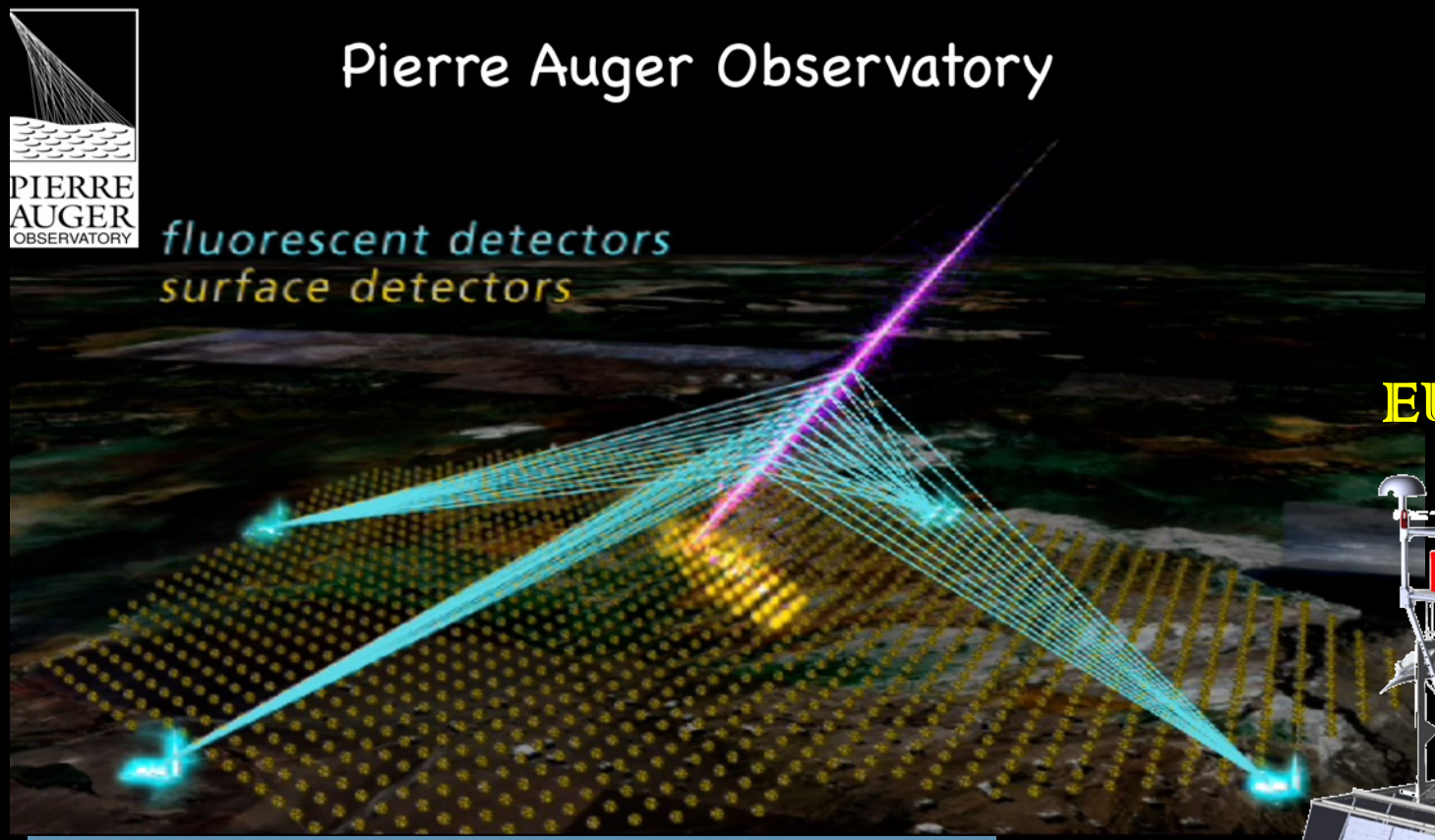
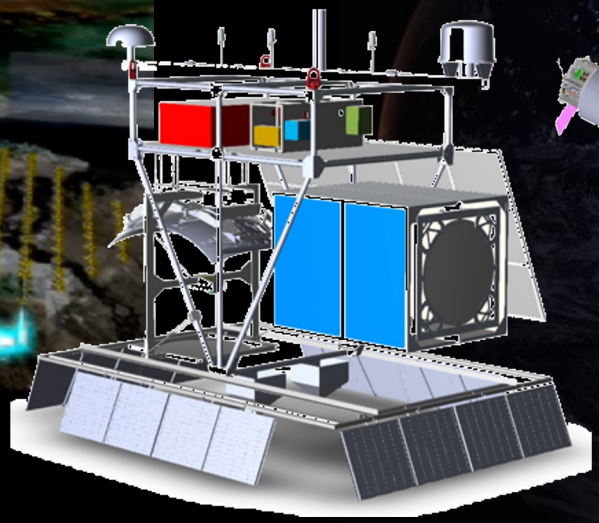
Cosmic Rays and Neutrinos at the Highest Energies





Gamma 2022

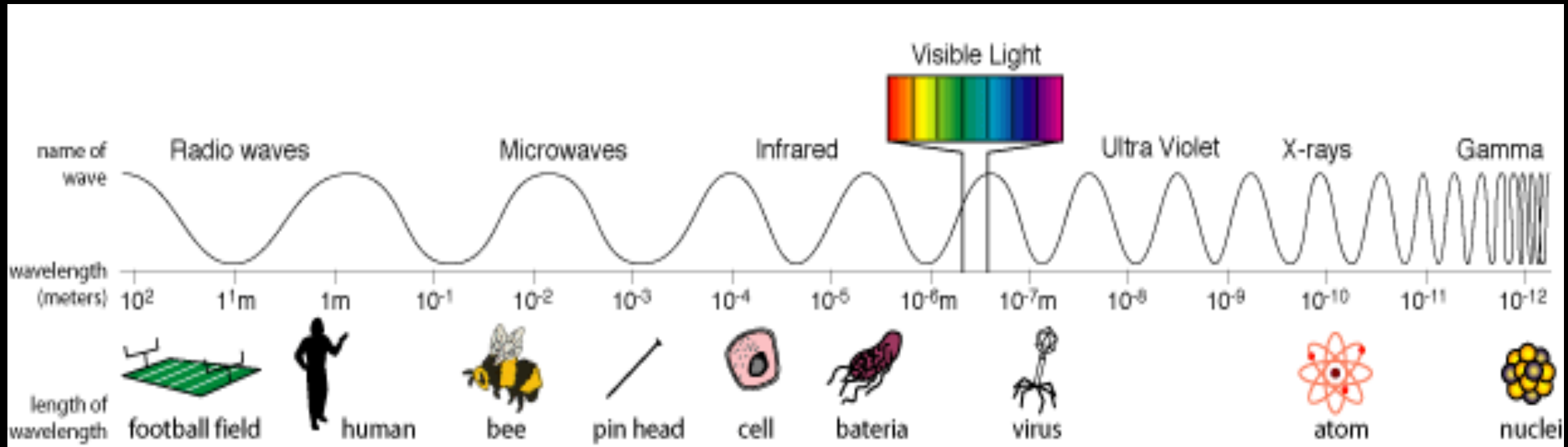
July 5, 2022

Angela V. Olinto

THE UNIVERSITY OF CHICAGO

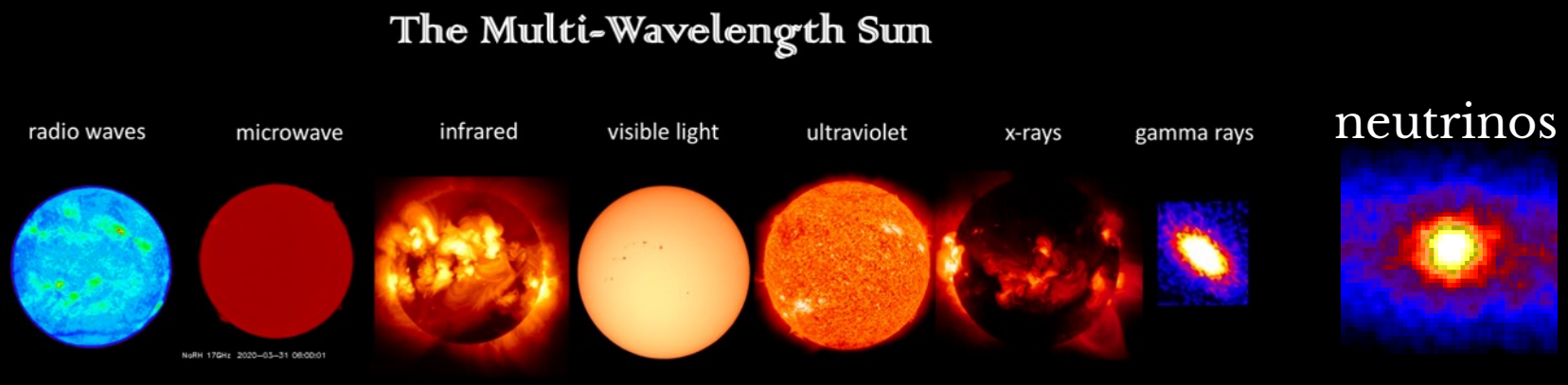
The Multi-Wavelength Sun

radio waves | microwave | infrared | visible light | ultraviolet | x-rays | gamma rays



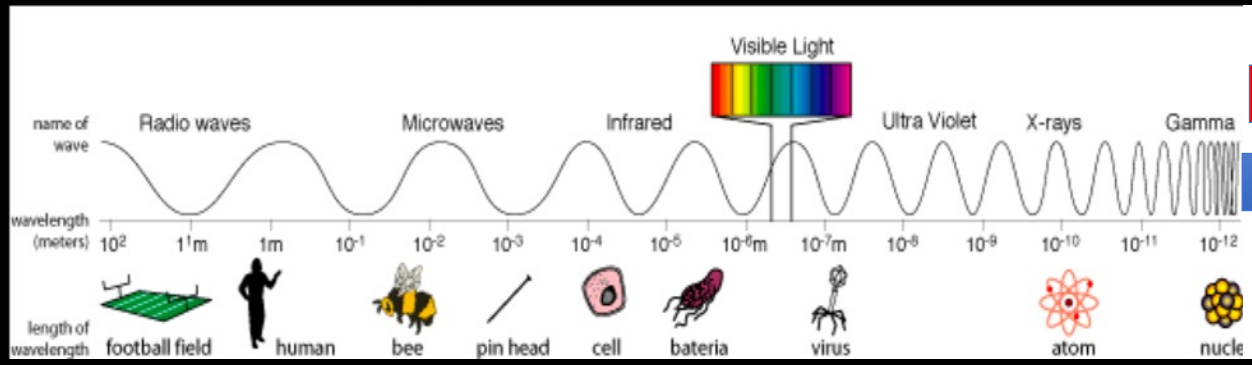
Cosmic Particles

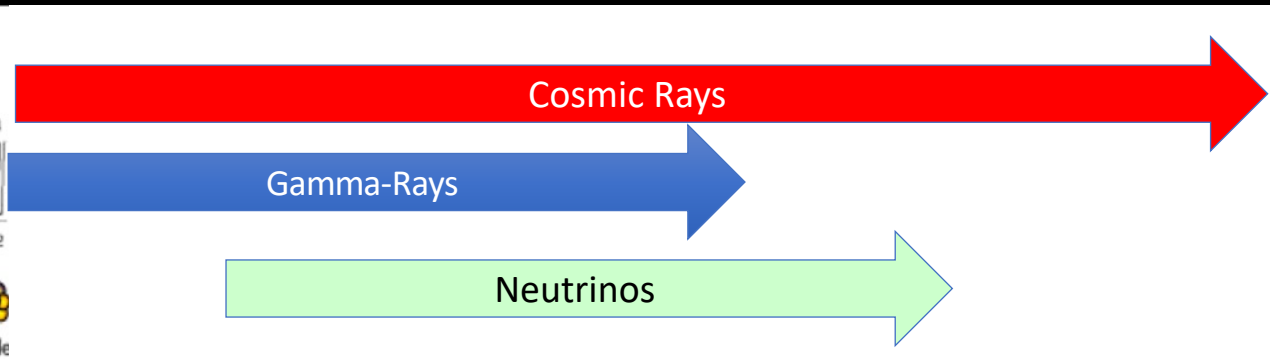
~ double the reach for Astrophysics



neutrinos

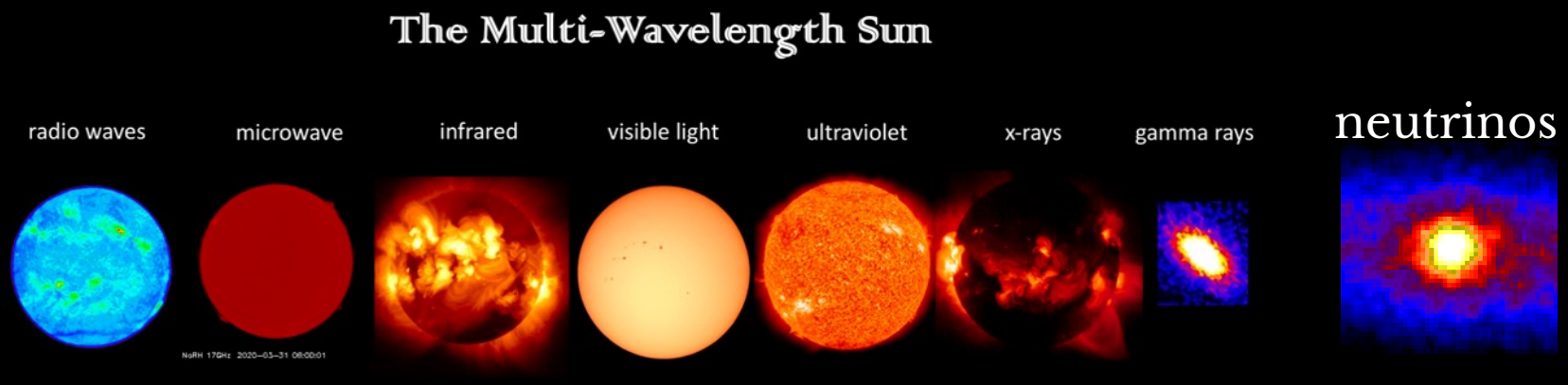
Gamma-rays
up to
10^{15}eV



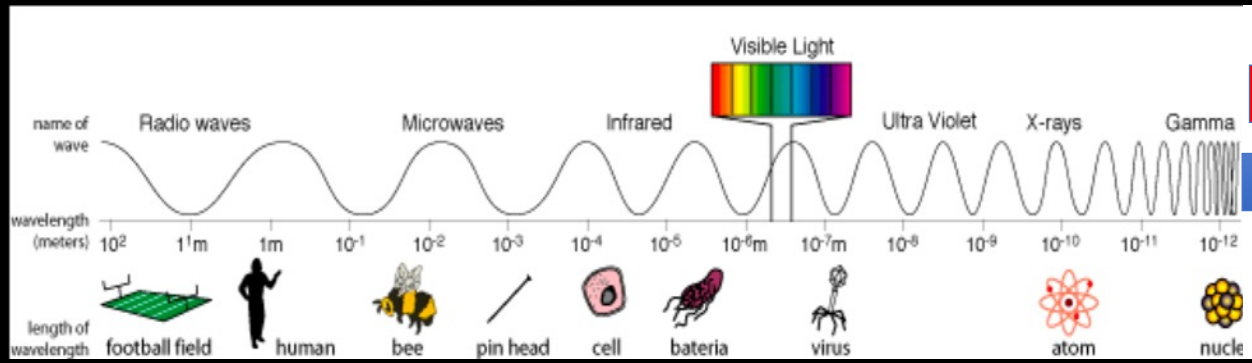


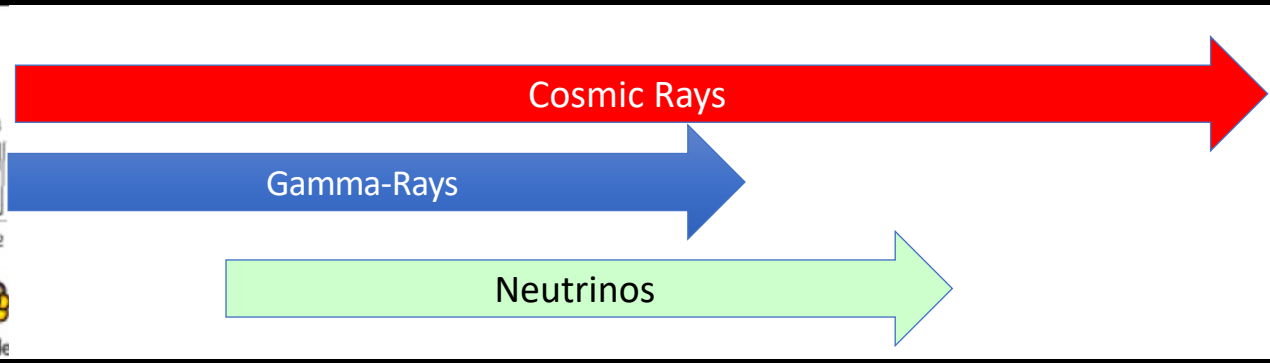
Cosmic Particles

~ double the reach for Astrophysics



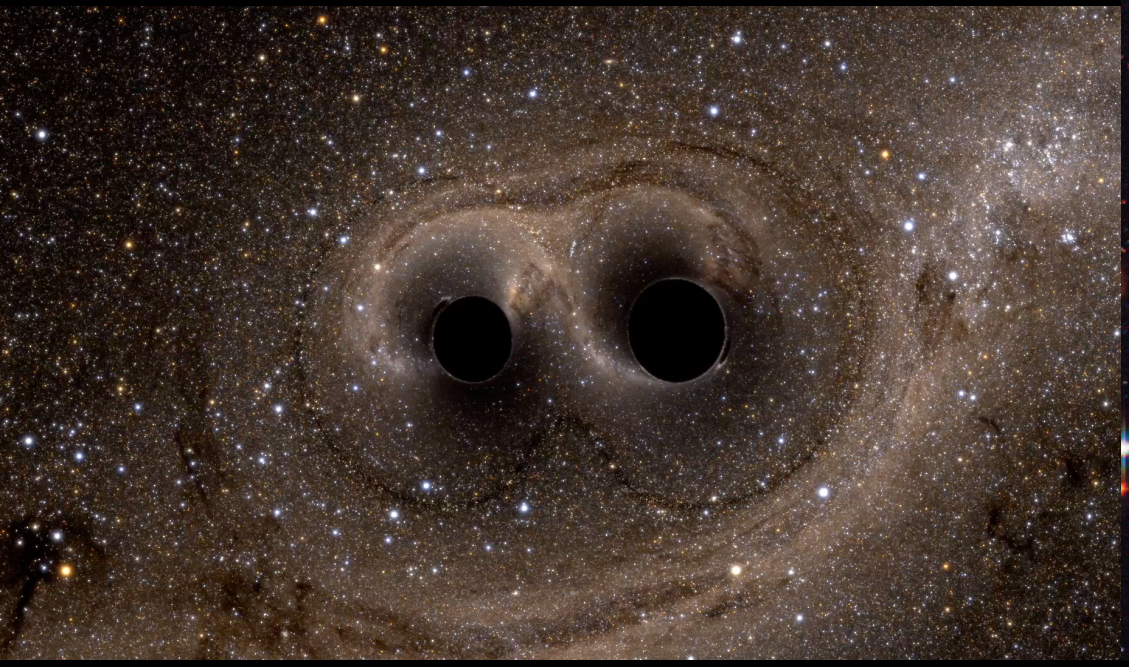
Cosmic Rays up to 10^{20}eV

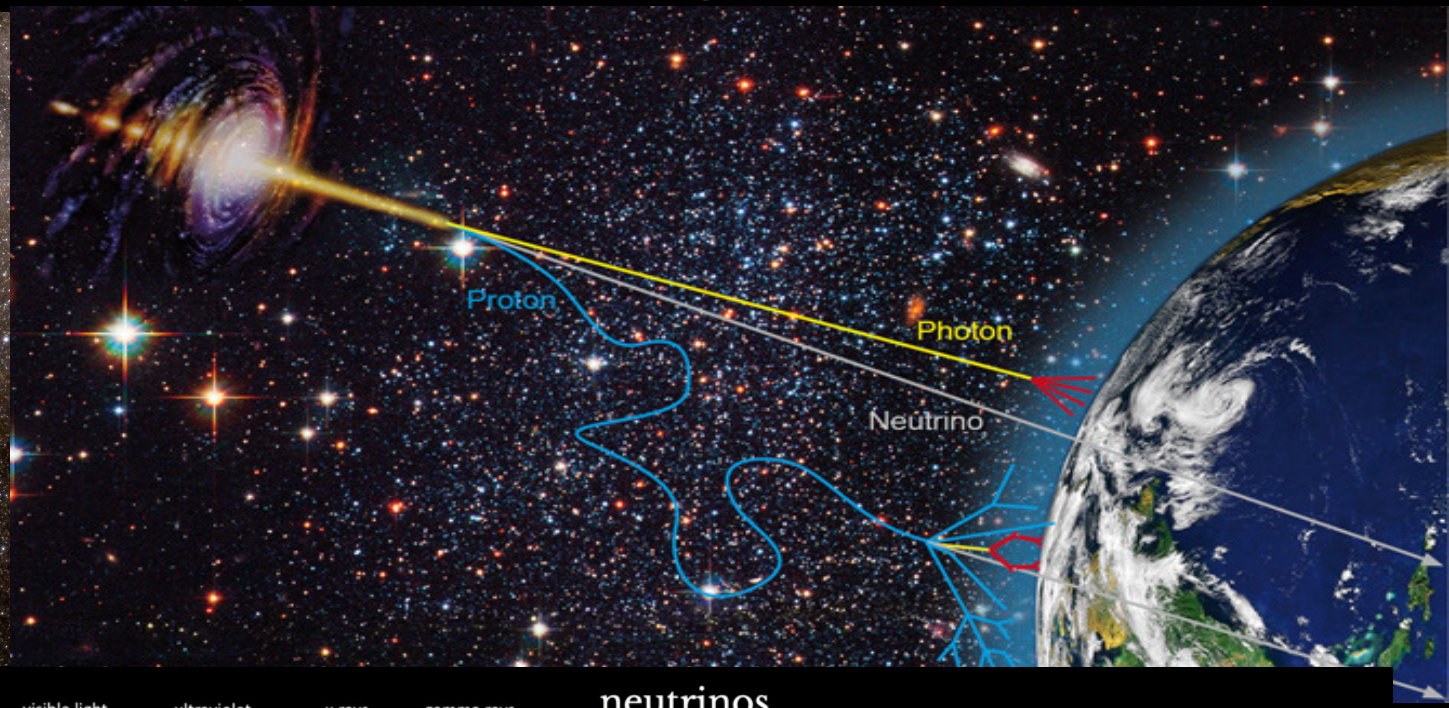


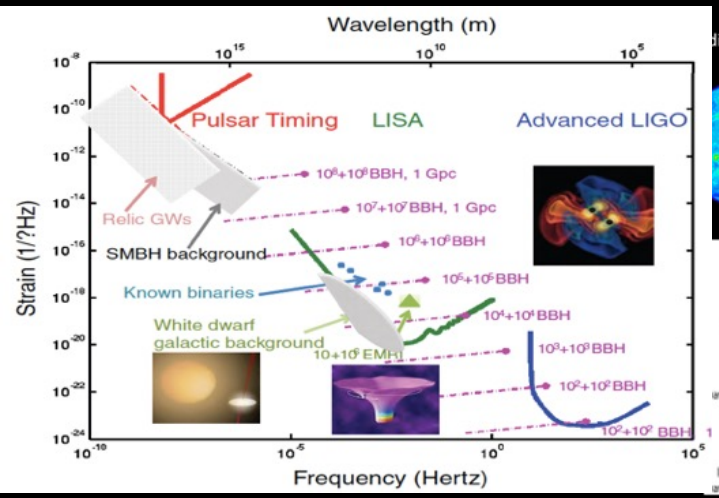


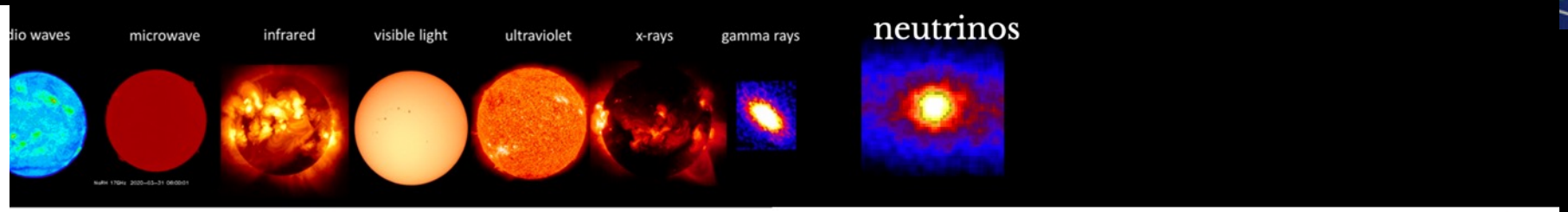
Multi-Messengers

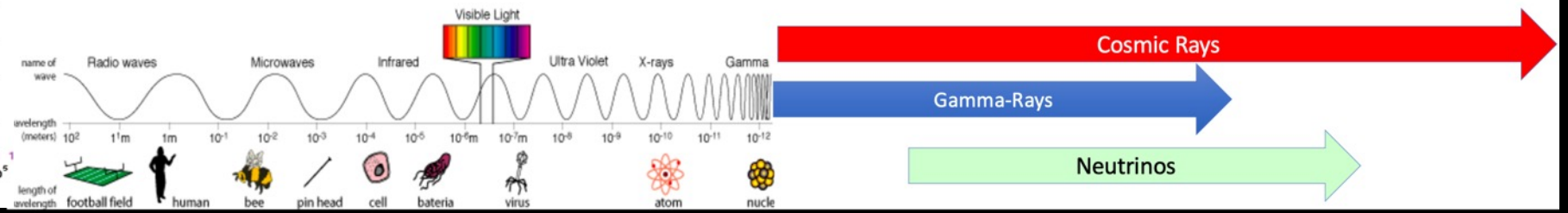
~ Triple the reach for Astrophysics – 40 orders of magnitude











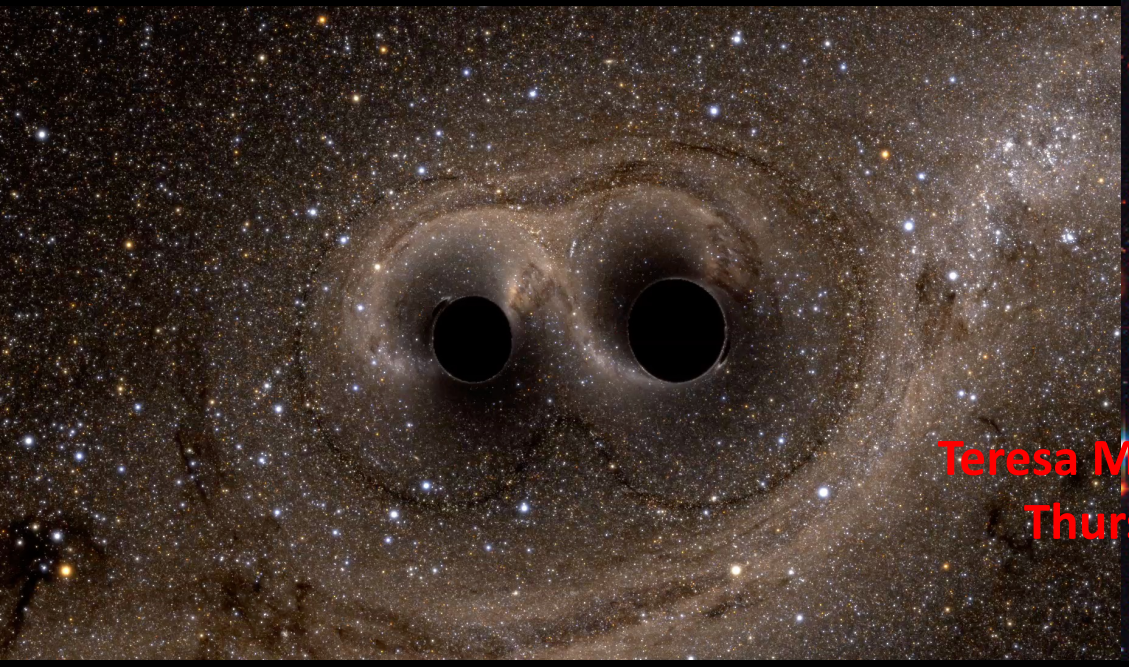
Gravitational Waves

Electromagnetic Waves

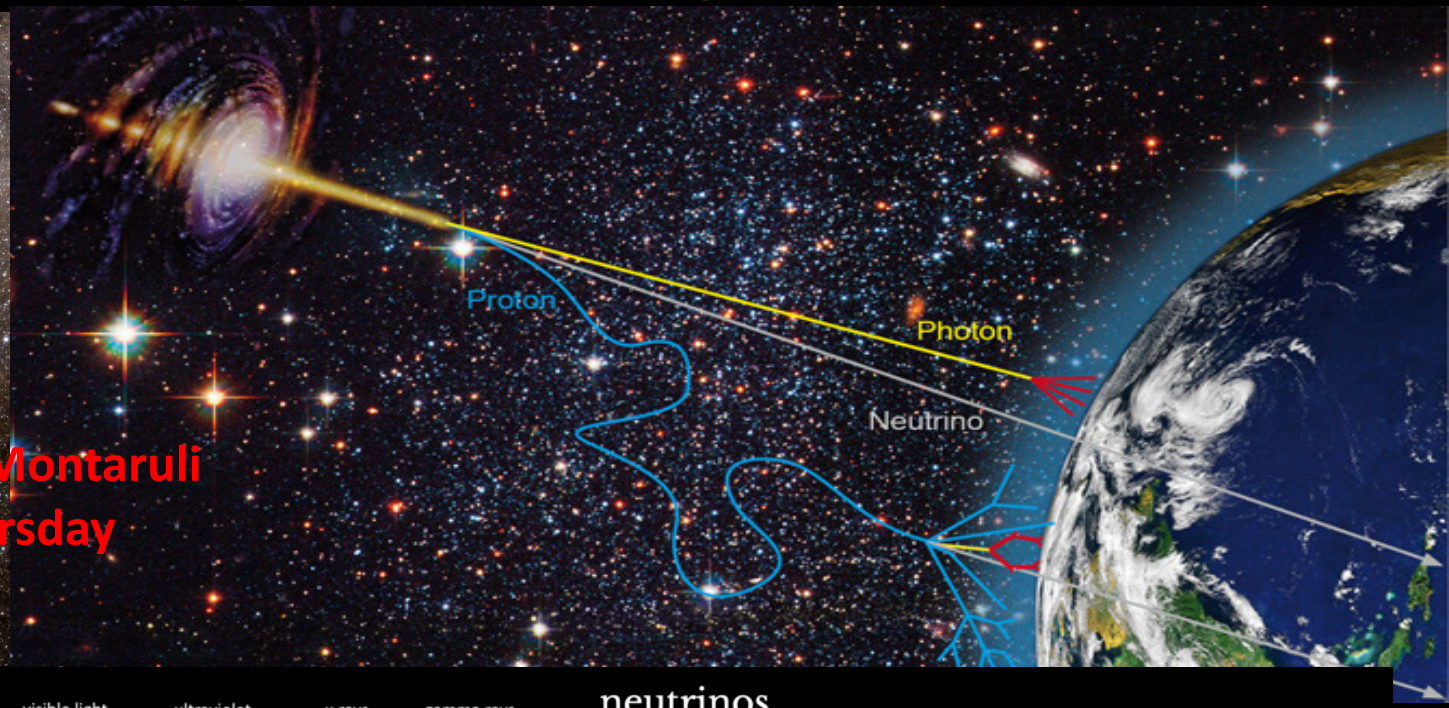
Cosmic Particles

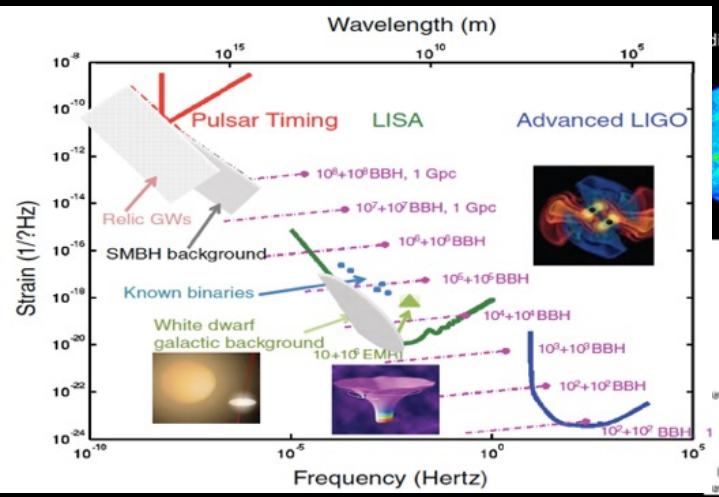
Multi-Messengers

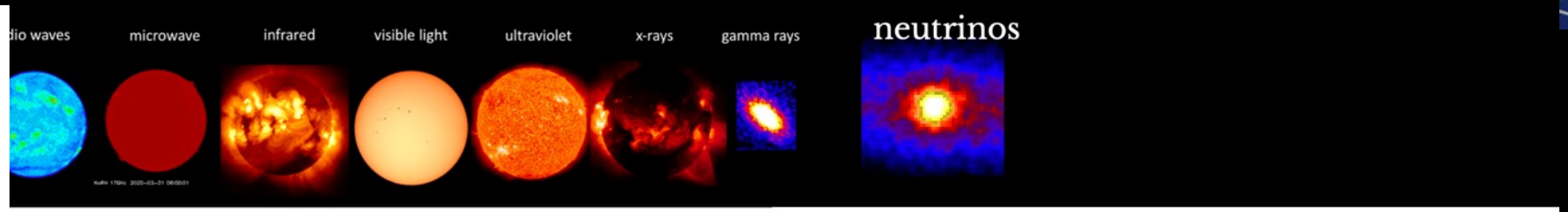
~ Triple the reach for Astrophysics – 40 orders of magnitude

