Review for the Dark Matter (including Higgs portal ones)

Shigeki Matsumoto (Kavli IPMU)

Kavli IPMU Thermal Dark Matter Project

Implication to (future) collider experiments from dark matter searches so far. The key question is " Where is a dark matter region attractive but not charted yet?".

Thermal DM hypothesis

Many dark matter candidates due to little knowledge of its nature!

$\lambda = 2\pi/mv <$ Gal. size

$\lambda = 2\pi/m \sim 2m/M_{pl}^2$

$m <$ Gal. mass

Mass

10^{-22} eV

10^{19} GeV

10^{40} g

Particle dark matter

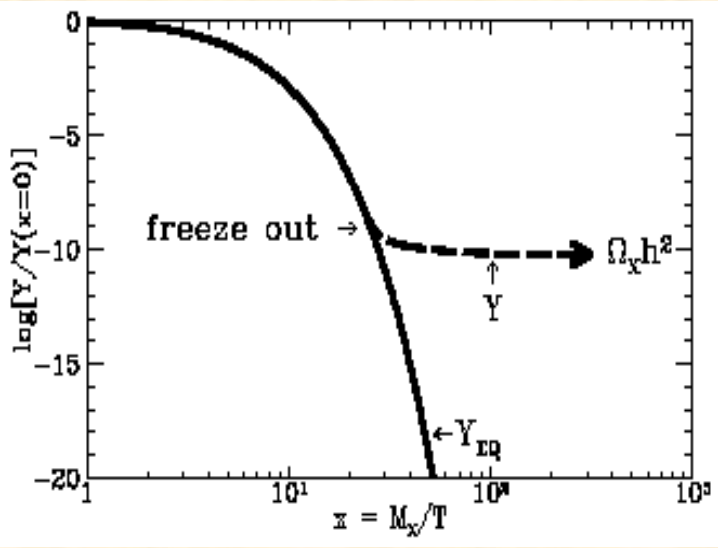
Dark matter searches are currently based on various hypotheses (e.g. WIMP, Axion, sterile ν, pBH, etc.) to cover such a huge DM mass region.

Thermal DM hypothesis

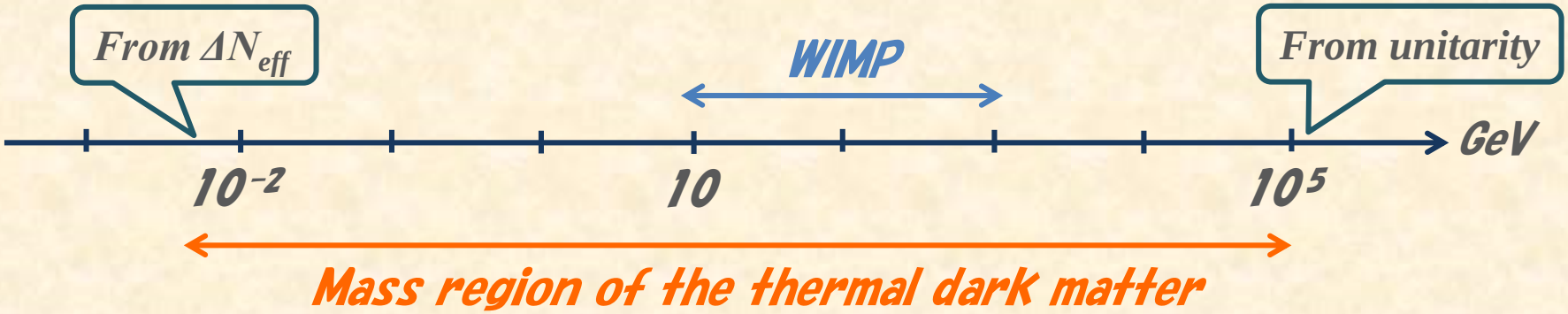
DM is a particle and its abundance today is fixed by the freeze-out mechanism.

Freeze-out MECH (BBN, Recombination)

Abundance of a species is determined by the competition between the expansion rate of the universe & the reaction rate maintaining an equilibrium of the species.

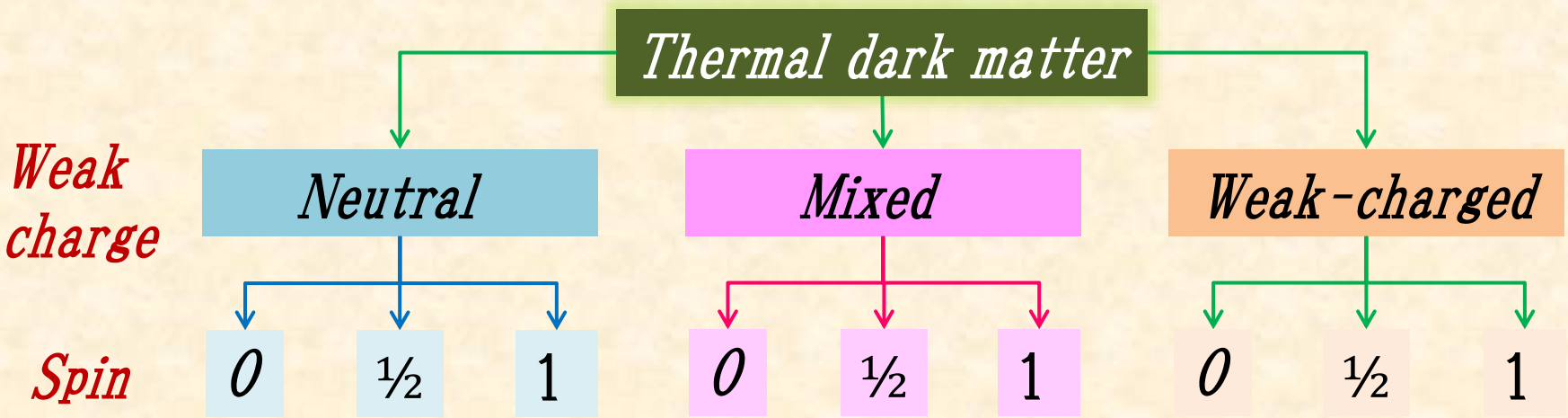


Thermal DM hypothesis



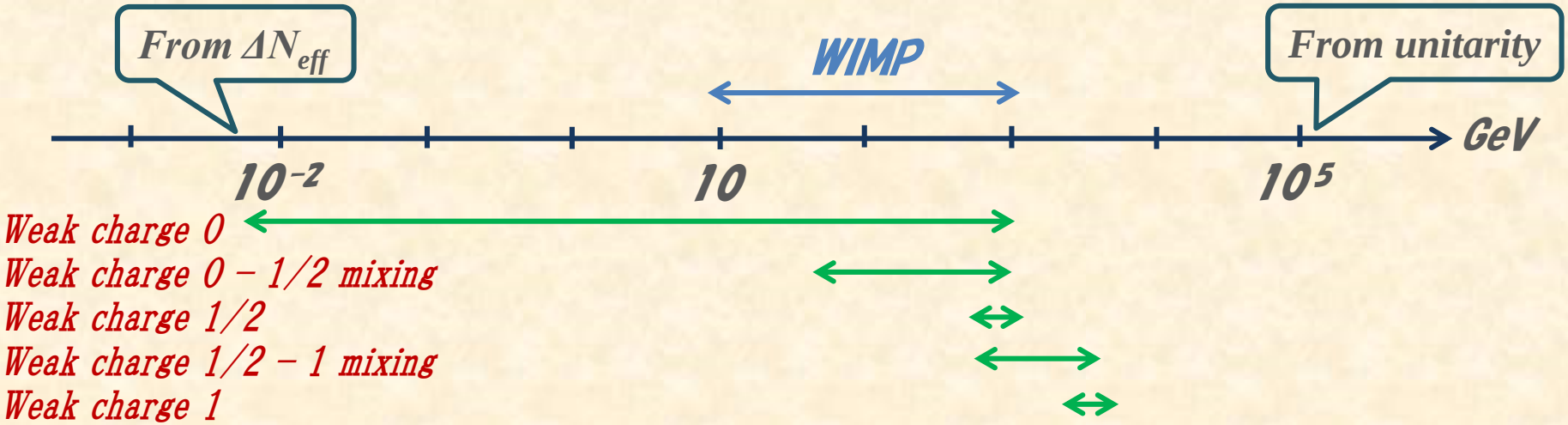
Which type of SM particle does the thermal DM mainly interacts with?

