TESTING WINO DARK MATTER WITH VERITAS DWARF GALAXY OBSERVATIONS

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VERITAS

VERITAS

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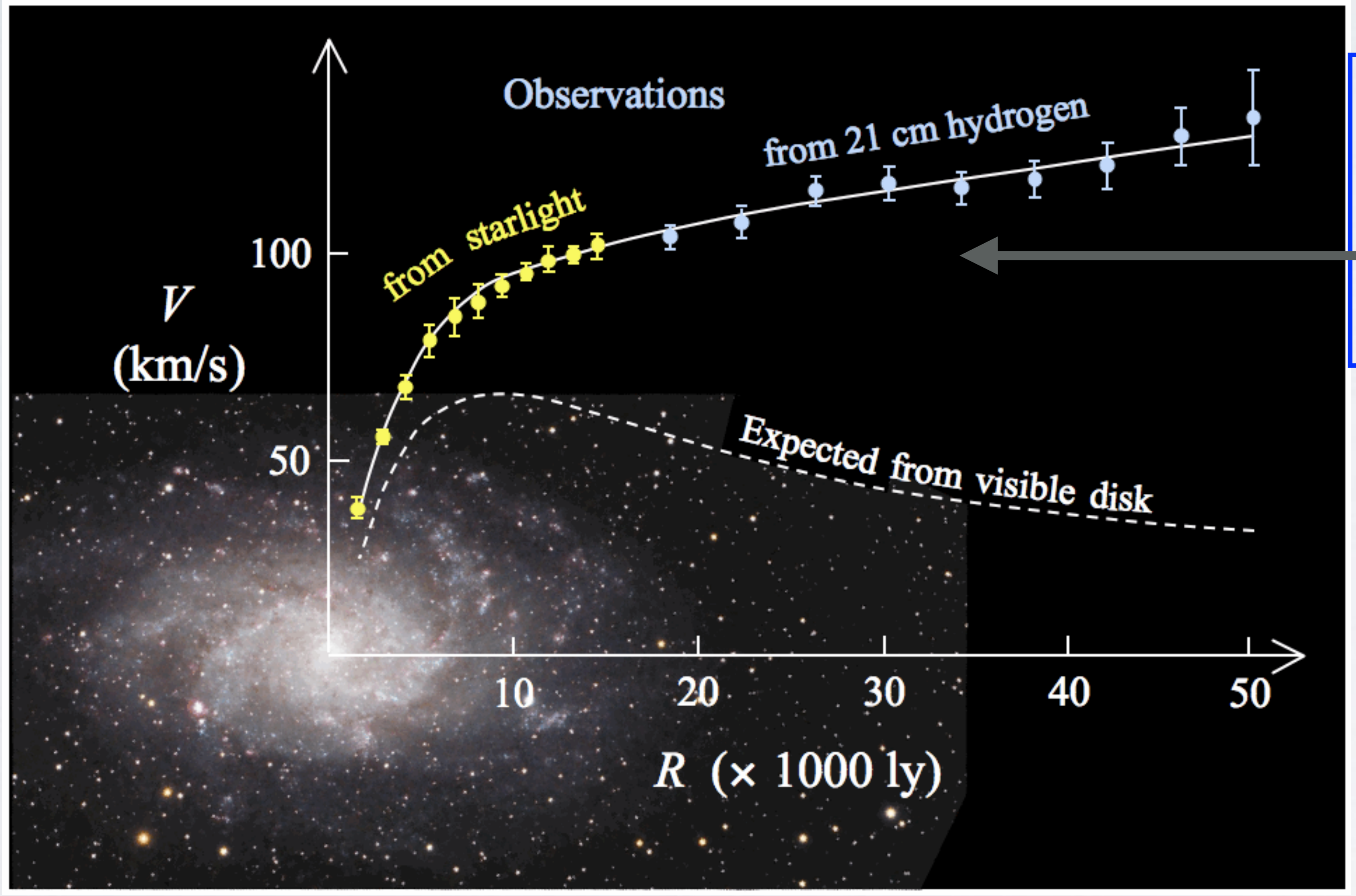
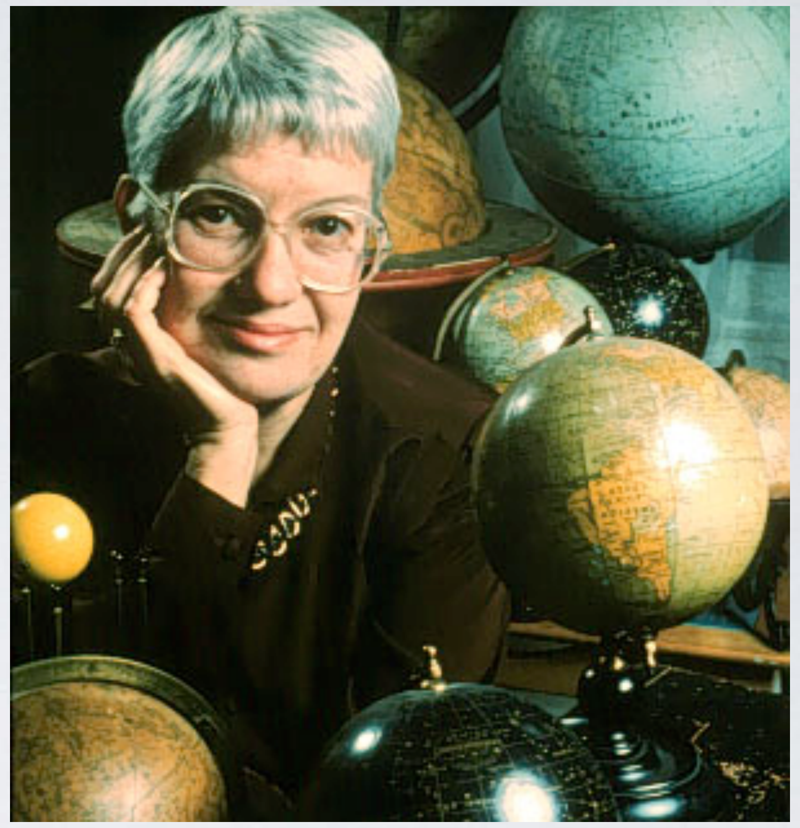
TeVPA 2024 Chicago 8/26/2024

WHY DARK MATTER?

Anomalies on 3 different astrophysical scales!

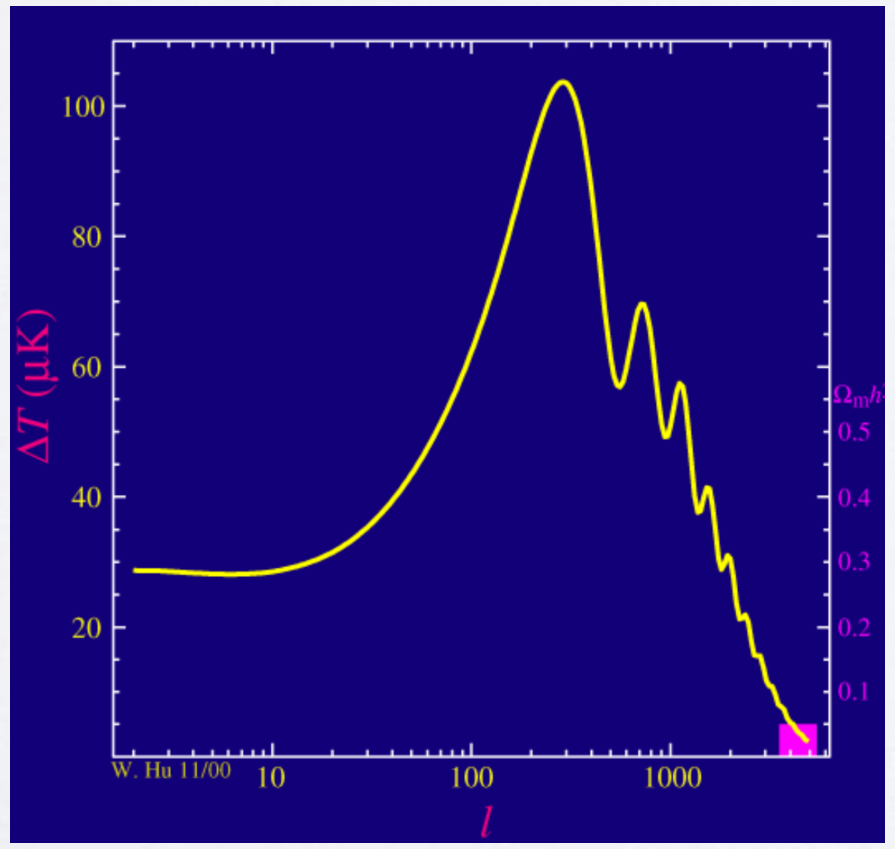


Galactic Rotation curves:
Stars move faster
than expected

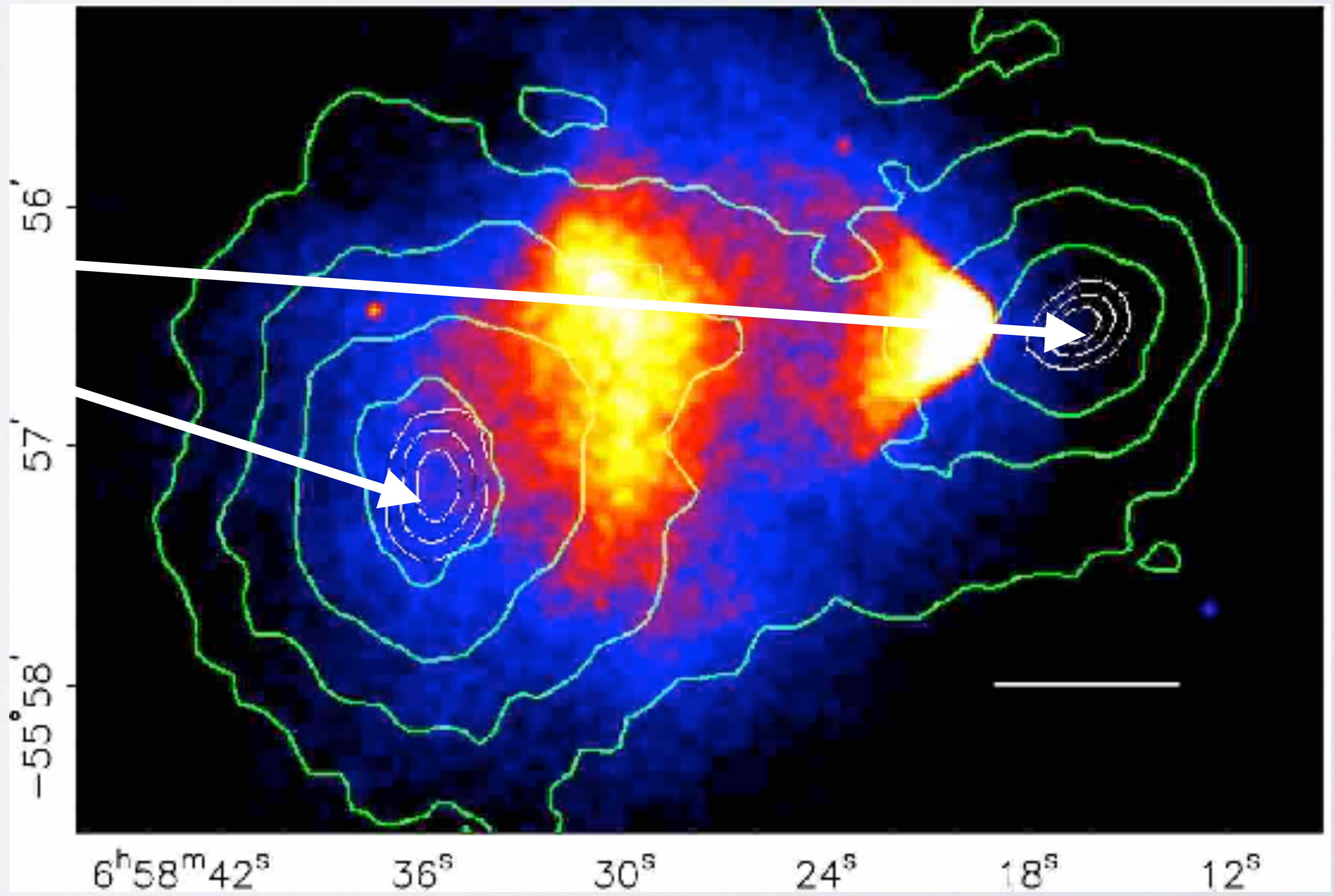


Vera Rubin 1928-2016
Established Rotation Curve anomaly

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

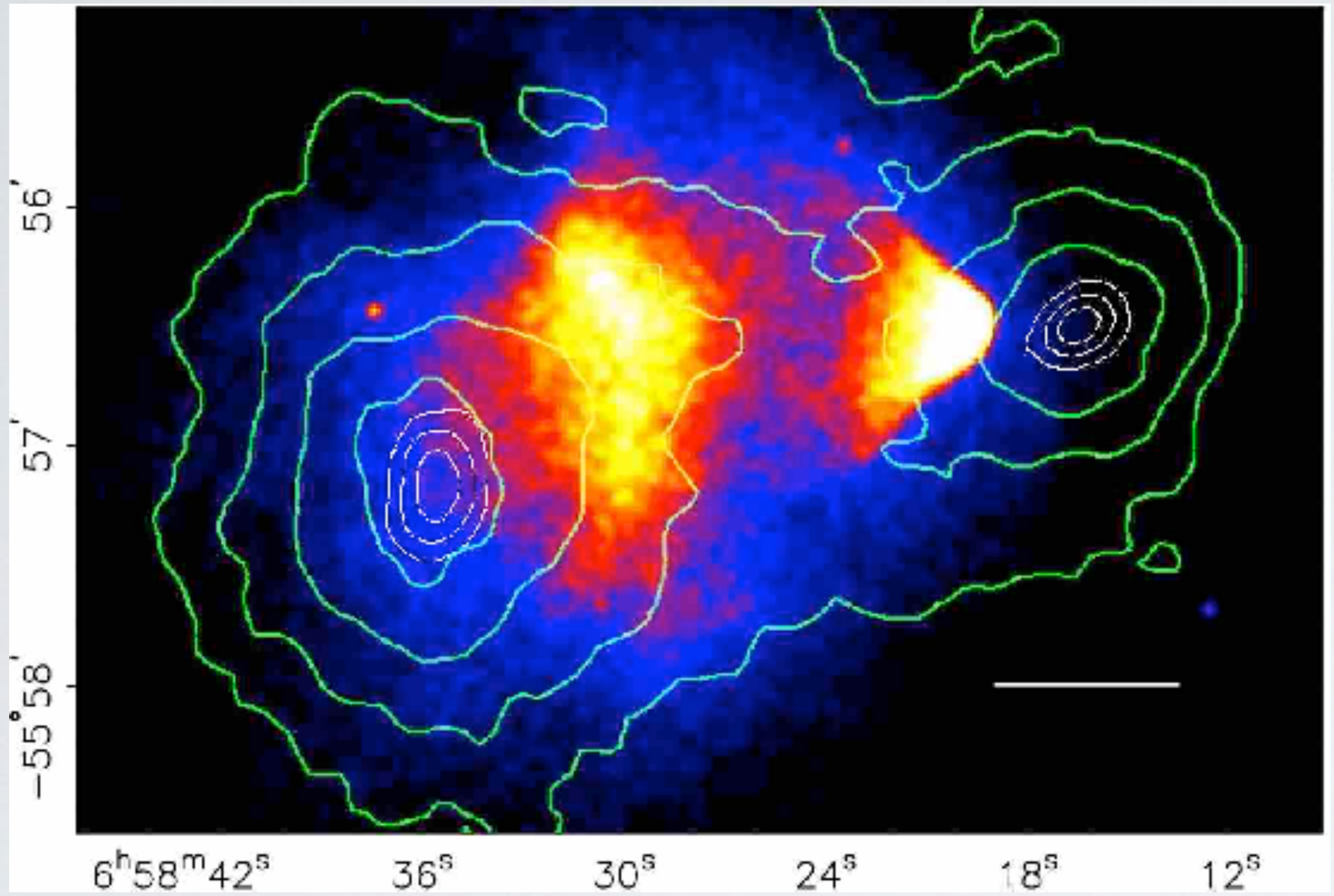


Colliding Clusters:
Gravitational wells
nowhere near visible peaks



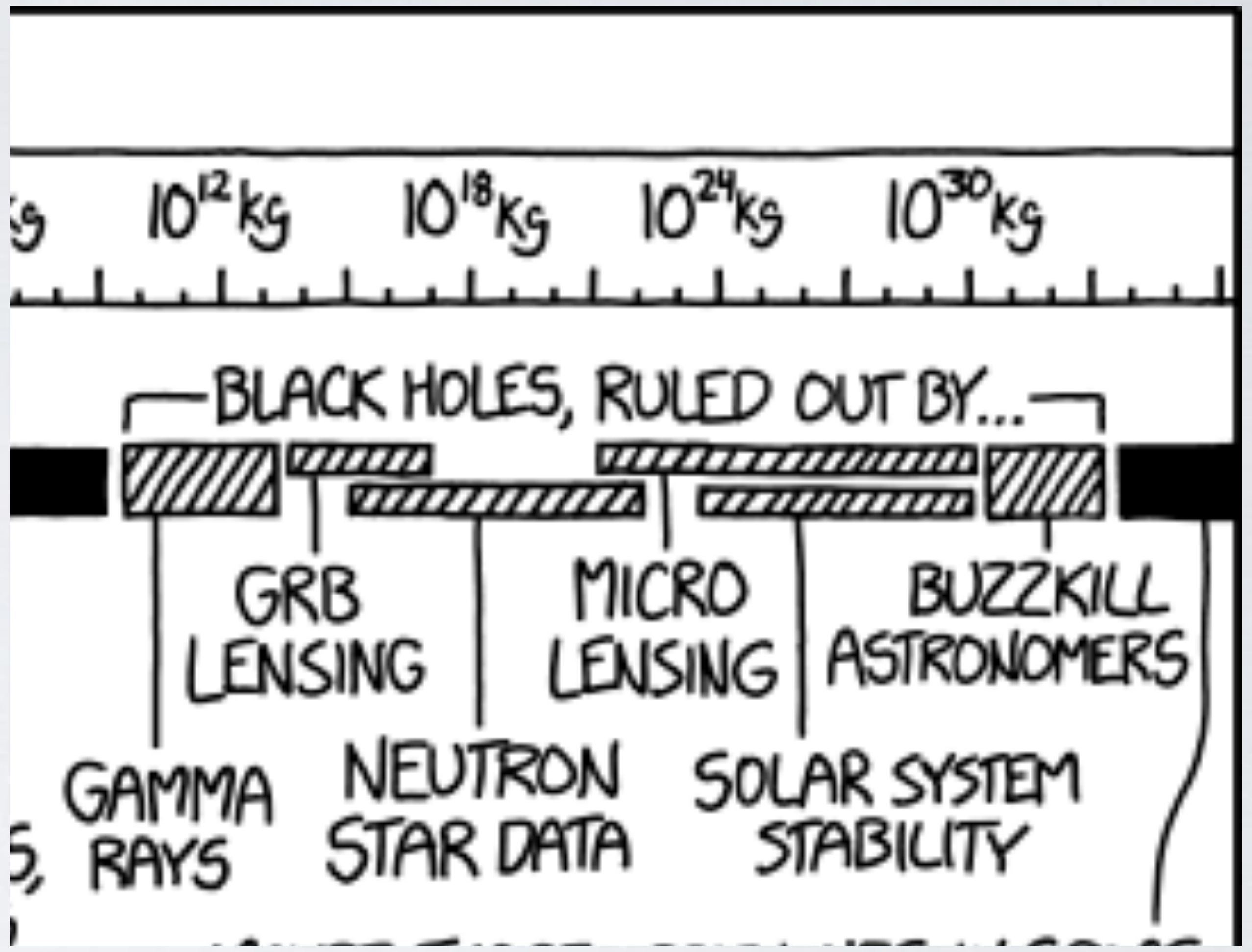
IS IT?

