LST COLLABORATION

TeVPA 2026 @天童市

KYOTO UNIVERSITY

GRADUATE SCHOOL OF FACULTY OF SCIENCE KYOTO UNIVERSITY

Search for Line-Like Gamma-Ray Signals from Dark Matter in the Galactic Center with CTAO LST-1

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*This work is being conducted in the context of the LST working group, while also aligned to the context of the CTAO DMEP working group.

Dark matter (DM) candidates still span tens of orders of magnitude in mass, while WIMPs and axion(-like) particles remain fundamentally well motivated.

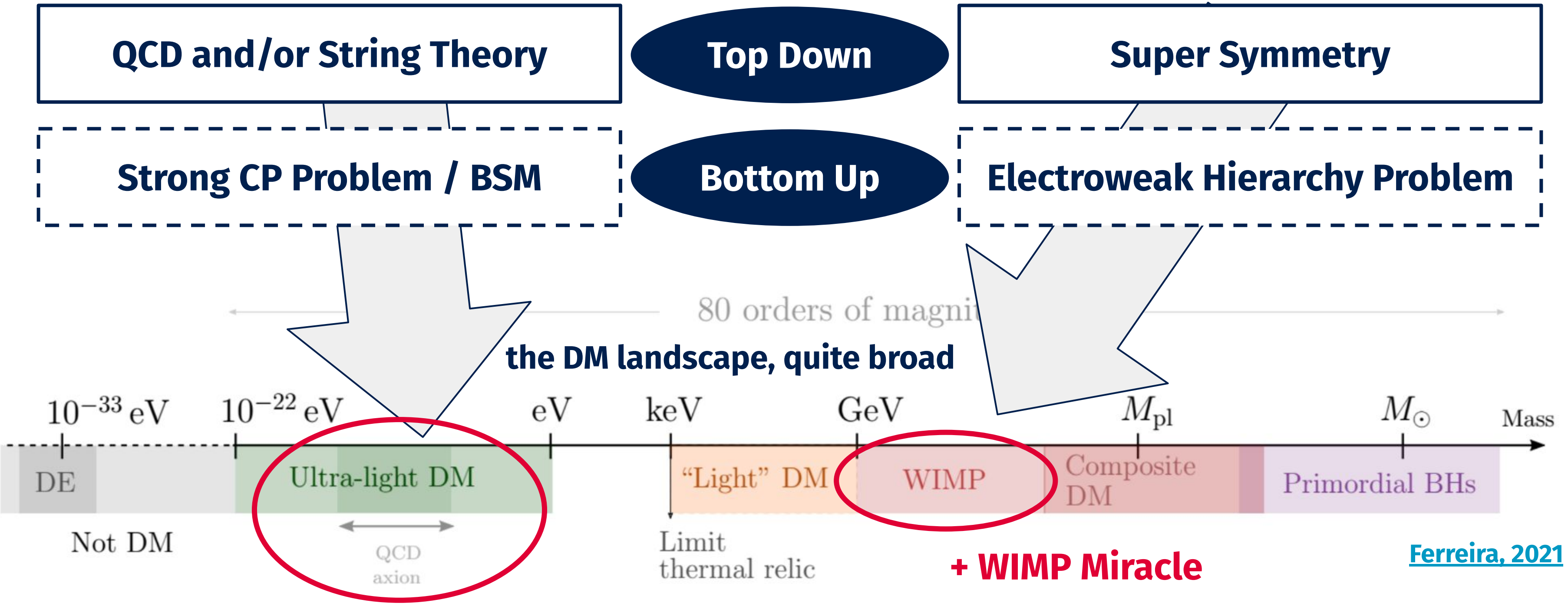


Fig. 1 Sketch (not to scale) of the huge range of possible DM models that have been conceived. They span many orders of magnitude in mass, with DM represented by very distinct phenomena, ranging from new elementary particles to black holes.

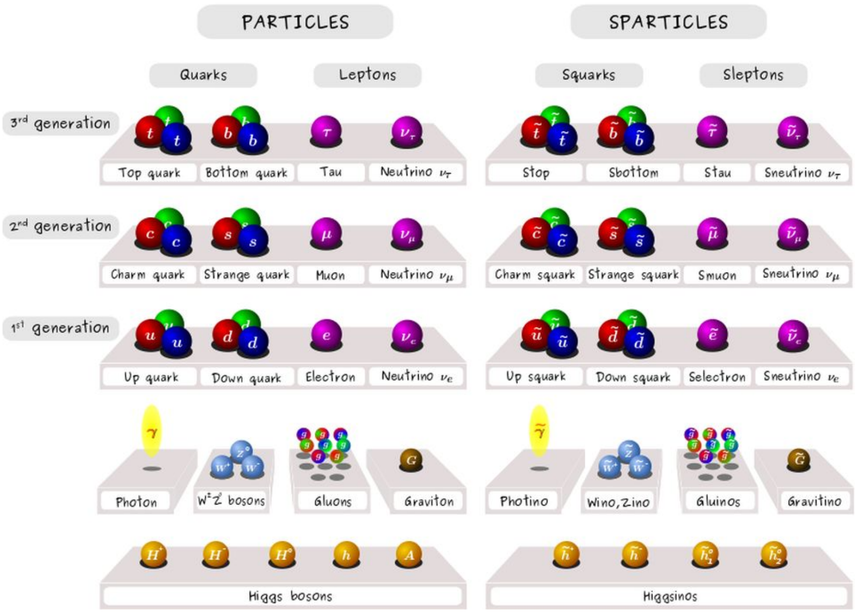
Higgsino and Wino DM represent some of the last viable parameter spaces for minimal WIMPs. Ruling these out is as scientifically impactful as a discovery.

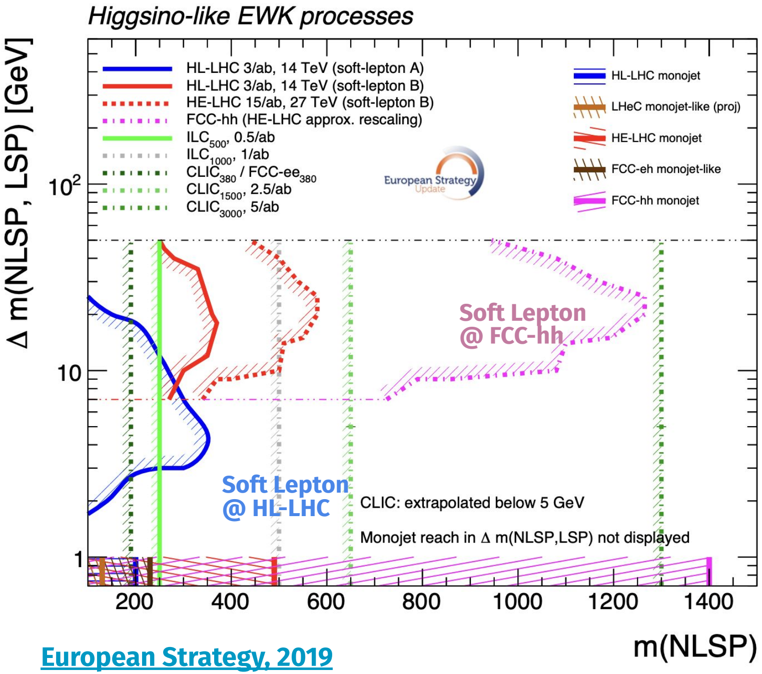
SUSY is NOT dead yet

e.g., Higgsino (~1 TeV) or Wino (~3 TeV), but still challenging even with HL-LHC

timely opportunity for next-gen telescopes

e.g., the Cherenkov Telescope Array Observatory (CTAO)





