WIMP DARK MATTER'S MICHELSON-MORLEY MOMENT

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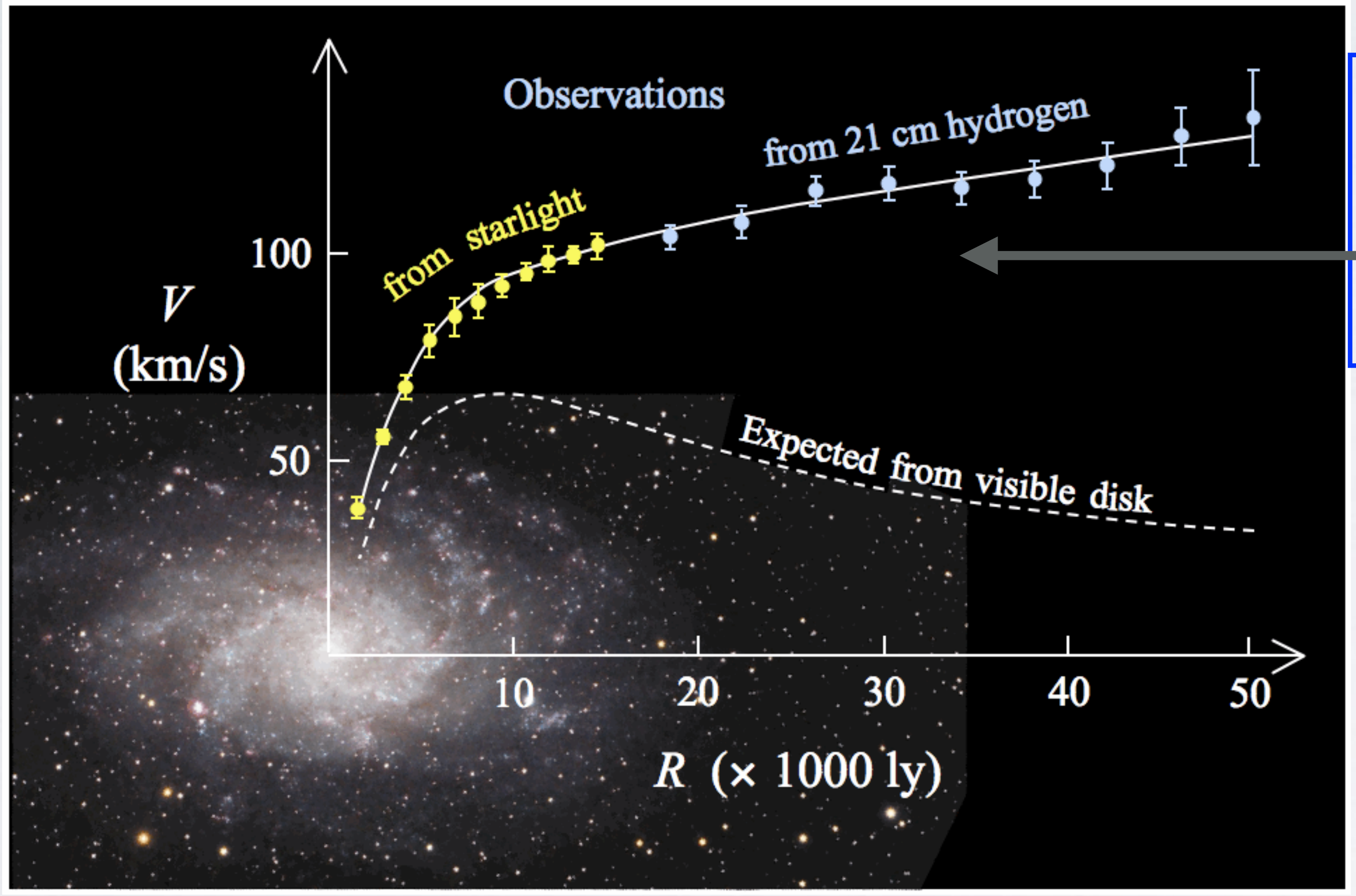
TeVPA 2025
Valencia, Spain
November 6th, 2025

VERITAS

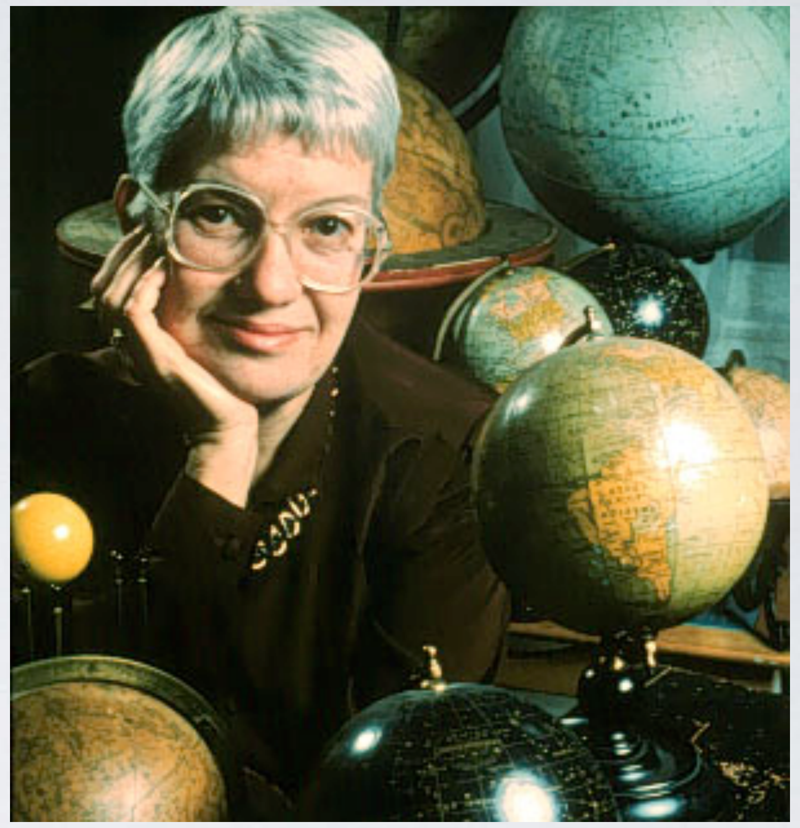
Arizona State University

WHY DARK MATTER?

Anomalies on 3 different astrophysical scales!

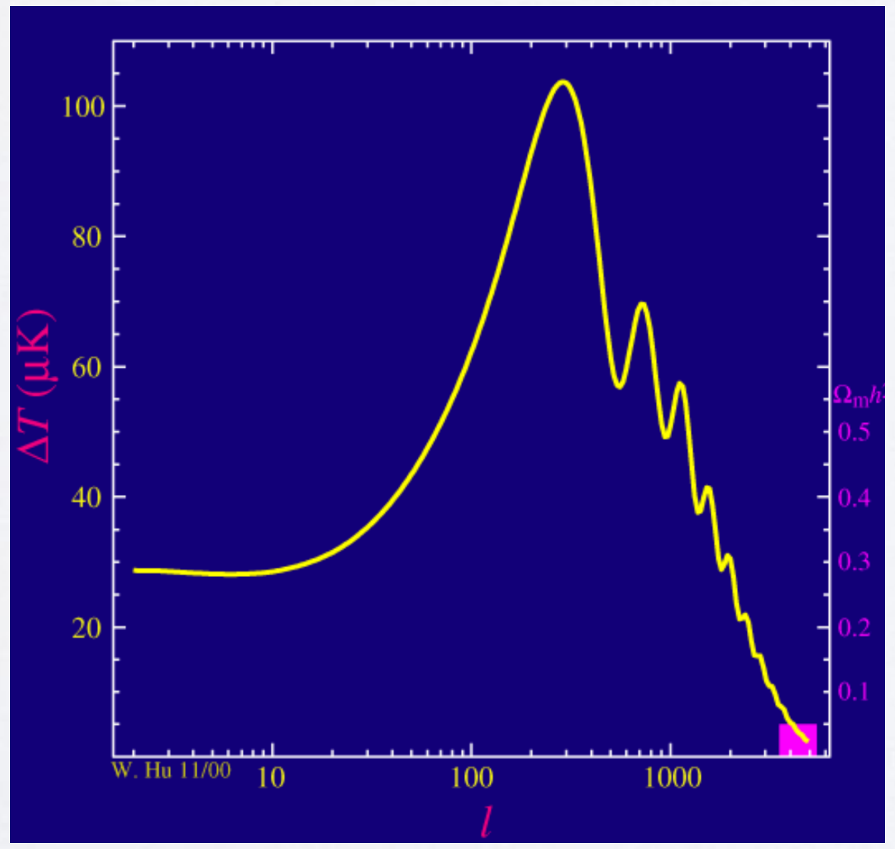


Galactic Rotation curves:
Stars move faster
than expected

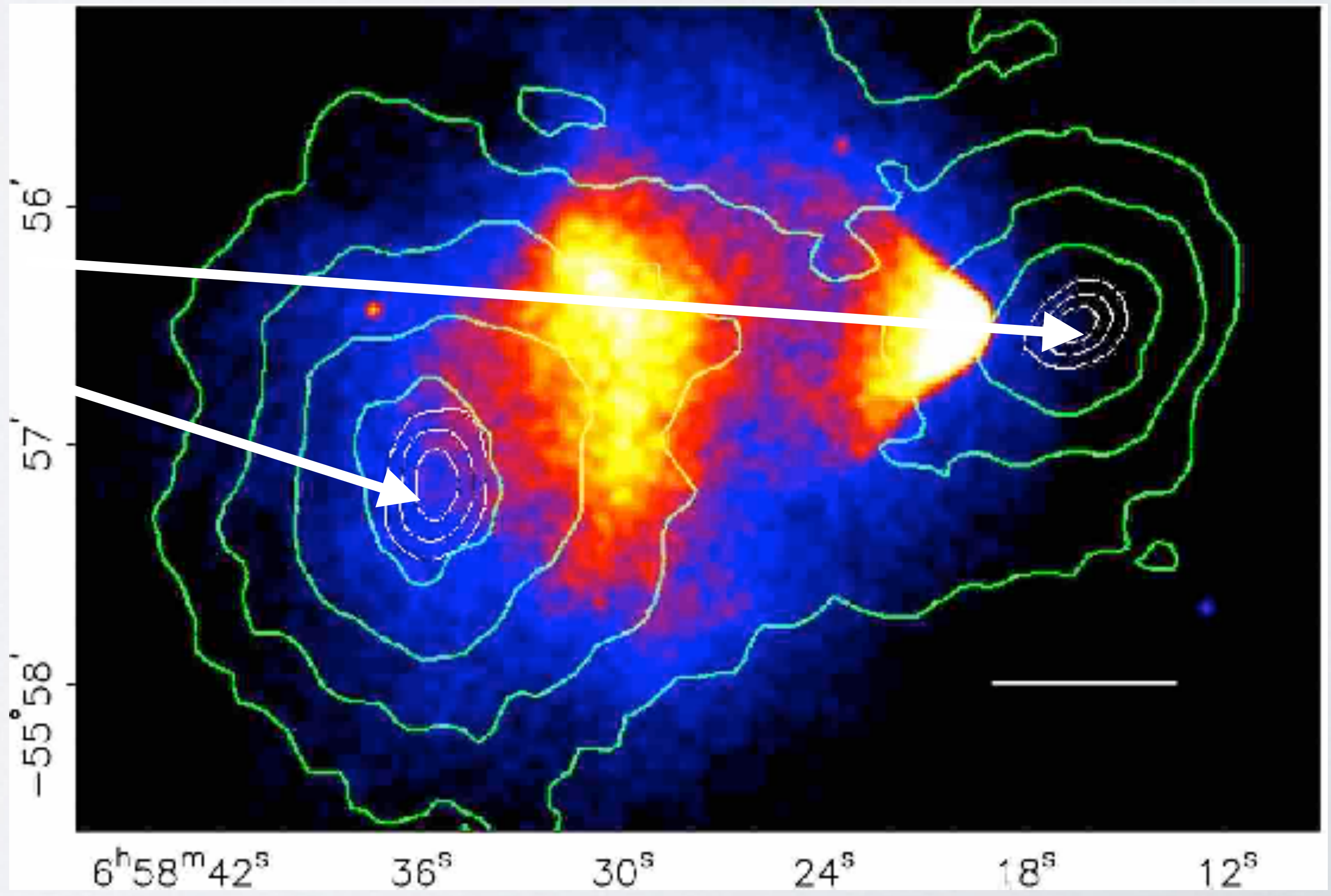


Vera Rubin 1928-2016
Established Rotation Curve anomaly

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

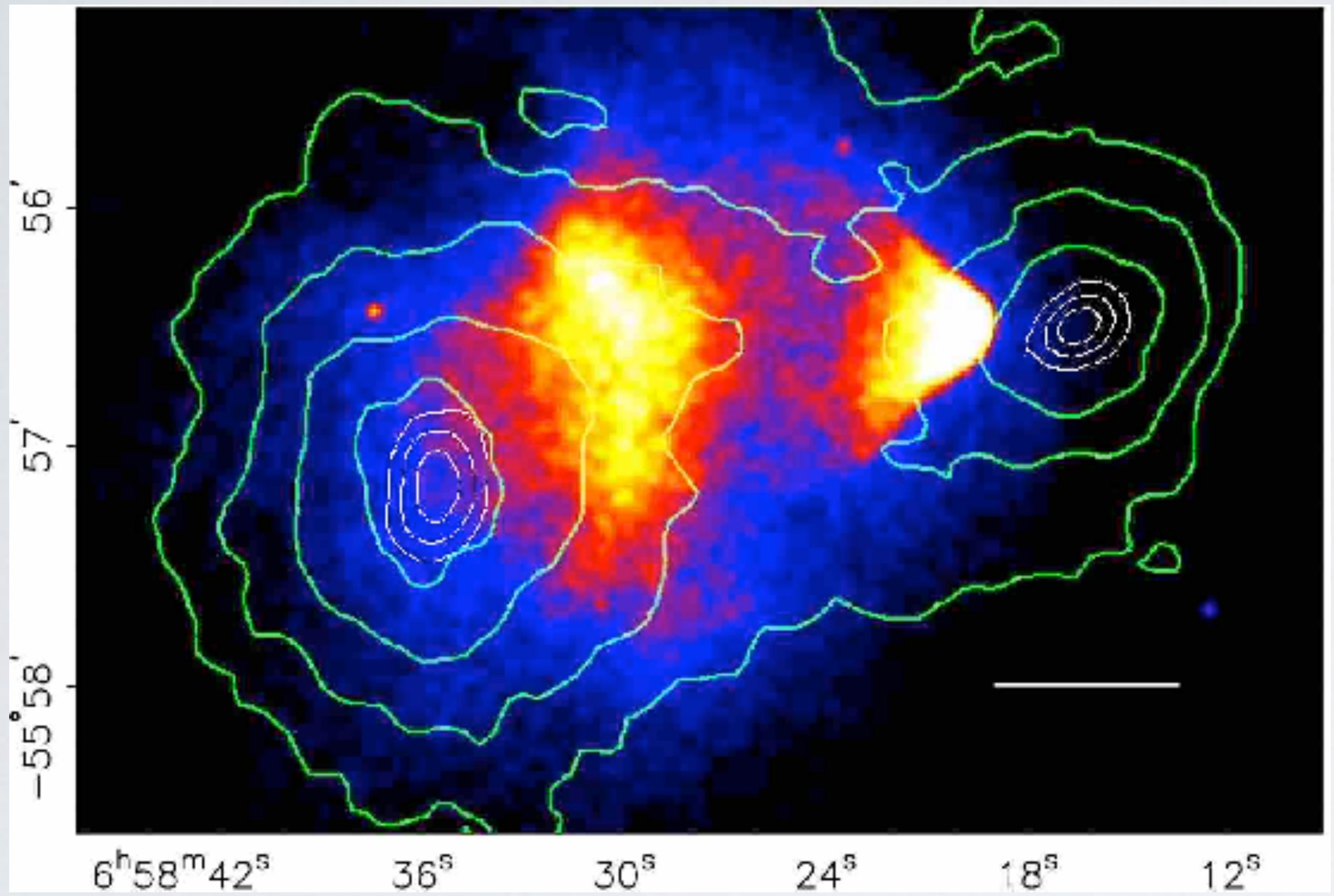


Colliding Clusters:
Gravitational wells
nowhere near visible peaks



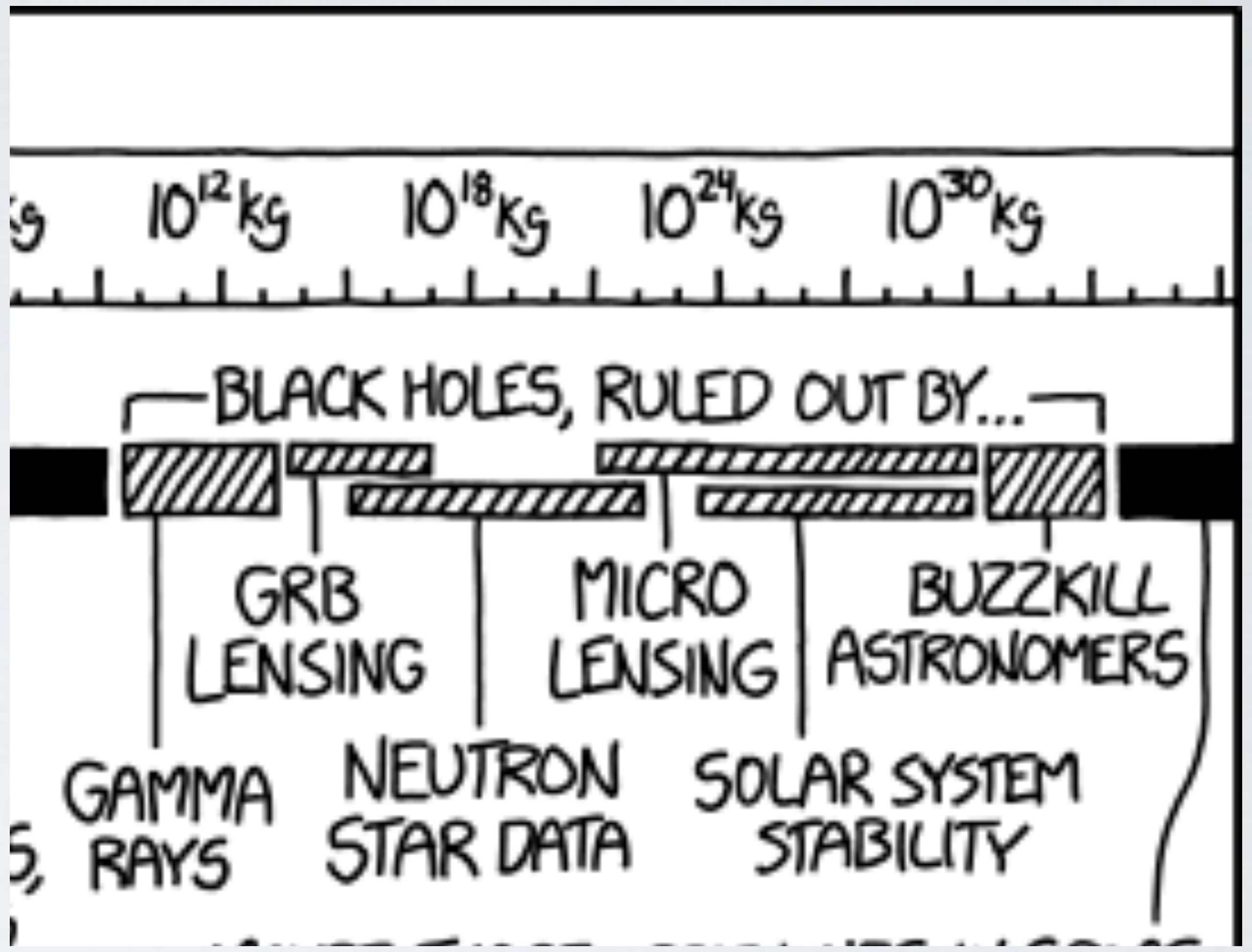
IS IT?

~~Something like Gravity?~~



Gravitational wells 10^5 parsecs from matter concentrations!

~~Something like Black Holes?~~



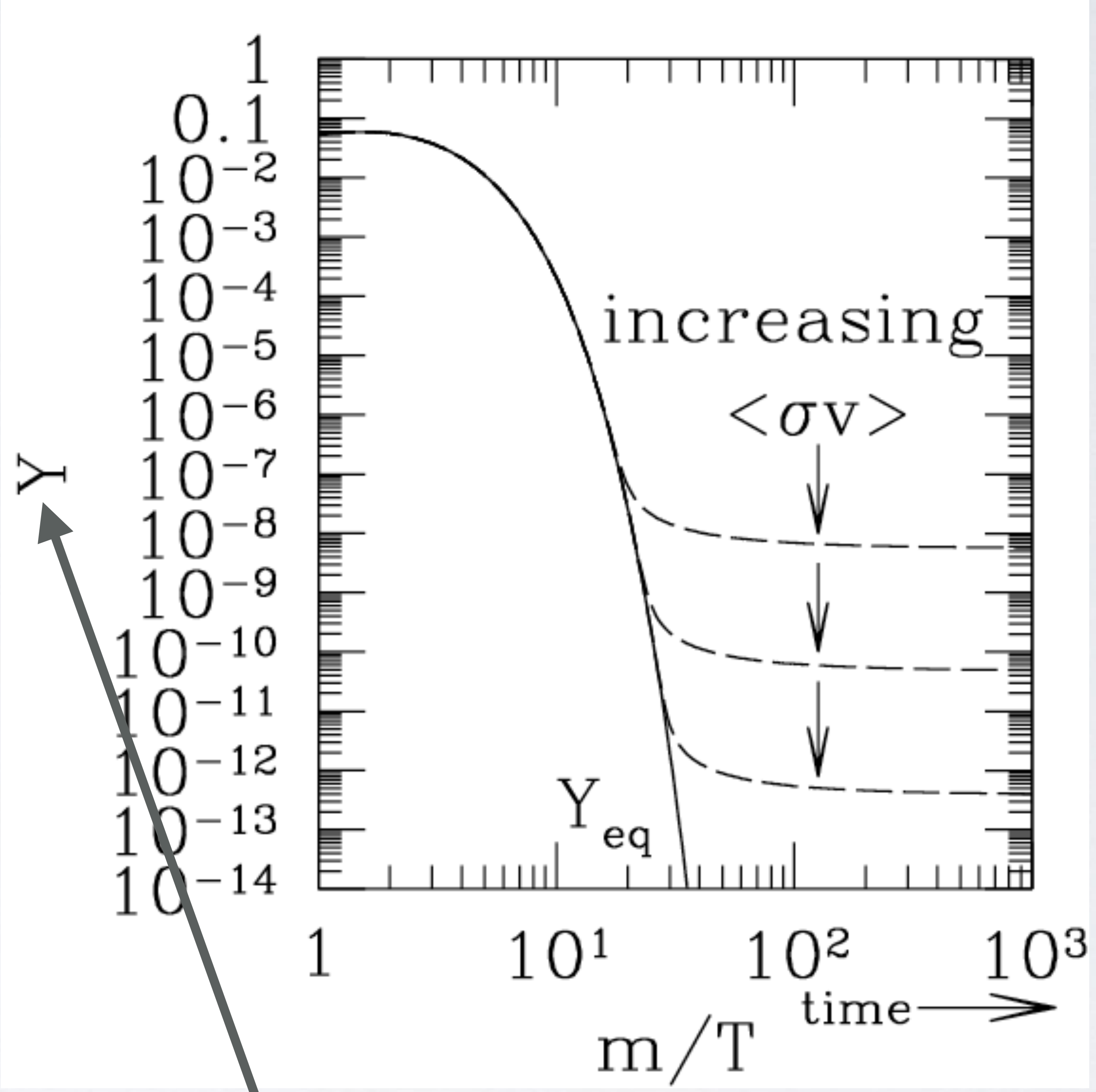
XKCD (2018) cf. 1705.05567

Something like a neutrino!

WIMP MIRACLE

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

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



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

"HEAVY NEUTRINO" WIMP

$\Omega_{DM} = 0.27$

Measured Dark Matter Density

Weak Force "Charges"

Simple Candidates!

Dark Matter ↔ Weak Scale:

Weak Triplet: "Wino"

Weak Doublet: "Higgsino"

Weak Quintuplet

$$\begin{pmatrix} e^{\pm} \\ \nu_e \end{pmatrix} \sim \begin{pmatrix} \chi^{\pm} \\ \chi^0 \end{pmatrix}$$

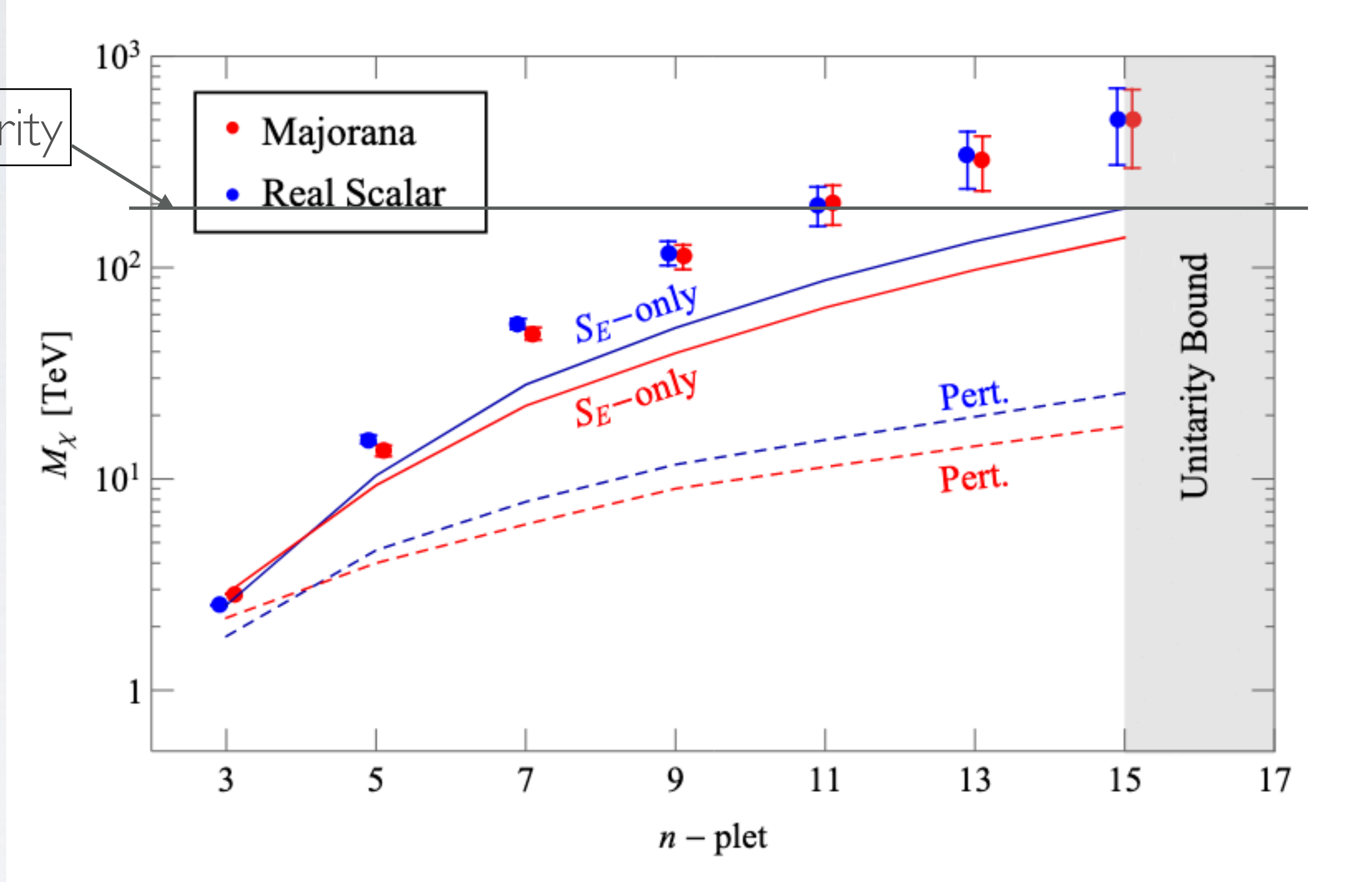
Correct Dark Matter Density fixes M_χ:

Wino: 3 TeV

Higgsino: 1 TeV

Quintuplet: 14 TeV

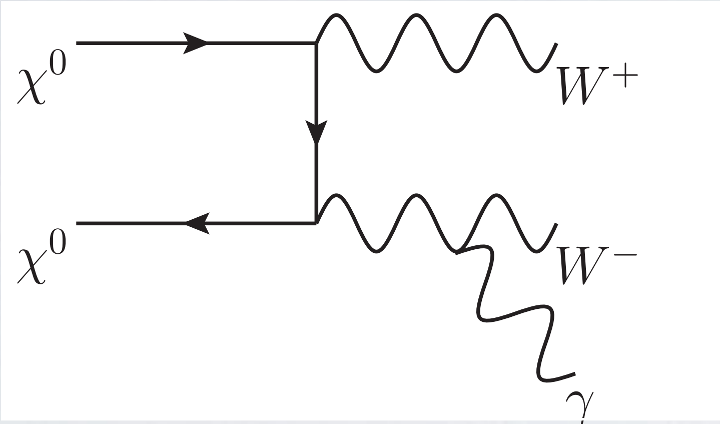
Naive Unitarity

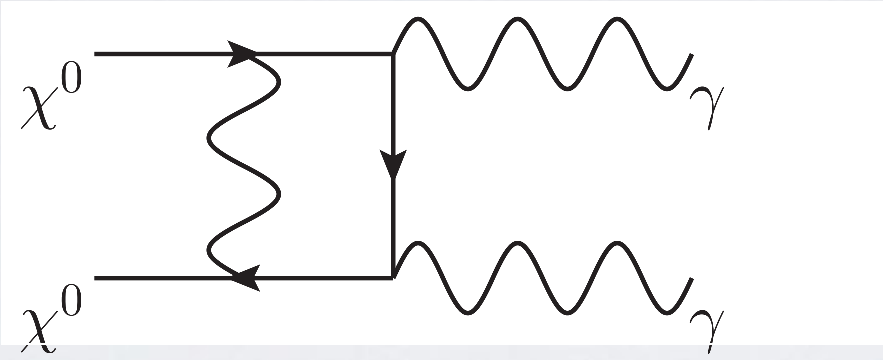


2107.09688: Bottaro et al. Simple thermal relic masses for real reps of SU(2)

"Minimal Dark Matter"
hep-ph/0512090: M. Cirelli, N. Fornengo, A. Strumia

ECHO OF THE WIMP MIRACLE

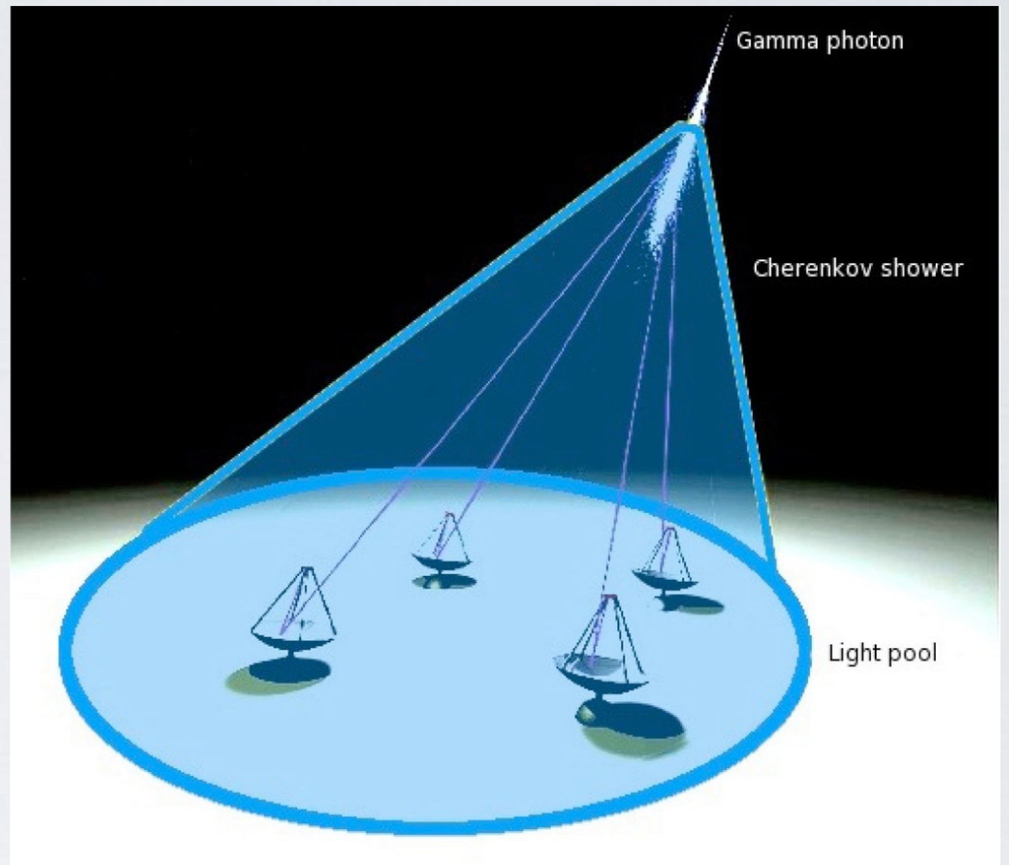




Indirect Detection:

