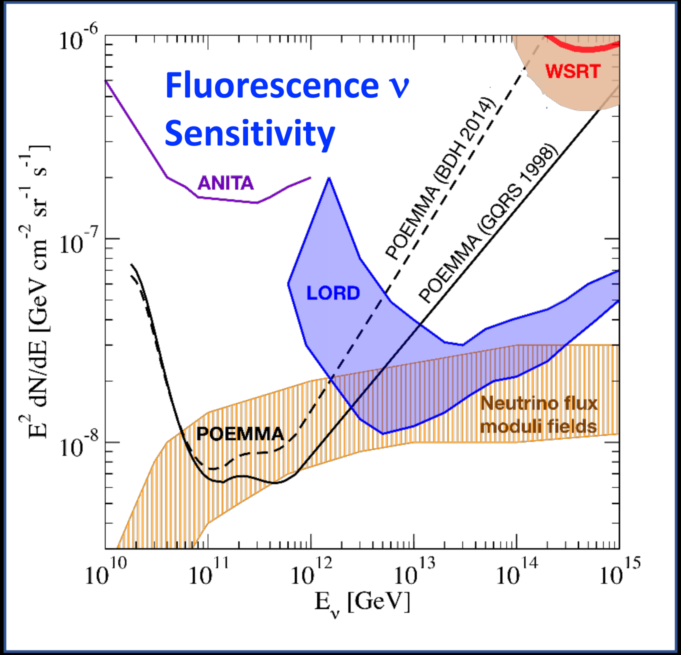
POEMMA: Probe Of Extreme Multi-Messenger Astrophysics

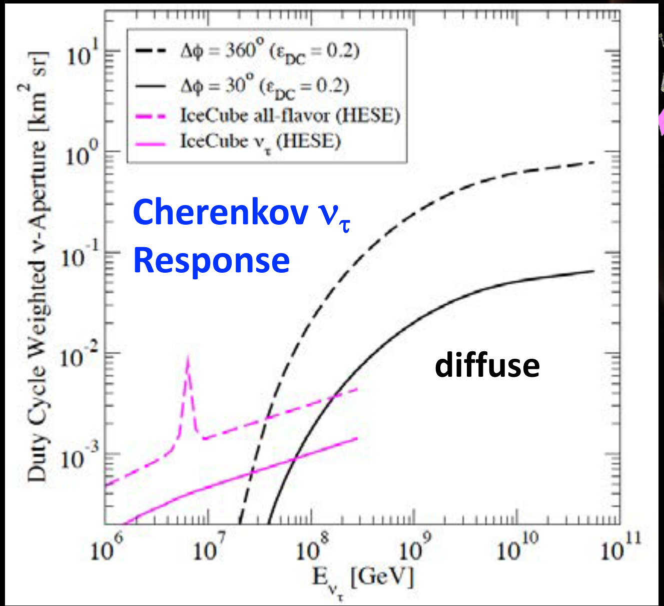
A NASA Probe-class mission to perform transformational measurements of UHECRs and Cosmic Neutrinos.



John Krizmanic

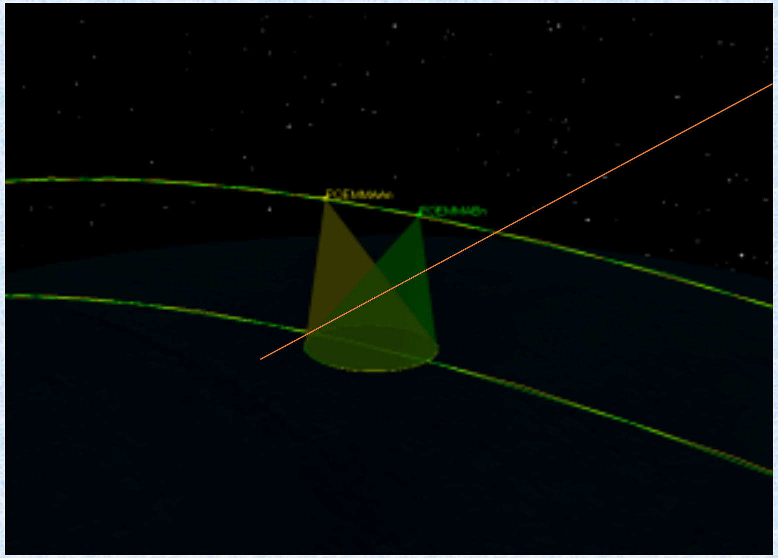
CRESST/NASA/GSFC/UMBC

for the POEMMA Collaboration

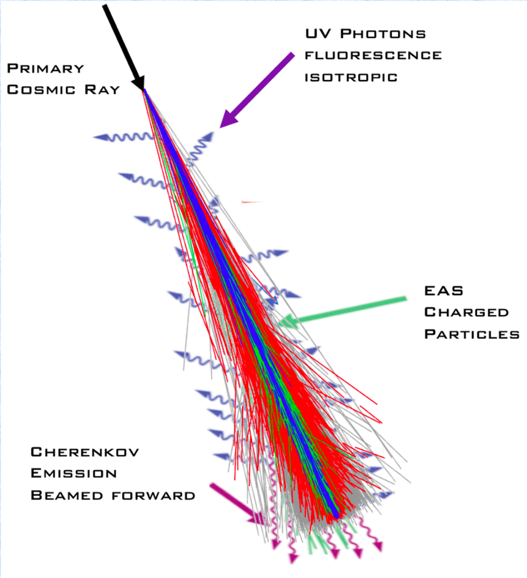


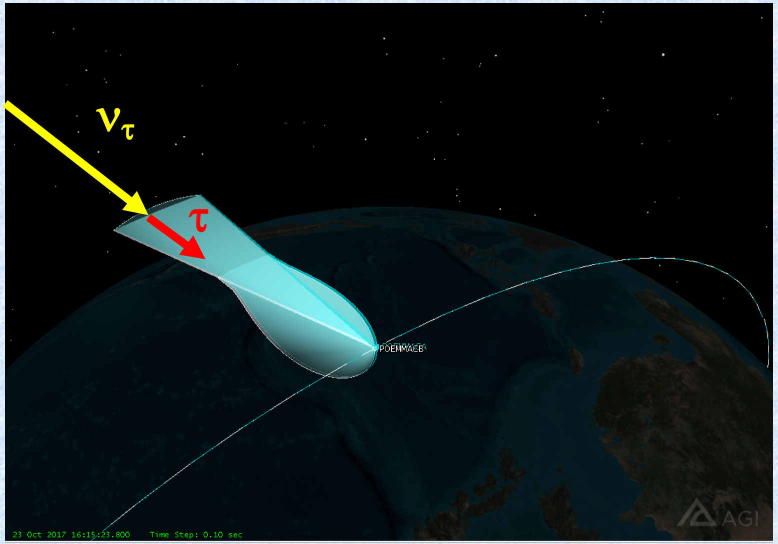
See Toni Venter's next talk on ToO!

Outline



Stereo Viewing of UHECRs E $\gtrsim$ 20 EeV
via Fluoresence: 10's of μsec timescale





Upward τ-lepton EAS E $\gtrsim$ 20 PeV
via Cherenkov: ~10 nsec timescale

1. Scientific and Experimental Motivation.
2. POEMMA & Mission Description:
   - *Summary of results presented in arXiv:2012.07945*
3. POEMMA UHECR & *UHE Neutrino Performance via air fluorescence* measurements.
   - *Summary of results presented in PhysRevD.101.023012*
4. POEMMA *VHE Neutrino Performance via optical Cherenkov measurements*.
   - *Summary of results presented in PhysRevD.100.063010 and PhysRevD.102.123013*
5. Summary & Comments

POEMMA Collaboration

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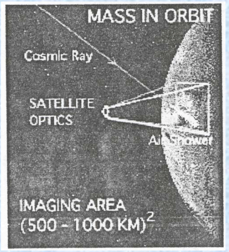
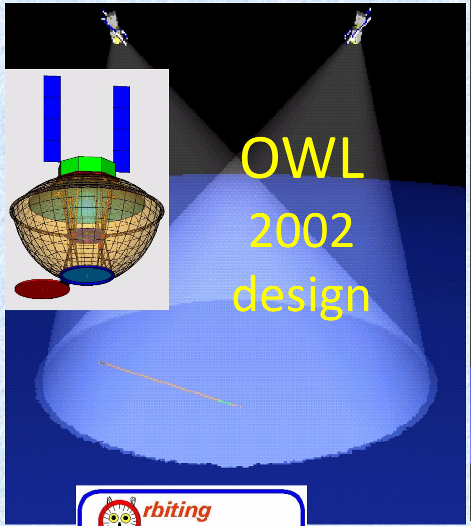
70+ scientists from 21+ institutions (US + 10+)
OWL, JEM-EUSO, Auger, TA, Veritas, CTA, Fermi, Theory

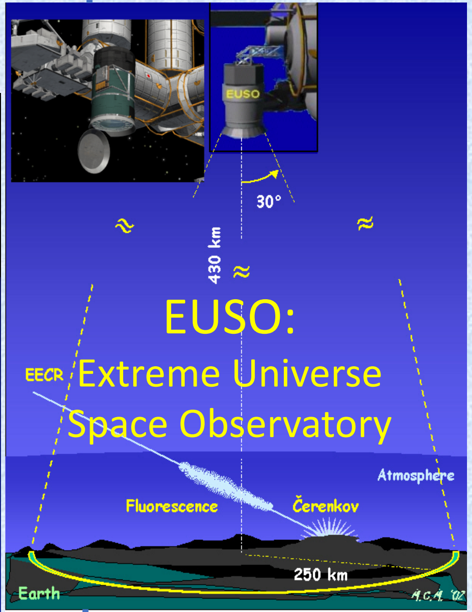
POEMMA: Heritage

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





Orbiting Wide-angle Light-collectors

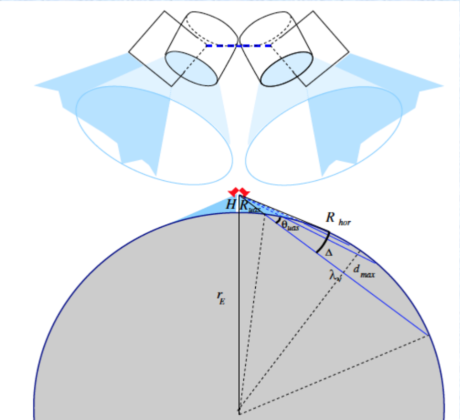


TUS, KLYPVE-EUSO

EUSO-Balloon
EUSO@TA
Mini-EUSO

EUSO-SPB2

CHANT



Cherenkov from Astrophysical Neutrinos Telescope

POEMMA: Science Goals

POEMMA Science goals:

primary

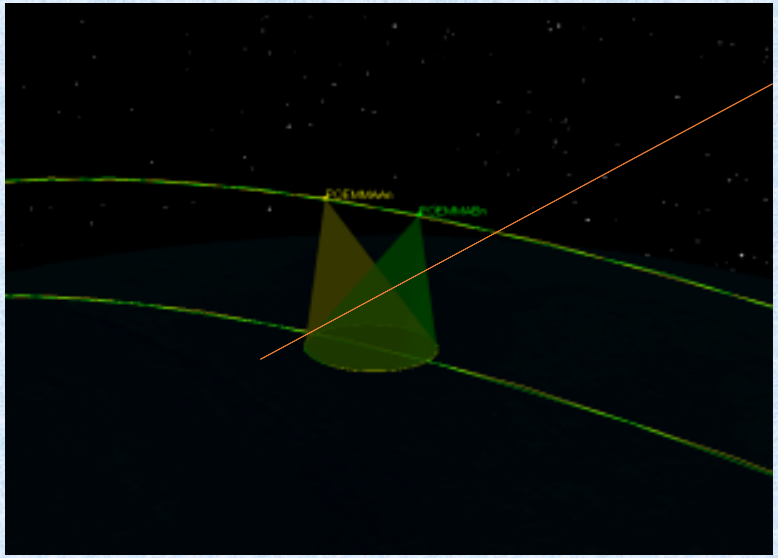
- **Discover the origin of Ultra-High Energy Cosmic Rays**
  Measure Spectrum, composition, full-Sky Distribution at Highest Energies **(E_{CR} > 20 EeV)**
  Requires very good angular, energy, and X_{max} resolutions: stereo fluorescence
  High sensitivity UHE neutrino measurements via stereo fluorescence 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

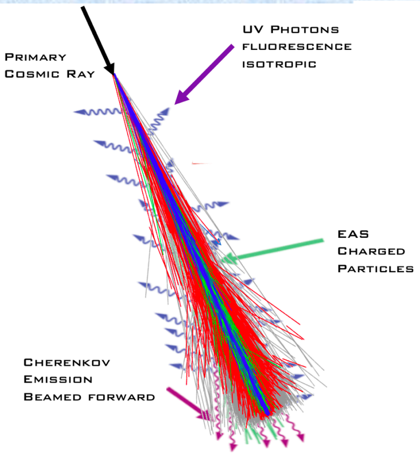
$\sqrt{s} \approx$ 450 TeV @ 100 EeV

- 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

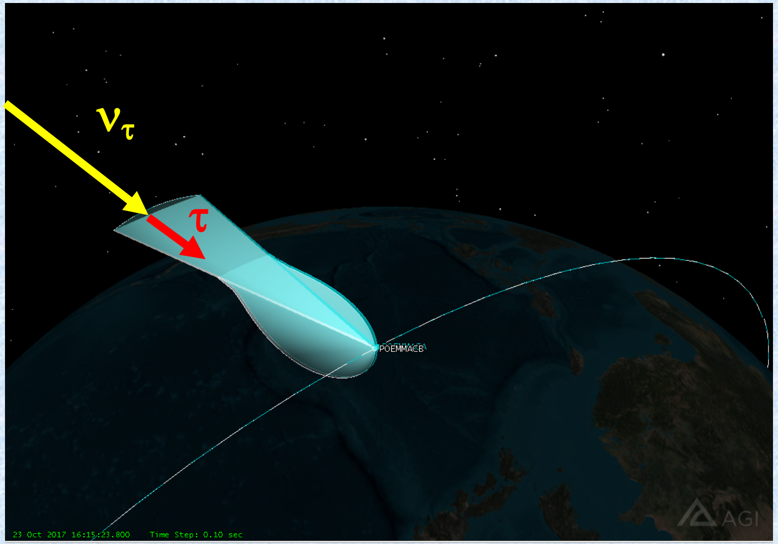
POEMMA Operational Modes: UHECR Stereo versus Limb-viewing Neutrino



Stereo Viewing of UHECRs E ≳ 20 EeV
via Fluoresence: 10’s of μsec timescale



Dark, quasi-moon less nights:
Fluorescence Duty Cycle: 11%
Cherenkov Duty Cycle: 20%



