CTAO
Cherenkov Telescope Array Observatory

SDU

erc

The Science Potential of the Cherenkov Telescope Array Observatory

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On behalf of the CTAO Consortium
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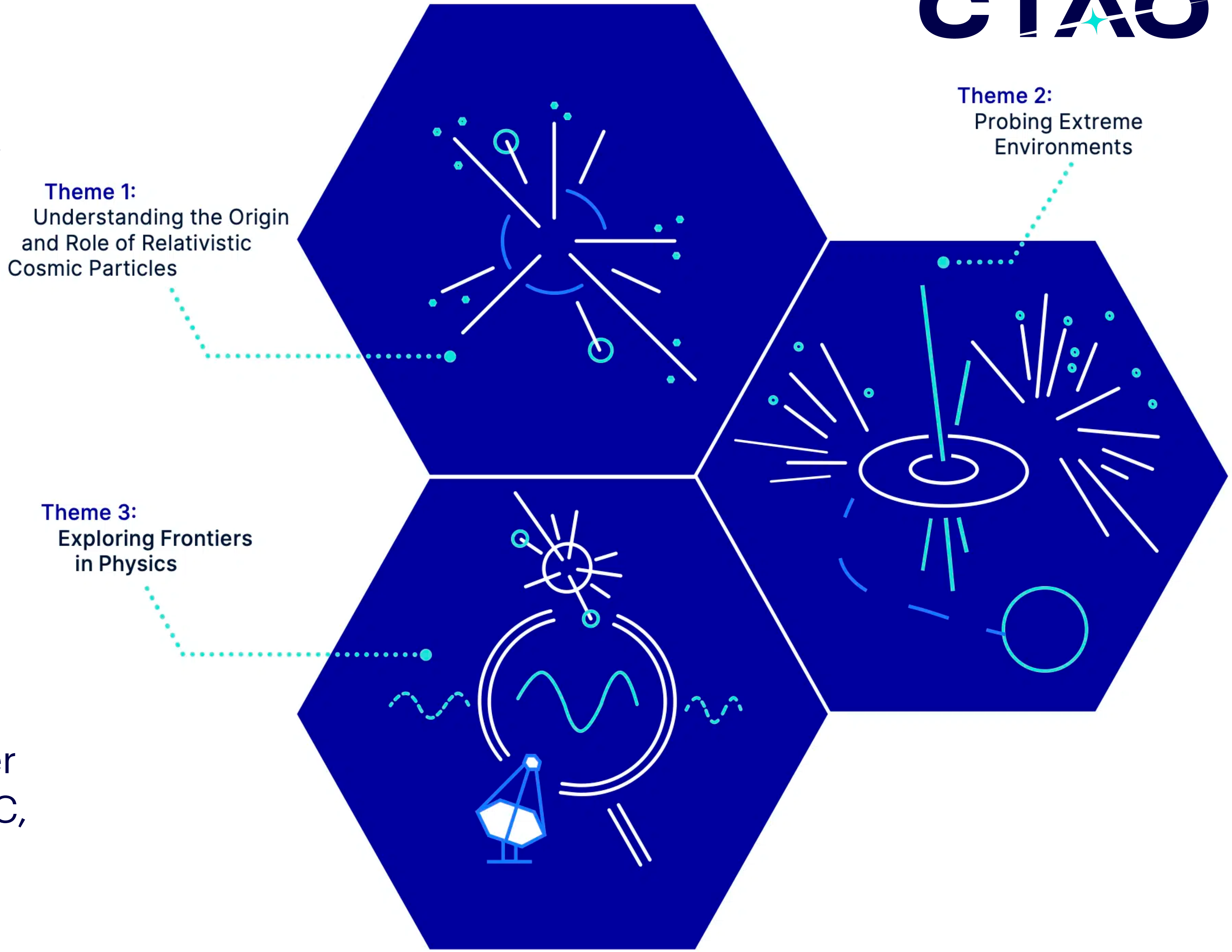
Outline

1. Status of CTAO
2. Recent Results for Sensitivity Projections for CTAO
   a. Galactic Science
   b. Extragalactic Science
   c. Fundamental Physics

The Cherenkov Telescope Array Observatory

- An astrophysics and particle physics scientific tool
- Observes the most extreme highest energy sources in the universe
- Builds on the success of smaller existing arrays - H.E.S.S., MAGIC, and VERITAS



[Slide adapted from Stuart McMuldroch]

The CTAO Consortium

- More than 1400 scientists
- ~ 200 institutes
- 25 countries on 6 continents

CTAO locations

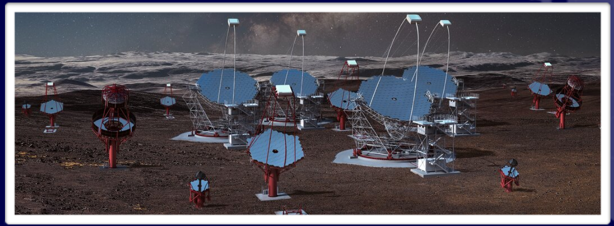

CTAO SDMC in Zeuthen, Germany (Credit: DESY)

Berlin — Science Data Management Center

La Palma
Northern Site

Bologna — Headquarters

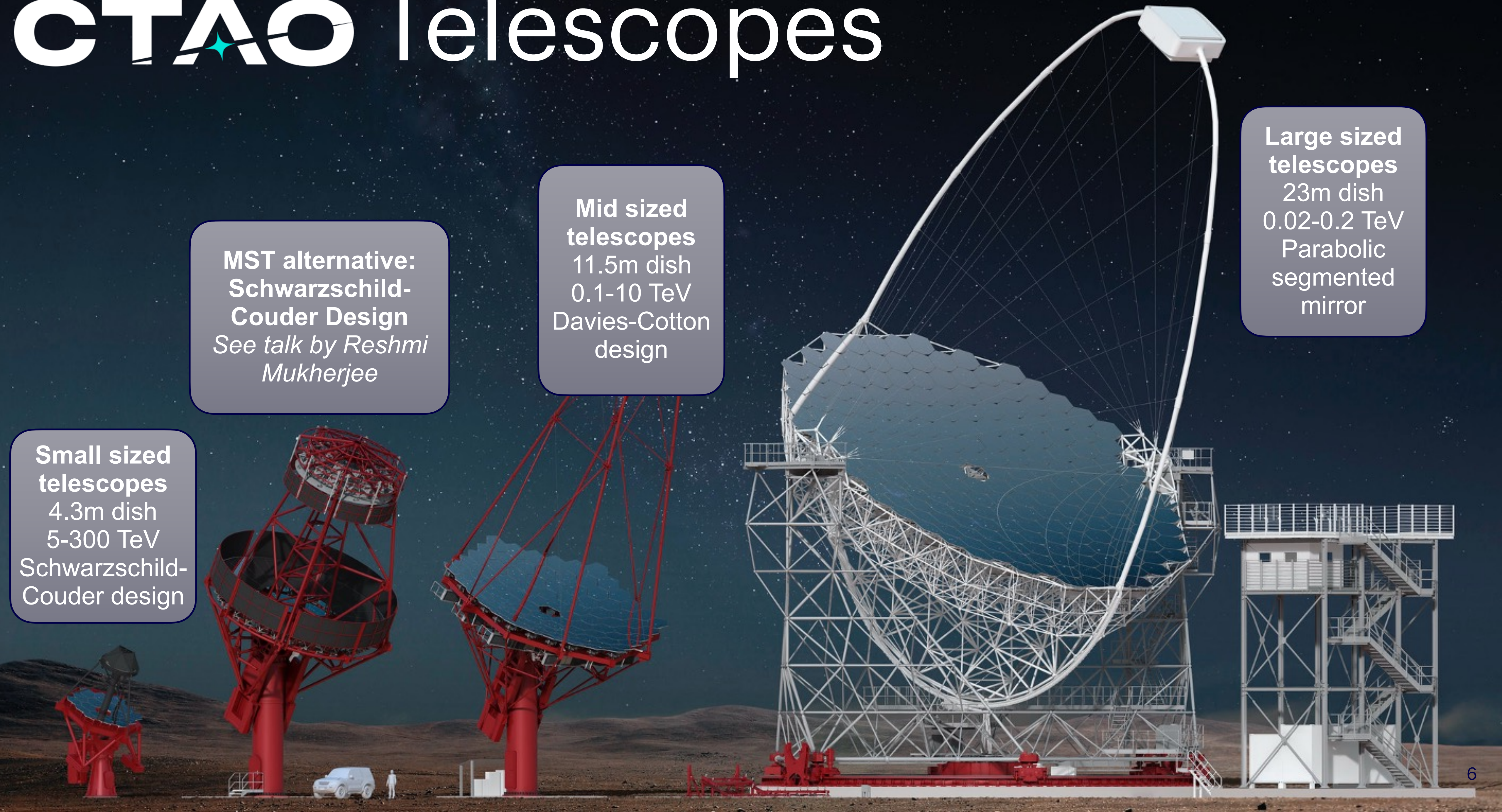

CTAO Headquarters in Bologna, Italy (Credit: Bologna Today)



Chile
Southern (ESO) Site

[map shows formal participants only]

CTAO Telescopes



Small sized telescopes
4.3m dish
5-300 TeV
Schwarzschild-Couder design

MST alternative: Schwarzschild-Couder Design
See talk by Reshmi Mukherjee

Mid sized telescopes
11.5m dish
0.1-10 TeV
Davies-Cotton design

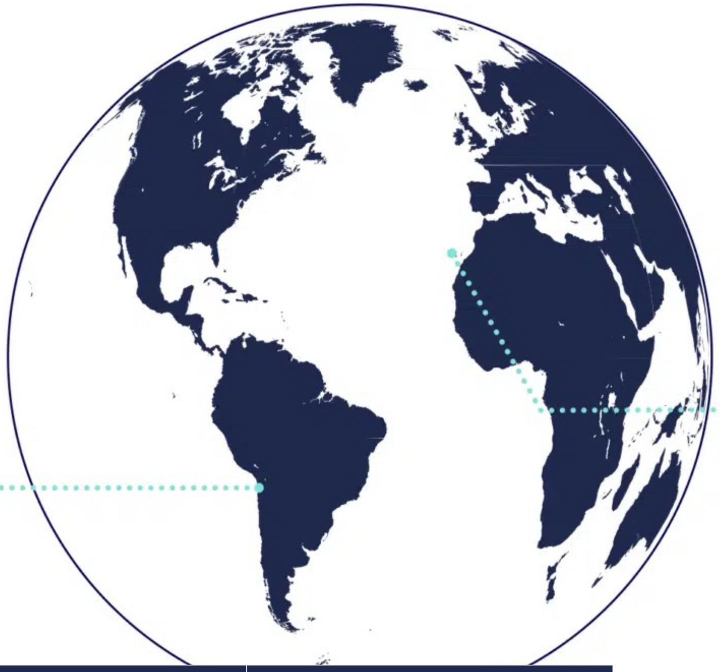
Large sized telescopes
23m dish
0.02-0.2 TeV
Parabolic segmented mirror

Array sites

Array Coordinates
Latitude: 24° 41′ 0.34″ South
Longitude: 70° 18′ 58.84″ West

~3 km²

area covered by the array of telescopes



~0.25 km²

area covered by the array of telescopes

Array Coordinates
Latitude: 28° 45′ 43.7904″ North
Longitude: 17° 53′ 31.218″ West

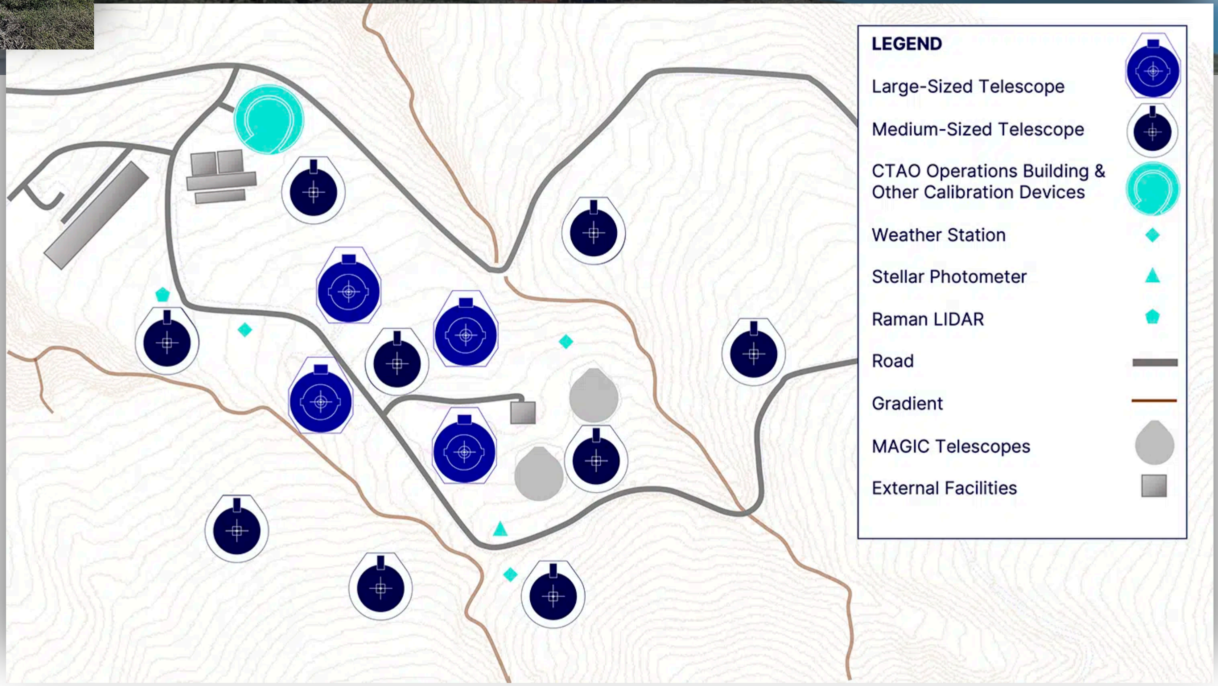
ALPHA CONFIGURATION	No. North	No. South	Energy Range (TeV)
Large Sized Telescopes	4	—	0.02-0.2
Mid Sized Telescopes	9	14	0.1-10
Small Sized Telescopes	—	37	5-300

Northern Array Site

CTAO

[Slide adapted from Stuart McMuldroch]

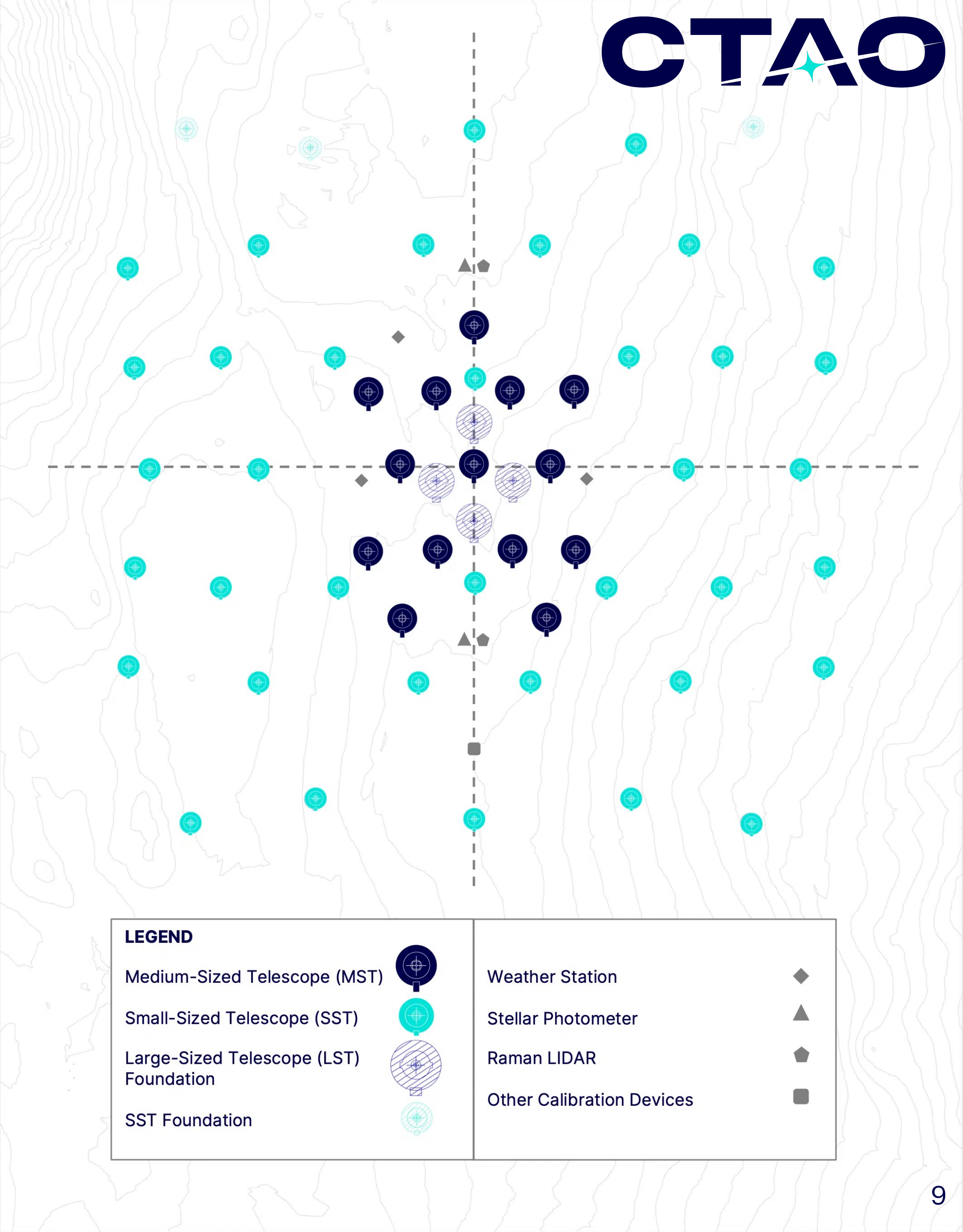
- Construction of 3 more LST telescopes progressing rapidly
- LSTNs foundations: completed!
- LSTN-02: azimuth ring, pins and boogies completed
- LSTN-03: most of the mount completed
- LSTN-04: Dish structure installed
- MSTNs: planning foundation work
- Infrastructure: almost complete



