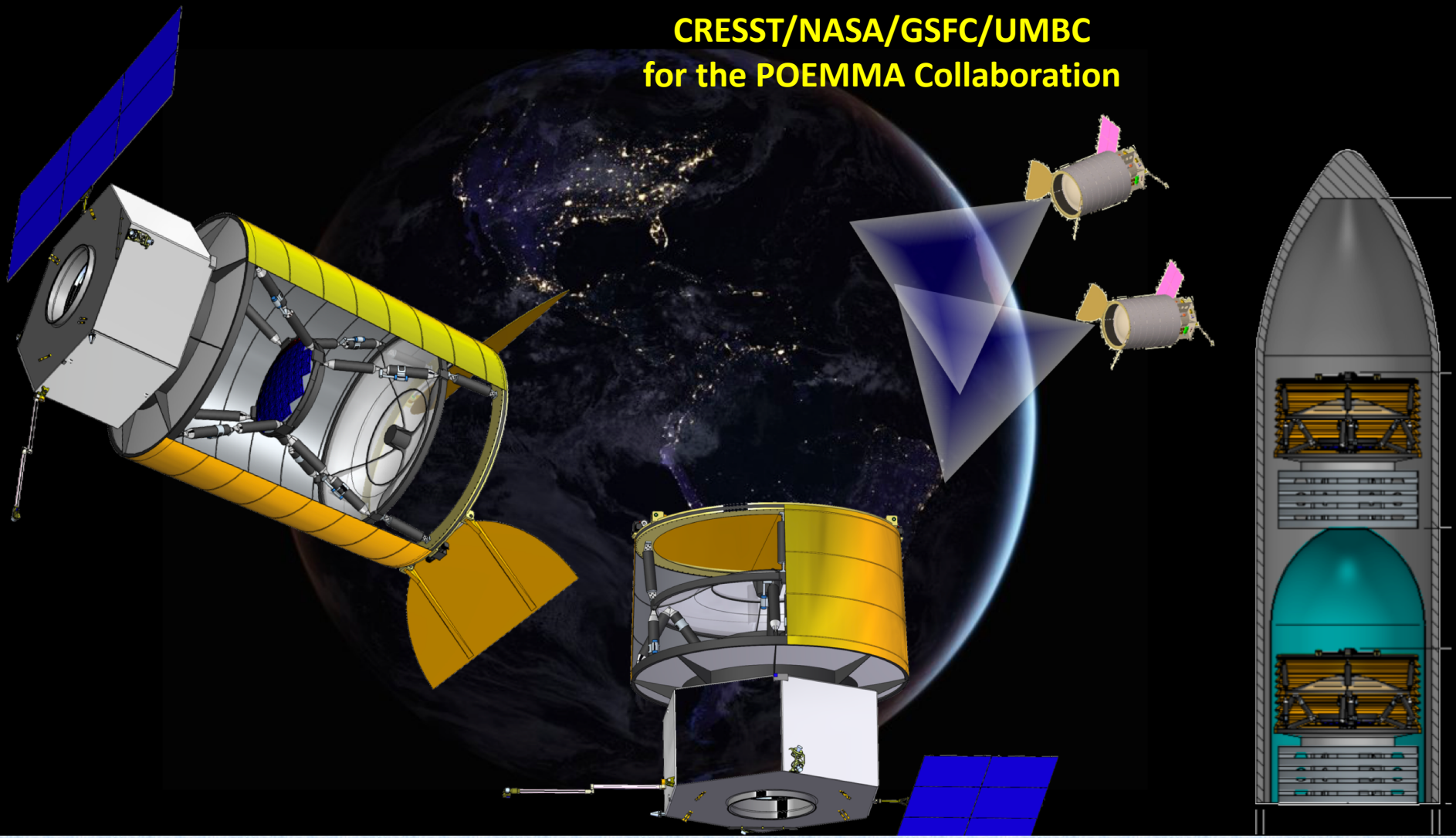
POEMMA

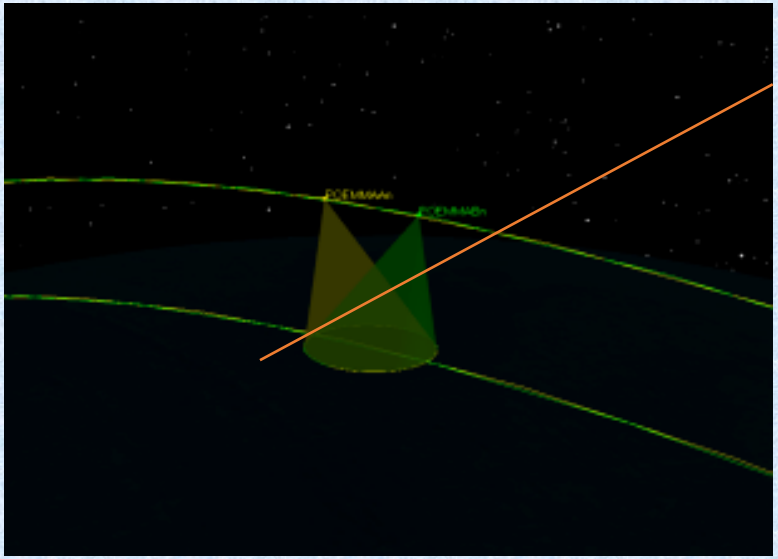
Probe of Extreme Multi-Messenger Astrophysics:

CRs and Neutrinos

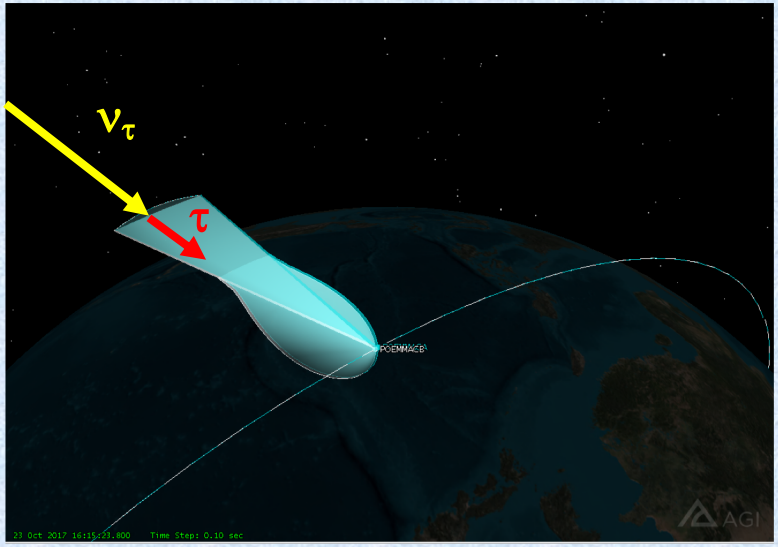
John Krizmanic
CRESST/NASA/GSFC/UMBC
for the POEMMA Collaboration



Outline



Stereo Viewing of UHECRs E ≳ 40 EeV



Upward τ-lepton EAS E ≳ 25 PeV

1. Introduction/Overview of study.
2. Instrument description.
3. Mission description.
4. Initial UHECR performance.
5. Initial tau neutrino sensitivity calculations and results.
6. Closing remarks.

NASA Astrophysics Probe Mission Concept Studies

***NASA Solicitation NNH16ZDA001N-APROBES* (Scope of Program):**

Announced: 19-Feb-16 ***Due Date: 15-Nov-16*** ***Selection: 17-Mar-17***

NASA has started preparations for the 2020 Astronomy and Astrophysics Decadal Survey (http://science.nasa.gov/astrophysics/2020-decadal-survey-planning/). One of the tasks of the 2020 Decadal Survey Committee will be to recommend a portfolio of astrophysics missions. The Decadal Survey Committee may choose to recommend a portfolio of missions containing a mix of prioritized large- and medium-size mission concepts, or even a program of competed medium-size missions. NASA and the community are interested in providing appropriate input to the 2020 Decadal Survey regarding medium-size mission concepts, also referred to as Astrophysics Probe concepts.

To this end, NASA is soliciting proposals to conduct mission concept studies for Astrophysics Probe missions. Following peer review of the proposed mission concept studies, NASA will select a small number of proposals for 1.5 year (18 month) funded studies. Results of the selected studies will be provided by NASA as input to the 2020 Decadal Survey.

Astrophysics Probes are envisioned to have a total lifecycle (NASA Phases A through E) cost between that of a MIDEX mission (~$400M) and ~$1B. Proposals for concept studies may envision missions that include contributions from other agencies (national or international), industry, and universities.

Should NASA choose to develop a mission that flows from any selected mission concept study, the responsibility for that mission will be assigned by NASA; there is no expectation that the mission concept study team or participating organization.

Specific instructions for a NASA Class B mission definition, eg launch date, costing, …
Funded instrument definition, eg IDL, and mission definition, eg MDL, studies
FINAL REPORT IN PREPARATION

POEMMA: study collaboration

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

NASA/MSFC: Mark J. Christl (Deputy PI), Roy M. Young, Peter Bertone, Jeff Apple, Gary Thornton, Brent Knight, Kurt Dietz, Mohammad Sabra

University of Alabama, Huntsville: James Adams, Patrick Reardon, Evgeny Kuznetsov, J. Watts Jr., J. Tubbs, M. Mastafa, NASA/GSFC: John W. Mitchell, John Krizmanic, Tonia Venters, Jeremy S Perkins, Julie McEnery, Elizabeth Hays, Floyd Stecker, Stan Hunter, Jonathan Ormes, Robert Streitmatter

University of Utah: Doug Bergman, John Matthews

Colorado School of Mines: Lawrence Wiencke, Frederic Sarazin

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

Georgia Institute of Technology: A. Nepomuk Otte

Space Sciences Laboratory, University of California, Berkeley: Eleanor Judd

University of Iowa: Mary Hall Reno

Jet Propulsion Laboratory: Insoo Jun, L. M. Martinez-Sierra

Vanderbilt University: Steven E Csorna

APC Univerite de Paris 7: Etienne Parizot, Guillaume Prevot

Universita di Torino: Mario Edoardo Bertaina, Francesco Fenu, Kenji Shinozaki

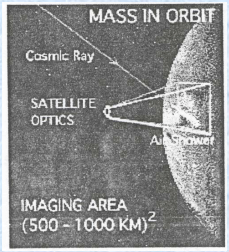
University of Geneva: Andrii Neronov

Gran Sasso Science Institute: Roberto Aloisio

Scientists from 16+ institutions from
OWL, JEM-EUSO, Auger, TA, Veritas, CTA, Fermi, Theory

