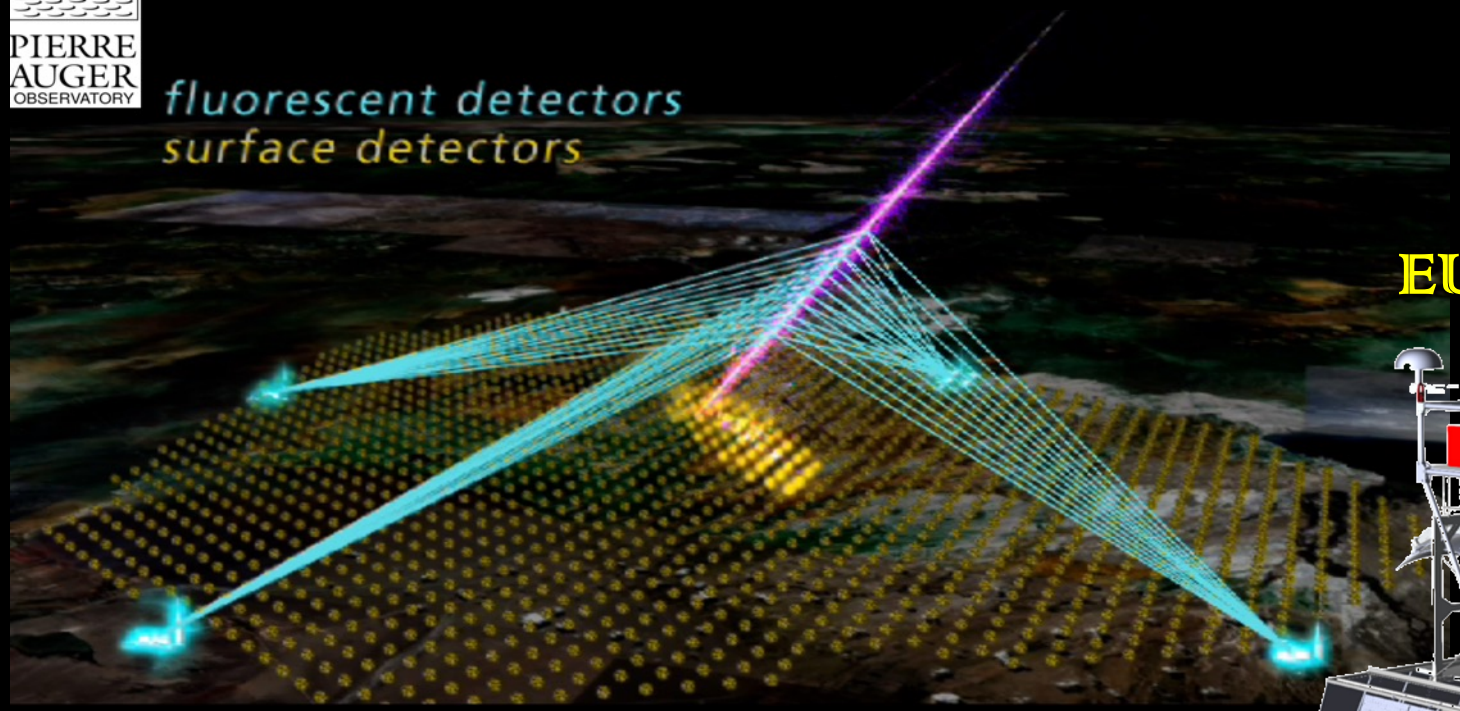
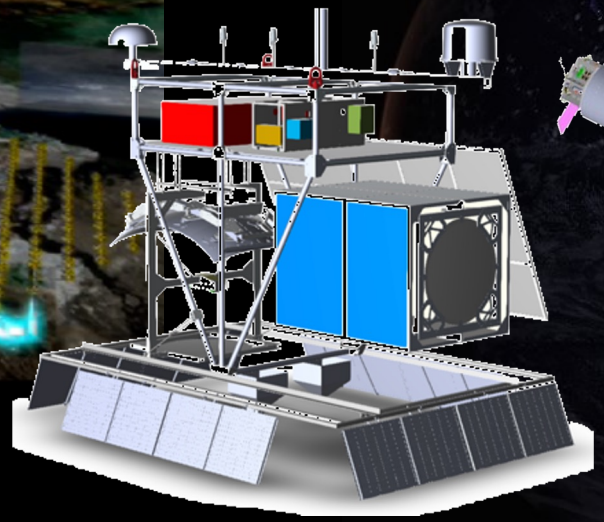
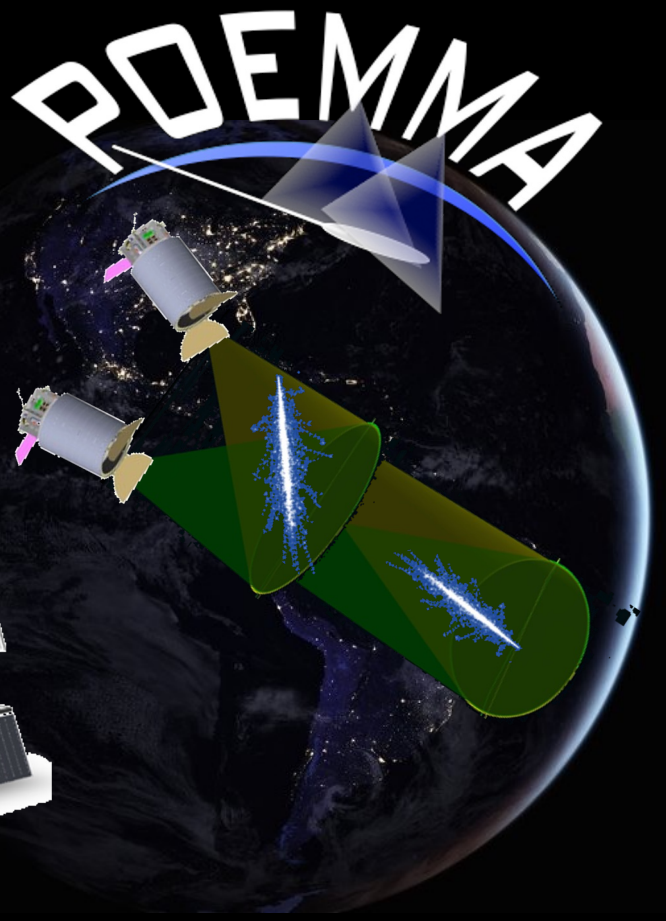
Space Observatories for the Highest Energy Cosmic Particles: POEMMA & EUSO-SPB



EUSO-SPB2





Fermilab

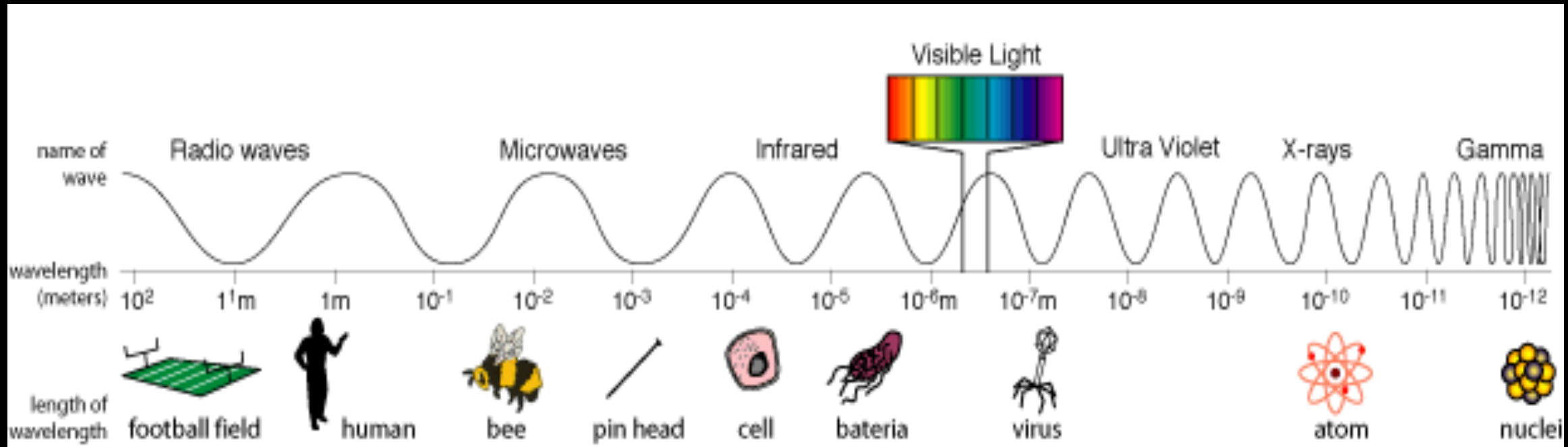
January 11, 2023

Angela V. Olinto

THE UNIVERSITY OF CHICAGO

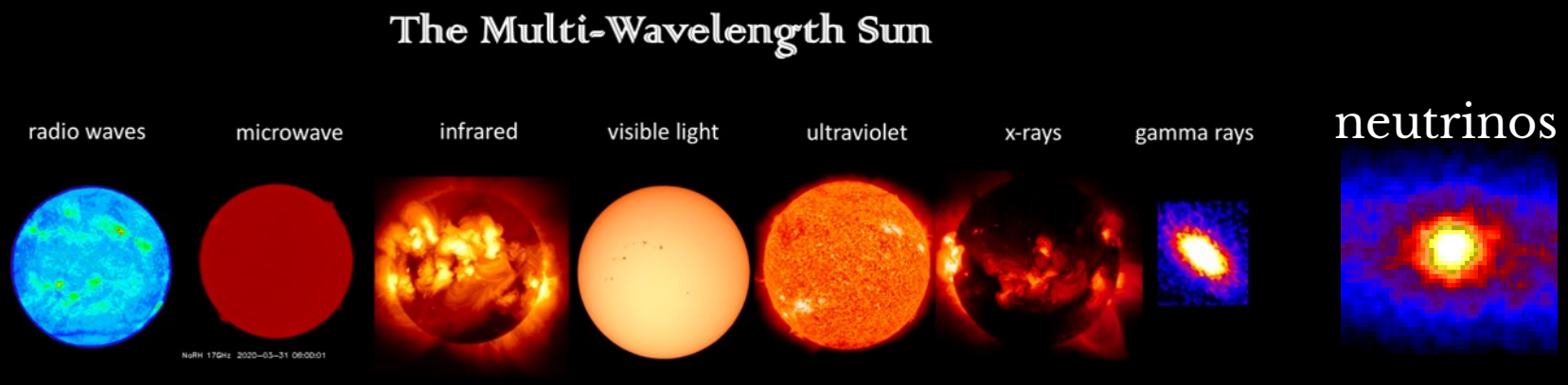
The Multi-Wavelength Sun

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



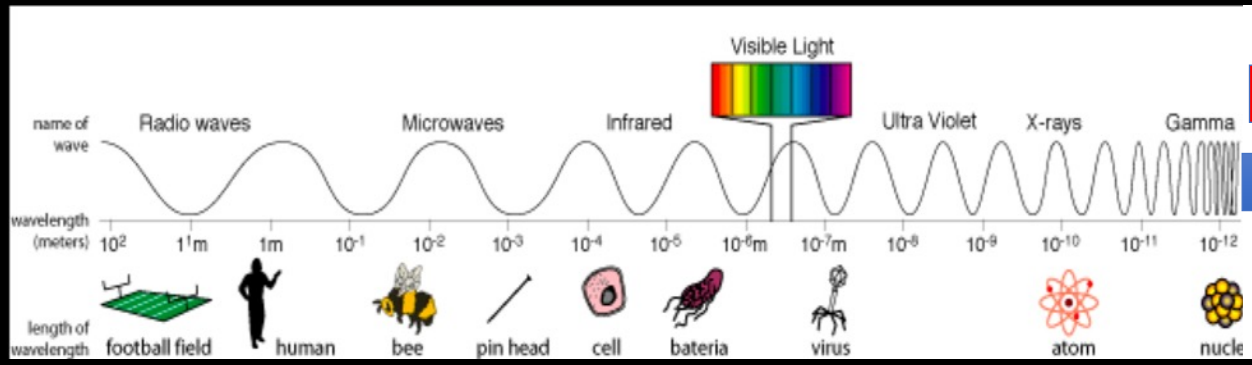
Cosmic Particles

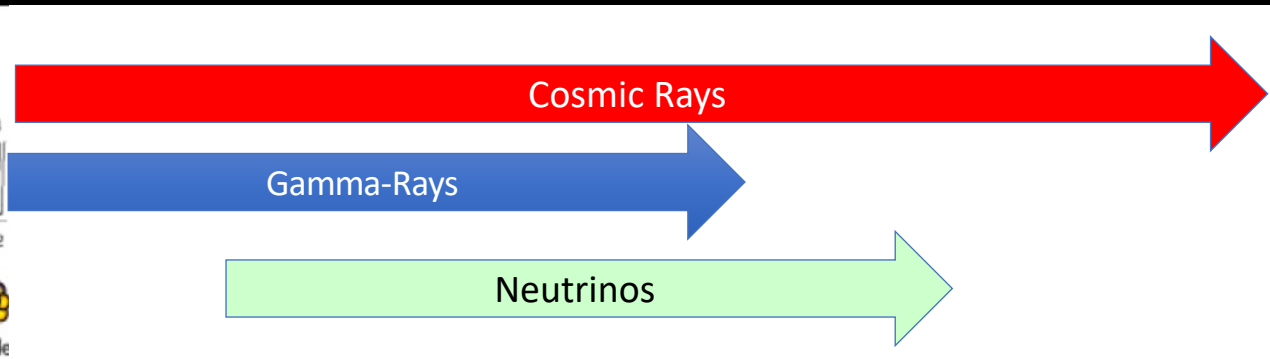
~ double the reach for Astrophysics



neutrinos

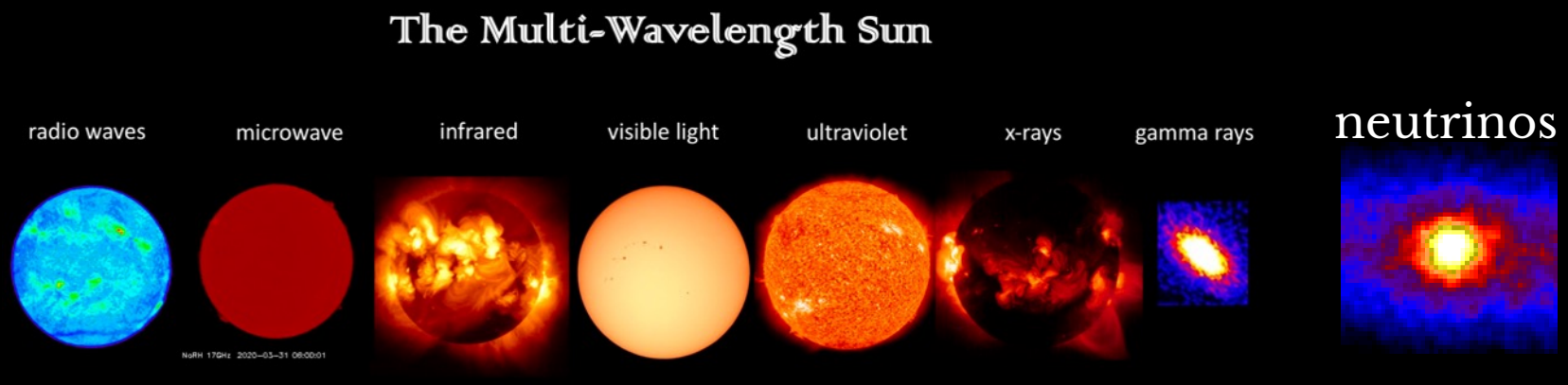
Gamma-rays up to 10^{15}eV



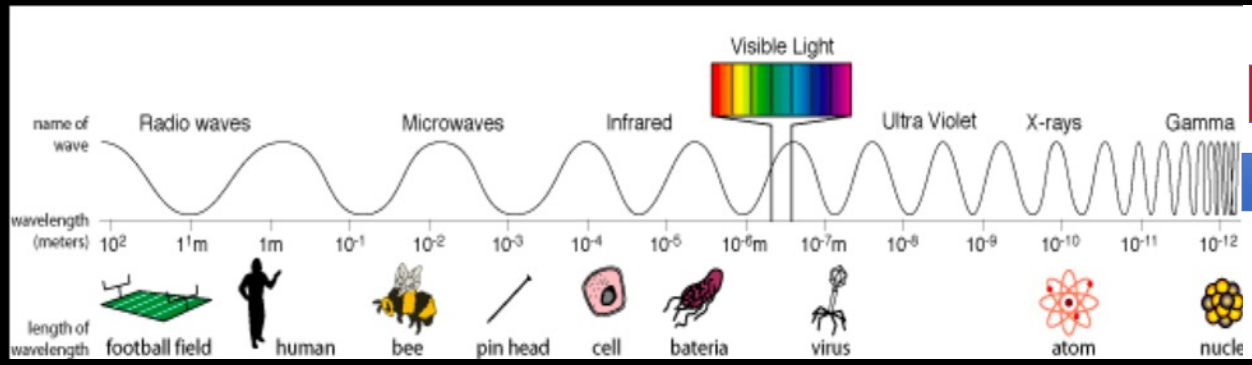


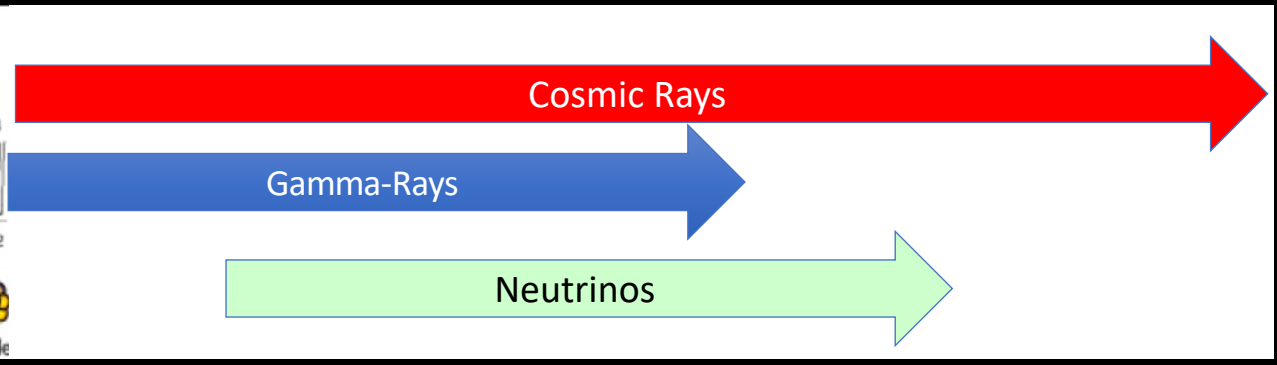
Cosmic Particles

~ double the reach for Astrophysics



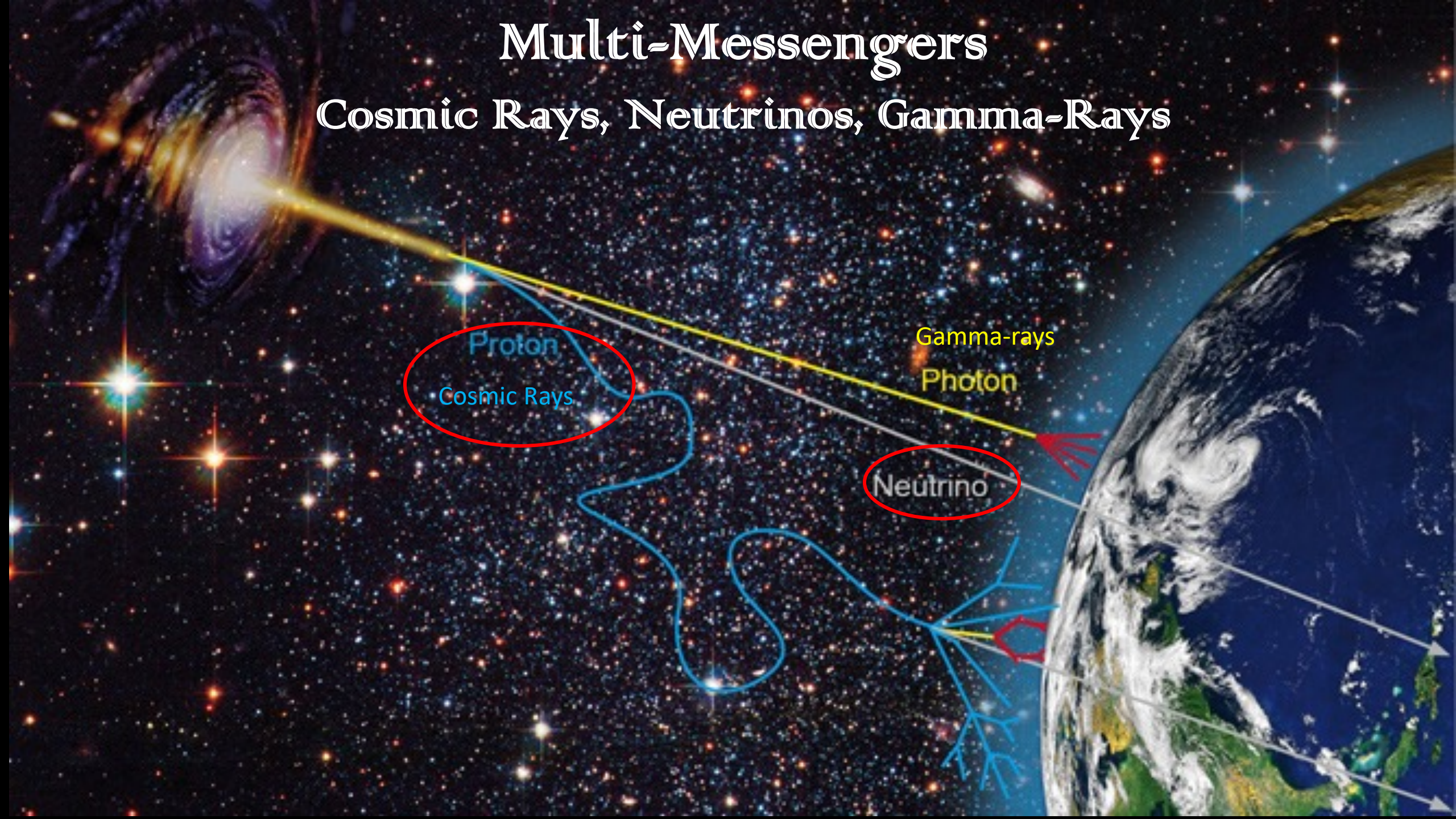
Cosmic Rays up to 10^{20}eV





Multi-Messengers

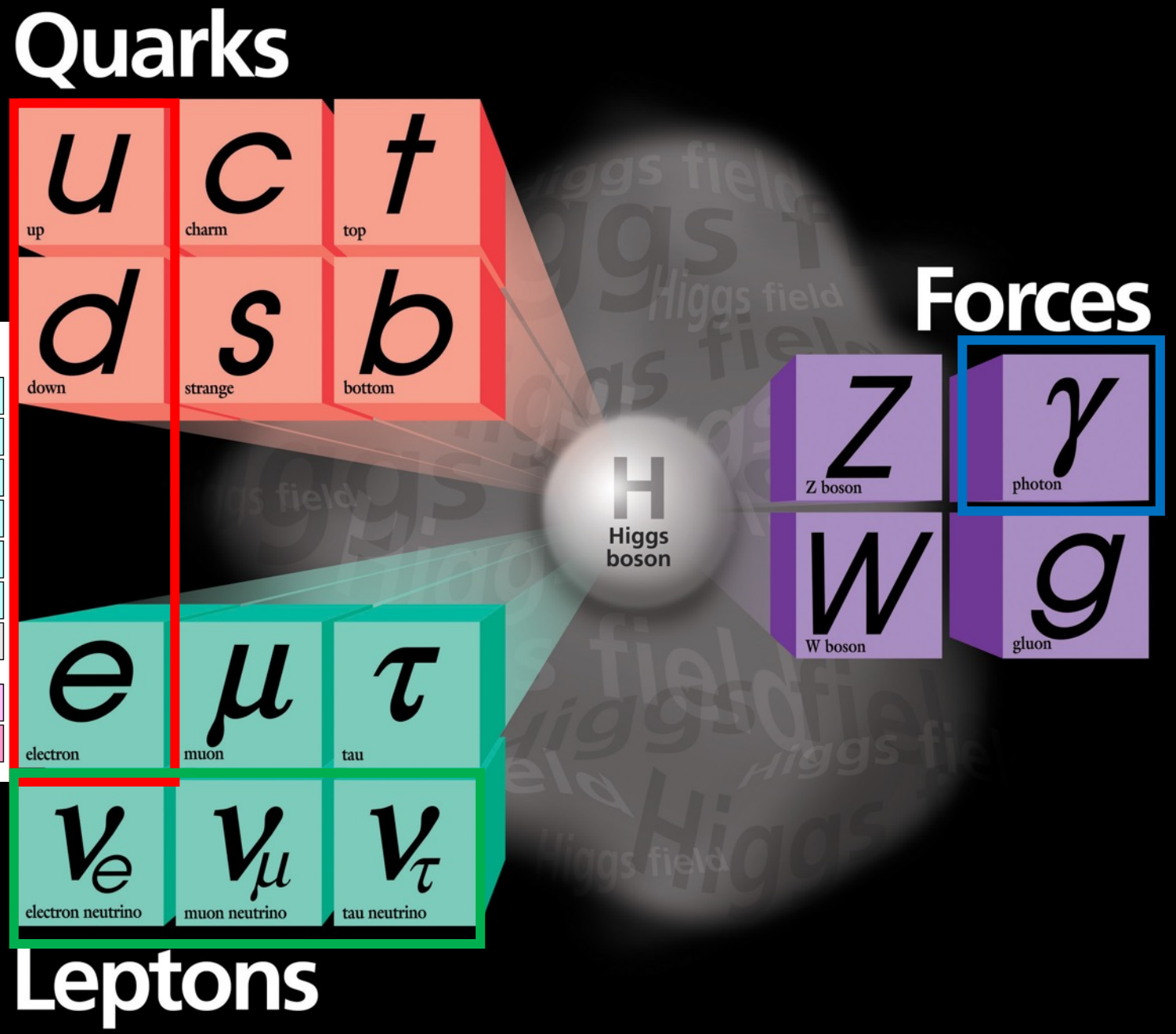
Cosmic Rays, Neutrinos, Gamma-Rays



Cosmic Rays

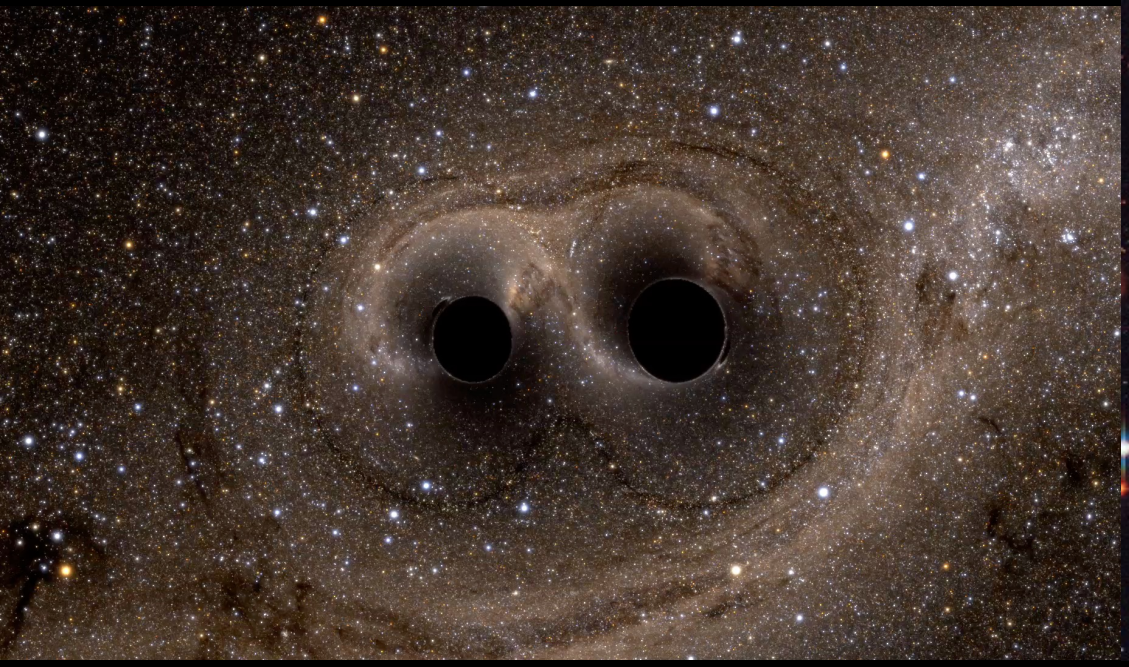
Group → / Period ↓	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
Lanthanides				57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides				89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

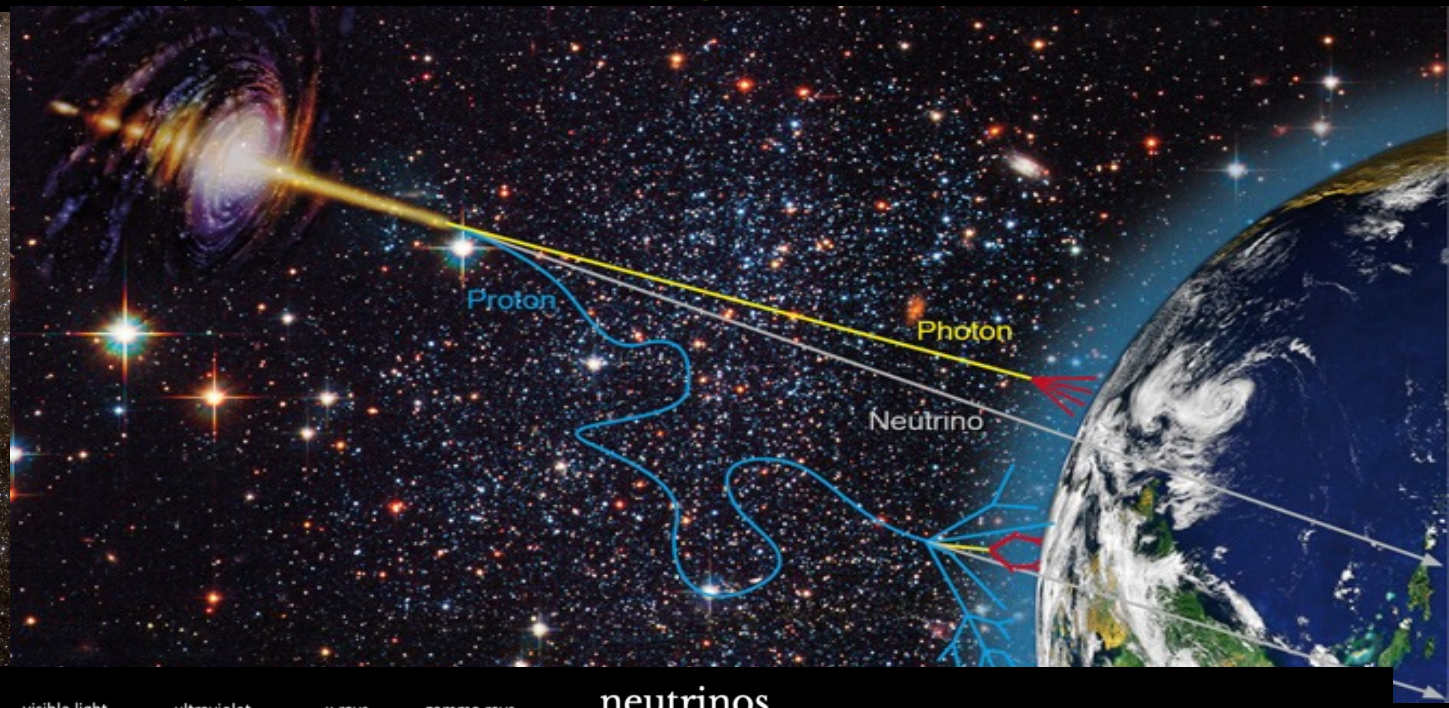
Neutrinos

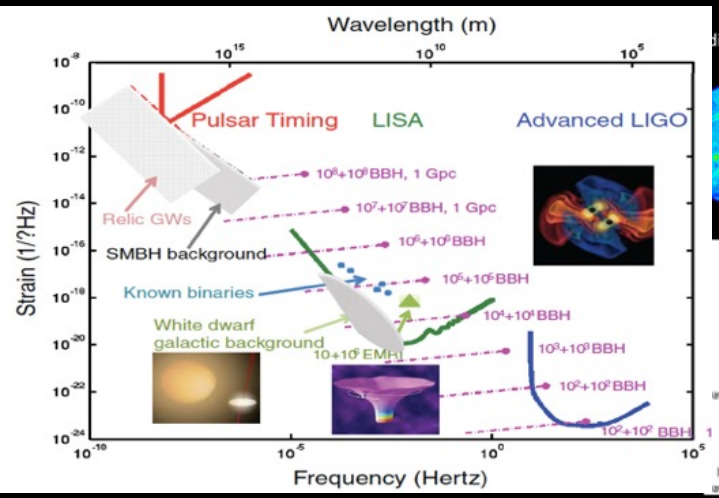


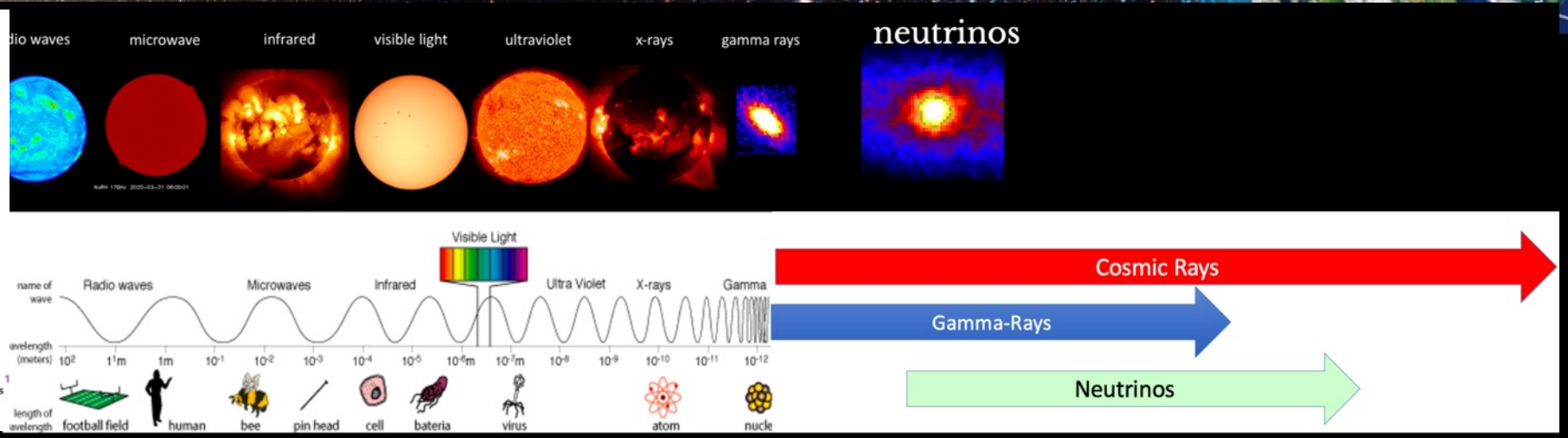
Multi-Messengers

~ Triple the reach for Astrophysics – 40 orders of magnitude









Gravitational Waves

Electromagnetic Waves

Cosmic Particles

Astroparticle Physics Open Questions:

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

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

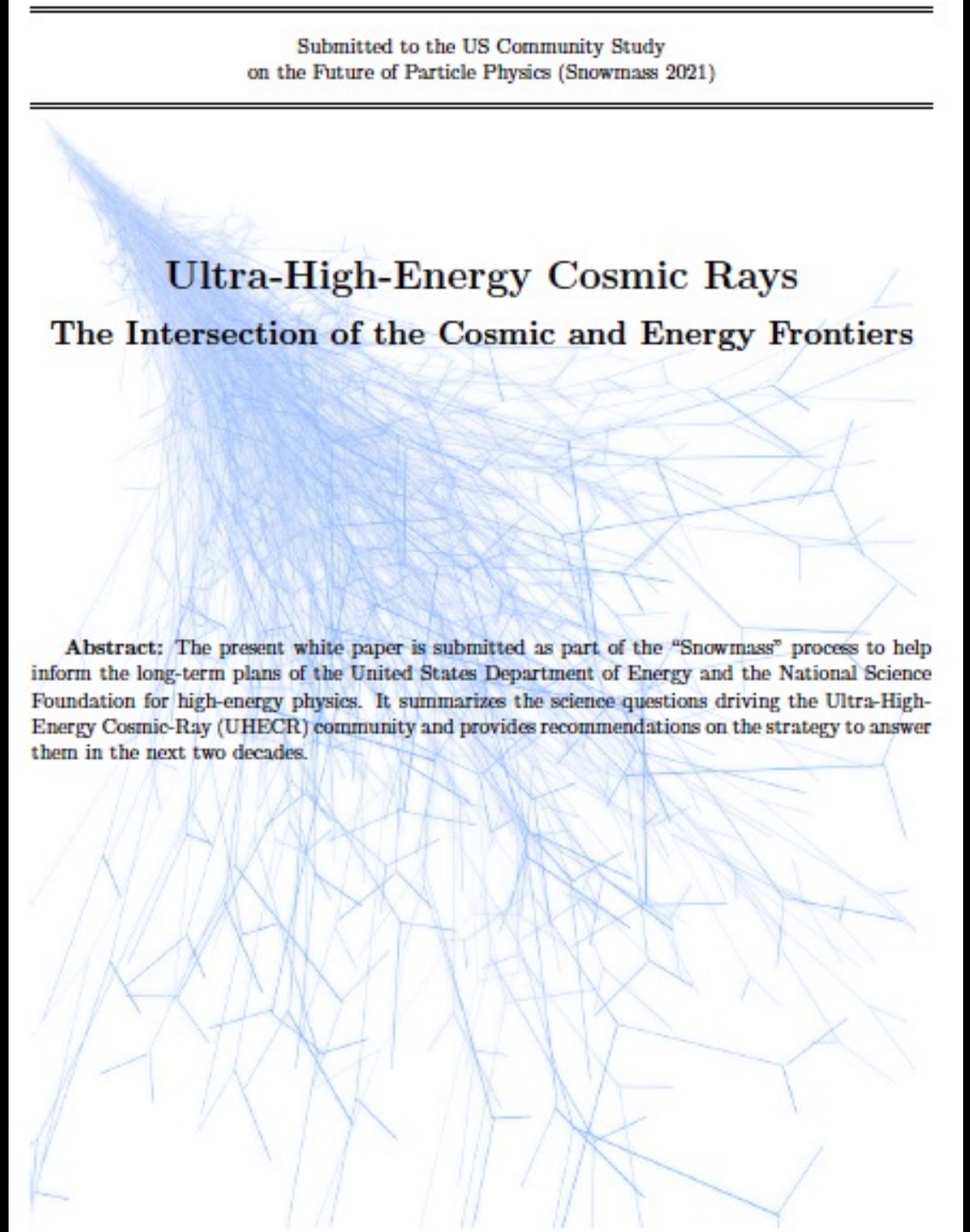
Outline:

What are the sources of the **Ultra-High Energy Cosmic Rays** (UHECRs)?
Cosmic rays with energy above 1 EeV $= 10^{18}$ 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?

