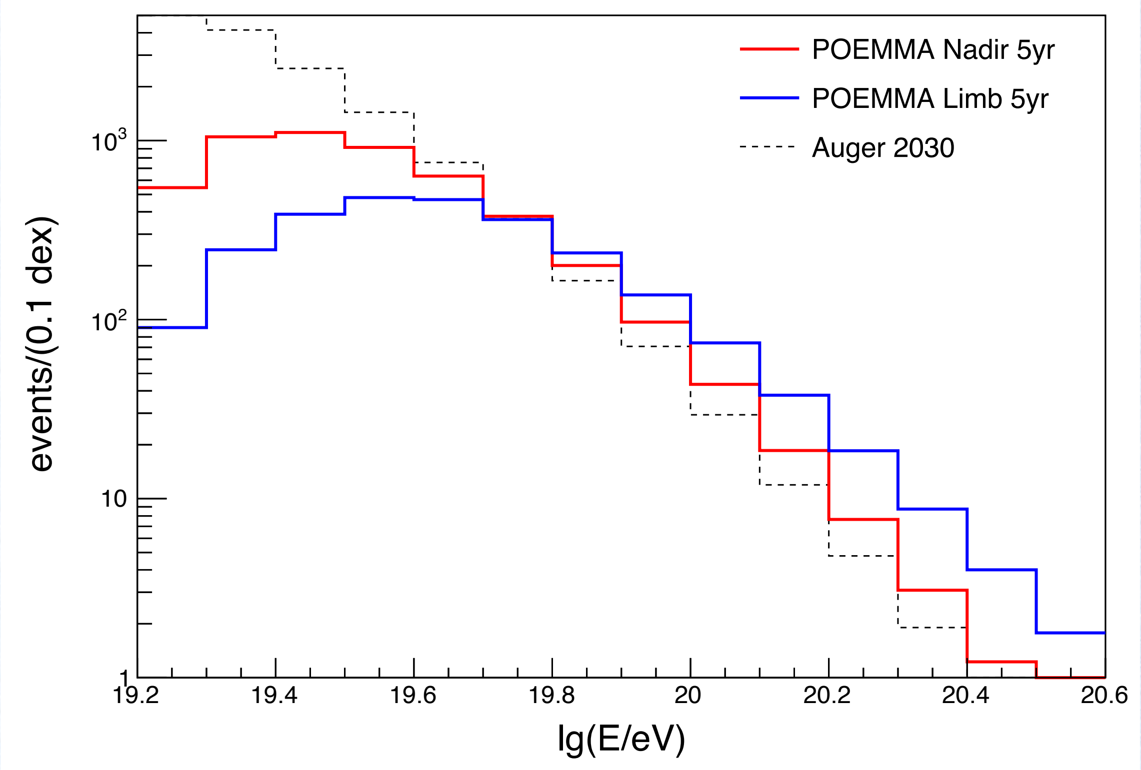
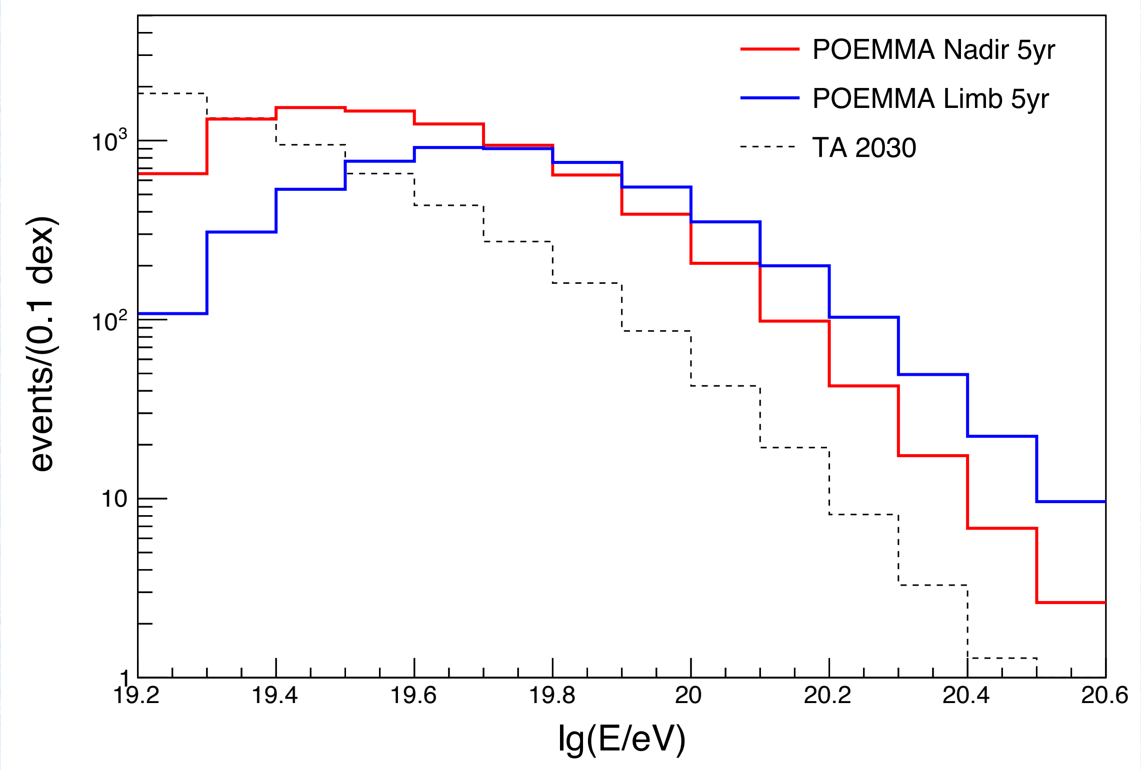