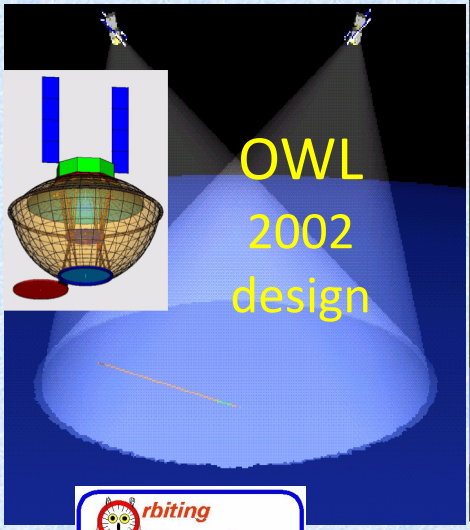
POEMMA: Heritage

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

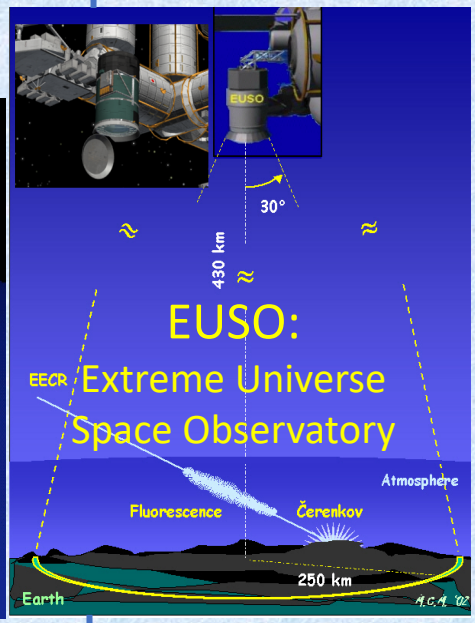


OWL AIRWATCH

TUS, KLYPVE-EUSO

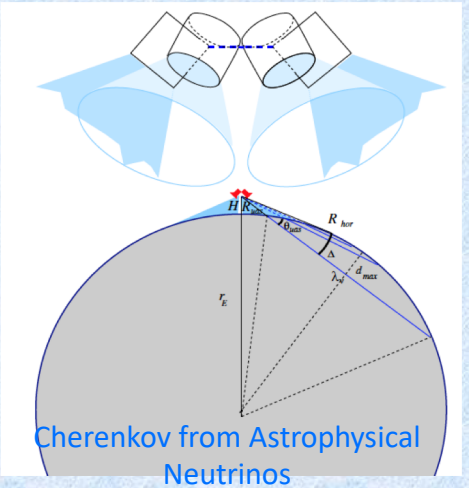


Orbiting Wide-angle Light-collectors





CHANT



Cherenkov from Astrophysical Neutrinos Telescope

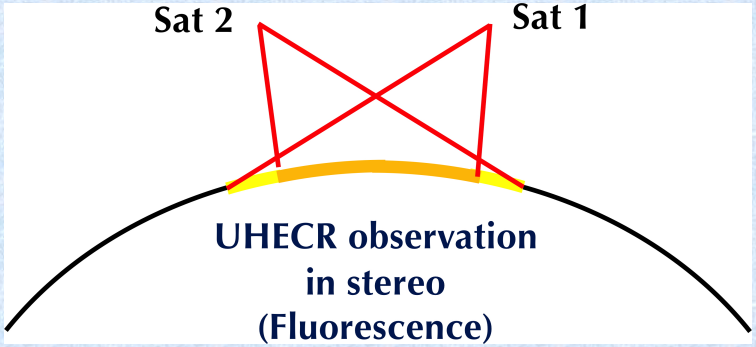
EUSO-Balloon
EUSO@TA
Mini-EUSO

EUSO-SPB2

POEMMA: UHECR and Neutrino Observation Modes

Stereo mode air fluorescence UHECR observation:

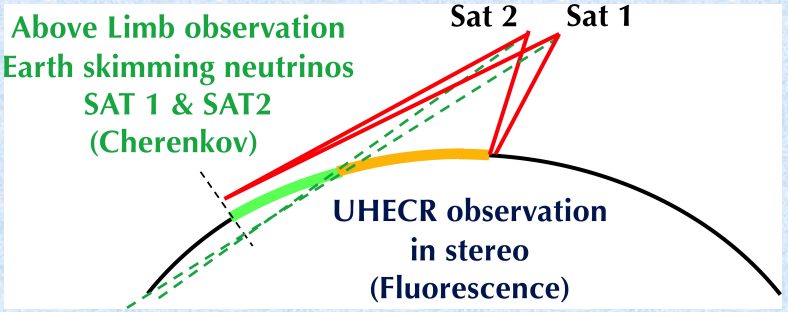
- Achieve significant increase in exposure via space-based observations (x10 arrays; x100 fluorescence) with full-sky coverage
- Achieve good angular and energy resolution
- Achieve sufficient X_{MAX} resolution to perform UHECR composition measurements
- UHE ν interactions in atmosphere, deeper in atmosphere (if sufficient flux)



Satellite Separation ~300 km
Maximize GF; Minimize E_{Thres}

Limb-viewing mode air fluorescence UHECRs:

- Achieve significant increase in exposure via space-based observations with full-sky coverage, *but at higher energy scales*
- Good energy resolution, angular resolution suffers
- X_{MAX} resolution degraded as well and low event statistics, *if no post-GZK recovery*

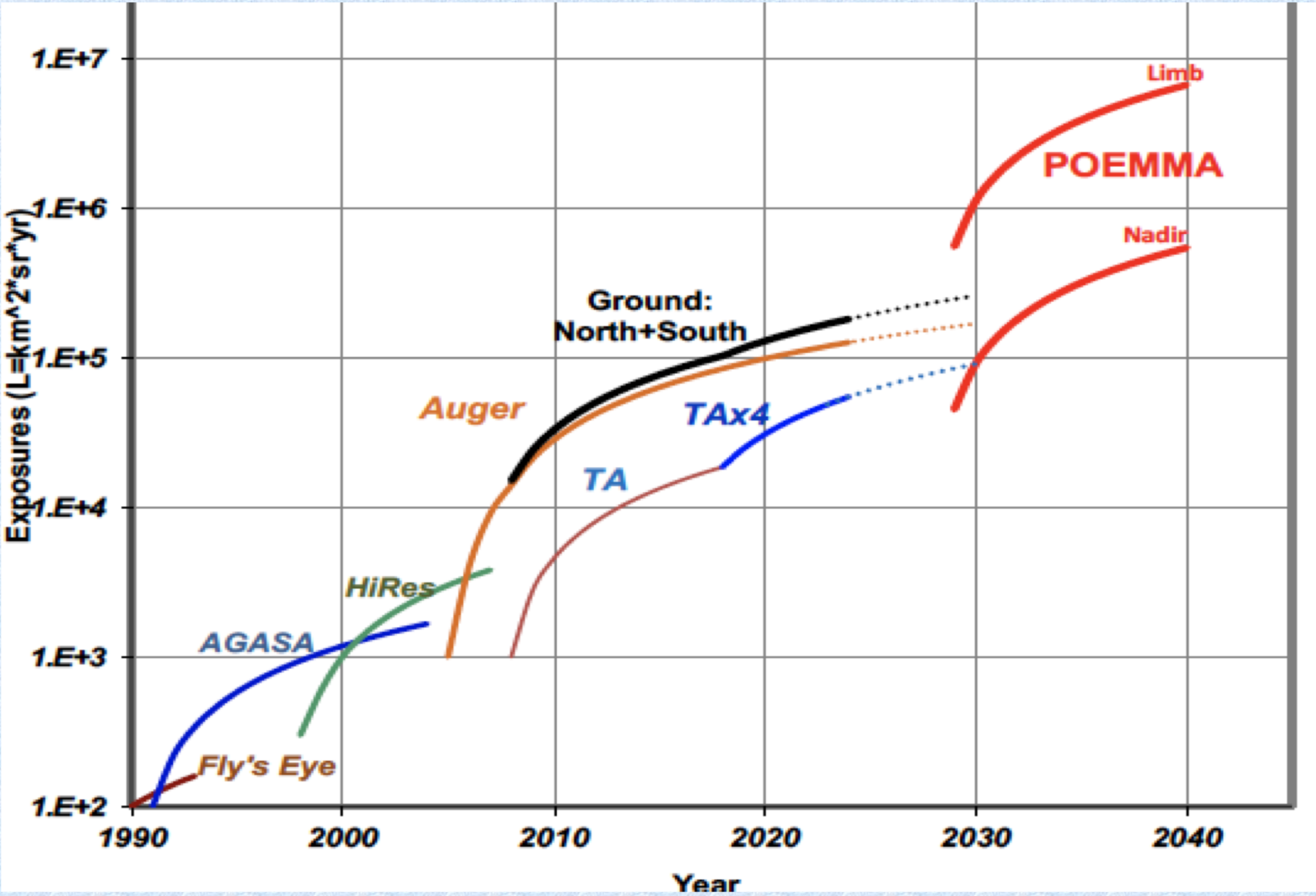


Limb-viewing mode Cherenkov upward tau-lepton EAS:

- Use Earth as ν_τ converter
- View near Earth limb for good HE acceptance
- Beamed Cherenkov signal allows for energy threshold ~ few 10 PeV.
- Target-of-Opportunity mode if receive a transient alert

Satellite Separation ~30 km
Both in Cherenkov light pool

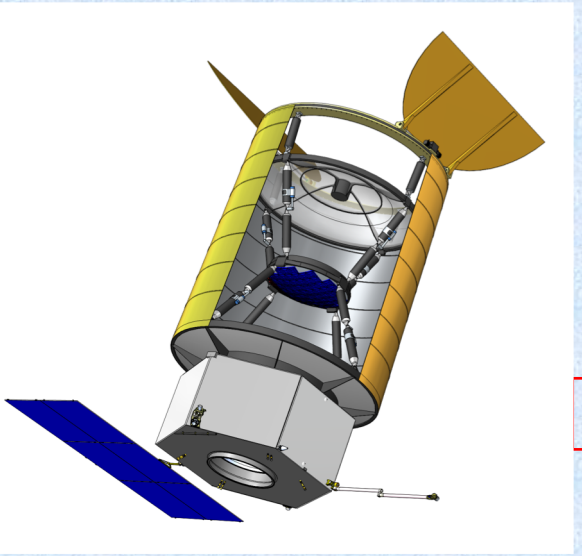
POEMMA: Exposure History



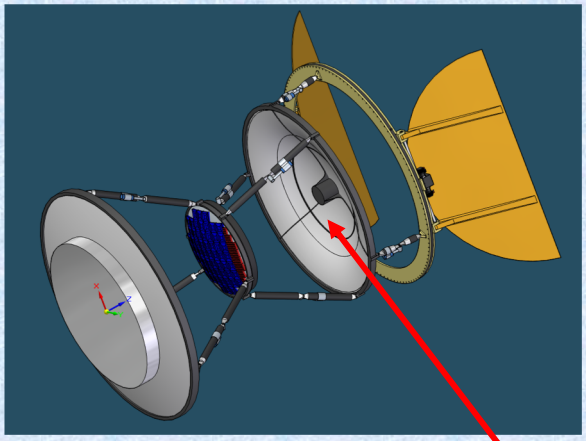
POEMMA: Instruments

Two 4 meter F/0.64 Schmidt telescopes: 45° FoV
Hybrid focal surface (MAPMTs and SiPM)
3 mm linear pixel size: 0.084 ° FoV

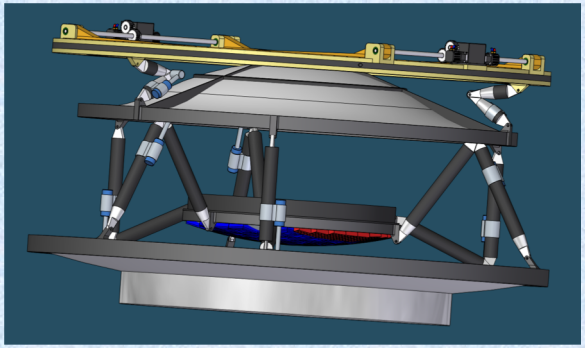
Instrument Mass:	1,550 kg
Primary Mirror:	4 meter diameter
Corrector Lens:	3.3 meter diameter
Focal Surface:	1.6 meter diameter
Optical Area$_{EFF}$:	~6 to 2 m^2
Instrument Power:	590 W
Science Data:	~1 GB/day



