



Discovering Dark Matter at CTA0



Motivation

The thermal WIMP remains deeply motivated and *discoverable*

Every chance of a discovery within the next decade

Motivation

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

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

Motivation

Top down: at low energies, can find

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

Assuming other states $\sim$ decoupled similarly predictive

Higgsino (1, 2, 1/2) and **wino** (1, 3, 0) can emerge as DM in split SUSY scenarios

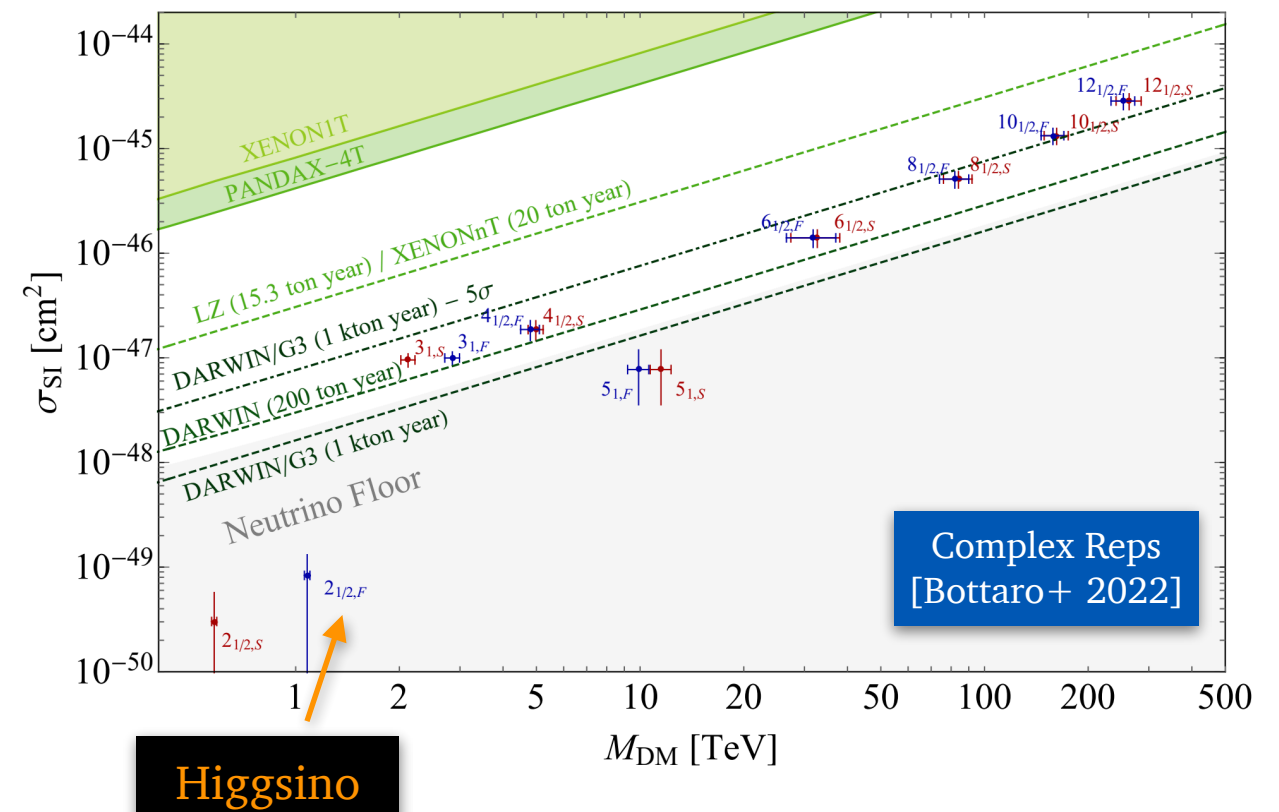
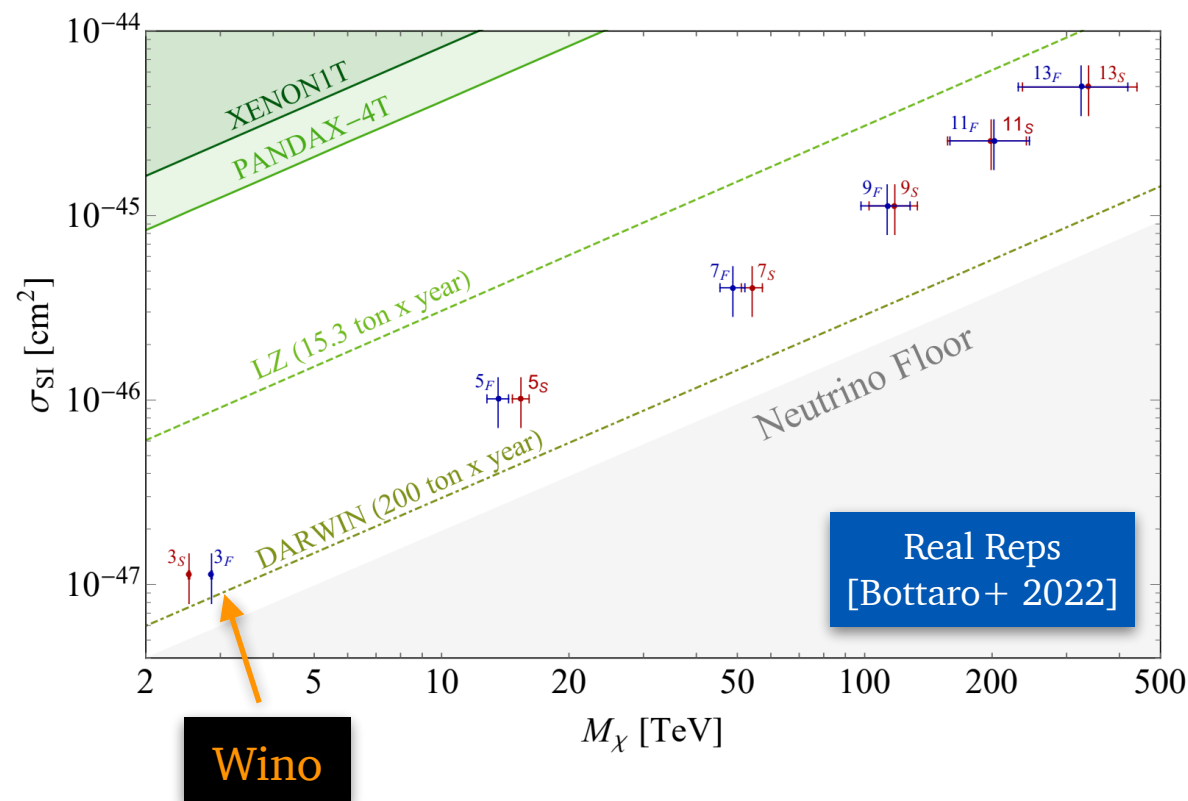
[Wells 2003], [Giudice, Romanino 2004],
[Arkani-Hamed, Dimopoulos 2005],
[Hall, Nomura 2012], ...

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]

Benchmark for Direct Detection

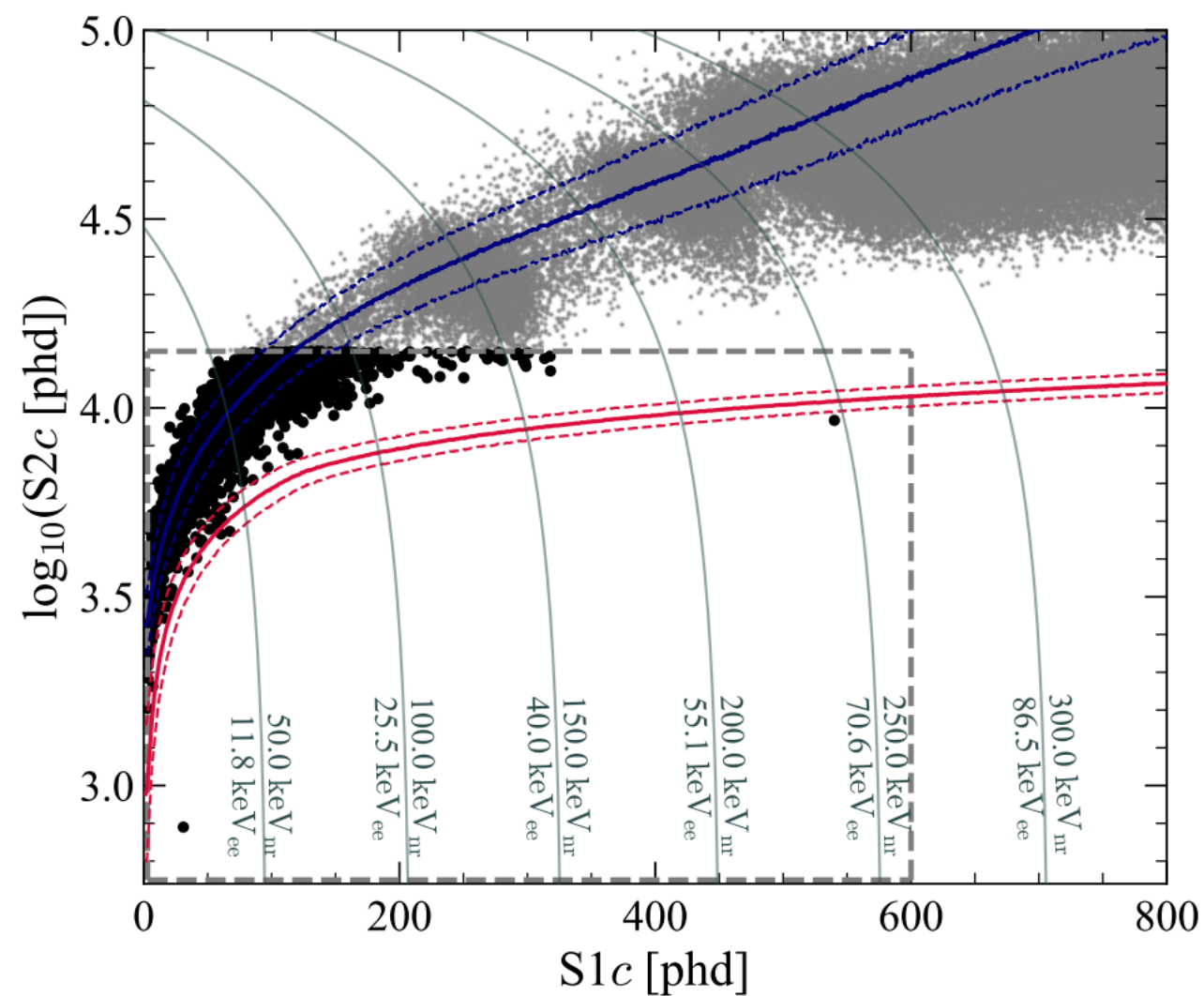
Most MDM models above neutrino floor
for elastic scattering



LZ sensitivity has already been achieved [2410.17036]

Inelastic Scattering

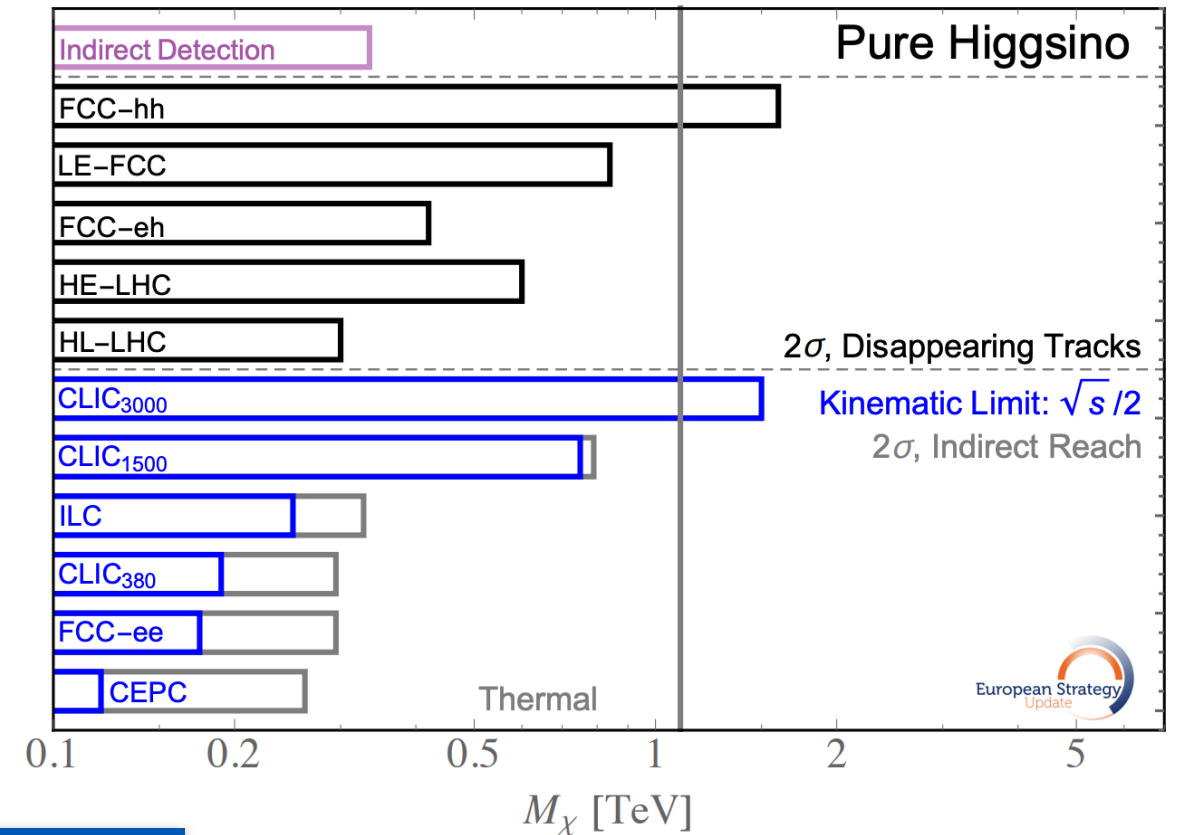
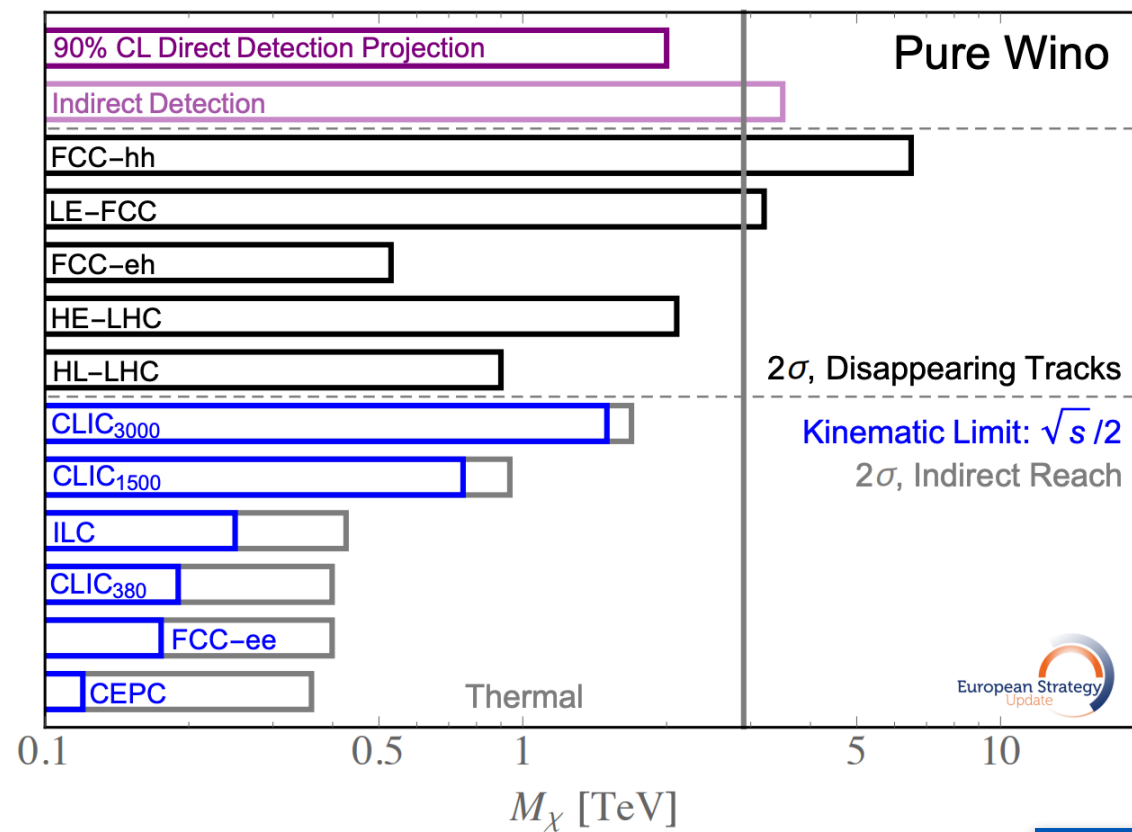
Depending on neutral mass splitting, higgsino can also have inelastic scattering



[LZ yesterday!]

