Dark Matter line search at Galactic Center using LST-1

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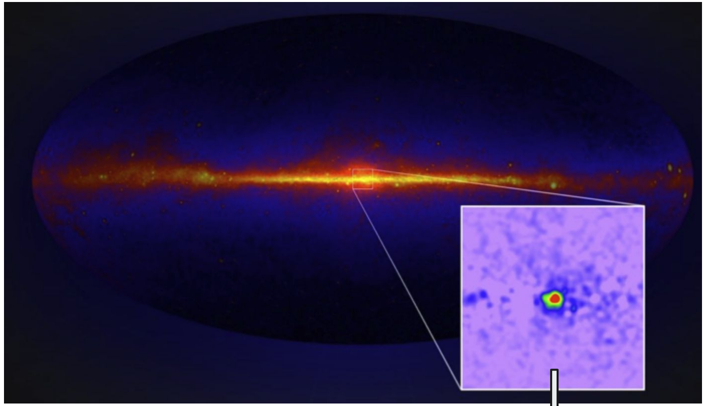
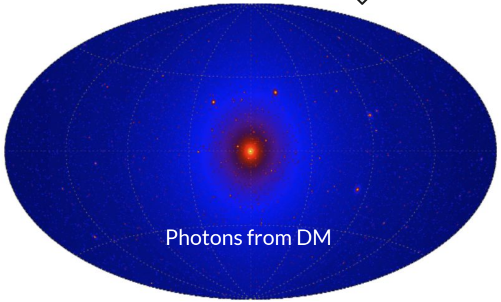
Dark Matter search at Galactic Center

The search for TeV-scale dark matter, particularly in the Galactic Center region, is a crucial objective for the Large-Sized Telescopes (LSTs) and the Cherenkov Telescope Array Observatory (CTAO).

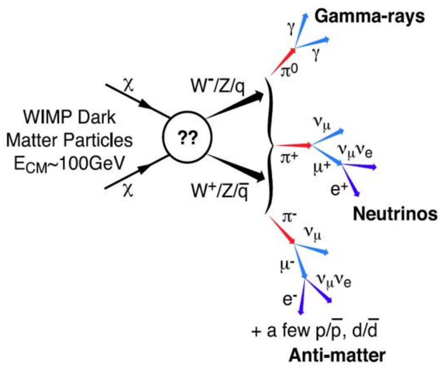


Tim Linden



Pieri+ 2011

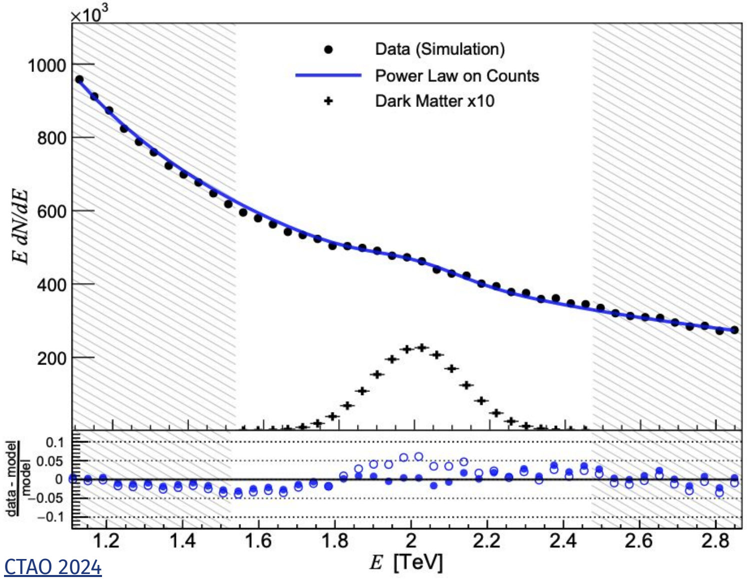
Fermi-LAT



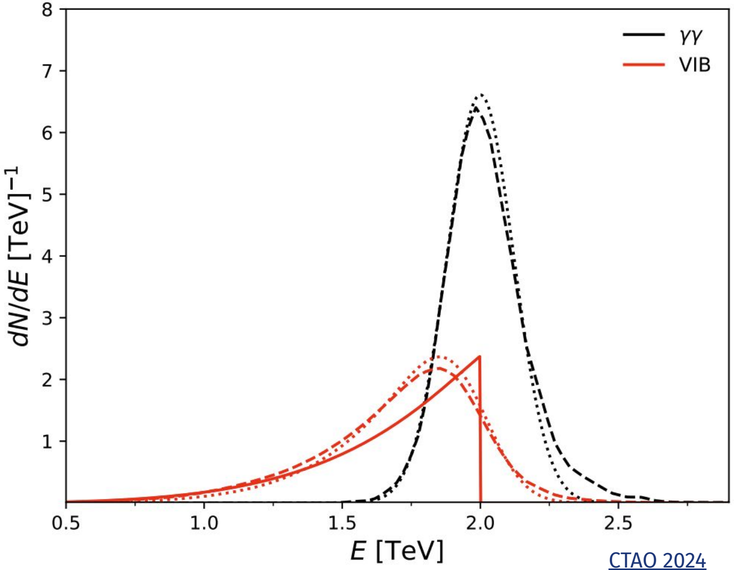
Dark Matter line signals from WIMPs

Monochromatic gamma-ray signals from WIMP DM interactions constitute a potential smoking gun signature for annihilating or decaying dark matter particles.