Southern Array Site

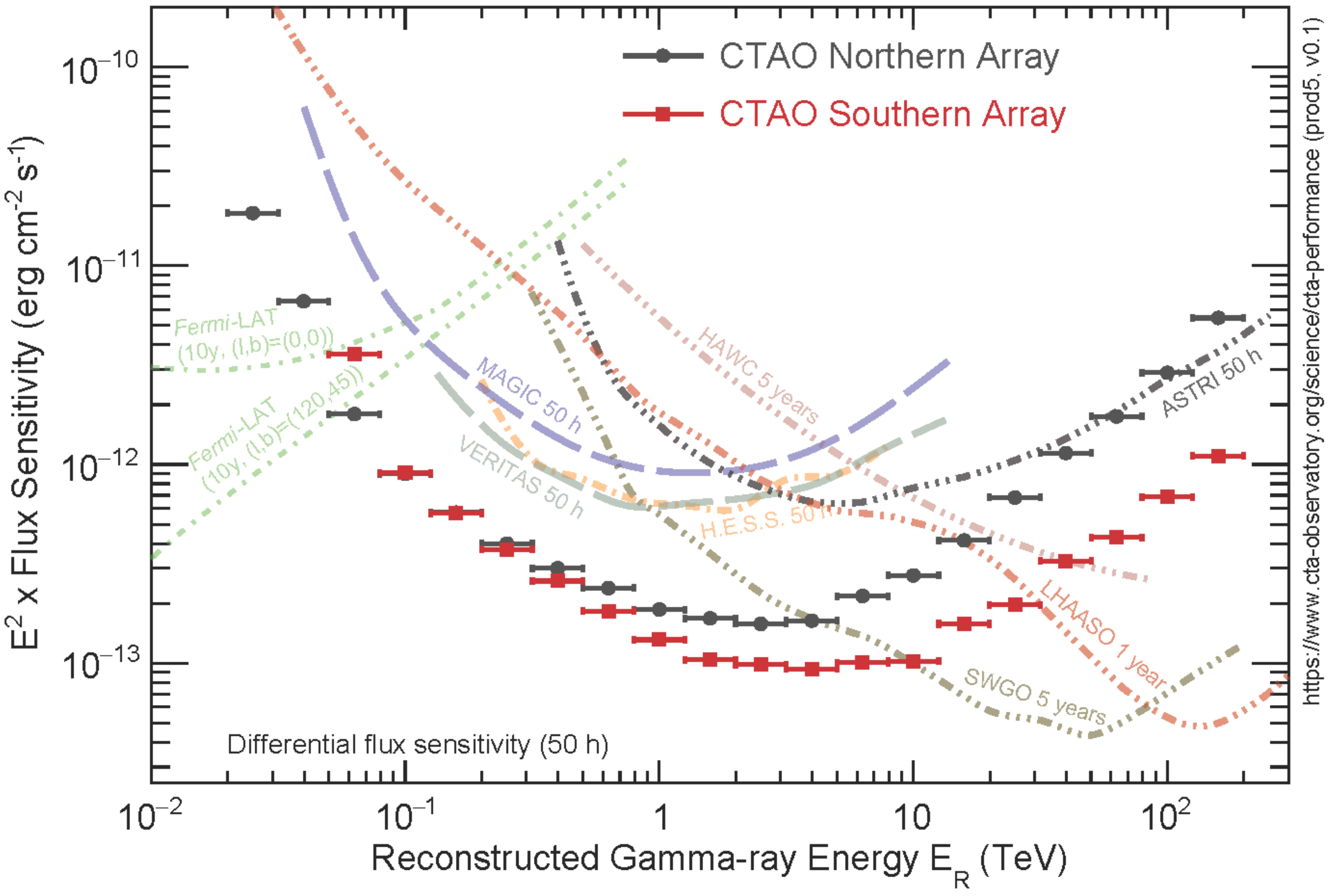
Getting ready for construction

- Topographical Survey: complete
- Geotechnical study: nearly complete
- 23kV electrical Overhead Line: under negotiation
- 10 kV Power Conditioning System: Out for tender
- Array Roads and Telescope Foundations: Contract late this year

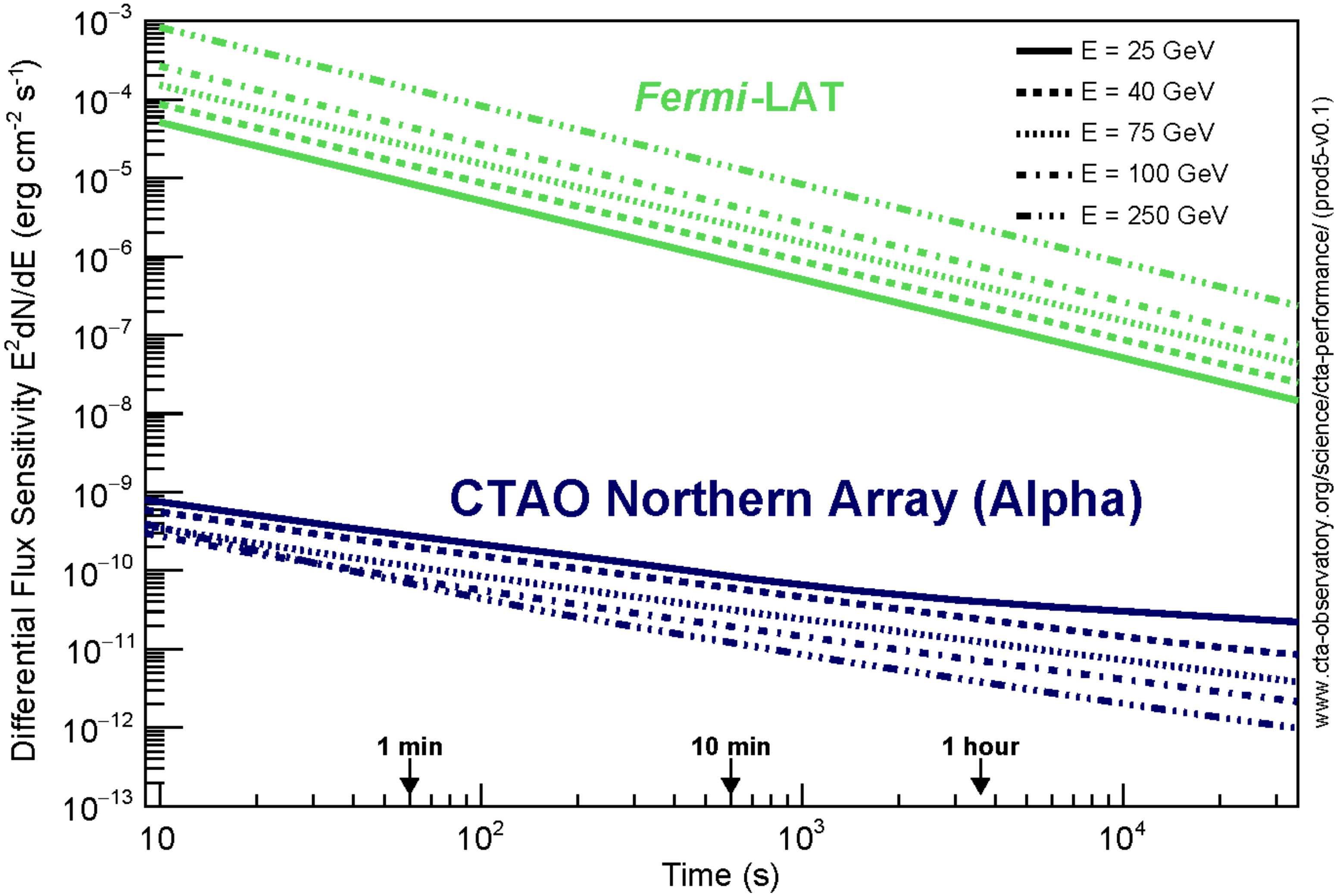


[Slide adapted from Stuart McMuldroch]

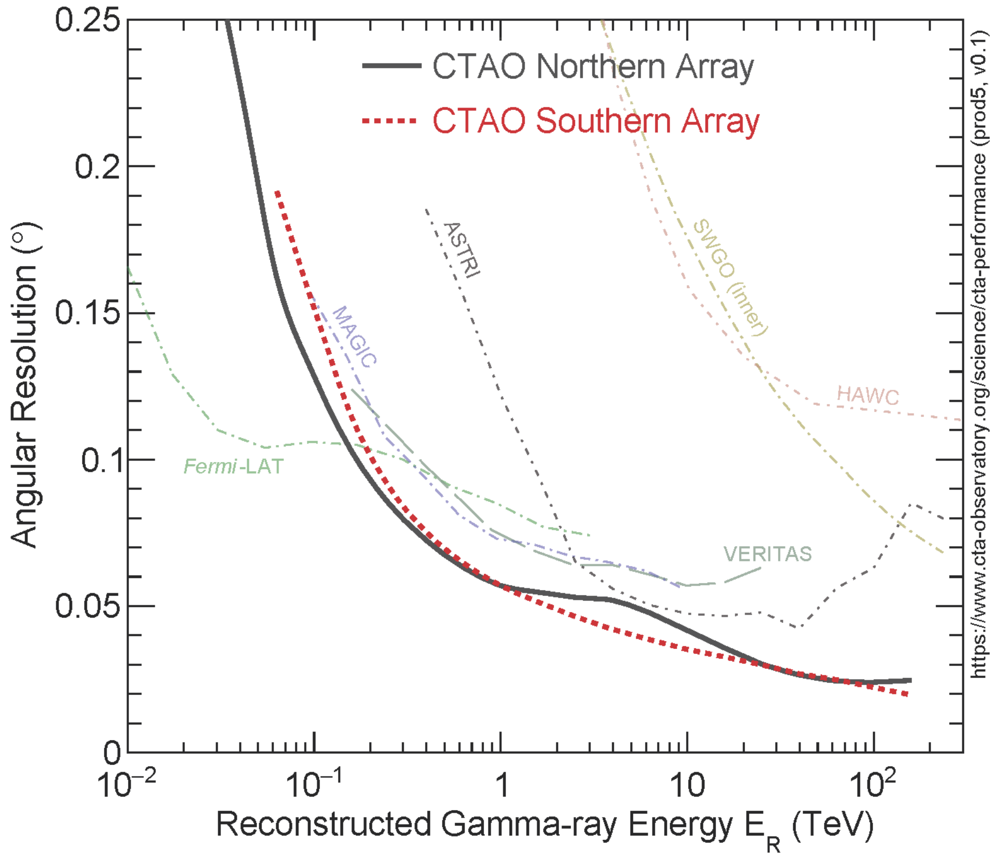
Performance: Sensitivity

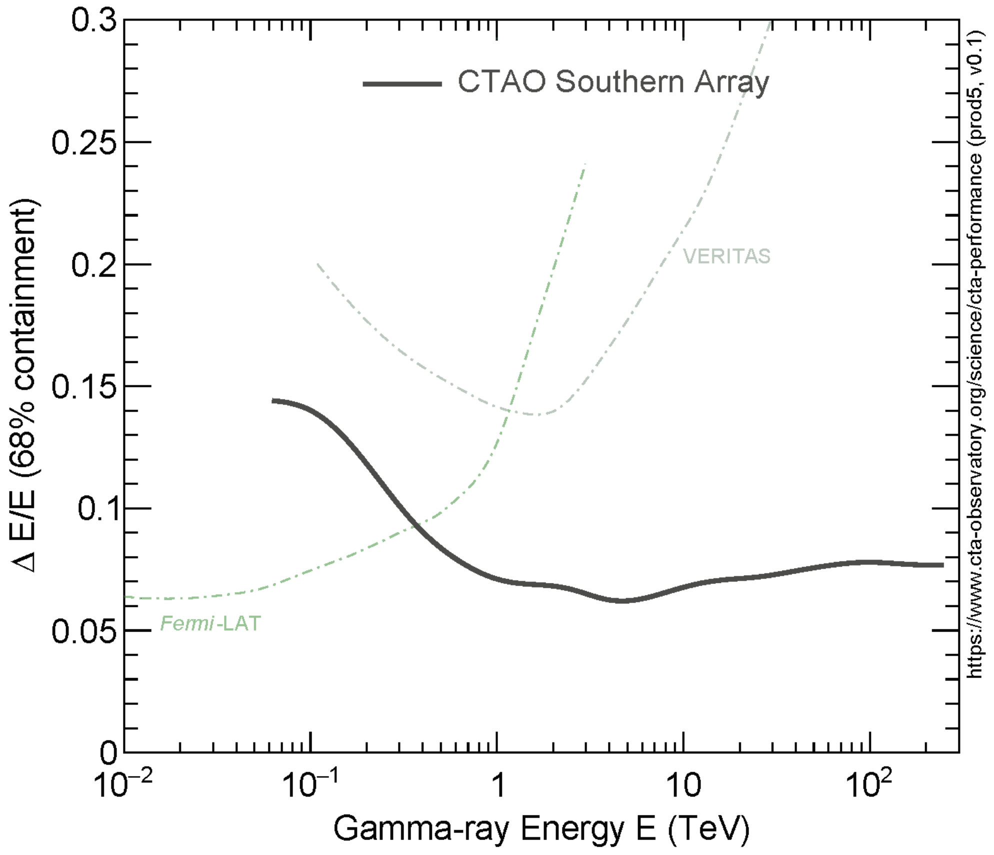


Performance: Sensitivity for Transient Sources



Performance: angular and energy resolution





Science with CTAO

- Laid out by CTAO Consortium in 2018
- Defines science themes and key science programs
- In the following: selected updates on sensitivity projections for key science programs

Not covered today

- **Transient science:**
  - CTAO will observe a large number of transient phenomena
    - GRBs
    - GW counterparts
    - Core collapse supernovae
    - …
- **Multi-messenger science:**
  - GW counterparts
  - Neutrino counterparts

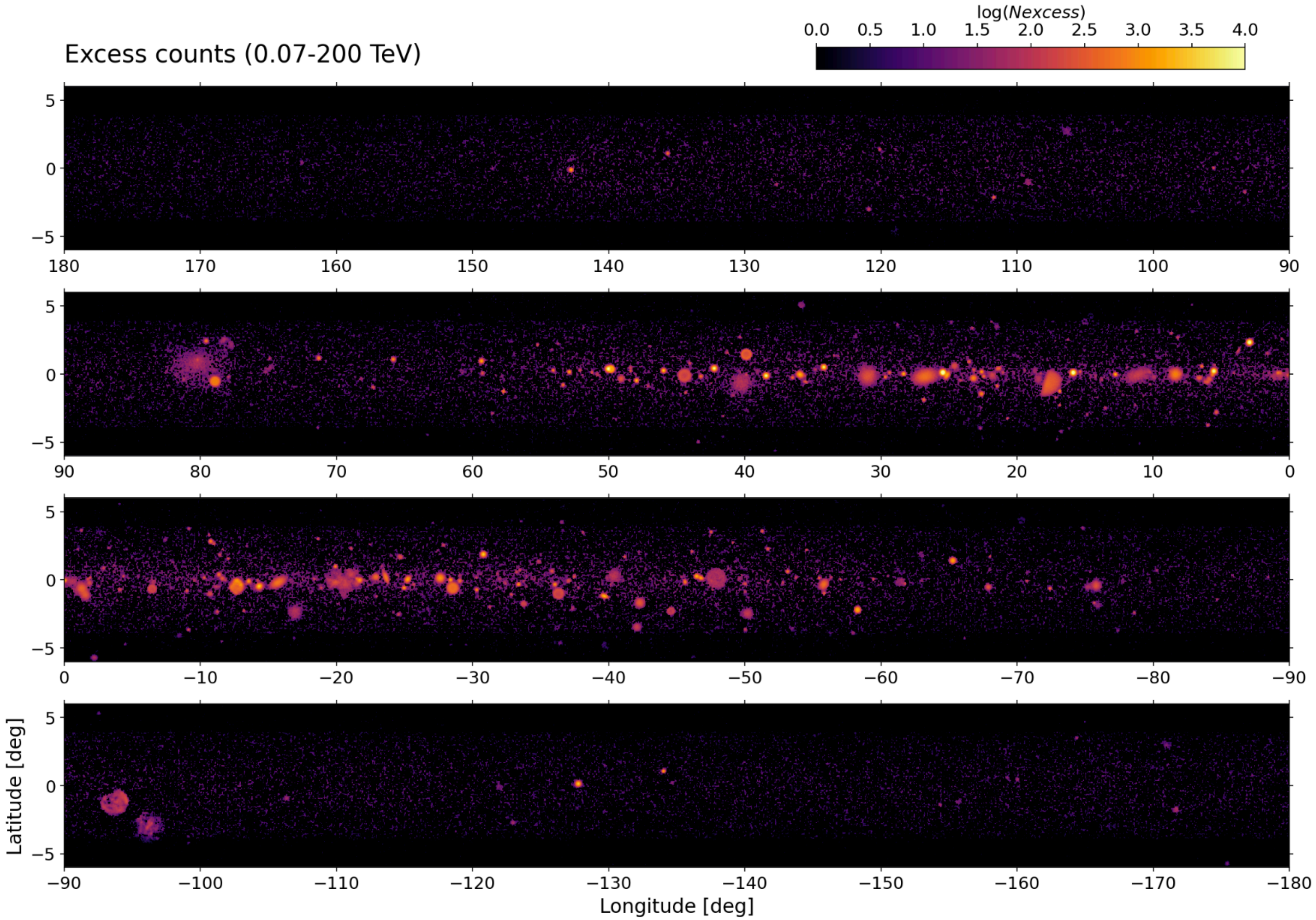
[CTAO Consortium, 2018]

Galactic Science with CTAO

[image credit: DESY/Scicom Lab]

Galactic Plane Survey

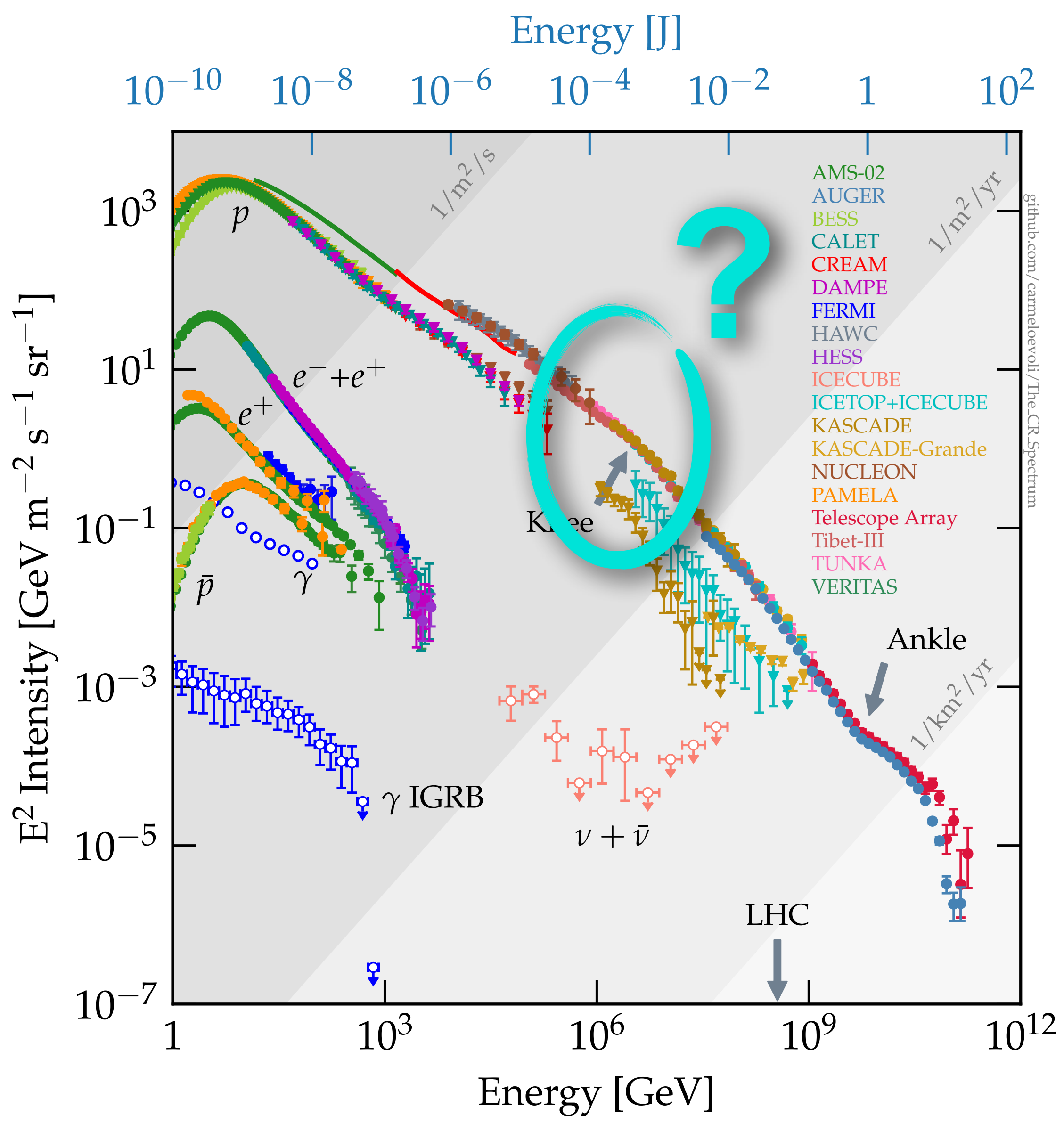
- 480 hours in first two years
- 1140 hours in following 8 years
- Up to 500 sources could be detected (5 times as much as H.E.S.S. or HAWC surveys)



[CTAO Consortium et al., accepted in JCAP, 2023]

