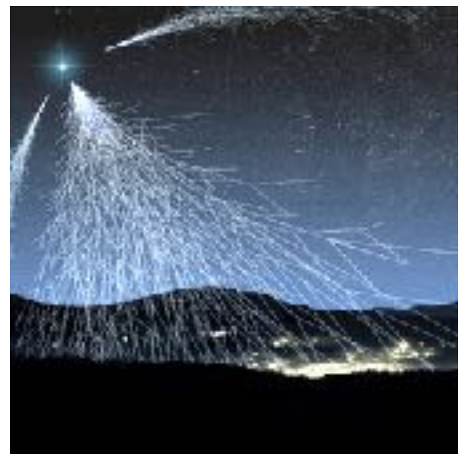
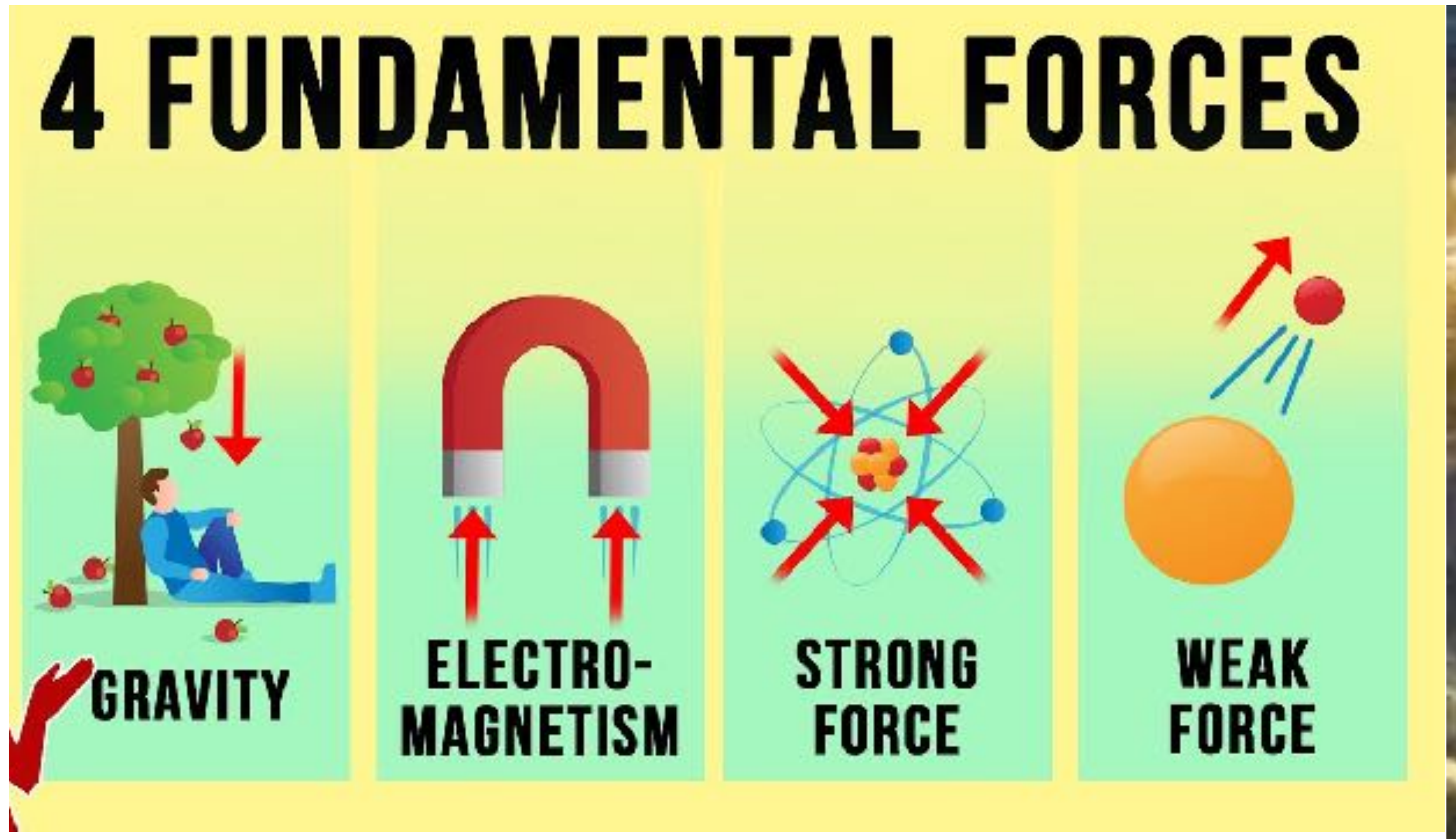
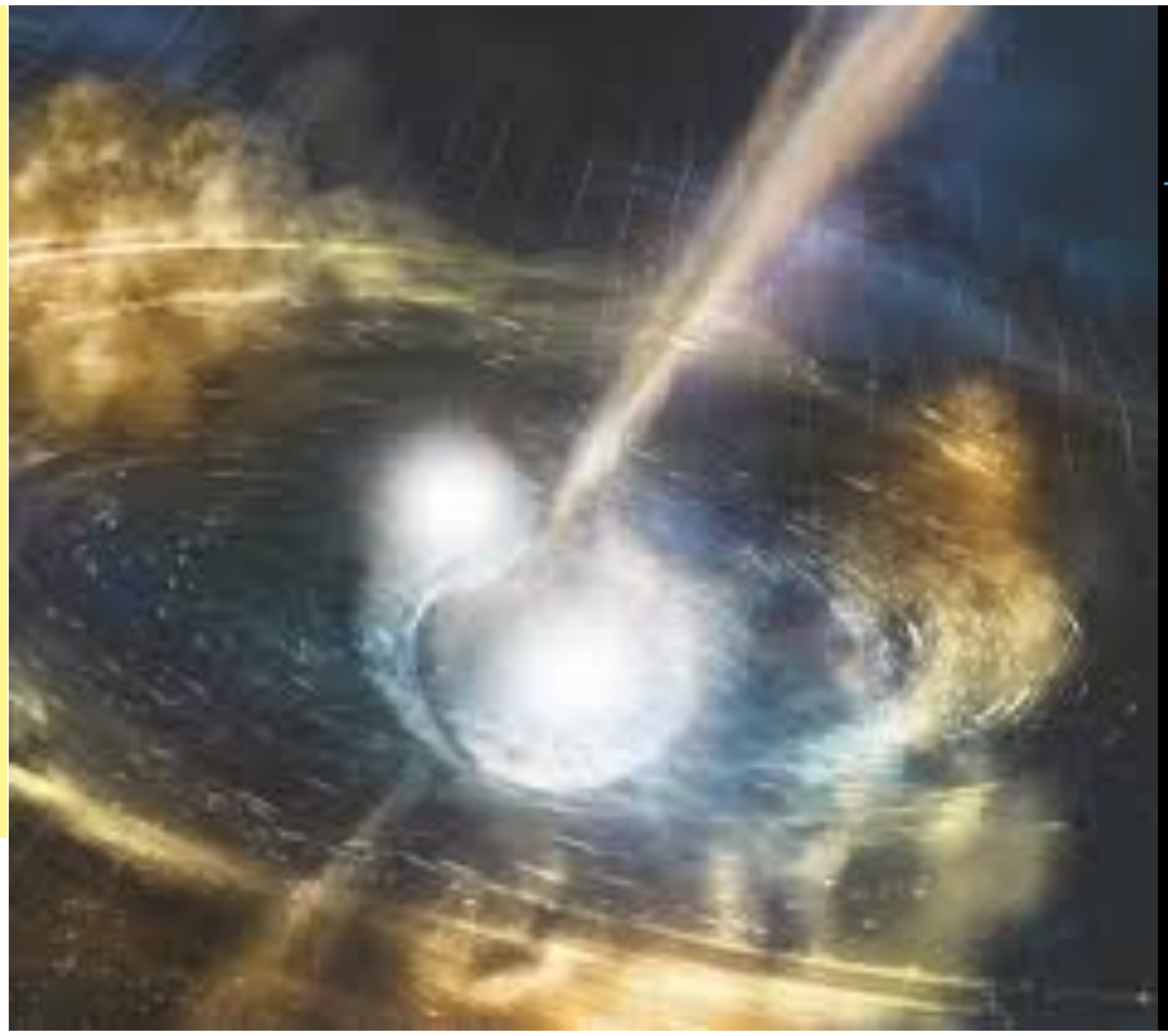
The Straw Man Design of the Global Cosmic Ray Observatory

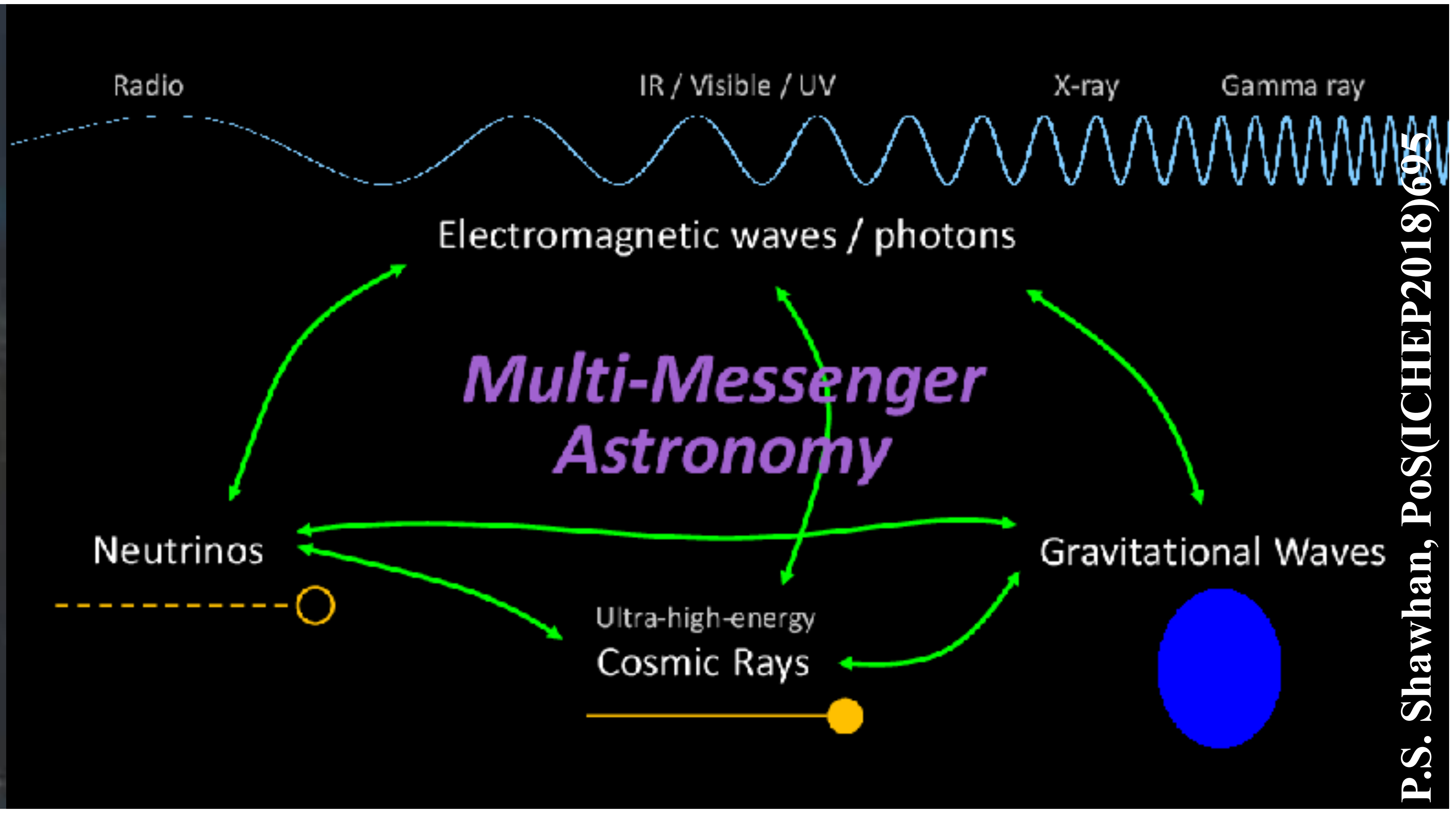


Multi-messenger astroparticle physics beyond 2035

nuclei, gamma rays, neutrinos, (gravitational waves)







Jörg R. Hörandel on behalf of GCOS
Radboud Universiteit Nijmegen - Vrije Universiteit Brussel - http://particle.astro.ru.nl

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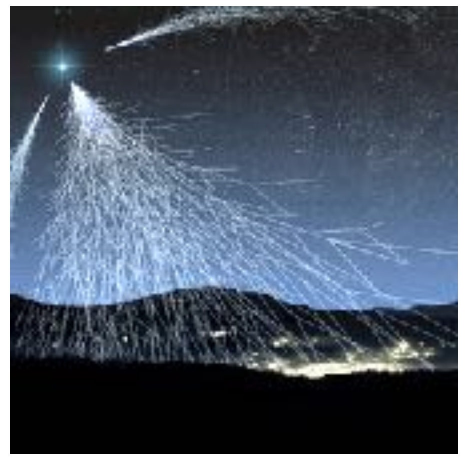
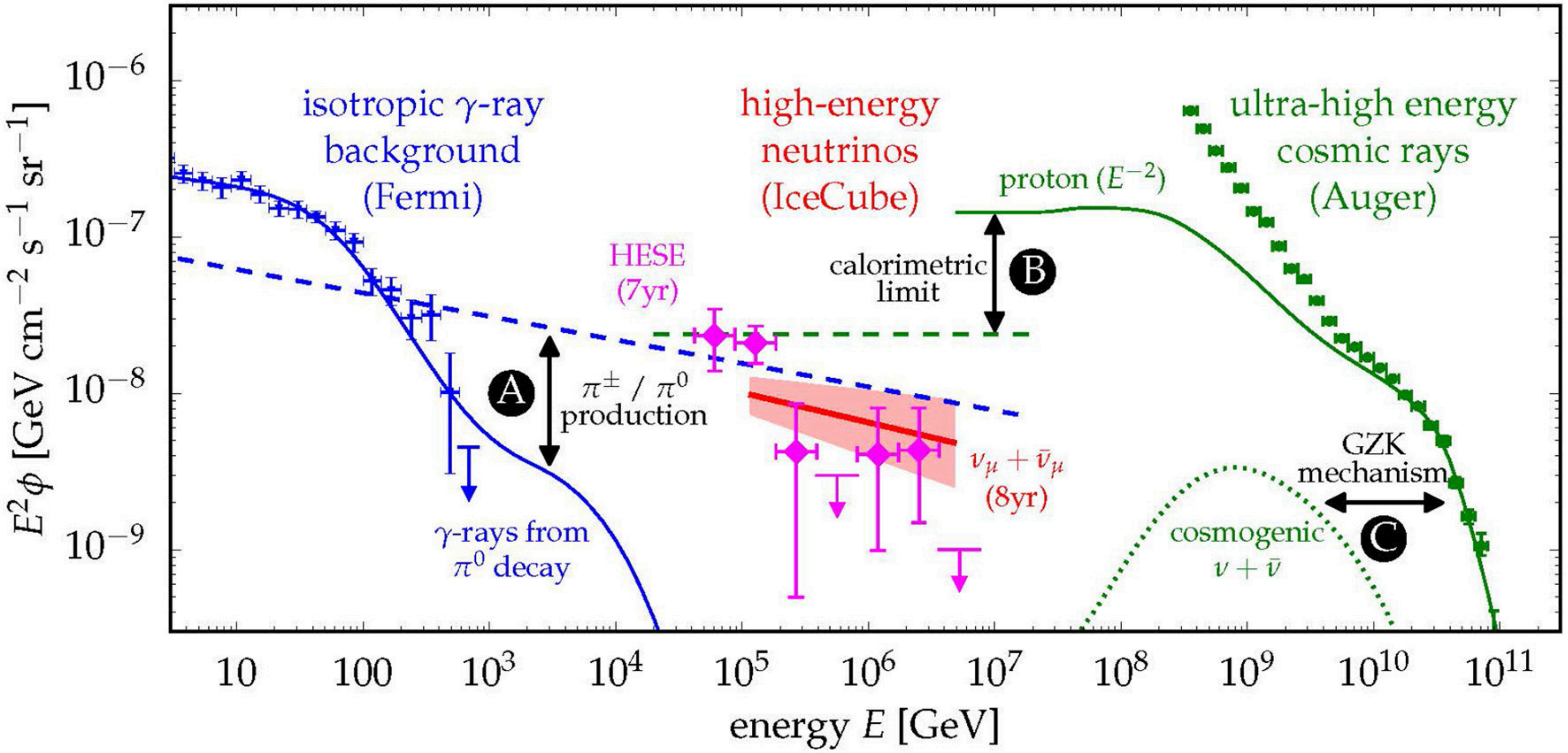
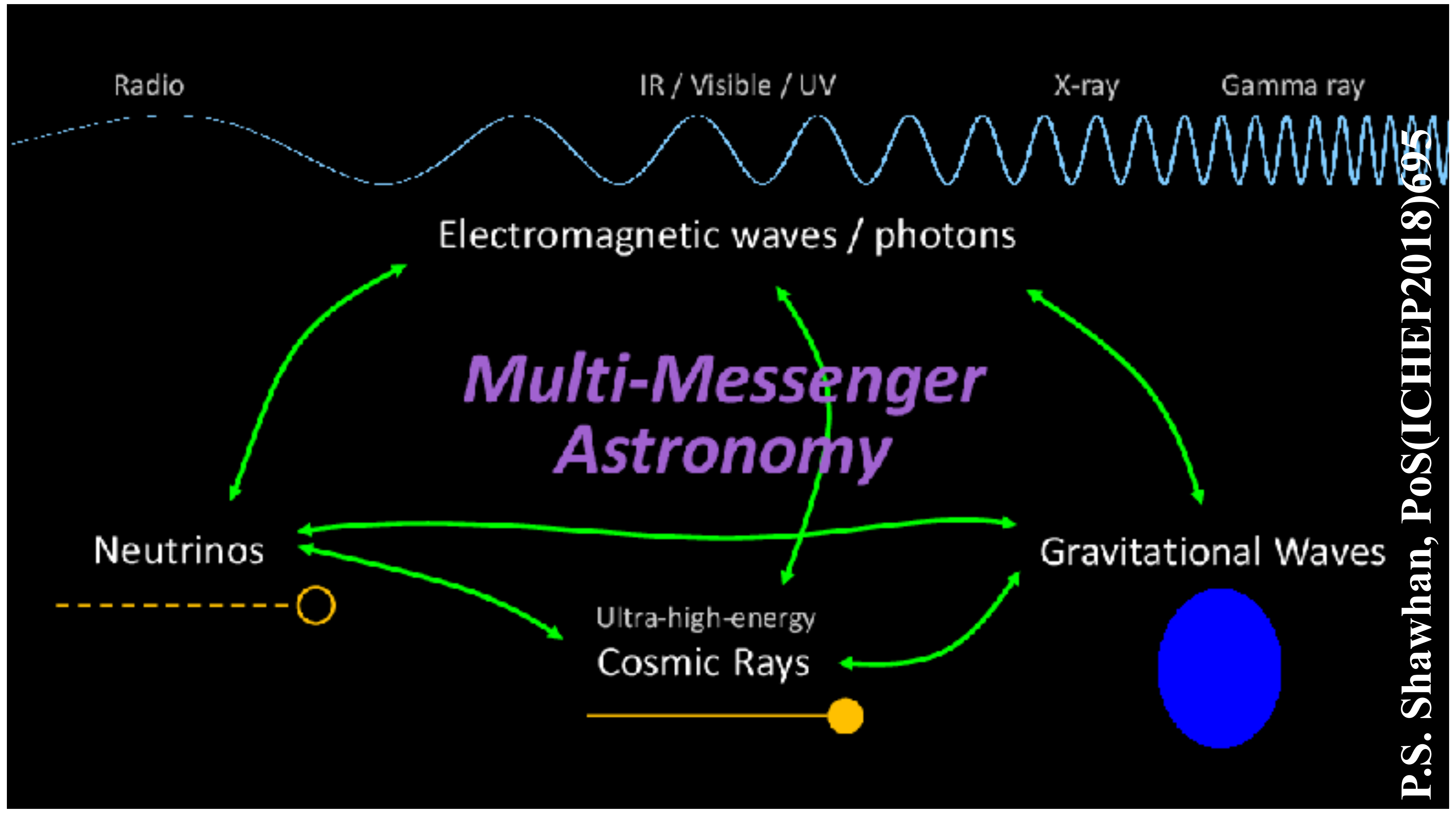