FIG. 41: The energy and X_{max} smeared distribution dN/dX_{max} for QGSJETII.04 (upper panels) and EPOS-LHC (lower panels) from the parameterization of Ref. [150] for $E_{CR} > 40$ EeV and p:N = 1:9, $\eta = 0.02$ (upper) and p:Si = 1:3, $\eta = 0.13$ (lower). The blue histograms show the full X_{max} distributions, while the green histograms show the proton components. The data points, with error bars, show the distribution of events for one sample of $N_{evts} = 1{,}400$ events with error bars according to $\sqrt{N_i}/N_{evts}$, for N_i the number of events in the bin i. The red data points show X_{max} bins above X_{max}^{start}. In the right panels, and shaded red band shows the slope of the tail determined by Λ_η^{opt} with 1σ statistical errors on Λ_η^{opt} and the number of events above X_{max}^{start}.

POEMMA: UHECR Spectra:





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POEMMA: Air fluorescence Neutrino Sensitivity is Robust

NASA Partner

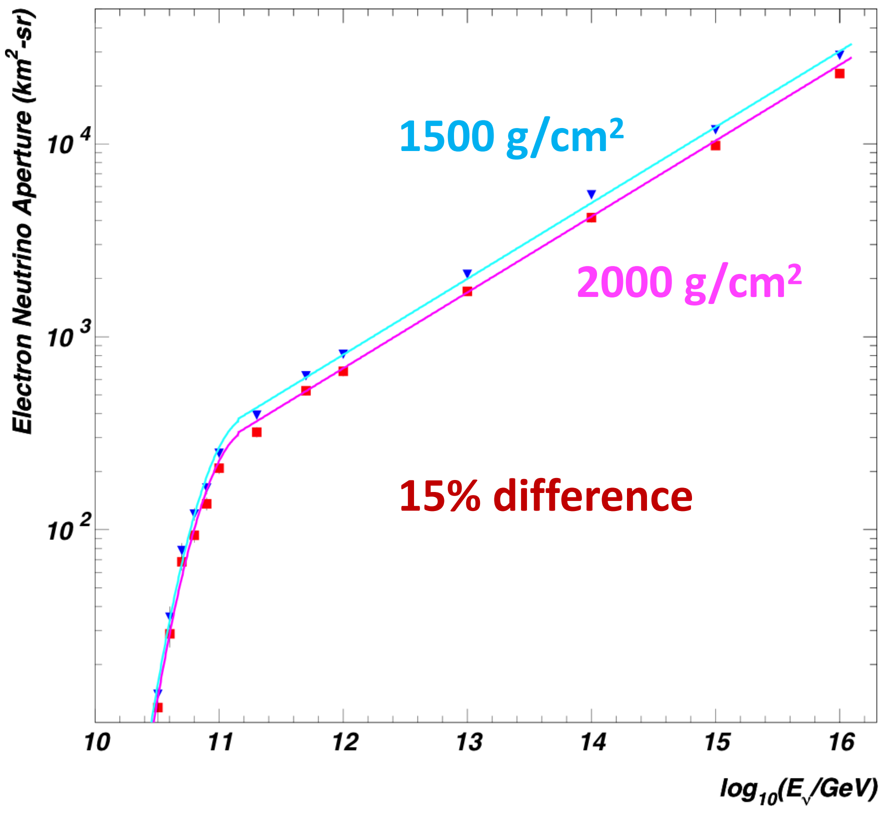


FIG. 43: Comparison of the instantaneous electron neutrino apertures based on stereo air fluorescence measurements. Upper points and curve are for $X_{Start} \geq 1500$ g/cm^2 while the lower points and curve are for $X_{Start} \geq 2000$ g/cm^2. The lower curve is 85% of the upper curve over the energy band.

UHECR observed proton background probabilities as a function of energy and observed X_{START} based on 5 year observation with the Auger and TA measured spectra.

X_{Start}	40 EeV	60 EeV	100 EeV	200 EeV	Sum
Auger Spectrum: $N_{Obs} \geq 1$					
≥ 1500 g/cm^2	1.5×10^{-4}	1.9×10^{-2}	3.8×10^{-2}	4.5×10^{-3}	6.1×10^{-2}
≥ 2000 g/cm^2	2.8×10^{-7}	1.3×10^{-3}	7.2×10^{-3}	1.0×10^{-3}	9.6×10^{-3}
Auger Spectrum: $N_{Obs} \geq 2$					
≥ 1500 g/cm^2	1.2×10^{-8}	1.9×10^{-4}	7.1×10^{-4}	1.0×10^{-5}	9.1×10^{-4}
≥ 2000 g/cm^2	3.9×10^{-14}	8.4×10^{-7}	2.6×10^{-5}	5.3×10^{-7}	2.8×10^{-5}
TA Spectrum: $N_{Obs} \geq 1$					
≥ 1500 g/cm^2	2.5×10^{-4}	6.4×10^{-2}	1.7×10^{-1}	9.0×10^{-3}	2.5×10^{-1}
≥ 2000 g/cm^2	4.7×10^{-7}	4.4×10^{-3}	3.5×10^{-2}	2.1×10^{-3}	4.2×10^{-2}
Ta Spectrum: $N_{Obs} \geq 2$					
≥ 1500 g/cm^2	3.0×10^{-8}	2.1×10^{-3}	1.6×10^{-2}	4.1×10^{-5}	1.8×10^{-2}
≥ 2000 g/cm^2	1.0×10^{-13}	9.8×10^{-6}	6.3×10^{-4}	2.1×10^{-6}	6.4×10^{-4}

