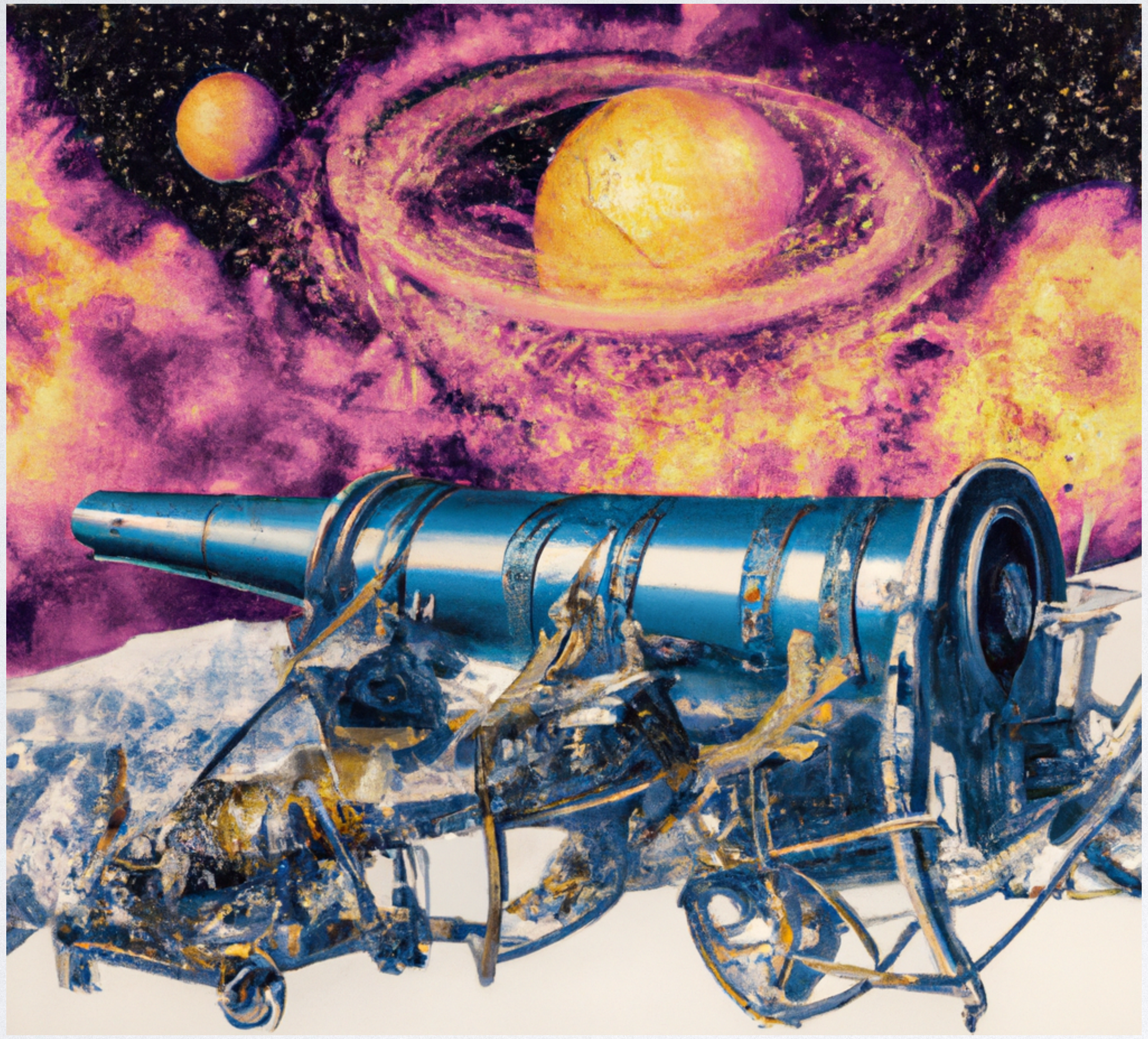
ATTACKING **HEAVY DARK MATTER** ON 2 FRONTS



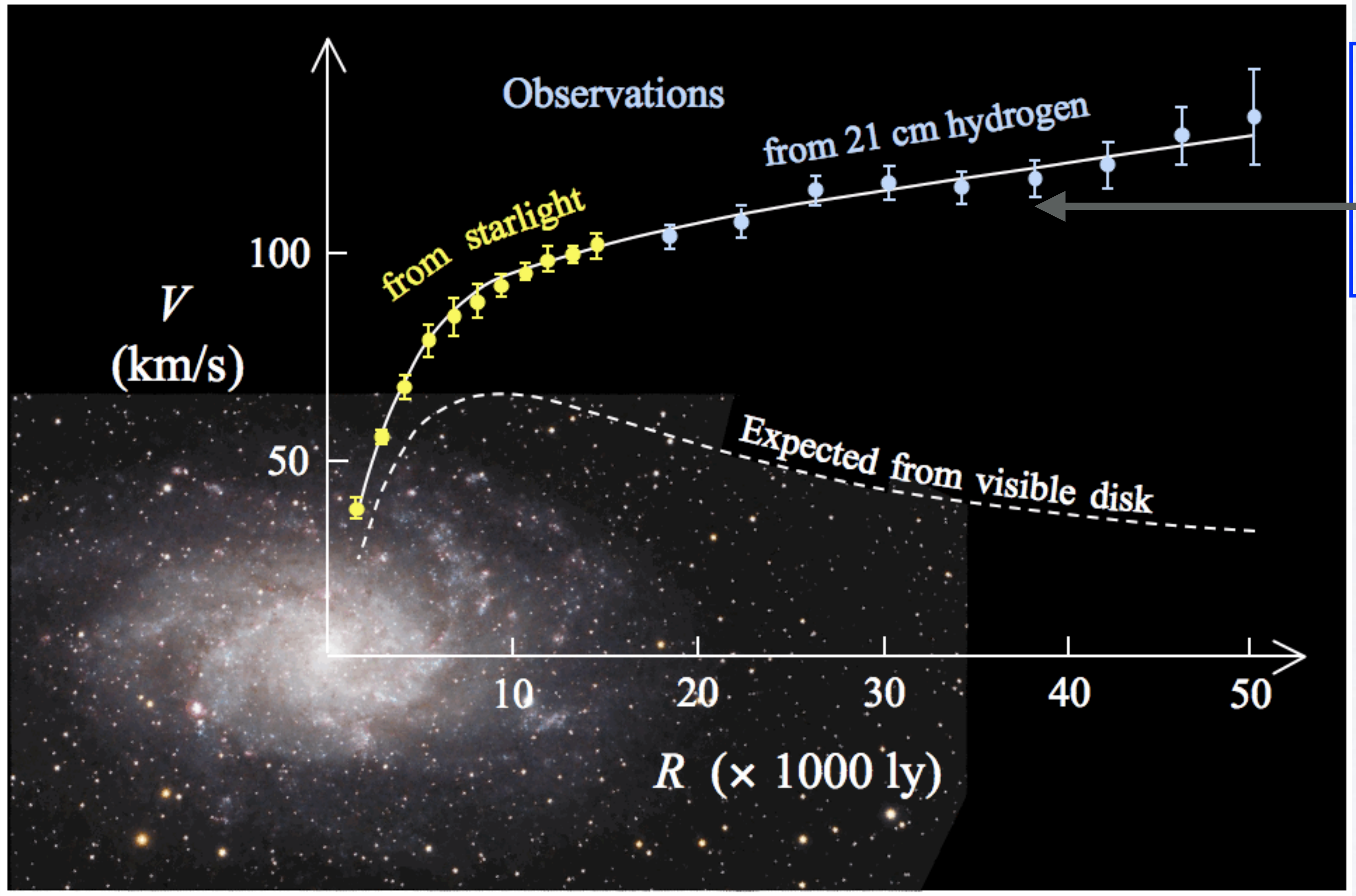
Matthew Baumgart (ASU)

Arizona State University

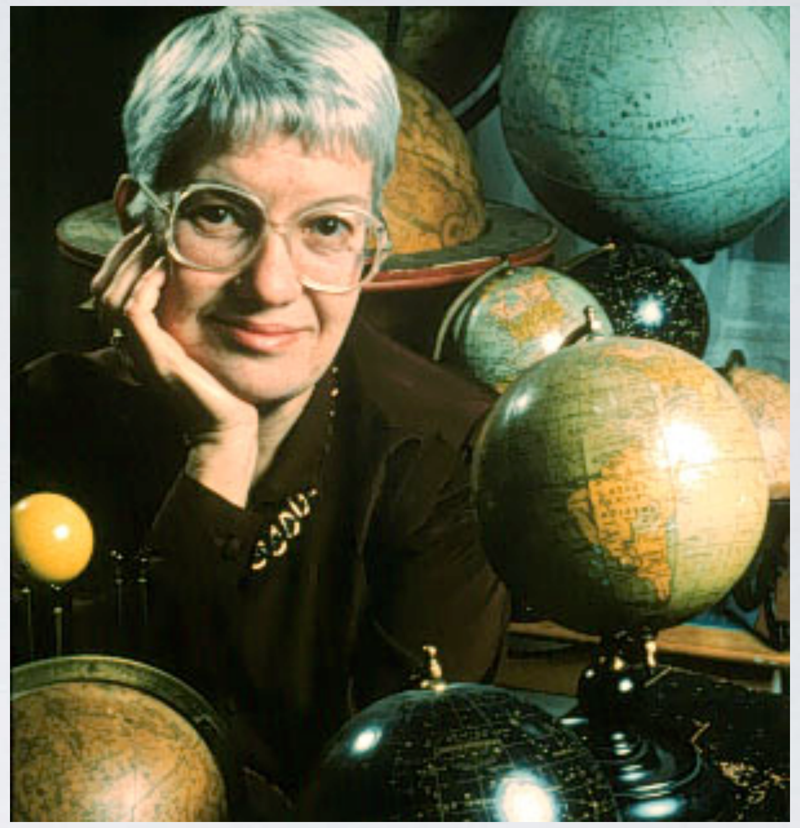
TeVPA 2023: Napoli 09/14/2023

WHY DARK MATTER?

Anomalies on 3 different astrophysical scales!



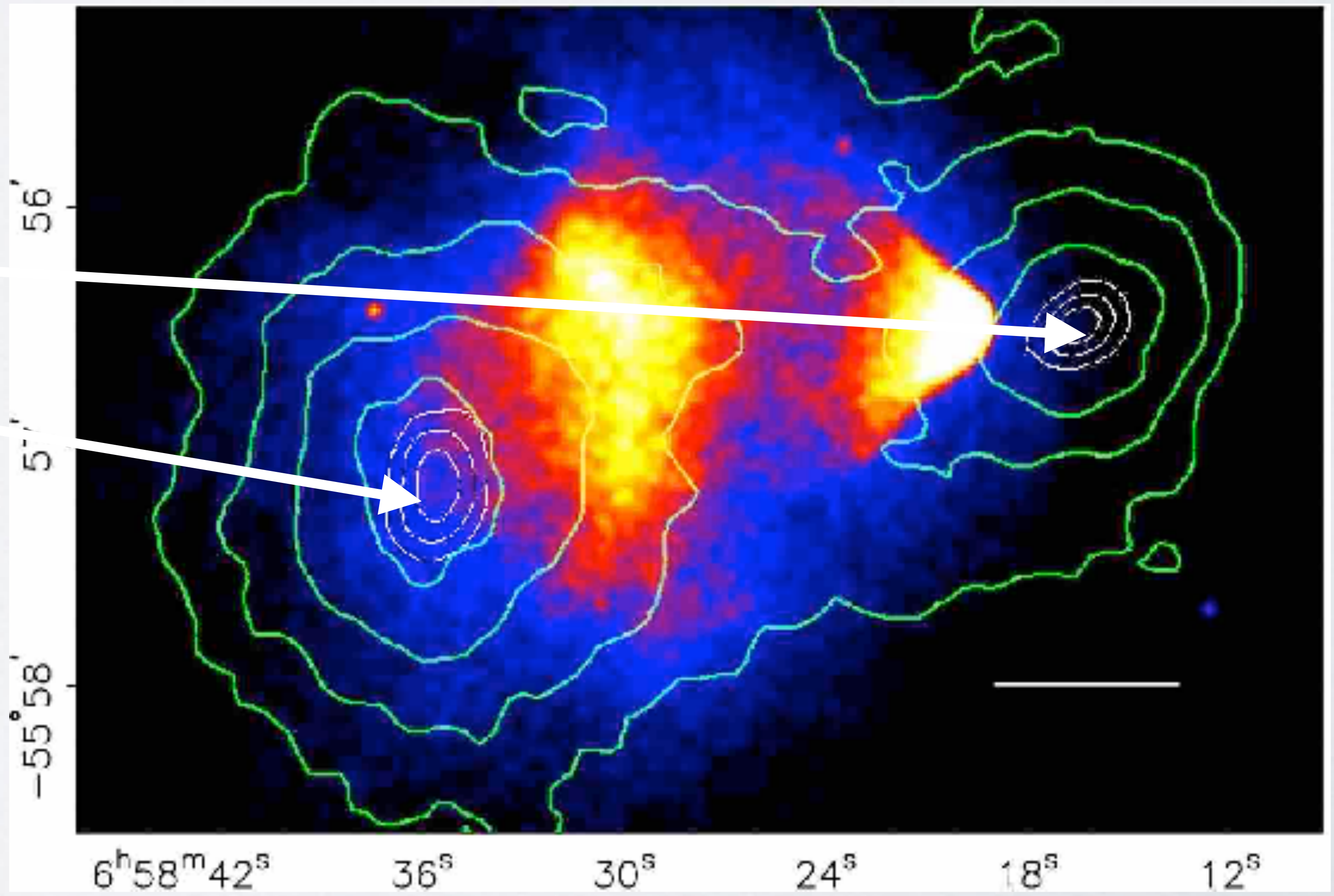
Galactic Rotation curves:
Stars move faster than expected



