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

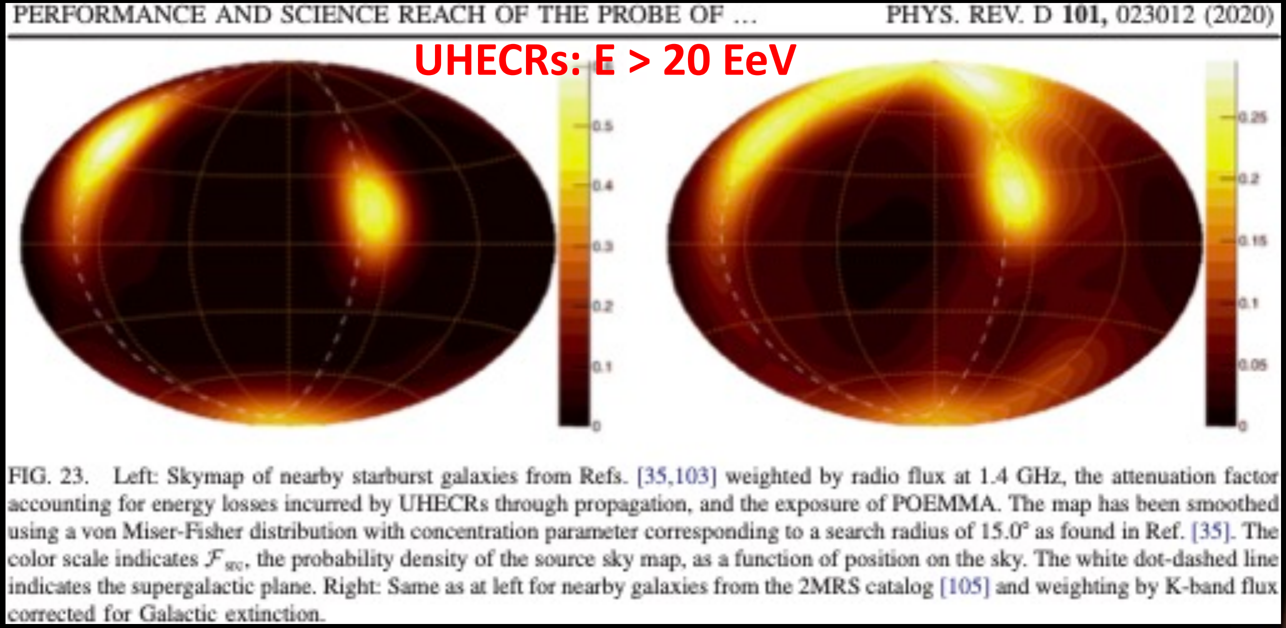

PERFORMANCE AND SCIENCE REACH OF THE PROBE OF … PHYS. REV. D **101**, 023012 (2020)

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.

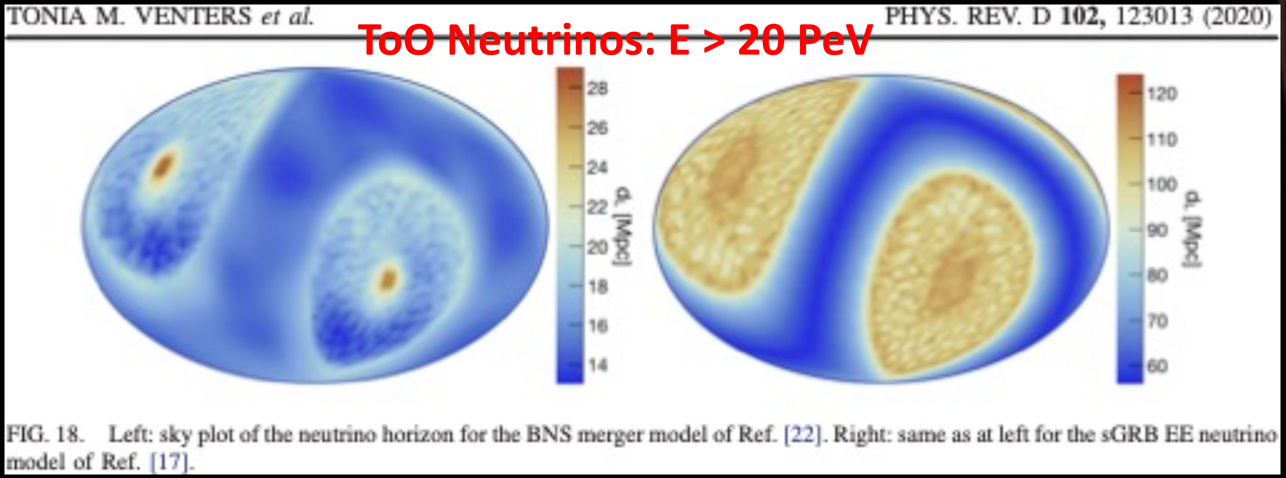
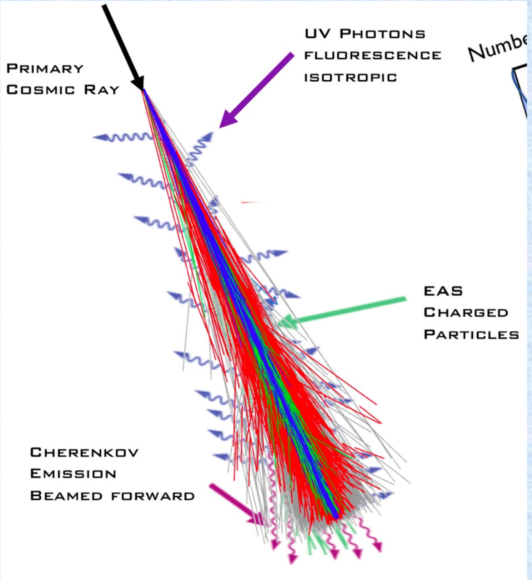
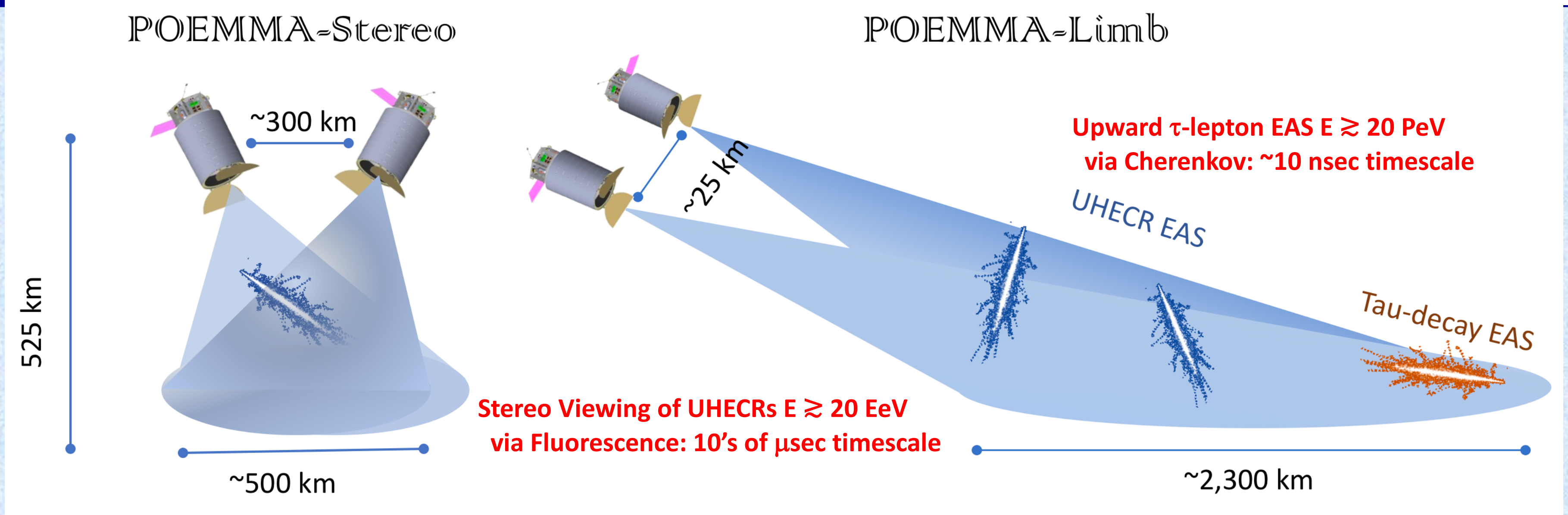

TONIA M. VENTERS *et al.* PHYS. REV. D **102**, 123013 (2020)

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

POEMMA Collaboration

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

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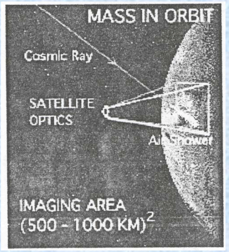
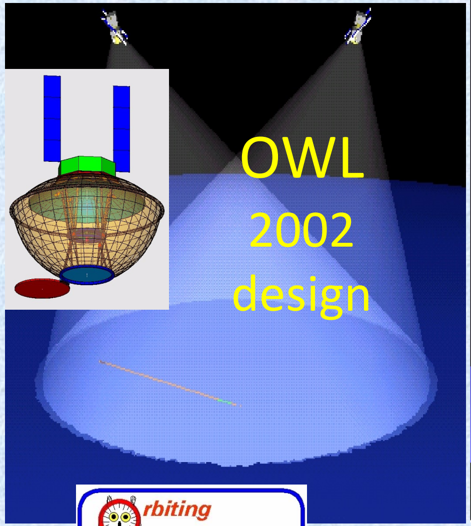
Based on OWL 2002 study, JEM-EUSO, EUSO balloon experience, and CHANT proposal



TUS, KLYPVE-EUSO



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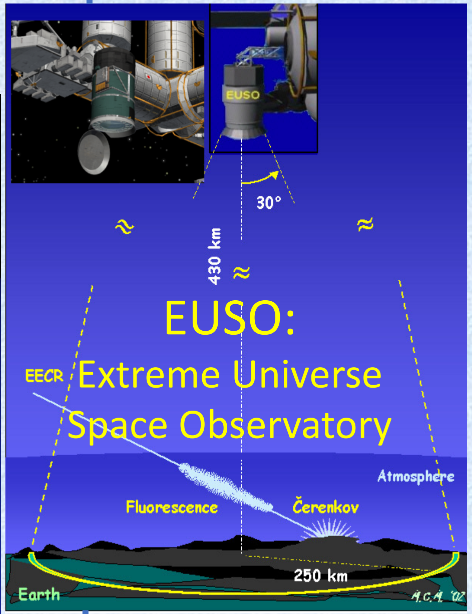
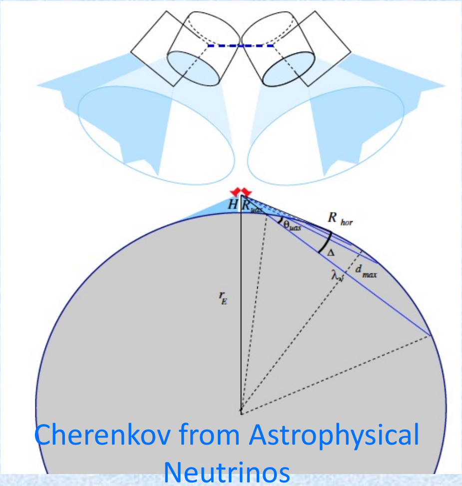


CHANT



Cherenkov from Astrophysical
Neutrinos
Telescope

EUSO-Balloon
EUSO@TA
Mini-EUSO

EUSO-SPB2

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

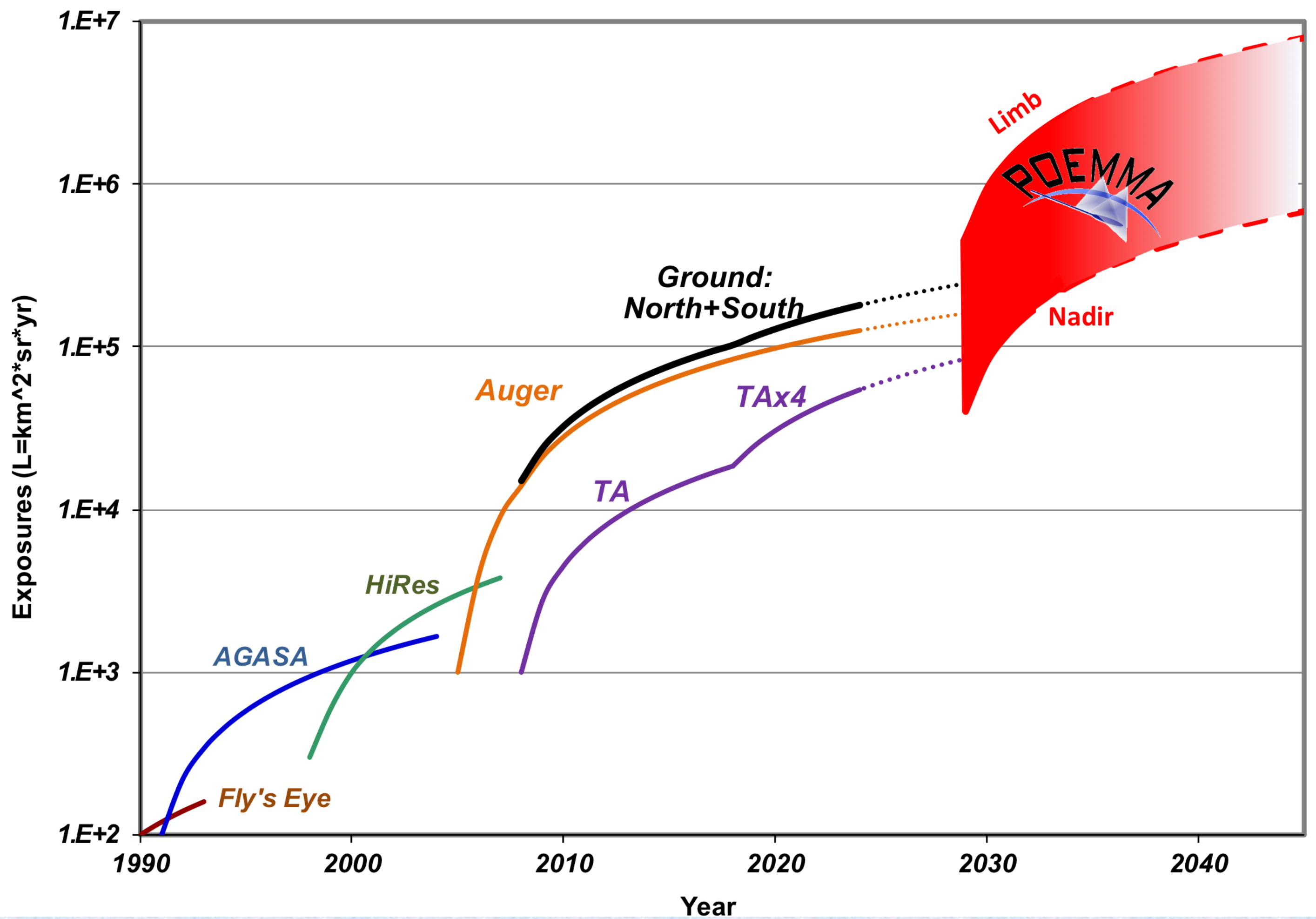
  Allows for tilted UHECR air fluorescence operation, higher GF but degraded resolutions

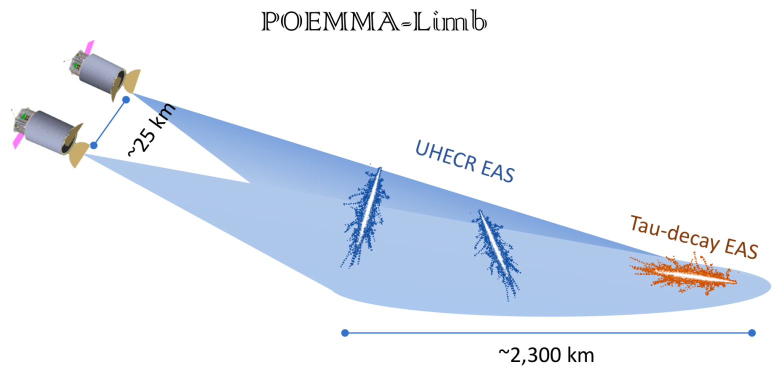
secondary

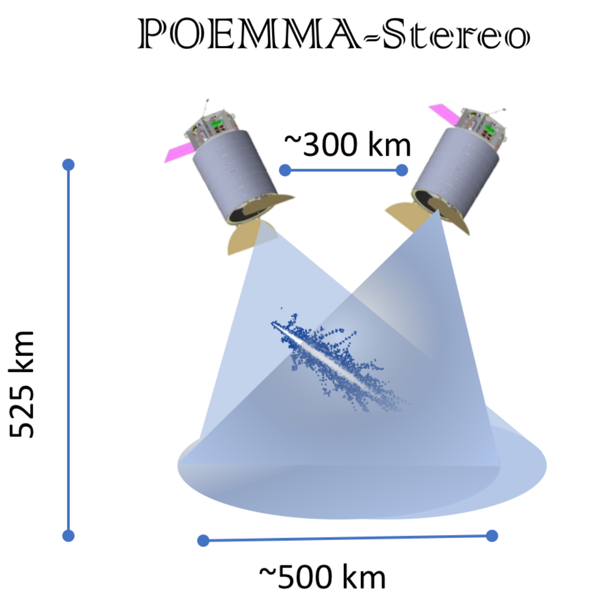
$\sqrt{s} \approx 450$ TeV @ 100 EeV

- 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: UHECR Exposure History







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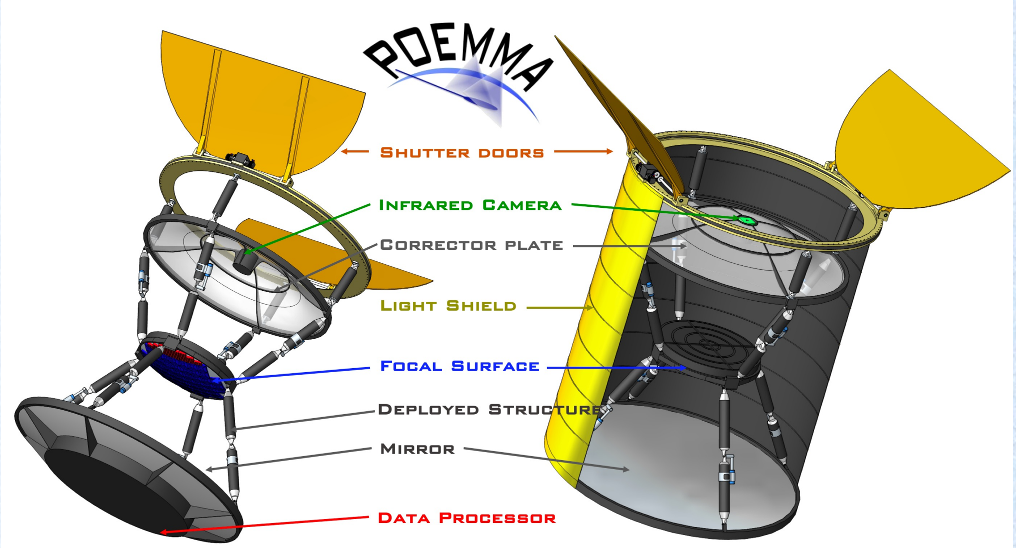
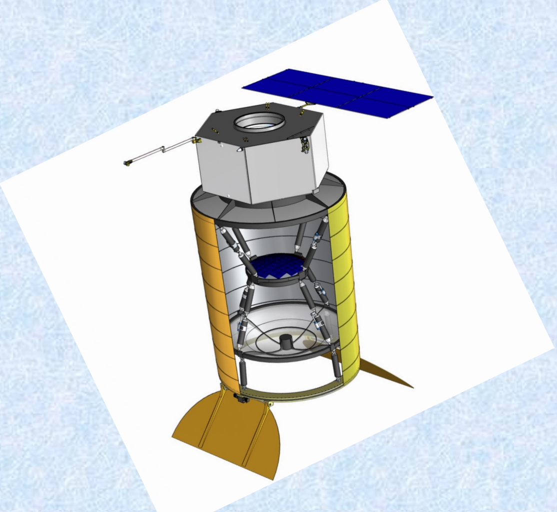
POEMMA: Instruments defined by weeklong IDL run at GSFC





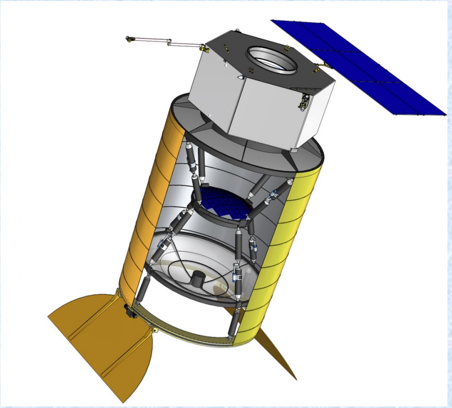
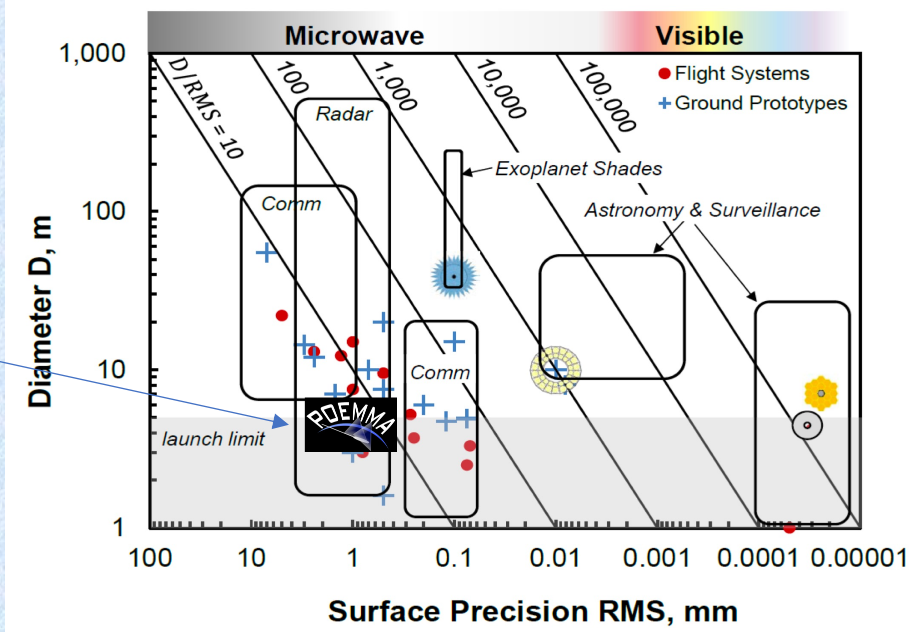


TABLE I: POEMMA Specifications:

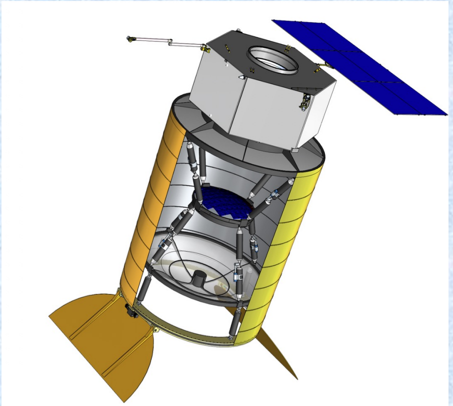
Photometer	Components		Spacecraft	
Optics	Schmidt	45° full FoV	Slew rate	90° in 8 min
	Primary Mirror	4 m diam.	Pointing Res.	0.1°
	Corrector Lens	3.3 m diam.	Pointing Know.	0.01°
	Focal Surface	1.6 m diam.	Clock synch.	10 nsec
	Pixel Size	3×3 mm^2	Data Storage	7 days
	Pixel FoV	0.084°	Communication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