European Strategy, 2019

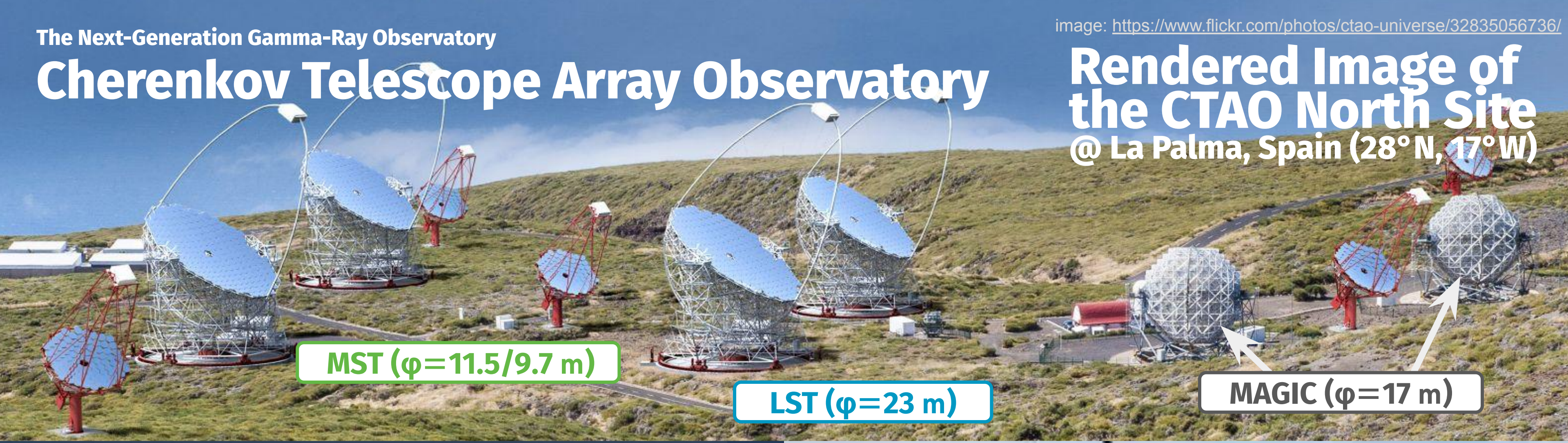
The Next-Generation Gamma-Ray Observatory

Cherenkov Telescope Array Observatory

image: https://www.flickr.com/photos/ctao-universe/32835056736/

Rendered Image of the CTAO North Site

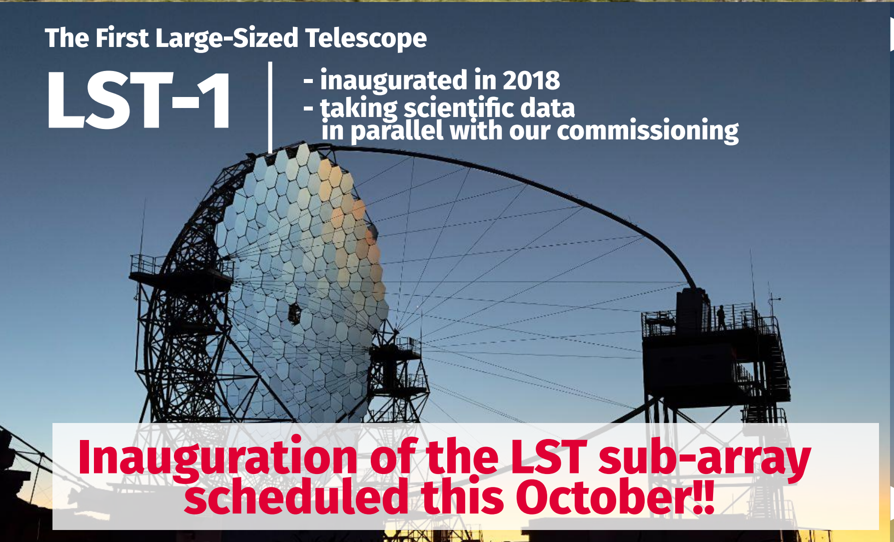
@ La Palma, Spain (28° N, 17° W)



The First Large-Sized Telescope

LST-1

- inaugurated in 2018
- taking scientific data in parallel with our commissioning



Inauguration of the LST sub-array scheduled this October!!

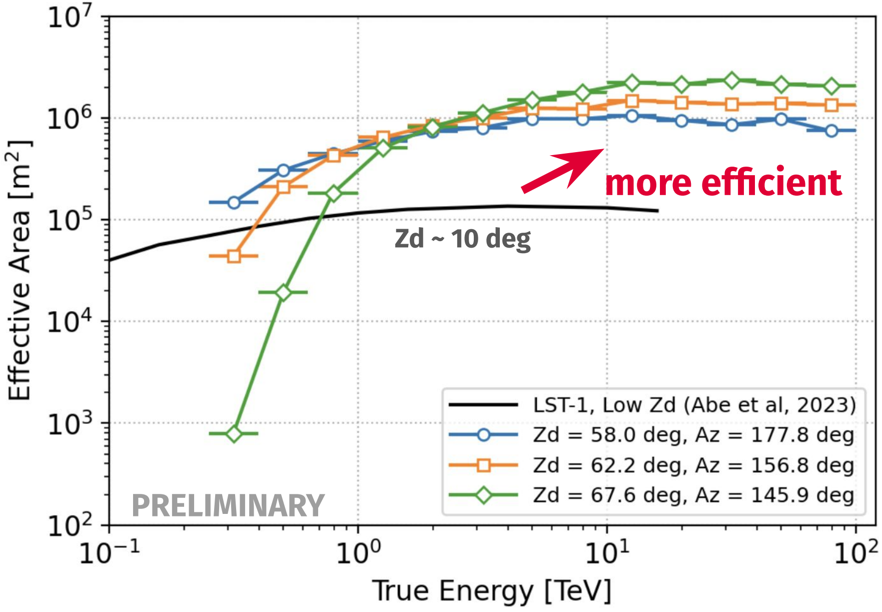
▶▶ and we are building more! ▶▶

Video: LST-3 Dish Lifted (June 2024)

Large zenith angles (about 60 deg) enhance the effective area by ~10 times. LST-1 has a wider FoV (~4.3 deg in diameter) than the other northern IACTs.

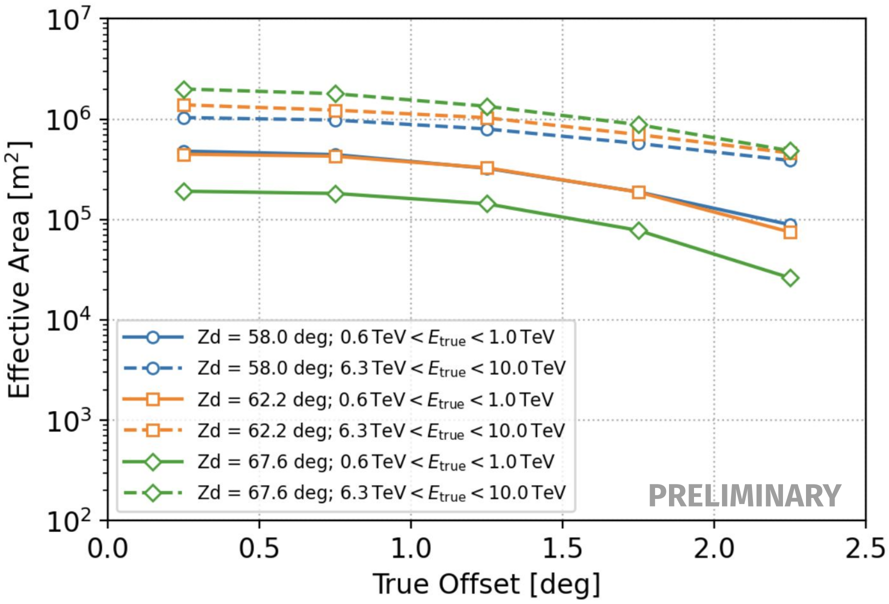
Beneficial at higher energy: Aeff ~ 10^6 m^2,

~10^5 m^2 even at E = 0.4 TeV at Zd = 62 deg
though strongly dependent on Zd



Keeping responses across energy & FoV,

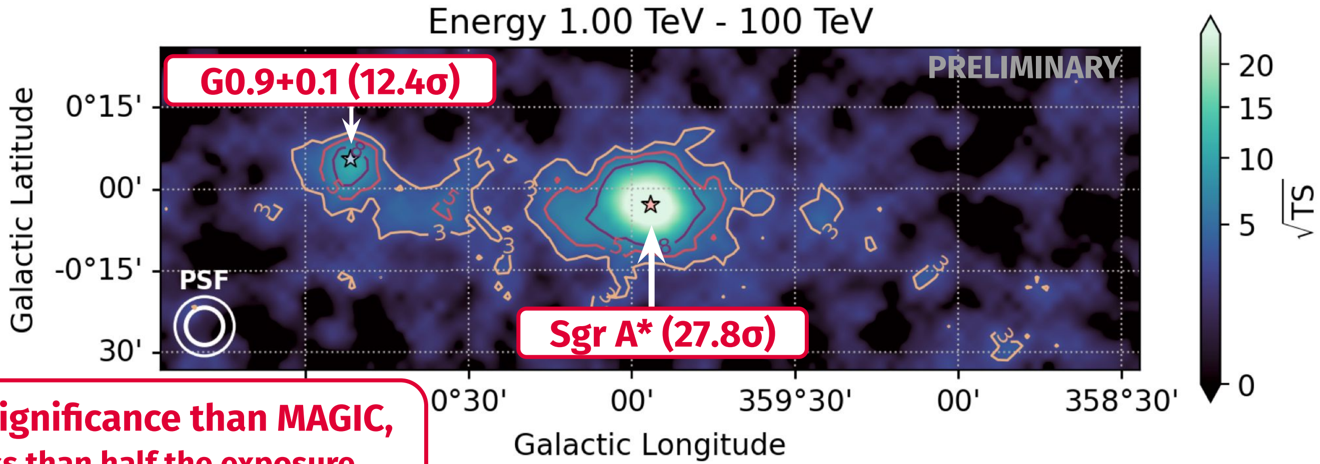
70% (50%) at the offset angle of 1.0 (1.5) deg
suitable for TeV extended sources: >1 deg



