Discovering Dark Matter with Indirect Detection

BERKELEY LAB

NICK RODD | Pheno 2026 | 11 May 2026

UC BERKELEY
LEINWEBER INSTITUTE
FOR THEORETICAL PHYSICS

Motivation

Thermal WIMPs remains deeply motivated and ***discoverable***

Every chance of a discovery within the next decade

Outline

1. Experimental Landscape

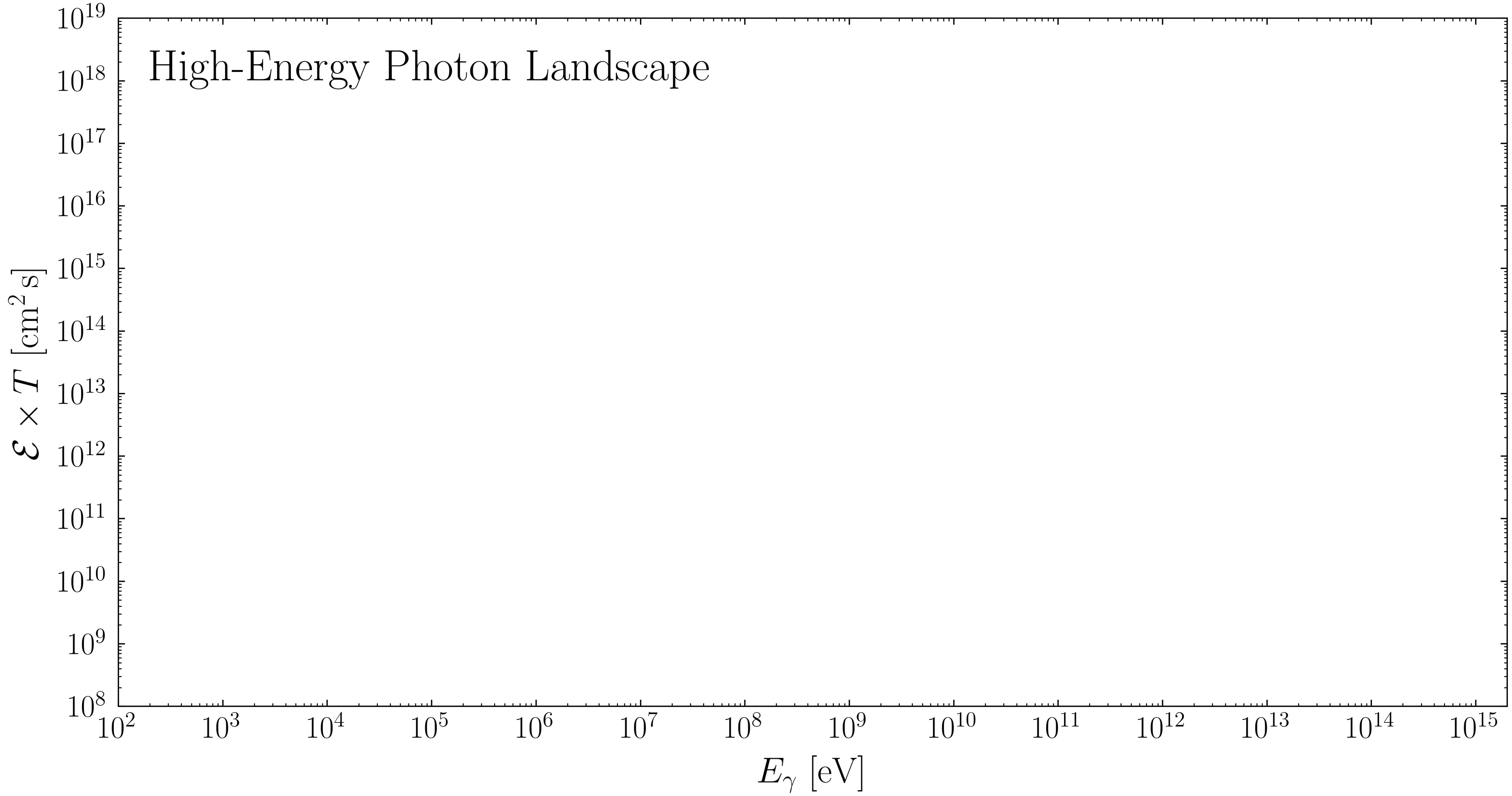
2. WIMPs in 2026

3. An Update on Uncertainties

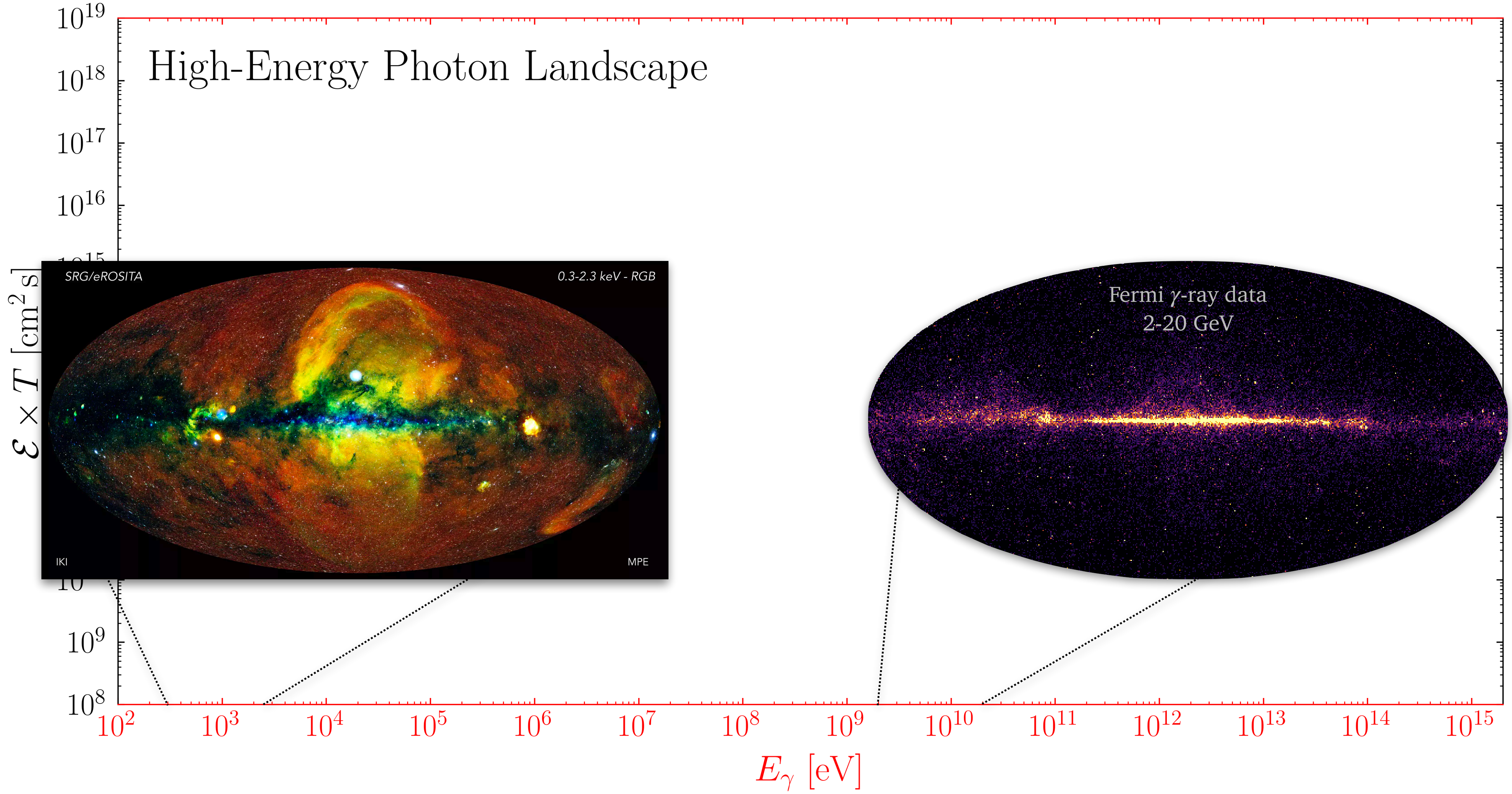
4. Discovery at CTAO

Experimental Landscape

Experimental Landscape



Experimental Landscape



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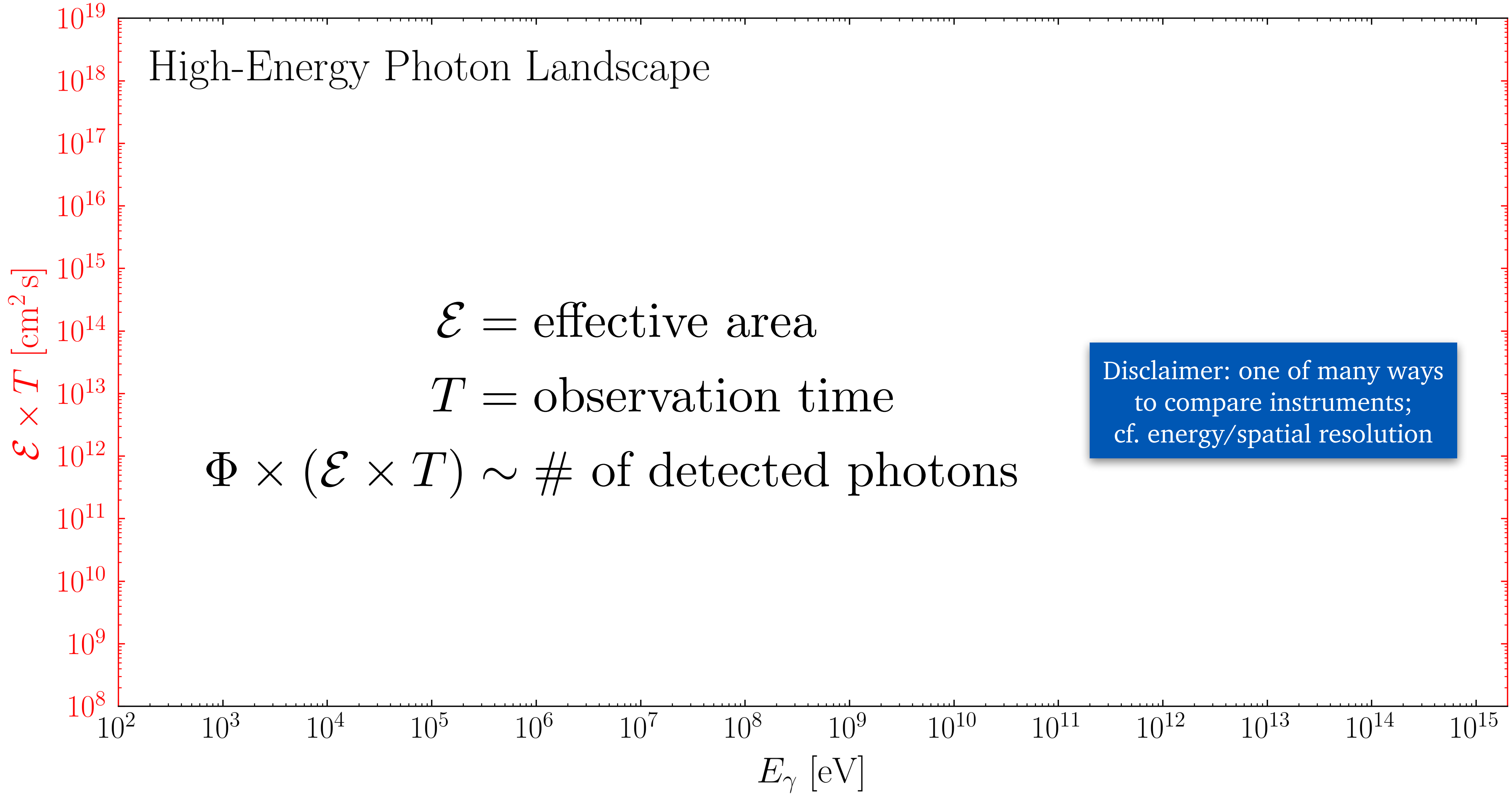
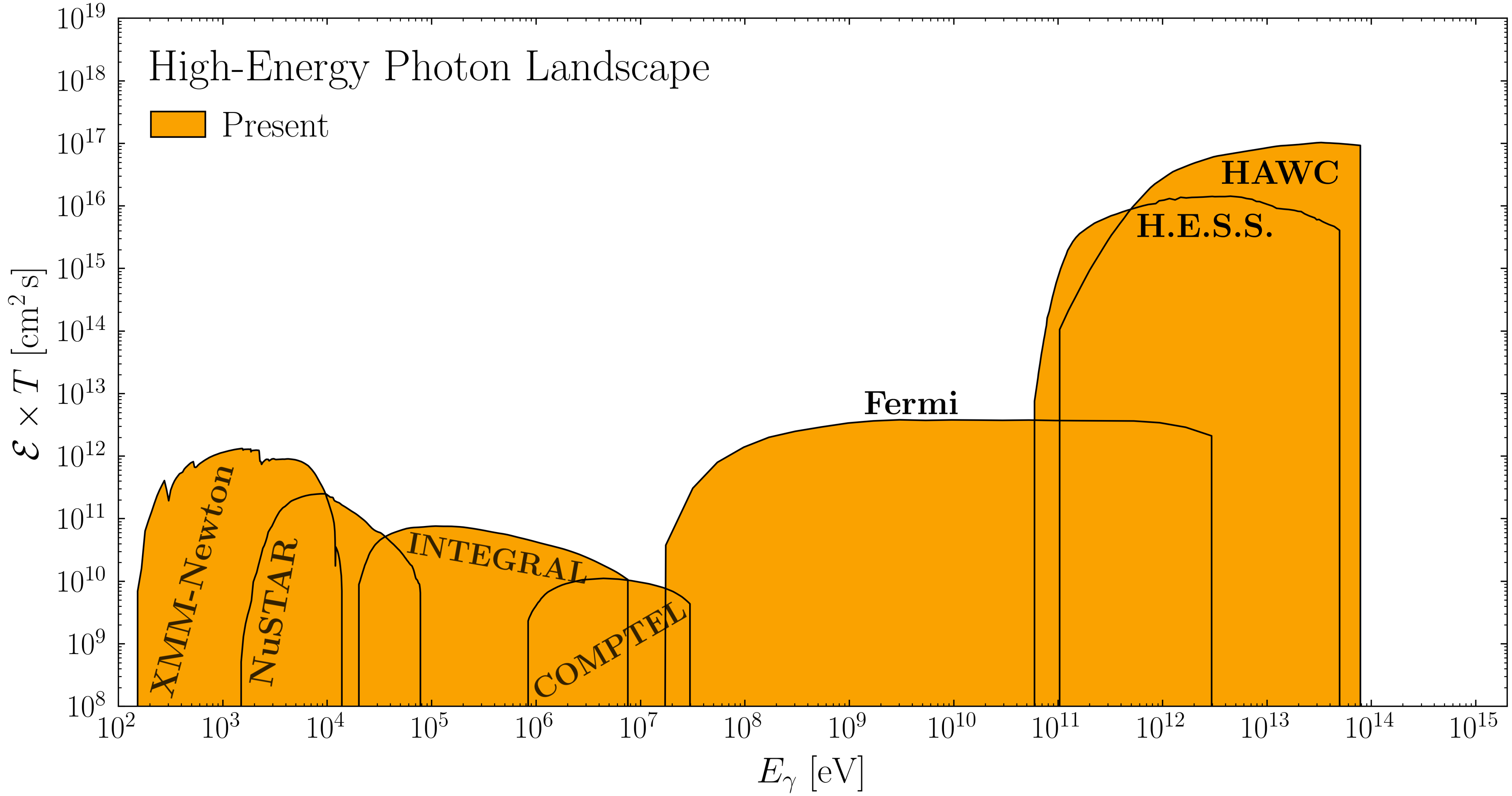


Disclaimer: one of many ways to compare instruments; cf. energy/spatial resolution

Experimental Landscape

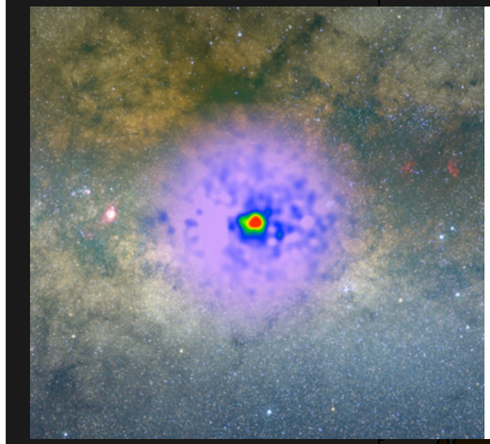


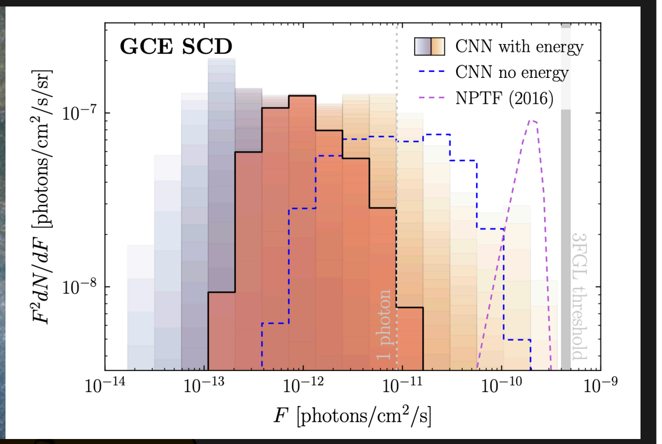
[Boddy, Lisanti, McDermott, NLR, Weniger+ 2022]

Experimental Landscape

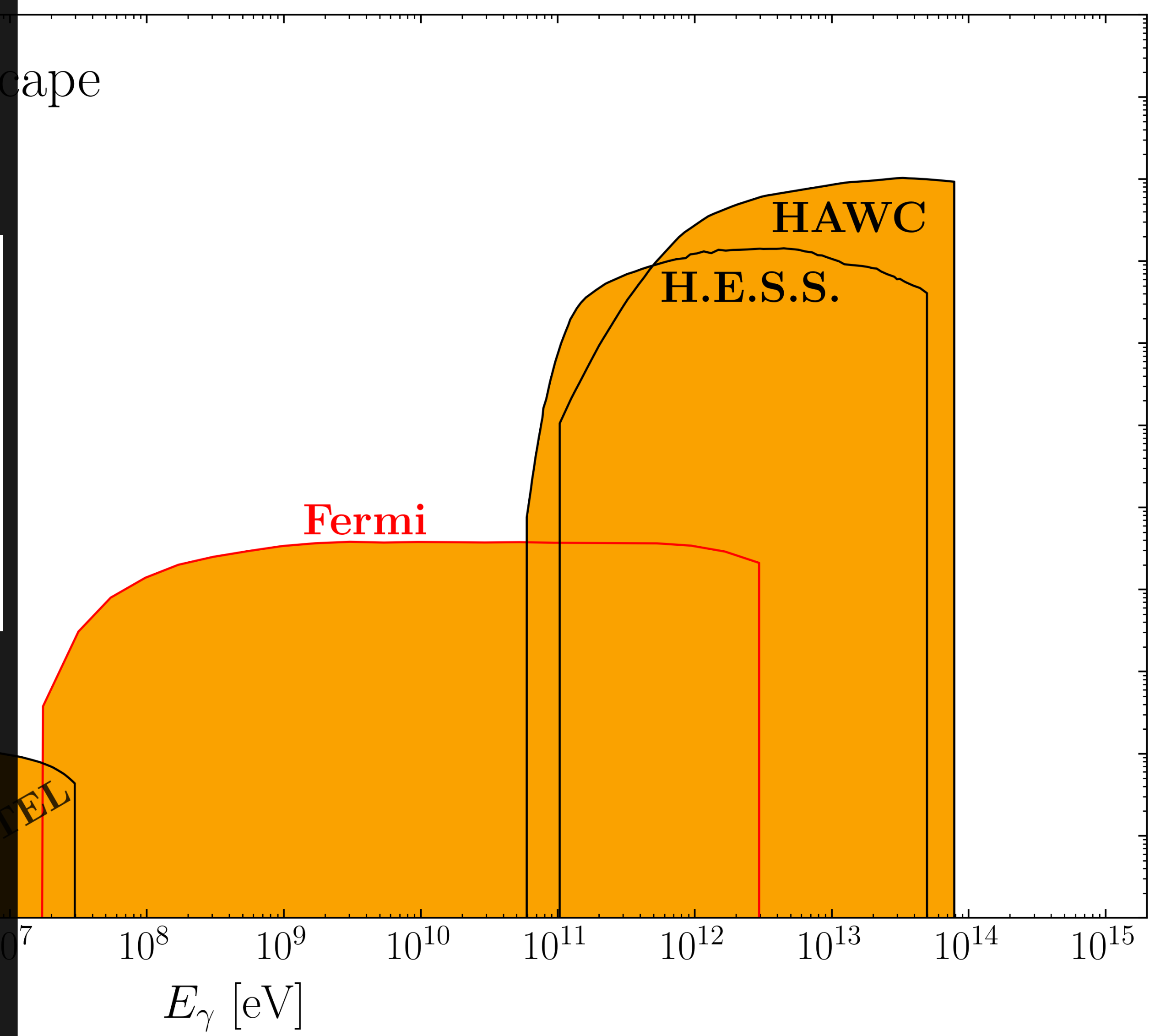
Did Fermi discover DM?