Benchmark for Future Colliders

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+ 2025]

An Update on Uncertainties

Update on Uncertainties

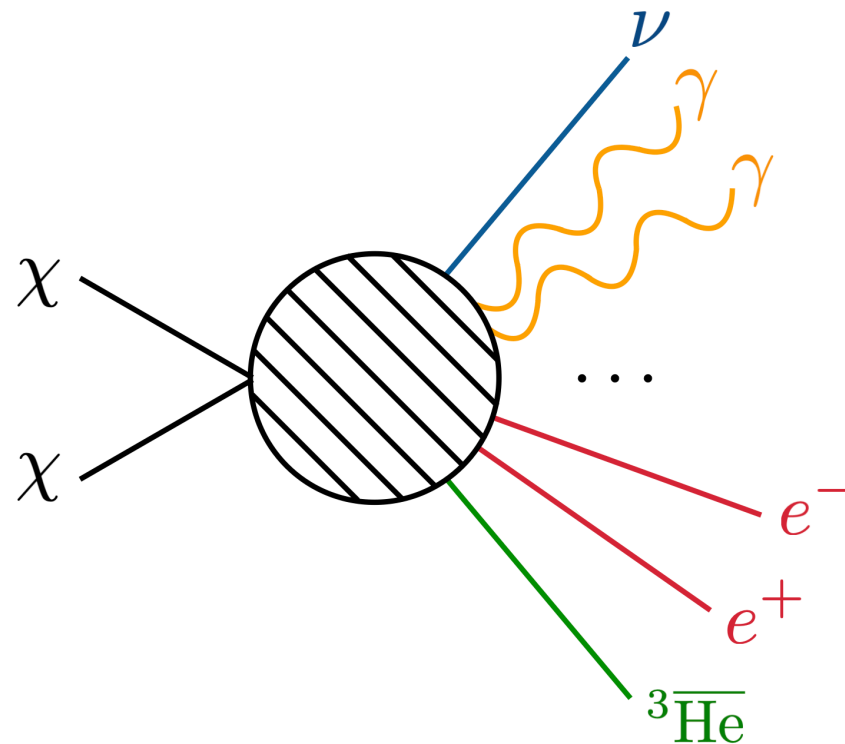
Dark matter annihilation flux

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

Update on Uncertainties

Dark matter annihilation flux

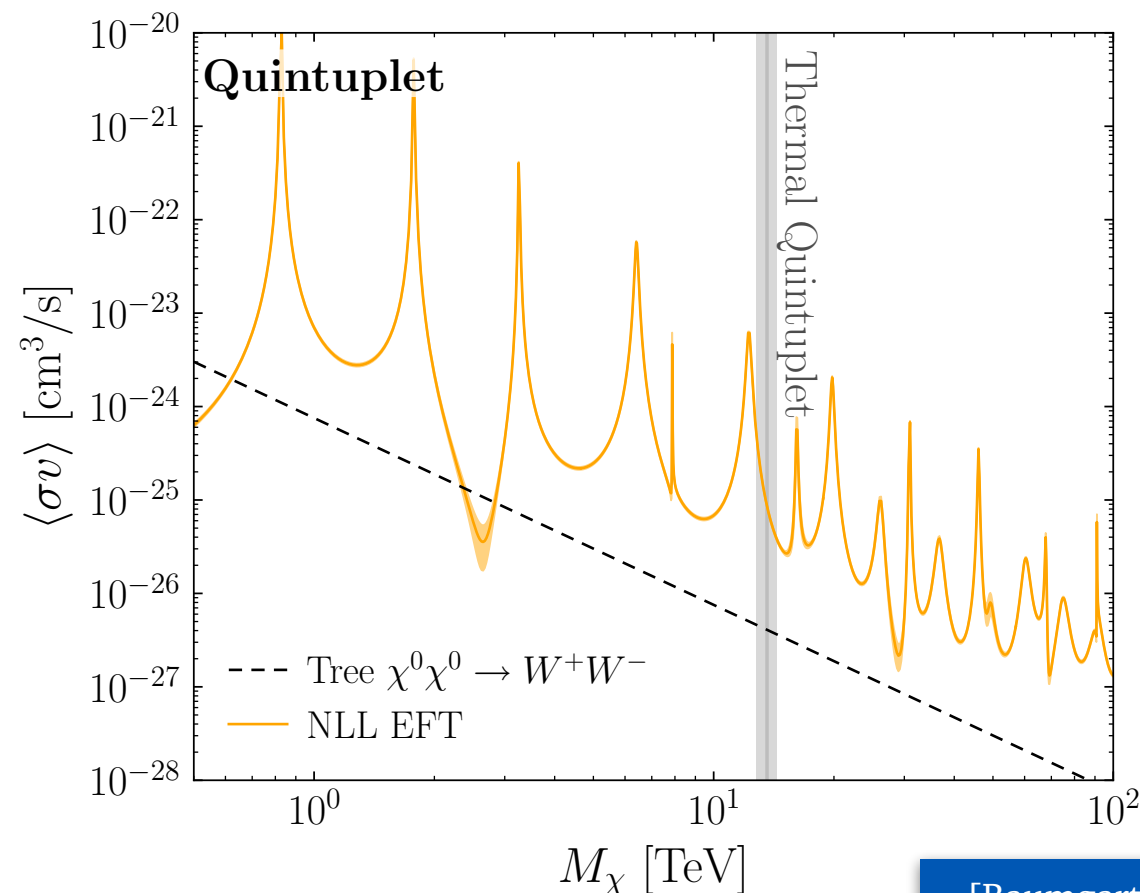
$$\frac{d\Phi}{dE} = \underbrace{\frac{\langle\sigma v\rangle}{8\pi M_\chi^2} \frac{dN}{dE}}_{\text{Particle Physics}} \times \int ds \rho_{\text{DM}}^2(s)$$



Update on Uncertainties

Dark matter annihilation flux

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



[Baumgart, NLR,
Slatyer, Vaidya 2024]

Update on Uncertainties

Dark matter annihilation flux

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

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

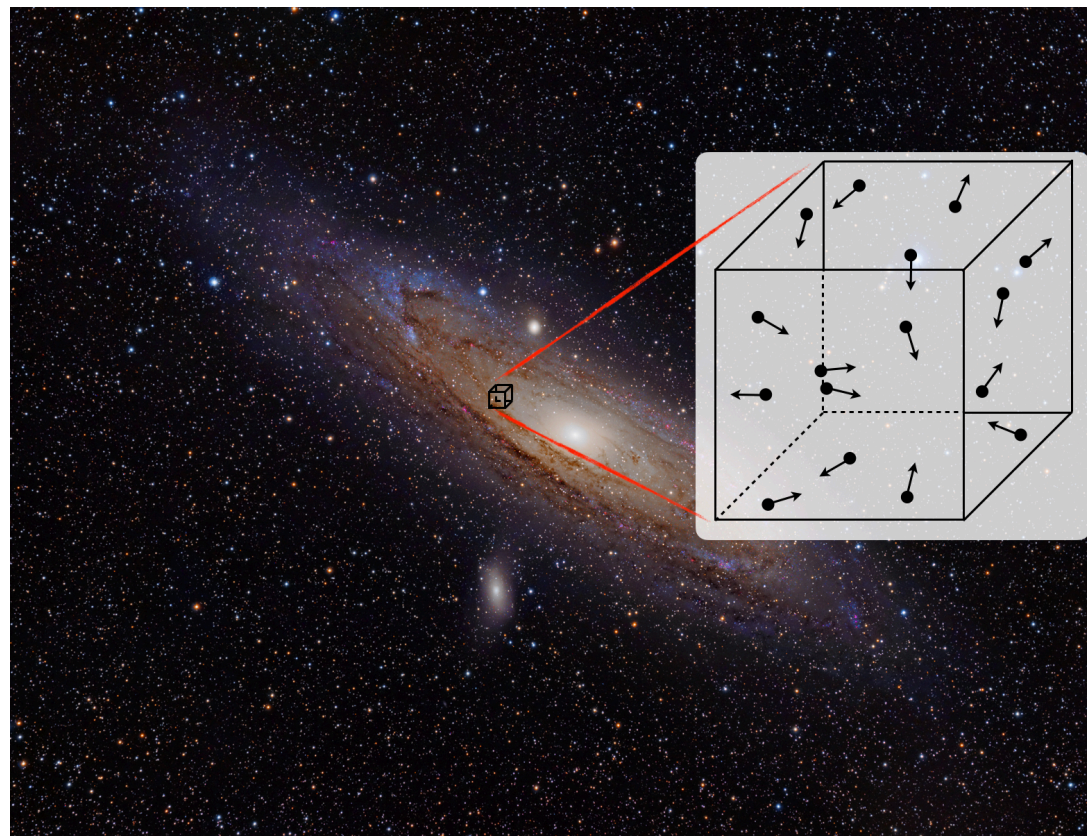
Results exist for: **wino** ([Baumgart, NLR+ 2018], [Beneke+ 2019]), **higgsino** [Beneke+ 2020],
quintuplet [Baumgart, NLR+ 2024], **all real MDM reps** [Baumgart, NLR+ 2026]

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

Update on Uncertainties

Dark matter annihilation flux

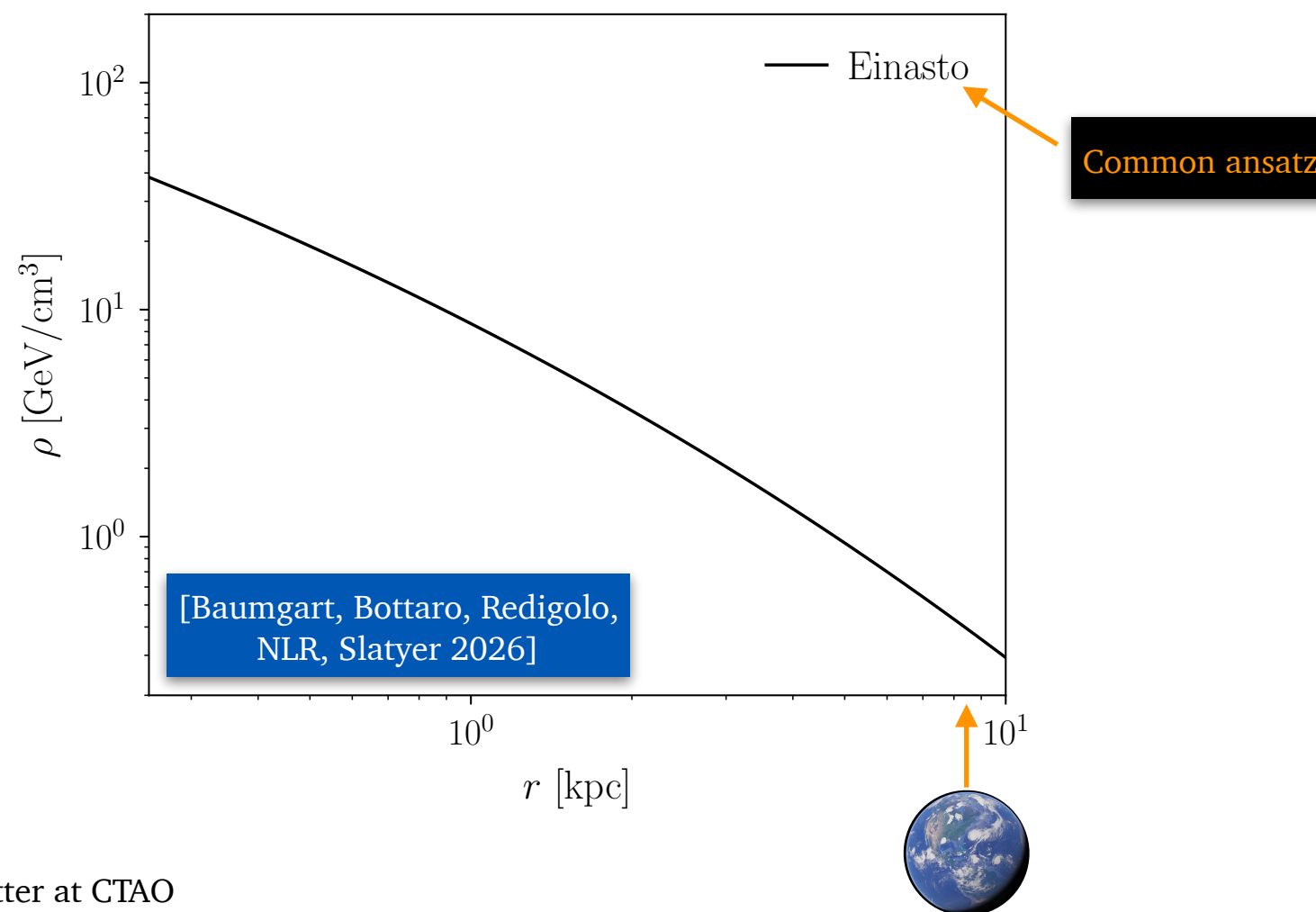
$$\frac{d\Phi}{dE} = \frac{\langle\sigma v\rangle}{8\pi M_\chi^2} \frac{dN}{dE} \times \underbrace{\int ds \rho_{\text{DM}}^2(s)}_{\text{Astrophysics}}$$



Update on Uncertainties

Dark matter annihilation flux

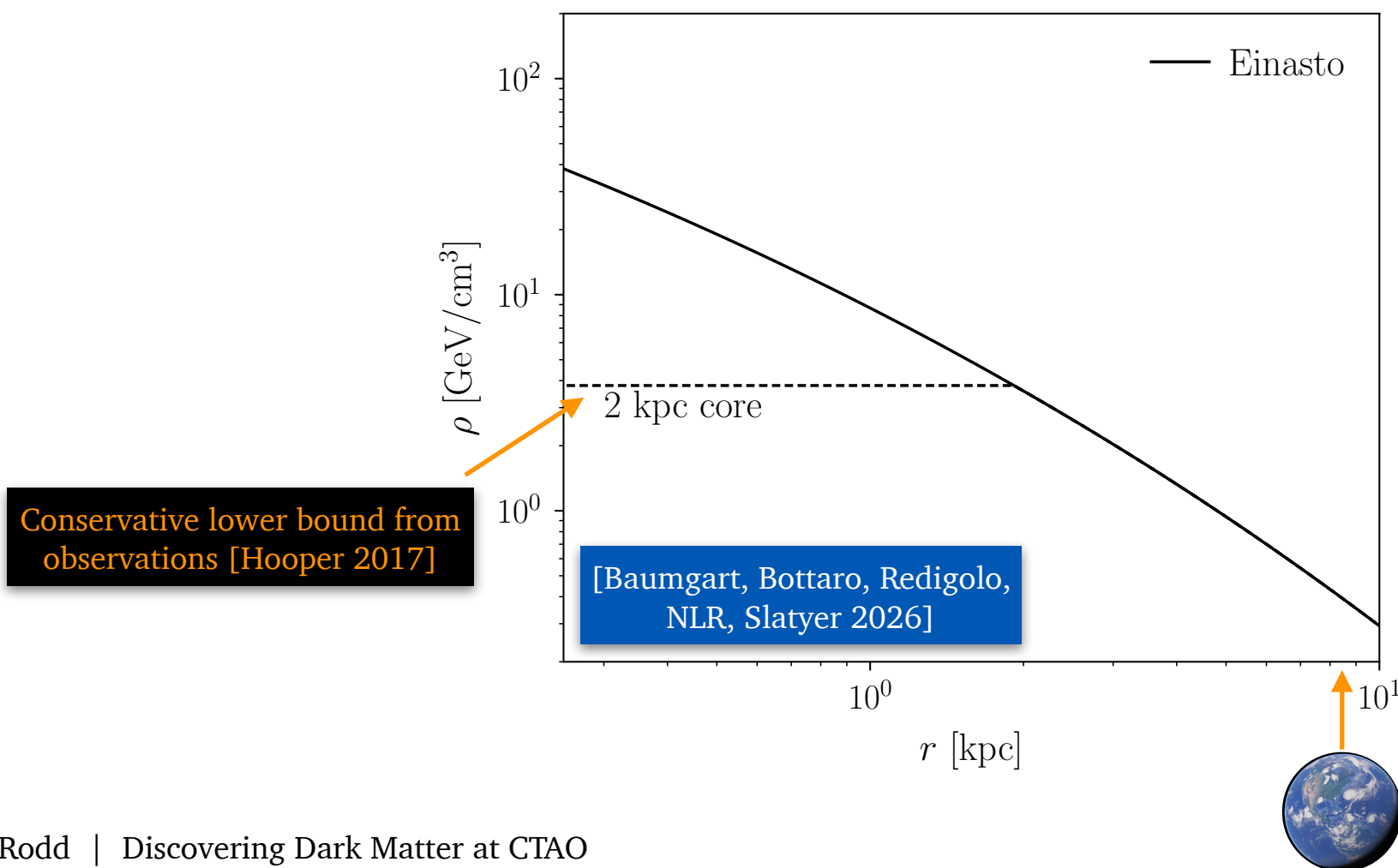
$$\frac{d\Phi}{dE} = \frac{\langle\sigma v\rangle}{8\pi M_\chi^2} \frac{dN}{dE} \times \underbrace{\int ds \rho_{\text{DM}}^2(s)}_{\text{Astrophysics}}$$



Update on Uncertainties

Dark matter annihilation flux

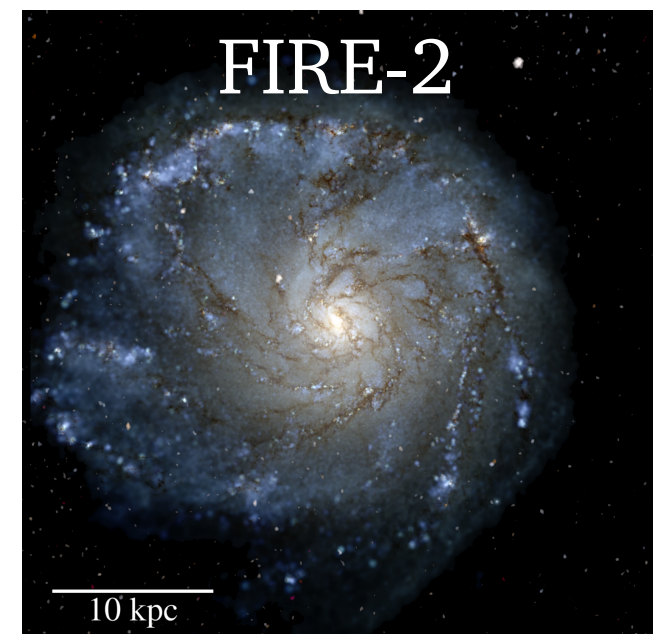
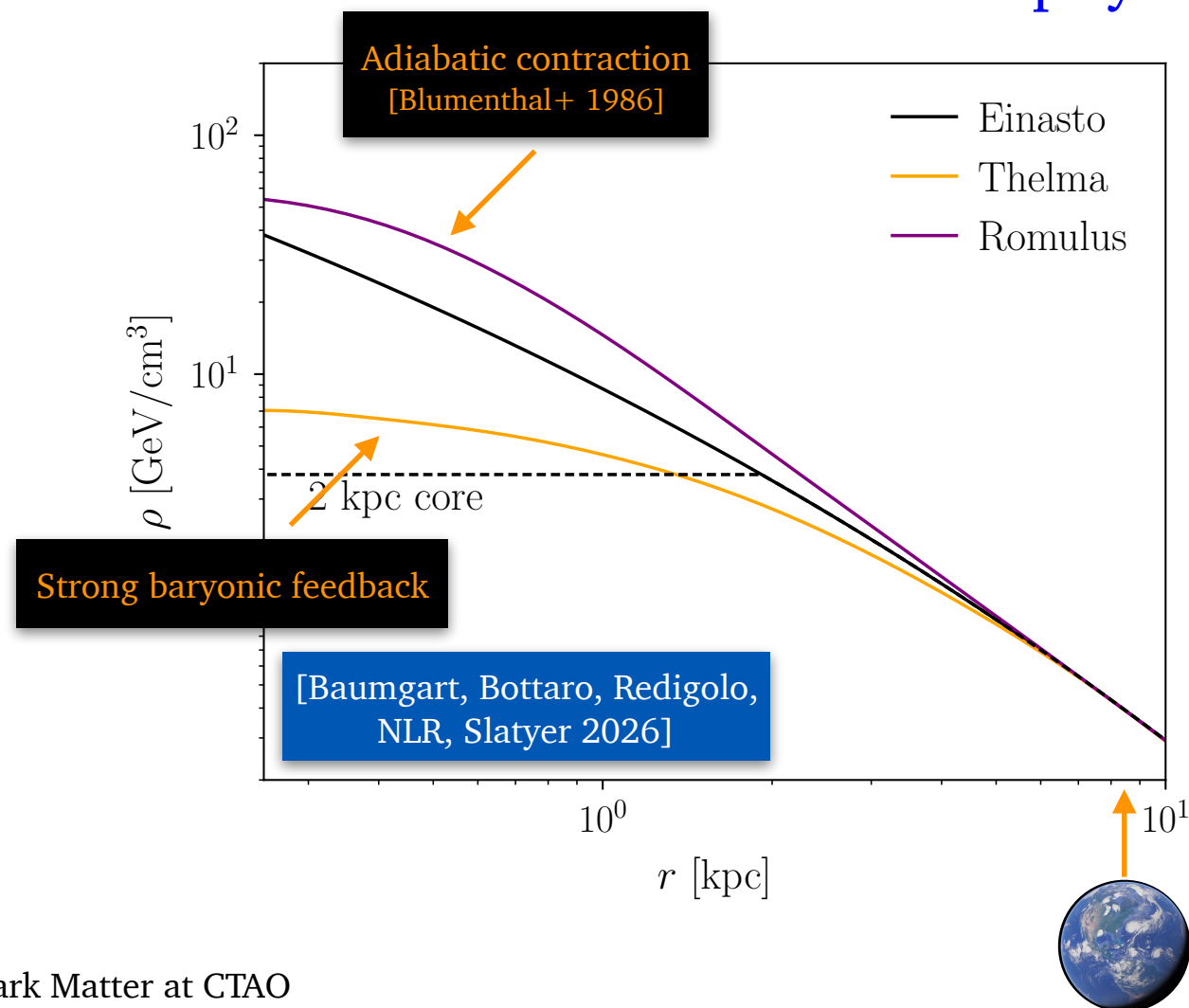
$$\frac{d\Phi}{dE} = \frac{\langle\sigma v\rangle}{8\pi M_\chi^2} \frac{dN}{dE} \times \underbrace{\int ds \rho_{\text{DM}}^2(s)}_{\text{Astrophysics}}$$