Search for a peak on ‘smooth’ counts spectrum majorly dominated by background. Currently we are focusing on direct $\gamma\gamma$ channel, plan to explore more sharp spectral features like VIB



CTAO 2024



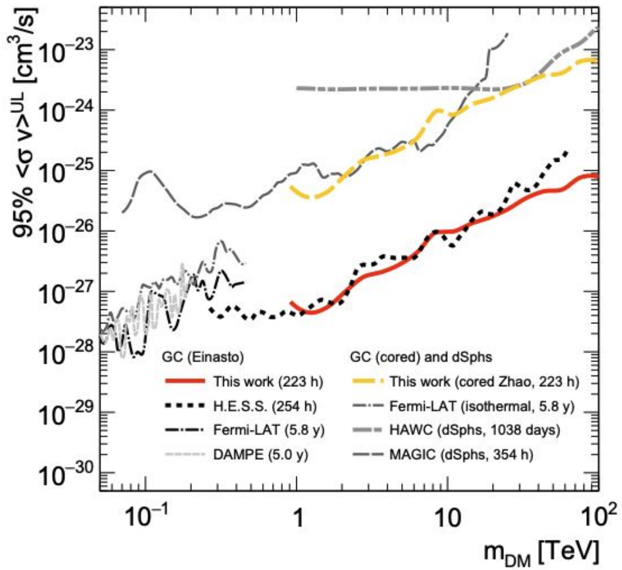
CTAO 2024

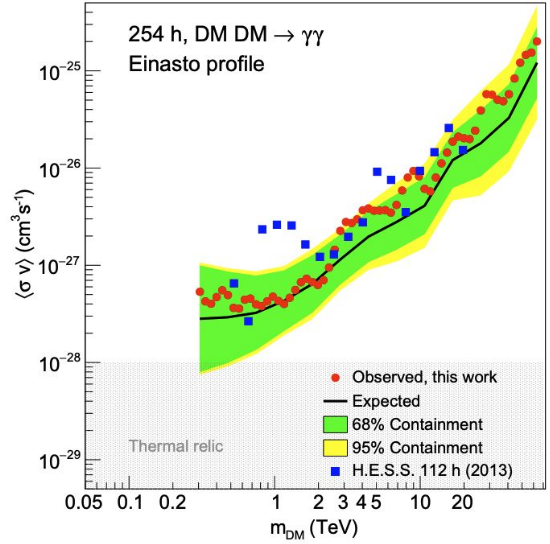
IACTs imposing strong constraints

HESS-2018 and MAGIC-2023 have provided stringent constraints, reaching very close to the thermal relic cross-section

MAGIC-2023 performed analysis on 223 hours data taken at large zenith angle, showing sensitivity boosted at higher energies than previously reported limits

HESS-2018 had shown the line search from low-zenith observations. Performed On-Off analysis; hence not optimal for Burkert like shallow-core models



