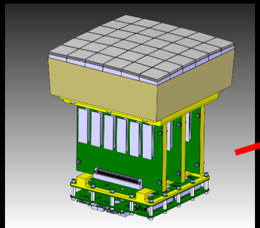
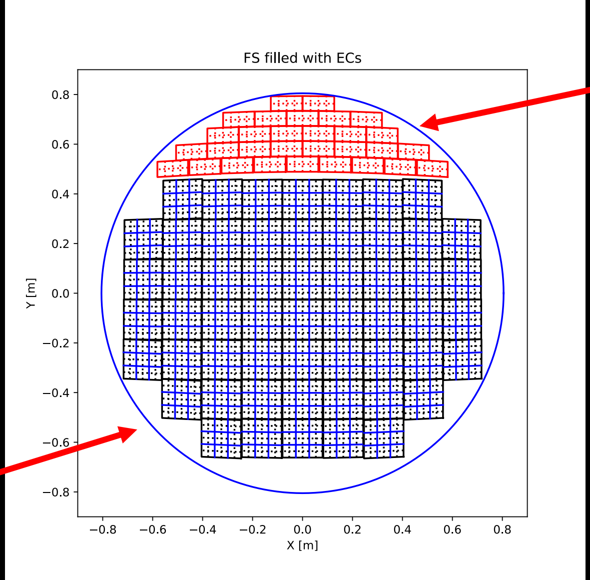
POEMMA: Probe Of Extreme Multi-Messenger Astrophysics

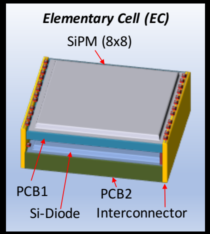
A NASA Probe-class mission to perform transformational measurements of UHECRs and Cosmic Neutrinos.

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

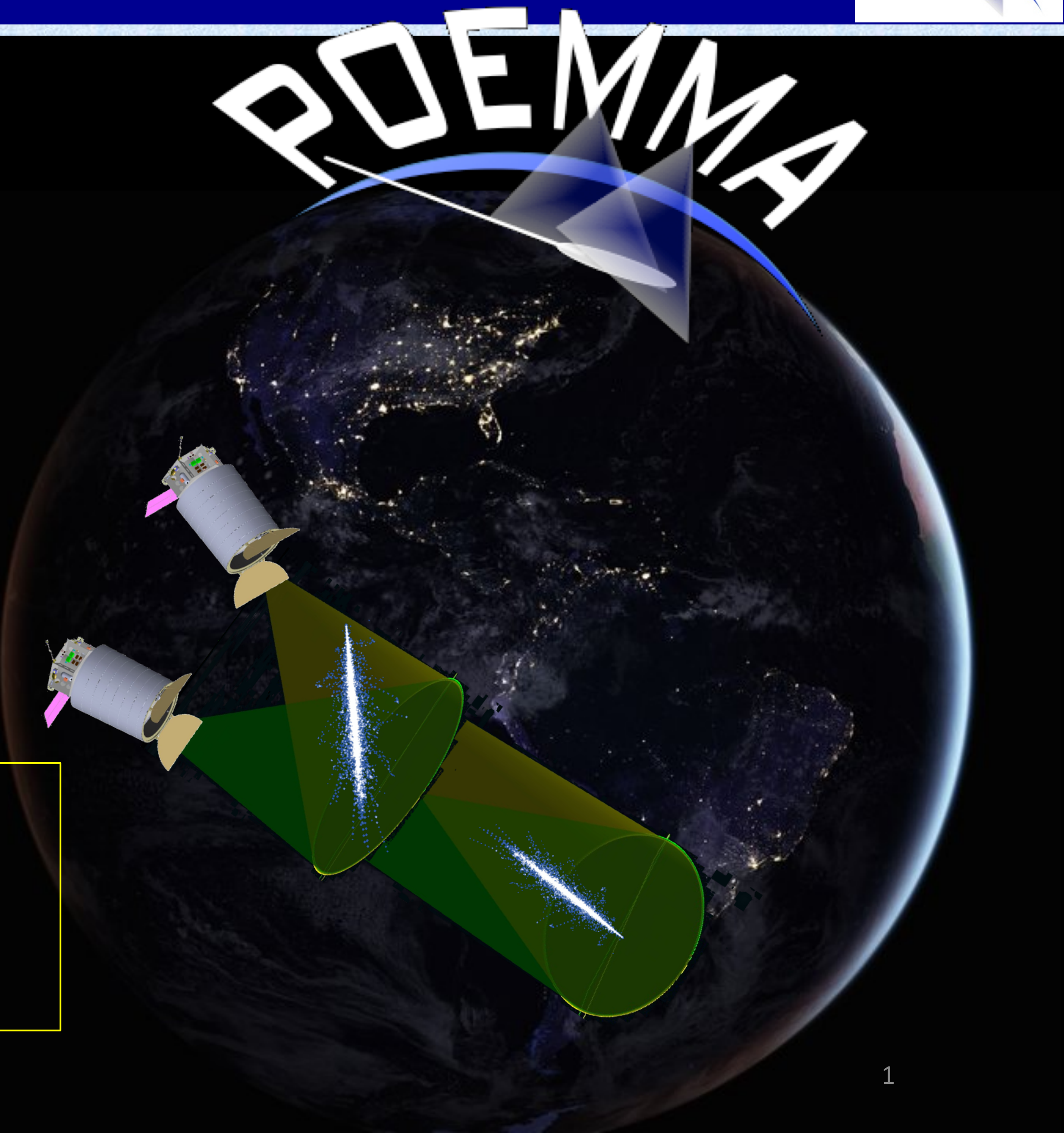
MAPMT arrays for EAS fluorescence light detection



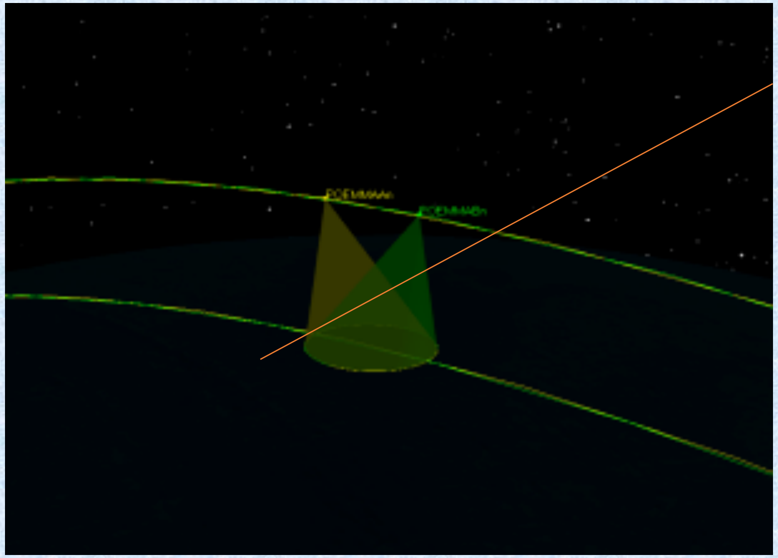




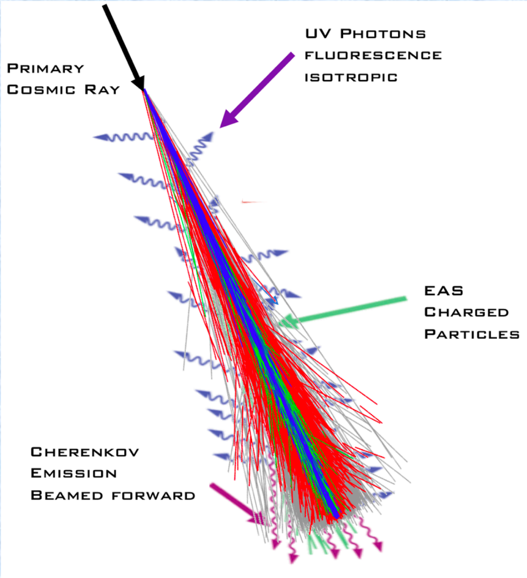
SiPM arrays for Cherenkov light detection from upward ν_τ induced EAS

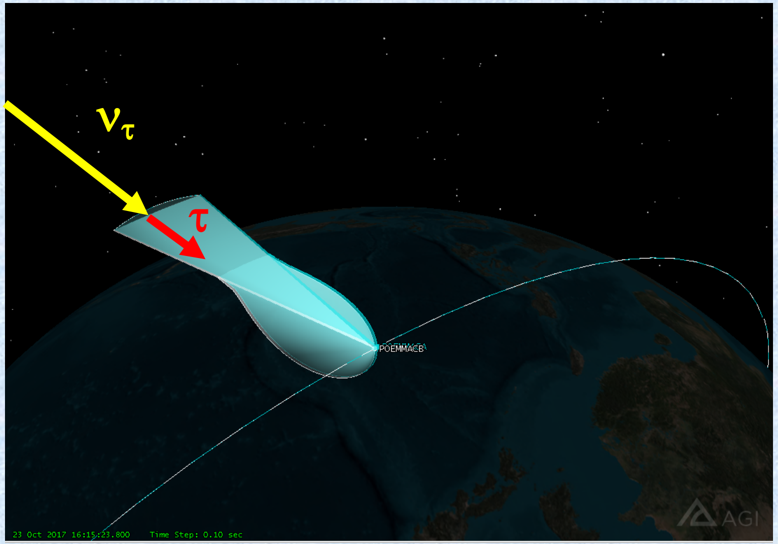


Outline



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





Upward τ-lepton EAS E ≳ 20 PeV via Cherenkov: ~10 nsec timescale

1. Scientific and Experimental Motivation
2. POEMMA & Mission Description.
3. POEMMA UHECR & UHE Neutrino Performance via air fluorescence measurements.
4. POEMMA VHE Neutrino Performance via optical Cherenkov measurements.
5. SiPM discussion regarding space-based optical Chernekov measurements.
6. SiPM discussion regarding space-based air fluorescence measurements.
7. Summary

POEMMA Study Collaboration

University of Chicago: *Angela V. Olinto (PI),* R. Diesing

NASA/GSFC: John Krizmanic (deputy PI), John W. Mitchell, Jeremy S Perkins, Julie McEnery, Elizabeth Hays, Floyd Stecker, Tonia Venters

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University of Utah: Doug Bergman

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City University of New York, Lehman College: Luis Anchordoqu, Thomas C. Paul, Jorge. F. Soriano

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ITALY: Universita di Torino: Mario Edoardo Bertaina, Francesco Fenu, Kenji Shinozaki; INFN Toriono: F. Bisconti;
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FRANCE: APC Univerite de Paris 7: Etienne Parizot, Guillaume Prevot; IAP, Paris: C. Guepin

SWITZERLAND: University of Geneva: Andrii Neronov

SLOVAKIA: IEP, Slovak Academy of Science: Simon Mackovjak

JAPAN: RIKEN: Marco Casolino

GERMANY: KIT: Michael Unger; ESO: F. Oikonomou

40+ scientists from 21+ institutions (US + 6)
OWL, JEM-EUSO, Auger, TA, Veritas, CTA, Fermi, Theory

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
  Allows for high sensitivity UHE neutrino measurements
- **Observe Neutrinos from Transient Astrophysical Events**
  Measure 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

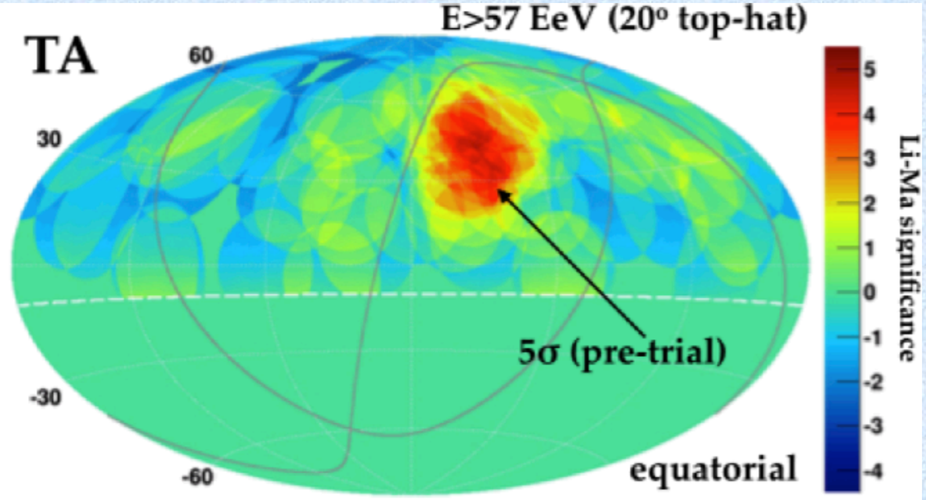
- study fundamental physics with the most energetic cosmic particles: CRs and Neutrinos
- search for super-Heavy Dark Matter
- study Atmospheric Transient Events, survey Meteor Population
-