Vera Rubin 1928-2016
Established Rotation Curve anomaly

Colliding Clusters:
Gravitational wells nowhere near visible peaks

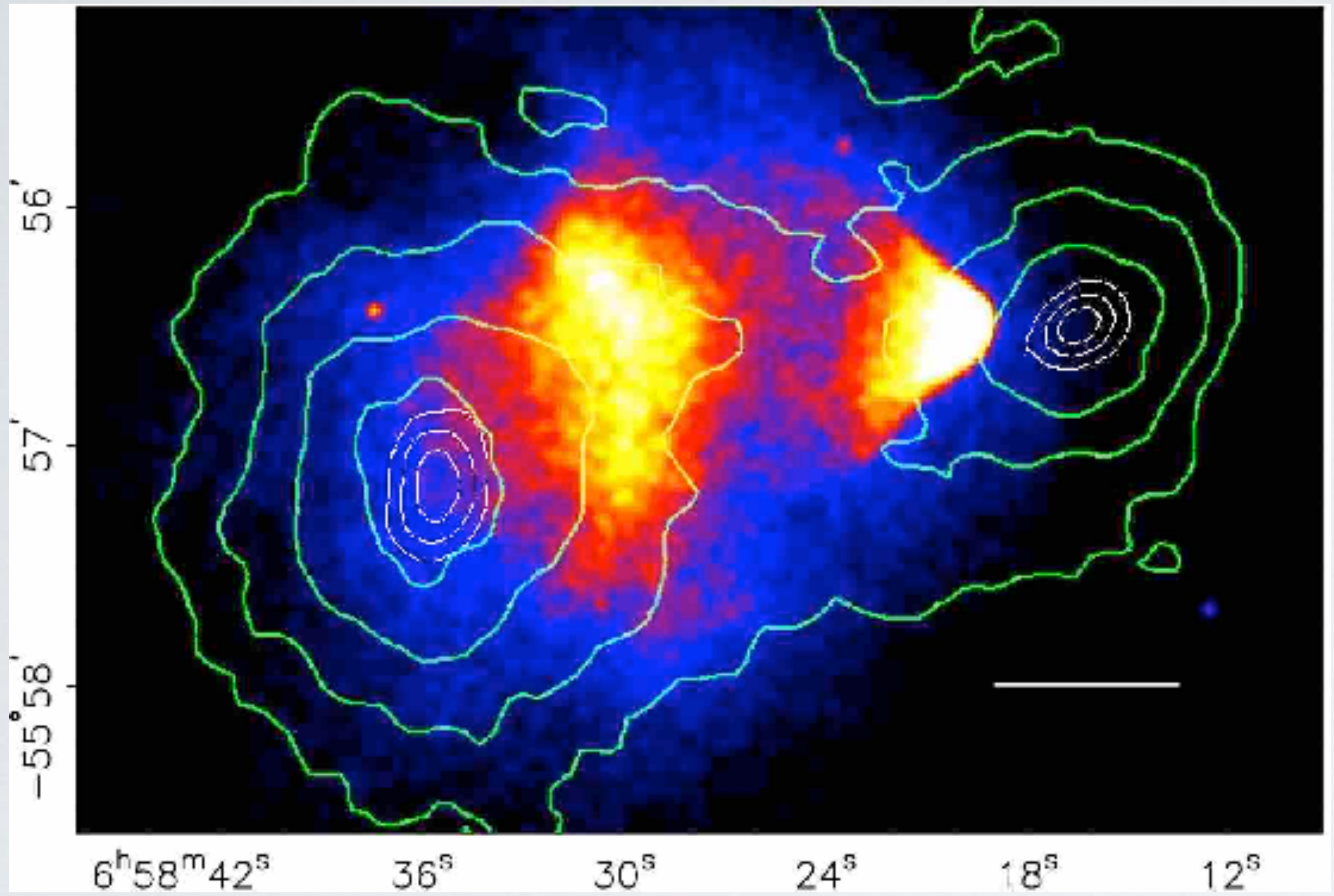
"Not modified gravity"



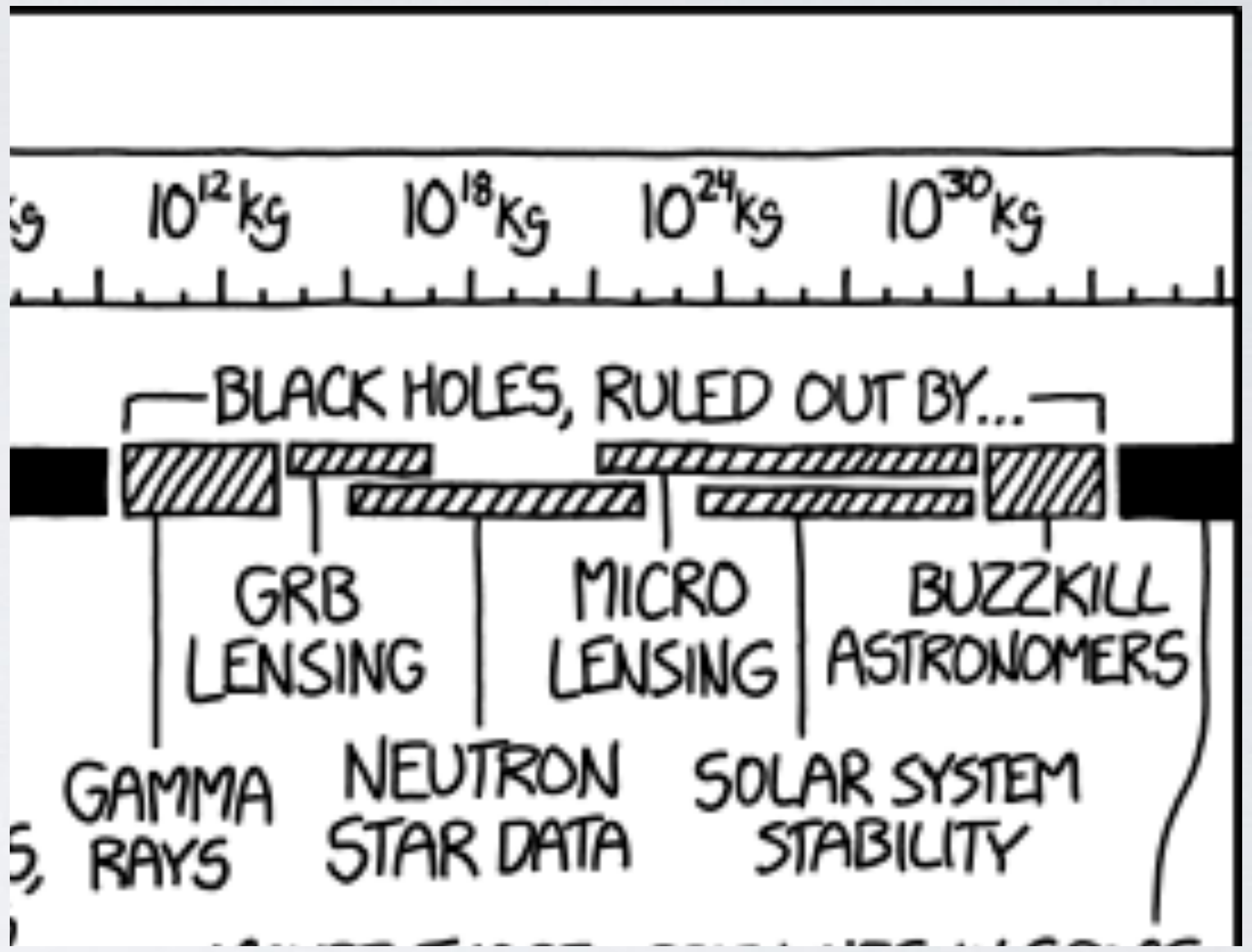
Cosmic Microwave Background:
Fluctuations measure Dark Matter as 27% of Universe's energy (Planck)

IS IT?

~~Something like Gravity?~~



~~Something like Black Holes?~~



XKCD (2018) cf. 1705.05567

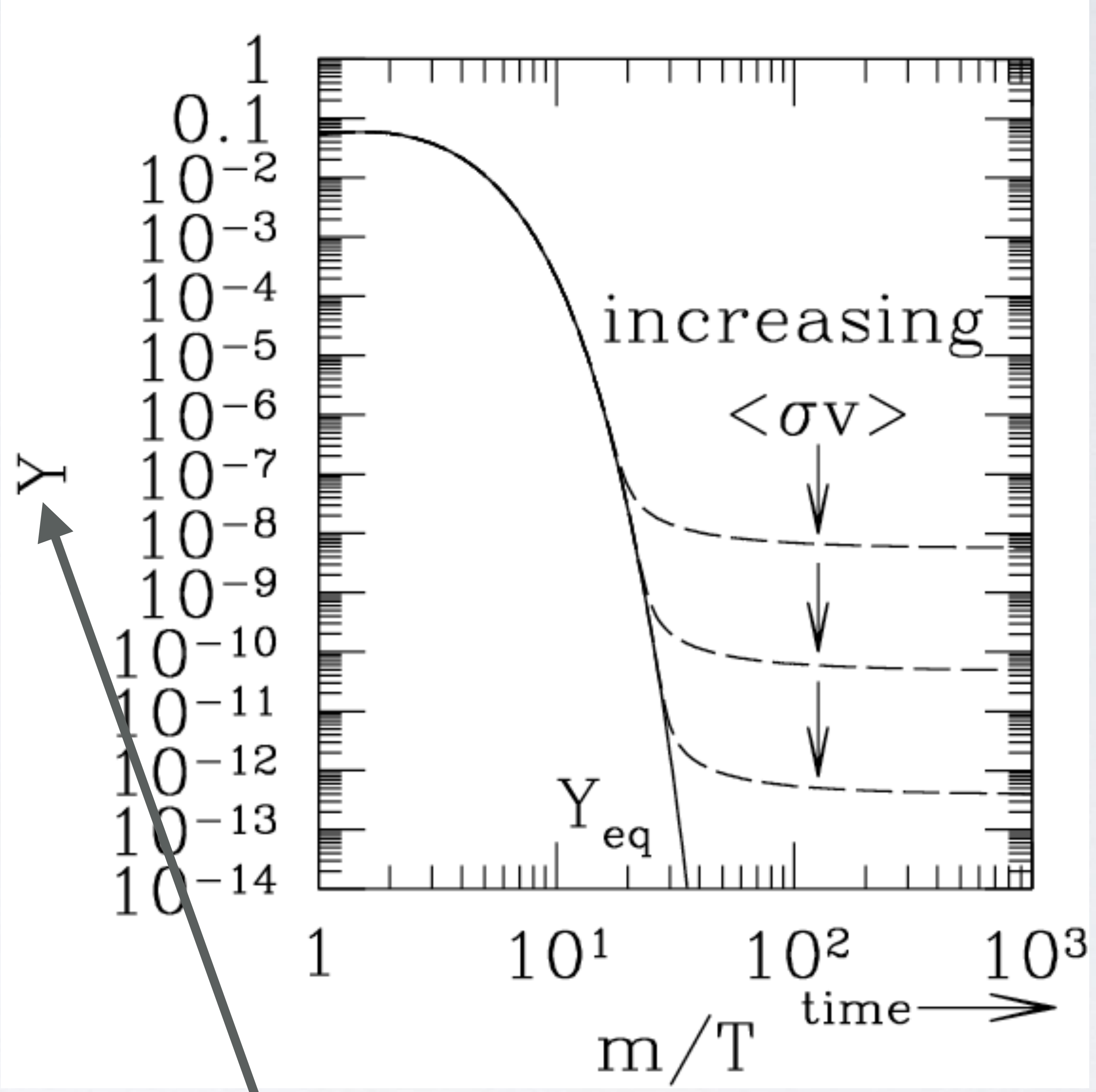
Cf. Serpico talk

Something like a neutrino!