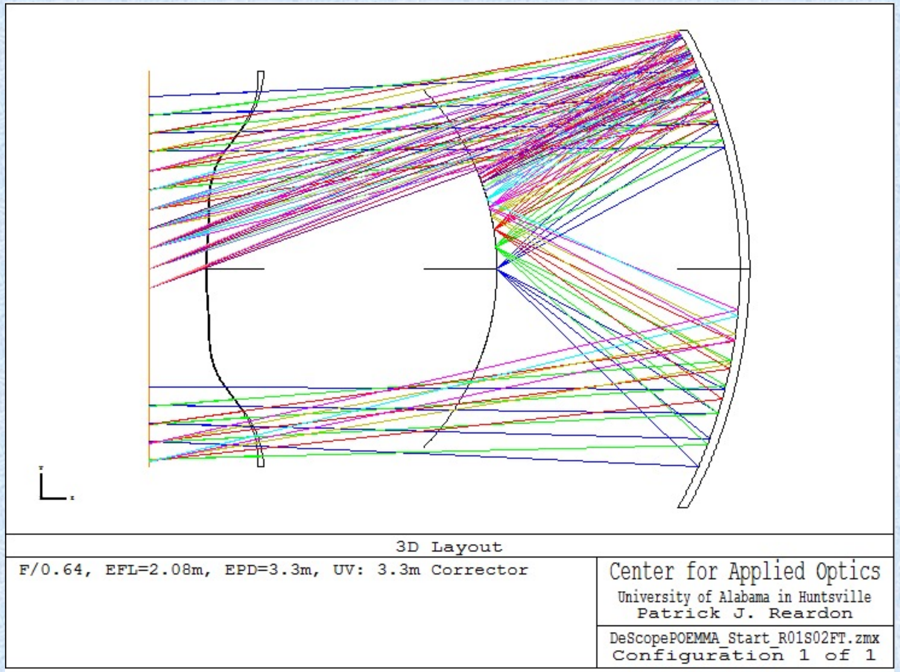
Each Observatory = Photometer + Spacecraft; POEMMA Mission = 2 Observatories

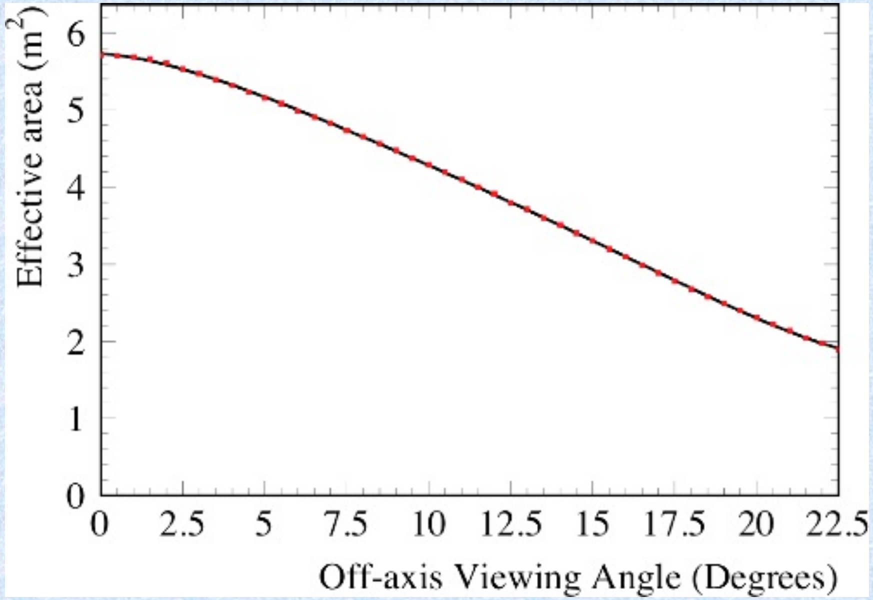


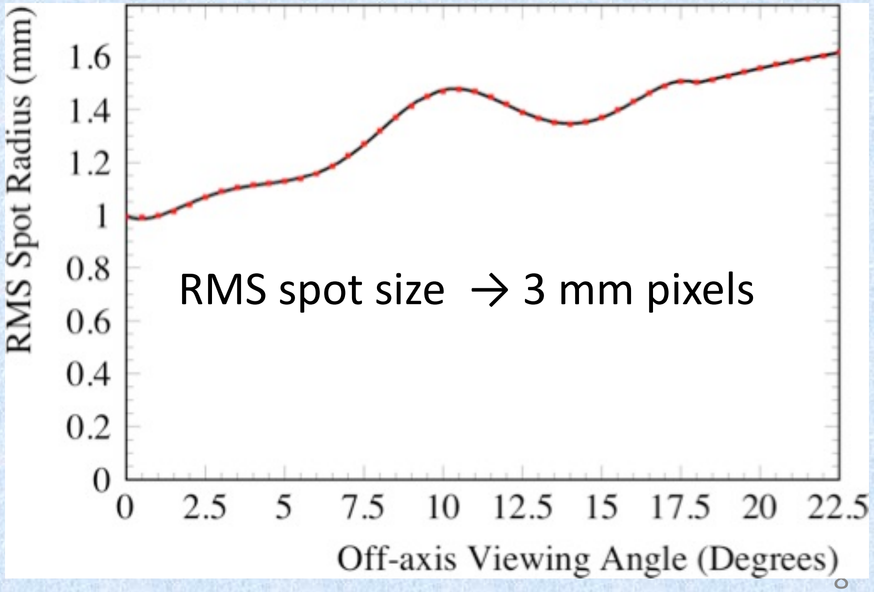
Imaging ~10^4 away from diffraction limit

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

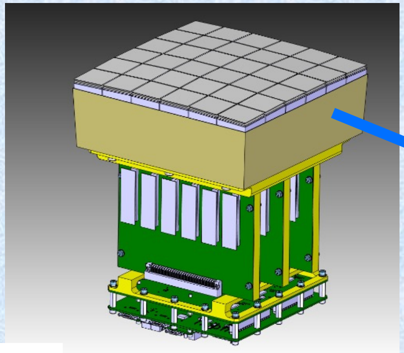
Optical Area$_{EFF}$: ~6 to 2 m^2

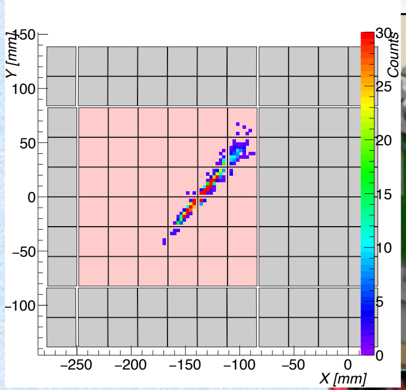
Hybrid focal surface (MAPMTs and SiPM)

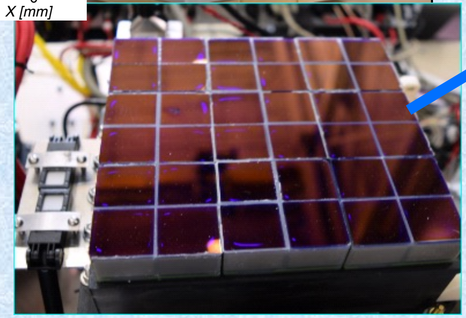
3 mm linear pixel size: 0.084° FoV

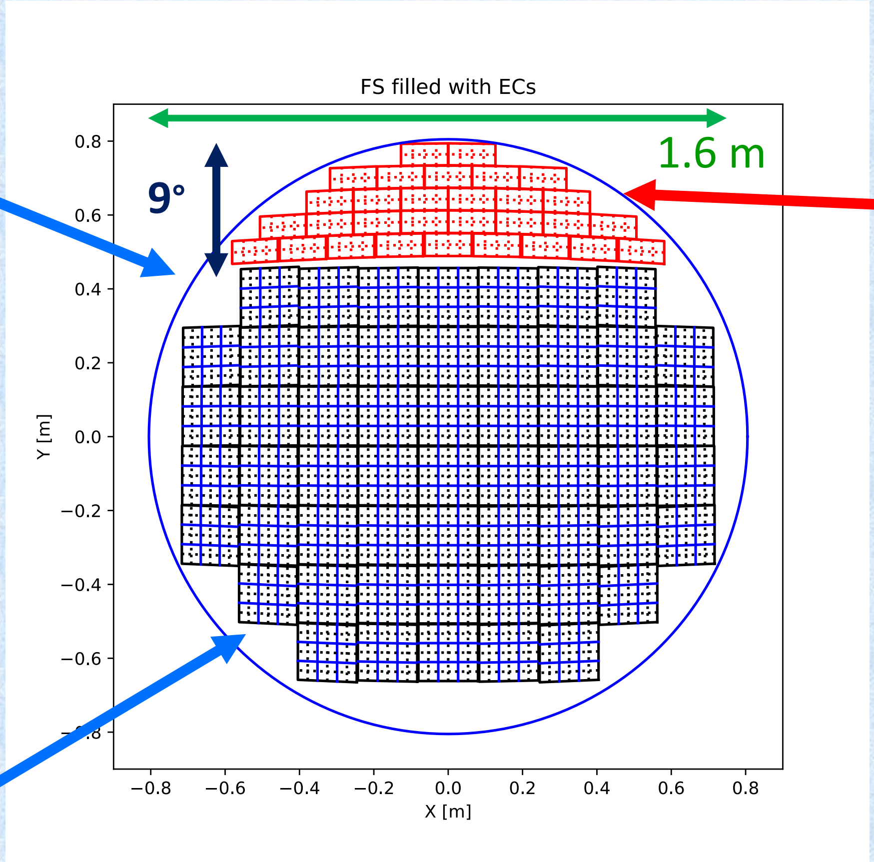
POEMMA: Hybrid Focal Plane

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





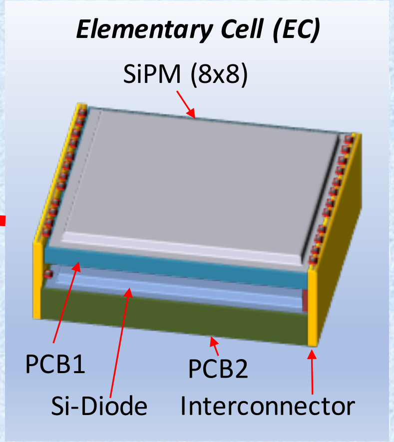




55 Photo Detector Modules (PDMs)= 126,720 pixels

1 PDM = 36 MAPMTs = 2,304 pixels

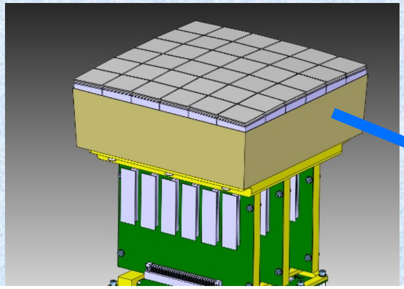
Cherenkov Detection with SiPMs (300 – 1000 nm): 20 nsec sampling

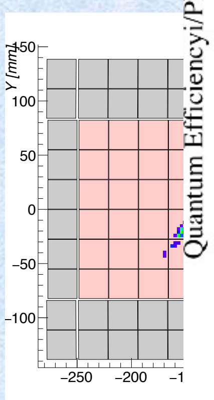


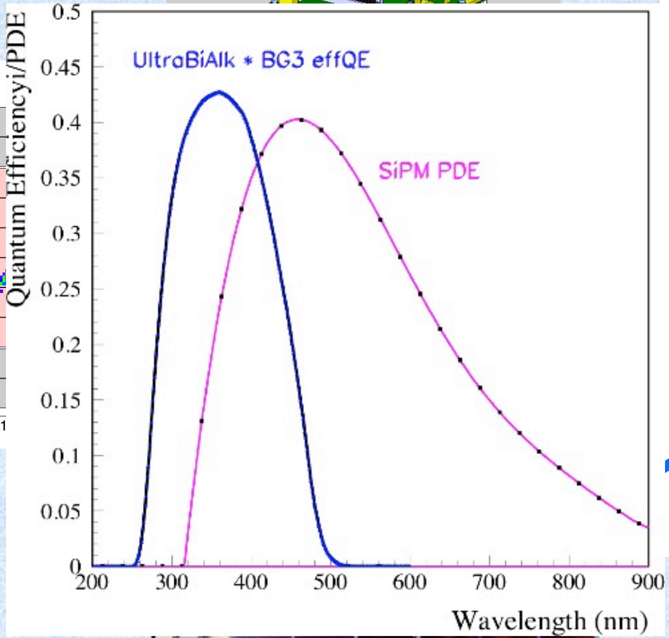
30 SiPM focal surface units
Total 15,360 pixels
512 pixels per FSU (64x4x2)
Si-Diode for LEO radiation backgrounds rejection

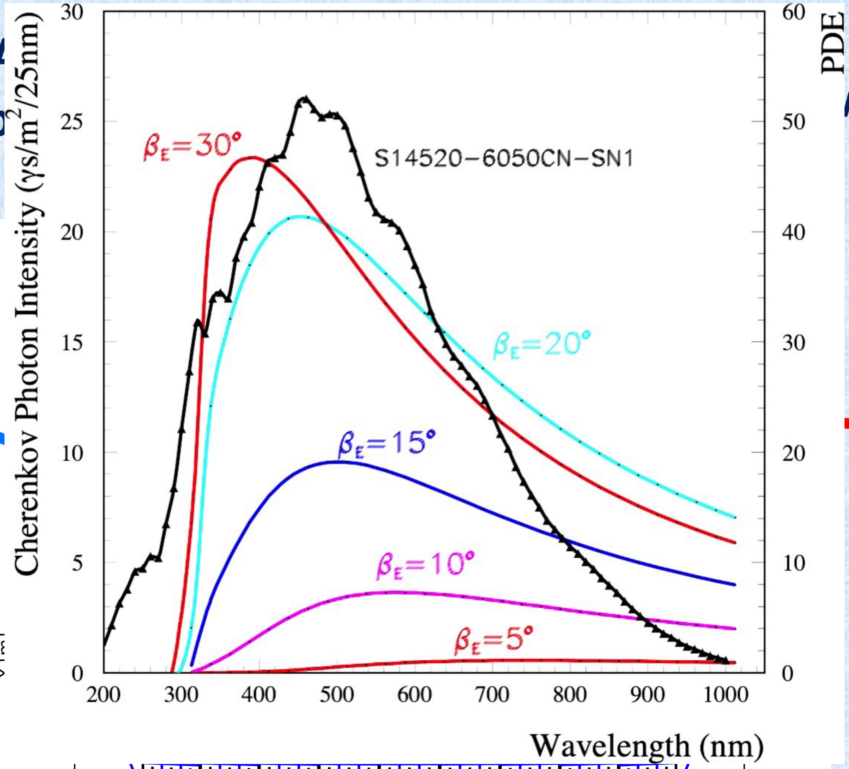
POEMMA: Hybrid Focal Plane

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

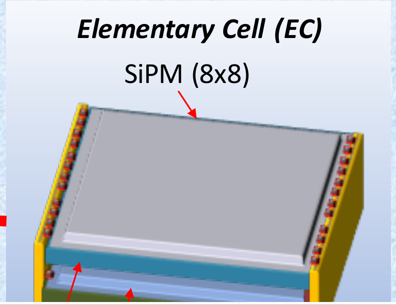


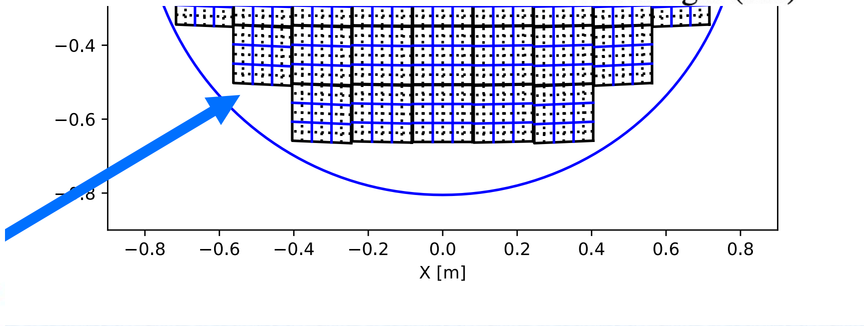


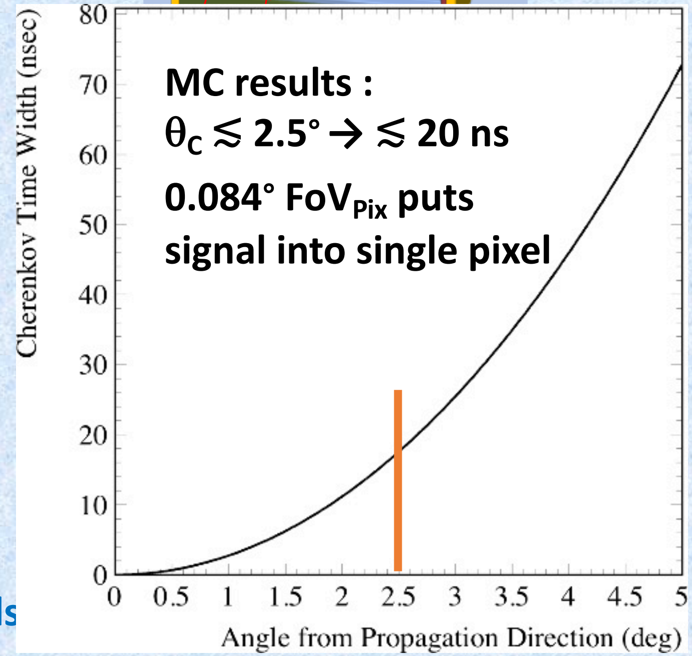




Cherenkov Detection
with SiPMs (300 – 1000 nm):
20 nsec sampling







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

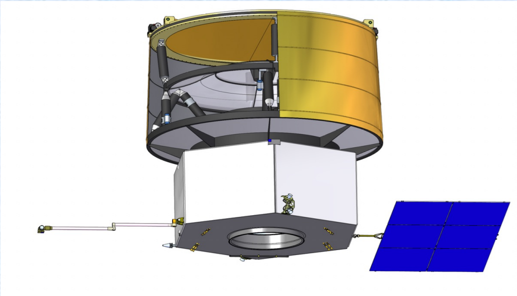
1 PDM = 36 MAPMTs = 2,304 pixels

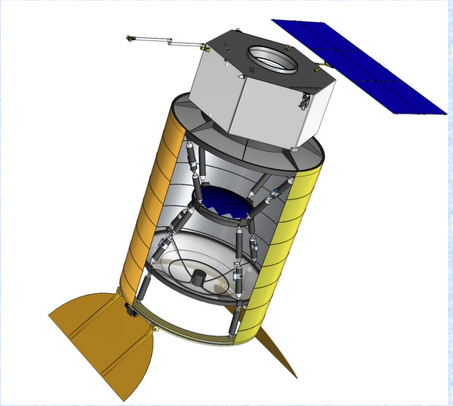
POEMMA: Mission (Class B) defined by weeklong MDL run at GSFC

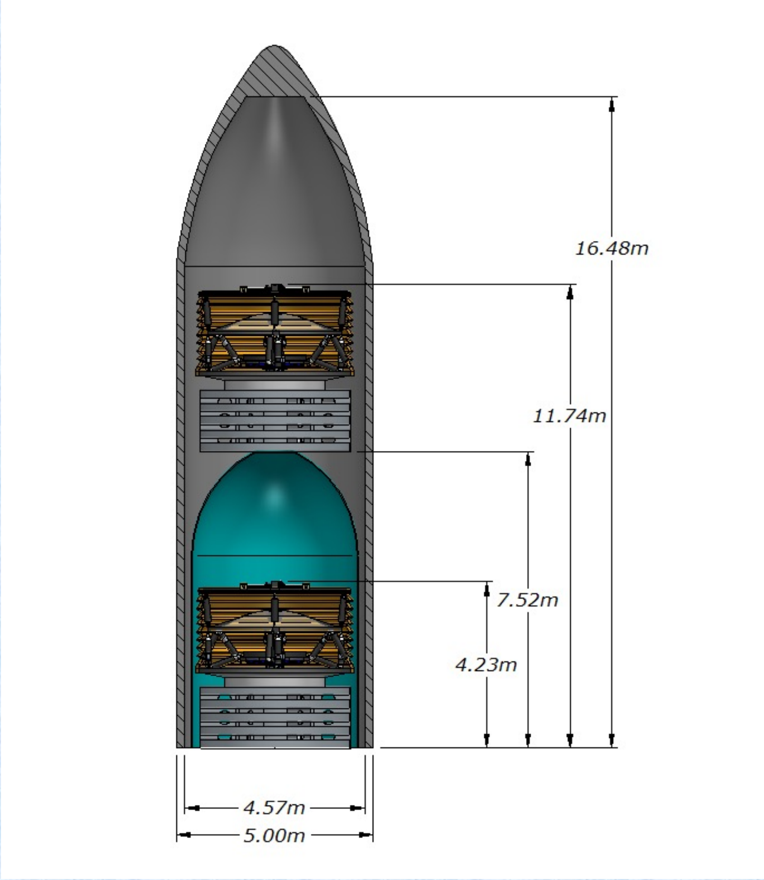
Mission Lifetime:	3 years (5 year goal)
Orbits:	525 km, 28.5° Inc
Orbit Period:	95 min
Satellite Separation:	~25 km – 1000+ km
Satellite Position:	1 m (knowledge)
Pointing Resolution:	0.1°
Pointing Knowledge:	0.01°
Slew Rate:	8 min for 90 °
Satellite Wet Mass:	3860 kg
Power:	1250 W (w/contig)
Data:	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

Flight Dynamics/Propulsion:

- 300 km $\Longrightarrow$ 50 km SatSep
  - Puts both in CherLight Pool
- Δt =3 hr, 9 times
- Δt 24 hr, 90 times





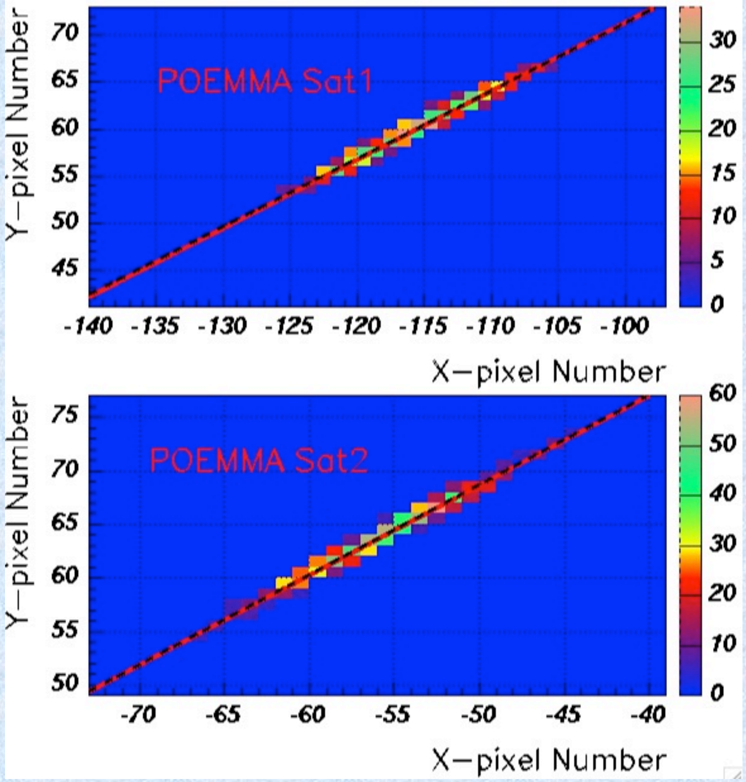


Dual Manifest Atlas V

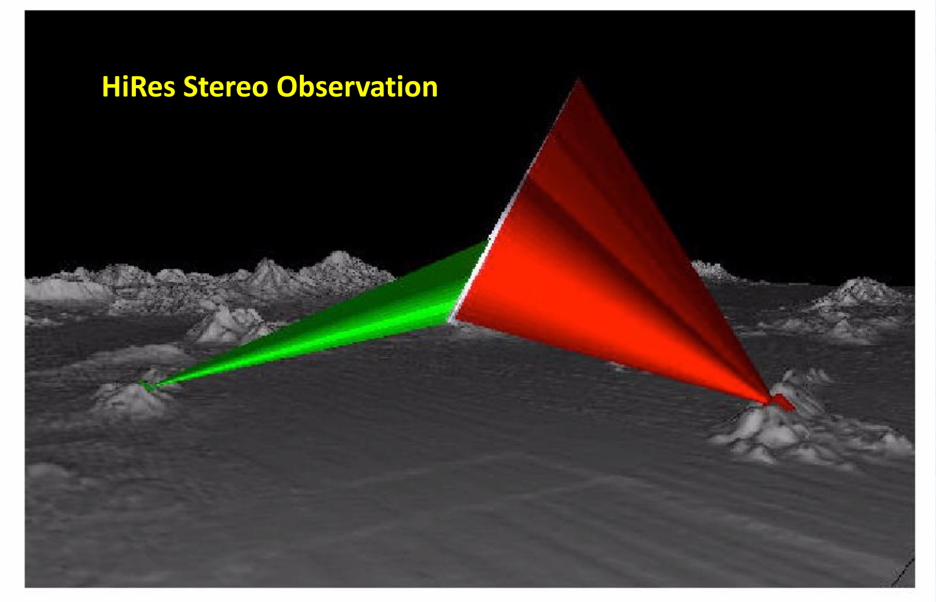
Operations:

- 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 Angular Resolution: *see PhysRevD.101.023012*

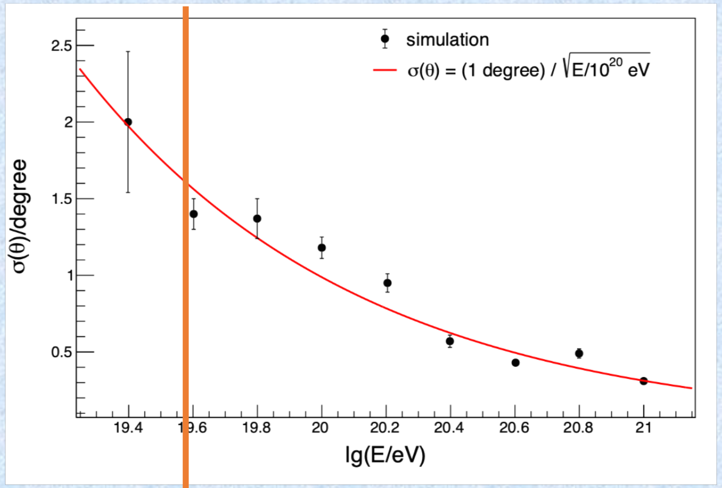


50 EeV simulated event

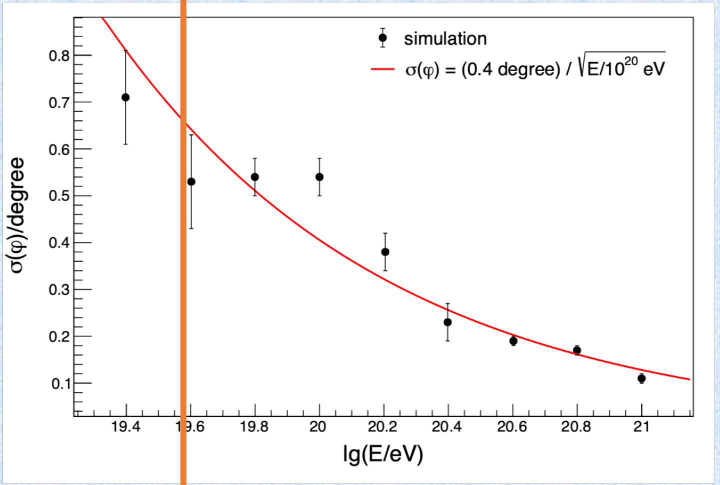


Stereo Geometric Reconstruction

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



Stereo Reconstructed Zenith Angle Resolution



Stereo Reconstructed Azimuth Angle Resolution

40 EeV

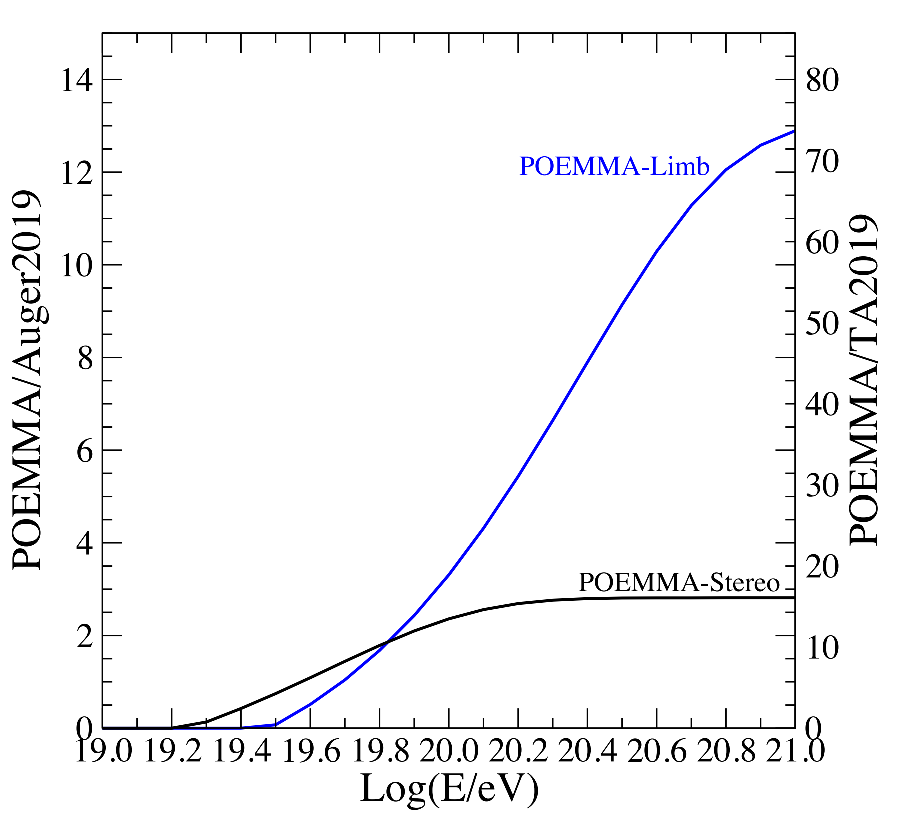
POEMMA: UHECR Performance: *see PhysRevD.101.023012*

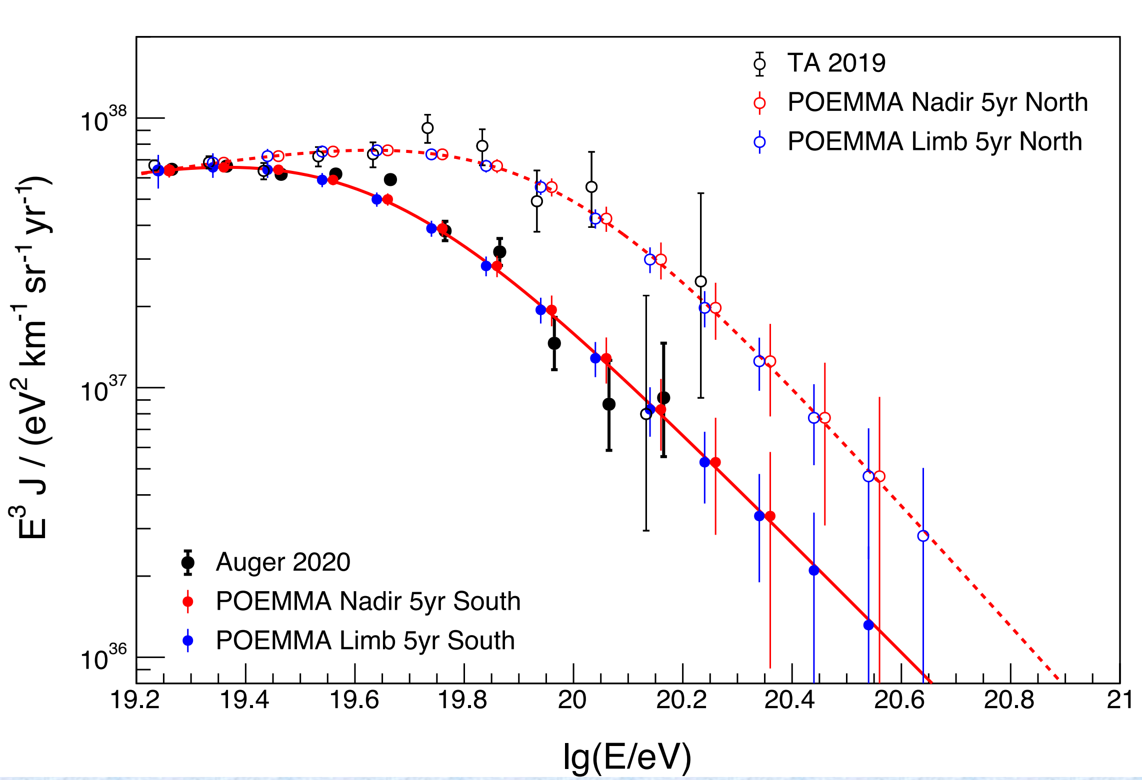
Significant increase in exposure with all-sky coverage

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

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

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



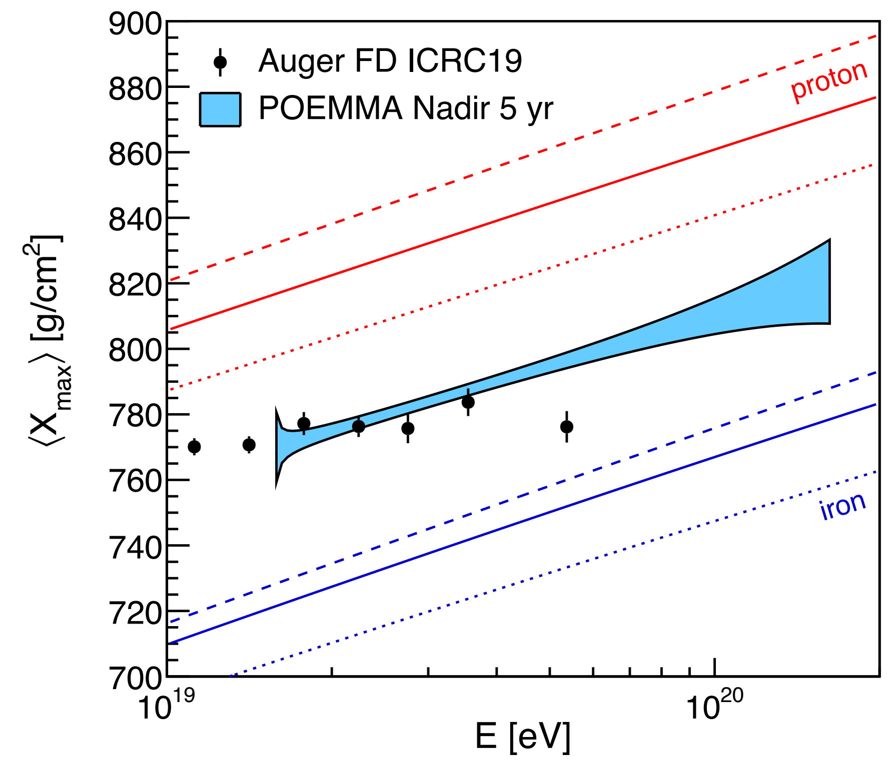


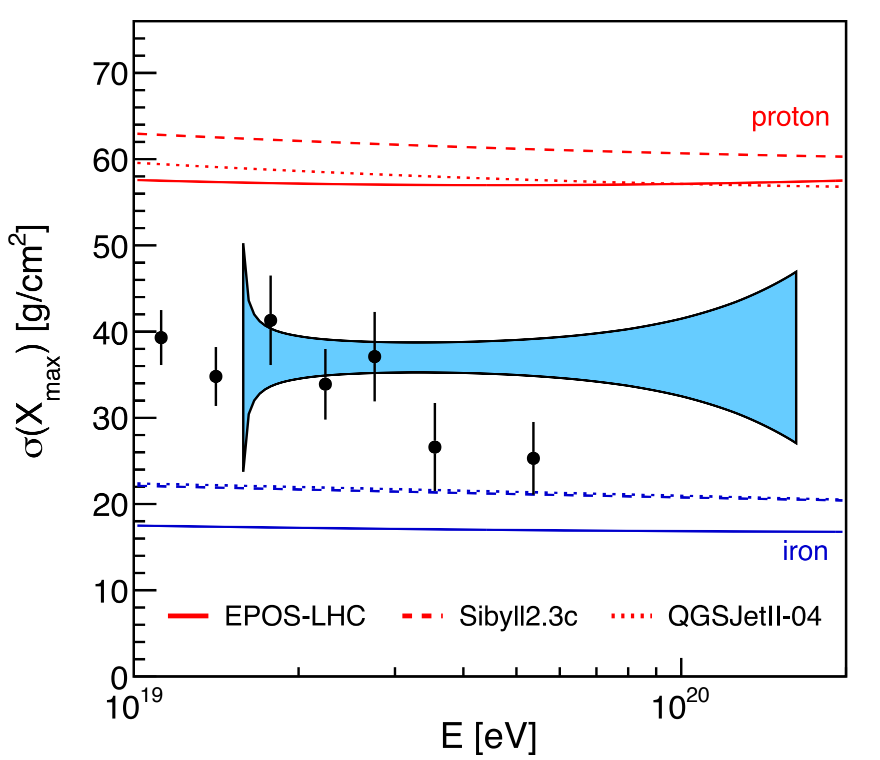
Olinto_2021_J._Cosmol._Astropart._Phys._2021_007

POEMMA: UHECR Performance: *see PhysRevD.101.023012*

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

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





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.

Olinto_2021_J._Cosmol._Astropart._Phys._2021_007

POEMMA: UHECR Sky Coverage: *see PhysRevD.101.023012*

Significant increase in exposure with all-sky coverage

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

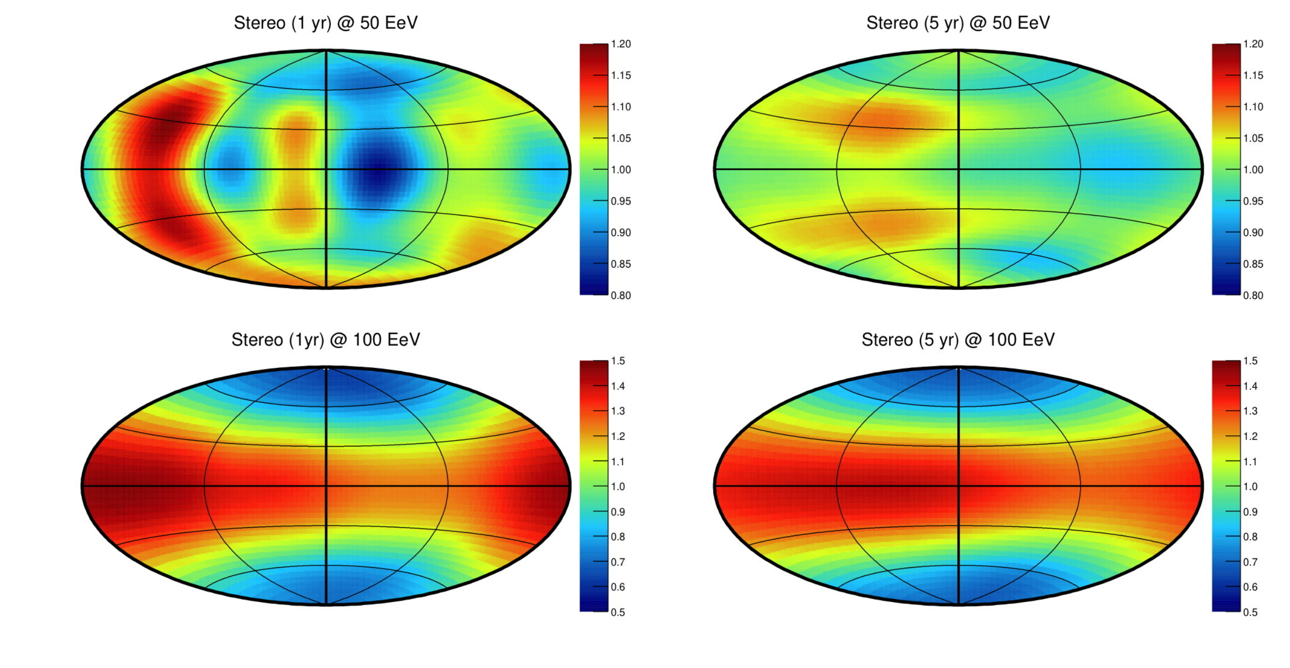
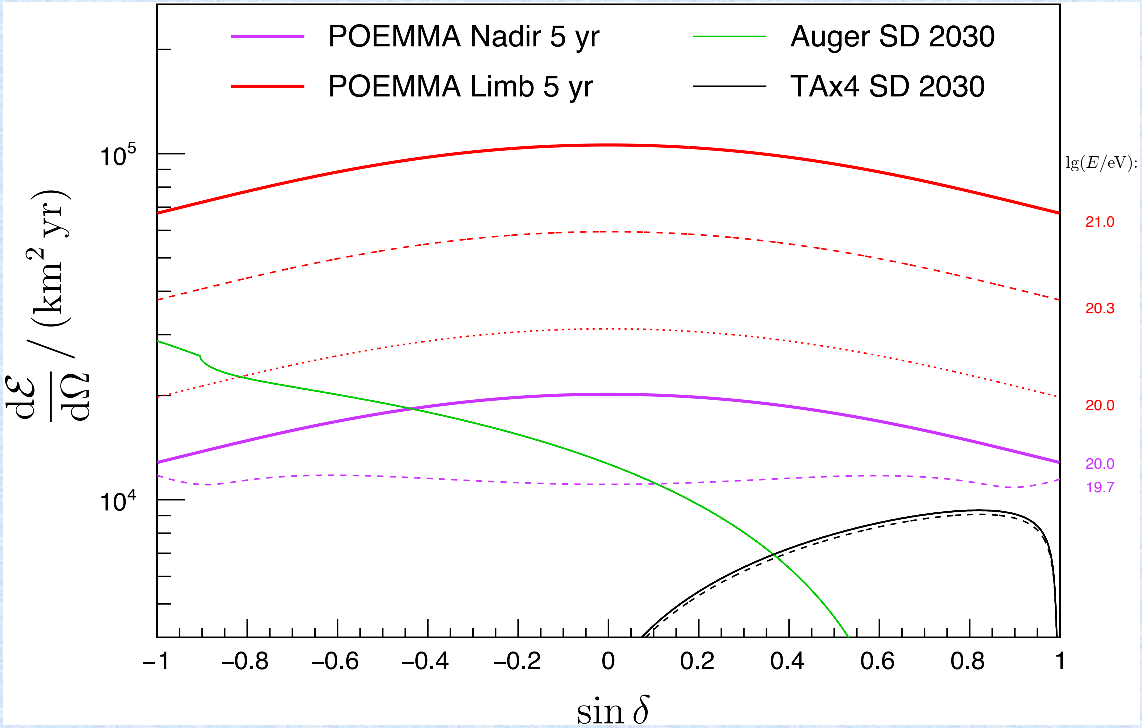


FIG. 13: POEMMA's UHECR sky exposures in declination versus right ascension. The color scale denoting the exposure variations in terms of the mean response taking into account the positions of the sun and the moon during the observation cycle.



POEMMA: UHECR Anisotropy Analysis *see PhysRevD.101.023012*

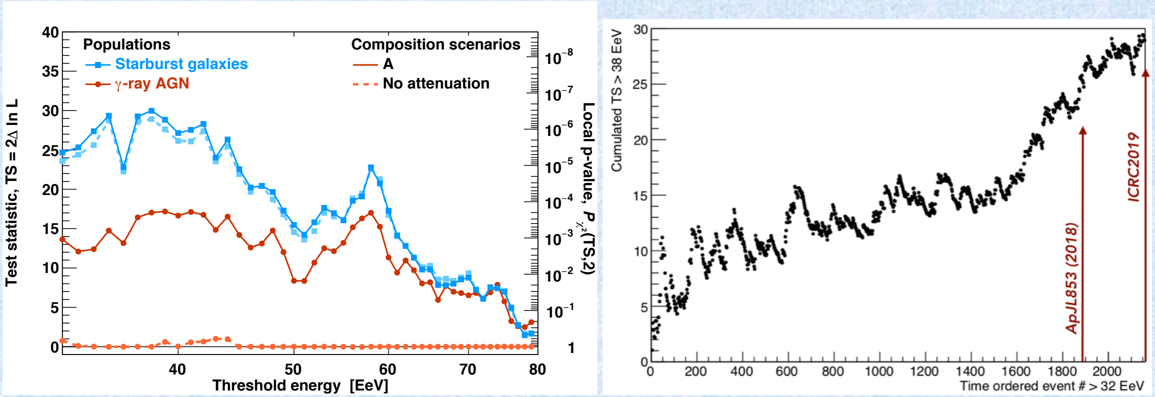


Figure 11: Left: Maximum likelihood-ratio as a function of energy threshold for the models based on SBGs and γAGNs. The results are shown in the attenuation (full line) and no-attenuation (dashed line) scenarios. Right: Cumulated test statistics for $E_{\mathrm{thr}} = 38$ EeV as a function of the time 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.

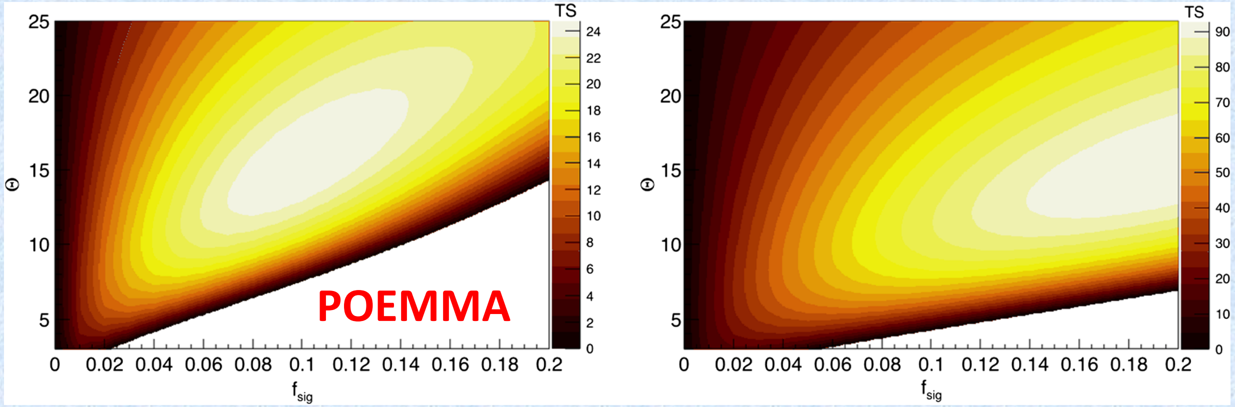


FIG. 24. TS profile for 1400 events for a particular scenario using the starburst source sky map in Fig. 23. In the scenario pictured here, the fraction of events drawn from the source sky map is $f = 10\%$ (left) and 20% (right), and the angular spread is $\Theta = 15°$.