~~Something like Gravity?~~



Gravitational wells 10^5 parsecs from matter concentrations!

~~Something like Black Holes?~~



XKCD (2018) cf. 1705.05567

Something like a neutrino!

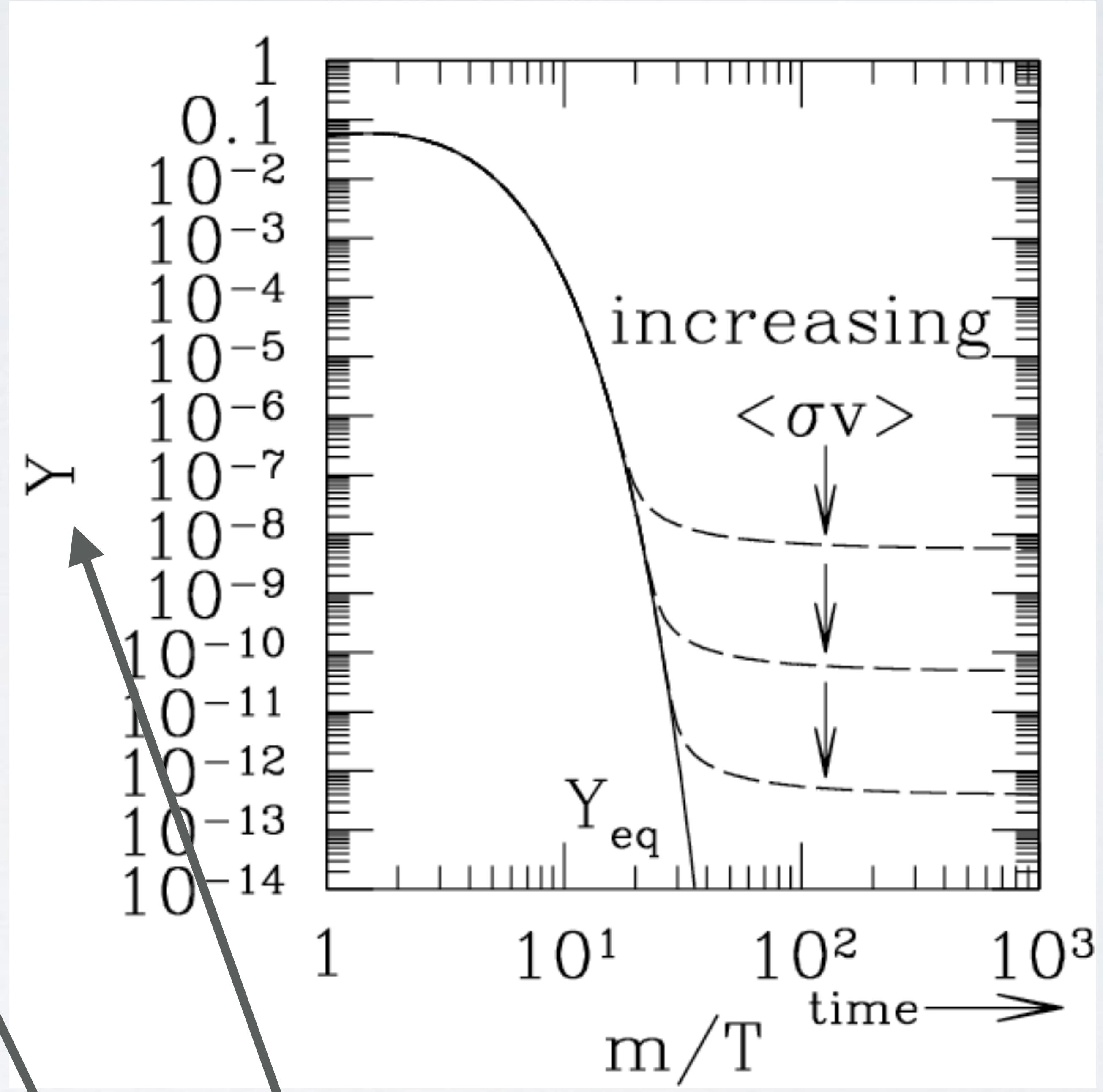
WIMP MIRACLE

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

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

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

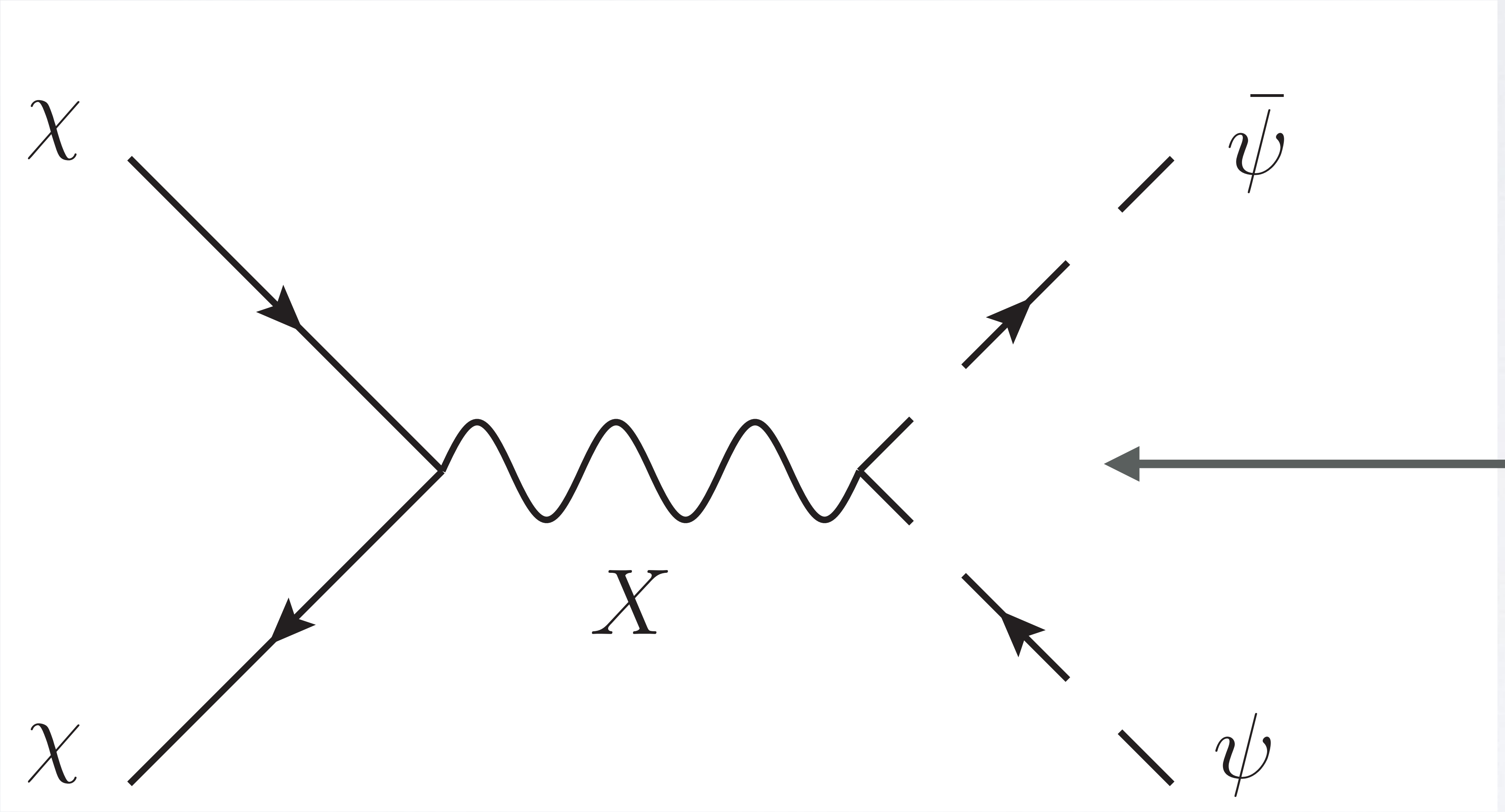
WIMP can be simple addition
to known particles & forces.
WHY?



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: Fermion, Higgs, Gauge boson?
α: α_{weak}?

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

"HEAVY NEUTRINO" WIMP

Weak Force "Charges"

$\Omega_{DM} = 0.27$

Measured Dark Matter Density

Simple Candidates!

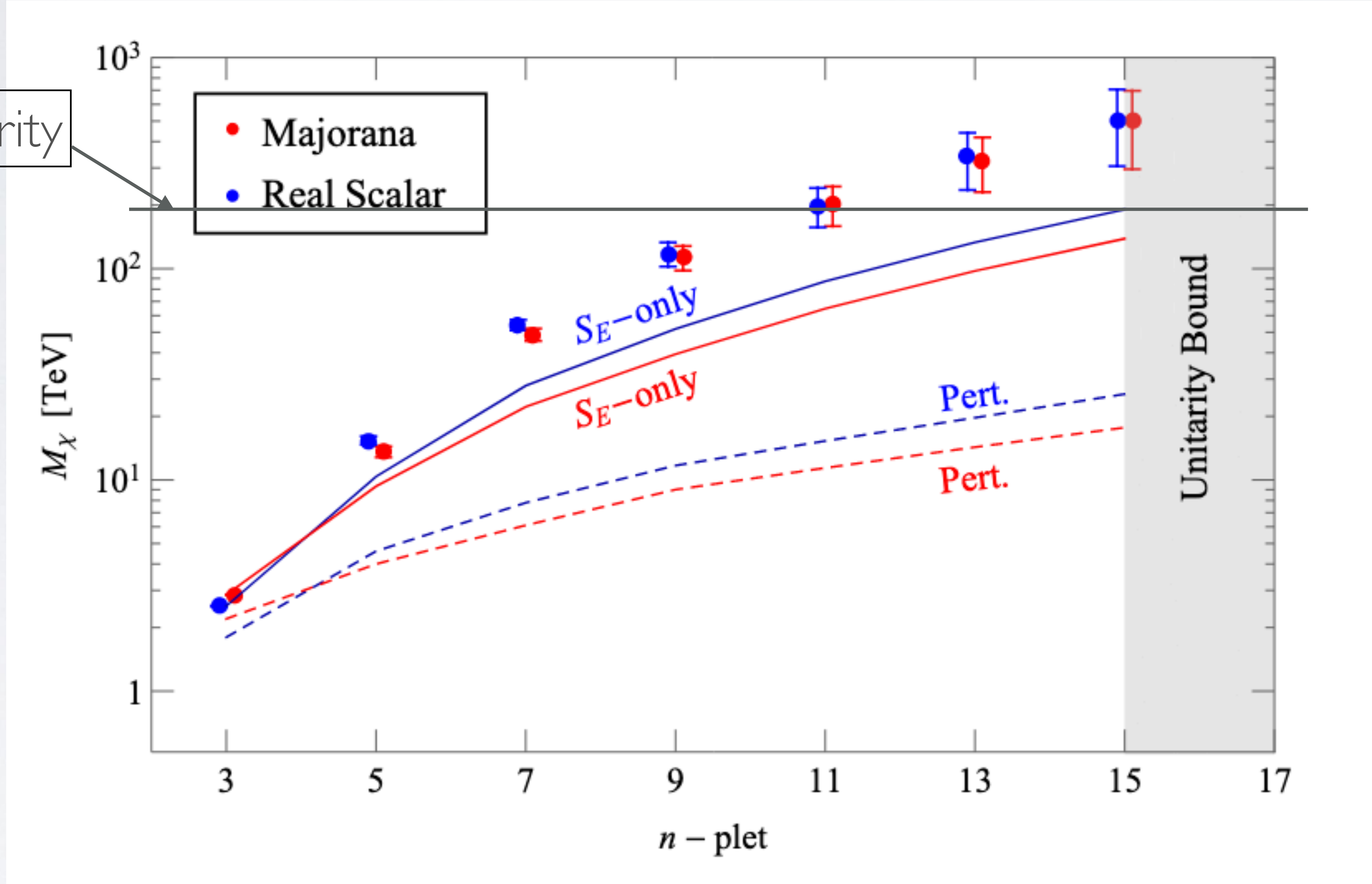
Dark Matter ↔ Weak Scale:

Weak Triplet: "Wino"

Weak Doublet: "Higgsino"

Weak Quintuplet

Naive Unitarity



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

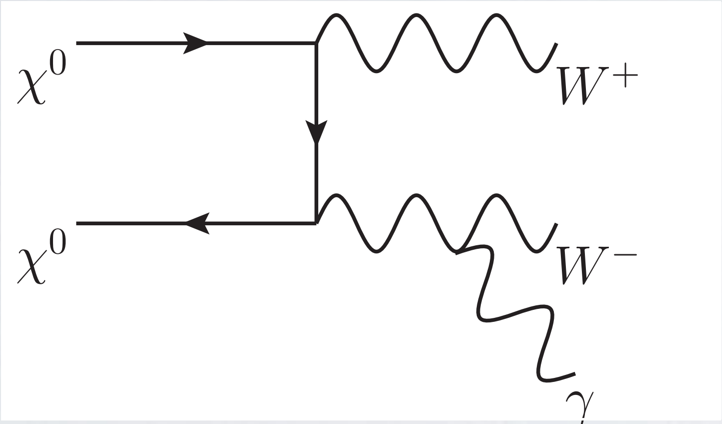
Correct Dark Matter Density fixes M_χ:

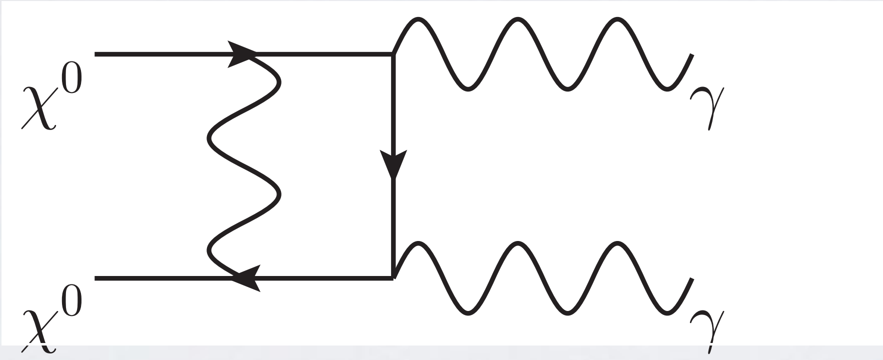
Wino: 3 TeV

Higgsino: 1 TeV

Quintuplet: 14 TeV

ECHO OF THE WIMP MIRACLE

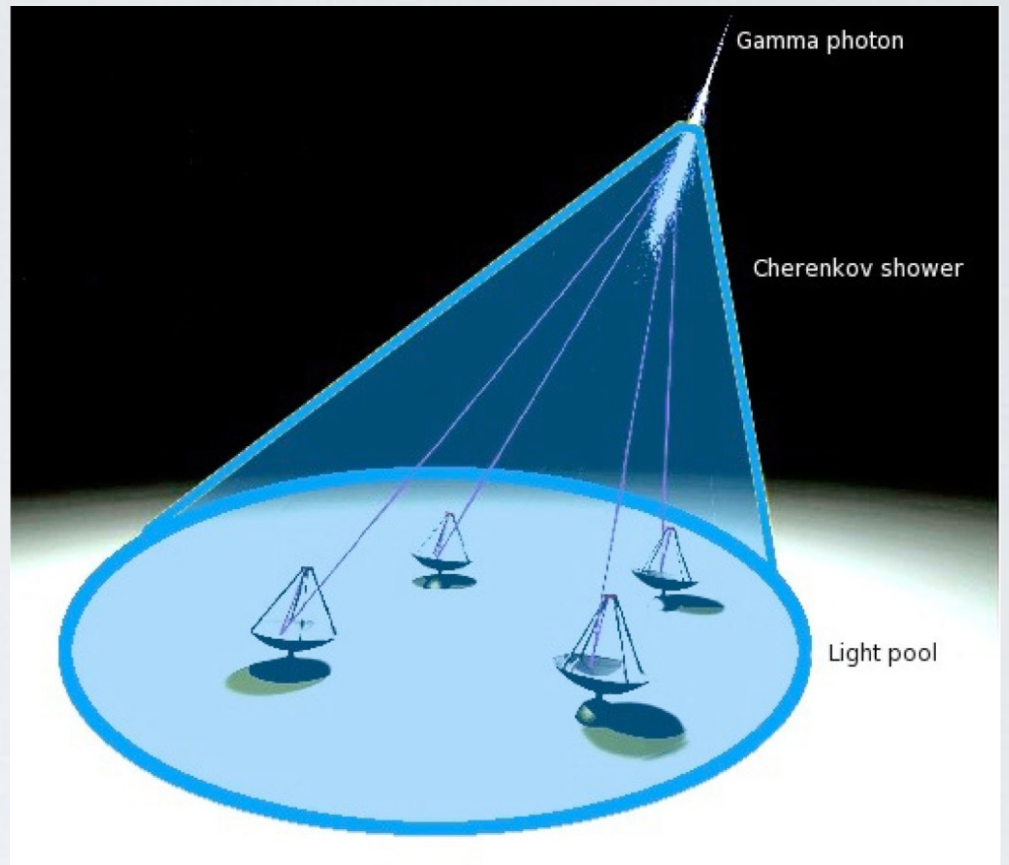




Indirect Detection:
Photons from Dark Matter Annihilation

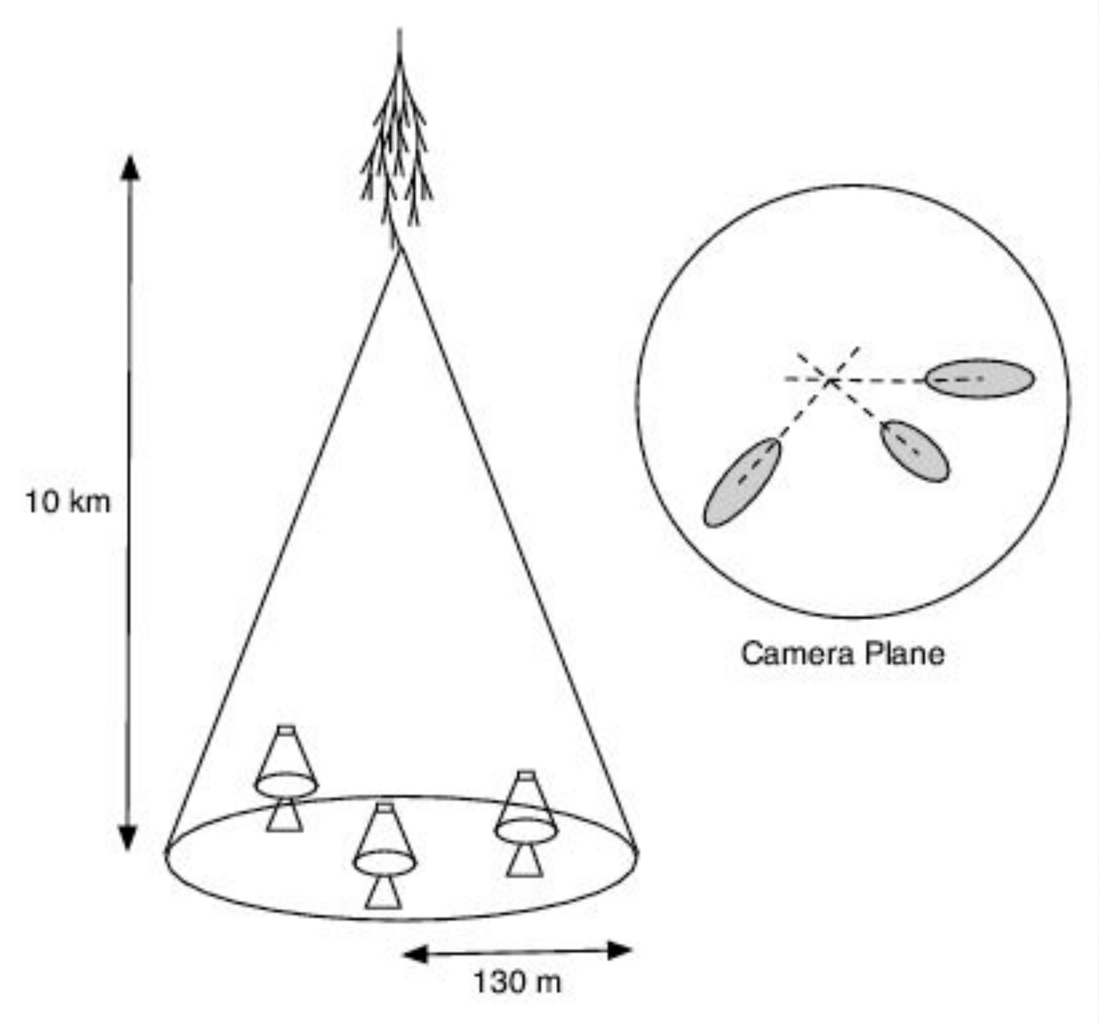
HESS/VERITAS/MAGIC can probe Dark Matter Masses **up to 30 PeV**

Successor **CTAO**,
will improve sensitivity by **Order of Magnitude**

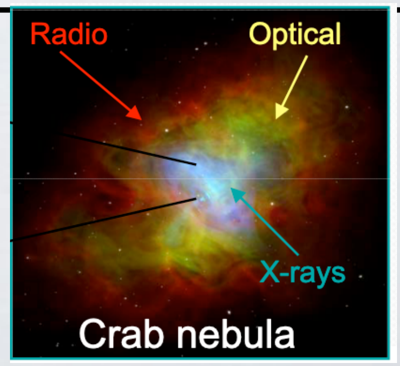


Schematic of air shower observed by Cherenkov Telescope (spie.org)

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



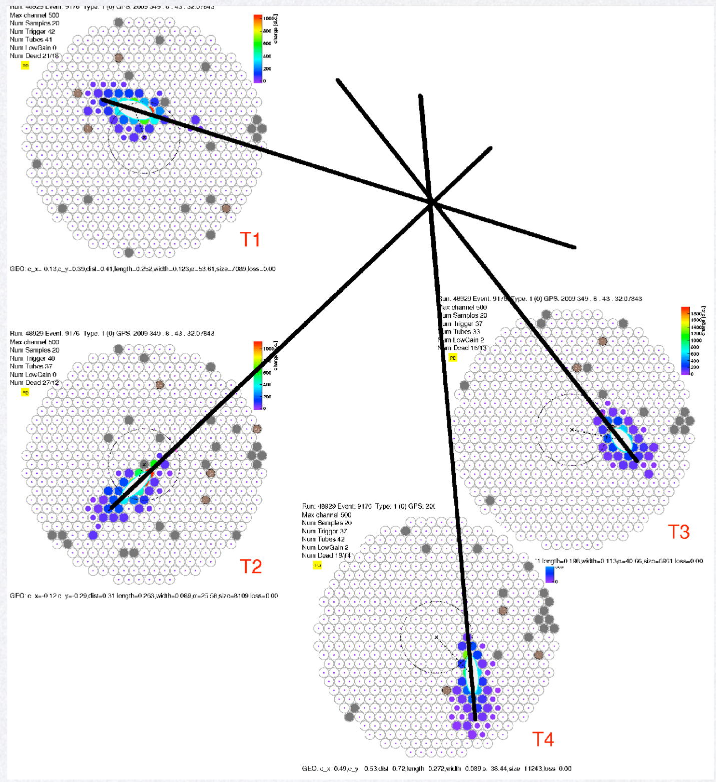
- Stereoscopic image reconstructs particle location
- Brightness reconstructs particle energy
- Technique first used to detect Crab Nebula in 1989.



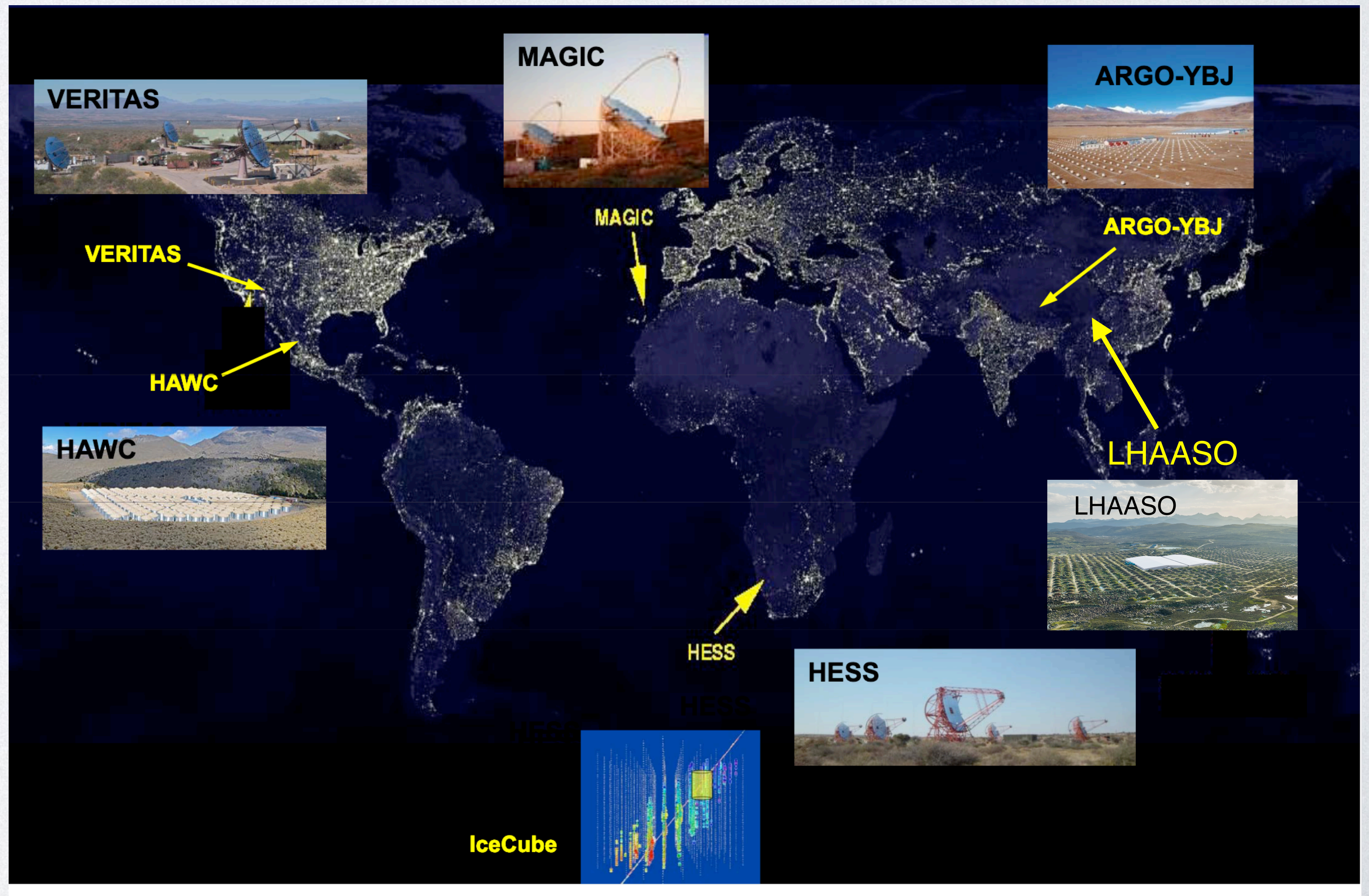
VERITAS OBSERVATORY

- There are 3 major operating Imaging Air-Cherenkov Telescopes in the world today (HESS, MAGIC, VERITAS)
- VERITAS is located outside Amado, Arizona
- Specs:
  - Energy range: 85 GeV to 30+ TeV
  - 3.5° field of view
  - Energy resolution 15-25%
  - Angular resolution <0.1° at 1 TeV
  - Peak effective area, 10^5 m^2
- 638 hours of observation time on Dwarf Spheroidal Galaxies (dSphs), promising dark matter targets

VERITAS at Fred Lawrence Whipple Observatory

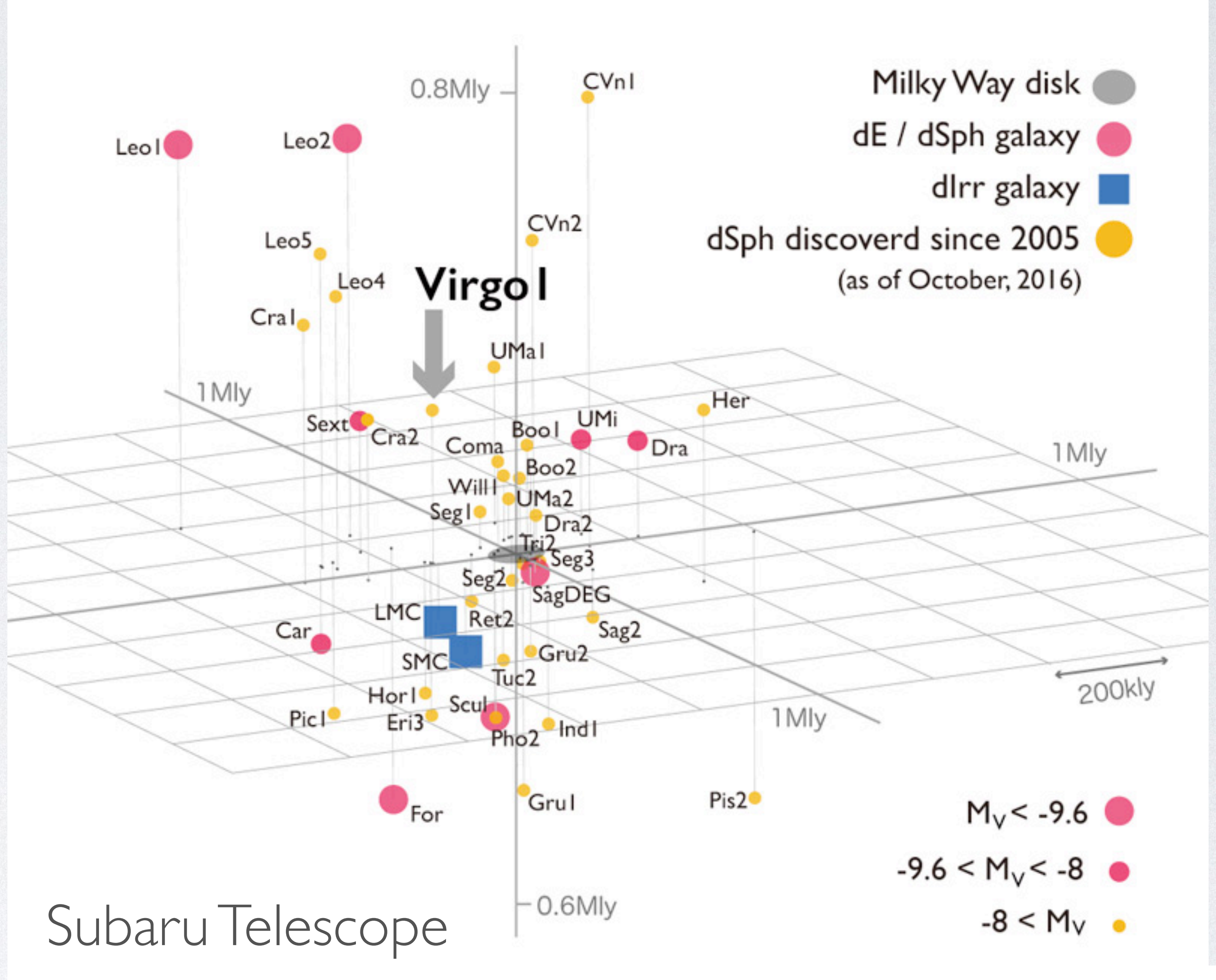


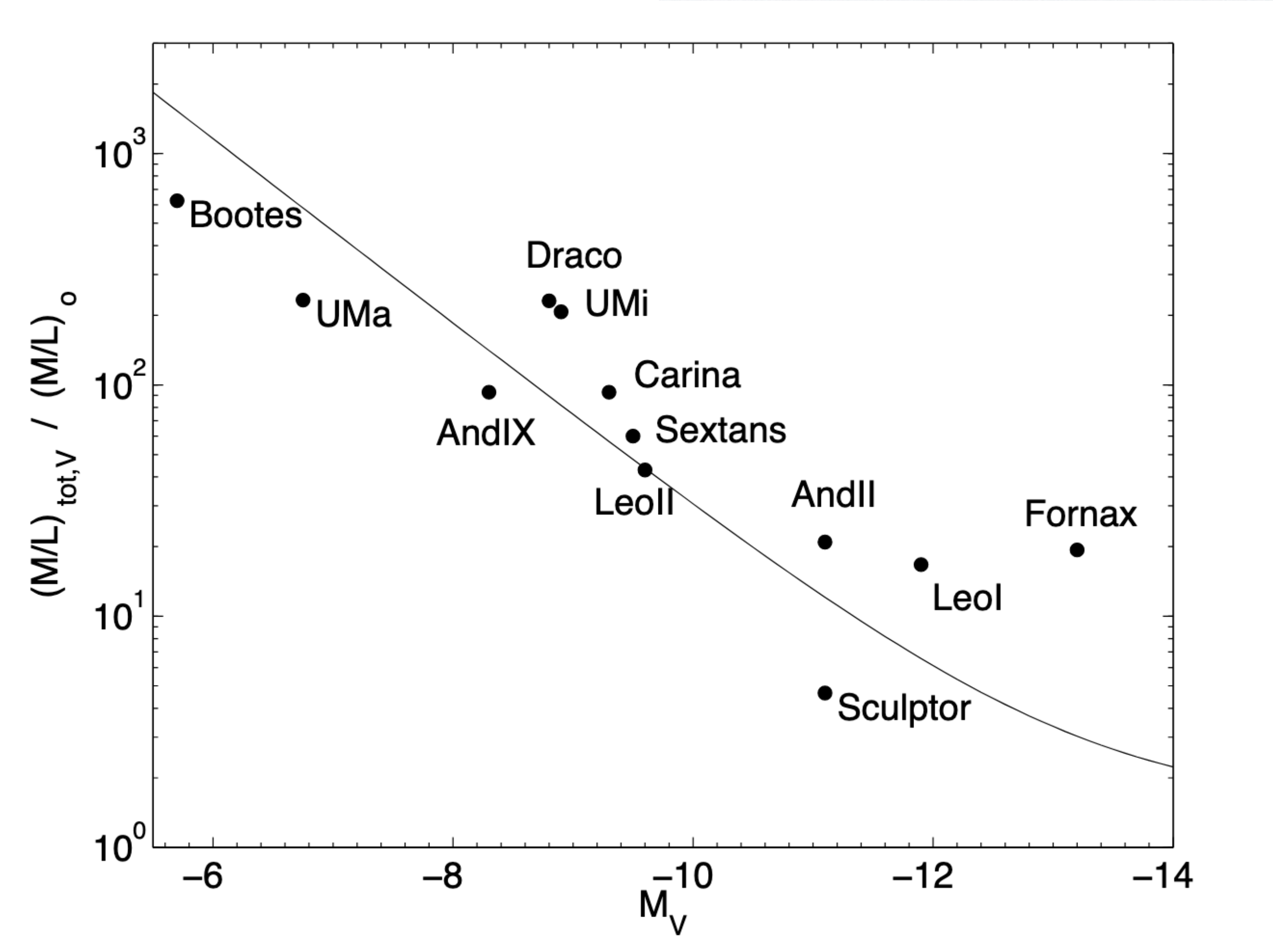
VERITAS event



DWARF SPHEROIDAL GALAXIES

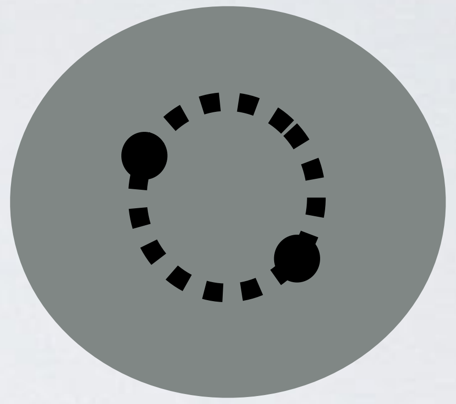
- As a **complimentary target**, one can also study **dwarf spheroidal galaxies (dSphs)**.
- Among the most dark matter-dominated objects in the Universe **(mass-to-light ratios (10-1,000+) higher than Milky Way and other spiral galaxies (1-10))**.
- Simpler backgrounds and **easier determination of dark matter distribution** from stellar kinematics.