Photons from Dark Matter Annihilation

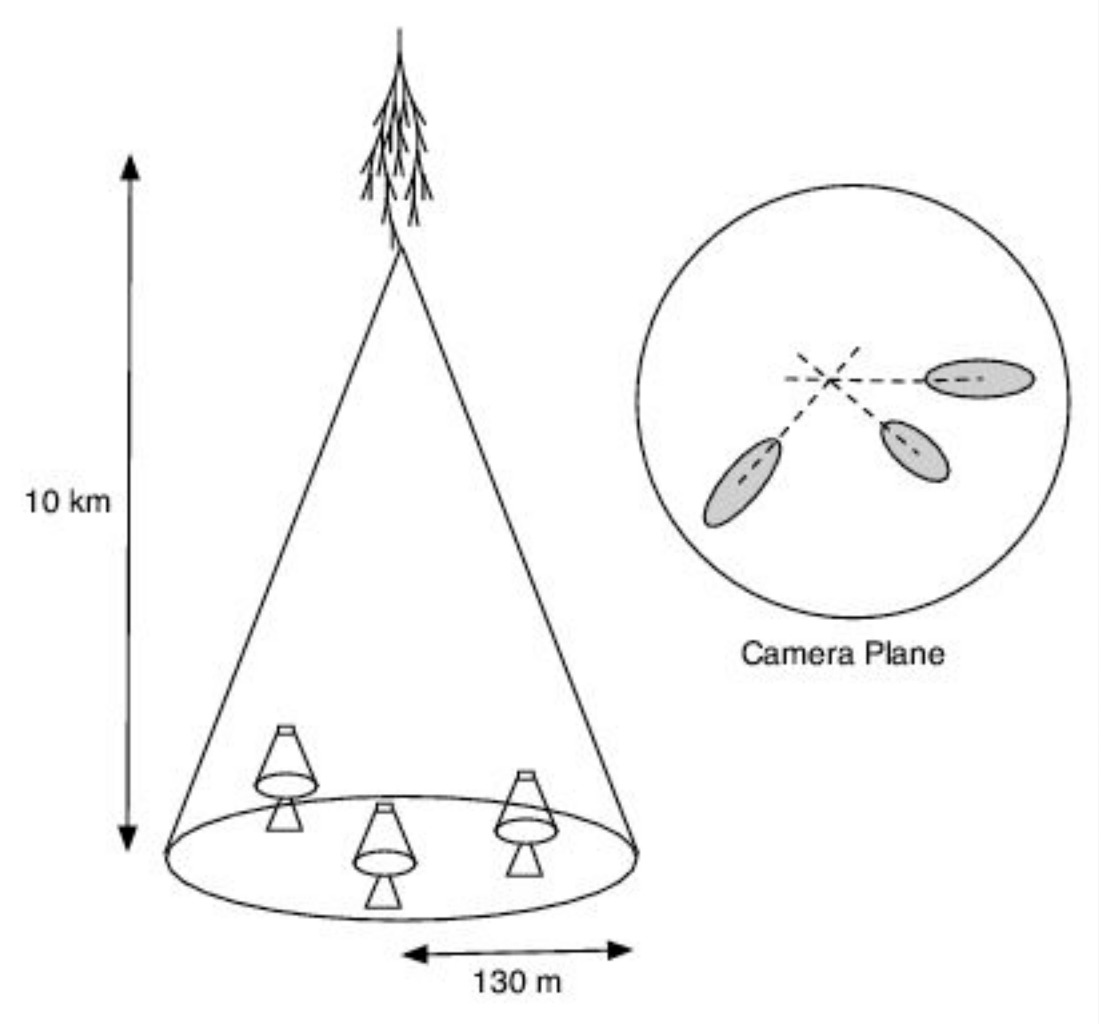
HESS/VERITAS/MAGIC can probe
Dark Matter Masses
up to 30 PeV



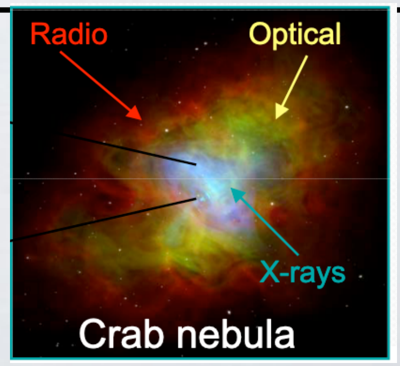
O(TeV) γ leads to $O(10^4 m)$ light pool on ground

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

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

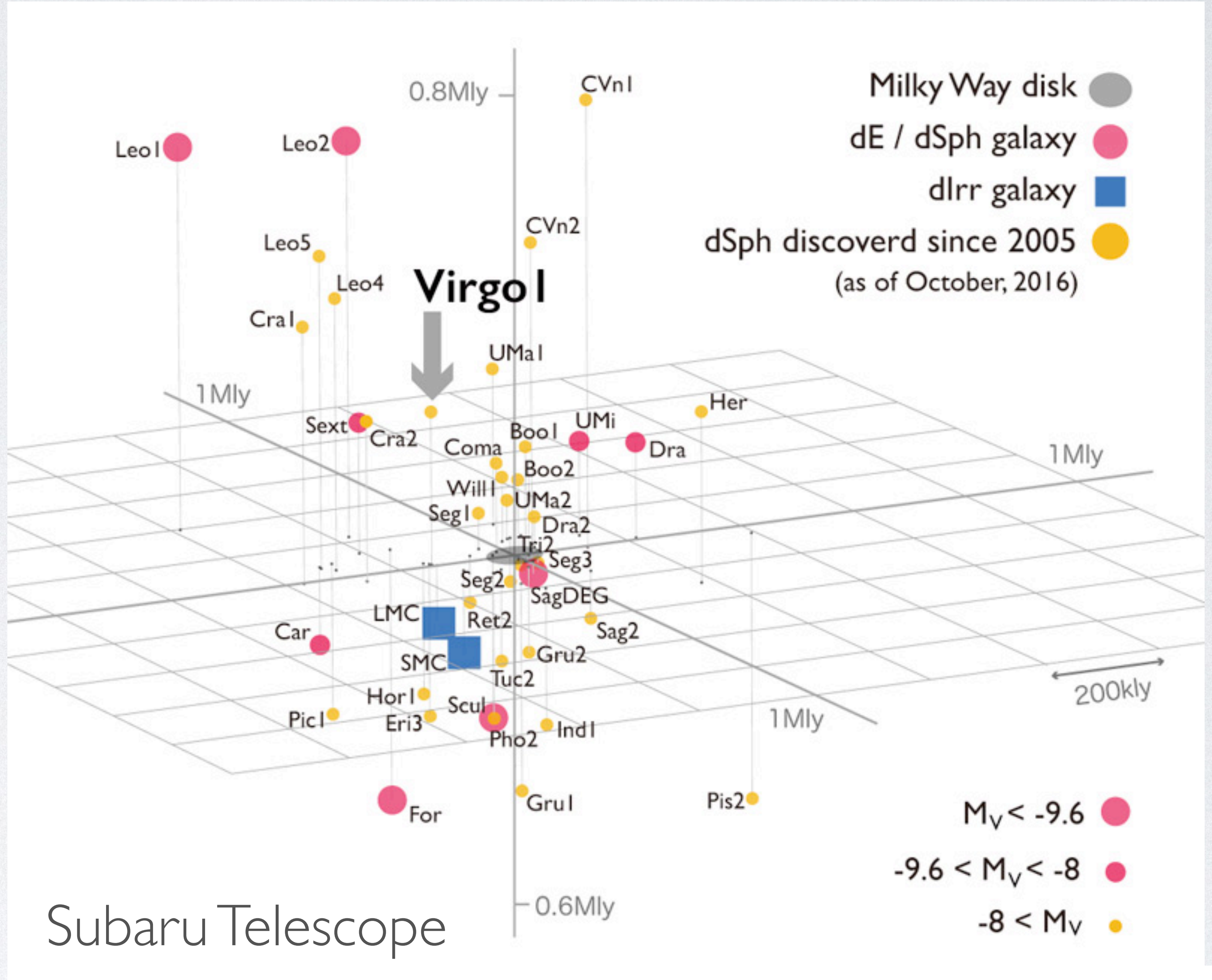


- Stereoscopic image reconstructs particle location
- Brightness reconstructs particle energy
- Technique first used to detect Crab Nebula in 1989.

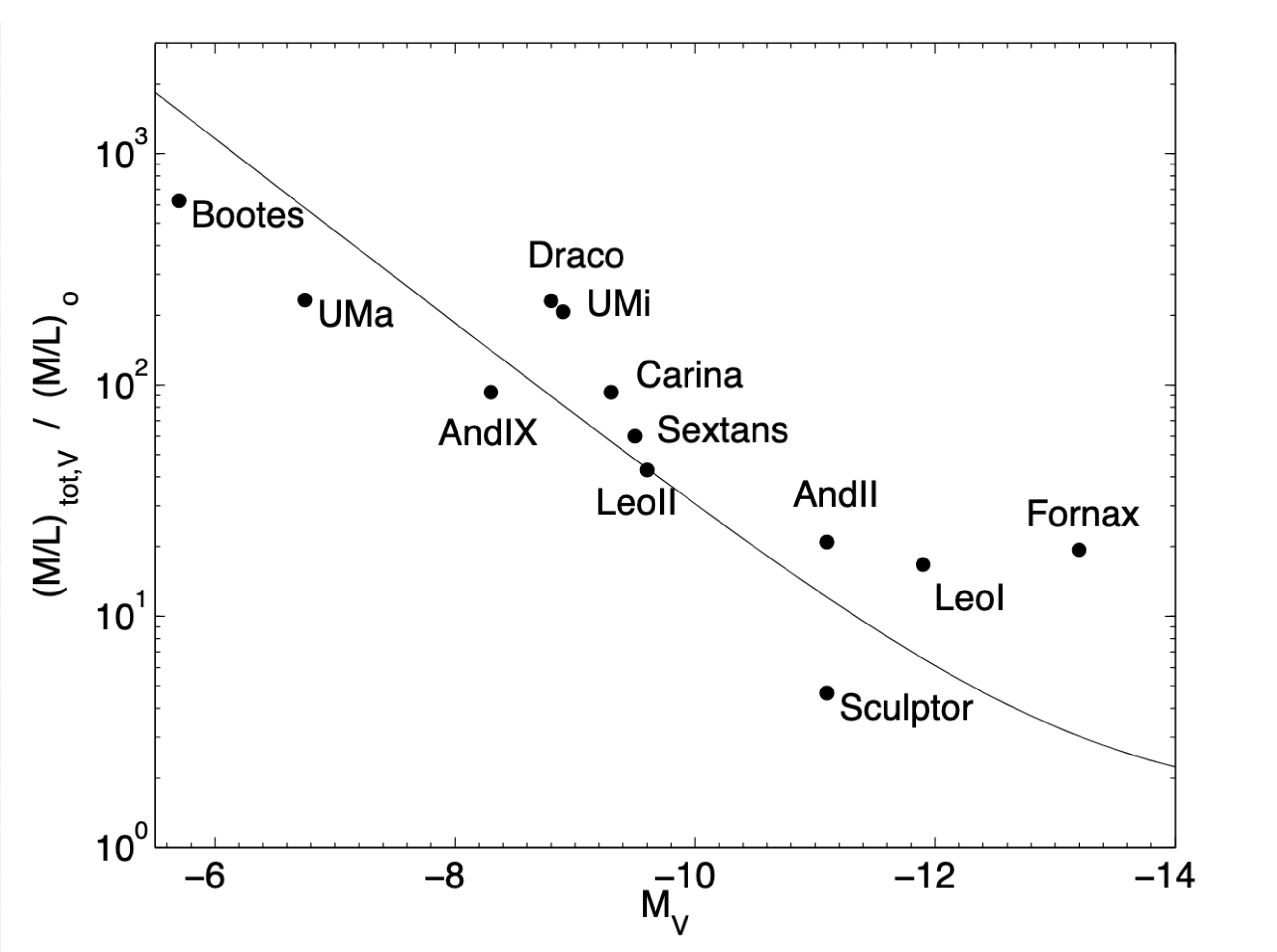


DWARF SPHEROIDAL GALAXIES

- As a **complimentary target to galactic center**, 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.

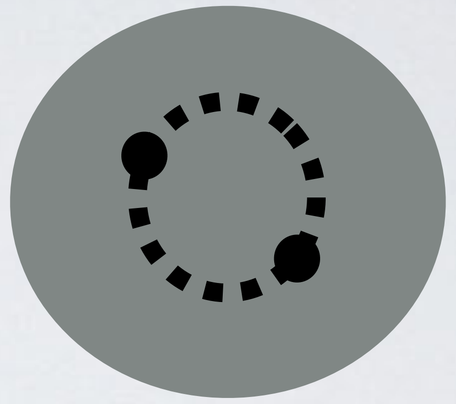


astro-ph/0703308: Gilmore et al.
Mass-to-light vs Magnitude
for several dwarf galaxies

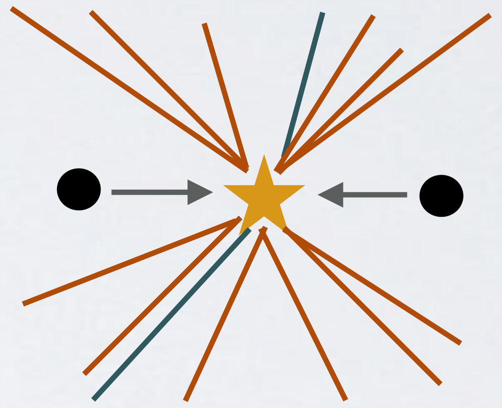


- **WIMPs: 3 separate threats to perturbation theory!**

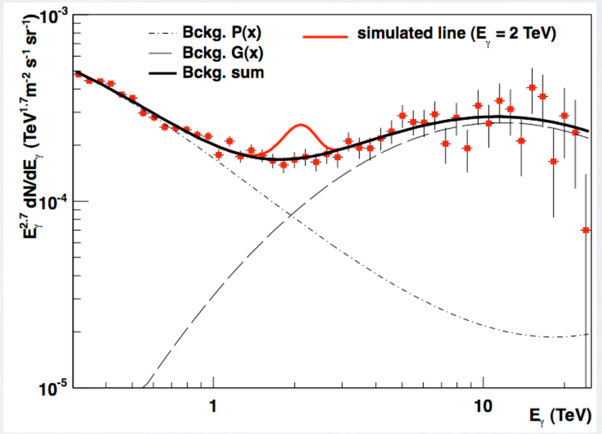
  - $M_\chi/m_W >> 1$ → Long range force (Sommerfeld, Bound States)



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



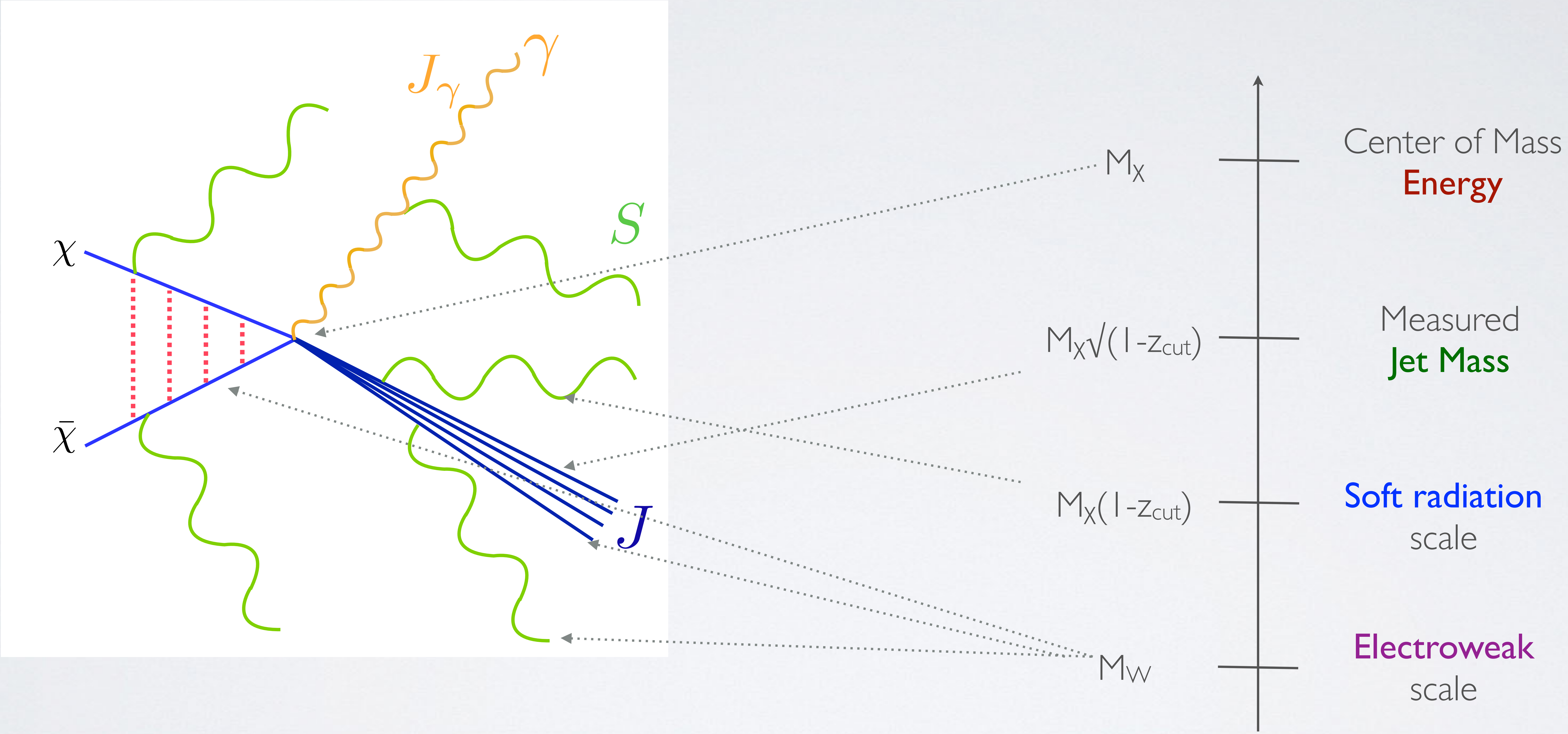
  - $\mathrm{Log}(1\text{-}z_{cut})$ → Detailed shape near M_{WIMP}



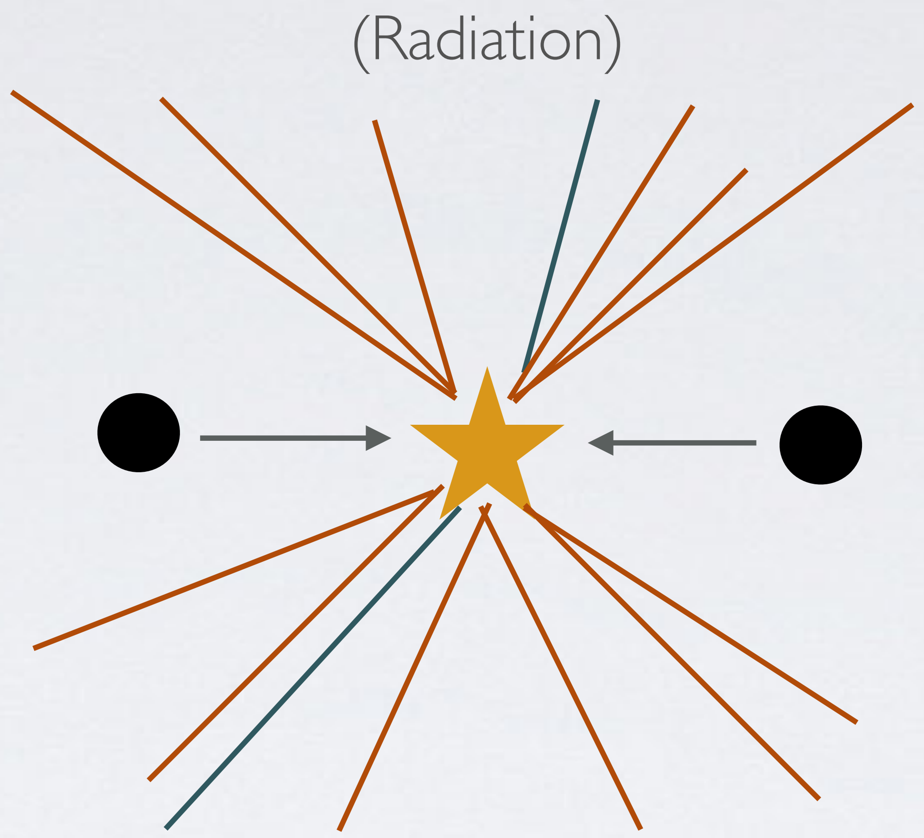
- Proliferation of scales → **Effective Field Theory**

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

EFFECTIVE FIELD THEORY PLAYGROUND



HUGE ACCELERATION → CLASSICAL RADIATION



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

Perturbative factor picks up kinematic enhancements "Sudakov double log"

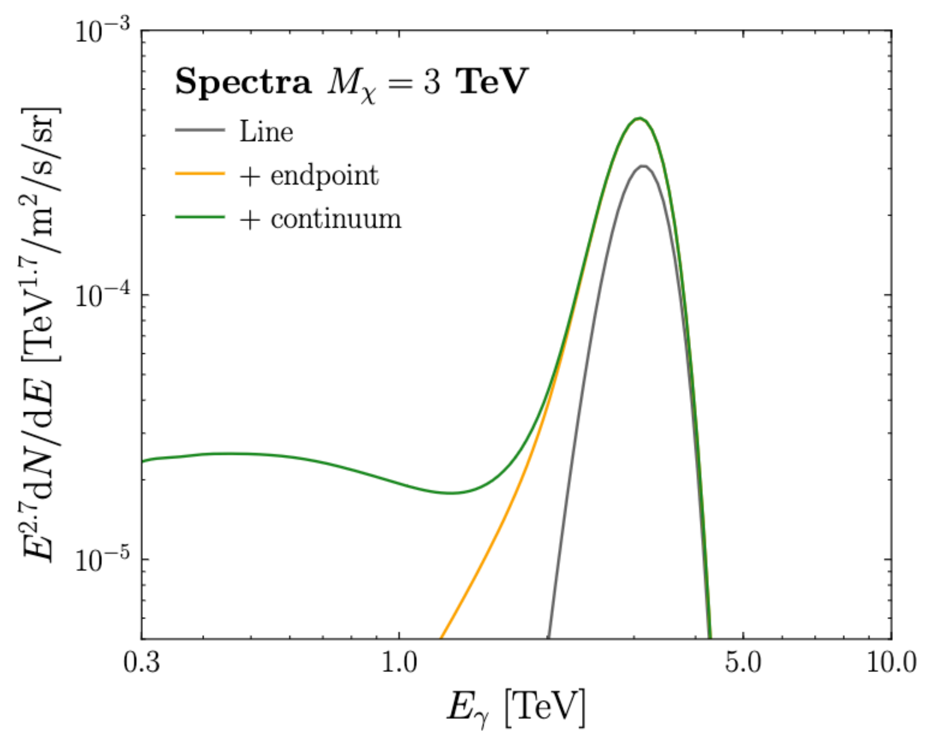
$$\sigma v = \sigma v_0 \exp\left[-\frac{\alpha}{2\pi}\log(E_{\text{high}}/E_{\text{collinear}})\log(E_{\text{high}}/E_{\text{low}})\right]$$

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

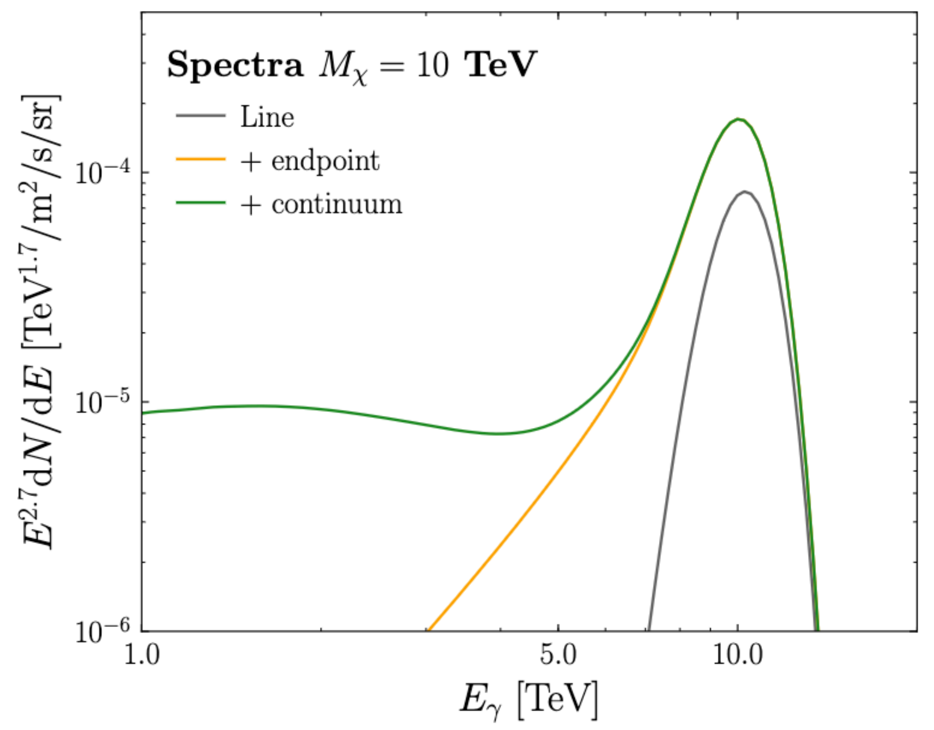
$$\frac{\alpha_W}{\pi}\log(M_{\text{wino}}^2/m_W^2)^2 \approx 0.6$$

Double log
Large correction!

NLL RESUMMED PHOTON SPECTRUM FROM WINO



(a)



(b)

MB et al.: 1712.07656
LL convolved with experimental smearing

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

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

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

UH is NLL ~ α Log generalization of Sudakov factor

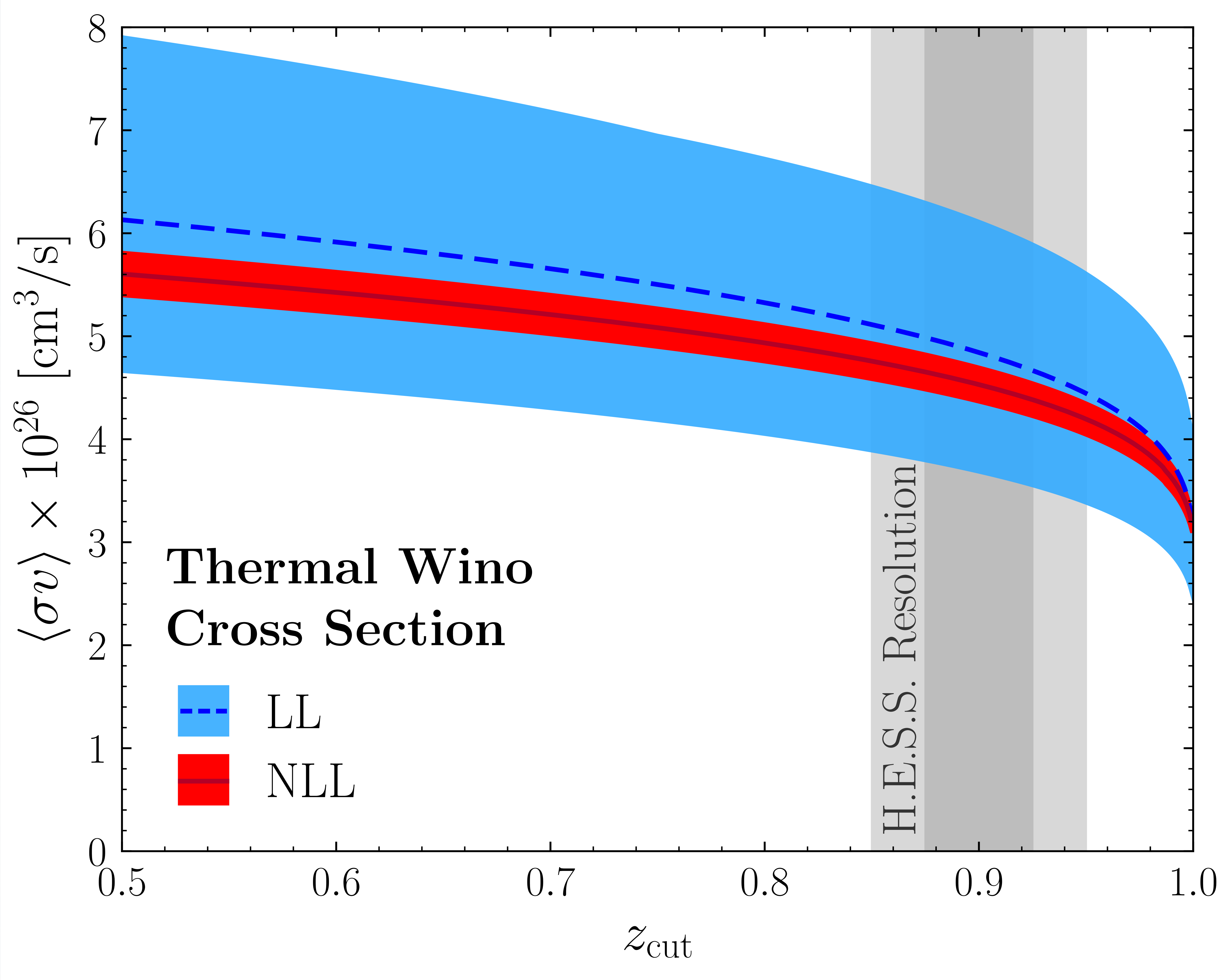
$$z = \frac{E_\gamma}{M_\chi}$$

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

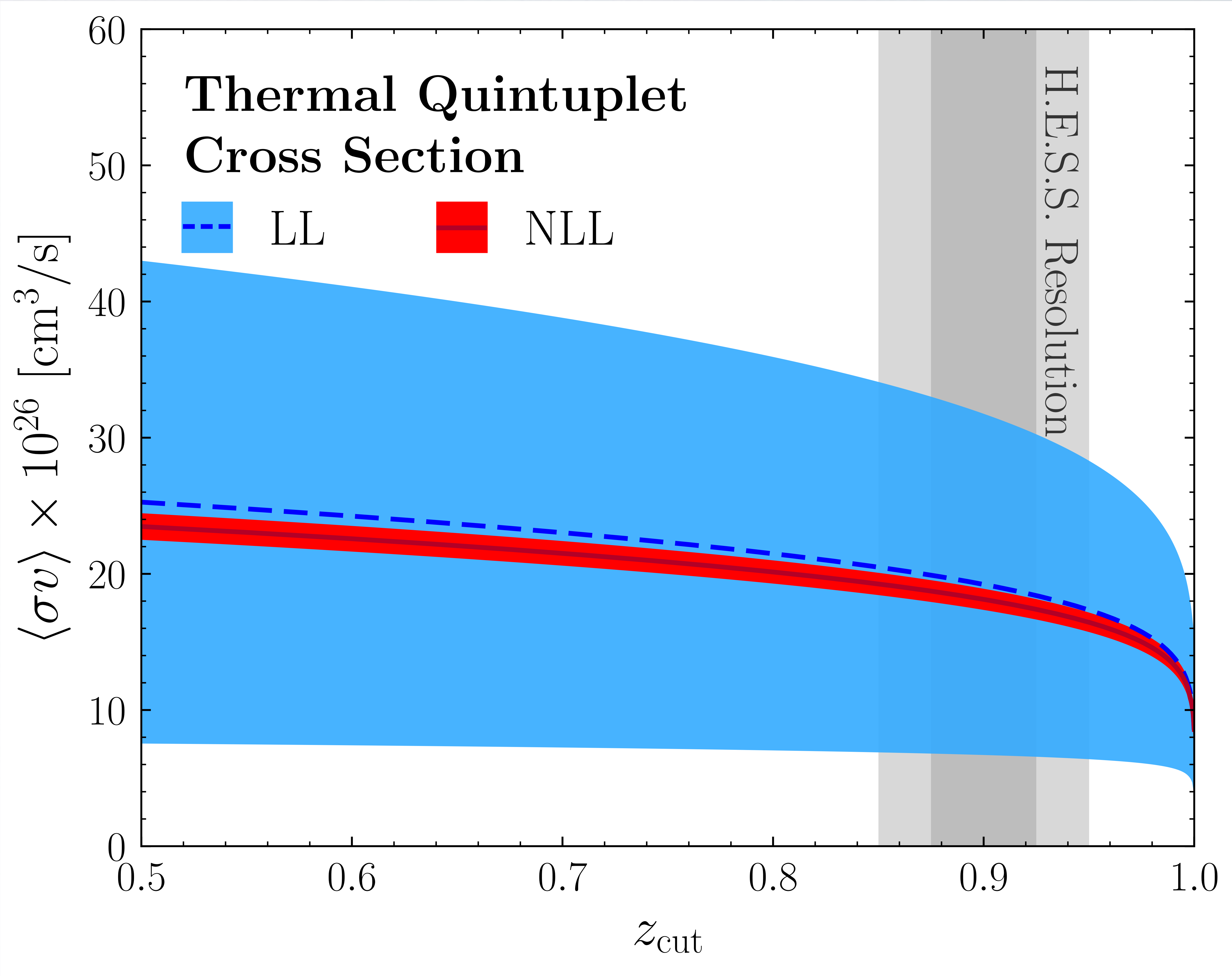
s_{00} and $s_{0\pm}$ are Sommerfeld factors