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

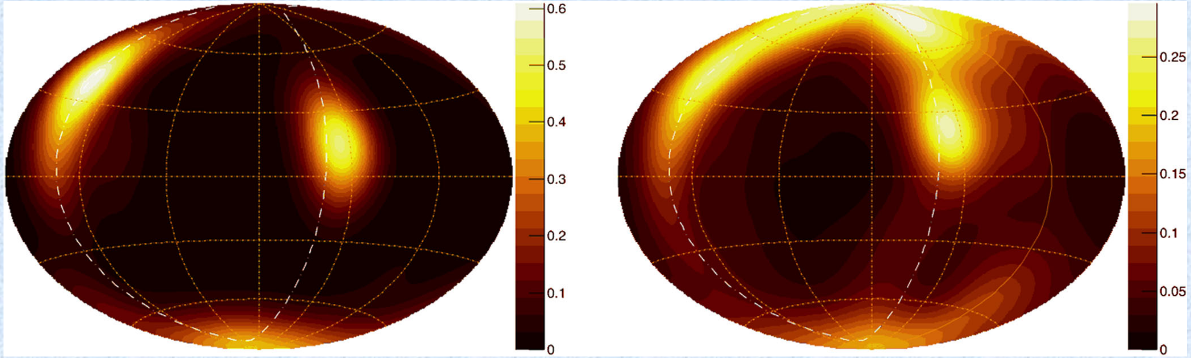
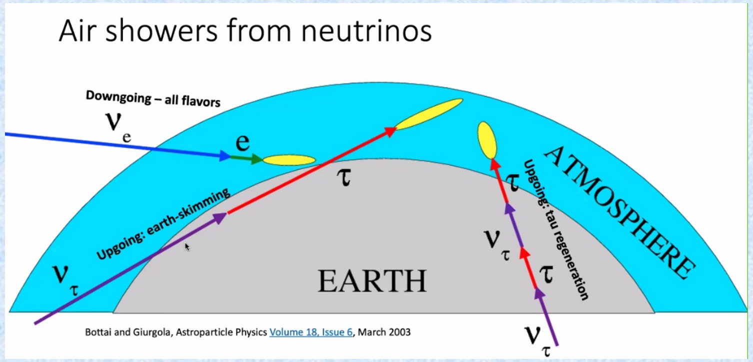
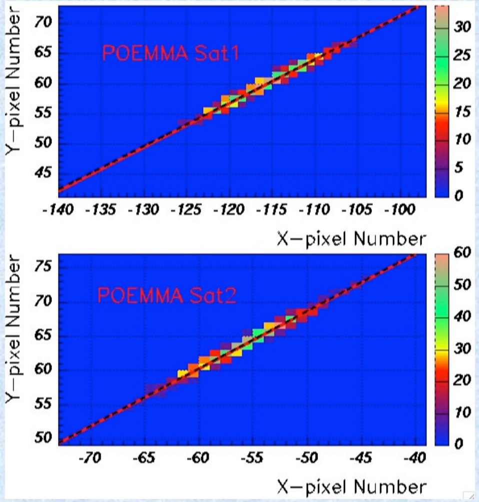


FIG. 23. Left: Skymap of nearby starburst galaxies from Refs. [35,103] weighted by radio flux at 1.4 GHz, the attenuation factor accounting for energy losses incurred by UHECRs through propagation, and the exposure of POEMMA. The map has been smoothed using a von Miser-Fisher distribution with concentration 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.

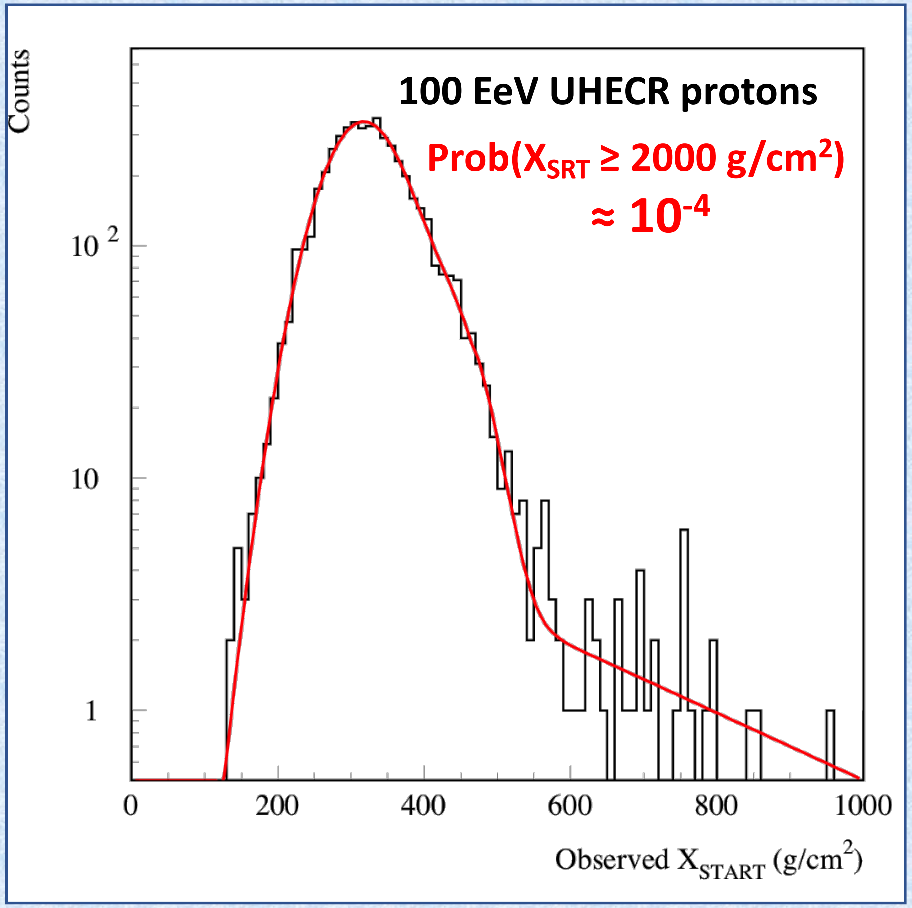
POEMMA: stereo reconstructed angular resolution: *see PhysRevD.101.023012*

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





50 EeV simulated event



UHECR 100% proton assumption most conservative

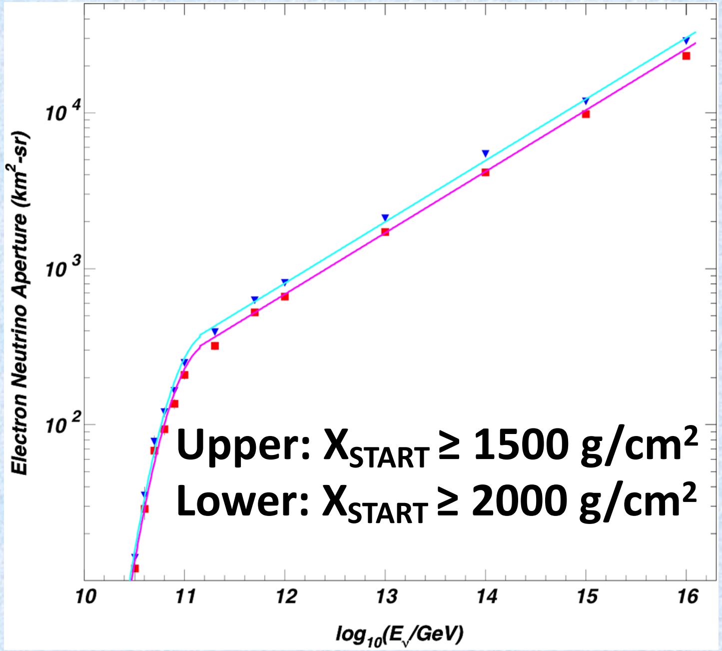


FIG. 42. Comparison of the instantaneous electron neutrino apertures based on stereo air fluorescence measurements. Upper points and curve are for $X_{\mathrm{Start}} \geq 1500$ g/cm^2 while the lower points and curve are for $X_{\mathrm{Start}} \geq 2000$ g/cm^2. The lower curve is 85% of the upper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

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

Effectively comes for free in stereo UHECR mode

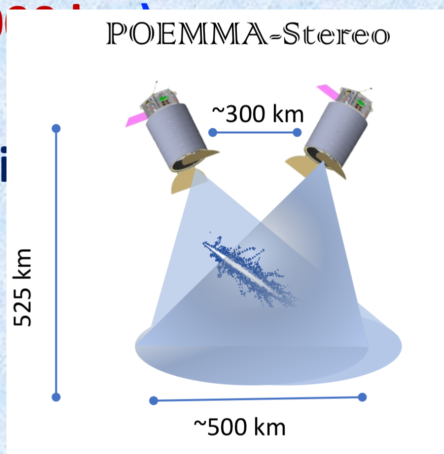
For $E_\nu \gtrsim$ 1 PeV, σ_{CC} & σ_{NC} virtually identical for ν & νbar

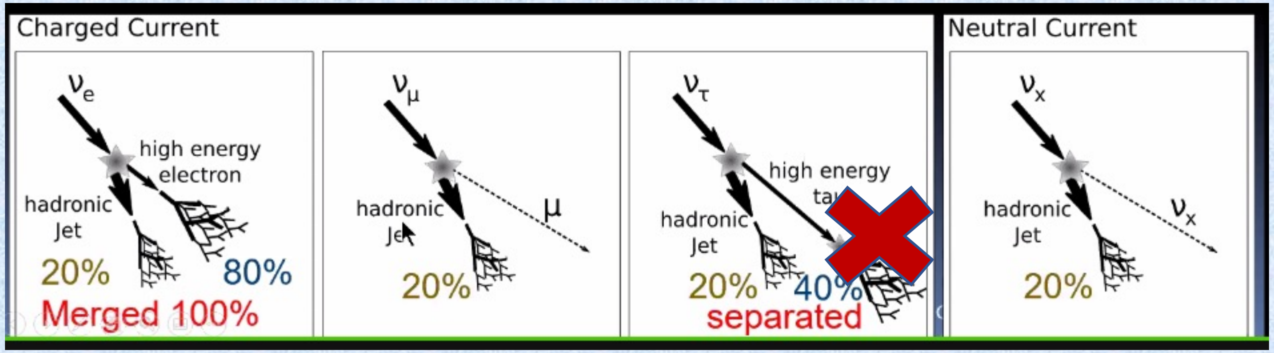
Assumptions:

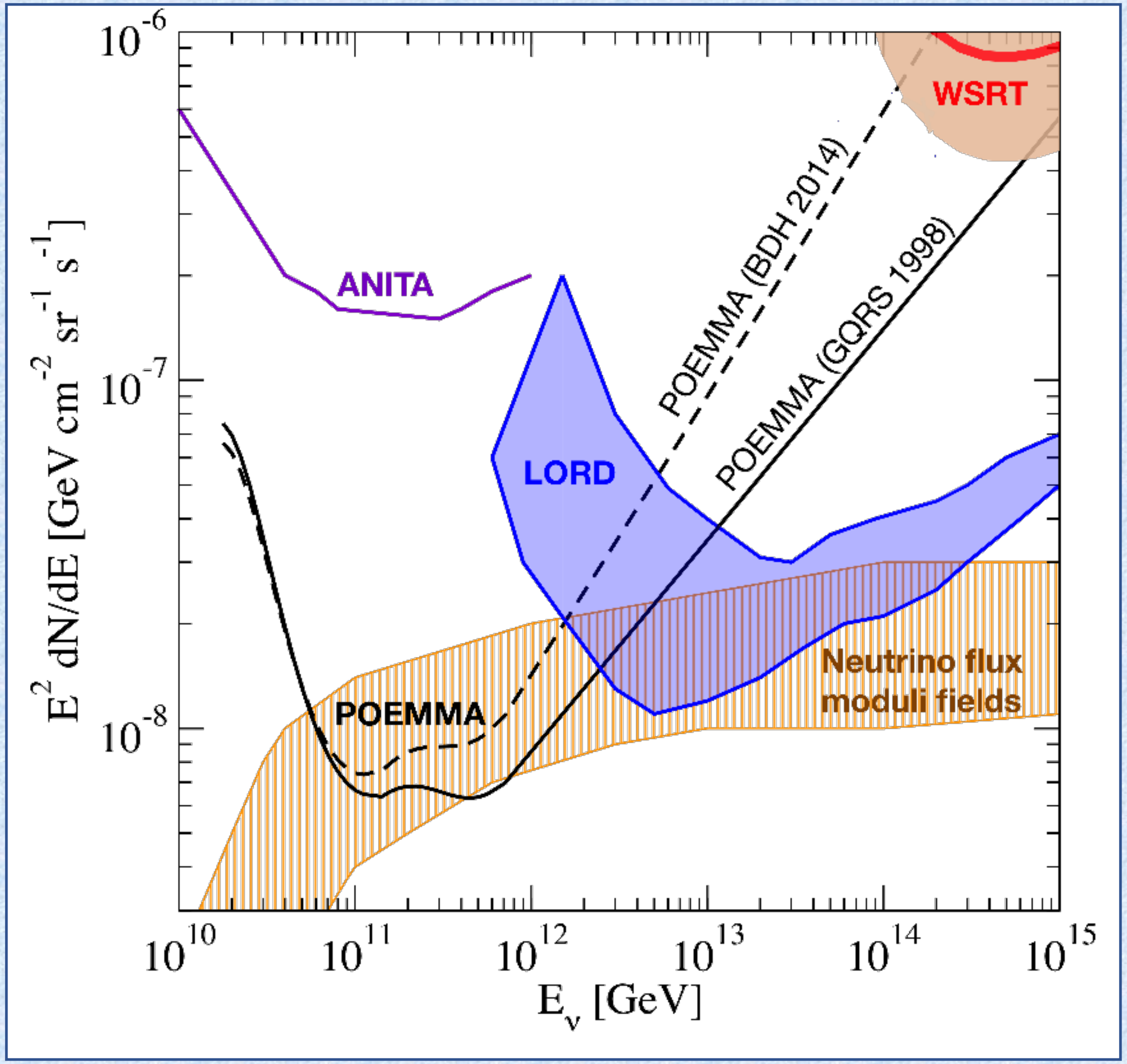
- CC ν_e : 100% E_ν in EAS
- CC ν_μ & ν_τ : 20% E_ν in EAS ($\gamma c \tau_\tau \approx$ 50
- NC ν_e & ν_μ & ν_τ : 20% E_ν in EAS

UHECR Background Probabilities (1 event i

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





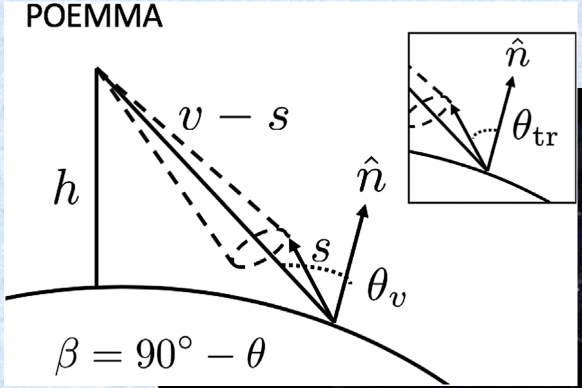


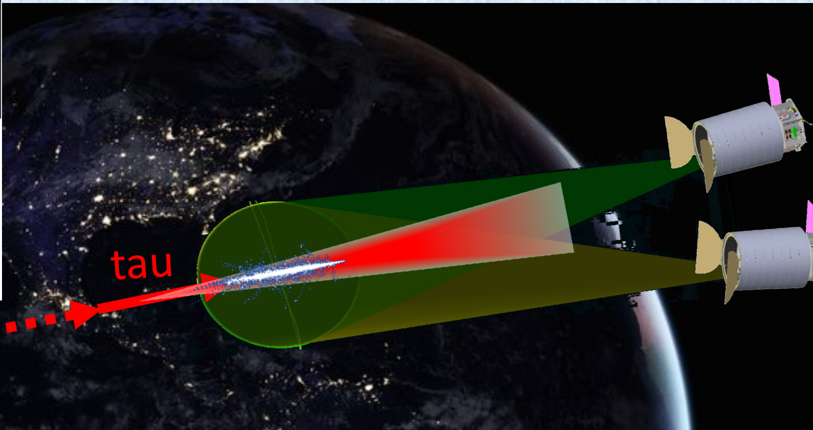
E. Zas: nuTau21: *The radio technique and UHE tau neutrino searches*

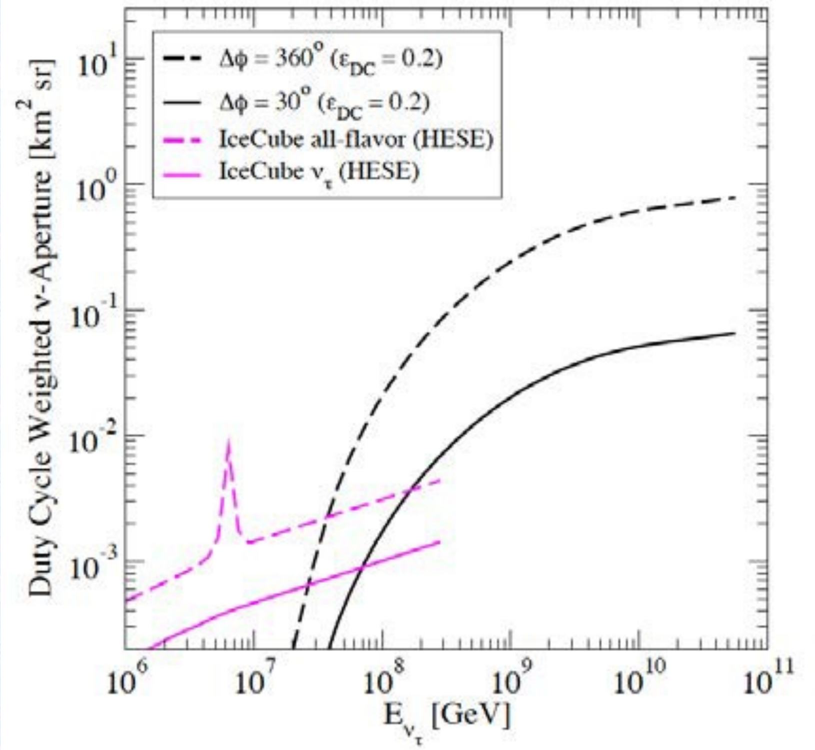
POEMMA Tau Neutrino Detection: *see PhysRevD.100.063010 and PhysRevD.102.123013*

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

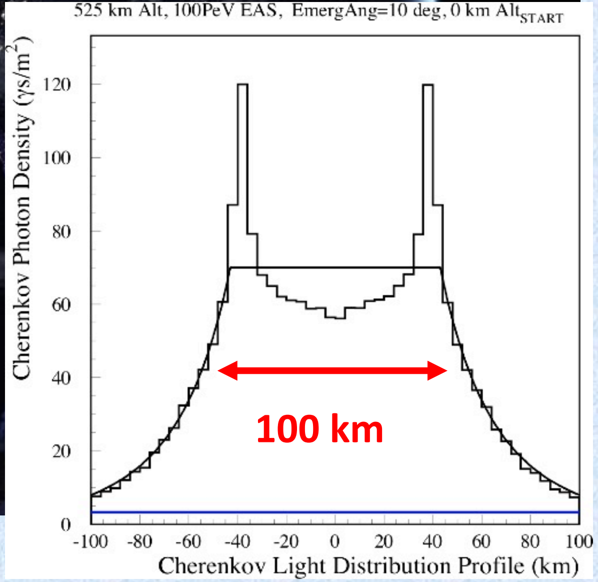
POEMMA designed to observe neutrinos with E > 20 PeV through Cherenkov signal of EASs from Earth-emerging tau decays.

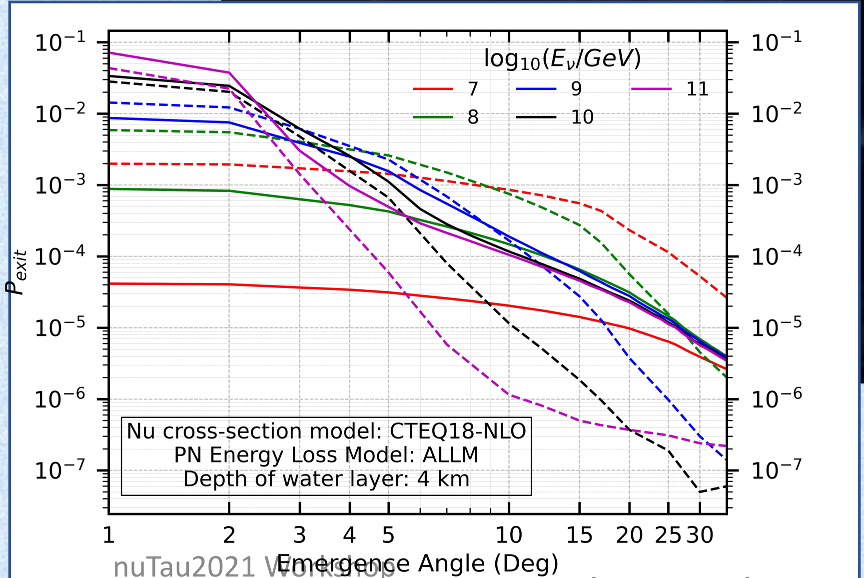






Astrophysics Measurements: Regeneration Important!





nuPyProp:S. Patel & M.H. Reno: PoS(ICRC2021)1203

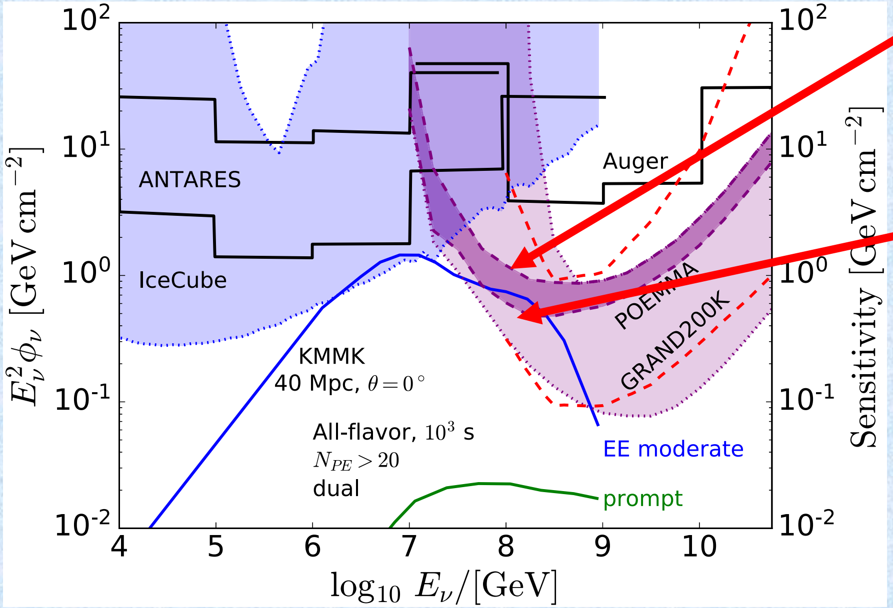
ToO Neutrino Sensitivity: *see PhysRevD.102.123013*

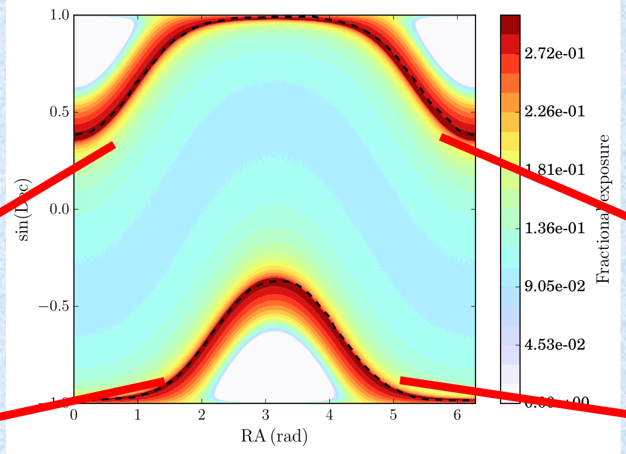
17% hit for ignoring $\tau \rightarrow \mu$ channel