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

Future Outlook

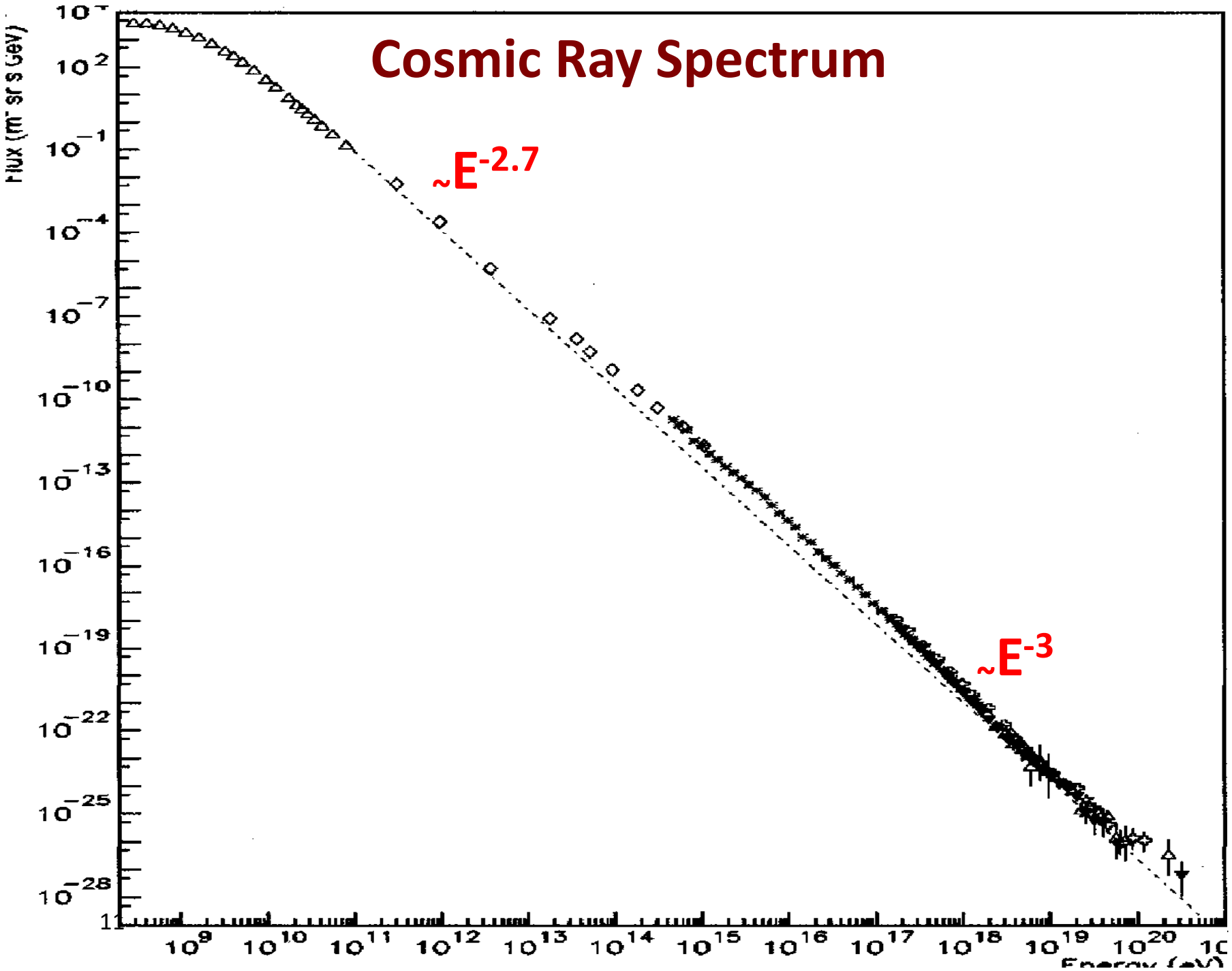


Coleman et al, 2022
arXiv:2205.05845

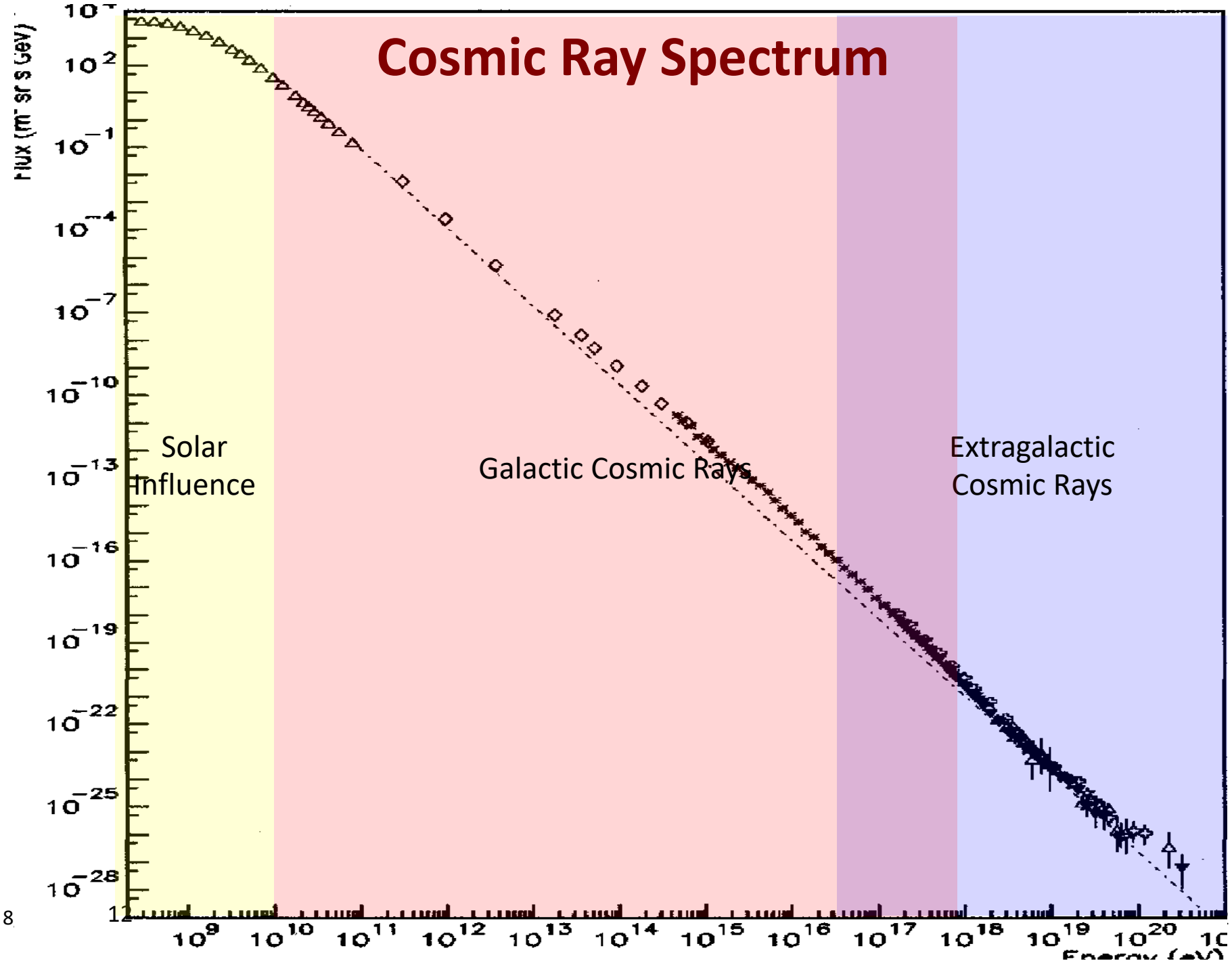
Snowmass Cosmic Frontier 7 report
Adhikari et al 2022
arXiv:2209.11726

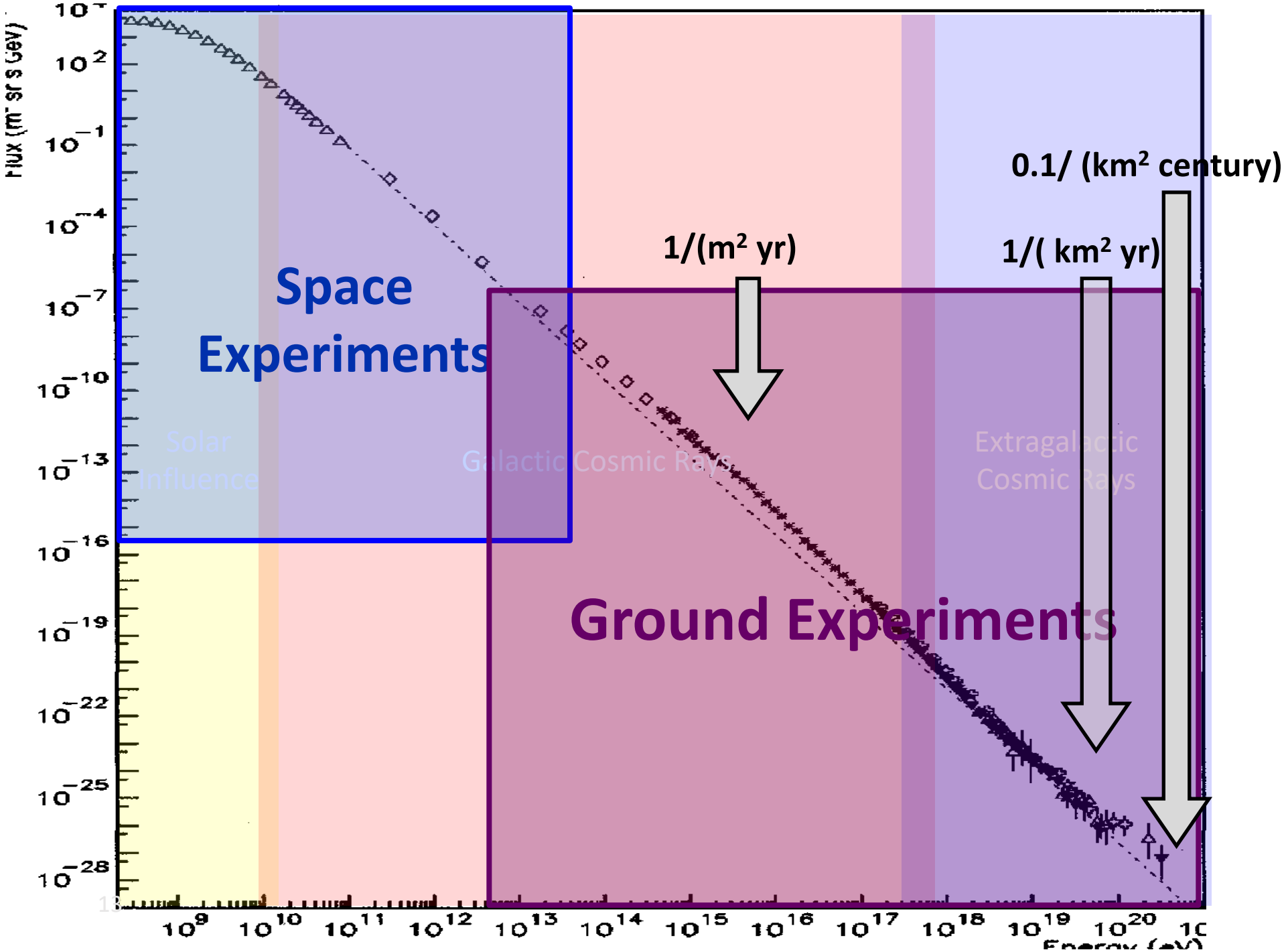
Open Questions in CRs at UHEs
Alves-Batista
arXiv:1903.06714

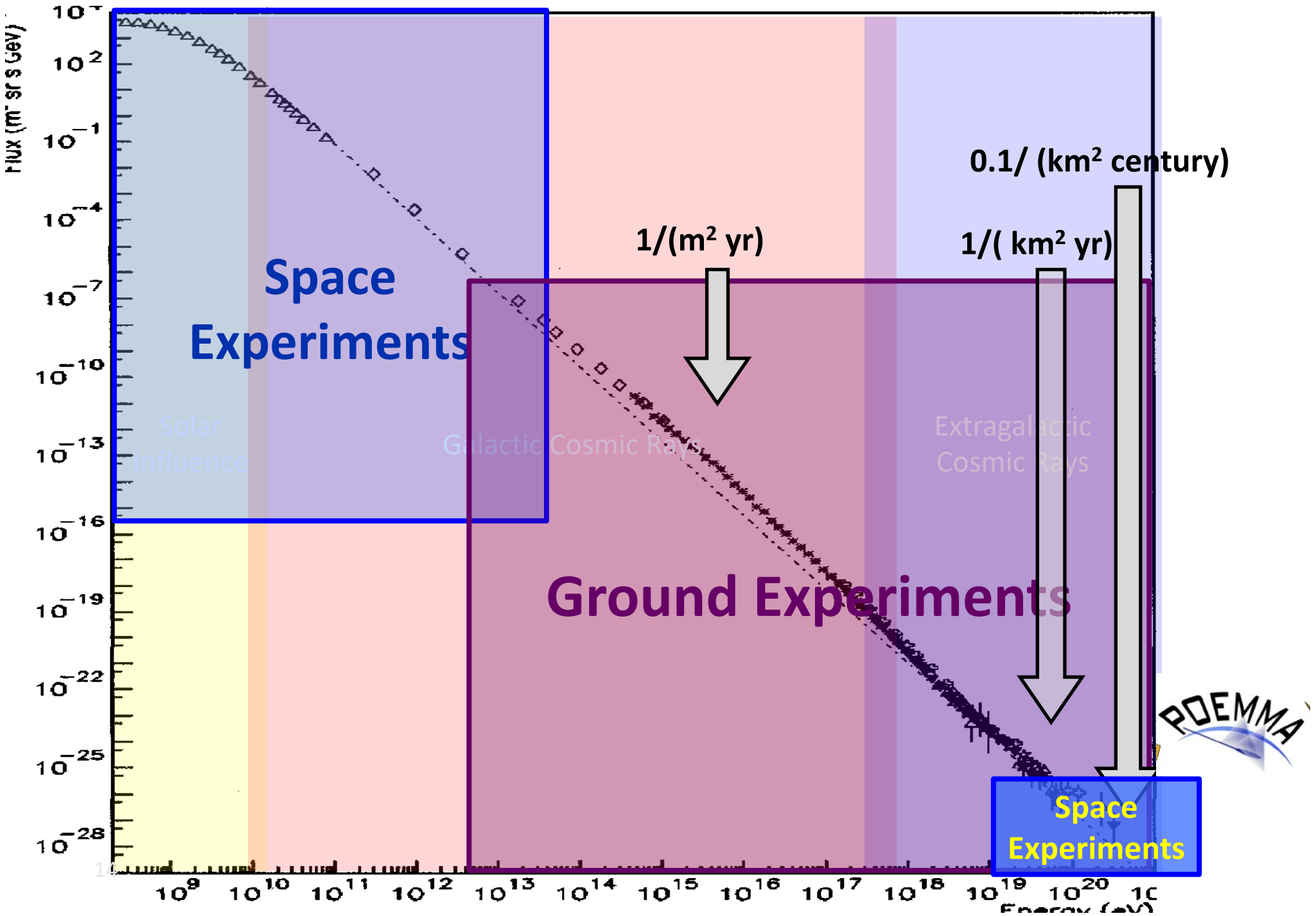
Cosmic Ray Spectrum



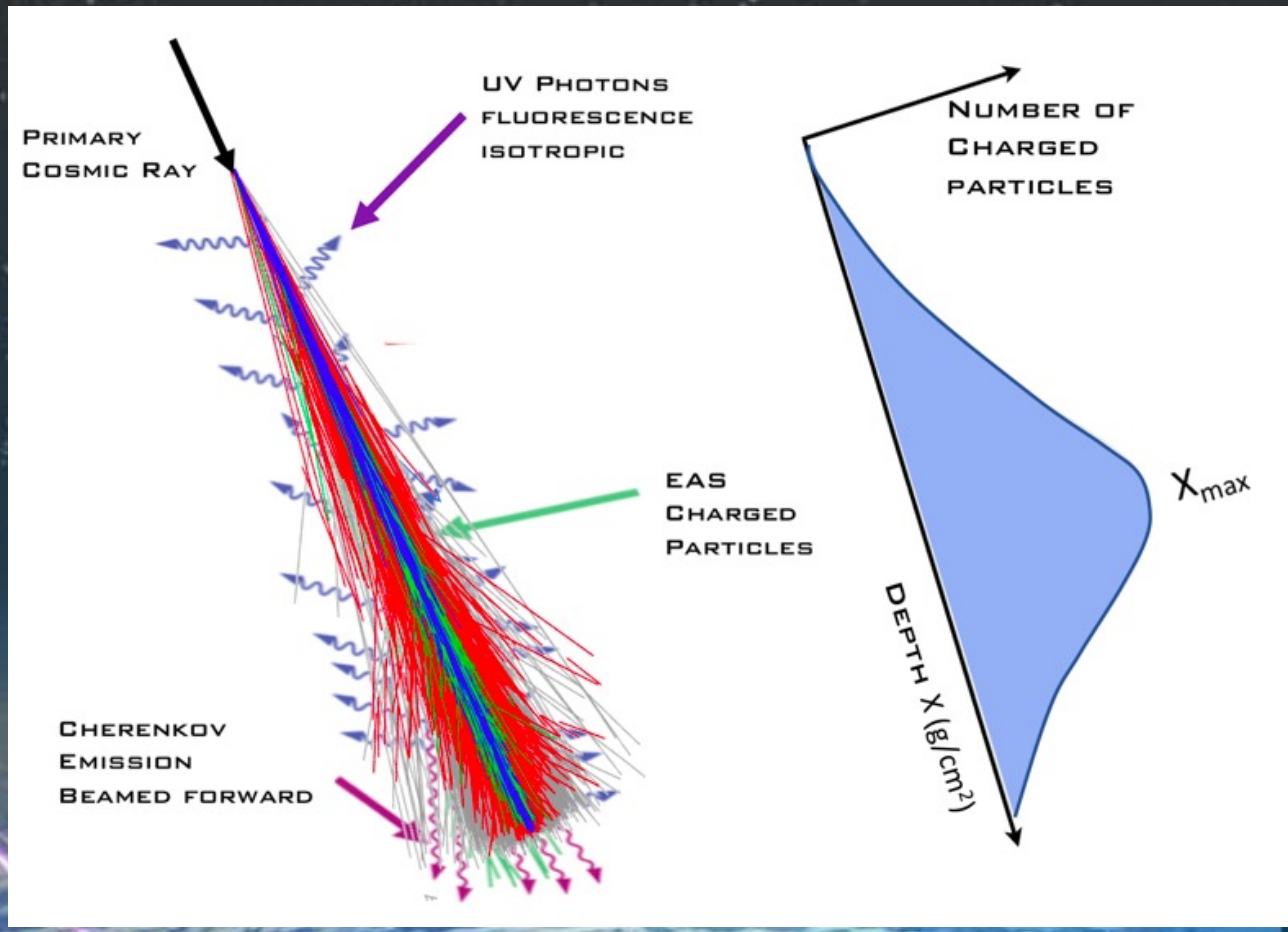
Cosmic Ray Spectrum



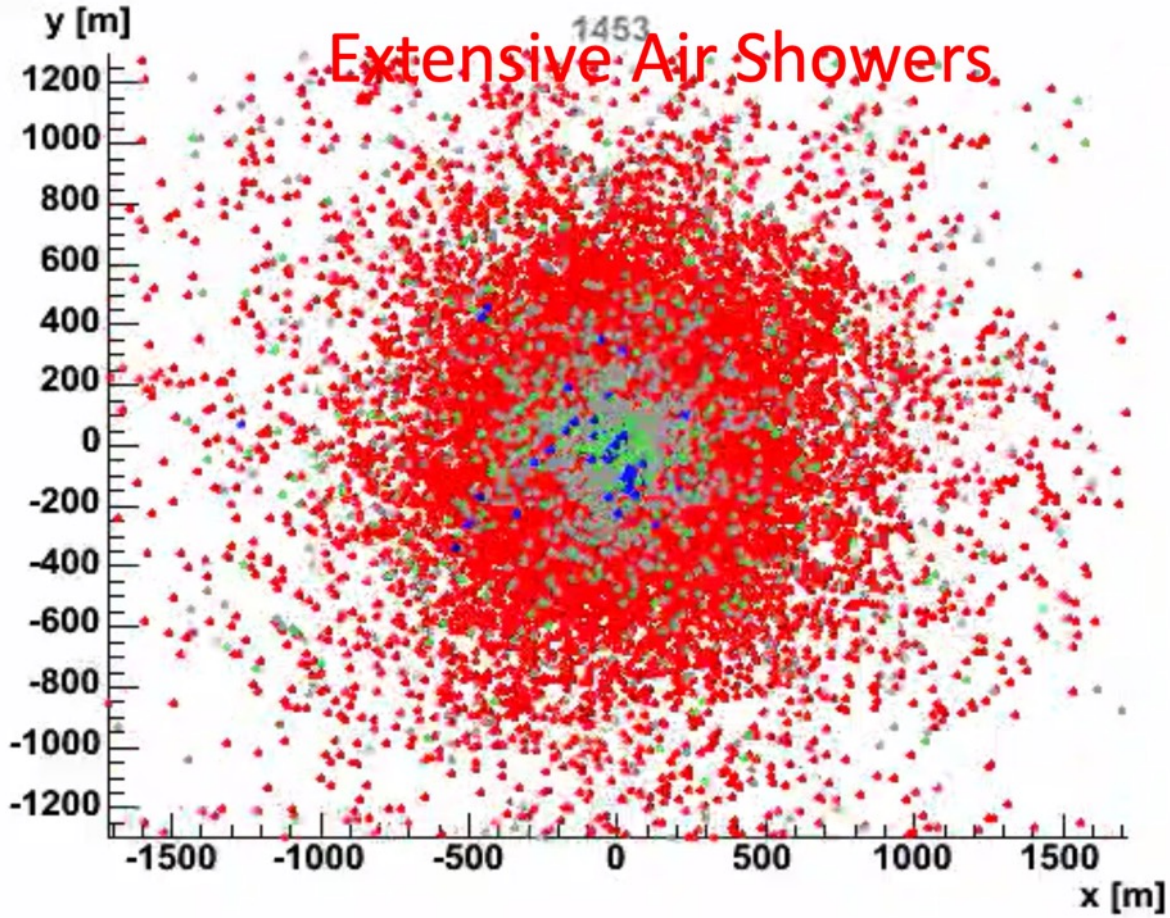

Space
Experiments
Ground Experiments
1/(m² yr)
1/(km² yr)
0.1/ (km² century)
Solar
Influence
Galactic Cosmic Rays
Extragalactic
Cosmic Rays

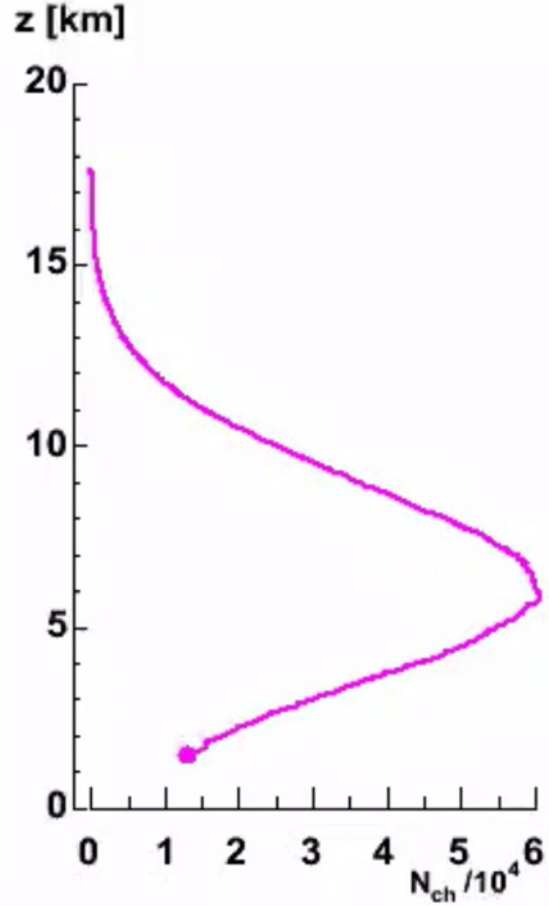

Space Experiments
Ground Experiments
1/(m² yr)
1/(km² yr)
0.1/ (km² century)
Solar Influence
Galactic Cosmic Rays
Extragalactic Cosmic Rays
Space Experiments
POEMMA

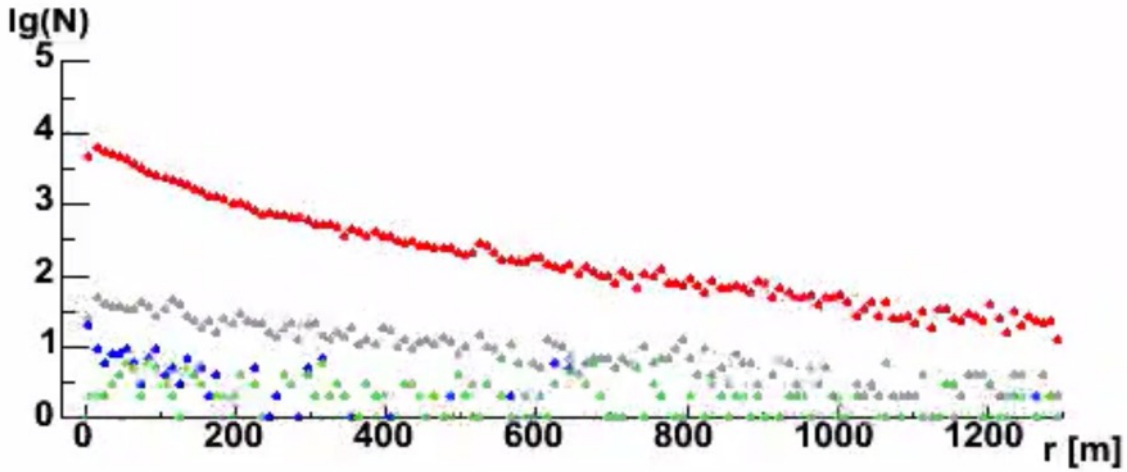
Extensive Air Showers



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

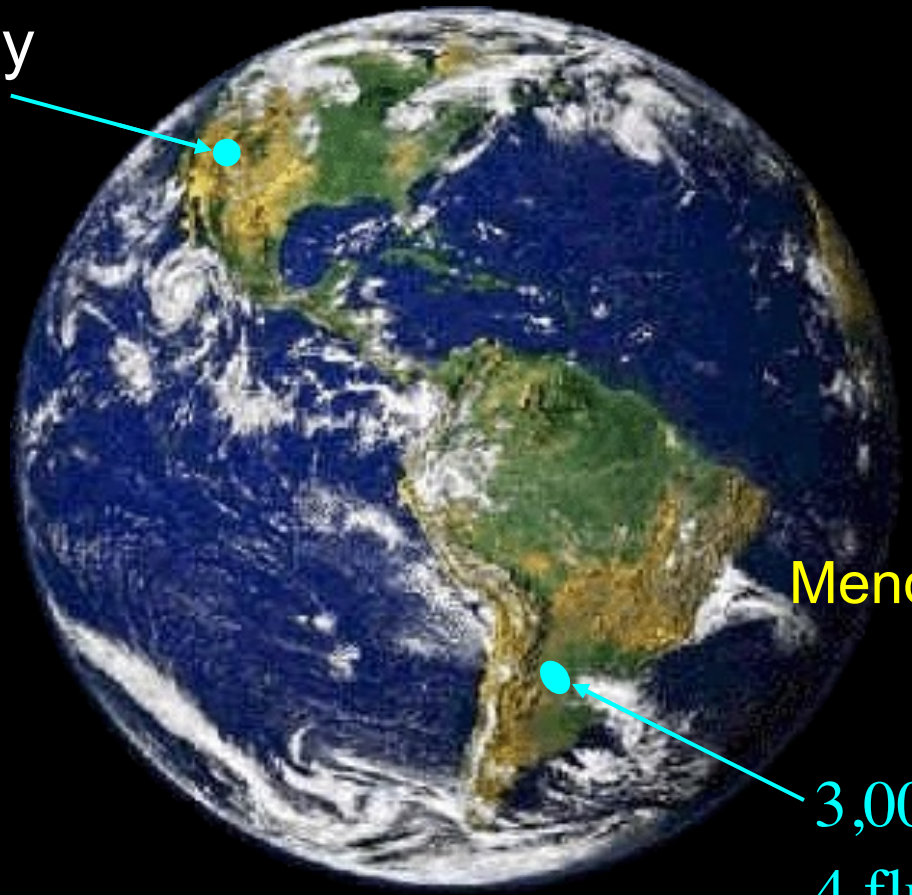
Telescope Array

Utah, USA

(5 country collaboration)

700 km^2 array

3 fluorescence telescopes



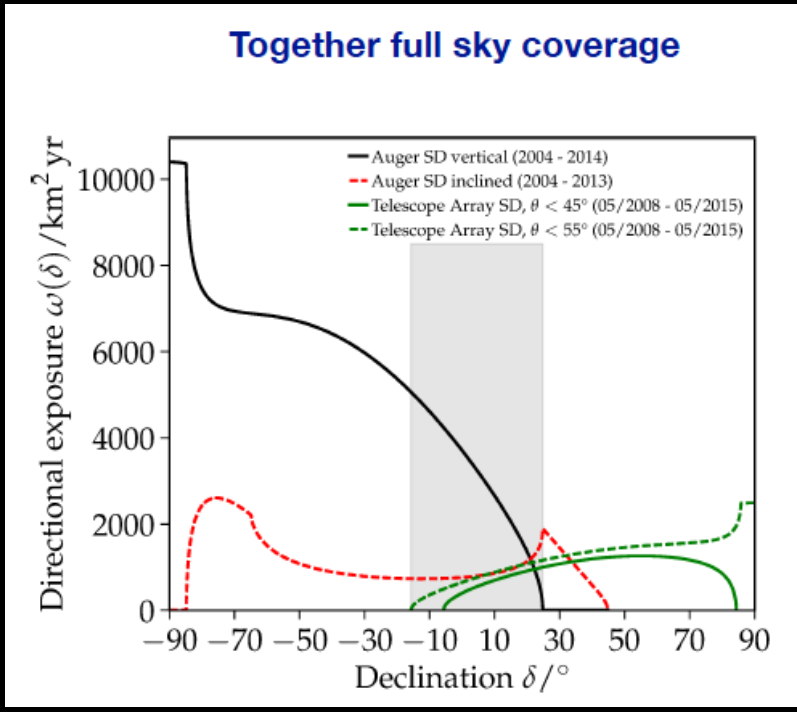
Pierre Auger Observatory

Mendoza, Argentina

(19 country collaboration)

3,000 km^2 array

4 fluorescence telescopes

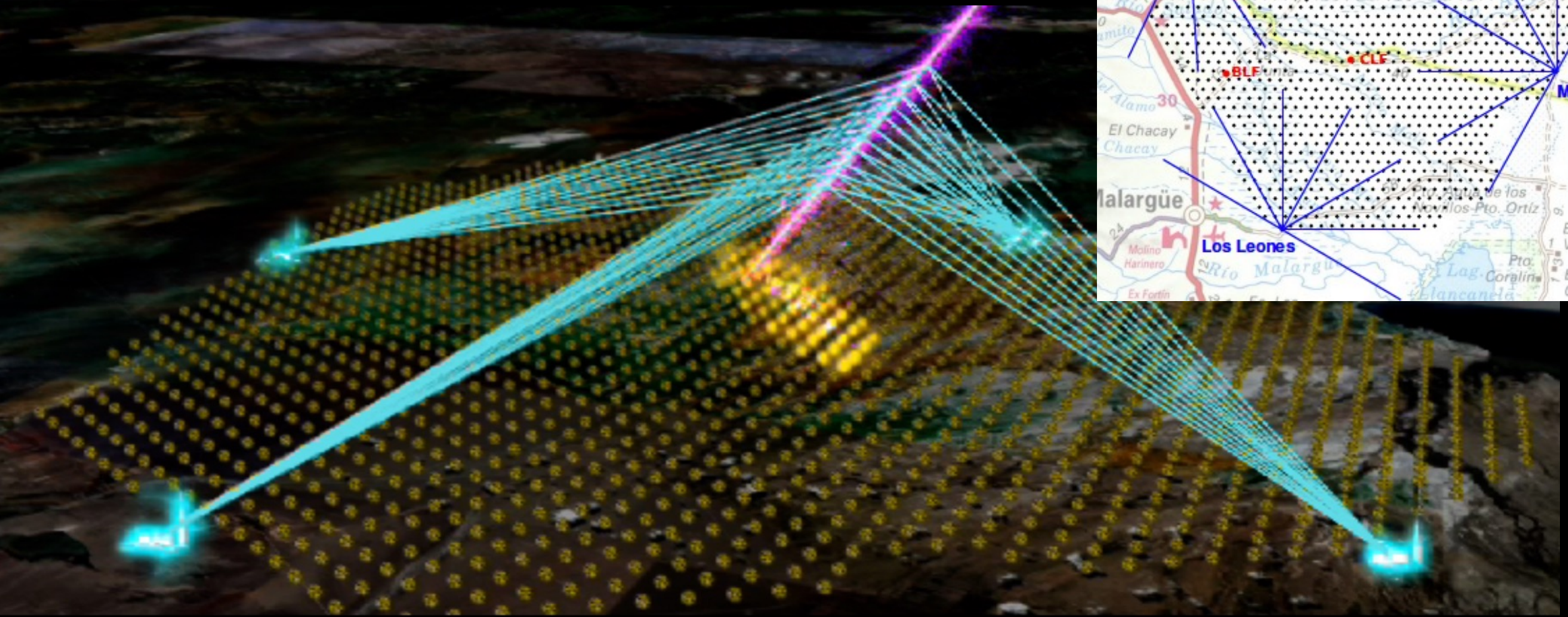


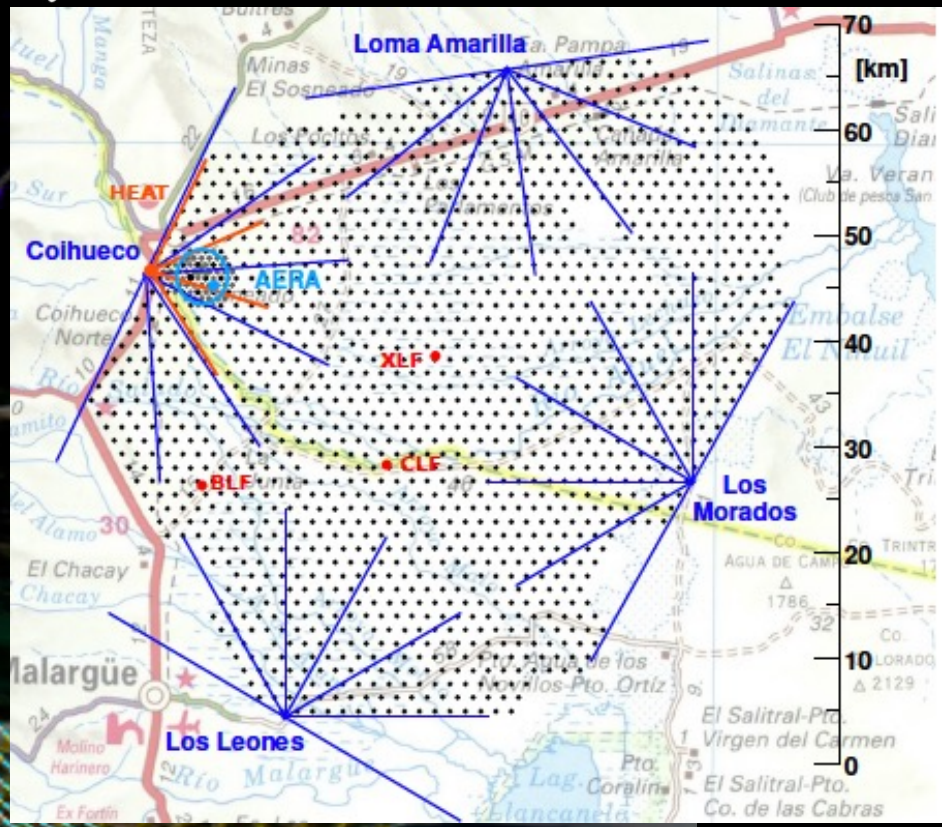
Pierre Auger Observatory

PIERRE AUGER OBSERVATORY

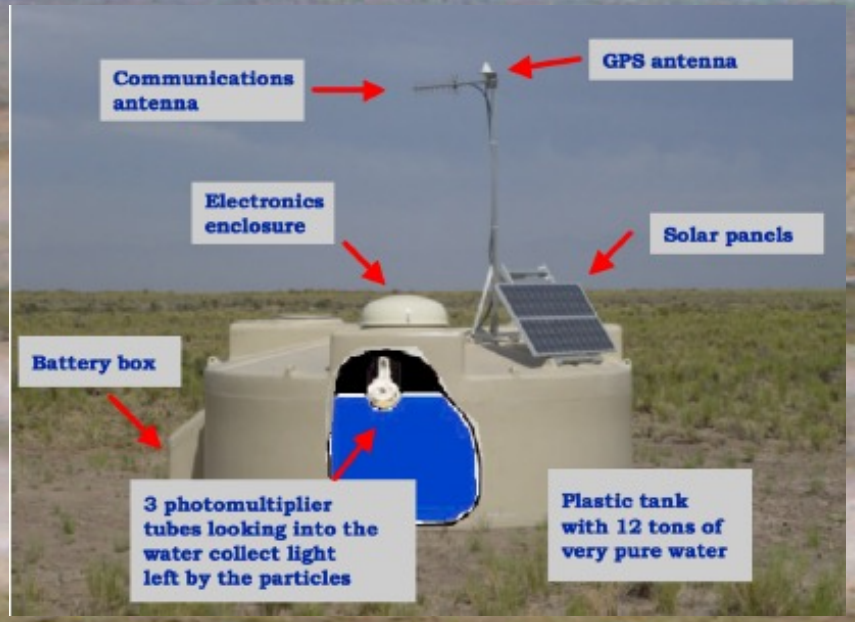
3,000 km^2 surface array=1665 water Cherenkov tanks

4 Fluorescence telescopes





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



4 Fluorescence telescopes overlooking the site

Telescope Array

Middle Drum: based on HiRes II

TALE (TA low energy extension)