Update on Uncertainties

Dark matter annihilation flux

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

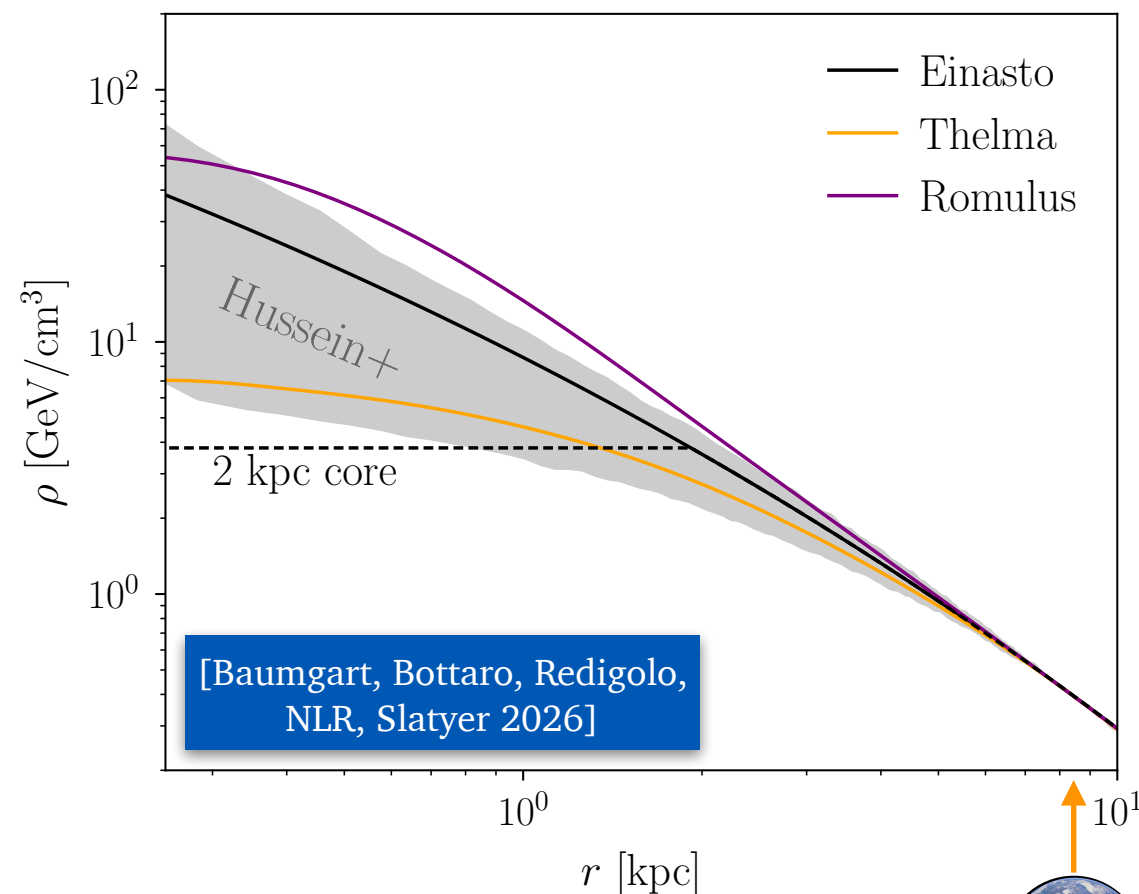


[Hopkins+ 2018]
[McKeown+ 2022]

Update on Uncertainties

Dark matter annihilation flux

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



[Hussein + 2025]

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

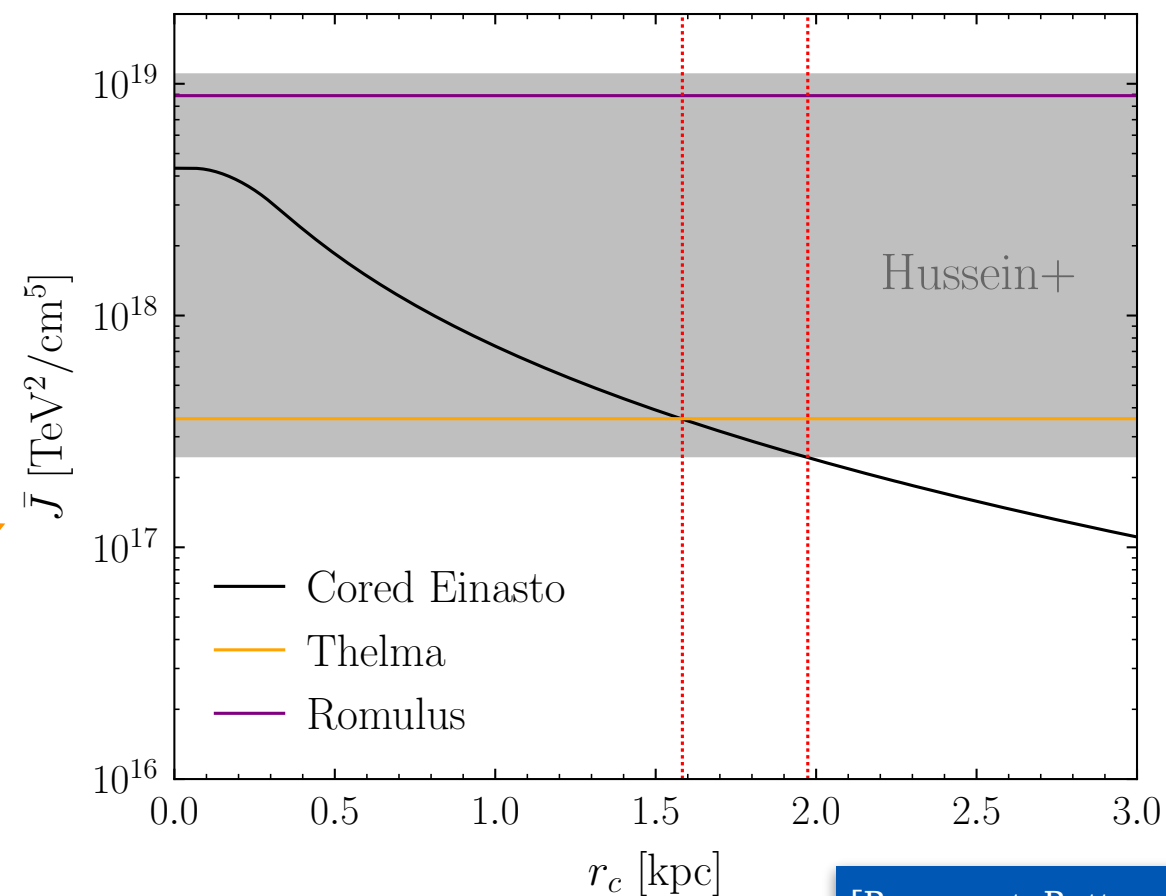


Update on Uncertainties

Dark matter annihilation flux

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

Average inner
galaxy J -factor



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

Update on Uncertainties

Dark matter annihilation flux

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

Dominant uncertainty, lower bound exists

Observational path extremely challenging, unlikely in 10 years
Simulations far more promising

Update on Uncertainties

Dark matter annihilation flux

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

Dominant uncertainty, lower bound exists

Observational path extremely challenging, unlikely in 10 years

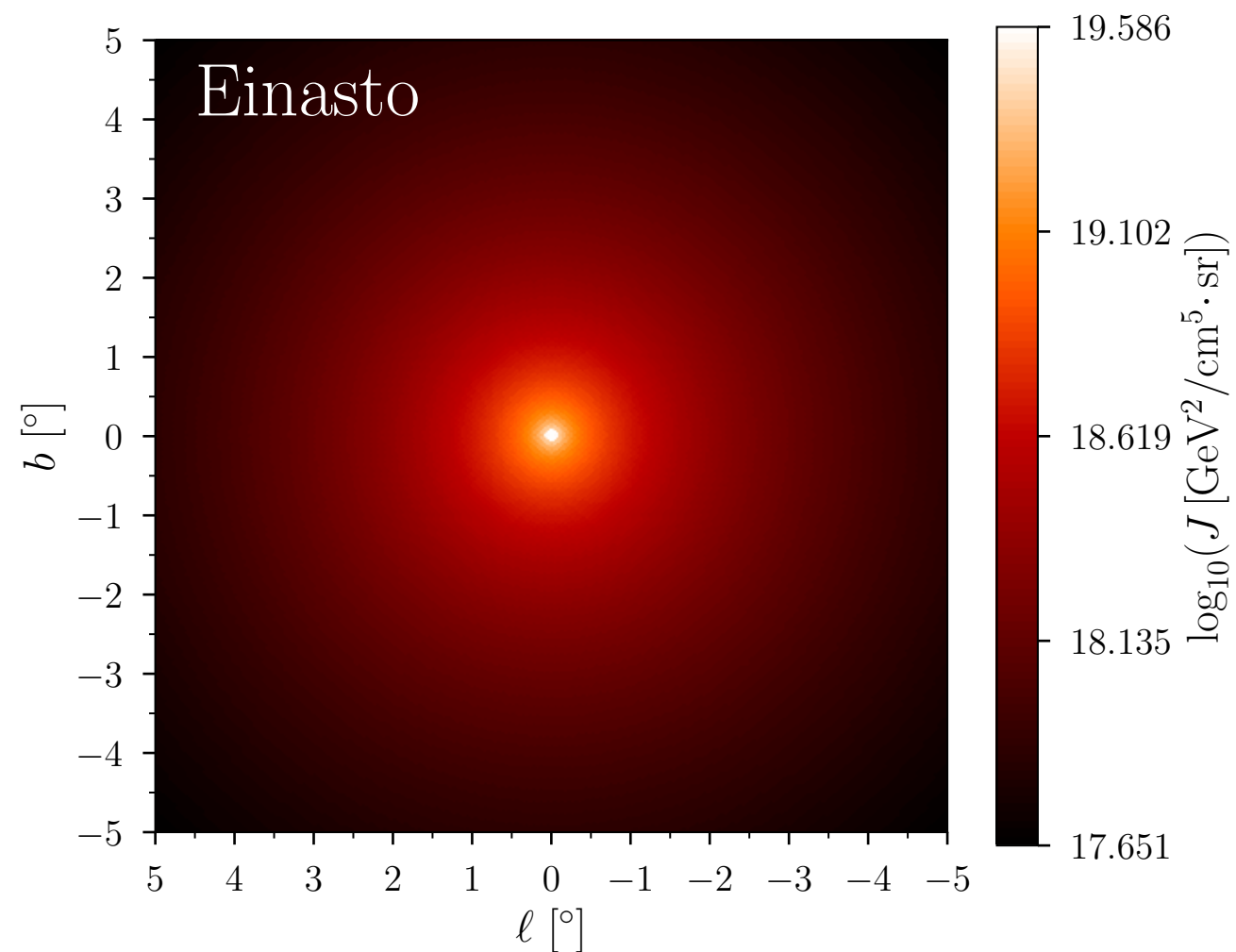
Simulations far more promising



Update on Uncertainties

The DREAMS Project

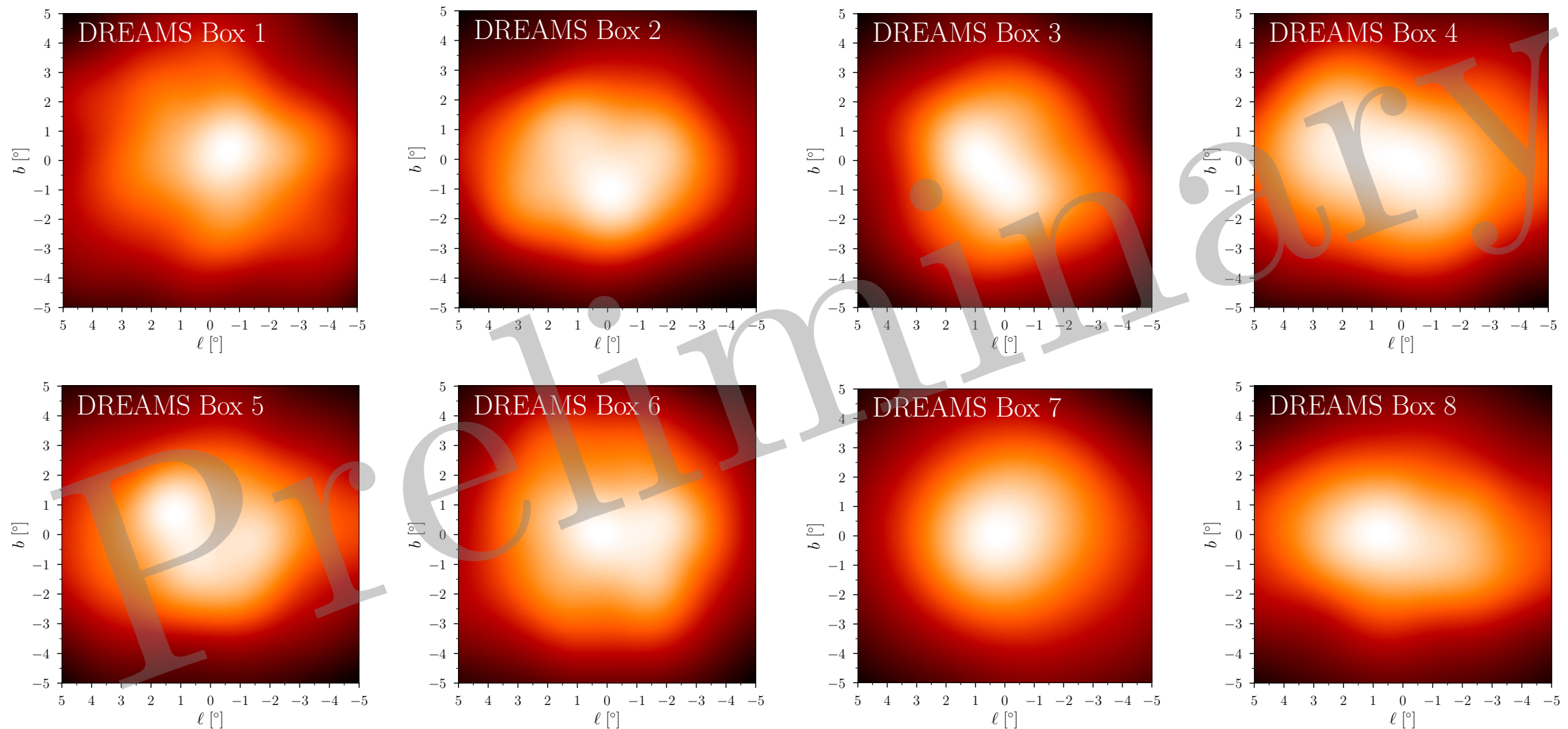
From 24 to 1,000 Milky Way like halos



Update on Uncertainties

The DREAMS Project

From 24 to 1,000 Milky Way like halos



Softening length is $400 \text{ pc} \sim 2.5^\circ$
Yet present in FIRE, where 200 pc

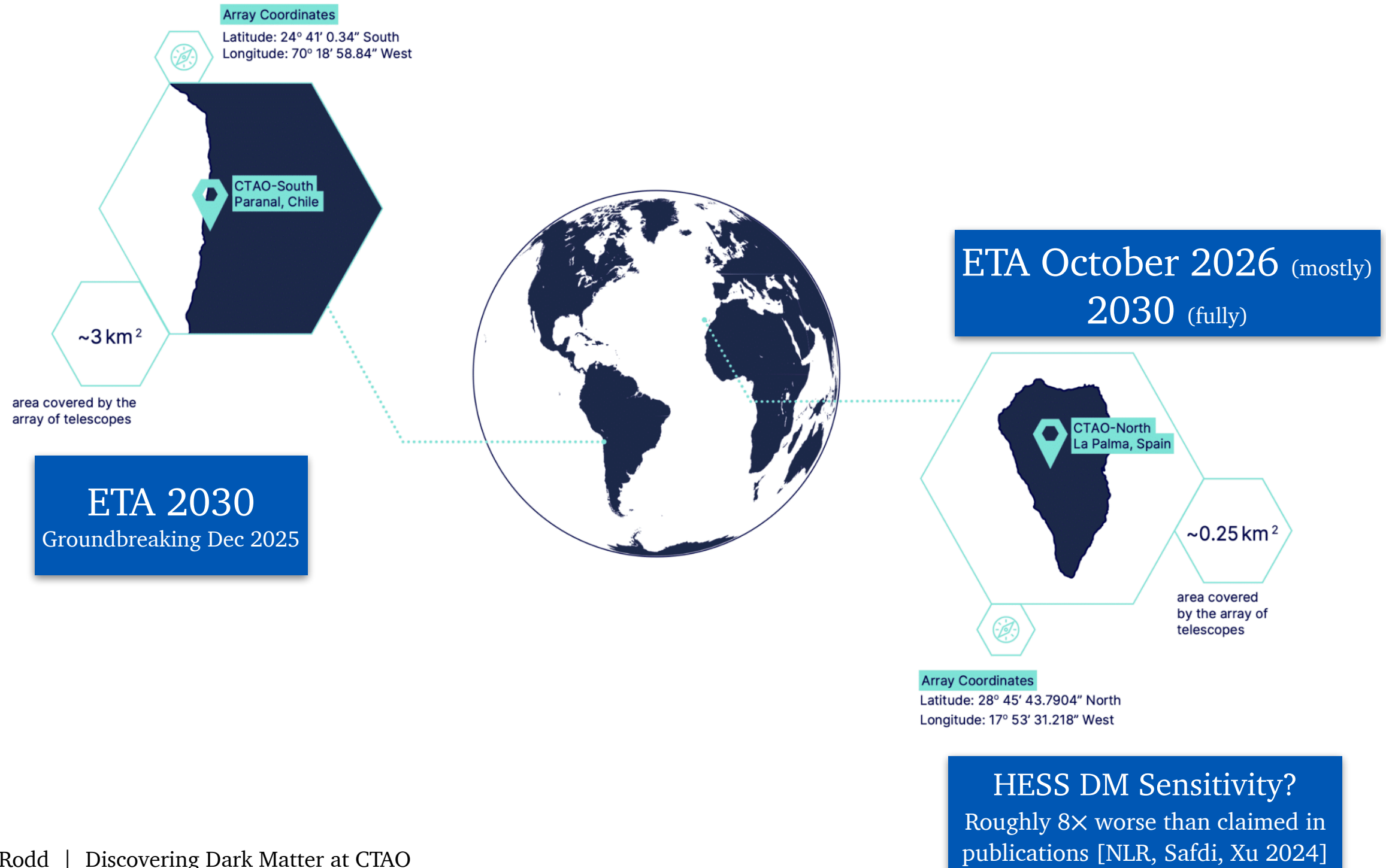
[Kuhlen+ 2013] 2° offset in Eris
[Schaller+ 2016] no offset in EAGLE
[Muru+ 2025] Asphericity in HESTIA

[DREAMS, Garcia,
NLR in prep.]

