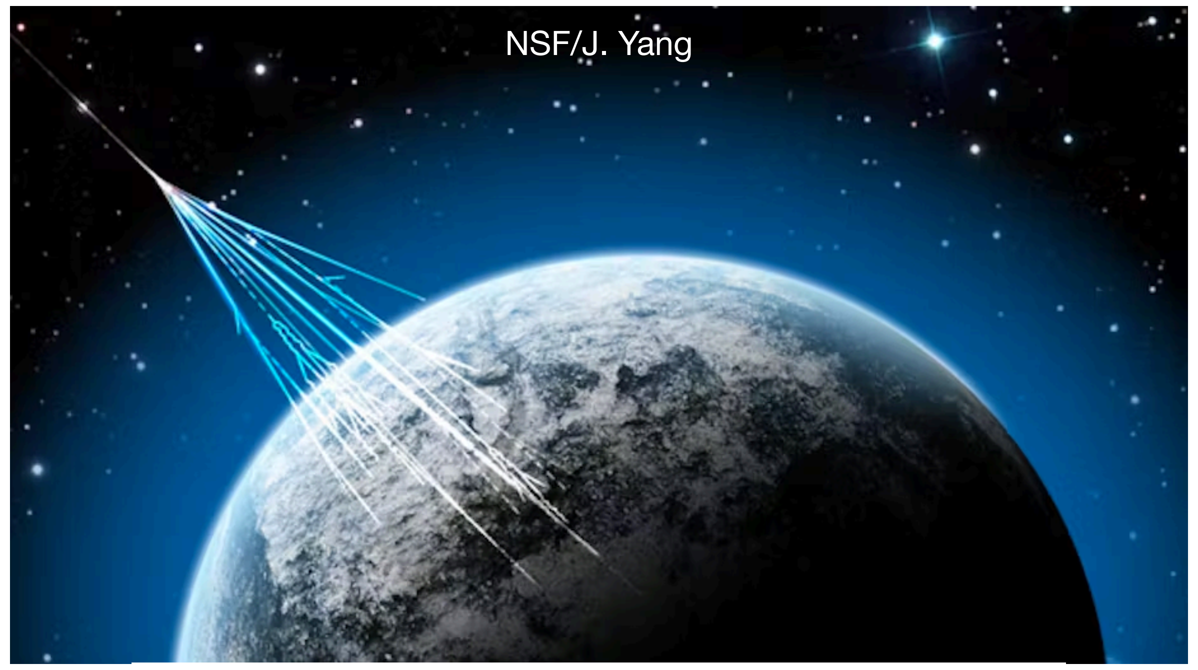
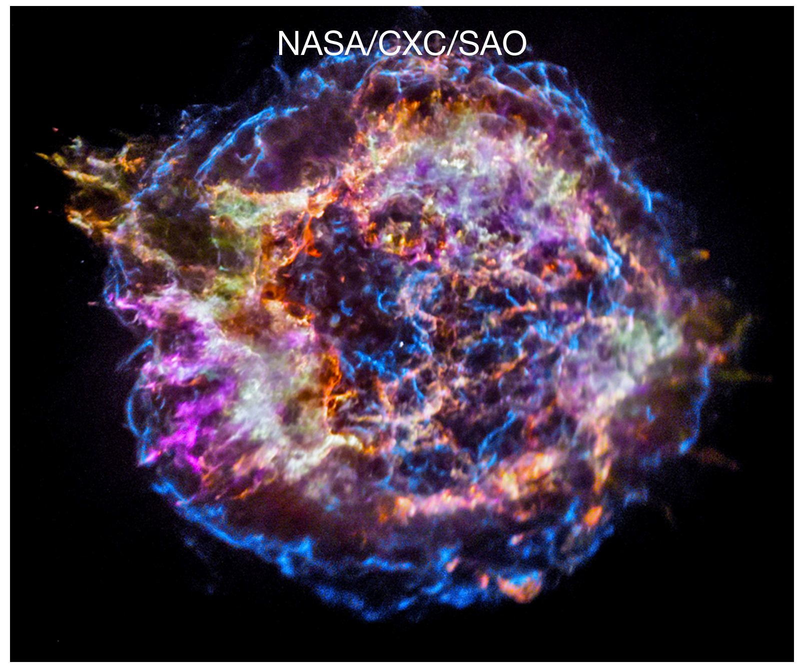
Search for Dark Matter spectral lines around the Galactic Centre with CTAO LST-1

Tomohiro Inada (Kyushu Univ)
S. Abe, A. Abhishek, M. Doro, M. Teshima, G. Verna, S. Ventura
on behalf of the CTAO-LST Collaboration