WIMP MIRACLE

$$\Omega_{\rm DM} \sim \frac{1}{10^3 \langle \sigma v \rangle} \frac{1}{T_{\rm CMB} M_{Planck}} \sim \frac{1}{10^3 \langle \sigma v \rangle} \frac{1}{{\rm TeV}^2}$$

$$\boxed{M_\chi \sim {\rm TeV}\left(10\sqrt{C}\alpha\right)\sqrt{\frac{\Omega_{\rm DM}}{0.27}}}$$

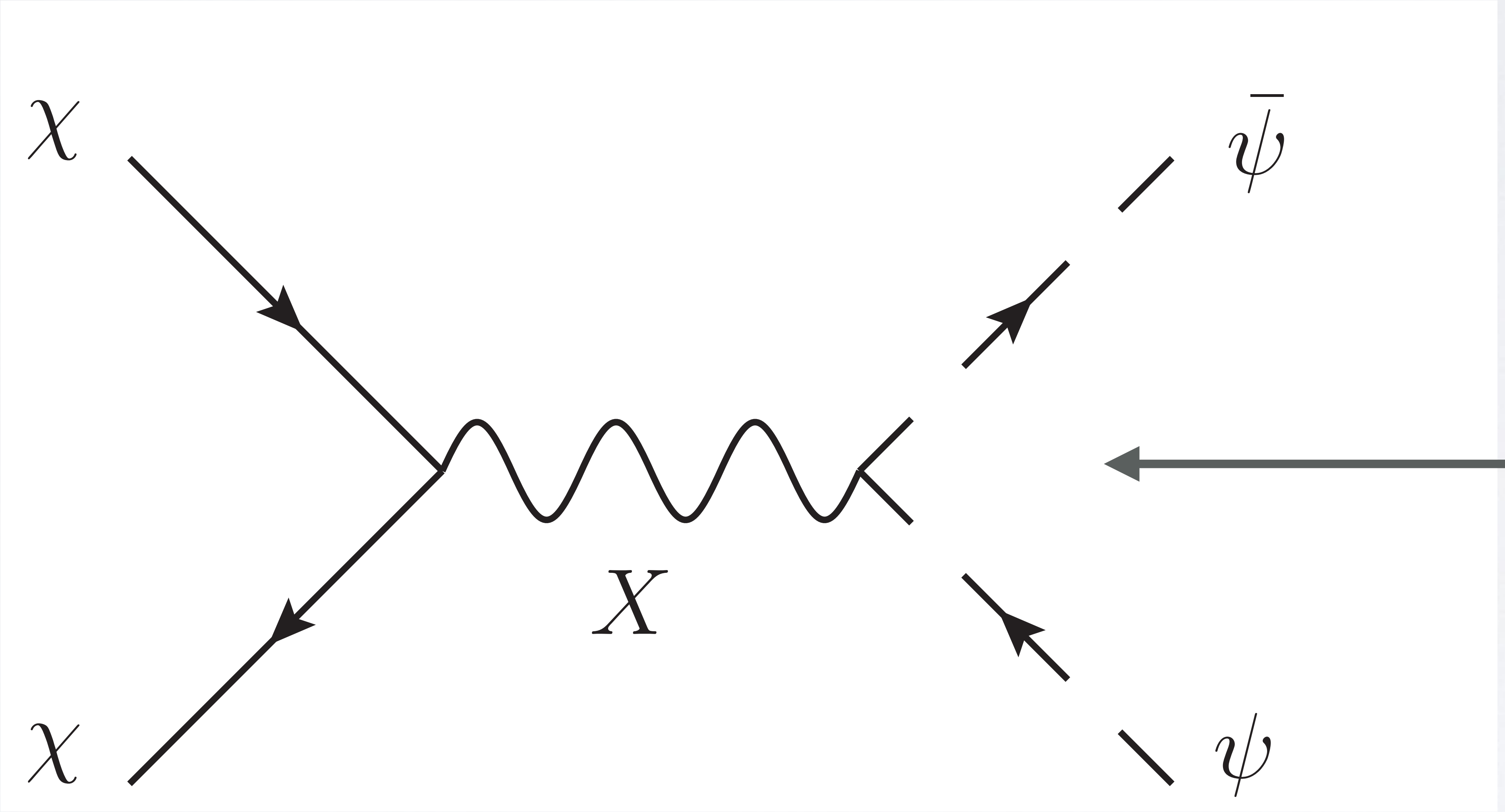


WIMP can be simple addition
to known particles & forces.
WHY?

DM density decreases:
Ω: Annihilation & expansion
Y: Annihilation

See Dimopoulos PLB 246(1990):347-52

STARTING SIMPLE W/ WIMPS



Maybe we already know
everything here **except χ?**
X: Z-boson, Higgs?
ψ: Elementary Fermion, Higgs?
α: α_{weak}?

$\langle\sigma v\rangle_{annihilation} \sim C\,\alpha^2/M_X^2$

UNITARITY LIMIT

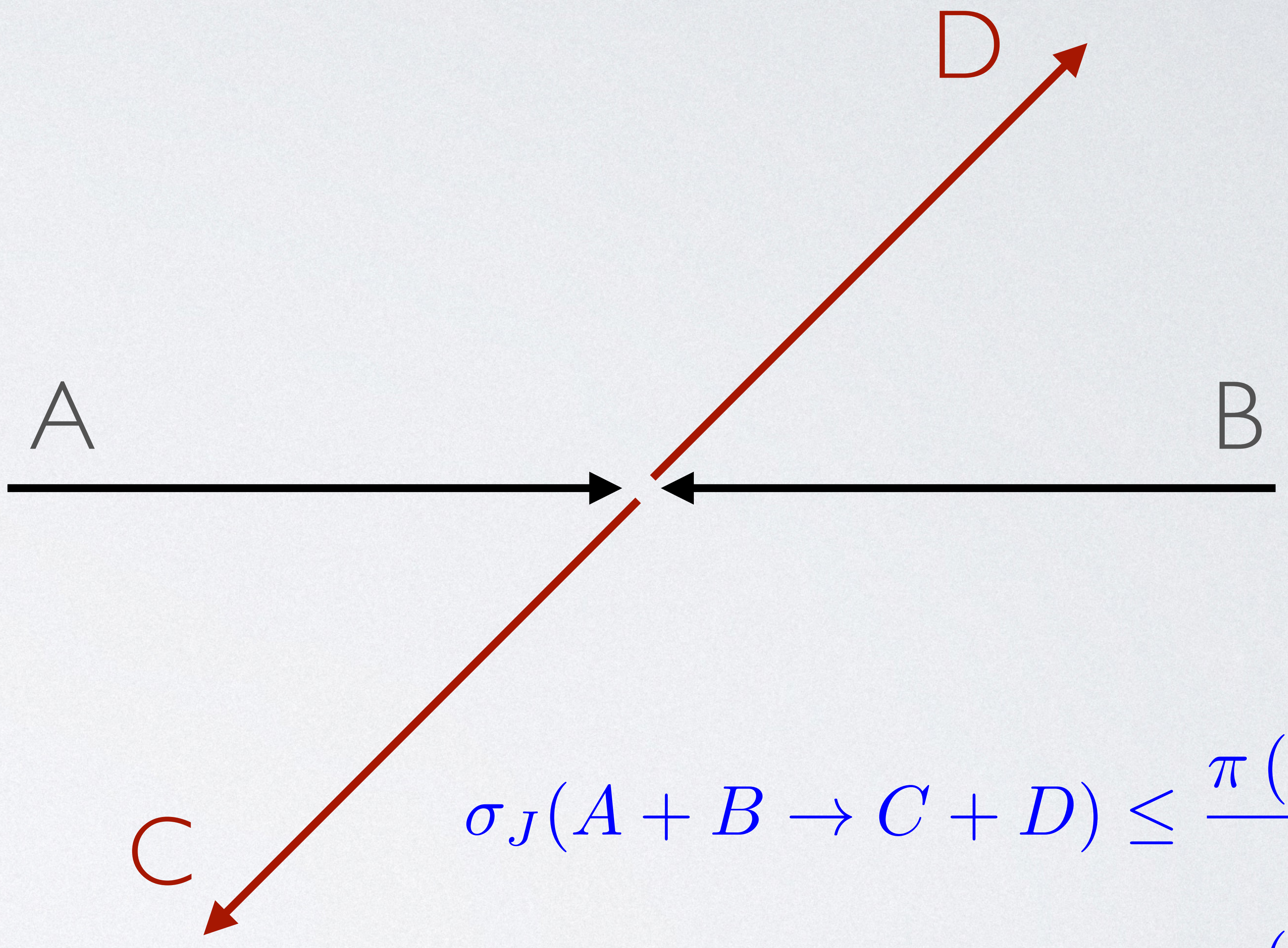
- Dark matter **relic abundance**
  $\Omega h^2 = 0.12$ set by annihilation cross section

- Unitarity precludes too-large DM mass

  - < 116 TeV (Unenhanced in early Universe)

  - **< 194 TeV** (Saturating Unitarity throughout)

- Particles with $\sigma v \ll 2.5 \times 10^{-26}$ cm^3/s inconsistent with observation.



$$\sigma_J(A + B \to C + D) \leq \frac{\pi\,(2J+1)}{p_i^2}$$

$$(\sigma_J)_{\max}\, v_{\rm rel} = \frac{\pi\,(2J+1)}{M_\chi^2 v_{\rm rel}}$$

K. Griest & M. Kamionkowski: PRL 64 (1990)

TWO FRONTS IN HEAVY DARK MATTER

- **Electroweak WIMPs** (Specific models, precise calculations, Effective Field Theory crucial)

- **Ultra-Heavy Dark Matter (UHDM)** (Bottom-up, precise cosmology unspecified, model-building opportunities)

- **"Right here, right now" tests** via indirect detection

VERITAS γ-ray telescope at dusk

FRONT 1: "HEAVY NEUTRINO" WIMP

Weak Force "Charges"

Simple Candidates!