Galactic PeVatrons

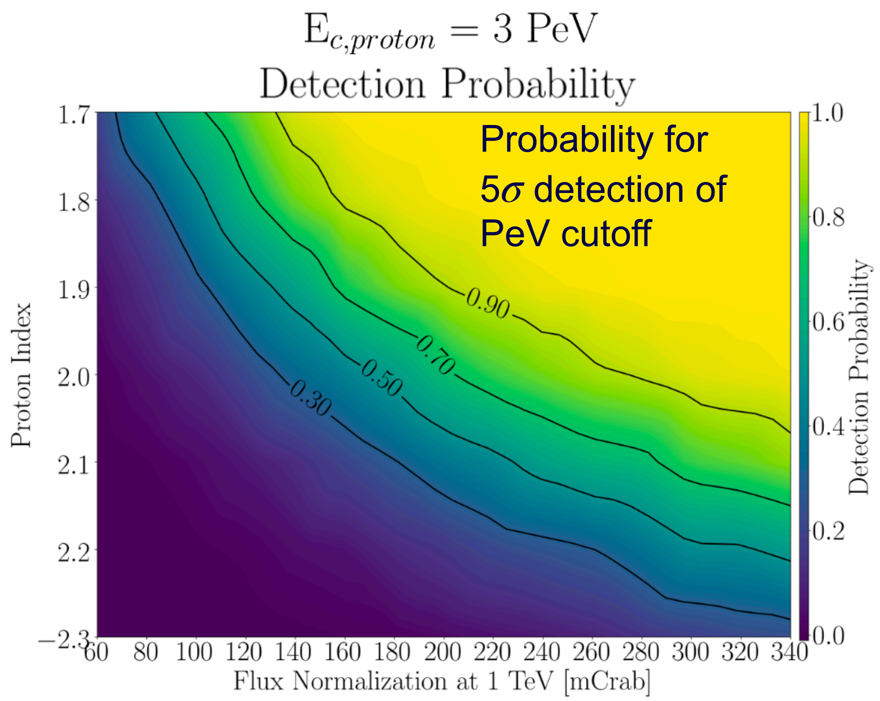
- Sources of Galactic cosmic rays (protons) up to 3 PeV still unknown
- Detection of $\gtrsim$ 100 TeV photons would suggest presence of freshly accelerated CR protons with PeV energies
- Gamma rays would be produced from π^0 decay produced in $p + p \rightarrow \pi + X$, leptonic scenarios suffer from Klein-Nishina suppression
- Usually SNRs are preferred candidates due to detected π^0 bump
- Recently: LHAASO detected several γ-ray sources $\gtrsim$ 100 TeV, likely associated with PWNe $\Rightarrow$ leptonic PeVatrons

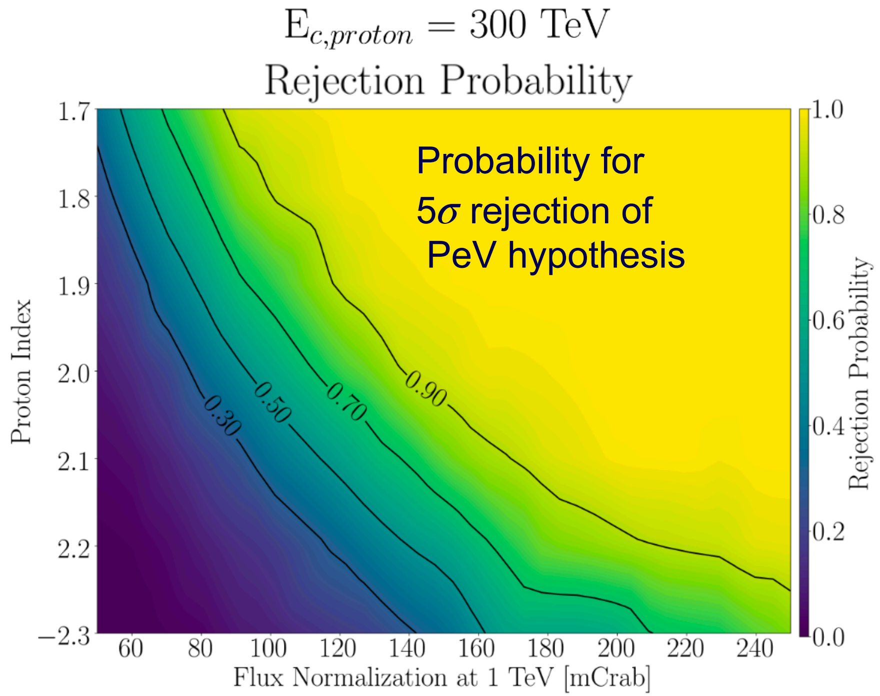


[e.g., Cardillo & Giuliani 2023 for a review]

Could CTAO detect high energy cutoff to identify hadronic PeVatrons?

- Model: gamma rays due to π^0 decay from CR interactions with molecular gas
- 10 hrs of observation time with southern array assumed
- Sources randomly distributed within $b \in [-0.5°, +0.5°]$ and $l \in [\pm 5°, \pm 60°]$ which are regions of the galactic plane survey
- Most likely: SNR hadronic PeVatrons detected in GPS if they have hard proton spectra and are point like
- If no cutoff detected: GPS will provide candidates for deep observations

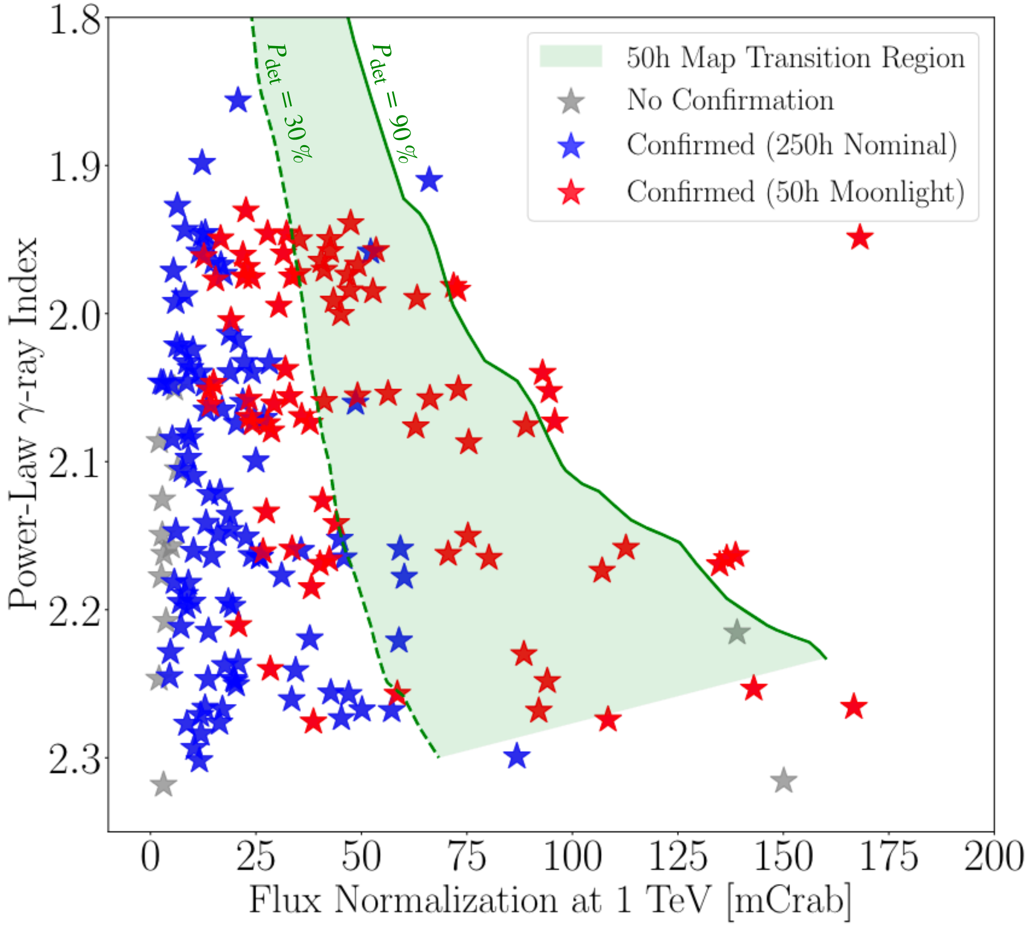




[CTAO Consortium: Acero et al. (2023)]

Could CTAO identify hadronic PeVatrons?

- For soft sources with $\Gamma_p \gtrsim 2.3$, 250 hours of observations can nail down PeV hypothesis
- Could be done with SST under moonlight conditions (with double observation time)

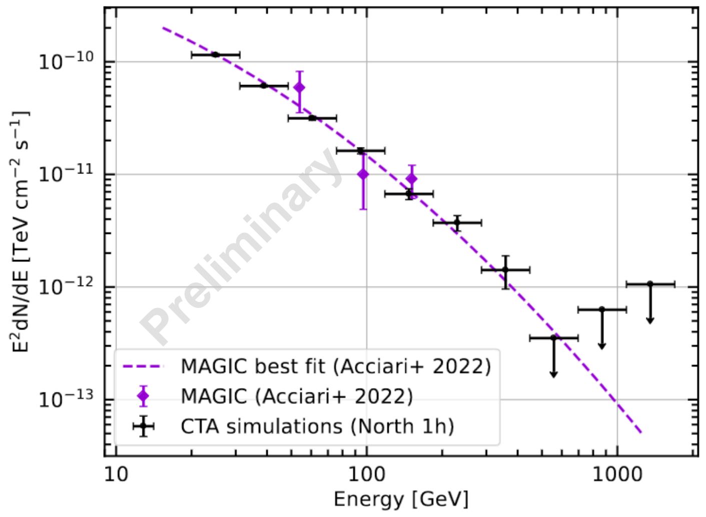


[CTAO Consortium: Acero et al. (2023)]

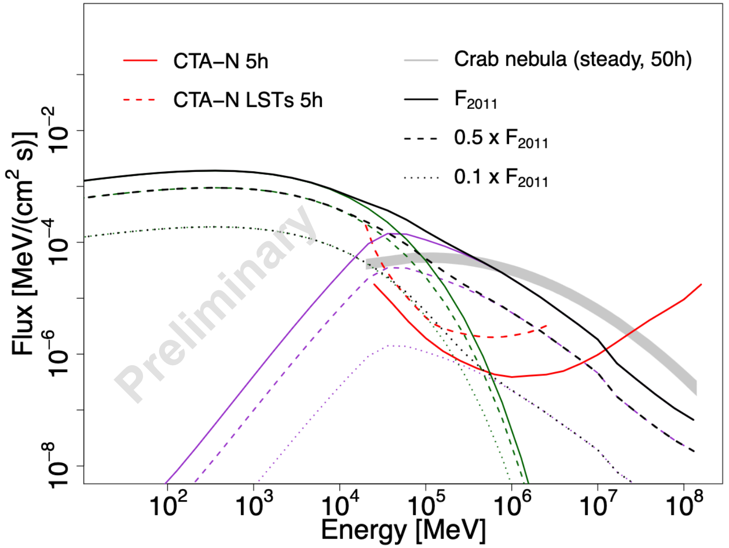
Galactic Transient Sources

- Microquasars like Cyg X-1 and Cyg X-3, SS 433
- Close-by novae like recurring RS Oph
- Flares from Crab Nebula with LSTs in less than 1 hour of observation time

RS Oph 1 day after outburst



Crab Nebula flares

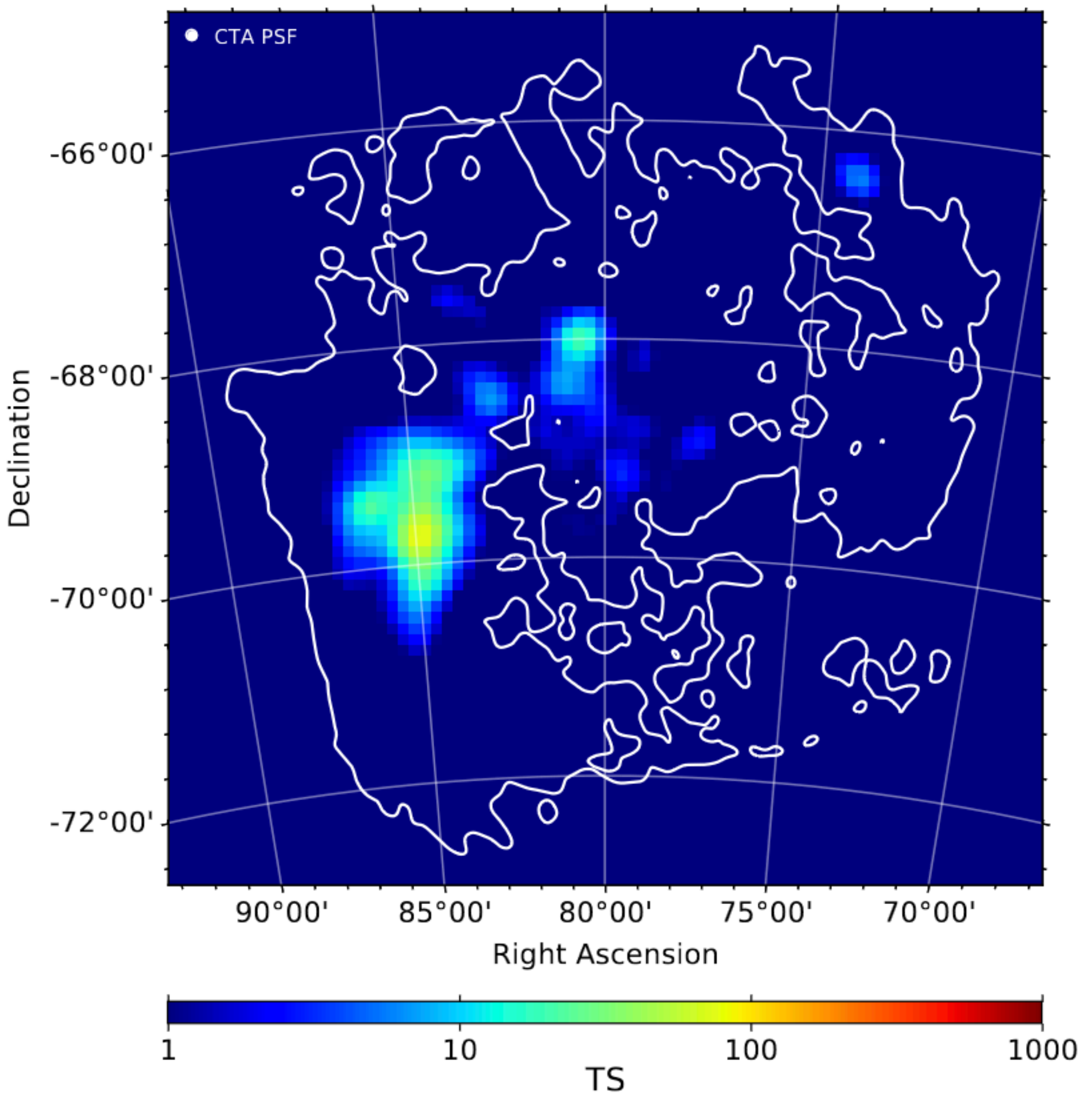


[CTAO Consortium: Abe et al. (2024)]

Survey of the Large Magellanic Cloud

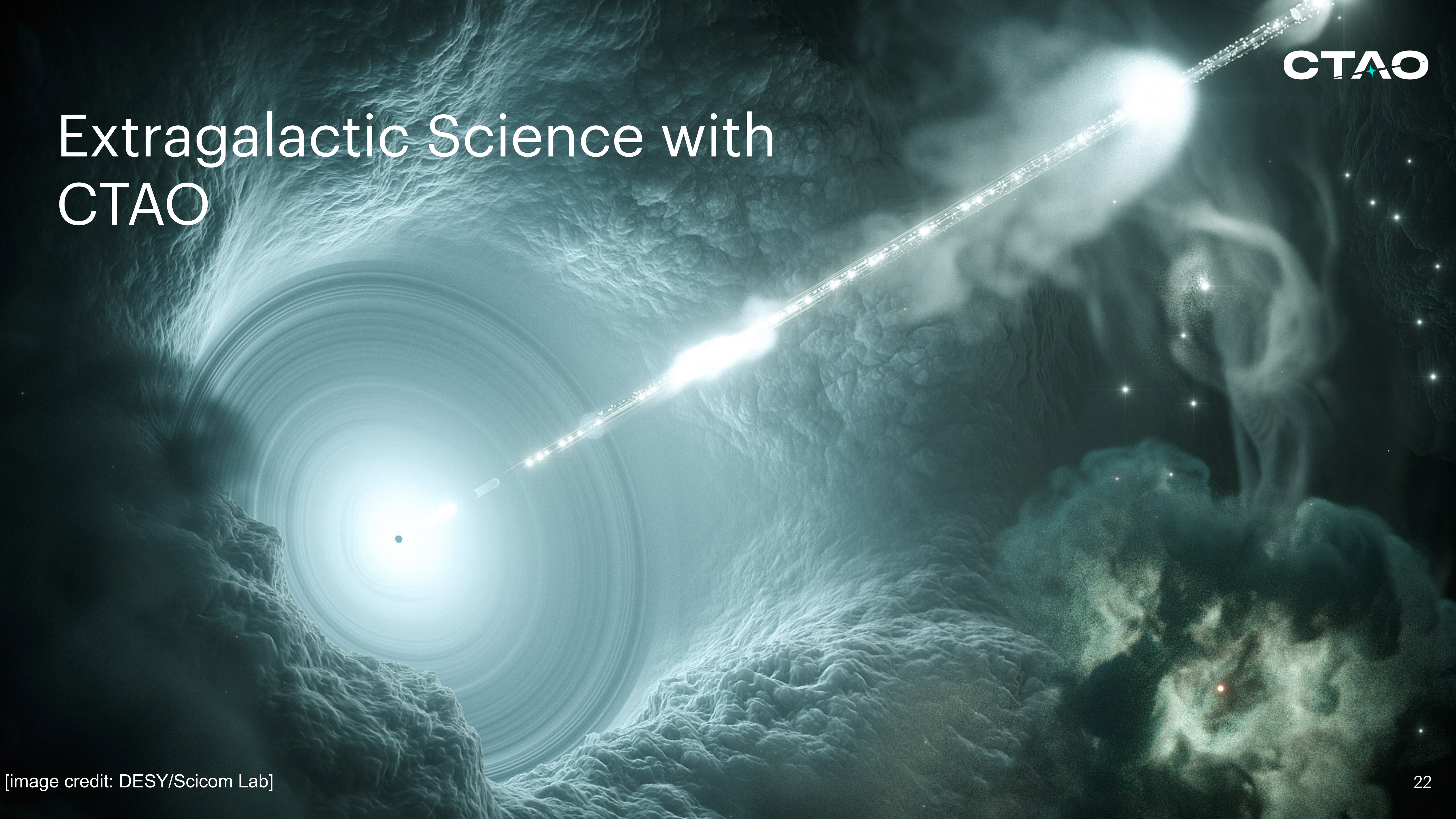
- 340 hours of observations foreseen
- Will probe particle acceleration in:
  - Star forming region 30 Doradus
  - Remnant of SN1987A

Simulated detection significance (for spectrally hard emission scenario)