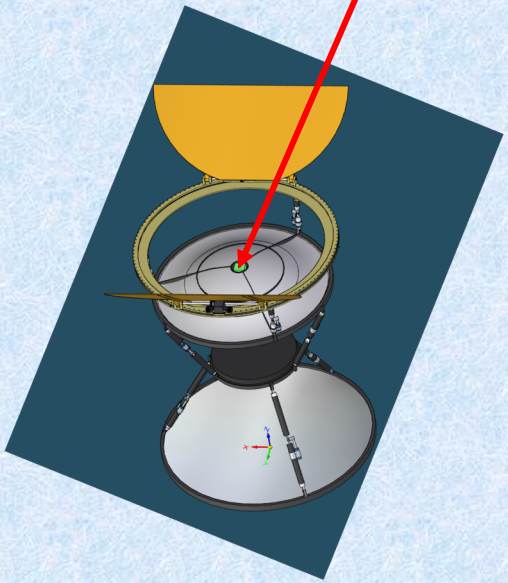
IR Camera



Calibration LEDs

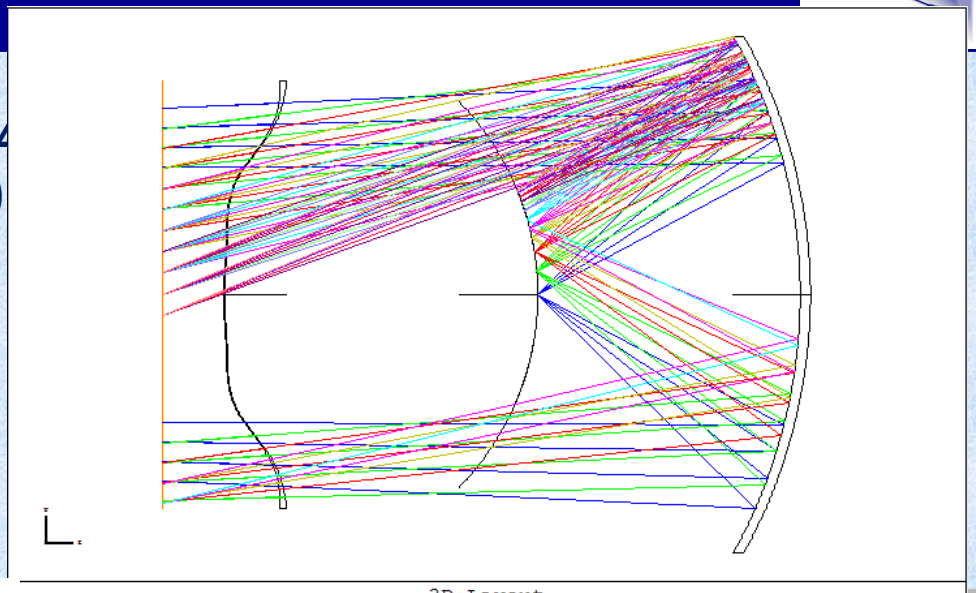


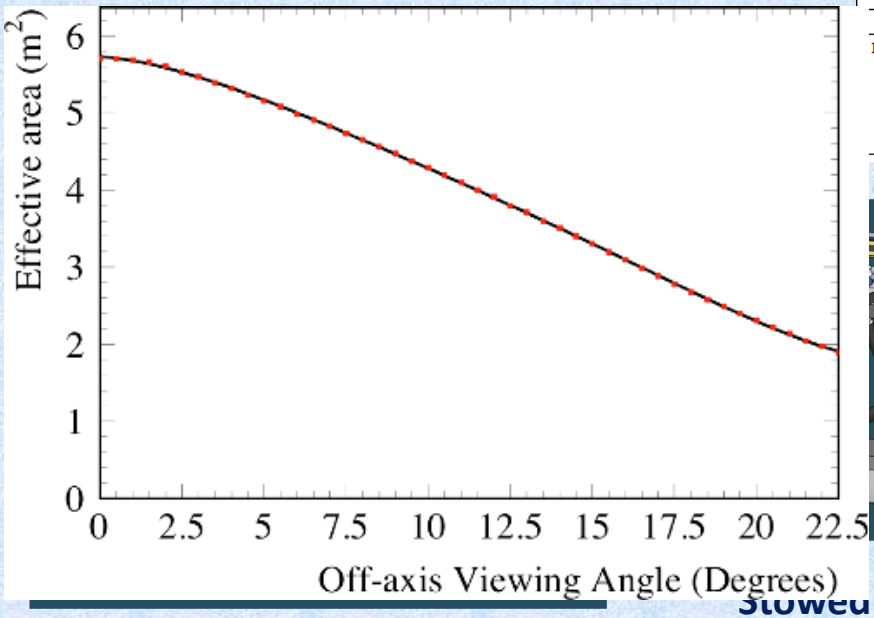
Stowed Configuration Launch

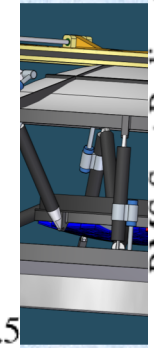


POEMMA: Optics Details

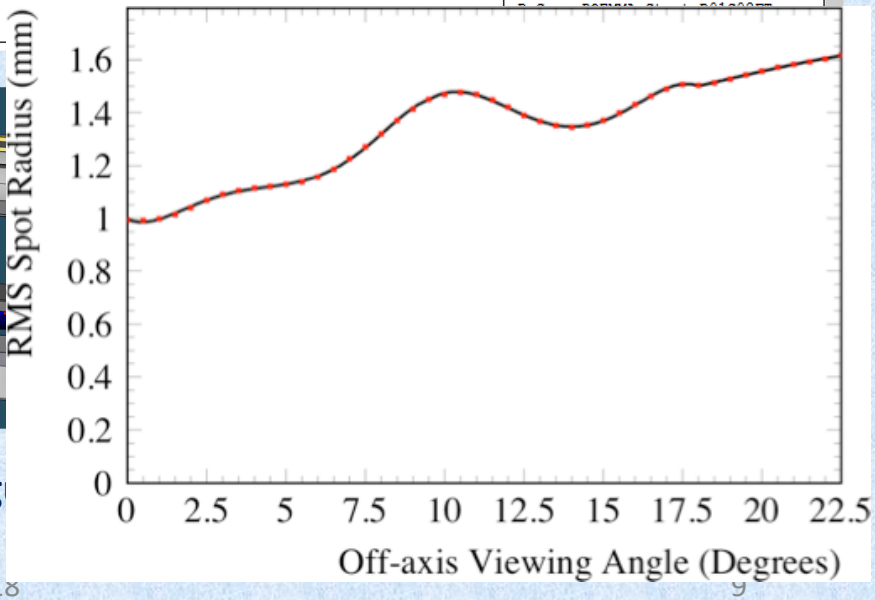
Two 4 meter F/0.64 Schmidt telescopes: 4
Hybrid focal surface (MAPMTs and SiPM)
3 mm linear pixel size: 0.084° FoV
Instrument Mass: 1,550 kg
Primary Mirror: 4 meter diameter
Corrector Lens: 3.3 meter diameter
Focal Surface: 1.6 meter diameter
Optical Area$_{EFF}$: ~6 to 2 m^2





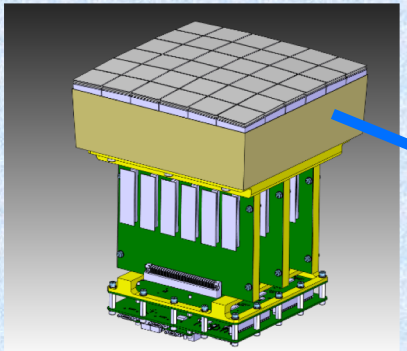


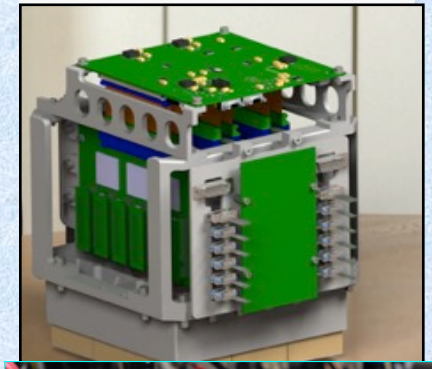
Stowed Config

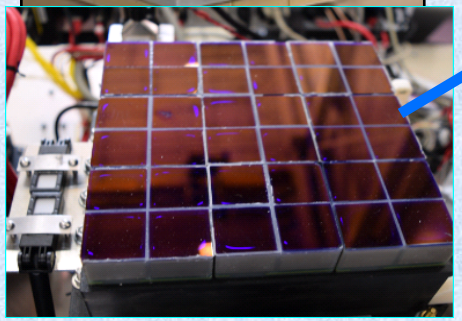


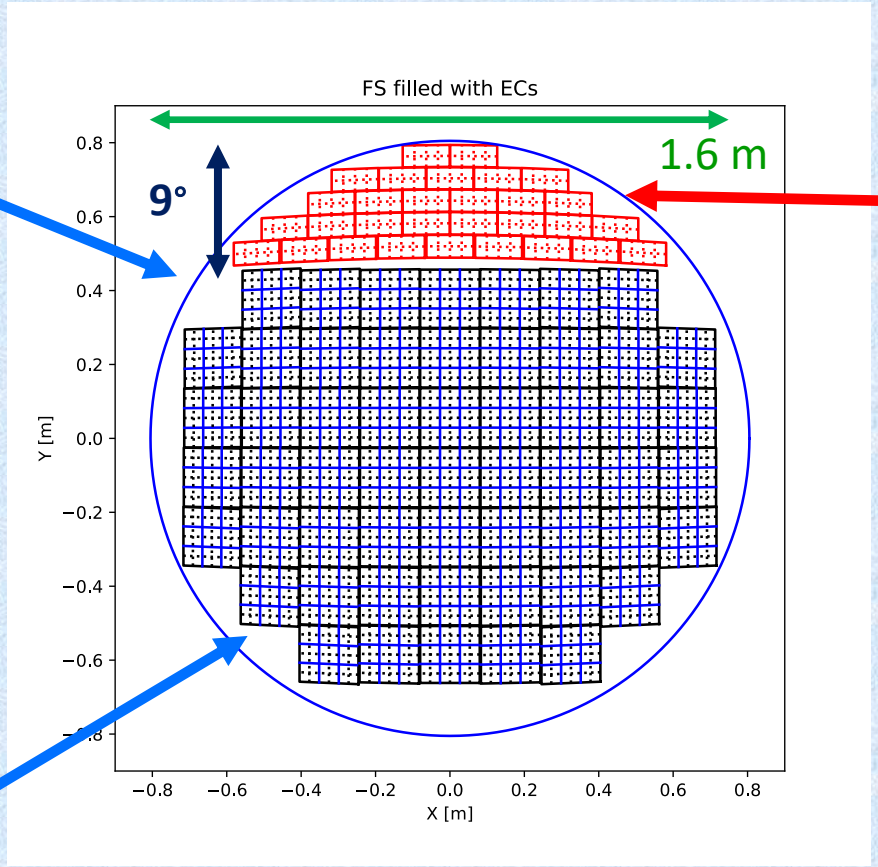
POEMMA: Hybrid Focal Plane

UV Fluorescence Detection using MAPMTs with BG3 filter: developed by JEM-EUSO: 1 usec sampling