UHECR Fake ν's Background (1 event in 5 years):
- **Auger Spectrum (100% H): < 1%**
- **TA Spectrum (100% H): ≈ 4%**

Over-the-Limb VHECR Cherenkov Observations

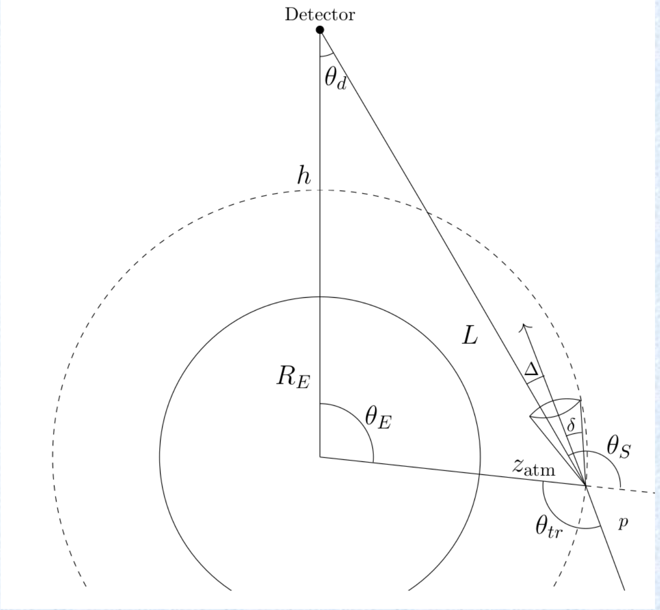
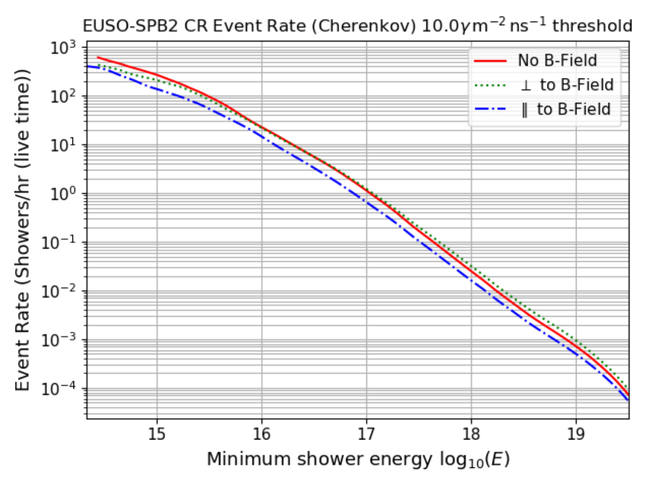
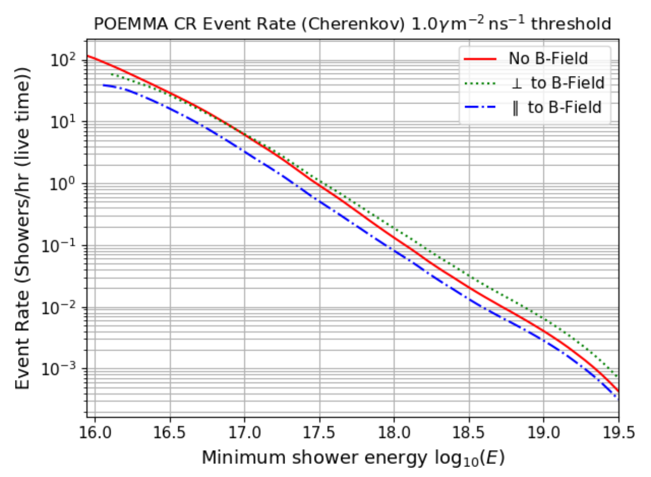
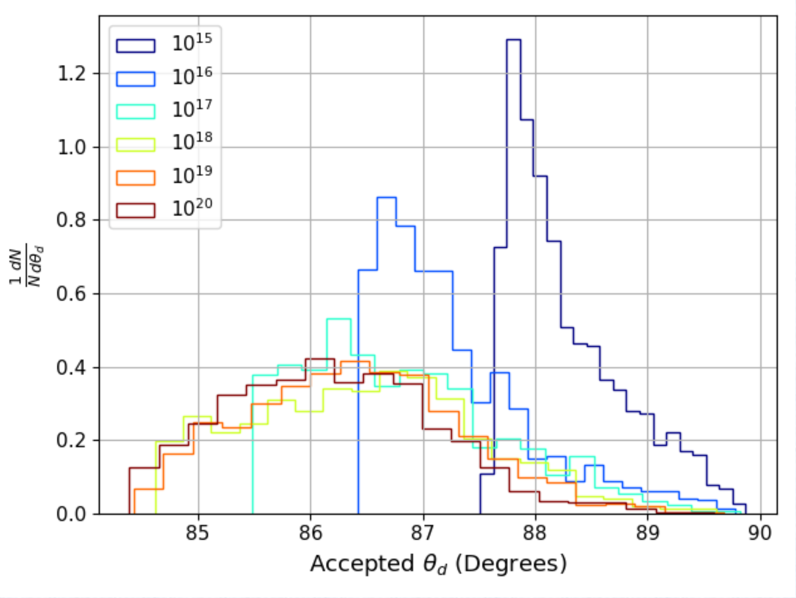
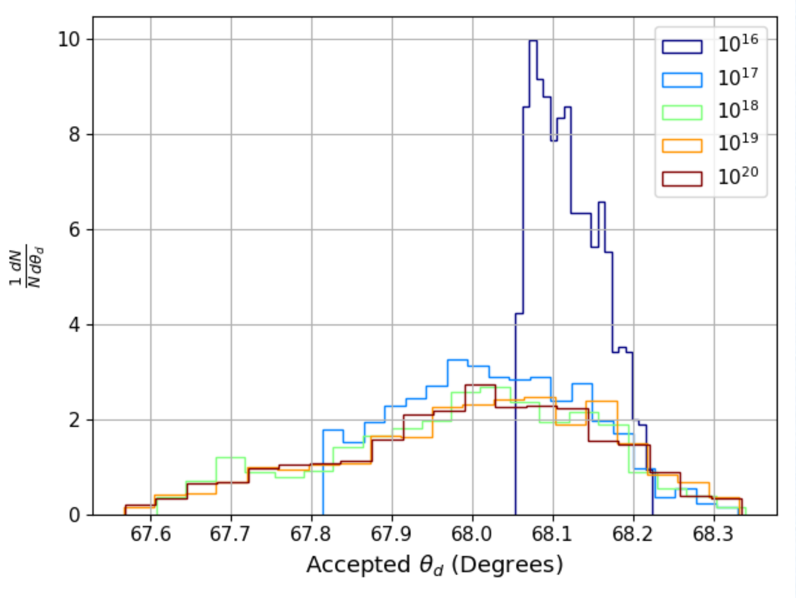