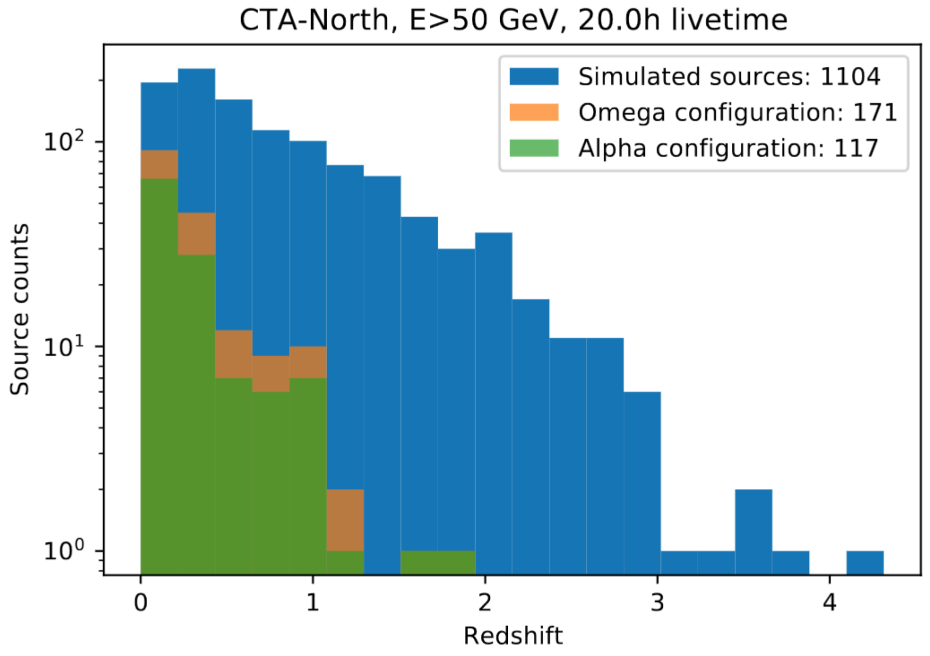
[CTAO Consortium: Acharyya et al. (2023)]

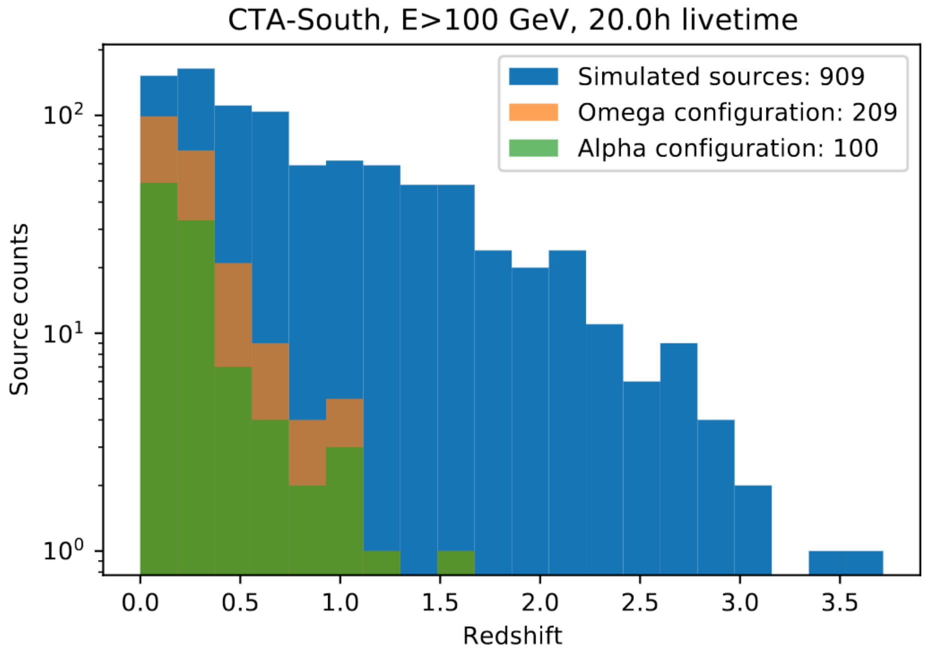
Extragalactic Science with CTAO



[image credit: DESY/Scicom Lab]

AGN population





Sources with known redshift from 4LAC catalog extrapolated with power law and EBL absorption

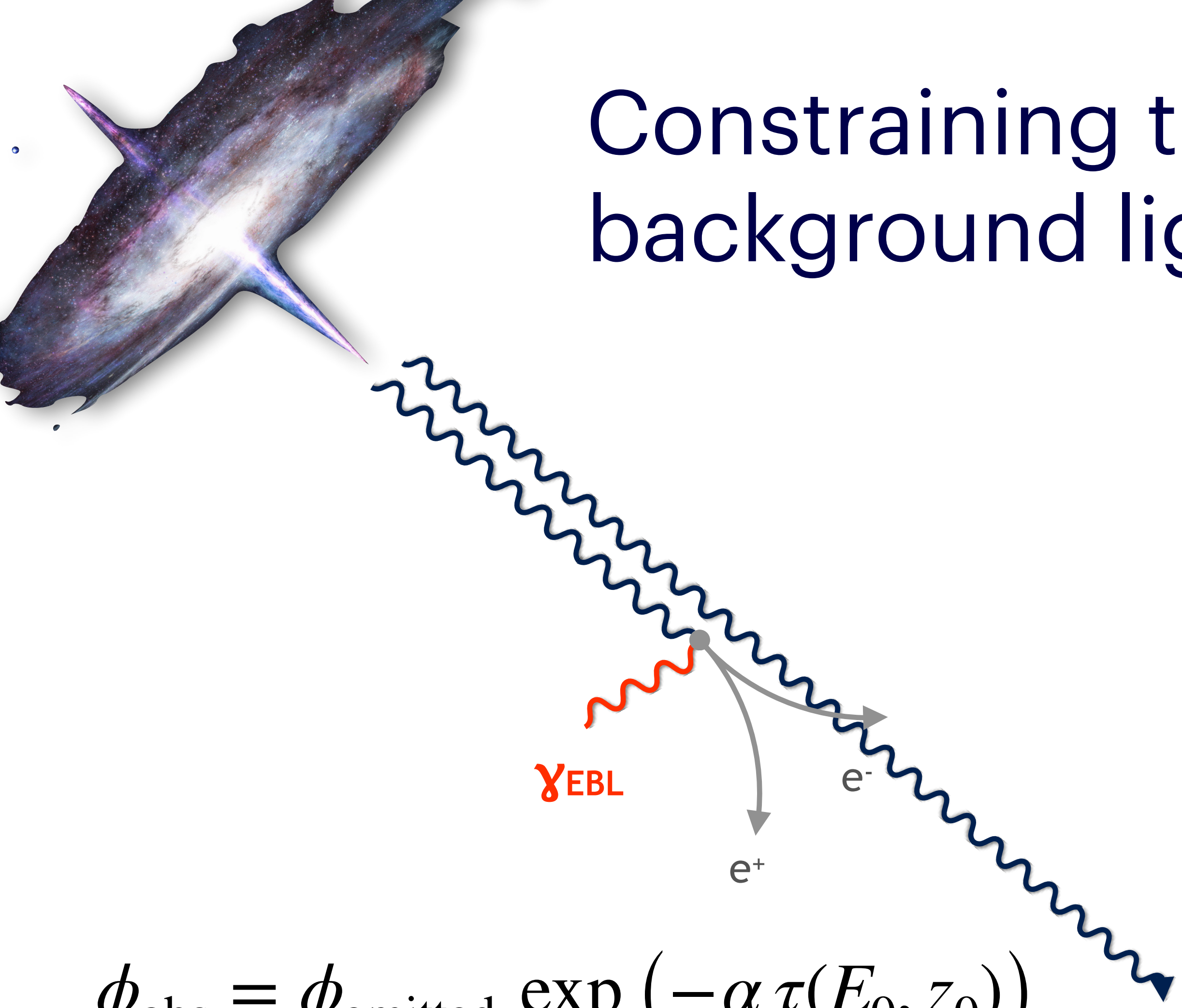
- CTAO will detect hundreds of AGN
  - Long term monitoring program
  - High quality spectra
  - Follow up of GeV and TeV flares
  - Extragalactic survey
- Will provide blazar luminosity function up to TeV energies

[Brown et al. 2021]

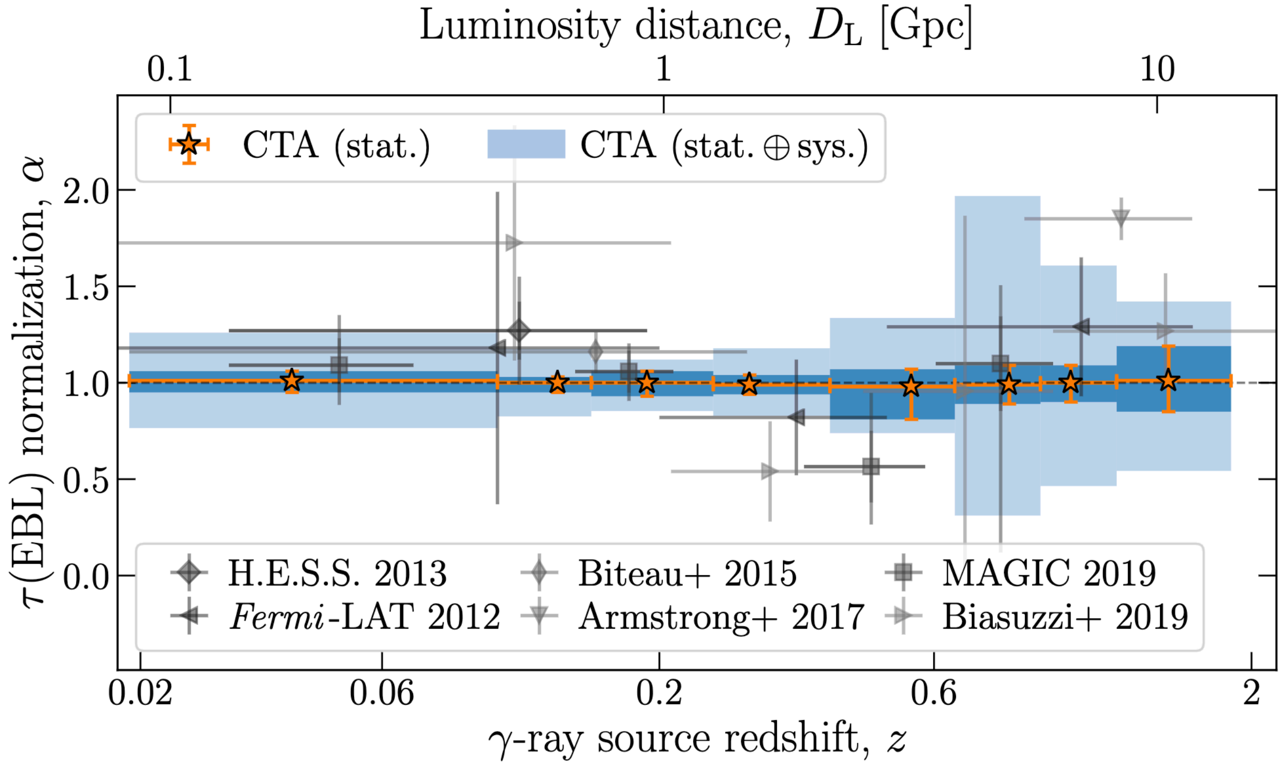
Recent extragalactic science highlights with LST1

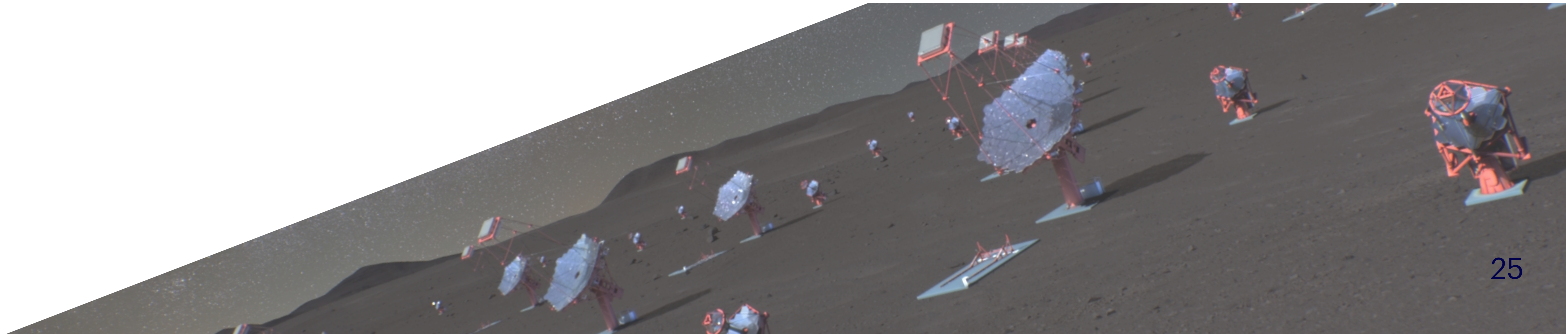
- Follow-up observations of GRB221009A with LST1
  — see talk by Kenta Terauchi
- Detection of OP313 at $z = 0.997$ with LST1
  — see talk by Mireia Nievas
- Study the variable VHE gamma-ray emission of bright AGN with LST 1
  — see talk by Ryuji Takeishi

Constraining the extragalactic background light



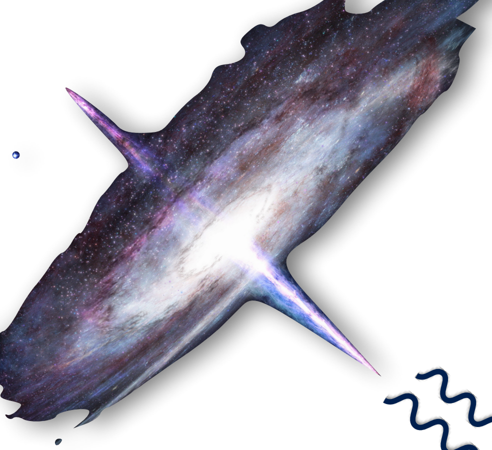
$$\phi_{\rm obs} = \phi_{\rm emitted}\, \exp\left(-\alpha\, \tau(E_0, z_0)\right)$$

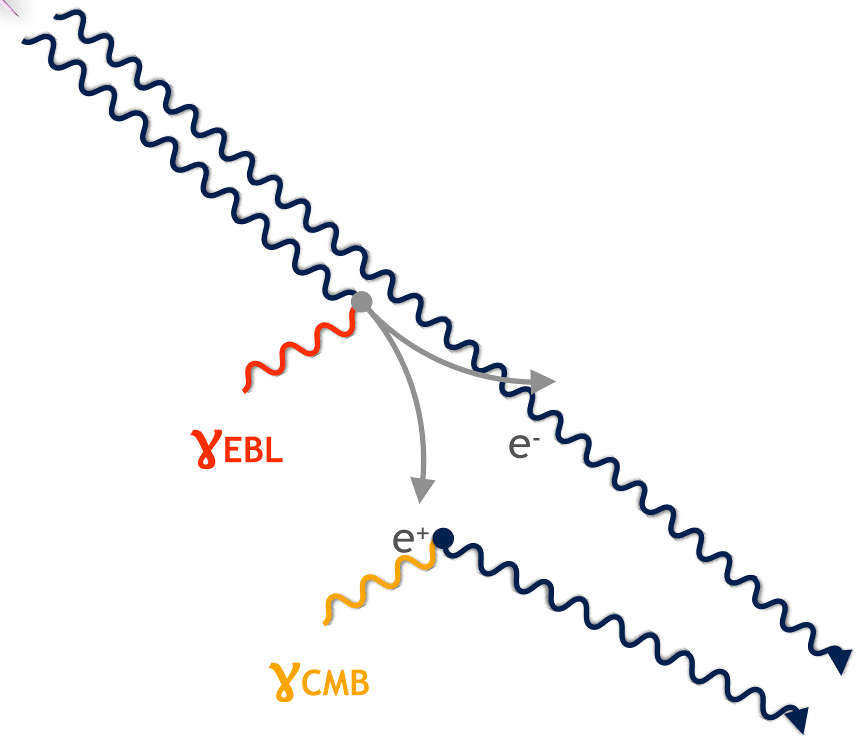




[CTAO Consortium: Abdalla et al. 2021]

Constraining intergalactic magnetic fields





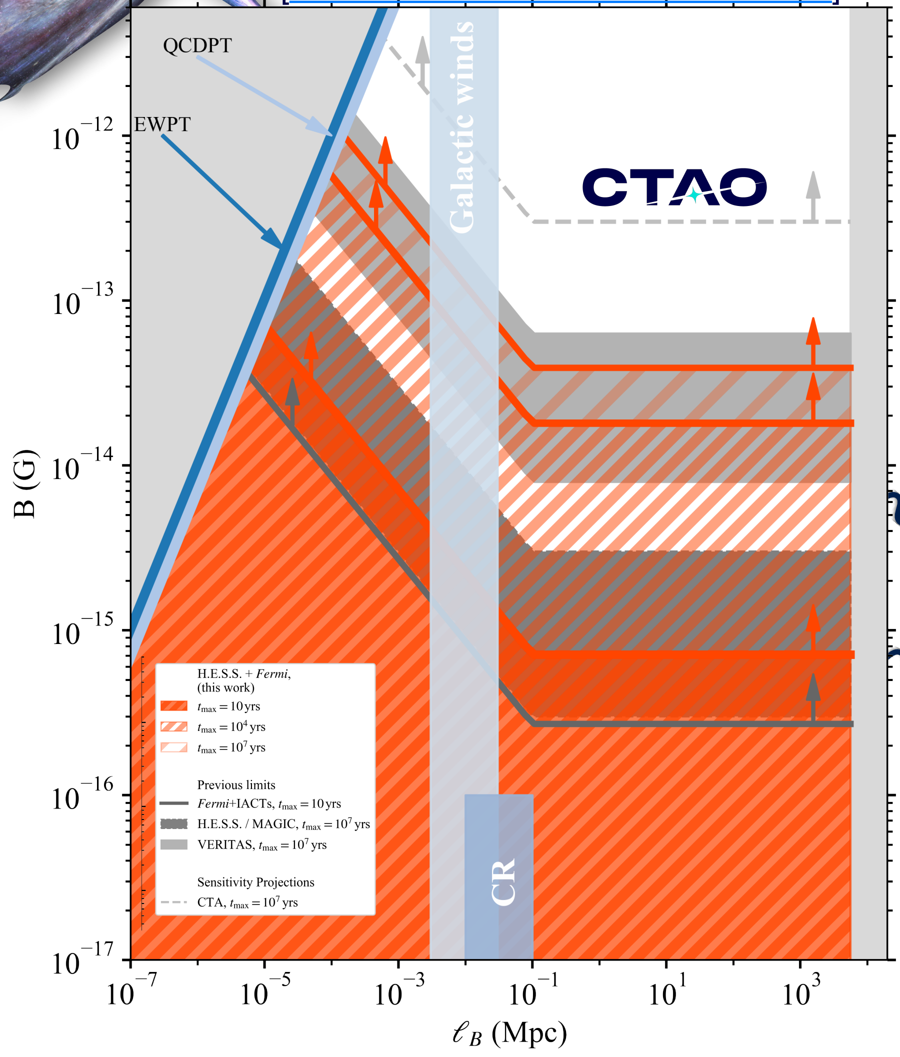
IGMF dependent observables:

- Excess ɣ rays at lower energies [e.g. Neronov & Semikoz 2008]
- Extended ɣ-ray halos [Aharonian et al. 1994]
- Time delayed ɣ-ray emission [Plaga 1995]

