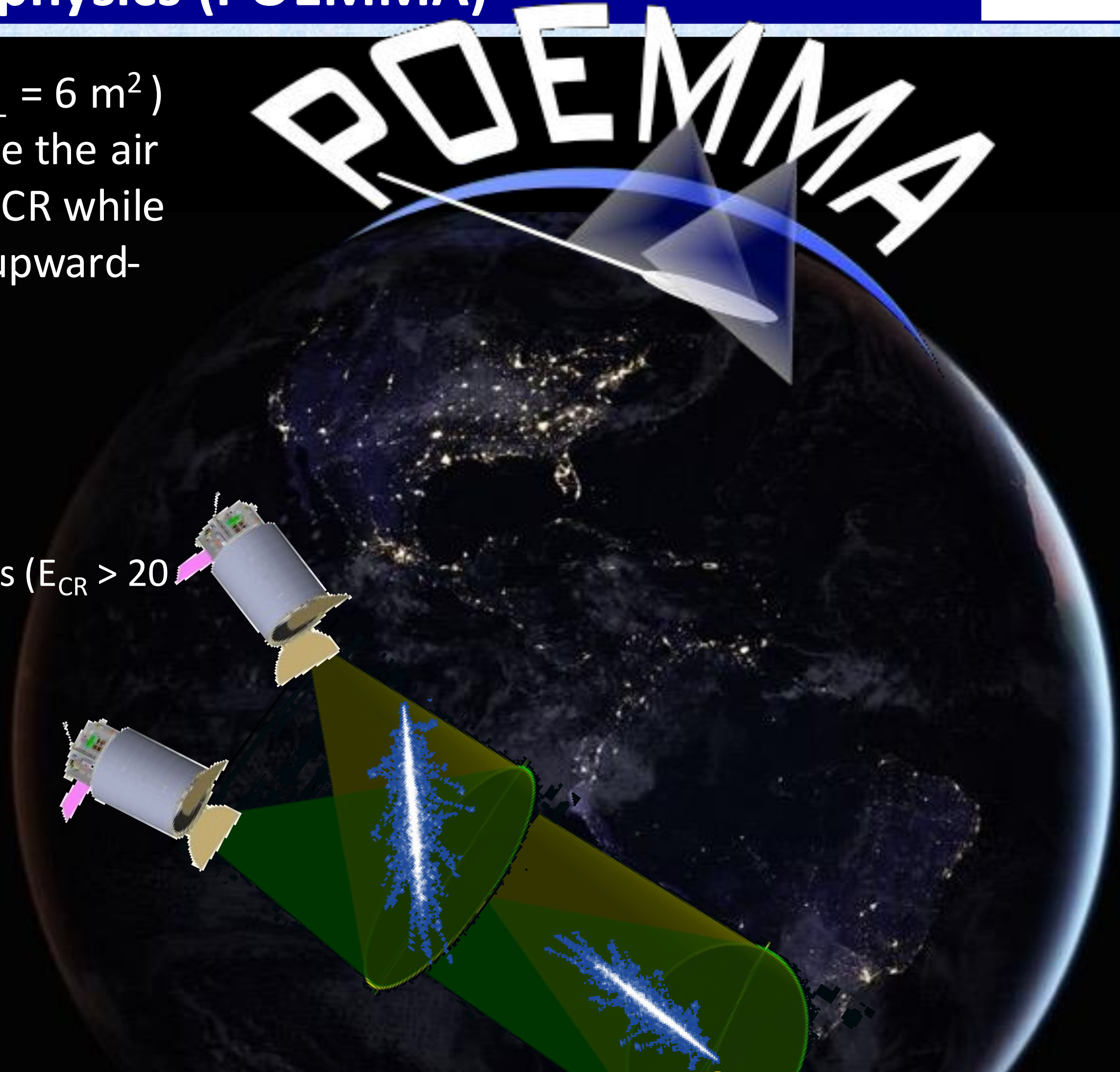
MultiMessenger Astrophysics with the Probe Of Extreme Multi-Messenger Astrophysics (POEMMA)

POEMMA is an observatory comprised of two large-area (A_{COLL} = 6 m^2) Schmidt telescopes that orbit in a loose formation and measure the air fluorescence from extensive air showers (EAS) induced by UHECR while also slewing to measure the beam Cherenkov radiation from upward-moving EAS source by neutrino interactions in the Earth.

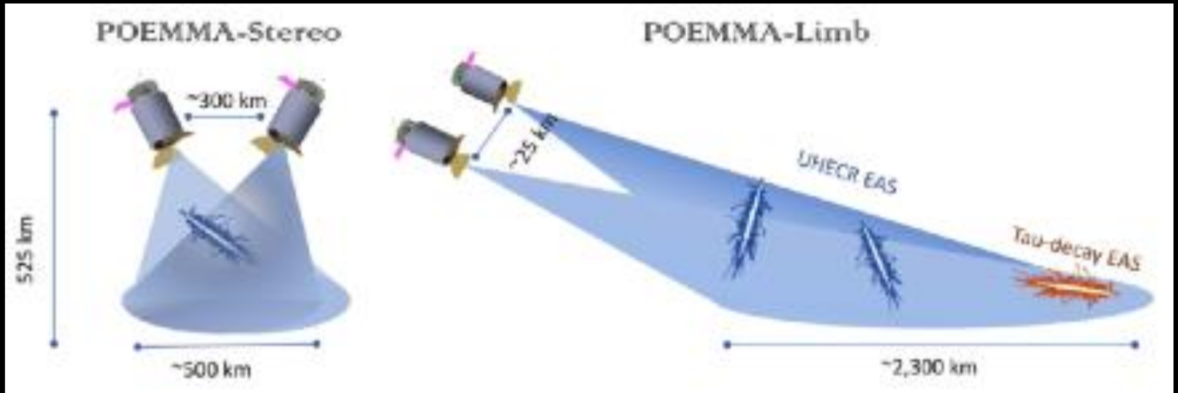
Development Supported under: **NNH16ZDA001N-APROBES**



Science Goals:

- **Discover the origin of Ultra-High Energy Cosmic Rays**

  Measure Spectrum, composition, Sky Distribution at Highest Energies (E_{CR} > 20 EeV) using stereo air fluorescence technique



- **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)

- **Probe particle physics at the highest energy scales**

John Krizmanic
NASA/GSFC
for the POEMMA Collaboration

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)

UHECRs: E > 20 EeV

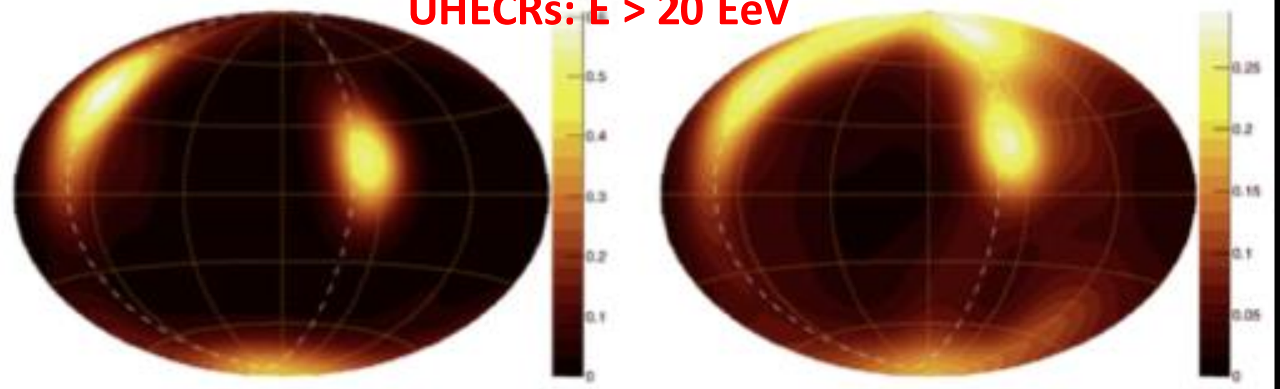
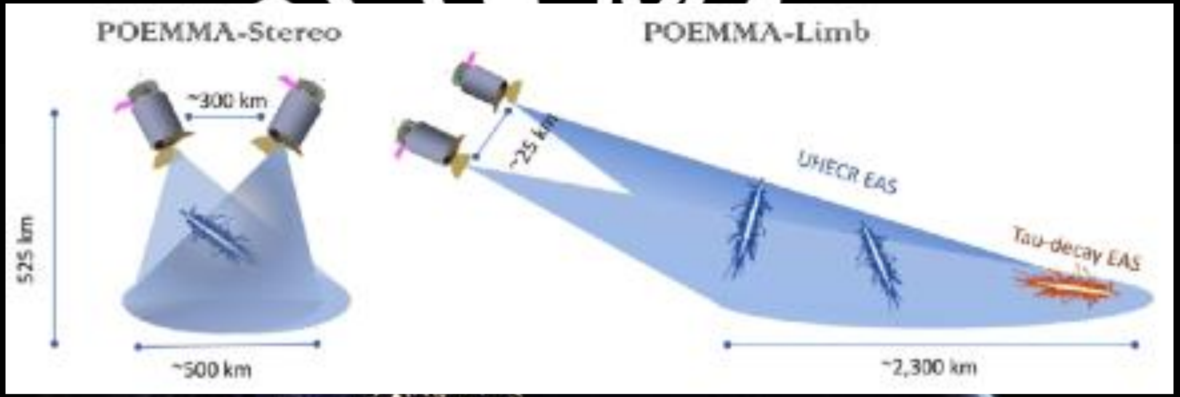
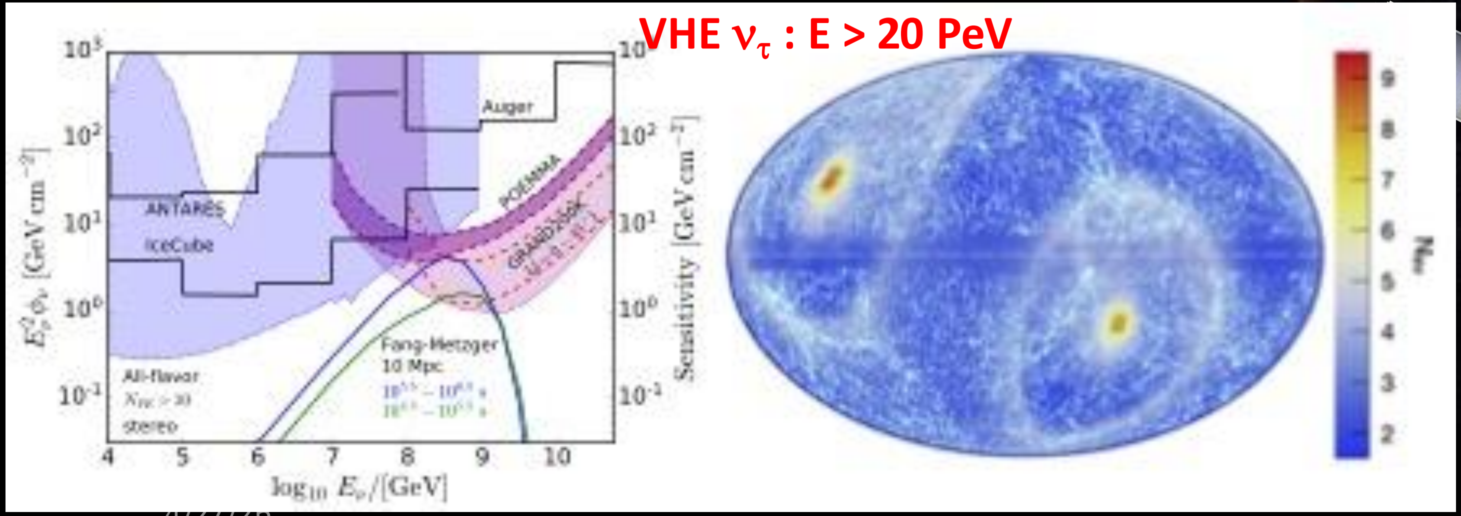


