The WIMP Paradigm and Beyond: Status and Future Directions

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WIMP Dark Matter (DM)

Dark Matter Problem

Current energy density:

$$\Omega_{\rm DM}h^2 = 0.120 \pm 0.001$$ [Planck 2018]

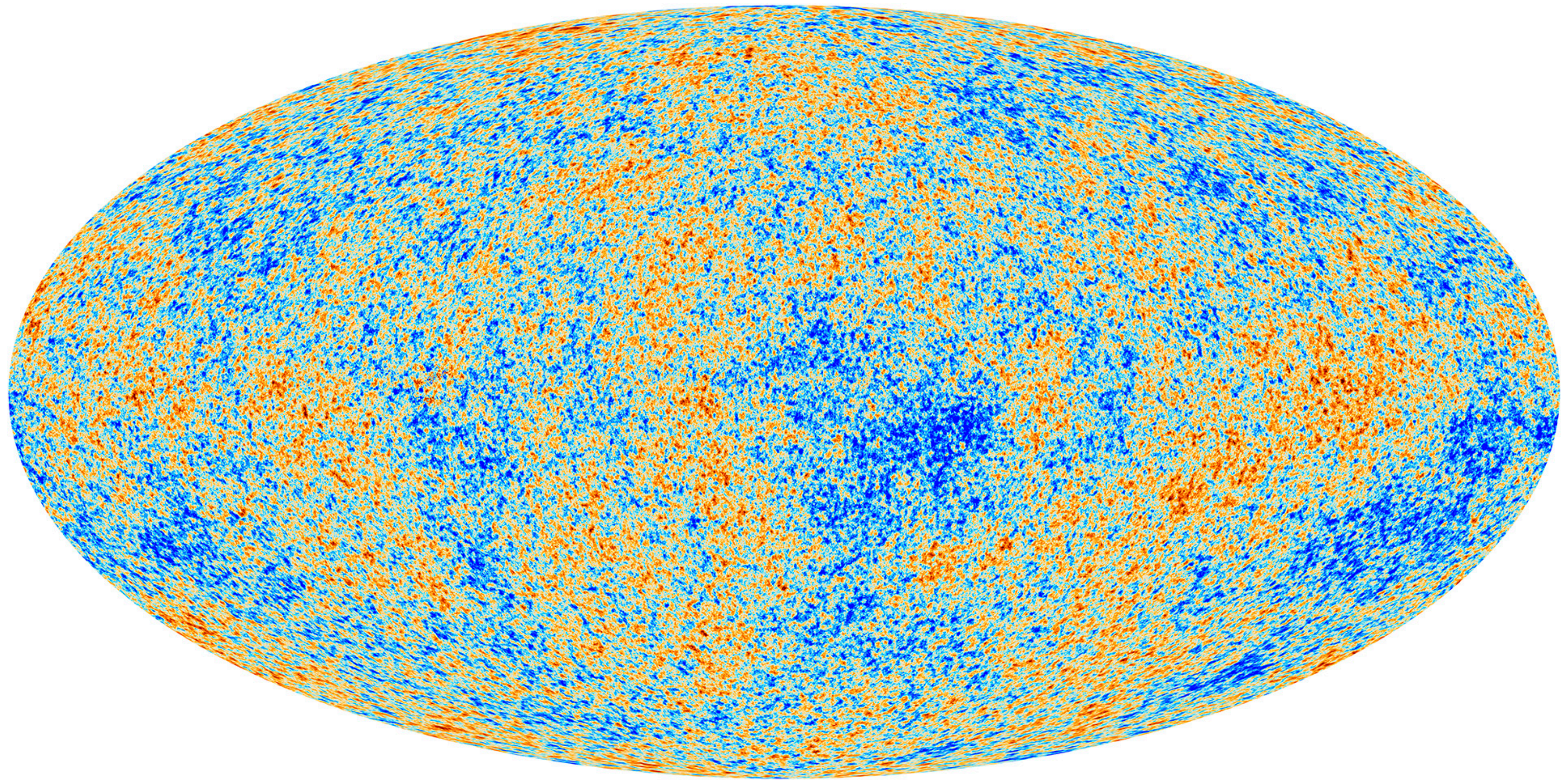
Boltzmann eq.: $$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_{\rm ann}v\rangle(n_\chi^2 - n_{\chi,\rm eq}^2)$$

WIMP approach

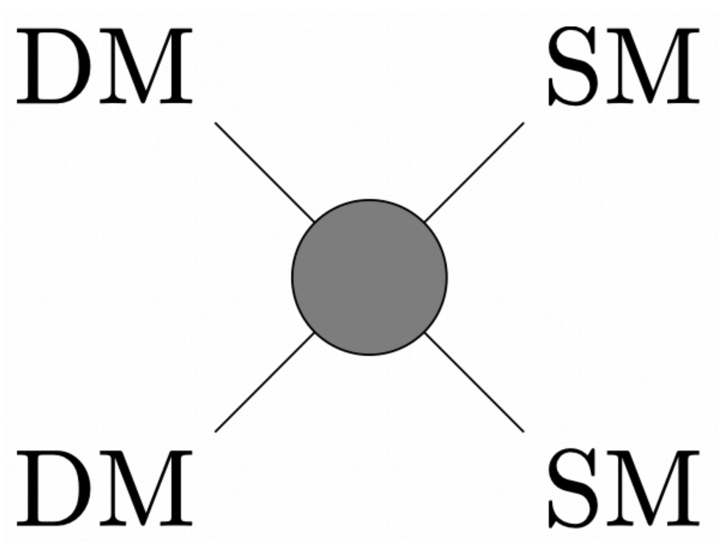
Weakly Interacting Stable & Neutral Particle

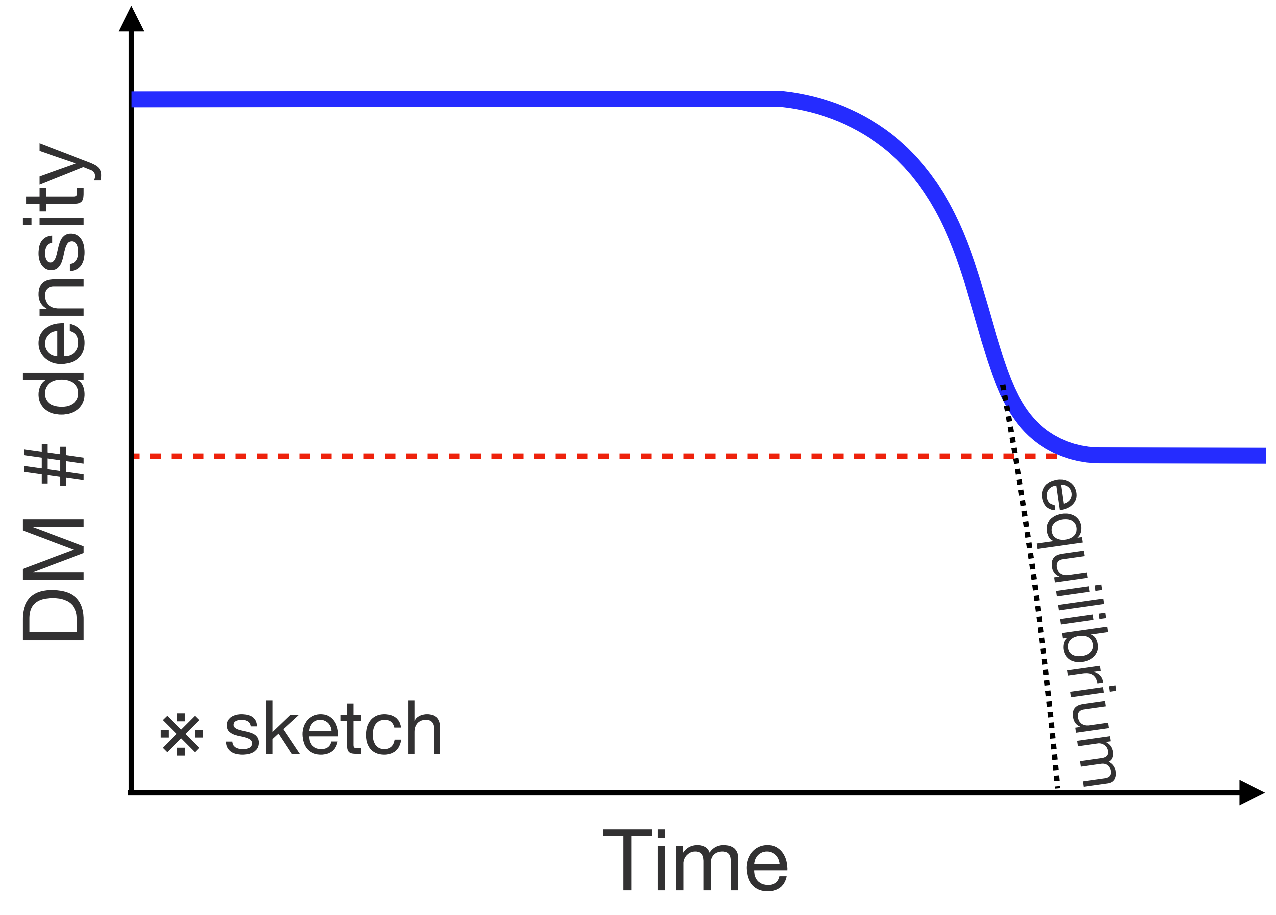
↪ thermalized in early universe

$$\langle\sigma_{\rm ann}v\rangle \sim 3\times10^{-26}\ {\rm cm^3/s}$$



Map of temperature fluctuation [Planck]



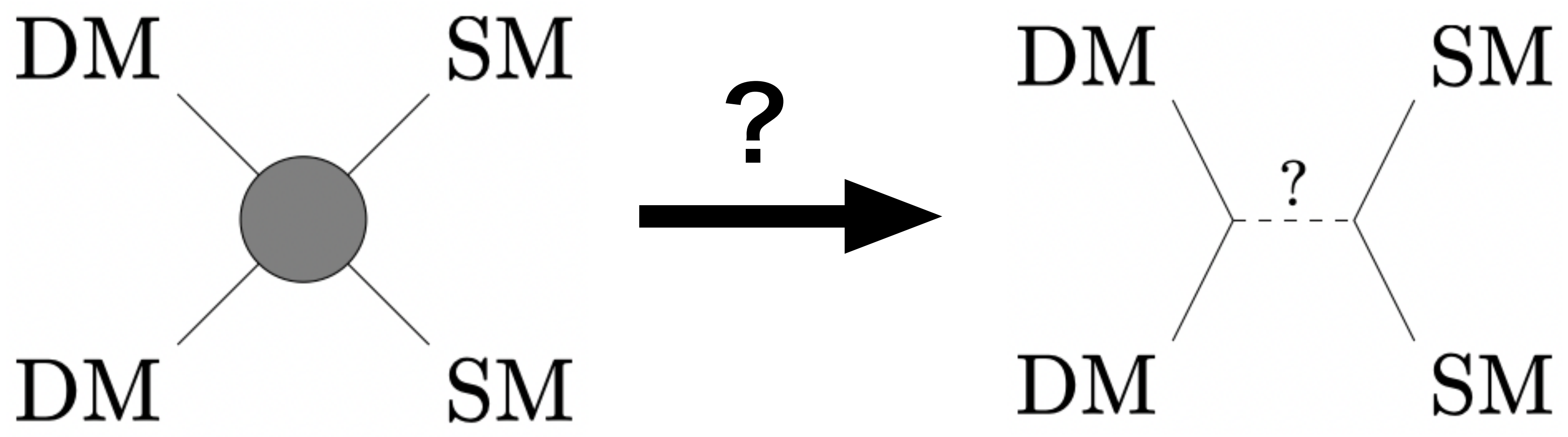


Classical WIMP paradigm (1/2)

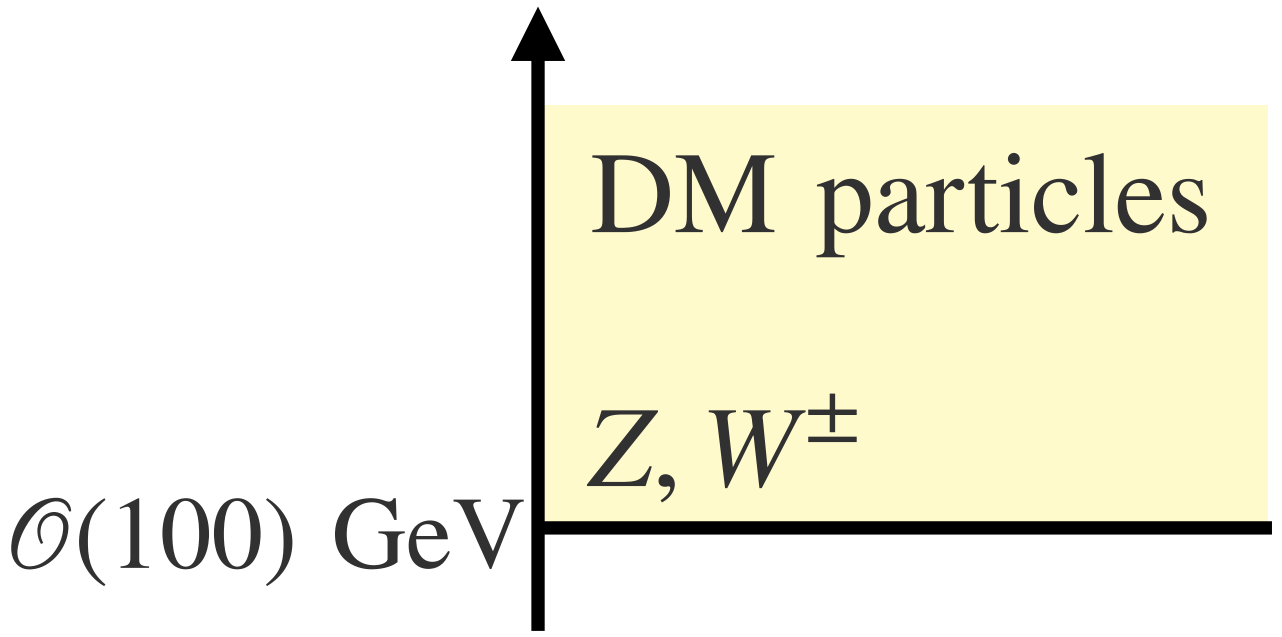
$1\ \mathrm{b} = 10^{-24}\ \mathrm{cm}^2$

$c = 3 \times 10^8\ \mathrm{m/s}$

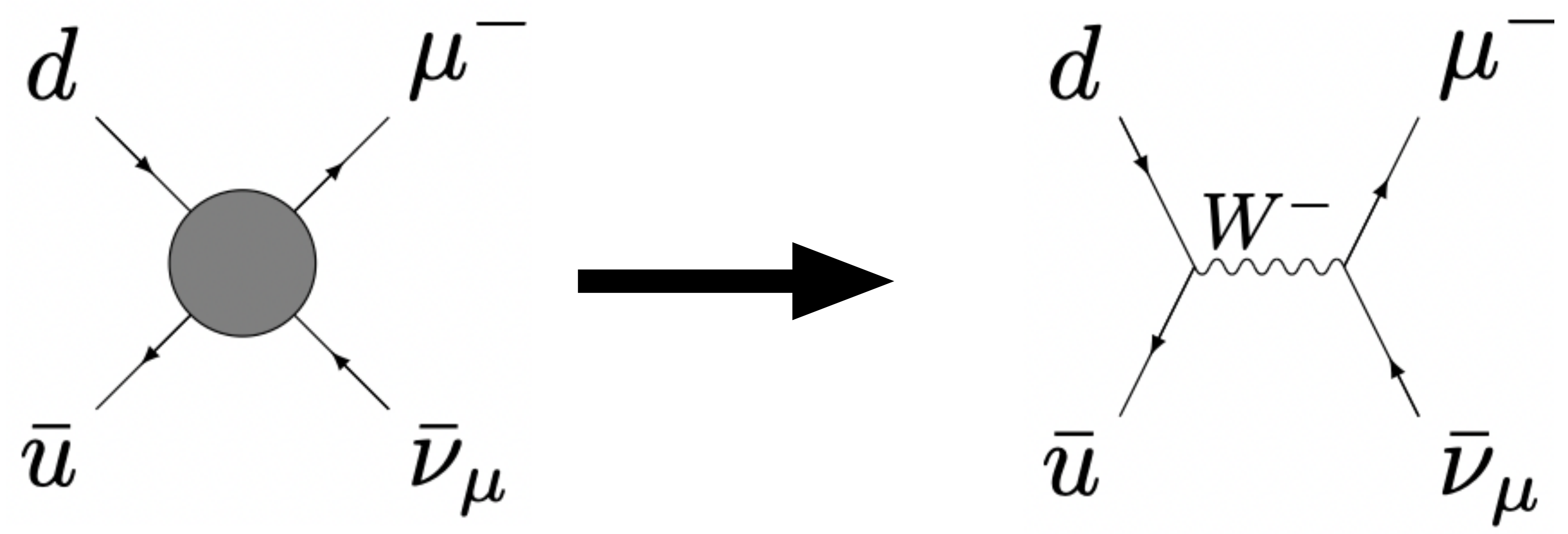
$\langle \sigma_{\mathrm{ann}} v \rangle \sim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s} \sim 1\ \mathrm{pb} \cdot c$ → Cross section for **Electroweak (EW) interaction**



New physics for ~EW scale?



