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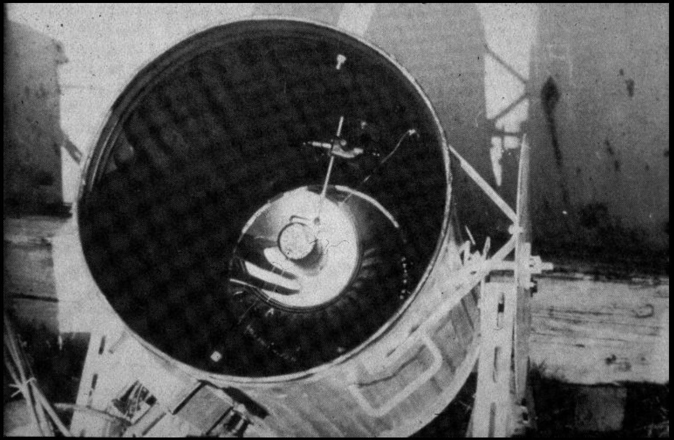
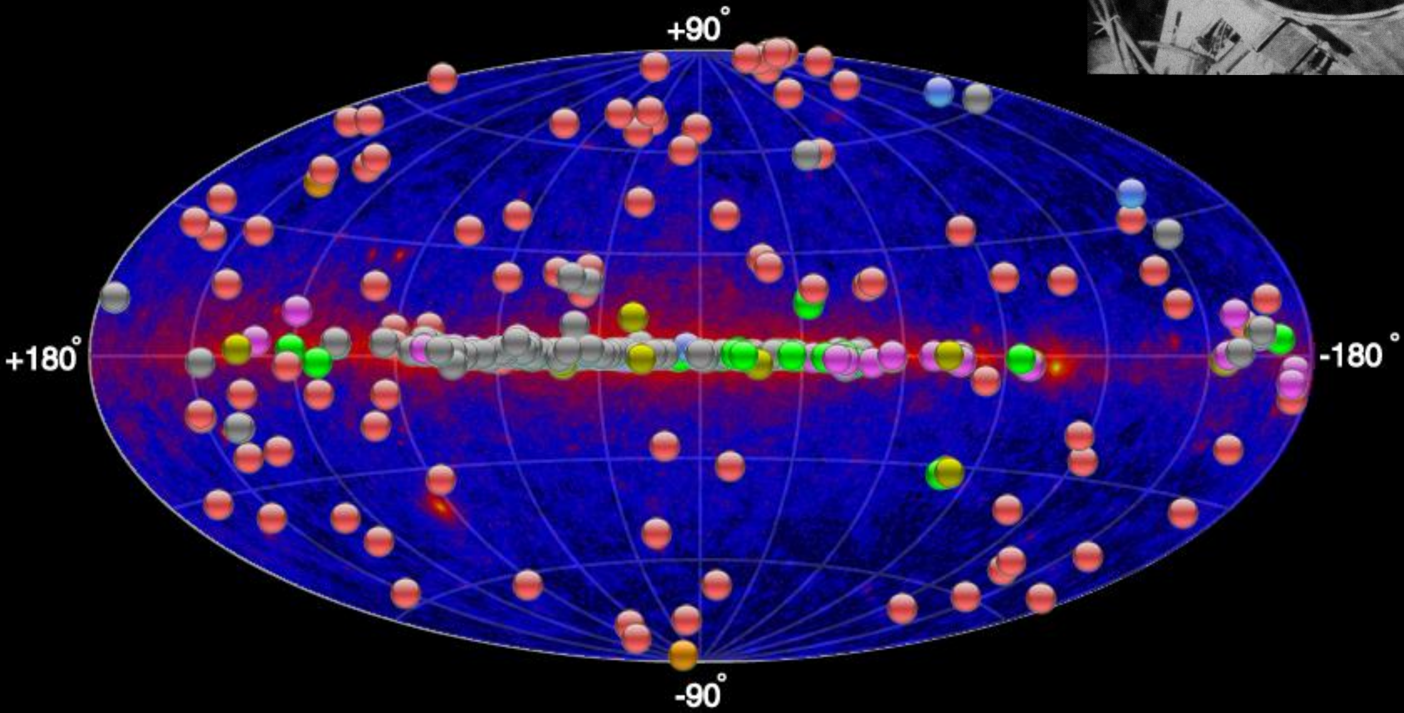




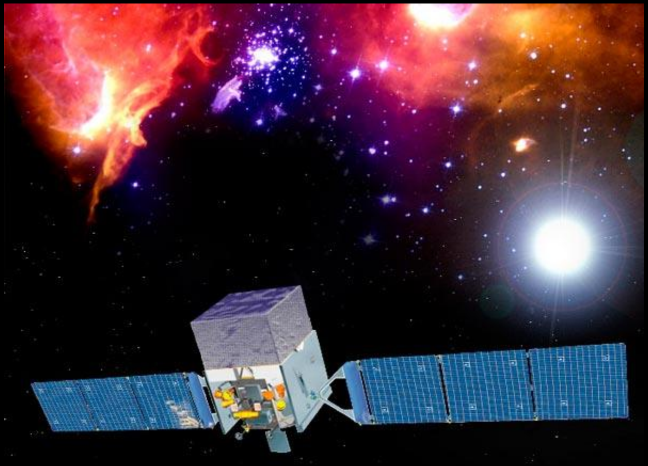
Gamma-ray Astronomy: A Unique Probe of the Universe

Durham University

Contents

- Space-based vs. ground-based gamma-ray astronomy
- A brief description of Fermi (LAT)
- Ground-based gamma-ray telescopes
  - Imaging Atmospheric Cherenkov Telescopes (IACTs)
  - Water Cherenkov Detectors (WCDs)
- The future: CTAO, SWGO & their science aims

Space vs. Ground in Gamma Rays



Space

MeV to ~100 GeV (Fermi: ~100 MeV to ~100 GeV)

Collection area ~ m^2 -> low instantaneous sensitivity, drop off at high energies

Poor angular resolution ~ 1 deg.

BUT large field-of-view, all-sky capability

Ground

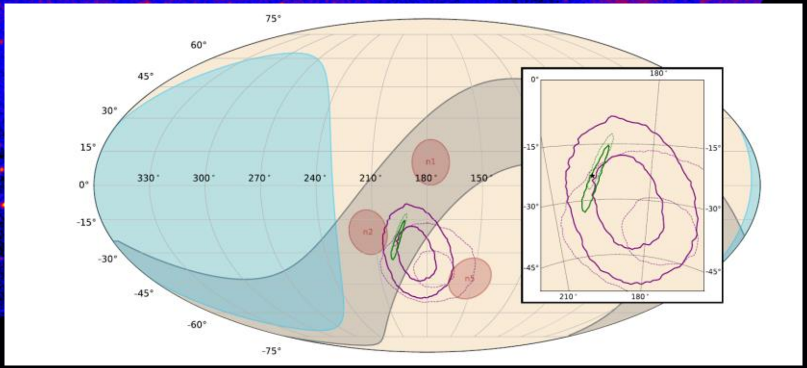
Few 10s of GeV to PeV +

Collection area ~ 10^4 m^2 + -> excellent instantaneous sensitivity

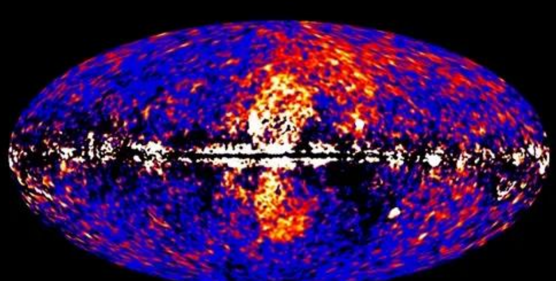
Better angular resolution ~0.1 deg.