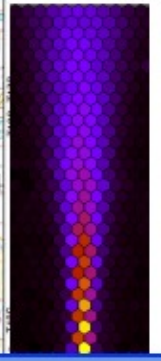
LIDAR
Laser facility

Infill array and high elevation telescopes

~30 km

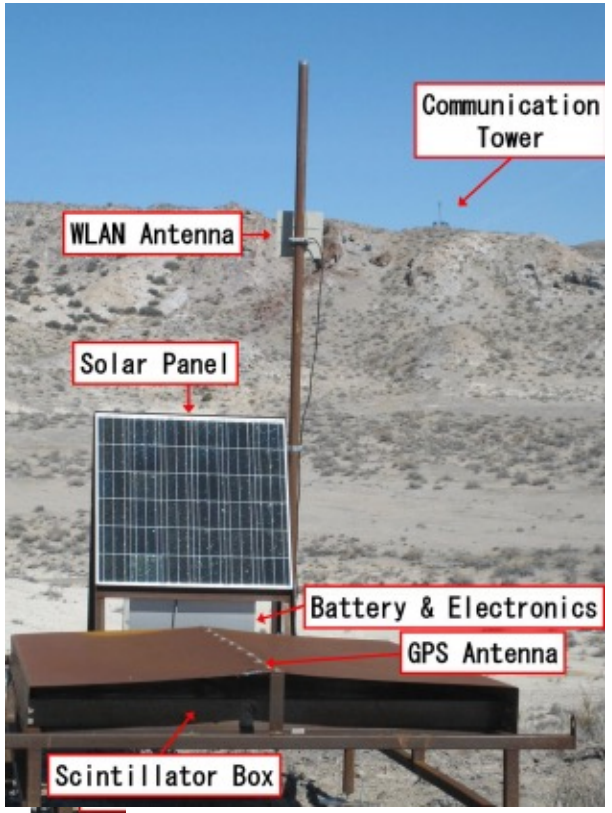
Test setup for radar reflection

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



Electron light source (ELS): ~40 MeV

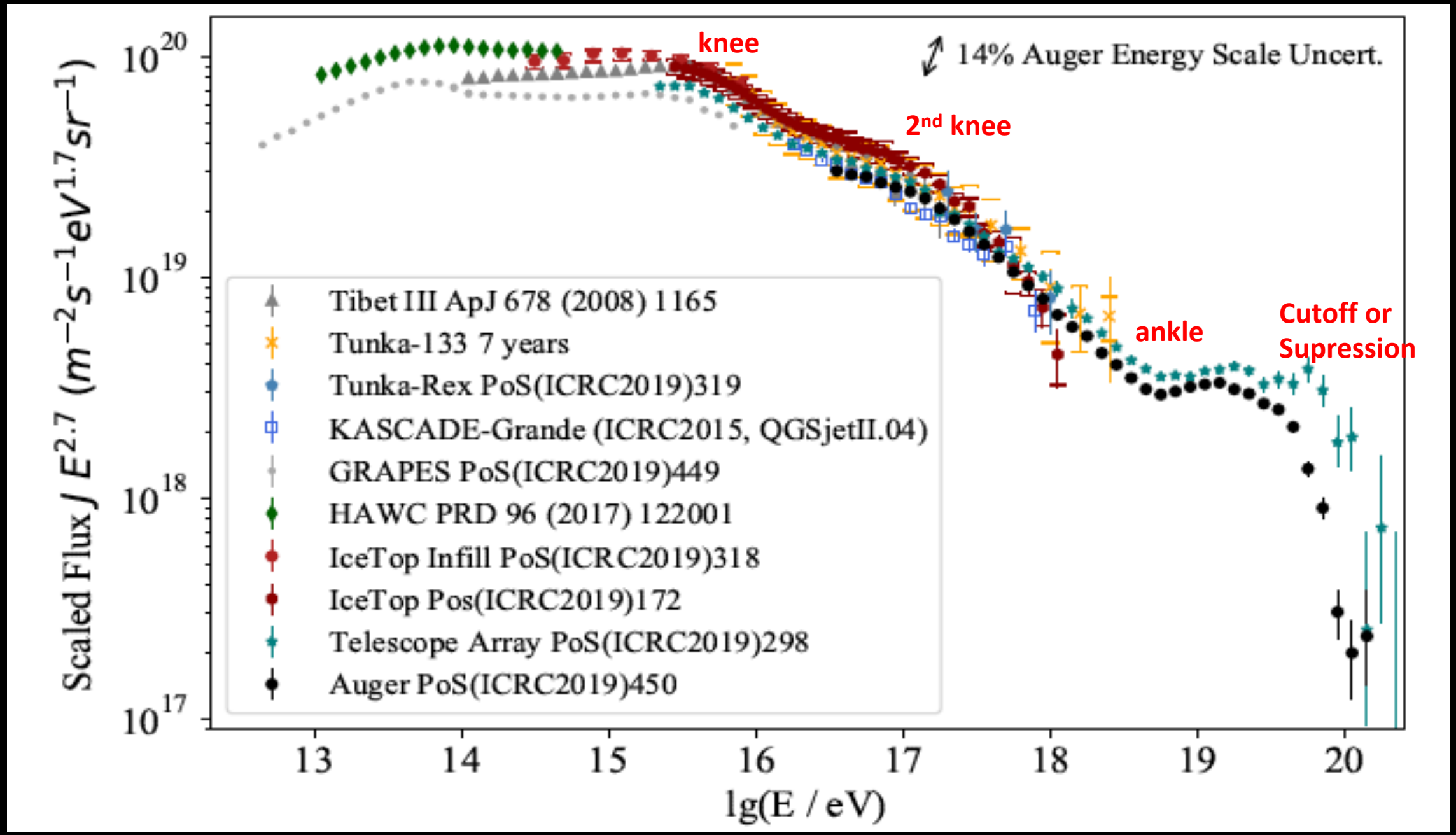
Northern hemisphere: Utah, USA



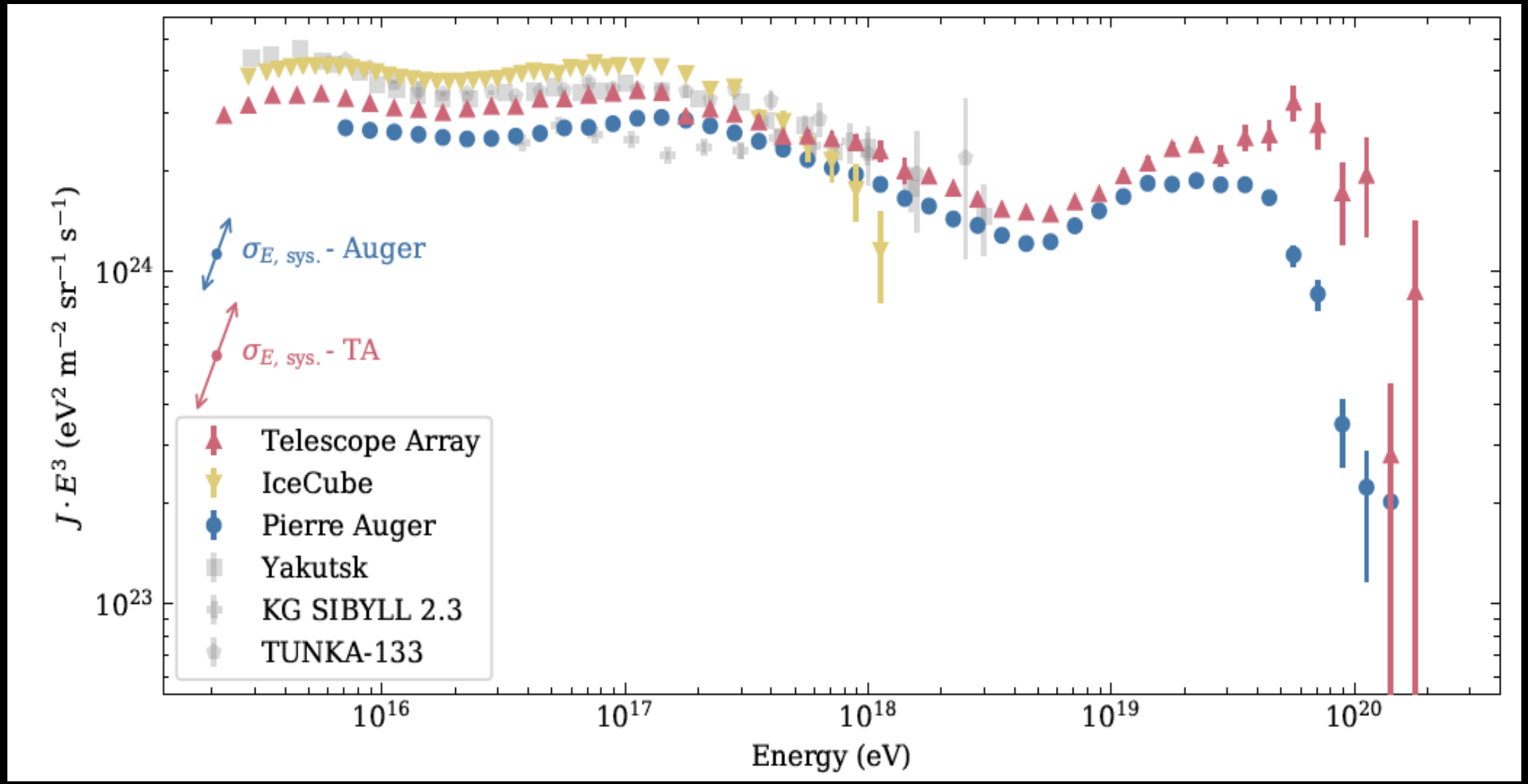
507 surface detectors:
double-layer scintillators
(grid of 1.2 km, 680 km^2)

from R. Engel 2017

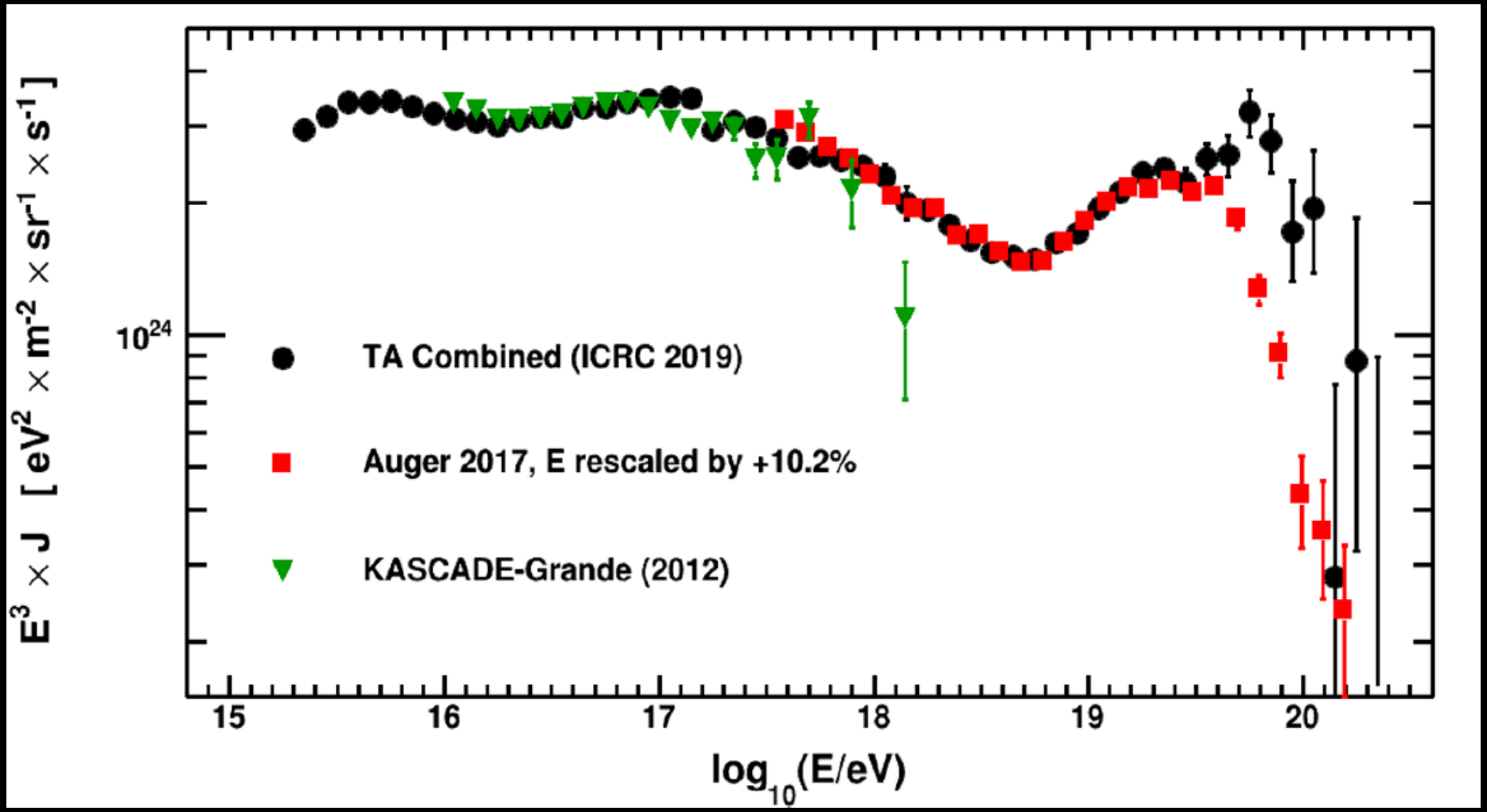
What is the spectrum of UHECRs?



F. G. Schröder '19

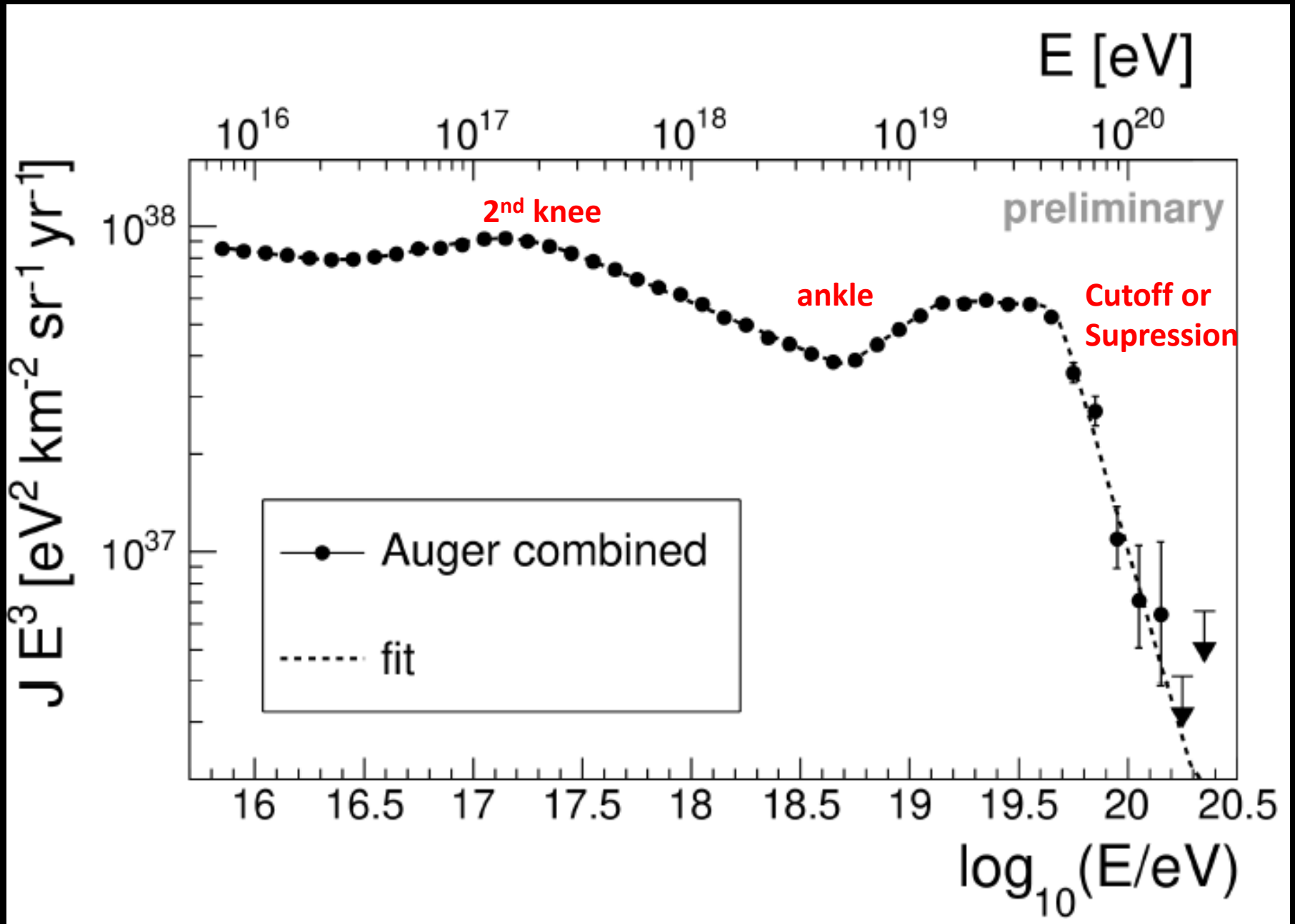


Coleman et al, 2022
arXiv:2205.05845

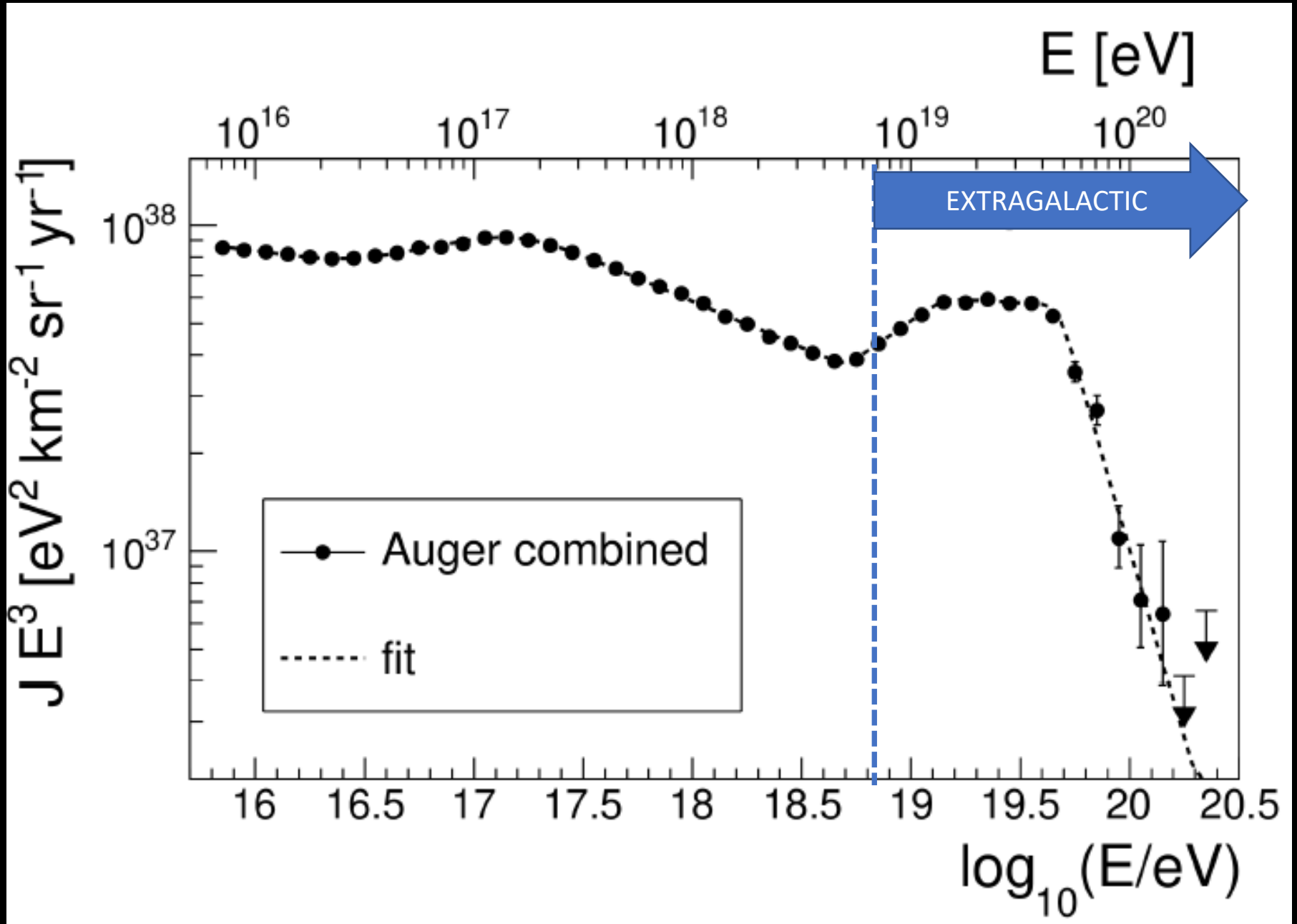


Coleman et al, 2022
arXiv:2205.05845

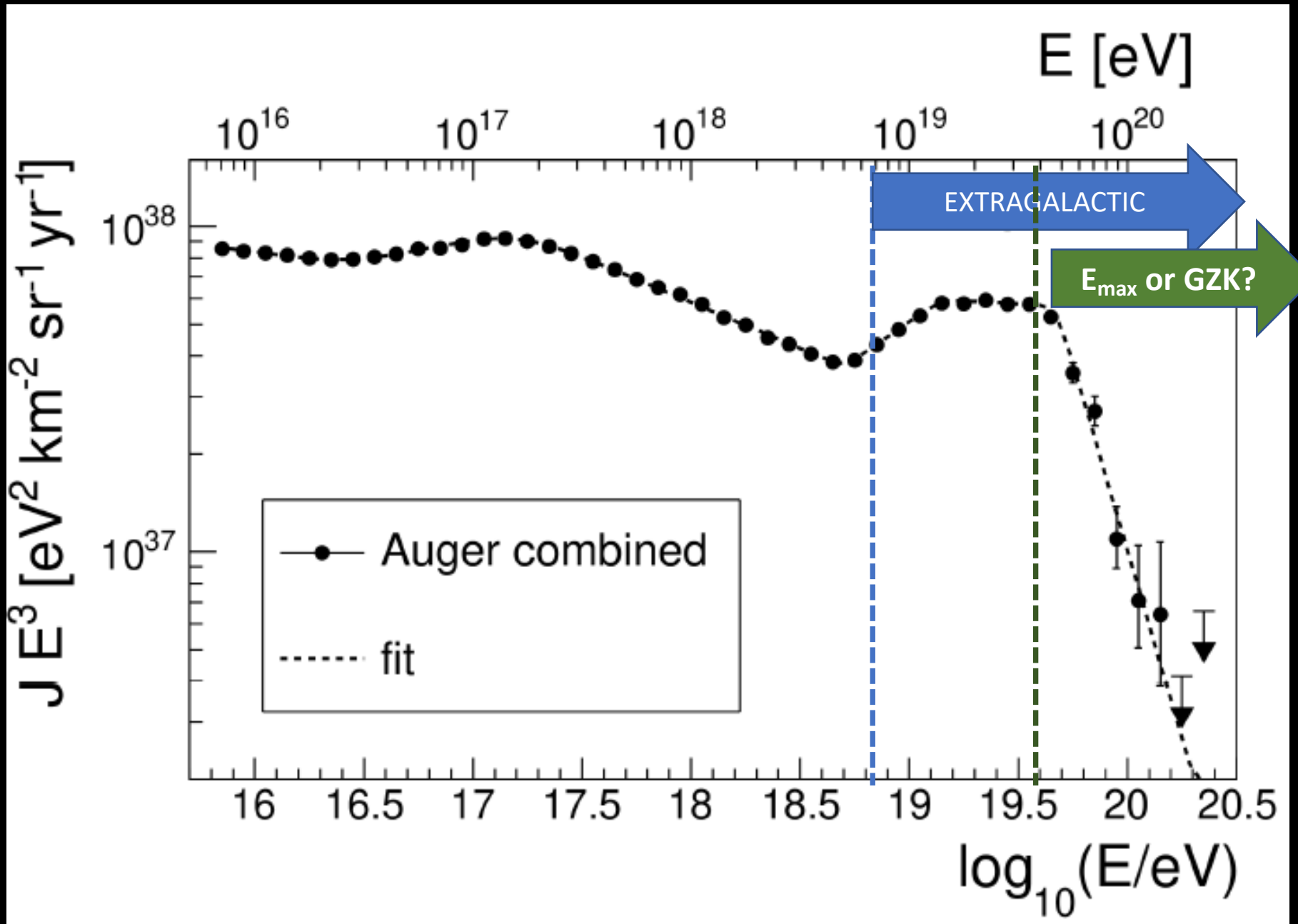
Auger Spectrum ICRC 2021



Auger Spectrum ICRC 2021



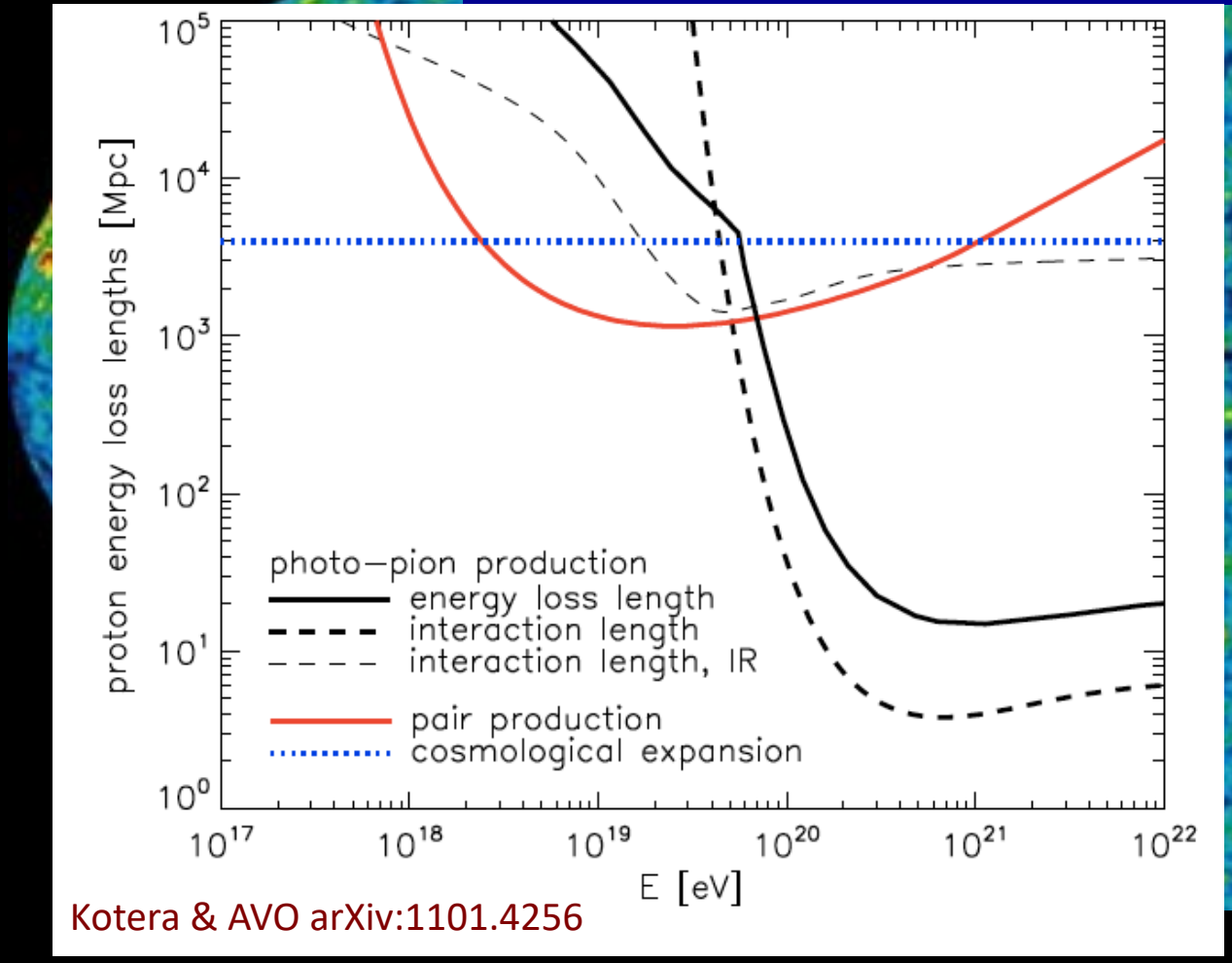
Auger Spectrum ICRC 2021



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,
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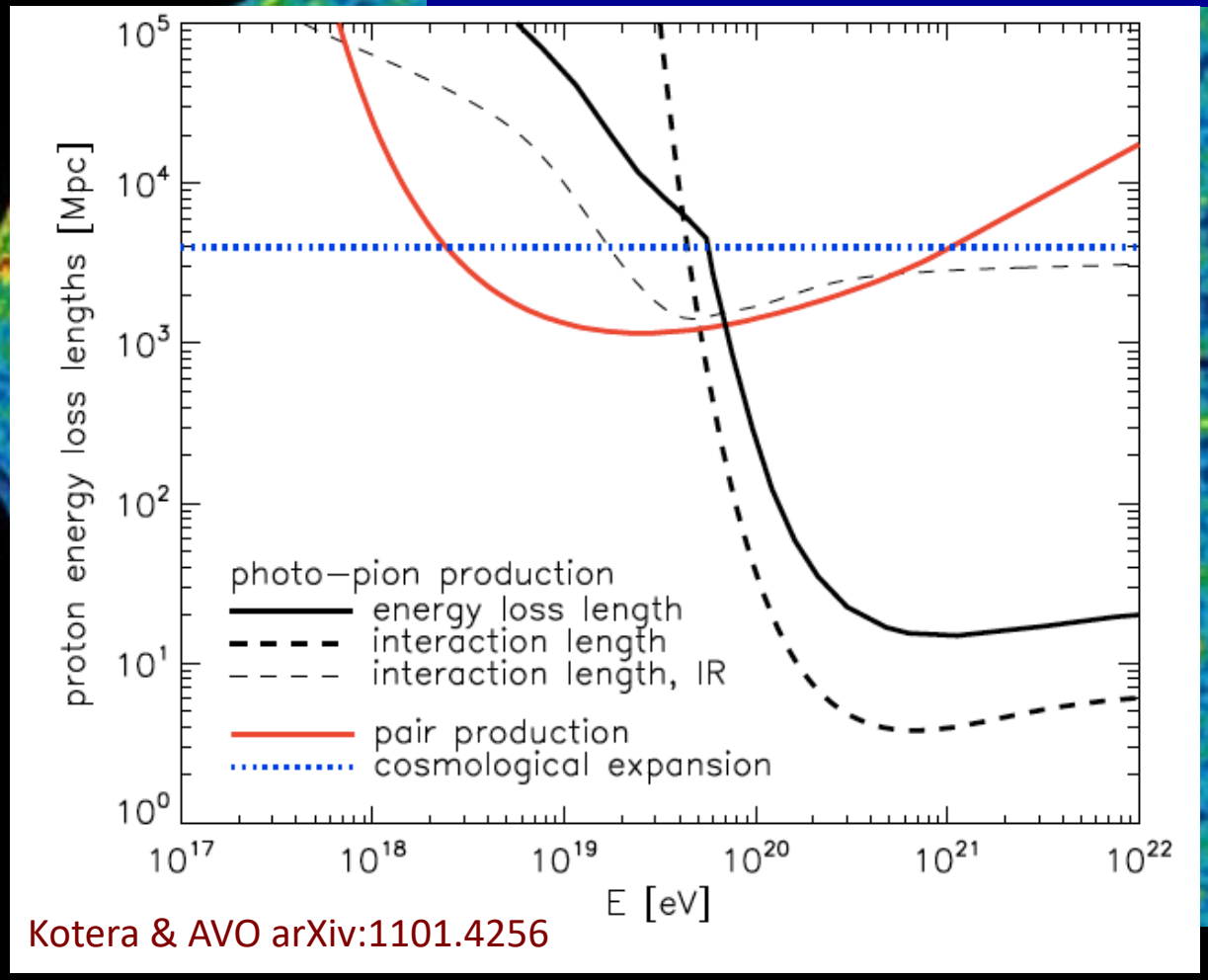
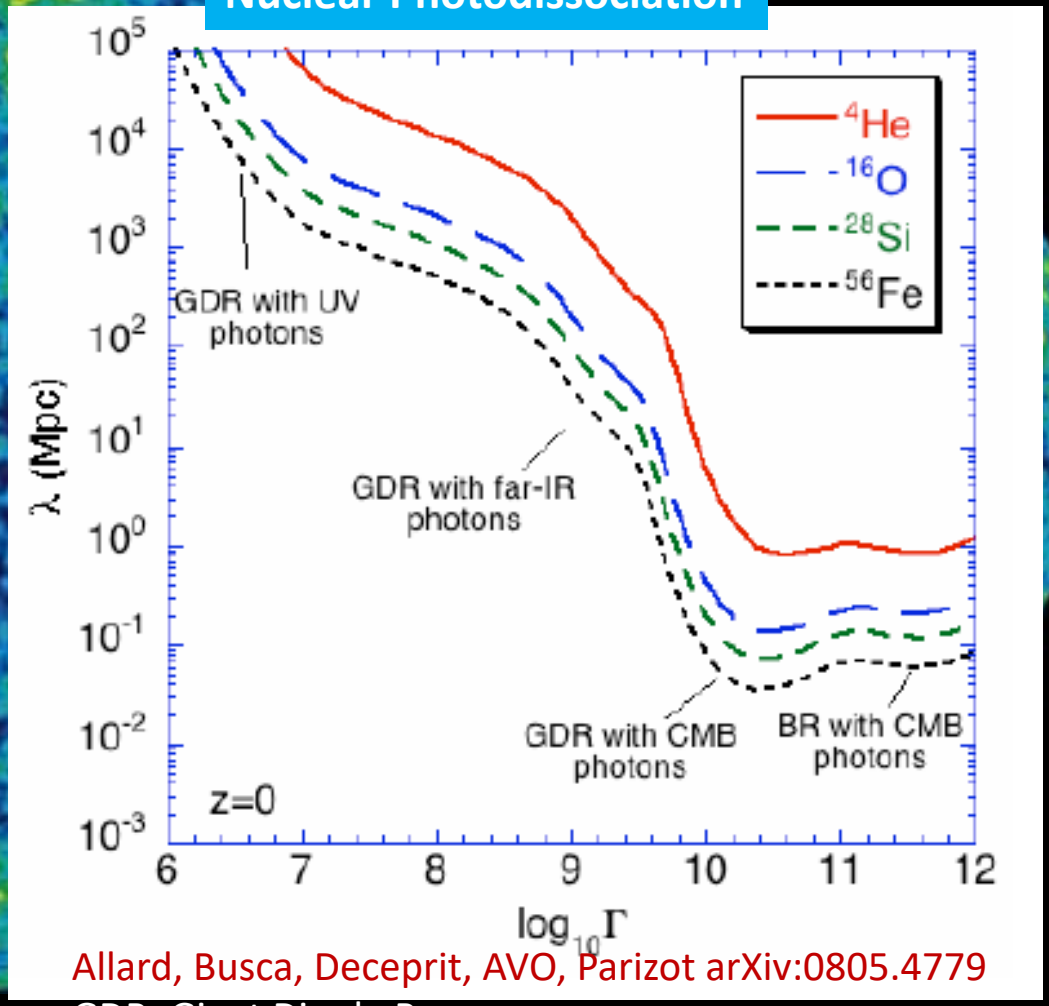


Kotera & AVO arXiv:1101.4256

Nuclear Photodissociation

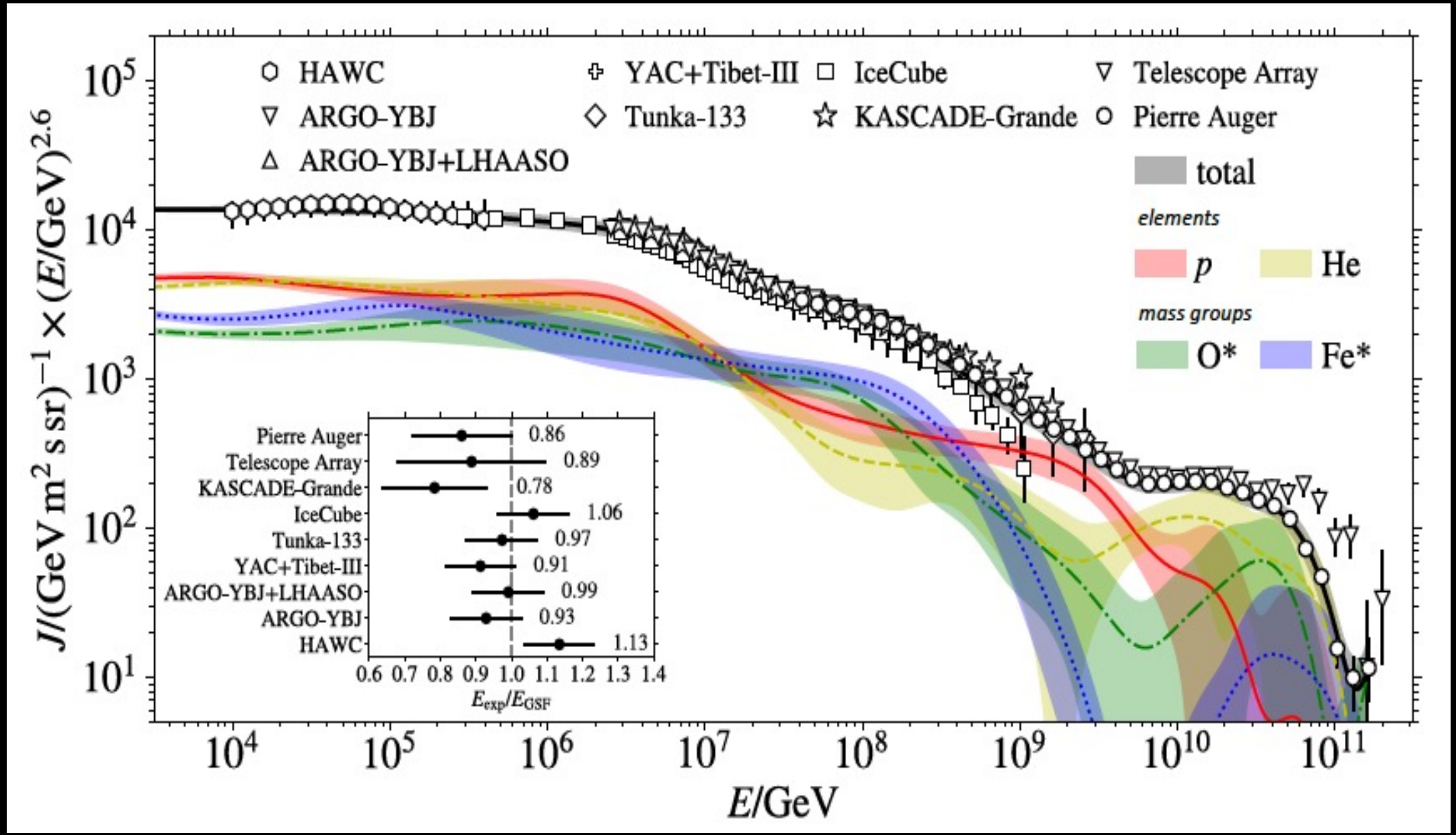


Allard, Busca, Deceprit, AVO, Parizot arXiv:0805.4779

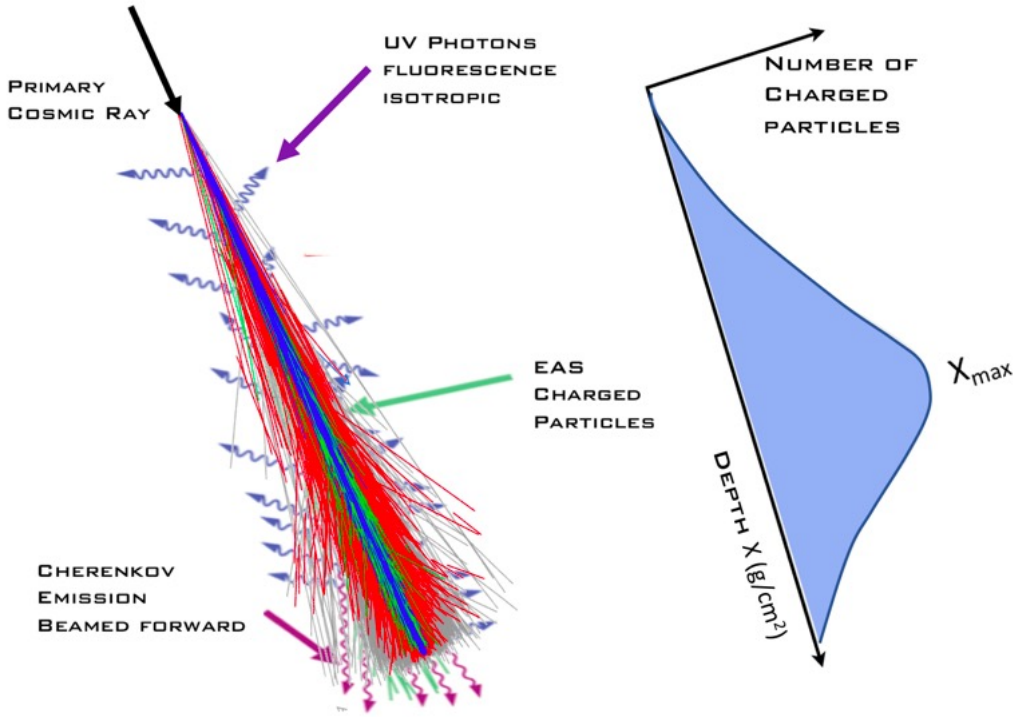
GDR: Giant Dipole Resonance

BR: Baryonic Resonances

What is the composition of UHECRs?



