WIMP DM phenomenology and ILC

Shigeki Matsumoto (Kavli IPMU)

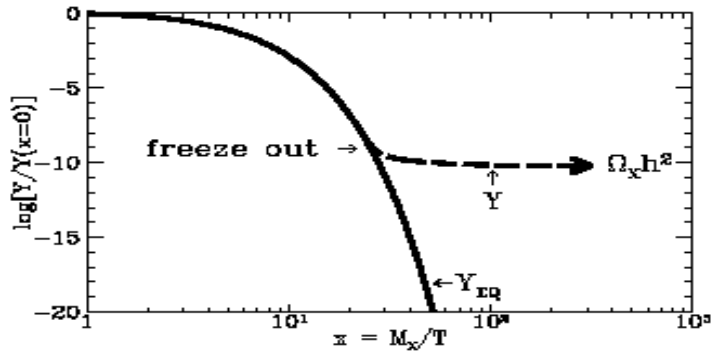
How important is the ILC for WIMPy DM detection?

Many dark matter experiments already exist and are planned. It is thus important to quantitatively figure out what kind of role the future collider plays compared to other experiments.

Thermal (WIMP) DM Hypothesis

We will focus on the thermal dark matter, where its abundance observed today is determined by the freeze-out mechanism.

The mechanism is known to describe the BBN & the recombination phenomena successfully.



To systematically study the DM, we take the following strategy.

1. Classifying the dark matter in terms of its quantum numbers and constructing the minimal renormalizable Lagrangian in each case.
2. Putting the thermal relic abundance condition and imposing all the (expected) limits from DM searches before future lepton colliders.
3. Discussing the role of the colliders in allowed parameter regions.

Hyper-charge assigned appropriately.

- Thermal dark matter
  - $SU(2)_L$ singlet-like
    - Fermionic
    - Bosonic
  - Mixed
    - Fermionic
    - Bosonic
  - $SU(2)_L$ non-singlet-like
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Thermal Dark Matter Hypothesis

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① The dark matter always has interactions DM-DM-H and DM-DM-Z, so that it is efficiently detected by direct dark matter detection.

② DM mass is predicted to be in TeV region (See Moroi-san's talk.)

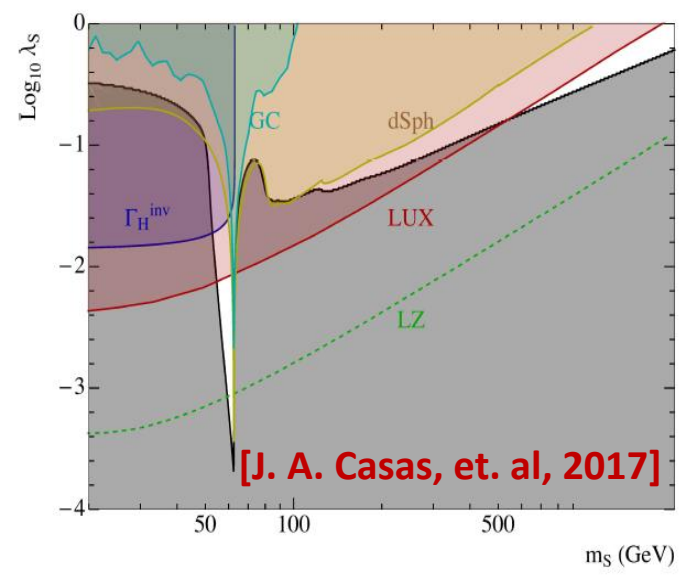
③ The minimal model for the dark matter is the so-called Higgs portal DM model,

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

Z_2 symmetry

which is efficiently being searched for by the direct dark matter detection.

④ We focus on singlet-like fermion DM!



Thermal Dark Matter Hypothesis

Thermal dark matter

$SU(2)_L$ singlet-like

Fermionic

- ✓ No renormalizable interactions at the SM + DM system due to SM and Z_2 symmetries, so that an additional new particle (mediator) is introduced.
- ✓ Dark matter phenomenology depends strongly on the property of the mediator(s) introduced.