Dark Matter ↔ Weak Scale:

Weak Triplet: "Wino"

Weak Doublet: "Higgsino"

Weak Quintuplet

$\Omega_{DM} = 0.27$

Measured Dark Matter Density

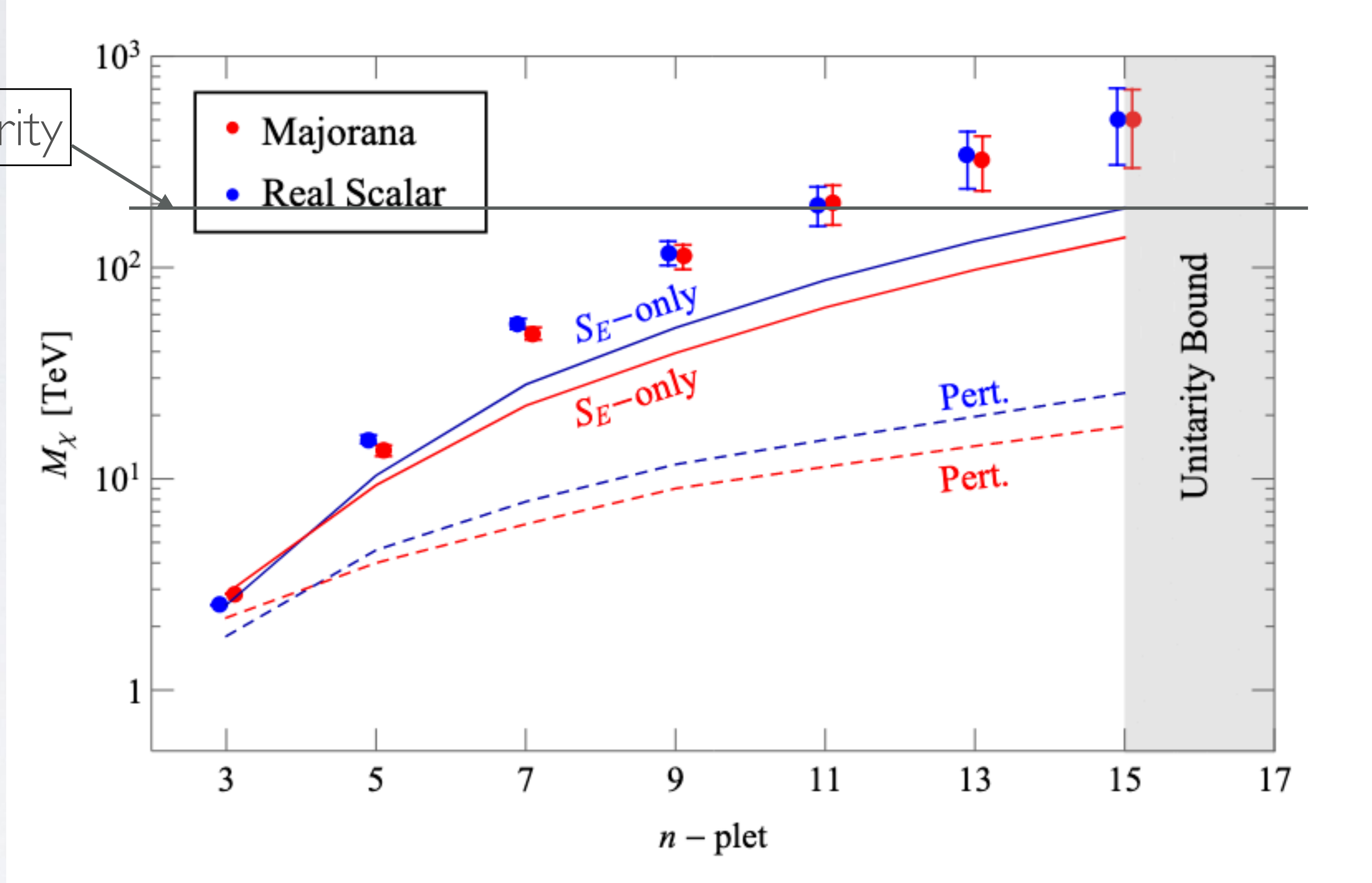
Correct Dark Matter Density fixes M_χ:

Wino: 3 TeV

Higgsino: 1 TeV

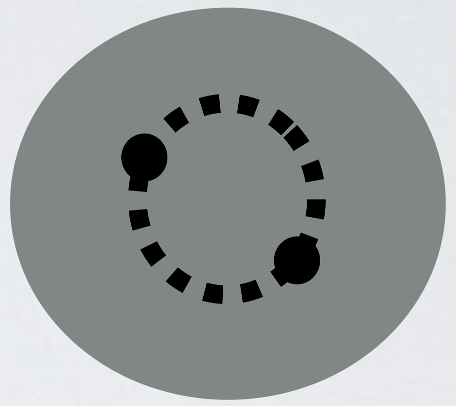
Quintuplet: 14 TeV

Naive Unitarity

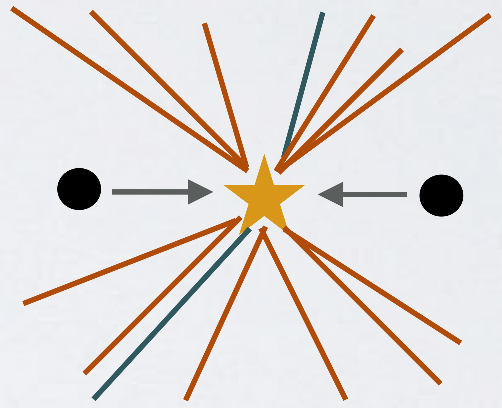


2107.09688: Bottaro et al.
Simple thermal relic masses for real reps of SU(2)

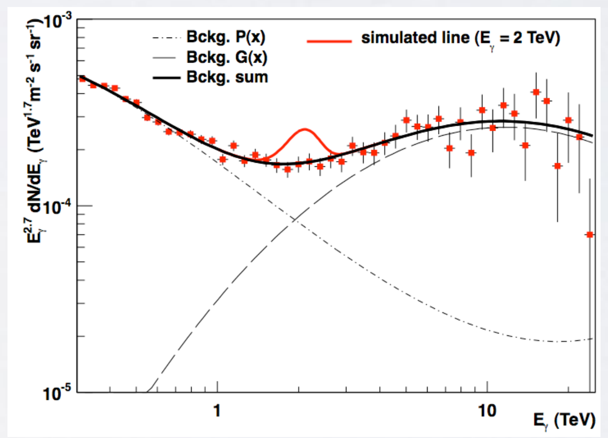
- **3 separate threats to perturbation theory!**
  - $M_X/m_W >> 1 \rightarrow$ Long range force



  - $M_X/m_W >> 1 \rightarrow$ Electroweak shower



  - $\text{Log}(1\text{-}z_{cut}) \rightarrow$ Phase space restriction



- Proliferation of scales $\rightarrow$ **Effective Field Theory**

EFTs: Modified versions of Soft-Collinear Effective Theory
&
NRQCD

LL RESUMMED PHOTON SPECTRUM FROM WINO

$$
\begin{aligned}
\frac{d\sigma}{dz} = \frac{\pi\alpha_W^2 \sin^2\theta_W}{2M_\chi^2 v} e^{\left[-2C_2(W)\frac{\alpha_W}{\pi}\log^2\left(\frac{2M_\chi}{M}\right)\right]} \Bigg\{ & (F_0 + F_1)\delta(1-z) \\
+ & \left(C_2(W)\frac{\alpha_W}{\pi}\log\left(\frac{4M_\chi^2(1-z)}{M^2}\right) \frac{e^{\left[C_2(W)\frac{\alpha_W}{2\pi}\log^2\left(\frac{M^2}{4M_\chi^2(1-z)}\right)\right]}}{1-z}\right)_+ F_0 \\
+ & \Bigg[\left(C_2(W)\frac{\alpha_W}{\pi}\log\left(\frac{4M_\chi^2(1-z)}{M^2}\right) + 3C_2(W)\frac{\alpha_W}{\pi}\log\left(\frac{M}{2M_\chi(1-z)}\right)\right) \\
\times & \left(\frac{e^{\left[-\frac{3}{2}C_2(W)\frac{\alpha_W}{\pi}\log^2\left(\frac{M}{2M_\chi(1-z)}\right) + C_2(W)\frac{\alpha_W}{2\pi}\log^2\left(\frac{M^2}{4M_\chi^2(1-z)}\right)\right]}}{1-z}\right)\Bigg]_+ F_1 \Bigg\}
\end{aligned}
$$

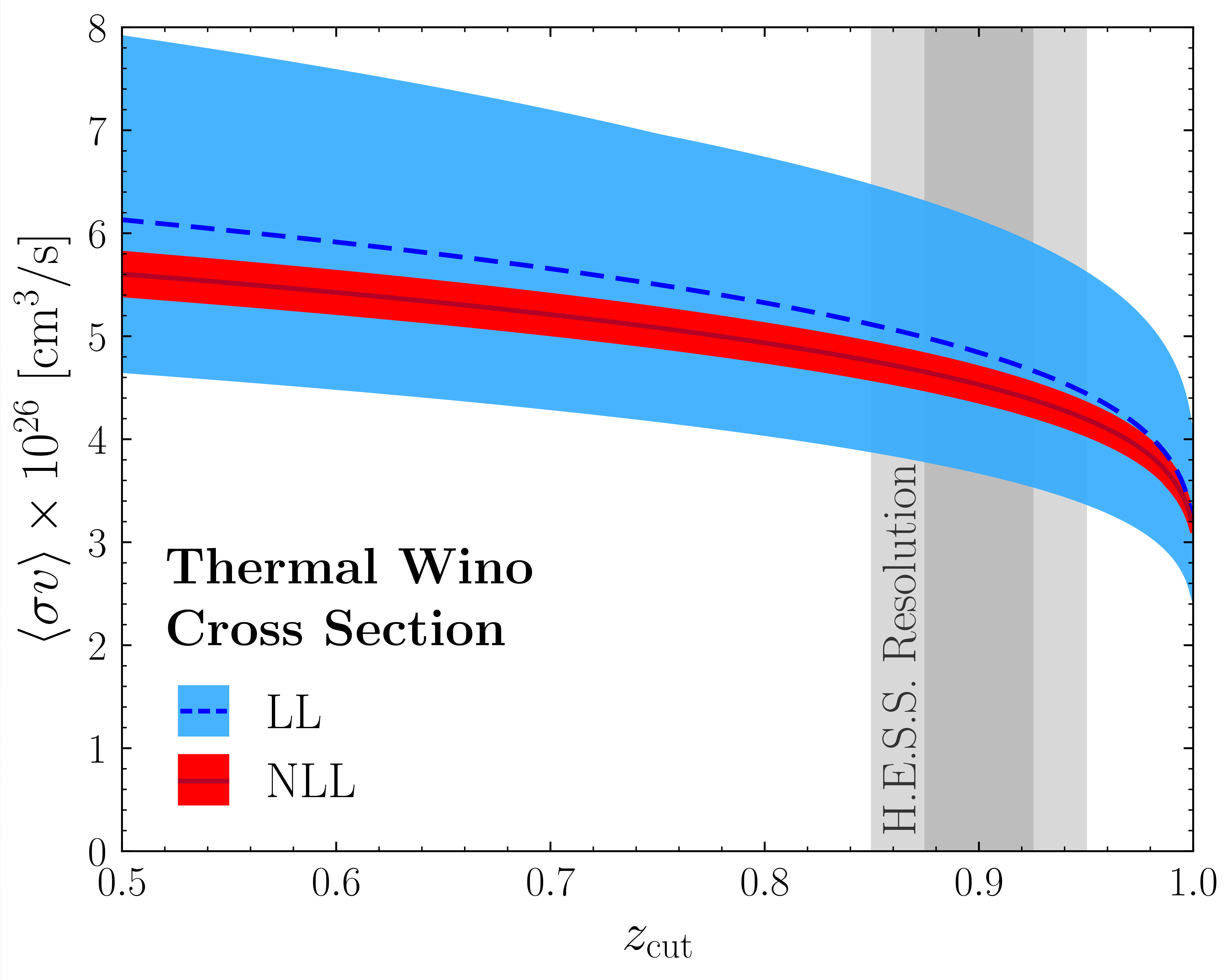
MB et al.: 1712.07656

MB, N. Rodd, T. Slatyer, and V. Vaidya: 2309.xxxxx
Same result for any real SU(2) representation with appropriate $F_{0,1}$

