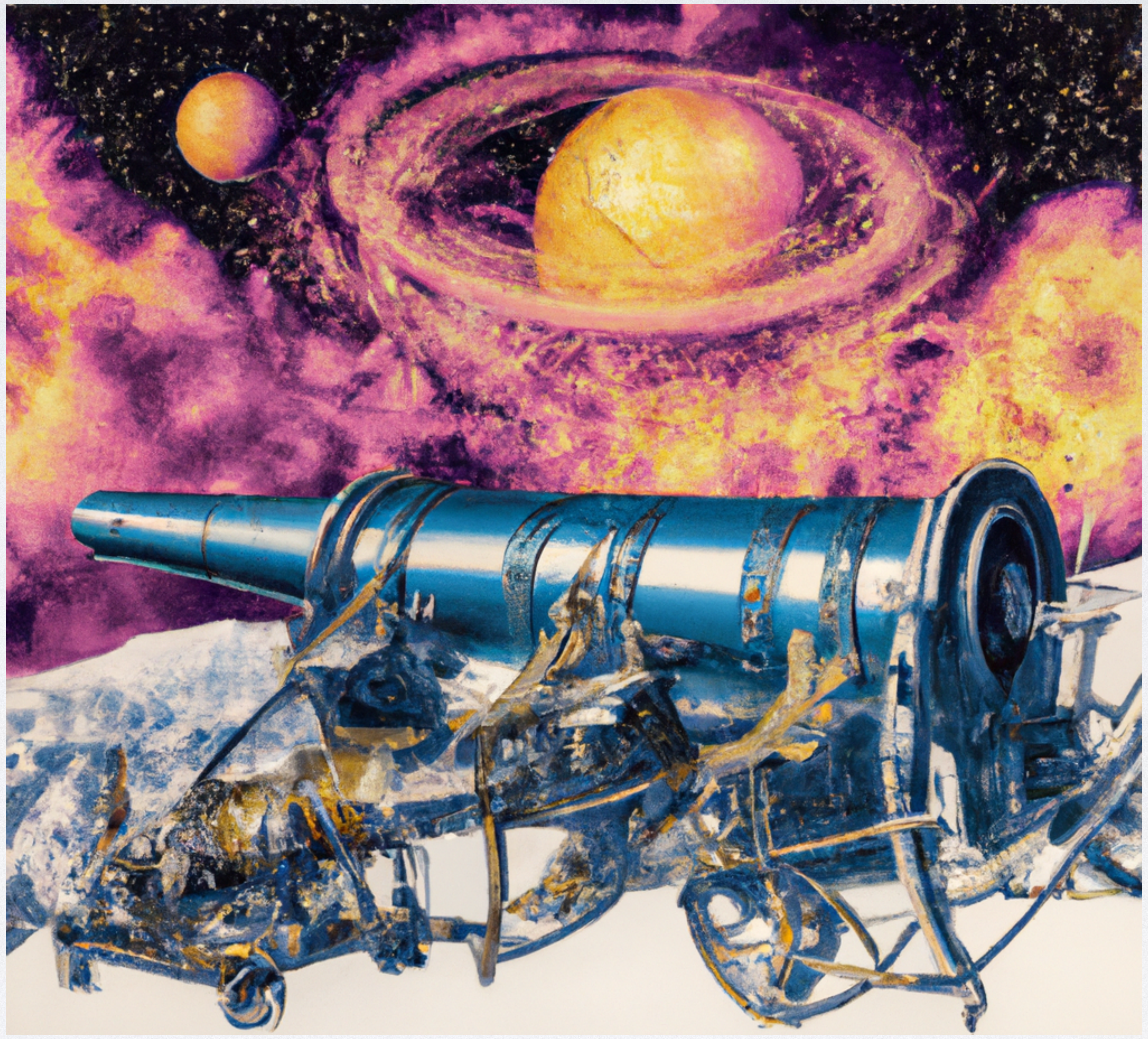
ATTACKING **HEAVY DARK MATTER** ON 2 FRONTS

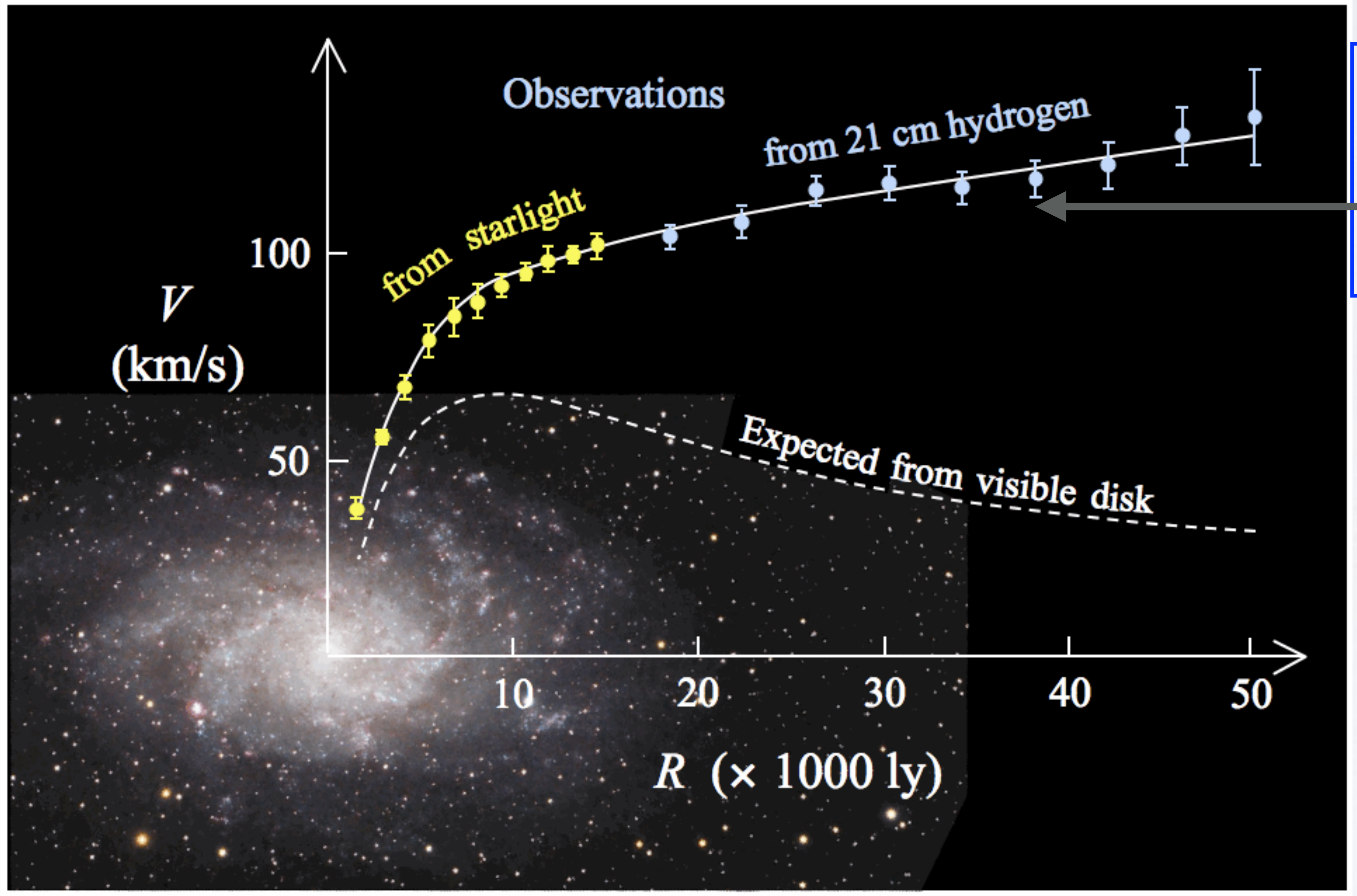


Matthew Baumgart (Arizona State University)

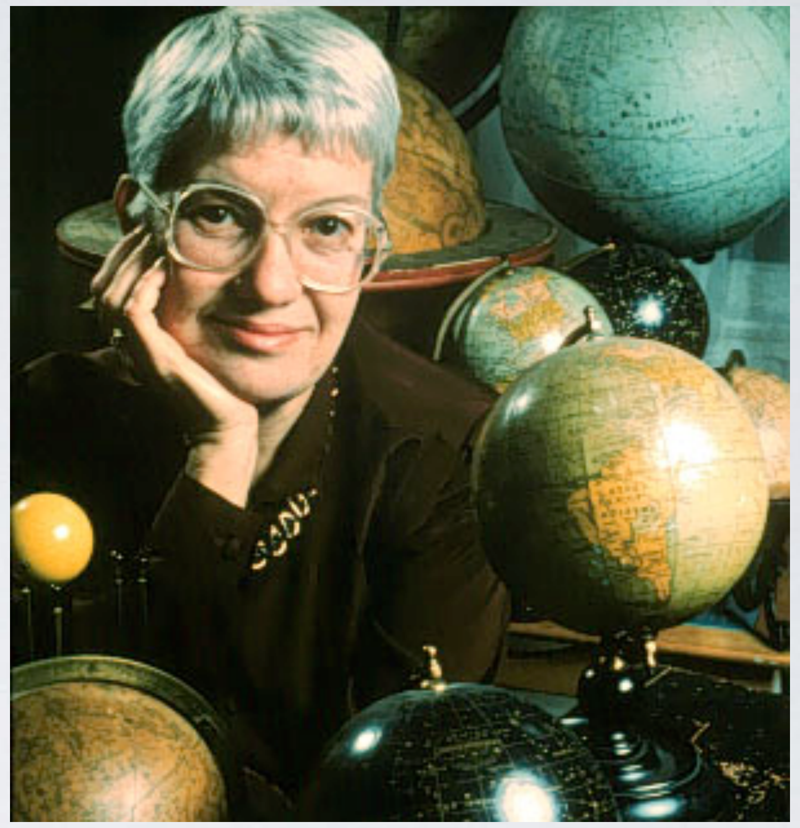
BNL Particle Theory Seminar 03/30/2023

WHY DARK MATTER?

Anomalies on 3 different astrophysical scales!



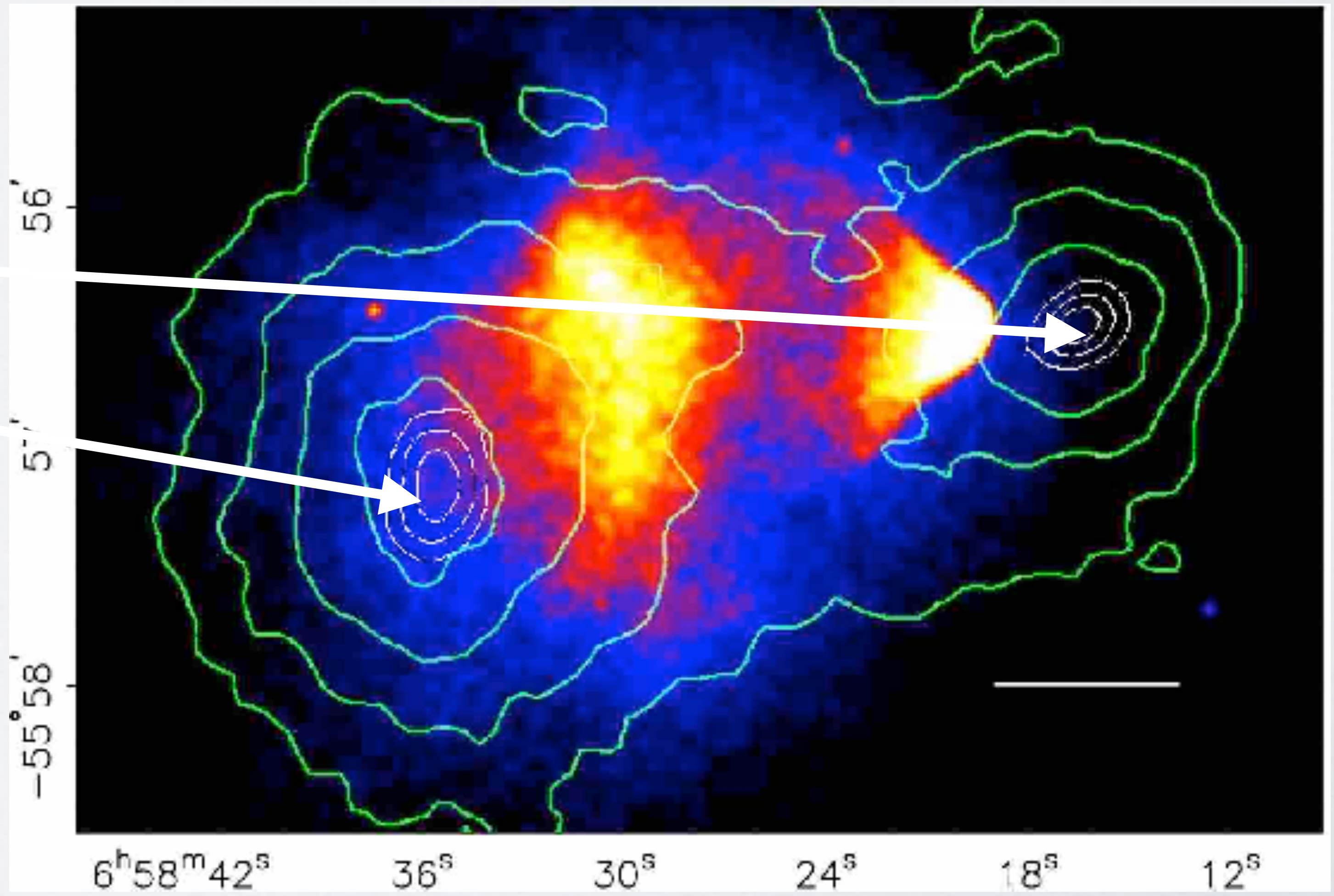
Galactic Rotation curves:
Stars move faster than expected



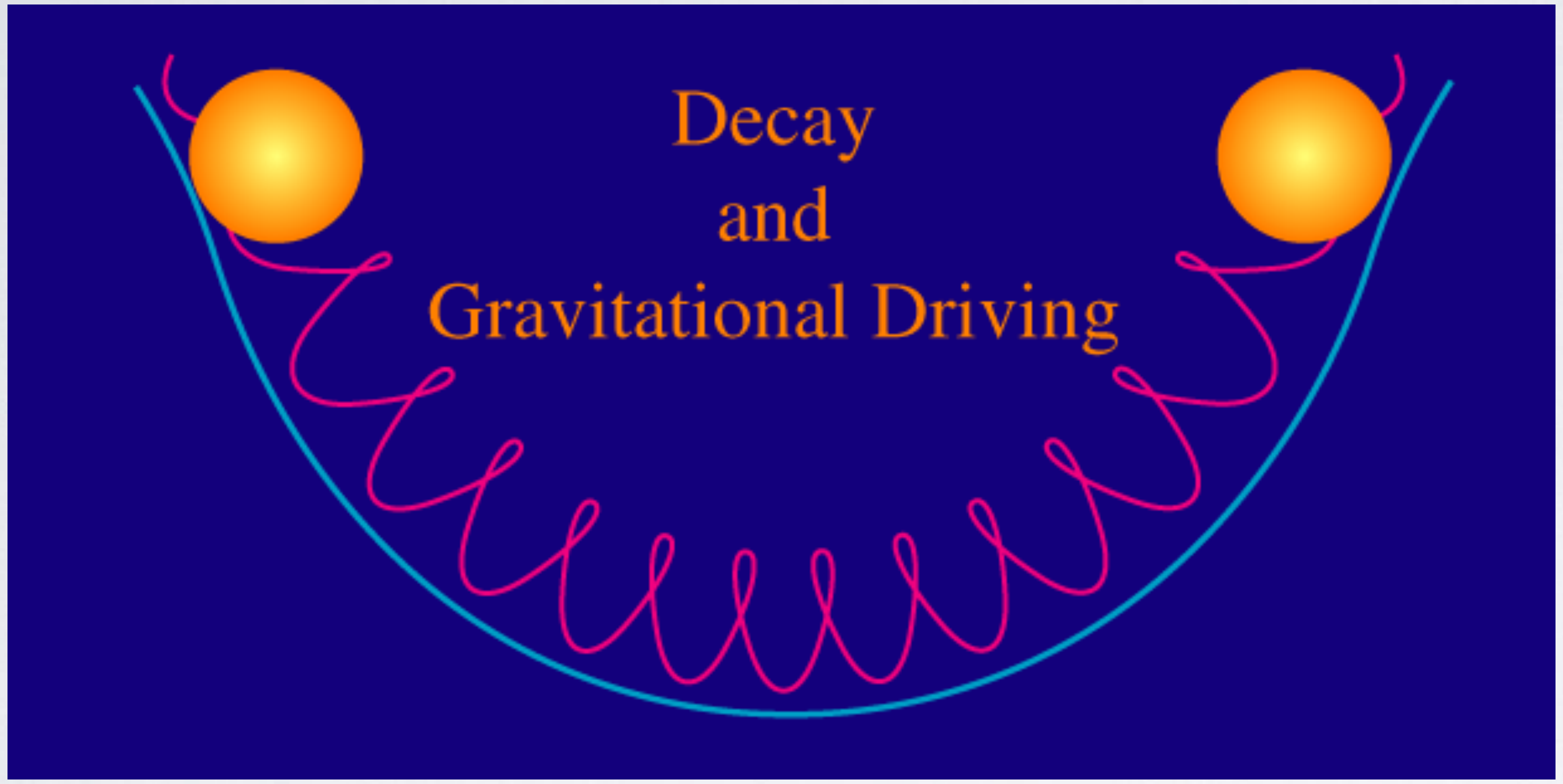
Vera Rubin 1928-2016
Established Rotation Curve anomaly

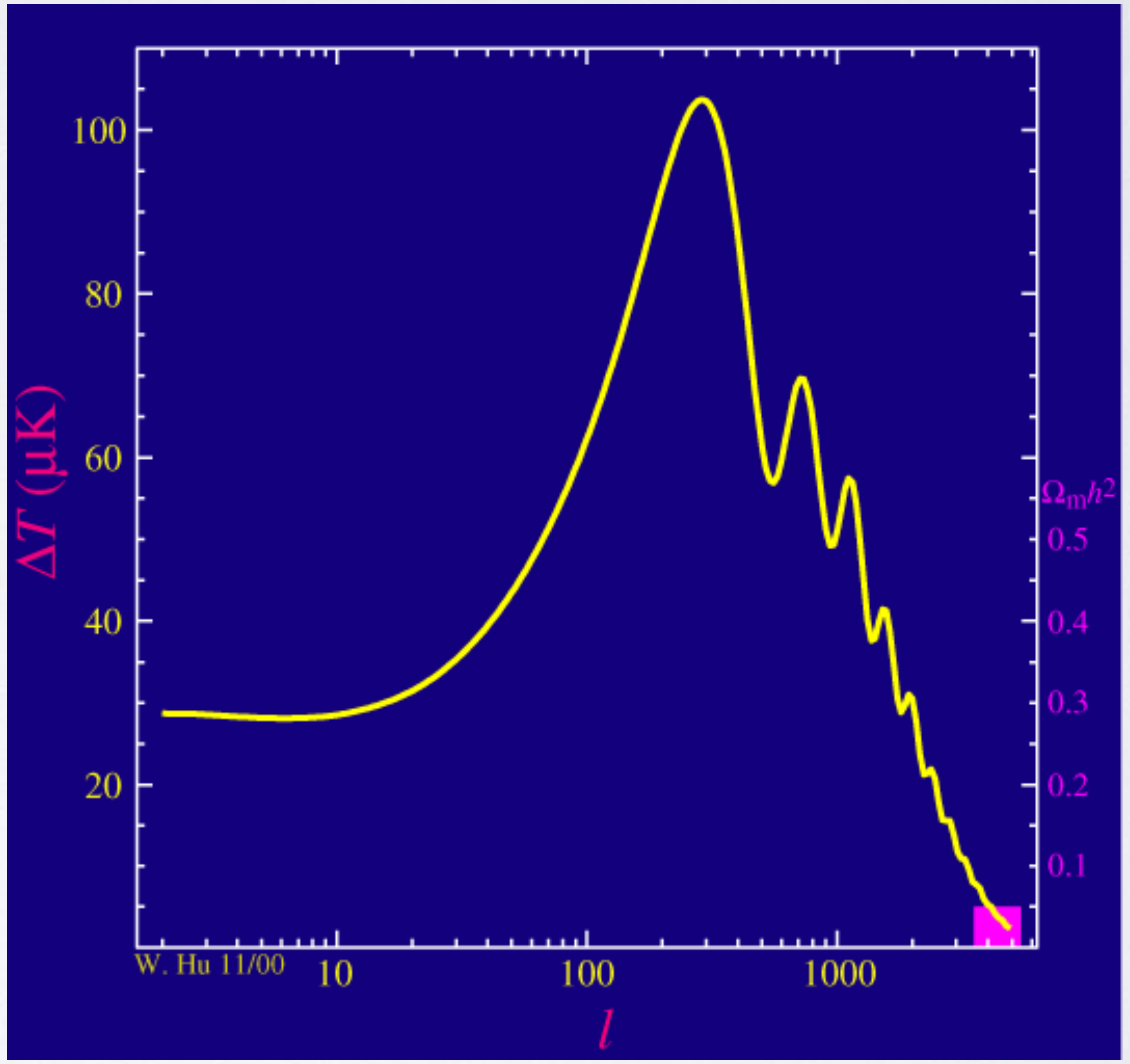
Colliding Clusters:
Gravitational wells nowhere near visible peaks

"Not modified gravity"