Upward τ-lepton EAS E ≳ 20 PeV
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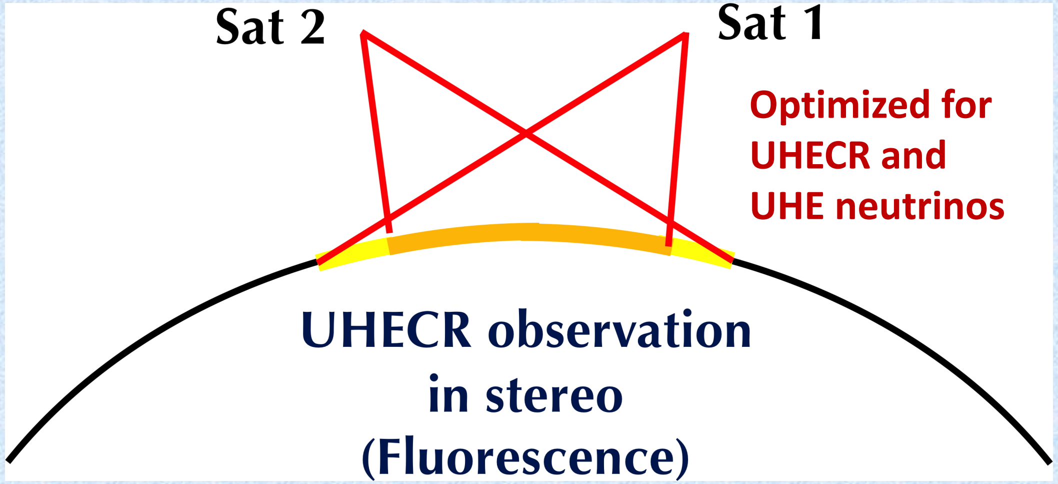
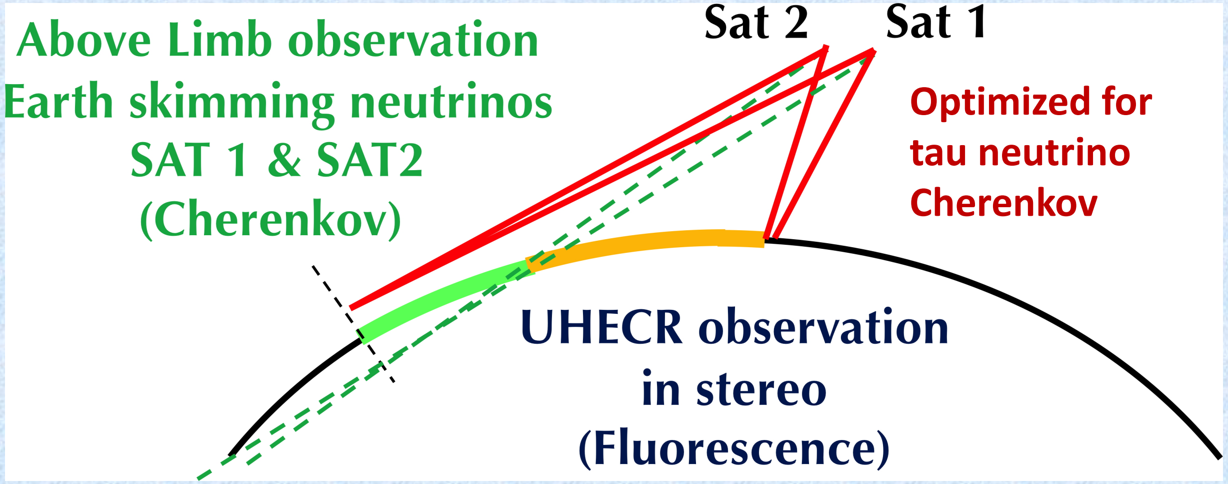
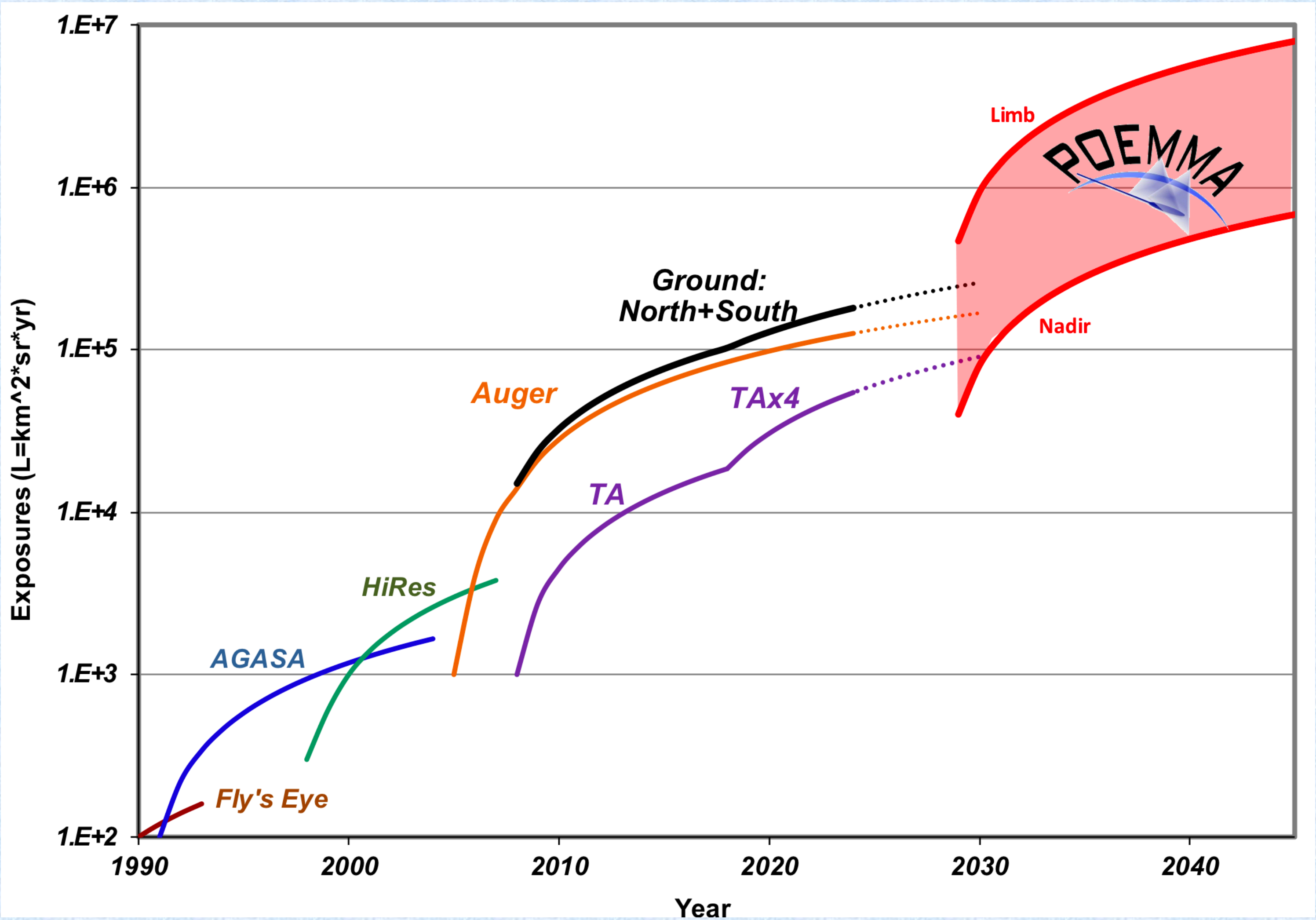
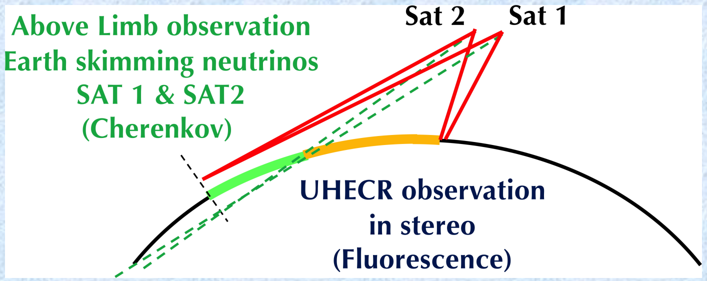




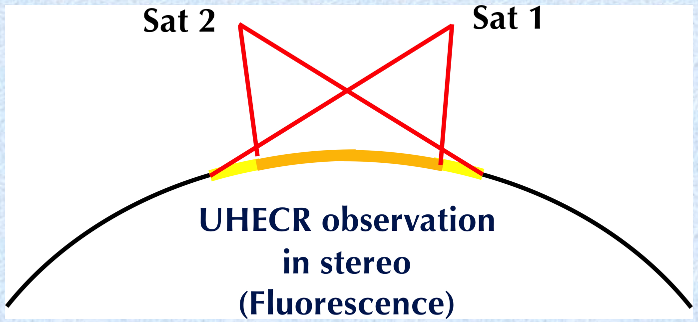
POEMMA: UHECR Exposure History



POEMMA-limb UHECR air fluorescence operation, higher UHECR geometry factor but degraded Angular, Energy, and X_{MAX} resolutions compared to that from POEMMA-stereo observations

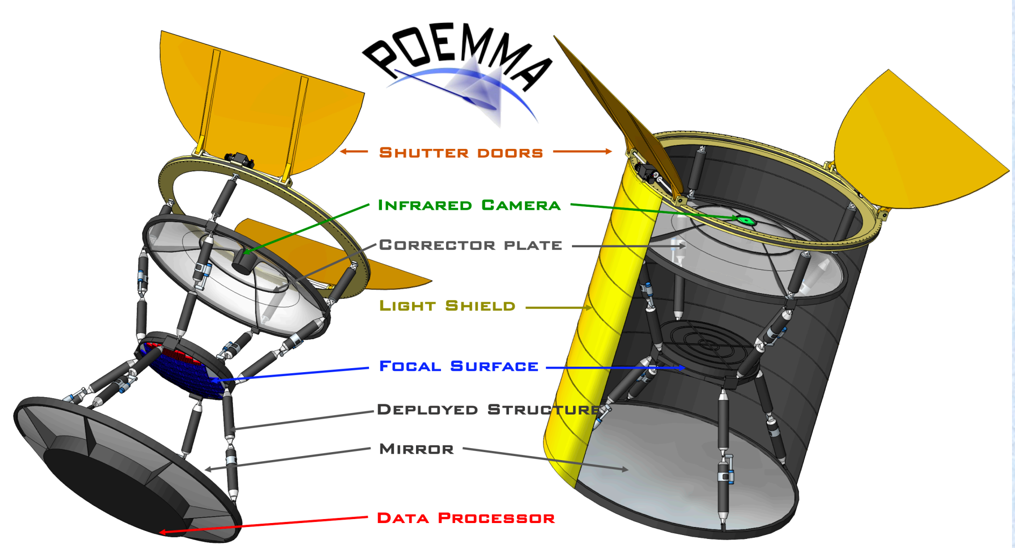


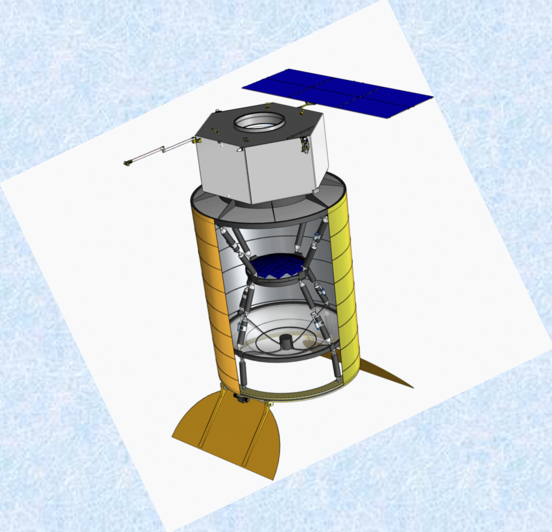
'Limb'



'Nadir'

POEMMA: Instruments defined by weeklong IDL run at GSFC





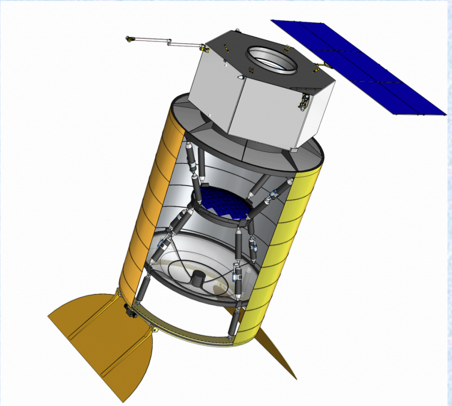
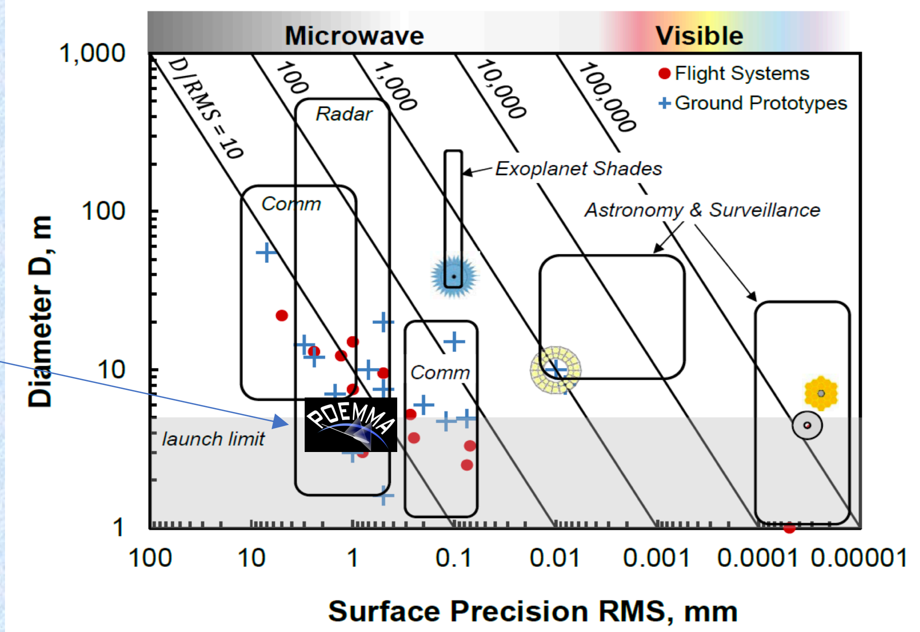


TABLE I: POEMMA Specifications:

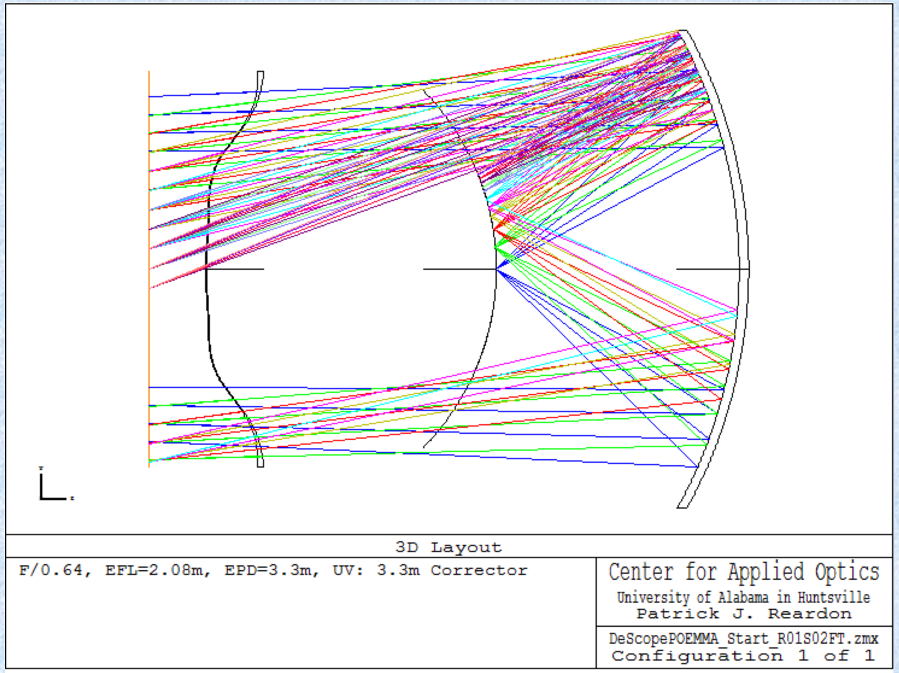
Photometer	Components		Spacecraft	
Optics	Schmidt	45° full FoV	Slew rate	90° in 8 min
	Primary Mirror	4 m diam.	Pointing Res.	0.1°
	Corrector Lens	3.3 m diam.	Pointing Know.	0.01°
	Focal Surface	1.6 m diam.	Clock synch.	10 nsec
	Pixel Size	3×3 mm^2	Data Storage	7 days
	Pixel FoV	0.084°	Communication	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

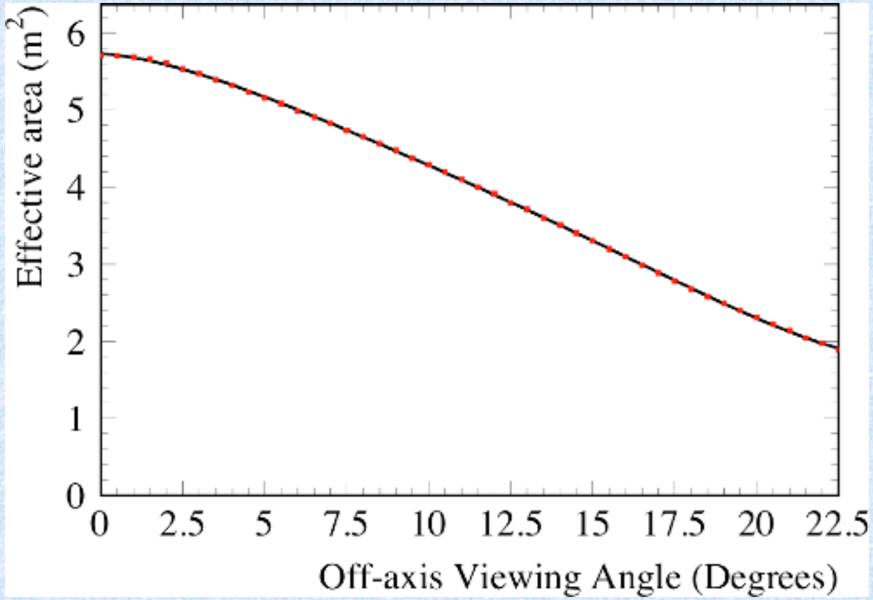
Each Observatory = Photometer + Spacecraft; POEMMA Mission = 2 Observatories



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

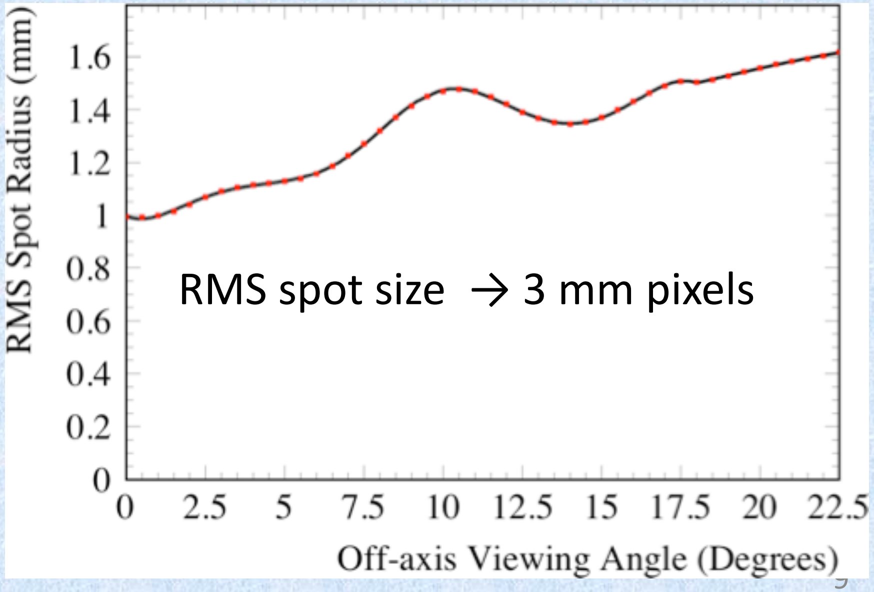
Corrector Lens: 3.3 meter diameter

Focal Surface: 1.6 meter diameter

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

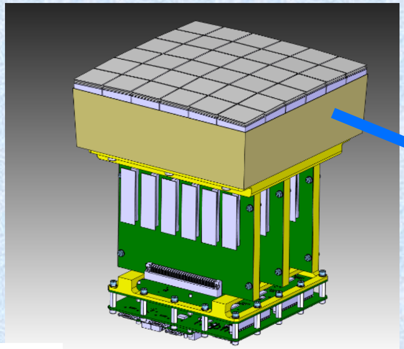
Hybrid focal surface (MAPMTs and SiPM)