UHECR Status

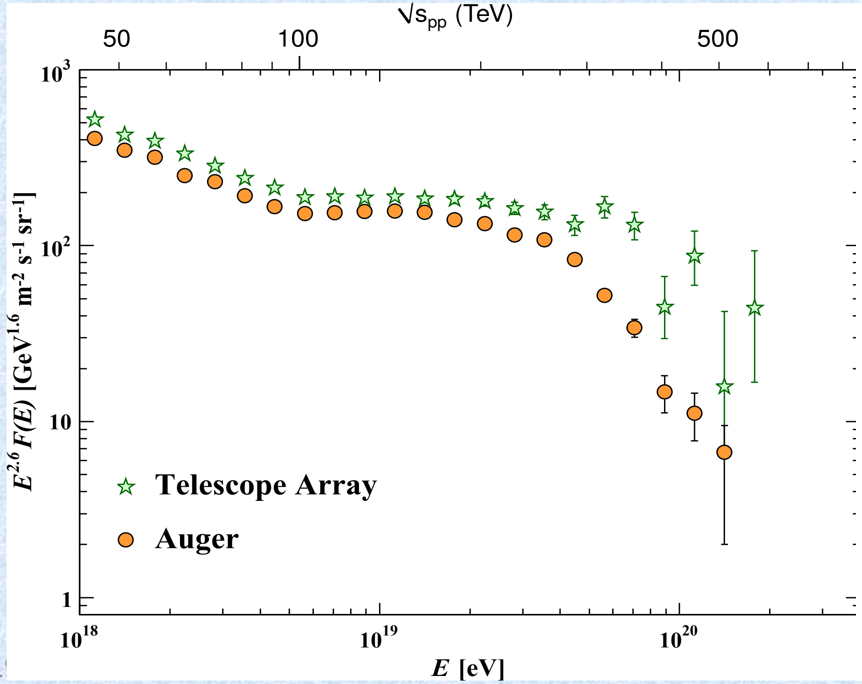
Origin UHECRs still unknown

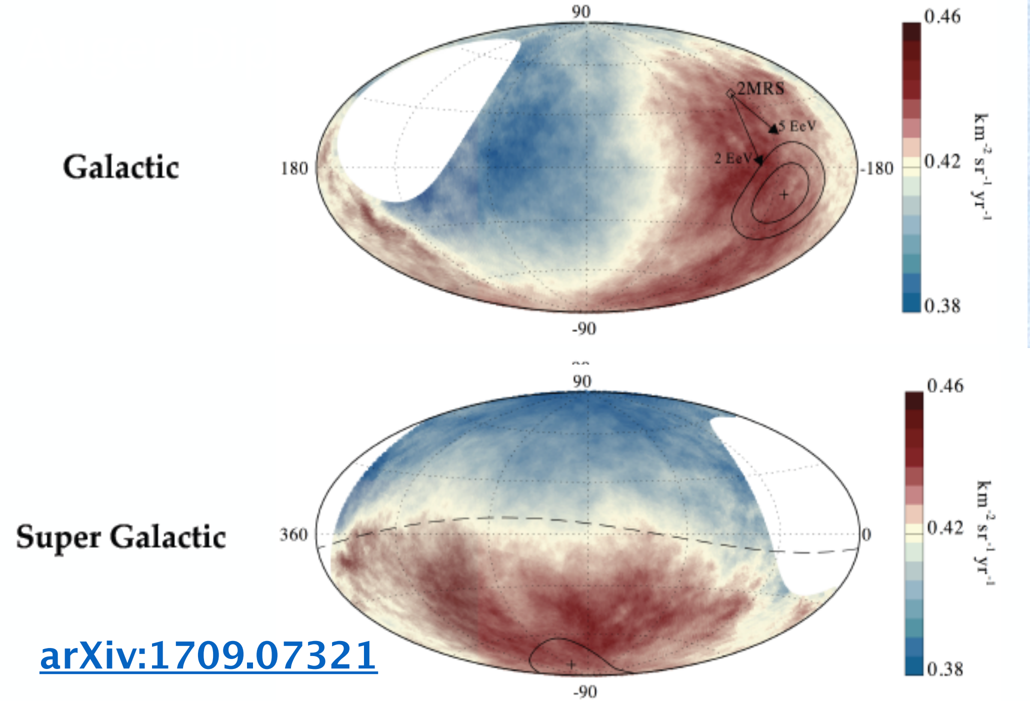
Giant ground Observatories: Auger & TA

- sources are extragalactic: Auger dipole > 8 EeV
- spectral features – discrepancies E > 50 EeV
- interesting Composition trends – unknown E > 50 EeV
- source anisotropy Hints E > 50 EeV



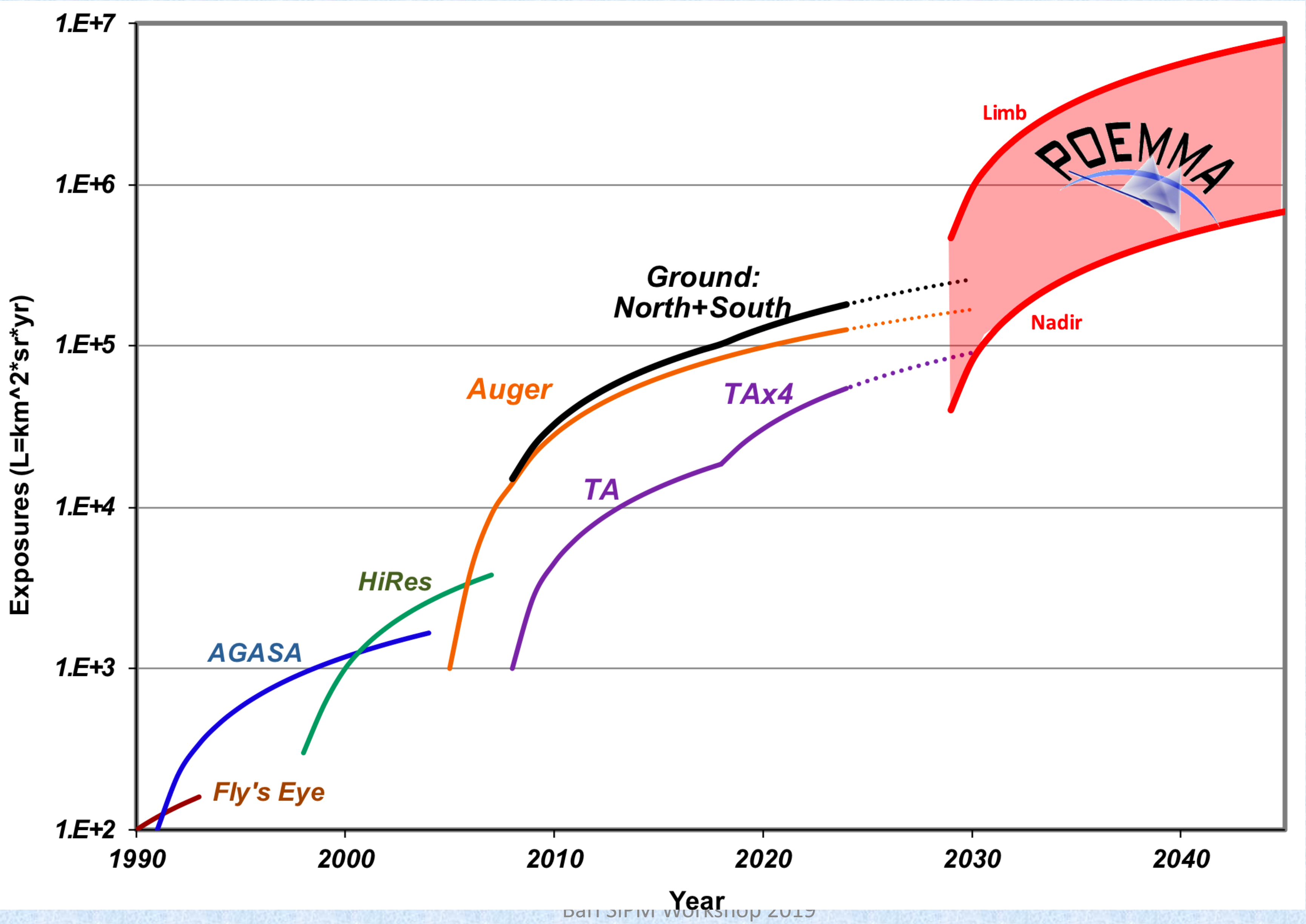
ApJ 790, L21 (2014)



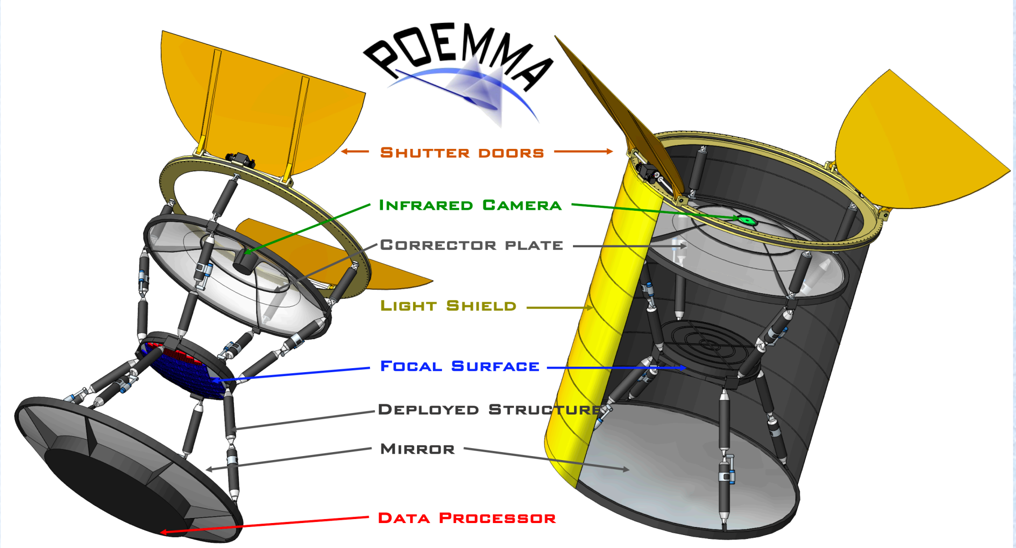


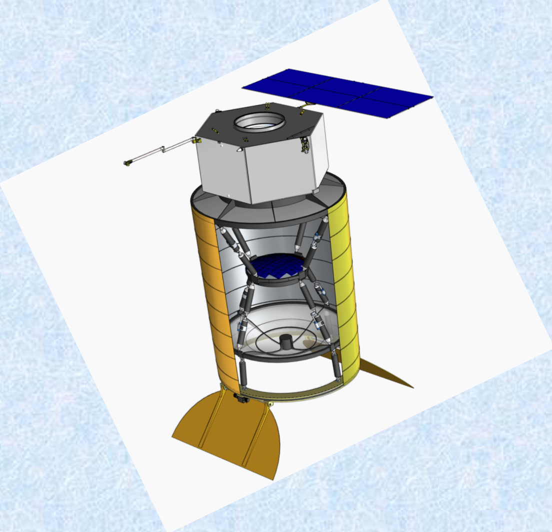
arXiv:1709.07321

POEMMA: UHECR Exposure History



POEMMA: Instruments





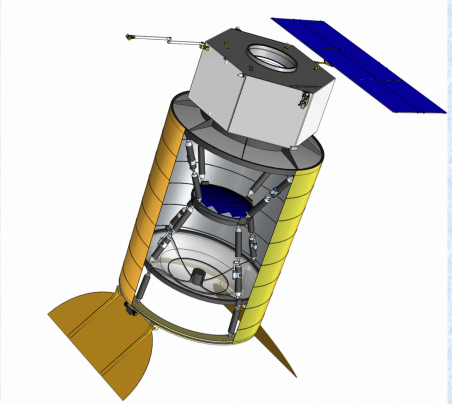
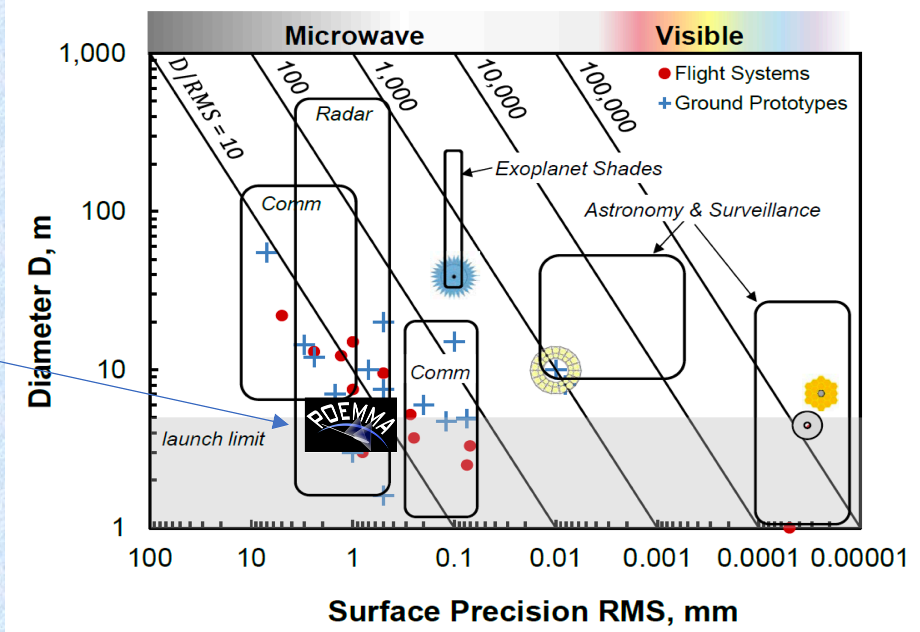


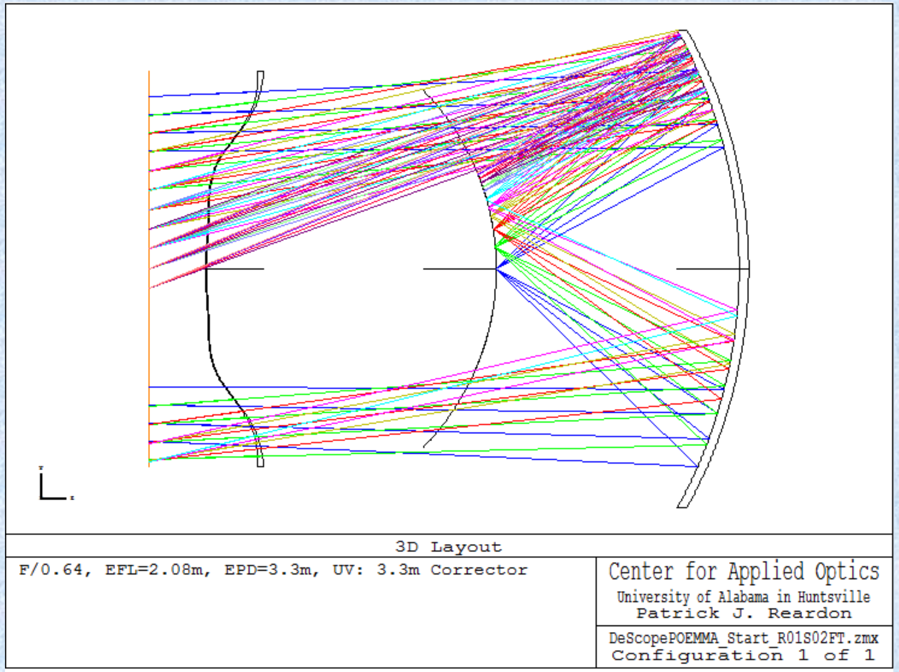
TABLE I: POEMMA Specifications:

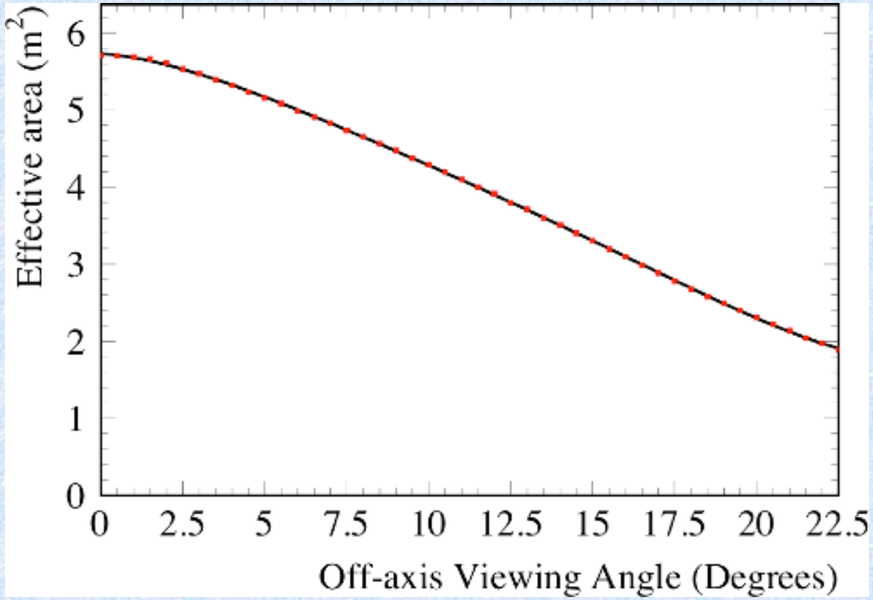
Photometer	Components		Spacecraft	
Optics	Schmidt	45° full FoV	Slew rate	90° in 8 min
	Primary Mirror	4 m diam.	Pointing Res.	0.1°
	Corrector Lens	3.3 m diam.	Pointing Know.	0.01°
	Focal Surface	1.6 m diam.	Clock synch.	10 nsec
	Pixel Size	3×3 mm^2	Data Storage	7 days
	Pixel FoV	0.084°	Communication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



POEMMA: Schmidt Telescope details





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

Primary Mirror: **4 meter diameter**

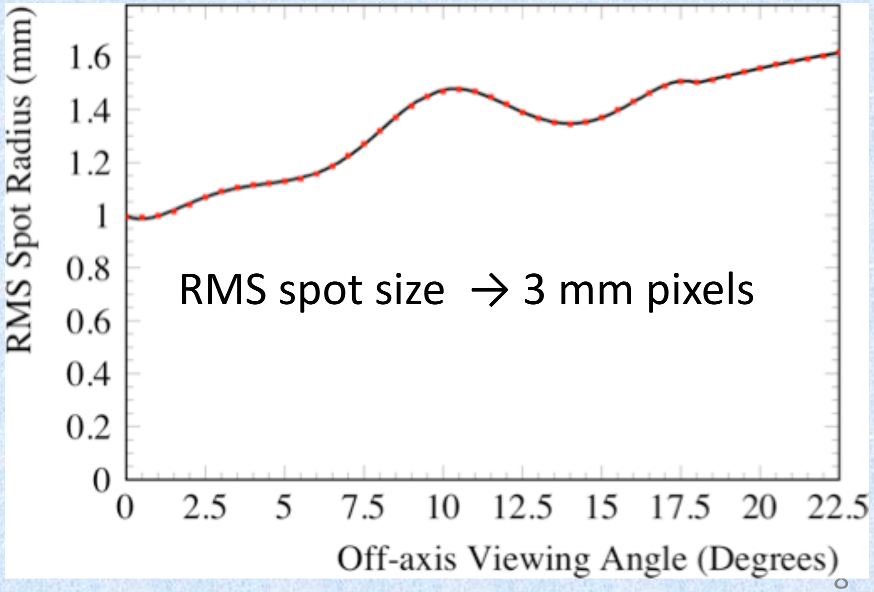
Corrector Lens: **3.3 meter diameter**

Focal Surface: **1.6 meter diameter**

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

Hybrid focal surface (MAPMTs and SiPM)

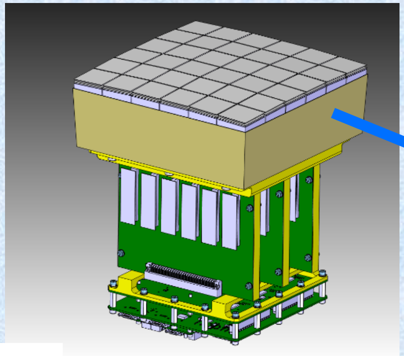
3 mm linear pixel size: 0.084° FoV

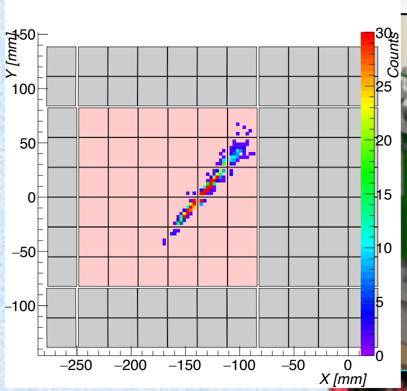


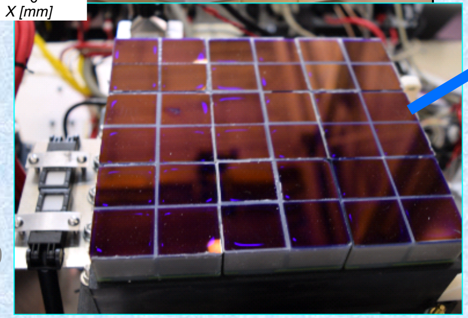
POEMMA: Hybrid Focal Plane

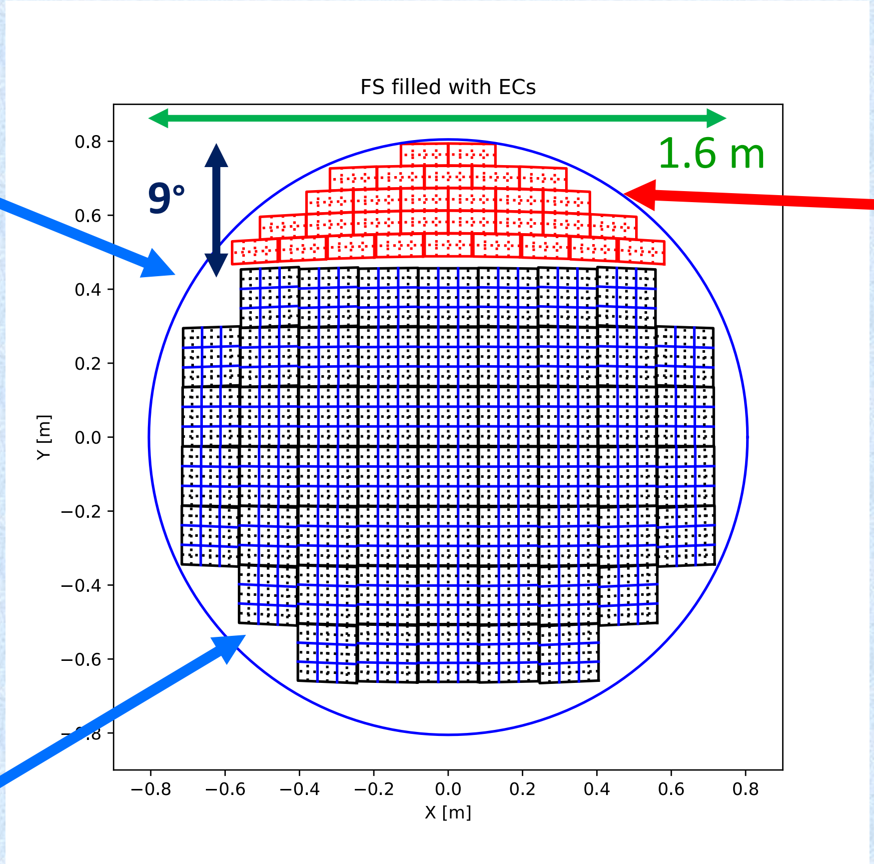
UV Fluorescence Detection using MAPMTs with BG3 filter (300 – 500 nm) developed by JEM-EUSO: 1 usec sampling

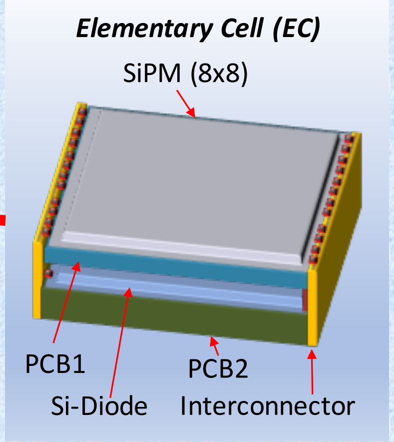
Cherenkov Detection with SiPMs (300 – 1000 nm): 20 nsec sampling











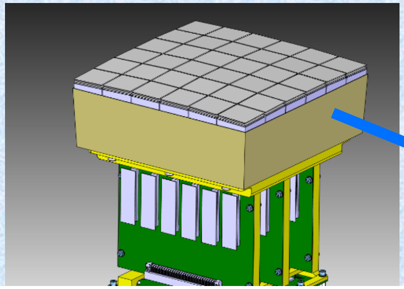
30 SiPM focal surface units
Total 15,360 pixels
512 pixels per FSU (64x4x2)
Si-Diode for LEO radiation backgrounds rejection

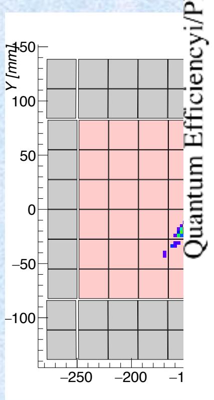
55 Photo Detector Modules (PDMs)= 126,720 pixels

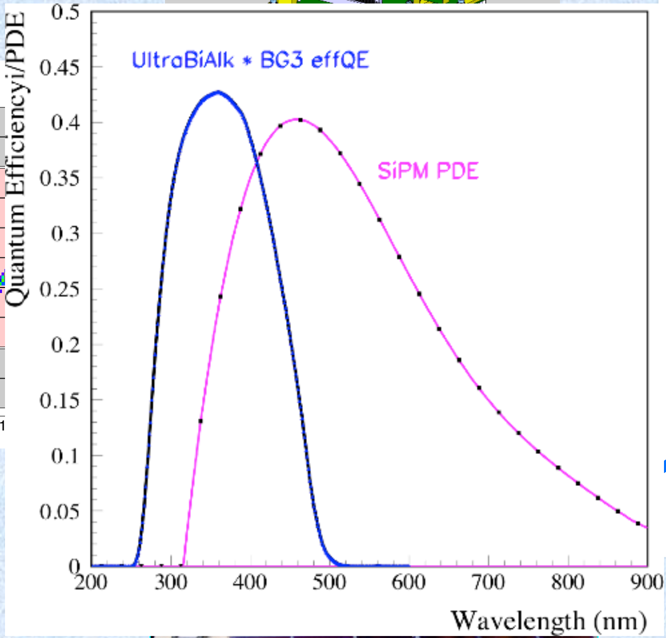
1 PDM = 36 MAPMTs = 2,304 pixels

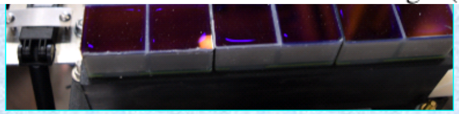
POEMMA: Hybrid Focal Plane

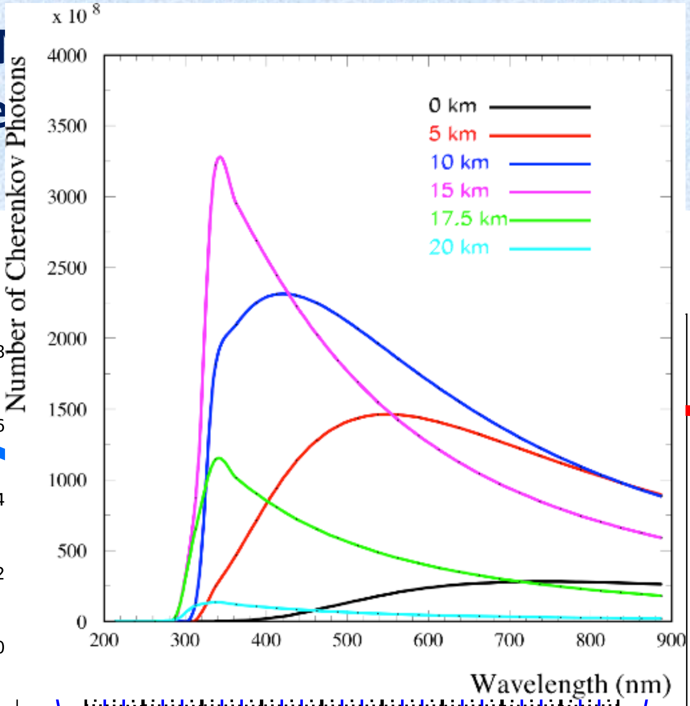
UV Fluorescence Detection using MAPMTs with BG3 filter (300 – 500 nm) developed by JEM-EUSO: 1 usec sampling

