Search for Dark Matter at 240-250 GeV Lepton Colliders

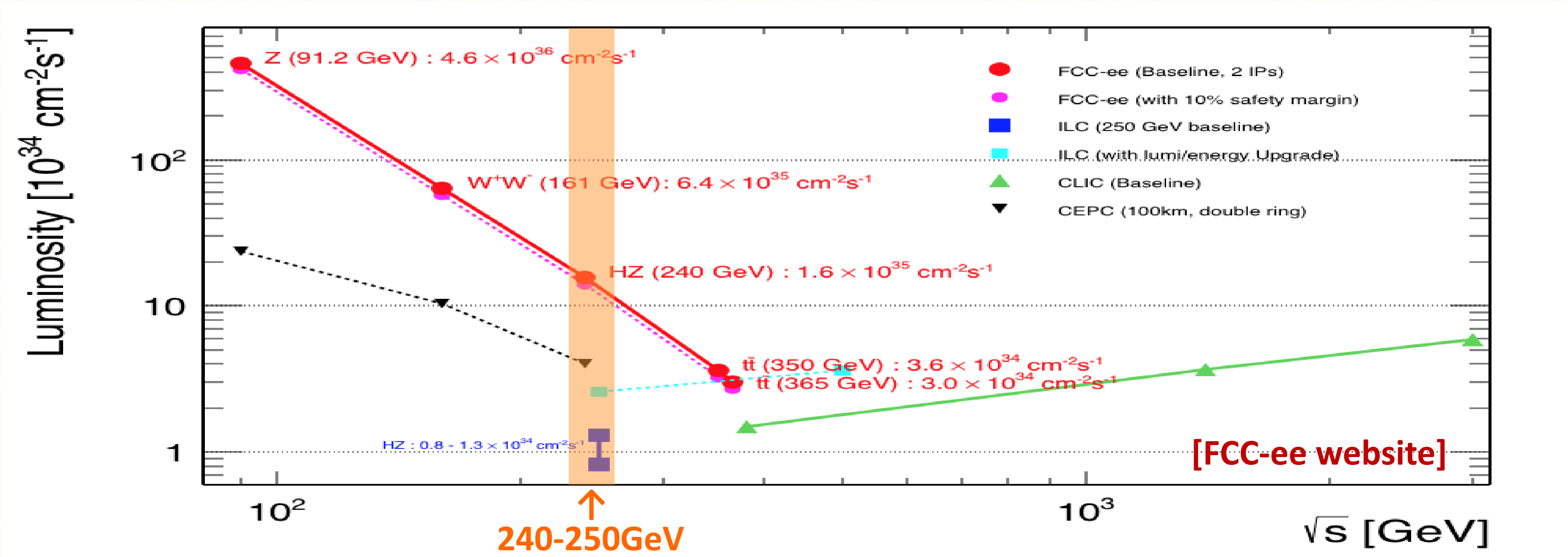
Shigeki Matsumoto (Kavli IPMU)

Various future lepton colliders (ILC, CEPC, FCC) are proposed and now seriously discussed, where their collision energies are designed to be 240-250GeV.

How important is the colliders for dark matter?

The Question

Future lepton colliders

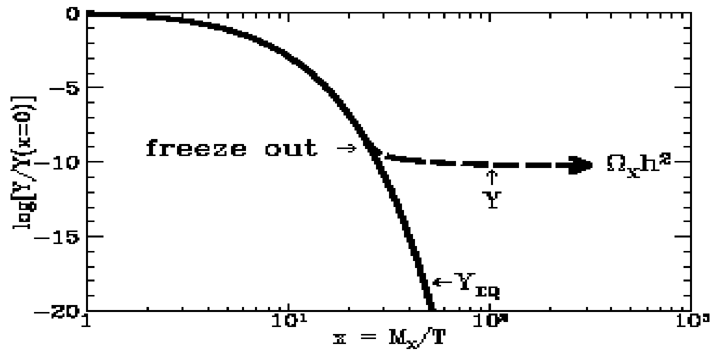


- ✓ *Main goal of the 240-250GeV lepton colliders is to precisely measure known Higgs couplings to tackle the EWSB problem.*
- ✓ *It is also interesting to discuss whether other new physics signals (in particular dark matter's) can be detected or not.*
- ✓ *Many dark matter experiments already exist and are planned. It is thus important to quantitatively figure out what kind of role the future colliders play compared to other experiments.*

Thermal Dark Matter 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.



We take the following strategy to systematically study the DM.

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

Thermal dark matter

- $SU(2)_L$ singlet-like
  - Fermionic
  - Bosonic
- Mixed
  - Fermionic
  - Bosonic
- $SU(2)_L$ non-singlet-like
  - Fermionic
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  - ② SU(2)$_L$ non-singlet-like
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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 The mass of the dark matter is predicted to be in the TeV region.