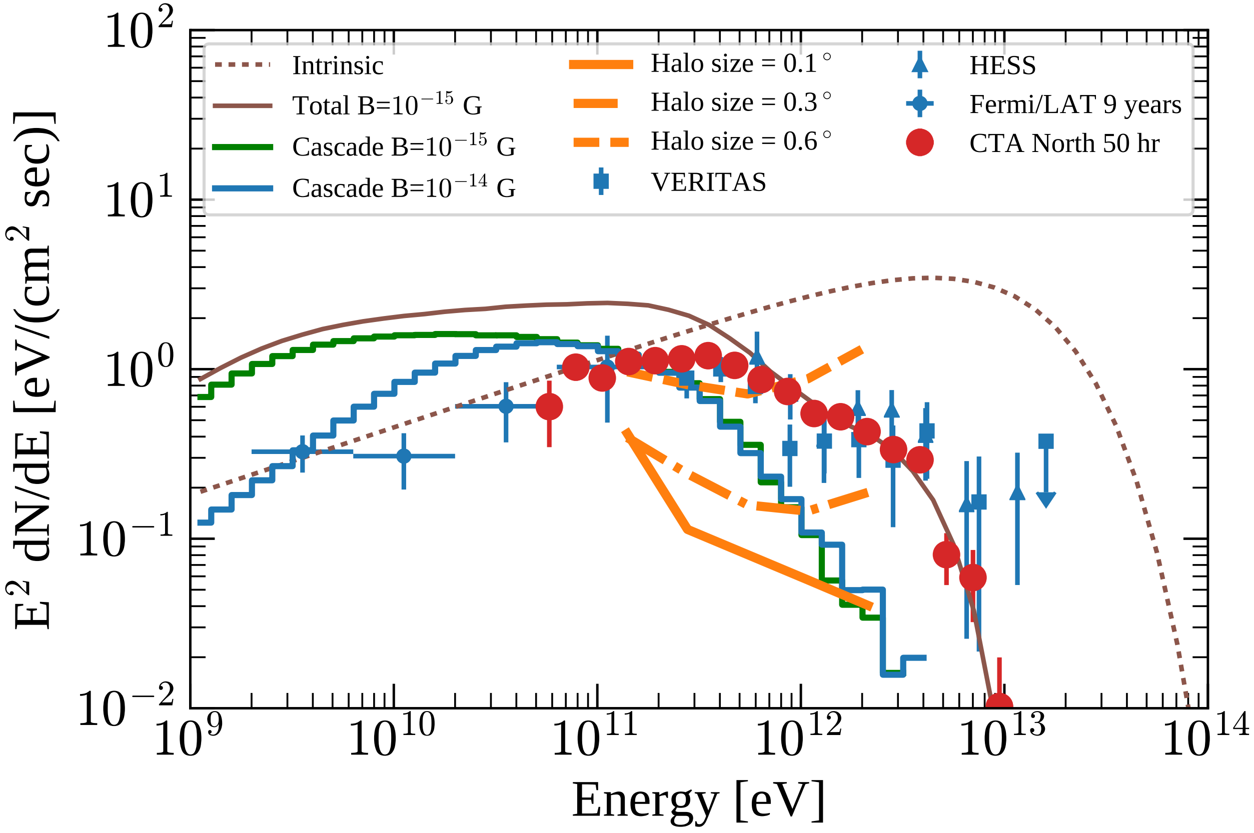
[CTAO Consortium: Abdalla et al. 2021]

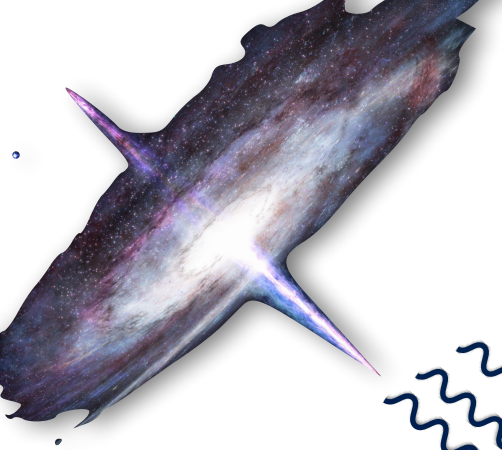
Constraining intergalactic magnetic fields

[H.E.S.S. Collab: Aharonian et al. 2023]

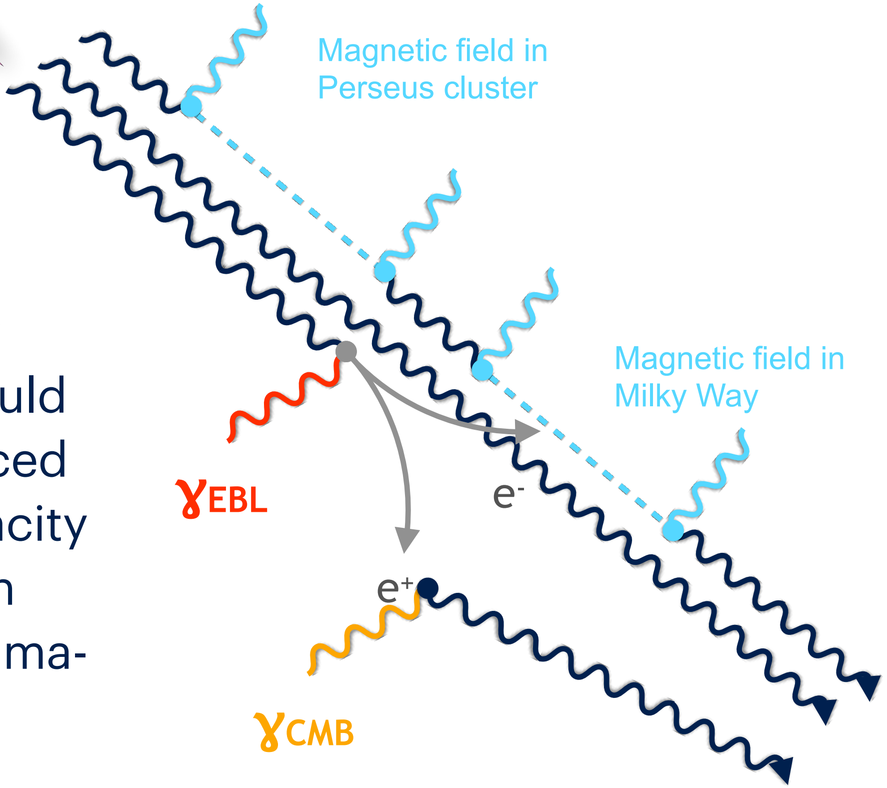


[CTAO Consortium: Abdalla et al. 2021]

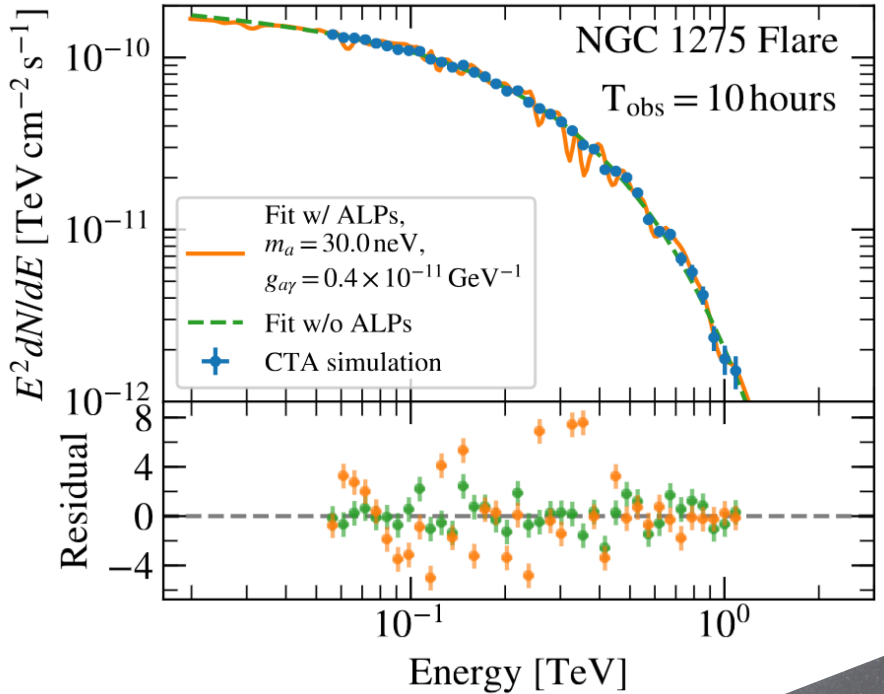


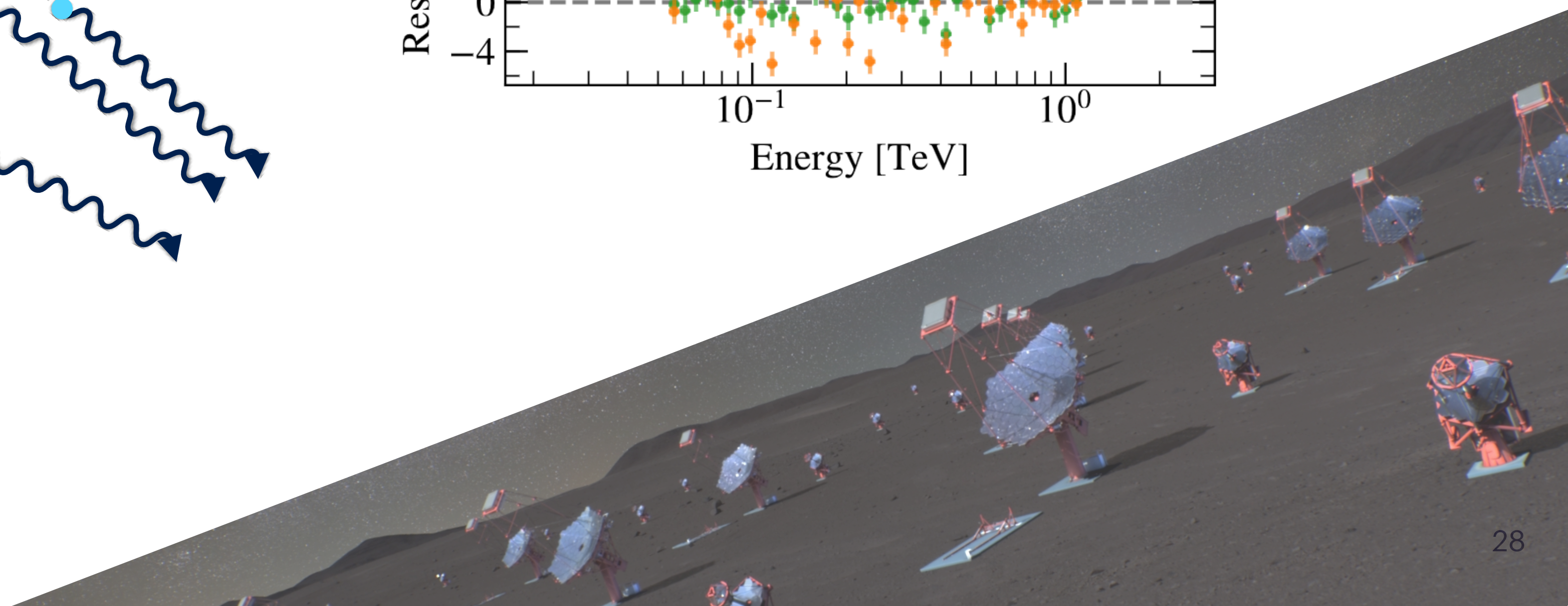


Searching for oscillations between gamma rays and axion-like particles



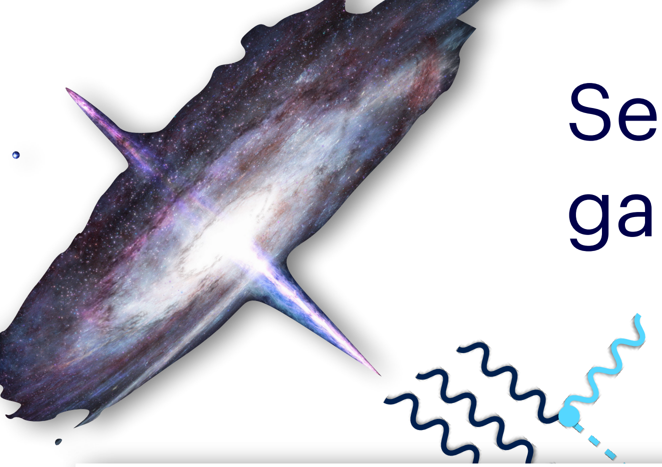
Photon-ALP oscillations could lead to a reduced gamma-ray opacity or oscillation features in gamma-ray spectra



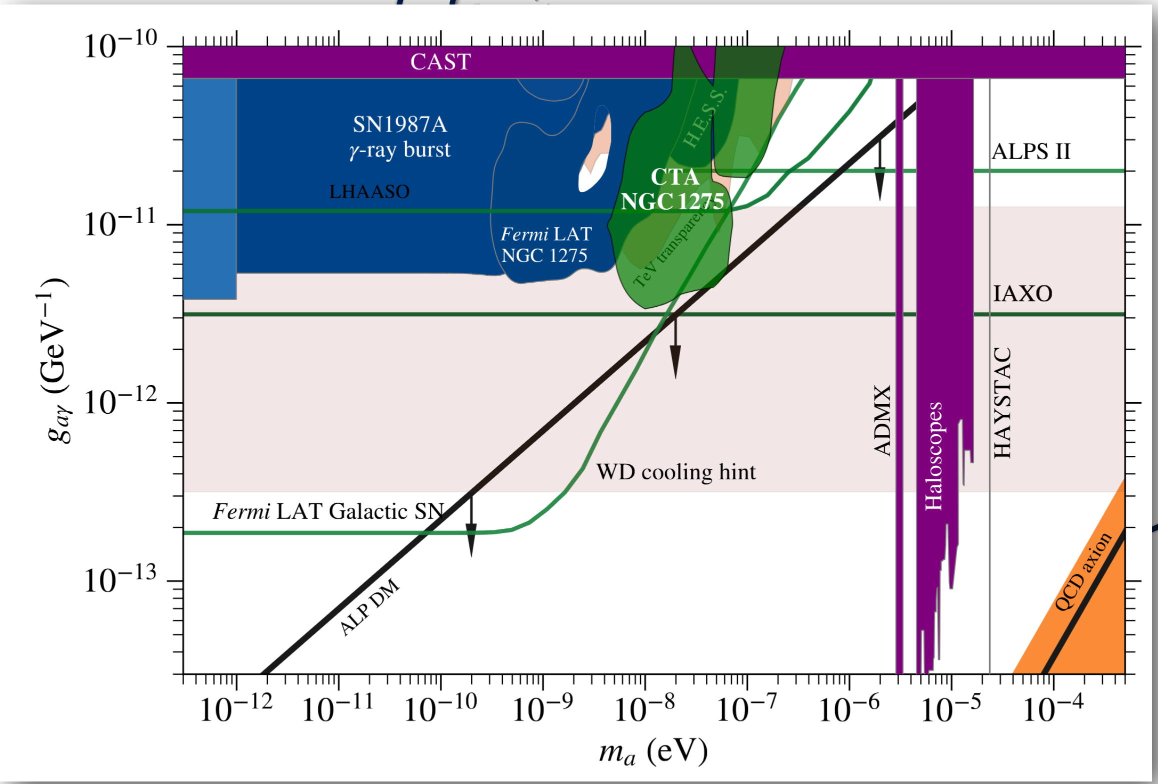


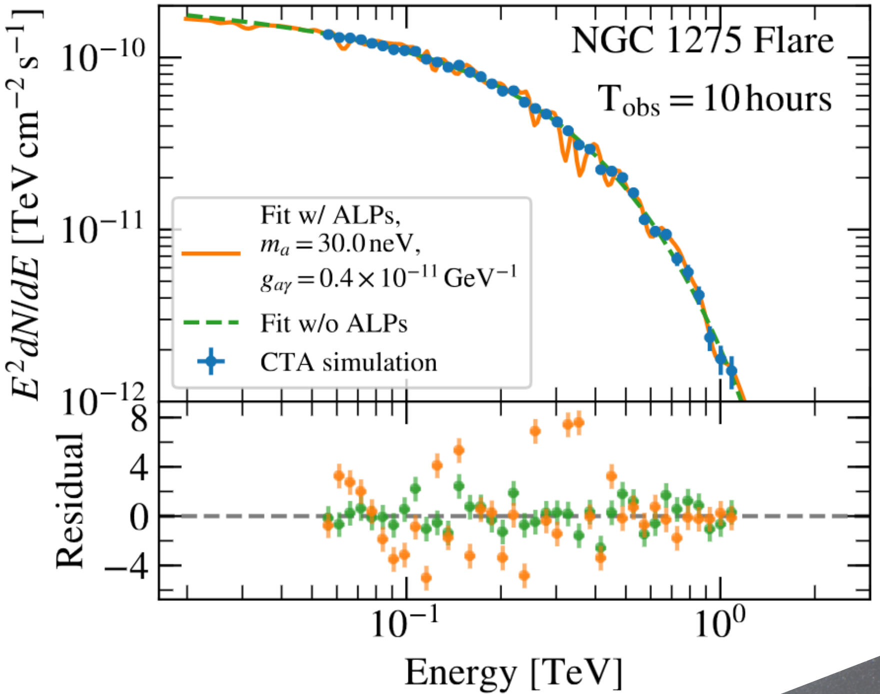
[CTAO Consortium: Abdalla et al. 2021]

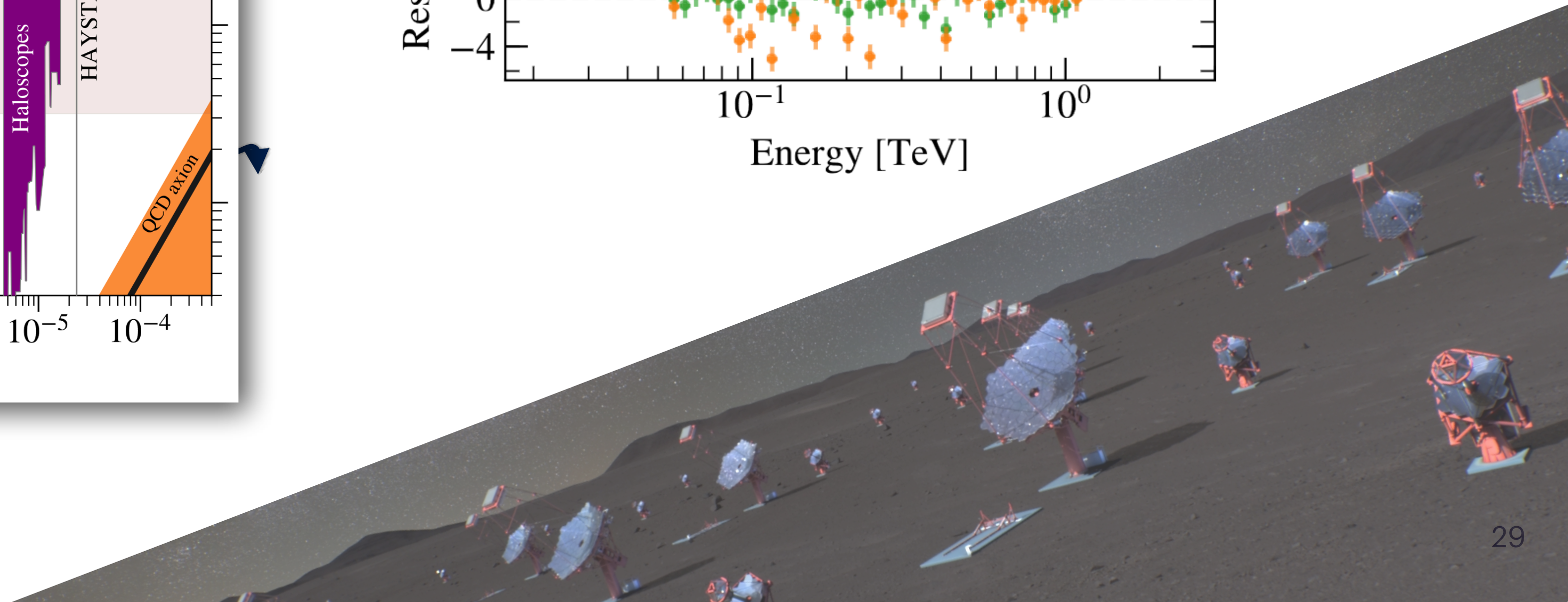
Searching for oscillations between gamma rays and axion-like particles