Clear & Wide Galactic Center View with LST-1

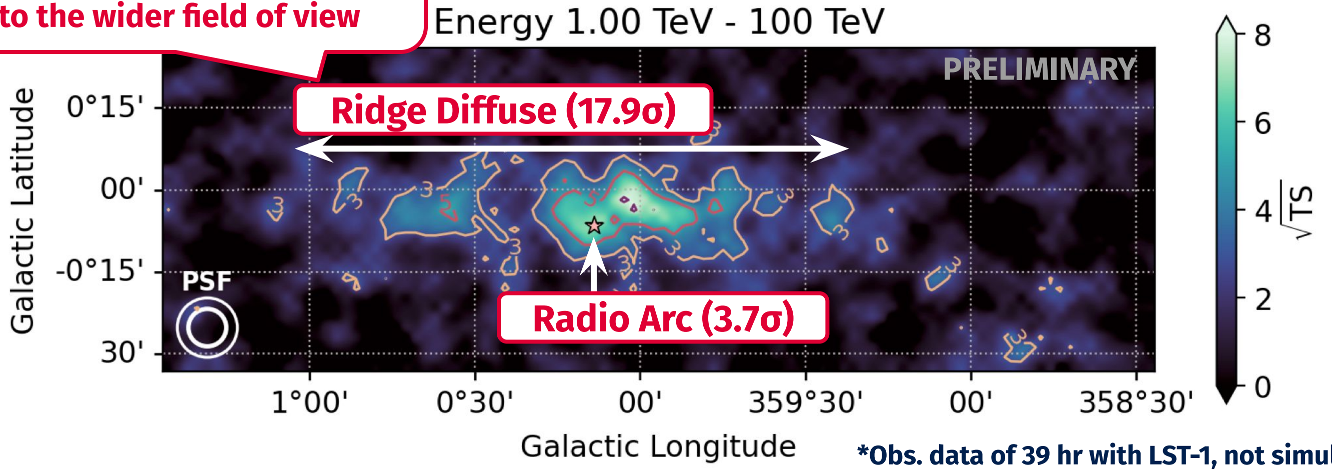
*Significance in this study: >398 GeV. PSF circles represent 39%/68% contaminants.
**cf. MAGIC 2020 (100hr, >1 TeV): Sgr A*: 48σ, G0901: 11σ, Arc: 6.4σ, Diffuse: 17σ.

TS Map



Higher significance than MAGIC,
with less than half the exposure, thanks to the wider field of view

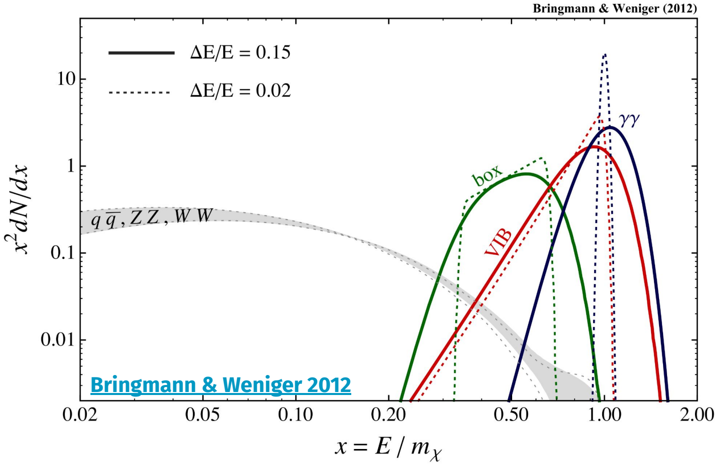
Sgr A* & G0.9+0.1 subtracted

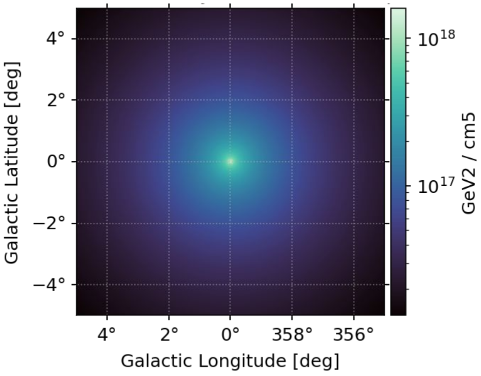


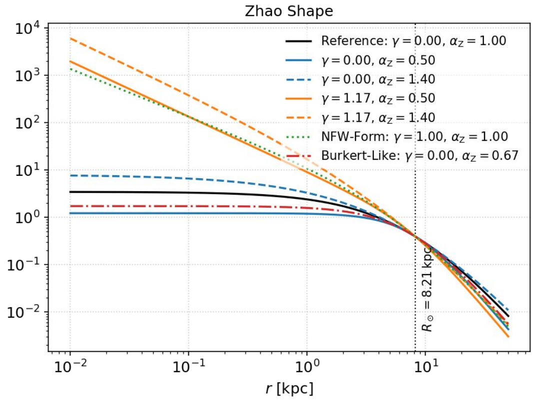
***Obs. data of 39 hr with LST-1, not simulation**

Trade-off: more sensitive approaches often introduce larger systematic uncertainties into the analysis. This study adopts the line plus radial profiles.

Energy Spectrum		Spatial Morphology	
Broad Continuum	(End-Point) Line	2-Dim Templates	Radial Profile







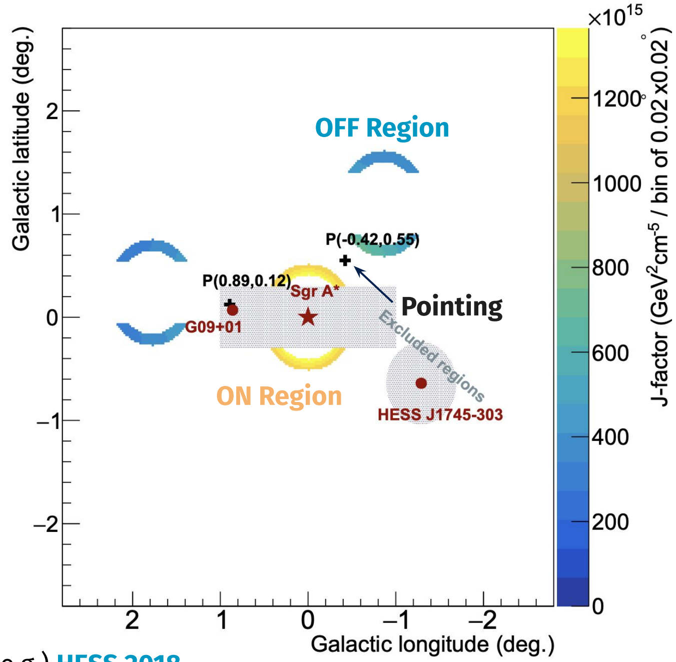
Broad Continuum
- +) more gamma rays
- -) difficult to separate background

(End-Point) Line
- +) more distinctable
- +) easier bkg modeling
- -) limited channels

2-Dim Templates
- +) ideally more sensitive
- -) astrophysical spatial models required

Radial Profile
- +) physically motivated
- -) sensitivity little improved from 1D analysis

The reflected-region background method, the most typical way of residual background estimation for Cherenkov telescopes, is not optimal for our case.



e.g.) [HESS 2018]

DM signals will appear
on top of astrophysical and instrumental background.

The most typical way to estimate the residual bkg is the reflected-region background method.

OFF regions taken at the opposite side of the camera w.r.t. the pointing.

+) the observational conditions identical between ON/OFF

+) both line and continuum analyzable

-) rely on the symmetric response; no longer the case for large zenith angles or large offset angles

-) renormalization of bkg usually not included in likelihood, unless you have bkg-control regions.