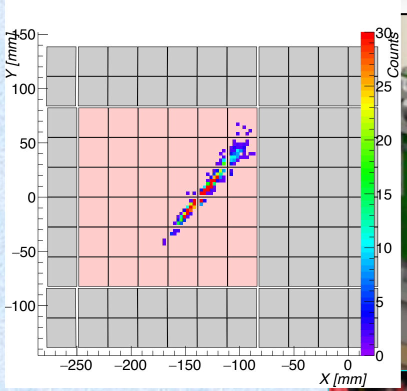
3 mm linear pixel size: 0.084° FoV

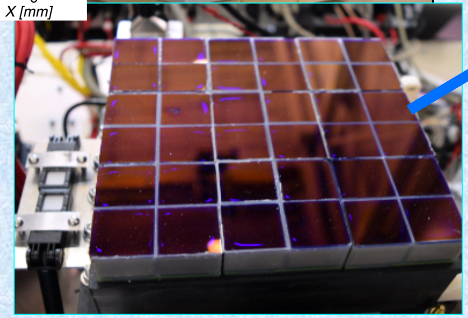


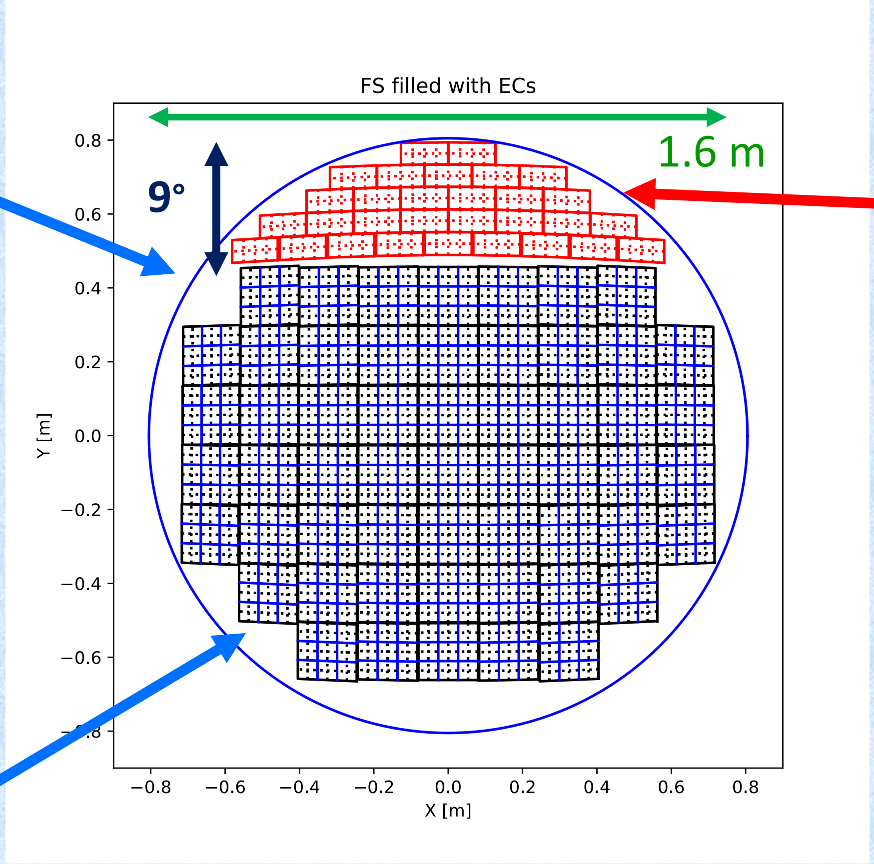
POEMMA: Hybrid Focal Plane

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





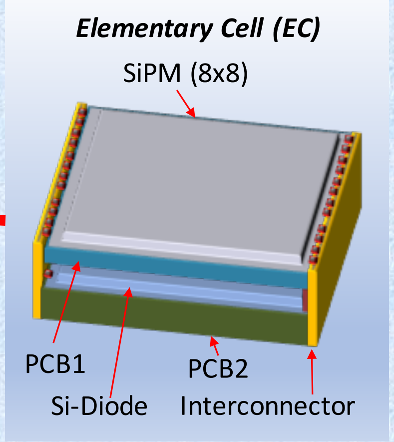




55 Photo Detector Modules (PDMs)= 126,720 pixels

1 PDM = 36 MAPMTs = 2,304 pixels

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



30 SiPM focal surface units

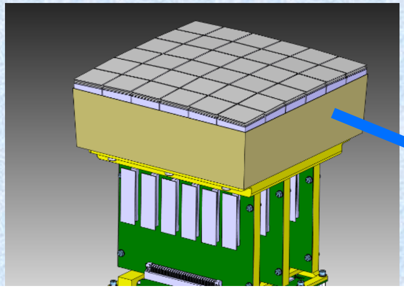
Total 15,360 pixels

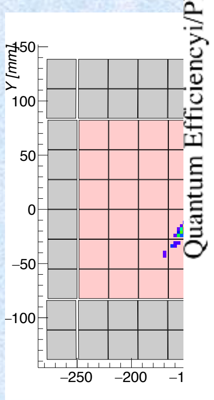
512 pixels per FSU (64x4x2)

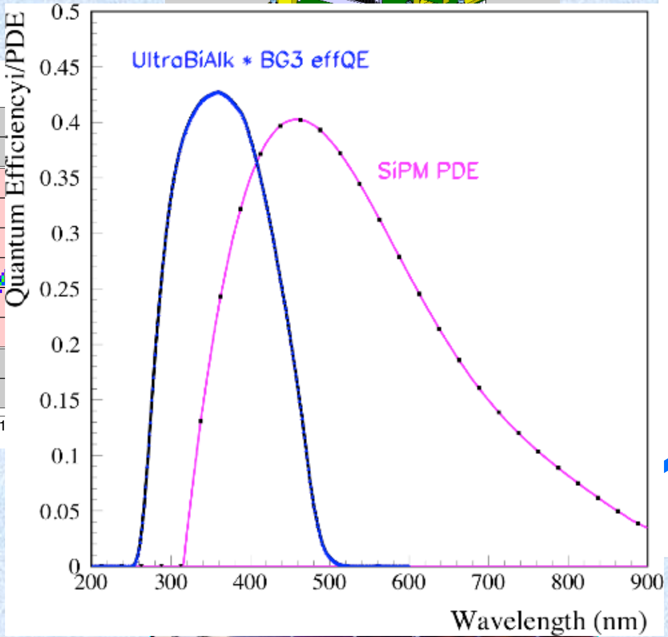
Si-Diode for LEO radiation backgrounds rejection

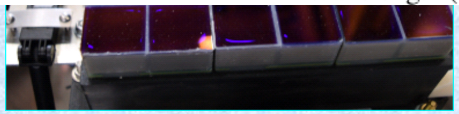
POEMMA: Hybrid Focal Plane

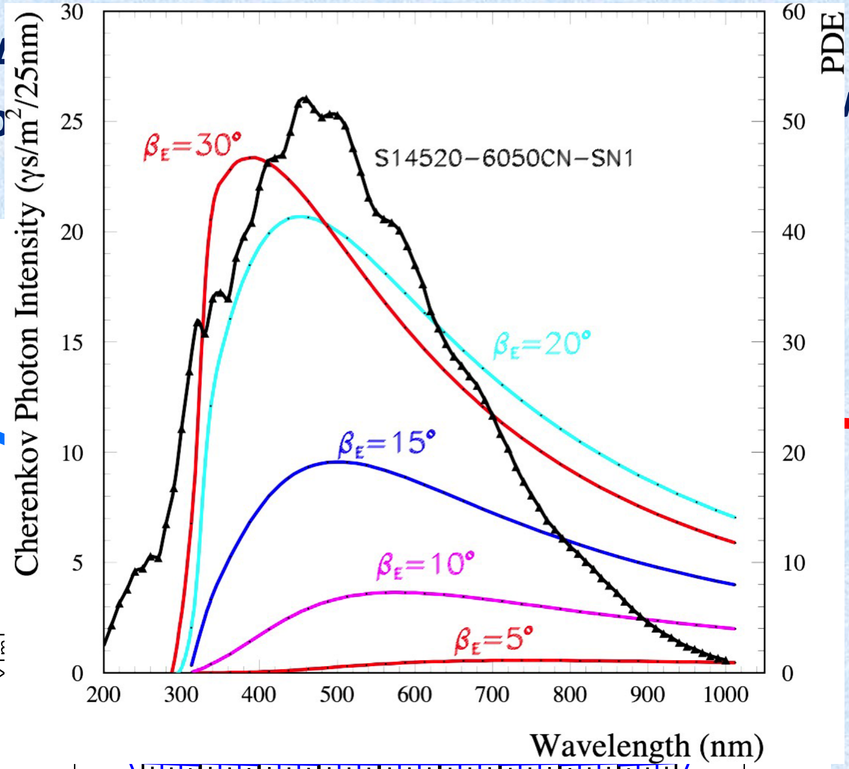
UV Fluorescence Detection using MA
with BG3 filter (300 – 500 nm) develo
JEM-EUSO: 1 usec sampling

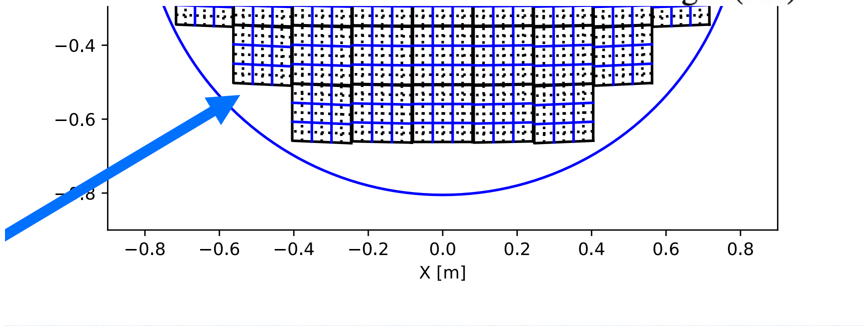












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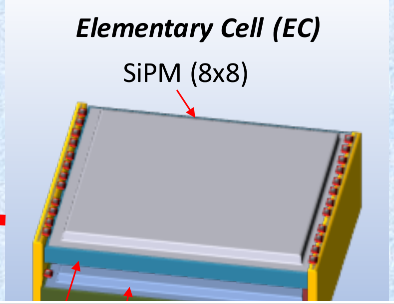
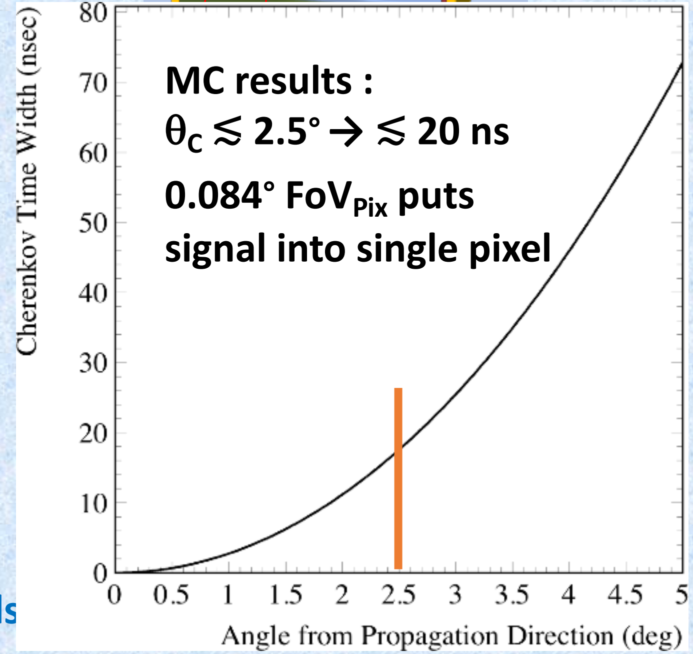
Cherenkov Detection
with SiPMs (300 – 1000 nm):
20 nsec sampling

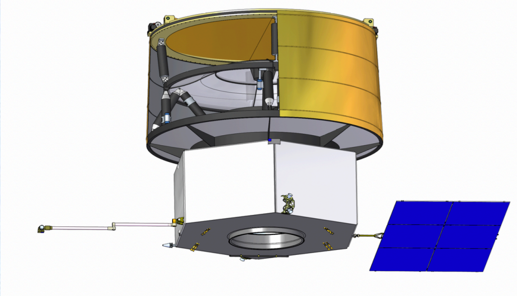


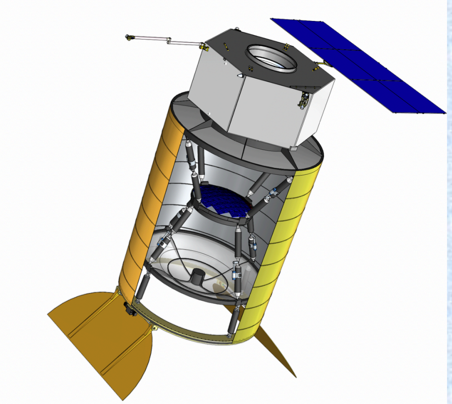


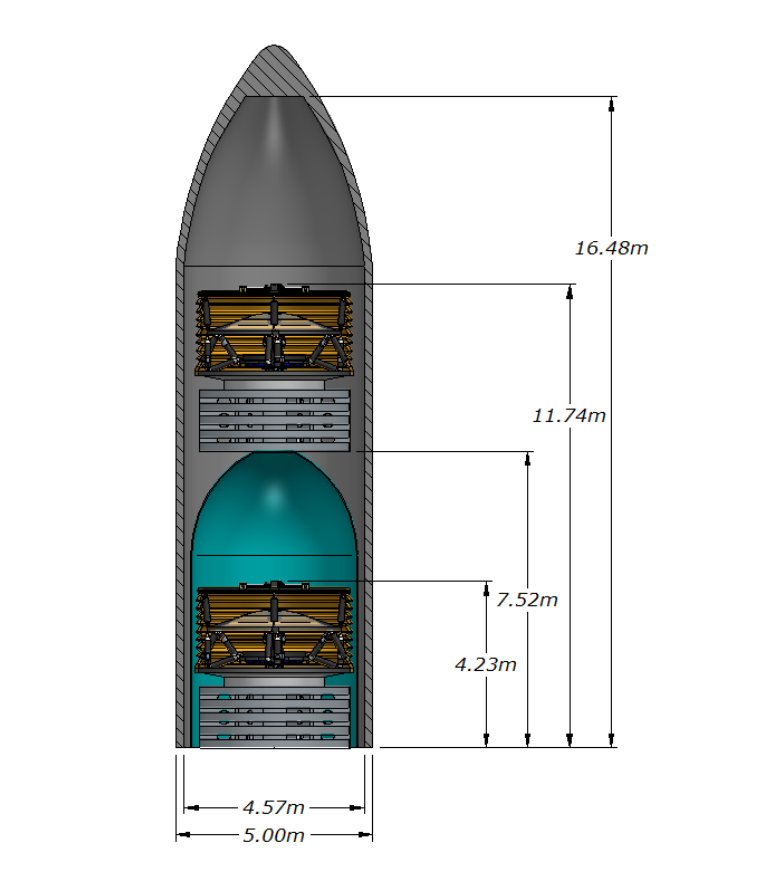
POEMMA: Mission (Class B) defined by weeklong MDL run at GSFC

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 ⟹ 50 km SatSep
  - Puts both in CherLight Pool
- Δt =3 hr, 9 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

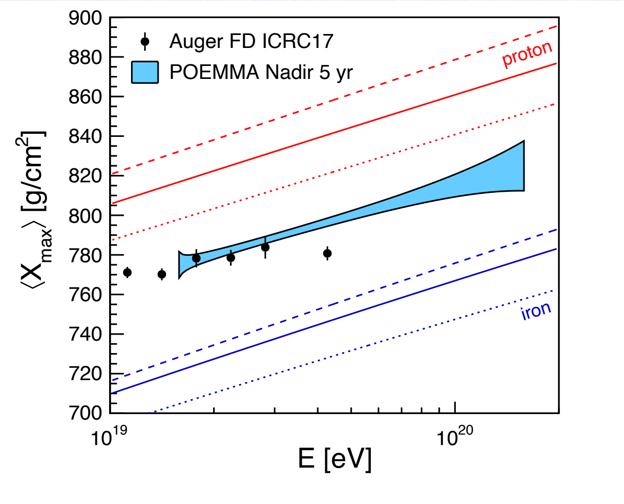
POEMMA: UHECR Performance: *see PhysRevD.101.023012*