Heavy mediator

→ ○ When the mediator is heavier enough than DM and EW scale, we can develop the DM phenomenology in general based on

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

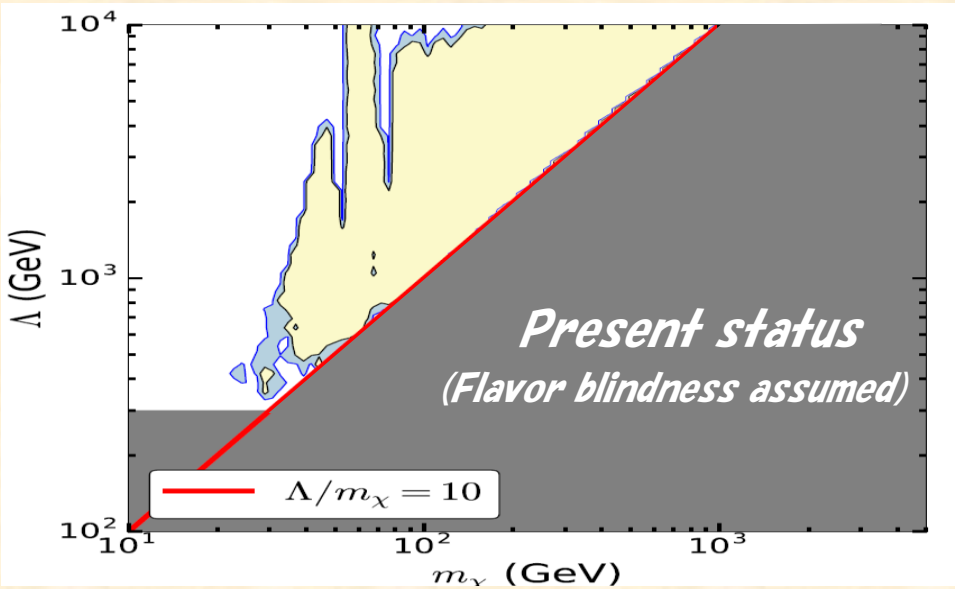
Light mediator

→ ○ When the mediator is light, a renormalizable lagrangian must be constructed in each case, leading to a large diversity!

Indeed, many cases are now being studied as so-called simplified models, assuming various types (quantum numbers) of the mediator.

Singlet Fermion DM with Heavy Med. (Case 1)

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



Scanning multi-dim parameter space via MCMC and cast the result onto the (m_χ, Λ)-plane.

The allowed region relies on the CPV coupling to satisfy the relic abundance condition without conflicting with the constraints from DM searches.

[S.M., S. Mukhopadhyay, Y. S. Tsai, 2014]

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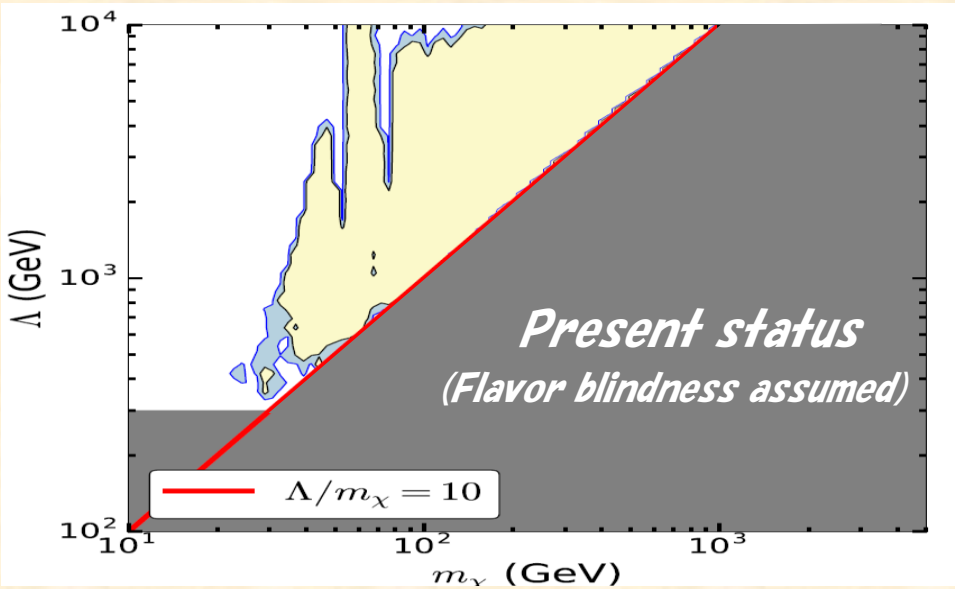