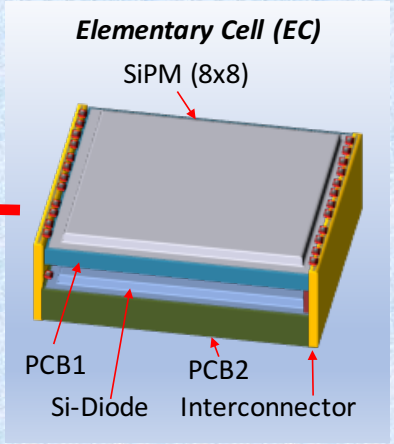








Cherenkov Detection with SiPMs: 20 nsec sampling



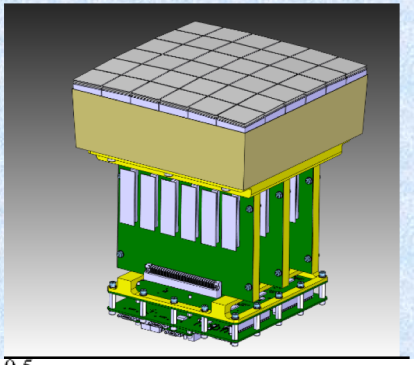
30 SiPM focal surface units
Total 15,360 pixels
512 pixels per FSU (64x4x2)
Si-Diode for LEO radiation backgrounds rejection

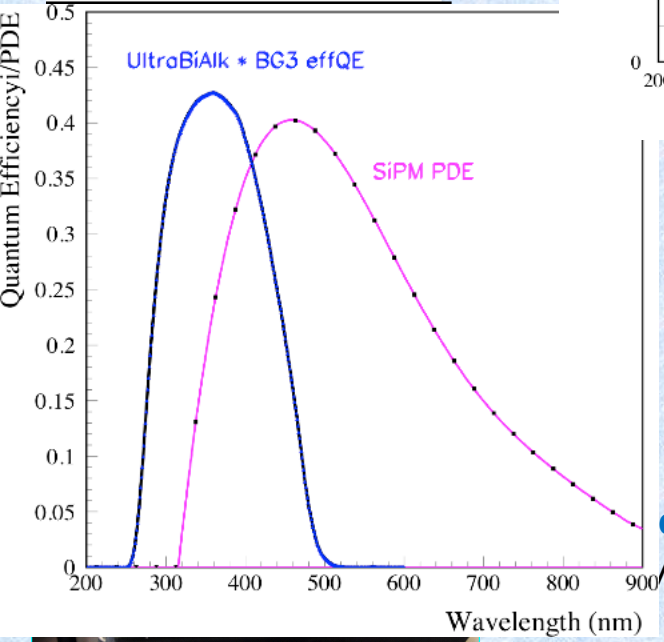
55 Photo Detector Modules (PDMs)= 126,720 pixels

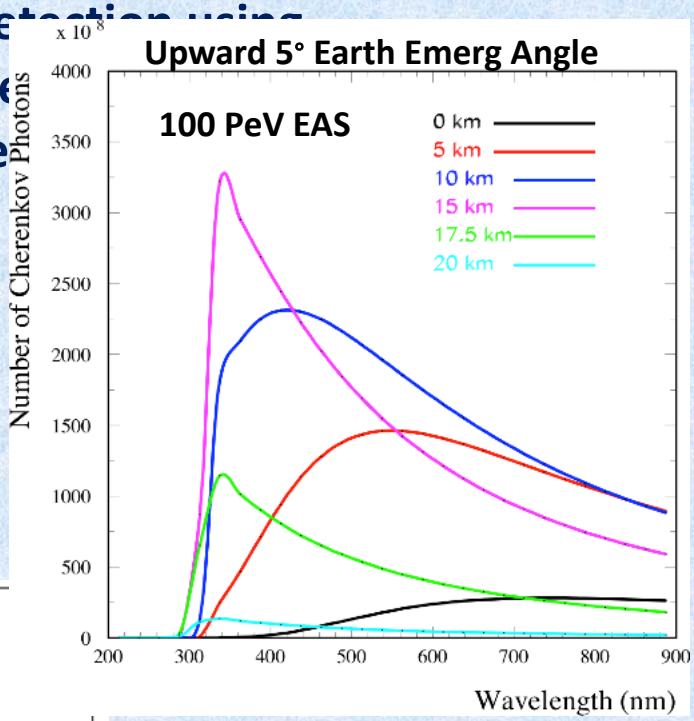
1 PDM = 36 MAPMTs = 2,304 pixels

POEMMA: Hybrid Focal Wavelength & Timing Response

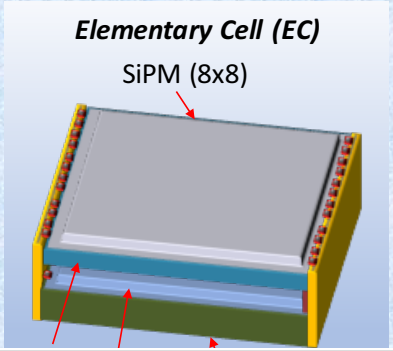
UV Fluorescence Detection using MAPMTs with BG3 filte
JEM-EUSO: 1 use

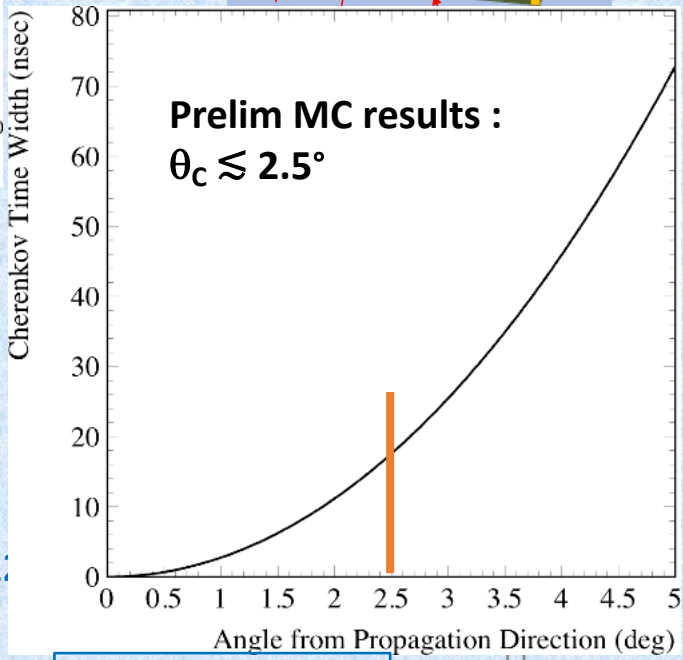






Cherenkov Detection with SiPMs: 20 nsec sampling





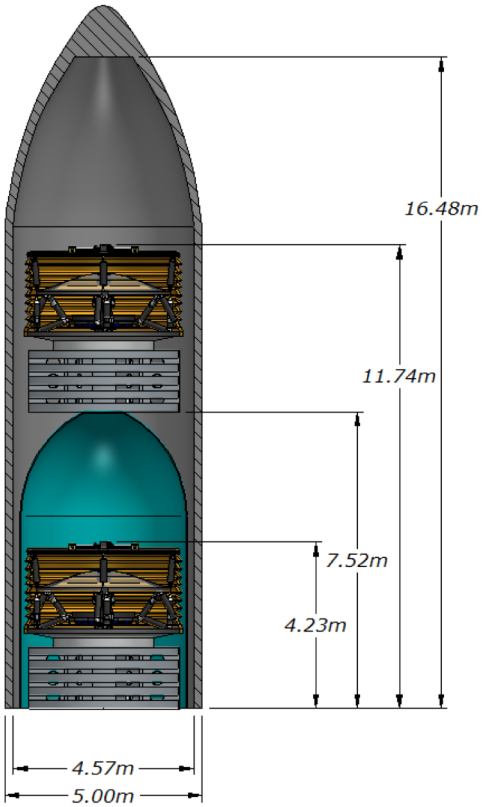
oto Detector Modules (PDMs)= 1

M = 36 MAPMTs = 2,304 pixels

Calc by D. Bergman

POEMMA: Mission

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:	2030 W
Data:	1 GB/day
Data Storage:	7 days
Communication:	S-band (X-band if needed)
Clock synch (timing):	10 nsec



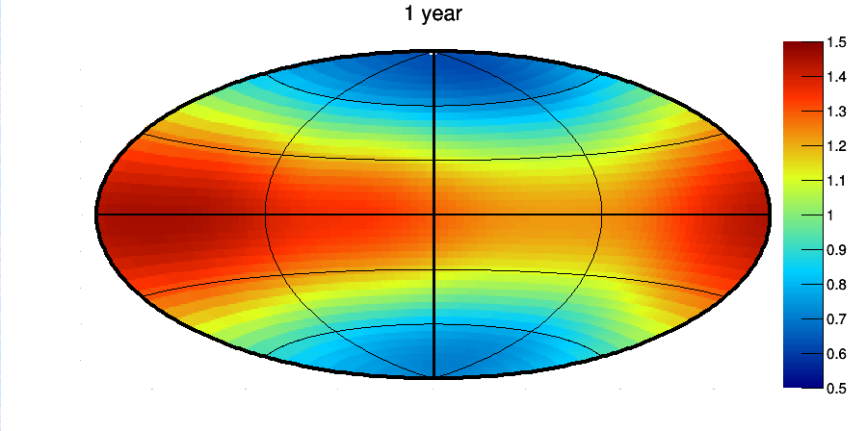
Dual Manifest Atlas V

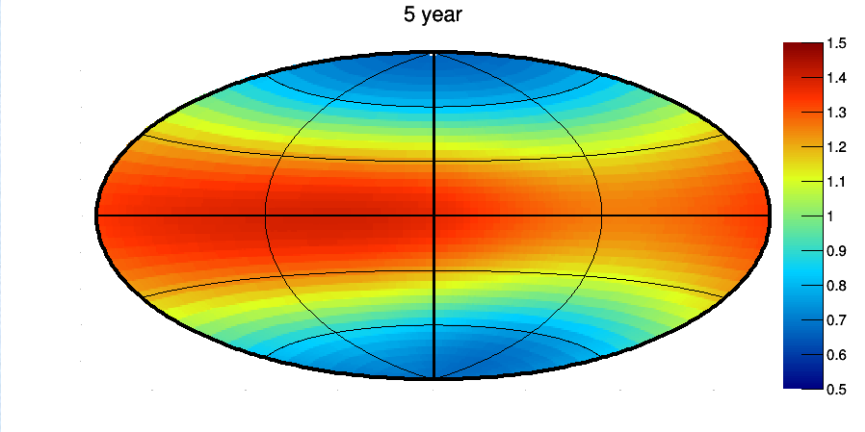
Operations:

- 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 and Neutrino Sky Coverage

