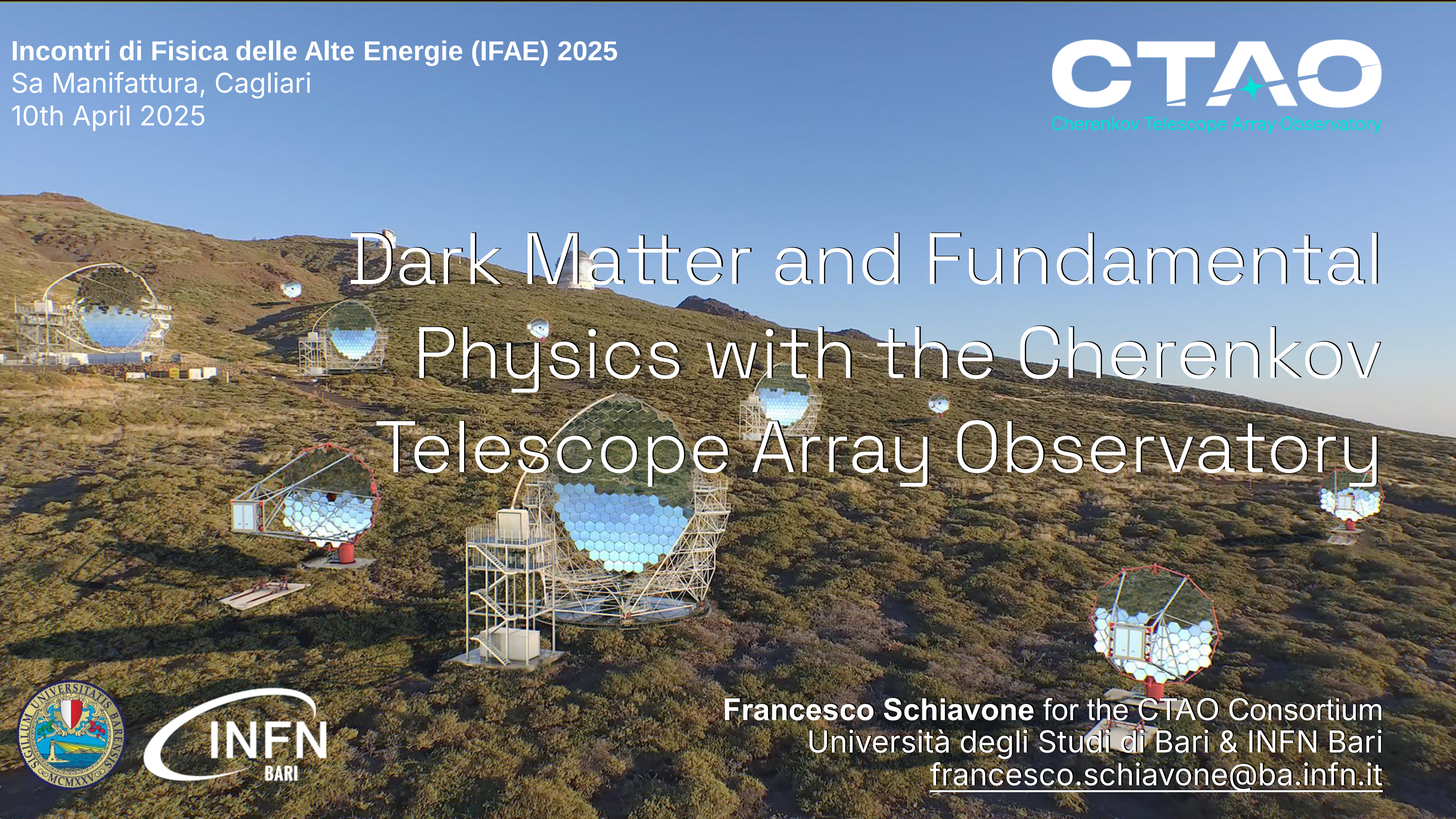


Incontri di Fisica delle Alte Energie (IFAE) 2025
Sa Manifattura, Cagliari
10th April 2025

CTAO
Cherenkov Telescope Array Observatory

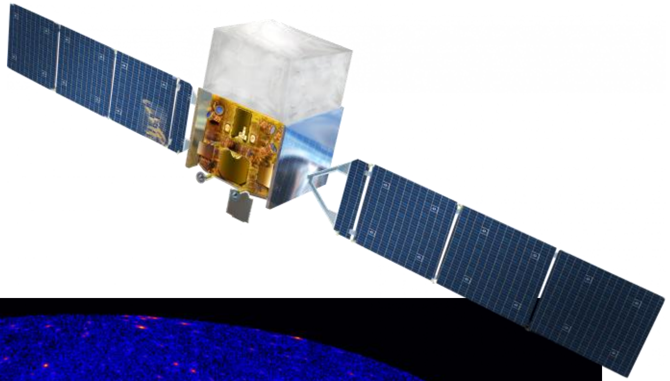
Dark Matter and Fundamental Physics with the Cherenkov Telescope Array Observatory

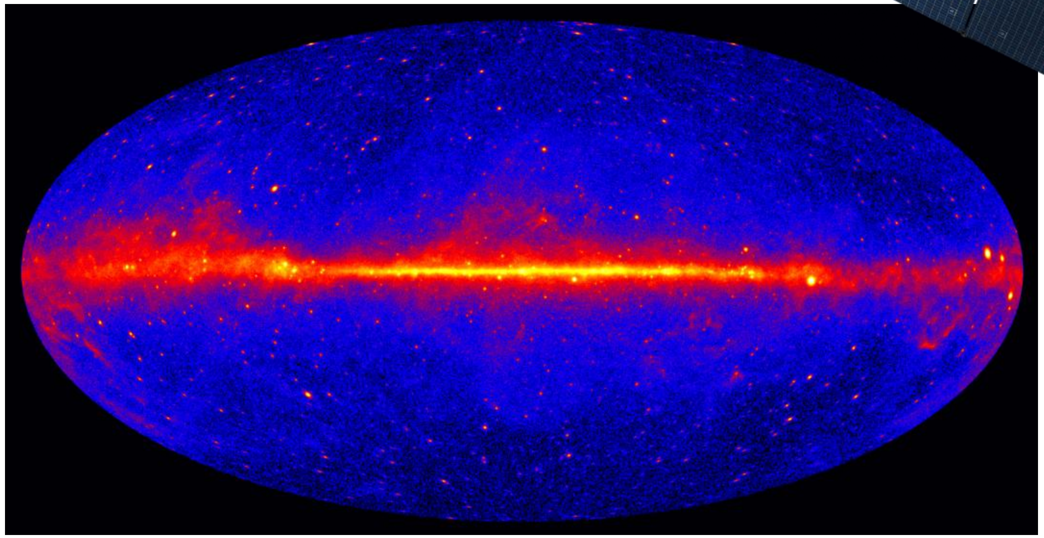
Francesco Schiavone for the CTAO Consortium
Università degli Studi di Bari & INFN Bari
francesco.schiavone@ba.infn.it