Thermal DM does not have EM & color charges, thus it is classified by



Thermal DM hypothesis

If thermal DM is assumed to be fermionic and has minimal interactions,



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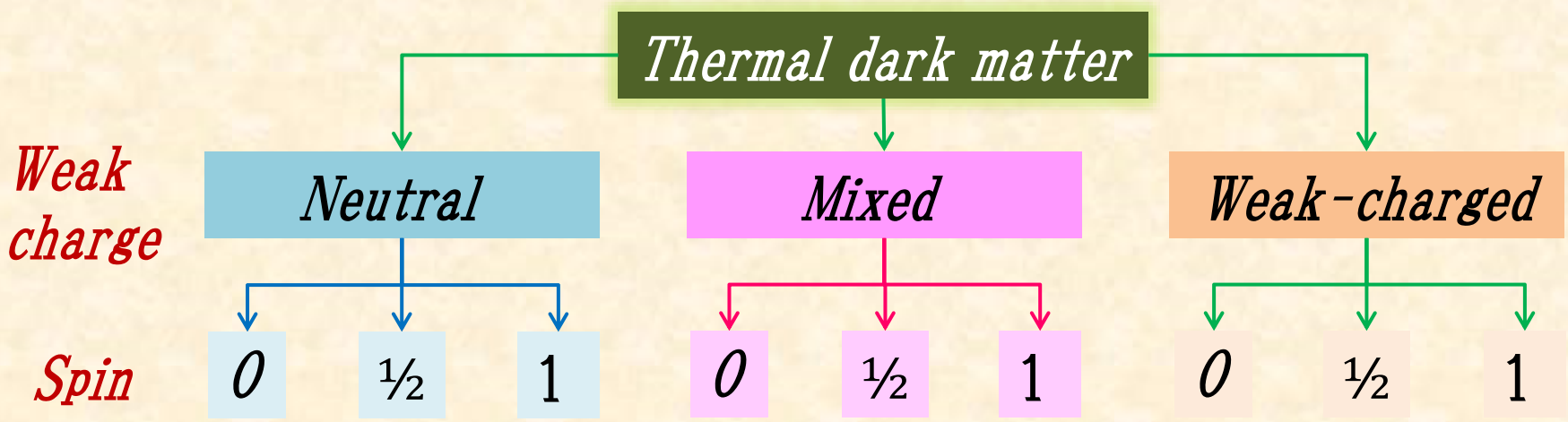
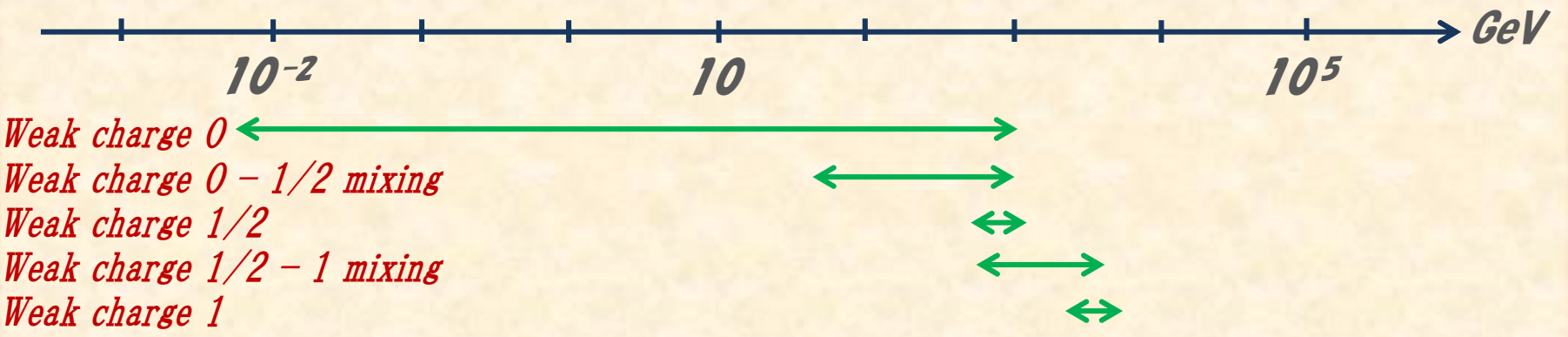


Present status & Implications



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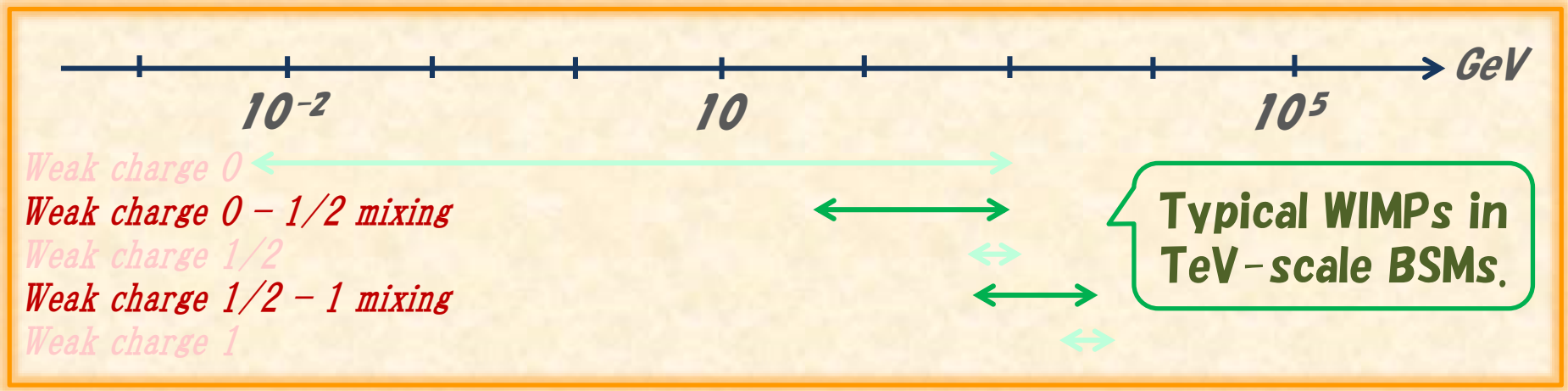
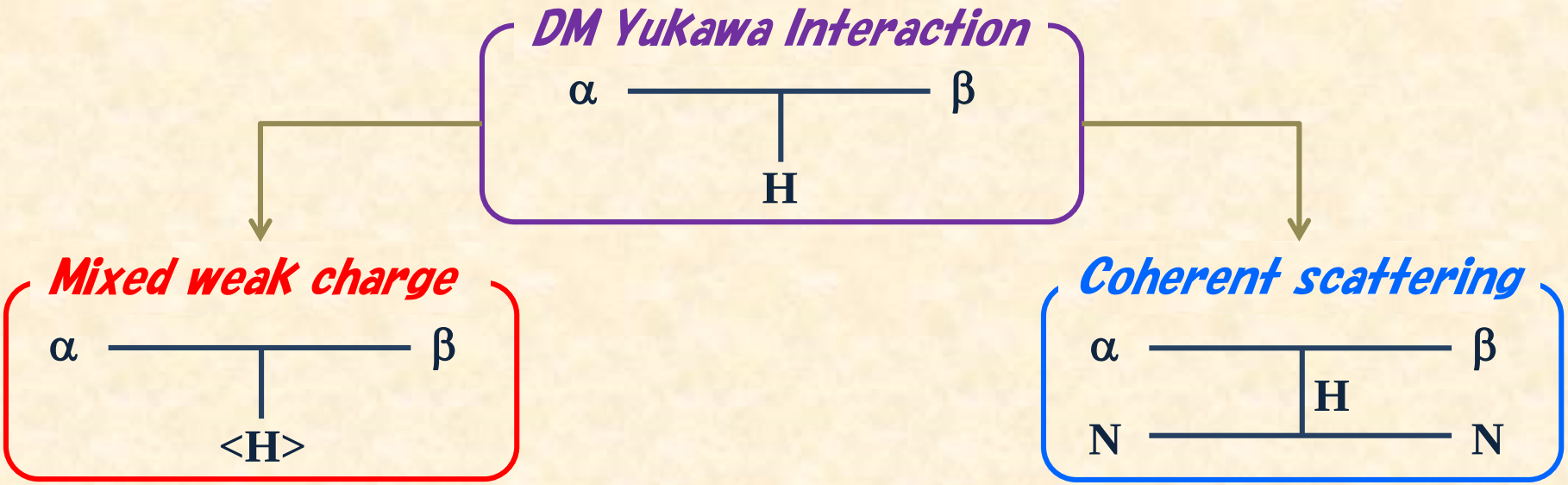