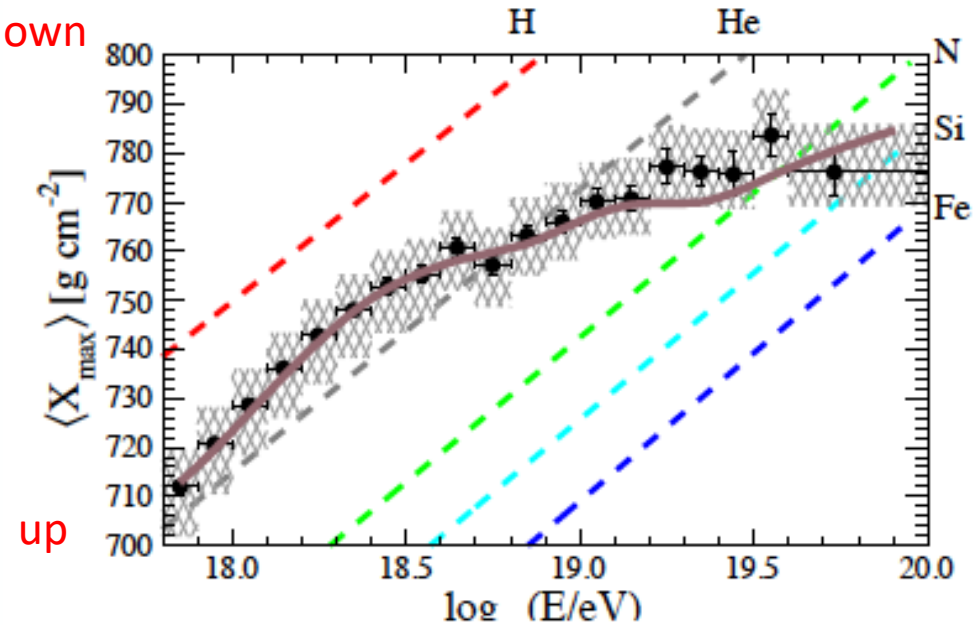
F. G. Schröder ‘19

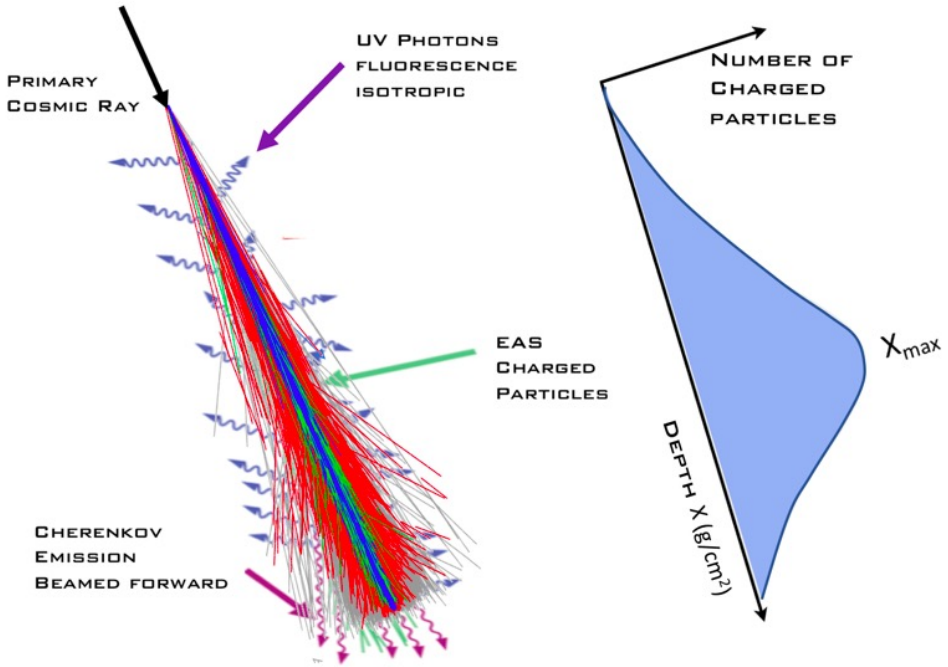


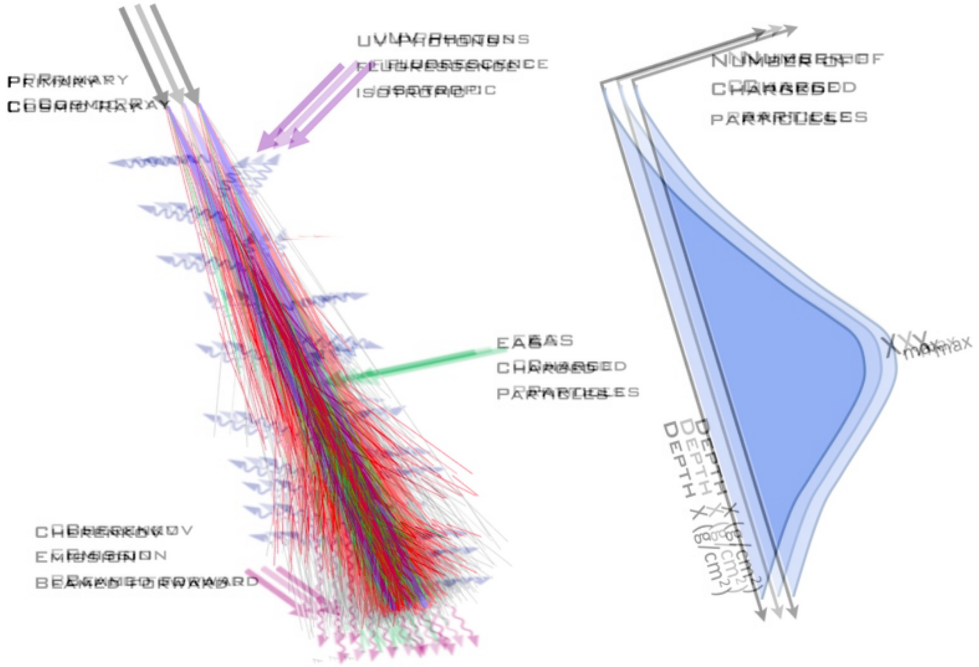
Higher E more penetrating

down

up



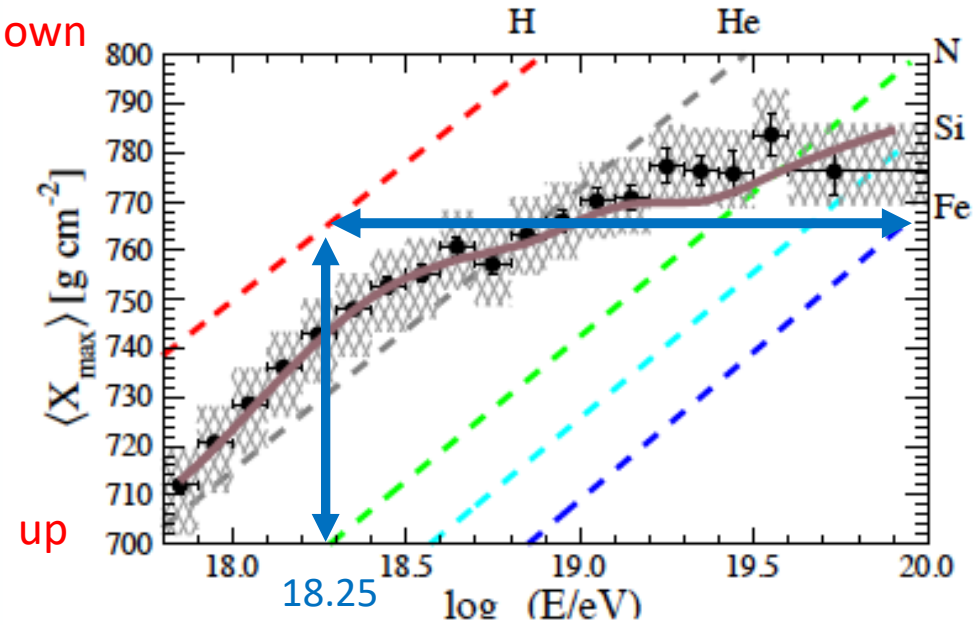




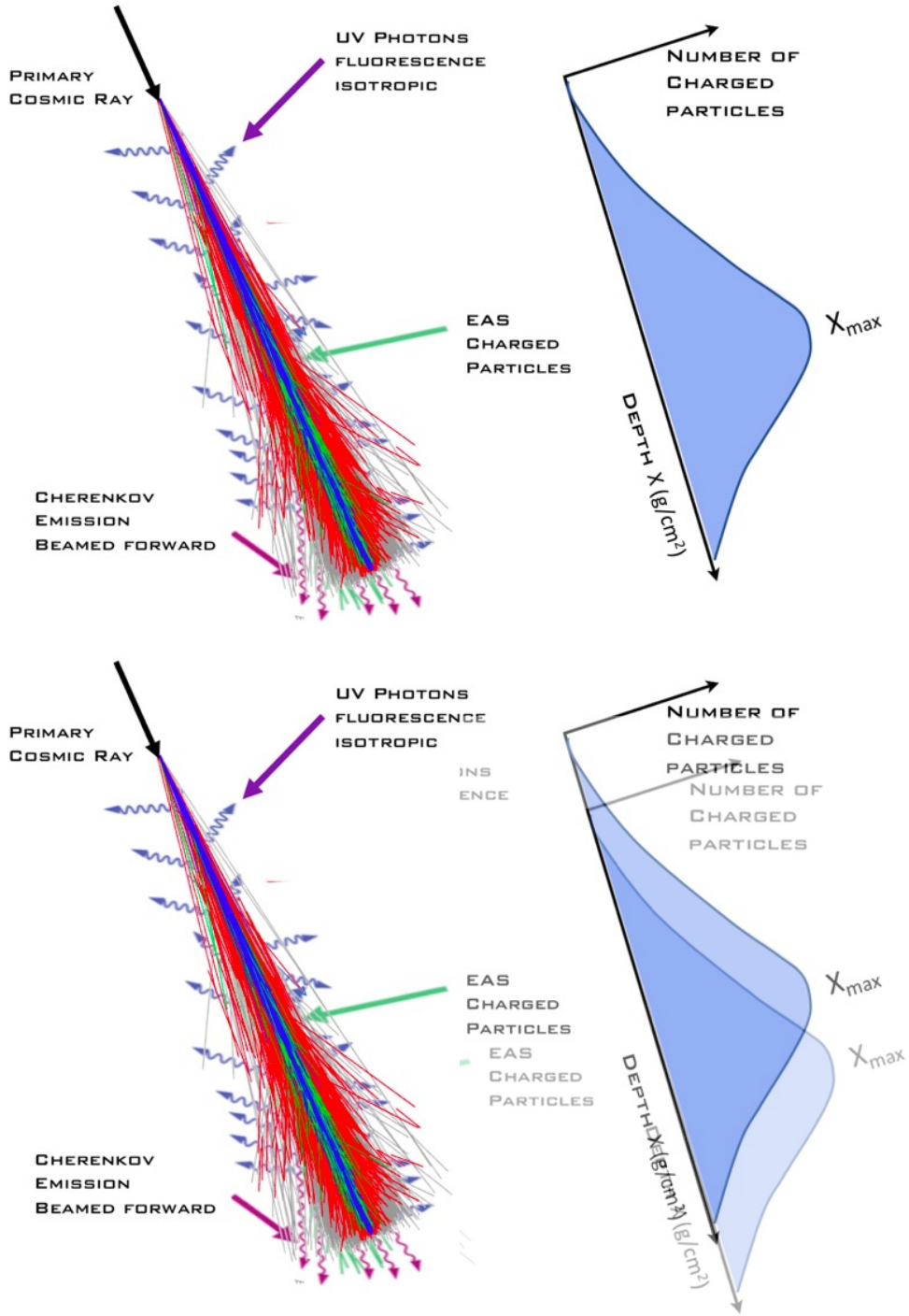
Higher E more penetrating

down

up



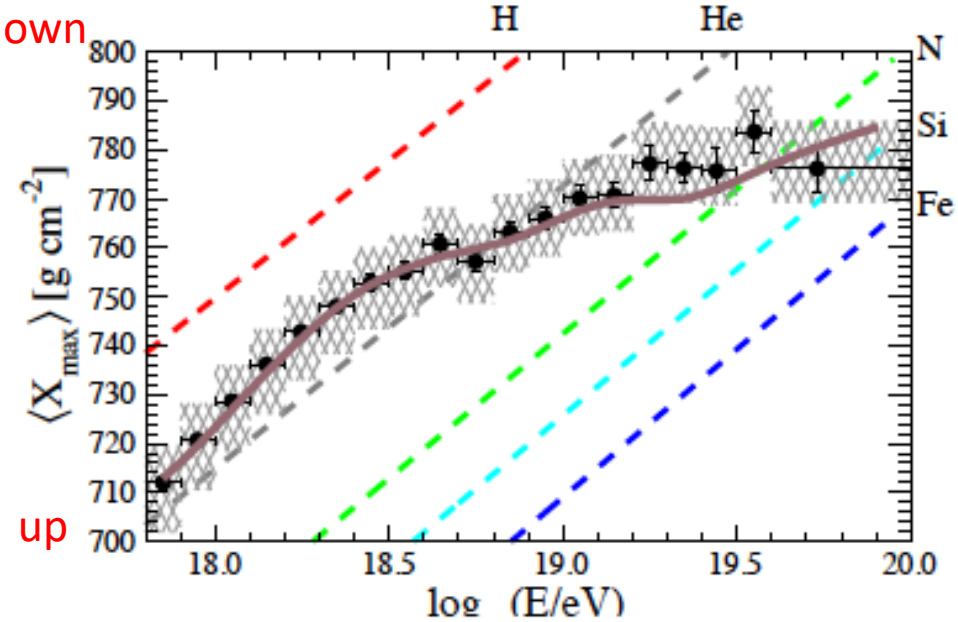
$X_{max}\ (E_A, A) \sim X_{max}\ (E_p / A)$



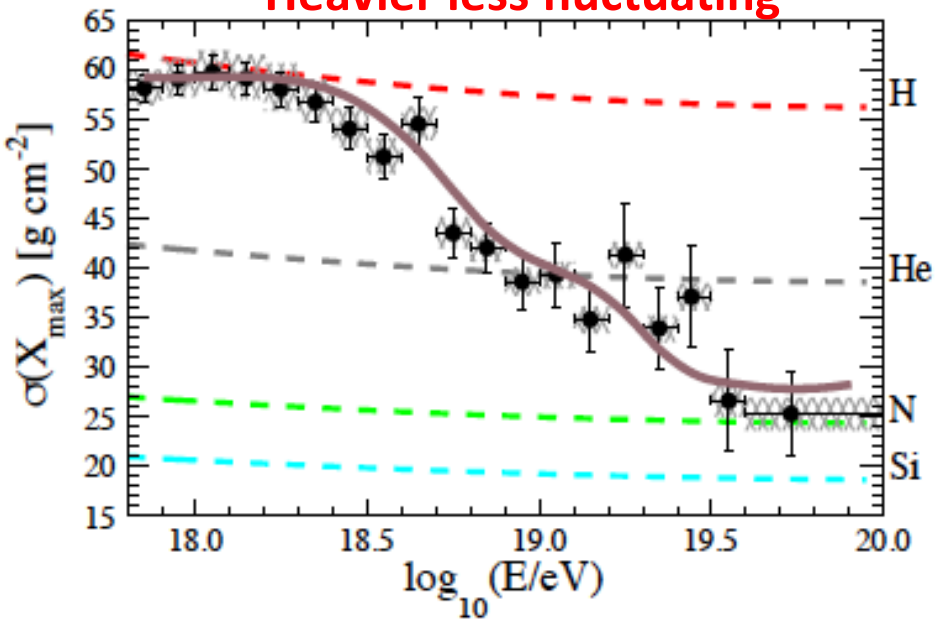
Higher E more penetrating

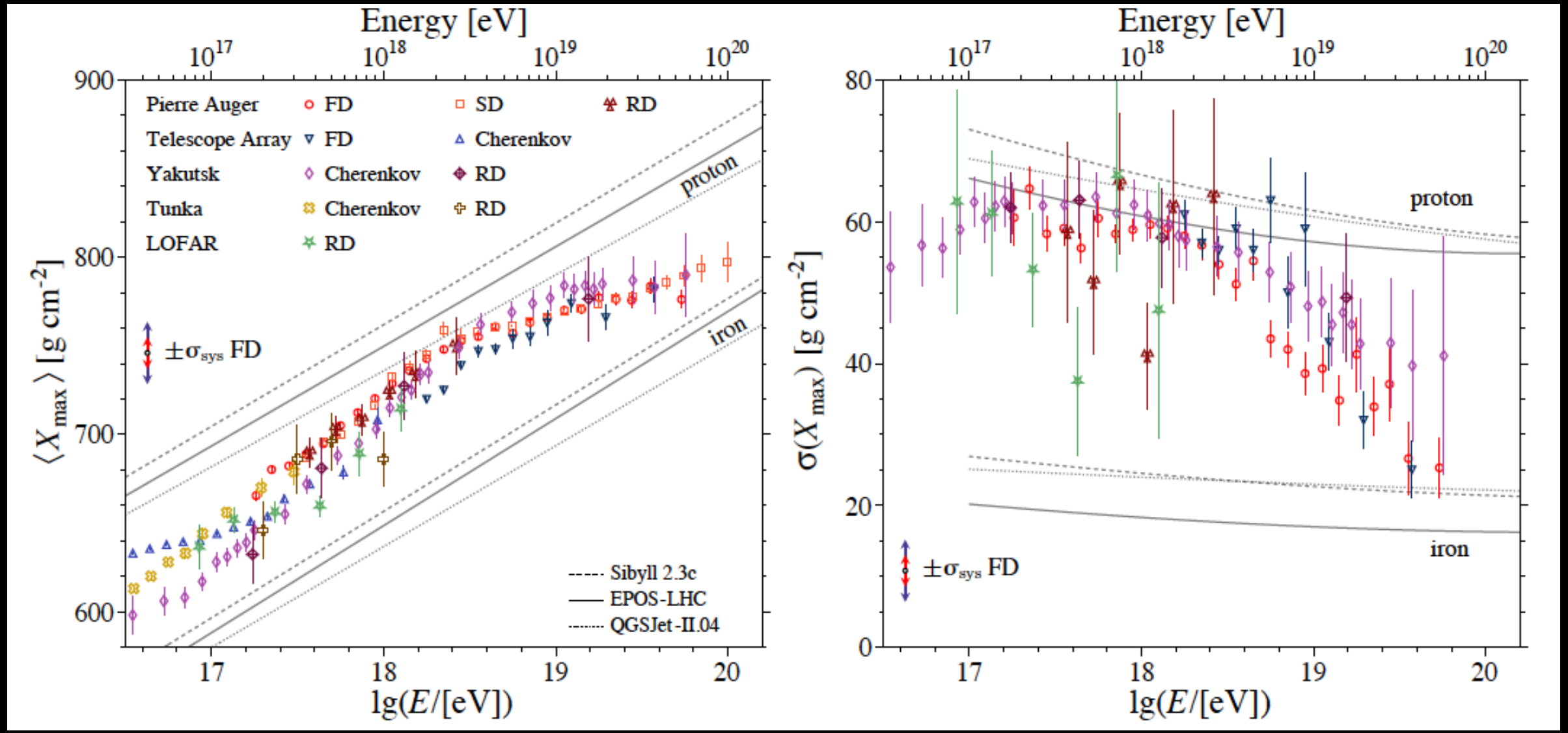
down

up

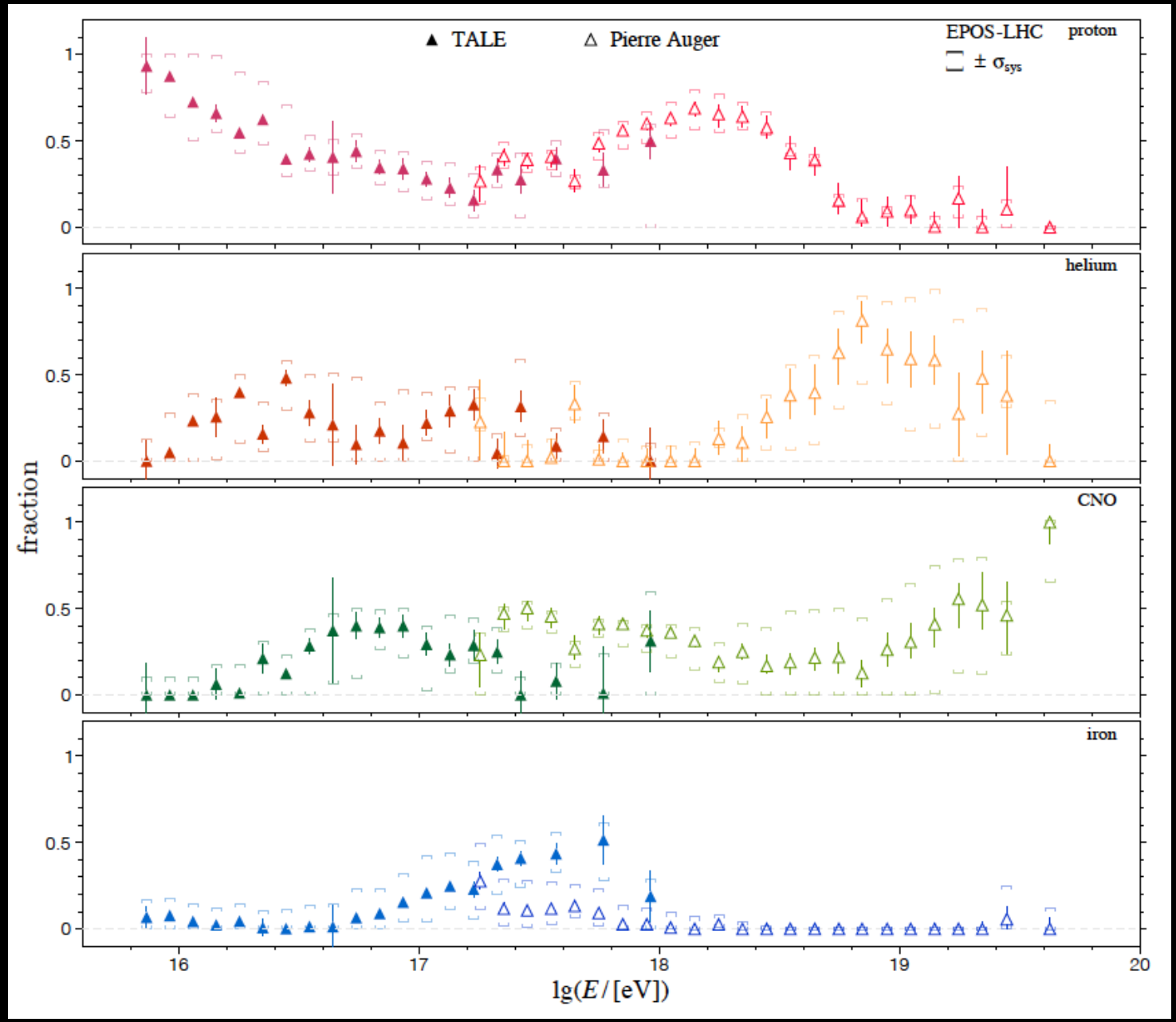


Heavier less fluctuating



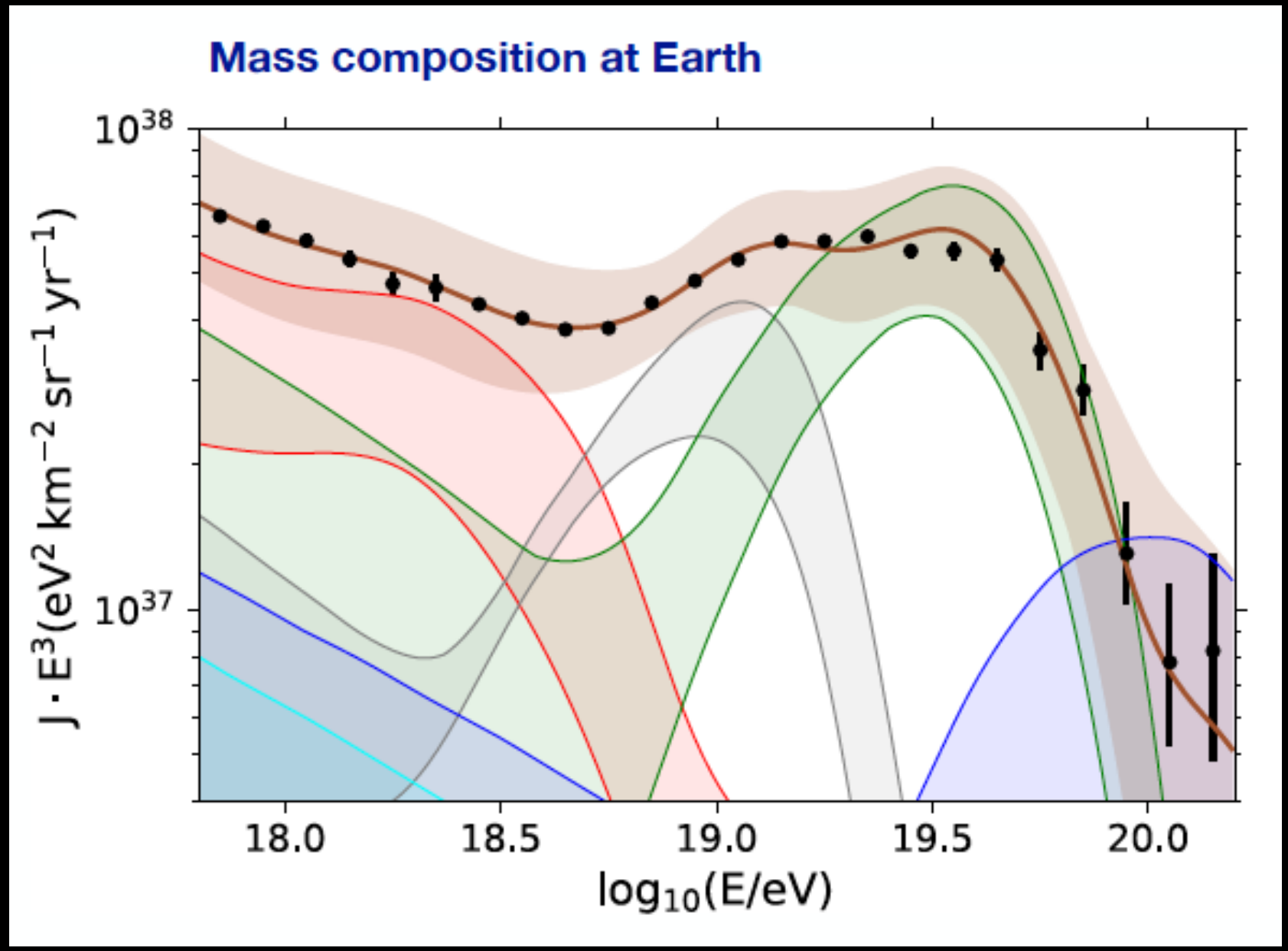


Coleman et al, 2022
arXiv:2205.05845

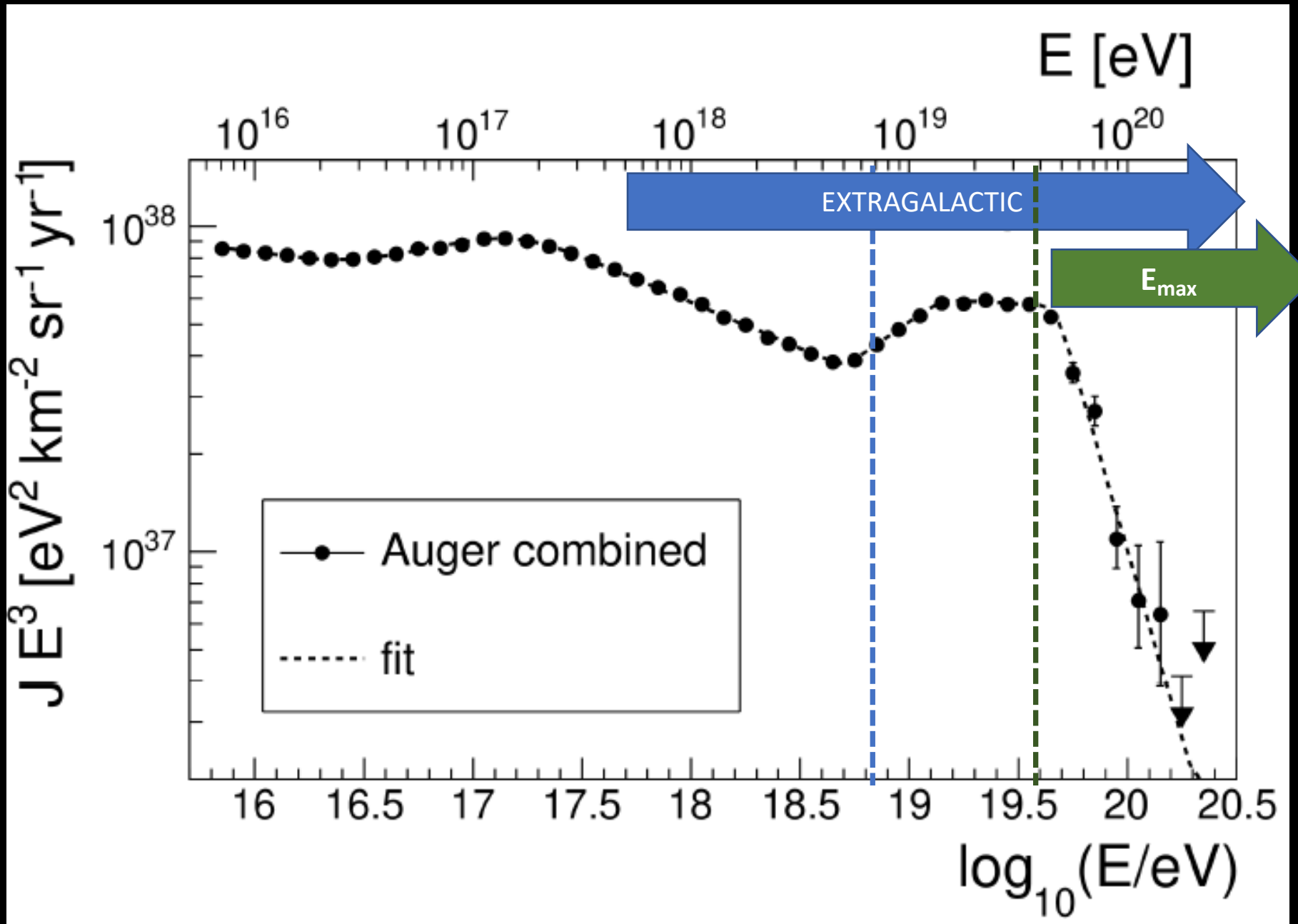


Coleman et al, 2022
arXiv:2205.05845

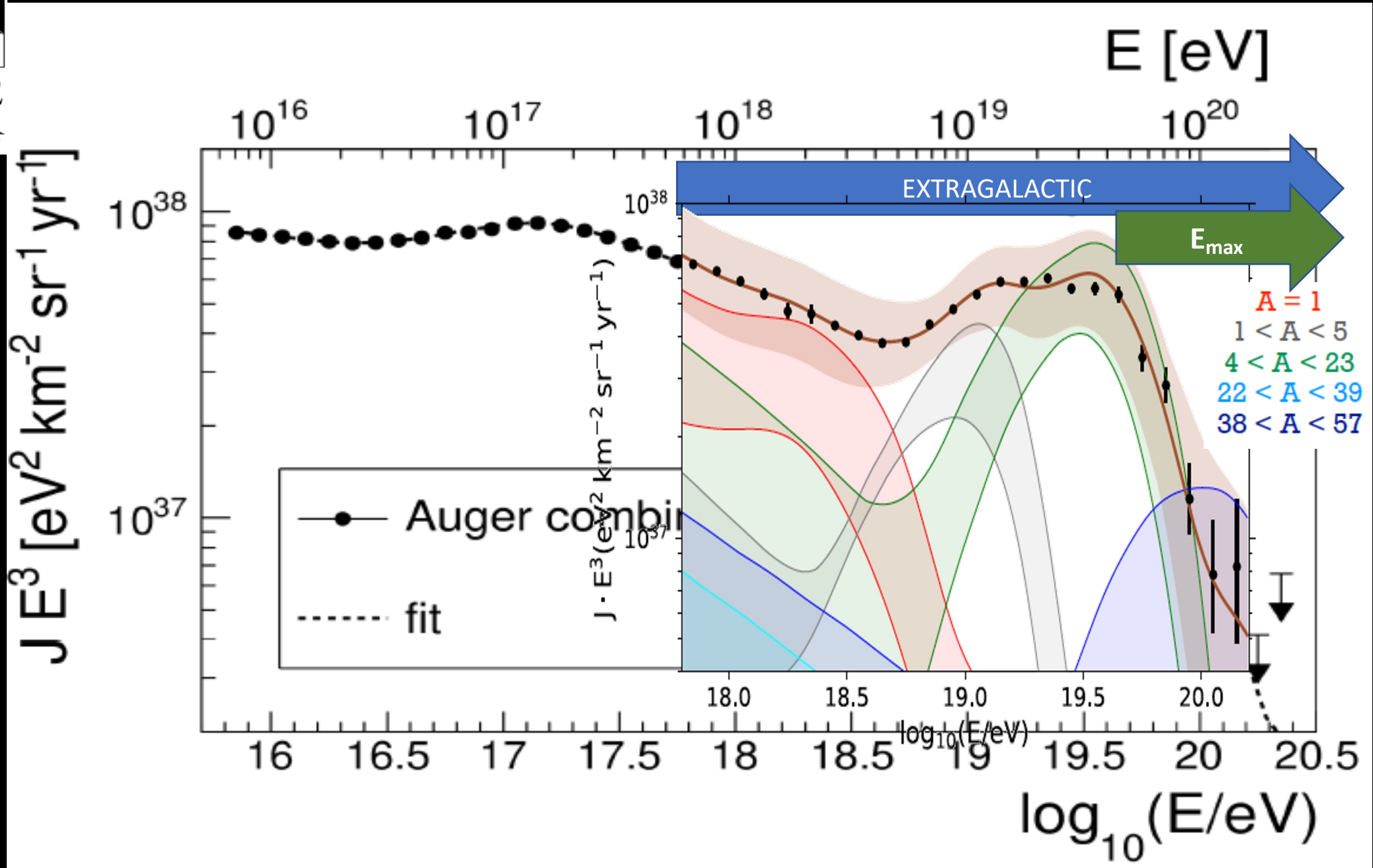
Auger Composition ICRC 2021



Auger Spectrum ICRC 2021



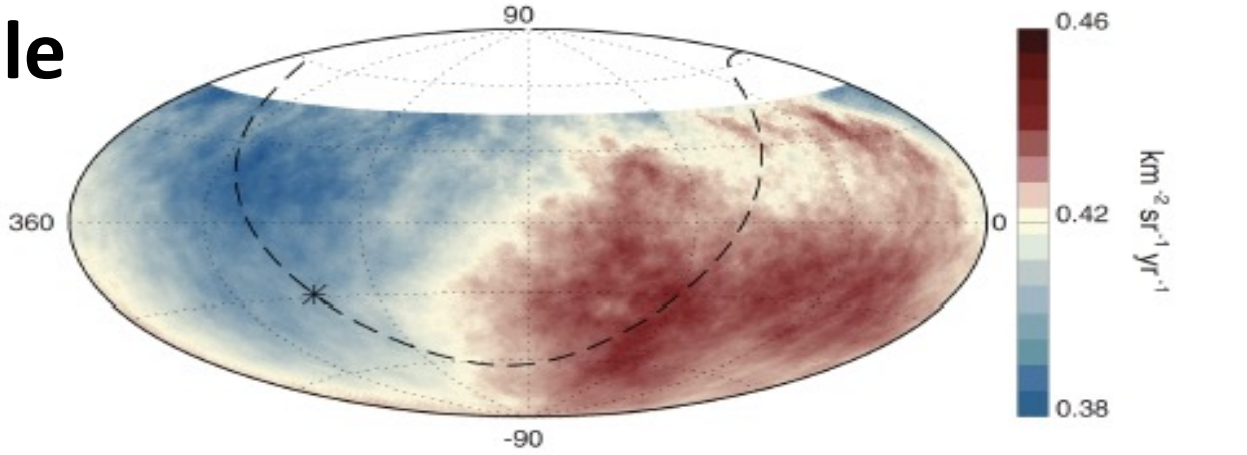
Auger Spectrum+Composition ICRC 2021

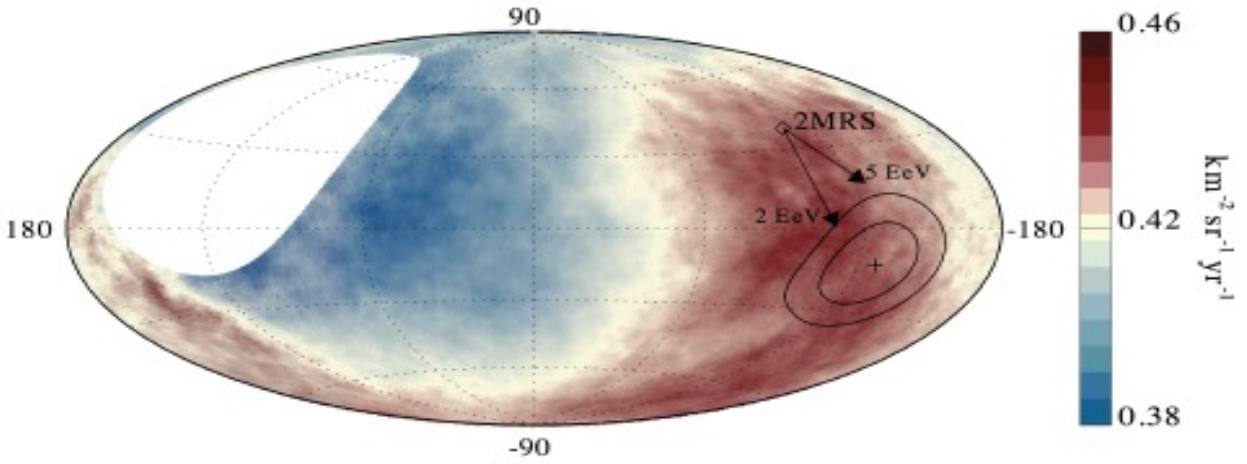


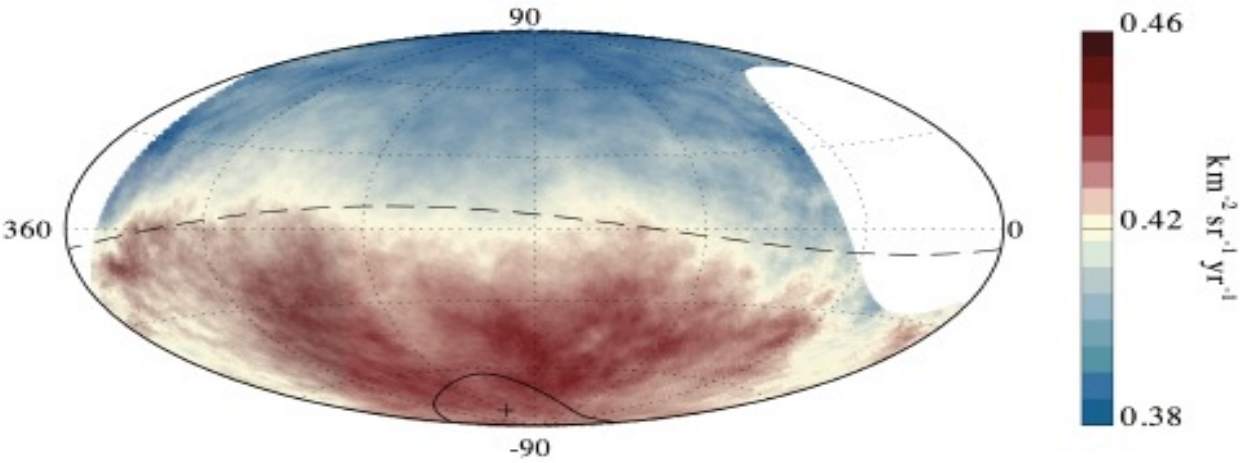
What is the sky distribution of arrival directions?

