Title: Science Capabilities of the Cherenkov Telescope Array Observatory

Speakers: Dave Kieda

Collection/Series: Particle Physics

Subject: Particle Physics

Date: October 29, 2024 - 1:00 PM

URL: https://pirsa.org/24100133

Abstract:

The Cherenkov Telescope Array Observatory (CTAO) is the upcoming next-generation ground-based very-high-energy (VHE) gamma-ray observatory. The CTAO will significantly advance the study of VHE gamma-rays through a combination of wider field of view, substantially increased detection area, and superior angular and spectral resolution over an energy range extending from tens of GeV to hundreds of TeV. Full-sky coverage will be achieved using two independent Imaging Air Cherenkov Telescope (IACT) arrays: one in the northern hemisphere (Canary Islands, Spain) and one in southern hemisphere (Paranal, Chile). The CTAO will explore a wide range of science topics in high-energy astrophysics, including the origin of higher-energy cosmic rays, mechanisms for particle acceleration in extreme environments, and astroparticle phenomena that may extend the Standard Model of particle physics. In this talk, I will outline the broad science potential of the CTAO and provide the CTAO's current status and timeline. I will also describe the contributions of the CTAO-US collaboration to CTAO, including the development of an ultra-high resolution Schwarzschild-Couder telescope for VHE astronomy and the emergence of UV-band optical astronomy at the sub-100 micro-arcsecond angular scale.

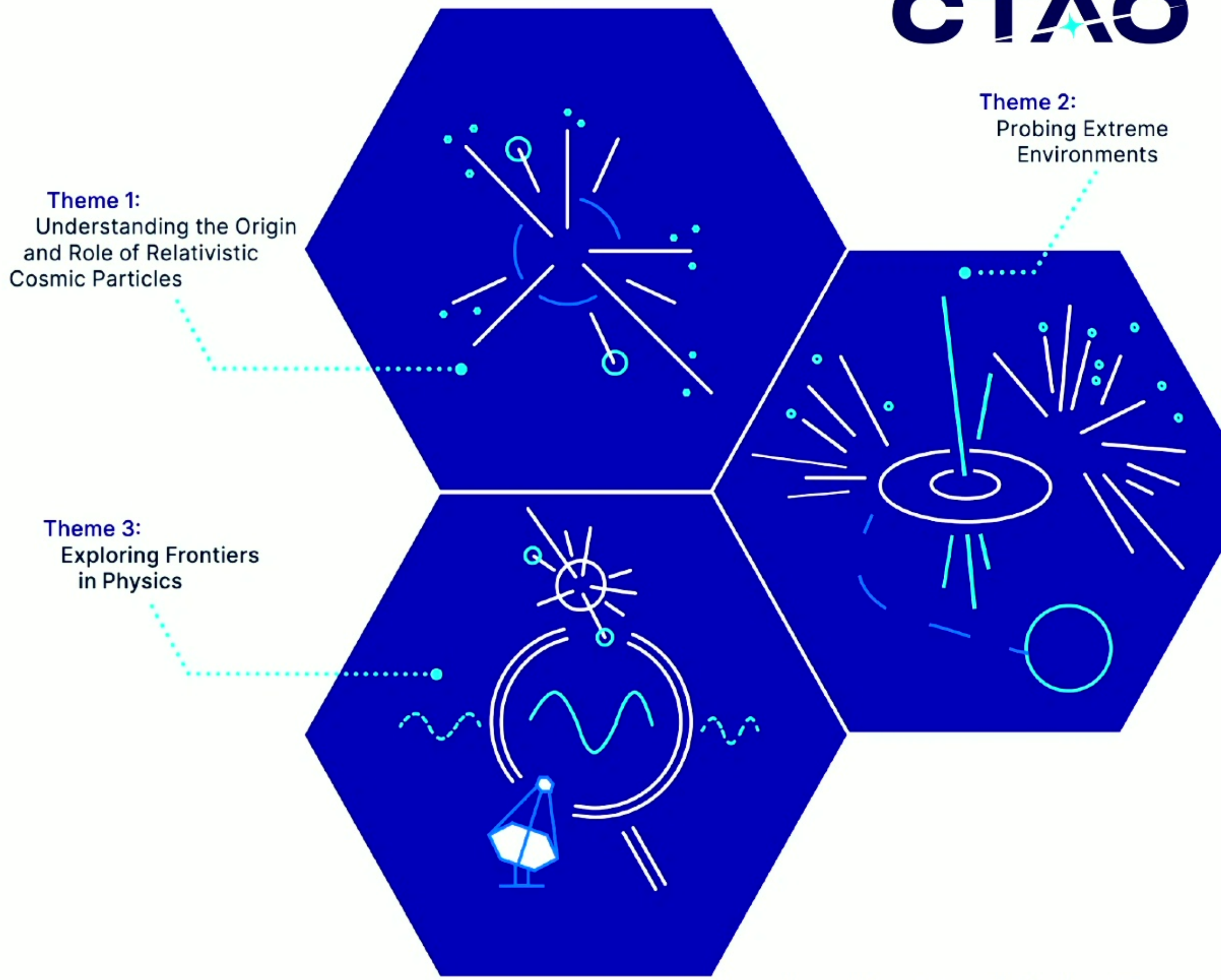

CTAO
Science Capabilities of the Cherenkov Telescope Array Observatory (CTAO)
High Energy Physics Seminar
Perimeter Institute, Waterloo, Ontario
October 29, 2024
Dave Kieda, University of Utah
Spokesperson, CTAO-US collaboration
dave.kieda@utah.edu

CTAO

1. CTAO Status
2. CTAO Sensitivity
   a) Galactic
   b) Extragalactic
   c) Fundamental Physics
3. CTAO-US Contributions

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]


Three types of telescopes
Medium-Sized Telescope (MST)
Core energies
E = 0.15 - 5 TeV
Large-Sized Telescope (LST)
Lowest energies
E = 0.02 - 0.15 TeV
Small-Sized Telescope (SST)
Highest energies
E = 5 - 300 TeV
23 m
1.8 m
4.3 m
11.5 m
3
Adapted from C. Aramo

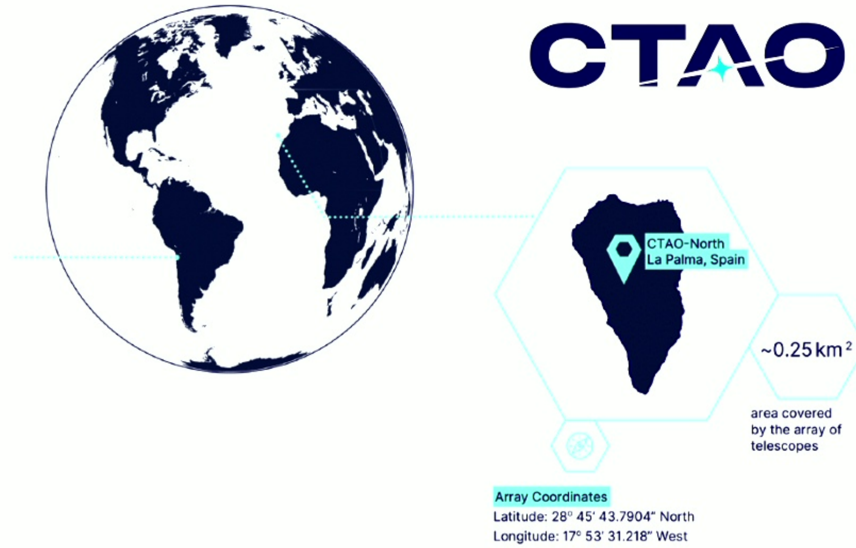
The CTAO Consortium

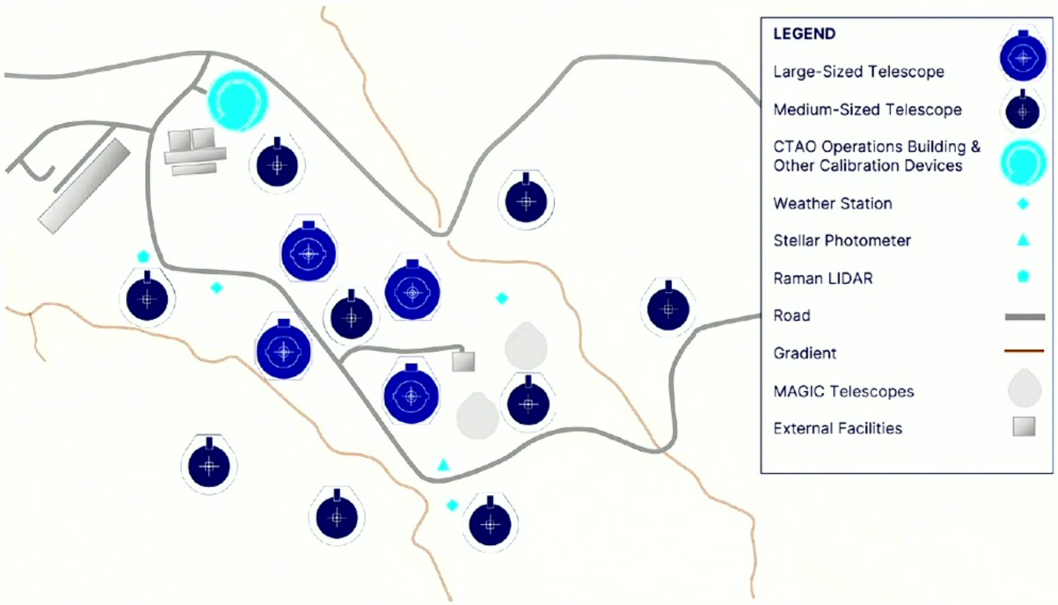
- More than 1400 scientists
- ~ 200 institutes
- 25 countries on 6 continents

CTAO locations

CTAO-Northern Array

Alpha Configuration

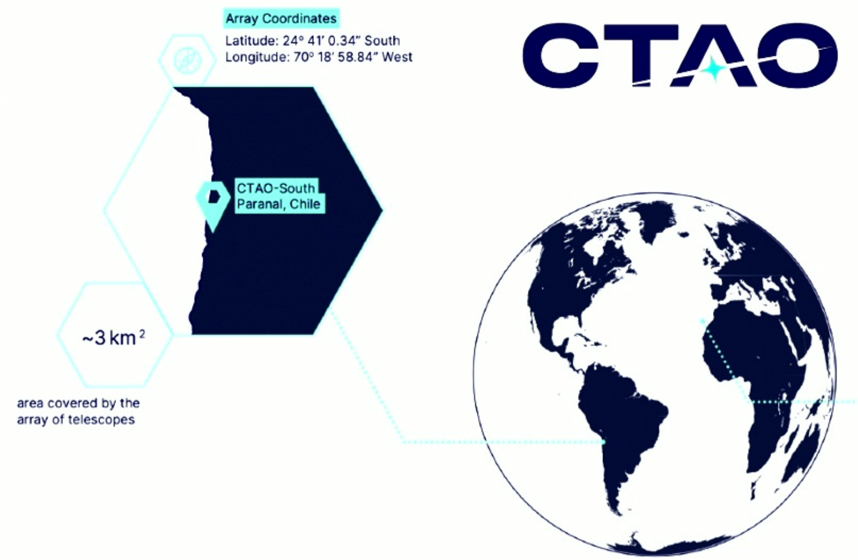




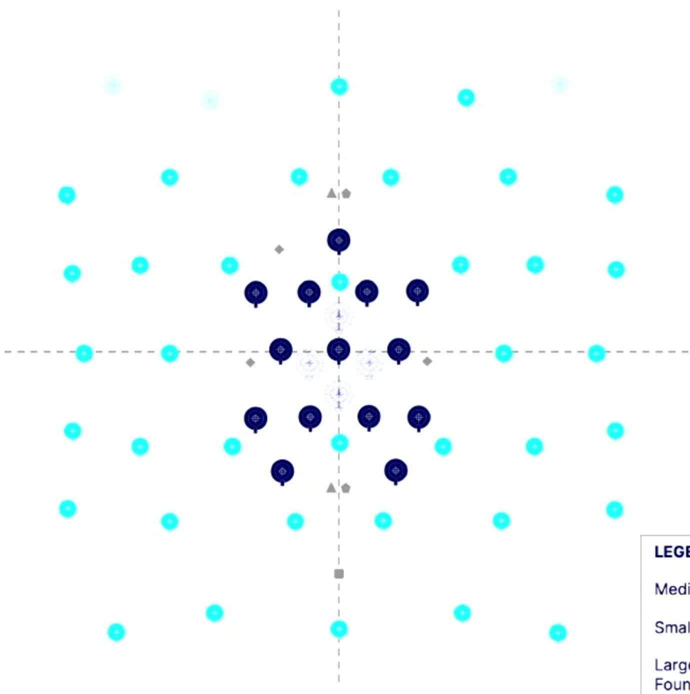
- Located at Observatorio Roque de los Muchachos (ORM), Spain
- 4 LSTs+ 9 MSTs

CTAO-Southern Array

Alpha Configuration



- Located at Atacama Desert, Chile
- 14 MSTs + 37 SSTs



LEGEND

Medium-Sized Telescope (MST)
Small-Sized Telescope (SST)
Large-Sized Telescope (LST) Foundation
SST Foundation
Weather Station
Stellar Photometer
Raman LIDAR
Other Calibration Devices