Fermi

- Fermi Gamma-ray Large Area Space Telescope
- Launched 11/6/08
- Covers whole sky in 180 min
- Nominal energy range 10 MeV – 300 GeV
- 2 instruments –
  - Large Area Telescope (LAT)
  - GLAST Burst Monitor (GBM)



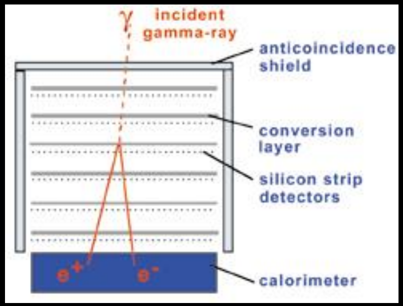
Goldstein et al., Ap.J. Lett, 848, L14 (2017)

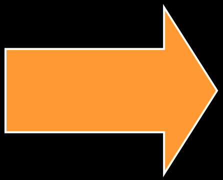


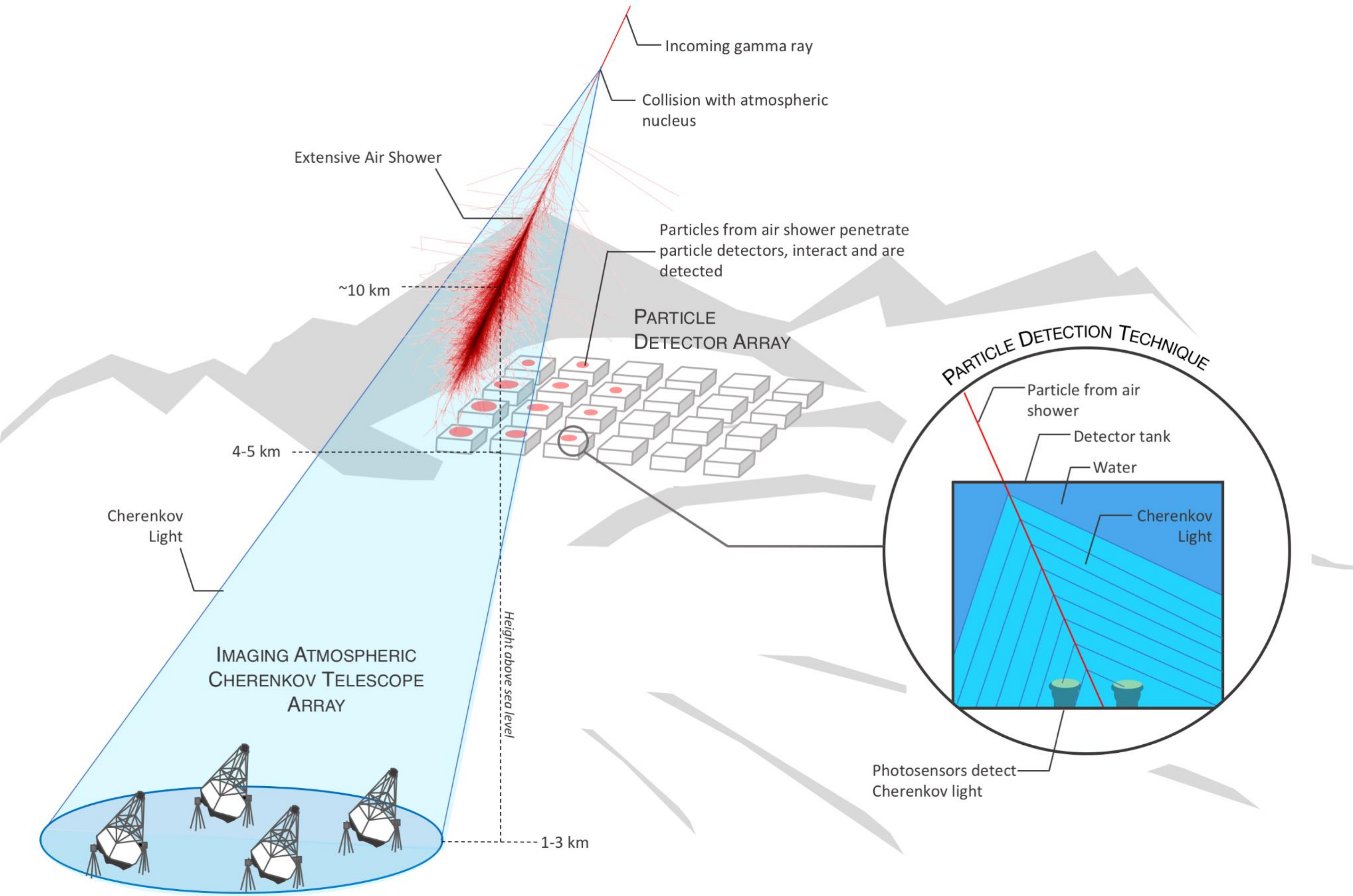
Su et al., https://arxiv.org/abs/1005.5480

Limitations…

Fermi detects high energy gamma-rays – from ~100 MeV to ~100 GeV.
It is hard for a space-based detector to do much better than this.







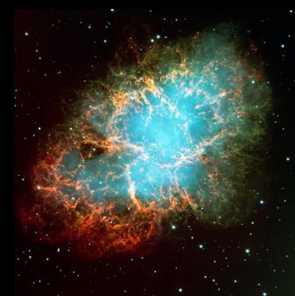
Shower image, 100 GeV γ-ray adapted from: F. Schmidt, J. Knapp, "CORSIKA Shower Images", 2005, https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

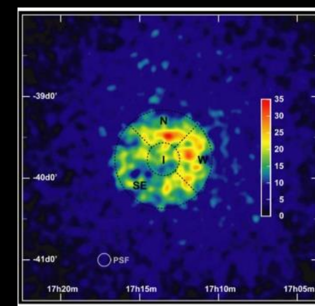
Current Imaging Atmospheric Cherenkov Telescopes

Typical requirement – clear, dry site around 1 – 3 km above sea level.