e.g. charged pion decay



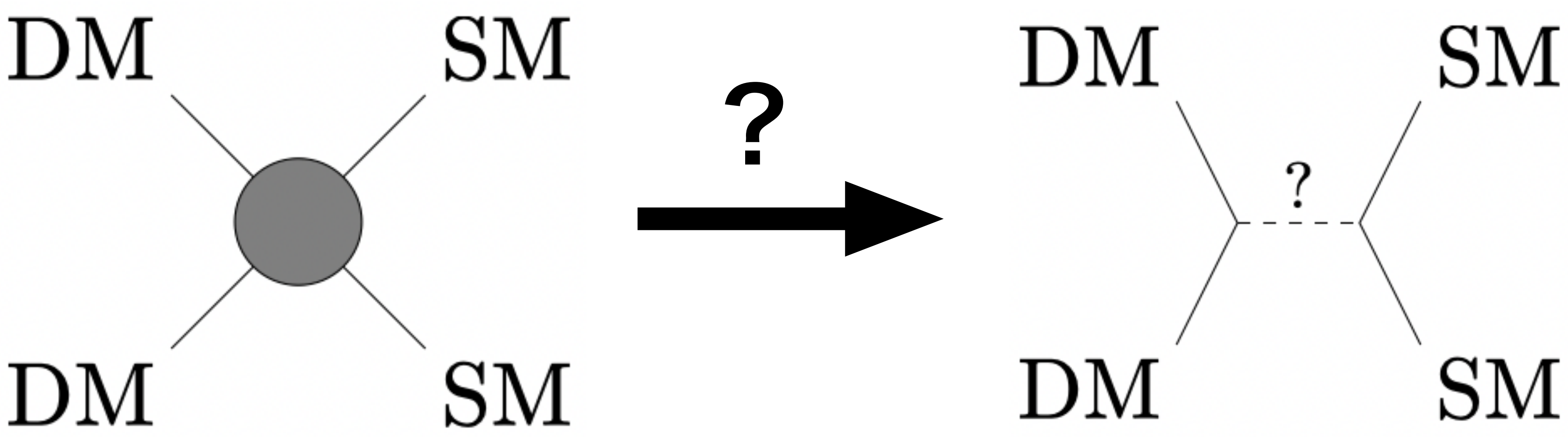
EW int. Mediated by $Z, W^{\pm}$
($m_W = 80.4$ GeV : EW scale)

Classical WIMP paradigm (2/2)

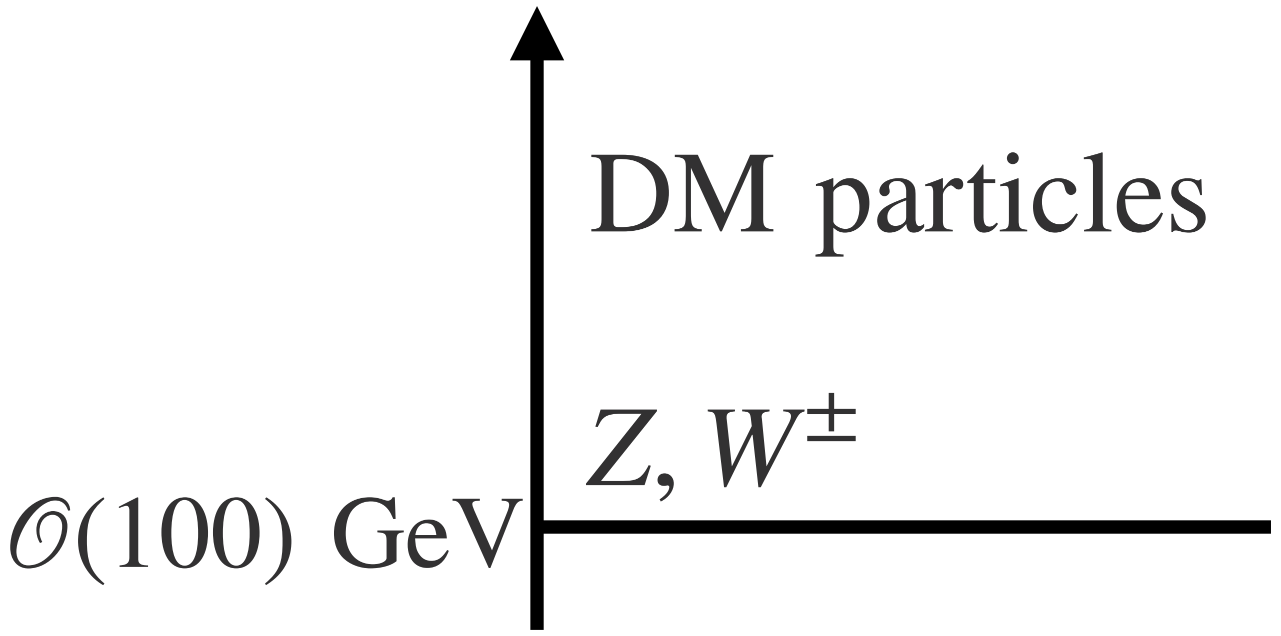
$1 \text{ b} = 10^{-24} \text{ cm}^2$

$c = 3 \times 10^8 \text{ m/s}$

$\langle \sigma_{\rm ann} v \rangle \sim 3 \times 10^{-26} \text{ cm}^3/\text{s} \sim 1 \text{ pb} \cdot c$ → Cross section for **Electroweak (EW) interaction**



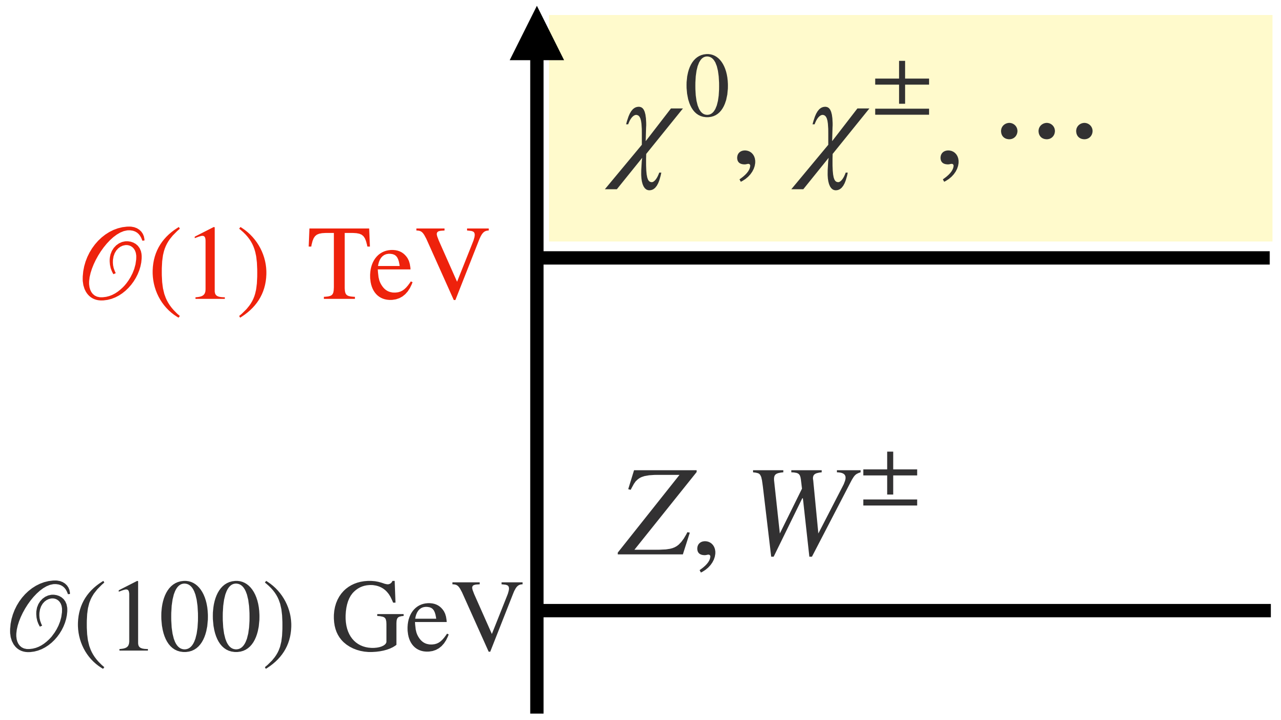
New physics for ~EW scale?



e.g. SUSY WIMP: Neutralino DM

- DM stability : R-parity
- Coupling : $\alpha_{\rm EW}(m_Z) \sim 0.033$
- DM mass : $\mathcal{O}(1)$ TeV

$\langle \sigma_{\rm ann} v \rangle \sim \dfrac{\alpha_{\rm EW}^2}{m_{\rm DM}^2}$



Typical spectrum of Classical WIMP → TeV-scale Dark Matter candidate

CTAO: New probe for TeV γ-ray

CTAO-North

- Location : La Palma, Spain
- Energy range : 20 GeV – 50 TeV

CTAO-South

- Location : Atacama desert, Chile
- Energy range : 80 GeV – 300 TeV

CTAO – A New Era for Astroparticle Physics at the Highest Energies

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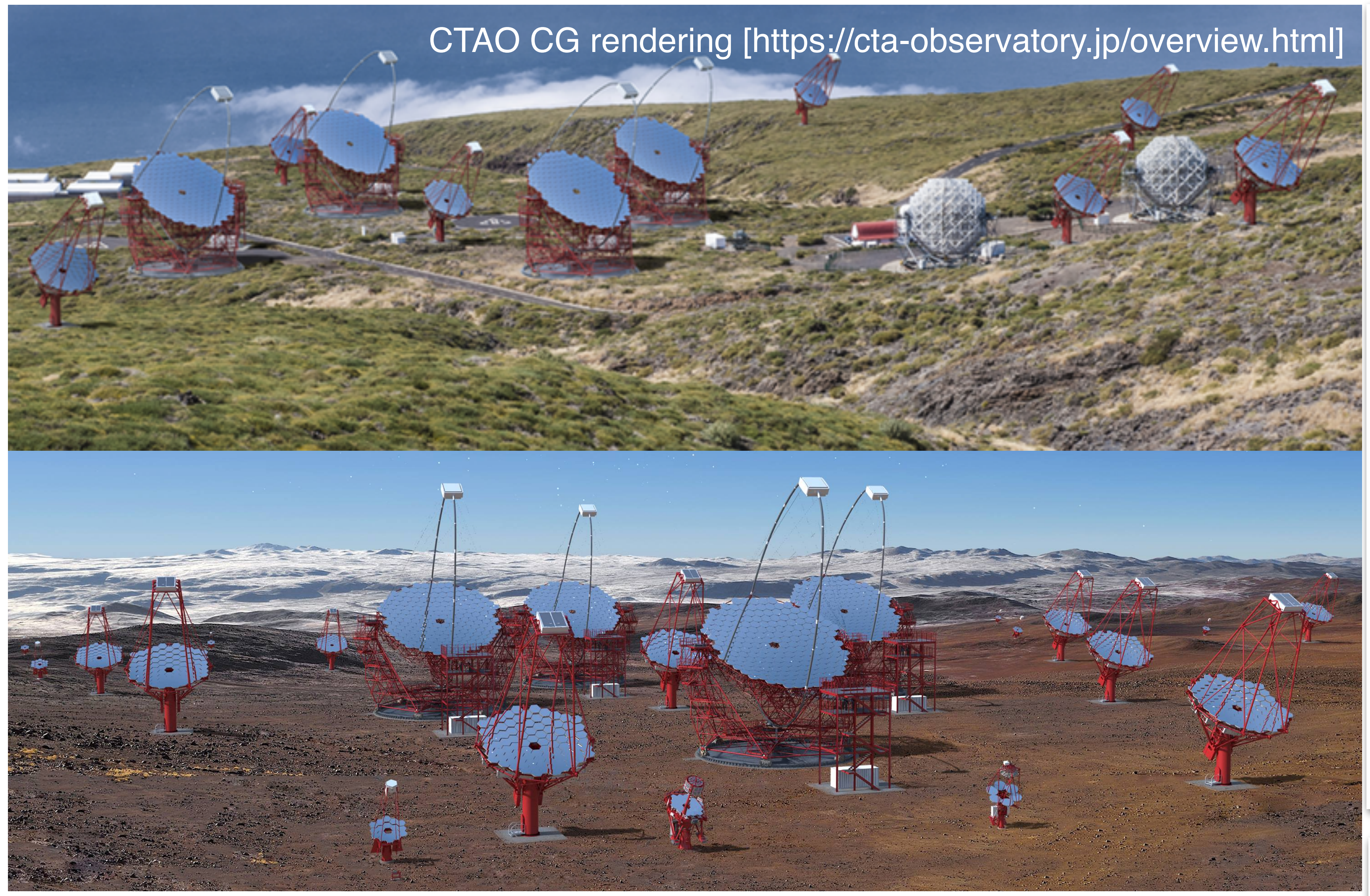
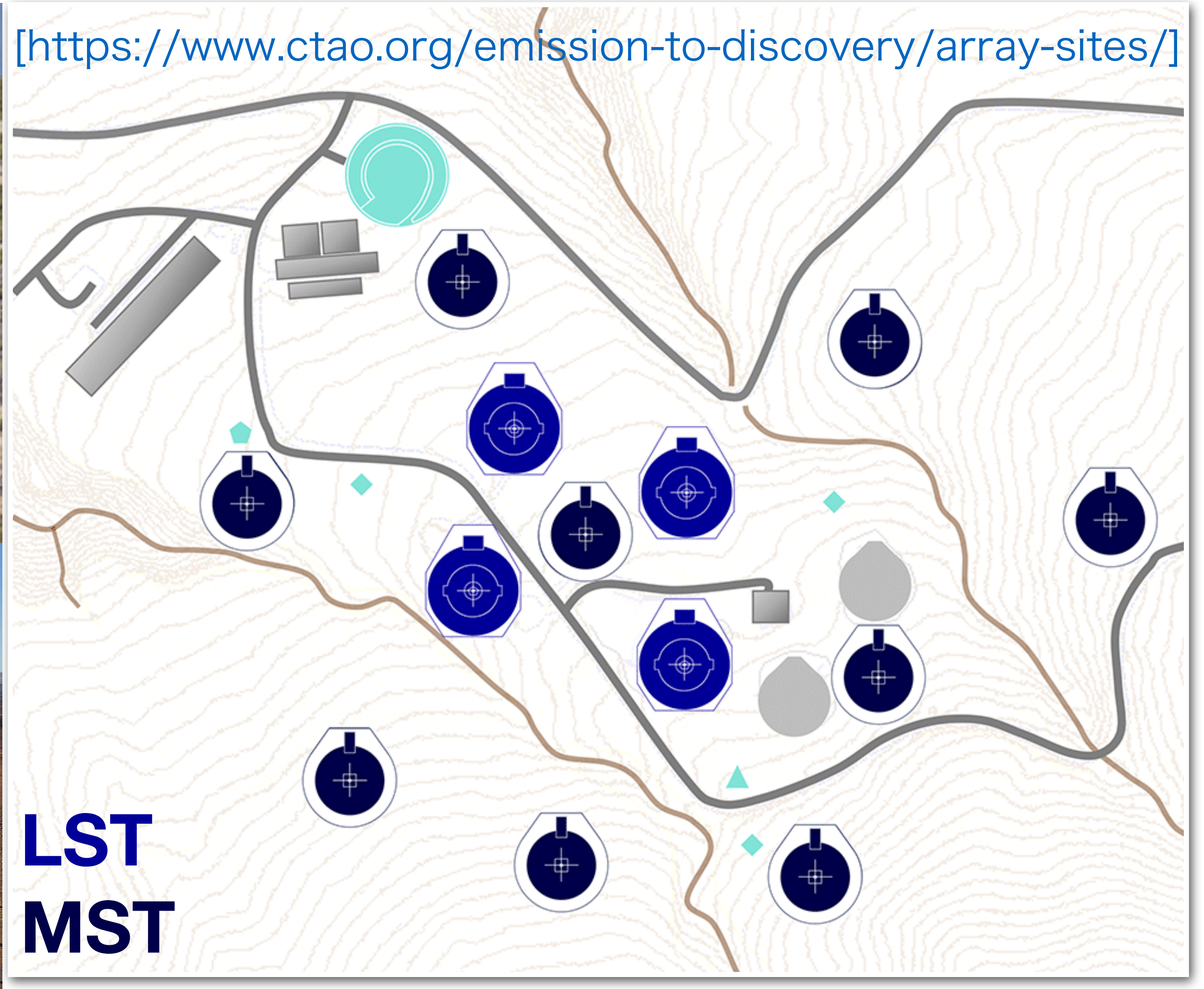
Oral · Gamma-rays · GR

