Science with the Global Cosmic-ray Observatory (GCOS)

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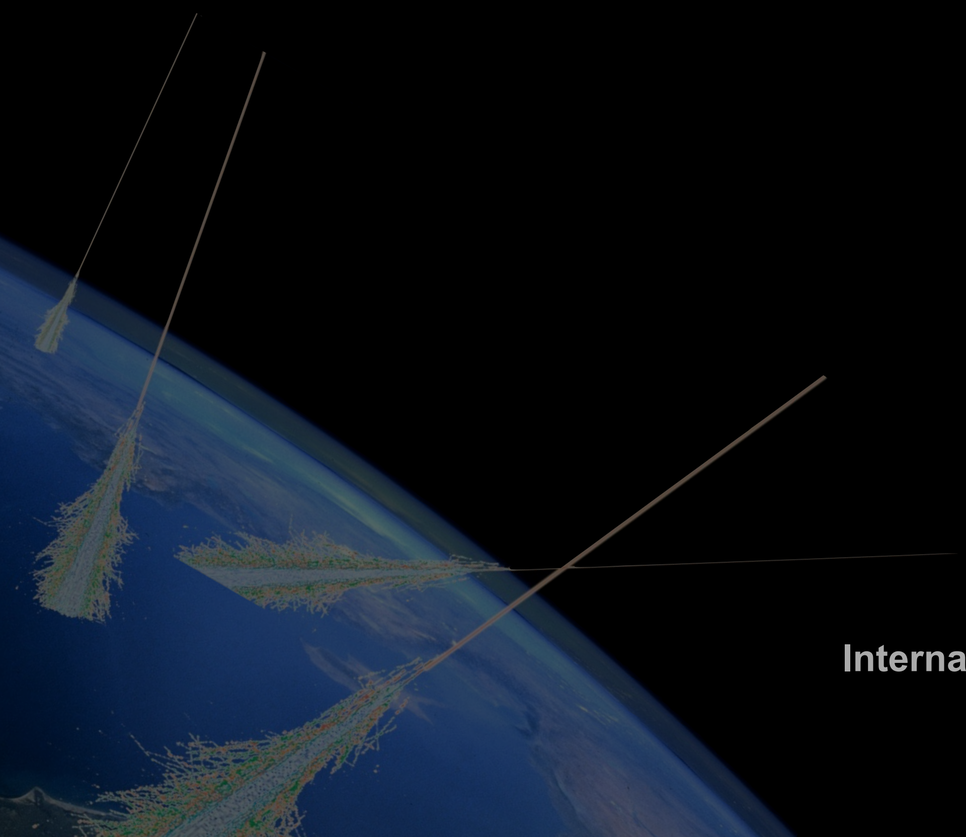
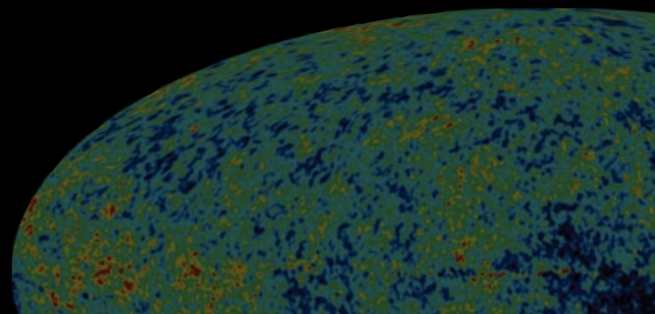


International Cosmic-Ray Conference (ICRC 2023)
Nagoya, Japan
29 July, 2023



what is GCOS?

- next-generation UHE observatory
- full sky coverage (at least 2 sites)
- area: between 40,000 and 80,000 km^2
- primary energy: full efficiency above ~10 EeV
- energy resolution: < 10%
- muon resolution: < 10%
- X_{max} resolution: < 20 g/cm^2
- angular resolution: < 1°

1st Workshop
17-21 May 2021
Nijmegen [online]

2nd Workshop
13-15 July 2022
Wuppertal

3rd Workshop
10-11 June 2023
Brussels

community effort

why GCOS?

one experiment, multiple purposes

UHE & multimessenger astrophysics

extreme environments
HE transients
particle acceleration
neutrino sources
MM follow-ups
cosmogenic neutrinos
UHE photons

solar physics

coronal mass ejections
solar wind

geo & atmospheric physics

elves
atmospheric monitoring
terrestrial gamma-ray flashes
lightning

fundamental physics

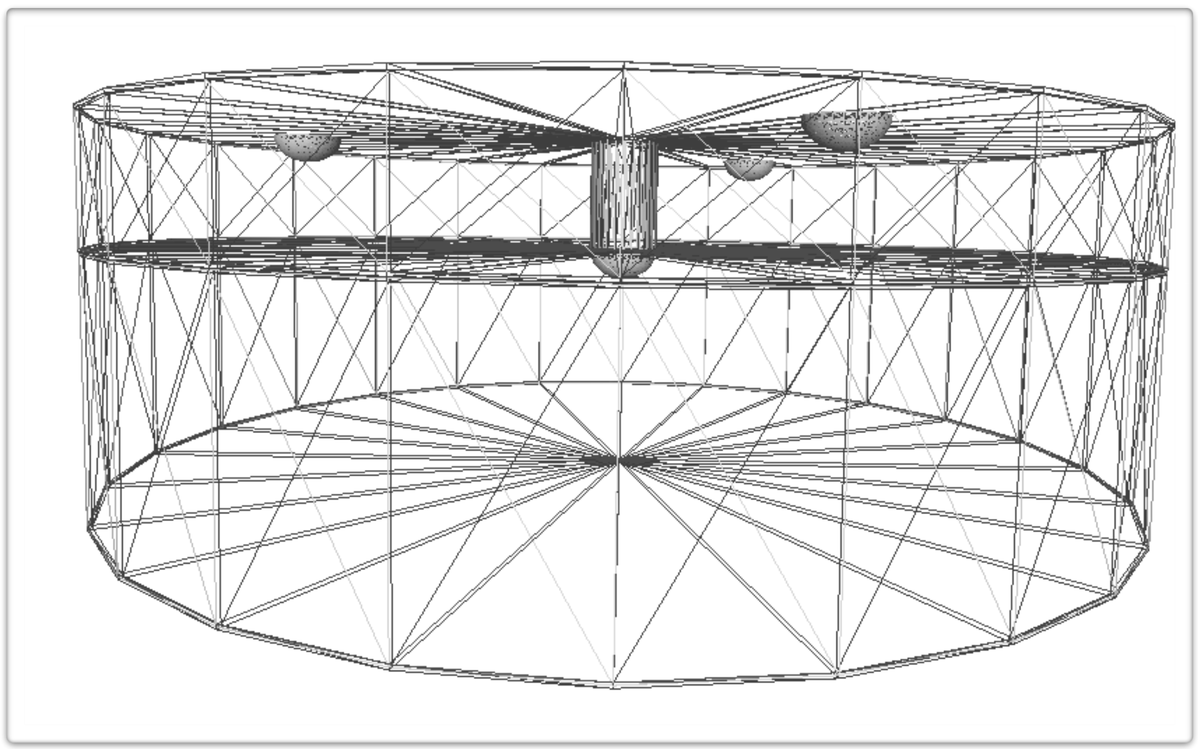
Lorentz invariance
superheavy dark matter
quantum gravity

particle physics

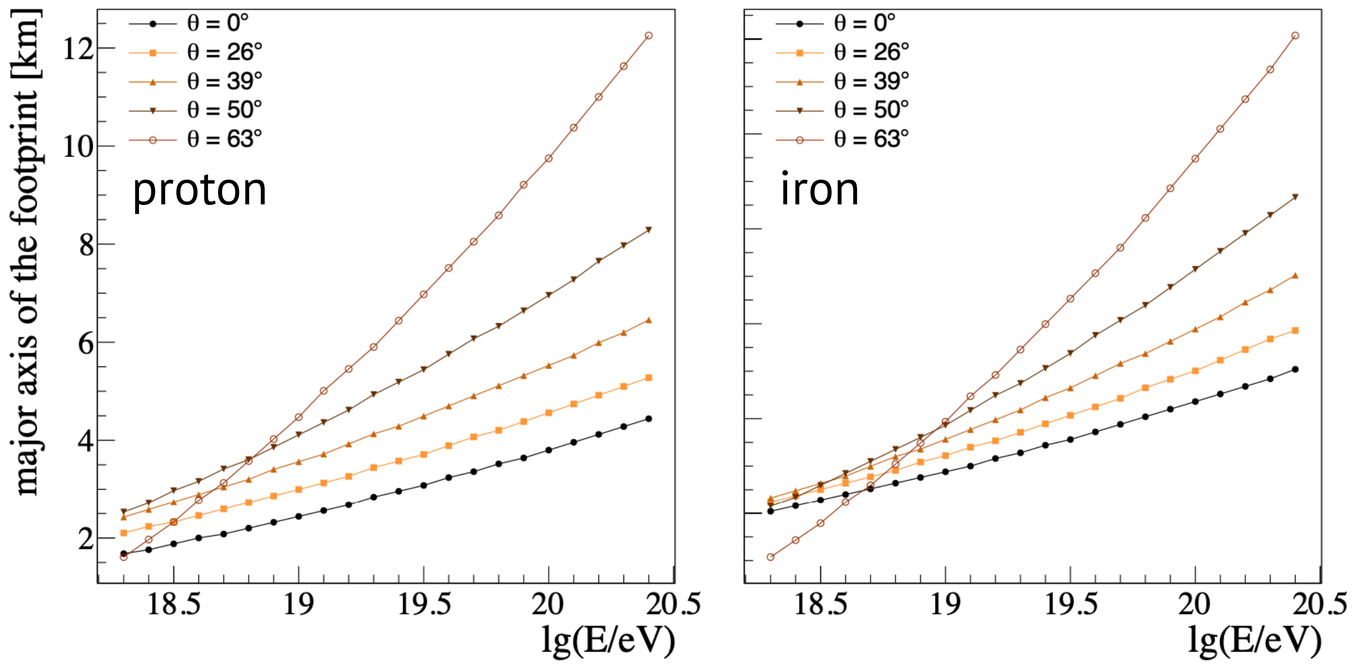
HE interactions
macroscopic dark matter
proton-air cross section

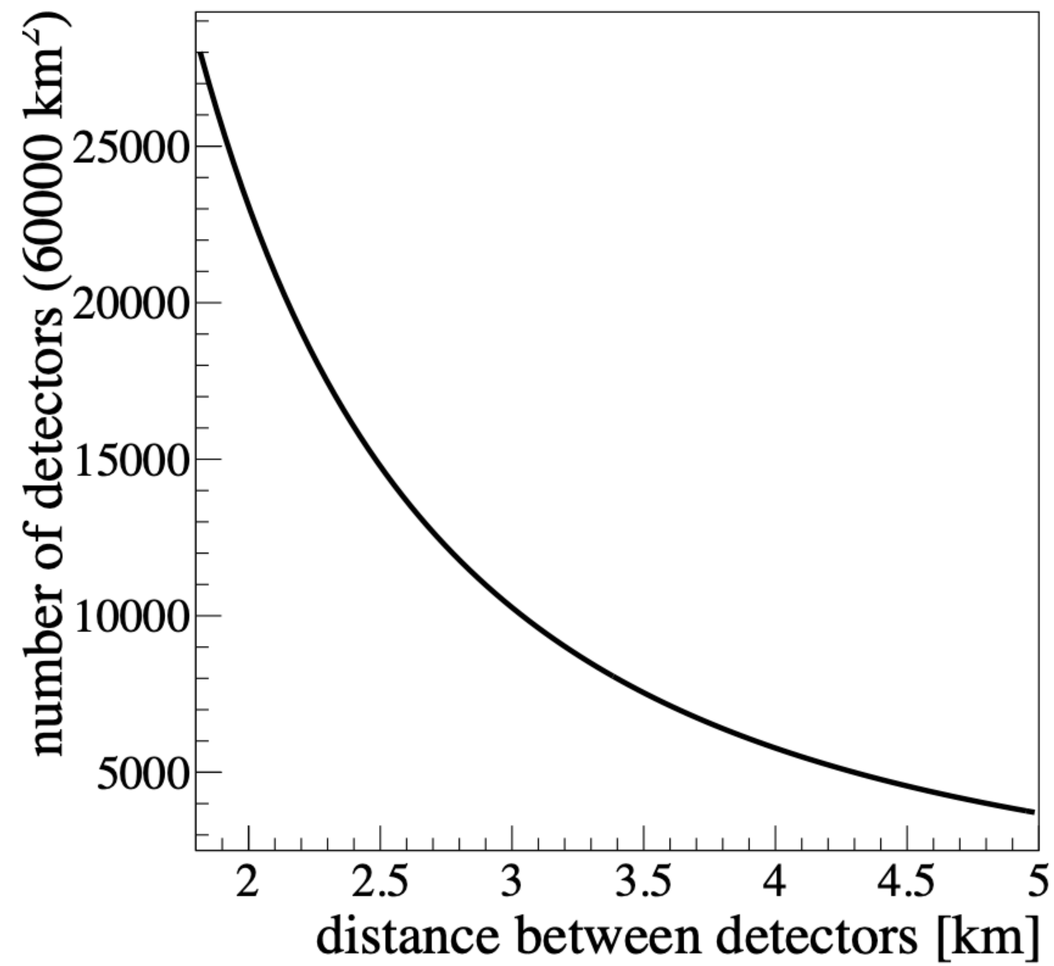
designing GCOS

- preferred designs use water Cherenkov detectors (WCDs)
- combination with other types of detectors (e.g., scintillators) also possible
- segmented tank (layered) design favoured at this stage
  - two prototypes being tested at Auger