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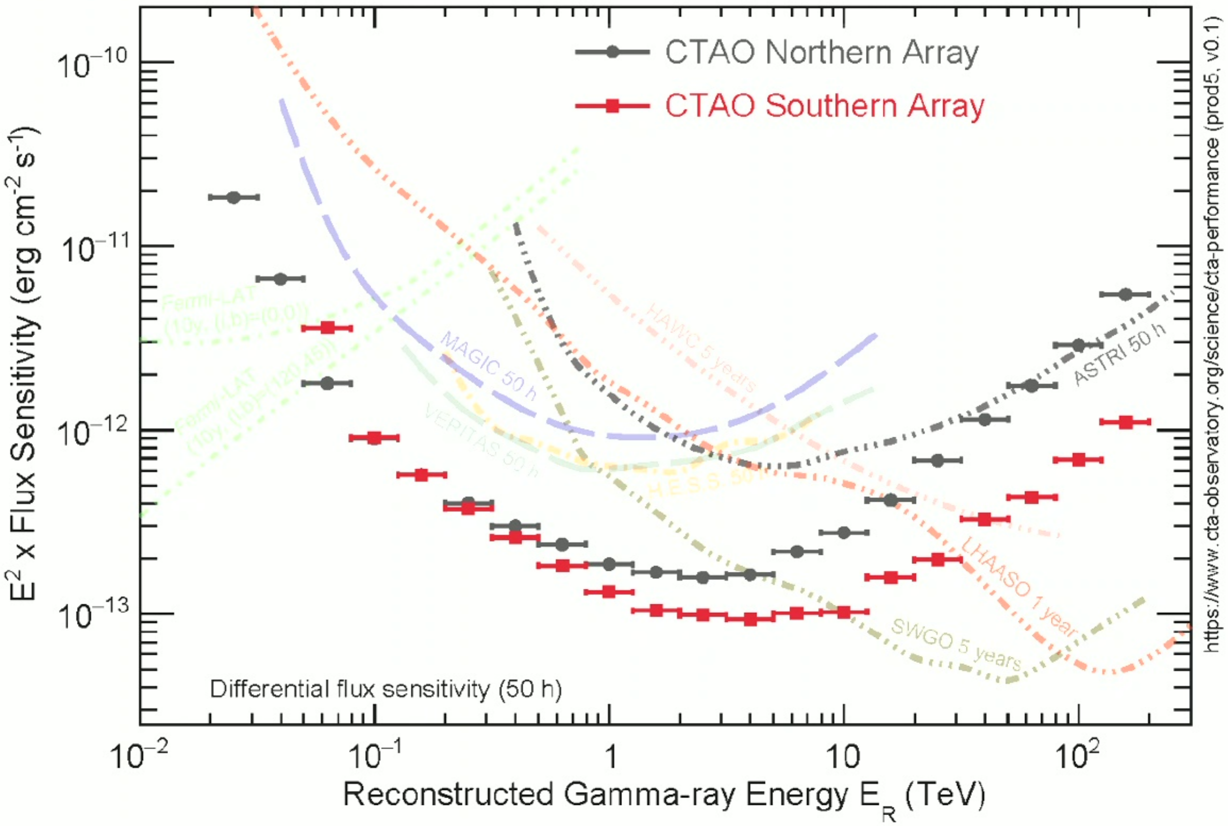
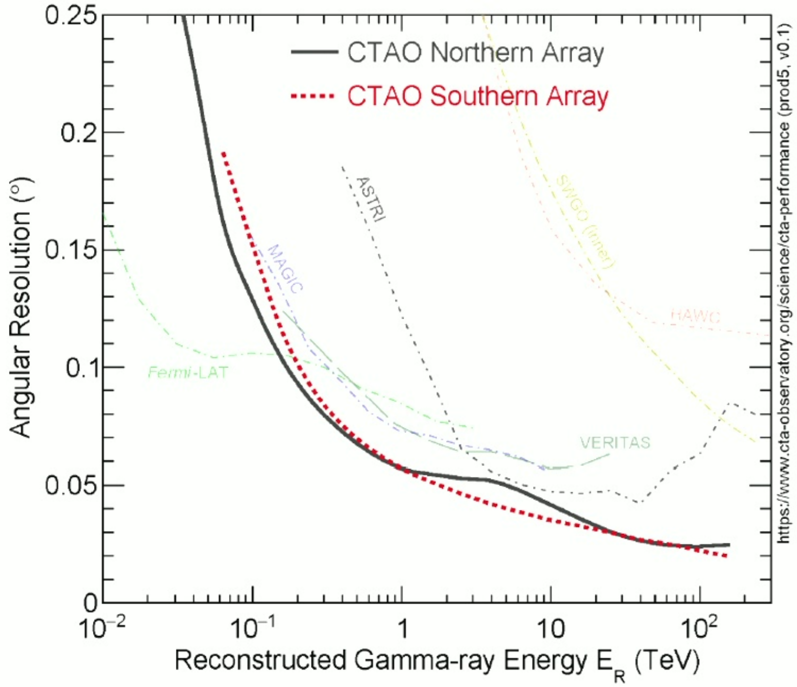
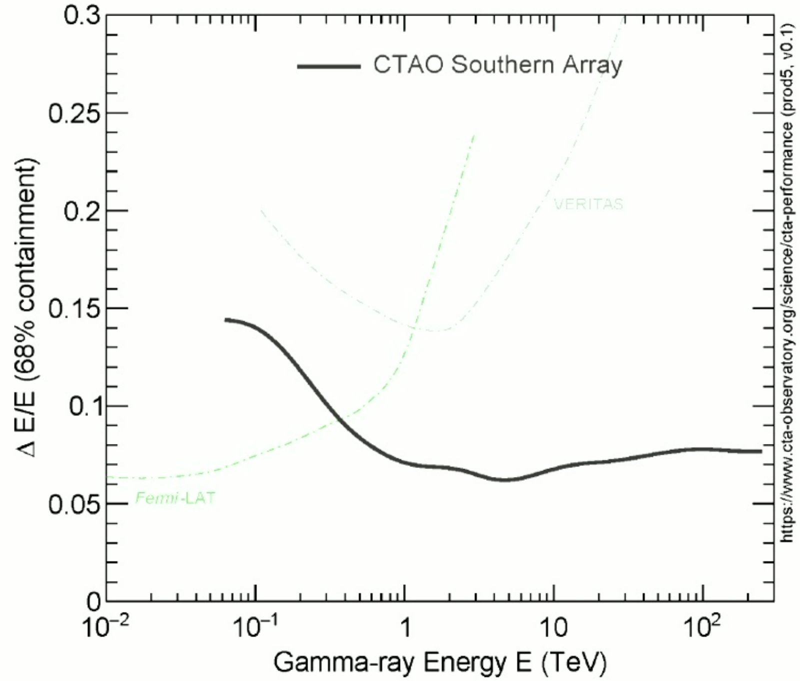
Sensitivity



Performance: angular and energy resolution





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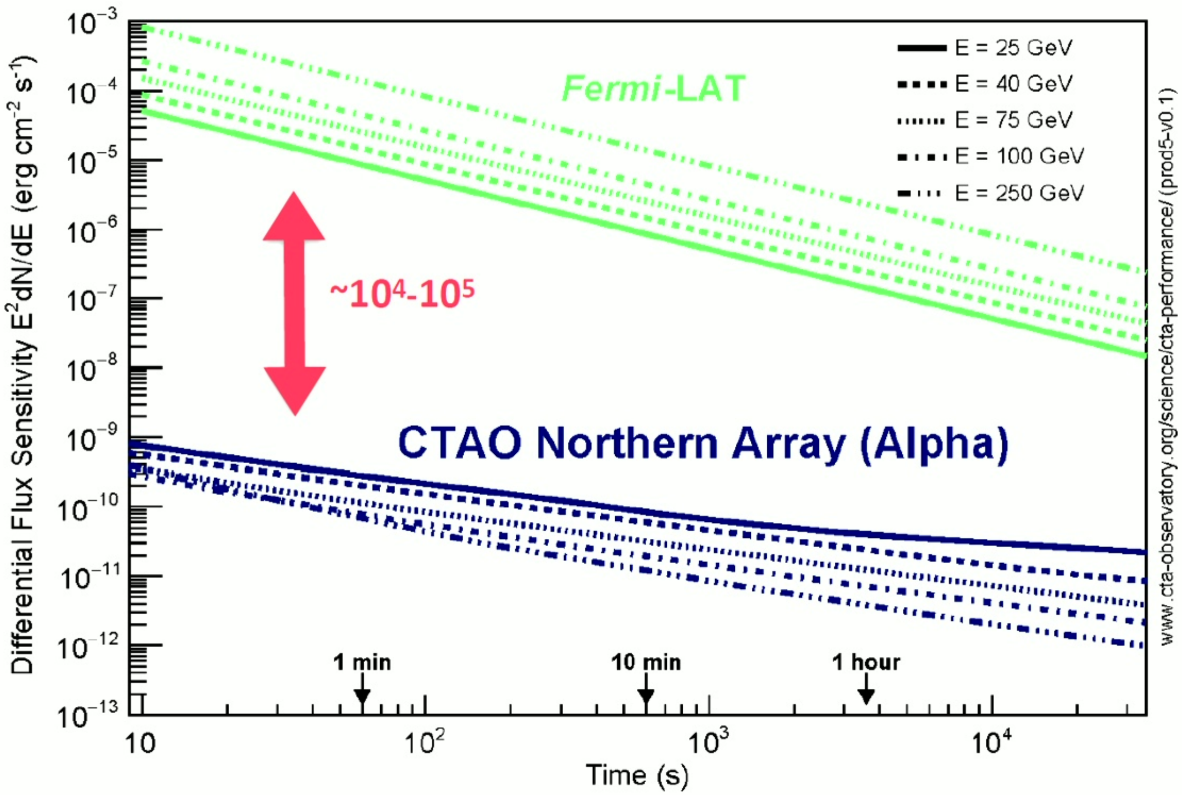
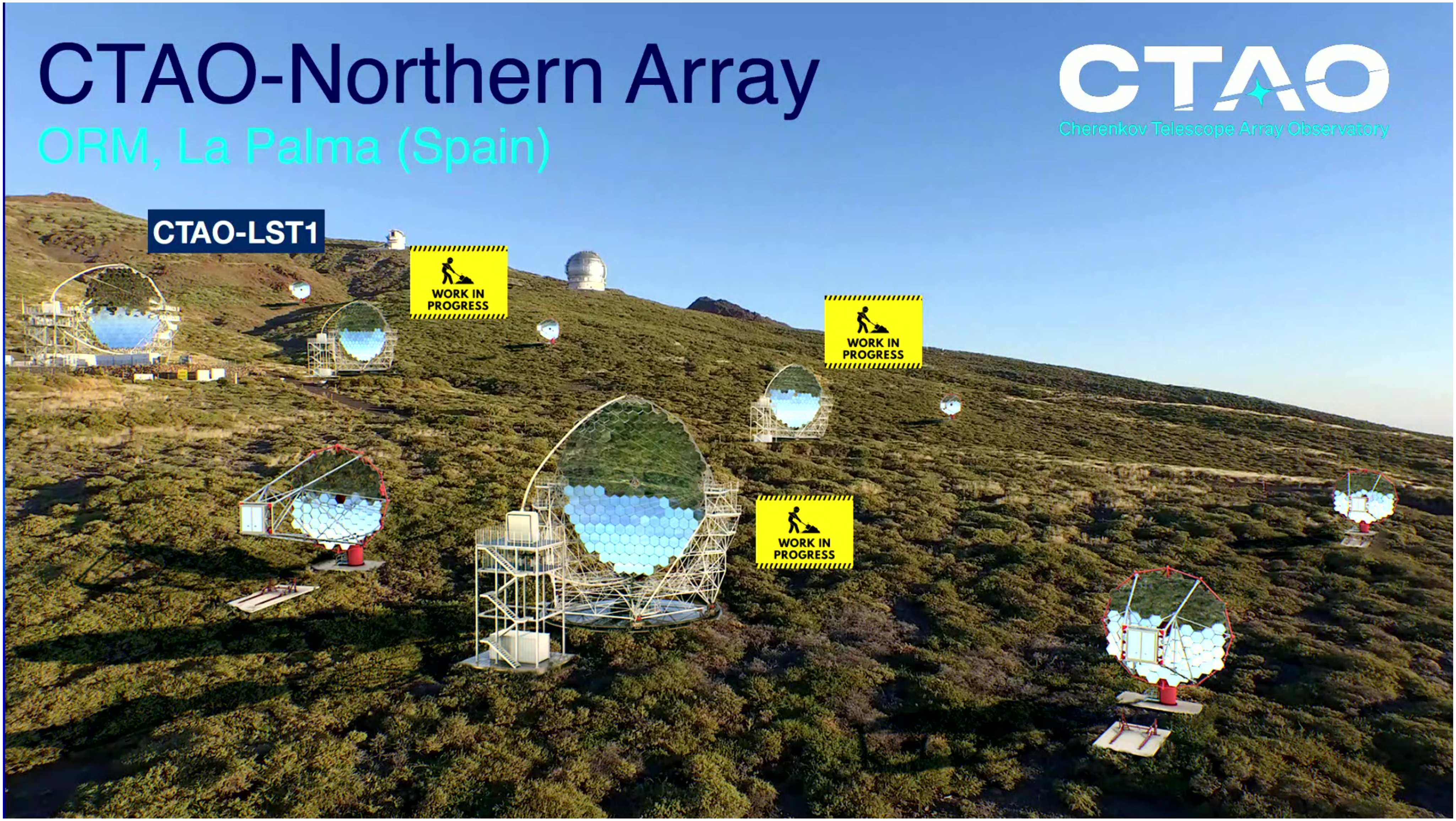
Short-time Sensitivity

CTAO

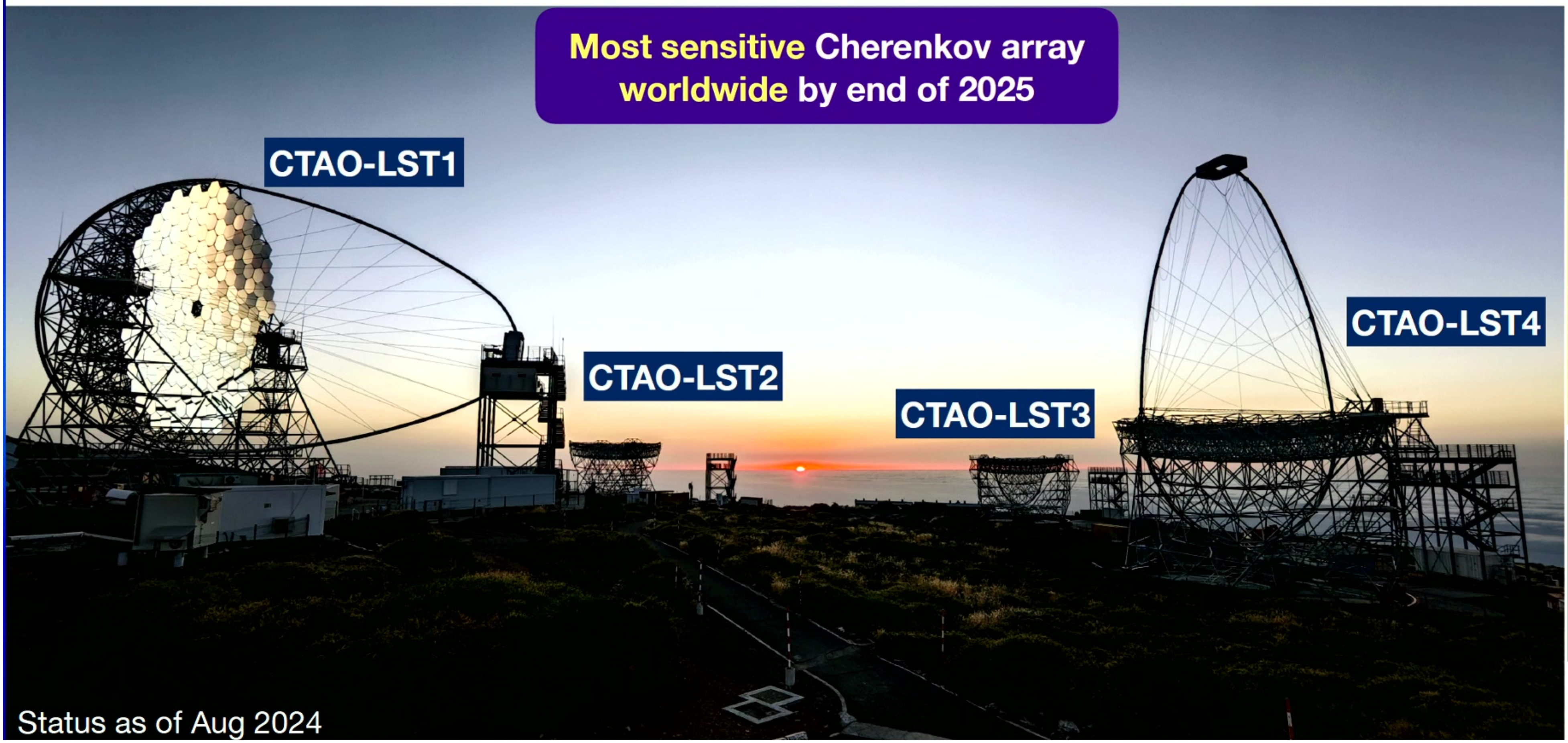


Optimal for transient detection

Current Status


CTAO-Northern Array
ORM, La Palma (Spain)
CTAO
Cherenkov Telescope Array Observatory
CTAO-LST1
WORK IN PROGRESS
WORK IN PROGRESS
WORK IN PROGRESS