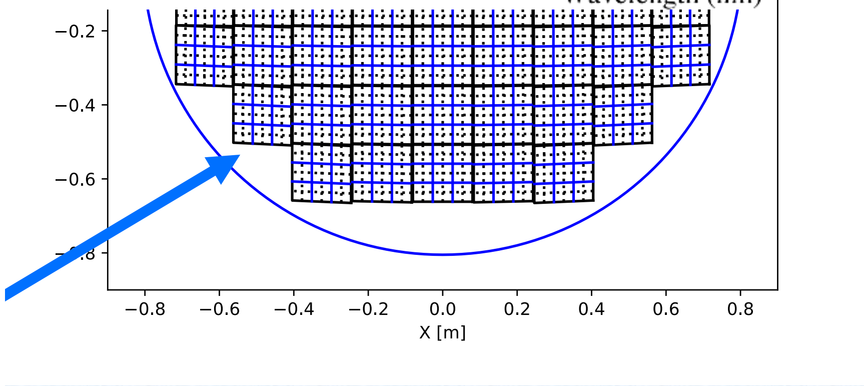




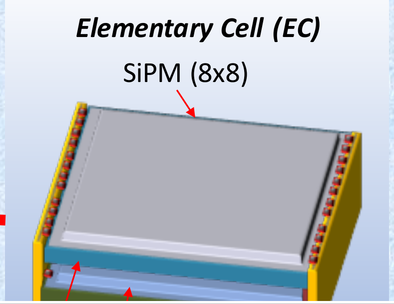


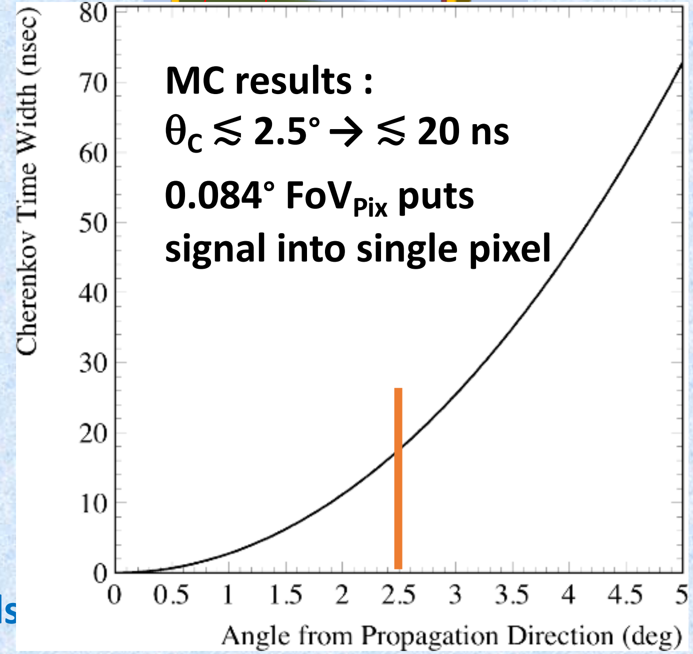






Cherenkov Detection with SiPMs (300 – 1000 nm): 20 nsec sampling



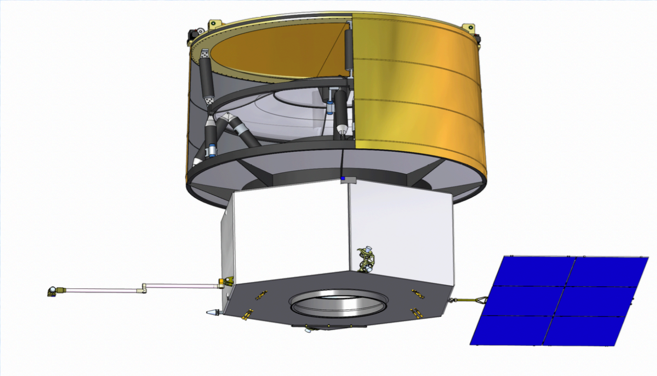


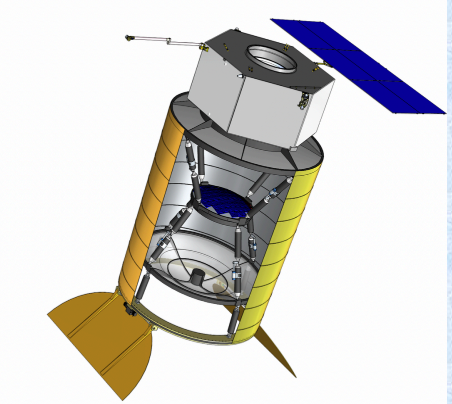
MC results :
$\theta_C \lesssim 2.5° \rightarrow \lesssim 20$ ns
$0.084°$ FoV_{Pix} puts signal into single pixel

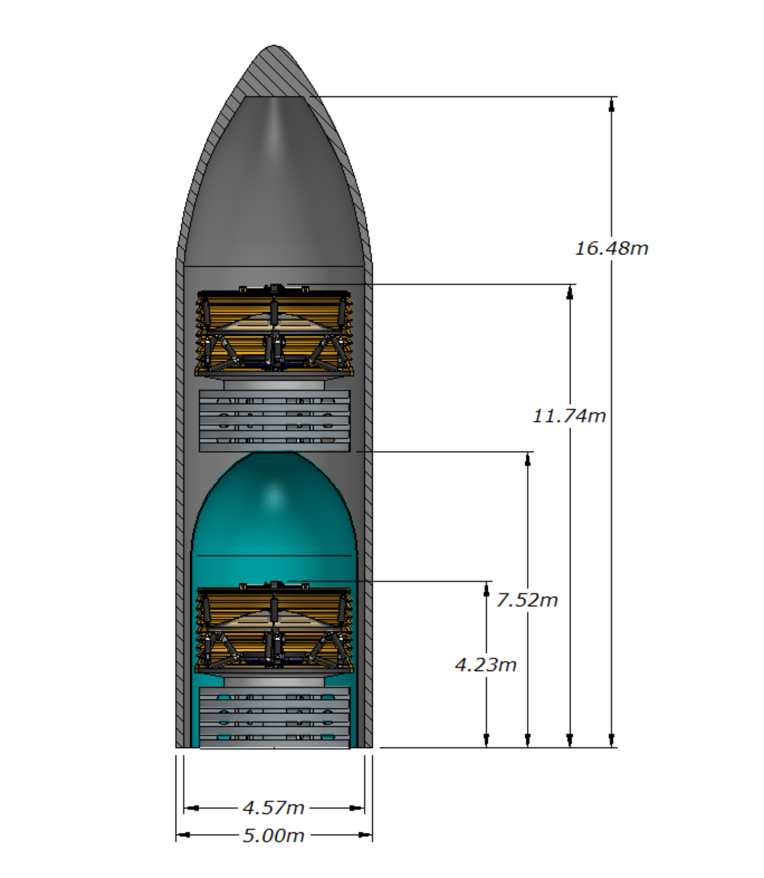
55 Photo Detector Modules (PDMs)= 126,720 pixels
1 PDM = 36 MAPMTs = 2,304 pixels

POEMMA: Mission (Class B)

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







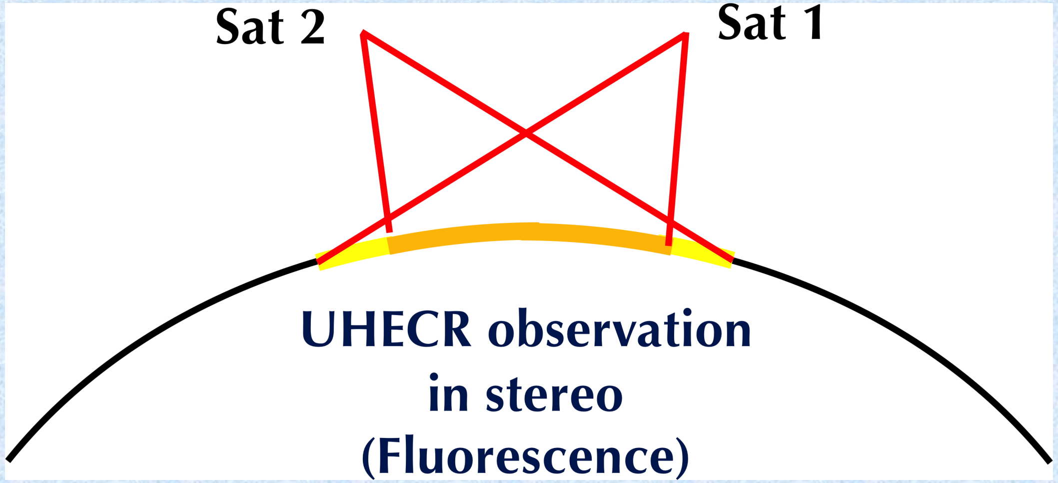
Dual Manifest Atlas V

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

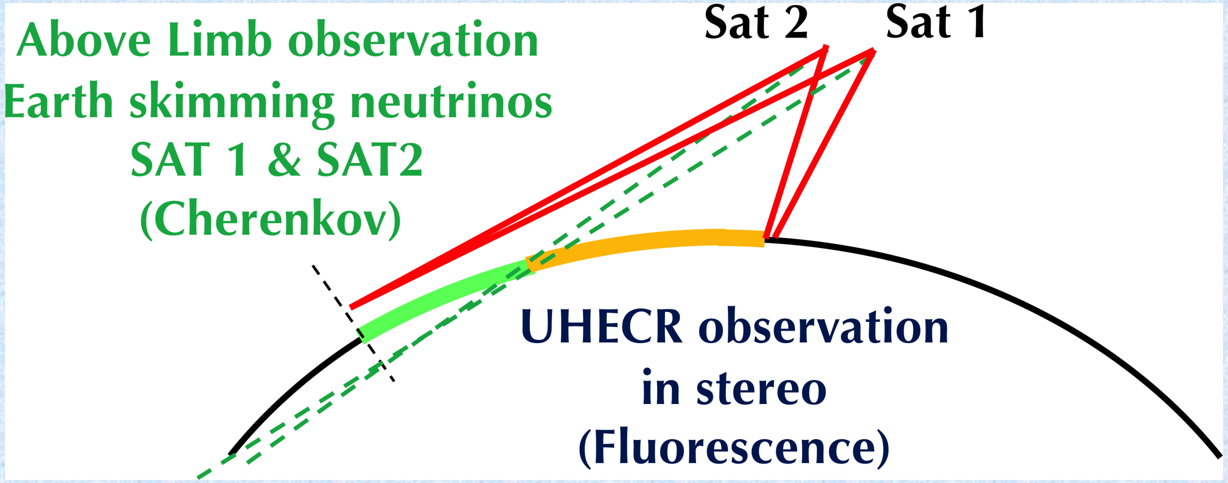
POEMMA: UHECR Stereo UHECR mode and limb-viewing neutrino mode

Quasi-nadir UHECR Stereo UHECR mode



Satellite Separation ~300 km
Larger SatSep maximizes GF
Lower SatSep minimizes E_{Thres}

Tilted limb-viewing neutrino mode



Satellite Separation ~30 km
When both in Cherenkov light pool can use time coincidence to reduce PE threshold in light of air glow background.

Measurements occur during dark, quasi-moon less nights:
- Fluorescence Duty Cycle: 11%
- Cherenkov Duty Cycle: 20%

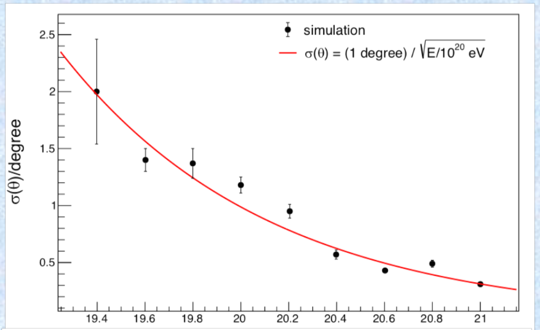
POEMMA: UHECR Performance: *see arXive: 1907.03694*

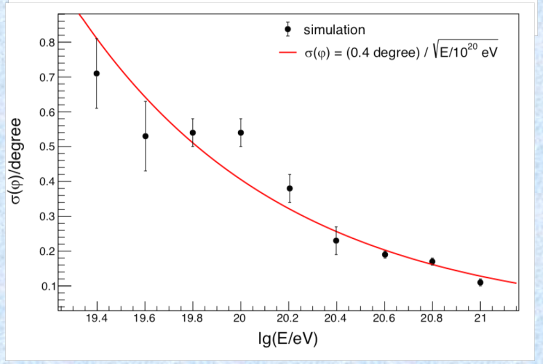
significant increase in exposure

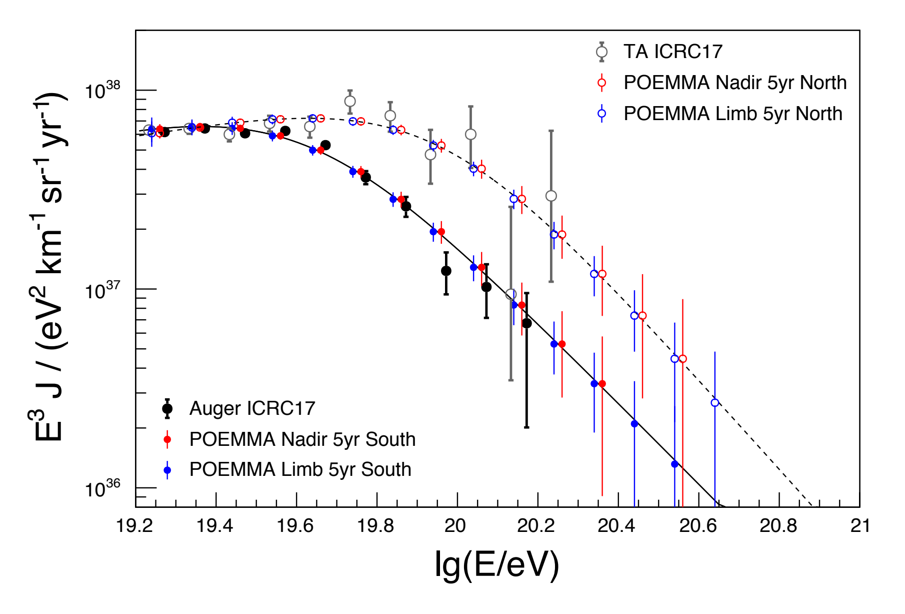
Uniform sky coverage to **guarantee the discovery of UHECR sources**

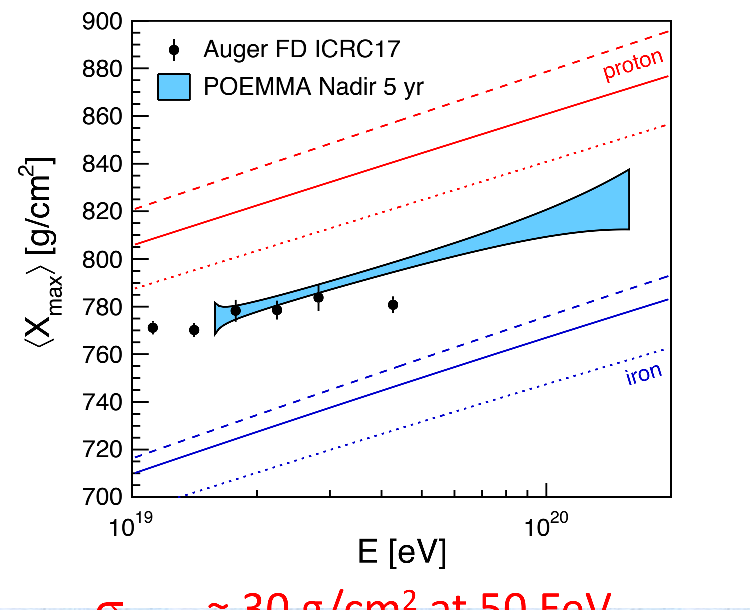
Spectrum, Composition, Anisotropy $E_{CR} \geq 50$ EeV