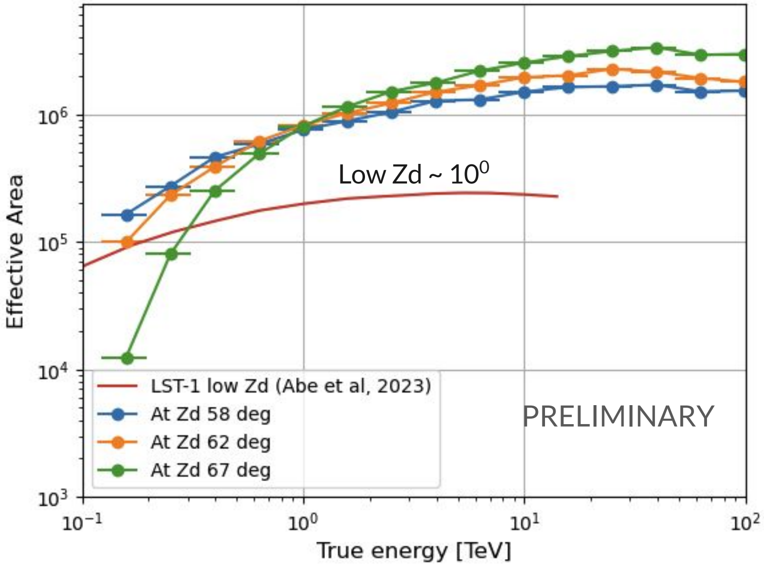


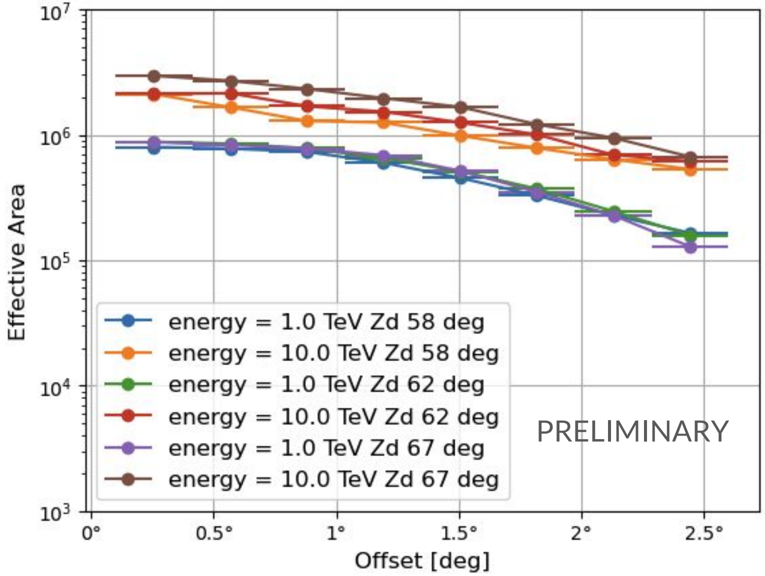
LST-1 observations of GC

LZA observations can boost effective area for up to ~100 TeV, LST-1 observes GC at large zenith angles, moreover it's wide field of view provides :

Boost in effective areas at higher energies ~ 10^6 m^2 and ~10^5 even at lower energies (0.4 TeV); strongly dependent on Zd

High effective area out upto 2.5^o, demonstrating uniform performance over extended off-axis angles, suitable for extended sources >1^o





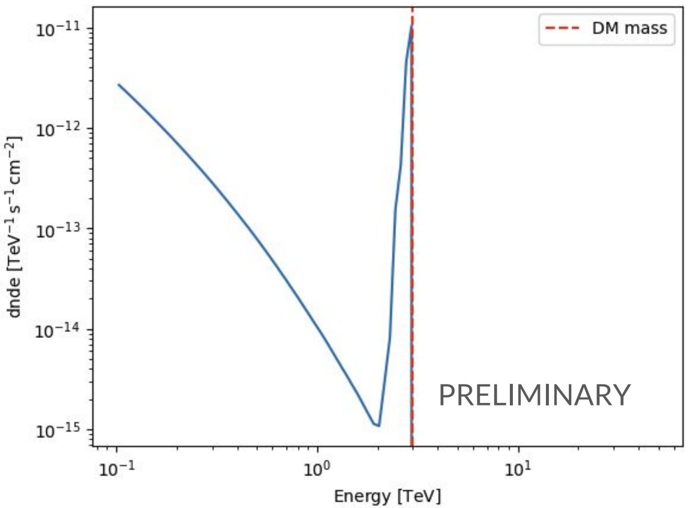
Line search implementation - Methods

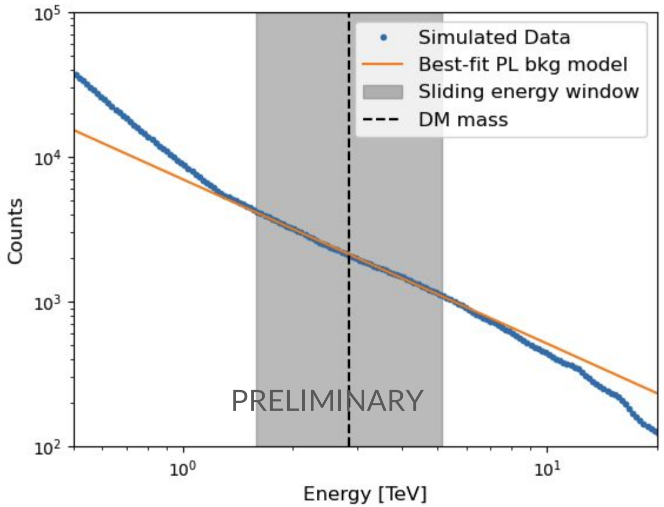
A. Abhishek

Spectral-only analysis; fitting a PL bkg and a DM signal to the energy distribution, isolating the spectral signature of dark matter annihilation without relying on spatial information.

DM is modelled using default gammapy DM class for $\gamma\gamma$ annihilation channel; includes continuum part also, but will barely contribute

Counts spectrum is modelled using a power-law within the **energy window** ($\pm 4\sigma$) around the expected DM mass.