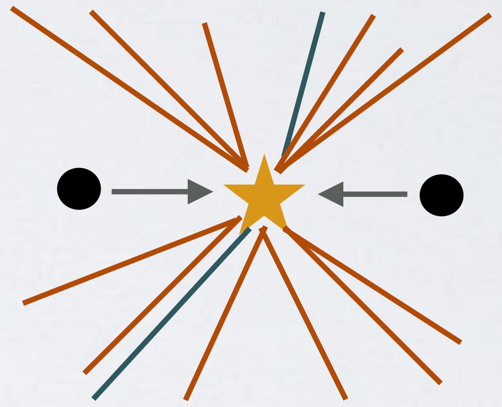


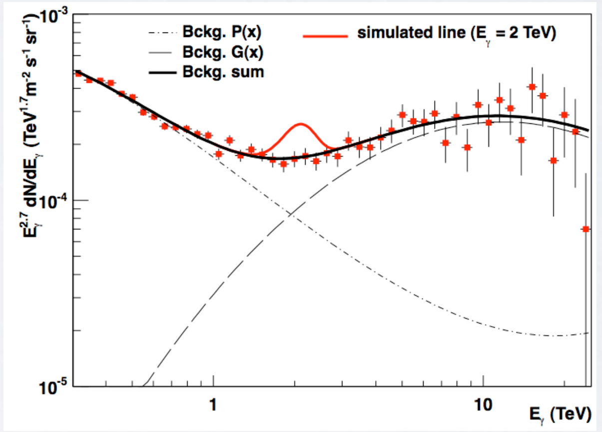


astro-ph/0703308: Gilmore et al.
Mass-to-light vs Magnitude
for several dwarf galaxies

- **WIMPs: 3 separate threats to perturbation theory!**
  - $M_\chi/m_W >> 1$ → Long range force
  - $M_\chi/m_W >> 1$ → Electroweak shower
  - $\text{Log}(1-z_{cut})$ → Detailed shape near bump
- Proliferation of scales → **Effective Field Theory**

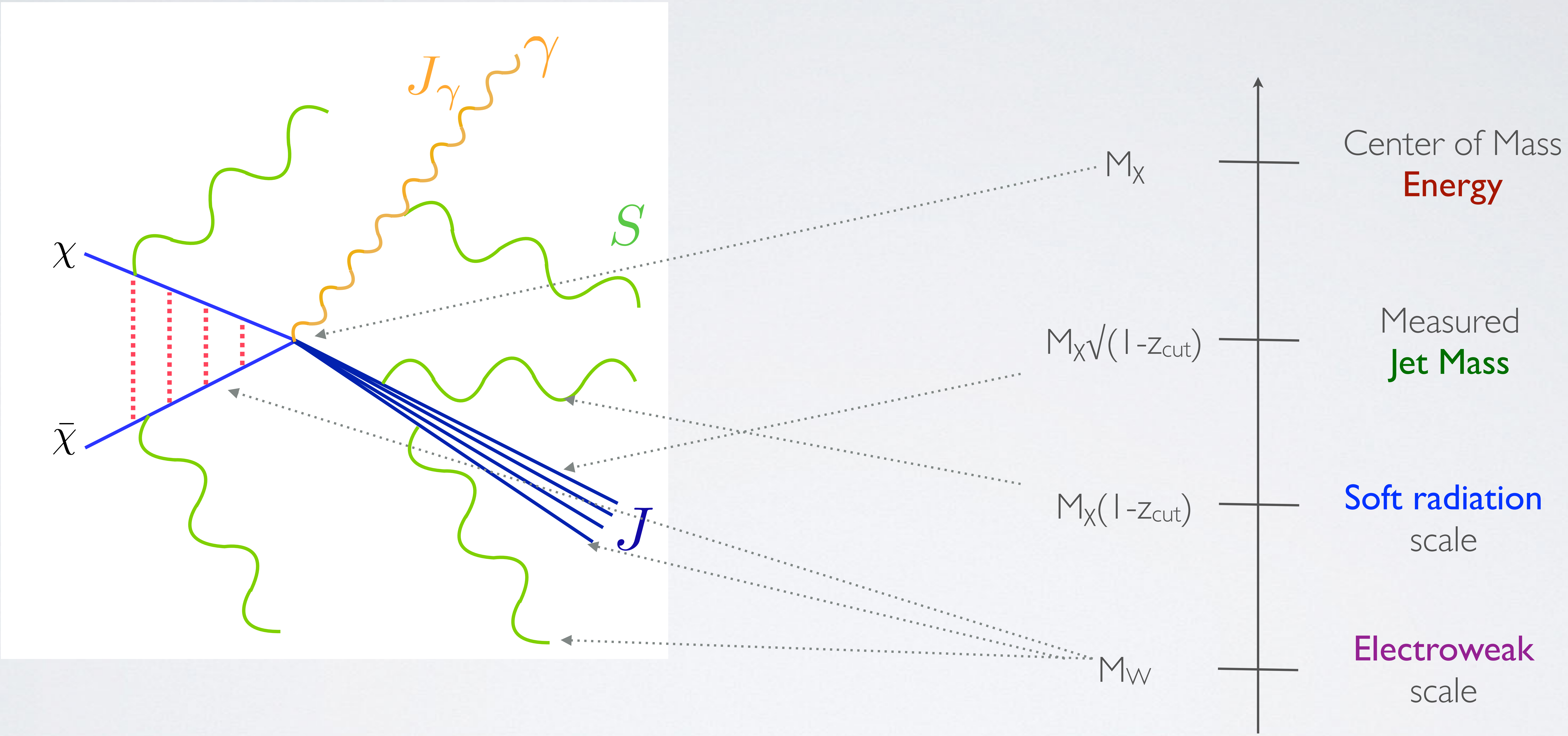




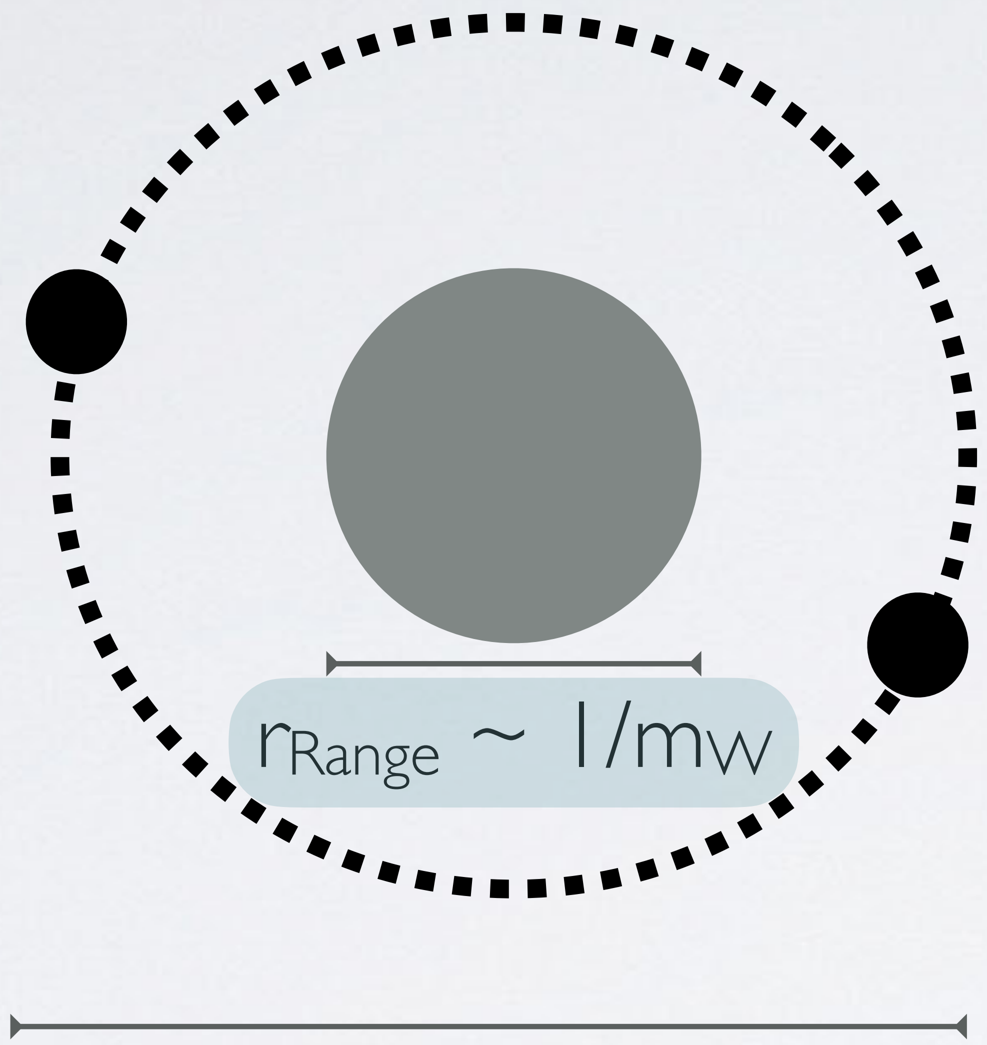


EFTs: Modified versions of Soft-Collinear Effective Theory
&
NRQCD

EFFECTIVE FIELD THEORY PLAYGROUND



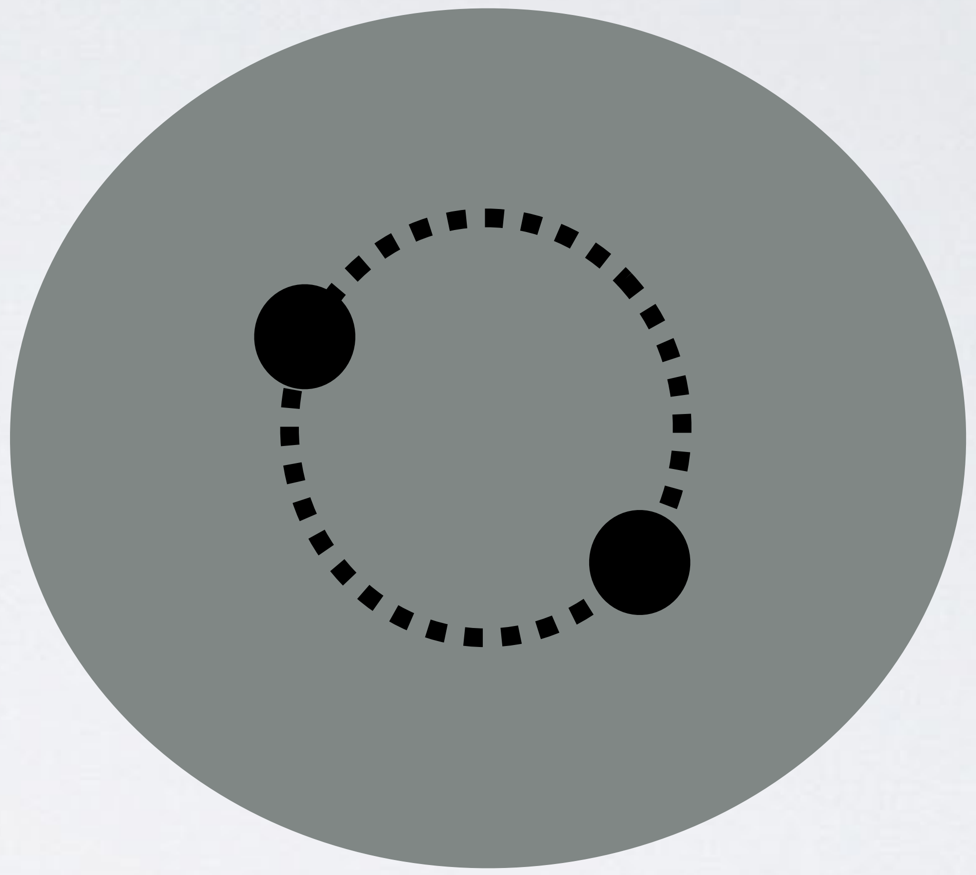
SOMMERFELD ENHANCEMENT



$r_{Bohr} \sim 1/\alpha M_\chi$

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

No bound state



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

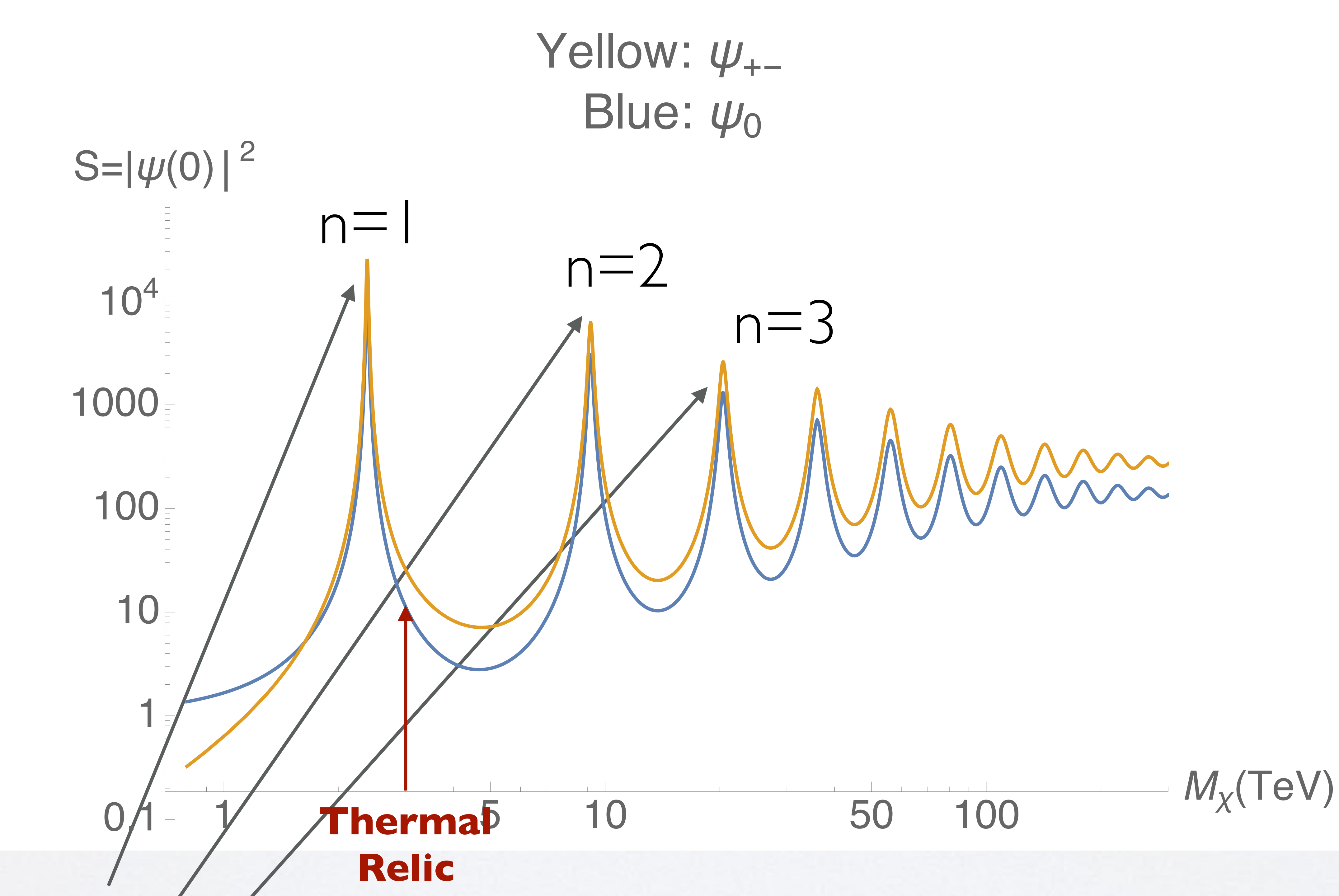
Bound state forms

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

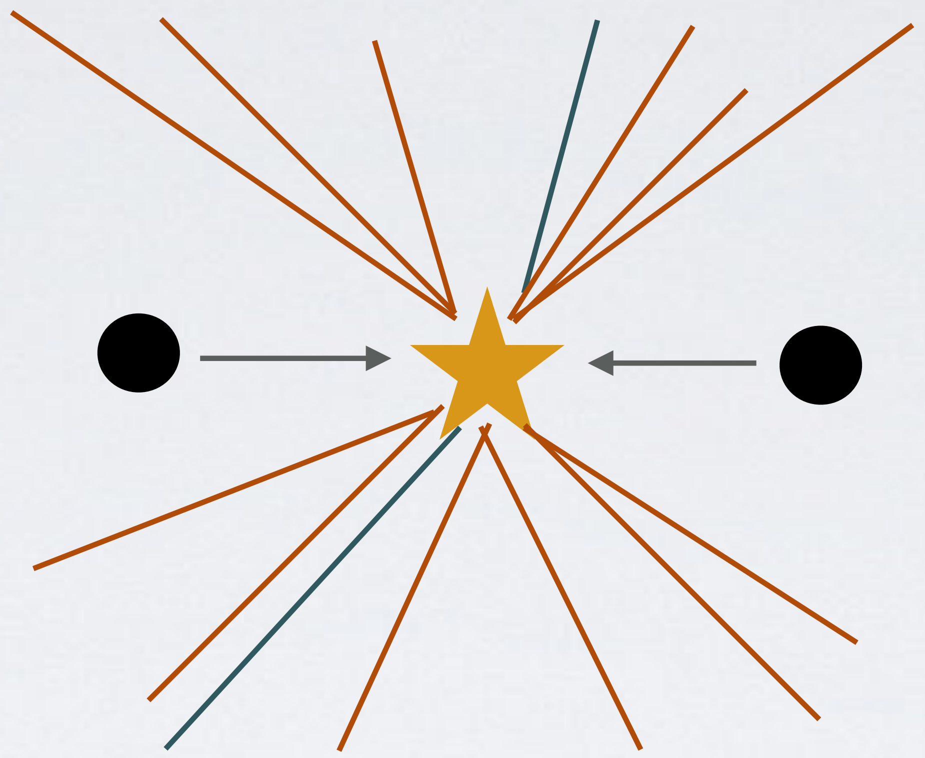
$\alpha_W M_\chi = n^2 m_W$

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

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

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"