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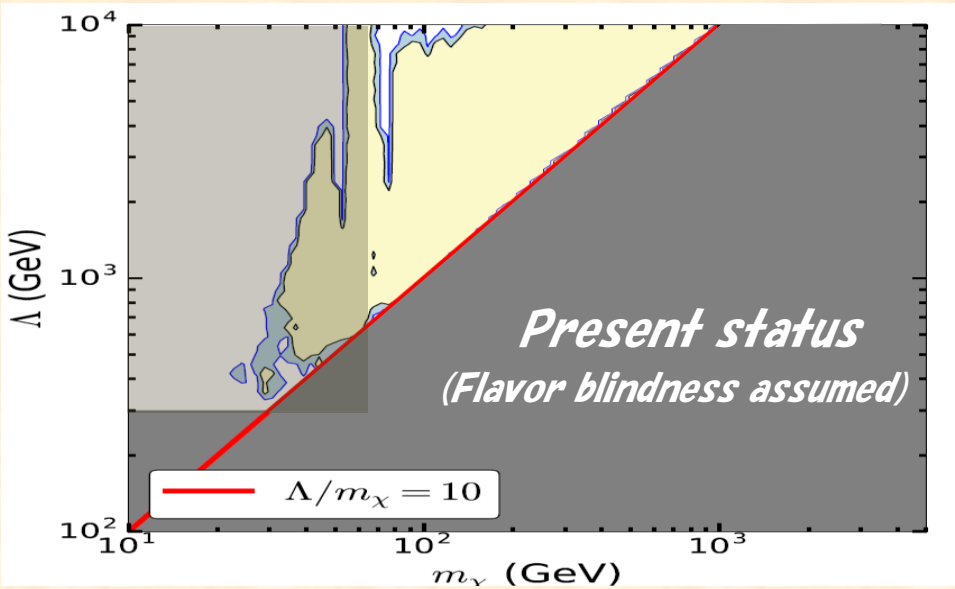

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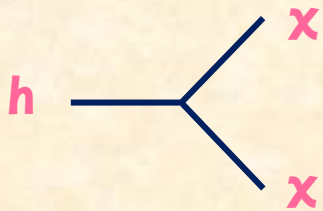

The interesting DM mass is below half a Higgs mass, it is thus efficiently searched for at the invisible H width search at future lepton colliders: $Br(h \to \chi\chi) < 0.004$!

Singlet Fermion DM with Heavy Med. (Case 2)

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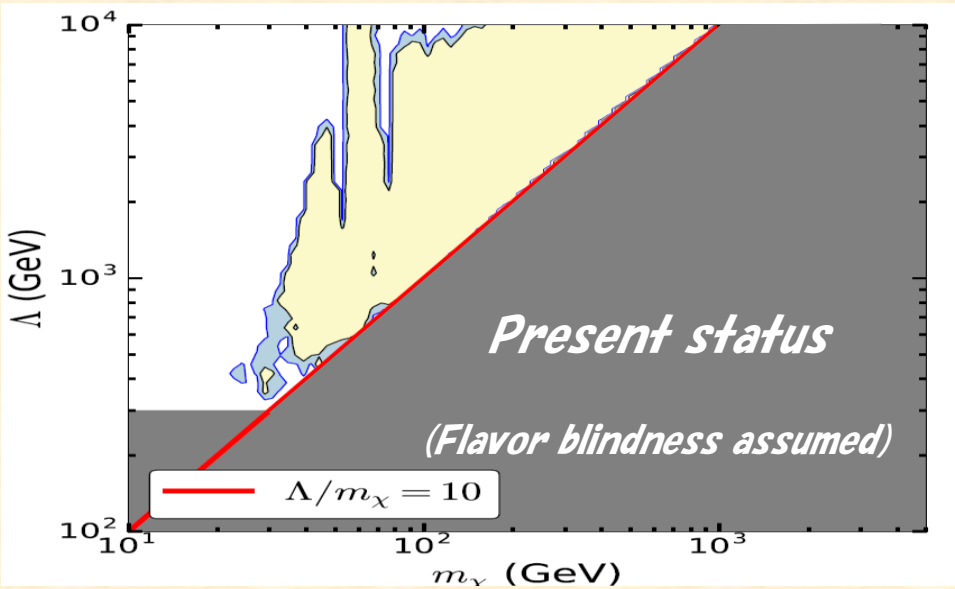

