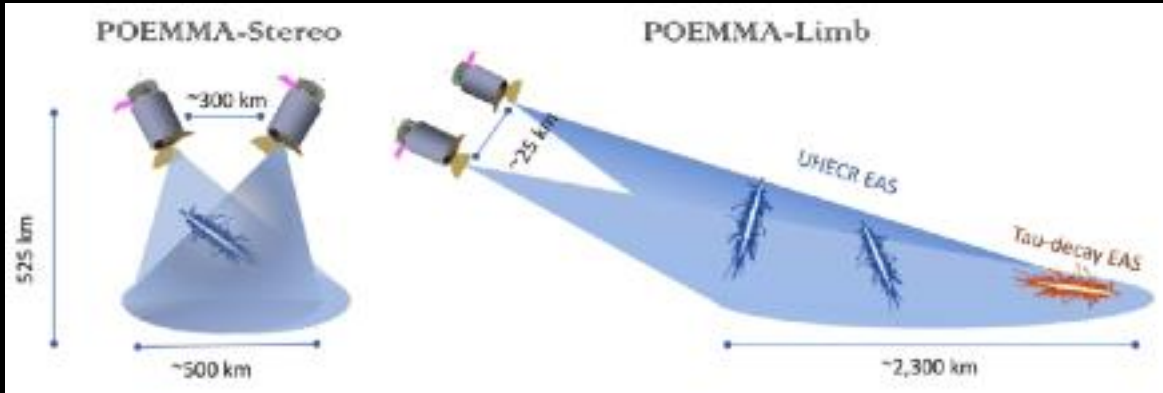


Science Goals:

- **Discover the origin of Ultra-High Energy Cosmic Rays**
Measure full-Sky Distribution, Spectrum, and composition at Highest Energies ($E_{CR} > 20$ EeV) using stereo air fluorescence technique

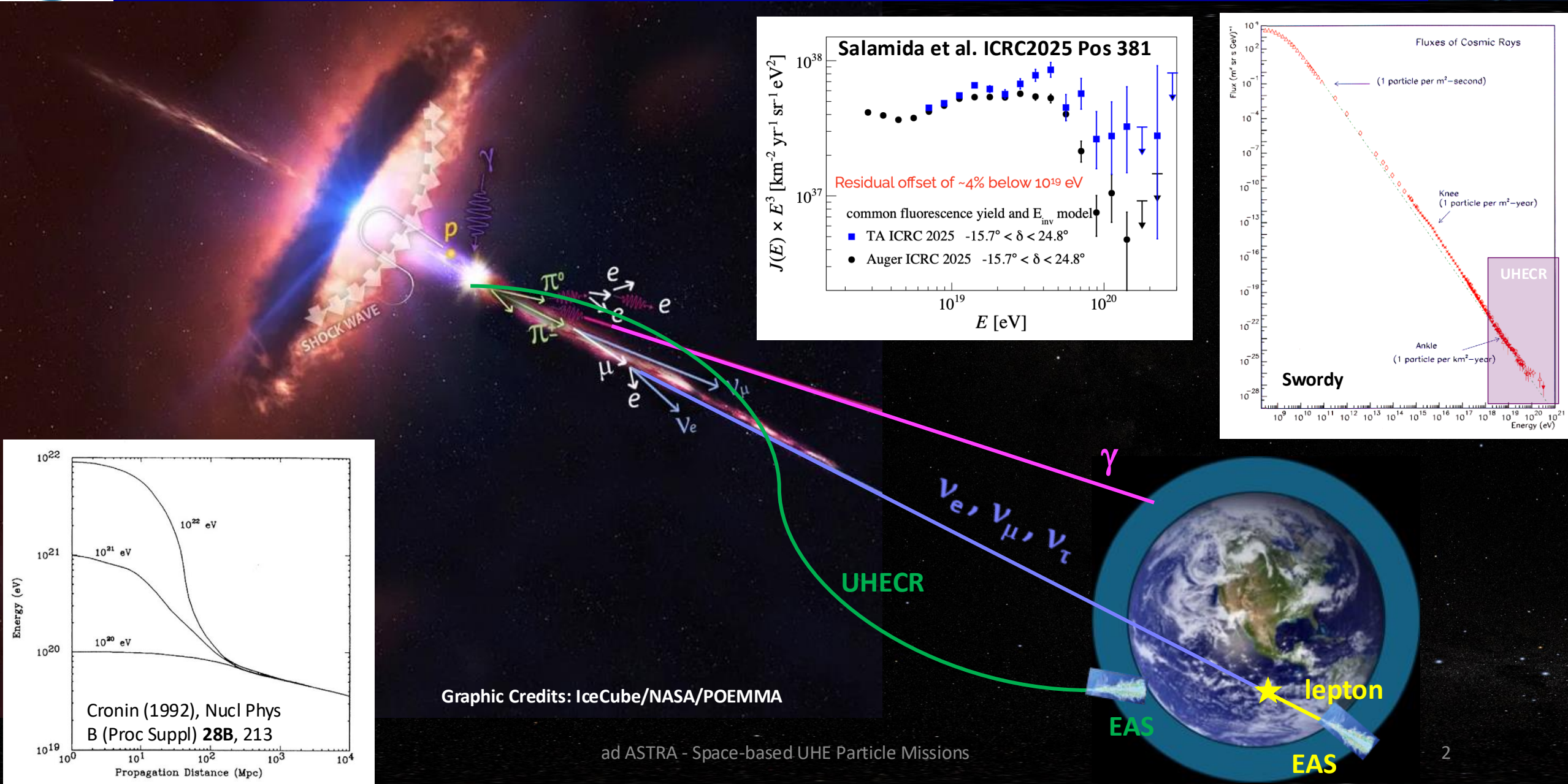


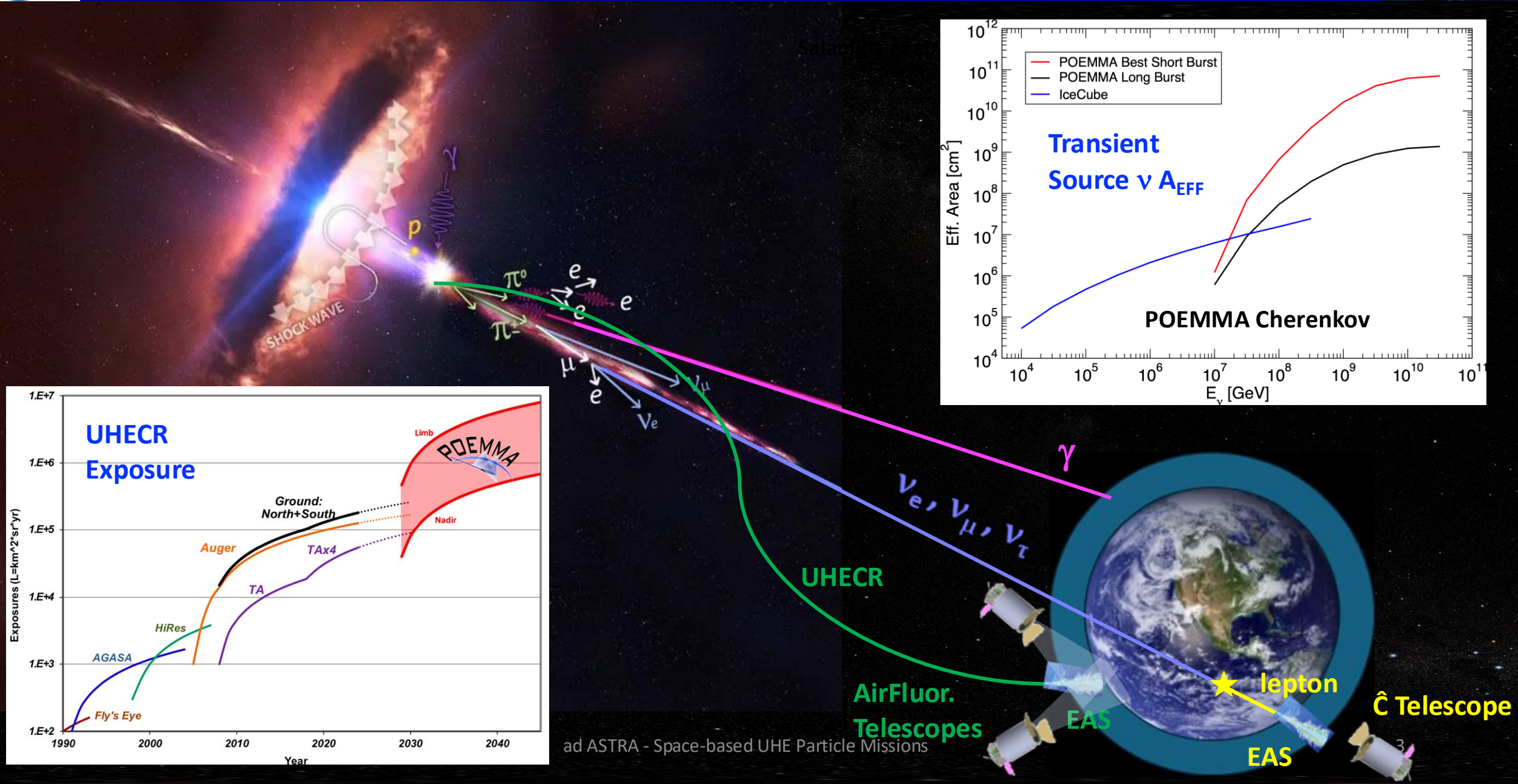
- **Observe Neutrinos from Transient Astrophysical Events**
Measure beamed Cherenkov light from upward-moving EAS from τ -leptons source by ν_τ interactions in the Earth ($E_\nu > 20$ PeV)
- **Probe particle physics at the highest energy scales**

POEMMA (Probe of Extreme MultiMessenger Astrophysics) is an observatory comprised of two large-area ($A_{COLL} = 6 \text{ m}^2$) 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.



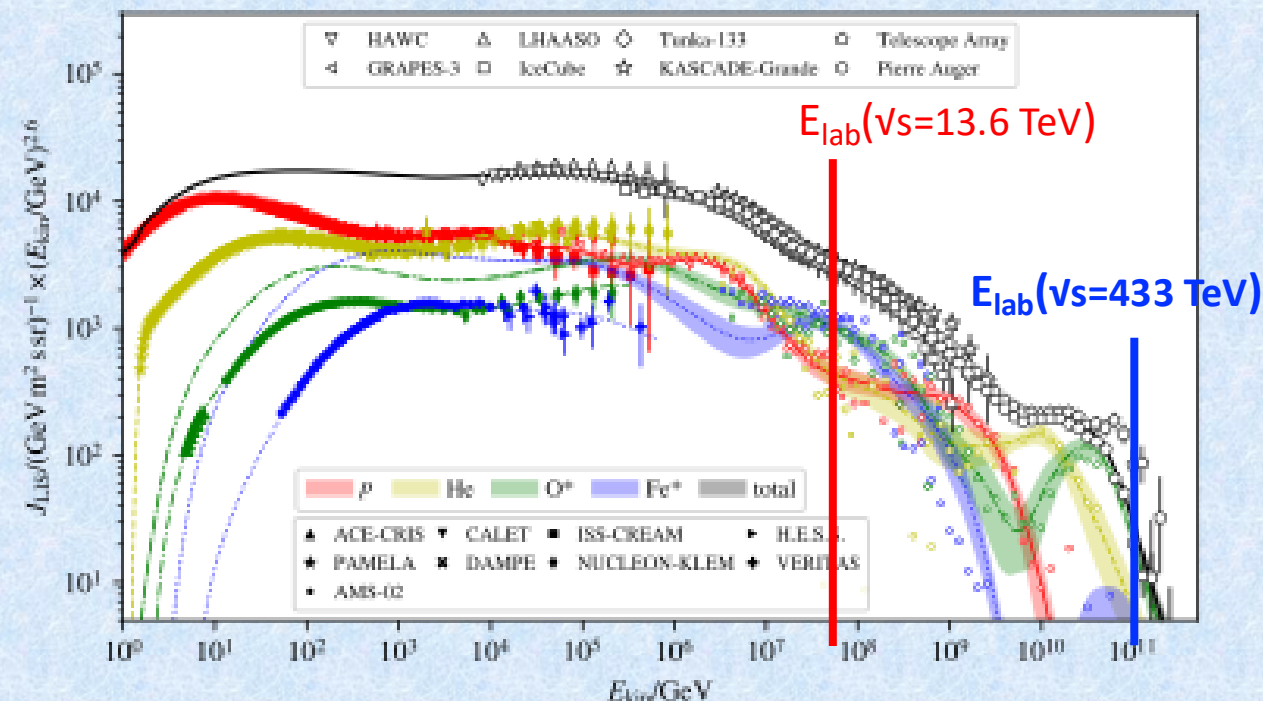
John Krizmanic
NASA/GSFC
for the POEMMA Collaboration





What is the nature and origin of UHECRs?