Multi-messenger astroparticle physics beyond 2035

nuclei, gamma rays, neutrinos, (gravitational waves)

Halzen et al, Frontiers in Astron. & Space Sci. (2019)





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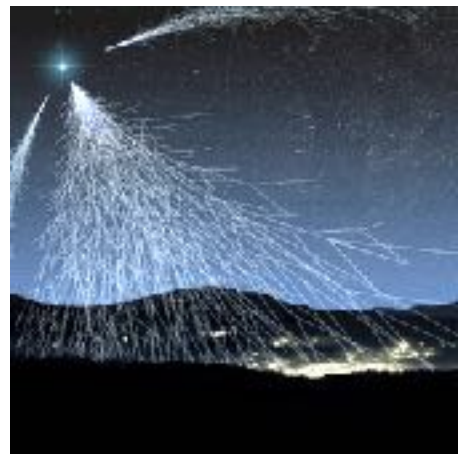
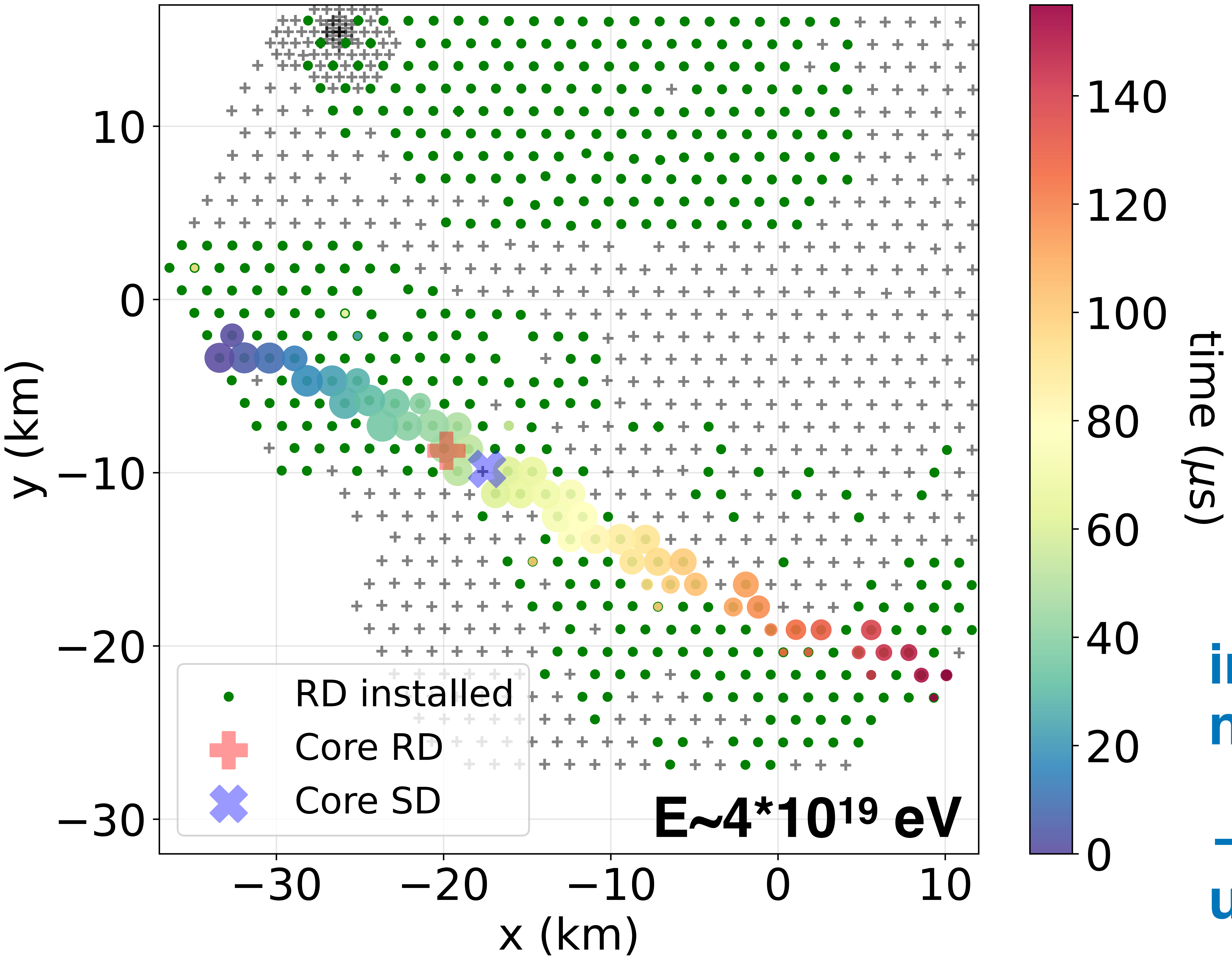
Upgraded Pierre Auger Observatory

with excellent mass separation operating until >2035



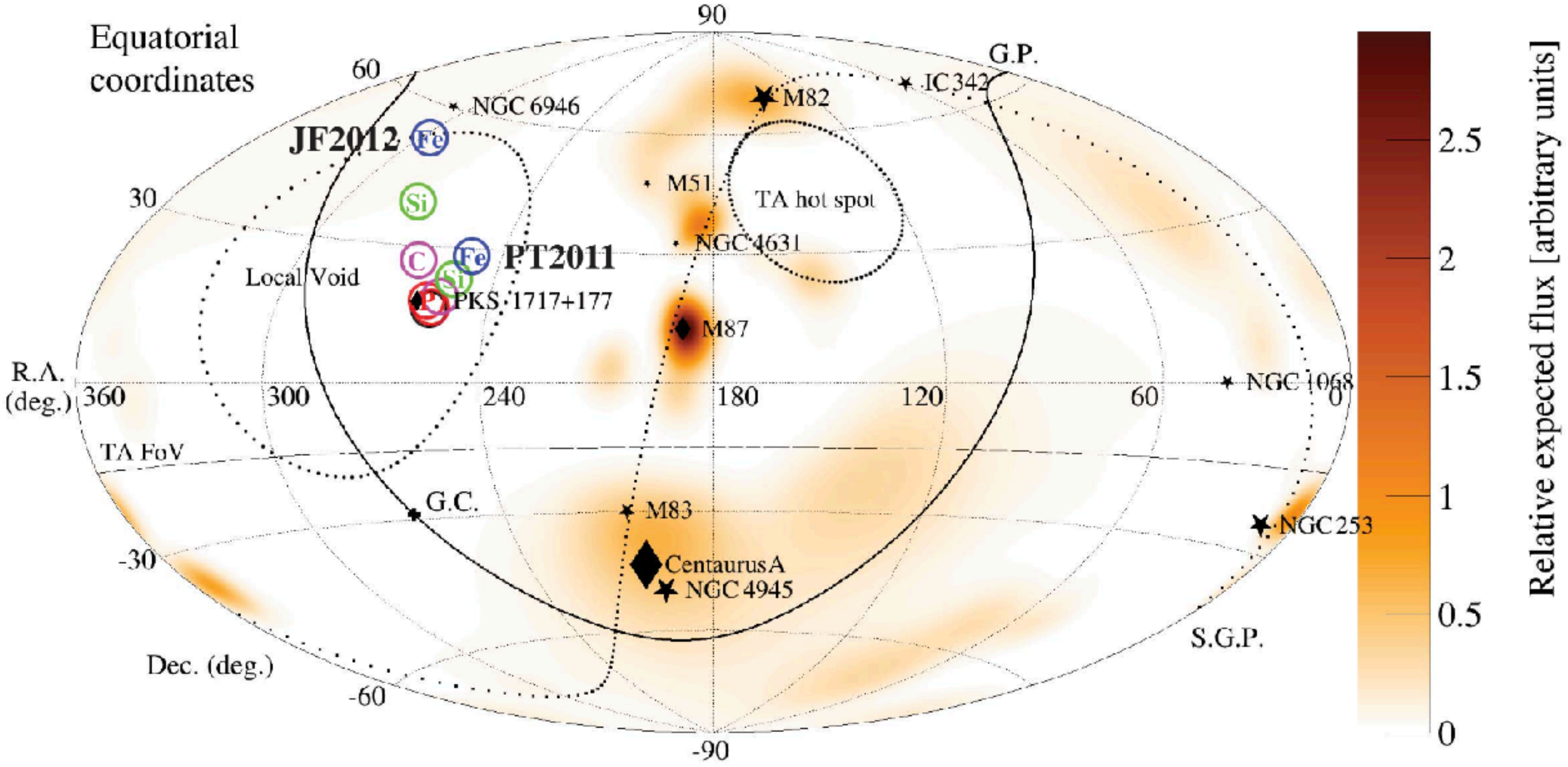


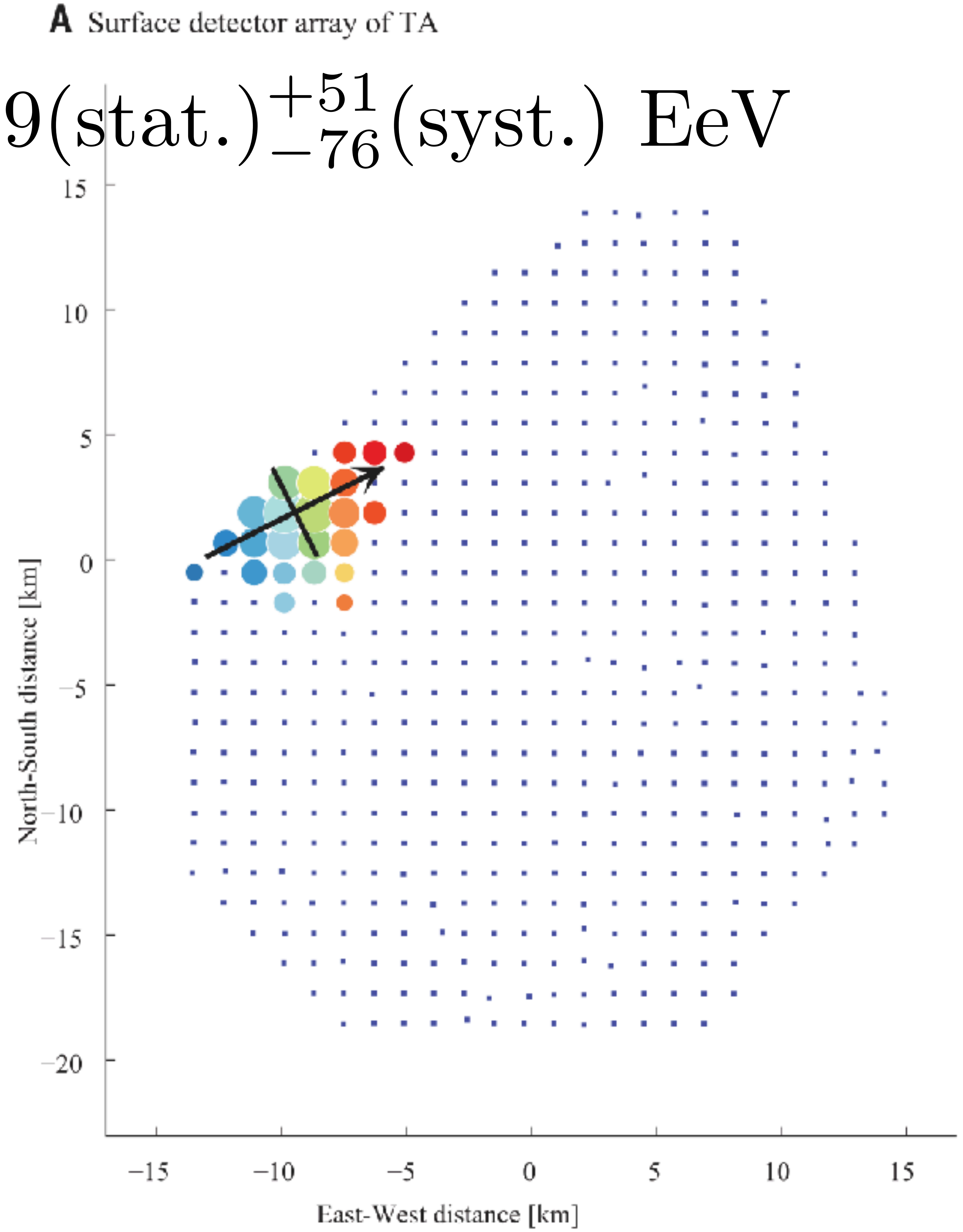
imagine this would be a photon or neutrino

—> new window to ultra-high-energy universe

An extremely energetic cosmic ray observed by a surface detector array

Telescope Array Collaboration*†



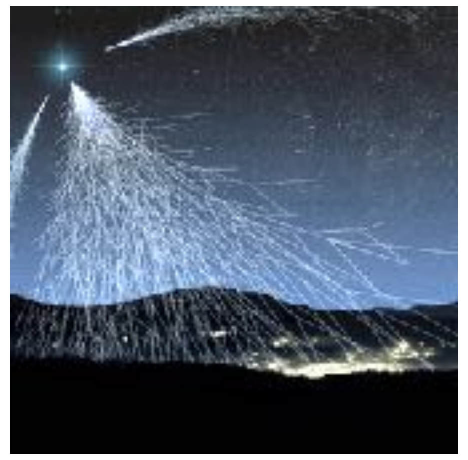


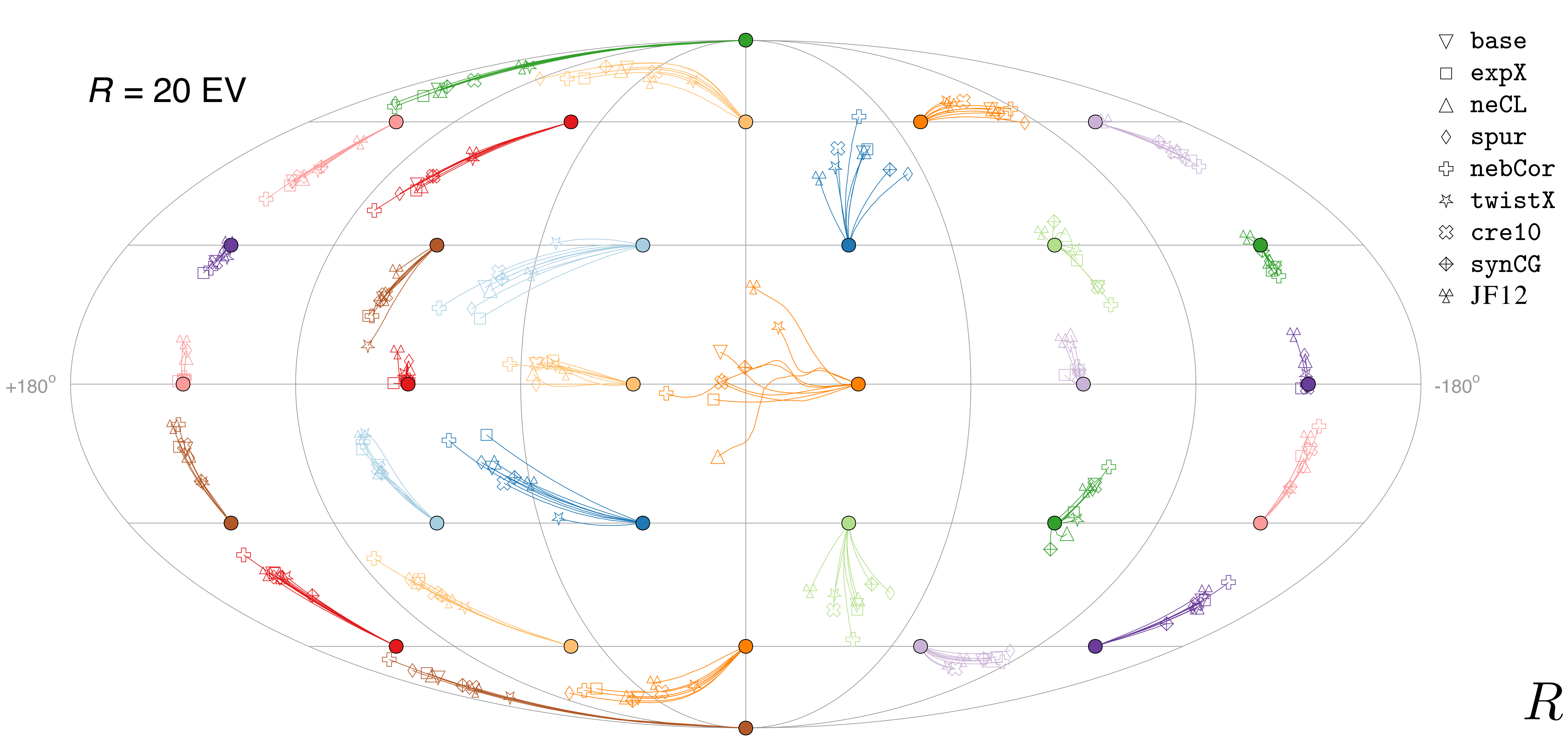
$$244 \pm 29(\text{stat.})^{+51}_{-76}(\text{syst.})\ \text{EeV}$$

imagine there would be more of those from the same direction —> hadron astronomy

Telescope Array Collaboration, *Science* **382**, 903–907 (2023)   24 November 2023

Deflection of cosmic rays in magnetic fields





$$R = \frac{E}{Z} \approx \frac{E}{A/2}$$

Figure 19. Angular deflections of ultrahigh-energy cosmic rays in the eight model variations derived in this paper and JF12. The cosmic-ray rigidity is 20 EV (2×10^{19} V). Filled circles denote a grid of arrival directions and the open symbols are the back-tracked directions at the edge of the Galaxy.