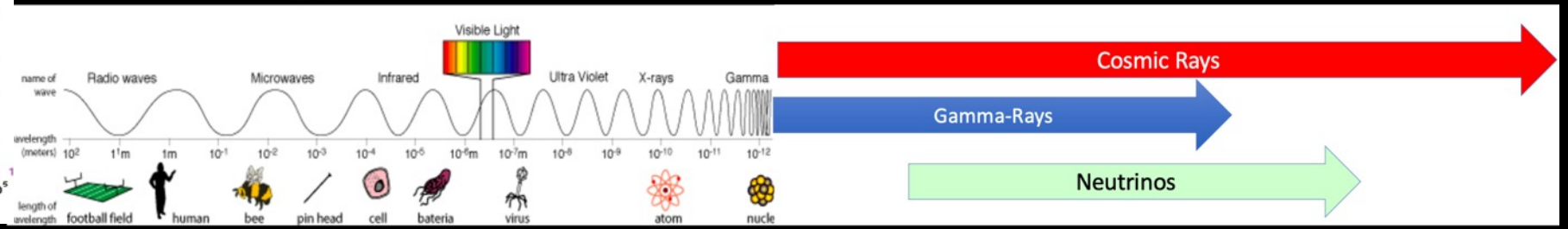


Teresa Montaruli
Thursday







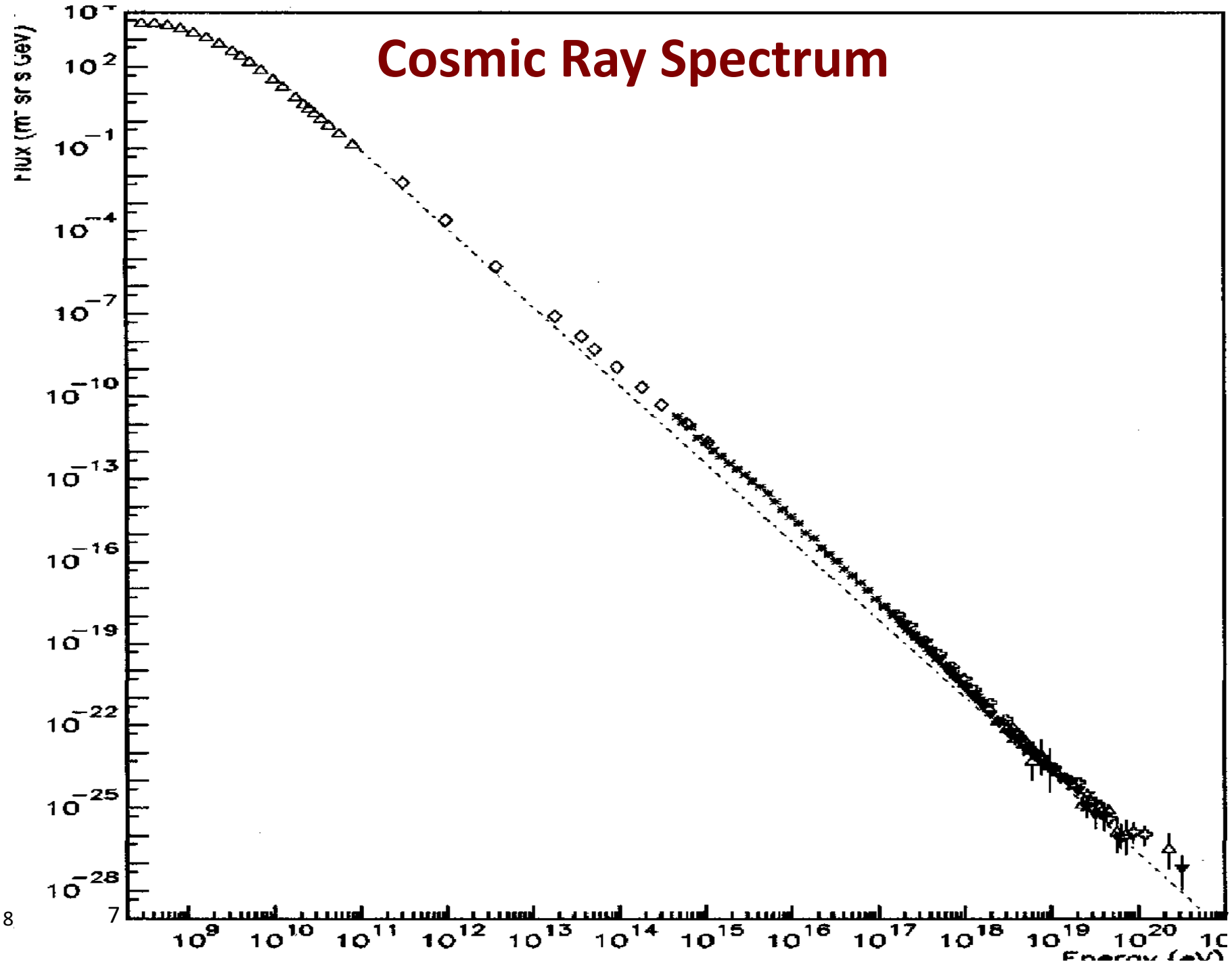


Gravitational Waves

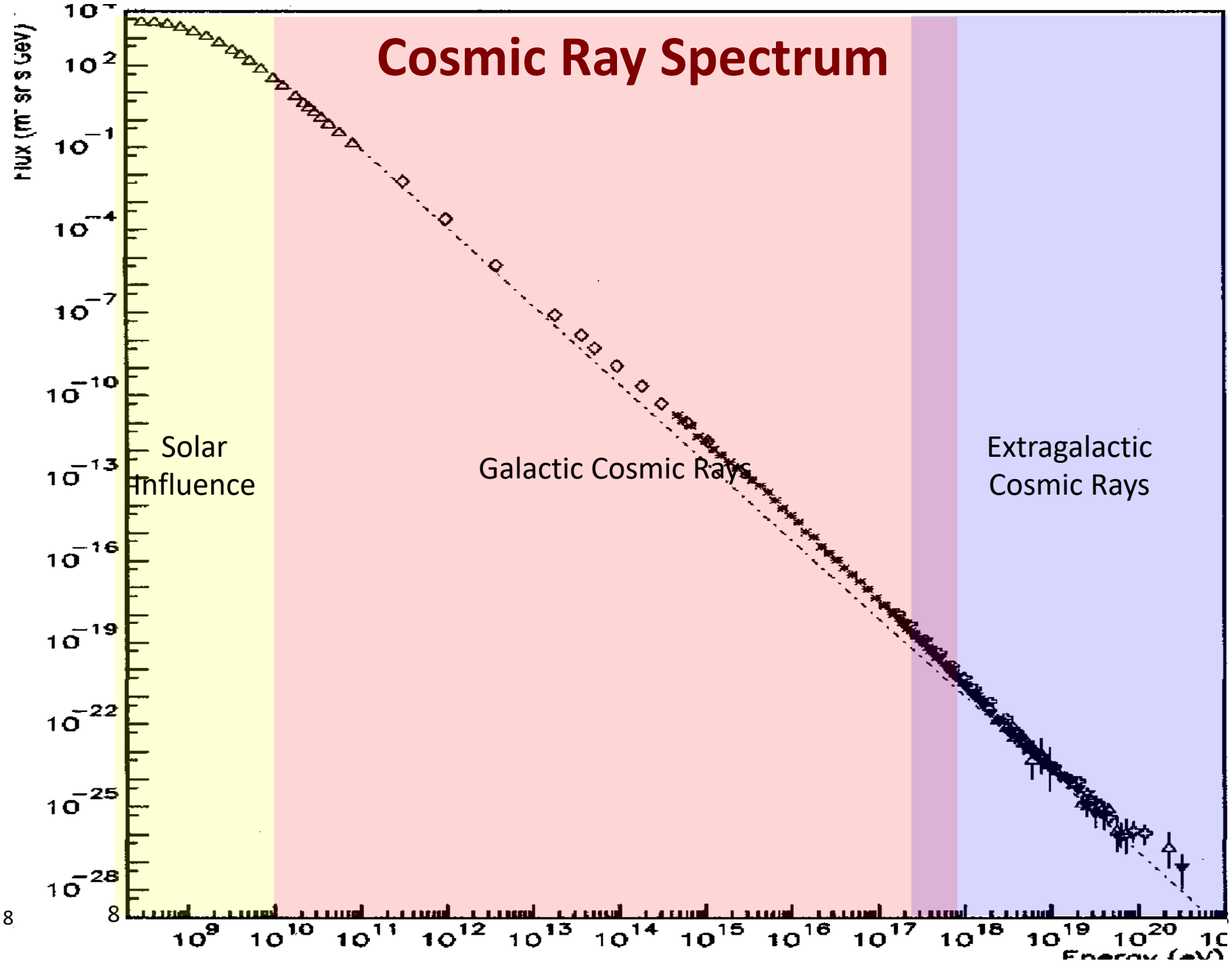
Electromagnetic Waves

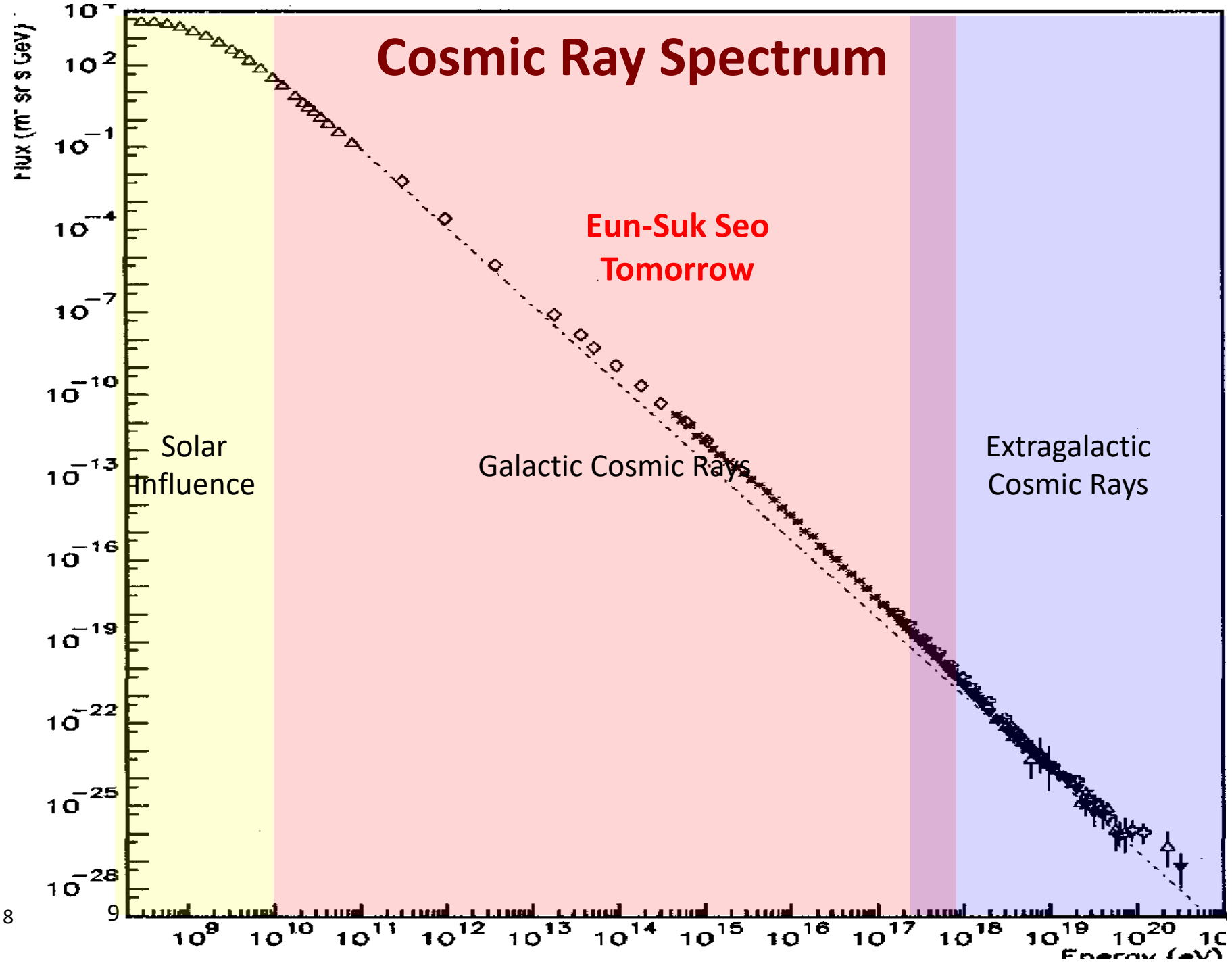
Cosmic Particles

Cosmic Ray Spectrum



Cosmic Ray Spectrum




Cosmic Ray Spectrum
Eun-Suk Seo
Tomorrow
Solar
Influence
Galactic Cosmic Rays
Extragalactic
Cosmic Rays
Flux (m² sr s GeV)
Energy (eV)

Astroparticle Physics Open Questions:

What are the sources of the **Ultra-High Energy Cosmic Rays** (UHECRs)?

What are the sources of **Astrophysical Neutrinos**?

Astroparticle Physics Open Questions:

What are the sources of the **Ultra-High Energy Cosmic Rays** (UHECRs)?

What are the sources of **Astrophysical Neutrinos**?

Elisa Resconi
Thursday

Astroparticle Physics Questions:

What are the sources of the **Ultra-High Energy Cosmic Rays** (UHECRs)?

Cosmic rays with energy above 1 EeV = 10^{18} eV, others E>100 PeV = 10^{17} eV

- What is the spectrum of UHECRs?
- What is the composition of UHECRs?
- What is the sky distribution of arrival directions?
- Where are the neutrino and gamma-ray secondaries?
- What physical processes do UHECRs probe?

Outline:

What are the sources of the **Ultra-High Energy Cosmic Rays** (UHECRs)?
Cosmic rays with energy above 1 EeV $= 10^{18}$ eV, others E>100 PeV $= 10^{17}$ eV

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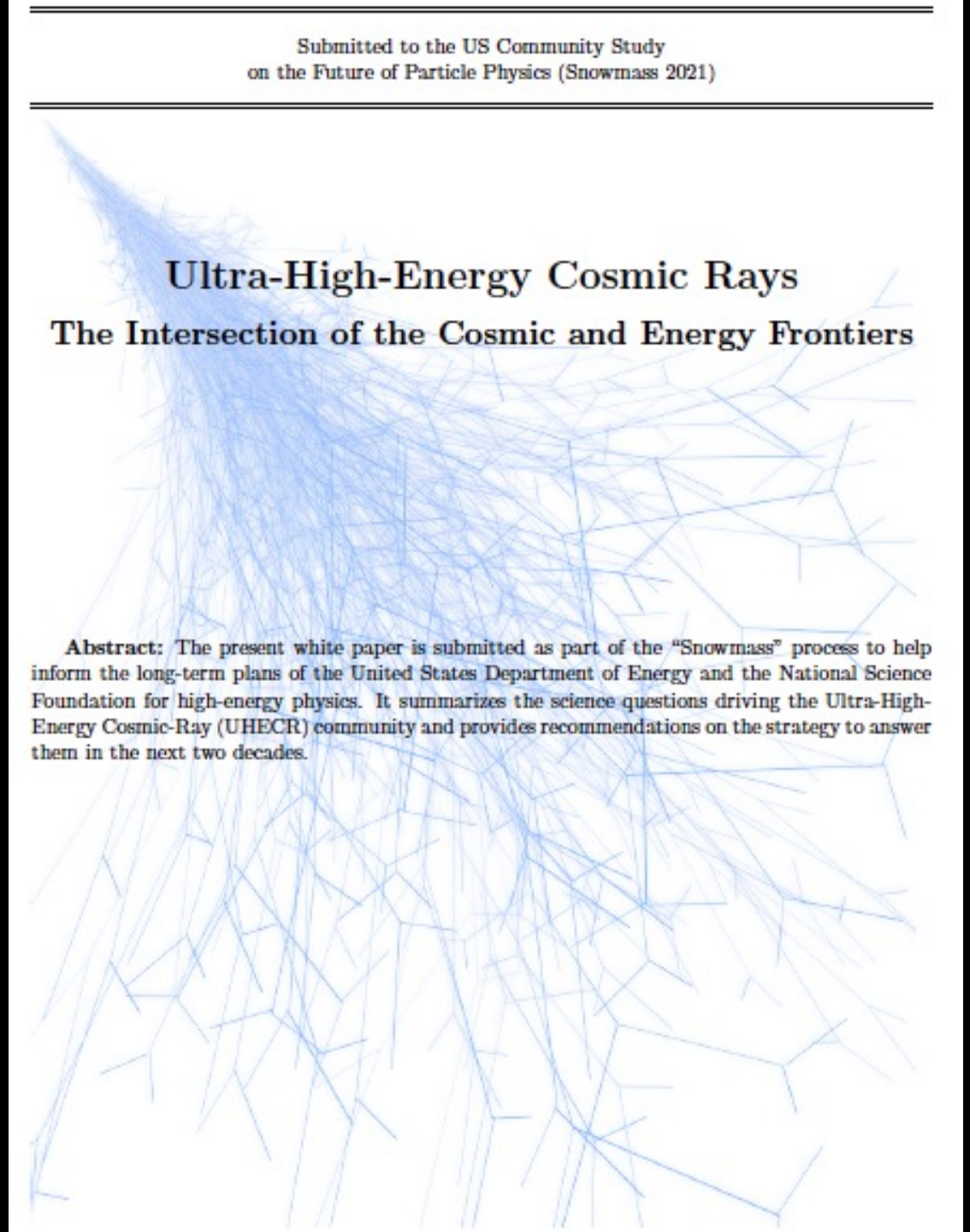
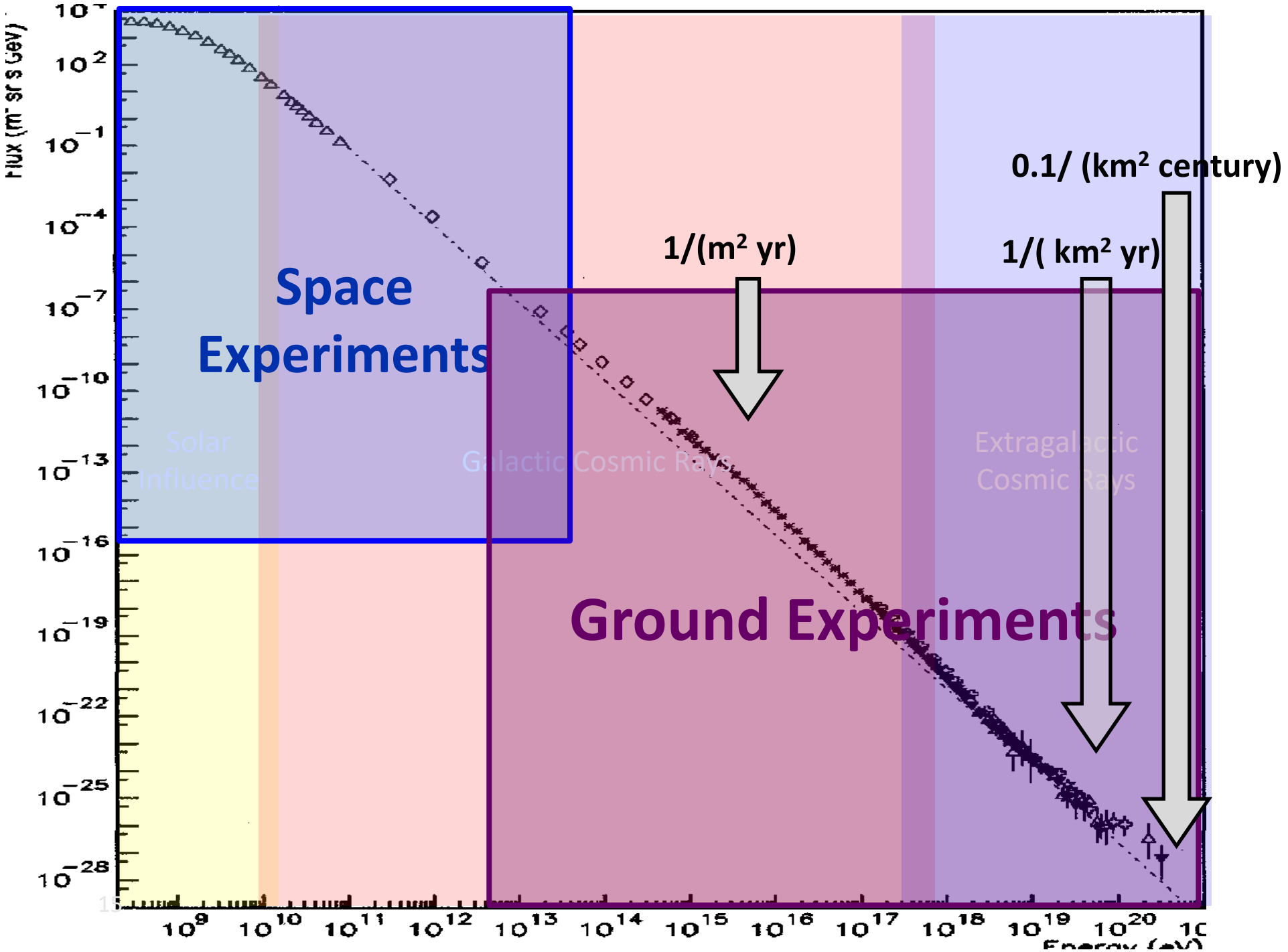
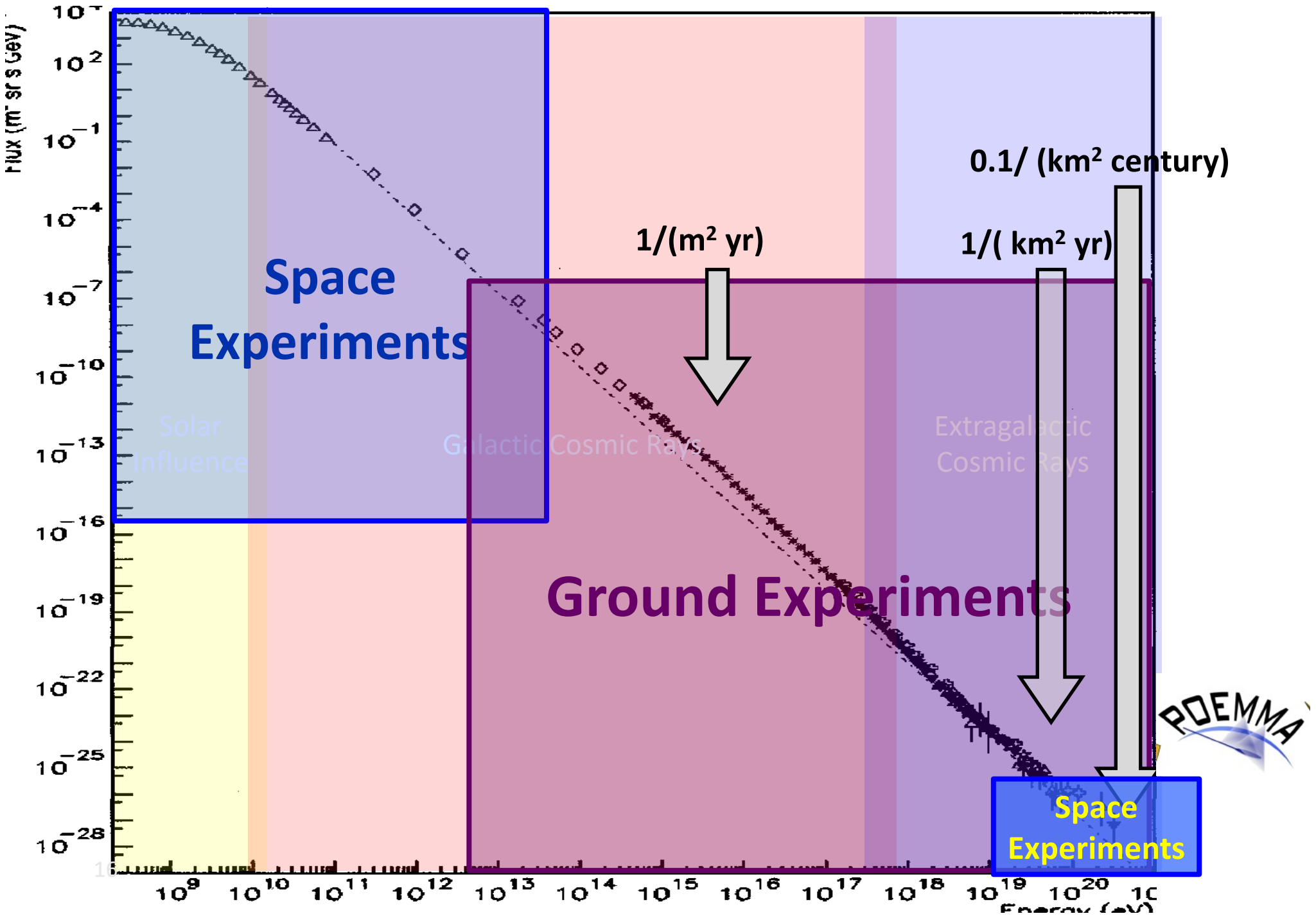
Future Outlook



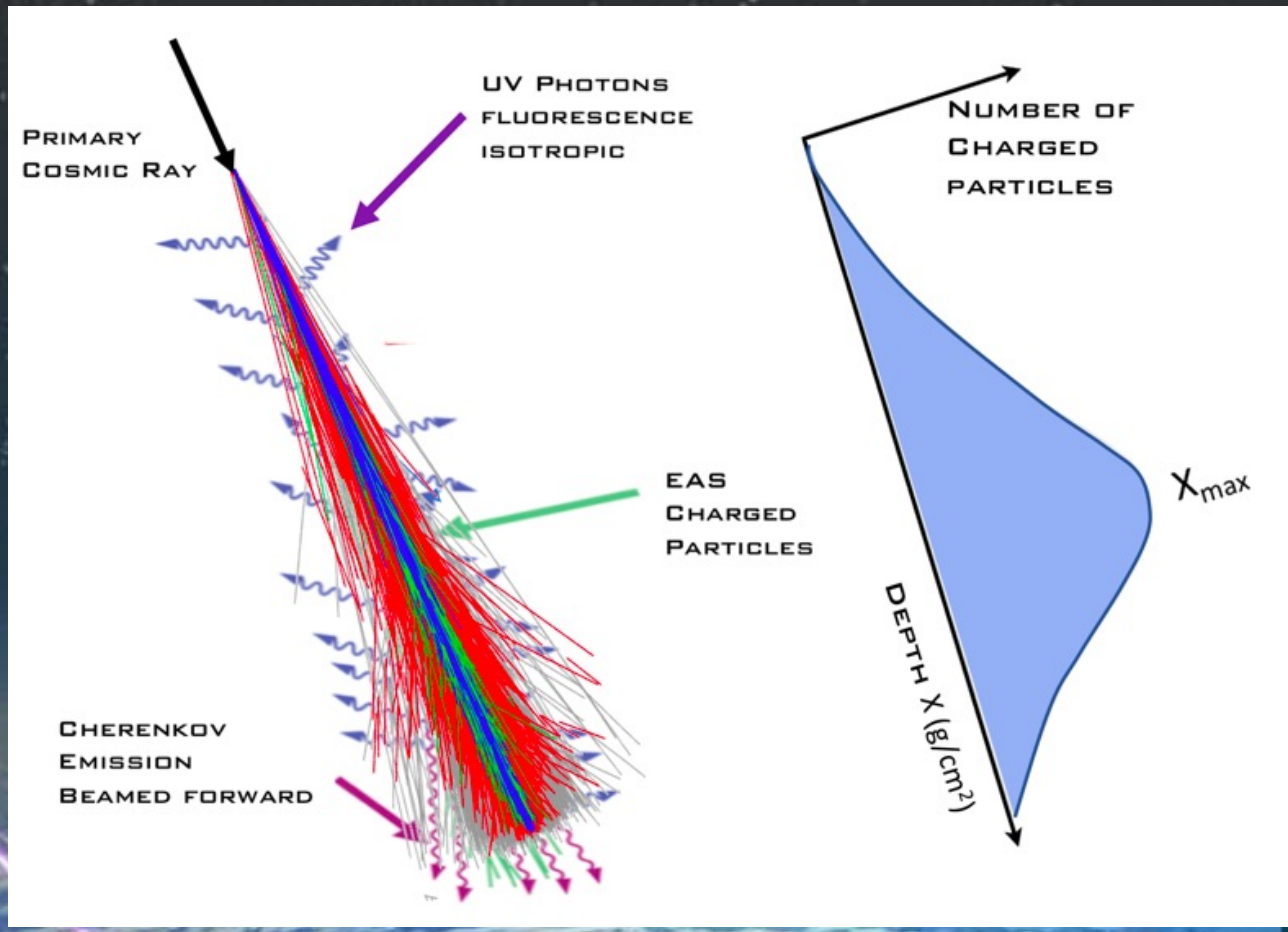
Coleman et al, 2022
arXiv:2205.05845

And the upcoming
Snowmass Cosmic Frontier 7 report
Adhikari et al 2022

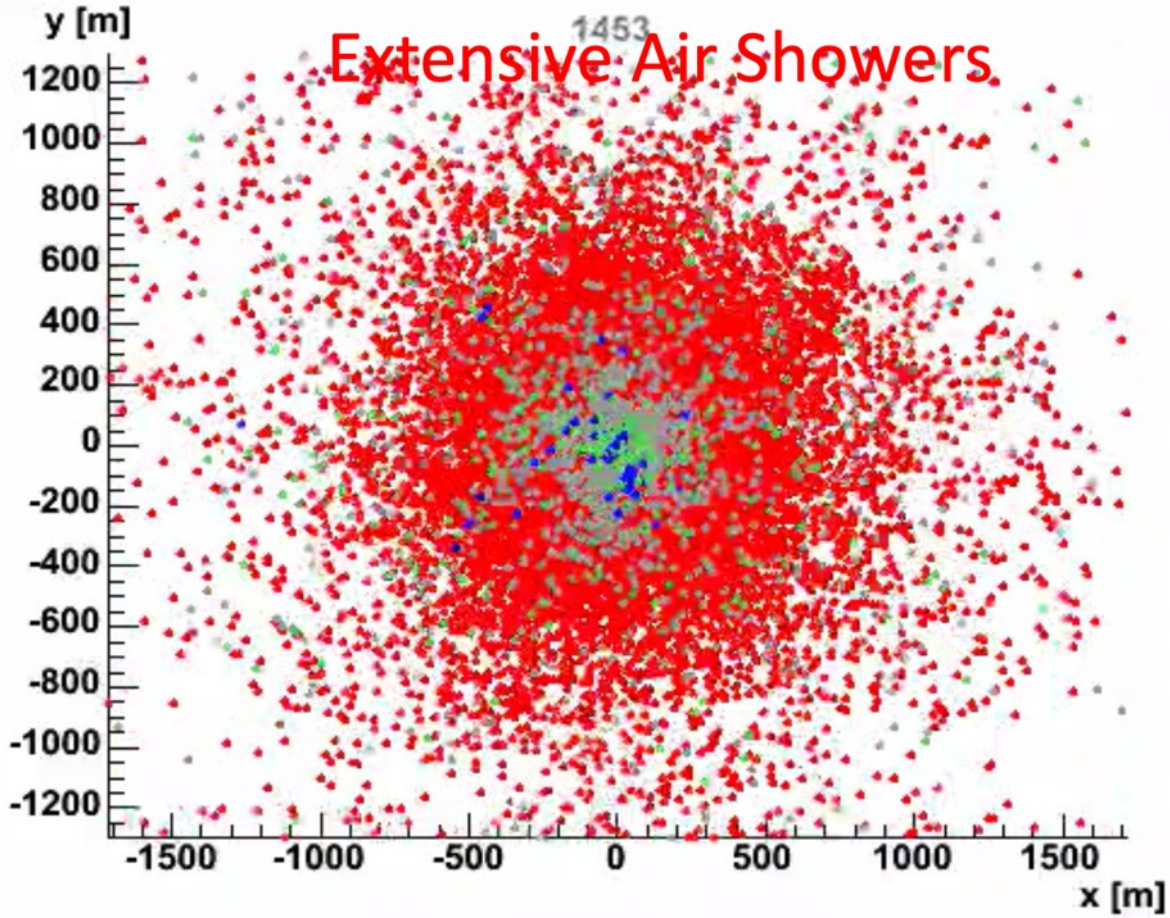

Space
Experiments
Ground Experiments
1/(m² yr)
1/(km² yr)
0.1/ (km² century)
Solar
Influence
Galactic Cosmic Rays
Extragalactic
Cosmic Rays

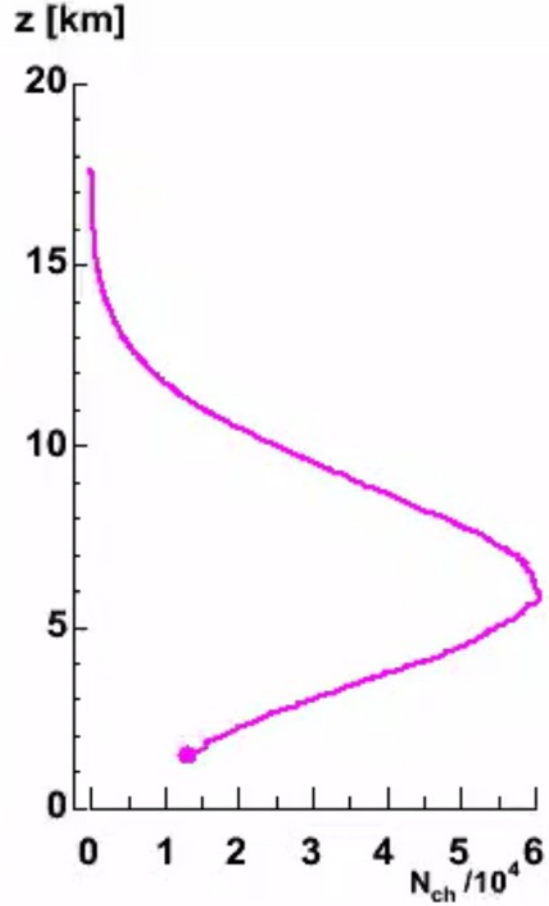

Space
Experiments
Ground Experiments
1/(m² yr)
1/(km² yr)
0.1/ (km² century)
Solar
Influence
Galactic Cosmic Rays
Extragalactic
Cosmic Rays
Space
Experiments
POEMMA

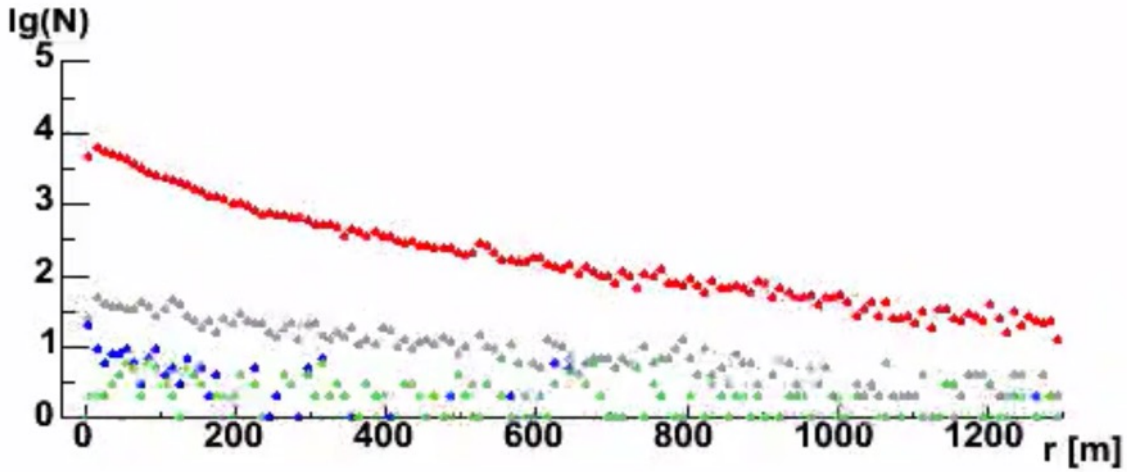
Extensive Air Showers



Extensive Air Showers







Proton 10^{14} eV

h^{1st} = 17642 m

hadrons muons

neutrons **electrs**

J.Oehlschlaeger,R.Engel,FZKarlsruhe

Leading Observatories of Ultrahigh Energy Cosmic Rays

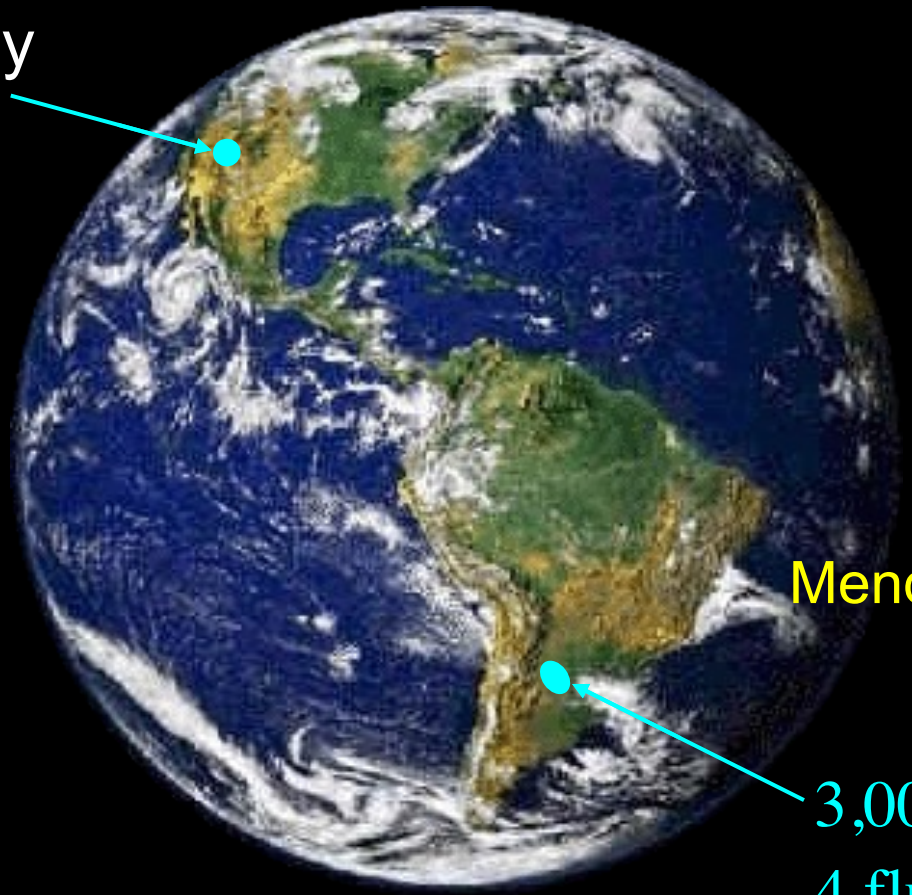
Telescope Array

Utah, USA

(5 country collaboration)

700 km^2 array

3 fluorescence telescopes



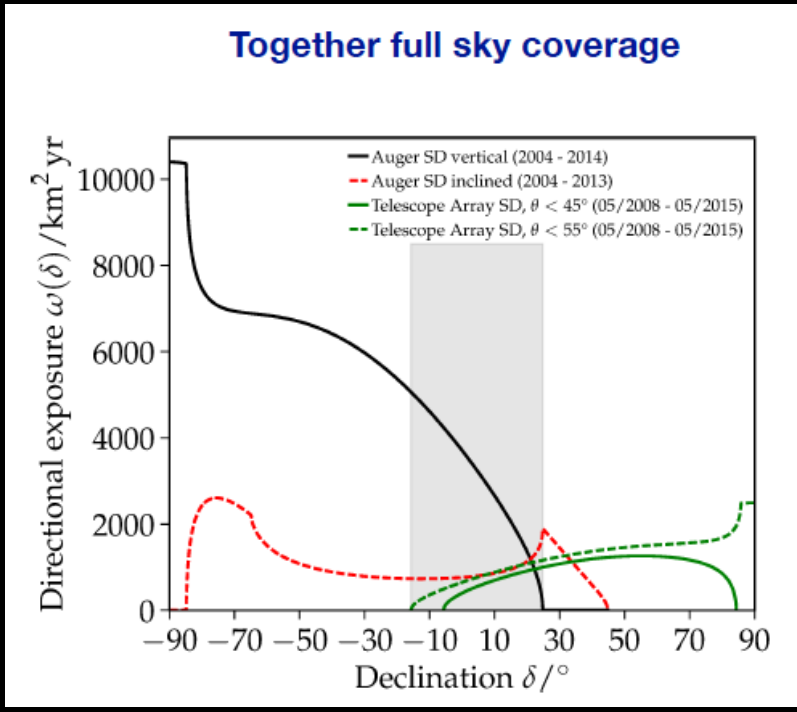
Pierre Auger Observatory

Mendoza, Argentina

(19 country collaboration)