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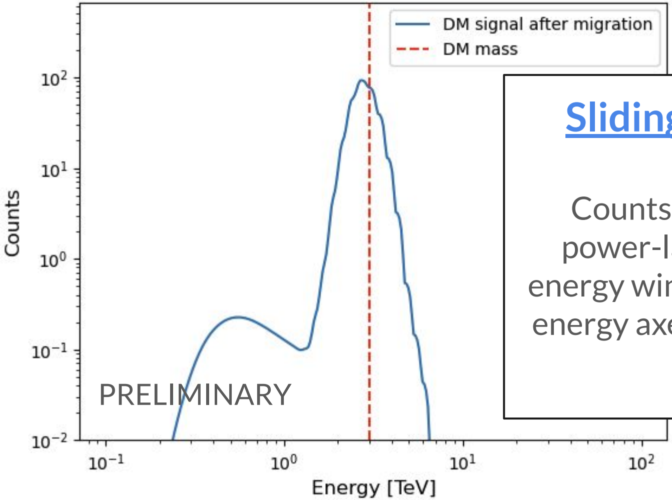
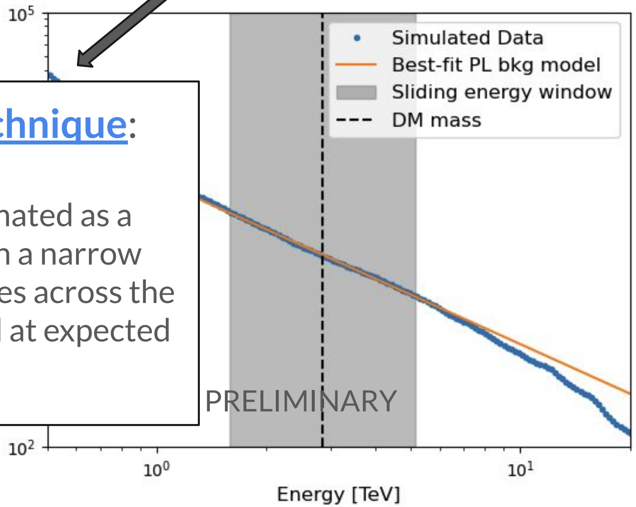


Sliding window technique:

Counts can be approximated as a power-law locally, within a narrow energy window, which slides across the energy axes with centered at expected DM mass



Line search implementation - Methods

A. Abhishek

Spatial profile of DM: The DM expected flux strongly depends on the density profile of DM in the GC. Here we discuss two profiles: Einasto (Cuspy) and Burkert (Cored) profiles

Estimated flux from DM annihilation; direct to $\gamma\gamma$ particle spectrum estimated using a Dirac delta function. Here we are using std gammapy function

J-Factor is computed using standard gammapy tools for Einasto (Cuspy) and Burkert (Cored) profiles within the ROI

scale

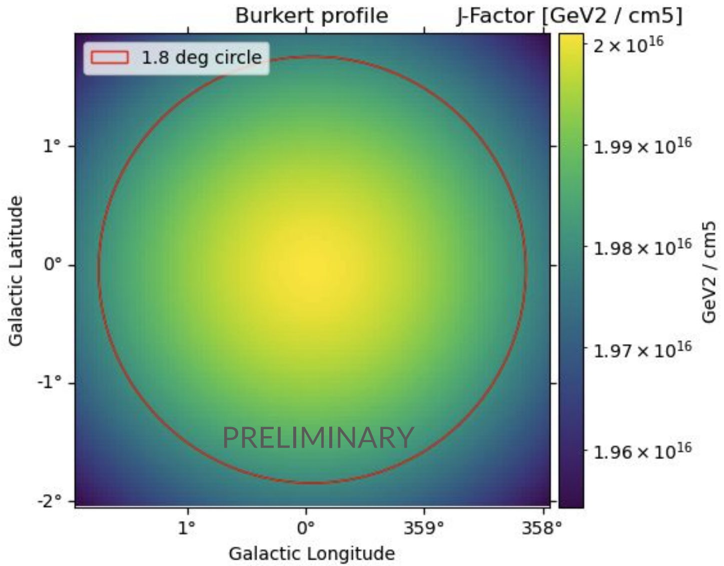
$$\frac{d\Phi_\gamma}{dE} = \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m_{\rm DM}^2} \frac{dN_\gamma}{dE} \times J(\Delta\Omega)$$

$$\frac{dN_\gamma}{dE} = 2\delta(E - m_{\rm DM})$$

$$J(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int_{\rm l.o.s.} \rho^2(l,\Omega)\, dl$$