CTAO | LST COLLABORATION (+400 scientists and engineers from 67 institutions, 12 countries)



Unión Europea
Fondo Europeo de desarrollo Regional
"Una manera de hacer Europa"

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Gobierno de Canarias
Agencia Canaria de Investigación, Innovación y Sociedad de la Información

CABILDO DE TENERIFE


CTAO-Southern Array
Paranal (Chile)

CTAO-Southern Array

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

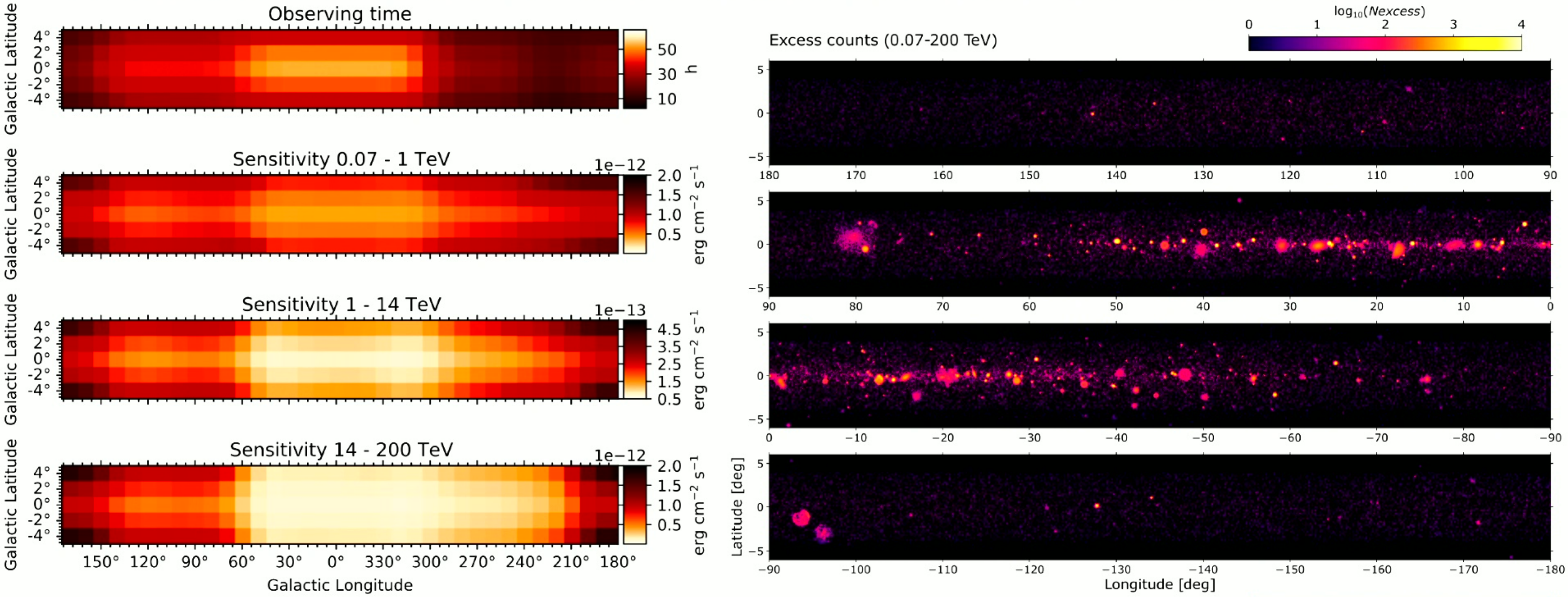
Adapted from S. McMuldroch

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

Survey of the Galactic Plane

- Total of 1620 hours spread over ten years
- Potential to increase the number of Galactic VHE emitters by a ~ factor of five



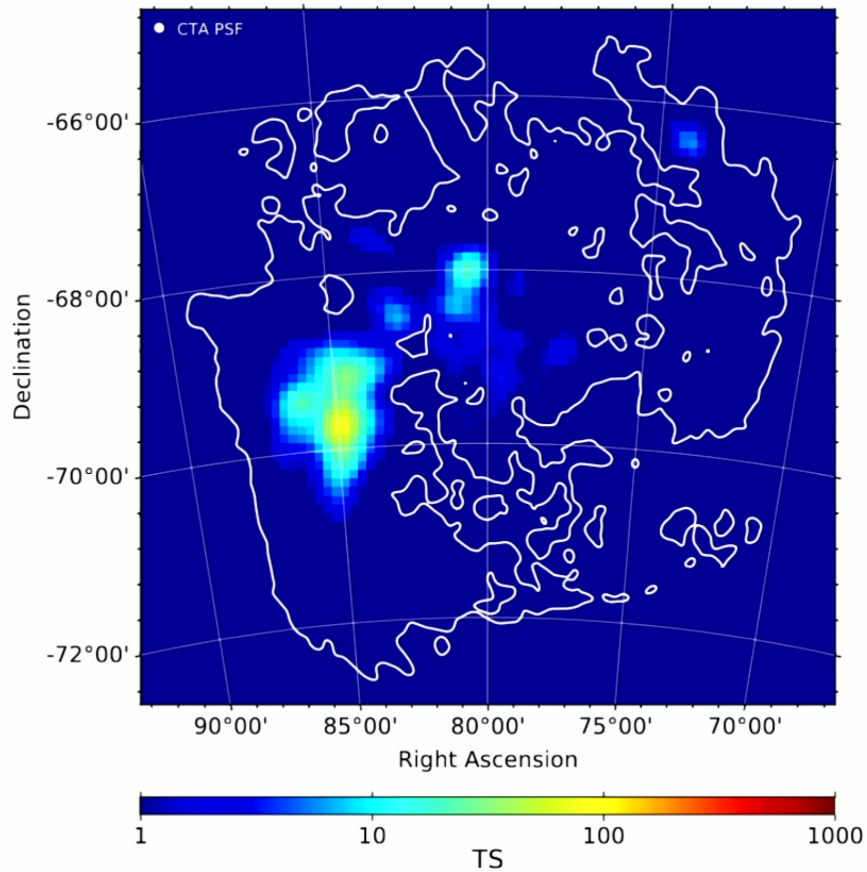
CTAO Consortium (accepted in JCAP) arXiv:2310.02828

500 sources expected

Survey of the Large Magellanic Cloud

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

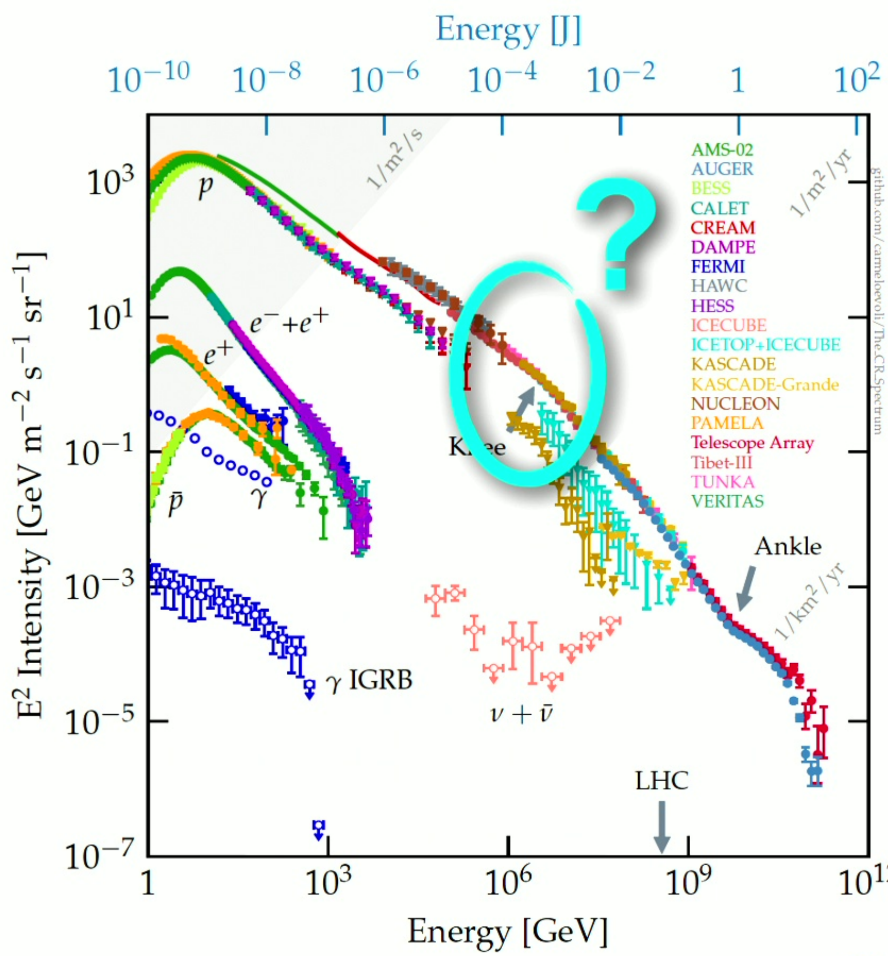
Simulated detection significance (for spectrally hard emission scenario)



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

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 $p + p \to \pi + X$, 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



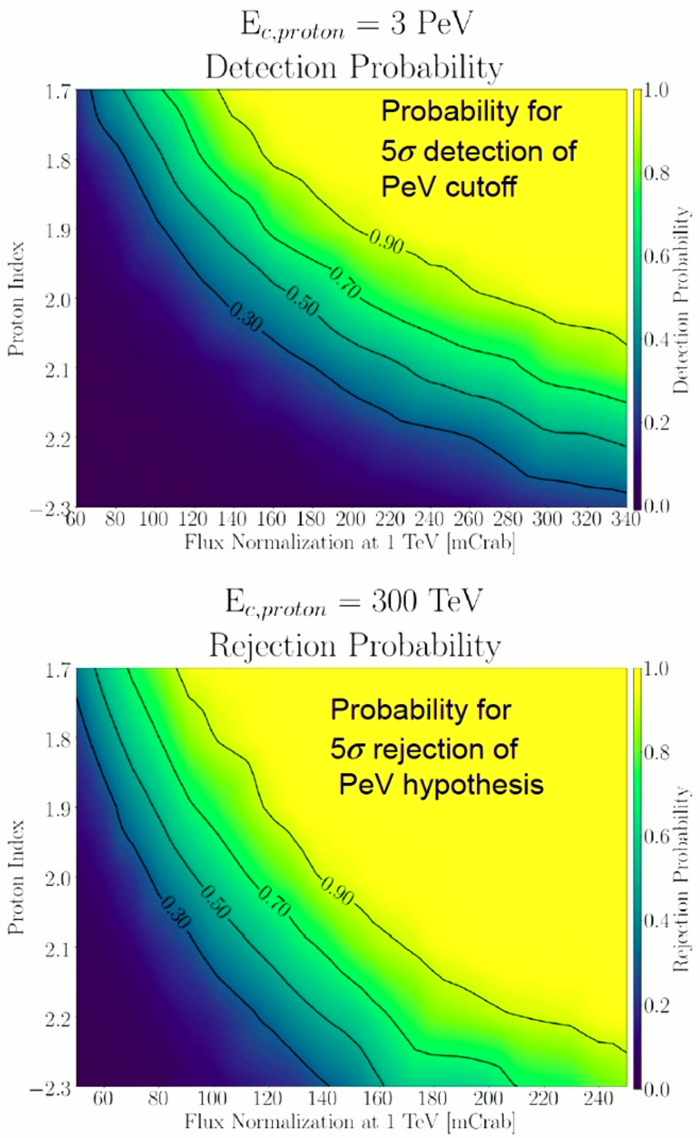
[e.g., Cardillo & Giuliani 2023 for a review]

CTAO

Could CTA 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
- 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)]



CTAO

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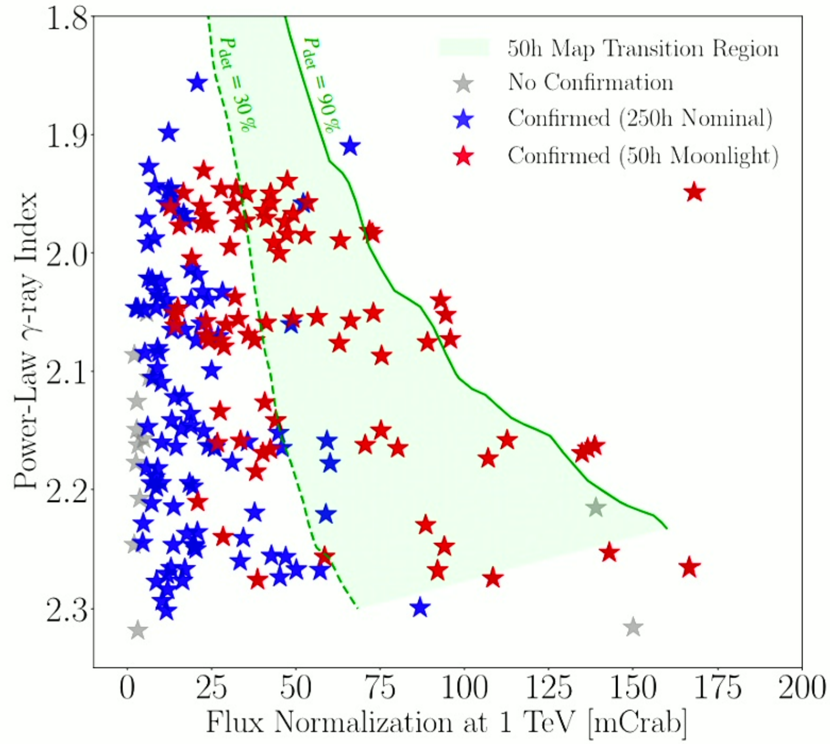


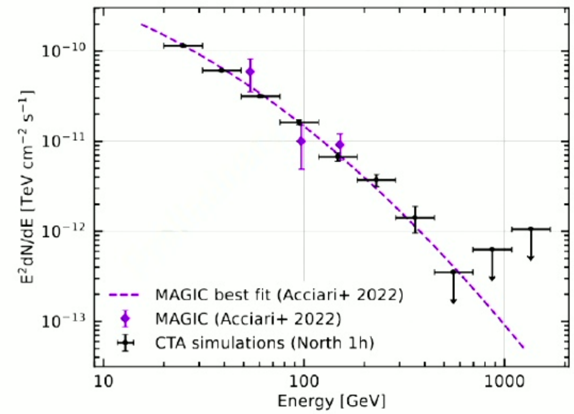
[CTAO Consortium: Acero et al. (2023)]