Auger Dipole

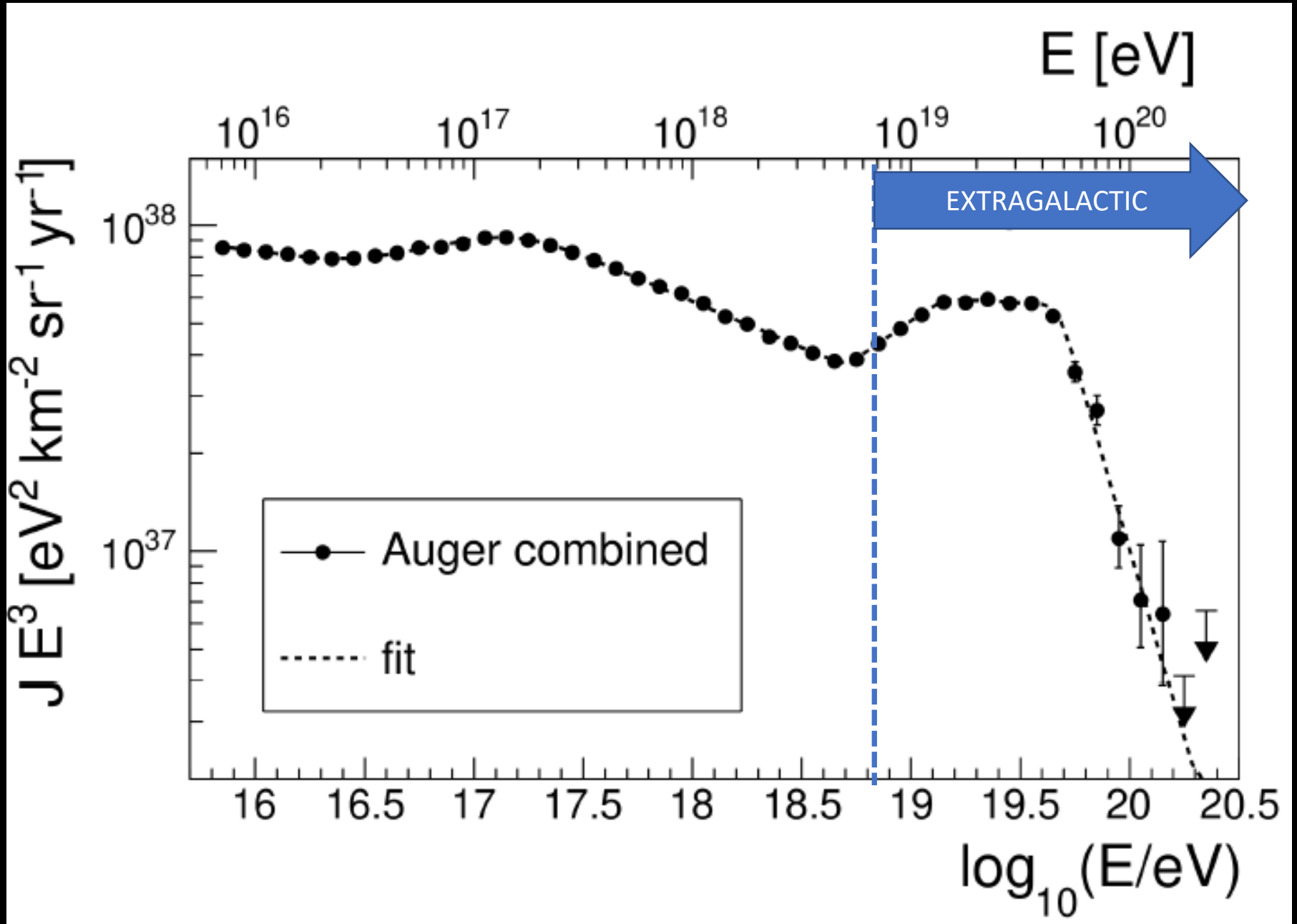
E > 8 EeV, 6.5%



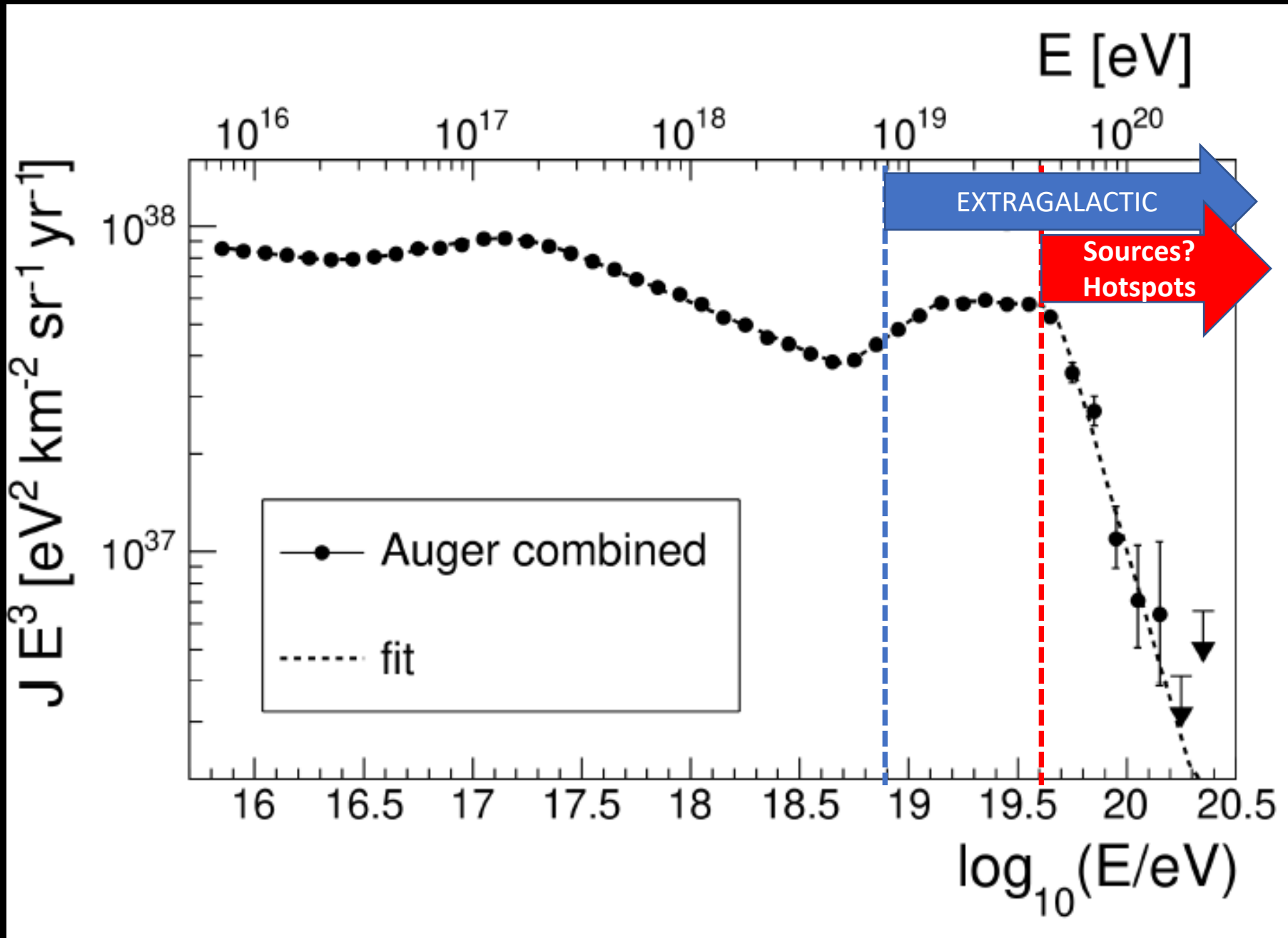




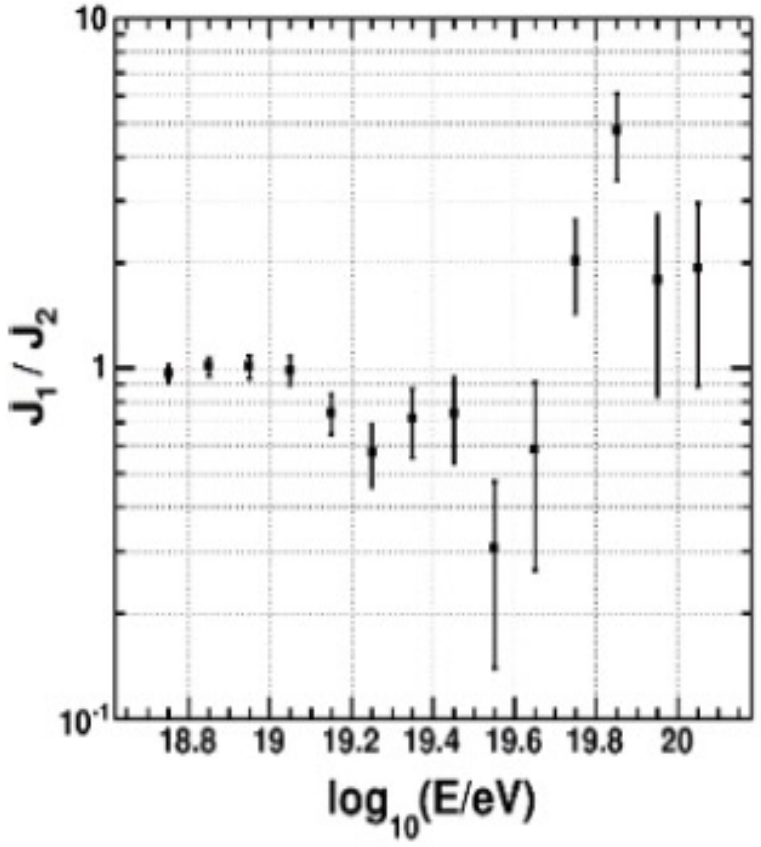
Auger Spectrum ICRC 2021

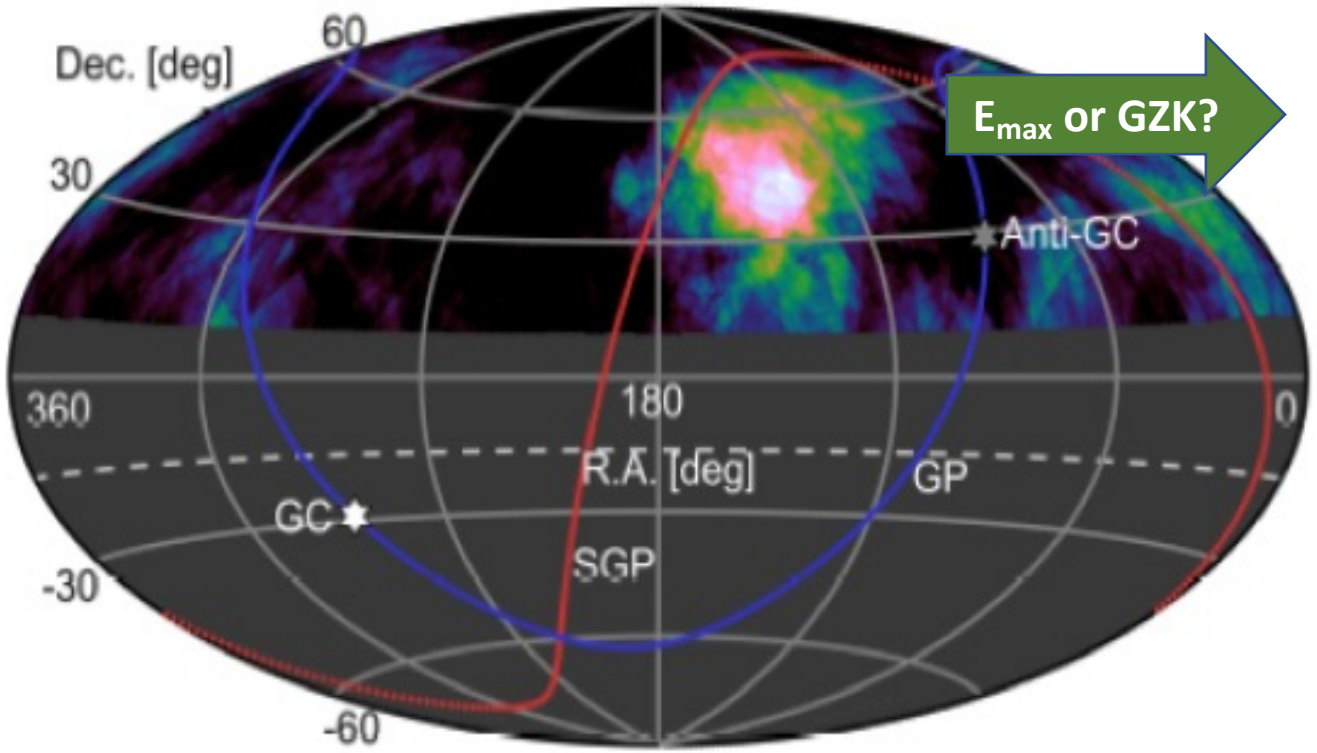


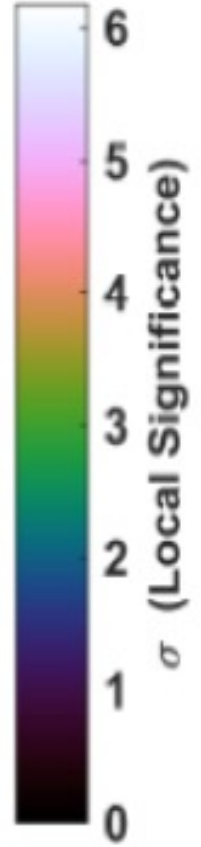
Auger Spectrum ICRC 2021



TA hotspot (E>50 EeV)



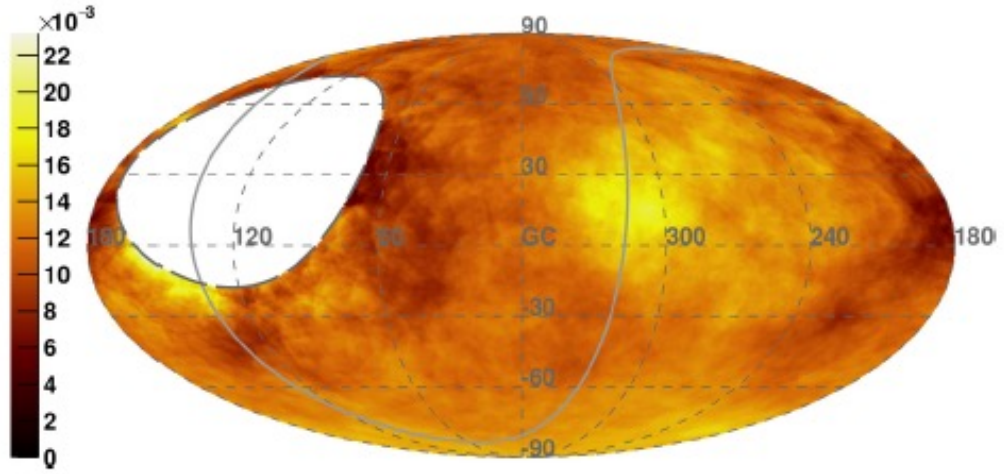


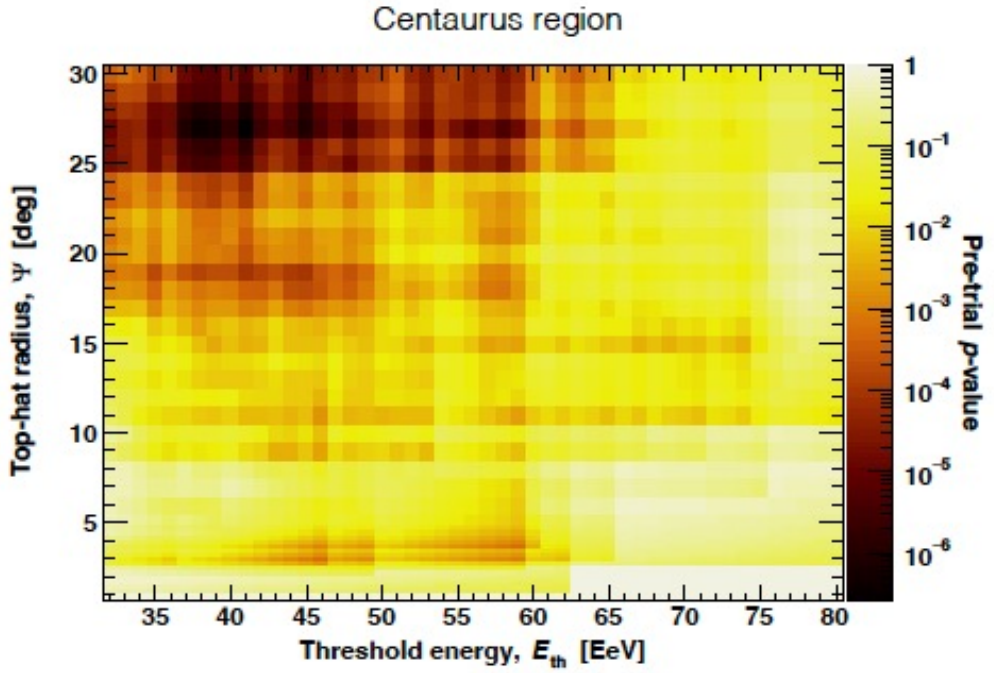


TA SD flux (7 years) inside the TA hotspot circle divided by that outside

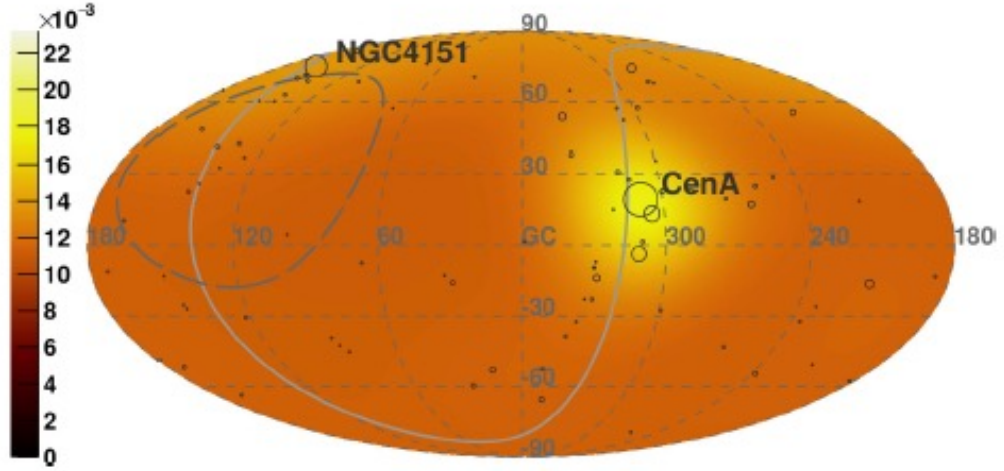
Coleman et al, 2022
arXiv:2205.05845

Auger skymaps (E>38 EeV and 41 EeV)

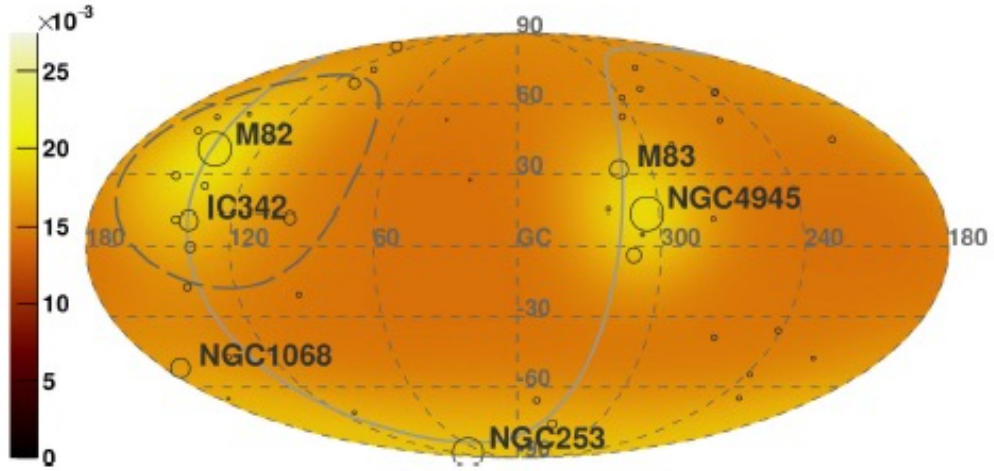




All AGN (hard X-rays) - expected $\Phi(E_{Auger} > 41\ EeV)$ [km^{-2} sr^{-1} yr^{-1}]



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



Coleman et al, 2022
arXiv:2205.05845

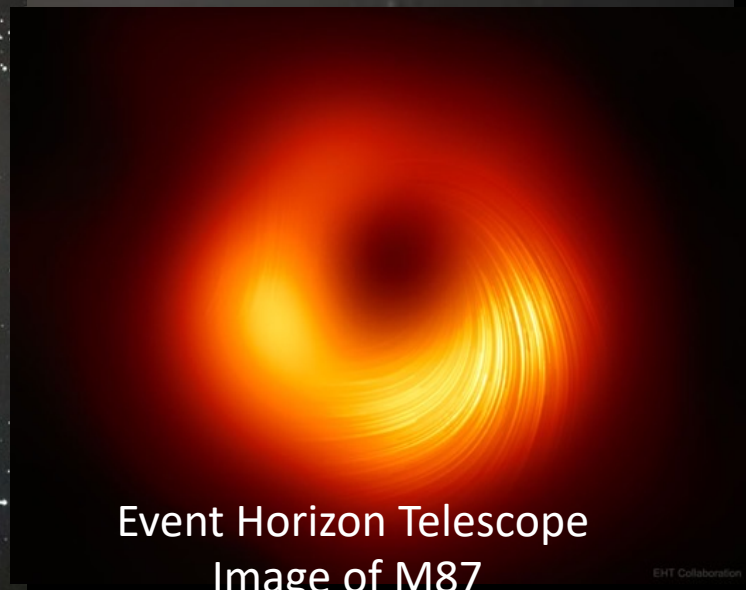
Starbursts Galaxies or Active Galactic Nuclei?

M82 – Starburst Galaxy

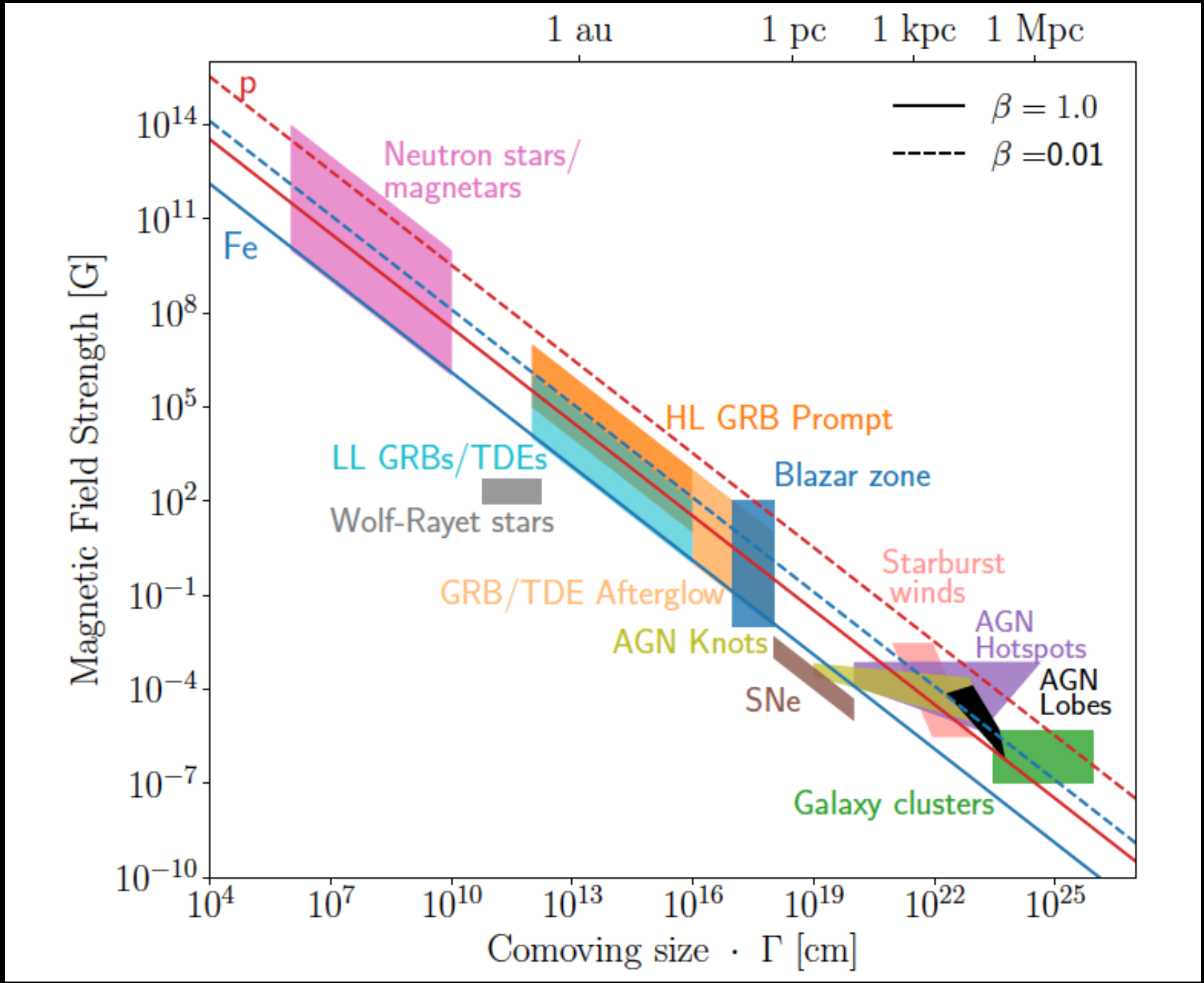
M87- AGN

Centaurus A – AGN

Sculptor Galaxy NGC 253

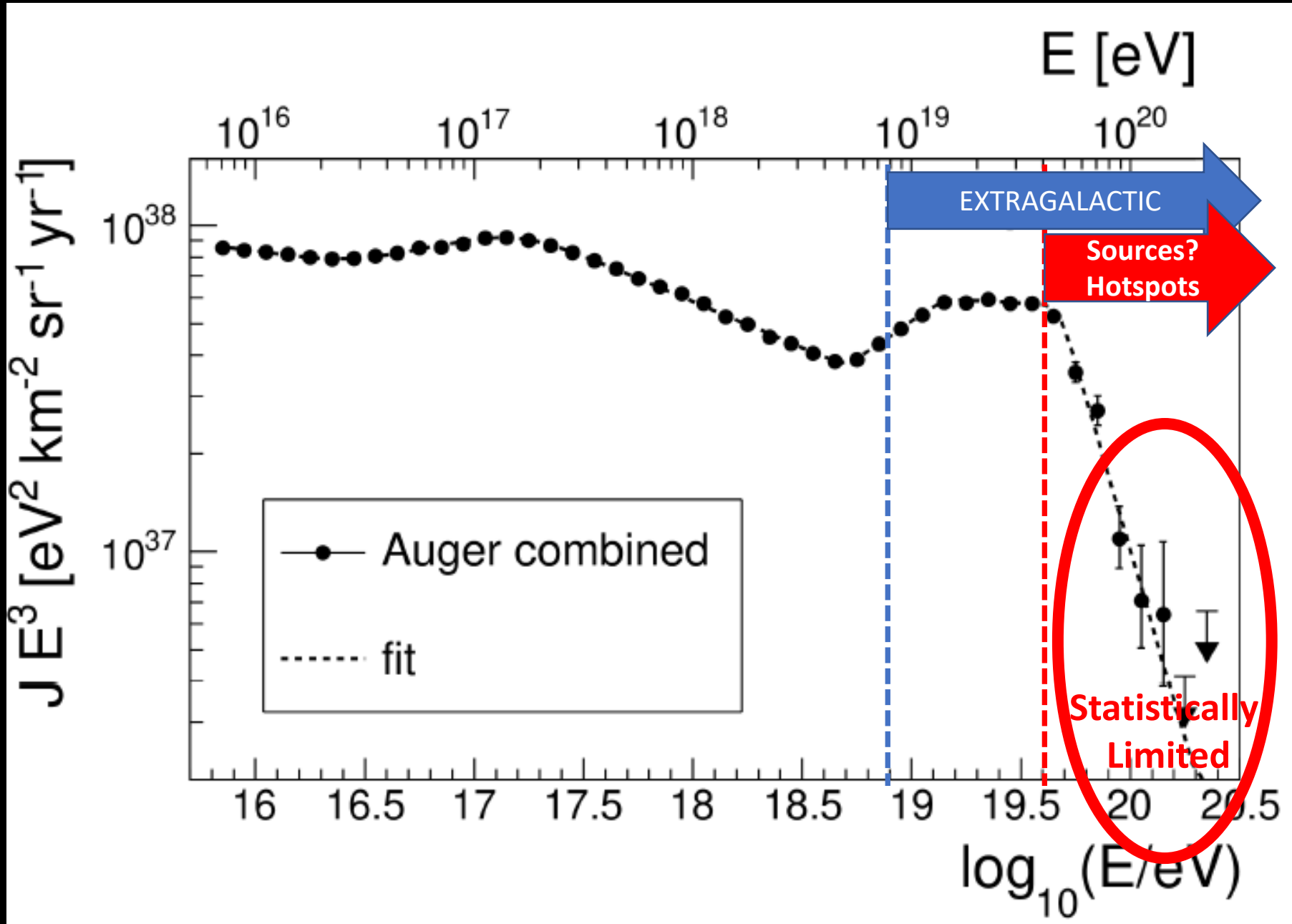


Event Horizon Telescope
Image of M87



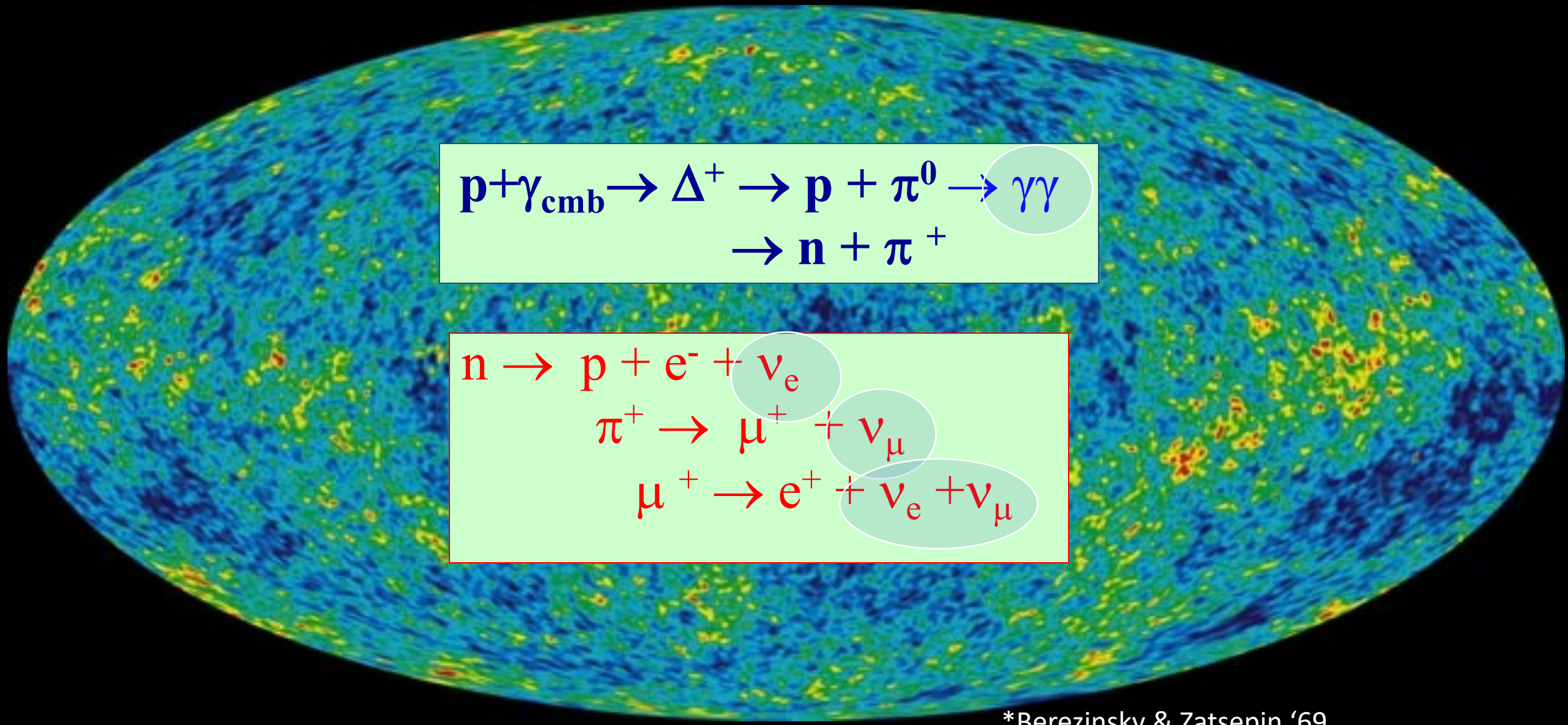
Coleman et al, 2022
arXiv:2205.05845

Auger Spectrum ICRC 2021



Where are the neutrino and gamma-ray secondaries?

Cosmogenic (GZK, BZ*) Neutrinos & Photons

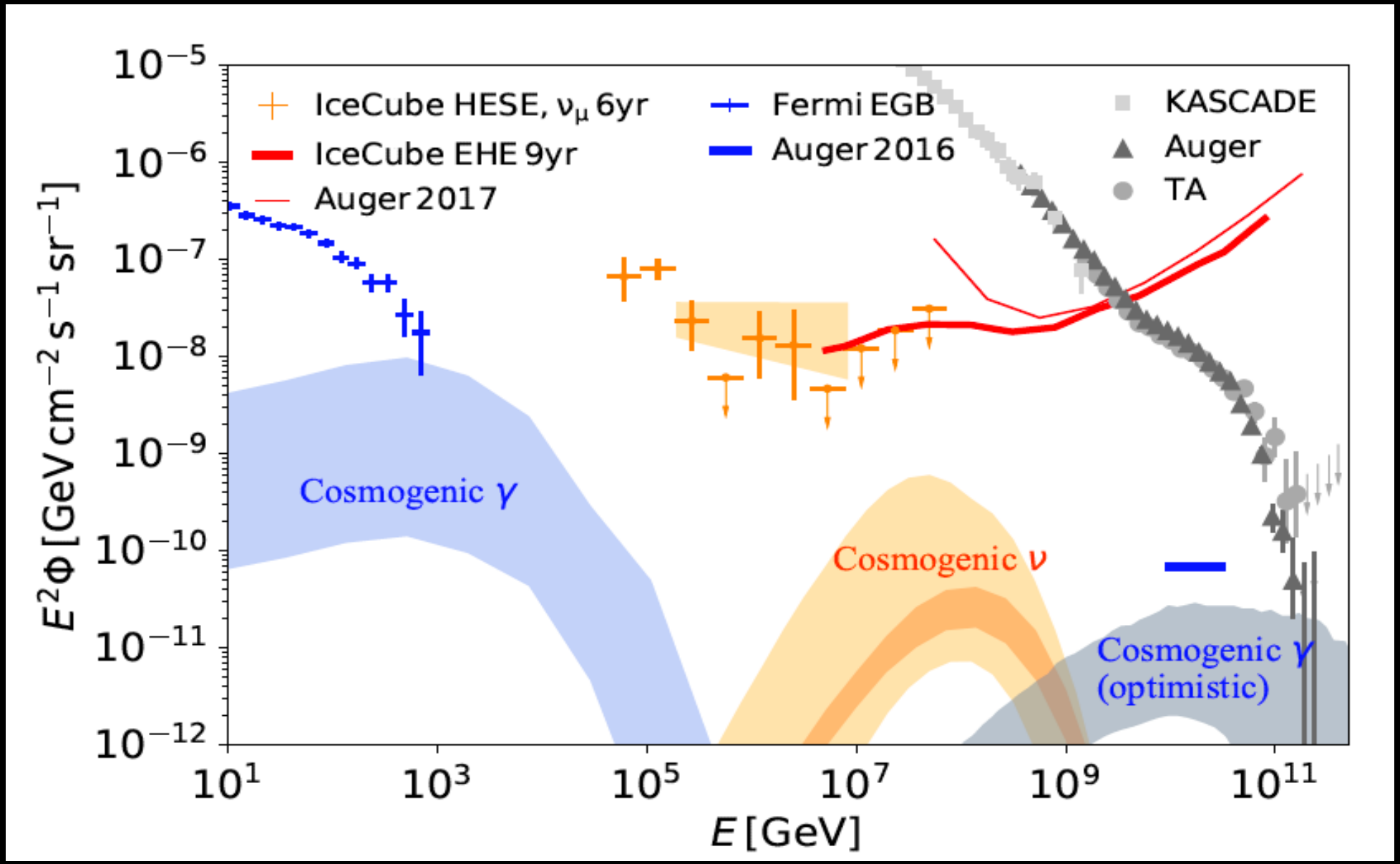


$$p + \gamma_{cmb} \rightarrow \Delta^{+} \rightarrow p + \pi^{0} \rightarrow \gamma\gamma$$
$$\rightarrow n + \pi^{+}$$