FIG. 1. Geometry of measuring the Cherenkov signal from cosmic rays arriving from above the Earth horizon in the case of a space based instrument.









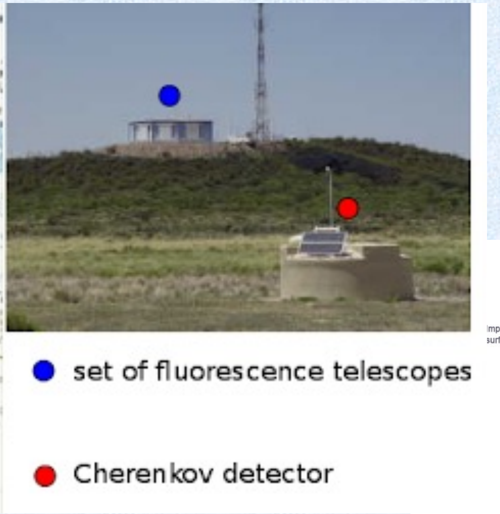
Modelling the Optical Cherenkov Signals by Cosmic Ray Extensive Air Showers Observed from Sub-Orbital and Orbital Altitudes

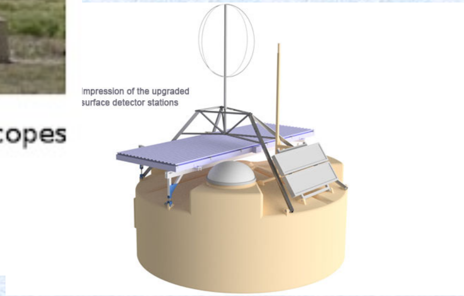
Cummings, A. L.; Aloisio, R.; Eser, J. Krizmanic, J. F.

Submitted to PhysRevd: arXiv:

Includes effects of geomagnetic field on upward-moving and high-altitude EAS

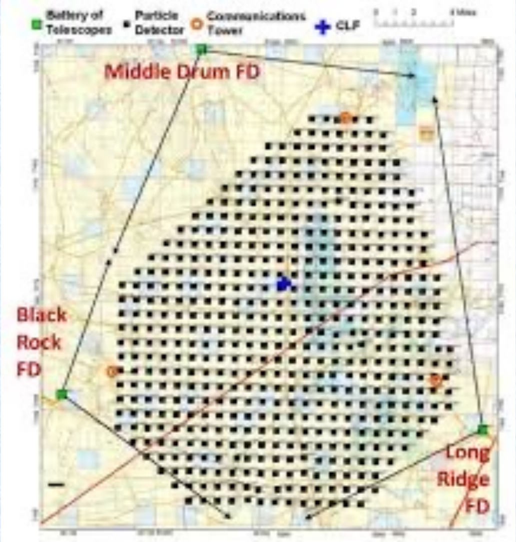
PAO and TA

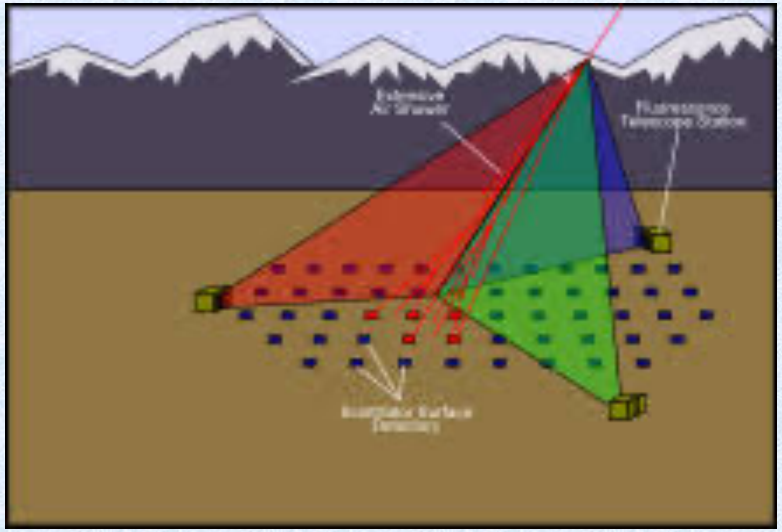




Pierre Auger Observatory

- Location: Malargüe, Argentina
- 2019 ICRC: 14 years of operation
- Cherenkov Tank Surface Array Area: ~3000 km^2
- Surface Array UHECR Aperture: ~6000 km^2 sr
- Fluorescence UHECR Aperture: ~ 600 km^2
- Upgrading SA detectors via Auger Prime
  - Increase EAS measurement precision via better e/μ separation including radio