Astrophysical spatial factor

DM density function

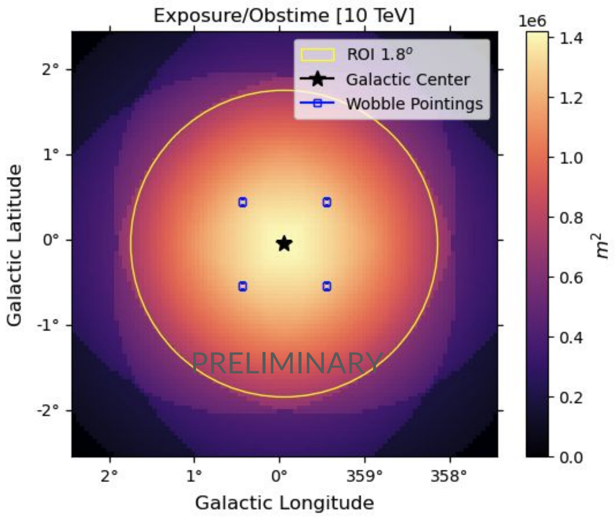


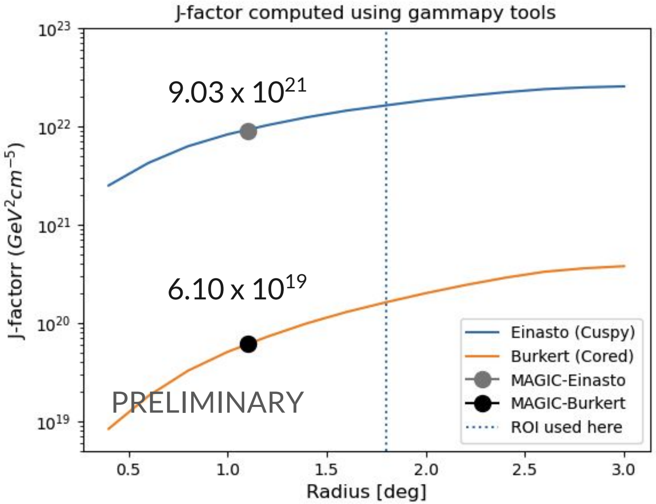
Dataset simulation using LST-1 IRFs

Simulated 3D datasets using LST-1 IRFs at zenith angle 62°. We use a wide (1.8° here) region of interest (ROI) and sum over spatial axes within the ROI to produce 1D dataset

Produce spectrum dataset of 40h by summing counts spatially within the ROI of 1.8°

J-Factor is computed using standard gammapy tools for Einasto (Cuspy) and Burkert (Cored) profiles within the ROI



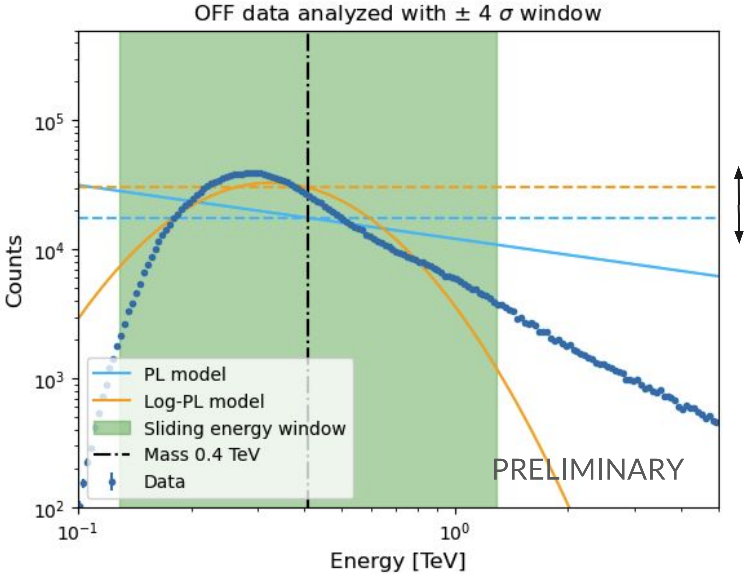


Systematic studies on the bkg spectra

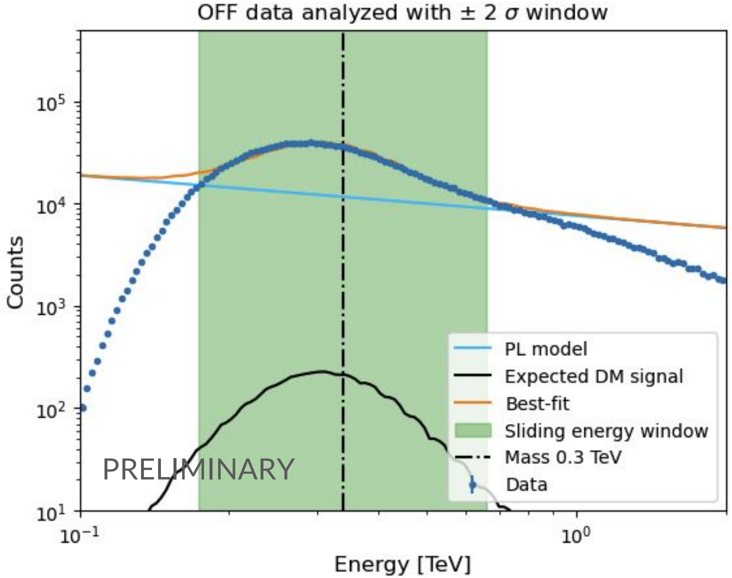
A. Abhishek

The sliding window technique is susceptible to a poor background modeling, which we will estimate by careful evaluation of the resulting systematic uncertainties