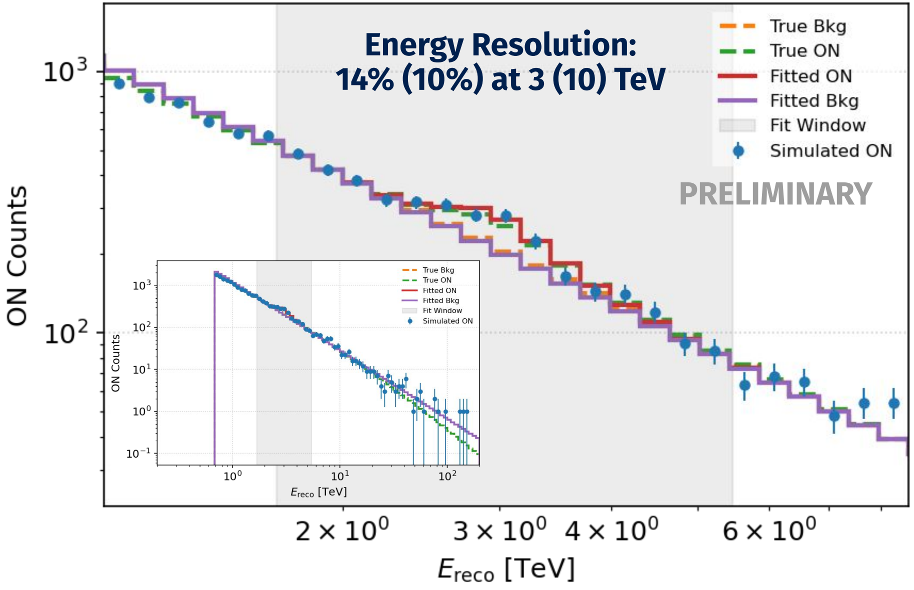
-) not very sensitive to the cored profiles

$$\mathcal{L}_{ij}(\mathbf{N}_{\mathrm{ON}}, \mathbf{N}_{\mathrm{OFF}}, \alpha | \mathbf{N}_{\mathrm{S}}, \mathbf{N}'_{\mathrm{S}}, \mathbf{N}_{\mathrm{B}}) = \frac{(N_{\mathrm{S,ij}} + N_{\mathrm{B,ij}})^{N_{\mathrm{ON,ij}}}}{N_{\mathrm{ON,ij}}!} e^{-(N_{\mathrm{S,ij}} + N_{\mathrm{B,ij}})} \frac{(N'_{\mathrm{S,ij}} + \alpha_i N_{\mathrm{B,ij}})^{N_{\mathrm{OFF,ij}}}}{N_{\mathrm{OFF,ij}}!} e^{-(N'_{\mathrm{S,ij}} + \alpha_i N_{\mathrm{B,ij}})}.$$

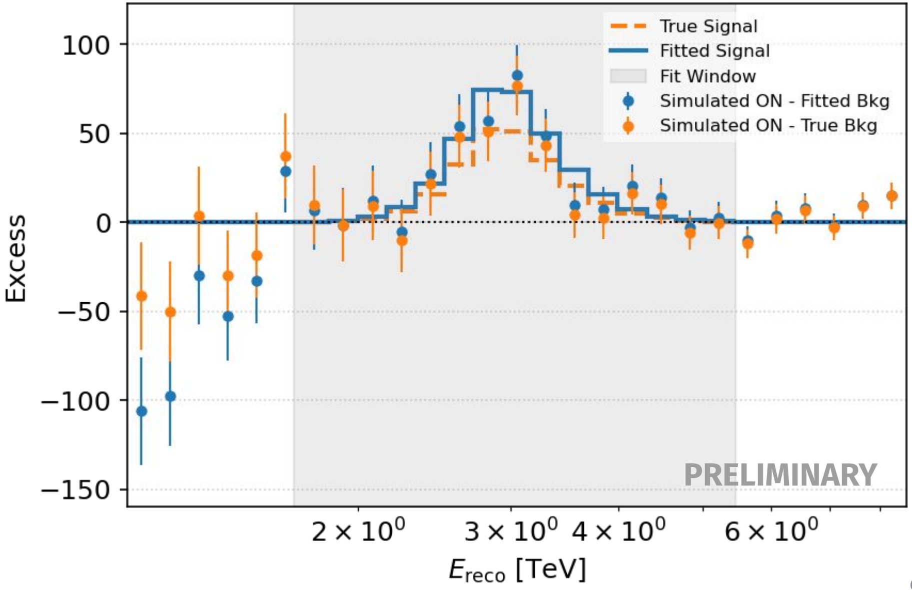
*plots here simulated just for demonstration; not real data.
*window = ±4σ width (resolution := 2σ), similarly to MAGIC 2023 and CTAO 2024

We modeled the ON-count spectrum with a DM model (with its mass fixed) and a power-law bkg spectral model: free params = DM scale & bkg norm/index.

bkg interpolated purely with a power law in the ON-count spectrum.



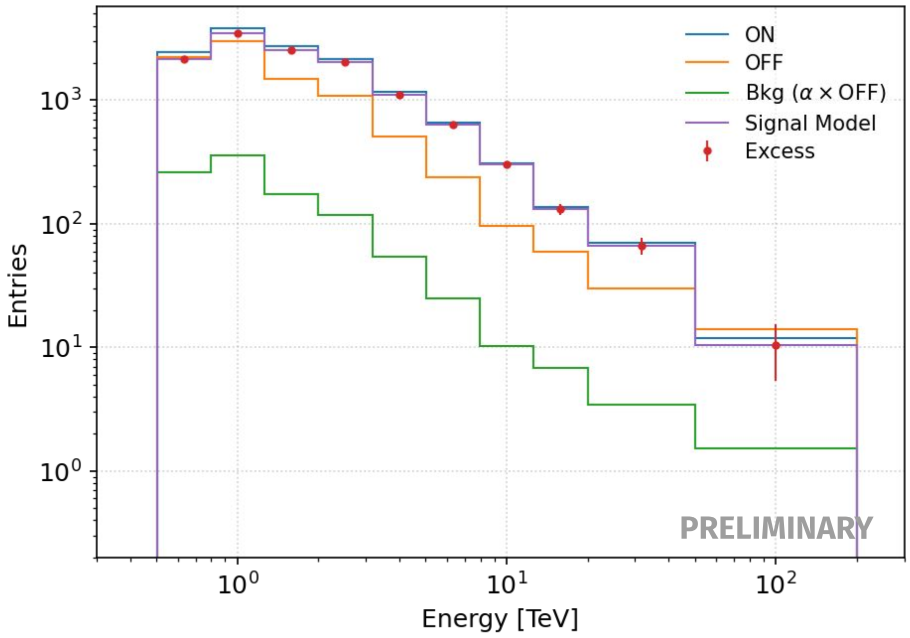
PL bkg + DM fitted to the ON count spectrum; DM signals well modeled.



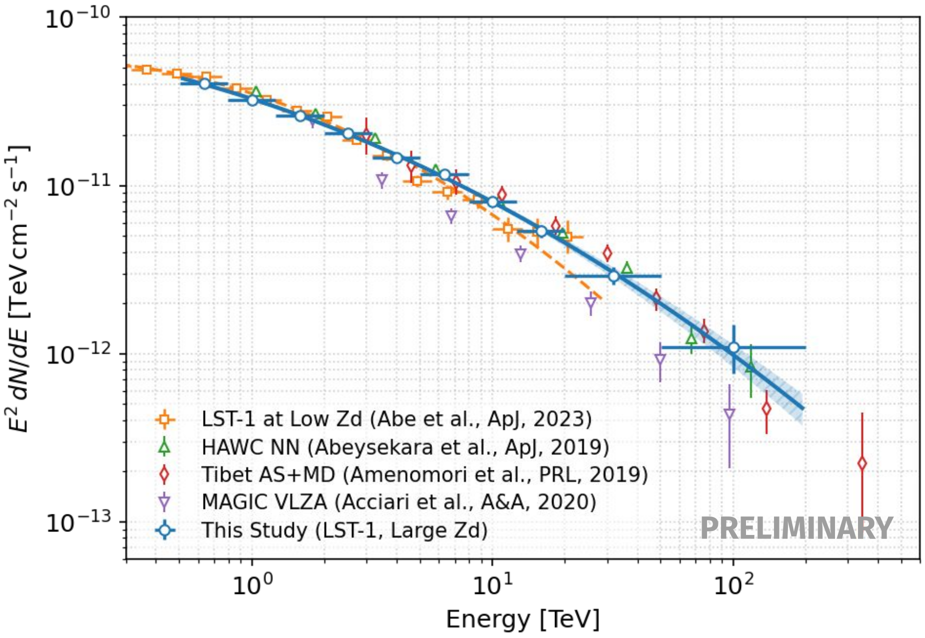
cuts: size > 150 phe, leakage < 0.2, theta < 0.1 deg, gammaness > 0.75 (for Crab).
safe mask: Ebias < 20%, to avoid Eth effects. Cuts optimized for the line search.

The bkg rejection factor optimized: about 40% gamma-ray event efficiency used. Tested on Crab data at Zd = 50-70 deg (39 hr). SEDs overall aligned.