INFN BARI

Gamma-ray astrophysics

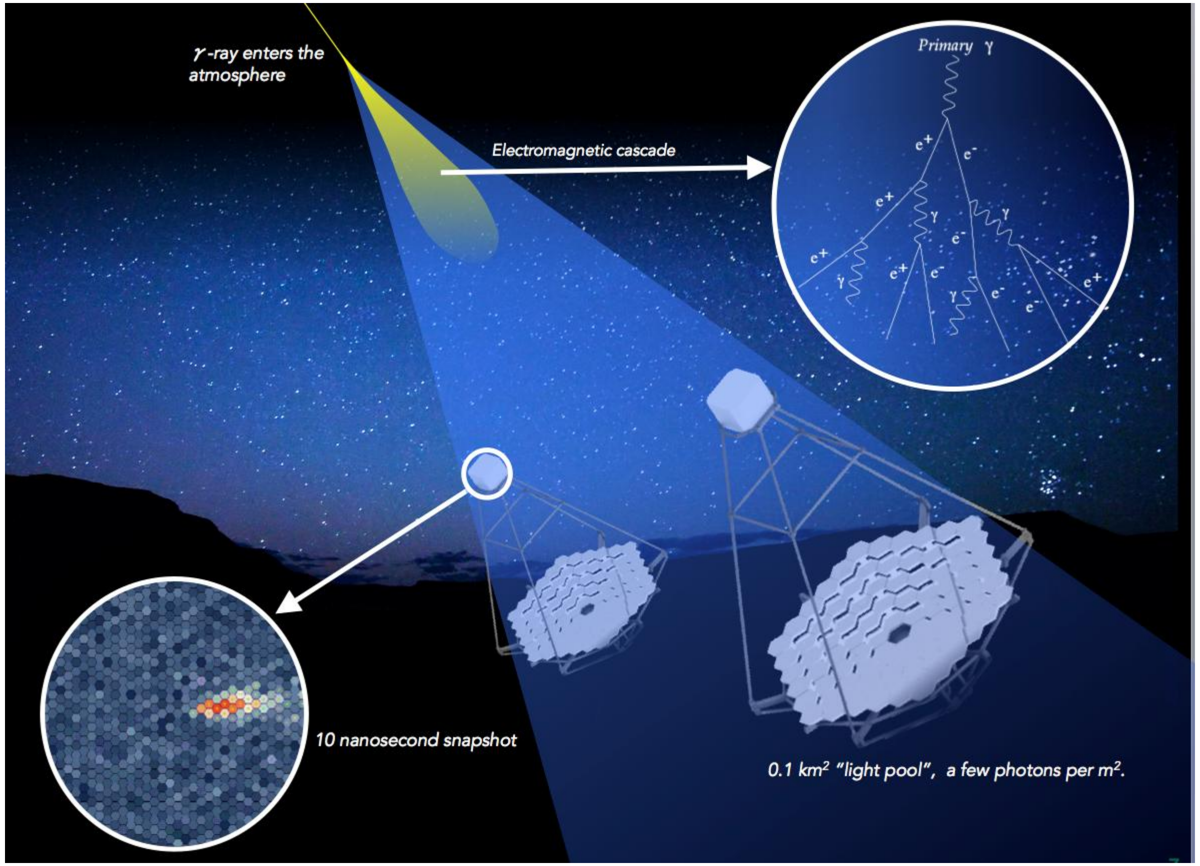
- Aim: characterise the high-energy processes in astrophysical objects (e.g. cosmic ray origin)
- Problem: gamma rays are (luckily for us!) absorbed by the Earth's atmosphere
- Solution: satellite-based telescopes (e.g. Fermi-LAT, AGILE)
- Results: excellent, but limited by effective area for photons above few hundreds GeV





Imaging atmospheric Cherenkov telescopes (IACTs)

- Gamma-rays detected from measurements of Cherenkov light emitted by EM showers
- Atmosphere used as a natural calorimeter
- Effective area ~ size of «light pool», $10^4\ \mathrm{m}^2$
- Sensitivity up to tens or hundreds of TeV



Credit: CTAO

Currently operating IACTs

Daniel López / Instituto de Astrofísica de Canarias

H.E.S.S. collaboration, Clementina Medina

https://veritas.sao.arizona.edu/about-veritas

MAGIC
Observatorio del Roque de Los Muchachos, La Palma (ES)
2 × 17 m reflectors

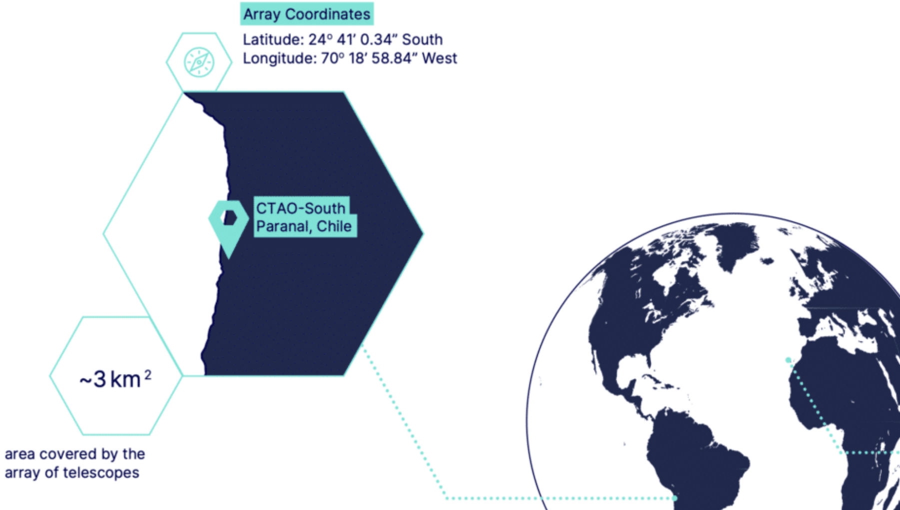
H.E.S.S.
Khomas highlands (NA)
4 × 12 m, 1 × 28 m reflectors

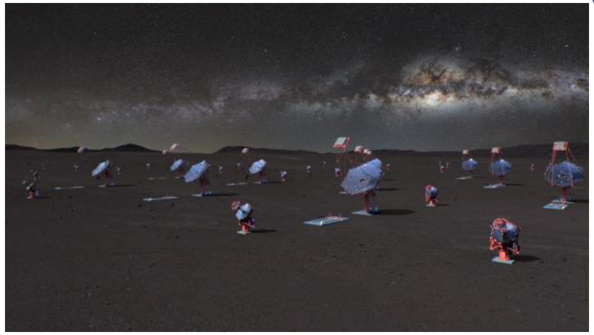
VERITAS
Fred Lawrence Whipple Observatory, Arizona (US)
4 × 12 m reflectors