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

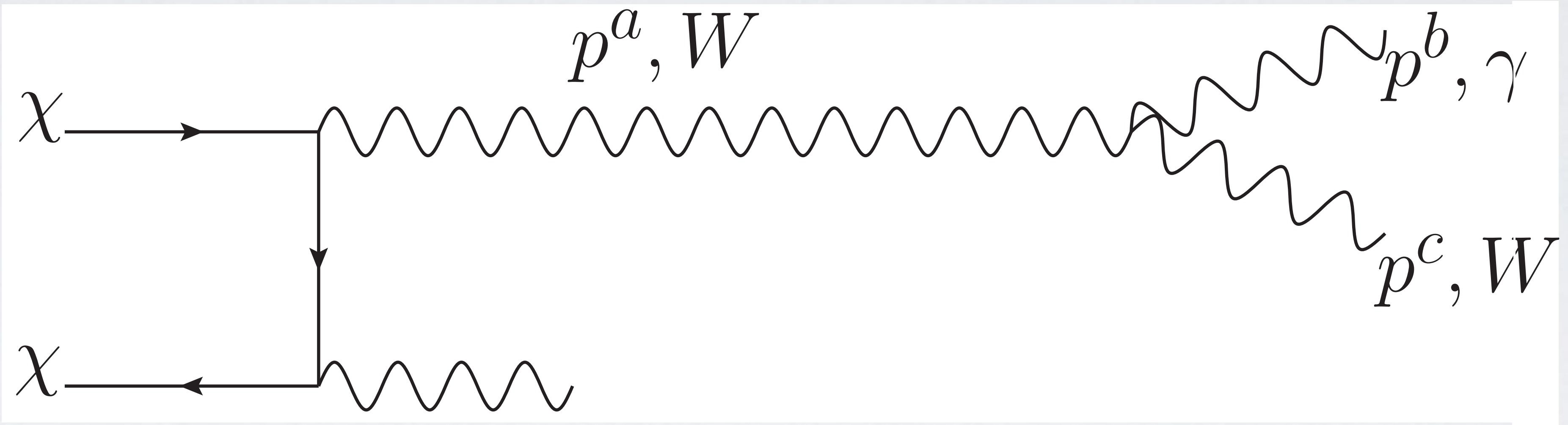
Above rate **produces classical spectrum**,
but **hard to see in quantum perturbation theory**

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

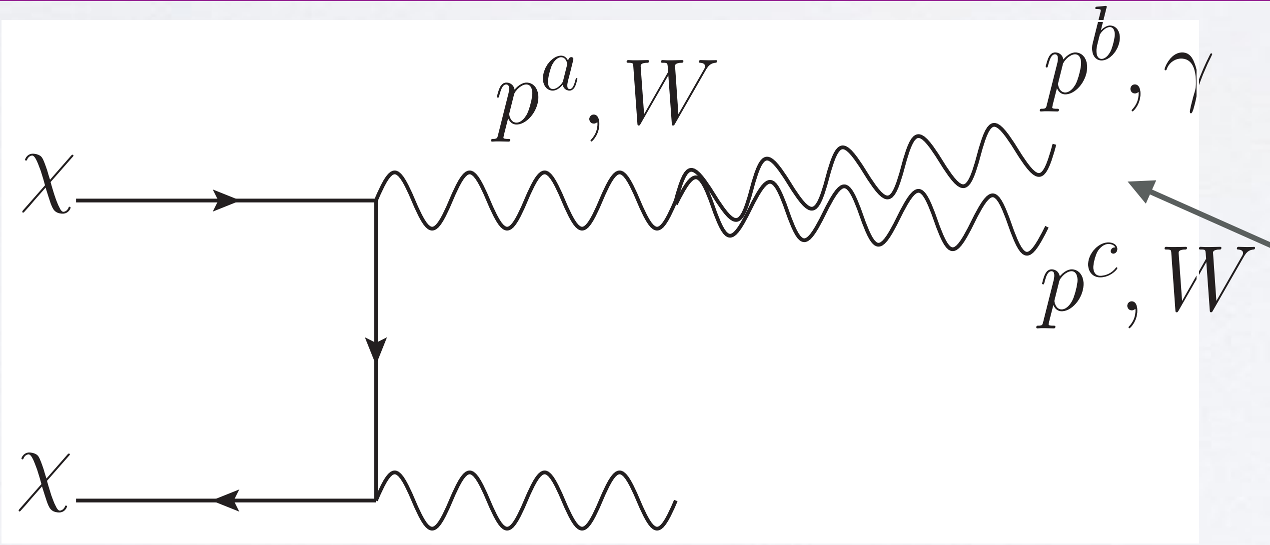
Double log
Large correction!

SOFT/COLLINEAR ENHANCEMENT

Soft radiation: Time-scales much longer than annihilation



Collinear Radiation: Narrow splitting of one particle into 2



θ

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

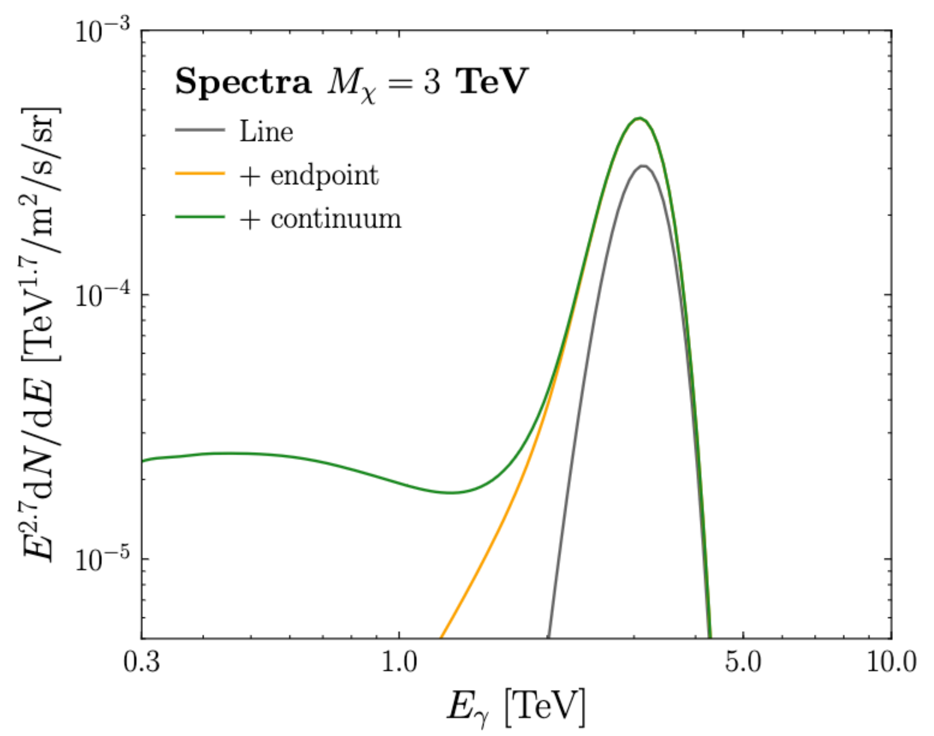
Keep modes with **kinematic enhancement** (soft, collinear)

SCET for
Dark Matter annihilation
[MB, Rothstein, I., Vaidya, V.: 1409.4415]

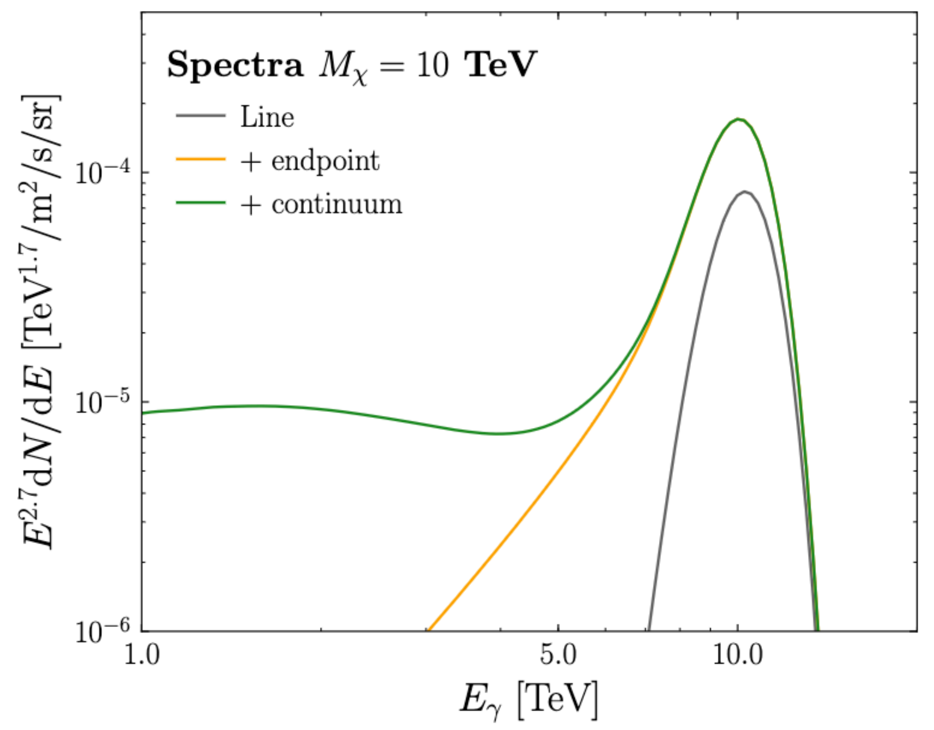
See also: ; 1409.7392: Bauer et al.
1409.8294: Ovanesyan, Slatyer, Stewart

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

NLL RESUMMED PHOTON SPECTRUM FROM WINO



(a)



(b)

MB et al.: 1712.07656
LL convoluted with
experimental smearing

$$
\begin{aligned}
\left(\frac{\mathrm{d}\sigma}{\mathrm{d}z}\right)^{\mathrm{NLL}} = {} & \frac{\pi\,\alpha_W^2(2\,M_\chi)\,s_W^2(m_W)}{9\,M_\chi^2\,v\,(1-z)}\,U_H\,\big((V_J-1)\,\Theta_J+1\big) \\
& \Bigg\{\bigg(\,|s_{00}|^2\Big[4\,\Lambda^d + 2\,r_{HS}^{12/\beta_0}\,\Lambda^c\Big] + |s_{0\pm}|^2\Big[8\,\Lambda^d + r_{HS}^{12/\beta_0}\,\Lambda^c\Big] \\
& \quad + \sqrt{2}\,\mathrm{Re}\Big[s_{00}\,s_{0\pm}^*\Big]\Big[8\,\Lambda^d - 2\,r_{HS}^{12/\beta_0}\,\Lambda^c\Big]\bigg)\frac{e^{\gamma_E\,\omega_J}}{\Gamma(-\omega_J)} \\
& + \big((V_S-1)\,\Theta_S+1\big)\,r_H^{6/\beta_0} \\
& \quad \bigg(\,|s_{00}|^2\Big[2\,r_{HS}^{6/\beta_0}\,\Lambda^a - 8\,c_H\,\Lambda^b\Big] + |s_{0\pm}|^2\Big[r_{HS}^{6/\beta_0}\,\Lambda^a + 8\,c_H\,\Lambda^b\Big] \\
& \quad + \sqrt{2}\,\mathrm{Re}\Big[s_{00}\,s_{0\pm}^*\Big]\Big[-2\,r_{HS}^{6/\beta_0}\,\Lambda^a - 4\,c_H\,\Lambda^b\Big] \\
& \quad + \sqrt{2}\,\mathrm{Im}\Big[s_{00}\,s_{0\pm}^*\Big]\Big[-12\,s_H\,\Lambda^b\Big]\bigg)\frac{e^{\gamma_E(\omega_J+2\,\omega_S)}}{\Gamma(-\omega_J-2\,\omega_S)}\Bigg\} \\
& + \sigma_{\mathrm{exc}}^{\mathrm{NLL}}\,\delta(1-z)\,.
\end{aligned}
\tag{4.11}
$$

Here $\sigma_{\mathrm{exc}}^{\mathrm{NLL}}$ is the NLL exclusive cross section, which is given by

$$
\begin{aligned}
\sigma_{\mathrm{exc}}^{\mathrm{NLL}} = {} & \frac{\pi\,\alpha_W^2(2\,M_\chi)\,s_W^2(m_W)}{9\,M_\chi^2\,v}\,U_H \\
& \times\Big\{\Big[4 + 4\,r_H^{12/\beta_0} - 8\,r_H^{6/\beta_0}\,c_H\Big]\,|s_{00}|^2 + \Big[8 + 2\,r_H^{12/\beta_0} + 8\,r_H^{6/\beta_0}\,c_H\Big]\,|s_{0\pm}|^2 \\
& \quad + \sqrt{2}\Big[8 - 4\,r_H^{12/\beta_0} - 4\,r_H^{6/\beta_0}\,c_H\Big]\,\mathrm{Re}\Big[s_{00}\,s_{0\pm}^*\Big] - 12\sqrt{2}\,r_H^{6/\beta_0}\,s_H\,\mathrm{Im}\Big[s_{00}\,s_{0\pm}^*\Big]\Big\}\,.
\end{aligned}
\tag{4.12}
$$