The VHE Catalogue (so far)

- As of 30th November 2023
  - ~270 sources detected
  - 96 as yet unidentified
  - Many spatially extended
- Galactic Sources
  - 1 pulsing pulsar – the Crab
  - 38 pulsar wind nebulae
  - 11 binary systems
  - 3 massive star clusters
  - 16 shell SNRs
  - 11 SNR/molecular cloud shocks
  - 1 star-formation region
  - 1 globular cluster (Terzan 5)
- AGN & Other Galaxies
  - 89 active galactic nuclei
  - 2 starburst galaxies, NGC253 & M82
  - Sources identified in the LMC





Current Water Cherenkov Detectors

Advantage: can operate 24/7
Disadvantages: high energy threshold, less good angular/energy resolution

HAWC (High Altitude Water Cherenkov) detector – on the flanks of the Sierra Negra volcano near Puebla, Mexico. Altitude 4.1 km asl.

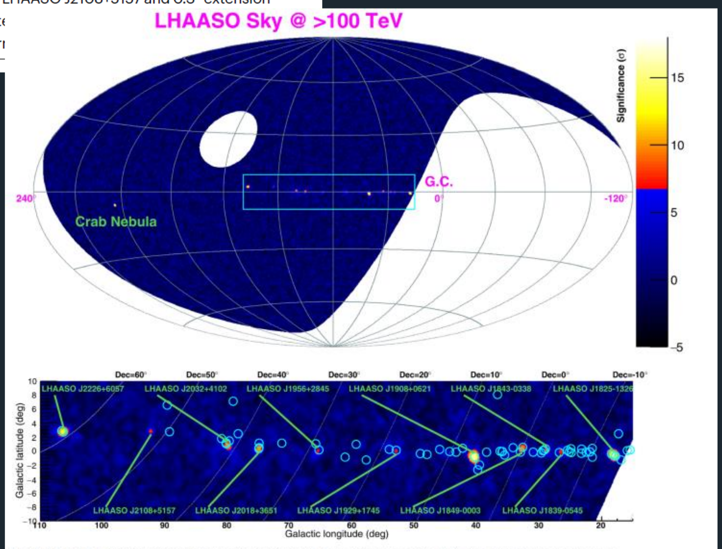
LHAASO in Tibet – huge observatory. Ultimately WCD, wide-angel Cherenkov telescopes, muon detectors and fluorescence detectors.

Results from LHAASO

Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	−3.65	8.5	$0.26 -0.10^{+0.16}$	0.73(0.17)
LHAASO J1849-0003	282.35	−0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71 -0.07^{+0.16}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)

Celestial coordinates (RA, dec.); statistical significance of detection above 100 TeV (calculated using a point-like template for the Crab Nebula and LHAASO J2108+5157 and 0.3° extension templates for the other sources); the corresponding differential photon fluxes at 100 TeV; and detected highest photon energies. Errors are estimate
contains ±34.14% of events with respect to the most probable value of the event distribution. In most cases, the distribution is a Gaussian and the err

All above 7 sigma significance



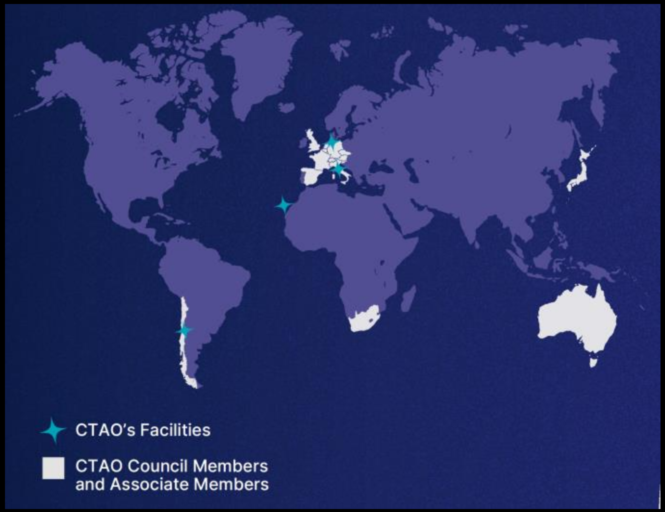
Extended Data Fig. 4 | LHAASO sky map at energies above 100 TeV. The circles indicate the positions of known very-high-energy γ-ray sources.

A big surprise – many accelerators producing gamma rays with energies over 10^{15} eV in the Galaxy.

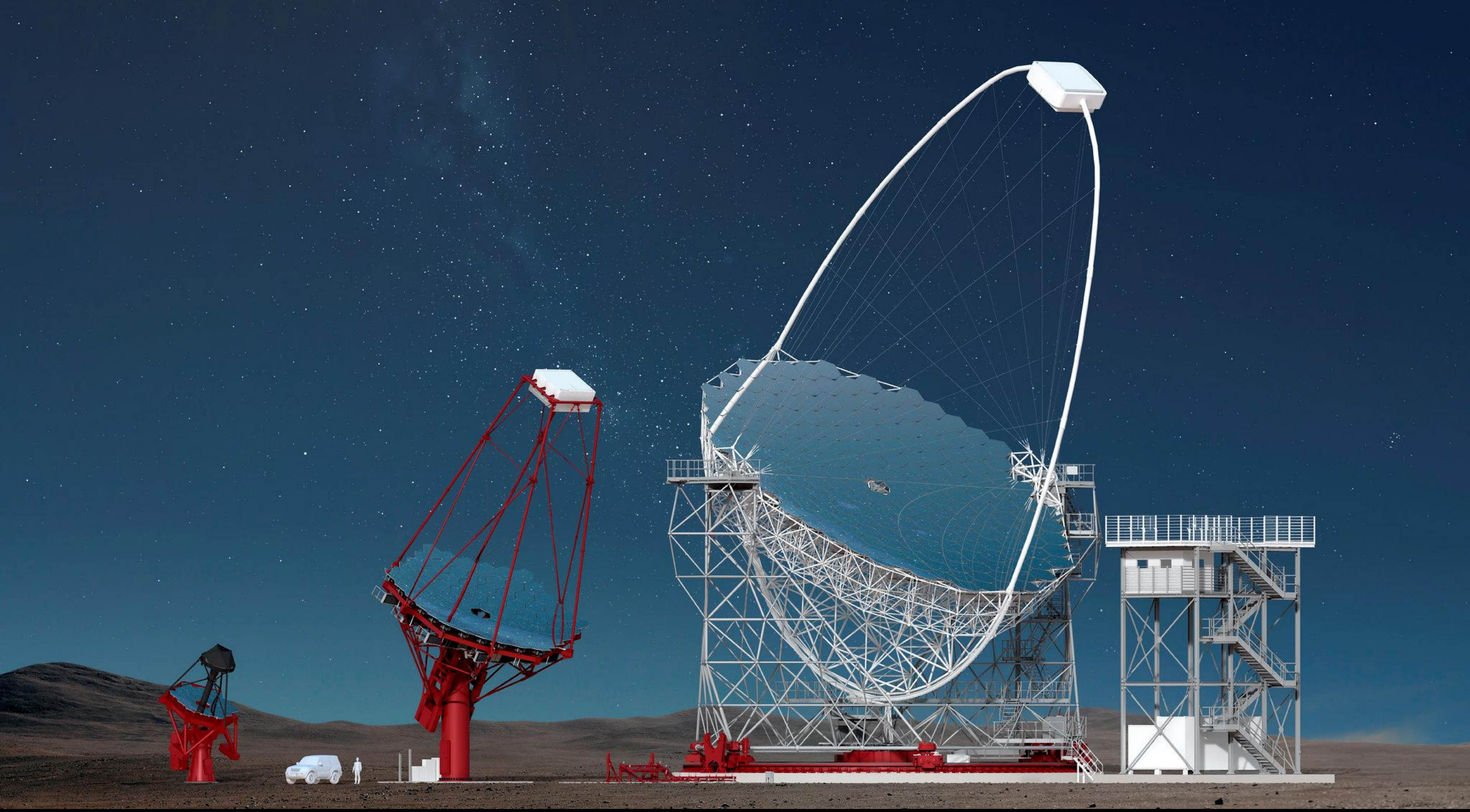
Cao et al, Nature (2021)
https://www.nature.com/articles/s41586-021-03498-z