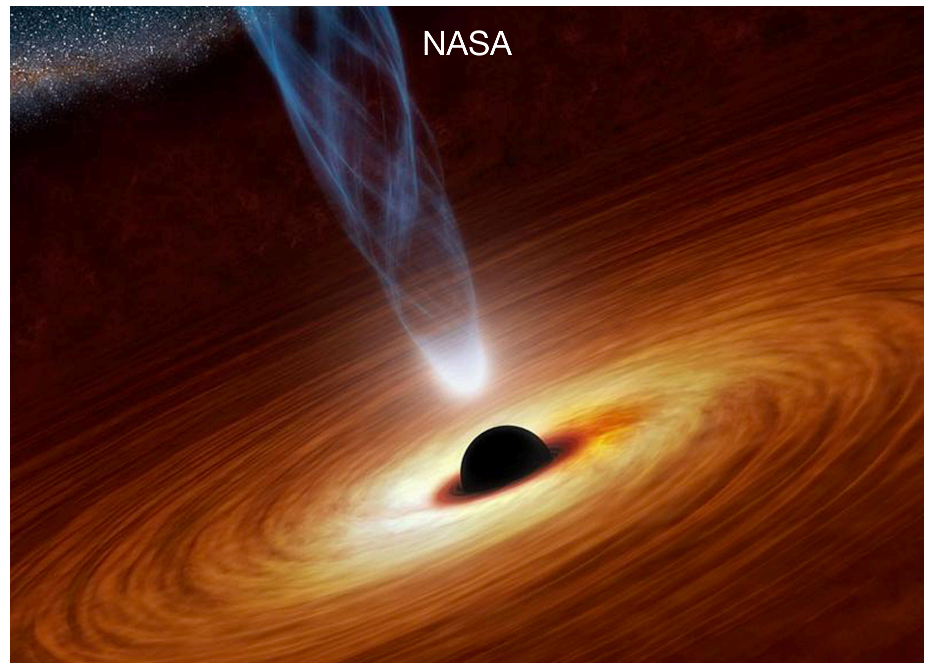
High energy phenomena in the universe



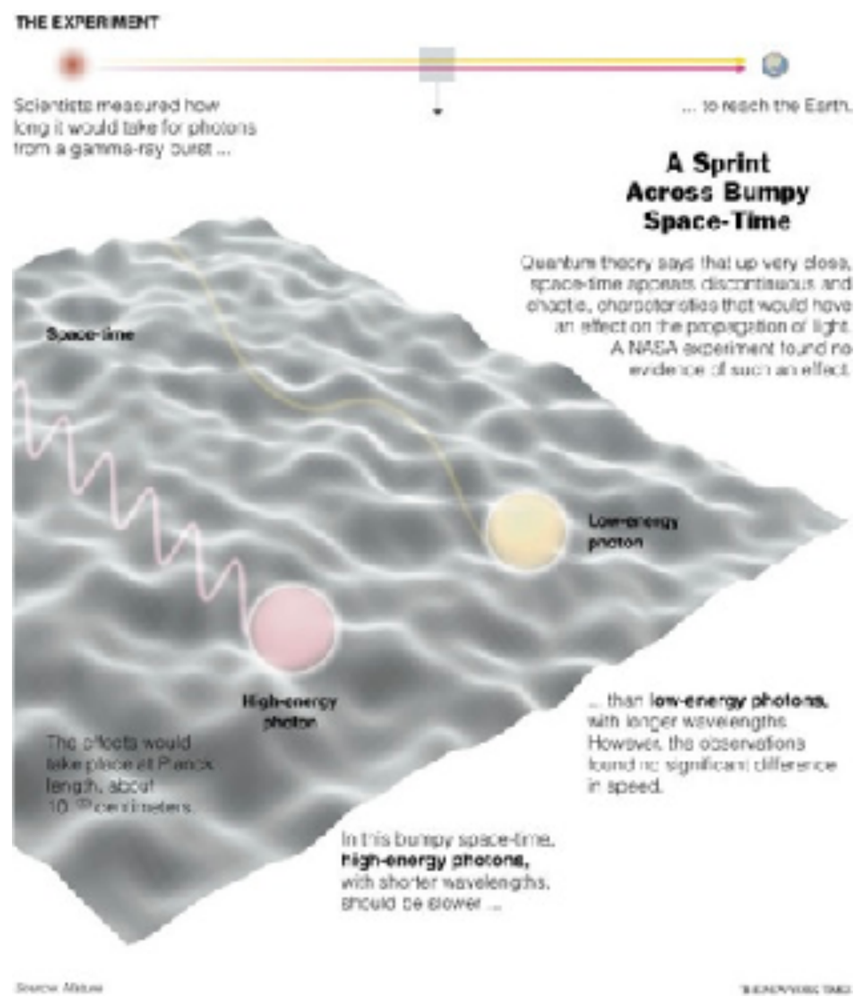
Origin of Cosmic Rays



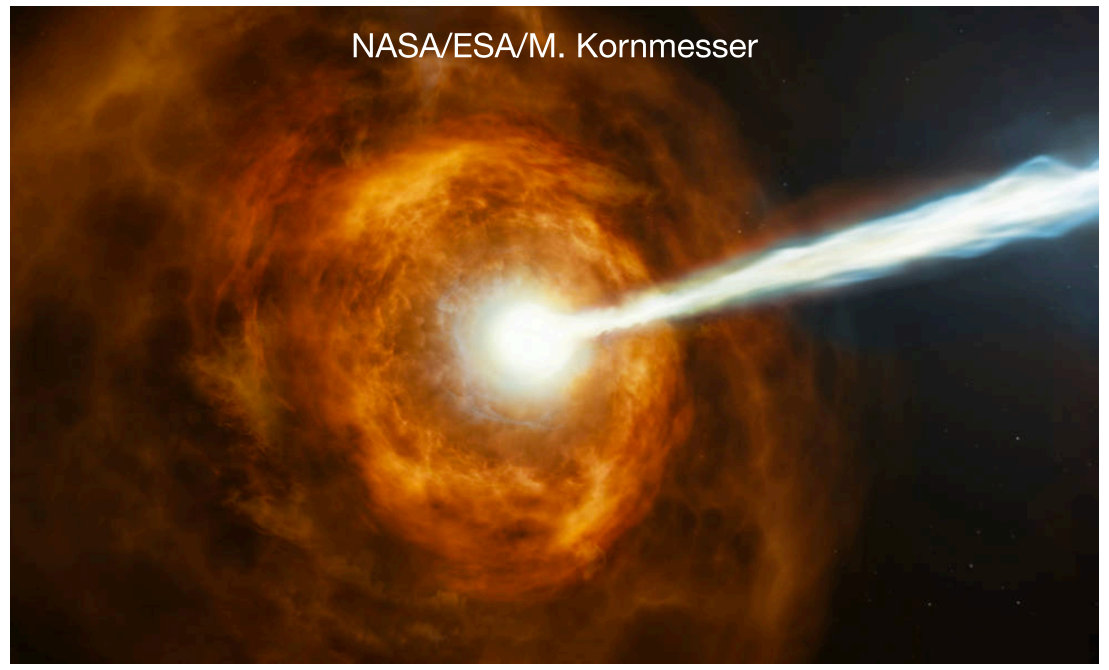
Supernova Remnant



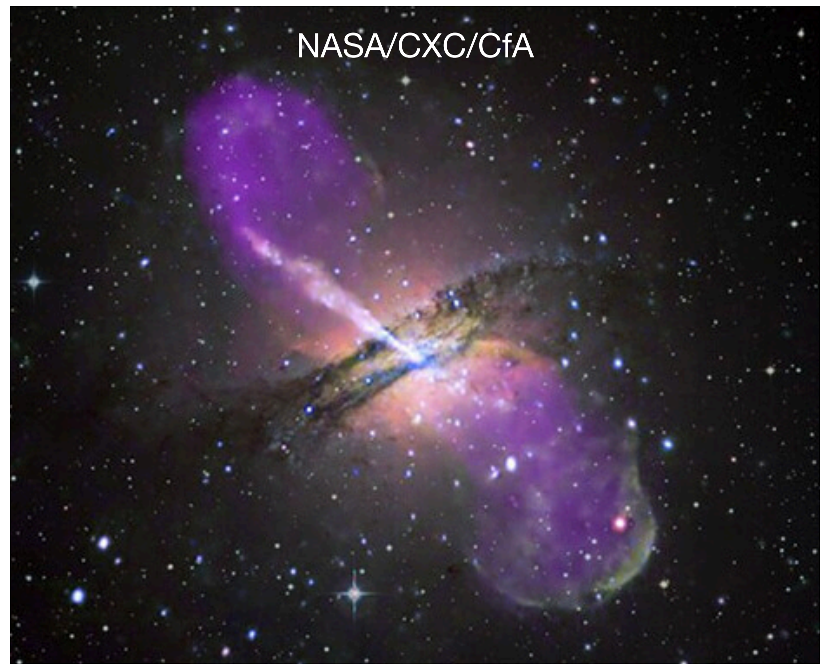
Supermassive Black Hole



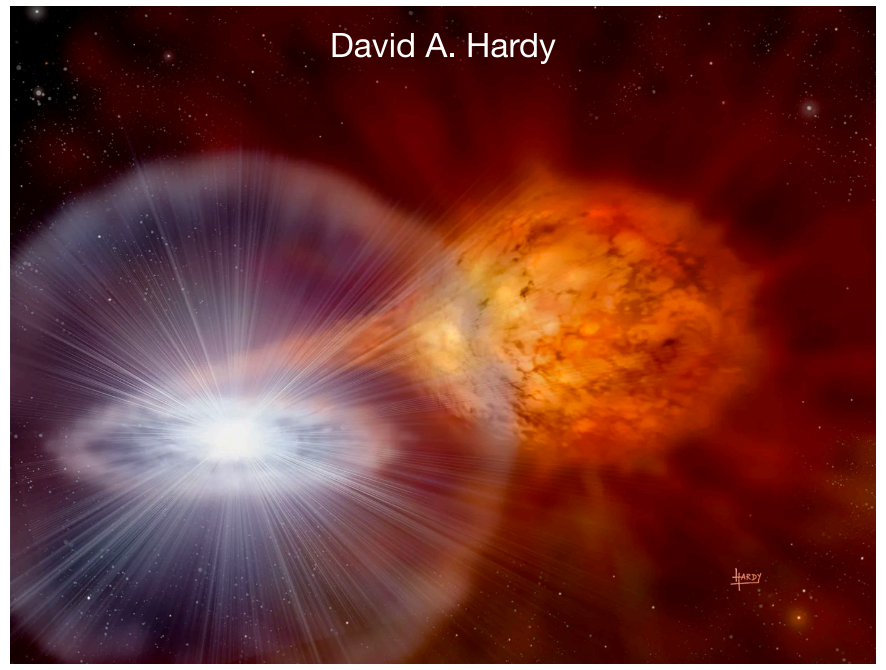
Bounds on Lorentz Invariance Violation



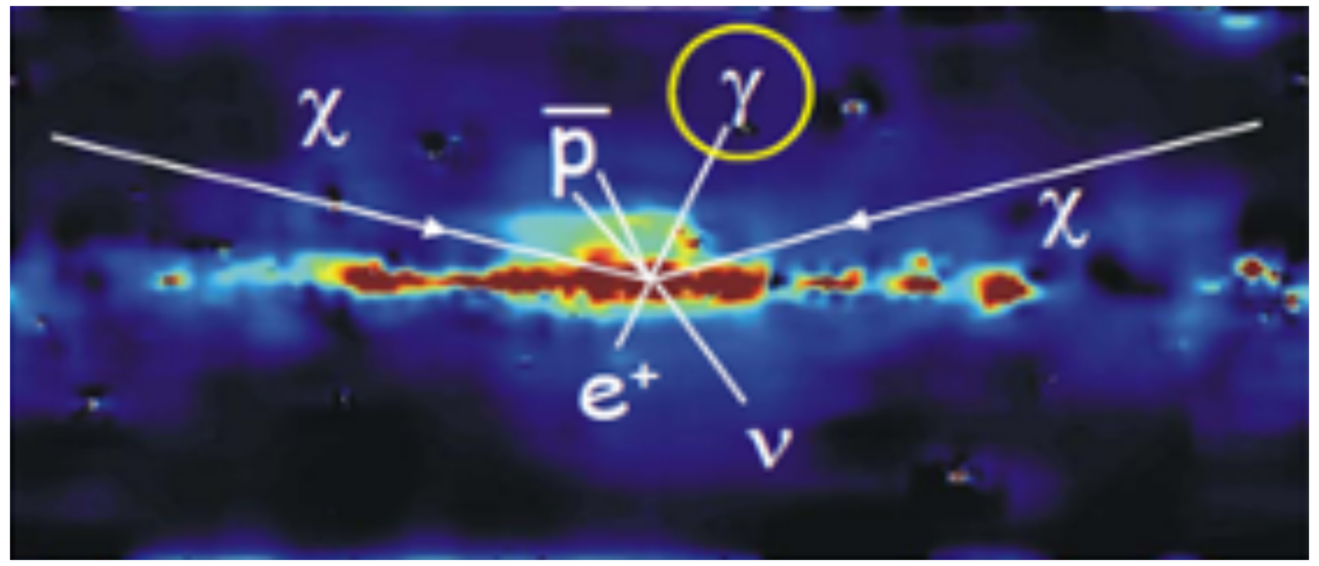
Gamma Ray Burst



Active Galactic Nuclei



Binary / Nova

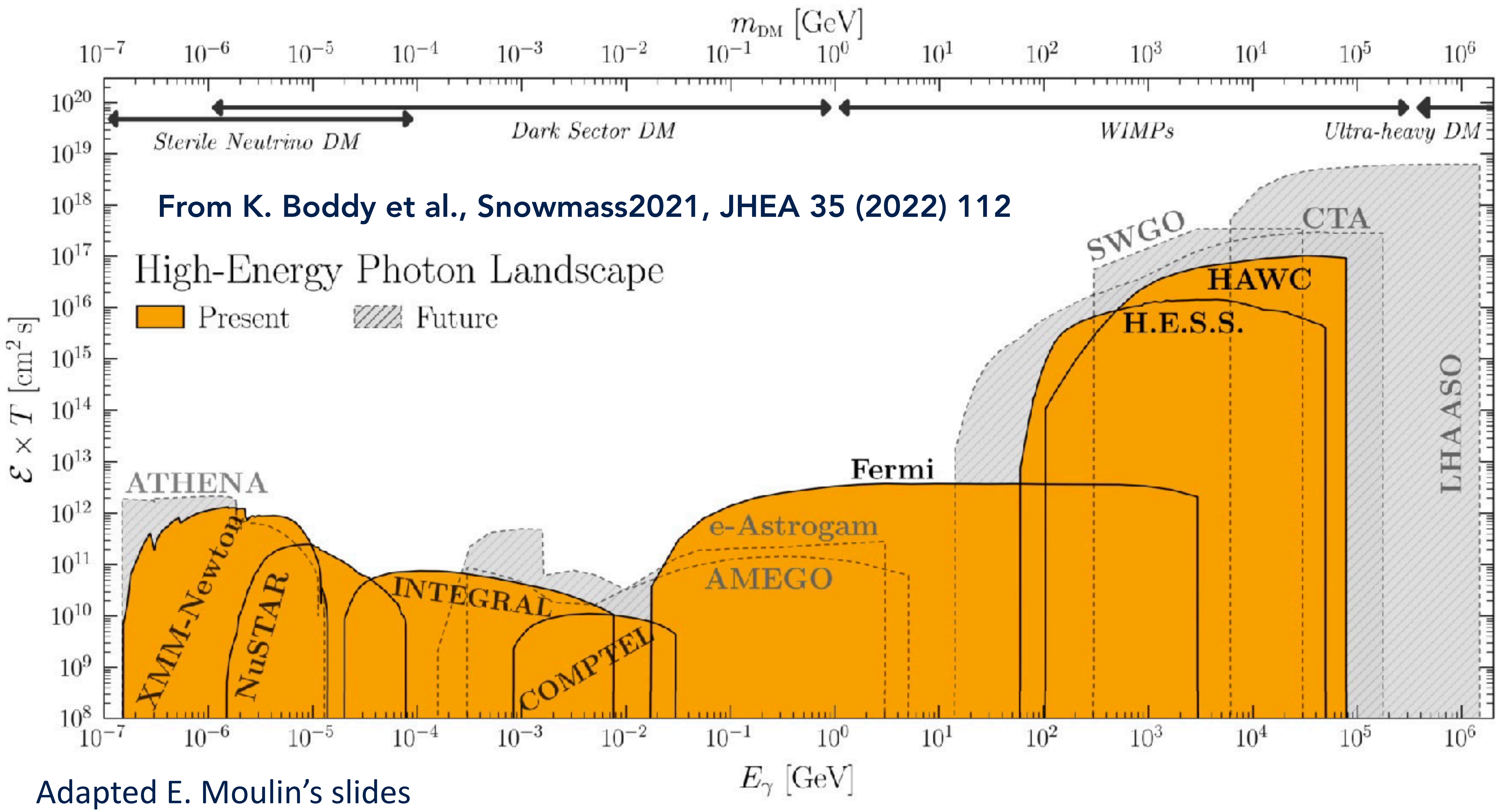


Dark Matter Search

There are plenty of interesting topics in High Energy Universe

We focus on the Dark Side of the Universe

Exposure of instruments for High-Energy Photons toward DM searches



Adapted E. Moulin's slides

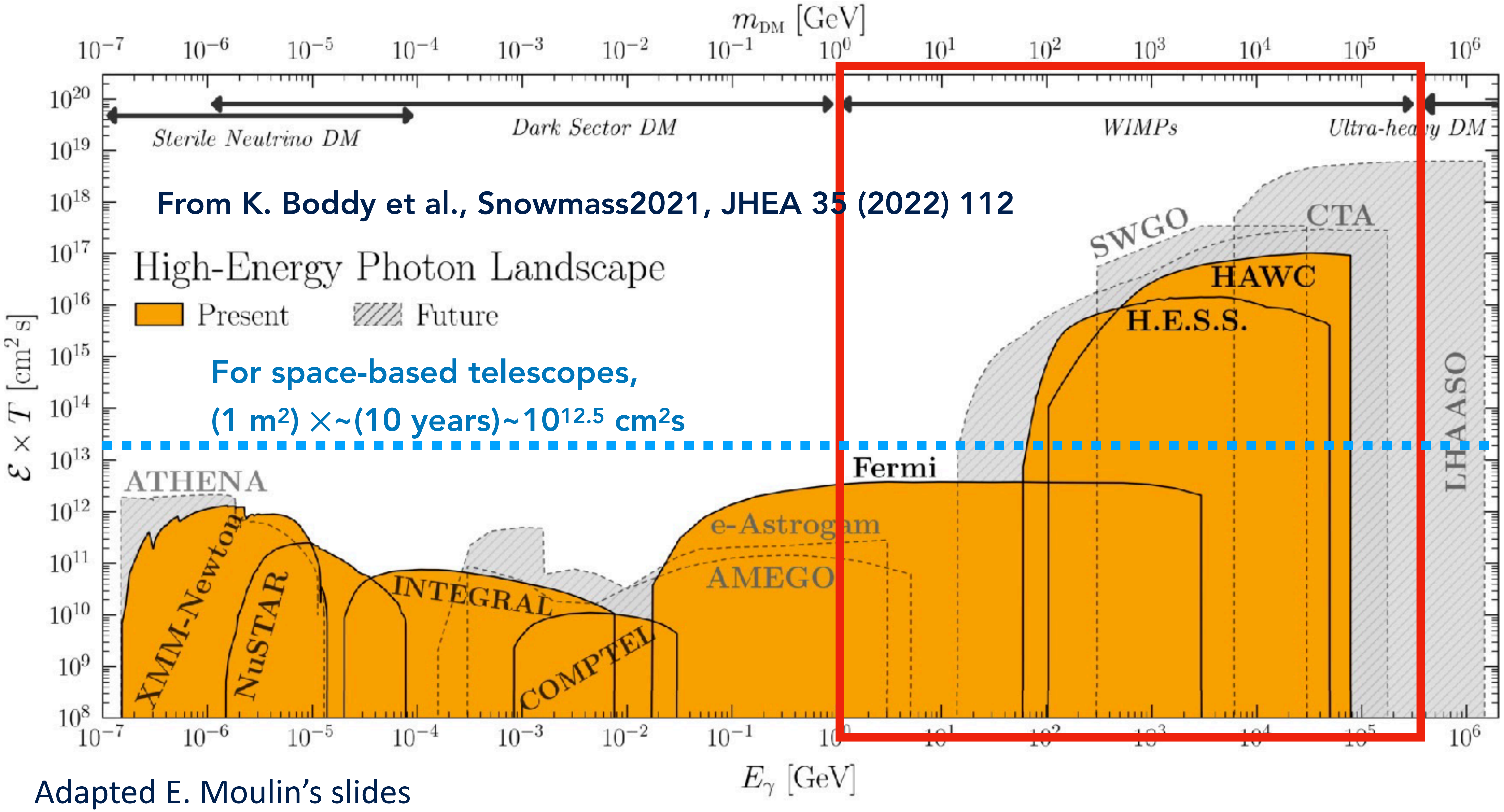
ε : Effective area
T : Observation time

Nb of detected photons :

$\propto \Phi \times \varepsilon \times T$

Disclaimer:
- one of the many ways to compare instruments
- for some DM searches, FoV or energy resolution can be critical as well

Exposure of instruments for High-Energy Photons toward DM searches



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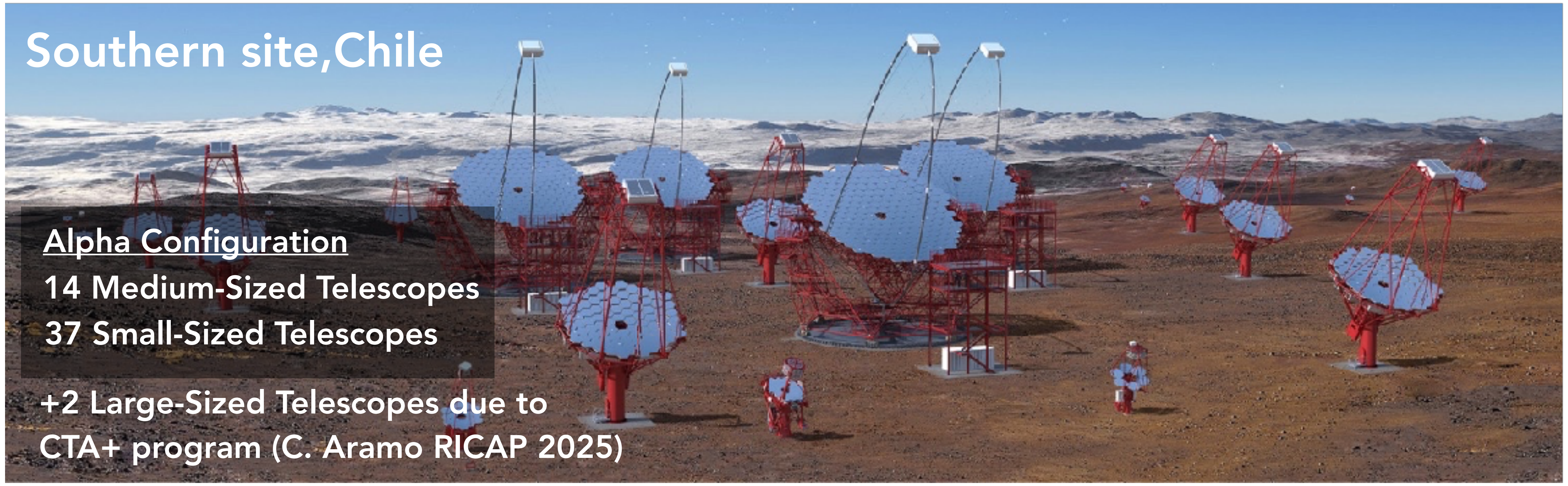
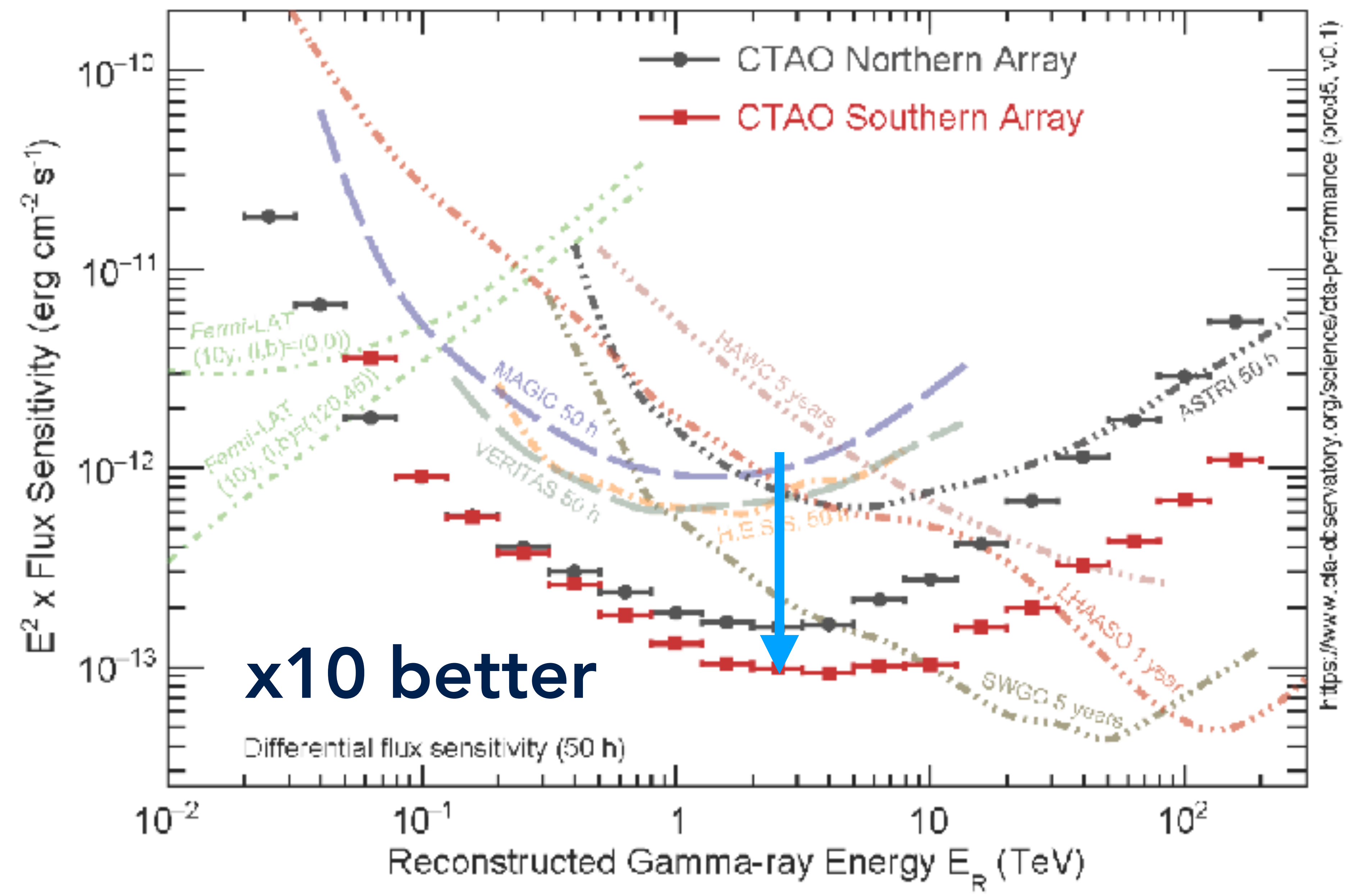
High Energies: dramatic improvement is expected within next decade