DARK MATTER ABUNDANCE



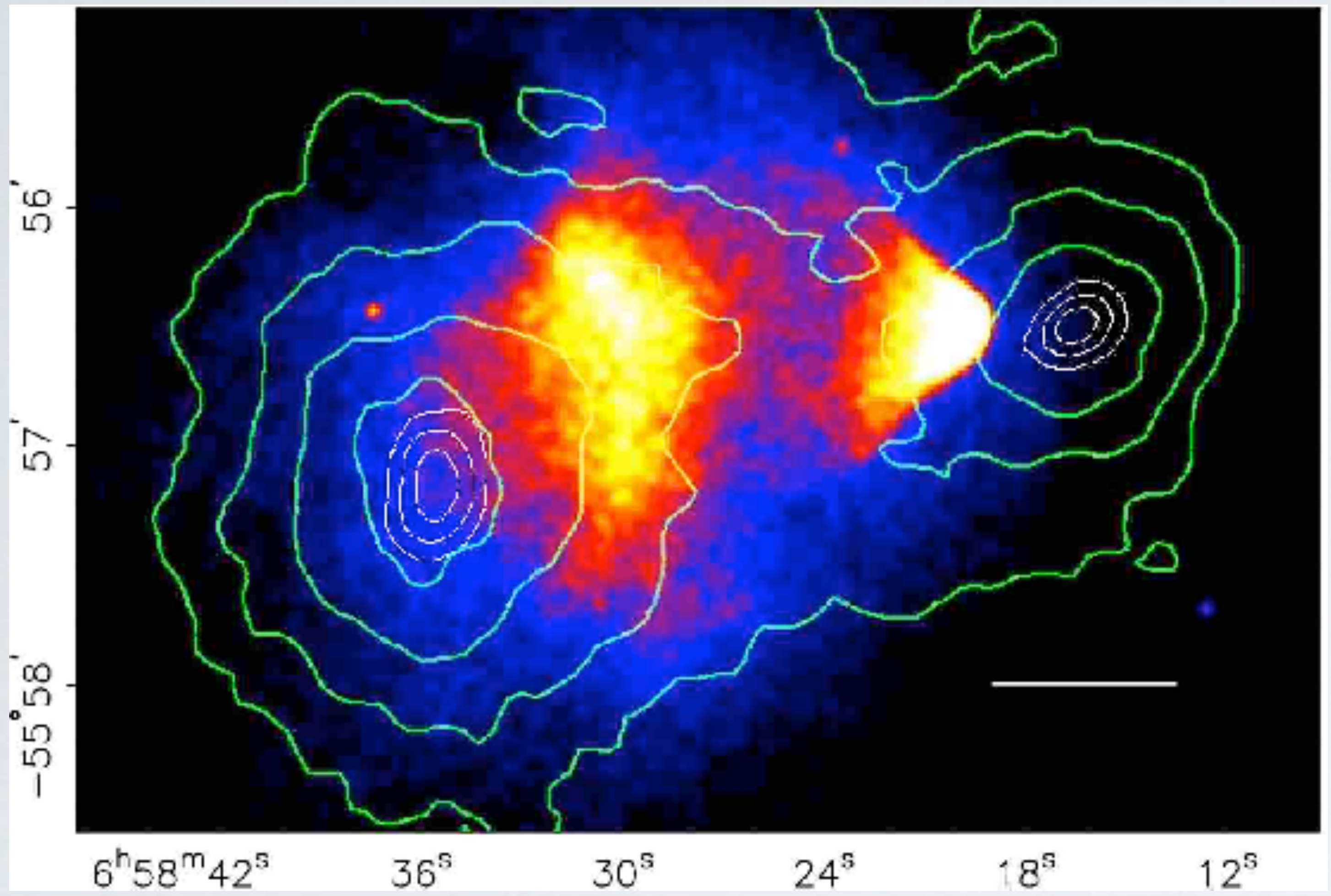


Cosmic Microwave Background:
Fluctuations measure Dark Matter as 27% of Universe's energy (Planck)

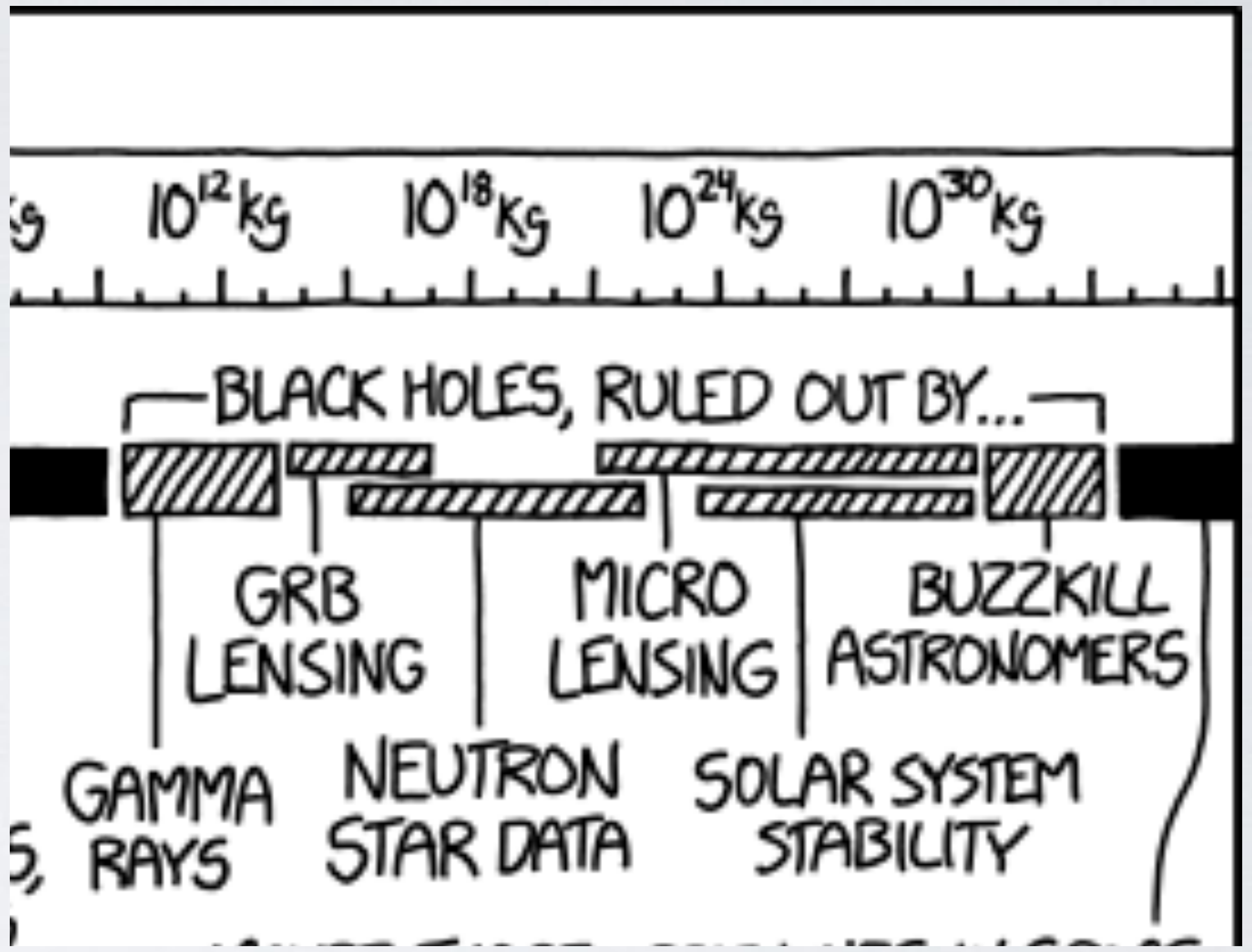
Animations from W. Hu

IS IT?

~~Something like Gravity?~~



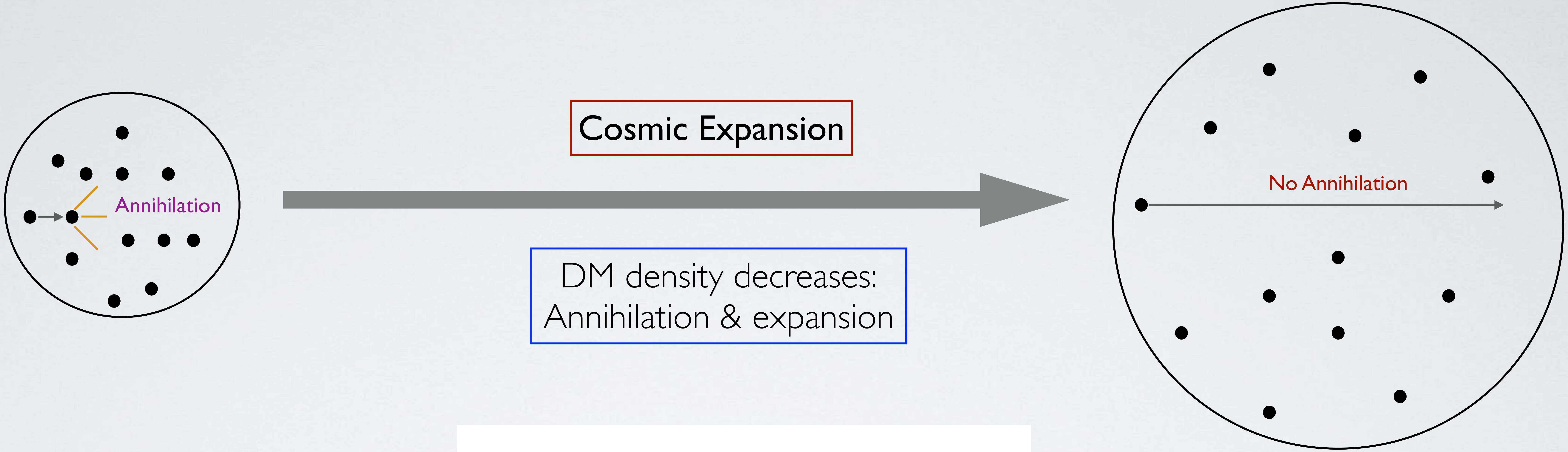
~~Something like Black Holes?~~

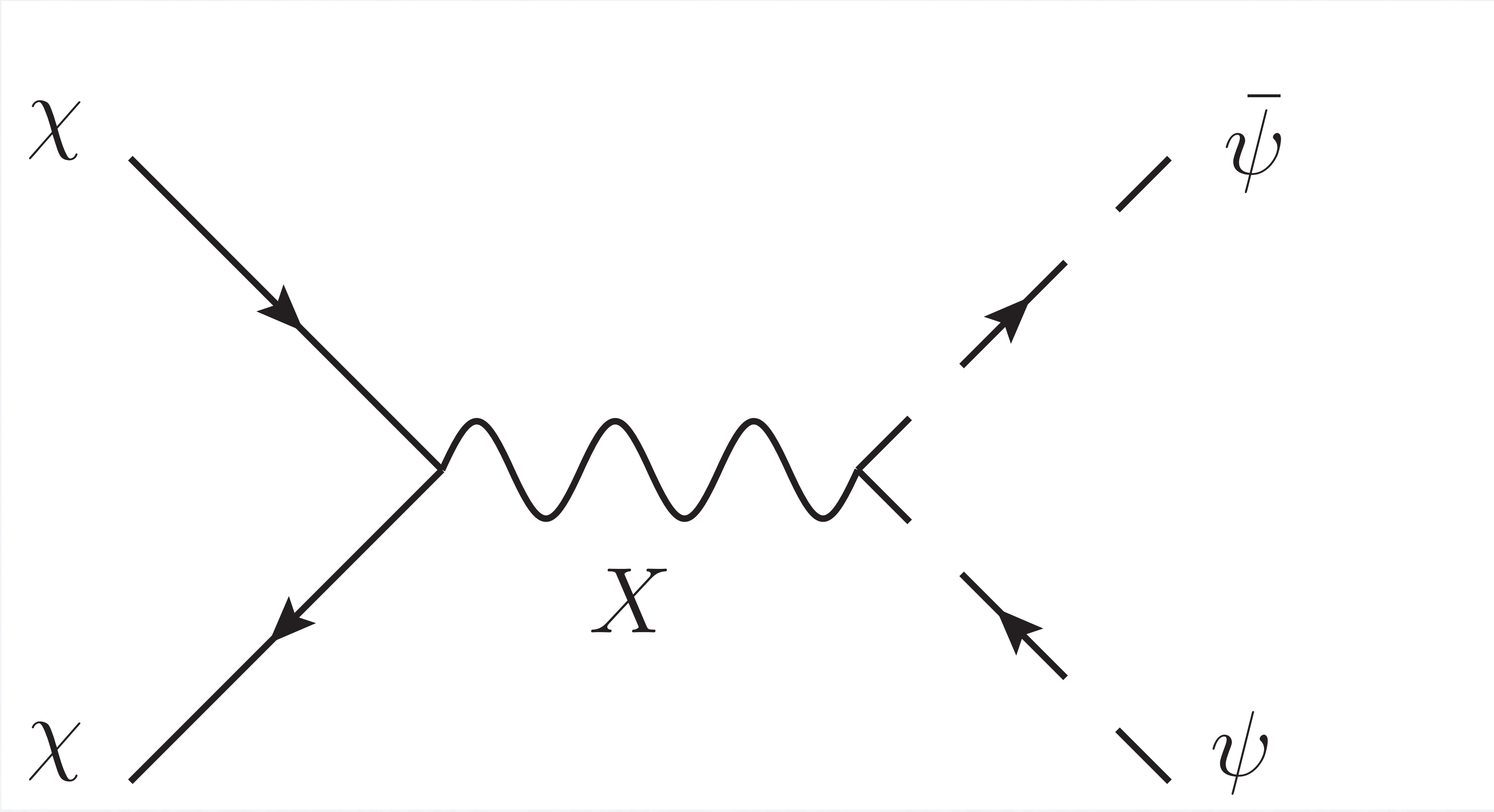


XKCD (2018) cf. 1705.05567

Something like a neutrino!

WHY WIMPS?



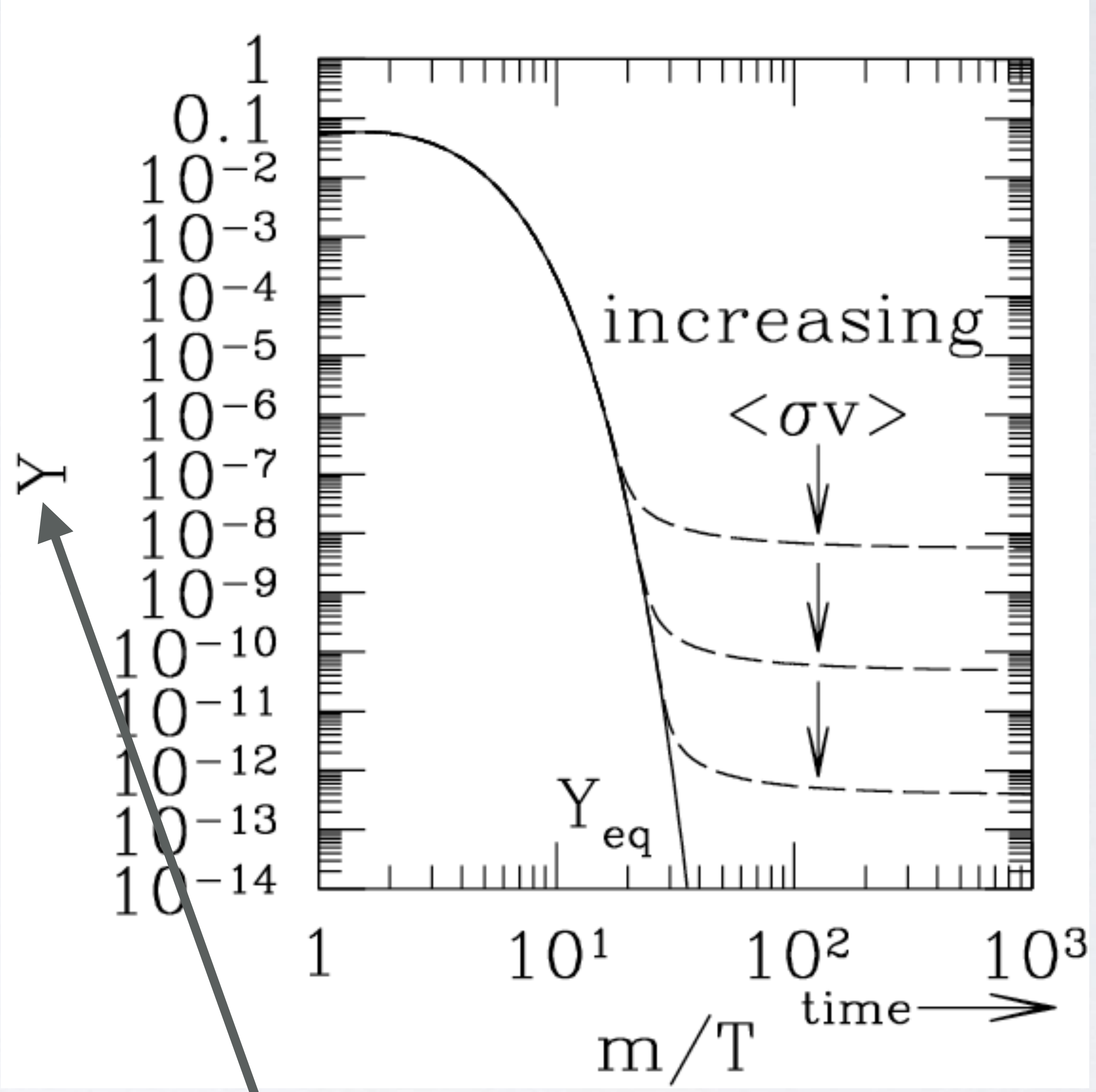


$$\langle \sigma v \rangle_{annihilation} \sim C\,\alpha^2/M_\chi^2$$

WIMP MIRACLE

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

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

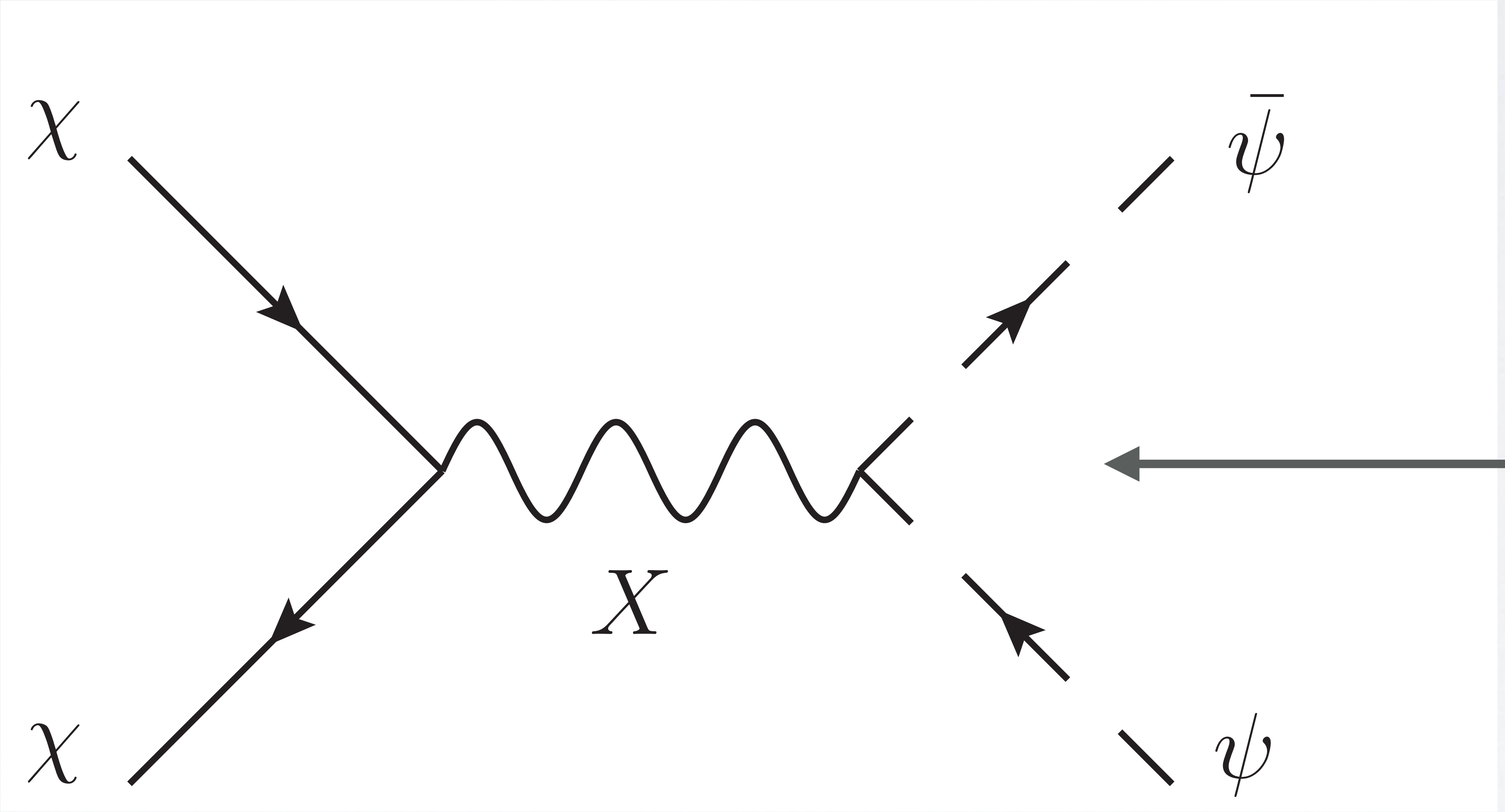


DM density decreases:
Ω: Annihilation & expansion
Y: Annihilation

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

See Dimopoulos PLB 246(1990):347-52

STARTING SIMPLE W/ WIMPS

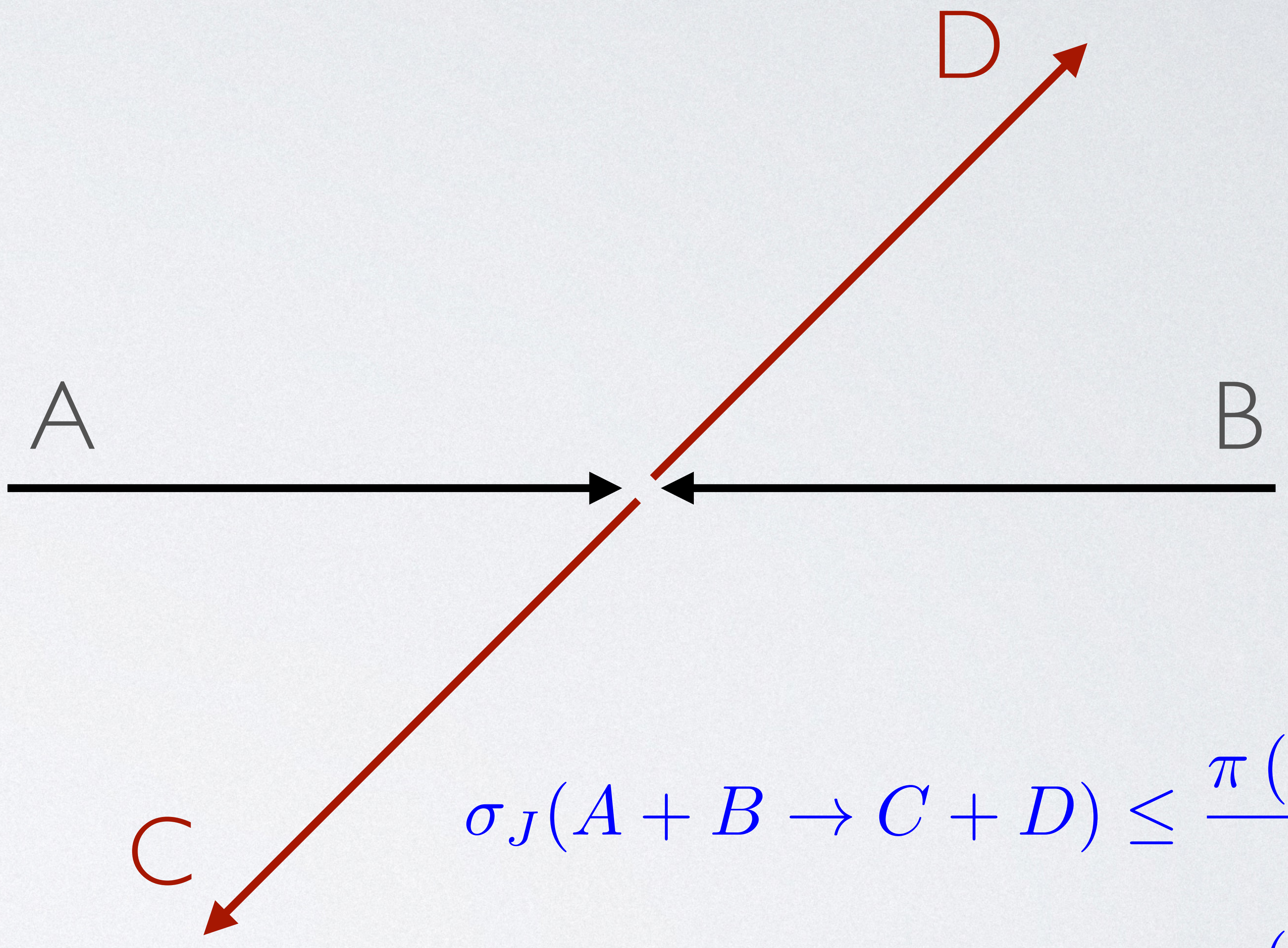


Maybe we already know
everything here **except χ?**
X: Z-boson, Higgs?
ψ: Elementary Fermion, Higgs?
α: α_{weak}?