Factorization holds to NLL!
MB et al.: 1808.08956

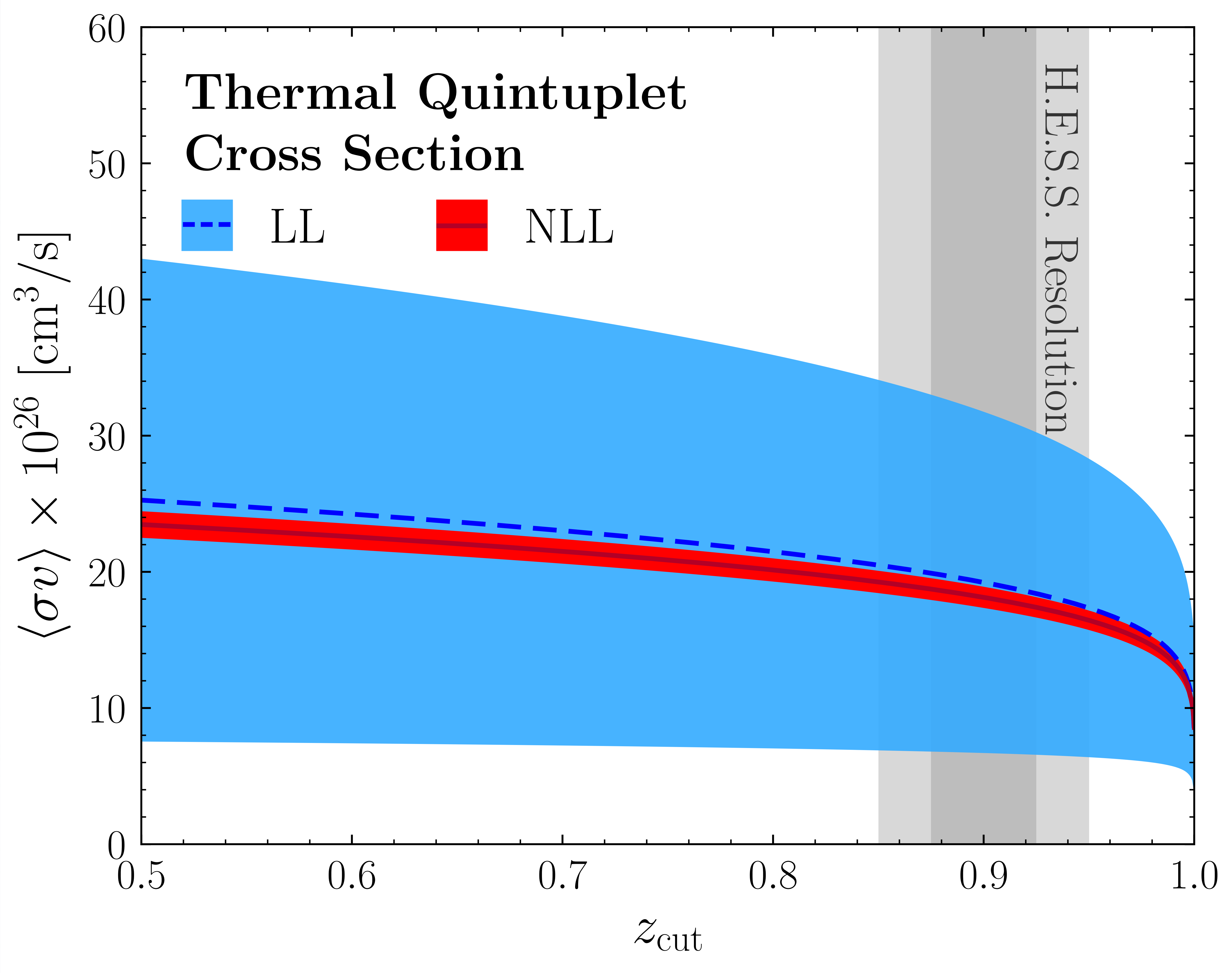
Linear combination of Sommerfeld factors

CUMULATIVE RESUMMED ANNIHILATION RATES
@THERMAL RELIC MASSES



Thermal relic wino rate vs. Energy fraction

MB et al.: 1808.08956

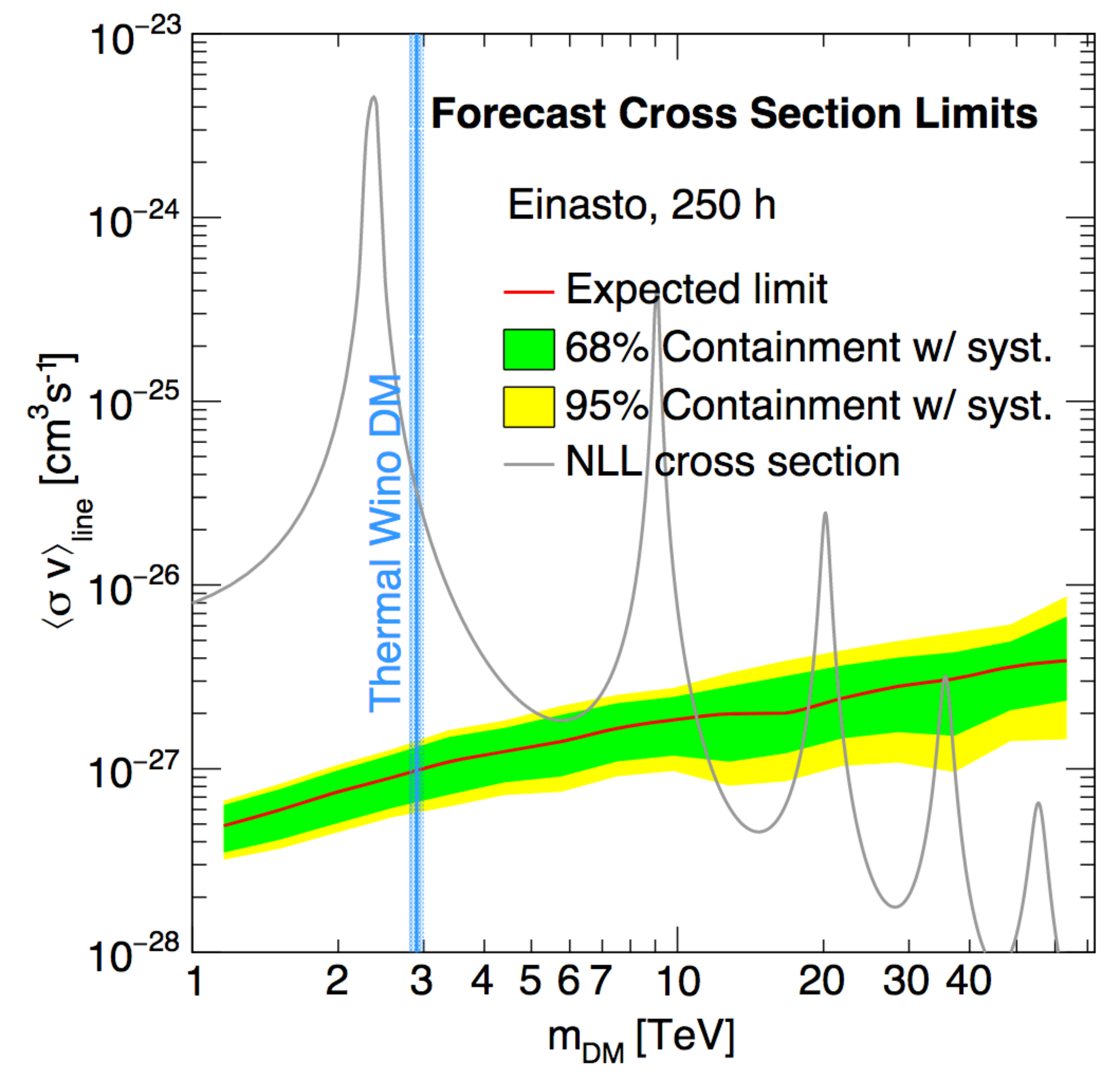


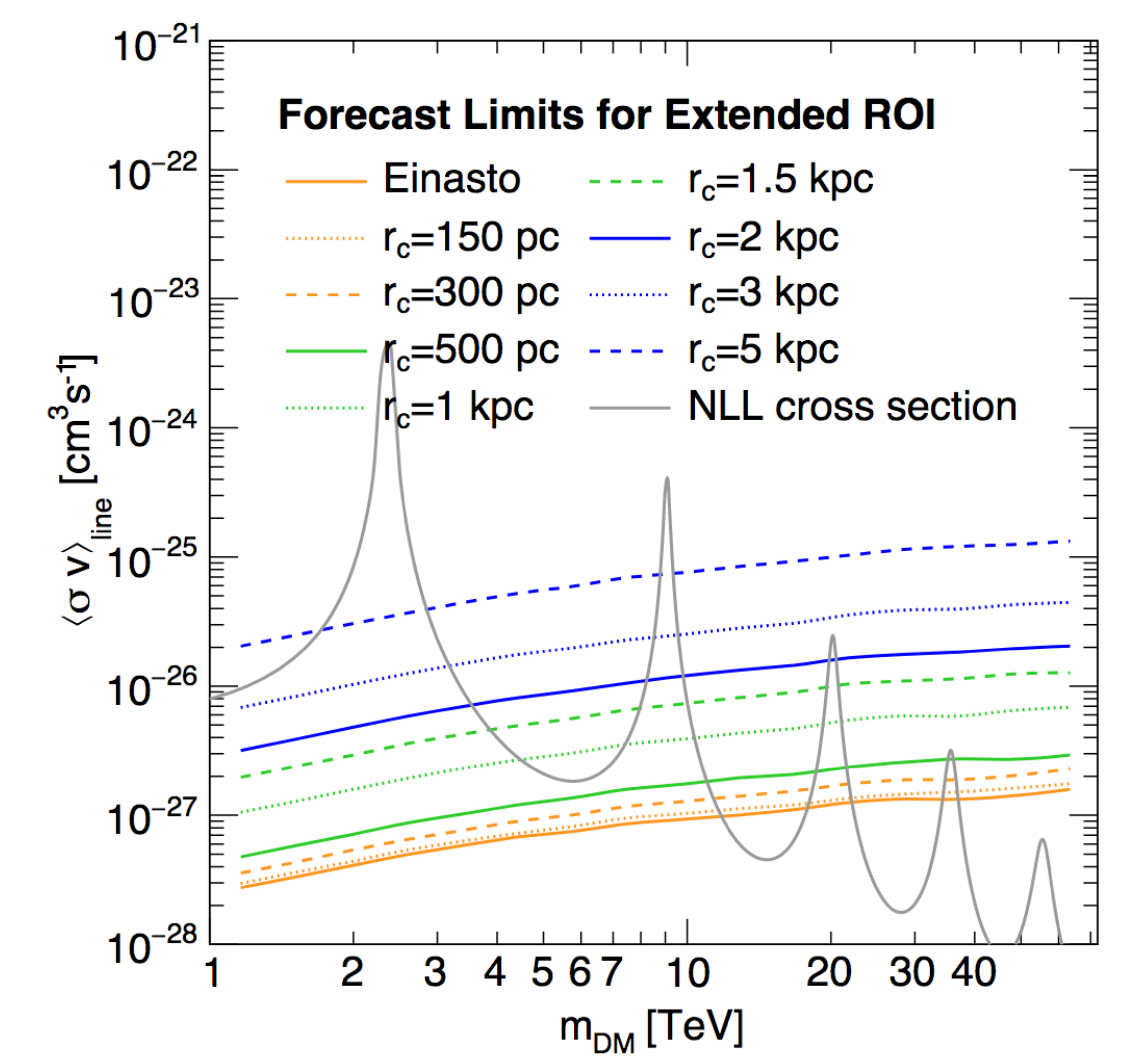
Thermal relic quintuplet rate vs. Energy fraction