Galactic Transient Sources

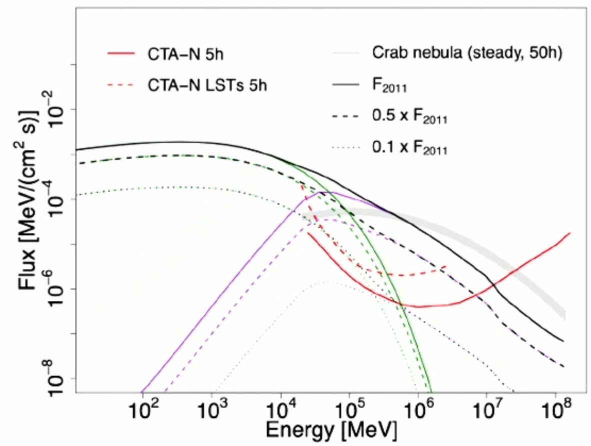
- Microquasars like Cyg X-1 and Cyg X-3, SS 433
- Flares from Crab Nebula with LSTs in less than 1 hour of observation time
- Close-by novae like re-current RS Oph

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

RS Oph 1 day after outburst

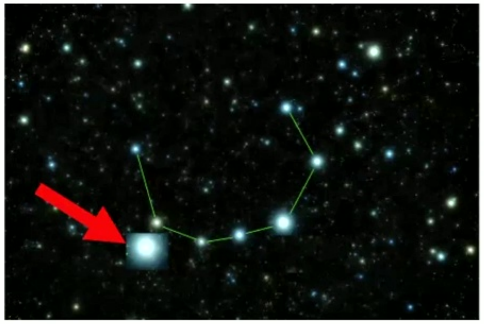


Crab Nebula flares



T Coronae Borealis: Another recurrent nova

CTAO



Symbiotic Binary: RG + WD
M_{WD}=1.37 $M_{\odot}$
M_{RG} = 1.12 $M_{\odot}$

Distance = 806 pc

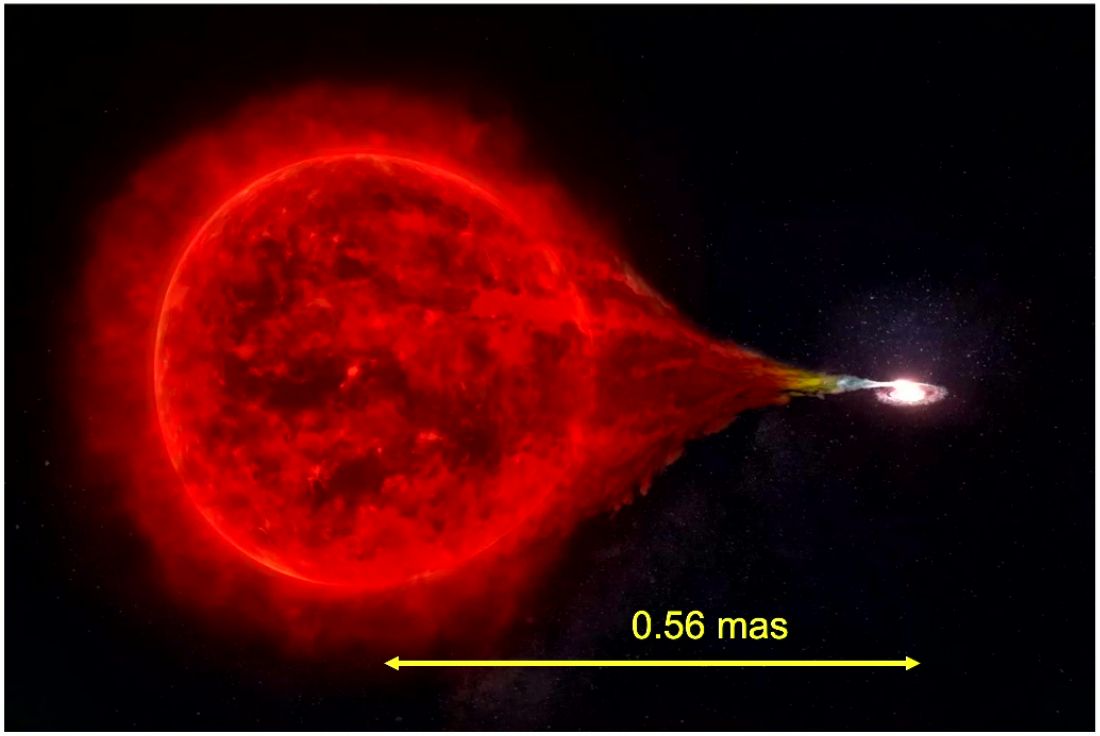
Orbital Period = 227 day
separation a = 0.54 AU
eccentricity = 0
inclination i = 67^0

Angular separation = 0.56 mas

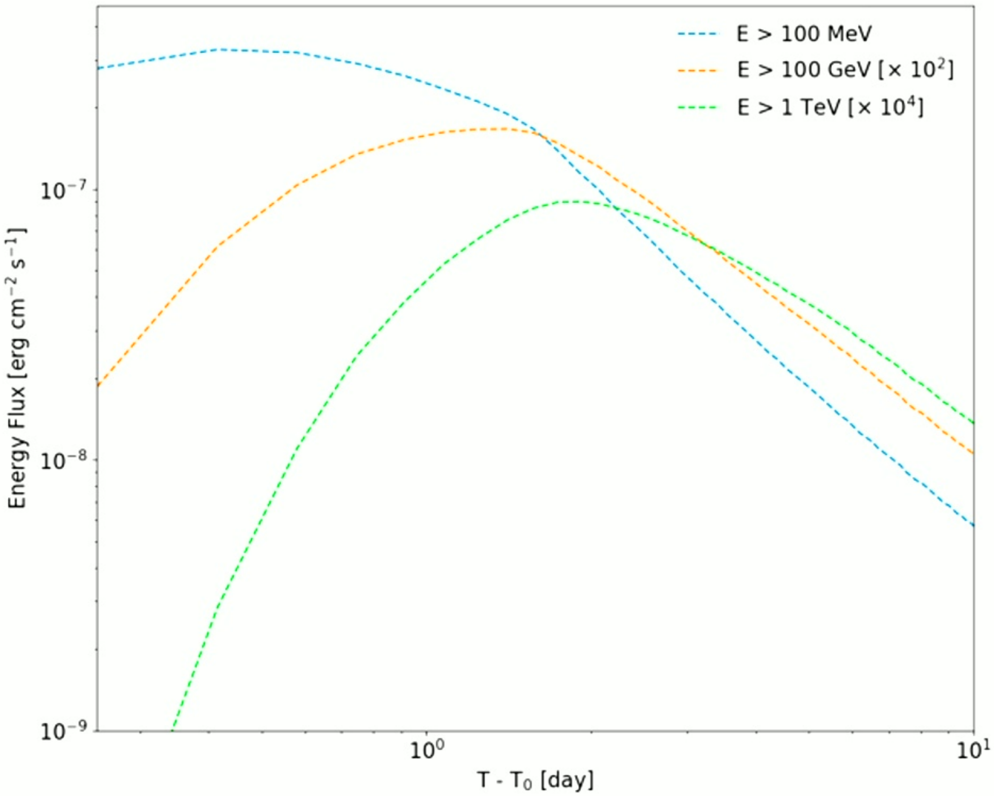
Quiescent V = 10+

Recurrent Nova (V= 2.0) every ~80 years

"Recent" Outbursts 1866, 1946
Some Evidence of Outburst 1787, 1217(!)
[See Brad Schafer's Sep 2023 AAVSO YouTube talk]



T Cor Bor GeV/TeV emission



D. Green, MPI Physics

Expect similar time dependent GeV/TeV emission

Expect peak T Cor Bor GeV/TeV to be >4x brighter than RS Oph

Expect faster evolution that RS Oph (1-2 days between GeV to TeV peaks)

Need to observe in VHE immediately when it goes off….

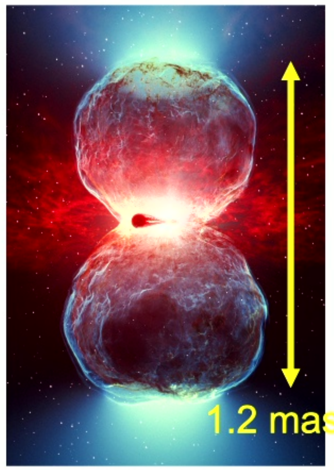
T Cor Bor Expansion Time

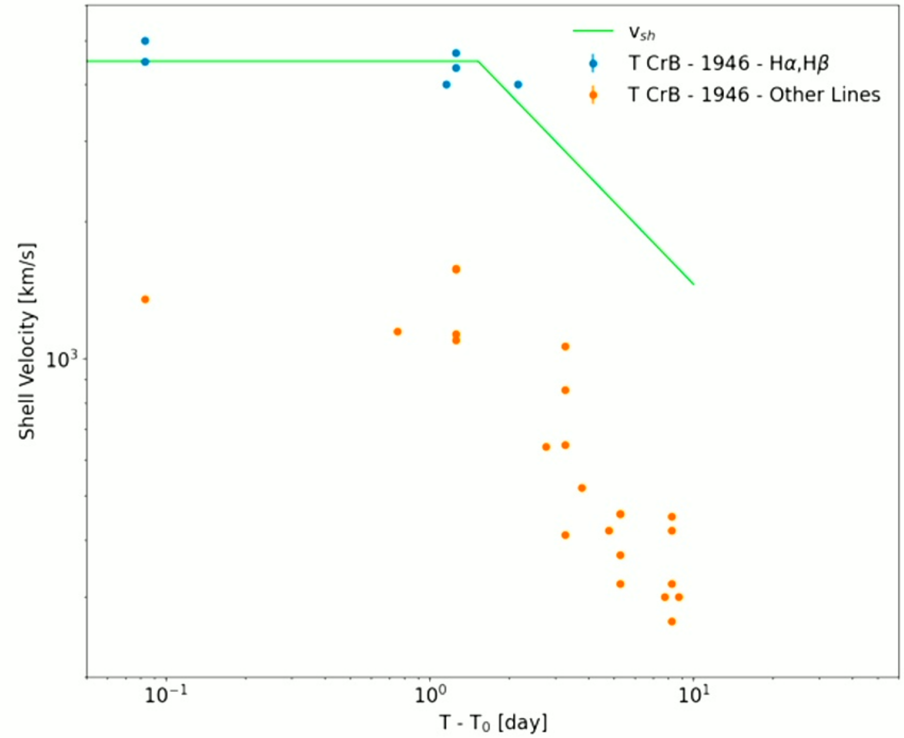
Hα , Hβ ~ 4000 km/sec
Expansion to 1.2 mas
~8 hours

But N, O, Si, Fe ~ 1000 km/sec
32 hour expansion?

What is the driving material?

Other angular scales may have longer timescales





Morgan, W. W., and Deutsch, A. J., 1947, Ap. J., 106, 362.
Herbig, G. H., and Neubauer, E. J., 1946, P, A. S. P., 58, 196.
McLaughlin, D. B., 1946, P. A. S. P., 58, 159.
Sanford, R. F.. 1947, P. A. S. P., 59, 87, 334.
Bloch, M., Dufay, J., Fehrenbach, C., and Tcheng Mao-Lin, 1946, Ann. d'Ap., 9, 157.

D. Green, MPI Physics

Current SII Instrument sensitivity

$M_V = 2.0$
>SII measures angular scale to 10%
in a few hours

Wavelength : 400-500 nm
Projected Telescope separation: 50-120 m
>Angular scales probed : 0.4-1.4 mas

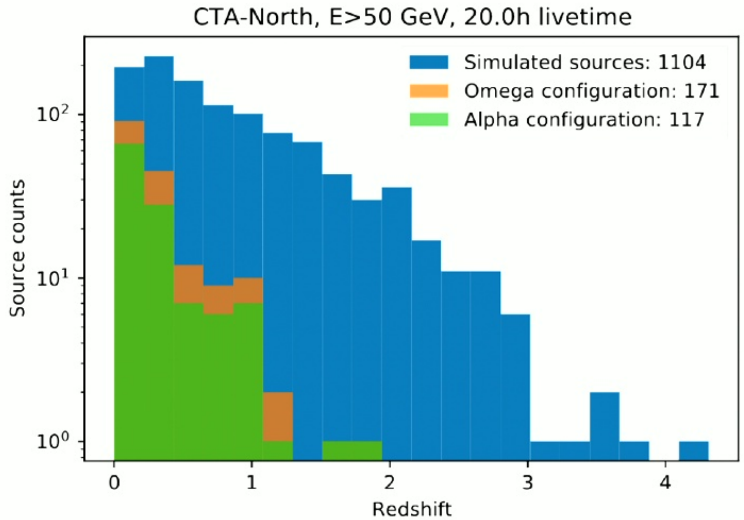
SII Needs to catch it early (10-30 hours):
✓ Bright
✓ Small angular scale

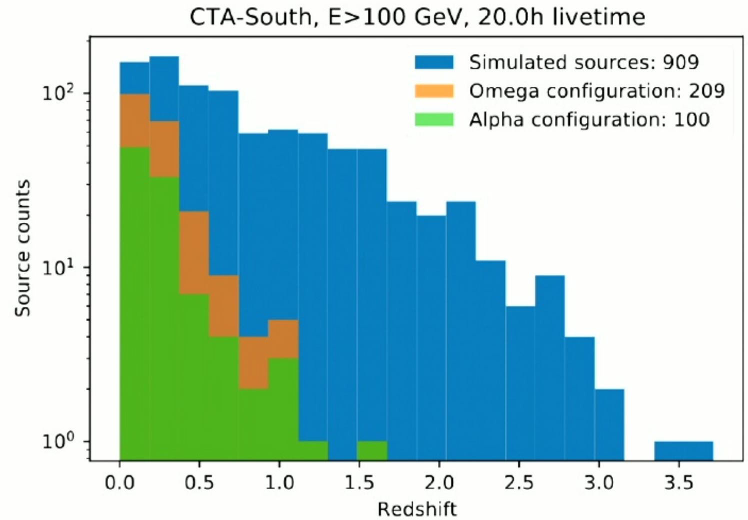
Competes with desire to observe GeV/TeV gamma-ray emission/evolution

Some luck needed as well:
✓ *start time (dusk/night)*
✓ *weather (good)*

CTAO: enough telescopes
To do both VHE & SII!