The next big step…

- The world's VHE gamma-ray telescope
- Explores top 4-5 decades in energy
- Factor of 10 improvement on current telescopes
- Full sky coverage
- Large community of users

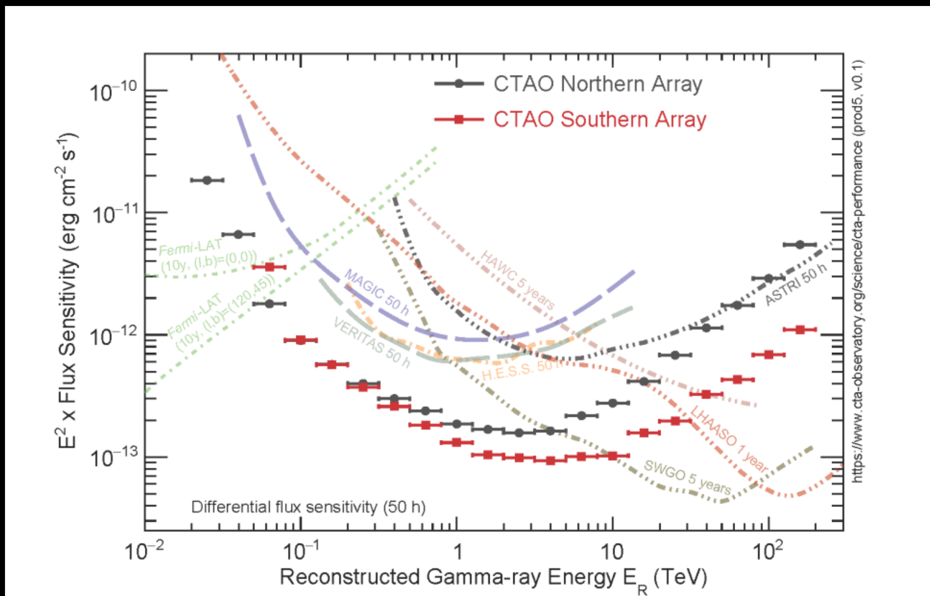


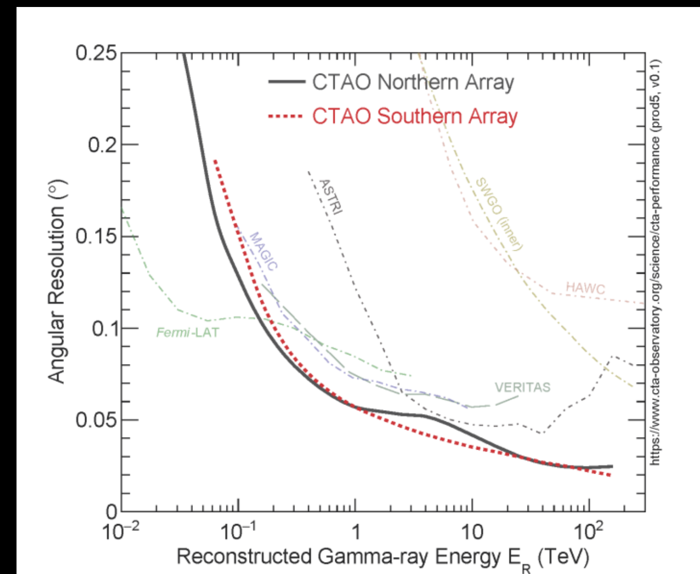
CTAO

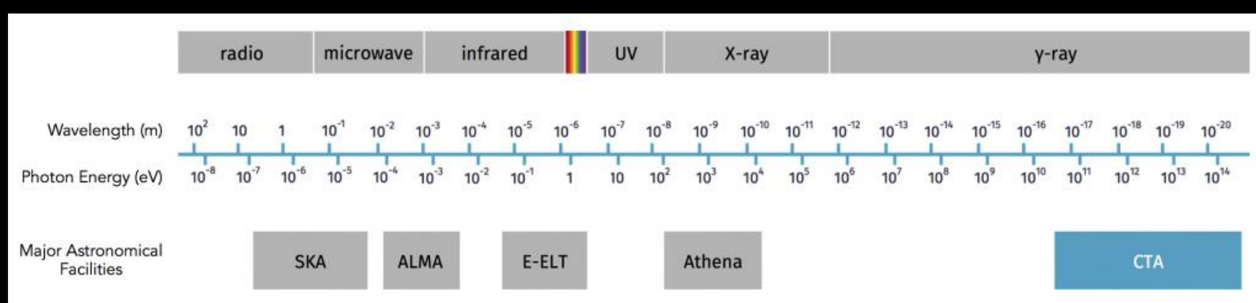


Multiple telescope designs to cover the full energy range – SST, MST and LST. More than 60 telescopes split between its two array sites.

CTAO Performance







CTAO Science

- Theme 1: Cosmic Particle Acceleration
  - How and where are particles accelerated?
  - How do they propagate?
  - What is their impact on the environment?
- Theme 2: Probing Extreme Environments
  - Processes close to neutron stars and black holes?
  - Processes in relativistic jets, winds and explosions?
  - Exploring cosmic voids
- Theme 3: Physics Frontiers – beyond the SM
  - What is the nature of dark matter? How is it distributed?
  - Is the speed of light constant for high energy photons?
  - Do axion-like particles exist?