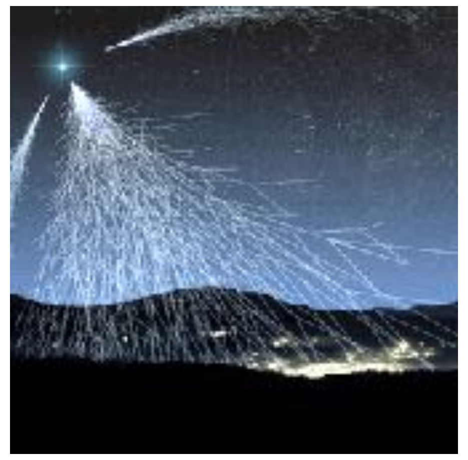
The Coherent Magnetic Field of the Milky Way

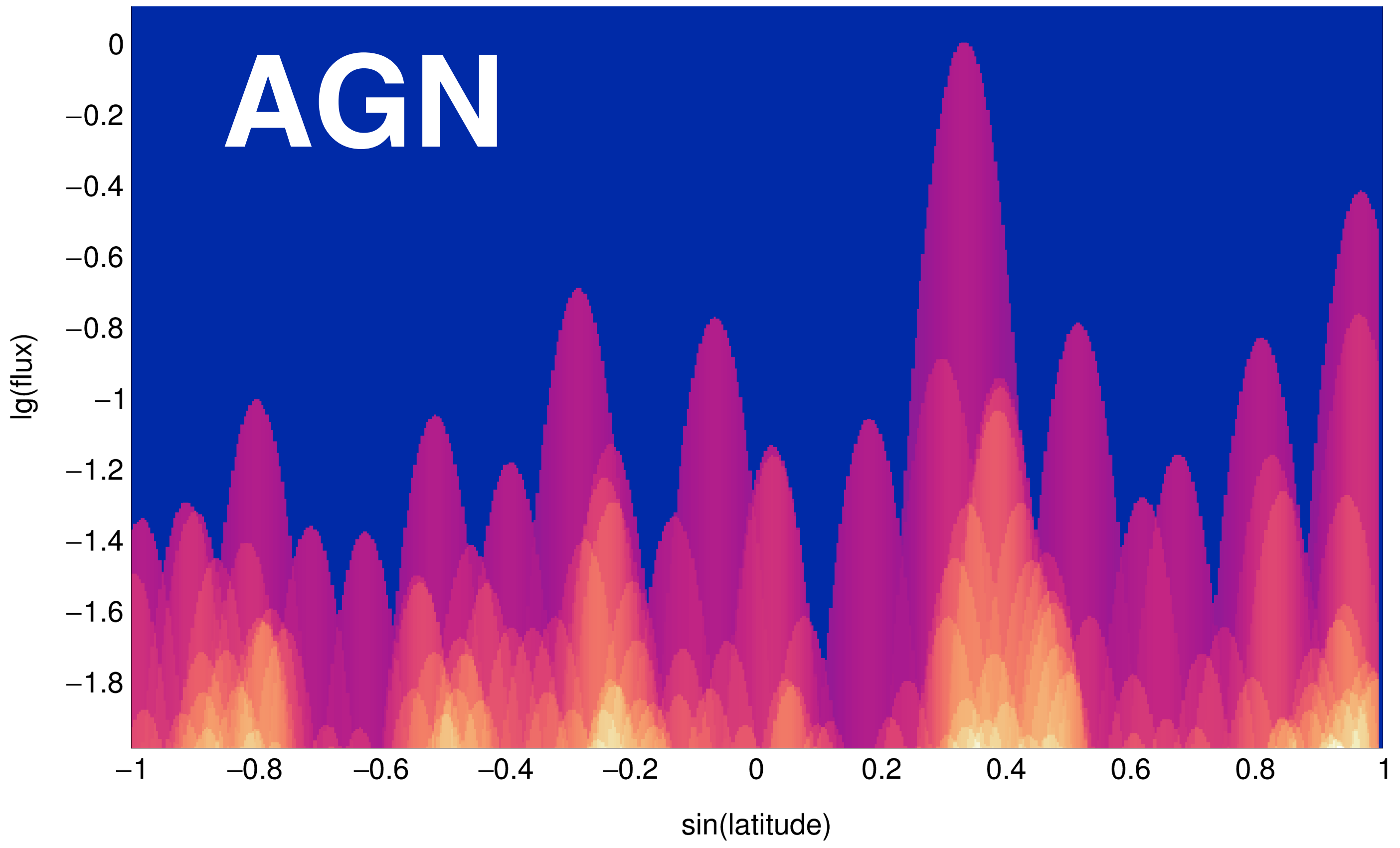
Michael Unger [1,2] and Glennys R. Farrar [3]

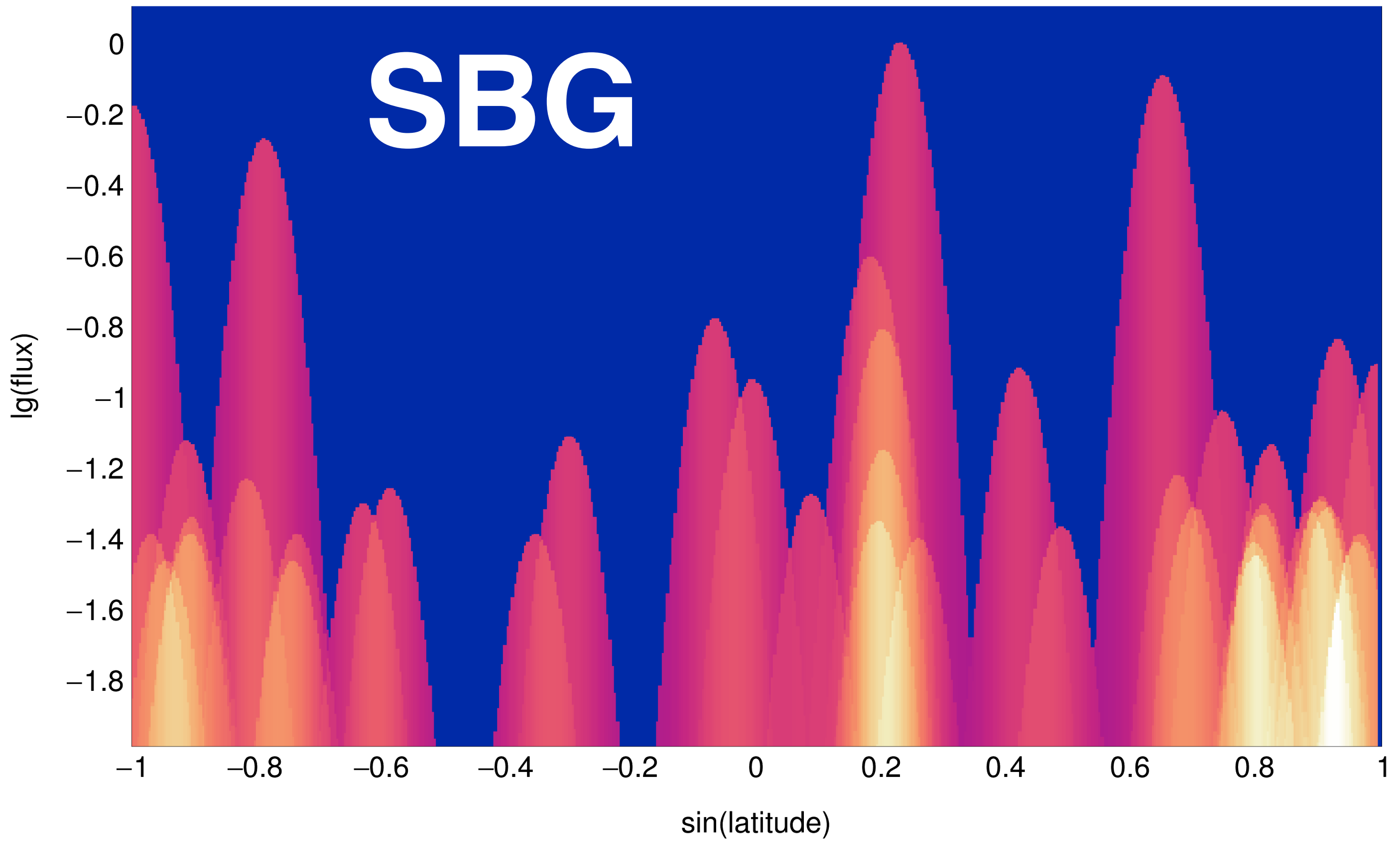
arXiv:2311.12120v3

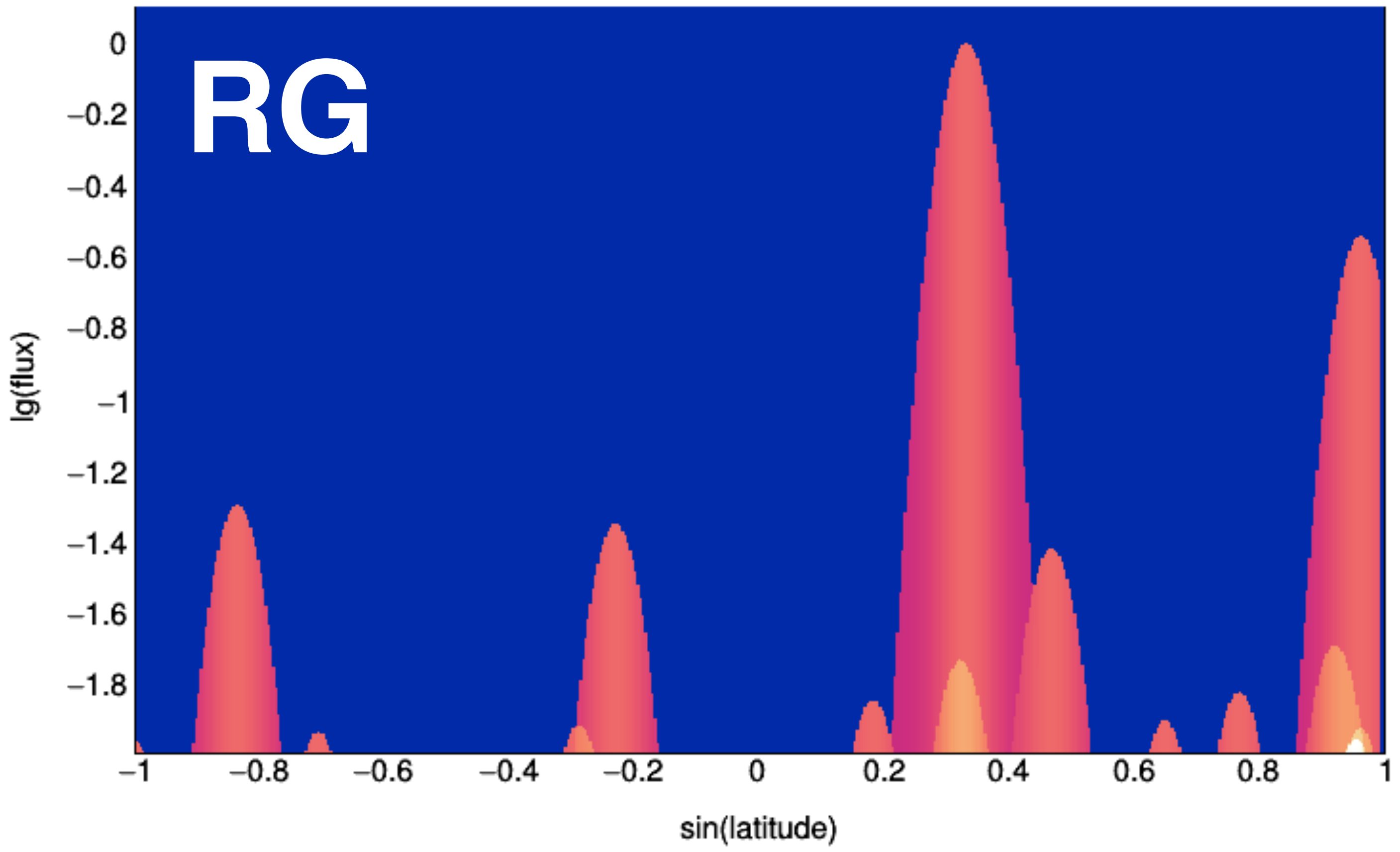
need to know rigidity (mass) of incoming cosmic rays

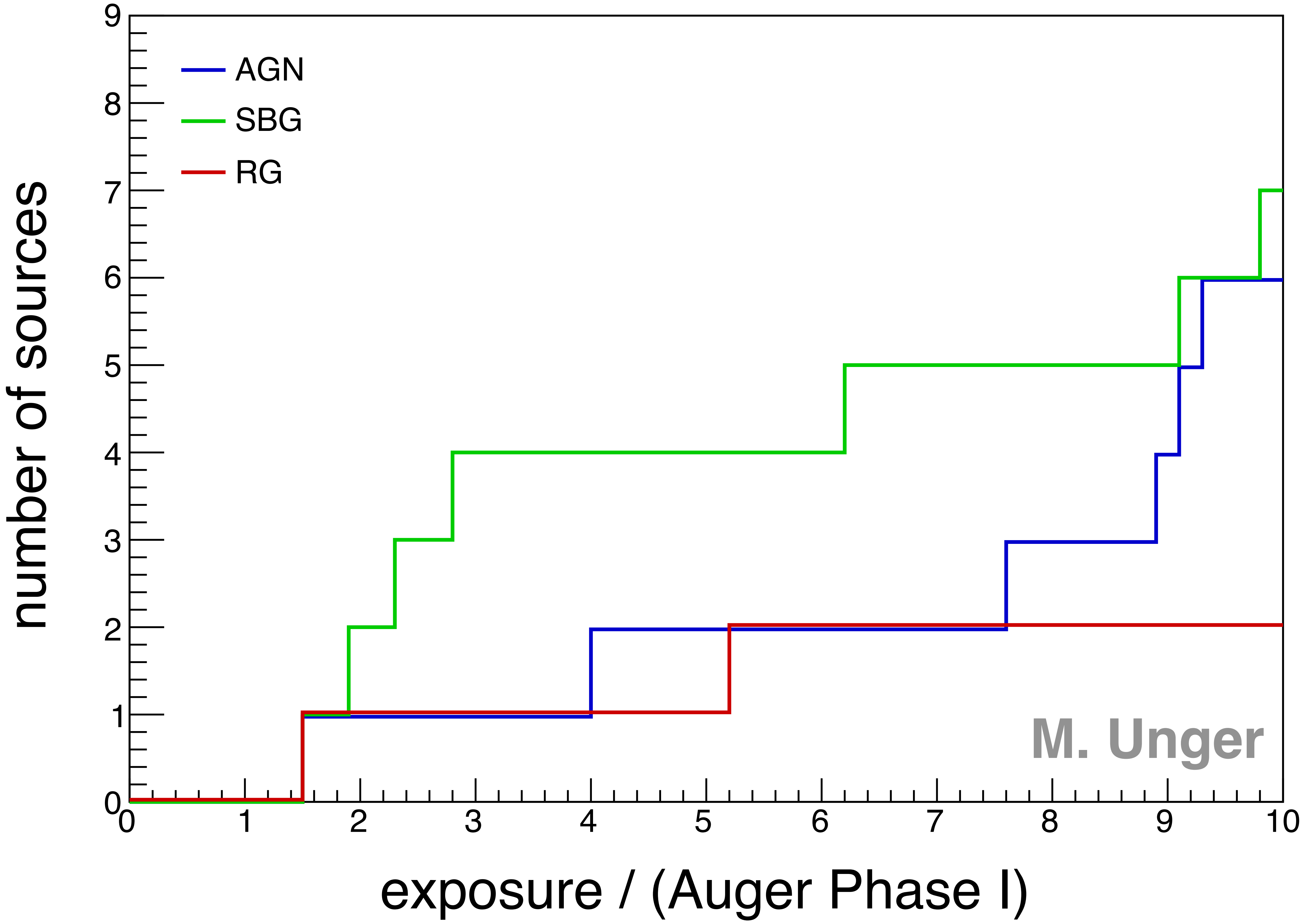
Expected number of sources







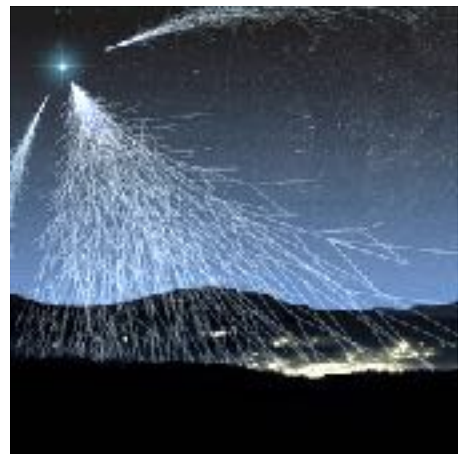




extrapolation, based on Centaurus excess from Auger, using different source catalogues

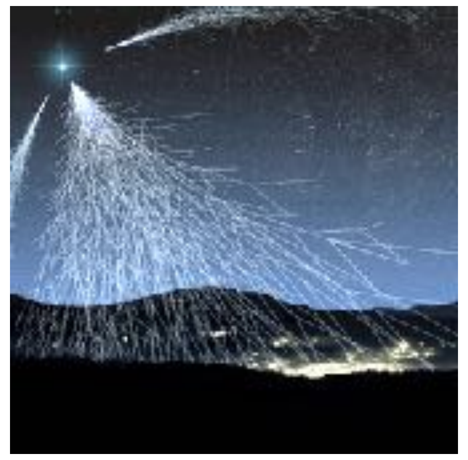
Expected number of source images as a function of exposure for different source classes

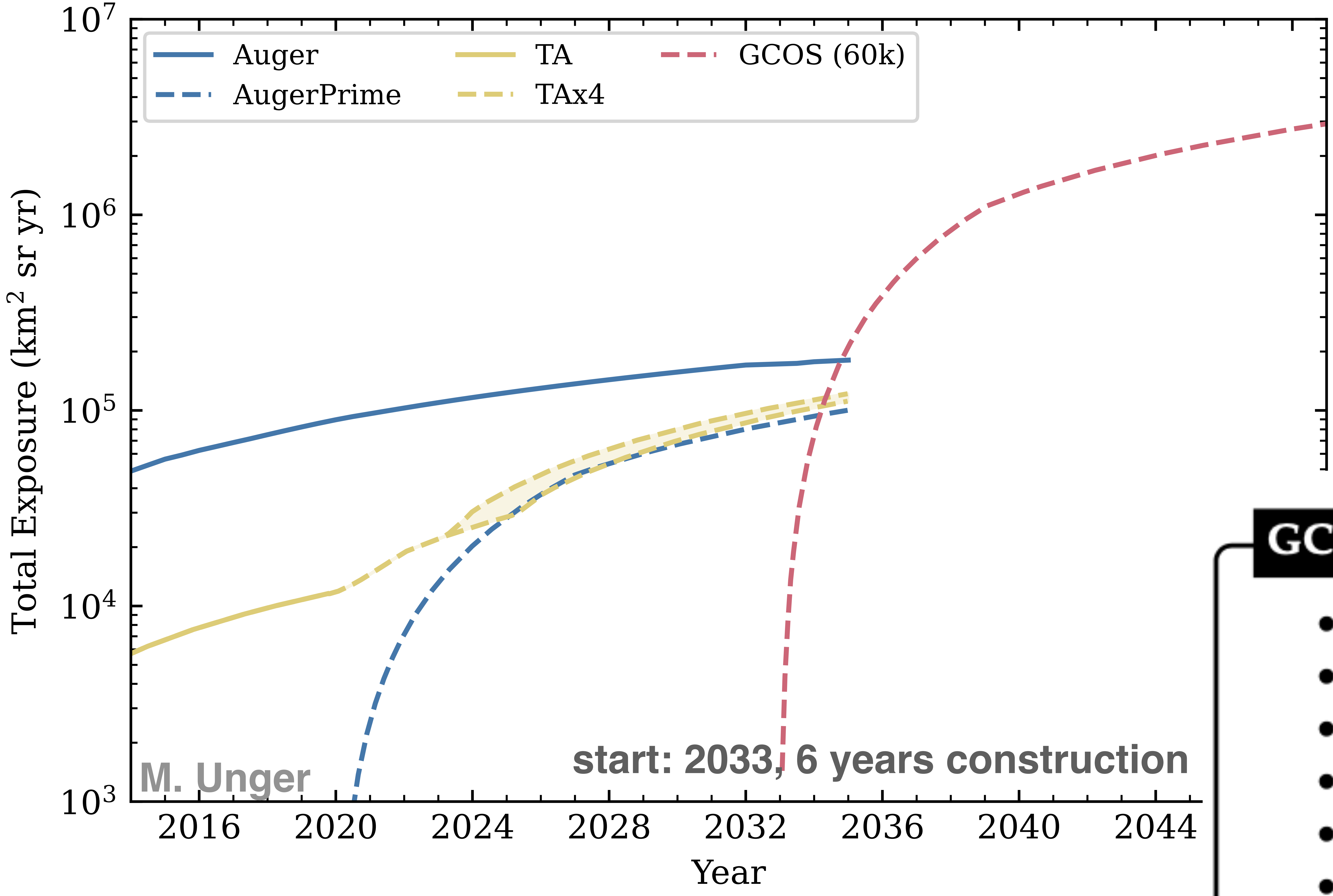
.. towards a straw man design ..