We continue to learn about the Galactic Center Excess





[List, Park, NLR, Schoen,Wolf 2025]



[Boddy, Lisanti, McDermott, NLR, Weniger+ 2022]

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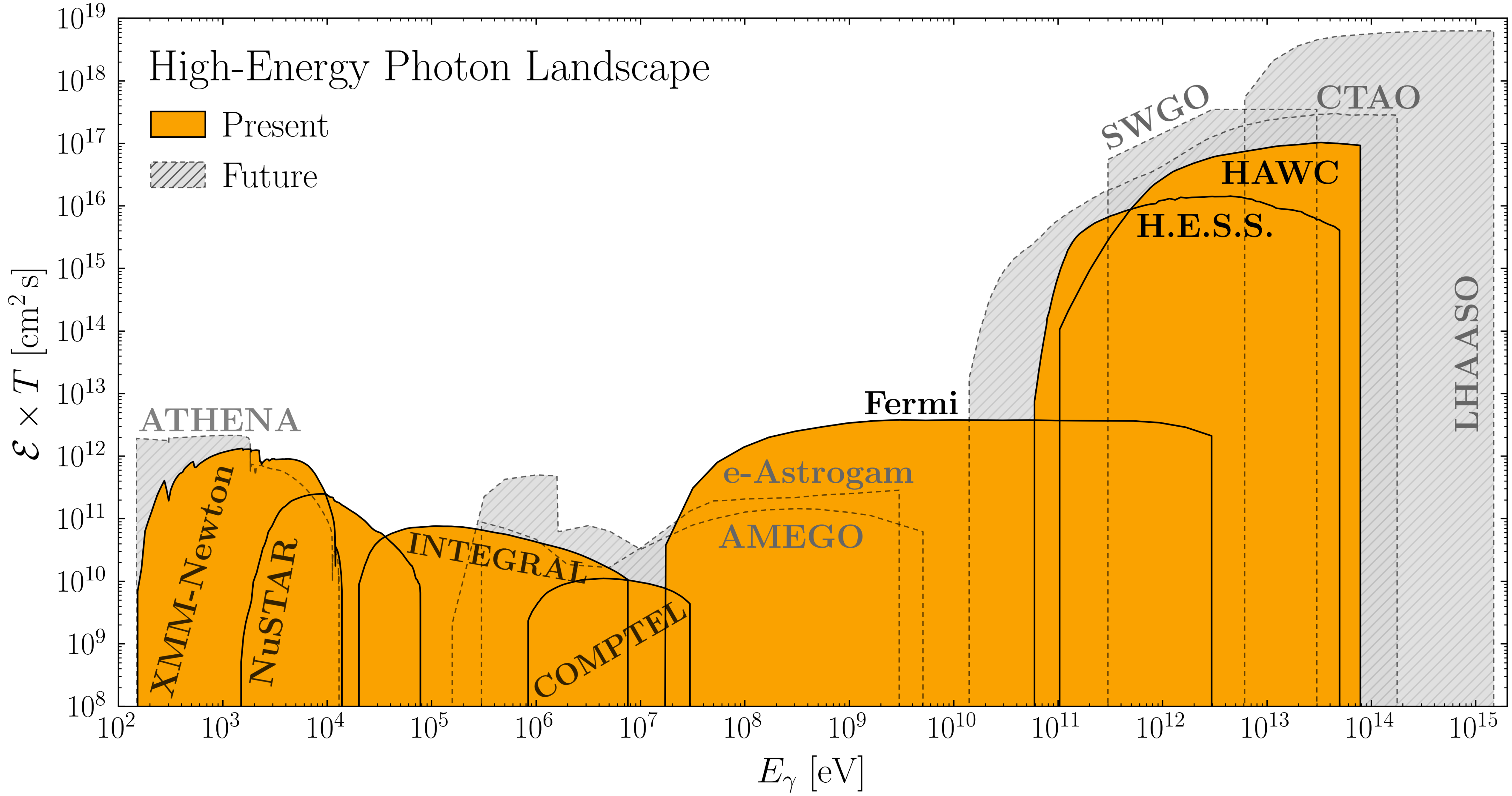
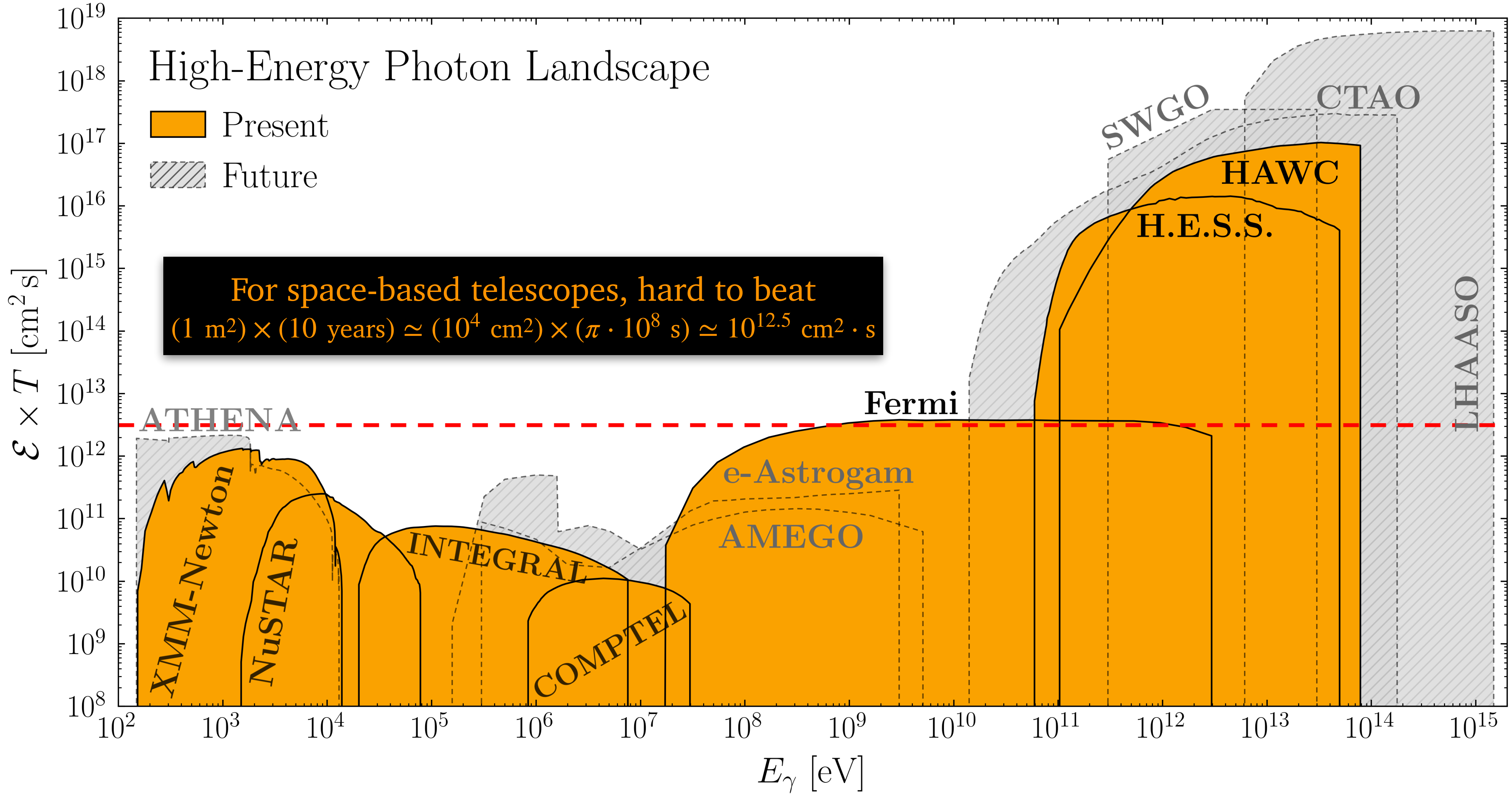


[Boddy, Lisanti, McDermott, NLR, Weniger+ 2022]

Experimental Landscape



[Boddy, Lisanti, McDermott, NLR, Weniger+ 2022]

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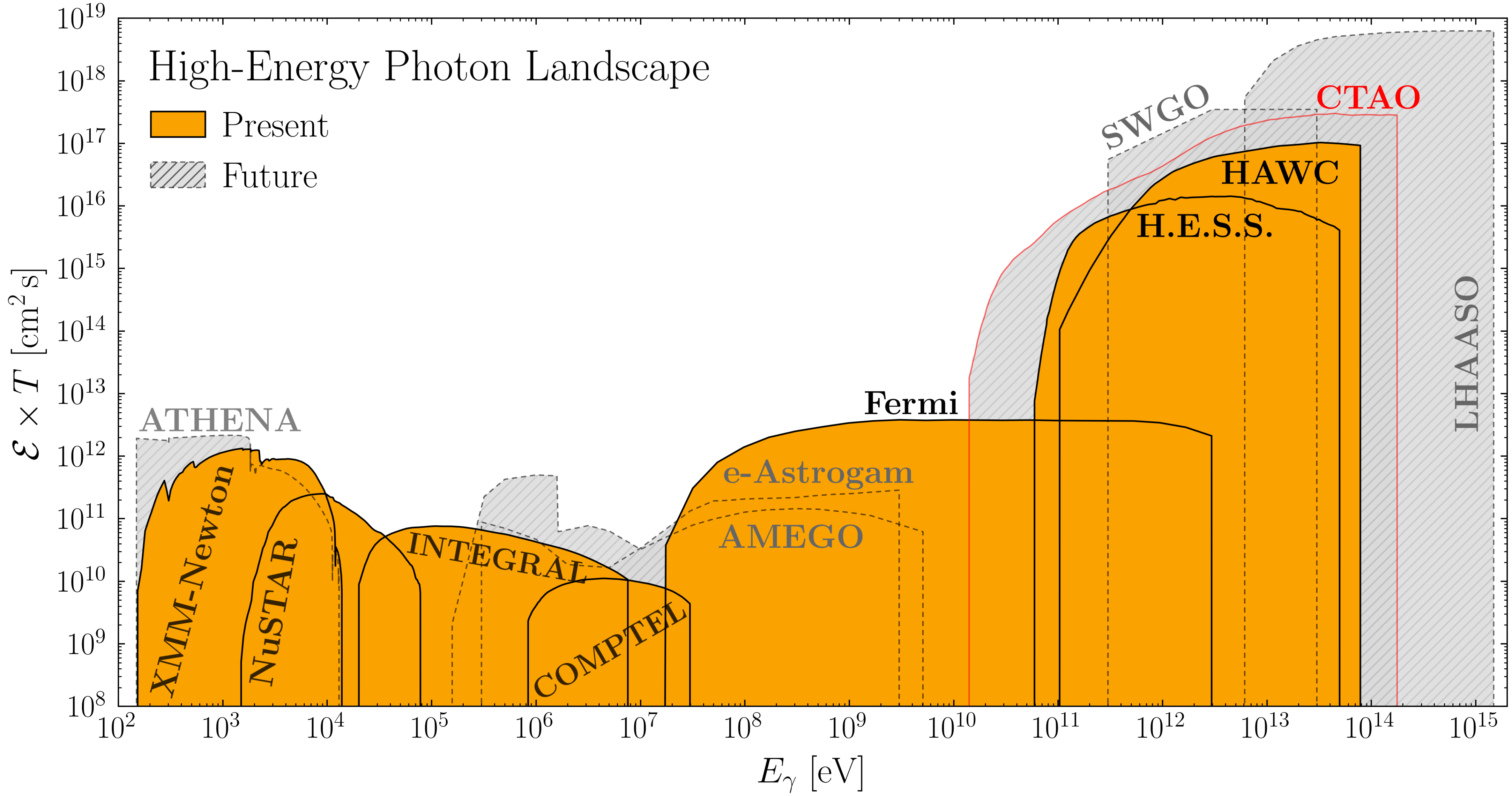


[Boddy, Lisanti, McDermott, NLR, Weniger+ 2022]

WIMPs in 2026

WIMPs in 2026

Bottom up: introduce one field with SM charge

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \bar{\chi}(i\not{D} + M_\chi)\chi$$

Minimal Dark Matter [Cirelli+ 2006]

Predictive: couplings and mass determined

E.g. quintuplet DM $(\mathbf{1}, \mathbf{5}, 0)$, $M_\chi \simeq 14\,\text{TeV}$

Notation indicates SM charges

$$\chi_{\mathbf{5}} = \begin{pmatrix} \chi^{++} \\ \chi^{+} \\ \chi^{0} \\ \chi^{-} \\ \chi^{--} \end{pmatrix}$$

WIMPs in 2026

Top down: at low energies, can find

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{\chi}(i\not{D} + M_\chi)\chi + \ldots$$

Assuming other states ~decoupled similarly predictive

Higgsino $(\mathbf{1}, \mathbf{2}, 1/2)$ and wino $(\mathbf{1}, \mathbf{3}, 0)$ can emerge as DM in split SUSY scenarios

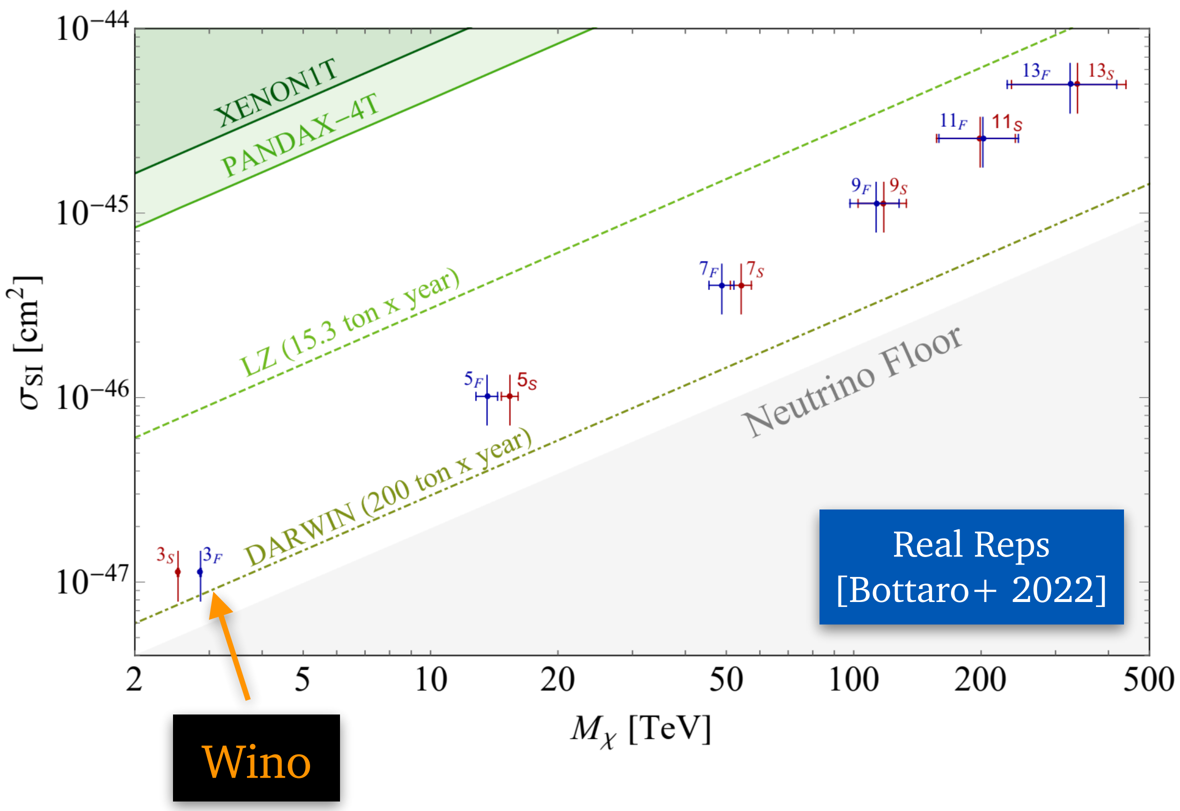
[Wells 2003], [Giudice, Romanino 2004], [Arkani-Hamed, Dimopoulos 2005], [Hall, Nomura 2012], …

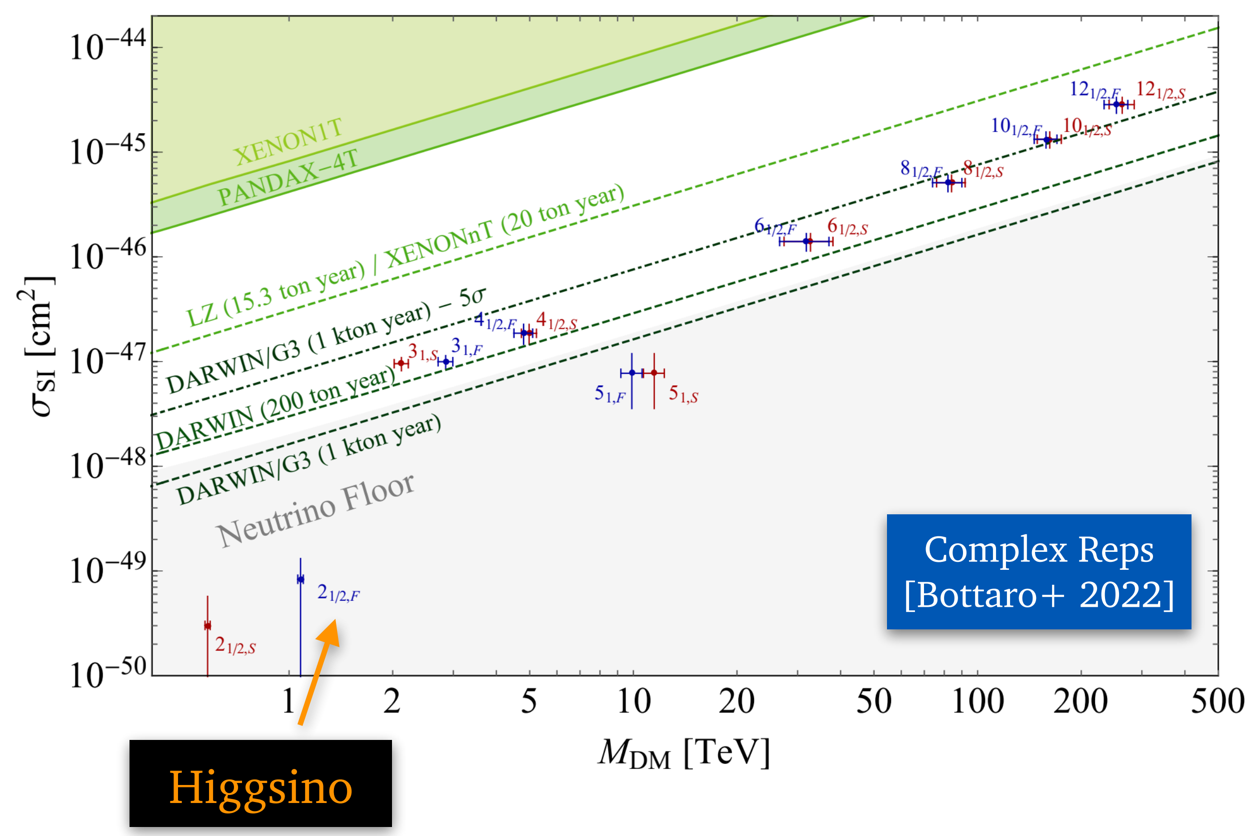
Additional UV realizations, e.g. Noble DM [Asadi, Batz, Kribs 2024]

SUSY DM also testable via electron-EDM (ACME, JILA), see e.g. [Cesarotti+ 2019], [Co+ 2022]

WIMPs in 2026

Most MDM models above neutrino floor





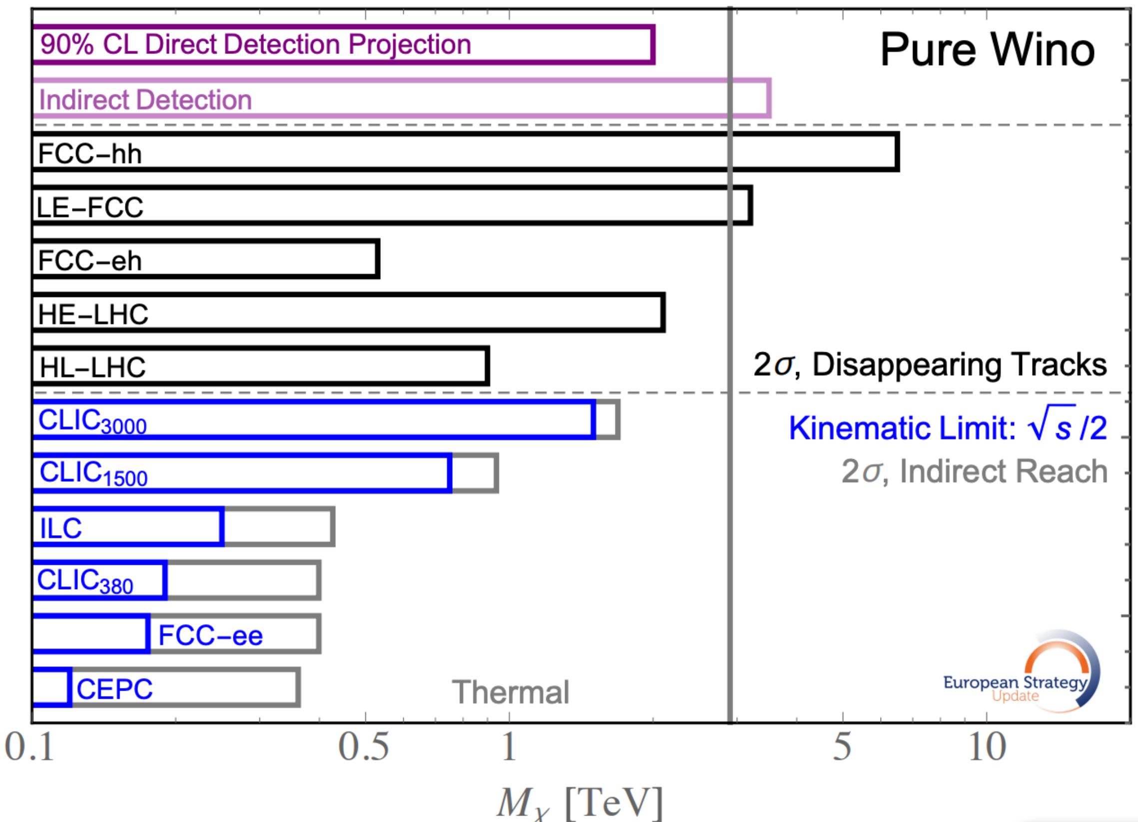
LZ sensitivity has already been achieved [2410.17036]

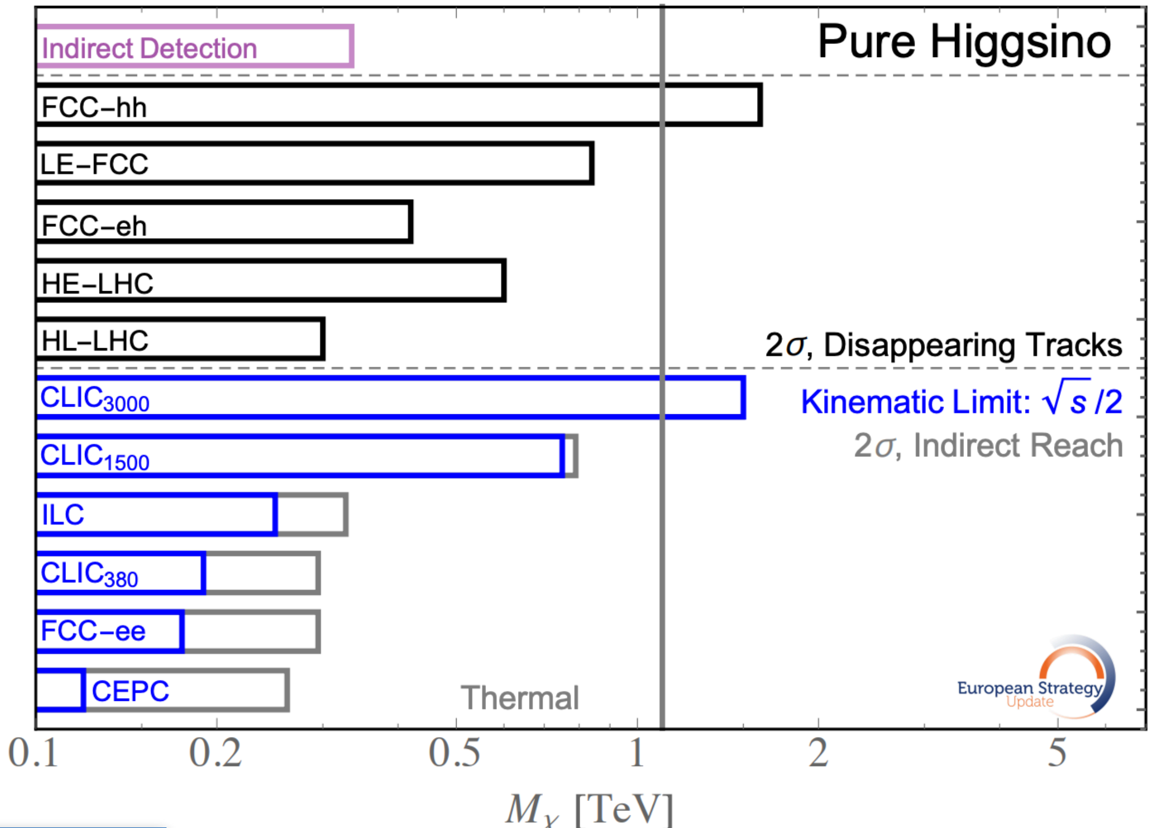
Another future option: PandaX-xT [2402.03596]

Assumes pure higgsino, for the more general case: [Martin 2024, 2025]

WIMPs in 2026

Higgsino within reach of future colliders





[Canepa, Han, Wang 2020]

Key target for muon collider, e.g. [Muon Collider Collab. 2022]
& plasma wakefield collider, e.g. [Chigusa, Knapen, Opferkuch, Savoray, Scherb, Xu 2025]