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

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



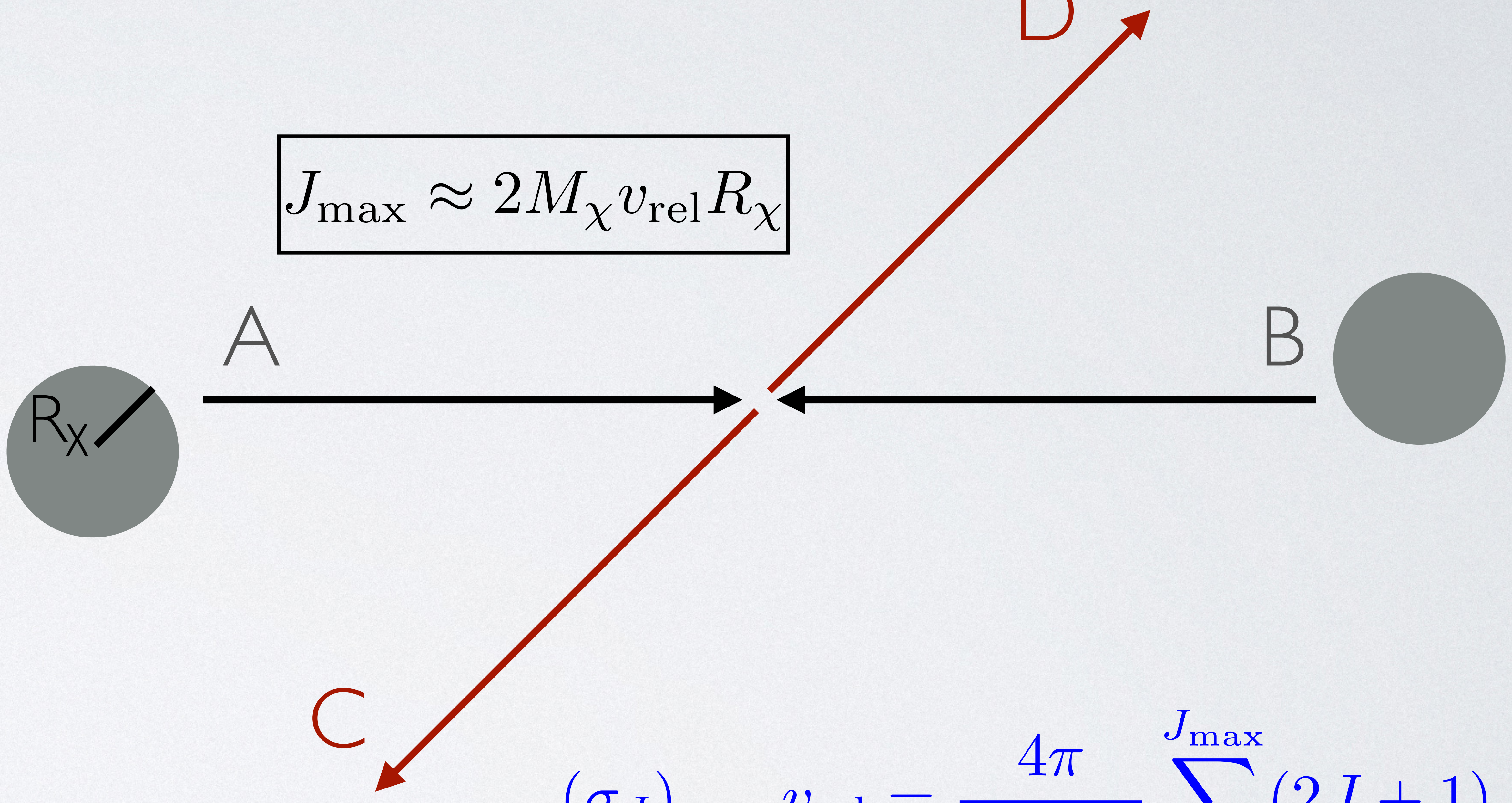
$$\sigma_J(A + B \to C + D) \leq \frac{\pi\,(2J+1)}{p_i^2}$$

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

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

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")



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

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

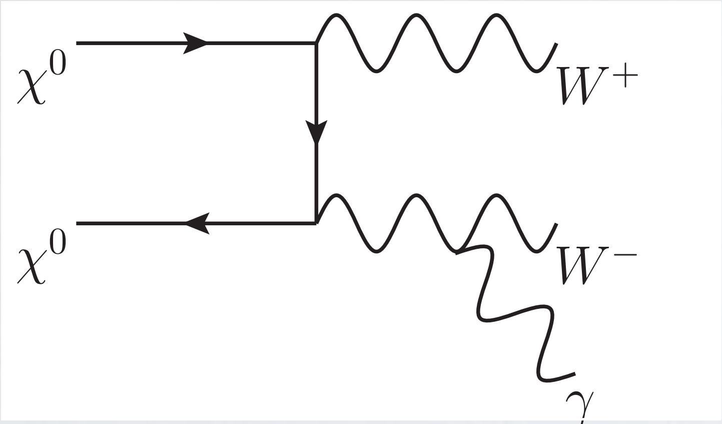
Cf. 1808.07720: Geller et al.

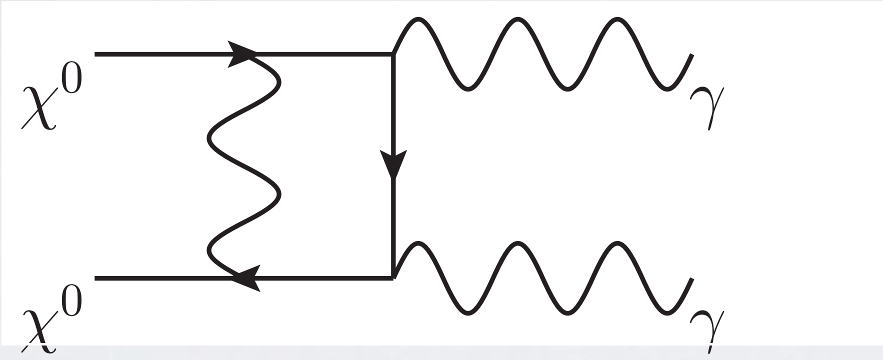
TWO FRONTS IN HEAVY DARK MATTER

- 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

ECHO OF THE WIMP MIRACLE



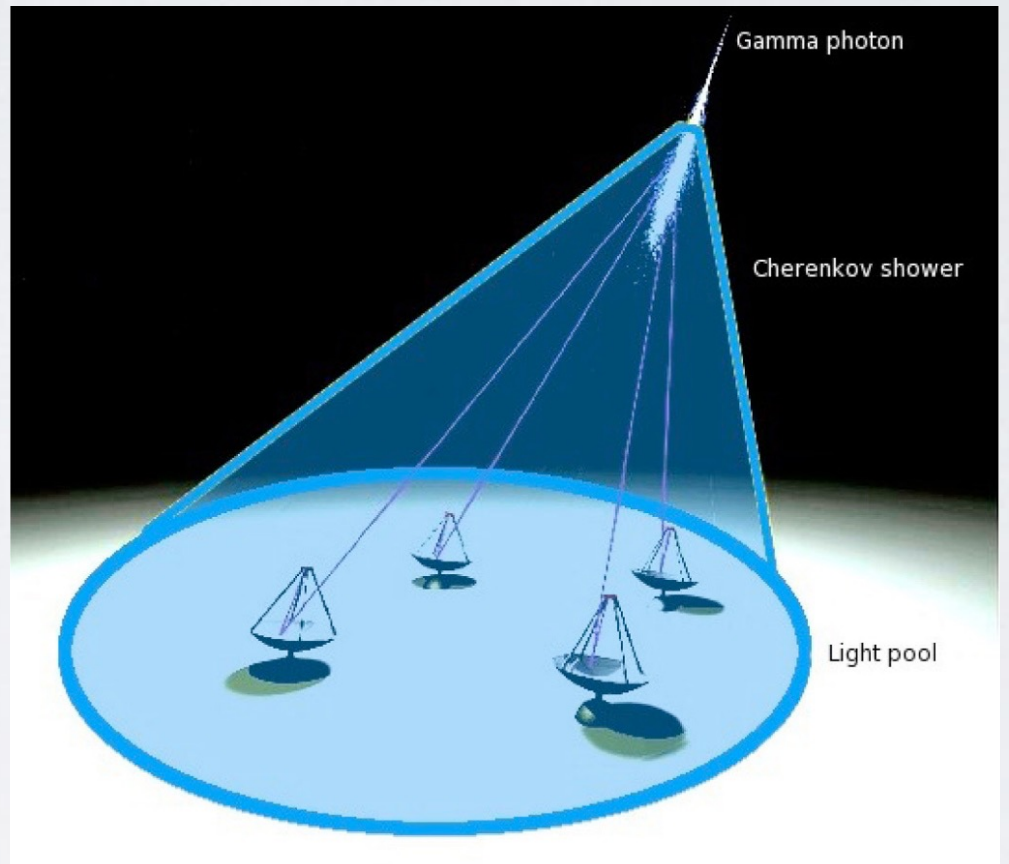


Indirect Detection:

Photons from Dark Matter Annihilation

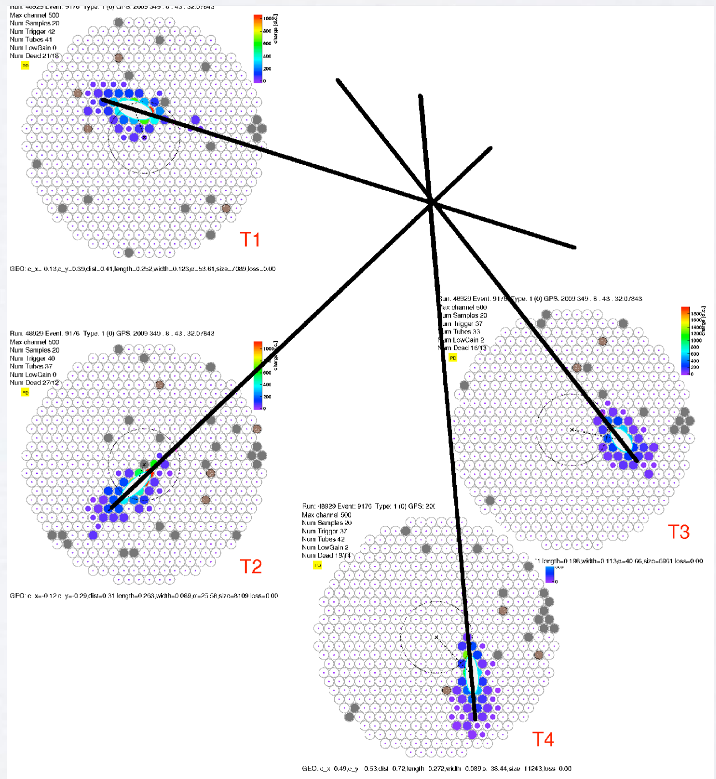
HESS/VERITAS can probe
Dark Matter Masses
up to 30 PeV

Successor **CTA**,
will improve by **Order of Magnitude**



O(TeV) γ leads to O(10^4m) light pool on ground

Schematic of air shower observed by Cherenkov Telescope
(spie.org)



VERITAS event

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

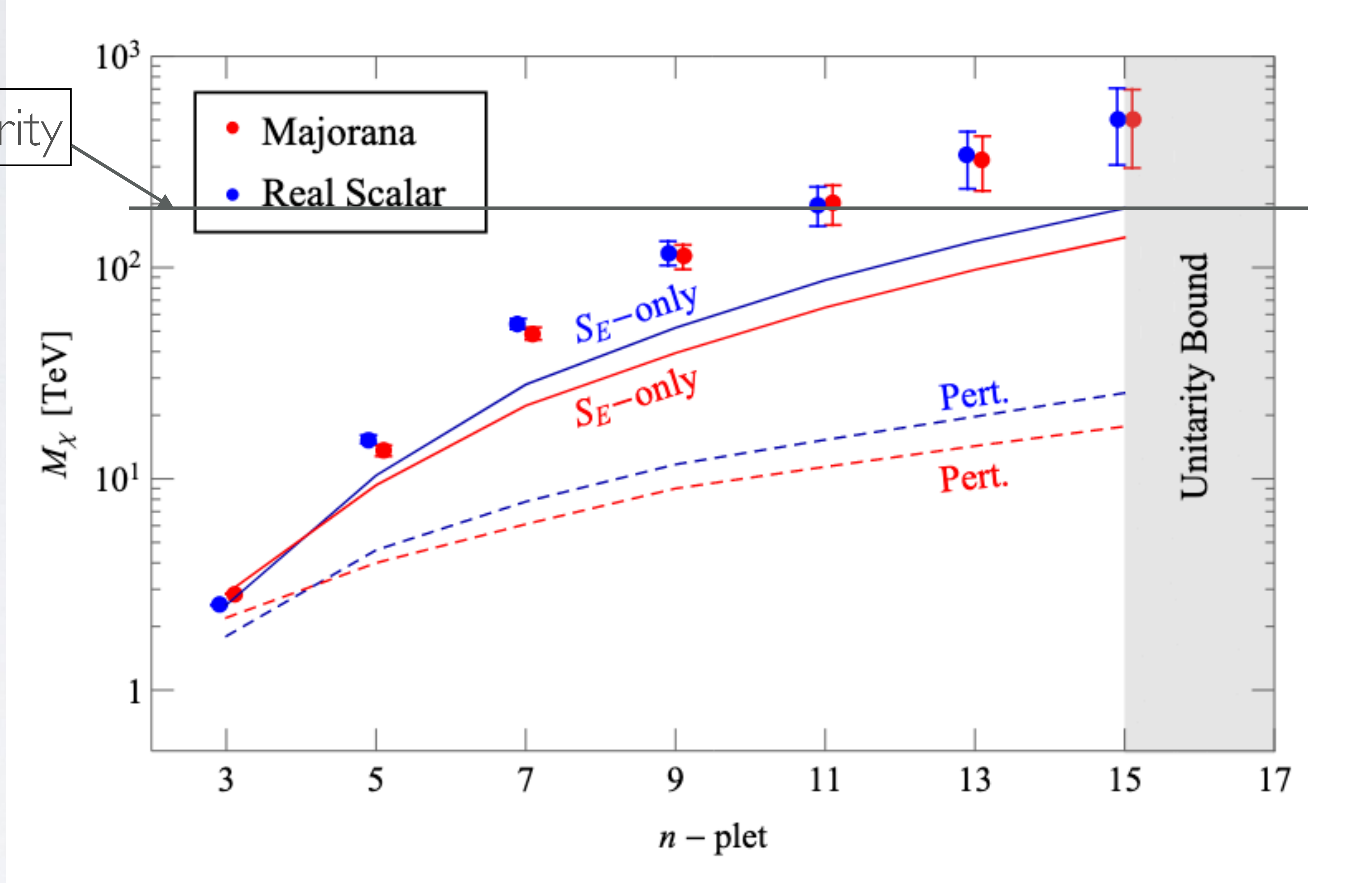
Correct Dark Matter Density fixes M_χ:

Wino: 3 TeV

Higgsino: 1 TeV

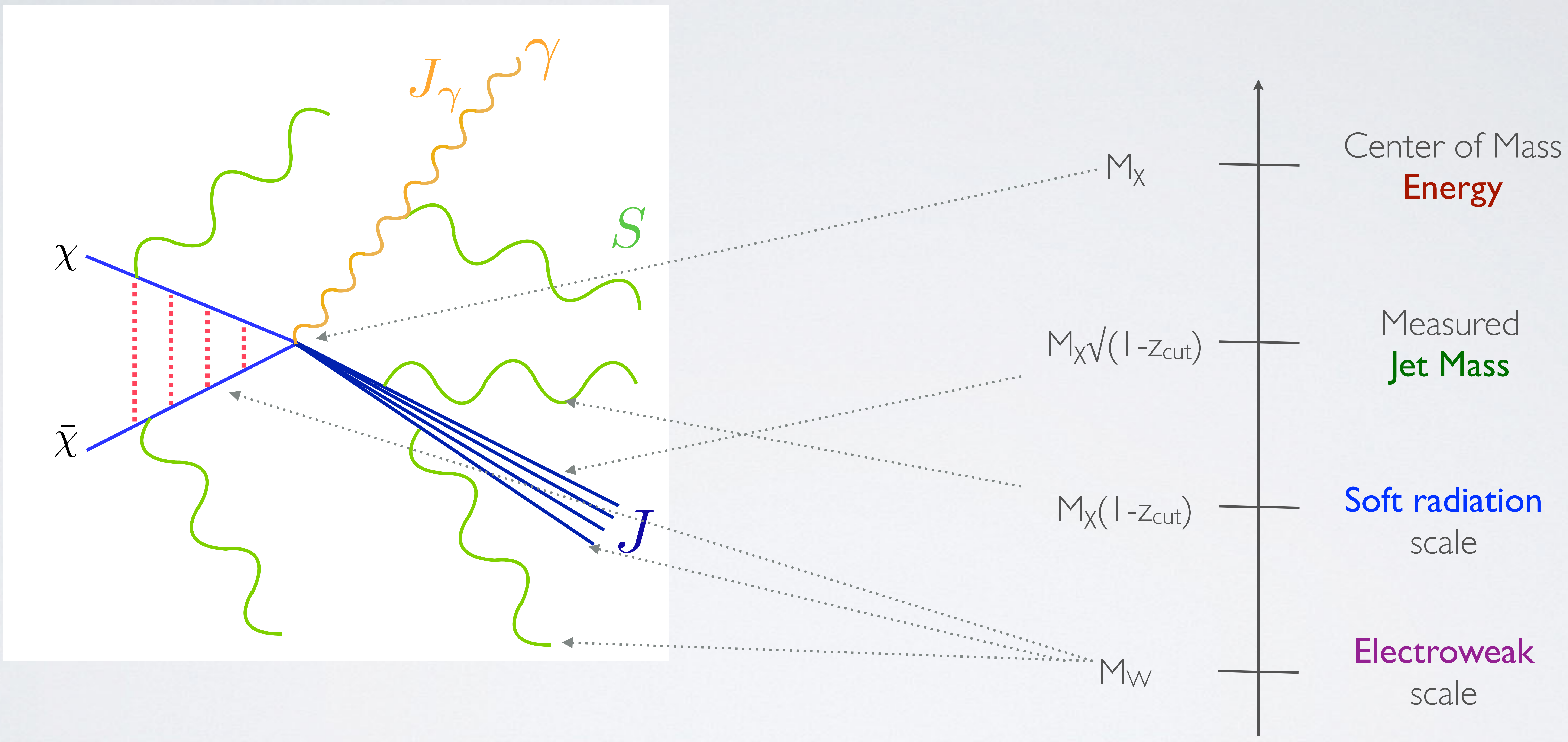
Quintuplet: 14 TeV

Naive Unitarity

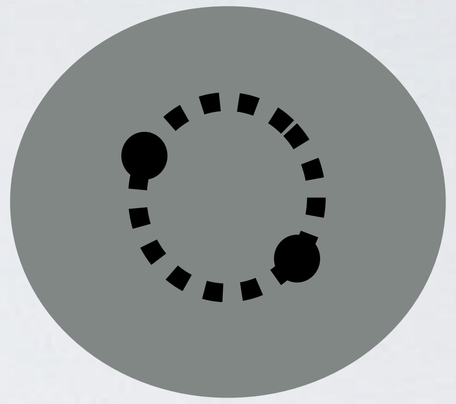


2107.09688: Bottaro et al. Simple thermal relic masses for real reps of SU(2)