MB, N. Rodd, T. Slatyer, and V. Vaidya: 2309.xxxxx

PROJECTED HESS WINO LIMITS

Rinchiuso et al.: 1808.04388



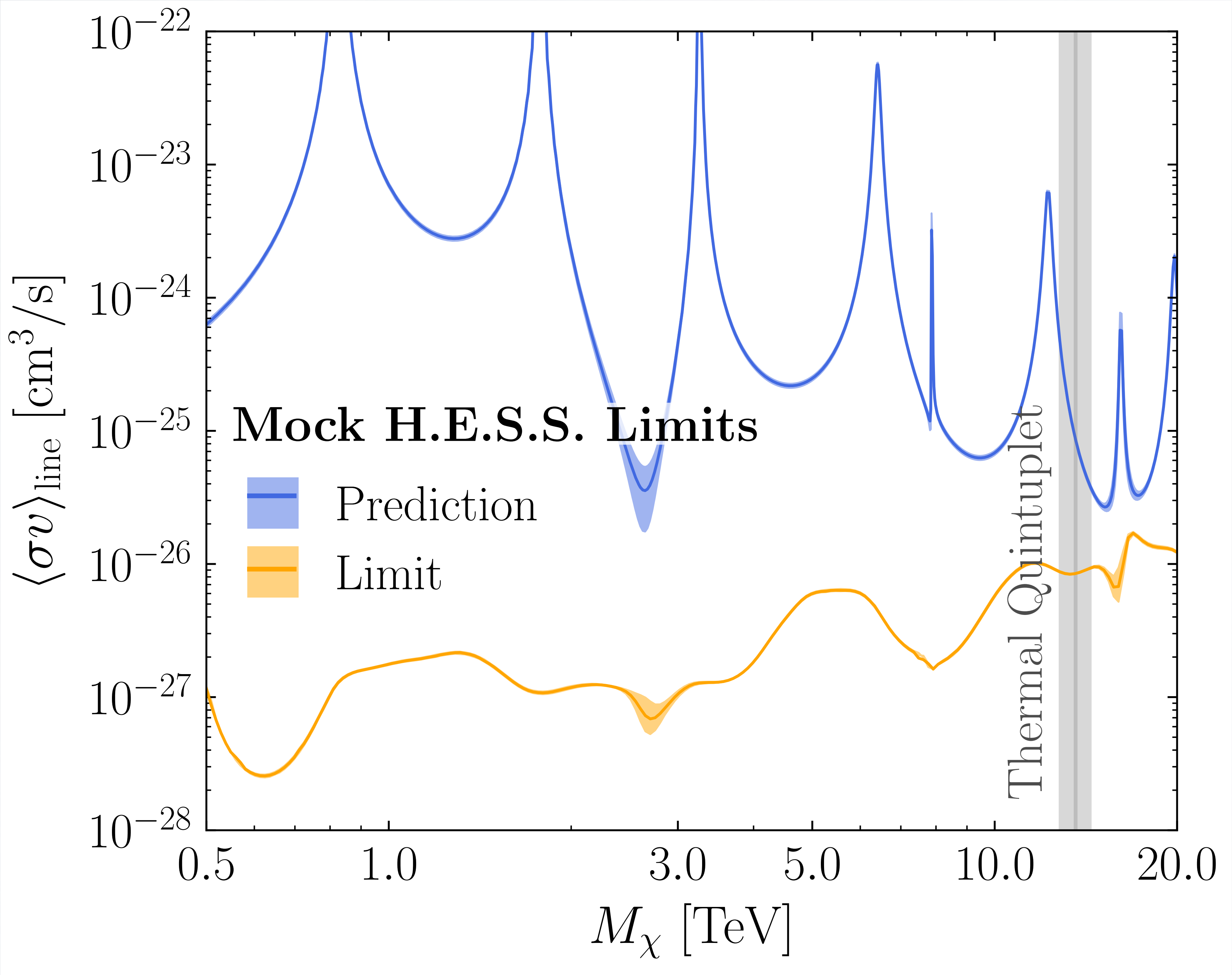


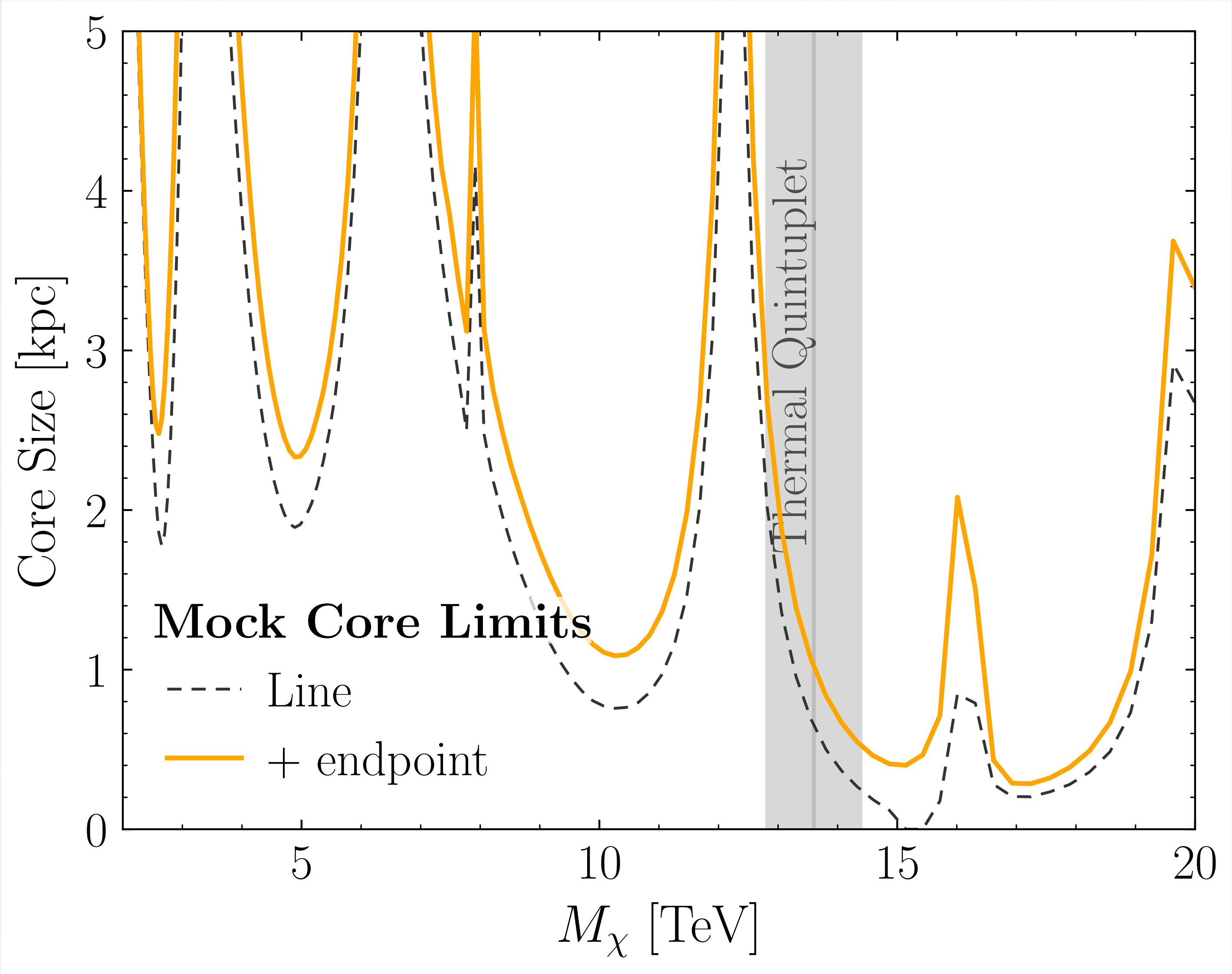
Update to HESS 2013
analysis projected to rule out by 30x,
halo loophole 1-1.5 kpc

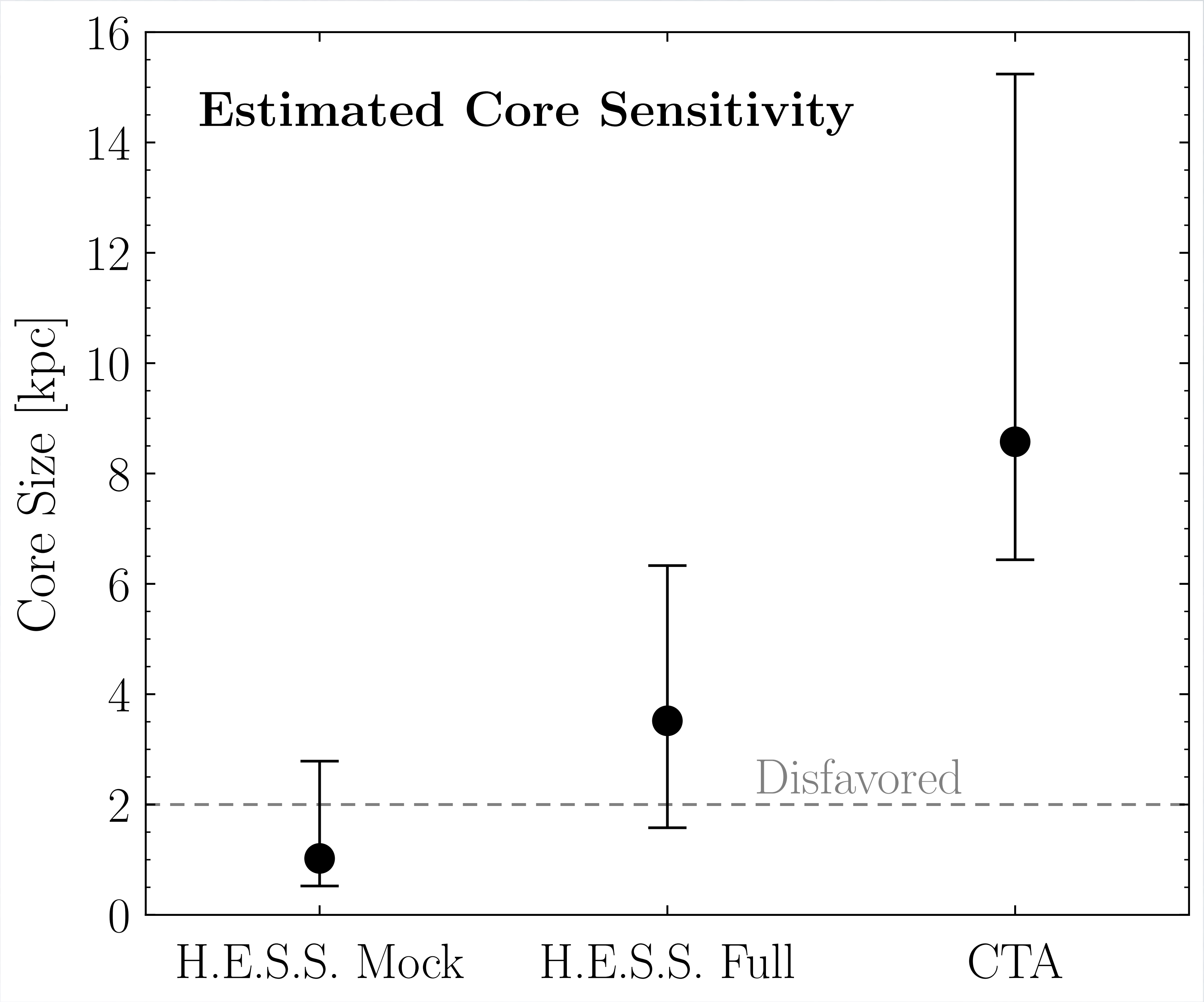
More aggressive analysis with
better galactic center understanding,
halo loophole closes, r_c>2.5 kpc