Cherenkov Telescope Array Observatory





Upcoming ground-based gamma-ray telescope: Two arrays of Cherenkov telescopes in **Chile/ La Palma**

- Over 100 telescopes, About 1500 scientists and engineers, About 200 institutes

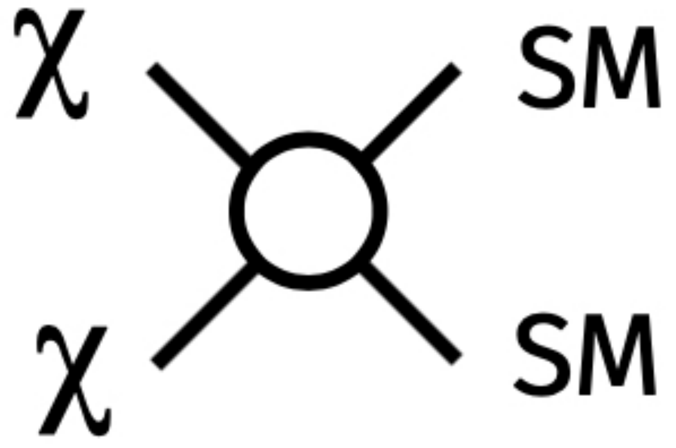
The first Large-sized Telescope (LST-1)

- Located at Roque de los Muchachos, La Palma, Spain
- 23m diameter mirror—delivering greater sensitivity for low energies
- Wide field of view (~4.5°) enables efficient mapping of extended regions, ideal for dark matter and Galactic Center studies
- Three more LSTs of CTAO North array are in the construction (will complete next year)

Expected gamma-ray flux from DM annihilation/decay

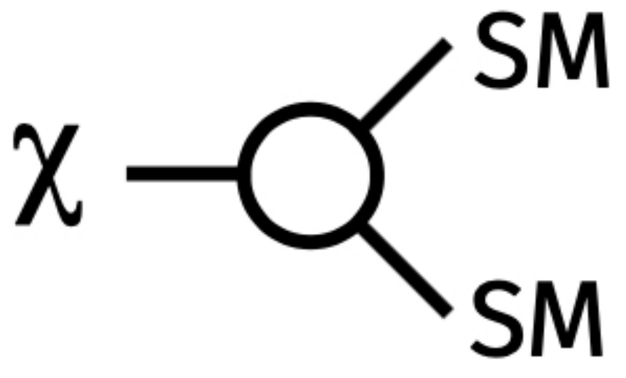
Annihilation

$$\frac{d\Phi^{ann.}}{dE_\gamma} = \frac{1}{4\pi}\frac{\sigma v}{2m_\chi^2} \times \sum_i Br_i \frac{dN_\gamma^i}{dE} \times \int_{\Delta\Omega}\int_{los} ds\ \rho^2(s,\Omega)$$



Decay

$$\frac{d\Phi^{dec.}}{dE_\gamma} = \frac{1}{4\pi}\frac{1}{m_\chi \tau_\chi} \times \sum_i Br_i \frac{dN_\gamma^i}{dE} \times \int_{\Delta\Omega}\int_{los} ds\ \rho(s,\Omega)$$



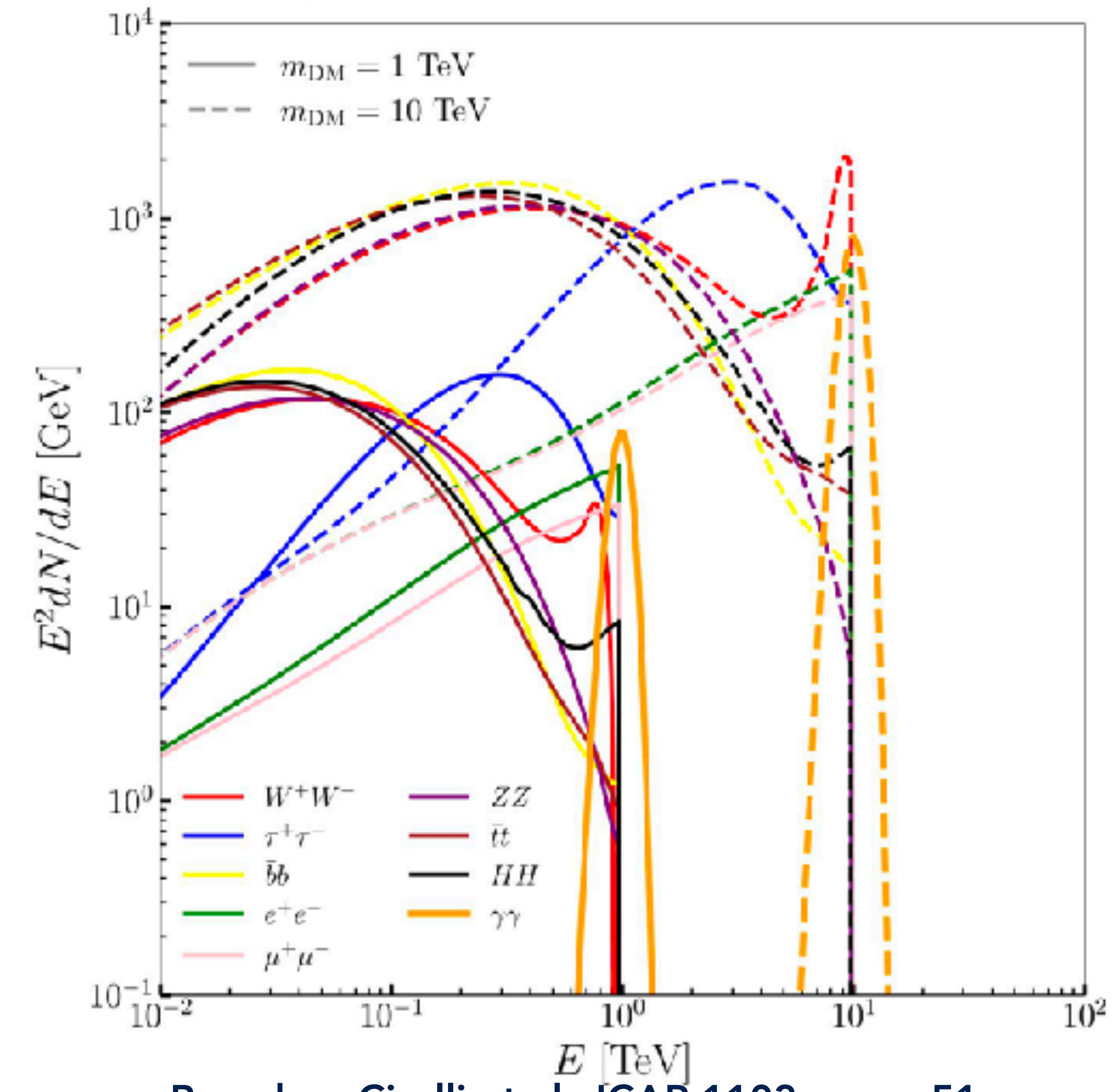
Particle physics term

σv : annihilation cross-section, τ : lifetime

mχ : Mass of DM particle

BR_i : branching ratio of each channel

dN^i/dE : differential gamma-ray yield of each channel



Based on Cirelli et al. JCAP 1103, page 51

Continuum spectra

- Sharp cut off at DM masses

Line-like emission

- clear peak, no contamination astrophysical component

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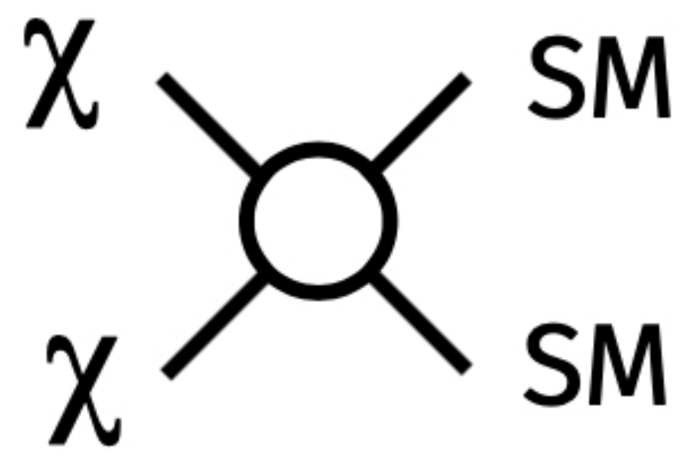

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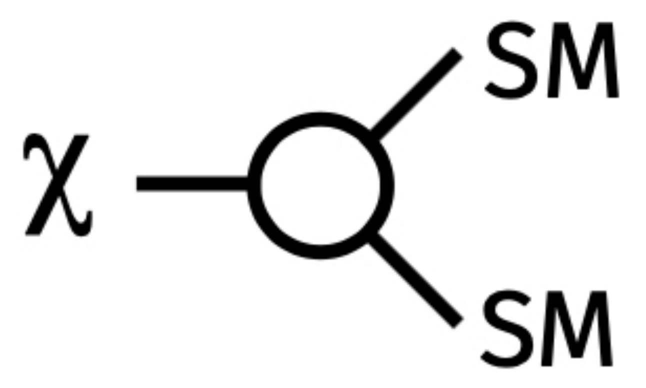
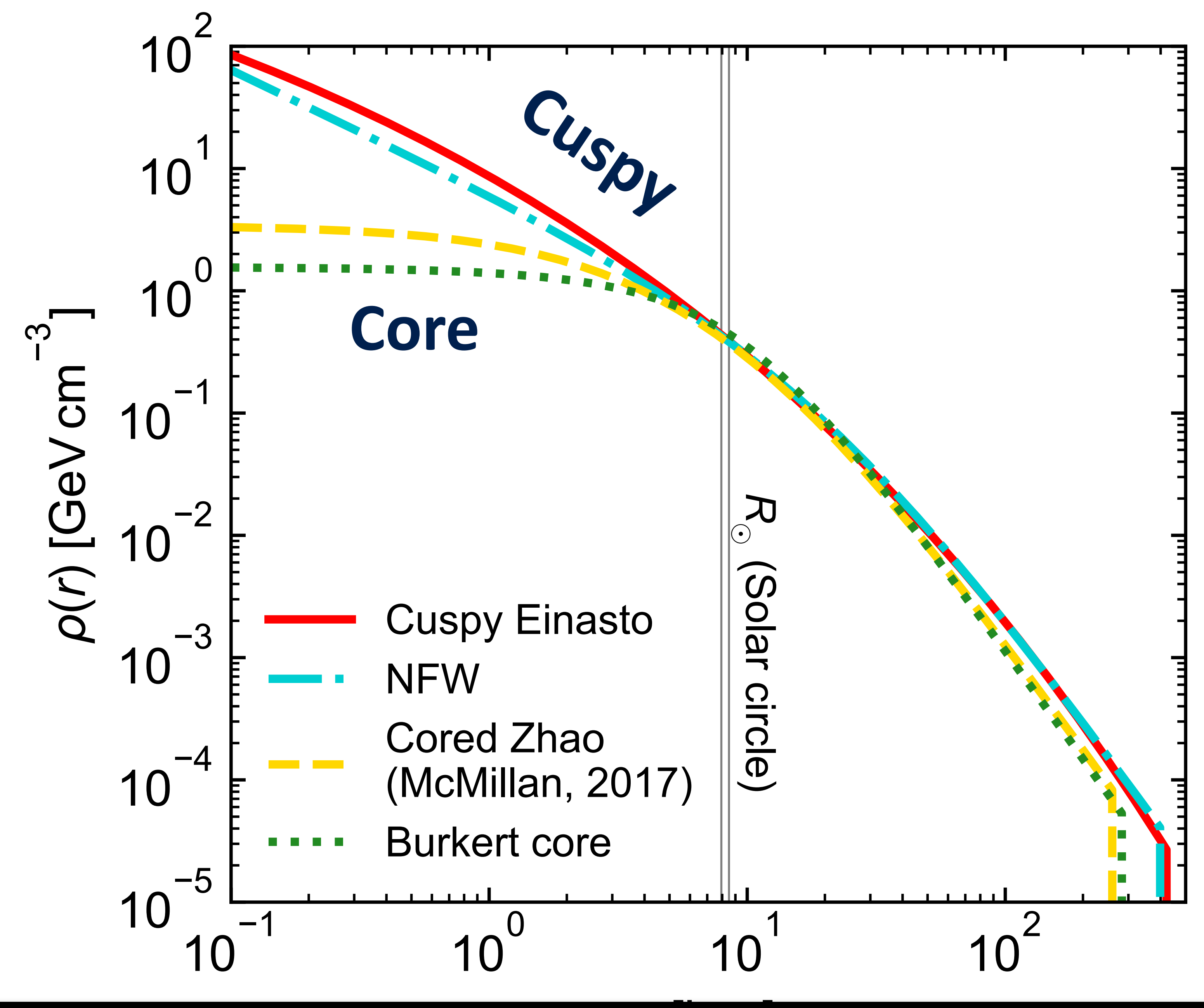




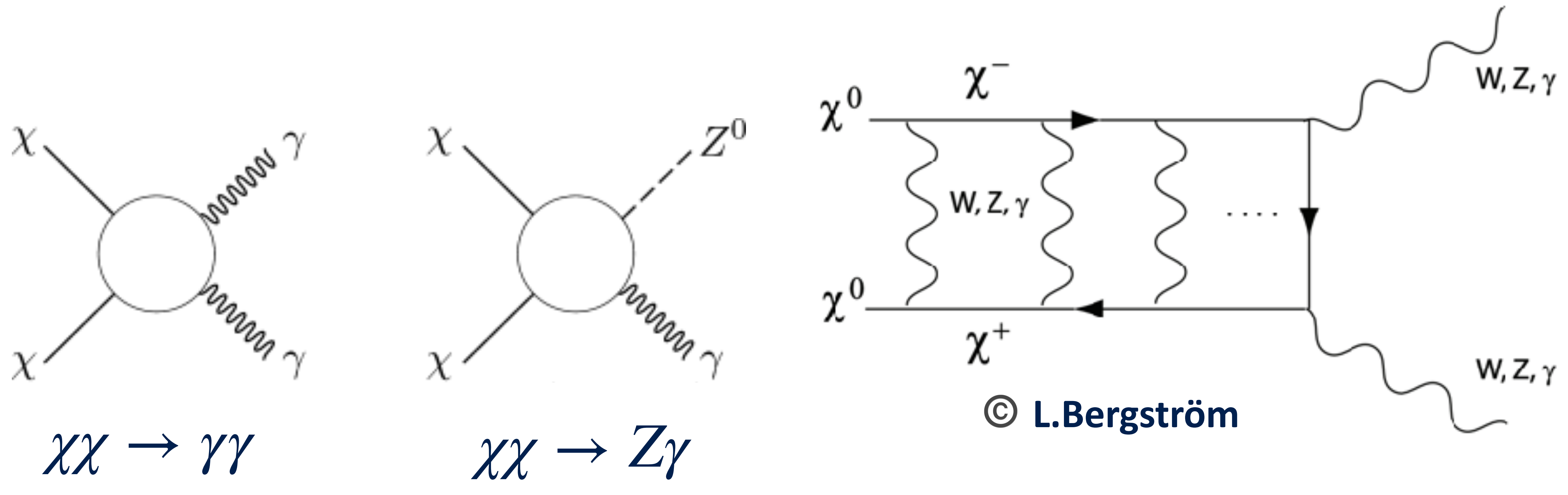
Astrophysics term

ρ : dark matter density (source-dependent)