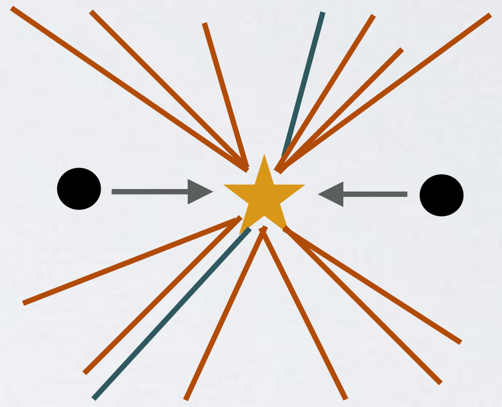
EFFECTIVE FIELD THEORY PLAYGROUND



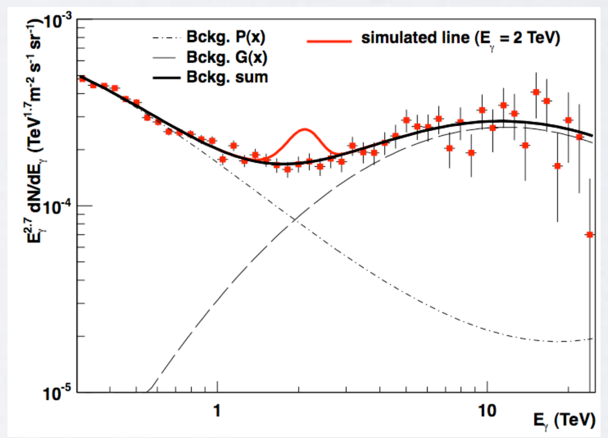
- **3 separate threats to perturbation theory!**
  - $M_\chi/m_W >> 1$ → Long range force



  - $M_\chi/m_W >> 1$ → Electroweak shower

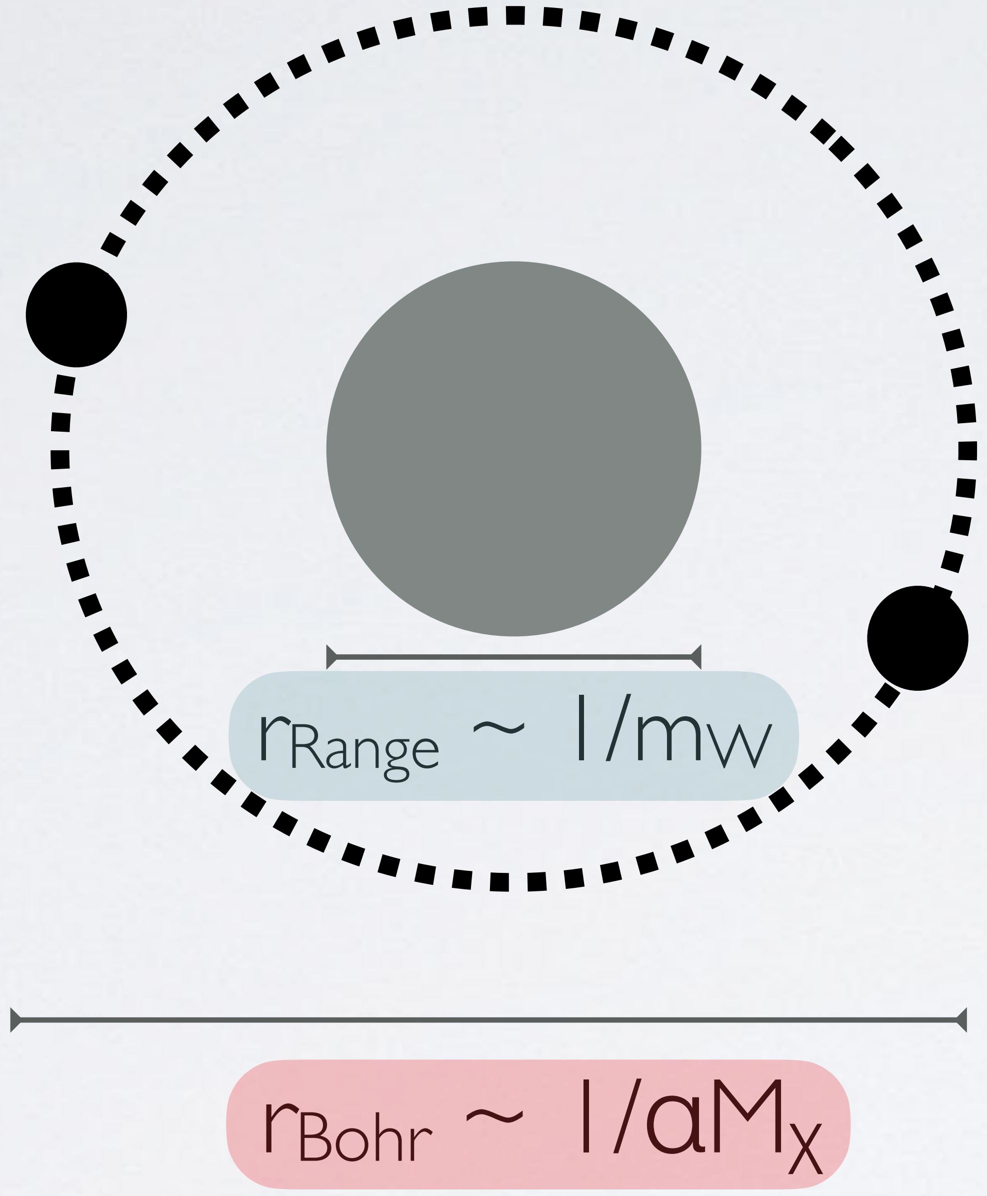


  - $\mathrm{Log}(1-z_{cut})$ → Phase space restriction



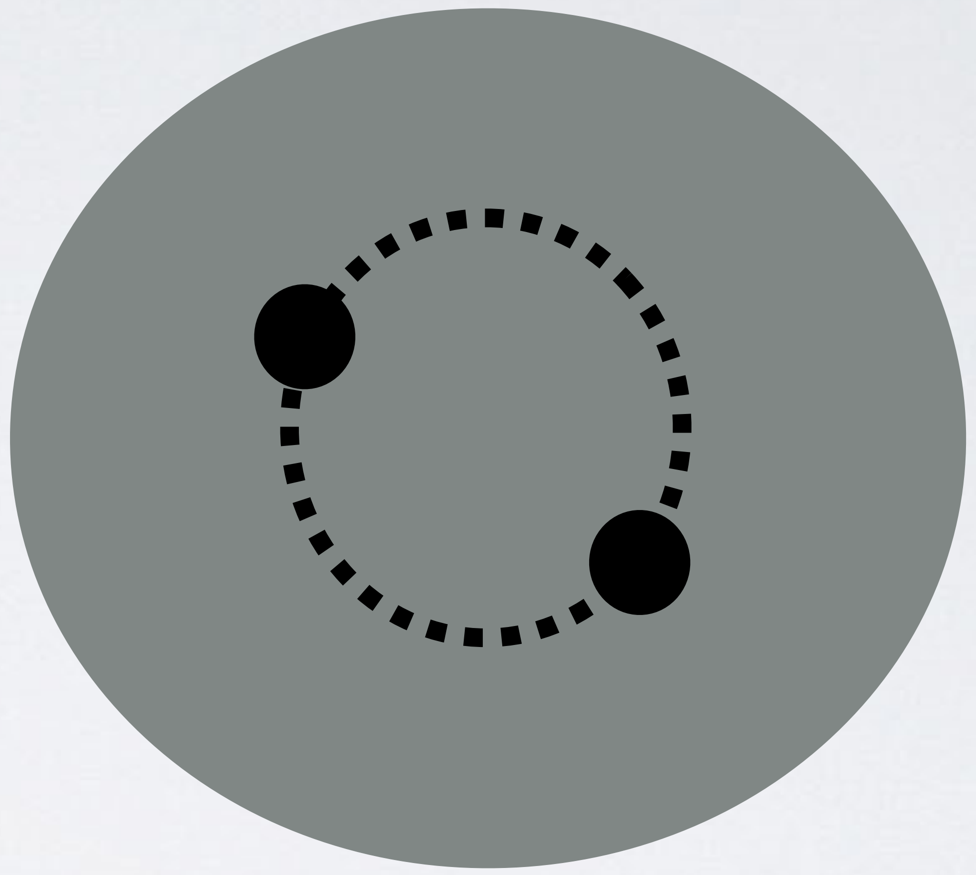
- Proliferation of scales → **Effective Field Theory**

SOMMERFELD ENHANCEMENT



$r_{Bohr} >> r_{Range}$

No bound state



$r_{Range} >> r_{Bohr}$

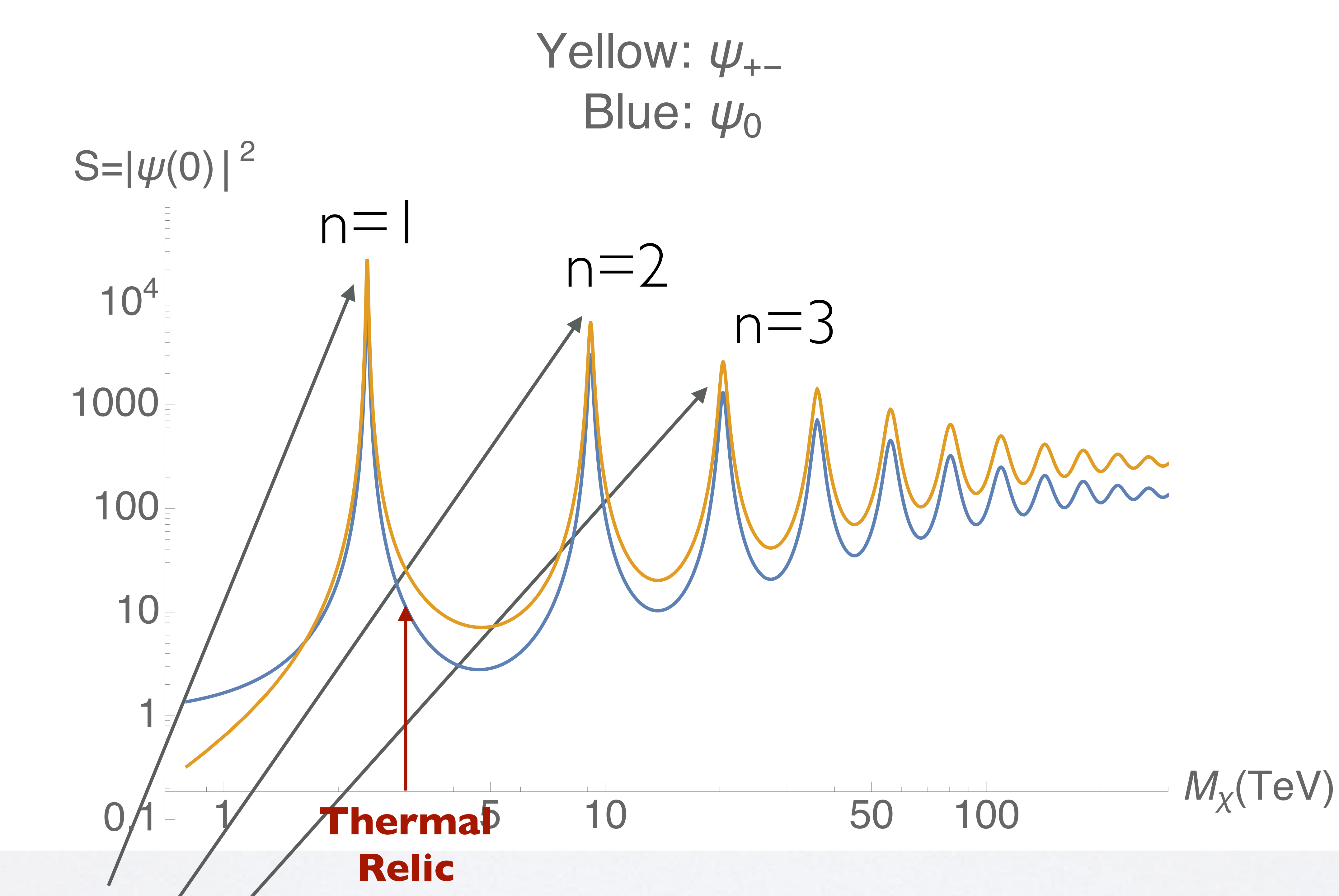
Bound state forms

For wino

$m_W = \alpha_W M_\chi$ @ $M_\chi = 2.4$ TeV

Transition from short to long-range force leads to **resonance**

WINO NR COMPUTATION



Zero-energy bound states → Peaks

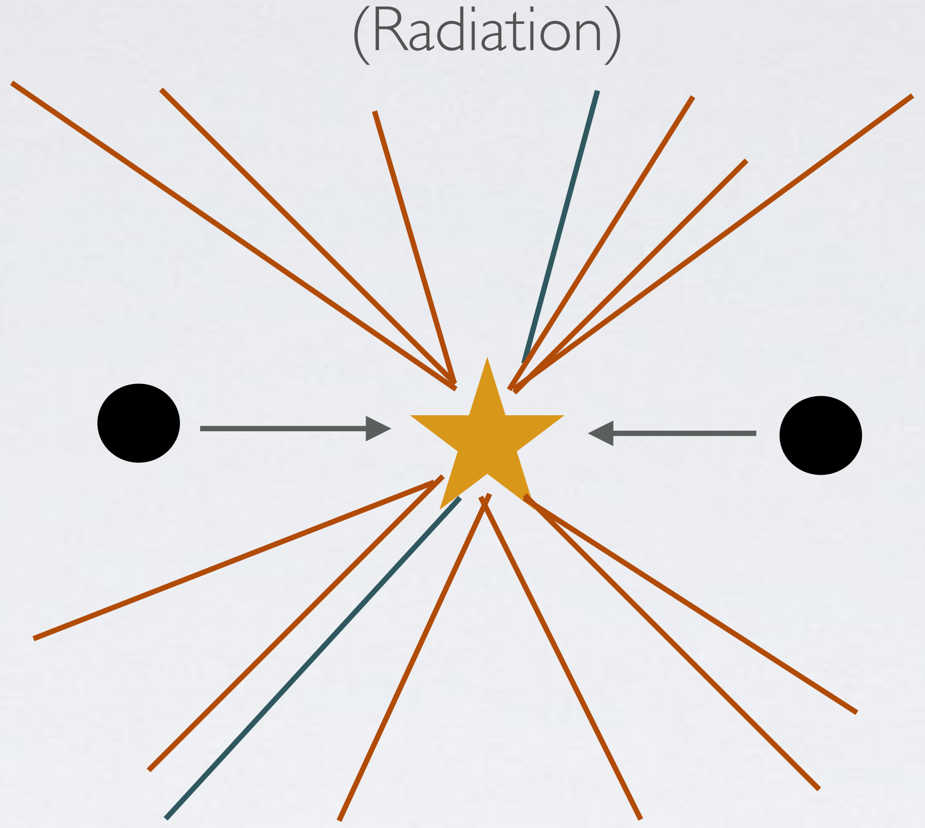
$\alpha_W M_\chi = n^2 m_W$

$$\left\langle 0 \right| \chi_v^{3\,T}\, i\sigma_2\, \chi_v^3 \left| (\chi^0\chi^0)_S \right\rangle = 4\sqrt{2}\, M_\chi\, s_{00}\,;$$

$$\left\langle 0 \right| \chi_v^{+T}\, i\sigma_2\, \chi_v^- \left| (\chi^0\chi^0)_S \right\rangle = 4\, M_\chi\, s_{0\pm}$$

Wavefunction at the origin

HUGE ACCELERATION → CLASSICAL RADIATION



Charged particles in annihilation process radiate (γ, W, Z) from acceleration

Perturbative factor picks up kinematic enhancements "Sudakov double log"

$$\sigma v = \sigma v_0 \left| \exp\left[-\frac{\alpha}{2\pi} \log(E_{\text{high}}/E_{\text{low}}) \log(E_{\text{high}}/E_{\text{collinear}}) \right] \right|^2$$

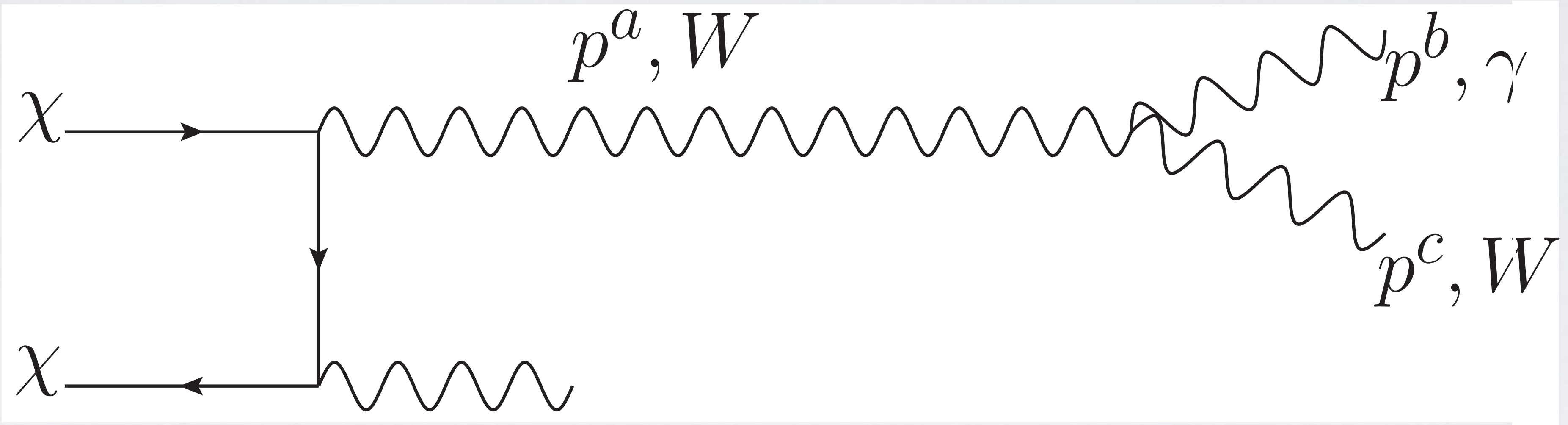
Above rate **produces classical spectrum**,
but **hard to see in quantum perturbation theory**

$$\frac{\alpha_W}{\pi} \log(M_{\text{wino}}^2/m_W^2)^2 \approx 0.6$$

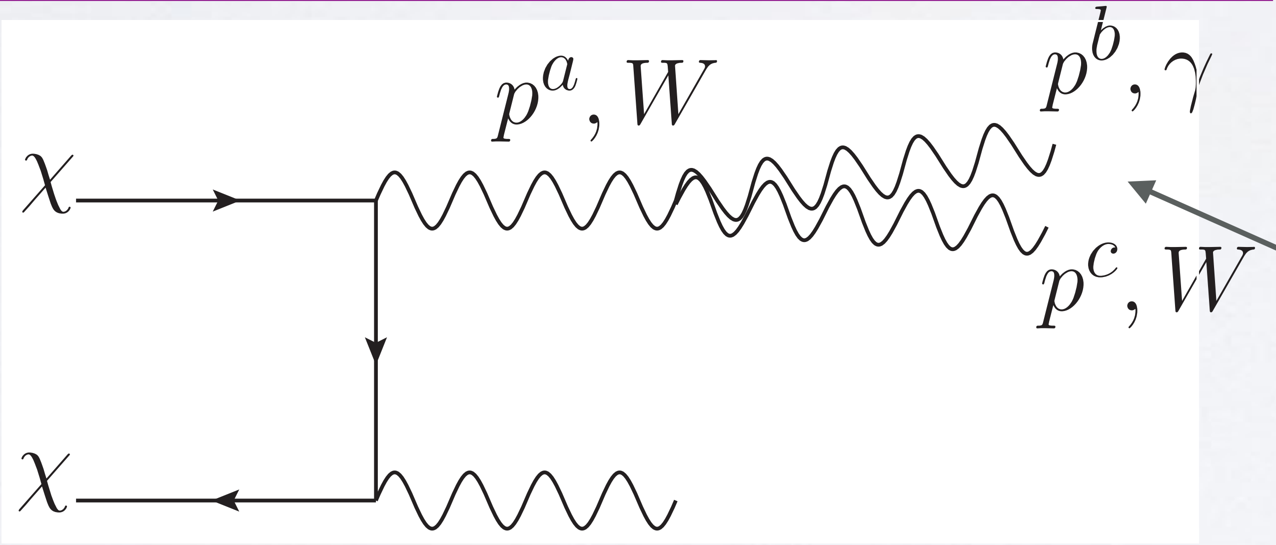
Double log
Large correction!

SOFT/COLLINEAR ENHANCEMENT

Soft radiation: Time-scales much longer than annihilation



Collinear Radiation: Narrow splitting of one particle into 2



θ

$$\propto \frac{1}{p_A^2} = \frac{1}{2E_bE_c(1-\cos\theta)}$$

Keep modes with **kinematic enhancement** (soft, collinear)

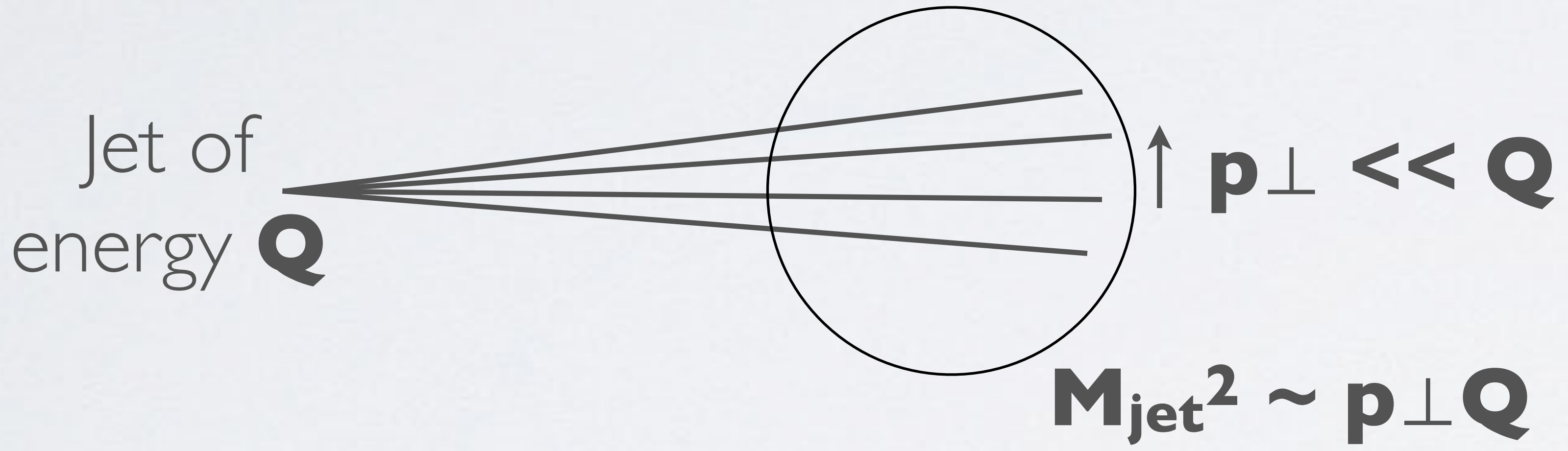
SCET for Dark Matter annihilation

[MB, Rothstein, I., Vaidya, V.: 1409.4415]

*Originally developed for study of QCD
hep-ph/0005275: Bauer, Fleming, Luke
hep-ph/0011336: Bauer et al.