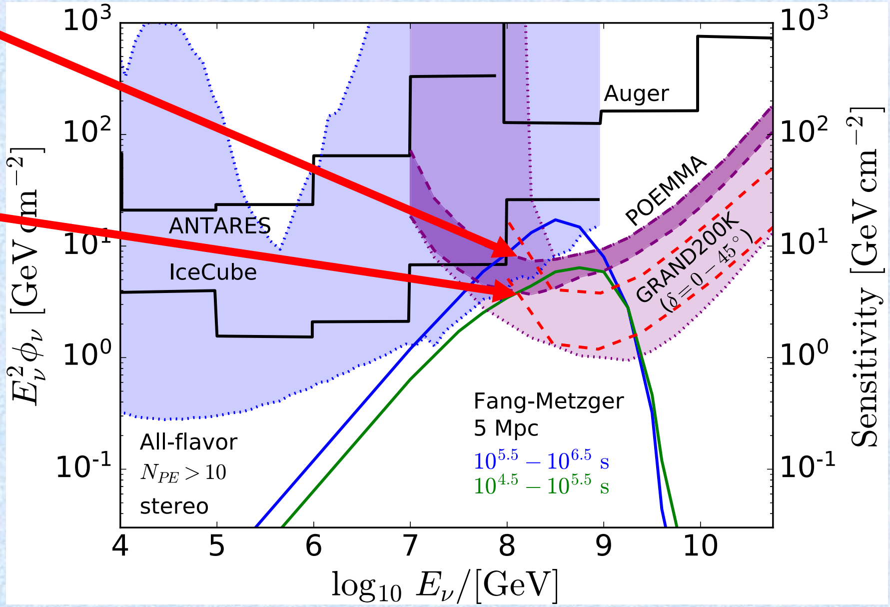
Short Bursts:
- 500 s to slew to source after alert
- 1000 s burst duration
- Source celestial location optimal
- Two independent Cher measurements
    - 300 km SatSep
- 20 PE threshold:
    - AirGlowBack < 10^{-3}/year

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

POEMMA ToO Neutrino Sensitivity: *see PhysRevD.102.123013*

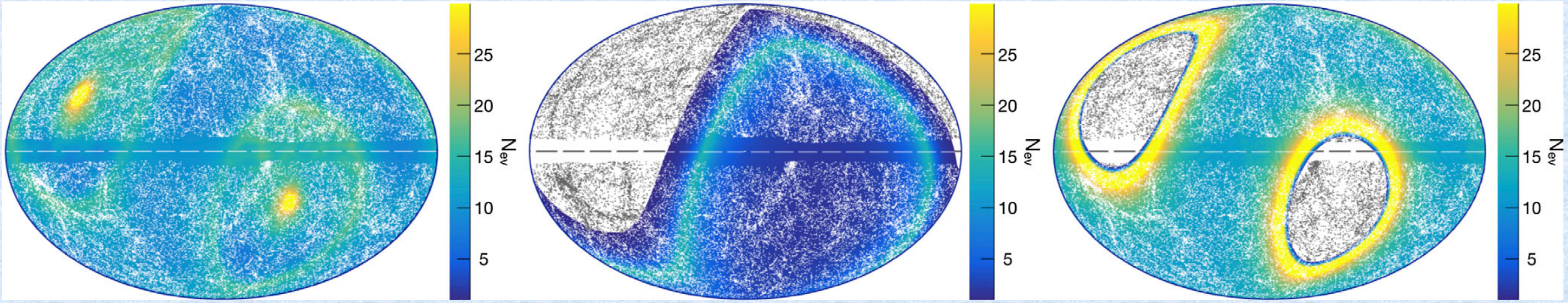


FIG. 7. Left: sky plot of the expected number of neutrino events as a function of galactic coordinates for POEMMA in the long-burst scenario of a BNS merger, as in the Fang and Metzger model [22], and placing the source at 5 Mpc. Point sources are galaxies from the 2MRS catalog [78]. Middle: same as 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.

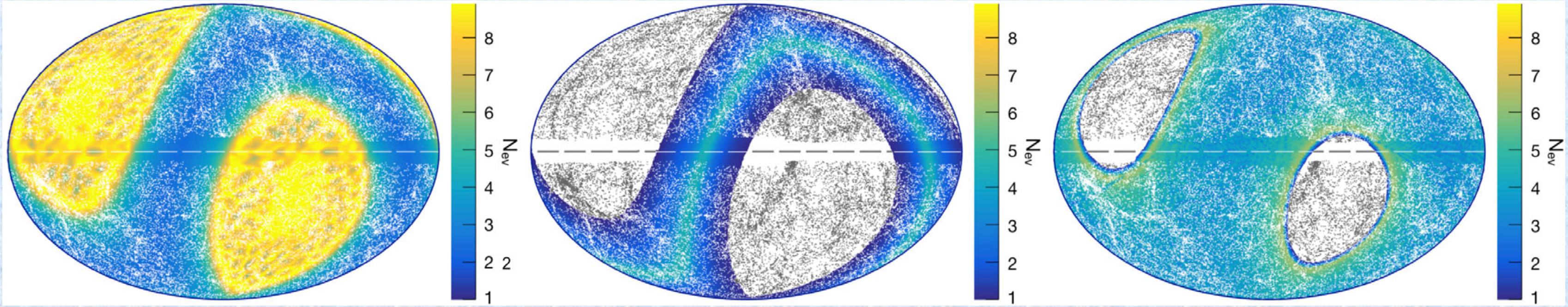
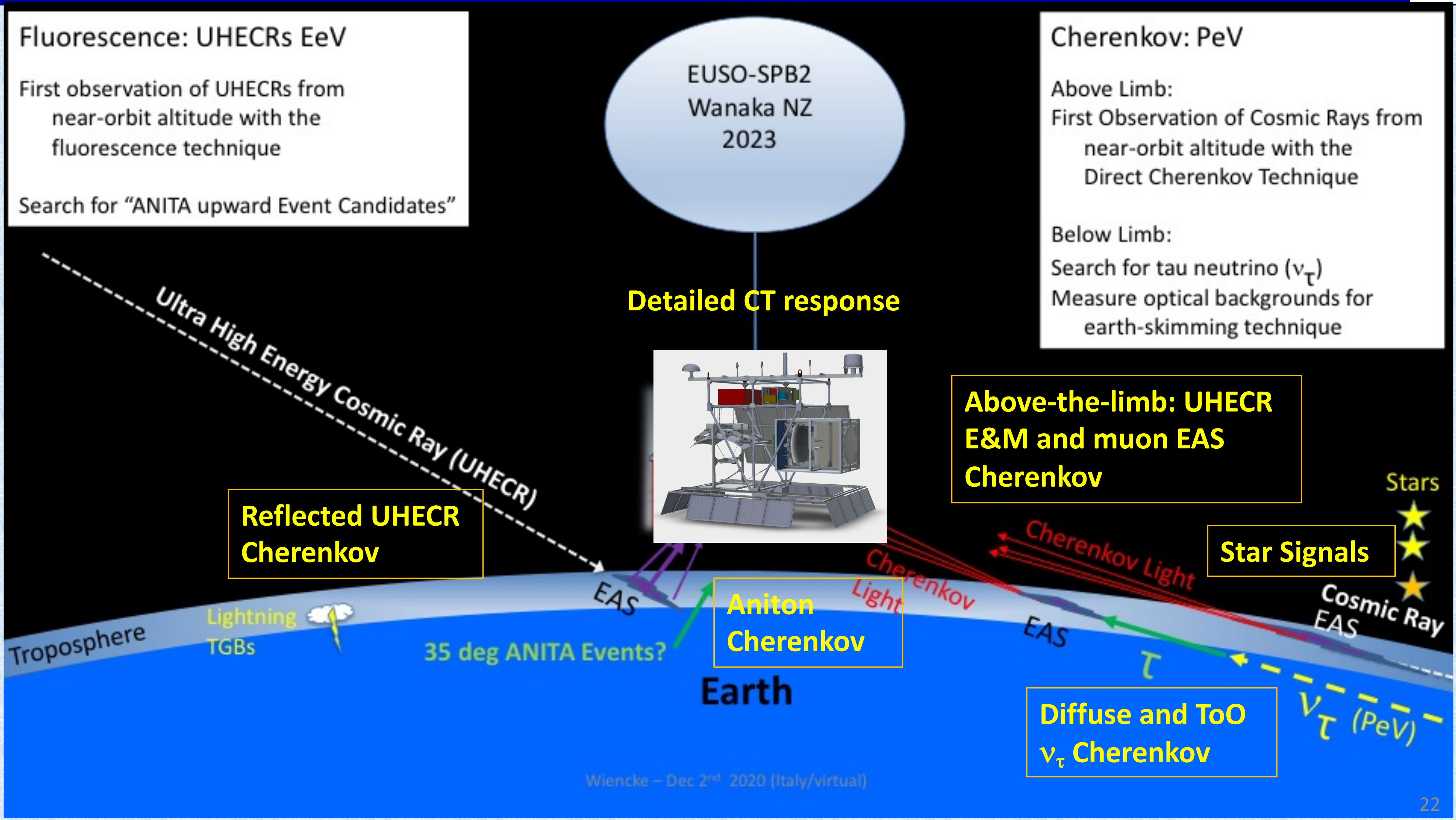


FIG. 8. Left: sky plot of the expected number of neutrino events as a function of galactic coordinates for POEMMA in the best-case short-burst scenario of an sGRB with moderate EE, as in the KMMK model [17], and placing the source at 40 Mpc. Point sources are galaxies from the 2MRS catalog [78]. Middle: 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.

EUSO-SPB2: Sources of Cherenkov Signals

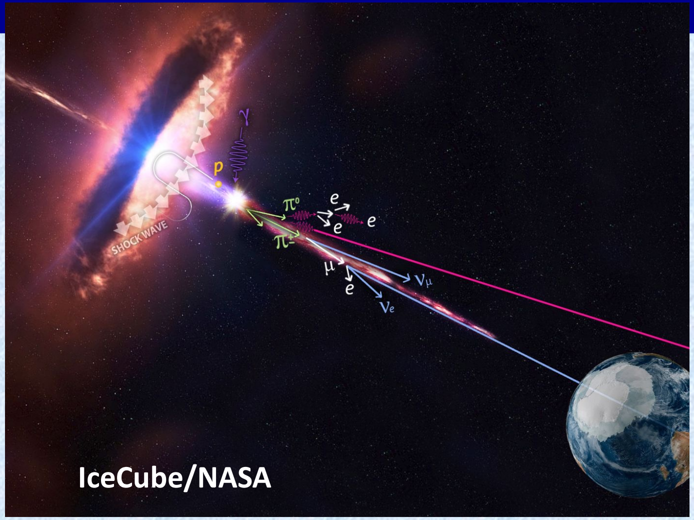


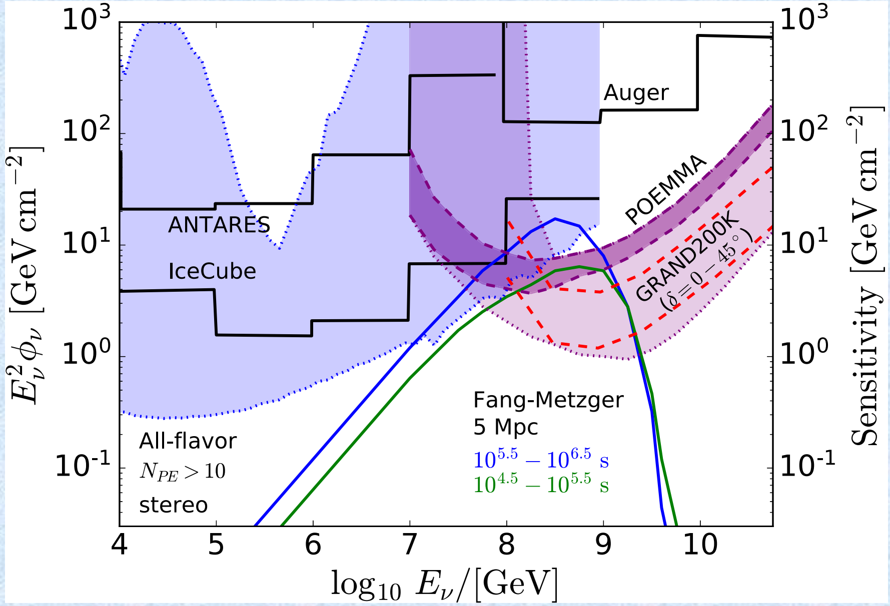
Future Modeling Motivation from initial Simulation Studies

Space-based Diffuse flux sensitivity limited by Field-of-View, exposure and or energy threshold:

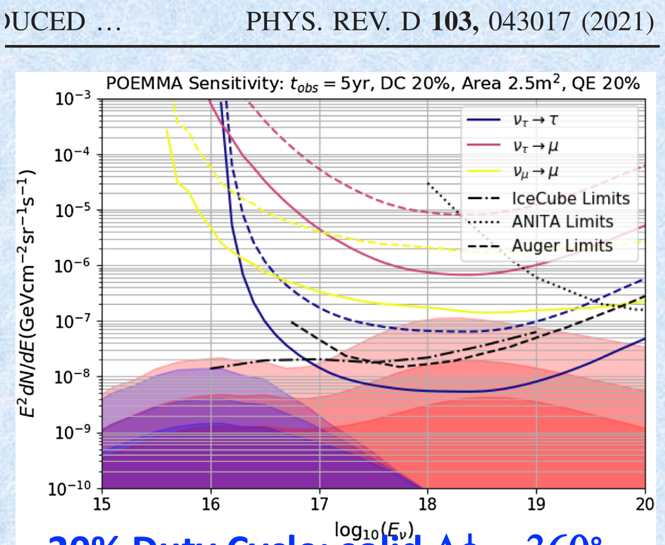
- For POEMMA:
  - **Optical Cherenkov: $E_\nu \gtrsim 20$ PeV,** but view of limb is $7^\circ \times 30^\circ$, exposure limited compared to current ground-based experiments → goto $\Delta\phi = 360^\circ$?
  - Fluorescence: large neutrino aperture, but $E_\nu \gtrsim 20$ EeV
- **However, sensitivity to transient sources ~ instantaneous neutrino aperture & can 'follow source' : sensitivity assumes A_{eff} = 2.5 m^2**

Motivates the development of a robust, versatile simulation tool and to include EAS radio signal generation.

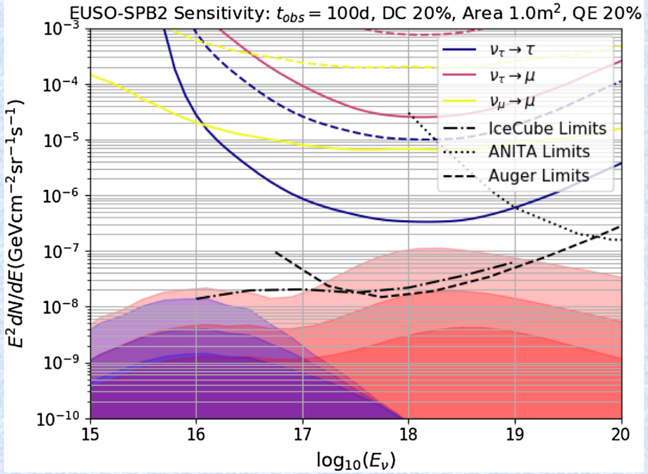




Venters et al, *PhysRevD.102.123013*



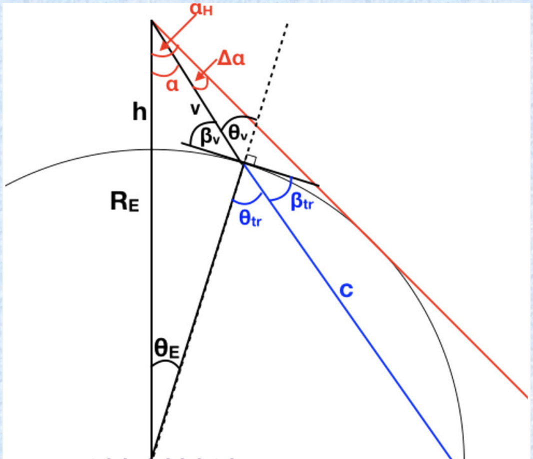
20% Duty Cycle; solid $\Delta\phi = 360^\circ$



PhysRevD.103.043017:
A.L. Cummings, R, Aloisi, J.F. Krizmanic

$\nu_\mu \to \mu \to$ EAS and $\nu_\tau \to \tau \to \mu \to$ EAS channels.

τ-lepton decay induced Upward-moving EAS properties



PhysRevD.100.063010:
M.H. Reno,, J.F. Krizmanic, & T.M Venters

FIG. 1. Geometry for detecting an EAS from an upward-moving tau neutrino. The angles β_v and θ_v label the elevation angle and local zenith angle for the point along the line of sight. Angles β_{tr} and θ_{tr} describe the emerging tau trajectory.

	Altitude [km]		
	3	33	525
HorizAng [deg]	88.24	84.18	67.50
HorizAng -Alpha [deg]	Earth Emerg Ang [deg]		
1	2.13	3.56	6.97
3	4.42	6.64	12.33
5	6.53	9.14	16.24
7	8.58	11.44	19.60
10	11.63	14.74	24.09
15	16.67	20.02	30.83
25	26.70	30.32	43.01
35	36.72	40.47	54.44

PoS(ICRC2021)1203 : S. Patel, M.H Reno, for νSpaceSim

Stochastic vs Continuous Eloss

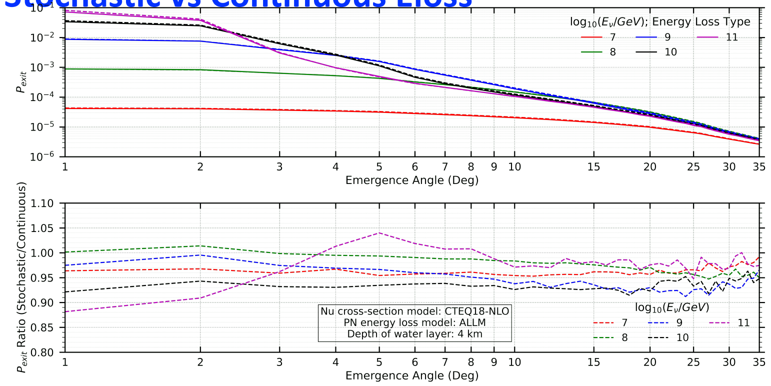


Figure 3: Exit probability P_{exit} versus Earth emergence angle β_{tr} for stochastic (solid) and continuous (dashed) energy loss modeling ($\nu_\tau \to \tau$) (upper) and the ratio of stochastic to continuous evaluation of P_{exit} (lower).

PoS(ICRC2021)1205 : νSpaceSim Collaboration

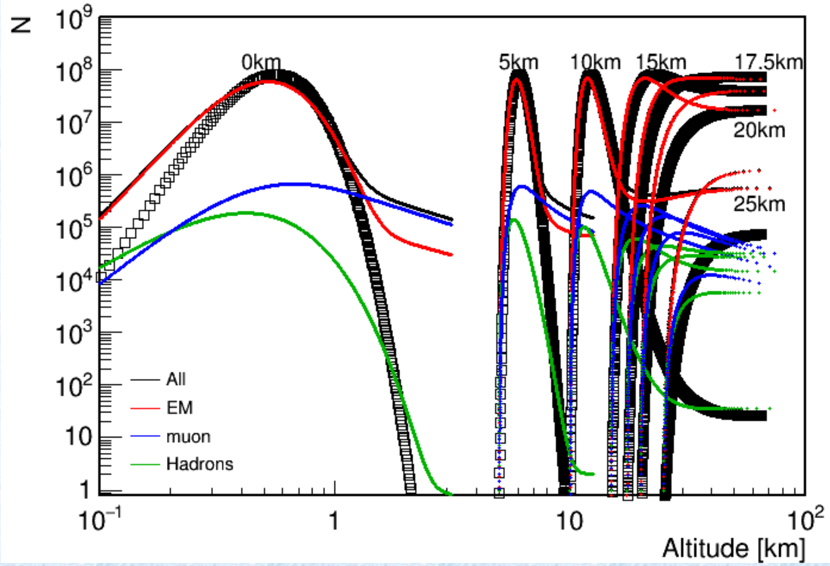
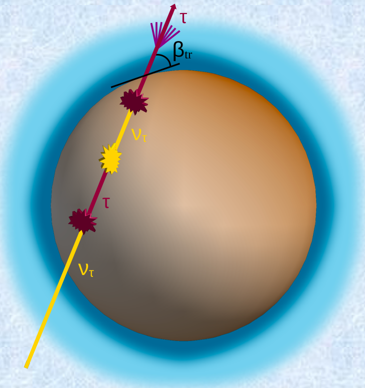


Figure 3: The average longitudinal EAS profiles from the CONEX simulation for 100 PeV pions for 5° Earth-emergence angle as a function of EAS starting altitudes. The various components (solid lines) are compared to the Greissen parameterization (black boxes).



PhysRevD.100.063010

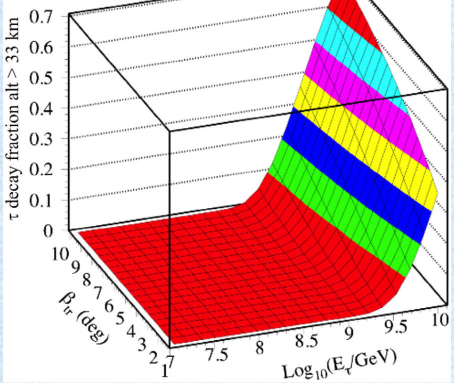
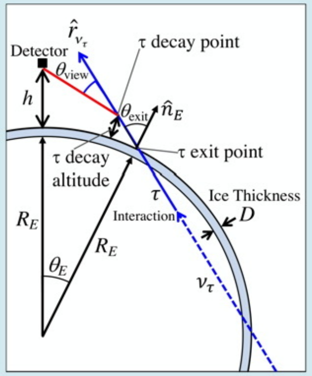


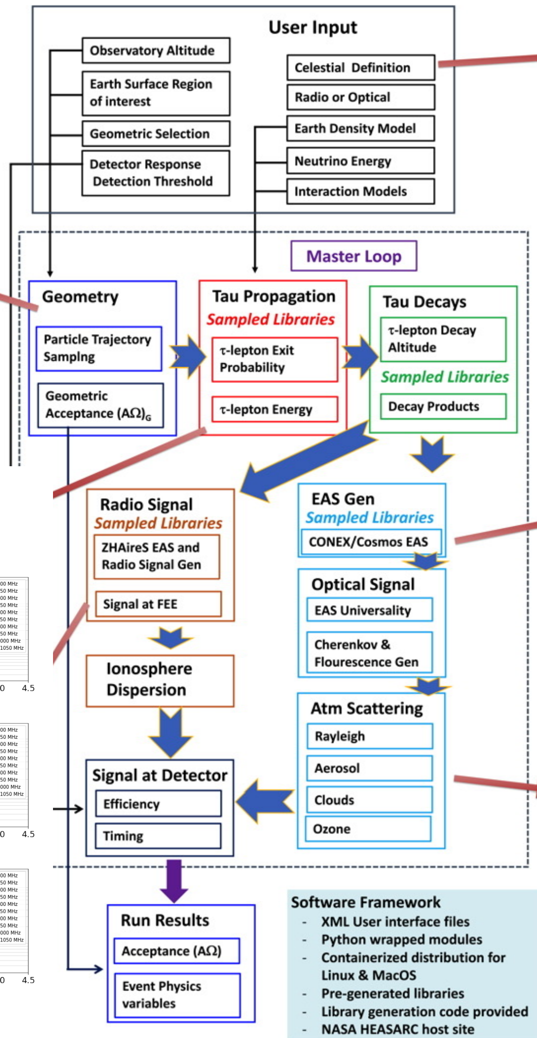
FIG. 17. The fraction of taus that decay at an altitude larger than 33 km, as a function of β_{tr} and $\log_{10}(E_\tau/\text{GeV})$. The colored bands show 0.1 increments of the tau decay fraction.