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

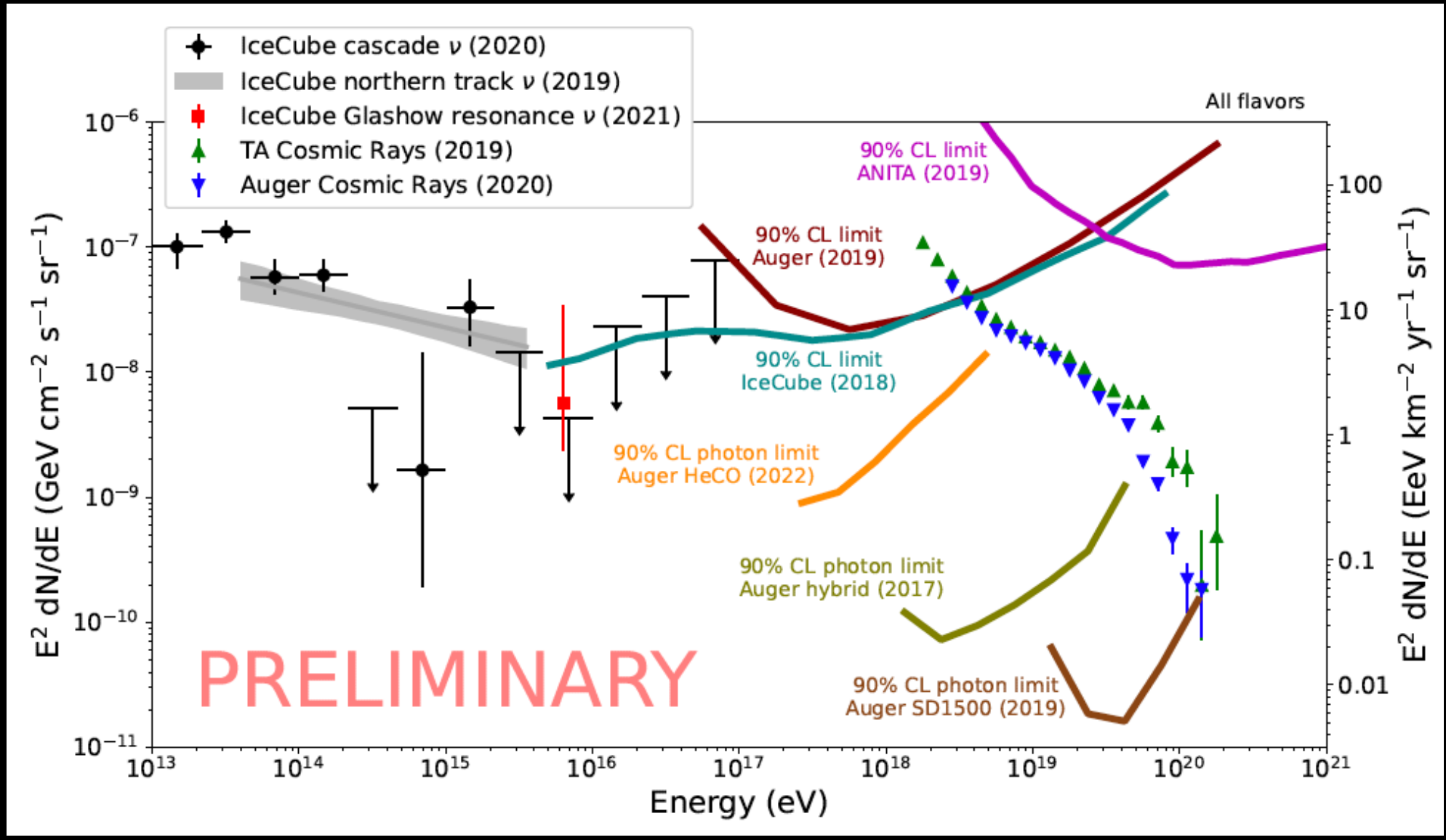
*Berezinsky & Zatsepin ‘69

Cosmogenic Messengers



Batista et al, arXiv:1903.06714.pdf

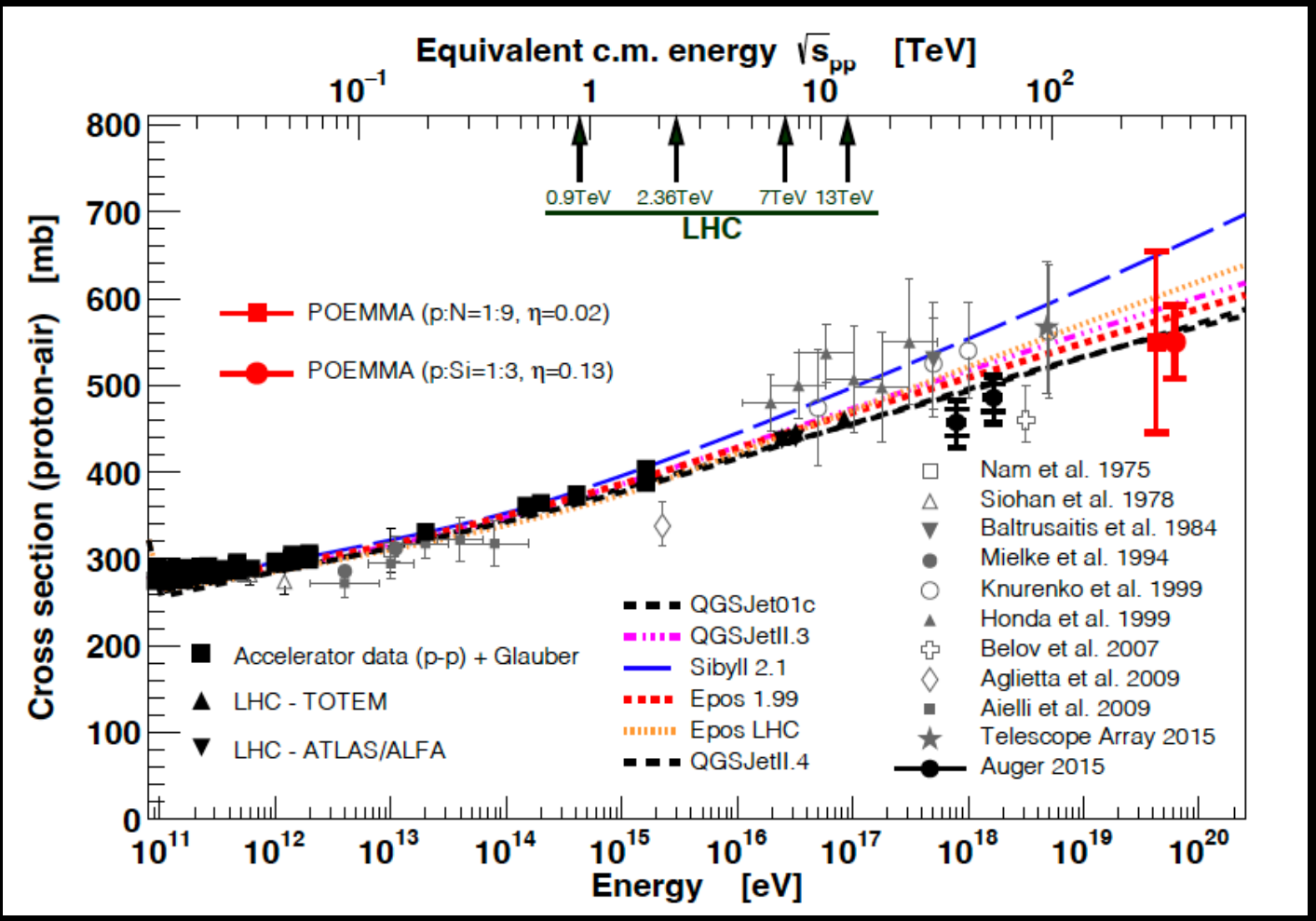
Limits on Neutrino and Gamma-Rays at UHE



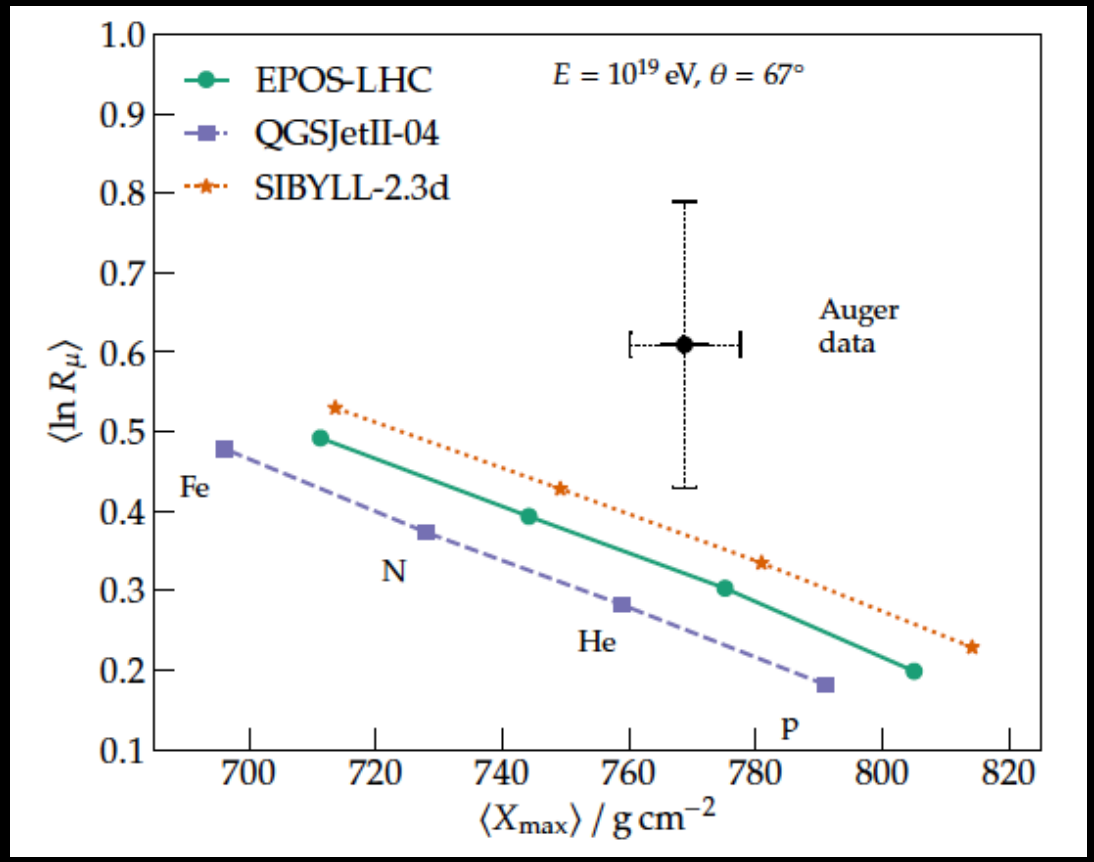
Coleman et al, 2022 arXiv:2205.05845

What physical processes do UHECRs probe?

Proton-Air cross section



Hadronic Interactions + muon content in EASs



Coleman et al, 2022 arXiv:2205.05845

Constraints on Super-Heavy Dark Matter

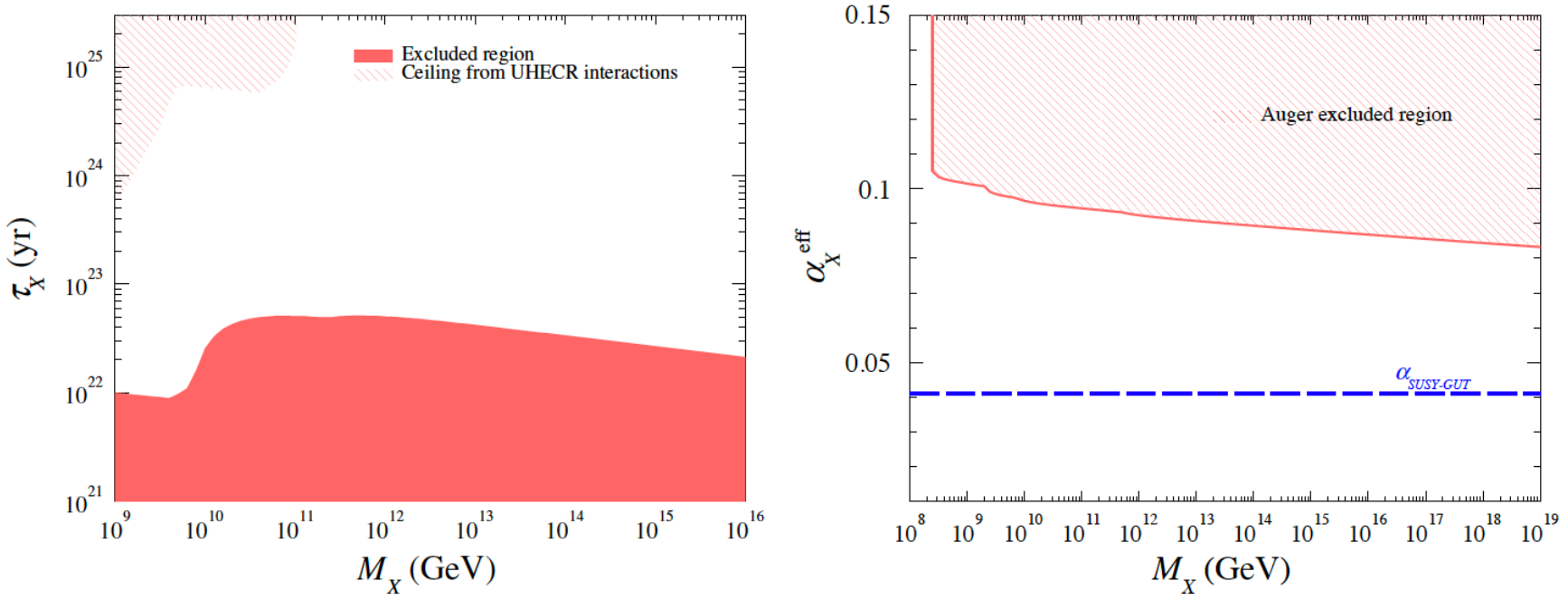
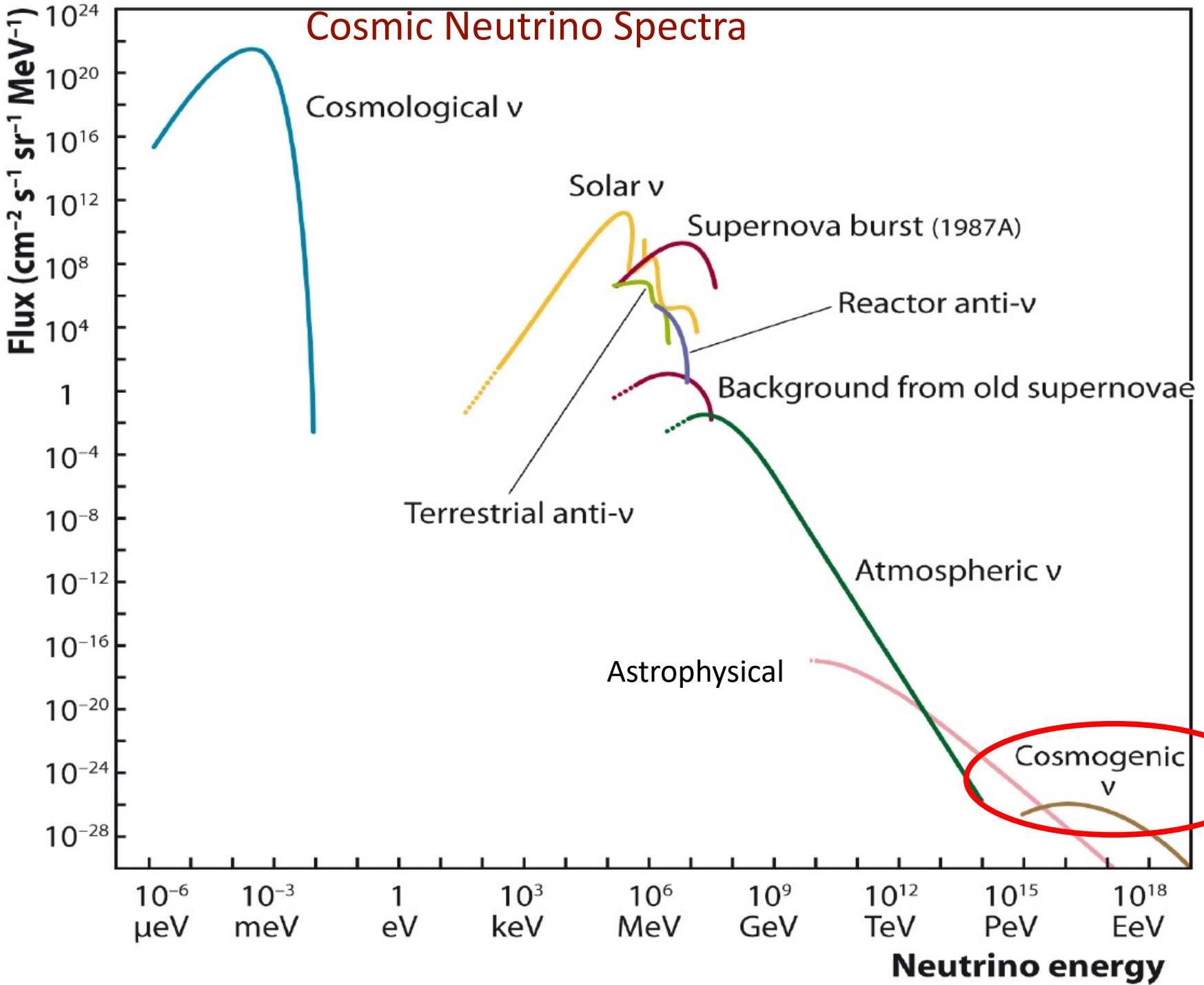


Figure 3.8: Constraints on the mass and lifetime of SHDM particles as obtained from the upper limits on photons [375] (left) and upper limits at 95% C.L. on the effective coupling constant of a hidden gauge interaction as a function of the mass for a dark matter particle decaying into $q\bar{q}$ [18] (right). For reference, the unification of the three SM gauge couplings is shown as the blue dashed line in the framework of supersymmetric GUTs [376]. Figures taken from Refs. [18, 375].

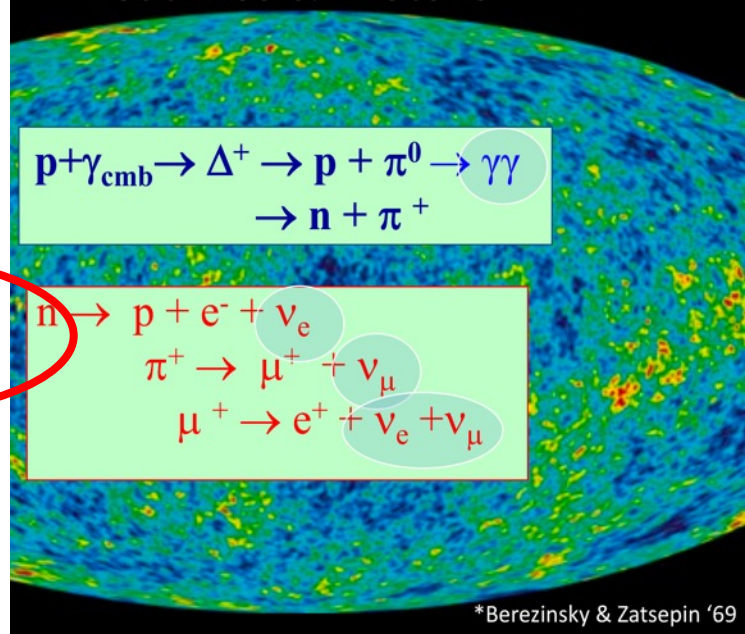
Coleman et al, 2022 arXiv:2205.05845

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

Cosmic Neutrino Spectra



Cosmogenic (GZK, BZ*) Neutrinos & Photons



*Berezinsky & Zatsepin '69

Cosmic Neutrino Spectra

Cosmological ν

Raymond Davis Jr.

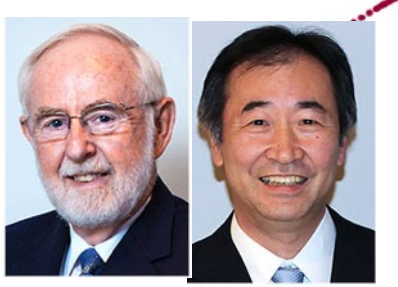
Masatoshi Koshiba

Solar ν

Supernova burst (1987A)

Reactor anti-ν

Background from old supernovae



Art McDonald SNO

Takaaki Kajita Super K

Atmospheric ν

ν from AGN

Astrophysical

Cosmogenic ν

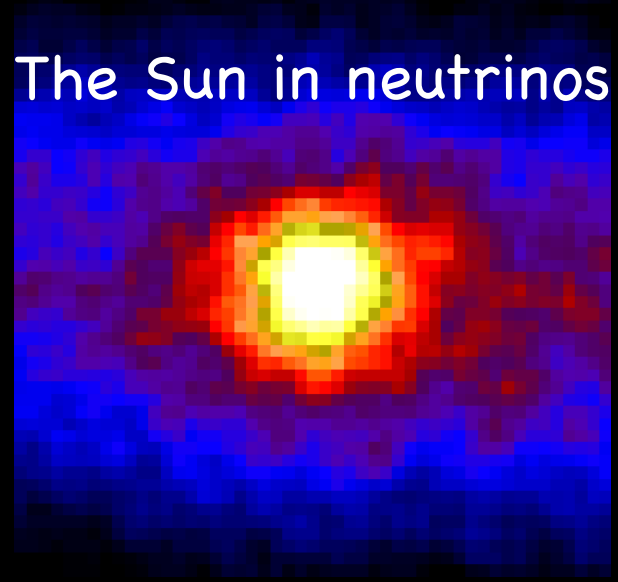
Flux ($cm^{-2}\ s^{-1}\ sr^{-1}\ MeV^{-1}$)

10^{24} 10^{20} 10^{16} 10^{12} 10^{8} 10^{4} 1 10^{-4} 10^{-8} 10^{-12} 10^{-16} 10^{-20} 10^{-24} 10^{-28}

10^{-6} μeV, 10^{-3} meV, 1 eV, 10^{3} keV, 10^{6} MeV, 10^{9} GeV, 10^{12} TeV, 10^{15} PeV, 10^{18} EeV

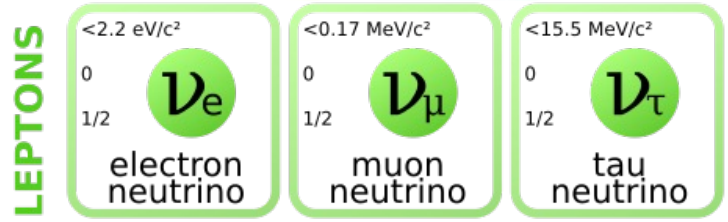
Neutrino energy

2002 Nobel Prize in Physics

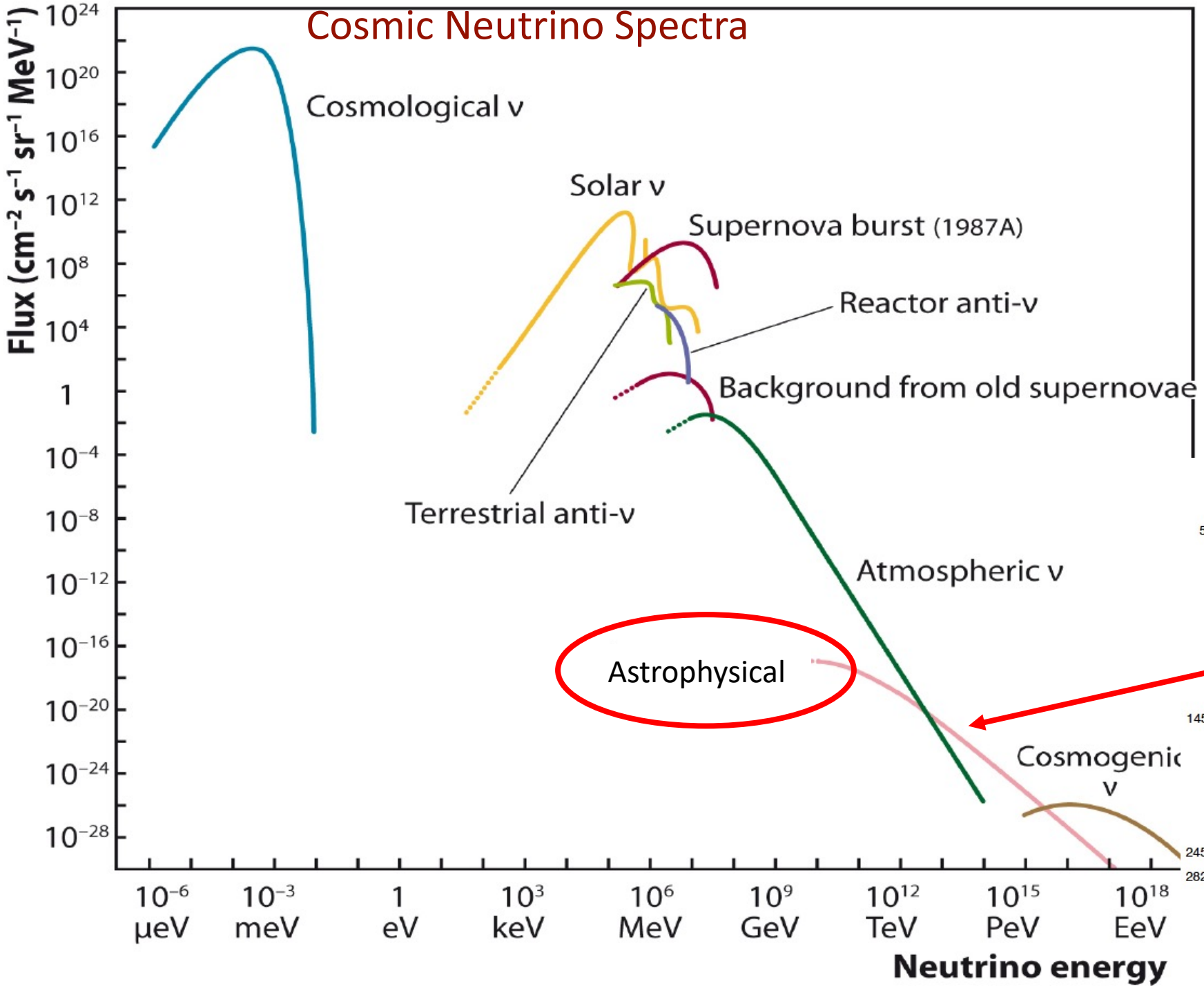


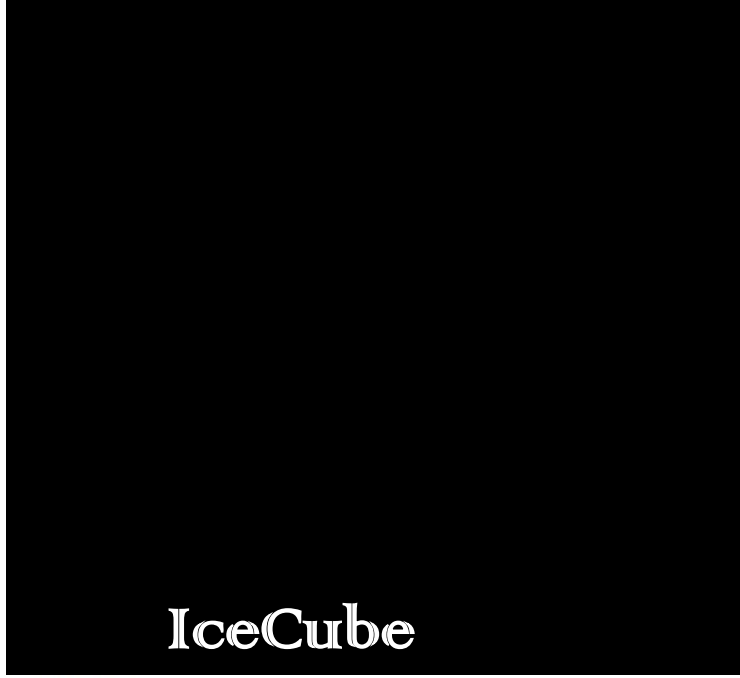
2015 Nobel Prize in Physics

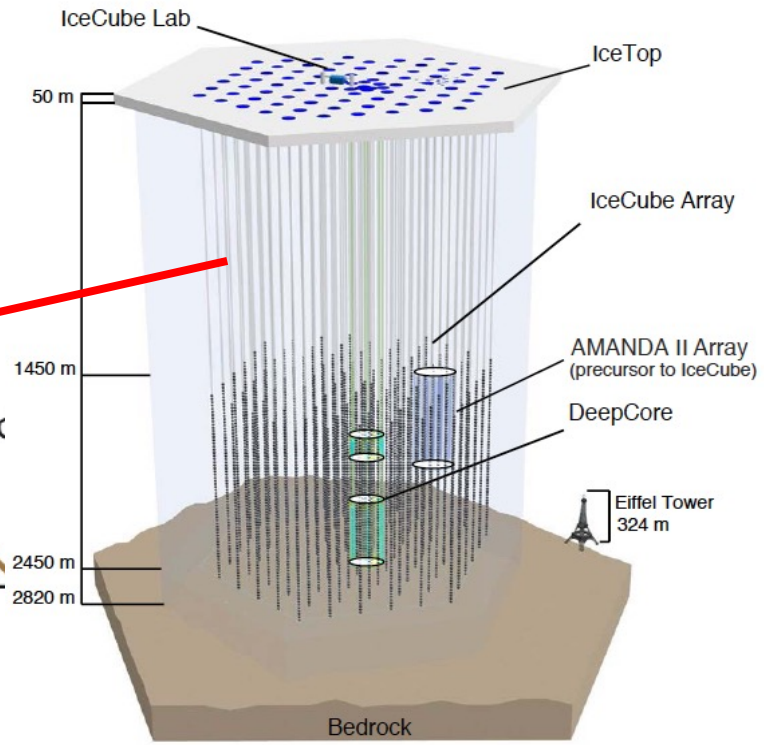
Neutrino Oscillations



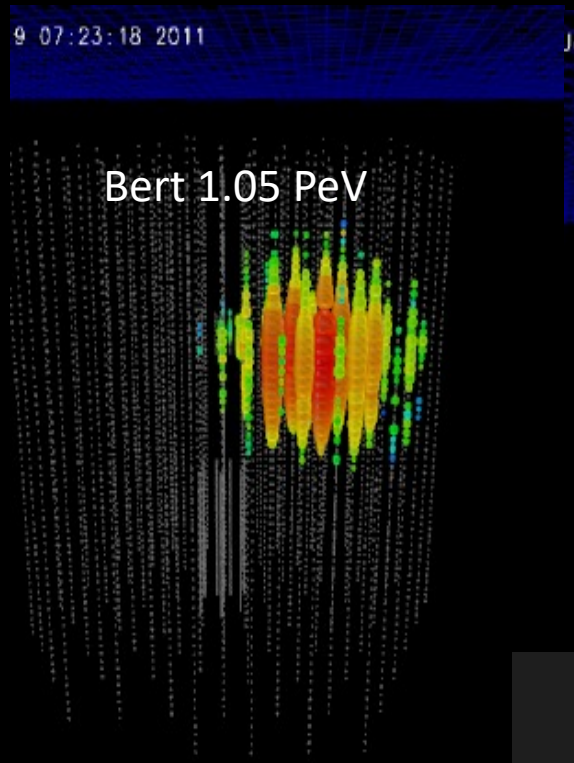
Cosmic Neutrino Spectra

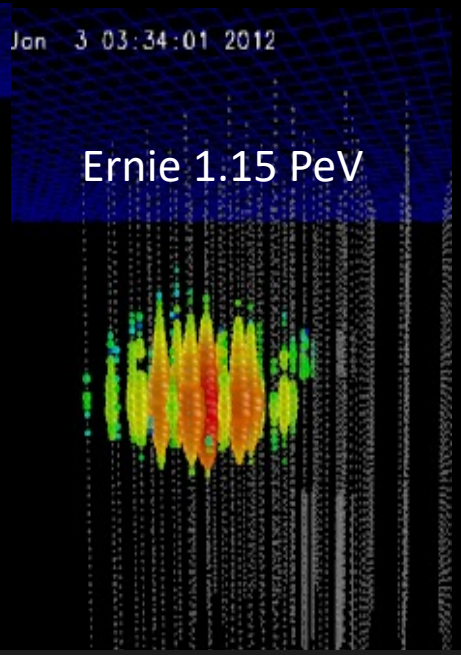


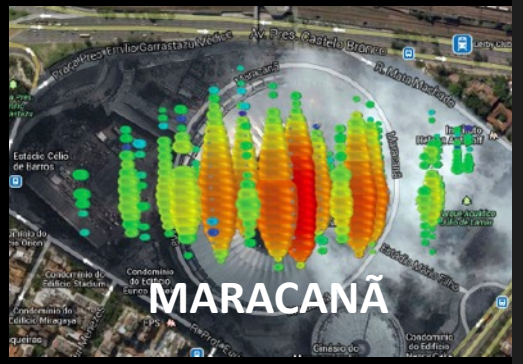


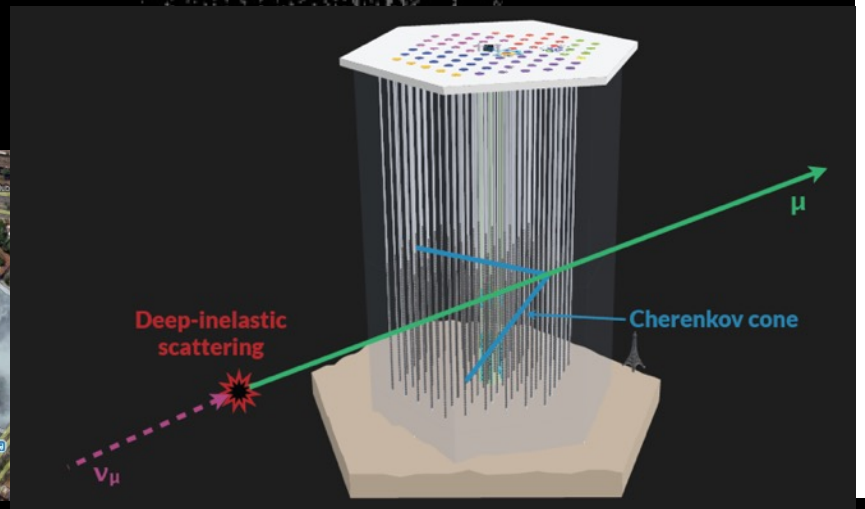


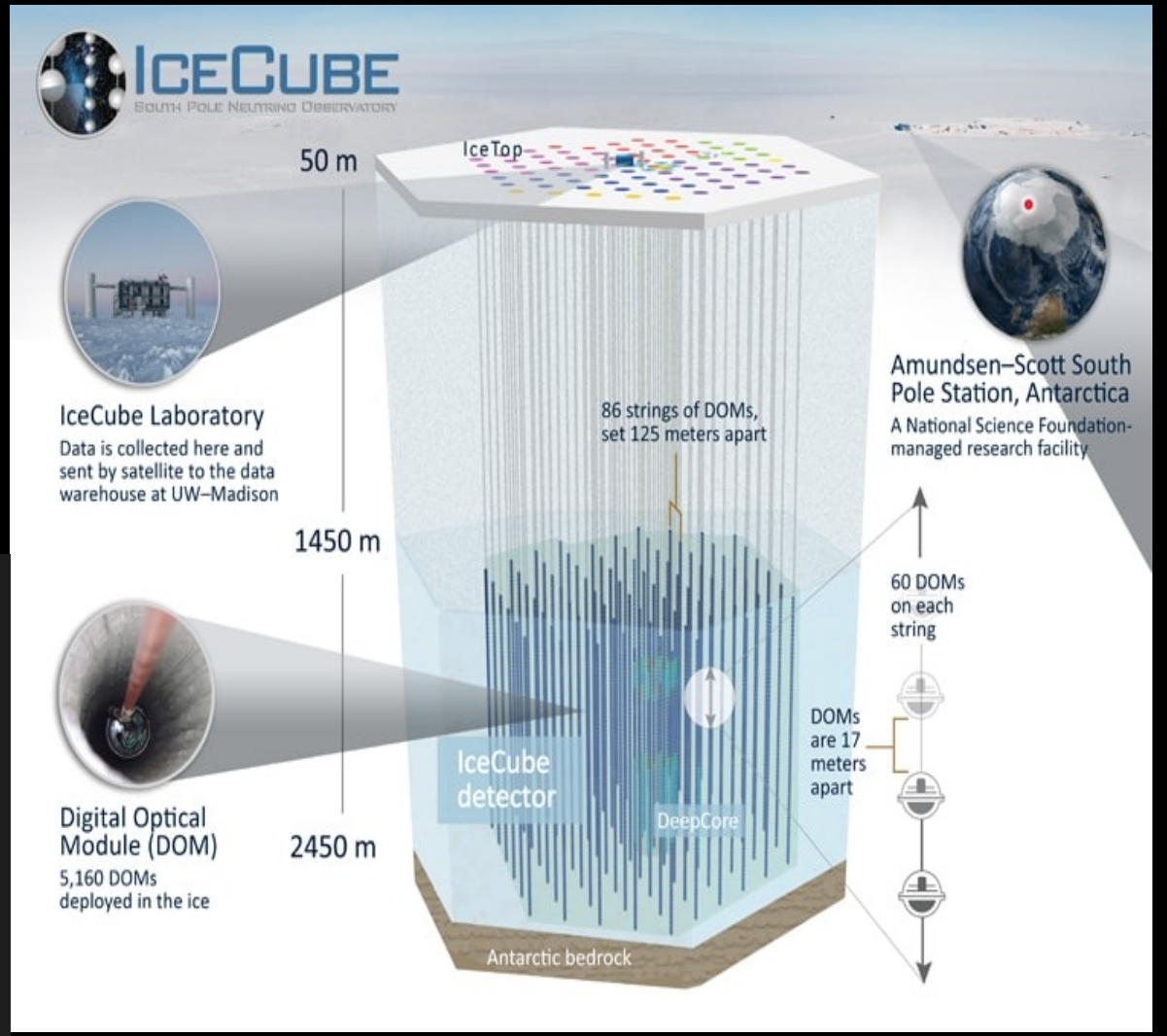
Extragalactic Neutrino Astronomy begins: IceCube (2013)