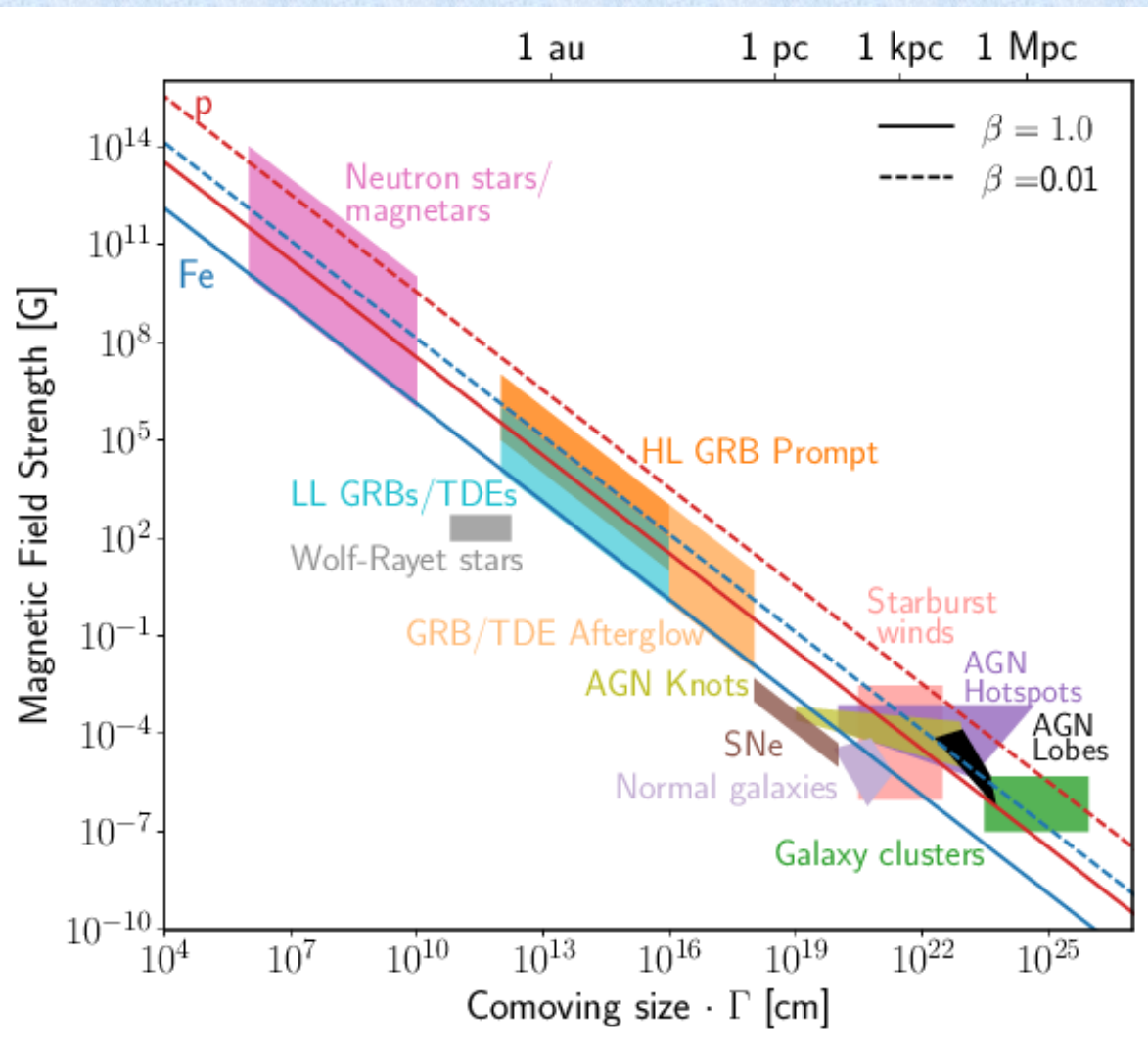
- What are the source(s) and acceleration mechanism of UHECRs?
- Are the TeV-PeV neutrinos and UHECRs produced in the same sources?
- What is the nature of the flux suppression at the highest energies?
- What is the composition evolution of the UHECR spectrum?
- Can UHECR charged-particle astronomy be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



Global Spline Fit of the cosmic ray nuclear composition based on scaled cosmic-ray flux per energy interval with all measurements adjusted to common energy scale.

[From Dembinski, Engel, Fedynith, and Fujisue ICRC2025 Pos 248]

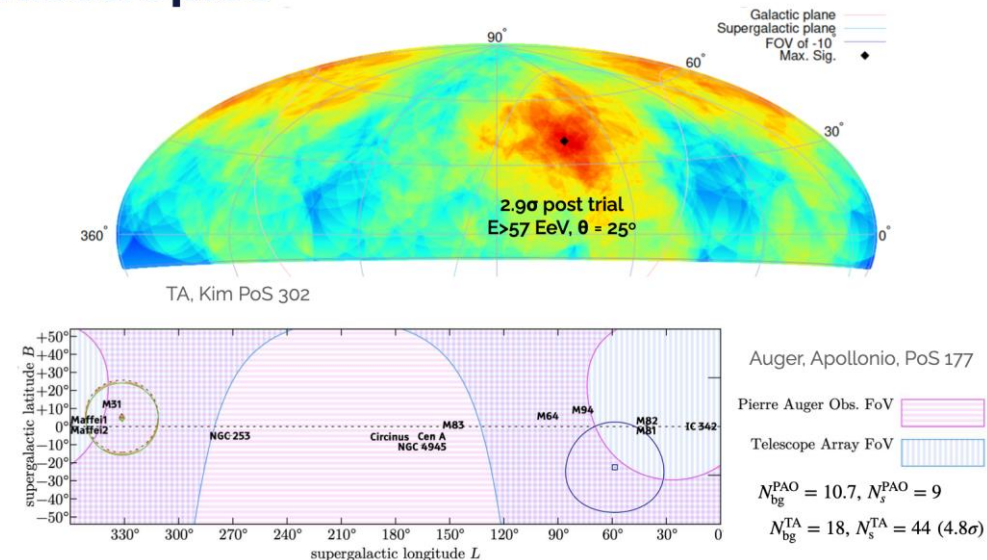
What are the sources of UHECR? What is the acceleration mechanism(s)?



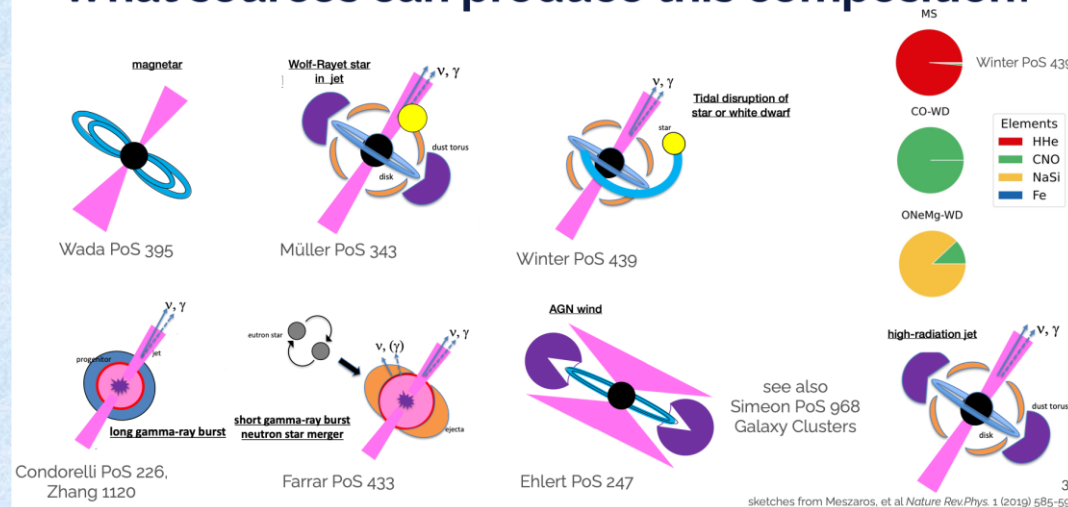
Ref: Batista et al., *Open Questions in Cosmic-Ray Research at Ultrahigh Energies*, Front. Astron. Space Sci 6 id.23 (2019)

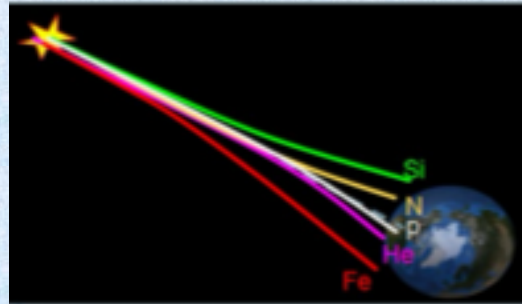
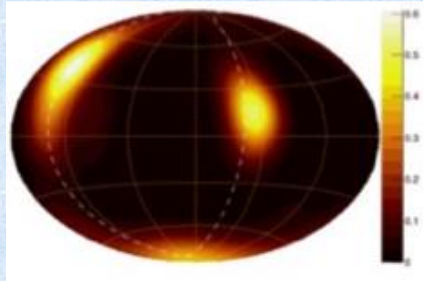
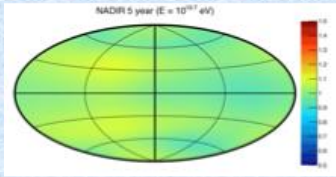
9/1/26