Counts:



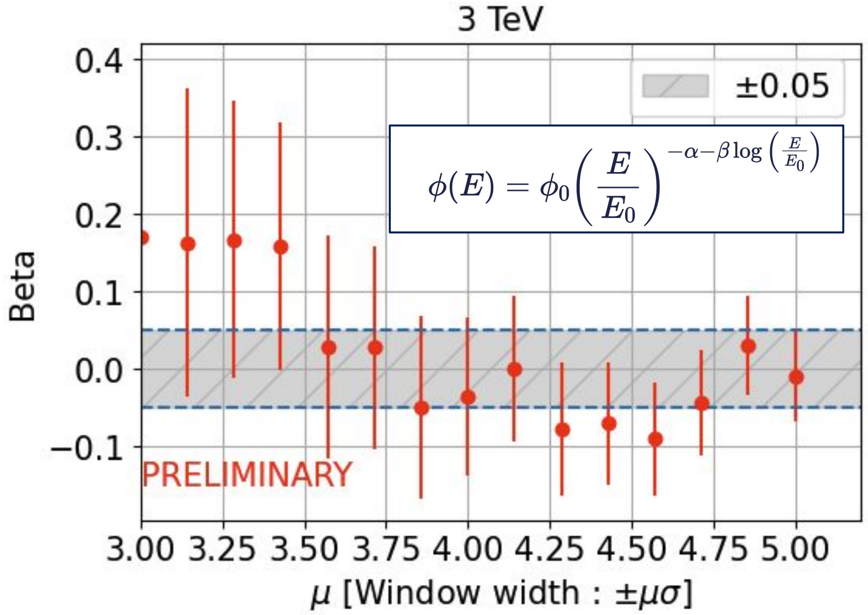
SED:



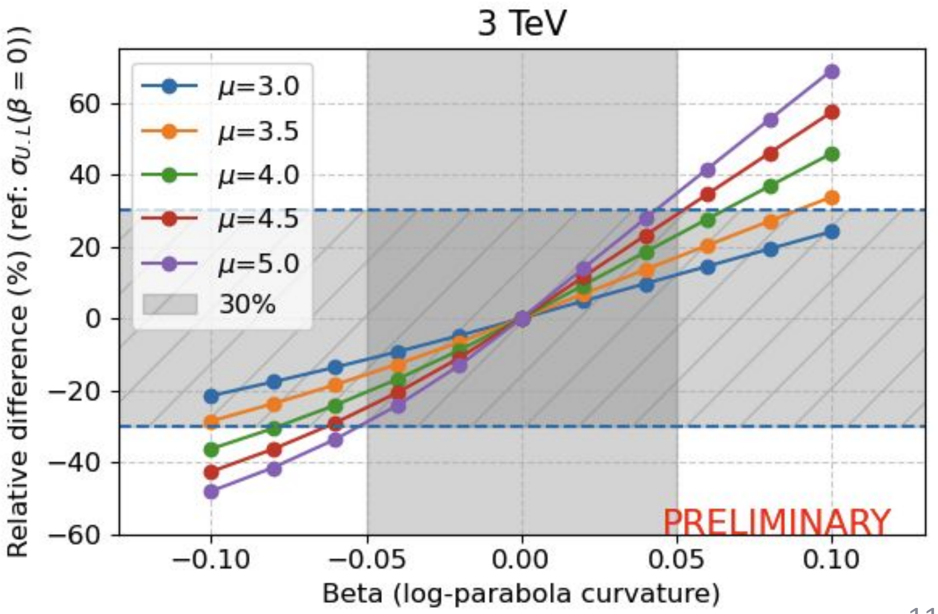
technical details can be found in [Abhishek+, ICRC 2025.]

The intrinsic spectral curvature of the cosmic-ray bkg quantified; the effect on the cross-section evaluation estimated to be < 20% above 1 TeV.

off-source data at large Zd used.
curvature quantified by *beta* in log-parabola.



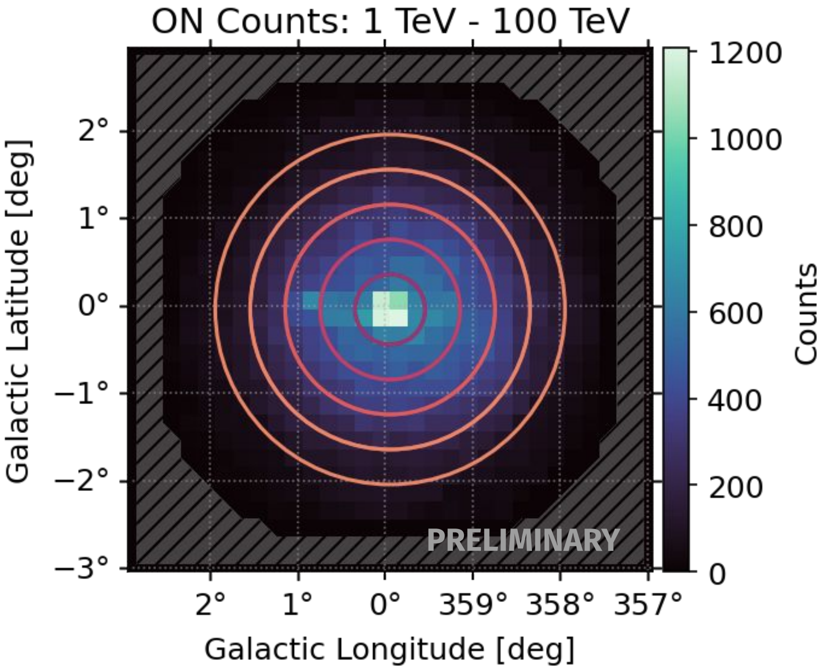
Simulated impact on the sensitivity by an artificial injection of the curvature



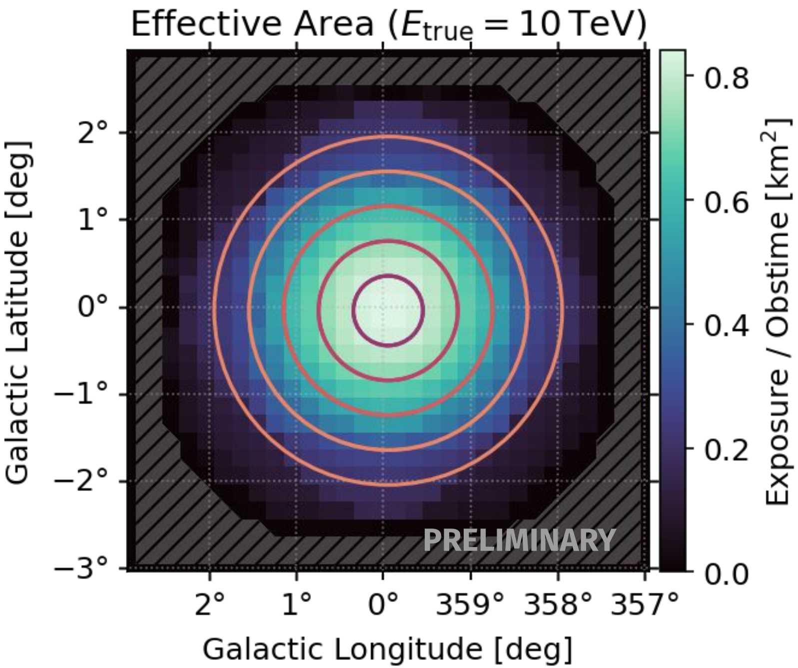
*RoI also selected by 2.0 deg from the Galactic center
**Orange lines: rings along which the likelihood divided

This study used good-quality data at the zenith angles < 62 deg, about 39.6 hours in total, and the field of view of 2 deg from the camera center.