intense discussions during Wuppertal (2022) and Brussels (2023) workshops

GCOS exposure



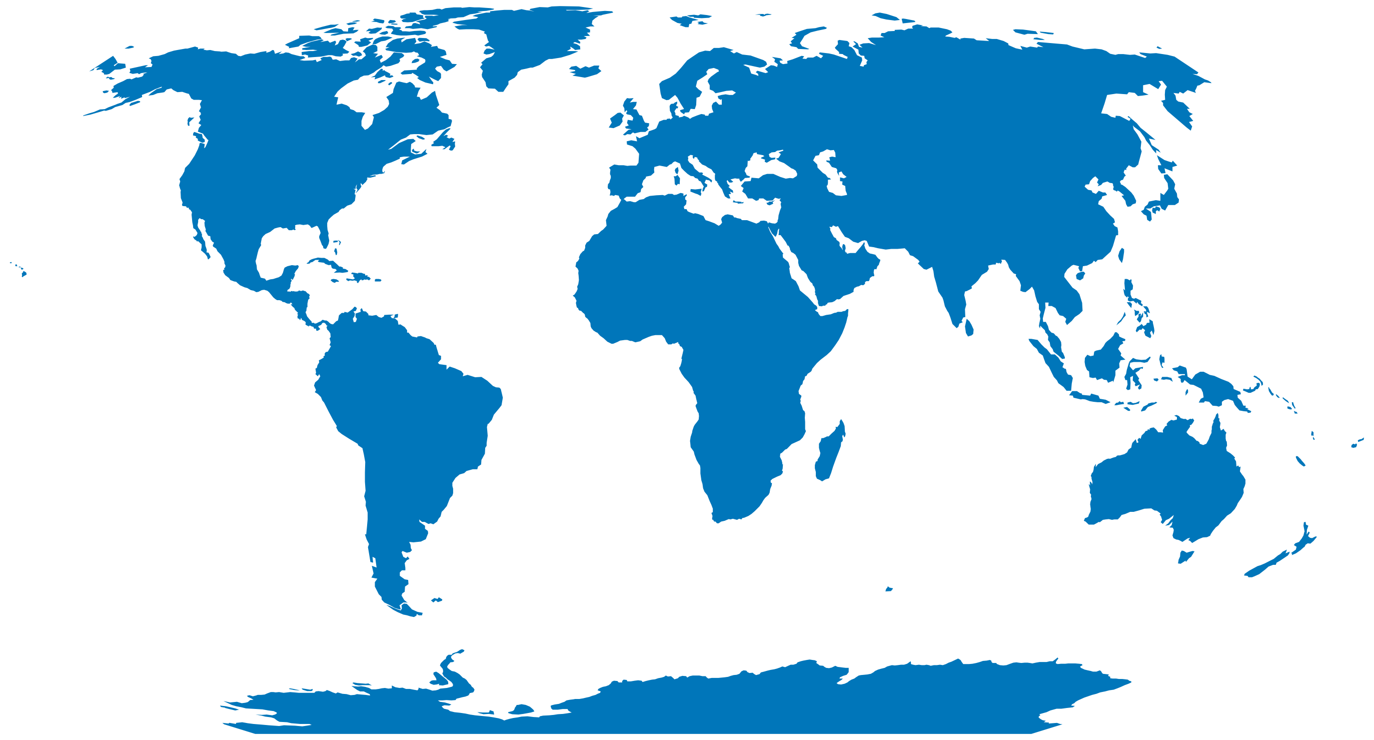


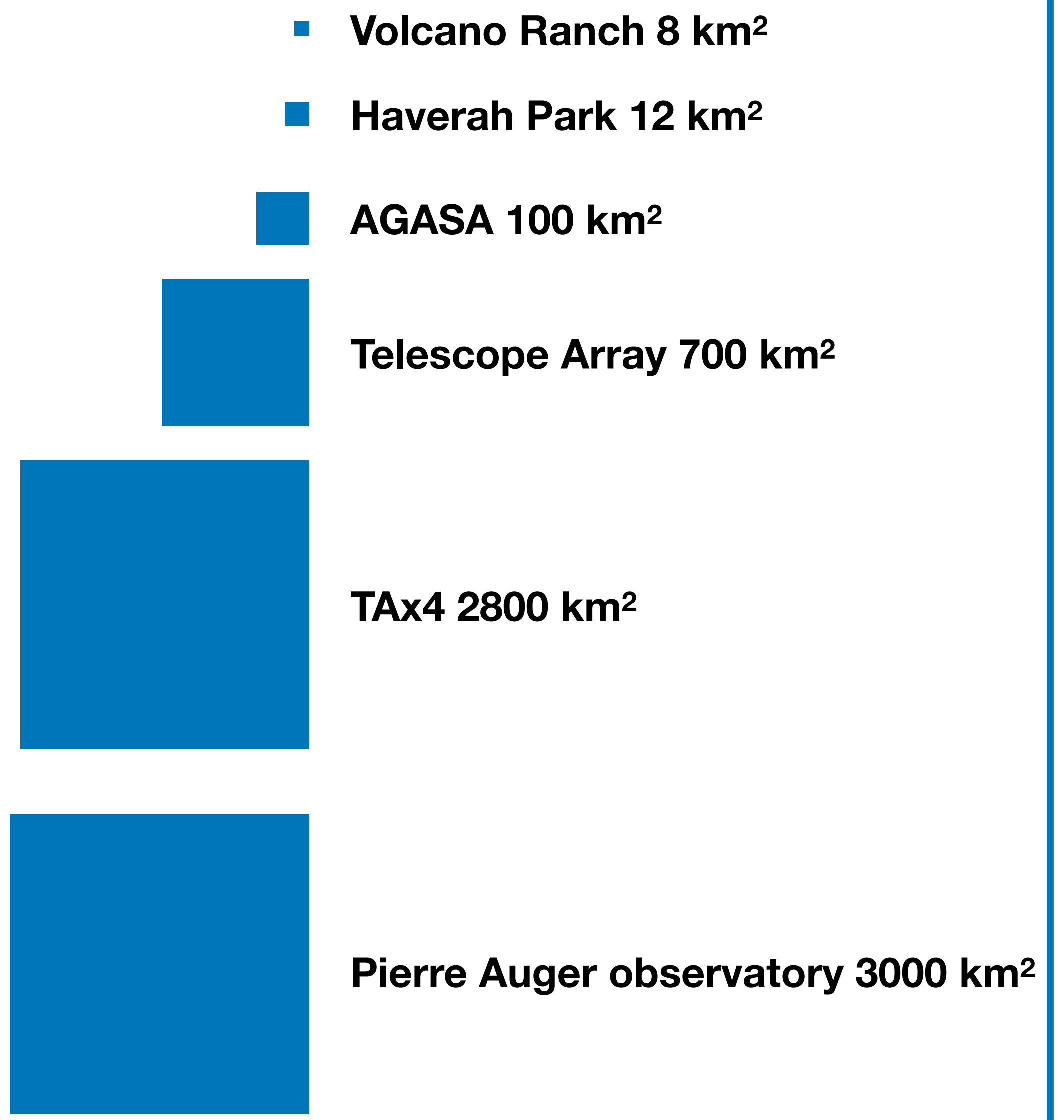
GCOS:
projected Auger exposure in 2030 in 1 year

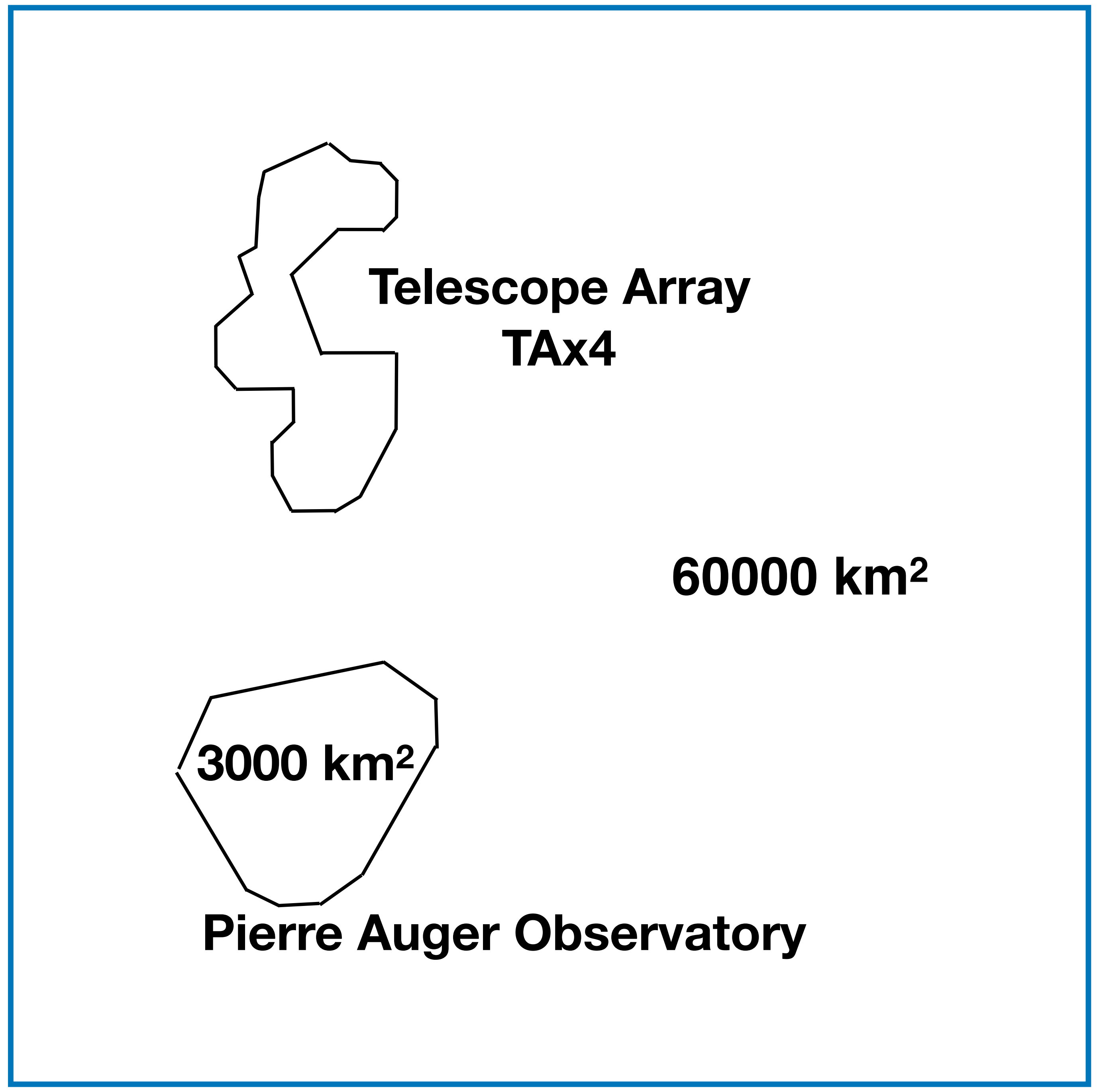
GCOS Requirements

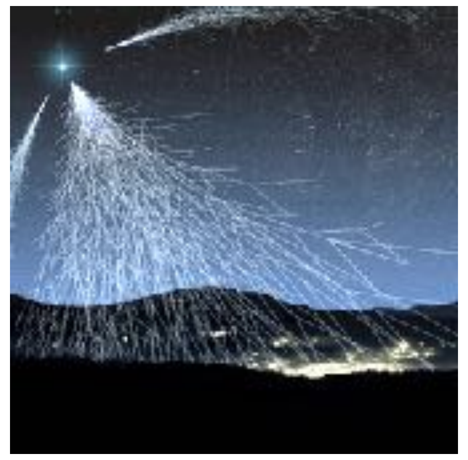
- total area: 60 000 km^2
- number of sites ≥ 2
- trigger threshold: 10^{19} eV
- high-quality threshold: 3×10^{19} eV
- σ_E: 10%, $\sigma_{\ln A}$: 1, σ_θ: 1°
- high duty cycle, low maintenance