CUMULATIVE RESUMMED ANNIHILATION RATES
@THERMAL RELIC MASSES



Thermal relic wino rate vs. Energy fraction

MB et al.: 1808.08956



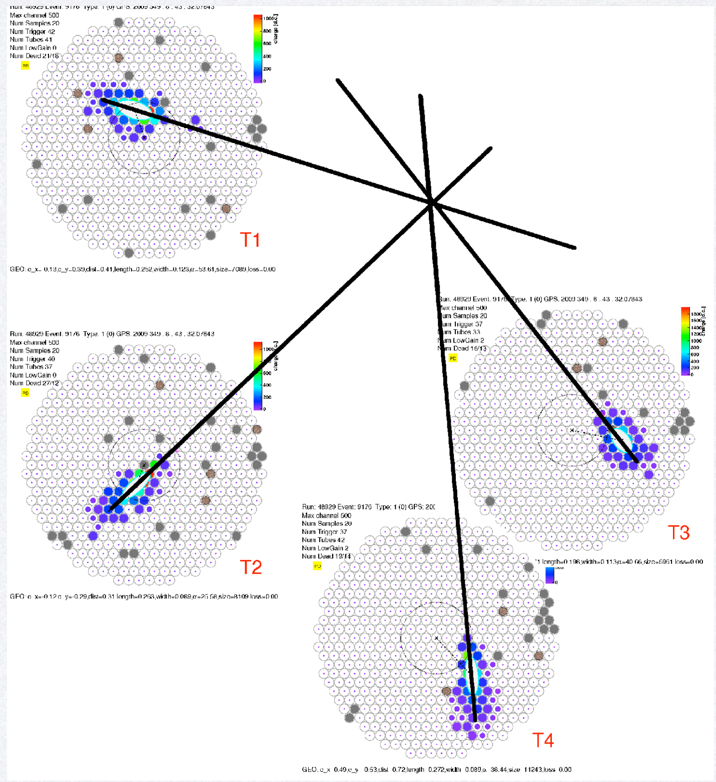
Thermal relic quintuplet rate vs. Energy fraction

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

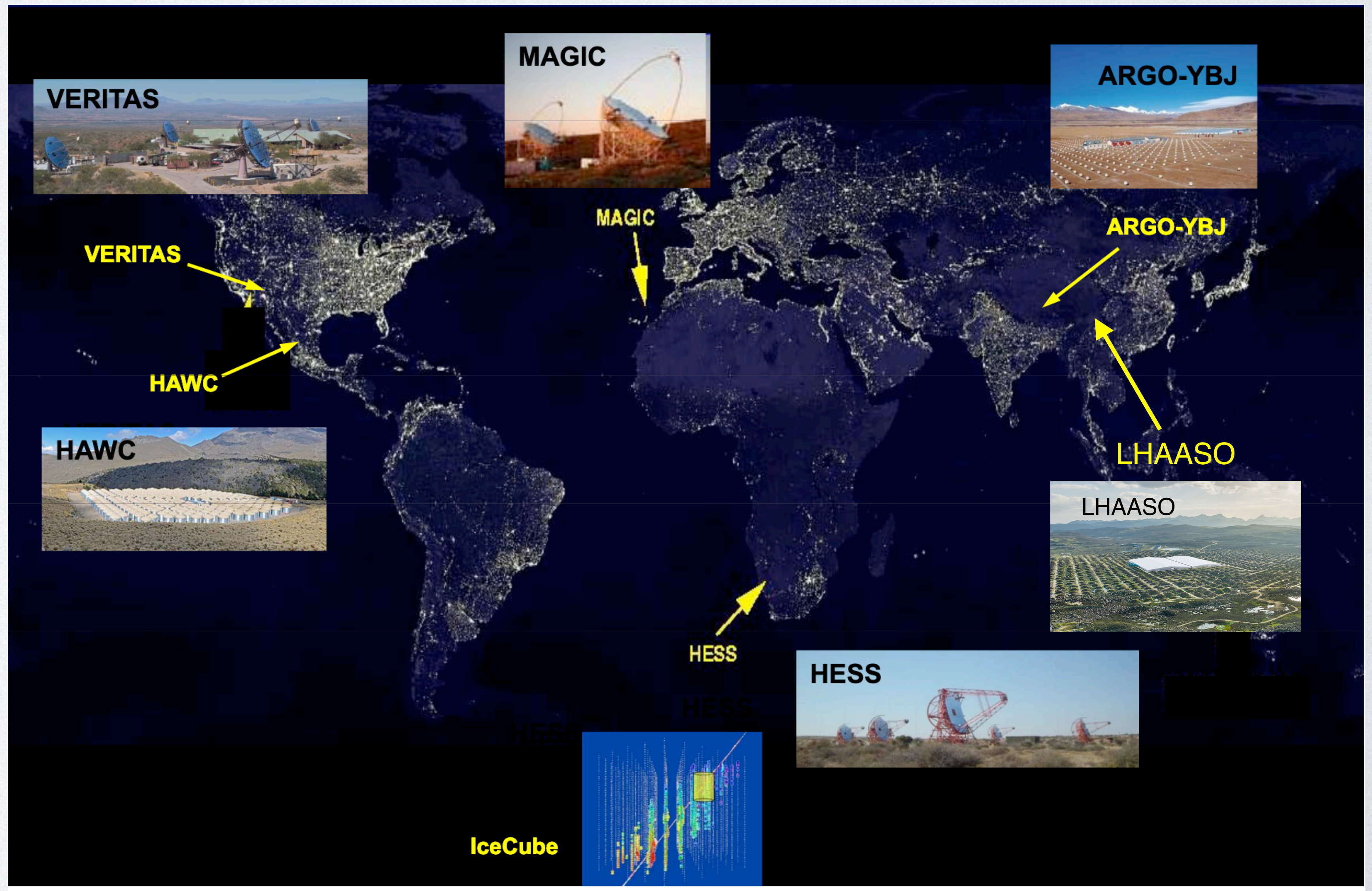
VERITAS OBSERVATORY

- There are **4 operating "Imaging Air-Cherenkov Telescopes" in the world today** (HESS, MAGIC, VERITAS, CTAO North)
- **VERITAS** is located outside **Green Valley, AZ**
- 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

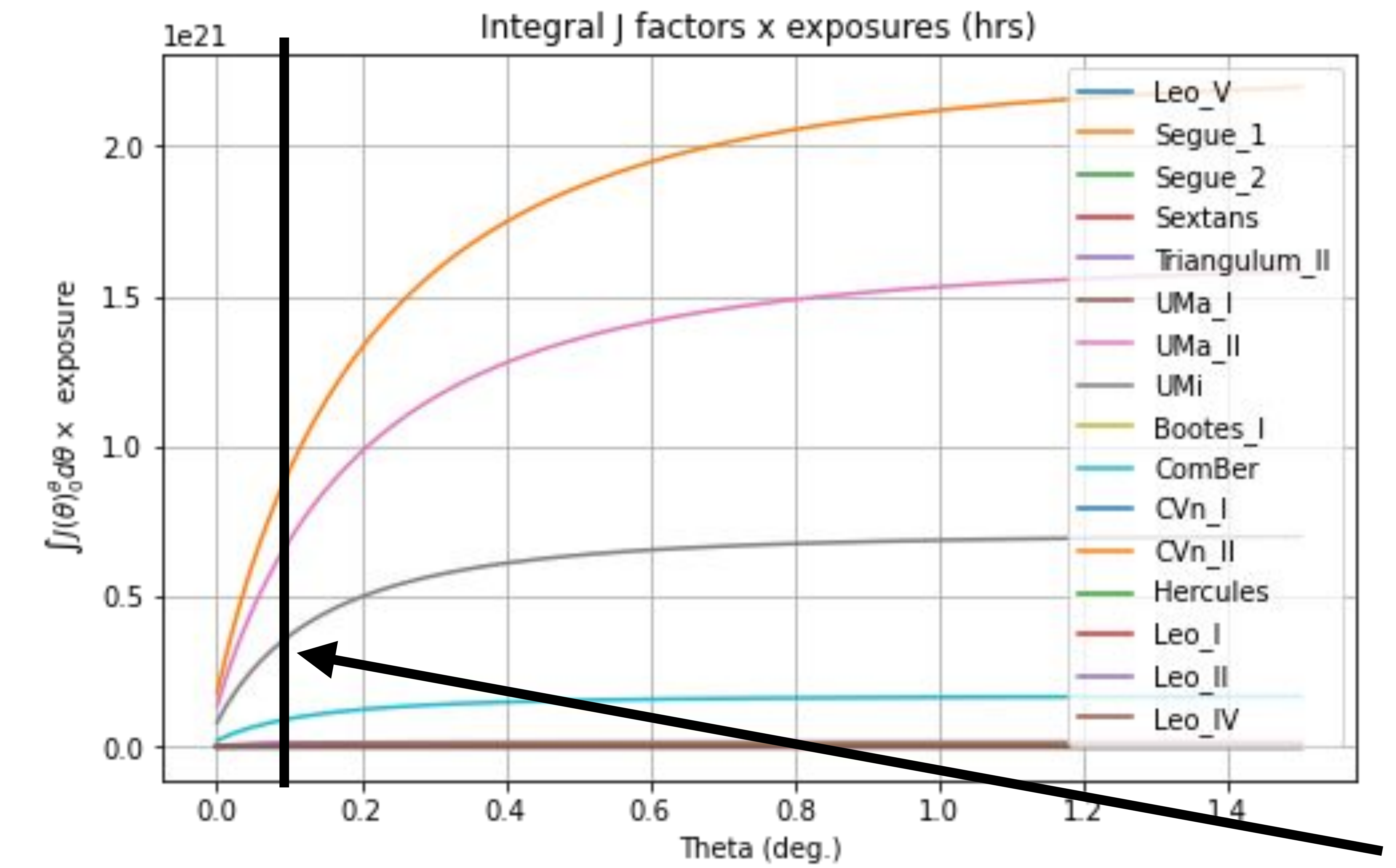
Nestled in the Santa Rita mountains 3 hours from my house



VERITAS event



DWARF SPHEROIDAL SEARCH



From C. McGrath
VERITAS Summer 2023 Meeting

Ando (2020) J-factors

Likelihood method

From D. Tak
TeVPA 2023

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

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

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

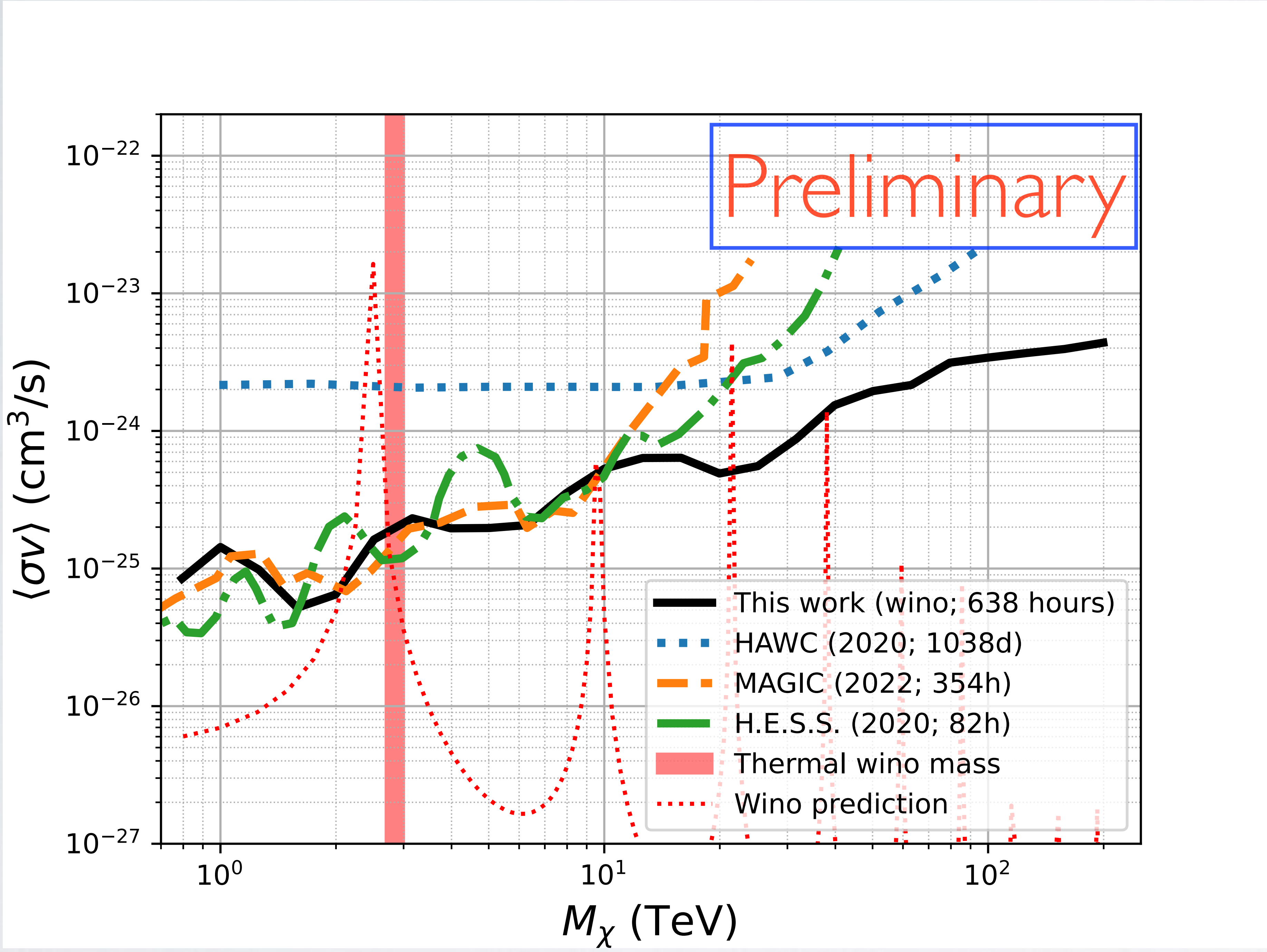
$$S = \int dE\, dE' d\Omega \frac{d\Phi_\gamma(E, \langle\sigma v\rangle)}{dE_\gamma} \times R(E, E', \Omega) \qquad \frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{4\pi} \frac{<\sigma v>}{\delta m_\chi^2} \frac{dN_\gamma}{dE_\gamma} \int\int \rho^2 ds d\Omega$$

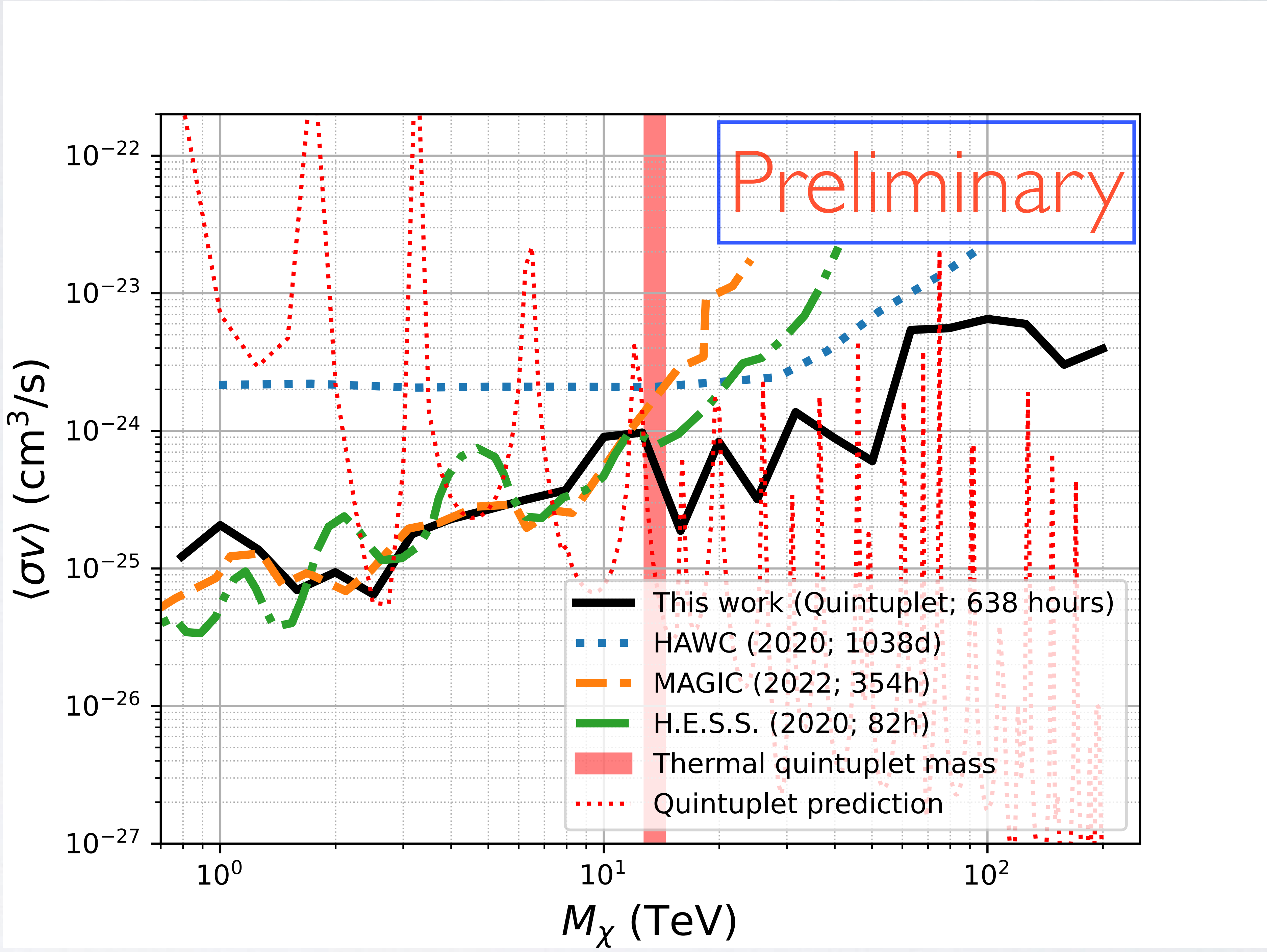
B: the expected background
α: a relative exposure time between on and off regions.

Typical Analysis Limit ~ 0.1°

Isotropic background from OFF region

VERITAS dSphs LIMITS





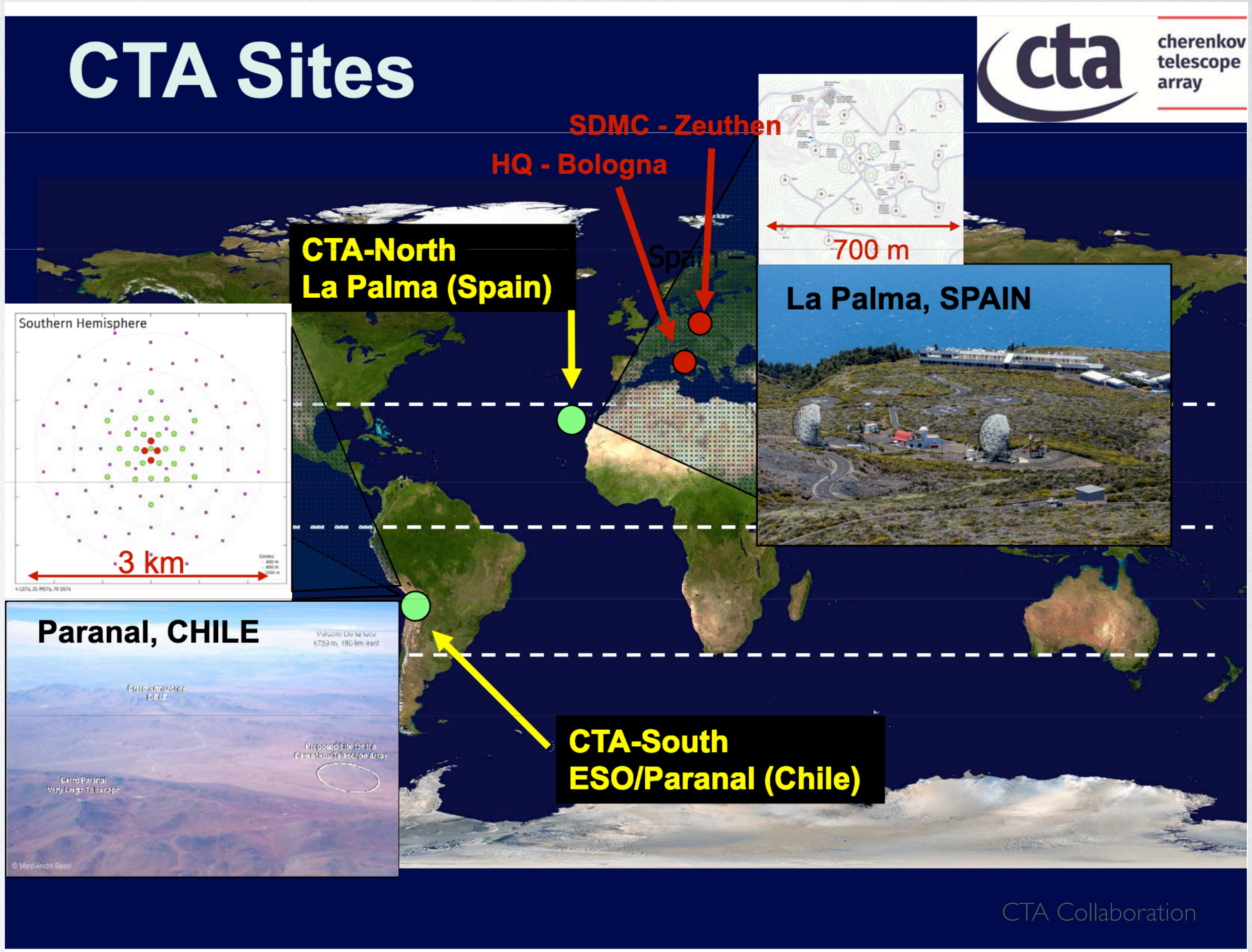
- Comparable limit to MAGIC (2022), HESS(2020) which used older, more aggressive J-factors
- Uncertainty dominated by J-factors
- The wino is cornered.
- Limits become **much stronger than MAGIC/HESS ≳ 10 TeV.** Our calculation includes continuum photons from signal.

Paper under VERITAS internal review

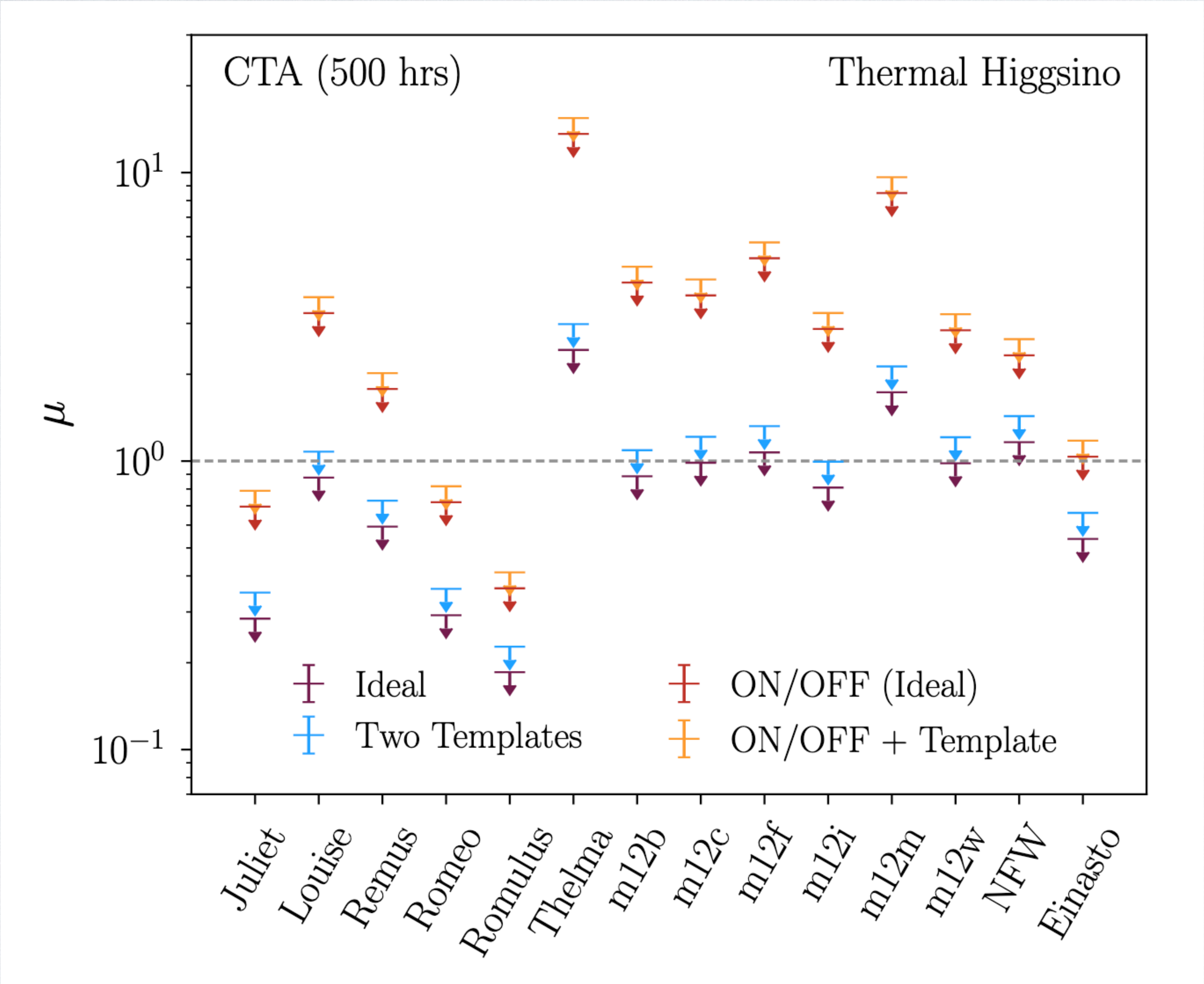
MB, **O. Calcerano**, C. McGrath, E. Pueschel, J. Quinn, & D. Tak

CHERENKOV TELESCOPE ARRAY (CTAO)

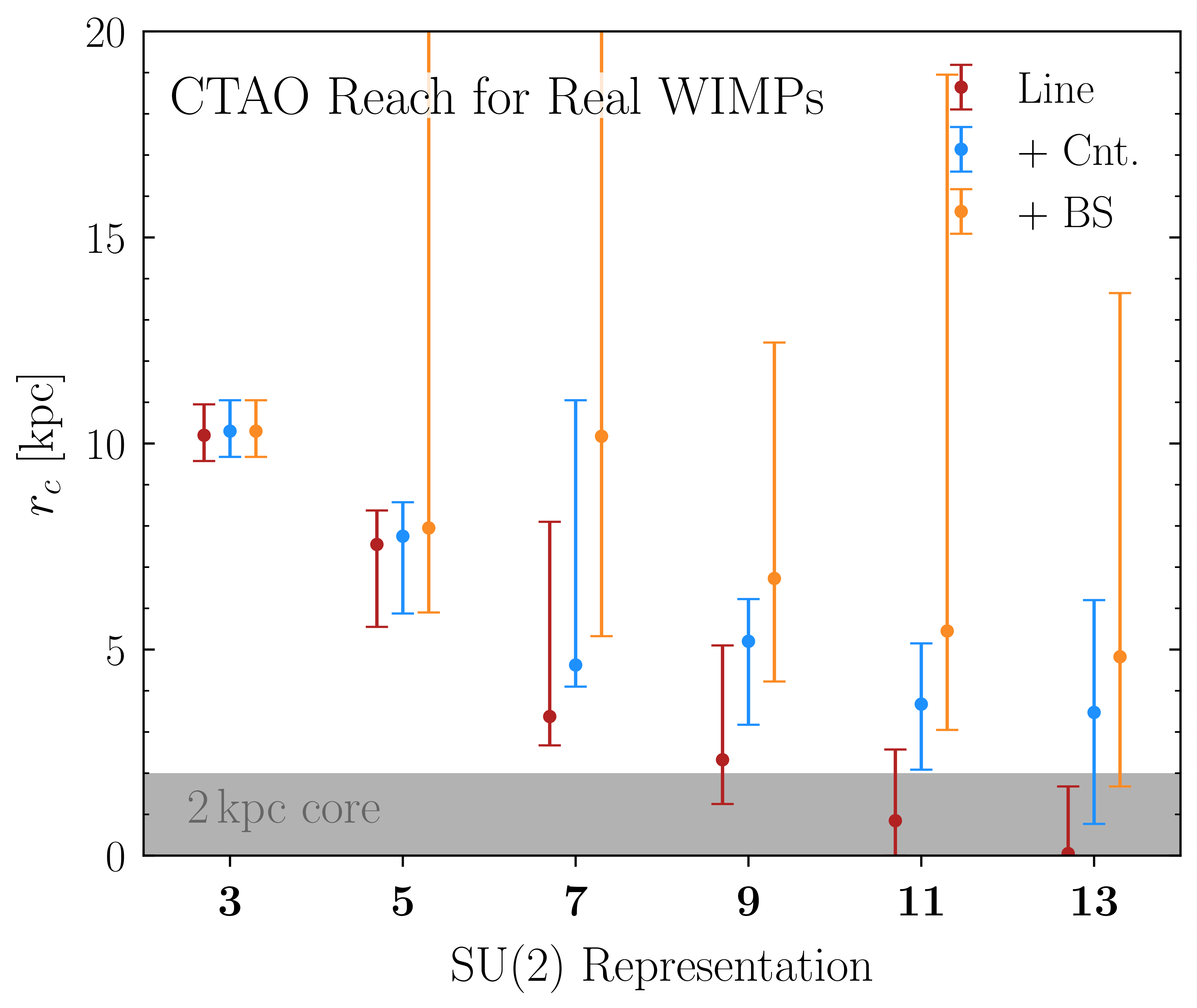
- The **next-generation** imaging air-cherenkov telescope, **CTAO**, is **under construction (and partially running!)** in Spain (19 detectors) & Chile (100+ detectors)
- 10x the effective area and sensitivity of the current IACTs
- **Will confirm or demolish the electroweak WIMP hypothesis**.
- Full operation in 2030s.