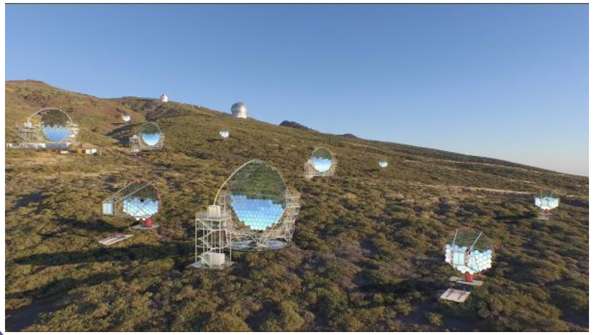
CTAO

Cherenkov Telescope Array Observatory

- Next-generation gamma observatory
- 2 arrays planned in the Northern and Southern hemispheres
- ~70 telescopes total
- Better energy and spatial resolution, faster time response to transients, full sky coverage
- 20 GeV to 300 TeV sensitivity

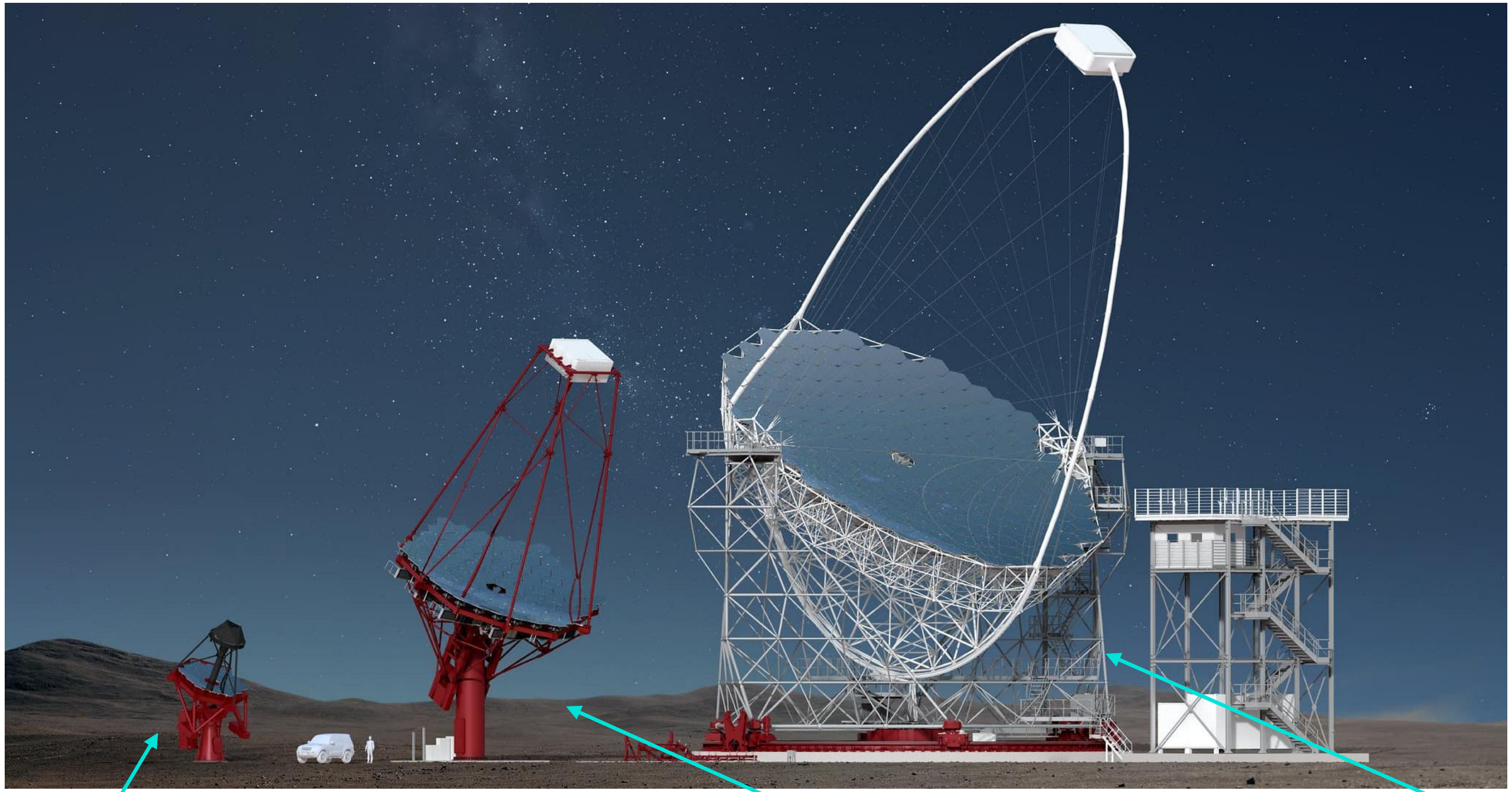






https://www.ctao.org/emission-to-discovery/array-sites/

CTAO telescopes



Working prototypes:
- LST-1 (La Palma)
- MST prototype (Berlin)
- ASTRI-Horn/SST-2M (Catania)
- ASTRI-1 (Tenerife)
- SST-1M (Prague)

+ Schwarzschild-Couder Telescope prototype (pSCT) in Arizona, US

Small-Sized Telescope (SST)
4.3 m primary reflector
9° FoV
5 to 300 TeV sensitivity

Medium-Sized Telescope (MST)
12 m reflector
8° FoV
150 GeV to 5 TeV sensitivity

Large-Sized Telescope (LST)
23 m reflector
4.3° FoV
20 GeV to 150 GeV sensitivity

https://www.ctao.org/emission-to-discovery/telescopes/

CTAO Key Science Projects

- CTAO will operate as an open gamma-ray observatory
- In its first 10 years, 40% of observational time will be devoted to various Key Science Projects (KSPs)
- Significant amount of time dedicated to dark matter and fundamental/exotic physics (DMEP) studies
- This interest is also shown in many of the recently published CTAO Consortium papers

Theme		Question	Dark Matter Programme	Galactic Centre Survey	Galactic Plane Survey	LMC Survey	Extra-galactic Survey	Transients	Cosmic Ray PeVatrons	Star-forming Systems	Active Galactic Nuclei	Galaxy Clusters
Understanding the Origin and Role of Relativistic Cosmic Particles	1.1	What are the sites of high-energy particle acceleration in the universe?		✔	✔✔	✔✔	✔✔	✔✔	✔	✔	✔	✔✔
	1.2	What are the mechanisms for cosmic particle acceleration?		✔	✔	✔		✔✔	✔✔	✔	✔✔	✔
	1.3	What role do accelerated particles play in feedback on star formation and galaxy evolution?		✔		✔				✔✔	✔	✔
Probing Extreme Environments	2.1	What physical processes are at work close to neutron stars and black holes?		✔	✔	✔			✔✔		✔✔	
	2.2	What are the characteristics of relativistic jets, winds and explosions?		✔	✔	✔	✔	✔✔	✔✔		✔✔	
	2.3	How intense are radiation fields and magnetic fields in cosmic voids, and how do these evolve over cosmic time?					✔	✔			✔✔	
Exploring Frontiers in Physics	3.1	What is the nature of Dark Matter? How is it distributed?	✔✔	✔✔		✔						✔
	3.2	Are there quantum gravitational effects on photon propagation?						✔✔	✔		✔✔	
	3.3	Do Axion-like particles exist?					✔	✔			✔✔	