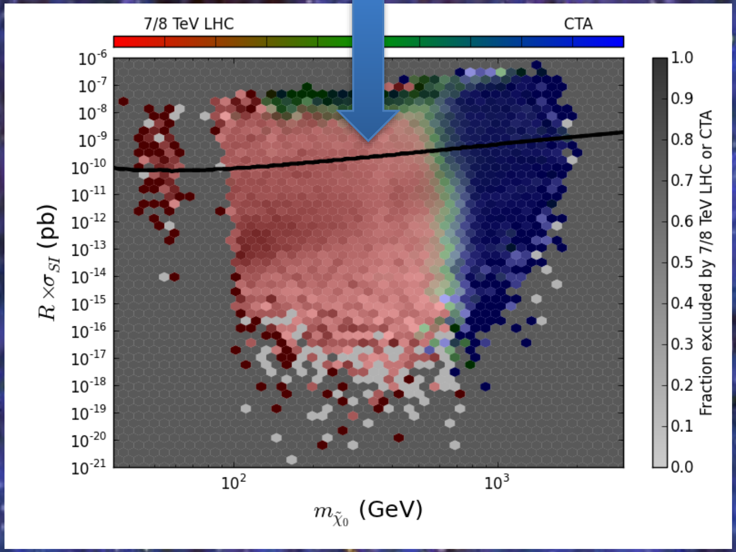
ArXiv: 1709.07997

CTA and the Hunt for Dark Matter

- CTA has excellent sensitivity to regions of the parameter space not accessible to the LHC or direct experiments
- Indirect detection experiments also give DM distribution

Models accessible to CTA in blue,
to LHC in red.

XENON1T Exclusion



Cahill-Rowley et al. ArXiv 1305.6921

(Image: Zarija Lukic/Lawrence Berkeley National Laboratory)

Indirect Detection of Dark Matter via γ-rays

Observation time

DM distribution in source & location relative to observer

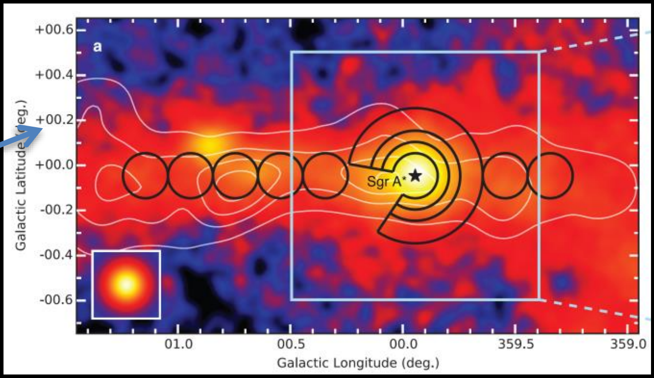
Detector effective area

$$N_{\gamma,DM} = \frac{t_{obs} J_{region} \langle \sigma v \rangle}{8\pi {M_\chi}^2} \int_{E_{min}}^{E_{max}} \frac{dN_{DM}}{dE}(E) A_{eff}(E) dE$$

No. of observed events

Energy spectrum of gamma rays produced in annihilation

So far, so good…but…there are significant astrophysical backgrounds. This is the HESS view of the central 200 pc of the Milky Way



HESS Collaboration: arXiv 1603.07730

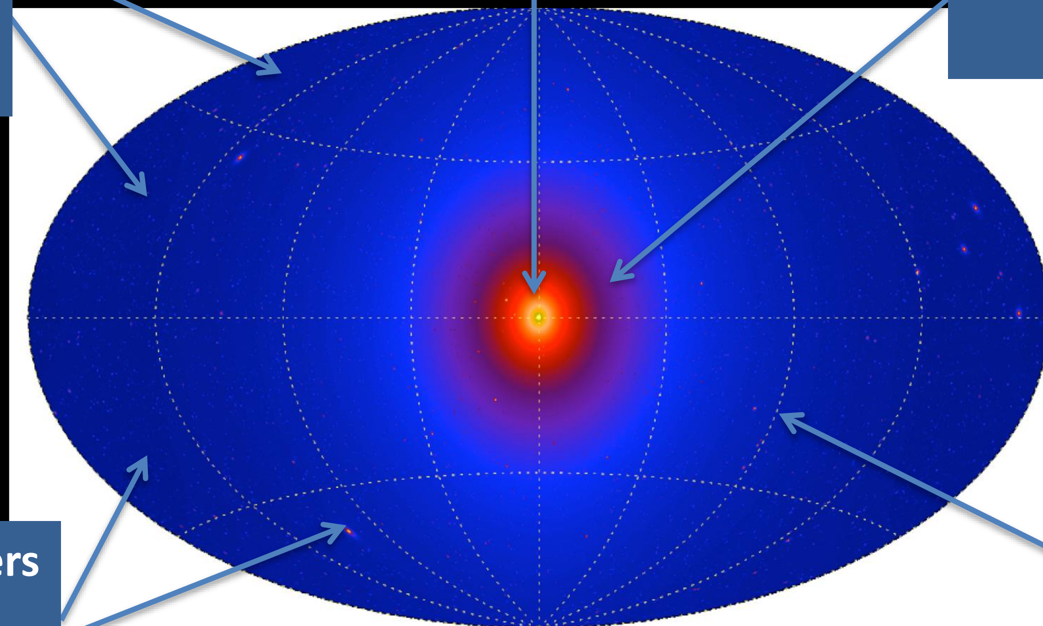
DM Search Targets

DM simulation from Pieri et al., arXiv:0908.0195 (photons > 3 GeV)

Galactic Centre
Great statistics, but source confusion/diffuse BG

Satellite Galaxies
Low BG and good source ID, but low statistics

MW Halo
Good statistics, but diffuse BG



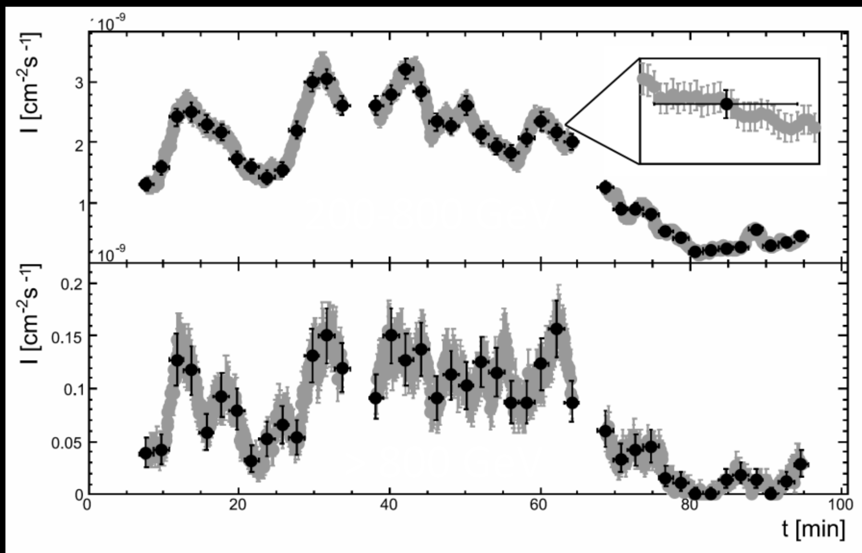
Spectral Lines
Little/no BG but low sensitivity*