UH is NLL ~ α Log
generalization of Sudakov factor

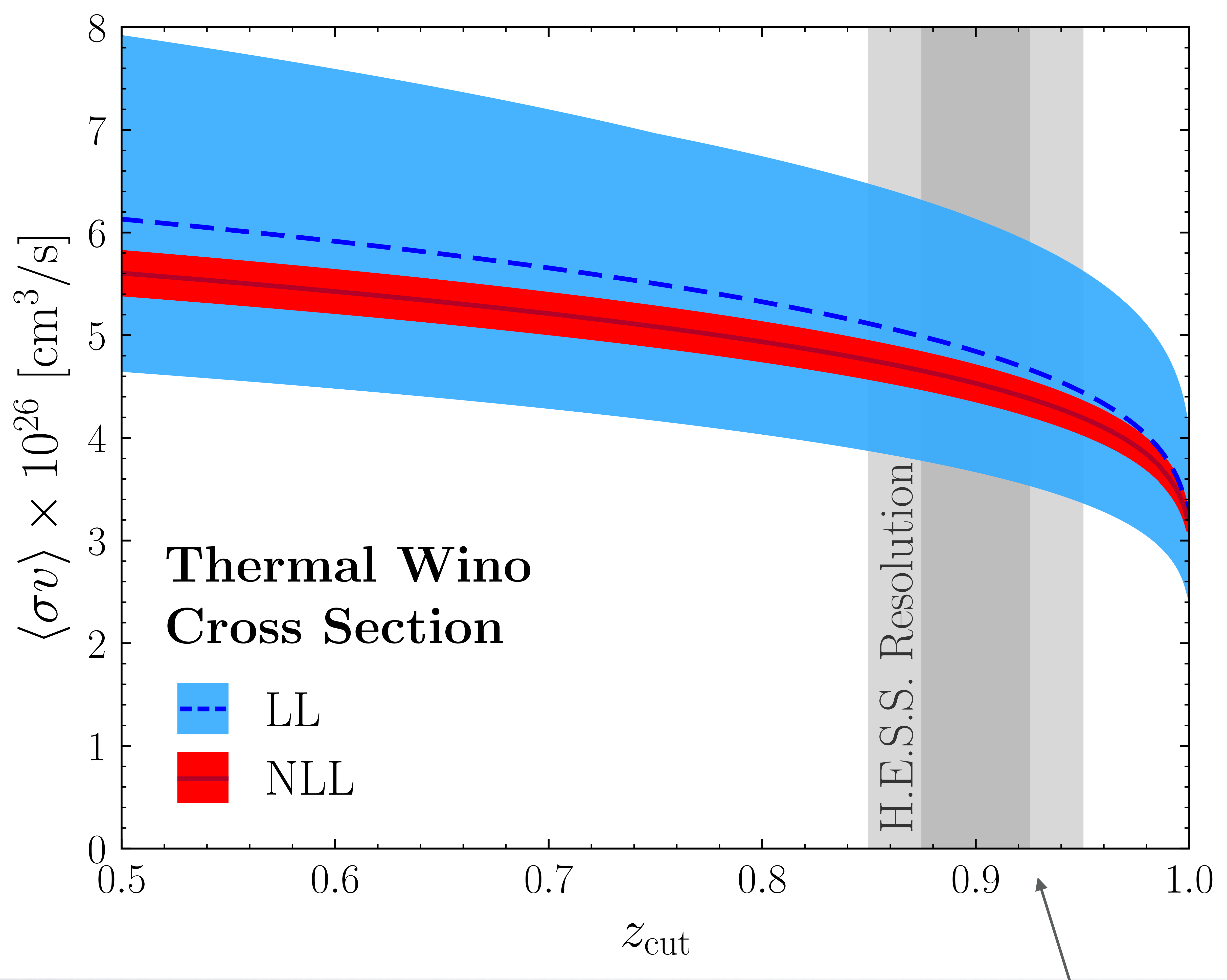
$$z = \frac{E_\gamma}{M_\chi}$$

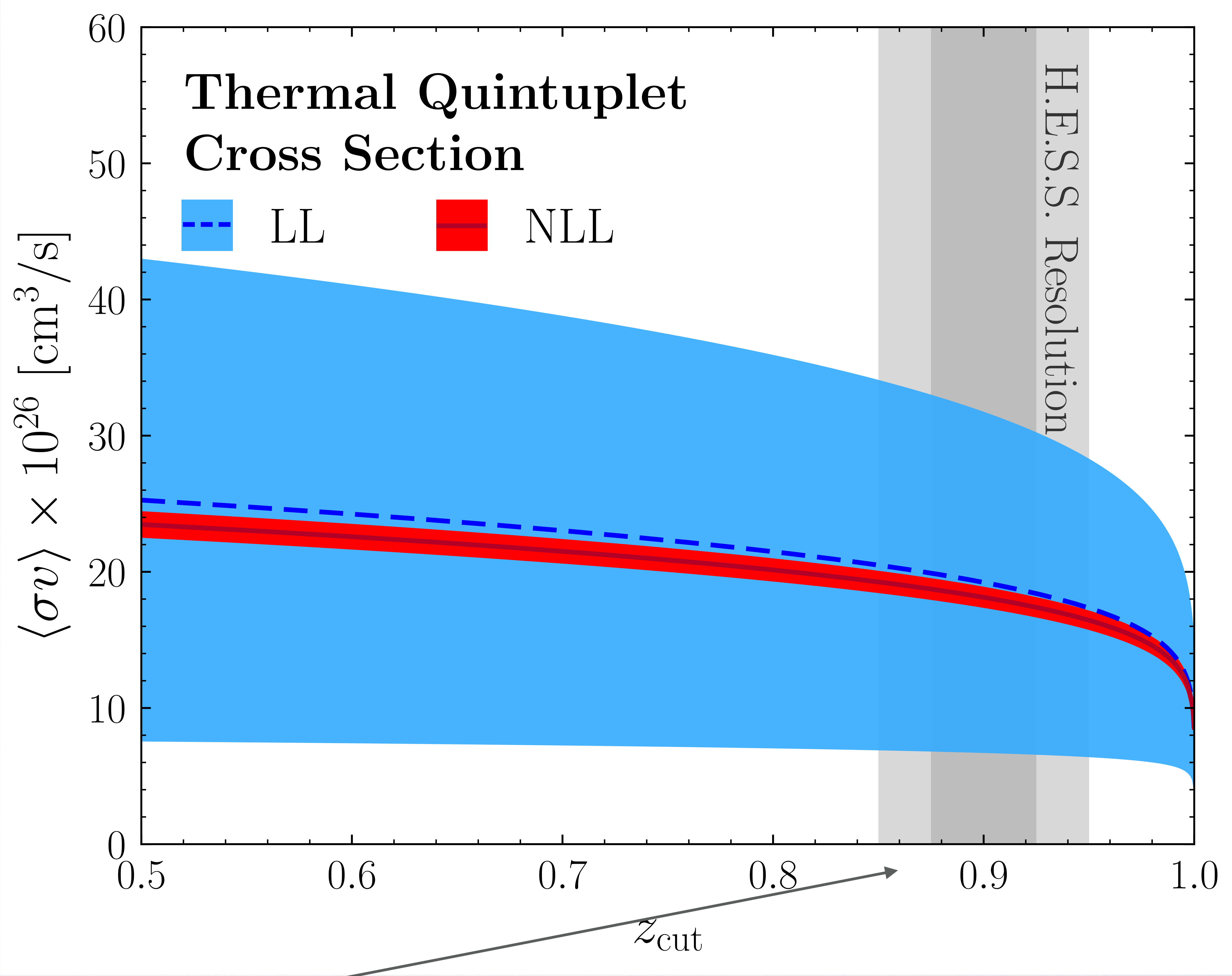
MB, N. Rodd, T. Slatyer, and V. Vaidya: 2309.11562
Same result for any real SU(2) representation
with appropriate $F_{0,1}$

Factorization holds to NLL!
MB et al.: 1808.08956

s_{00} and $s_{0\pm}$ are Sommerfeld
factors

CUMULATIVE RESUMMED ANNIHILATION RATES @THERMAL RELIC MASSES





Typical IACT Resolution

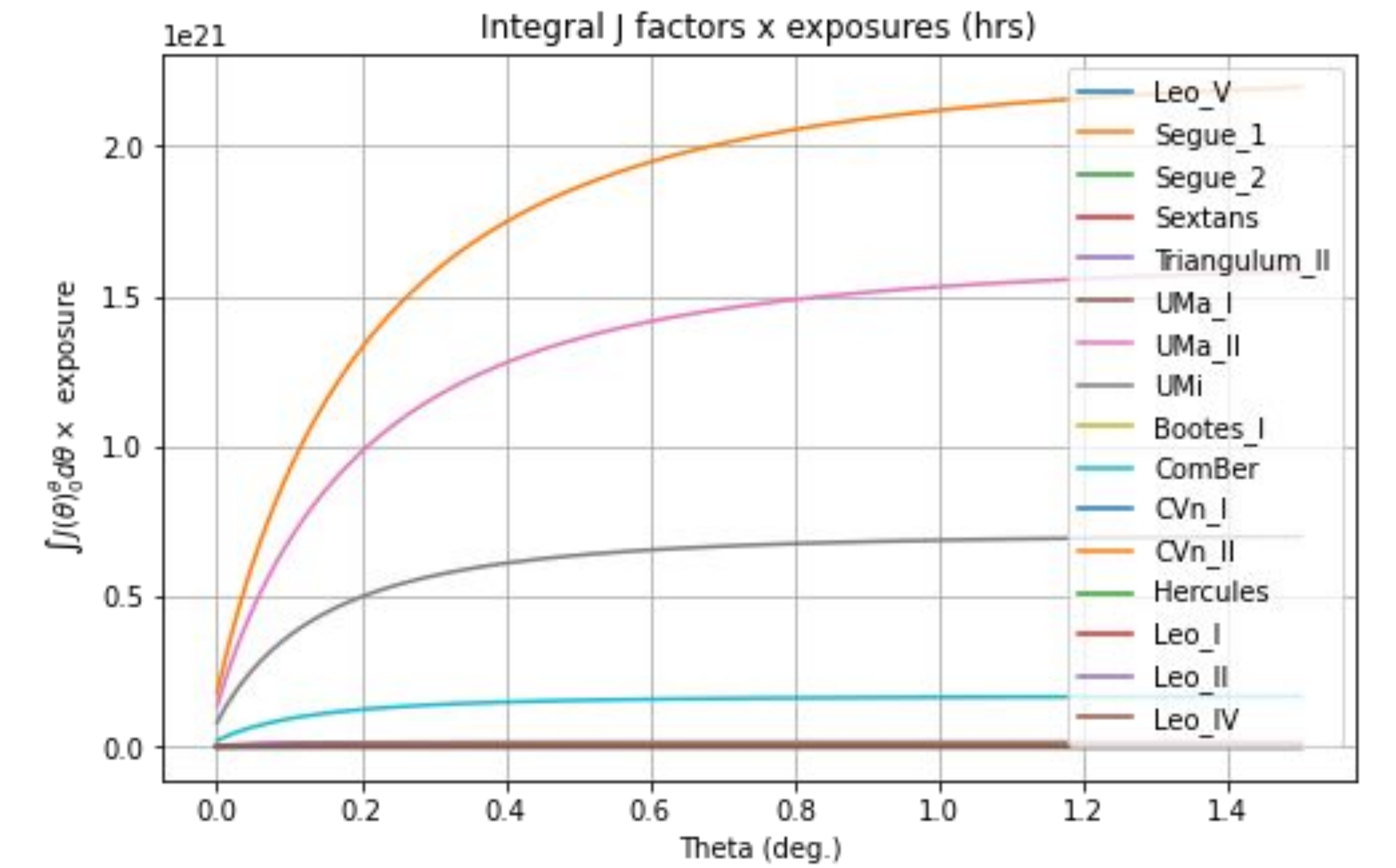
Thermal relic wino rate vs. Energy fraction

MB et al.: 1808.08956

Thermal relic quintuplet rate vs. Energy fraction

MB, N. Rodd, T. Slatyer, and V. Vaidya: 2309.11562

DWARF SPHEROIDAL SEARCH



Likelihood method

$$\mathcal{L} = \frac{(\mathcal{S}+\alpha\mathcal{B})^{N_{on}} e^{-(\mathcal{S}+\alpha\mathcal{B})}}{N_{on}!} \frac{\mathcal{B}^{N_{off}} e^{-\mathcal{B}}}{N_{off}!} \prod_{i=1}^{N_{on}} P_i(E_i|M_\chi, \langle\sigma v\rangle),$$

$$\log\mathcal{L} = N_{off}\log\mathcal{B} - \mathcal{S} - (1+\alpha)\mathcal{B} + \sum_{i=1}^{N_{on}} \log\left(\alpha\mathcal{B}\,p_{b,i} + \mathcal{S}\,p_{s,i}\right),$$

N_{on}: the total number of events from on region
N_{off}: the total number of events from off regions
S: the expected number of the DM signal from dSphs, which is a function of the DM cross section

$$S = \int dE\, dE'\, d\Omega \frac{d\Phi_\gamma(E,\langle\sigma v\rangle)}{dE_\gamma} \times R(E,E',\Omega) \qquad \frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{4\pi}\frac{<\sigma v>}{\delta m_\chi^2}\frac{dN_\gamma}{dE_\gamma}\int\int \rho^2 ds d\Omega$$

B: the expected background
α: a relative exposure time between on and off regions

From C. McGrath
VERITAS Summer 2023 Meeting

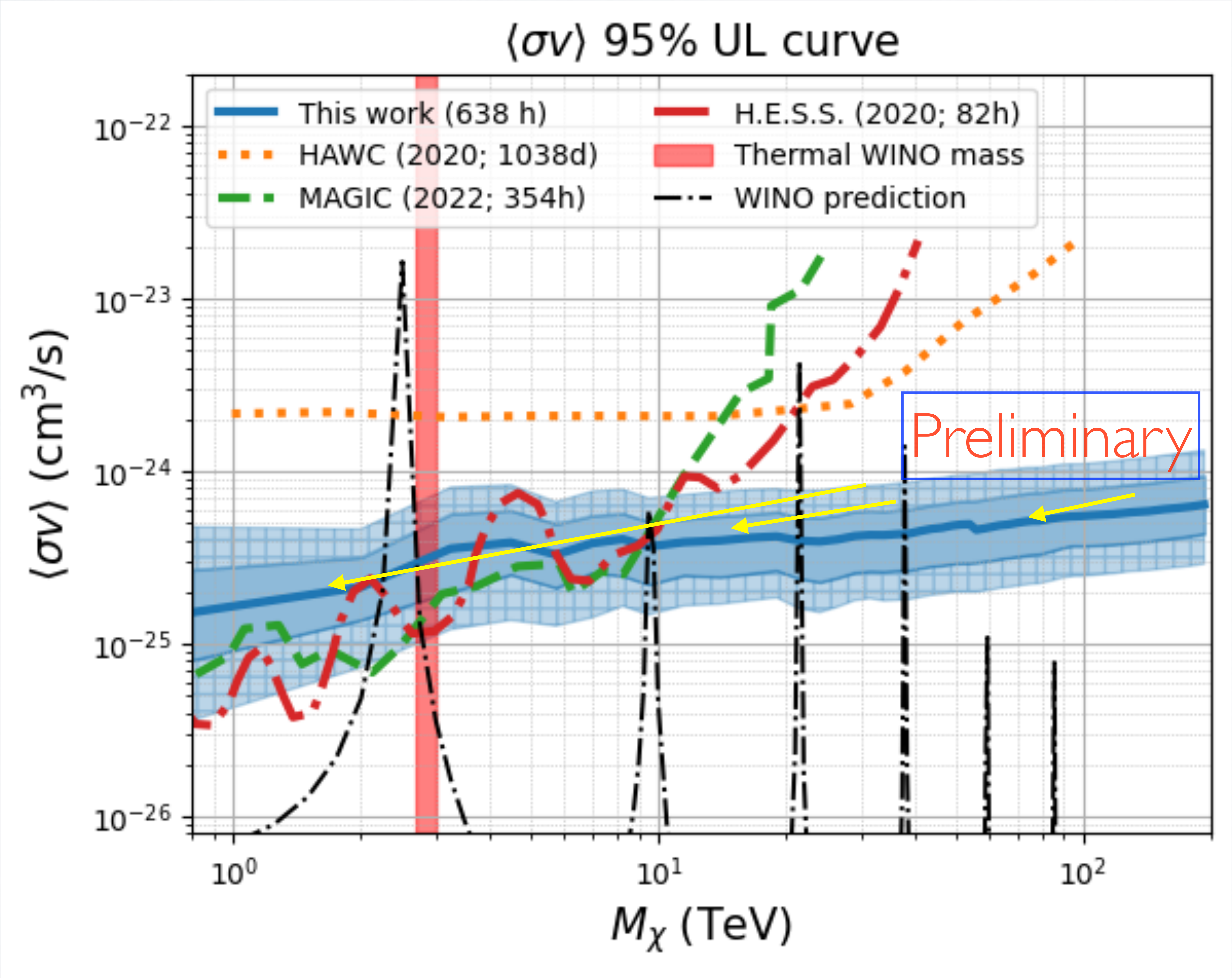
Ando (2020) J-factors

Typical Analysis
Limit ~ 0.1°

From D. Tak
TeVPA 2023

Nuisance
Parameter
Strongly Constrained
by Off-region events

PRELIMINARY VERITAS dSphs LIMIT



- Our new dSphs search for the wino!
- Comparable limit to MAGIC (2022), HESS(2020) which used older, more aggressive J-factors
- Uncertainty dominated by J-factors.
- Binned analysis with bin size set by experimental resolution
- The wino is cornered, but still viable
- Limits become much stronger than MAGIC/HESS $\gtrsim$ 10 TeV. Our calculation includes continuum photons from signal.

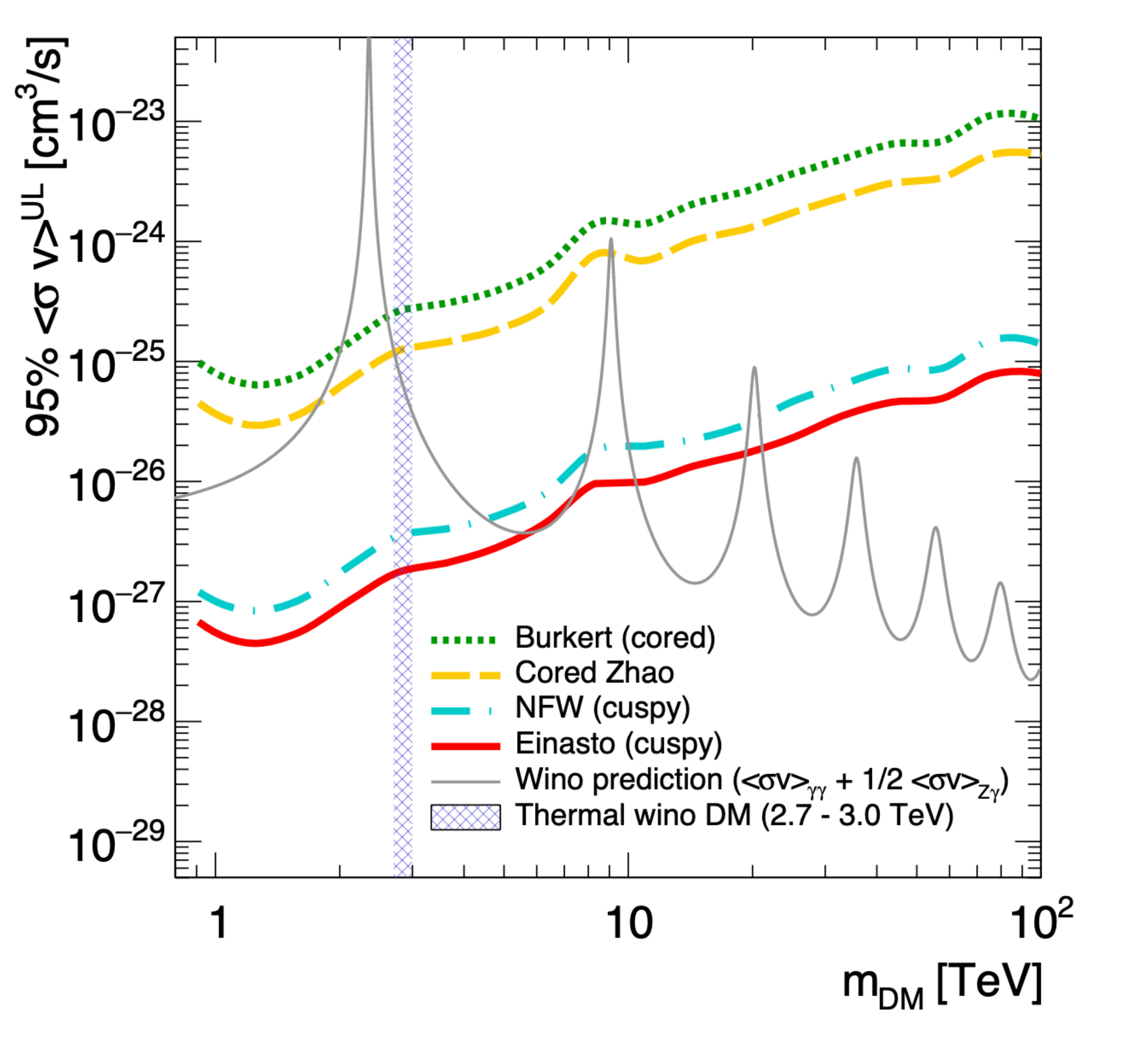
MB, **O. Calcerano**, C. McGrath, E. Pueschel, J. Quinn, D.Tak & VERITAS

FUTURE DIRECTIONS

- Simple, electroweak **thermal relic dark matter…is alive!**
- Under pressure in the galactic center, **dSphs offer an orthogonal probe**
- Straightforward to **extend for quintuplet**. Naively, our bound looks stronger than MAGIC at thermal relic mass (14 TeV)
- **Our simple analysis already competitive with MAGIC & HESS**
- **Can we push to thermal relic exclusion?**
  - Take more dSphs data (**Ursa Major III as new, attractive target**)
  - Extend spatial region
  - Gaussian process modeling for background as in 2405.13104: N. Rodd, B. Safdi, W. Xu.
  - **Combine with other telescopes (à la Glory Duck). MAGIC and VERITAS so close individually, maybe we get there together along with HESS.**