An Update on Uncertainties

Update on Uncertainties

Dark matter annihilation flux

$$\frac{d\Phi}{dE} = \frac{\langle \sigma v \rangle}{8\pi M_\chi^2} \frac{dN}{dE} \times \int ds \, \rho_{\rm DM}^2(s)$$

Update on Uncertainties

Dark matter annihilation flux

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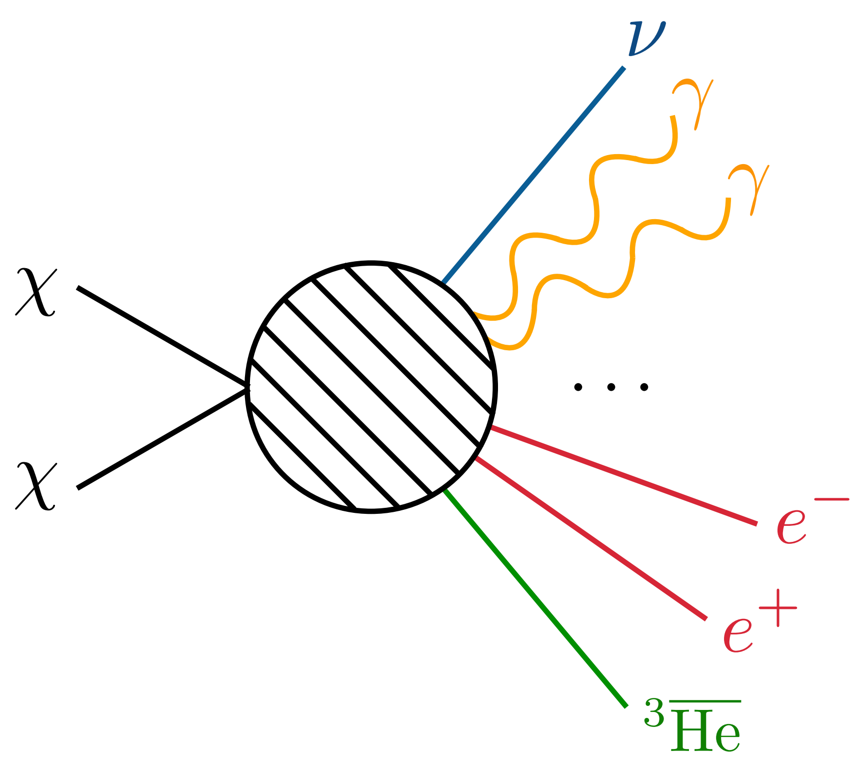

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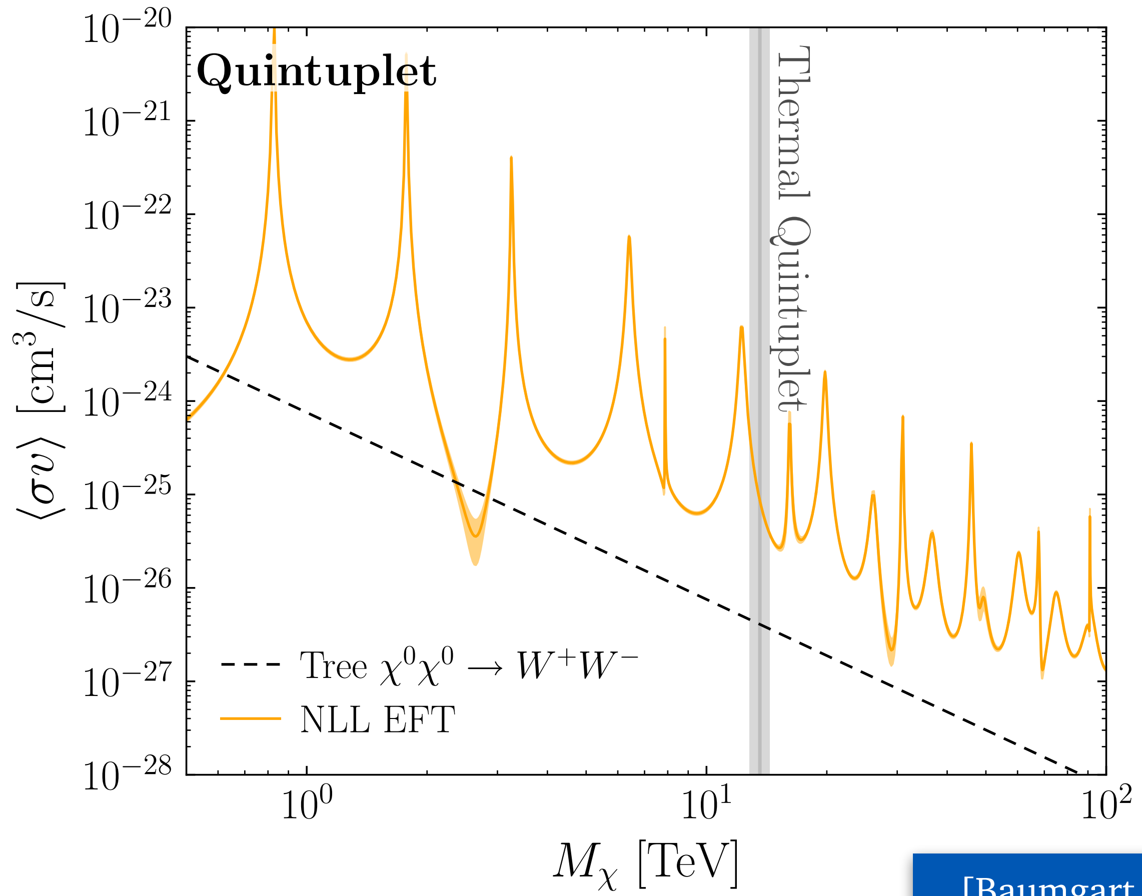

[Baumgart, NLR, Slatyer, Vaidya 2024]

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Particle physics factor can be computed to $\mathcal{O}(10\%)$

Results exist for: wino ([Baumgart, NLR+ 2018], [Beneke+ 2019]), higgsino [Beneke+ 2020], quintuplet [Baumgart, NLR+ 2024], all real MDM reps [Baumgart, NLR+ 2026]

Open questions: spectrum of complex MDM reps
& impact on higgsino, continuum spectrum for $M_\chi \gg m_W$

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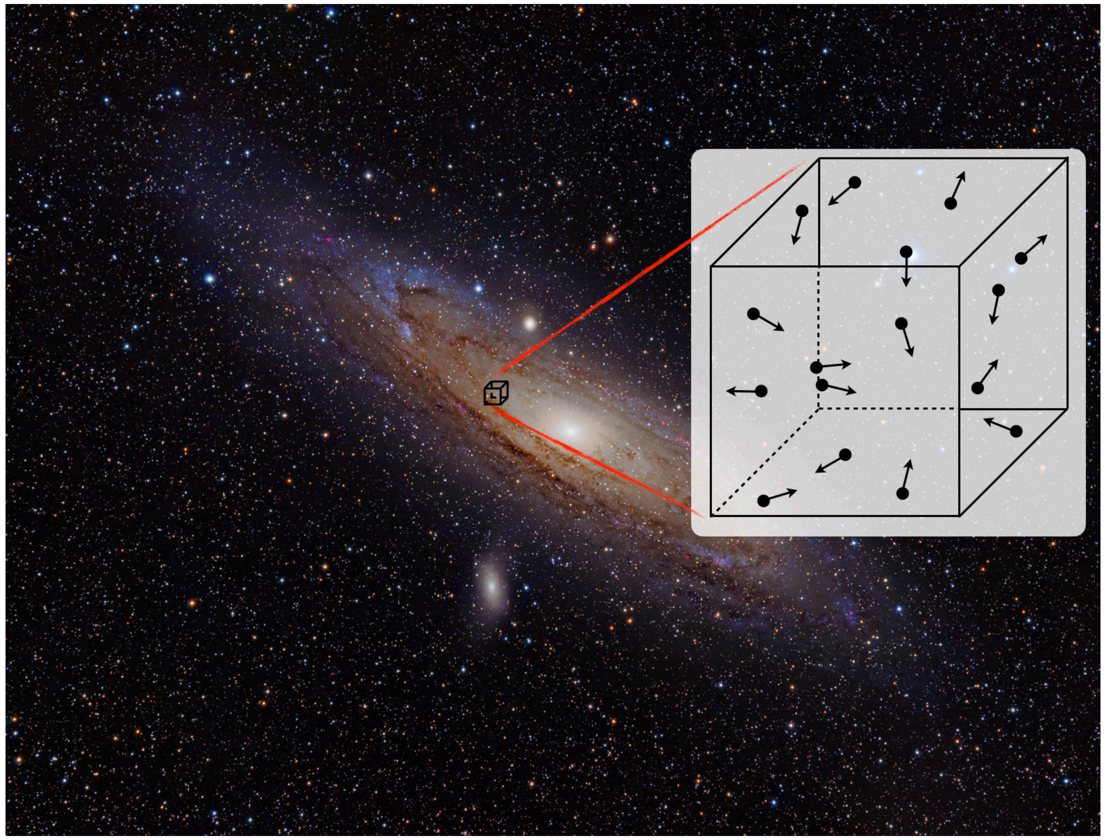

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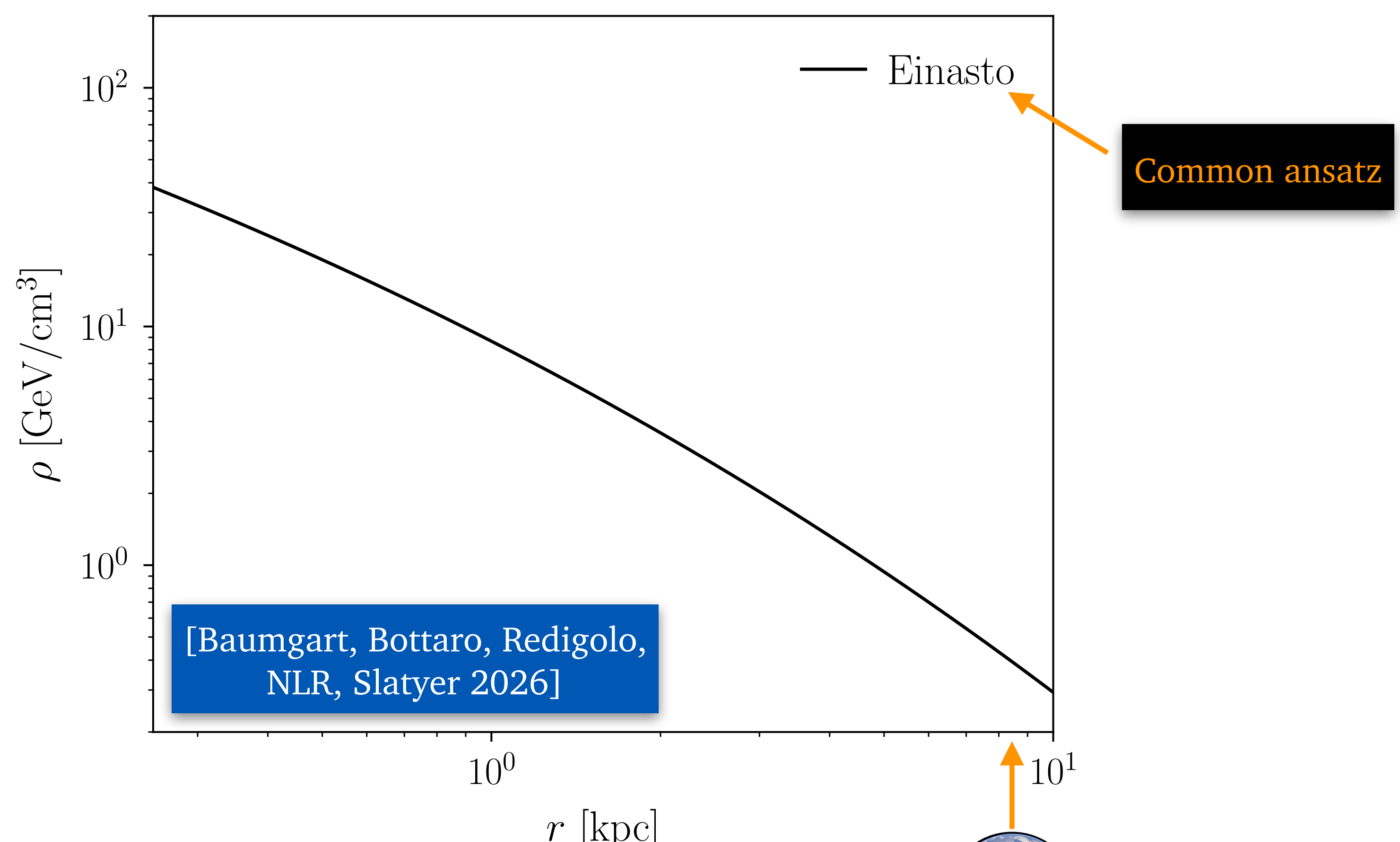

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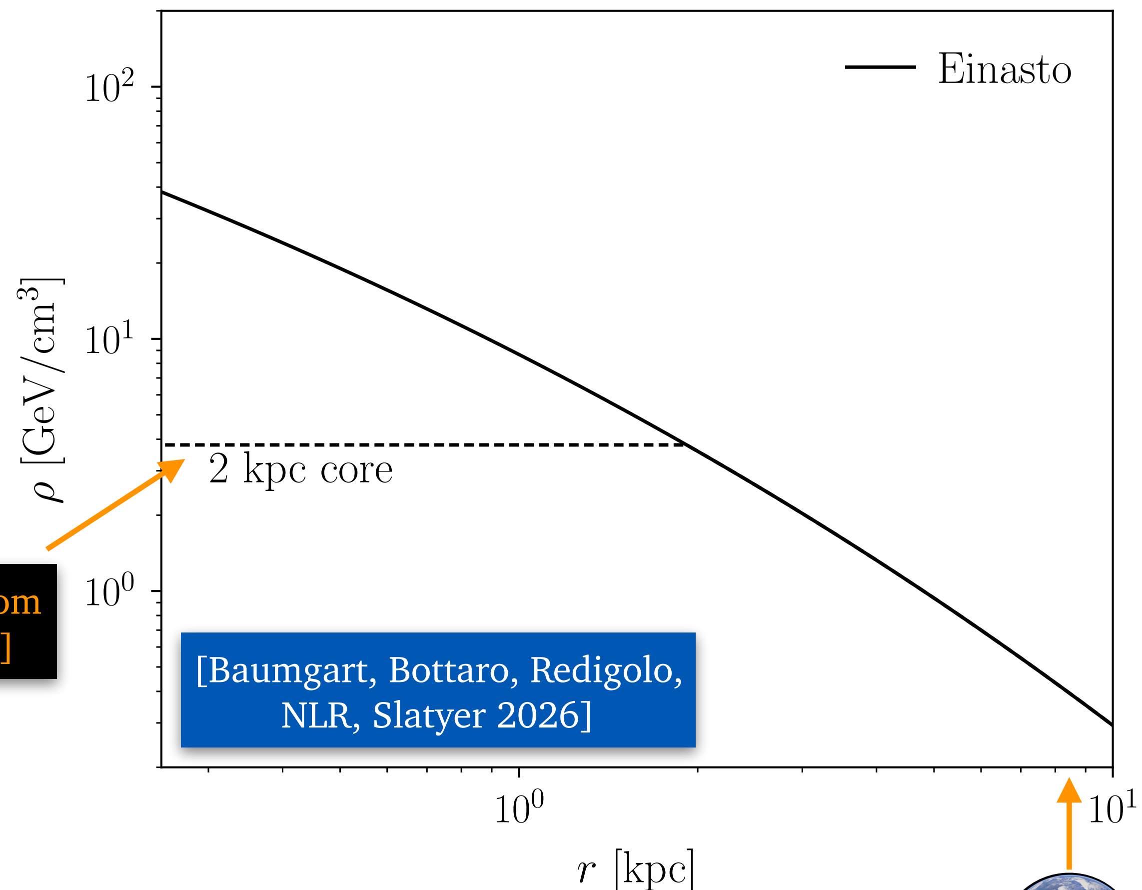

Conservative lower bound from observations [Hooper 2017]

Update on Uncertainties

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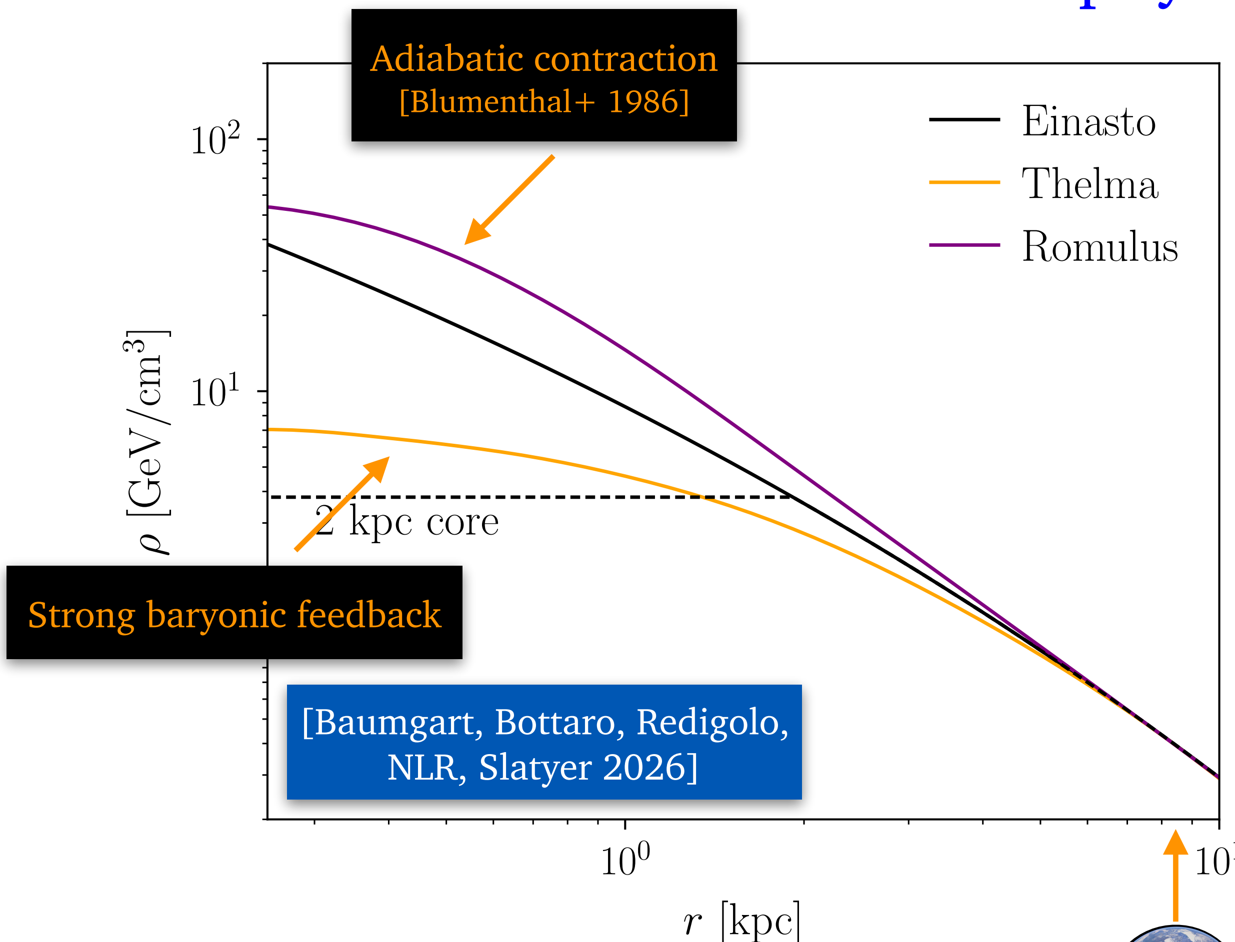
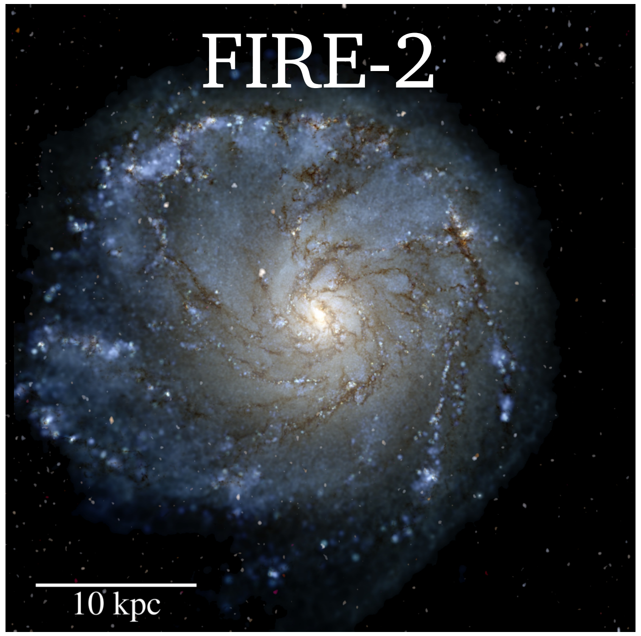


[Baumgart, Bottaro, Redigolo, NLR, Slatyer 2026]



[Hopkins+ 2018]
[McKeown+ 2022]

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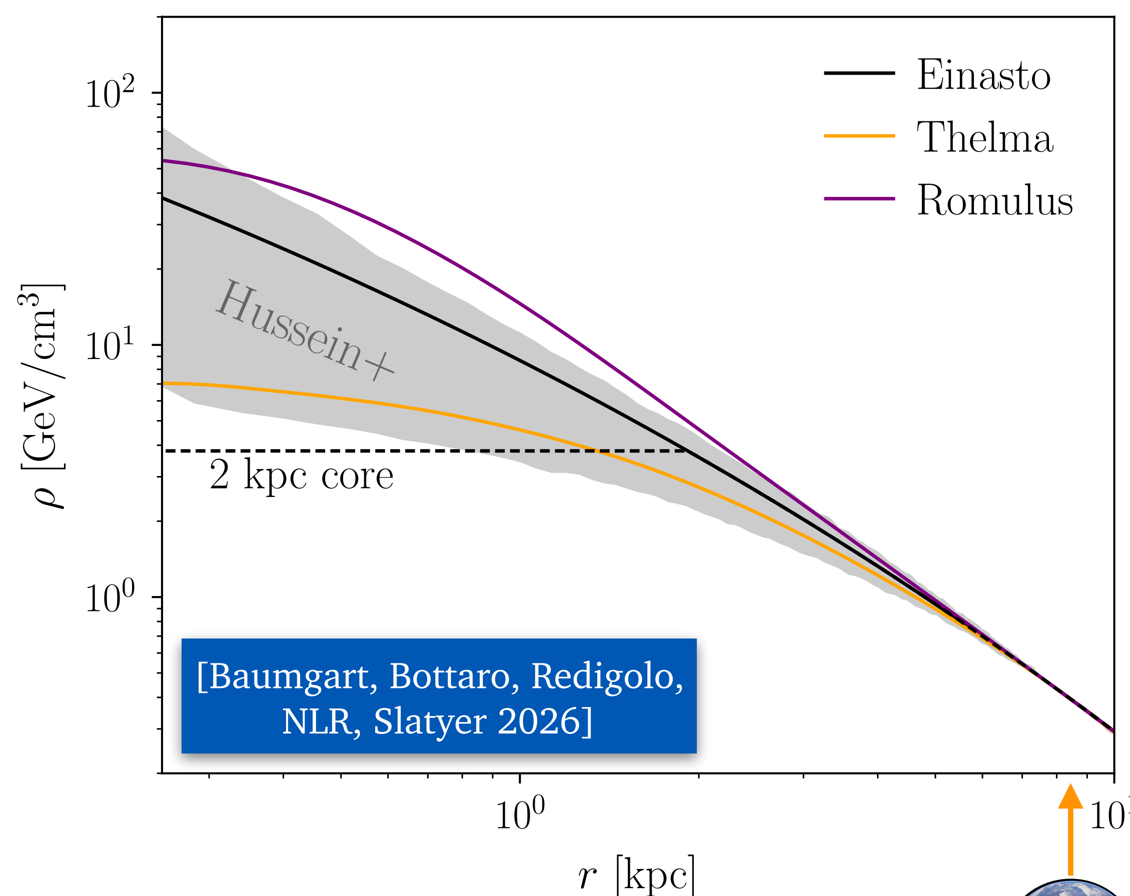