PROJECTED CTAO GALACTIC CENTER LIMITS



2405.13104: N. Rodd, B. Safdi, W. Xu

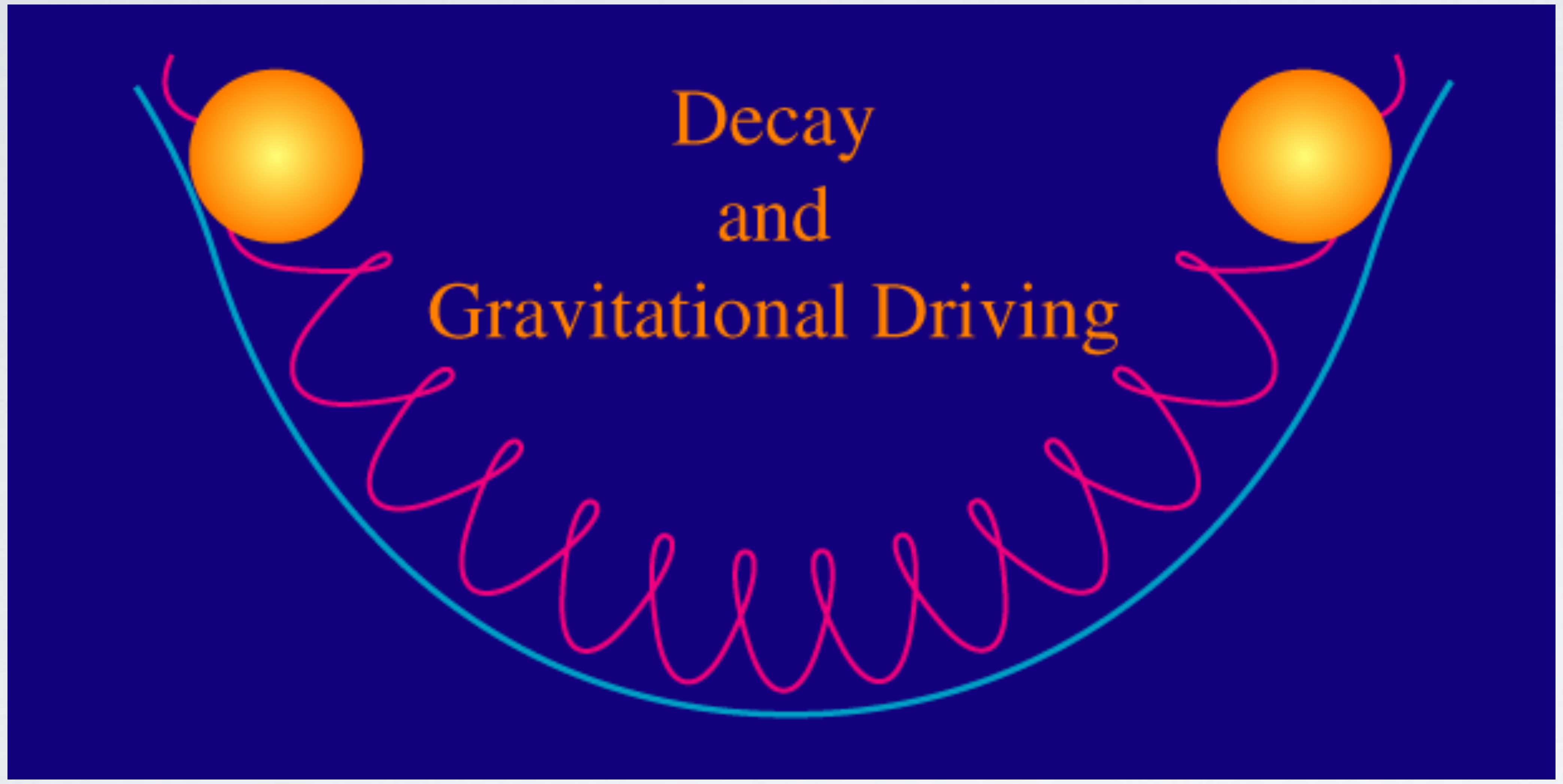


2507.15937: MB, S. Bottaro, D. Redigolo, N. Rodd, T. Statyer

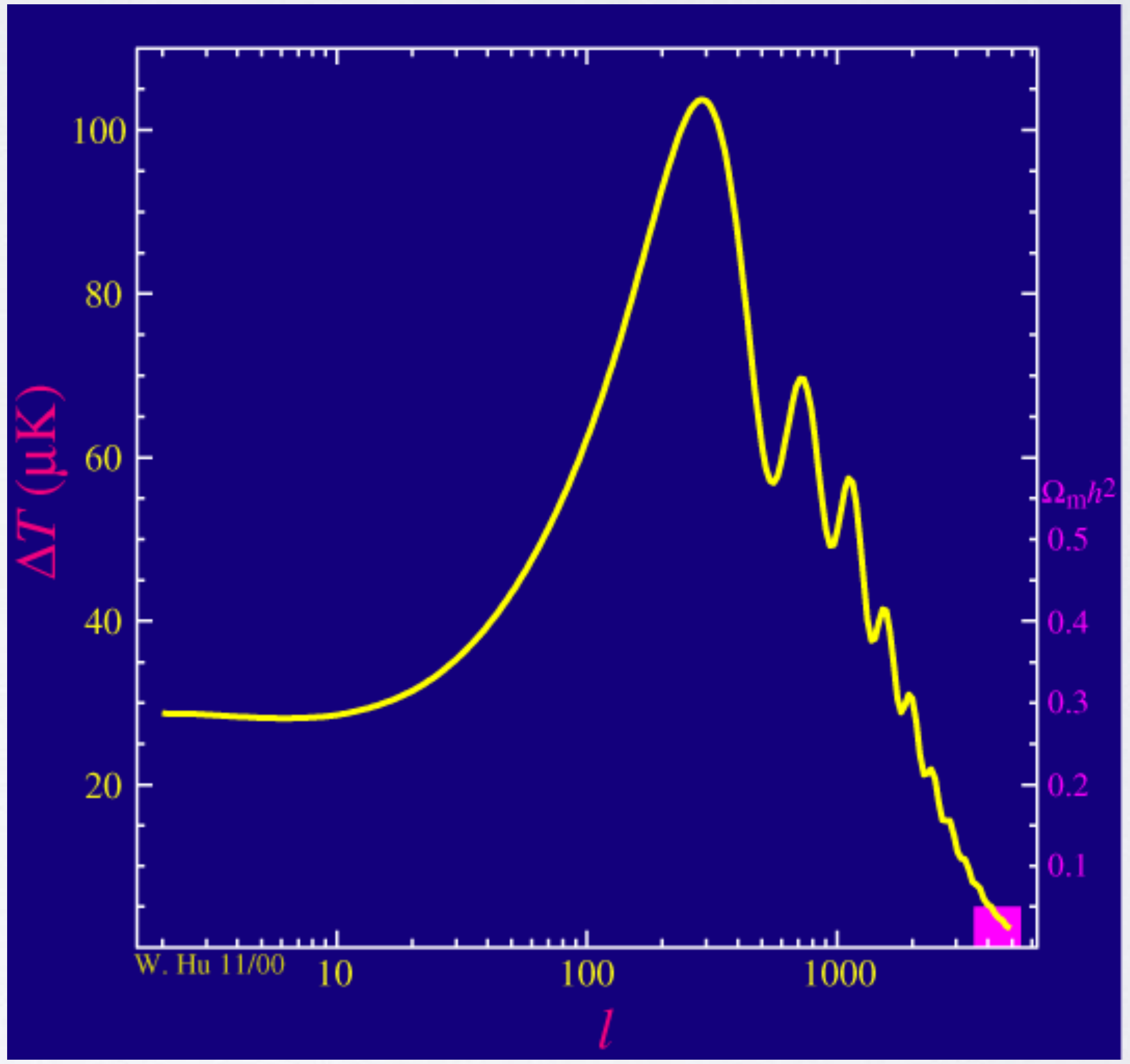
UP NEXT

- The simplest models of WIMP Dark Matter are all alive, but will be hunted down in he next decade. We will soon know if Nature realized its simplest option for Dark Matter. Complete EFT analysis of complex representations.
- Complete VERITAS dSphs search for wino and quintuplet signals for limits independent of Milky Way halo modeling. Already competitive. Combine all dSphs data à la Glory Duck?
- Take more data (VERITAS running until 2028), e.g. Ursa Major III, new competitive dSph with 100x the J-factor of current targets (2311.14611: M. Crnogorcevic & T. Linden).
- Representations larger than 3 incompatible with string theory? (2412.13192 MB, P. Christeas, J. Heckman, R. Hicks).
- Beyond WIMPs, what's our next move with Dark Matter?
  - Geometric cross sections at high mass, really? (Lattice & Schrödinger calculations: B. Assi, MB, D. Stolarski, M. Wagman)
  - How to realize UHDM with complex structure as thermal or nonthermal relic?

DARK MATTER ABUNDANCE



High-l fluctuations show radiation-to-matter transition

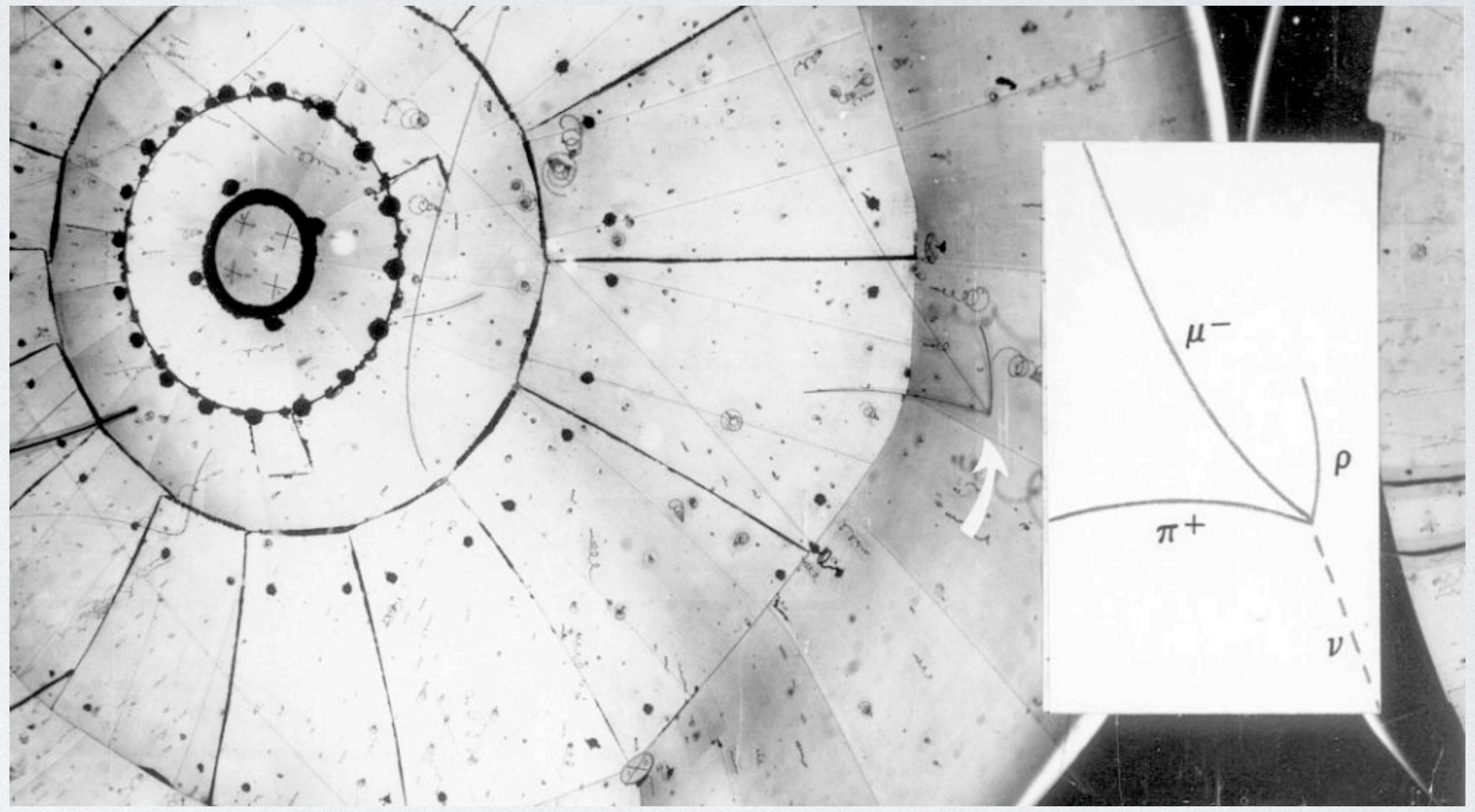


Cosmic Microwave Background:
Fluctuations measure Dark Matter as 27% of Universe's energy (Planck)

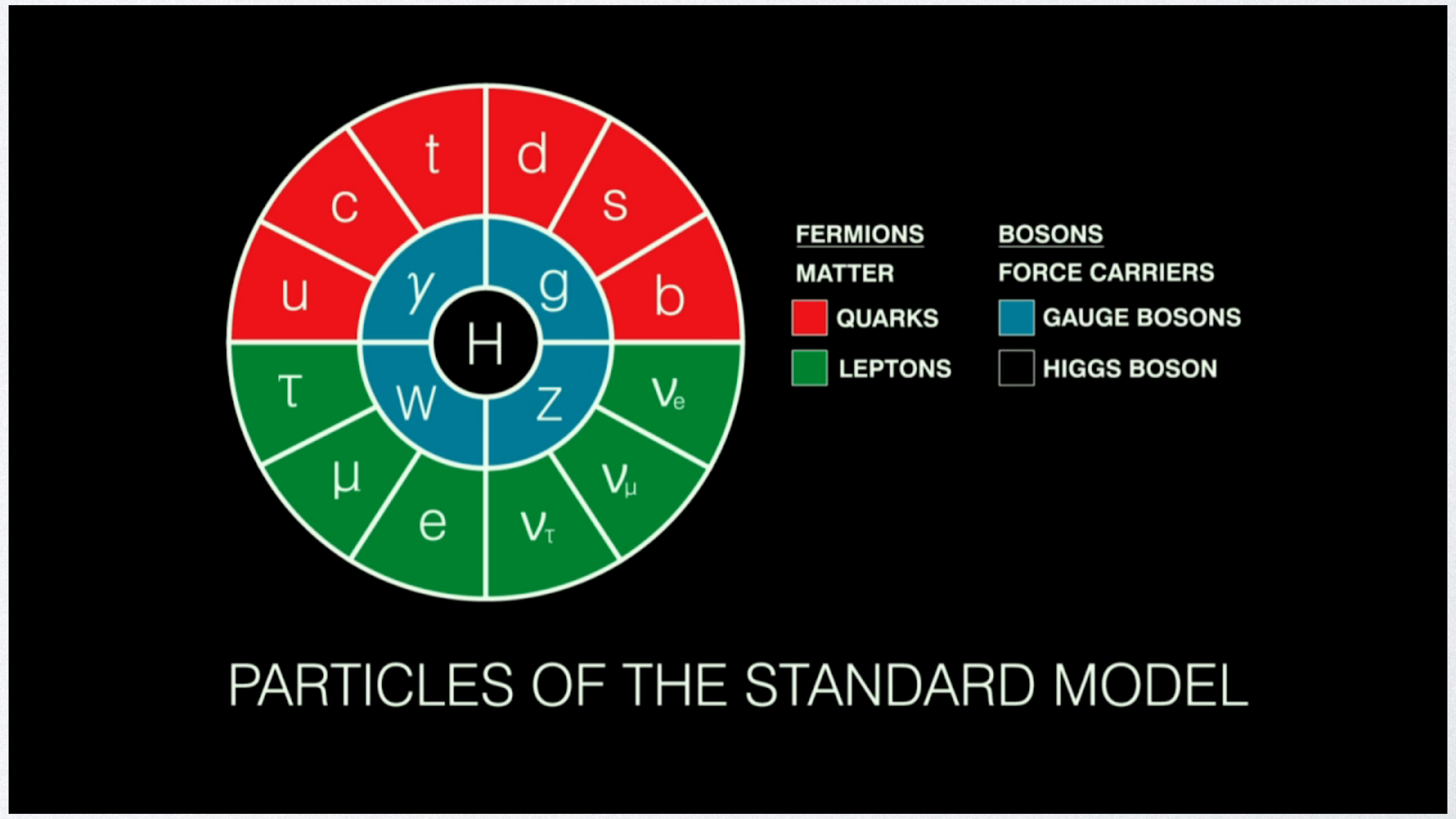
Animations from W. Hu

NEUTRINOS, THE ORIGINAL DARK MATTER

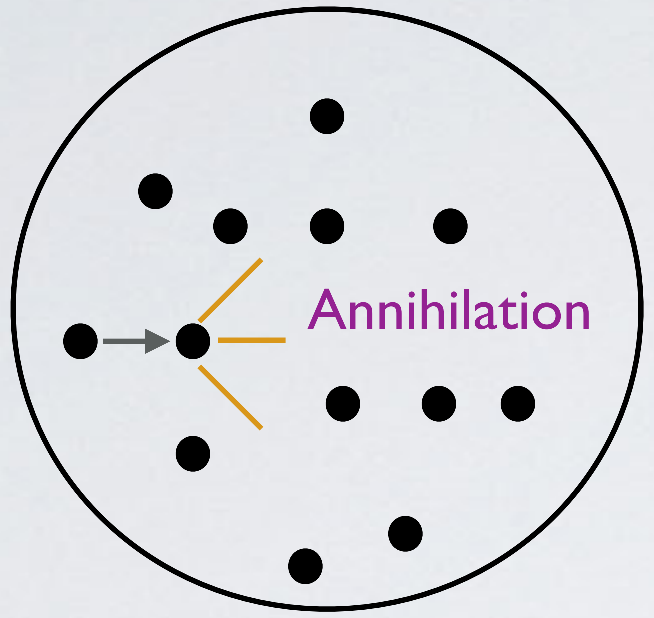
- At the Earth's surface, **neutrino flux is 65 billion (6.5×10^{10}) per second per cm^2!**
- Electrically neutral, nearly (but not exactly!) massless.
- Presently ~**10^{-3} of the Universe's energy density**.
- Originally explained energy non-conservation in nuclear beta decays:
  $n \rightarrow p + e + \nu_e$.
- Now a fundamental part of **Standard Model** along with quarks, charged leptons, Higgs, and SU(3)xSU(2)xU(1) gauge bosons



Circa 1970: Neutrino event in bubble Chamber

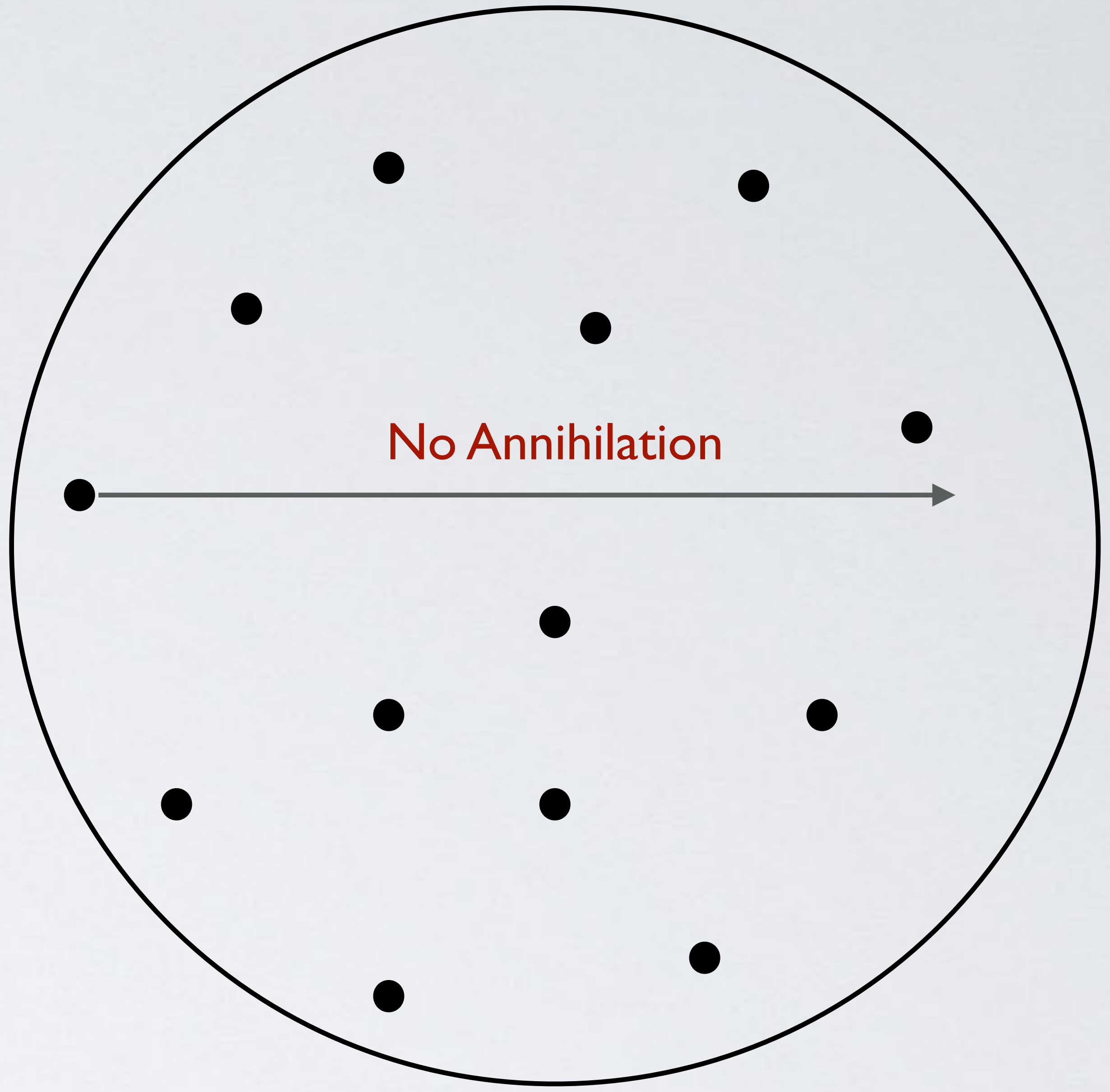


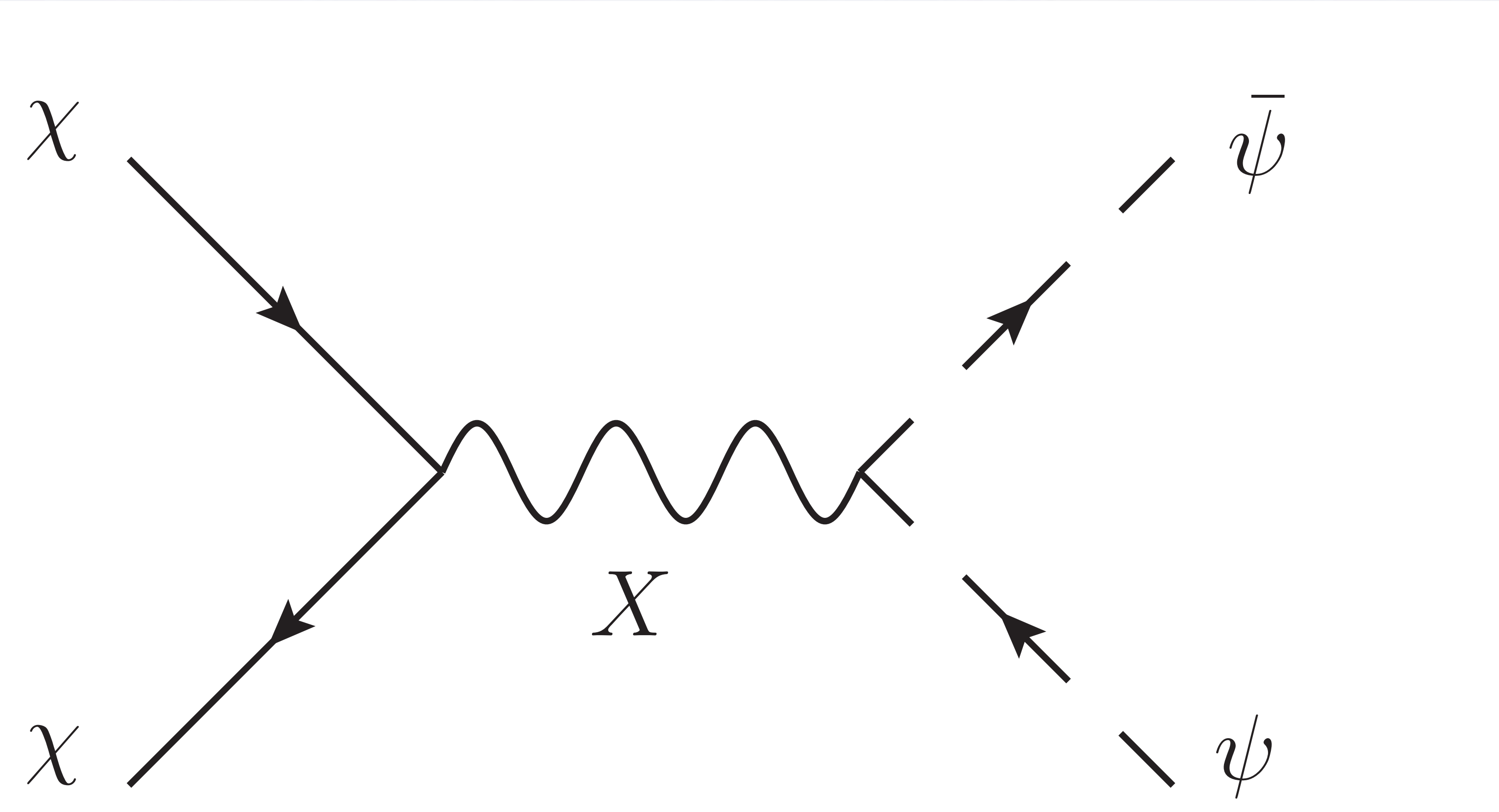
WHY WIMPs?



Cosmic Expansion

DM density decreases:
Annihilation & expansion

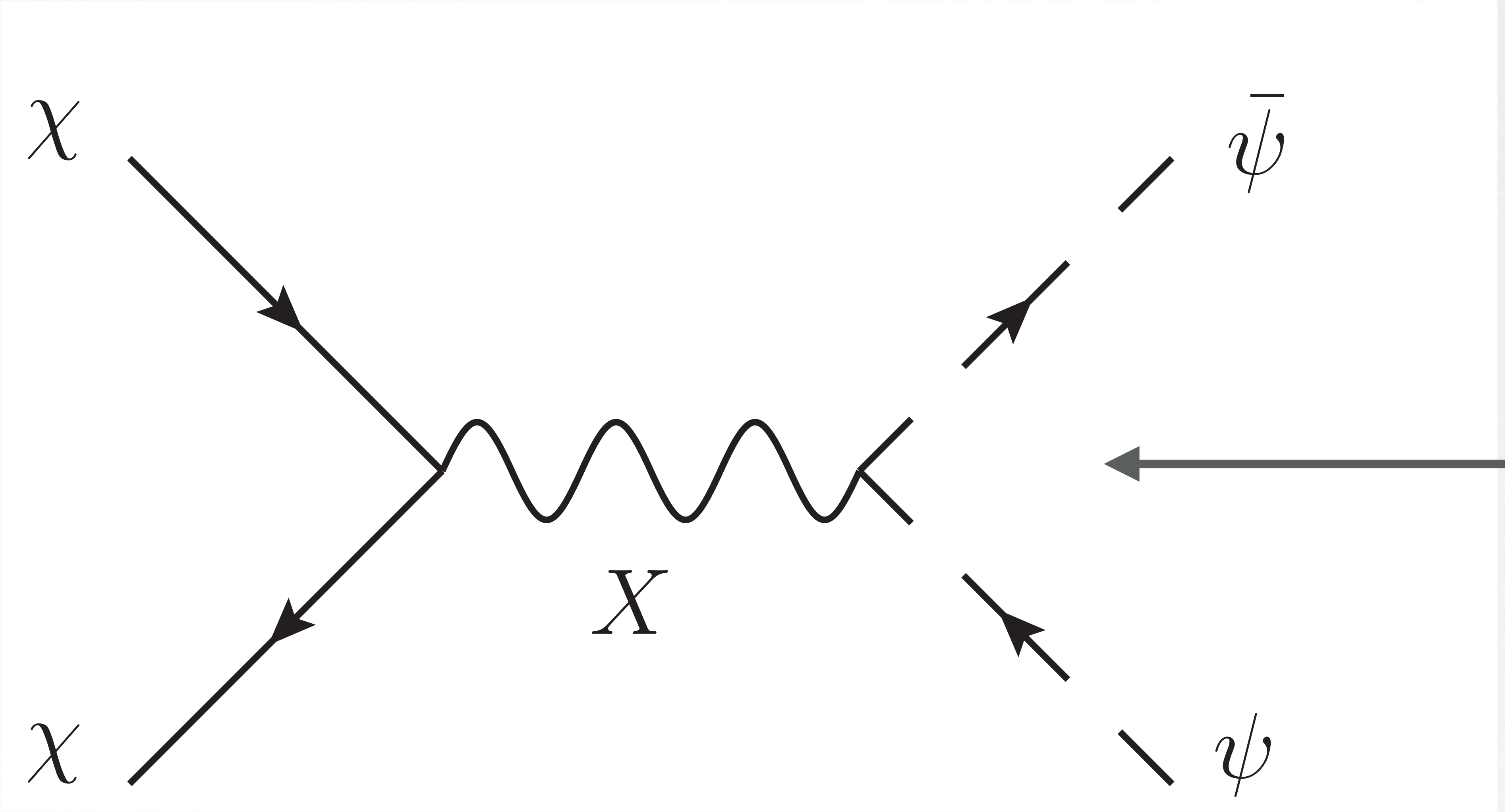




$<\sigma v>_{annihilation} \sim C\,\alpha^2/M_\chi^2$

WIMP: Weakly-Interacting Massive Particle

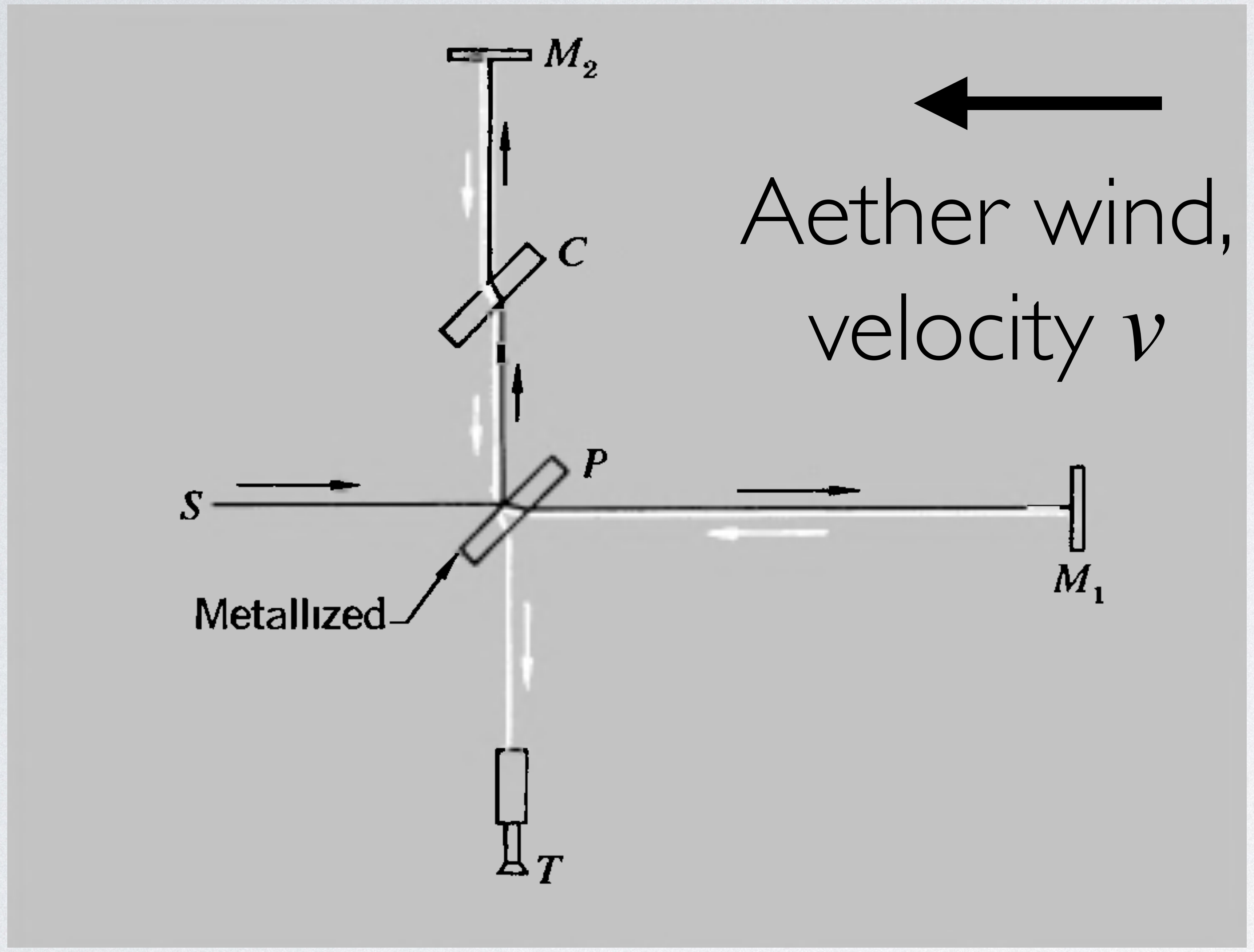
STARTING SIMPLE W/ WIMPs



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

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

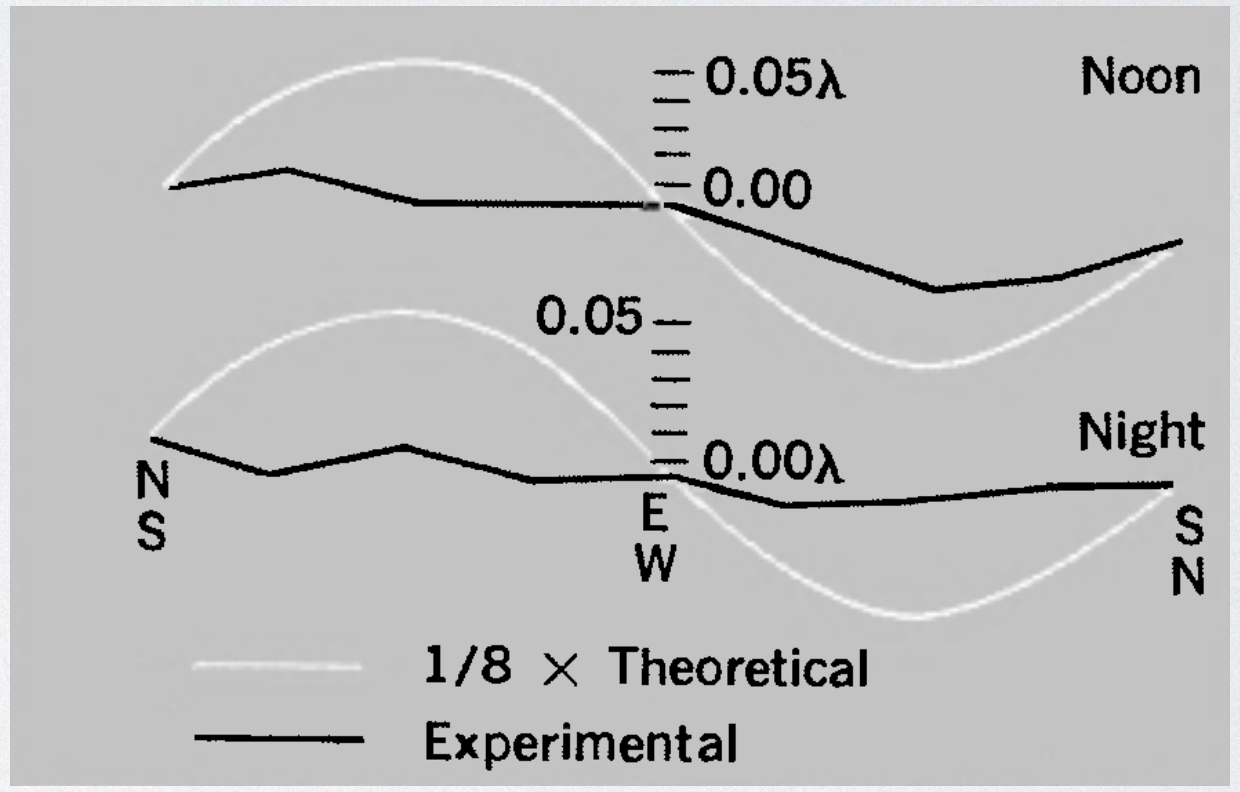
MICHELSON-MORLEY EXPERIMENT



19th Century Physicists thought light waves propagated in a medium, the *luminiferous aether*.