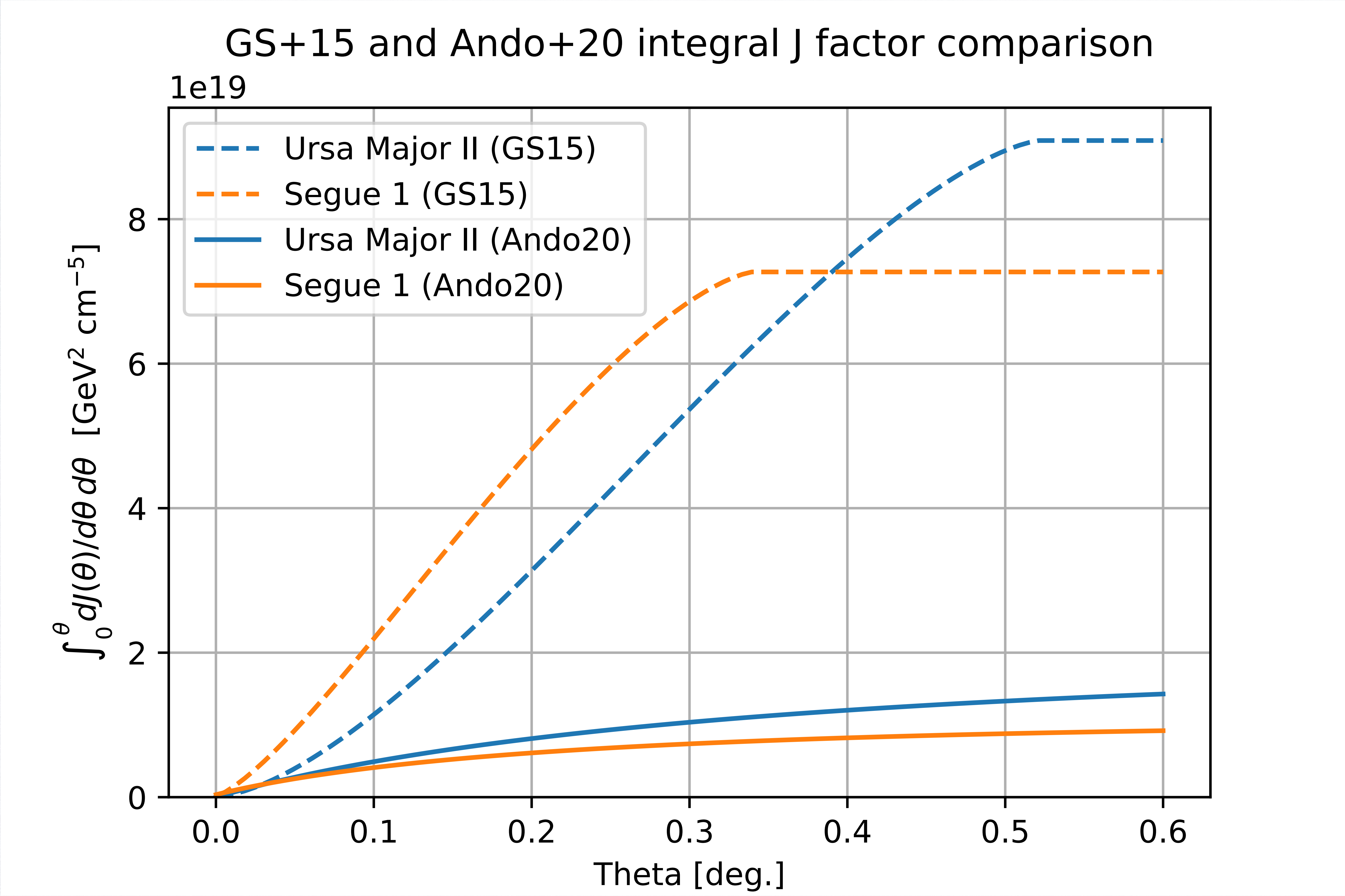
MAGIC GALACTIC CENTER LIMITS

MAGIC
Galactic Center Limits
2212.10527



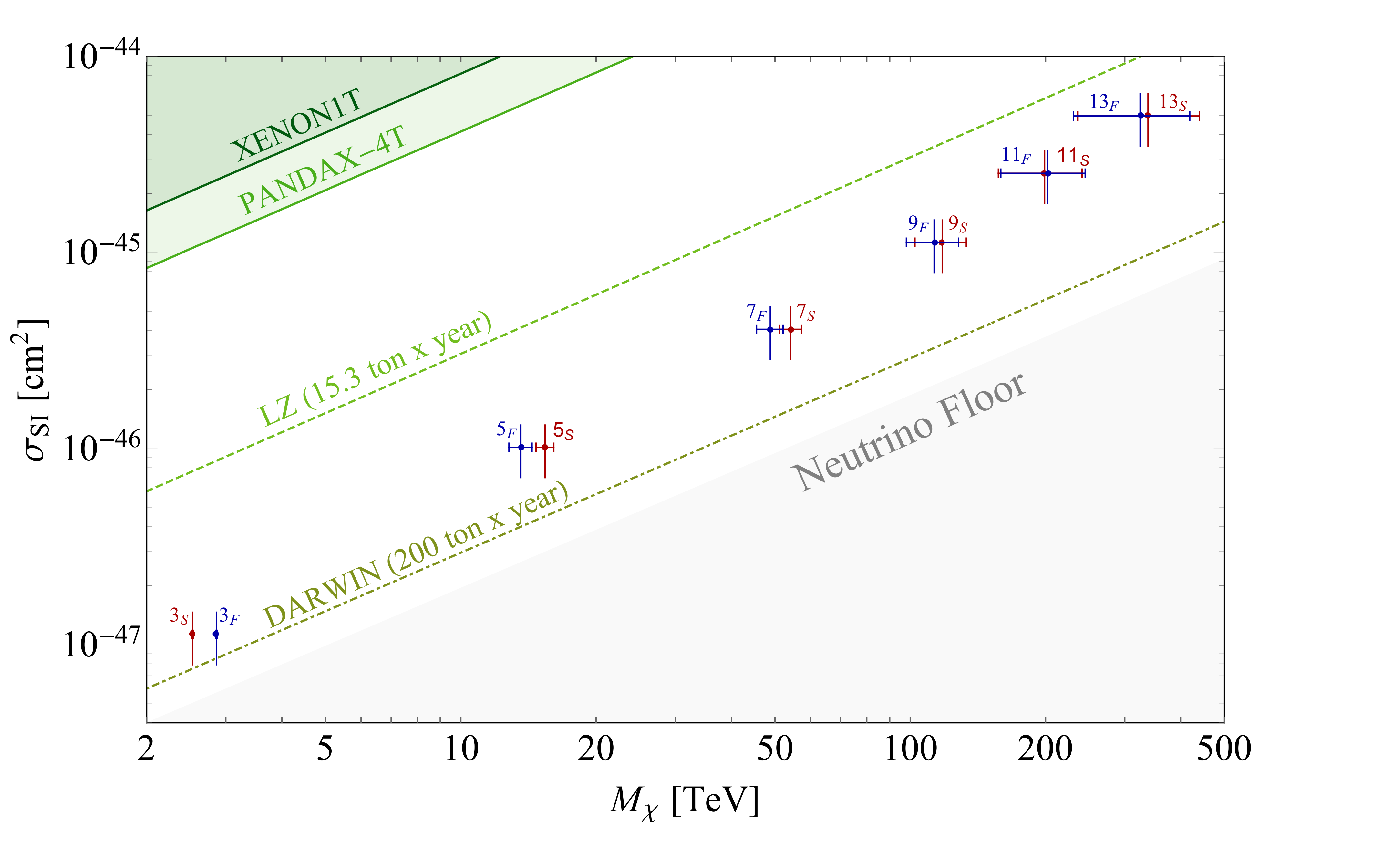
For cored profiles, MAGIC achieves similar sensitivity to our dSphs result

J-FACTOR COMPARISON

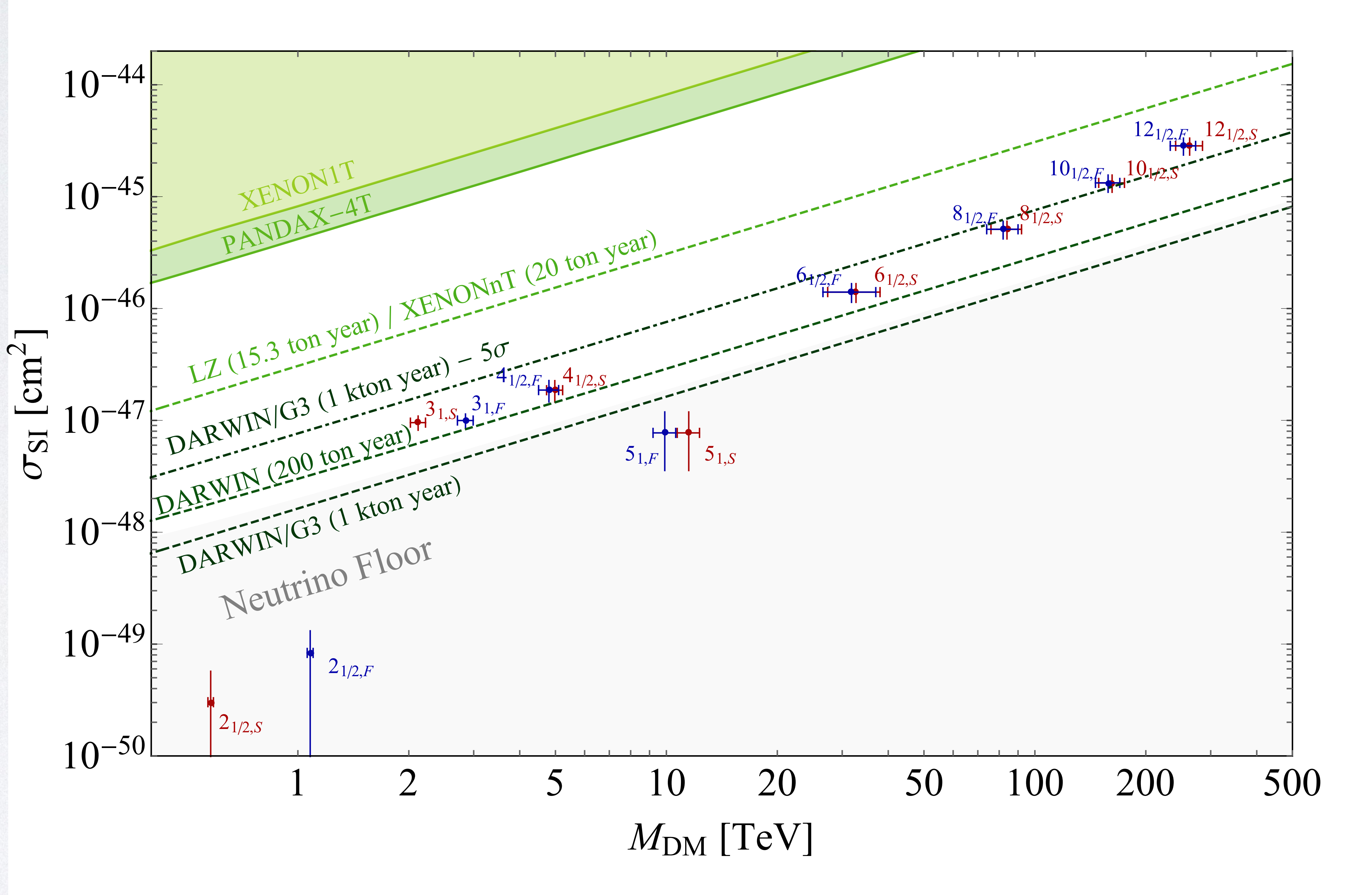


From J. Quinn

DIRECT DETECTION?



2107.09688: Bottaro et al.

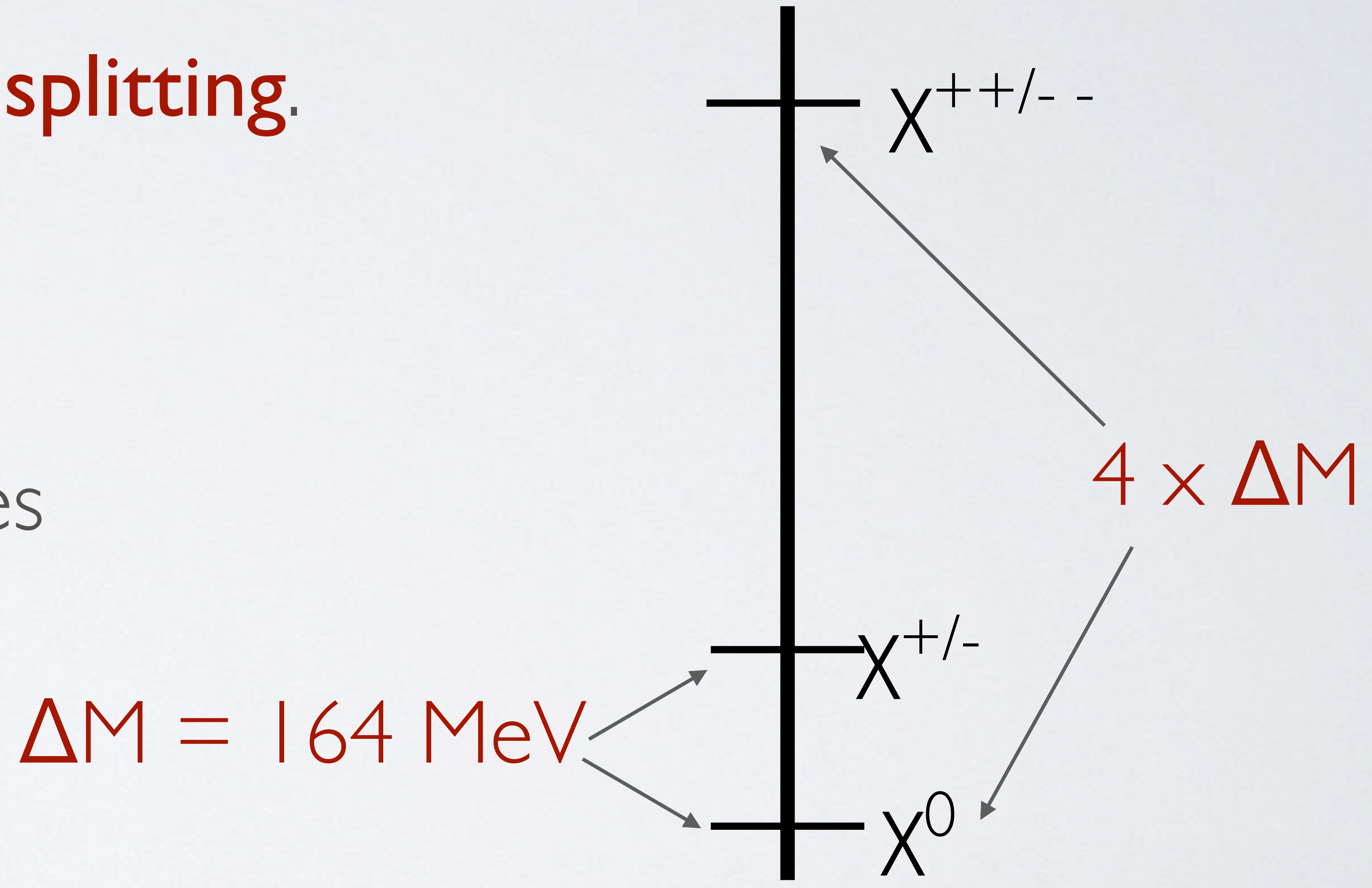


2205.04486: Bottaro et al.

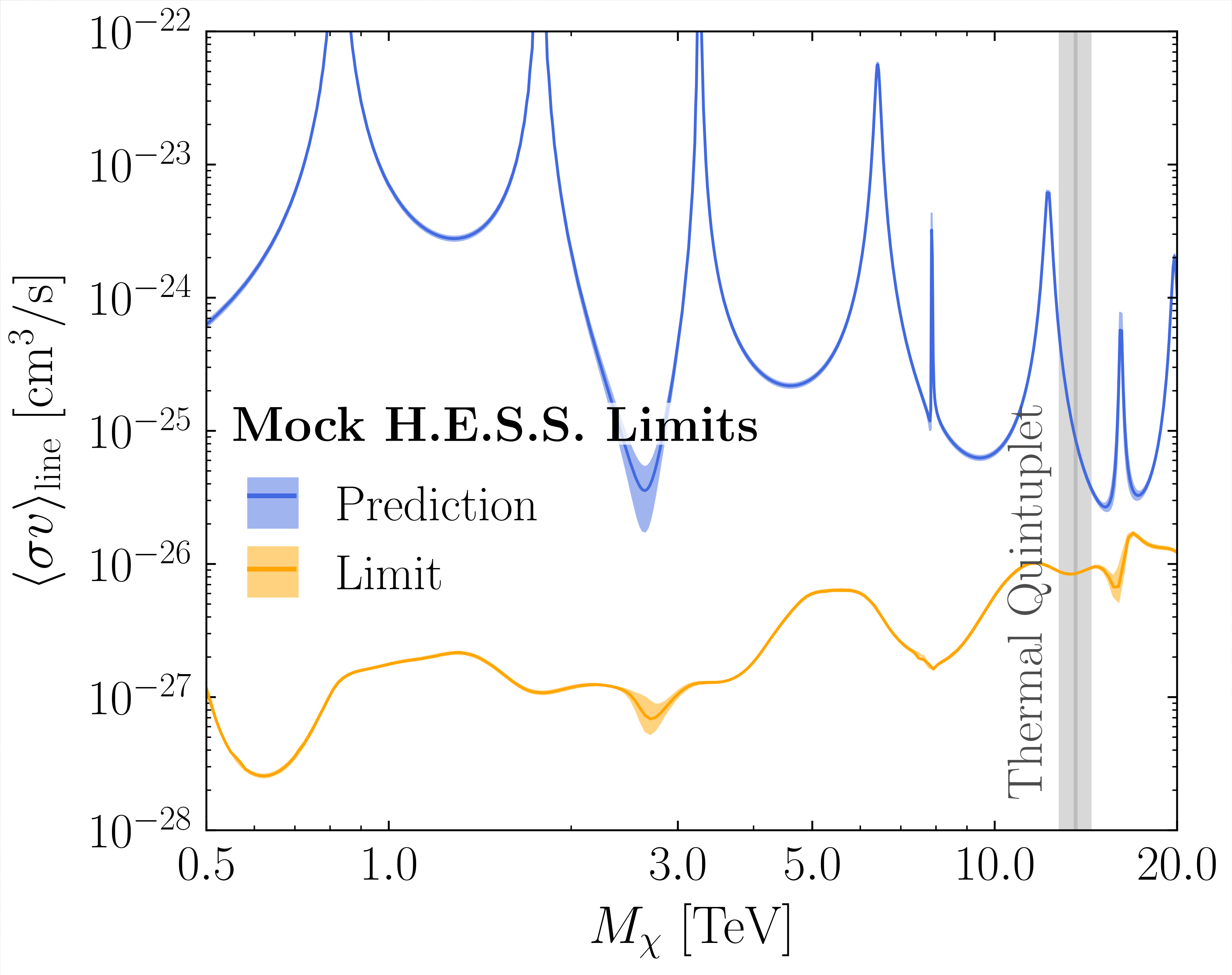
"MINIMAL DARK MATTER"