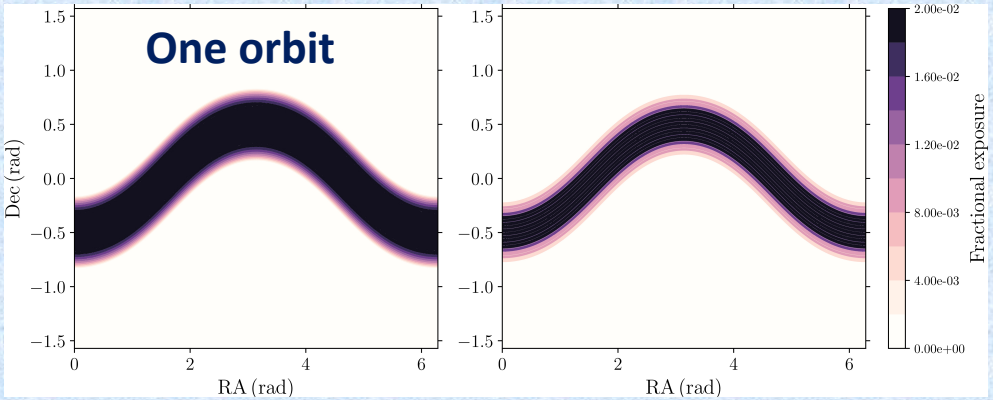
UHECR Stereo Mode



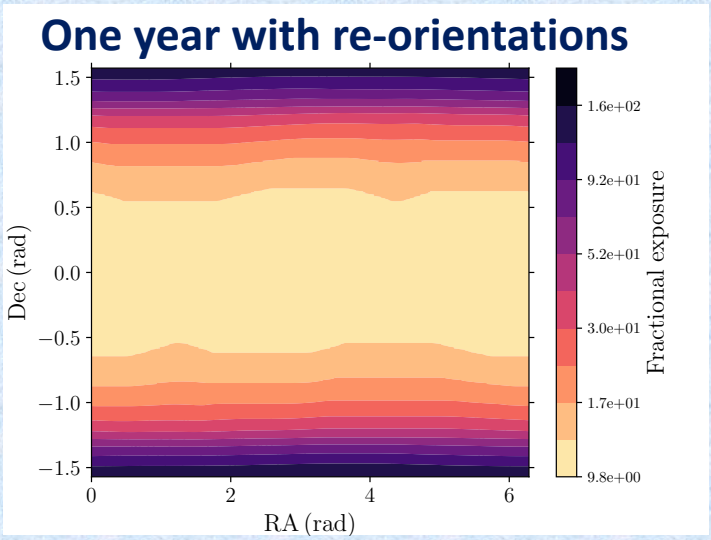


Calcs & plots by K. Shinozaki

Neutrino Mode: SiPM part of focal plane



One year with re-orientations



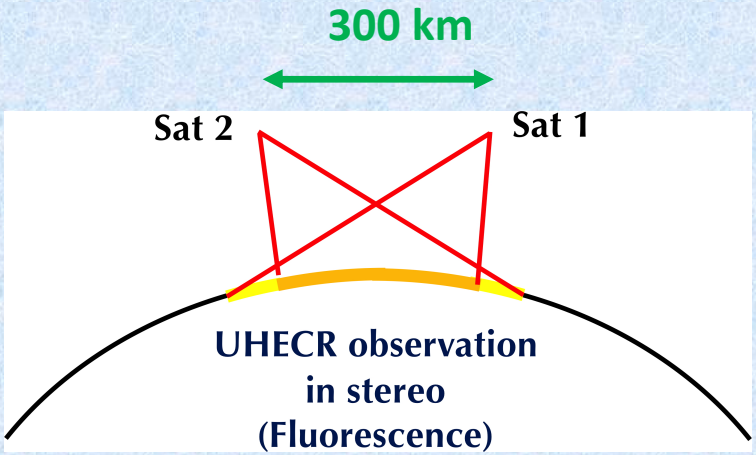
Calcs & plots by C. Guépin & F. Sarazin

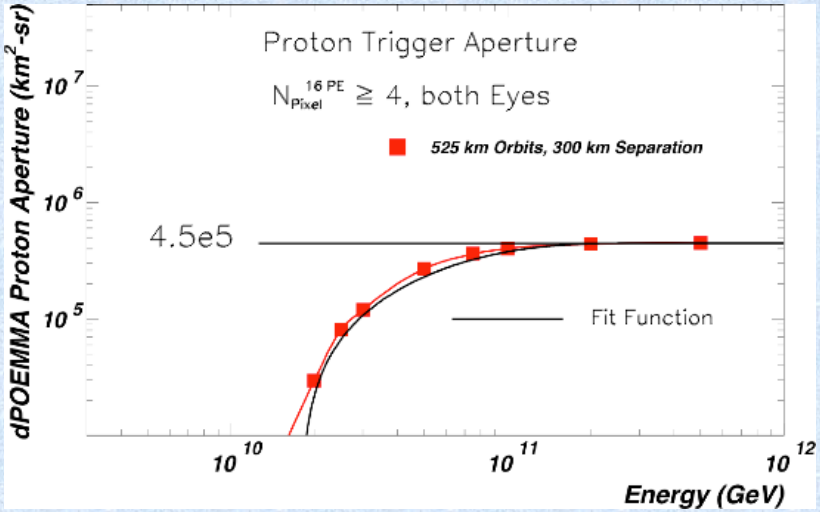
Paper in preparation

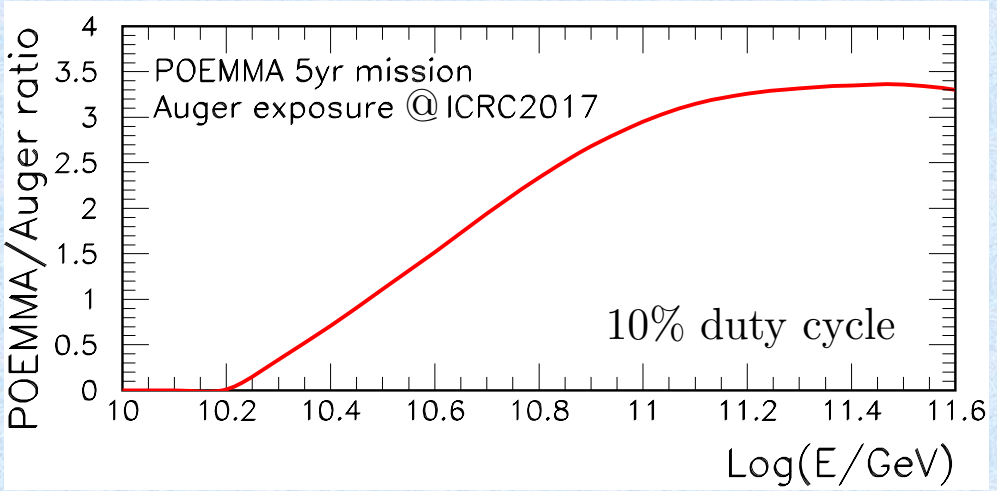
POEMMA: Preliminary Stereo UHECR Performance

POEMMA Parameterized Optics implemented in updated OWL simulation:

- 3 mm pixels, uniform layout
- uBiAlkali PMT QE: λ dependence w/~40% at peak
- Int time 1 usec
- 90% factor to account for SiPM area
- 500 photons/nsec/m²/sr background used to set MC trigger threshold: < 1 kHz focal plane rate (matches well to ESAF results for nadir pointing)
- Trigger requires same trigger in each satellite
- Duty cycle 10%

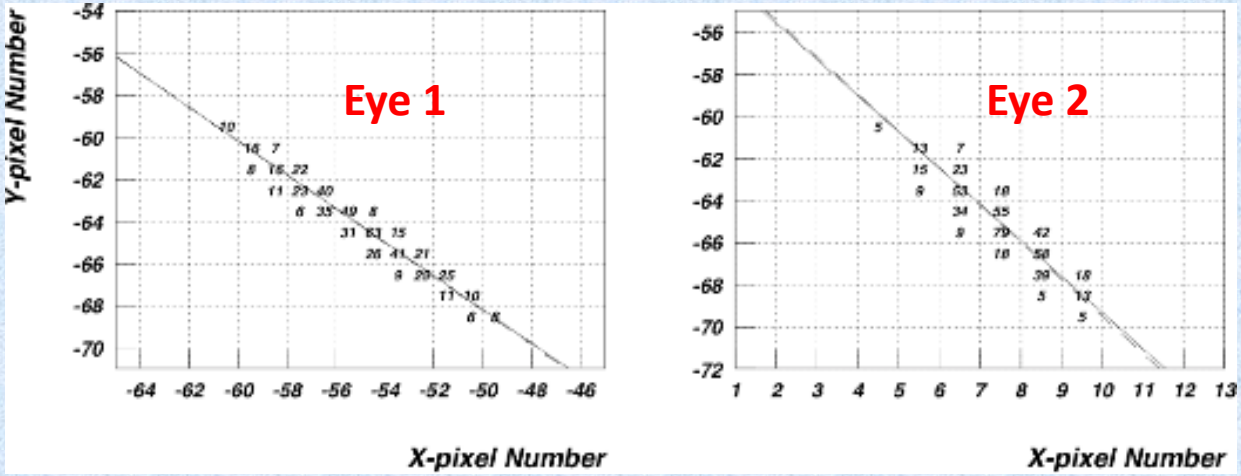


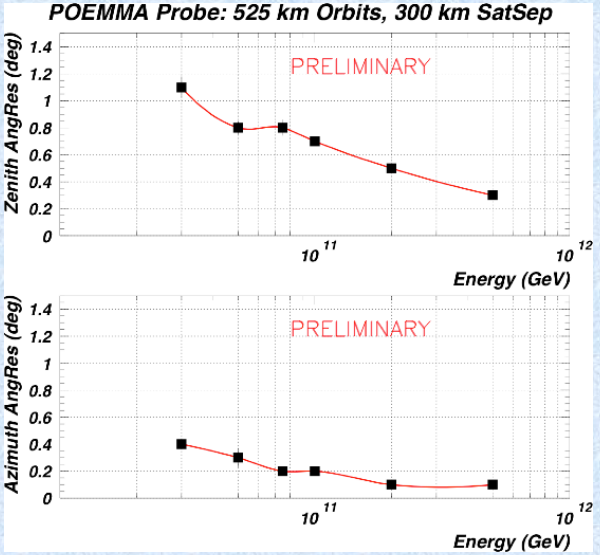




POEMMA: Preliminary Stereo UHECR Performance

Simulated 50 EeV triggered event



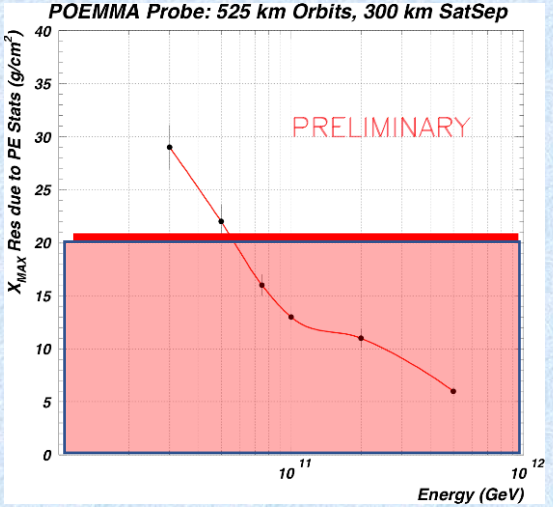


Small 0.084° coupled with small RMS spot size allows to use geometric reconstruction:

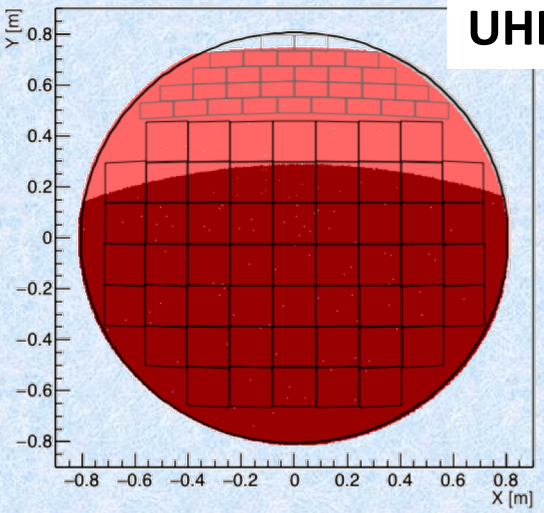
- plane opening angle > 3°
- track length > 4 pixels
- Leads to excellent angular resolution
- Leads to 80+% acceptance of triggered events