AGN population





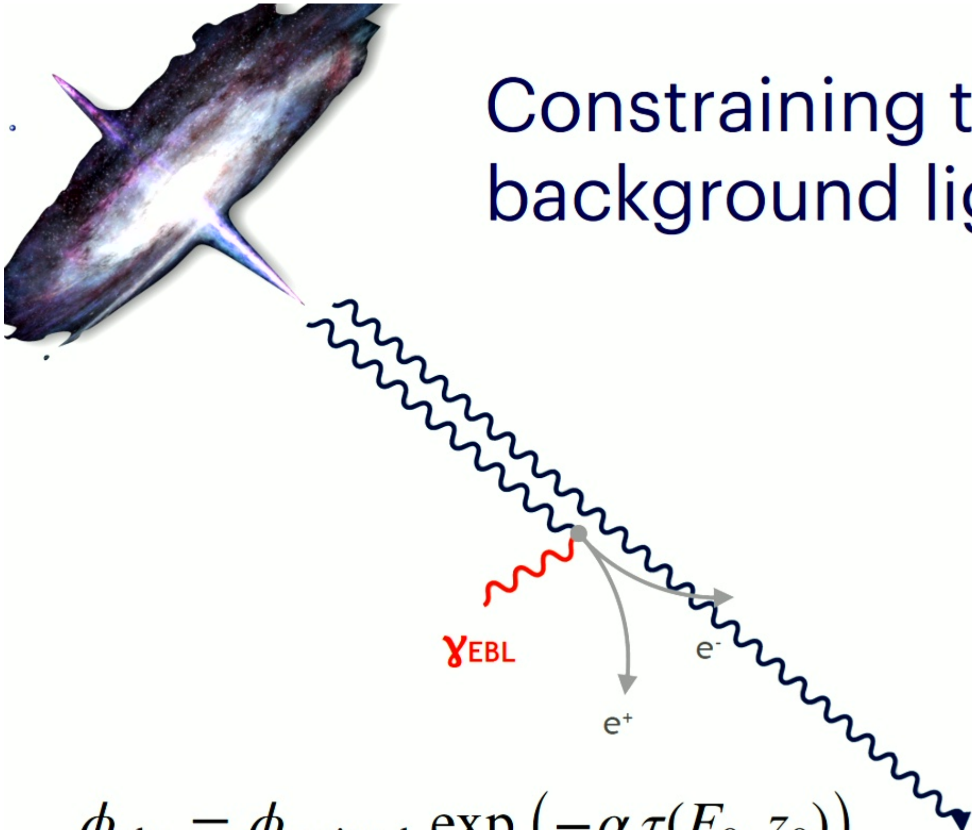
Sources with known redshift from 4LAC catalog extrapolated with power law and EBL absorption

- CTAO will detect hundreds of AGN
  - Long term monitoring program
  - High quality spectra
  - Follow up of GeV and TeV flares

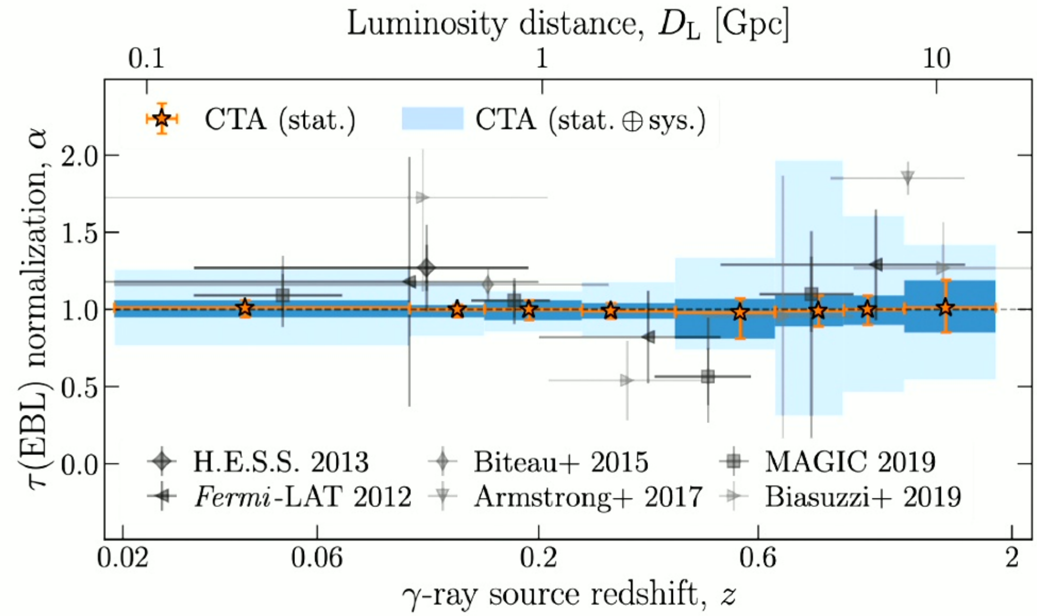
- Extragalactic survey
- Will provide blazar luminosity function up to TeV energies

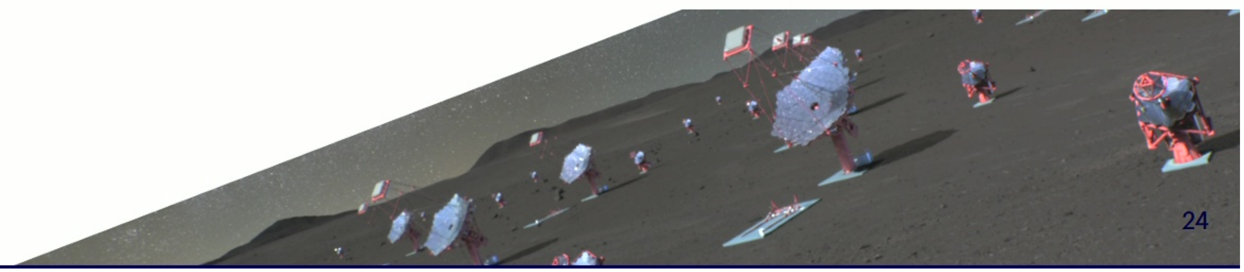
[Brown et al. 2021]

Constraining the extragalactic background light



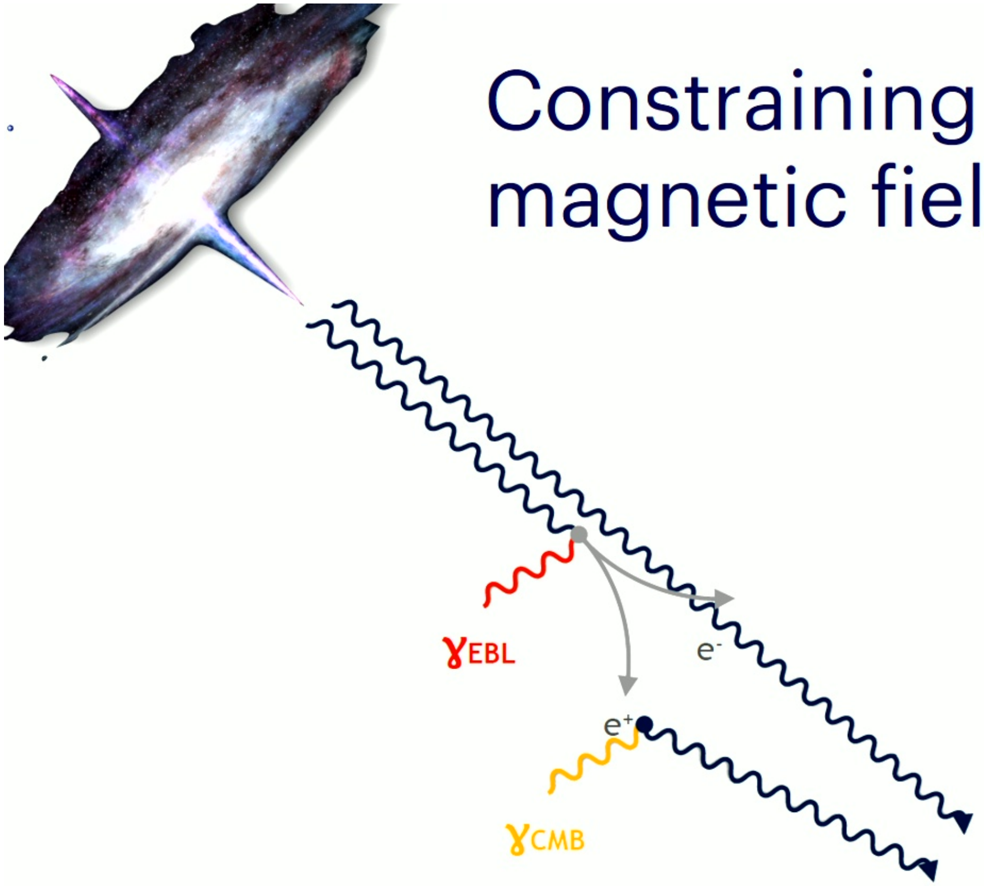
$$\phi_{\text{obs}} = \phi_{\text{emitted}} \exp\left(-\alpha\, \tau(E_0, z_0)\right)$$





[CTAO Consortium: Abdalla et al. 2021]

Constraining intergalactic magnetic fields

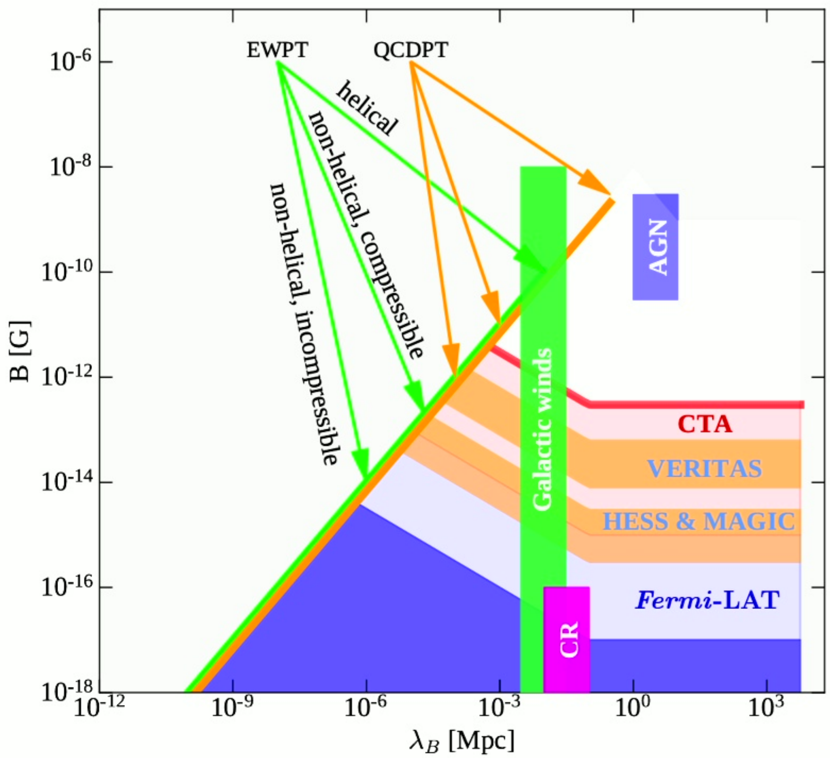


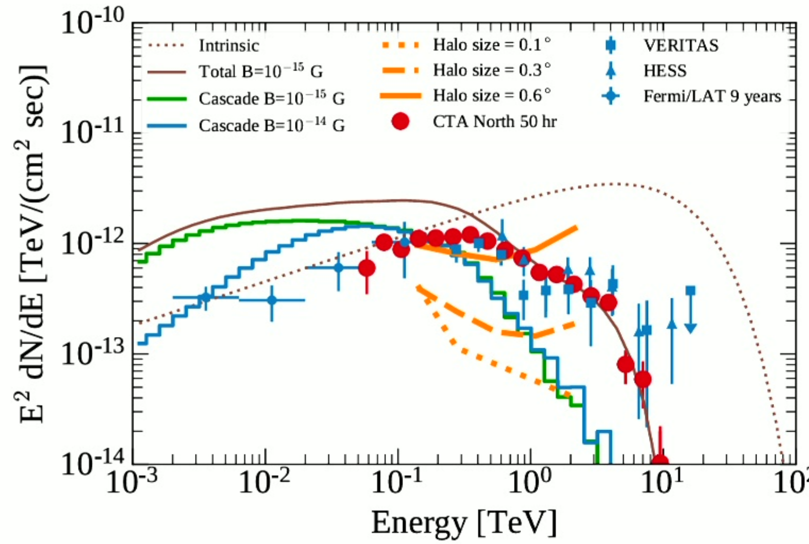
IGMF dependent observables:

- 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]

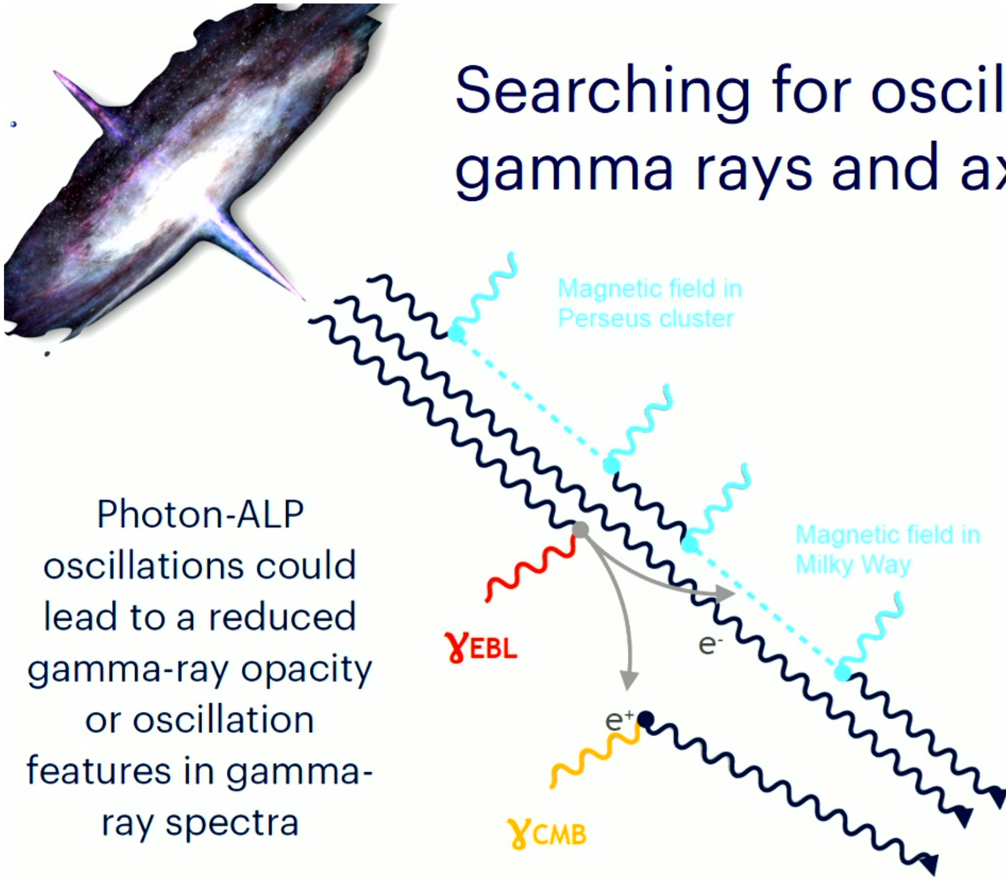
Constraining intergalactic magnetic fields