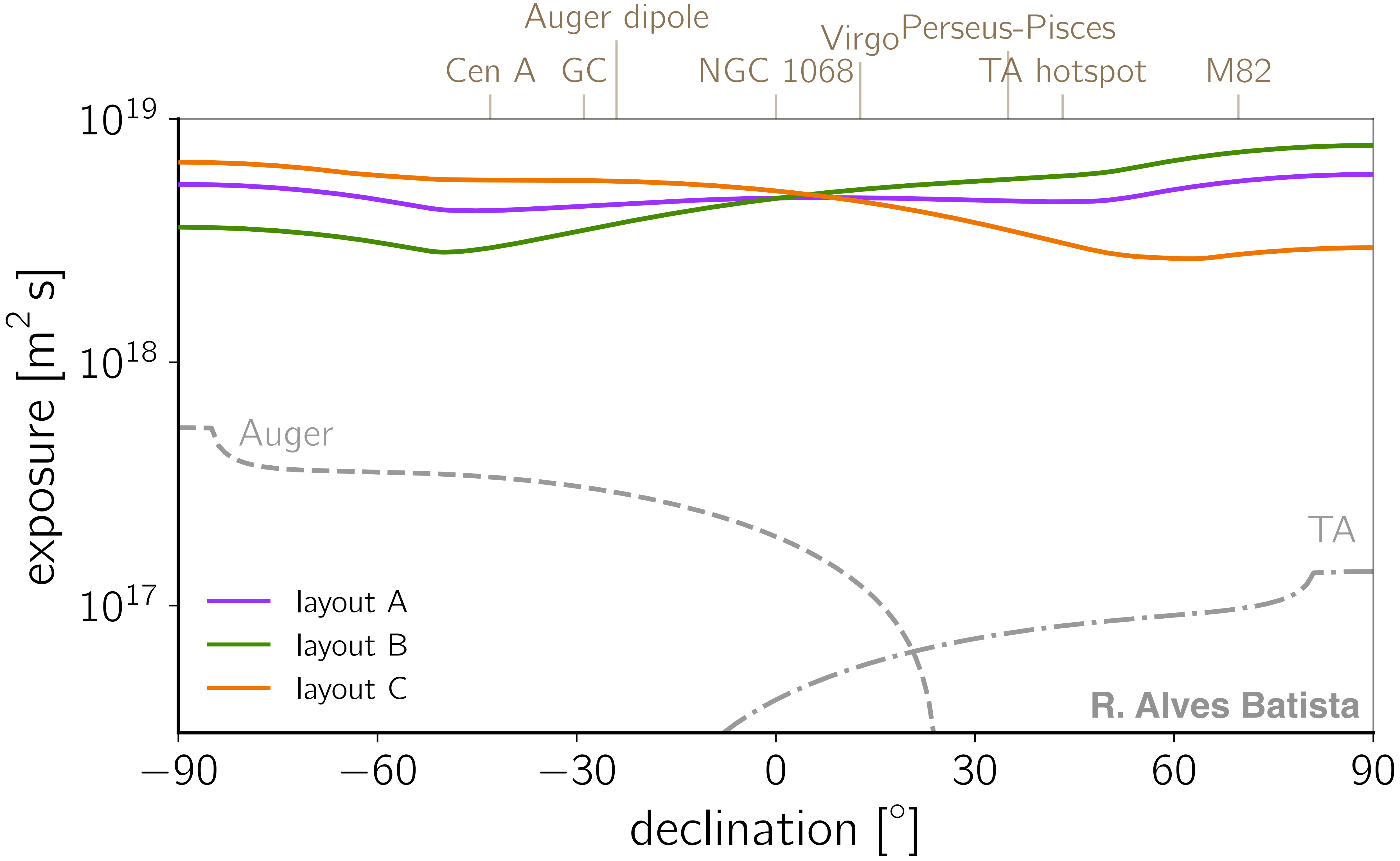
GCOS sites











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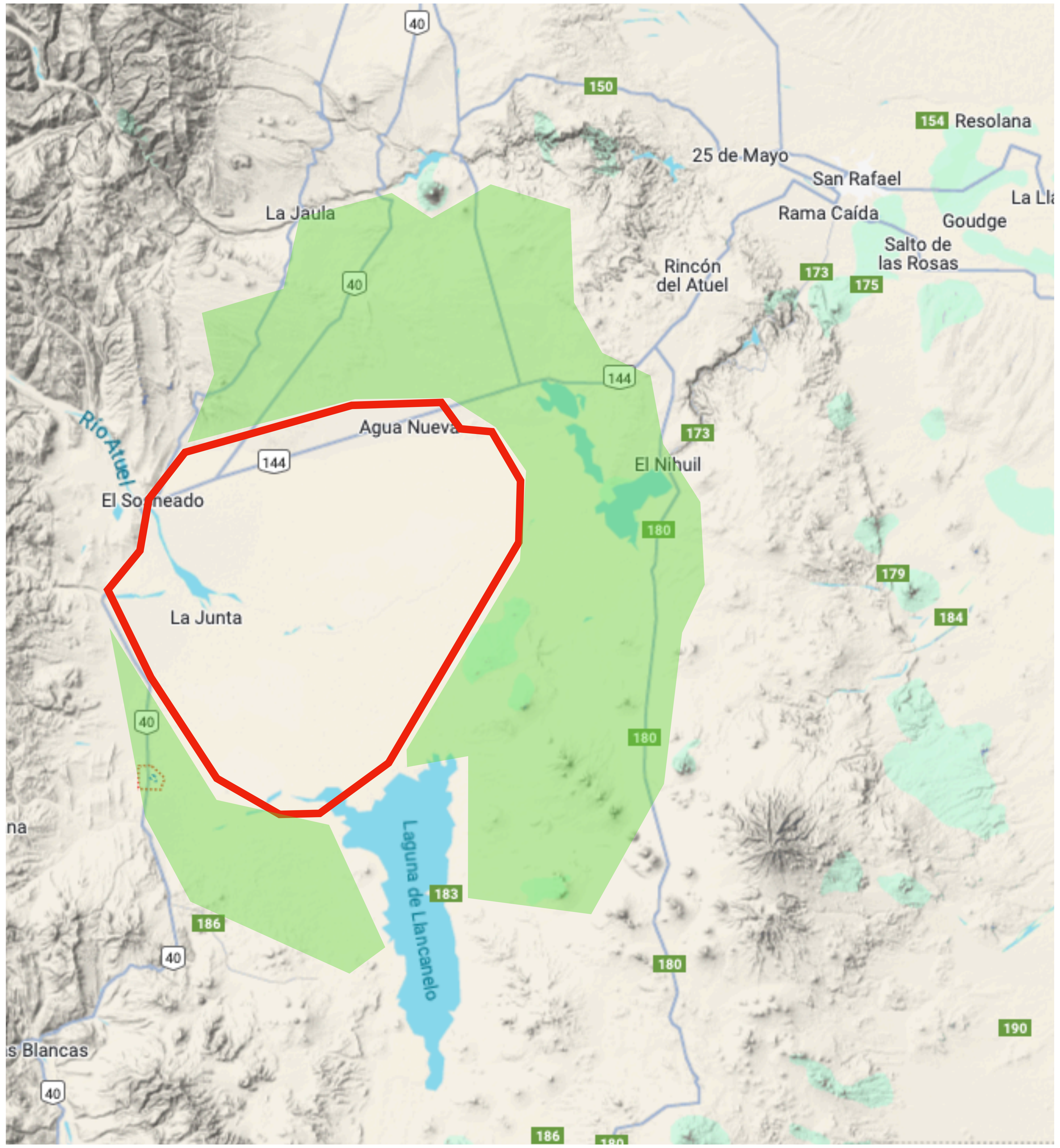
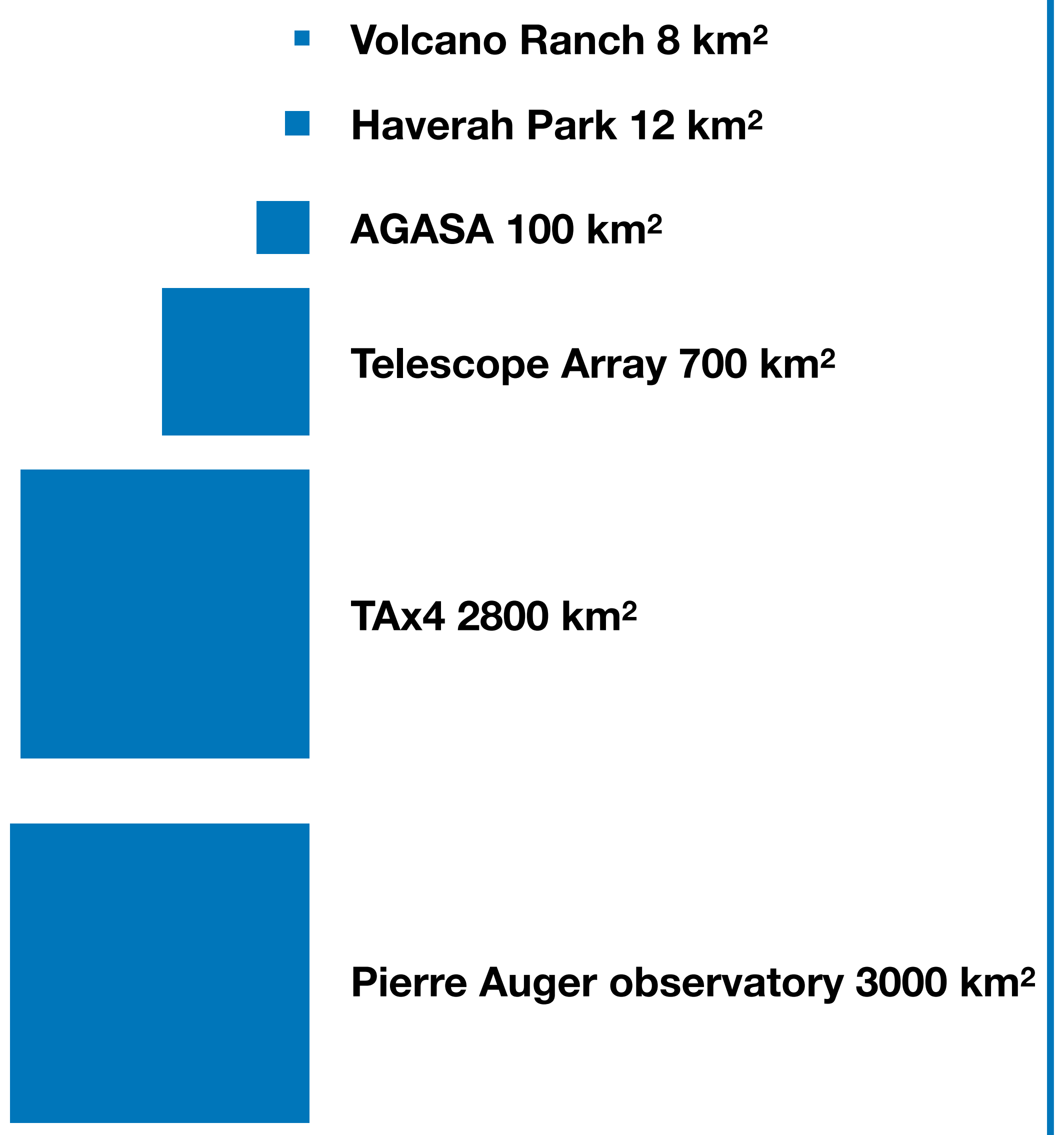
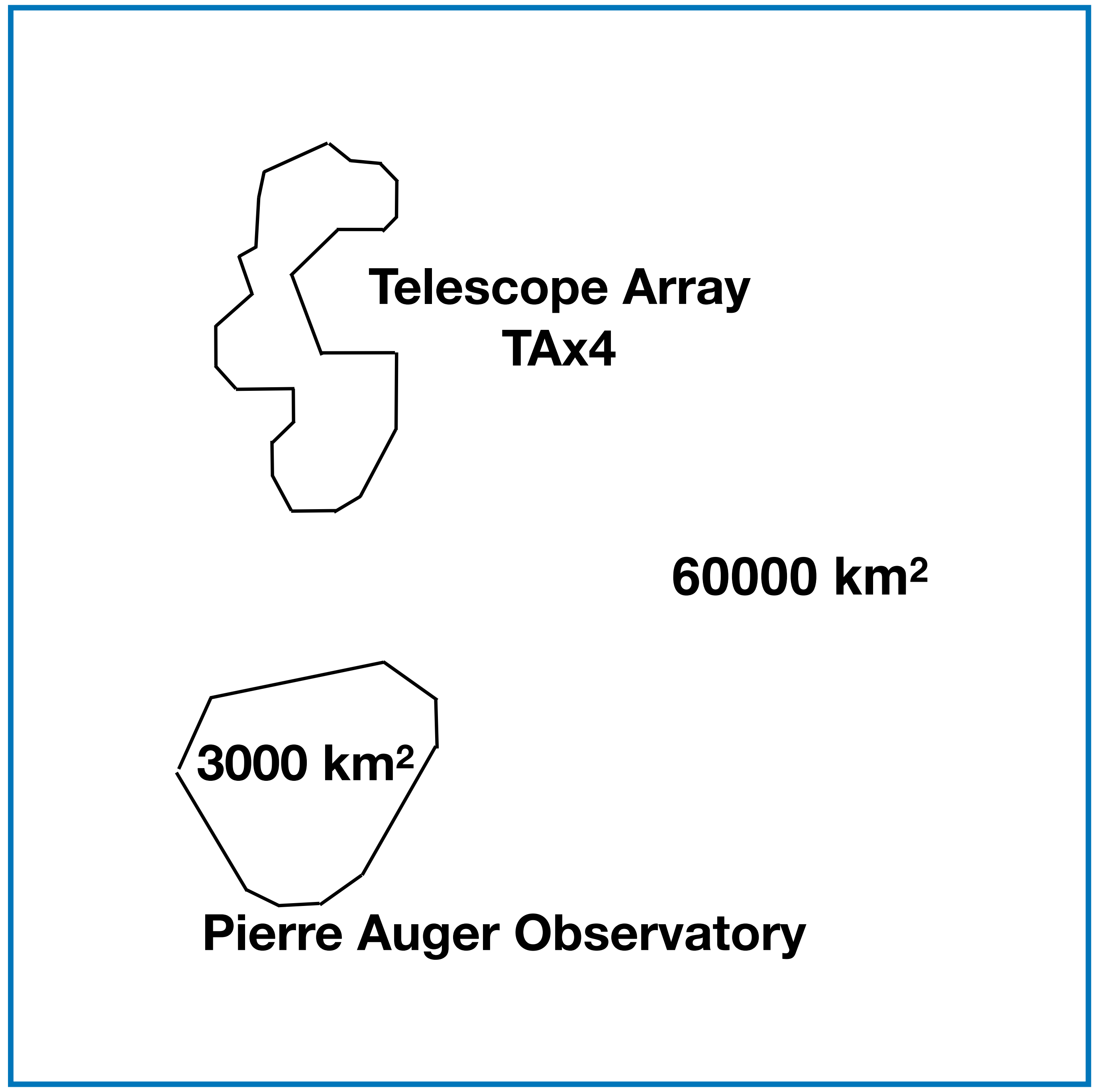
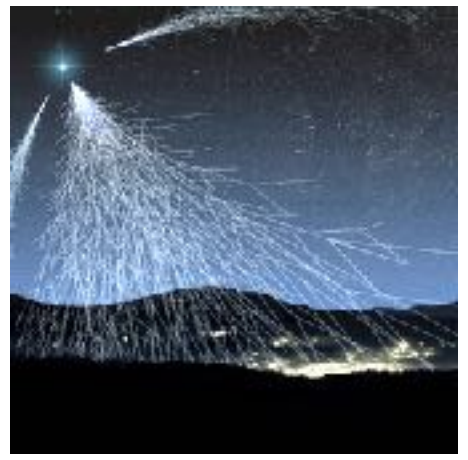
GCOS sites

Could we extend Auger to build a 1st GCOS (R&D) site?









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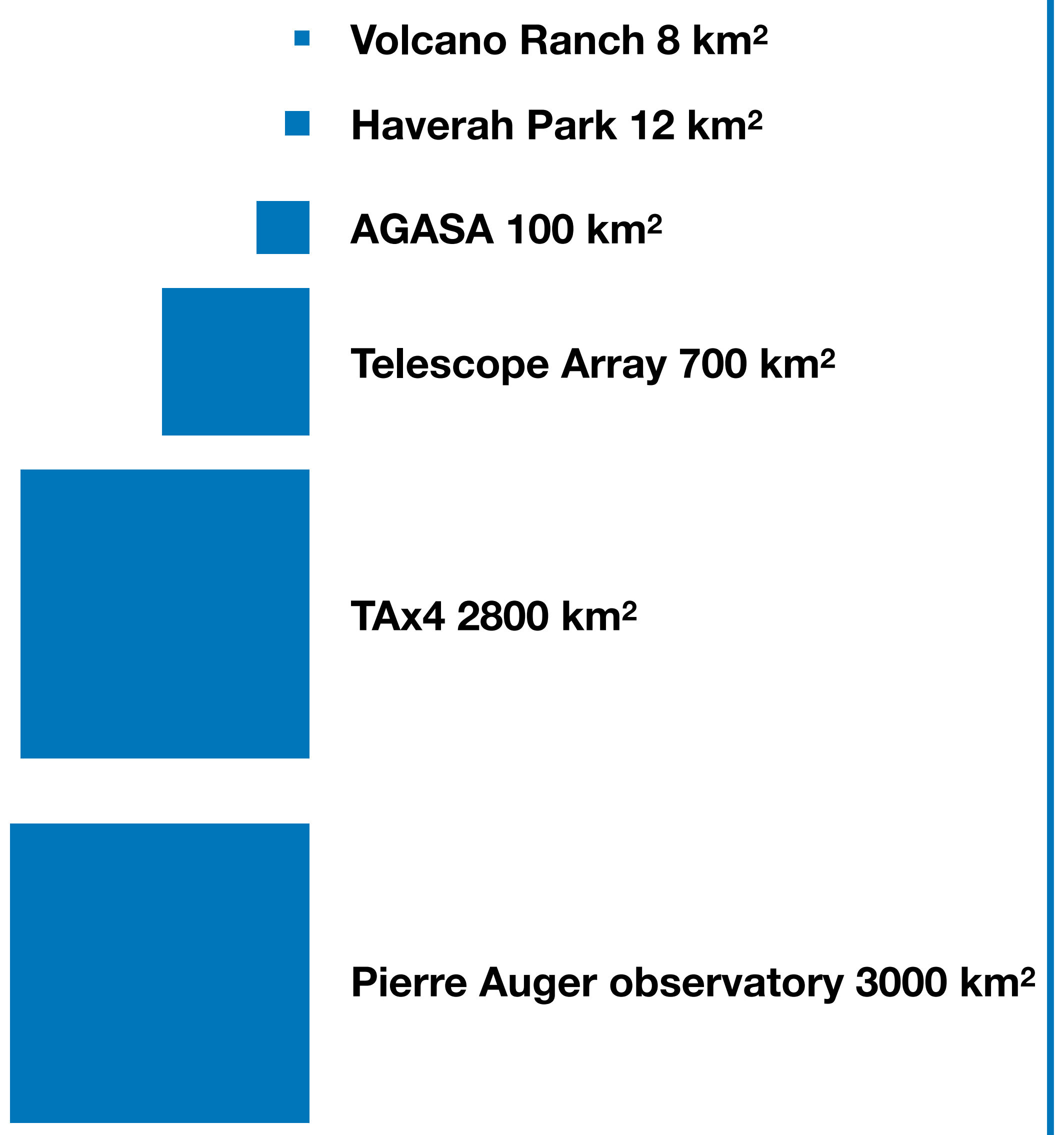
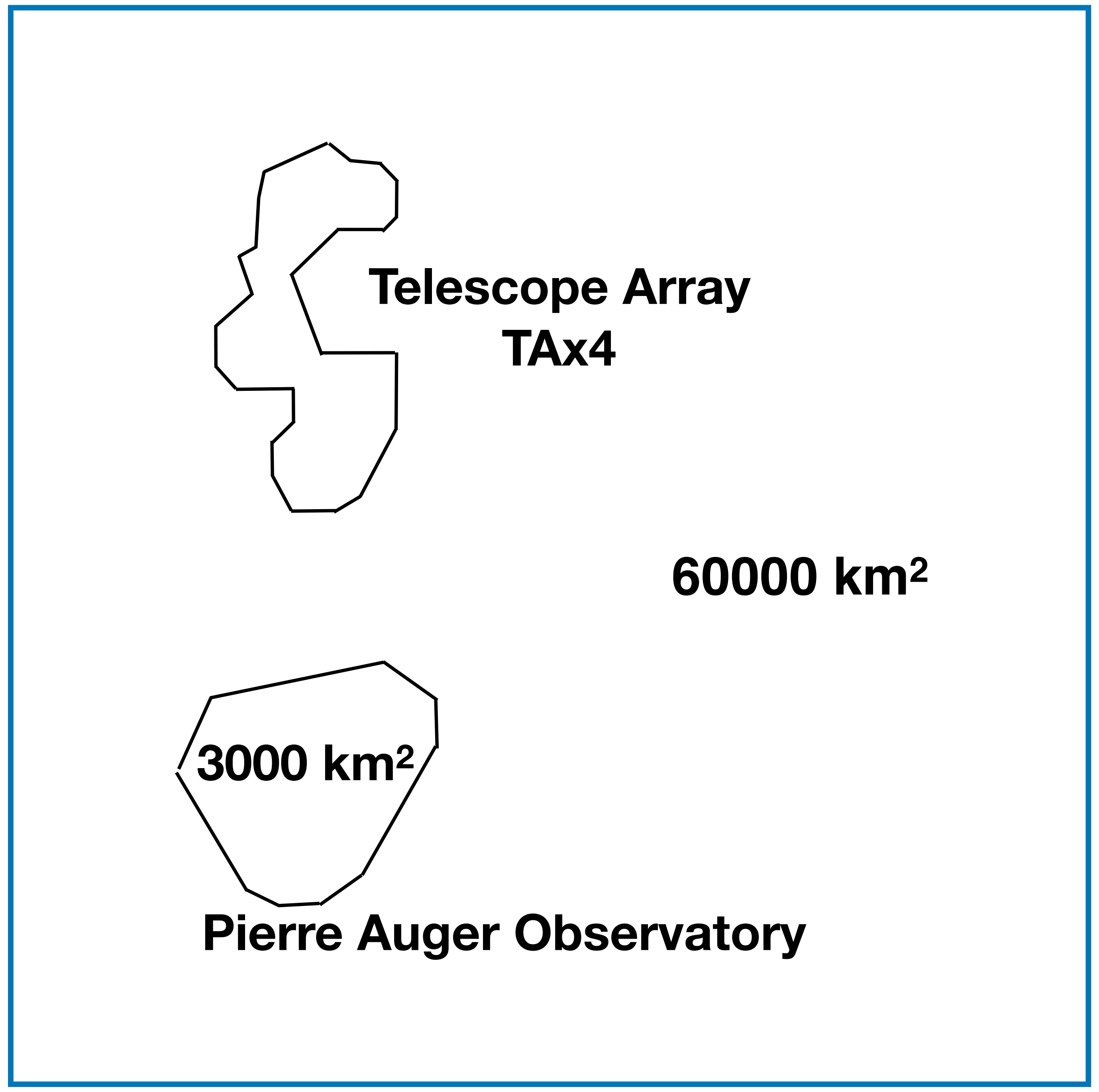
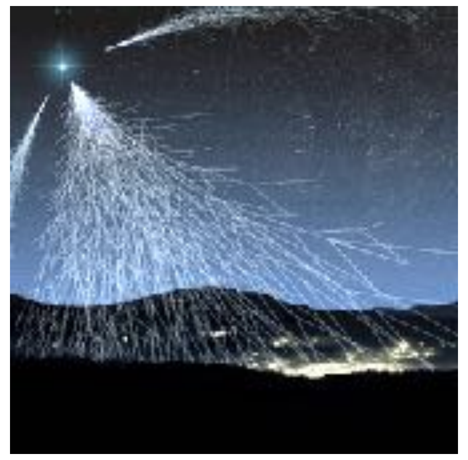
- high duty cycle, low maintenance