wobble observations around Sgr A*

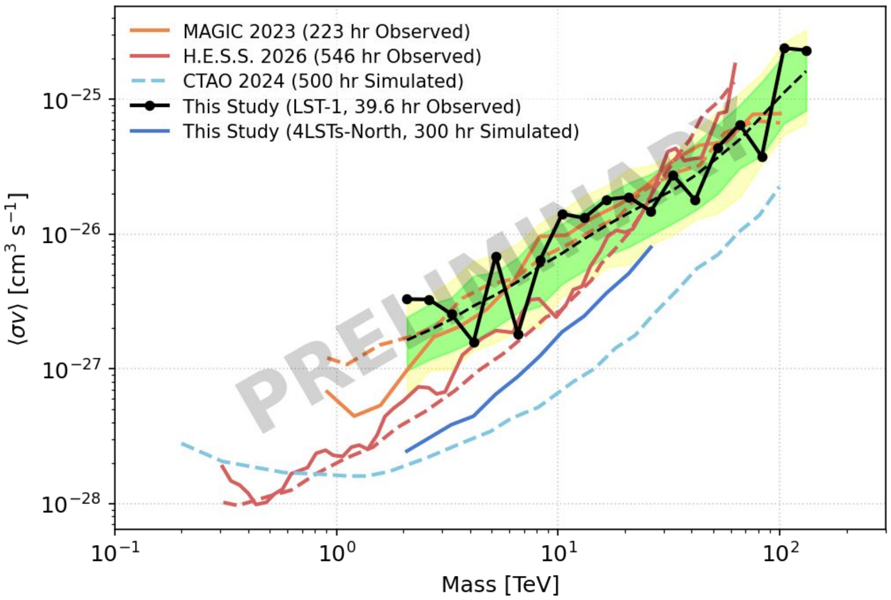


Relatively flat field of view

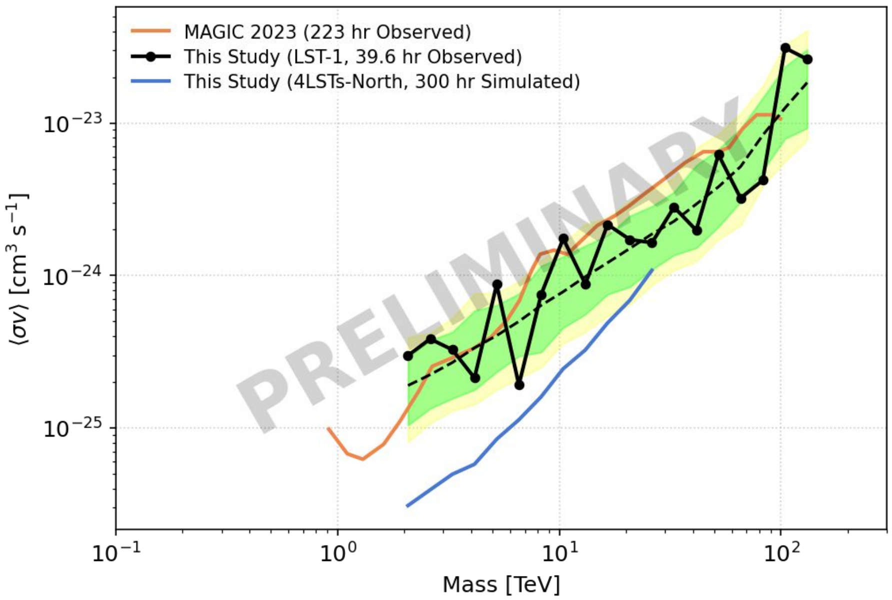


LST-1 already competitive; the world-leading sensitivity at mass >10 TeV for the cored profiles; the first line search from Cherenkov telescopes beyond 100 TeV.

Einasto (cuspy):



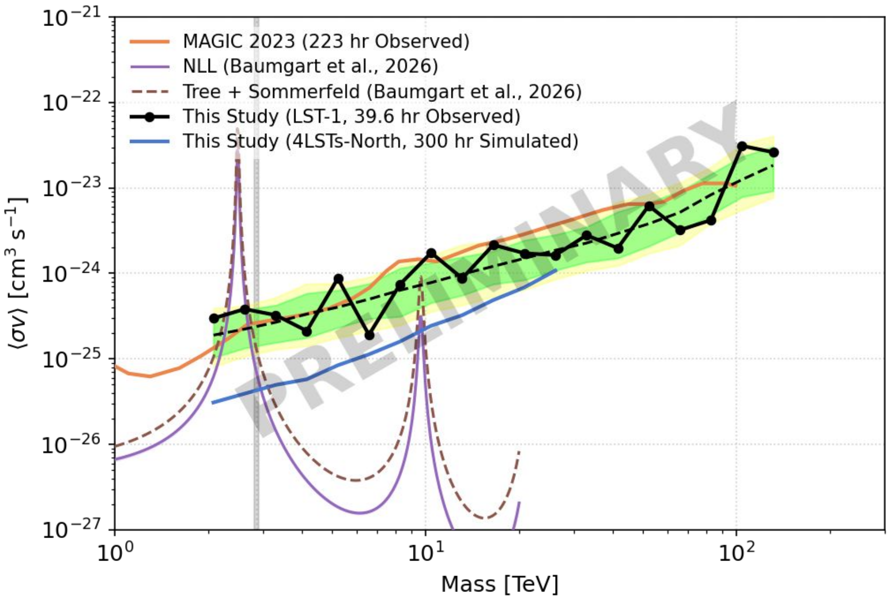
Burkert (cored):



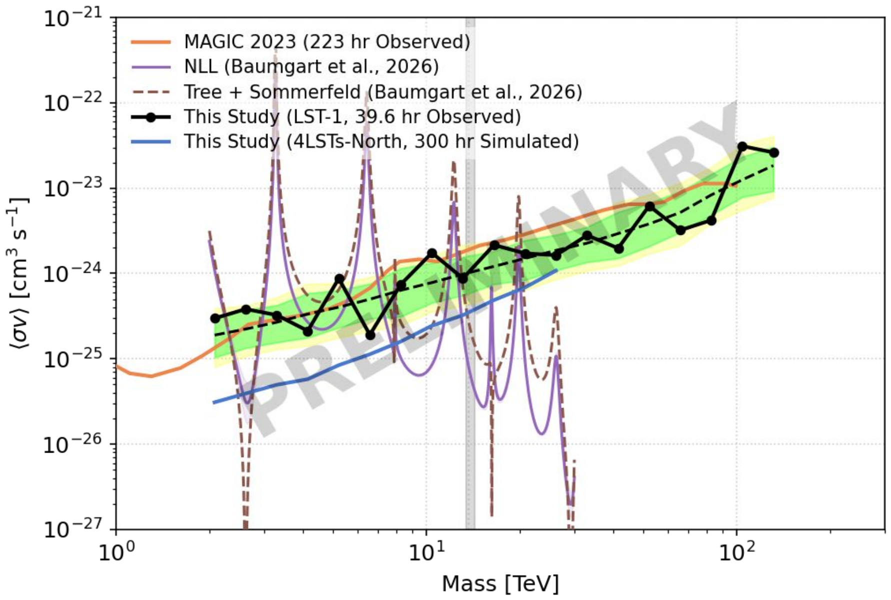
* The Burkert case, the most conservative one, shown here.

As a demonstration based on first real data from the CTAO telescope, the test of minimal DM candidates proven feasible

Wino, SU(2) triplet @ 2.86 TeV



Quintuplet @ 13.7 TeV



We are finally realizing the breakthrough of γ-ray observations, with results expected for CTAO in the decadal time frame, beginning with the LSTs.

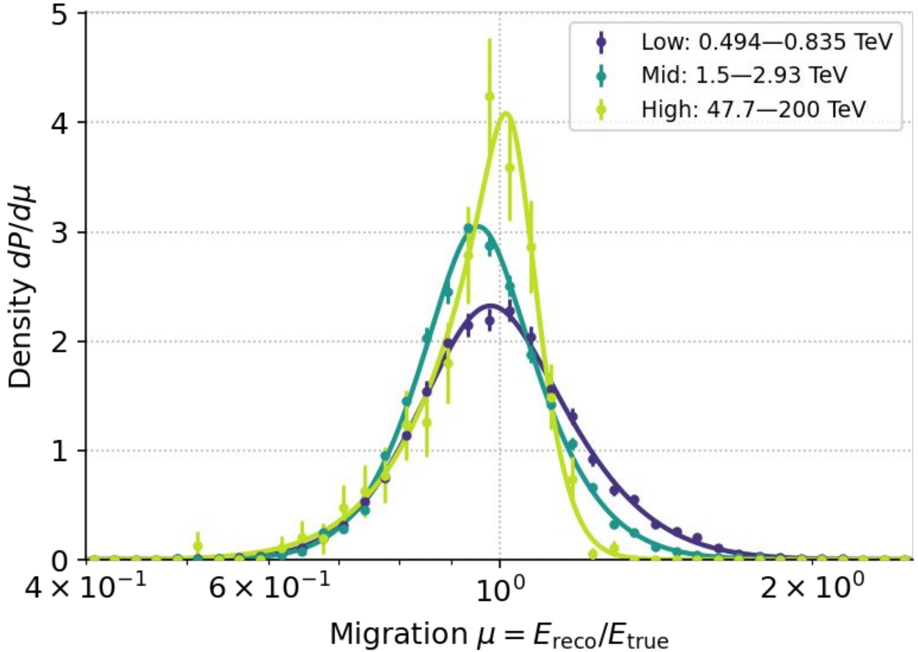
- For LST-1, large-zenith-angle observations and a wide field of view enhance sensitivity to extended TeV sources, making the Gal. Centre an excellent test case.
- We have developed a line DM search with LST-1, achieving a sensitivity already competitive to that of current-generation telescopes, despite the limited 40-hr exposure compared to >200 hours for other Cherenkov tels.
- this study marks:
  - the first results based on real data from LST-1, one of the CTAO telescopes,
  - the first line-search results extending beyond 100 TeV from the Cherenkov telescopes,
  - and the world-leading sensitivity for the cored profile cases, particularly for >10 TeV mass.
- Looking ahead, we should definitely further explore these DM topics in the Galactic Centre region with the forthcoming intermediate and full arrays of the CTAO.