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

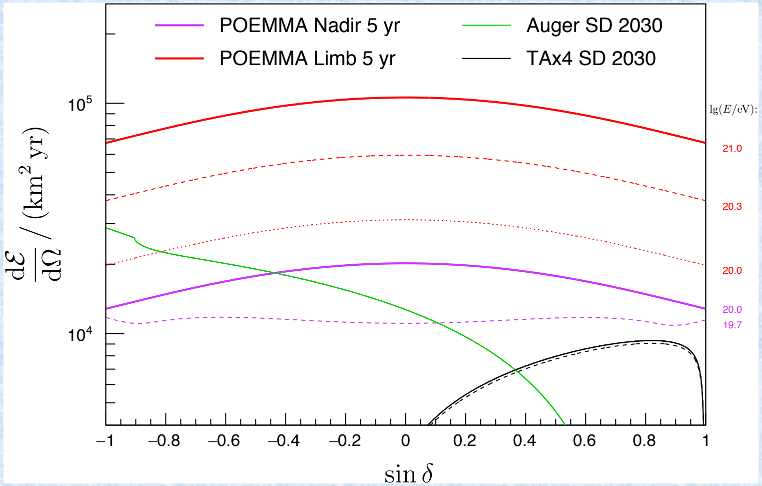








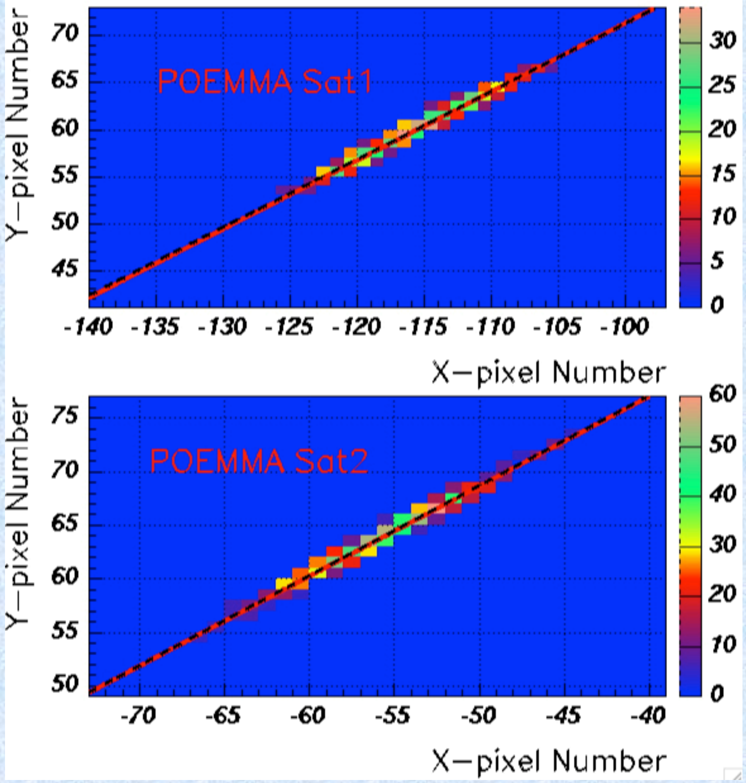
$\sigma_{Xmax} \approx 30\ g/cm^2$ at 50 EeV



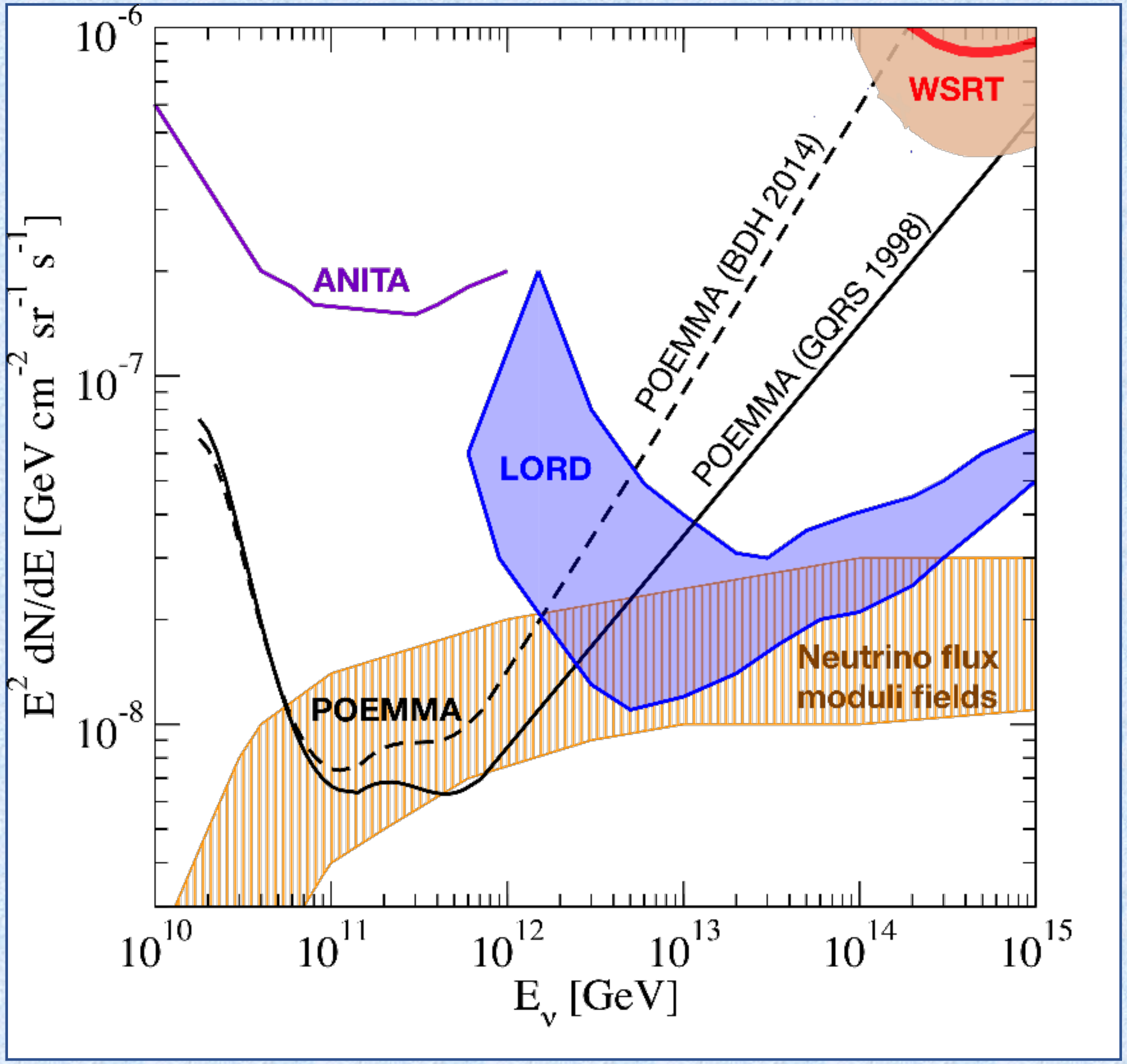
POEMMA: Air fluorescence Neutrino Sensitivity

Effectively comes for free in stereo UHECR mode:

POEMMA's excellent angular resolution allows for efficiently selecting neutrino events started ≥ 2000 g/cm² atmospheric column depth.

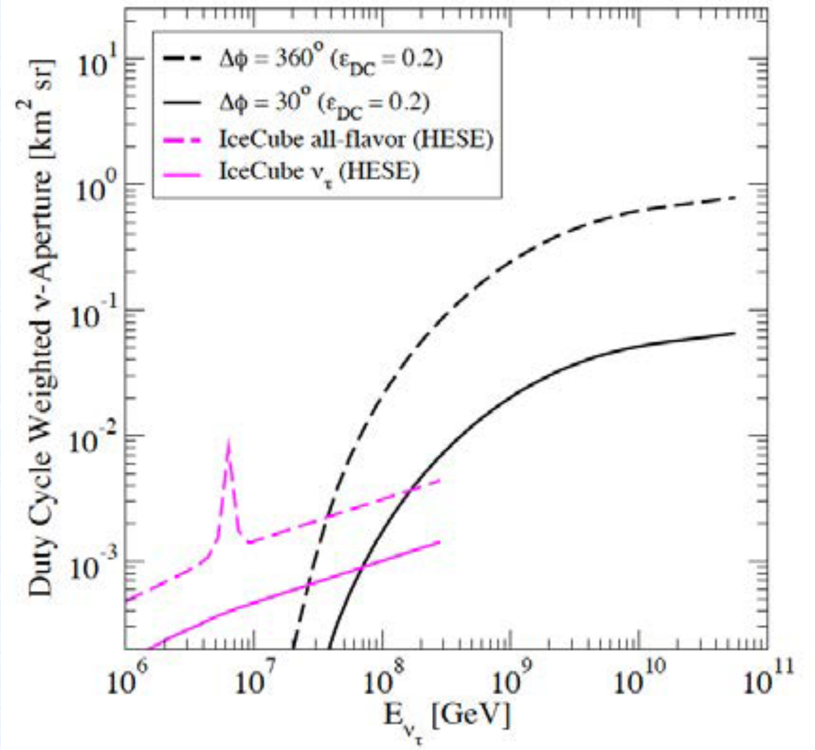


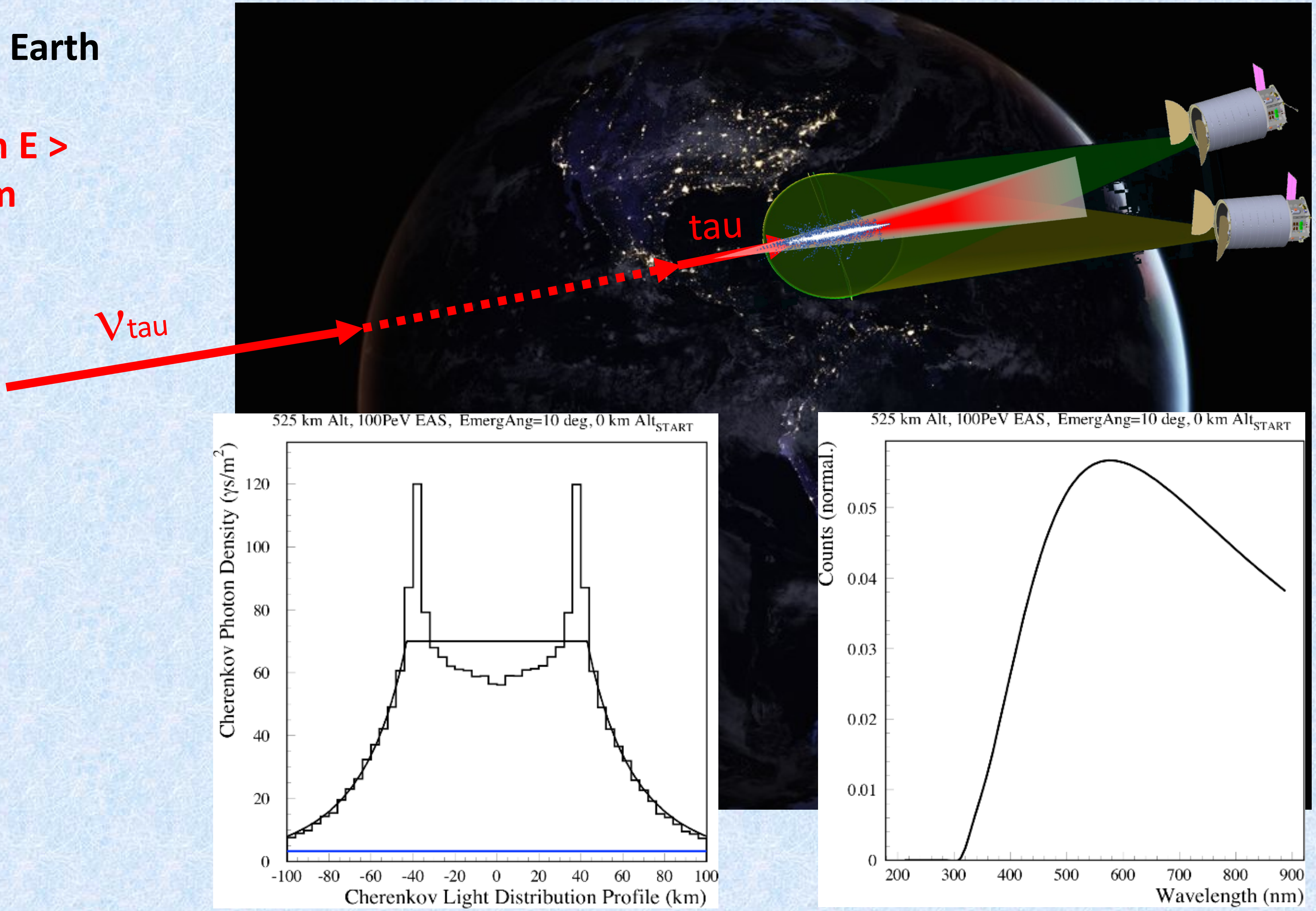
50 EeV simulated event



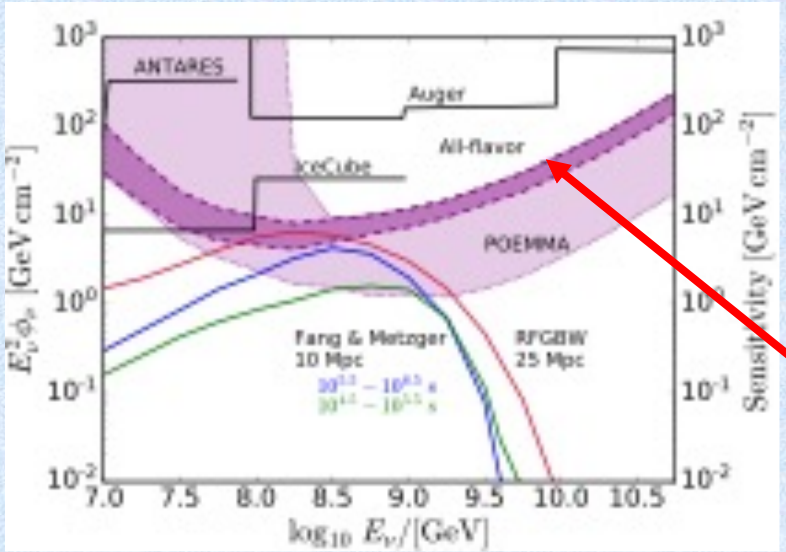
High-Energy Astrophysical Events generates neutrinos (ν_e,ν_μ) and 3 neutrino flavors reach Earth via neutrino oscillations.