surface array. possible layouts



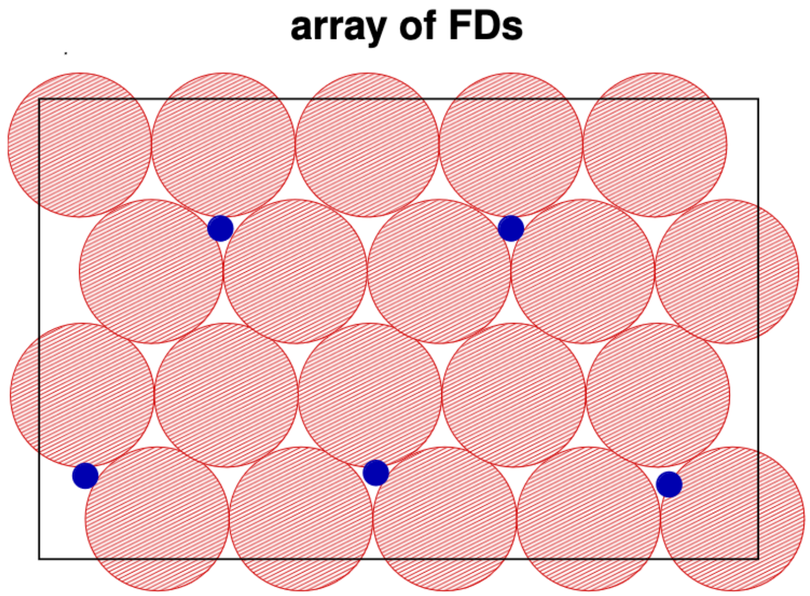


- **area:** 60,000 km²
- **energy:** 100% efficiency at ~30 EeV
- **grid geometry:** hexagonal
- **spacing:** 2-2.5 km
- **number of detectors**: 15-22k stations

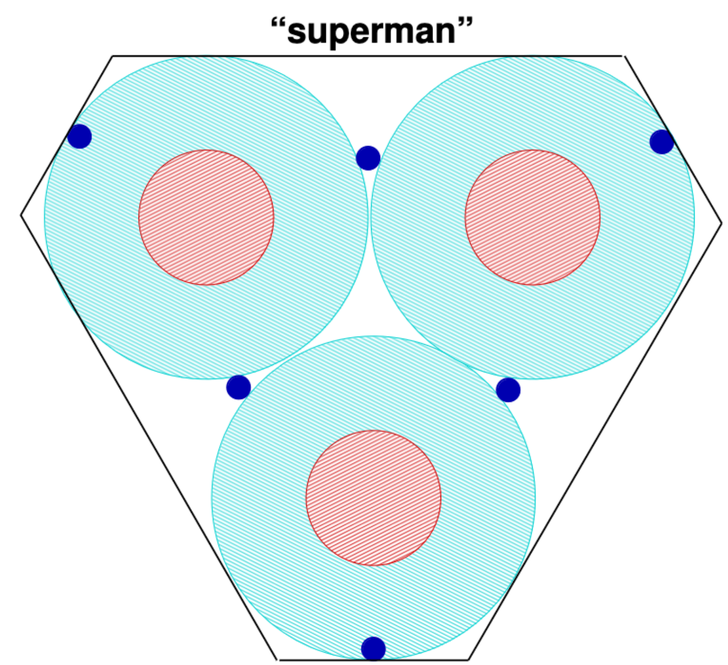
presented by I. Maris at UHECR2022

- ongoing developments:
  - FAST (Fluorescence detector Array of Single-pixel Telescopes)
  - CRAFFT (Cosmic-Ray Fluorescence Fresnel Lens Telescope)
  - MACHETE (as in Trinity)

FAST/CRAFFT site
cyclops
laser facility



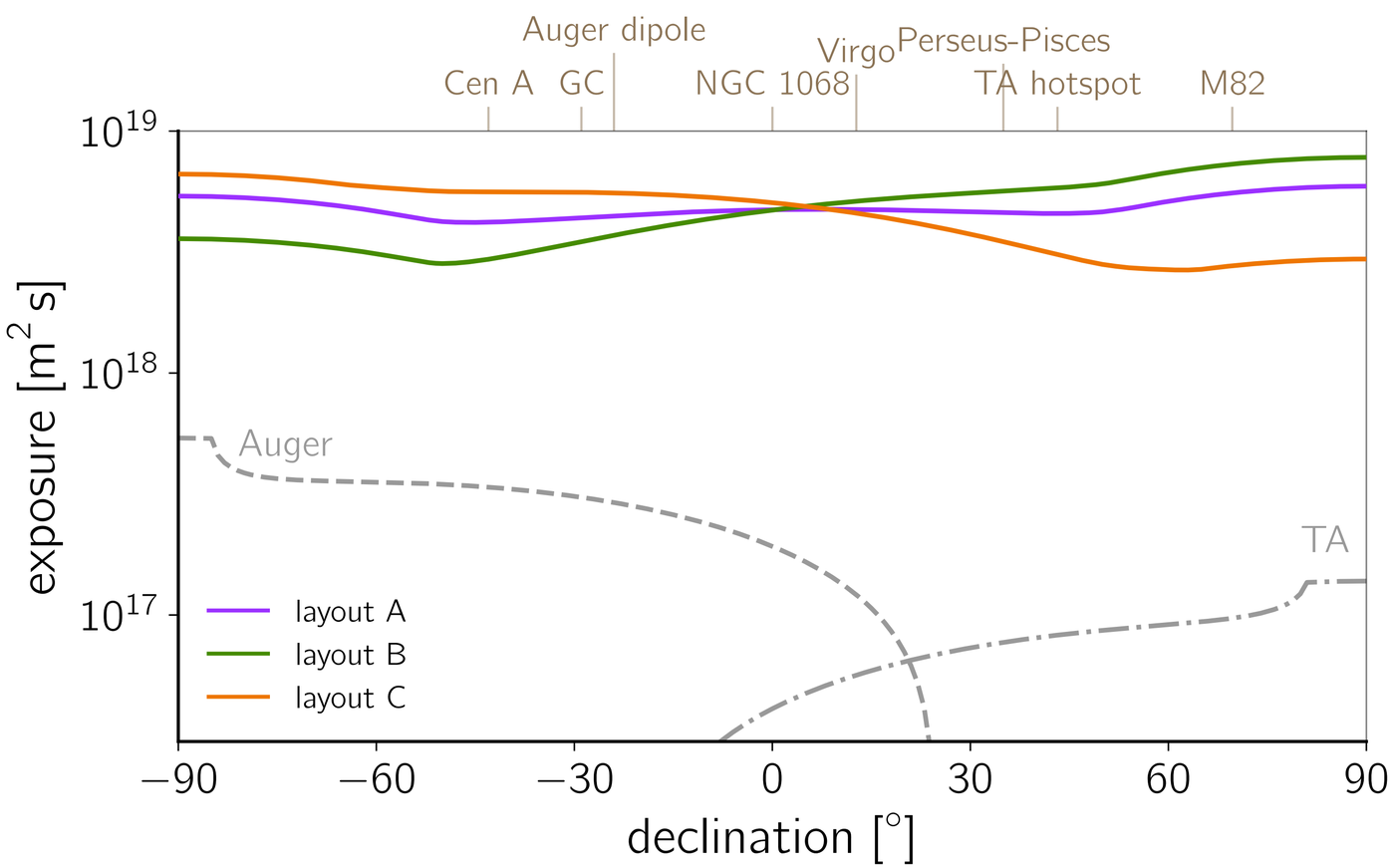
250×160 km^2 rectangle
20 FAST sites
?? laser facilities

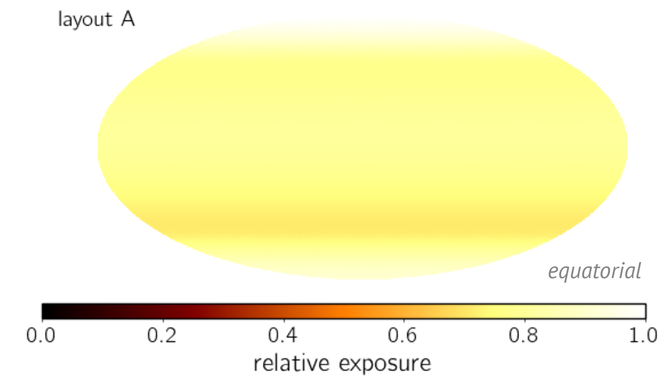


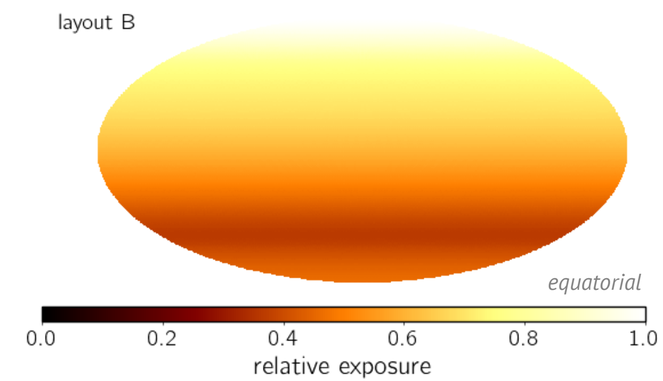
$\sim$ equilateral triangle, 300 km side length
3 sites with one FAST and cyclops each
$\gtrsim$ 6 laser facilities

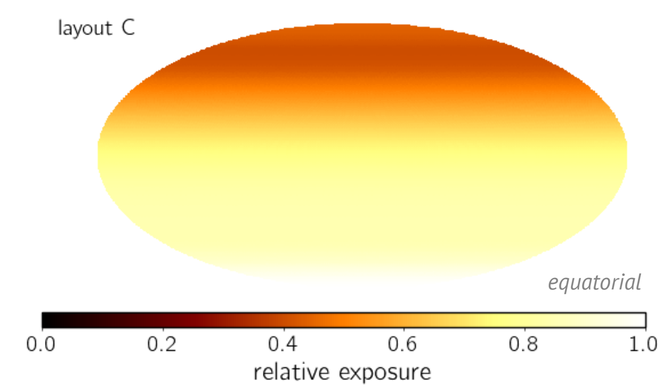
presentation by M. Unger at 3rd GCOS Workshop

	site Auger	site TA	(43°, 103°)	(-25°, 137°)
layout	**A_1 [km²]**	**A_2 [km²]**	**A_3 [km²]**	**A_4 [km²]**
A	30k	30k	-	-
B	20k	20k	20k	-
C	15k	15k	15k	15k