Discovery at CTAO

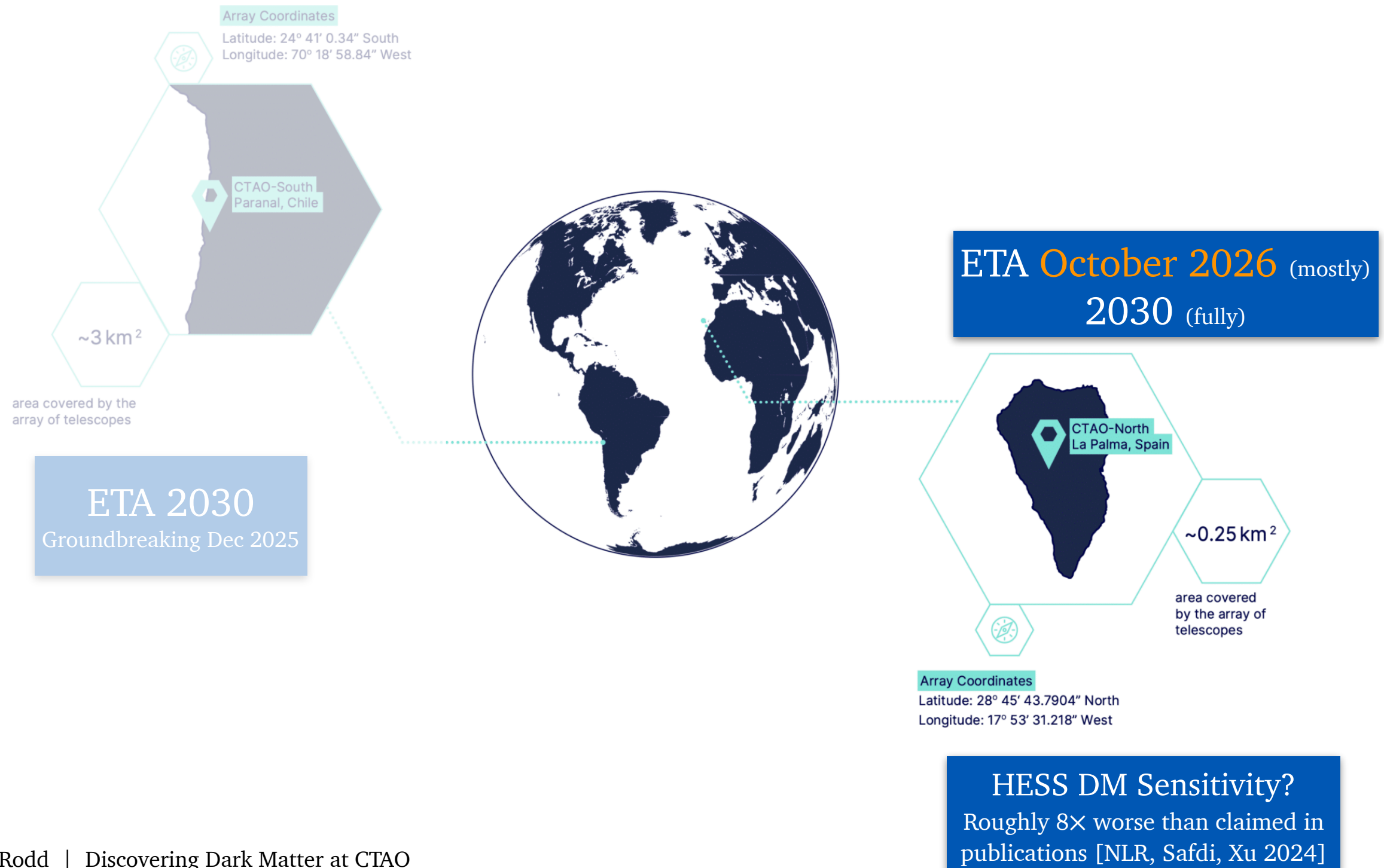
Towards Discovery

CTAO is a distributed across two sites



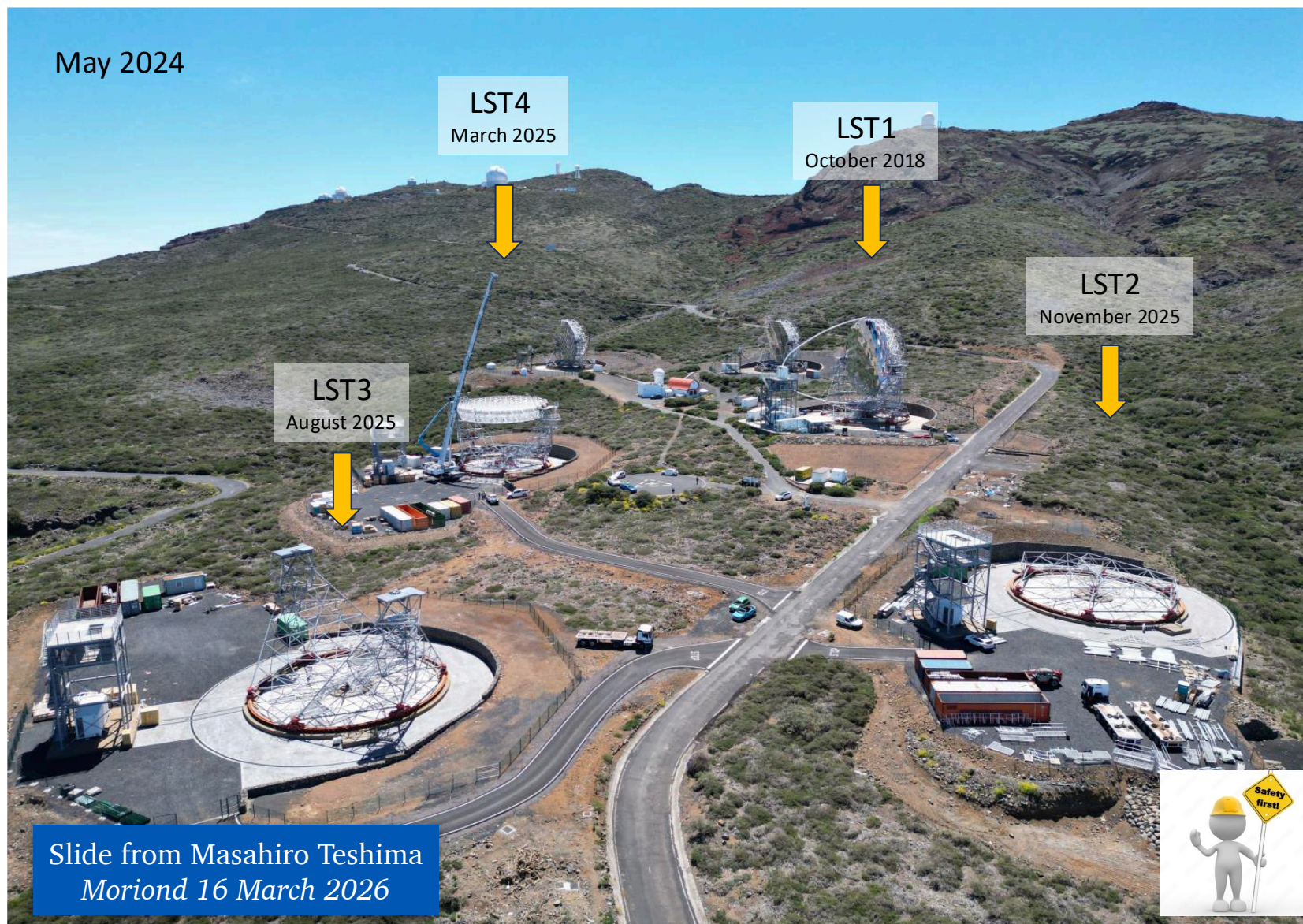
Towards Discovery

CTAO is a distributed across two sites

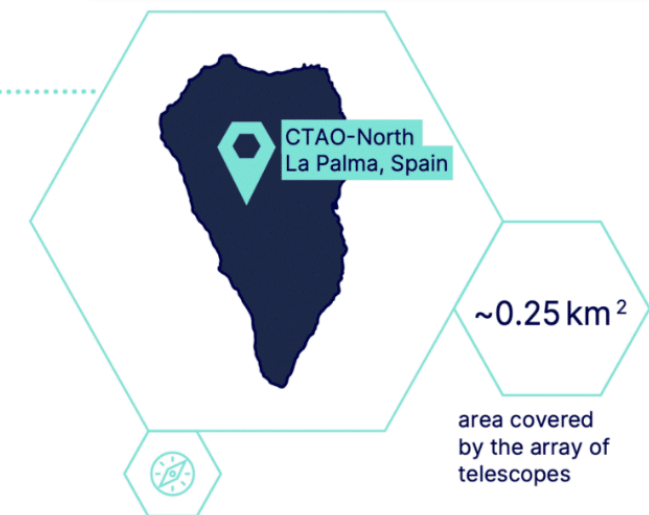


Towards Discovery

CTAO is a distributed across two sites



ETA **October 2026** (mostly)
2030 (fully)



Array Coordinates
Latitude: 28° 45' 43.7904" North
Longitude: 17° 53' 31.218" West

HESS DM Sensitivity?
Roughly 8× worse than claimed in
publications [NLR, Safdi, Xu 2024]

Towards Discovery

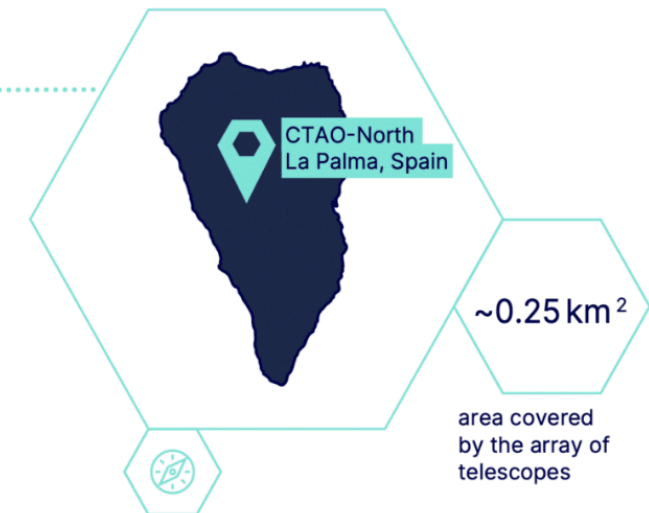
CTAO is a distributed across two sites

December 2024



Slide from Masahiro Teshima
Moriond 16 March 2026

ETA **October 2026** (mostly)
2030 (fully)



Array Coordinates
Latitude: 28° 45' 43.7904" North
Longitude: 17° 53' 31.218" West

HESS DM Sensitivity?

Roughly 8× worse than claimed in
publications [NLR, Safdi, Xu 2024]

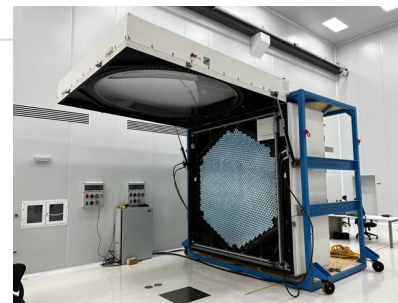
Towards Discovery

CTAO is a distributed across two sites

CTAO

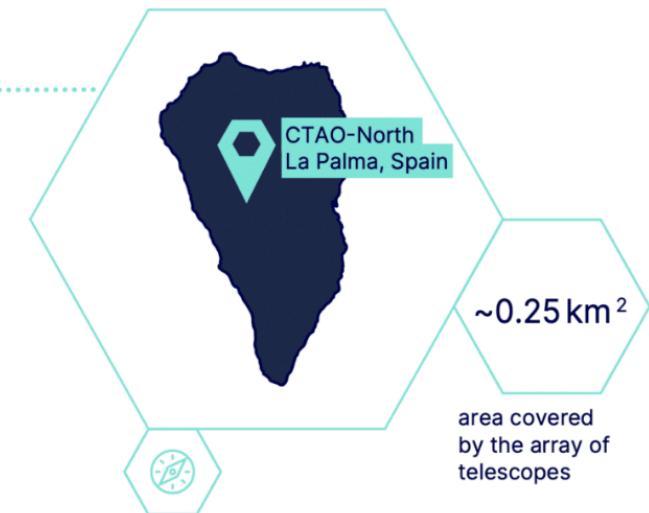
LSTs in October 2025

- 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

ETA **October 2026** (mostly)
2030 (fully)

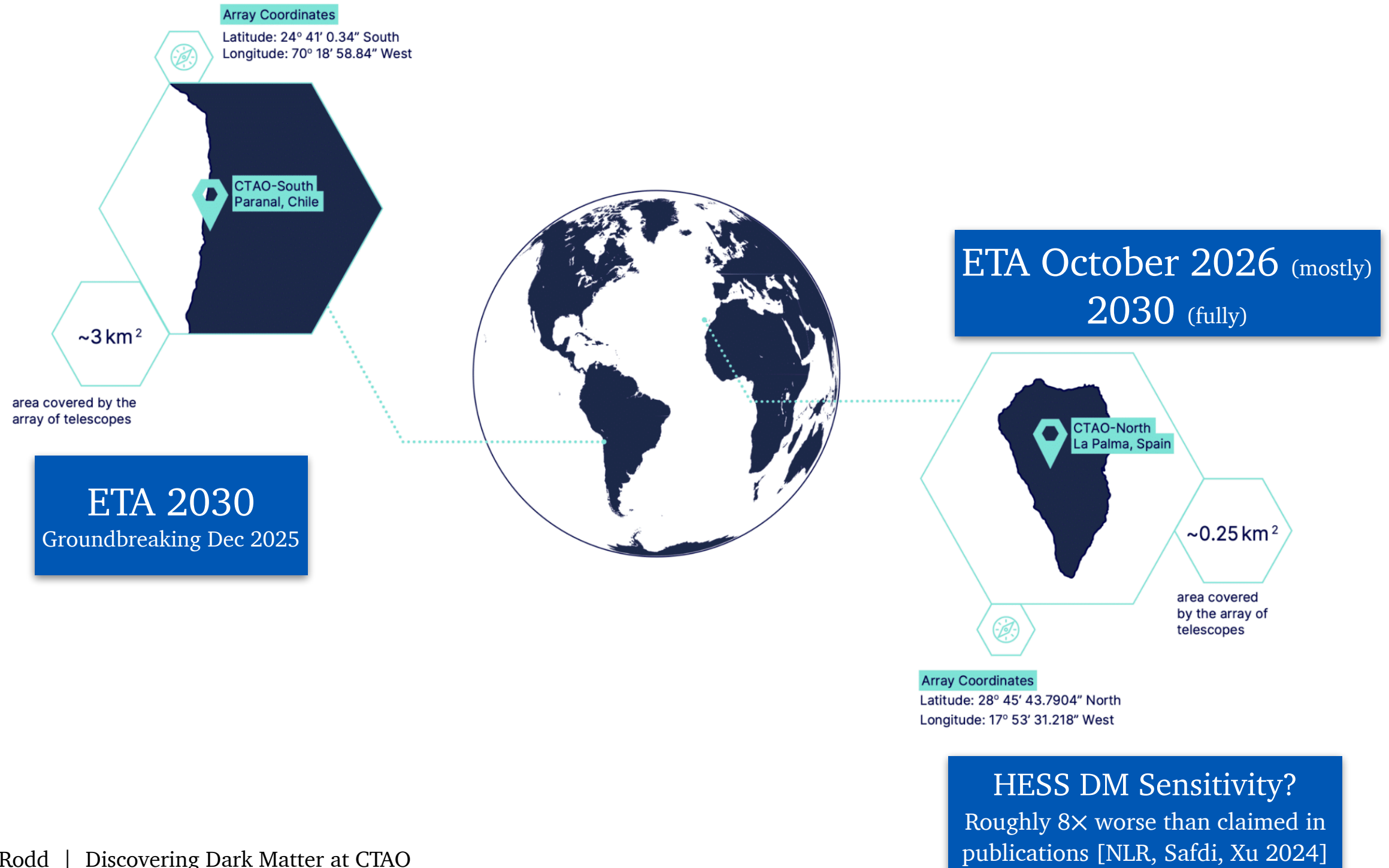


Array Coordinates
Latitude: 28° 45' 43.7904" North
Longitude: 17° 53' 31.218" West

HESS DM Sensitivity?
Roughly 8× worse than claimed in
publications [NLR, Safdi, Xu 2024]