Science with the Cherenkov Telescope Array [arXiv:1709.07997]

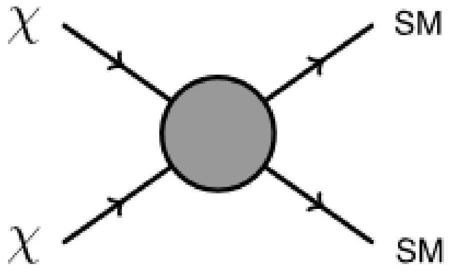
Theme		Question	Dark Matter Programme	Galactic Centre Survey	Galactic Plane Survey	LMC Survey	Extra-galactic Survey	Transients	Cosmic Ray PeVatrons	Star-forming Systems	Active Galactic Nuclei	Galaxy Clusters
Understanding the Origin and Role of Relativistic Cosmic Particles	1.1	What are the sites of high-energy particle acceleration in the universe?		✔	✔✔	✔✔	✔✔	✔✔	✔	✔	✔	✔✔
	1.2	What are the mechanisms for cosmic particle acceleration?		✔	✔	✔		✔✔	✔✔	✔	✔✔	✔
	1.3	What role do accelerated particles play in feedback on star formation and galaxy evolution?		✔		✔				✔✔	✔	✔
Probing Extreme Environments	2.1	What physical processes are at work close to neutron stars and black holes?		✔	✔	✔			✔✔		✔✔	
	2.2	What are the characteristics of relativistic jets, winds and explosions?		✔	✔	✔	✔	✔✔	✔✔		✔✔	
	2.3	How intense are radiation fields and magnetic fields in cosmic voids, and how do these evolve over cosmic time?					✔	✔			✔✔	
Exploring Frontiers in Physics	3.1	What is the nature of Dark Matter? How is it distributed?	✔✔	✔✔		✔						✔
	3.2	Are there quantum gravitational effects on photon propagation?						✔✔	✔		✔✔	
	3.3	Do Axion-like particles exist?					✔	✔			✔✔	

Science with the Cherenkov Telescope Array [arXiv:1709.07997]

Dark matter indirect detection

The WIMP hypothesis

- DM is made up by weakly interacting massive particles (WIMPs) whose abundance sets in via *freeze-out*

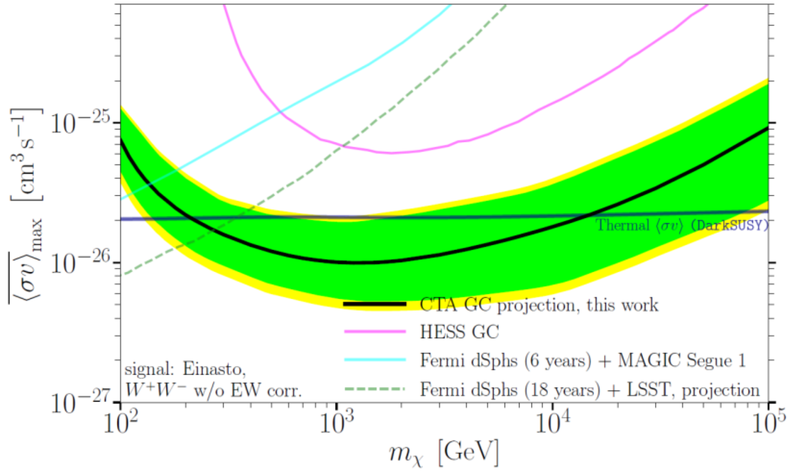


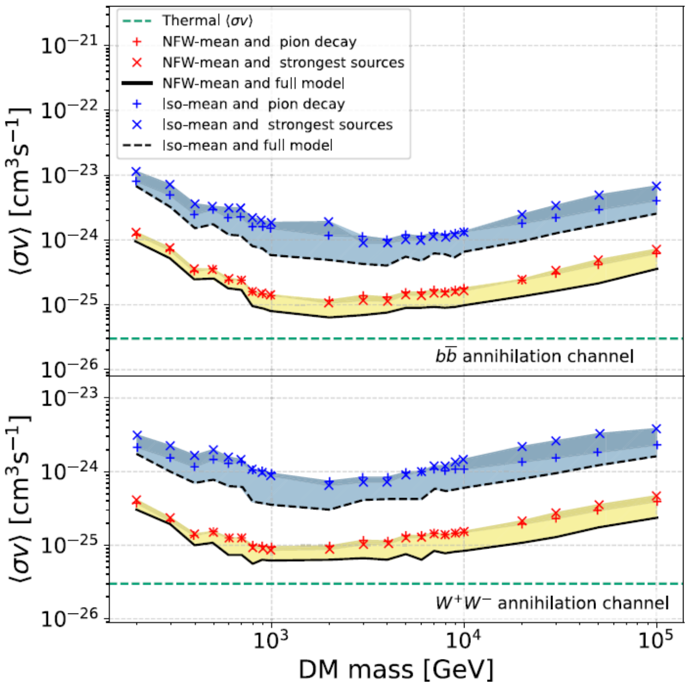
- Benchmark value for annihilation cross-section into Standard Model particles: $\langle \sigma v \rangle = 3 \times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$ («WIMP miracle»)

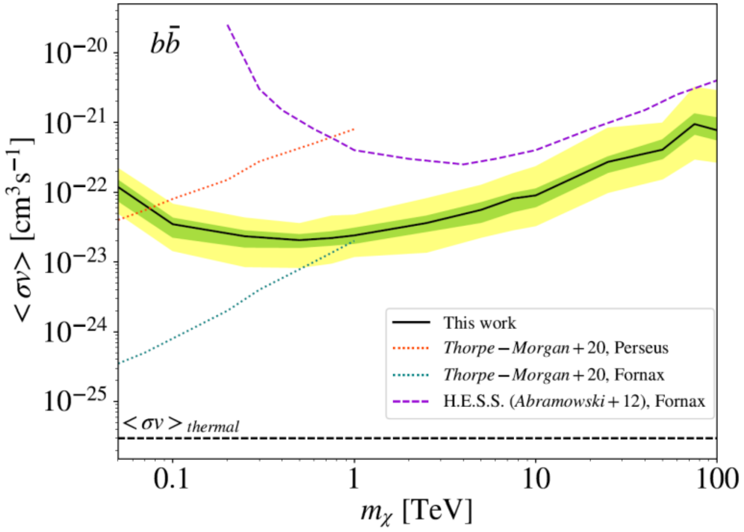
Candidate targets for searches

- Galactic Centre (GC) of the Milky Way – strong signal but large background
- Large Magellanic Cloud (LMC) – intermediate signal and background
- Perseus Galaxy Cluster – intermediate signal and background
- Dwarf spheroidal galaxies (dSphs) – weak but distinct signal, almost no background

Estimated DM sensitivity (diffuse)