Hooper: 1608.00003 limit of 2 kpc

PROJECTED QUINTUPLET LIMITS





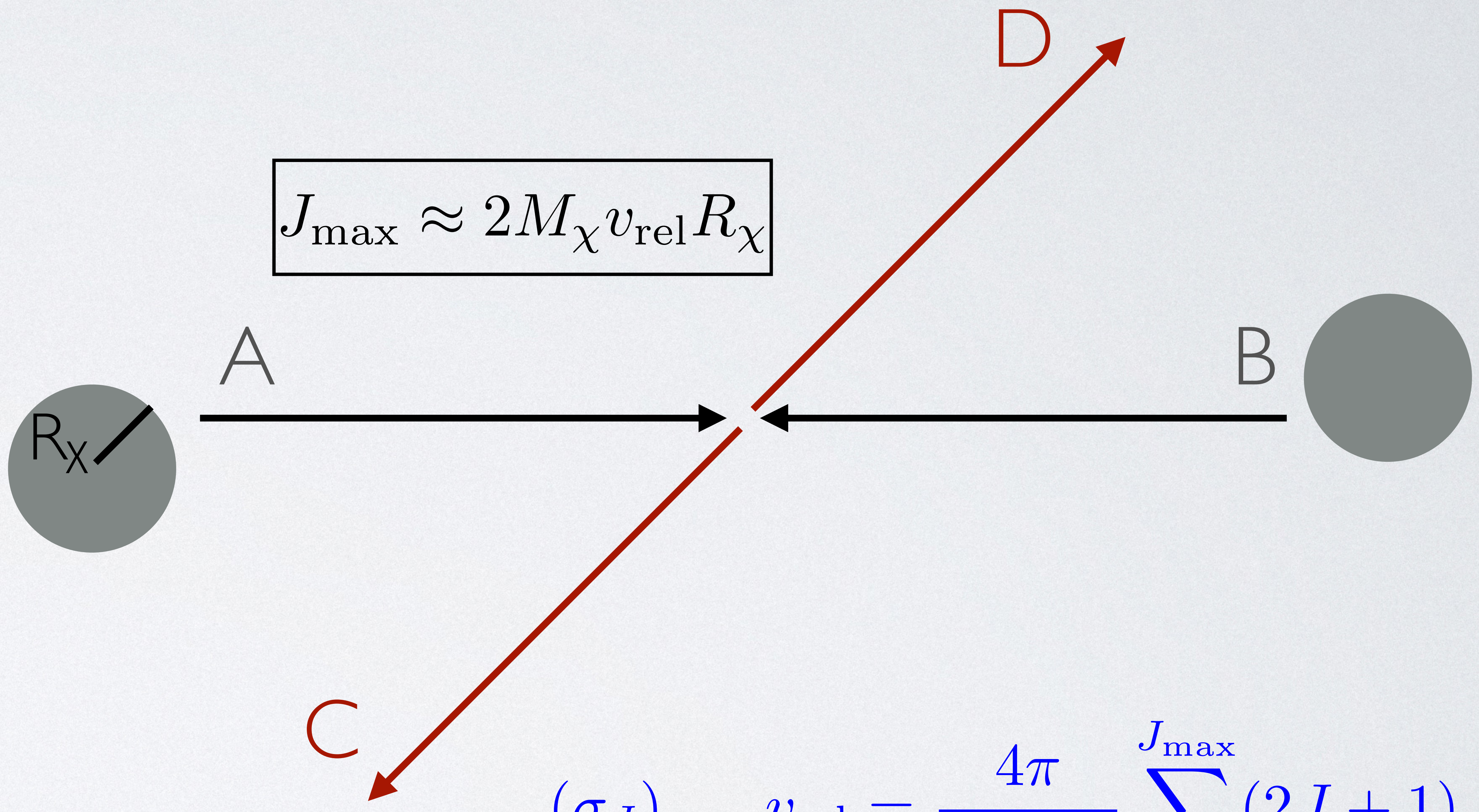


At **thermal relic M_χ = 13.6 TeV**
Error bar from thermal mass uncertainty

X. Ou, A-C. Eilers, L. Necib, A. Frebel: 2303.12838
Some evidence for few-kpc core in Milky Way

EVADING UNITARITY

- Unitarity limit assumes **maximal coupling, but structureless particles**.
- **Heavier-mass DM** allowed if abundance set by **multiple angular momentum channels**. E.g.:
    - Capture to bound states
    - Composite dark matter
- **Geometric cross section observed in hydrogen/anti-hydrogen scattering** ("rearrangement reaction")

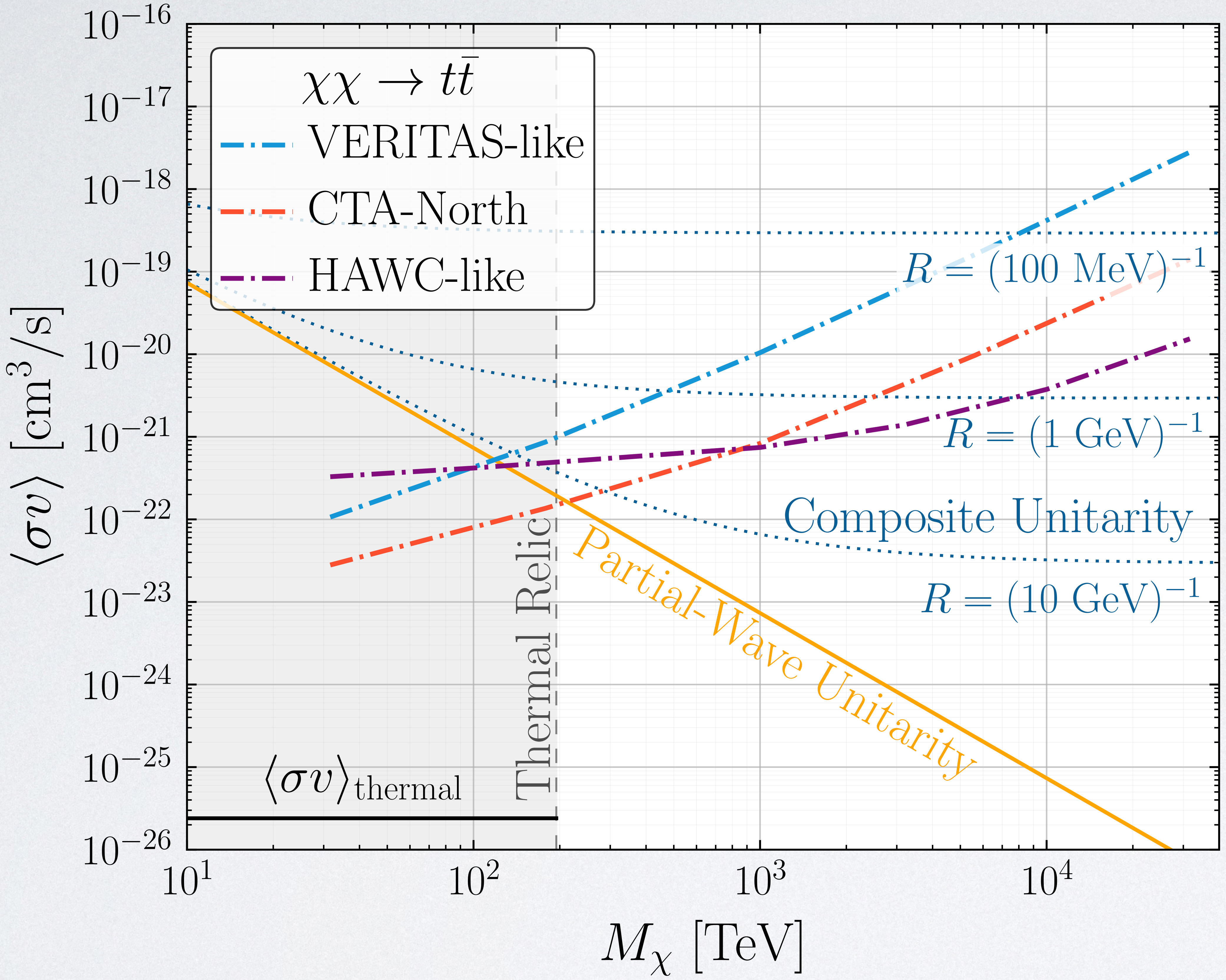


$$\boxed{J_{\max} \approx 2 M_\chi v_{\rm rel} R_\chi}$$

$$(\sigma_J)_{\max} v_{\rm rel} = \frac{4\pi}{M_\chi^2 v_{\rm rel}} \sum_{J=0}^{J_{\max}} (2J+1)$$
$$\approx 16\pi R_\chi^2 v_{\rm rel}$$

Cf. 1808.07720: Geller et al.

FRONT 2: UHDM



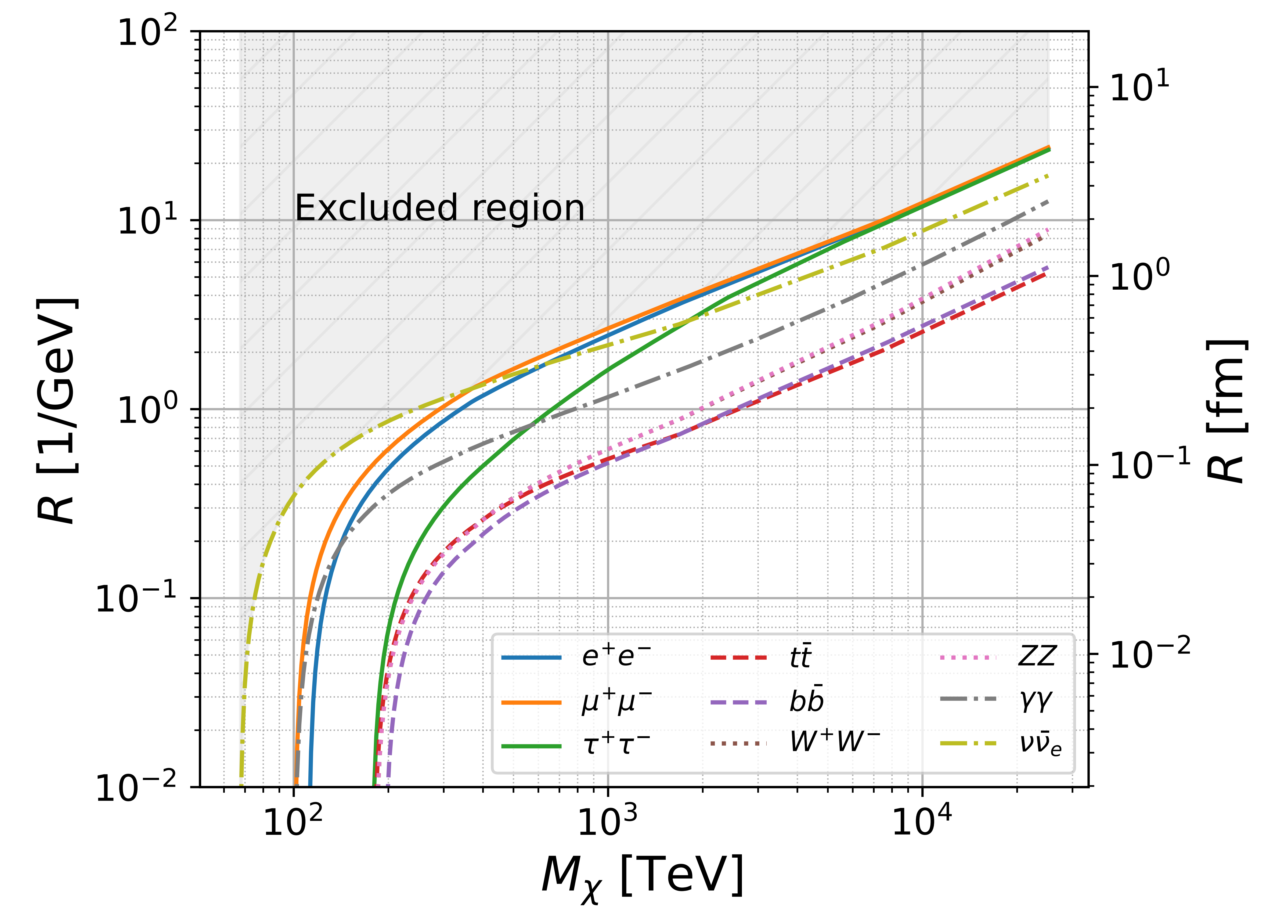
Projected Limits from observing Segue 1

Using **compositeness to evade Unitarity** limit, We can **bound size of UHDM** at a given mass with **ON/OFF maximum likelihood analysis**

2208.11740: D. Tak, MB, N. Rodd, E. Pueschel

Using HDMSpectra (2007.15001): C. Bauer, N. Rodd, B. Webber for signal

TESTING DARK MATTER TO 30 PEV, TODAY!