Case 1: Thermal DM has a mixed weak charge ($|DM\rangle = z_a |\alpha\rangle + z_b |\beta\rangle$).



Direct detection experiments are efficiently testing DMs of this kind.

[S. Banerjee, S. M., K. Mukaida and Y. L. S. Tsai, JHEP1611]

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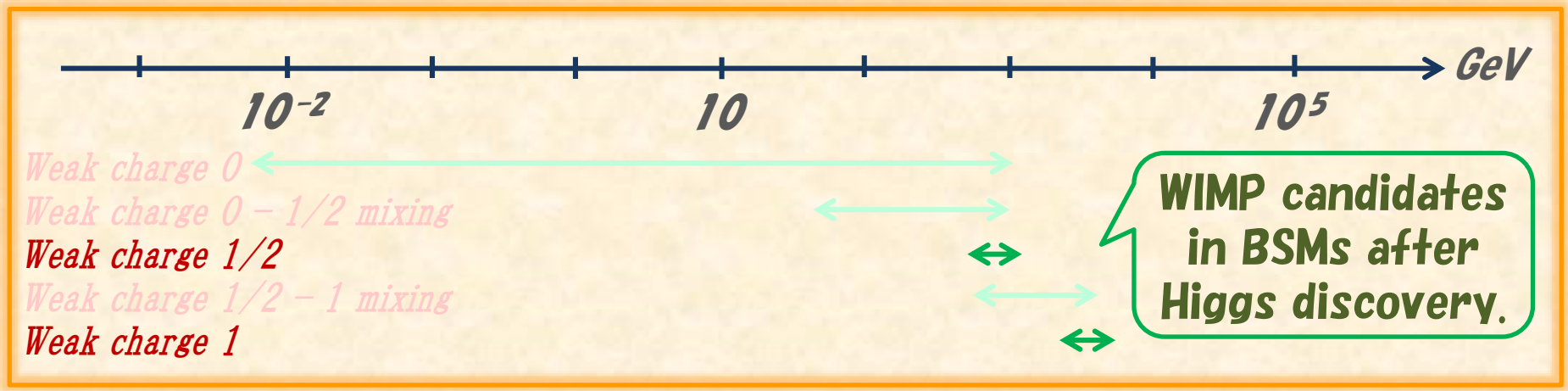
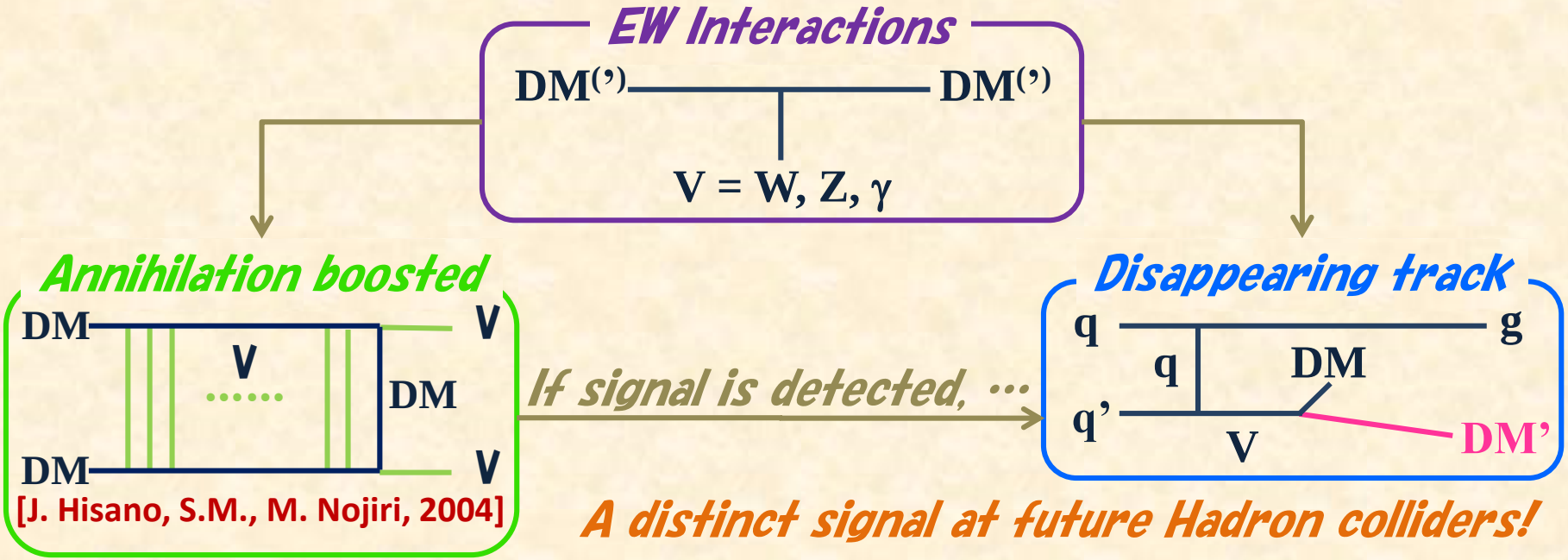


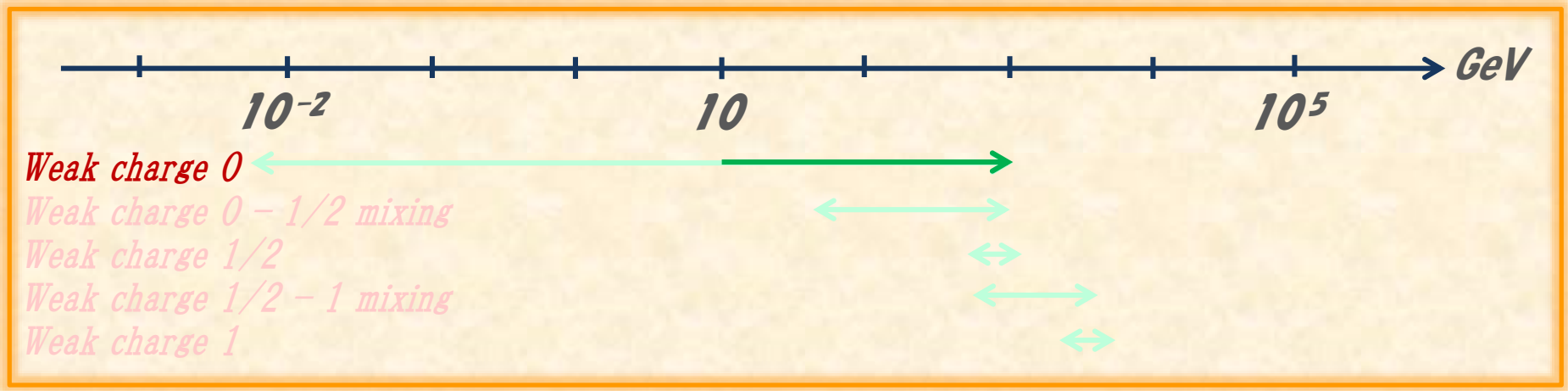
Case2: Thermal DM has a non-0 weak charge (≃ a $SU(2)_L$ eigenstate).