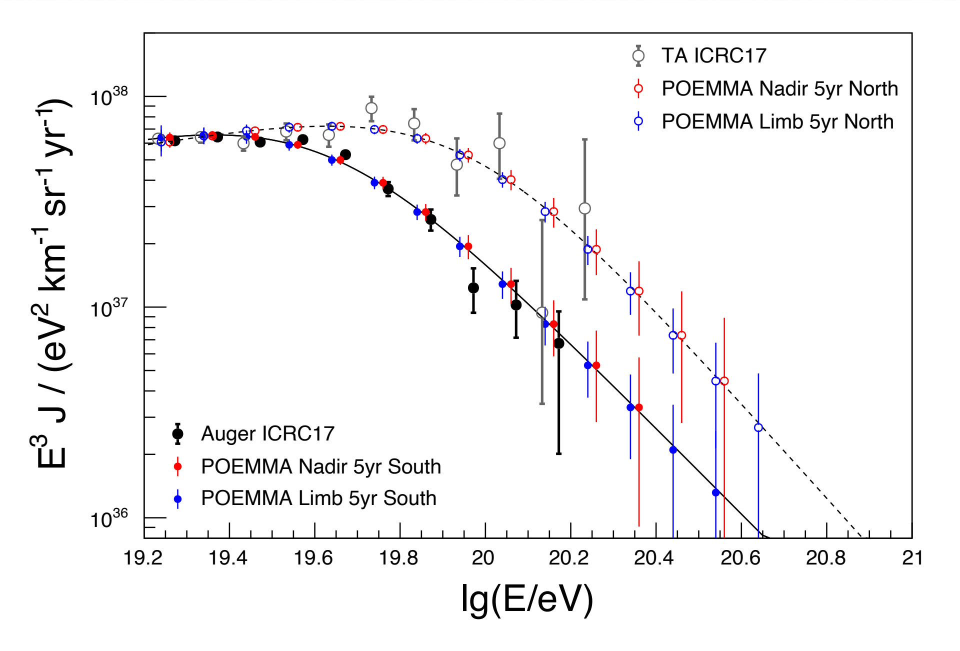
Significant increase in exposure with all-sky coverage

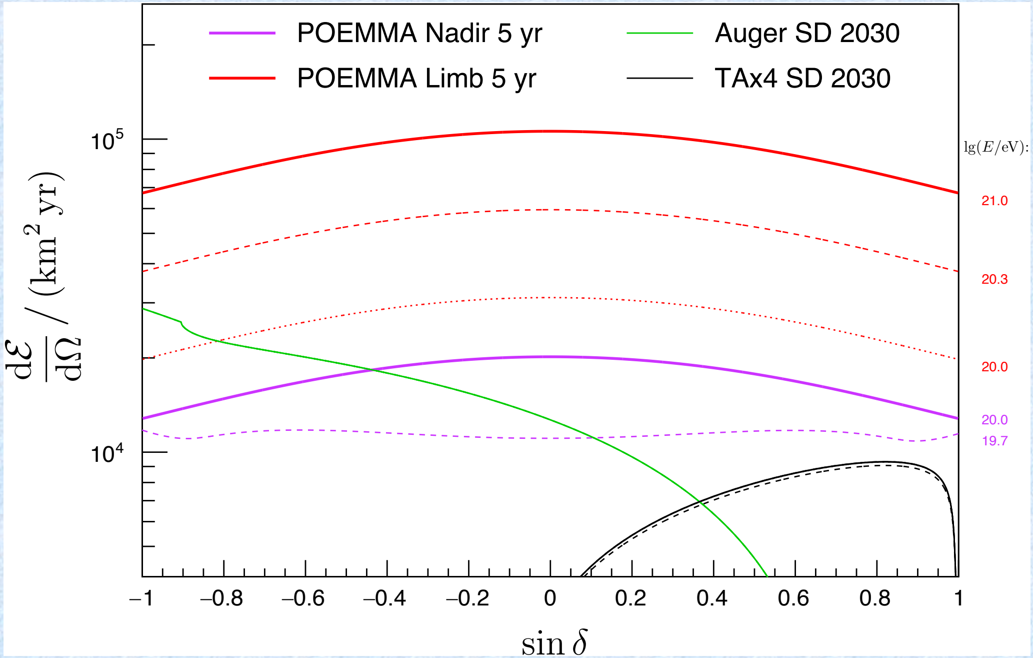
Uniform sky coverage to **guarantee the discovery of UHECR sources**

Spectrum, Composition, Anisotropy $E_{CR} \geq 50$ EeV

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



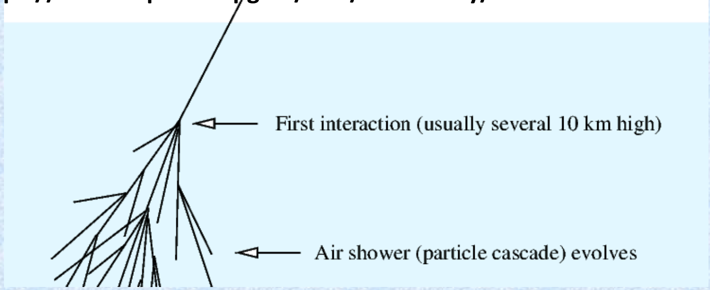


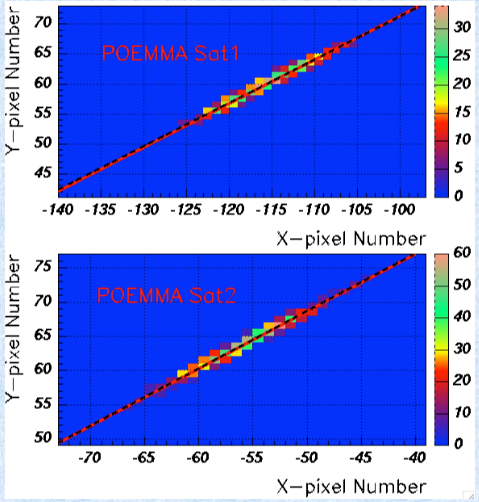


POEMMA: stereo reconstructed angular resolution: *see PhysRevD.101.023012*

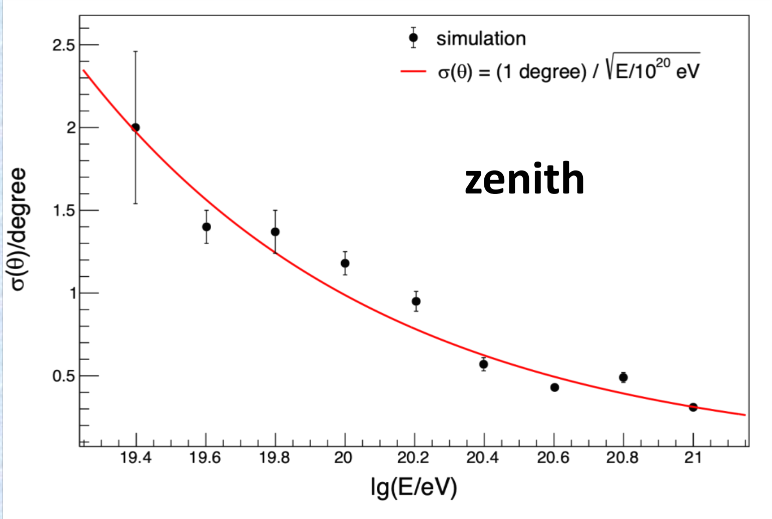
Excellent angular resolution → accurate determination of slant depth of EAS starting point

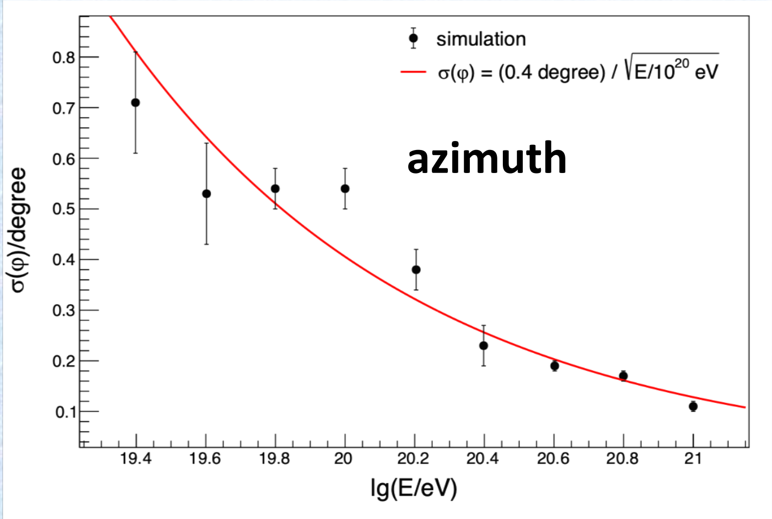
https://www.mpi-hd.mpg.de/hfm/CosmicRay/ShowerDetection.html

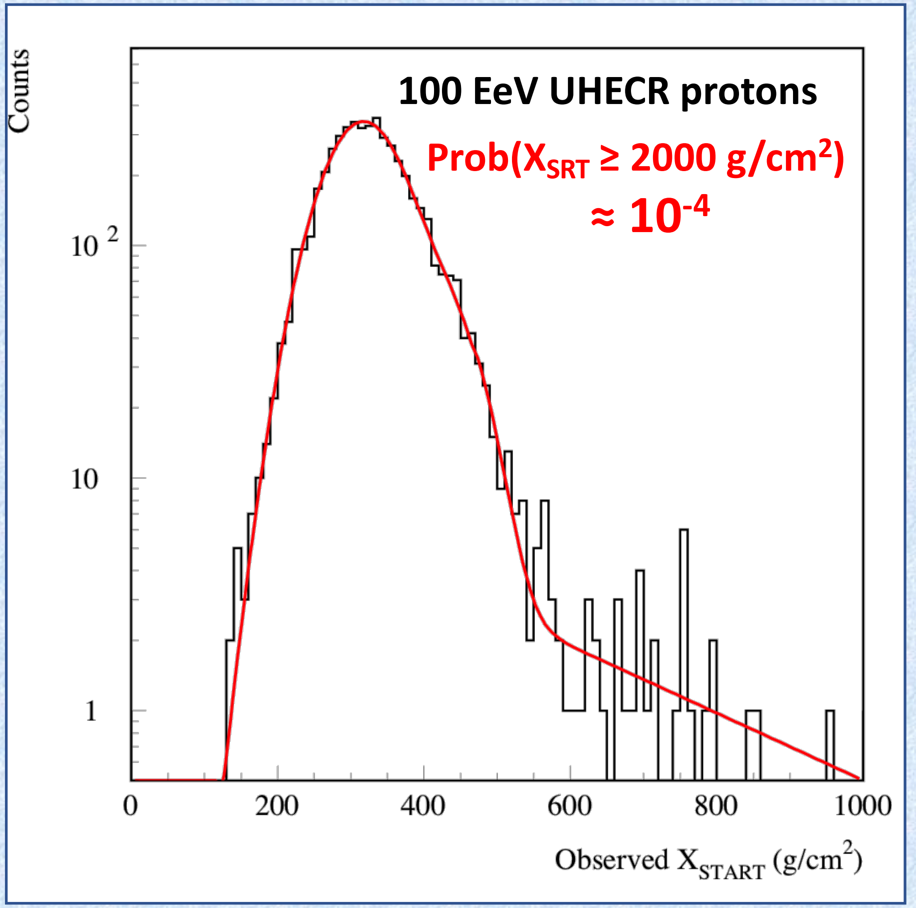




50 EeV simulated event







UHECR 100% proton assumption most conservative

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

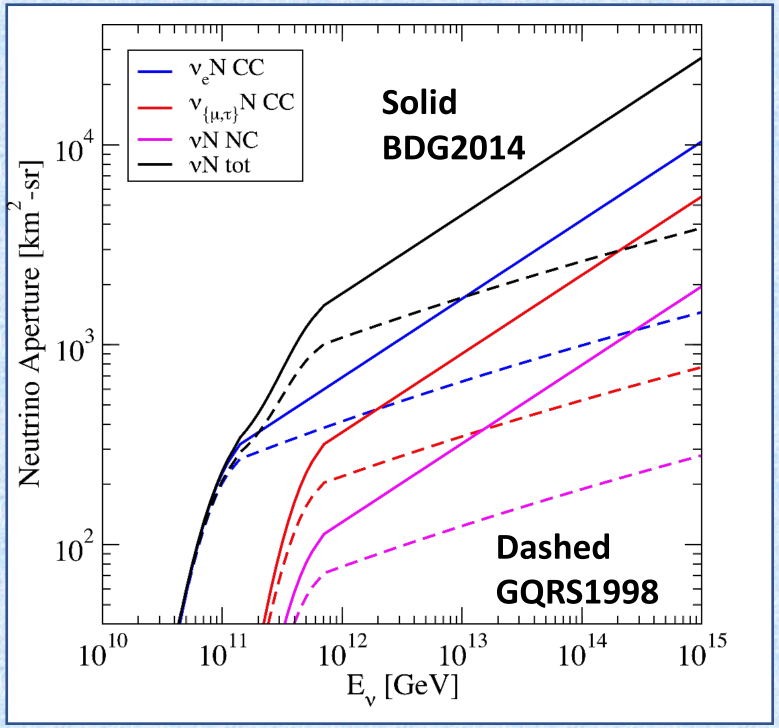
Effectively comes for free in stereo UHECR mode

Assumptions:

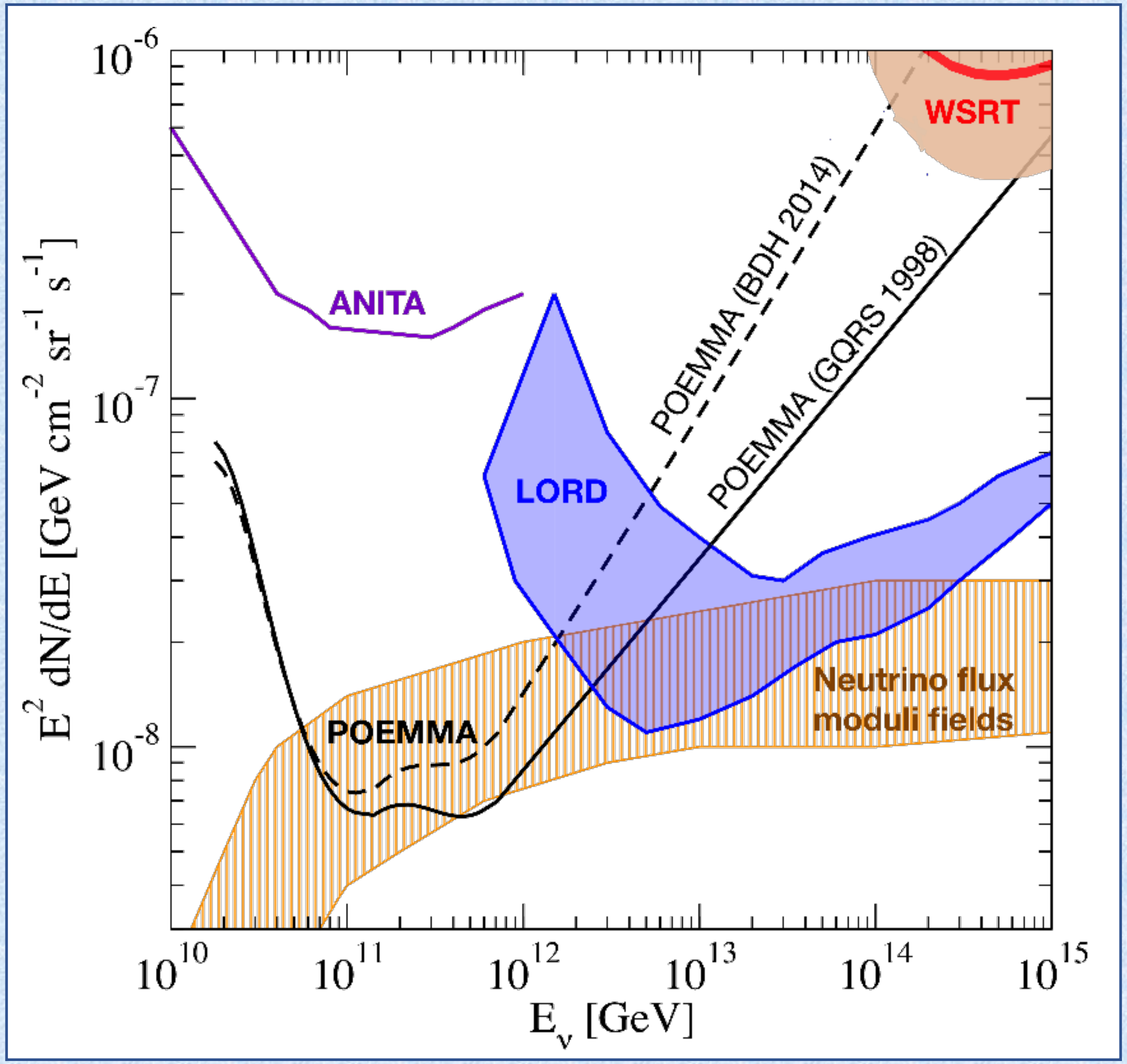
- CC ν_e : 100% E_ν in EAS
- CC ν_μ & ν_τ : 20% E_ν in EAS ($\gamma c\tau_\tau \approx$ 5000 km)
- NC ν_e & ν_μ & ν_τ : 20% E_ν in EAS