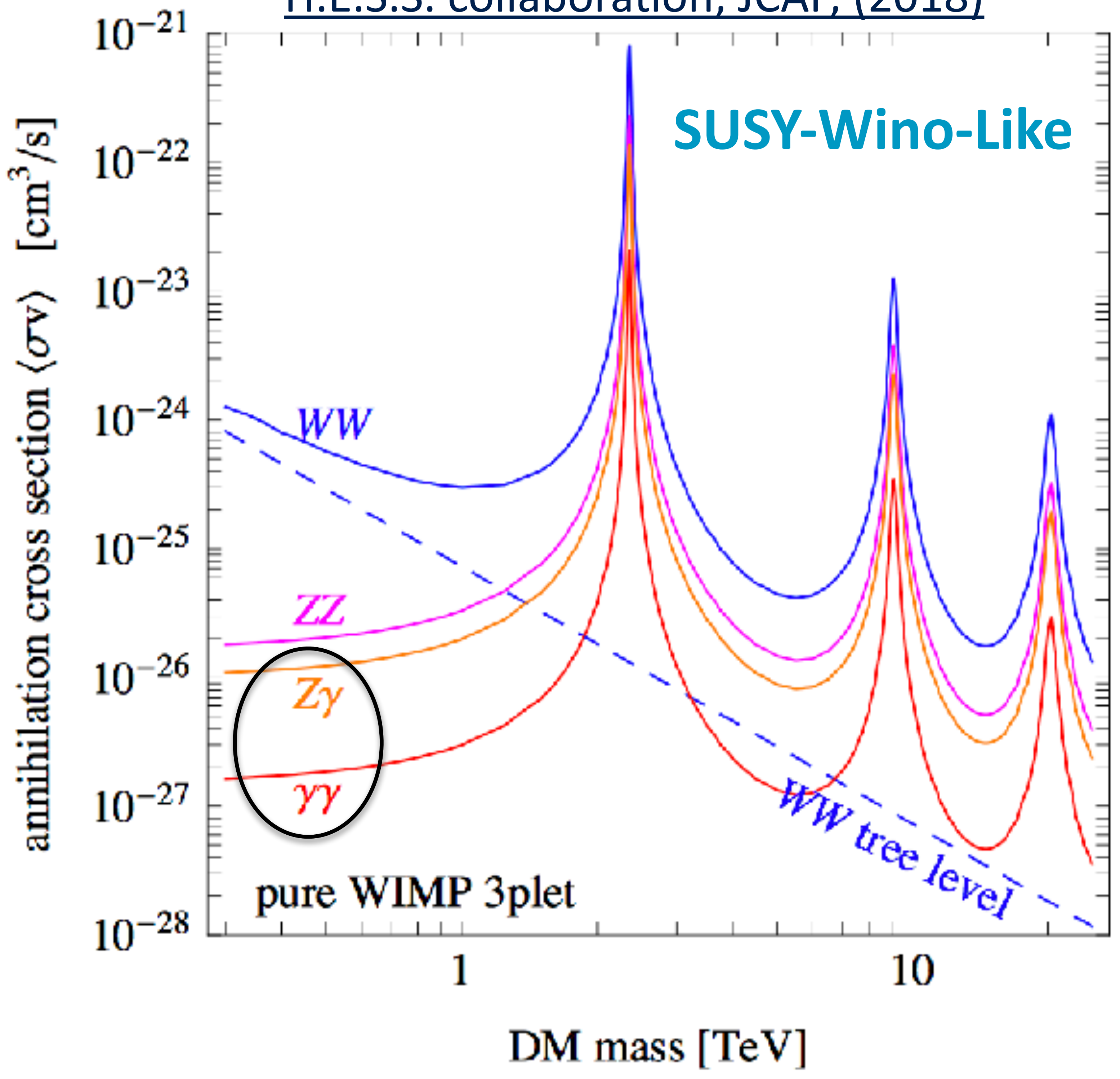
J-factor : Integrated DM density along the line of sight (in case of decay, called “D-factor”)

Motivation for Gamma-ray Line signal searches

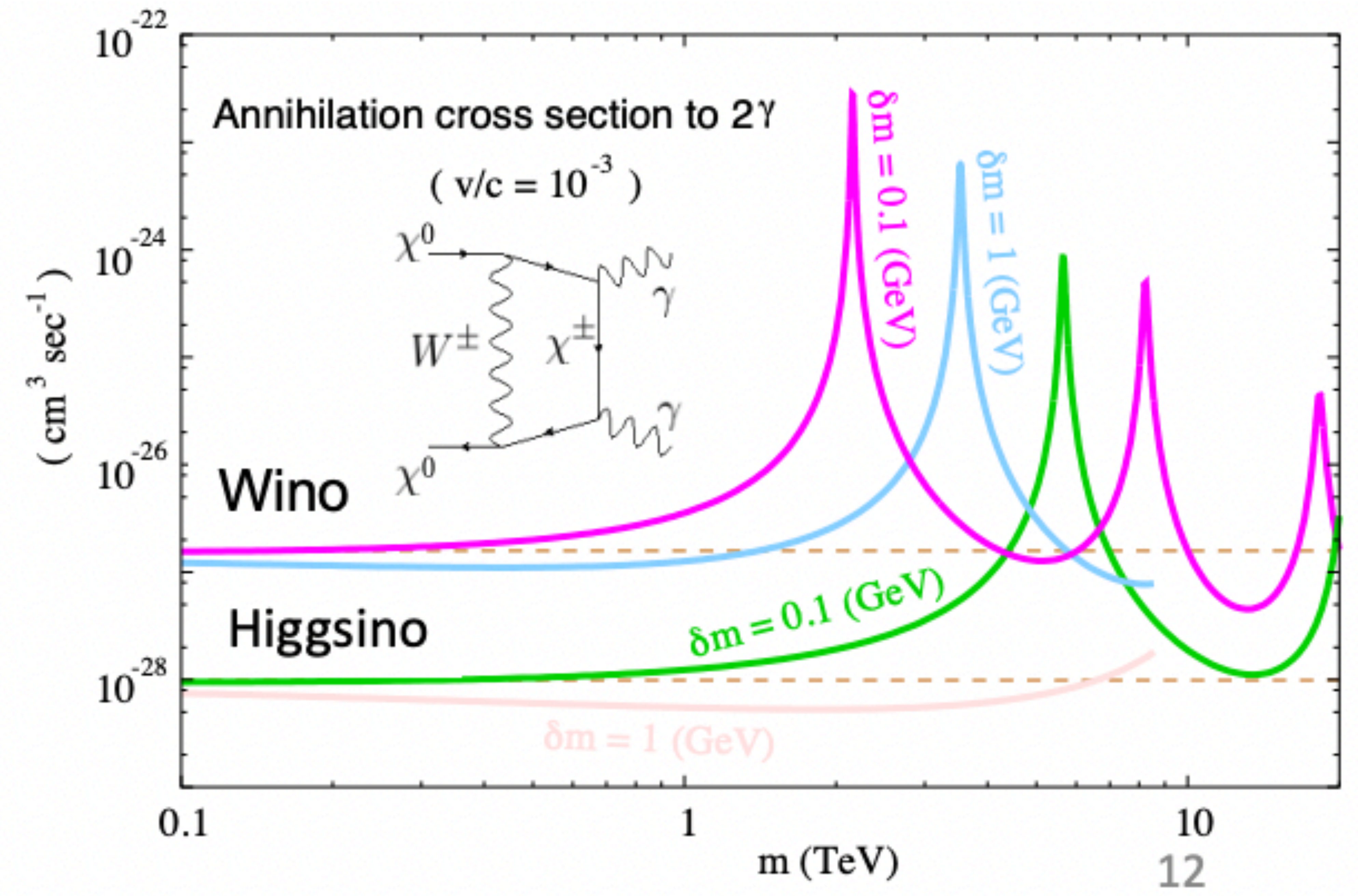
- **Clear peak at DM mass:** No astrophysical contamination
- Loop-suppressed by α^2 (i.e. the fine-structure constant)
- Some heavy DM (e.g. SUSY) models enhance their annihilation rate, called **Sommerfeld enhancement**



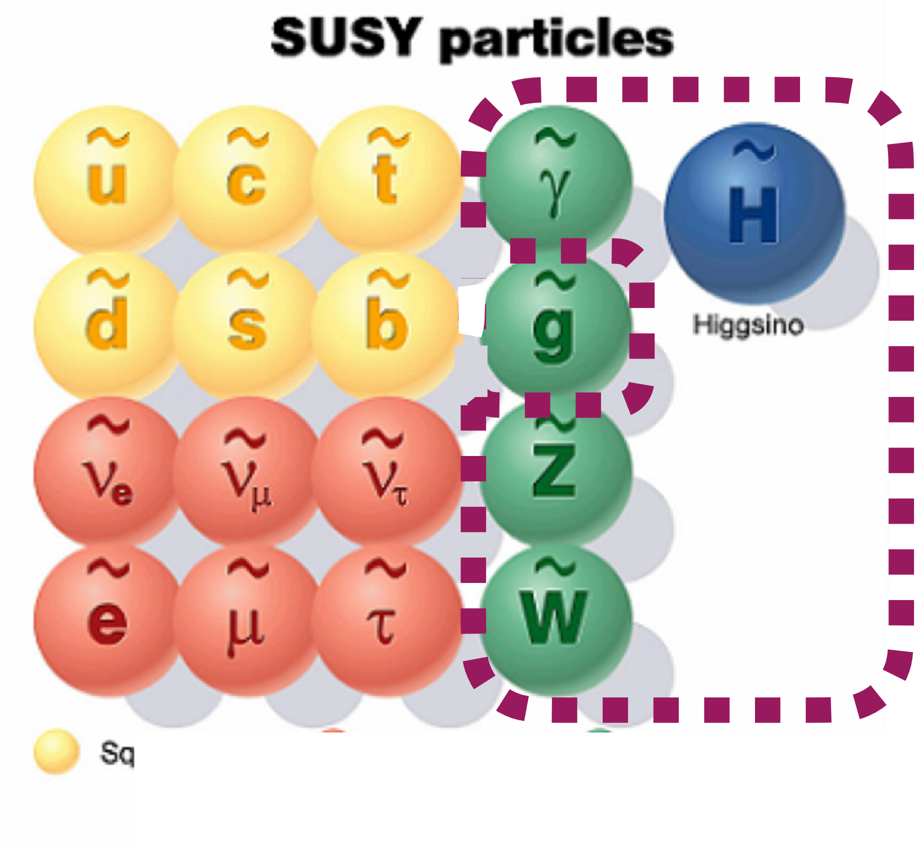
H.E.S.S. collaboration, JCAP, (2018)



J. Hisano, S. Matsumoto, and M. M. Nojiri (2004)



Benchmark models



Weak Eigenstates

Bino (M_1): $\tilde{B}$

Winos (M_2): $\tilde{W}^0, \tilde{W}^{\pm}$

Higgsinos (μ): $\tilde{H}_u^0, \tilde{H}_d^0, \tilde{H}_u^+, \tilde{H}_d^-$

Mass Eigenstates

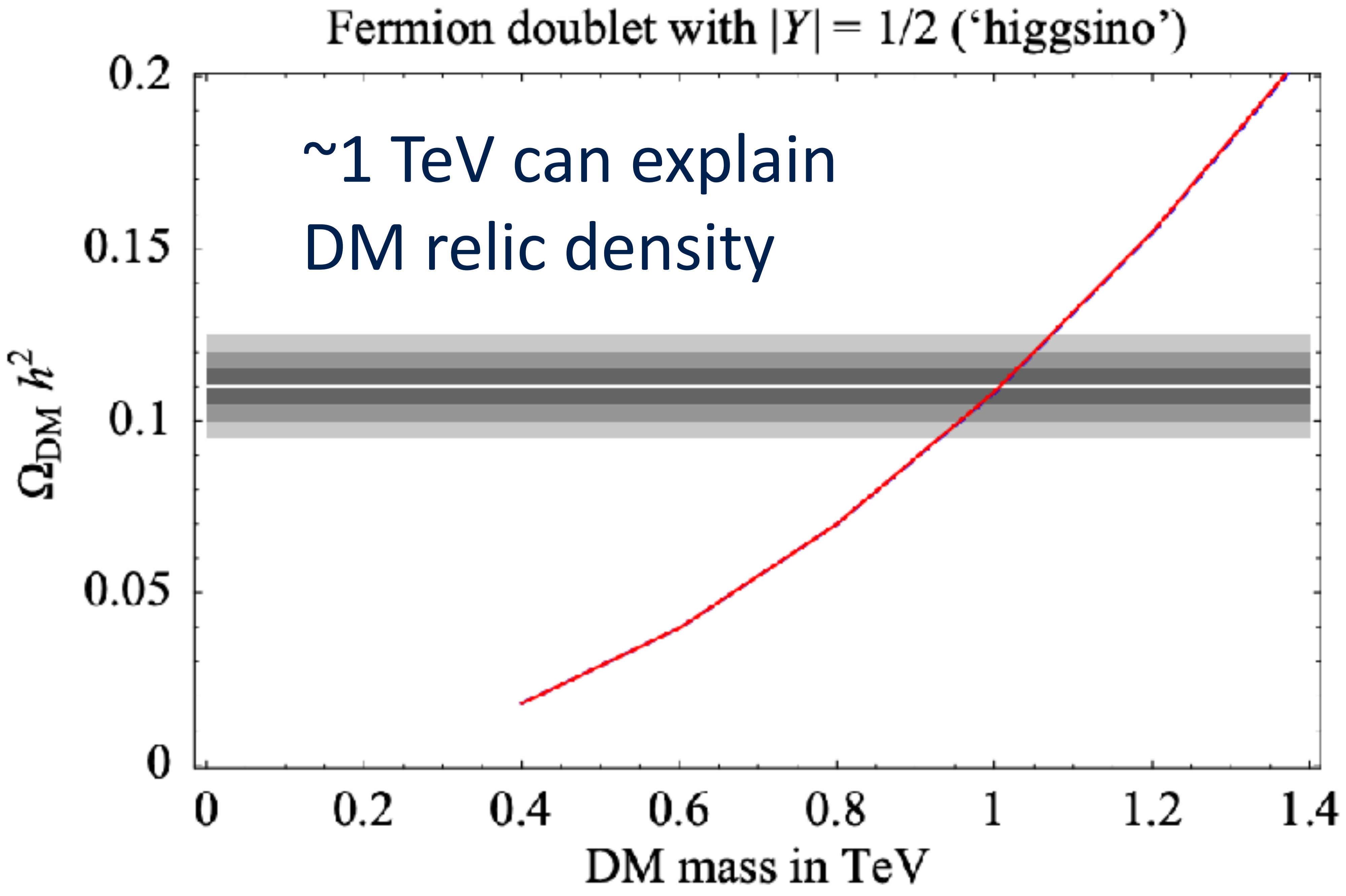
Neutralinos: $\tilde{\chi}^0_{1,2,3,4}$

Charginos: $\tilde{\chi}^{\pm}_{1,2}$

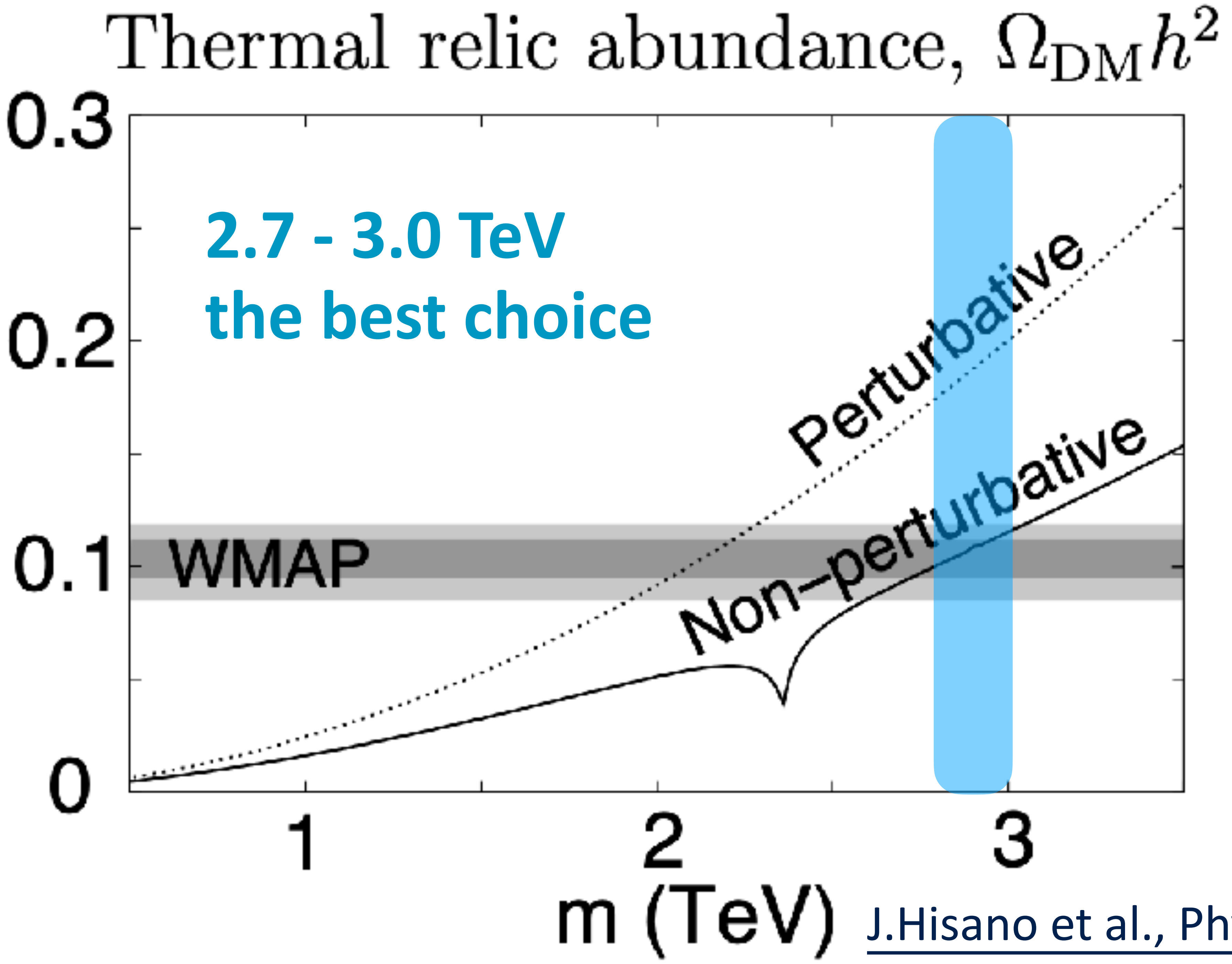
The Neutralino

$$\chi = a_1\tilde{B} + a_2\tilde{W}^0 + a_3\tilde{H}_1^0 + a_4\tilde{H}_2^0$$

bino $\tilde{B}$ wino $\tilde{W}^0$ higgsino $\tilde{H}_1^0, \tilde{H}_2^0$



arXiv:0706.4071



J.Hisano et al., Phys. Lett.B 646 (2007)