Magnetic field in Perseus cluster



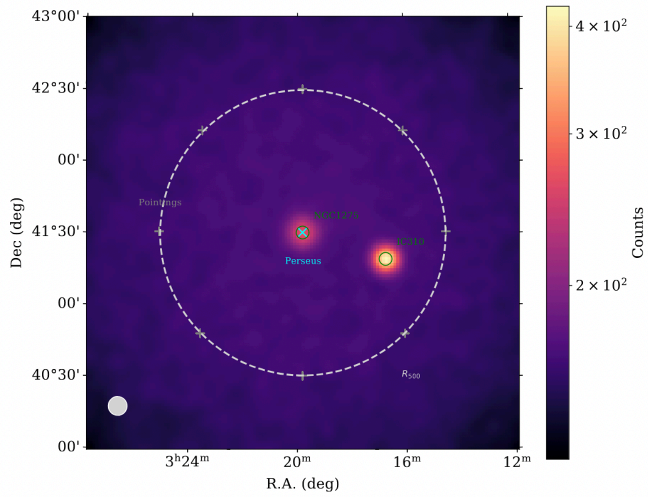


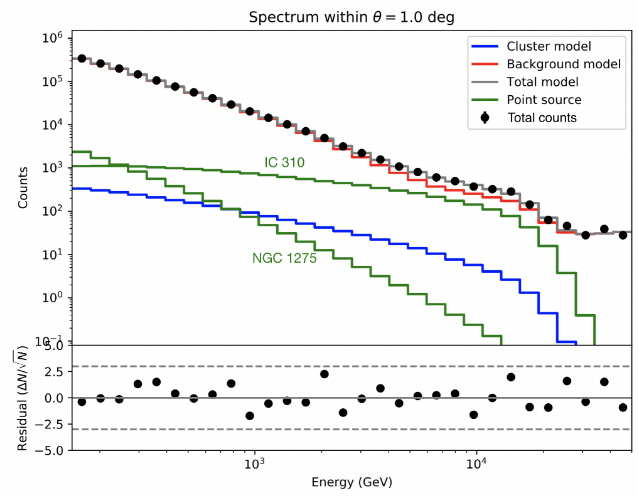


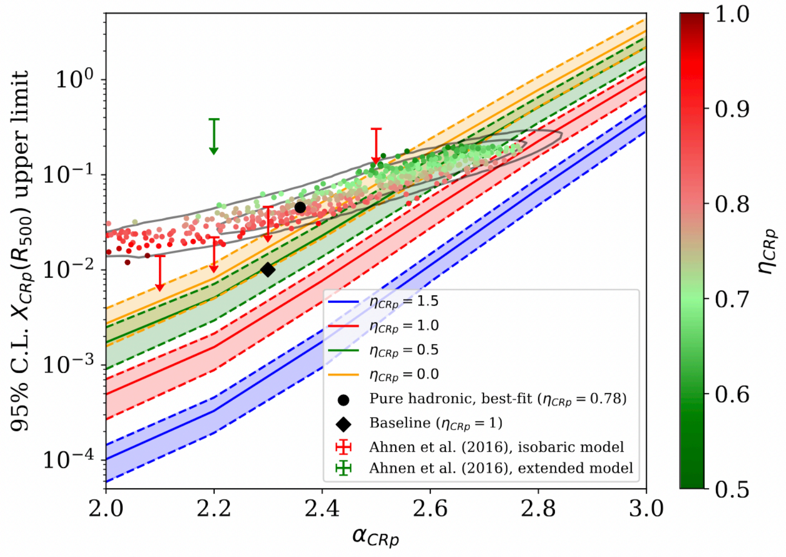
[CTAO Consortium: Abdalla et al. 2021]

Perseus Galaxy Cluster

- Most promising target to find diffuse gamma-ray emission from accelerated CRp
- Non-thermal emission from p-p interactions
- Power law in CRp momentum distribution modeled with index $\alpha_{\mathrm{CR_p}}$ and radial profile following electron density with slope $\eta_{\mathrm{CR_p}}$
- 300 hours of observations assumed with 15 MSTs and 4 LSTs
- In case of non-detection: constraints on $X_{\mathrm{CR_p}} = U_{\mathrm{CR_p}}/U_{\mathrm{th}}$ would improve by ~ one order of magnitude
- Purely hadronic model could be detected with CTAO
- CTAO will test an unexplored region of the dark matter decay parameter space for TeV WIMPs



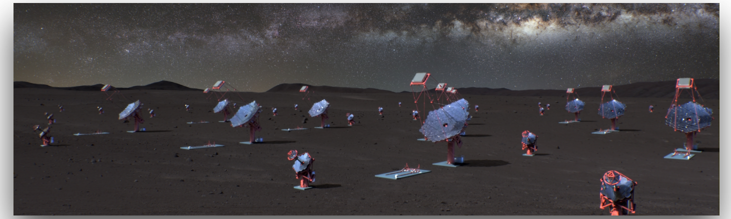




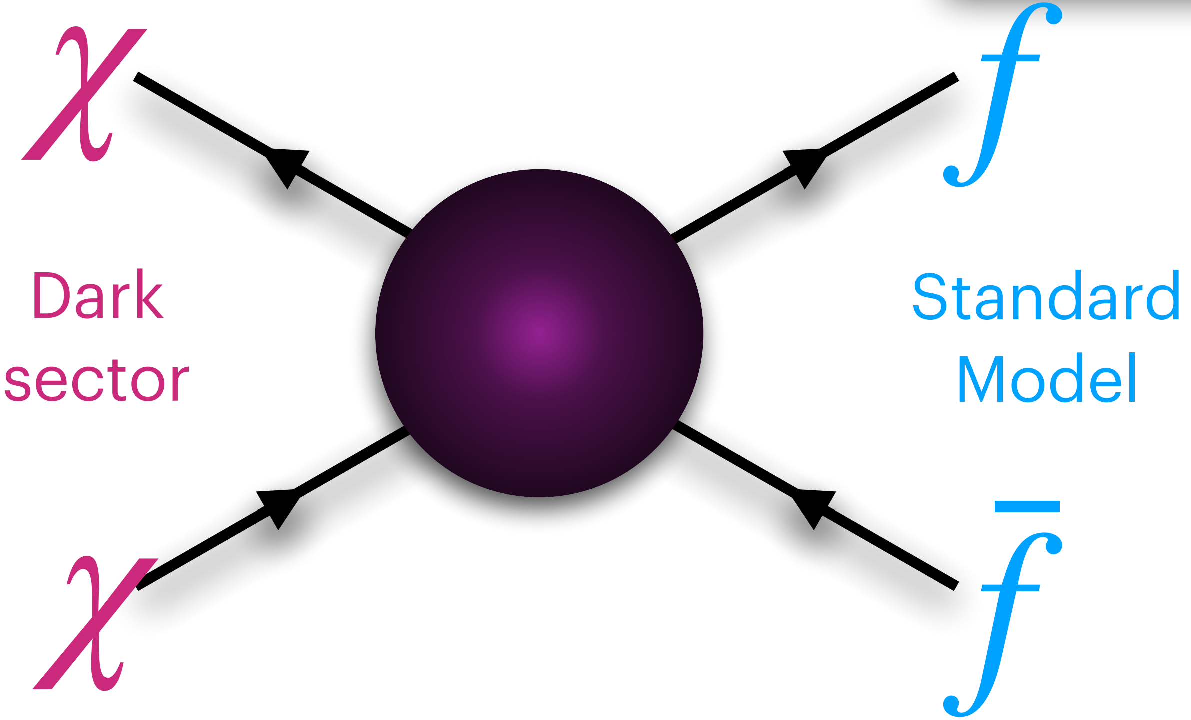
[CTAO Consortium: Abe et al. (2023)]

Indirect Dark matter searches with CTAO

indirect detection



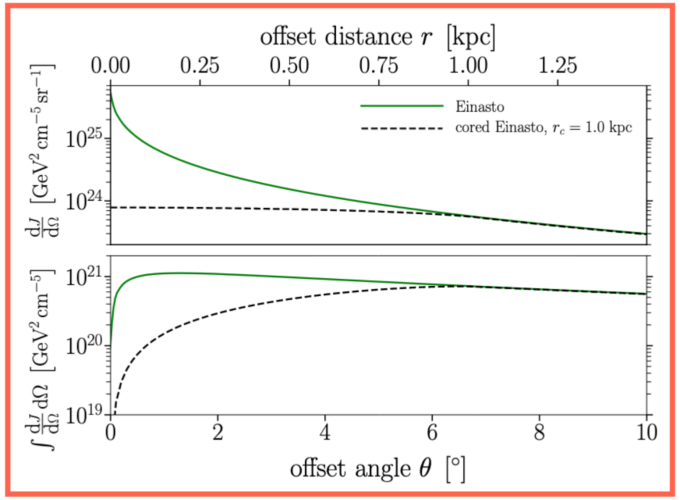
+ cosmic rays, neutrinos



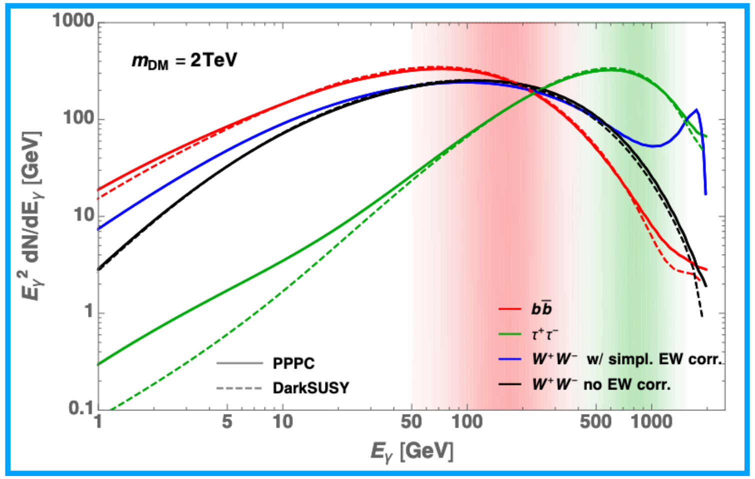
Expected photon flux from WIMP annihilation

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \Delta\Omega) = \left(\frac{1}{4\pi}\int_{\Delta\Omega} d\Omega \int_{\text{l.o.s.}} \rho_\chi^2(\mathbf{r})\, d\ell(\psi)\right) \left(\frac{\langle \sigma v\rangle_{\text{ann}}}{2 S_\chi m_\chi^2} \sum_f \frac{dN_\gamma^f}{dE_\gamma} B_f\right)$$

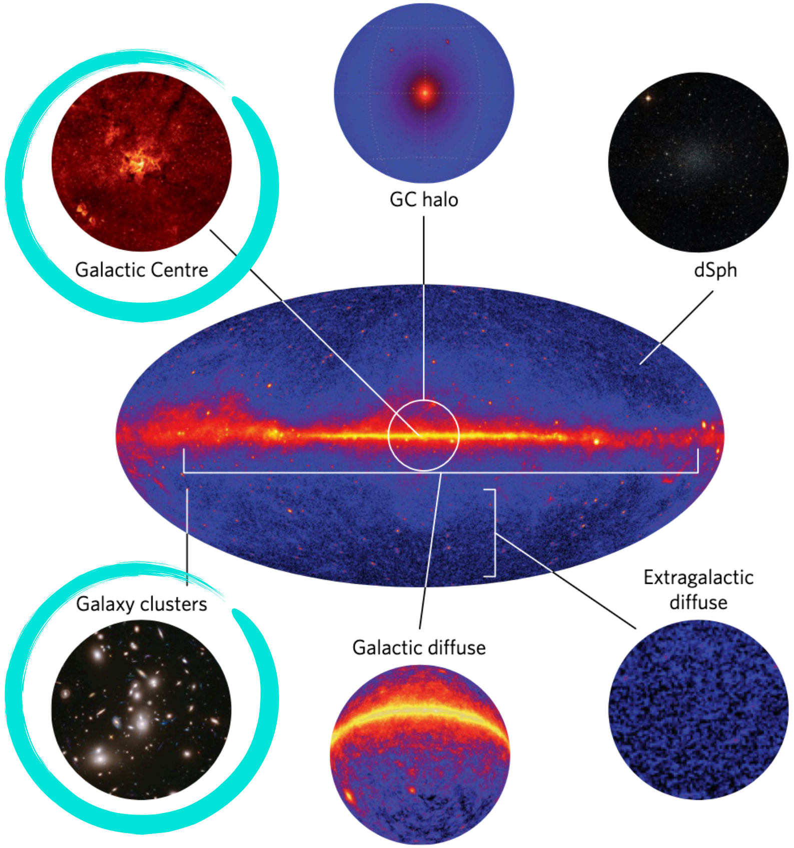
J factor — Particle physics



J factor for Galactic center of the Milky Way



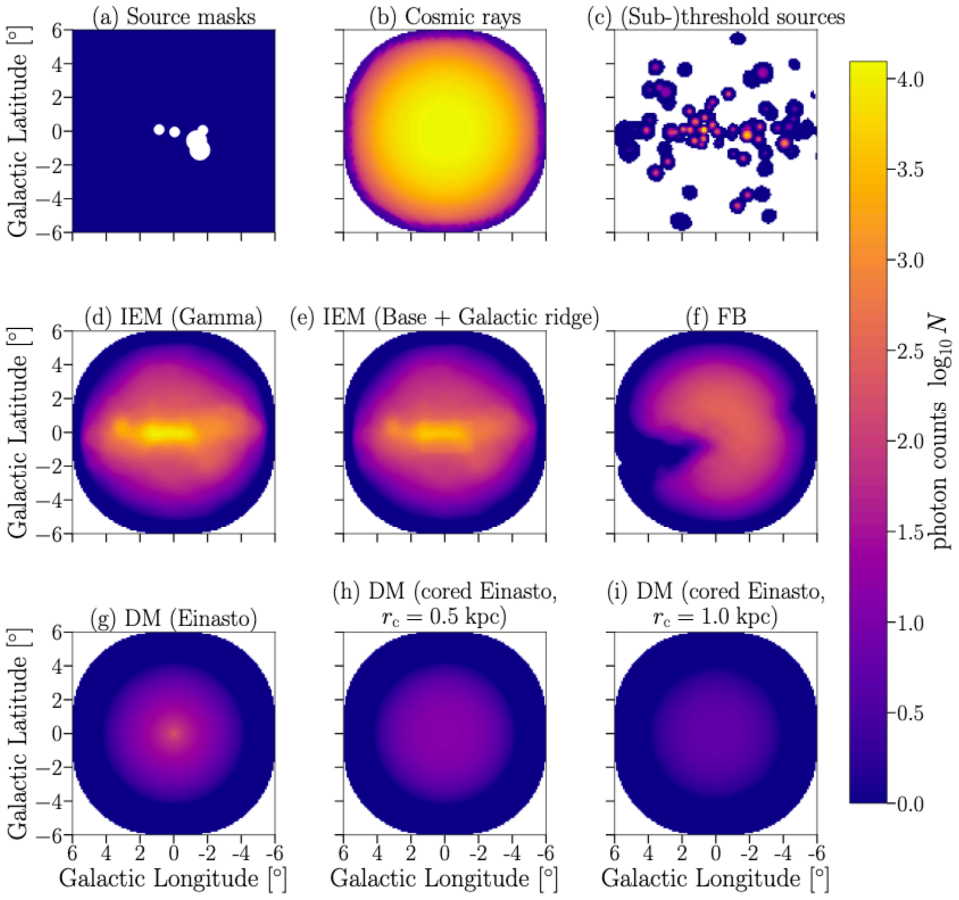
Targets for DM searches

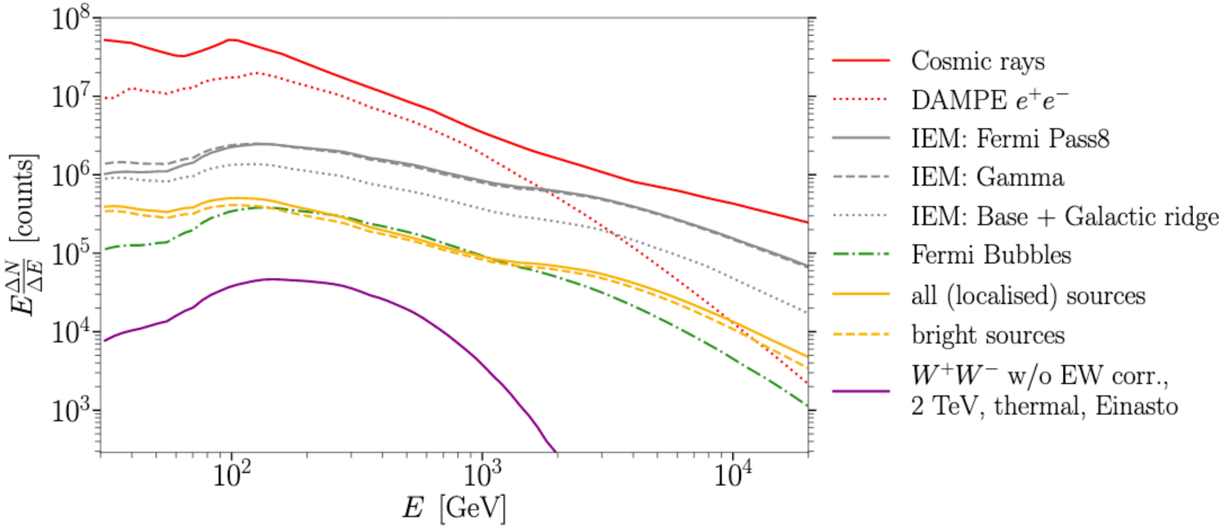


[Conrad & Reimer 2017]

[CTAO Consortium: Archaryya et al. 2021]

Modeling Galactic Center Region for CTA sensitivity study

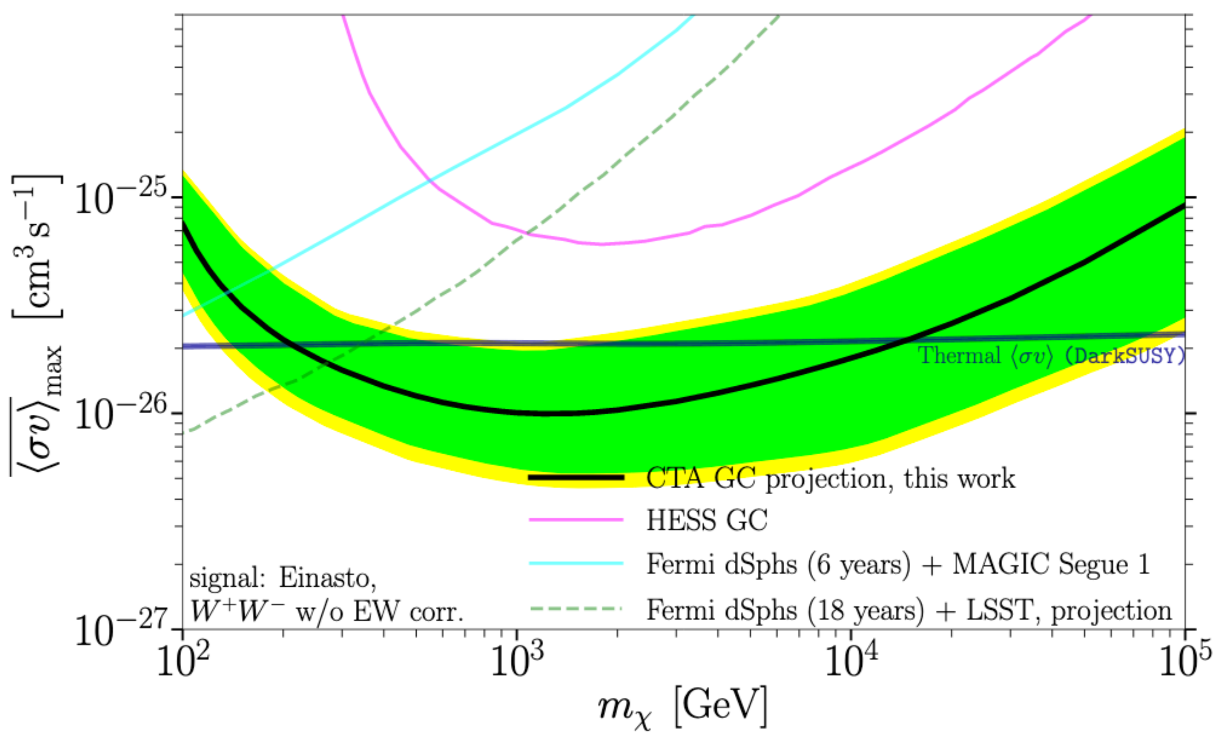


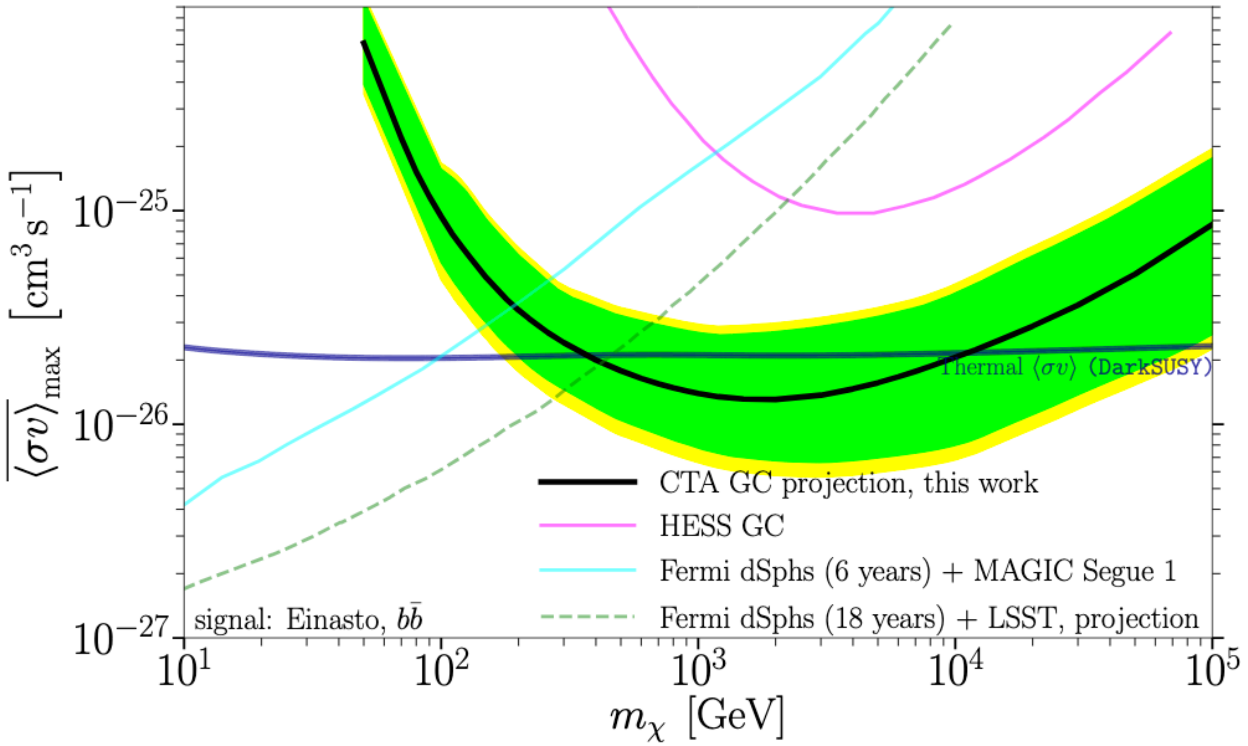


- **Galactic center survey**: 525 hours over first 10 years
- **Extended survey**: additional 300 hours