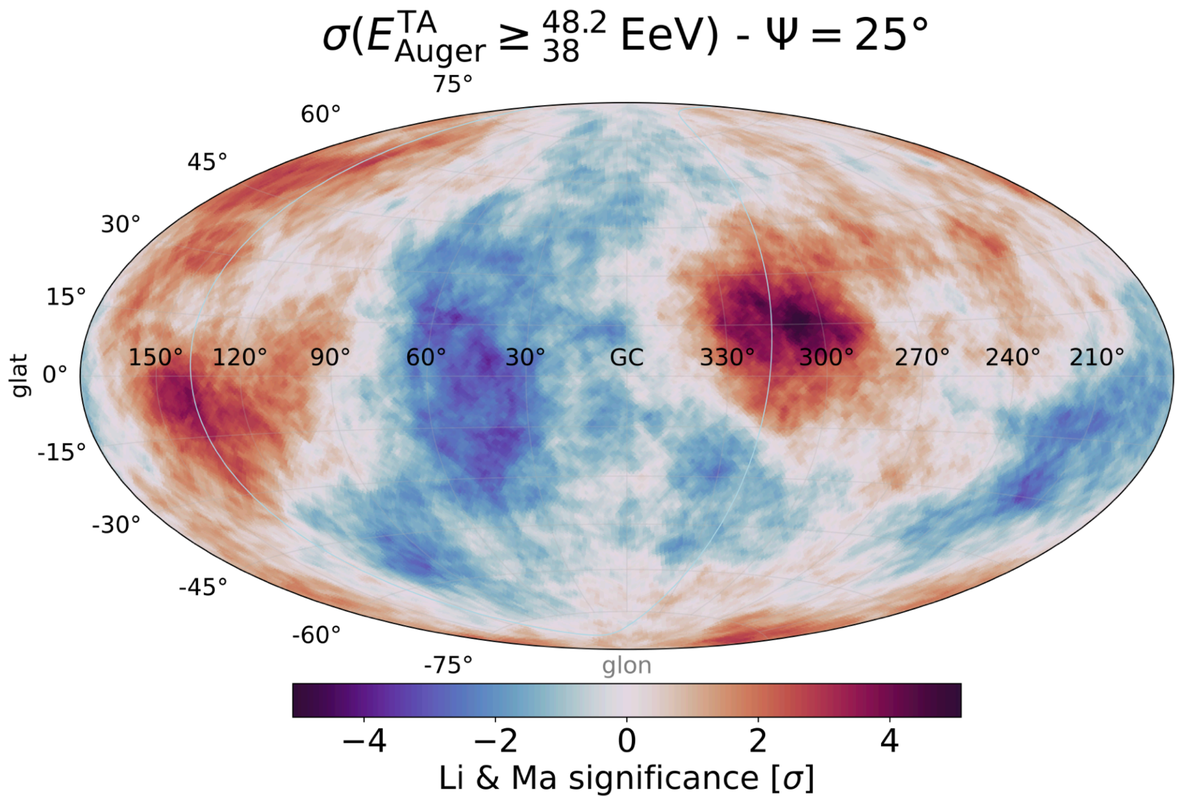


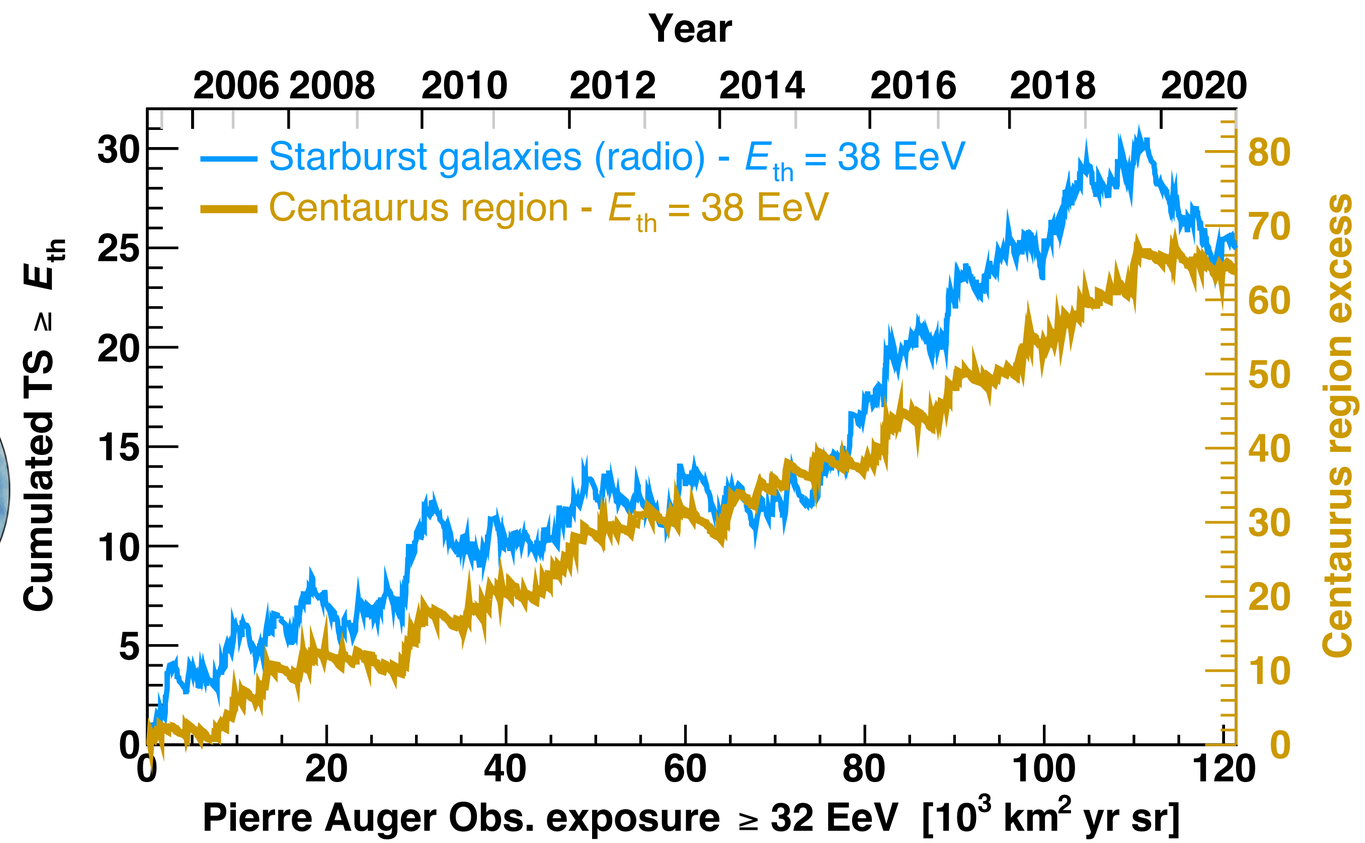
science

science case. intermediate-scale anisotropies

Pierre Auger Collaboration. ApJ. 938 (2022) 170. arXiv:2206.13492

Caccianiga et al. for the Auger and TA Collaborations. PoS (ICRC2023) 521.

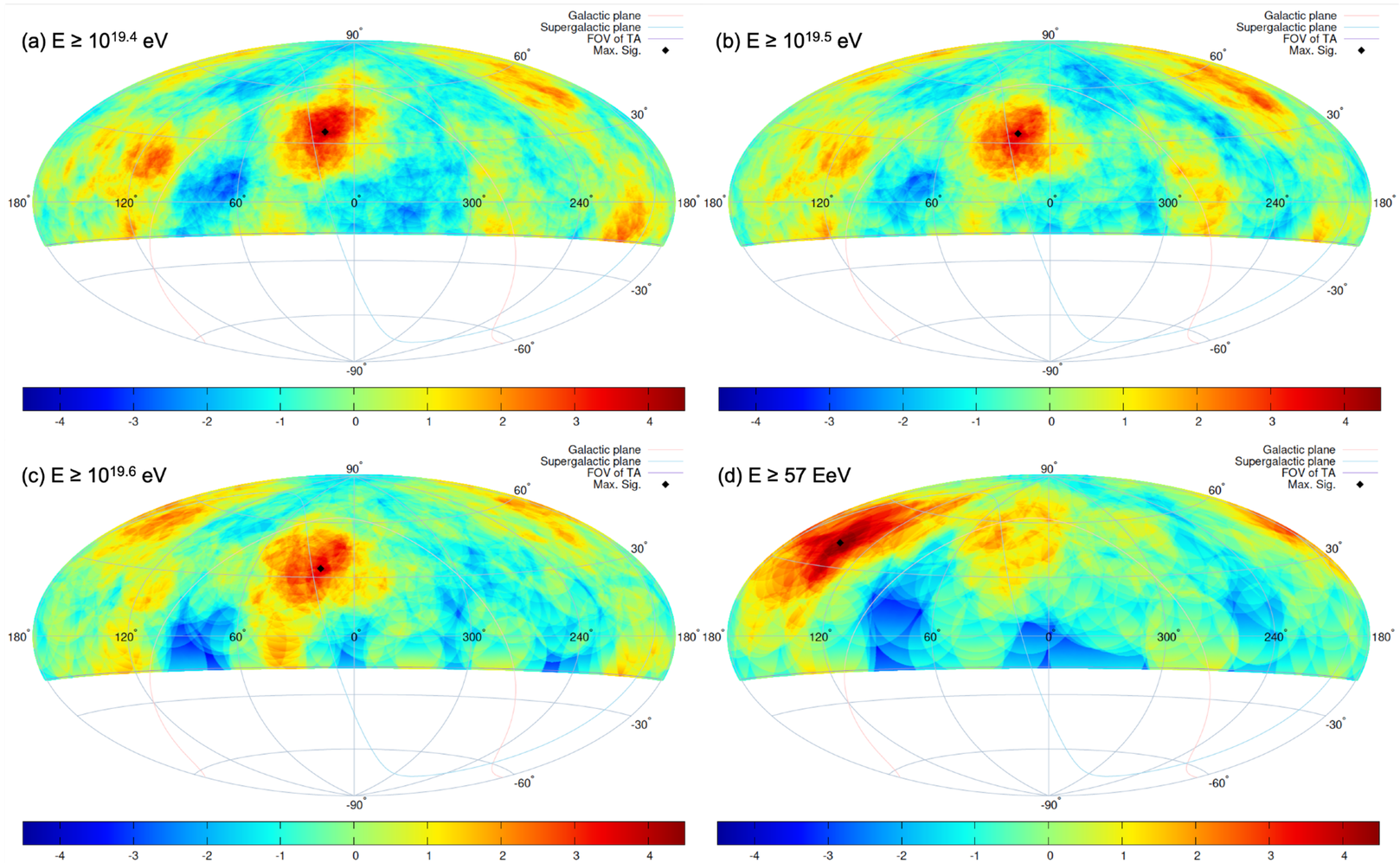




- **current observatories**: 5σ before 2027, assuming linear growth of TS
- **GCOS** with 60k km^2: 5σ in less than ~1.5 years of observations

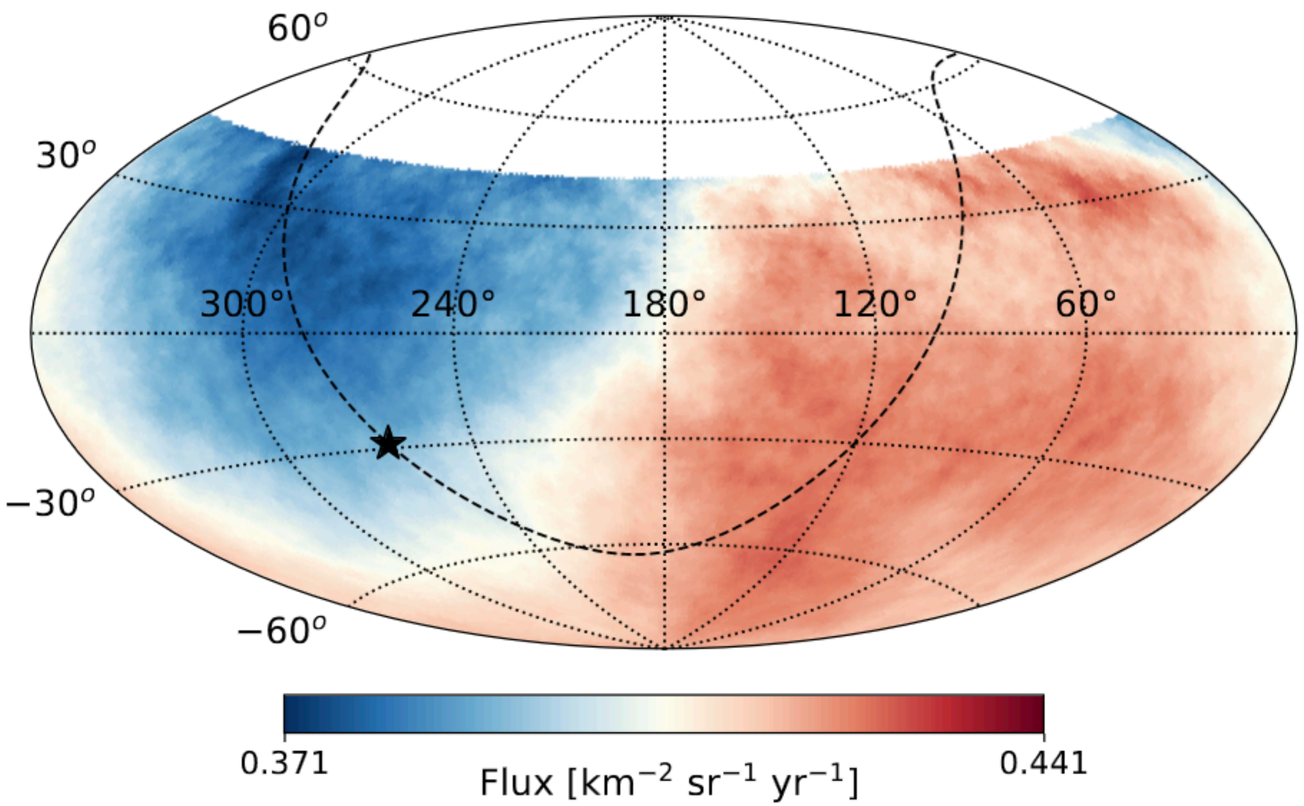
science case. intermediate-scale anisotropies