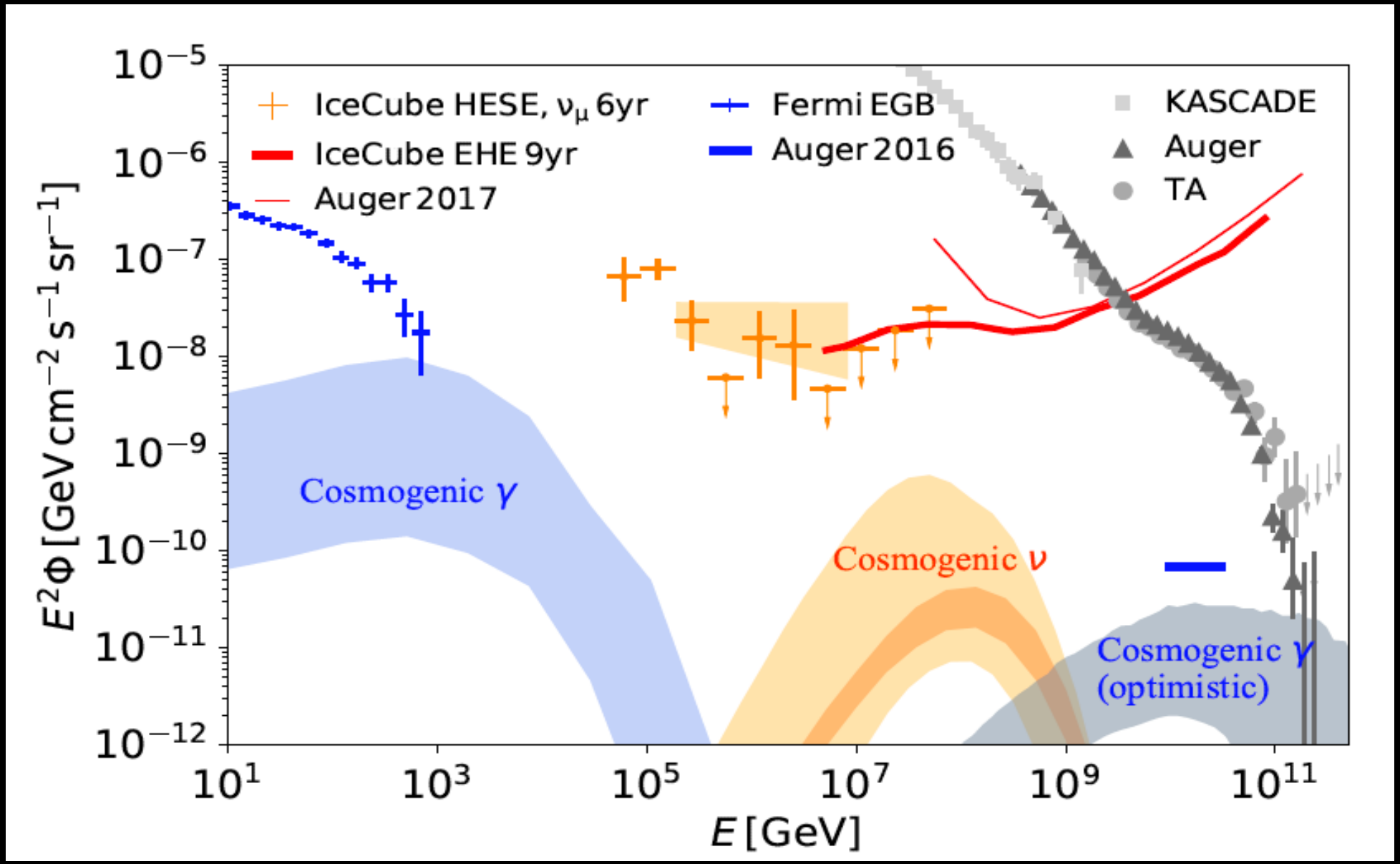






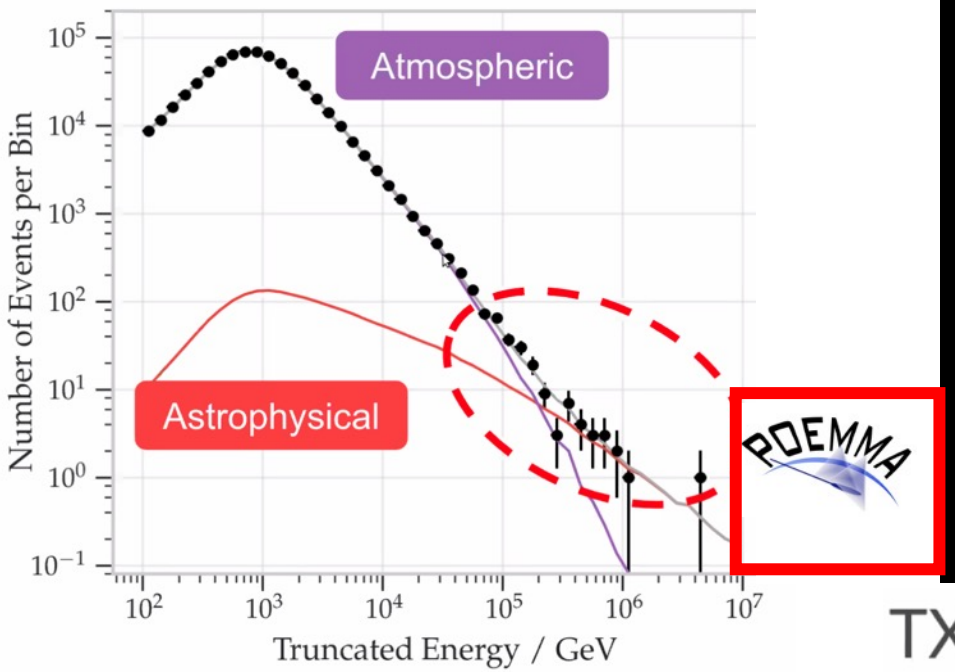


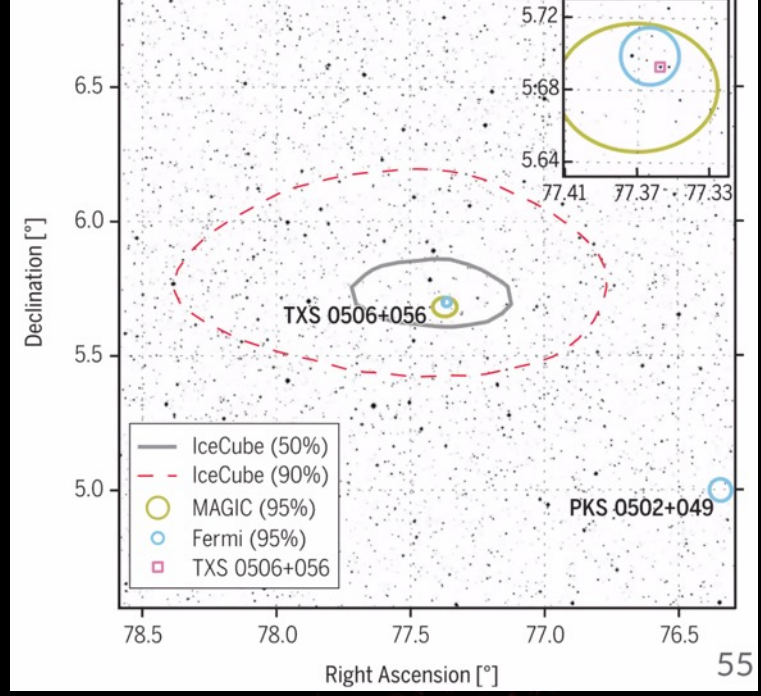
Cosmogenic Messengers

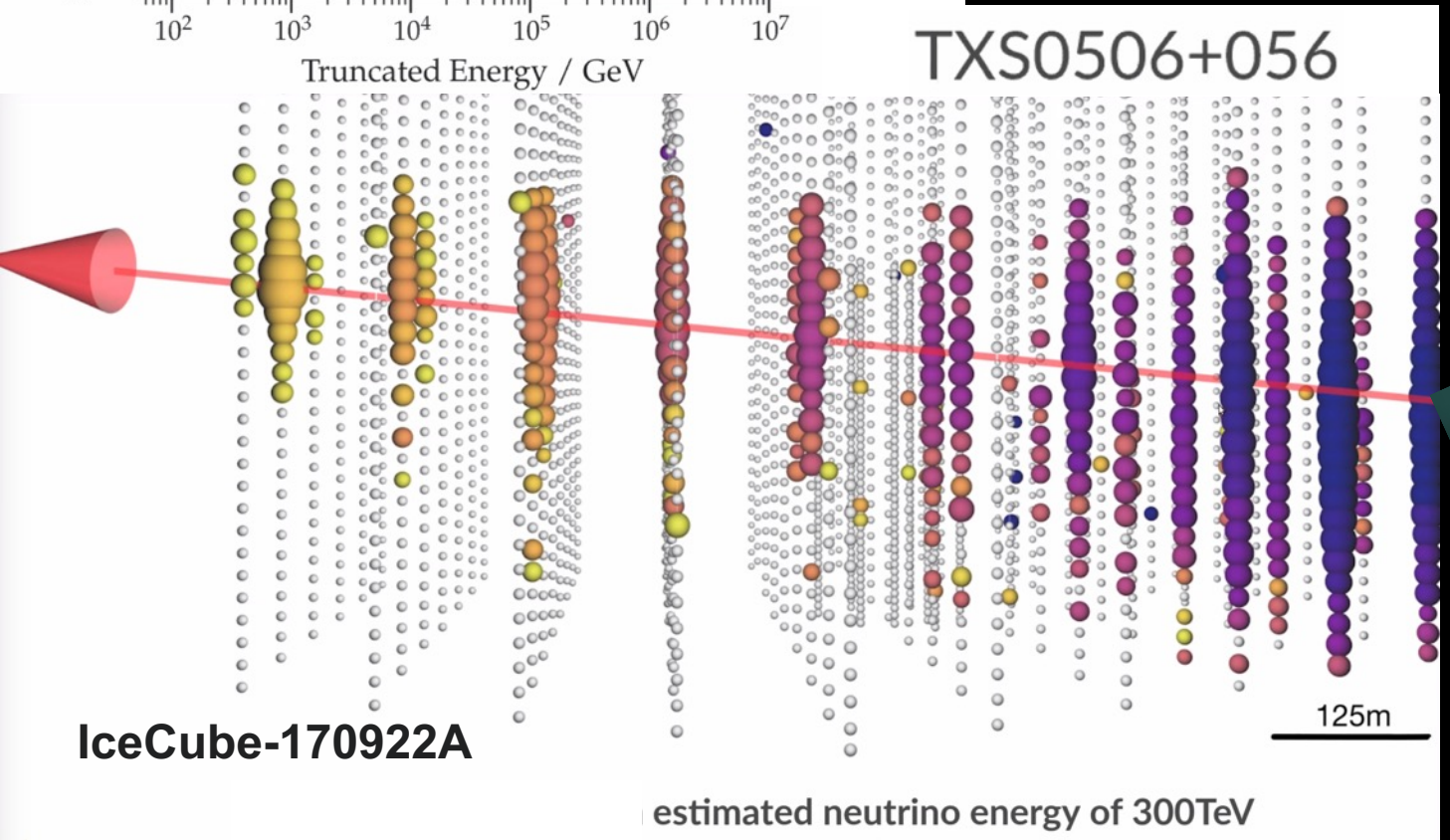


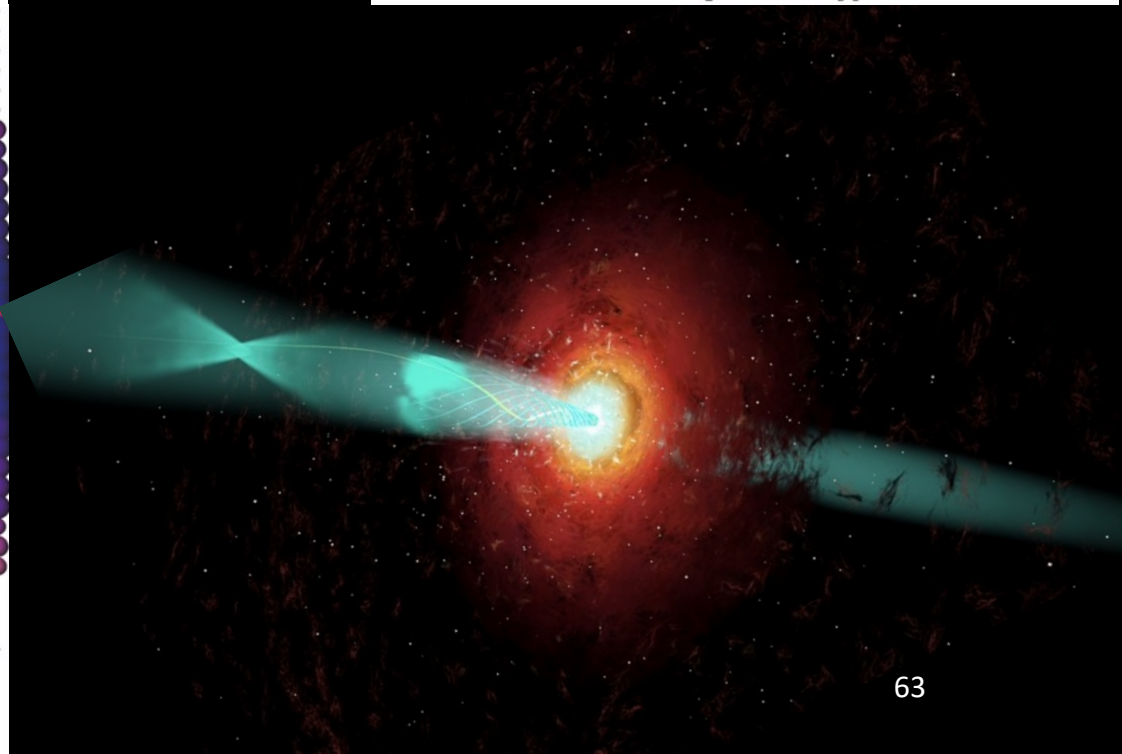
Batista et al, arXiv:1903.06714.pdf

Astrophysical Neutrinos

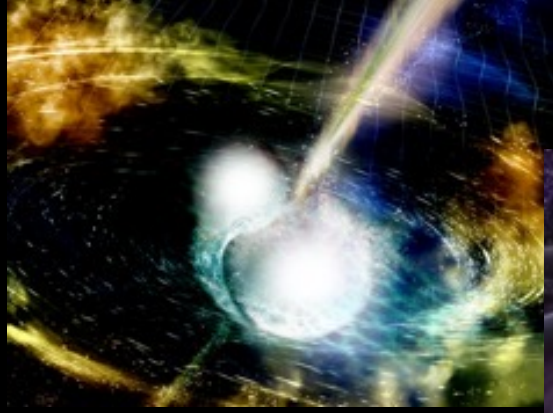




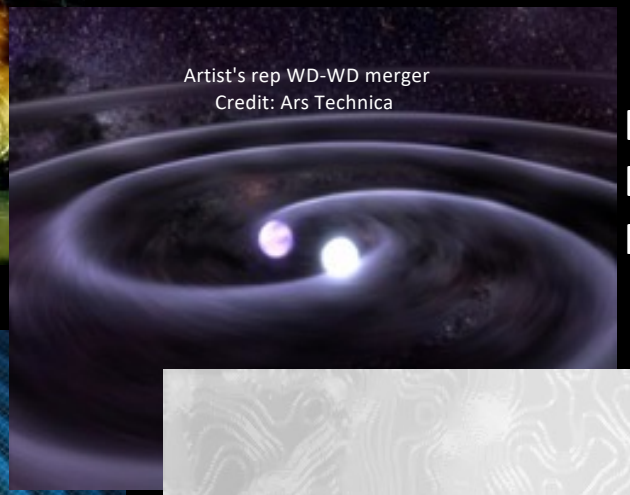




Transient Energetic Cosmic Events



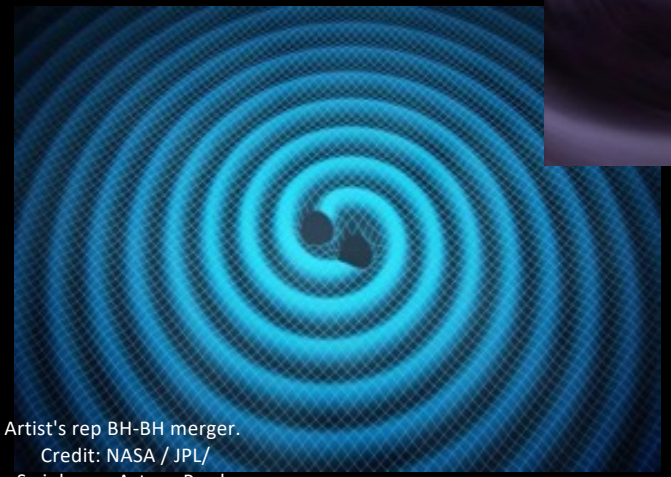
Artist's rep NS-NS merger.
Credit: NSF/LIGO/SSU/A. Simonnet.



Artist's rep WD-WD merger
Credit: Ars Technica

Binary Neutron Star Mergers
Binary Black Hole Mergers
Neutron Star –Black Hole Merge

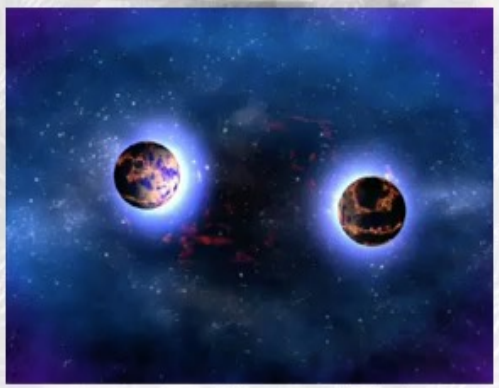
NS-NS m
Credit: NASA,



Artist's rep BH-BH merger.
Credit: NASA / JPL/
Swinburne Astron.Prods

Blazar Flares

SWIFT NEUTRON STAR
COLLISION V. 2



ANIMATION: DANA BERRY
310-441-1735
PRODUCED BY ERICA DREZEK

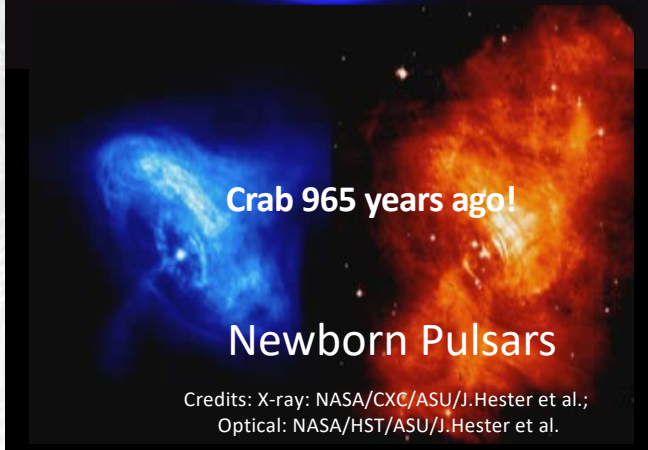
Artist's rep TDE (star torn BH).
Credit: NASA / CXC / M. Weiss

Tidal Disruption Events

M87

EVENT HORIZON TELESCOPE
COLLABORATION/MAUNAKEA
OBSERVATORIES/ASSOCIATED PRESS

Gamma Ray Bursts



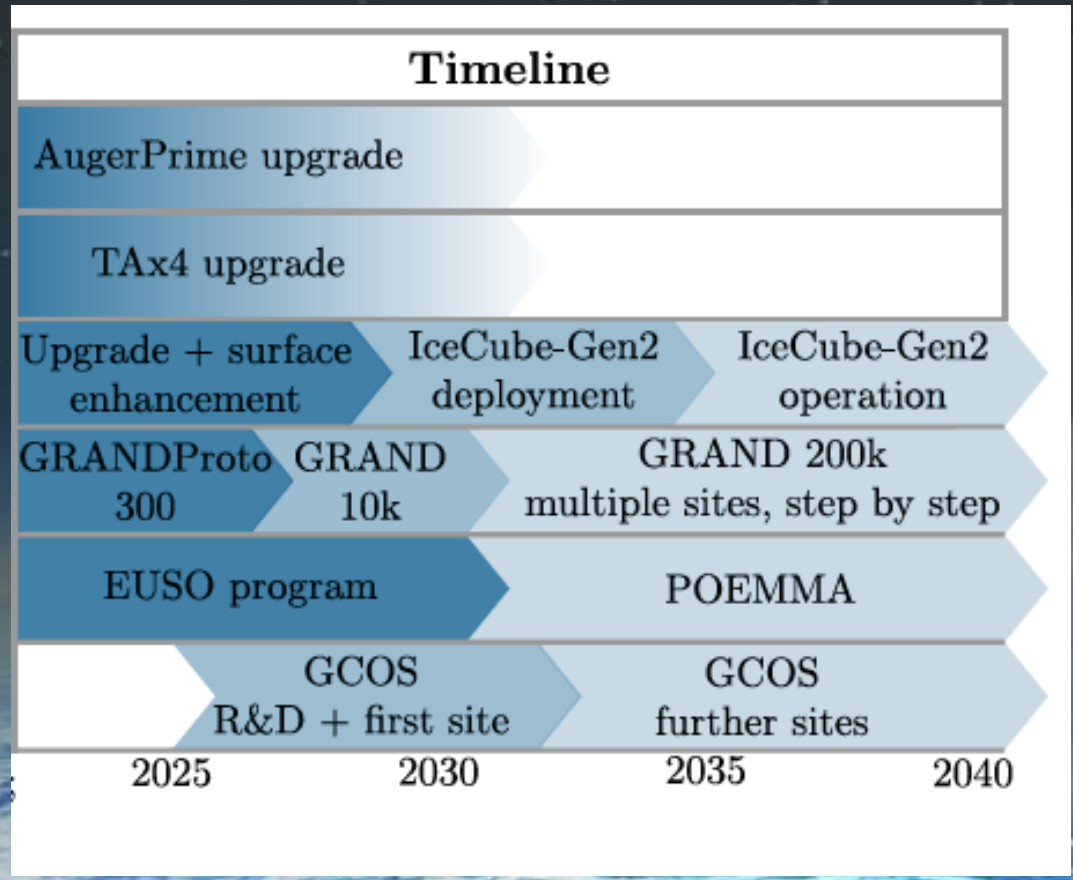
Crab 965 years ago!

Newborn Pulsars

Credits: X-ray: NASA/CXC/ASU/J.Hester et al.;
Optical: NASA/HST/ASU/J.Hester et al.

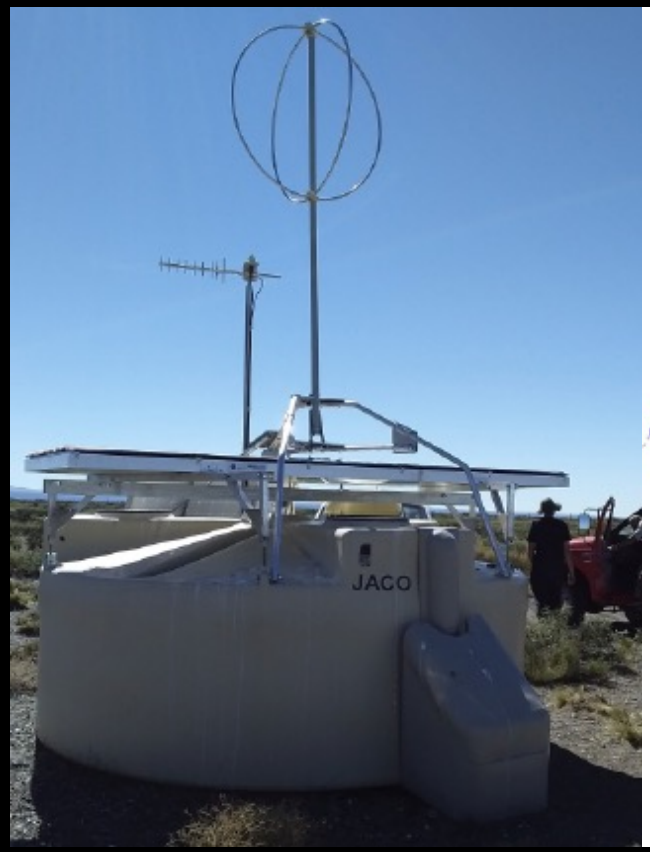
Future Outlook

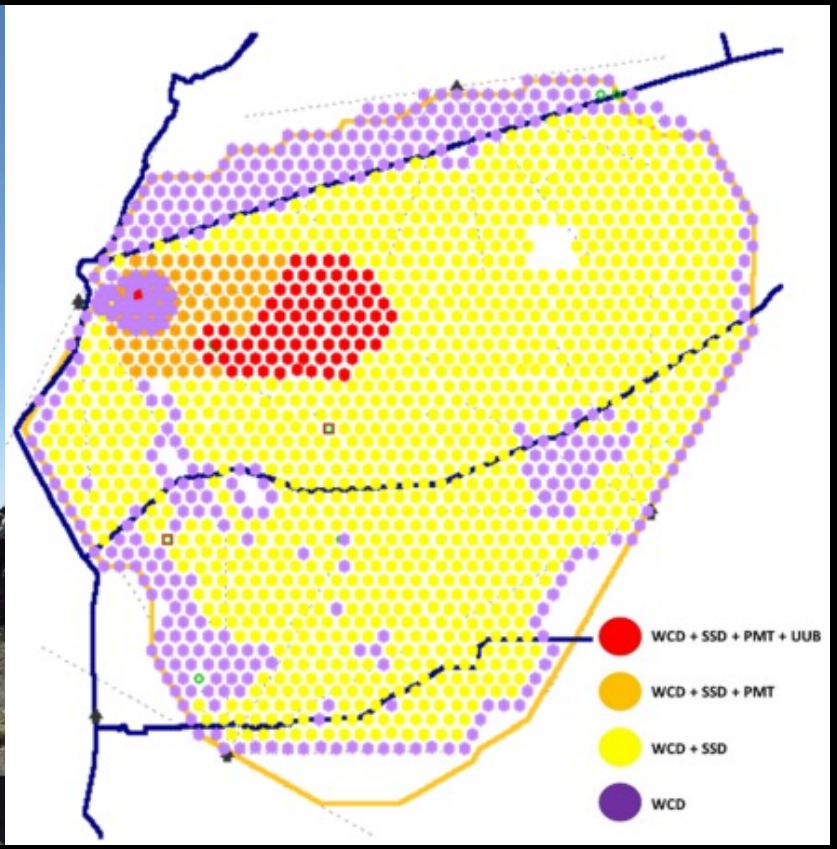
Future Outlook



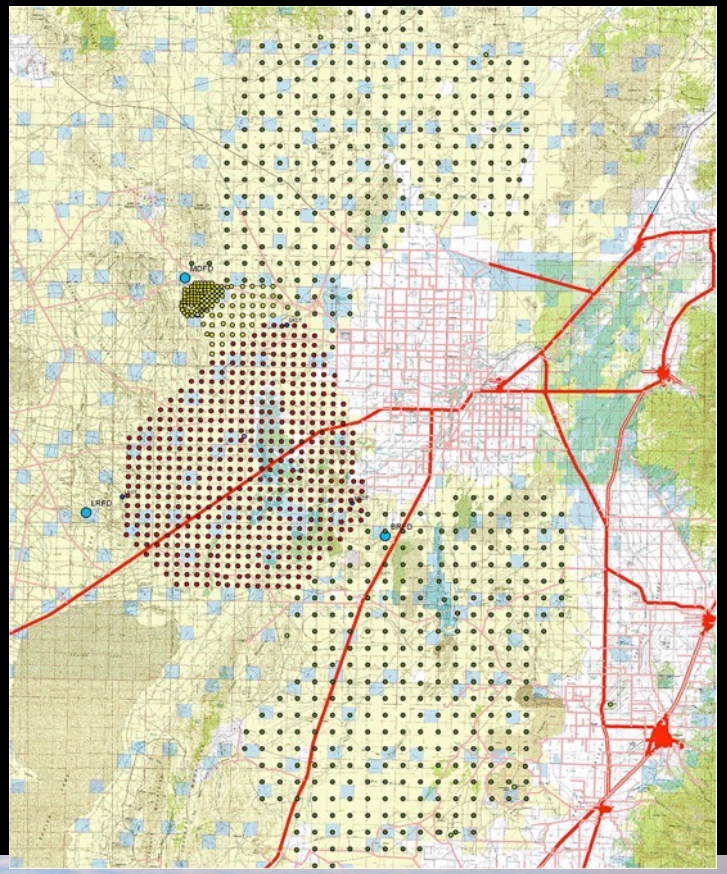
Coleman et al, Snowmass, arXiv:2205.05845

AugerPrime





TAx4



IceCube-Gen2

IceCube Upgrade (planned 2023-)

Optimized for

- GeV neutrinos
- Calibration of the IceCube detector

IceCube (2005-)

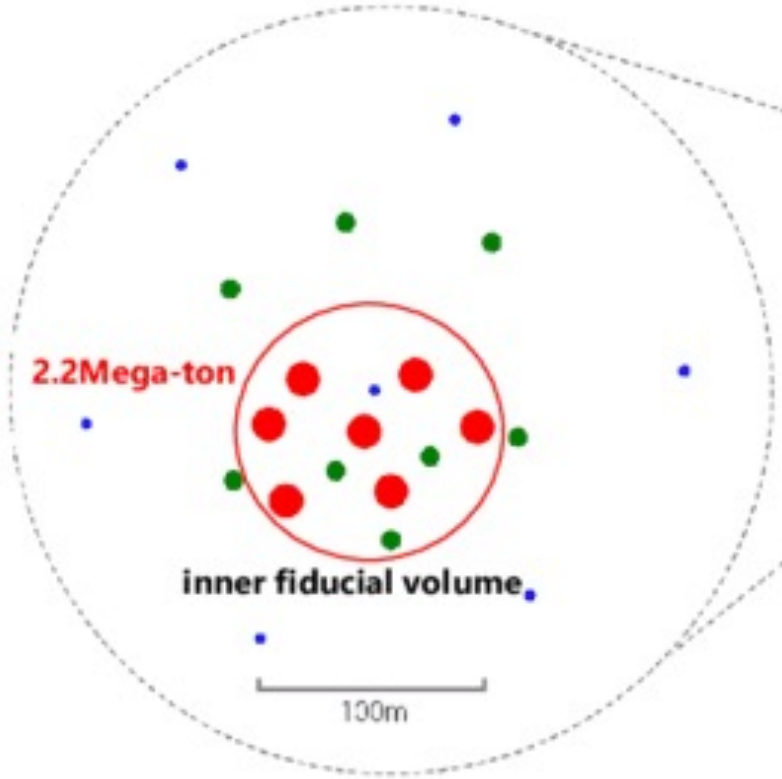
Optimized for

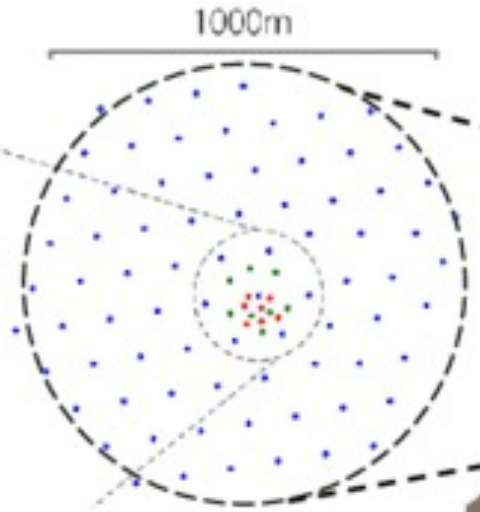
- Diffuse high energy cosmic neutrinos

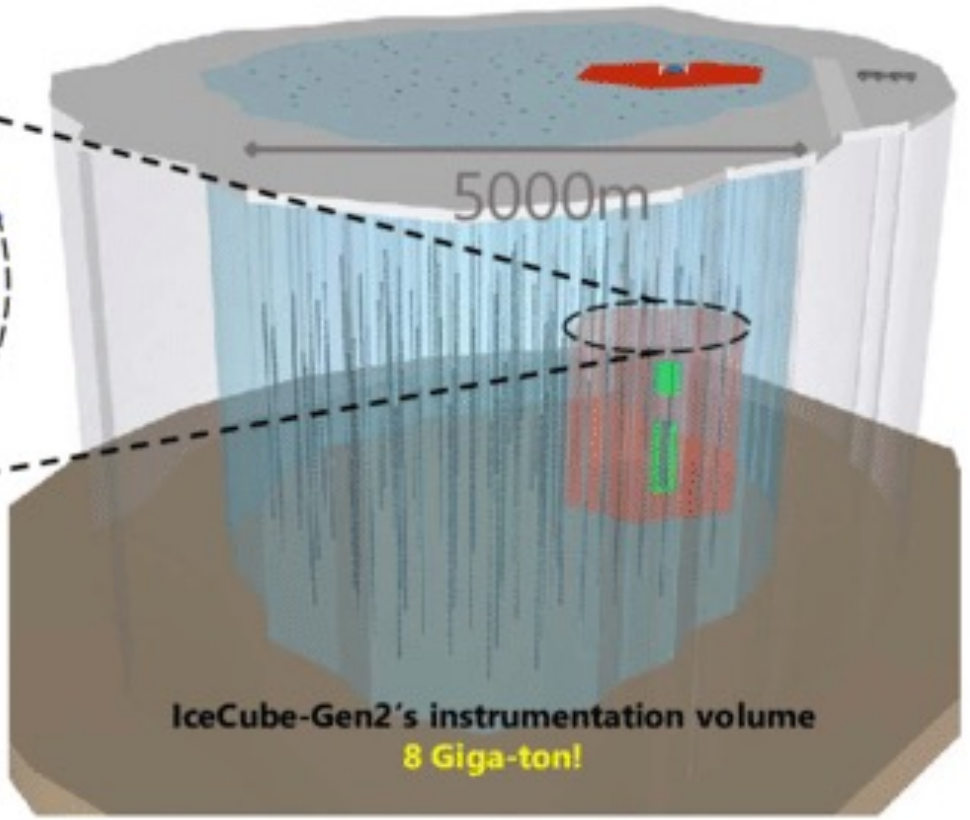
IceCube-Gen2 (planned 2026-)

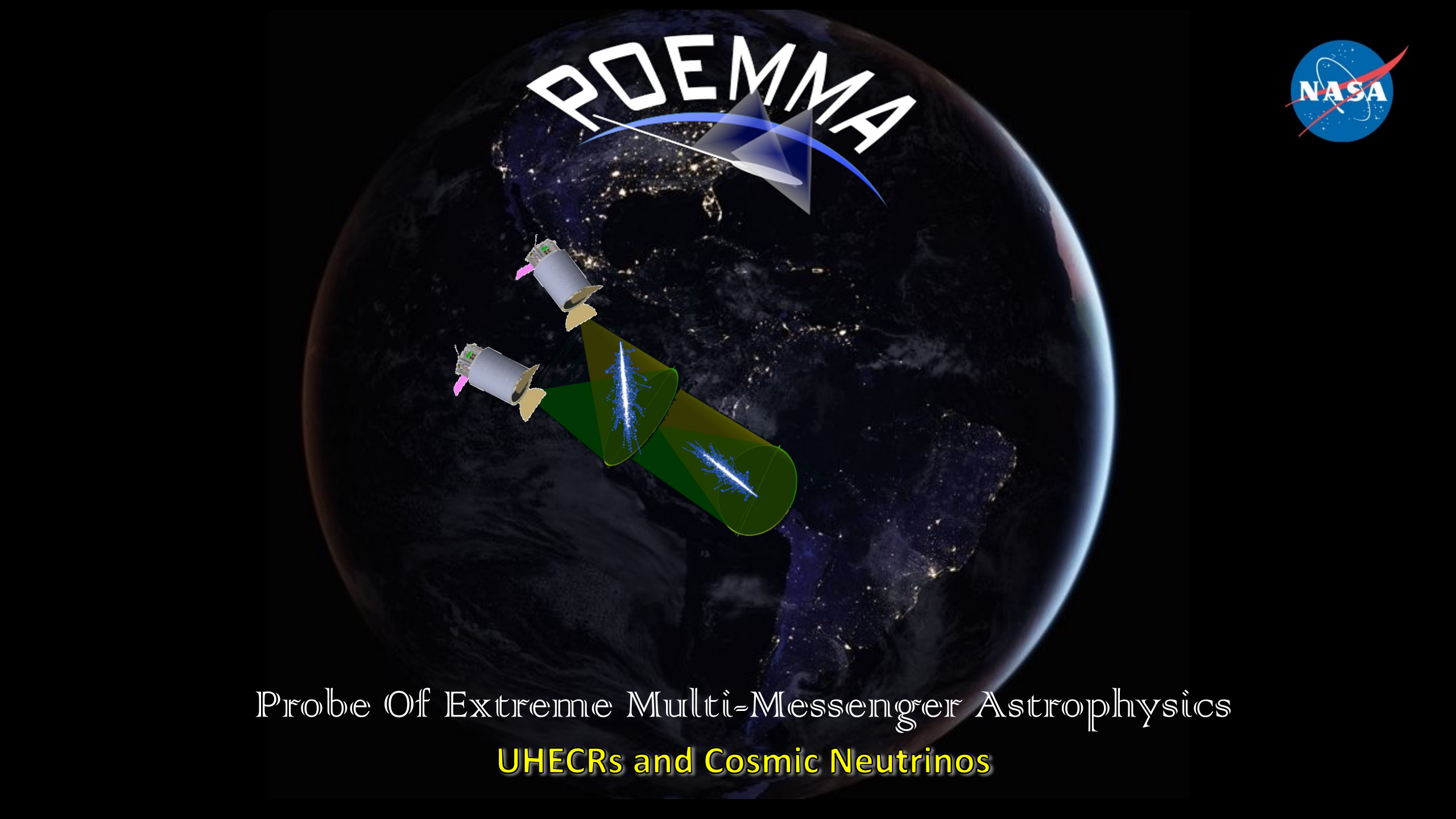
Optimized for

- Cosmic neutrino point sources



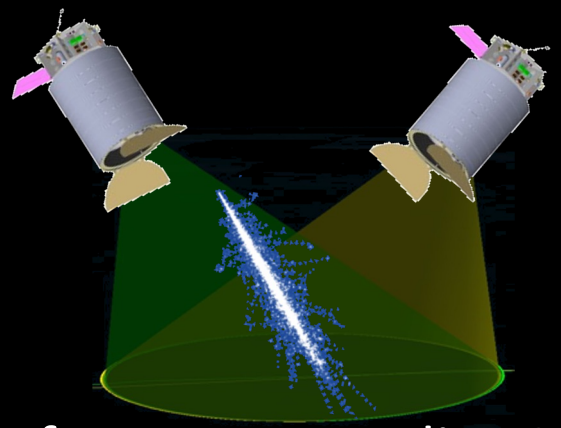






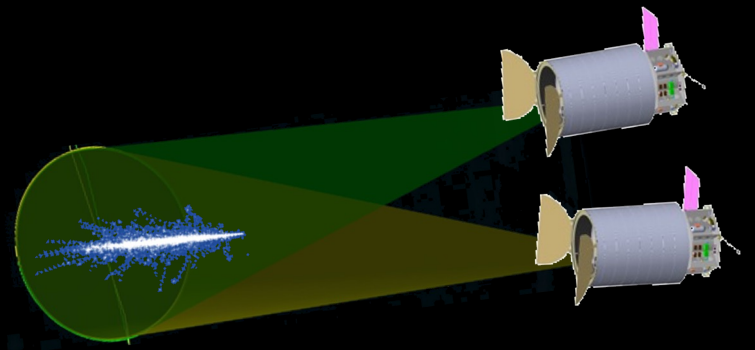
Probe Of Extreme Multi-Messenger Astrophysics