BackUp

*sinh-arcsinh (SHASH): by Jones and Pewsey, 2009
**double Gaussian often subject to local peaks

Although a simple Gaussian can provide a reasonable formulation, a model that is a single-peak and can capture both skewness and tail-weight is preferable.

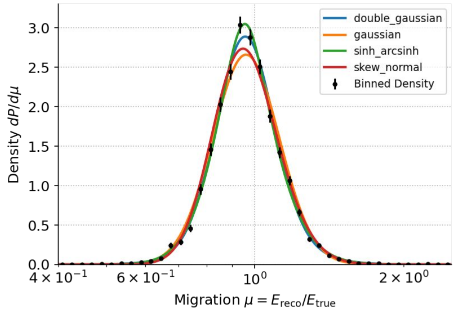
energy-dependent shapes
of the energy migration smoothly modeled

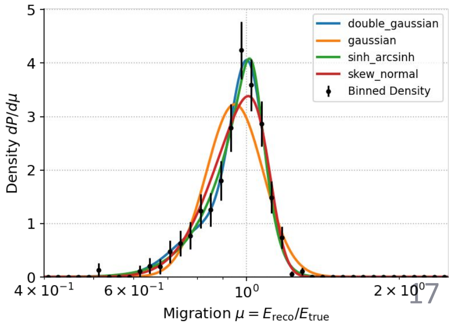


more leptokurtic at low/mid energies
more skewed at high energies

against (skewed) Gaussian, SHASH yielded:
ΔAIC = 118 (67) for mid E, 50 (6.3) for high E

$$f_\mu(\mu;\eta_0,\sigma,\kappa,\tau) = \frac{\tau\cosh\left[\tau\,\mathrm{asinh}\left(\frac{\ln\mu-\eta_0}{\sigma}\right)-\kappa\right]}{\mu\sigma\sqrt{2\pi}\sqrt{1+\left(\frac{\ln\mu-\eta_0}{\sigma}\right)^2}} \times \exp\left\{-\frac{1}{2}\sinh^2\left[\tau\,\mathrm{asinh}\left(\frac{\ln\mu-\eta_0}{\sigma}\right)-\kappa\right]\right\}$$

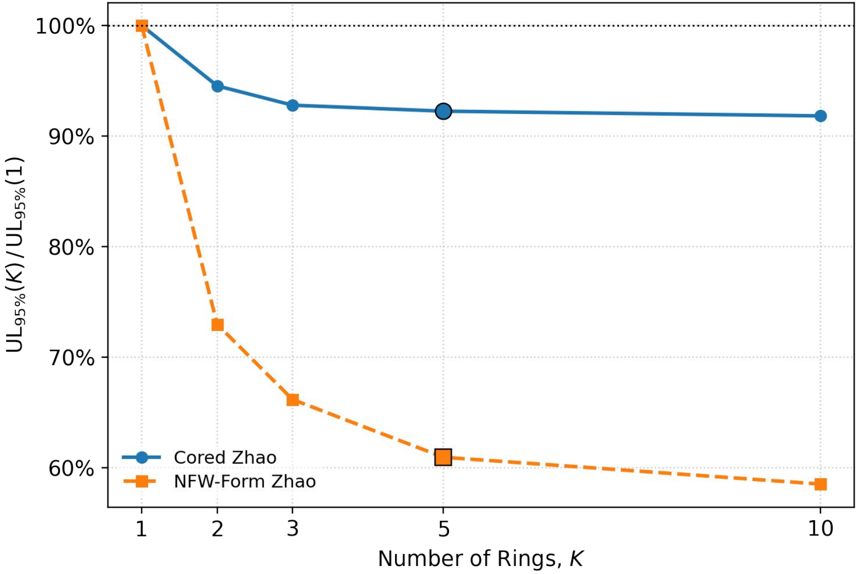




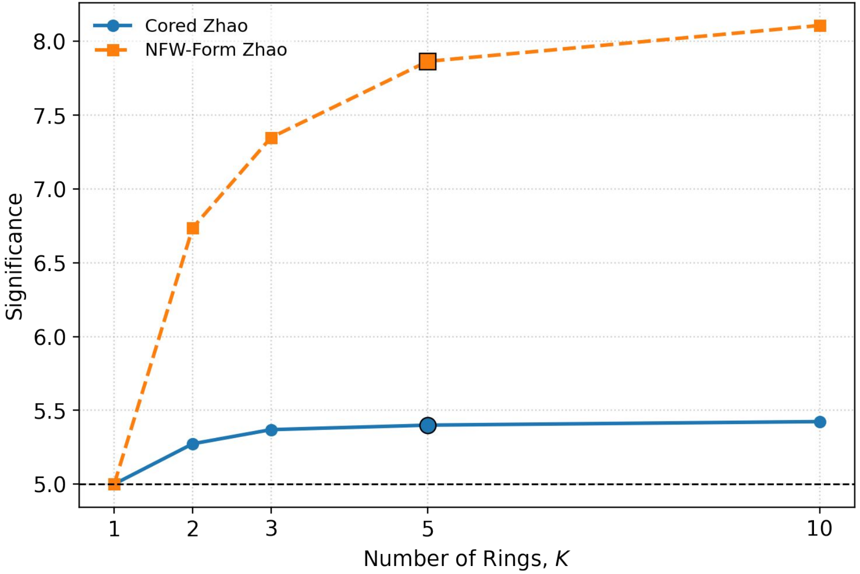
*K = 1 is effectively the case for the spectrum-only search

A 2-dim likelihood in annulus–energy space, 5 regions up to 2.0 deg, used. The sensitivity improved by about 8% (40%) for the cored (cuspy) profile.

Upper limit scan, for the null case

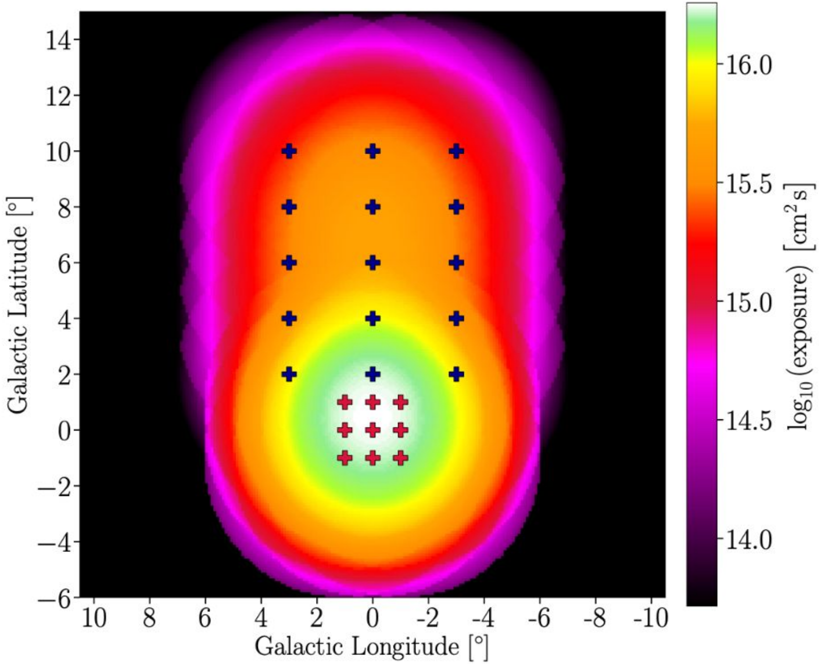


Significance scan, for the discovery case

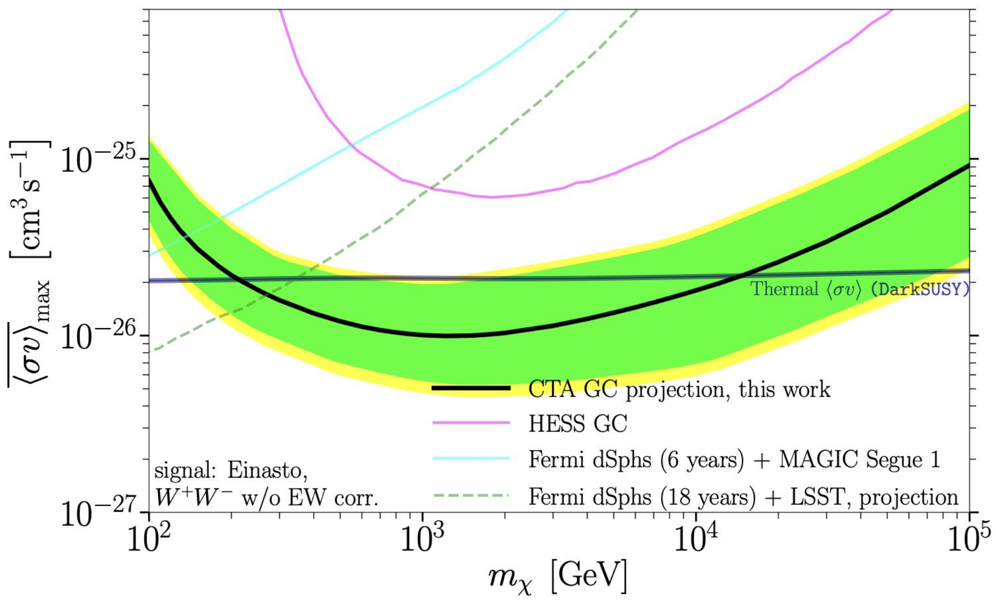


Given the relevance, the Gal. Center region will be deeply and widely observed in the framework of the *Key Science Project*, the consortium-official programme.