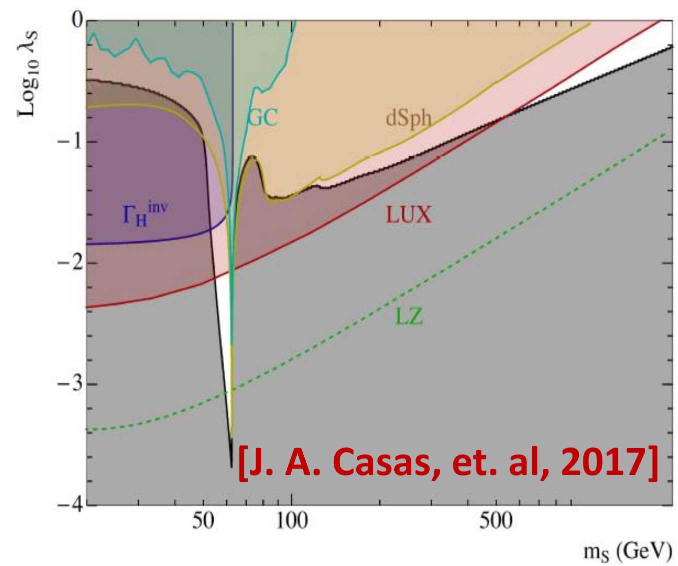
③ The minimal model for the dark matter is the so-called Higgs portal DM model,

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

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, we have to use a renormalizable Lagrangian in each case, meaning there is a large diversity!

Many cases are now being studied as so-called simplified models, assuming various types (quantum numbers) of the mediator. For instance, quarkophilic, leptophilic, hidden photon (scalar) models.

Singlet Fermion DM with Heavy Mediator (Case 1)

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

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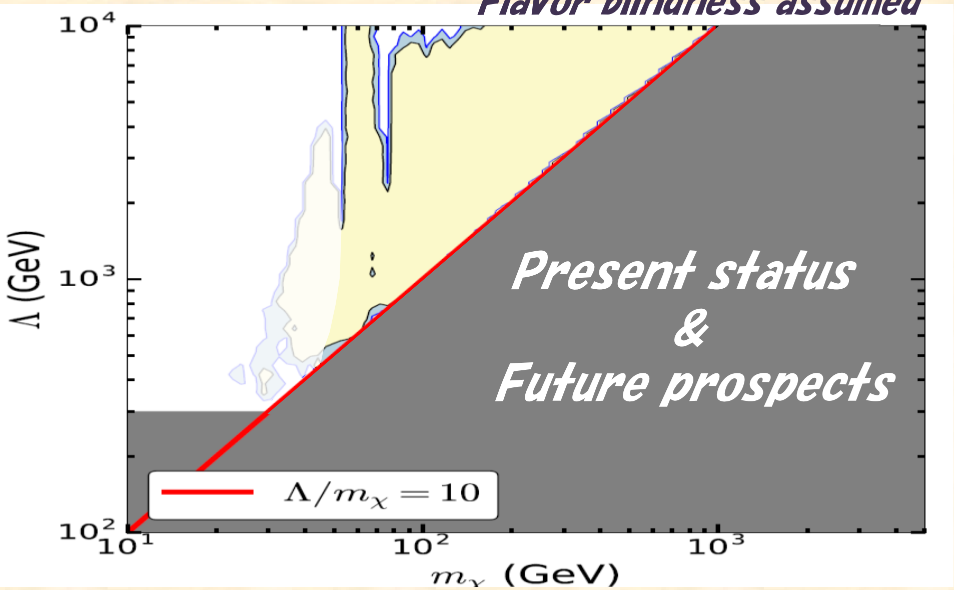
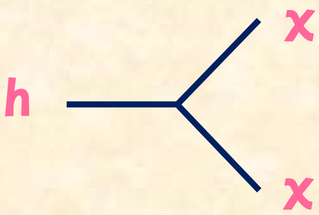


Scanning multi-dim parameter space via MCMC and cast the result onto the (m_χ, Λ)-plane.

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]

This CPV H-portal dark matter is known to be the simplest model to explain the GeV gamma-ray excess from G.C. when its mass is about 50GeV, though the excess is likely to be from … [Fermi-LAT, arXiv:1704.03910]



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: $Br(h \to \chi\chi) < 0.004$!