[Hussein+ 2025]

Use 24 Milky Way analog galaxies (4 simulation suites) to construct uncertainty band

Update on Uncertainties

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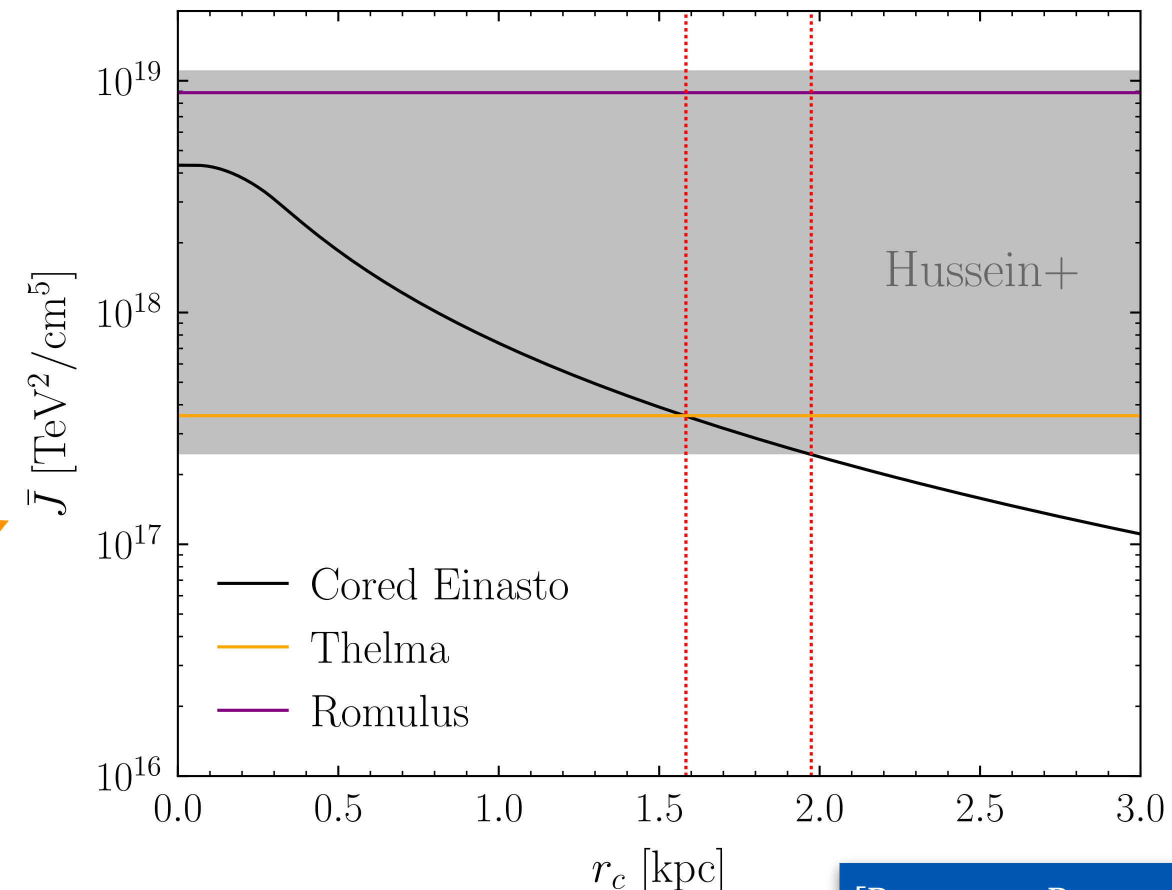
Average inner galaxy J-factor



[Baumgart, Bottaro, Redigolo, NLR, Slatyer 2026]

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Dominant uncertainty, lower bound exists

Observational path extremely challenging, unlikely in 10 years

Simulations far more promising

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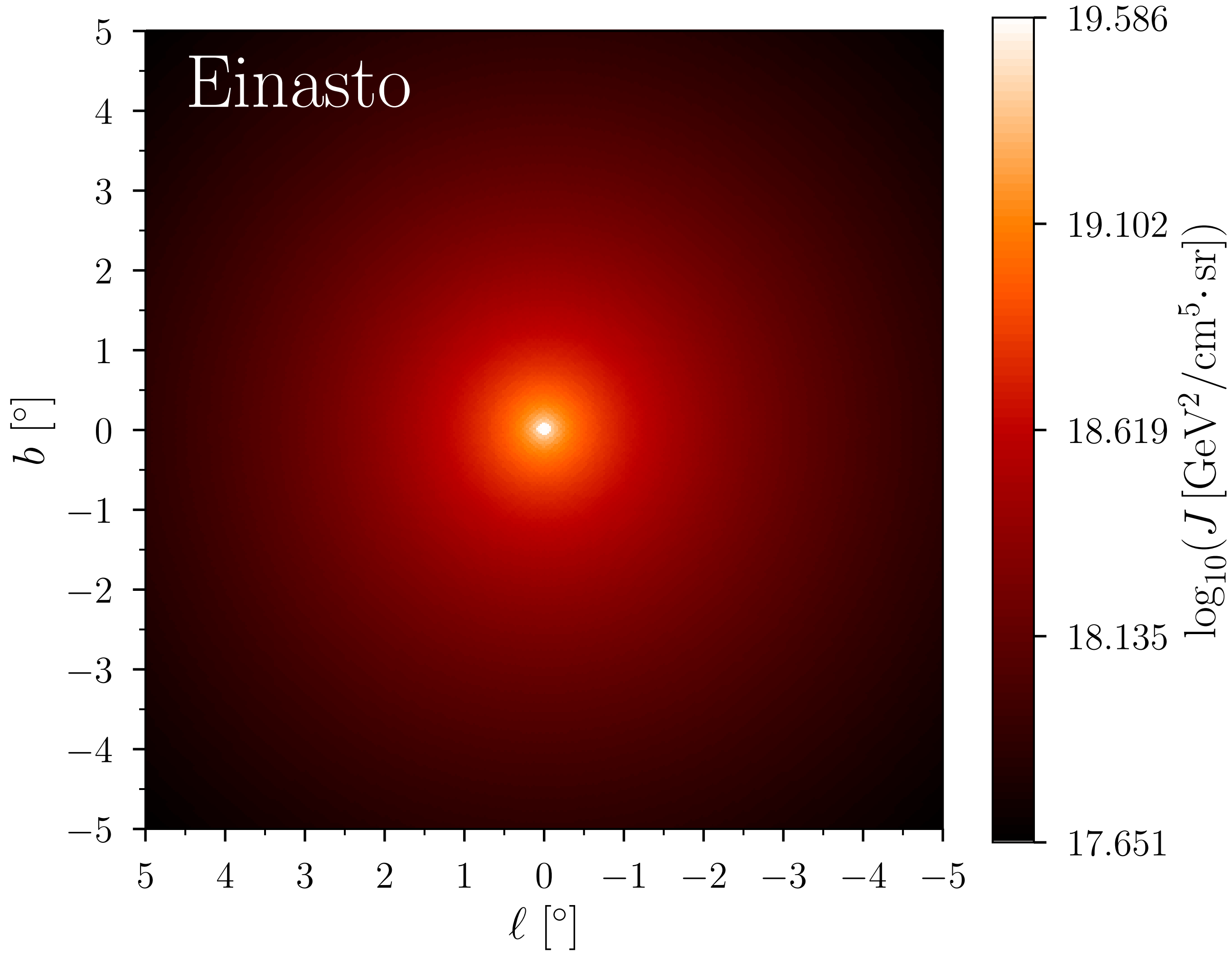
Update on Uncertainties

From 24 to 1,000 Milky Way like halos



[DREAMS, Garcia, NLR in prep.]

Update on Uncertainties

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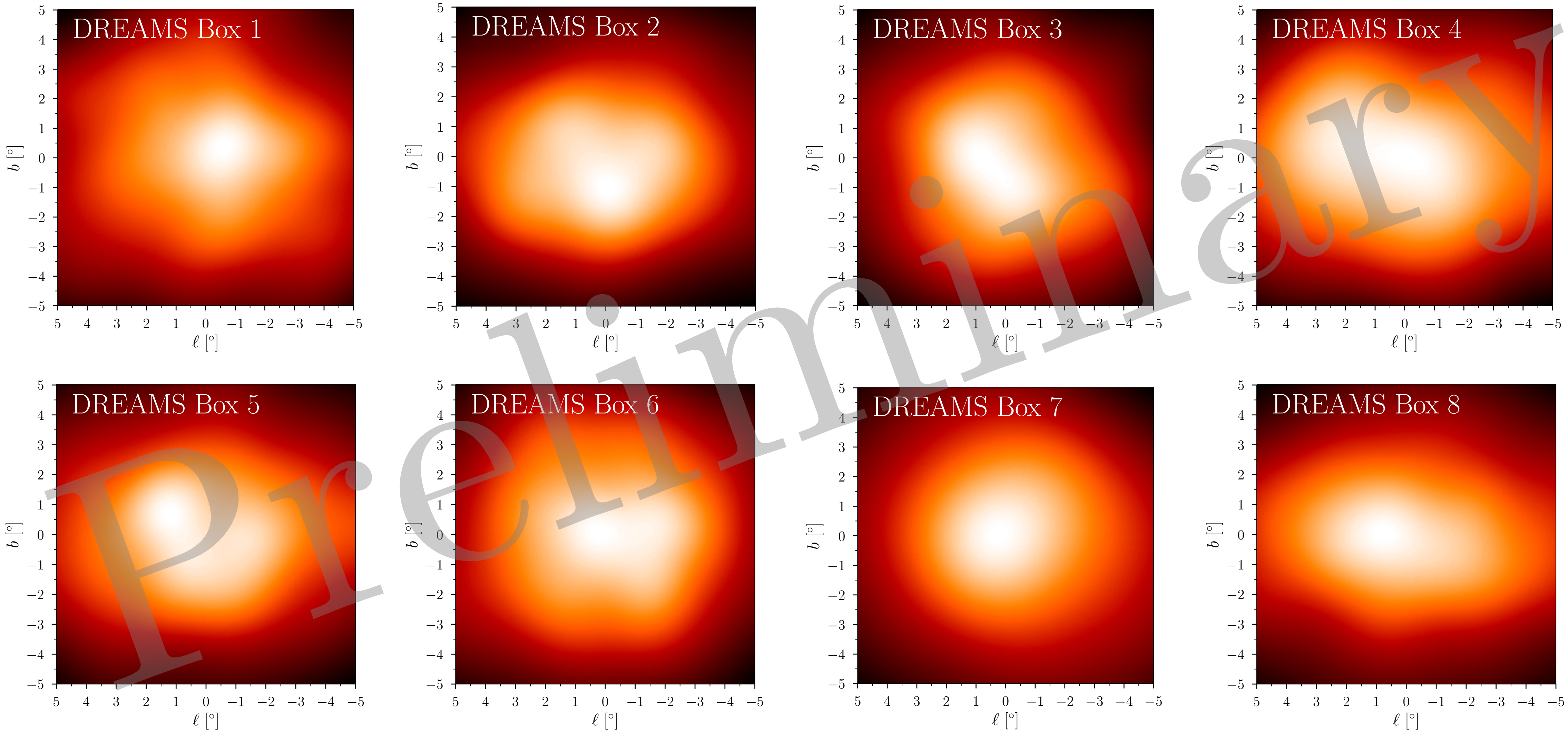


Softening length is 400 pc ~ 2.5°
Yet present in FIRE, where 200 pc

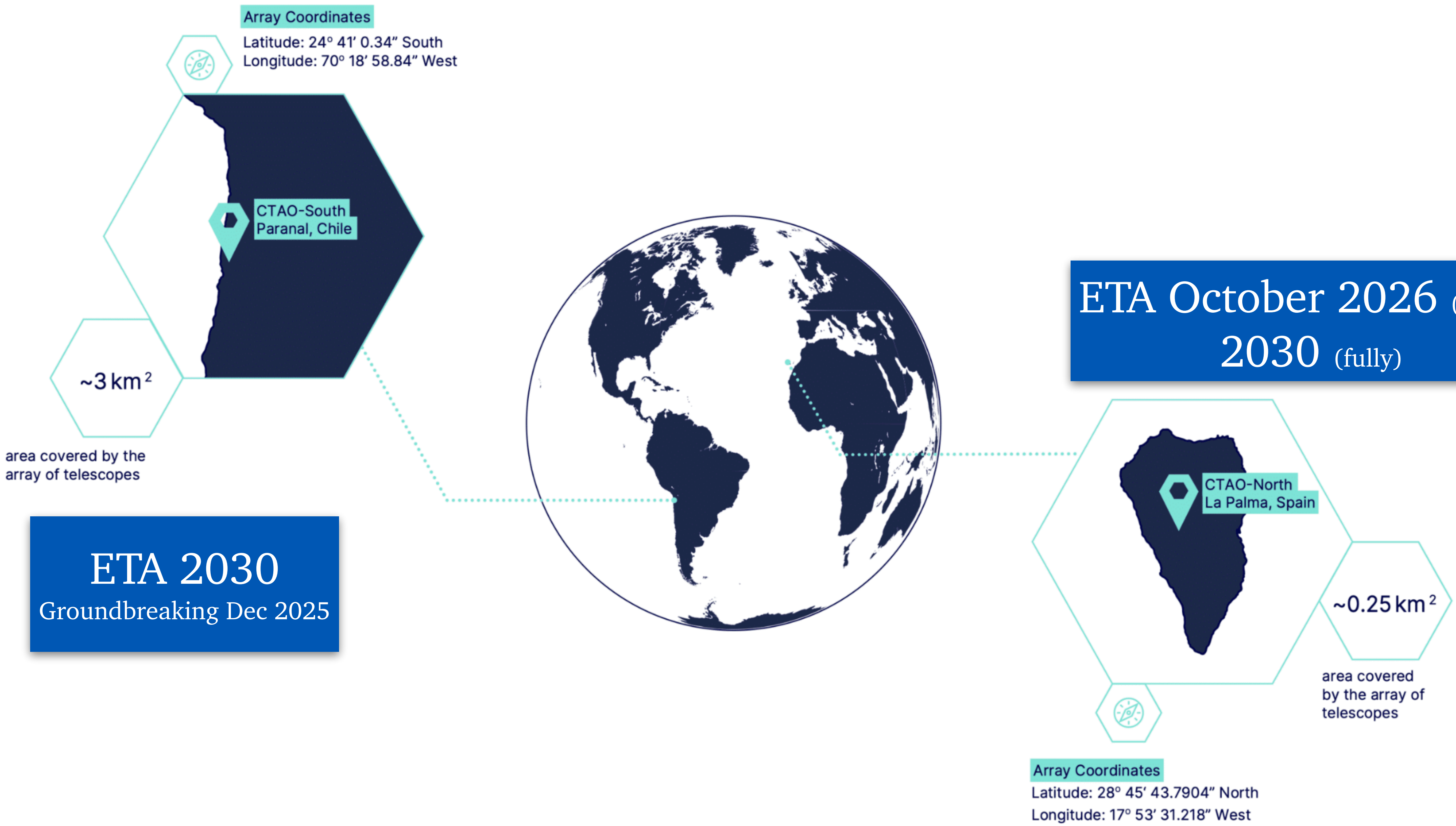
[Kuhlen+ 2013] 2° offset in Eris
[Schaller+ 2016] no offset in EAGLE
[Muru+ 2025] Asphericity in HESTIA

[DREAMS, Garcia, NLR in prep.]

Discovery at CTAO

Discovery at CTAO

CTAO is a distributed across two sites



ETA October 2026 (mostly)
2030 (fully)

ETA 2030
Groundbreaking Dec 2025

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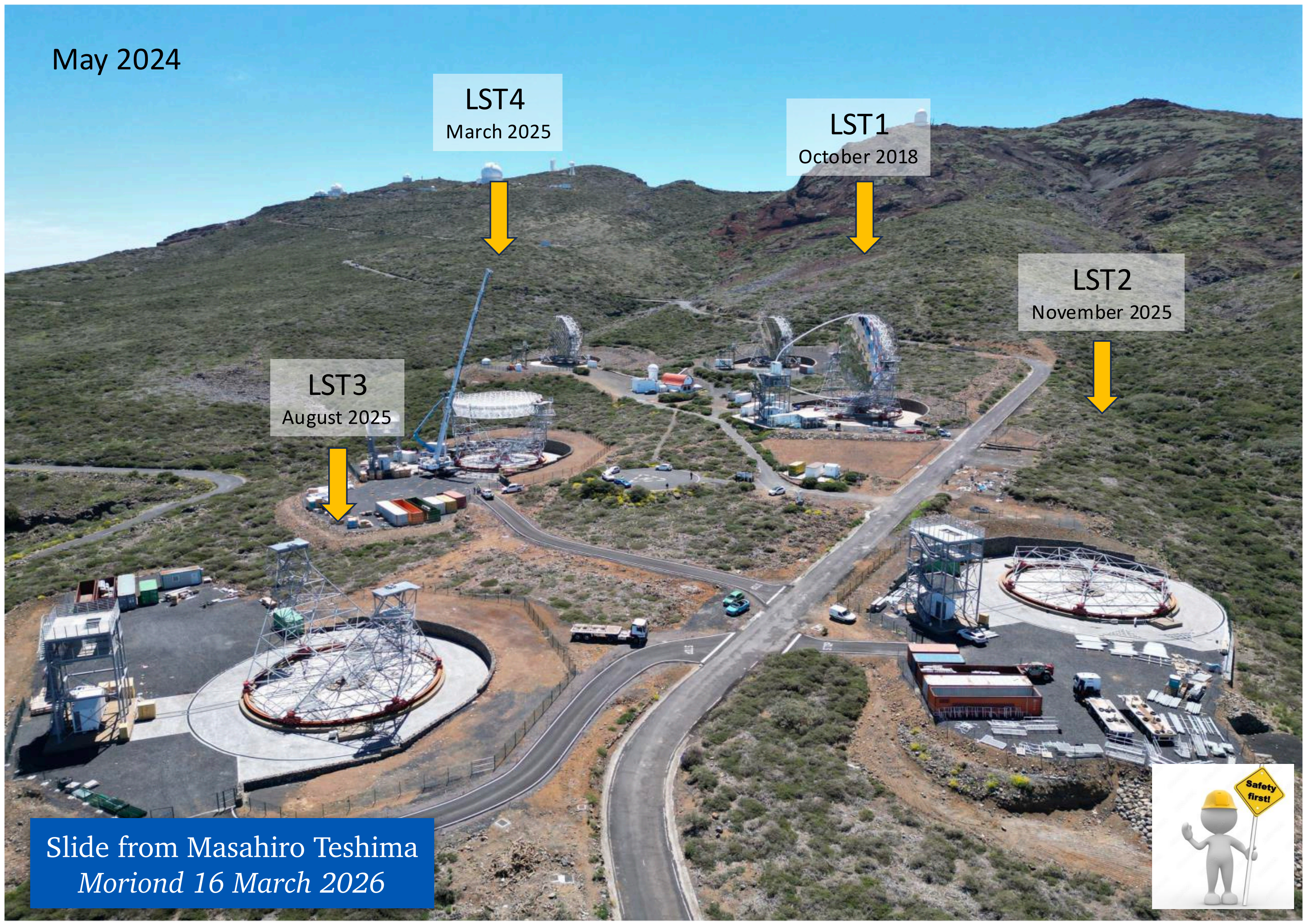

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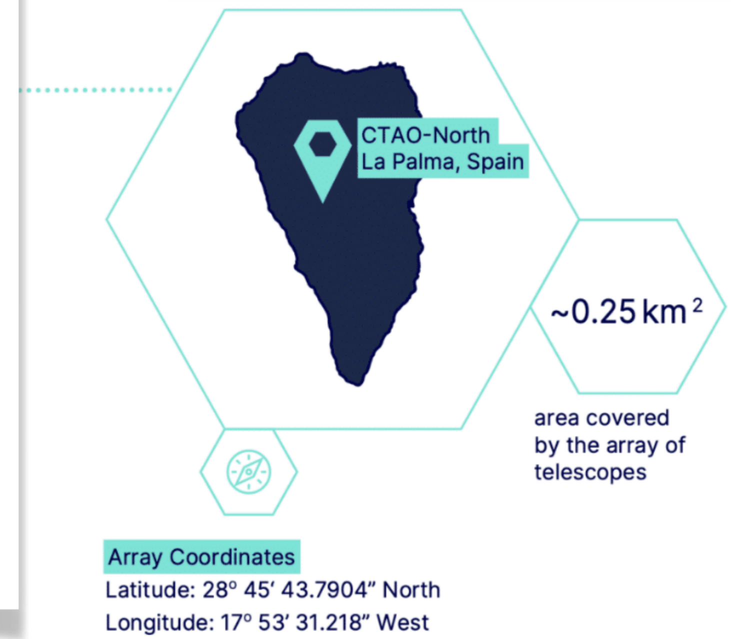

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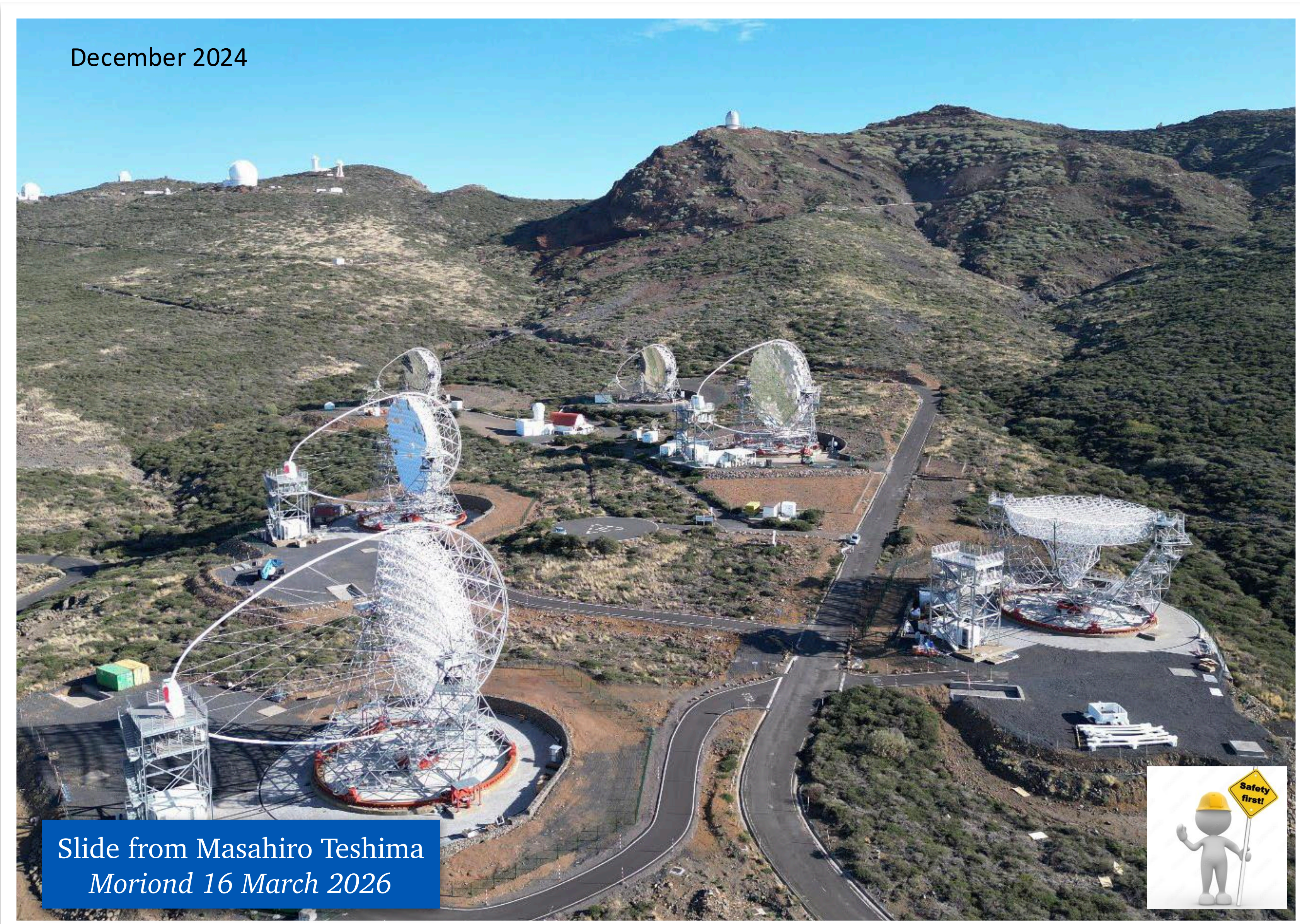