Telescope Array

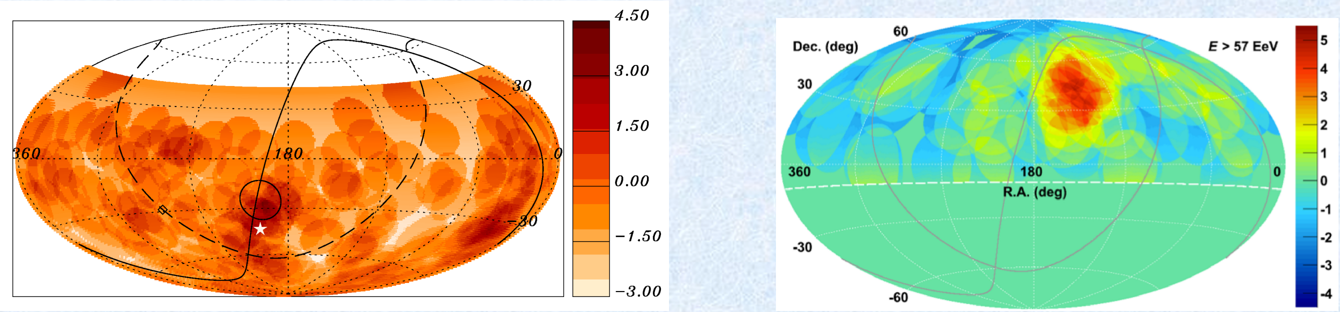
- Location: Delta, Utah,
- 2019 ICRC: 11 years of operation
- Cherenkov Tank Surface Array Area: ~700 km^2
- Surface Array UHECR Aperture: ~1300 km^2 sr
- Fluorescence UHECR Aperture: ~ 130 km^2
- Upgrading SA and FT to TAx4 (4 x area of TA)
  - More modest precision: E_{RES} ~ 25% (from GCOS discussion)

UHECR Anisotropy for full-sky using PAO and TA subject to systematics

NASA Partner

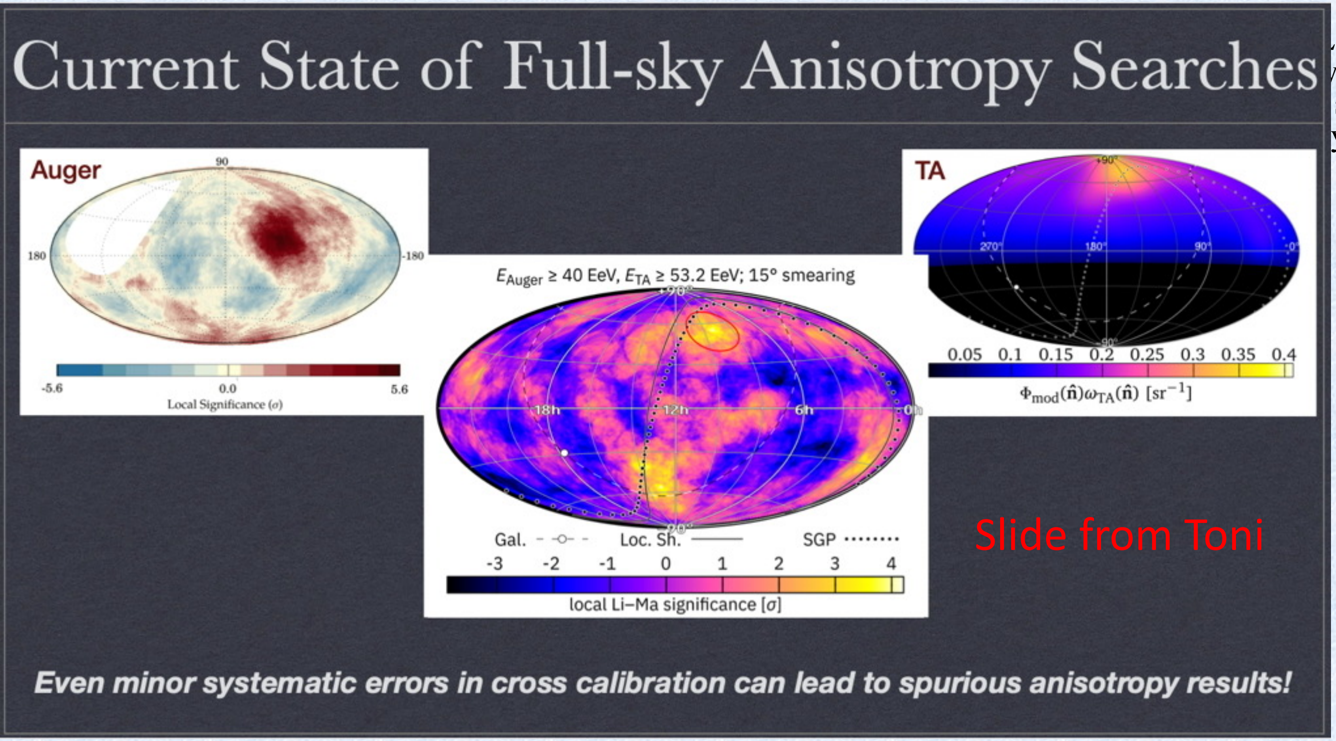
POEMMA

Alves Batista et al. **Open Questions in Cosmic-Ray Research at Ultrahigh Energies**