[CTAO Consortium: Archaryya et al. 2021]

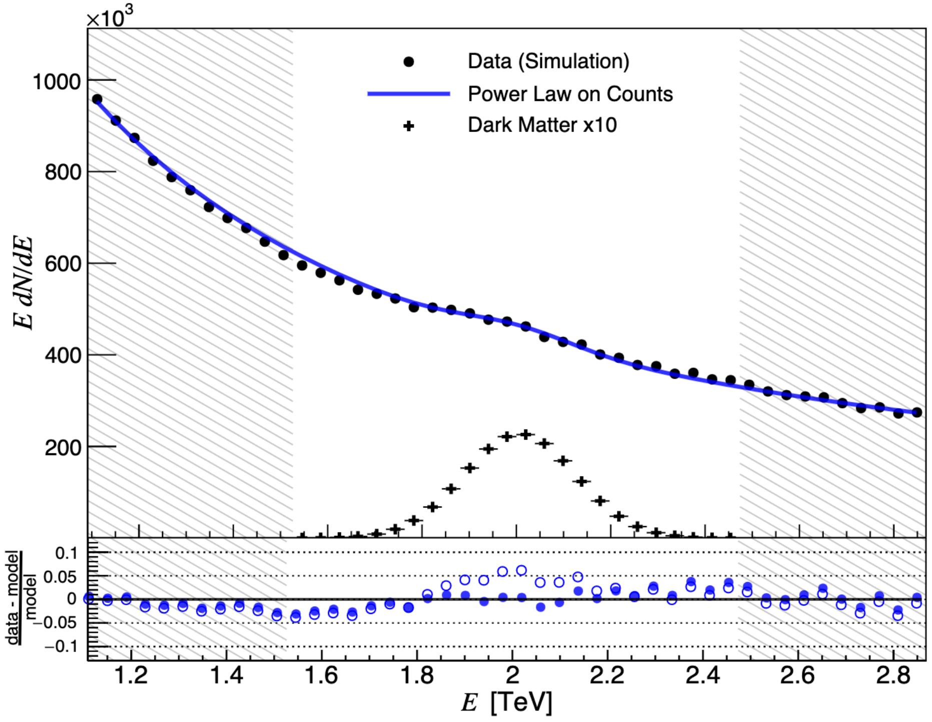
Projected CTA sensitivity for DM annihilation

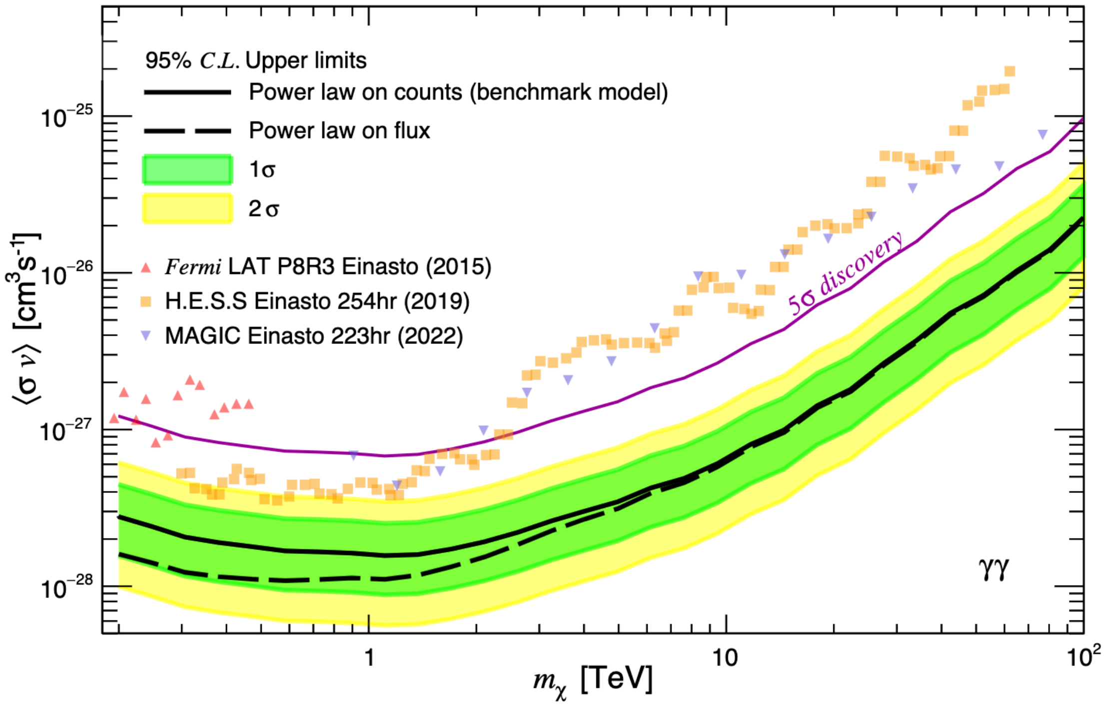




[CTAO Consortium: Archaryya et al. 2021]

Sensitivity for Dark matter annihilation line searches





[CTAO Consortium: Abe et al. (2024)]

Conclusions

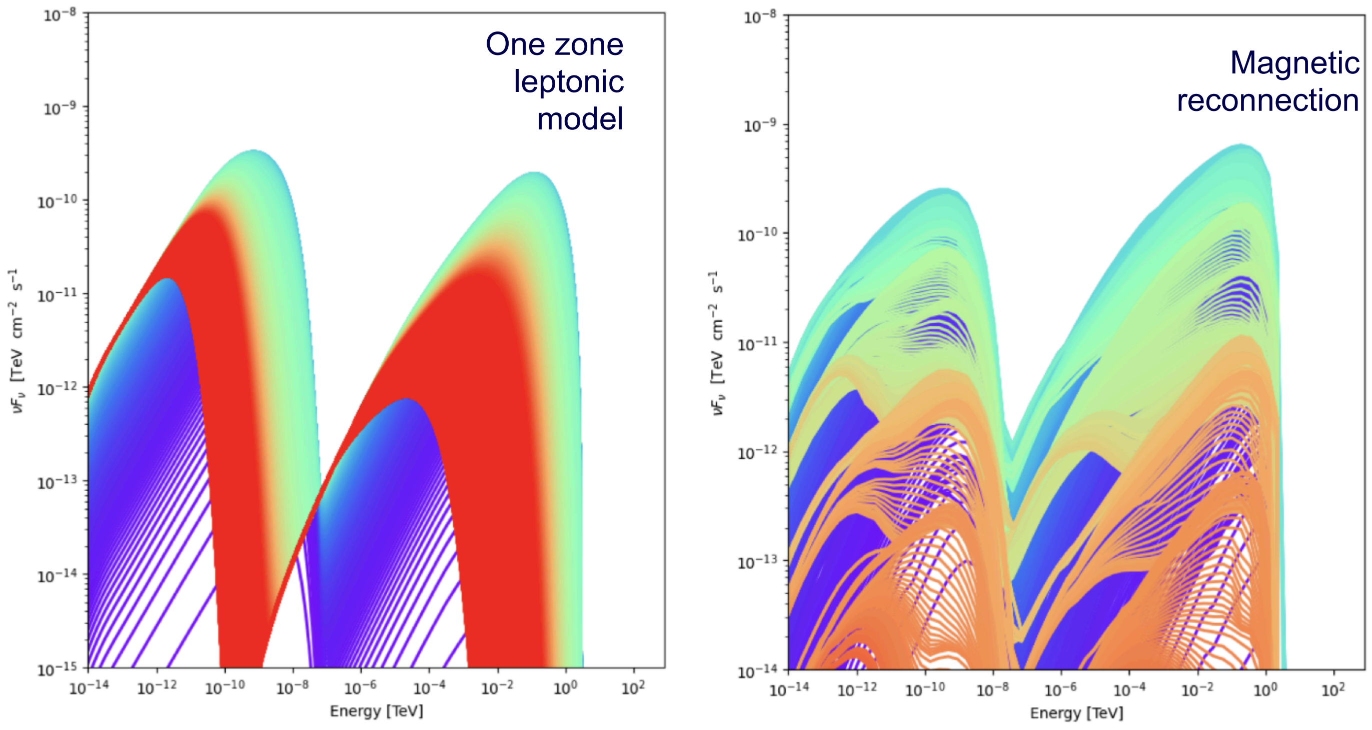
- CTAO is happening!
  - All LSTs under construction on Northern Site
  - Construction of first MSTs on both sites to begin 2025-2026
- Wealth of science discoveries awaits us:
  - Galactic hadronic PeVatrons
  - Galactic Transient Sources
  - AGN population and identification of emission mechanisms in blazars (see backup)
  - Probing gamma-ray propagation over cosmological distances (EBL, IGMF, axions)
  - Searches for TeV WIMP dark matter

Back up

Short term Blazar variability

- Assumed models:
  - one-zone leptonic model with power-law injection and radiative cooling (no specific acceleration mechanism)
  - Particle acceleration via magnetic reconnection
- Models tuned to reproduce variability observed from close-by blazar Mkn 421
- CTA observations can shed light on acceleration mechanism

Models: time-dependent spectral energy distributions

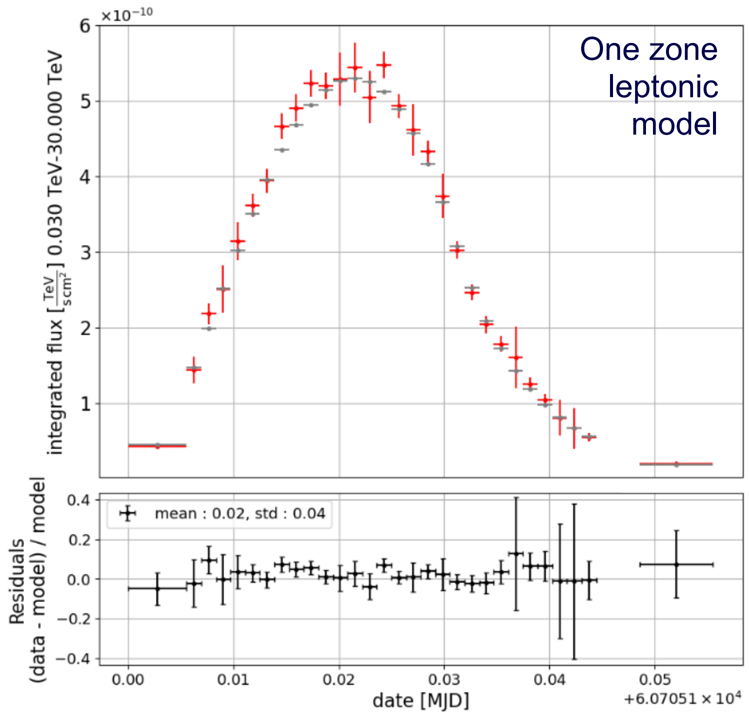


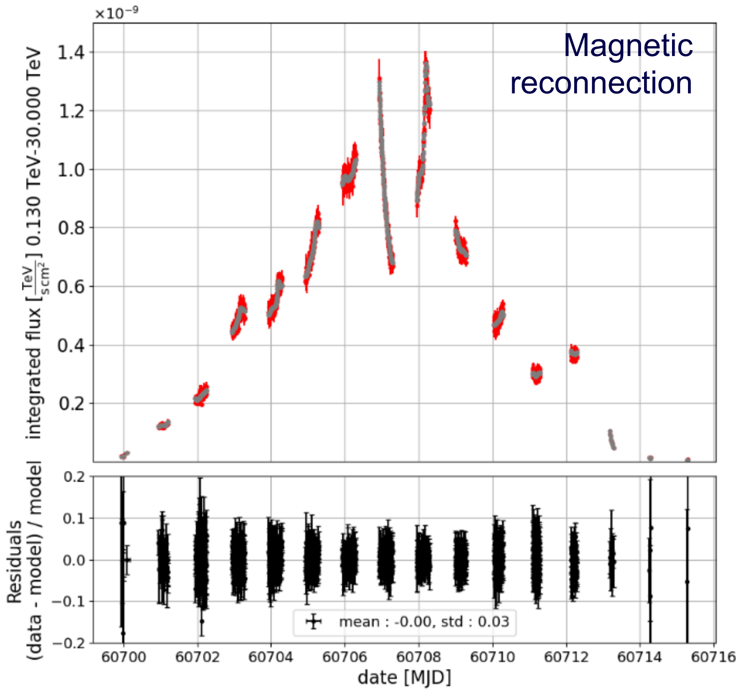
[Cerruti et al. (2023)]

Short term Blazar variability

- Assumed models:
    - one-zone leptonic model with power-law injection and radiative cooling (no specific acceleration mechanism)
    - Particle acceleration via magnetic reconnection
- Models tuned to reproduce variability observed from close-by blazar Mkn 421
- CTA observations can shed light on acceleration mechanism

Simulated light curves





[Cerruti et al. (2023)]

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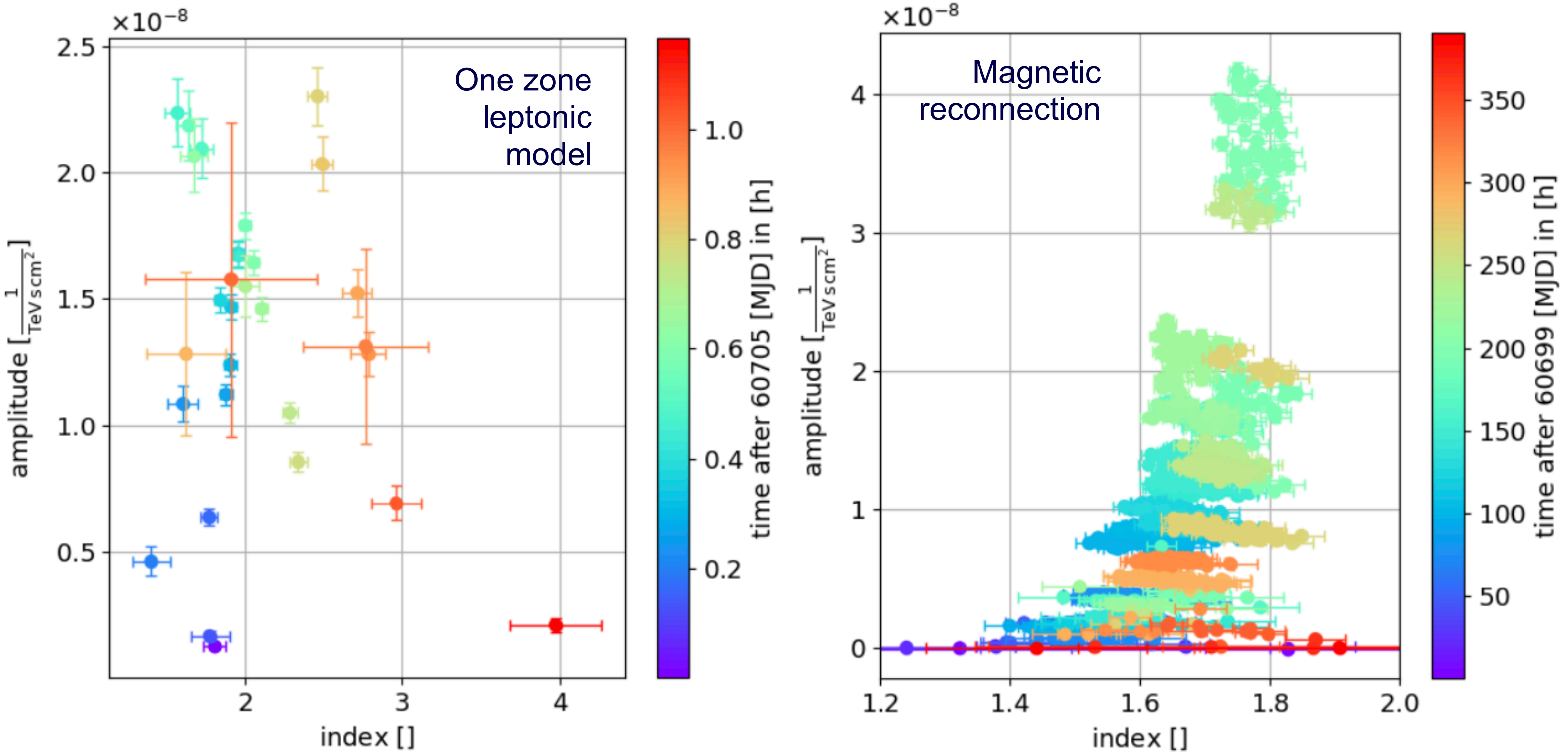
“Observed” spectral parameters



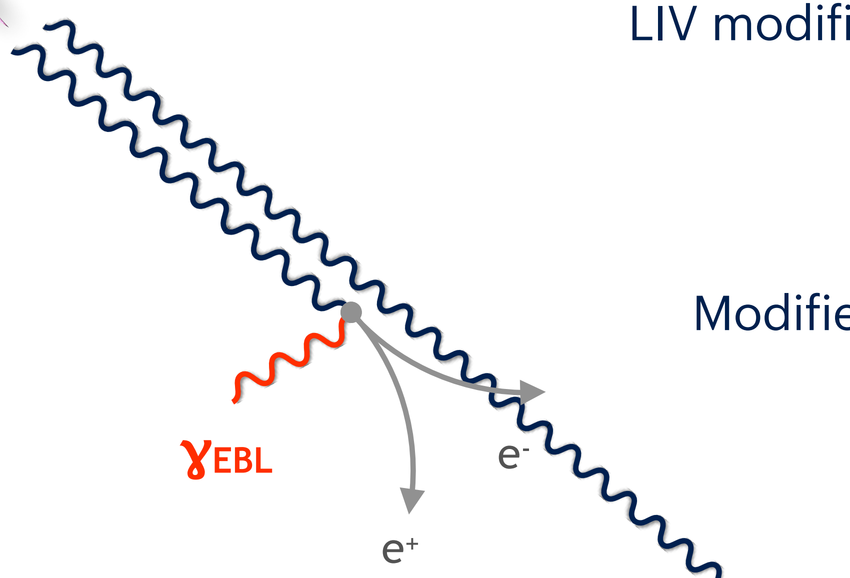
[Cerruti et al. (2023)]