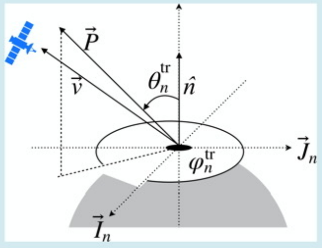
Simulation Architecture

- **Vectorized Python wrapper than schedules modules written in higher-level languages, C, C++, Fortran.**
  - Inherent multi-core processing via *Dask*
  - XML input format and HDF5 library and output format
  - Led by Alex Reustle (GSC)
- **Libraries pre-generated, with code of user to re-generate:**
  - τ-lepton exit Probability (nuPyProp, nuTauSim)
  - τ-lepton decay tables (Pythia)
  - EAS longitudinal profiles (CONEX)
- **Optical:**
  - Optical Cherenkov properties via EAS age
  - Atmosphere definition:
    - Baseline for Rayleigh scattering, aerosol & ozone absorption
    - Cloud libraries from MERRA-2 databas
  - Detailed Optical Detector modeling
- **Radio: based on ZHAireS simulated libraries**

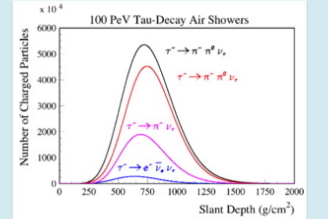


The geometry of Earth-emerging τ–lepton decays. Source Romero-Wolf et al. (arXiv:1811.07261).

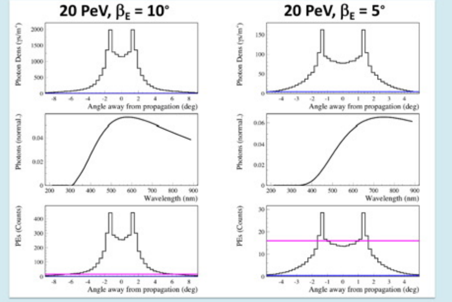




Neutrino trajectory vector ($\vec{v}$) in relation to equatorial celestial coordinate: $\vec{I}$ is the vernal equinox direction and $\hat{n}$ is the north pole direction).



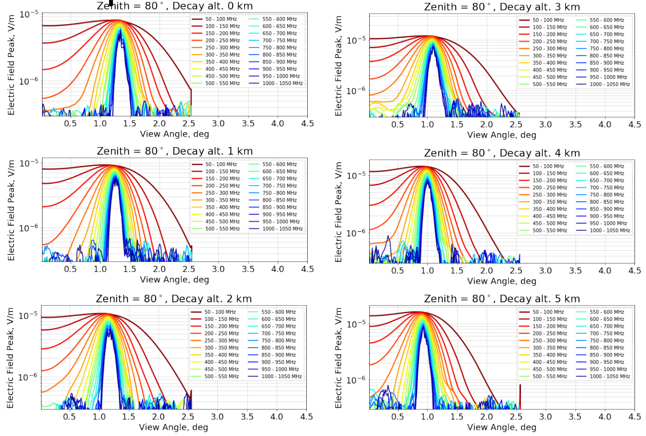
From top down, the 1st decay has 82% of the initial τ-lepton energy in the hadronic system the 2nd has 62%, the 3rd has f_π=62%, while the 4th has f_e=3%.



The optical Cherenkov signal at 33 km altitude for 20 PeV EASs starting at sea level for 10° (left) and 5° (right) Earth-emergence angles. Rayleigh, aerosol, and ozone attenuation define the Cherenkov spectrum while a standard SiPM response defines the PE signal using a 1 m² collecting area. The air glow background determines the PE detection threshold (magenta lines) for 0.1° pixels and < 0.1 background events in 100 days.

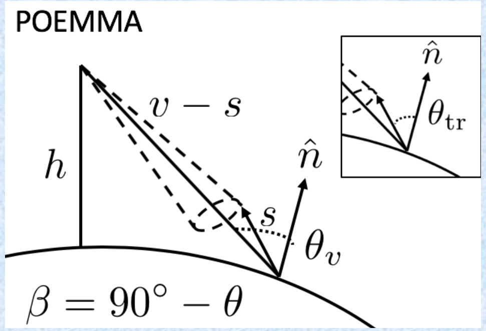
Altitude dependence

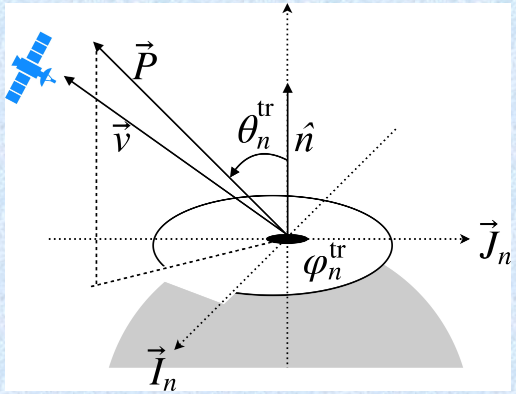
Upward EAS Radio

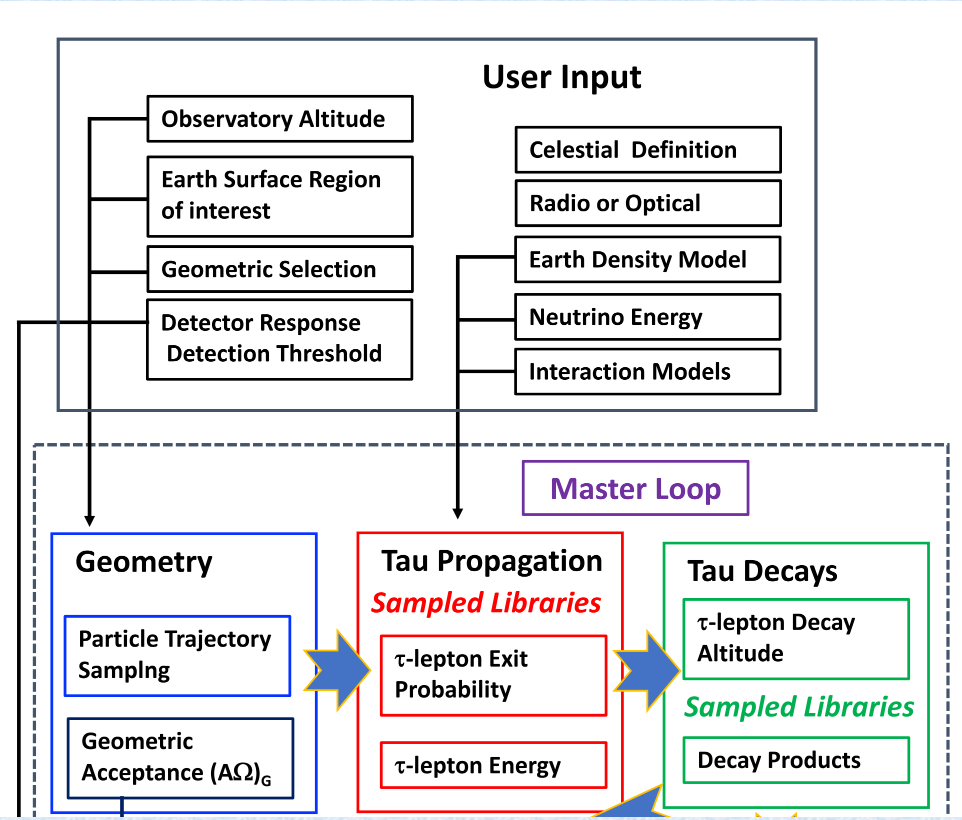


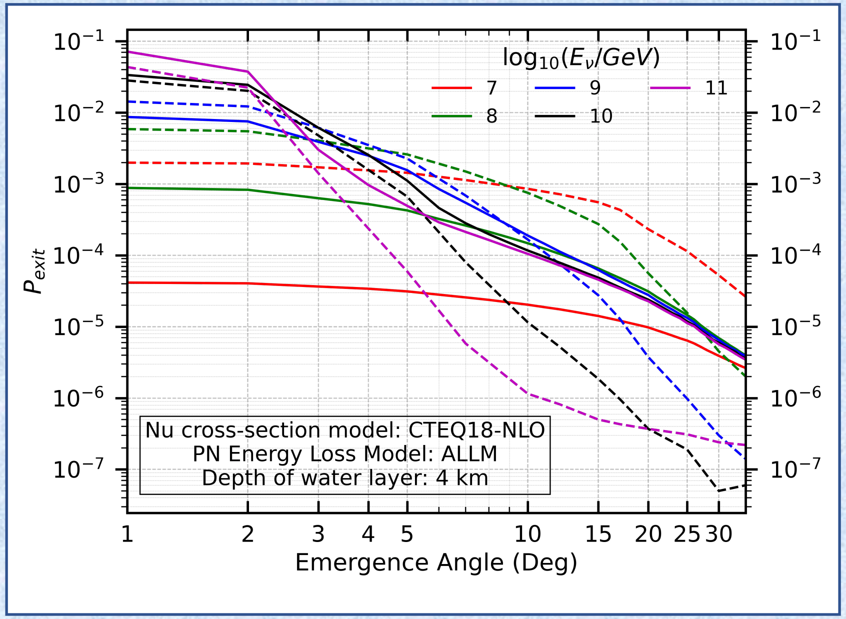
Radio signal at 37 km altitude from an upward, 100 PeV τ-lepton EAS derived from ZHAireS simulations [Alvarez-Muñiz et al. (arXiv:1107.1189)]

User Input, Geometry, Tau Yield, EAS Generation



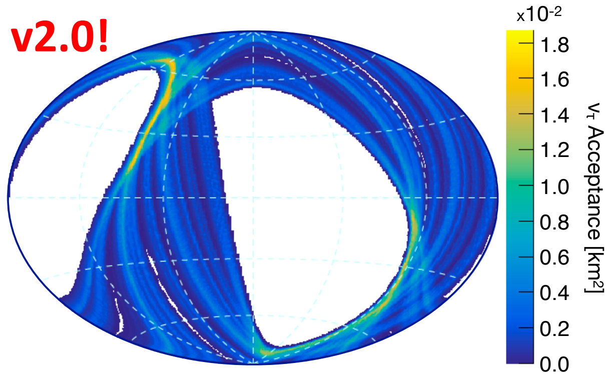


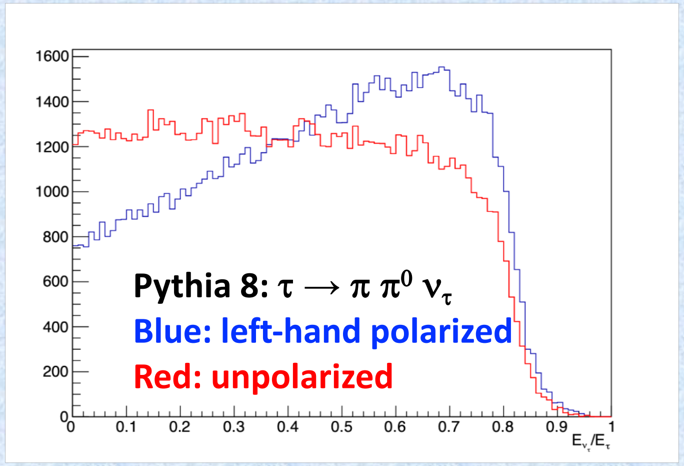




nuPyProp:S. Patel & M.H. Reno: PoS(ICRC2021)1203

Will also include nuTauSim P_{Exit}





T. Venters, M.H. Reno, J.F. Krizmanic
PoS(ICRC2021)977

Sky map of the sensitivity to transient neutrino fluxes for the EUSO-SPB2 ULDB instrument assuming observations in astronomical night near new moon. ***implementation in progress.***

Software Website: https://heasarc.gsfc.nasa.gov/docs/nuSpaceSim/

nuPyProp has been released!