3,000 km^2 array

4 fluorescence telescopes

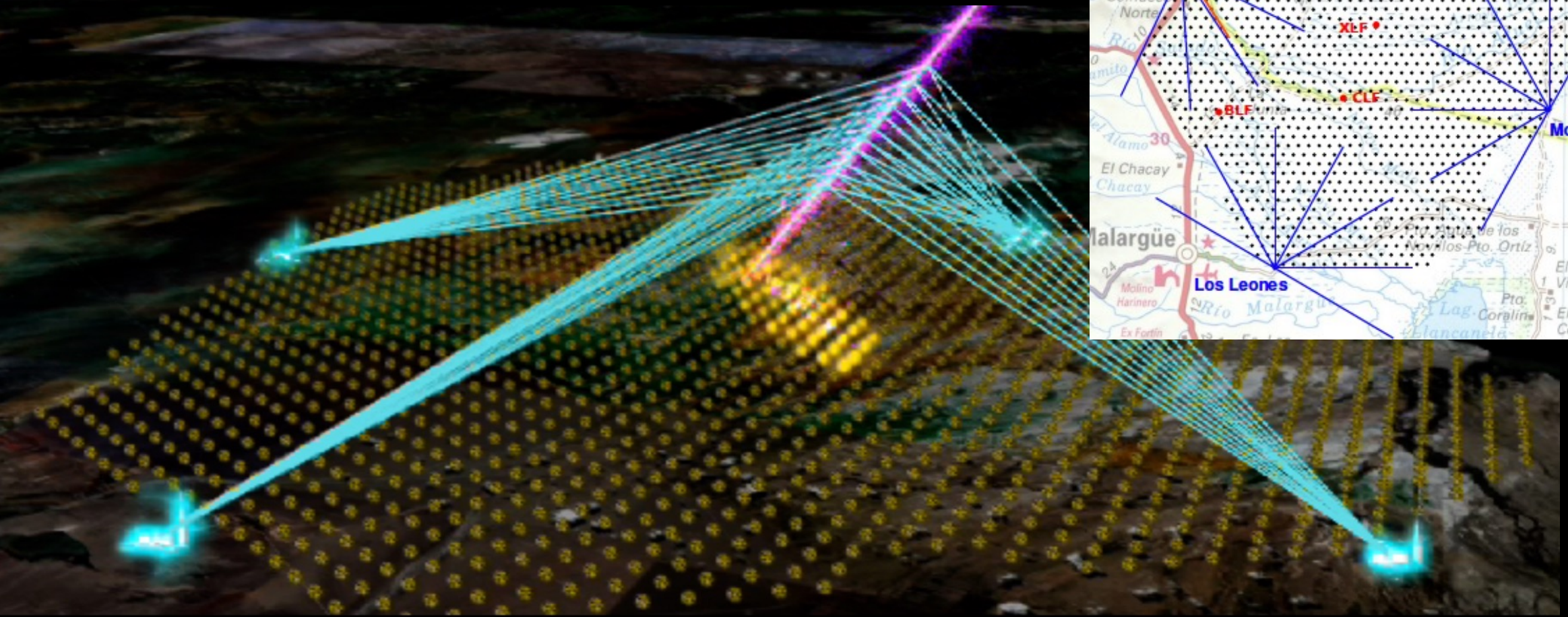


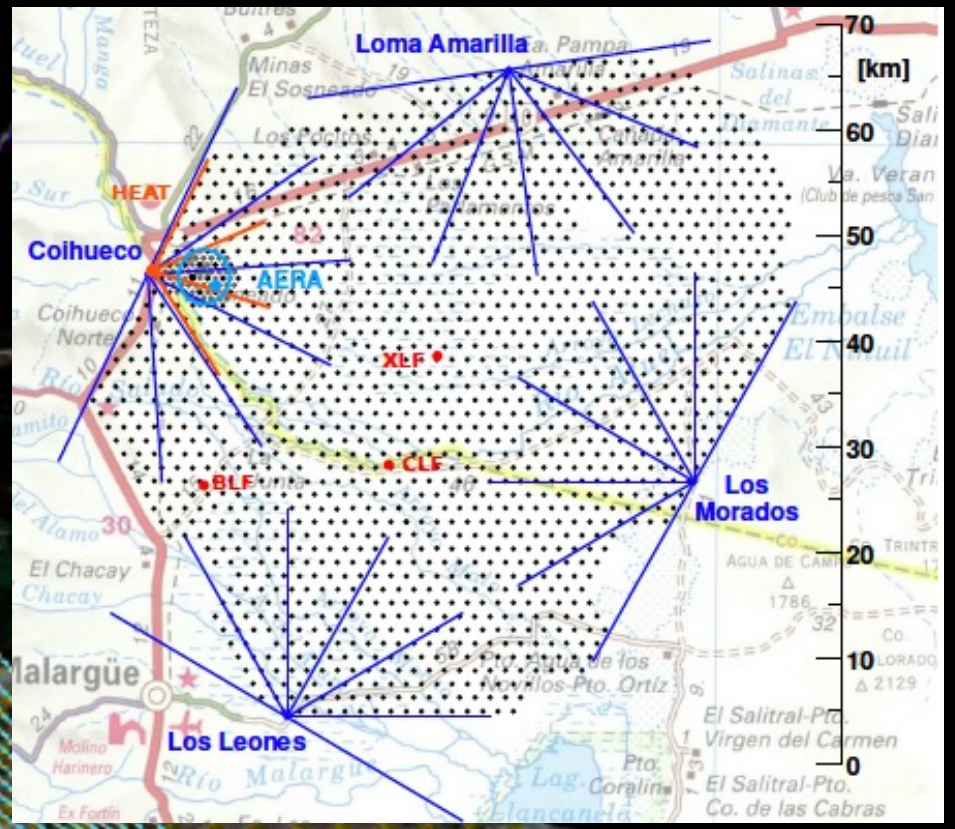
Pierre Auger Observatory

PIERRE AUGER OBSERVATORY

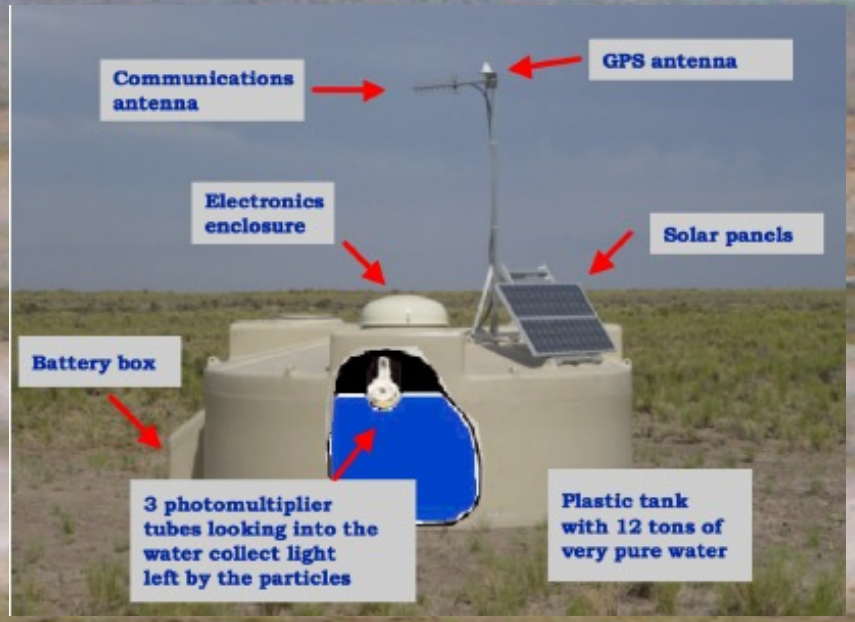
3,000 km^2 surface array=1665 water Cherenkov tanks

4 Fluorescence telescopes





3,000 km^2 array of 1665 water Cherenkov tanks with 1.5km distancing



4 Fluorescence telescopes overlooking the site

Telescope Array

Middle Drum: based on HiRes II

TALE (TA low energy extension)

LIDAR
Laser facility

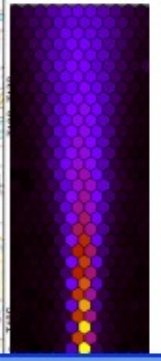
Infill array and high elevation telescopes

~30 km

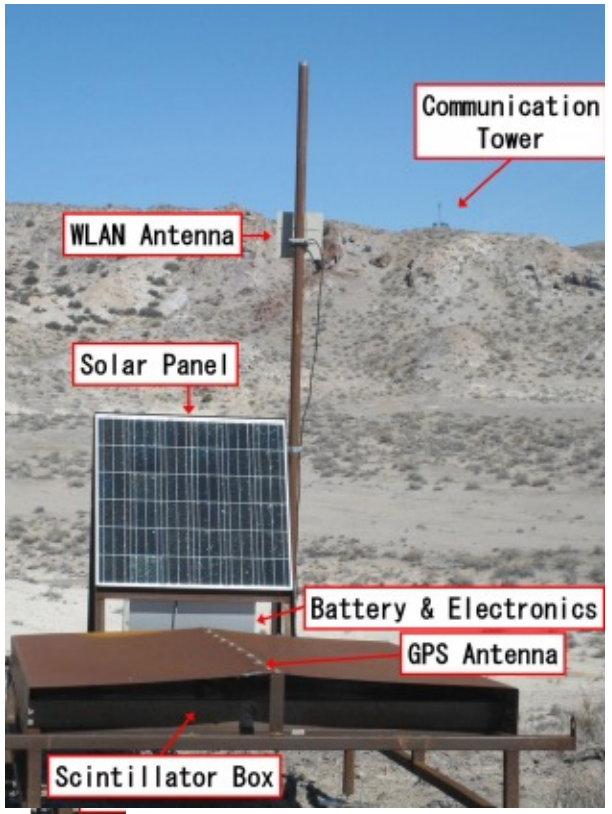
Test setup for radar reflection

3 fluorescence detectors
(2 new, one station HiRes II)

Northern hemisphere: Utah, USA



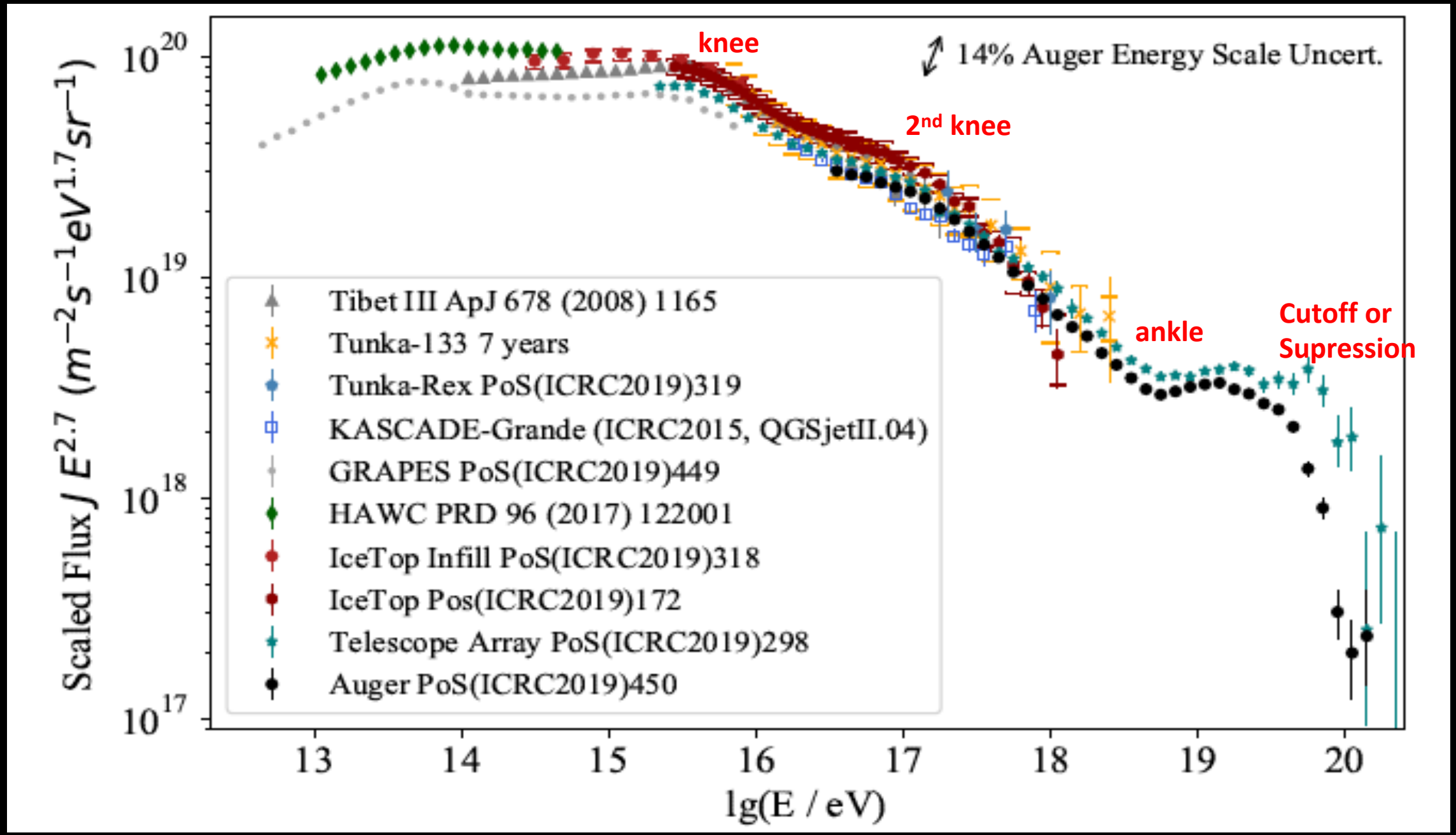
Electron light source (ELS): ~40 MeV



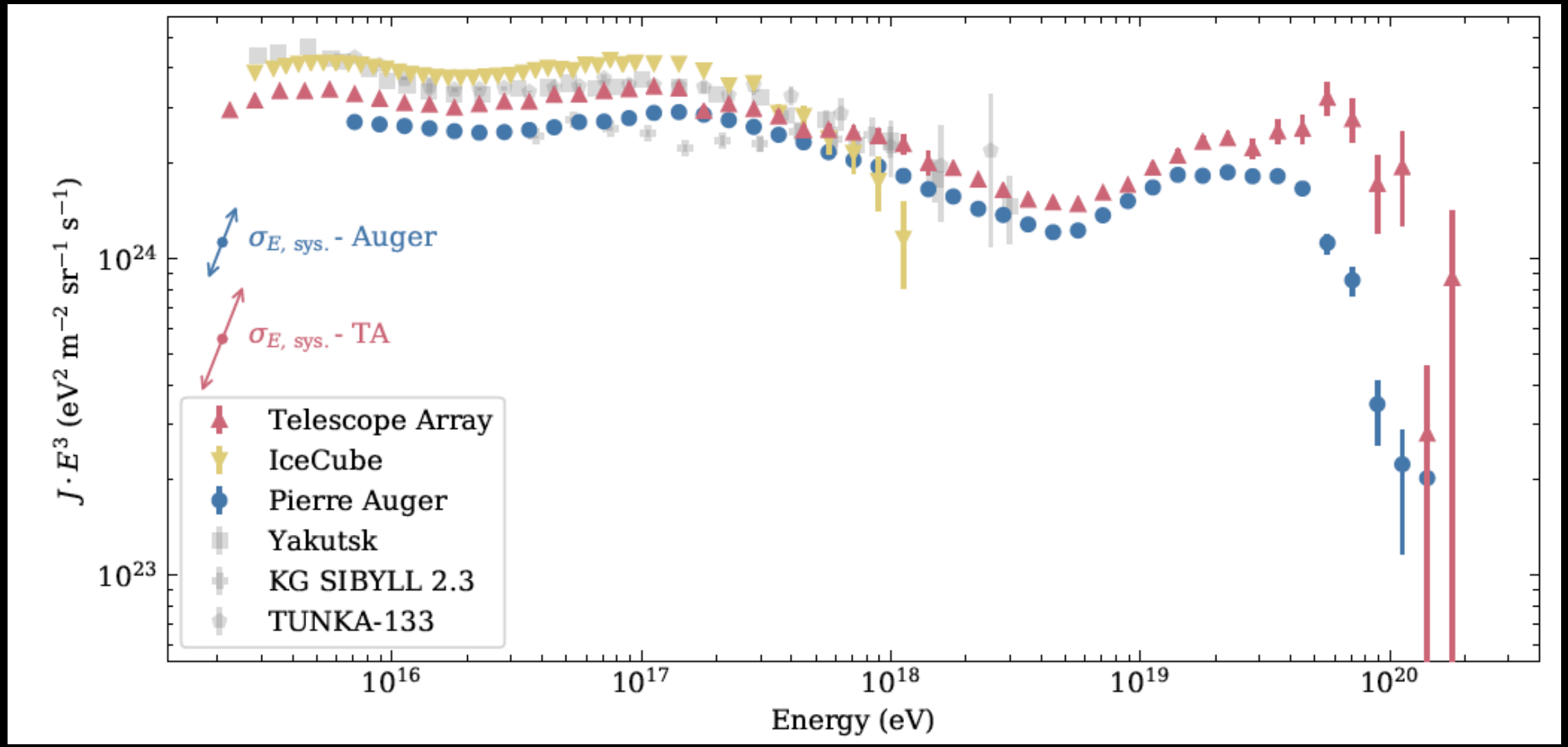
507 surface detectors:
double-layer scintillators
(grid of 1.2 km, 680 km^2)

from R. Engel 2017

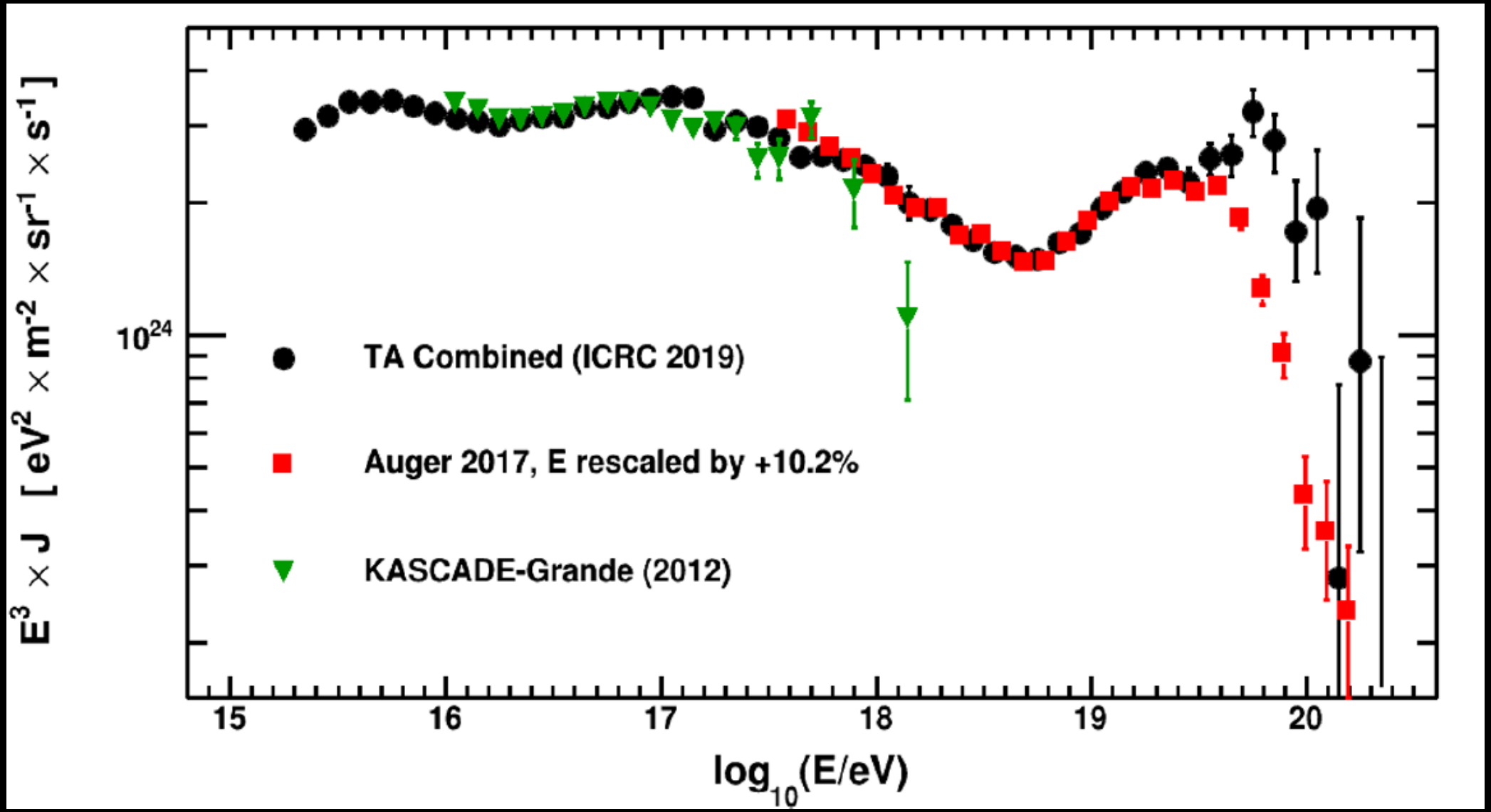
What is the spectrum of UHECRs?



F. G. Schröder '19



Coleman et al, 2022
arXiv:2205.05845



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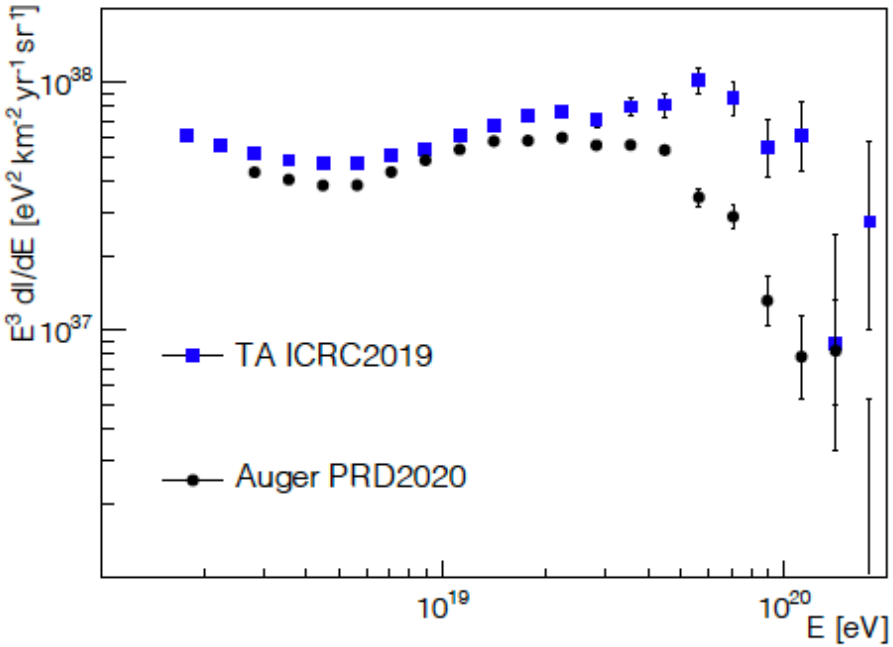
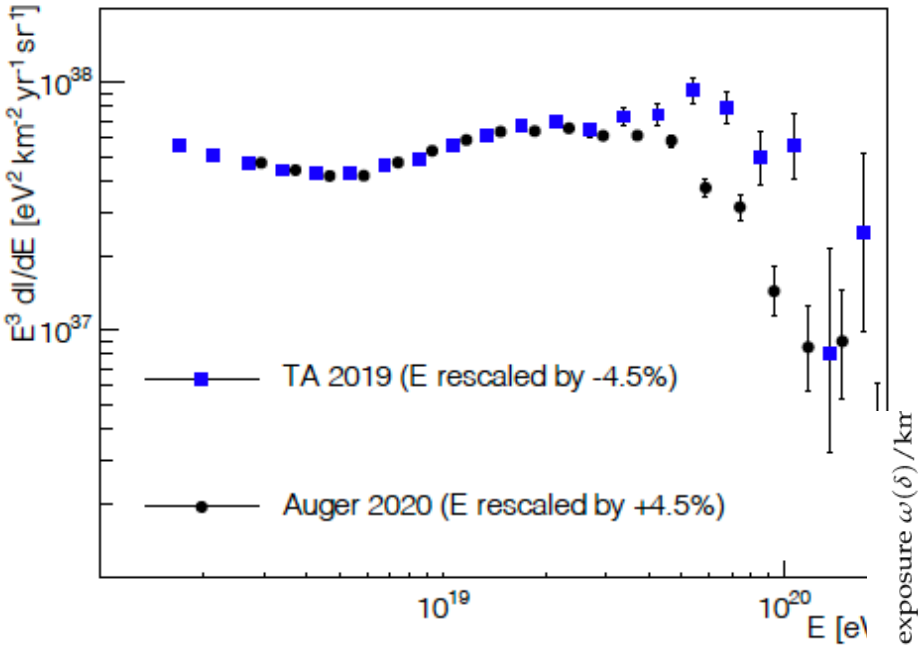
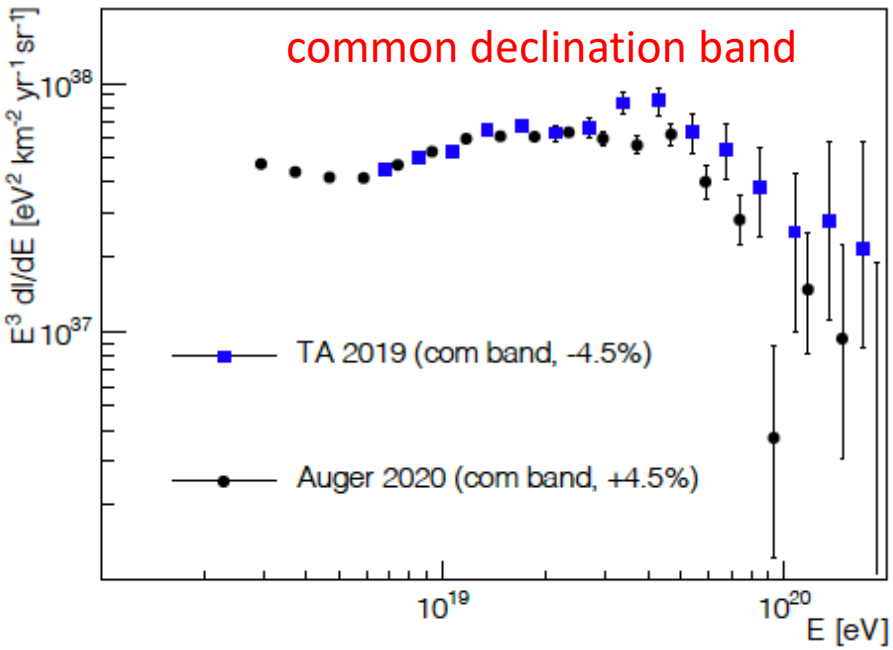
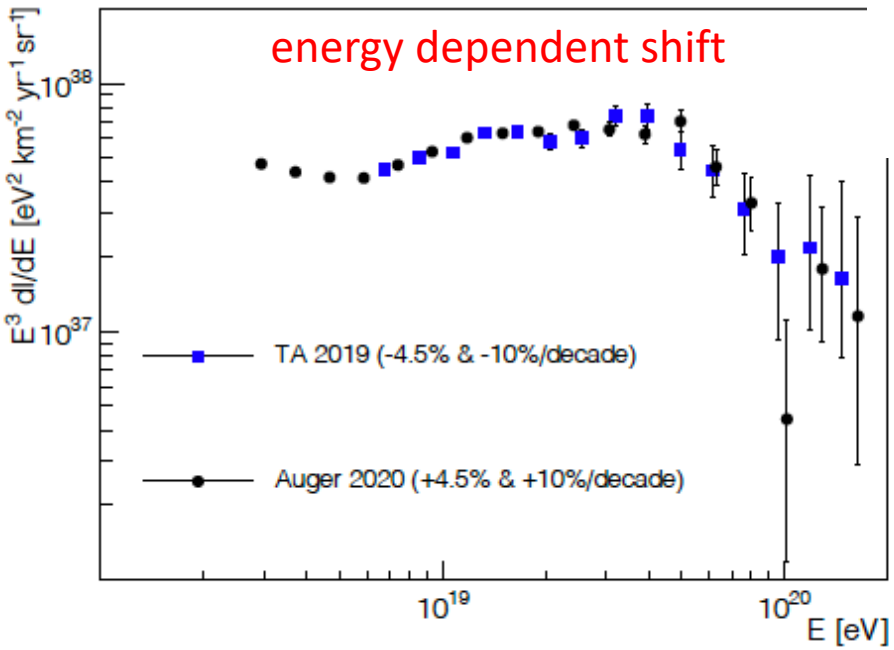
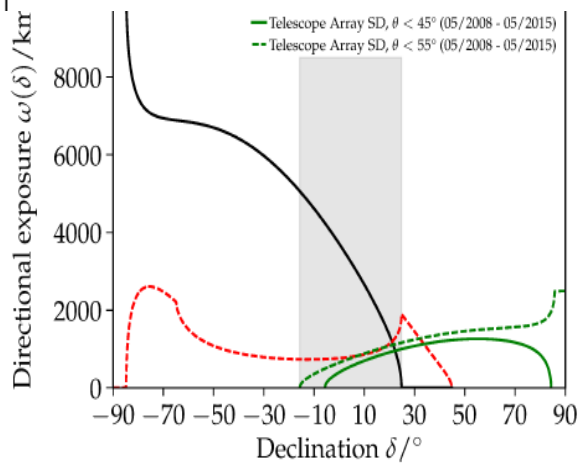

E^3 dI/dE [eV^2 km^{-2} yr^{-1} sr^{-1}]
10^{38}
10^{37}
TA ICRC2019
Auger PRD2020
10^{19}
10^{20}
E [eV]

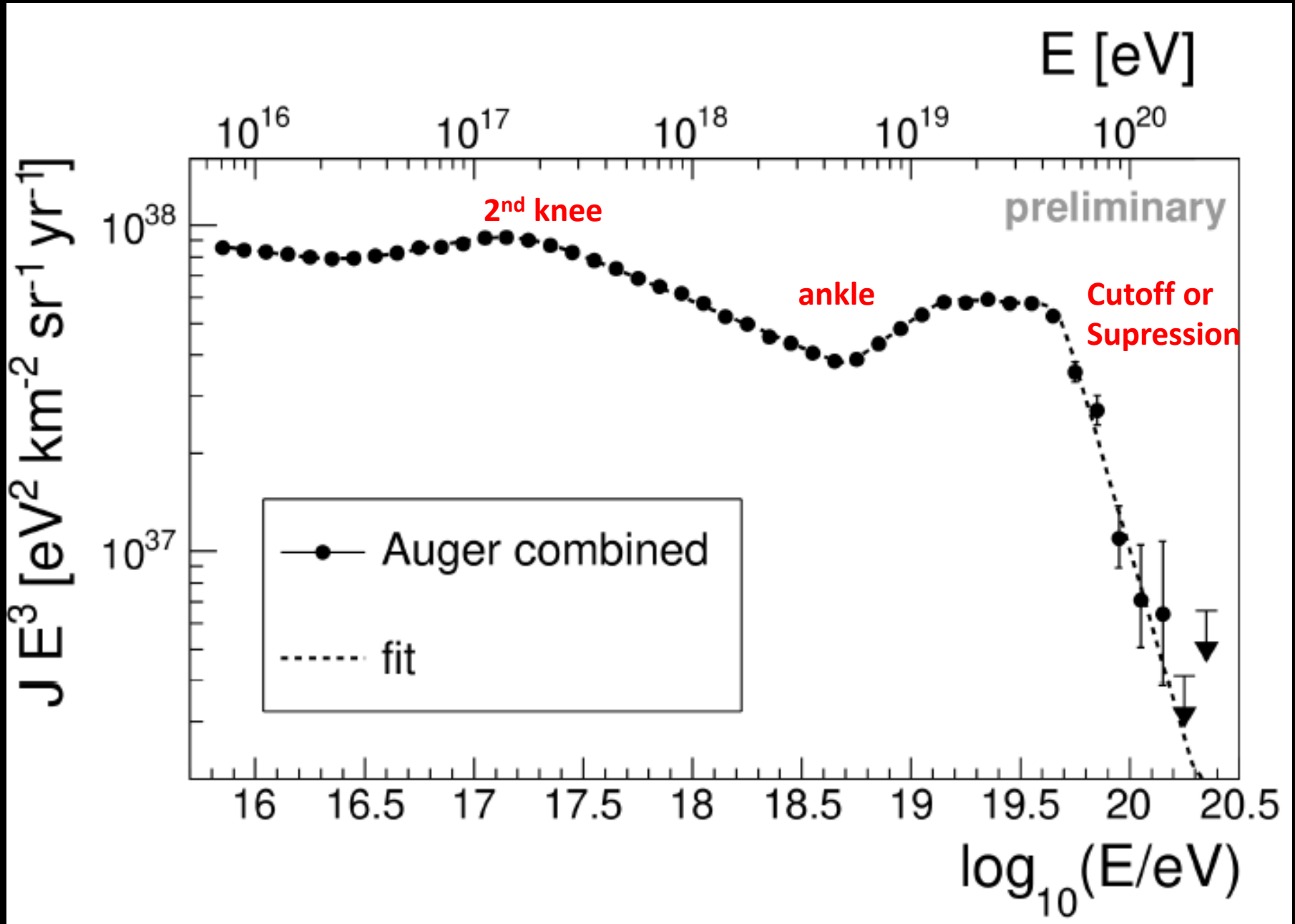

E^3 dI/dE [eV^2 km^{-2} yr^{-1} sr^{-1}]
10^{38}
10^{37}
TA 2019 (E rescaled by -4.5%)
Auger 2020 (E rescaled by +4.5%)
10^{19}
10^{20}
E [eV]


common declination band
E^3 dI/dE [eV^2 km^{-2} yr^{-1} sr^{-1}]
10^{38}
10^{37}
TA 2019 (com band, -4.5%)
Auger 2020 (com band, +4.5%)
10^{19}
10^{20}
E [eV]

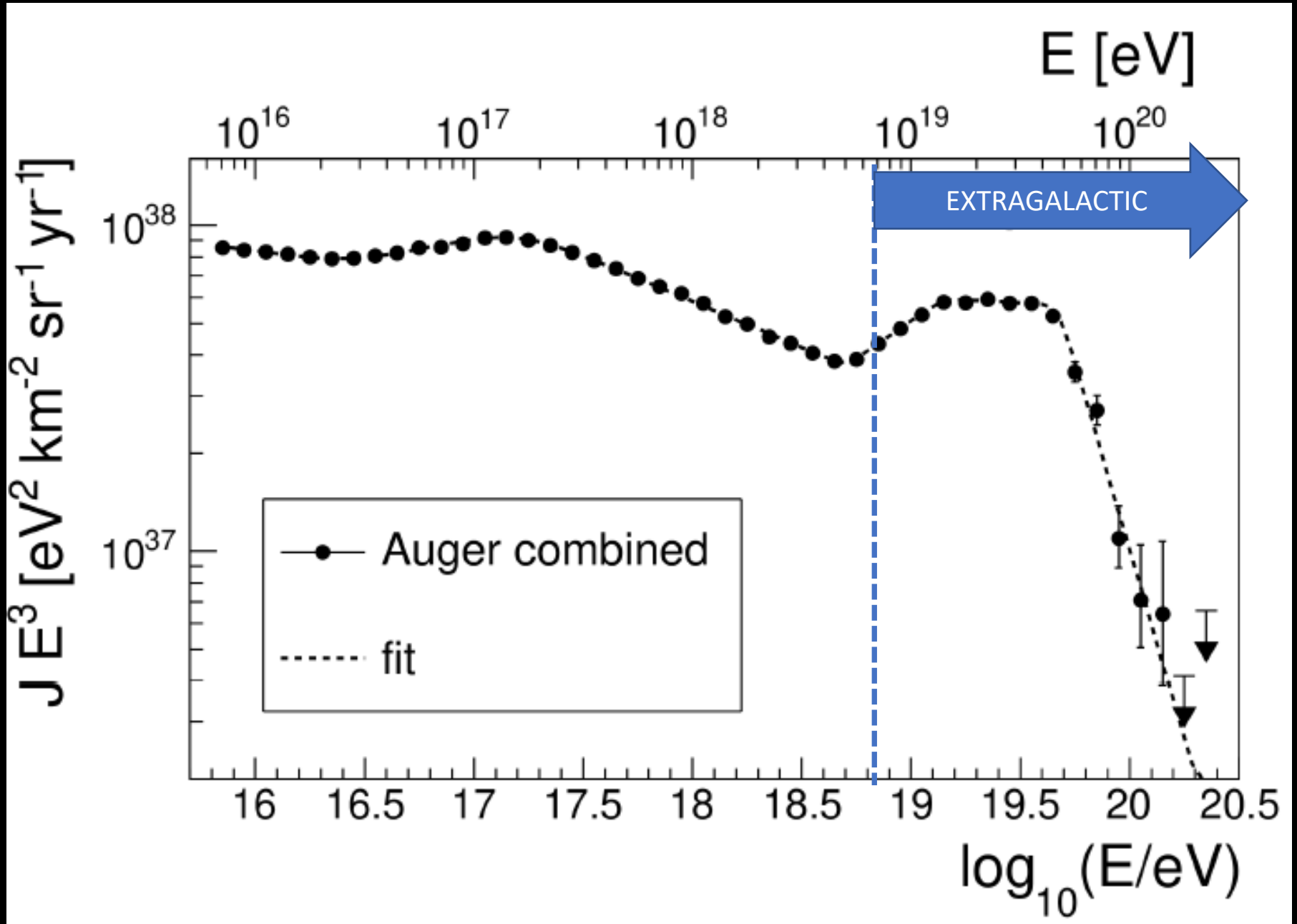

energy dependent shift
E^3 dI/dE [eV^2 km^{-2} yr^{-1} sr^{-1}]
10^{38}
10^{37}
TA 2019 (-4.5% & -10%/decade)
Auger 2020 (+4.5% & +10%/decade)
10^{19}
10^{20}
E [eV]


Telescope Array SD, $\theta < 45°$ (05/2008 - 05/2015)
Telescope Array SD, $\theta < 55°$ (05/2008 - 05/2015)
Directional exposure $\omega(\delta)$ /km
8000
6000
4000
2000
0
−90 −70 −50 −30 −10 10 30 50 70 90
Declination δ/°