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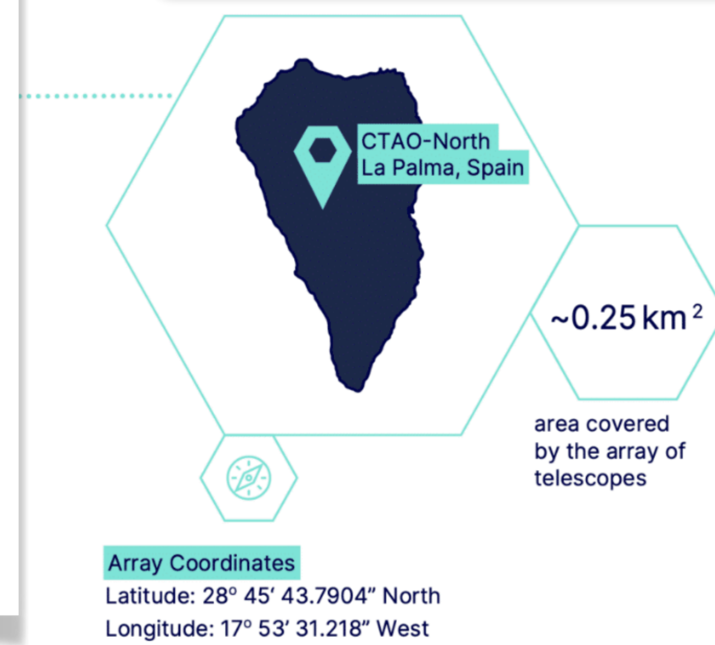

Discovery at CTAO

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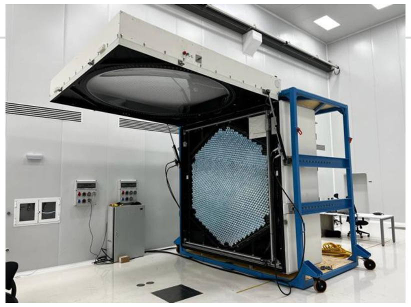
CTAO

LSTs in October 2025

- Telescope structures and mirror facets are completed.
- We are missing the cameras and cabling for LST2 and LST3
- LST4 is now in commissioning (in drive test).



Slide from Masahiro Teshima
Moriond 16 March 2026

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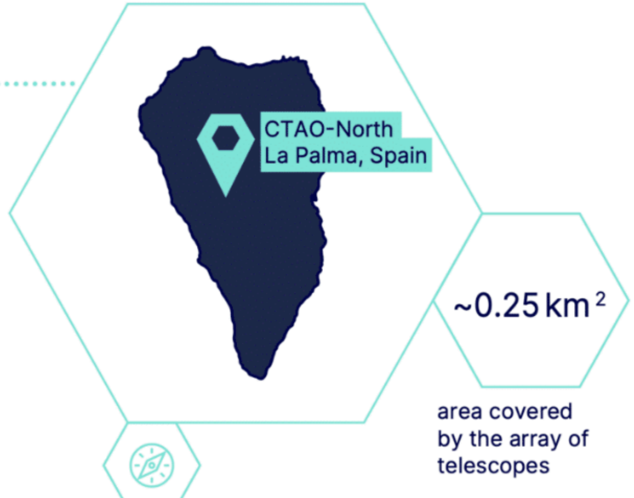
2030 (fully)



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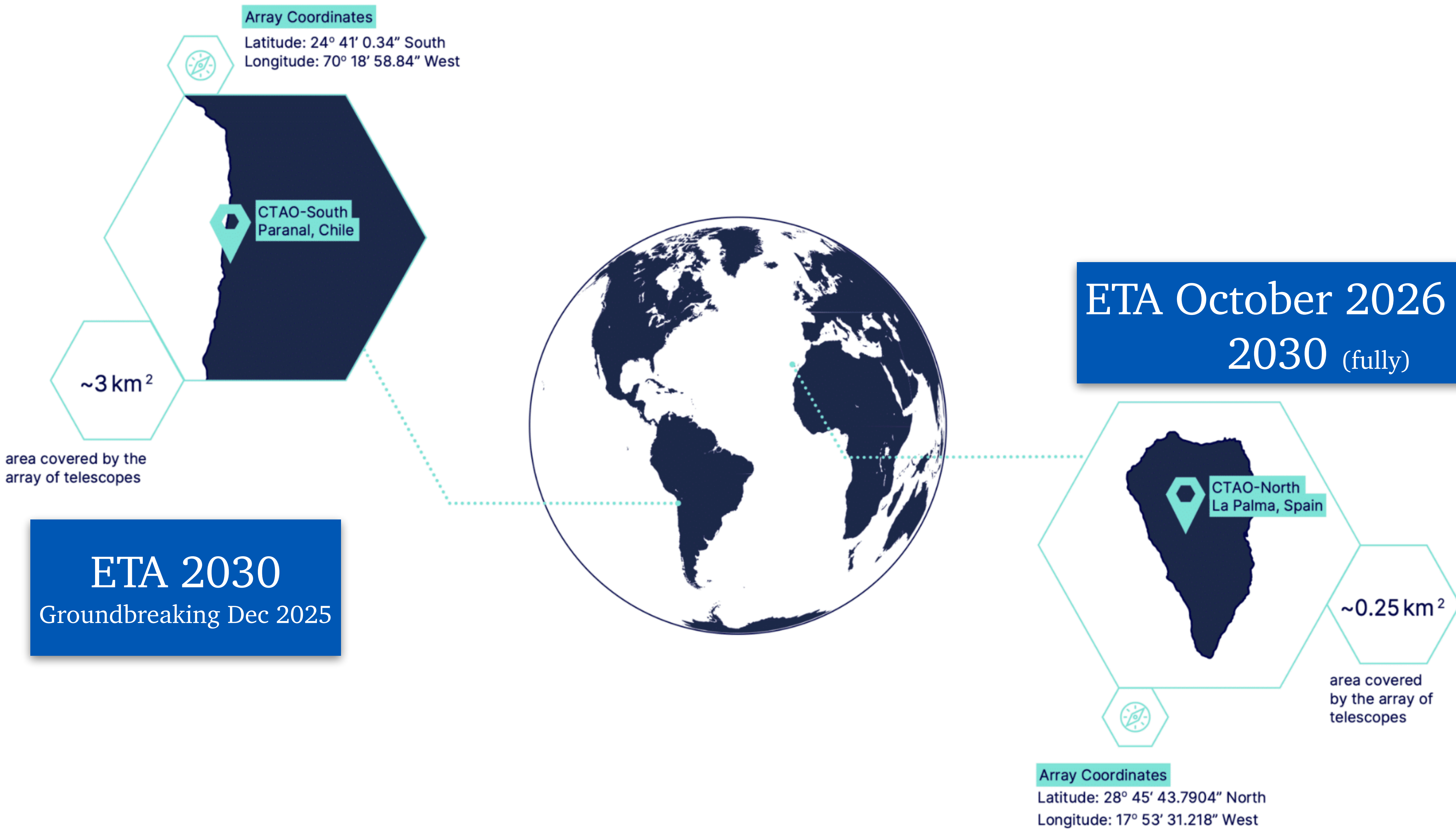

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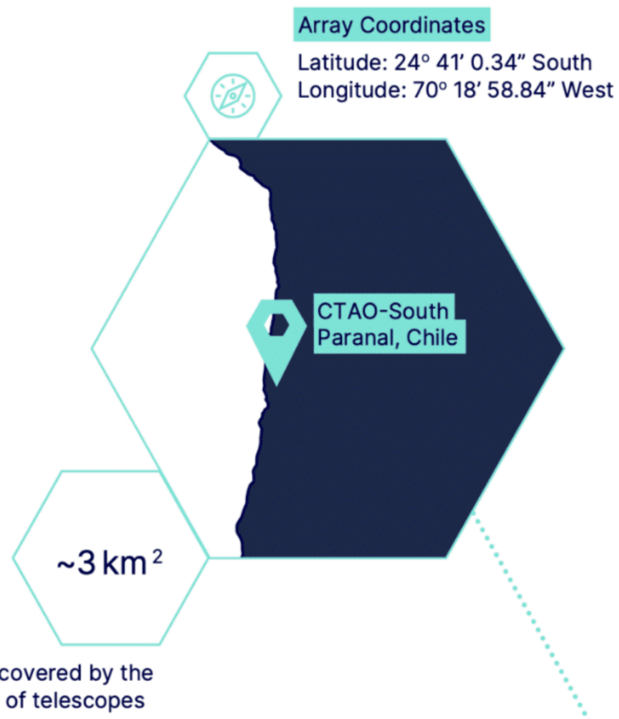

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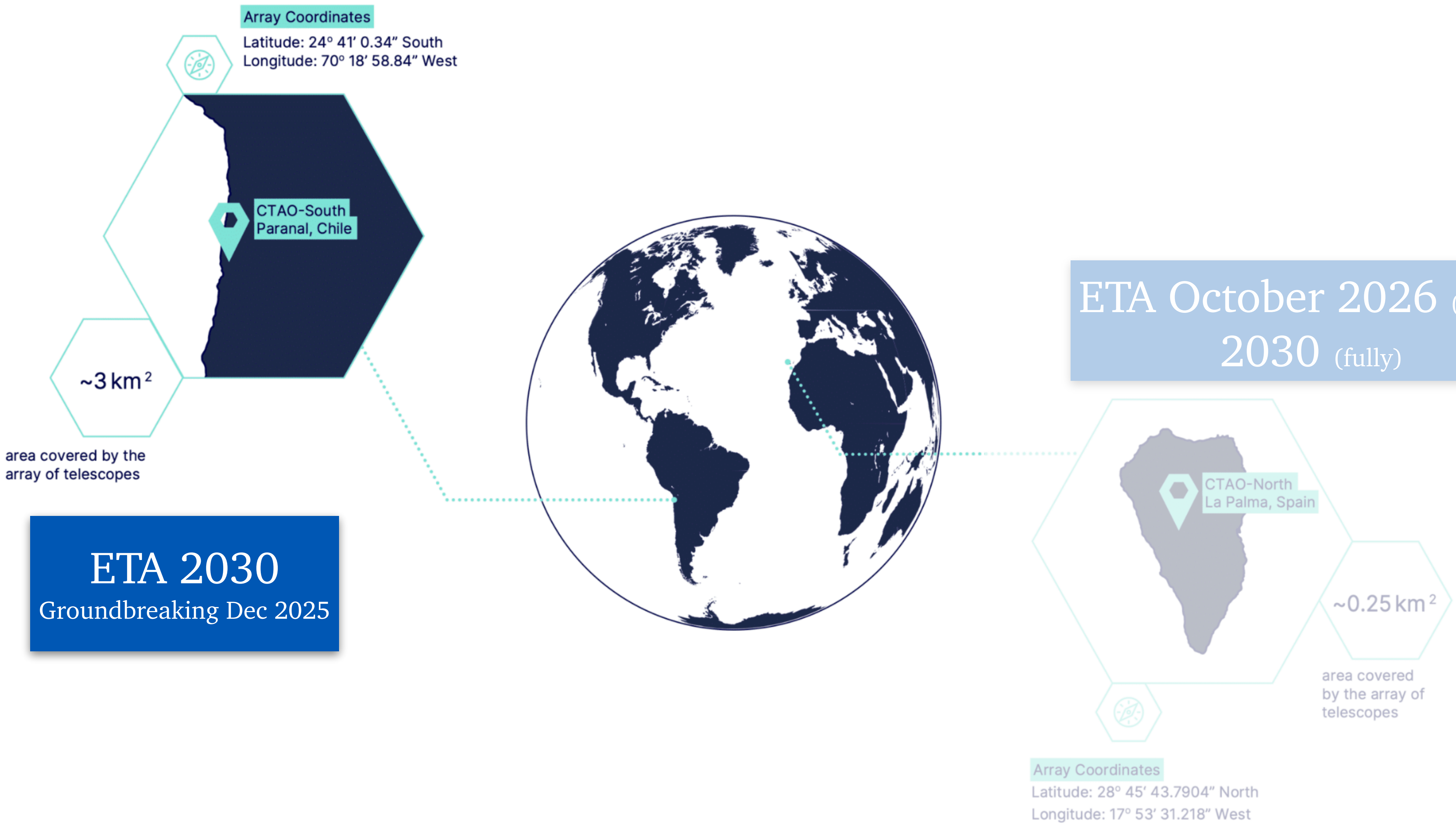

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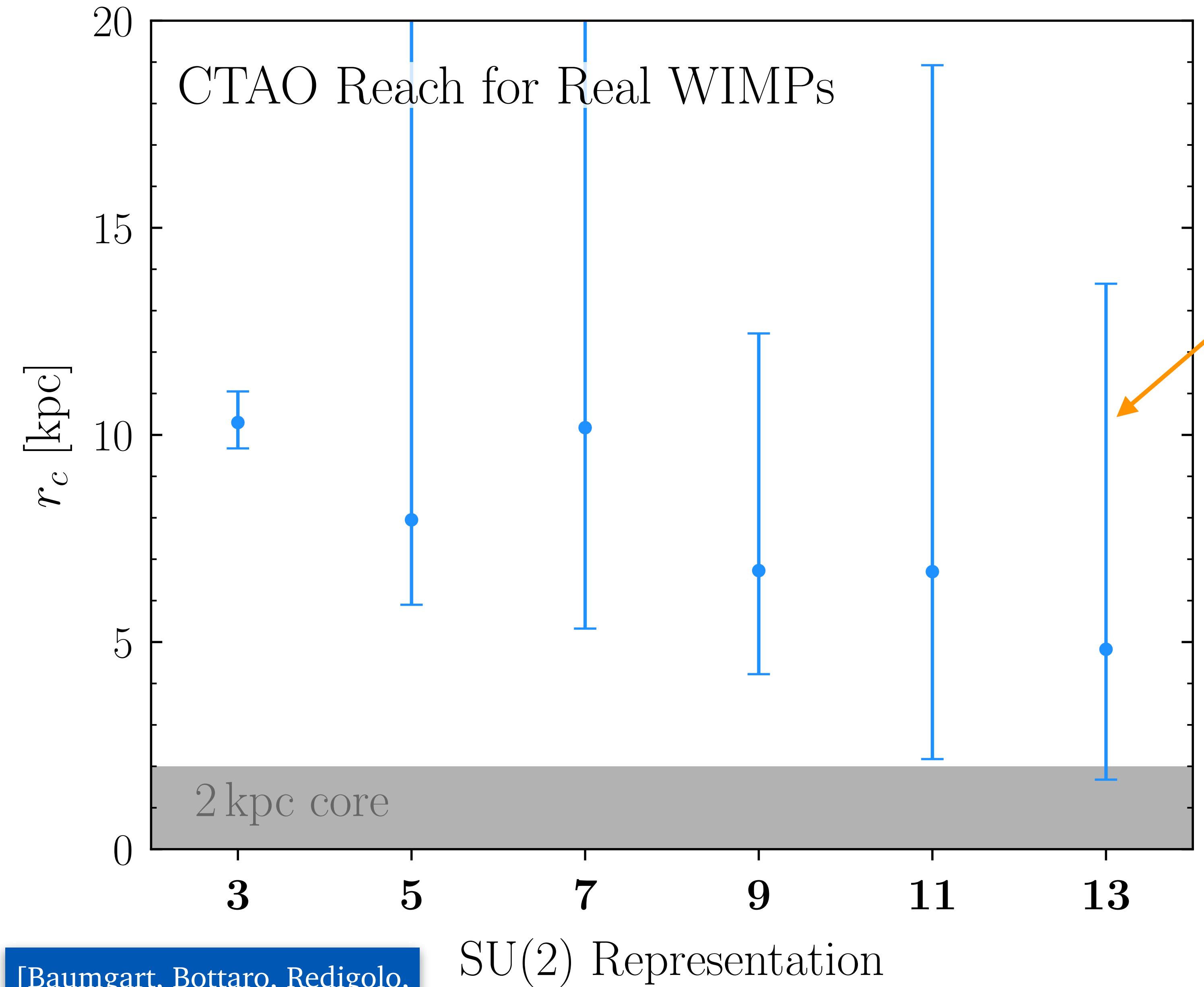
Discovery at CTAO

CTAO-South sensitivity to MDM in 2035



Points: central estimate of thermal mass
Band: strongest/lowest limit

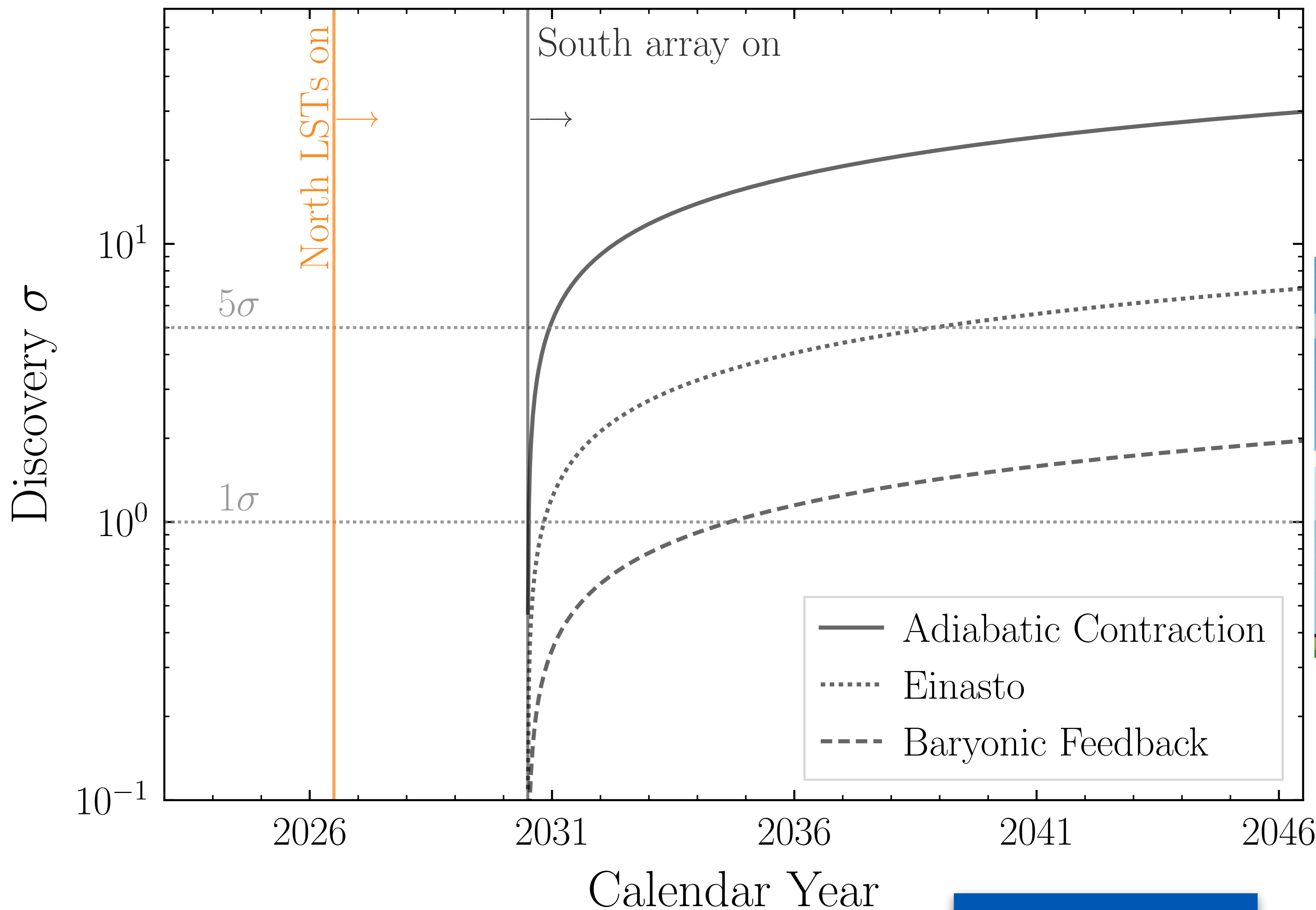
5 already excluded by Fermi?