ocal-significance maps from searches for localized excess in Equatorial coordinates. *Left:* / observed at $E_{\mathrm{Auger}} > 54\,\mathrm{EeV}$ smeared on a 12° angular scale. The solid and long-dashed lines supergalactic and Galactic plane, respectively. *Reproduced with permission from* [4]. *Right:* y observed at $E_{\mathrm{TA}} > 57\,\mathrm{EeV}$ smeared on a 20° angular scale. *Reproduced with permission*

arXiv:1903.06174

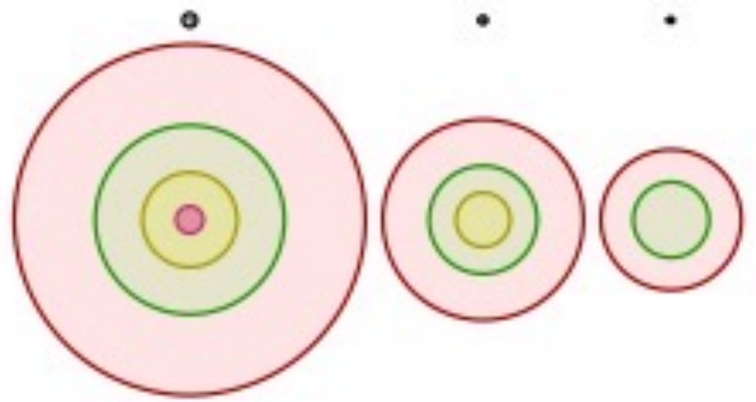


POEMMA: Astrophysics from UHECR composition analysis

NASA Partner

POEMMA

Use differences in angular deflections and flux attenuation for light vs heavy nuclei to assess “hot spot” sources.



Small -> Wide: H, He, N, Si, Fe

FIG. 21: Circles representing the composition-layered structure of hotspots at different energies, for proton sources (top) and nuclei sources (bottom). The radii of the circles respect the proportions of the angular sizes given by (2), for protons (black), helium (magenta), nitrogen (yellow), silicon (green) and iron (red); and for 40 EeV (left), 70 EeV (center) and 100 EeV (right).

Source, Bfield, and distance dependent!

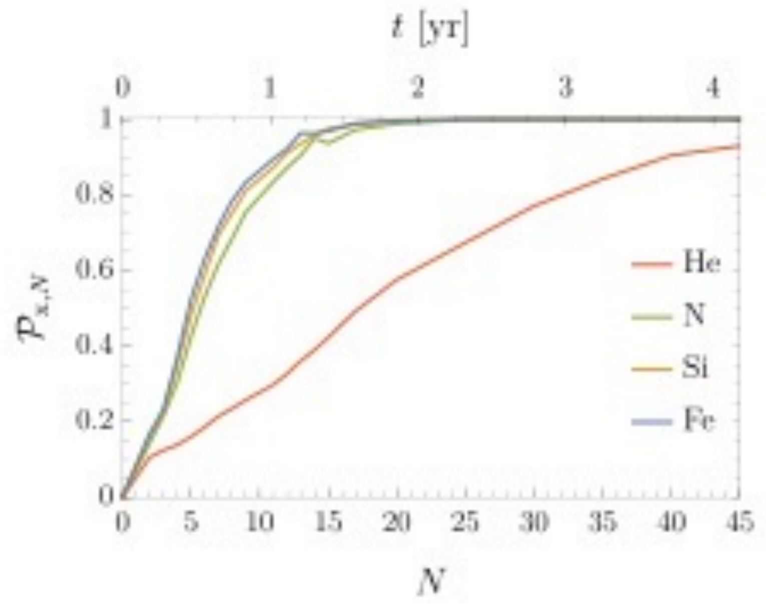


FIG. 22: Power of the statistical test for different alternative hypotheses, that is different nuclei and number of events per hot spot. The horizontal axis on the top indicates the projected time-scale for POEMMA.