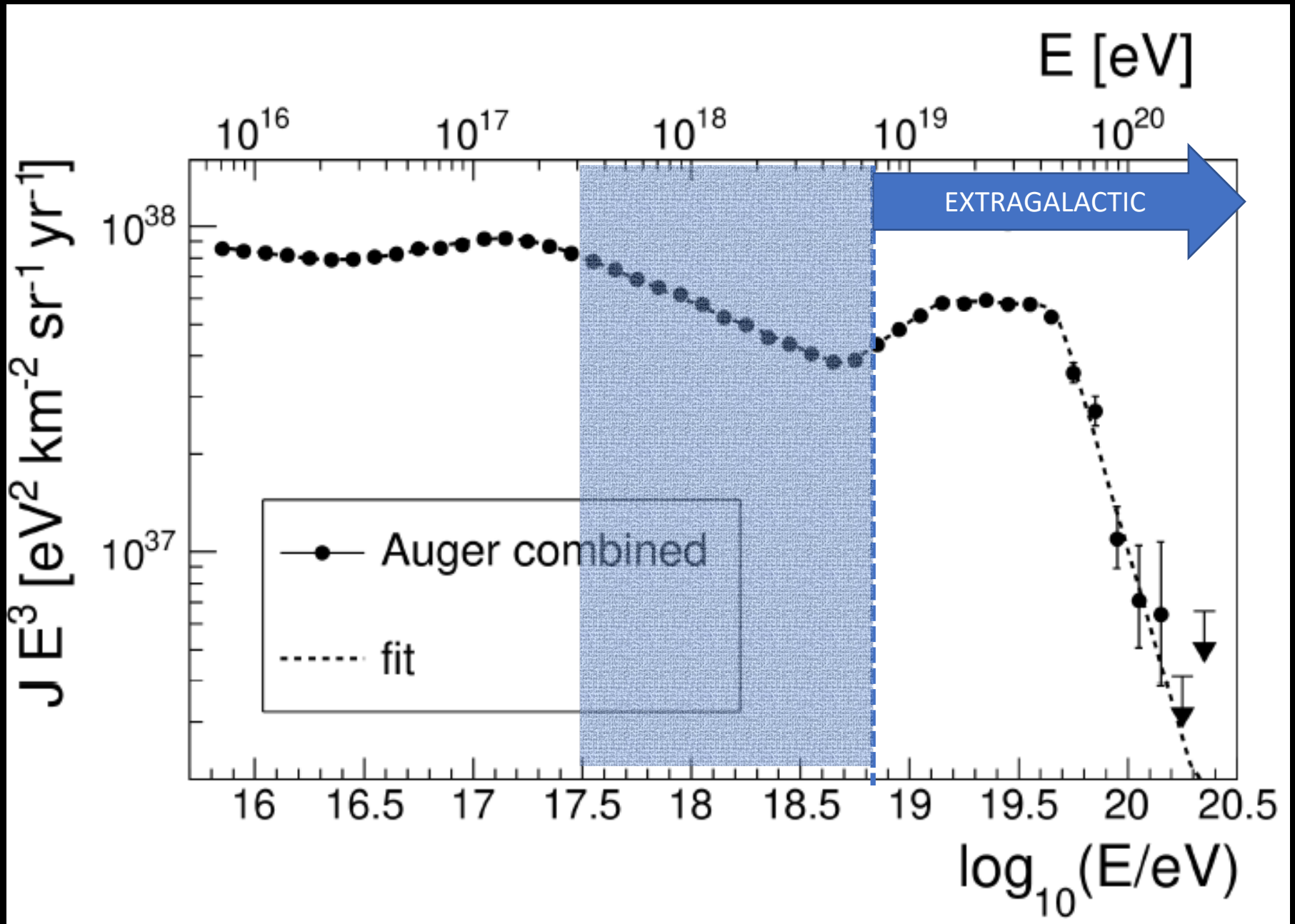
Auger Spectrum ICRC 2021



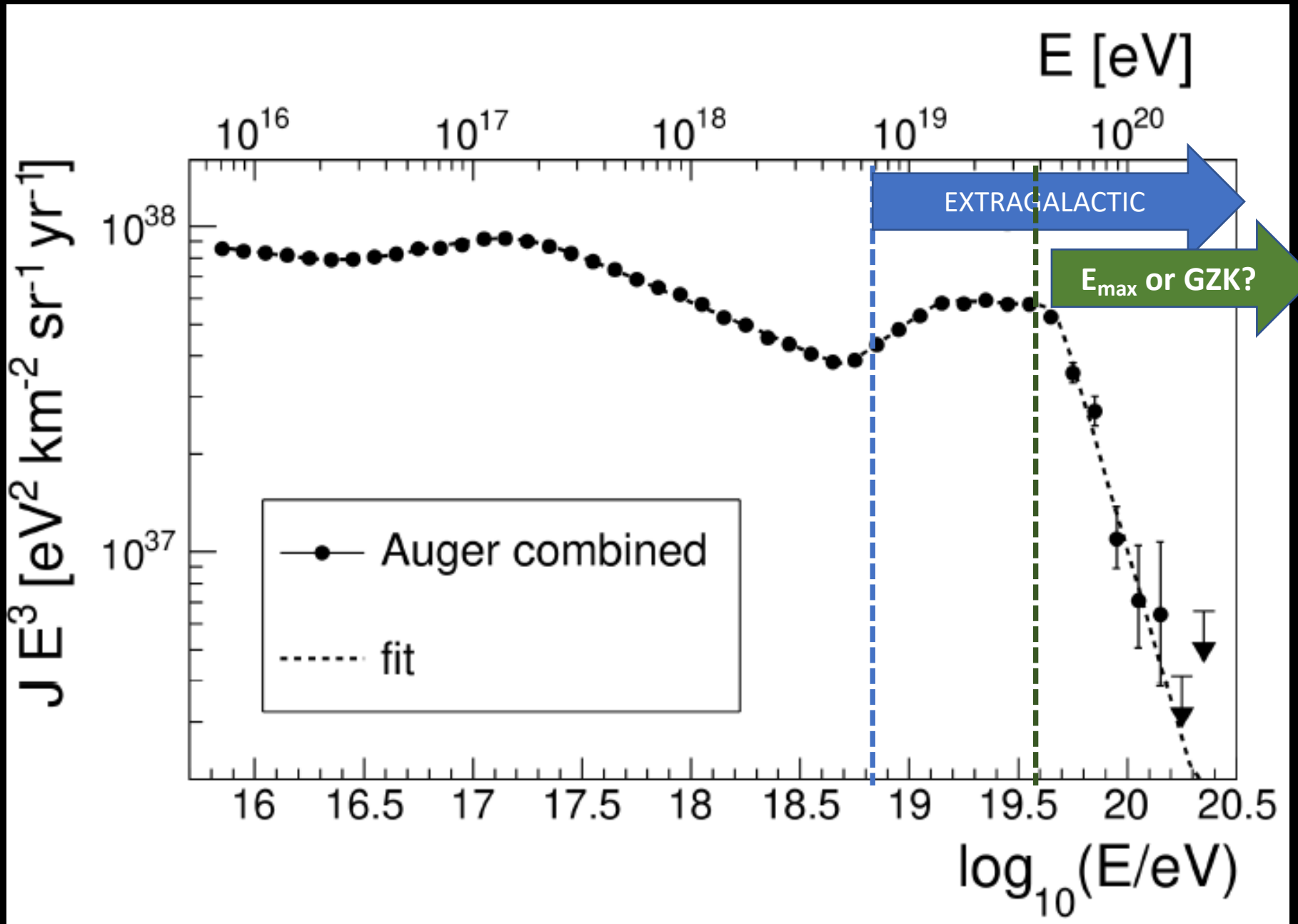
Auger Spectrum ICRC 2021



Auger Spectrum ICRC 2021



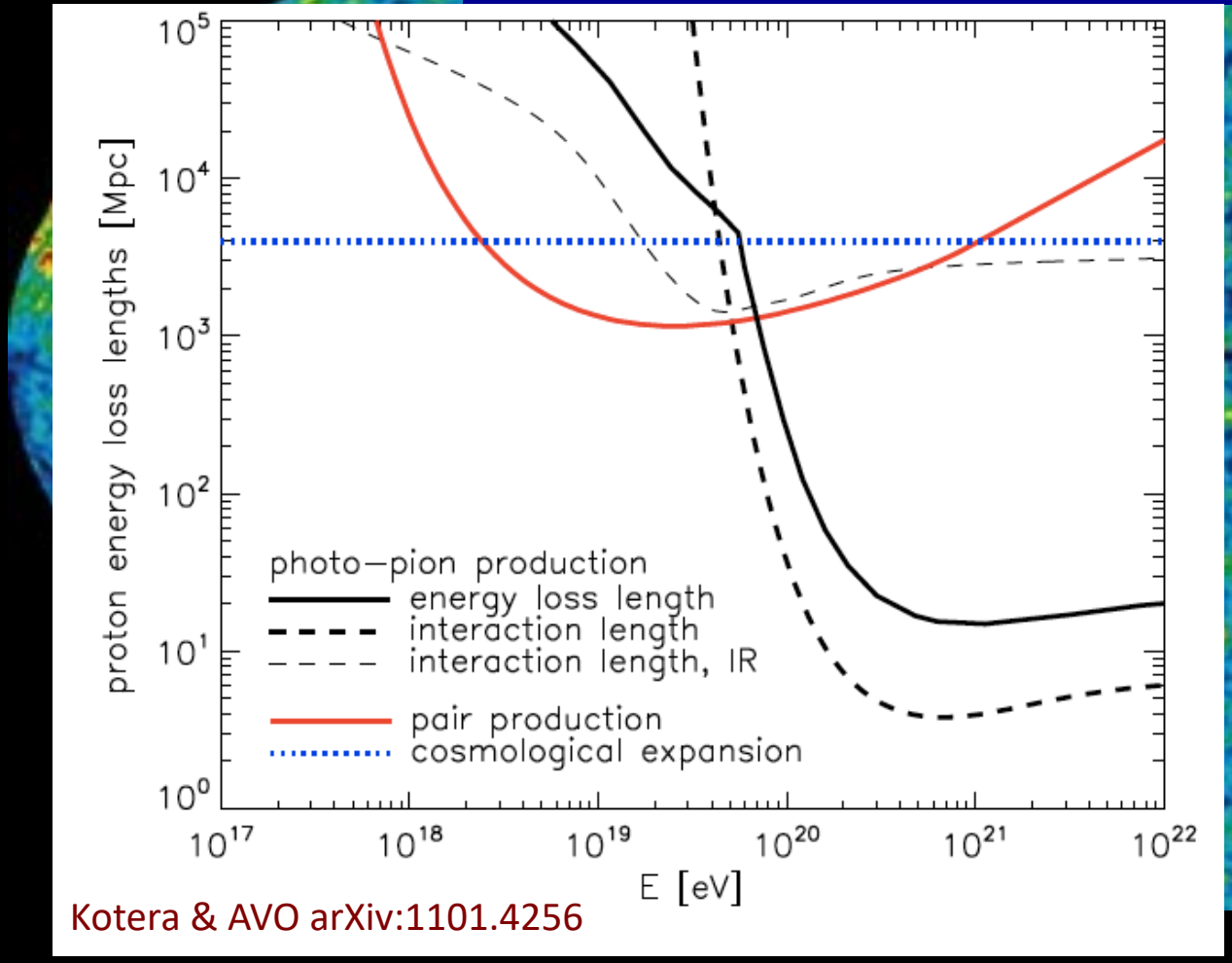
Auger Spectrum ICRC 2021



GZK Cutoff
Greisen,
Zatsepin, Kuzmin
1966

Greisen-Zatsepin-Kuzmin Effect

$$p + \gamma_{cmb} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$
$$\rightarrow n + \pi^{+}$$

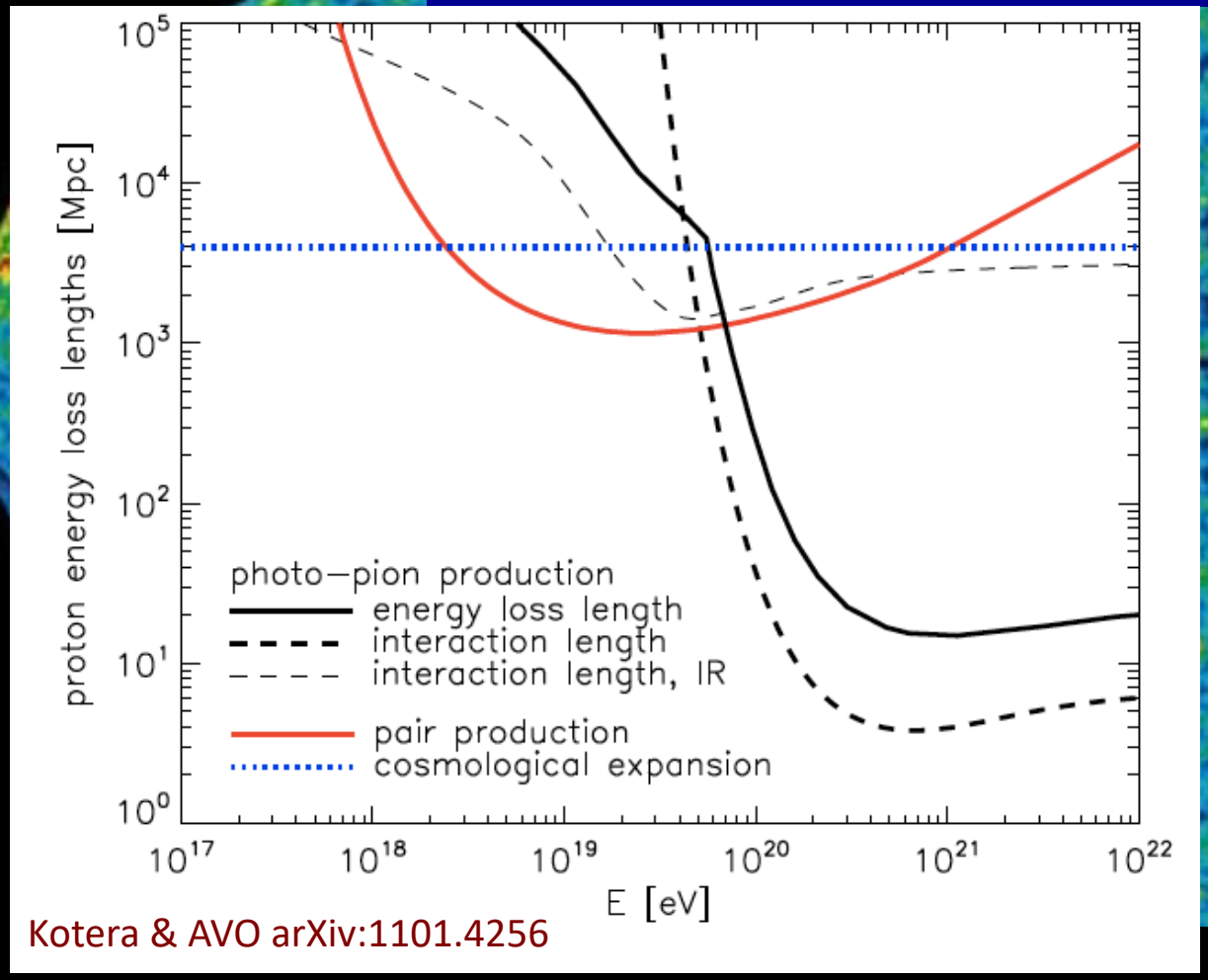


Kotera & AVO arXiv:1101.4256

GZK Cutoff
Greisen,
Zatsepin, Kuzmin
1966

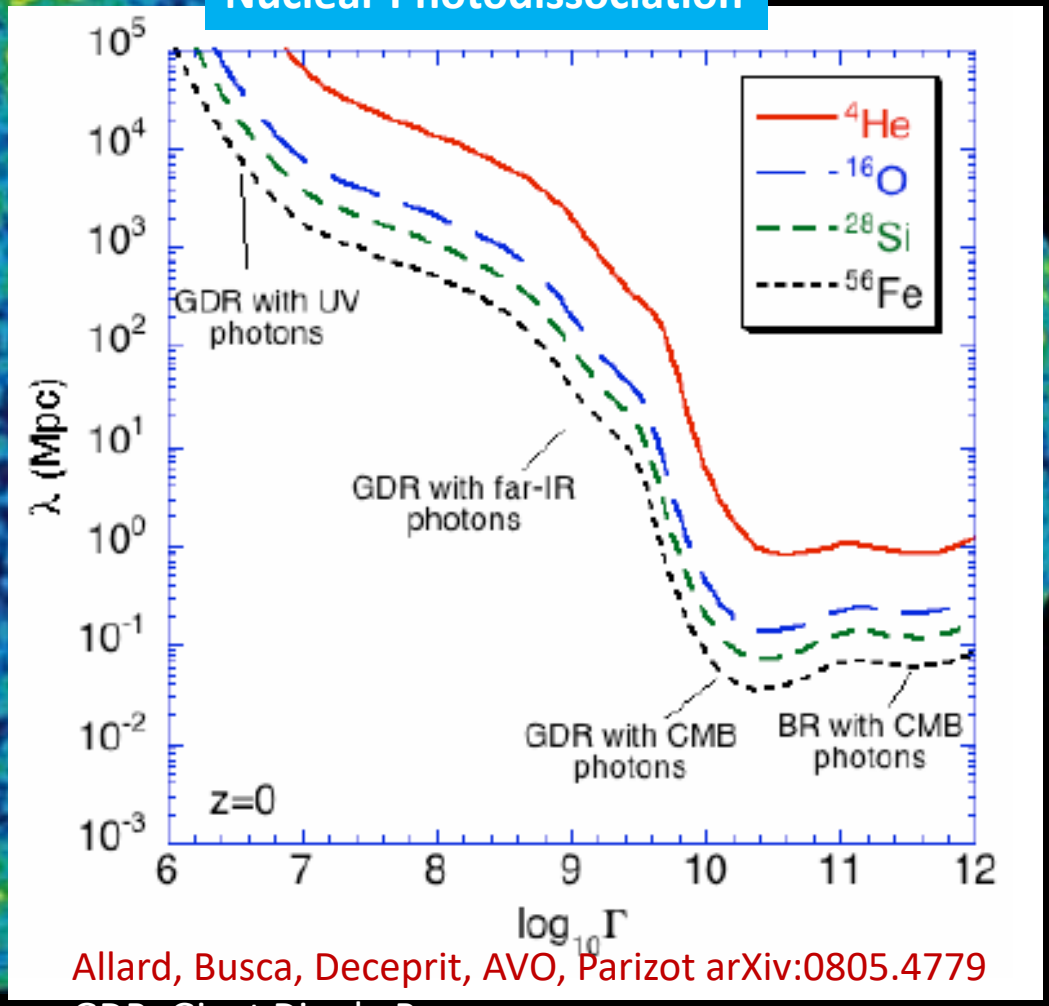
Greisen-Zatsepin-Kuzmin Effect

$$p + \gamma_{cmb} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$
$$\rightarrow n + \pi^{+}$$



Kotera & AVO arXiv:1101.4256

Nuclear Photodissociation

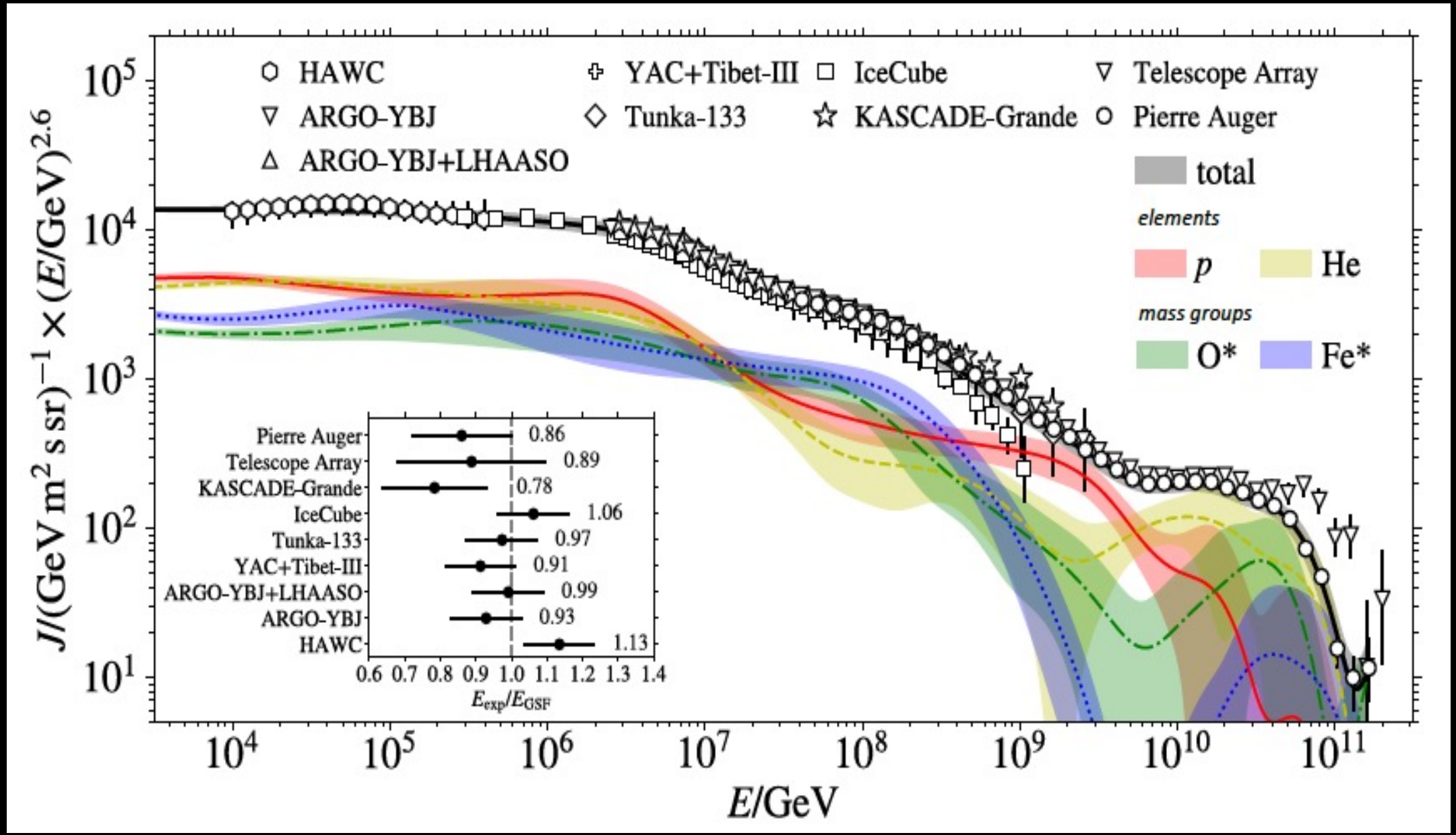


Allard, Busca, Deceprit, AVO, Parizot arXiv:0805.4779

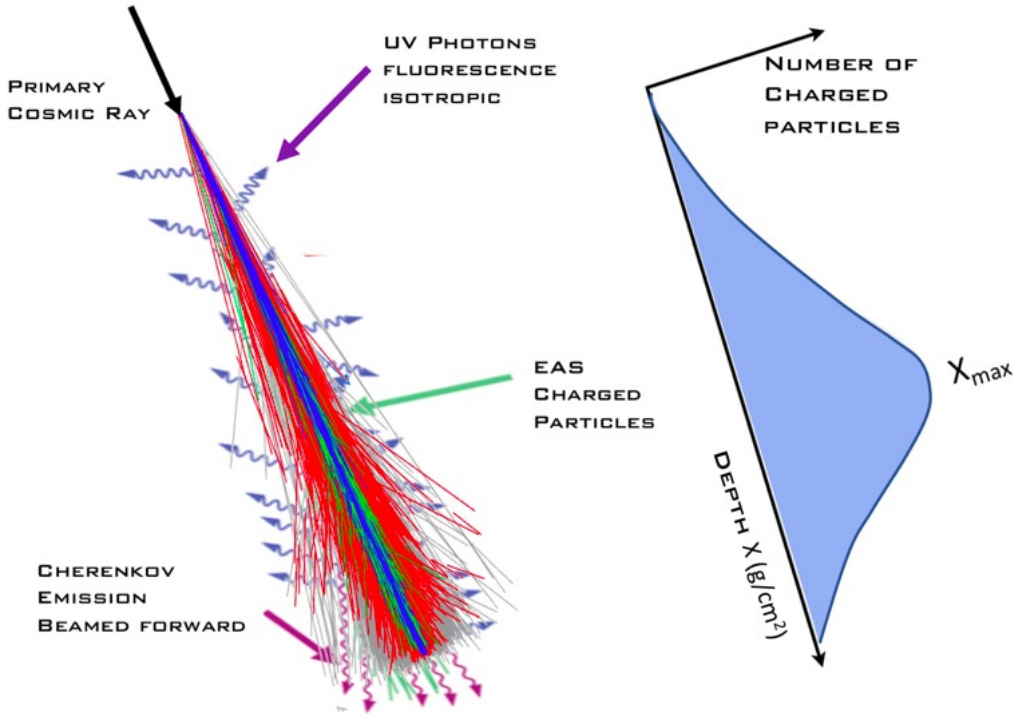
GDR: Giant Dipole Resonance

BR: Baryonic Resonances

What is the composition of UHECRs?



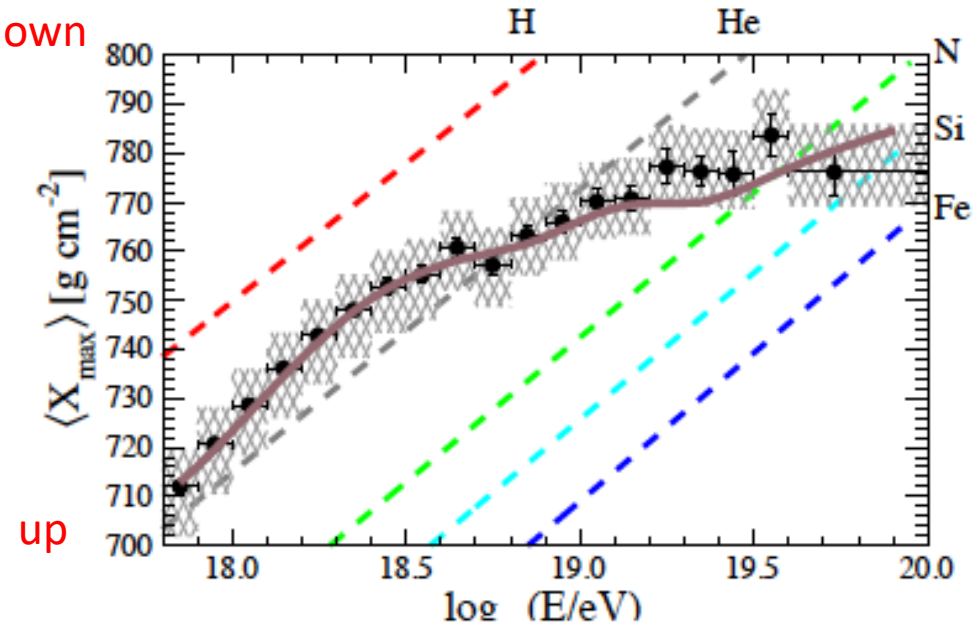
F. G. Schröder ‘19

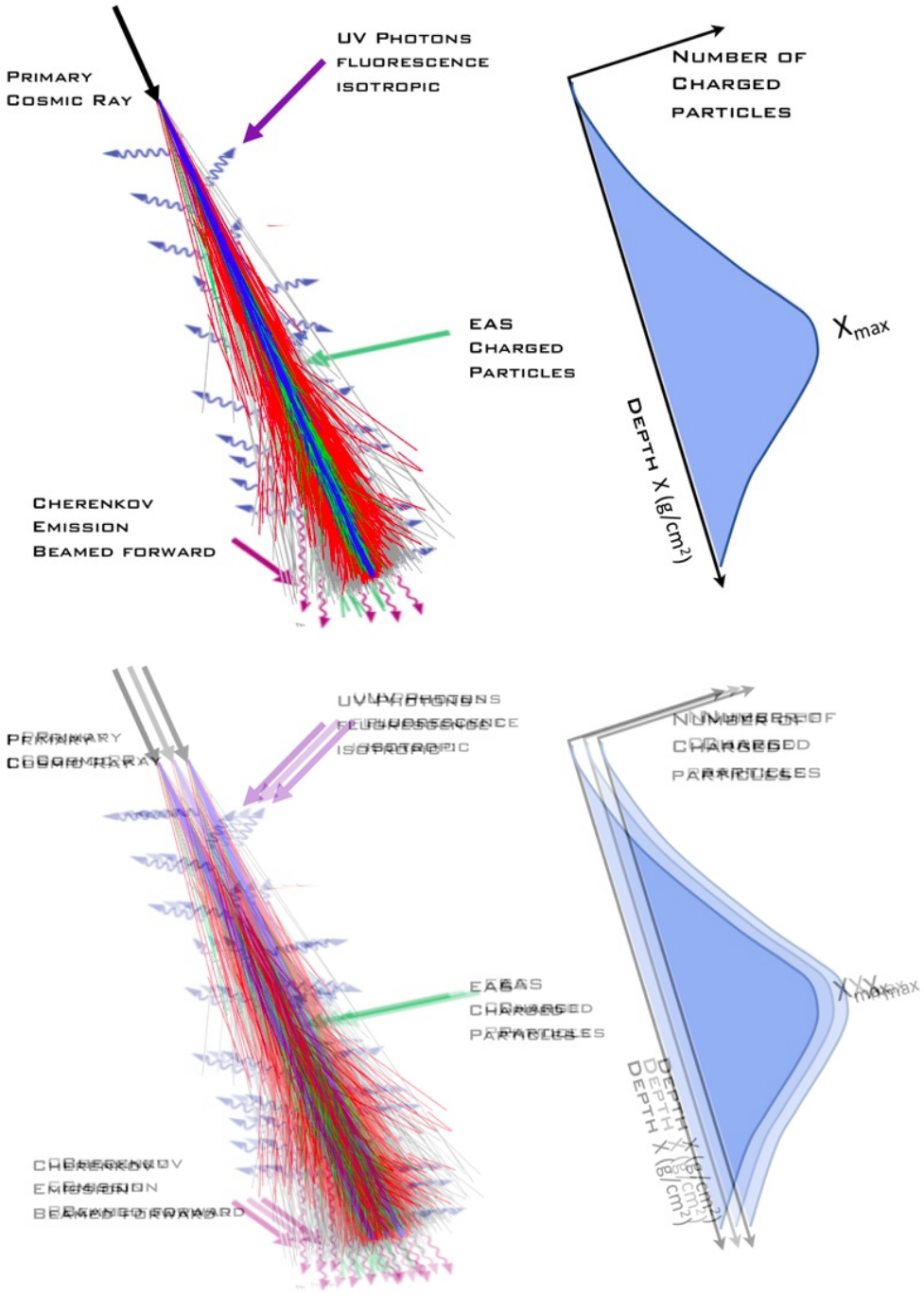


Higher E more penetrating

down

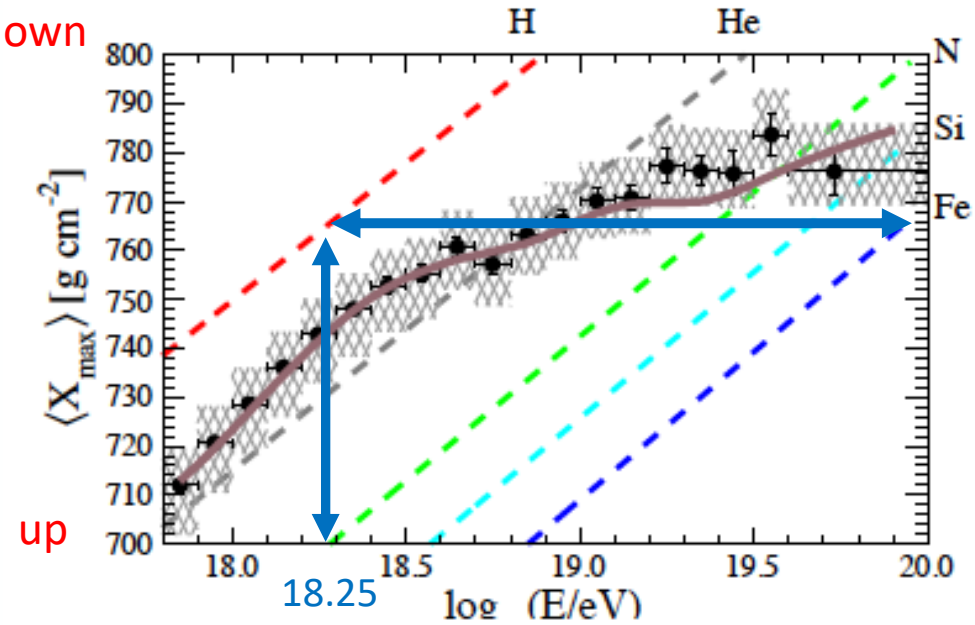
up





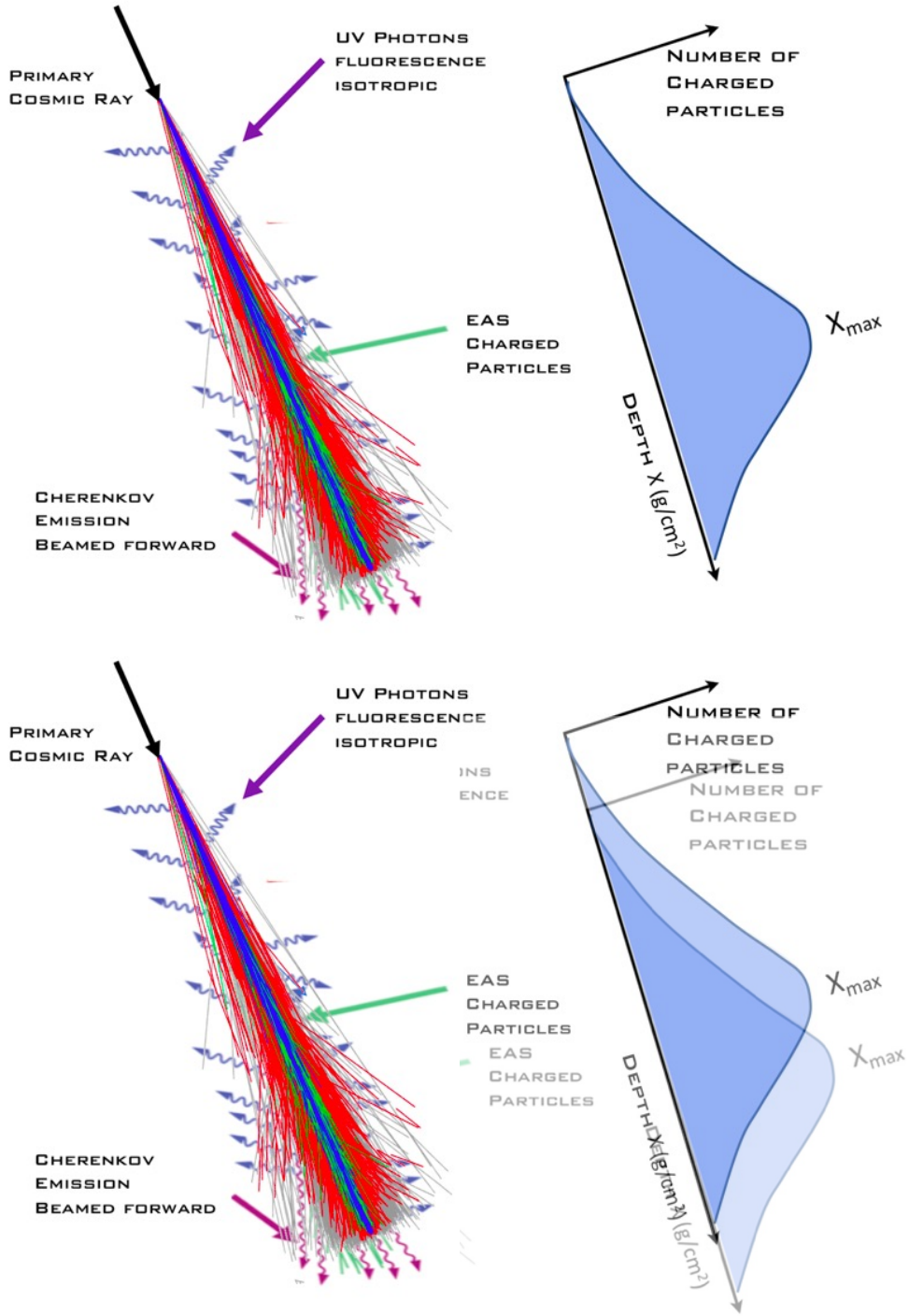
Higher E more penetrating

down



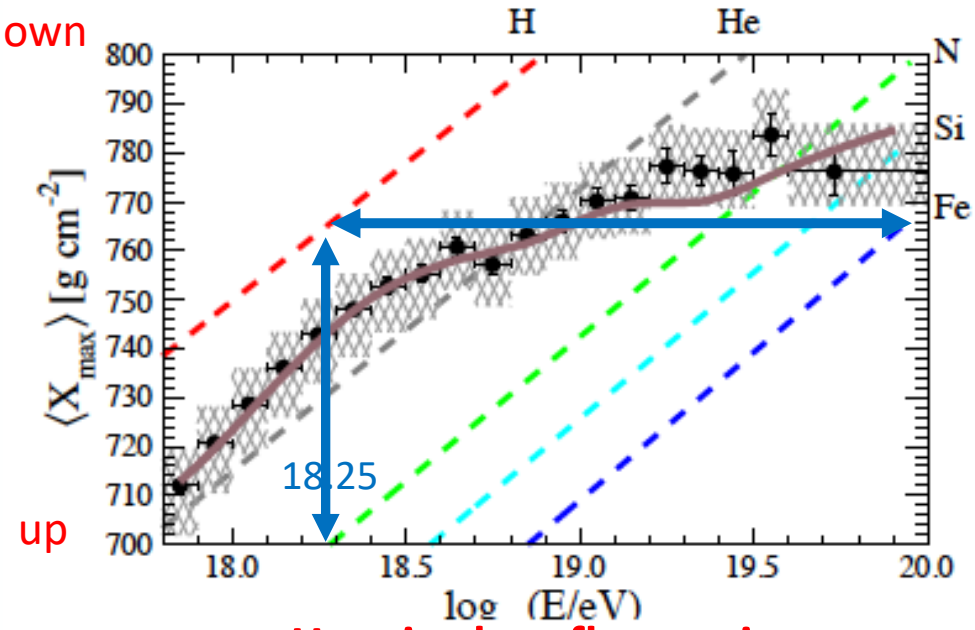
up

X_{max} (E_A,A) ~ X_{max} (E_p /A)