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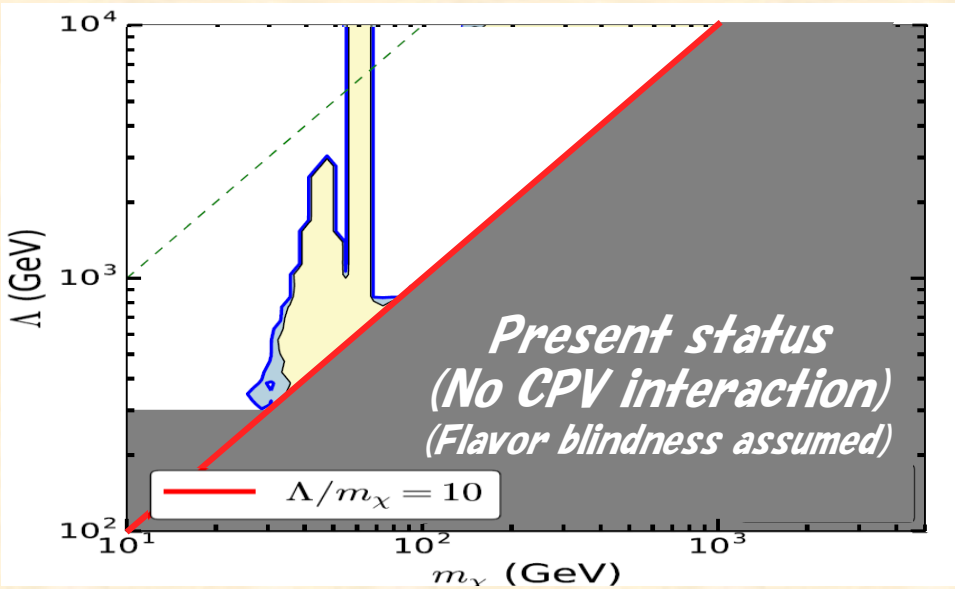

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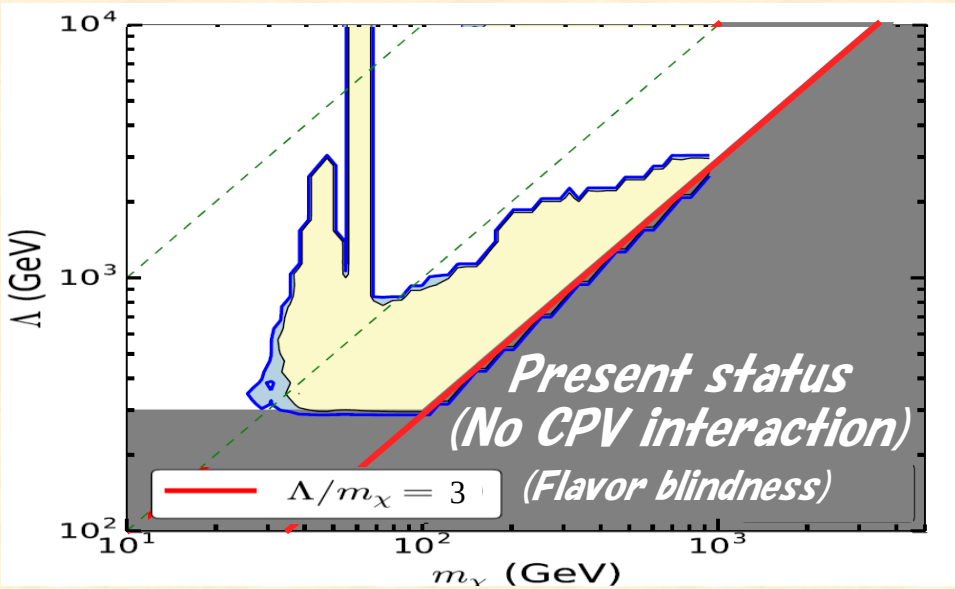

When we look into the region, $3 < \Lambda/m_\chi < 10$, there exists a allowed region even in future.