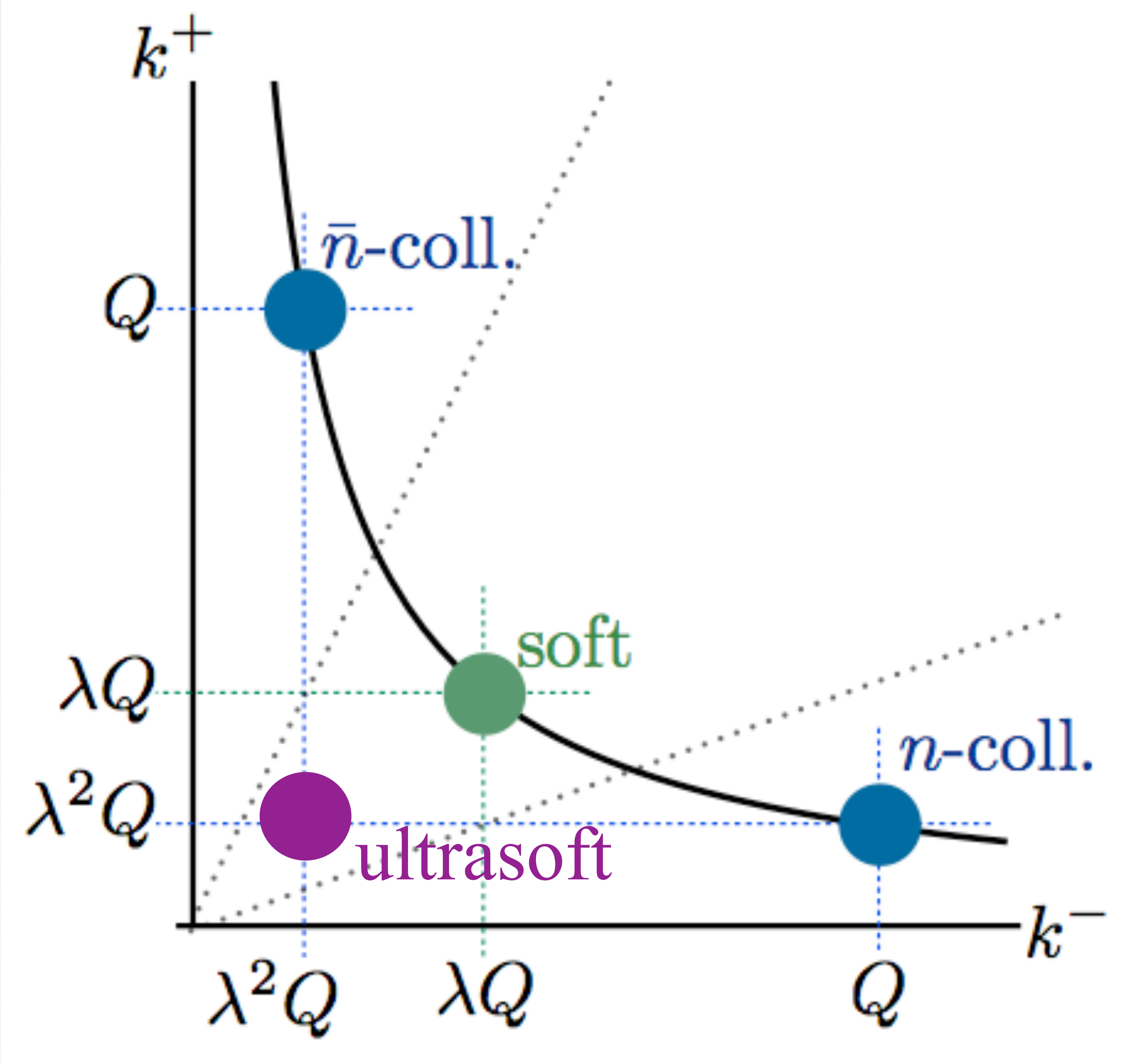
SOFT-COLLINEAR EFFECTIVE THEORY

- Large scale-hierarchies can arise within one field



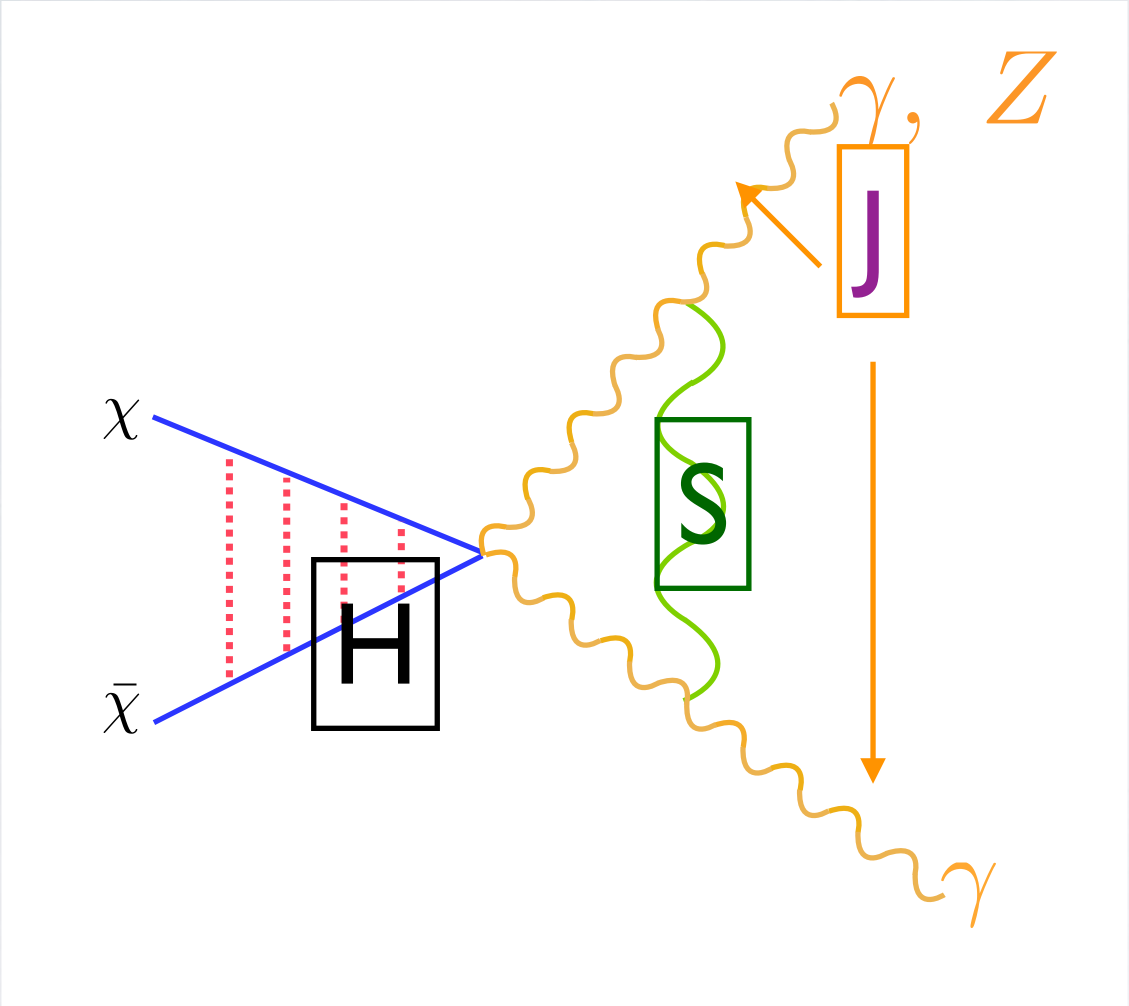
- We can **use Renormalization Group to resum** kinematic logs

Lightcone momenta
$k^+ = k^0 + k^3$
$k^- = k^0 - k^3$



Integrate out hard modes, separate fields for those **collinear** to null directions and **soft** momenta.

SCET OBSERVABLES



Factorized Hilbert Space:

$$|X\rangle = |X_{\text{collinear}}\rangle |X_{\text{soft}}\rangle$$

$$d\sigma = H(Q)\, J(Q, z_{\text{collinear}}) \otimes S(z_{\text{soft}})$$

Squared Wilson coefficient

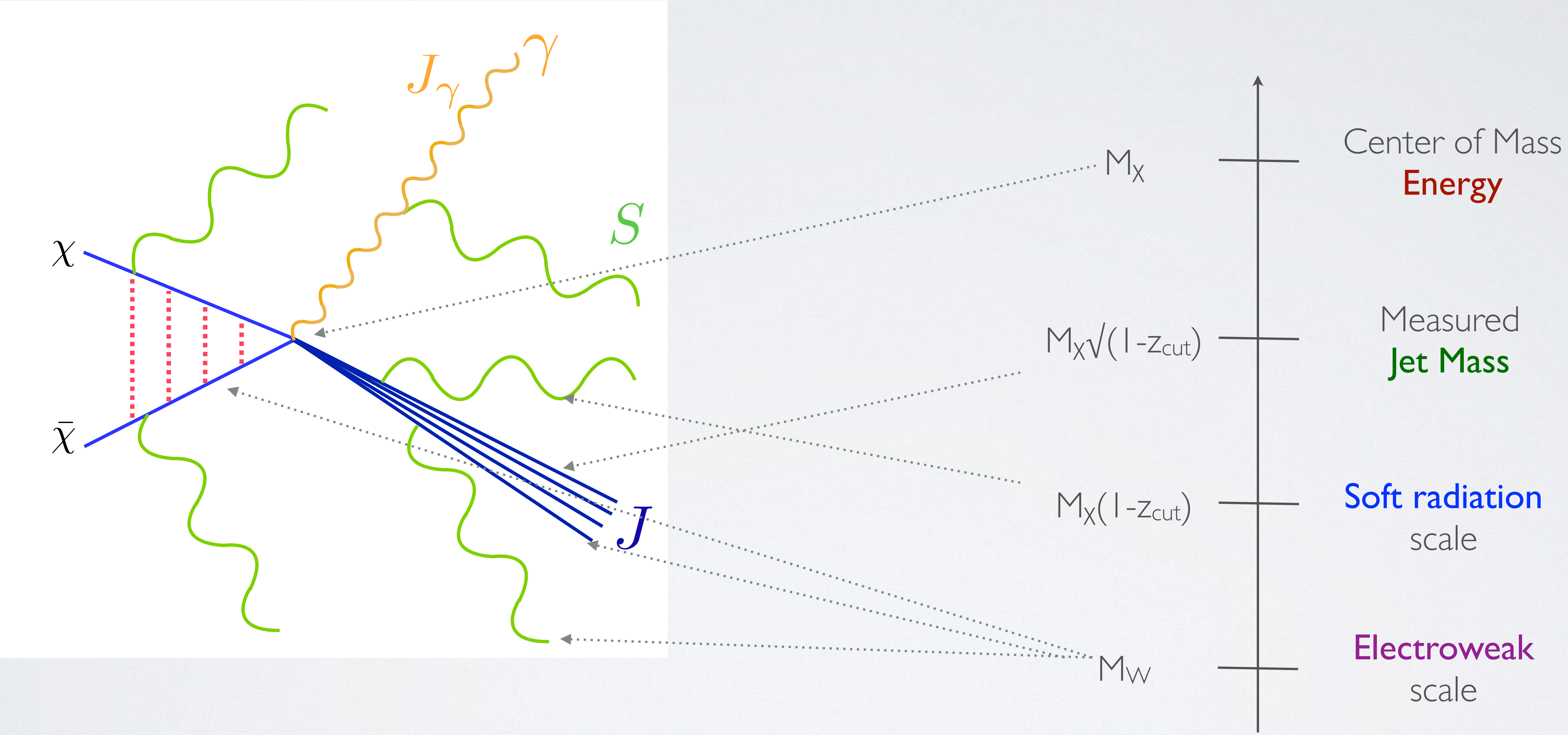
$$S = \langle 0 | (YY)^{\dagger}\, \delta\left[f(z_{\text{soft}})\right] (YY) | 0 \rangle$$

Collinear Gauge field

Soft Wilson Line

$$J_n = \langle 0 | B_{n\perp} \delta\left[f(Q, z_{\text{collinear}})\right] | X_n \rangle \langle X_n | B_{n\perp} | 0 \rangle$$

SCET W/ 2 EXPANSIONS



SOFT REFACTORIZATION

S: Perform matching

@ $M_\chi\sqrt{(1-z_{cut})}$

$S \rightarrow H_S(M_\chi\sqrt{(1-z_{cut})})S(m_W)$

???

Remaining **soft:**

$(p_+, p_-, p_\perp) \sim M(\lambda, \lambda, \lambda)$

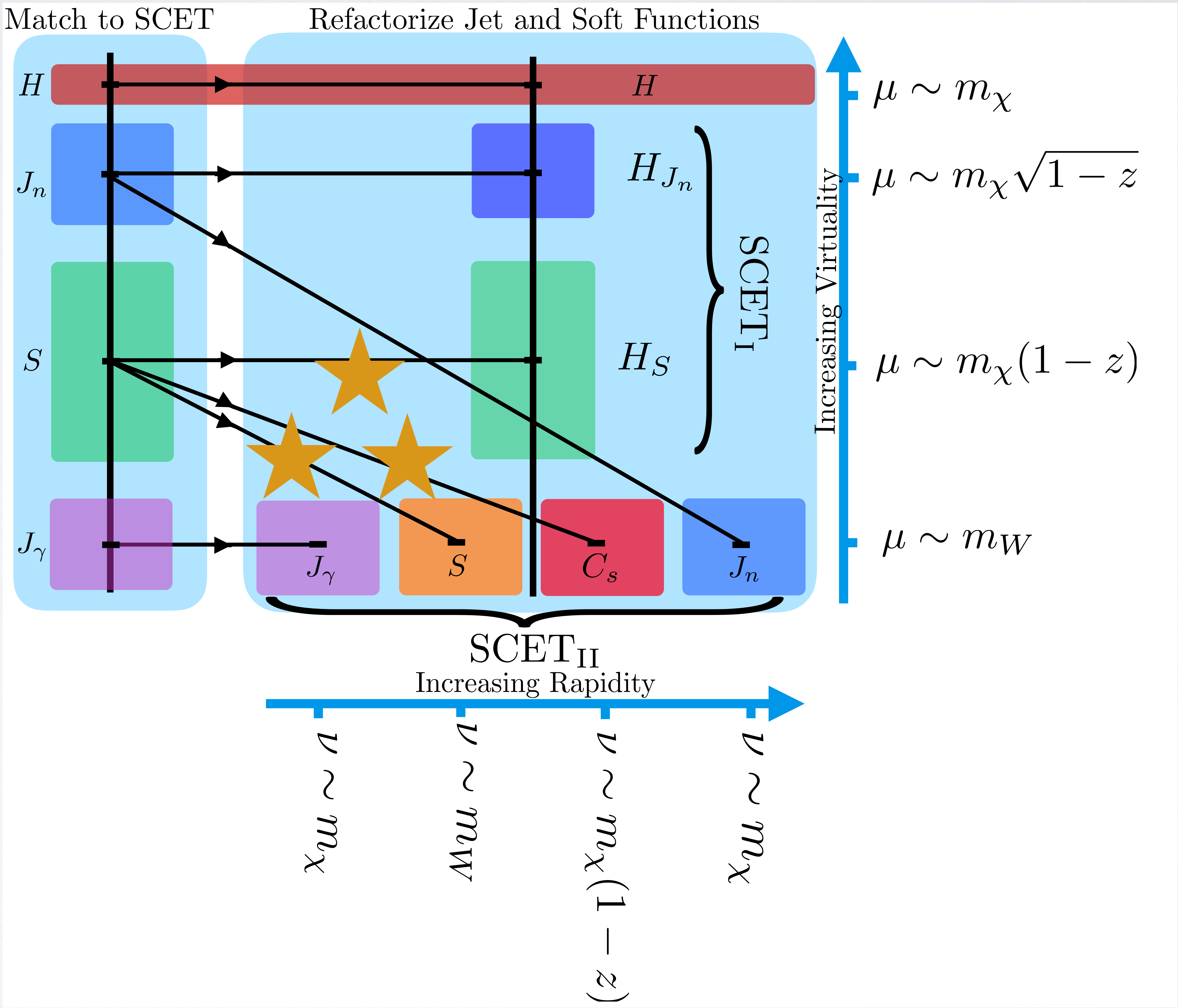
$\lambda = m_W/M_\chi$

BUT...

what about measurement function?

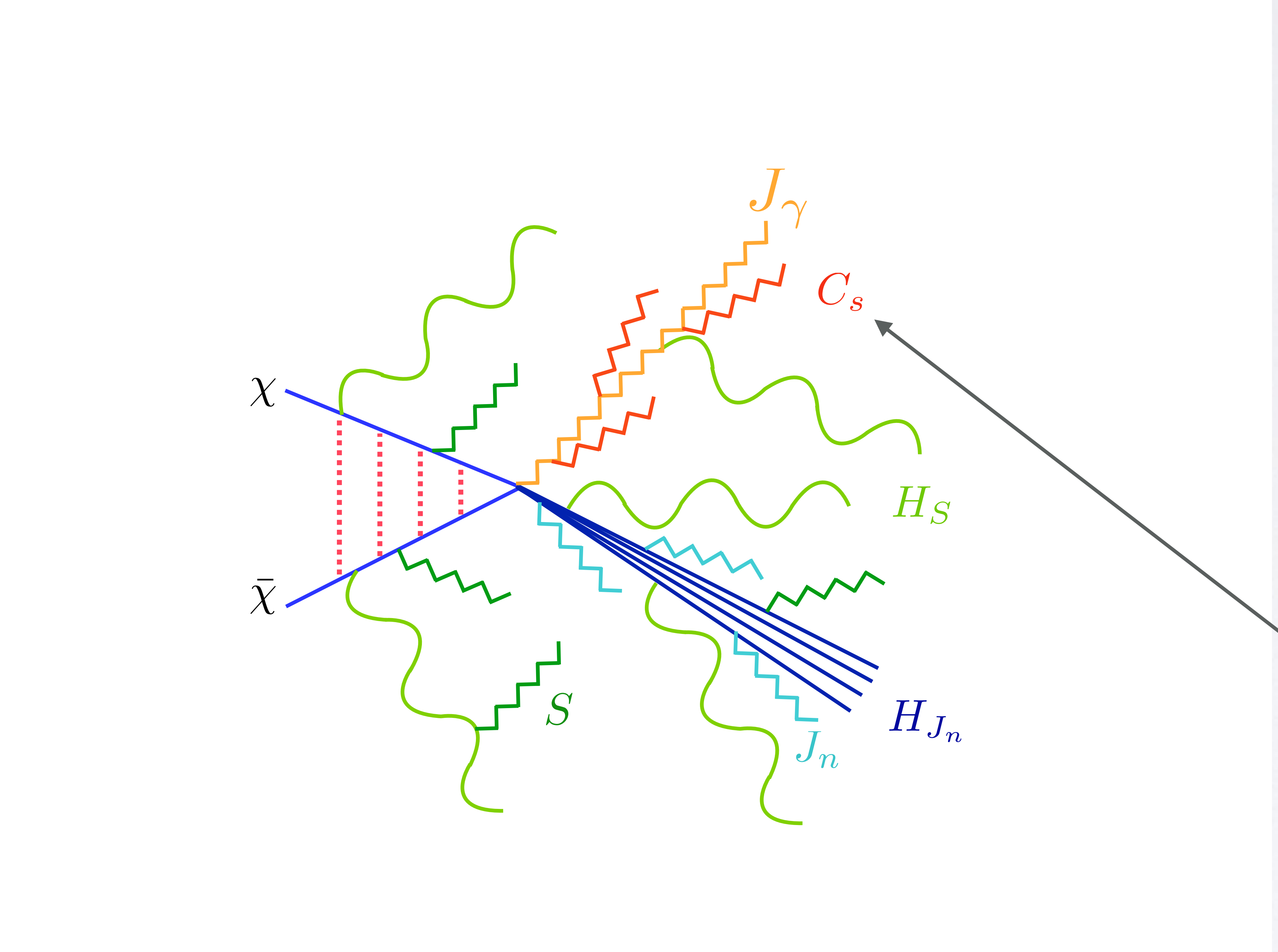
$$(1-z) = \frac{1}{4\,M_\chi^2}\,m_X^2 = \frac{1}{4\,M_\chi^2}\left(\sum_{i\in X_s} p_i^\mu + \sum_{i\in X_c} p_i^\mu\right)^2$$

$$\equiv (1-z_s) + (1-z_c) + \mathcal{O}(\lambda^2)$$



FULLY FACTORIZED THEORY

$$\frac{d\sigma}{dz} = H(m_\chi, \mu) \cdot H_{J_n}(m_\chi, (1-z), \mu) \cdot H_S(m_\chi, (1-z), \mu) \cdot J_\gamma(m_W, \mu, \nu) \cdot S(m_W, \mu, \nu) \cdot C_S(m_\chi, (1-z), m_W, \mu, \nu) \cdot J_n(m_W, \mu, \nu)$$



Alternate **collinear-soft scaling:**

$(p_+, p_-, p_\perp) \sim M(1-z_{cut})(\lambda^2, 1, \lambda)$

$\lambda = m_W/M_\chi(1-z_{cut})$

Factorization holds to NLL!
MB et al.: 1808.08956

Collinear soft modes account for **radiation along photon direction**, but contribute to recoil jet mass

LL RESUMMED PHOTON SPECTRUM

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

$$+ \left(C_2(W)\frac{\alpha_W}{\pi}\log\left(\frac{4M_\chi^2(1-z)}{M^2}\right) \frac{e^{\left[C_2(W)\frac{\alpha_W}{2\pi}\log^2\left(\frac{M^2}{4M_\chi^2(1-z)}\right)\right]}}{1-z} \right)_+ F_0$$

$$+ \Bigg[\left(C_2(W)\frac{\alpha_W}{\pi}\log\left(\frac{4M_\chi^2(1-z)}{M^2}\right) + 3C_2(W)\frac{\alpha_W}{\pi}\log\left(\frac{M}{2M_\chi(1-z)}\right)\right)$$