A distinct signal at future Hadron colliders!

[M. Low, L. Wang, 2014; T. Han, S. Mukhopadhyay, X. Wang, 2018]

Present status & Implications

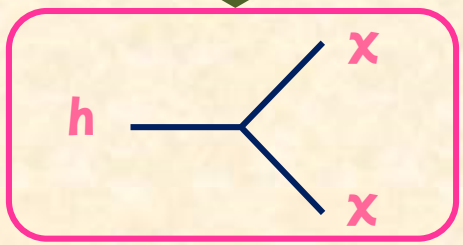


Case3: Thermal DM is singlet under the $SU(2)_L \times U(1)_Y$ symmetries.

Recent searches remain CPV H-portal & leptophilic region uncharted.

CPV H-portal

$$\frac{c_P}{2\Lambda}(\bar{\chi} i\gamma_5 \chi)|H|^2$$

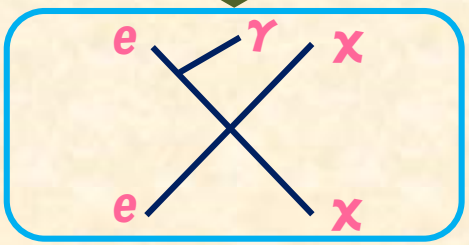


No renormalizable interaction between DM and SM particles.

→ ∃New particle (Mediator)

Leptophilic

$$\frac{c_f}{2\Lambda^2}(\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{l}\gamma_\mu l)$$

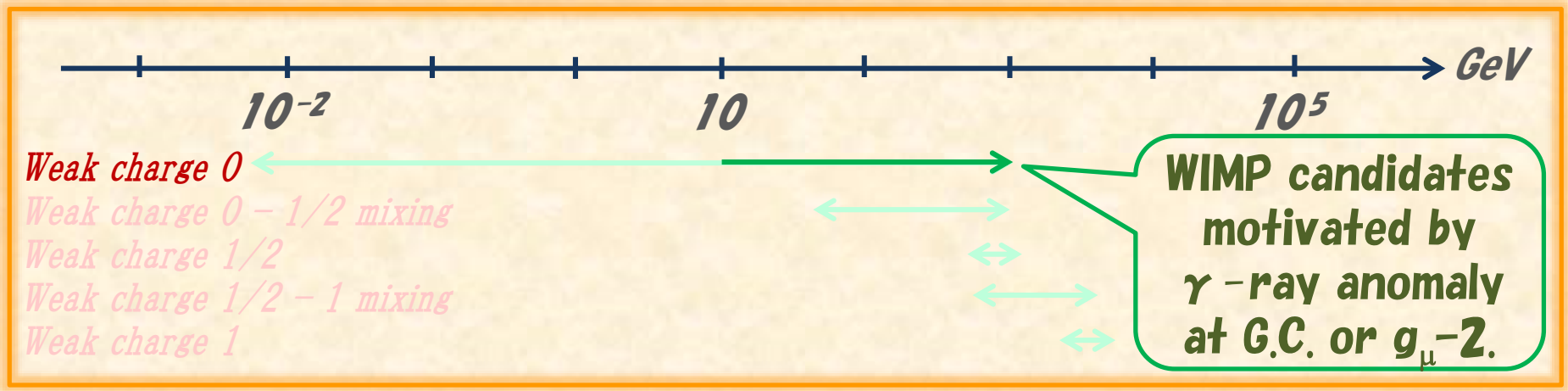


Thermal DM region is covered by H-factories if $m_\chi < m_h/2$.

Lepton colliders can test the thermal DM region if $2m_\chi < s^{1/2}$.

[S.M., S. Mukhopadhyay, Y. L. S. Tsai, JHEP 1410] [S. M., S. Mukhopadhyay, Y. L. S. Tsai, PRD94, 2016]

Present status & Implications



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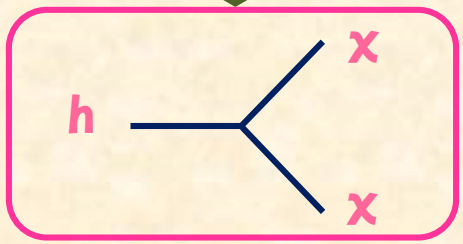

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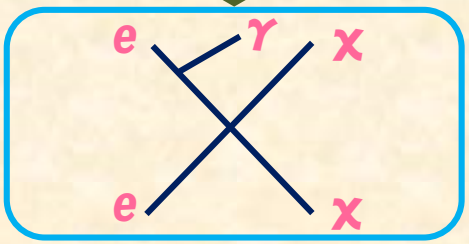

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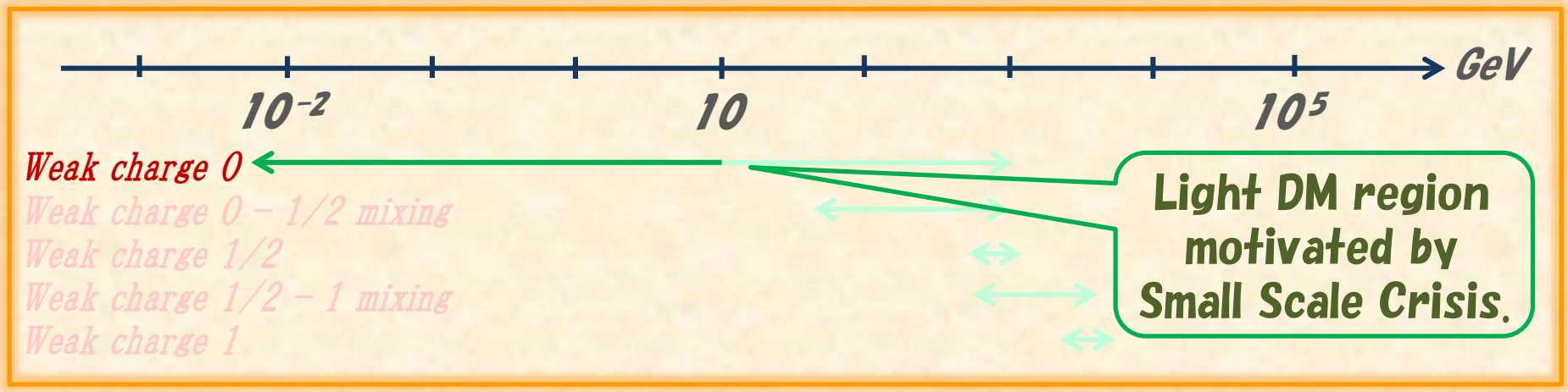
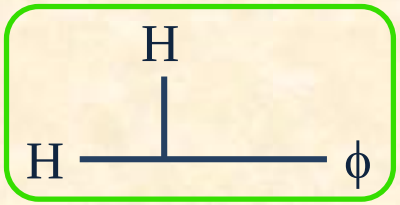


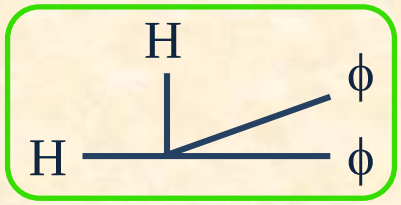
Case3: Thermal DM is singlet under the $SU(2)_L \times U(1)_Y$ symmetries.