Anisotropies



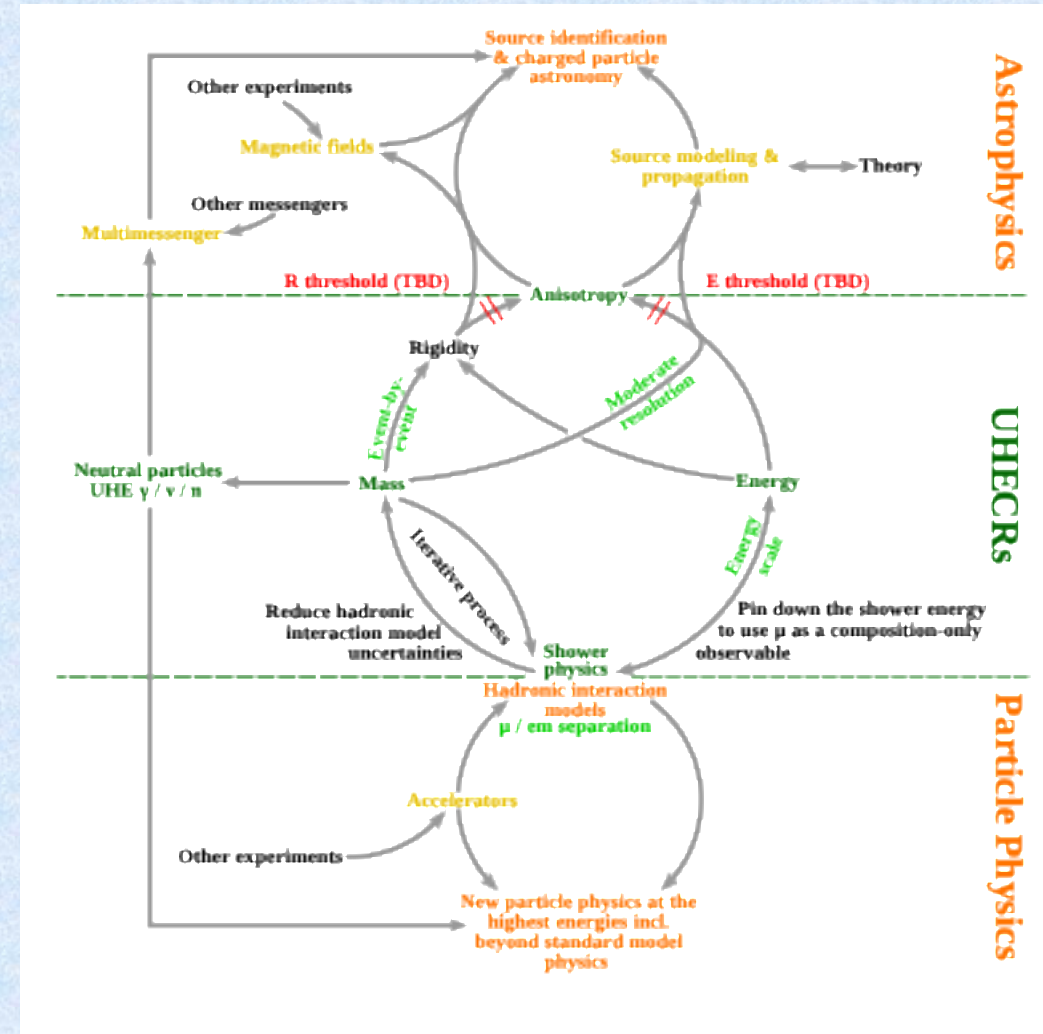
What sources can produce this composition?





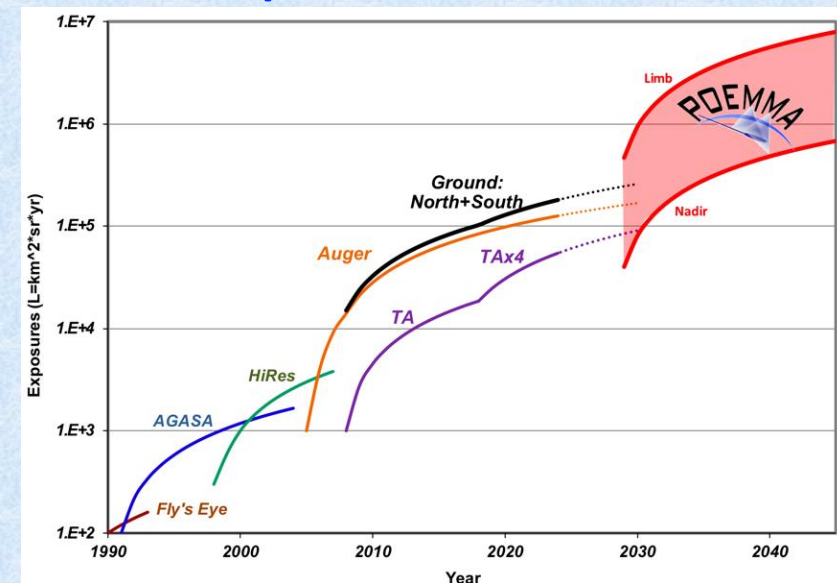
UHECR Measurements:

- Event-by-event Rigidity
 - Requires high accuracy for mass and energy of primary particle.
 - Enables rigidity selection to search for sources in distribution of arrival directions.
 - Helpful for rigidities $R > 10$ EeV stem from mixed composition.
 - Requires knowledge of galactic/intergalactic B-fields.
 - Ground-based detection can measure EAS particle component, e.g. muons.
- Huge Exposure and Full-sky coverage
 - Required for full anisotropy measurements with very high statistics while searching for declination dependence.
 - Search of recovery in UHECR spectrum.
- Particle Physics at the highest-energy scales
 - Is BSM at these extreme energies?
 - Do fundamental symmetries in Nature, e.g. Lorentz Invariance, break down?
 - What do UHECR, UHE photons, and VHE neutrinos say about dark matter

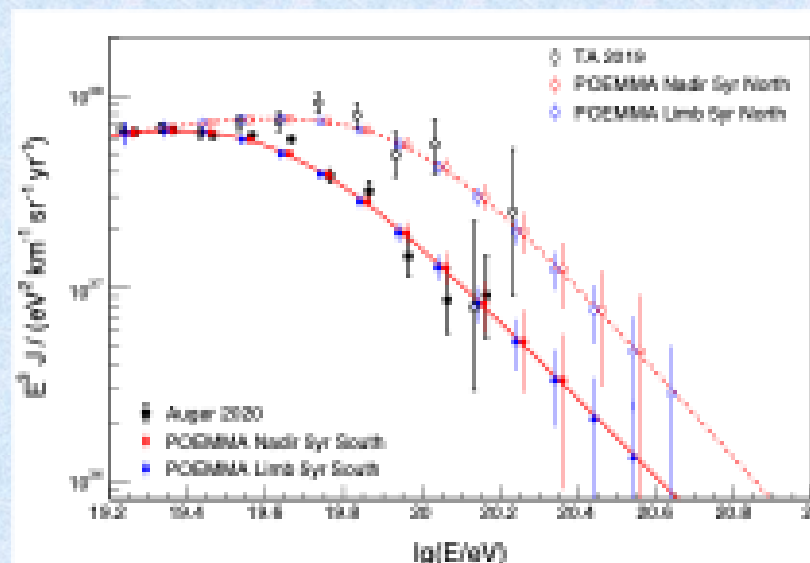


Ultra-High-Energy Cosmic Rays: The Intersection of the Cosmic and Energy Frontiers (SnowMass WP), Coleman et al., AstroPart Phys 149 id.102819 (2023)

Exposure Evolution



Simulated Spectrum (Auger vs TA)

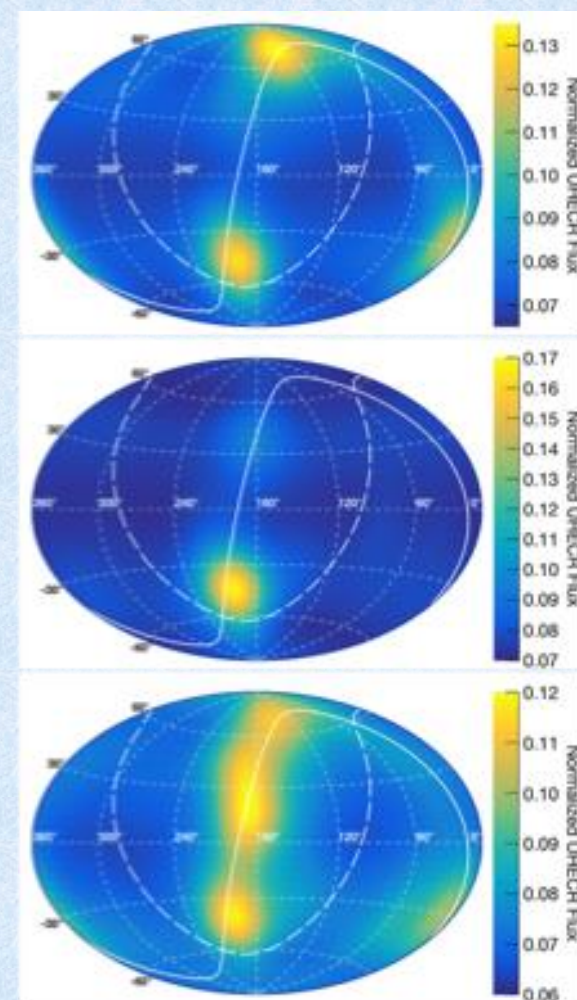


UHECR Source Model

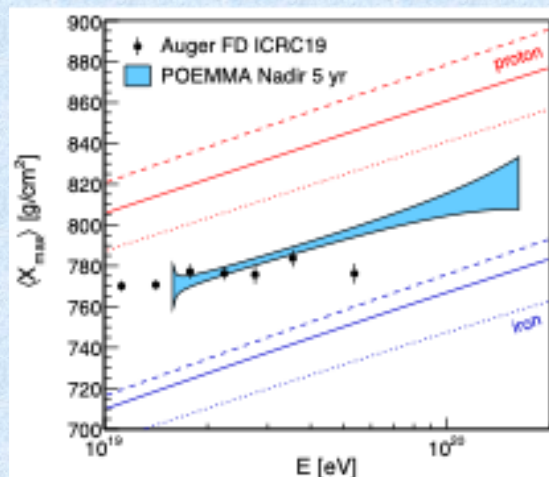
Starburst
Galaxies:
11% anisotropy
15% angular spread

Swift-BAT AGNs:
8% anisotropy
15% angular spread

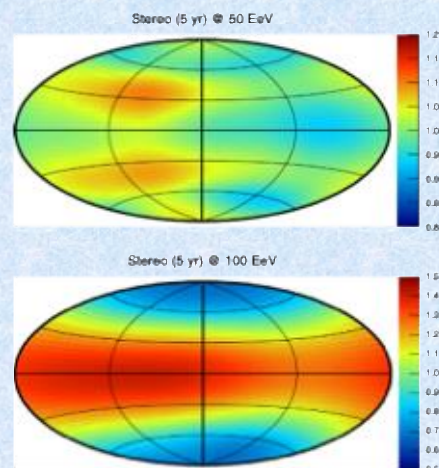
2MRS Galaxies:
19% anisotropy
15% angular spread