Debated, cf. [Safdi, Xu 2025] & [Aghaie, Dondarini, Marino, Panci 2025]

[Baumgart, Bottaro, Redigolo, NLR, Slatyer 2026]

Discovery at CTAO

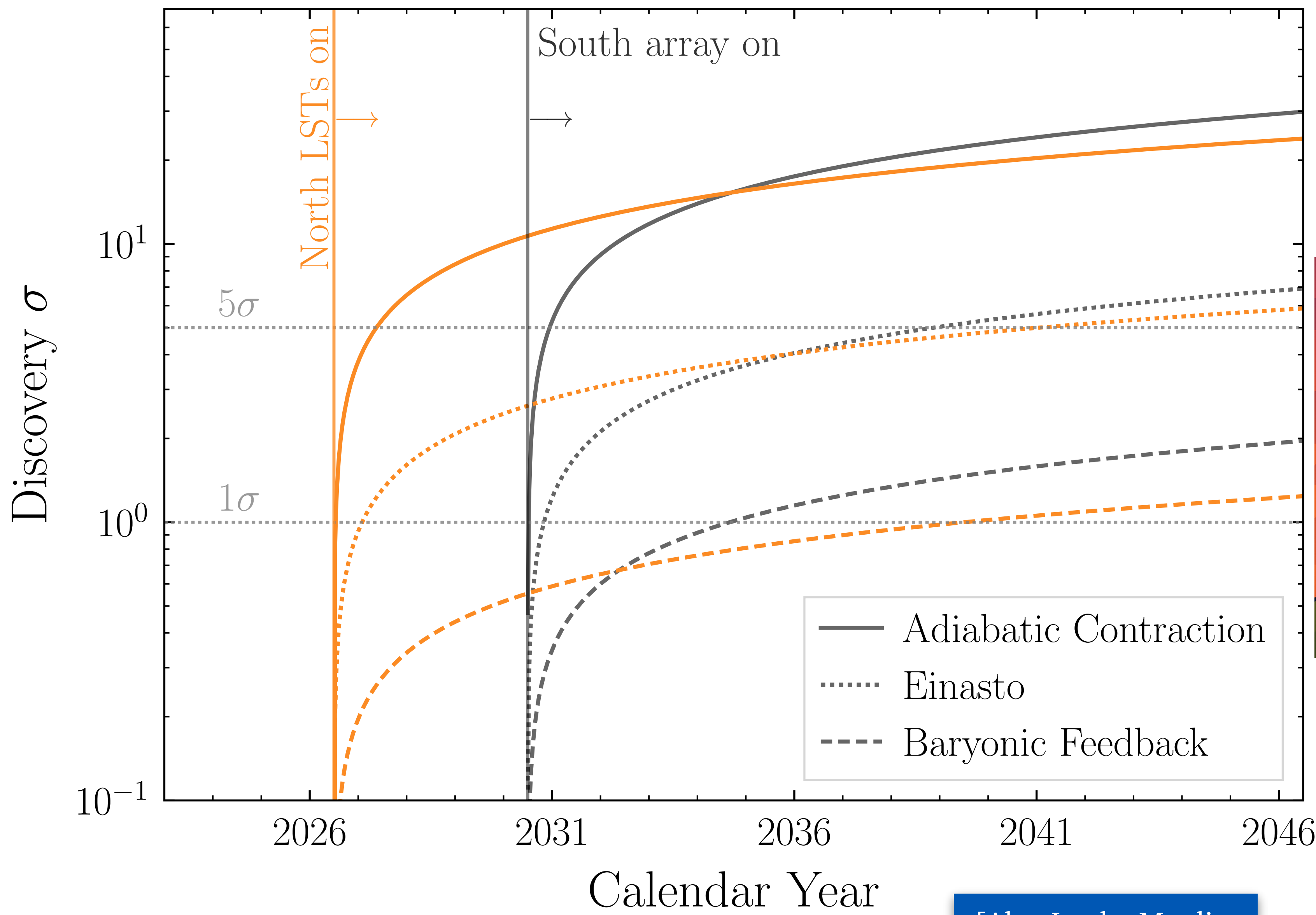
CTAO-South sensitivity to thermal higgsino

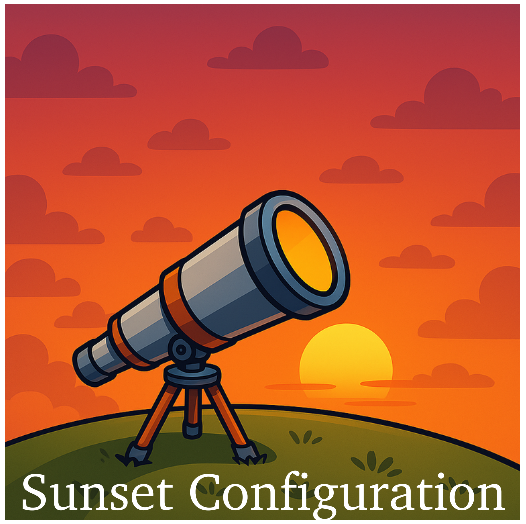


[Abe, Inada, Moulin, NLR, Safdi, Xu 2025]

Discovery at CTAO

CTAO-North sensitivity to thermal higgsino



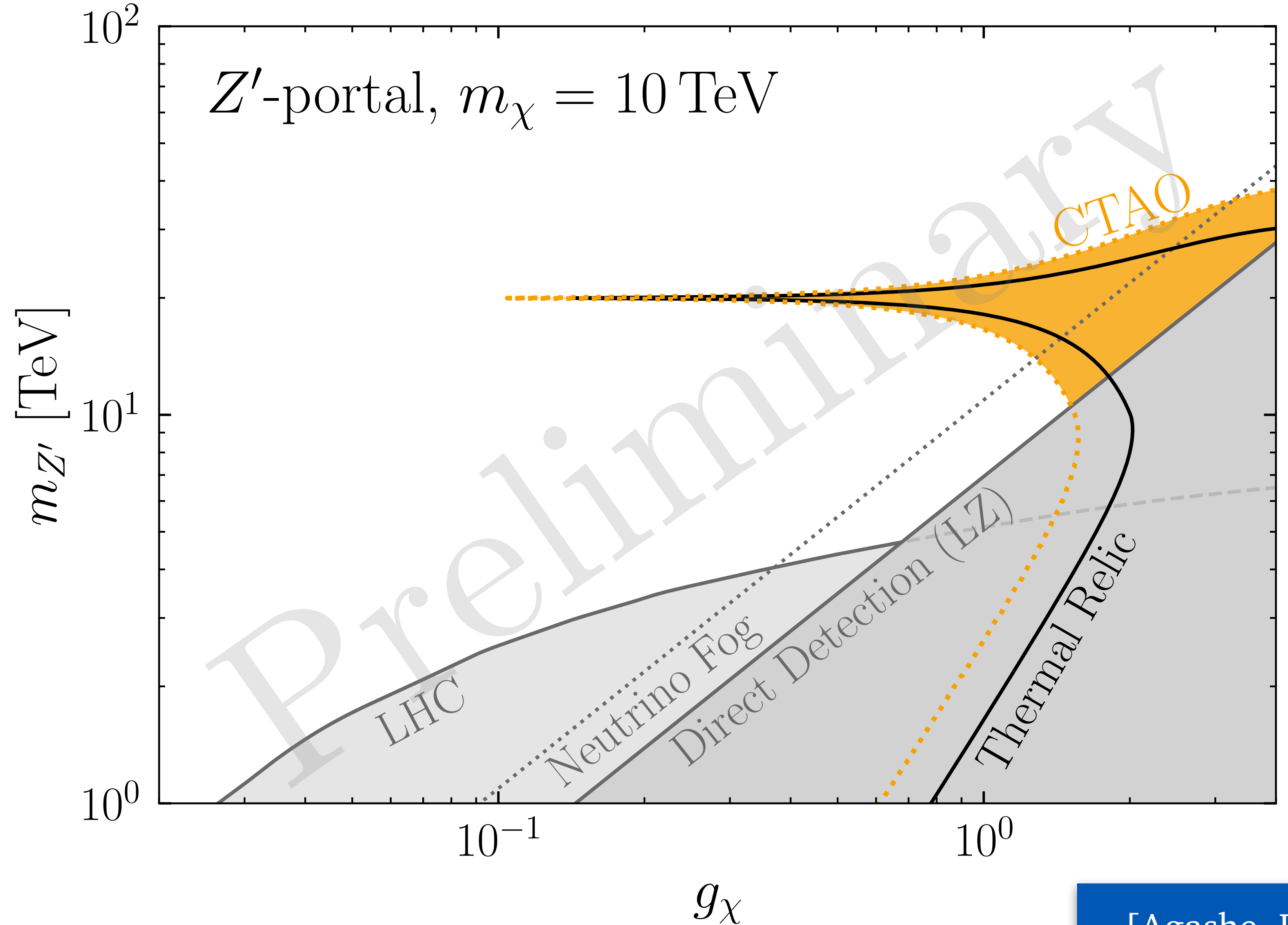


[Abe, Inada, Moulin, NLR, Safdi, Xu 2025]

Discovery at CTAO

CTAO is a strong probe of thermal TeV scale DM

Another example: extra dimensions



[Agashe, Banerjee, Buen-Abad, Panchal, NLR in prep.]

Conclusion

Indirect detection could be on the verge of discovery

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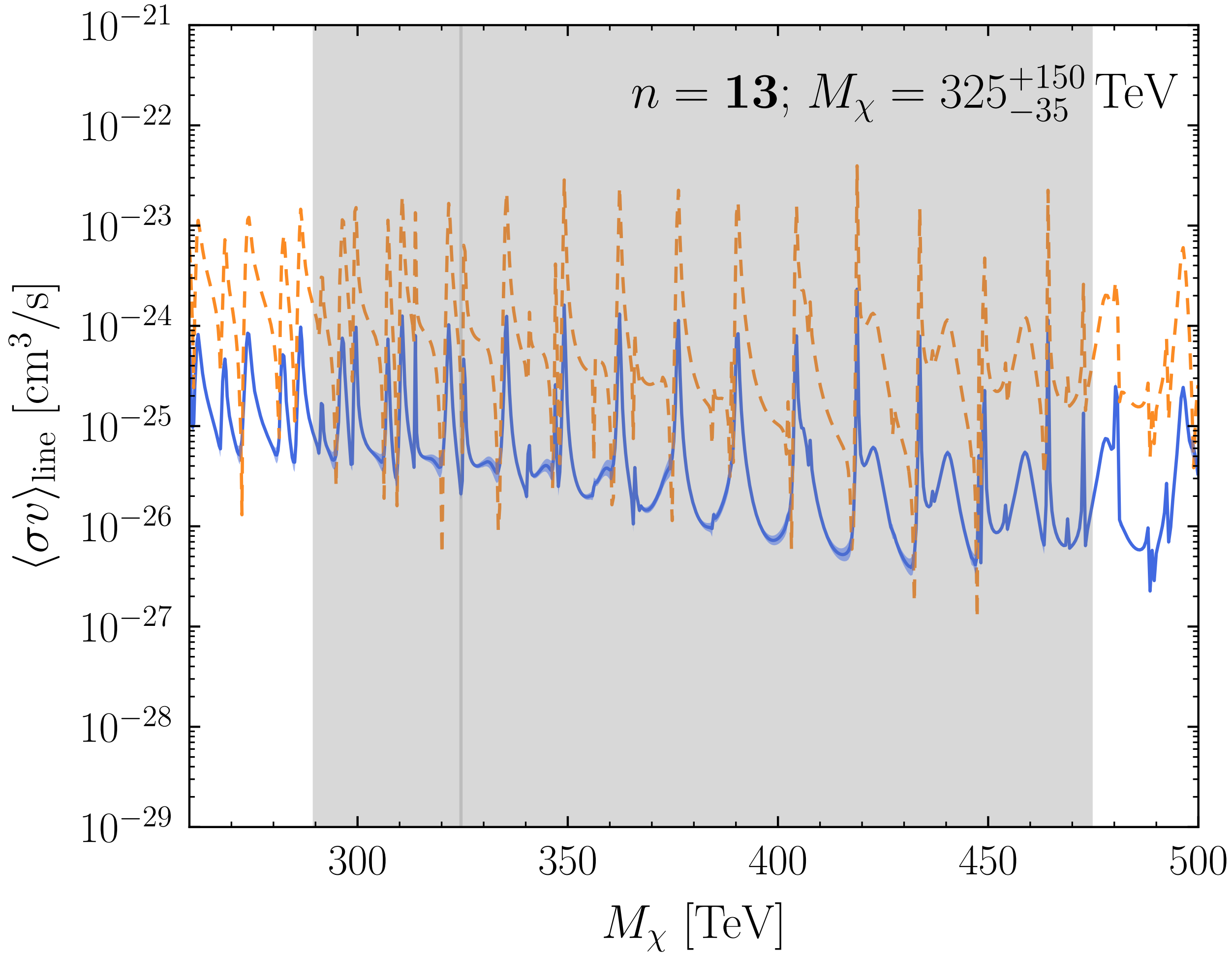
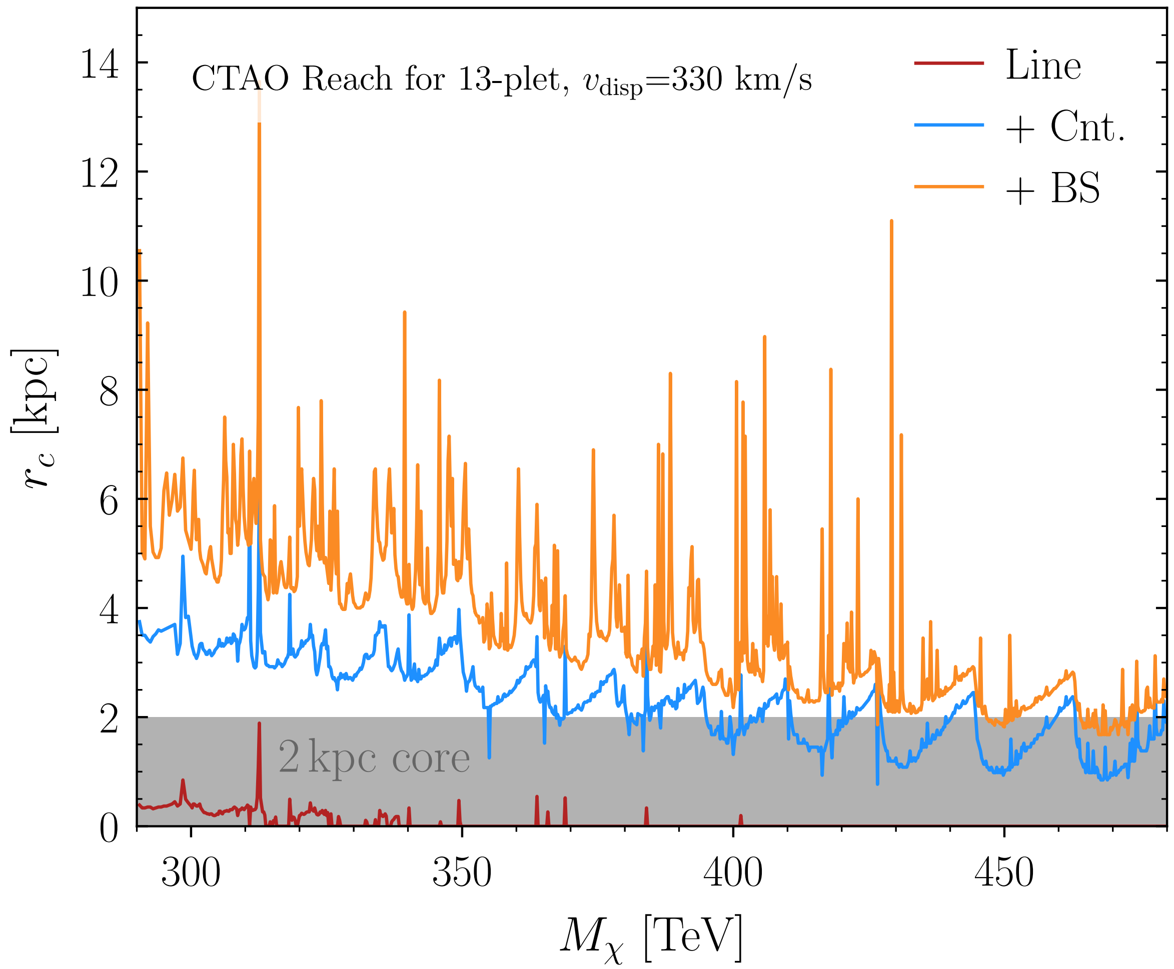
Backup Slides

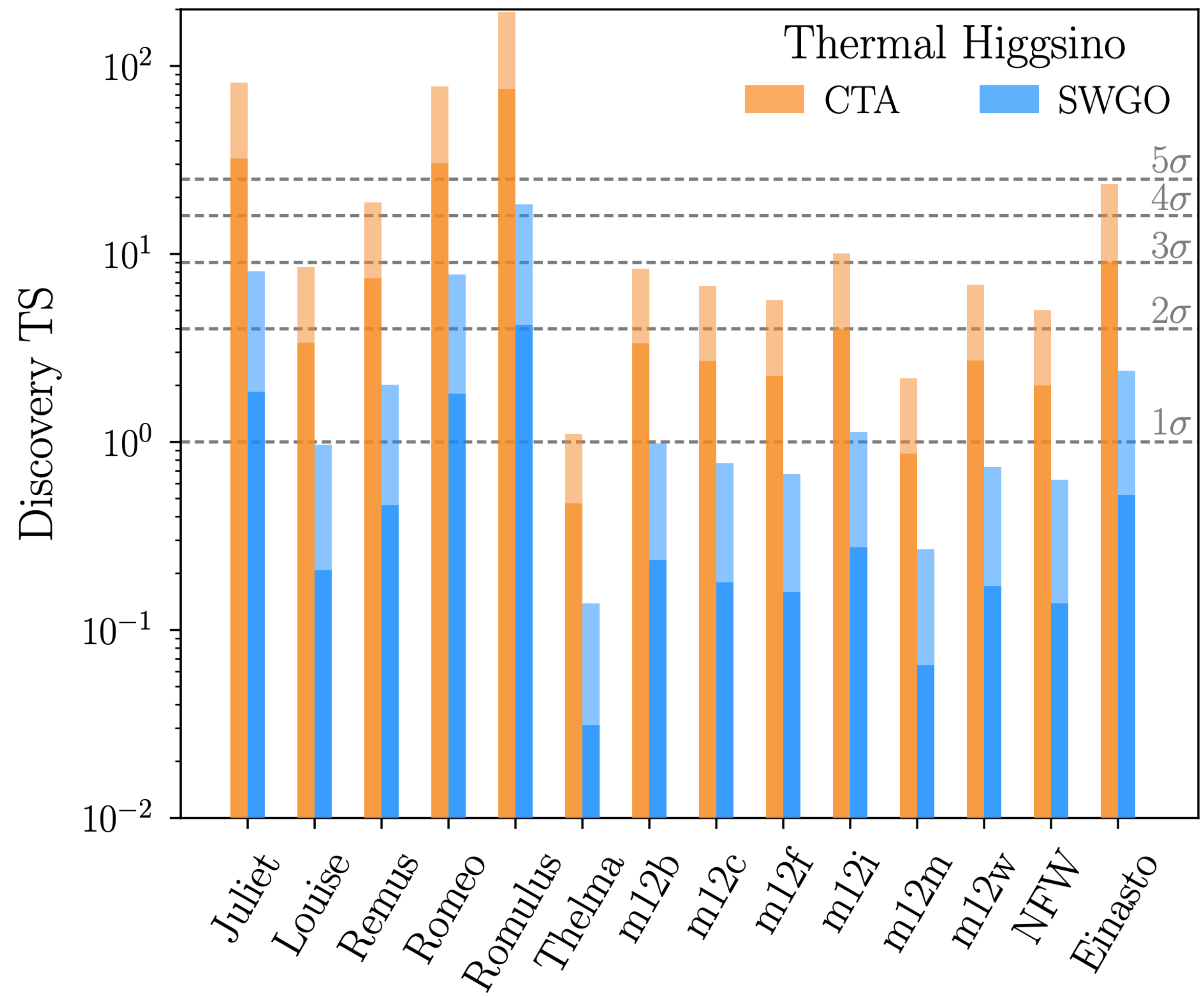
Tredecuplet





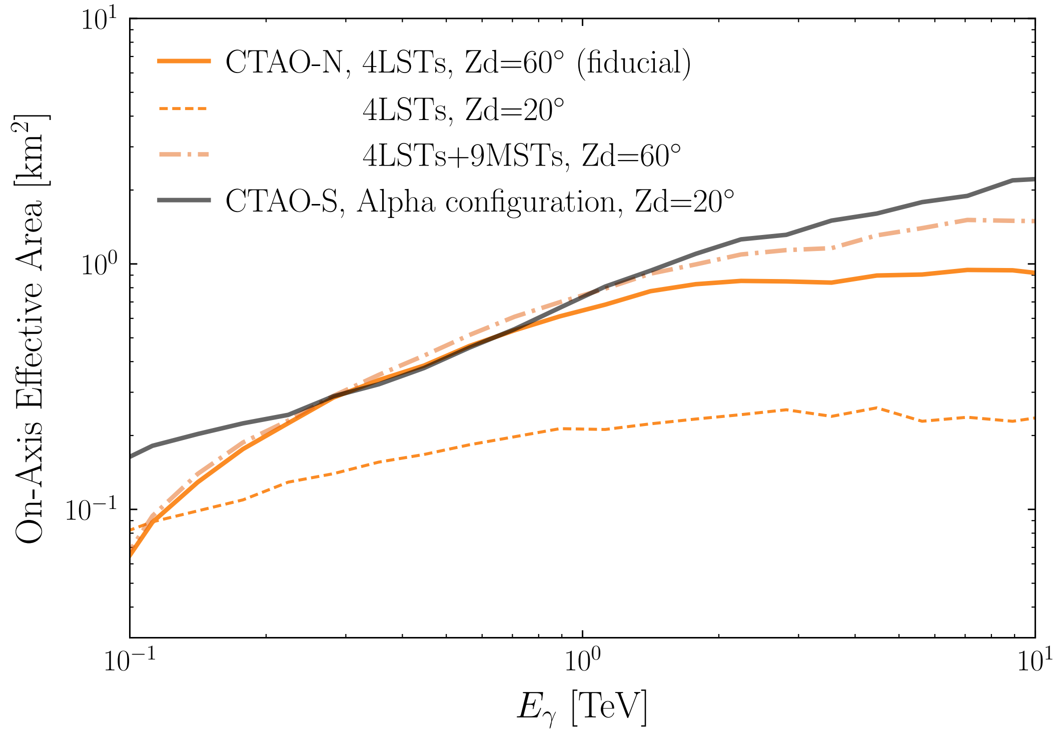
[Baumgart, Bottaro, Redigolo, NLR, Slatyer 2026]

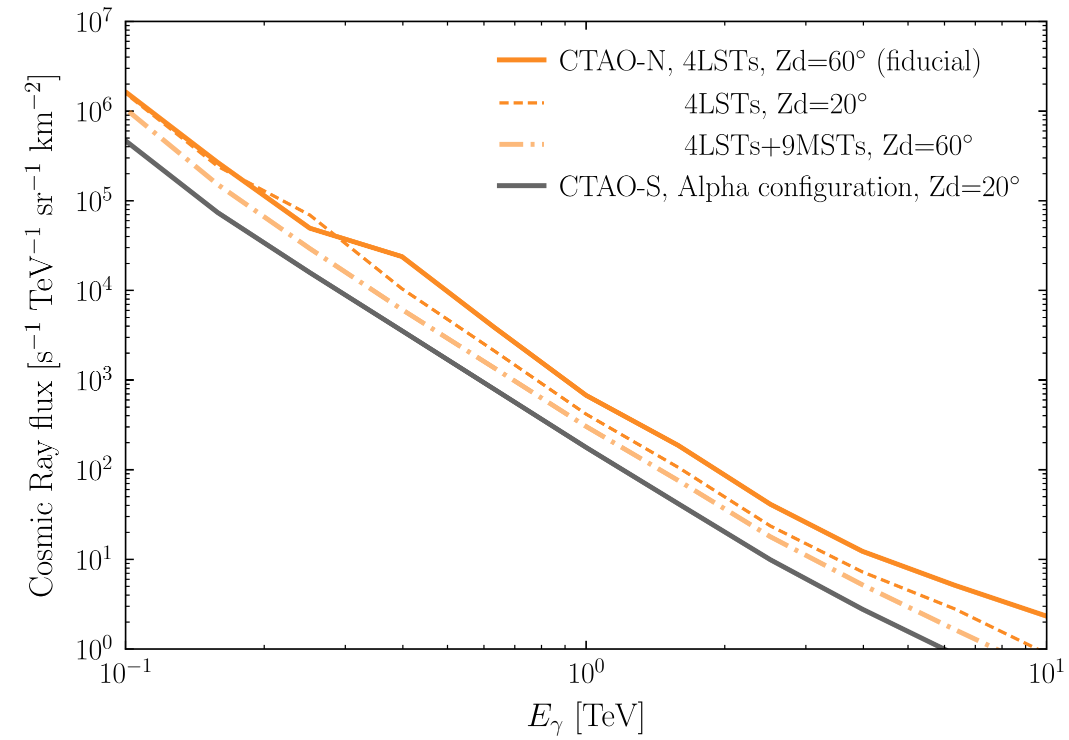
CTAO-South & SWGO

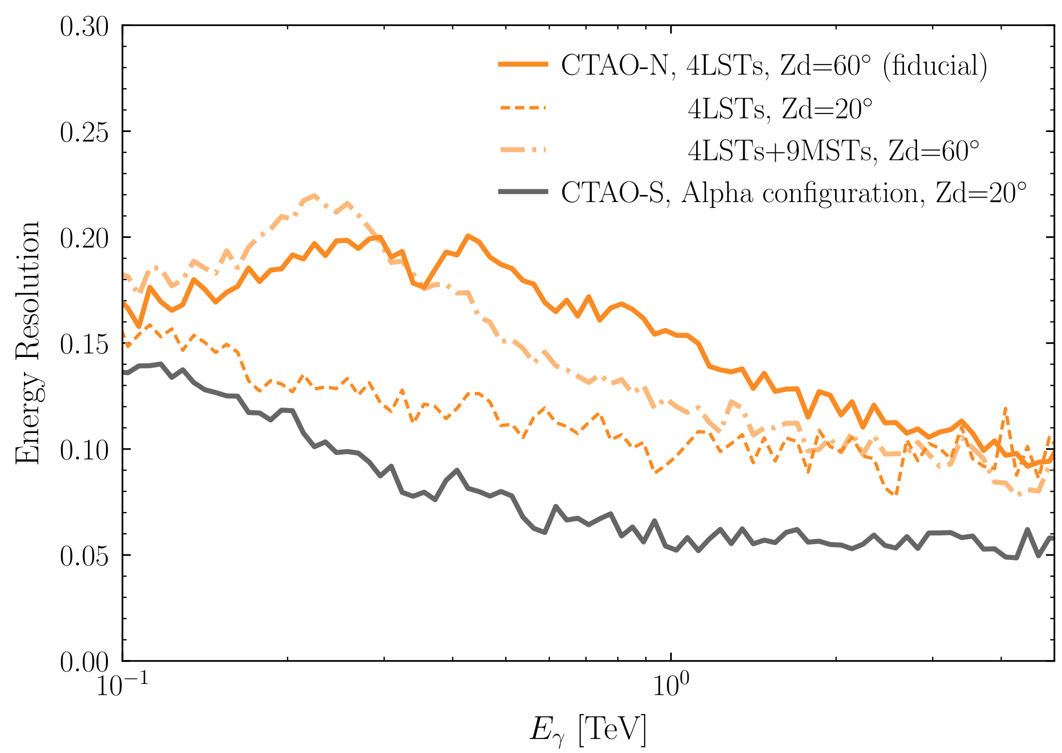


[NLR, Safdi, Xu 2024]