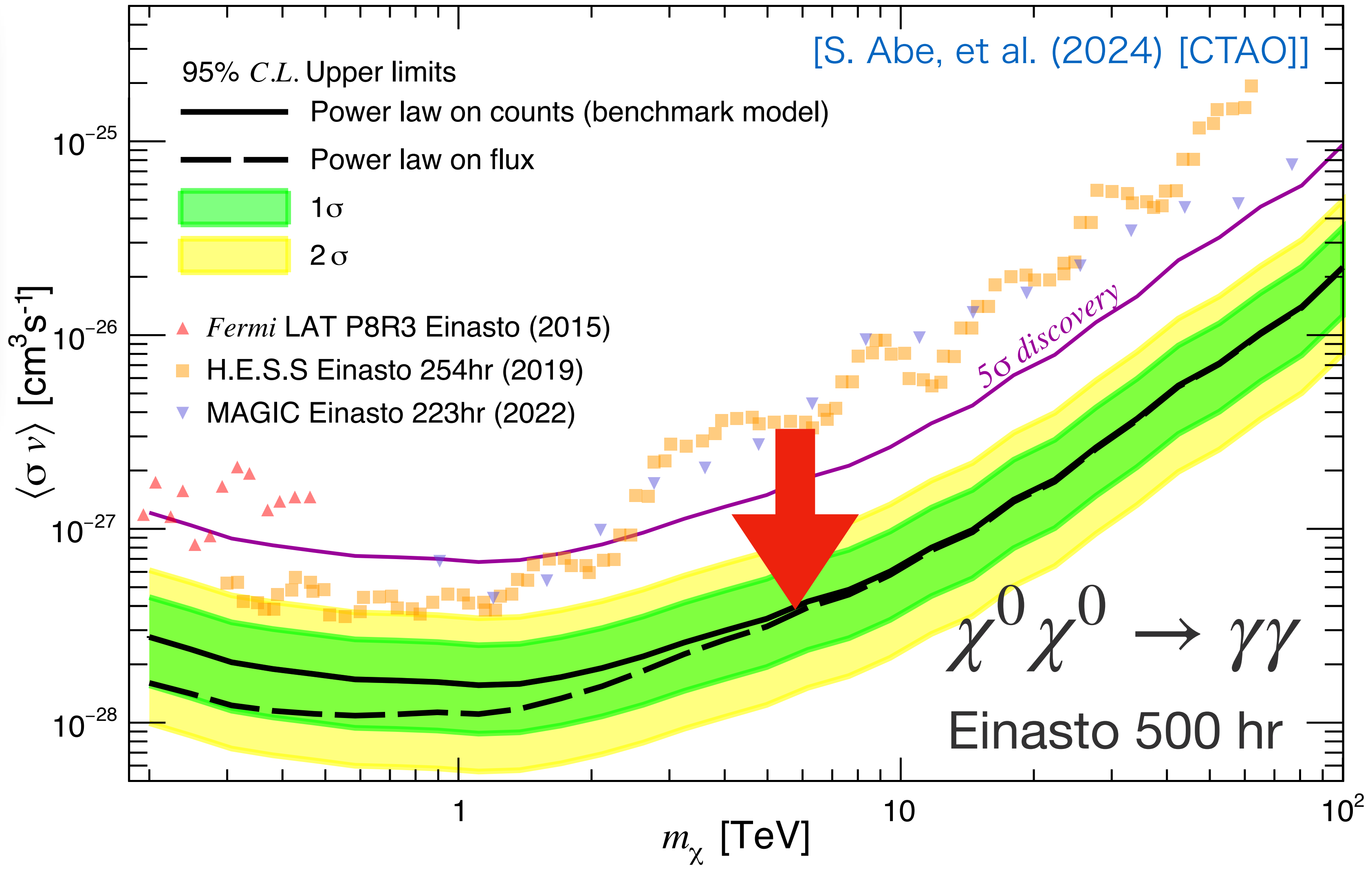
CTAO Current Status
by Ivana Batković

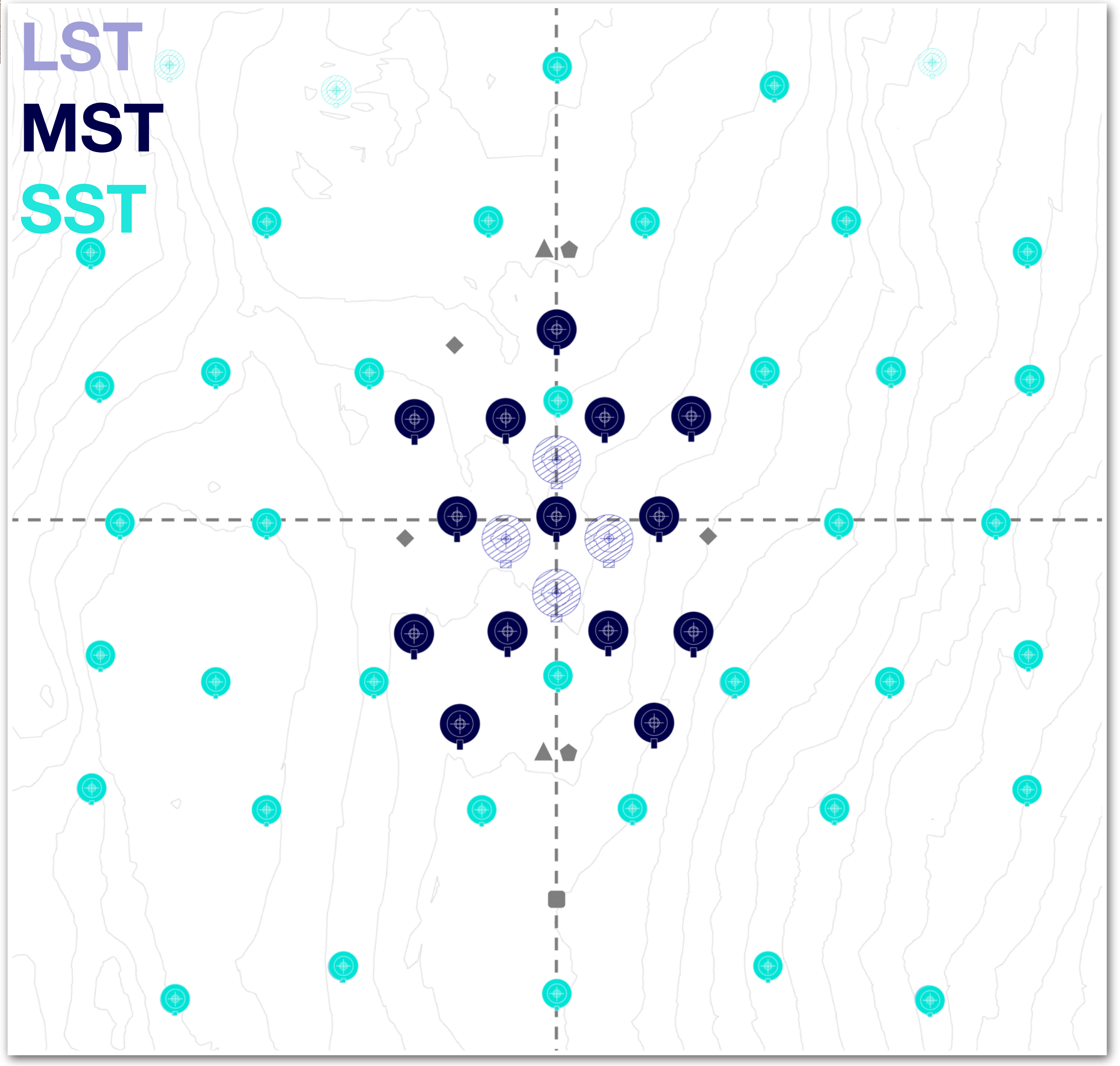
Speaker
Ivana Batković (Cherenkov Telescope Array Observatory)

TeV line gamma-ray sensitivity
→ $\times 10$ @CTAO



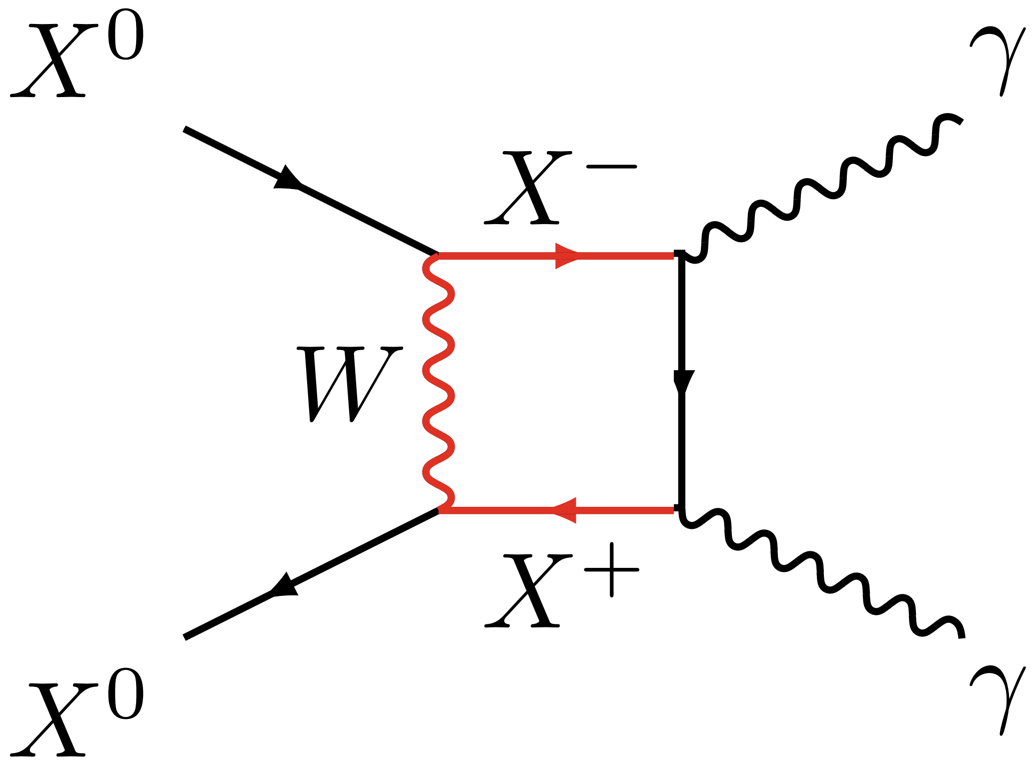




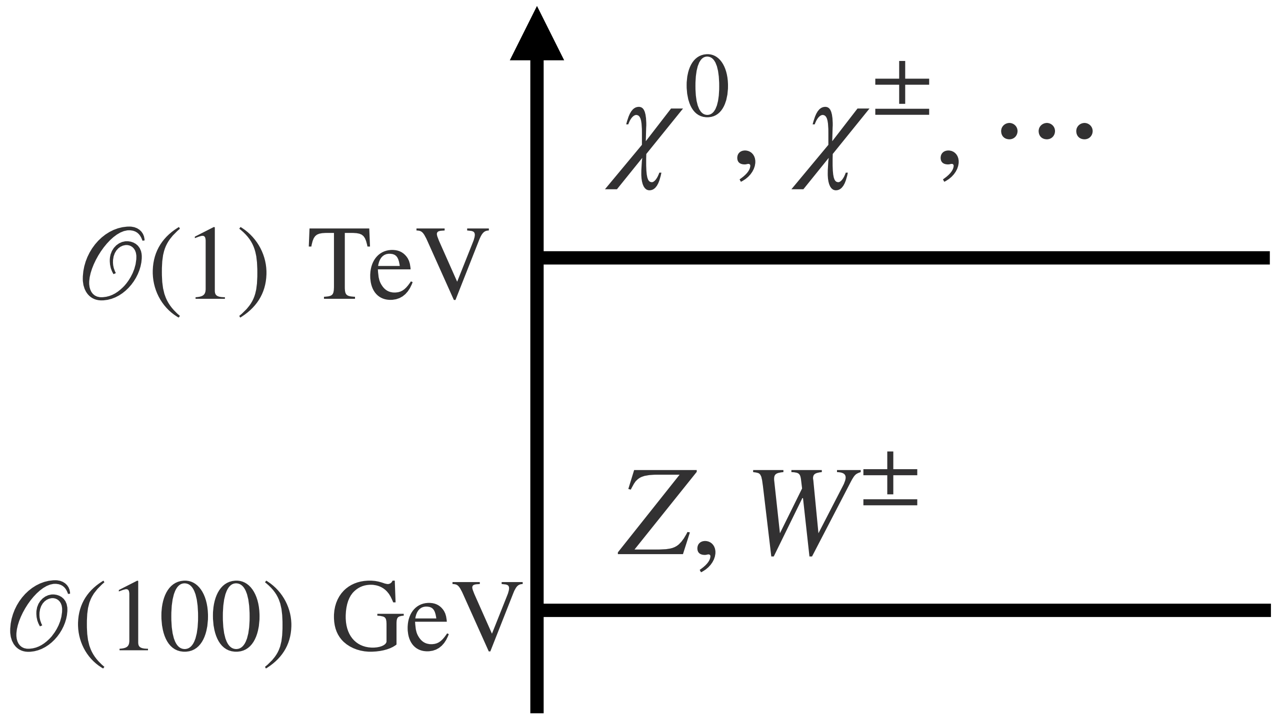


γ-ray annihilation?

Initial DM pair
(non-relativistic)

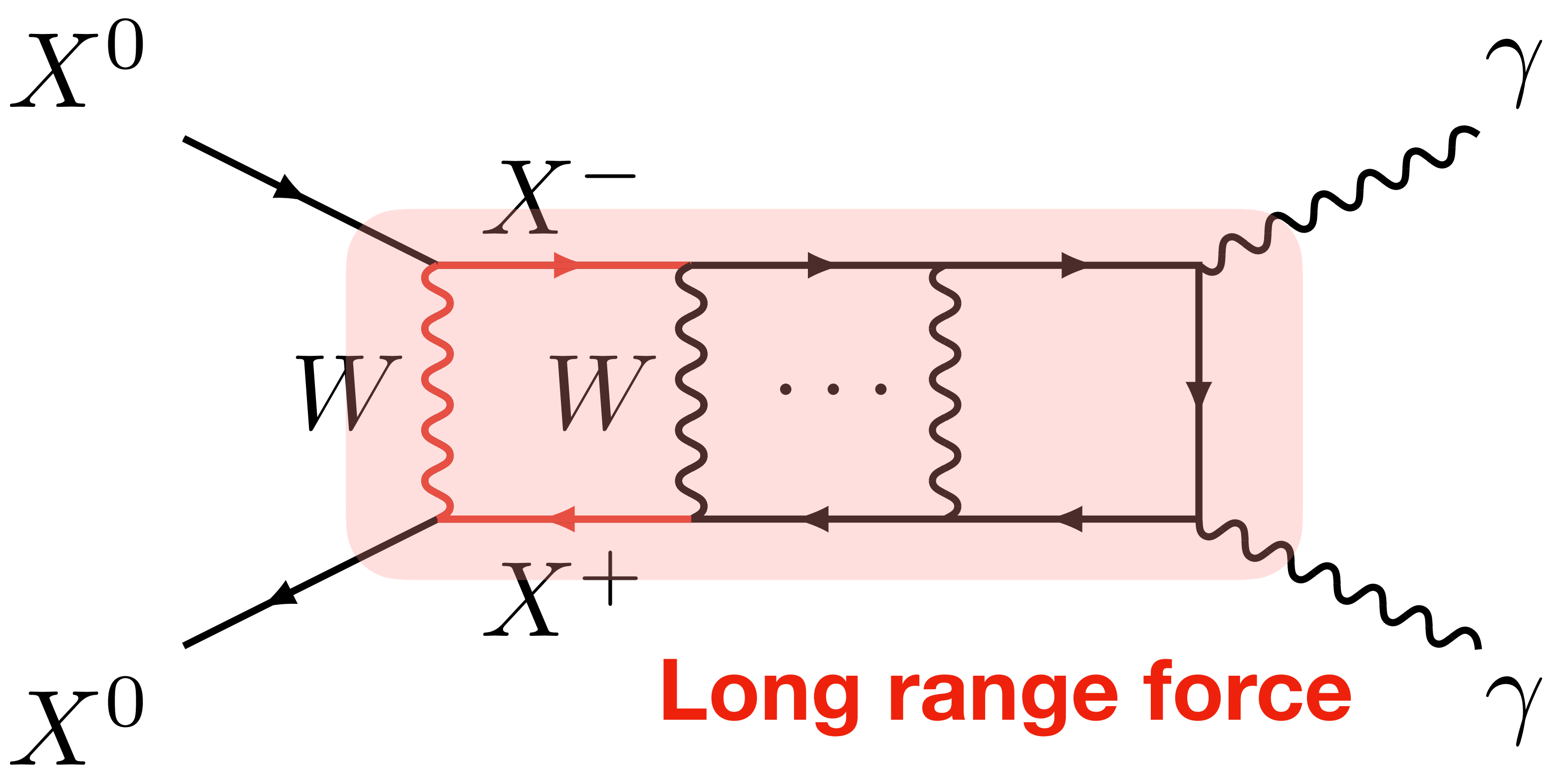


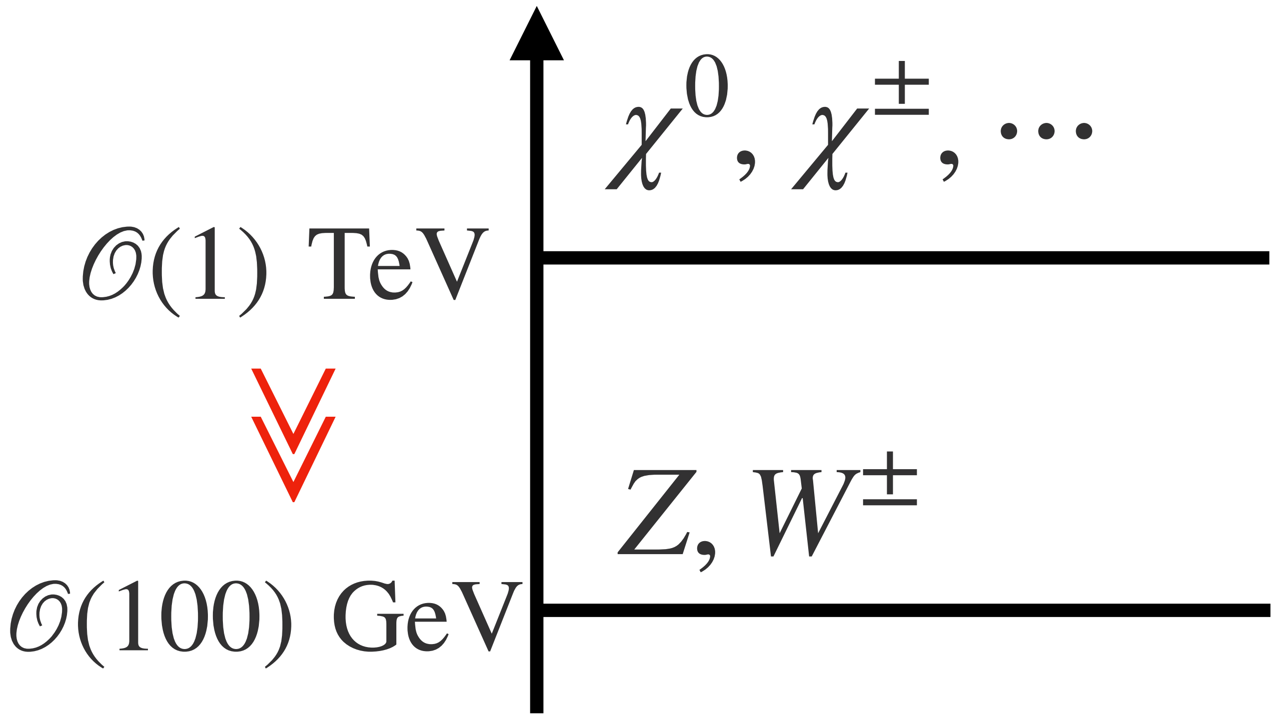
Loop suppressed?