Science Interpretation



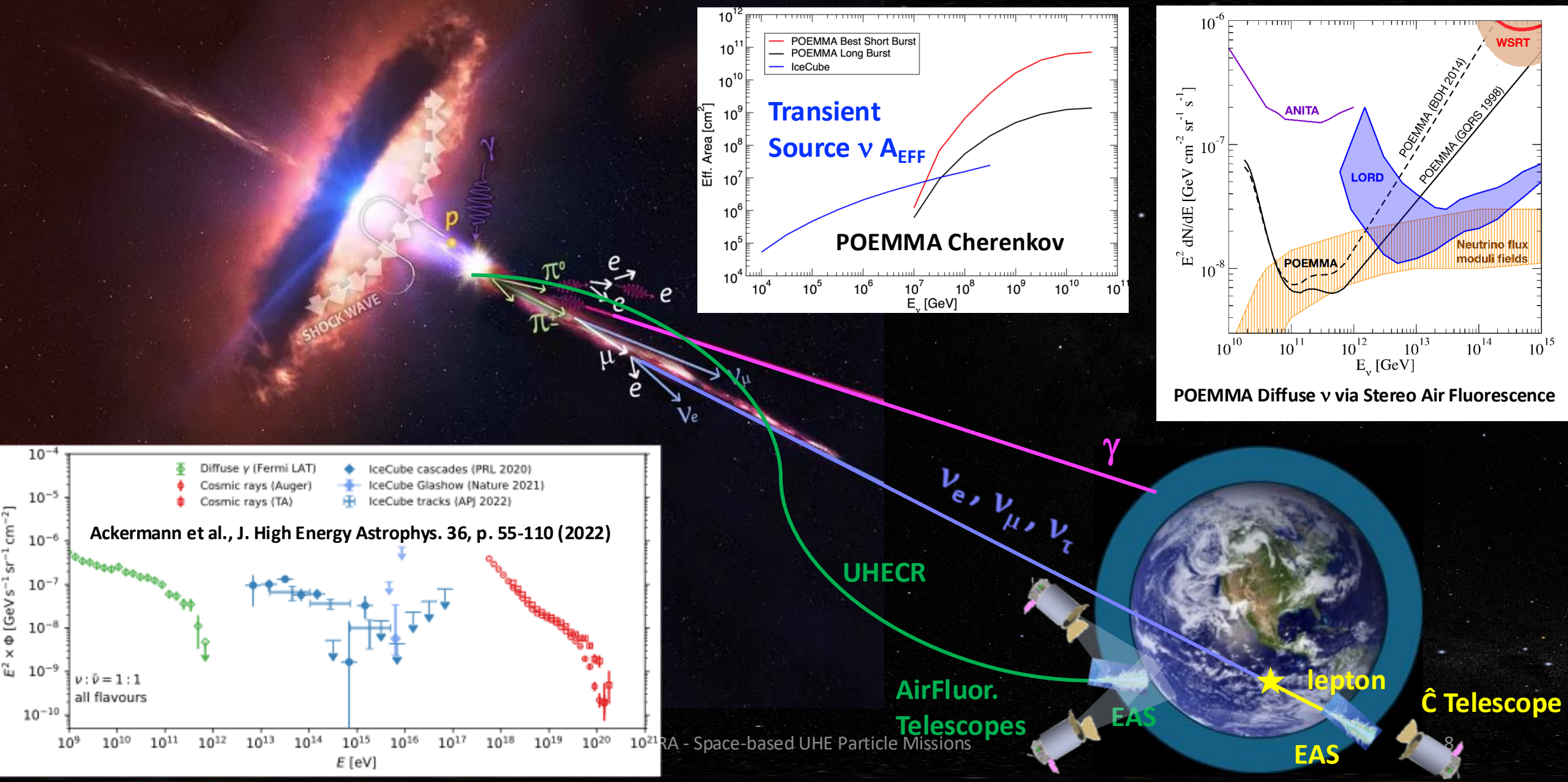
Simulated Sky Coverage

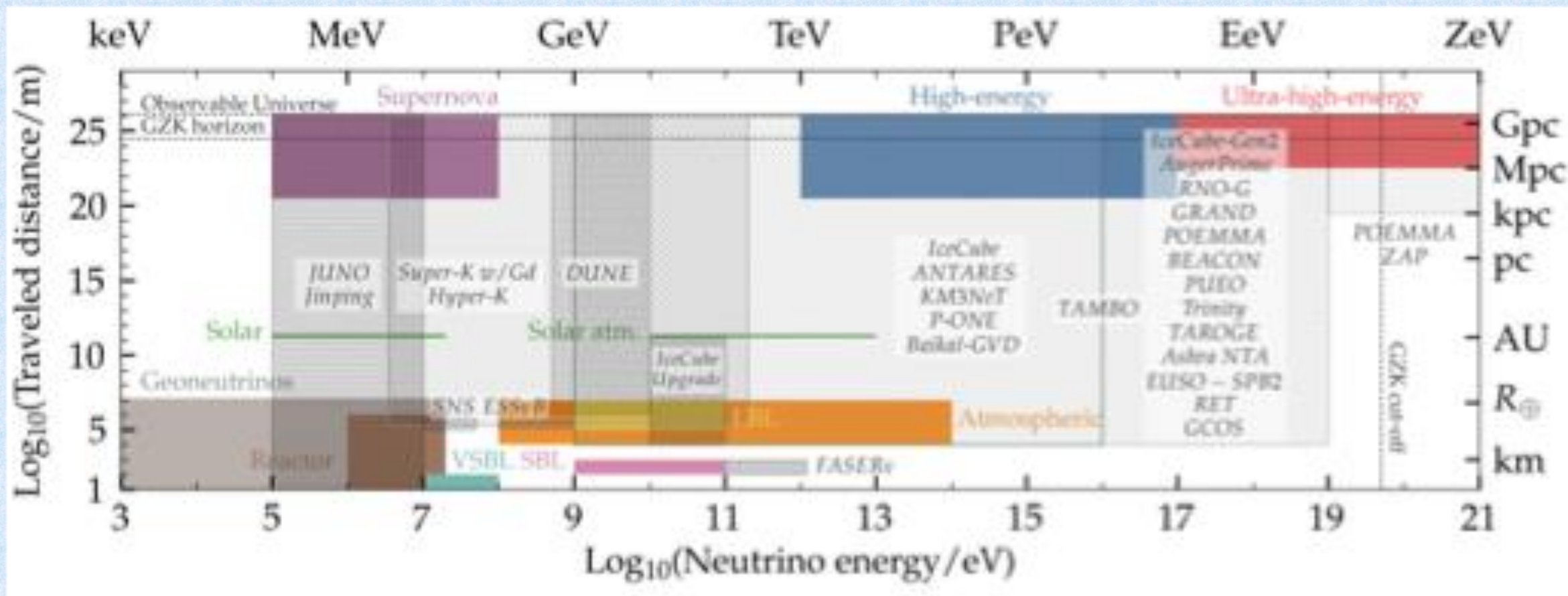


Simulated Composition



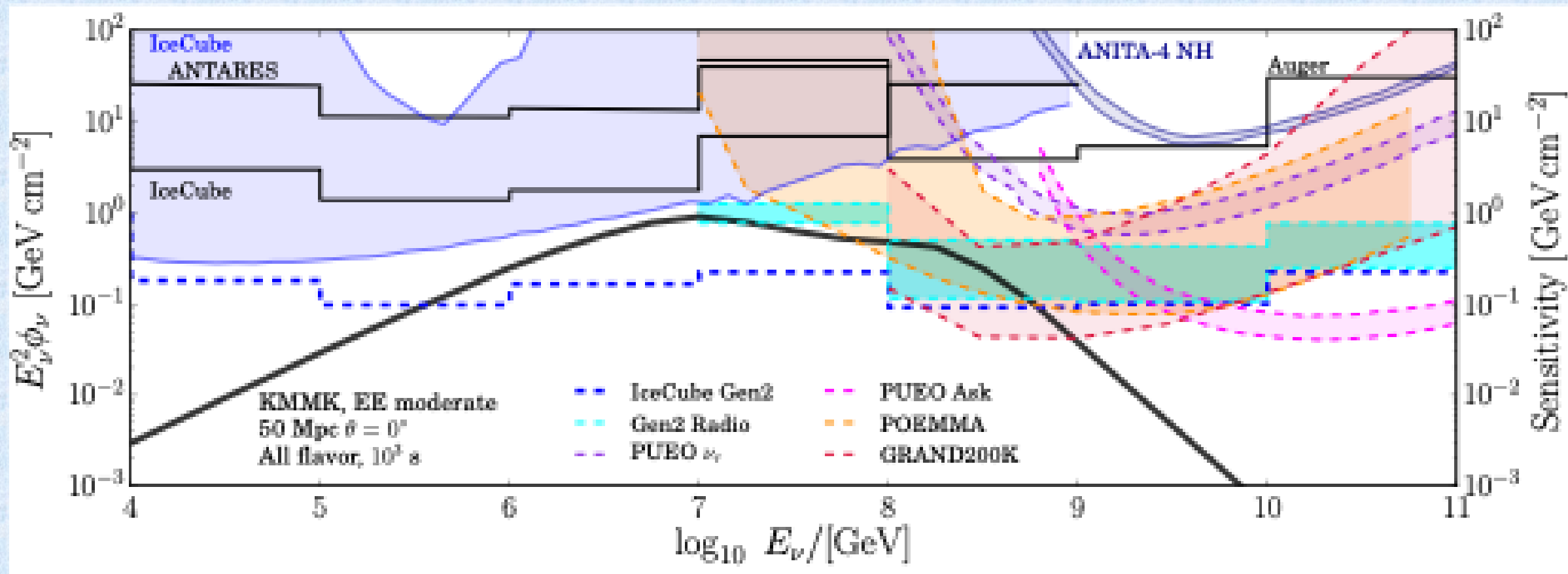
Impact of a Space-based Mission for VHE-UHE Cosmic Neutrinos





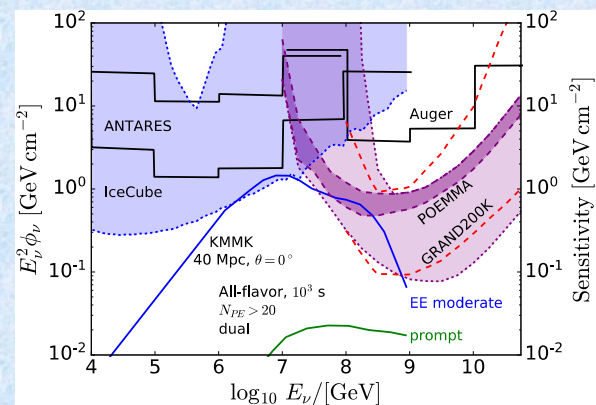
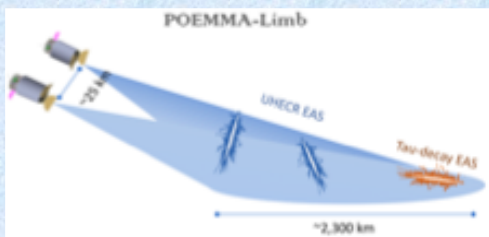
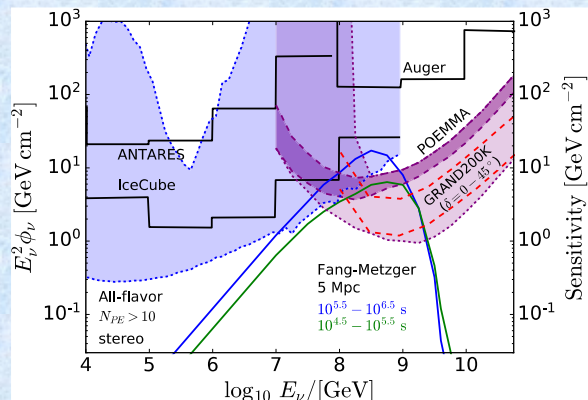
Distribution of neutrino sources in energy and distance traveled to the detector, and present and future experiments aimed at detecting them.

Ref: *High-energy and ultra-high-energy neutrinos: A Snowmass white paper*, Ackermann et al., J. High Energy Astrophys. 36, p. 55-110 (2022)



Sensitivity to short (1000 s) burst all-flavor neutrino for current and future experiments.

Ref: Ackermann et al., J. High Energy Astrophys. 36, p. 55-110 (2022)



POEMMA'S TARGET-OF-OPPORTUNITY SENSITIVITY TO ...