CTAO-South vs North



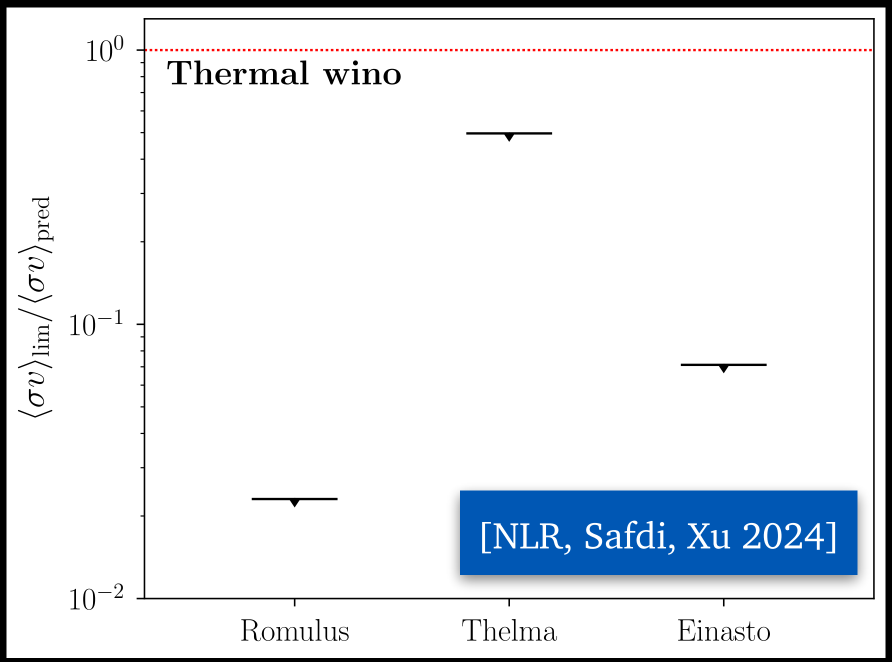




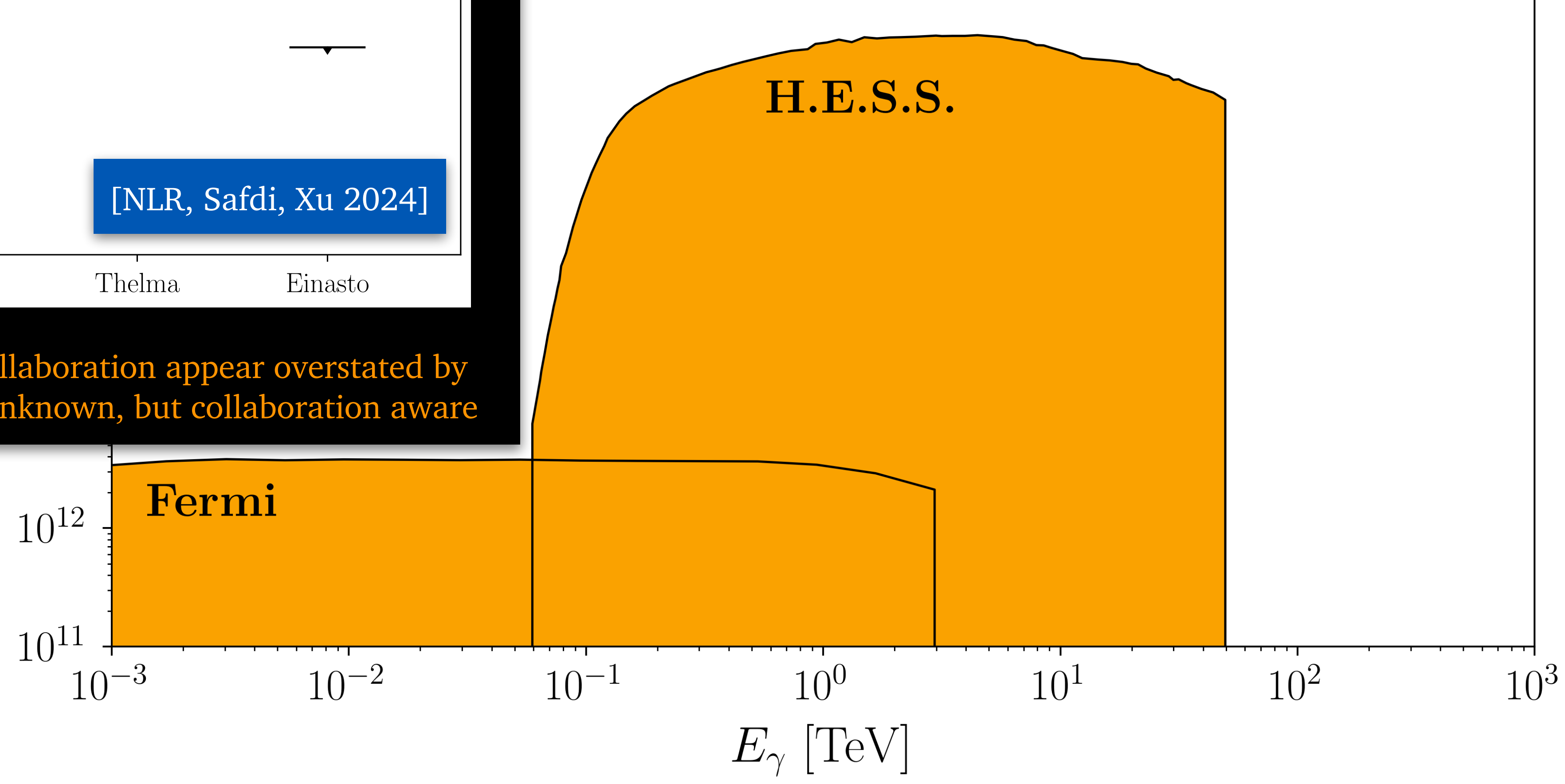
[Abe, Inada, Moulin, NLR, Safdi, Xu 2025]

Towards Discovery

HESS already excludes thermal wino

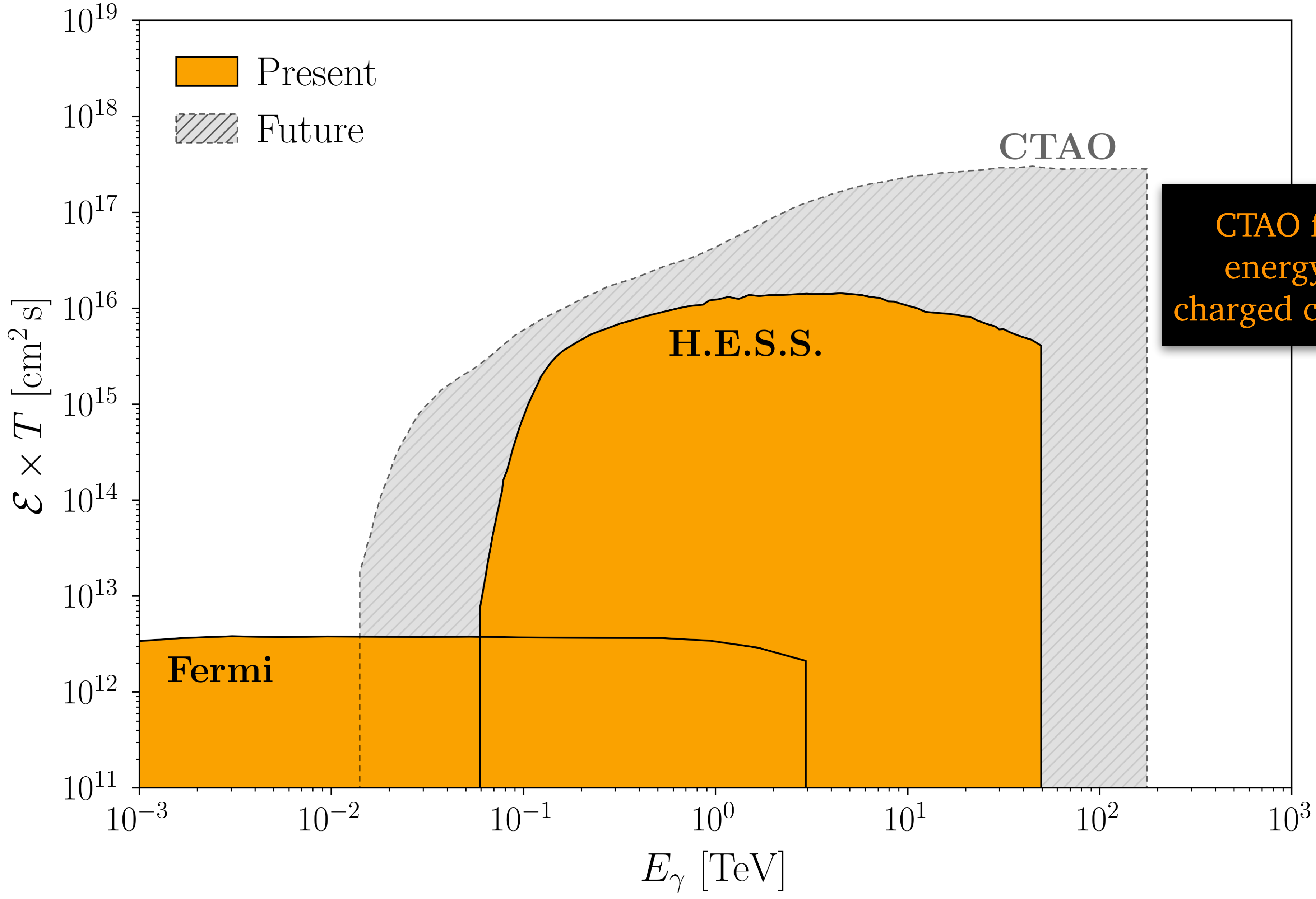


Limits from HESS Collaboration appear overstated by factor of ~8. Origin unknown, but collaboration aware



Based on review of present and future indirect detection instruments [Boddy, NLR+ 2022]

Towards Discovery

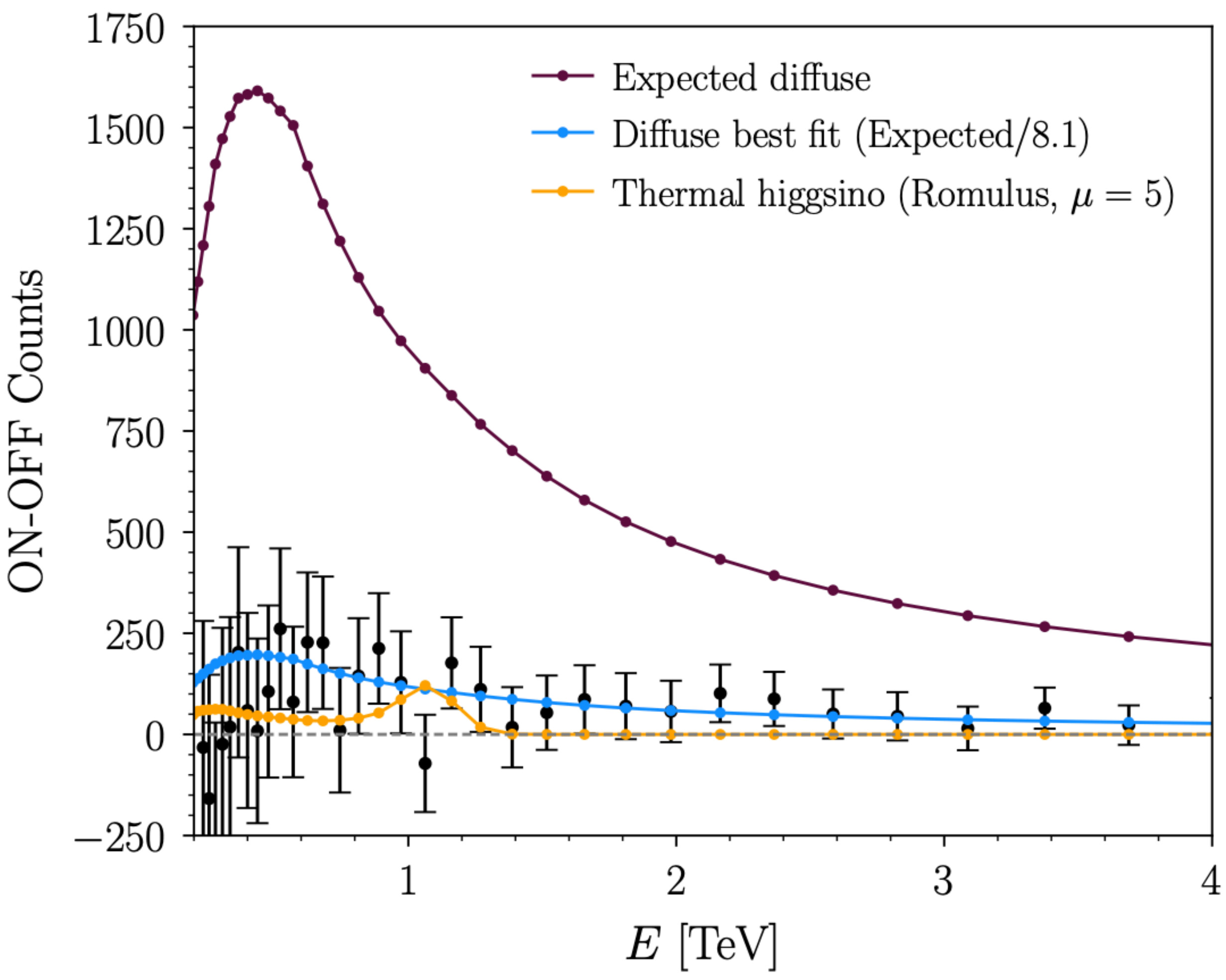


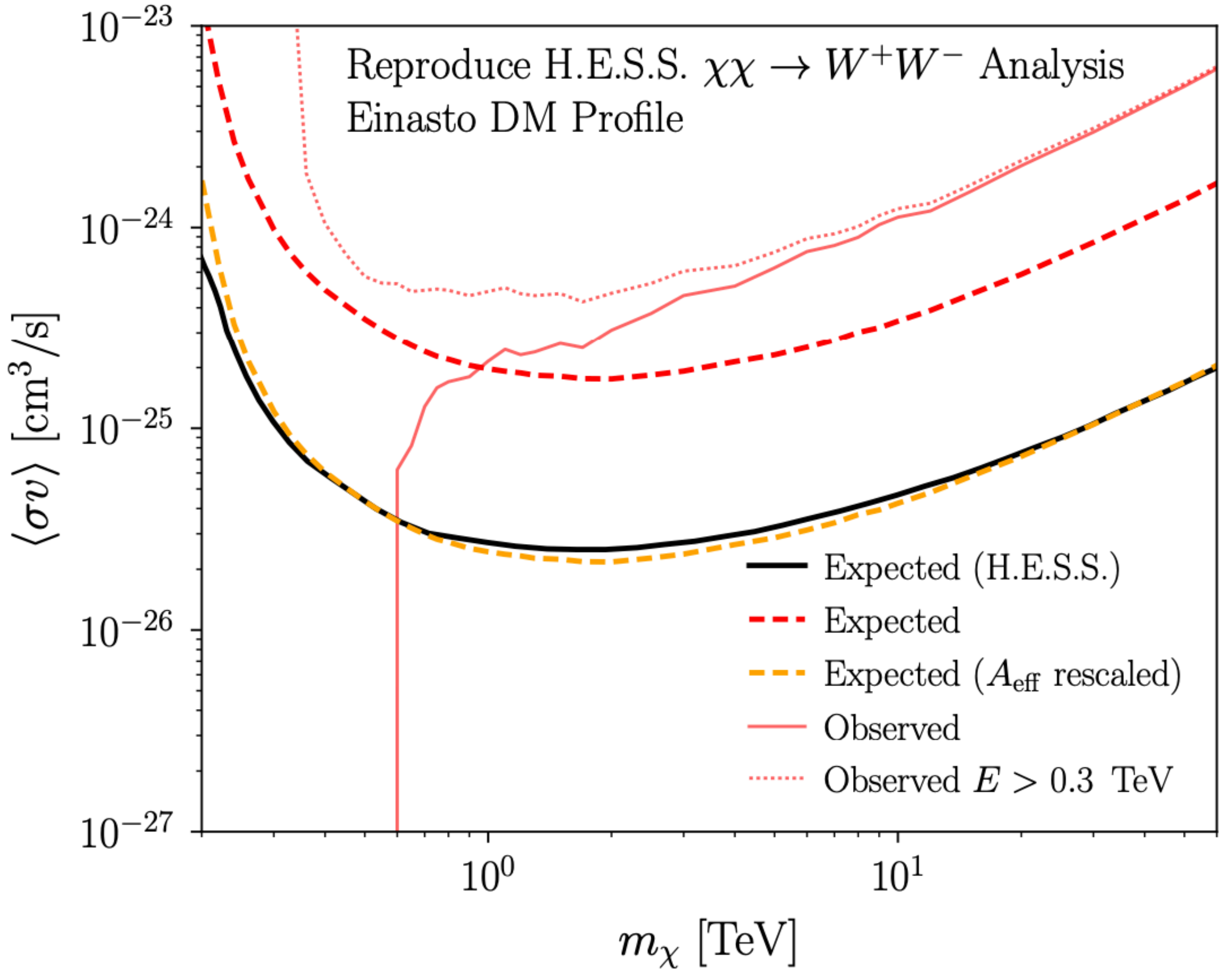
CTAO further improves energy resolution and charged cosmic-ray rejection

Based on review of present and future indirect detection instruments [Boddy, NLR+ 2022]

An Issue with HESS?

HESS data appears inconsistent with expected diffuse emission

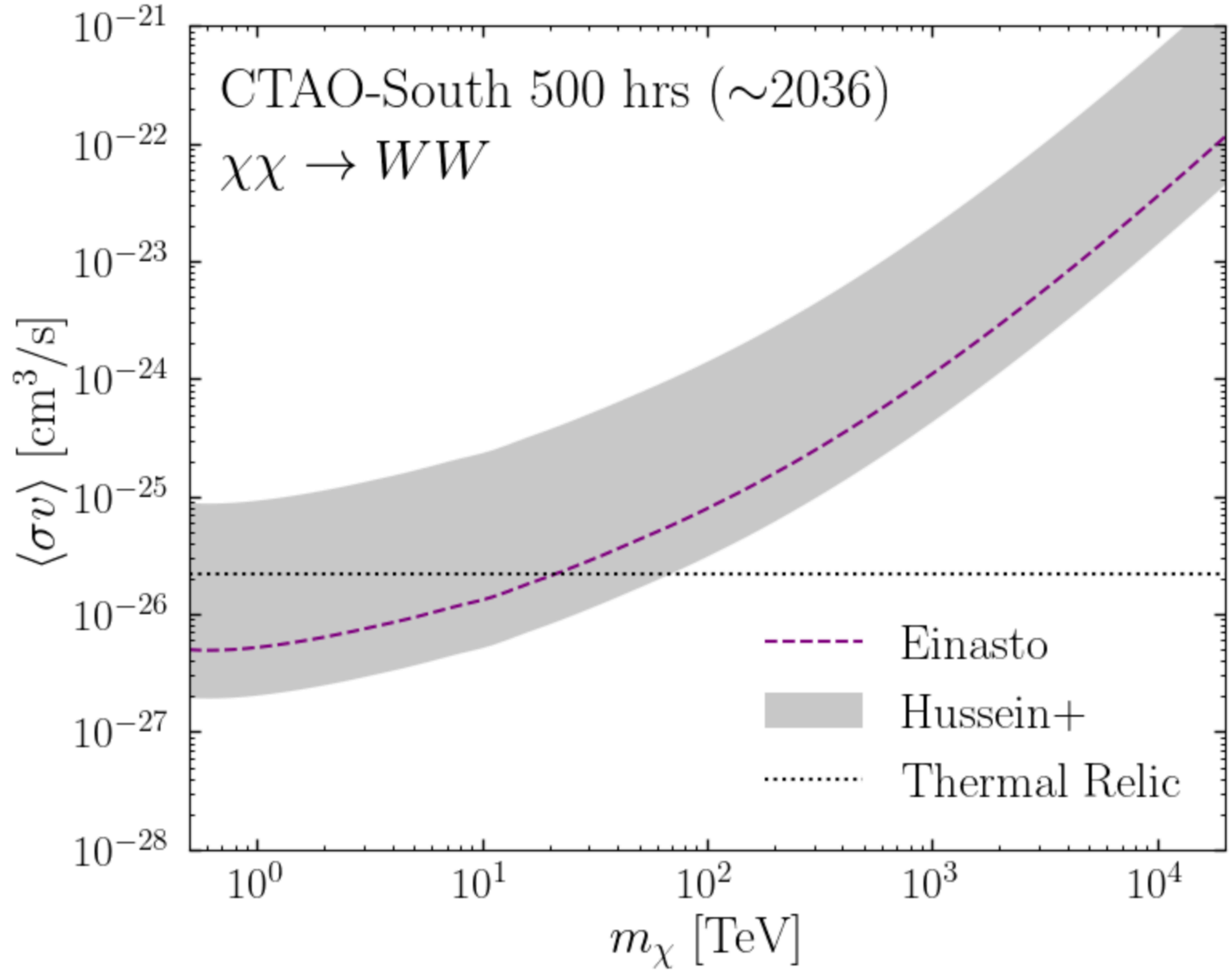




[NLR, Safdi, Xu 2024]