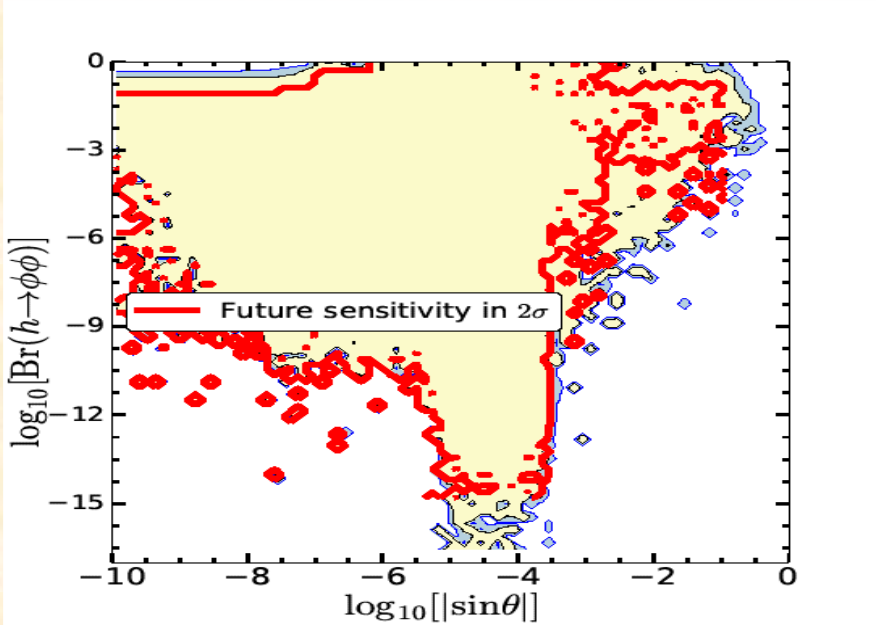
Light DM – Light mediator – SM

↑ ↑

Interactions w/ enough magnitudes.







Above interactions induce H—ϕ mixing and Higgs exotic decays.

→ High-L collider & H-factory!

[S.M., Y. L. S. Tsai, P. Y. Tseng, arXiv:1811.03292]

Summary

We have systematically investigated the thermal dark matter (WIMP) to find a parameter region that is attractive but not charged yet. Implications to (future) collider experiments are obtained as follows:

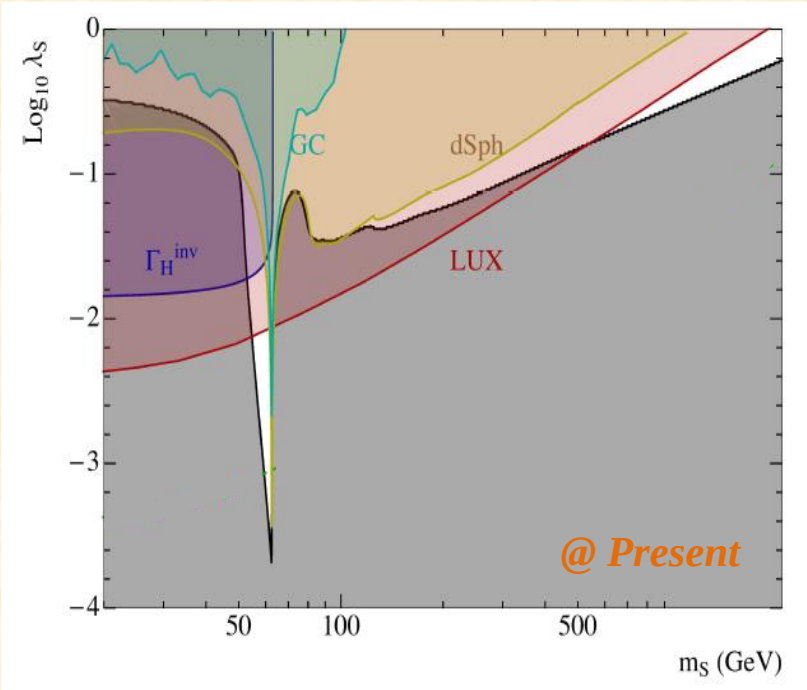
DM candidates	Collide signatures	Motivation
✓ TeV-scale DM	Disappearing track	BSM after H discovery
✓ H-funnel (CPV) DM	Invisible H-decay	G.C. γ-ray anomaly
✓ Leptophilic DM	Mono-γ search	$g_\mu - 2$ anomaly
✓ Light DM	Exotic H-decay	Small scale crisis

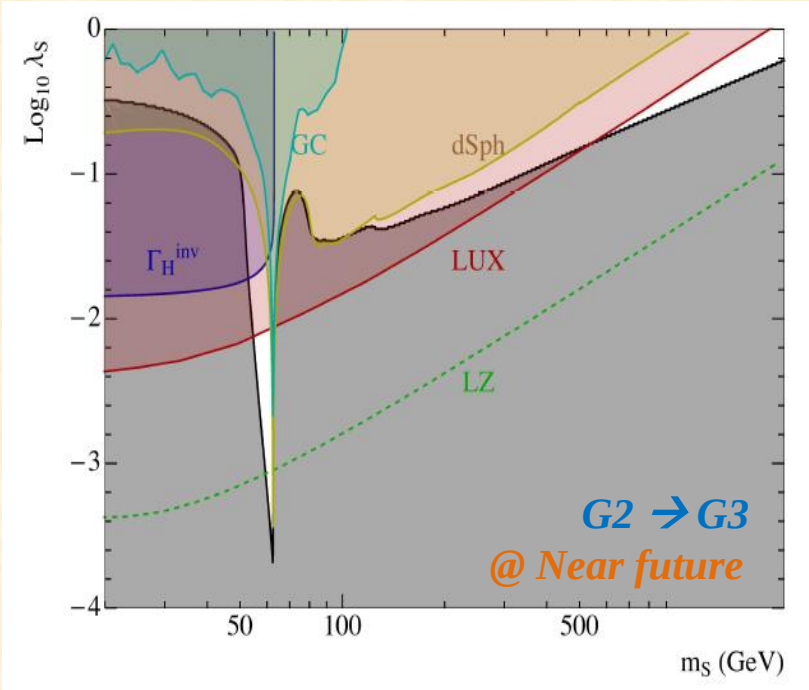
Since our investigation is based on the minimal setup for dark matter interactions at each quantum number of the dark matter field, there must exist other attractive DM regions if we go beyond the minimality.

Backup Slides

Singlet Scalar Thermal Dark Matter

$$\mathcal{L}_{\rm SHP} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_0^2 S^2 - \frac{1}{2}\lambda_S |H|^2 S^2 - \frac{1}{4!}\lambda_4 S^4$$