PHYS. REV. D **102**, 123013 (2020)

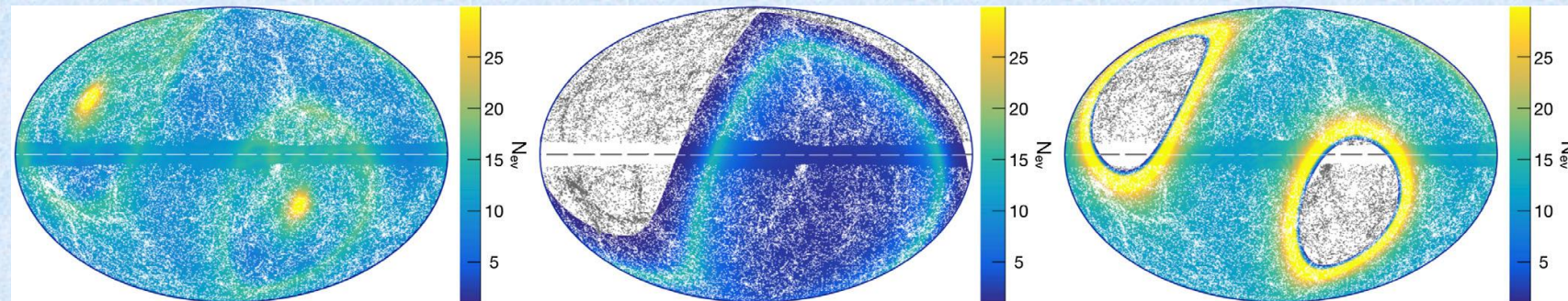


FIG. 7. Left: sky plot of the expected number of neutrino events as a function of galactic coordinates for POEMMA in the long-burst scenario of a BNS merger, as in the Fang and Metzger model [22], and placing the source at 5 Mpc. Point sources are galaxies from the 2MRS catalog [78]. Middle: same as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

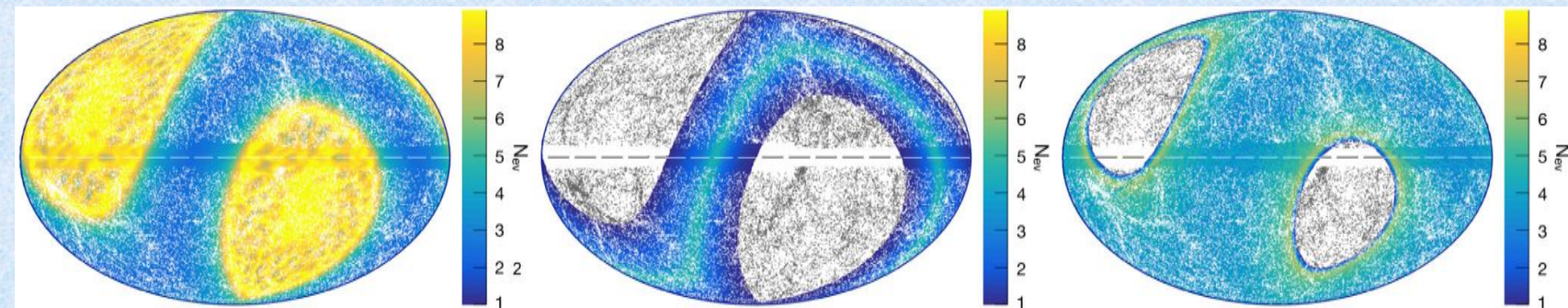


FIG. 8. Left: sky plot of the expected number of neutrino events as a function of galactic coordinates for POEMMA in the best-case short-burst scenario of an sGRB with moderate EE, as in the KMMK model [17], and placing the source at 40 Mpc. Point sources are galaxies from the 2MRS catalog [78]. Middle: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

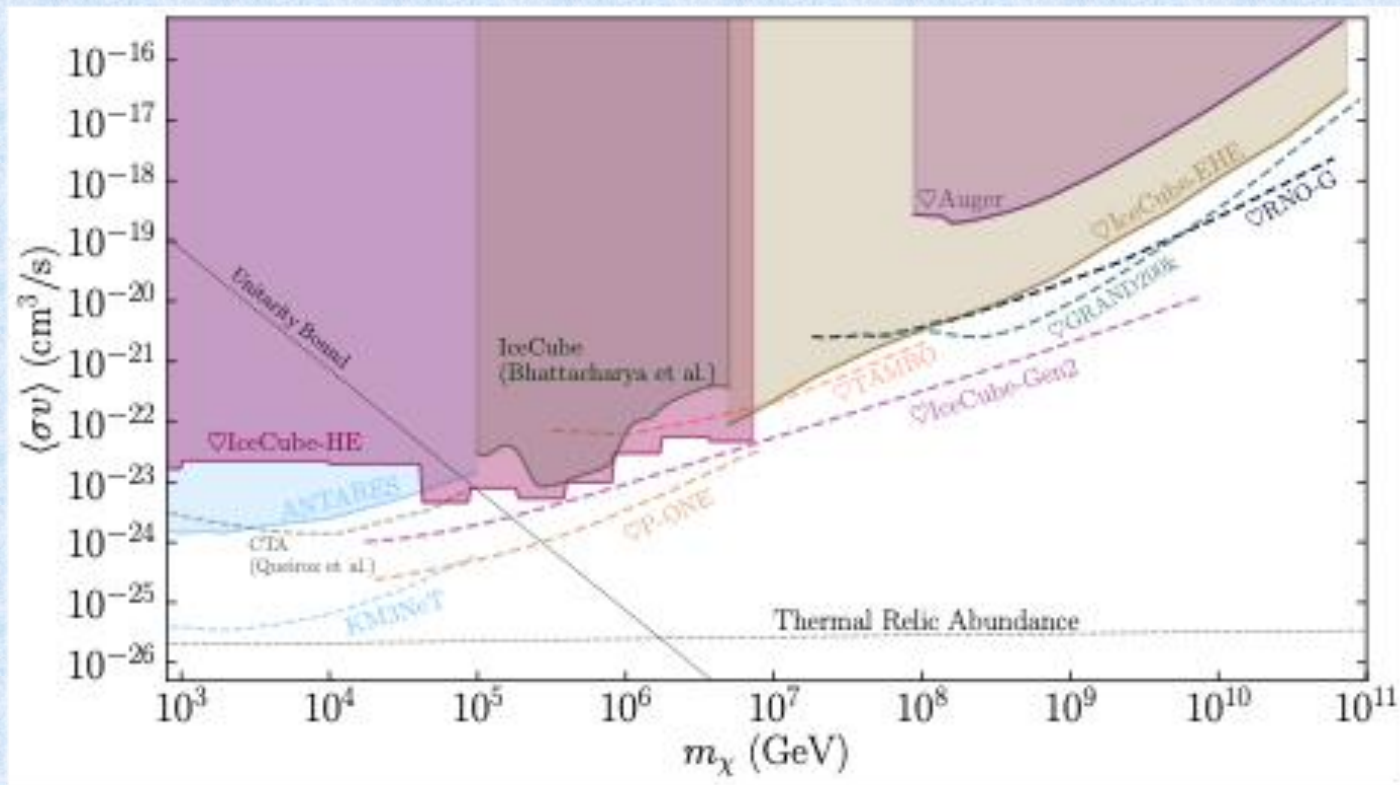


Figure 7. Constraints on the velocity-averaged annihilation cross section, $\langle\sigma v\rangle$, of supra-TeV dark-matter particles, with mass m_χ , into neutrinos. Solid and dashed lines represent, respectively, 90% C.L. existing limits and sensitivities. Figure reproduced from Ref [216]; heart symbols show new constraints introduced therein.

Ref: Ackermann et al., J. High Energy Astrophys. 36, p. 55-110 (2022)

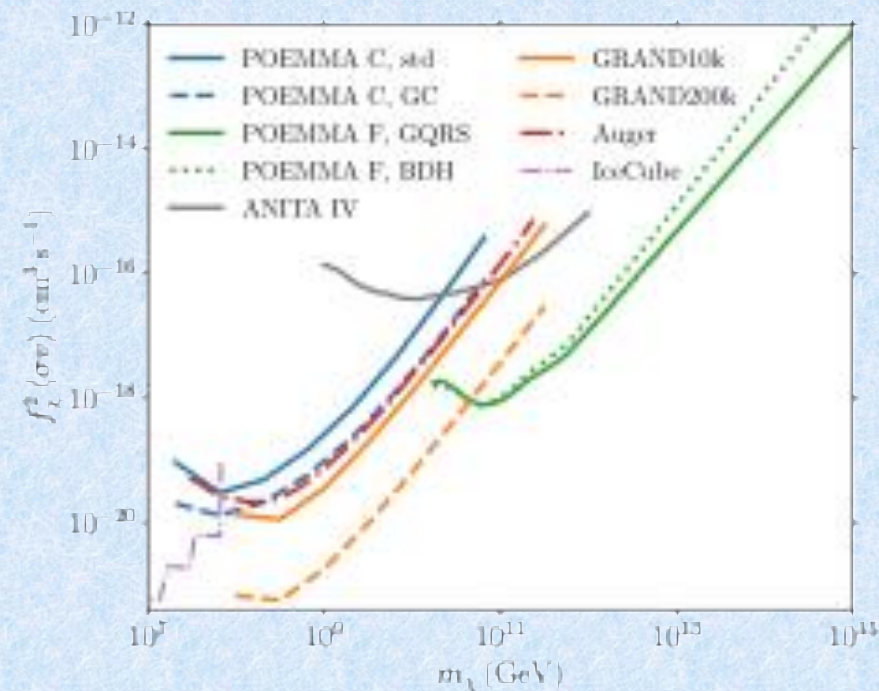


FIG. 3. Sensitivities to dark matter thermally averaged annihilation cross section, $\nu\bar{\nu}$ channel (summed over neutrino flavors), multiplied by $f_\chi^2 = (\rho_\chi/\rho_{DM})^2$. Five-year sensitivities of POEMMA for the Cherenkov standard [(std), solid blue] and Galactic Center [(GC), dashed blue], and the fluorescence (green) observation modes, GRAND10k (solid orange), and GRAND200k (dashed orange). Sensitivities of ANITA IV (gray), Auger (dot-dashed red), and IceCube [61] (dot-dashed purple).

Guépin et al., Indirect dark matter searches at ultrahigh energy neutrino detectors, PRD 104, 083002 (2021)



- In this talk, we discussed the unique capabilities of space-based UHECR and VHE-UHE cosmic neutrino measurements in the context of POEMMA as it was developed as a NASA Astrophysics Probe mission (starting in 2016) and with the constraints of the program.
- Since then, more capable launch vehicles have been developed included Space X Starship and SLS that have nearly doubled the allowable diameter of a payload from 4.6 m to 8 m:
 - Allows for larger diameter mirrors which would lead to significant improvements in UHECR exposure and neutrino sensitivity to transient sources.
 - There also has been a significant development in meter-size lightweight optics in part due to use of additive manufacturing and driven by increased aerospace applications.
- While the JEM-EUSO/POEMMA collaboration has been developing ULDB balloon missions to proof the technology and measurement concepts, including the EUSO-SPB1, EUSO-SPB2 completed missions and the PBR mission currently in development (including a FT/CT hybrid focal plane and EAS radio detection), and the Terzina satellite mission, there are several technology developments that are highly desired:
 - Milliwatt per channel SiPM ASIC readout: MIZAR ASIC development has shown 5 mW/channel
 - Fluorescence telescope use of SiPM (or SiPM+filter): wavelength response with negligible PDE above 500 nm is required to eliminate the dominant air glow background above 500 nm
 - Algorithms based on ML: preliminary research has shown that space-based EAS profile measurements using ML can obtain moderate-resolution event-by-event rigidity reconstruction.