Limits on DM size given mass and annihilation channel

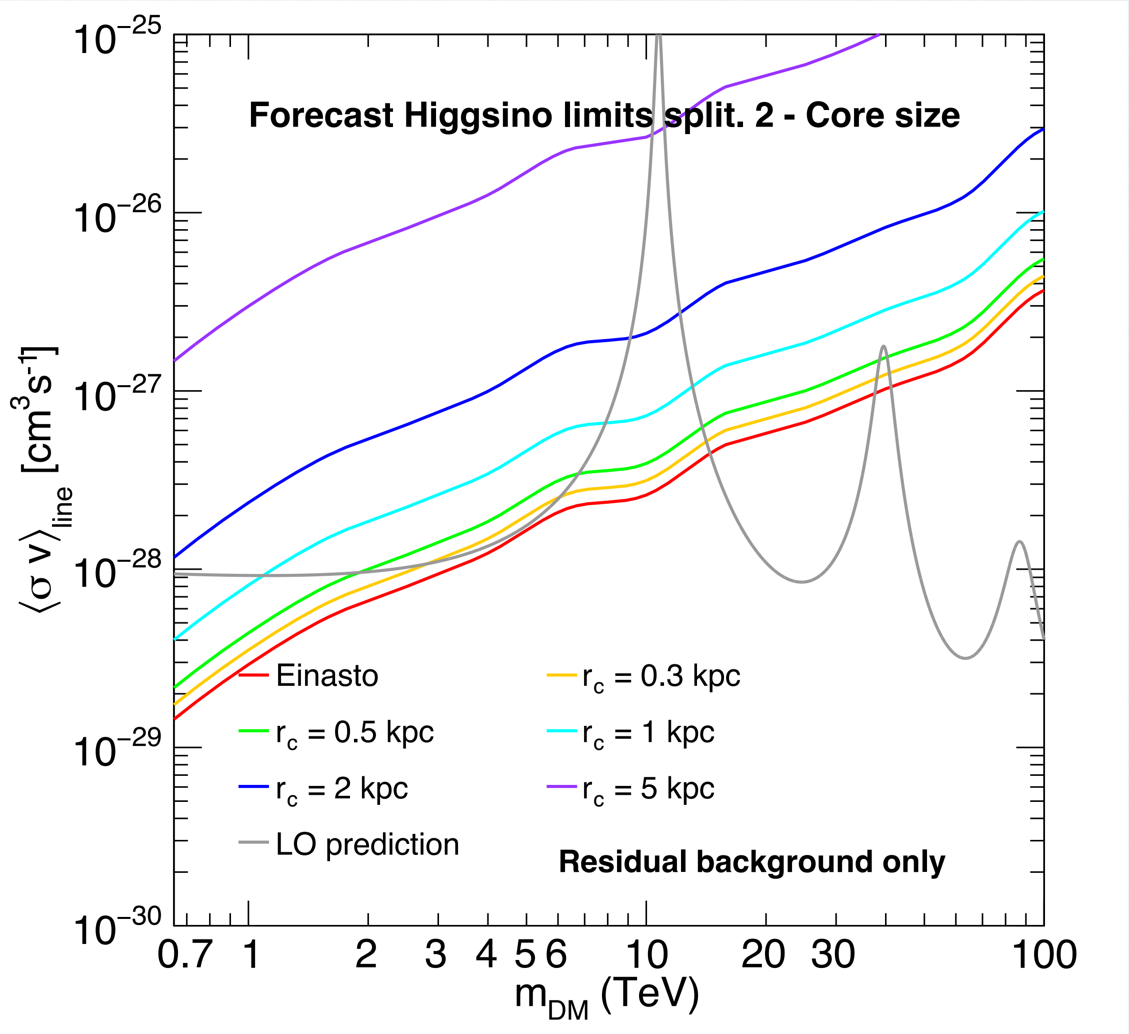
VERITAS data for 4 DSphs

See D. Tak's TeVPA 2023 talk for a preliminary update

2302.08784: D. Tak, MB, N. Rodd, E. Pueschel, & VERITAS

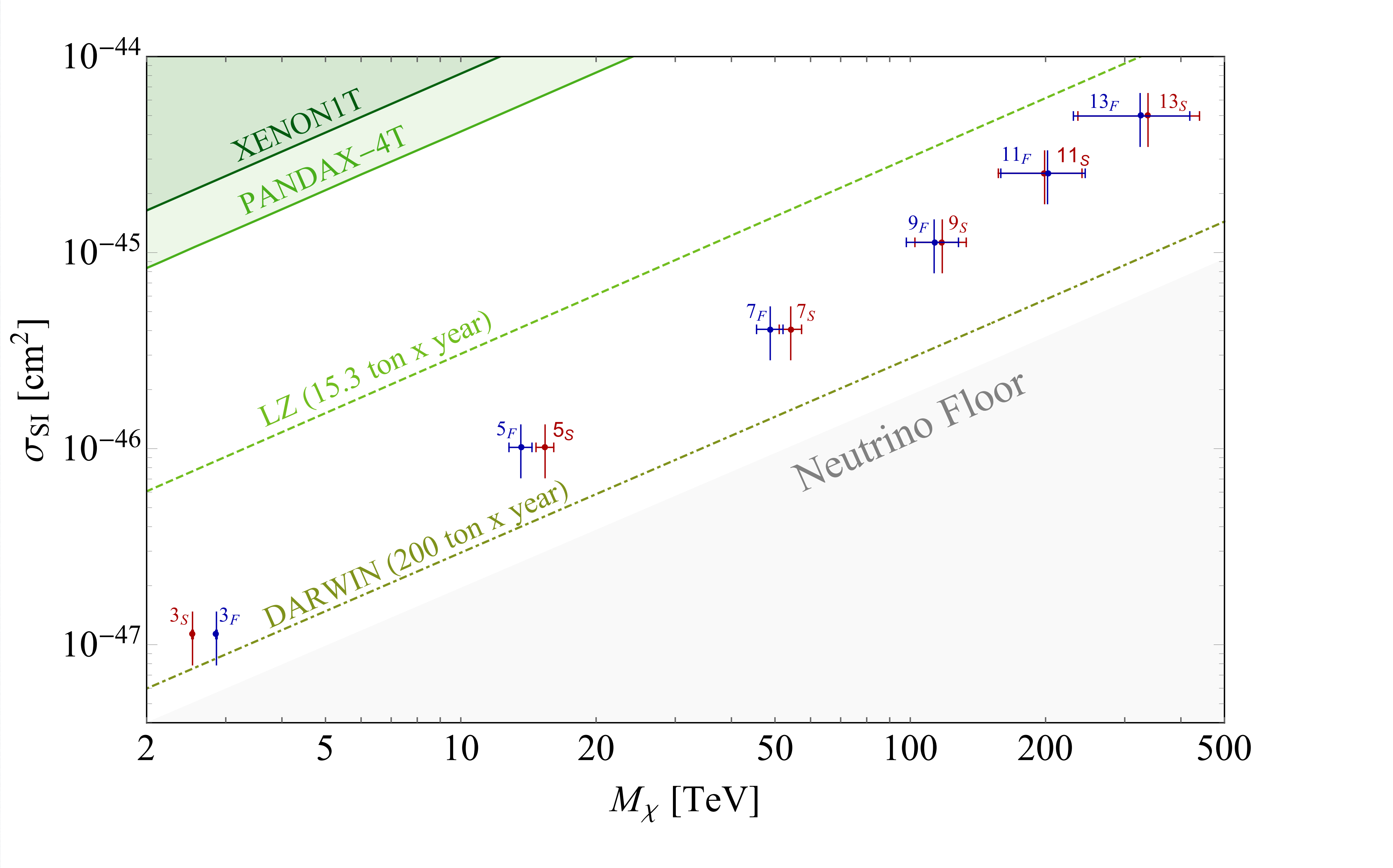
UP NEXT

- The simplest models of WIMP Dark Matter are all alive, but will be hunted down in he next decade.
- Computation of thermal relic masses with NLO potential greatly needed!
- Higgsino also isn't a simple reshuffling of group theory factors
    - Low thermal-relic mass (1 TeV) means poor convergence in EFT
    - Power-suppressed operators may be needed
- Combine VERITAS DSphs data with wino and quintuplet signals for limits independent of Milky Way halo modeling
- Model Building challenges for UHDM
    - Geometric cross sections, really?
    - How to realize UHDM with complex structure as thermal or nonthermal relic?

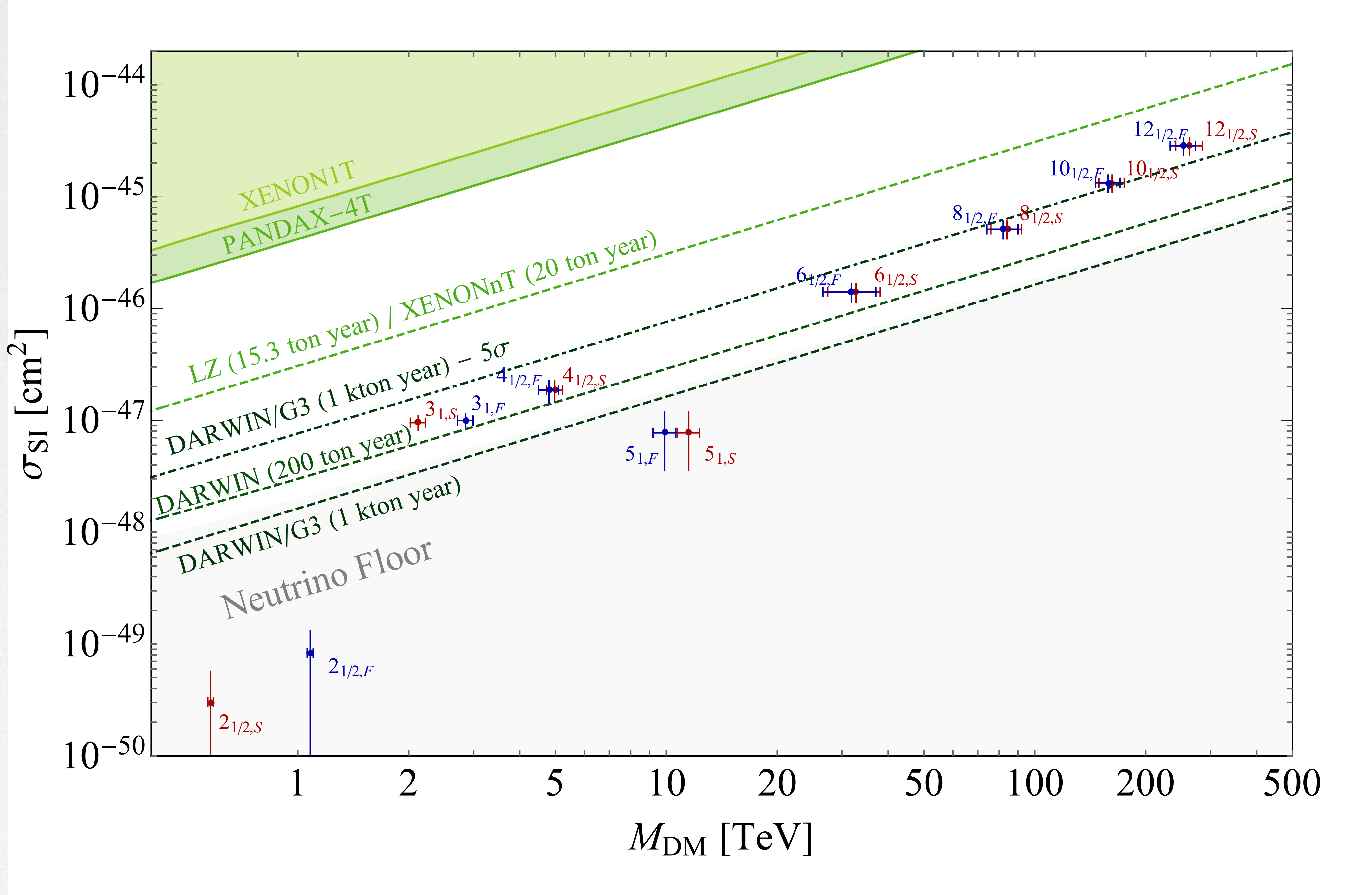


2008.00692: Rinchiuso et al.

DIRECT DETECTION?



2107.09688: Bottaro et al.



2205.04486: Bottaro et al.