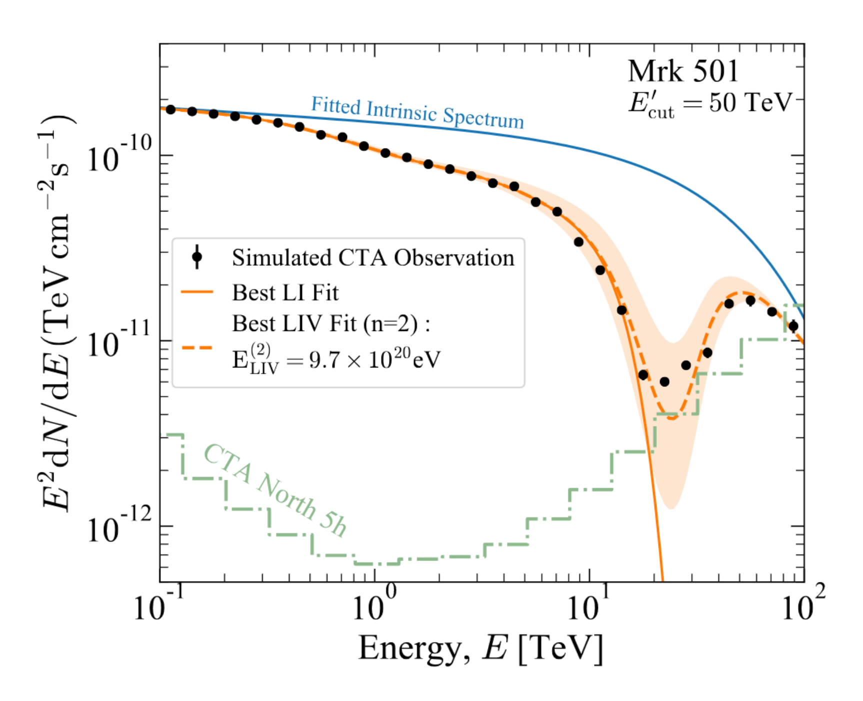
Searching for signatures of Lorentz invariance violation

LIV modifies dispersion relation of photon (subluminal case):

$$E_\gamma^2 - p_\gamma^2 = -\frac{E_\gamma^{n+1}}{E_{\mathrm{LIV}}^n}$$

Modifies the energy threshold for pair production





[CTAO Consortium: Abdalla et al. 2021]

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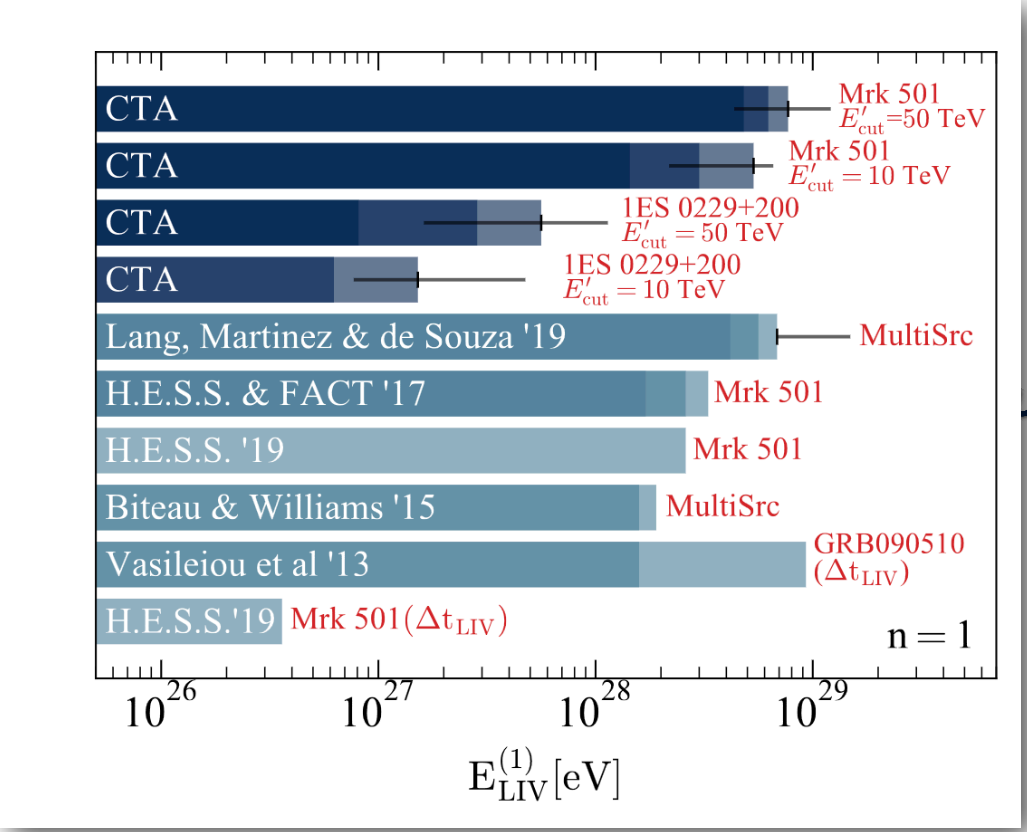
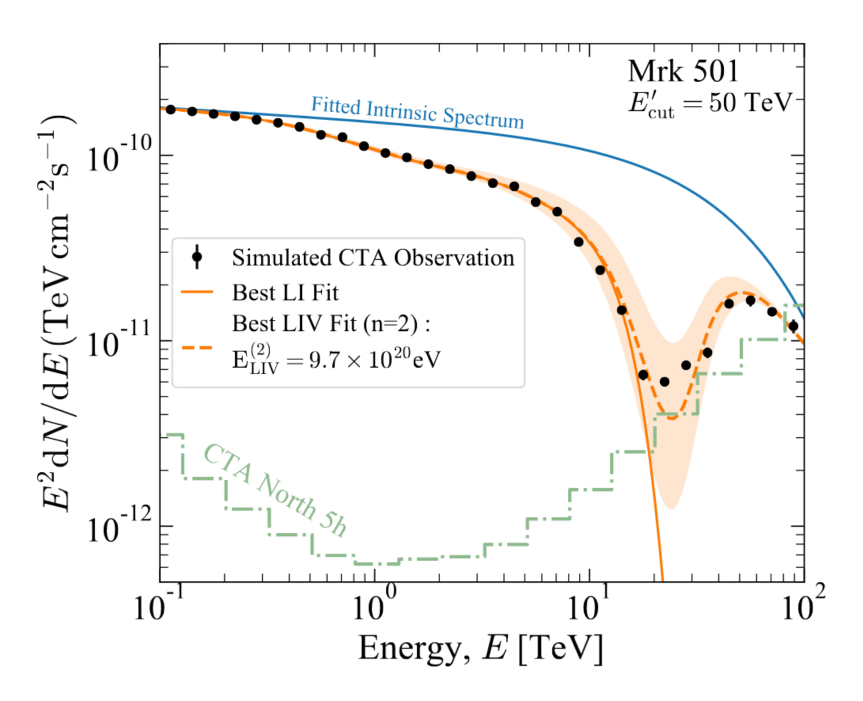
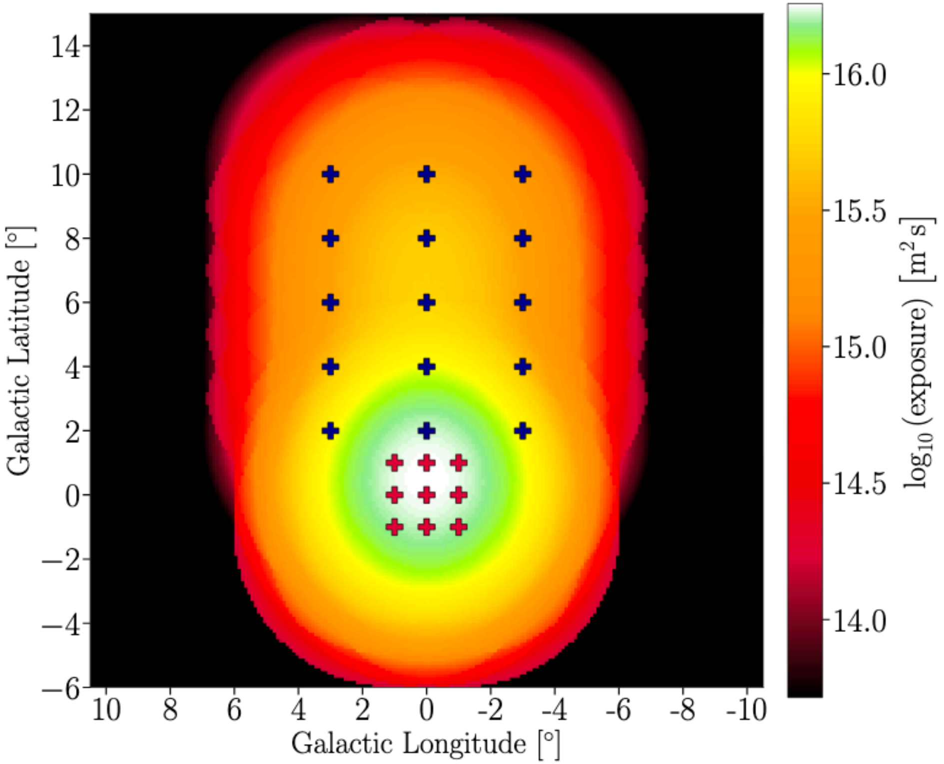




[CTAO Consortium: Abdalla et al. 2021]

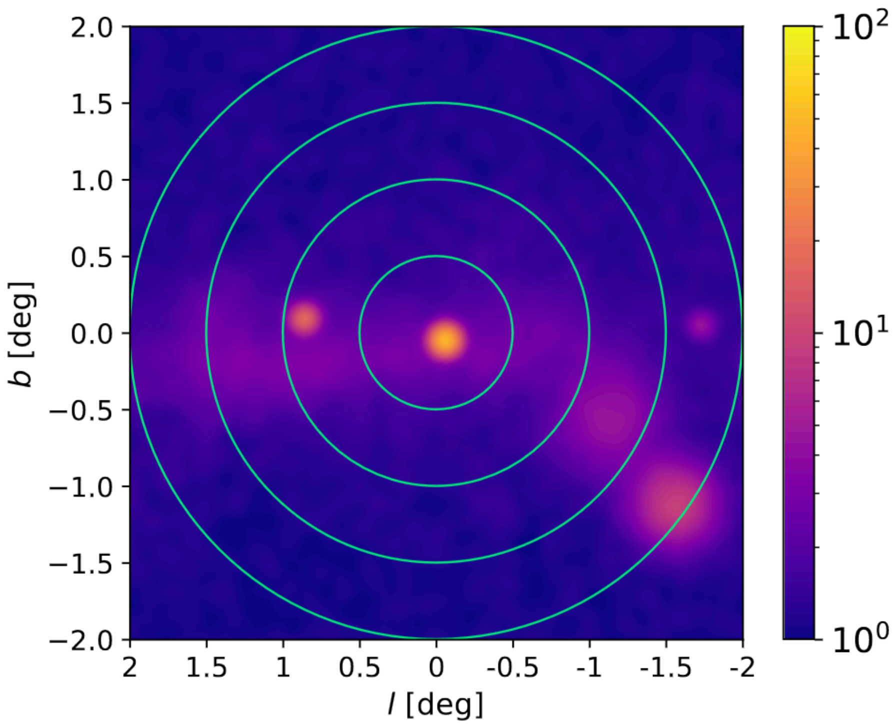
Foreseen CTA observations of the Galactic Center

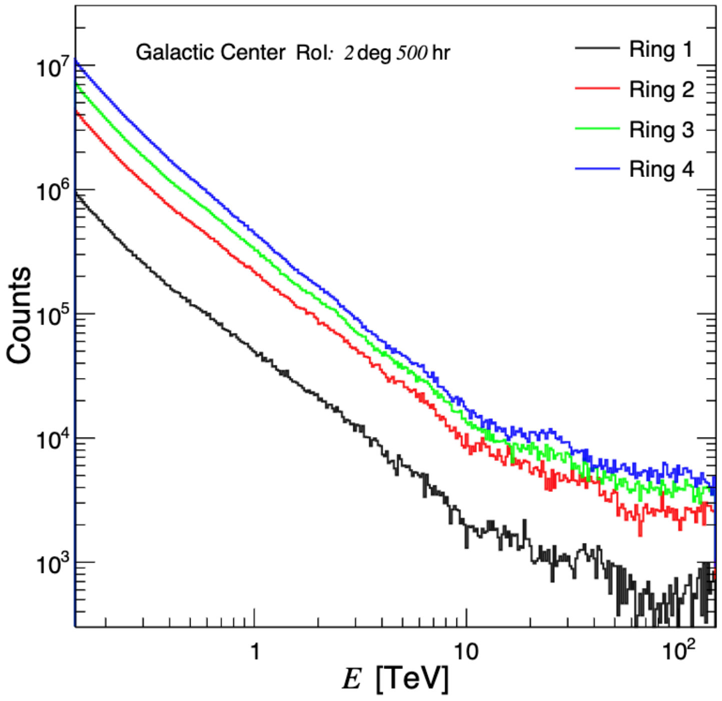
- **Galactic center survey**: 525 hours over first 10 years
- **Extended survey**: additional 300 hours



[CTAO Consortium: Archaryya et al. 2021]

Observational setup for DM line search

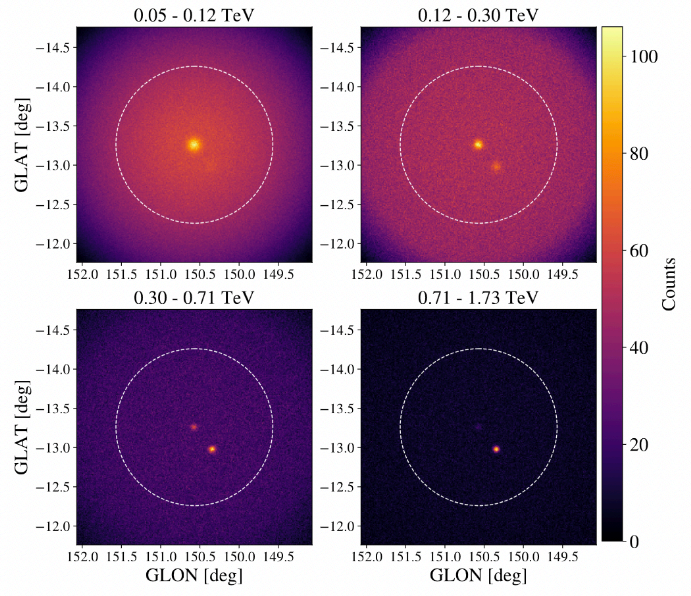


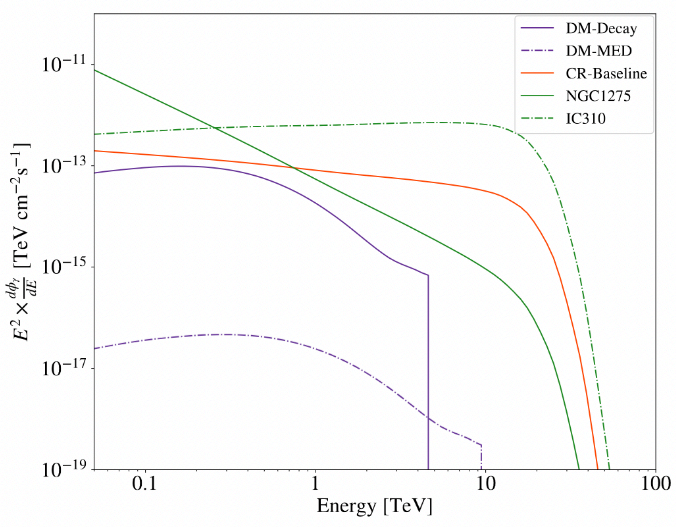


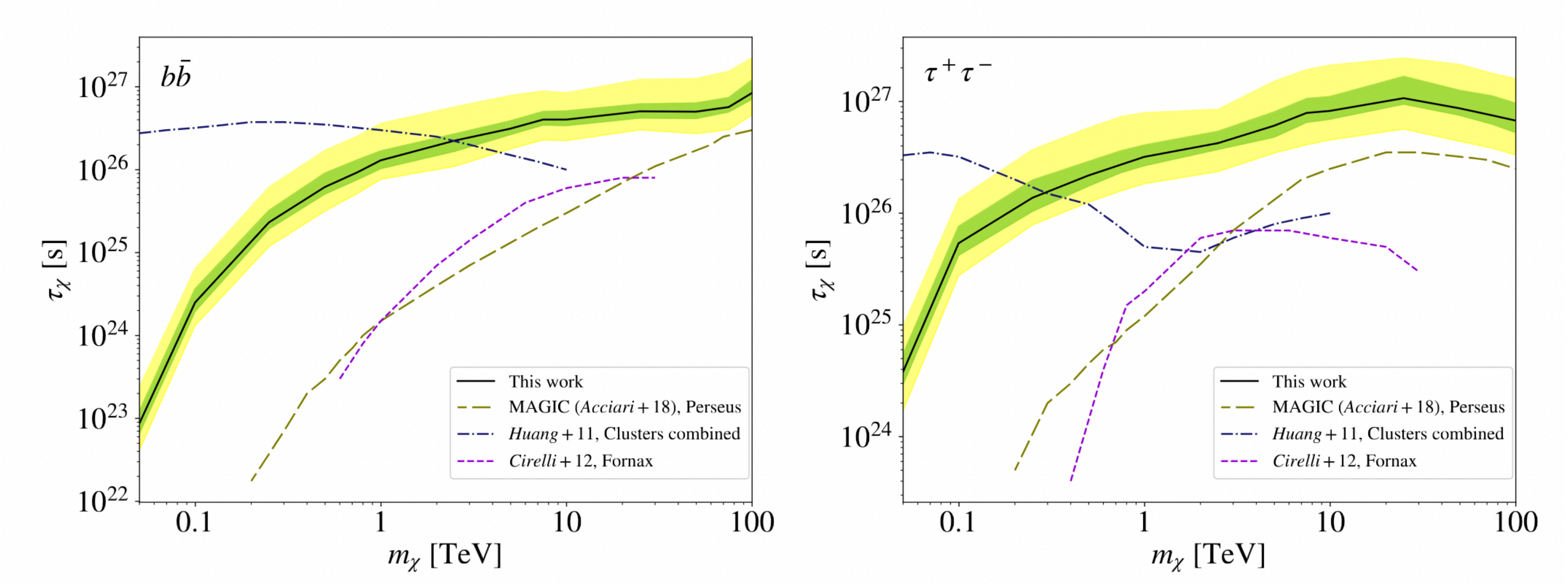
	Galactic Centre	dSphs
Exposure time	500 hr	100 hr per target
DM density profile	Einasto [7.1]	J-factors in Tab. 2
RoI and binning	4 rings of width 0.5°deg [A.2]	Single RoI per dSphs, 0.5°
Mask	none [7.2]	none
IEM	Base MAX [7.3]	none
Analysis method	Sliding energy window, PL assumption on counts	
Window size	$8\sigma_{\rm res}(E_0)$ [A.1]	
Systematic uncertainty	2.5%, per energy bin [7.4]	

[CTAO Consortium: Abe et al. (2024)]

Dark matter Decay sensitivity from Perseus







[CTAO Consortium: Abe et al. (2023)]