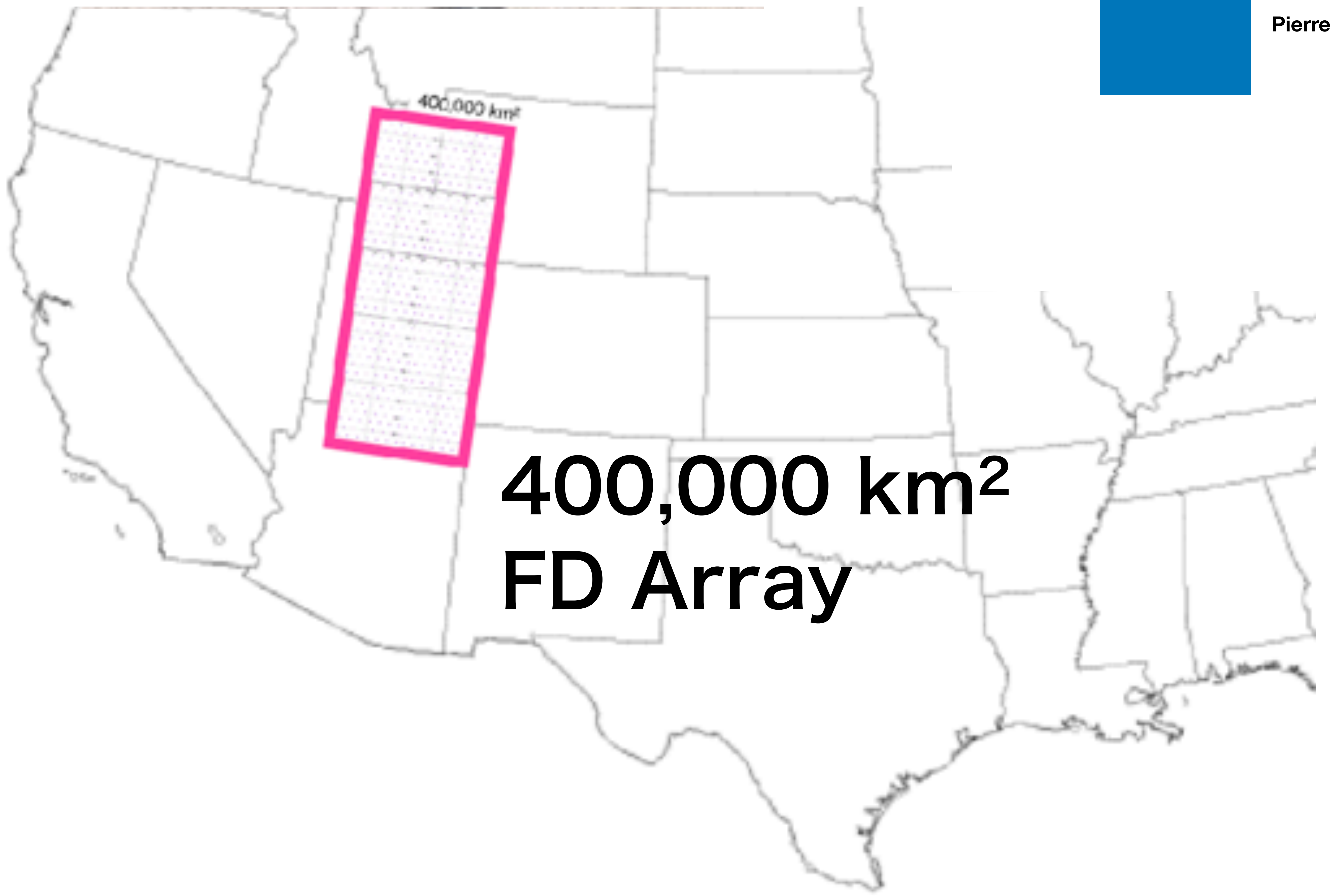
GCOS sites

… starting to look at various site options … e.g. USA









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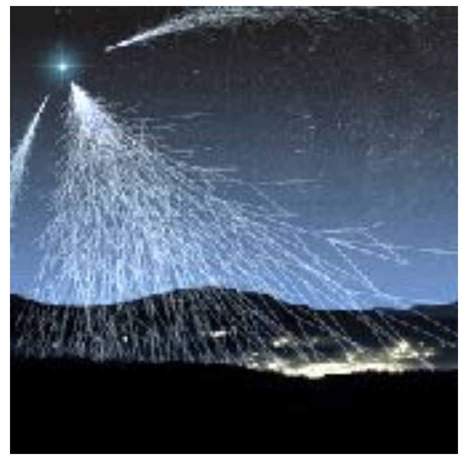
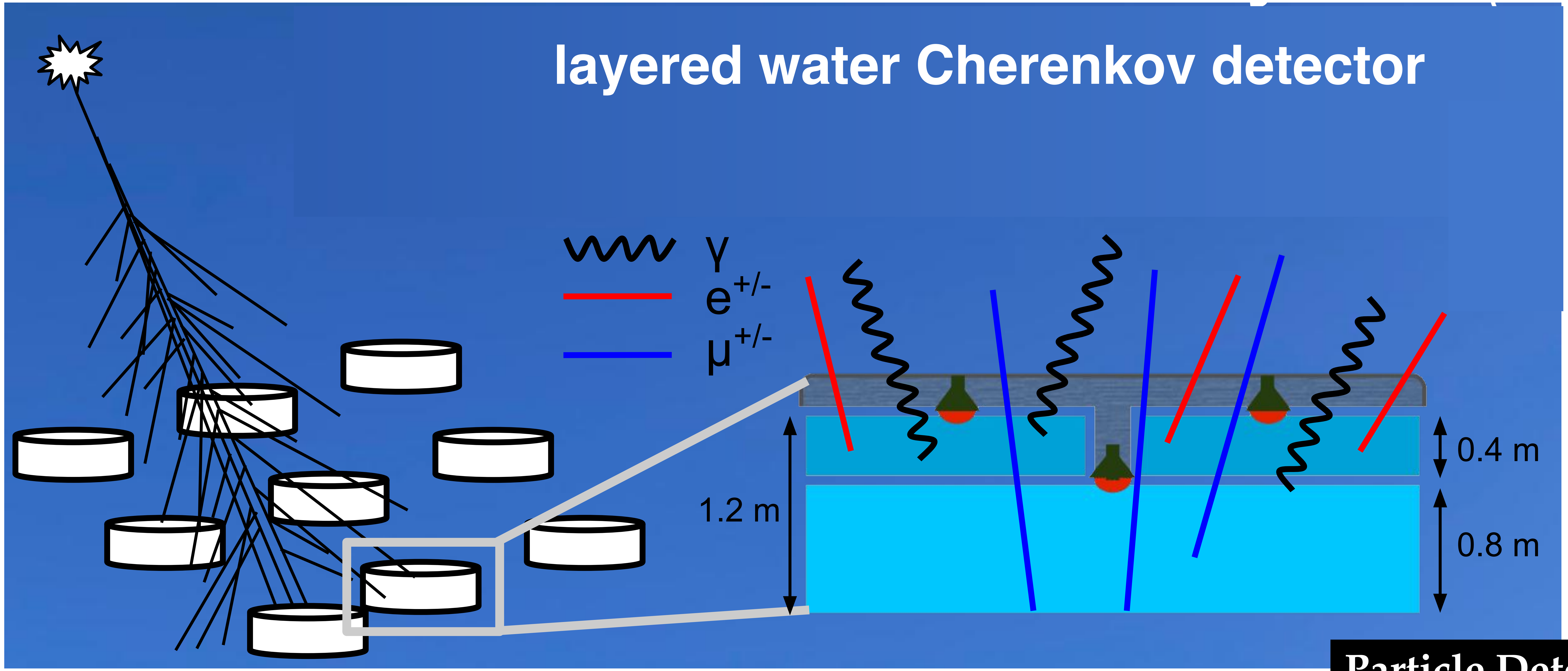
GCOS - particle detector array





see poster B. Flaggs

$$\begin{pmatrix} S_{\rm top} \\ S_{\rm bot} \end{pmatrix} = \mathcal{M} \begin{pmatrix} S_{\rm EM} \\ S_\mu \end{pmatrix} = \begin{pmatrix} a & b \\ 1-a & 1-b \end{pmatrix} \begin{pmatrix} S_{\rm EM} \\ S_\mu \end{pmatrix}$$

a + b → from simulations, depend on detector specifics

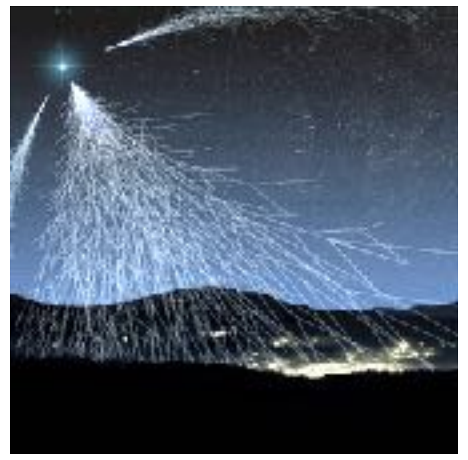
S_{top} + S_{bot} → from calibrated PMT signals

Particle Detector Design

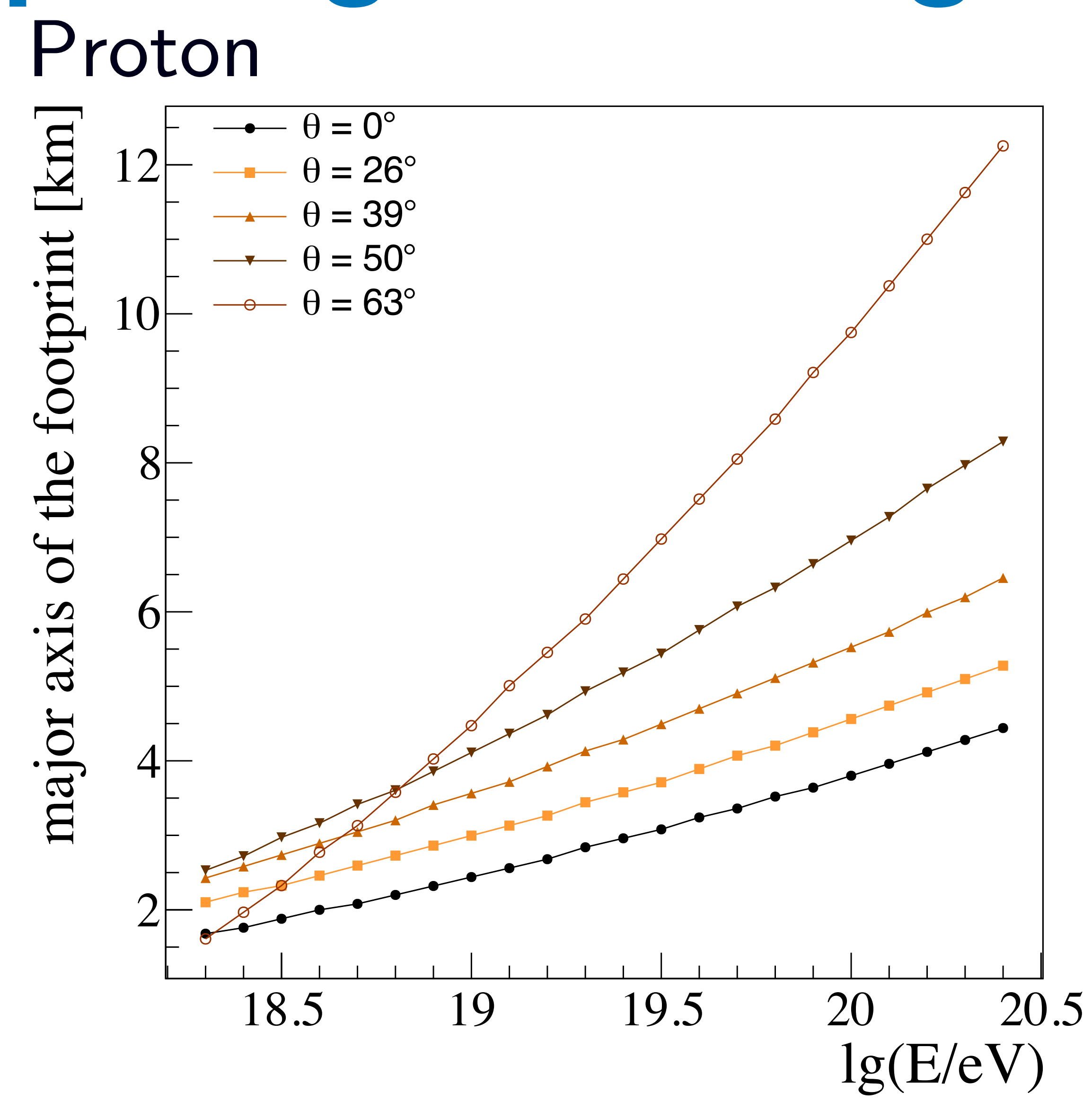
- layered water Cherenkov detectors
- emag. and muonic EAS component
- detector spacing: 2.2 km
- number of stations: 18 000
- σ_S: 10%, σ_{N_μ}: 10%, $\sigma_{X_{\max}}$: 30 g/cm^2

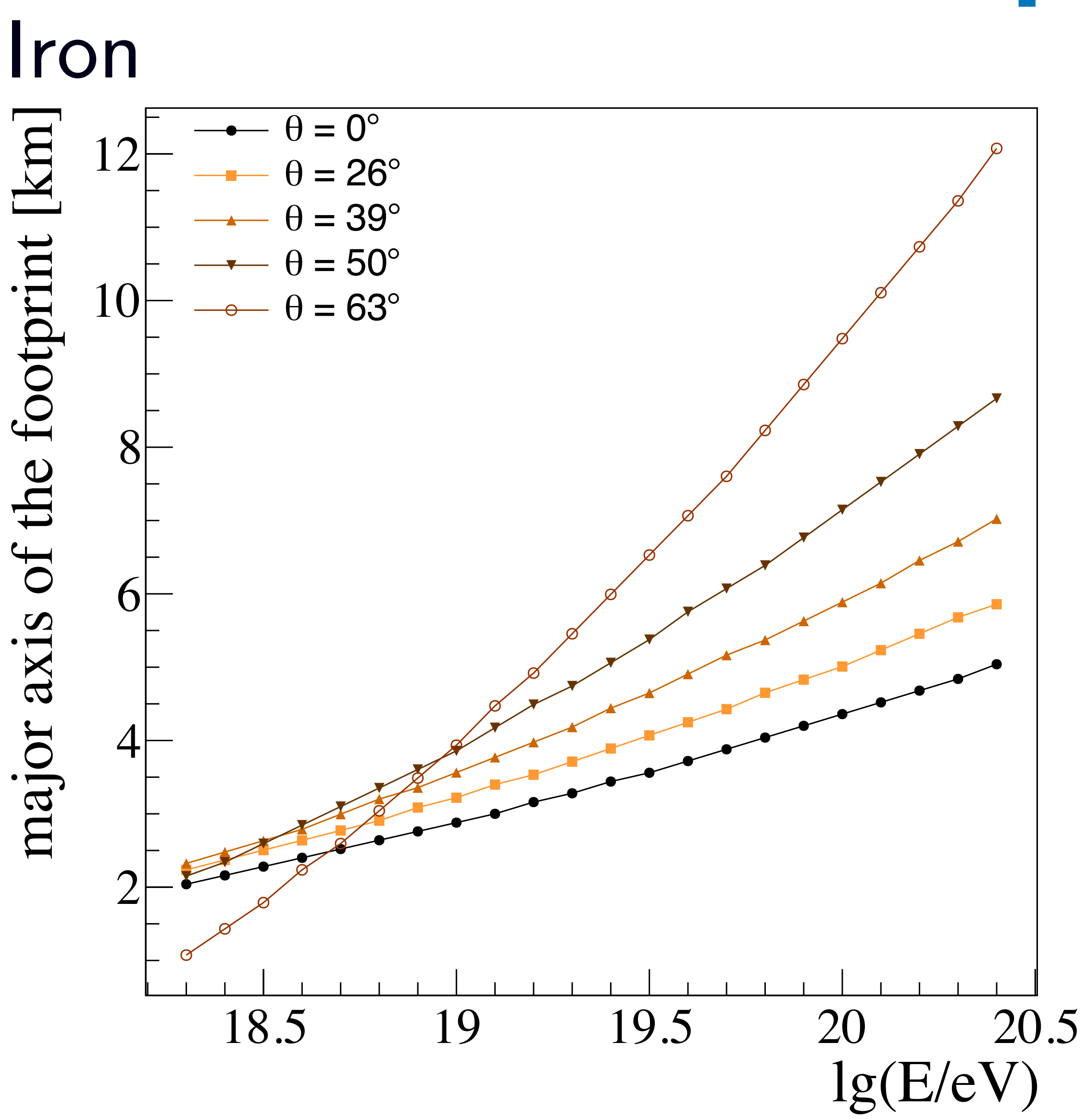
Antoine Letessier-Selvon et al., Nucl. Instr. Meth. A 767 (2014) 41–49