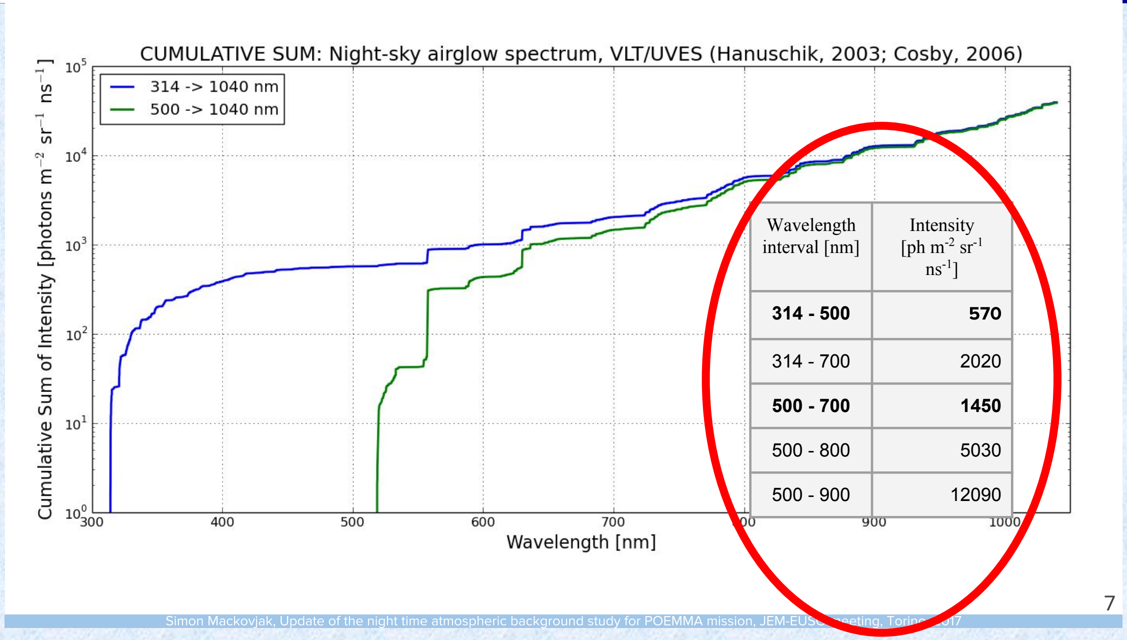
PhysRevD98, 123018

Hot Spot Analysis:

- Discriminate protons (vs using X_{MAX}) from CNO and heavies by looking at the distribution of arrival directions.
- If source emits protons, then AngRes should improve ~ $1/E_{CR}$
- If mixed composition, picture is more complicated
- If the hot spot is nuclei heavier than nitrogen, in two years of operation POEMMA will be able to exclude a pure-proton origin at the 95% CL.

Air Glow Background in Cherenkov Band: Ref 10.1016/j.nima.2020.164614

Partner



Wavelength interval [nm]	Intensity [ph m^{-2} sr^{-1} ns^{-1}]
314 - 500	**570**
314 - 700	2020
500 - 700	**1450**
500 - 800	5030
500 - 900	12090

314 nm – 900 nm

Use to calculate effective PDE (for SiPM): <PDE> = 0.1

12,660 photons/m^2/sr/ns

314 nm – 1000 nm

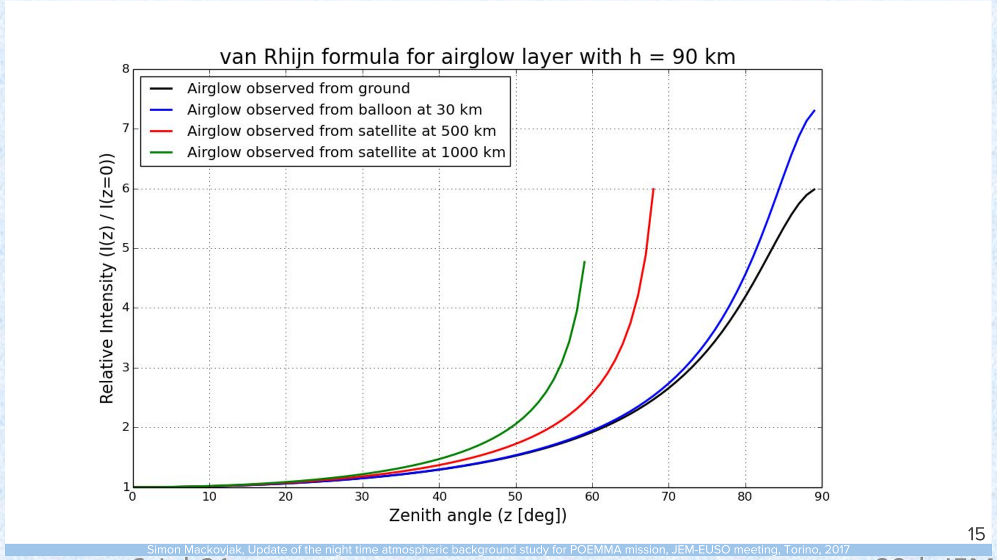
~25,000 photons/m^2/sr/ns

314 nm – 500 nm

570 photons/m^2/sr/ns

Requirement for < 1e-2 background events per year leads to high PE thresholds

- **10 PE (coincident Cher measurement)**
- **20 PE (individual Cher measurement)**



Viewing at angles away from nadir views more optical depth of air glow layer.