Towards Discovery

CTAO is a distributed across two sites



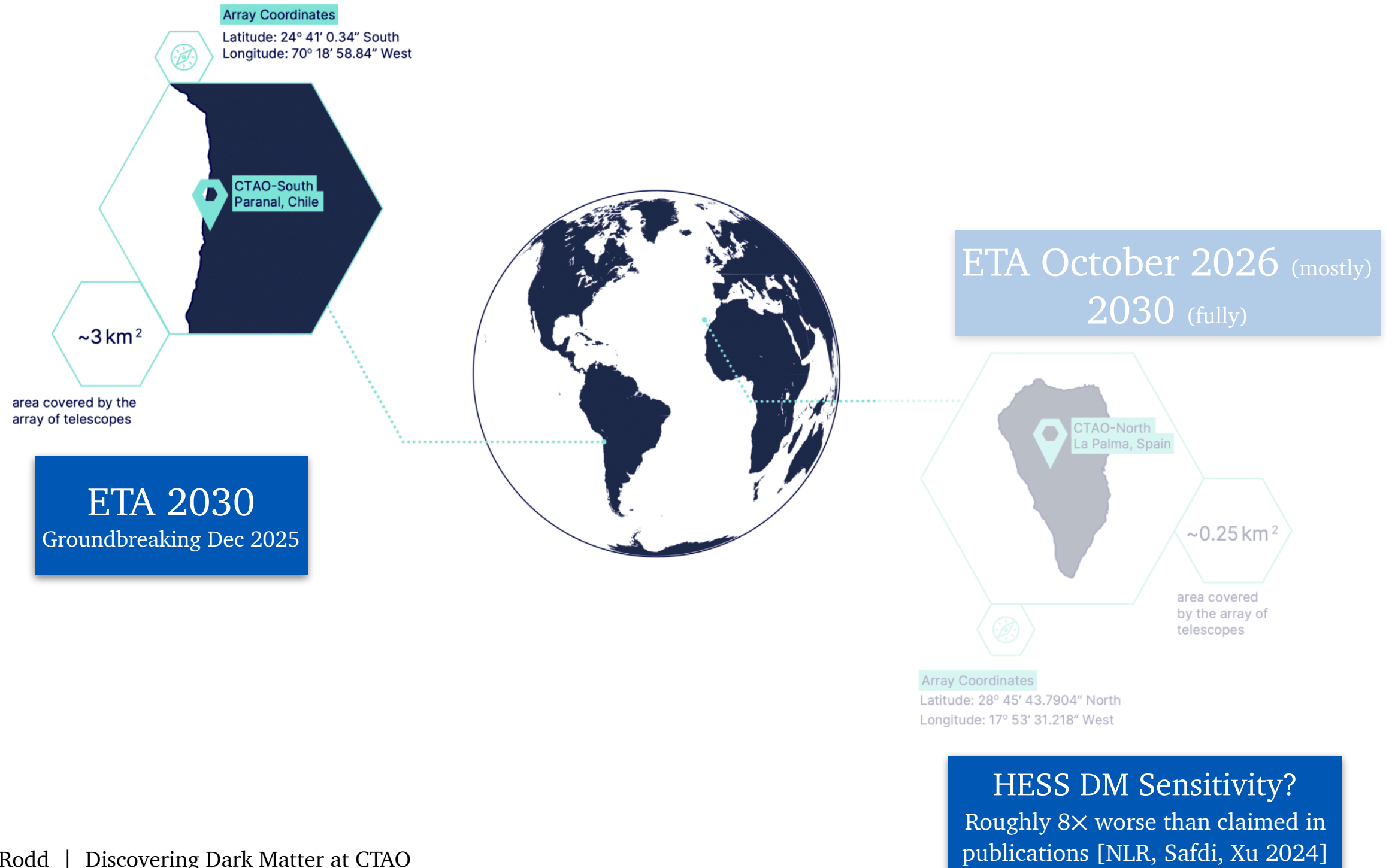
Towards Discovery

CTAO is a distributed across two sites



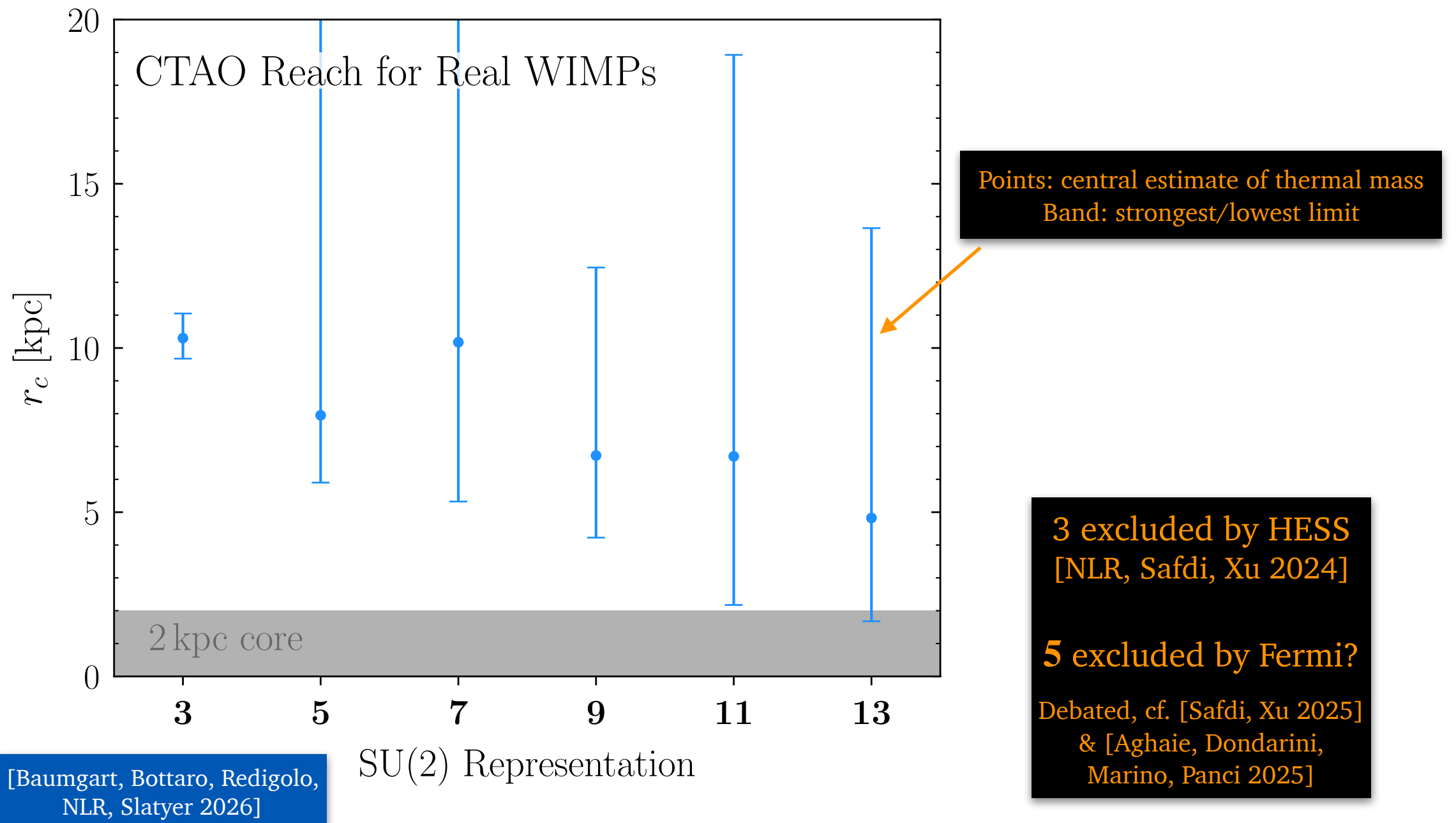
Towards Discovery

CTAO is a distributed across two sites



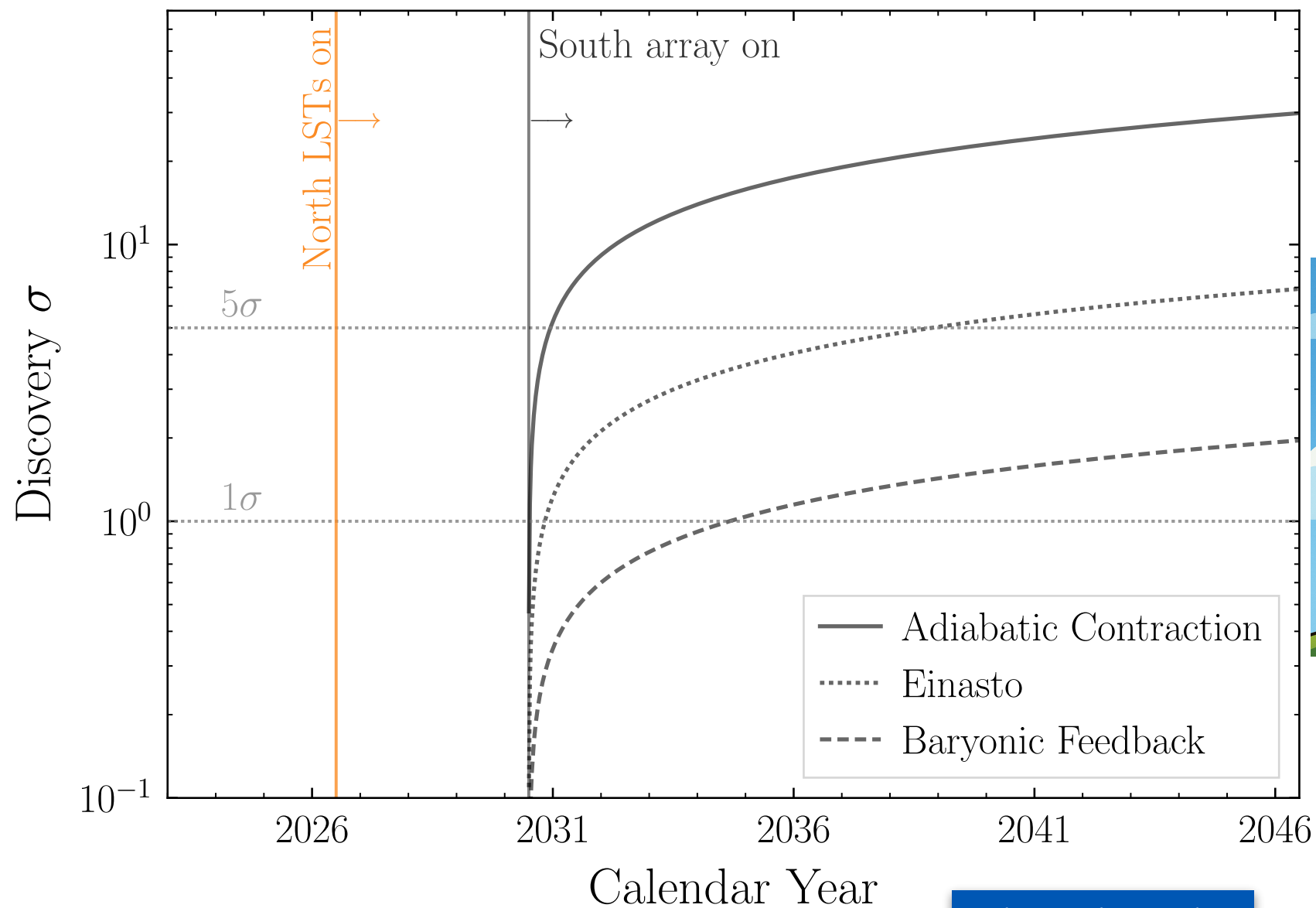
Towards Discovery

CTAO-South sensitivity to MDM in 2035

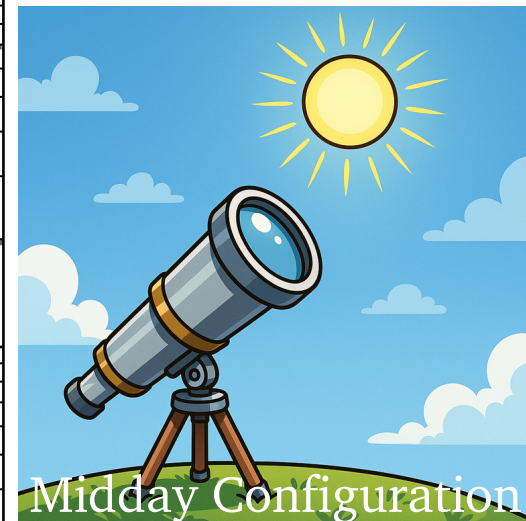


Towards Discovery

CTAO-South sensitivity to thermal higgsino

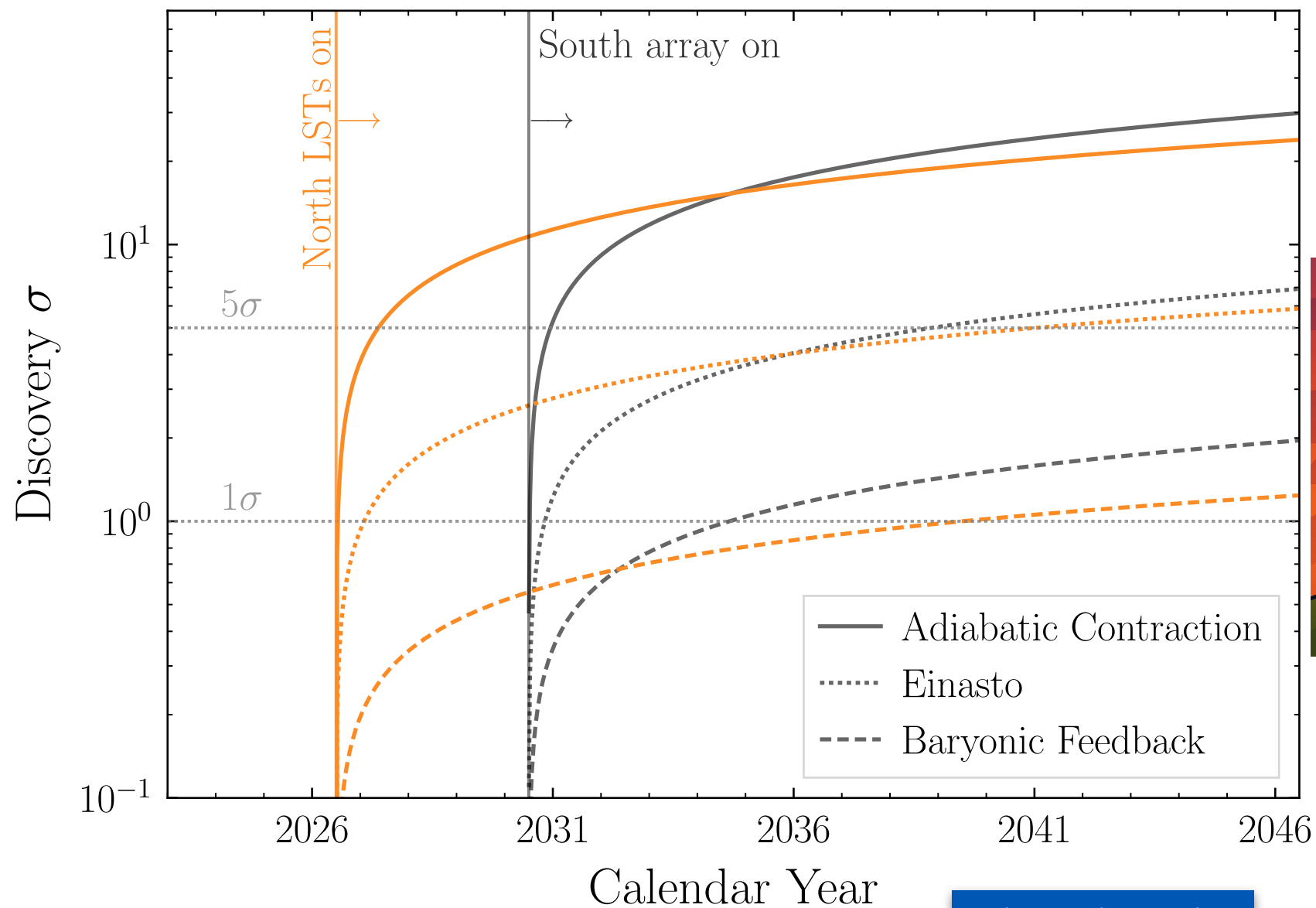


[Abe, Inada, Moulin,
NLR, Safdi, Xu 2026]

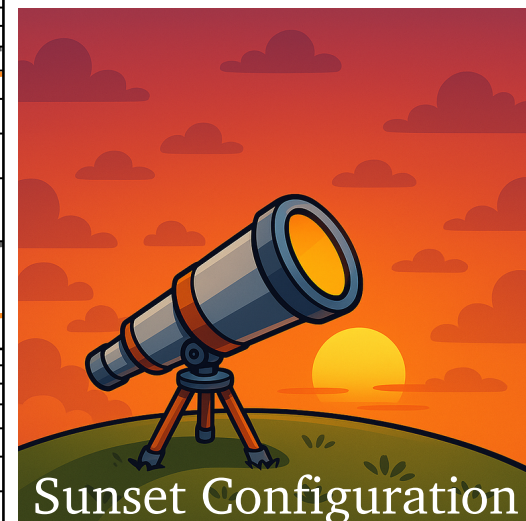


Towards Discovery

CTAO-North sensitivity to thermal higgsino

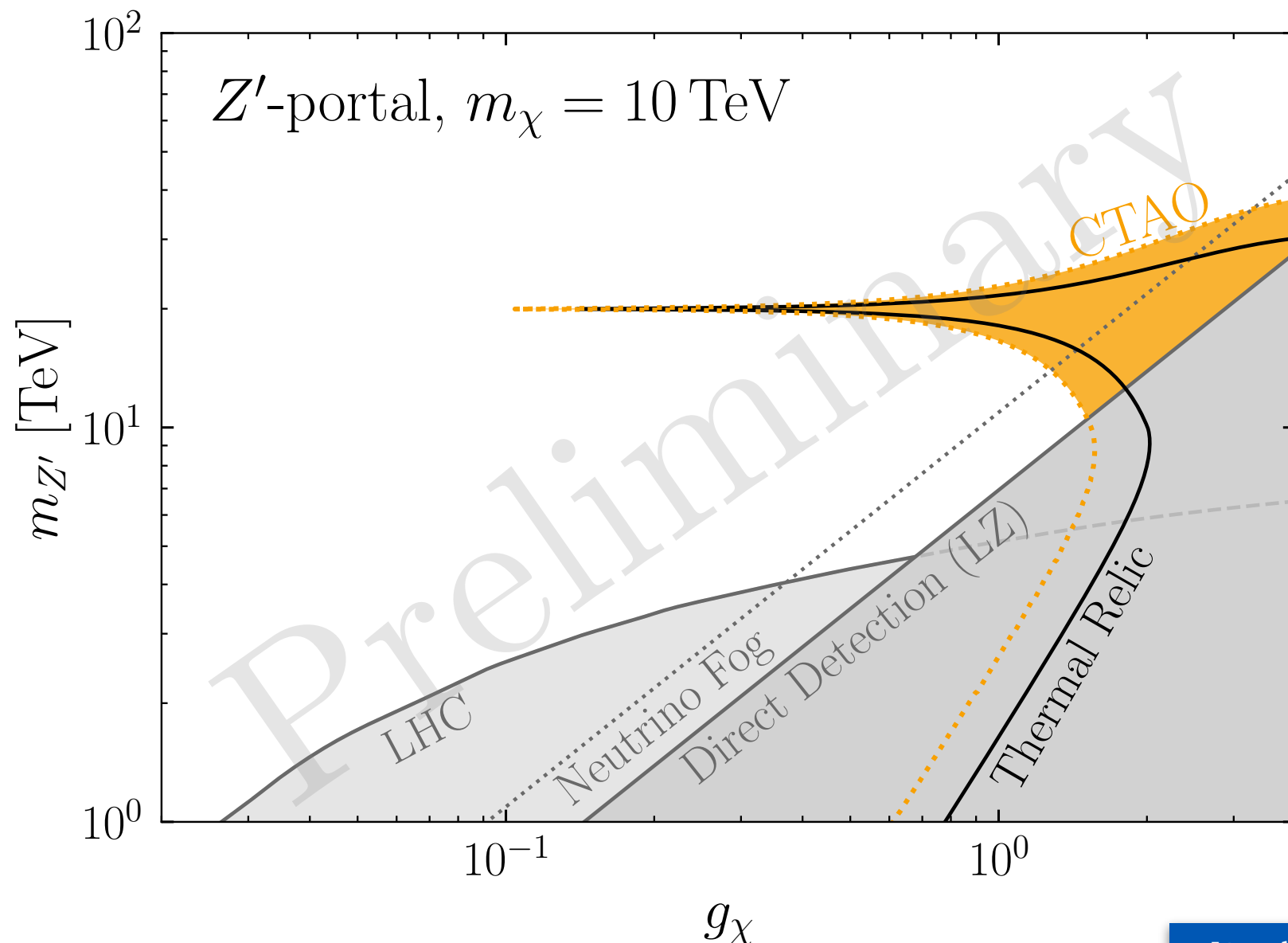


[Abe, Inada, Moulin,
NLR, Safdi, Xu 2026]