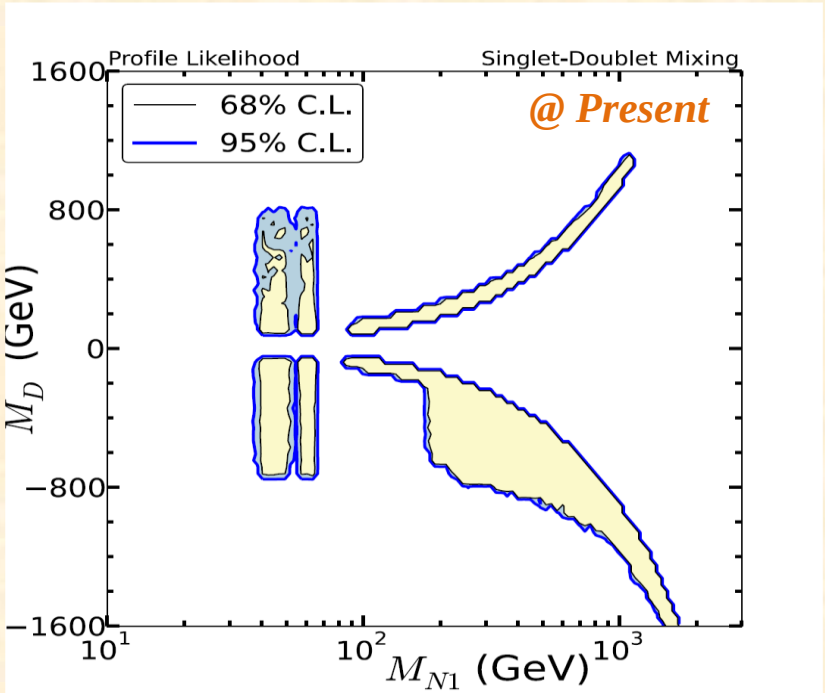


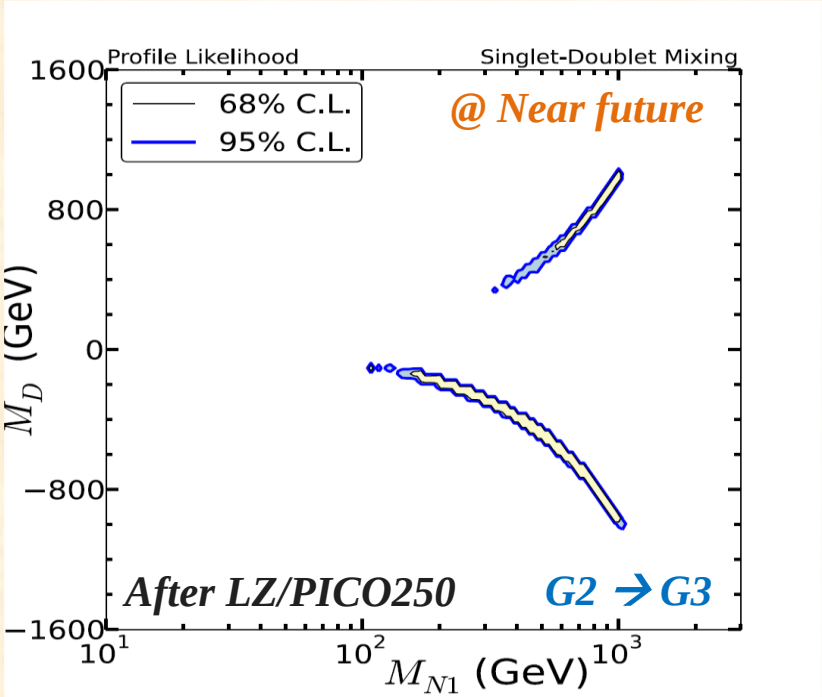
[J. A. Casas, et. al, 2017]

Mixed (1_0 – $2_{\pm 1/2}$) Fermion Thermal DM

$$\mathscr{L}_{\rm SD} = \mathscr{L}_{\rm kin} - \left[\frac{1}{2}M_S SS + M_D D_1 \cdot D_2 + y_1 S D_1 \cdot \tilde{H} + y_2 S D_2 \cdot H + \text{H.c.}\right]$$

Direct dark matter detection @ Under ground laboratories

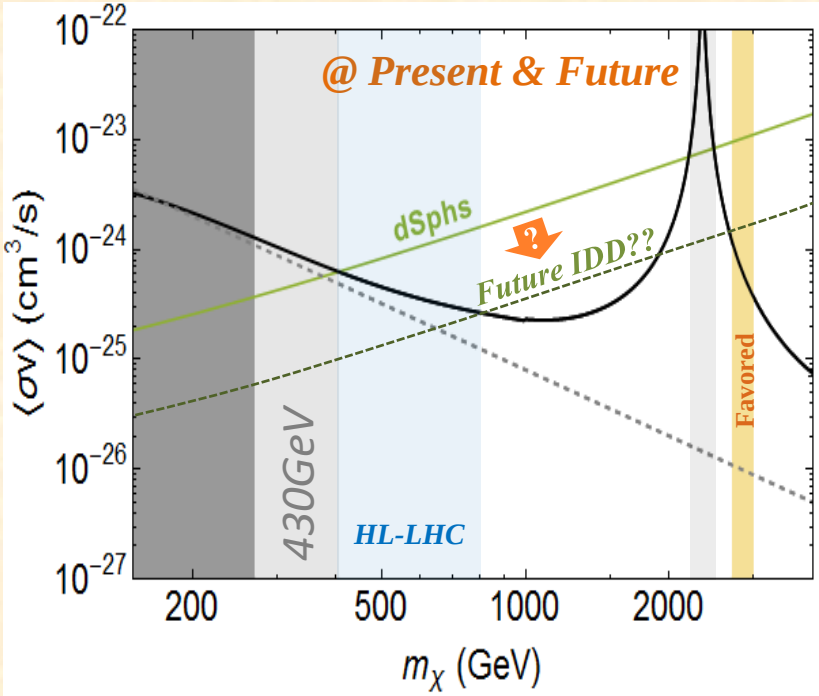


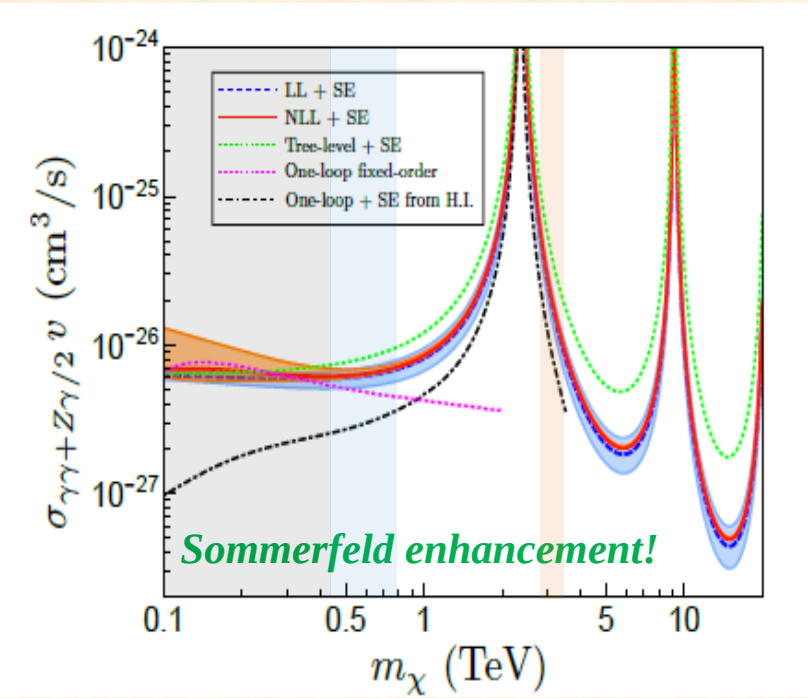


[S. Banerjee, S. M., K. Mukaida and Y. L. S. Tsai, JHEP1611]

Triplet Fermion Thermal Dark Matter

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\bar{T}\left(\not{D} - M_T\right)T$$





Non-perturbative Sommerfeld Effect (SE) [J. Hisano, S.M., M. Nojiri, 2004]

SE + Perturbative one-loop correction [A. Hryczuk, R. Iengo, 2013]

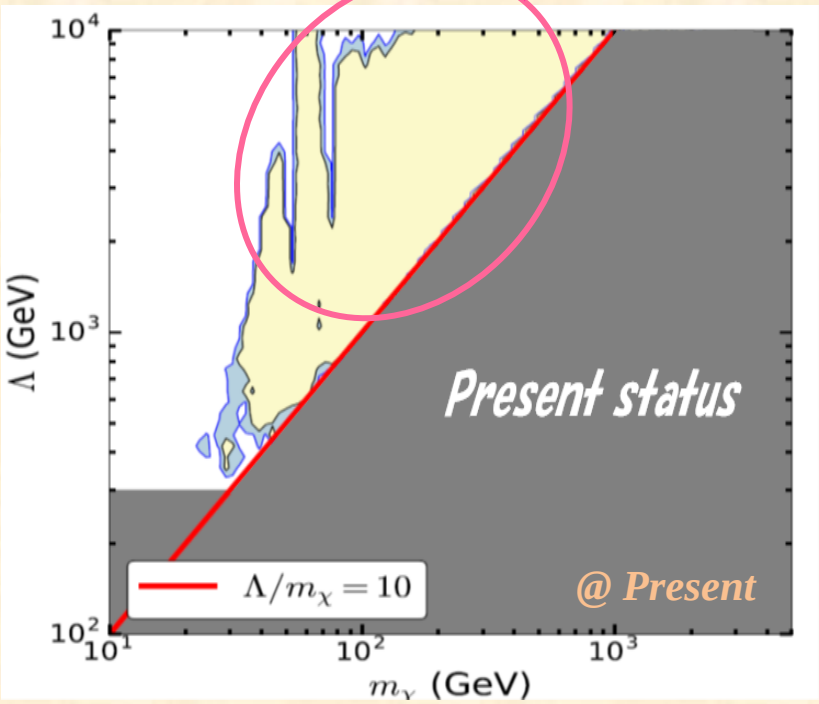
SE + Perturbative Sudakov logarithms (LL & NLL)
[M. Bauer, T. Cohen, Ri. Hill, M. Solon, 2014; G. Ovanesyan, T. Slatyer, I. Stewart, 2014]