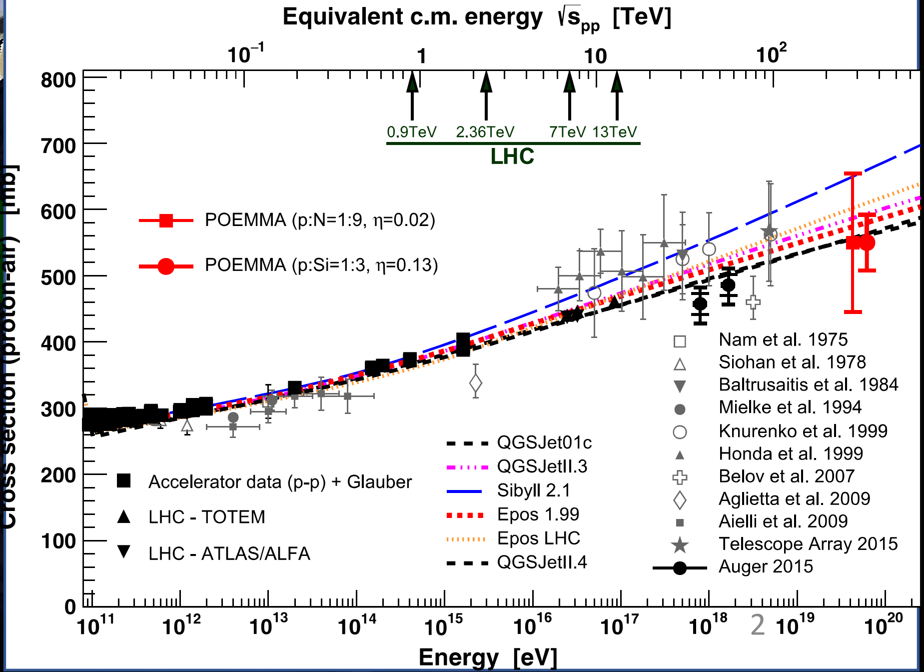
FIG. 23. Left: Skymap of nearby starburst galaxies from Refs. [35,103] weighted by radio flux at 1.4 GHz, the attenuation factor accounting for energy losses incurred by UHECRs through propagation, and the exposure of POEMMA. The map has been smoothed using a von Miser-Fisher distribution with concentration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



VHE ν_τ : E > 20 PeV



P-air cross section measurement at √s ≈ 300 TeV



POEMMA Collaboration

A. V. Olinto,[1] J. Krizmanic,[2,3] J. H. Adams,[4] R. Aloisio,[5]
L. A. Anchordoqui,[6] M. Bagheri,[7] D. Barghini,[8] M. Battisti,[8]
D. R. Bergman,[9] M. E. Bertaina,[8] P. F. Bertone,[10] F. Bisconti,[11]
M. Bustamante,[12] M. Casolino,[13,14] K. Černý,[15] M. J. Christl,[10]
A. L. Cummings,[5] I. De Mitri,[5] R. Diesing,[1] R. Engel,[16] J. Eser,[1]
K. Fang,[17] F. Fenu,[8] G. Filippatos,[18] E. Gazda,[7] C. Guepin,[19]
A. Haungs,[16] E. A. Hays,[2] E. G. Judd,[20] P. Klimov,[21] V. Kungel,[18]
E. Kuznetsov,[4] Š. Mackovjak,[22] D. Mandát,[23] L. Marcelli,[14]
J. McEnery,[2] G. Medina-Tanco,[24] K.-D. Merenda,[18] S. S. Meyer,[1]
J. W. Mitchell,[2] H. Miyamoto,[8] J. M. Nachtman,[25] A. Neronov,[26]
F. Oikonomou,[27] Y. Onel,[25] A. N. Otte,[7] E. Parizot,[28] T. Paul,[6]
M. Pech,[23] J. S. Perkins,[2] P. Picozza,[14,29] L.W. Piotrowski,[30]
Z. Plebaniak,[8] G. Prévôt,[28] P. Reardon,[4] M. H. Reno,[25] M. Ricci,[31]
O. Romero Matamala,[7] F. Sarazin,[18] P. Schovánek,[23]
K. Shinozaki,[32] J. F. Soriano,[6] F. Stecker,[2] Y. Takizawa,[13]
R. Ulrich,[16] M. Unger,[16] T. M. Venters,[2] L. Wiencke,[18] D. Winn,[25]
R. M. Young,[10] M. Zotov[21]

[1]The University of Chicago, Chicago, IL, USA
[2]NASA Goddard Space Flight Center, Greenbelt, MD, USA
[3]Center for Space Science & Technology, University of Maryland, Baltimore County, Baltimore, MD, USA
[4]University of Alabama in Huntsville, Huntsville, AL, USA
[5]Gran Sasso Science Institute, L'Aquila, Italy
[6]City University of New York, Lehman College, NY, USA
[7]Georgia Institute of Technology, Atlanta, GA, USA
[8]Universita' di Torino, Torino, Italy
[9]University of Utah, Salt Lake City, Utah, USA
[10]NASA Marshall Space Flight Center, Huntsville, AL, USA
[11]Istituto Nazionale di Fisica Nucleare, Turin, Italy
[12]Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark
[13]RIKEN, Wako, Japan
[14]Istituto Nazionale di Fisica Nucleare, Section of Roma Tor Vergata, Italy
[15]Joint Laboratory of Optics, Faculty of Science, Palacký University, Olomouc, Czech Re public
[16]Karlsruhe Institute of Technology, Karlsruhe, Germany
[17]Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, C 94305, USA
[18]Colorado School of Mines, Golden, CO, USA
[19]Department of Astronomy, University of Maryland, College Park, MD, USA
[20]Space Sciences Laboratory, University of California, Berkeley, CA, USA
[21]Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow Russia
[22]Institute of Experimental Physics, Slovak Academy of Sciences, Kosice, Slovakia
[23]Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
[24]Instituto de Ciencias Nucleares, UNAM, CDMX, Mexico
[25]University of Iowa, Iowa City, IA, USA
[26]University of Geneva, Geneva, Switzerland
[27]Institutt for fysikk, NTNU, Trondheim, Norway
[28]Université de Paris, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France
[29]Universita di Roma Tor Vergata, Italy
[30]Faculty of Physics, University of Warsaw, Warsaw, Poland
[31]Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali di Frascati, Frascati, Italy
[32]National Centre for Nuclear Research, Lodz, Poland

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

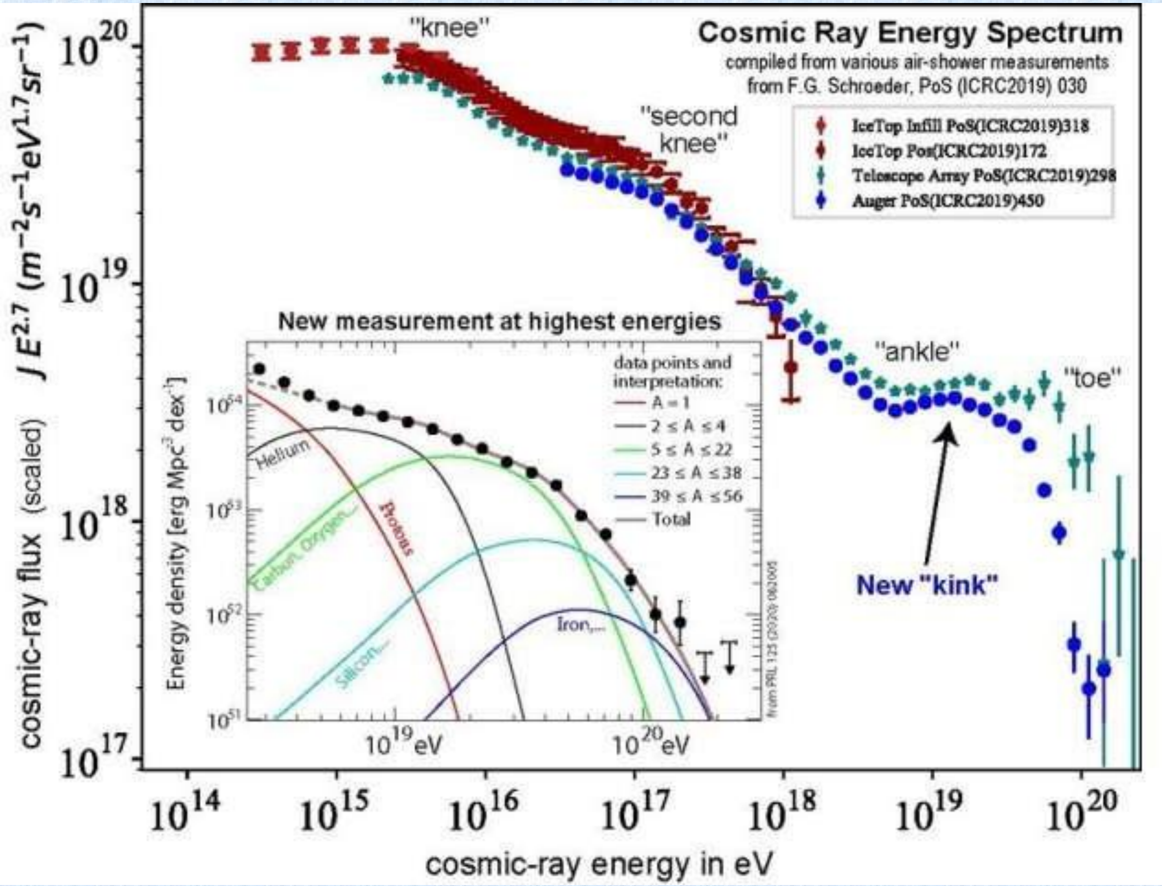
author list for *The POEMMA (Probe Of Extreme Multi-Messenger Astrophysics)*, JCAP 2021, id.007