Towards Discovery

CTAO is a strong probe of thermal TeV scale DM
Another example: extra dimensions



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

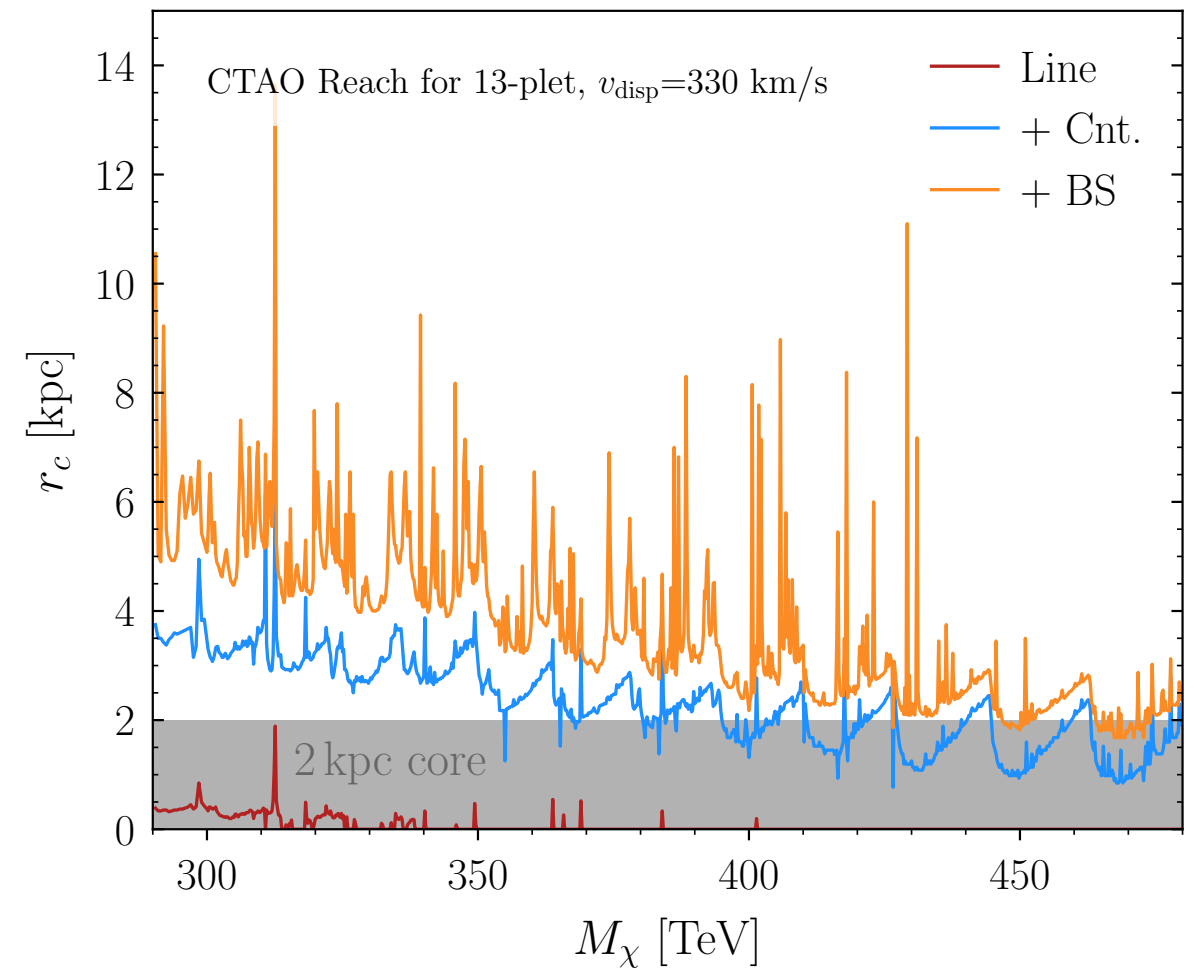
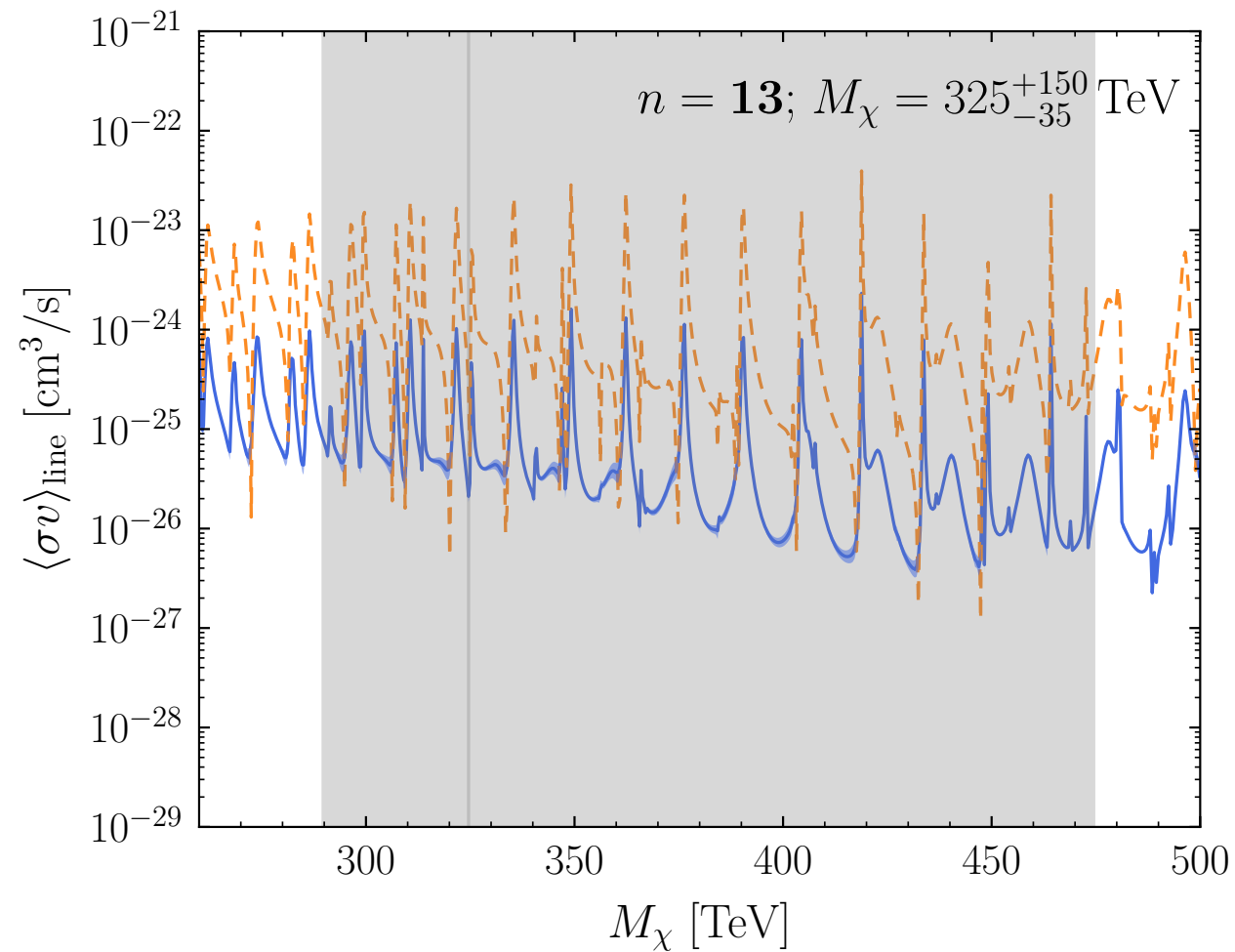
Conclusion

CTAO could be on the verge of discovery



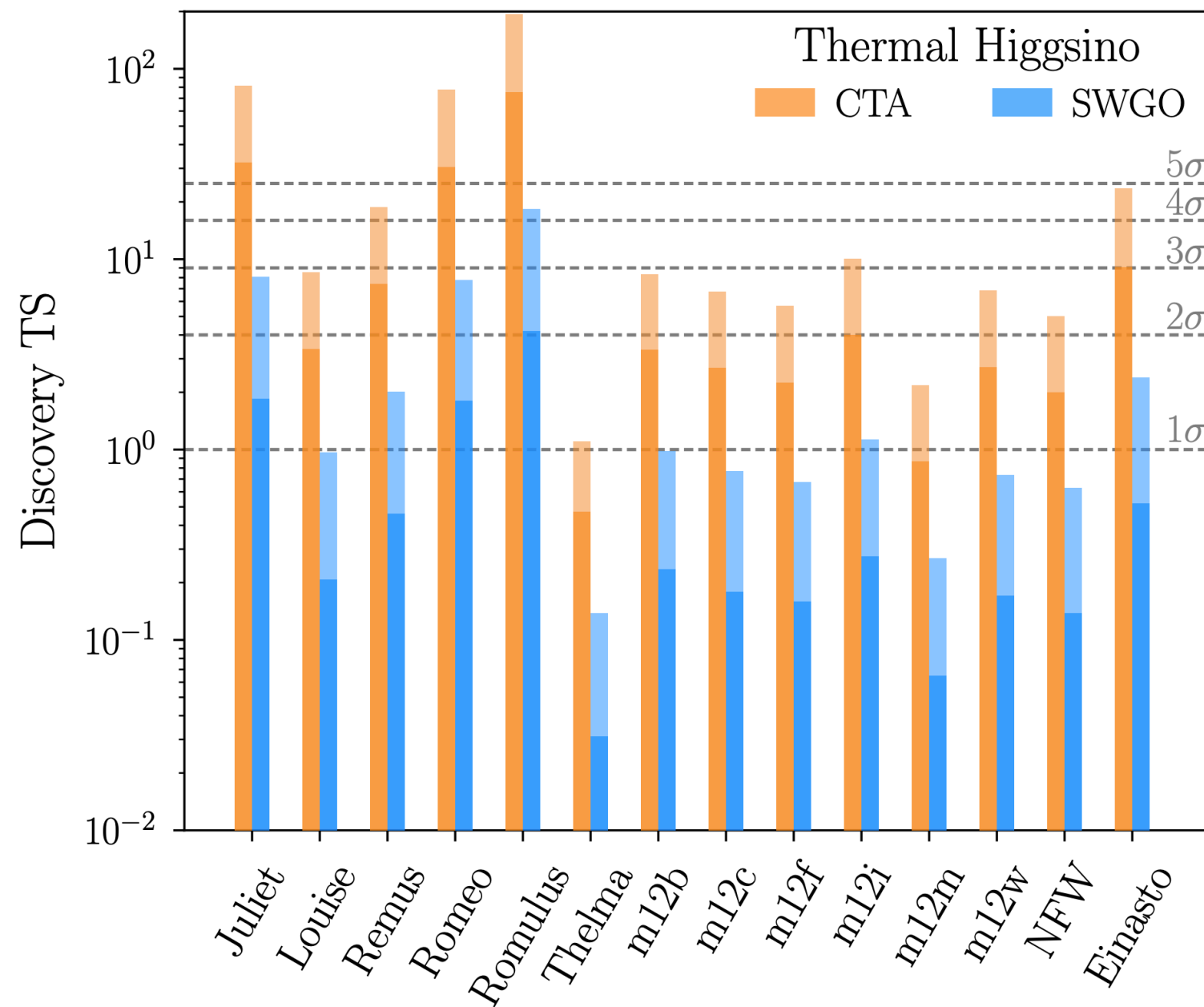
Backup Slides

Tredecuplet



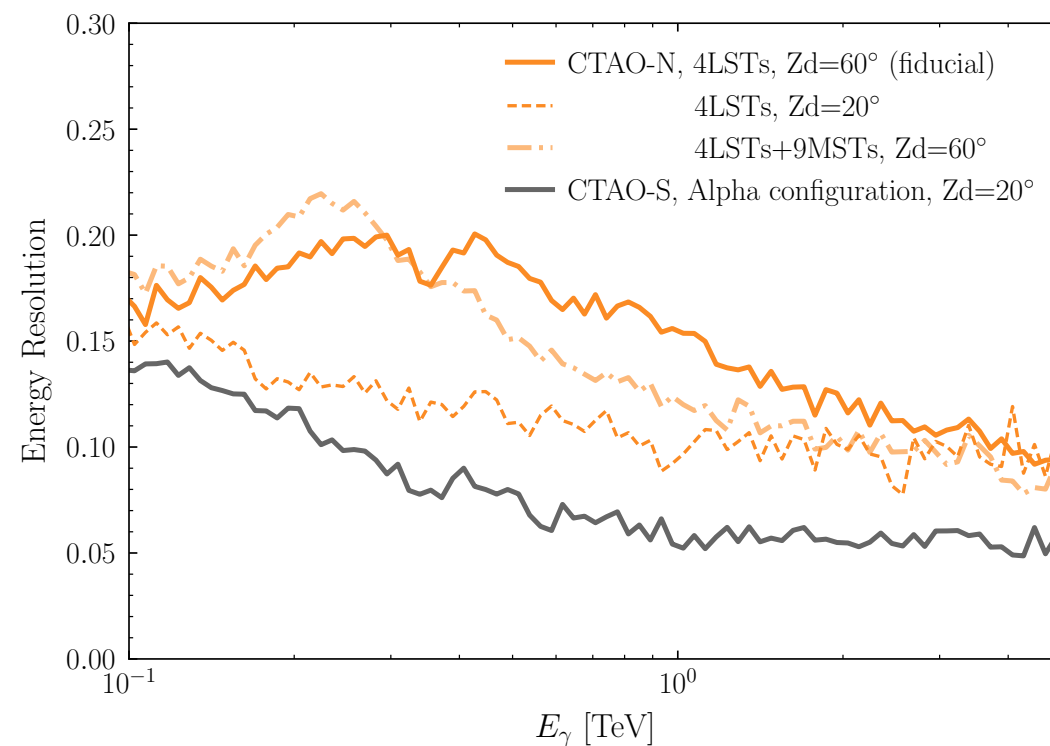
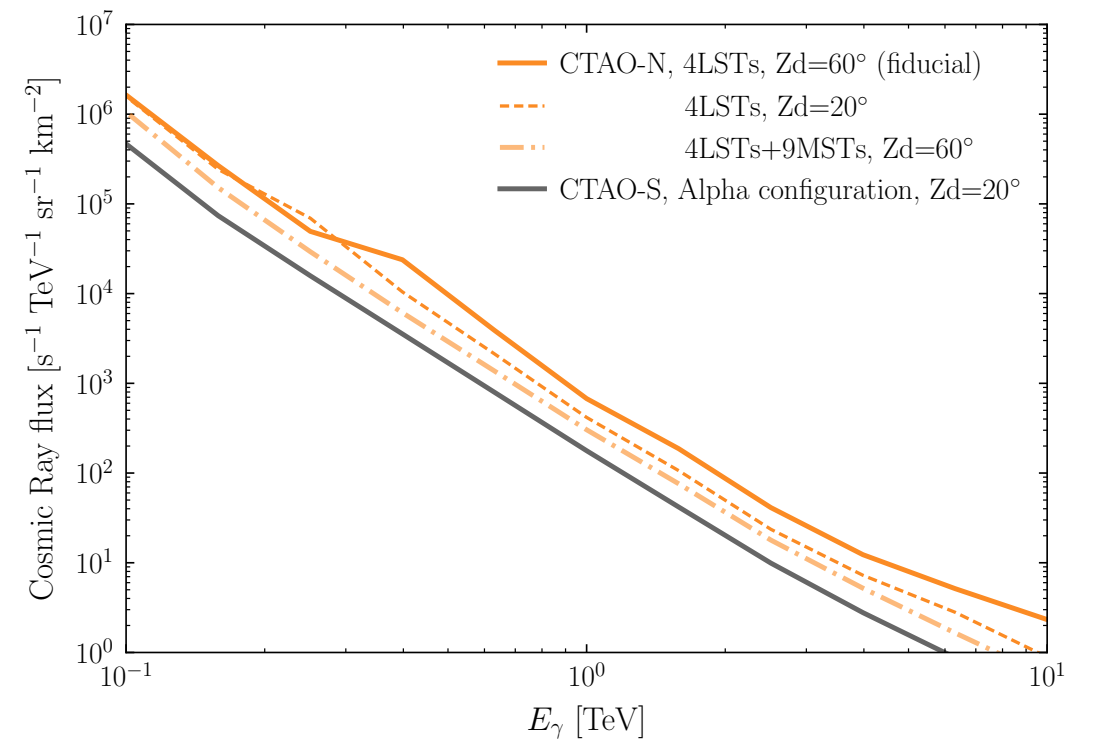
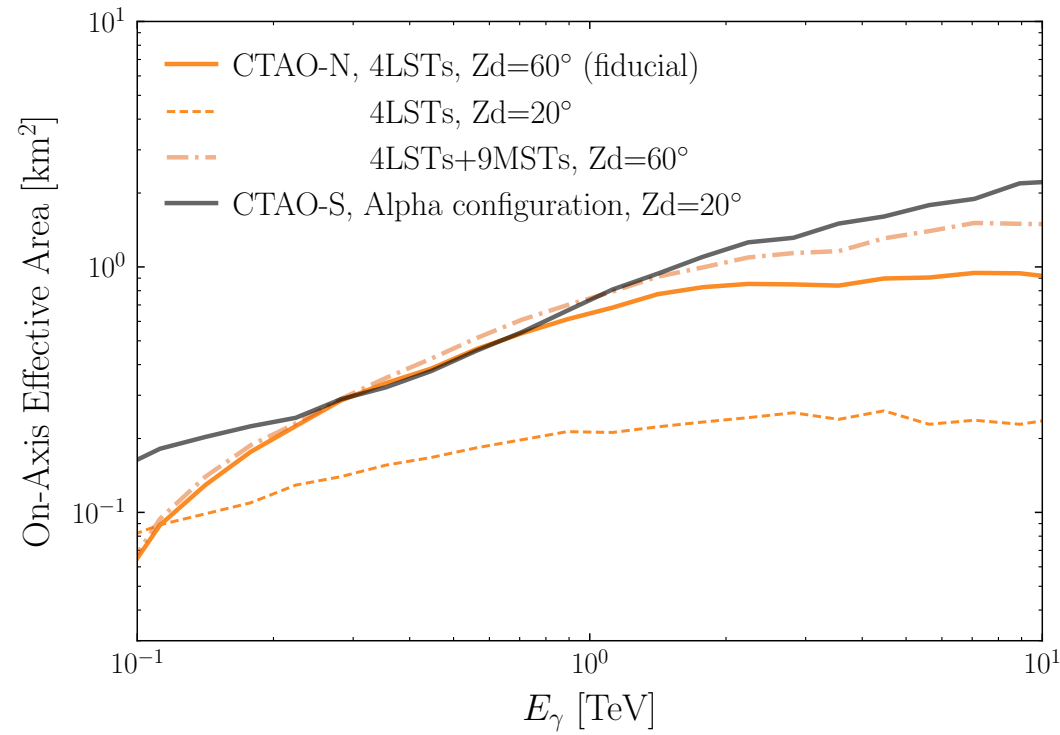
[Baumgart, Bottaro, Redigolo,
NLR, Slatyer 2026]