γ-ray annihilation w/ Sommerfeld effect

Initial DM pair
(non-relativistic)





Intuitive condition: $$\frac{1}{m_{\rm DM}} \lesssim \frac{\alpha_{\rm EW}}{m_W}$$

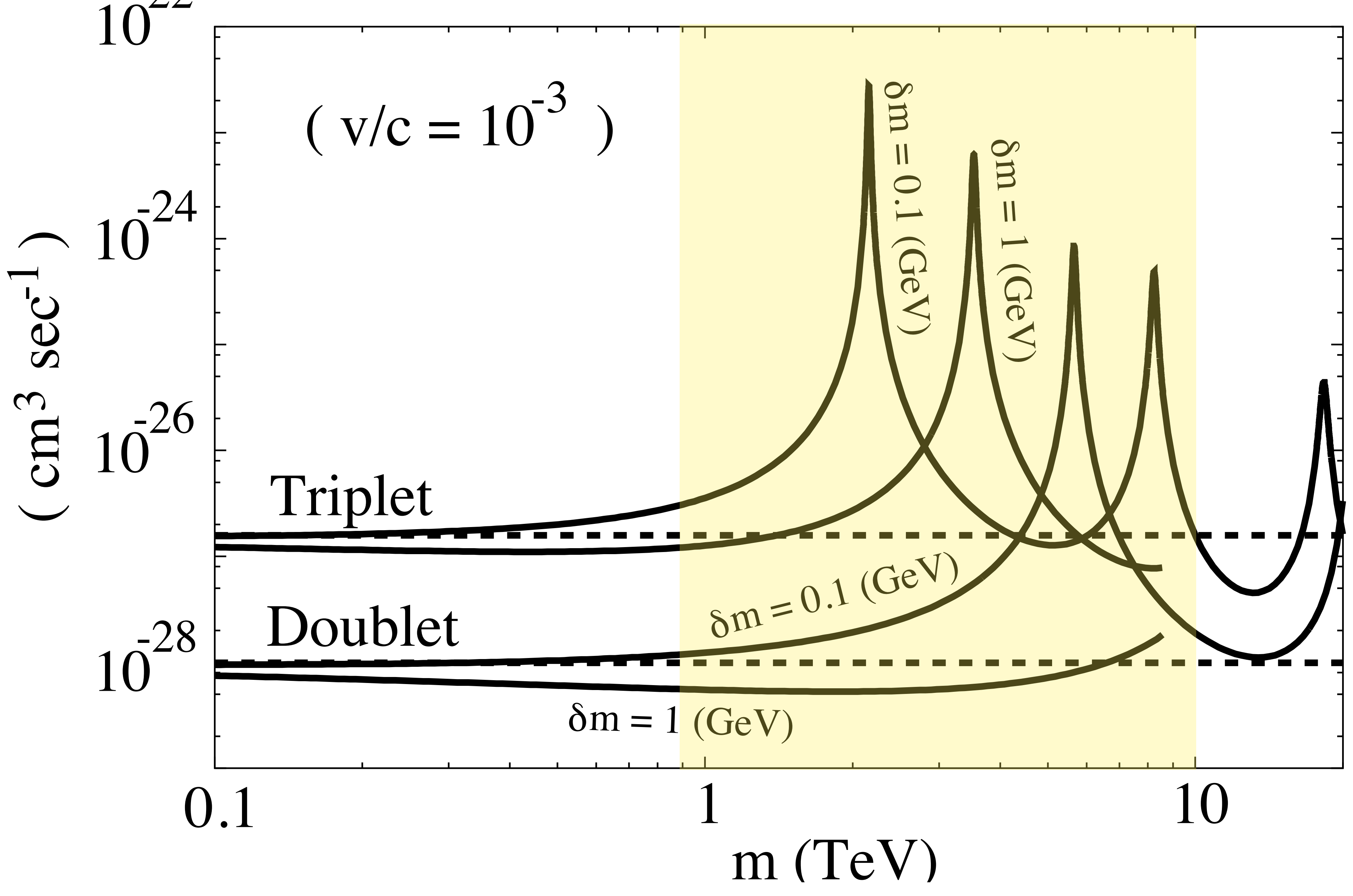
Spatial extent of DM wave func. v.s. **EW Potential**

→ Inclusion of potential effect by solving Schrödinger eq.

$$S_{\rm eff} = \sum_{J,J_z,Q} \int d^4R\, d^3r\, \Phi_Q^{J,J_z\dagger} \left(i\partial_{R^0} + \frac{\nabla_R^2}{4m_{\rm DM}} + \frac{\nabla_r^2}{m_{\rm DM}} - \hat{V}(\mathbf{r}) \right) \Phi_Q^{J,J_z}$$

Φ_Q^{J,J_z} : Dark Matter two-body state w/ charge Q & spin (J, J^z)

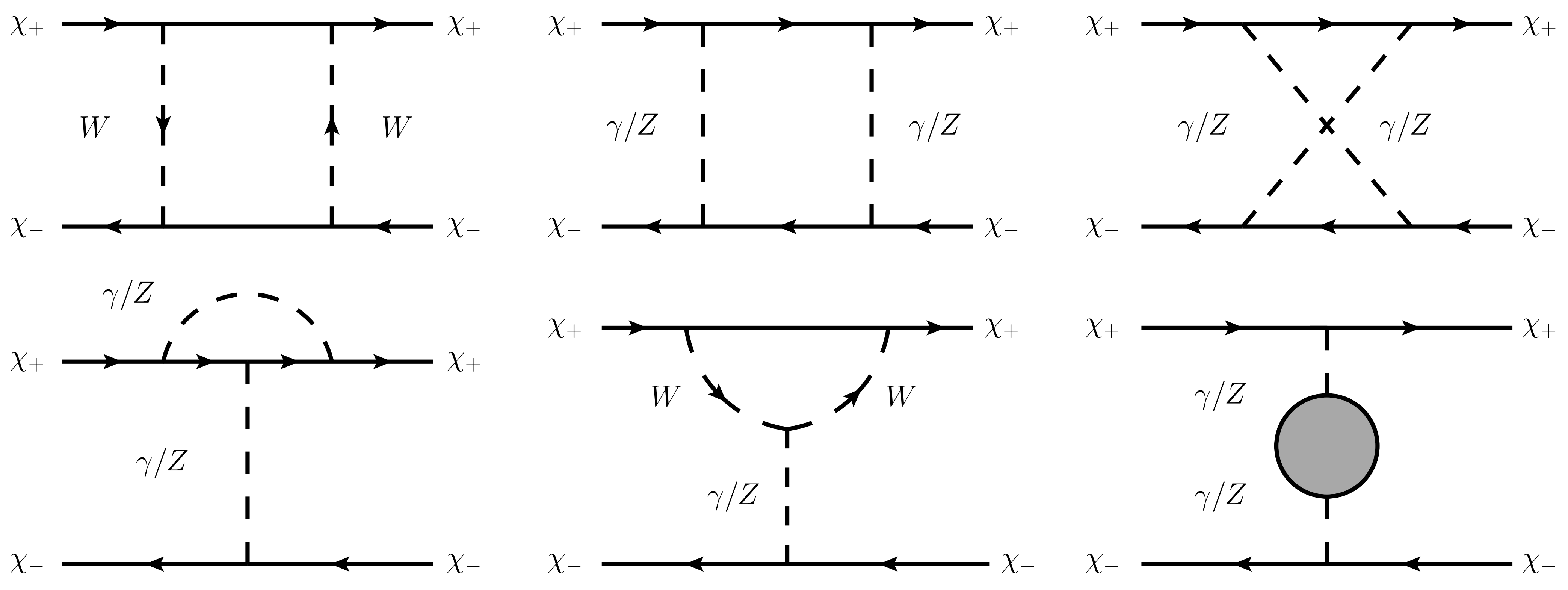
[J. Hisano, S. Matsumoto, N. M. Mihoko, S. Saito (2005)]



Precision 1: Correction in EW potential

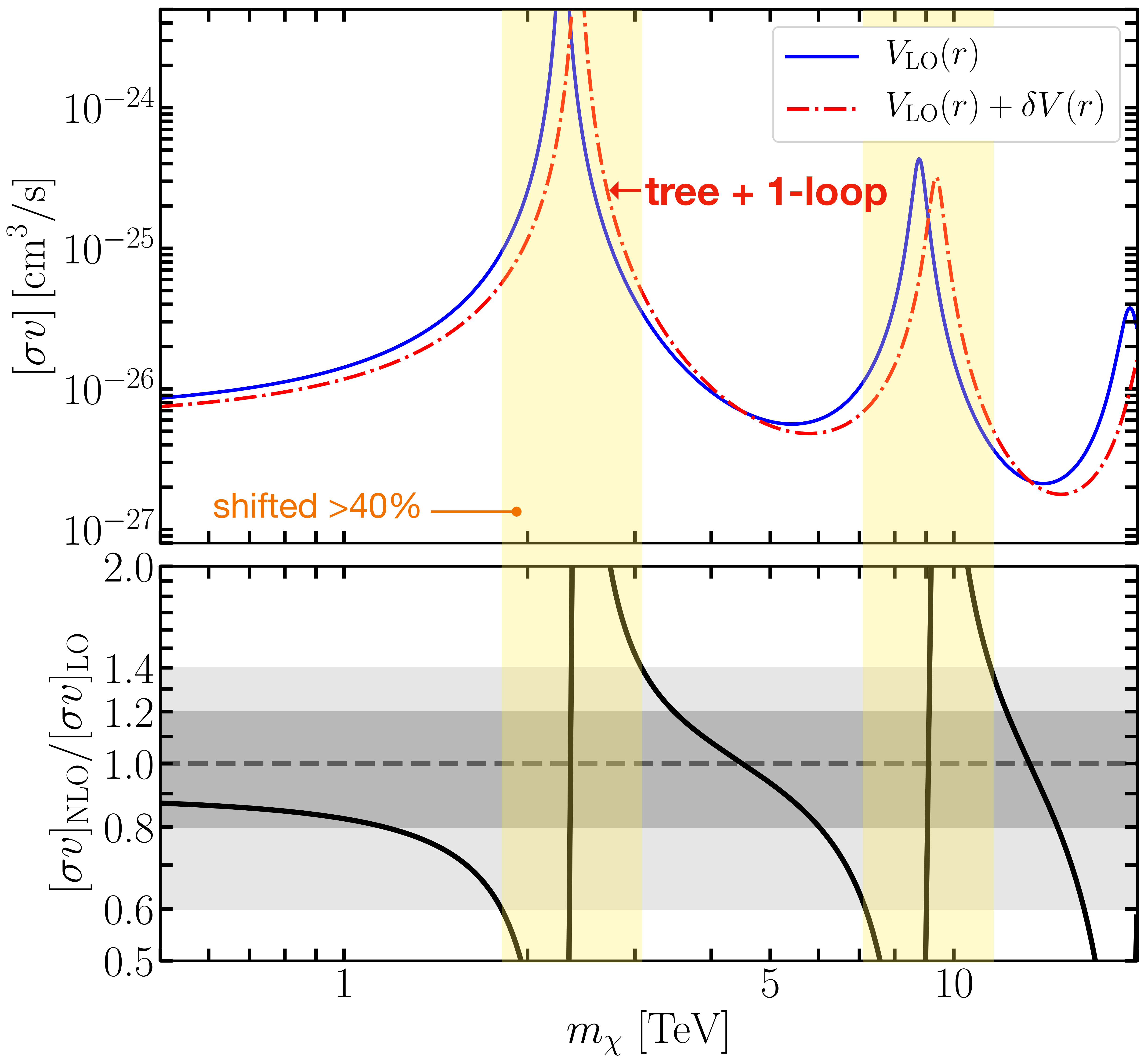
Correction to Potential

- e.g. Pure Wino [SU(2)$_L$ triplet, spin-1/2]
- Feature: thermal DM mass is **around resonance**
- Tree-level v.s. 1-loop
  → DM mass for resonance: shifted by ~3%
- Cross section drastically changes around peak



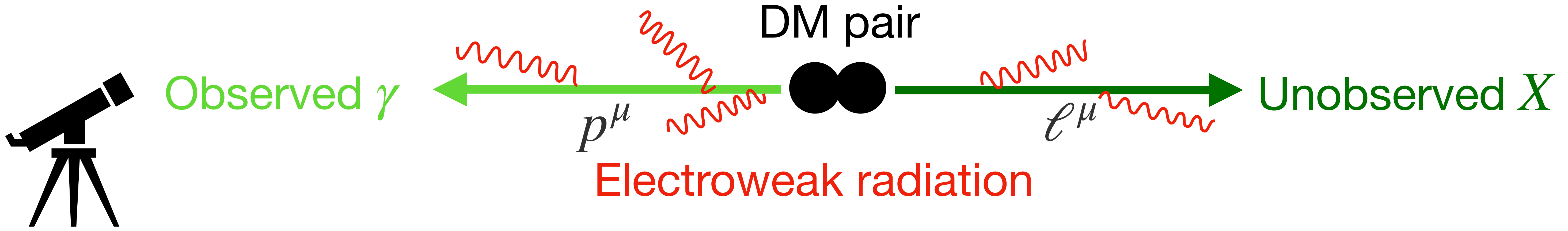
Correction: $> \mathcal{O}(10)\ \%$ **around resonance**

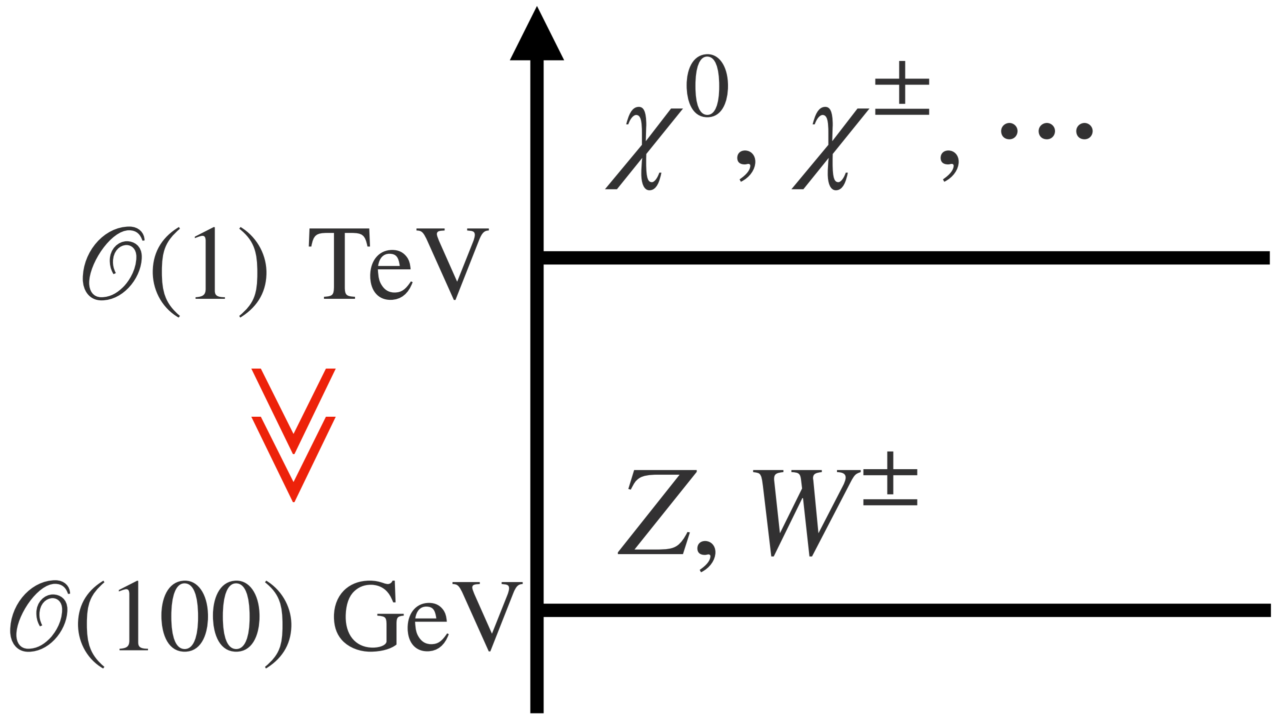
[M. Beneke, R. Szafron, K. Urban (2020)]



Precision 2: Log correction (1/3)

Kinematics

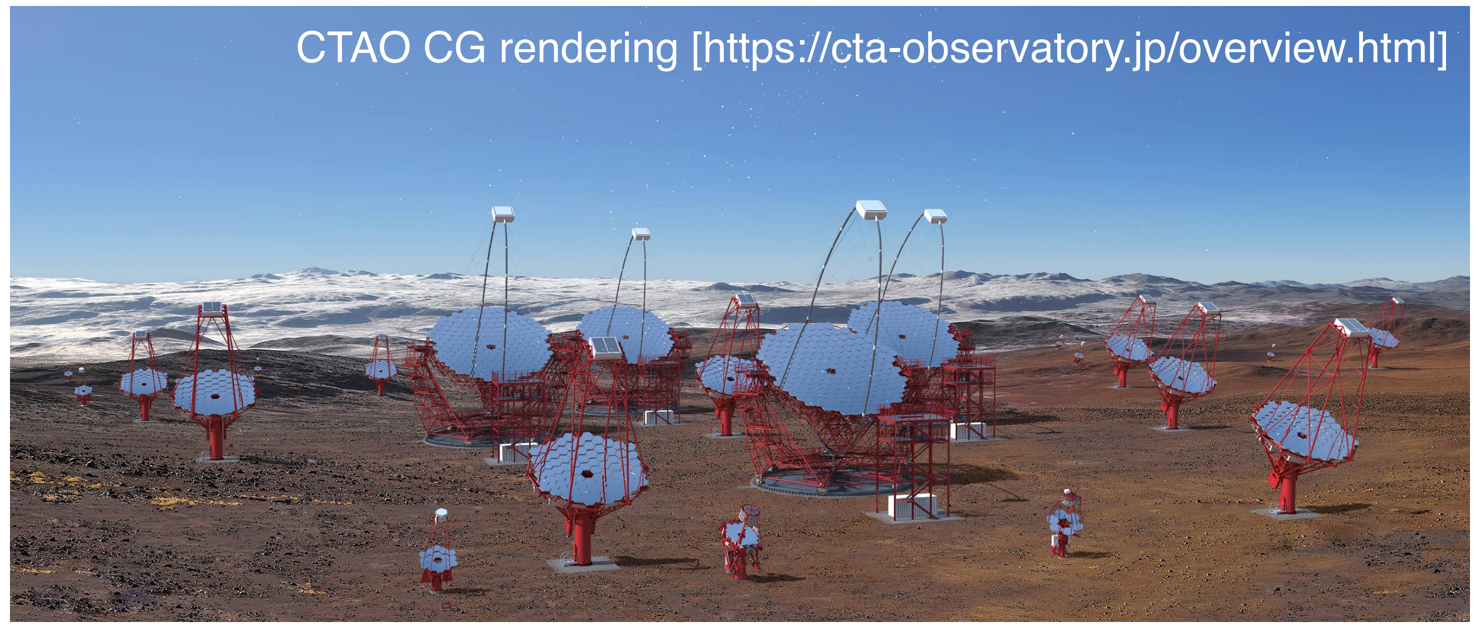




- Non-relativistic DM pair : $q^\mu \sim (2m_{\rm DM}, \mathbf{0})$ $\parallel$ $q^2 \sim m_{\rm DM}^2 \equiv Q^2$
- Collinear EW boson : $p^\mu \sim m_{\rm DM}(1, \lambda, \lambda, 1)$ $\parallel$ $p^2 \sim Q^2 \times \lambda^2$
- Anti-collinear EW boson : $\ell^\mu \sim m_{\rm DM}(1, \lambda, \lambda, -1)$ $\parallel$ $\ell^2 \sim Q^2 \times \lambda^2$
- Soft EW radiation : $k^\mu \sim m_{\rm DM}(\lambda^2, \lambda^2, \lambda^2, \lambda^2)$ $\parallel$ $k^2 \sim Q^2 \times \lambda^4$

Perturbative parameter: $\lambda \sim \dfrac{m_W}{2m_{\rm DM}}$

Amplitude: $\supset \# \log\left(\dfrac{q^2, p^2, \ell^2, k^2}{\mu^2}\right) + \# \left[\log\left(\dfrac{q^2, p^2, \ell^2, k^2}{\mu^2}\right)\right]^2 + \cdots$ v.s. $\longleftrightarrow$



How to control uncertainty in estimating Scale in Multi-energy system?