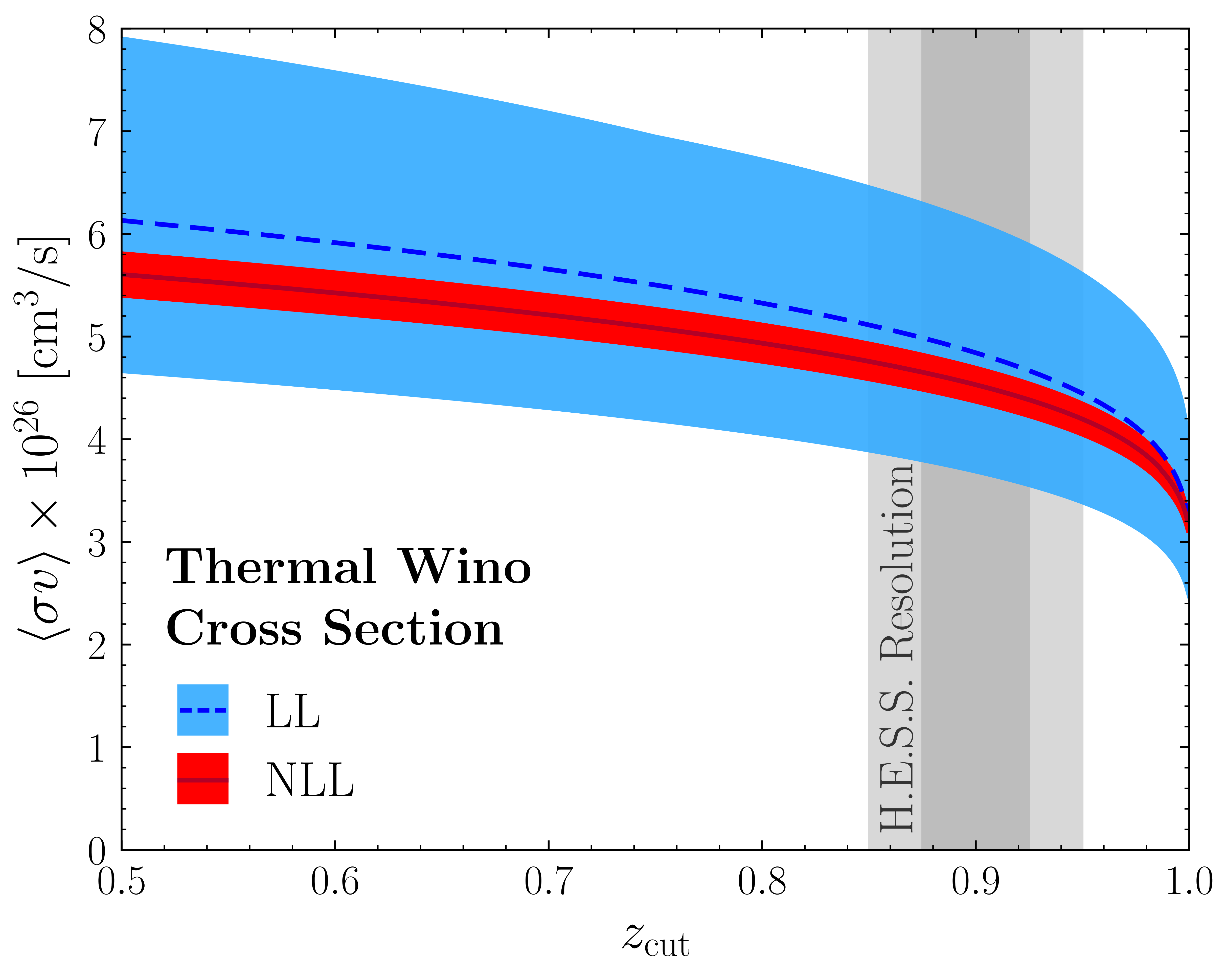
$$\times \left(\frac{e^{\left[-\frac{3}{2}C_2(W)\frac{\alpha_W}{\pi}\log^2\left(\frac{M}{2M_\chi(1-z)}\right) + C_2(W)\frac{\alpha_W}{2\pi}\log^2\left(\frac{M^2}{4M_\chi^2(1-z)}\right)\right]}}{1-z} \right) \Bigg]_+ F_1 \Bigg\}$$

Squared Wilson Coefficient for wino annihilation

MB et al.: 1712.07656

Linear combination of Sommerfeld factors

CUMULATIVE RESUMMED ANNIHILATION RATE

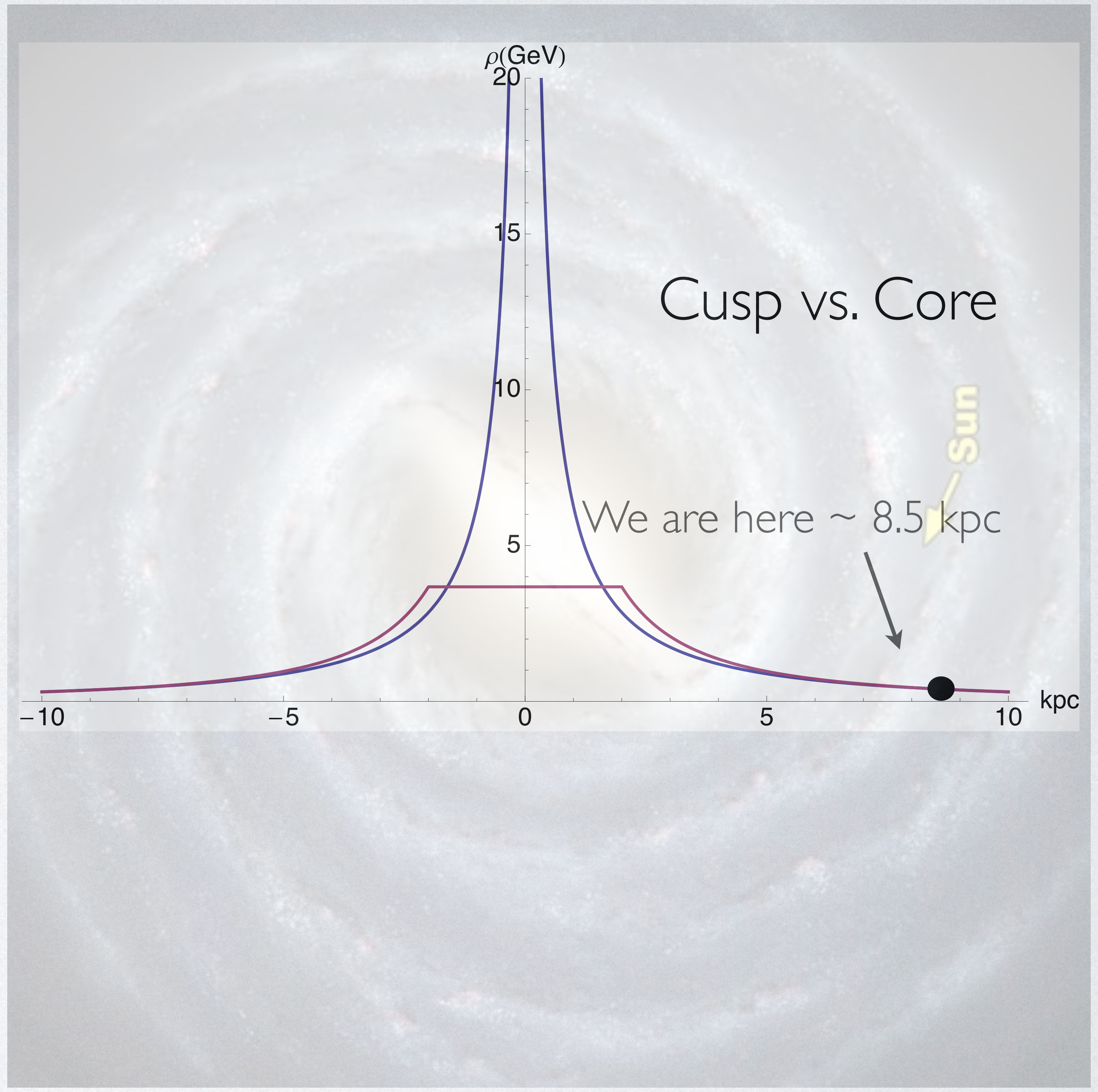


Thermal relic wino rate vs. Energy fraction

MB et al.: 1808.08956

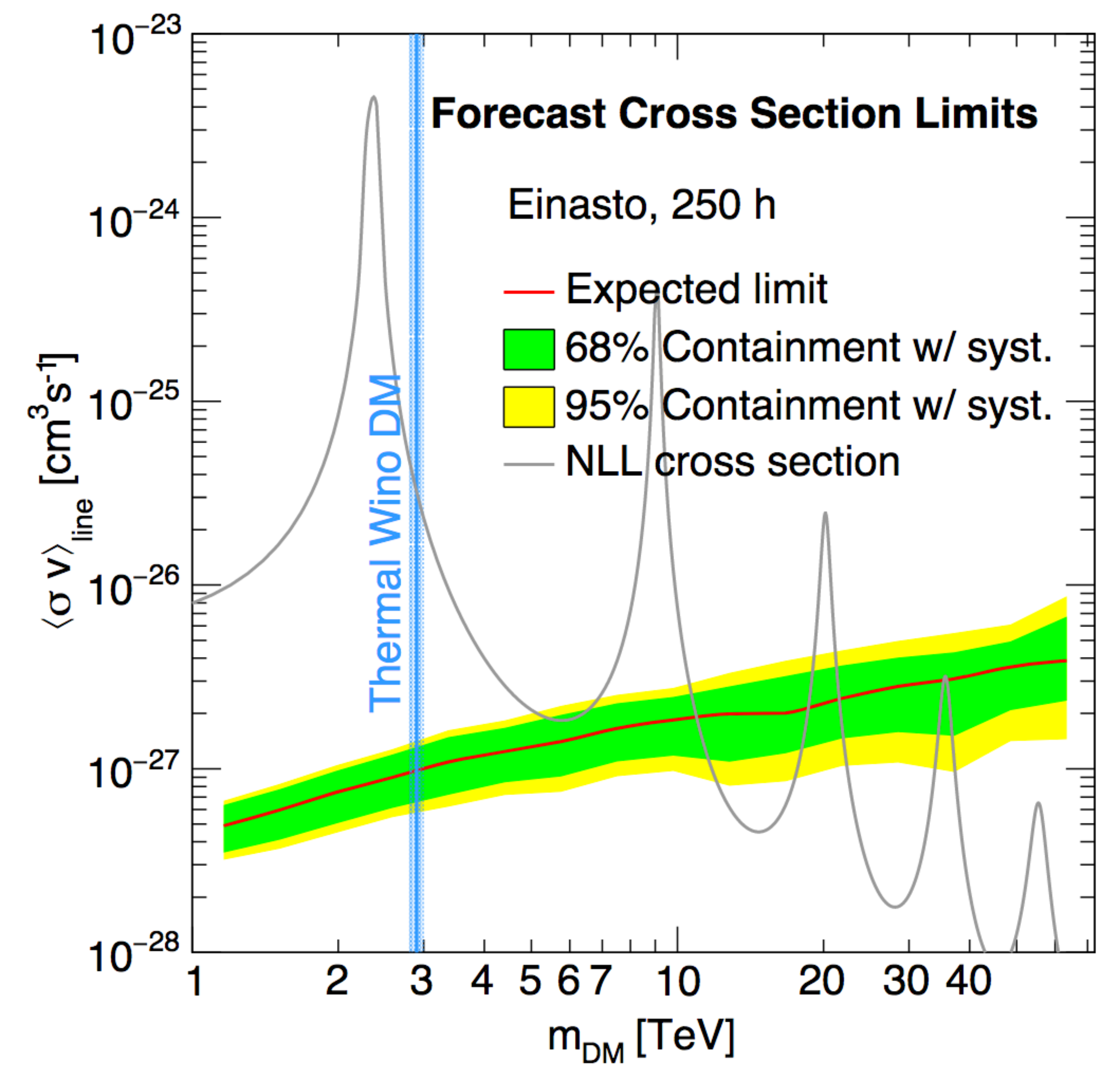
THE LOOPHOLE

- **Indirect detection must assume something about DM distribution** in its target
- We take a **cored Einasto** (pure Einasto is cusped) profile
- Ask **what size core is needed for consistency with DM limit**, is that size constrained?
- **Use a mix of targets** (i.e. dwarf spheroidals (DSphs) in addition to Milky Way Center)

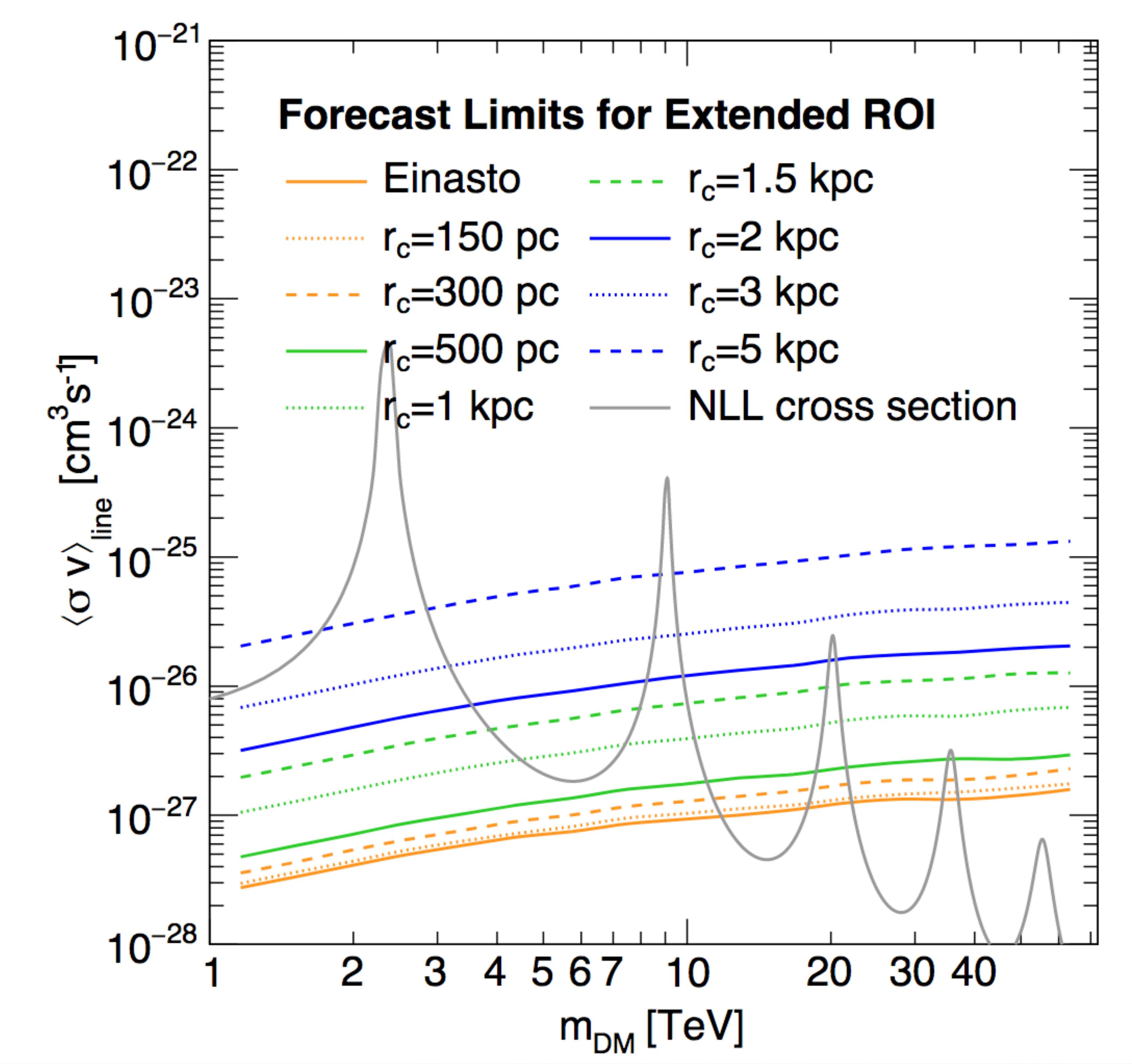


HESS WINO LIMITS

Rinchiuso et al.: 1808.04388



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



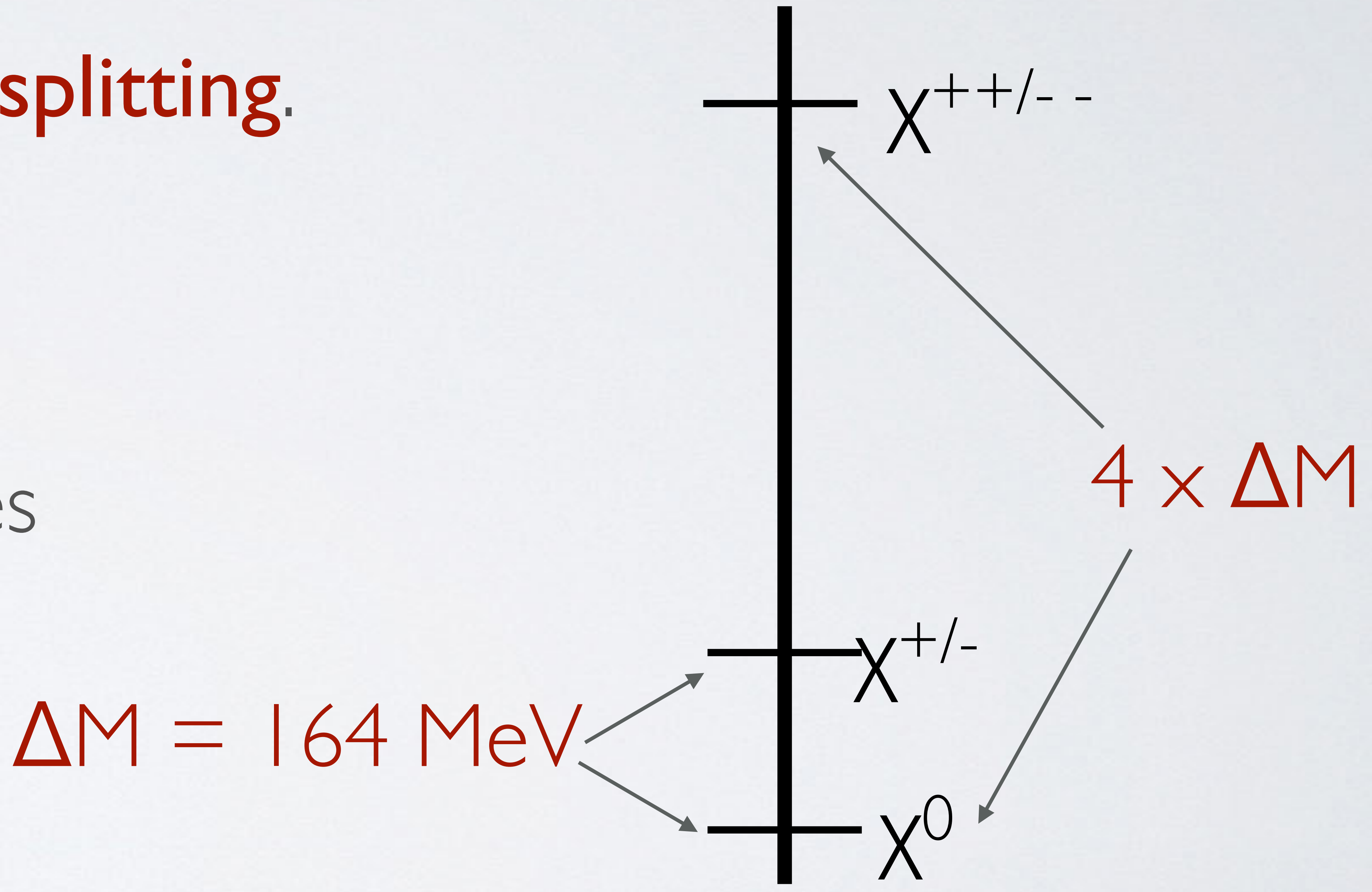
More aggressive analysis with
better galactic center understanding,
halo loophole closes, r_c>2.5 kpc

Hooper: 1608.00003 limit of 2 kpc

"MINIMAL DARK MATTER"

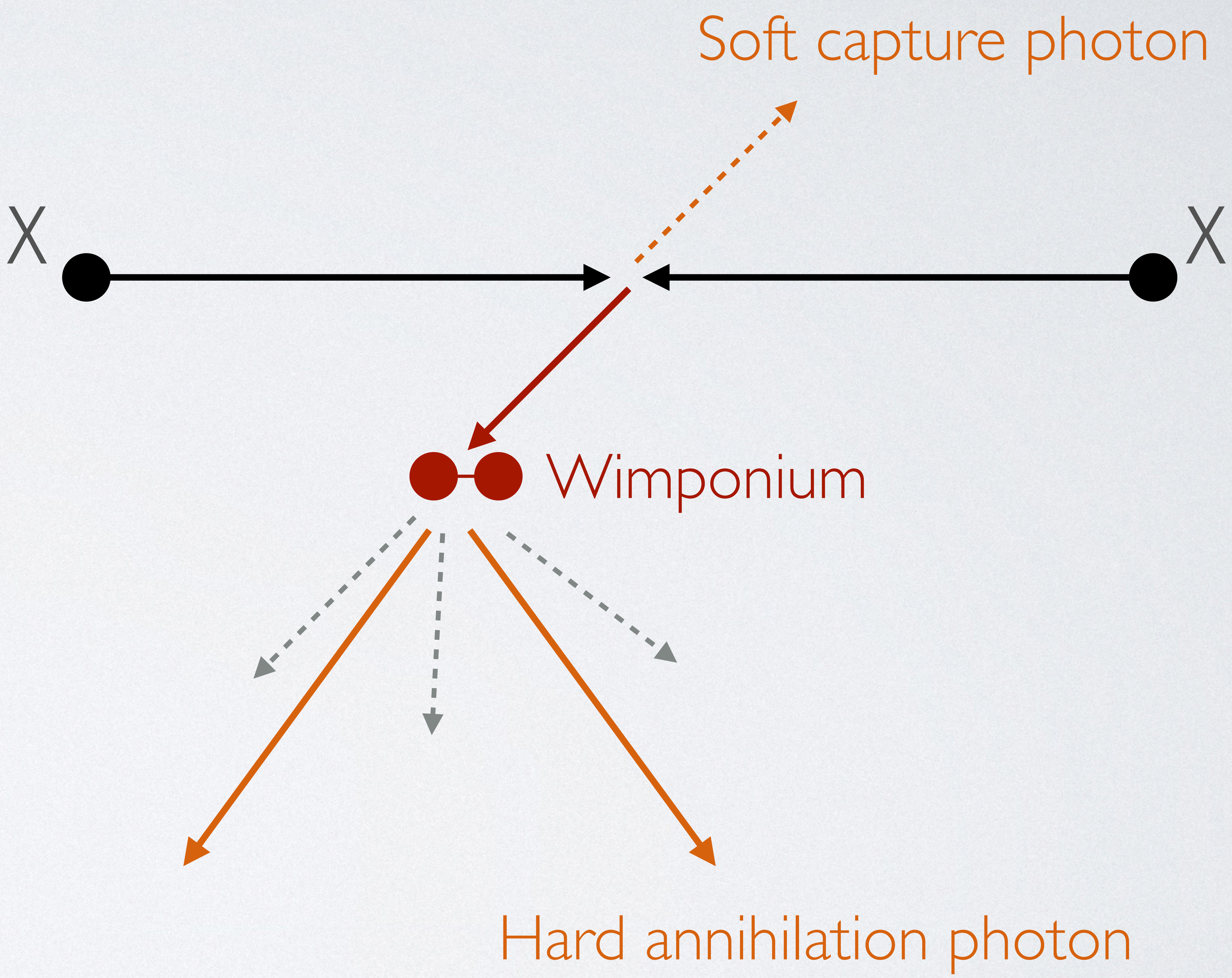
- **SU(2) quintuplet** (Y=0) has neutral **DM candidate**.
- Charged and doubly-charged states with **narrow mass splitting**.
- Keeps SU(2) Landau pole above GUT scale
- **Cosmologically stable** just under SM symmetries

$$\mathcal{O}_{\rm decay} = \frac{c}{\Lambda^2}\chi_{abcd}\, L^a H^b H^c H^d$$



REPEAT FOR QUINTUPLET?