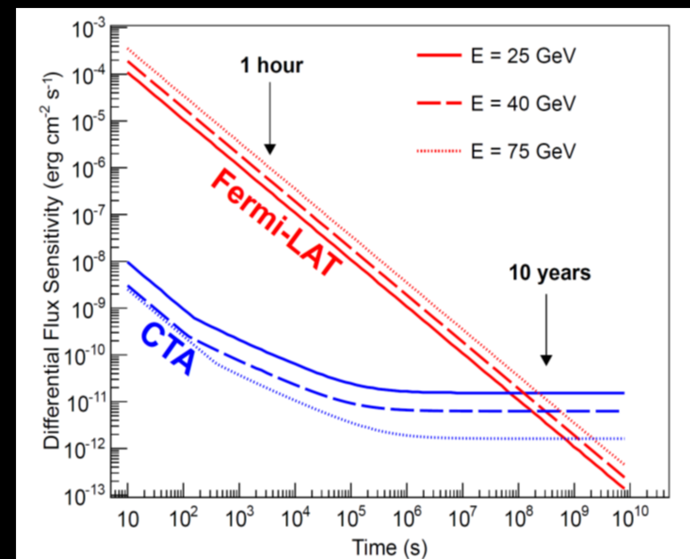
"Isotropic" Contributions
Great statistics, but BG (inc. Galactic diffuse)

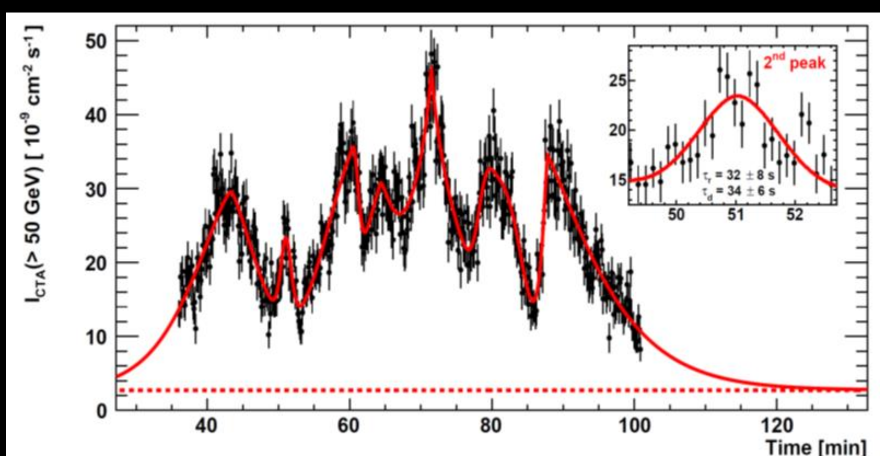
Galaxy Clusters
Low BG, but low statistics

* https://arxiv.org/abs/2403.04857

LIV: Energy-dependent Dispersion



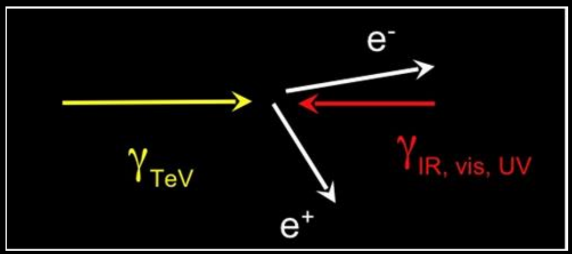




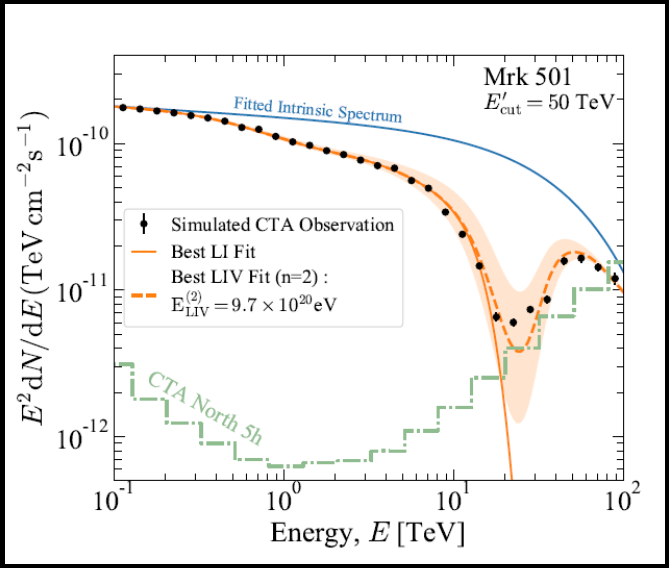
H.E.S.S. measurements of an extremely bright flare from PKS 2155-304 (top). Simulation of CTA measurement of the same flare (below).

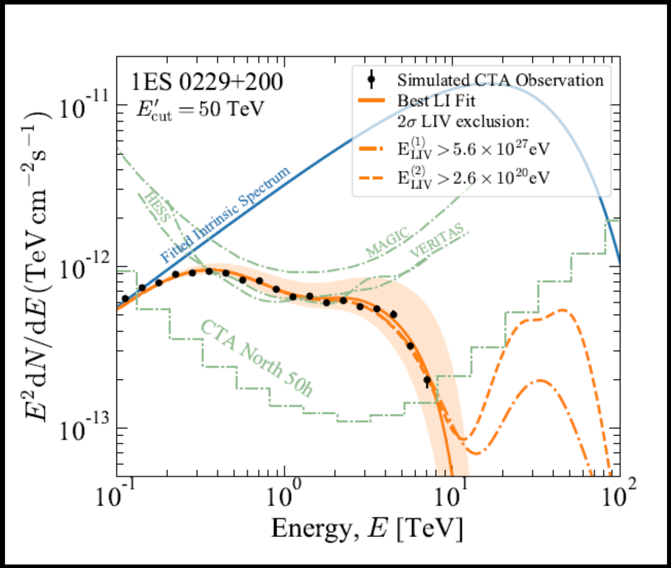
H.E.S.S. Collaboration, PRL 101.170402 (2008)

LIV: modifications to pair-production threshold on EBL



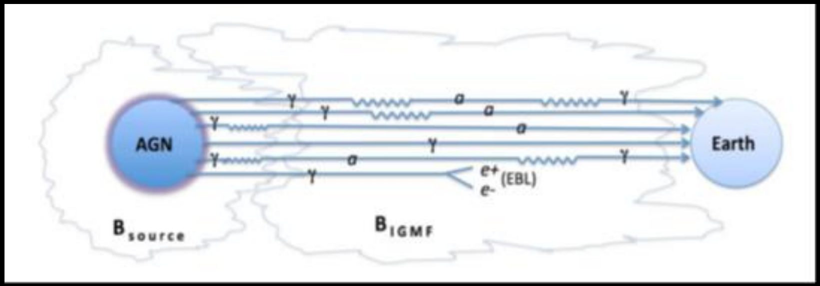
$$\epsilon'_{th} = \frac{m_e^2}{E'_\gamma} + \frac{E'^{\,n+1}_\gamma}{4\left(E^{(n)}_{\rm LIV}\right)^n}.$$