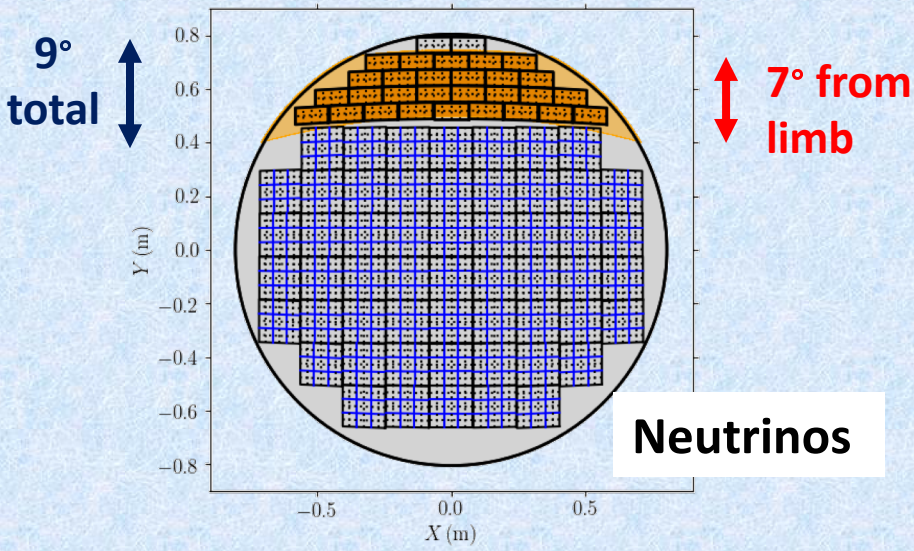
Further work needed to determine energy and X_{MAX} resolution via full event reconstruction:

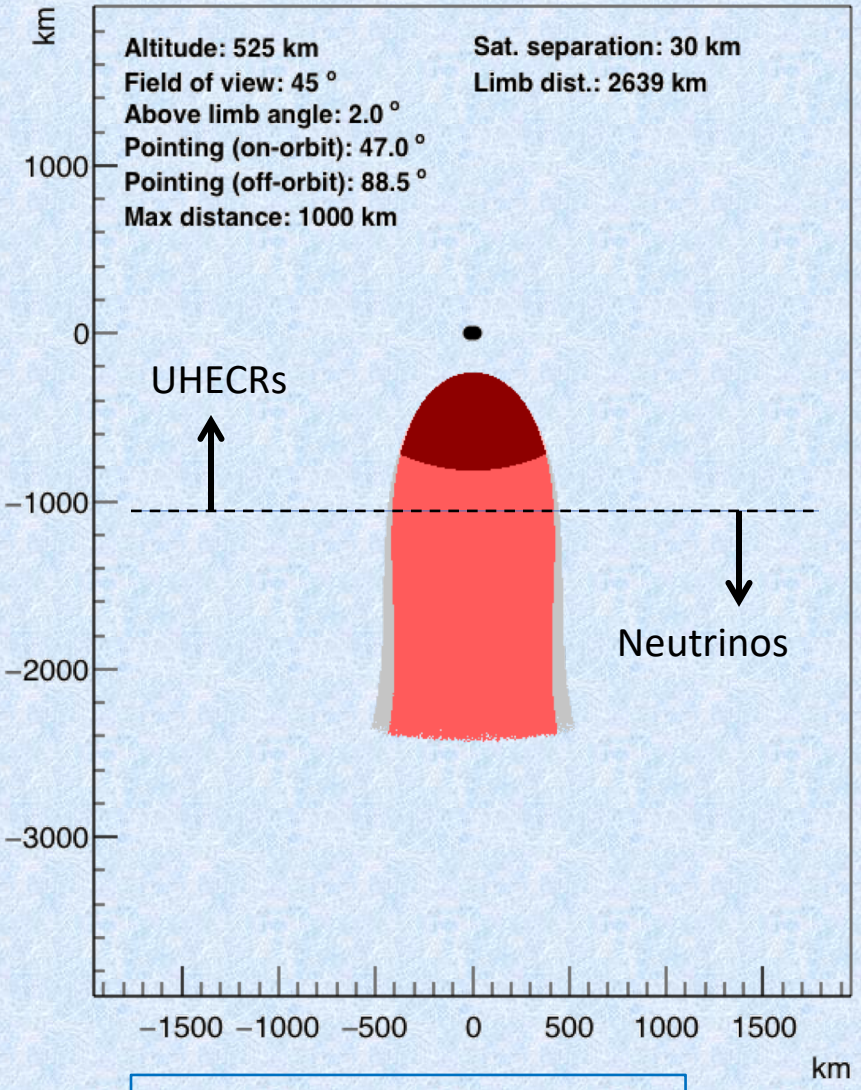
- E_{RES} at least as good from monocular reconstruction: ≲ 20%
- X_{MAX} resolution not dominated by PE statistics above ~ 50 EeV



POEMMA: Neutrino mode example configuration





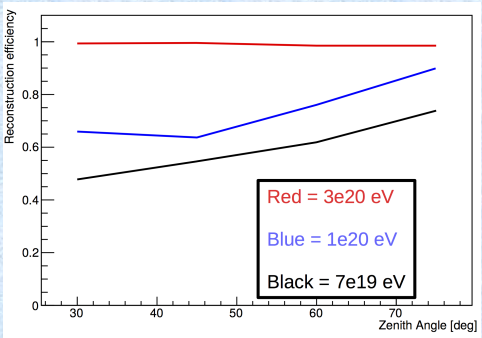


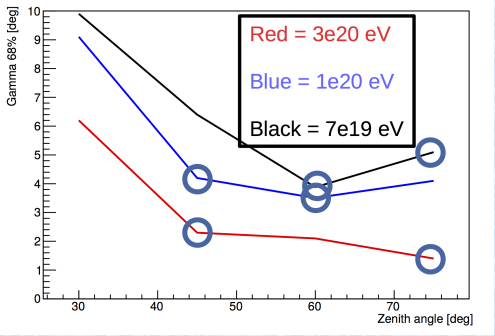
Calcs & plots by F. Sarazin

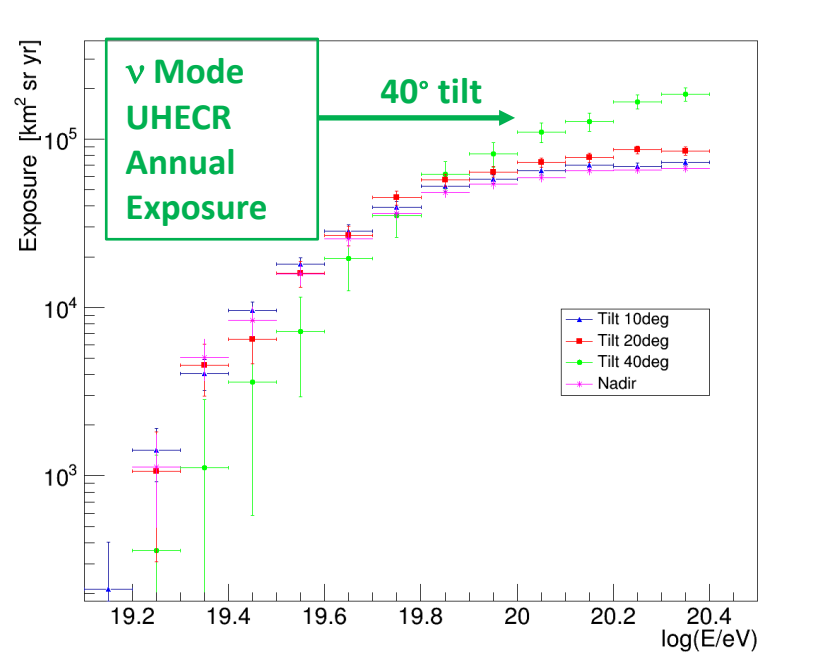
POEMMA: Preliminary Monocular UHECR performance

POEMMA Parameterized Optics implemented in ESAF (JEM-EUSO simulation and analysis code)

- JEM-EUSO layout of focal plane
- JEM-EUSO PMT QE 27%
- GTU time 2.5 usec
- 500 photons/nsec/m²/sr air glow background
- Duty cycle 14.4%







Monocular Performance ≲ ν Mode UHECR

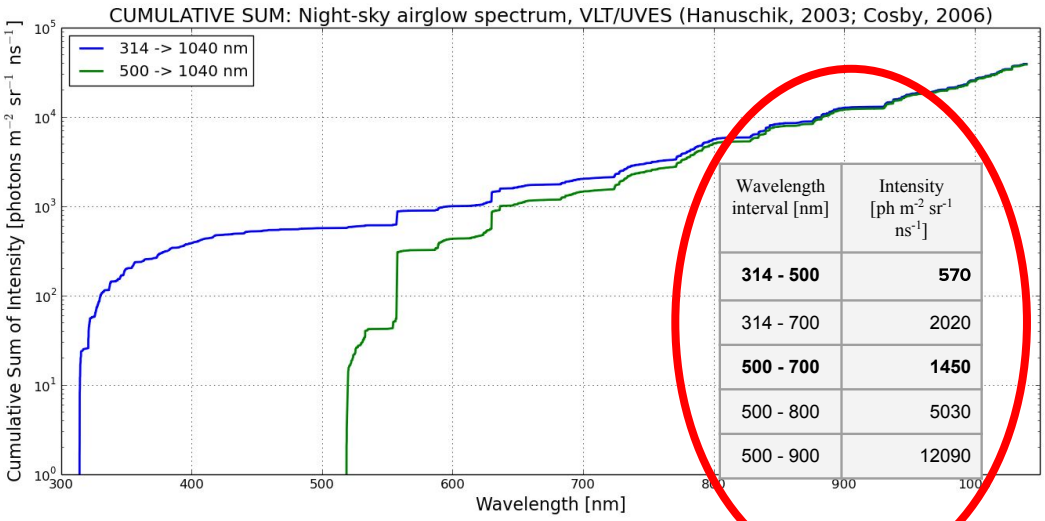
- Annual exposure ≳ 10^5 km² sr above 10^{20} eV
- Energy resolution: 20 – 25%
- Angular Resolution: several degrees (*anticipated to improve once GTU = 1 usec*)
- X_{MAX} resolution: ~100 g/cm²

Lower E	
Bias	21%
Resolution	37%
Higher E	
Bias	4%
Resolution	20%
Lower E	
Bias	9%
Resolution	30%
Higher E	
Bias	0.5%
Resolution	27%

X_{max} Cherenkov method [g/cm²]	Bias	σ
Automatic	12	128
Manual	-13	107
E Cherenkov method (%)	Bias	σ
Automatic	-10	25
Manual	-11	25
X_{max} Slant depth method [g/cm²]	Bias	σ
Automatic	37	100
Manual	34	110
E Slant depth method (%)	Bias	σ
Automatic	8	21
Manual	11	21