10.1088/1475-7516/2021/06/007

UHECR/ν questions from the Astro2020 Decadal Review

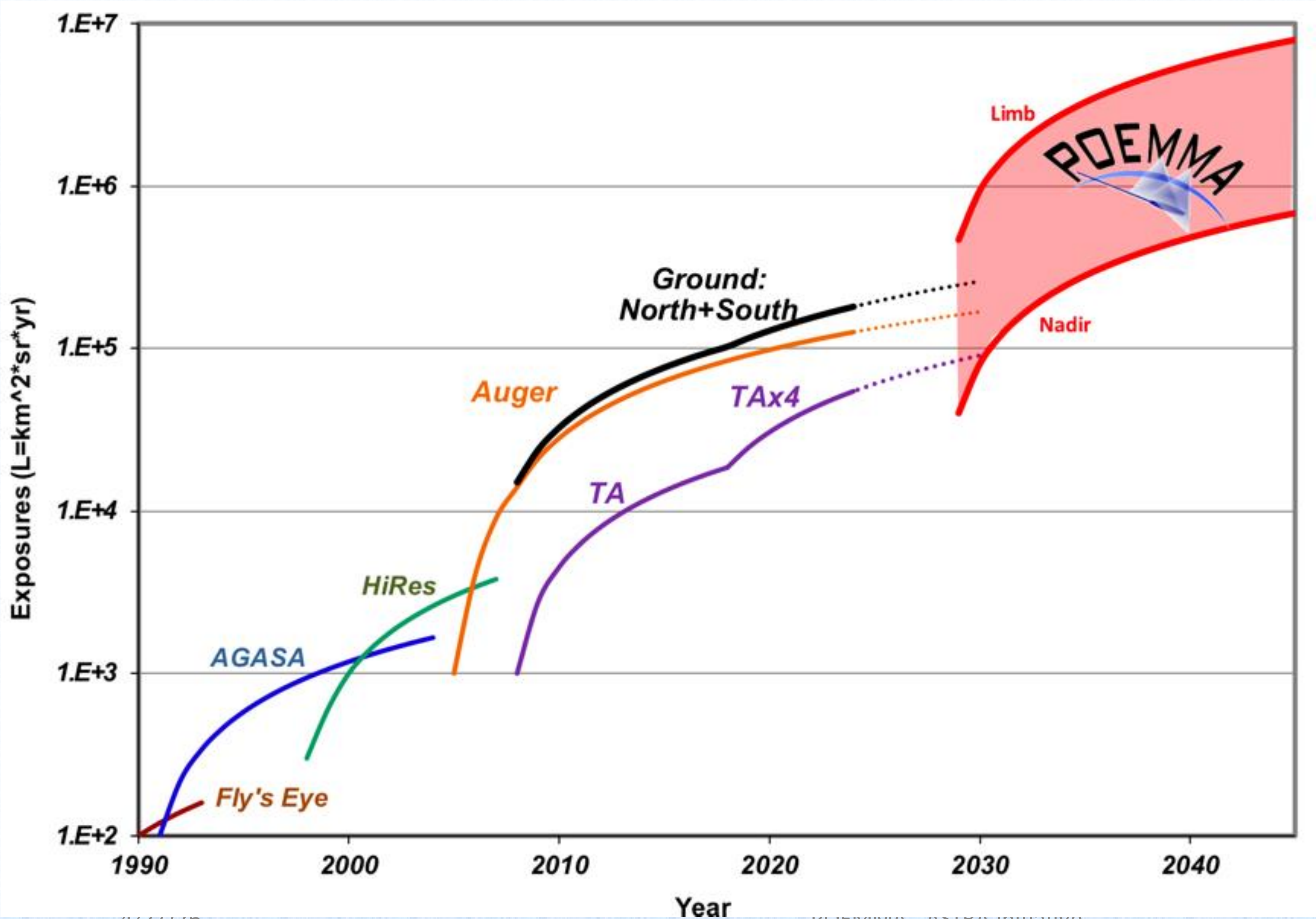
What is the nature and origin of UHECRs?

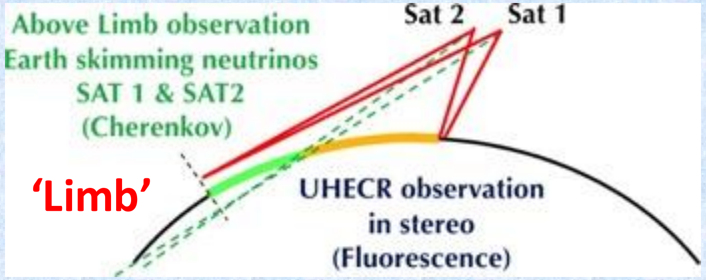
- What are the source(s) and acceleration mechanism of UHECRs?
- Are the TeV-PeV neutrinos and UHECRs produced in the same sources?
- What is the nature of the flux suppression at the highest energies?
- What is the composition evolution of the UHECR spectrum?
- Can UHECR charged-particle astronomy be able to study individual or classes of sources, considering the dependence on UHECR composition and understanding on galactic and extragalactic magnetic fields? HE neutrino detection from would help.
- Are there new interactions and physics waiting to be discovered at energies beyond those achievable at the LHC?

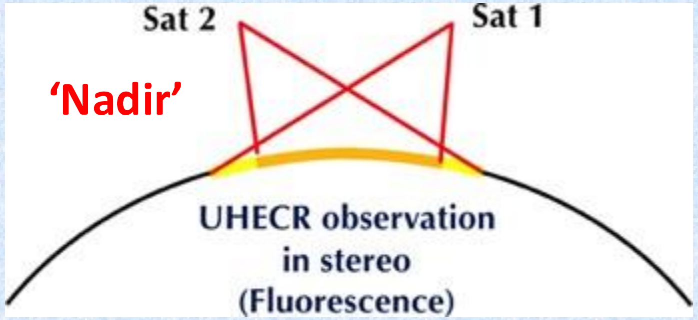


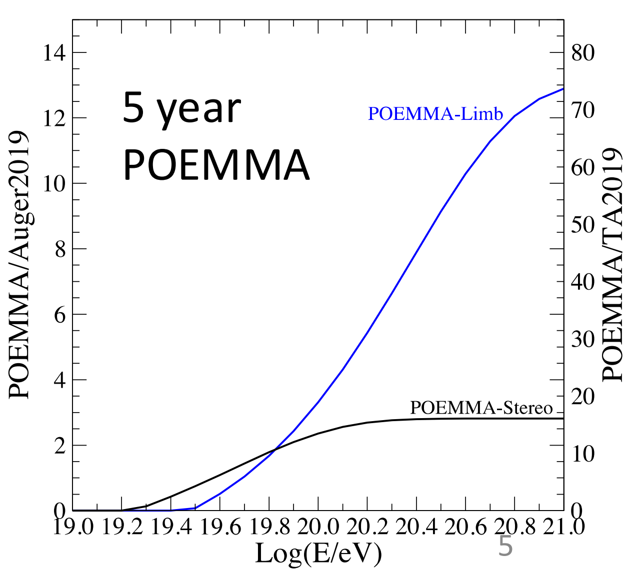
Note Compressed Scale on y-axis: $10^{2.7} \approx 500$

POEMMA: UHECR Exposure History:

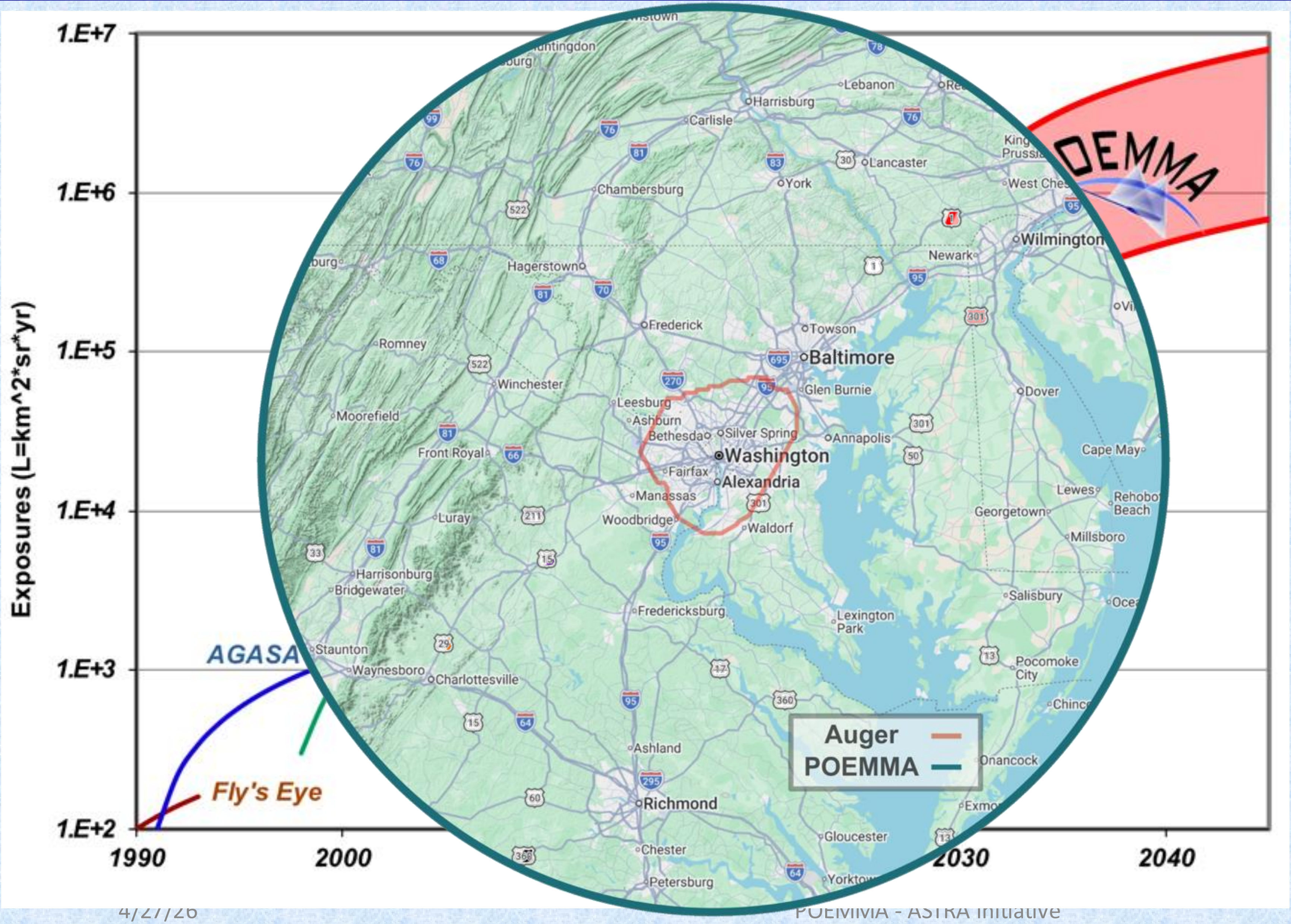


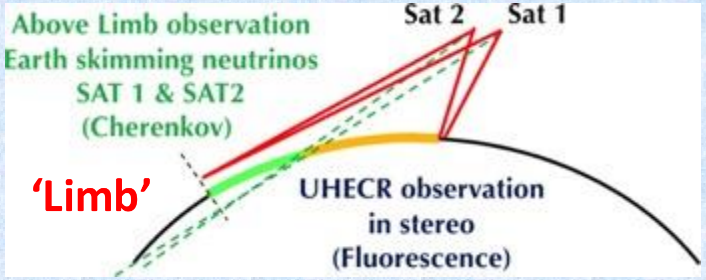


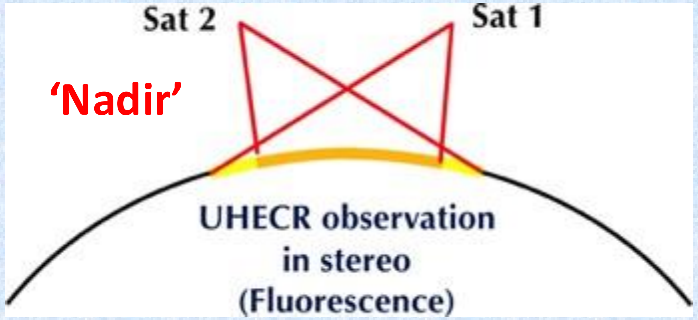


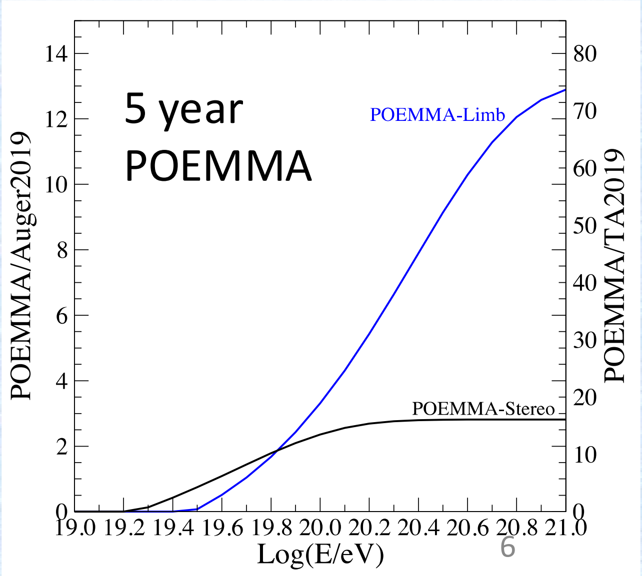


POEMMA: UHECR Exposure History:



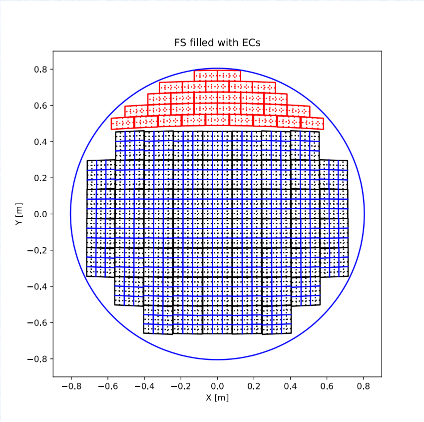


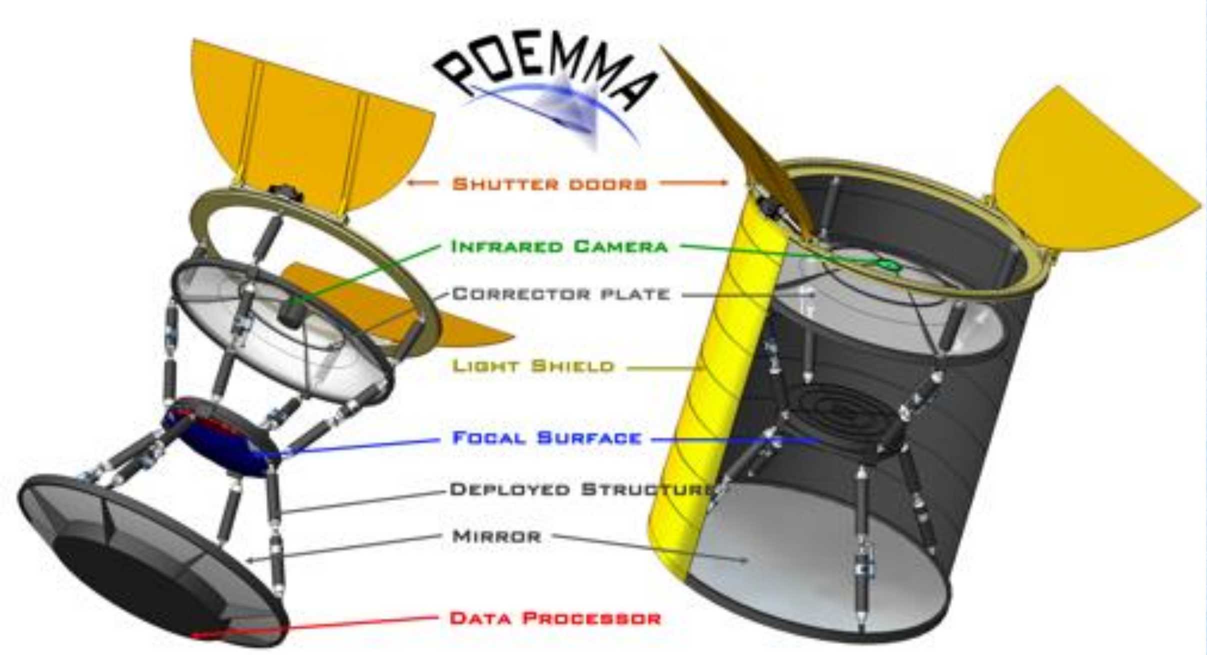


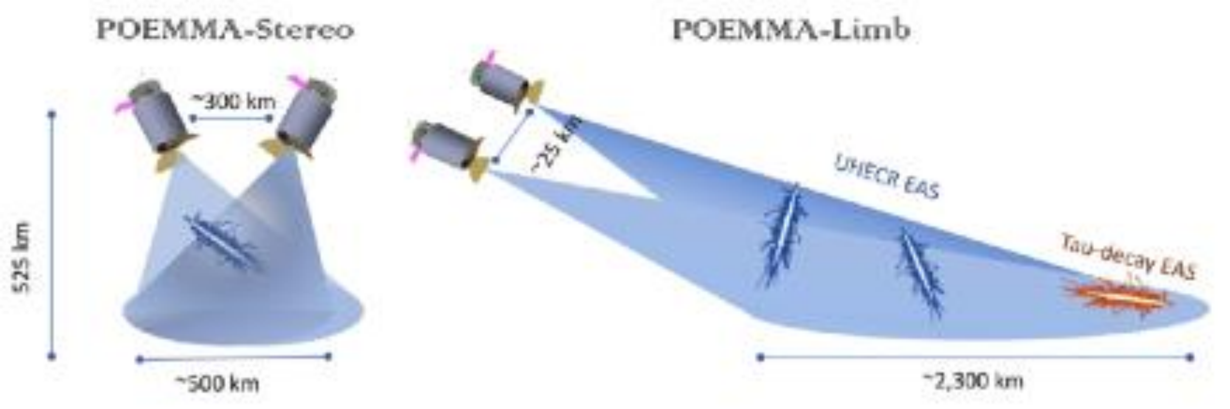


POEMMA: Mission and Instrument

- 3-5 year dual satellite mission in loose formation
- Orbit: **525km**, 28.5° inc, Δt:95min
- Slew rate: **8min/90deg**
- 3.3m diameter Schmidt optics telescope
  - Full FoV: 45°
  - Pixel FoV: 0.084°
- **Hybrid** focal surface
  - 126720 MAPMT px (1μs)
  - 15360 SiPM px (10ns)
- **Two** observation modes
  - **Stereo** for UHECR, separation 300km
  - **Limb** for ToO, separation 25km
  - 300 km → 25 km Satellite Separation
    - Puts both into Cherenkov Light Pool
    - Δt: 3h
    - 8-15 times during mission



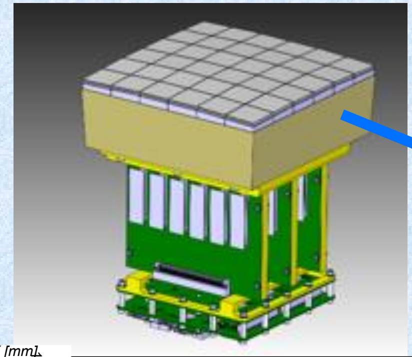


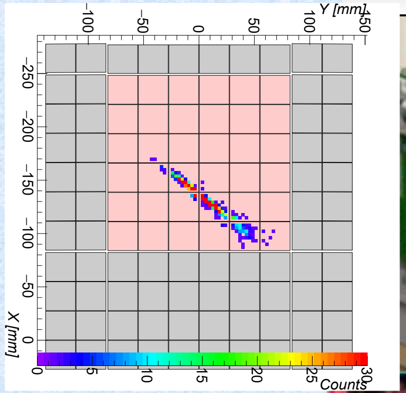


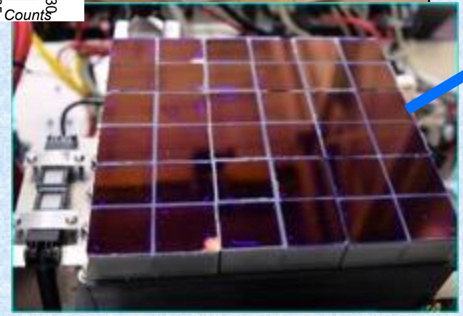
POEMMA: Hybrid Focal Plane

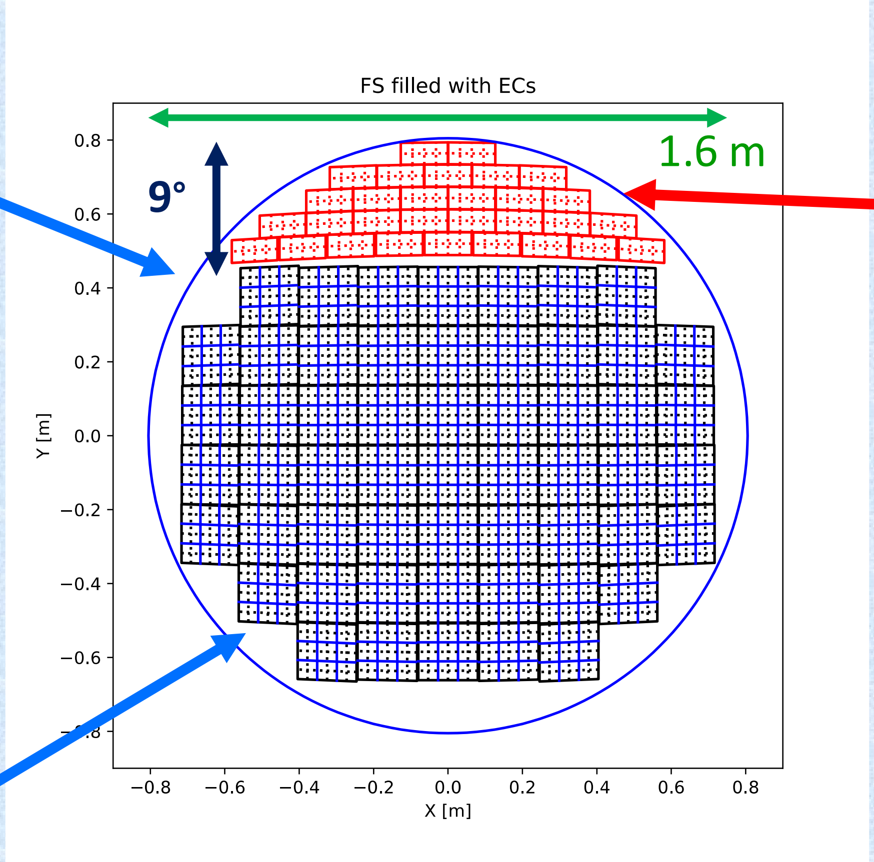
UV Fluorescence Detection using MAPMTs with BG3 filter (300 – 500 nm) proofed on Mini-EUSO: 1 usec sampling, 3 mm pixel size