The sensitivity in the TeV-scale is a key ingredient

The Galactic Centre from North

- The Galactic Centre is considered as a southern source - *no results from north for DM for 15 years*
- But past years, MAGIC in La Palma demonstrated the potential for the GC observation with large-zenith angle observation
  - Can be significantly impacted by instrumental systematics, care required
  - Not a simple observation

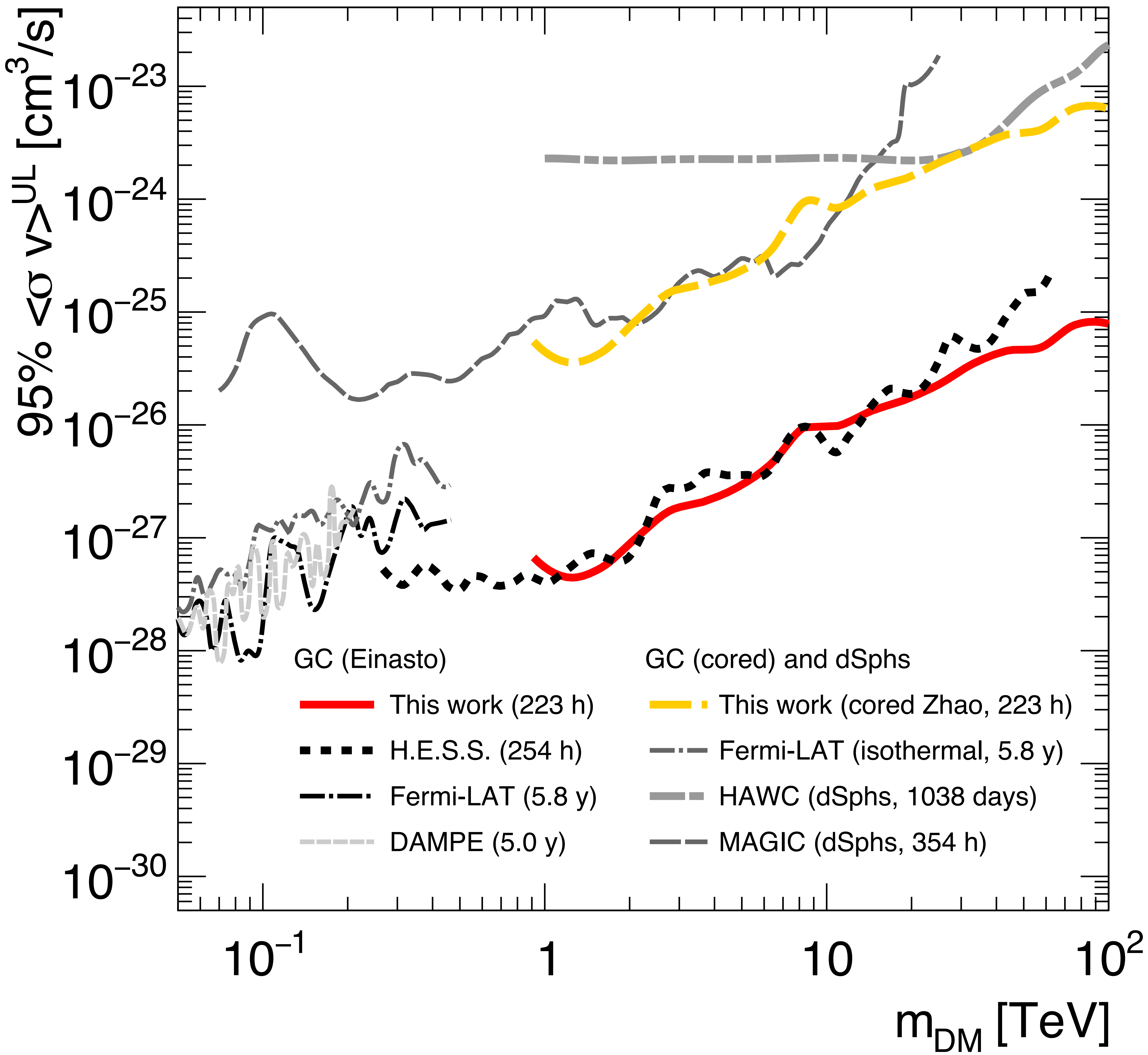
Continuum spectra searches arxiv:2111.01198

Target	Year	Time [h]	IACT	Limit	Ref.
The Milky Way central region & halo					
MW Centre	2004	(48.7)	H.E.S.S.	Ann.	Aharonian et al. (2006)
MW Inner Halo	2004 – 2008	(112)	H.E.S.S.	Ann.	Abramowski et al. (2011)
	2010	9.1		Ann.	Abramowski et al. (2015)
	2004 – 2014	254		Ann.	Abdallah et al. (2016)
	2014 – 2020	546	H.E.S.S.†	Ann.	Montanari et al. (2021)

Line searches **15 years**

Line searches					
MW Inner Halo	2004 – 2008	(112)	H.E.S.S.	Ann.	Abramowski et al. (2013c)
	2014	15.2	H.E.S.S.†	Ann.	Abdalla et al. (2016)
	2004 – 2014	(254)	H.E.S.S.	Ann.	Abdalla et al. (2018b)
	2013 – 2019	204	MAGIC	Ann.	Inada et al. (2021)

DM line searches

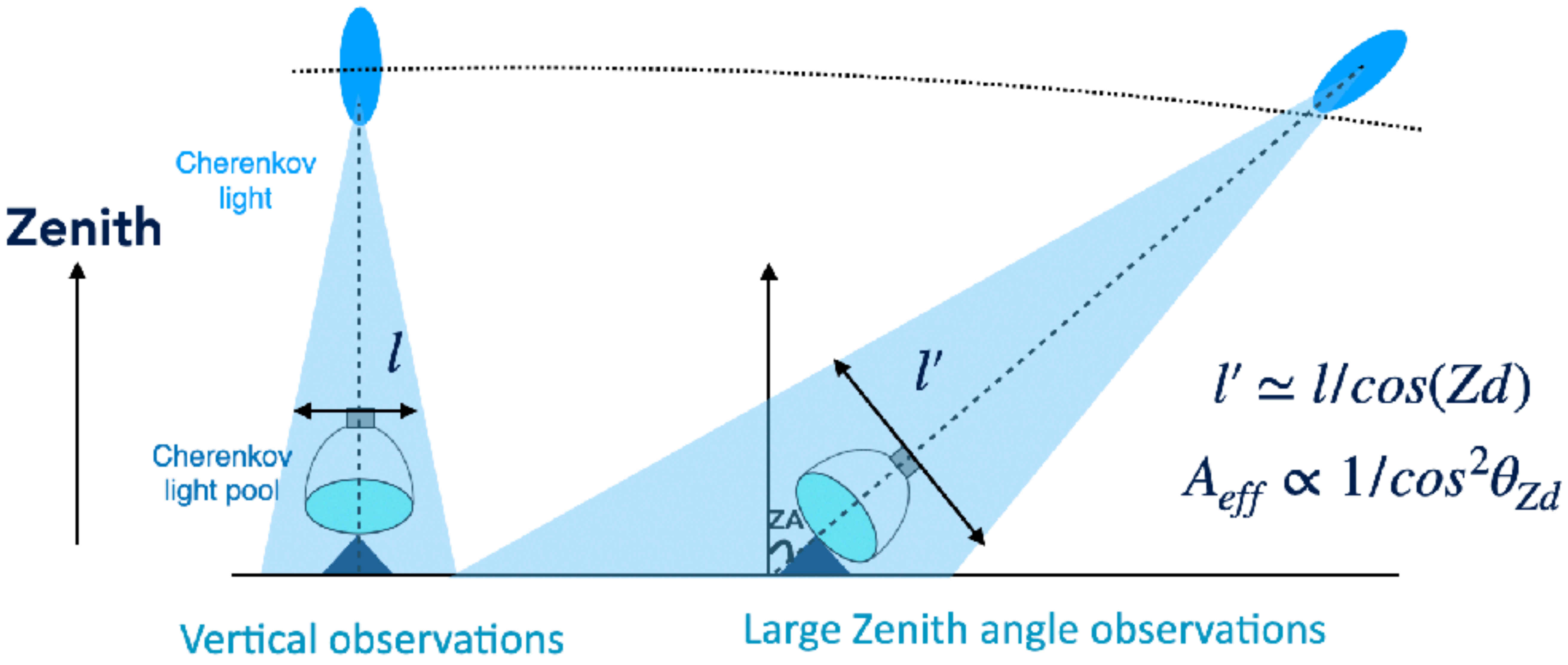


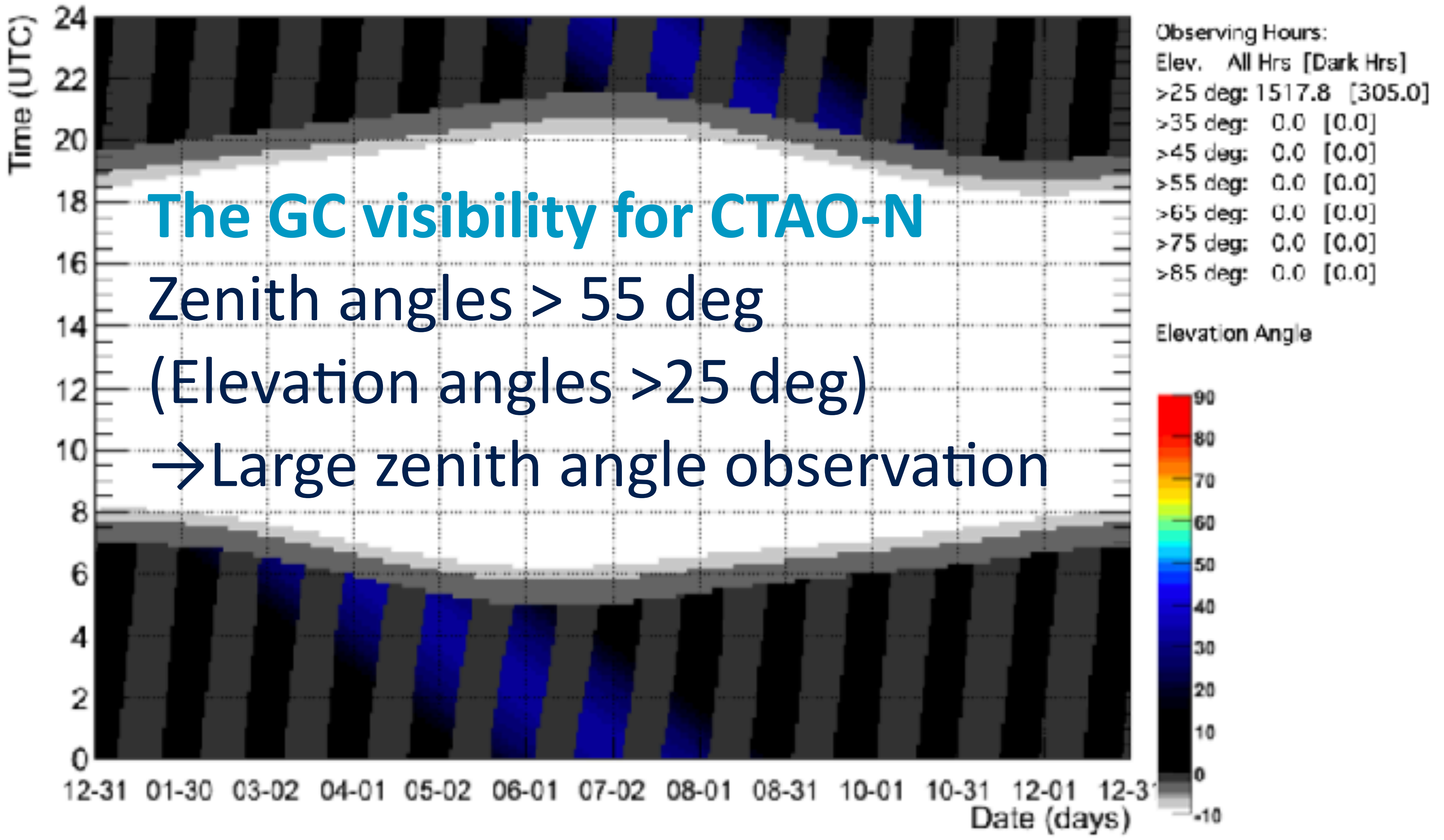
MAGIC Collaboration, Phys. Rev. Lett. (2023)