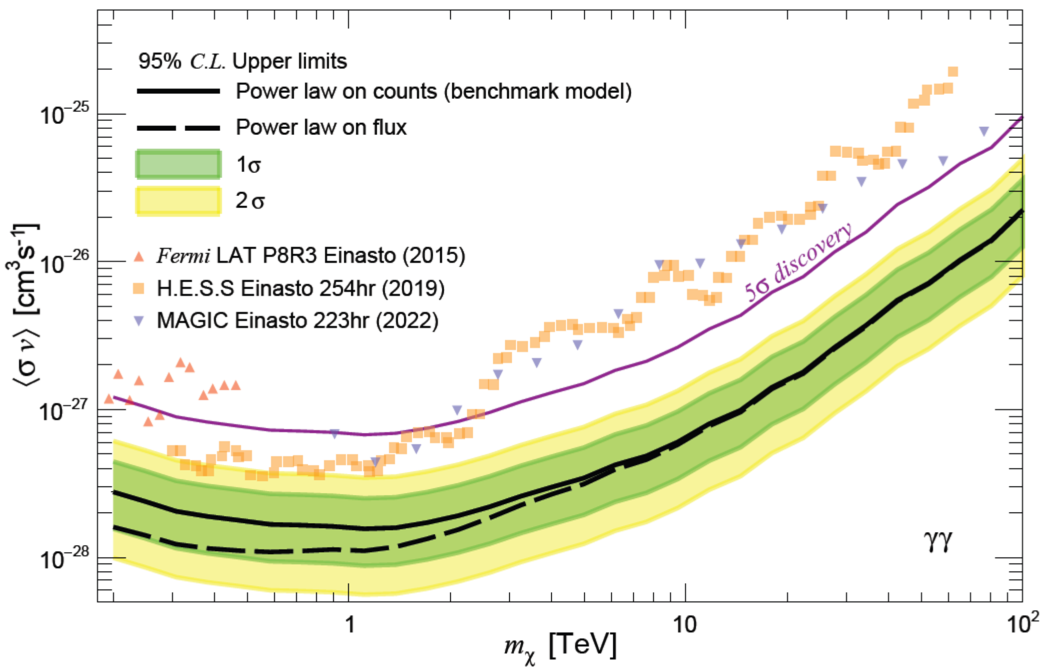


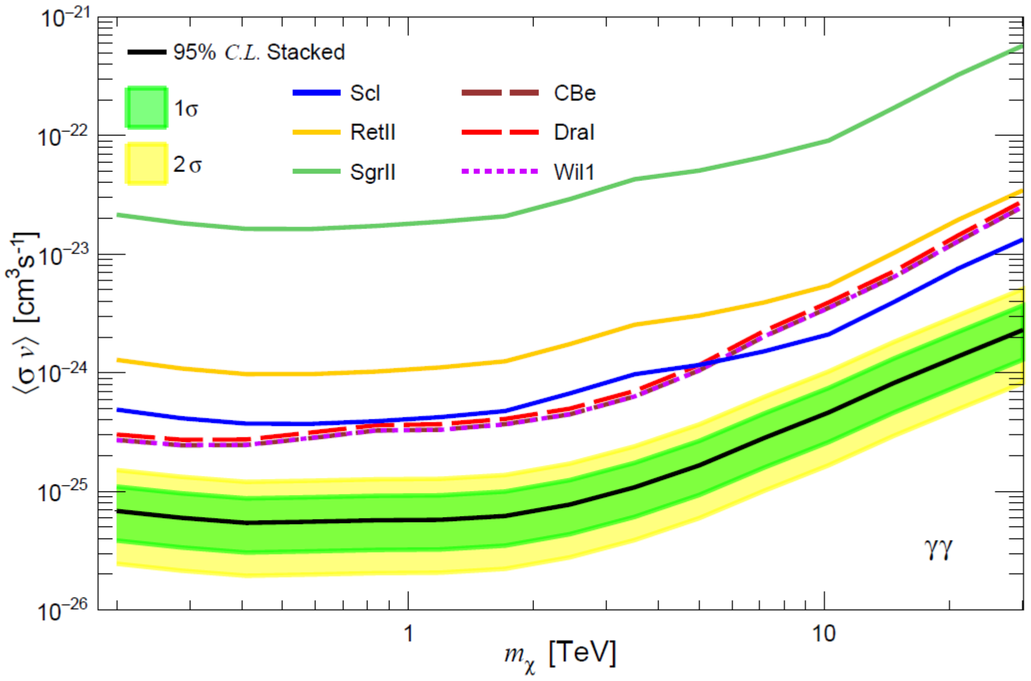
Galactic Centre
525 h (center) + 300 h (extended)
Channel $\chi\chi \rightarrow W^+W^-$
Ref: JCAP01(2021)057

Large Magellanic Cloud
340 h
Channels $\chi\chi \rightarrow b\bar{b}, W^+W^-$
Ref: *MNRAS* 523, 4 (2023), 5353

Perseus Galaxy Cluster
300 h
Channel $\chi\chi \rightarrow b\bar{b}$
Ref: JCAP10(2024)004

Estimated DM sensitivity (lines)





Galactic Centre and dwarf spheroidal galaxies

500 h (GC)

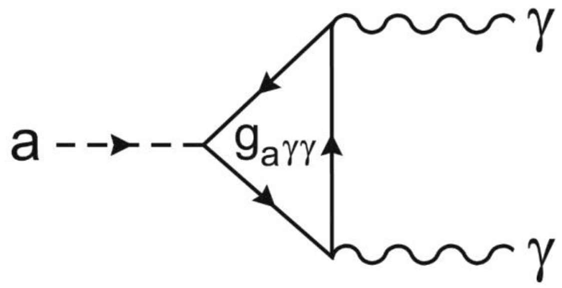
100 h per target (dSphs)

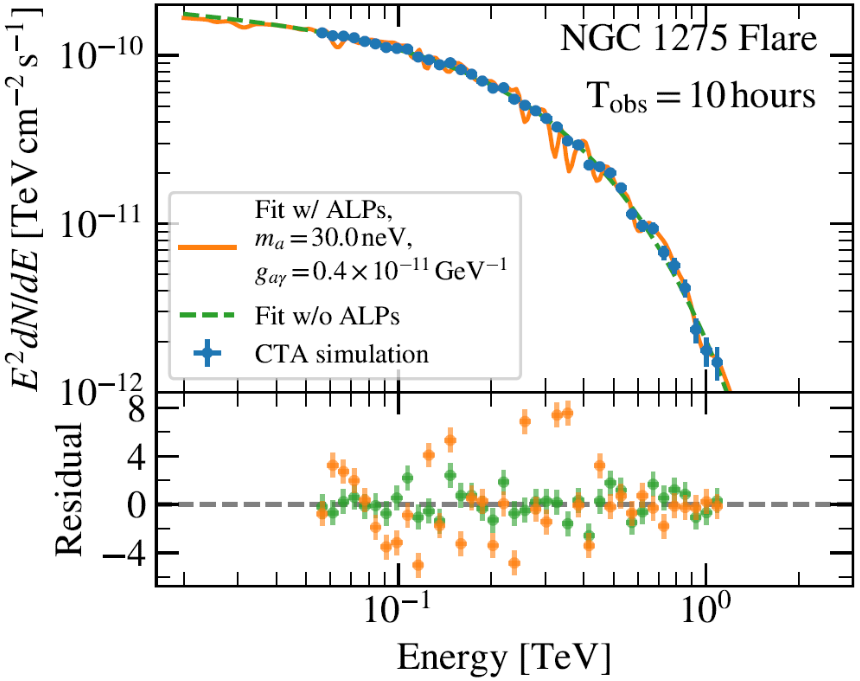
Search for monochromatic spectral lines

Ref: JCAP07(2024)047

Axion-like particles (ALPs)