Precision 2: Log correction (2/3)

$$i\mathcal{M} = \left(\text{complicated func. of } \{Q^2, P^2, L^2, \Lambda_s^2\}\right)$$

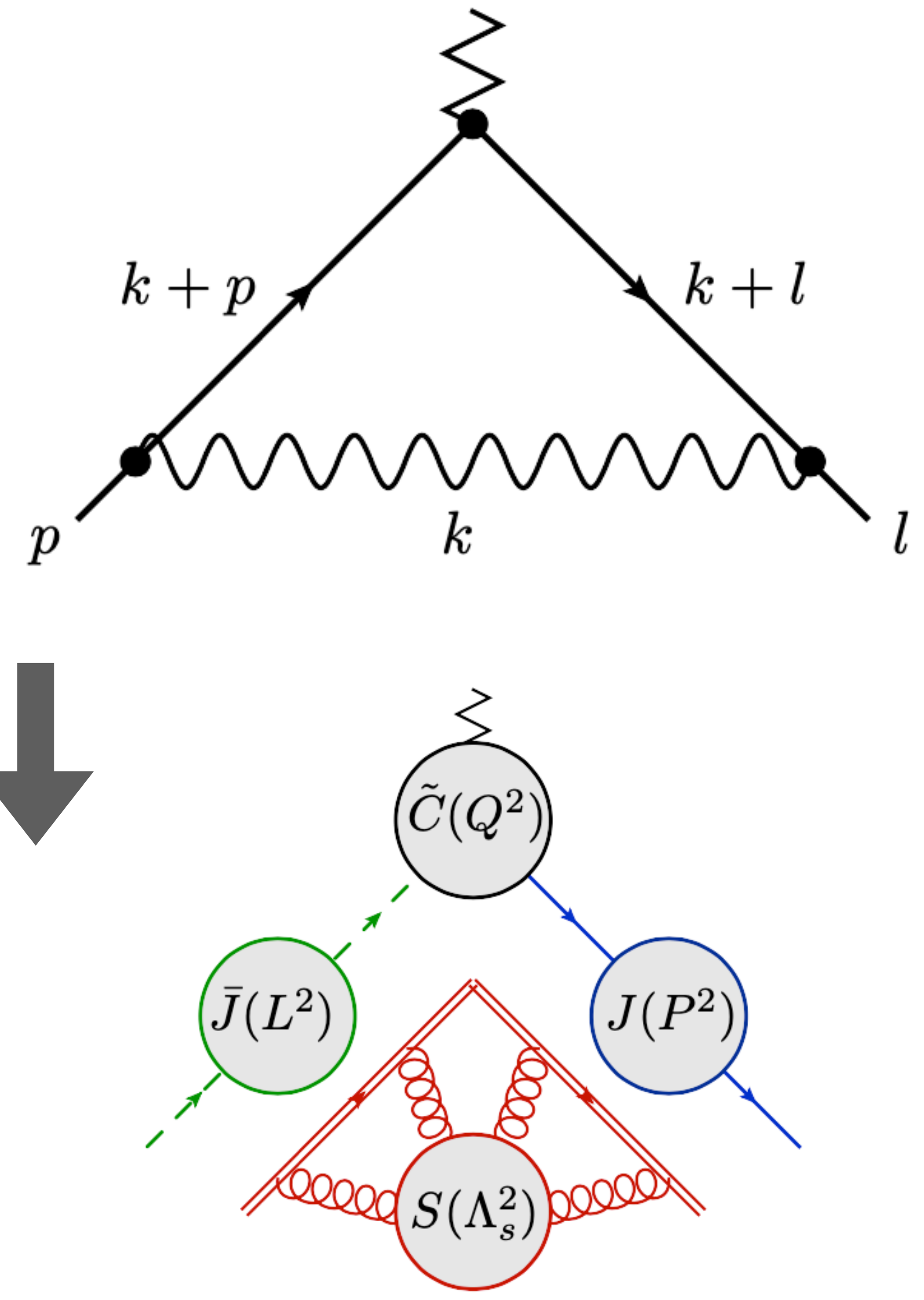
Factorization of energy scale in amplitude
(Strategy of region + dim. reg.)

$$= \underbrace{C(Q^2,\mu)}_{\text{hard}} \times \underbrace{J(P^2,\mu)}_{\text{anti-collinear}} \times \underbrace{\bar{J}(L^2,\mu)}_{\text{collinear}} \times \underbrace{S(\Lambda_s^2,\mu)}_{\text{soft}}$$

Full theory

Matching

SCET



Soft Collinear Effective Theory (SCET)

Factorize interaction effects @each energy scale by neglecting power-suppressed correction

- Hierarchical energy scales: **hard, collinear, anti-collinear, soft**

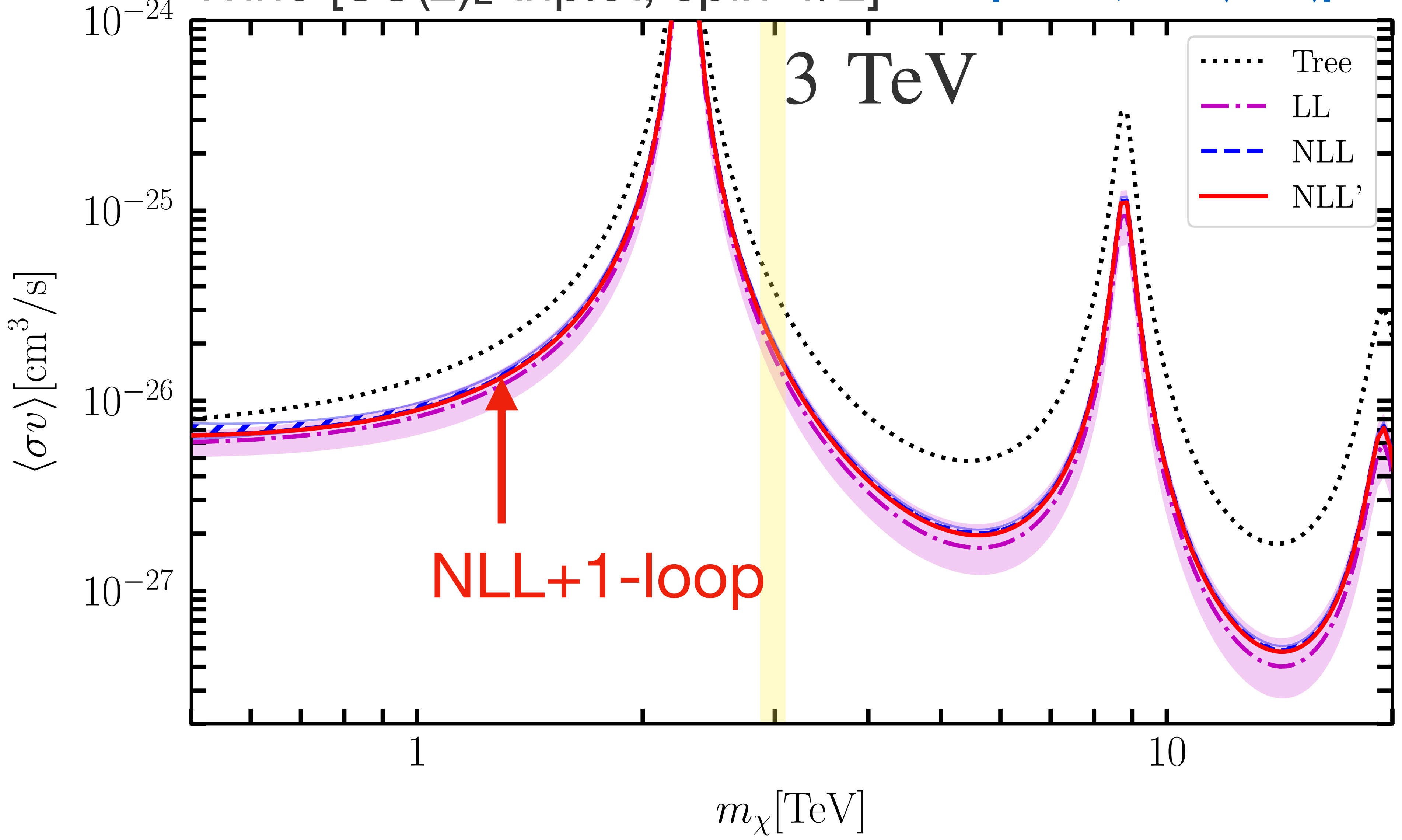
  (system w/ 4 different energy scales) $\Leftarrow$ matching $\Rightarrow$ (single energy system) $\times 4$

  suppress log correction systematically

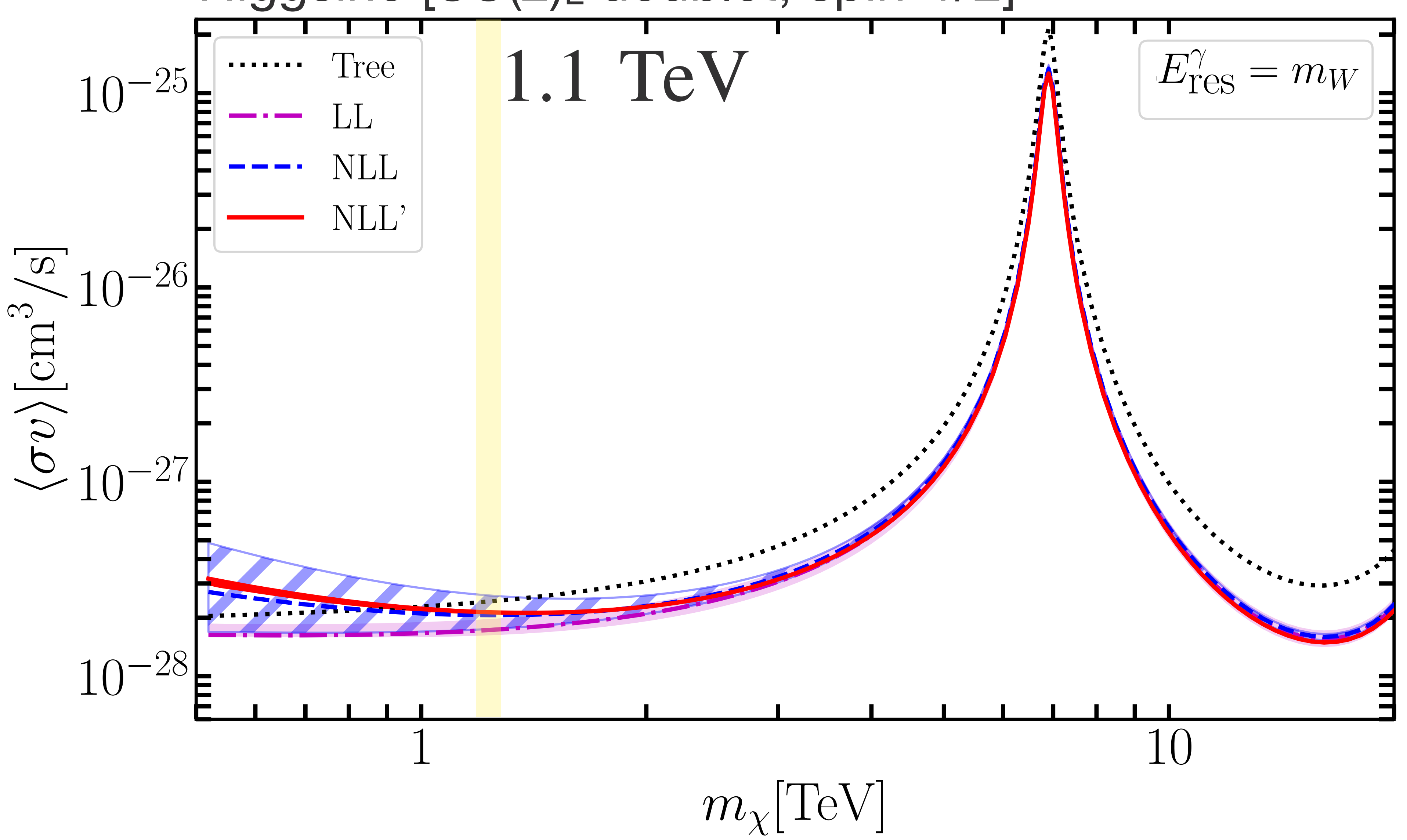
Precision 2: Log correction (3/3)

Annihilation rate

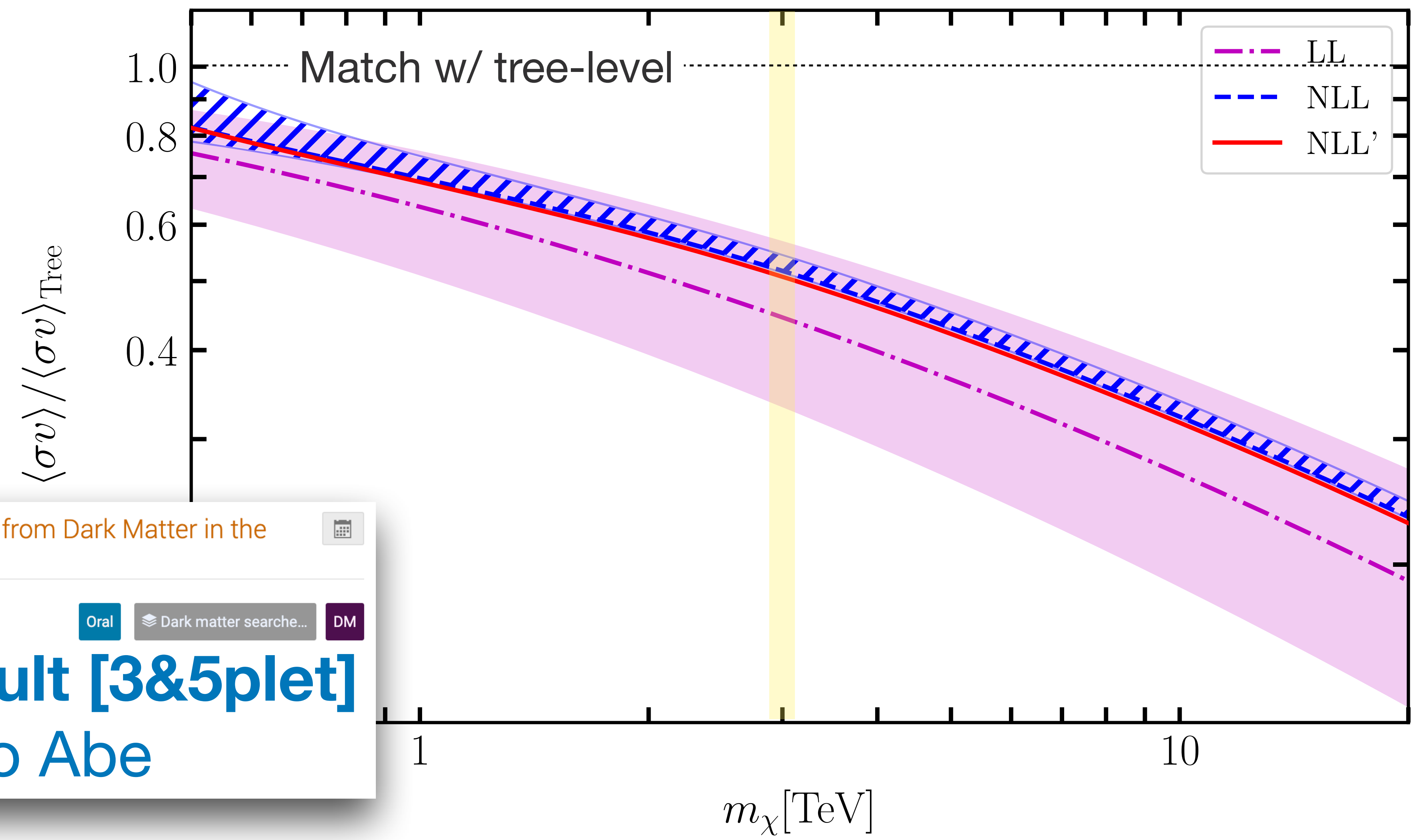
Wino [SU(2)$_L$ triplet, spin-1/2] [Beneke, et al. (2018)]