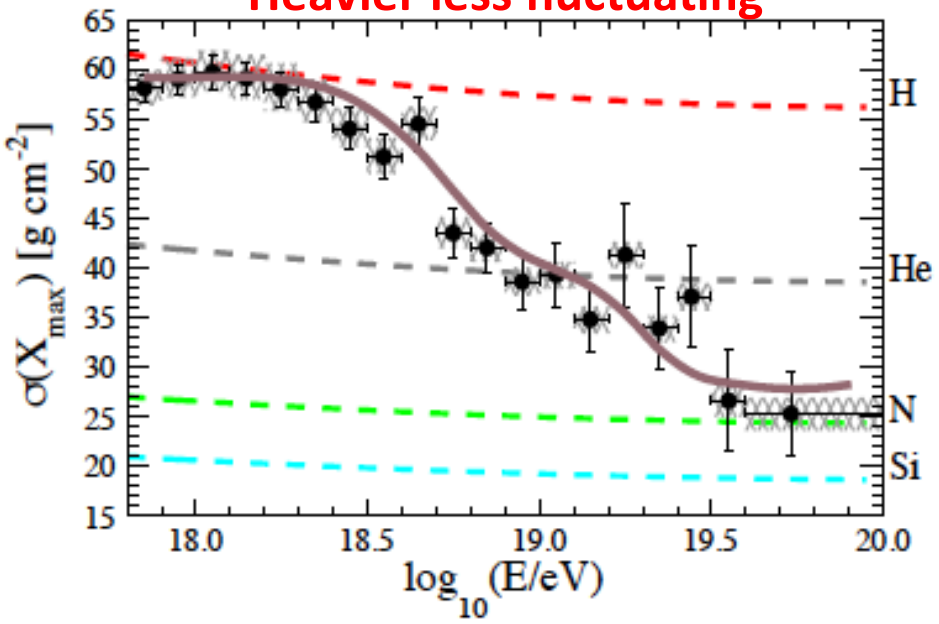
Higher E more penetrating

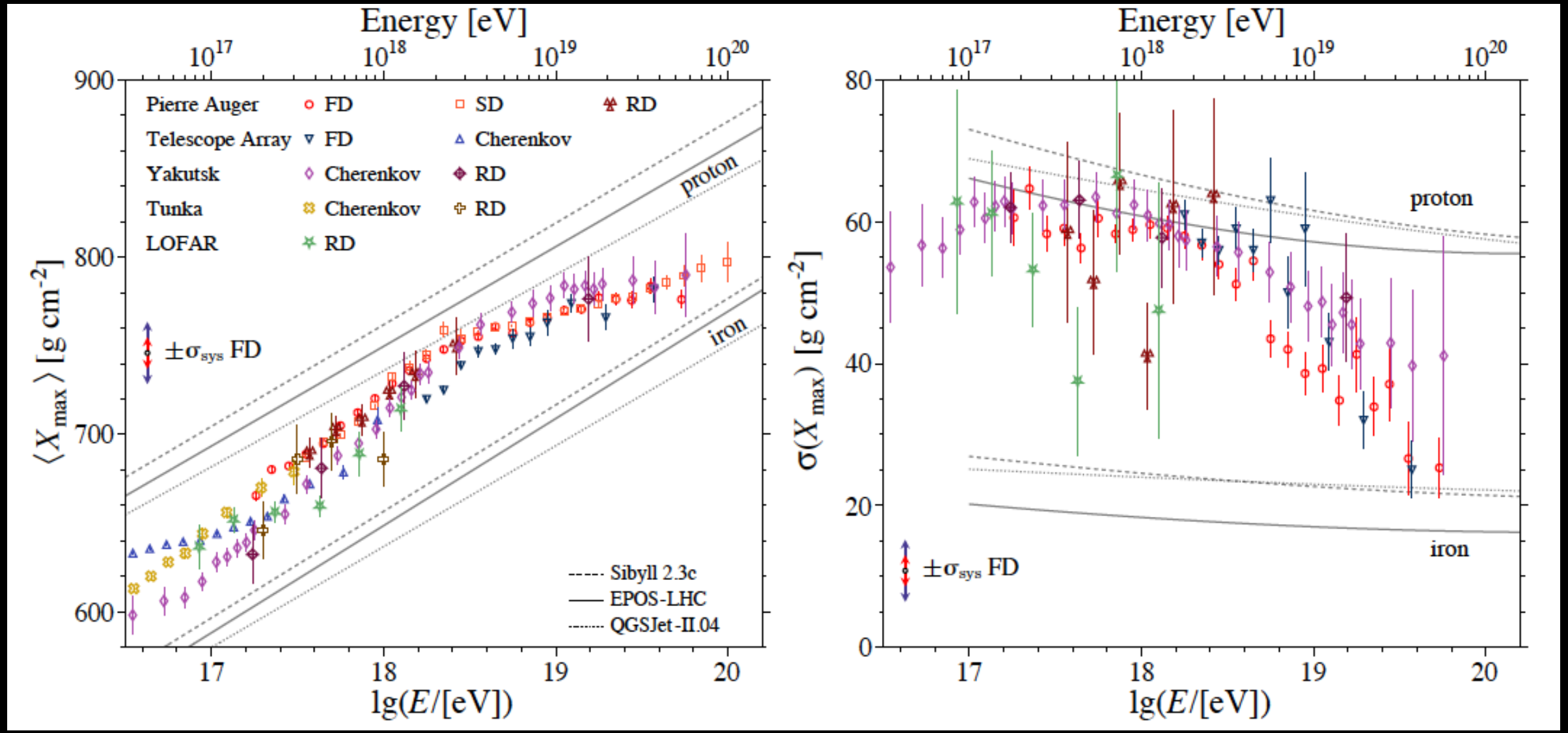
down



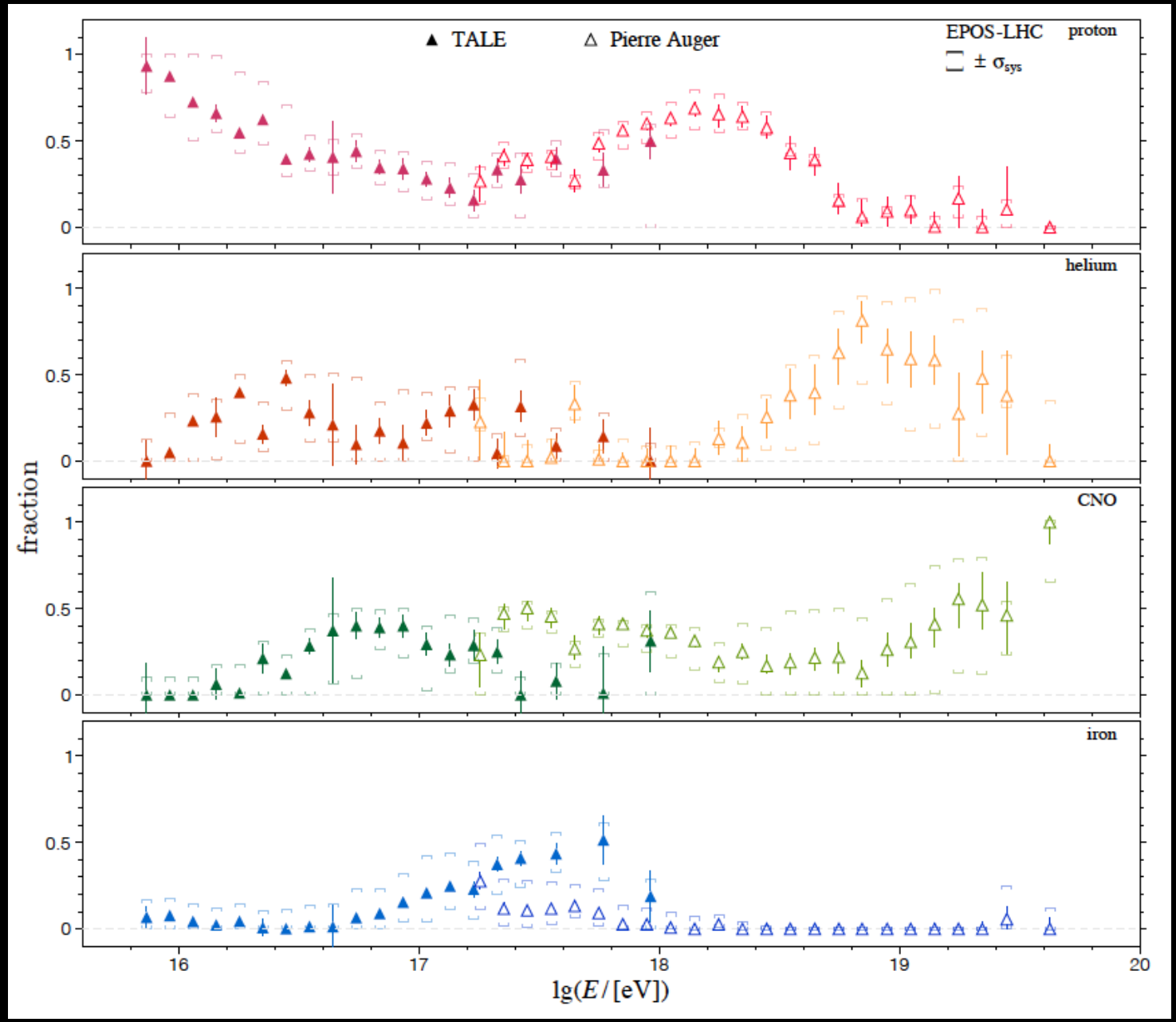
up

Heavier less fluctuating



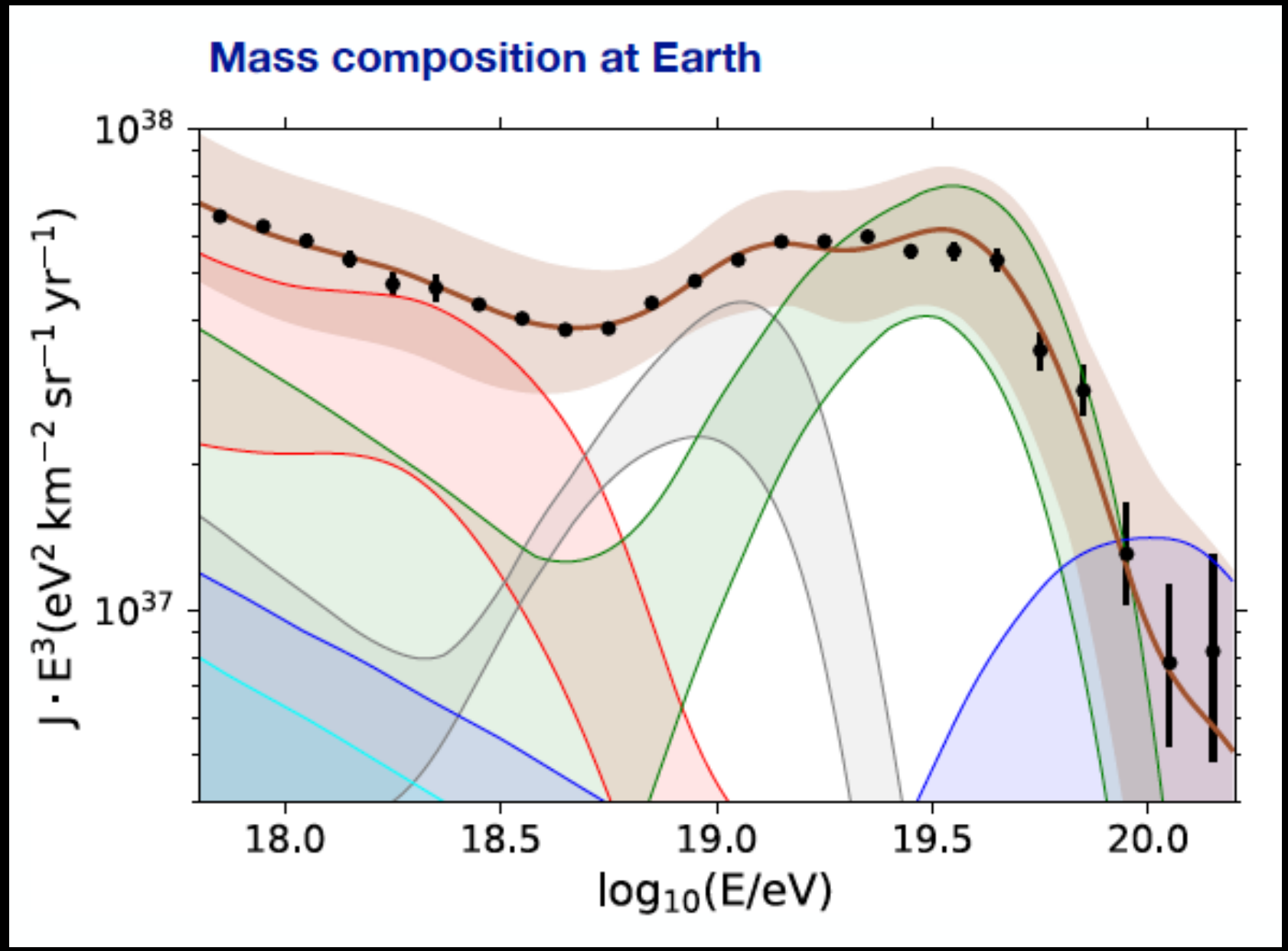


Coleman et al, 2022
arXiv:2205.05845

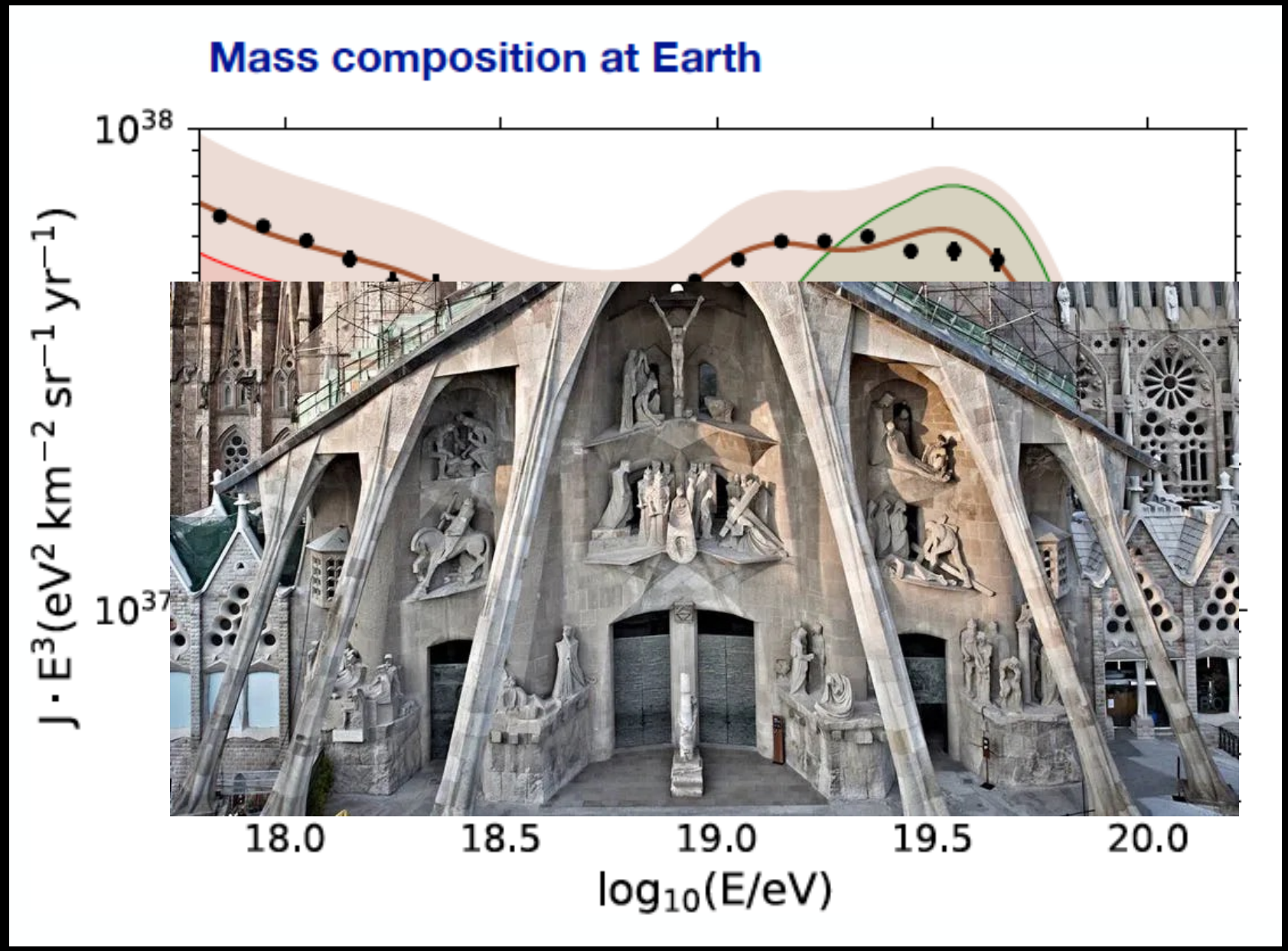


Coleman et al, 2022
arXiv:2205.05845

Auger Composition ICRC 2021

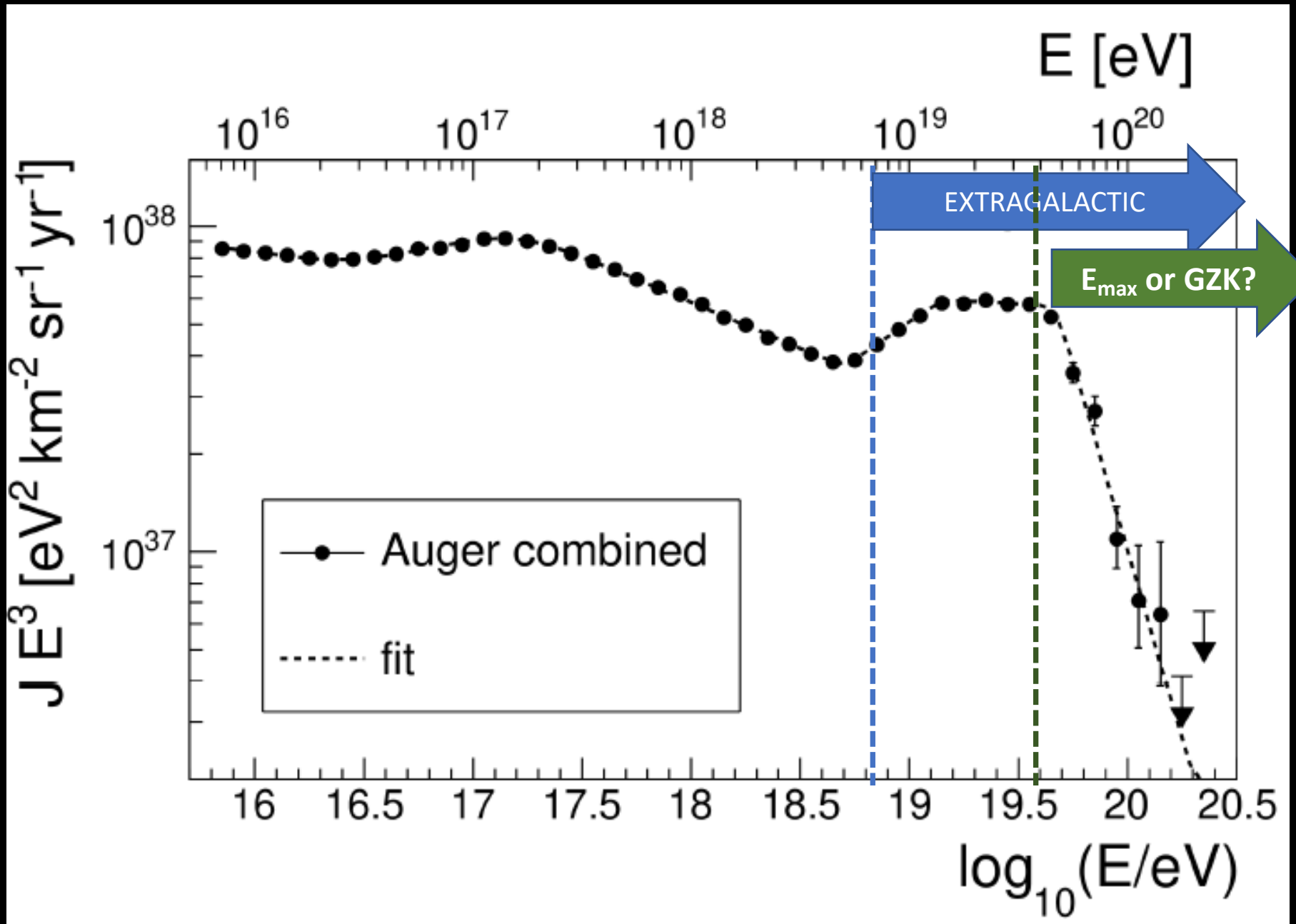


Auger Composition ICRC 2021

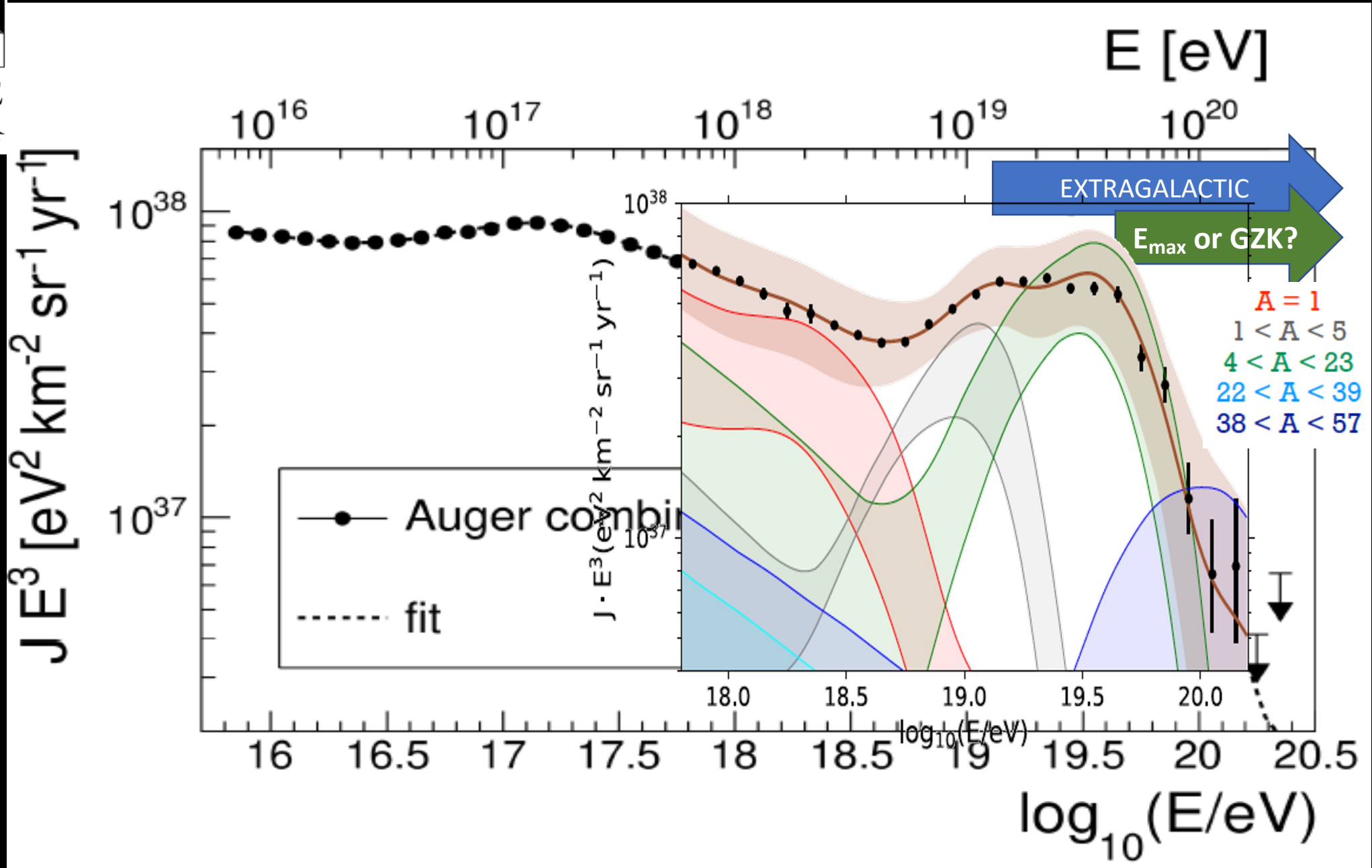


A = 1
1 < A < 5
4 < A < 23
22 < A < 39
38 < A < 57

Auger Spectrum ICRC 2021



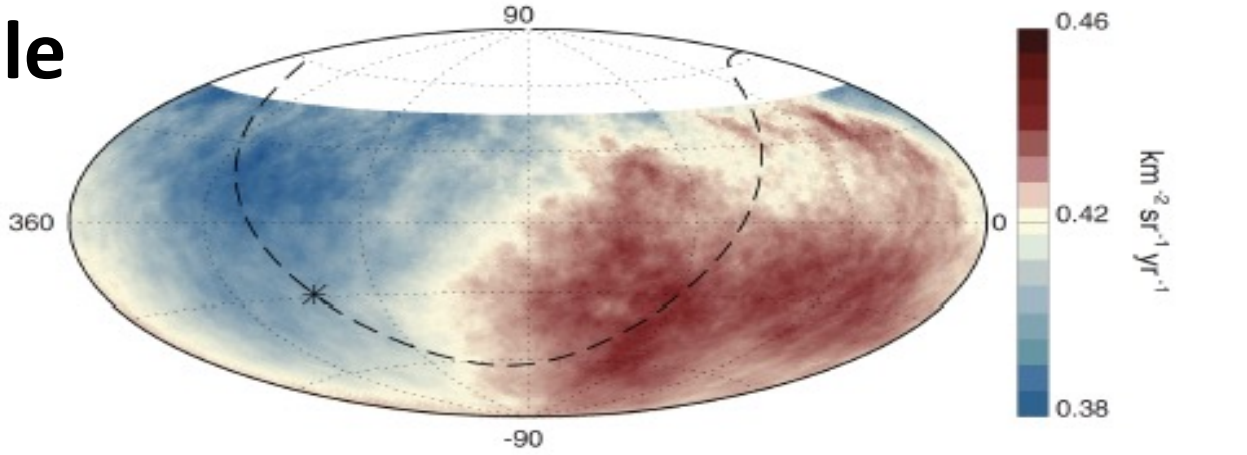
Auger Spectrum+Composition ICRC 2021

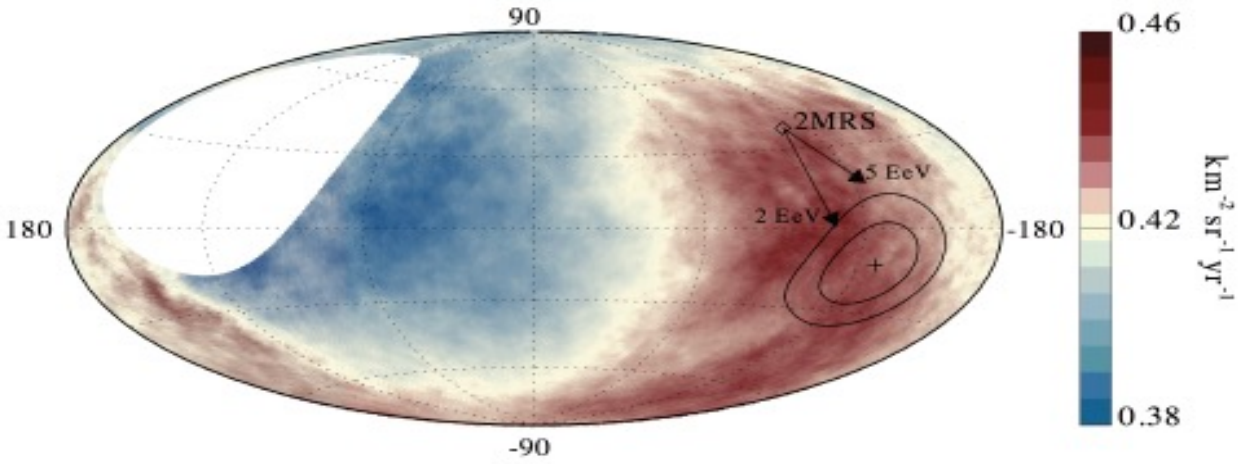


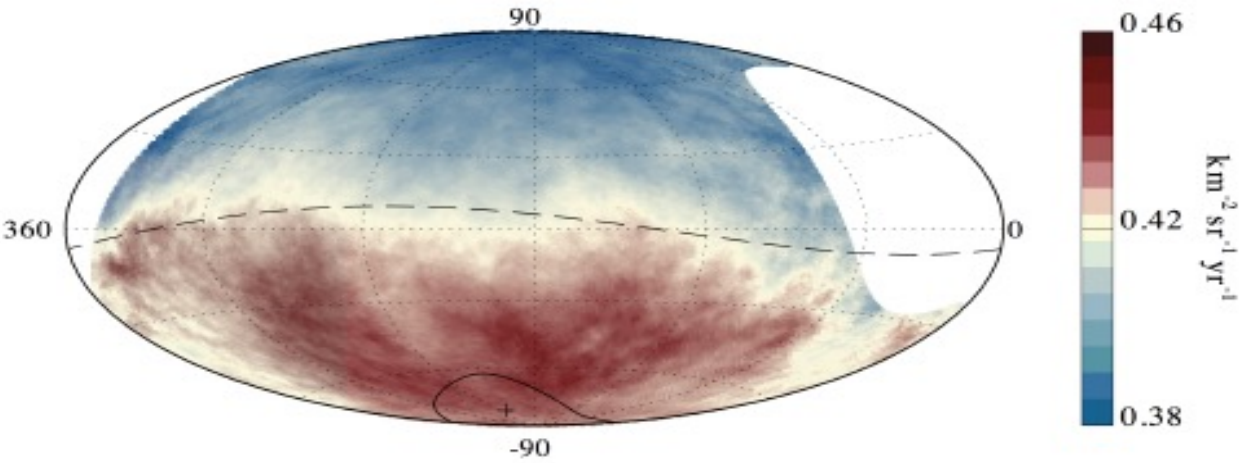
What is the sky distribution of arrival directions?

Auger Dipole

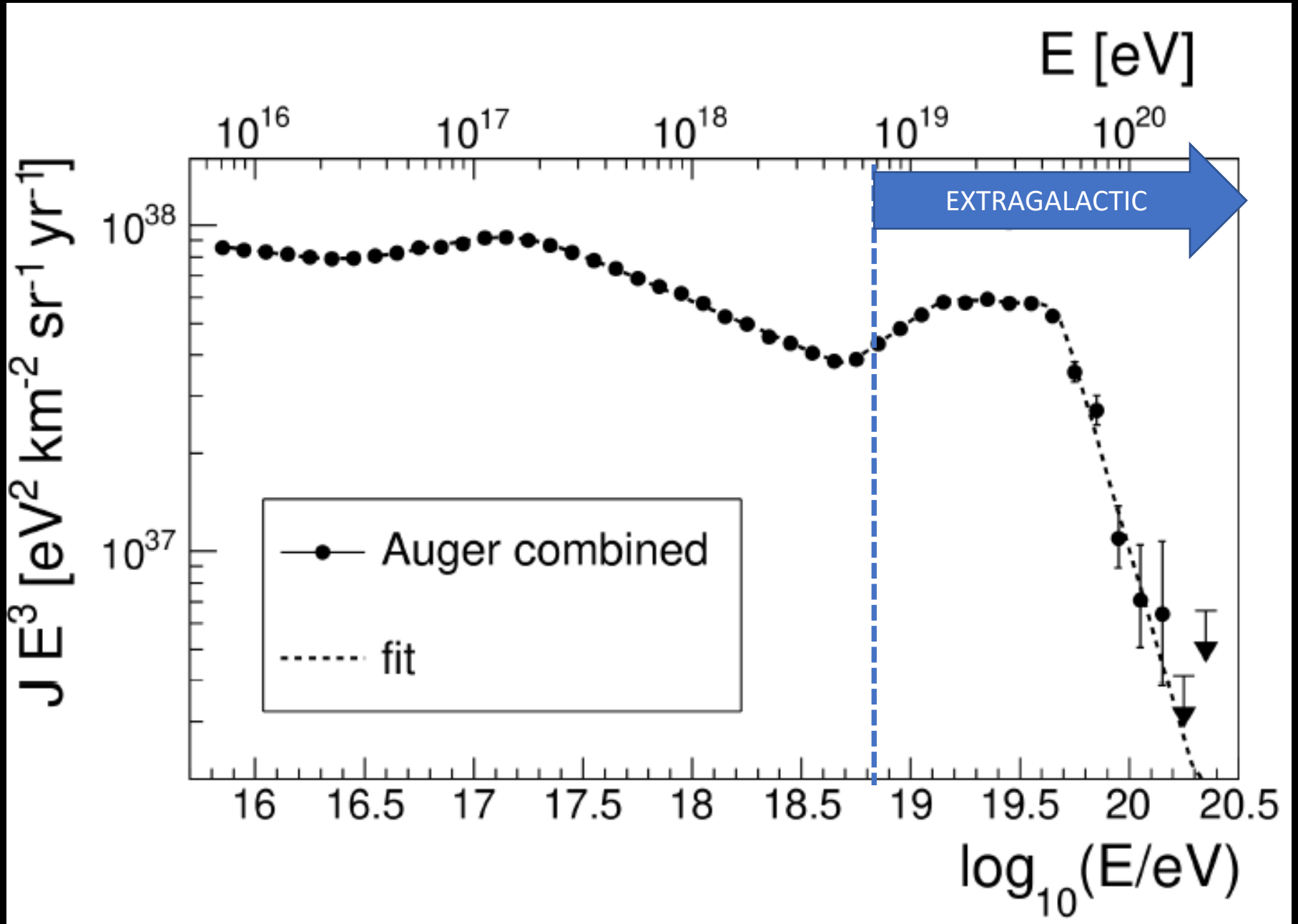
E > 8 EeV, 6.5%



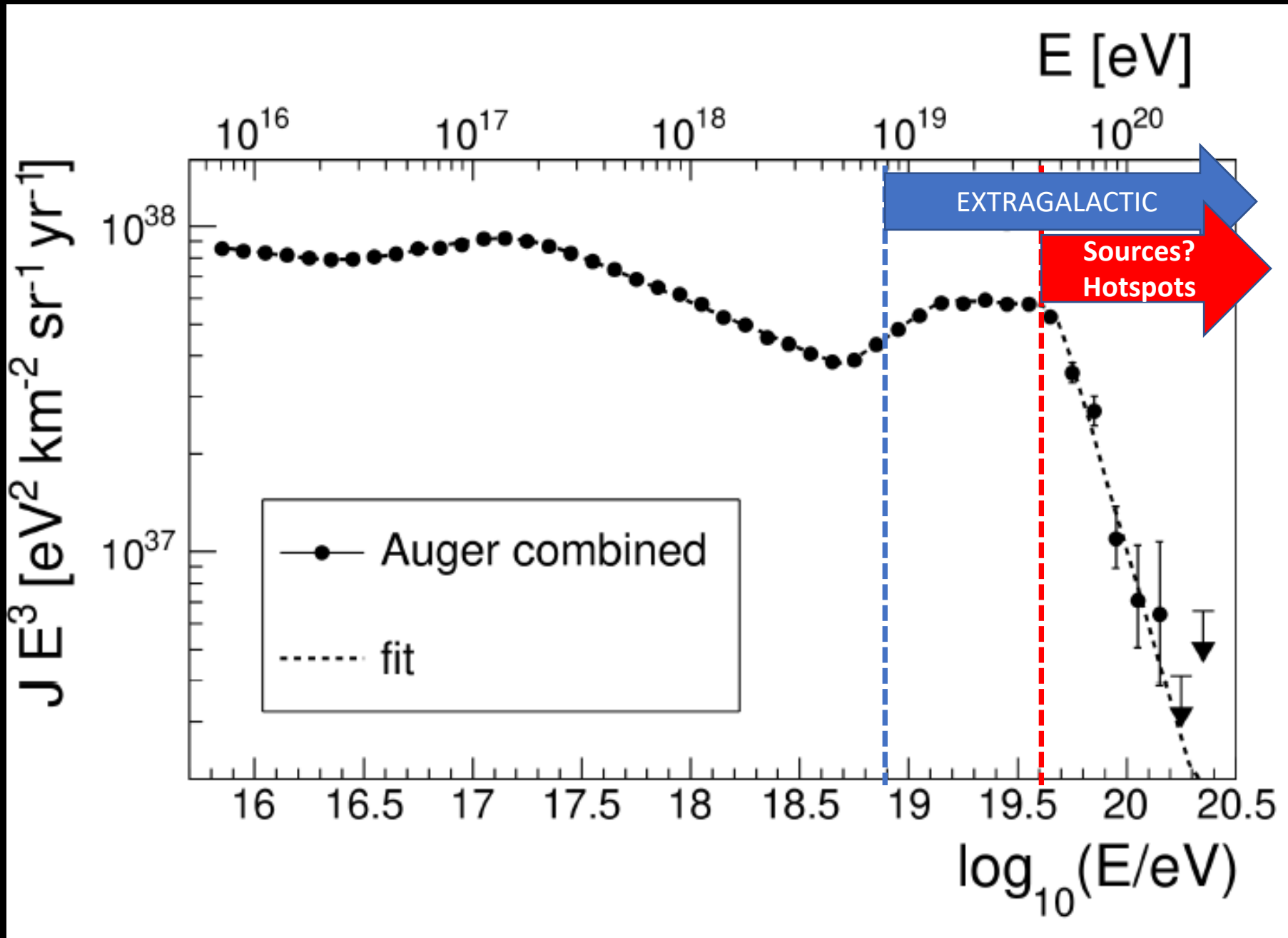




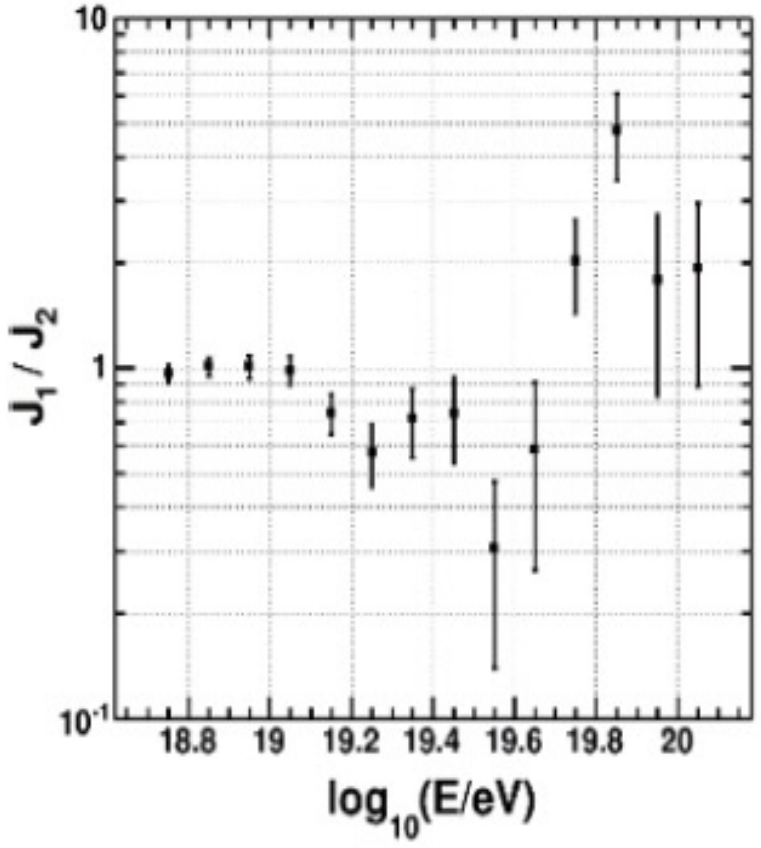
Auger Spectrum ICRC 2021

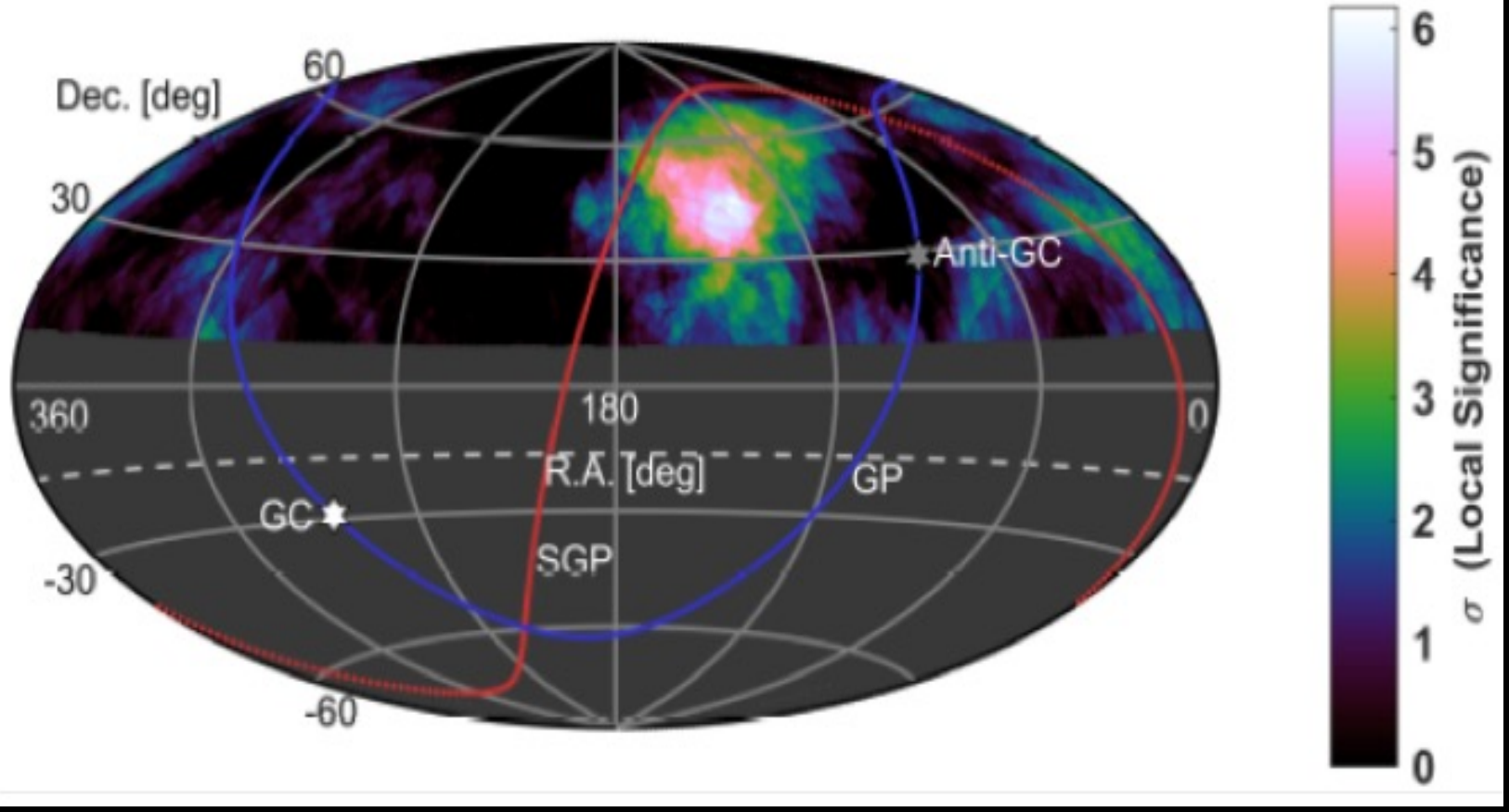


Auger Spectrum ICRC 2021



TA hotspot (E>50 EeV)