- Hypothetical, pseudo-scalar particles with mass m_a and coupling to photons $g_{a\gamma}$, potential dark matter candidates
- The $g_{a\gamma}$ coupling allows for ALP-gamma oscillations in magnetic fields
- The following modification on photon propagation would leave imprints on observed gamma-ray spectra

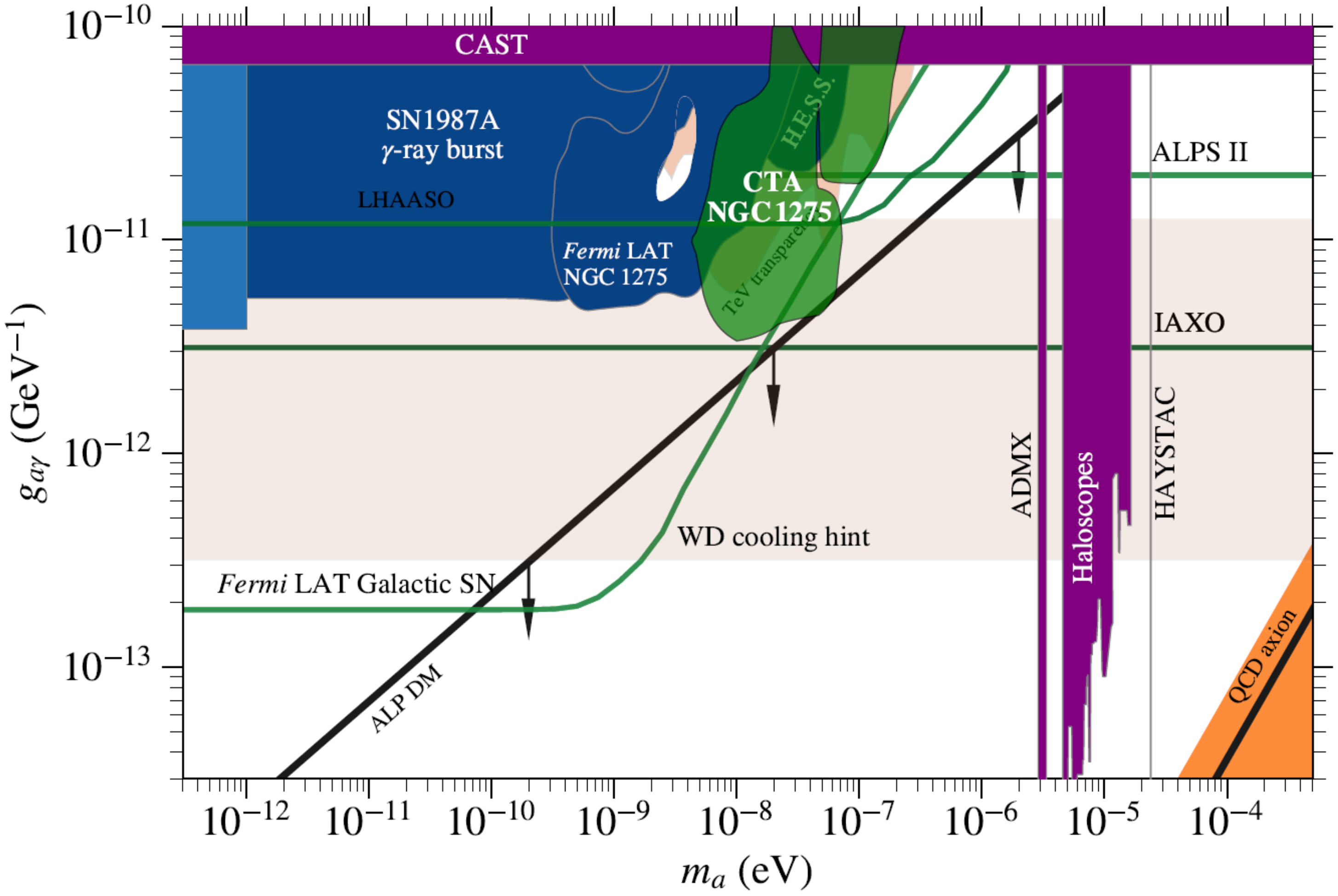




Candidate targets for searches

- Active galactic nuclei (AGNs) – cosmological distances and magnetized environments

Estimated ALP sensitivity

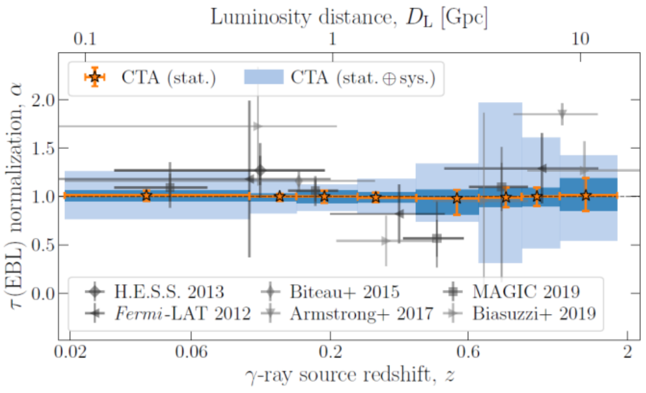


NGC 1275 inside Perseus Galaxy Cluster
10 h flaring state
Ref: JCAP02(2021)048

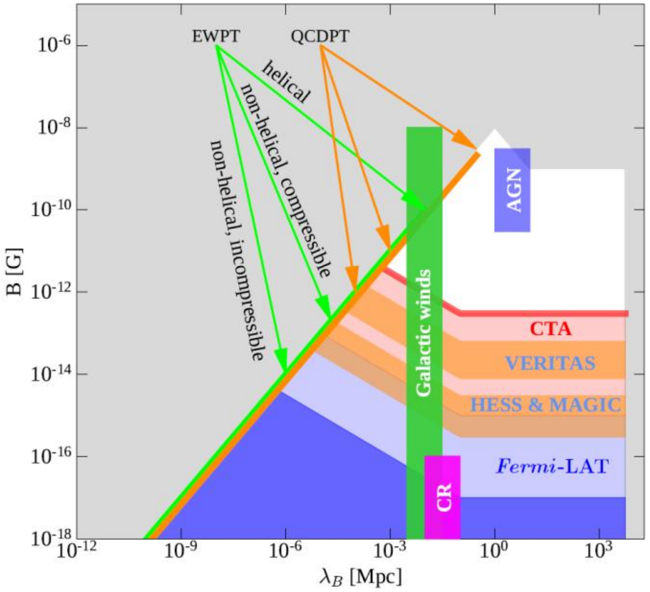
... many more targets to explore!