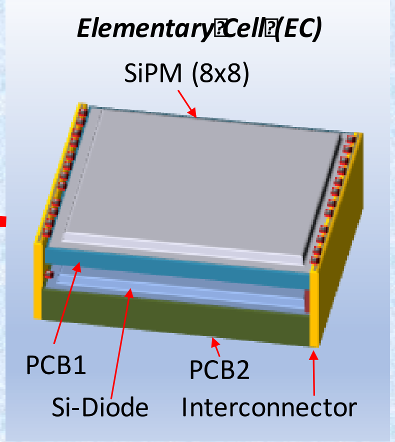
Cherenkov Detection with SiPMs (300 – 1000 nm): 10 nsec sampling









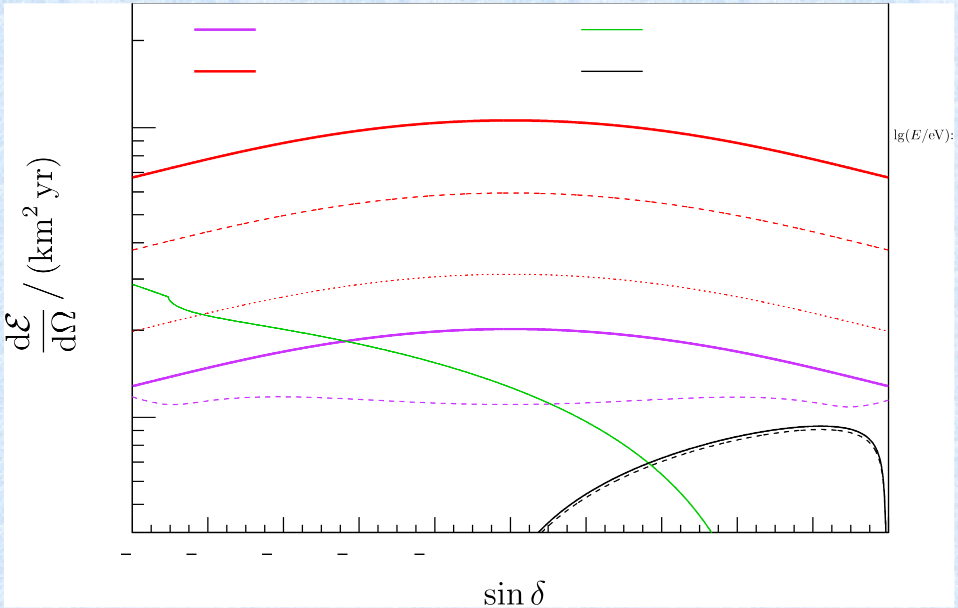


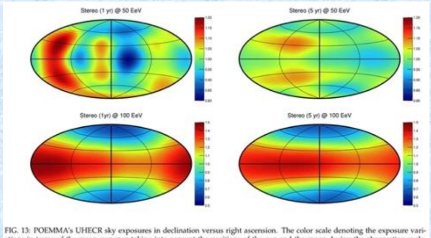
30 SiPM focal surface units
Total 15,360 pixels
512 pixels per FSU (64x4x2)
3 mm pixel size

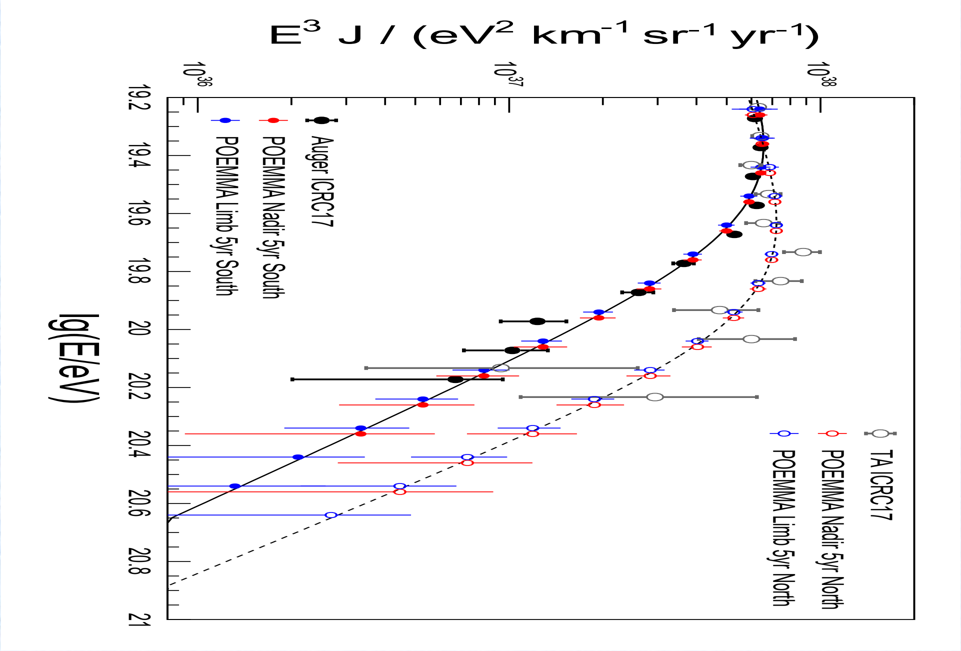
55 Photo Detector Modules (PDMs)= 126,720 pixels
1 PDM = 36 MAPMTs = 2,304 pixels

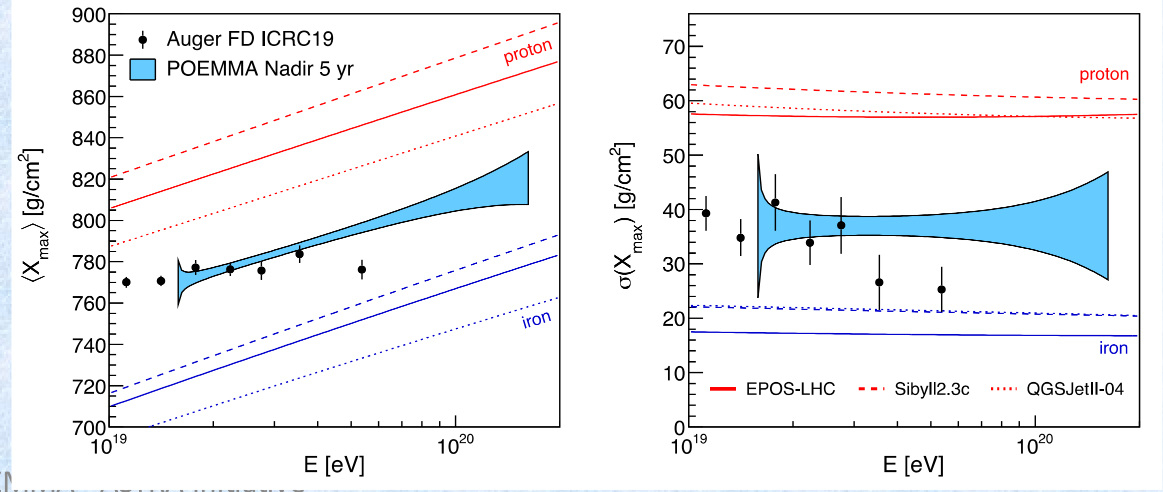
POEMMA: UHECR Performance: *see PhysRevD.101.023012*

- Significant increase in exposure with all-sky coverage to *guarantee the discovery of UHECR sources*
- Spectrum, Composition, Anisotropy: **E_{CR} > 20 EeV**
  - Very good energy (< 20%), angular ($\lesssim$ 1.2°), and composition ($\sigma_{X_{max}} \lesssim 30\ g/cm^2$) resolutions