The GC Observation with LST-1

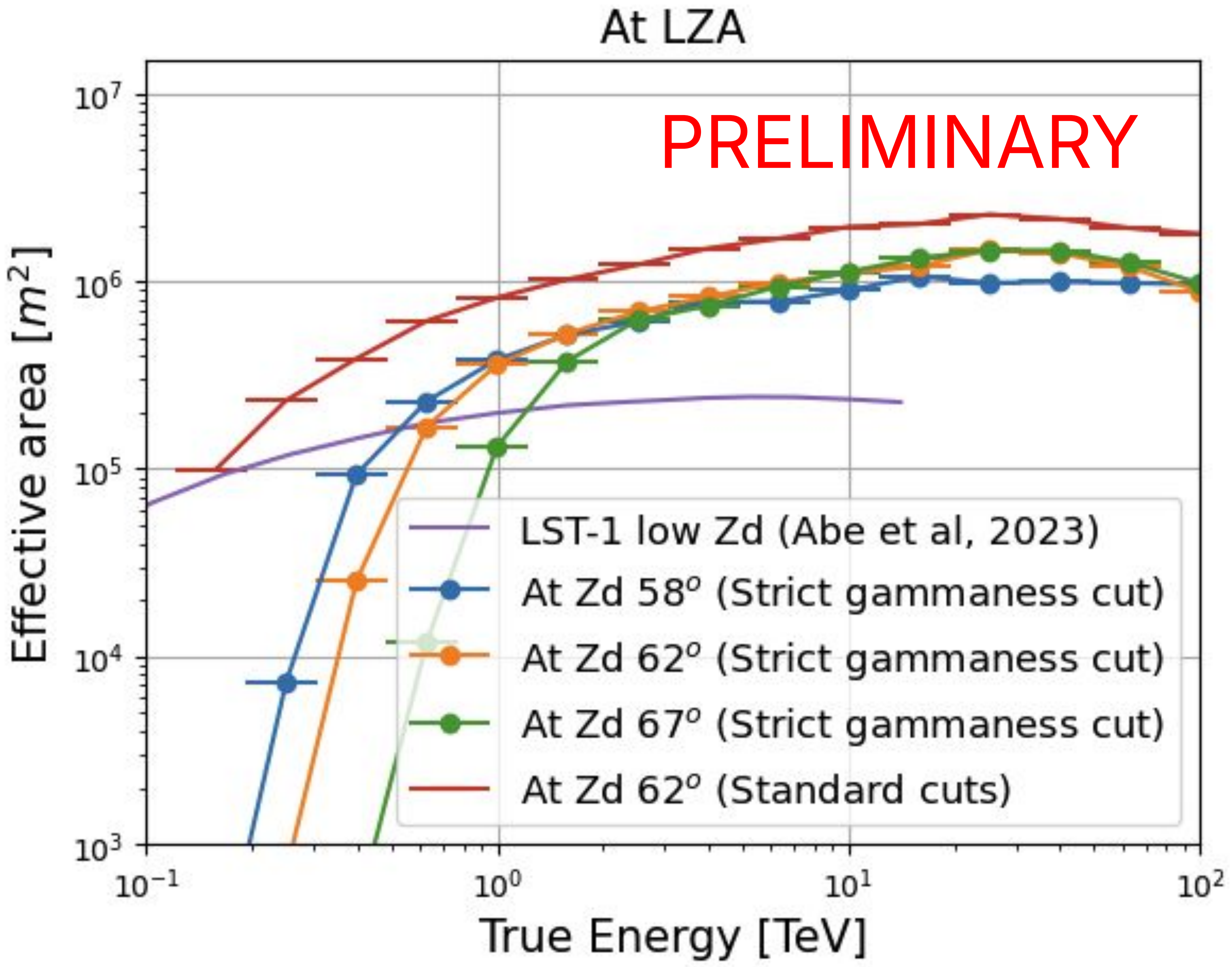
- **Key experimental fact:**
  - IACT performance depends on zenith angles because of difference in a shower distance

- **Large zenith angle observation**
  - Energy threshold: worse
  - Energy resolution: worse
  - Effective collection area: **better**
    - Good for **higher energetic** events



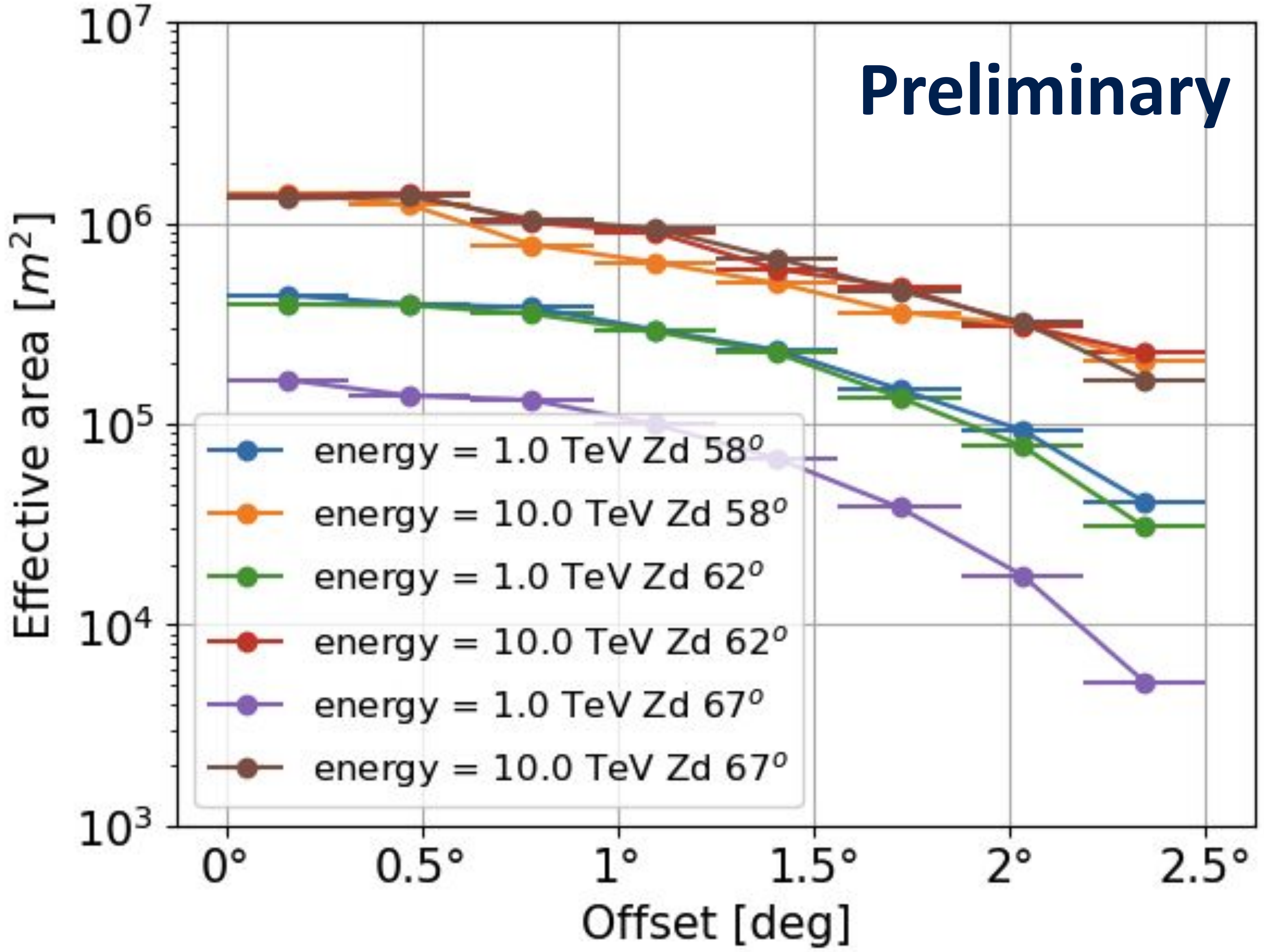


http://tevcat.uchicago.edu

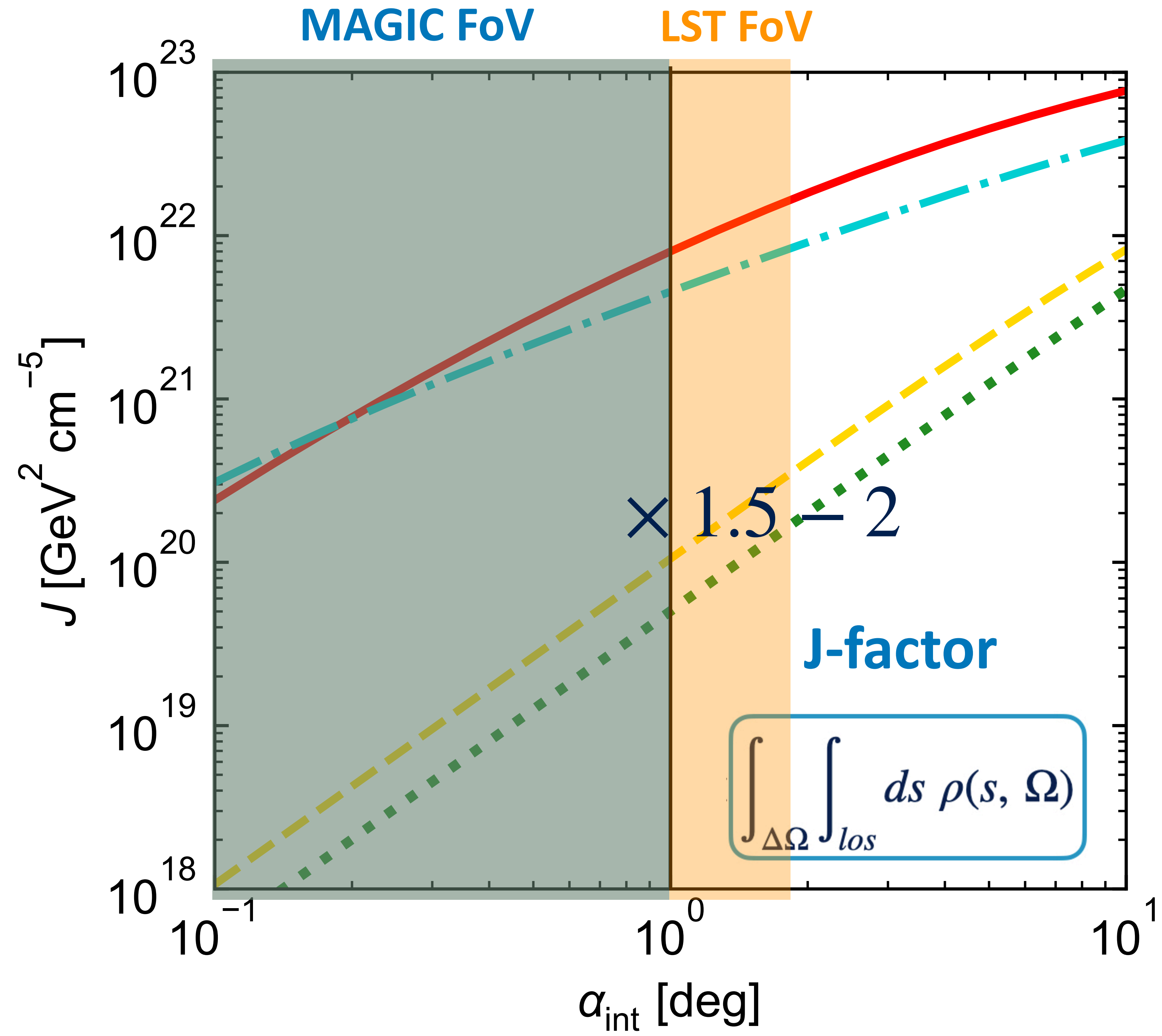


Extended Sources Analysis with LST-1

- Effective area stays > 10^5 m^2 for higher energies up to 2^o from camera center
- Allows using wider region of interests (ROIs) and improves sensitivity for extended regions



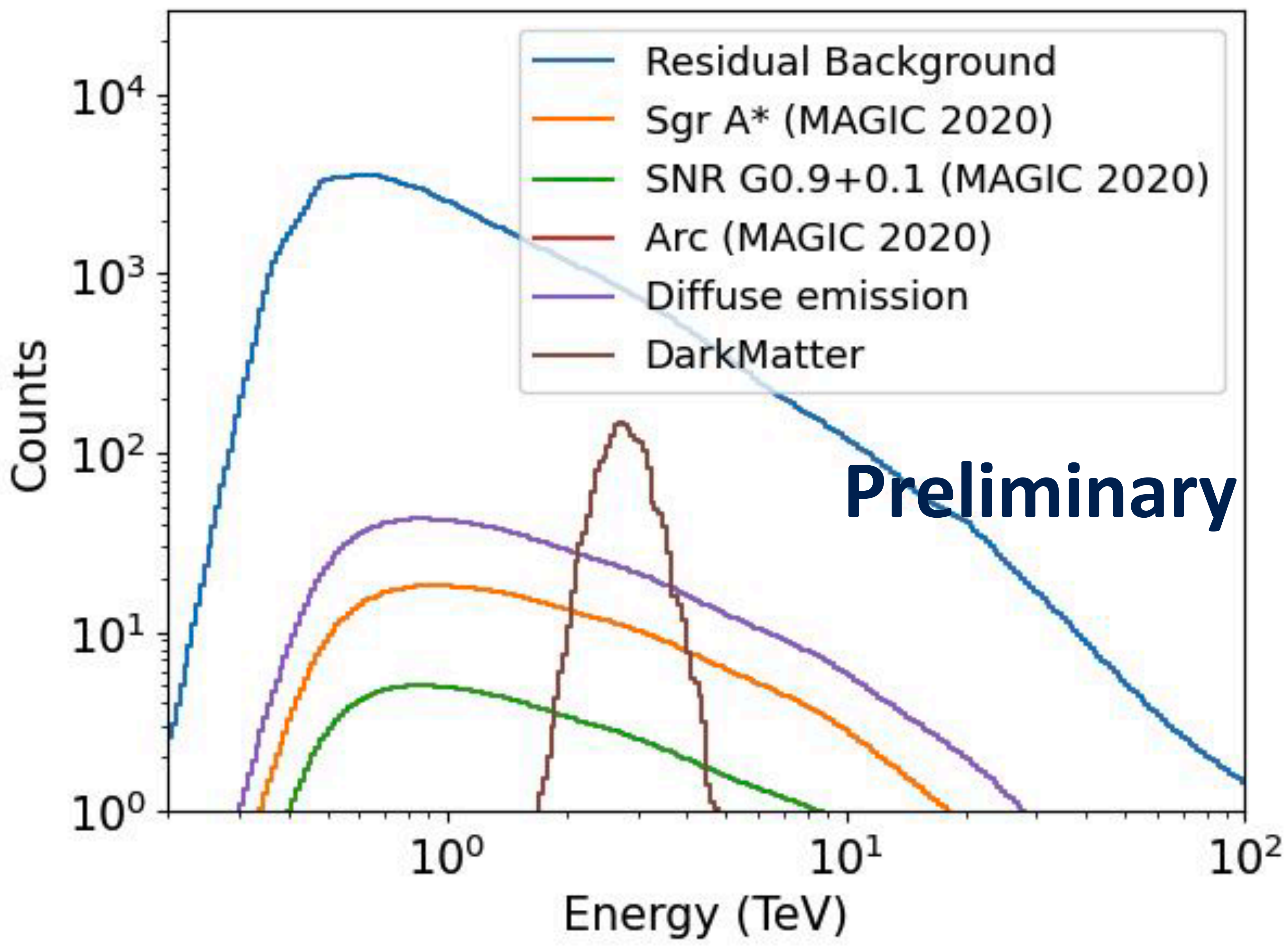
Galactic Center observations	HESS	MAGIC	VERITAS	LST-1
Zenith Angle	Low Zd	Large Zd	Large Zd	Large Zd
Field of View	5.0 deg	3.5 deg	3.5 deg	4.5 deg