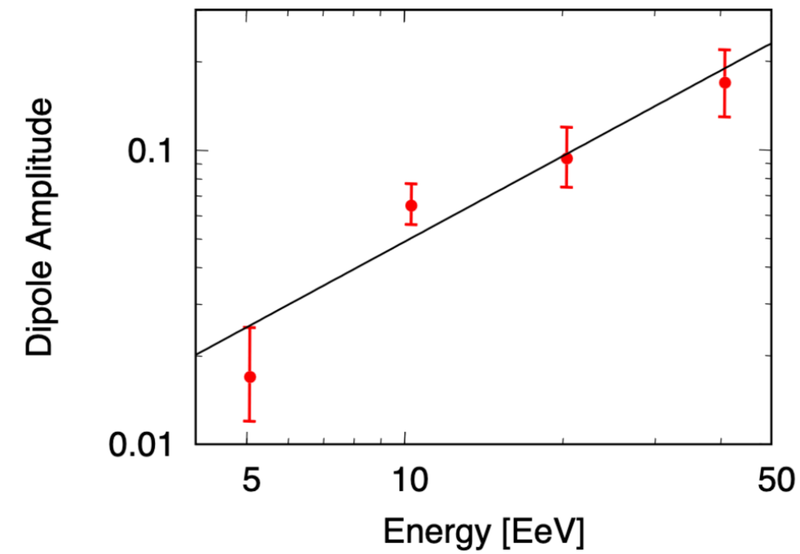
Telescope Array Collaboration. ApJ Lett. 938 (2022) 170. arXiv:2206.13492

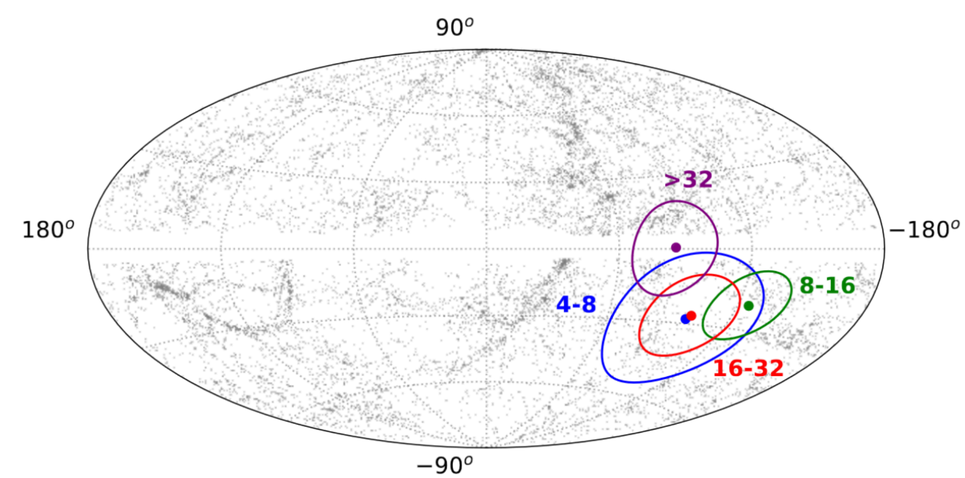


- Northern hemisphere hotspots (possible Perseus-Pisces supercluster correlation)
- **GCOS** with 20k km^2 Northern exposure: 5σ in ~ 2 years

Golup for the Auger Collaboration. PoS (ICRC2023) 252.



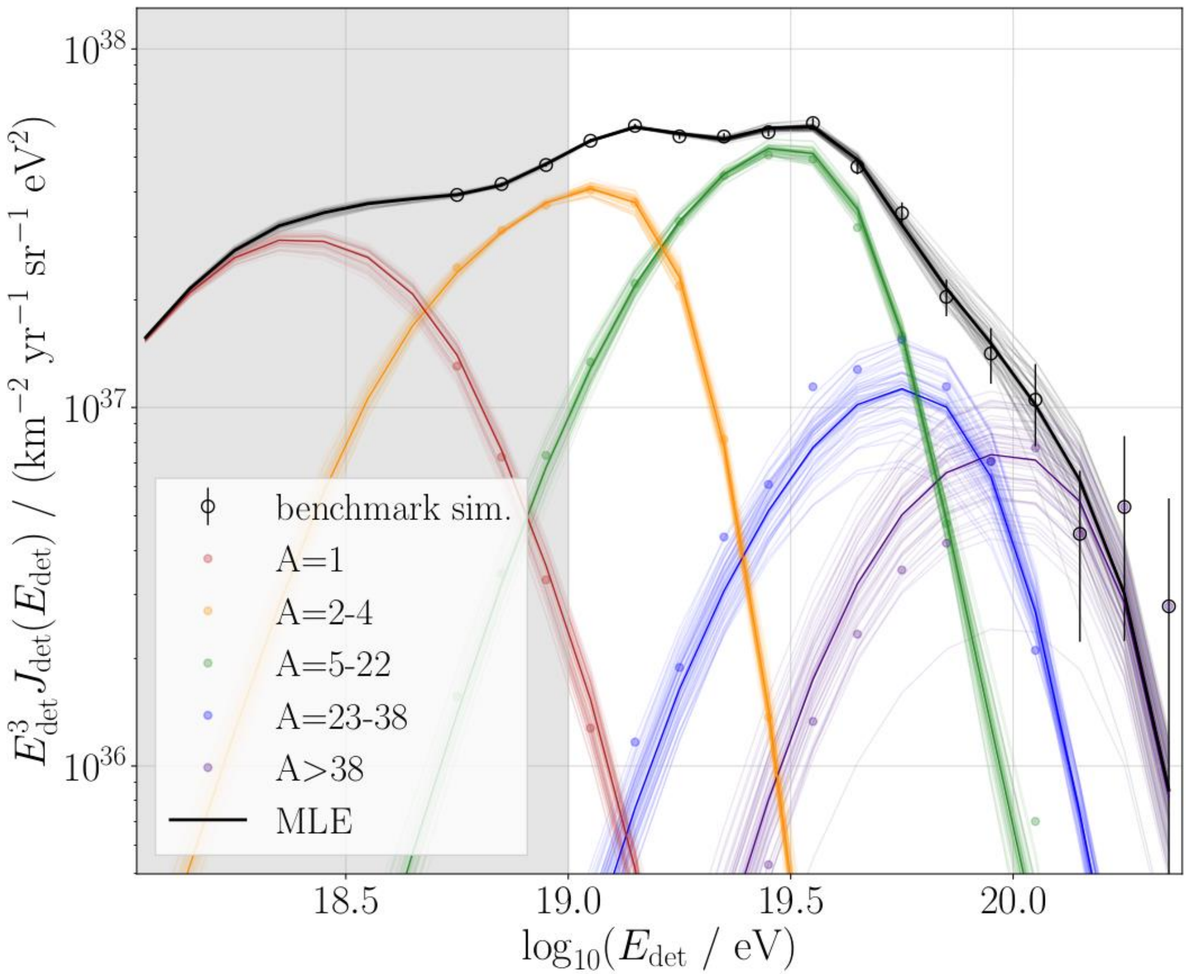


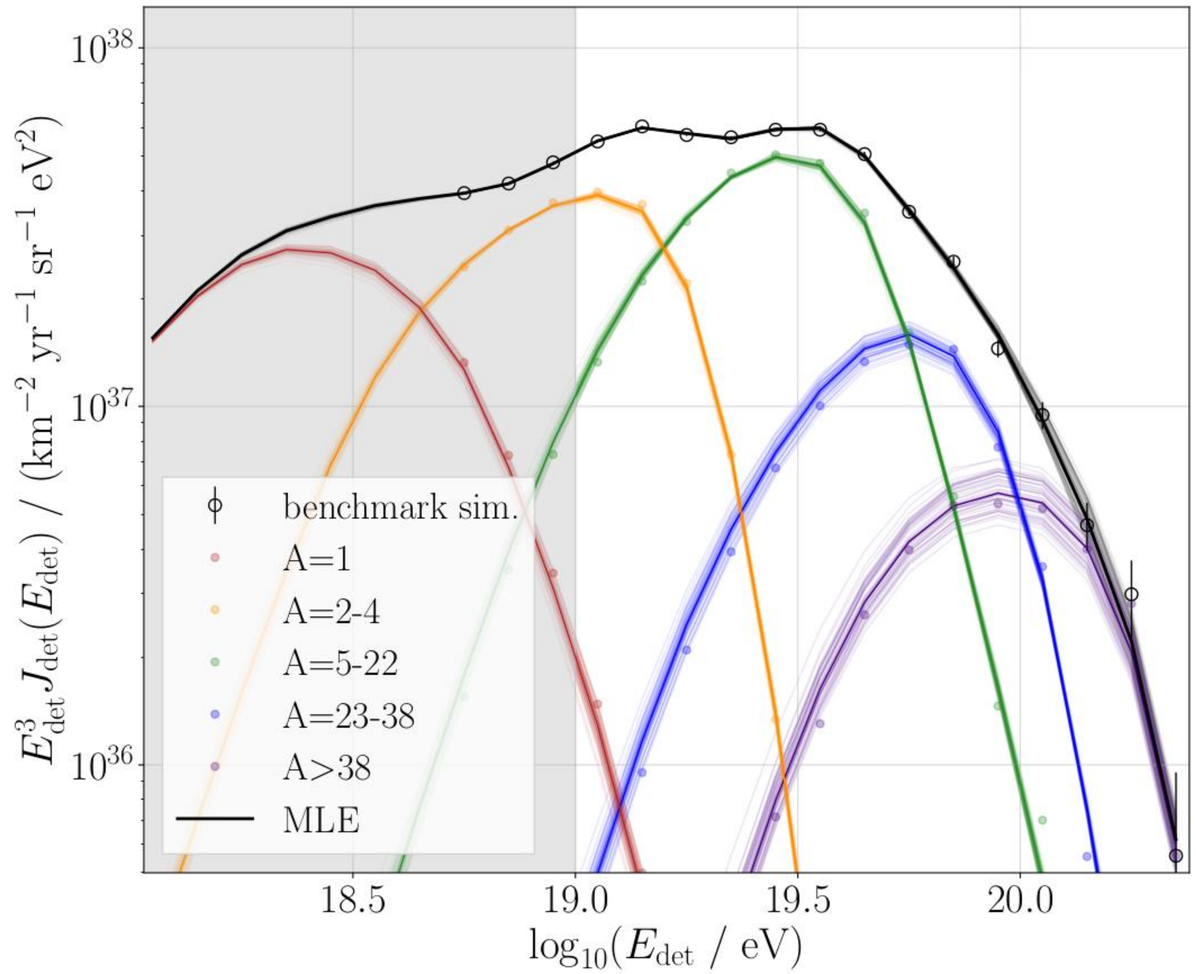


- **GCOS** with 60k km^2
  - would enable the measurement of the dipole above 32 EeV with Northern exposure: 5σ in ~ 2 years

science case. phenomenological models (combined fits)