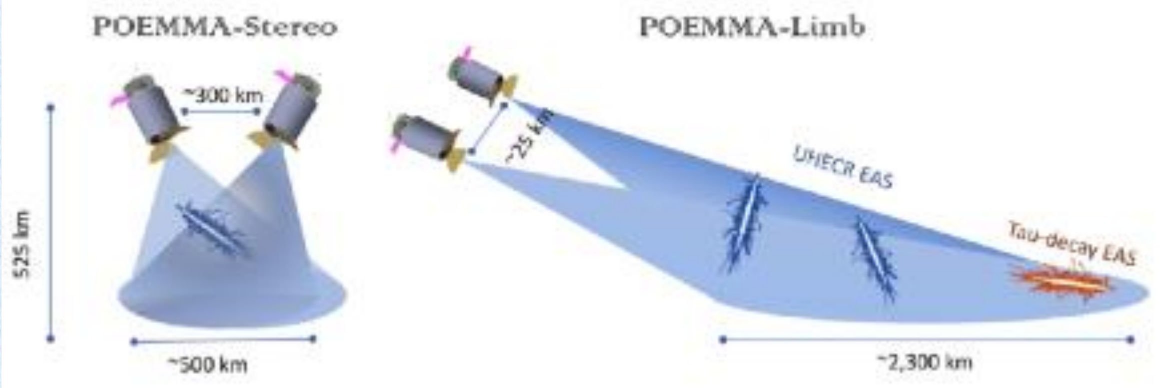


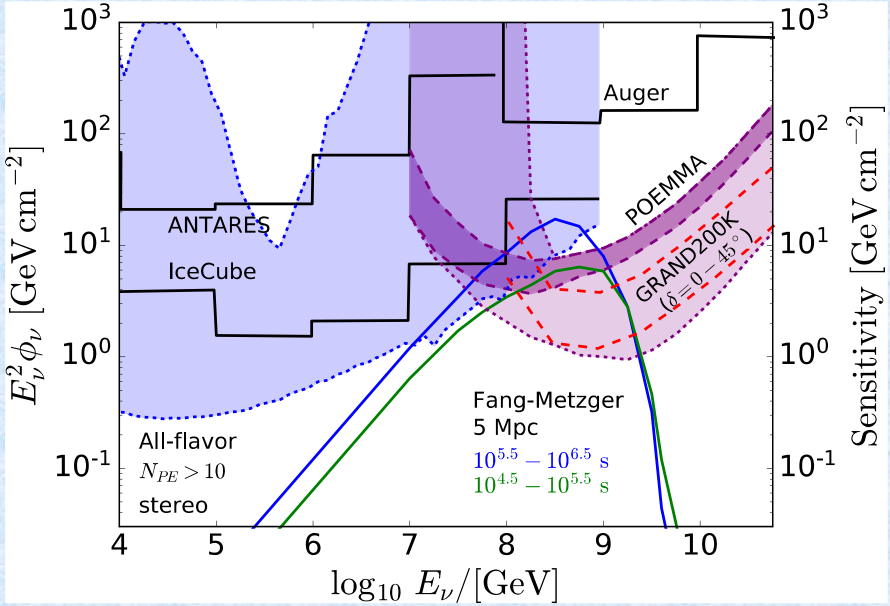


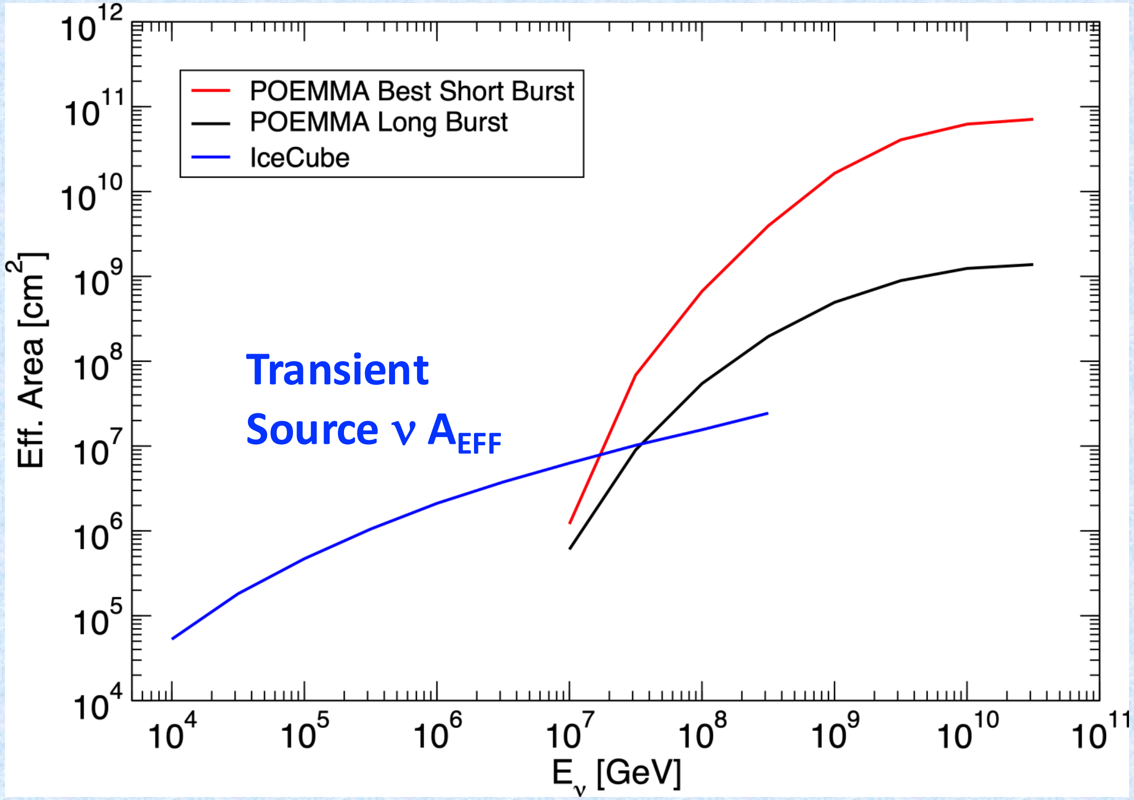


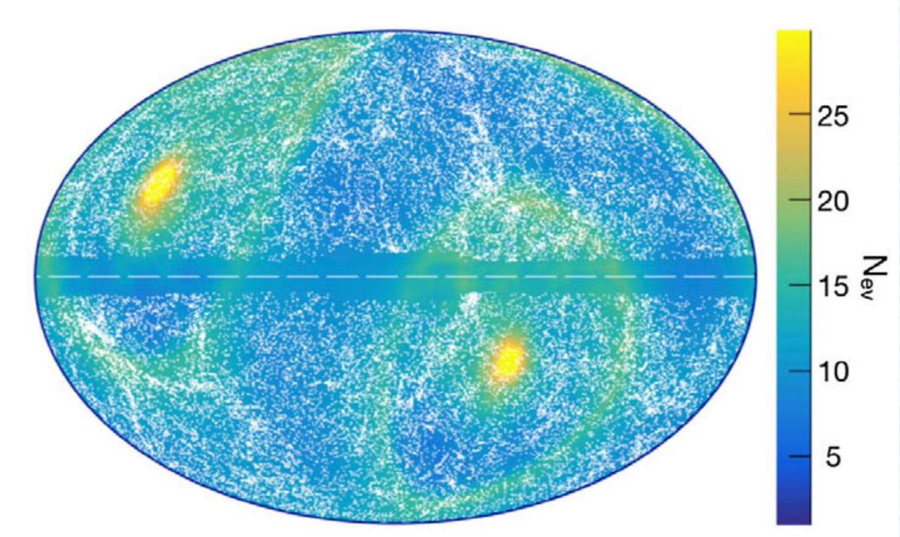
Auger-inspired Composition Evolution Model