CTAO-South & SWGO



[NLR, Safdi, Xu 2024]

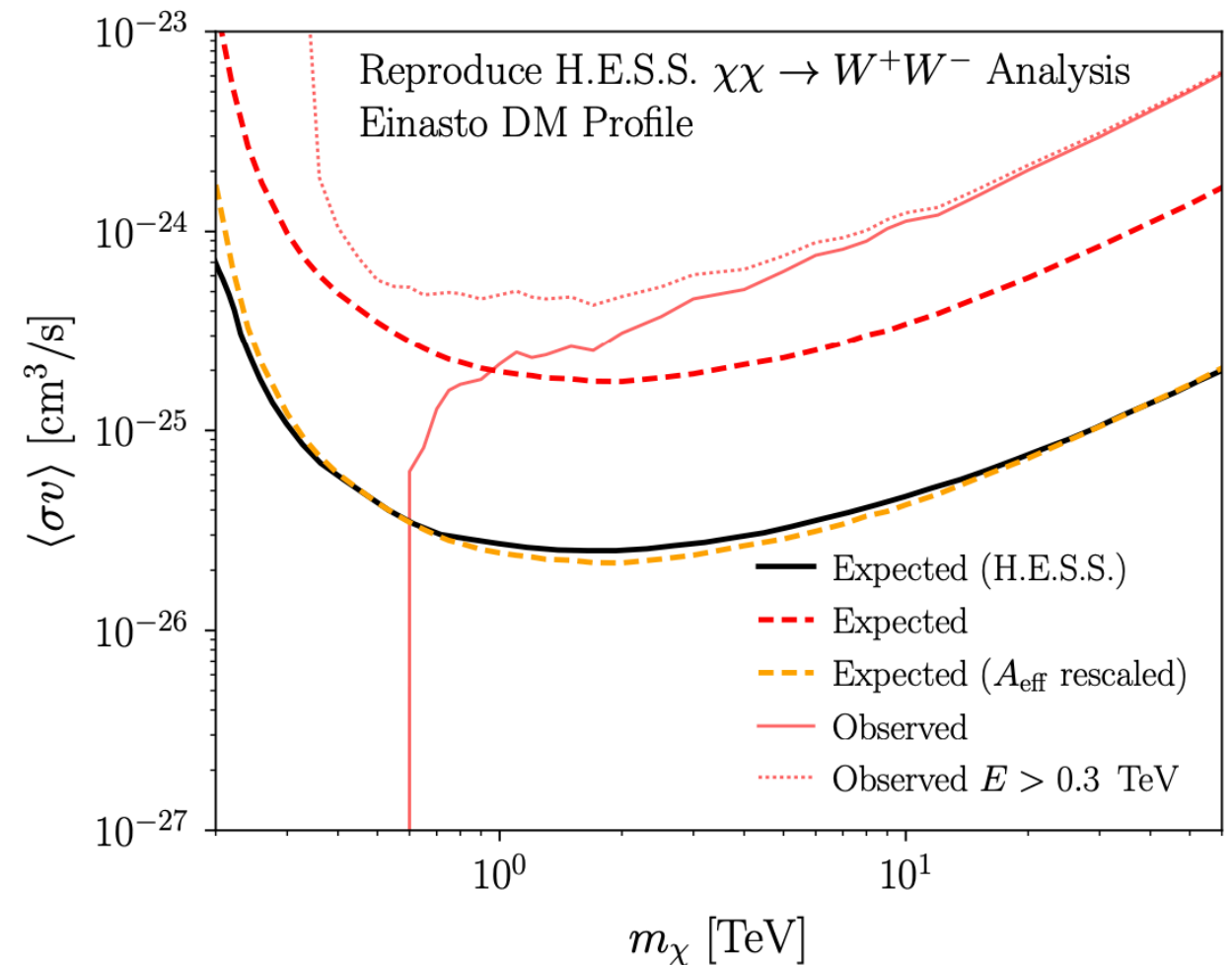
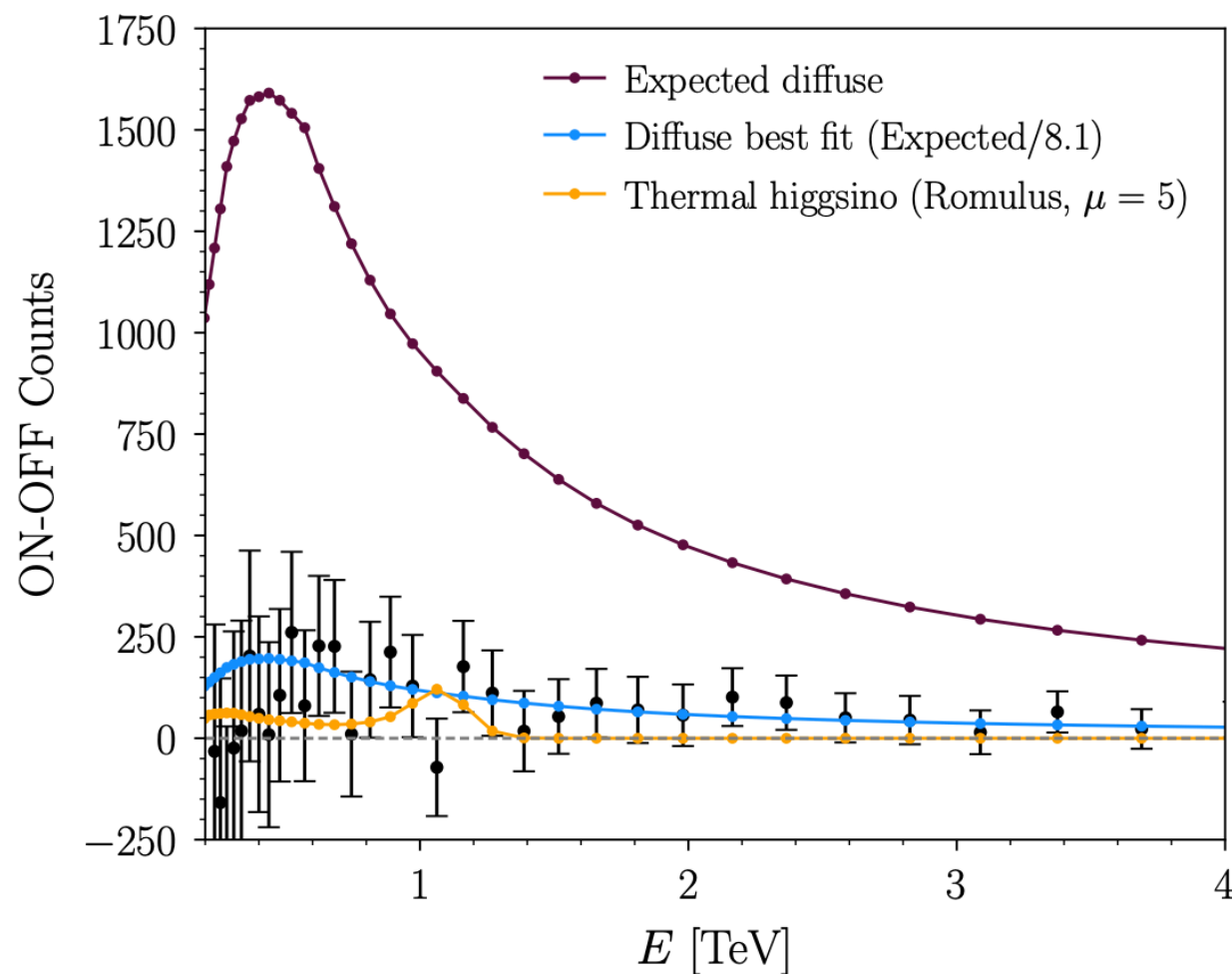
CTAO-South vs North



[Abe, Inada, Moulin,
NLR, Safdi, Xu 2026]

An Issue with HESS?

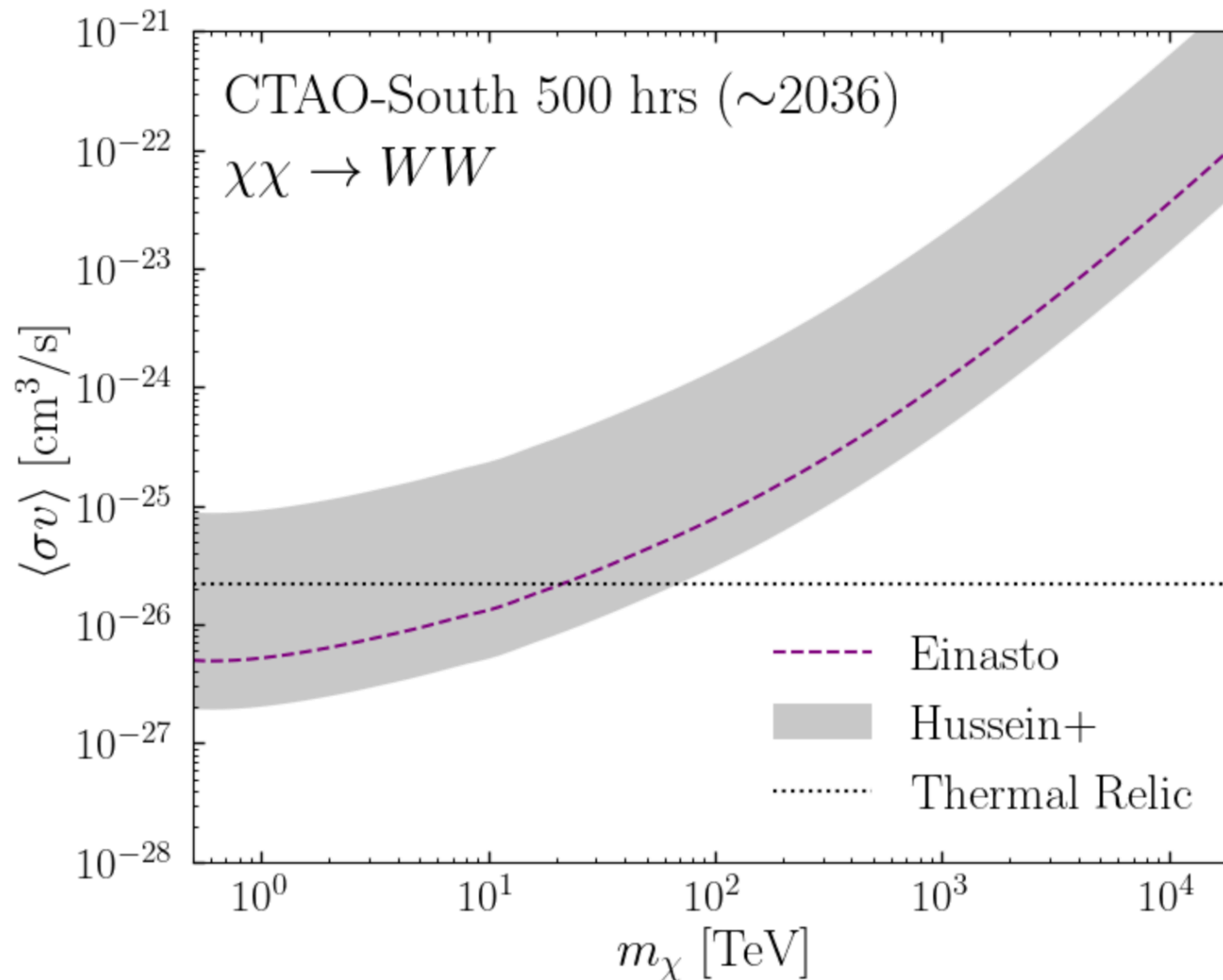
HESS data appears inconsistent with expected diffuse emission



[NLR, Safdi, Xu 2024]

Generic CTA0 Sensitivity

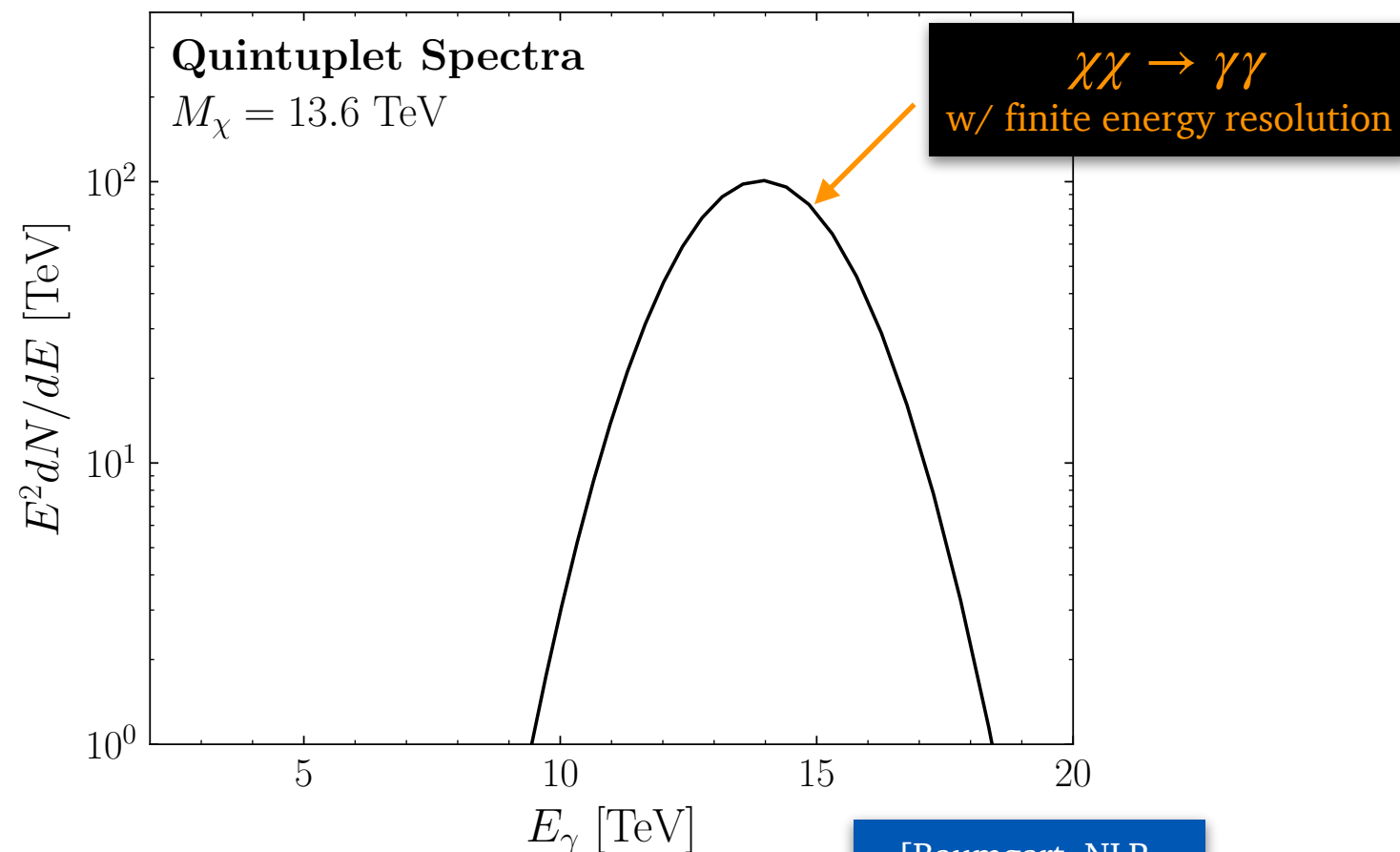
CTAO-South sensitivity w/ 5 years of data