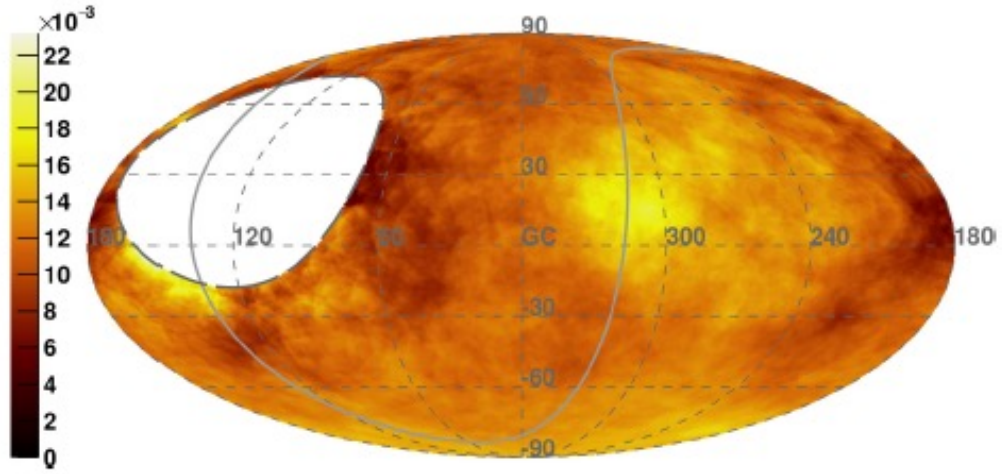


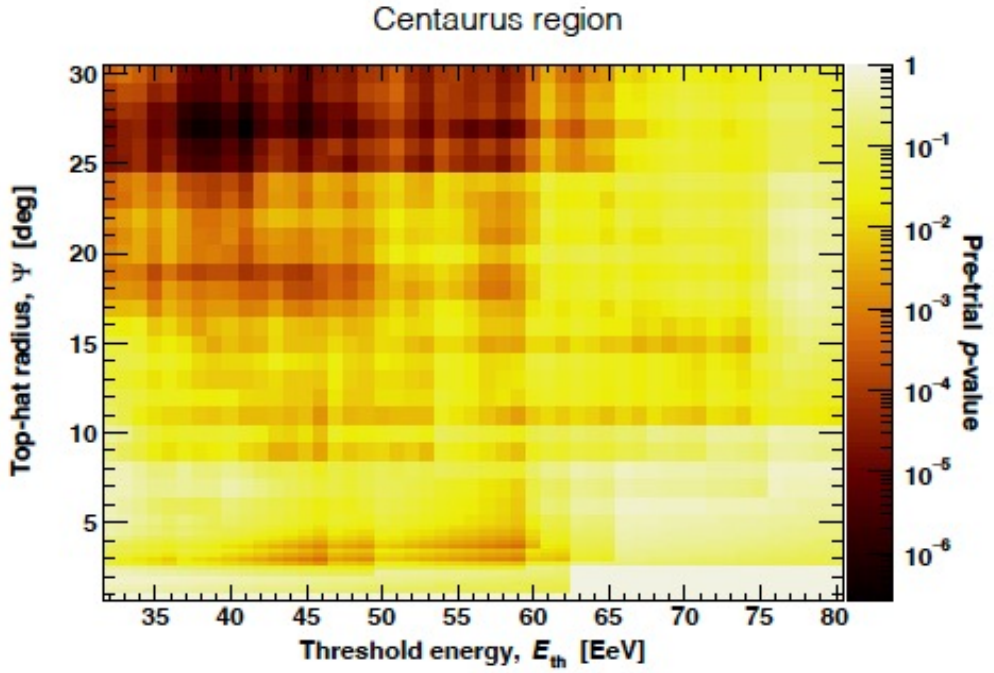


TA SD flux (7 years) inside the TA hotspot circle divided by that outside

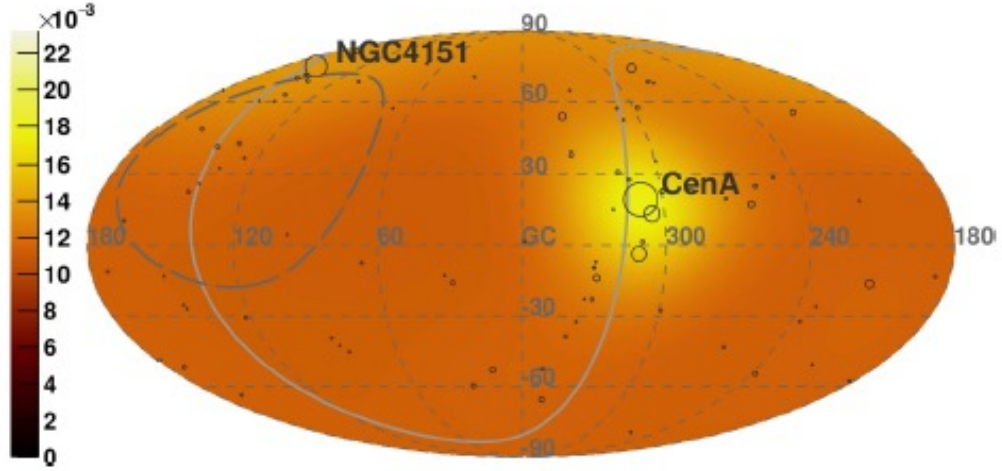
Coleman et al, 2022
arXiv:2205.05845

Auger skymaps (E>38 EeV and 41 EeV)

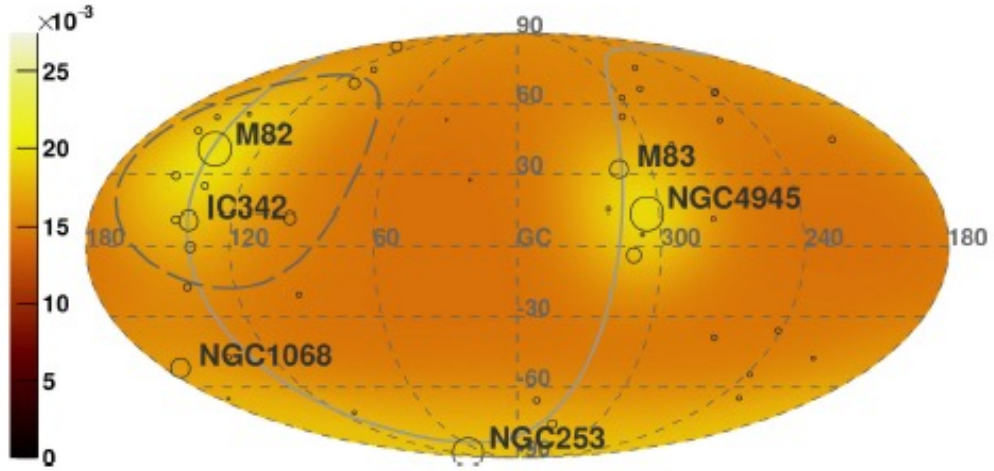




All AGN (hard X-rays) - expected $\Phi(E_{Auger} > 41\ EeV)$ [km^{-2} sr^{-1} yr^{-1}]



Starburst galaxies (radio) - expected $\Phi(E_{Auger} > 38\ EeV)$ [km^{-2} sr^{-1} yr^{-1}]



Coleman et al, 2022
arXiv:2205.05845

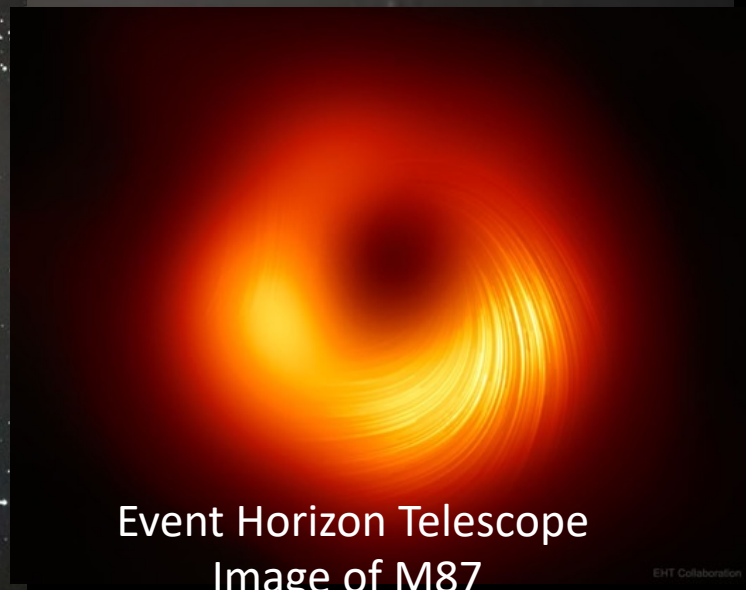
Starbursts Galaxies or Active Galactic Nuclei?

M82 – Starburst Galaxy

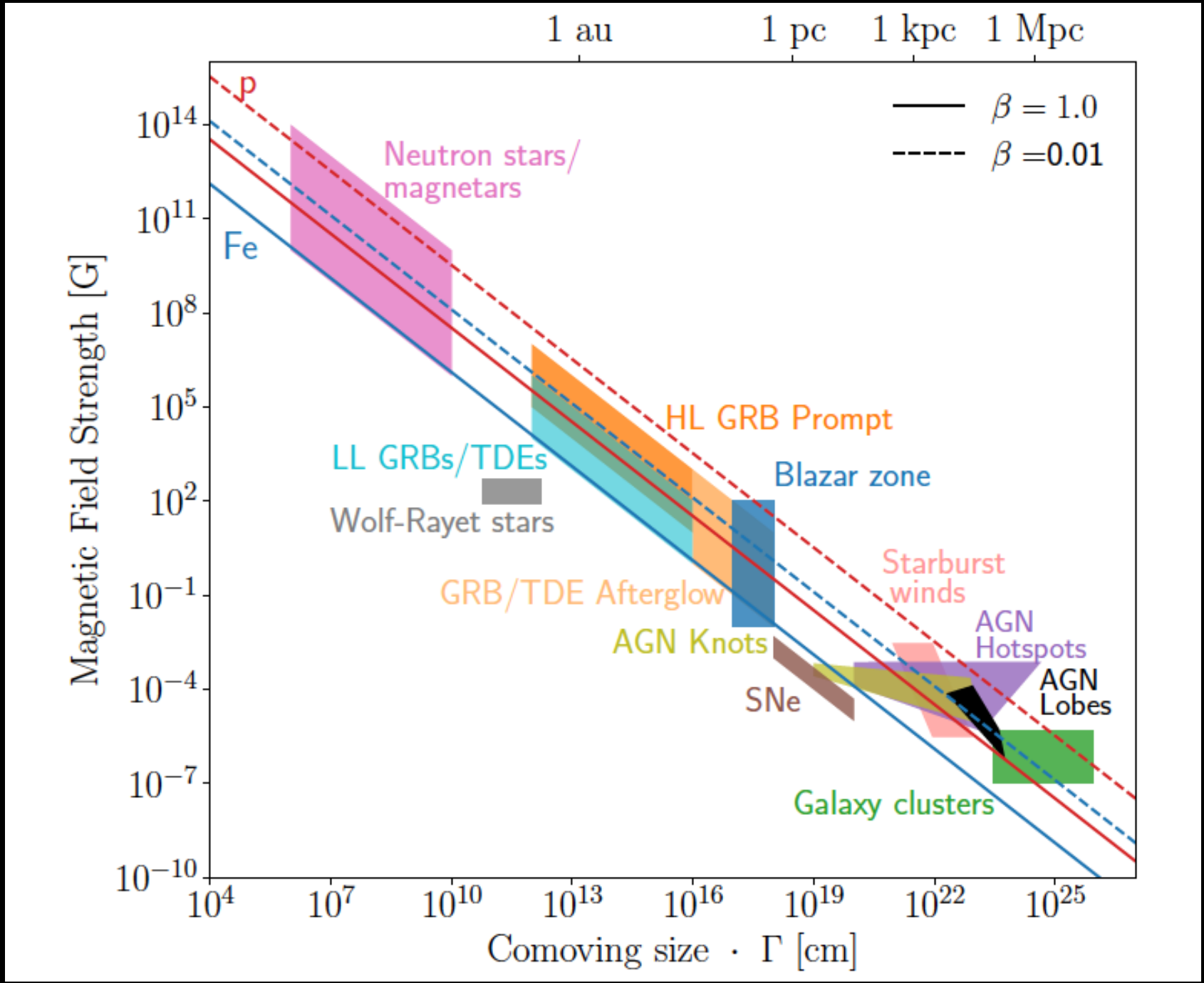
M87- AGN

Centaurus A – AGN

Sculptor Galaxy NGC 253

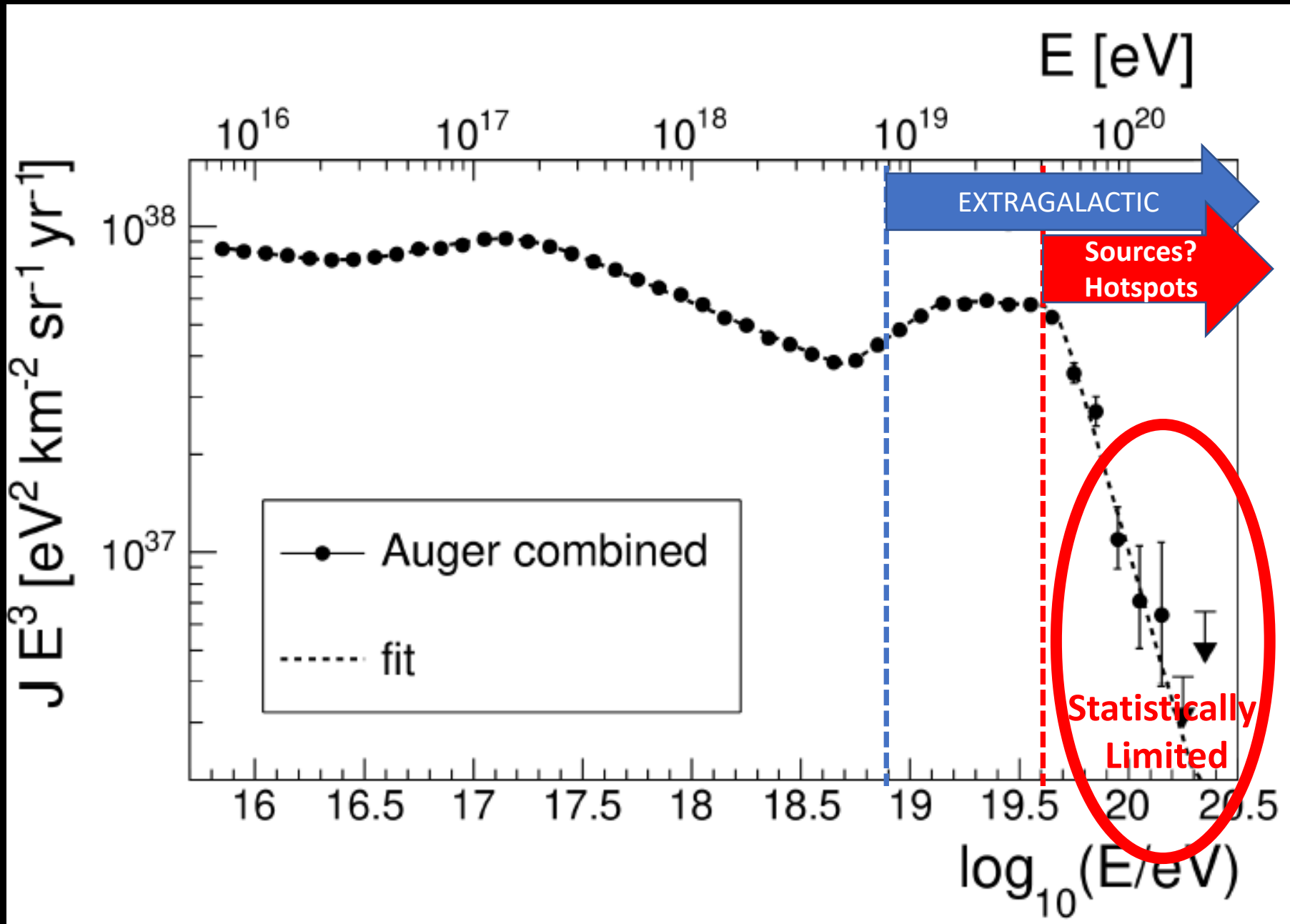


Event Horizon Telescope
Image of M87



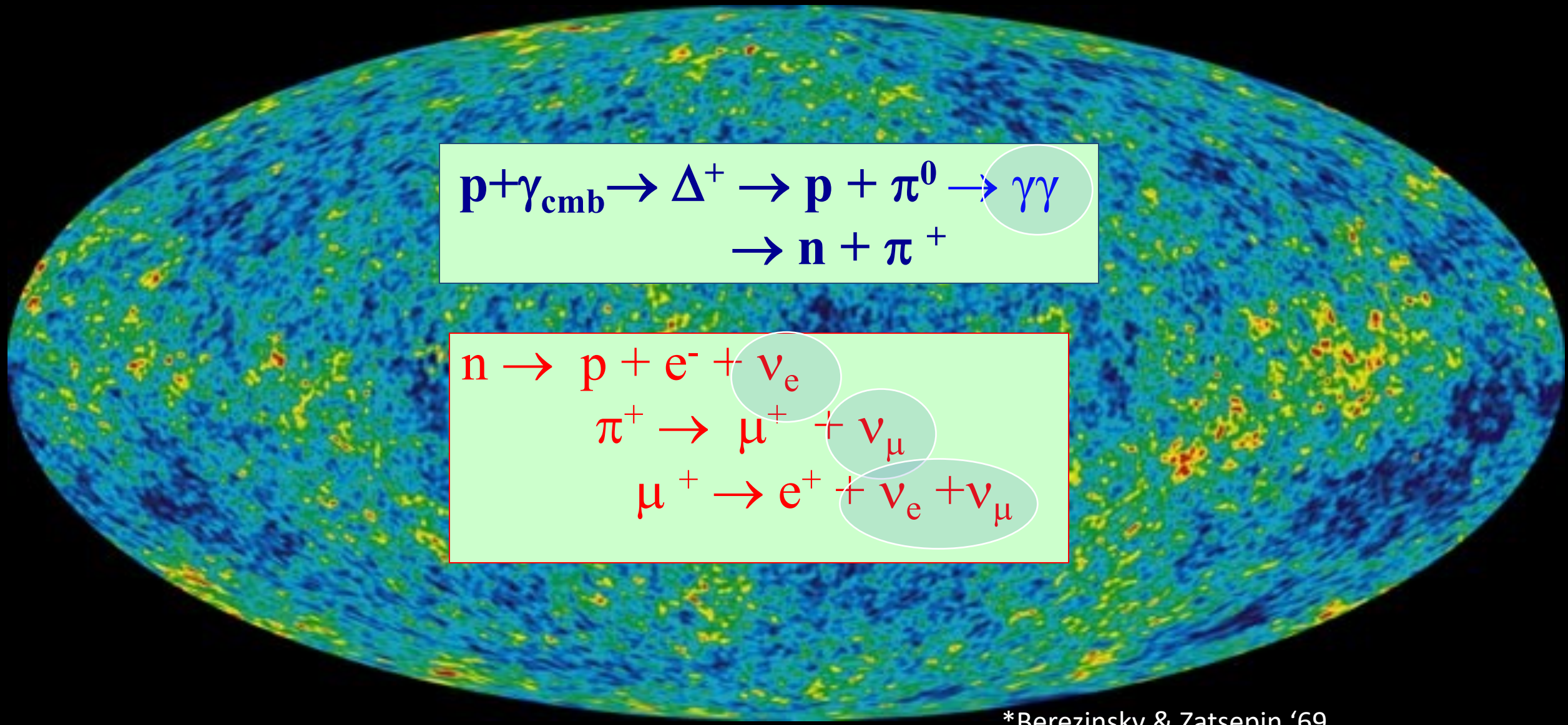
Coleman et al, 2022
arXiv:2205.05845

Auger Spectrum ICRC 2021



Where are the neutrino and gamma-ray secondaries?

Cosmogenic (GZK, BZ*) Neutrinos & Photons

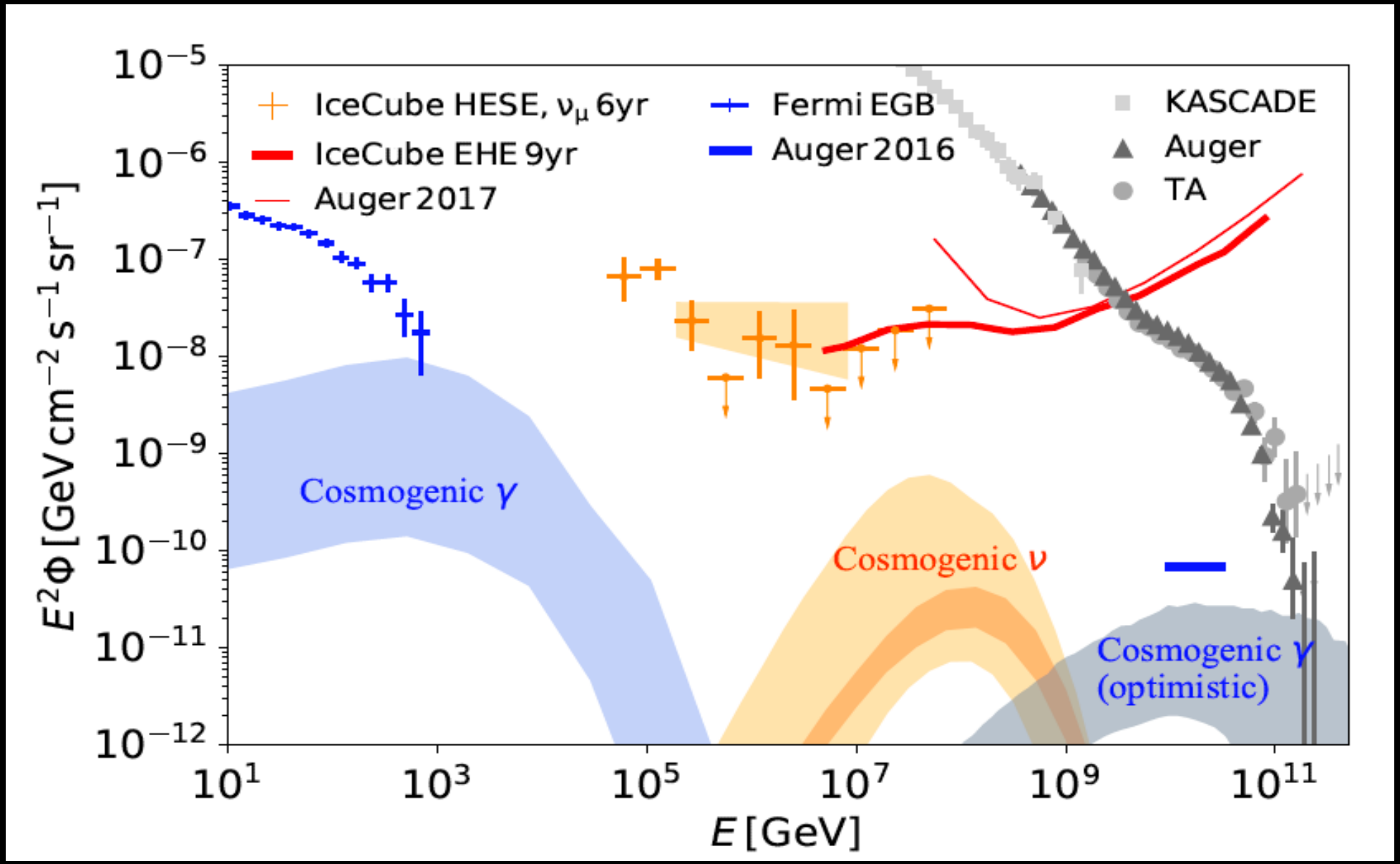


$$p + \gamma_{cmb} \rightarrow \Delta^{+} \rightarrow p + \pi^{0} \rightarrow \gamma\gamma$$
$$\rightarrow n + \pi^{+}$$

$$n \rightarrow p + e^{-} + \nu_e$$
$$\pi^{+} \rightarrow \mu^{+} + \nu_\mu$$
$$\mu^{+} \rightarrow e^{+} + \nu_e + \nu_\mu$$

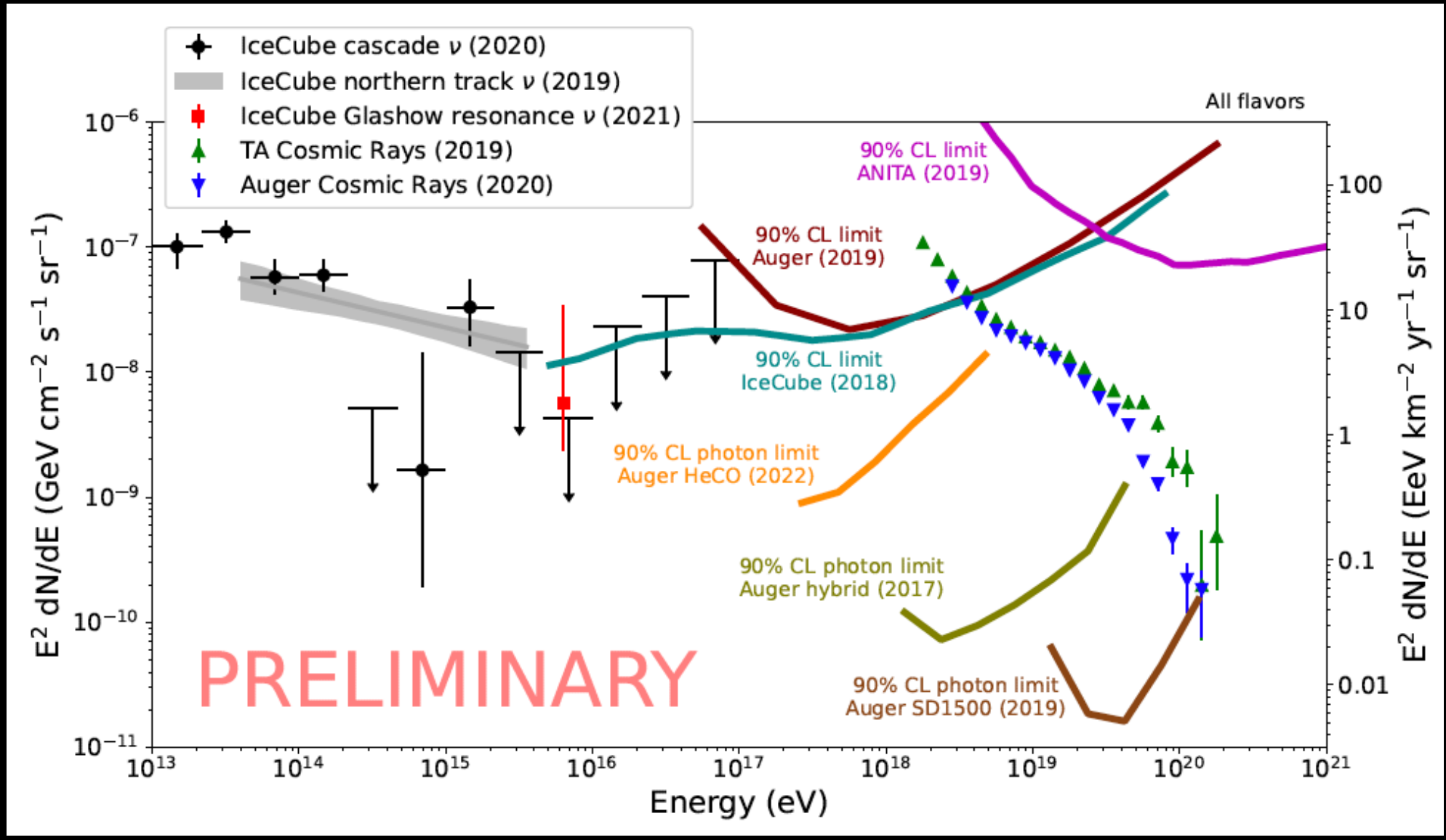
*Berezinsky & Zatsepin ‘69

Cosmogenic Messengers



Batista et al, arXiv:1903.06714.pdf

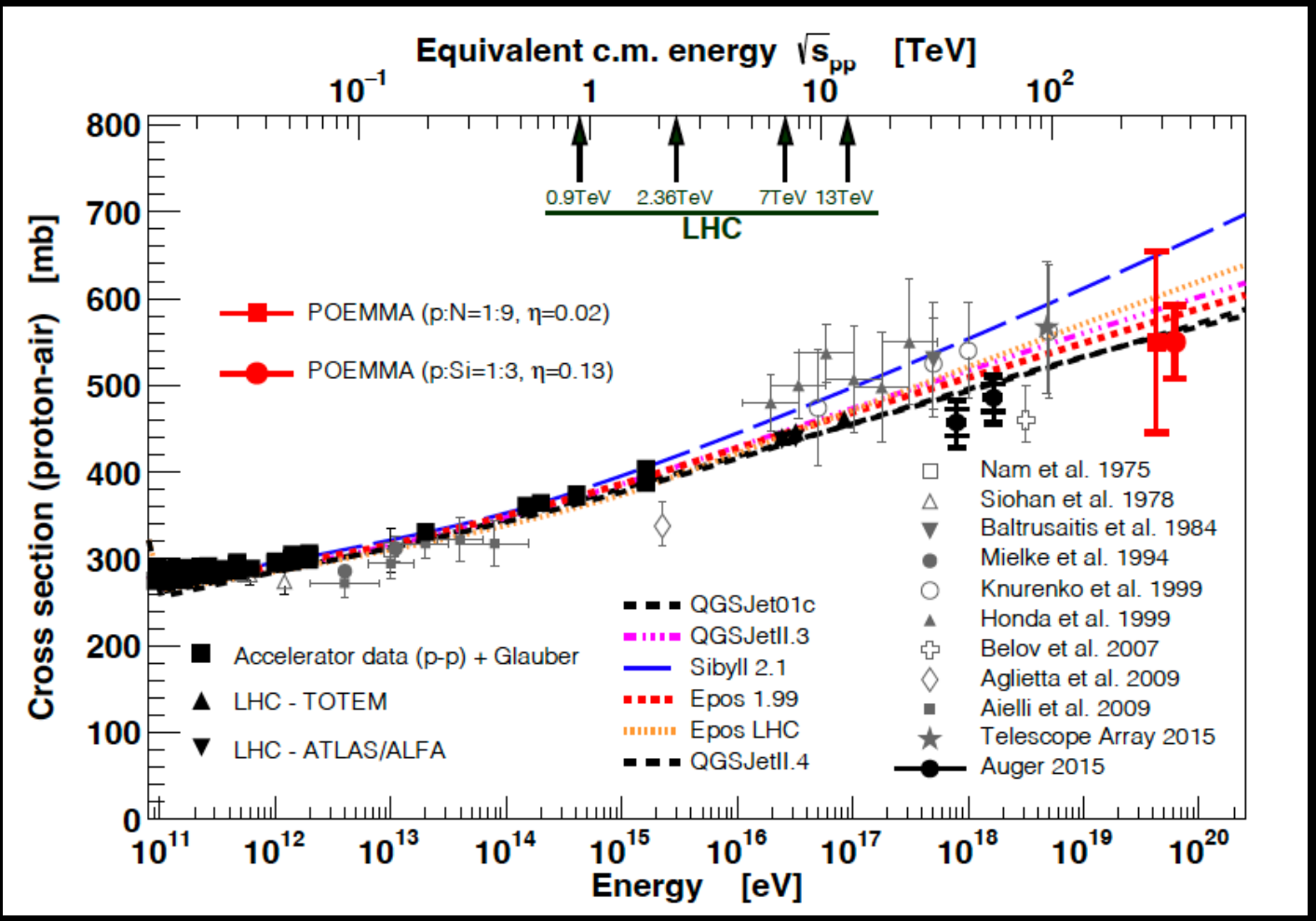
Limits on Neutrino and Gamma-Rays at UHE



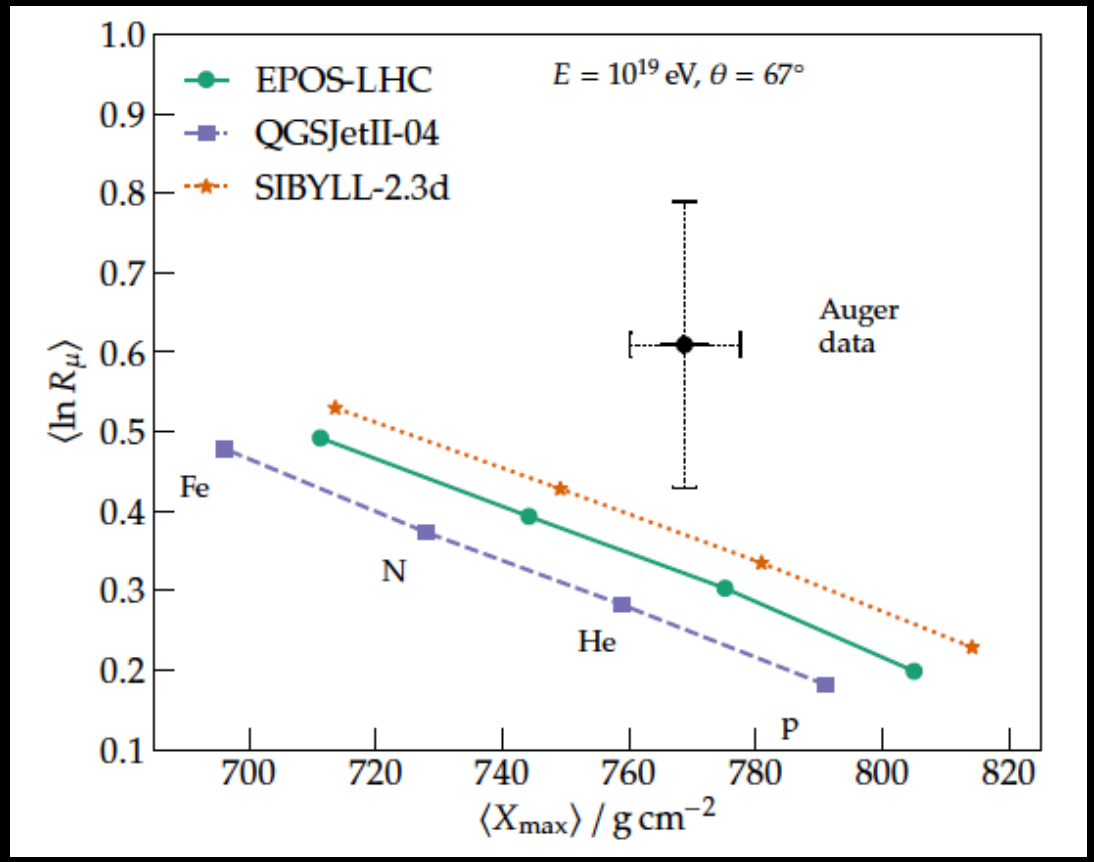
Coleman et al, 2022 arXiv:2205.05845

What physical processes do UHECRs probe?

Proton-Air cross section



Hadronic Interactions + muons in EASs



Future Outlook

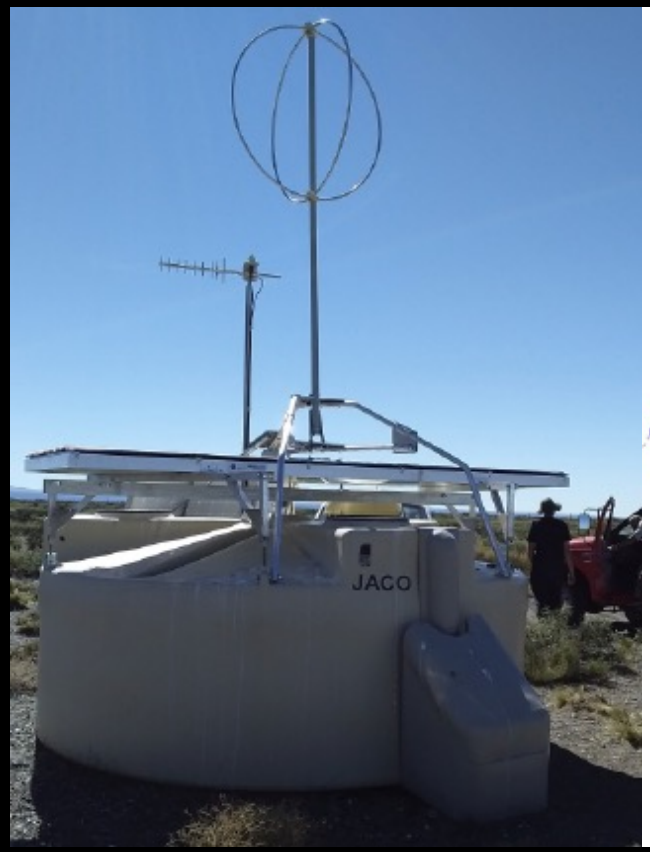
Experiment	Feature	Cosmic Ray Science*	Timeline
Pierre Auger Observatory	Hybrid array: fluorescence, surface e/μ + radio, 3000 km^2	Hadronic interactions, search for BSM, UHECR source populations, $\sigma_{\text{p-Air}}$	AugerPrime upgrade
Telescope Array (TA)	Hybrid array: fluorescence, surface scintillators, up to 3000 km^2	UHECR source populations proton-air cross section ($\sigma_{\text{p-Air}}$)	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, $\sigma_{\text{p-Air}}$	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, $\sigma_{\text{p-Air}}$	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, $\sigma_{\text{p-Air}}$	GCOS R&D + first site; GCOS further sites

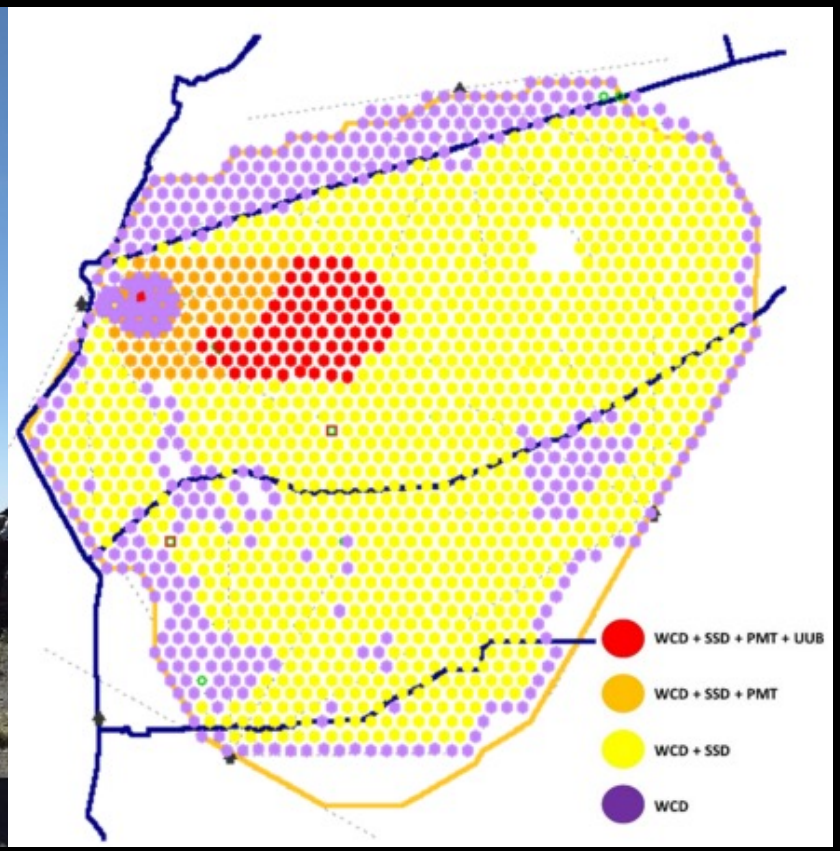
2025 2030 2035 2040

*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.