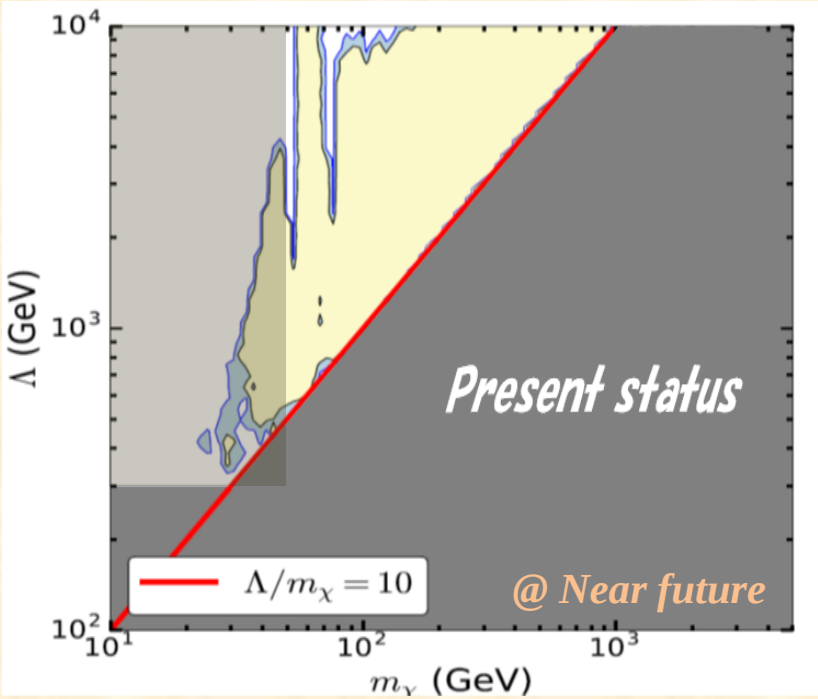
SE + NL + NLL + Inclusive effects
[M. Baumgart, I. Rothstein, V. Vaidya, 2015; G. Ovanesyan, N. Rodd, T. Slatyer, I. Stewart, 2016]

Singlet Fermion Thermal DM (CPV H-portal)

$$\mathcal{L}_{\rm EFT} \supset \frac{c_S}{2\Lambda}(\bar{\chi}\chi)|H|^2 + \frac{c_P}{2\Lambda}(\bar{\chi}i\gamma_5\chi)|H|^2 + \sum_f \frac{c_f}{2\Lambda^2}(\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{f}\gamma_\mu f) + \frac{c_H}{2\Lambda^2}(\bar{\chi}\gamma^\mu\gamma_5\chi)(H^\dagger i\overleftrightarrow{D}_\mu H)$$

Direct dark matter detection
@ Under ground laboratories
(Spin-dependent scattering)





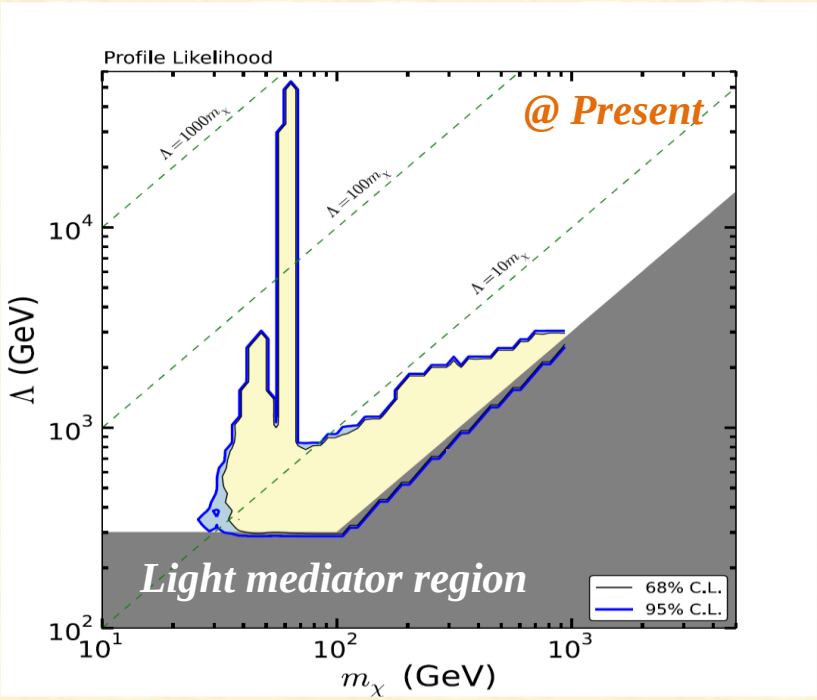
[S.M., S. Mukhopadhyay, Y. L. S. Tsai, JHEP 1410]

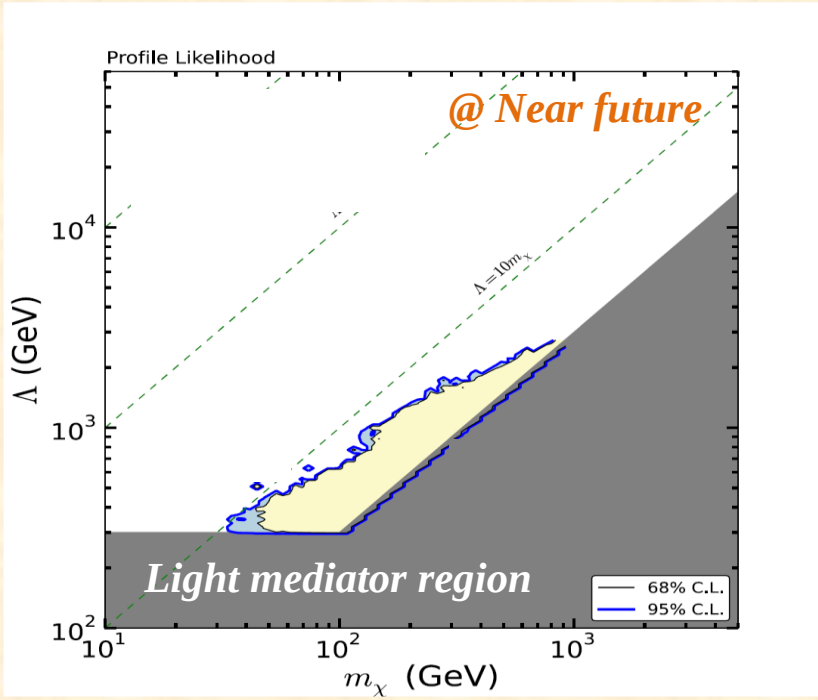
Singlet Fermion Thermal DM (Leptophilic)

$$\mathcal{L}_{\rm EFT} \supset \frac{c_S}{2\Lambda}(\bar{\chi}\chi)|H|^2 + \frac{c_P}{2\Lambda}(\bar{\chi}i\gamma_5\chi)|H|^2 + \sum_f \frac{c_f}{2\Lambda^2}(\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{f}\gamma_\mu f) + \frac{c_H}{2\Lambda^2}(\bar{\chi}\gamma^\mu\gamma_5\chi)(H^\dagger i\overleftrightarrow{D}_\mu H)$$

Flavor blindness assumed.

Direct dark matter detection @ Under ground laboratories
Mono-jet search @ Hi-Luminosity Large Hadron Collider.