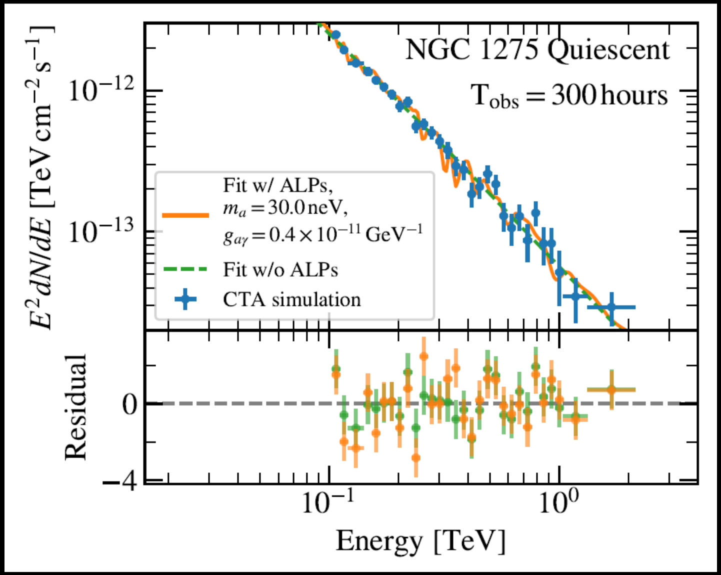




CTA Collaboration, https://arxiv.org/abs/2010.01349

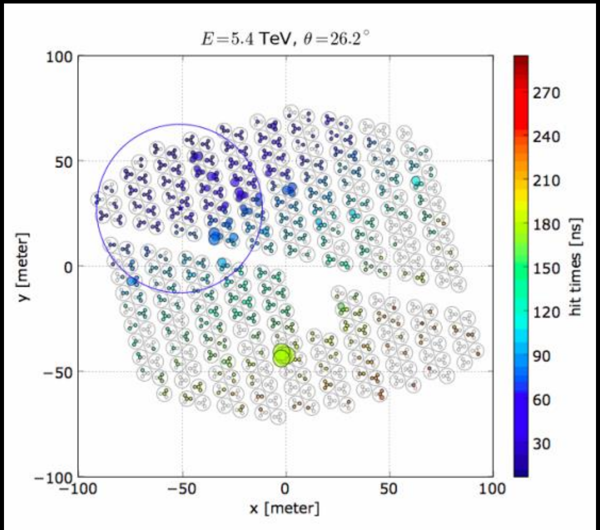
Sensitivity to ALPs

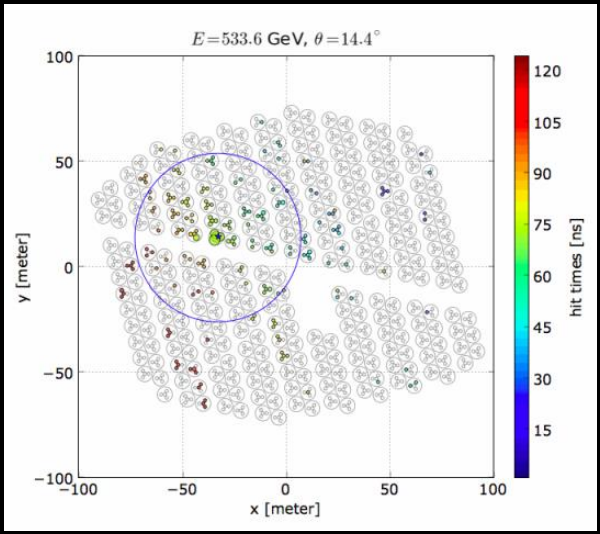




Spectral effects on individual objects likely to be subtle (though detectable). Observation of a statistically significant number of ever more distant objects violating what we know of the EBL likely to be more powerful.

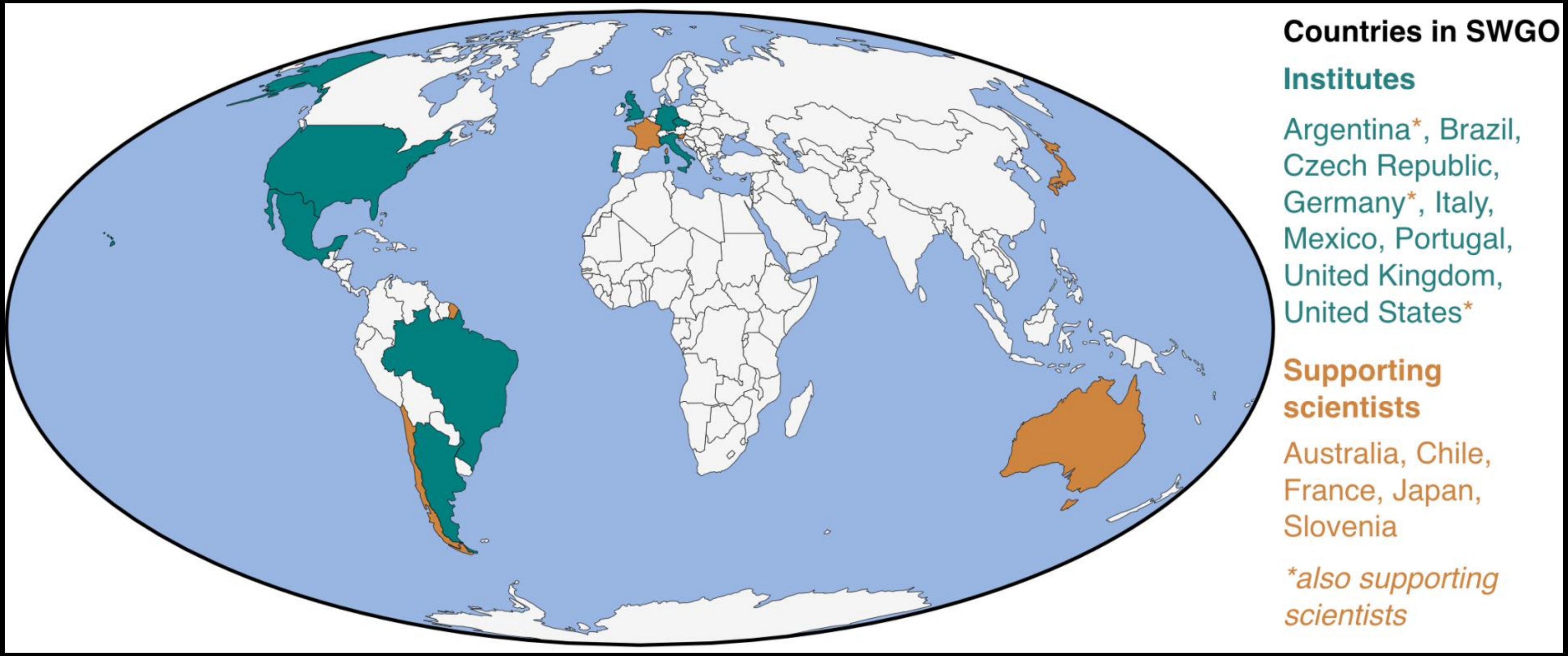
CTA Collaboration: https://arxiv.org/abs/2010.01349





Energy threshold is around 1 TeV, 99% gamma-hadron separation achieved via looking at the spatial and temporal data of the incoming events.