x6 for viewing limb from 525 km

Work by Simon Mackovjak

Indirect CR Measurements

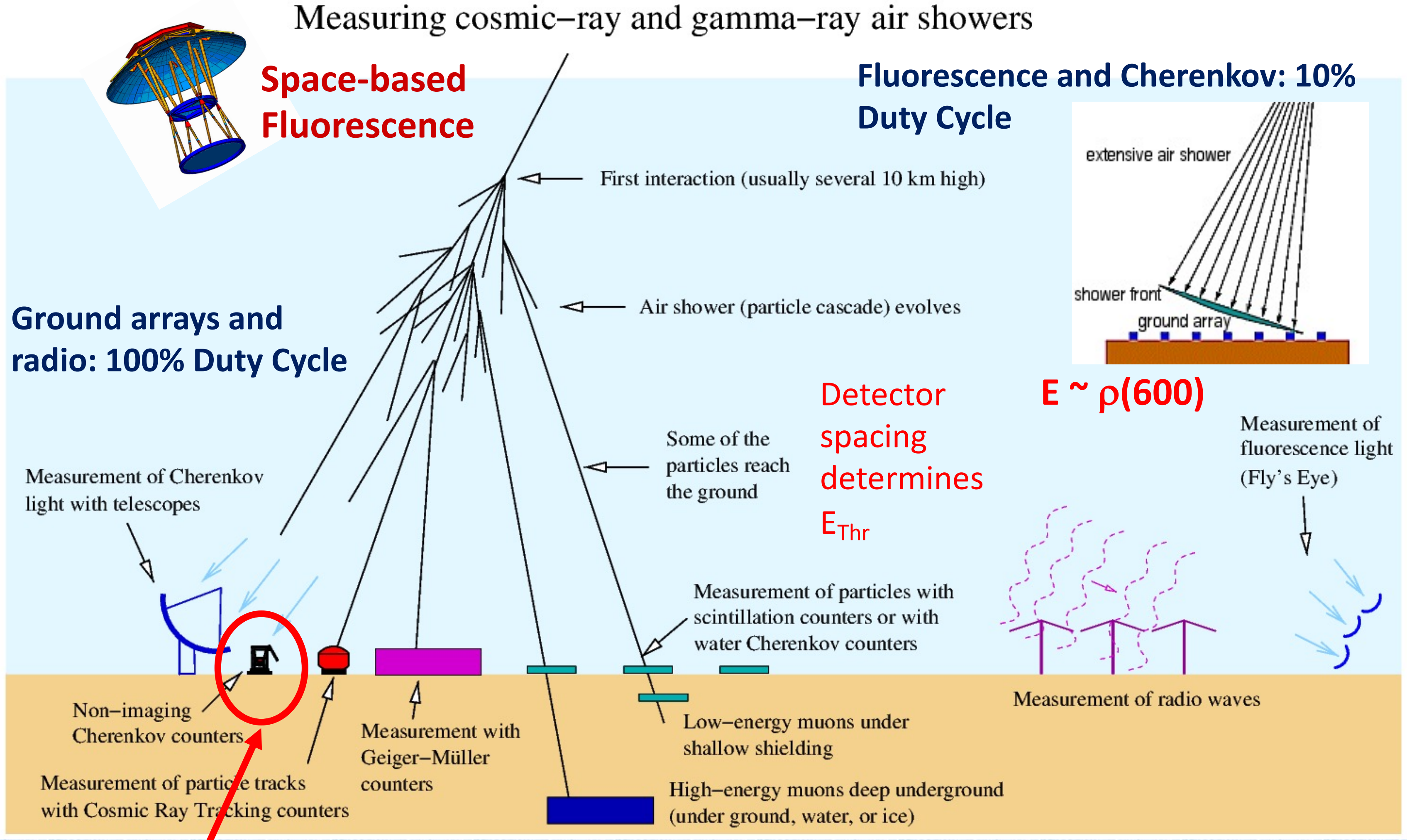
Space-based Fluorescence

Fluorescence and Cherenkov: 10% Duty Cycle

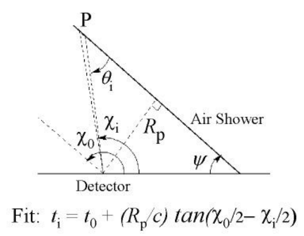
Ground arrays and radio: 100% Duty Cycle

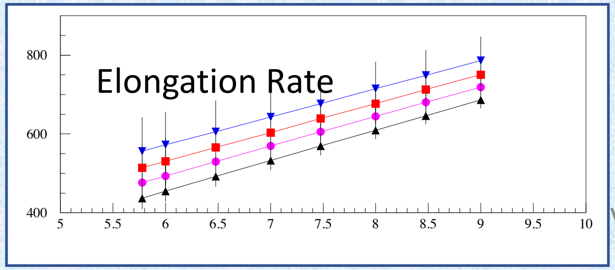
Detector spacing determines E_{Thr}

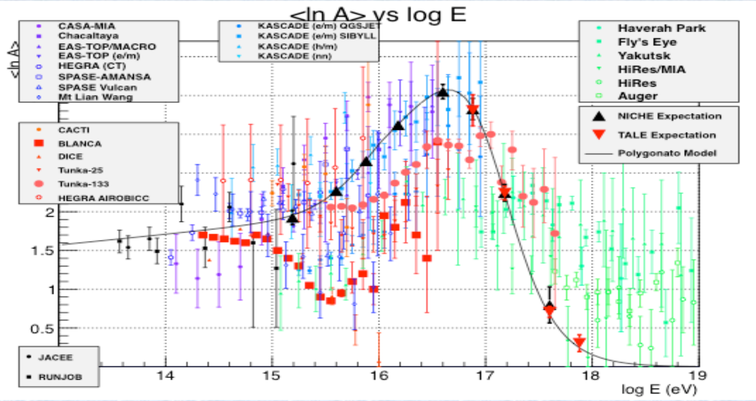
E ~ ρ(600)



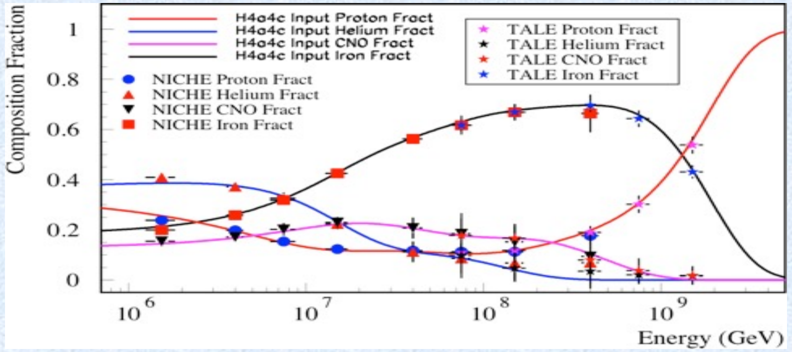
NICHE







NICHE Results: 2013ICRC...33.1900K (arXiv:1307.3918)



X_{MAX} resolution of ~25 g/cm^2 leads to 4-component unfolding

Direct vs Indirect Measurements

Cosmic Rays provide a measure on how the Universe processes and distributes matter.