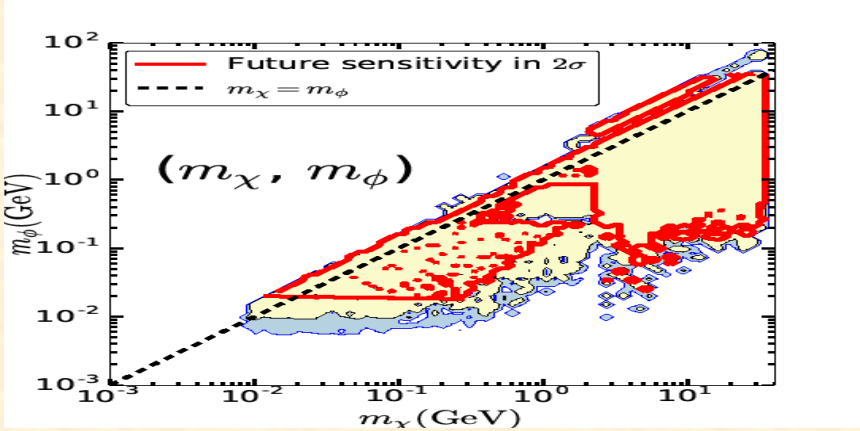


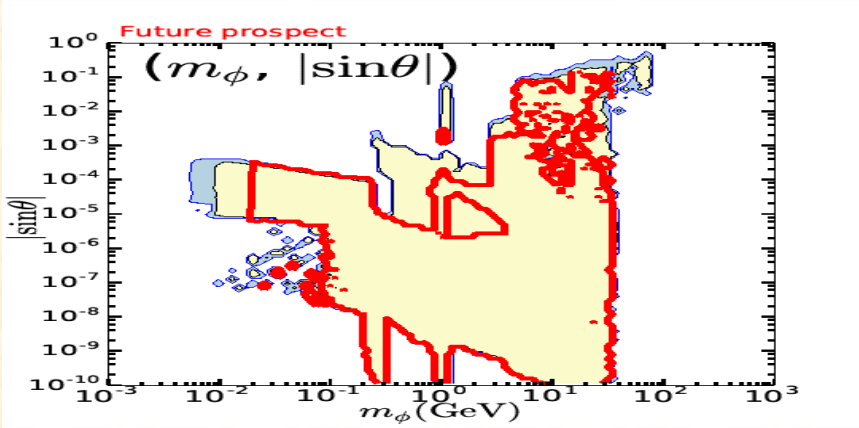


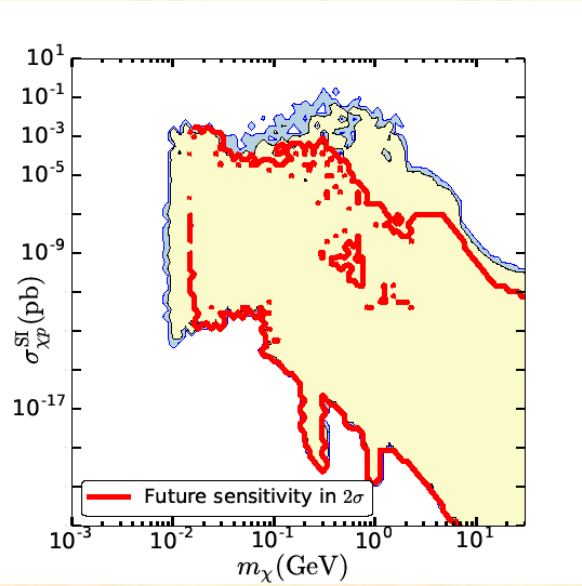
[S. M., S. Mukhopadhyay, Y. L. S. Tsai, PRD94, 2016]

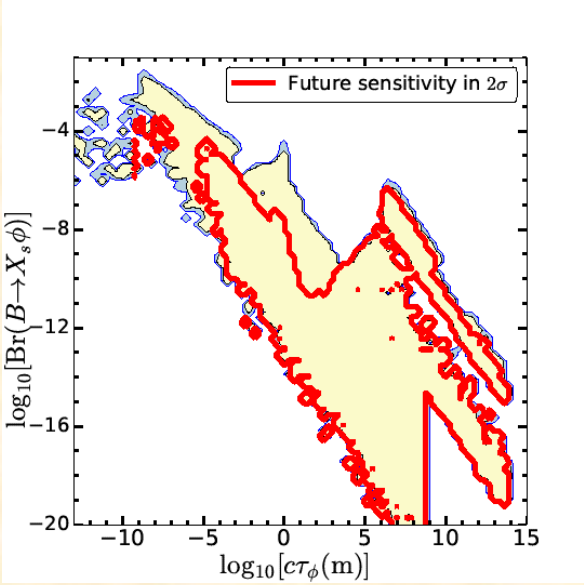
Light Fermion Thermal Dark Matter

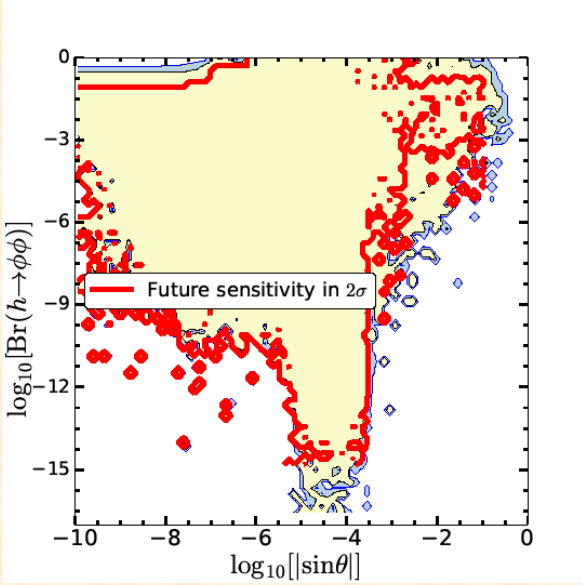
$$\mathscr{L} \supset -\frac{c_s}{2}\phi\bar{\chi}\chi - \frac{c_p}{2}i\phi\bar{\chi}\gamma^5\chi + A_\phi\,\phi H^\dagger H + \frac{\lambda_\phi}{2}\phi^2 H^\dagger H + \mu_1^3\phi + \frac{\mu_\phi^2}{2}\phi^2 + \frac{\mu_3}{3!}\phi^3 + \frac{\lambda_4}{4!}\phi^4$$











Light Fermion Thermal Dark Matter

Answer to the question why a singlet scalar mediator is introduced?

SM + DM system → No renormalizable interaction (SM, Z_2 symmetries).

↓

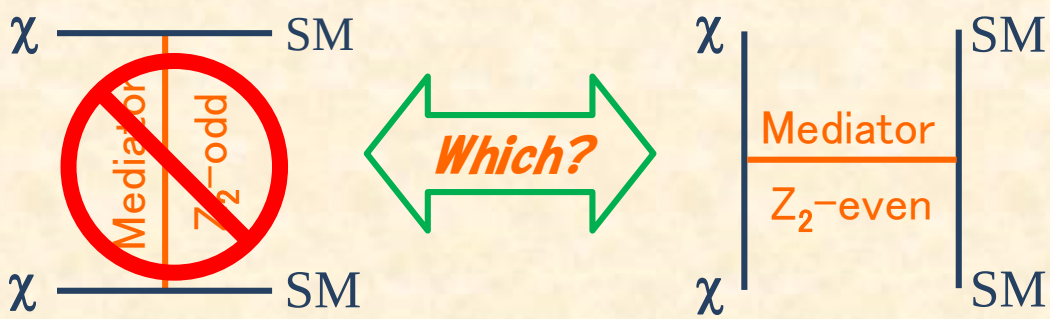
New particle (mediator) must be introduced to have the interaction.

↓

The mediator is as light as DM to explain DM density observed today.

↓

The mediator must be singlet under the SM gauge group and bosonic.



The vector mediator is difficult to evade the constraint from CMB.

(A careful model building is required.)