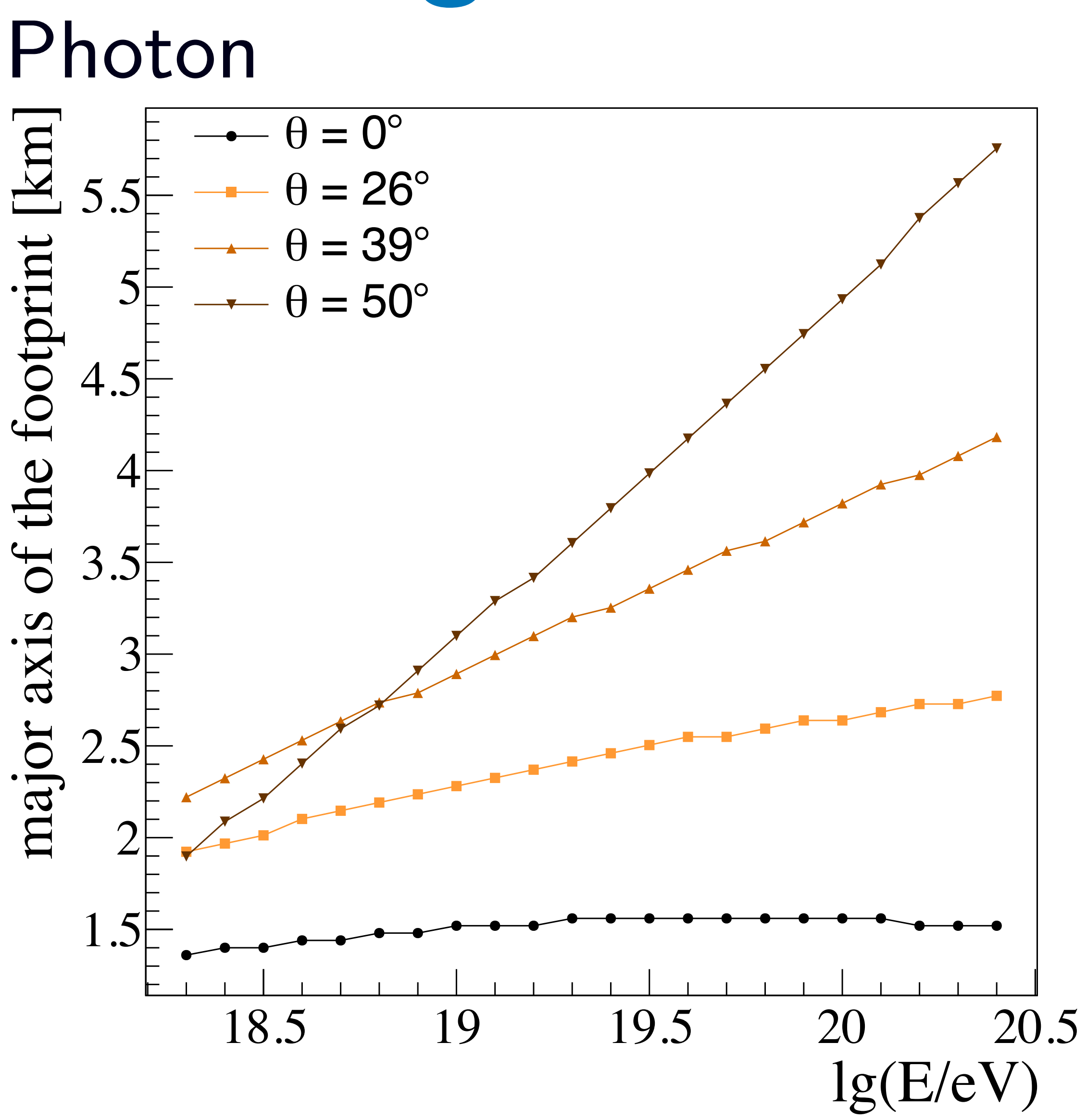
GCOS - particle detector array

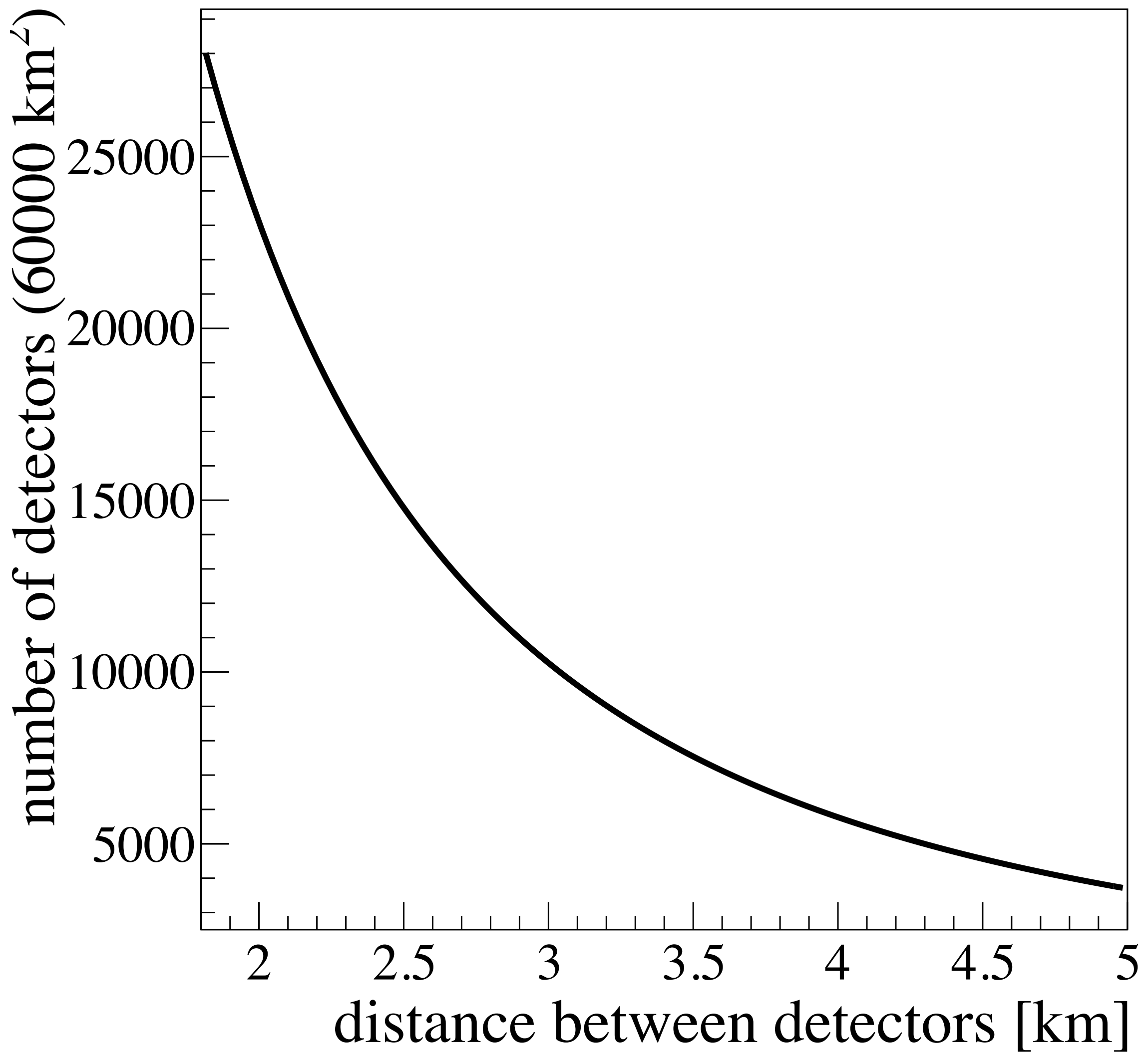


Spacing: How large is the air-shower footprint on the ground?







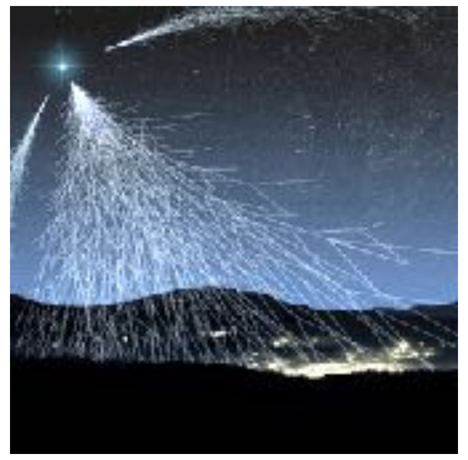


Spacing between detectors cannot be larger than about 2-2,5 km to reach 100% efficiency at 10-30 EeV.

On a triangular grid: 15k - 22k detectors for 60000 km².

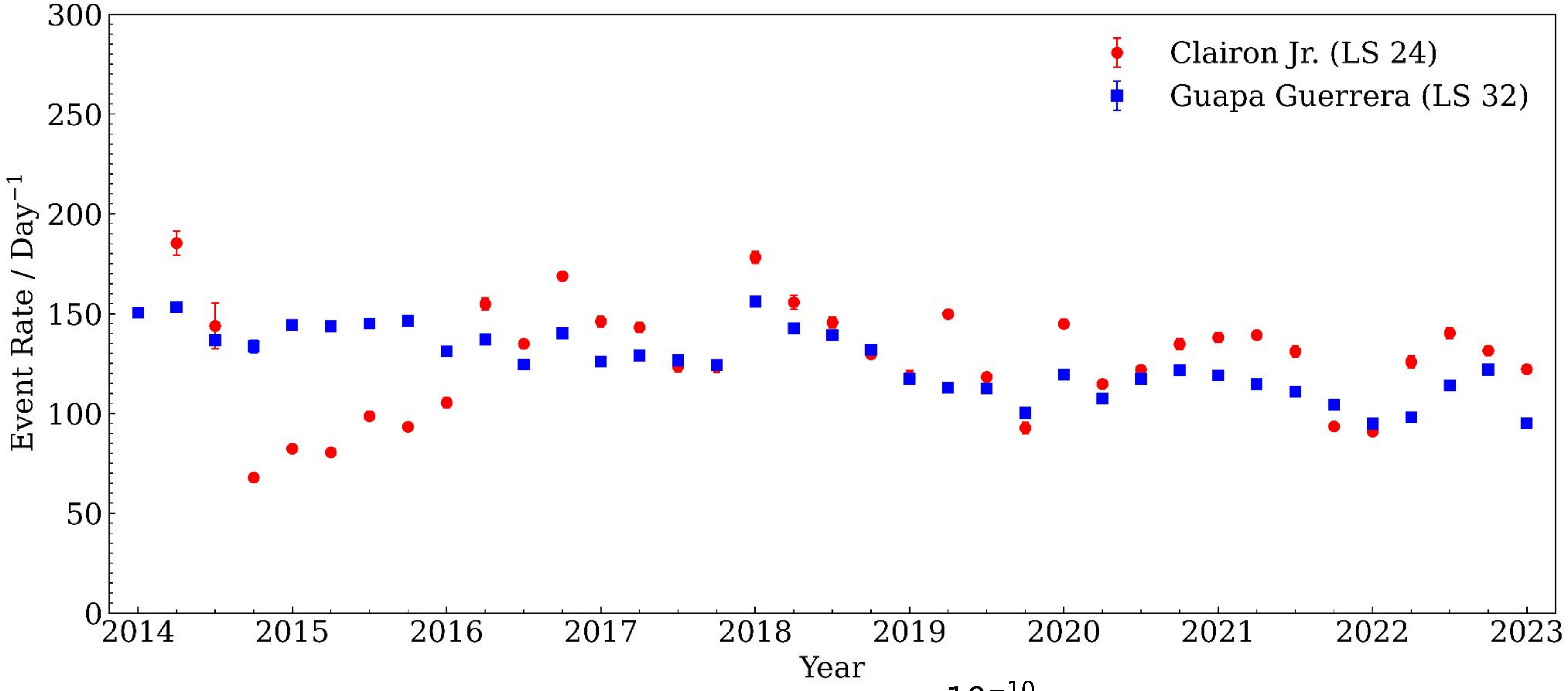
I. Maris

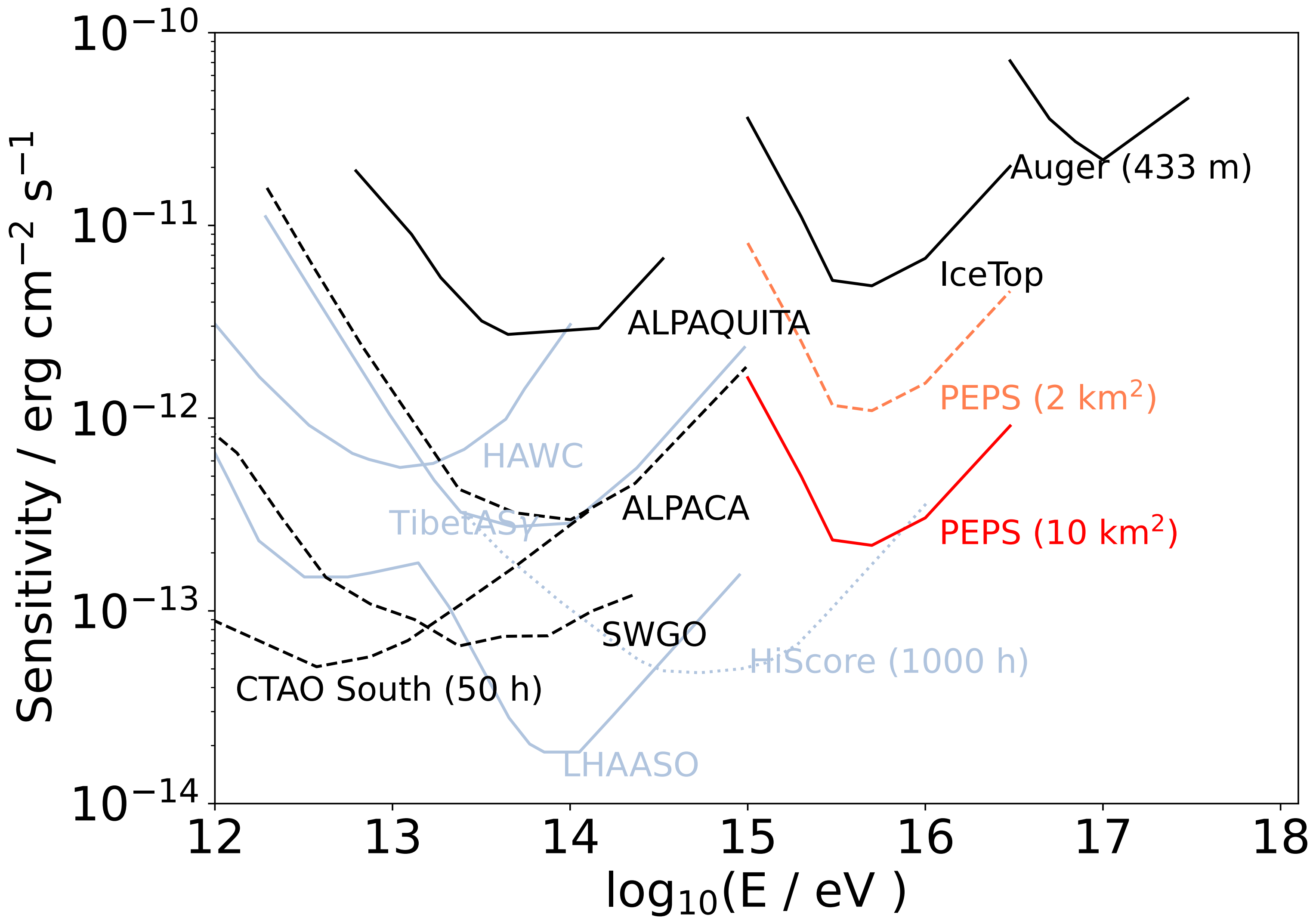
GCOS - particle detector array



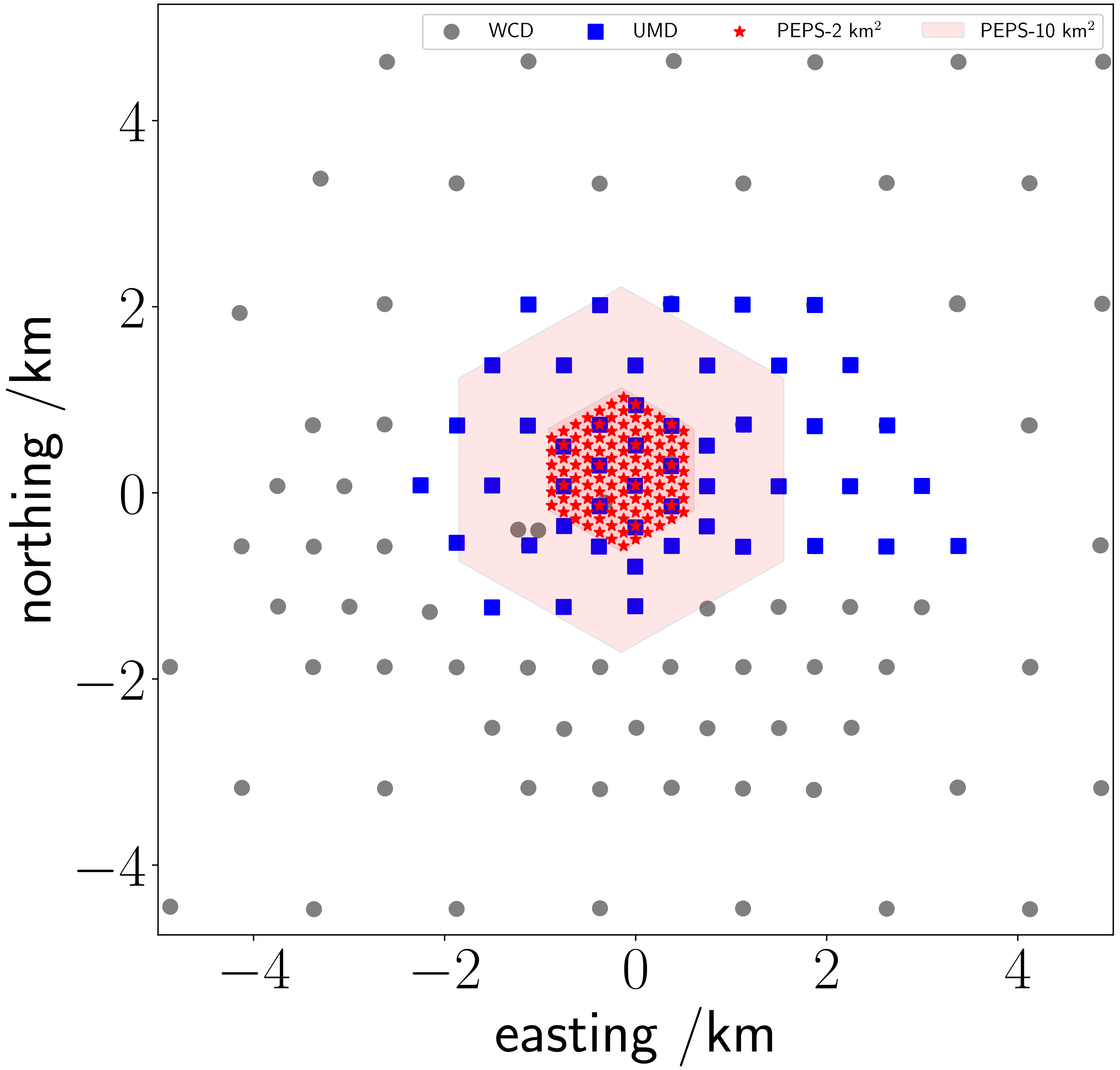
Layered water Cherenkov detector

prototype @Auger, operated since a decade



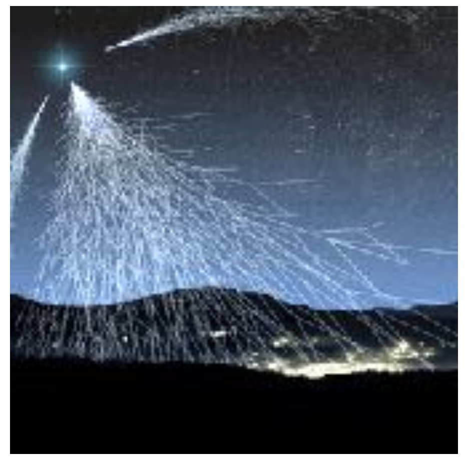


PEPS:
PeV gamma rays @Auger



B. Flaggs, I. Maris

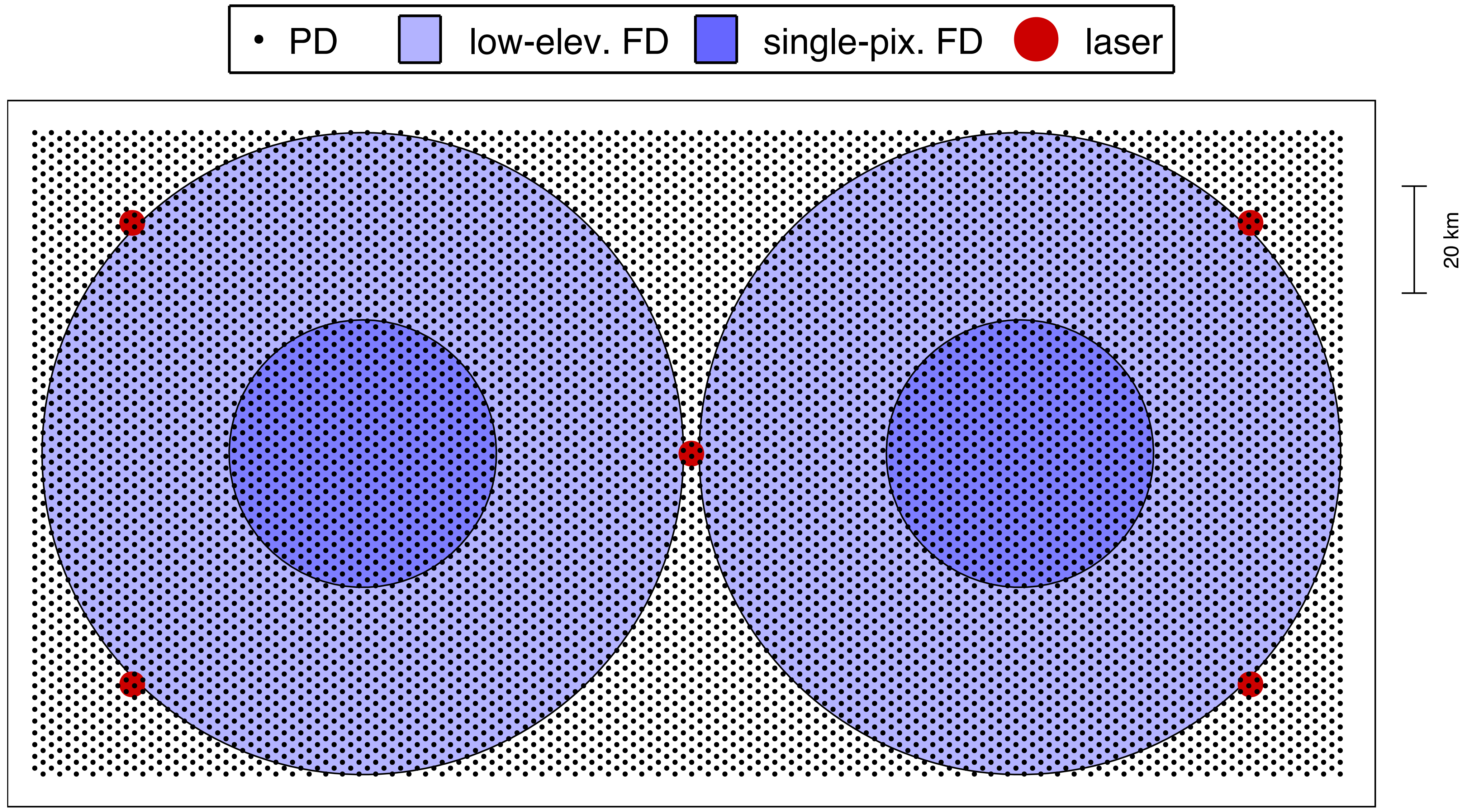
GCOS - options FD



- fluorescence telescopes provide good measurement of longitudinal shower component
  —> calorimetric energy
  —> depth of shower maximum (mass)

- **purpose for GCOS:**
  calibrate energy scale (<10% unc.)
  calibrate mass scale (<15 g/cm² unc.)