UHECR Background Probabilities (1 event in 5 years):

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



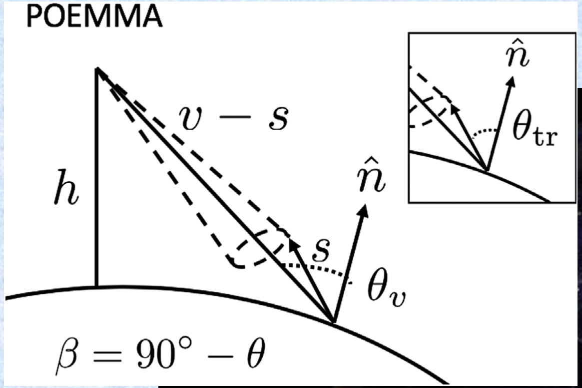
For $E_\nu \gtrsim$ 1 PeV, σ_{CC} & σ_{NC} virtually identical for ν & νbar

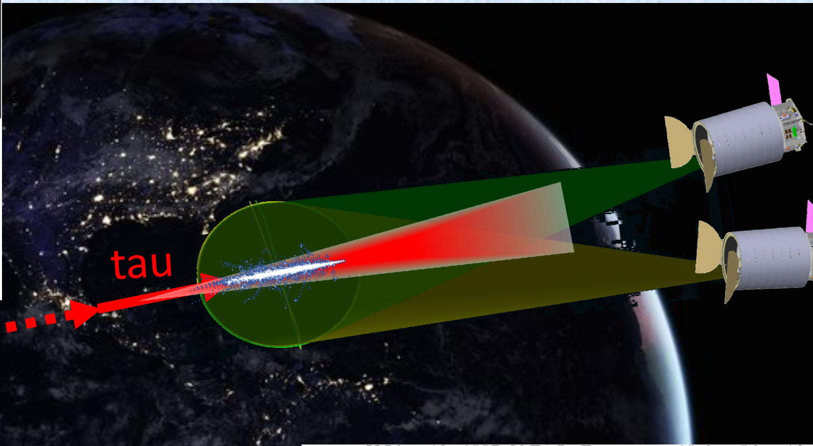


POEMMA Tau Neutrino Detection: *see PhysRevD.100.063010 and PhysRevD.102.123013*

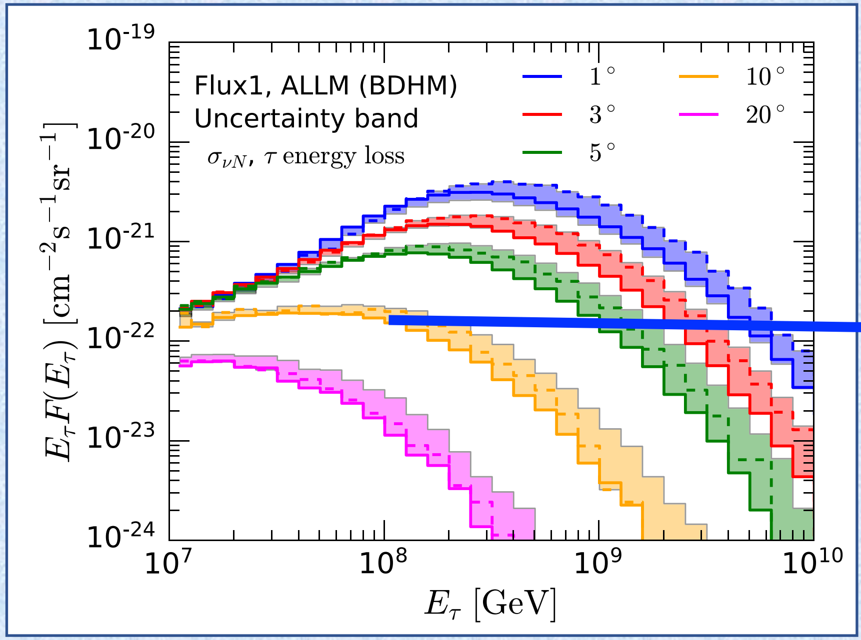
High-Energy Astrophysical Events generates neutrinos (ν_e,ν_μ) and 3 neutrino flavors reach Earth via neutrino oscillations: $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$

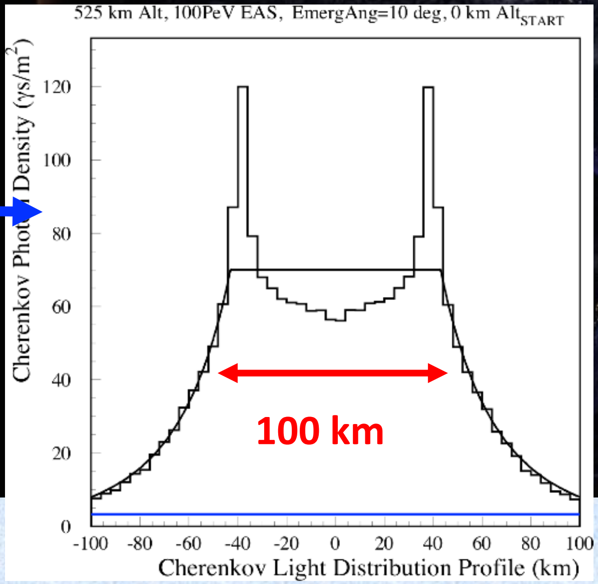
POEMMA designed to observe neutrinos with E > 20 PeV through Cherenkov signal of EASs from Earth-emerging tau decays.

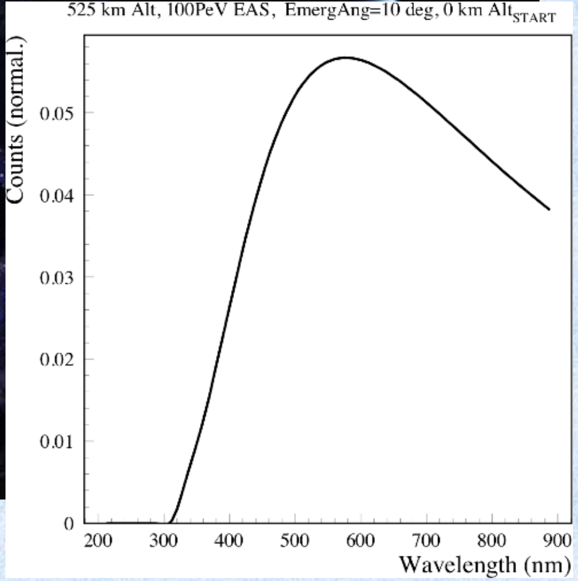




ν_{tau}







τ-lepton Yield Calc: PREM Earth Model: Kotera2010 mixed UHECR composition cosmogenic ν flux

ToO Neutrino Sensitivity: *see PhysRevD.102.123013*

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

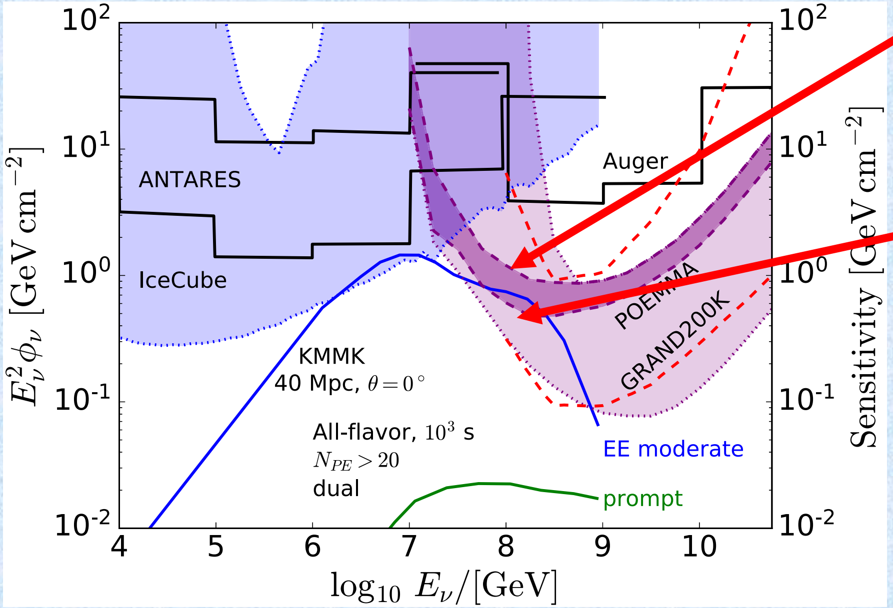
Short Bursts:

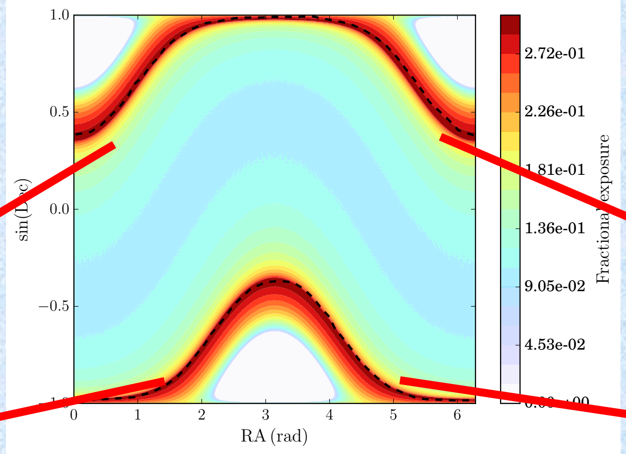
- 500 s to slew to source after alert
- 1000 s burst duration
- Source celestial location optimal
- Two independent Cher measurements
  - 300 km SatSep
- 20 PE threshold:
  - AirGlowBack < 10^{-3}/year

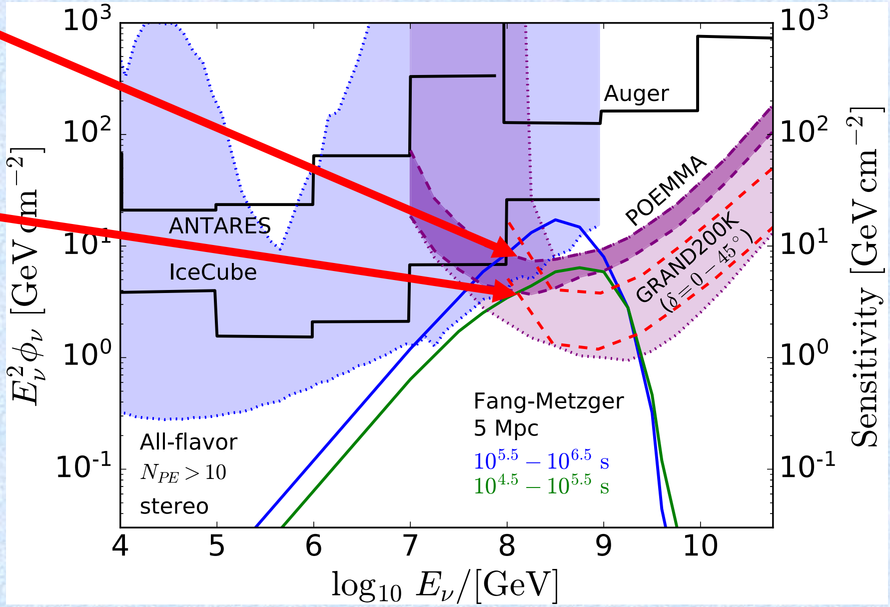
One orbit sky exposure assuming slewing to source position

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





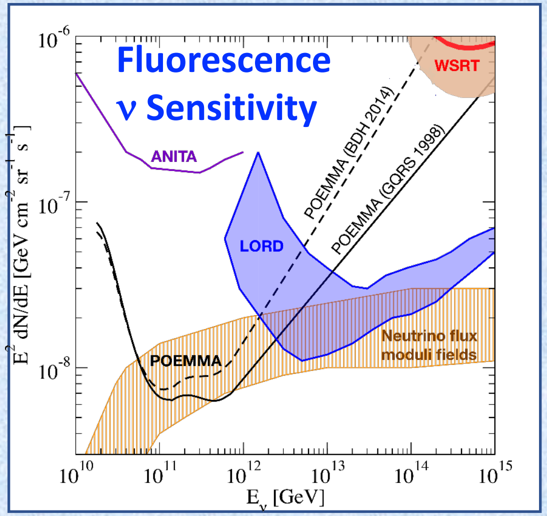


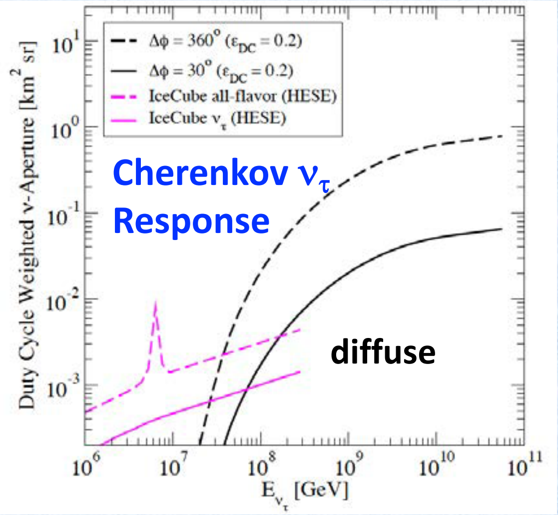
IceCube, ANTARES, Auger Limits for NS-NS merger GW170817

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 ($\lesssim 1.2°$), 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 10% – 20%**
- **PAPERs in progress (including ICRC) regarding POEMMA sensitivity to SHDM → ν's (C. Guepin et al..)**

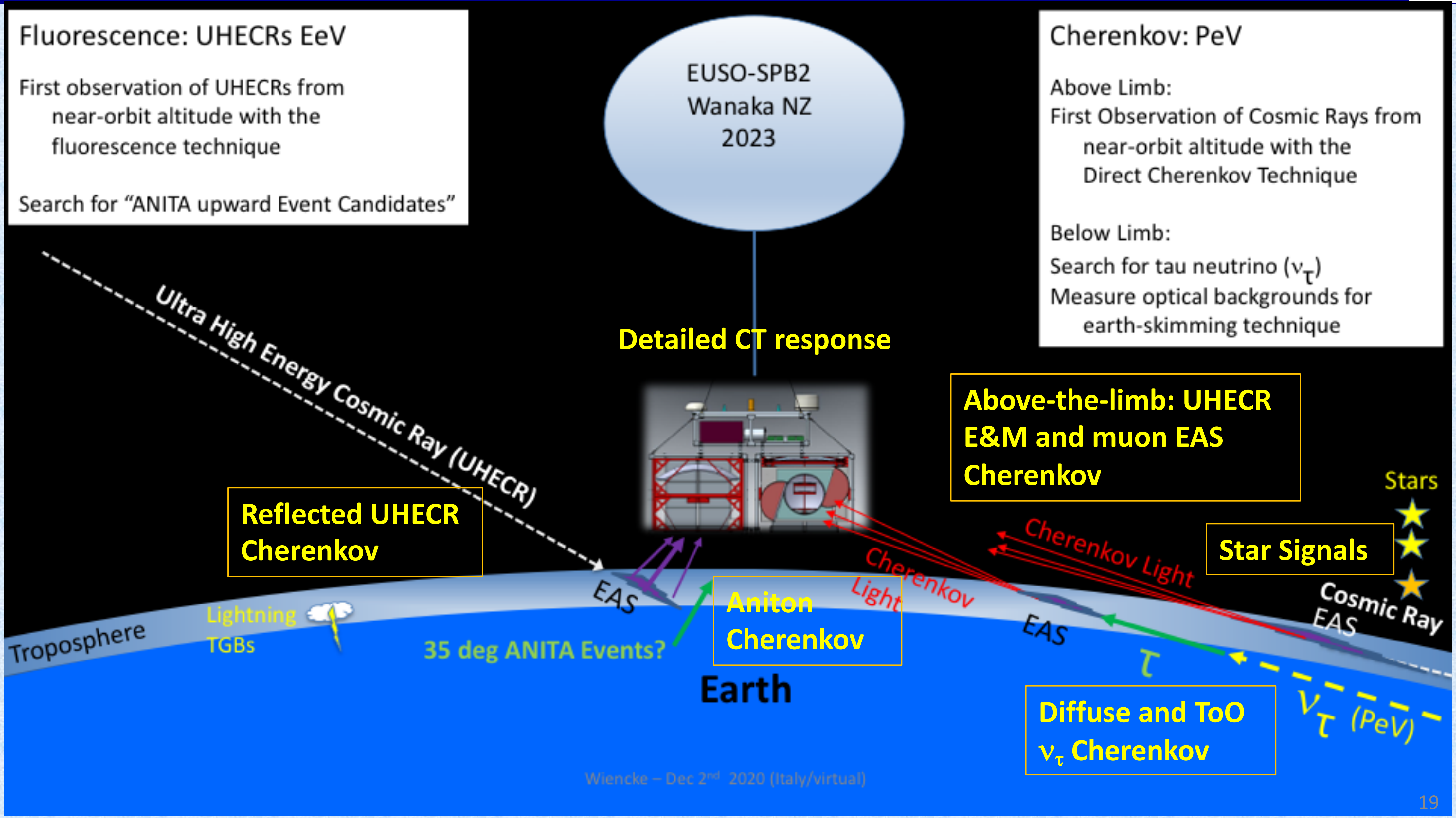




Work in Progress:

- **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



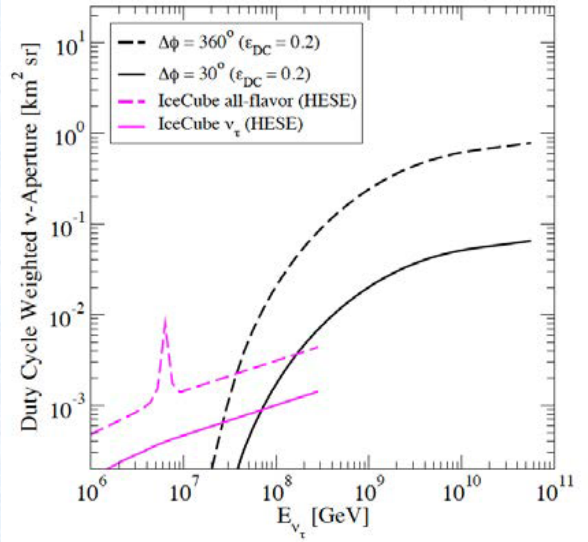
Backup Slides

POEMMA: Diffuse neutrino flux sensitivity

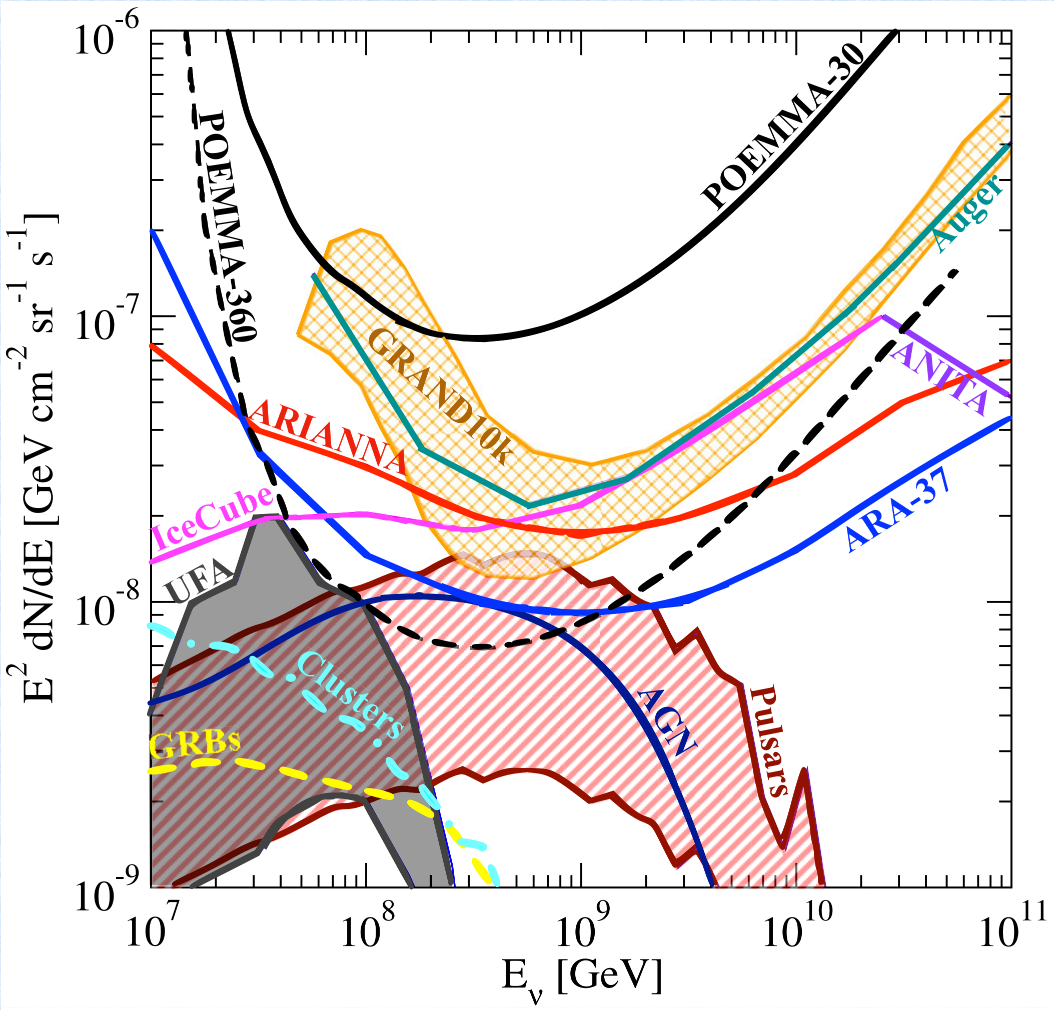
All flavor Sensitivity Limit:

- 5 year
- 20% duty cycle
- 10 PE threshold with time coincidence to reduce air glow background ‘false positives’
- 2.44 events/decade (90% CL)
- 17% hit for ignoring μ channel
- Viewing to 7° away from Limb (or to ~20° Earth Emerg Angle)
- $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$

Air fluorescence UHE limits not included in plot



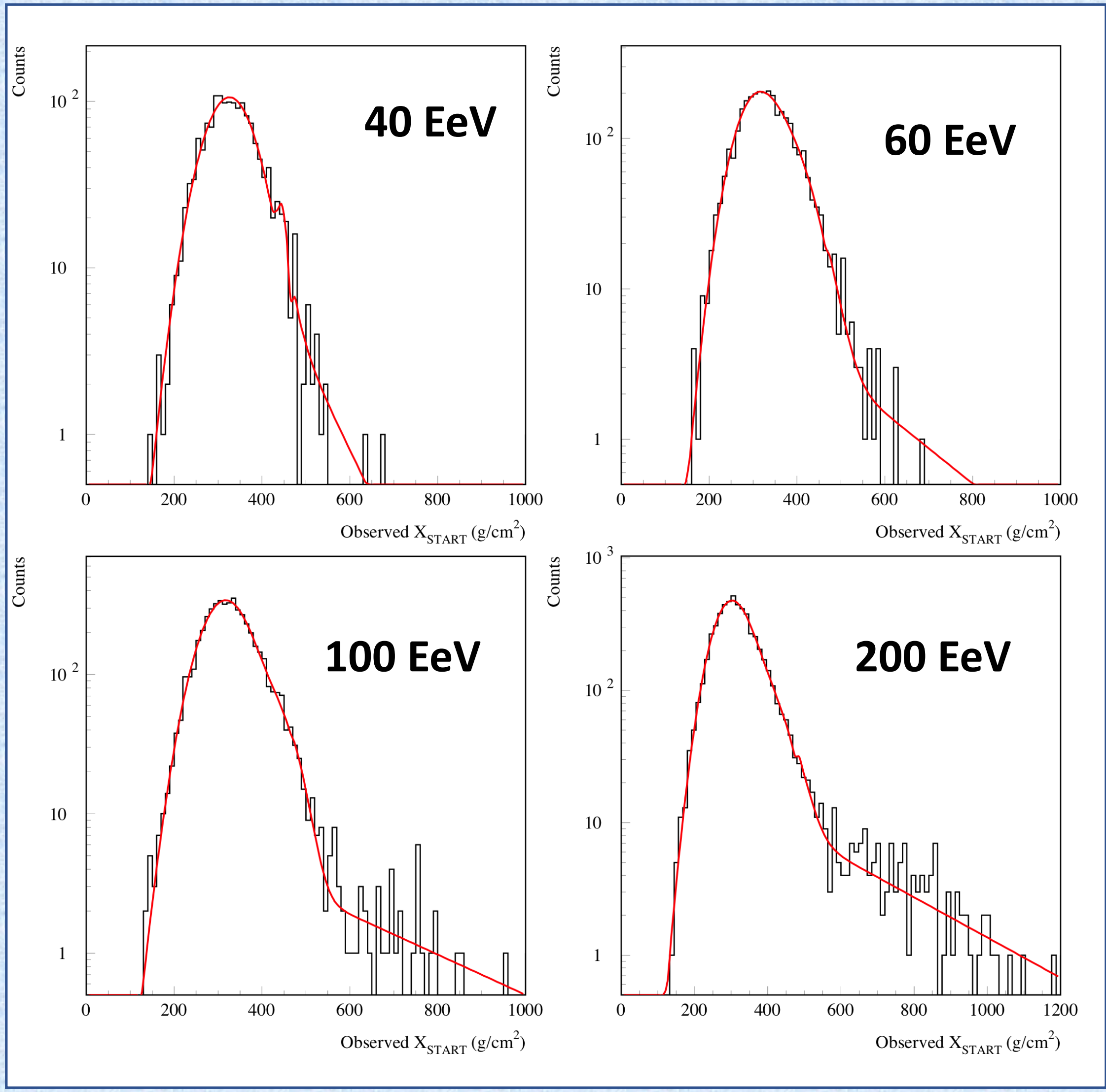
PhysRevD.100.063010 Fig. 22



POEMMA: UHECR Background Probability Analysis

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: $N_{Obs} \geq 1$			
$\geq 1500\ g/cm^2$	1.5×10^{-4}	1.9×10^{-2}	3.8×10^{-2}	4.5×10^{-3}	6.1×10^{-2}
$\geq 2000\ g/cm^2$	2.8×10^{-7}	1.3×10^{-3}	7.2×10^{-3}	1.0×10^{-3}	9.6×10^{-3}
		Auger Spectrum: $N_{Obs} \geq 2$			
$\geq 1500\ g/cm^2$	1.2×10^{-8}	1.9×10^{-4}	7.1×10^{-4}	1.0×10^{-5}	9.1×10^{-4}
$\geq 2000\ g/cm^2$	3.9×10^{-14}	8.4×10^{-7}	2.6×10^{-5}	5.3×10^{-7}	2.8×10^{-5}
		TA Spectrum: $N_{Obs} \geq 1$			
$\geq 1500\ g/cm^2$	2.5×10^{-4}	6.4×10^{-2}	1.7×10^{-1}	9.0×10^{-3}	2.5×10^{-1}
$\geq 2000\ g/cm^2$	4.7×10^{-7}	4.4×10^{-3}	3.5×10^{-2}	2.1×10^{-3}	4.2×10^{-2}
		Ta Spectrum: $N_{Obs} \geq 2$			
$\geq 1500\ g/cm^2$	3.0×10^{-8}	2.1×10^{-3}	1.6×10^{-2}	4.1×10^{-5}	1.8×10^{-2}
$\geq 2000\ g/cm^2$	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%**

Effect on X_{START} Selection for UHECR rejection

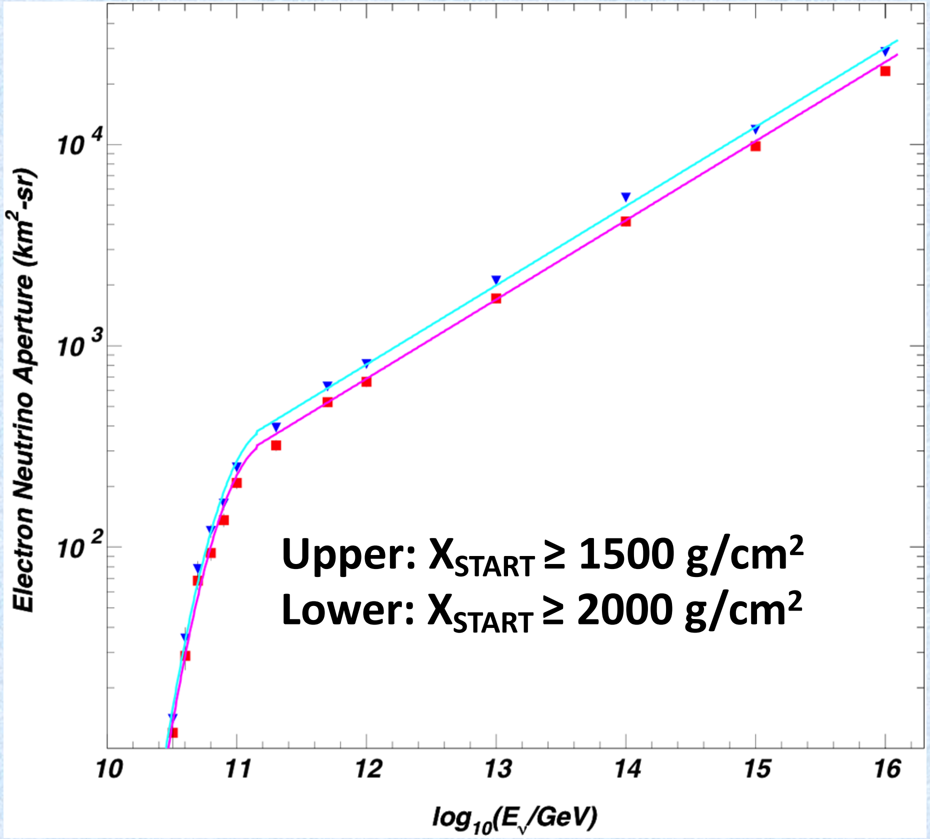


FIG. 42. Comparison of the instantaneous electron neutrino apertures based on stereo air fluorescence measurements. Upper points and curve are for $X_{\rm Start} \geq 1500$ g/cm^2 while the lower points and curve are for $X_{\rm Start} \geq 2000$ g/cm^2. The lower curve is 85% of the upper curve over the energy band.

POEMMA: anomalous ANITA upward EAS

arXiv:1803.05088v1

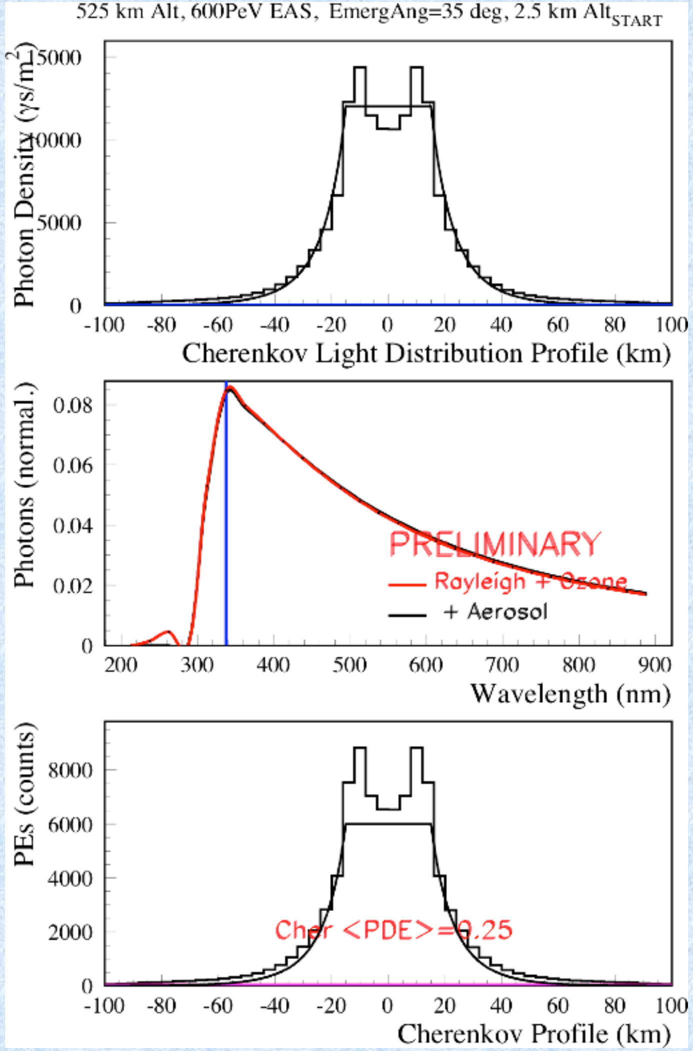
TABLE I: *ANITA-I,-III anomalous upward air showers.*

event, flight	3985267, ANITA-I	15717147, ANITA-III
date, time	2006-12-28,00:33:20UTC	2014-12-20,08:33:22.5UTC
Lat., Lon.[1]	-82.6559, 17.2842	-81.39856, 129.01626
Altitude	2.56 km	2.75 km
Ice depth	3.53 km	3.22 km
El., Az.	$-27.4 \pm 0.3°, 159.62 \pm 0.7°$	$-35.0 \pm 0.3°, 61.41 \pm 0.7°$
RA, Dec[2]	282.14064, +20.33043	50.78203, +38.65498
E_{shower}[3]	0.6 ± 0.4 EeV	$0.56^{+0.3}_{-0.2}$ EeV

[1] Latitude, Longitude of the estimated ground position of the event.
[2] Sky coordinates projected from event arrival angles at ANITA.
[3] For upward shower initiation at or near ice surface.

alt [km]	elevation [deg]	alpha [deg]	beta_e [deg]
34	-27.4	62.6	26.8
34	-35	55	34.6

POEMMA can tilt to view 9° × 30° 'spot'
But these events may be bright enough to be seen in the UV fluorescence detector with ~1 usec coincidence.