β Version Optical Cherenkov Results

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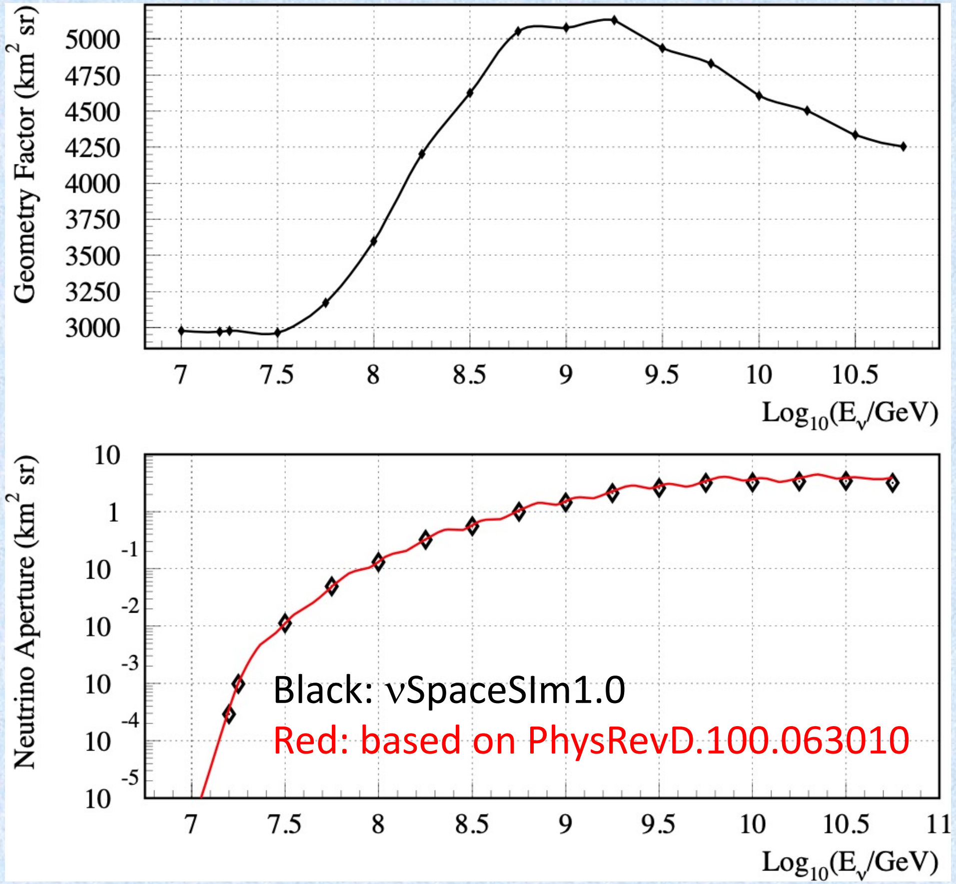
    <TelescopeEffectiveArea
Unit="Sq.Meters">2.5</TelescopeEffectiveArea>
    <PhotoElectronThreshold Preset="True">
      <NPE>10</NPE>
    </PhotoElectronThreshold>
    <DetectorAltitude Unit="km">525.0</DetectorAltitude>
    <InitialDetectorRightAscension
Unit="Degrees">0.0</InitialDetectorRightAscension>
    <InitialDetectorDeclination
Unit="Degrees">0.0</InitialDetectorDeclination>
  </DetectorCharacteristics>
  <SimulationParameters DetectionMode="Diffuse">
    <MaximumCherenkovAngle
Unit="Degrees">3.0</MaximumCherenkovAngle>
    <AngleFromLimb Unit="Degrees">7.0</AngleFromLimb>
    <TauShowerType Preset="True">
      <FracETauInShower>0.5</FracETauInShower>
    </TauShowerType>
    <NuTauEnergySpecType SpectrumType="Mono">
      <NuTauEnergy>8.0</NuTauEnergy>
    </NuTauEnergySpecType>
    <AzimuthalAngle Unit="Degrees">360.0</AzimuthalAngle>
    <NumTrajs>1000000</NumTrajs>
  </SimulationParameters>
</NuSpaceSimParams>
```



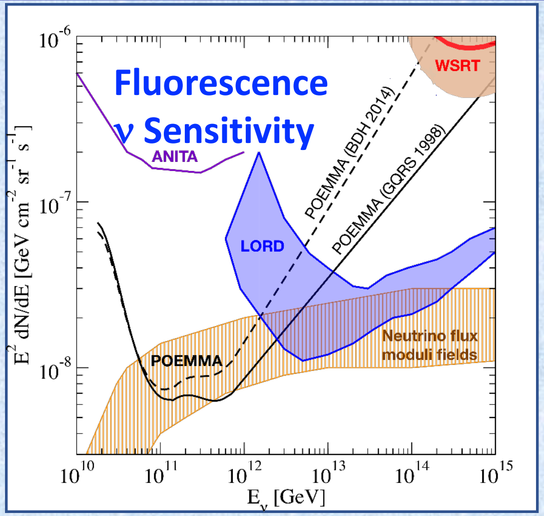
Vectorized Python wrapped higher-level language code with inherent multi-processing: takes ~ 5 hours to do this energy scan on my Mac

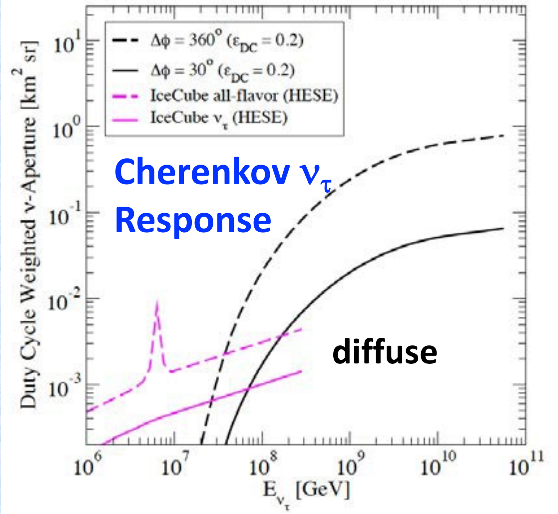
Summary

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/cm²) 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%**
- **Astrophysics work continues including POEMMA sensitivity to SHDM → ν's**

C. Guepin et al.: arXiv:2106.04446 accepted in PhysRevD





Work in Progress:

- **Awaiting Results from Astro2020**
- **νSpaceSim: Neutrino Simulation Devlopment:**
- **EUSO-SPB2 (with Cherenkov Camera) under development to ULDB fly in 2023.**
- **Future Experimental Development:**
  - **POEMMA360: 360° azimuth FoV to optimize for cosmic diffuse neutrino detection**
  - **Meter-sized A_{EFF} Optical Cherenkov telescope for cosmic neutrino transients: ISS & SmallSat**
  - **GSSI-lead Italian, SmallSat Terzina mission to use Optical Cherenkov to measure over-the-limb UHECRs**

νSpaceSim Collaboration

John Krizmanic1,2,3, Yosui Akaike[4], Luis Anchordoqui[5], Douglas Bergman[6], Isaac Buckland[6], Austin Cummings[7], Johannes Eser[8], Claire Guepin[9], Simon Mackovjak[10], Angela Olinto[8], Thomas Paul[5], Sameer Patel[11], Alex Reustle[3], Andres Romero-Wolf[12], Mary Hall Reno[11], Fred Sarazin[13], Tonia Venters[3], Lawrence Wiencke[13], Stephanie Wissel[14], Eric Mayotte[13], Sonja Mayotte[13], undergrad Fred Garcia (UMCP)

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10 Institute of Experimental Physics, Slovak Academy of Sciences, Kosice, Slovakia
11 Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa 52242 USA
12 Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA
13 Department of Physics, Colorado School of Mines, Golden, Colorado 80401 USA
14 Department of Physics, Pennsylvania State University, State College, Pennsylvania 16801 USA

νSpaceSim is funded by grants 80NSSC19K0626 (UMBC), 17-APRA17-0066 (GSFC & JPL), 80NSSC19K0460 (Colorado School of Mines), 80NSSC19K0484 (University of Iowa), 80NSSC19K0485 (University of Utah)

nuPyProp has been released!

νSpaceSim1.0 to be released this fall, including MERRA-2 cloud cover tool

Backup

POEMMA: UHECR Energy Resolution: *see PhysRevD.101.023012*

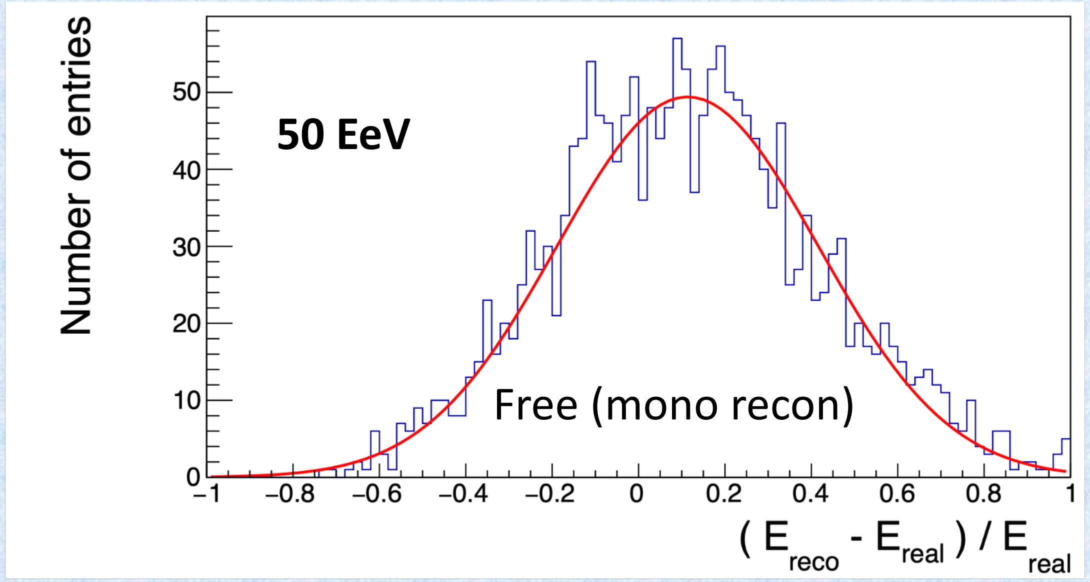
Description:

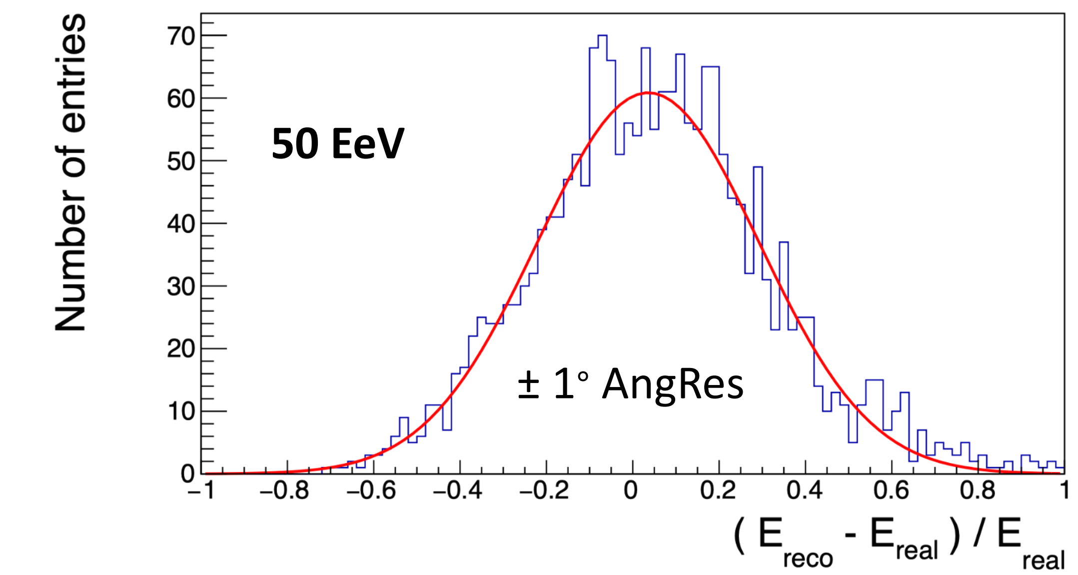
- ESAF UHECR simulations using POEMMA parameterized optics
- 2.5 μsec GTU timing, ESAF parameters:
  - QE: 0.2695
  - PMT separation: 27mm
  - Lateral dead space: 1.6692mm
  - Time resolution FEE: 10 ns
  - FOV: 22.5 deg
  - Optics Radius: 1650mm
  - FS radius: 830mm
  - Spot size, defined by POEMMA parameterized optics