- different layouts possible, e.g.
  - combine low-elevation FD with single-pixel FD
  - cover area with single-pixel FD

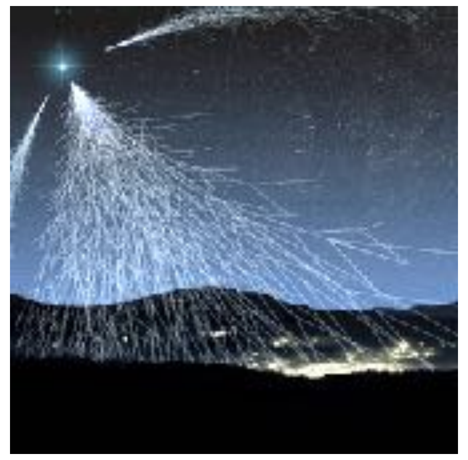


Layout A of the FD at one 30 000 km^2 GCOS site.

Fluorescence Detector Tasks

- calibration of PD energy scale
- calibration of PD mass scale
- $\sigma_E < 10\%$, $\sigma_{\ln A} \sim 0.4$
- duty cycle 20%

GCOS - options FD

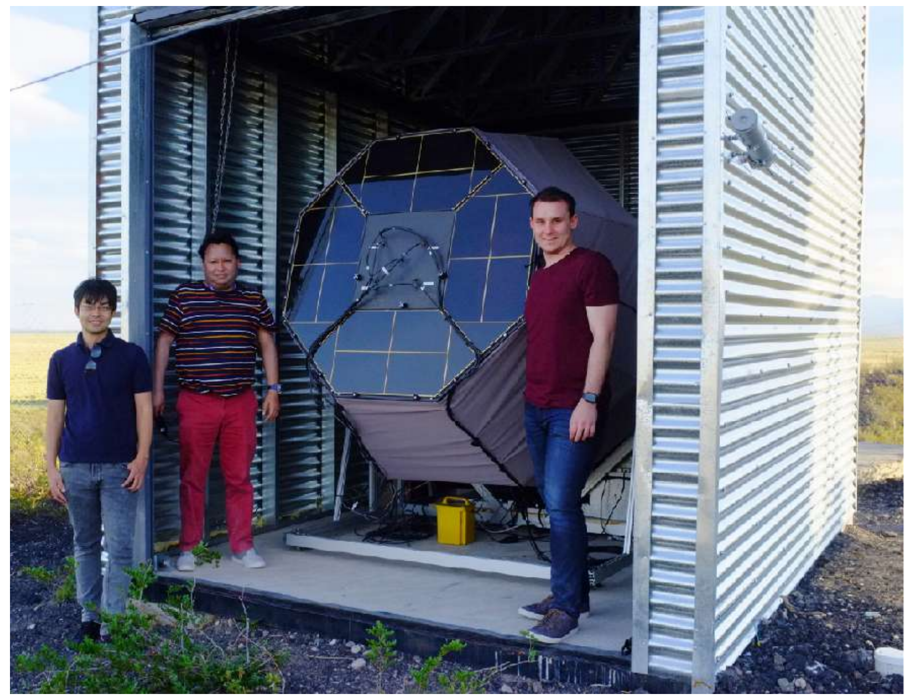


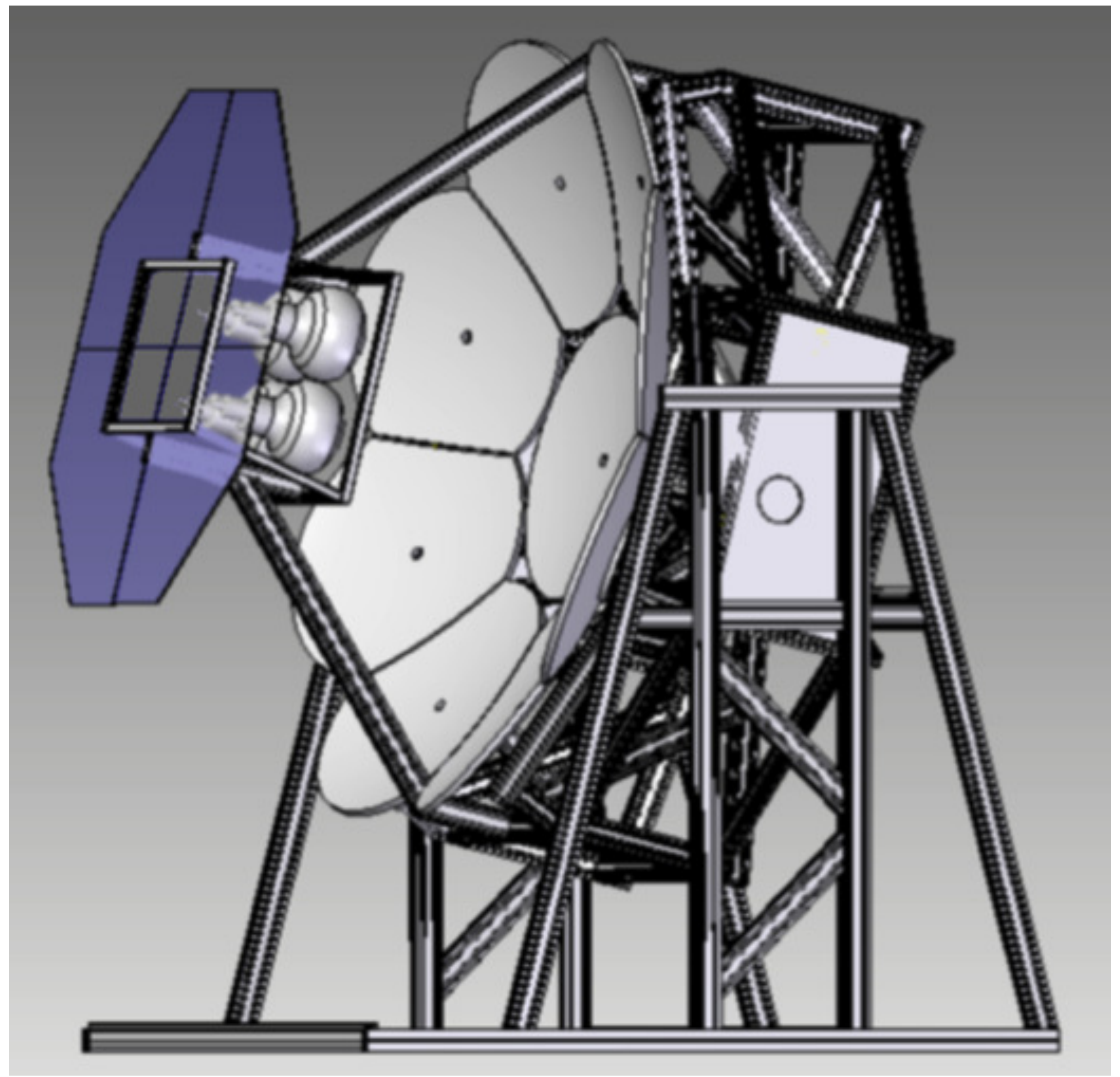
ongoing R&D for future large arrays

FAST: array of low-cost telescopes

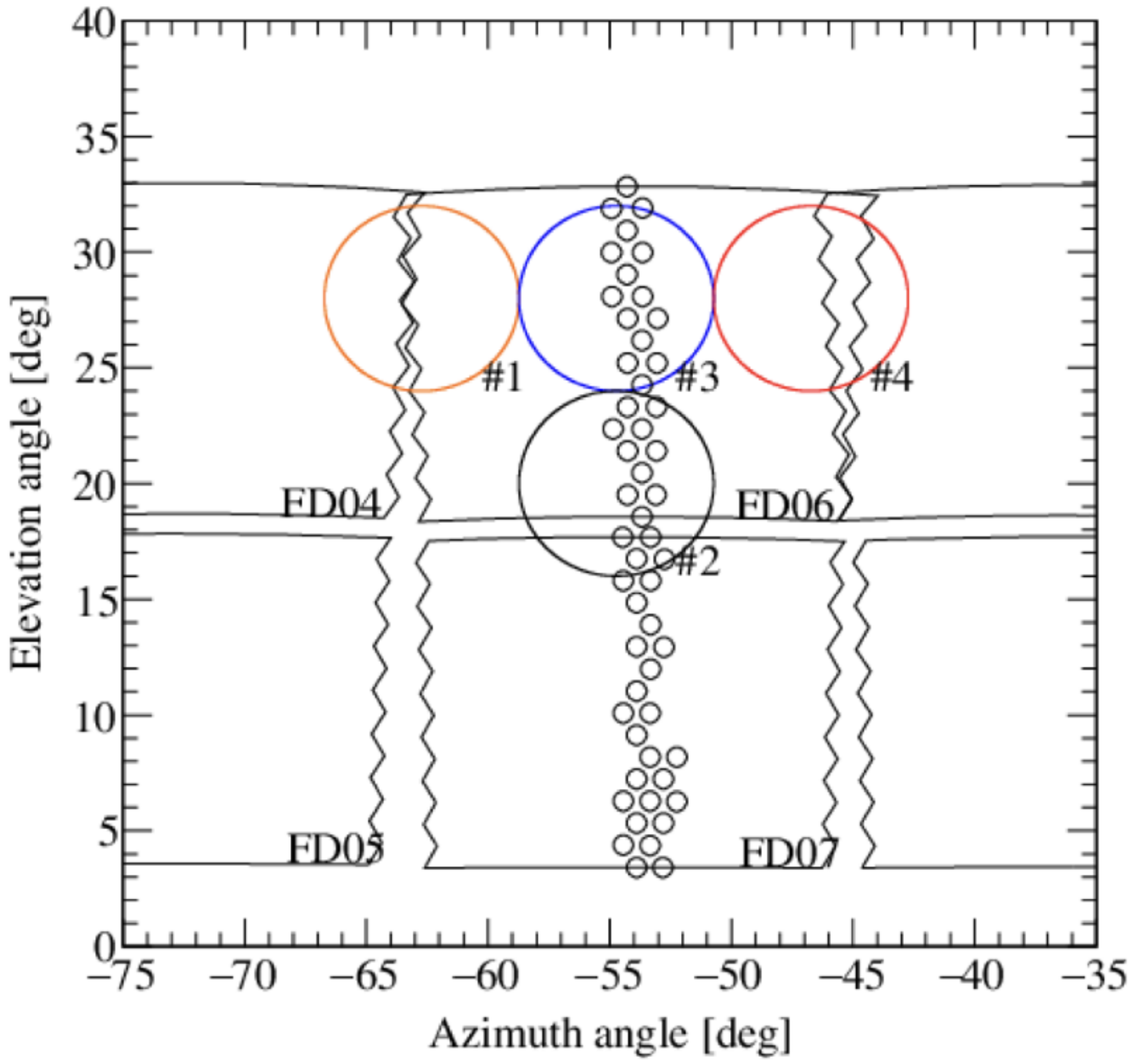
FAST@TA

FAST@Auger



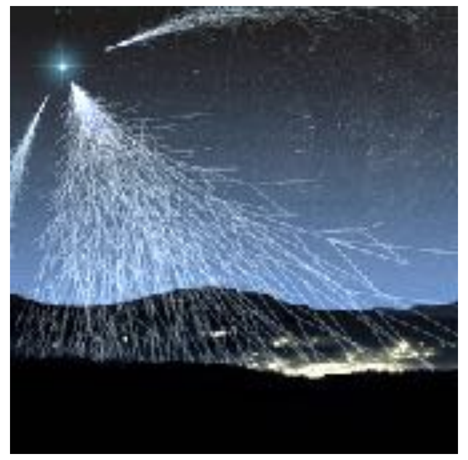


CRAFFT @ TA



a measured air shower

GCOS - options RD

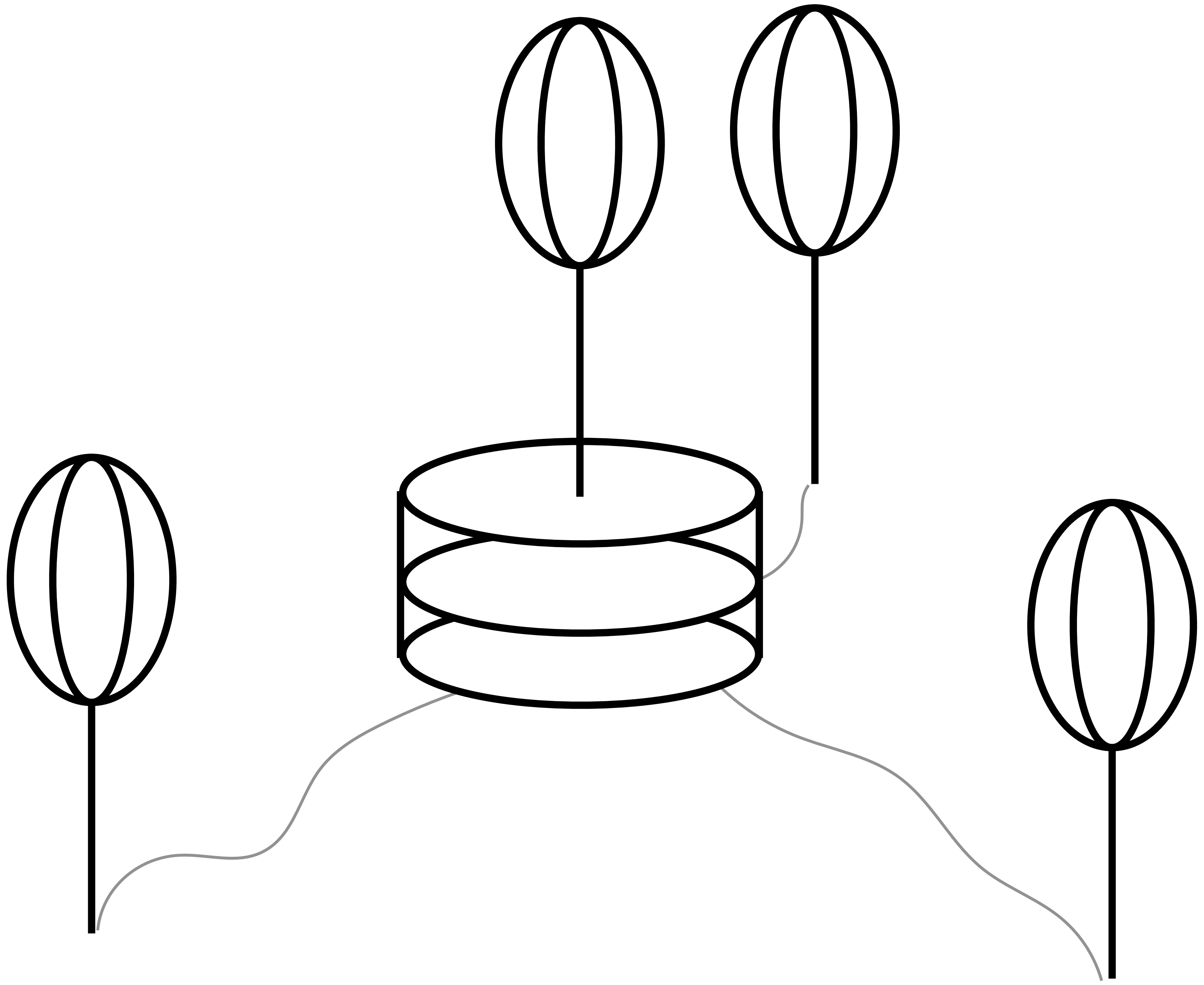


- radio detection provides clean measurement of e/m shower component

- can provide independent energy scale with accuracy comparable to state-of-the-art FD methods

- lateral distribution steeper than e/m and μ components
  —> satellite stations?

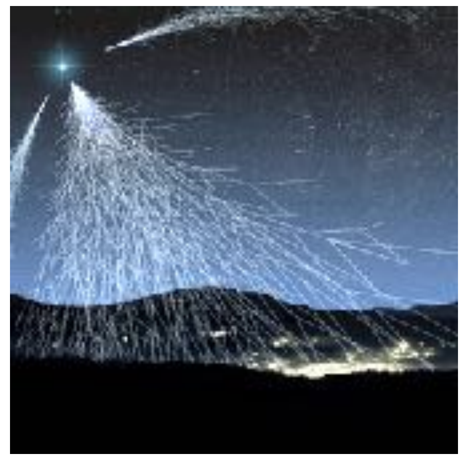
- # of polarizations?
  frequency range?
  ns time resolution —> interferometry



Radio Detector Potential

- $\sigma_{e/m} < 10\%$
- independent energy scale, $\sigma_E < 10\%$
- hybrid μ & e/m $\rightarrow$ mass
- interferometry $\rightarrow$ mass

GCOS in Snowmass White Paper



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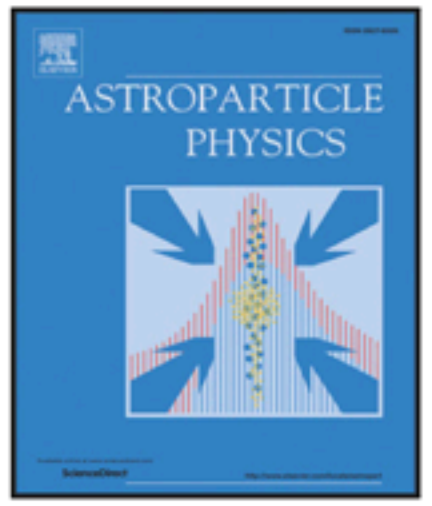
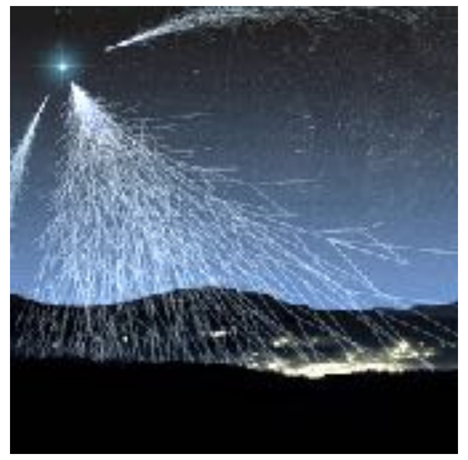


Ultra high energy cosmic rays
The intersection of the Cosmic and Energy Frontiers☆

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.

GCOS next steps



- straw man design together with write-up of Brussels and Wuppertal workshops will be put on arXiv before the end of 2024
- GCOS Japan has regular meetings to coordinate R&D
- also in Europe R&D on potential detectors has started
- GCOS workshop 2025 in Japan?

Further reading:
- ICRC 2021
- ICRC 2023
- UHECR 2022
- 1st GCOS workshop 2021
- 2nd GCOS workshop 2022
- 3rd GCOS workshop 2023

Science Targets of GCOS

- discovery of UHE accelerators
- charged-particle astronomy
- UHE neutrinos and photons
- BSM physcs
- cosmic magnetism
- multi-messenger studies