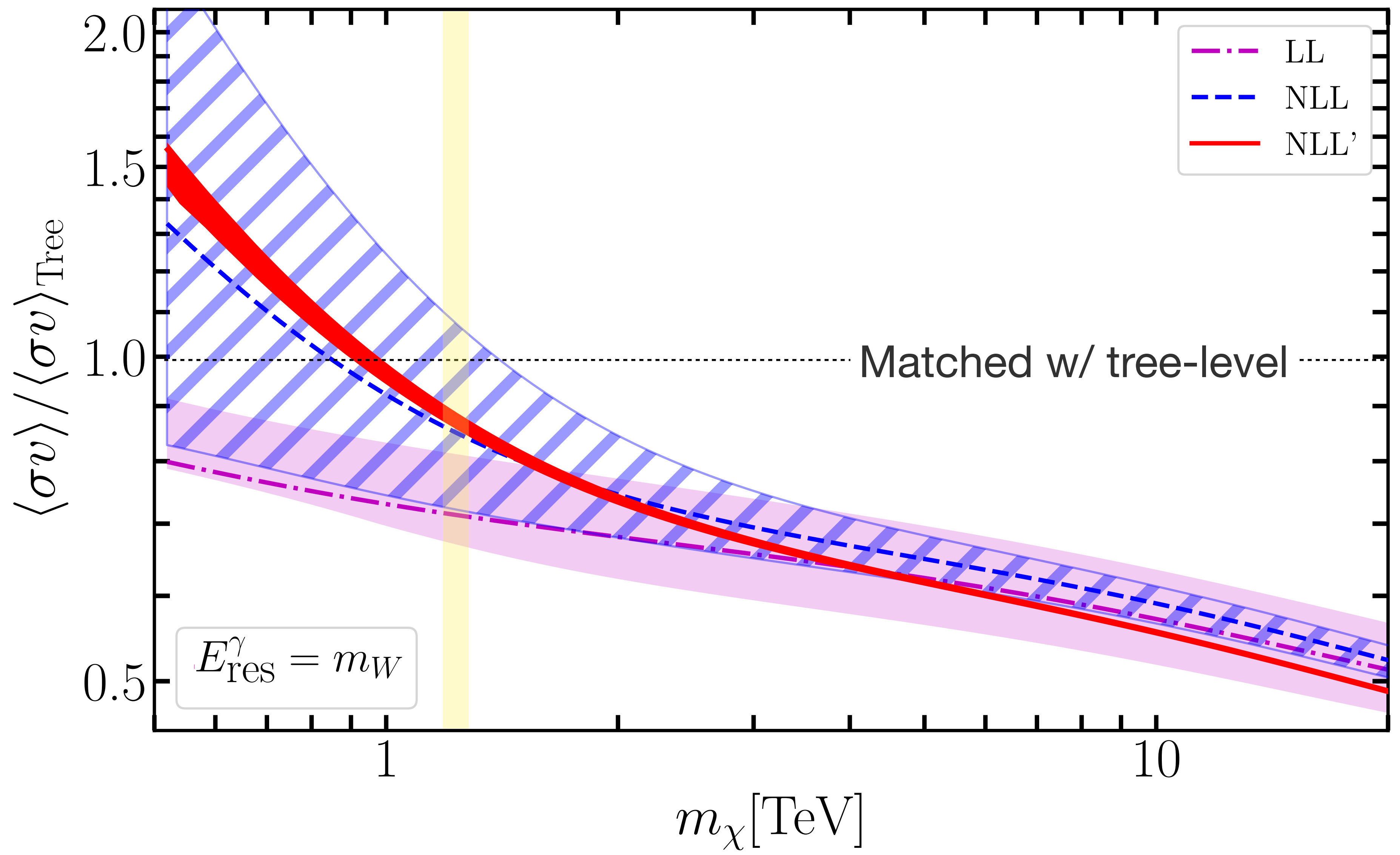


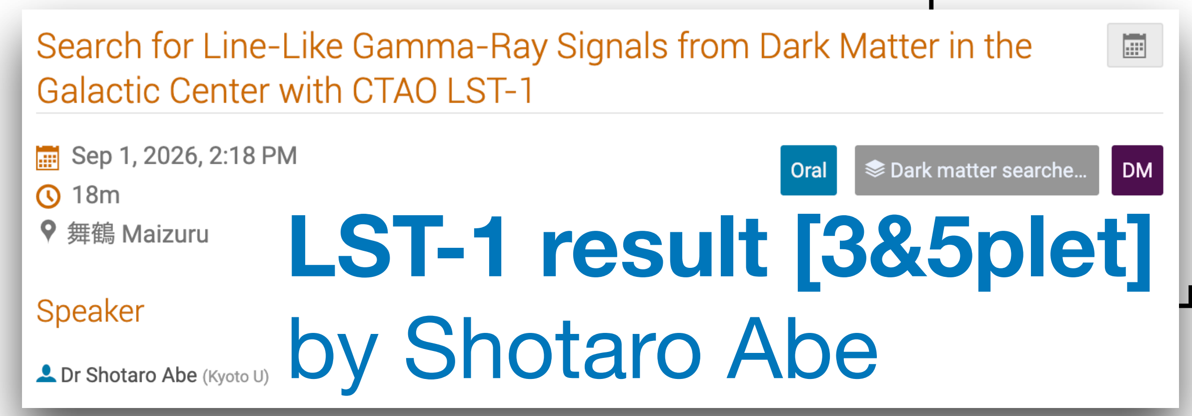
Higgsino [SU(2)$_L$ doublet, spin-1/2] [Beneke, et al. (2020)]



vs. tree prediction

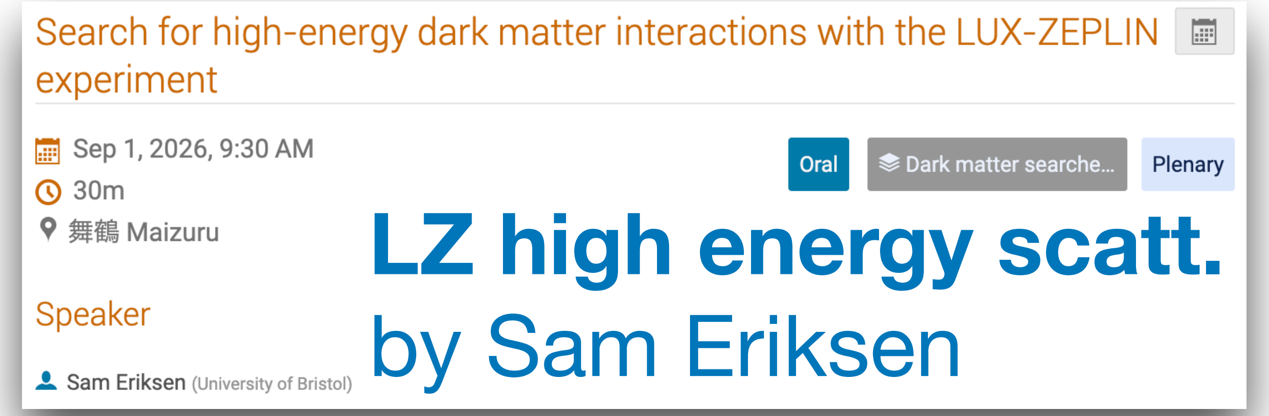






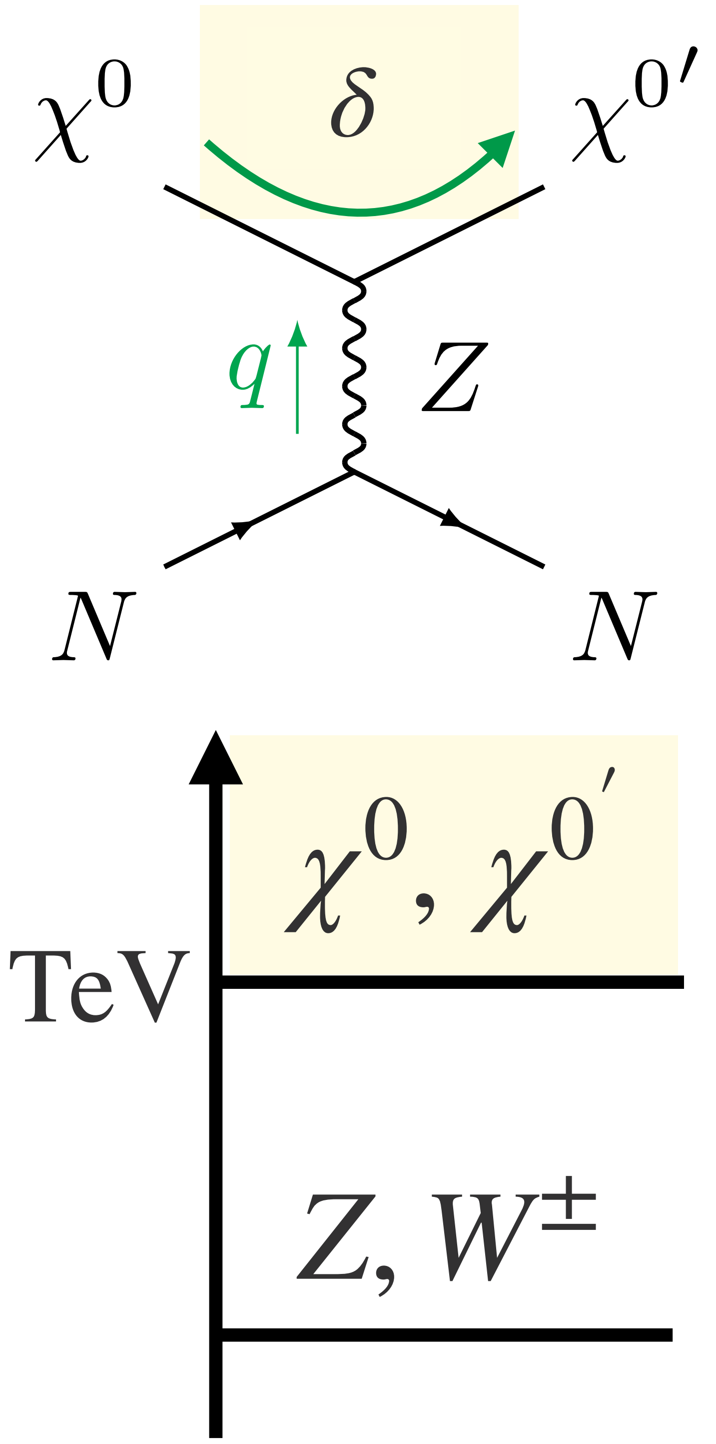
LST-1 result [3&5plet]
by Shotaro Abe

Higgsino: Current Status

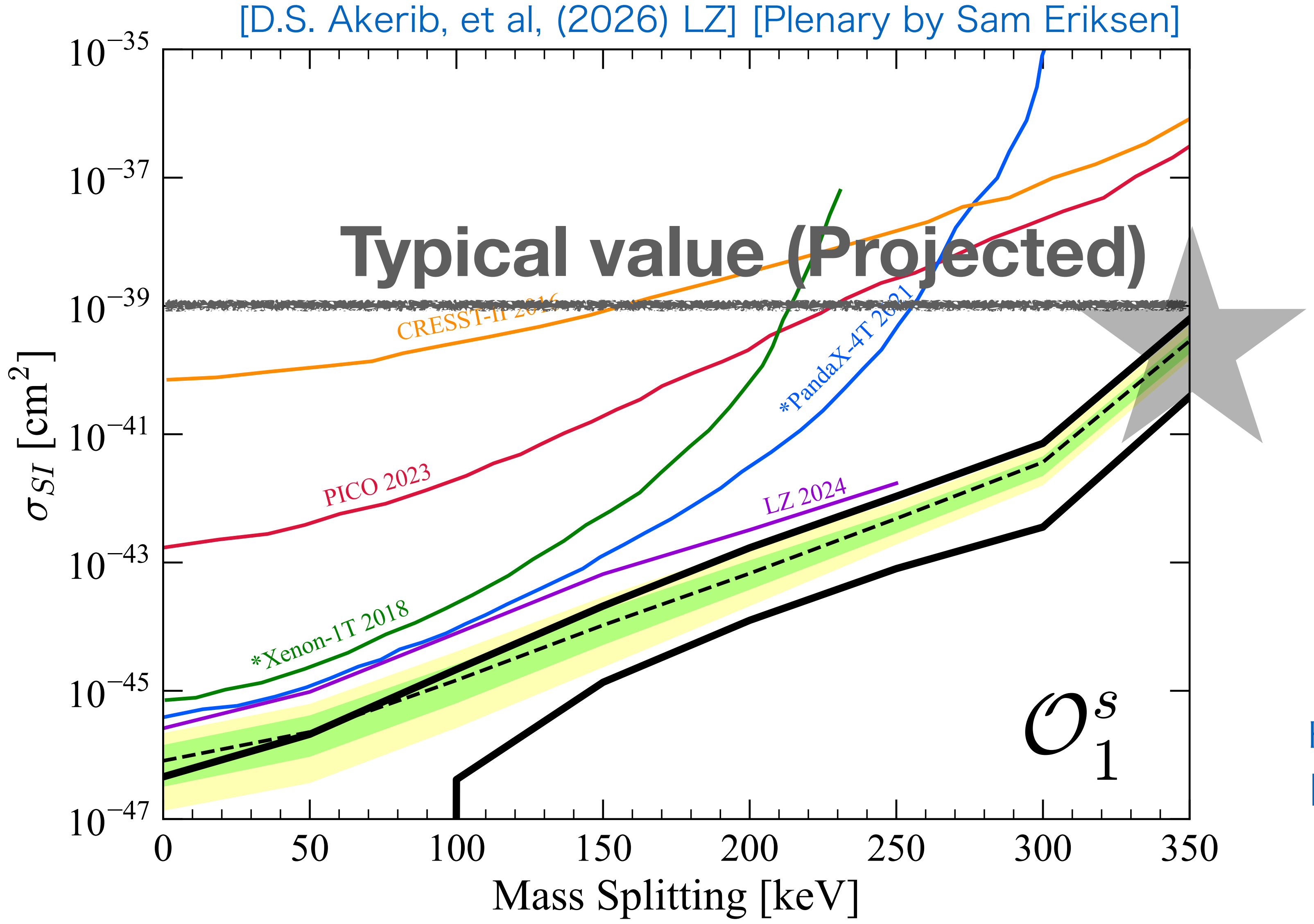


Inelastic scattering

- Higgsino spectrum: slightly heavier mode
  → Inelastic scat. for low mass splitting: δ
- Pure Higgsino DM → $1.1\ \mathrm{TeV}$

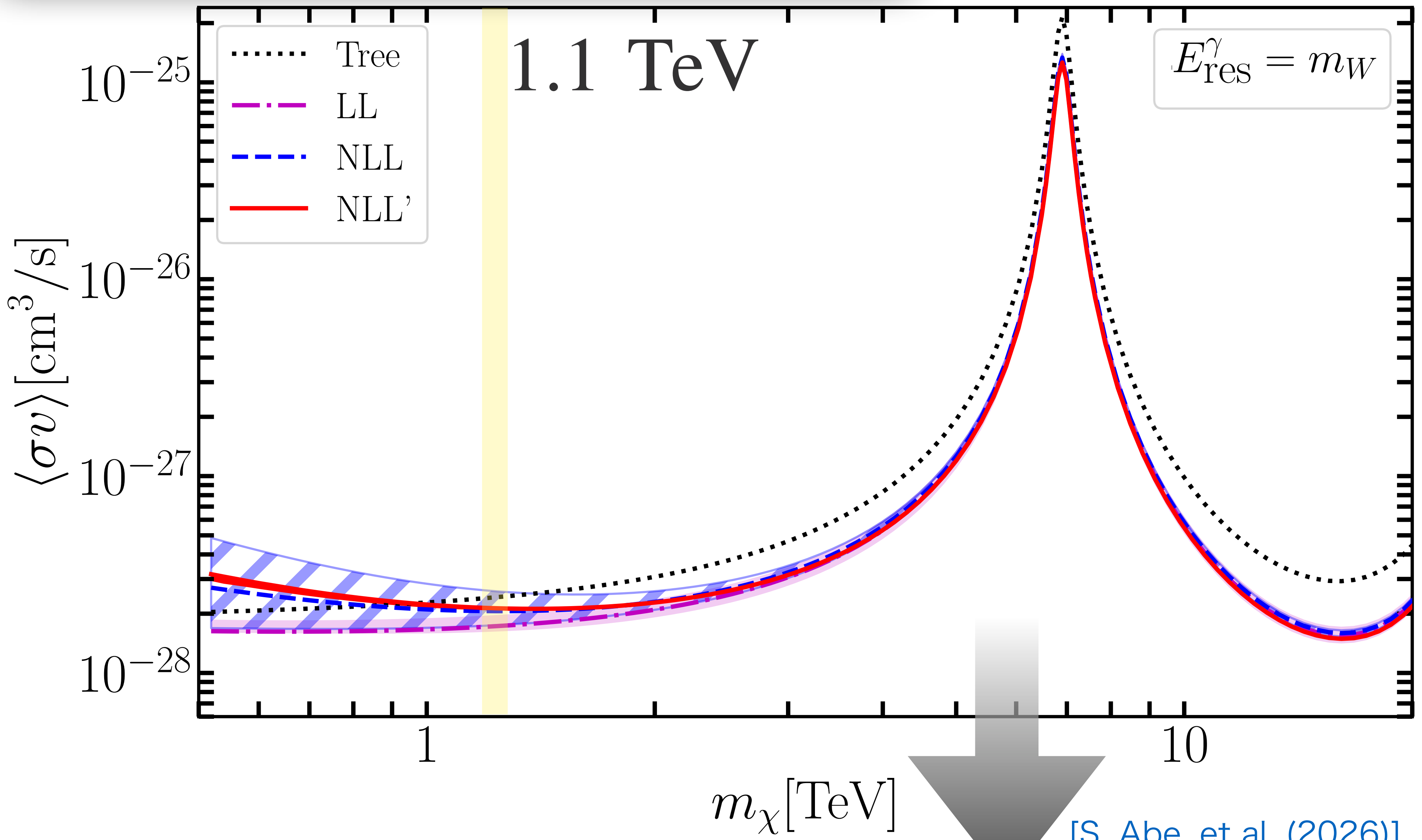


[D.S. Akerib, et al, (2026) LZ] [Plenary by Sam Eriksen]