  - Altitude: 525km
  - Background: 1.54 CTS/μs (rescaled JE value)

Results (Monocular Reconstruction):

- 1e20 eV FIX: -1% +- 22%:
- **1e20 eV +- 1deg: -1.5% +- 24% → 24%/√2 = 17.0% POEMMA Stereo Eres**
- 1e20 eV FREE: -2.5% +- 28%

- 5e19 eV FIX: 4.4% +- 25%
- **5e19 eV +- 1deg: 3.5% +- 26% → 26%/√2 = 18.4% POEMMA Stereo Eres**
- 5e19 eV FREE: 11% +- 30%

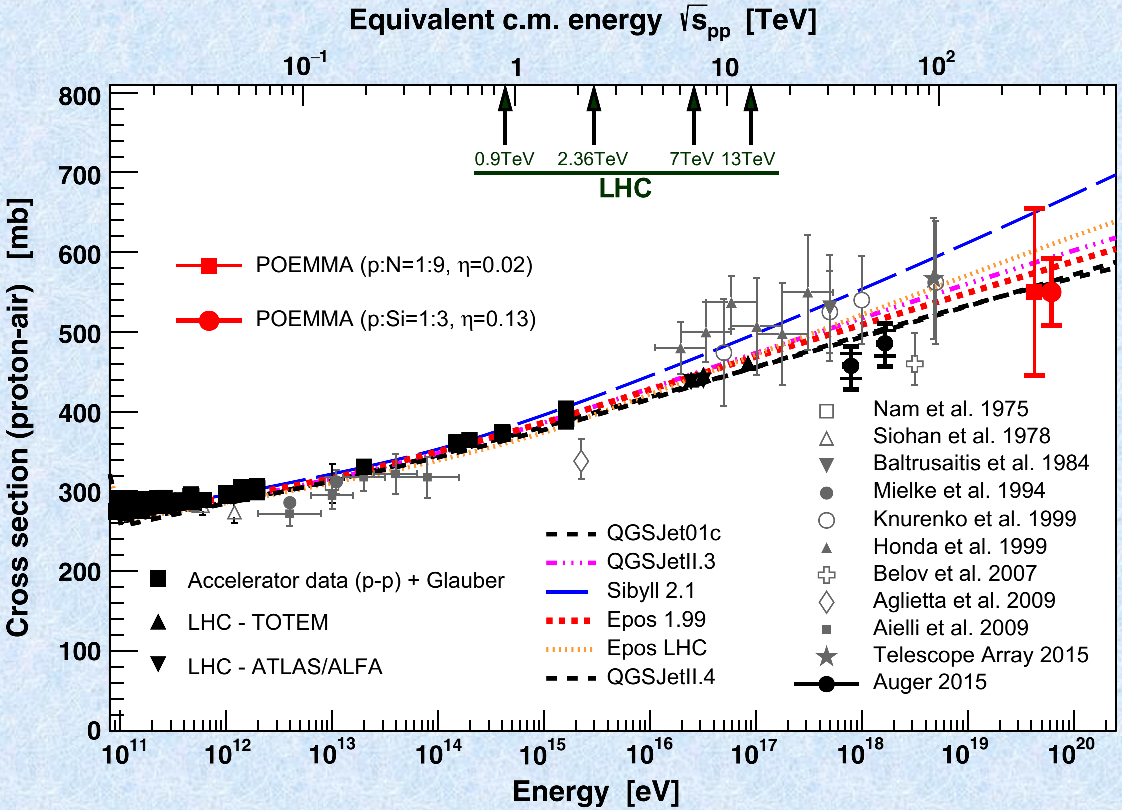




POEMMA: proton-Air Cross Section Measurements

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

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



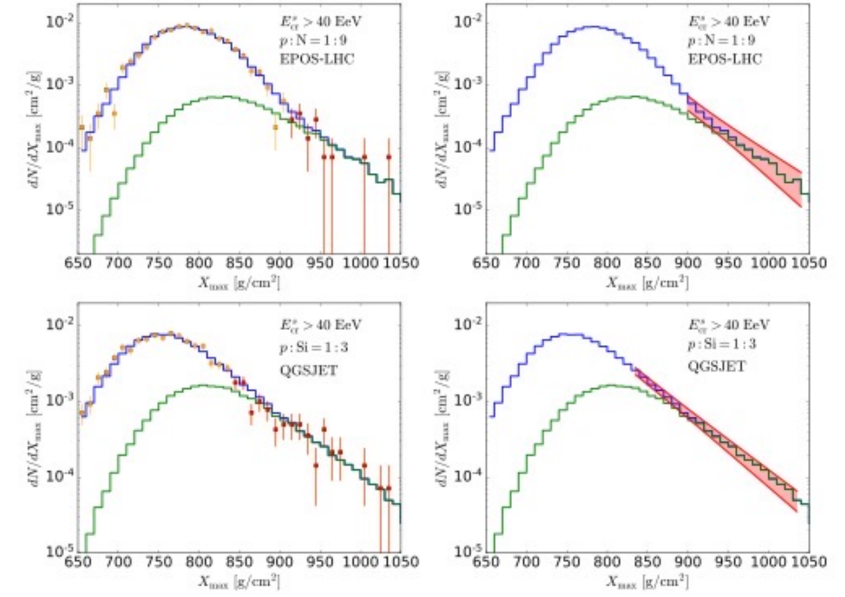


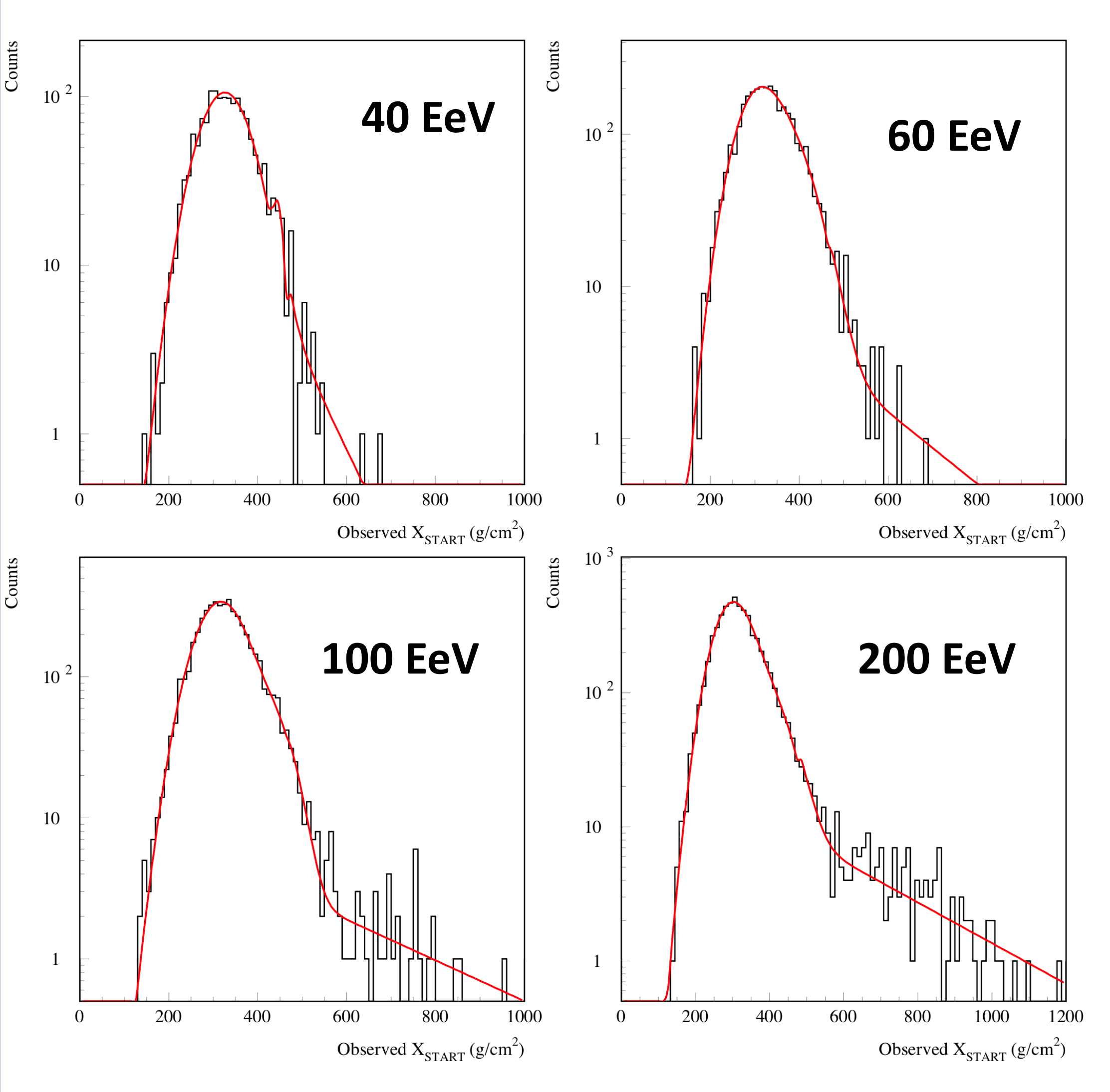
FIG. 41: The energy and X_{max} smeared distribution dN/dX_{max} for QGSJETII.04 (upper panels) and EPOS-LHC (lower panels) from the parameterization of Ref. [150] for $E_{CR} > 40$ EeV and p:N = 1:9, $\eta = 0.02$ (upper) and p:Si = 1:3, $\eta = 0.13$ (lower). The blue histograms show the full X_{max} 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}.

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.

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



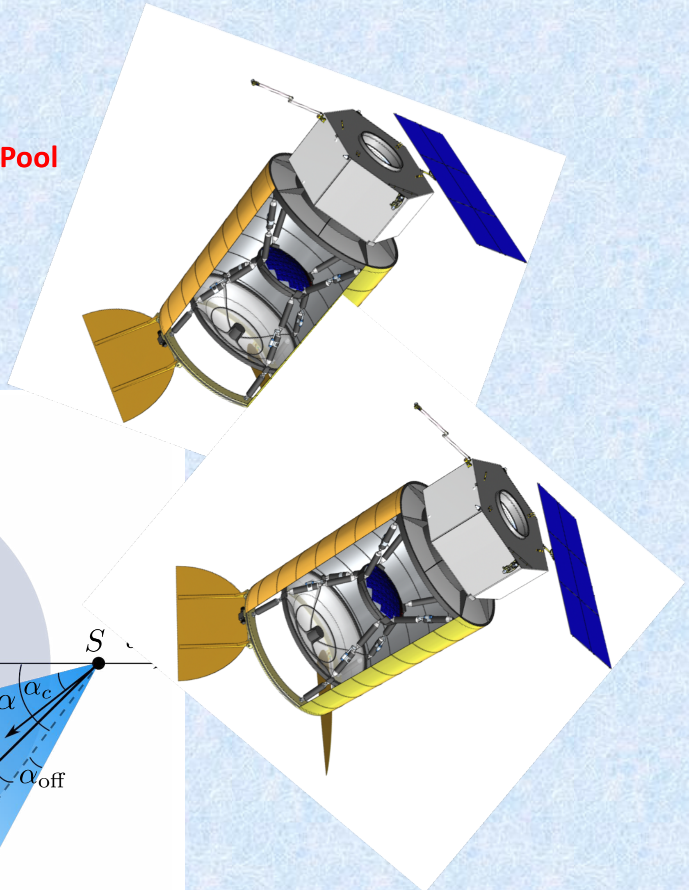
UHECR Fake ν's Background (1 event in 5 years):

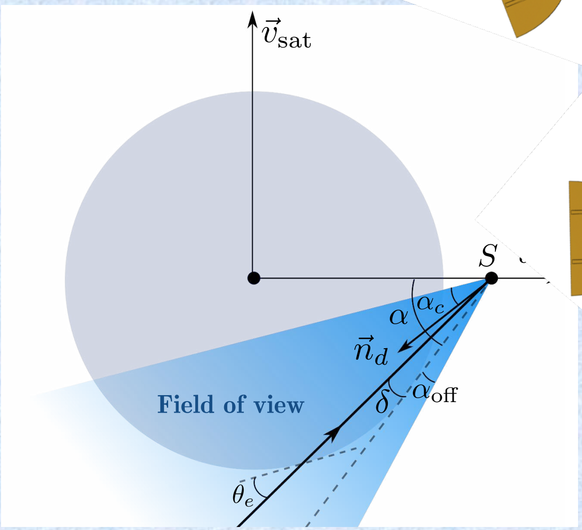
- **Auger Spectrum (100% H): < 1%**
- **TA Spectrum (100% H): ≈ 4%**

POEMMA Transient Neutrino Detection

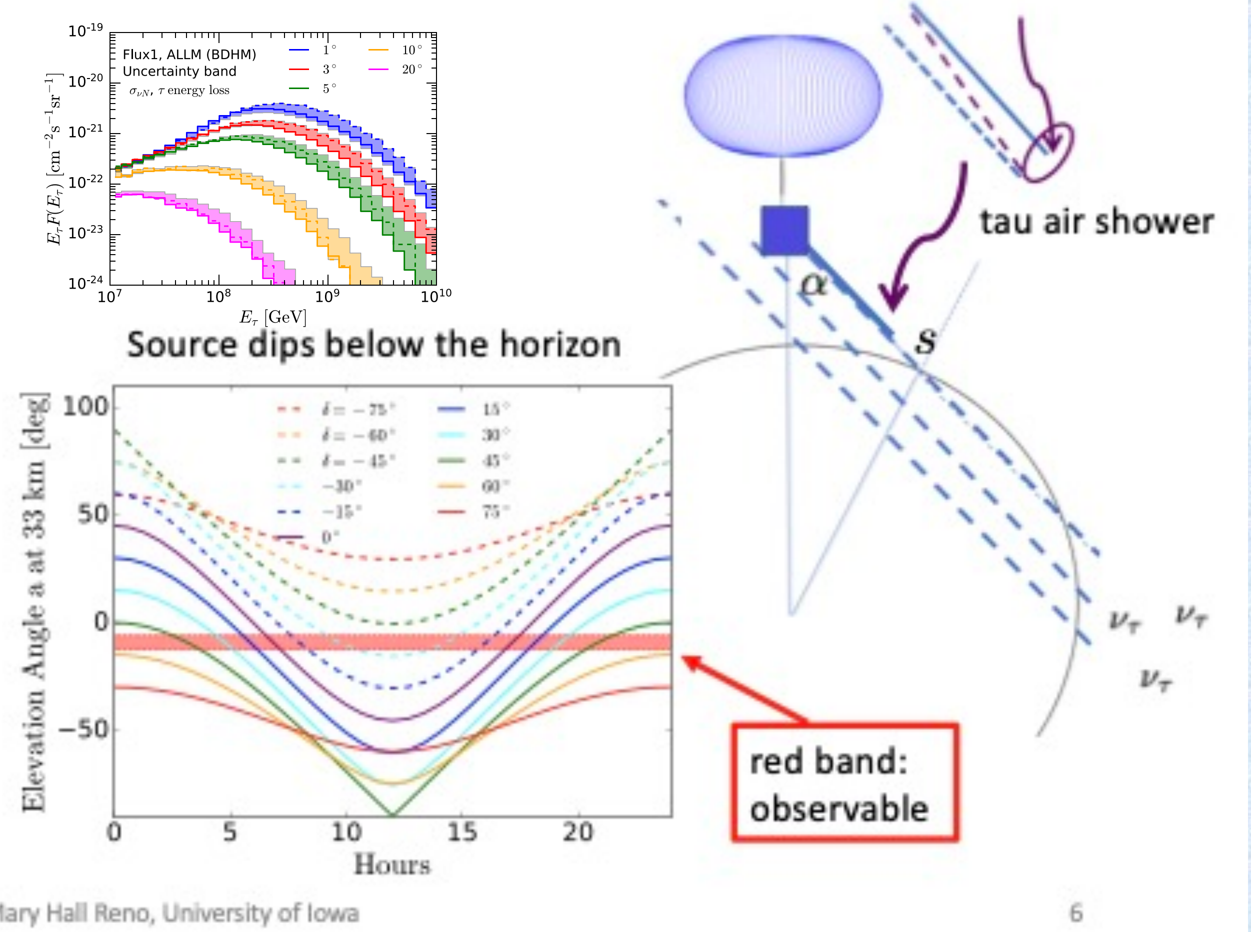
Flight Dynamics/Propulsion:

- 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)

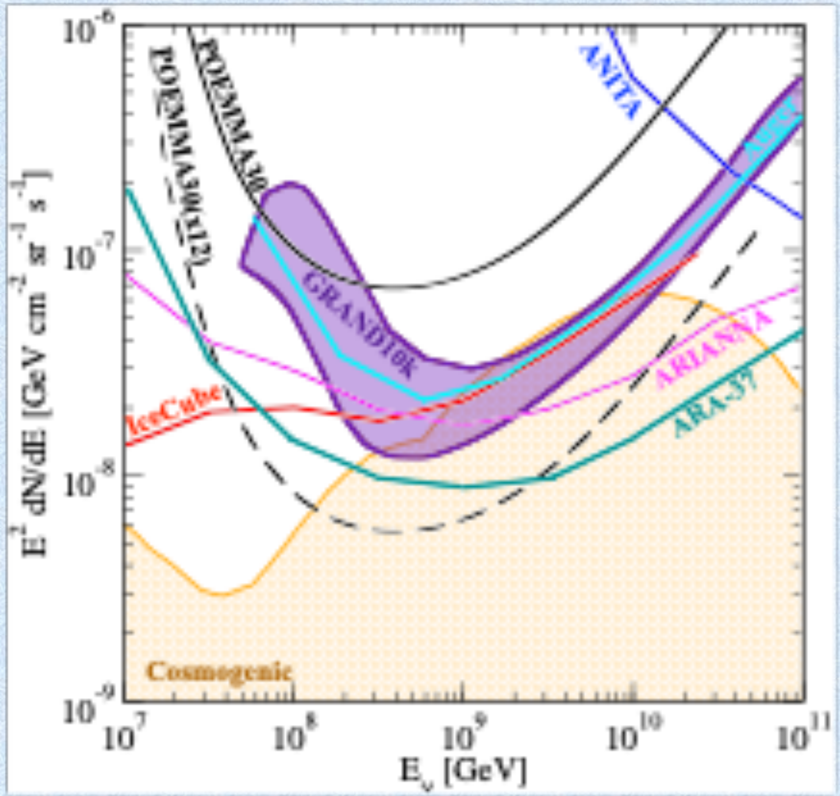


Avionics on each POEMMA satellite allow for slewing : 90° in 500 sec

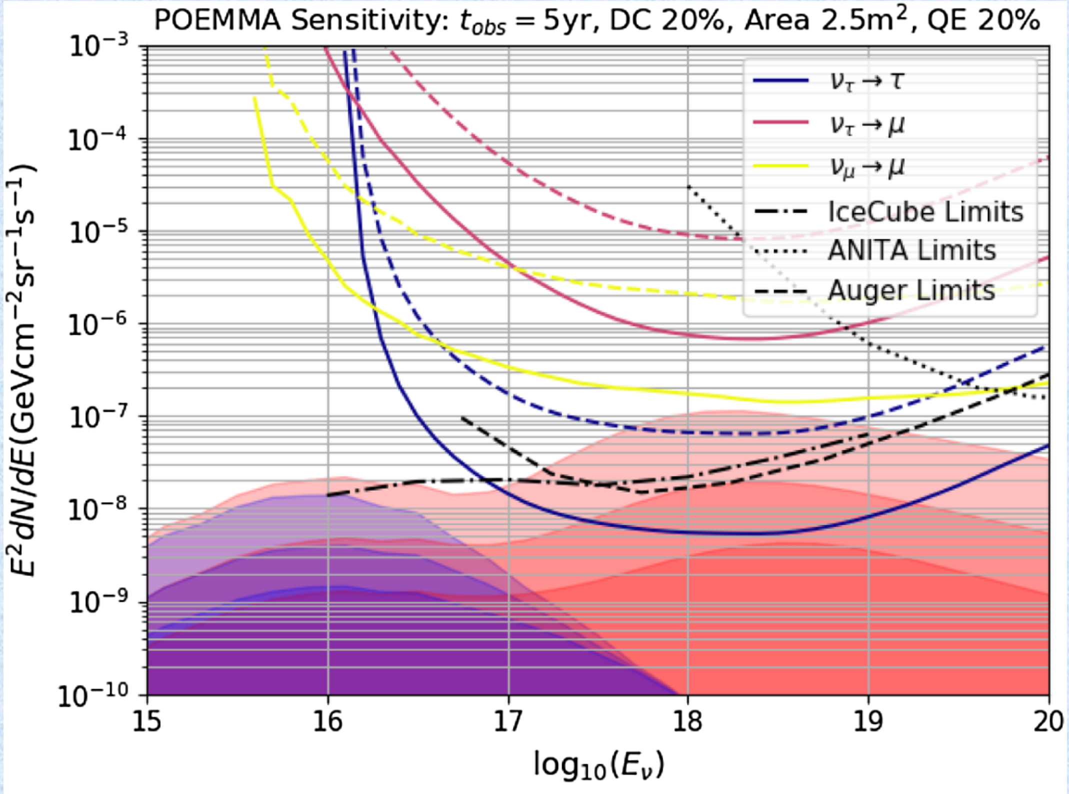
POEMMA Cosmic Neutrino Flux Sensitivity

Air fluorescence UHE limits not included in plot

Olinto_2021_J._Cosmol._Astropart._Phys._2021_007



…UCED … PHYS. REV. D **103,** 043017 (2021)



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)
- $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$

Over-the-Limb VHECR Cherenkov Observations:

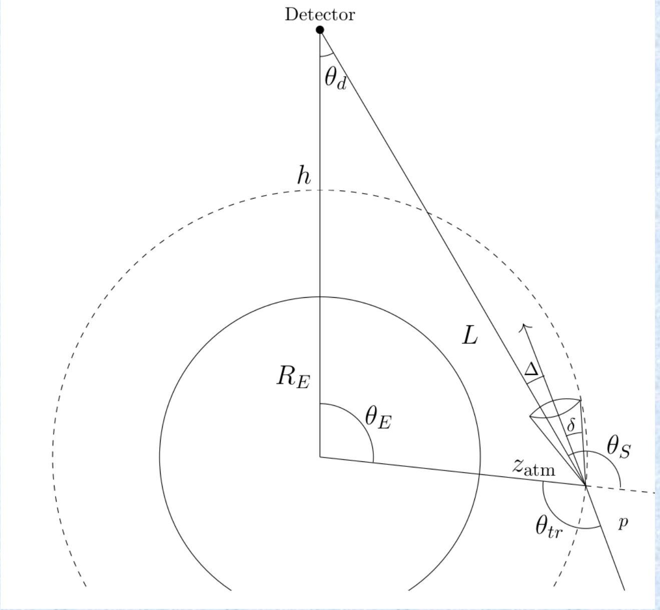
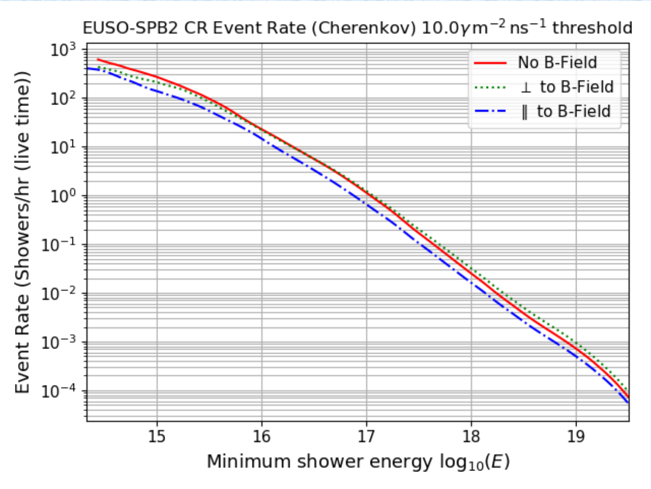
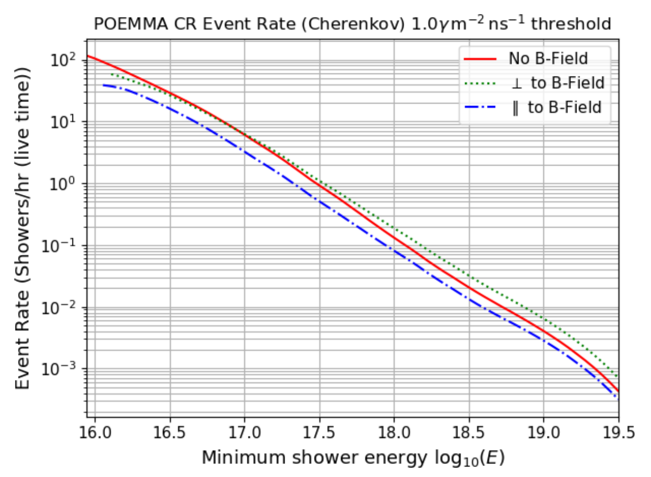
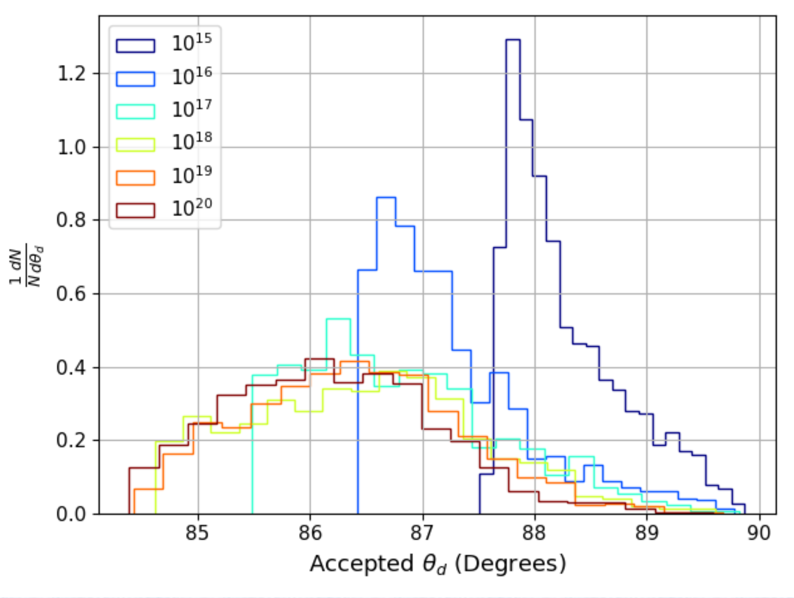
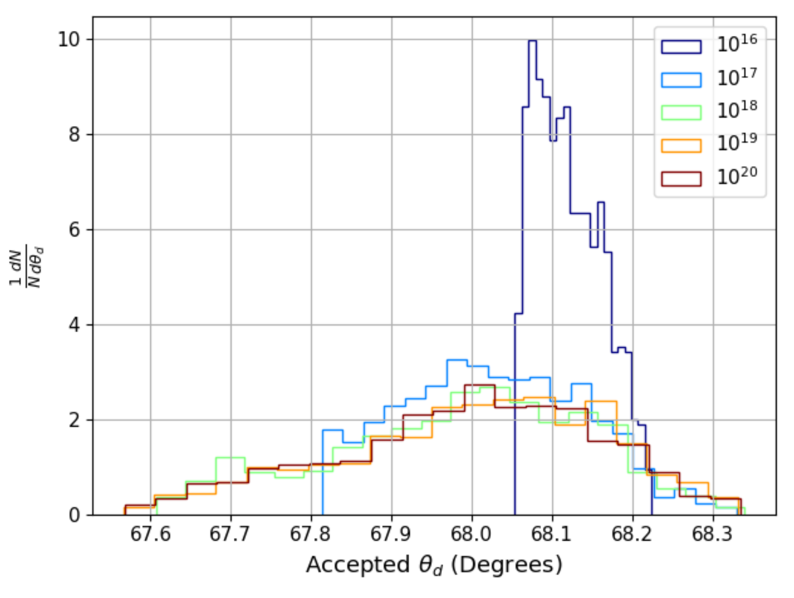


FIG. 1. Geometry of measuring the Cherenkov signal from cosmic rays arriving from above the Earth horizon in the case of a space based instrument.









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.

PhysRevD.104.063029

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

POEMMA: anomalous ANITA upward EAS

arXiv:1803.05088v1

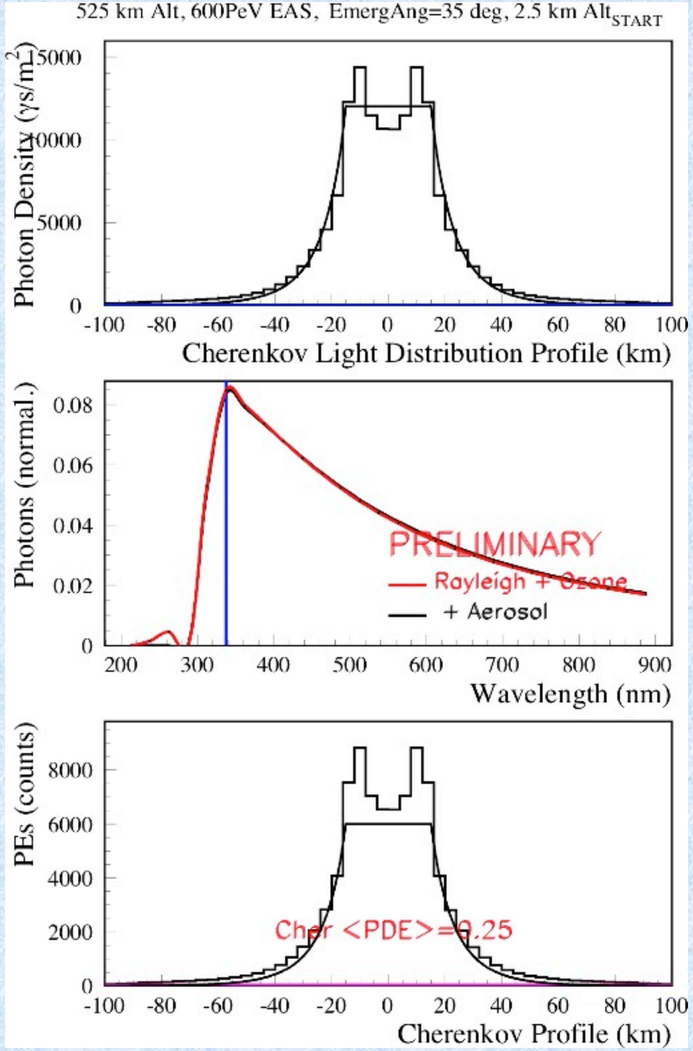
TABLE I: *ANITA-I,-III anomalous upward air showers.*

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.



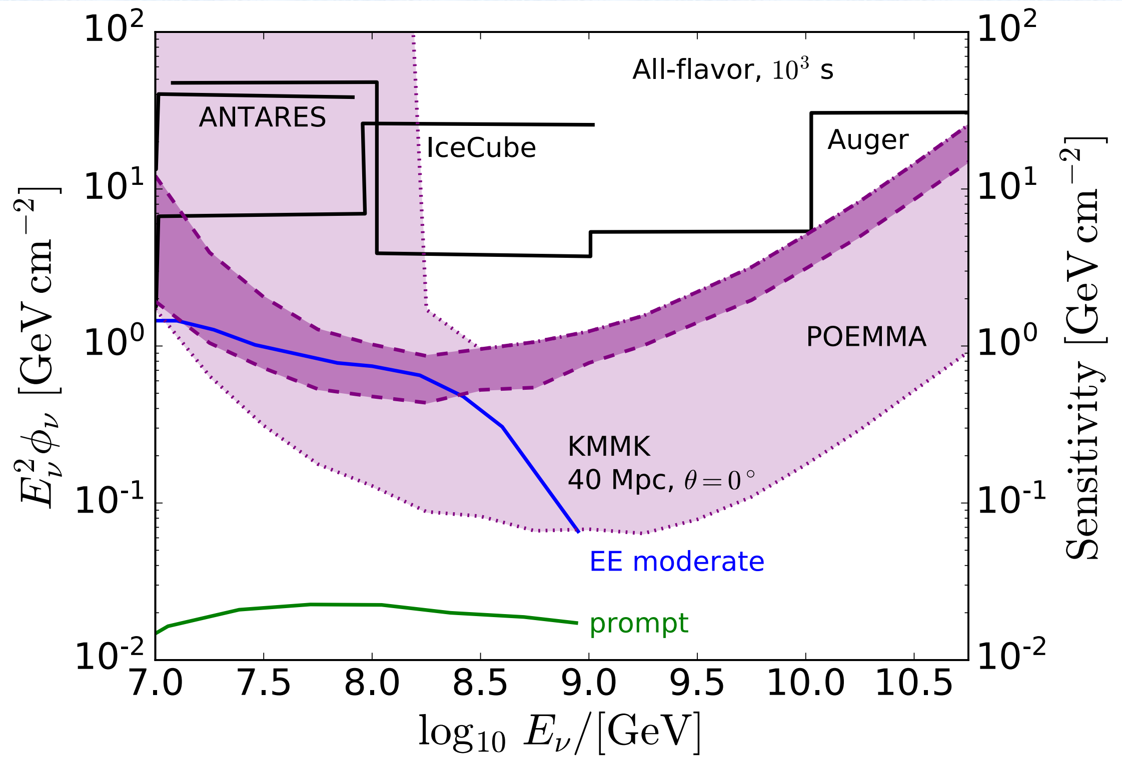
θ_{CONE}= 1.0 deg
$\omega \approx$ 1.e-3 sr

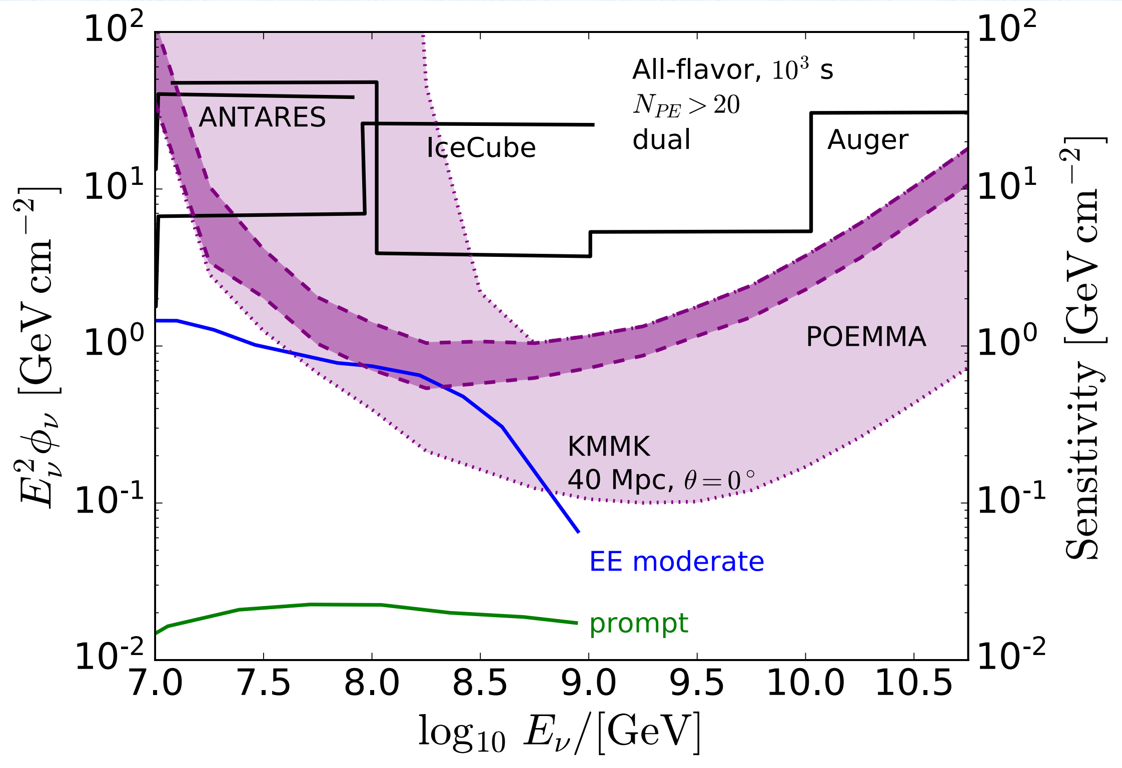
$\theta_{EFF} \approx$ 4.5 deg
$\omega \approx$ 2.e-2 sr

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

POEMMA signal size ~6000 PEs in cone

POEMMA Short Burst: 10 PE versus 20 PE comparison

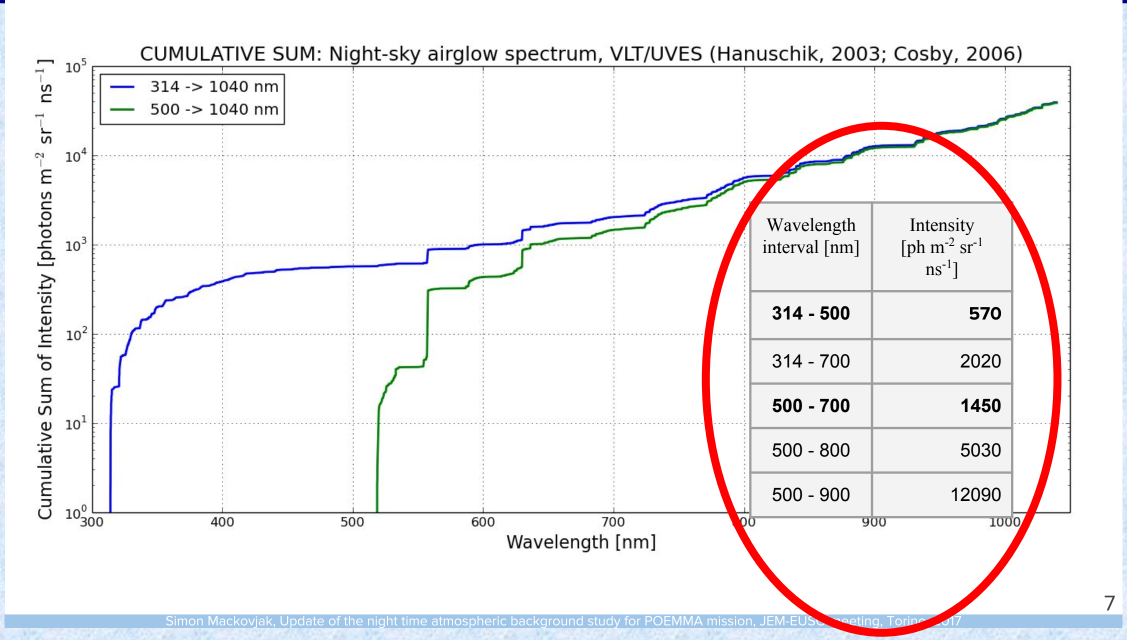




10 PE threshold with simultaneous viewing of Cherenkov light pool and time coincidence (60 ns)

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

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

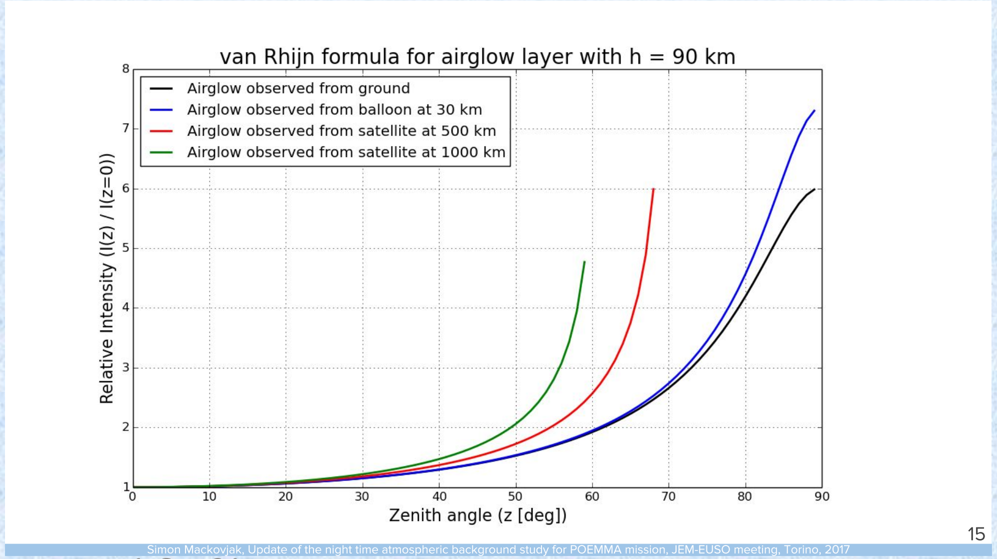
~25,000 photons/m²/sr/ns

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)**

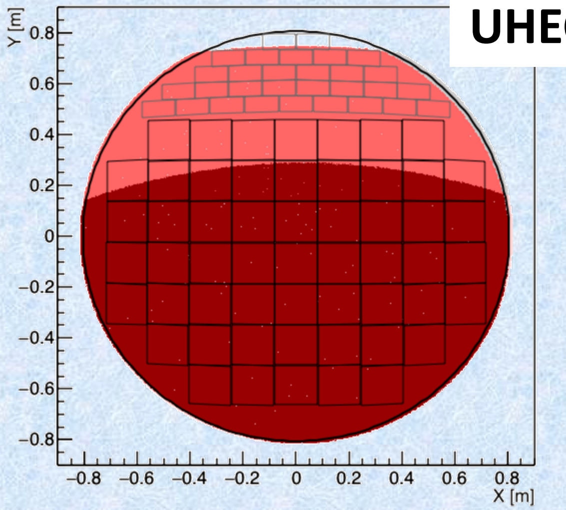


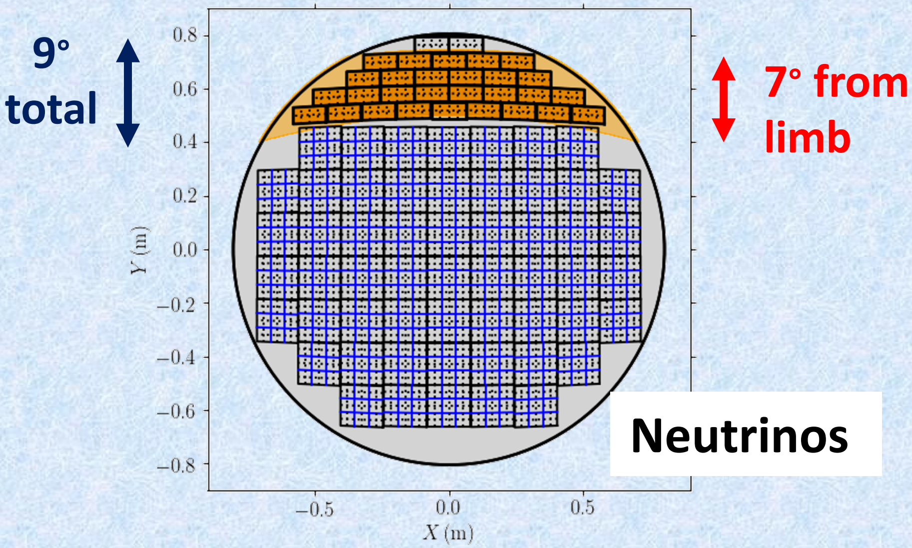
Viewing at angles away from nadir views more optical depth of air glow layer.

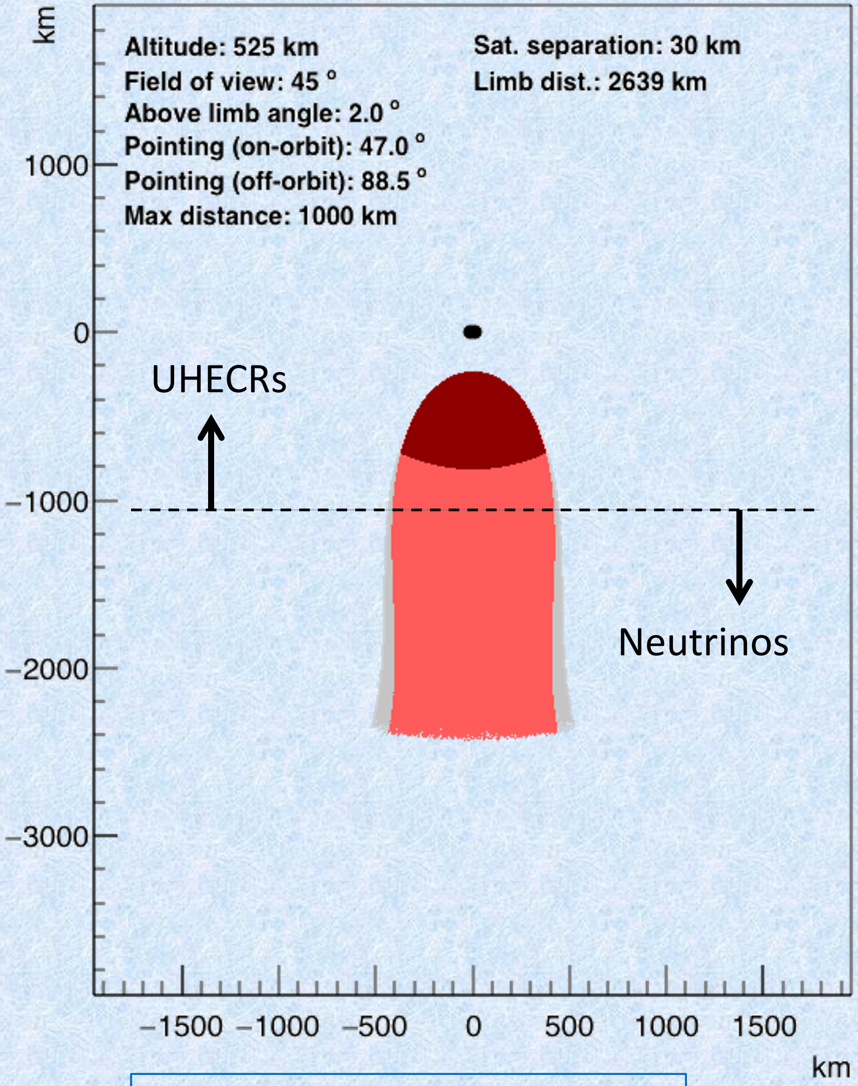
x6 for viewing limb from 500 km

Work by Simon Mackovjak

POEMMA: Neutrino mode example configuration







Calcs & plots by F. Sarazin