Who’s involved?

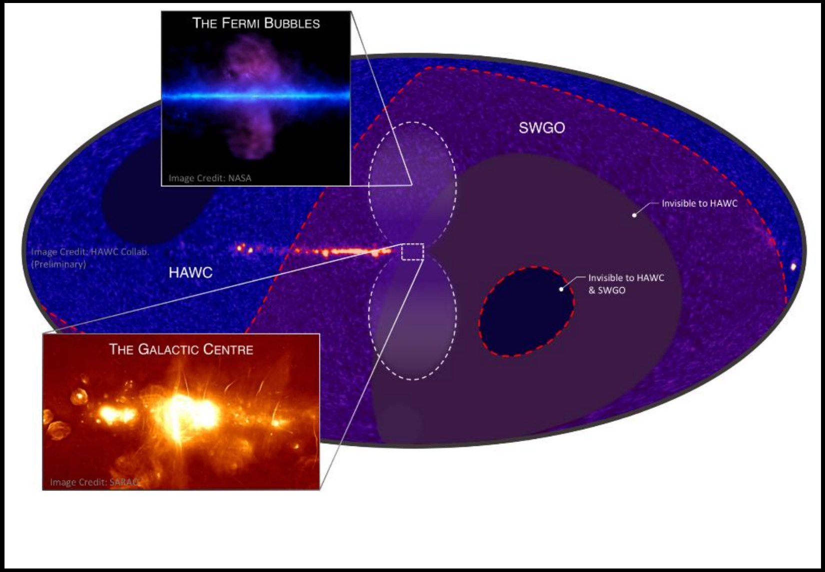


In the UK of course it’s Durham, Leicester, Liverpool and Oxford a.k.a. the CTA-UK hardware team.

Science with SWGO

- Genuinely unbiased survey of the Galactic Plane/Centre
- The Fermi Bubbles
- Transient Objects

BIG advantage for SWGO…



Transients

- Obvious targets:
  - Blazars (a better chance to spot periodicity)
  - Galactic transients (binary systems)
  - Gravitational wave events
  - Gamma-ray bursts (esp. short)

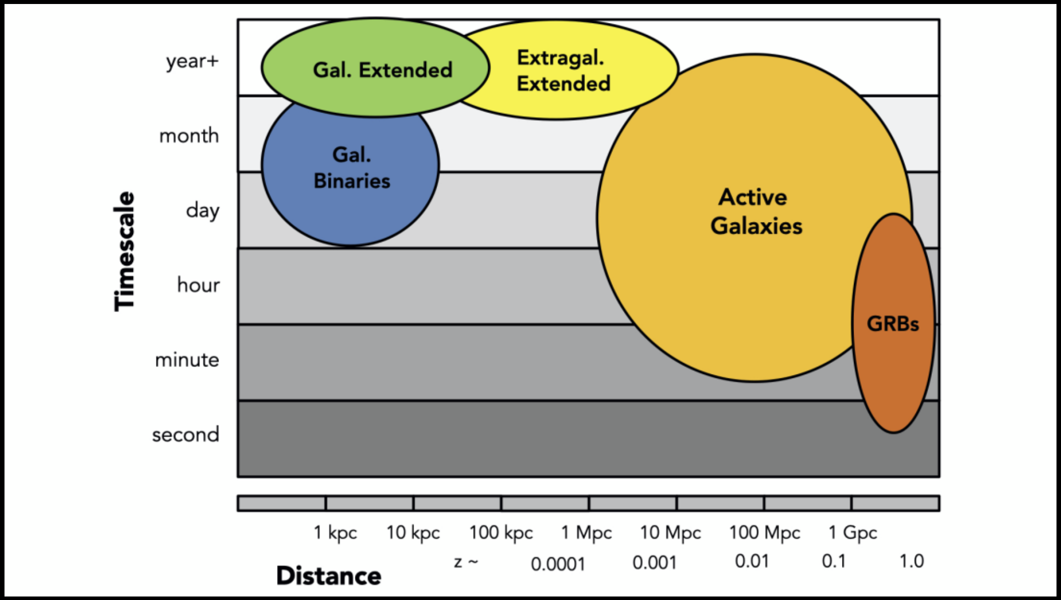


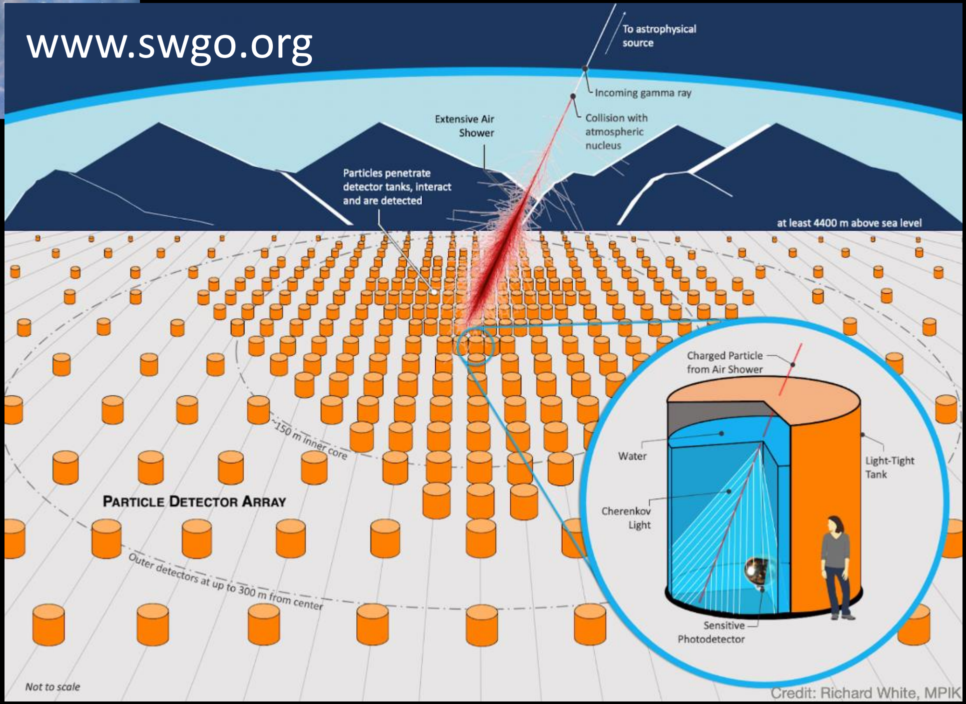
Image: Jim Hinton

Possible (likely) locations

- Somewhere in South America
  - Latitude between 10 and 30 deg. South
  - Altitude at least 4.4 km a.s.l.
- 100s of GeV to 100s of TeV energy range
- Current options:
  - Argentina
  - Bolivia
  - Chile
  - Peru

To keep up with HESS:
https://www.mpi-hd.mpg.de/HESS/

VERITAS:
https://veritas.sao.arizona.edu/



HAWC:
https://www.hawc-observatory.org/

LHAASO:
http://english.ihep.cas.cn/lhaaso/