θ_{CONE}= 1.0 deg
$\omega \approx$ 1.e-3 sr

$\theta_{EFF} \approx$ 4.5 deg
$\omega \approx$ 2.e-2 sr

τ-lepton
$\gamma c\tau$ ~ 60 km
for 1.2 EeV

POEMMA signal size ~6000 PEs in cone

POEMMA: UHECR X_{MAX} analysis

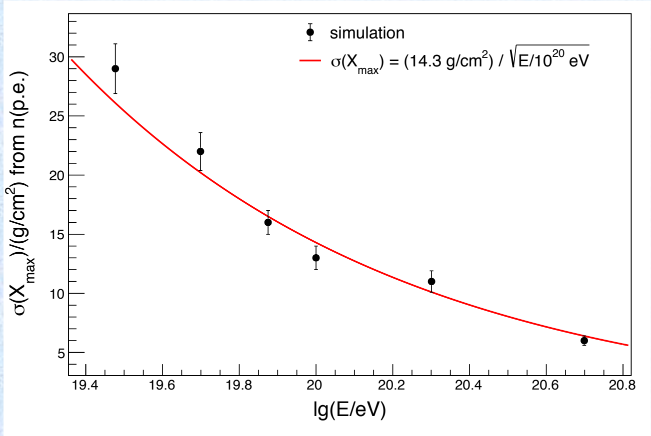


FIG. 9: Single-photometer X_{max}-resolution from photo-electron statistics.

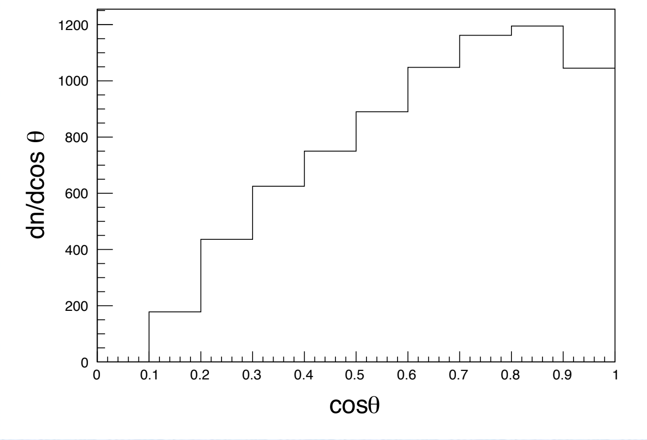


FIG. 7: Distribution of zenith angles of triggered events above 50 EeV.

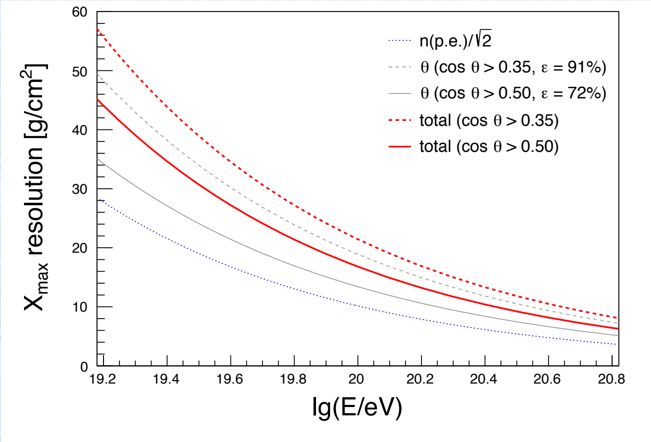


FIG. 18: Preliminary estimate of the X_{max} resolution of POEMMA in stereo mode. The contributions from the photo-electron statistics and angular resolution are shown in blue and gray respectively. The total resolution, obtained by adding both contributions in quadrature is shown in red for two cuts on the maximum zenith angle.

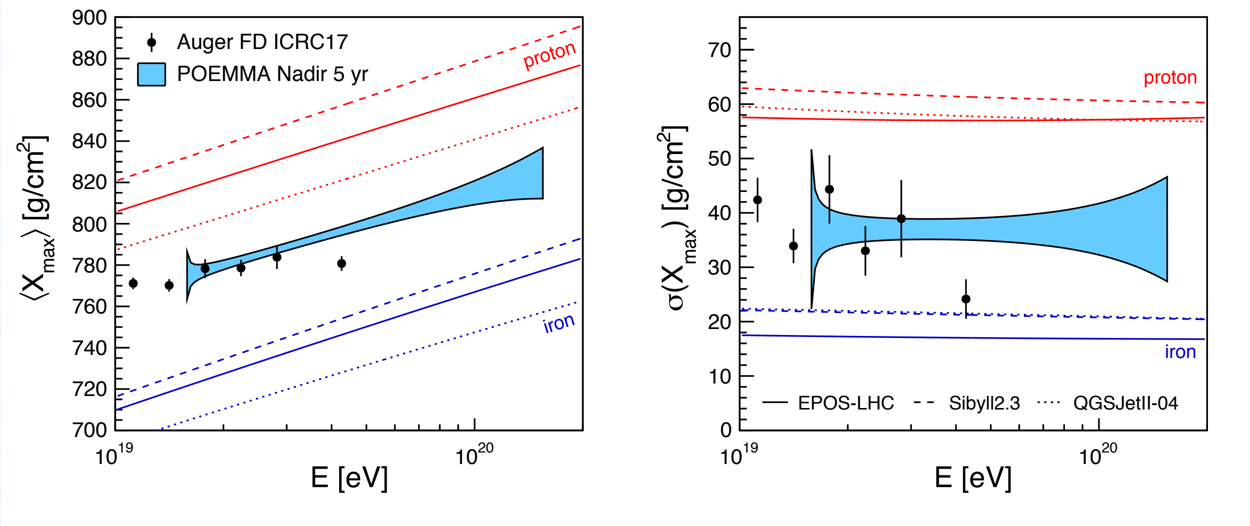
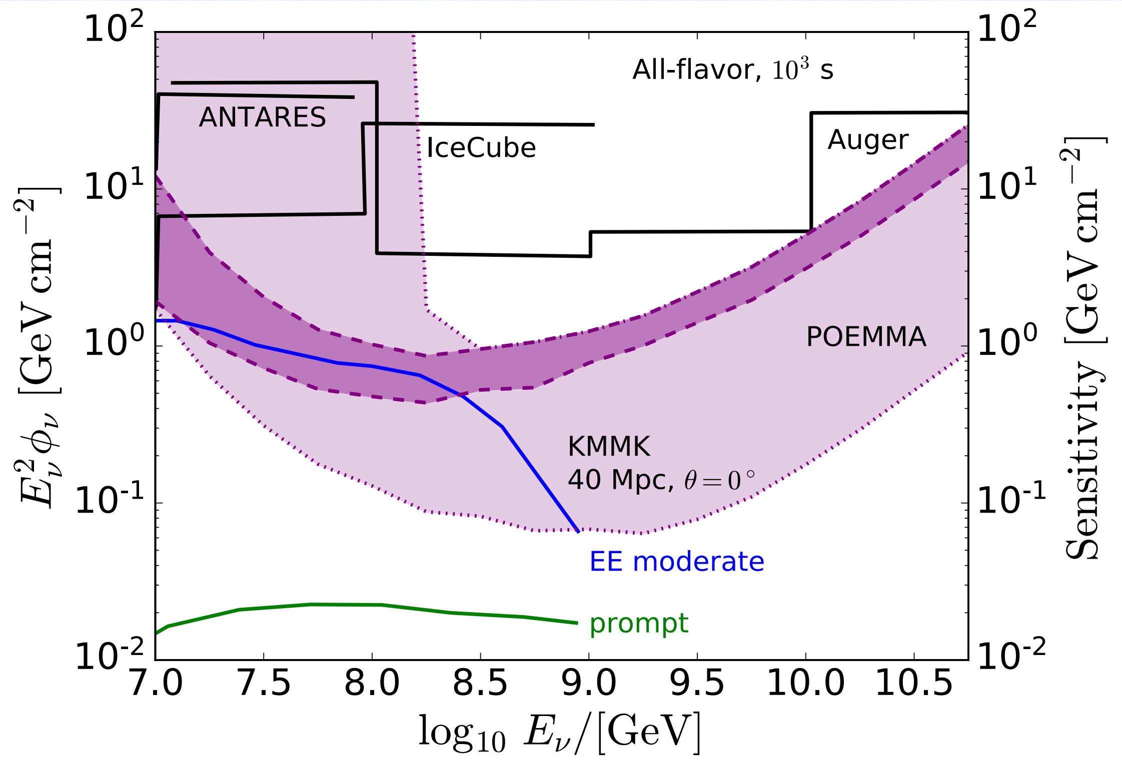
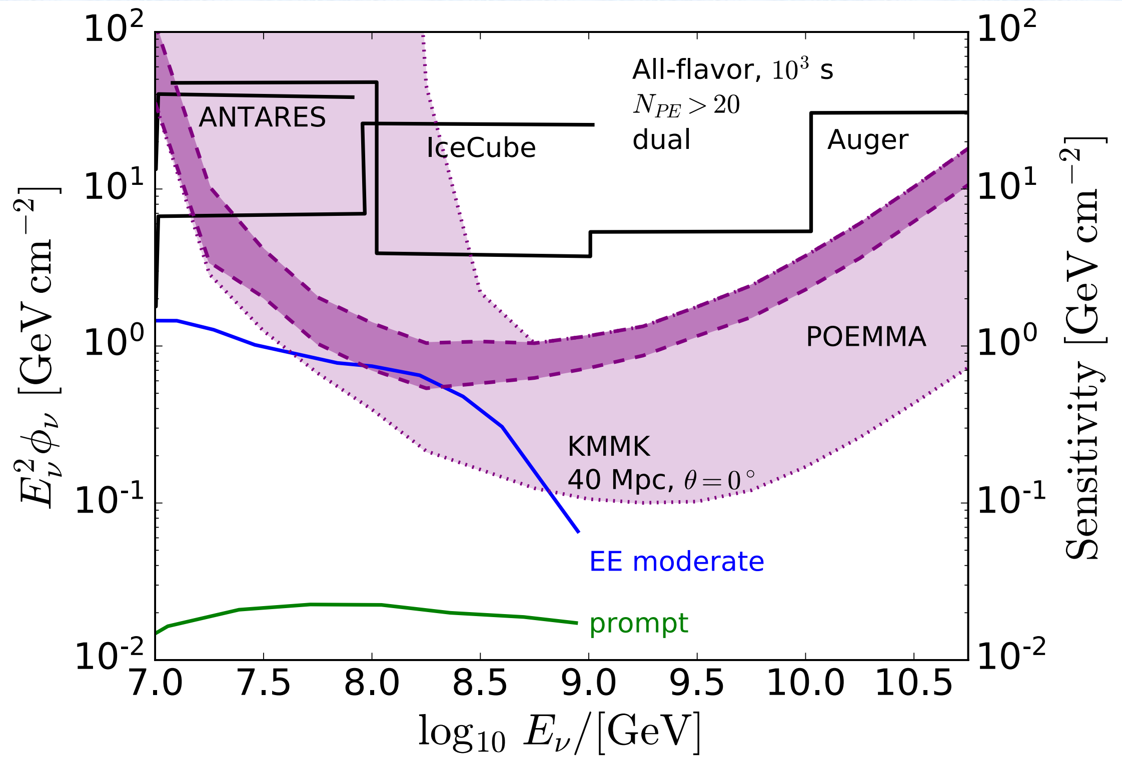


FIG. 20: Capability of POEMMA to measure $\langle X_{max}\rangle$ and $\sigma(X_{max})$ for composition studies at UHE. The width of the blue band illustrates the expected statistical uncertainties given the number of events per 0.1 in logarithm of energy in five year stereo operation, the X_{max} resolution and efficiency from Fig. 18 for $\theta < 70^\circ$ and intrinsic shower-to-shower fluctuations of 40 g/cm^2. The band spans the energy range for which more than 10 events are within a 0.1 dex bin.

POEMMA Short Burst: 10 PE versus 20 PE comparison





10 PE threshold with simultaneous viewing of Cherenkov light pool and time coincidence (60 ns)

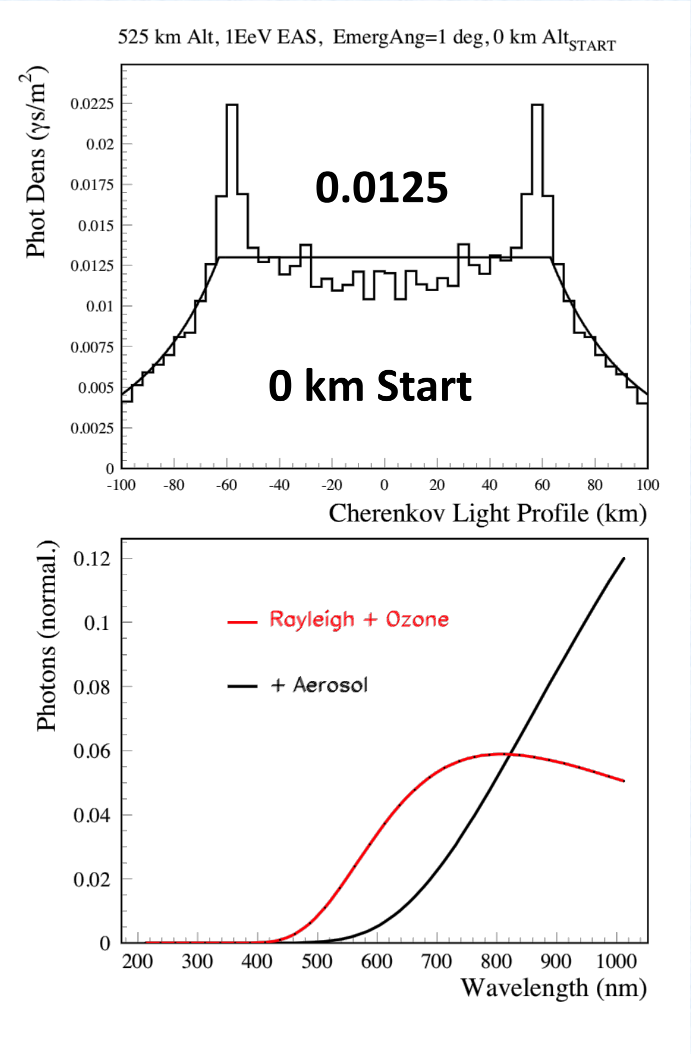
20 PE threshold with separate viewing of different Cherenkov light pool and times

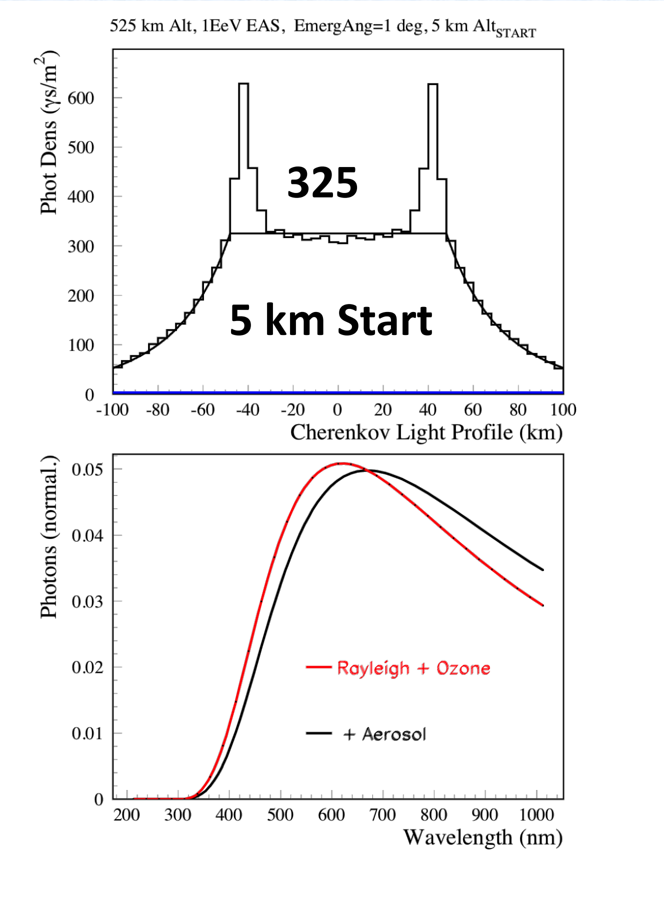
POEMMA: upward τ-lepton EAS Cherenkov spectrum variability

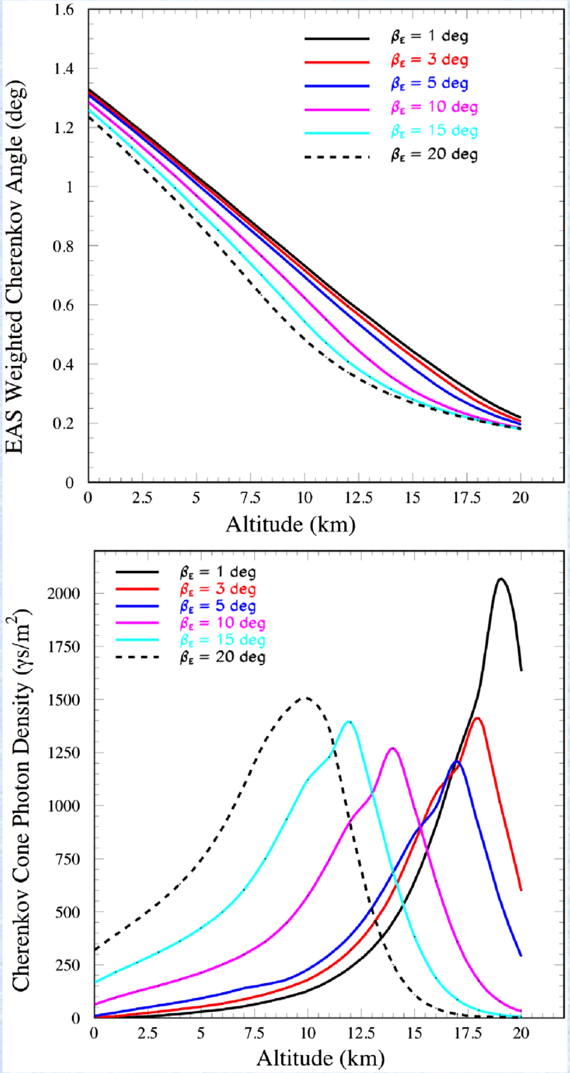
Atmospheric optical attenuation:

- **Rayleigh Scattering**
- **Aerosols (scale height ~ 1 km)**
- **Ozone (decimates signal ≲ 300 nm)**

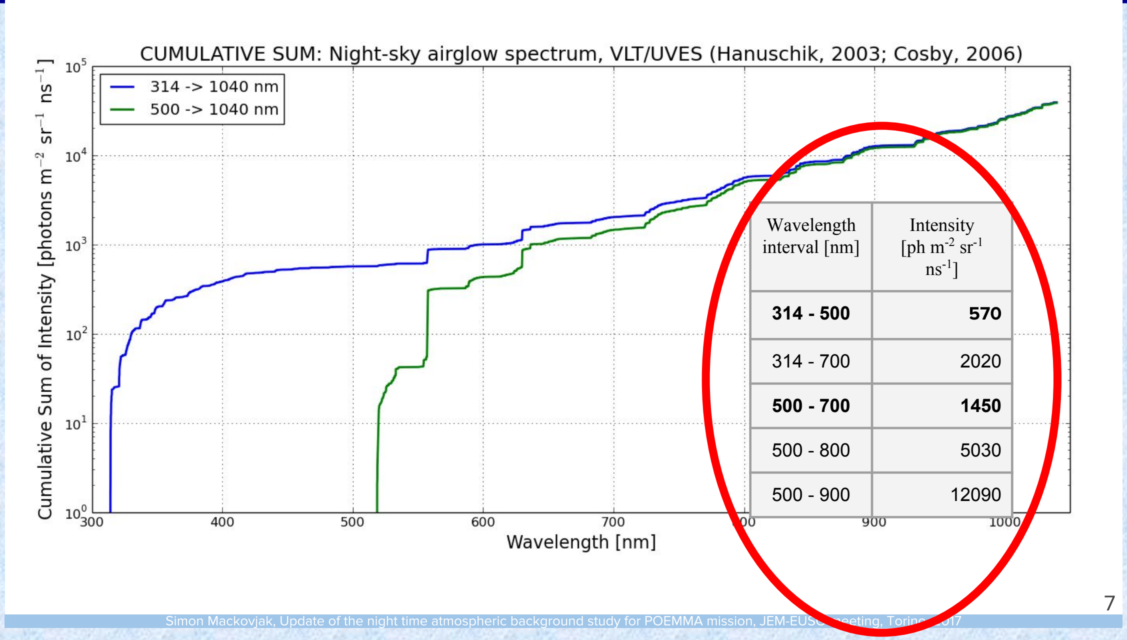
PhysRevD.100.063010 Fig. 18







Air Glow Background in Cherenkov Band



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

12,090 photons/m²/sr/ns

314 nm – 1000 nm

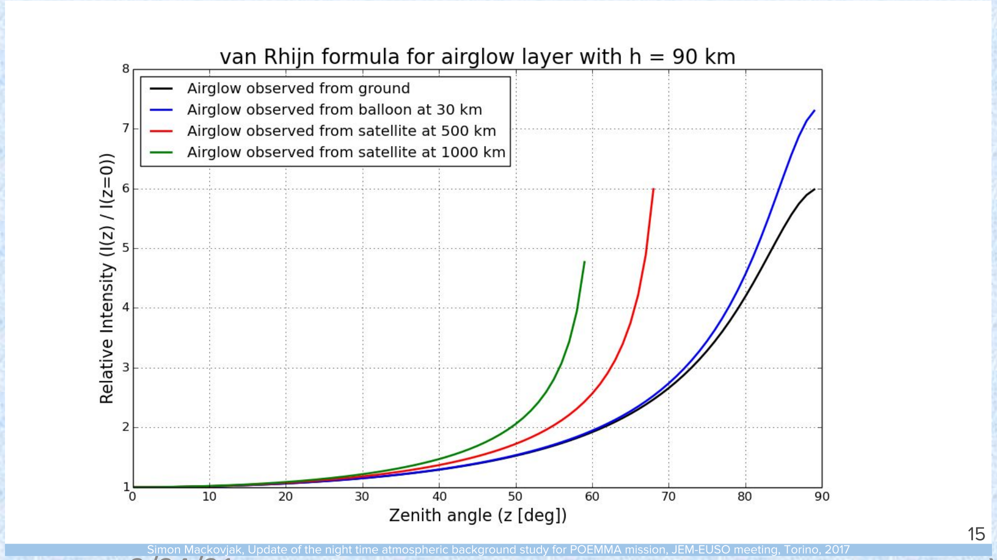
~25,000 photons/m²/sr/ns

314 nm – 500 nm

570 photons/m²/sr/ns

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

10 PE (dual Cher measurement)
20 PE (single Cher measurement)

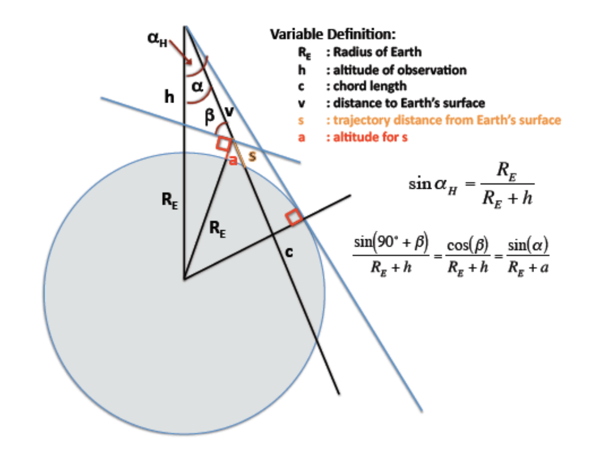


Viewing at angles away from nadir views more optical depth of air glow layer.

x6 for viewing limb from 500 km

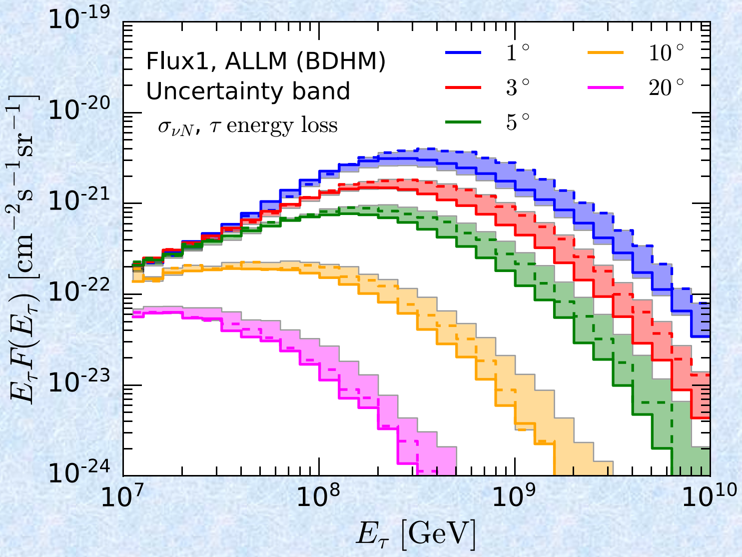
Work by Simon Mackovjak

POEMMA: upward τ-lepton EAS Cherenkov considerations

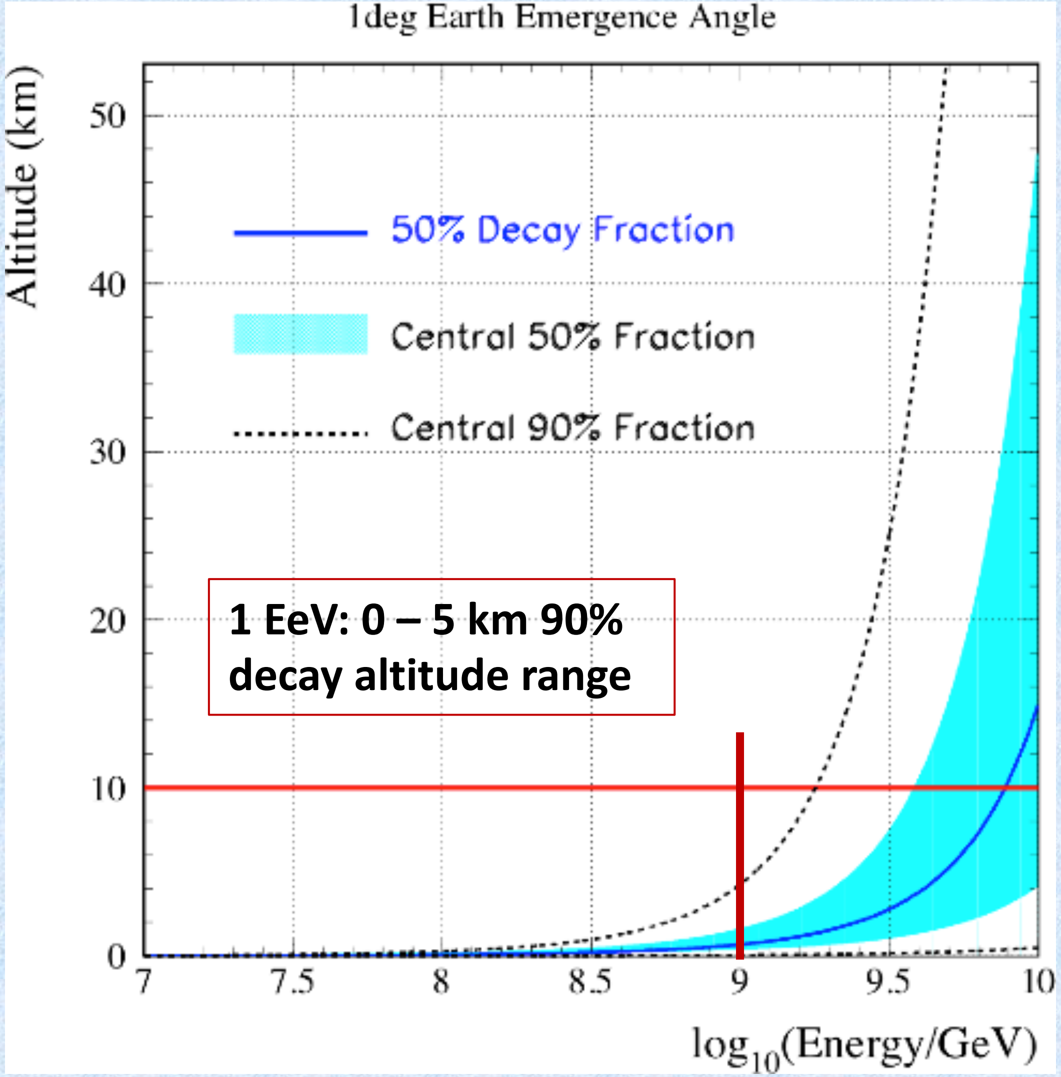


$\Delta\alpha$	β_E(33 km)	β_E(525 km)	β_E(1000 km)
1	3.6	7.0	8.2
2	5.2	10.0	11.7
3	6.6	12.3	14.5
4	7.9	14.4	16.9
5	9.1	16.2	19.0
6	10.3	18.0	21.0
7	11.4	19.6	22.8
8	12.6	21.2	24.6

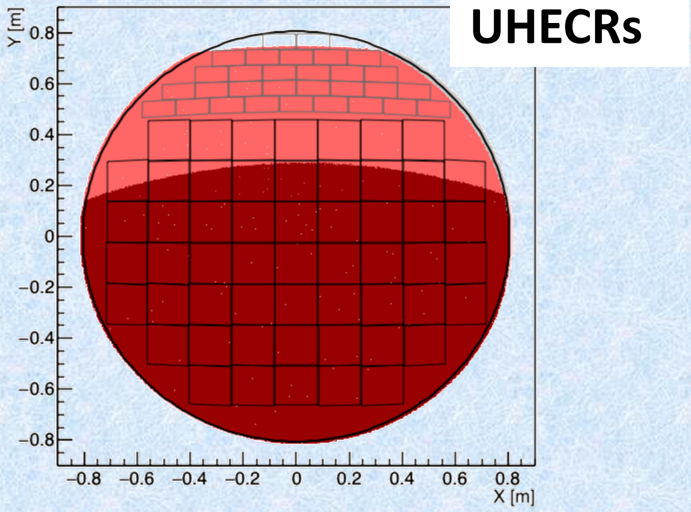
PhysRevD.100.063010 Fig. 12



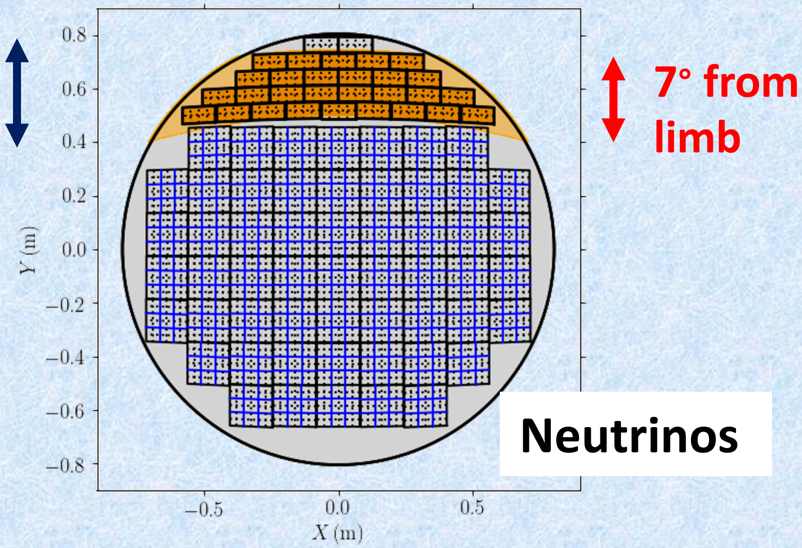
τ-lepton Yield Calc:
- PREM Earth Model
- Kotera2010 mixed UHECR composition cosmogenic ν flux



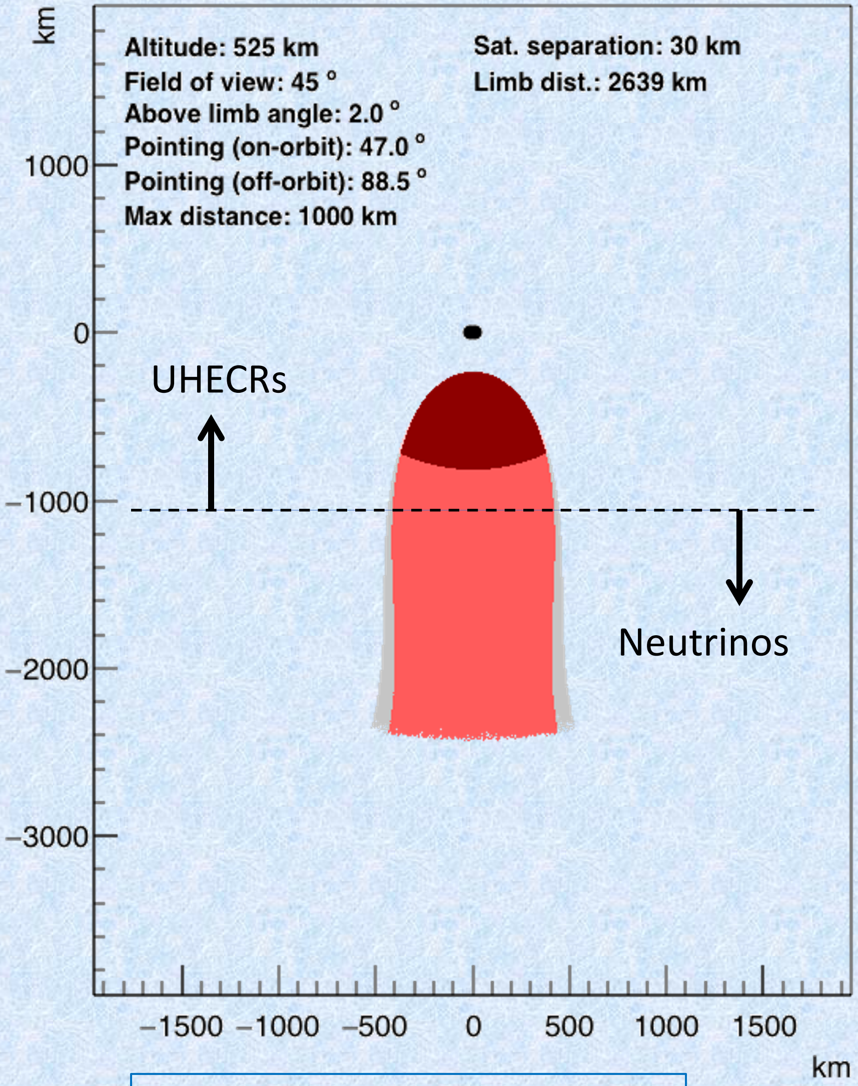
POEMMA: Neutrino mode example configuration



9° total



7° from limb



Calcs & plots by F. Sarazin