Shift in interference fringes:

$$\delta = \frac{2(v/c)^2}{\lambda/l}$$



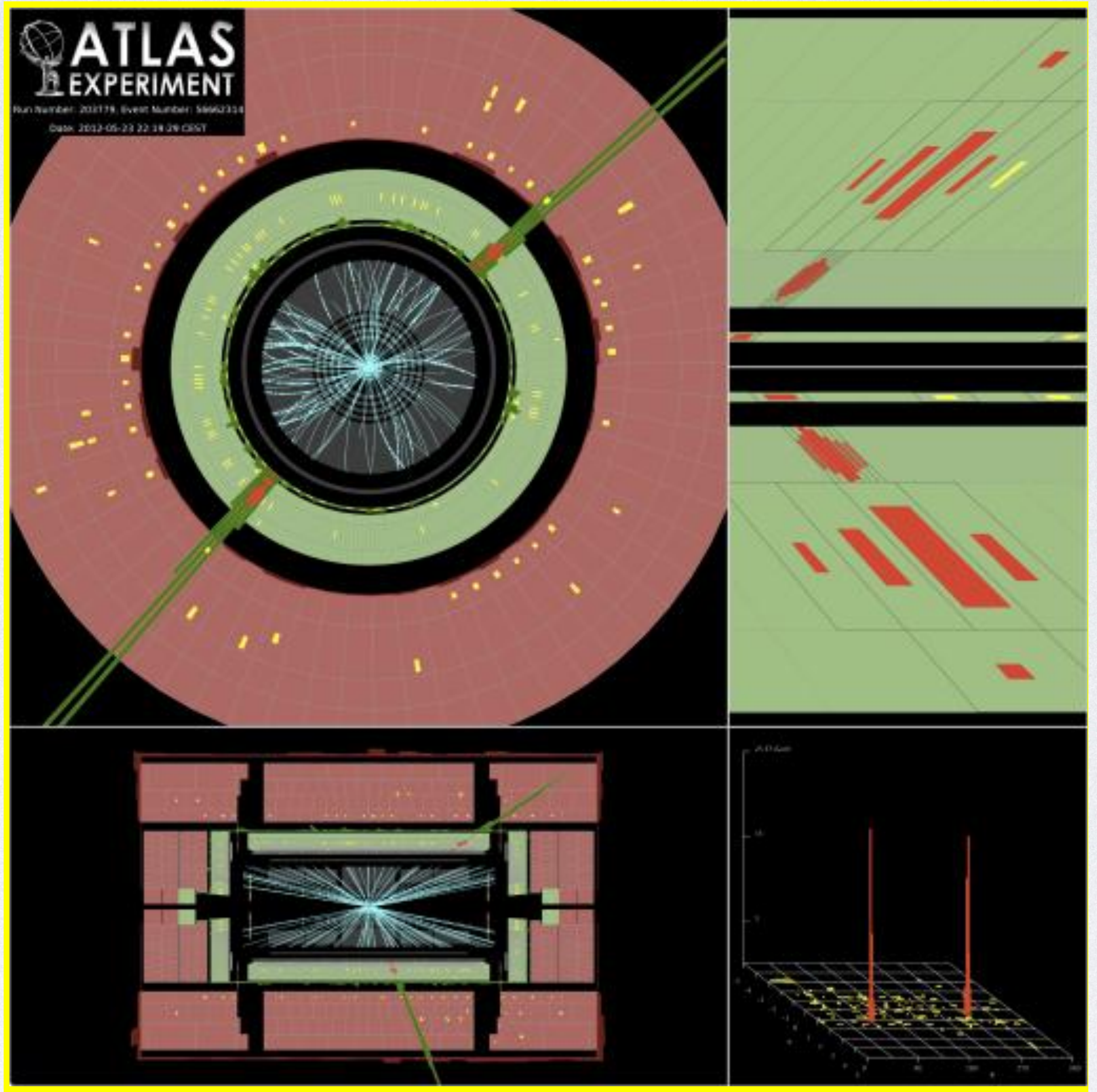
"The result of the hypothesis of a stationary ether is thus shown to be incorrect."
-A.A. Michelson (1881)

- **But, there is no aether**
- **speed of light the same in all reference frames**
- **special relativity!**

Figures from A.P. French, *Special Relativity*

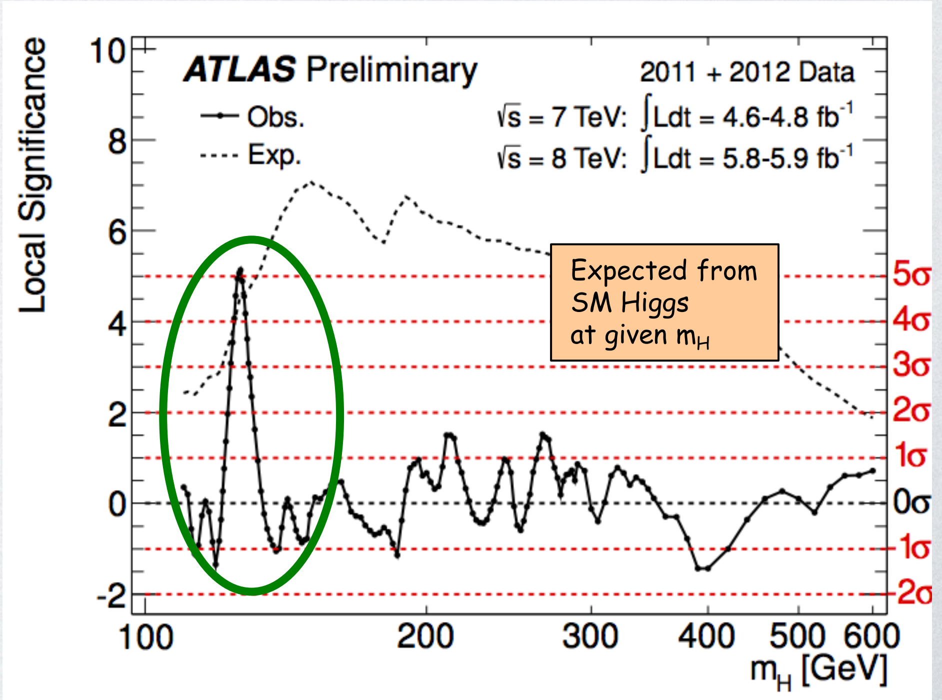
HIGGS@LHC: NO-LOSE SCENARIO

- Before the LHC, particle physics had a no-lose scenario.
- 1: Find a Standard Model-like Higgs, first new elementary particle in over decade, understand electroweak symmetry breaking (exciting!)
- 2: Find even more exotic weak-scale physics (low-scale supersymmetry, technicolor, composite Higgs, Higgs triplet, composite W bosons, violate quantum mechanics…)
- Nature chose Option 1. **We are in same position right now with WIMP dark matter…**



h→γγ event at ATLAS

Higgs Boson discovery in 2012 at 125 GeV



Figures from F. Gianotti 2012 ATLAS Higgs discovery talk

INDIRECT DETECTION TARGETS

- Can attempt indirect detection with many probes (**photons**, neutrinos, electrons, light nuclei).
- Primary **photons offer near-straight-line propagation** from origin.
- Point telescope to region with high concentration of dark matter, like **Milky Way Galactic Center**.
- Galactic Center Challenges
  - **Nontrivial astrophysical backgrounds**
  - **2 order of magnitude Dark Matter profile uncertainty** (inner 1 kpc very baryon-dominated)

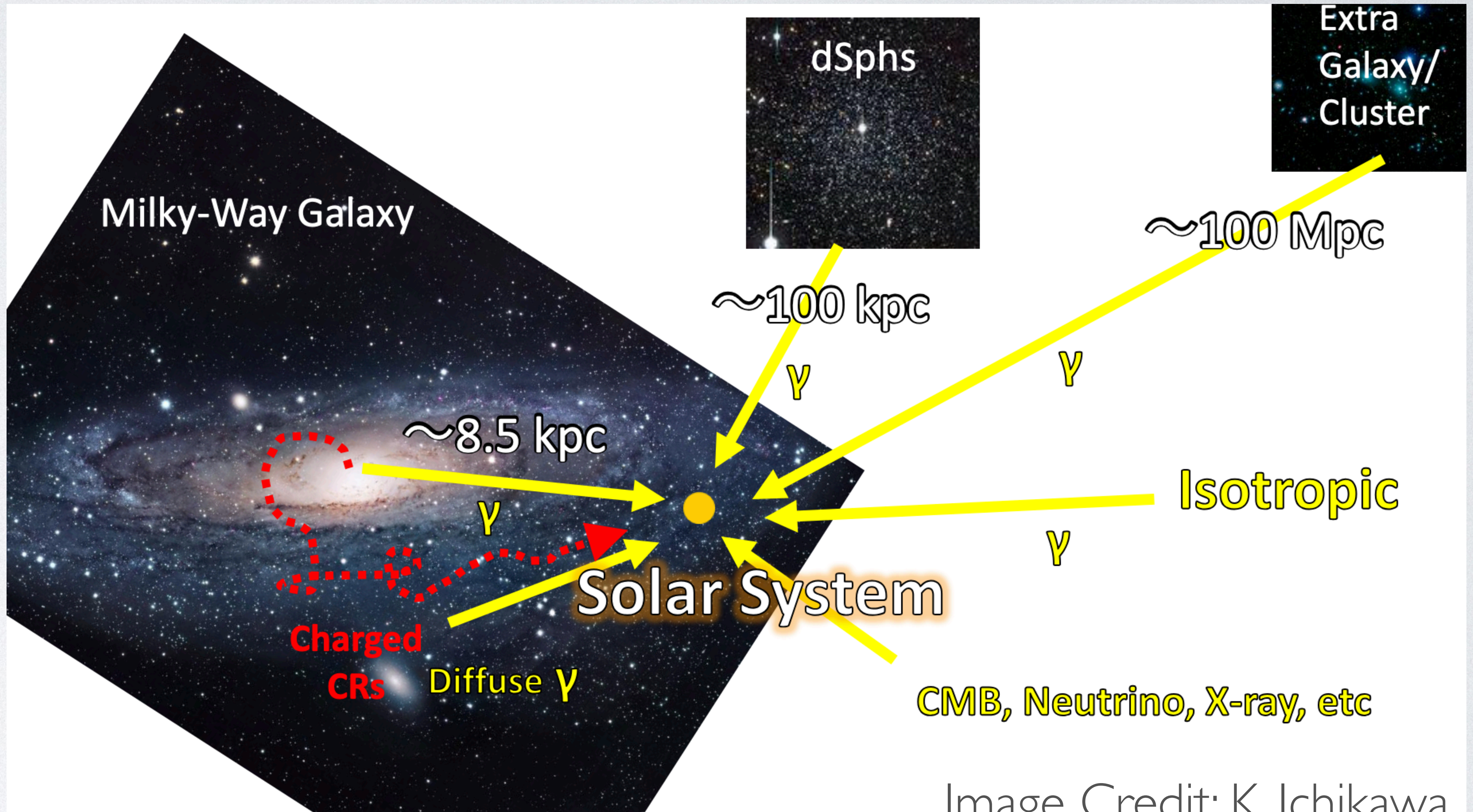
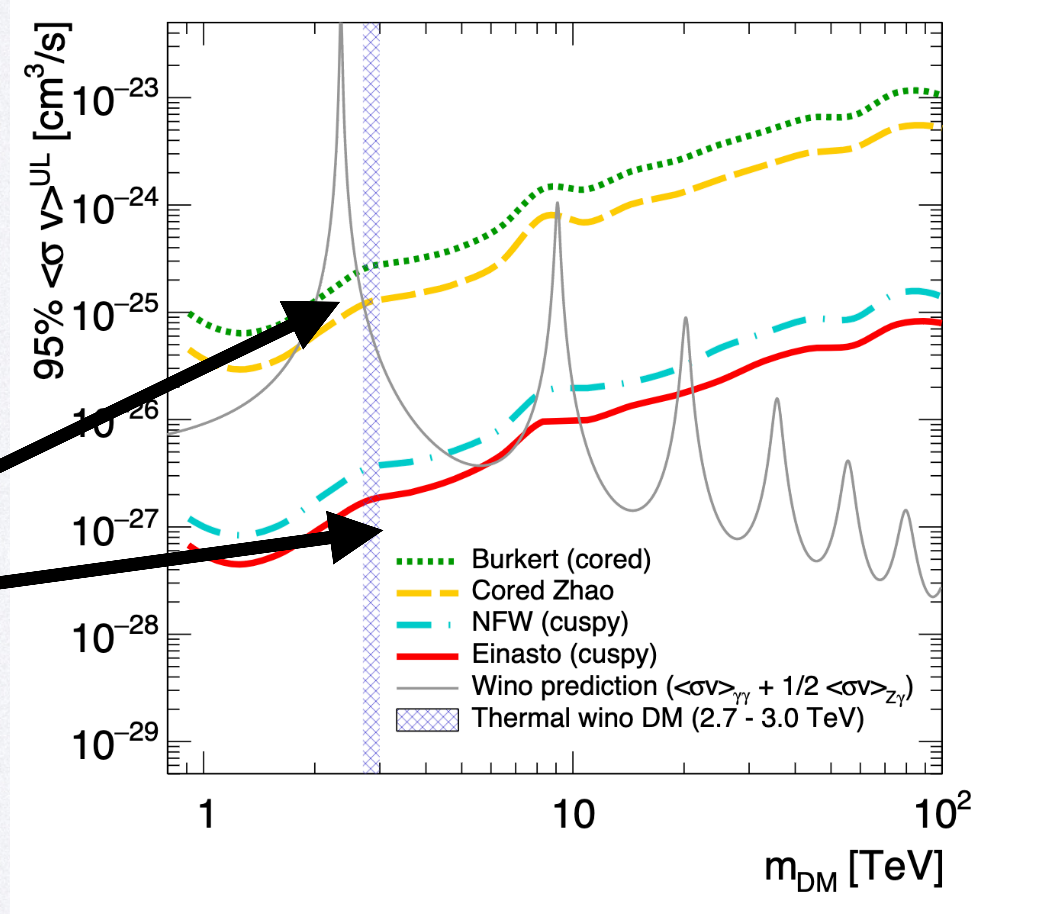


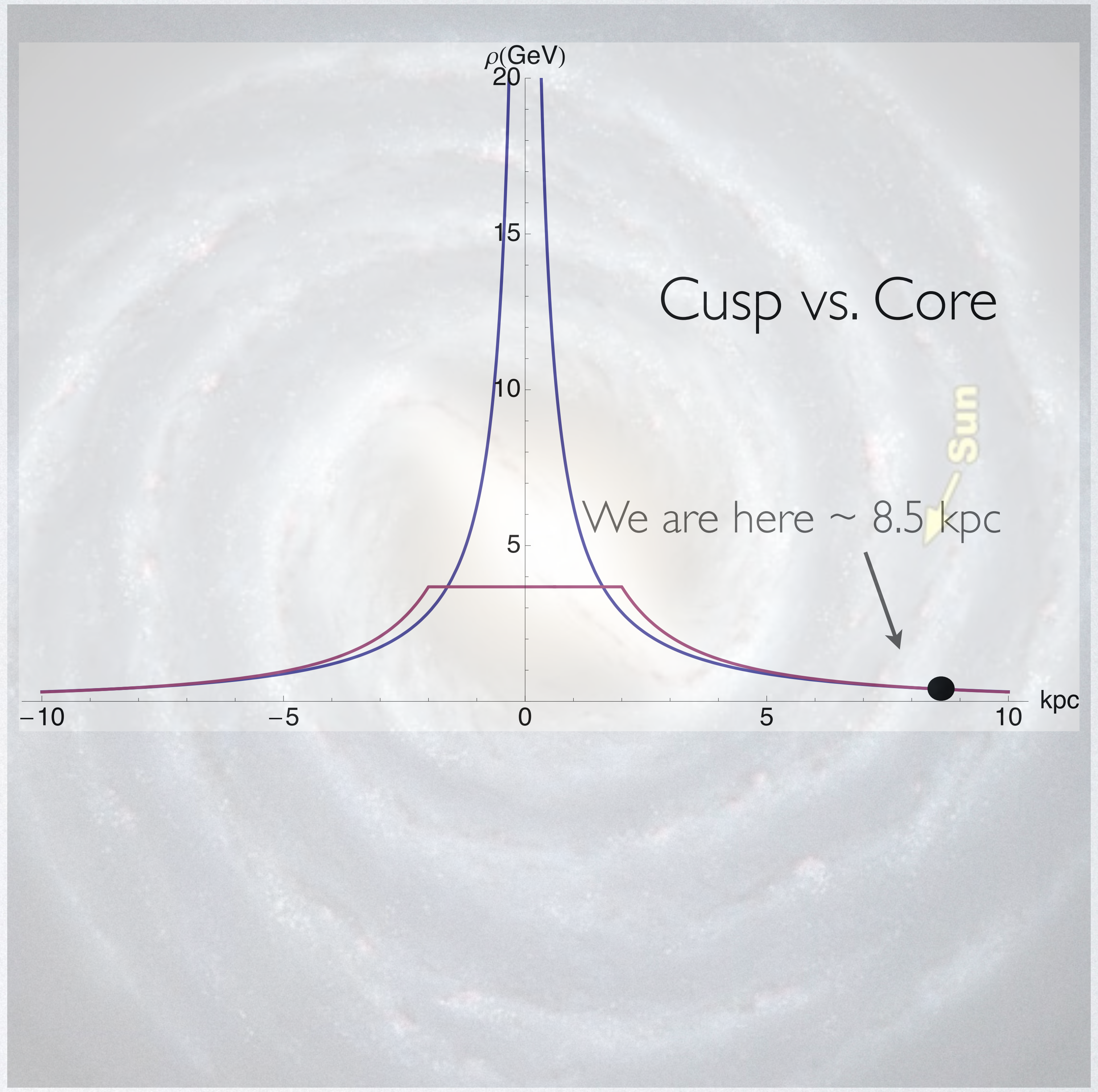
Image Credit: K. Ichikawa



MAGIC
Galactic Center Limits
2212.10527

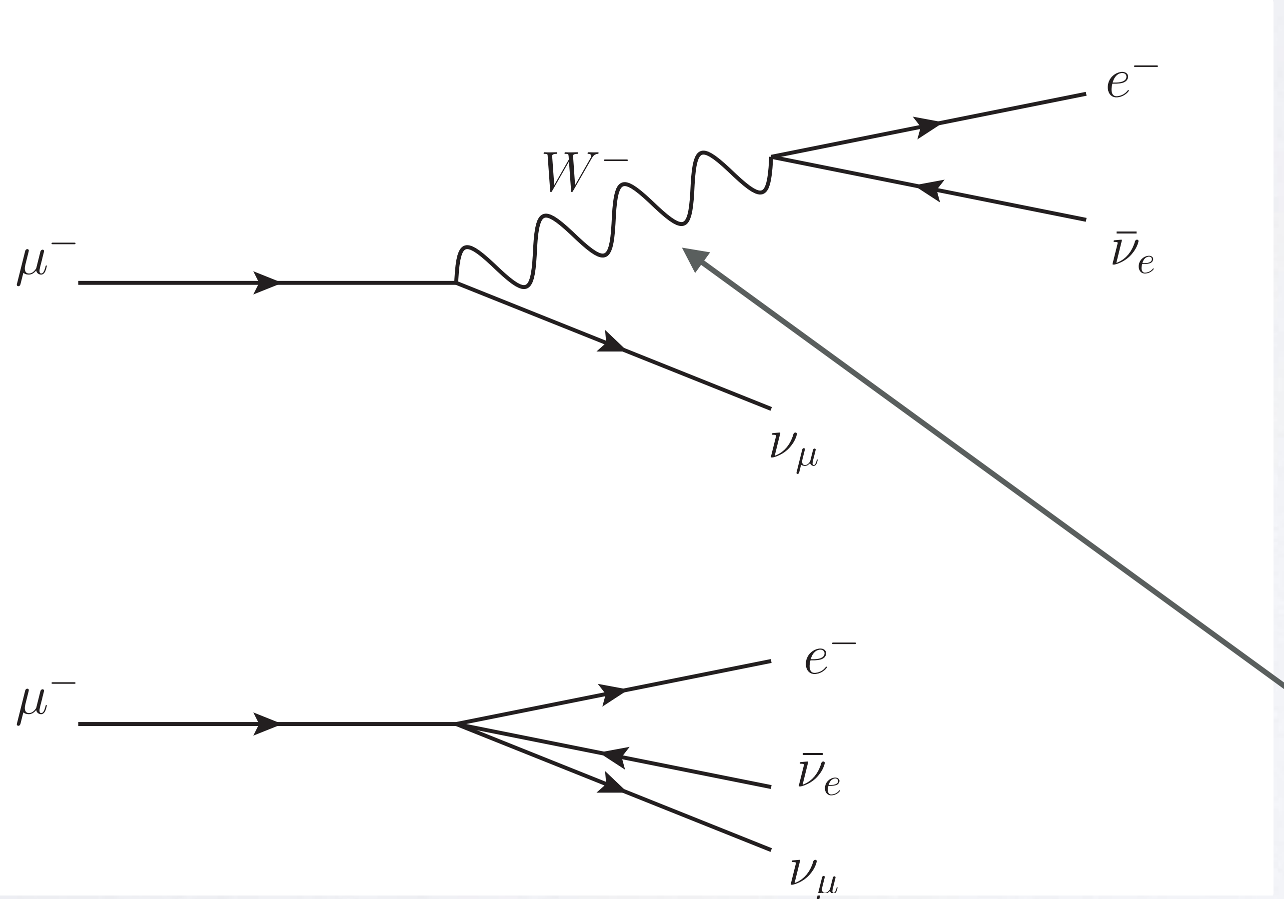
THE LOOPHOLE

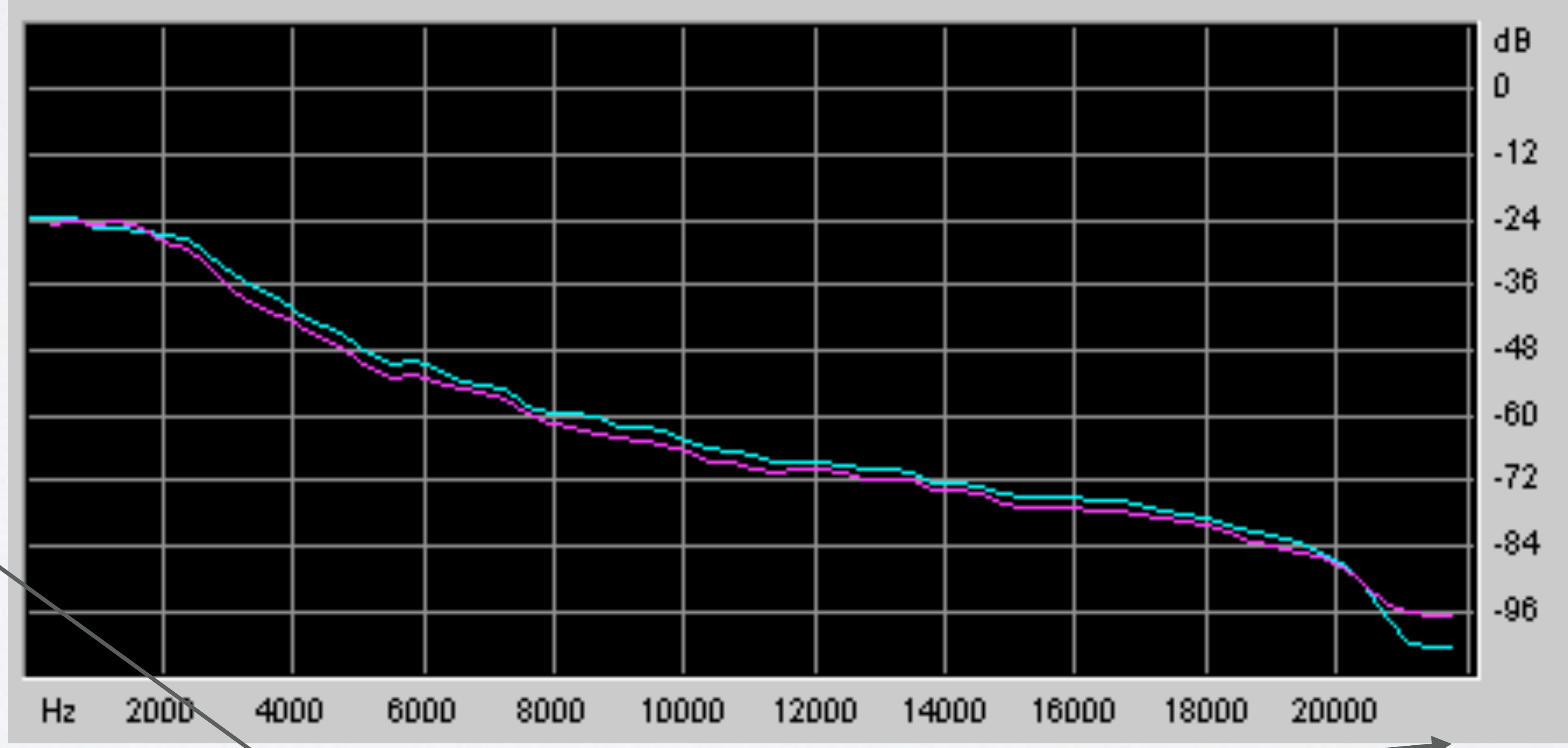
- **Indirect detection must assume something about DM distribution** in its target
- We take a **cored Einasto** (pure Einasto is cusped) profile
- Ask **what size core is needed for consistency with DM limit**, is that size constrained?
- **Use a mix of targets** (i.e. dwarf spheroidals (dSphs) in addition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



DIGITAL SIGNAL PROCESSING AND QUANTUM FIELD THEORY

Effective Field Theory:
Systematically decouple
High-Energy Physics





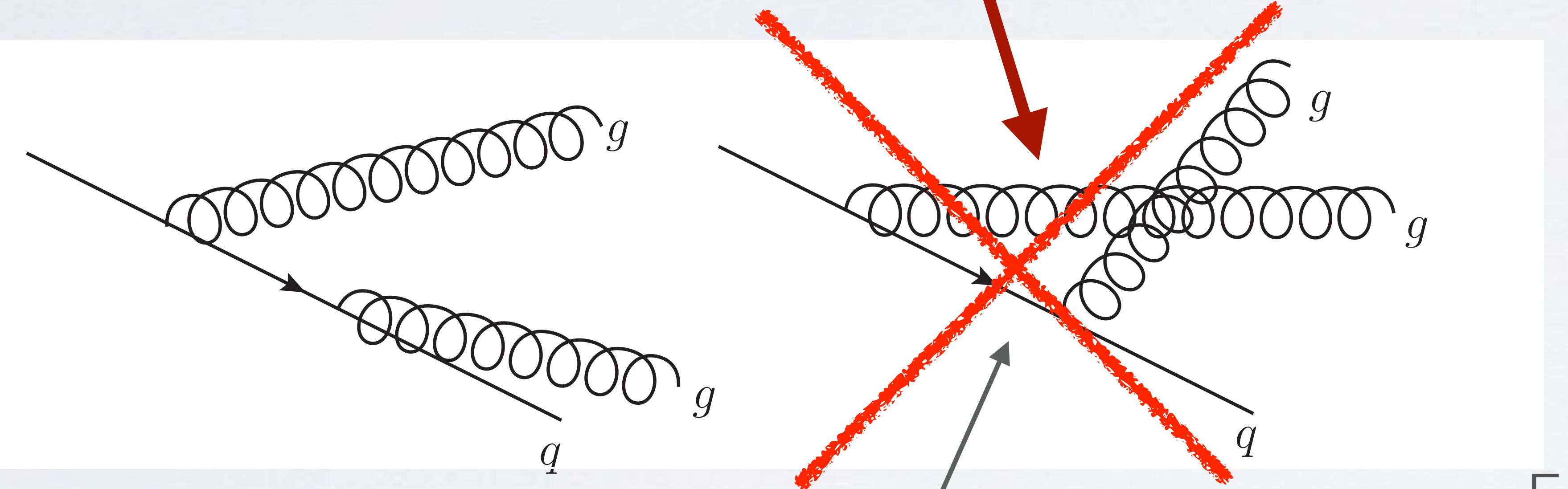
1 min
10 MB

Dropping high-frequency modes can suffice

Quantum relativist terminology:
Energy=Mass=Momentum=Frequency

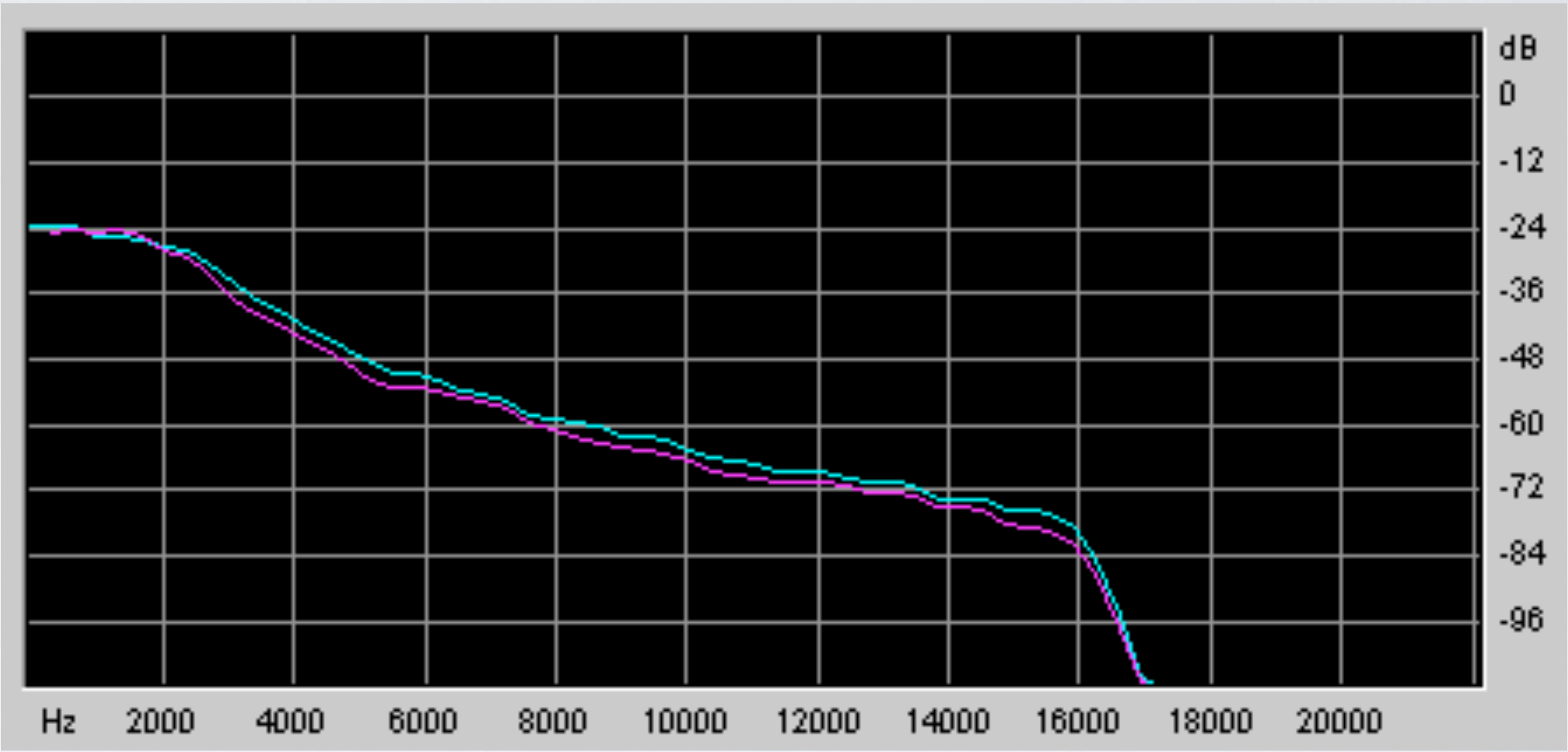
MODERN EFFECTIVE FIELD THEORY

Eliminate modes
MP3: Psychoacoustics
Effective Field Theory:
Kinematics

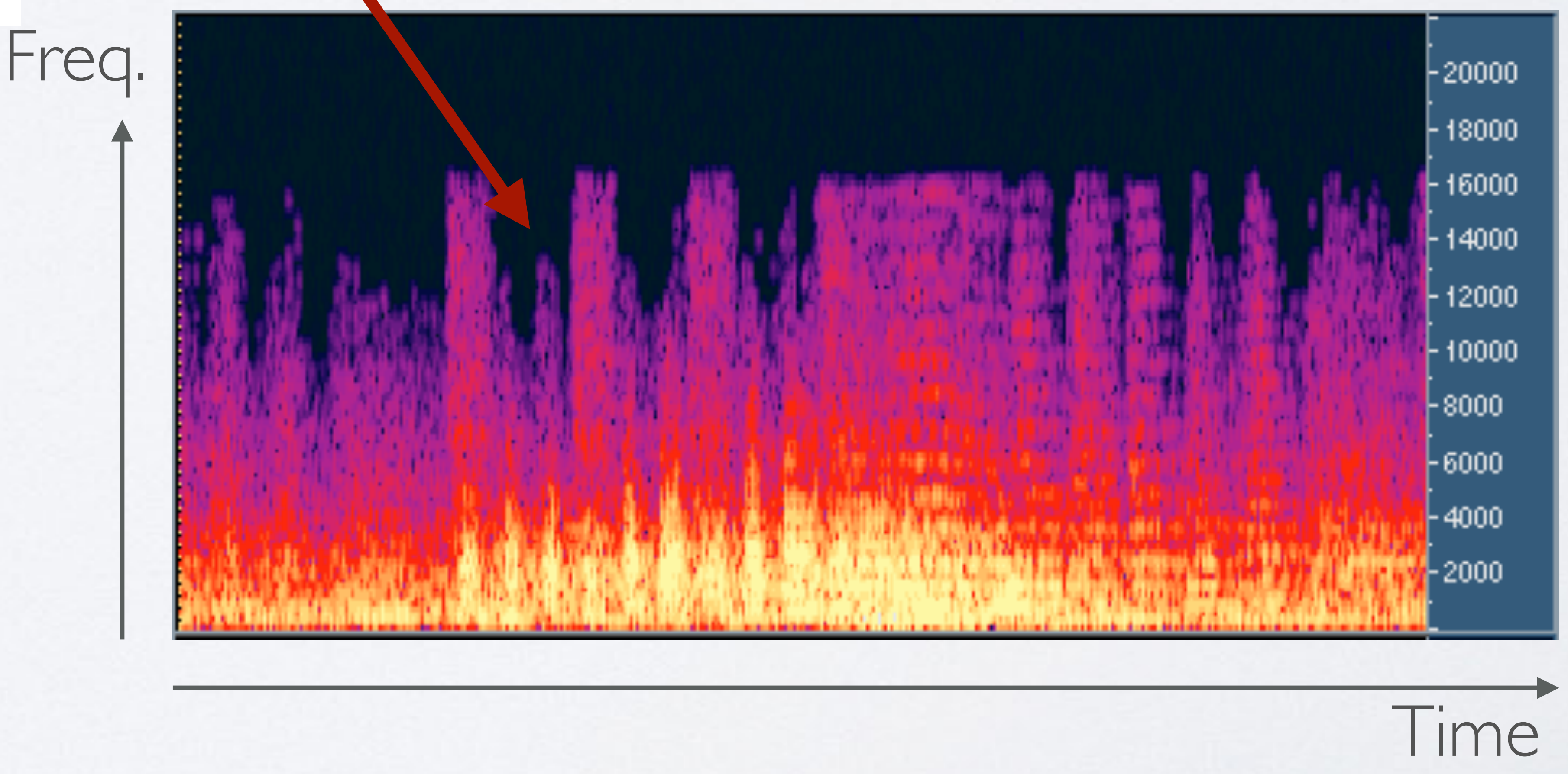


1007.0758: **MB**, Marcantonini, C., Stewart, I.