The region relies on 4-Fermi interactions with a lepton for the relic abundance condition without conflicting with the constraints from DM searches.

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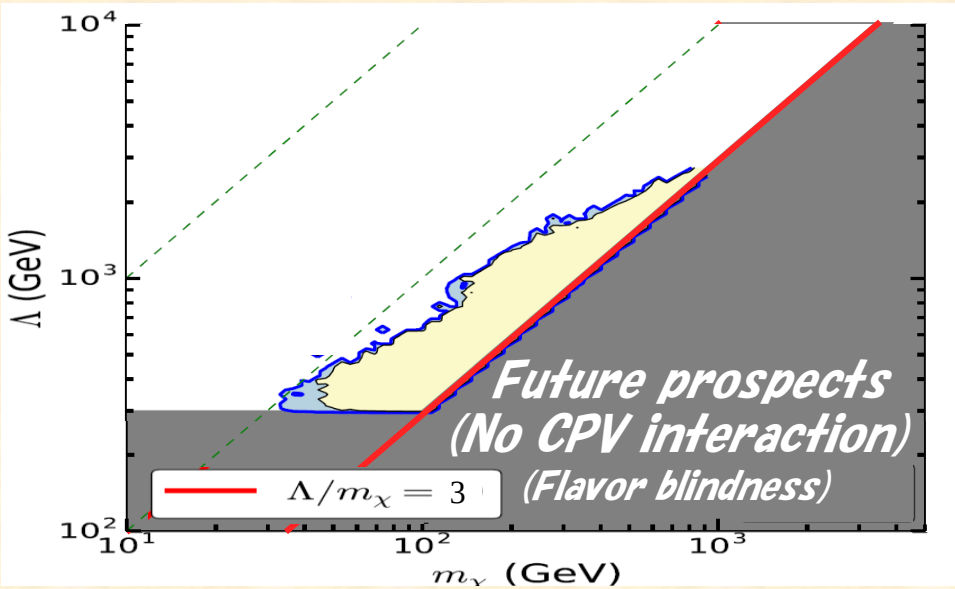

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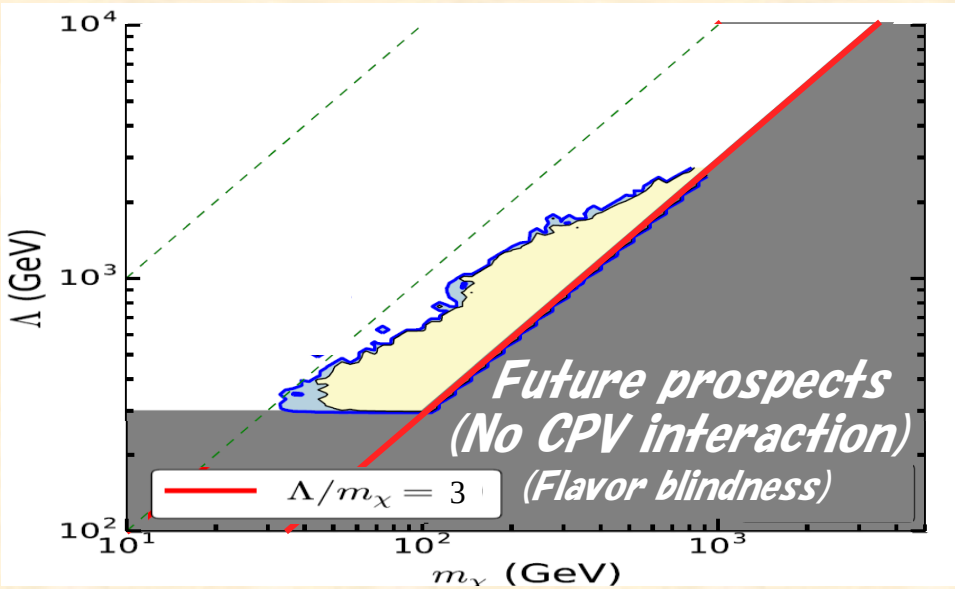