Generic CTAO Sensitivity

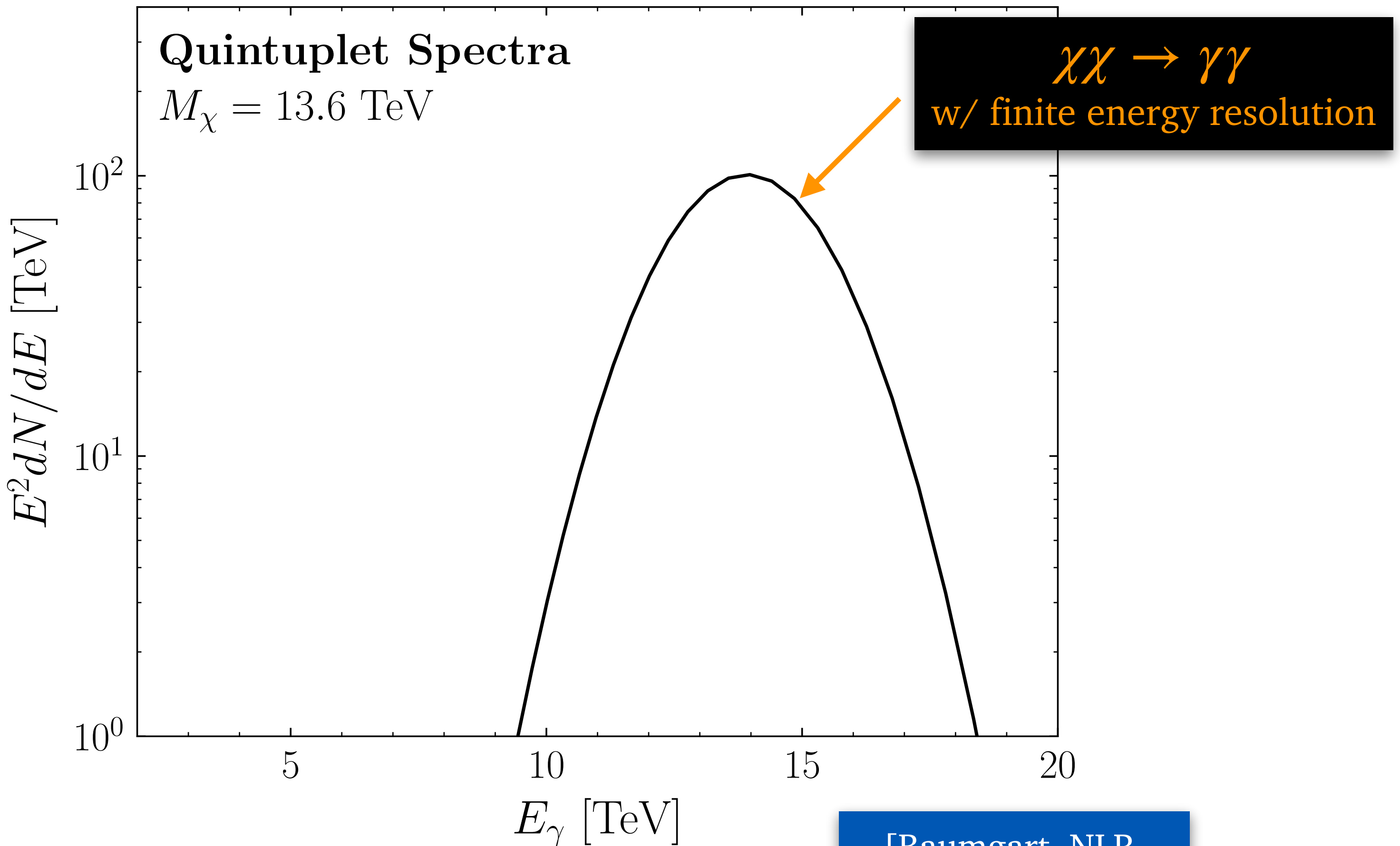
CTAO-South sensitivity w/ 5 years of data



EFT Calculations

Dark matter annihilation flux

$$\frac{d\Phi}{dE} = \underbrace{\frac{\langle \sigma v \rangle}{8\pi M_\chi^2} \frac{dN}{dE}}_{\text{Particle Physics}} \times \int ds\, \rho_{\rm DM}^2(s)$$



[Baumgart, NLR, Slatyer, Vaidya 2024]

EFT Calculations

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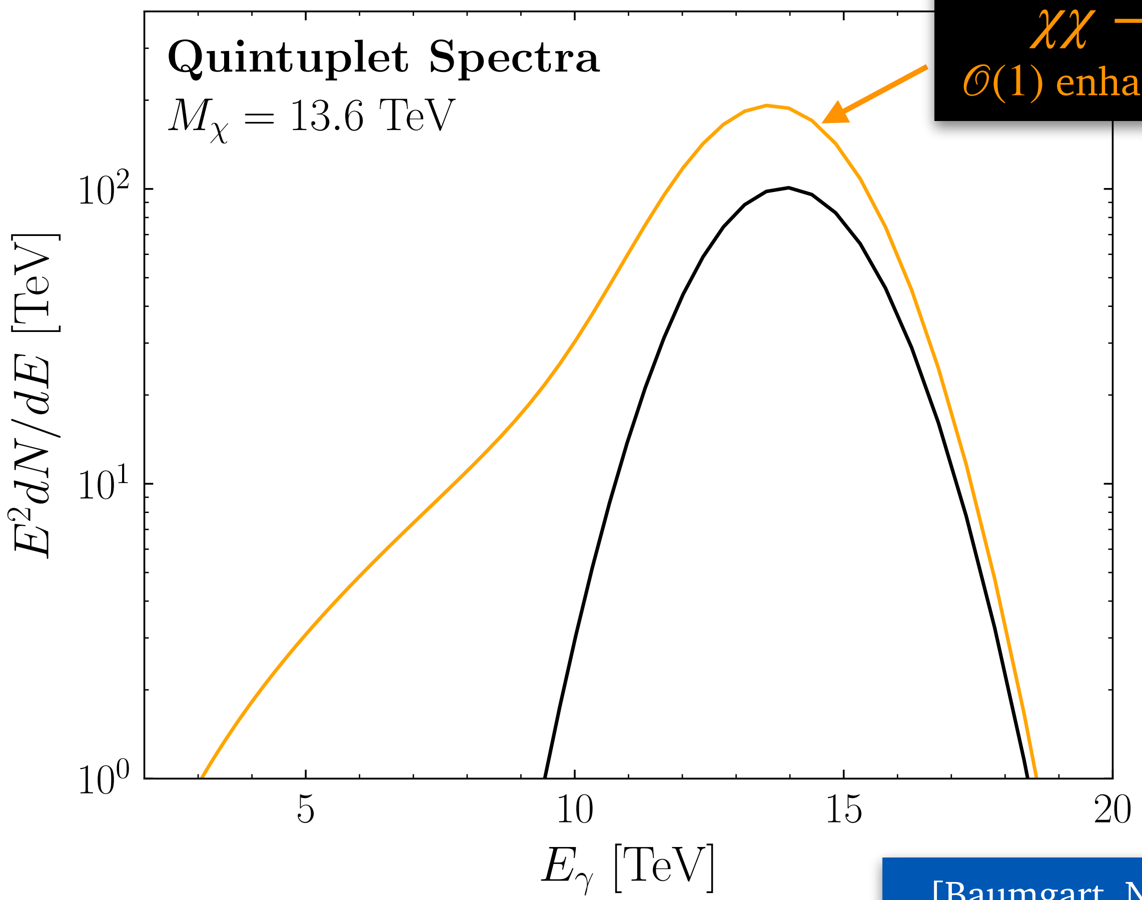
Particle Physics



$\chi\chi \to \gamma + \text{jet}$
$\mathcal{O}(1)$ enhancement to line

[Baumgart, NLR, Slatyer, Vaidya 2024]

EFT Calculations

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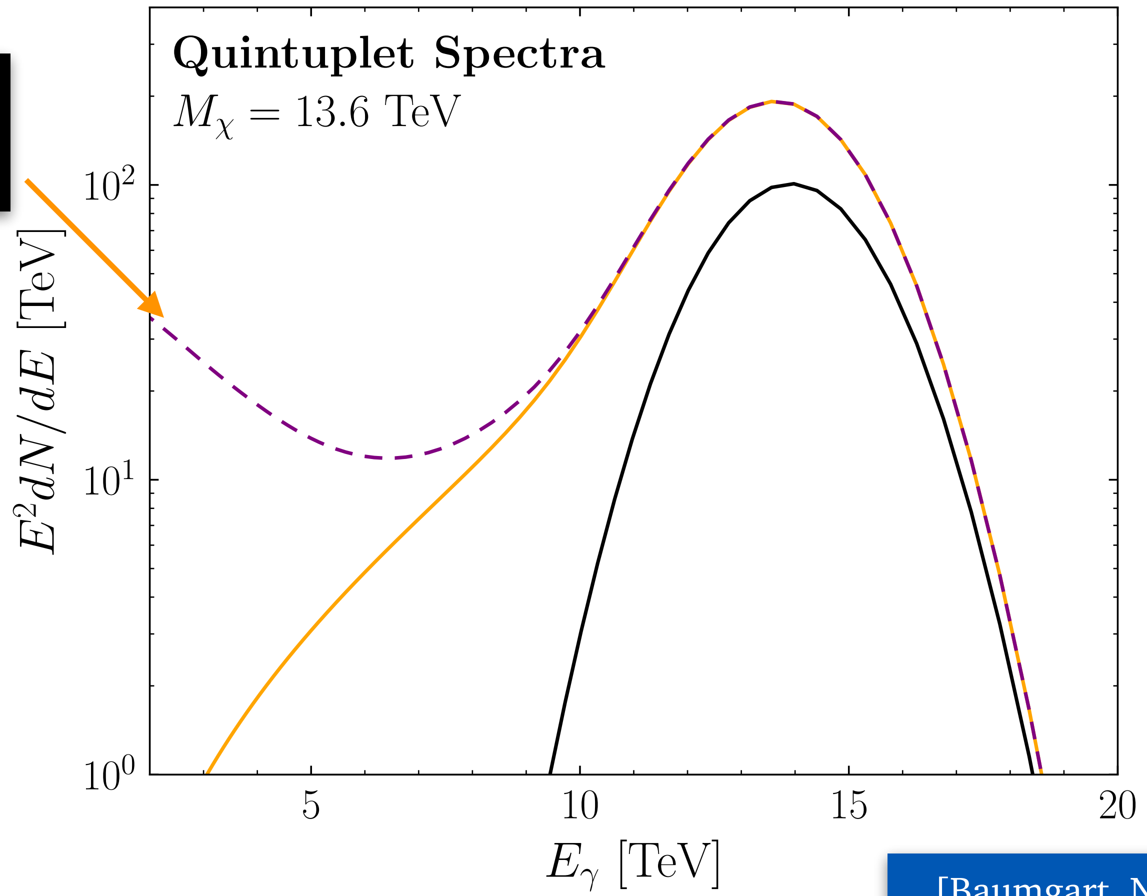
$\chi\chi \to WW, ZZ, \mathrm{BS}$
Dominates at low energies



[Baumgart, NLR, Slatyer, Vaidya 2024]

EFT Calculations

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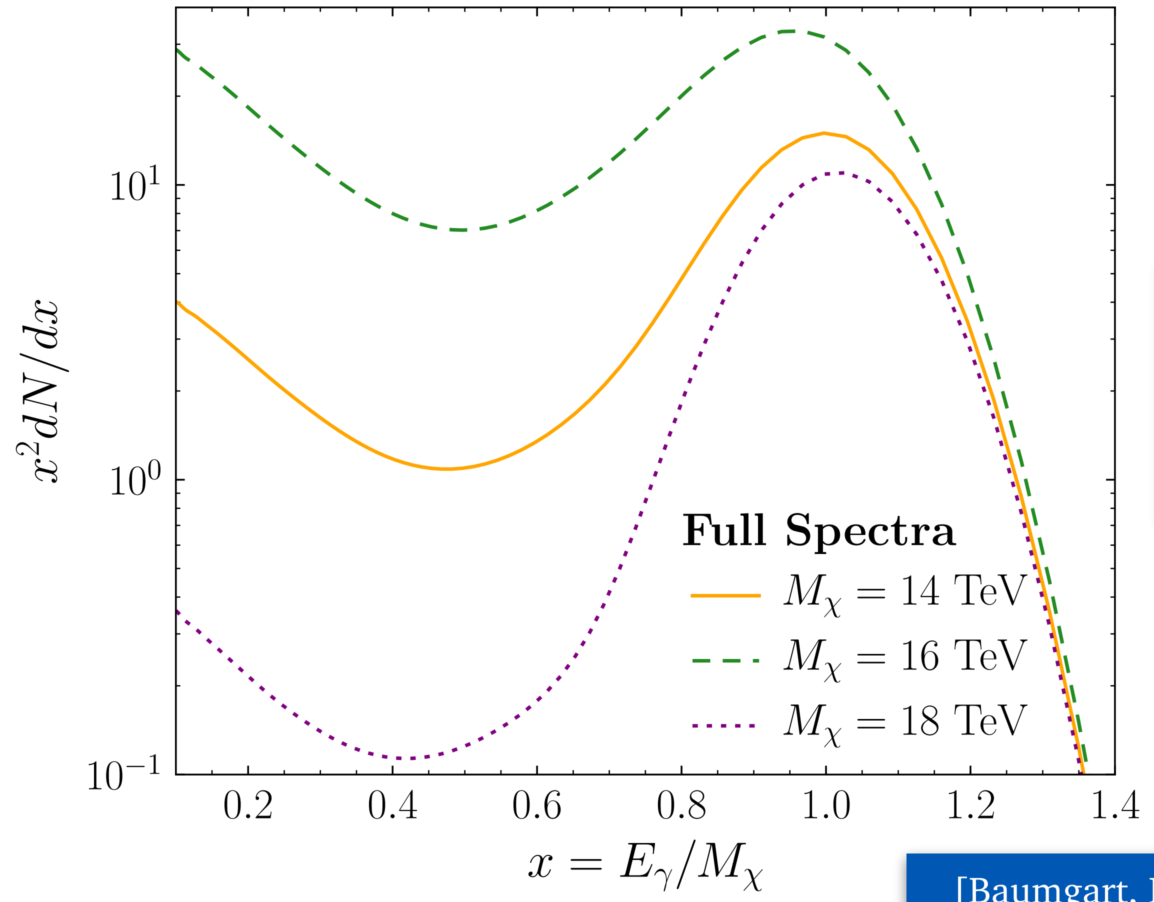


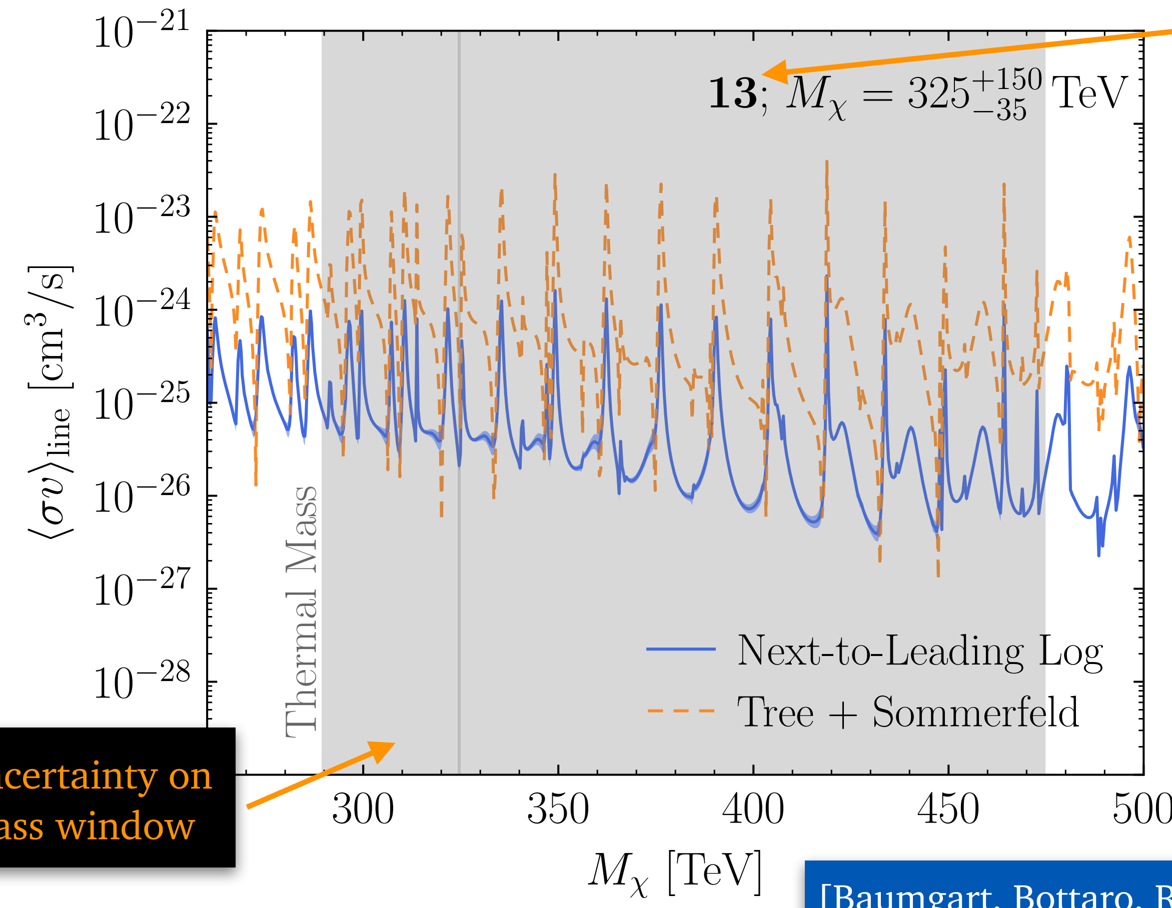
Novel effect for higher reps: Sommerfeld channels interfere ⇒ spectrum depends strongly on mass

[Baumgart, NLR, Slatyer, Vaidya 2024]

EFT Calculations

Dark matter annihilation flux

$$\frac{d\Phi}{dE} = \underbrace{\frac{\langle \sigma v \rangle}{8\pi M_\chi^2} \frac{dN}{dE}}_{\text{Particle Physics}} \times \int ds\, \rho_{\rm DM}^2(s)$$



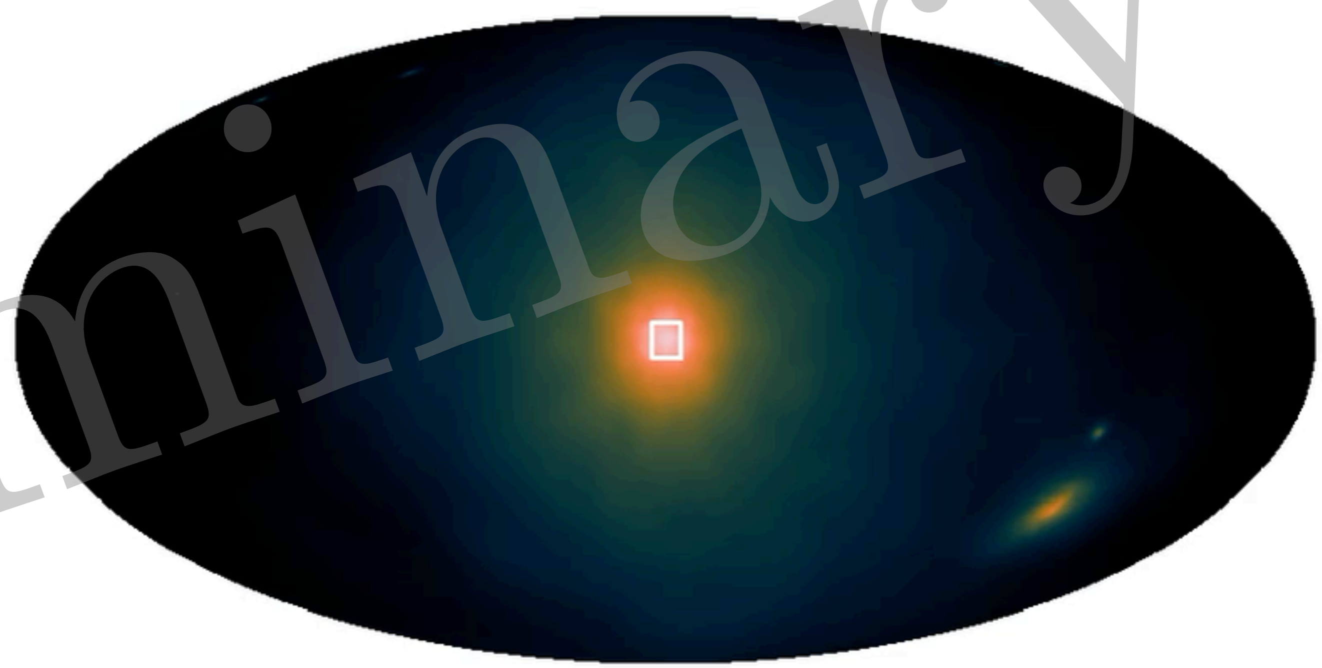
Tredecuplet
$(\chi^{6+}, \ldots, \chi^0, \ldots, \chi^{6-})$

Large theory uncertainty on the thermal mass window

[Baumgart, Bottaro, Redigolo, NLR, Slatyer 2026]

Indirect Detection

From 24 to 1,000 Milky Way like halos



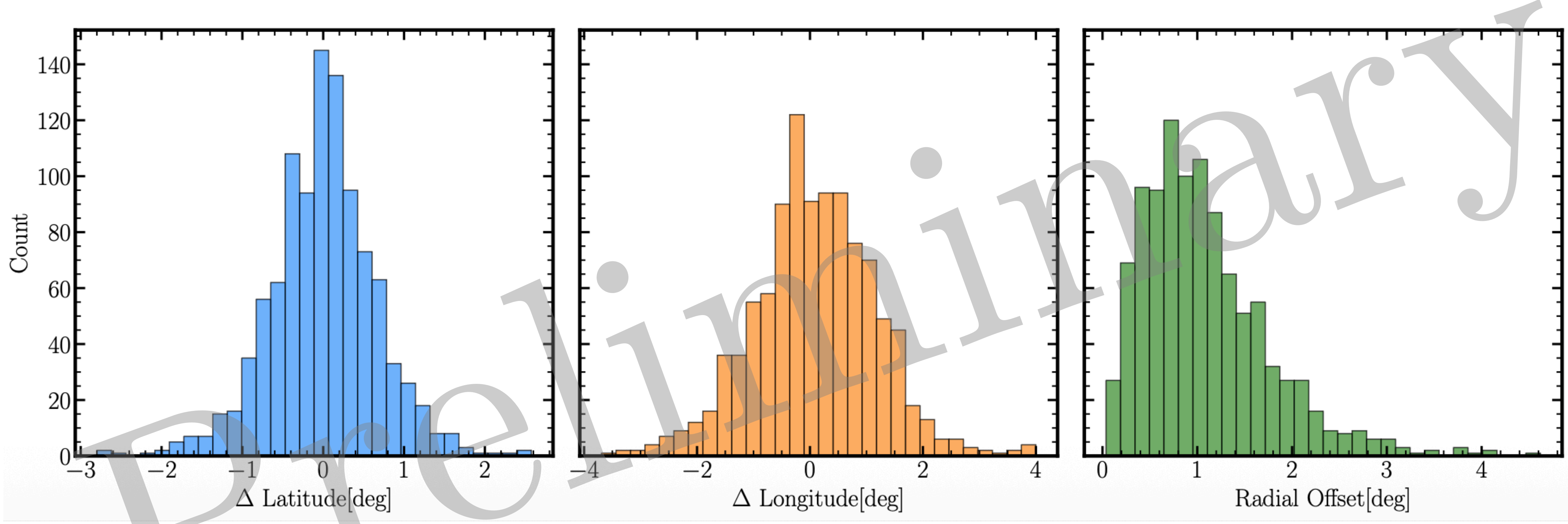
Preliminary

Inner 8x8 degrees
Rotation around the solar circle

[DREAMS, Garcia, NLR in prep.]

Indirect Detection

From 24 to 1,000 Milky Way like halos



Generically off-center
Elongated along the plane

[DREAMS, Garcia, NLR in prep.]