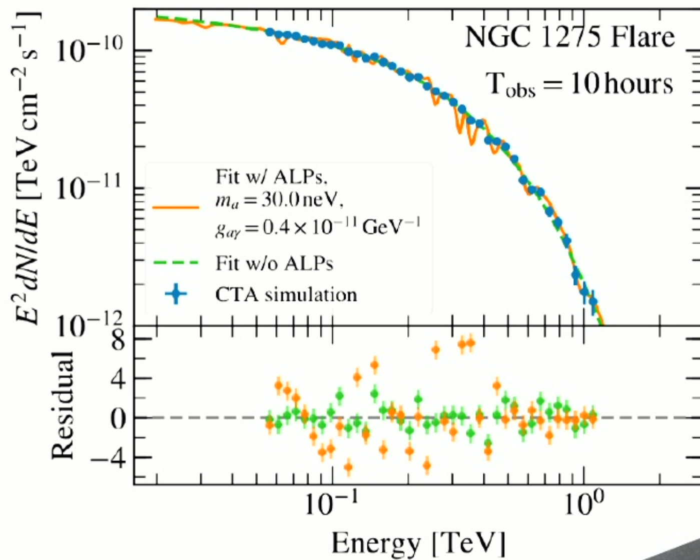


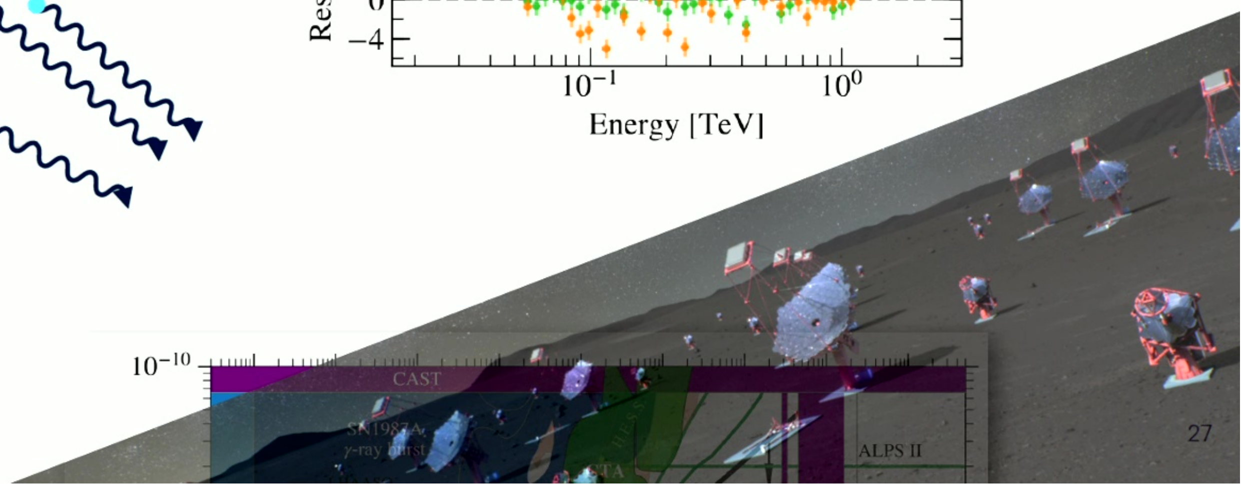
[CTAO Consortium: Abdalla et al. 2021]

Searching for oscillations between gamma rays and axion-like particles



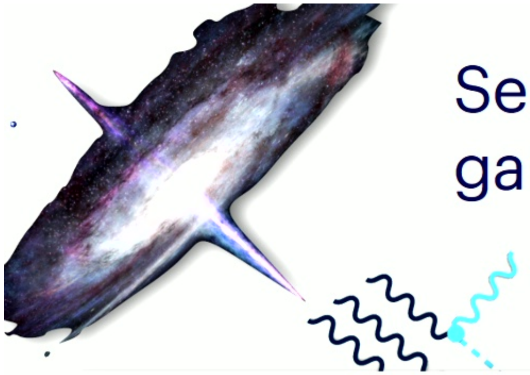
Photon-ALP oscillations could lead to a reduced gamma-ray opacity or oscillation features in gamma-ray spectra

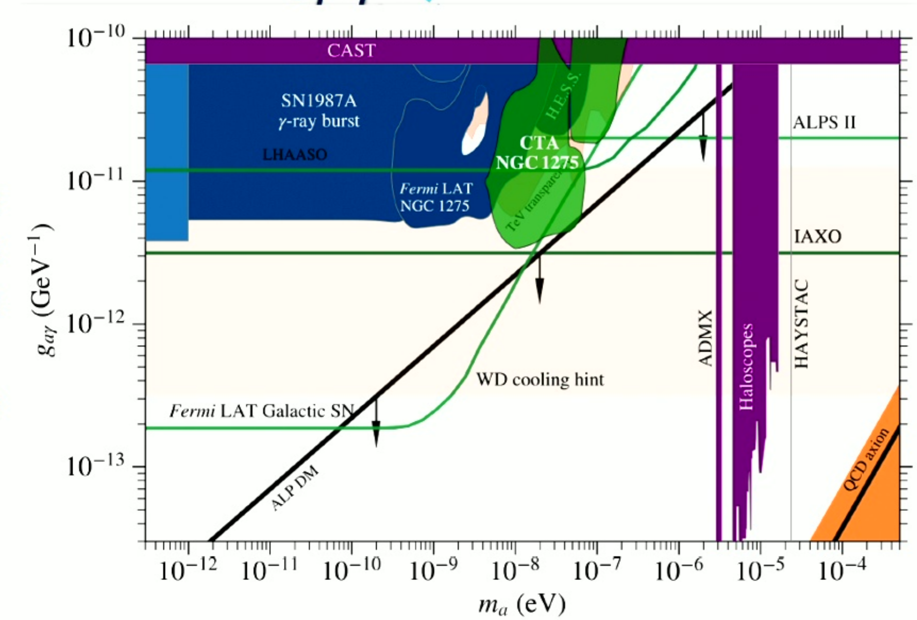


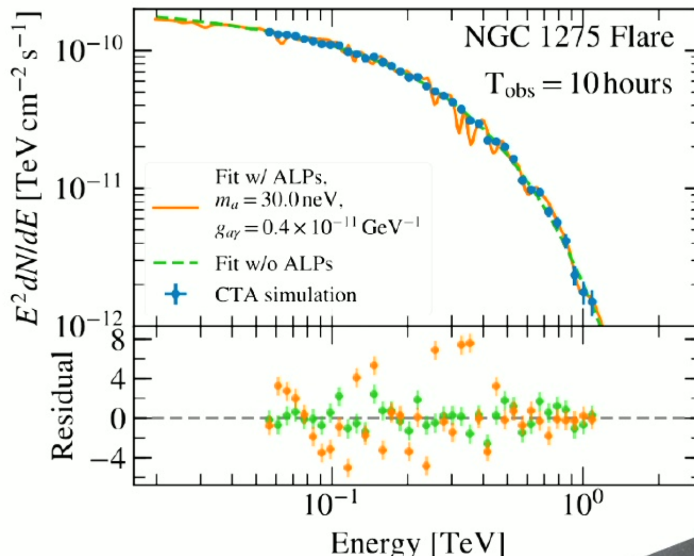


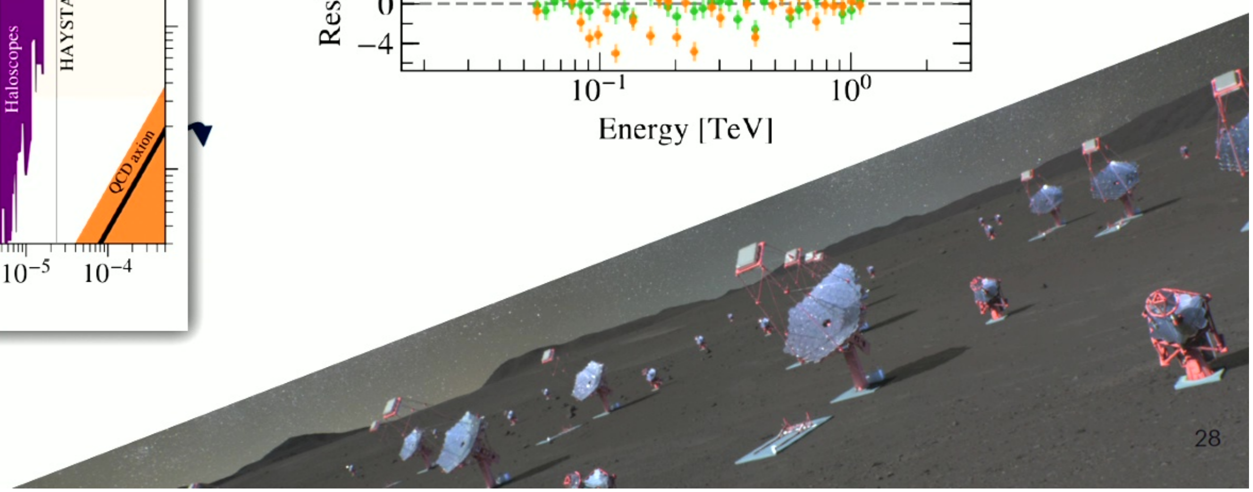
[CTAO Consortium: Abdalla et al. 2021]

Searching for oscillations between gamma rays and axion-like particles



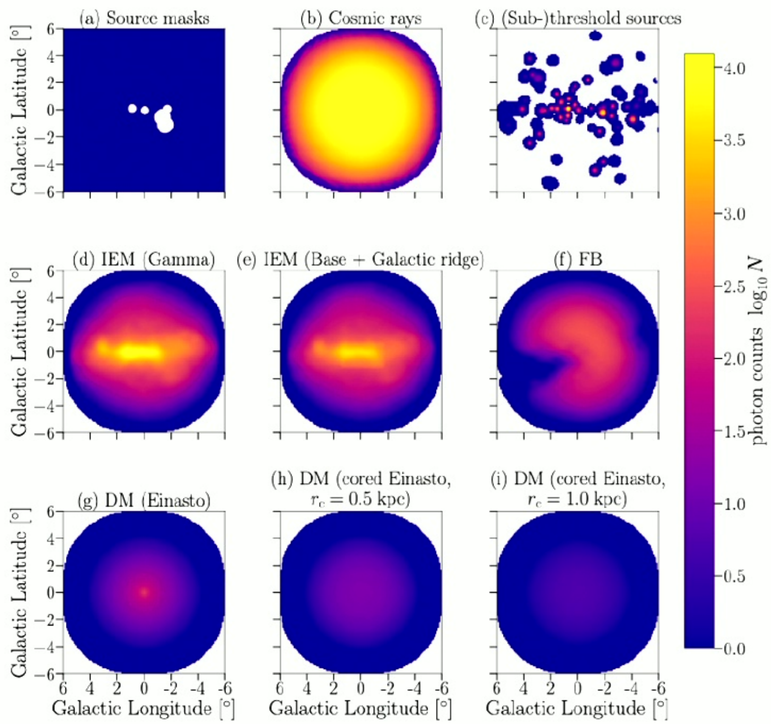


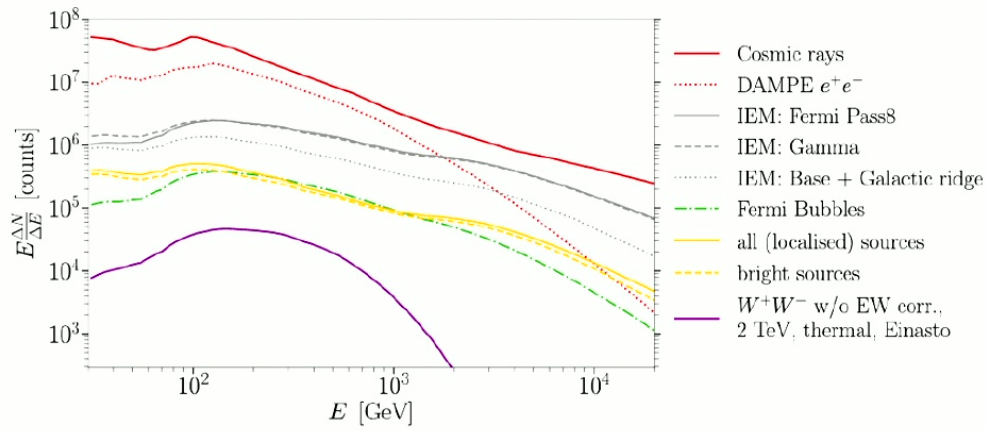




[CTAO Consortium: Abdalla et al. 2021]

Modeling Galactic Center Region for CTA sensitivity study

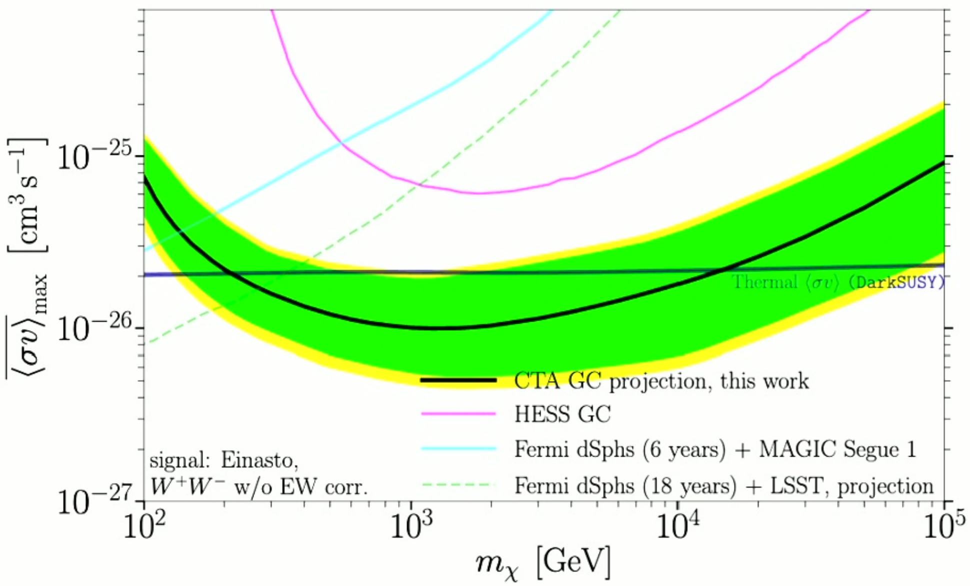


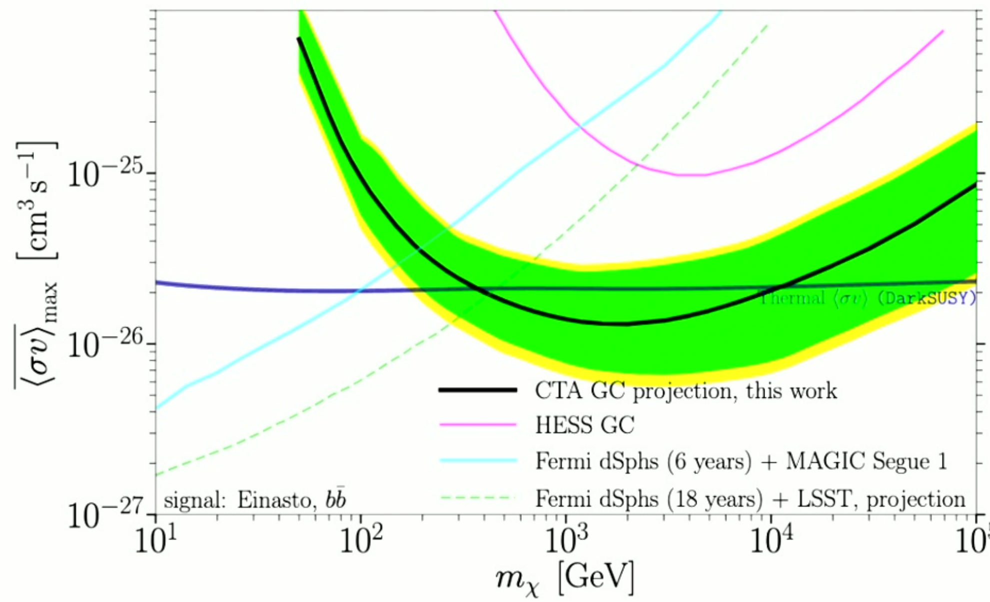


- **Galactic center survey**: 525 hours over first 10 years
- **Extended survey**: additional 300 hours