- Naively, **redoing analysis** for any electroweak WIMP **just seems to involve shuffling group theory** factors from wino.
- In practice, capture to and annihilation of **bound states contributes to "endpoint" photons**.
- **Narrow-width approximation** allows **separation of this process** from direct annihilation.

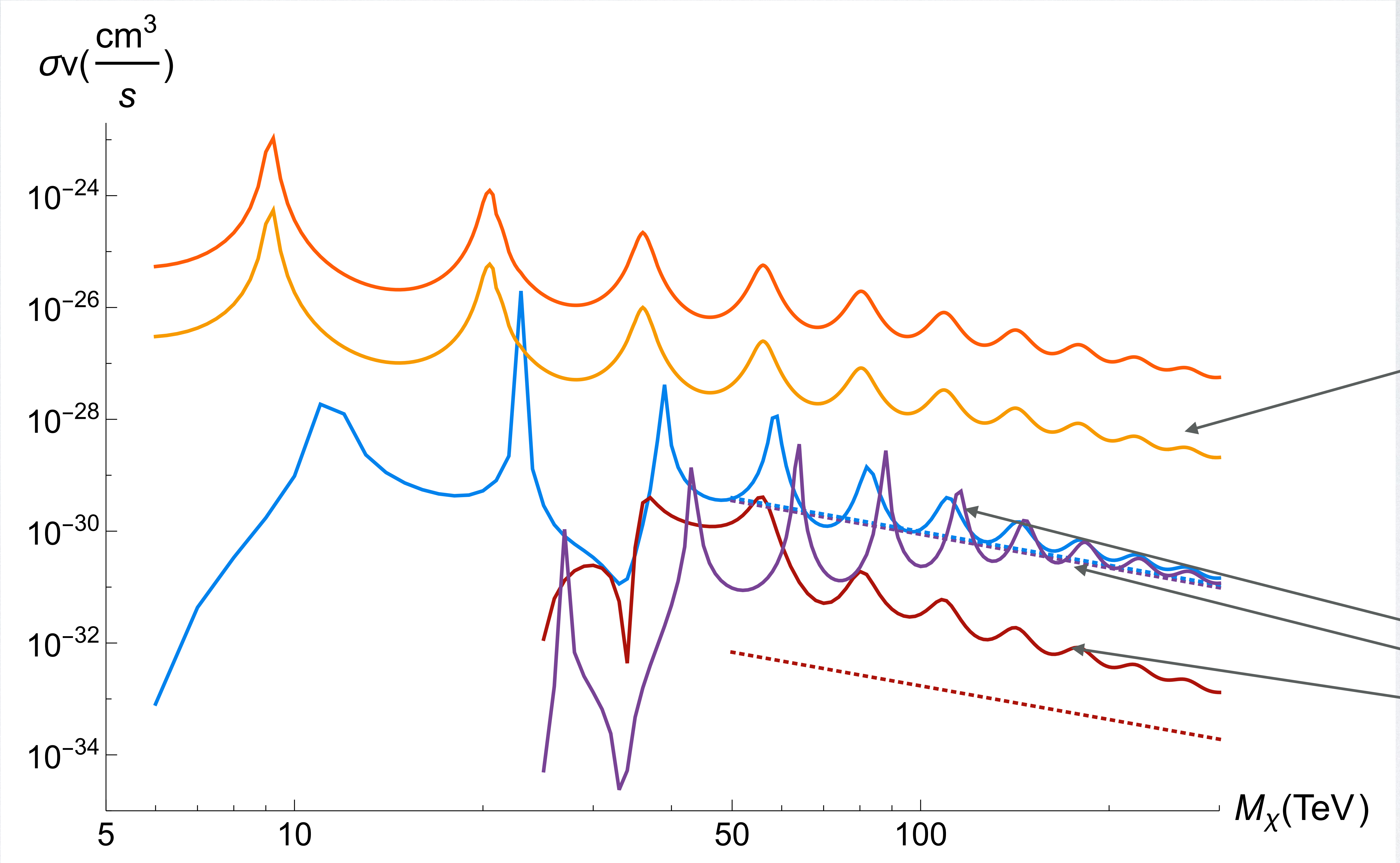


$$\frac{d\sigma}{dz} = \sigma(\chi_0\chi_0 \to B + \gamma_{\rm us})\frac{1}{\Gamma}\frac{d\Gamma_{B\to\gamma+X}}{dz}$$

WHAT ABOUT WINO-ONIUM?

SU(2) symmetric calculation:

- e^{-8n} suppression
- P-wave → 1S vanishes



Direct annihilation γ

Bound-state captures

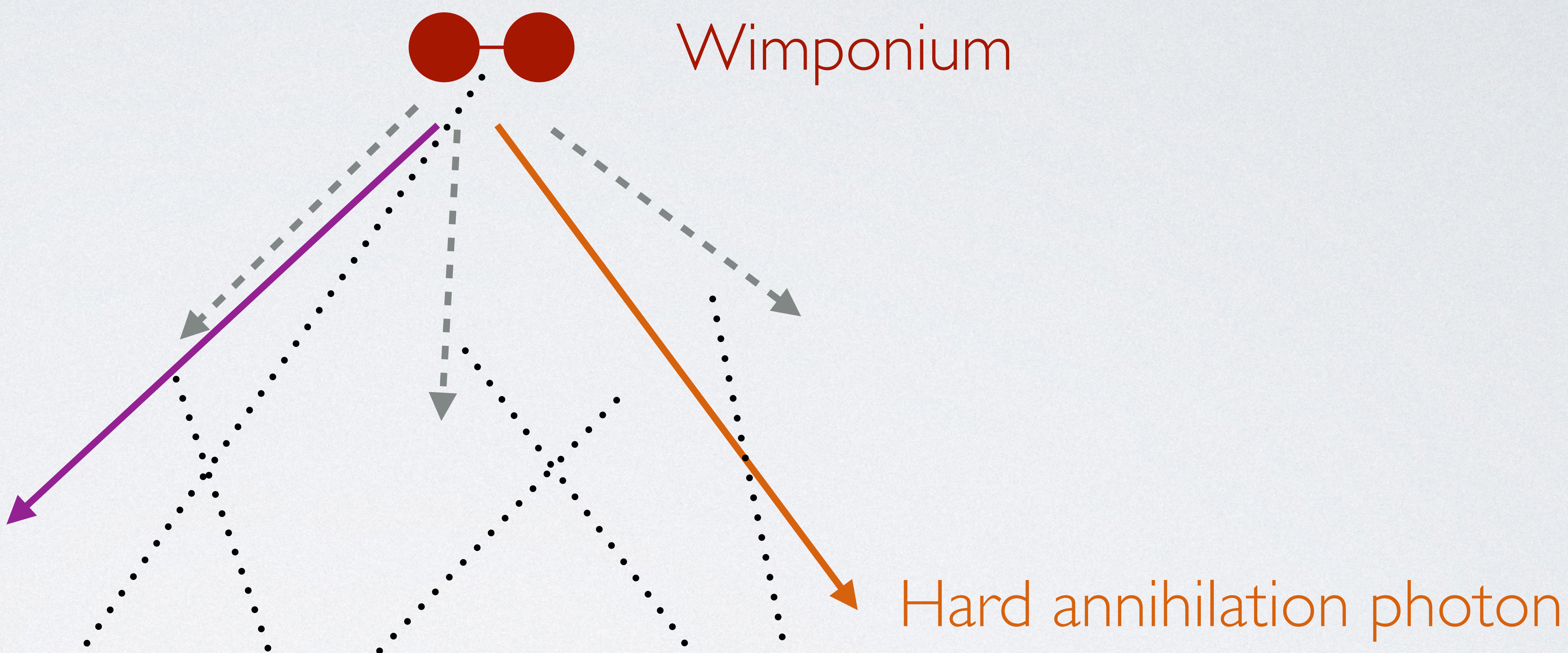
BR to γ <1% for all these channels

1610.07617: P. Asadi, MB et al.
Wino Annihilation & Capture rates

QUINTUPLET IS STICKIER

SU(2) symmetric calculation:

- **2-3 order of magnitude enhancement over wino**
- 2 attractive channels in 3x3 potential
- P-wave → 1S exists

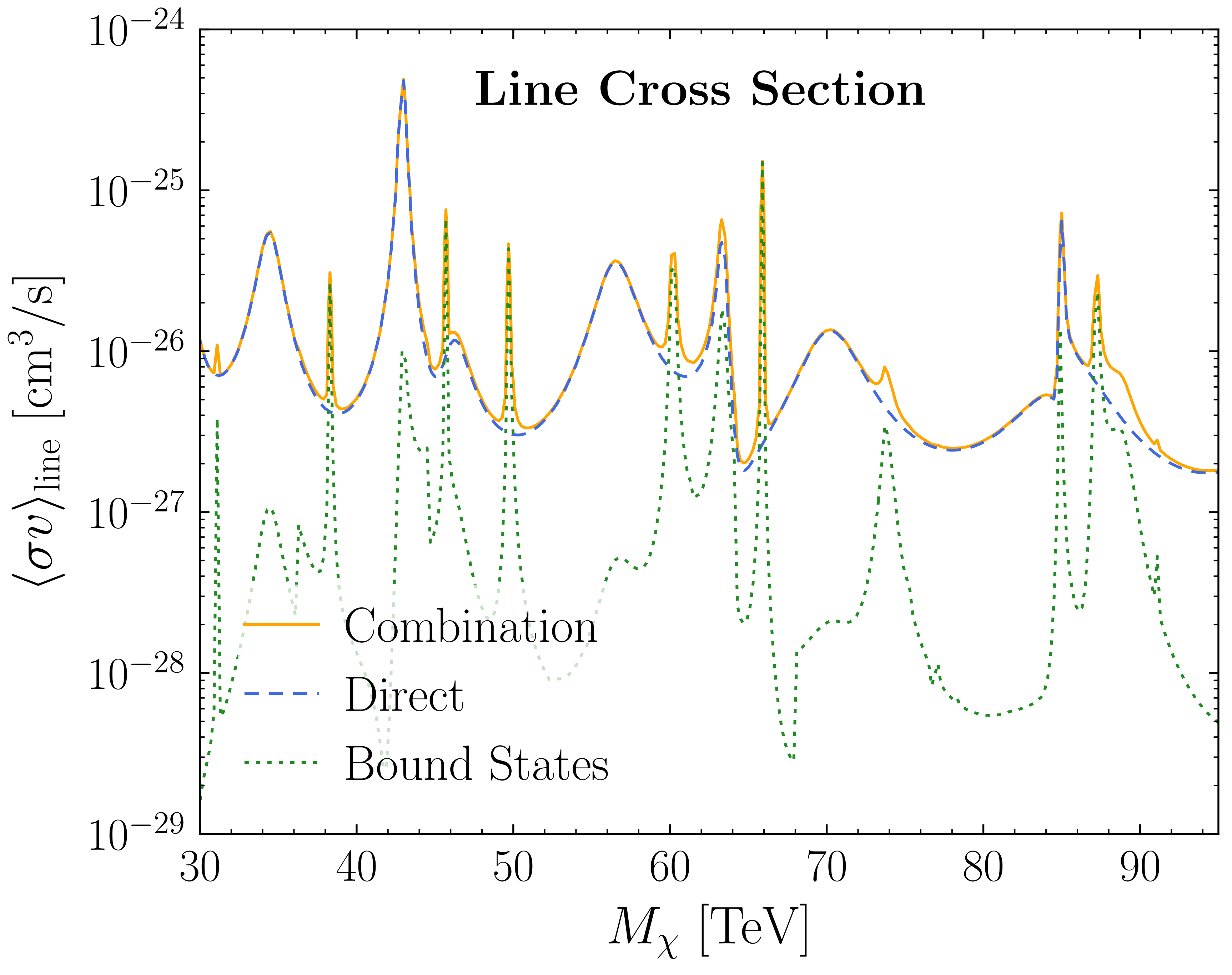


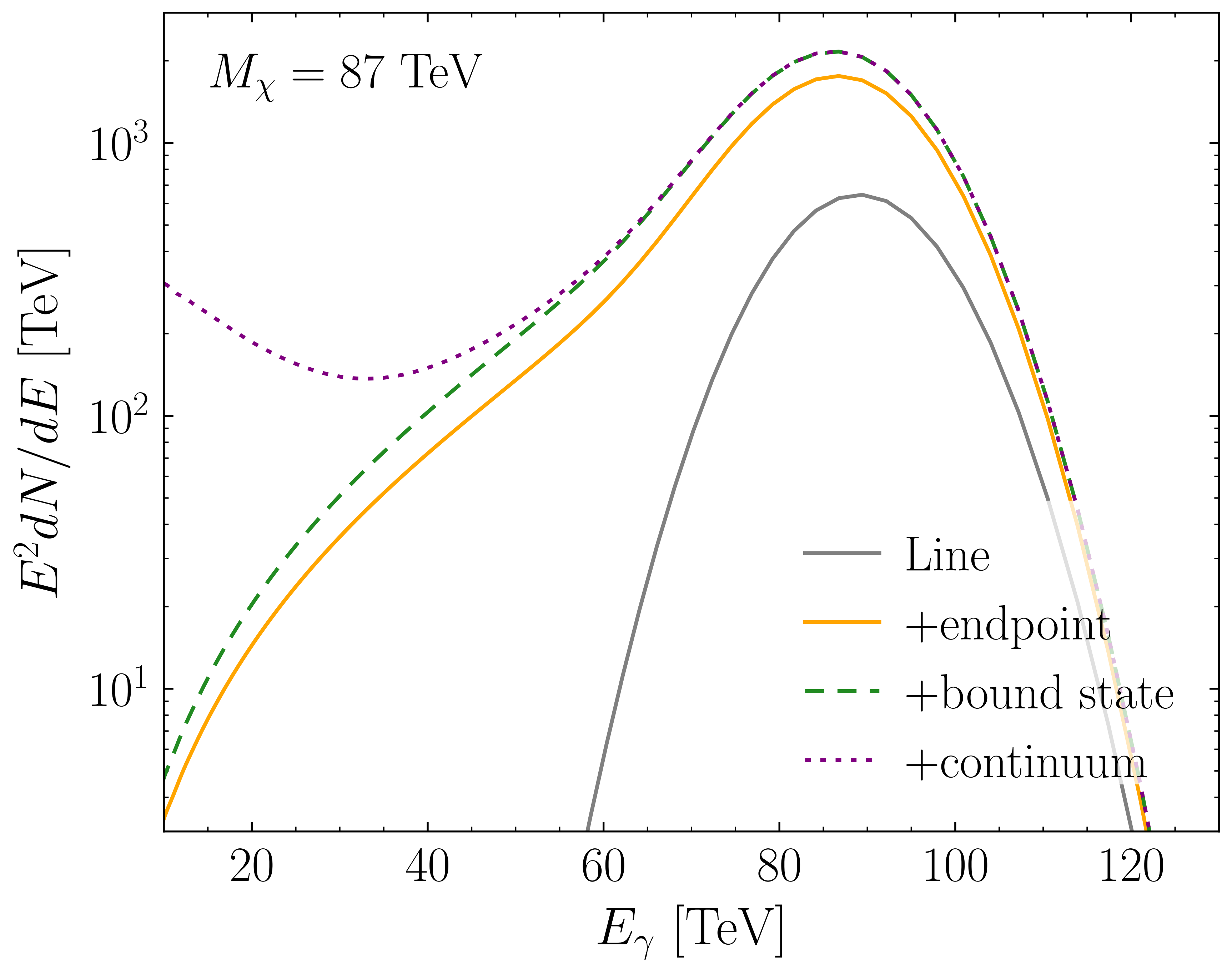
$$\frac{d\Gamma}{dz} = \left[\int \frac{d\Omega_\gamma}{4\pi} L^{aba'b'}\right] J_\gamma \int \frac{dk^+}{2\pi} J_n(k^+) \int \frac{dq^+}{2\pi} \left(\sum_{i=1}^{4} C_{s,i} S_i^{aba'b'}(q^+)\right) \delta(2M_\chi(1-z) - k^+ - q^+)$$