Difference in normalisation of bkg due to possible curvature



Fake line-like signal due to possible curvature



LST-1 expected results

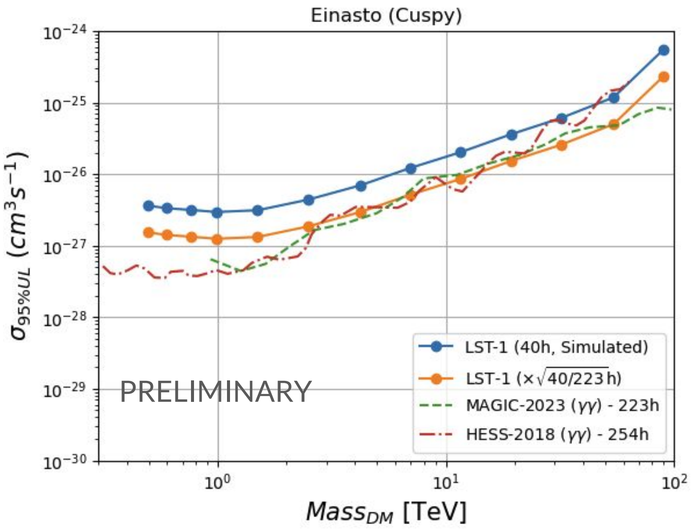
Line search implementation - Results

A. Abhishek

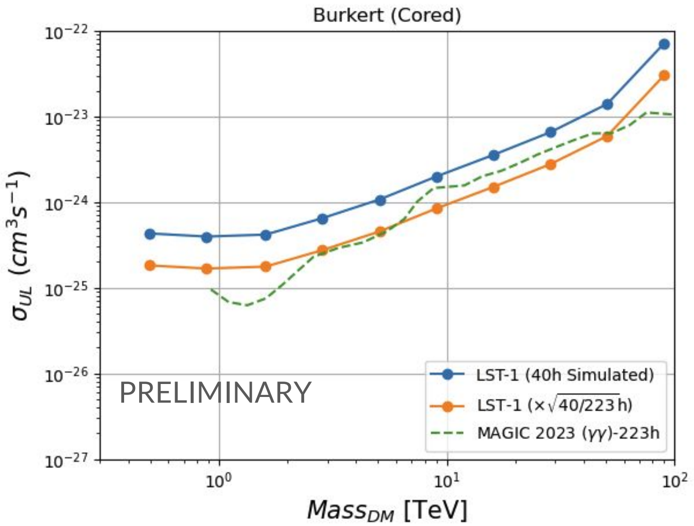
Results shows are from fitting PL bkg + DM on best-fit PL background of the Asimov datasets. Current limits are already competitive

With the same 223-hour exposure as MAGIC-2023, LST-1 suggests improvement from MAGIC in the $\langle\sigma v_{UL}\rangle$ by 26% (36%) and 21% (33%) for Einasto (Burkert) case at 10 and 30 TeV respectively.

Competitive with HESS from 30 TeV



Almost reaching MAGIC limits at > 10 TeV already

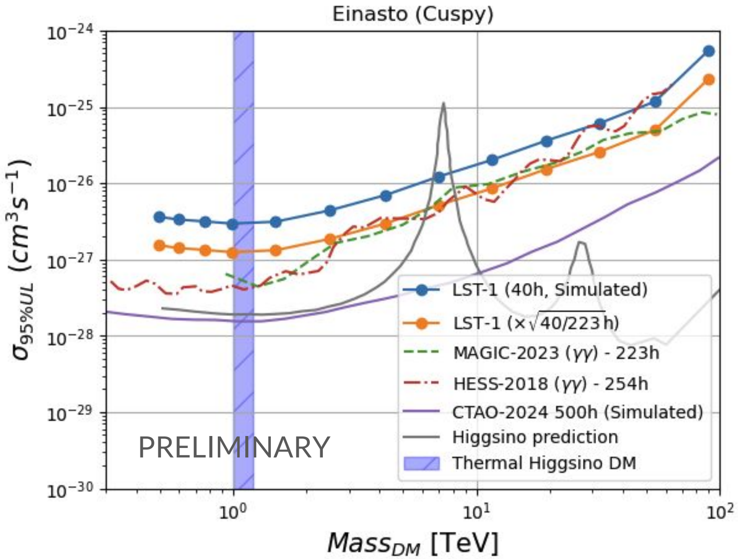


Line search implementation - Results

A. Abhishek

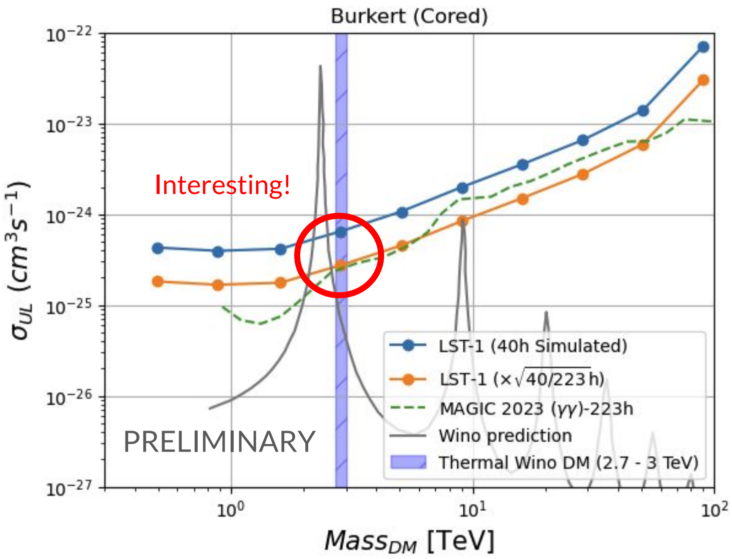
Thanks to its large mirror and wide field of view, and sensitivity at large zenith angles, LST-1 shows potential in probing of Wino and Higgsino models with shorter observation time

Current limits are 1.5 orders of magnitude away from the thermal Higgsino prediction



[CTAO 2024]

Current limits are <1 (0.78) orders of magnitude away from the thermal Wino prediction



Summary

A dedicated line-search pipeline has been developed for LST-1, already showcasing competitive sensitivity !