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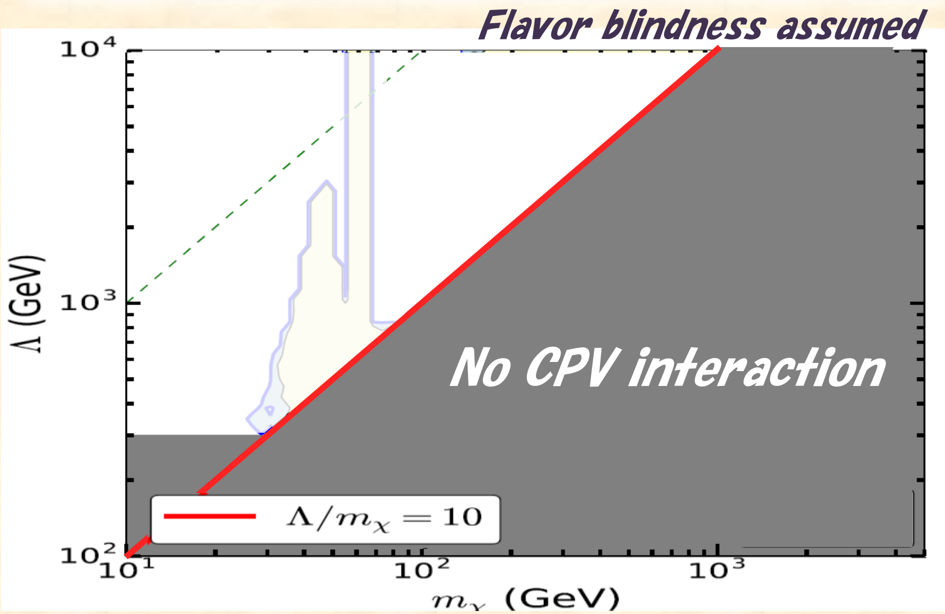

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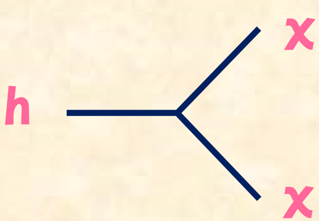

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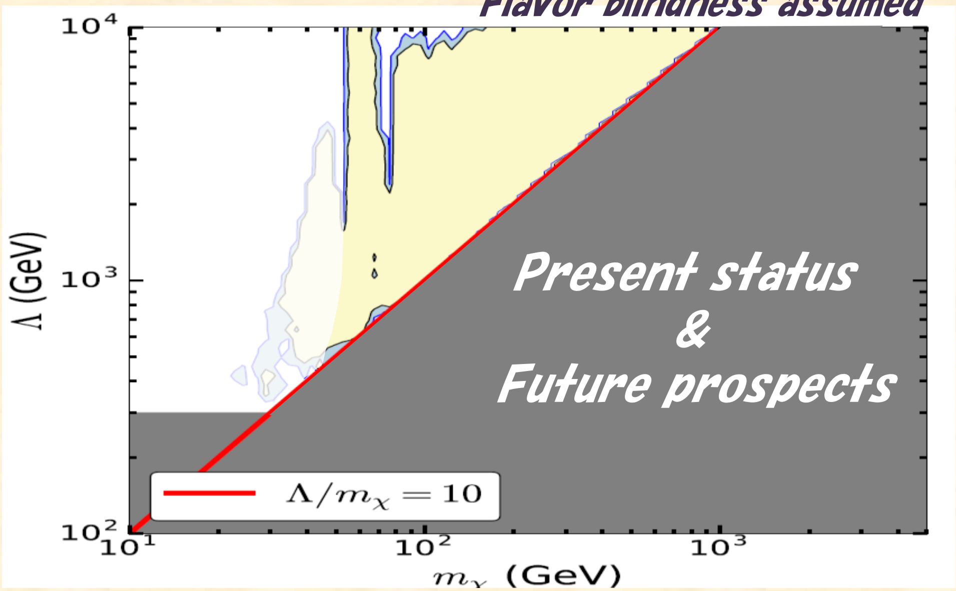

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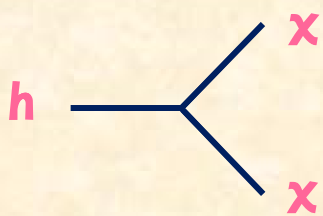