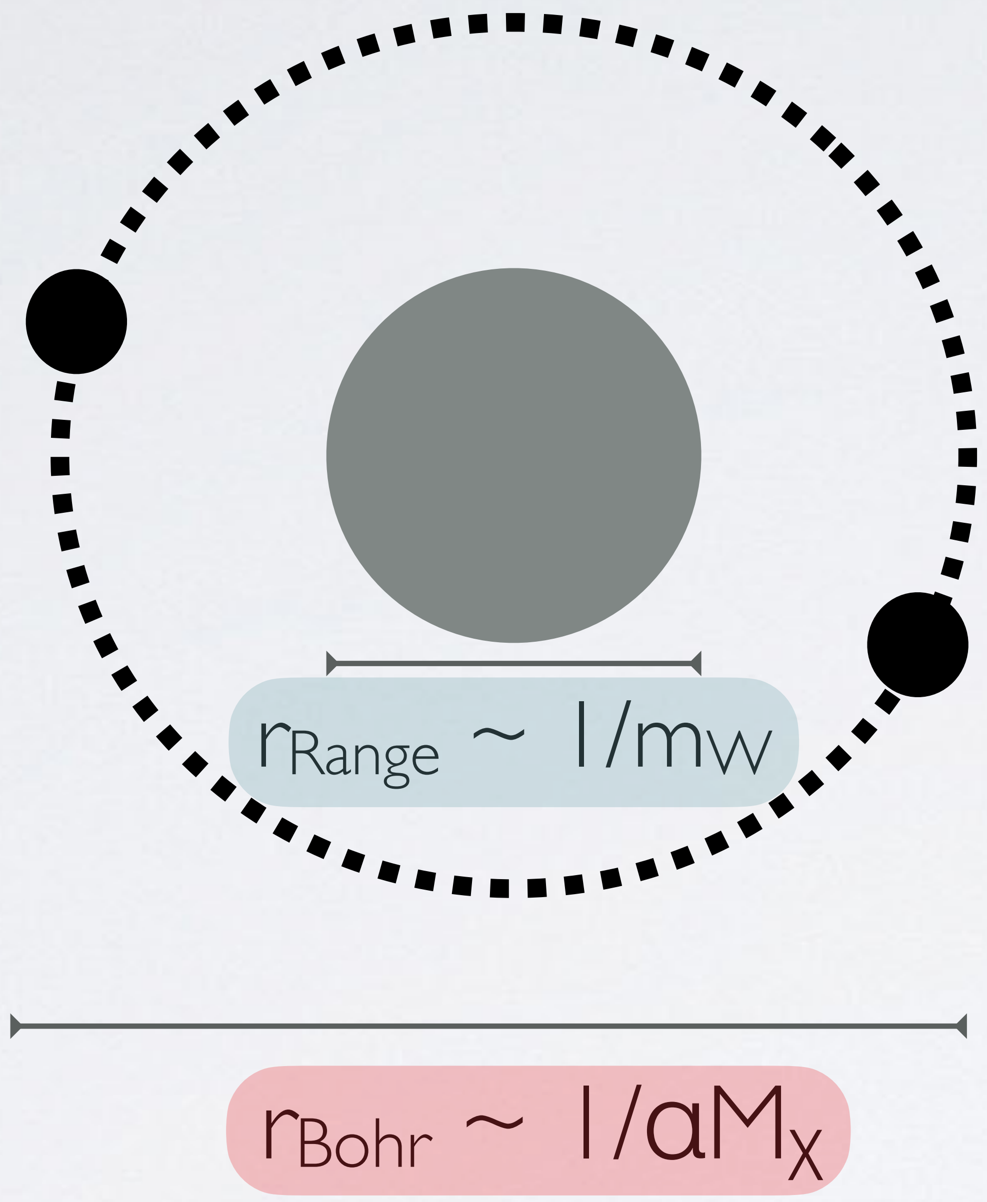
Shower of radiation:
Less Low-energy and Collinear enhancement



1 min
1 MB

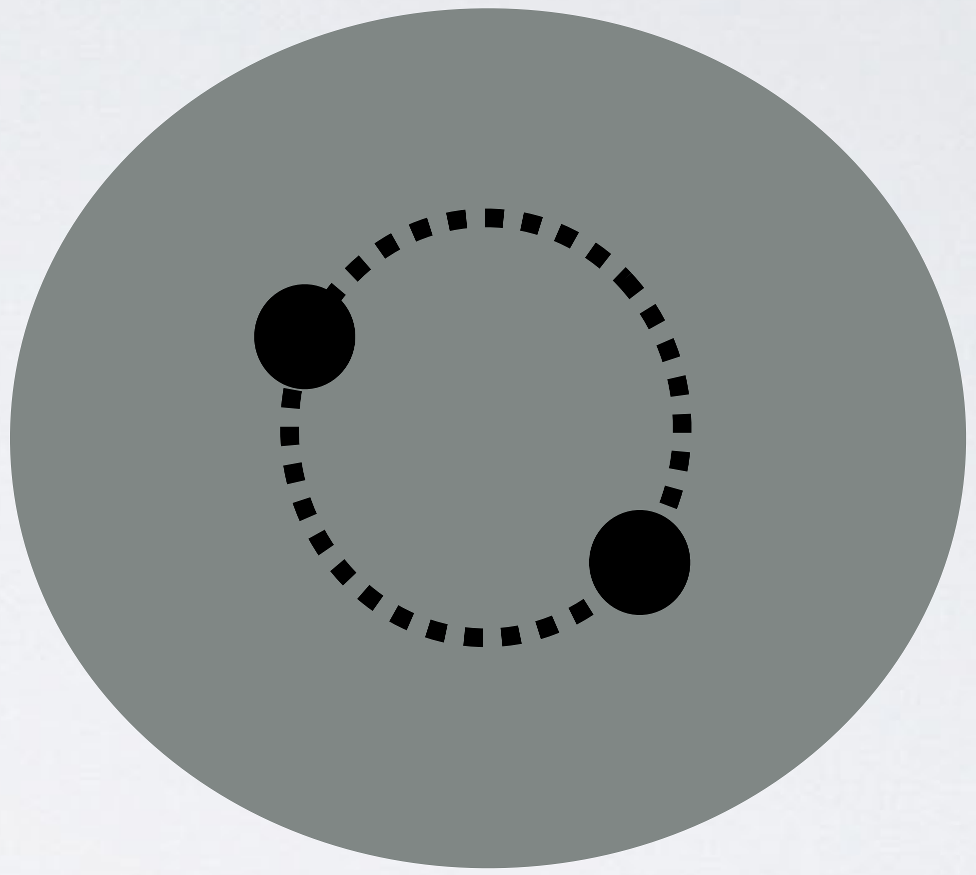


SOMMERFELD ENHANCEMENT



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

No bound state



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

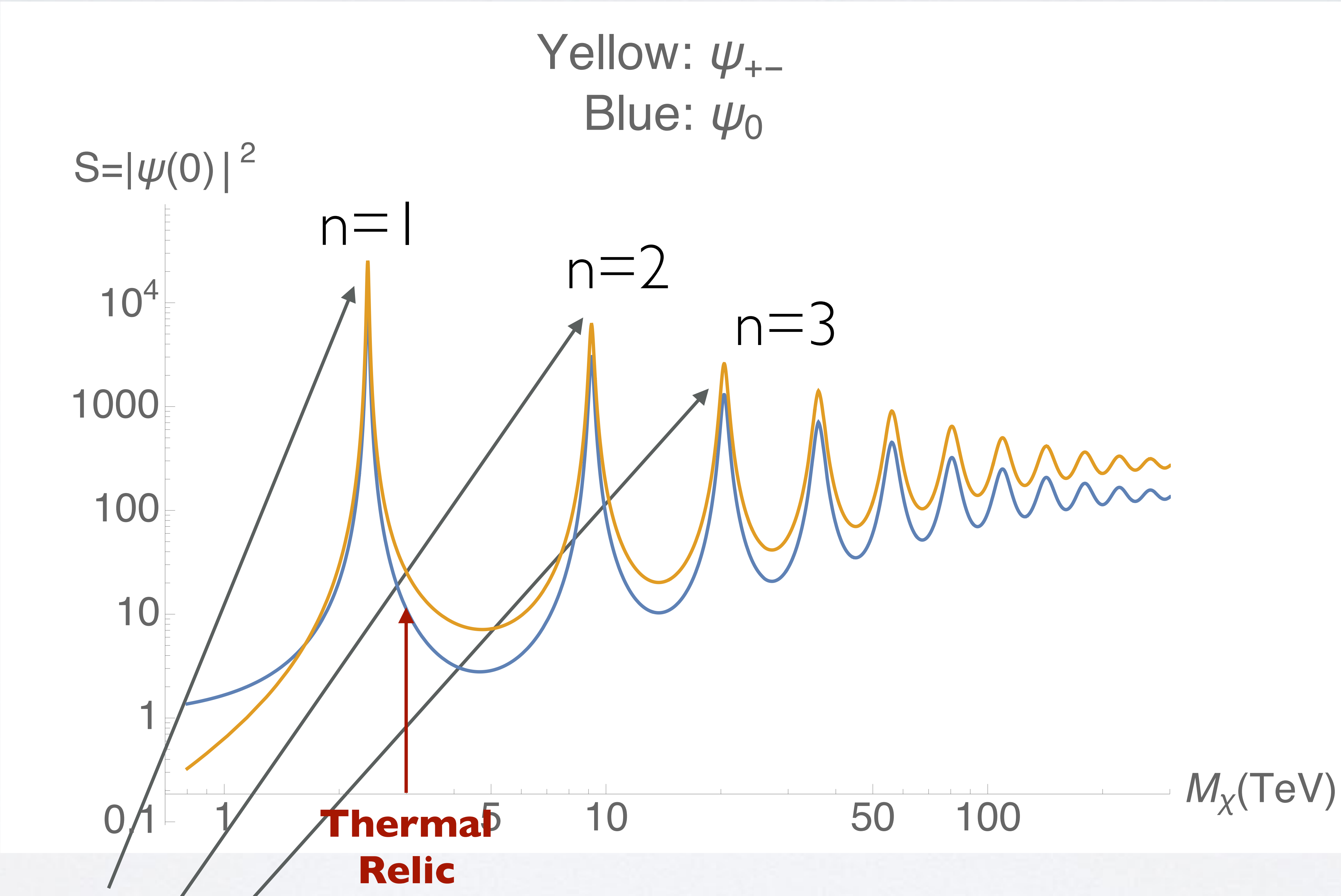
Bound state forms

For wino

$m_W = \alpha_W M_X$ @ $M_X = 2.4$ TeV

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

WINO NR COMPUTATION



Zero-energy bound states → Peaks

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

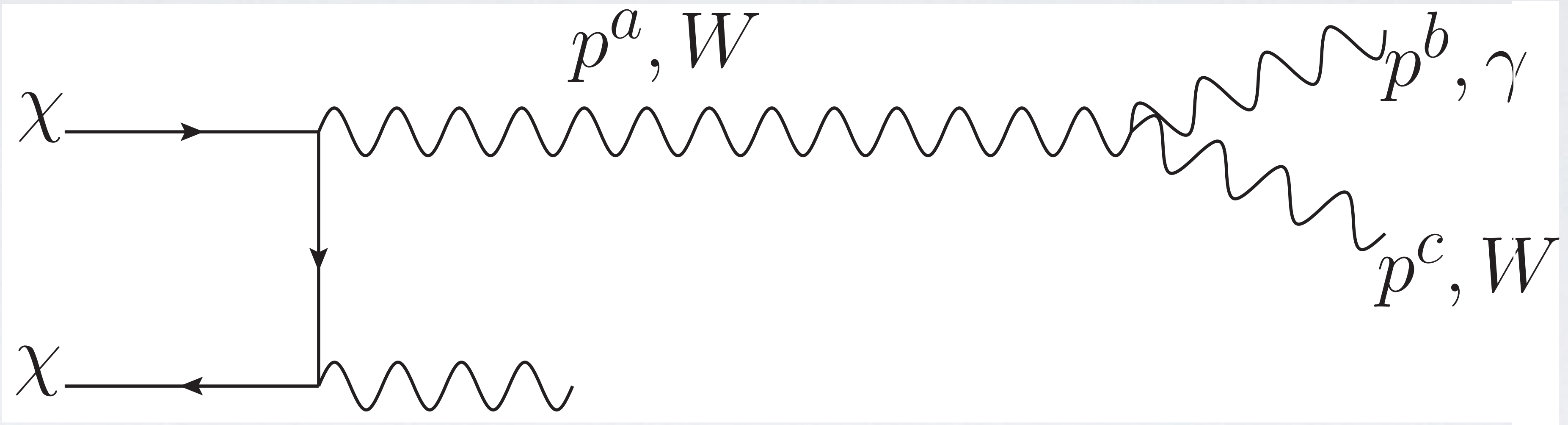
$$\left\langle 0 \middle| \chi_v^{3\,T}\, i\sigma_2\, \chi_v^3 \middle| (\chi^0\chi^0)_S \right\rangle = 4\sqrt{2}\, M_\chi\, s_{00}\,;$$

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

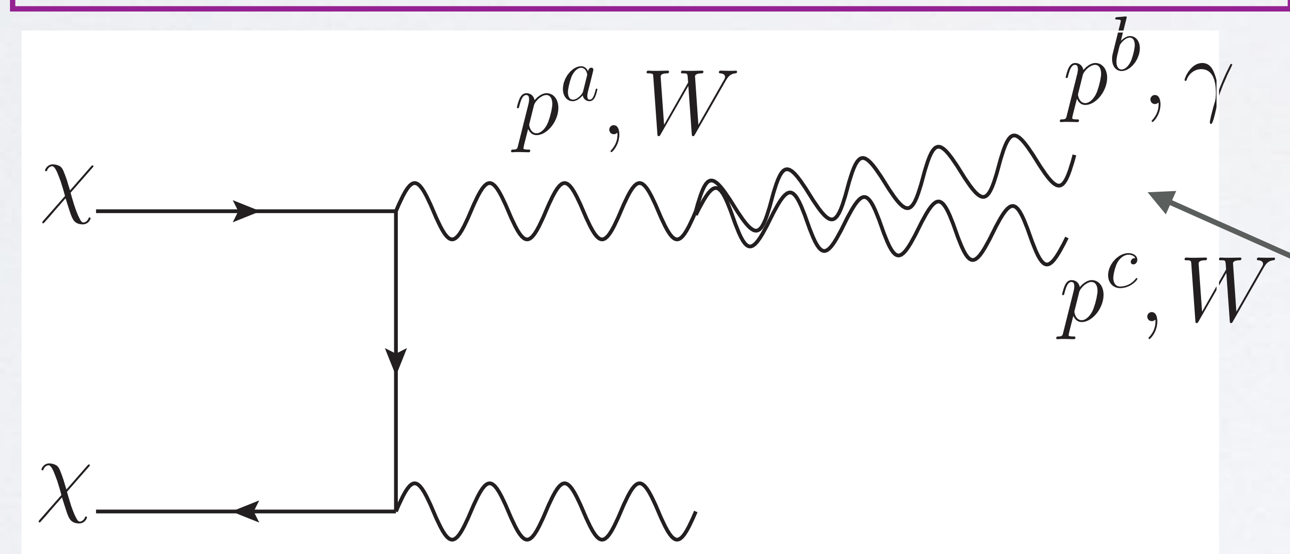
Wavefunction at the origin

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)

For a pedagogical Introduction to SCET and EFTs, see Petrov & Blechman *Effective Field Theories*

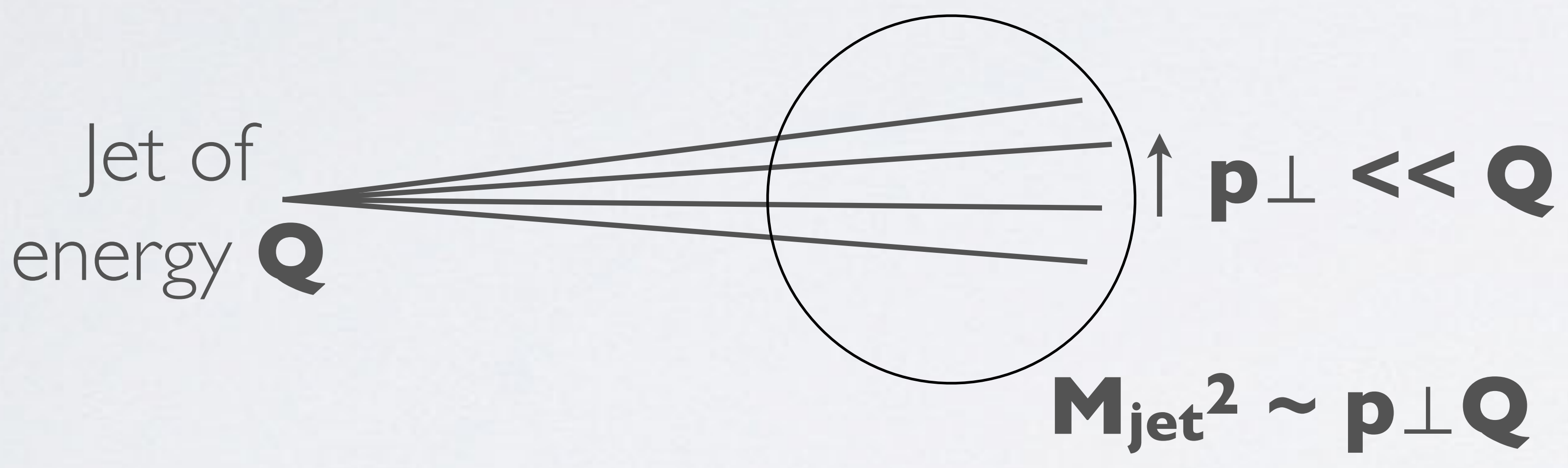
Soft-Collinear Effective Theory for Dark Matter annihilation

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

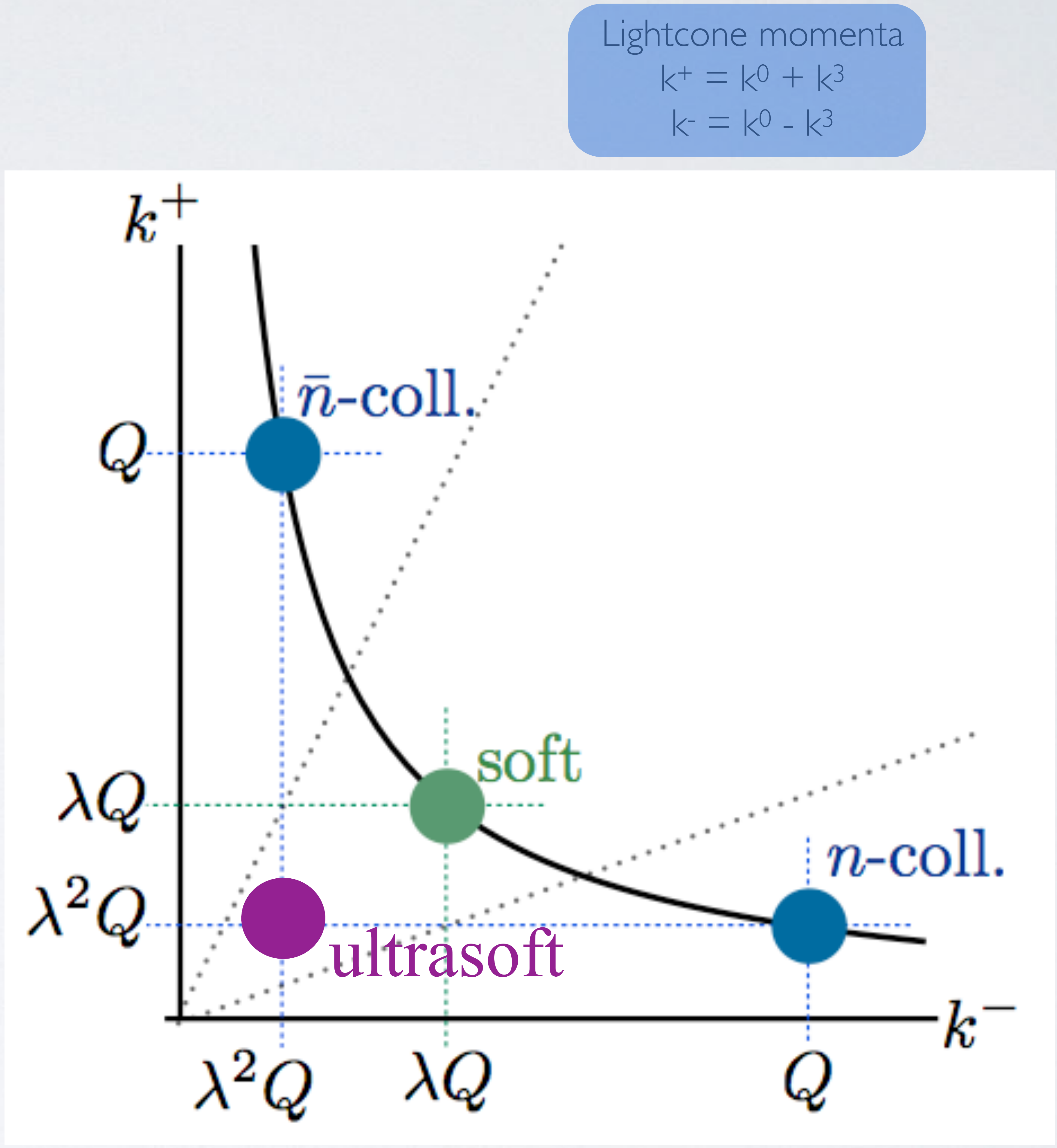
*Originally developed for study of QCD
hep-ph/0005275: Bauer, Fleming, Luke
hep-ph/0011336: Bauer et al.

SOFT-COLLINEAR EFFECTIVE THEORY

- Large scale-hierarchies can arise within one field

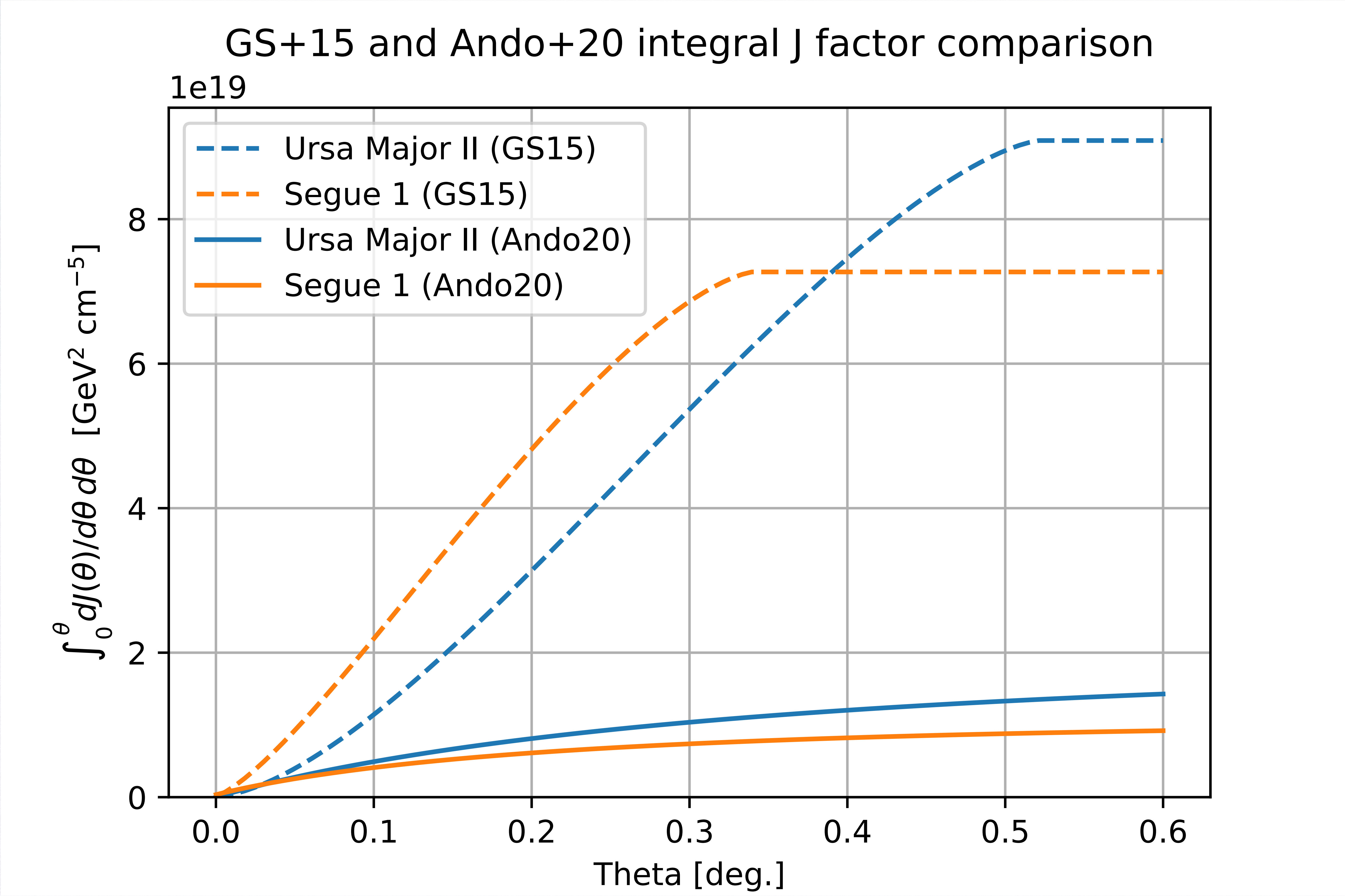


- We can **use Renormalization Group to resum** kinematic logs



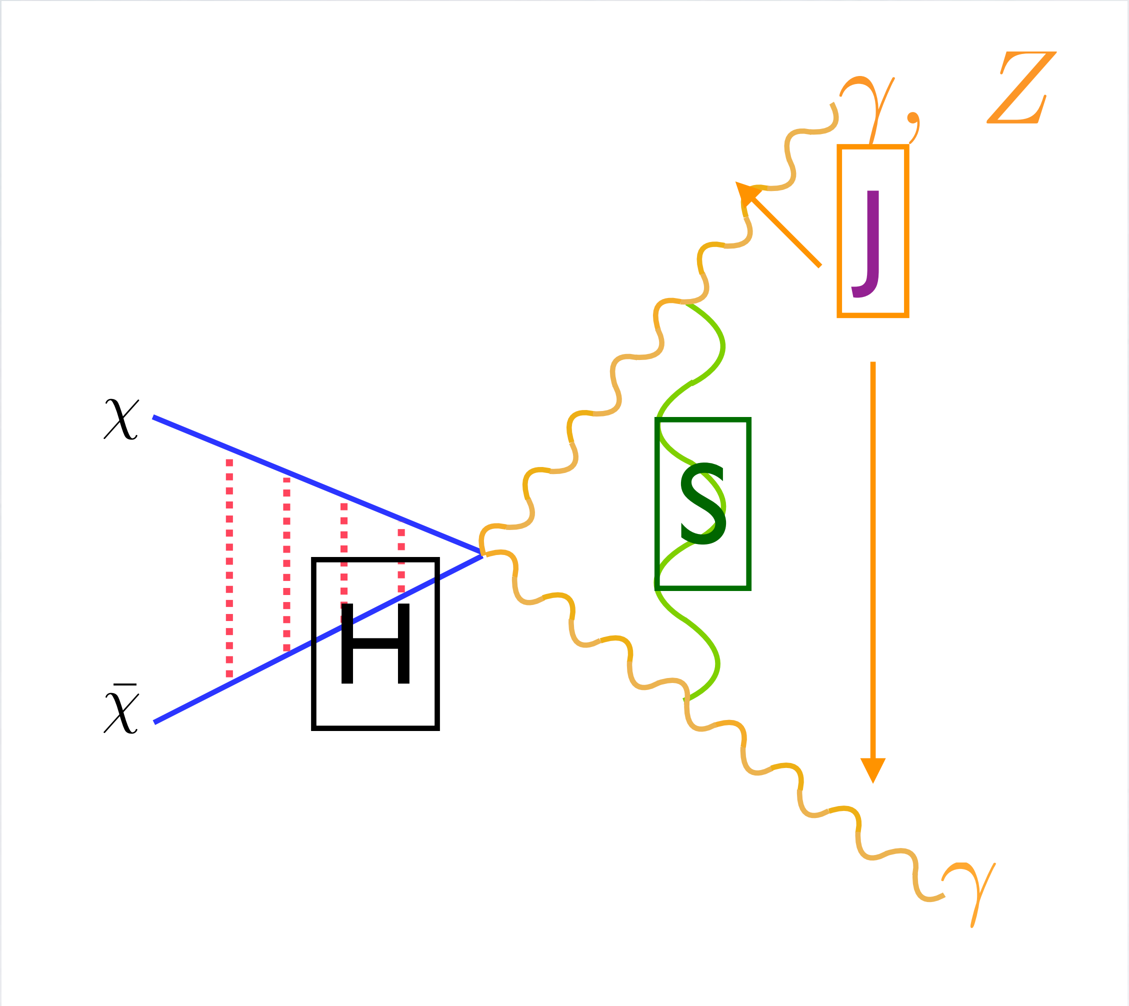
Integrate out hard modes, separate fields for those collinear to null directions and soft momenta.