- We explored the potential for detecting sharp spectral features from dark matter annihilation using simulations for LST-1.
  - LST-1 has been observing GC at LZA since 2021 has collected ~ 40h of data
  - LST-1 IRFs at LZA are used to simulate datasets for 40h and estimate the sensitivity for DM lines
- A sliding-window technique was applied to fit background-only and DM+background models on 1D energy spectra.
- Projected upper limits were derived for an Einasto and Burkert dark matter density profiles across a range of masses.
- Our limits are competitive with the current constraints, shows potential in probing SUSY Wino and Higgsino cases.

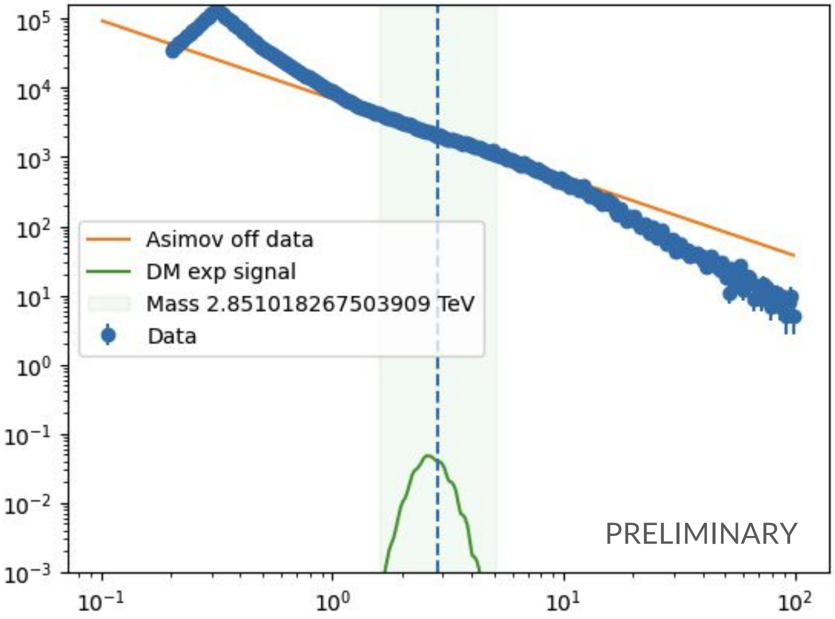
References

- MAGIC-2023: https://ui.adsabs.harvard.edu/abs/2023PhRvL.130f1002A/abstract
- HESS-2018: https://ui.adsabs.harvard.edu/abs/2018PhRvL.120t1101A/abstract
- CTAO-2024: https://ui.adsabs.harvard.edu/abs/2024JCAP...07..047A/abstract
- Abe et al. -2023: https://www.aanda.org/articles/aa/abs/2023/12/aa46927-23/aa46927-23.html
- Pieri et al -2011: https://ui.adsabs.harvard.edu/abs/2011PhRvD..83b3518P/abstract

Back-up

Back-up

For each mass, we fit the background with power-law, produce a new Asimov datased accordingly and fit the DM model with the power-law



Back-up

MAGIC-2023 used CLYMPY to get the J-factor values, we are using JFactory class in gammapy

Profile name	Profile type	α	β	γ	ρ_s [GeV cm^{-3}]	r_s [kpc]	$\rho_\odot$ [GeV cm^{-3}]	$R_\odot$ [kpc]	$R_{\max}$ [kpc]	Reference
Cuspy Einasto	Einasto	0.17	–	–	0.0790	20	0.388	8.5	433	[26, 32, 46]
NFW	Zhao	1	3	1	0.0768	21	0.384	8.5	402	[26, 32, 46]
Cored Zhao	Zhao	1	3	0	0.431	7.7	0.391	8.21	265	[55]
Burkert core	Burkert	–	–	–	1.568	9.26	0.487	7.94	291	[52]

Profile name	$J(0.5°)$	$J(1.0°)$	$J(1.1°)$
Cuspy Einasto	3.14×10^{21}	8.01×10^{21}	9.03×10^{21}
NFW	2.18×10^{21}	4.55×10^{21}	5.02×10^{21}
Cored Zhao	2.66×10^{19}	1.06×10^{20}	1.28×10^{20}
Burkert core	1.26×10^{19}	5.04×10^{19}	6.10×10^{19}

Our integrated and summed J-factor values: (1.1^{o})

- Cuspy Einasto: 9.33 x 10^{21}
- NFW: 6.14 x 10^{19}
- Cored Zhao: 1.28 x 10^{20}
- Burkert core: 6.14 x 10^{19}

Back-up

We have used Cash statistics, eventually we will incorporate the systematic uncertainties in the likelihood function as was done in MAGIC-2023