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

UHECRs: $E > 20$ EeV

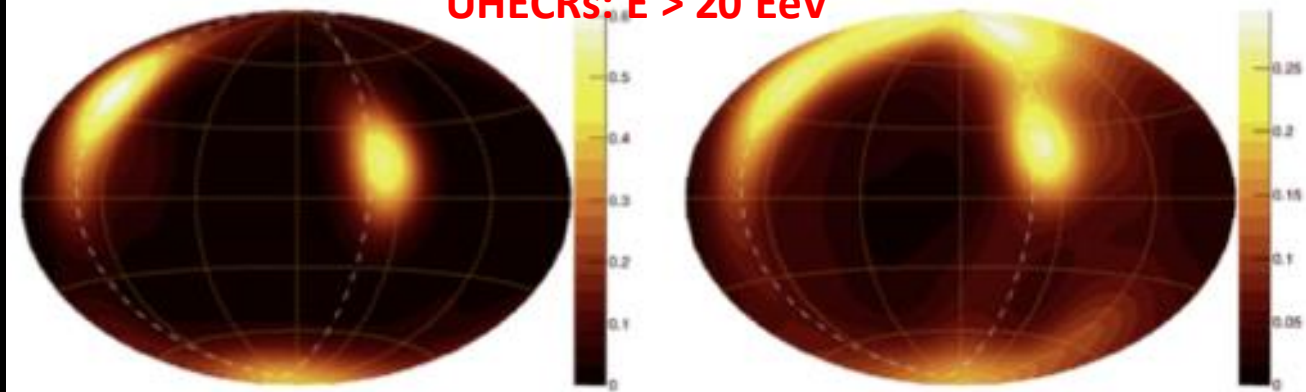
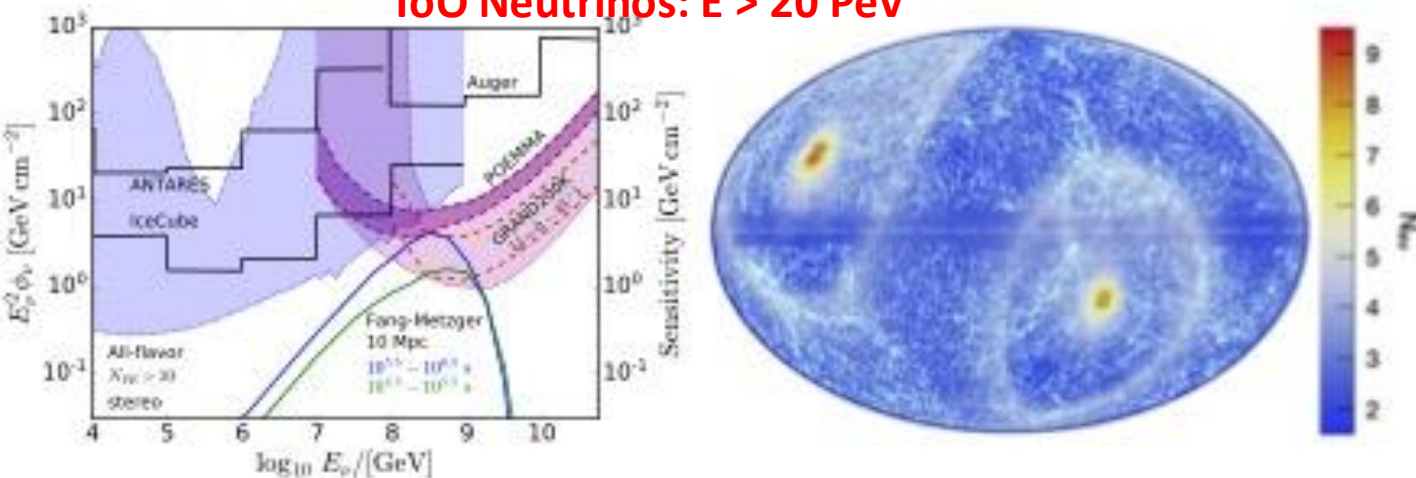


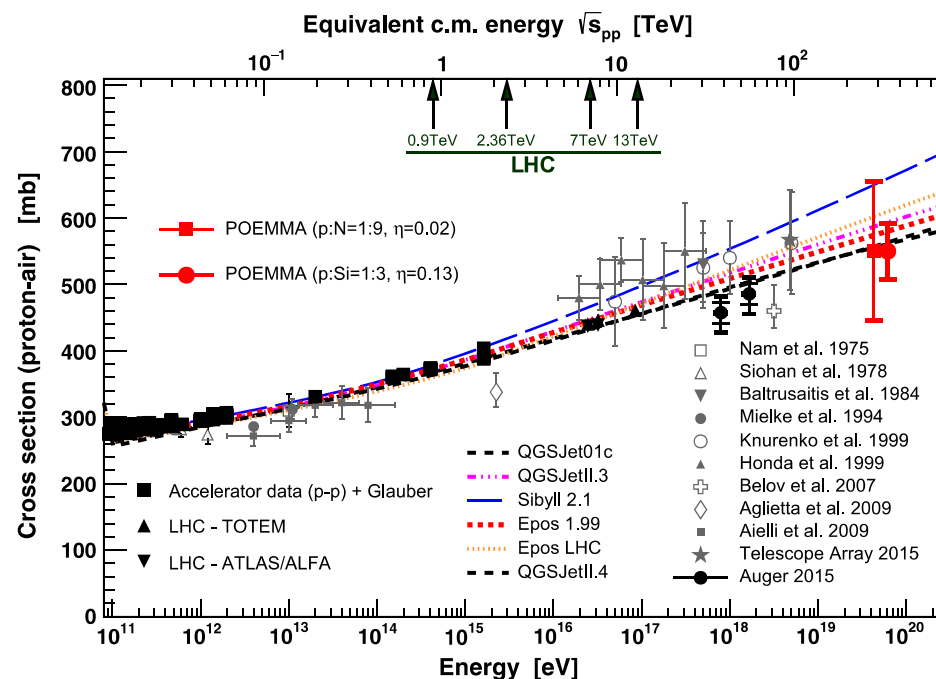
FIG. 23. Left: Sky map of nearby starburst galaxies from Refs. [35,103] weighted by radio flux at 1.4 GHz, the attenuation factor accounting for energy losses incurred by UHECRs through propagation, and the exposure of POEMMA. The map has been smoothed using a von Mises-Fisher distribution with concentration parameter corresponding to a search radius of 15.0° as found in Ref. [35]. The color scale indicates $\mathcal{F}_{sc}$, 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.

ToO Neutrinos: $E > 20$ PeV



POEMMA

Thank you !!



P-air cross section measurement at $\sqrt{s} \approx 300$ TeV



Backup Slides





A. V. Olinto,¹ J. Krizmanic,² J. H. Adams,³ R. Aloisio,⁴ L. A. Anchordoqui,⁵ A. Anzalone,^{6,7} M. Bagheri,⁸ D. Barghini,⁹ M. Battisti,⁹ D. R. Bergman,¹⁰ M. E. Bertaina,⁹ P. F. Bertone,¹¹ F. Bisconti,¹² M. Bustamante,¹³ F. Cafagna,¹⁴ R. Caruso,^{15,7} M. Casolino,^{16,17} K. Černý,¹⁸ M. J. Christl,¹¹ A. L. Cummings,¹⁹ I. De Mitri,⁴ R. Diesing,²⁰ R. Engel,²¹ J. Eser,¹ K. Fang,²² F. Fenu,⁹ G. Filippatos,²⁰ E. Gazda,⁸ C. Guepin,²⁴ A. Haungs,²¹ E. A. Hays,² E. G. Judd,²⁵ P. Klimov,²⁶ V. Kungel,²³ E. Kuznetsov,³ Š. Mackovjak,²⁷ D. Mandát,²⁸ L. Marcelli,¹⁷ J. McEnery,² G. Medina-Tanco,²⁹ K.-D. Merenda,²⁵ S. S. Meyer,²⁰ J. W. Mitchell,² H. Miyamoto,⁹ J. M. Nachtman,³⁰ A. Neronov,³¹ F. Oikonomou,³² Y. Onel,³⁰ G. Osteria,³³ A. N. Otte,⁸ E. Parizot,³⁴ T. Paul,¹ M. Pech,²⁸ J. S. Perkins,² P. Picozza,^{17,35} L.W. Piotrowski,³⁶ Z. Plebaniak,⁹ G. Prévôt,³⁴ P. Reardon,³ M. H. Reno,³⁰ M. Ricci,³⁷ O. Romero Matamala,⁸ F. Sarazin,²³ P. Schovánek,²⁸ V. Scotti,^{33,38} K. Shinozaki,³⁹ J. F. Soriano,⁵ F. Stecker,² Y. Takizawa,¹⁶ R. Ulrich,²¹ M. Unger,²¹ T. M. Venters,² L. Wiencke,²³ D. Winn,³⁰ R. M. Young,¹¹ M. Zotov²⁶

¹Columbia University, New York, NY, USA

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¹⁴Istituto Nazionale di Fisica Nucleare, Bari, Italy

¹⁵Università di Catania, Catania Italy

¹⁶RIKEN, Wako, Japan

¹⁷Istituto Nazionale di Fisica Nucleare, Section of Roma Tor Vergata, Italy

¹⁸Joint Laboratory of Optics, Faculty of Science, Palacký University, Olomouc, Czech Republic

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²⁰University of Chicago, Chicago, IL, USA

²¹Karlsruhe Institute of Technology, Karlsruhe, Germany

²²University of Wisconsin, Madison, WI, USA

²³Colorado School of Mines, Golden, CO, USA

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²⁷Institute of Experimental Physics, Slovak Academy of Sciences, Kosice, Slovakia

²⁸Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic

²⁹Instituto de Ciencias Nucleares, UNAM, CDMX, Mexico

³⁰University of Iowa, Iowa City, IA, USA

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³⁴Université de Paris, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France

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³⁶Faculty of Physics, University of Warsaw, Warsaw, Poland

³⁷Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali di Frascati, Frascati, Italy