J-FACTOR COMPARISON



From J. Quinn

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 & Sommerfelds

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

Collinear Gauge field

Soft Wilson Line

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

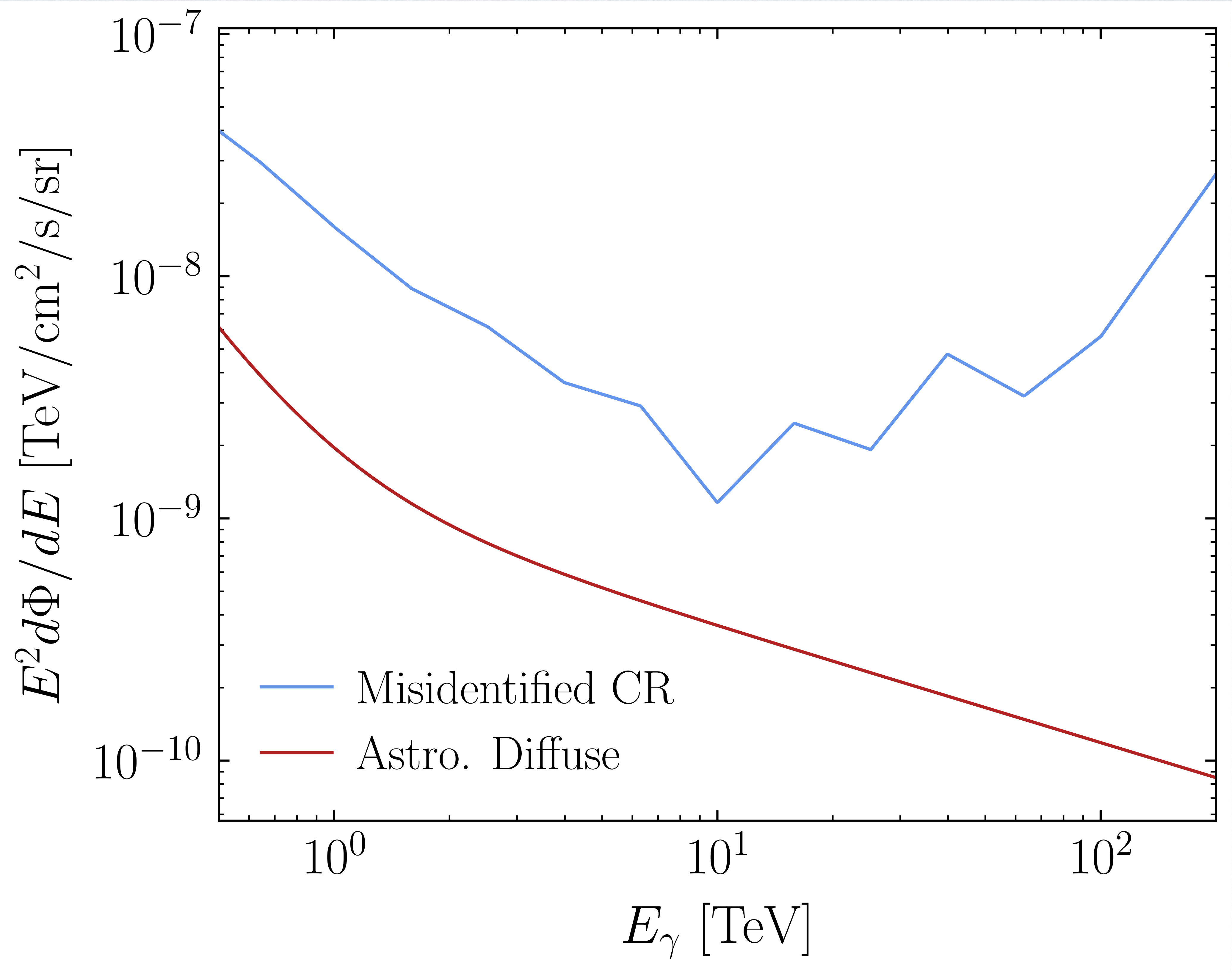
SEARCH & BACKGROUNDS

- We follow **CTAO dark matter "line" search strategy** detailed in 2403.04857

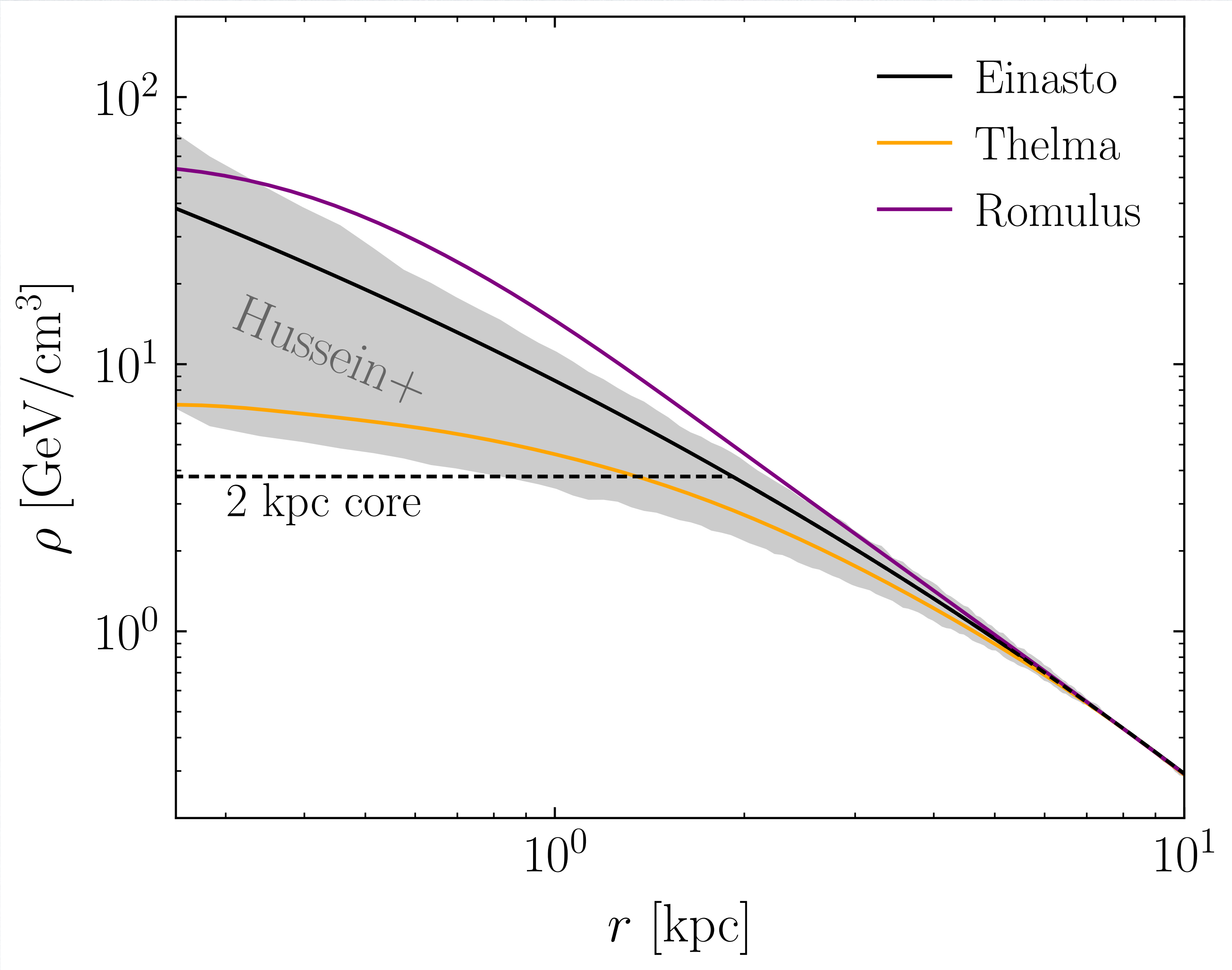
- **ROI in inner 2° of galaxy** with plane masked, 9 observation regions totaling 500 hours.

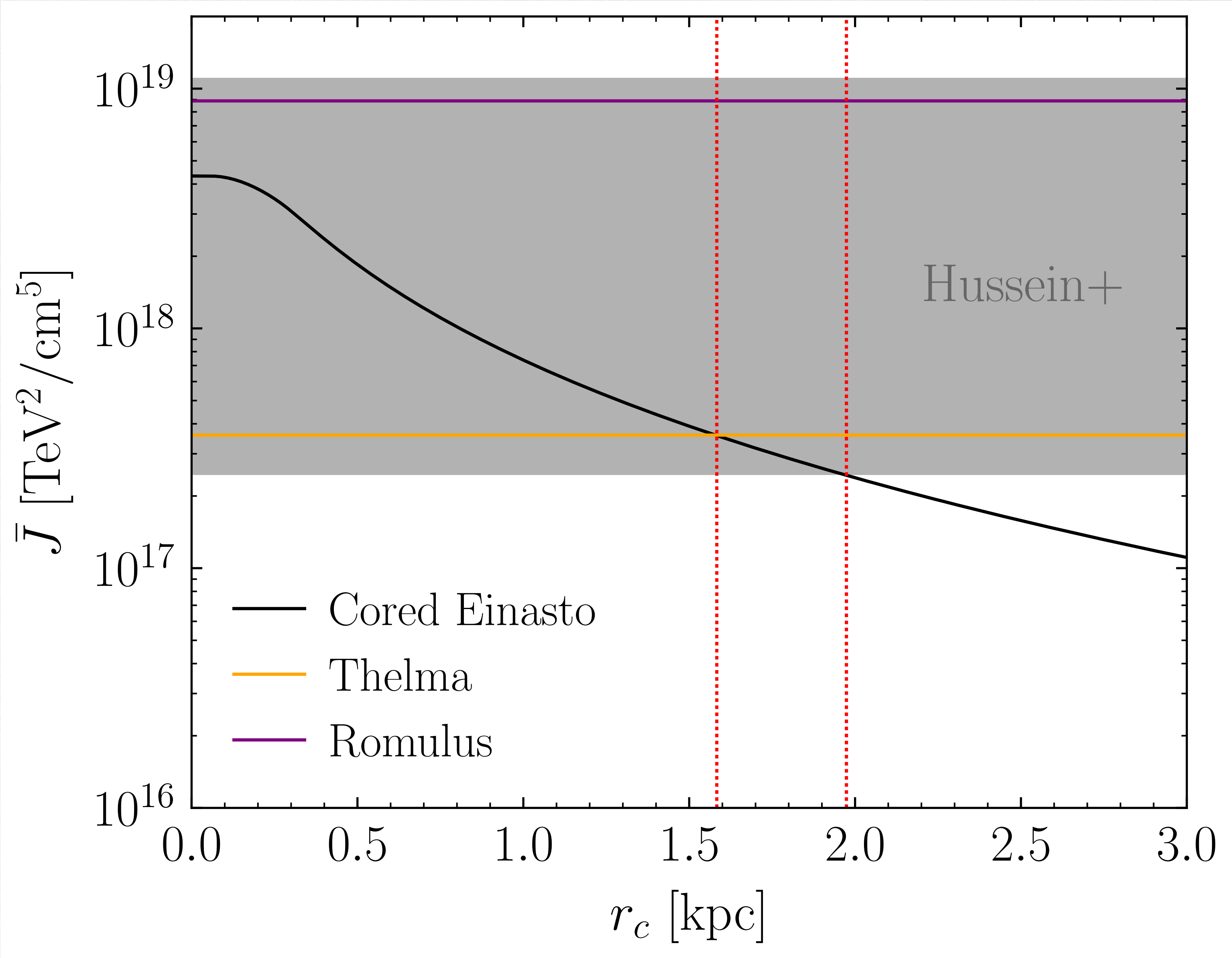
- Background dominated by **cosmic rays**, we use **CTAO's public model**. (Alpha Configuration, CTAO South only)

- For **anisotropic diffuse emission**, we take **simplified GDE scenario 2** from 2008.00692: L. Rinchiuso et al.



DM DENSITY

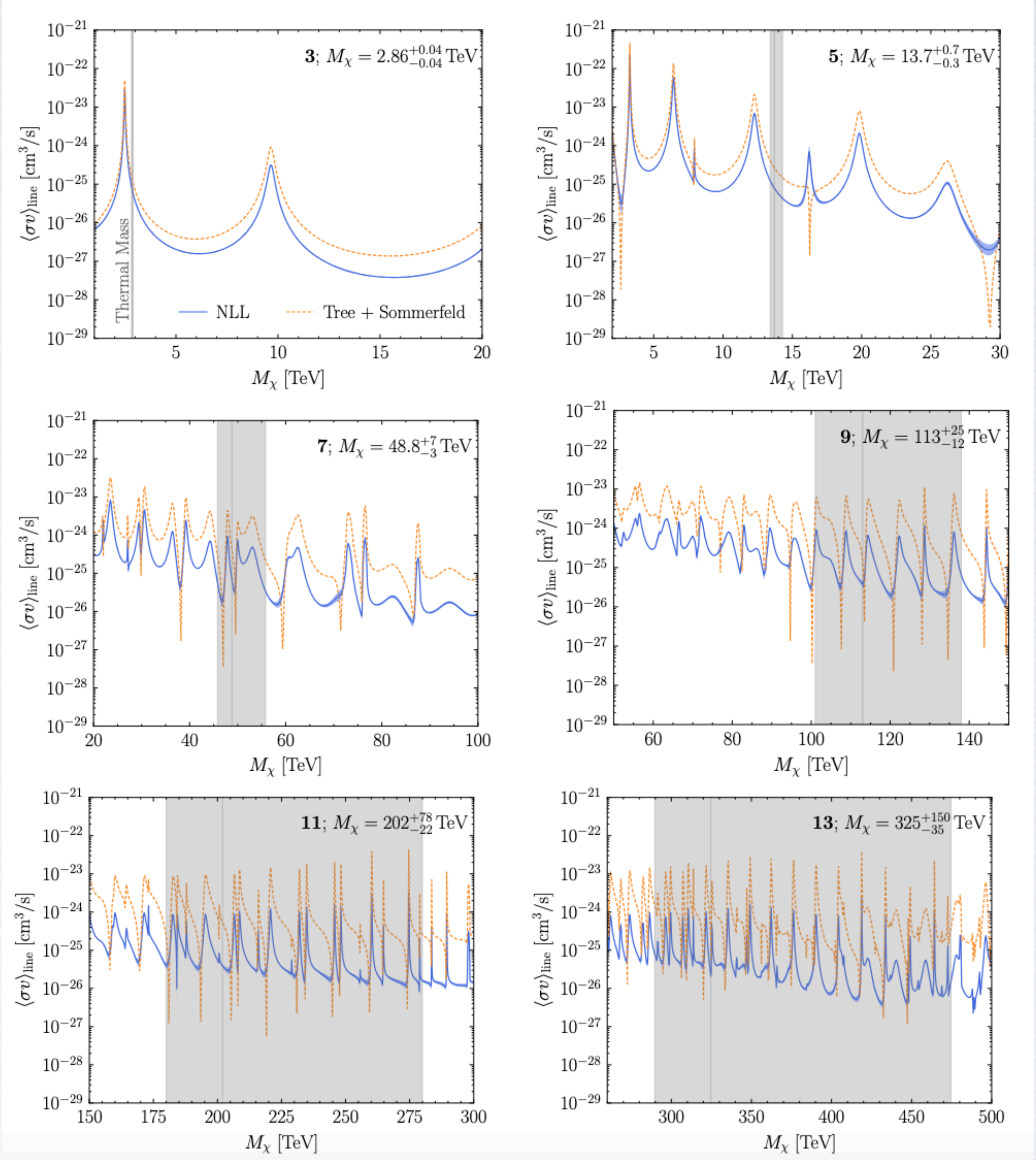




We consider a model **excluded** when its J-factor requires a **cored radius larger than 2 kpc**
2501.14868: Hussein et al.

LINE CROSS SECTIONS

- WIMP annihilation signal dominated by line-like feature
- Radiative corrections significantly deplete exclusive rate
- These contributions come back in real-emission processes (z<1)
- Nontrivial structure at higher-reps from bound states in spectrum…



Real-rep exclusive cross-section to γ near thermal relic masses

J-FACTOR

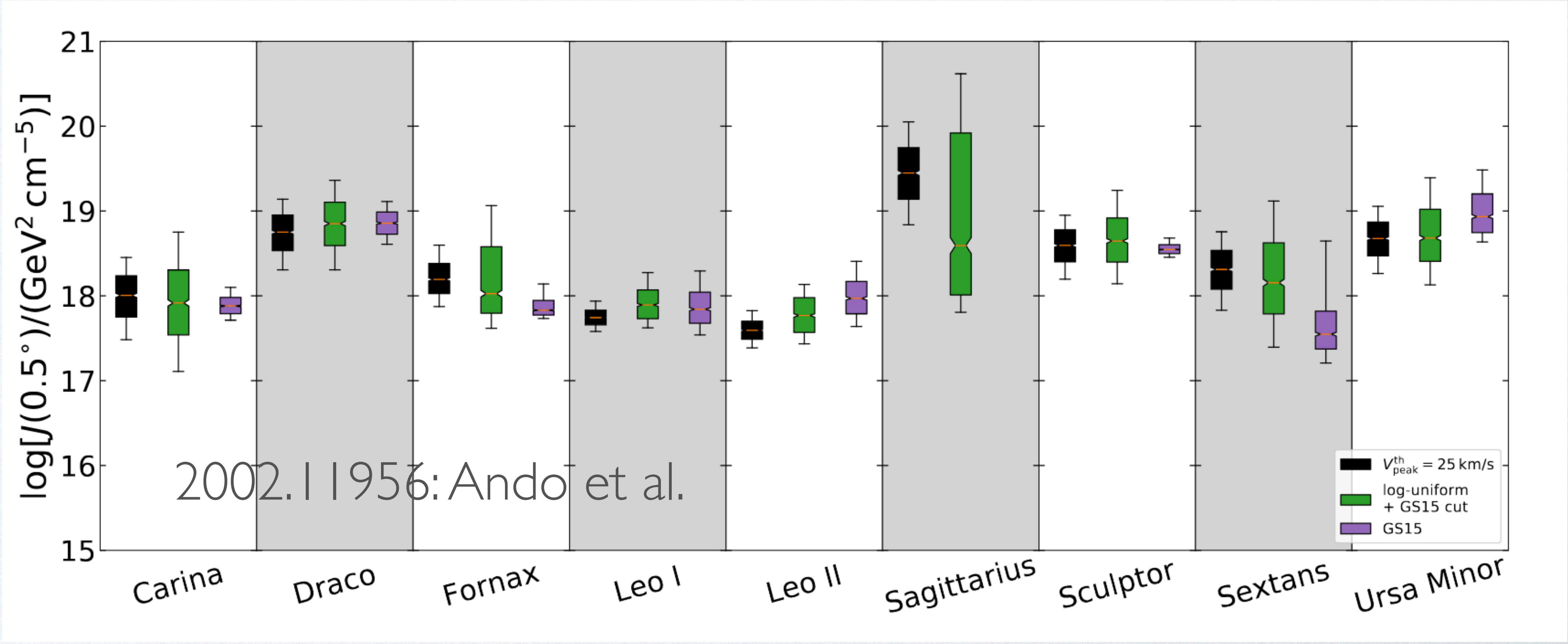
- Flux & spectrum of observed photons depends on:
  - Underlying particle physics/QFT
  - Dark Matter density in target
  - Observational region
- Star line-of-sight velocities and dSphs' surface brightness fed into Jeans Equation to determine underlying mass-distribution and ρ_{DM}.

First principles
Quantum Field Theory

Astrophysical
measurement/
modeling

$$\frac{d\Phi_\gamma^{\rm DM}}{dE} = \frac{\langle \sigma v \rangle}{8\pi M_{\rm DM}^2} \frac{dN_\gamma(E)}{dE} J(\Delta\Omega)$$

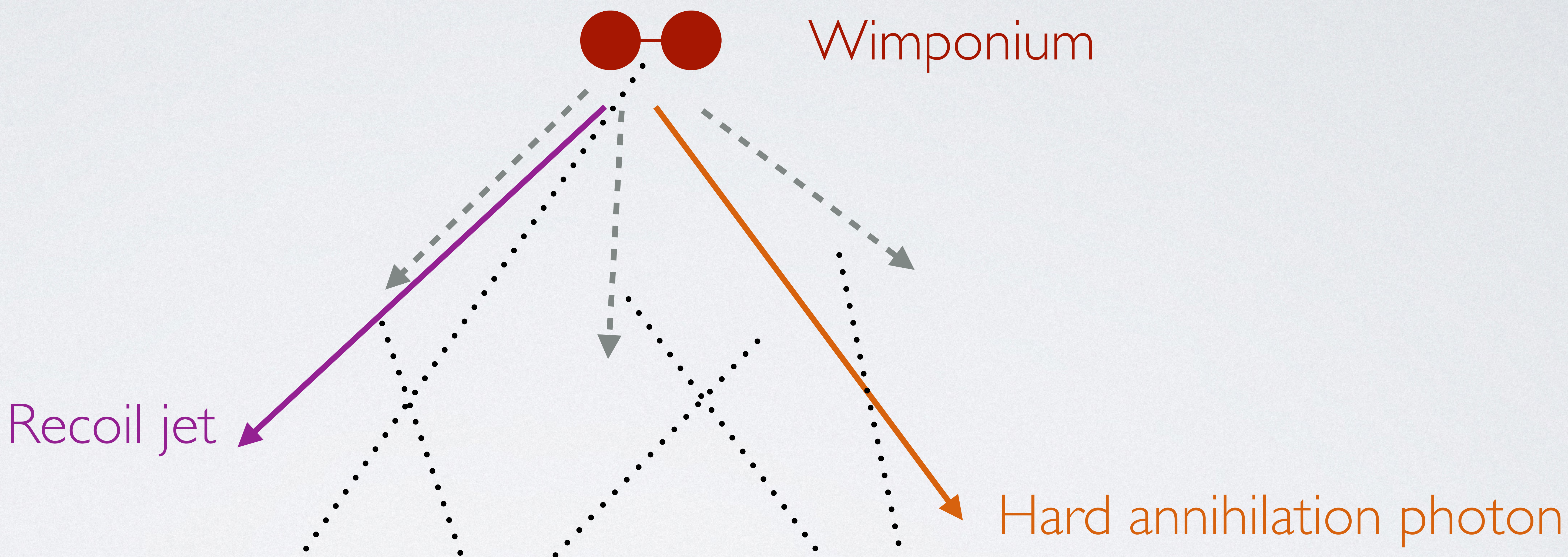
$$J(\Delta\Omega) \equiv \int_{\Delta\Omega} d\Omega \int_0^\infty ds\, \rho_{\rm DM}(r(s,\theta))^2$$



2002.11956: Ando et al.

PHOTONS FROM WIMPONIUM

- **Electroweak long-range force → bound state capture**
- Important for larger reps
- Multiple attractive channels, multiple partial waves
- Evade partial wave unitarity limit at 194 TeV

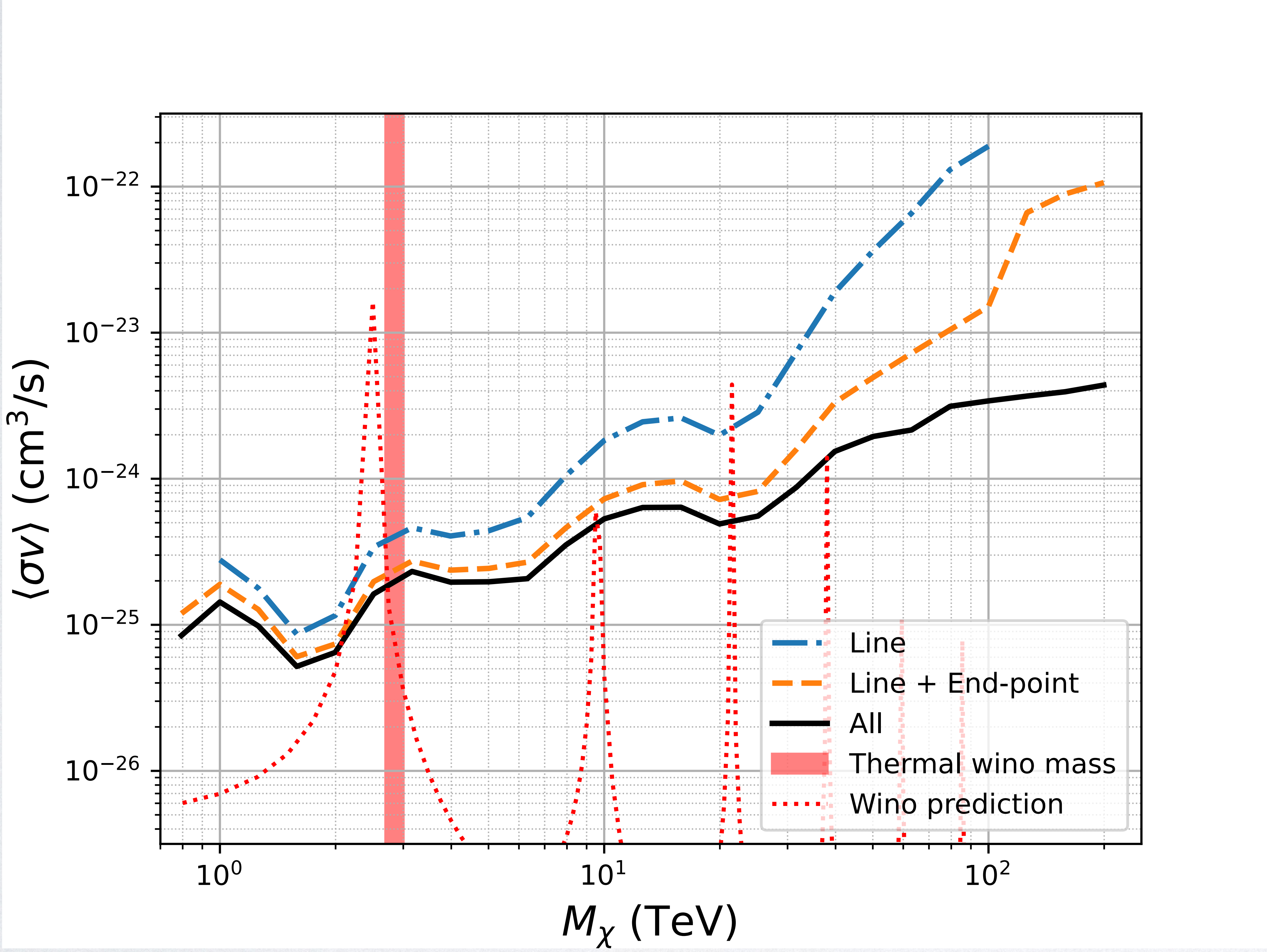


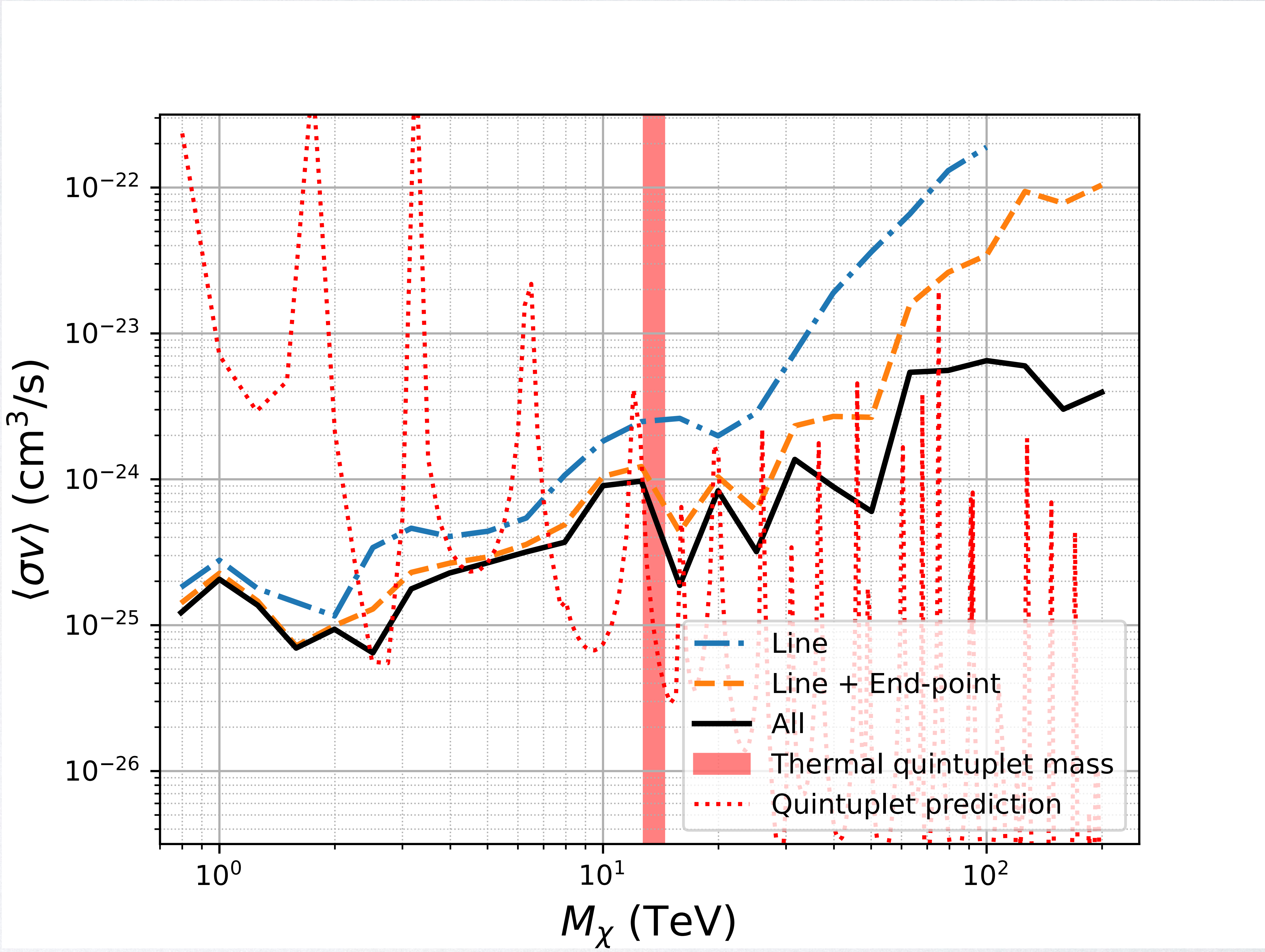
$$\frac{d\Gamma}{dz} = \left[\int \frac{d\Omega_\gamma}{4\pi} L^{aba'b'} \right] J_\gamma \int \frac{dk^+}{2\pi} J_n(k^+) \int \frac{dq^+}{2\pi} \left(\sum_{i=1}^{4} C_{s,i} S_i^{aba'b'}(q^+) \right) \delta(2M_\chi(1-z) - k^+ - q^+)$$