KSP Observation Plan for CTAO-South

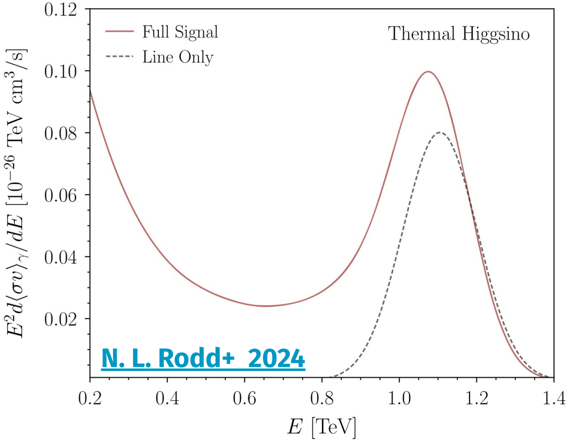


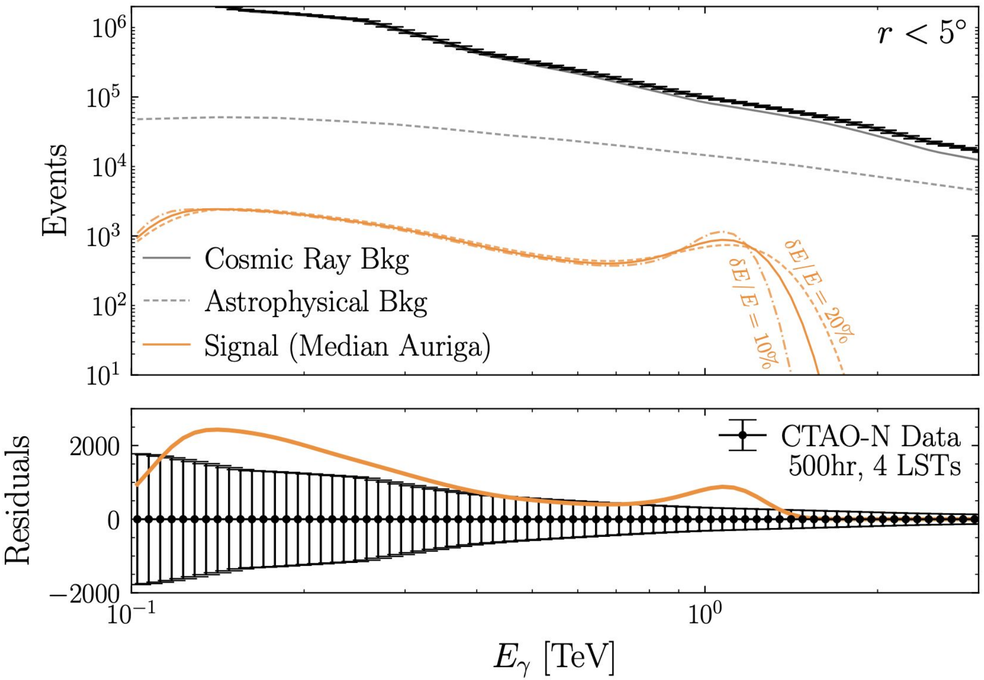
Continuum search reaching the thermal-relic level from 200 GeV

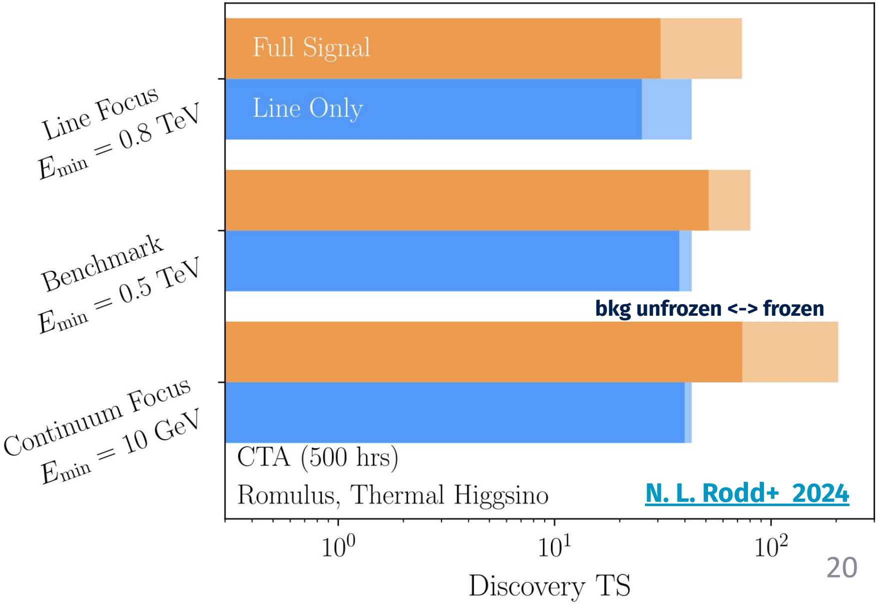


To envision the maximum science capabilities, the continuum used with bkg-related parameters fixed.

A similar significance over the bkg provided by line/continuum
-> important to study this aspect including bkg systematics





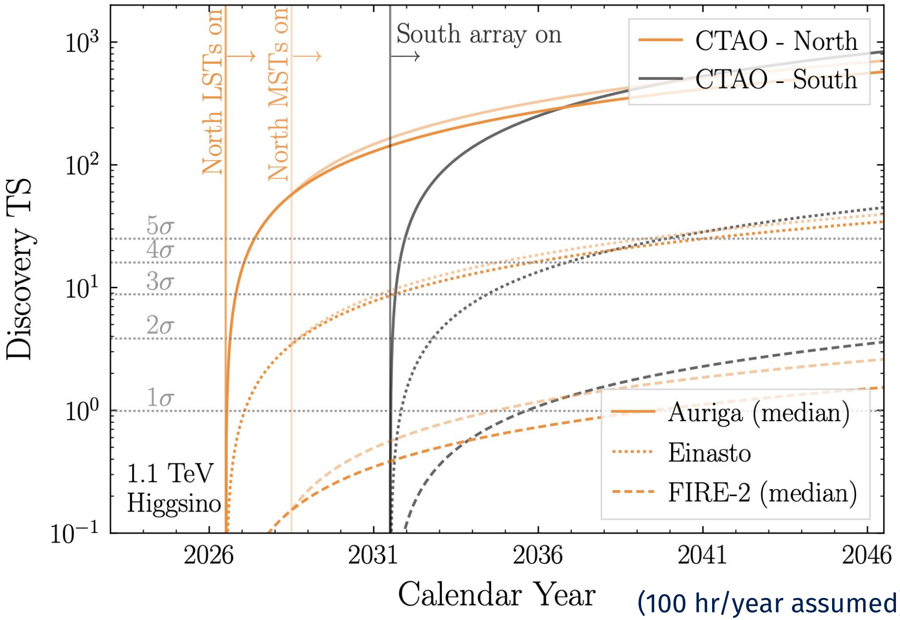


*The first five SSTs and two MSTs are expected to be delivered by 2026 (see here or here). In this work, however, we assume that the full array of CTAO-South in the alpha configuration starts taking data from 2031, while no intermediate array configuration is assumed.

CTAO-North could discover the Higgsino DM within the current decade. An earlier deployment of CTAO-South may accelerate the study more.

details can be found in: Abe+, PRD 2026

CTAO-North will face a timely opportunity to potentially discovery Higgsino.



(100 hr/year assumed)

We have discussed a variety of DM profiles. Would be interesting to study other bkg.