[CTAO Consortium: Archaryya et al. 2021]

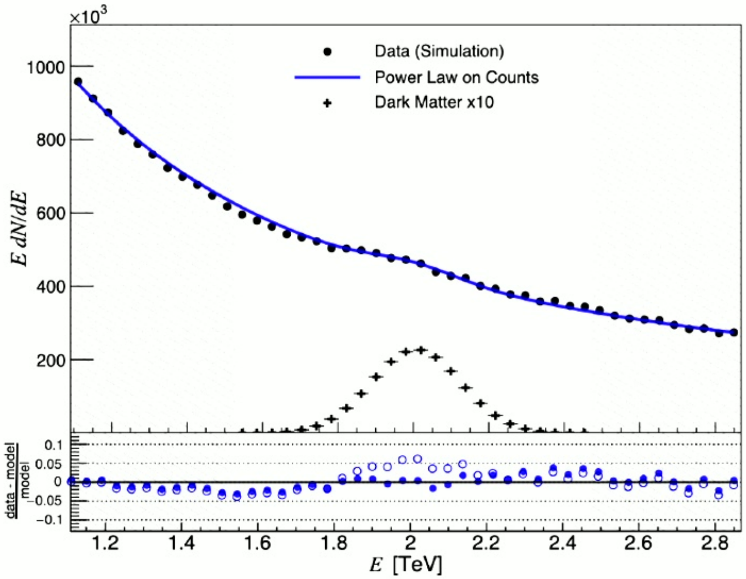
Projected CTA sensitivity for DM annihilation

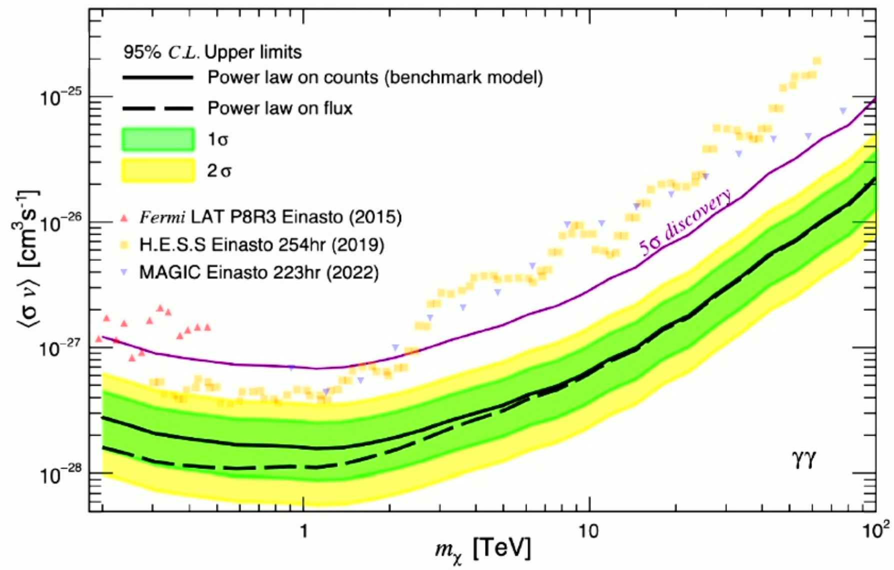




[CTAO Consortium: Archaryya et al. 2021]

Sensitivity for Dark matter annihilation line searches





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

CTAO

CTAO-US Contributions

1. Development of SCT Telescope Optics
   - Baseline design for the SST telescopes
   - Development of MST-SCT telescope
     Funded 2023, 2018
2. Instrumentation for MST and SST Telescopes
   - MST Optical Alignment systems
     Funded 2023
   - SST Camera Electronics
     Proposed Nov 2024
   - MST Telescope positioner & optical supports
     Proposed Nov 2024
3. Stellar Intensity Interferometry
   - Ongoing development (funded)

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Need for fine angular resolution

- At lower energies (< 1 TeV), the telescope operates in a background dominated regime
  - Gamma-ray showers: clean and narrow
  - Hadronic showers: broad and messy
- The angular resolution has a major impact on gamma-ray sensitivity
- Transverse angular size of the gamma-ray shower core is $\sim$ 1 minute of arc
- Current generation IACT instruments have pixel size of 9 arcmin (far from optimal!)

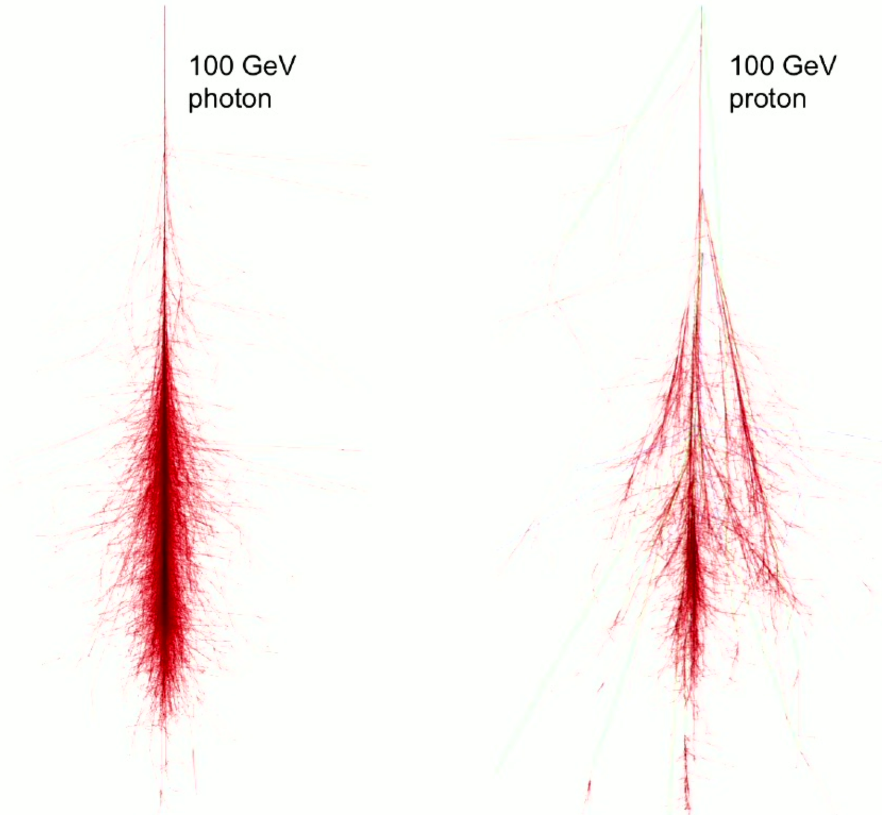
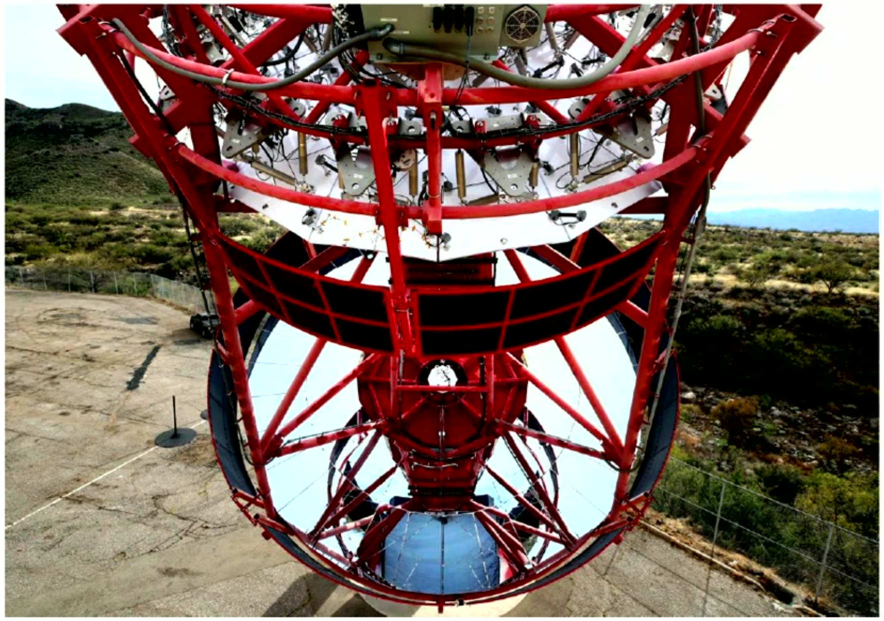


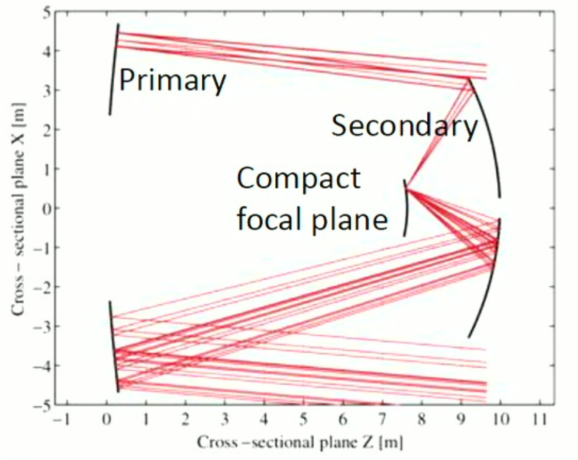
Image from: J. Holder arXiv:1510.05675

6

The Schwarzschild-Couder Telescope (SCT)



- Novel dual-mirror optical system
- >10,000 channel state-of-the-art SiPM camera



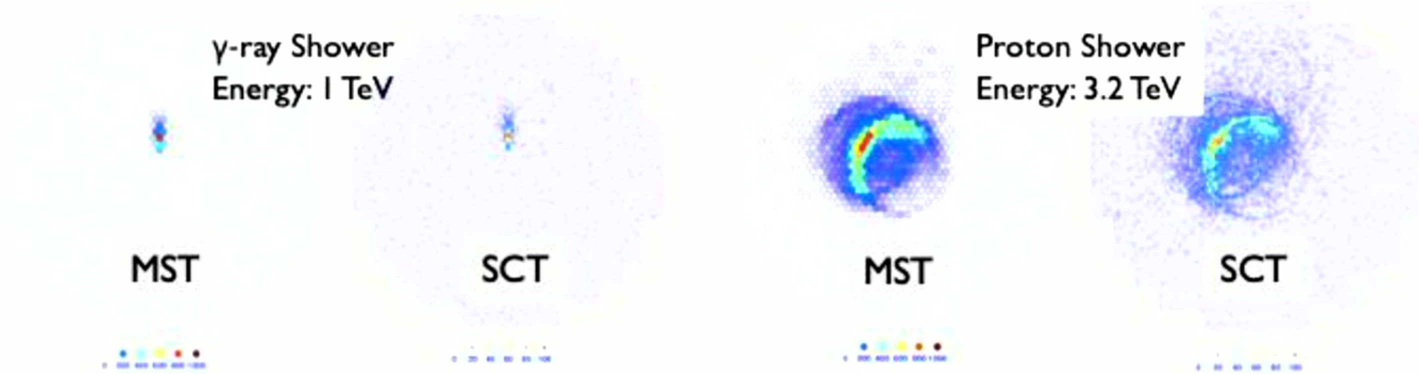
- By focusing the light on a smaller surface, the technique enables the use of state-of-the-art sensors (SiPMs) and electronics
- Better sensitivity and reduced observation time

V. Vassiliev et al. Astroparticle Physics 28 (2007) 10

CTAO-US Contributions

1. Development of SCT Telescope Optics
   - Baseline design for the SST telescopes
   - Development of MST-SCT telescope
     Funded 2023, 2018
2. Instrumentation for MST and SST Telescopes
   - MST Optical Alignment systems
     Funded 2023
   - SST Camera Electronics
     Proposed Nov 2024
   - MST Telescope positioner & optical supports
     Proposed Nov 2024
3. Stellar Intensity Interferometry
   - Ongoing development (funded)

The SCT: big eyes with a sharper view



DC-MST Images
7.7° field of view, 0.17° pixels
1,855 channels

SCT Images
8° field of view, 0.067° pixels
11,328 channels`

- Superior optical angular resolution over a wide (~8°) field of view
- By focusing the light on a smaller surface, enables the use of state-of-the-art sensors
- Better sensitivity and reduced observation time
- Better gamma-ray PSF across the FoV for morphology, survey, and transients

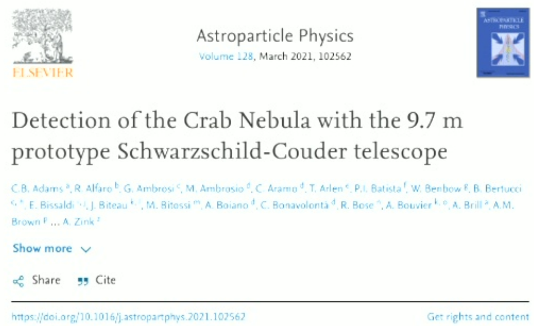
Key Characteristics of the prototype (p)SCT

- **Dual-mirror design:**
  - Correct for spherical and comatic aberrations
  - Small plate scale
  - Large field of view
  - Large telescope aperture
- **Compact high-resolution camera:**
  - Silicon photomultipliers
  - 11328 pixels
  - Each pixel 0.067°(6 mm) square (PSF 0.05-0.07 °)
  - 8° field of view
- R&D funded by NSF + international partners happening in the US
- US contribution aims for best enhancement of CTAO science capabilities depending on the available US funding. Favored strategy at present: Add SCTs to Southern Array

The pSCT at the FLWO, Arizona

Detection of Crab Nebula

- Crab Nebula is detected at 8.6σ in 2019 with a partial camera.
- A major milestone for the demonstration of the viability of SCT technology for CTA.
- The co-location of SCT project with VERITAS observatory at FLWO and simultaneous operation of both instruments has been critical ingredient of this success!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Astroparticle Physics
Volume 128, March 2021, 102562

Detection of the Crab Nebula with the 9.7 m prototype Schwarzschild-Couder telescope

C.B. Adams, R. Alfaro, G. Ambrosi, M. Ambrosio, C. Aramo, T. Arlen, P.I. Batista, W. Benbow, B. Bertucci, E. Bissaldi, J. Biteau, M. Bitossi, A. Boiano, C. Bonavolontà, R. Bose, A. Bouvier, A. Brill, A.M. Brown ... A. Zink