Wavefunction at the origin factor

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

LIMIT BREAKDOWN BY CONTRIBUTION

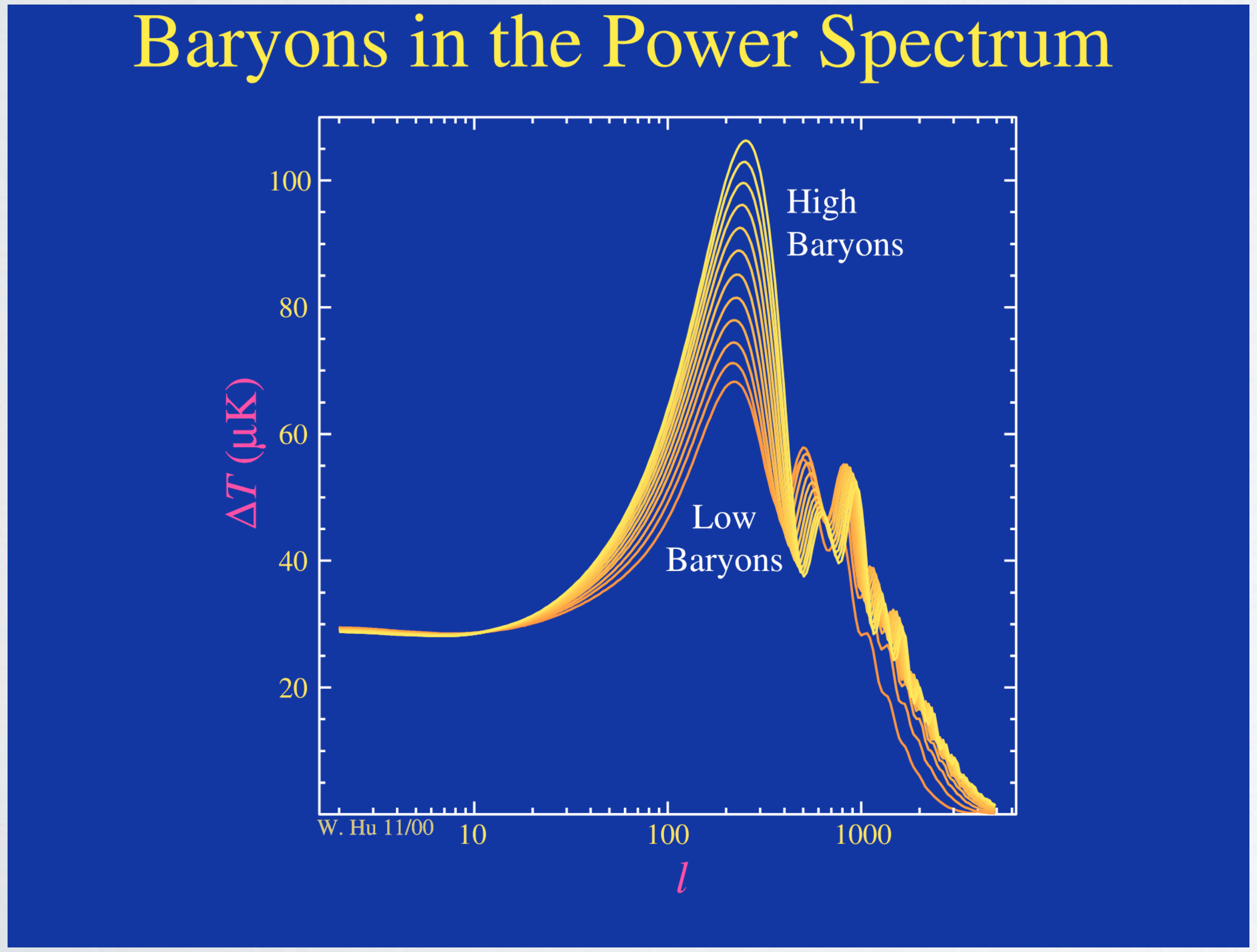




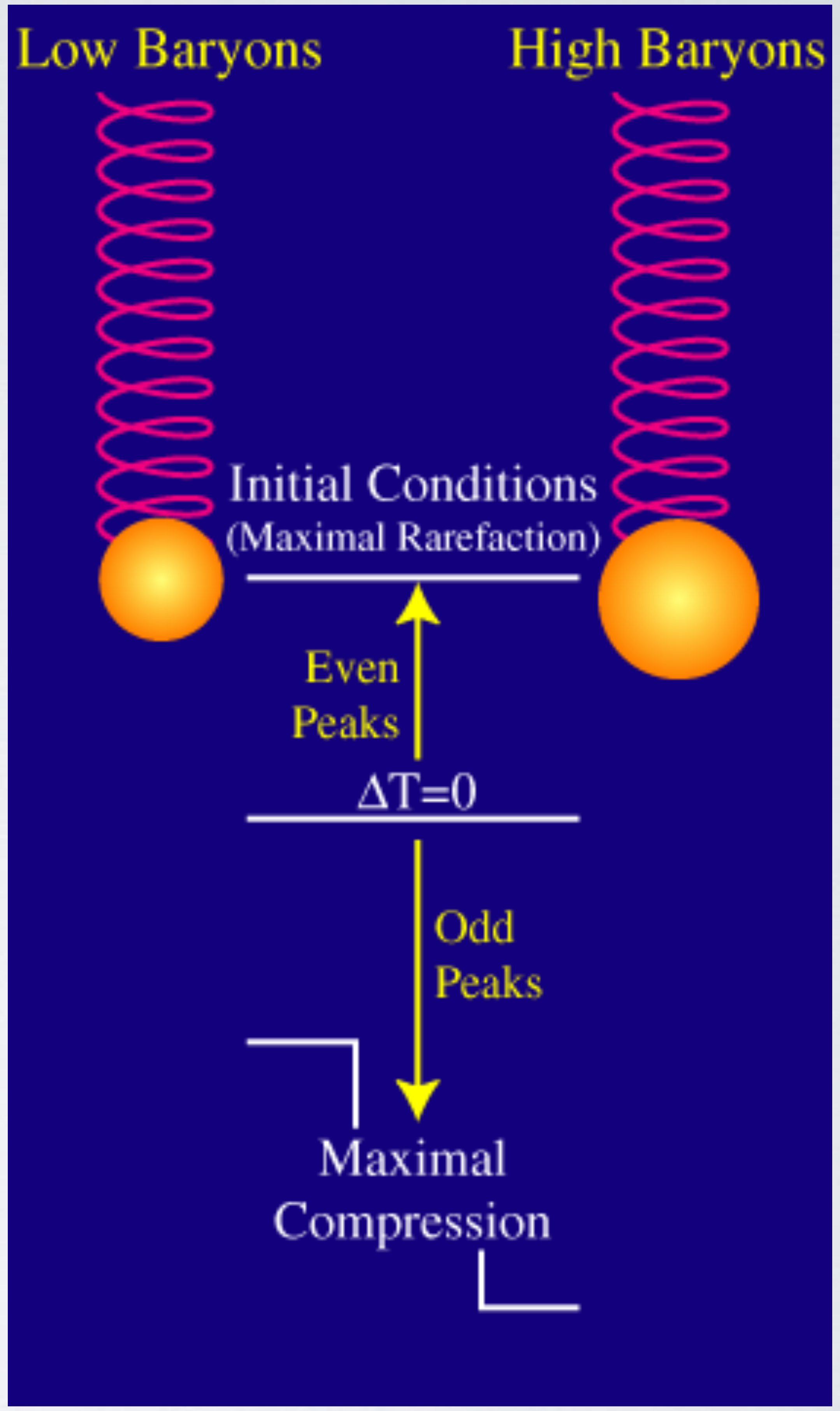
VERITAS Preliminary Results

BARYON ABUNDANCE

CMB **even(compression)/ odd(rarefaction) fluctuations distinguish baryons from dark matter**



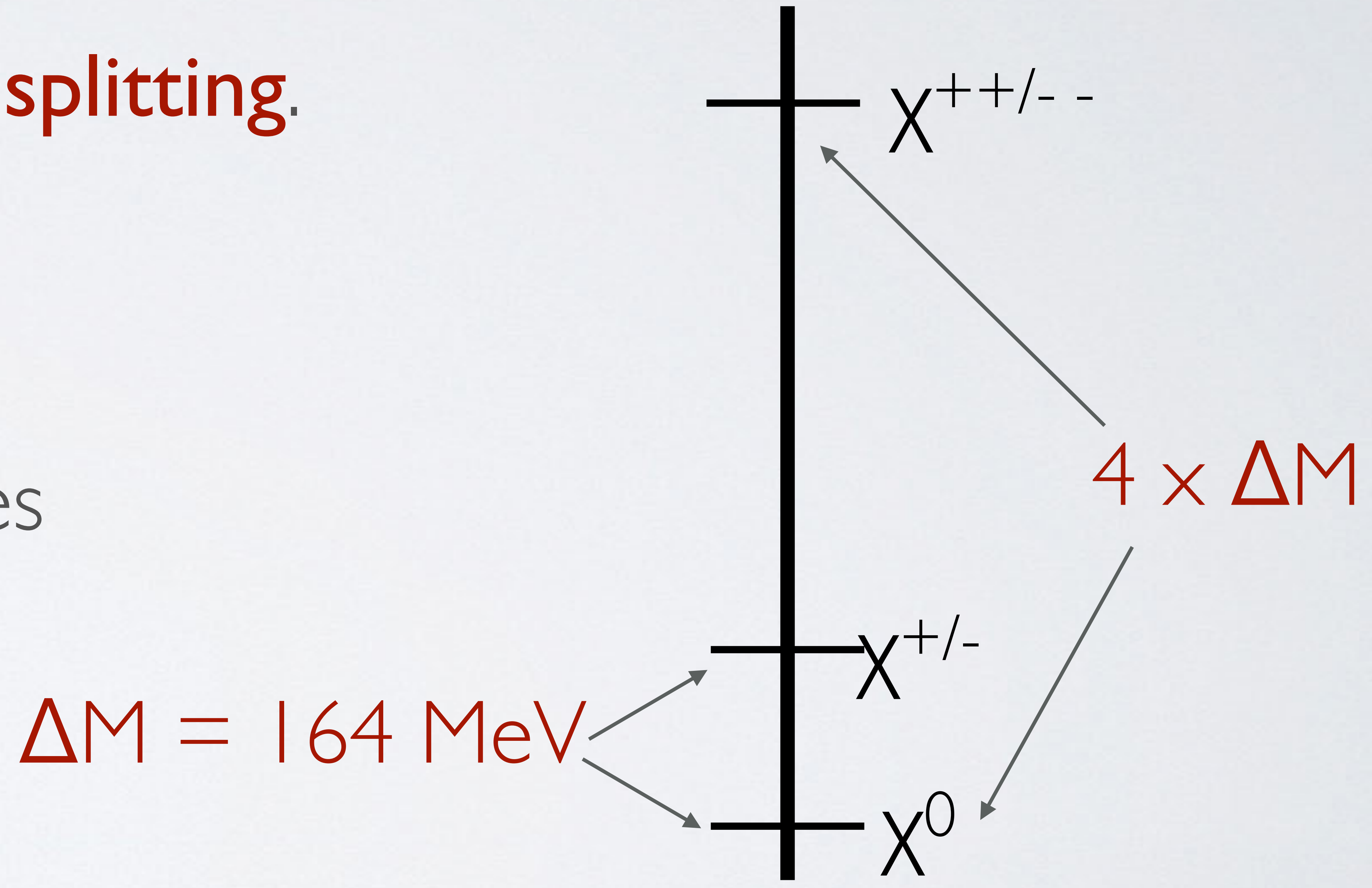
Conclusion: Significant portion of the Universe's mass has feeble coupling to photons!



"MINIMAL DARK MATTER"

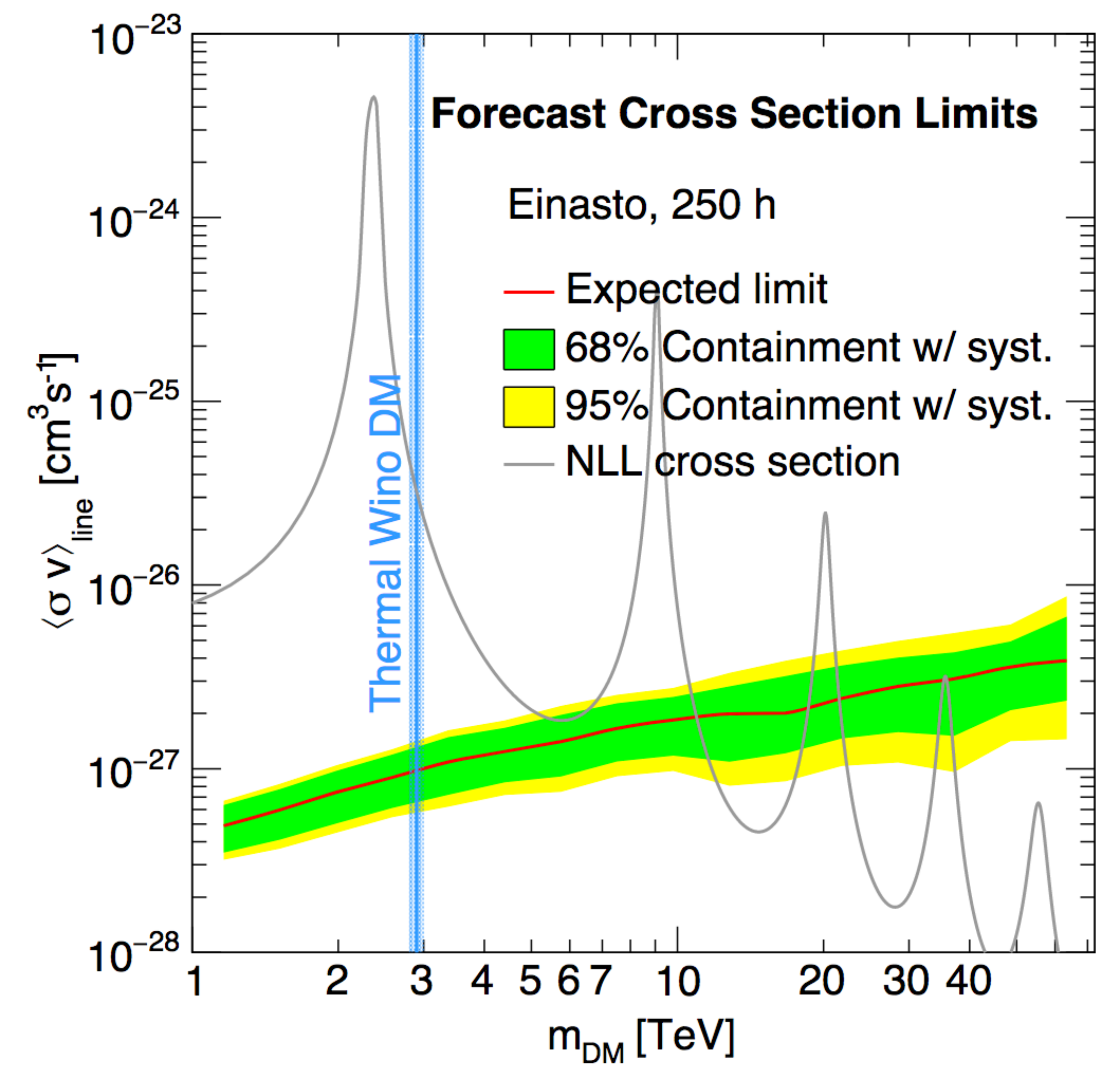
- **SU(2) quintuplet** (Y=0) has neutral **DM candidate**.
- Charged and doubly-charged states with **narrow mass splitting**.
- Keeps SU(2) Landau pole above GUT scale
- **Cosmologically stable** just under SM symmetries

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

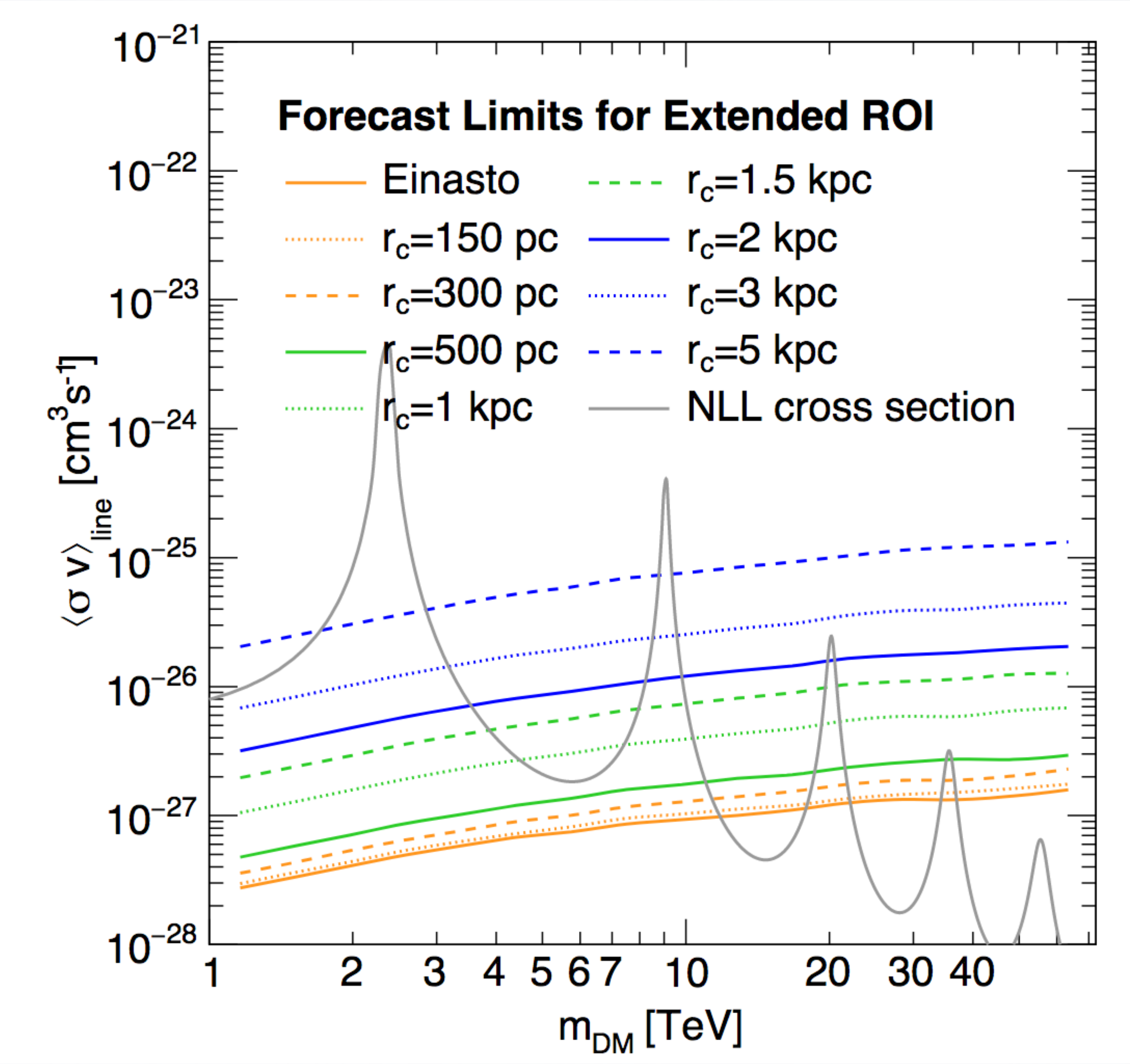


PROJECTED HESS GALACTIC CENTER WINO LIMITS

Rinchiuso et al.: 1808.04388



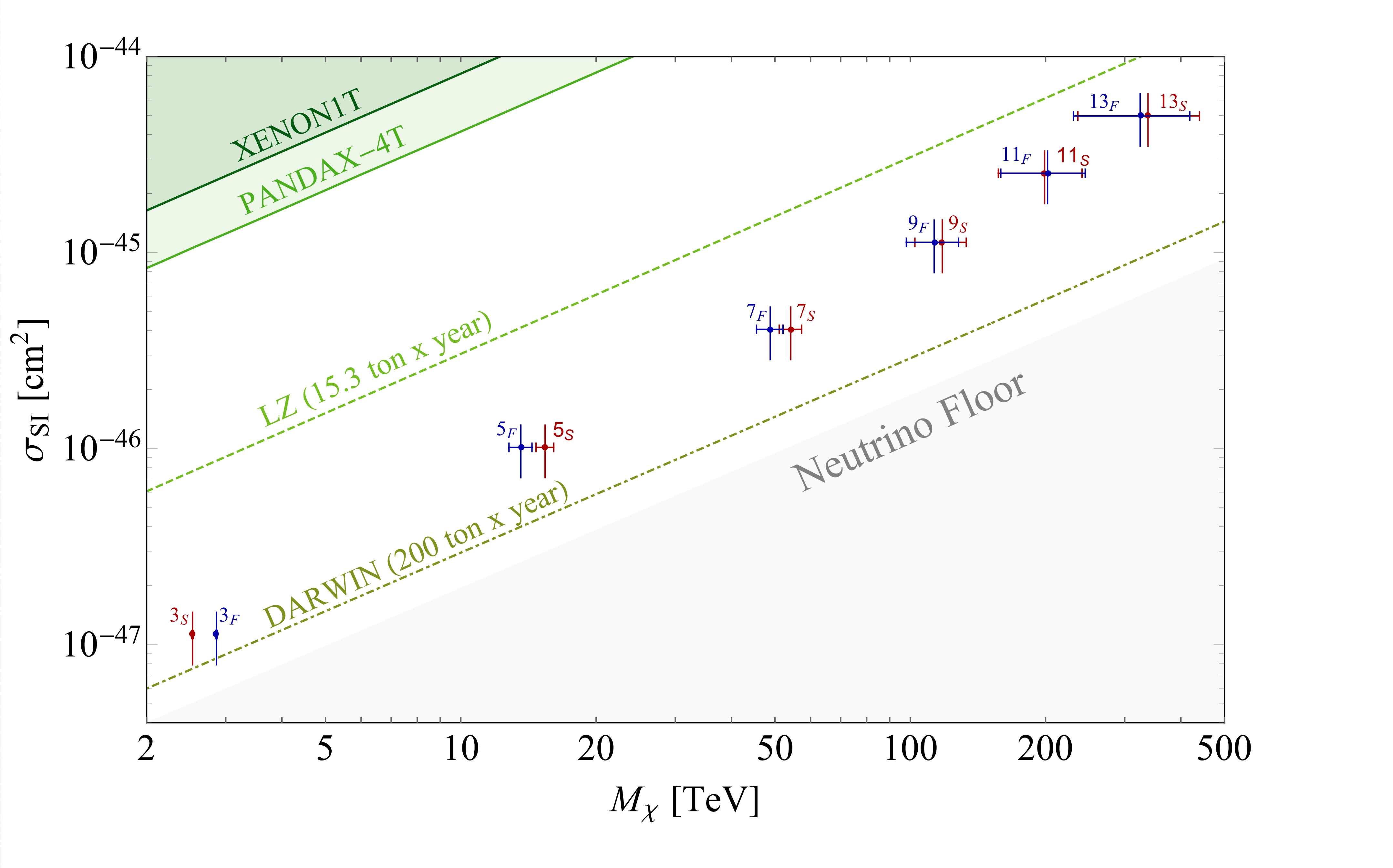
Update to HESS 2013
analysis projected to rule out by 30x,
halo loophole 1-1.5 kpc



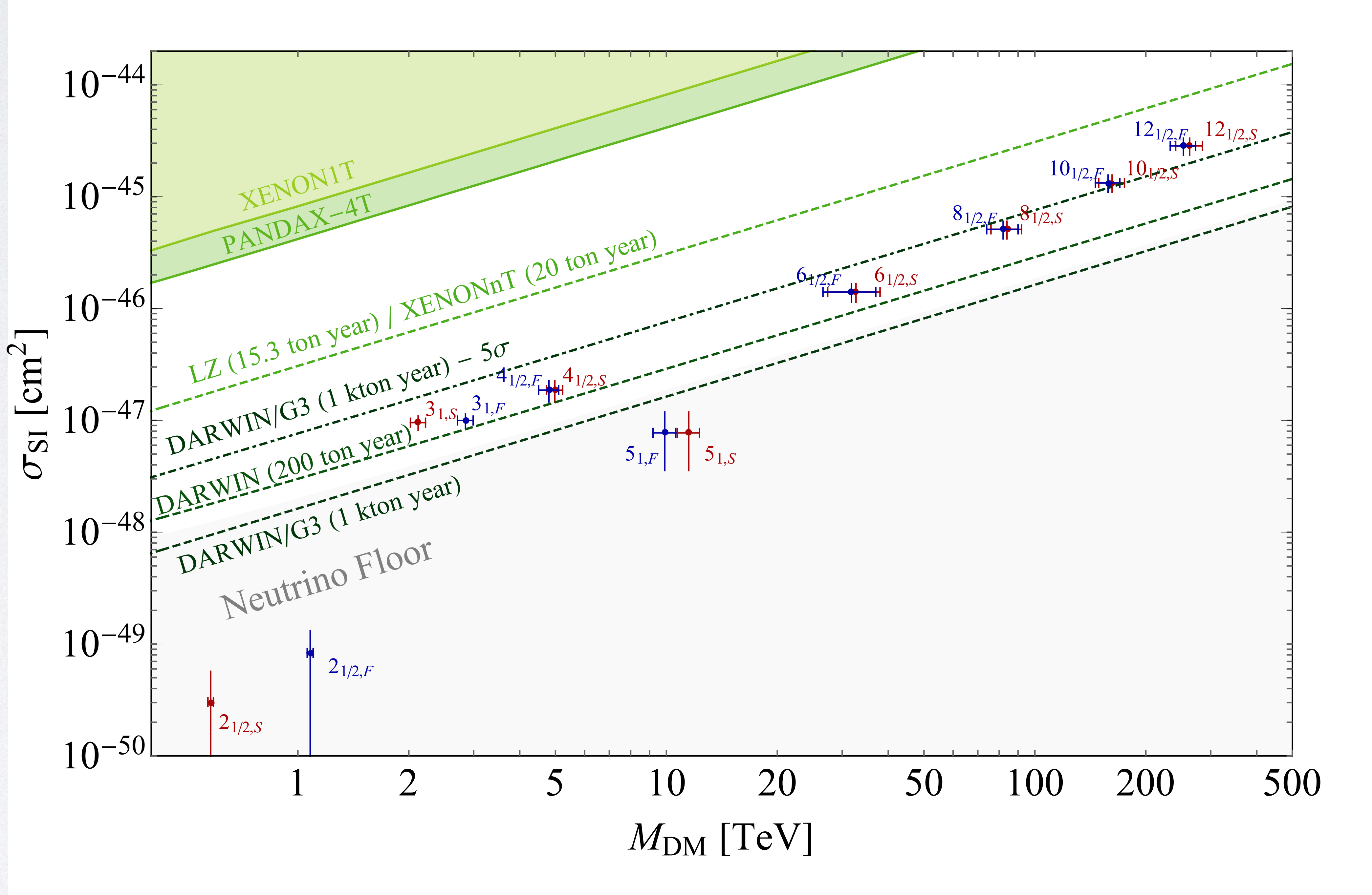
More aggressive analysis with
better galactic center understanding,
halo loophole closes, r_c>2.5 kpc

Hooper: 1608.00003 limit of 2 kpc

DIRECT DETECTION?



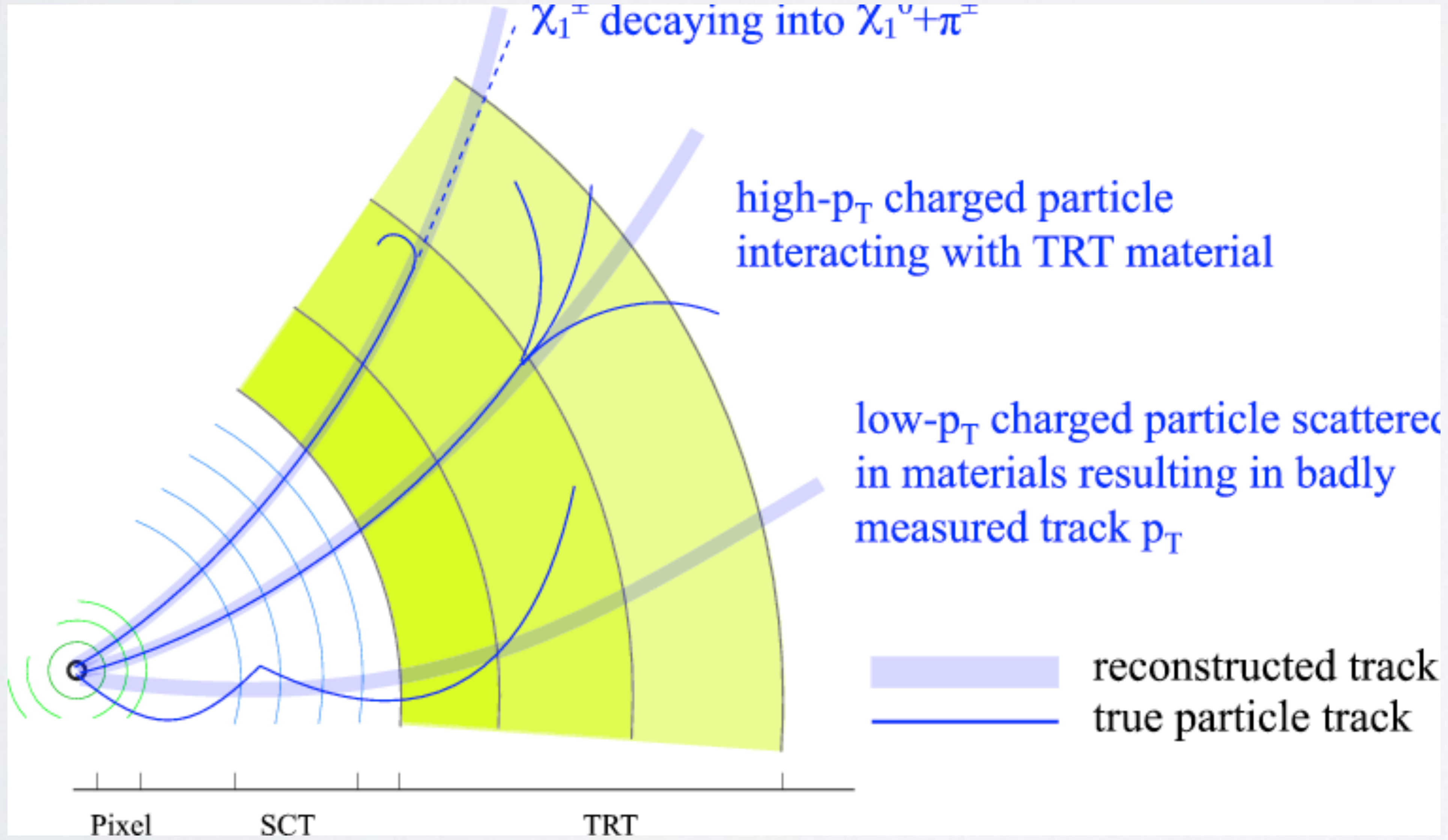
2107.09688: Bottaro et al.



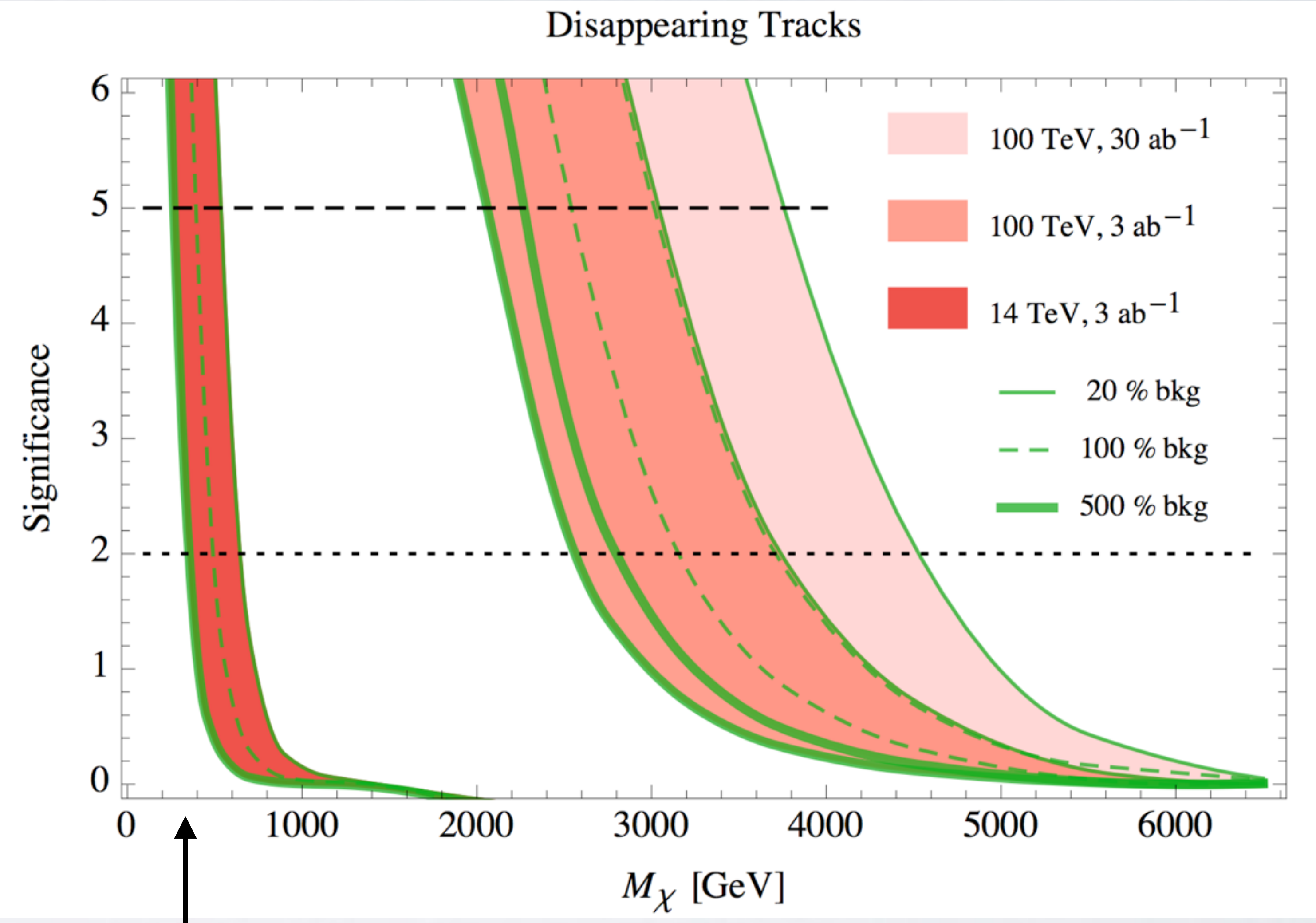
2205.04486: Bottaro et al.

MAKIN' IT AT THE LHC? NO

Find Winos
by their charged partner's
disappearing track
M_χ > 270 GeV



1202.4847 (ATLAS)



From Cirelli et al. 1407.7058

500 GeV,
LHC Wino reach

Higgsino reach
may not improve
over LEP: 110 GeV

Han et al.: 1401.1235

SOFT REFACTORIZATION

S: Perform matching

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

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

???

Remaining **soft:**

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

$\lambda = m_W/M_X$

BUT...

what about measurement function?

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

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