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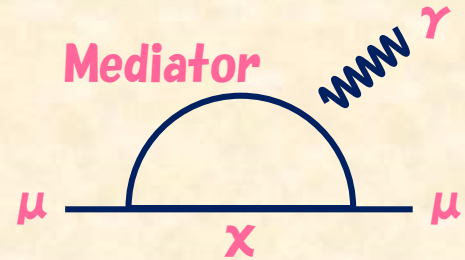

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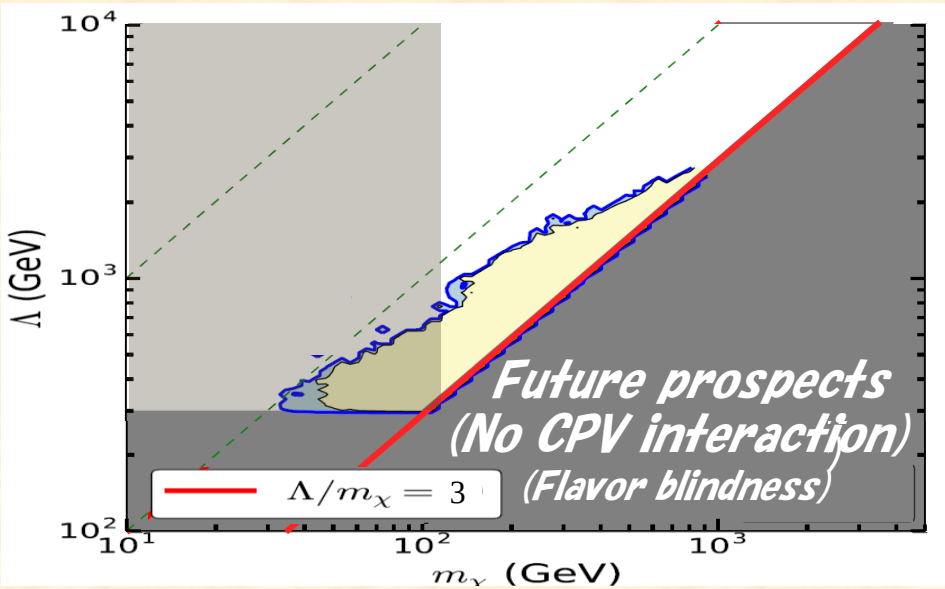

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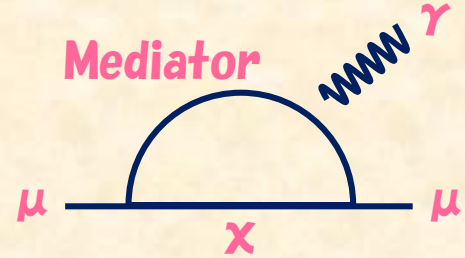
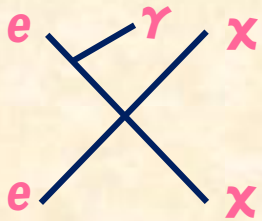
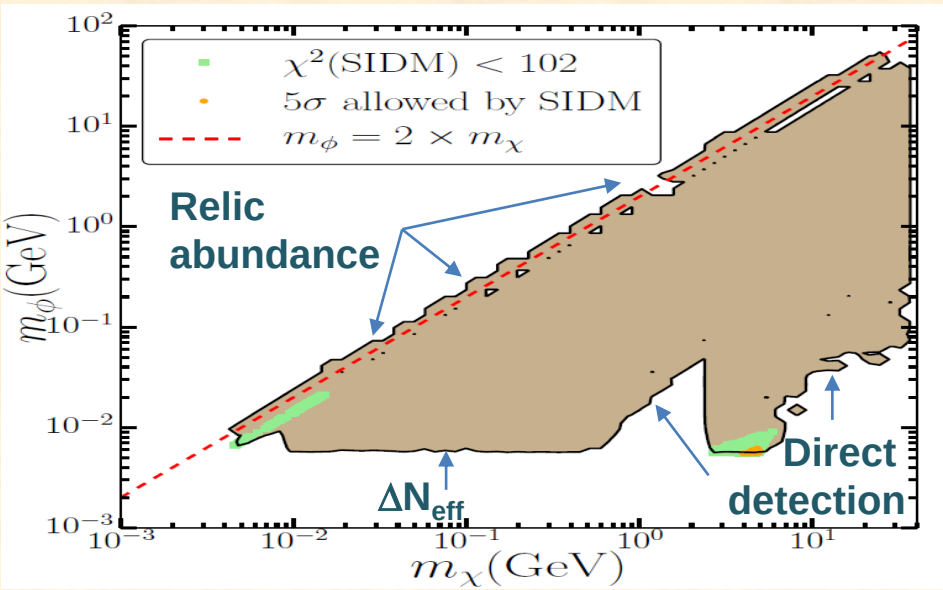