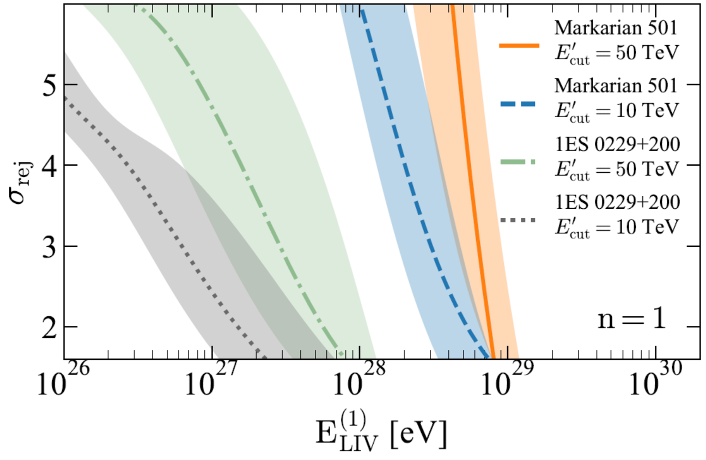
More fundamental physics from AGNs

- Extragalactic background light (EBL)
- Intergalactic magnetic field (IGMF)
- Lorentz invariance violation (LIV)
- …



Ref: [JCAP02(2021)048]()





Conclusions

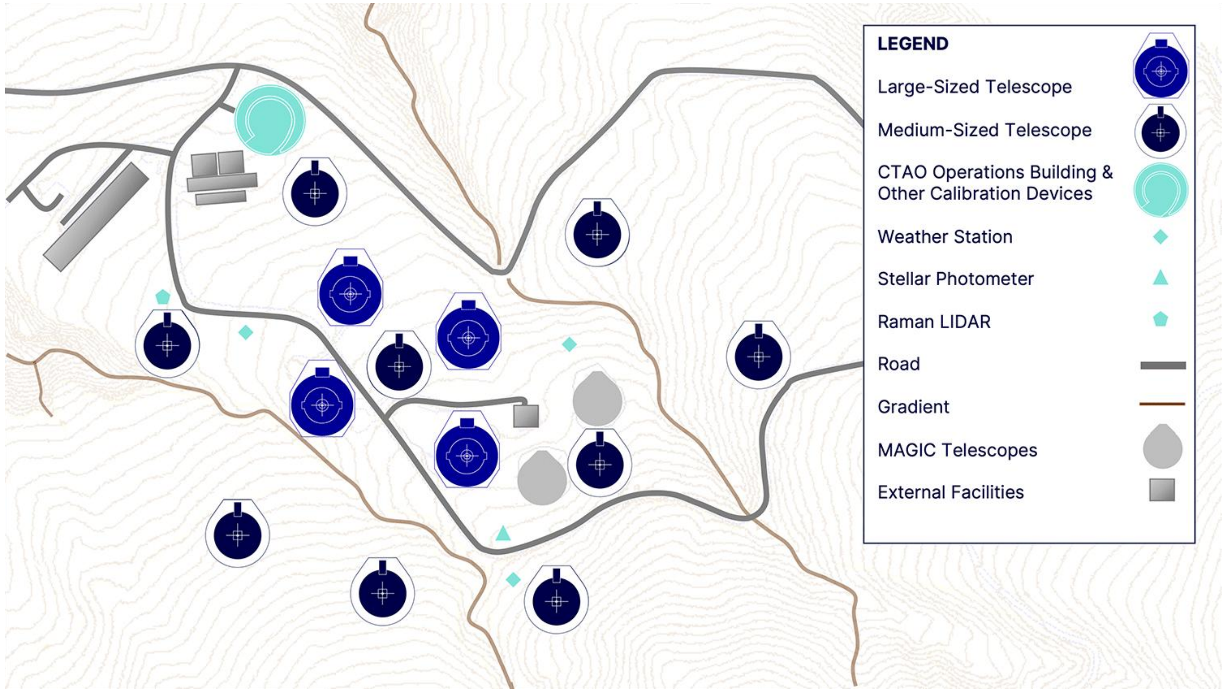
- CTAO will considerably improve upon every aspect of current IACT performance
- Dark matter searches in particular will play an important role in the definition of its scientific programme
- Similarly, it will be possible to study several fundamental and exotic physics scenarios in gamma-ray cosmology
- Many exciting advancements to be expected!

Thank you for your attention!

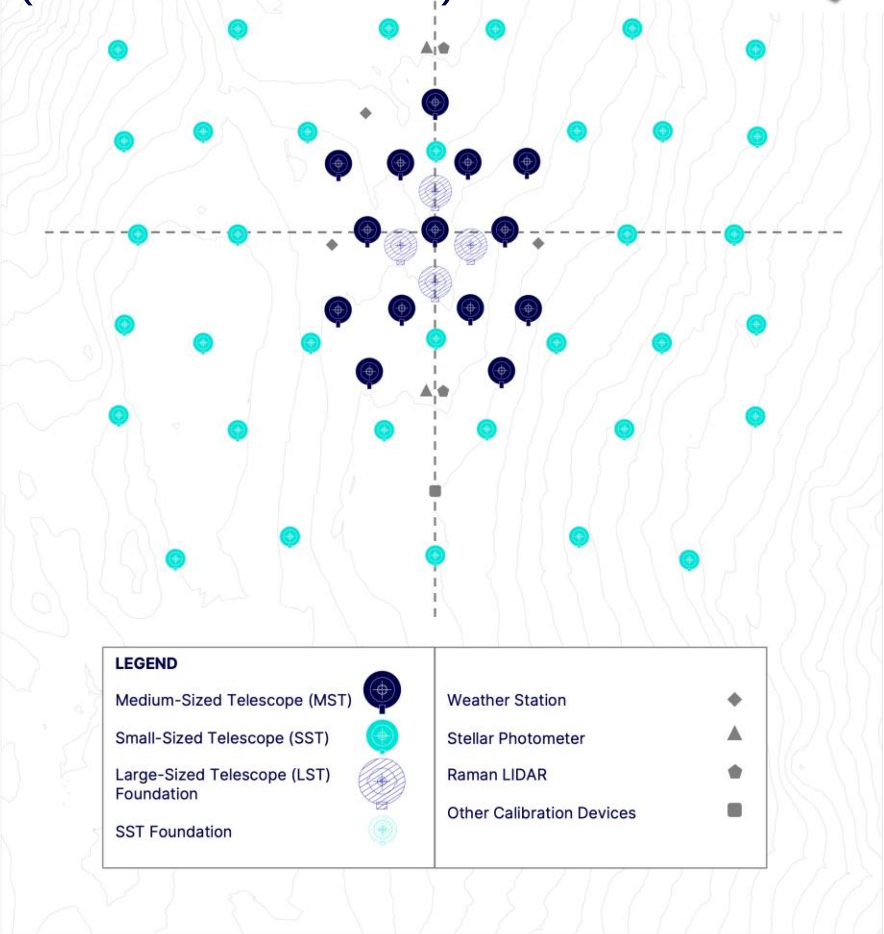
Backup

Planned CTAO «Alpha» configuration

Northern Array (La Palma, ES)
4 LSTs + 9 MSTs



Southern Array (Paranal, CL)
14 MSTs + 37 SSTs
(+ 2 LSTs + 5 SSTs)