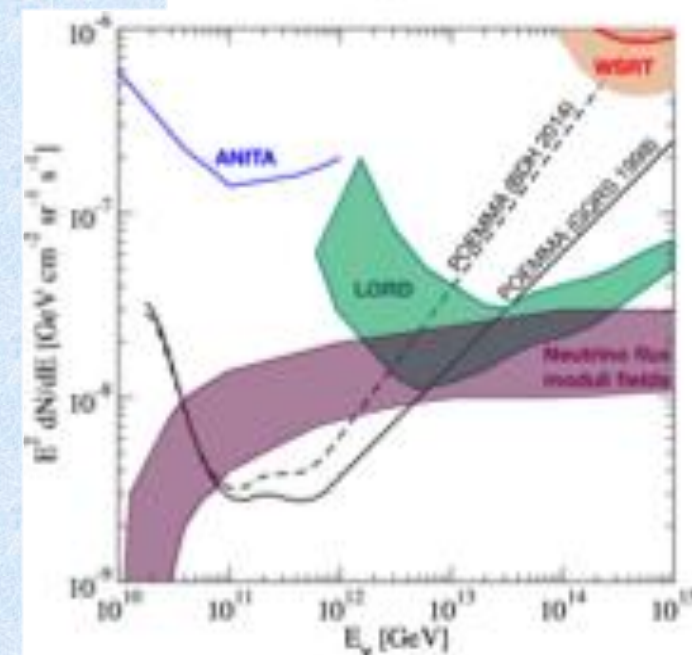
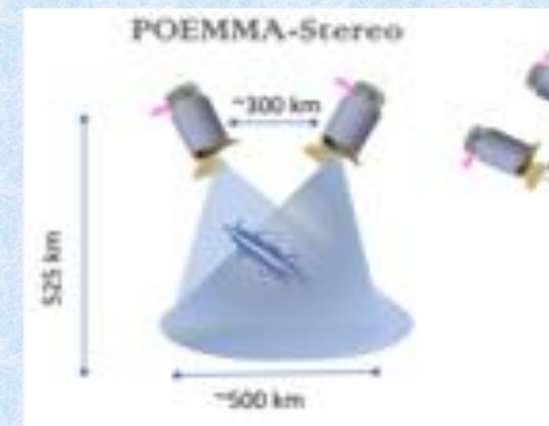
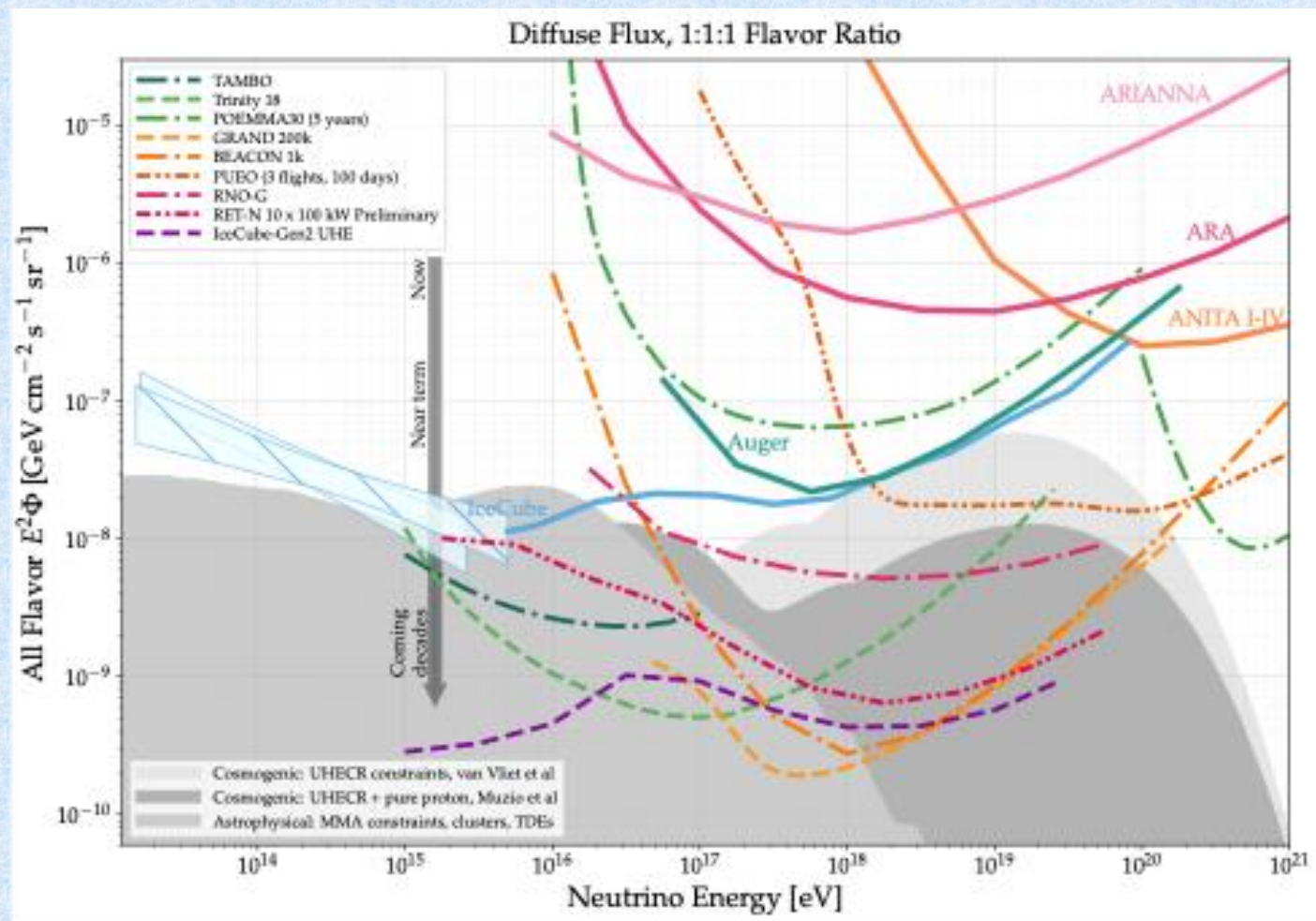
³⁸Università di Napoli Federico II, Napoli, Italy

³⁹National Centre for Nuclear Research, Lodz, Poland

Acknowledgements

The conceptual design of POEMMA was supported by NASA Probe Mission Concept Study grant NNX17AJ82G for the 2020 Decadal Survey Planning. Contributors to this work were supported in part by NASA awards 16-APROBES16-0023, 17-APRA17-0066, NNX17AJ82G, NNX13AH54G, 80NSSC18K0246, 80NSSC18K0473, 80NSSC19K0626, and 80NSSC18K0464, US Department of Energy grant DE-SC0010113, and the U.S. National Science Foundation (NSF Grant PHY-1620661). MB is supported by the VILLUM FONDEN under project no. 29388. The authors from University of Torino acknowledge support from Compagnia di San Paolo within the project 'ex-post-2018'. The Czech authors are supported by the Ministry of Education, Youth and Sports of the Czech Republic. GMT is supported by PAPIIT IN111621/DGAPA/UNAM.

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

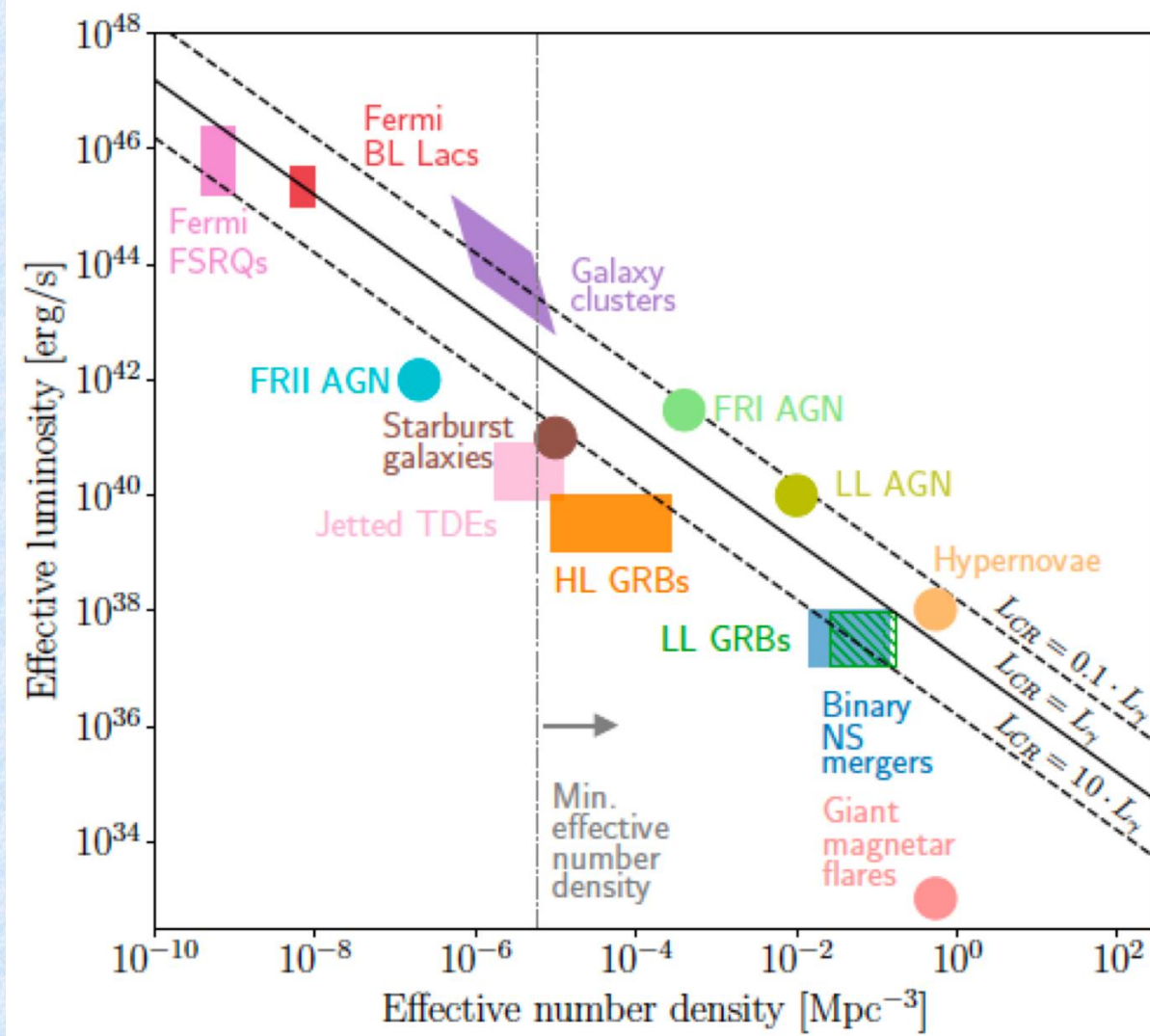


Sensitivity to all-flavor neutrino diffuse flux for current and future experiments.

Ref: Ackermann et al., J. High Energy Astrophys. 36, p. 55-110 (2022)

What is the nature and origin of UHECRs?

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Ref: Batista et al., *Open Questions in Cosmic-Ray Research at Ultrahigh Energies*, Front. Astron. Space Sci 6 id.23 (2019)

Significant increase in **exposure with all-sky coverage**

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

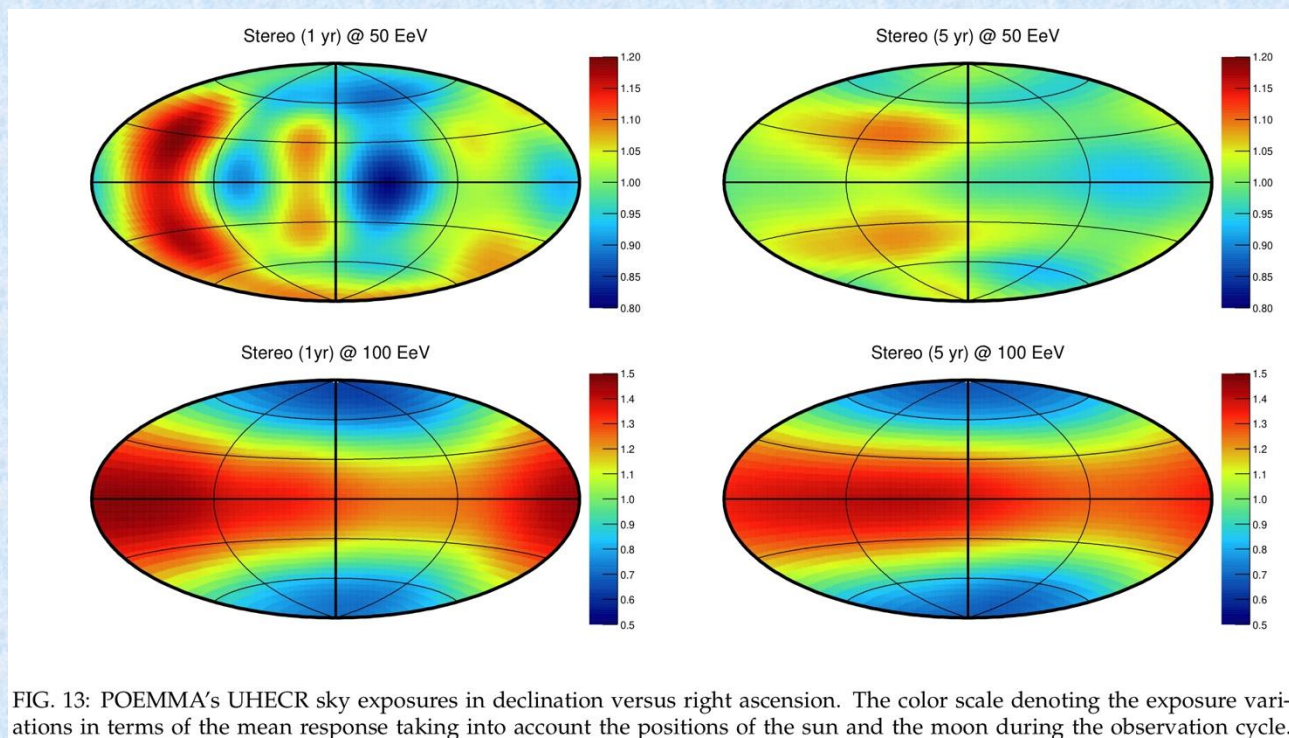
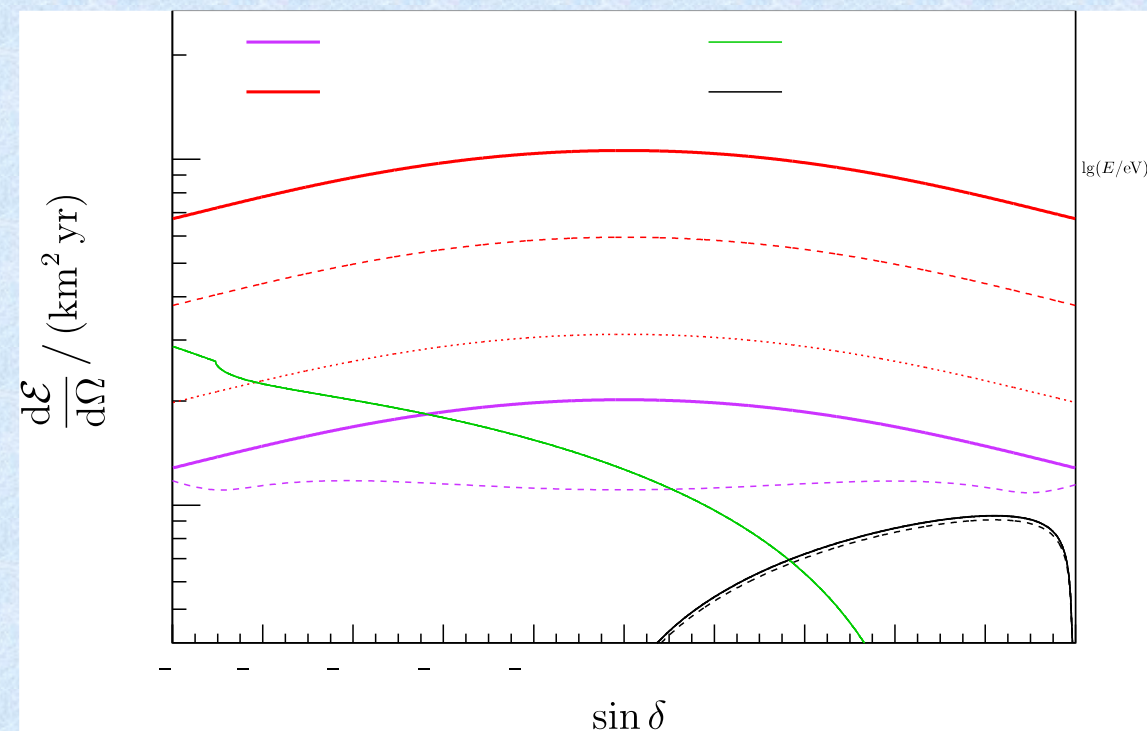