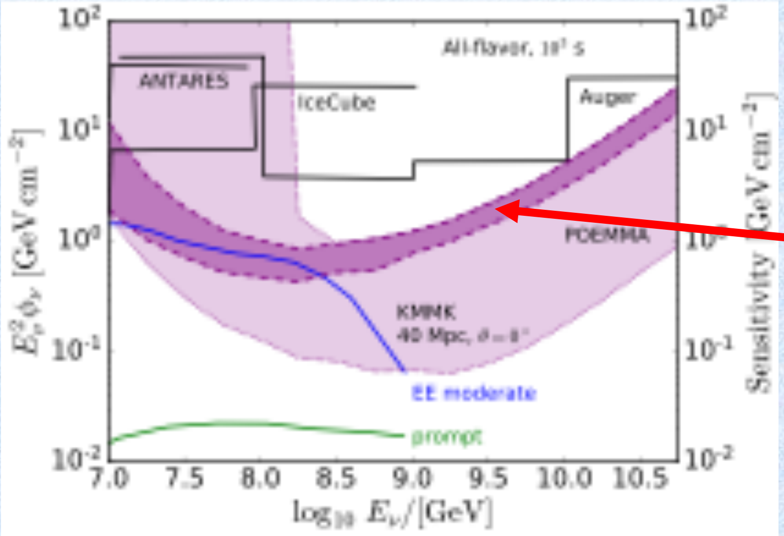
POEMMA designed to observe neutrinos with E > 20 PeV through Cherenkov signal of EASs from Earth-emerging tau decays.





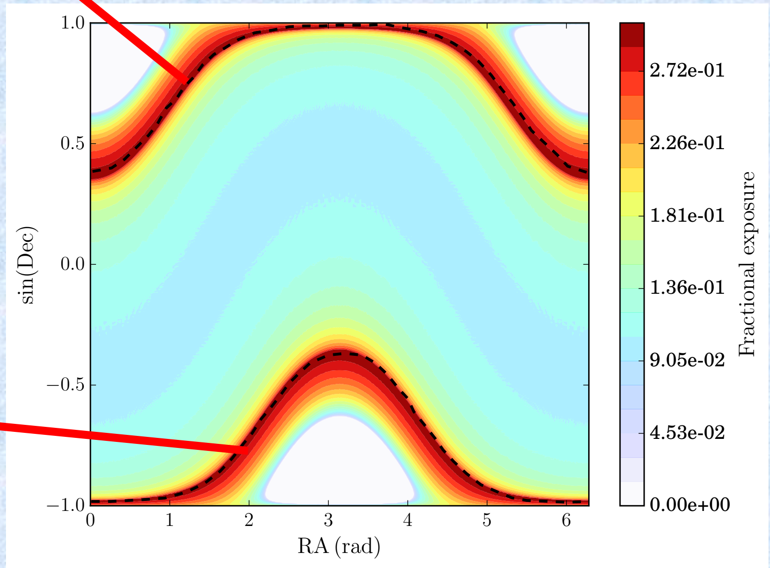
ToO Neutrino Sensitivity: *see arXiv:1906.07209*





IceCube, ANTARES, Auger Limits for binary neutrino star merger GW170817

One orbit sky exposure assuming slewing to source position



Long Bursts

Source Class	No. of ν's at GC	No. of ν's at 3 Mpc	Largest Distance for 1.0 ν per event	Model Reference
TDEs	1.12×10^5	0.77	2.64 Mpc	Dai and Fang [17] average
TDEs	5.62×10^5	3.88	5.91 Mpc	Dai and Fang [17] bright
TDEs	$\mathbf{2.23 \times 10^8}$	$\mathbf{1.44 \times 10^3}$	**115.20 Mpc**	**Lunardini and Winter [18] $M_{\rm SMBH} = 5 \times 10^6 M_\odot$ Lumi Scaling Case**
TDEs	**NA***	$\mathbf{1.07 \times 10^3}$	**100.03 Mpc**	**Lunardini and Winter [18] $M_{\rm SMBH} = 1 \times 10^5 M_\odot$ Strong Scaling Case**
Blazar Flares	**NA***	$\mathbf{1.91 \times 10^2}$	**42.96 Mpc**	**RFGBW [19] – FSRQ proton-dominated advective escape model**
lGRB Reverse Shock (ISM)	9.88×10^4	0.69	2.49 Mpc	Murase [15]
lGRB Reverse Shock (wind)	2.05×10^7	143.75	37.36 Mpc	Murase [15]
BH-BH merger	6.94×10^6	47.84	20.75 Mpc	Kotera and Silk [20] – $t_{\rm dur} \sim 10^4$ s
BH-BH merger	$\mathbf{3.48 \times 10^9}$	$\mathbf{2.4 \times 10^4}$	**477.8 Mpc**	**Kotera and Silk [20] – $t_{\rm dur} \sim 10^{6.7}$ s**
NS-NS merger	$\mathbf{3.58 \times 10^6}$	**24.75**	**12.76 Mpc**	**Fang and Metzger [21]**
WD-WD merger	20.06	0	33.46 kpc	XMMD [22]
Newly-born Crab-like pulsars (p)	1.56×10^2	1.07×10^{-3}	98.27 kpc	Fang [23]
Newly-born magnetars (p)	2.1×10^4	0.13	1.1 Mpc	Fang [23]
Newly-born magnetars (Fe)	4.07×10^4	0.26	1.53 Mpc	Fang [23]

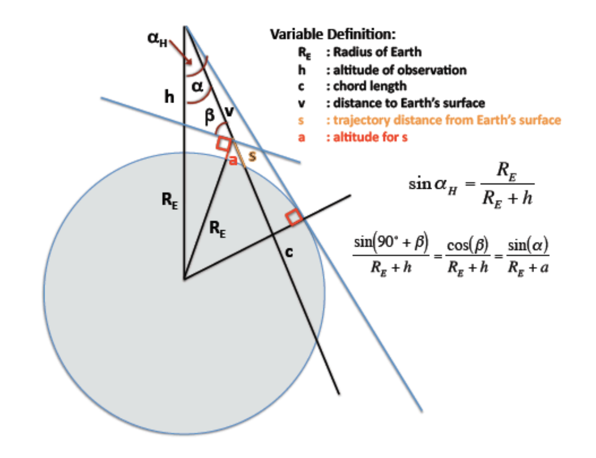
Short Bursts

Source Class	No. of ν's at GC	No. of ν's at 3 Mpc	Largest Distance for 1.0 ν per event	Model Reference
sGRB Extended Emission (moderate)	2.23×10^8	1.55×10^3	117.44 Mpc	KMMK [16]
sGRB Prompt	8.10×10^6	69.19	26.66 Mpc	KMMK [16]

(*) Not applicable due to mismatch with mass of SMBH at the GC and/or lack of blazar-like jet.

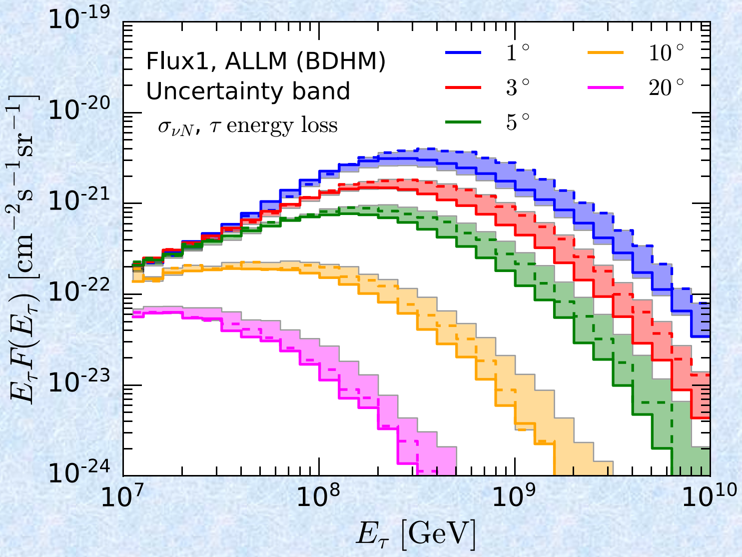
Bold: ≳20% Prob of an event in 5 years

POEMMA: upward τ-lepton EAS Cherenkov considerations

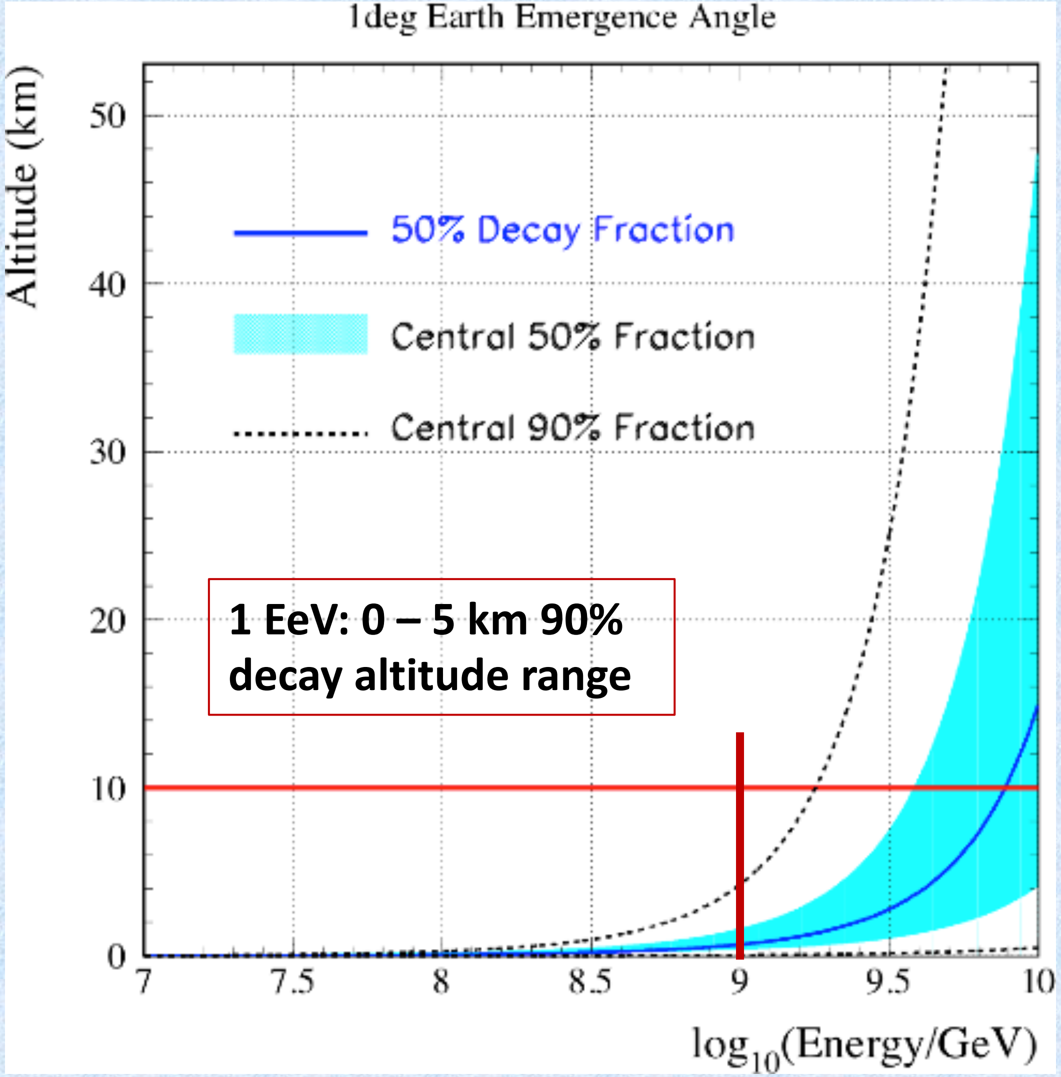


$\Delta\alpha$	β_E(33 km)	β_E(525 km)	β_E(1000 km)
1	3.6	7.0	8.2
2	5.2	10.0	11.7
3	6.6	12.3	14.5
4	7.9	14.4	16.9
5	9.1	16.2	19.0
6	10.3	18.0	21.0
7	11.4	19.6	22.8
8	12.6	21.2	24.6