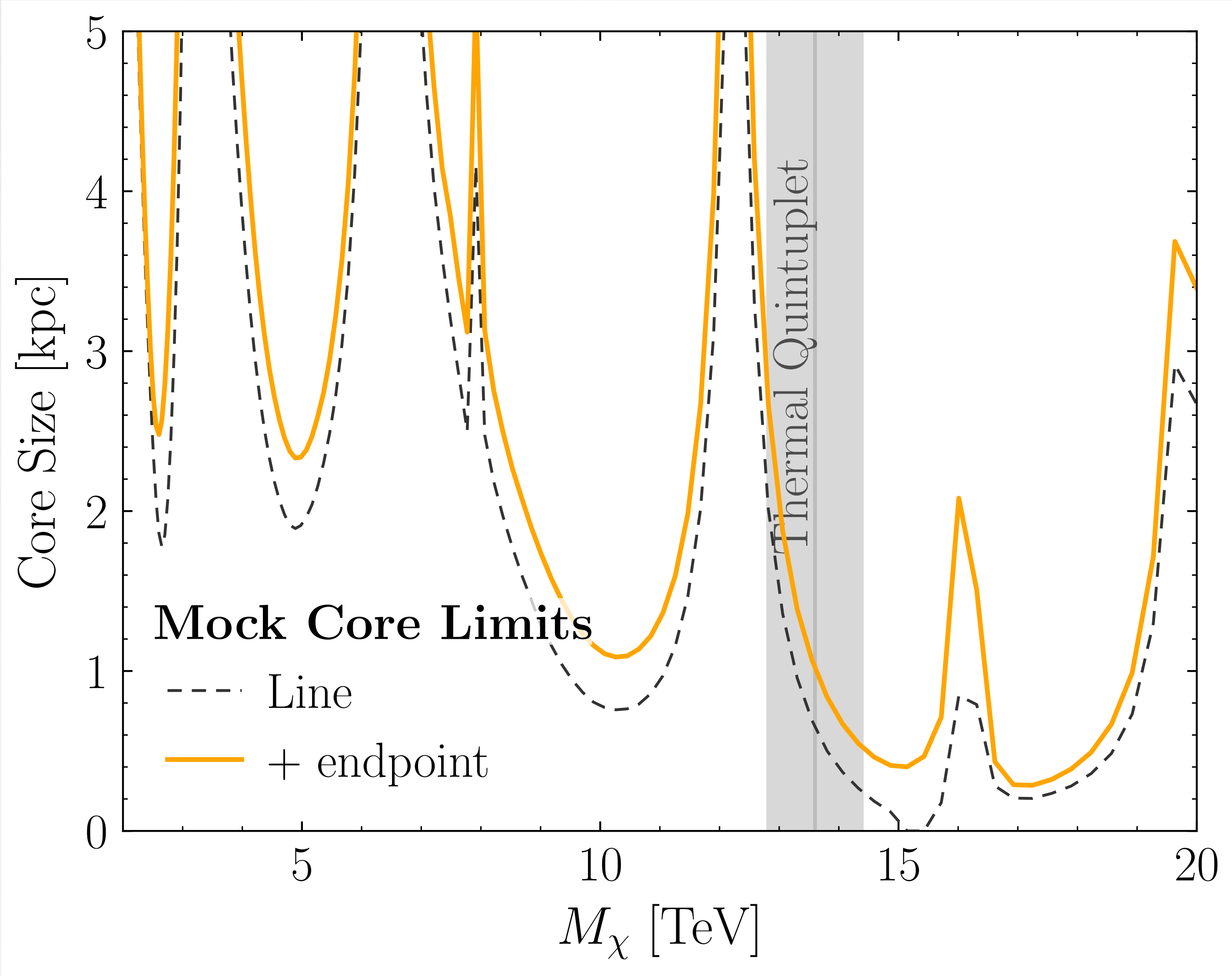
- **SU(2) quintuplet** (Y=0) has neutral **DM candidate**.
- Charged and doubly-charged states with **narrow mass splitting**.
- Keeps SU(2) Landau pole above GUT scale
- **Cosmologically stable** just under SM symmetries

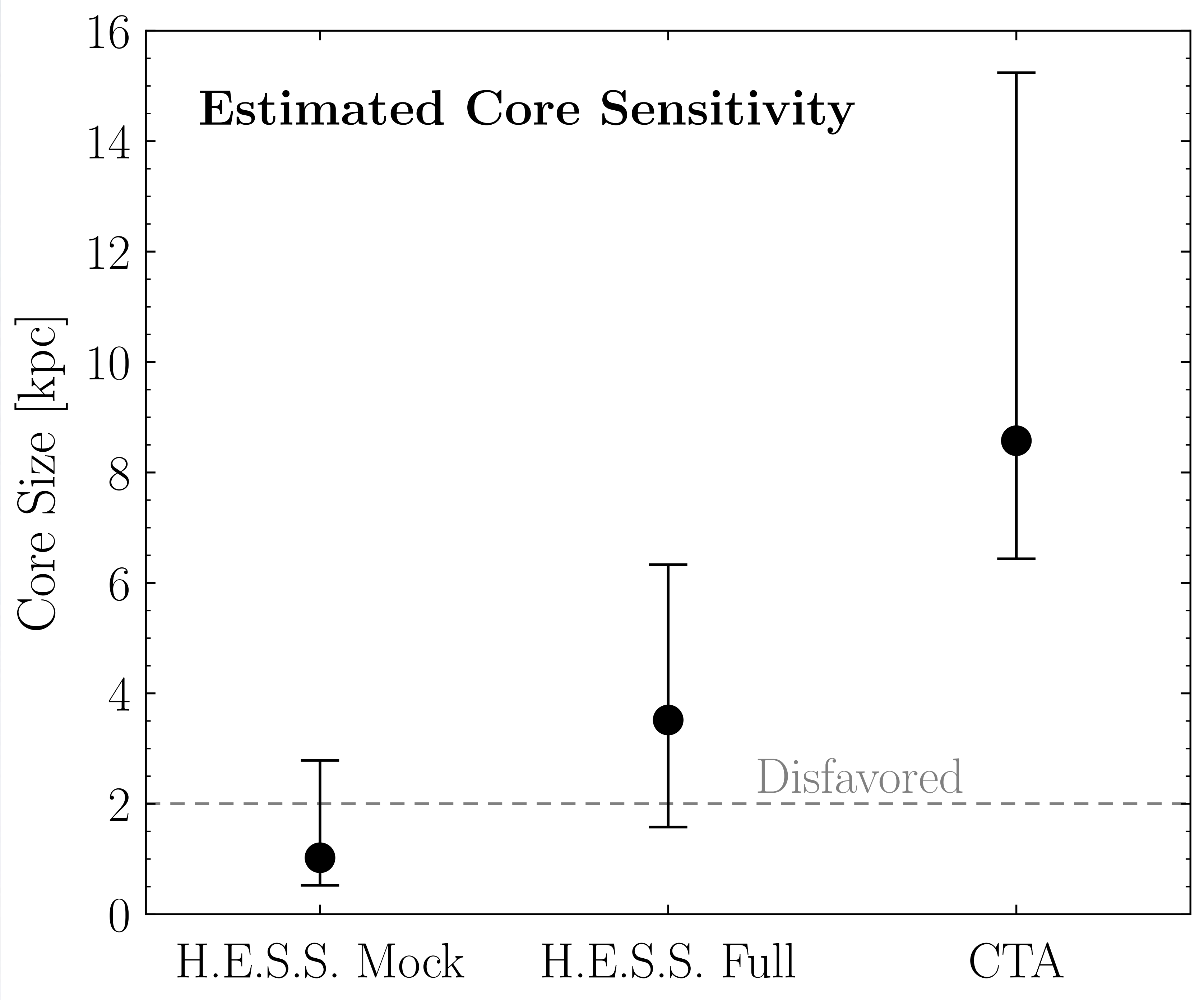
$$\mathcal{O}_{\rm decay} = \frac{c}{\Lambda^2}\chi_{abcd}\, L^a H^b H^c H^d$$



PROJECTED QUINTUPLET LIMITS





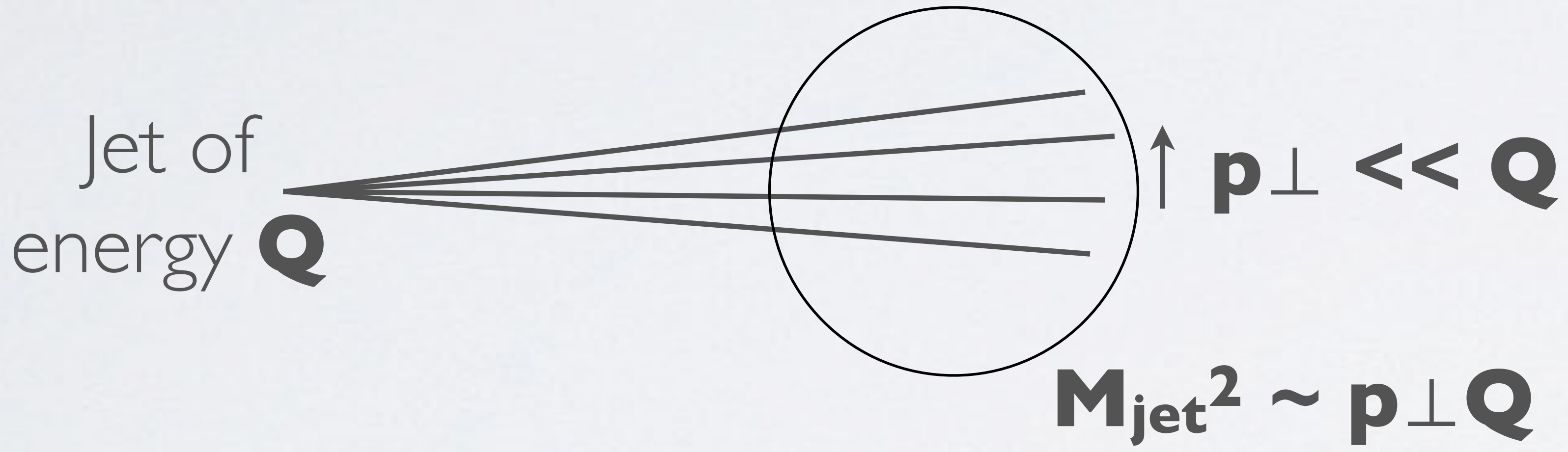


At **thermal relic M_χ = 13.6 TeV**
Error bar from thermal mass uncertainty

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

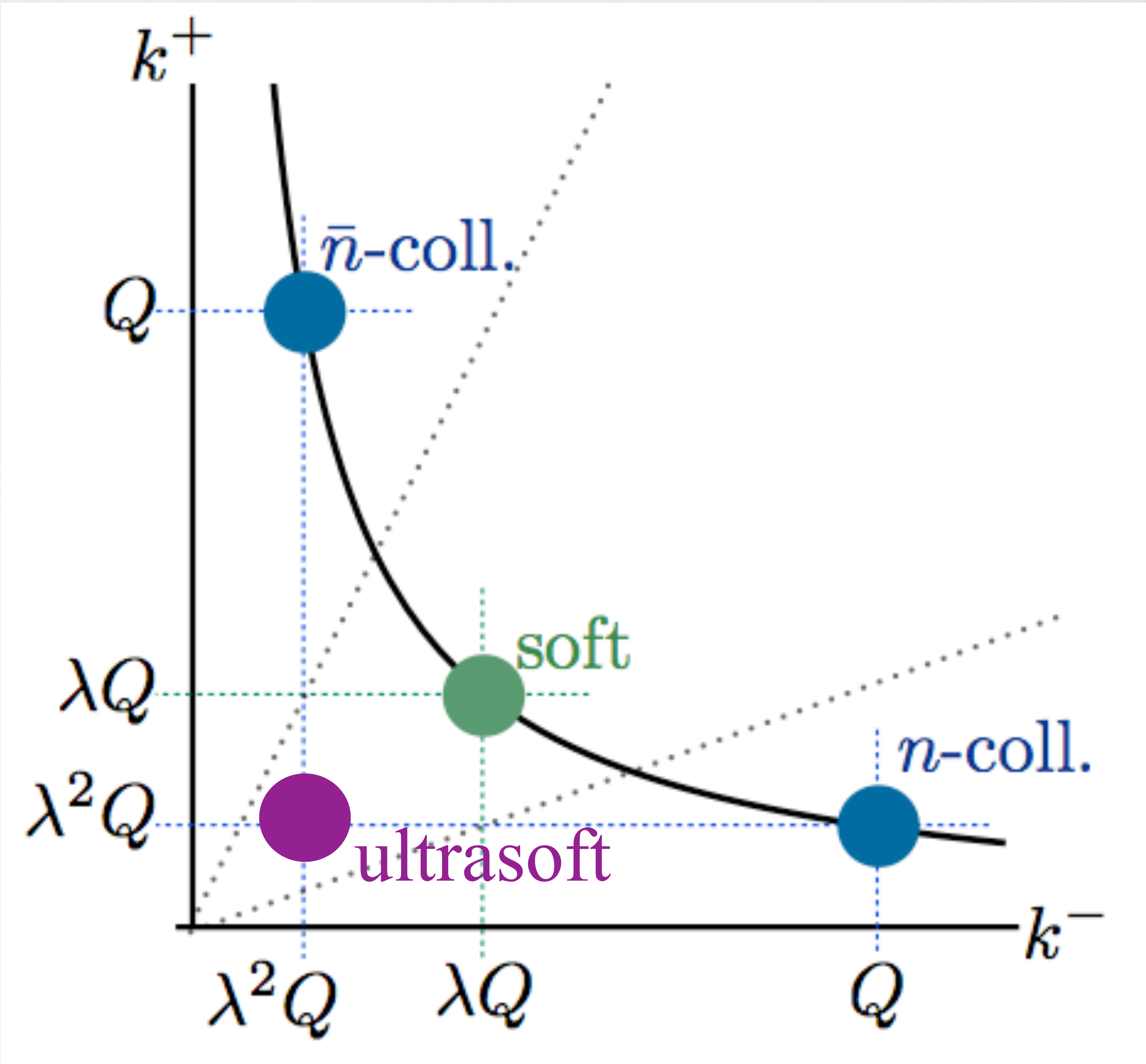
SOFT-COLLINEAR EFFECTIVE THEORY

- Large scale-hierarchies can arise within one field



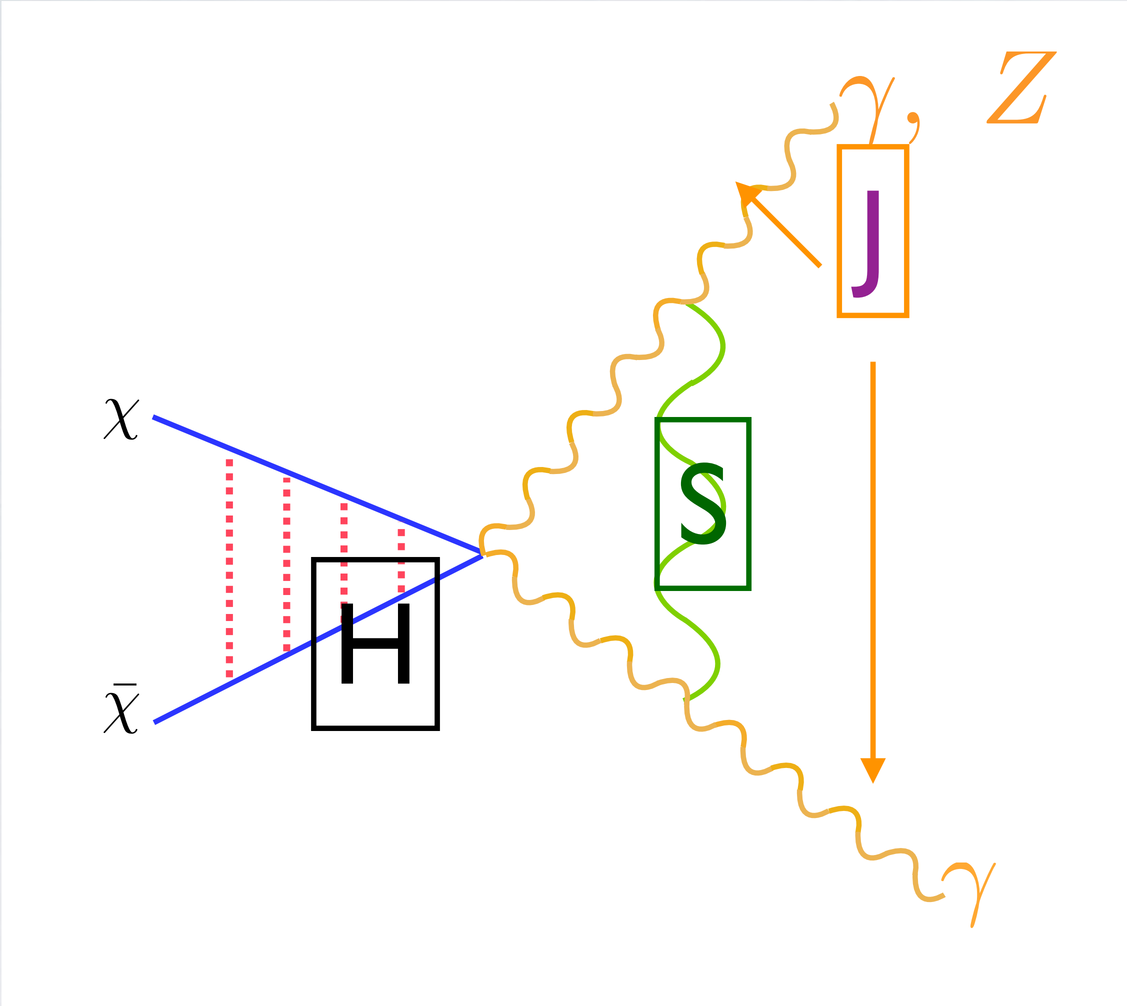
- We can **use Renormalization Group to resum** kinematic logs

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:

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

EFT Benefit:
S & J representation independent!
Compute once and for all.

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

Squared Wilson coefficient

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

Collinear Gauge field

Soft Wilson Line

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

SOFT REFACTORIZATION

S: Perform matching

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

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

???

Remaining **soft:**

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

$\lambda = m_W/M_\chi$

BUT...

what about measurement function?

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

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