POEMMA Transient Neutrino Detection via external alert



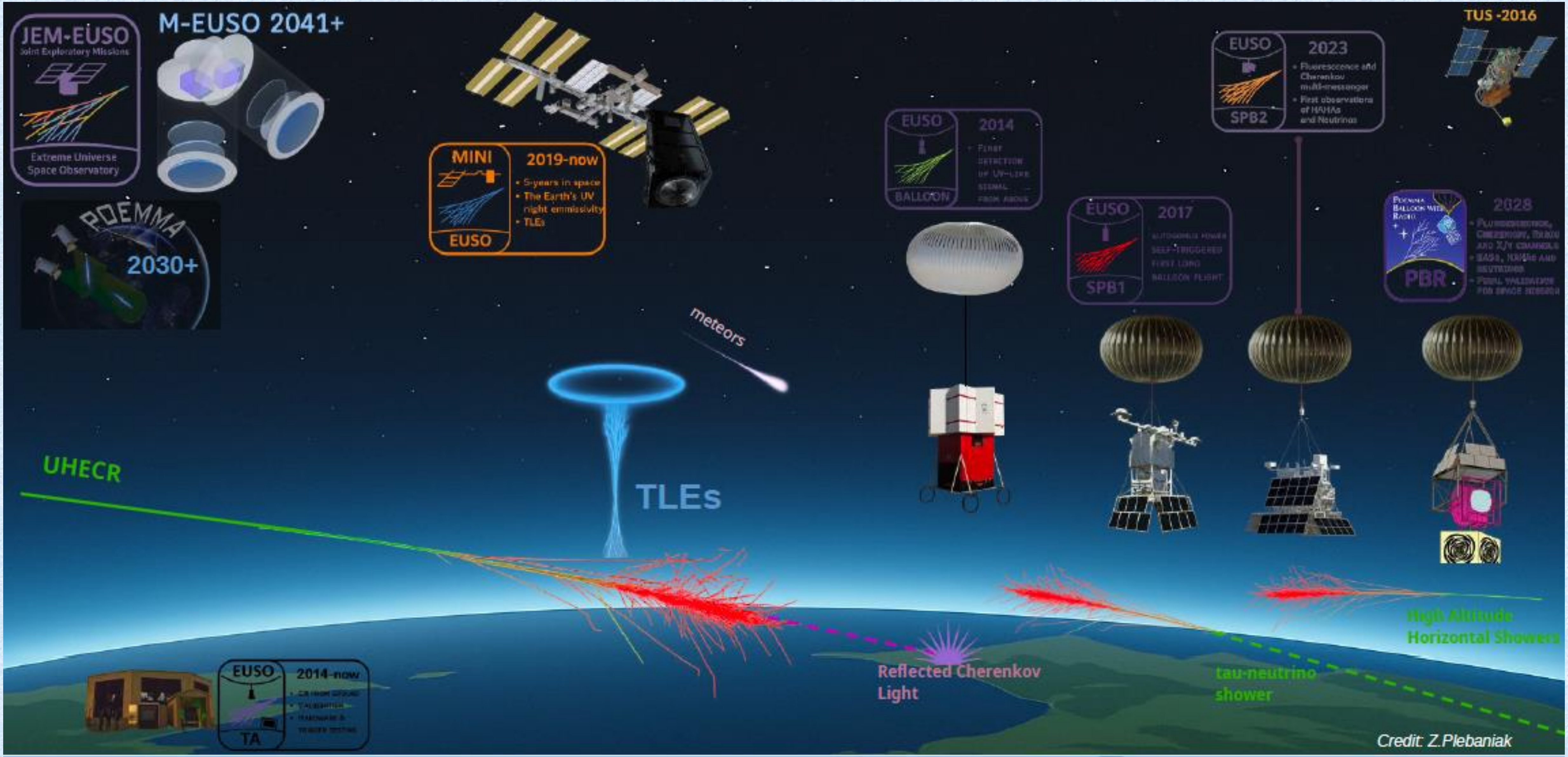




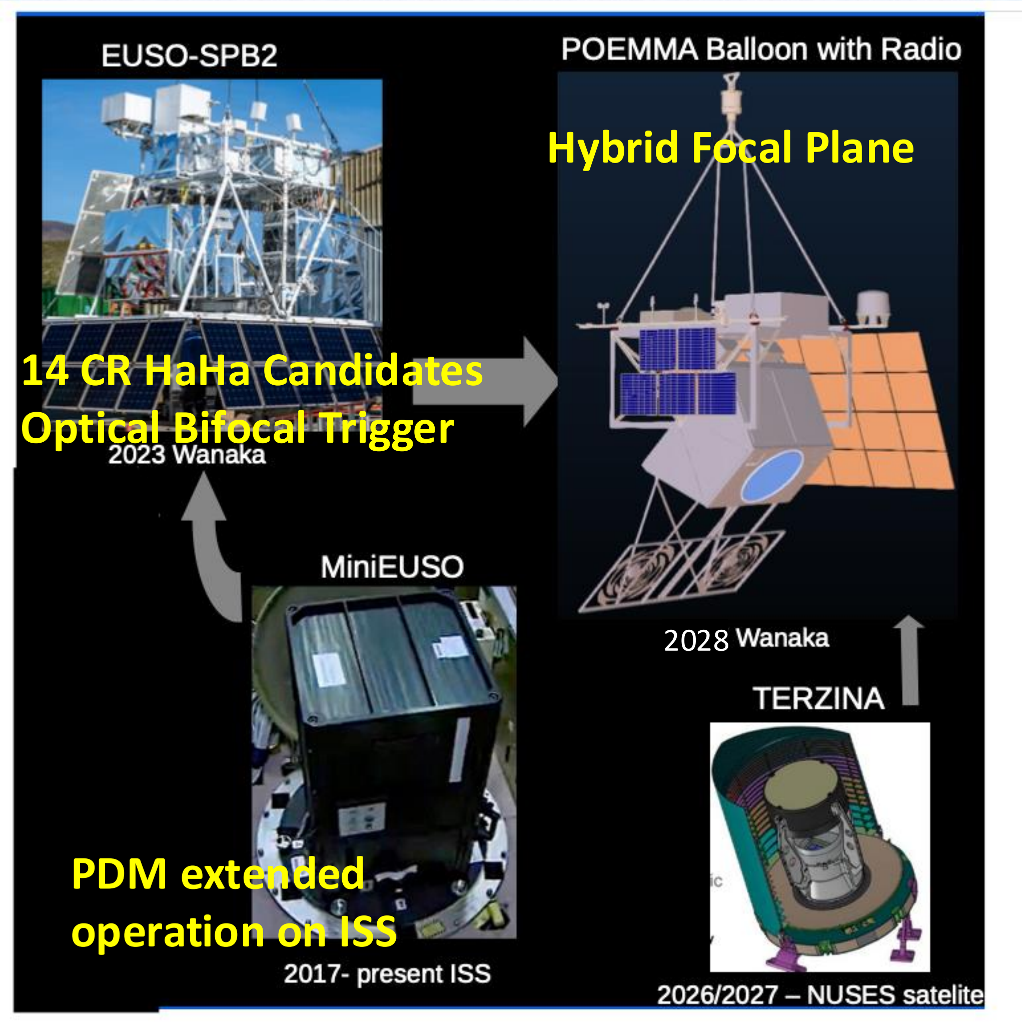


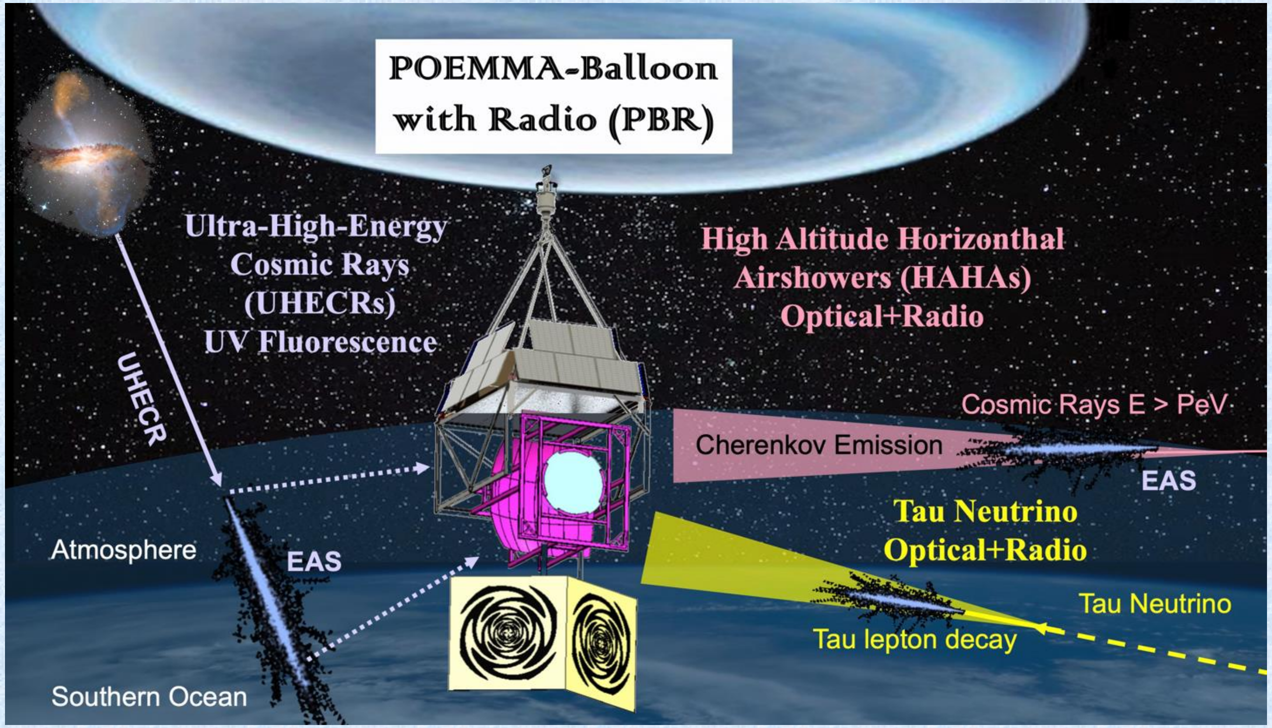
Sky plot of the expected number of neutrino events as a function of source position (GalCoord) for POEMMA for Fang-Metzger BNS merger model at 5 Mpc.

POEMMA within the JEM-EUSO Program



Technology Development supporting POEMMA & M-EUSO





TERZINA:

- Space-based Cherenkov Telescope with SiPM focal plane readout
- Science Goal to measure HaHa CRs above few hundred PeV from Low Earth Orbit.

Summary and Status

Results of NASA POEMMA Probe study:

- determined *No new technology needed*, could benefit from technology developments.
- SnowMass UHECR whitepaper, *Ultra-High-Energy Cosmic Rays The Intersection of the Cosmic and Energy Frontiers,* arXiv:2205.05845 recommends proceeding with the development of POEMMA as one of the next generation UHECR experiments (along with GCOS and GRAND).
- Rich portfolio of POEMMA science papers helped perception (at least within NASA community) that a mission like POEMMA, using UHECR, UHE & VHE neutrinos, probes unique and interesting high-energy astrophysics phenomena.
- EUSO-SPB2, POEMMA Balloon w/radio and TERZINA have kept technical development moving forward along with other projects JEM-EUSO program

POEMMA Mission and Science Performance Publications

1. C. Guepin, F. Sarazin, J. Krizmanic, J. Loerincs, A. Olinto, and A. Piccone, ***Geometrical Constraints of Observing Very High Energy Earth-Skimming Neutrinos from Space***, JCAP 2019, 03, 021, arXiv:1812.07596
2. M. H. Reno, J. F. Krizmanic, and T. M. Venters, ***Cosmic tau neutrino detection via Cherenkov signals from air showers from Earth-emerging taus***, PhysRevD 100, 063010, (2019), arXiv:1902.1128
3. L. A. Anchordoqui, D. R. Bergman, M. E. Bertaina, F. Fenu, J. F. Krizmanic, A. Liberatore, A. V. Olinto, M. Hall Reno, F. Sarazin, K. Shinozaki, J. F. Soriano, R. Ulrich, M. Unger, T. M. Venters, and L. Wiencke, ***Performance and science reach of POEMMA for ultrahigh-energy particles,*** *PhysRevD.101.023012, arXiv:1907.03694*T.
4. M. Venters, M. Hall Reno, J. F. Krizmanic, L. A. Anchordoqui, C. Guépin, and A. V. Olinto, ***POEMMA's target of opportunity sensitivity to cosmic neutrino transient sources***, *PhysRevD.102.123013, arXiv:1906.07209*
5. *A.L. Cummings, R. Aloisio, R., J.F. Krizmanic,* ***Modeling of the Tau and Muon Neutrino-induced Optical Cherenkov Signals from Upward-moving Extensive Air Showers,*** PhysRevD.103.043017, arXiv:2011.09869
6. A.V Olinto, J.F. Krizmanic, and the POEMMA Collaboration***, The POEMMA (Probe of Extreme Multi-Messenger Astrophysics) Observatory,*** *JCAP 2021, 06, 007*
7. A.L. Cummings, R. Aloisio, R., J.Eser, J.F. Krizmanic, ***Modeling the optical Cherenkov signals by cosmic ray extensive air showers directly observed from suborbital and orbital altitudes***, PhysRevD.104.063029, arXiv:2105.03255
8. C. Guépin, A. Aloisio, L.A. Anchordoqui, A. Cummings, J. Krizmanic, A.V. Olinto, M.H. Reno, T.M. Venters, ***Indirect dark matter searches at ultrahigh energy neutrino detectors***, PhysRevD.104.083002, arXiv:04446
9. L. A. Anchordoqui, M. E. Bertaina, M. Casolino, J. Eser, J.F. Krizmanic, A.V. Olinto, A.N. Otte, T.C. Paul, L.W. Piotrowski, M.H. Reno, F. Sarazin, K. Shinozaki, J.F. Soriano, T.M. Venters, L. Wiencke, **Prospects for macroscopic dark matter detection at space-based and suborbital experiments,** Europhysics Letters 135, id.51001, arXiv: 2104.05131
10. M.H. Reno, L. A. Anchordoqui, A. Bhattacharya, A. Cummings, J. Eser, C. Guépin, J.F. Krizmanic, A.V. Olinto, T. Paul, I. Sarcevic, T. M. Venters, ***Neutrino constraints on long-lived heavy dark sector particle decays in the Earth***, PhysRevD.105.055013

Backup

POEMMA UHECR Science in Context of Community Road Map

Ultra-High-Energy Cosmic Rays

The Intersection of the Cosmic and Energy Frontiers

10.1016/j.astropartphys.2023.102819

Snowmass Report Recommendations addressed by POEMMA:

Experiment	Feature	Cosmic Ray Science*	Timeline
Pierre Auger Observatory	Hybrid array: fluorescence, surface e/μ + radio, 3000 km^2	Hadronic interactions, search for BSM, UHECR source populations, $\sigma_{p\text{-}Air}$	AugerPrime upgrade
Telescope Array (TA)	Hybrid array: fluorescence, surface scintillators, up to 3000 km^2	UHECR source populations proton-air cross section ($\sigma_{p\text{-}Air}$)	TAx4 upgrade
IceCube / IceCube-Gen2	Hybrid array: surface + deep, up to 6 km^2	Hadronic interactions, prompt decays, Galactic to extragalactic transition	Upgrade + surface enhancement; IceCube-Gen2 deployment; IceCube-Gen2 operation
GRAND	Radio array for inclined events, up to 200,000 km^2	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{p\text{-}Air}$	GRANDProto 300; GRAND 10k; GRAND 200k multiple sites, step by step
POEMMA	Space fluorescence and Cherenkov detector	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{p\text{-}Air}$	JEM-EUSO program; POEMMA
GCOS	Hybrid array with X_{max} + e/μ over 40,000 km^2	UHECR sources via event-by-event rigidity, forward particle physics, search for BSM, $\sigma_{p\text{-}Air}$	GCOS R&D + first site; GCOS further sites

Timeline: 2025 2030 2035 2040

*All experiments contribute to multi-messenger astrophysics also by searches for UHE neutrinos and photons; several experiments (IceCube, GRAND, POEMMA) have astrophysical neutrinos as primary science case.

- The next-generation experiments (GCOS, GRAND, and POEMMA) will provide complementary information needed to meet the goals of the UHECR community in the next two decades. They should proceed through their respective next stages of planning and prototyping.
- Full-sky coverage with low cross-hemisphere systematic uncertainties is critical for astrophysical studies. To this end, next generation experiments should be space-based or multi-site. Common sites between experiments are encouraged.
- As a complementary effort, experiments with sufficient exposure (5×10^5 km^2 sr yr) are needed to search for LIV, SHDM, and other BSM physics at the Cosmic and Energy Frontiers, and to identify UHECR sources at the highest energies.
- A robust effort in R&D should continue in detector developments and cross-calibrations for all air-shower components, and also in computing techniques. This effort should include, whenever possible, optimized triggers for photons, neutrinos and transient events.