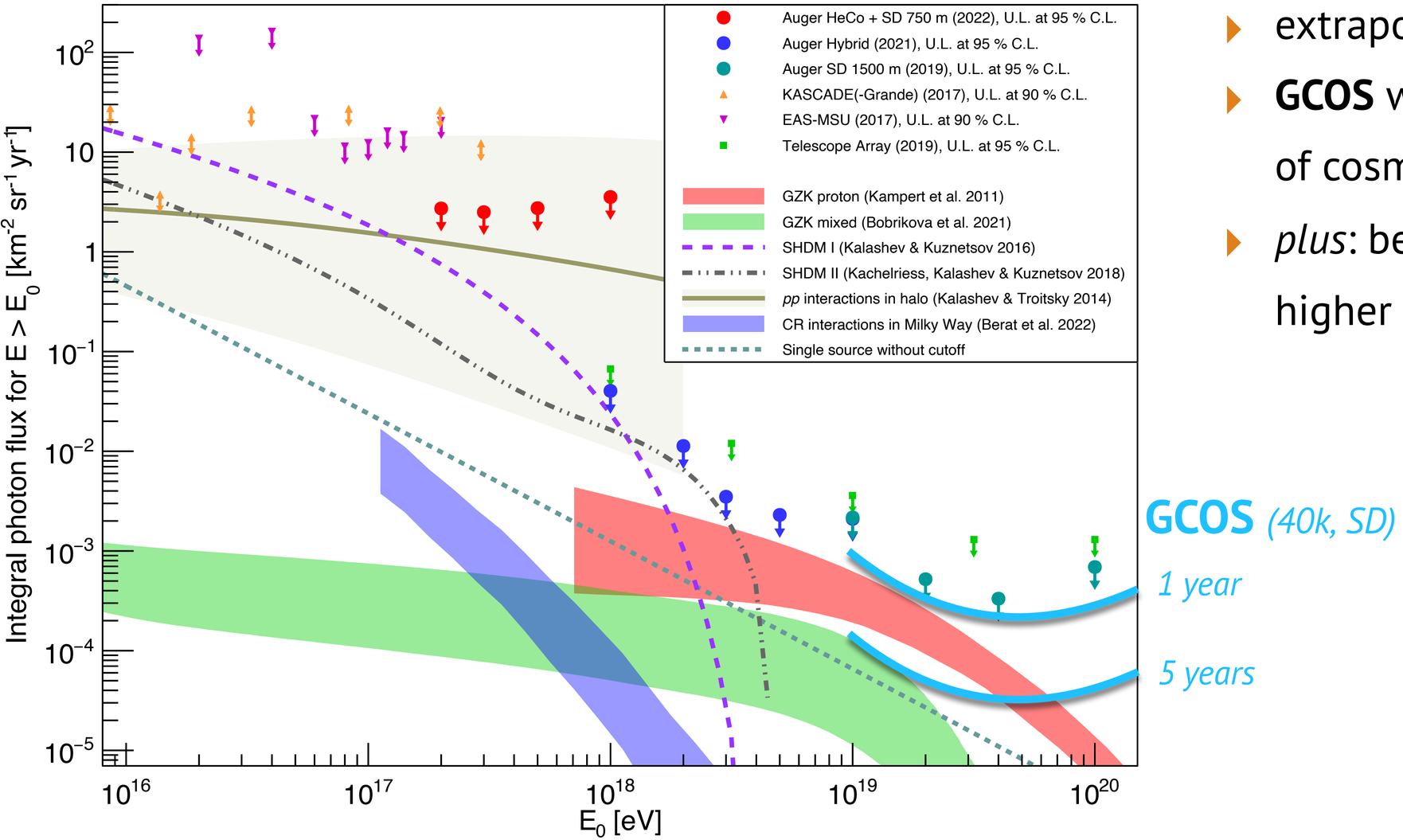
Auger → *(10x more events)* → **GCOS**





- significance increases from 5.4σ to >20σ to identify a contribution of SBGs over gamma-ray-emitting AGNs

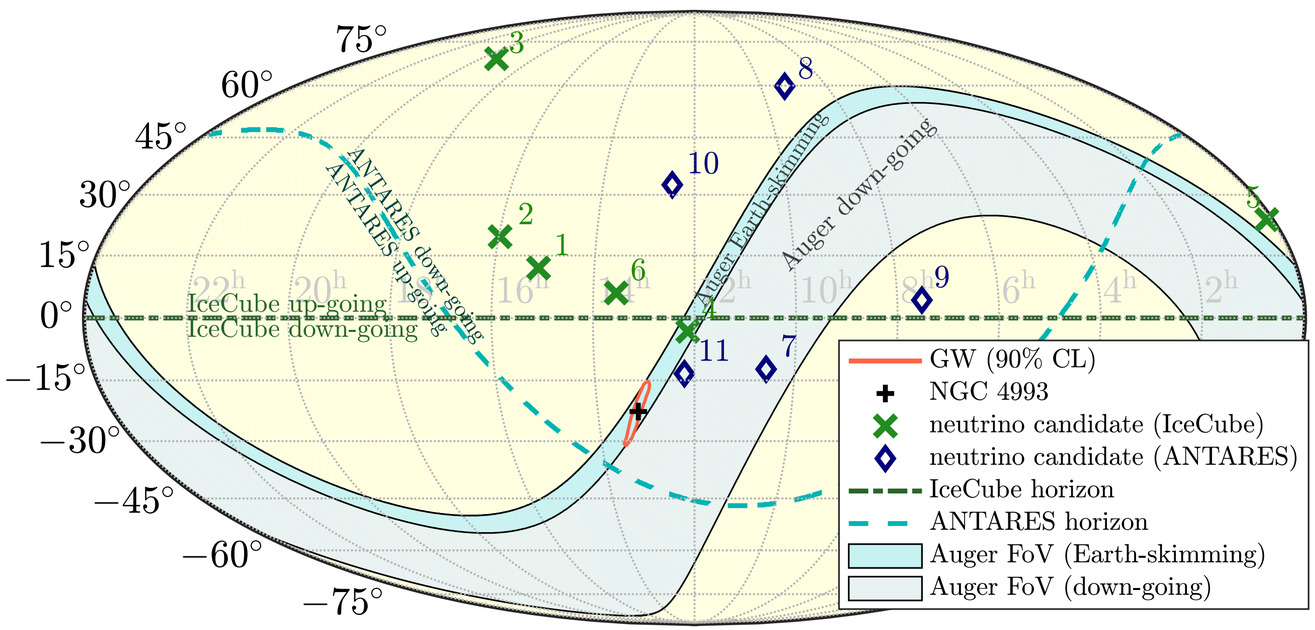
presentation by T. Bister 2nd GCOS Workshop



- extrapolating Auger limits
- **GCOS** will be able to constrain the flux of cosmogenic photons
- *plus*: better X_{max} resolution → even higher statistics

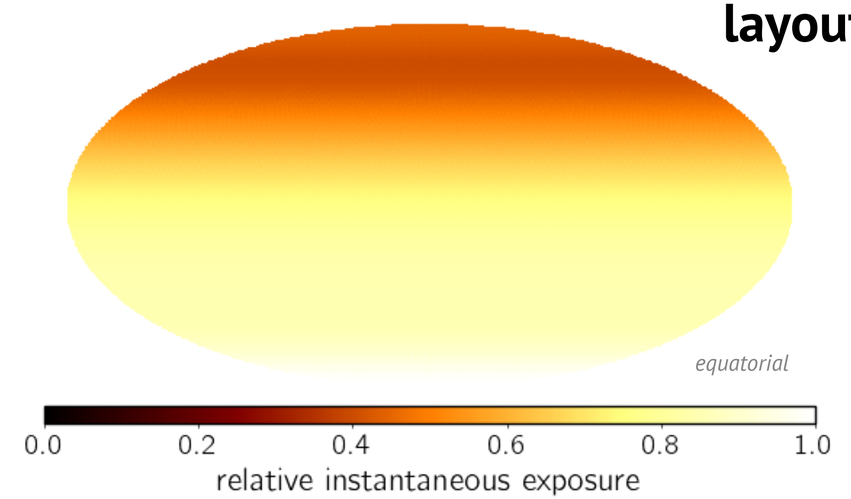
presentation by M. Risse, 2nd GCOS Workshop.

ANTARES, IceCube, Pierre Auger, LIGO, Virgo Collaborations. Astrophys. J. Lett. 850 (2017) L35.