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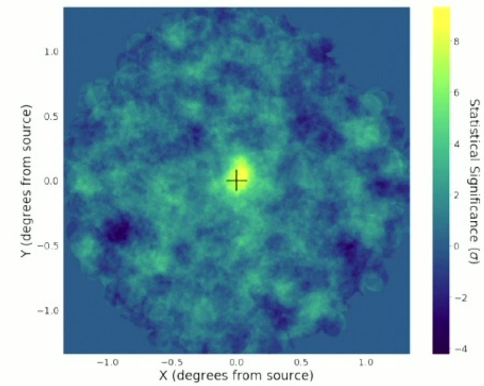
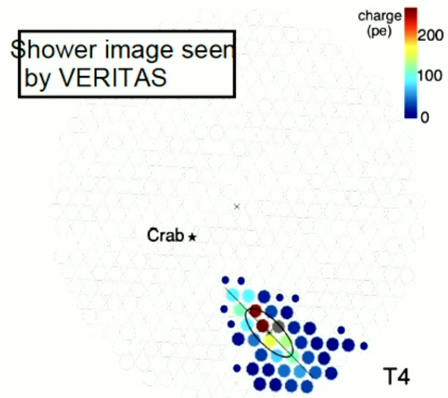
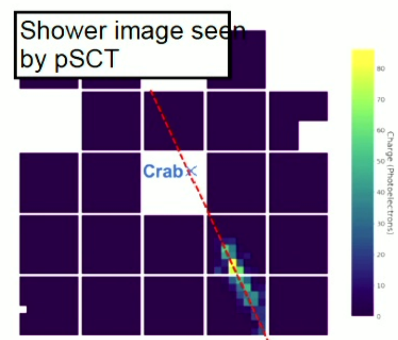
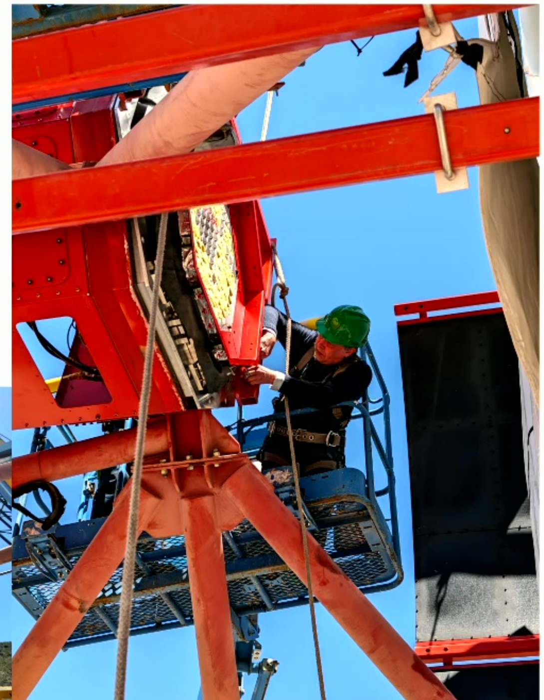
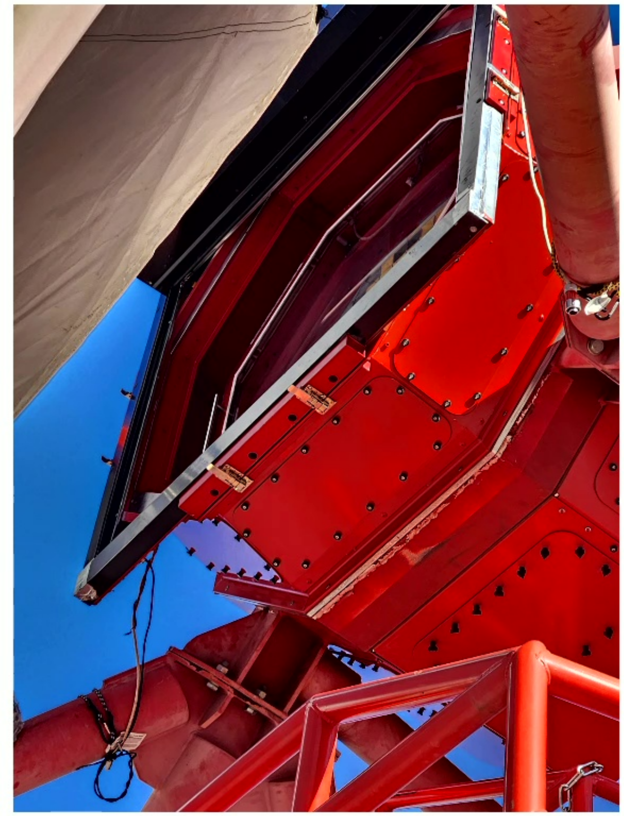






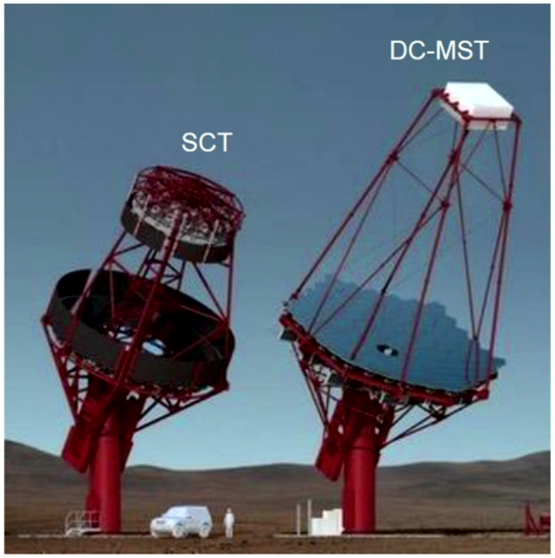
SCT Camera Upgrade : March 26, 2024

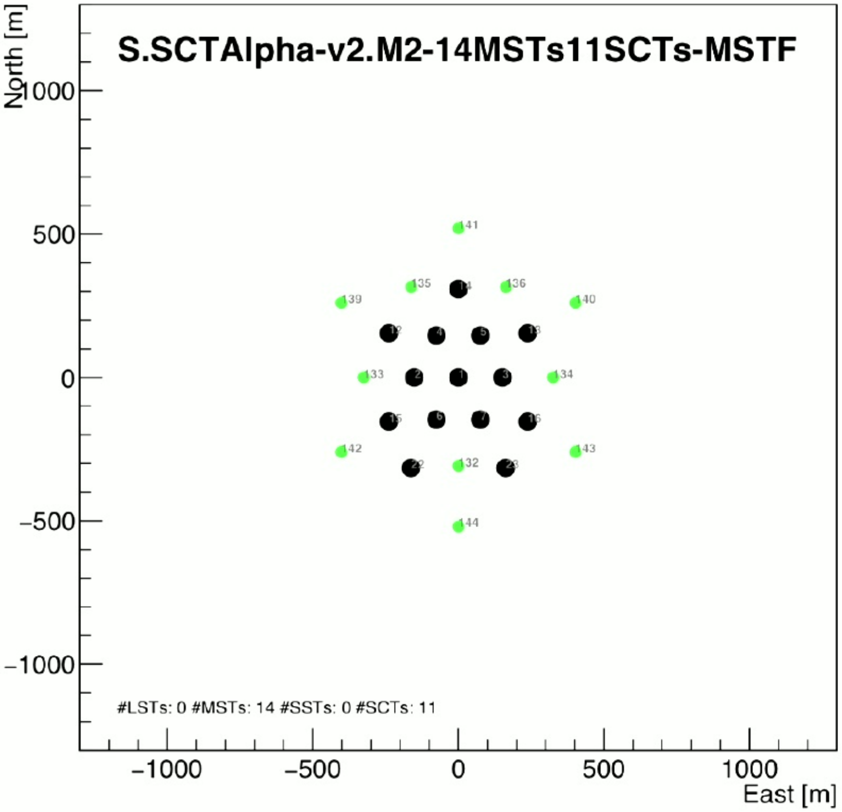




CTA South configuration

- Nominal CTA South alpha configuration includes 14 DC-MSTs (black dots)
- We consider + 11 SCTs (green dots) configuration as a hypothetical enhancement exercise





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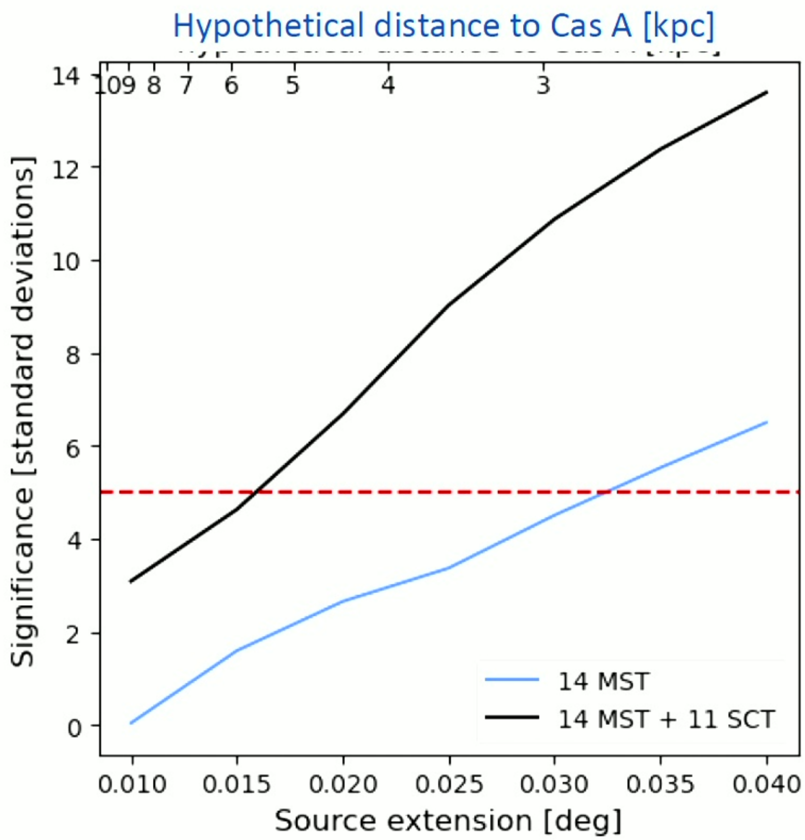
Gamma-ray performance

- The addition of 11 SCTs to CTA will improve the ability in resolving sources with small extensions.
- Simulation of ©-ray emission from a source similar to Cas A, placed a different distances, is used to test the capability of detecting the source extension.
- The ability to resolve a radius = 1' source means that CTA and NuSTAR/XMM/Chandra can observe a source at different wavelength with a similar angular-size scale.



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Gamma-ray performance

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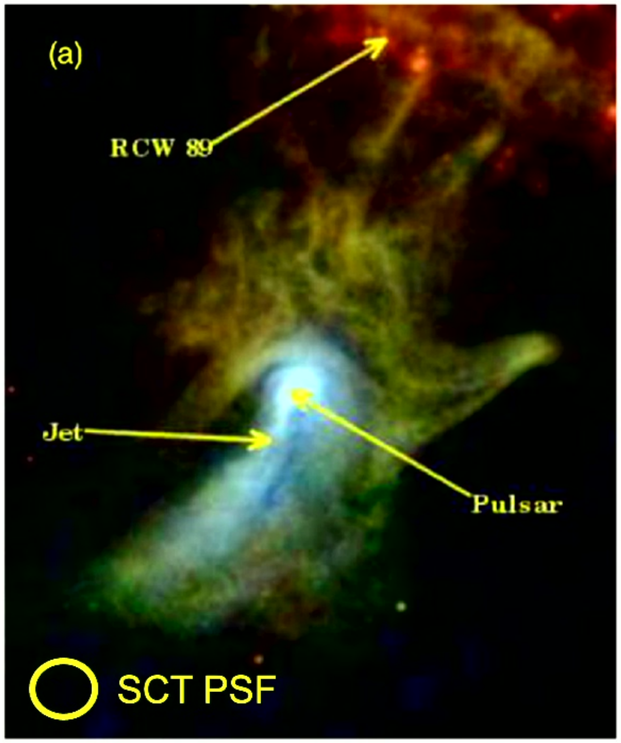


MSH 15–52 images measured with NuSTAR and Chandra in a 10' × 12' rectangular region
https://iopscience.iop.org/article/10.1088/0004-637X/793/2/90/pdf

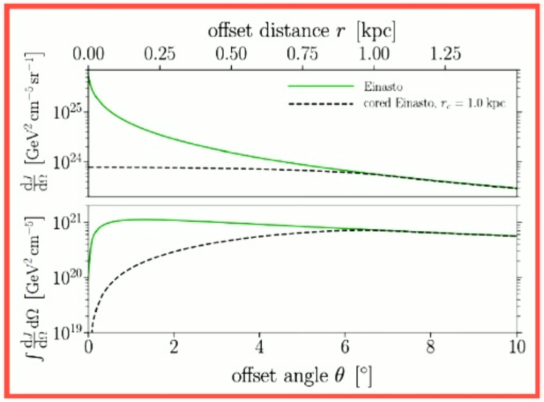
Conclusions

- CTAO is the next Generation VHE observatory
- Northern LSTs operational end of 2025
- MST installation begins 2025-2026
- CTAO brings wealth of science opportunities
    - Search for PeVatrons
    - Galactic Transients & potential joint VHE/Optical SII campaigns
    - AGN populations
    - EBL, IGMF, Axion physics
    - Astrophysical sources of TeV WIMP dark matter

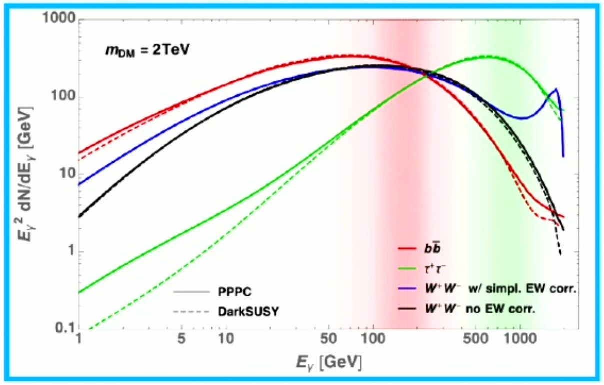
Expected photon flux from WIMP annihilation

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

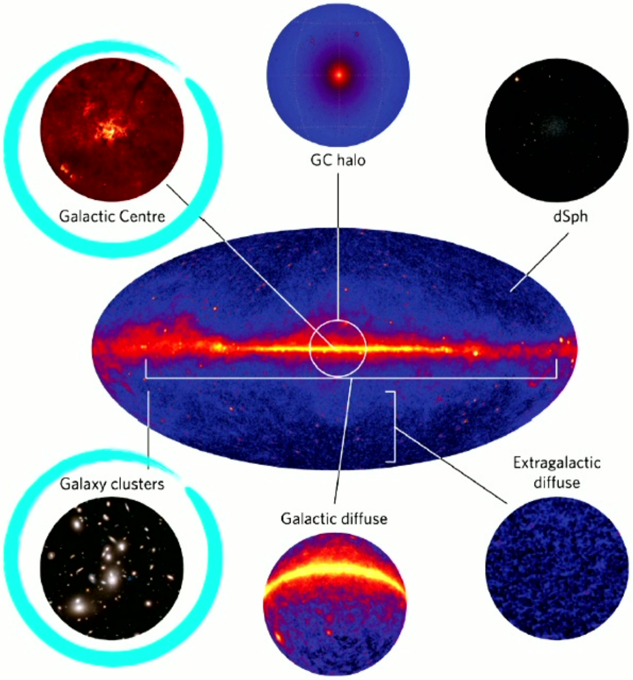
J factor | Particle physics



J factor for Galactic center of the Milky Way



Targets for DM searches



[Conrad & Reimer 2017]

[CTAO Consortium: Archaryya et al. 2021]