A. Liberatore, F. Fenu, M. Bertaina

POEMMA: 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

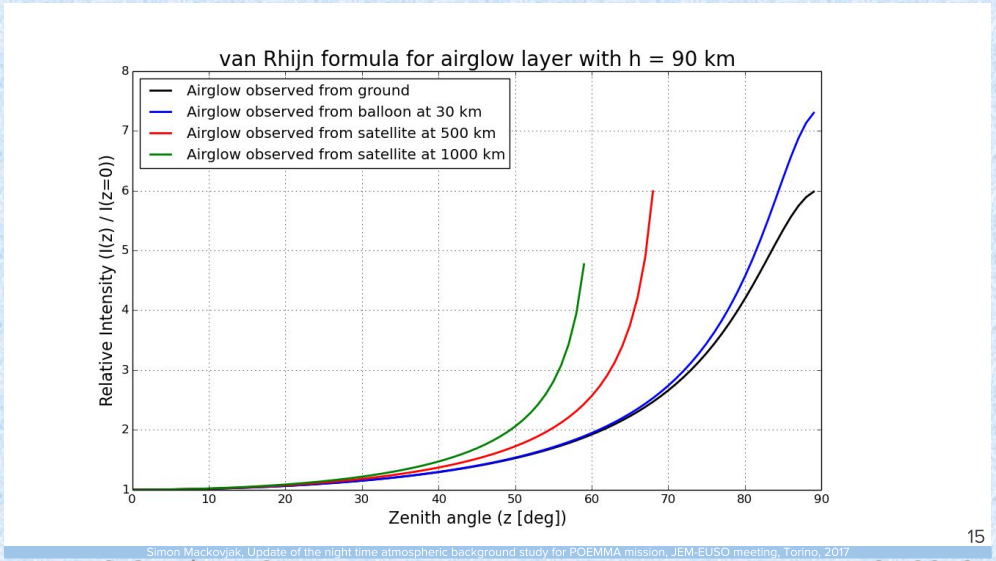
7

Simon Mackovjak, Update of the night time atmospheric background study for POEMMA mission, JEM-EUSO meeting, Torino, 2017

314 nm – 900 nm

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

12,090 photons/m^2/sr/ns vs
570 photons/m^2/sr/ns (λ < 500 nm)



15

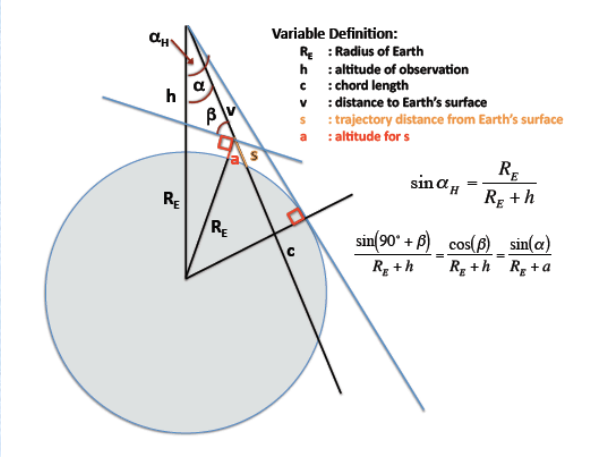
Simon Mackovjak, Update of the night time atmospheric background study for POEMMA mission, JEM-EUSO meeting, Torino, 2017

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

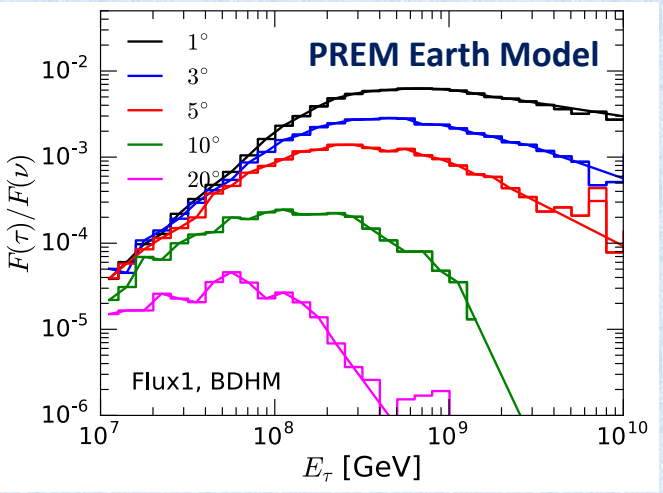
x6 for viewing limb from 500 km

Work by Simon Mackovjak

POEMMA: upward tau EAS Cherenkov simulations



$\Delta\alpha$	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



M. Hall Reno: Preliminary

Baseline Simulation: $\nu_\tau \rightarrow \tau \rightarrow$ EAS $\rightarrow$ Cherenkov $\rightarrow$ atmosphere $\rightarrow$ detector

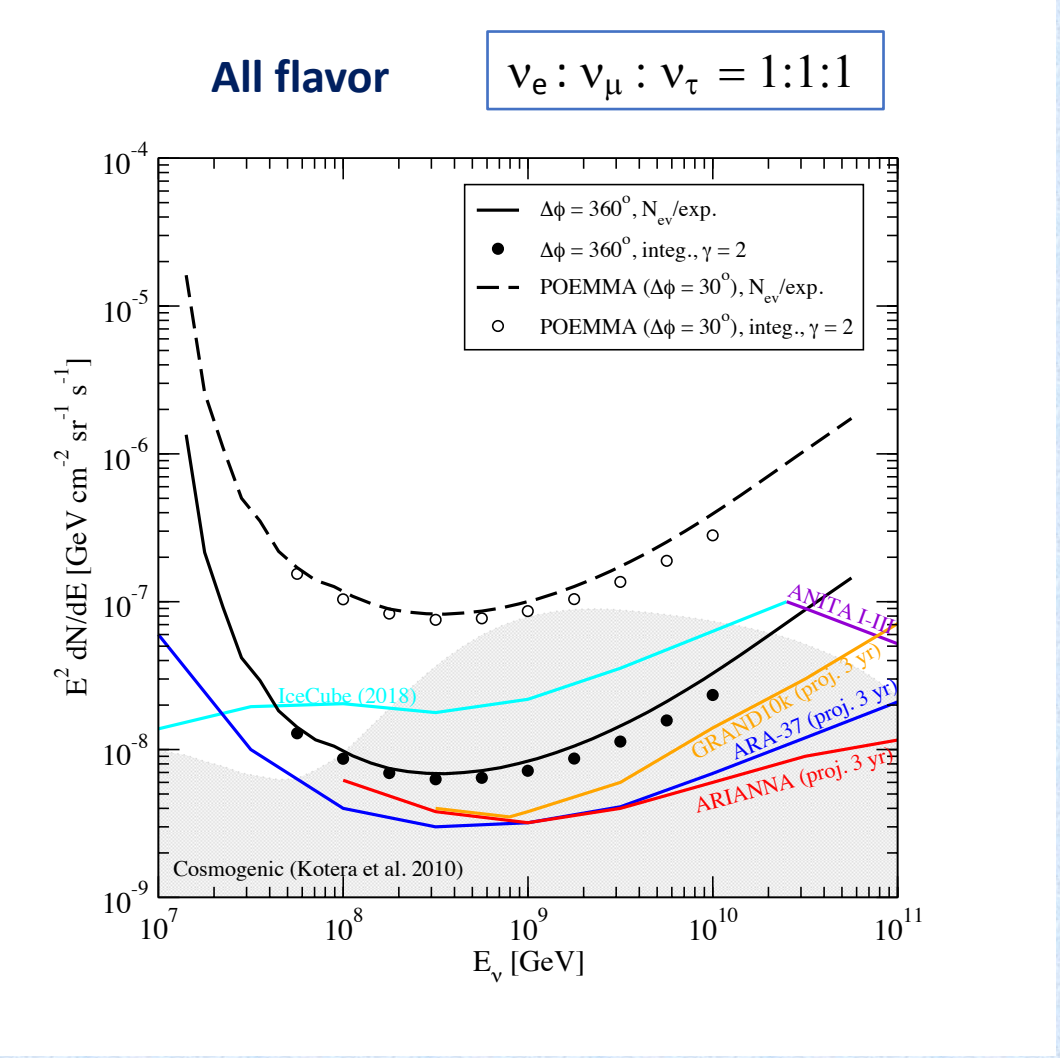
- Work by M. Hall Reno, T. Venters, and J. Krizmanic
- New tau yield calculations by M. Reno
- Parameterized EAS with Hillas-based Cherenkov generation
- Static atmosphere with aerosol, ozone, and molecular absorption
- Two different implementations
- Assumptions: $E_{EAS} = 0.5\ E_\tau$; Ignore muon channel (for now)
- Cherenkov light strength and angle as a function of β_E and EAS altitude (≤ 20 km)
- POEMMA Instrument Model: $A_{EFF} = 2.5\ m^2$; <PDE> = 0.2 for signal

Paper in preparation

POEMMA: preliminary neutrino 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 Emergence Angle)**



References:

- Kotera et al. (2010): arXiv:1009.1382
- IceCube (2018): arXiv:1807.01820, Fig 6
- ANITA: arXiv:1803.02719, Fig 6
- ARIANNA: arXiv:1410.7352, Fig 6
- ARA-37: arXiv:1105.2854, Fig 29
- GRAND10k: arXiv:1708.05128, Fig 1

POEMMA: preliminary neutrino sensitivity

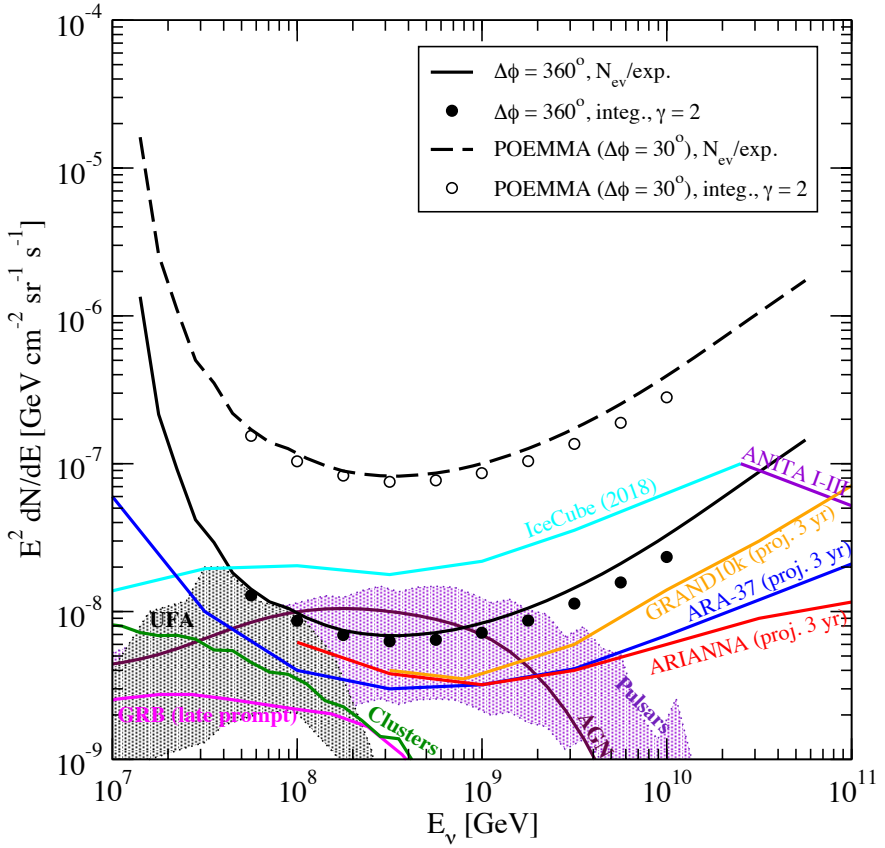
All flavor Sensitivity Limit:

- **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 Emergence Angle)**

Thanks to Ke Fang for the source models: see arXiv: 1708.05128, Fig 3

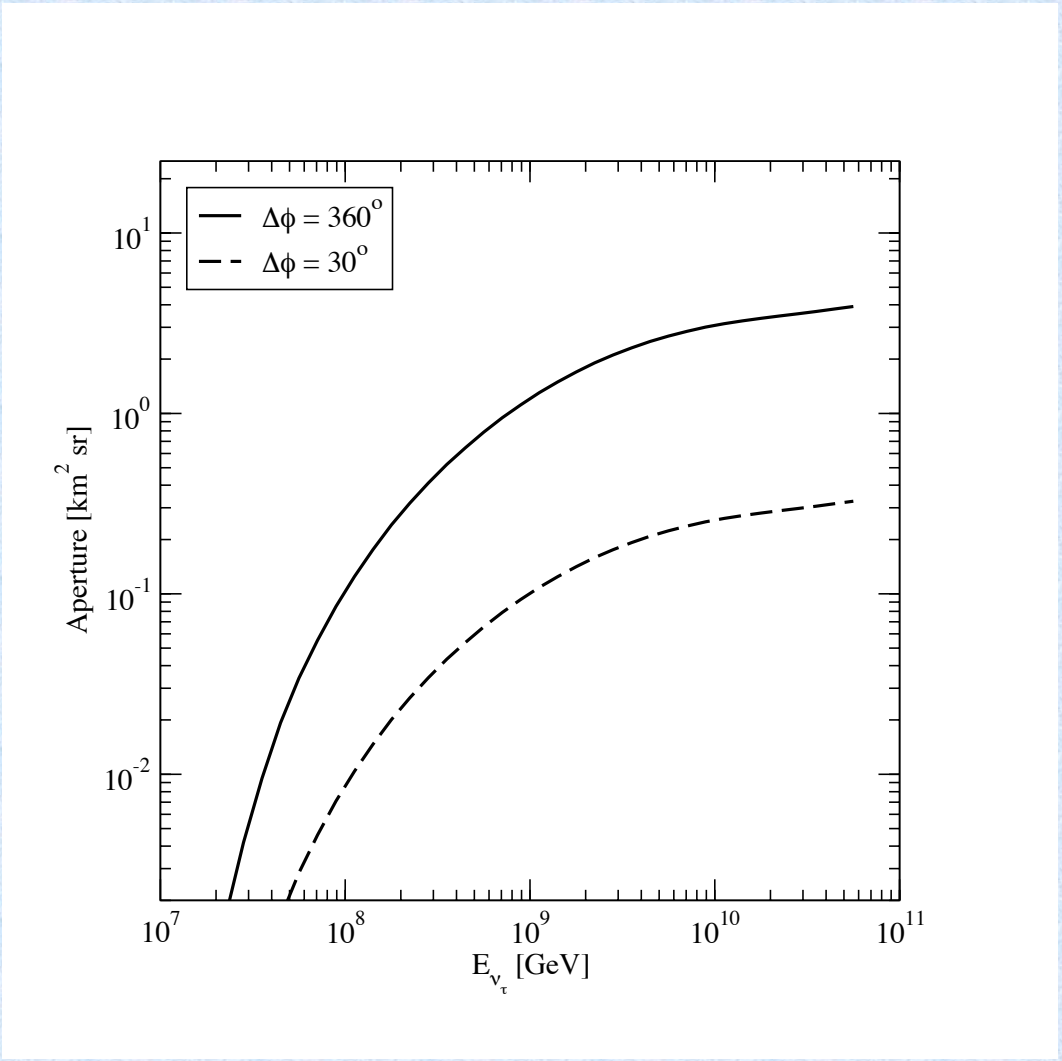
UFA: arXiv:1505.02153, Figs 5 & 12

All flavor $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$



POEMMA: preliminary tau neutrino aperture (Earth Skimming)

- Viewing to 7° away from Limb (or to ~20° Earth Emergence Angle)



POEMMA: anomalous ANITA upward EAS

arXiv:1803.05088v1

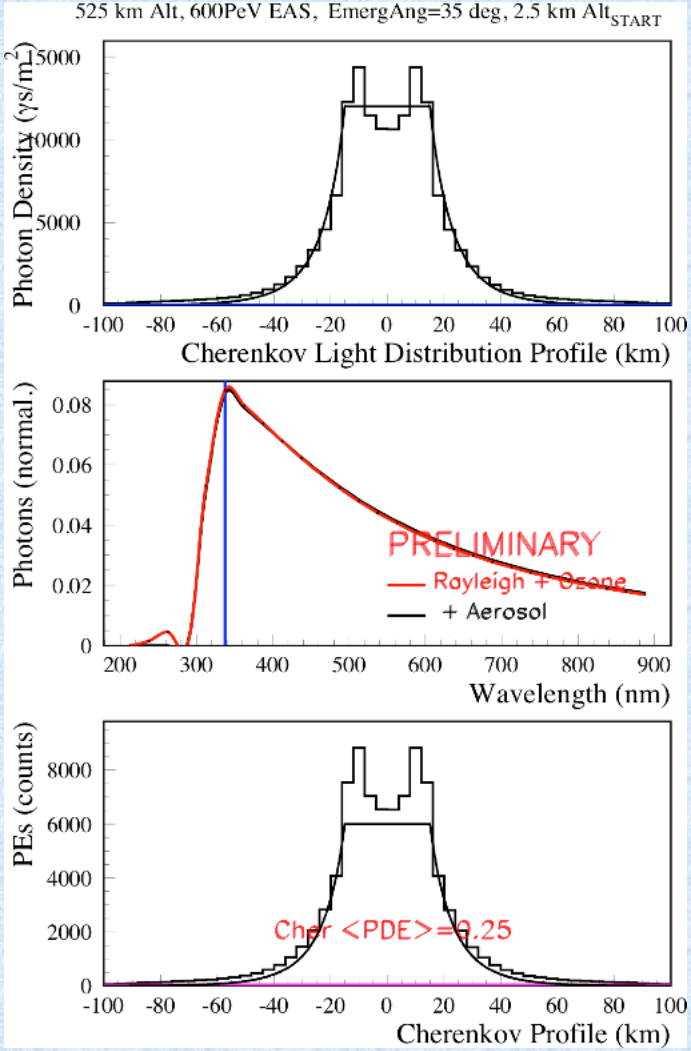
TABLE I: *ANITA-I,-III anomalous upward air showers.*

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

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

POEMMA: Summary

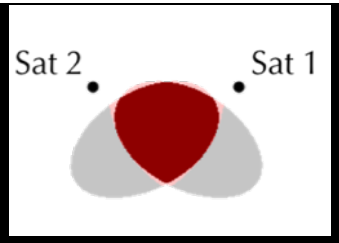
- POEMMA was funded for a NASA Astrophysics Probe Study and we have completed an instrument and mission design within Study constraints with the goal of maximizing the UHECR and Earth-skimming tau neutrino performance.
- Initial simulation results yield:
  - UHECR Stereo performance with all-sky coverage:
    - 5 Year exposure: 5e5 (1.5e6) km^2 sr yr at 40 (100) EeV
    - Angular resolution: $\lesssim 1^\circ$ for $E_{CR} \geq 40$ EeV
    - Energy resolution: ~20%
    - X_{MAX} resolution: ~20 g/cm^2 above 40 EeV (PE statistics term); *work in progress*
  - UHECR tilted performance:
    - 5 Year exposure: 5e5 (1.5e6) km^2 sr yr at 40 (100) EeV ; 2e6 km^2 sr yr at 130 EeV
    - Angular resolution: $\lesssim 5^\circ$ for $E_{CR} \geq 100$ EeV (zenith angle dependent), work in progress
    - Energy resolution: ~20-25%
    - X_{MAX} resolution: ~100 g/cm^2
  - Earth-skimming tau neutrino differential sensitivity (E^2 dN/dE [GEV cm^{-2} sr^{-1} s^{-1}]):
    - 10^{-6} at 25 PeV with minimum of 10^{-7} at 300 PeV [5 year, 90% CL]
    - Expanding azimuthal energy range to 360° increases sensitivity by 12
  - Target-of-Opportunity mode for neutrino observations allows for transient follow up observations (if in available celestial sky): model with 10^4 sec to peak ν flux presented at this conference.
  - **ANITA anomalous events would be very bright in POEMMA**

POEMMA: Future

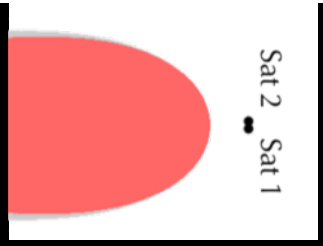
- POEMMA simulations will continue to better quantify performance for the final report.
- **This work is in support of NASA hoping to define a new, Probe Class of mission; input to decadal review, (hopefully) recommendation for Probe Class; agency enactment; then (hoperfully) AO for actual mission in 2020's**
- **Thus there is an opportunity to improve performance such as focused technology development, especially in large scale optics: UV measurements with 1 km spatial resolution from 1000 km distance is 10^4 away from the diffraction limit.**

- **Neutrino Simulation work will continue via a recently selected NASA APRA proposal:**
  - J. Krizmanic (PI), Co-Is: T. Venter, M. Hall Reno, D. Bergman, F. Sarazin, A. Romero-Wolf, Y. Akaike, Collabs: A. Olinto, S. Wissel, L. Anchordoqui, S. Mackovjak, & L. Wiencke.
  - Goal to develop *robust* end-to-end neutrino simulation package for space-based and sub-orbital experiments: focus on upward τ-lepton from Earth ***optical Cherenkov and radio signals*** (at first) ,e.g. put in tau decay fractions to form composite EAS, muonic EAS, variable atmosphere and other atmospheric effects, determine backgrounds, etc.
  - 3 year proposal: target is to release package to the community early in the third year.

- See paper by R. dos Anjos et al. (arXiv:1810.04251) which has evaluated impact of POEMMA UHECR measurement capability on understanding UHECR composition.

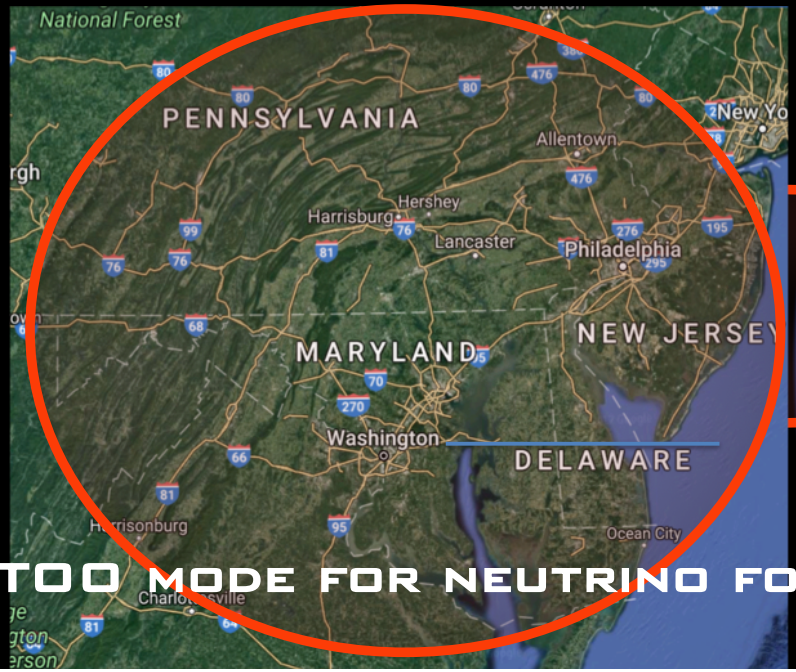


POEMMA



Nadir for UHECR:
Radius 200-400 km

Limb for Neutrinos:
Radius 2.6-3.7 10^3 km





TOO mode for neutrino follow up of special events

14