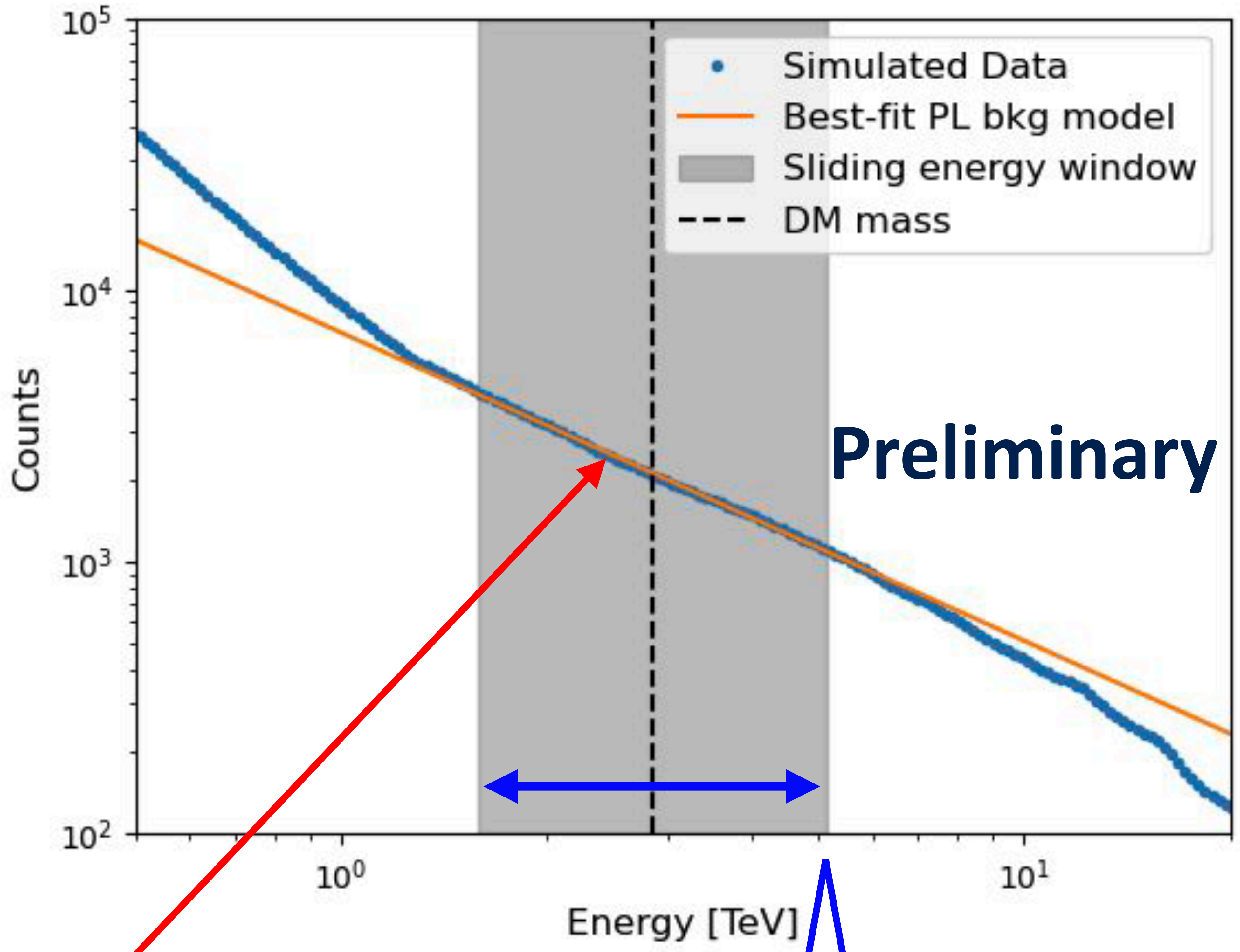
Allows studying wider region around GC for DM search (upto 1.8^o ROI), than MAGIC-2022 (<1.1^o ROI)

Signal and Background modeling

- Simulations of 40h – At GC using LST Instrumental Response Functions (IRFs)



Count spectra summed over 1.8° ROI :the residual CR bkg is dominant

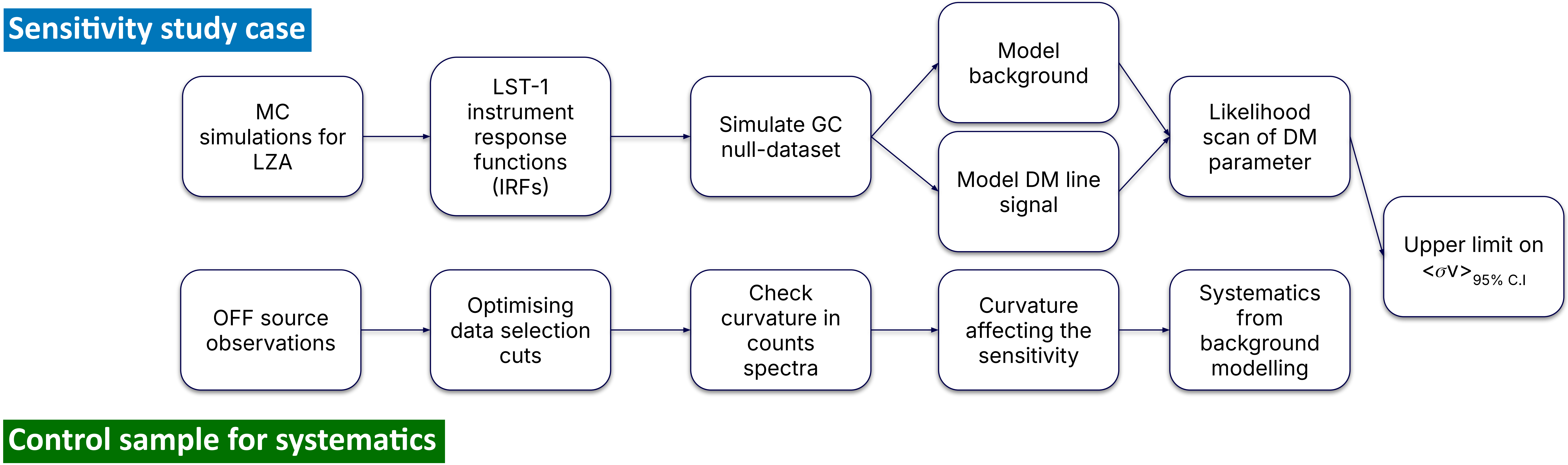


Background – modelled as power law (PL)

PL Assumption within a sliding window technique

Analysis Overview

- Search for a peak on ‘smooth’ counts spectrum majorly dominated by background
- Compute expected limits on DM parameter: annihilation cross-section <σv>
- Study systematics from background modelling using OFF-source data



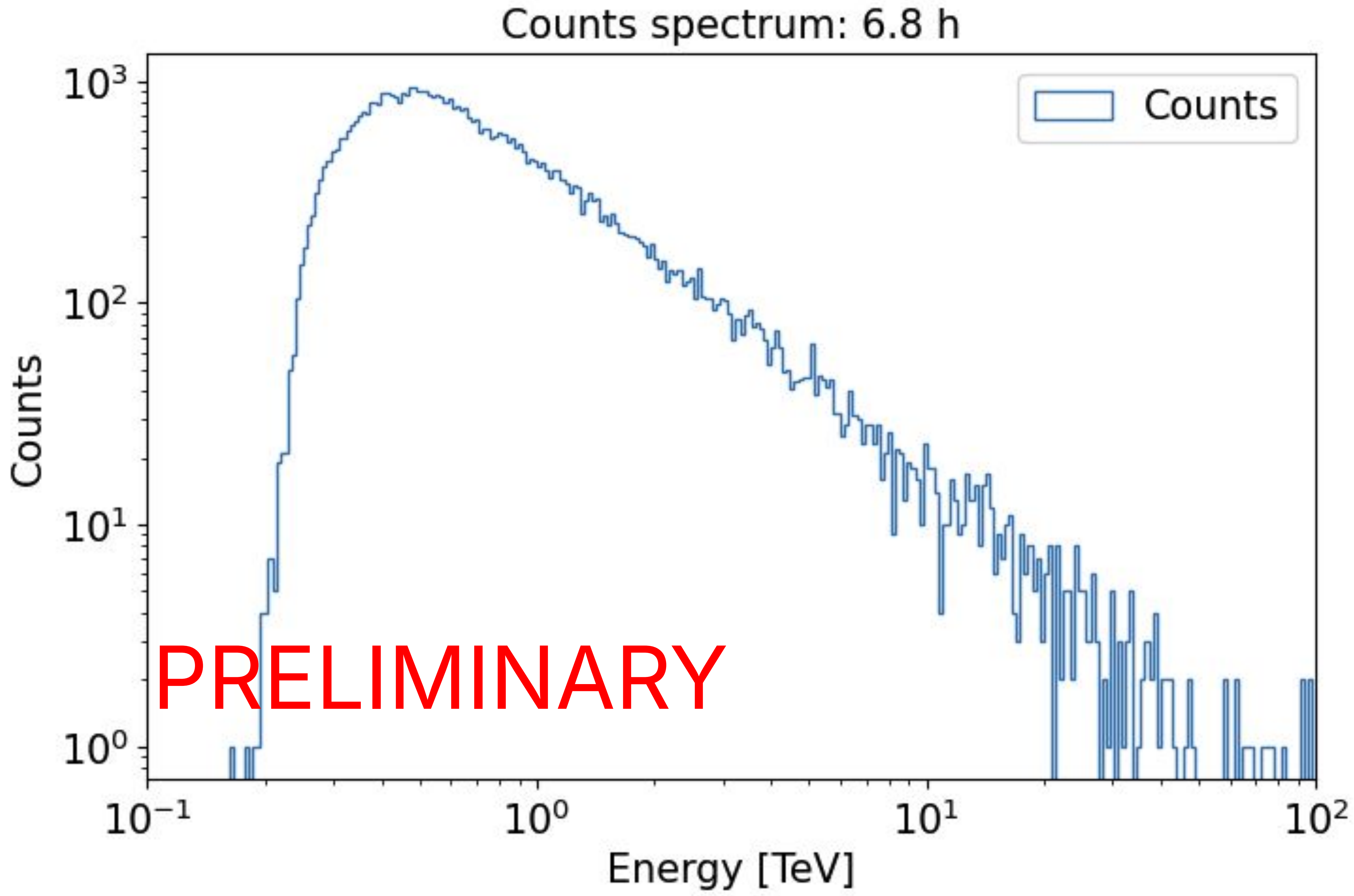
Off source data for systematics assessment

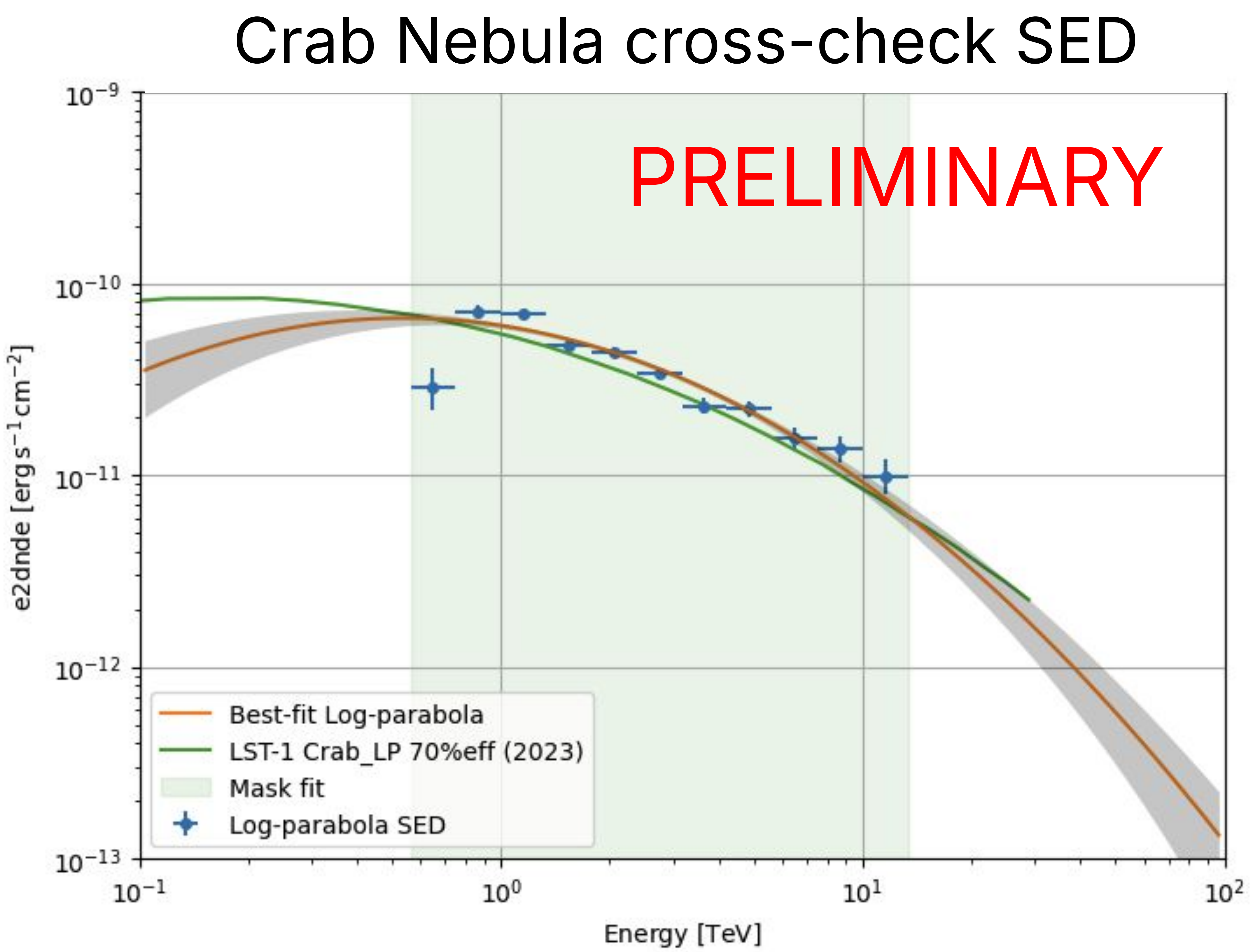
Systematics – background modelling in OFF source data

- LST-1 observations at LZA and dark conditions
  - mimicking GC observations
- Q-factor -based optimized cuts for event selection

- Optimised cut verified – reproducing Crab SED
  - consistent with the previous studies within 25%
- OFF counts spectrum – curvature effect studied