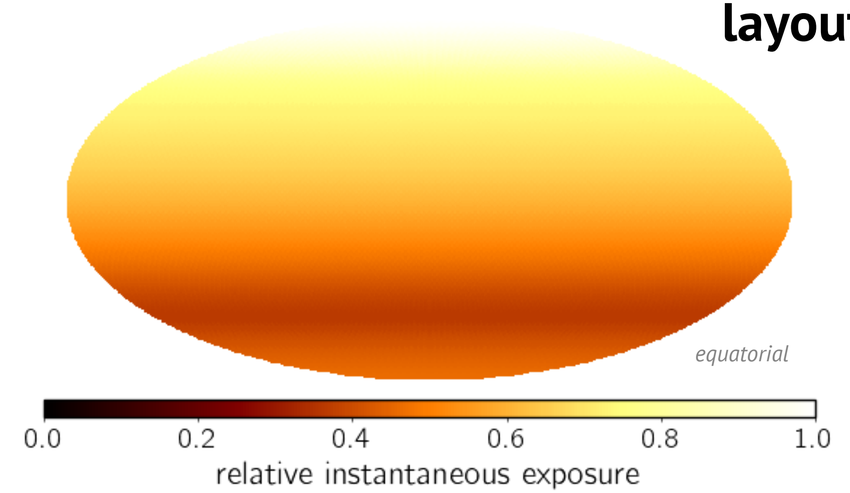


instantaneous FoV for inclined events

layout C

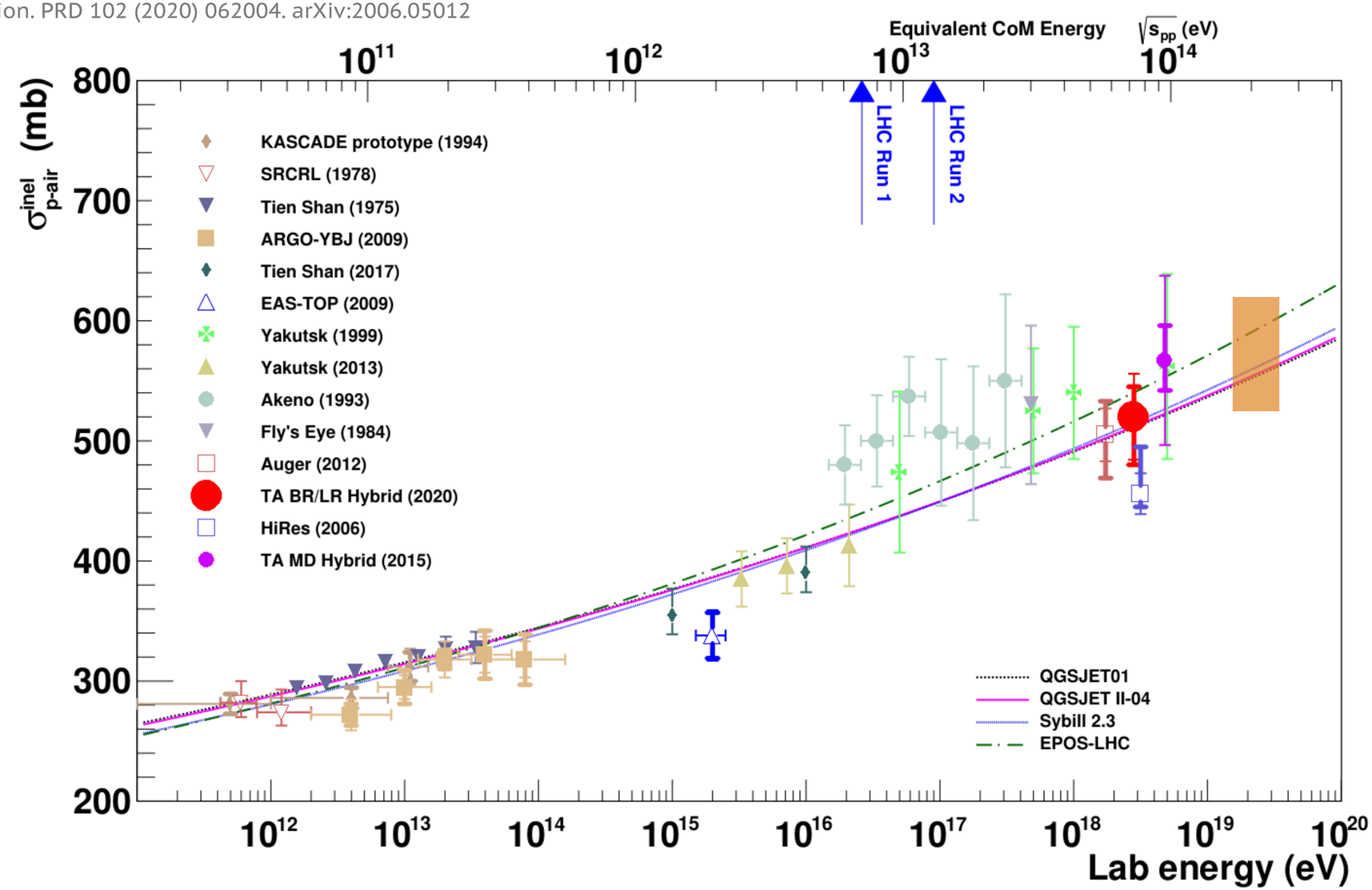


layout B



- full-sky coverage at all times is important for multimessenger studies

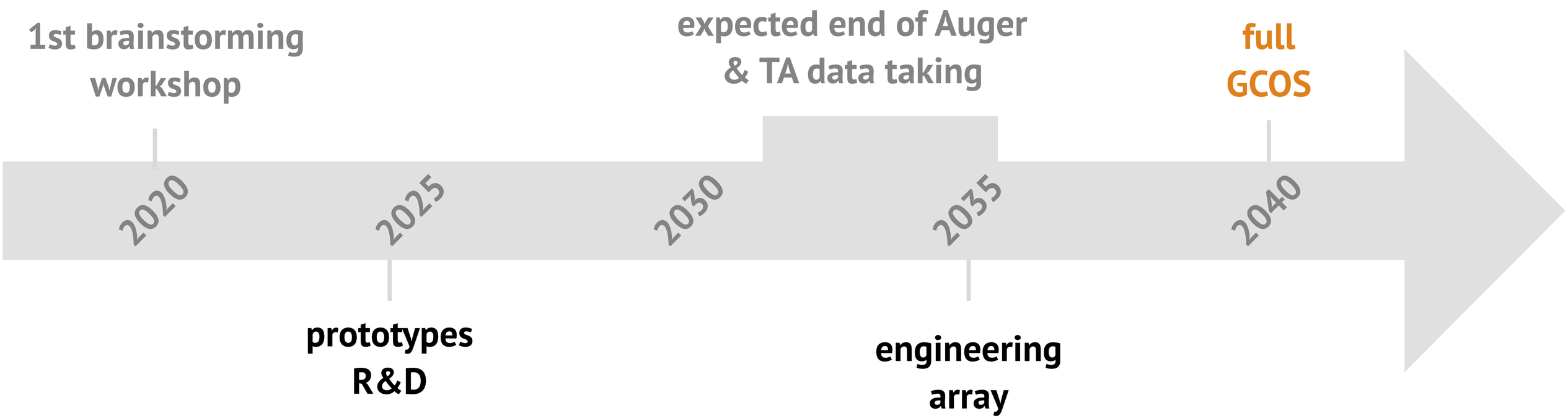
Telescope Array Collaboration. PRD 102 (2020) 062004. arXiv:2006.05012



- **GCOS** will be able to measure the cross section at higher energies and *exclude* hadronic interaction models

outlook

outlook



- **area:** 40,000 to 80,000 km^2 (⩾ 2 sites)
- **energy range:** full efficiency above ~10 EeV
- **energy resolution:** < 10%
- **muon resolution:** < 10%
- **X_{max} resolution:** < 20 g/cm^2
- **angular resolution:** < 1°

thank you 😊

"la Caixa" Foundation

back-up

mass composition sensitivity

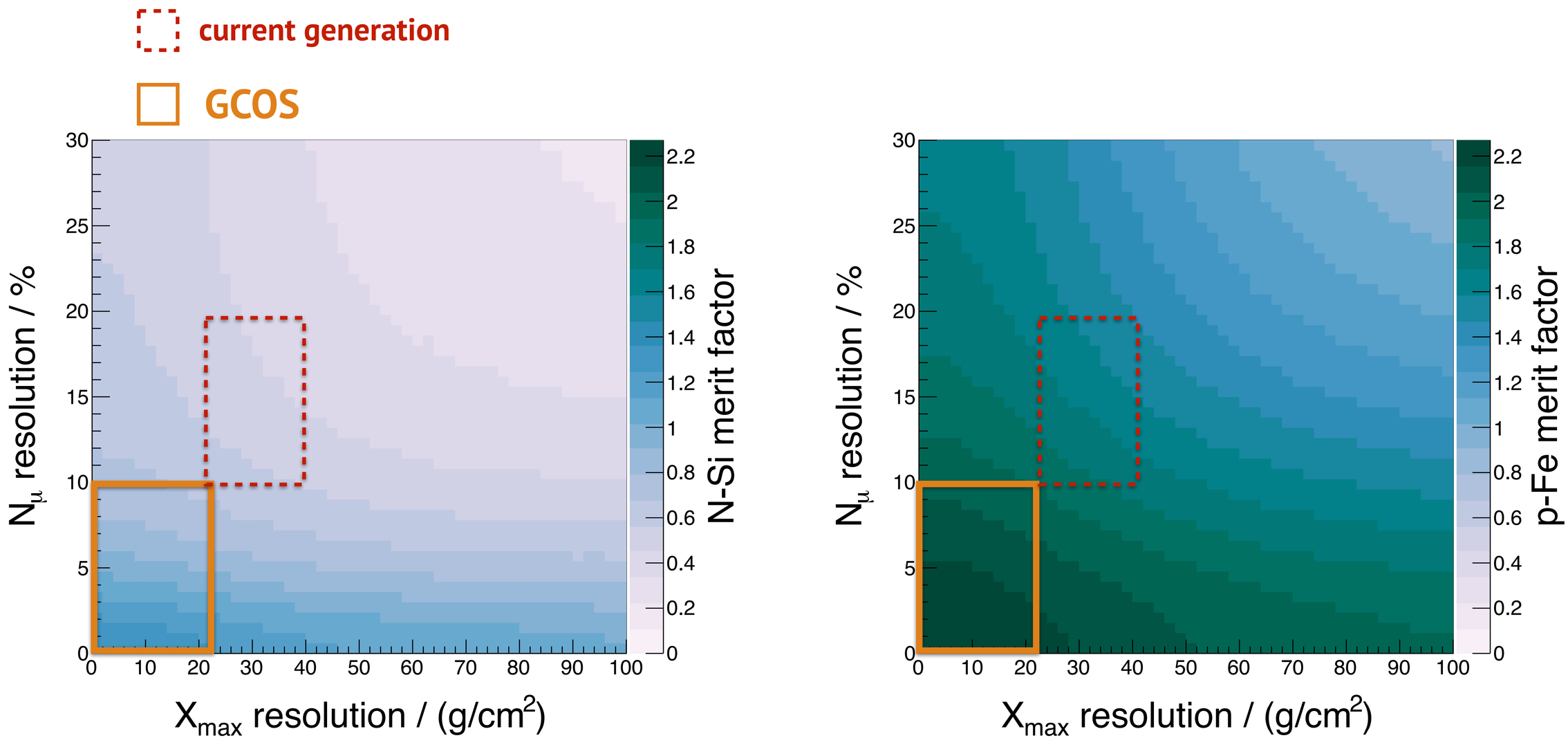
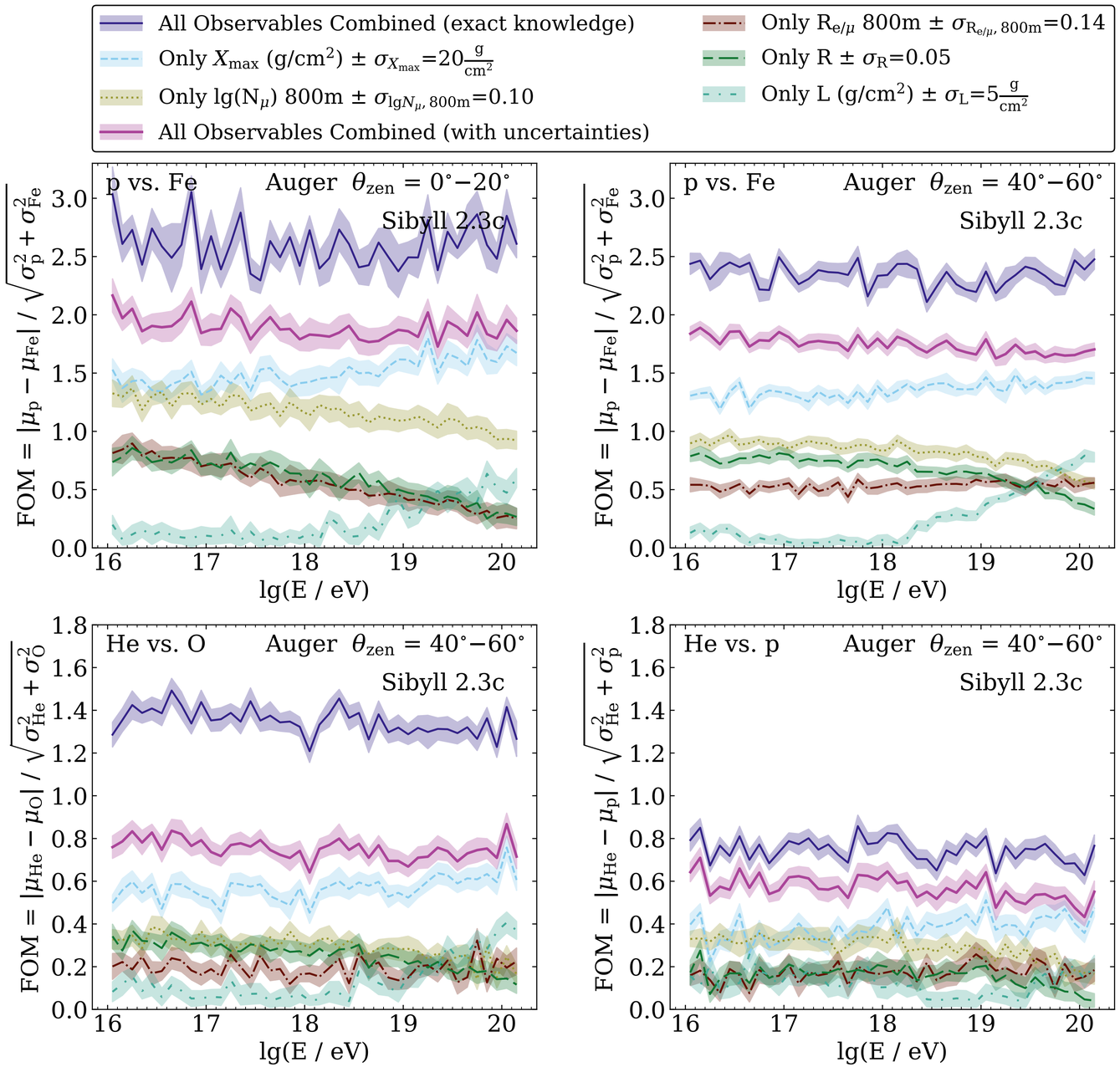