Expected dark matter signal

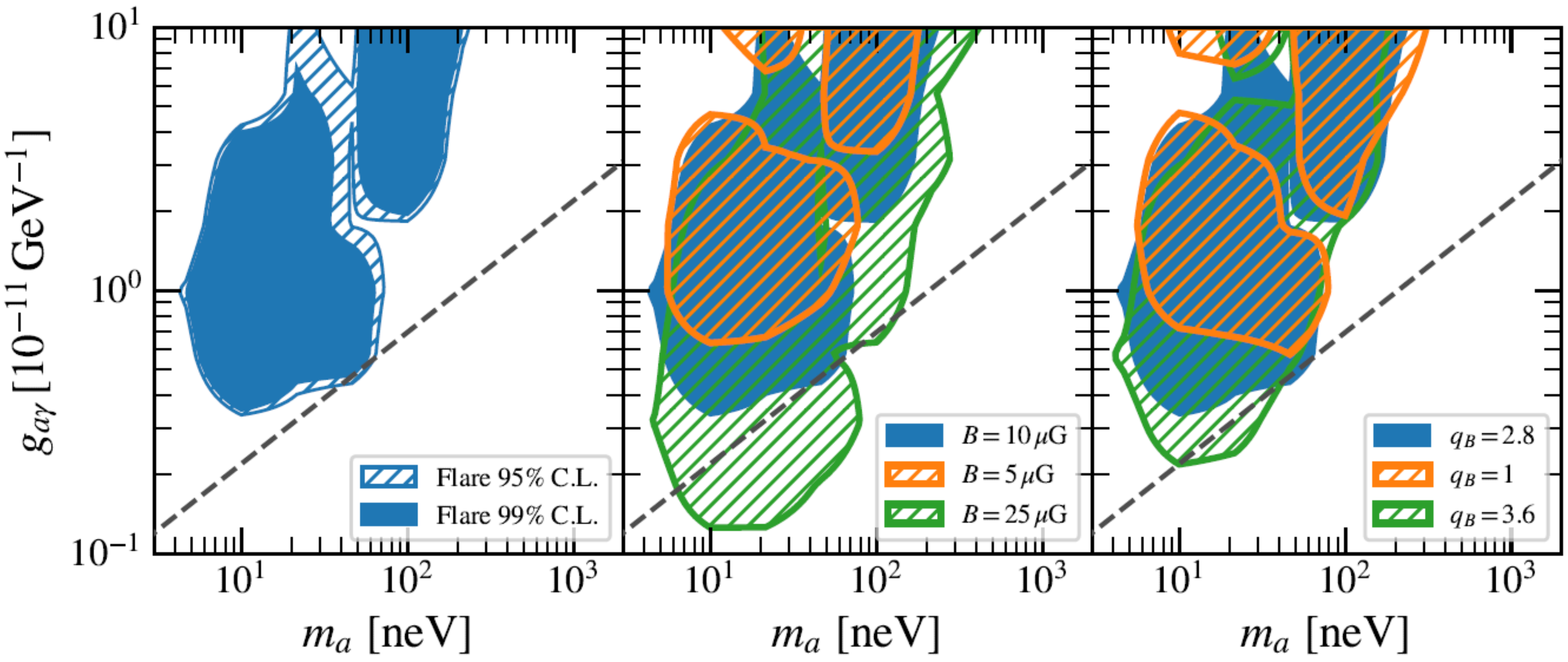
$$\frac{\mathrm{d}\Phi}{\mathrm{d}E} = \underbrace{\frac{1}{8\pi}\frac{\langle\sigma v\rangle}{m_\chi^2}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E}}_{\text{Particle physics factor}} \underbrace{\int_{\Delta\Omega}\int_{\mathrm{l.o.s}} \rho^2(\ell)\,\mathrm{d}\ell}_{\text{Astrophysical factor (J-factor)}}$$

Particle physics factor

- diffuse
- monochromatic line
- box-shaped
- …

Astrophysical factor
(J-factor)

Estimated ALP sensitivity

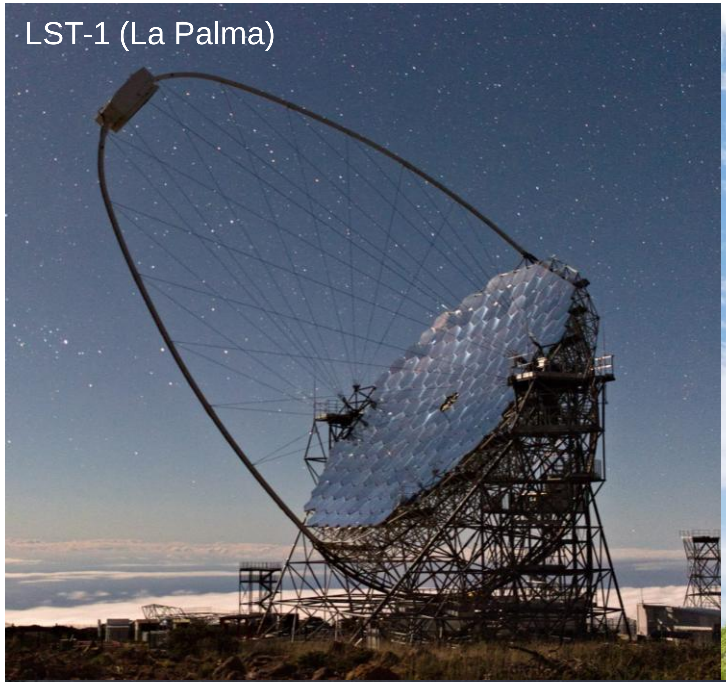


NGC 1275 inside Perseus Galaxy Cluster
10 h flaring state
Ref: JCAP02(2021)048

… many more targets to explore!

CTAO telescope prototypes

https://www.ctao.org/emission-to-discovery/telescopes/mst/


LST-1 (La Palma)


MST prototype (Berlin)


pSCT (Arizona)


SST-1M (Prague)

https://jointlab.upol.cz/jlo/en/content/sst-1m-captured-first-light-ondrejov-observatory


ASTRI-Horn/SST-2M (Catania)

http://www.inaf.it/en/inaf-news/astri-telescope-2020-vision


ASTRI-1 (Tenerife)

Daniel López / Instituto de Astrofísica de Canarias