Cash statistics

$$C = 2 \times (\mu_{\text{sig}} + \mu_{\text{bkg}} - n \times log(\mu_{\text{sig}} + \mu_{\text{bkg}}))$$

Extended likelihood (MAGIC-2023)

$$\begin{aligned}\mathcal{L}_i(\langle\sigma v\rangle; \boldsymbol{\nu}_i \,|\boldsymbol{\mathcal{D}}_i) &= \mathcal{L}_i(\langle\sigma v\rangle; b_i, \tau_i \,|\{E'_j\}_{j=1,\ldots,N_{\text{ON},i}}, N_{\text{ON},i}) \\ &= \underbrace{\frac{(g_i + \tau_i b_i)^{N_{\text{ON},i}}}{N_{\text{ON},i}!} e^{-(g_i+\tau_i b_i)}}_{\text{(a)}} \times \underbrace{\prod_{j=1}^{N_{\text{ON},i}} \frac{1}{g_i + \tau_i b_i} (g_i f_g(E'_j) + \tau_i b_i f_b(E'_j))}_{\text{(b)}} \times \underbrace{\mathcal{T}(\tau_i|\tau_{\text{obs}}, \sigma_\tau)}_{\text{(c)}}\end{aligned}$$

Term (c) corresponds to the likelihood term for the normalization of the background, parametrized by a Gaussian function

Line search implementation - JFactor computation

A. Abhishek

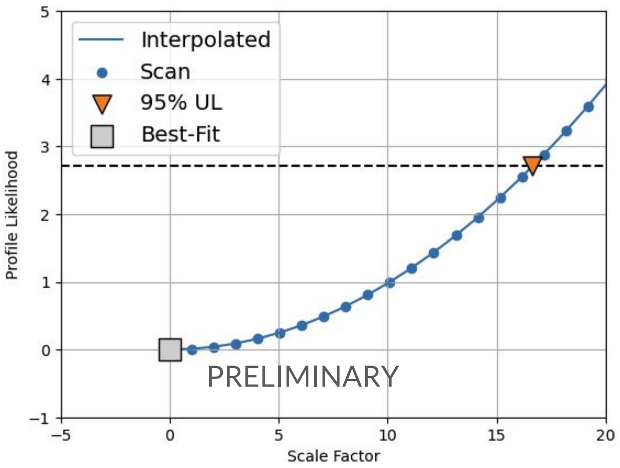
J-factor computed using gammapy tools, consistent with MAGIC-2024

Einasto profile:	Burkert profile:
ROI 1.1°: [$GeV^2\ cm^{-5}$] • MAGIC-2024 : 9.03 x 10^{21} • This study : 9.33 x 10^{21} ROI 1.8o - we used: 1.64 x 10^{22} $GeV^2\ cm^{-5}$	ROI 1.1°: [$GeV^2\ cm^{-5}$] • MAGIC-2024 : 6.10 x 10^{19} • This study : 6.14 x 10^{19} ROI 1.8o - we used: 1.63 x 10^{20} $GeV^2\ cm^{-5}$

Line search implementation - U.L computation

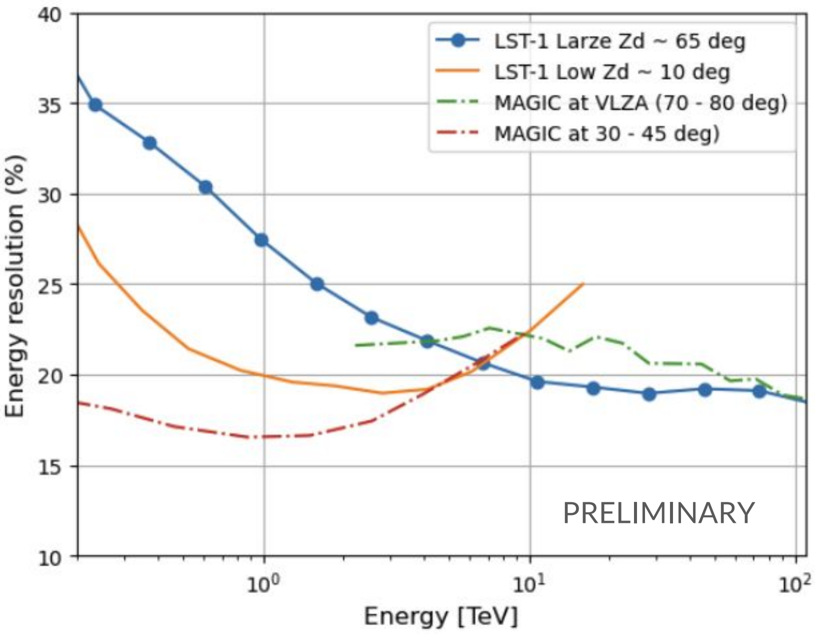
The analysis is performed with a 1D log-likelihood ratio test statistics (TS) using the spectral features of the DM line signal in energy windows centered at DM mass

Profile likelihood scan for computing upper limits at 95% C.L



Energy resolution

LST-1 alone shows descent energy resolution at higher energies compared to MAGIC telescopes at large zenith angles



[MAGIC-2020]
[MAGIC-2015]