Since the leptophilic dark matter has interactions with leptons with a certain strength, it is possible to search for it by the mono-gamma signal: $\sigma(ee \to \chi\chi\gamma) < O(1)$fb!

Singlet Fermion DM with Light Mediator

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{2}\bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial\phi)^2 - \frac{c_s}{2}\phi\bar{\chi}\chi - \frac{c_p}{2}i\phi\bar{\chi}\gamma^5\chi - V(\phi, H)$$



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Direct detection plays a crucial role for DM.

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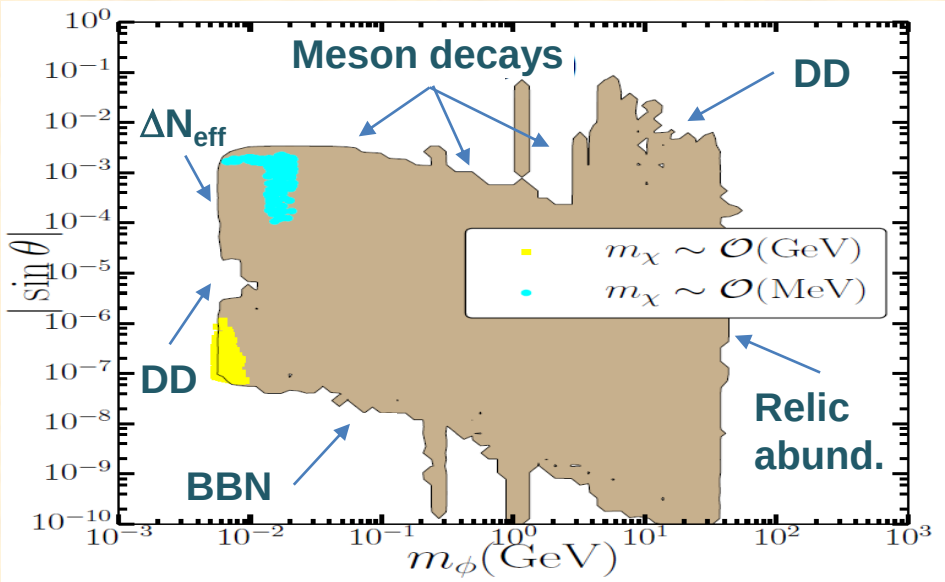

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Direct detection plays a crucial role for DM, but the first BSM signal can be from the mediator.

Interaction strength between ϕ and SM particles is controlled by "sinθ".

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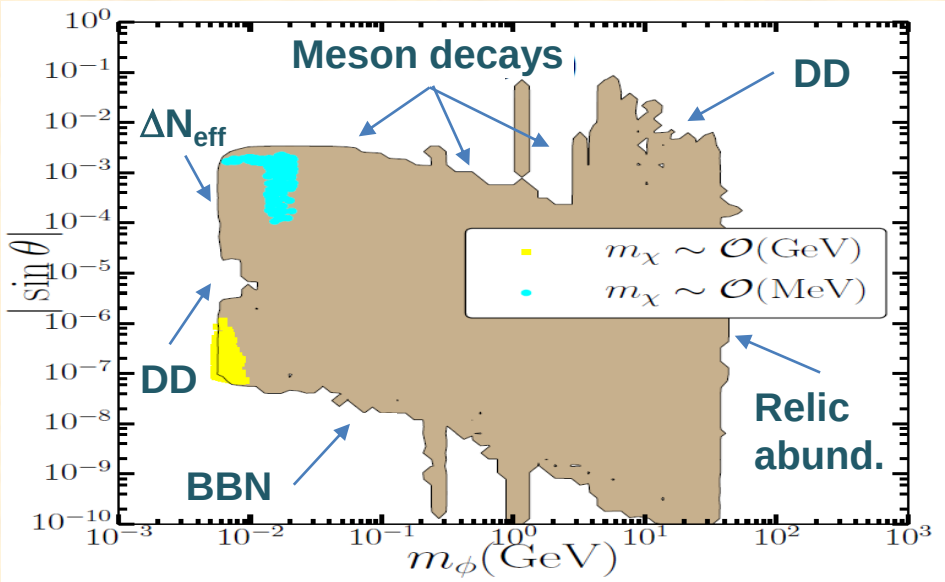