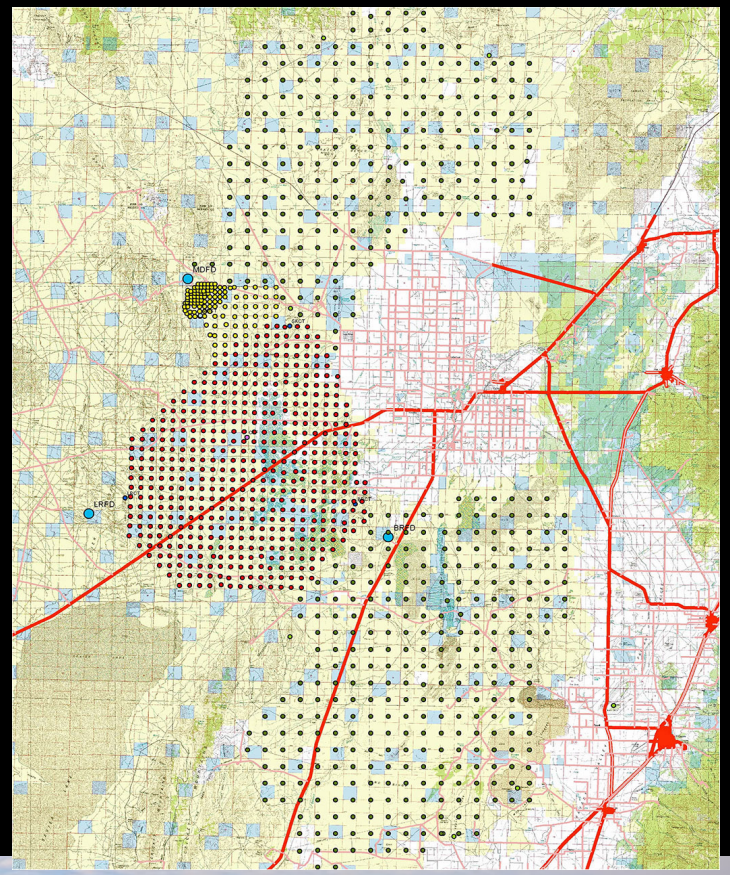
Coleman et al, Snowmass, arXiv:2205.05845

AugerPrime





TAx4



IceCube-Gen2

IceCube Upgrade (planned 2023-)

Optimized for

- GeV neutrinos
- Calibration of the IceCube detector

IceCube (2005-)

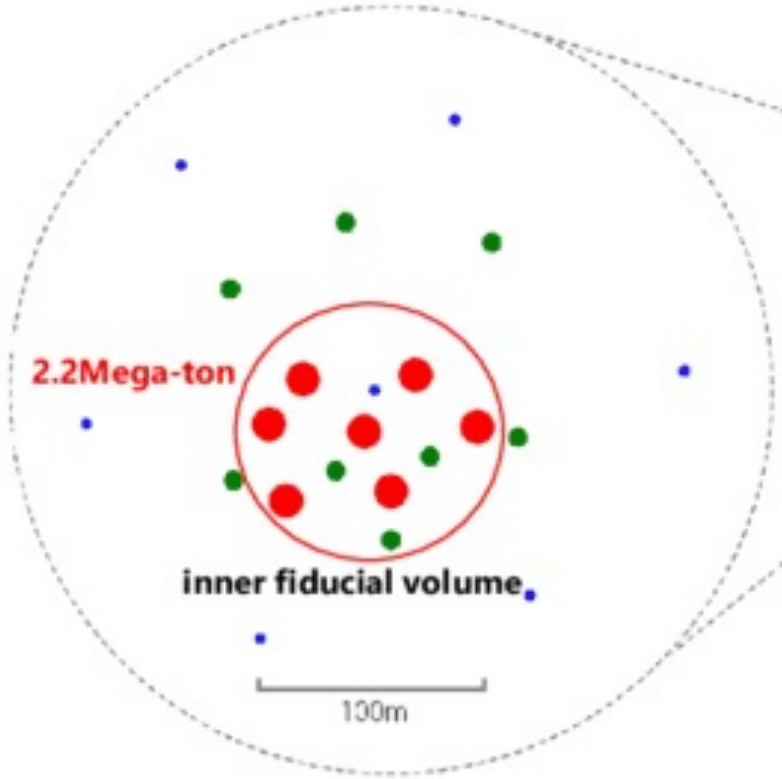
Optimized for

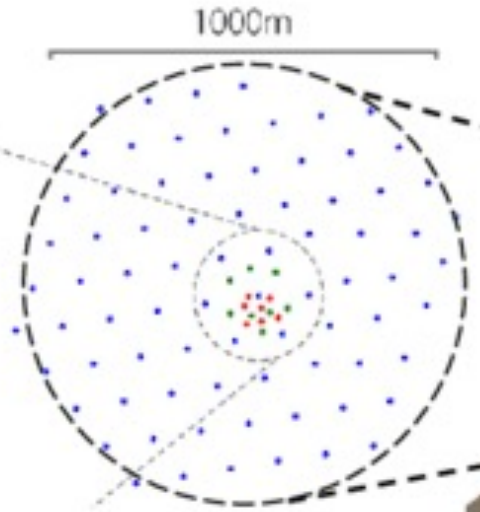
- Diffuse high energy cosmic neutrinos

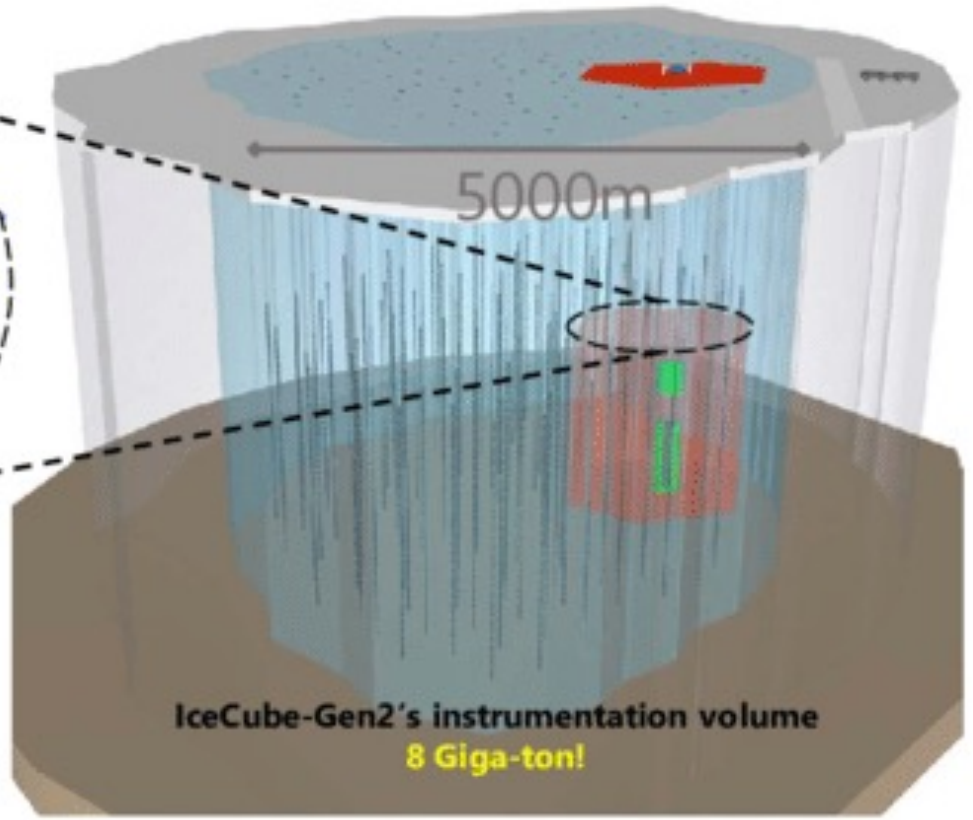
IceCube-Gen2 (planned 2026-)

Optimized for

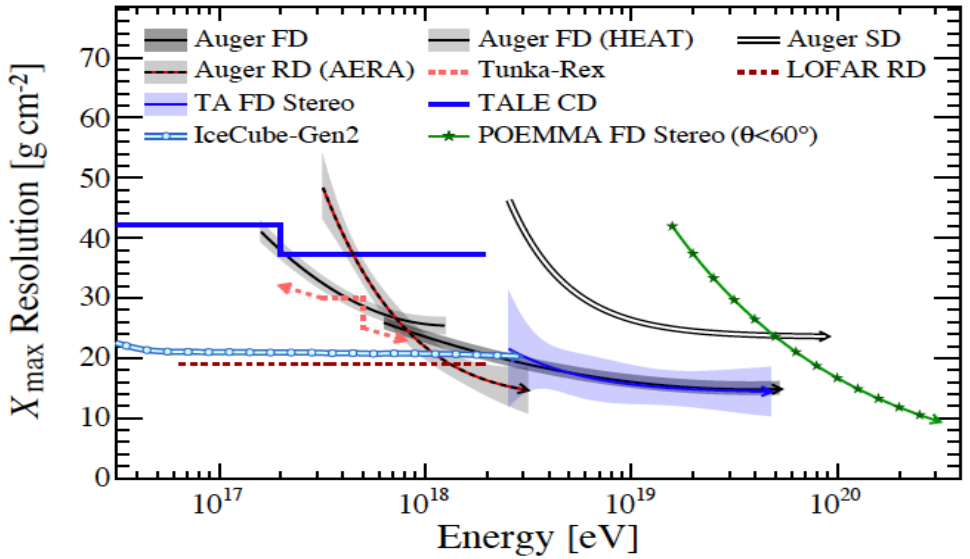
- Cosmic neutrino point sources

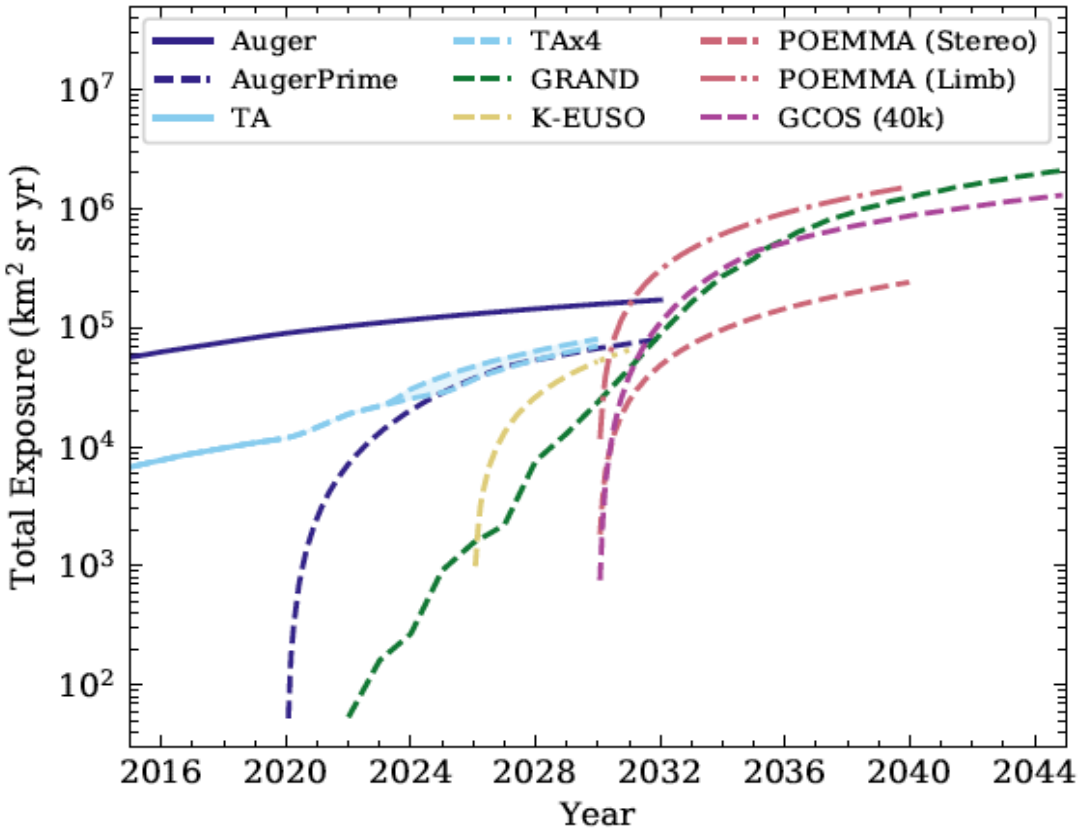


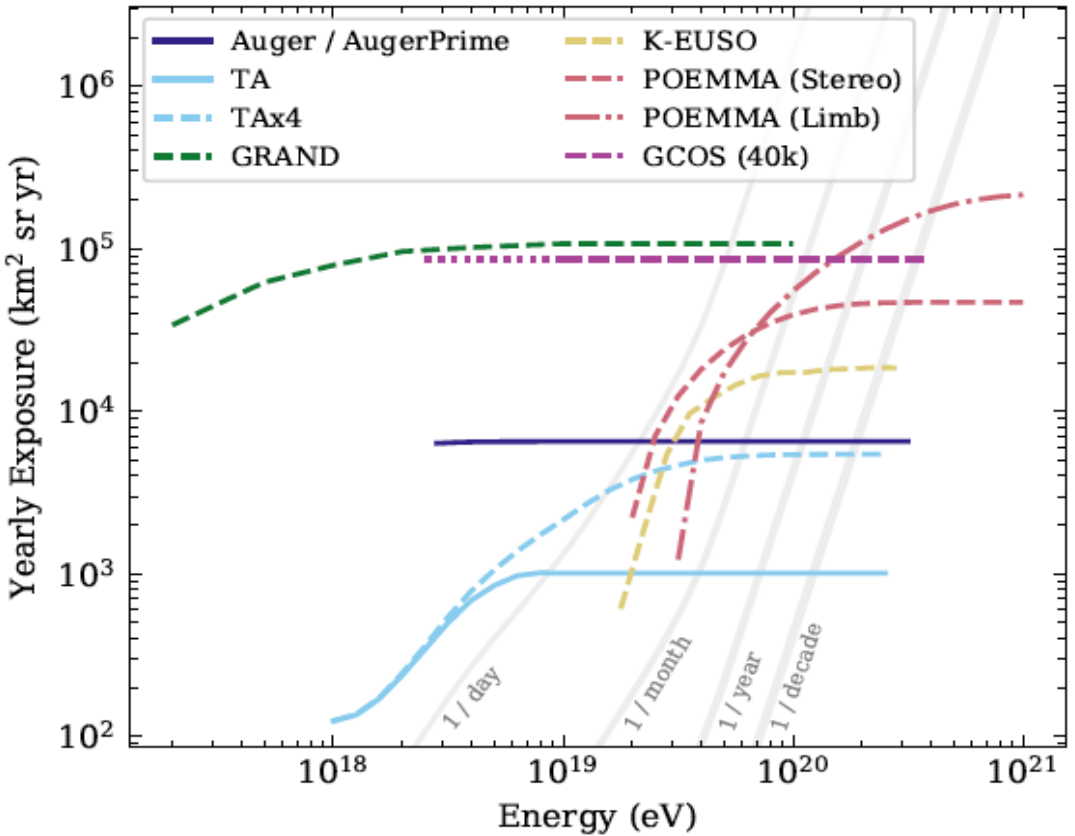


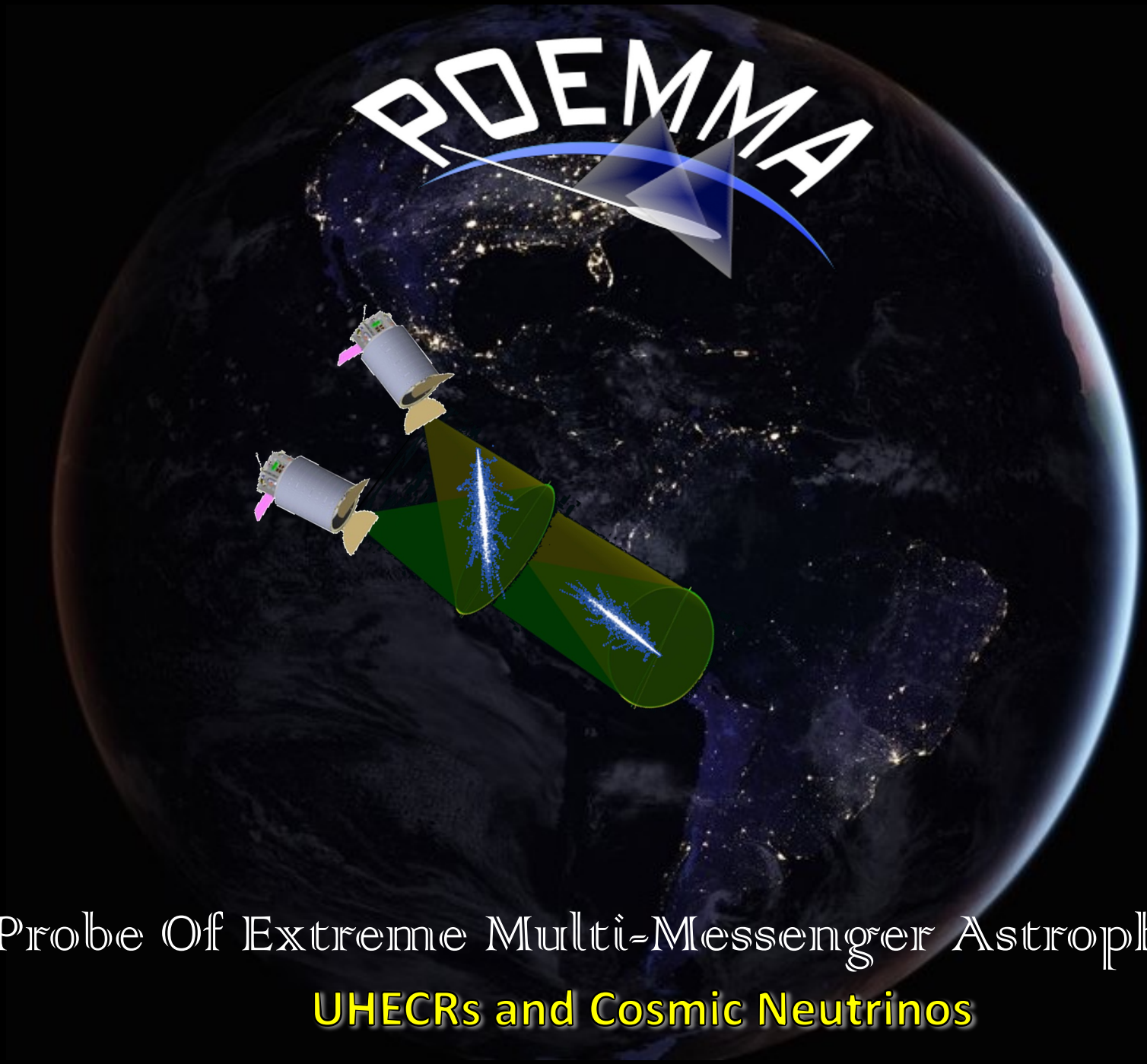


Future Outlook



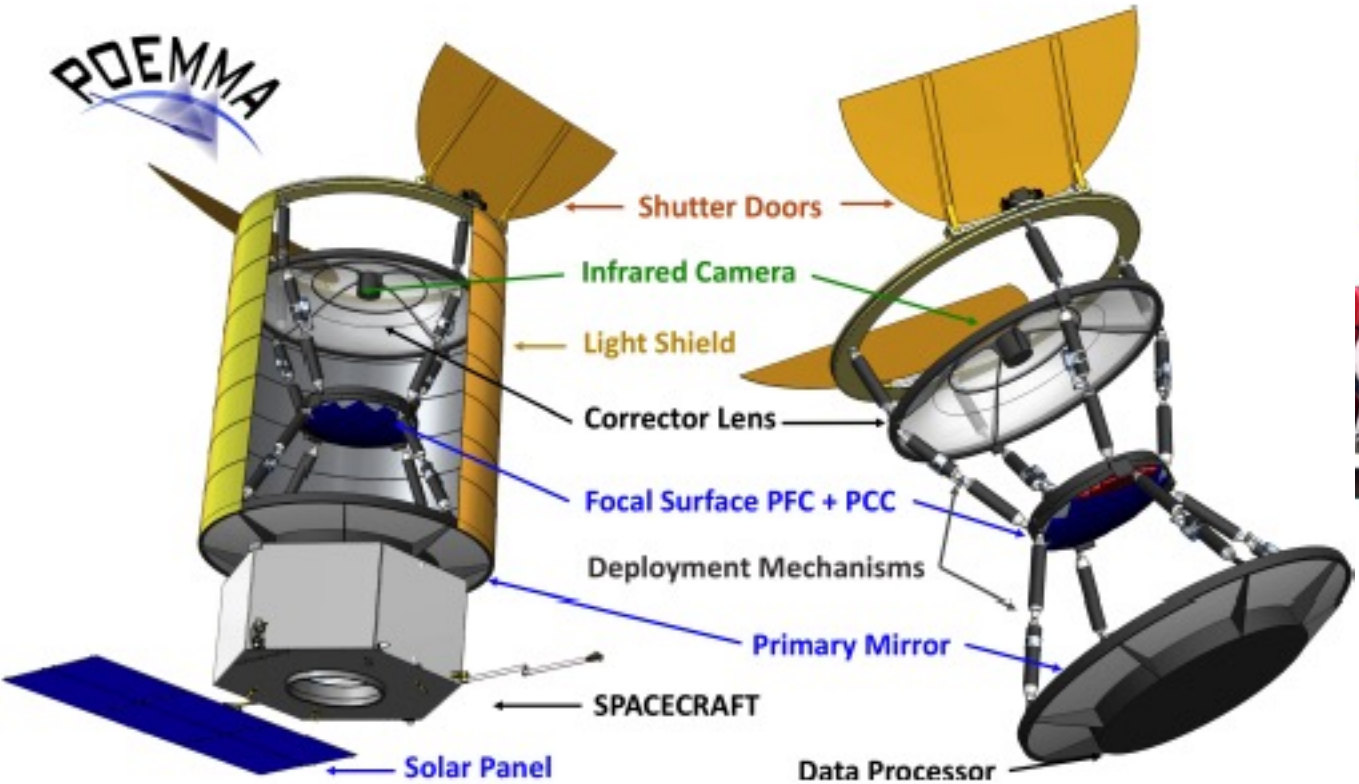




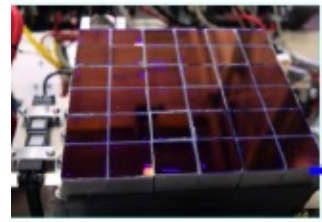


Probe Of Extreme Multi-Messenger Astrophysics

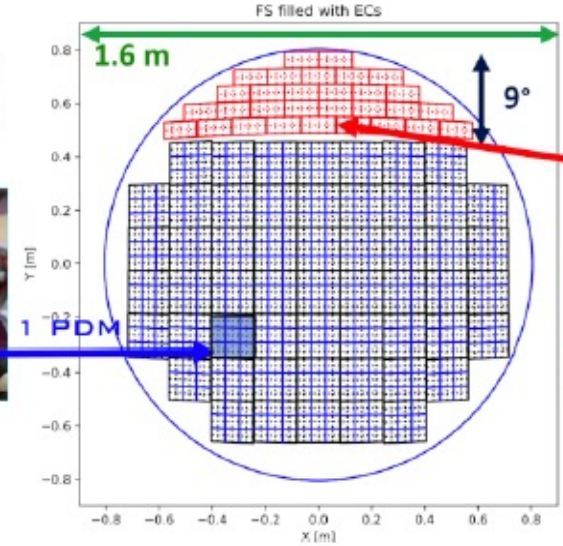
UHECRs and Cosmic Neutrinos



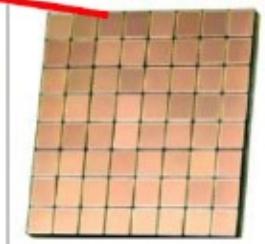
PFC: POEMMA Fluorescence Camera



MAPMTs

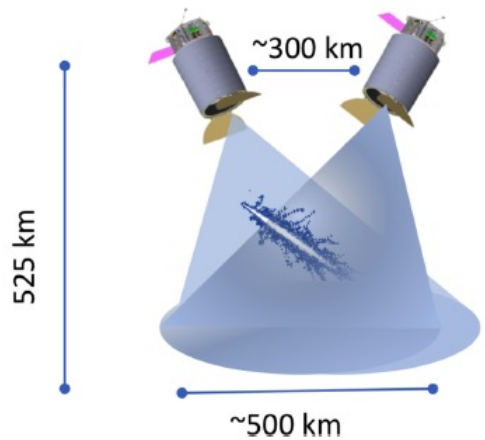


PCC: POEMMA Cherenkov Camera

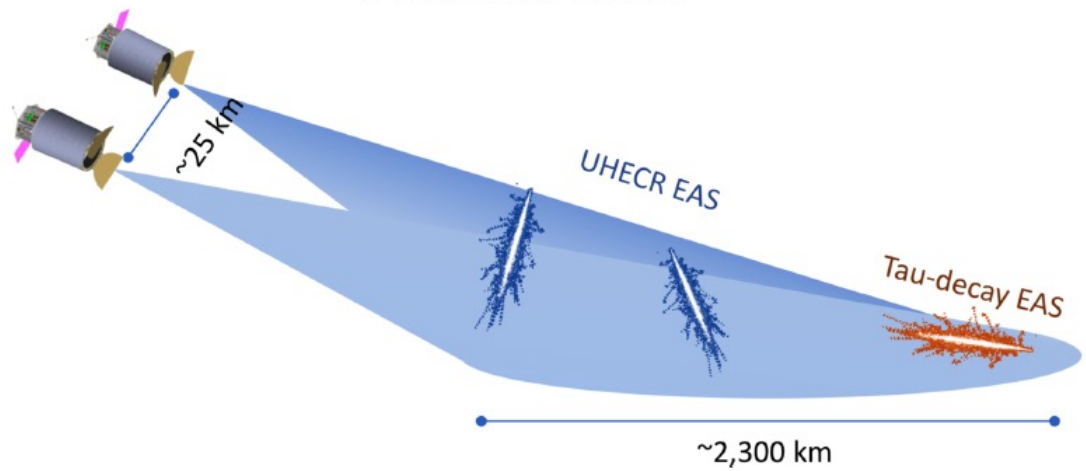


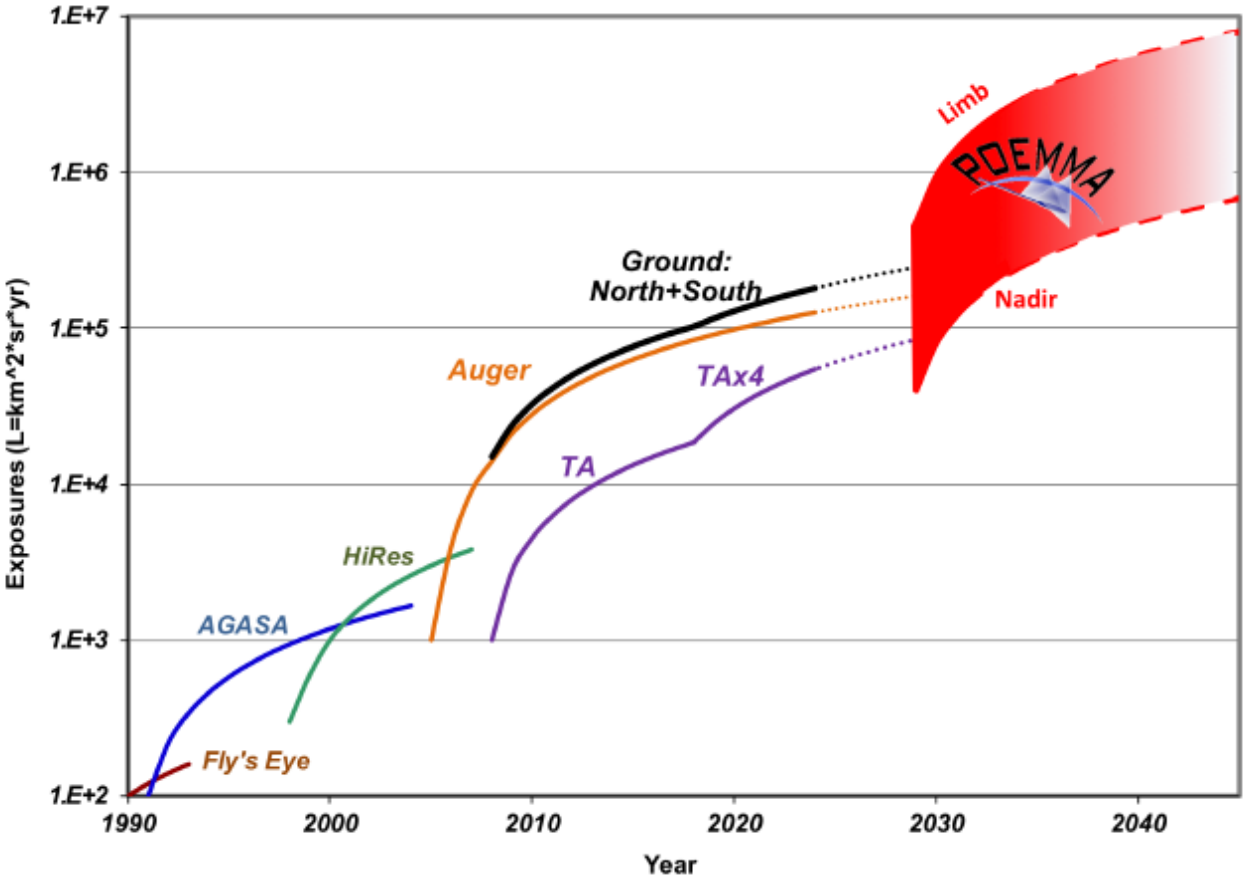
SiPMs

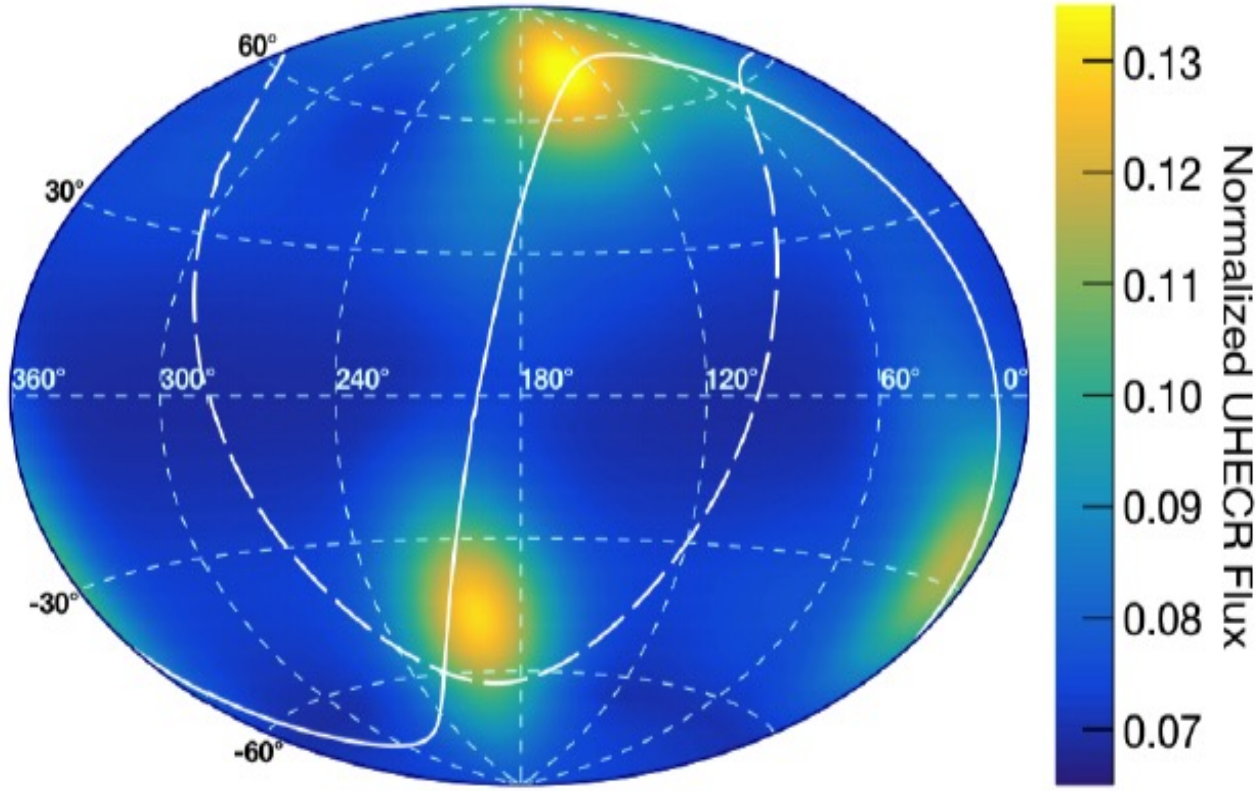
POEMMA-Stereo



POEMMA-Limb

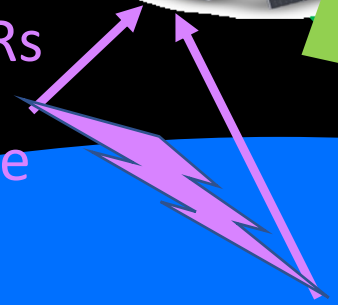


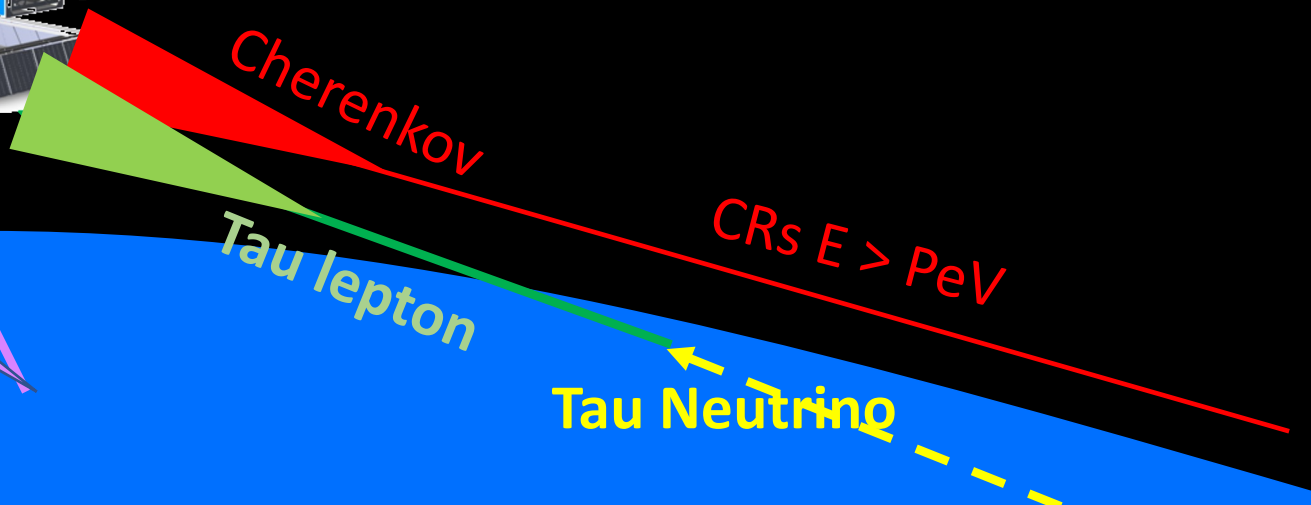

1.E+7
1.E+6
1.E+5
1.E+4
1.E+3
1.E+2
Exposures (L=km^2*sr*yr)
1990
2000
2010
2020
2030
2040
Year
Limb
POEMMA
Nadir
Ground:
North+South
Auger
TAx4
TA
HiRes
AGASA
Fly's Eye


60°
30°
360°
300°
240°
180°
120°
60°
0°
-30°
-60°
0.13
0.12
0.11
0.10
0.09
0.08
0.07
Normalized UHECR Flux