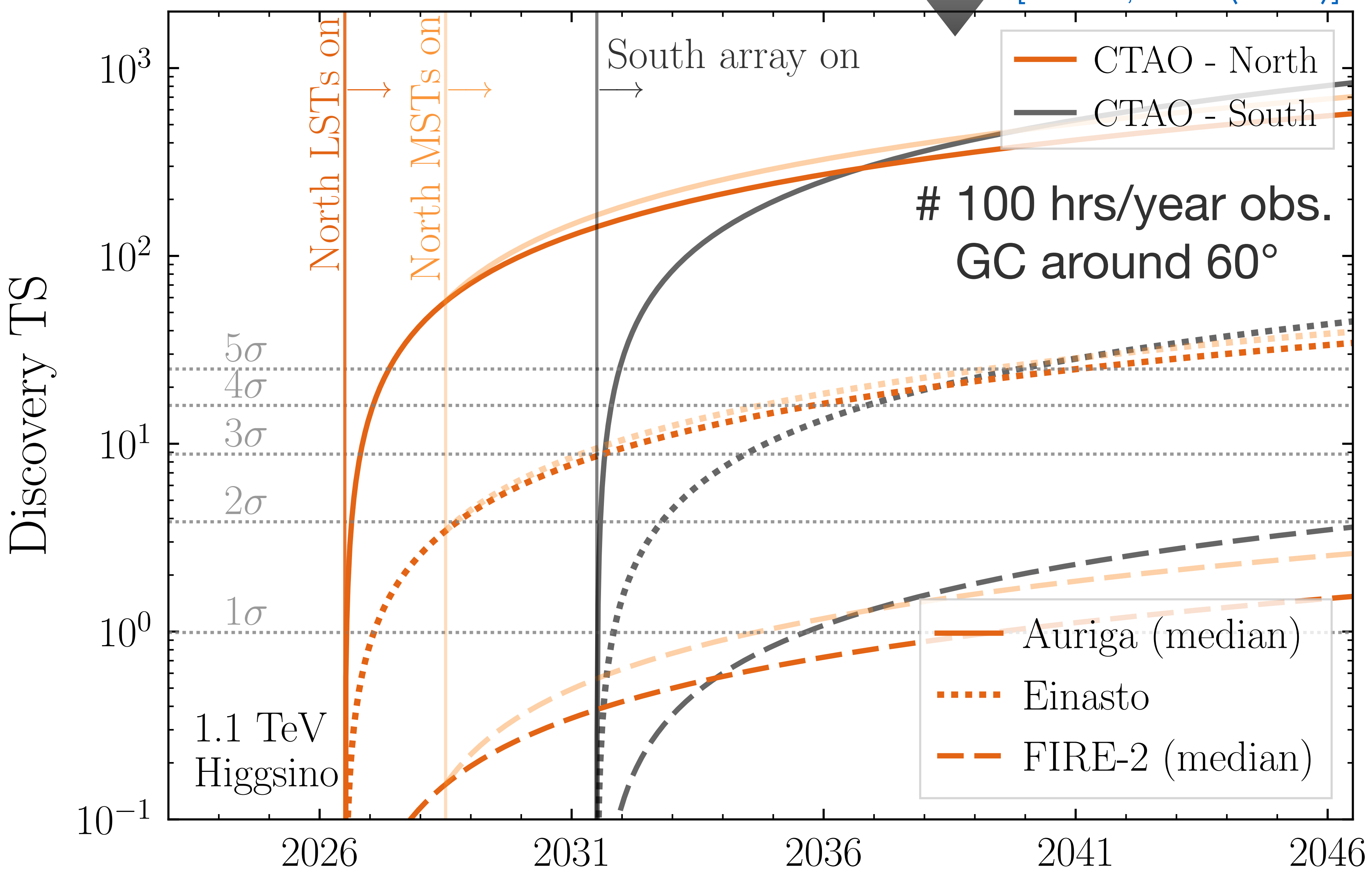


Higgsino interpretation (arXiv on 2/9/2026):
[2609.01504] [2609.01583] [2609.01590]

[Beneke, et al. (2020)]



[S. Abe, et al. (2026)]

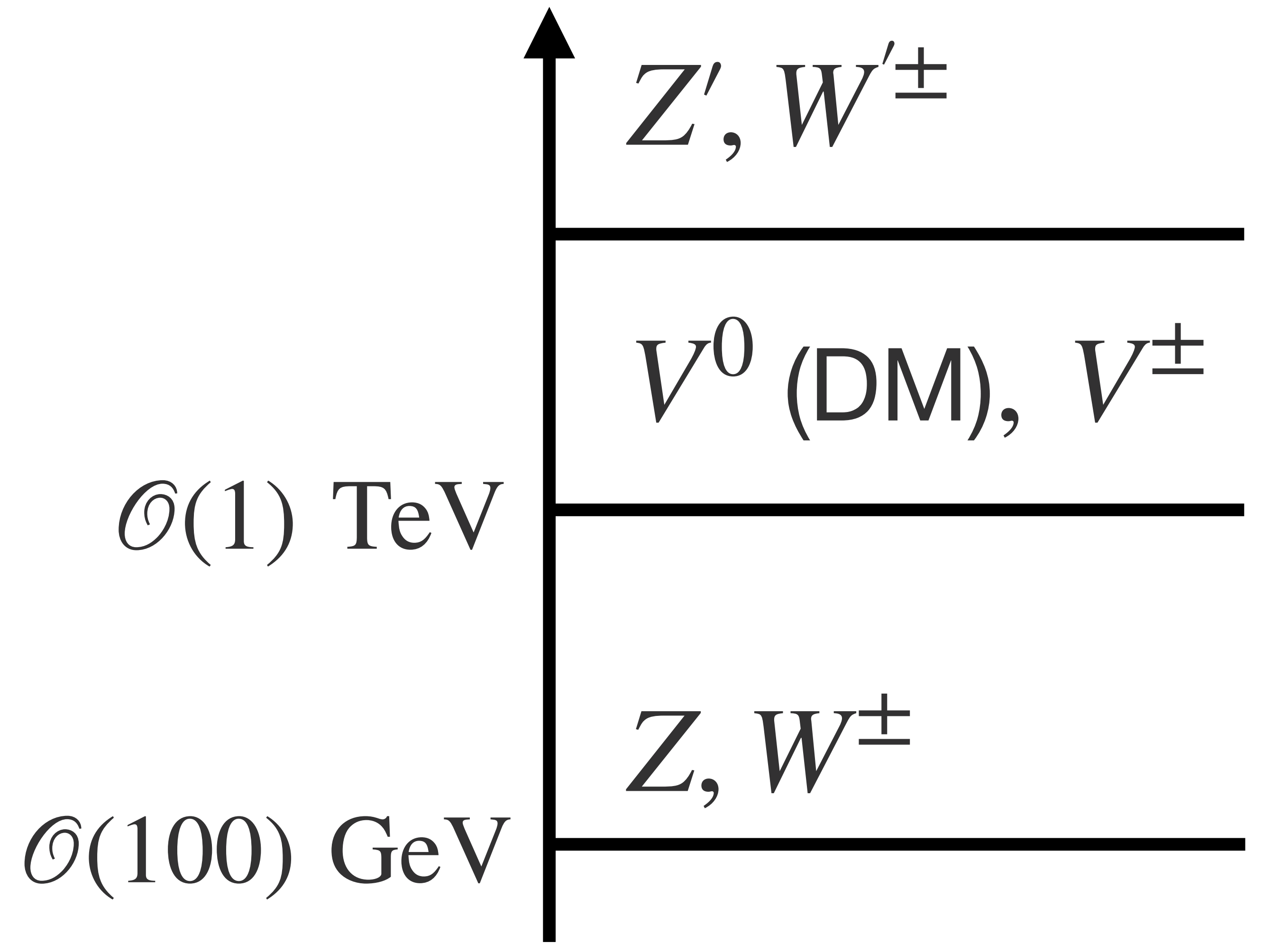


CTAO could test Hggsino γ-ray within decade

Power of Effective Theory

SCET approach	$SU(2)_L$ odd	$SU(2)_L$ even
Spin-0	**Framework completed** M. Bauer, et al. (2015) [triplet]	
Spin-1/2	G. Ovanesyan, et al. (2018) [triplet] M. Beneke, et al. (2019) [triplet] M. Baumgart, et al. (2024) [quintuplet] M. Baumgart, et al. (2026) [<13plet]	M. Beneke, et al. (2020) [doublet] **Generalization to Neutralino DM** M. Beneke, et al. (2022) [public code] M. Beneke, S. Lederer, C. Peset (2023)
Spin-1	MF, M. Vollmann (2025) [triplet]	

- Motivation: Extra dimensional DM candidate [T. Flacke, et al. (2017)]
  → **$SU(2)_L$ triplet Spin-1 DM**, stabilized by KK-parity
- Setup : Renormalizable simplified model [T. Abe, MF, J. Hisano, K. Matsushita (2020)]
  - Key1 : DM-spin dependence lives in hard physics
  - Key2 : Spin-dependence decouples from non-relativistic DM annihilation

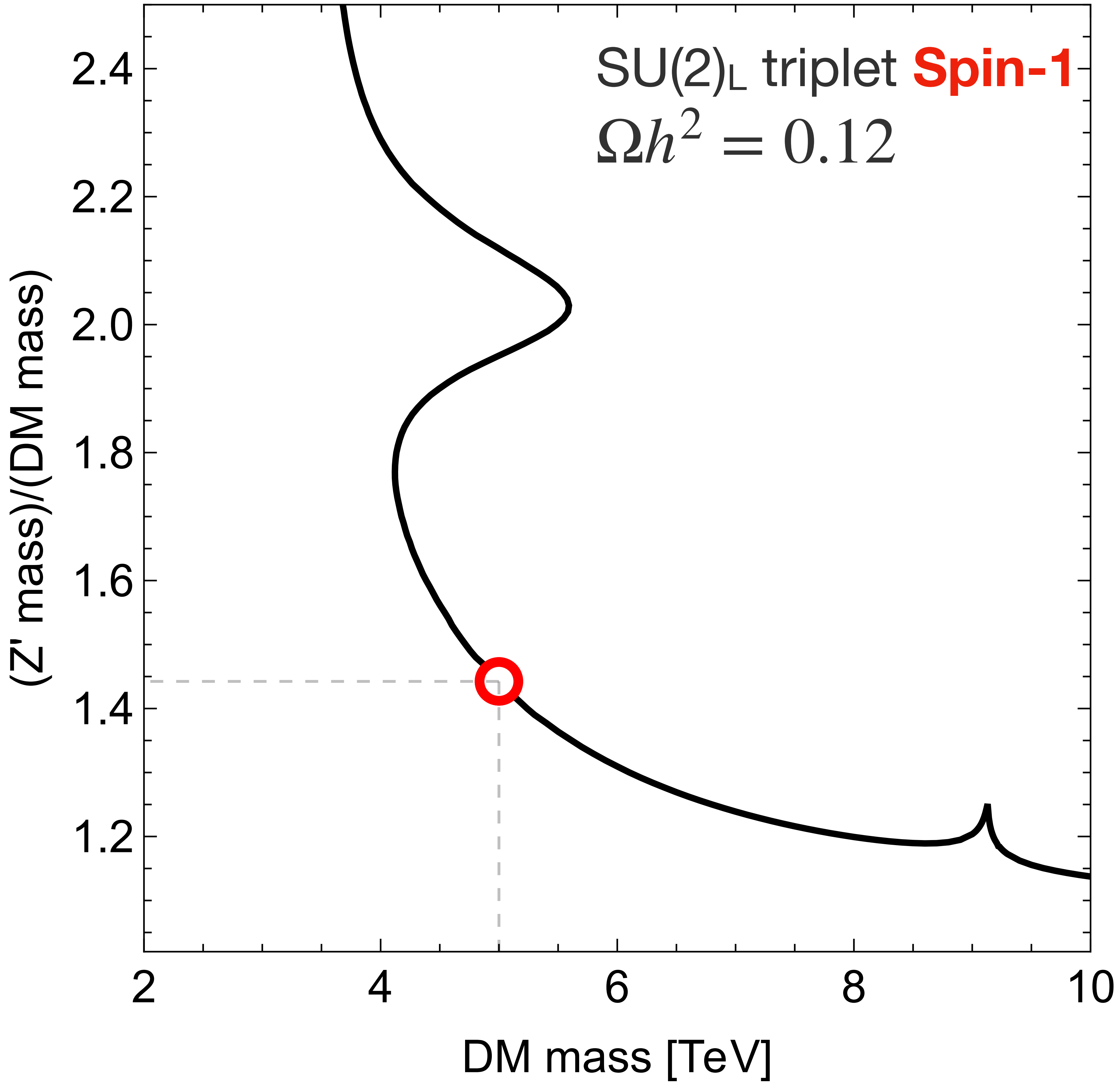


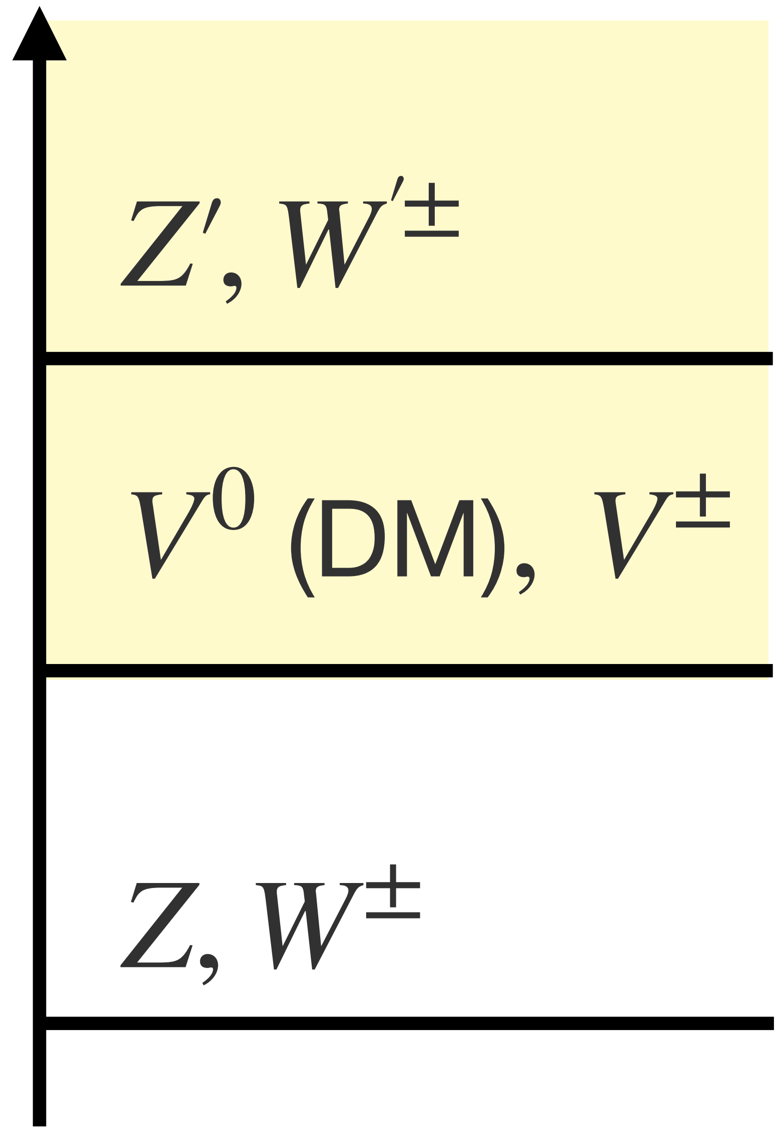
SCET formalism → largely common for $SU(2)_L$ charge & DM spin

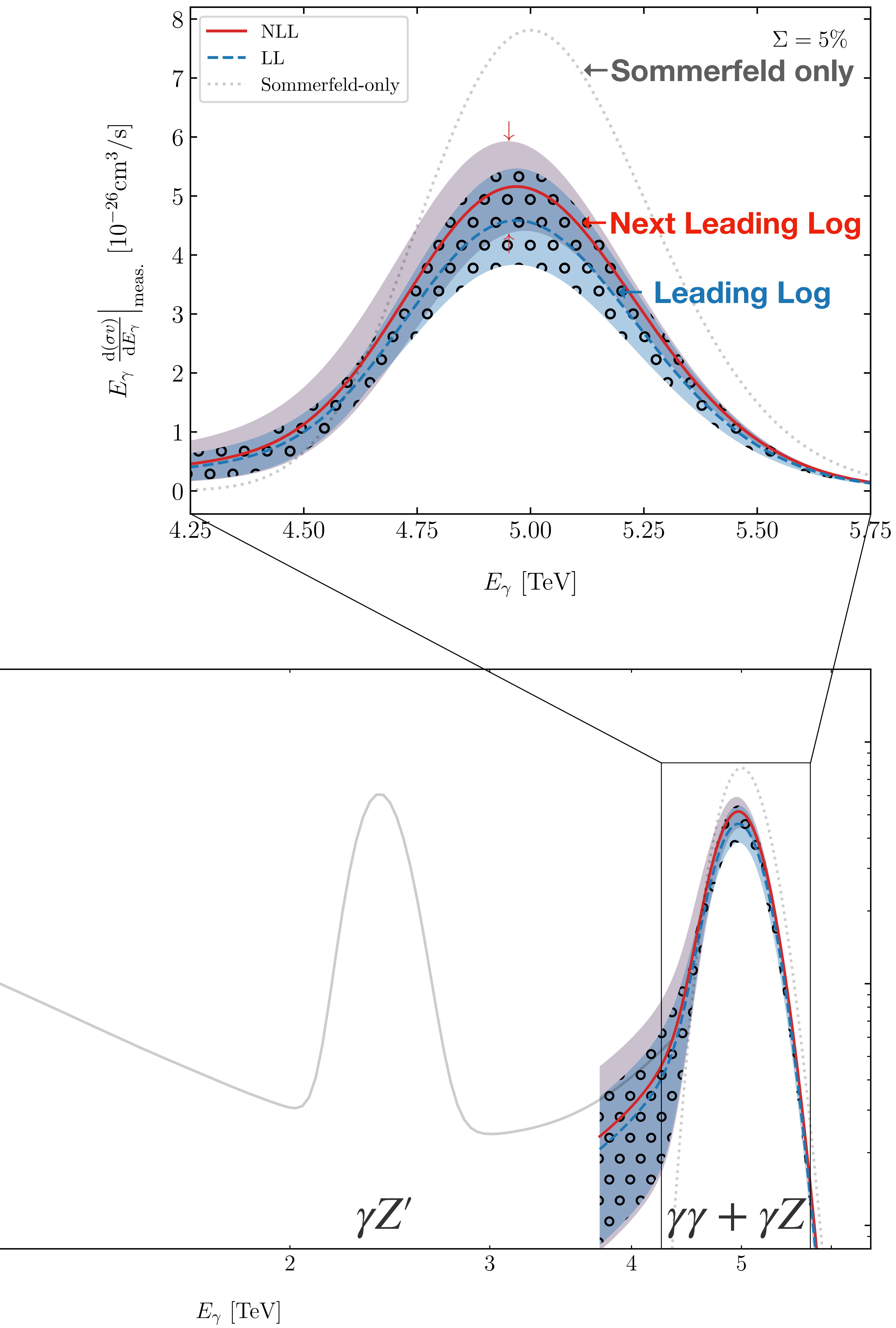
Spin-1 analysis

Double-peak signature @CTAO

(peak locations ↔ spectrum)