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This light dark matter (with a light mediator) predicts a large enough dark matter self-interaction and frequently addressed for the small scale structure problem of the universe. [L. Calibbi, et. al, arXiv:1804.00009]

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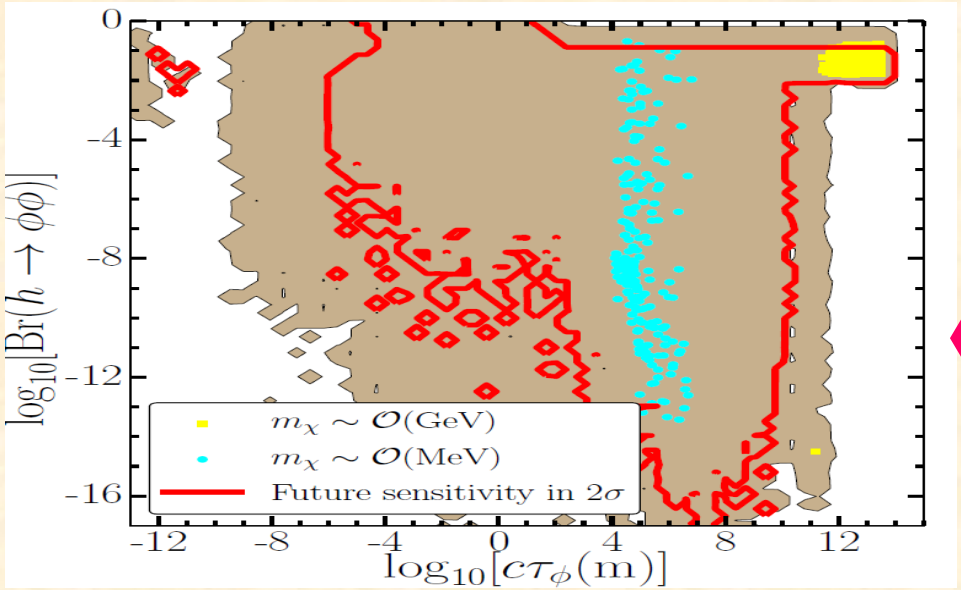

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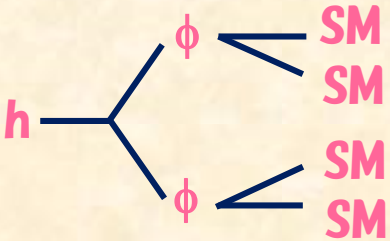

Though most of the ϕ detection relies on $\sin\theta$ ($\subset \phi|H|^2$), future lepton colliders offer complementary detections via exotic Higgs decays originating in a operator $\phi^2|H|^2$.

Summary

The future lepton colliders play a leading role to detect the singlet fermion thermal dark matter. Well-motivated concrete examples are

DM candidates	Motivation	Signal @ Lepton Collides
✓ CPV H-funnel DM	γ & $\bar{p}$ excesses	Invisible H-decay
✓ Leptophilic DM	$g_\mu - 2$	Mono-γ search
✓ Light DM	Core-Cusp prob.	Exotic H-decays

There would be more thermal dark matter candidates that 240-250 GeV future lepton colliders play an leading role for their detections.

- when we introduce the flavor-dependent interactions.
- when we consider various types (quantum numbers) of the mediator.
- when we go beyond the minimality at each thermal dark matter case.