EUSO-SPB2
2023 flight

Fluorescence from UHECRS
Cherenkov Emission from UHECRs
Tau Neutrino Events

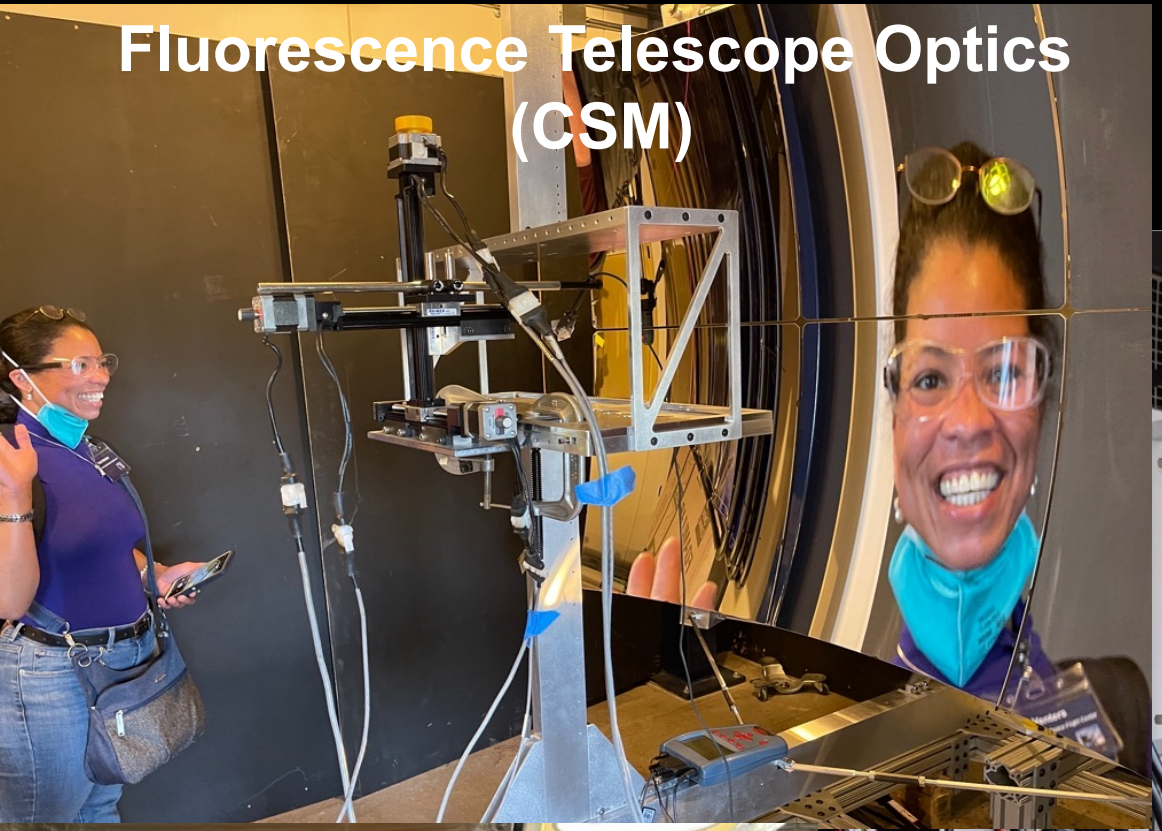




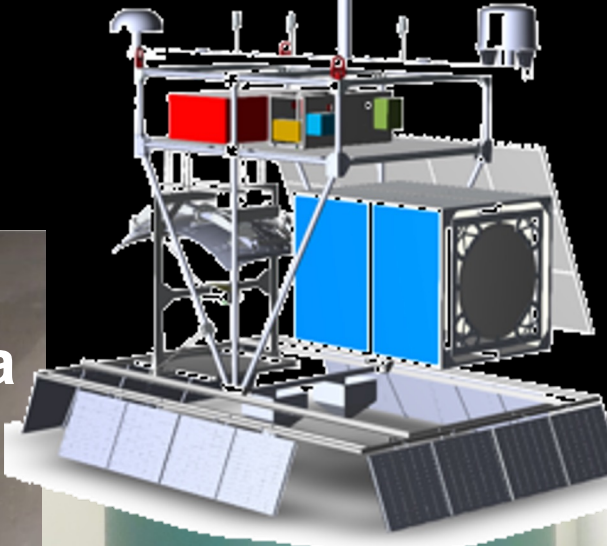
Science Results:

- Fluorescence from ~30 UHECRS
- CR spectrum from 10^{15} eV to **10^{17}eV**
- 2 Tau Neutrino candidates from GW230423
- Constraints on ANITONs

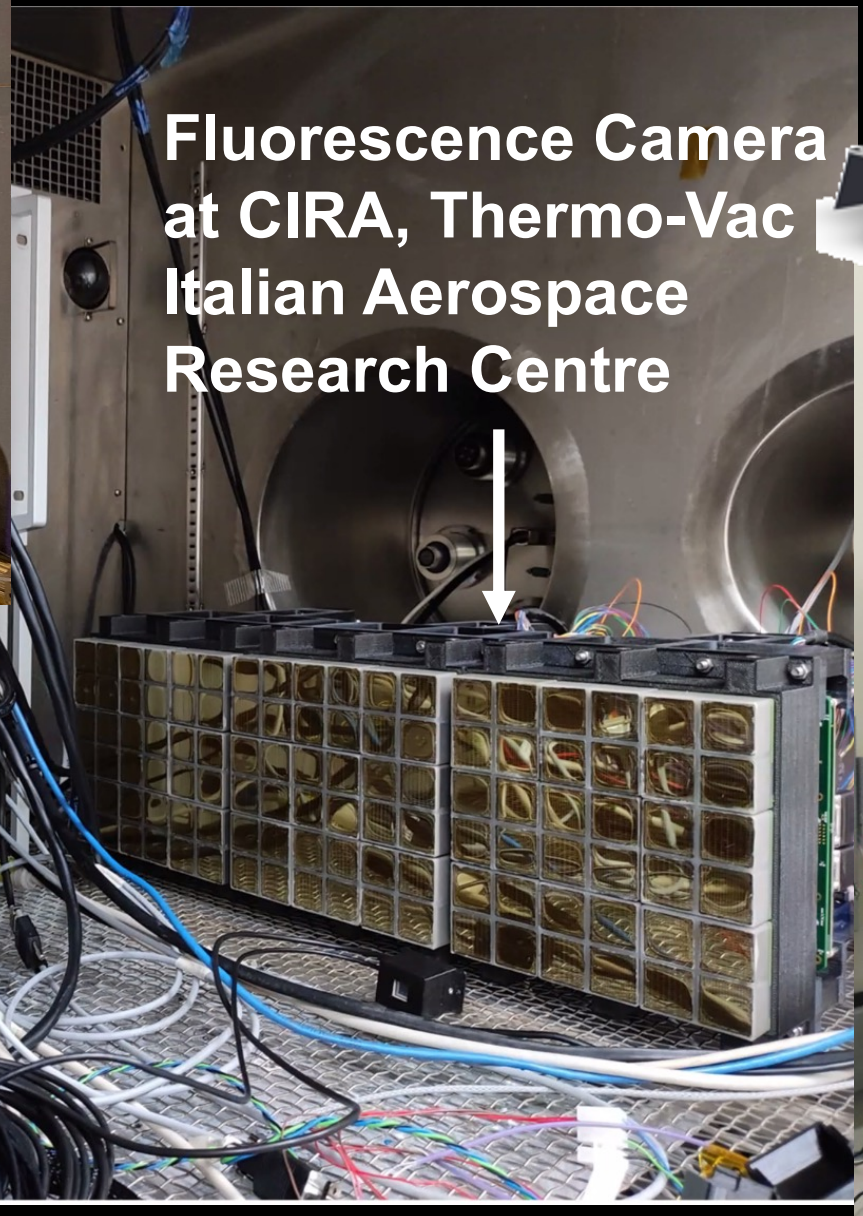
Fluorescence Telescope Optics (CSM)



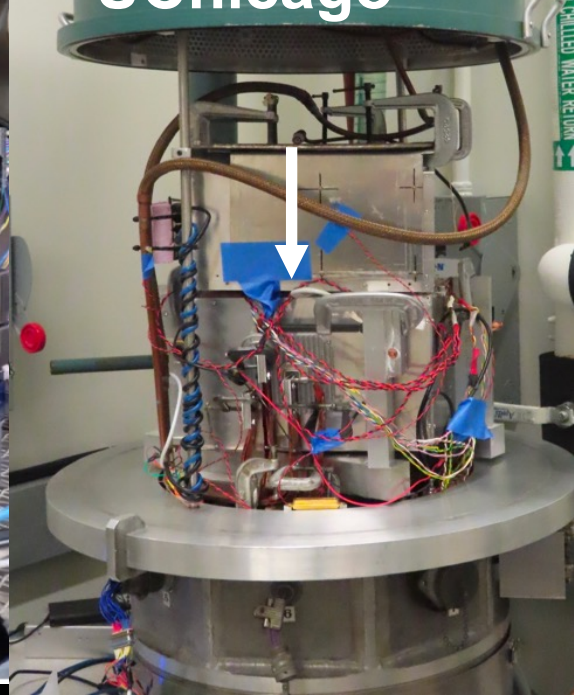
JEM-EUSO Collaboration Meeting
June 2022



Fluorescence Camera at CIRA, Thermo-Vac Italian Aerospace Research Centre



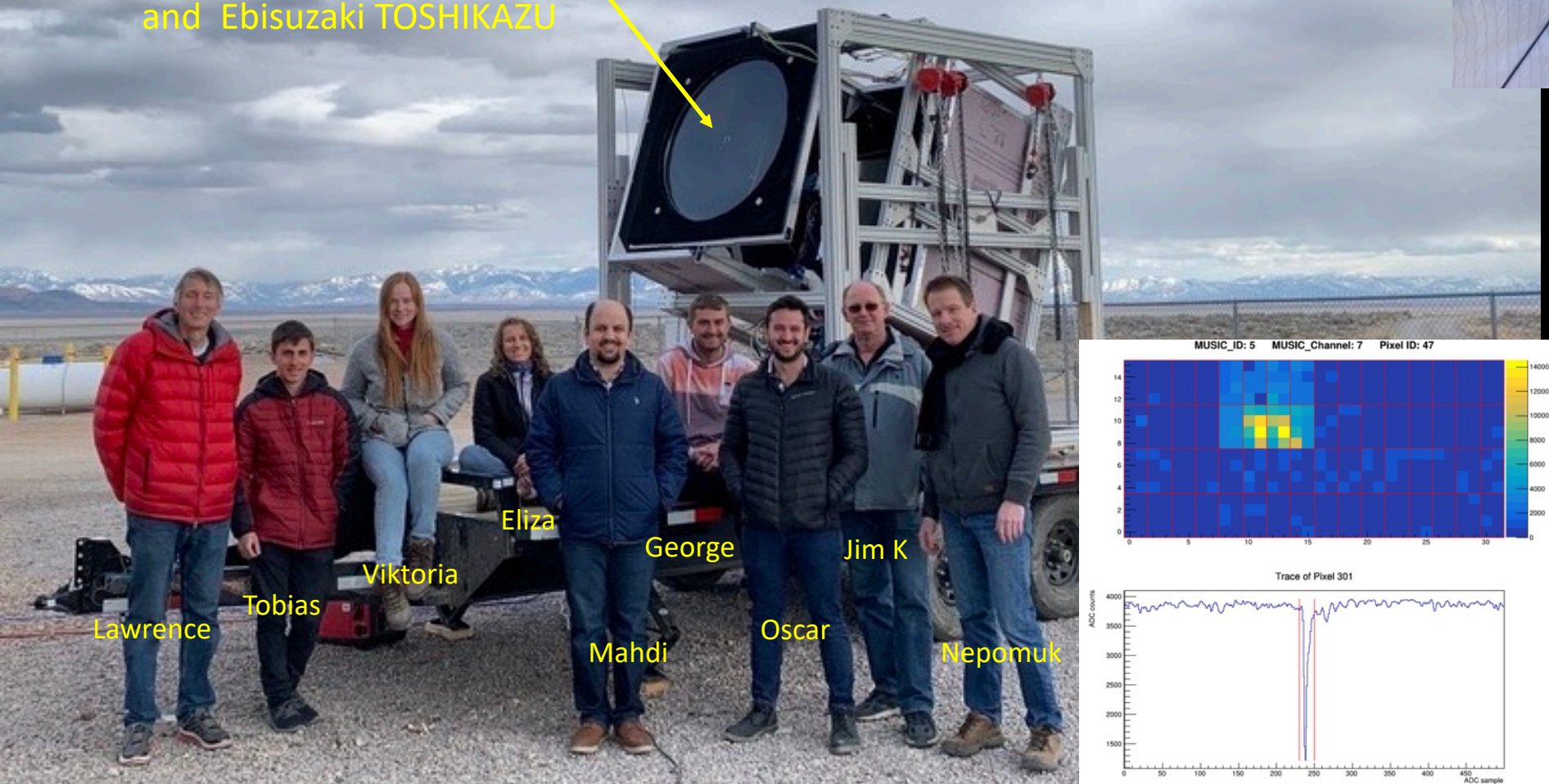
Infrared Camera In Thermo Vac UChicago

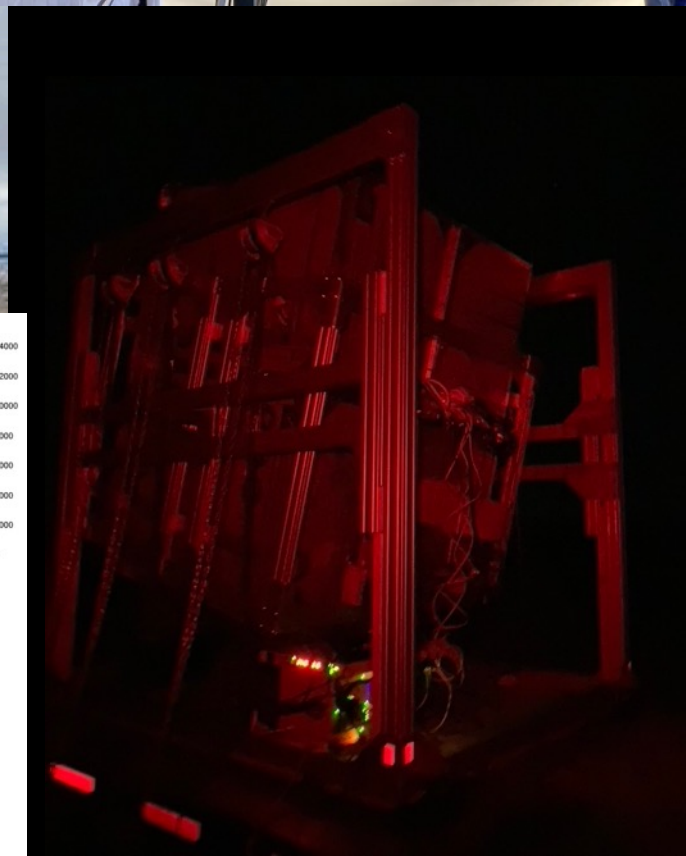


Laser Filed Tests (CSM)

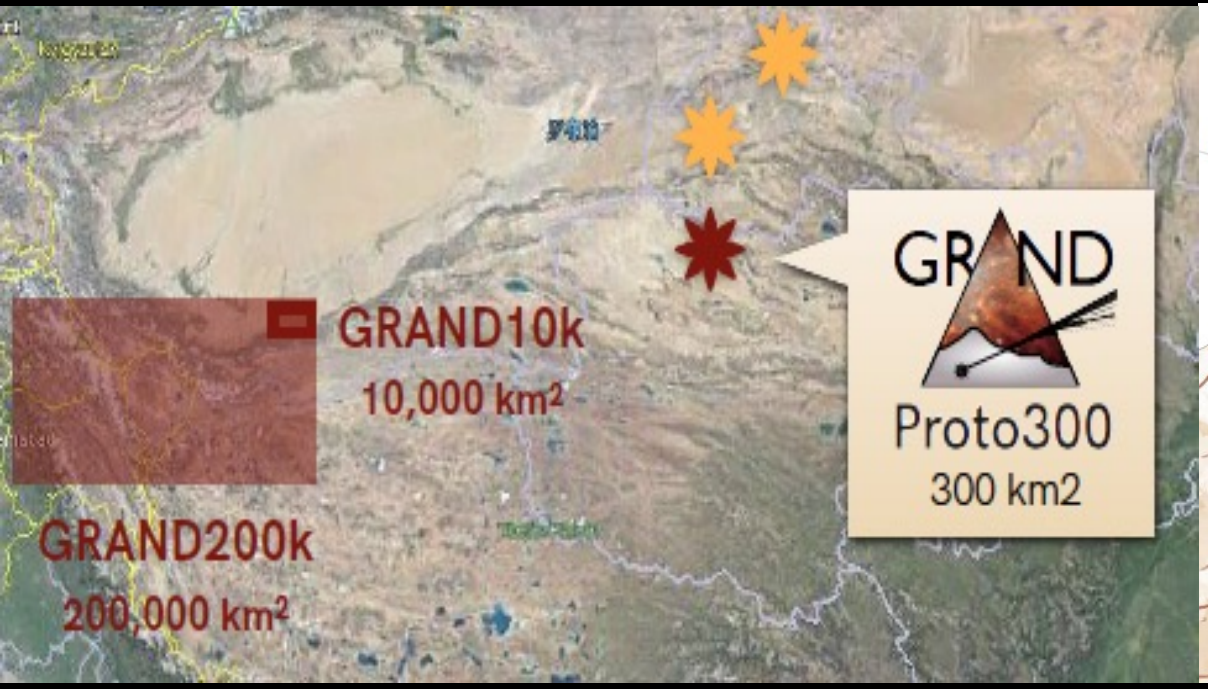
Field Test of the Cherenkov Telescope
Telescope Array site in Utah
March 2022

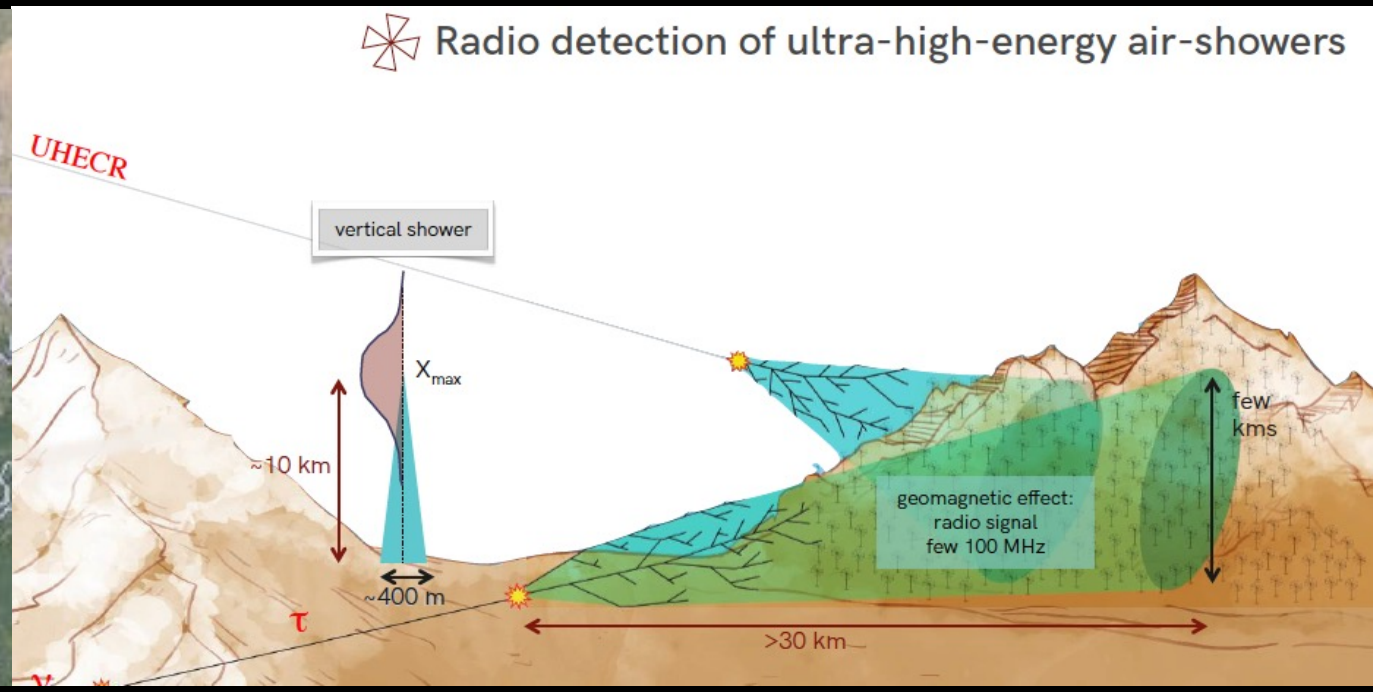
Produced at RIKEN
under Yoshiyuki TAKIZAWA
and Ebisuzaki TOSHIKAZU





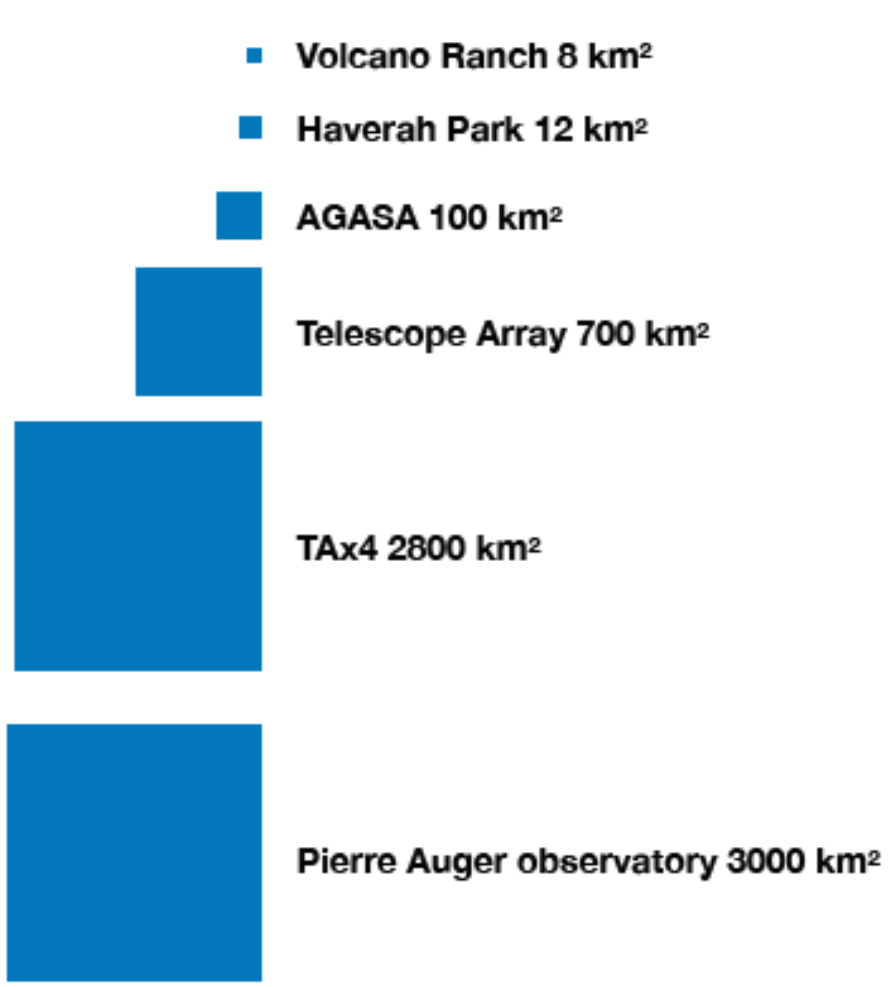
Giant Radio Array for Neutrino Detection (GRAND)

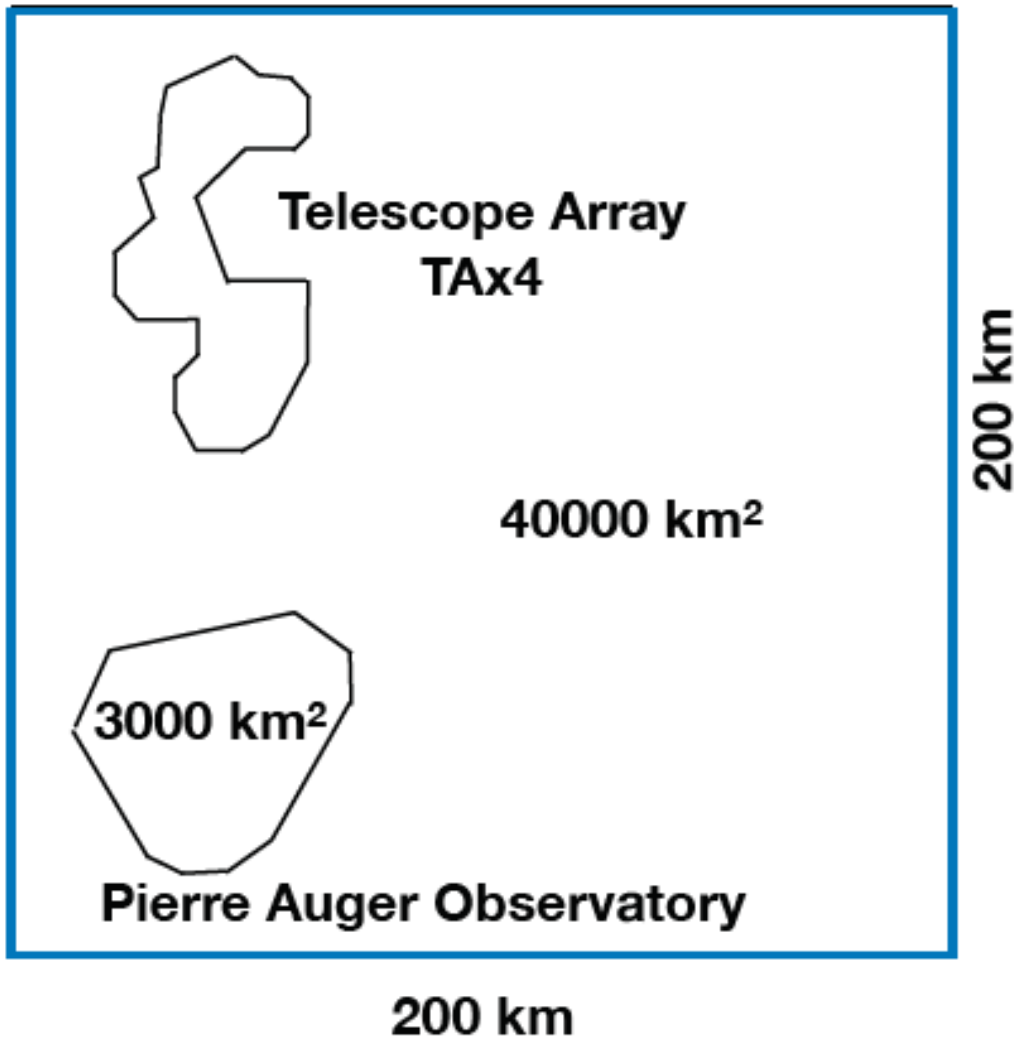




GRANDProto300	GRAND10k	GRAND200k
2022	2025	203X

Global Cosmic Ray Observatory (GCOS)





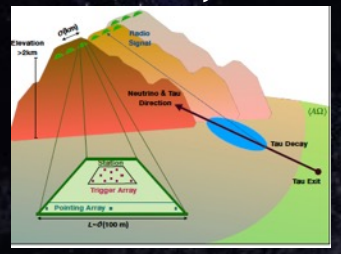
Future detectors of UHE CRs and Neutrinos

Future Looks Brigth!

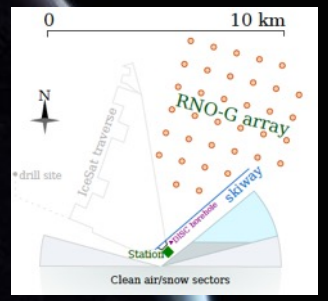
GRAND

Giant Radio Array for Neutrino Detection

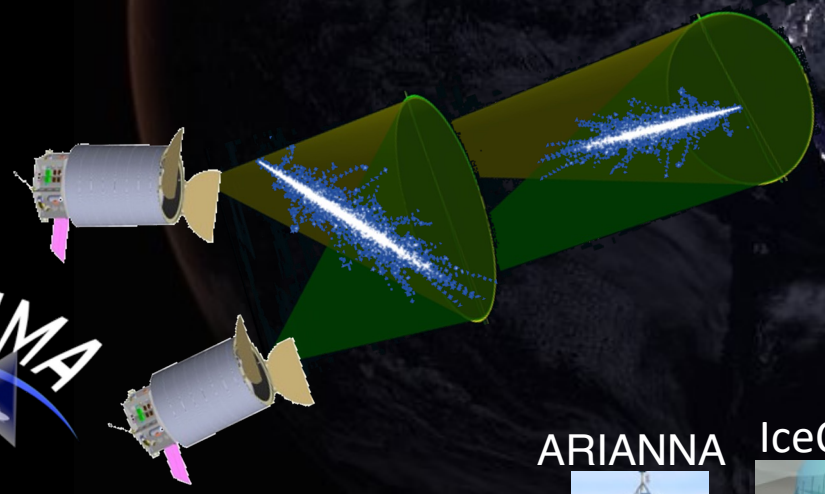
BEACON, Trinity, AshraNTA, TAROGE



RNO-G

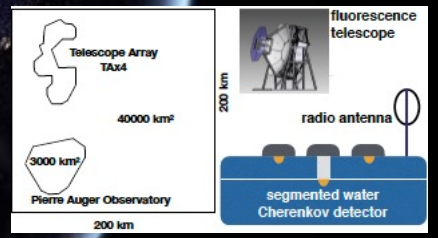


ZAP



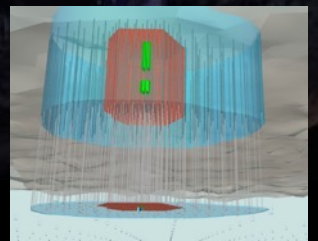
POEMMA

GCRO



ARIANNA

IceCube-Gen2

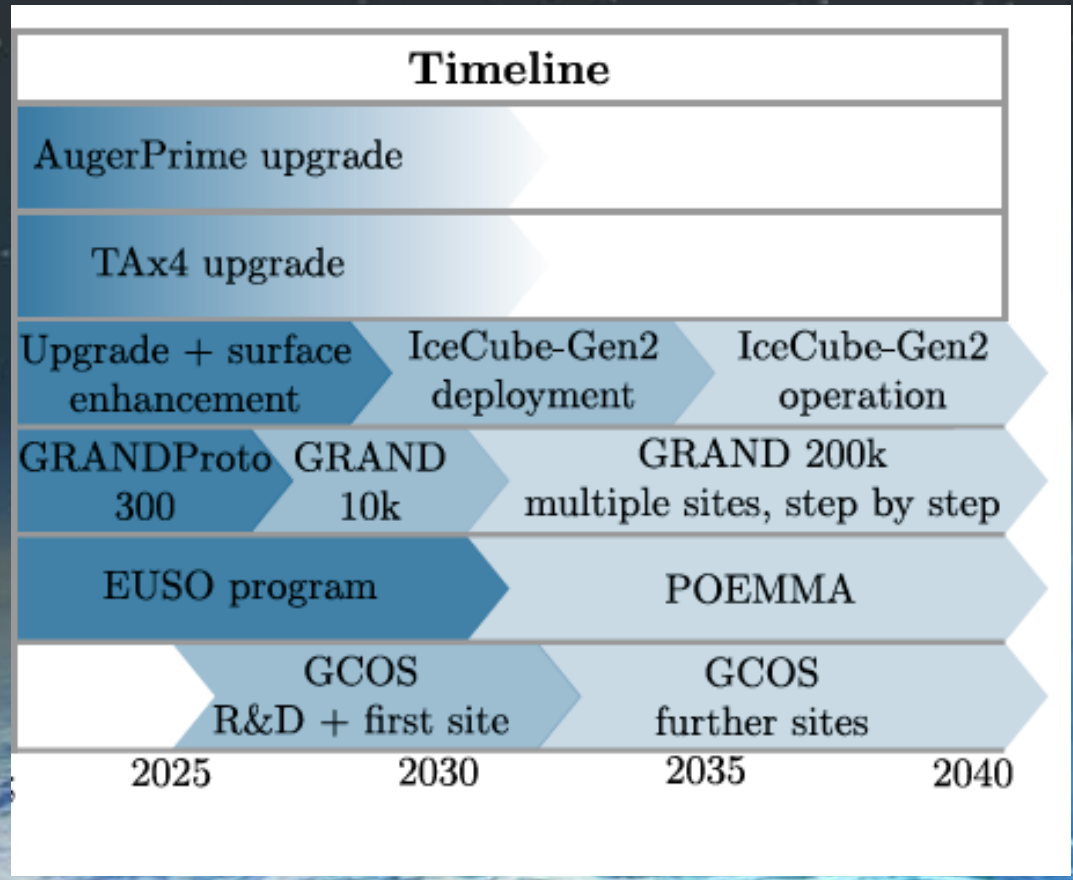


Gràcies

Y

Gracias

Future Outlook



Gràcies

Y

Gracias

NASA WANAKA Campaigns

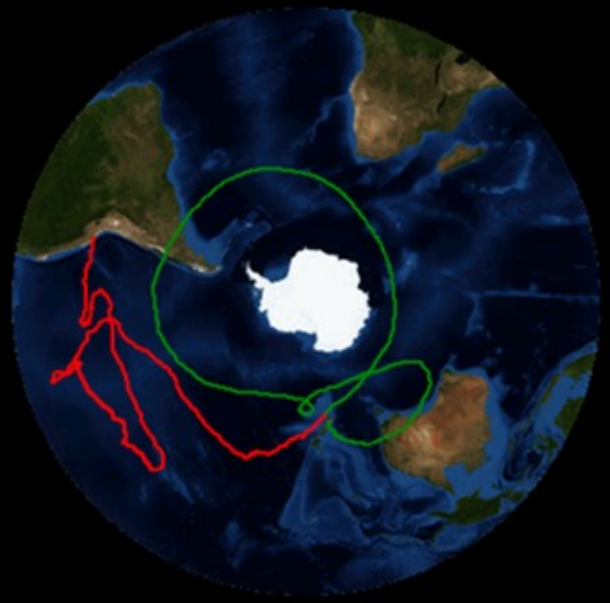
Super Pressure Balloon (SPB)

EUSO mission 2017 & 2023

2015
NASA **Engineering** Flight

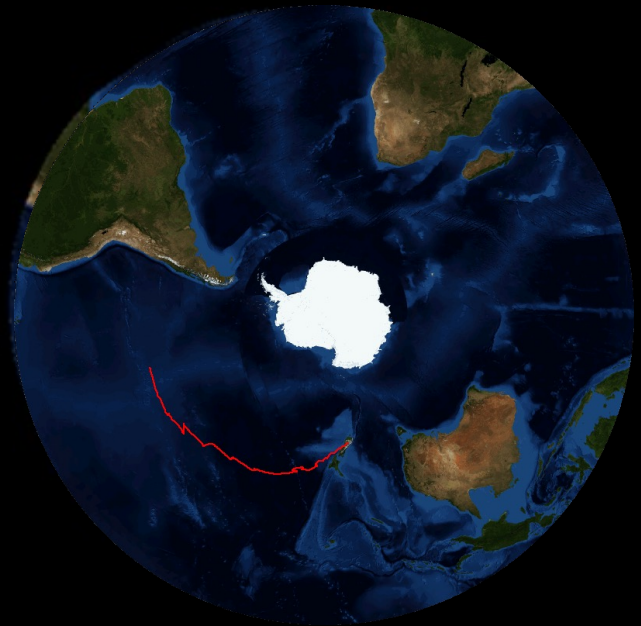
32 d 5 h

2016
COSI



46 d 20 h

2017
EUSO-SPB



12 d 4 h

2023
EUSO-SPB2

100 d!!!

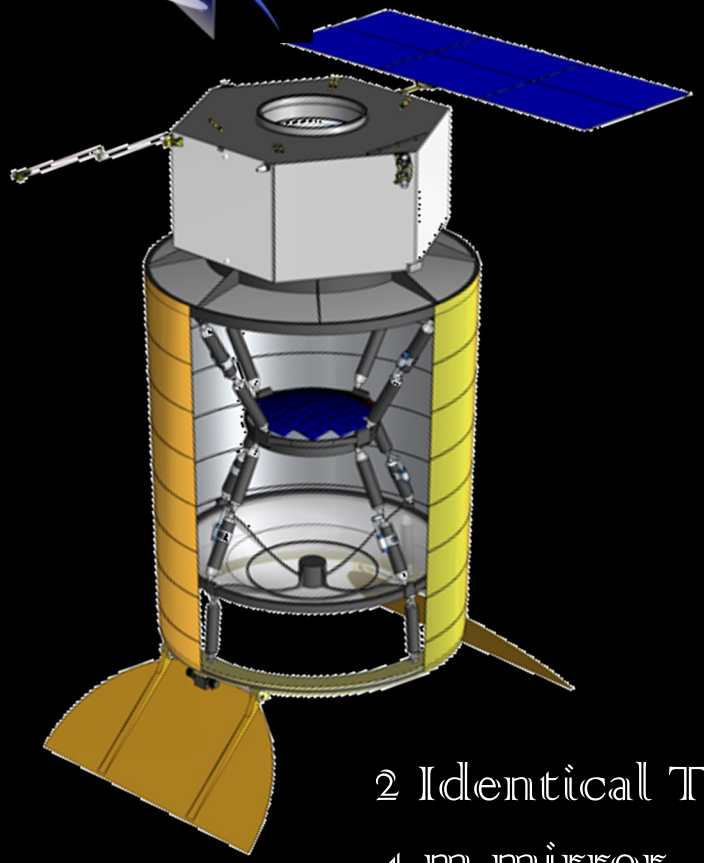
EUSO-SPB 1

launch, April 24, 2017

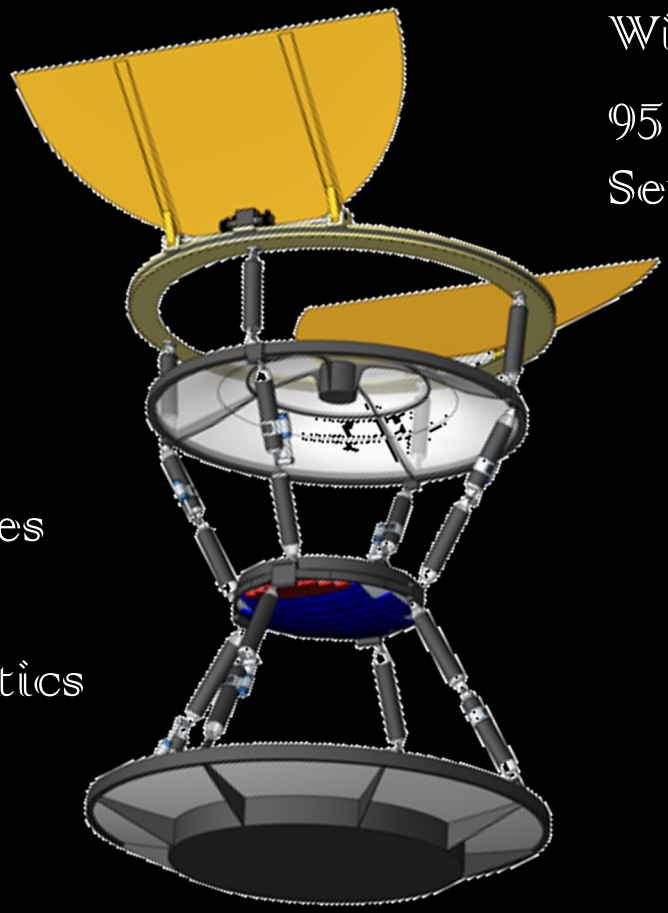
23:51 UTC

POEMMA at NASA-GSFC

Instrument and Mission Design in 2017-2019



2 Identical Telescopes
4 m mirror
45° FoV Schmidt Optics
1,550 kg mass
590 W power
Data 1 GB/day



5yr Mission
Alt 525 km
Wide28.50 Inclination
95 min orbits
Separation 100s km