FIG. 13: POEMMA's UHECR sky exposures in declination versus right ascension. The color scale denoting the exposure variations in terms of the mean response taking into account the positions of the sun and the moon during the observation cycle.



15° Angular Spread, 10% StarBurst Fraction

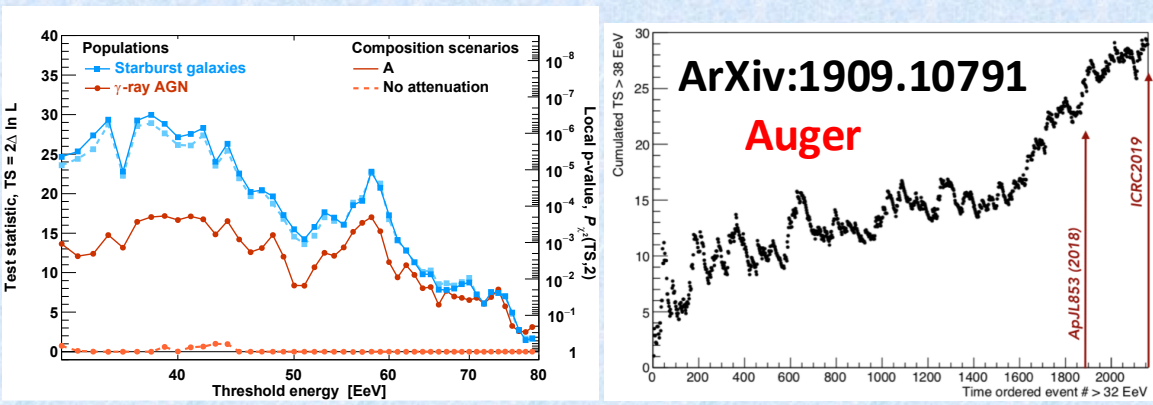


Figure 11: Left: Maximum likelihood-ratio as a function of energy threshold for the models based on SBGs and $gAGNs$. The results are shown in the attenuation (full line) and no-attenuation (dashed line) scenarios. Right: Cumulated test statistics for $E_{thr} = 38$ EeV as a function of the time ordered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

TABLE II. TS values for scenarios with $\Theta = 15^\circ$.

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

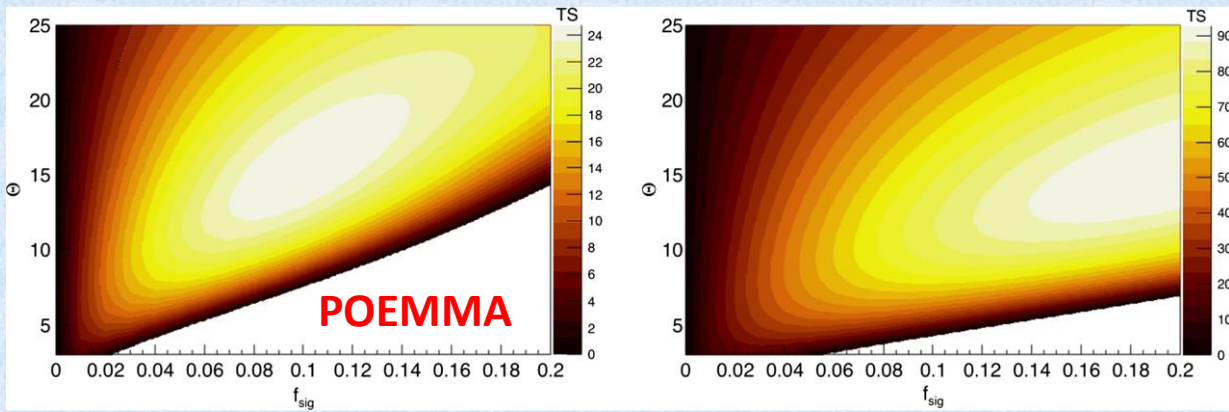


FIG. 24. TS profile for 1400 events for a particular scenario using the starburst source sky map in Fig. 23. In the scenario pictured here, the fraction of events drawn from the source sky map is $f = 10\%$ (left) and 20% (right), and the angular spread is $\Theta = 15^\circ$.

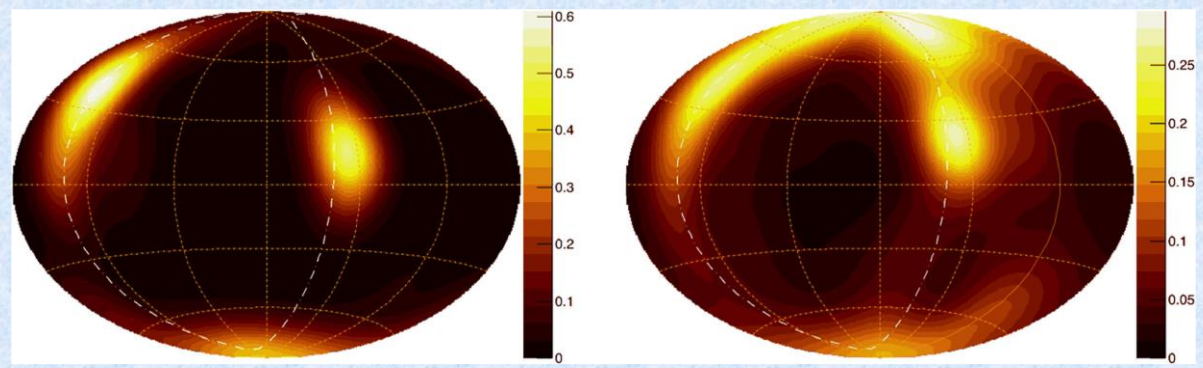
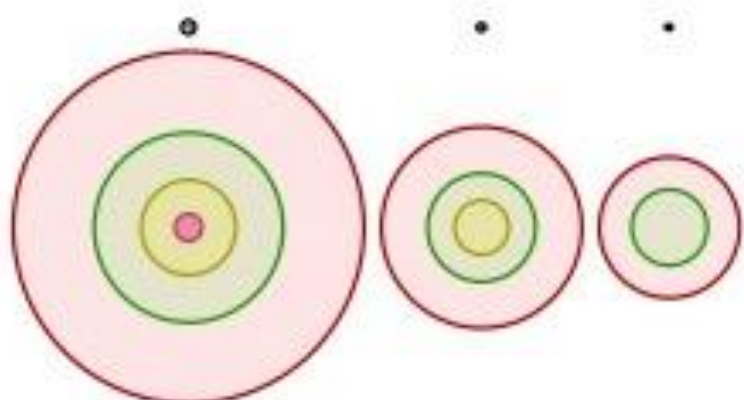


FIG. 23. Left: Skymap of nearby starburst galaxies from Refs. [35,103] weighted by radio flux at 1.4 GHz, the attenuation factor accounting for energy losses incurred by UHECRs through propagation, and the exposure of POEMMA. The map has been smoothed using a von Mises-Fisher distribution with concentration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

Use differences in angular deflections and flux attenuation for light vs heavy nuclei to assess “hot spot” sources.



Small -> Wide: H, He, N, Si, Fe

FIG. 21: Circles representing the composition-layered structure of hotspots at different energies, for proton sources (top) and nuclei sources (bottom). The radii of the circles respect the proportions of the angular sizes given by (2), for protons (black), helium (magenta), nitrogen (yellow), silicon (green) and iron (red); and for 40 EeV (left), 70 EeV (center) and 100 EeV (right).

Source, Bfield, and distance dependent!

PhysRevD98, 123018

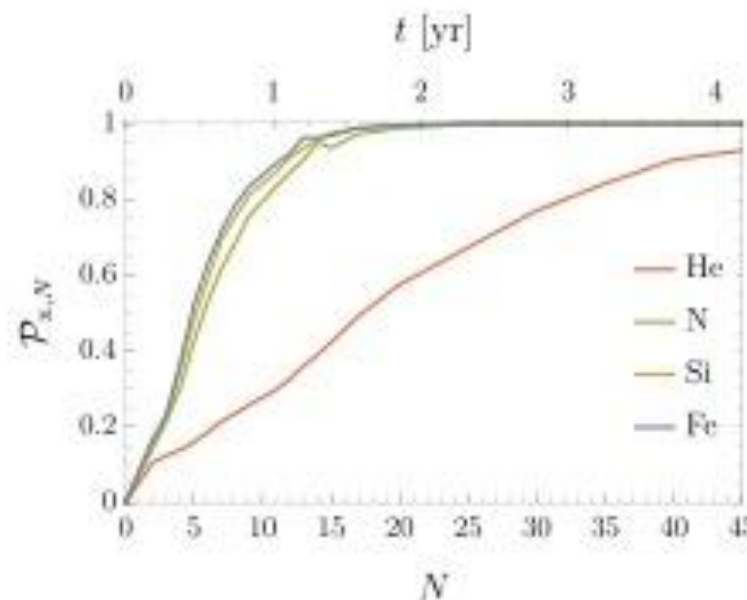


FIG. 22: Power of the statistical test for different alternative hypotheses, that is different nuclei and number of events per hot spot. The horizontal axis on the top indicates the projected time-scale for POEMMA.

Hot Spot Analysis:

- Discriminate protons (vs using X_{MAX}) from CNO and heavies by looking at the distribution of arrival directions.
- If source emits protons, then AngRes should improve $\sim 1/E_{\text{CR}}$
- If mixed composition, picture is more complicated
- If the hot spot is nuclei heavier than nitrogen, in two years of operation POEMMA will be able to exclude a pure-proton origin at the 95% CL.