UHECRs and Cosmic Neutrinos



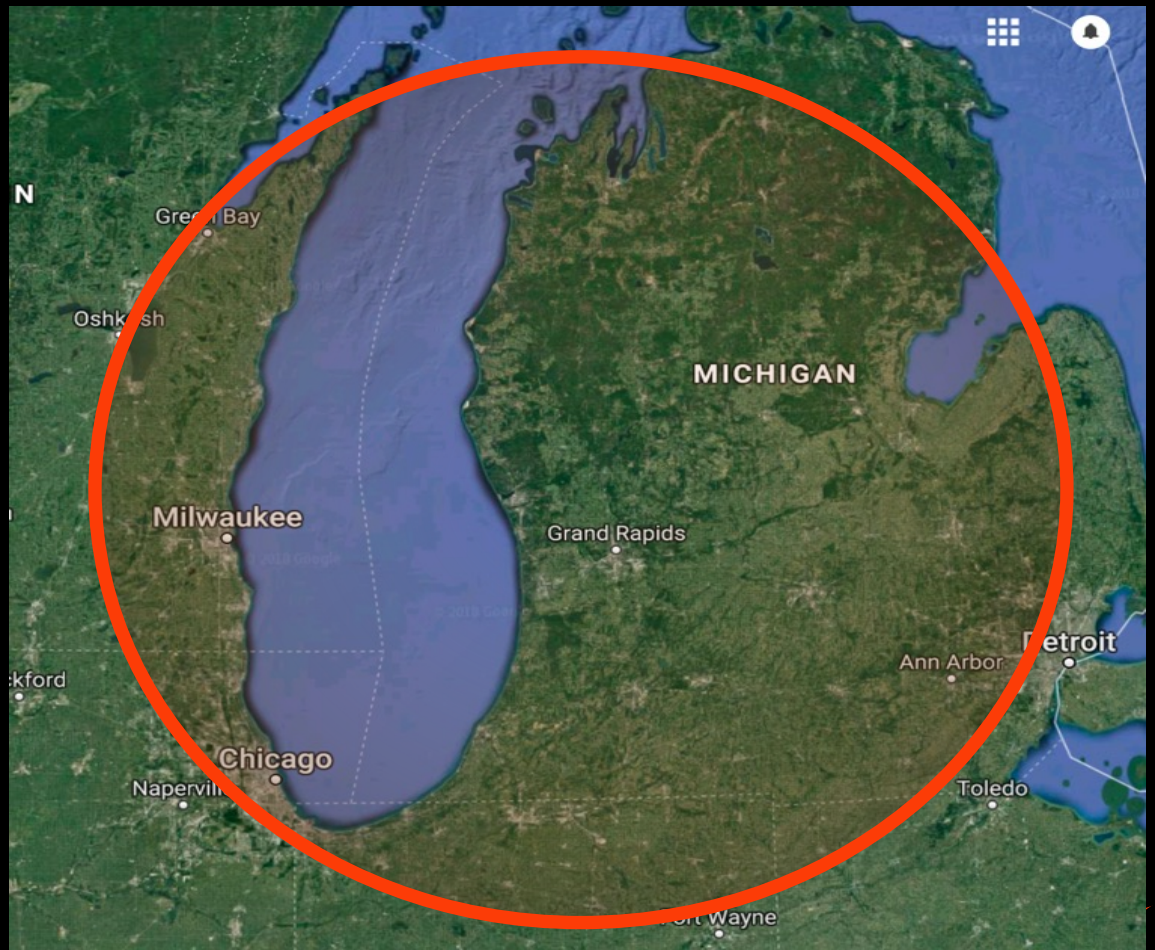
POEMMA

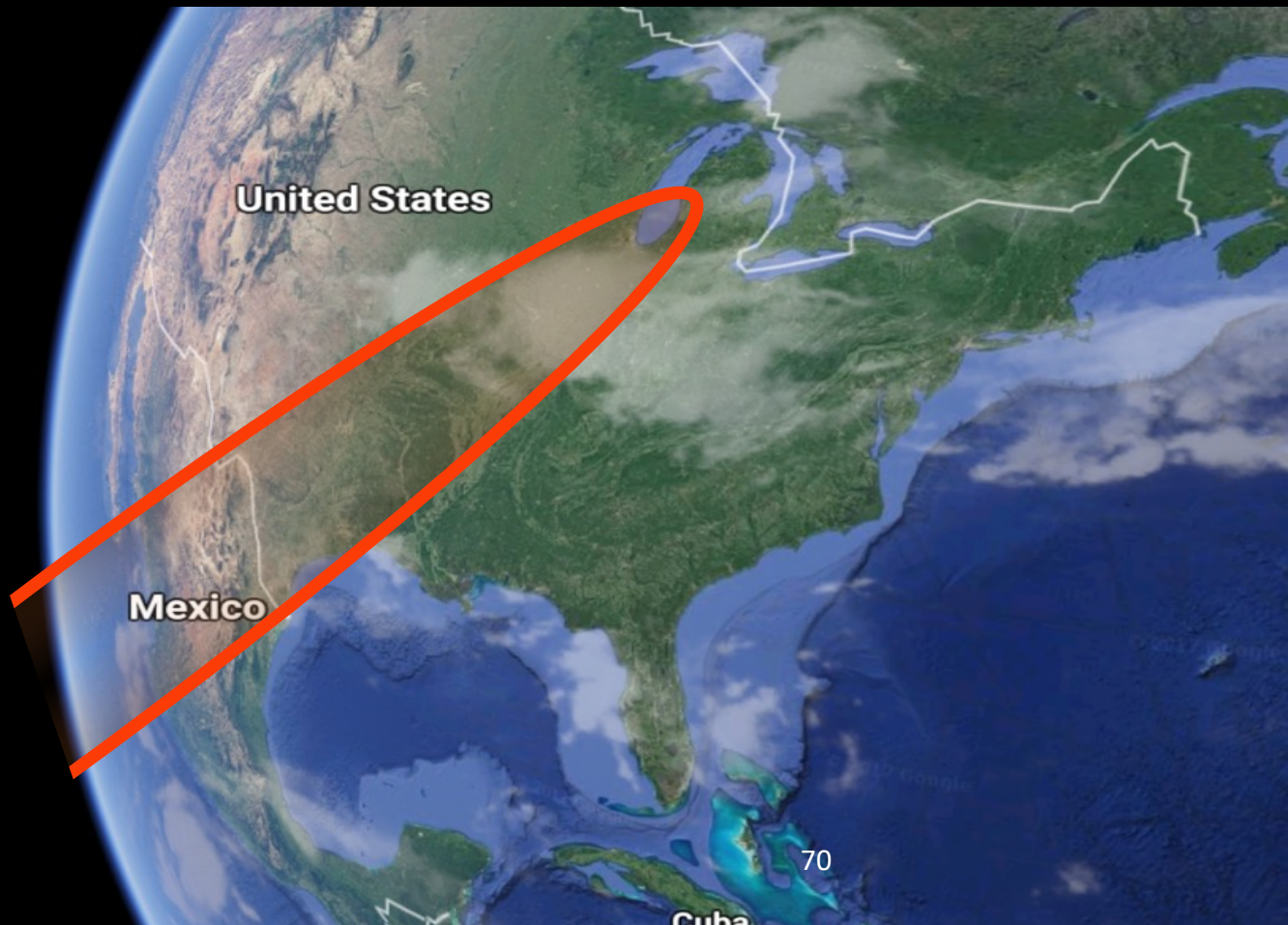
Observing Modes

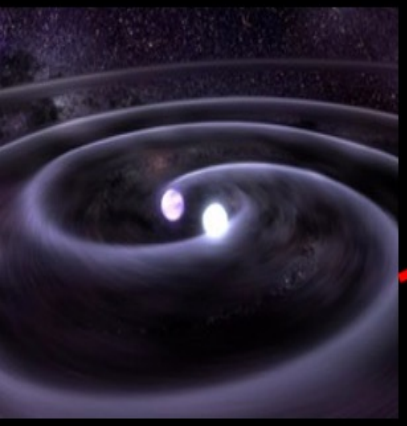


Nadir for UHECR: Radius 200-400 km

Limb for Neutrinos UHECR: 2-4 10^3 km

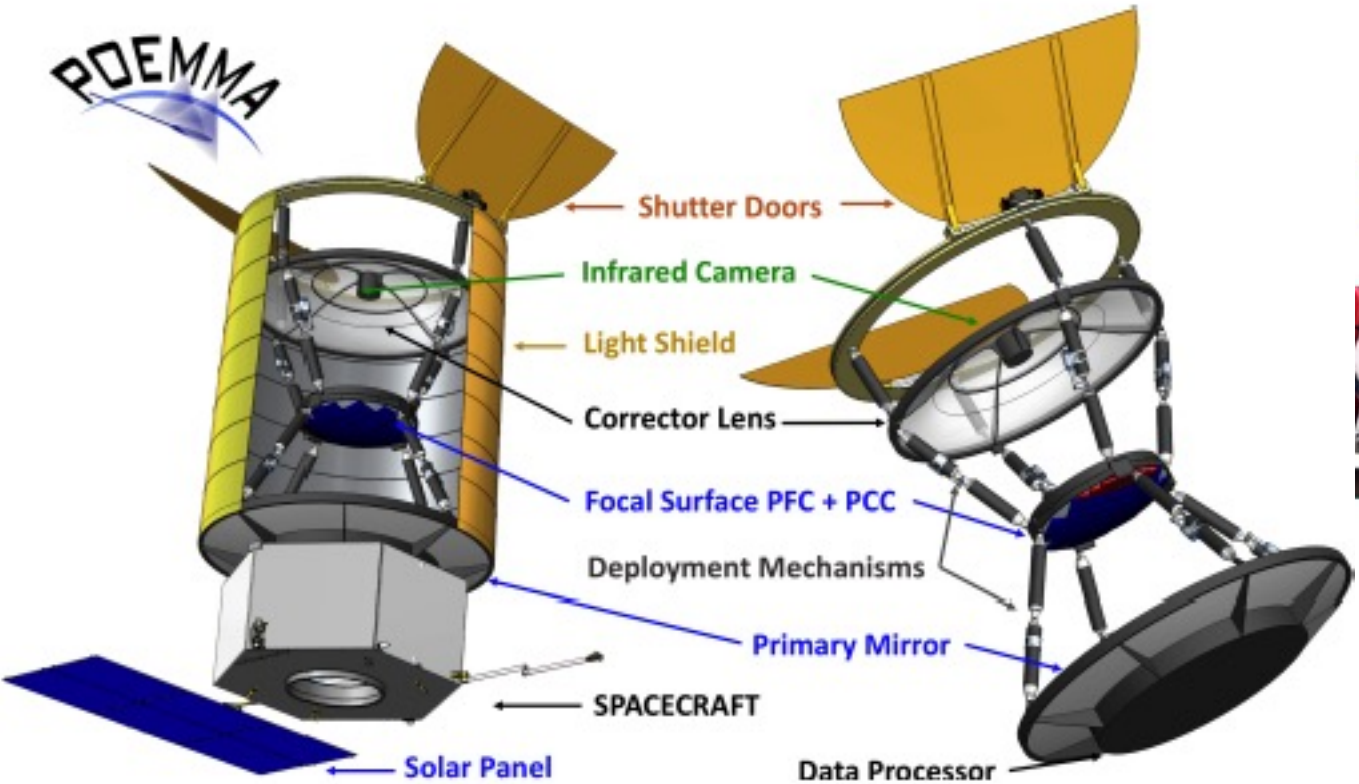




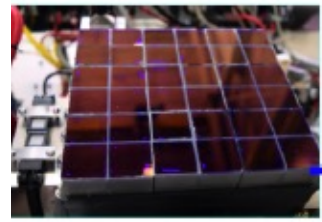


Tau-neutrino

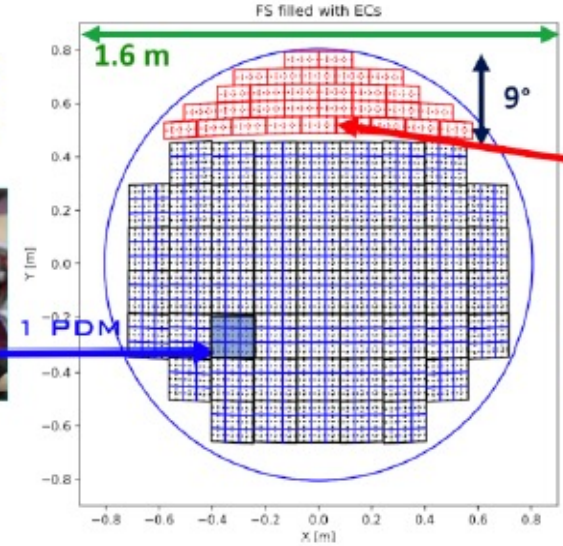
Tau-lepton



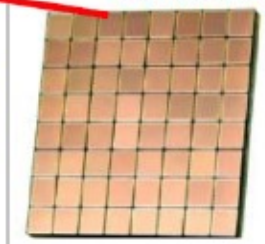
PFC: POEMMA Fluorescence Camera



MAPMTs

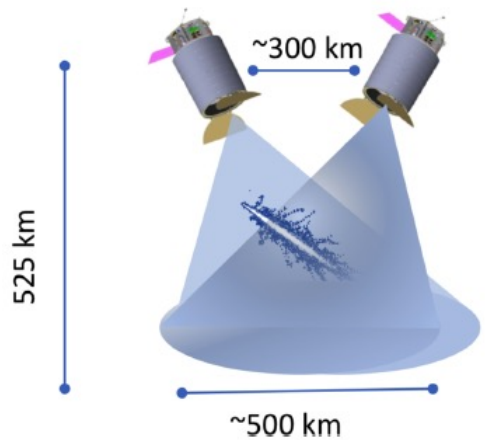


PCC: POEMMA Cherenkov Camera

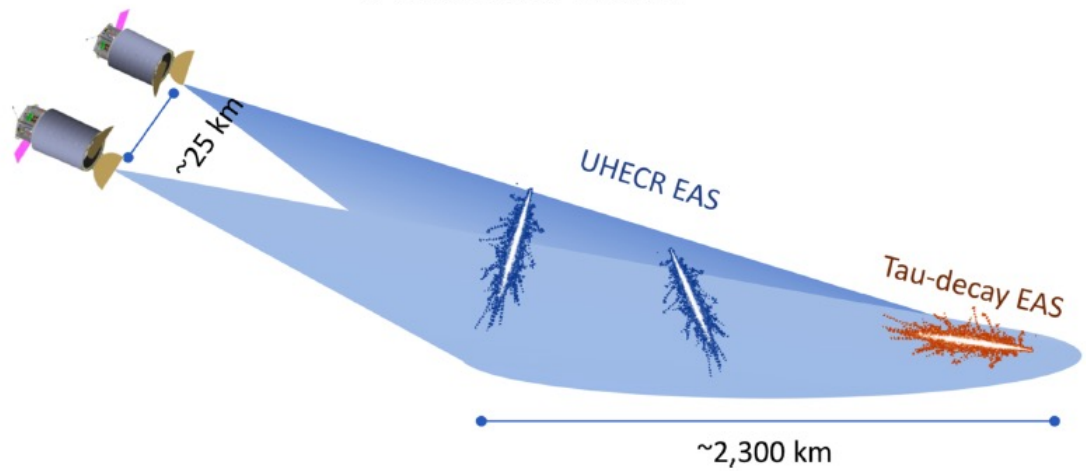


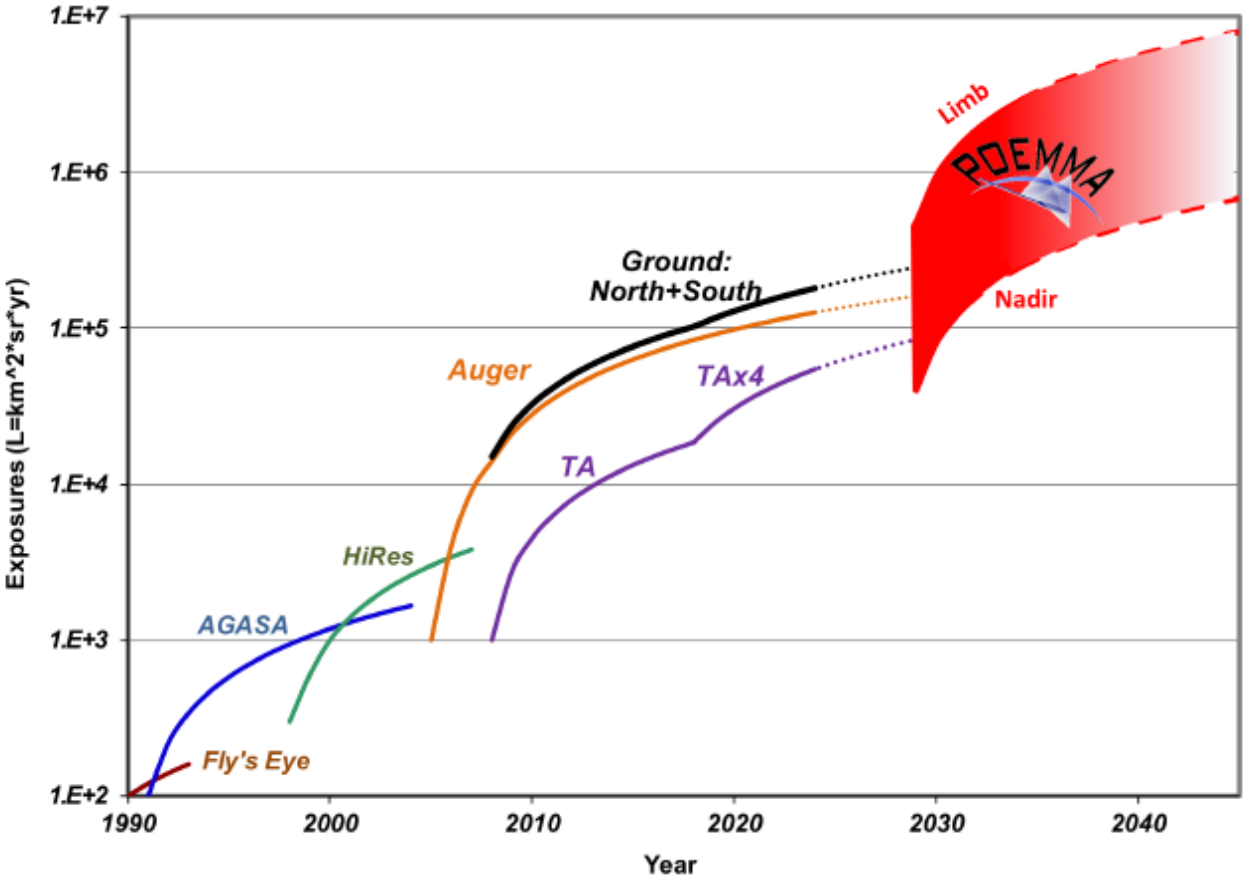
SiPMs

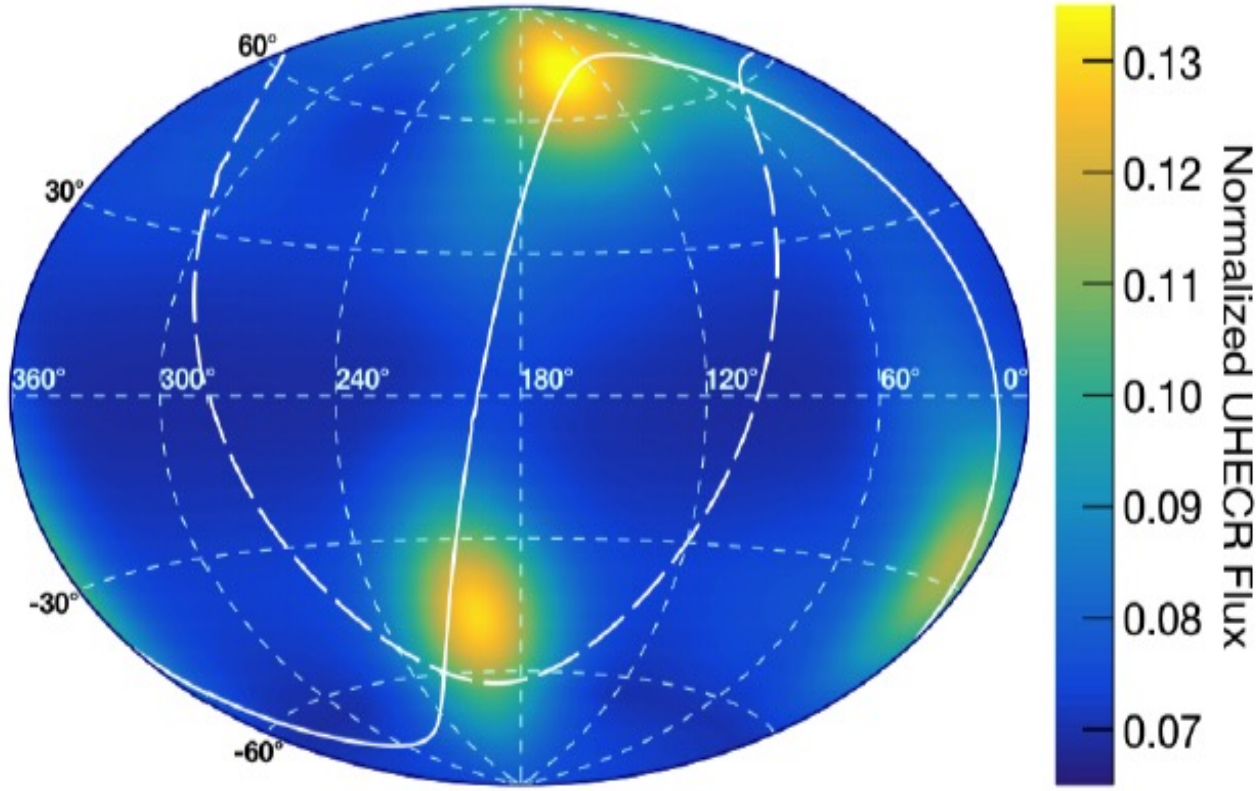
POEMMA-Stereo



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

JEM-EUSO program

Joint Experiment Missions
Extreme Universe Space Observatory

300 researchers from 16 countries

EUSO-TA (2013-)

EUSO-Balloon (2014)

EUSO-SPB1 (2017)

Mini-EUSO (2019)

EUSO-SPB2 (2023)

K-EUSO (2025+)

POEMMA (2030+)

EUSO-SPB2
2023 flight

Fluorescence from UHECRS
Cherenkov Emission from UHECRs
Tau Neutrino Events

UHECRs

Fluorescence

Cherenkov

CRs E > PeV

Tau lepton

Tau Neutrino

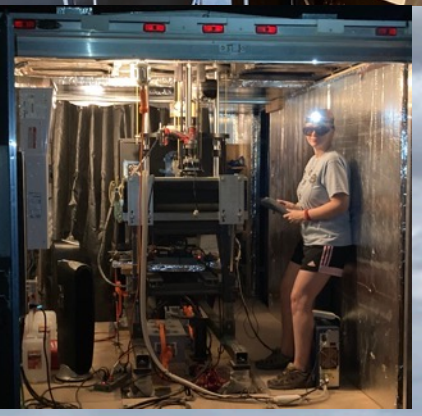
Science Results:

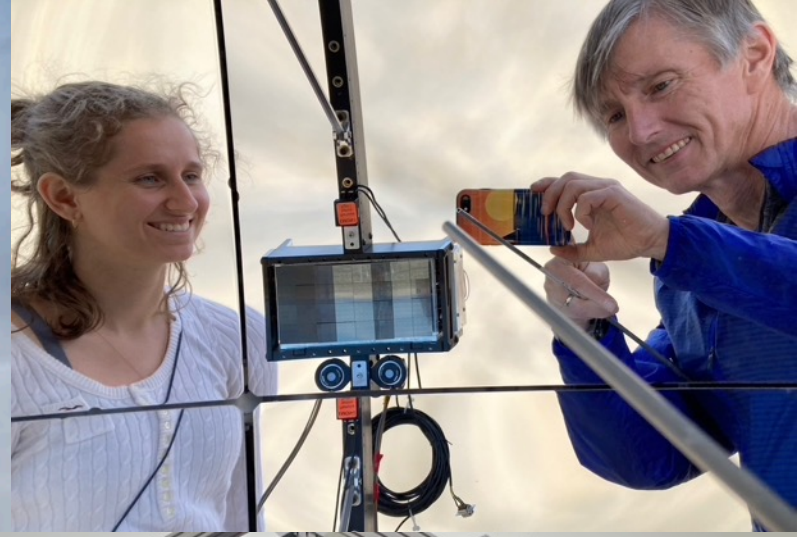
- Fluorescence from ~30 UHECRS
- CR spectrum from 10^{15} eV to **10^{17}eV**
- Tau Neutrino candidates from transients

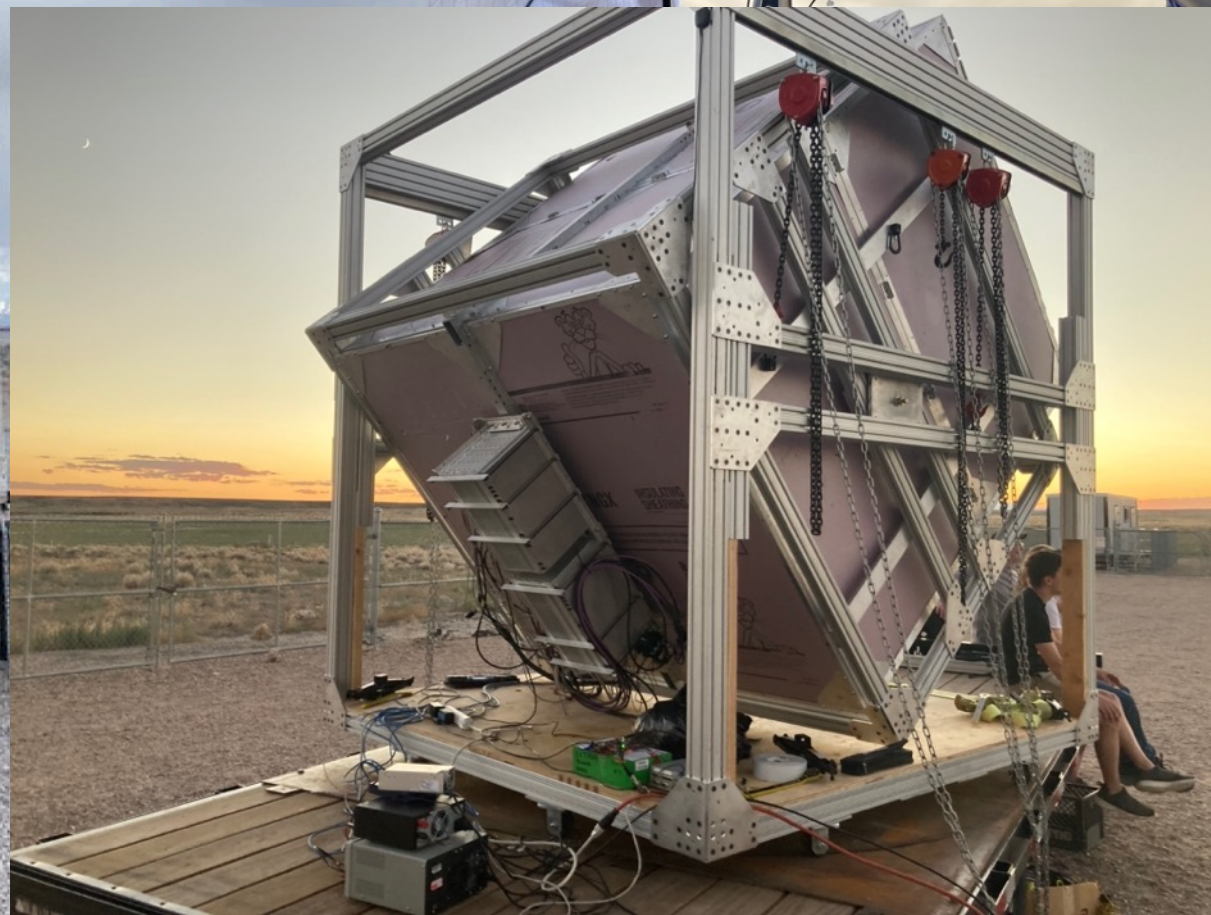
EUSO-SPB2

Field Tests, Integration, Hang Test

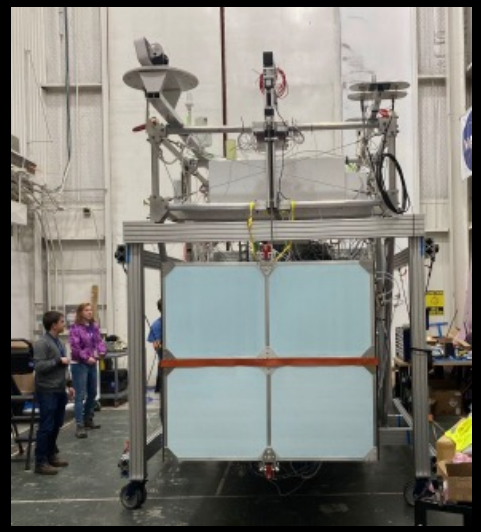
Flight Ready Match 2023

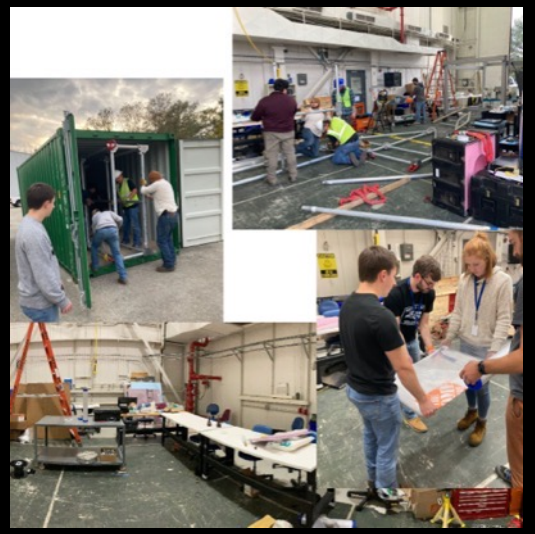






EUSO-SPB2 Hang Test & Packing November-December 2022





IKSU2587018

SeaLines
Hapag-Lloyd

A

New Orleans

08 Dec 2022 - Arrival in
12 Dec 2022 - Departure from

New Orleans - Charleston — 5 days

12 Dec 2022 - 17 Dec 2022

Charleston

17 Dec 2022 - Arrival in
19 Dec 2022 - Departure from
19 Dec 2022 - Arrival in
23 Dec 2022 - Loaded (Vessel name : OLUF MAERSK)
24 Dec 2022 - Vessel departed (Vessel name : OLUF MAERSK)

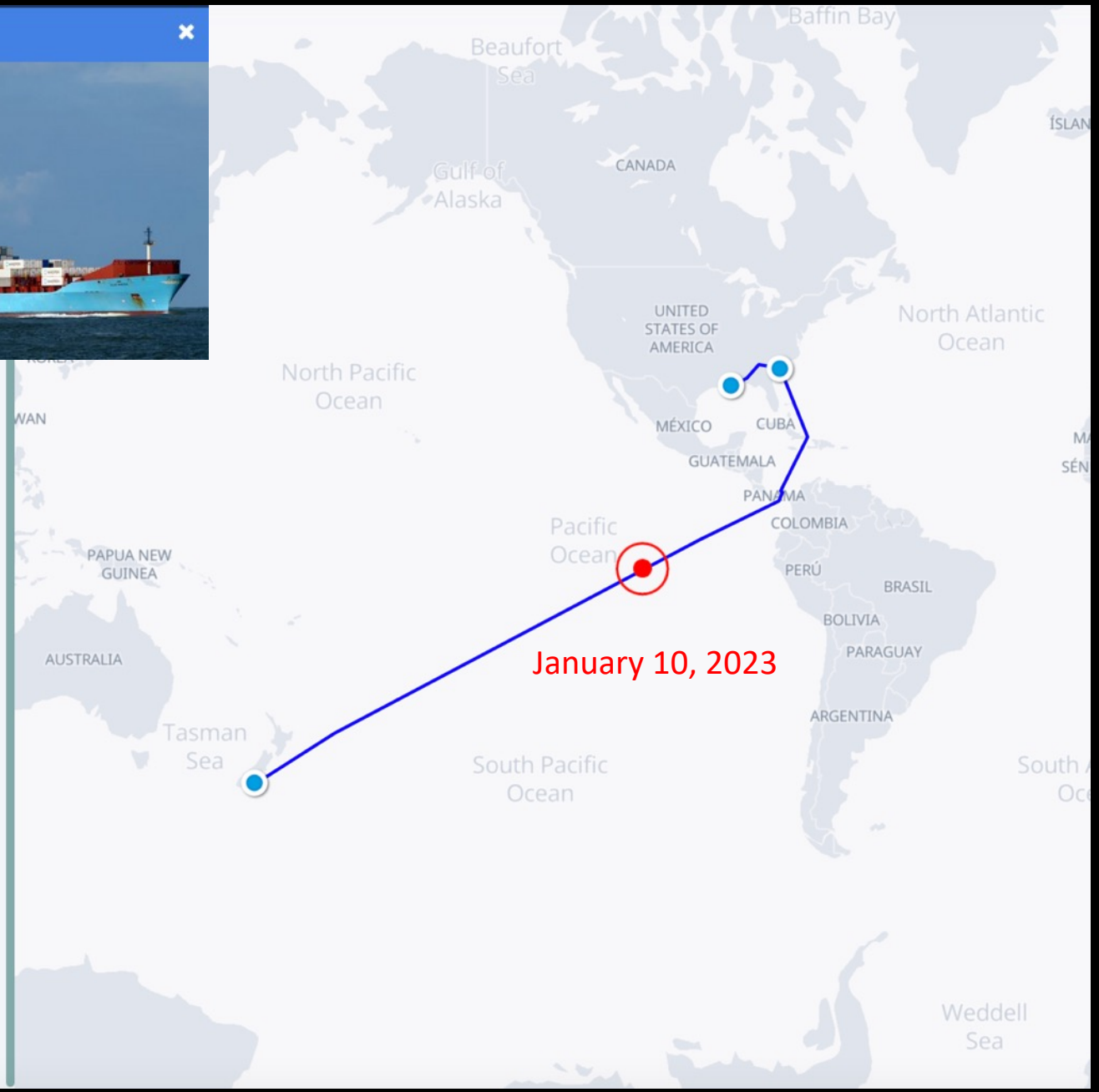
Charleston - Port Chalmers — 41 days

24 Dec 2022 - 04 Feb 2023

B

Port Chalmers

04 Feb 2023 - Vessel arrival (Vessel name : OLUF MAERSK)

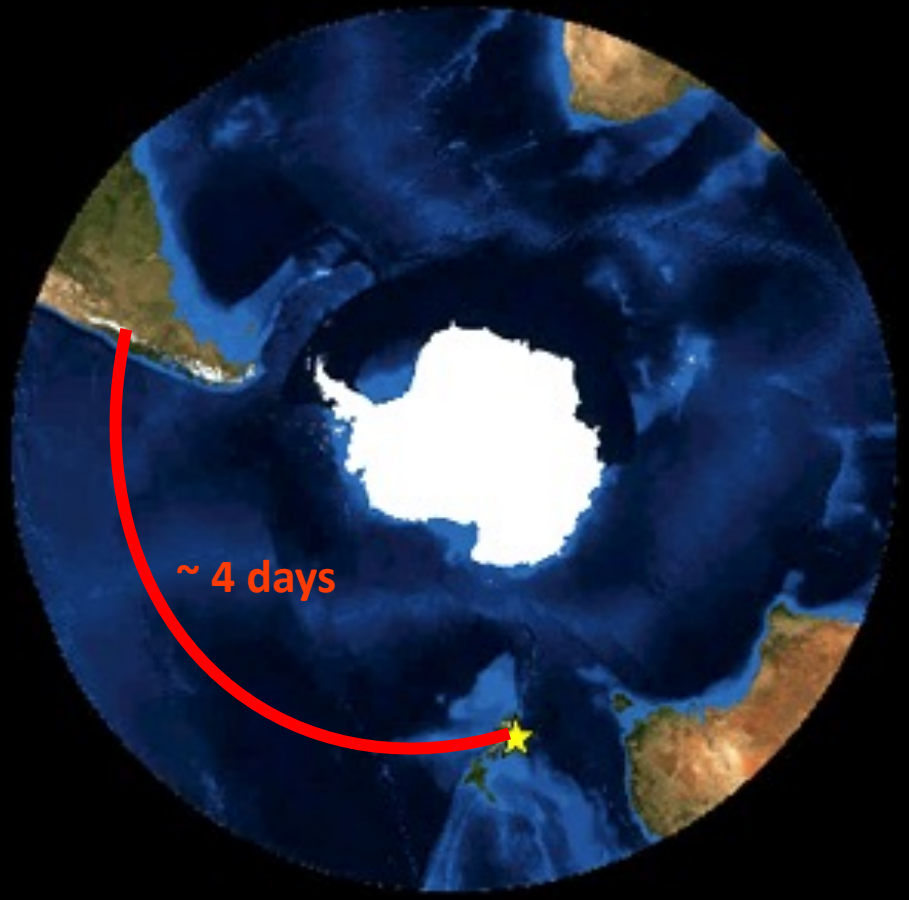


EUSO-SPB 1

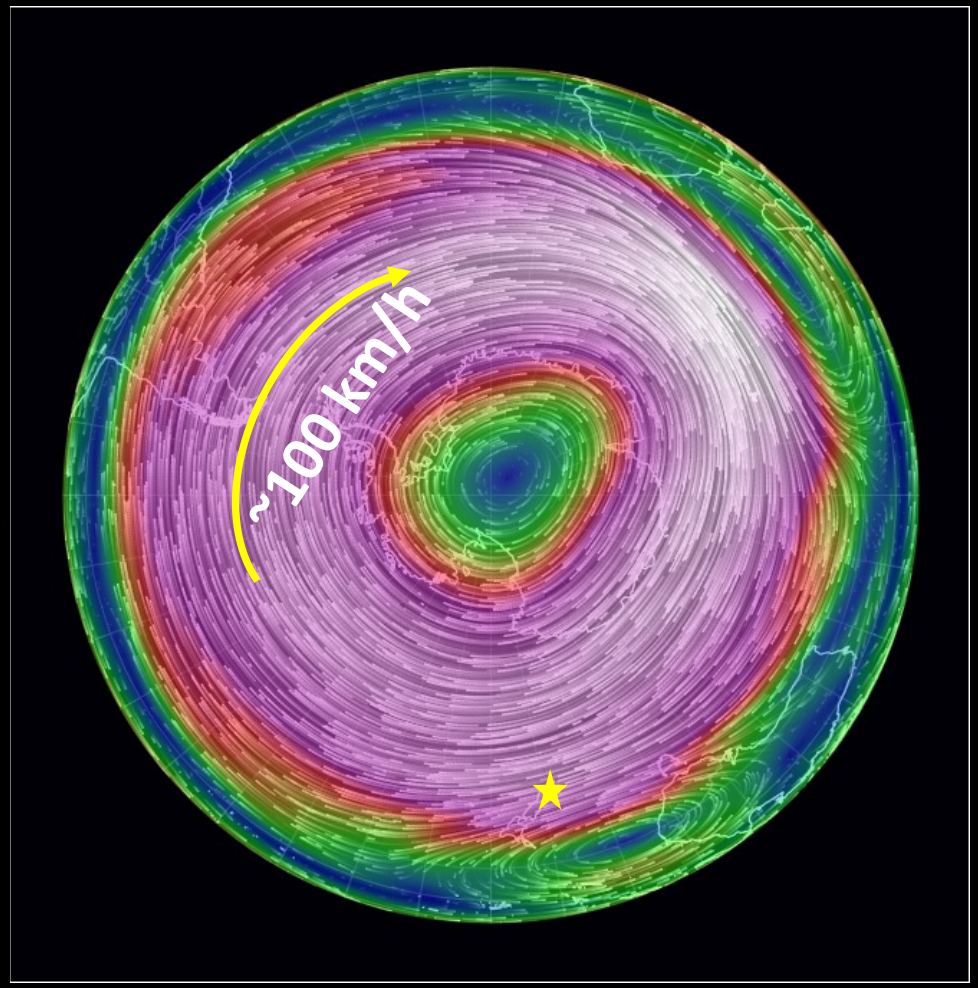
launch, April 24, 2017

23:51 UTC

Why New Zealand?



Wanaka
South Island
New Zealand



air flow at ~30 km June 9th 2017

https://earth.nullschool.net/#current/wind/isobaric/10hPa/orthographic=180,-90,300

NASA WANAKA Campaigns

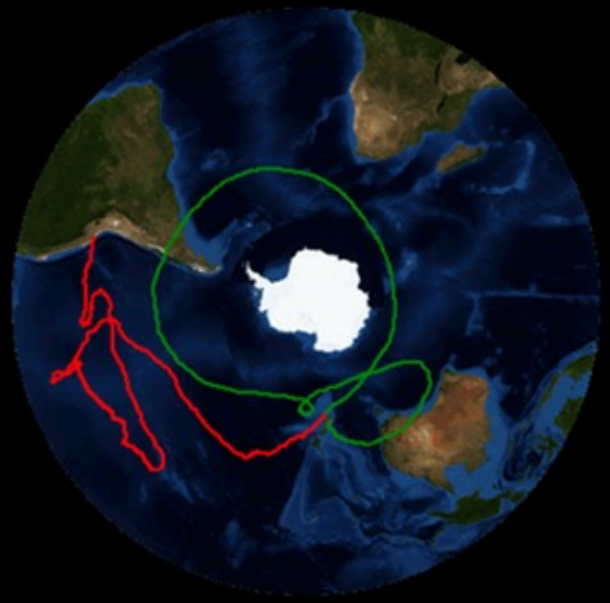
Super Pressure Balloon (SPB)

EUSO mission 2017 & 2023

2015
NASA **Engineering** Flight

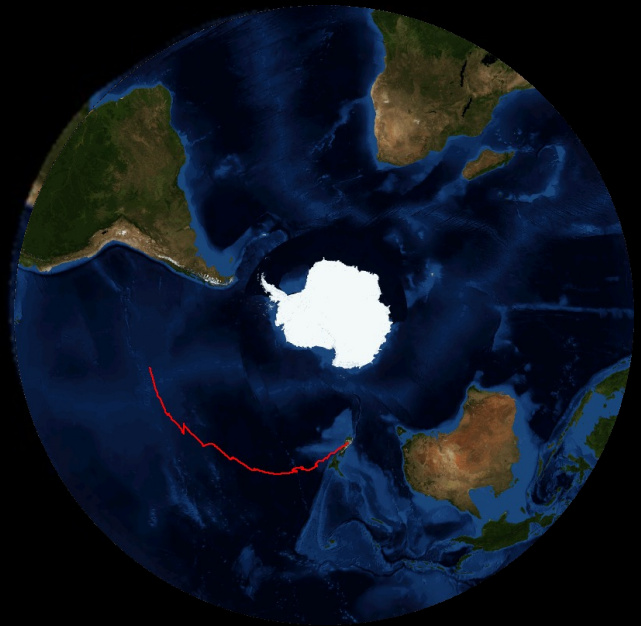
32 d 5 h

2016
COSI



46 d 20 h

2017
EUSO-SPB



12 d 4 h

2023
EUSO-SPB2

100 d!!!

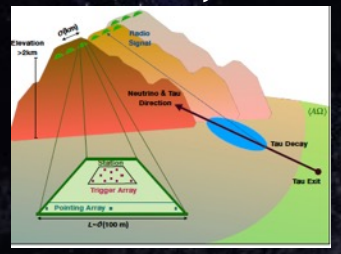
Future detectors of UHE CRs and Neutrinos

Future Looks Bright!

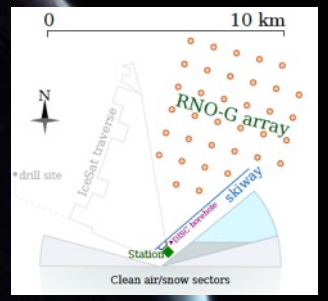
GRAND

Giant Radio Array for Neutrino Detection

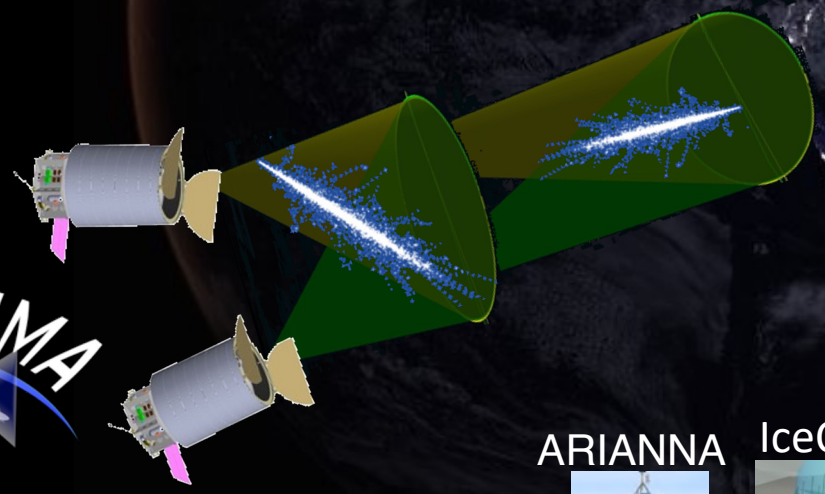
BEACON, Trinity, AshraNTA, TAROGE



RNO-G

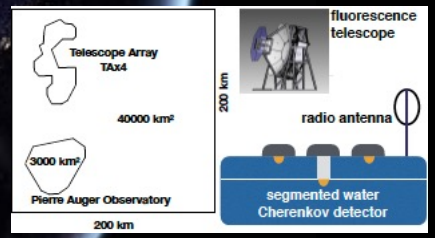


ZAP



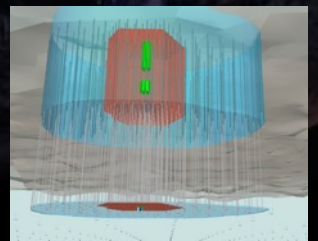
POEMMA

GCRO



ARIANNA

IceCube-Gen2



EUSO-SPB1 Launch from Wanaka, NZ
April 24, 2017