POEMMA UHECR Science in Context of Community Road Map

Ultra-H

The Intersection

10.1016

Snowmass
addressed I

- The next-g
  meet the g
  stages of p
- Full-sky co
  next gener
- As a comp
  and other
- A robust e
  componer
  for photor

CLAIRE GUÉPIN *et al.* PHYS. REV. D **104,** 083002 (2021)

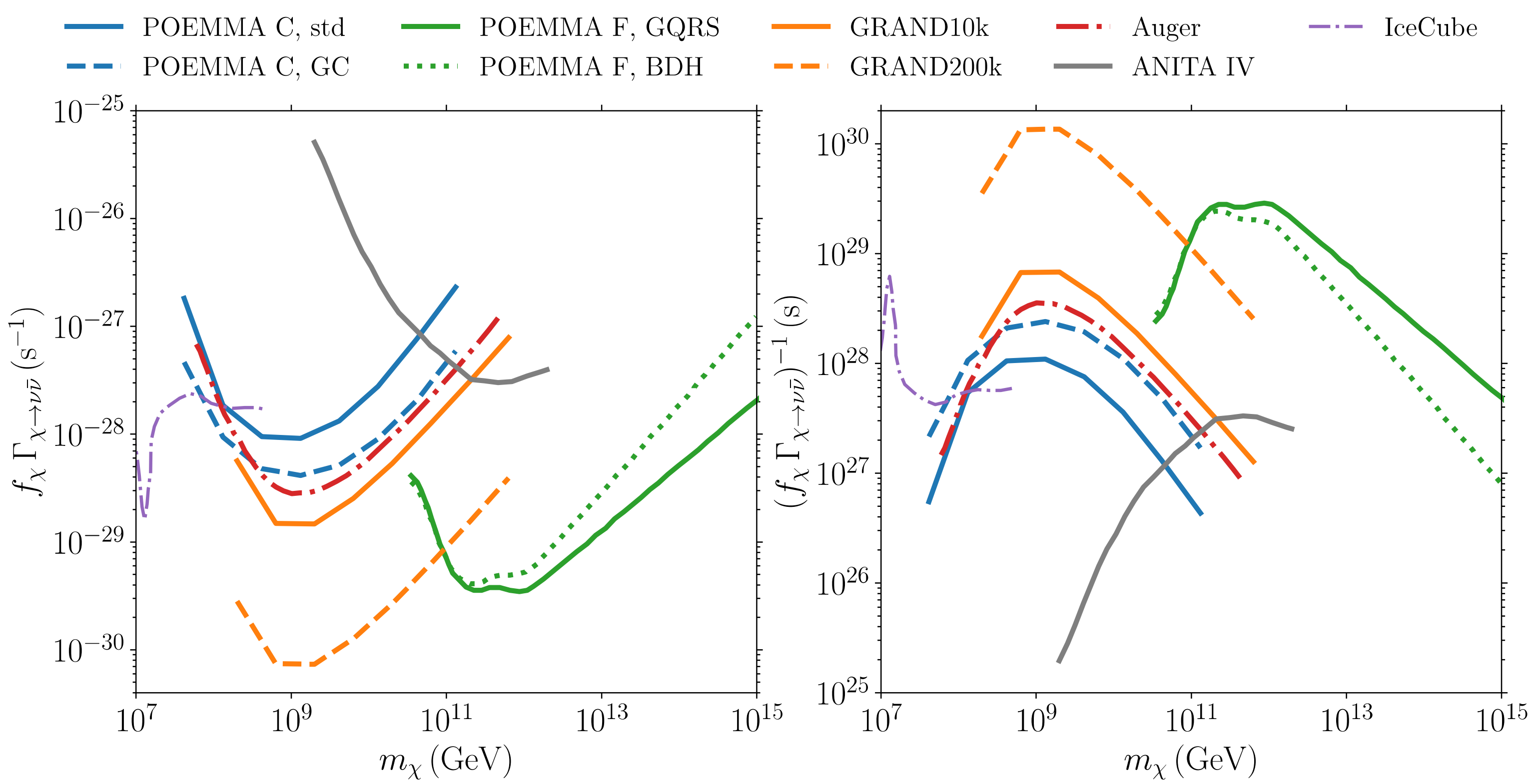
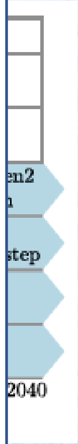


FIG. 4. Sensitivities to dark matter decay width (left) and inverse of the decay width (right), $\nu\bar{\nu}$ channel. Five-year sensitivities of POEMMA for the Cherenkov standard [(std), solid blue] and Galactic Center [(GC), dashed blue], and the fluorescence (green) observation modes, GRAND10k (solid orange), and GRAND200k (dashed orange). Sensitivities of ANITA IV (gray), Auger (dot-dashed red), and the IceCube [84] (dot-dashed purple). Allowed regions are below (above) the curves in the left (right) figure.



POEMMA Detailed Science Goals

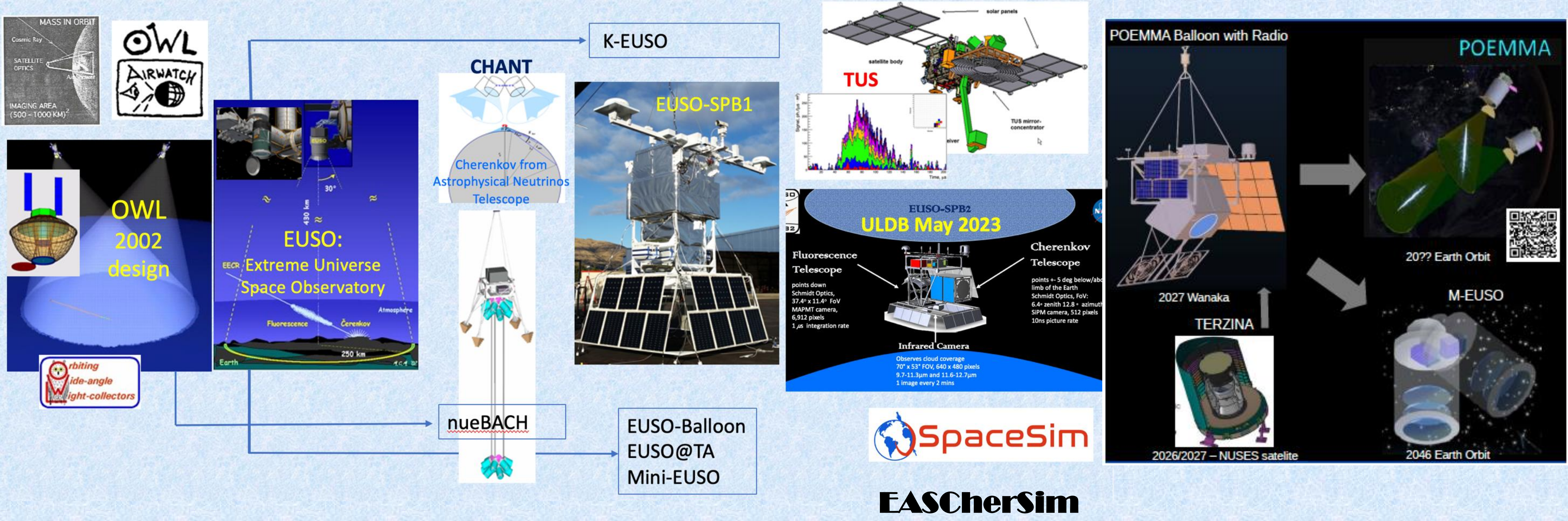
- Discover the origin of Ultra-High Energy Cosmic Rays
  - *Measure Spectrum, composition, full-sky Distribution* at Highest Energies (E_{CR} > 20 EeV)
  - Requires very good angular, energy, and X_{max} resolutions: *stereo fluorescence*
  - High sensitivity UHE neutrino measurements via stereo fluorescence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

UHECR Questions stated in the Astro2020 Decadal Review

... experiments have detected ultra-high-energy cosmic rays (UHECRs, in the ~10^{18} eV [EeV] range).

- What produces these remarkably energetic particles?
- Are the TeV-PeV neutrinos and ultra-high-energy cosmic rays produced in the same sources?
- They are widely surmised to be accelerated in the relativistic jets of accreting supermassive black holes or gamma-rays bursts, but this has yet to be tested observationally.
- Unfortunately, direct identification of a cosmic-ray source is difficult, since UHECRs are charged particles and are thus deflected as they travel through magnetic fields that permeate the universe.
- However, a clear directional signature would be provided by the high-energy neutrinos that the UHECRs produce in the regions where they are accelerated. Higher sensitivity neutrino observations with better sky localization are critical for unraveling how nature’s most extreme particle accelerators work.“

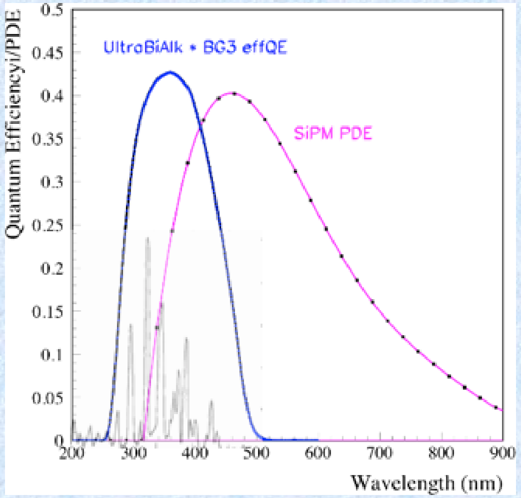
POEMMA: History and Heritage

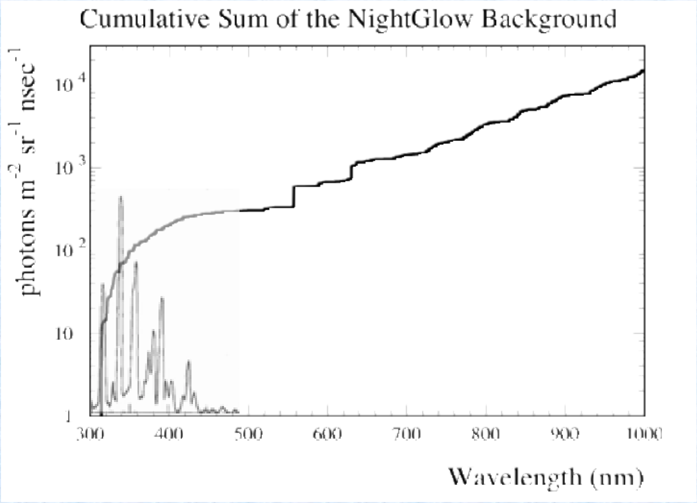


Technology Development for Enhanced Performance

Mass and power reduction of the instruments:

1. Lightweight, deployable optics
2. Low-power (< 1 mW) FEE for SiPM readout
   - See Terzina-inspired development for SiPM readout https://doi.org/10.3390/particles9010016
3. SiPMs in focal plane for EAS air fluorescence measurement
   - Requires large FoV filter to retain air fluorescence signal ($\lambda \lesssim 500$ nm) but eliminate dominant night-glow background at higher wavelengths.





NIMA 985.164614 (2021)