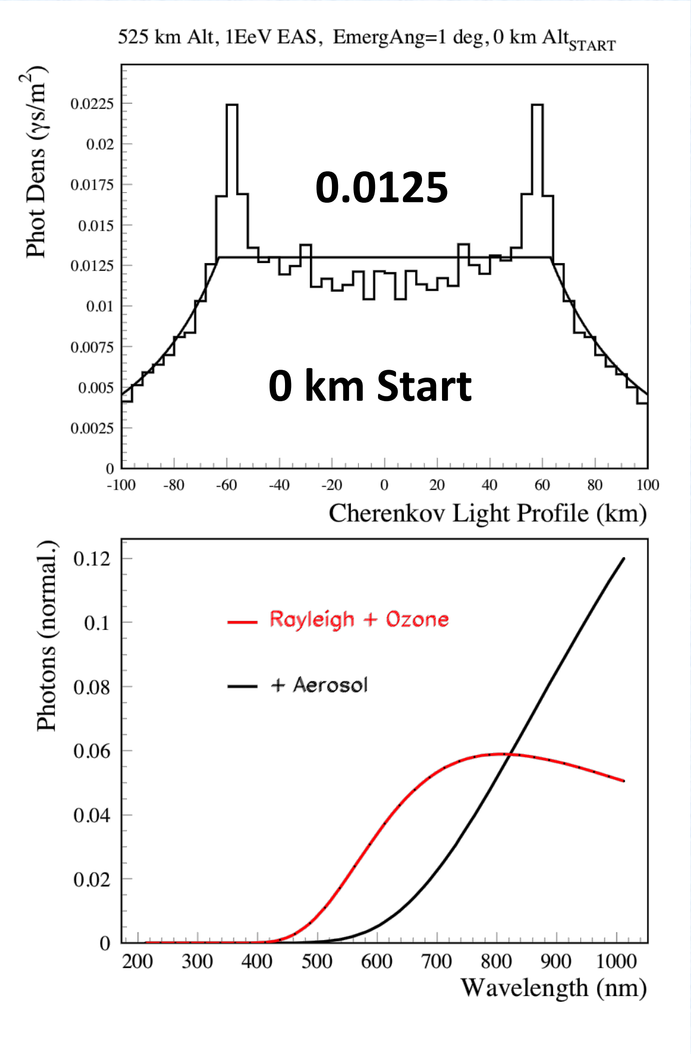
PhysRevD.100.063010 Fig. 12



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

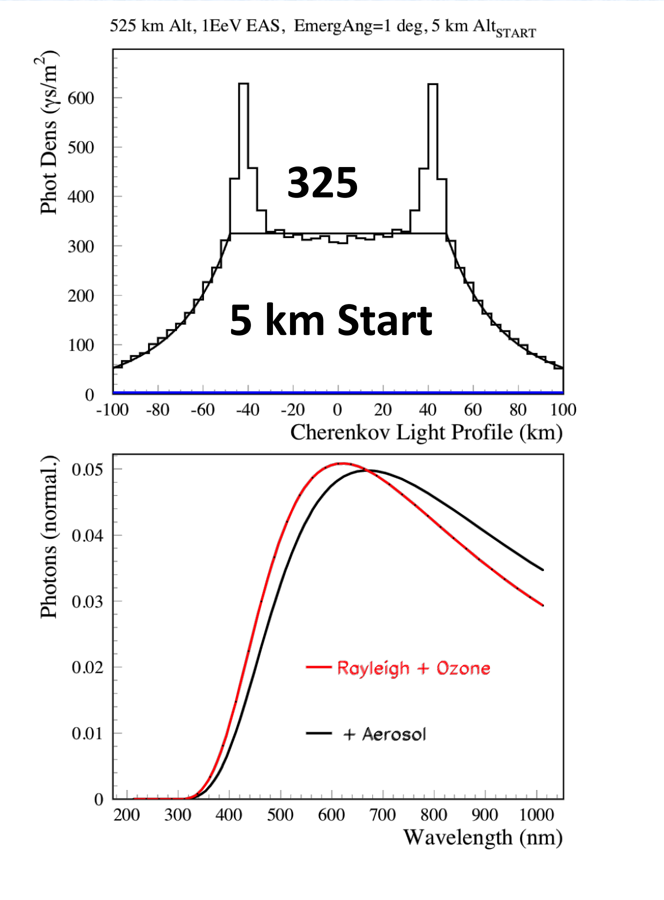


POEMMA: upward τ-lepton EAS Cherenkov spectrum variability

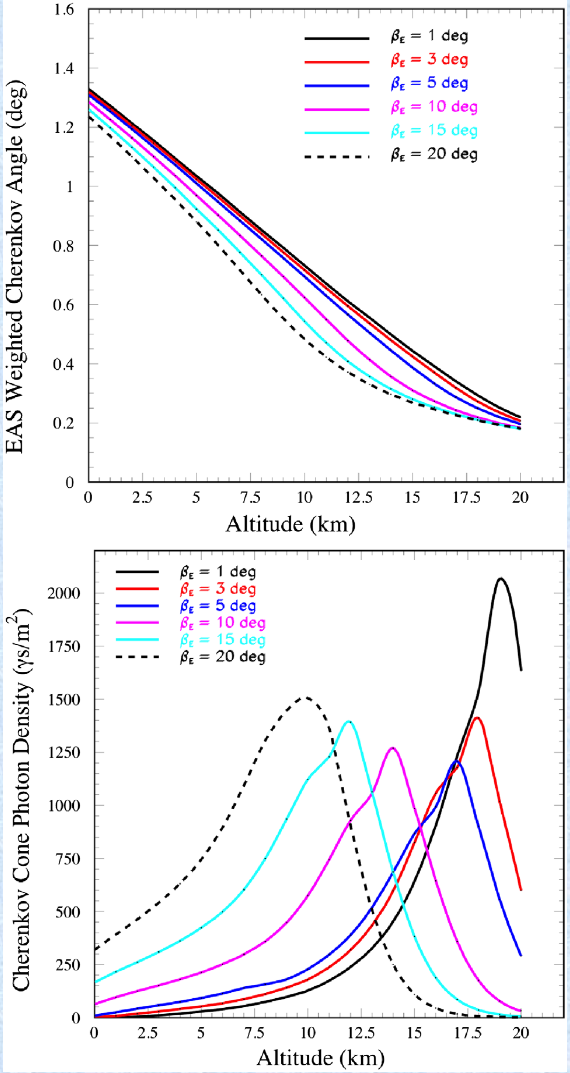


Atmospheric optical attenuation:

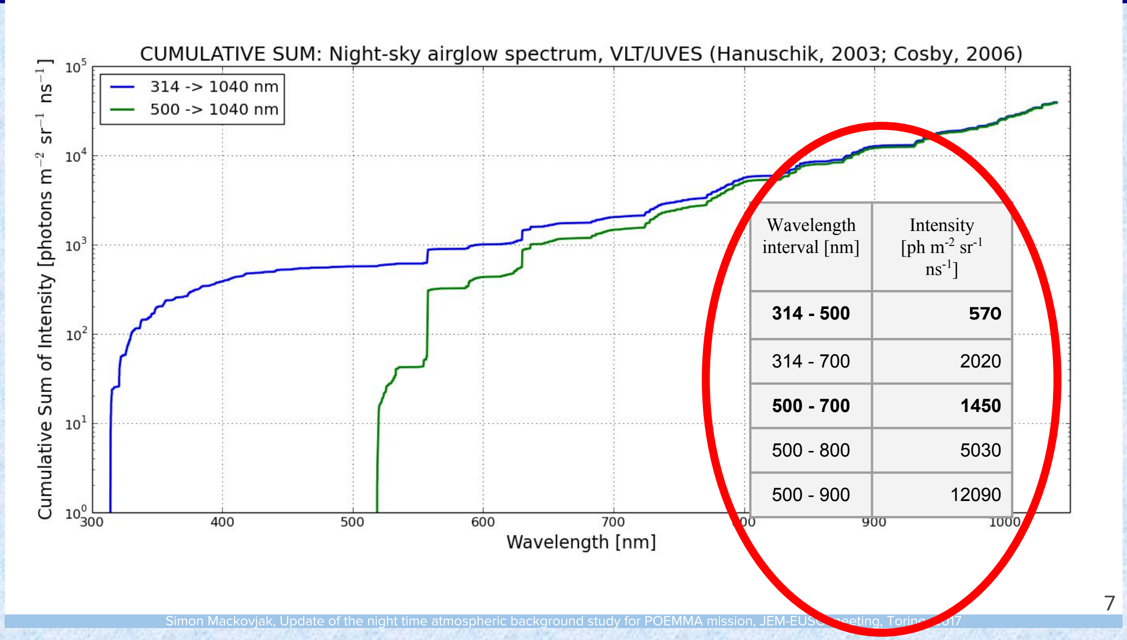
- **Rayleigh Scattering**
- **Aerosols (scale height ~ 1 km)**
- **Ozone (decimates signal ≲ 300 nm)**



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

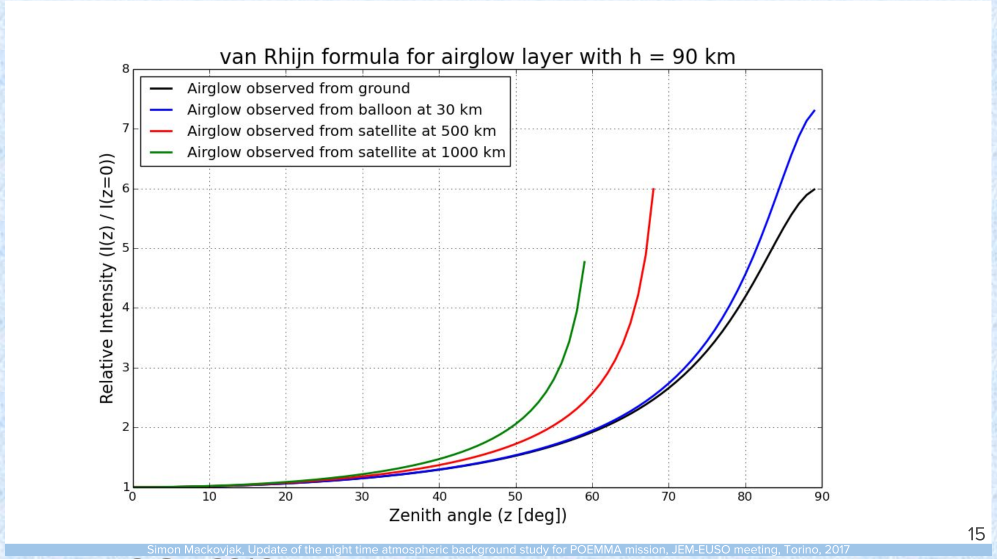
~25,000 photons/m²/sr/ns

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)**



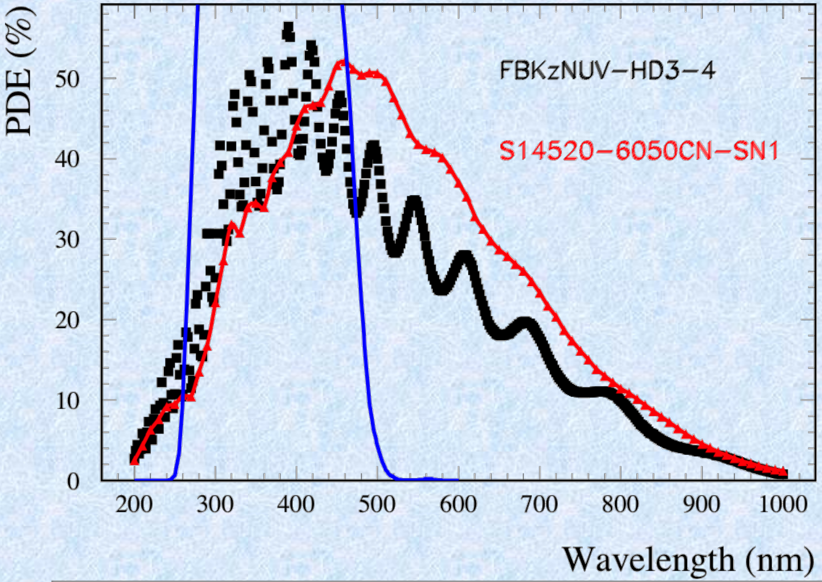
Viewing at angles away from nadir views more optical depth of air glow layer.

x6 for viewing limb from 500 km

Work by Simon Mackovjak

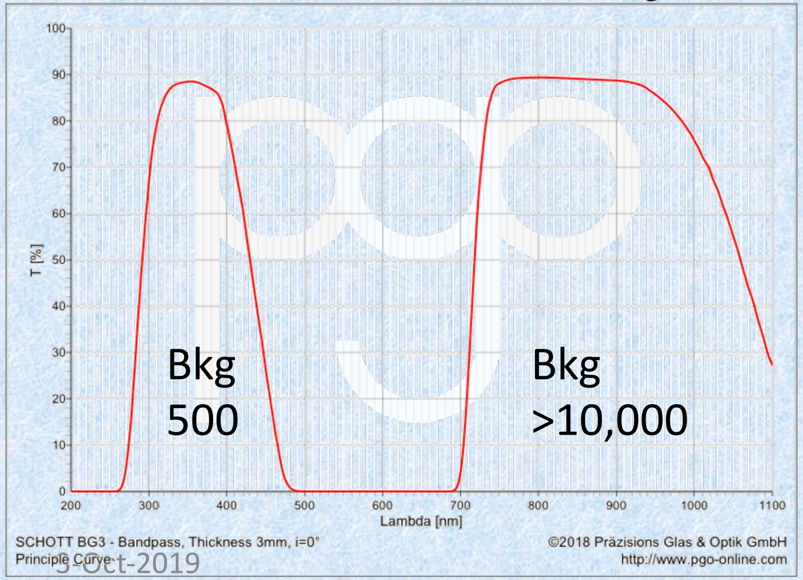
SiPMs now have high PDE in Fluorescence Band but …

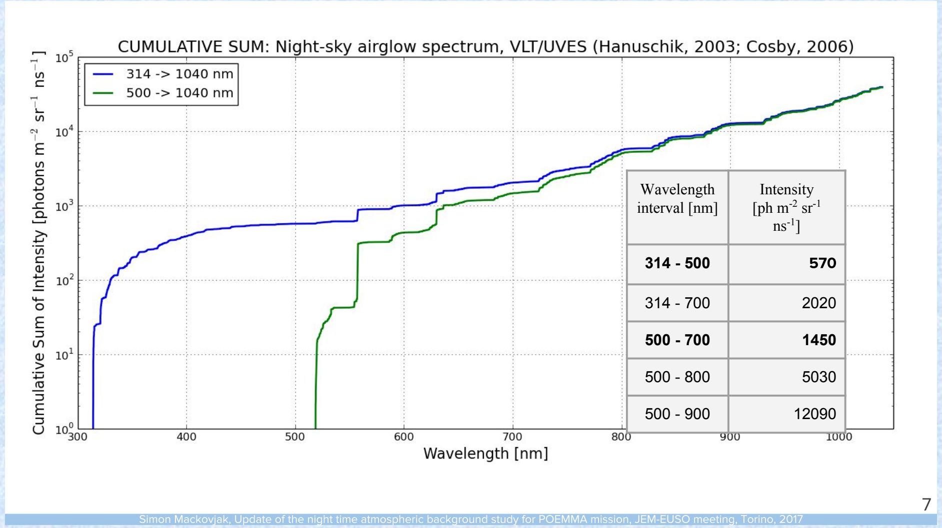
PDE results: Nepomuk Otte



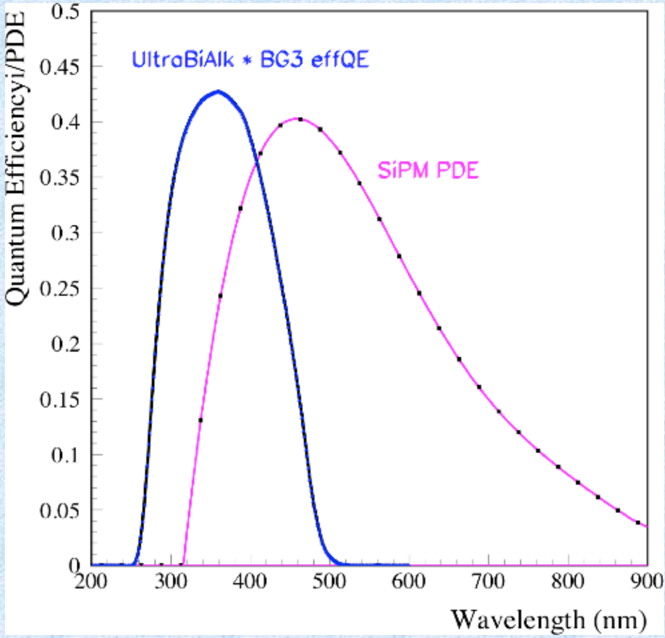
Nitrogen Fluorescence:

- λ band from < 300 nm → > 1000 nm
- Dominated by lines around 337.1, 357.7, 391.4 nm
- QE/PDE needs to be optimal in this band
- Use filter (usually BG3) to constrain wavelength band to reduce background from air glow
- Issue with this filter with transmission above 700 nm





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



Summary

- POEMMA will open two new Cosmic Windows:
  - Space-based measurements provides order of magnitudes improved sensitivity
  - UHECRS (> 20 EeV), to identify the source(s) of these extreme energy messengers
  - neutrinos from astrophysical Transients (> 20 PeV), and high sensitivity to UHE neutrinos (> 20 EeV)
- Neutrino τ-lepton induced Cherenkov signals span 300 nm $\leq \lambda \leq$ 1000 nm:
  - Wide spectral range of SiPM's and nsec time response critical in the detection
  - PE signal range: 10 PE to 10,000+
  - Advances in PDE improvements helpful
  - Large air glow background leads to high PE thresholds (for triggering and analysis)
- UHECR and UHE neutrino measurements *may* benefit for PDE improvement in fluorescence band
  - Huge air glow background and wide SiPM spectral requires additional constraints on UV filter
    - If leads to significant reduction if effective PDE, science affected via increased UHECR and UHE neutrino EAS energy thresholds
  - However, benefits do exist:
    - Lower mass for SiPMs vs PMTs, SiPMs do not require high voltage
    - Leads to mass savings … in Space MASS = COST!