EFT Calculations

Dark matter annihilation flux

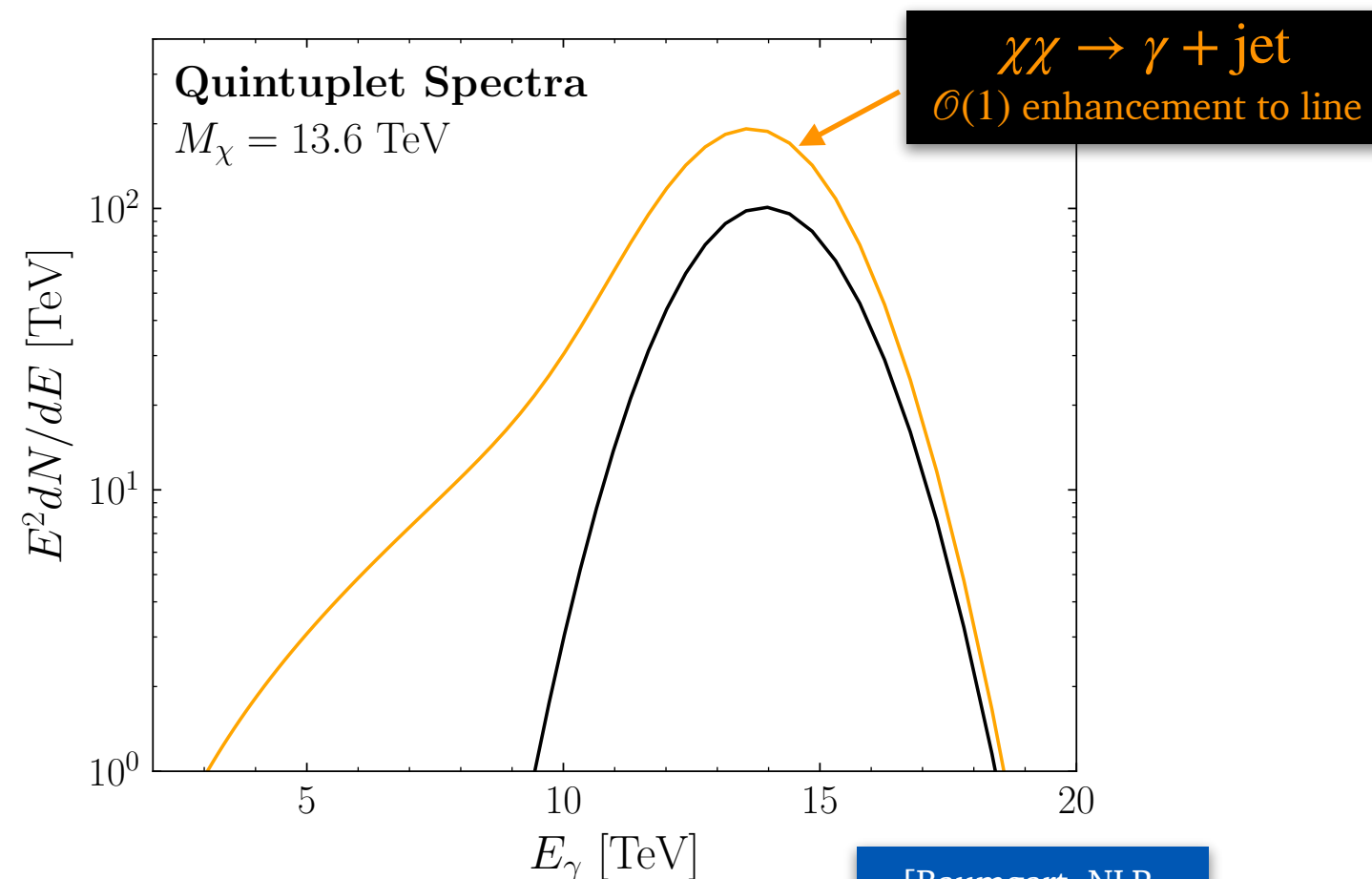
$$\frac{d\Phi}{dE} = \underbrace{\frac{\langle\sigma v\rangle}{8\pi M_\chi^2}}_{\text{Particle Physics}} \frac{dN}{dE} \times \int ds \rho_{\text{DM}}^2(s)$$



EFT Calculations

Dark matter annihilation flux

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

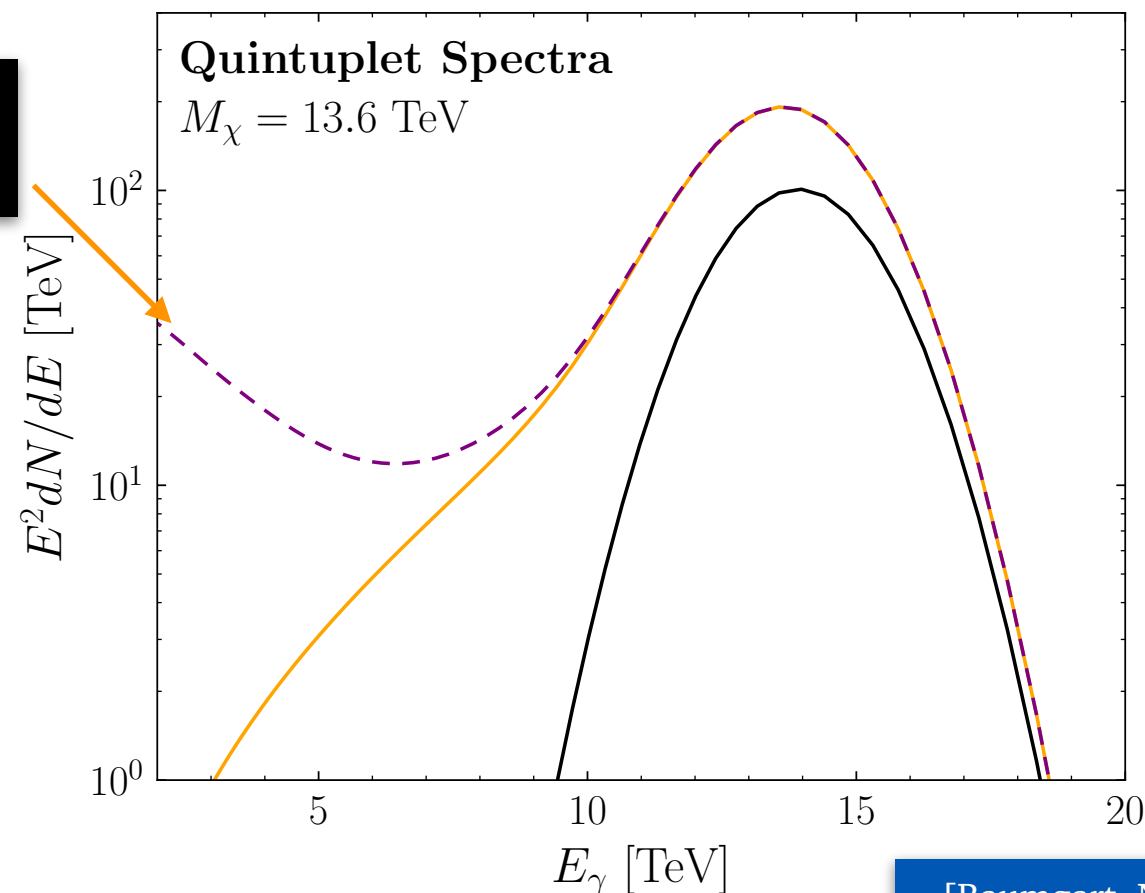


EFT Calculations

Dark matter annihilation flux

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

$\chi\chi \rightarrow WW, ZZ, BS$
Dominates at low energies

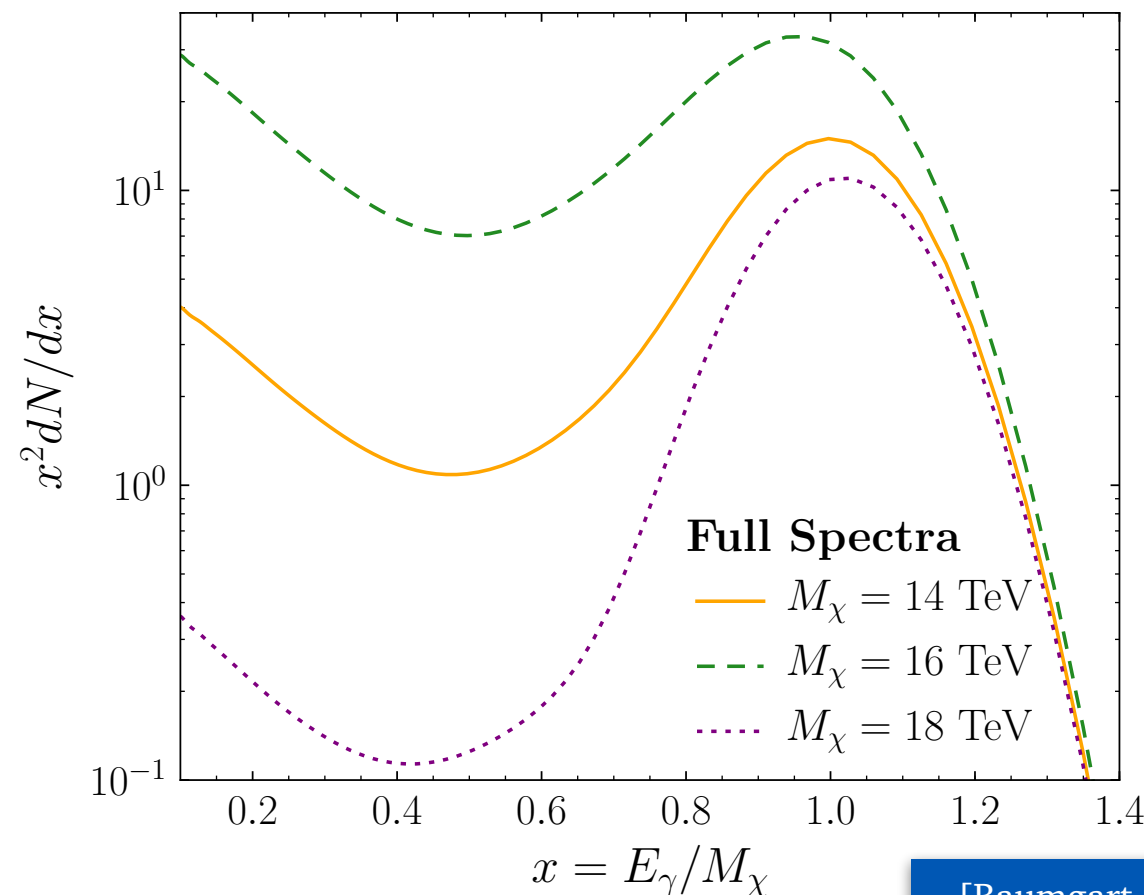


[Baumgart, NLR,
Slatyer, Vaidya 2024]

EFT Calculations

Dark matter annihilation flux

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



Novel effect for higher reps:
Sommerfeld channels interfere
 $\Rightarrow$ spectrum depends strongly
on mass

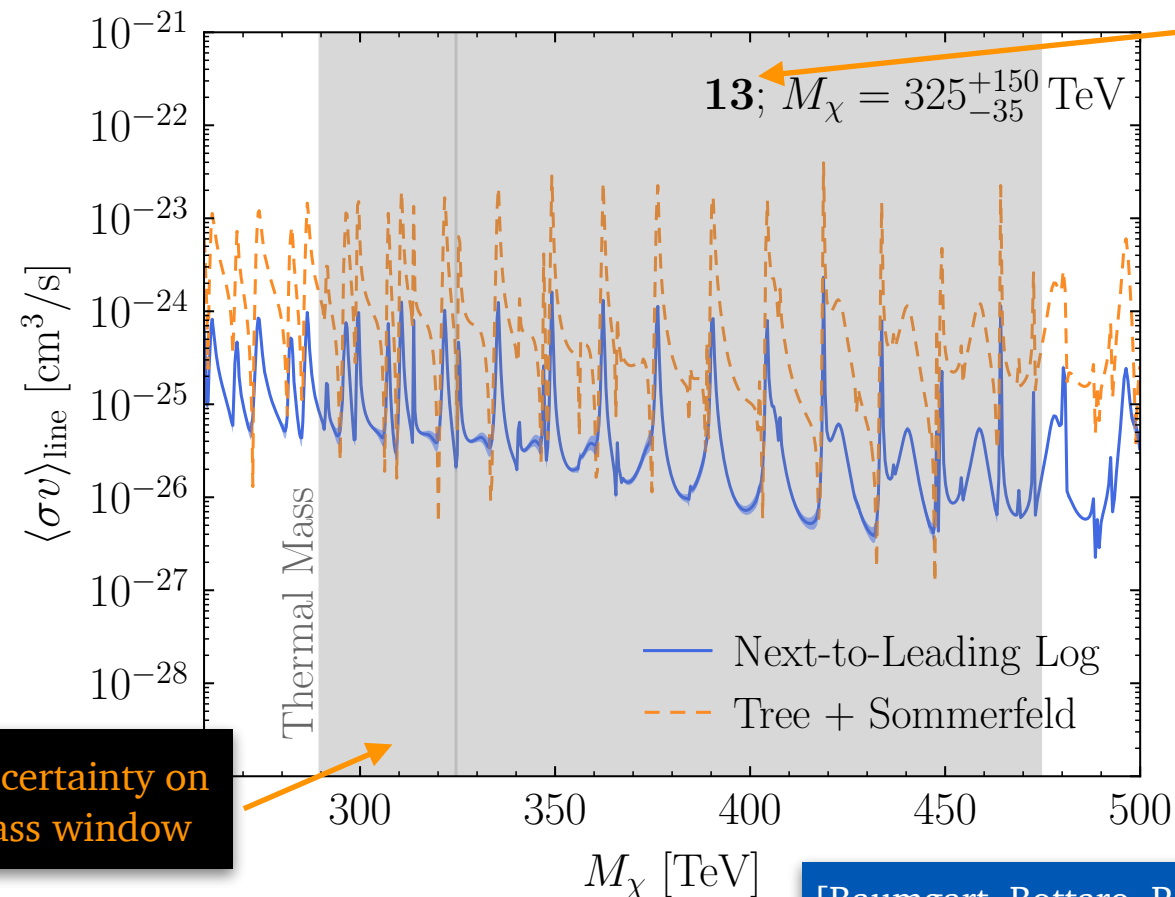
EFT Calculations

Dark matter annihilation flux

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

Particle Physics

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



Large theory uncertainty on the thermal mass window

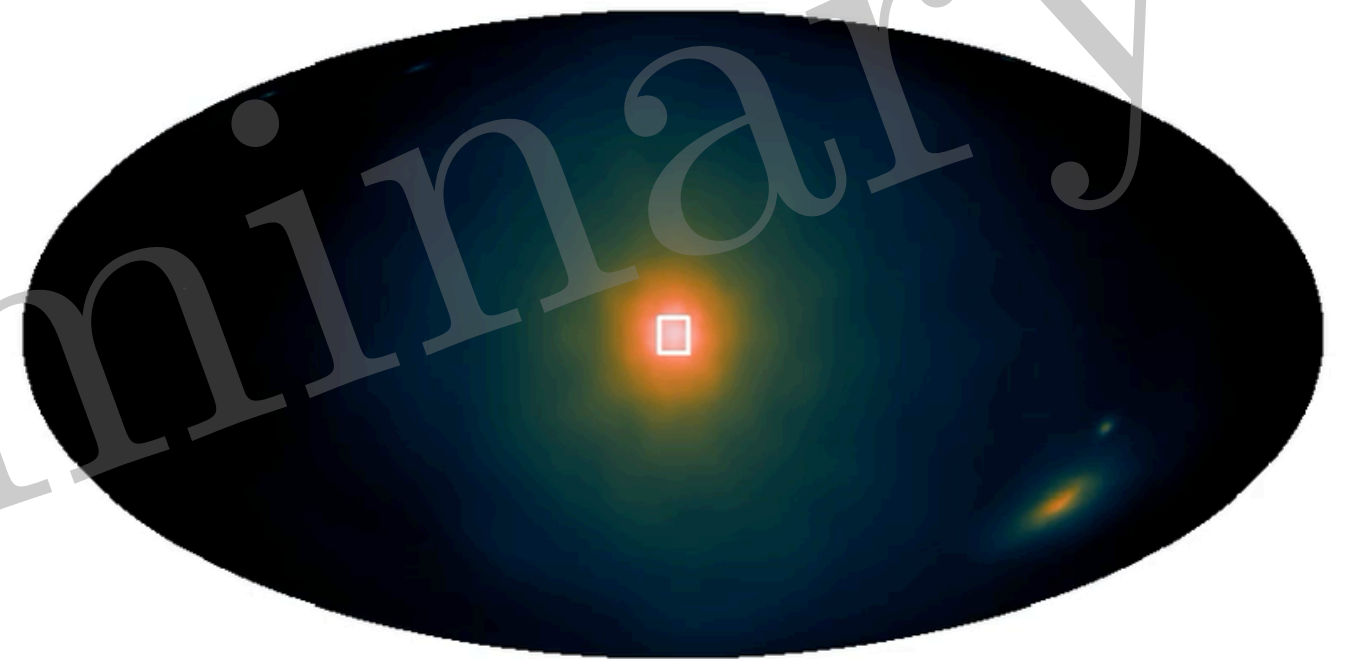
[Baumgart, Bottaro, Redigolo, NLR, Slatyer 2026]

Indirect Detection

The DREAMS Project

DaRk mattEr and Astrophysics with Machine learning and Simulations

From 24 to 1,000 Milky Way like halos

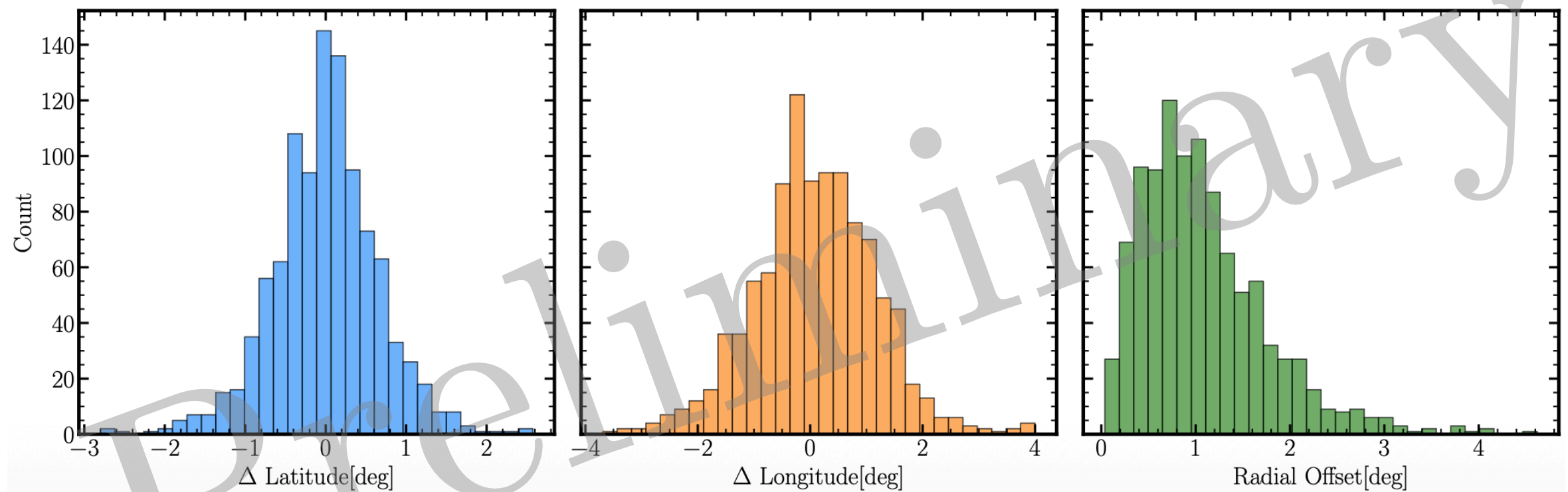


Indirect Detection

The DREAMS Project

DaRk mattEr and Astrophysics with Machine learning and Simulations

From 24 to 1,000 Milky Way like halos



Generically off-center
Elongated along the plane