Wavefunction at the origin factor

2304.xxxxx: MB, N. Rodd, T. Slatyer, V. Vaidya

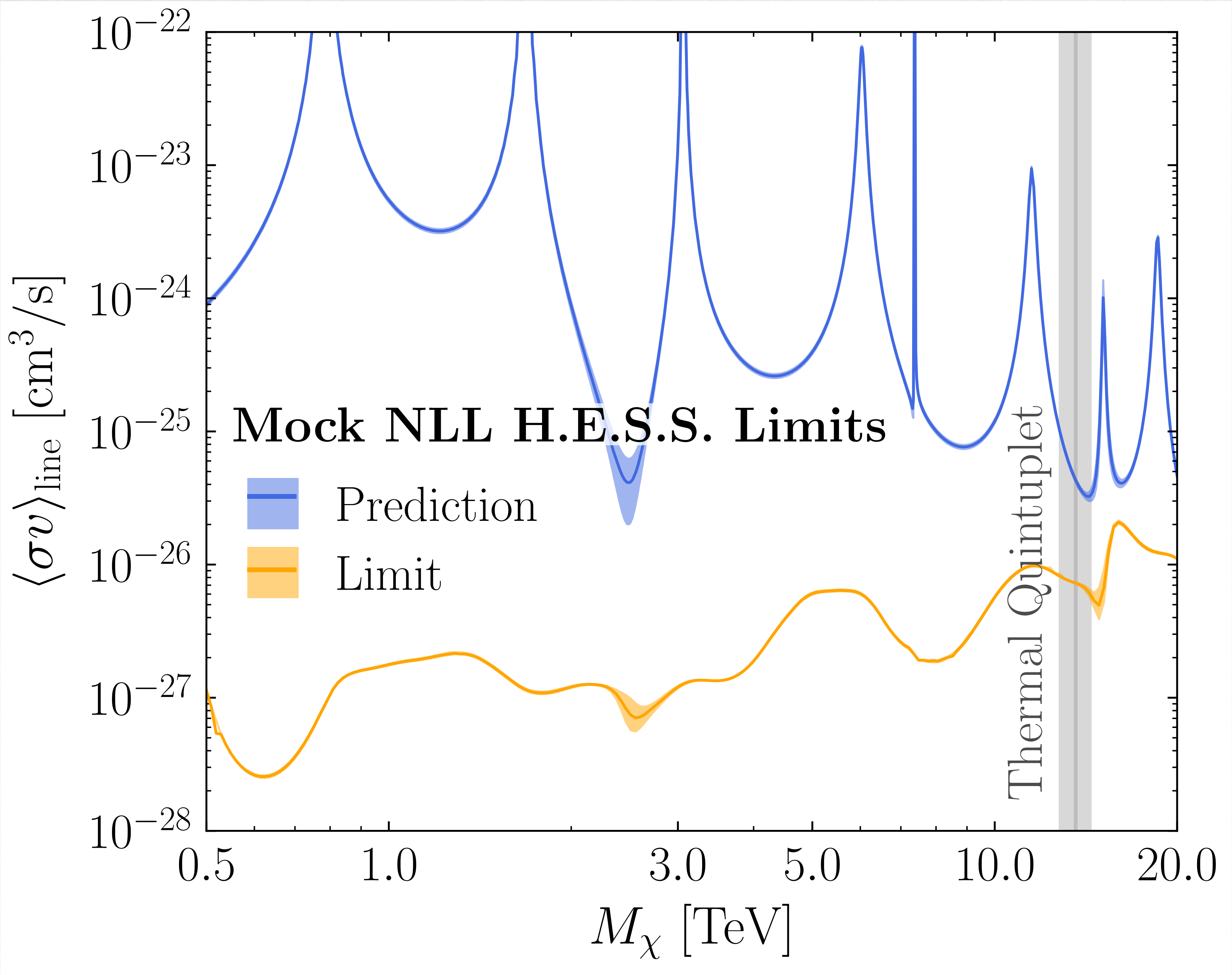
QUINTUPLET PHOTON SPECTRA

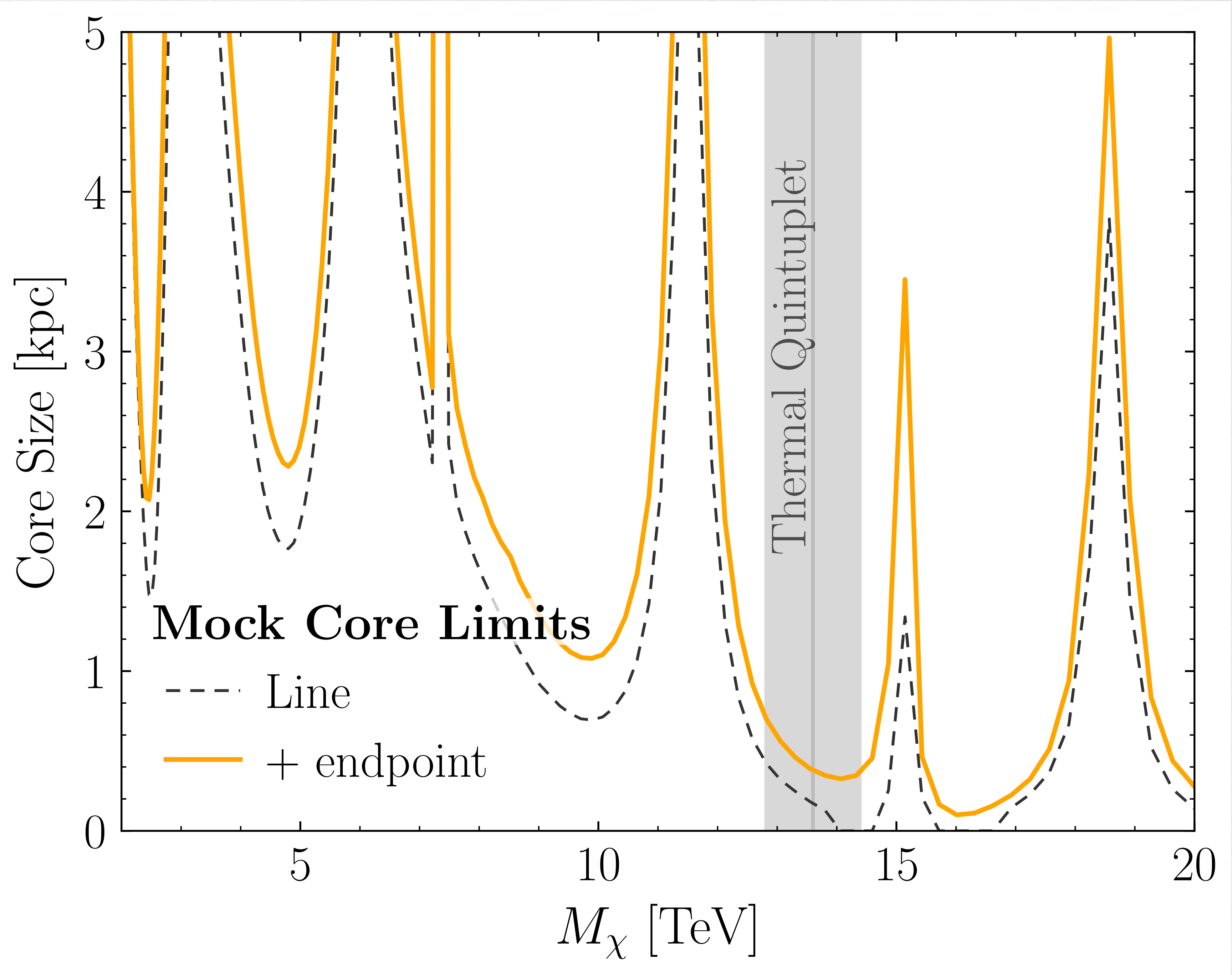




Presence of bound states (Green lines)
can give significant correction

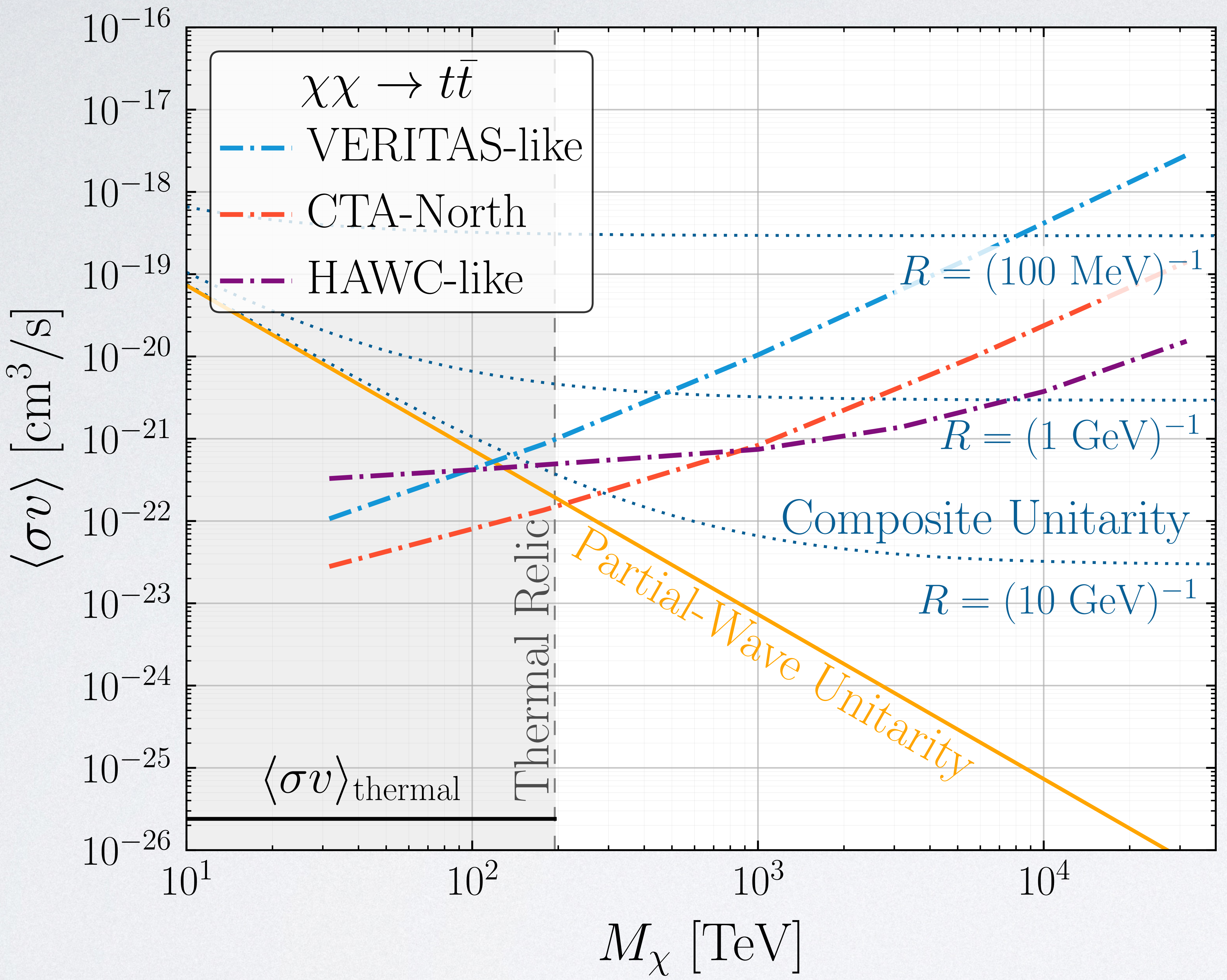
THE QUINTUPLET IS STILL ALIVE!





Quintuplet needs **as little as 0.5 kpc of coring** to be viable

FRONT 2: UHDM



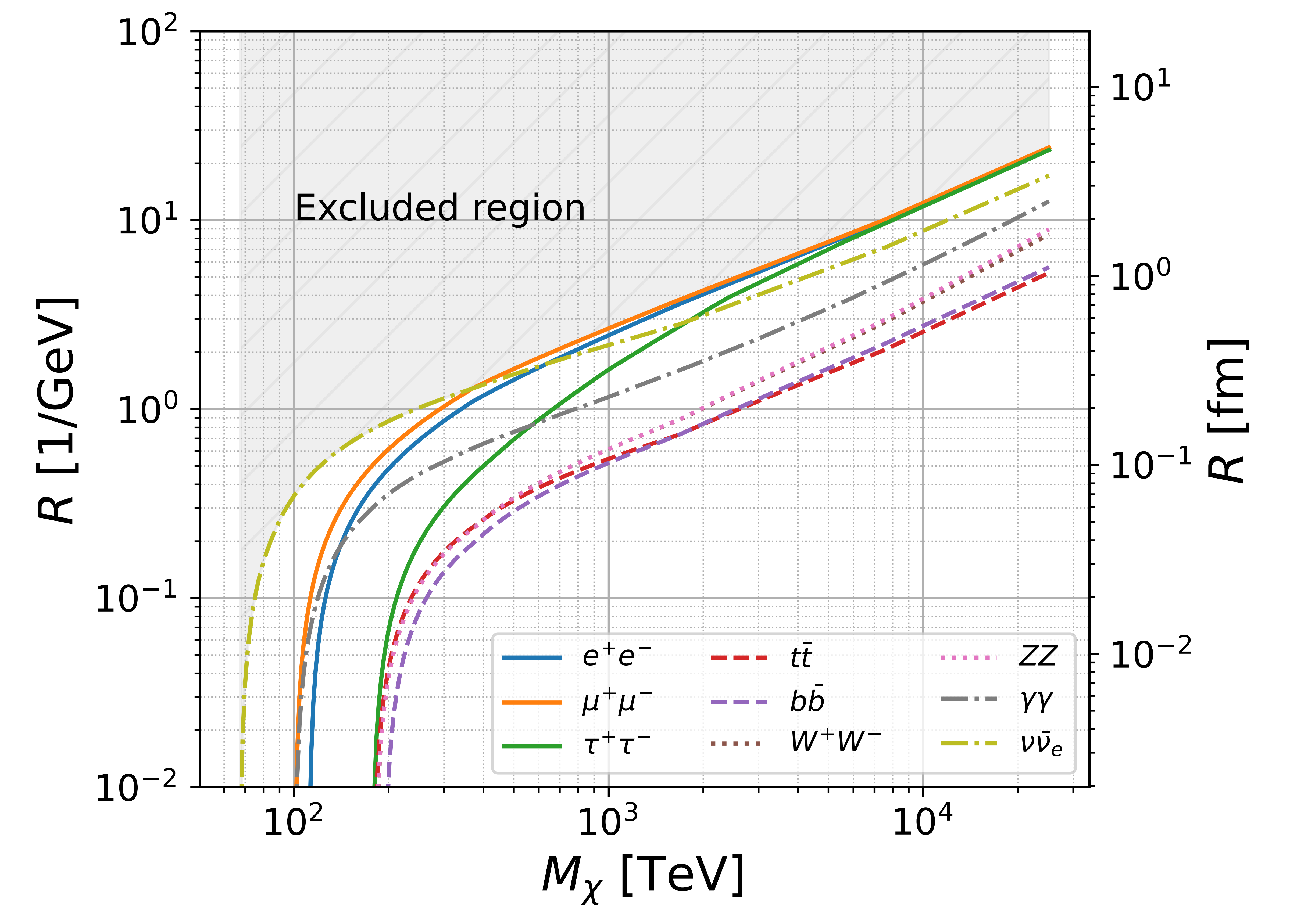
Projected Limits from observing Segue 1

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!

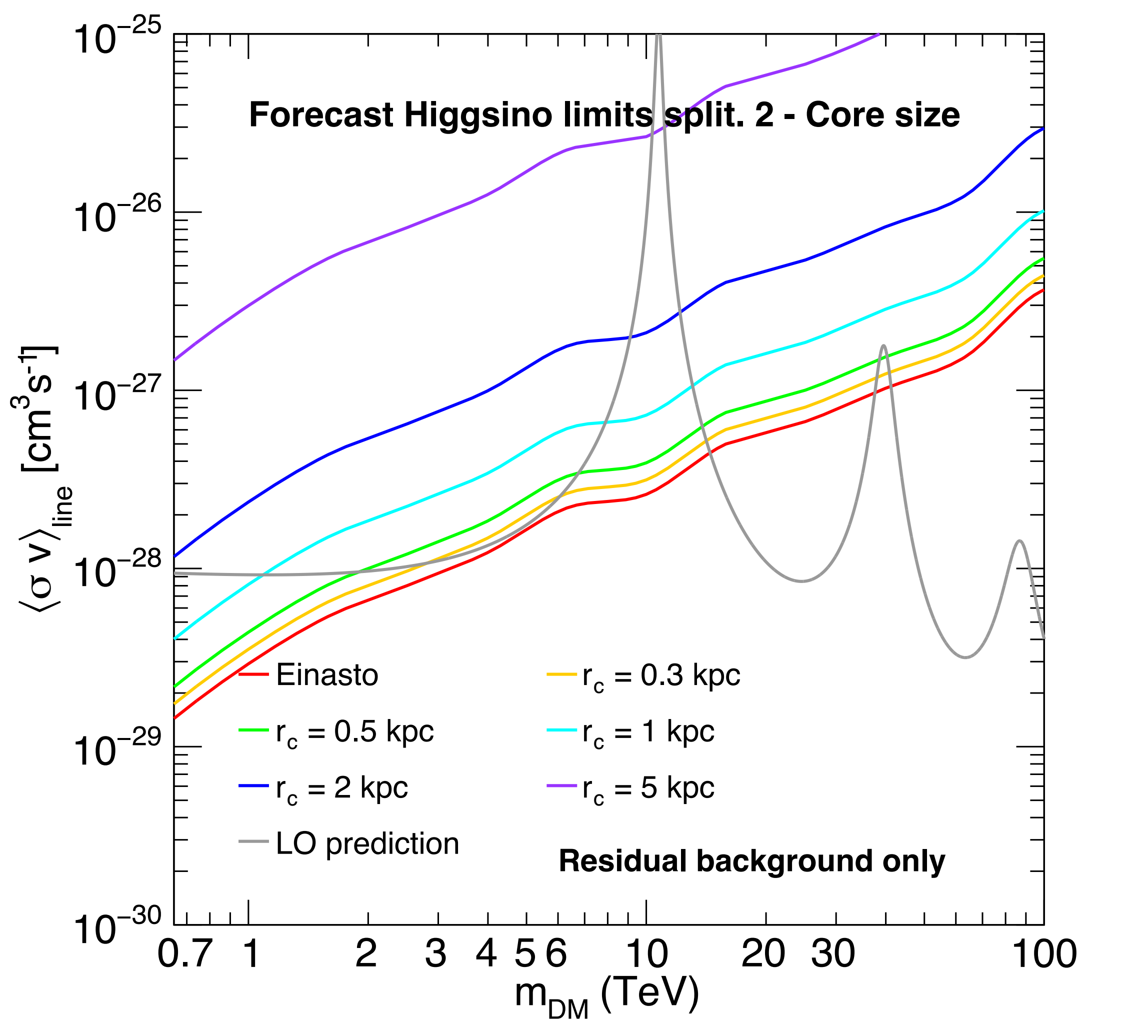


Limits on DM size given mass and annihilation channel

VERITAS data for 4 DSphs

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

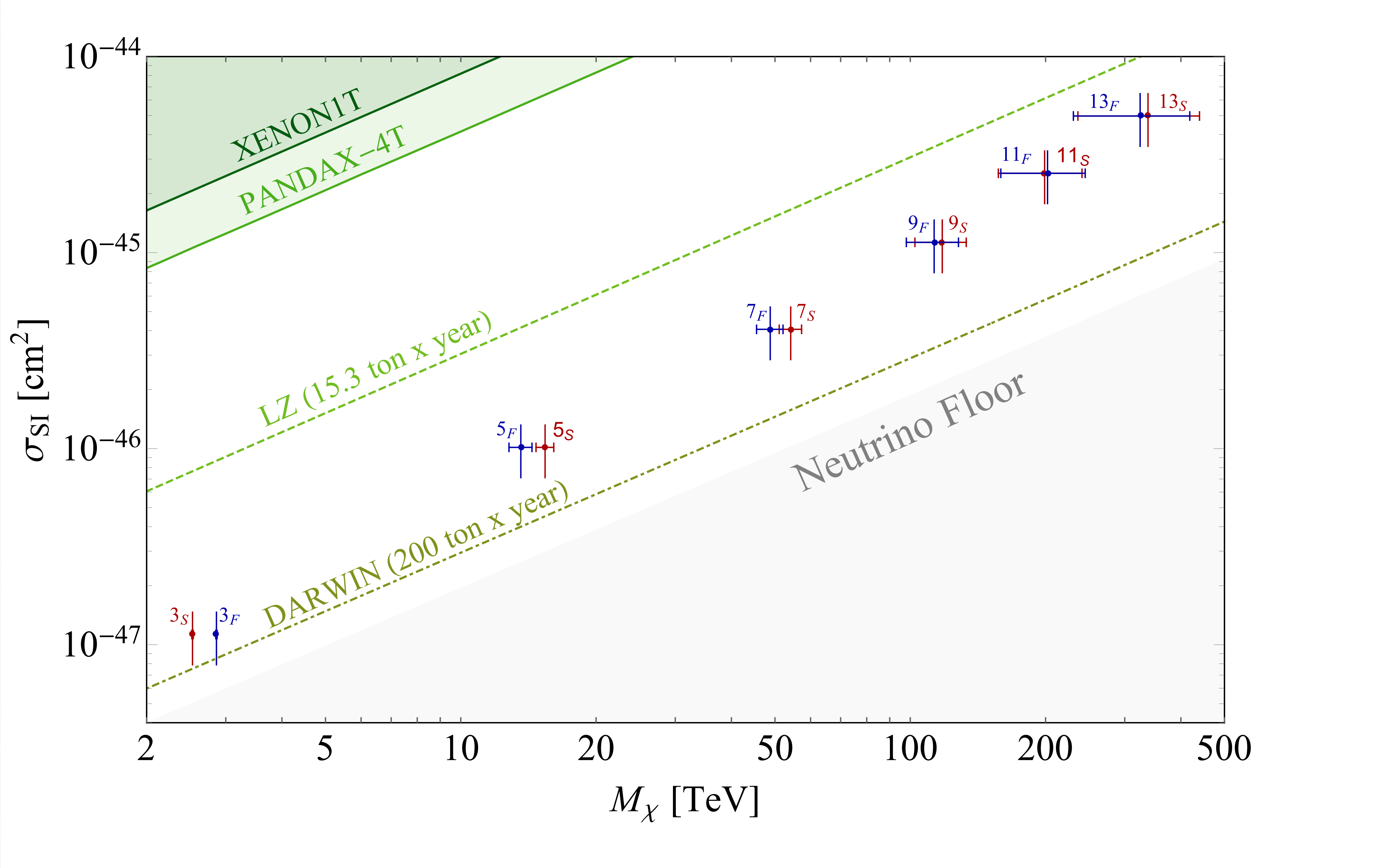
UP NEXT



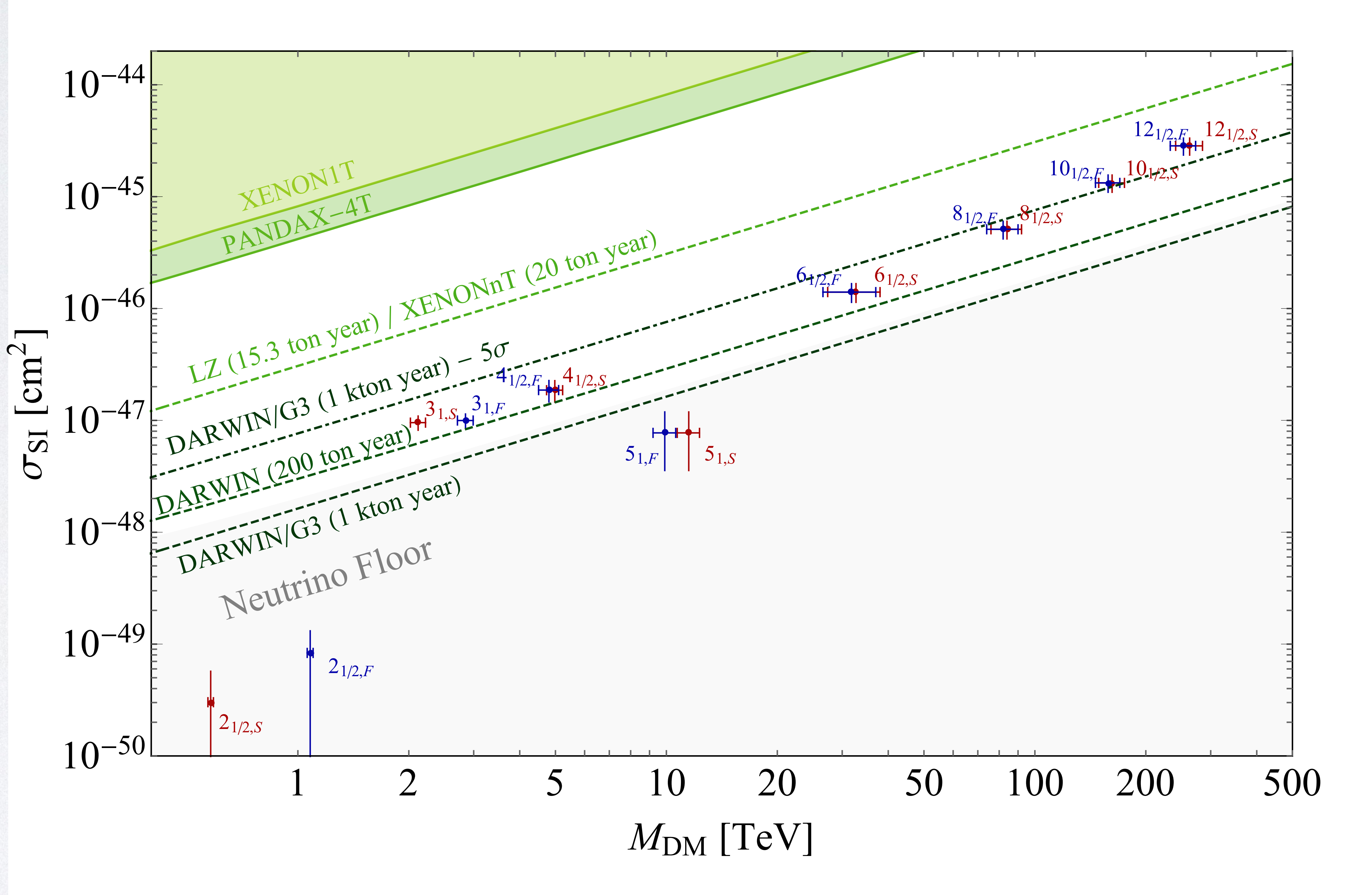
2008.00692: Rinchiuso et al.

- 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?

DIRECT DETECTION?



2107.09688: Bottaro et al.



2205.04486: Bottaro et al.