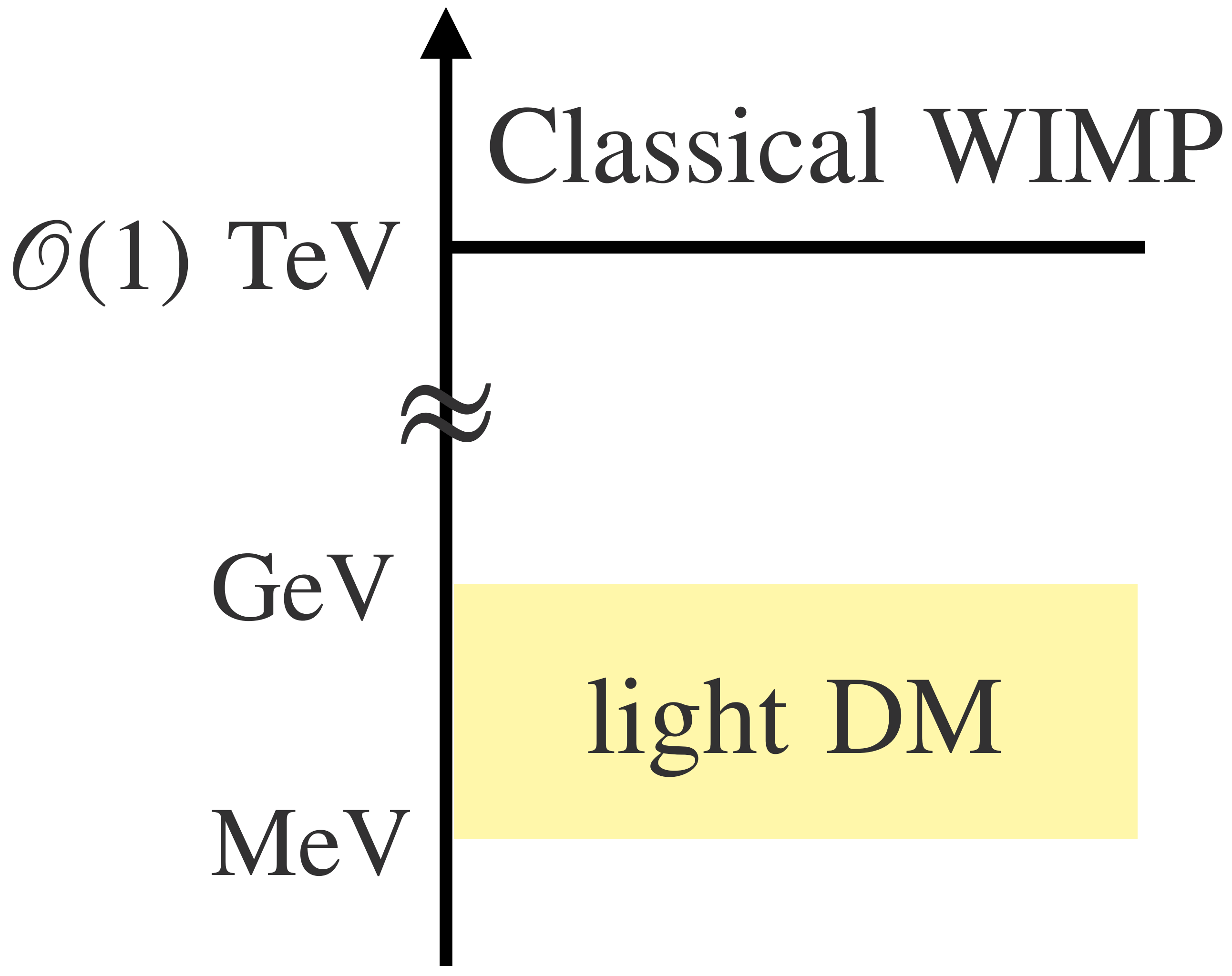
cf. [J. L Feng, et al. (2008)]

Recently considered scenarios

Recap: Origin of TeV scale (cf. Neutralino DM)

- DM stability : R-parity
- Coupling : $\alpha_{\rm EW}(m_Z) \sim 0.033$
- DM mass : $\mathcal{O}(1)$ TeV

$\langle \sigma_{\rm ann} v \rangle \sim \dfrac{\alpha_{\rm EW}^2}{m_{\rm DM}^2}$



Mass for Dark Matter?

- DM stability → **New symmetry to address BSM issue**
  - Baryon asymmetry → Accidental symmetry (cf. asymmetric DM: ~5 GeV DM)
  - Neutrino mass generation → Global symmetry to control tiny mass
- Coupling → $\alpha_{\rm BSM} = ???$
- DM mass → $m_{\rm DM} = ???$

$\langle \sigma_{\rm ann} v \rangle \sim \dfrac{\alpha_{\rm BSM}^2}{m_{\rm DM}^2}$ (for $2 \to 2$)

Broader possibility for DM mass … but what about search network?

[J. Aalbars, et al. (2025)]

e.g. Direct detection

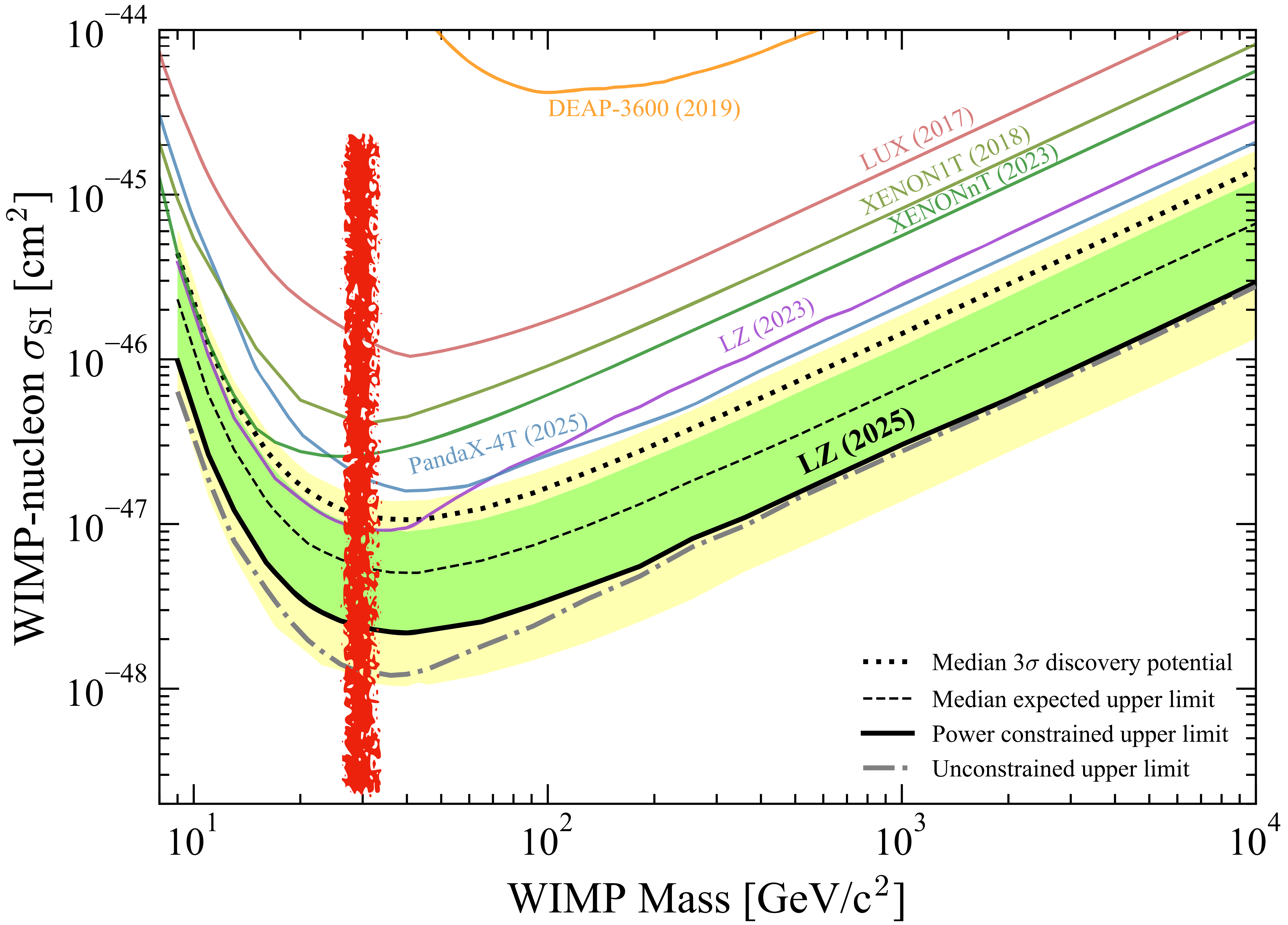
Condition to detect WIMP recoil:

$$E_{\rm th} \overset{!}{<} E_{\rm recoil} \sim \frac{(m_{\rm DM} v)^2}{m_T}$$

Ordinary setup:

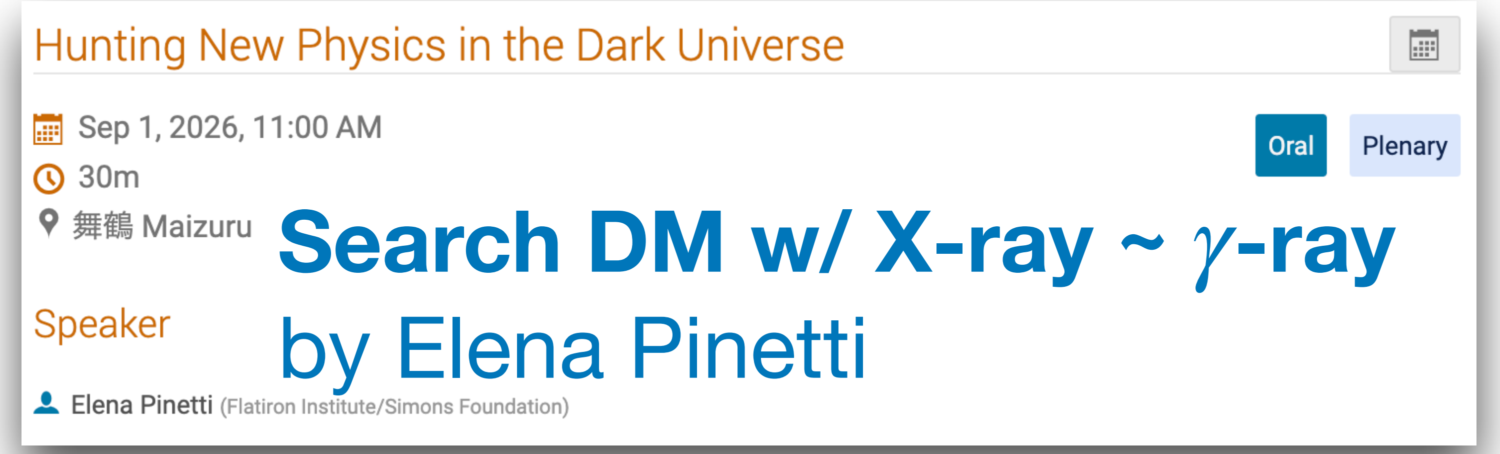
- Energy threshold : $E_{\rm th} \sim \mathrm{keV}$
- Average velocity : $v \sim 10^{-3}$
- Target mass : $m_T \sim 100\ \mathrm{GeV}$

$\Rightarrow$ $m_{\rm DM} \gtrsim 10\ \mathrm{GeV}$



Sub-GeV: less constrained

same for indirect detection & collider (∵ SM background)



[Betancourt-Kaminetskaia, MF, Ibarra, Toma (2025)]

Semi-annihilation Boosted DM

Boost by particle process

- (Initial DM #) > (Final DM #) → Kinematical acceleration
- $\chi\chi \to \chi\nu$: Semi-relativistic DM flux $(E_{\rm kin} \sim m_\chi/4)$
- Symmetry behind semi-annihilation? → Z_3 symmetry
  - BSM scenario: Radiative ν-mass model [MF, Toma (2026)]

Boosted dark matter from semi-annihilation in a neutrino mass model

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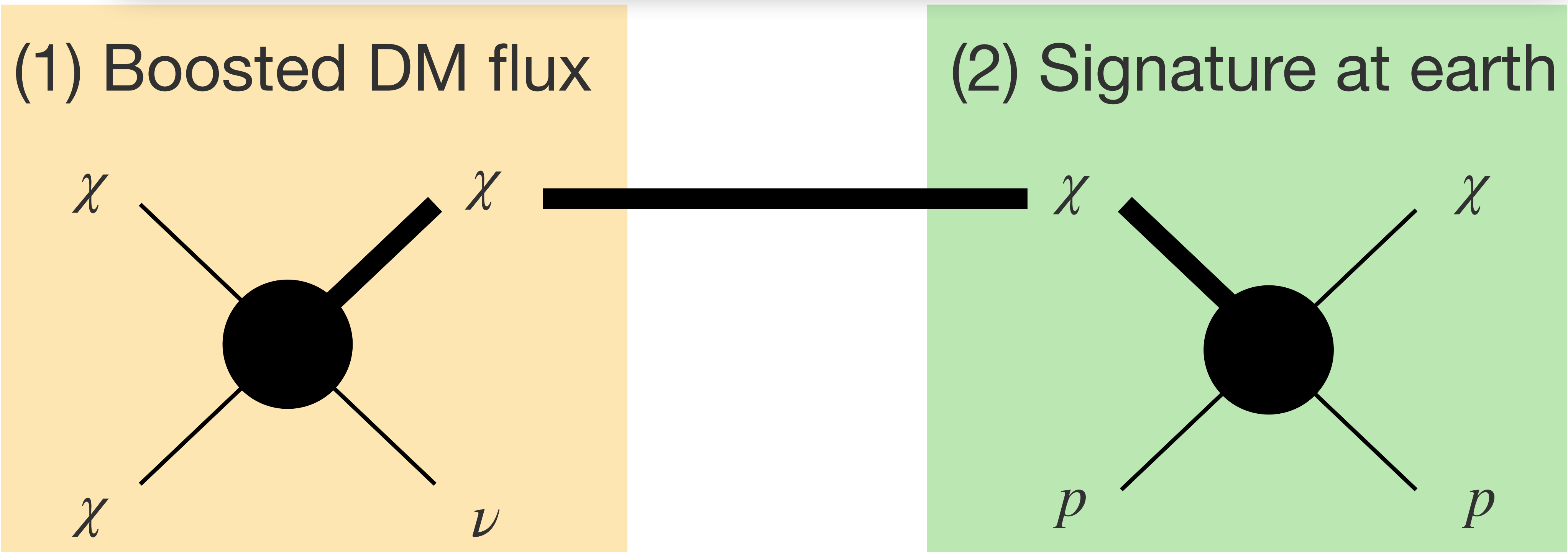
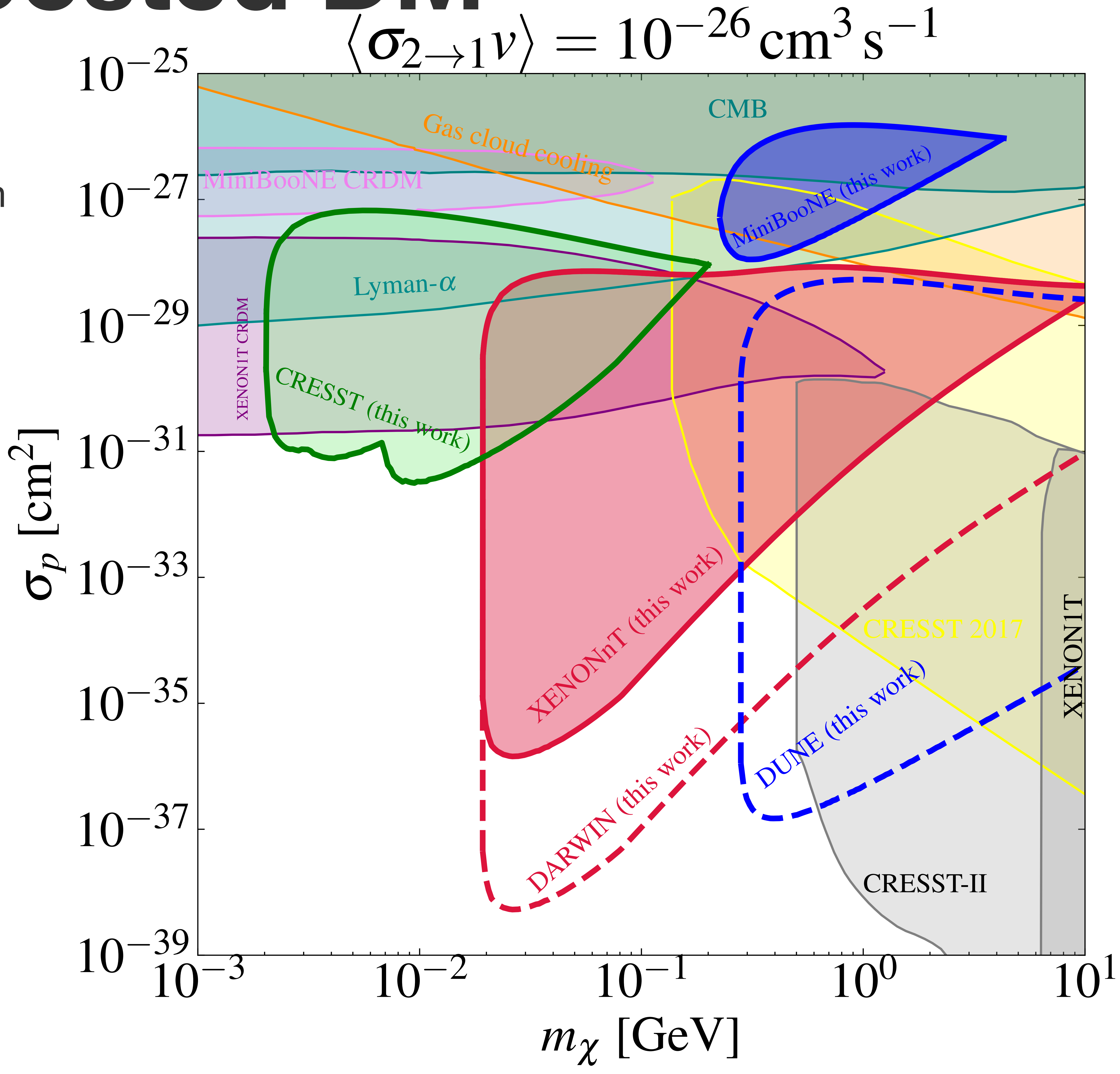
Boosted DM + Radiative ν-mass

by Takashi Toma

Speaker

Takashi Toma (Kanazawa University)





Summary

Classical WIMP Paradigm

- **TeV scale DM** w/ EW interaction (e.g. SUSY neutralino)
  - Theory : Sommerfeld effect in $\gamma\gamma$ channel
  - Observation : TeV γ-ray search
- Precision frontiers → Common framework for various scenarios!
  - Correction in Potential
  - Log correction

Beyond Classical WIMP

- Candidates exist but we need to extend **search network**
  - Development of new probe, analysis & scenario

Let's continue to explore WIMP landscape!