figure by M. Unger

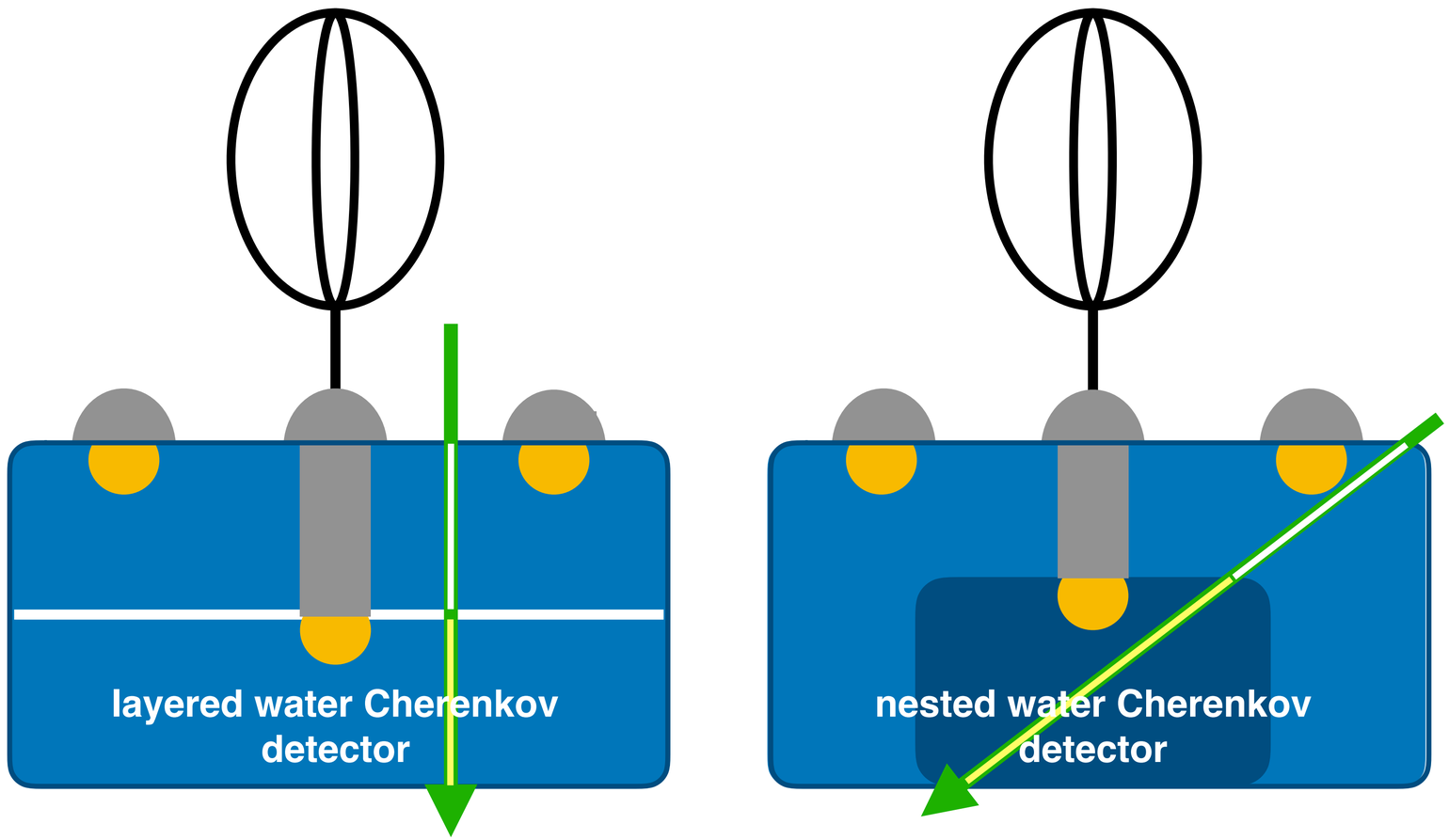
mass discrimination sensitivity



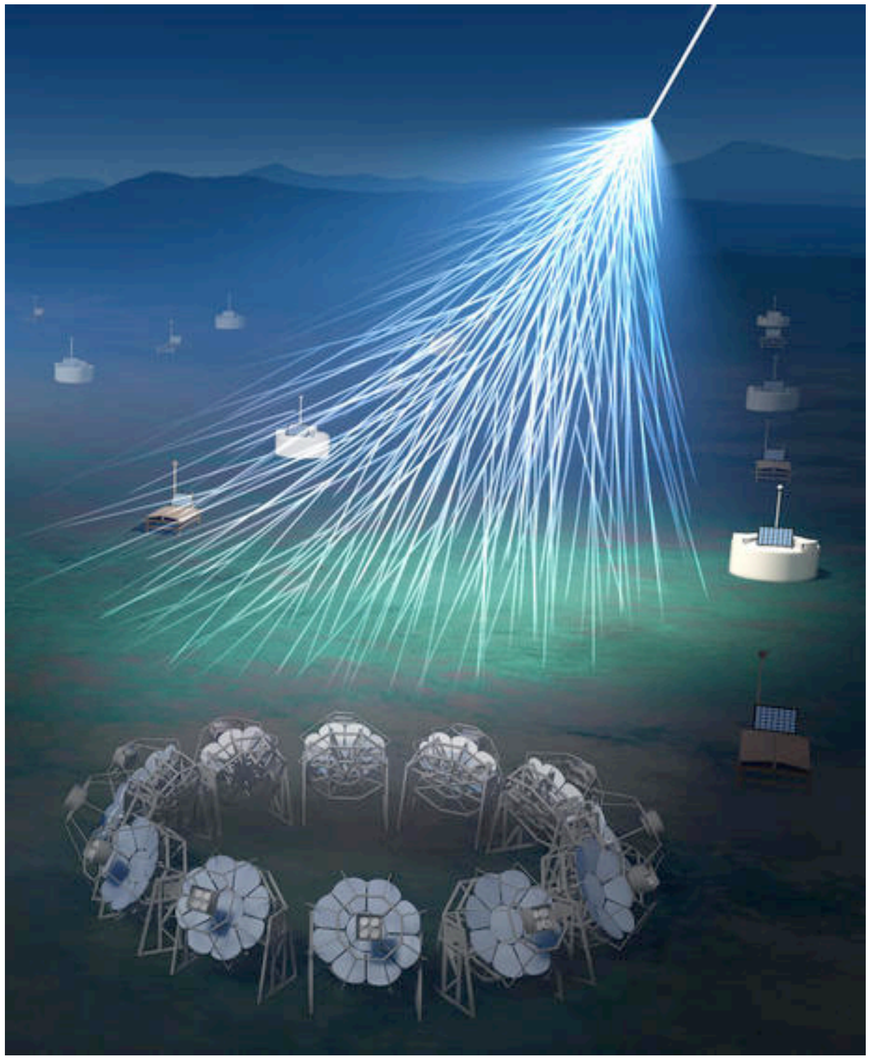
- all observables needed → surface + fluorescence (+ radio)
- but X_{max} measurements with SD alone have been improving (neural networks)
- sub-array (FD and/or RD) for calibration?

presentation by Ben Flaggs, 3rd GCOS Workshop.

surface array. which types of detectors?

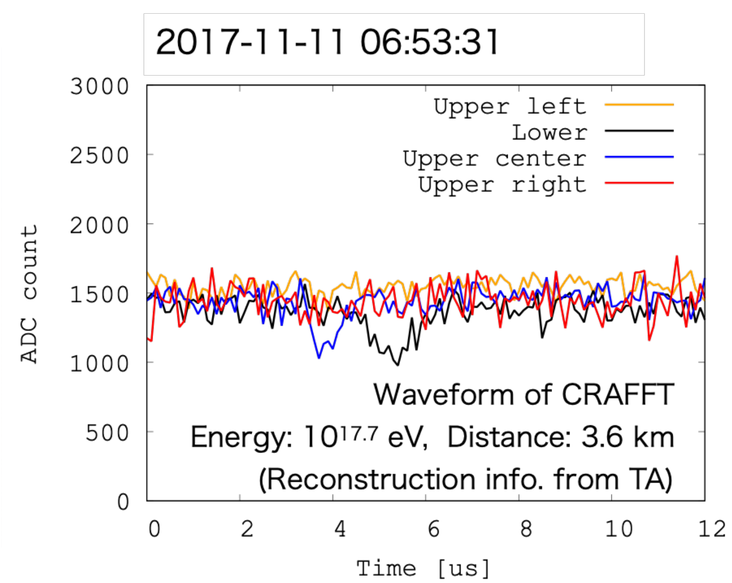


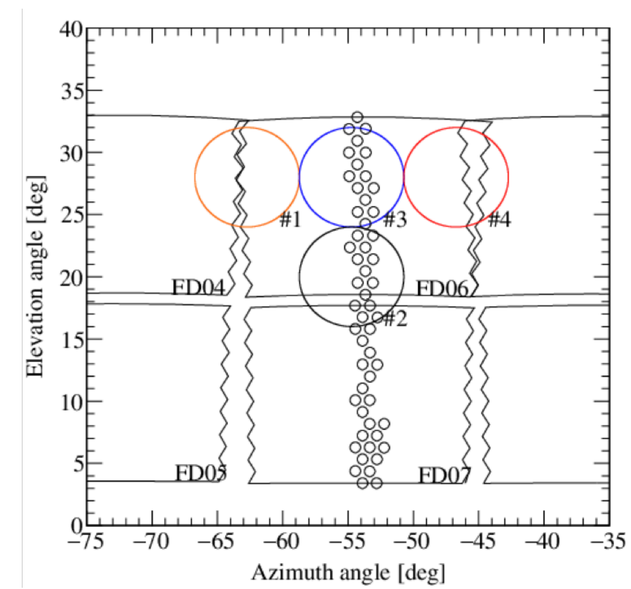
fluorescence detectors. FAST



- FAST = Fluorescence detector Array of Single-pixel Telescopes
- low cost, tested at Auger sites
- energy resolution: 8%
- X_{max} resolution: 30 g/cm^2
- angular resolution: 2°

- CRAFFT = Cosmic-Ray Fluorescence Fresnel Lens Telescope
- low cost
- energy resolution: 8%
- X_{max} resolution: 30 g/cm2
- angular resolution: 2°





e.g. MACHETE Design J. Cortina et al. APP (2016) 46

Nepomuk Otte PoS ICRC19

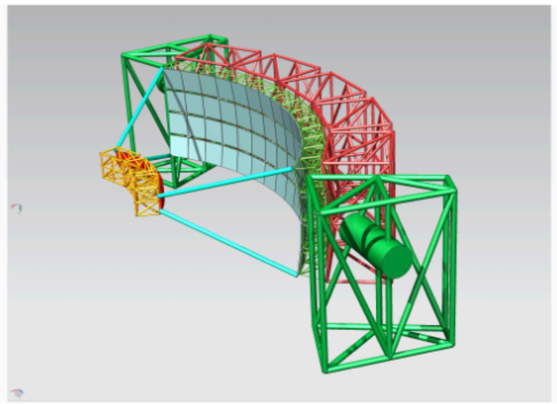


Figure 7: Proposed optics for *Trinity* based on the MACHETE optics. The primary mirror is composed of 68, 1 m^2 mirrors. the focal plane (red curved surface) is populated with 3,300 pixels each consisting of a solid non-imaging light concentrator coupled to an SiPM. The field of view covered by one telescope is $5° \times 60°$.

- 2 MACHETE rings $\rightarrow 360° \times 10°$ FoV
- cost: $\sim$ 10 M$ Trinity whitepaper arXiv:1907.08727
- $0.3°$ pixel, effective aperture 10 m^2
- $(S/N)_{\text{FD}} \propto \sqrt{A/\Omega_{\text{pix}}} \rightarrow (S/N)_{\text{Cyclops}}/(S/N)_{\text{Auger}} = \sqrt{10\ \text{m}^2/0.3°^2}\Big/\sqrt{3\ \text{m}^2/1.5°^2}$ = **9**

$\rightarrow$ optimization for GCOS needed & check dual use ν+UHECR

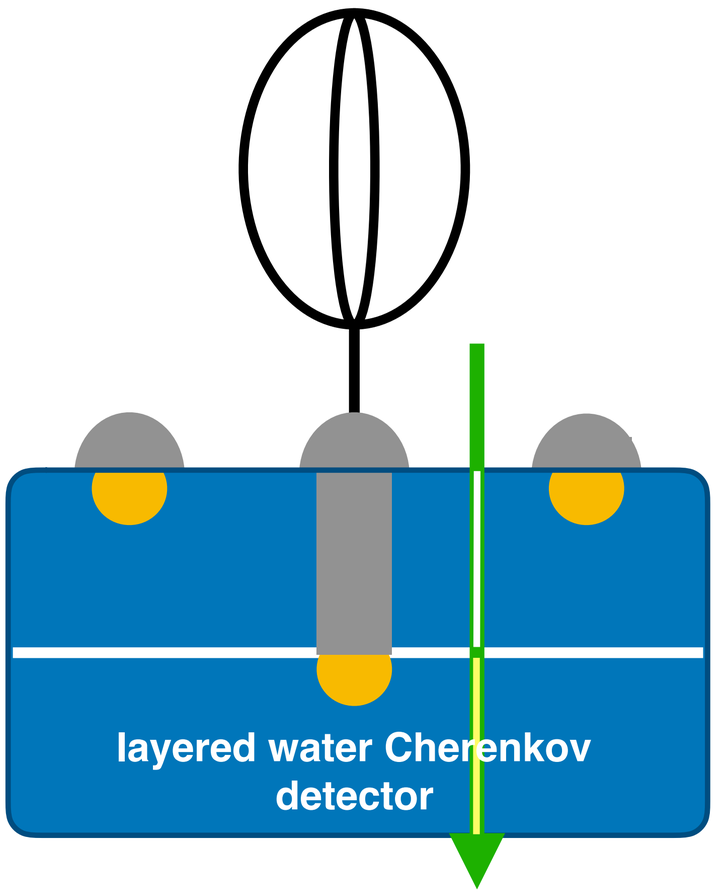
5

presentation by M. Unger, 2nd GCOS Workshop.