Backup Slides

POEMMA: Diffuse neutrino flux sensitivity

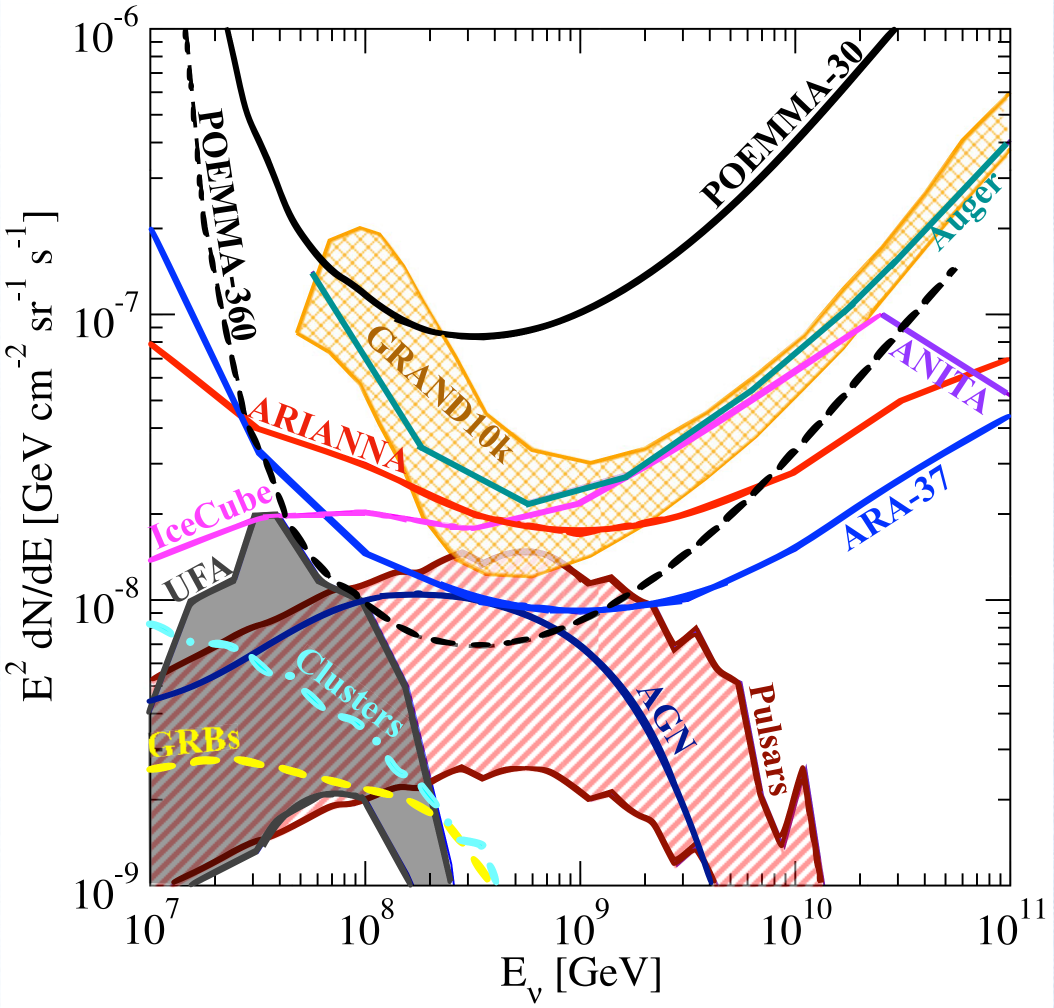
PhysRevD.100.063010 Fig. 22

All flavor Sensitivity Limit:

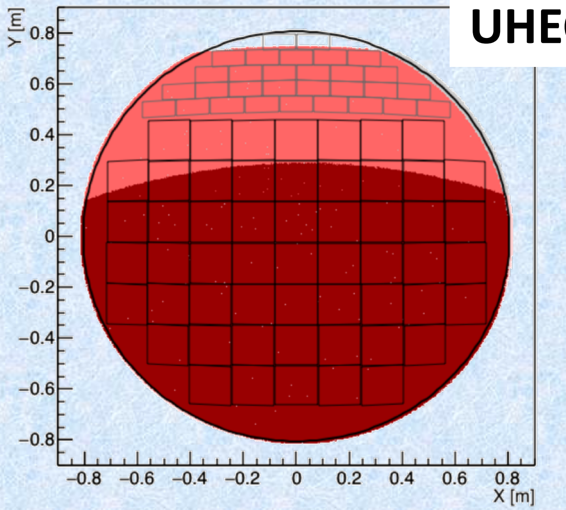
- 5 year
- 20% duty cycle
- 10 PE threshold with time coincidence to reduce air glow background 'false positives'
- 2.44 events/decade (90% CL)
- 17% hit for ignoring μ channel
- Viewing to 7° away from Limb (or to ~20° Earth Emergence Angle)

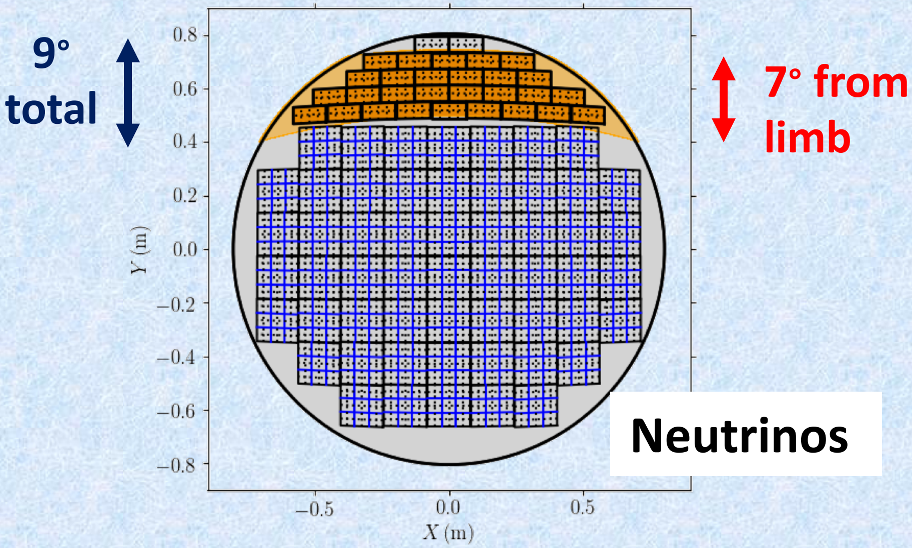
PhysRevD.100.063010 Fig. 12

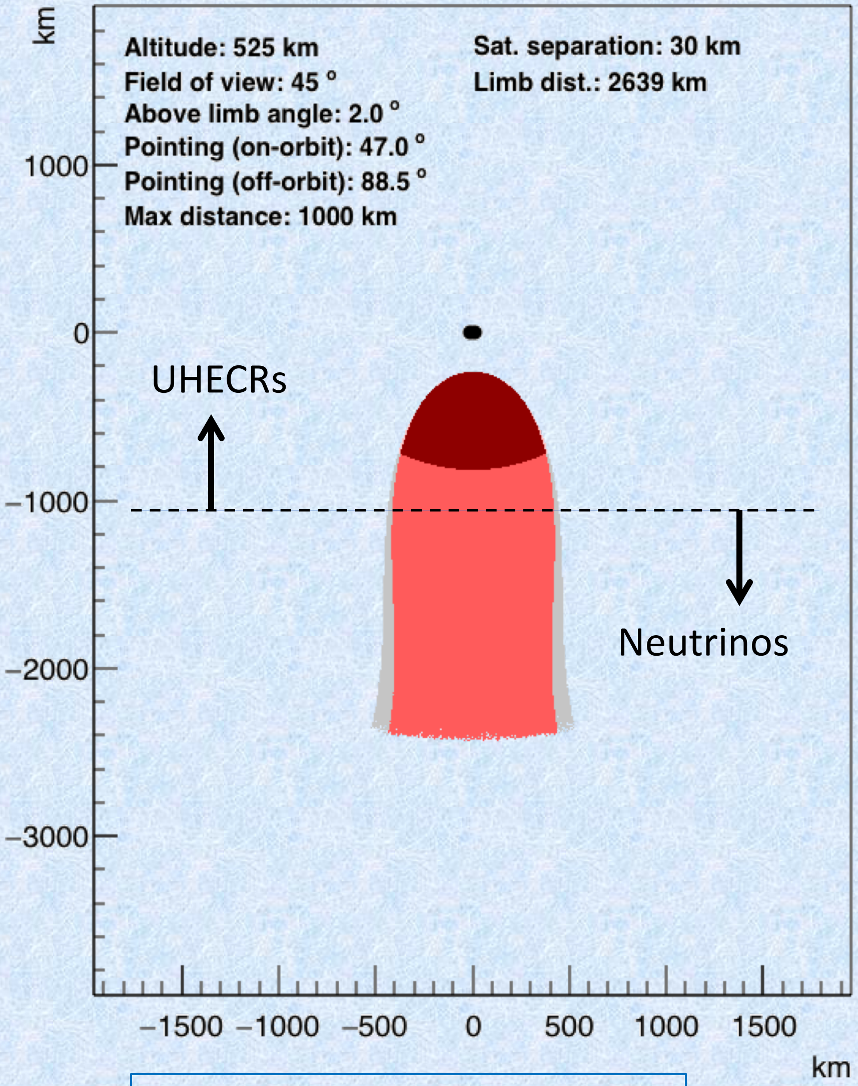
- $\nu_e : \nu_\mu : \nu_\tau = 1{:}1{:}1$



POEMMA: Neutrino mode example configuration







Calcs & plots by F. Sarazin

POEMMA: anomalous ANITA upward EAS

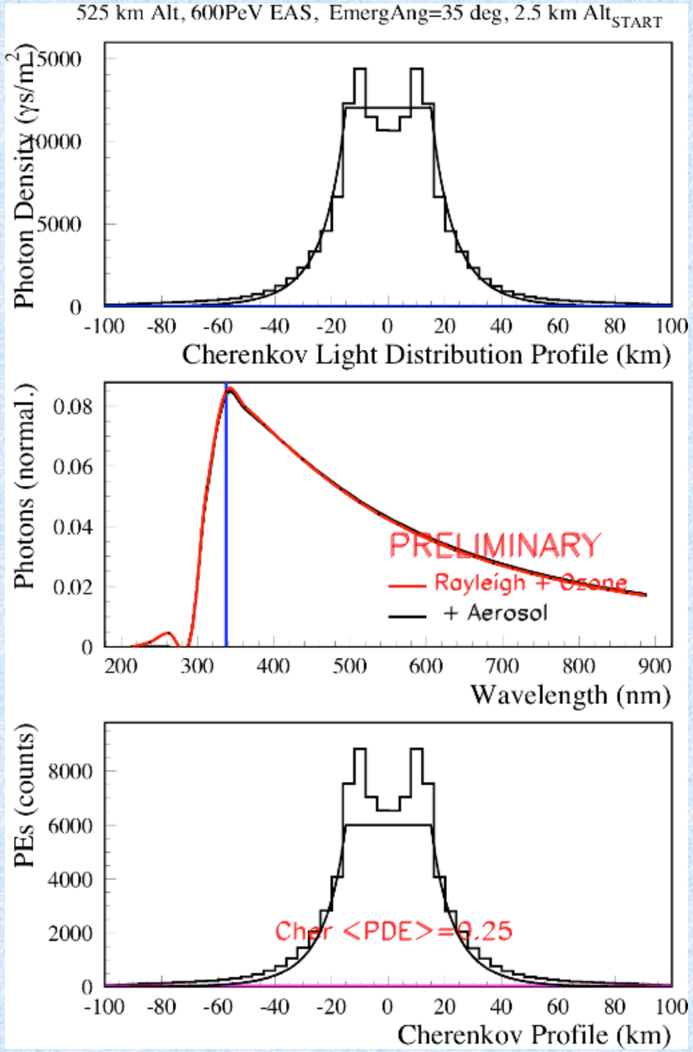
arXiv:1803.05088v1

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.	$-27.4\pm0.3°, 159.62\pm0.7°$	$-35.0\pm0.3°, 61.41\pm0.7°$
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
ω ≈ 1.e-3 sr

θ_{EFF} ≈ 4.5 deg
ω ≈ 2.e-2 sr

τ-lepton
γcτ ~ 60 km
for 1.2 EeV

POEMMA signal size ~6000 PEs in cone

GF's similar (~200 km² sr): 2 events/70 days (ANITA 1-3) -> ~2 events per year for POEMMA