using log parabola fit to counts



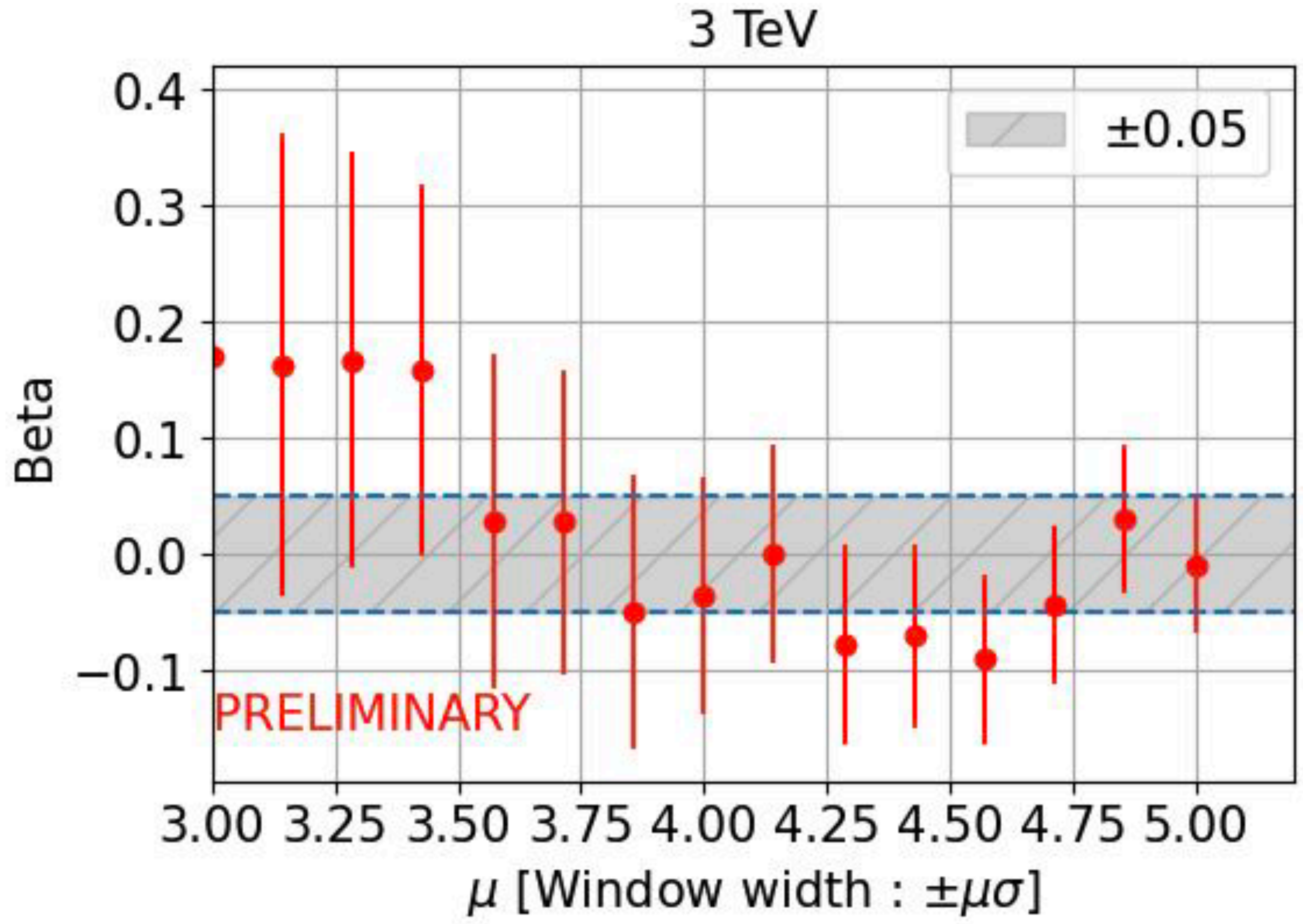


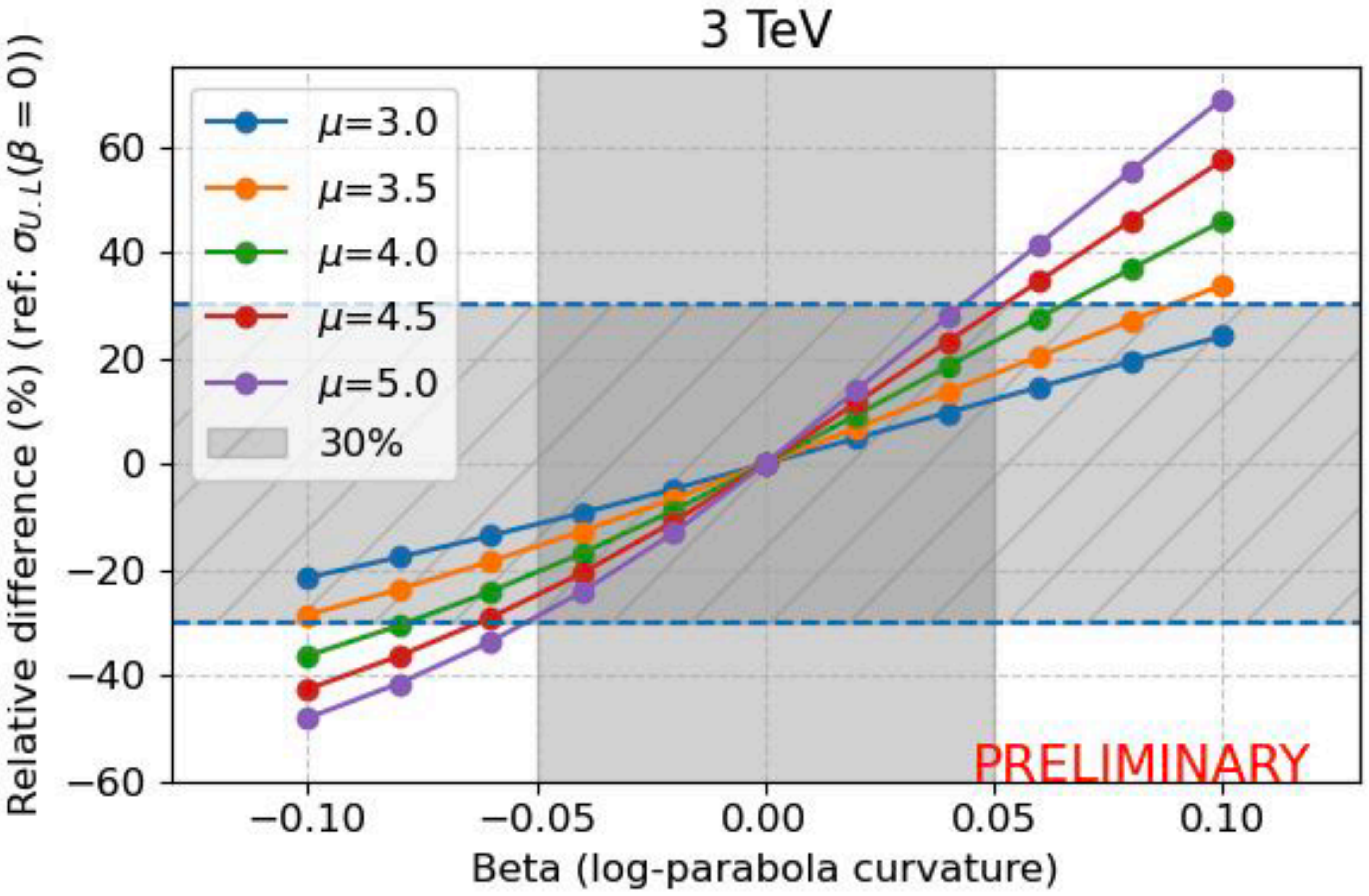
Results: systematics in background modeling

Analysed 6.8h of OFF source data – systematics from PL modelling of background

- Curvature effect (β for log parabola fit) within the window width $[E/(1+\sigma_E)^{\mu}, E(1+\sigma_E)^{\mu}]$,
- β ≠ 0 affecting DM line sensitivity (relative to β = 0)
- Estimating systematic uncertainty of 10%, 20% and 30% for 3, 4, and 5σ_E width at 3 TeV

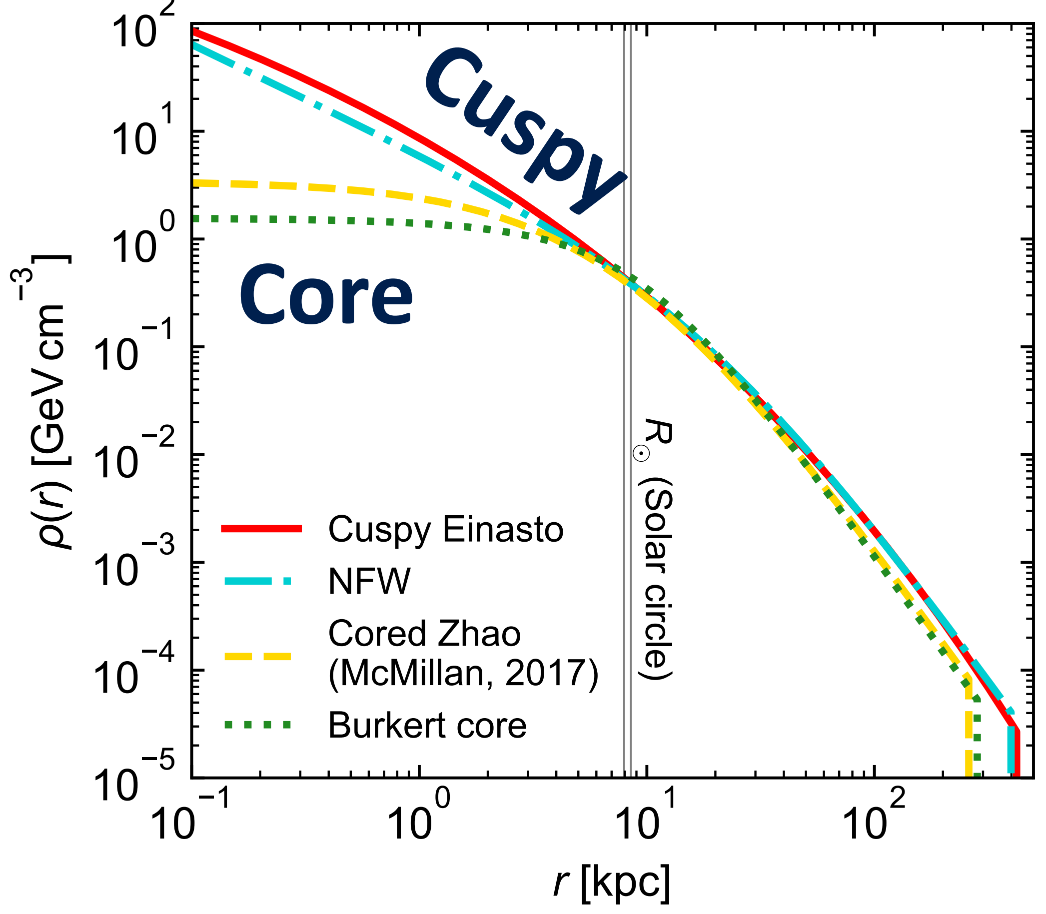
$$\Phi(E) = \Phi_0\left(\frac{E}{E_0}\right)^{-\alpha-\beta\times log(\frac{E}{E_0})}$$

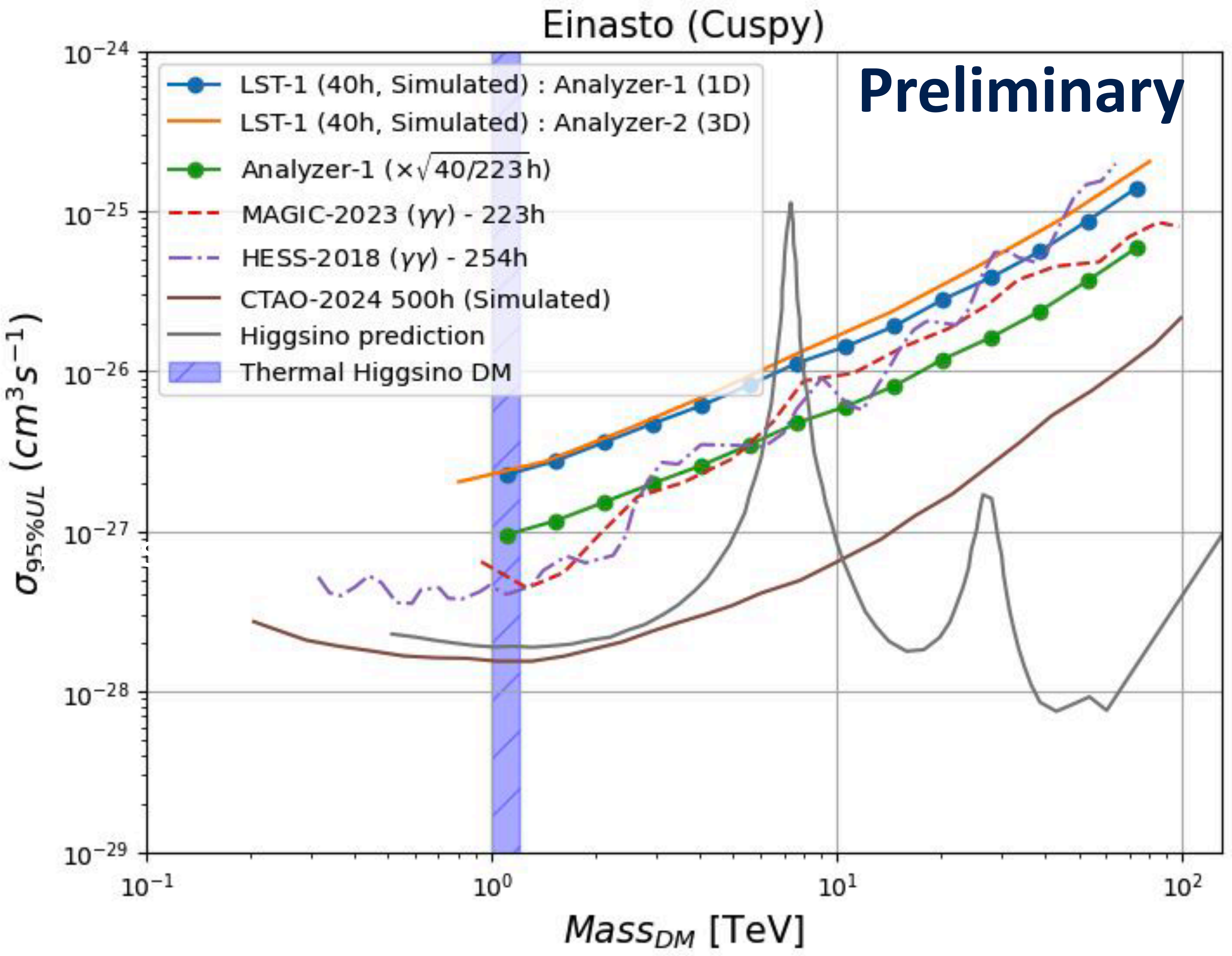


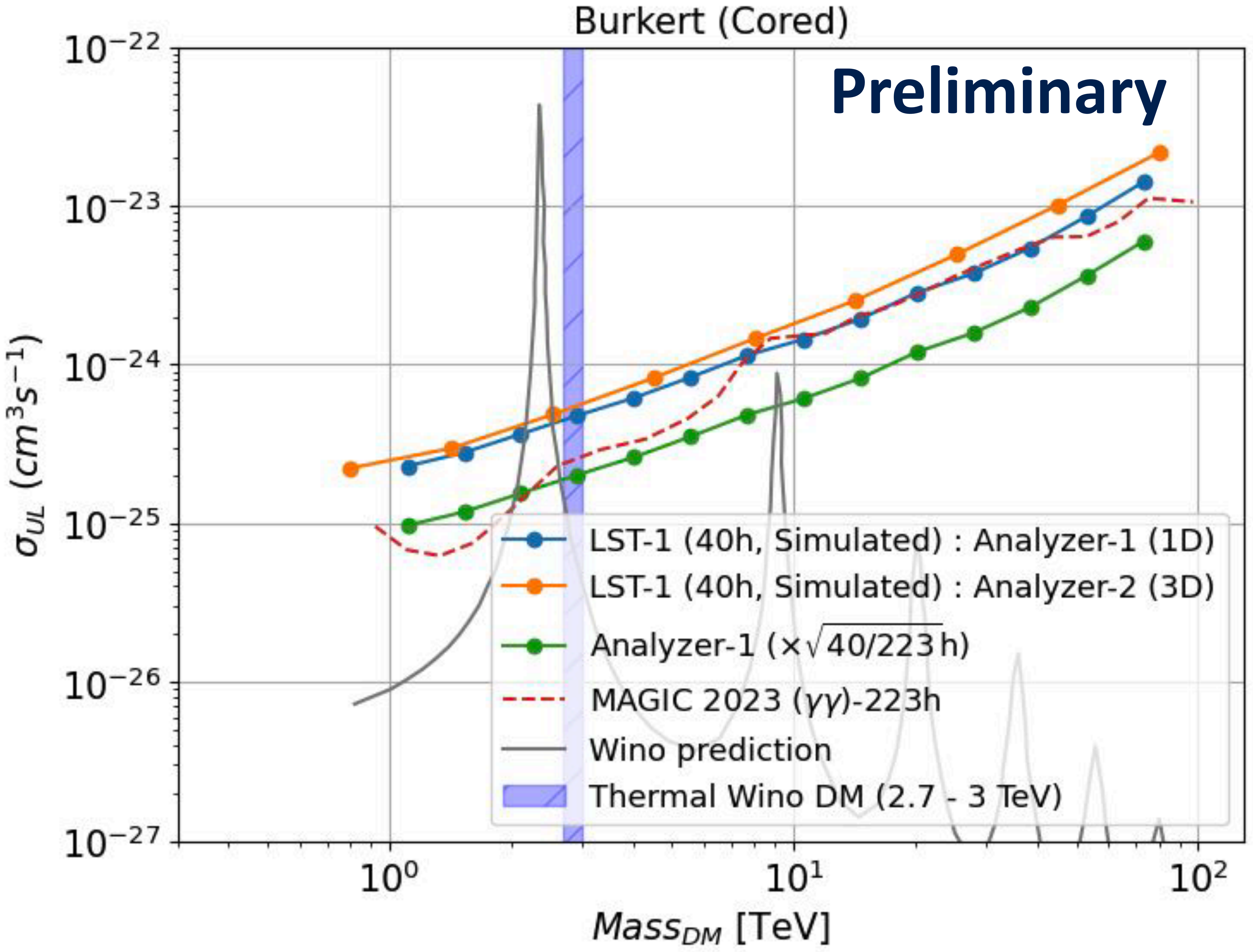


Results: DM line sensitivity

- Explored both, cuspy (Einasto) and cored (Burkert) types of DM density profiles
- LST-1 shows potential in probing SUSY DM models
  - like Higgsino and Wino at ~ 1.1 TeV and ~3 TeV respectively
  - 4 LSTs array would improve this sensitivity significantly







Summary

- Our study with LST-1 could provide more stringent constraints on DM line signals at higher energies, among the current IACTs
- This study on systematics from modelling and analysis methods could be used to define an energy dependent sliding window for more robust limits
- Our aim is to probe SUSY models using LST-1 with more exposure in the coming years
- Upcoming LST array would be crucial in better background rejection and probing lower mass DM candidate like Higgsino

Back Up