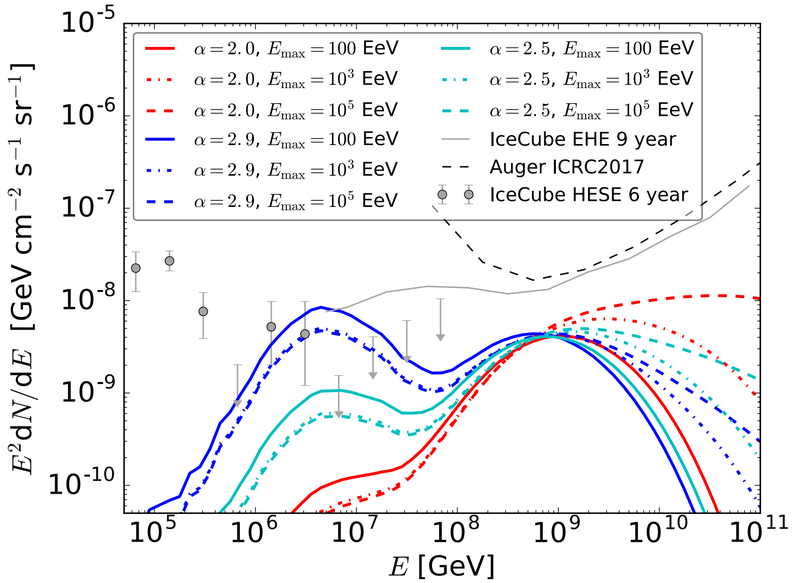
parameter	resolution learning machine (1st step)	Reconstruction bias learning machine (1st step)	resolution top down (2nd step)
Shower axis	2.76°	$< 0.75°$	0.3 °
Core	256 m	< 50 m	45 m
X_{max}	60 g/cm^2	< 30 g/cm^2	10 g/cm^2
Energy	25%	$< 15\%$	2.5%

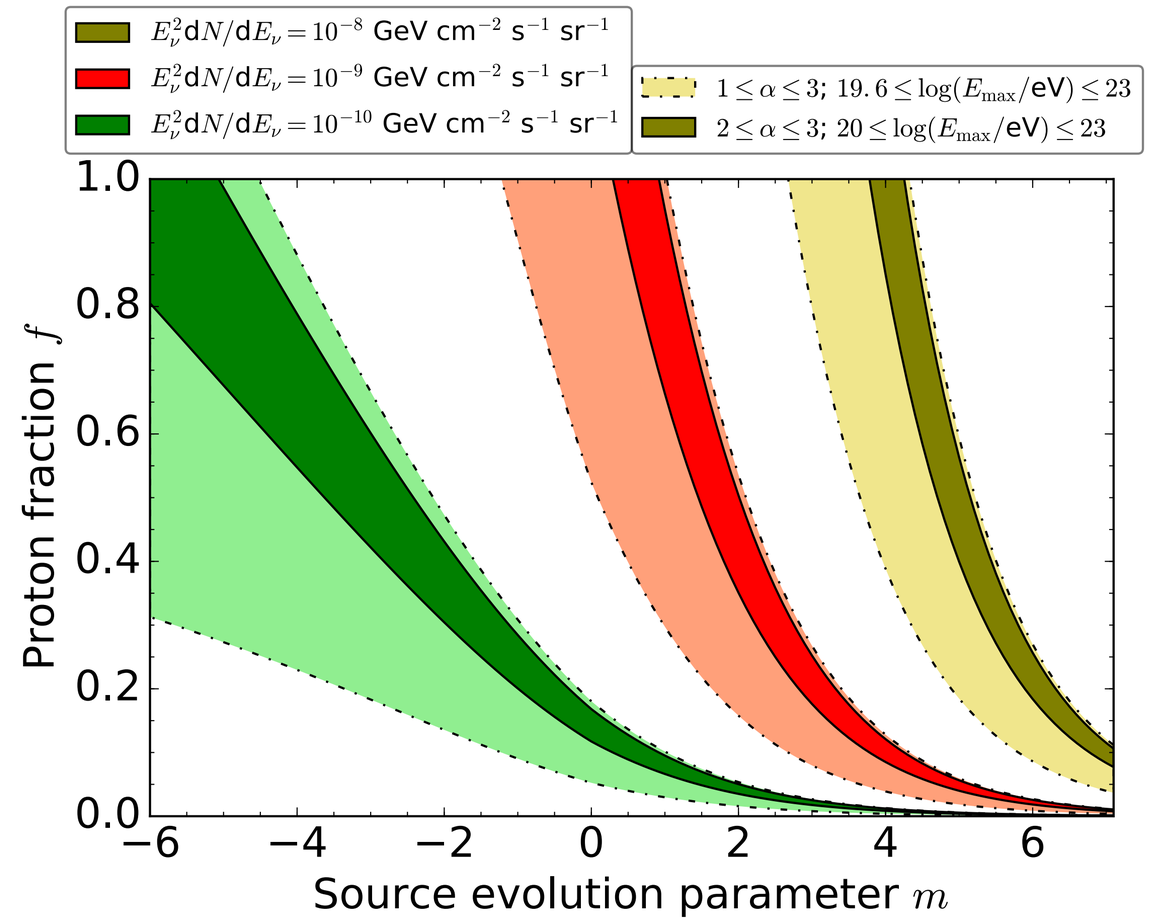
Table 1: Performance for the learning machine and Top Down reconstruction algorithms.

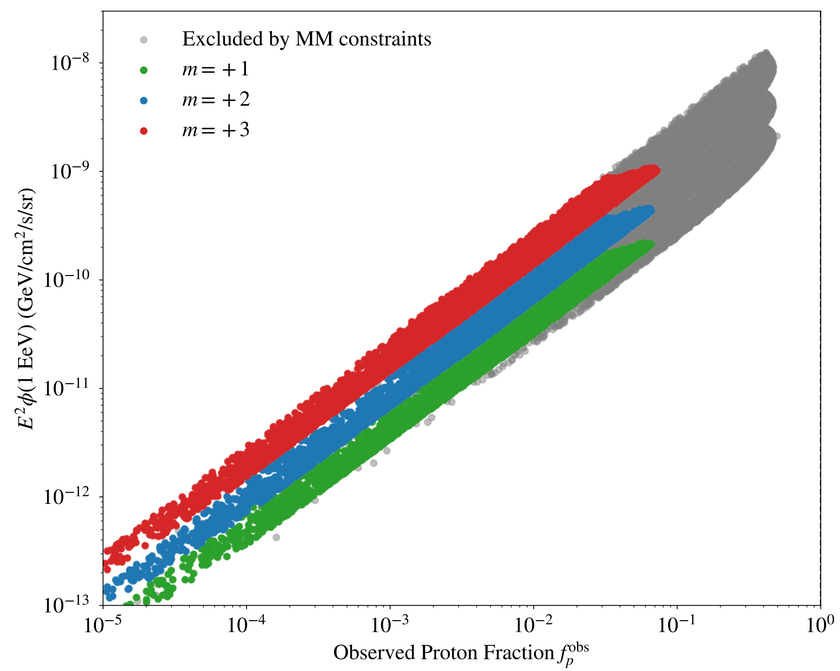
Jose Bellido, GCOS Compendium of Ideas. arXiv:2308.XXX



- combine radio antennas with WCDs
- multiple polarisation detectors
- energy resolution: ~10%
- time resolution < 1 ns (for interferometry)
- radio-only measurements or external trigger?
- very low cost (~1000 EUR per station)
- limitations: large grid spacing (> 1.5 km)







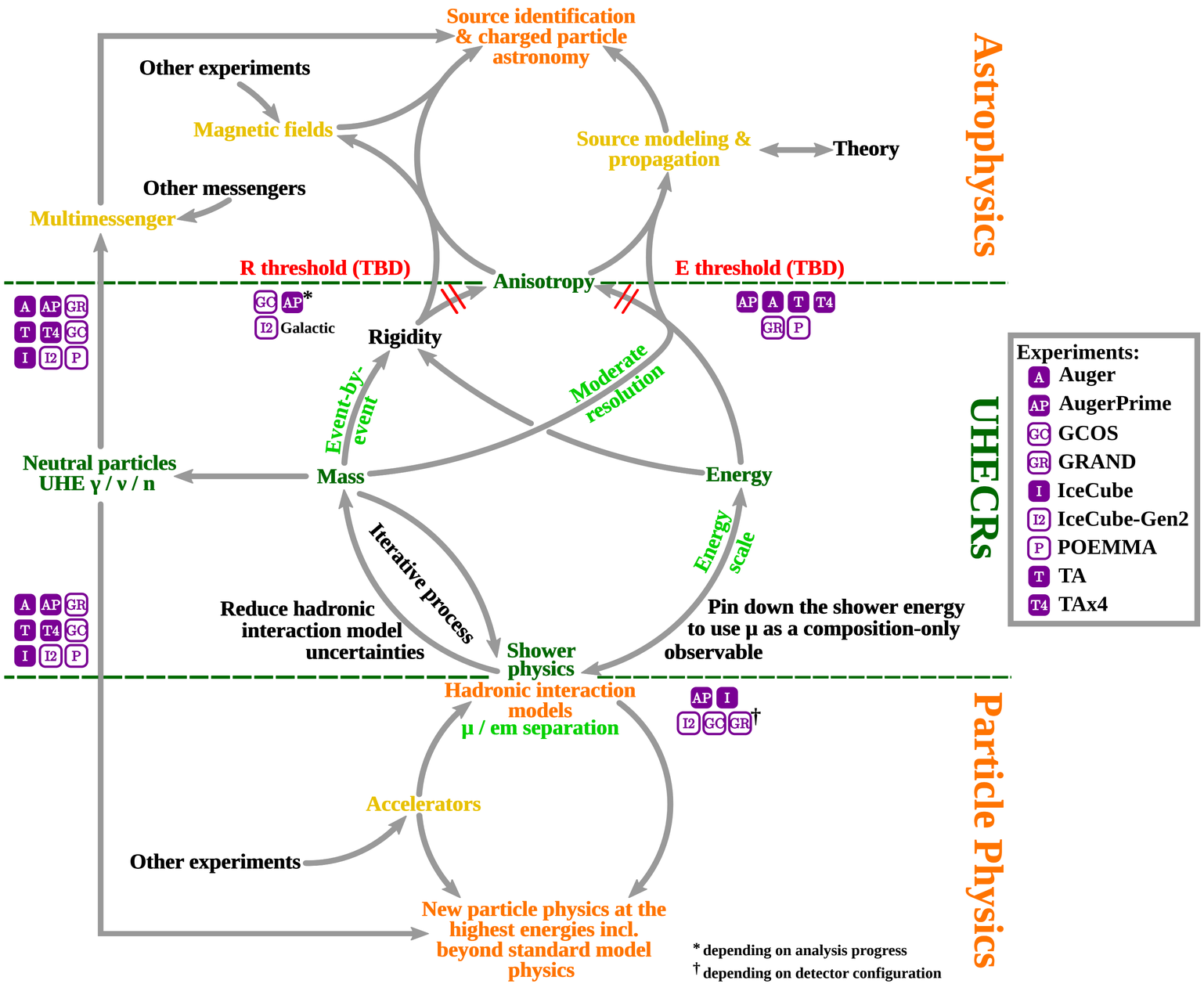
van Vliet, Alves Batista, Hörandel. Physical Review D 100 (2019) 02312. arXiv:1901.01899

Stein Muzio, Unger, Wissel. Physical Review D 107 (2023) 103030. arXiv:2303.04170

- **GCOS** would enable constraints on the source evolution using cosmogenic neutrinos *AND* a precise measurement of the proton content

the future

ANTARES, IceCube, Pierre Auger, LIGO, Virgo Collaborations. Astrophys. J. Lett. 850 (2017) L35.



timeline experiments

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
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