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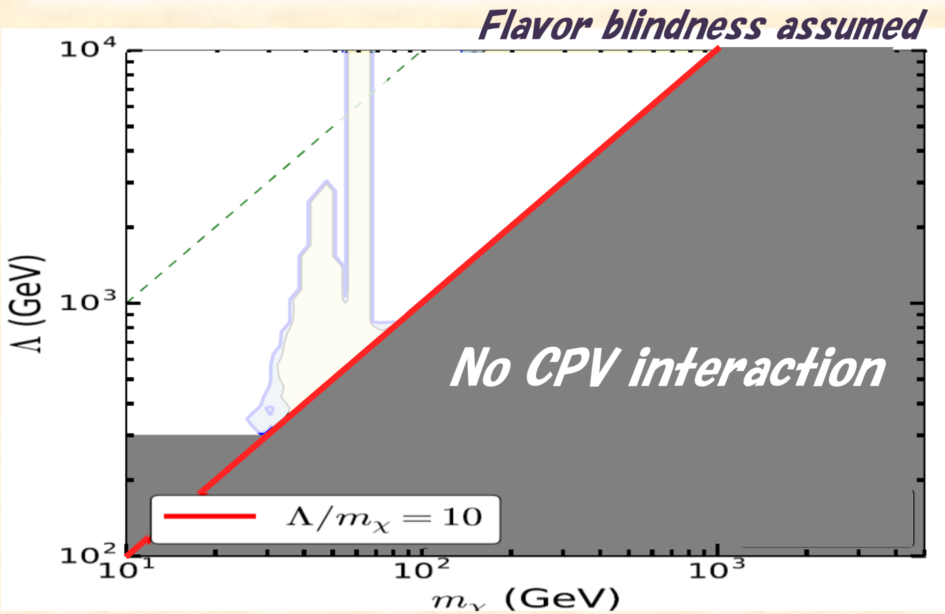

When we look into the region, $3 < \Lambda/m_\chi < 10$, there exists a allowed region even in future.

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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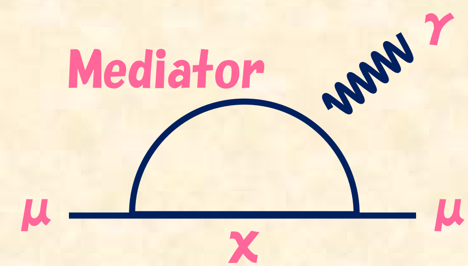
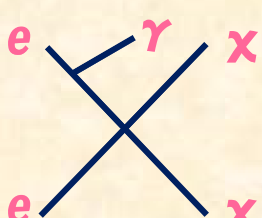
This leptophilic dark matter is known to be one of the models for explaining the muon anomalous magnetic moment, $g_\mu - 2$. [L. Calibbi, et. al, arXiv:1804.00009]





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!

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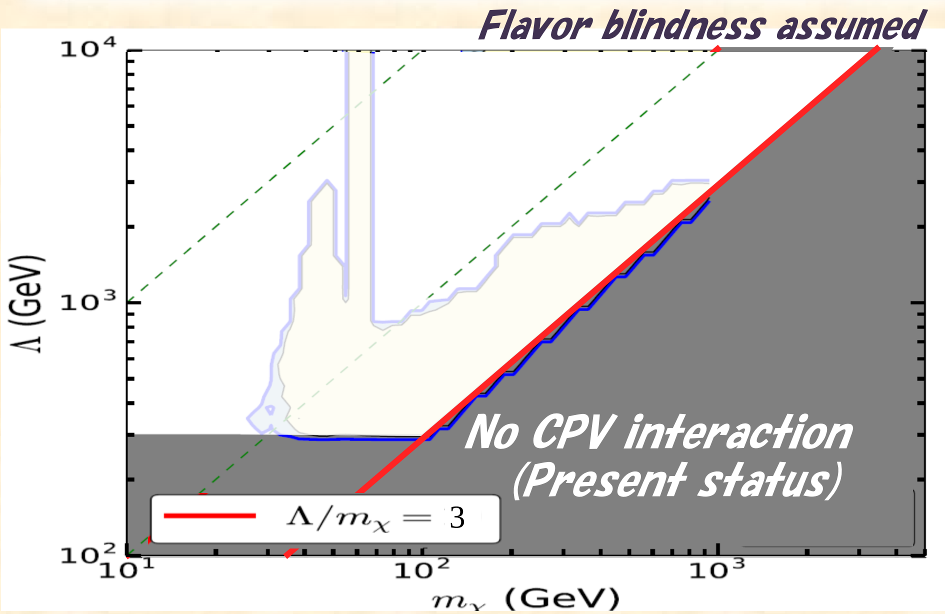

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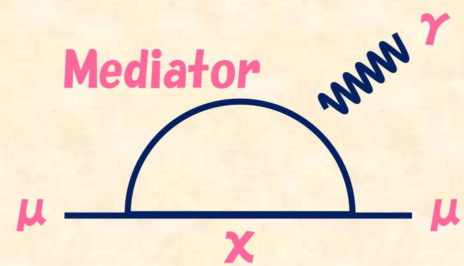

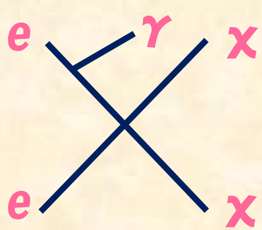

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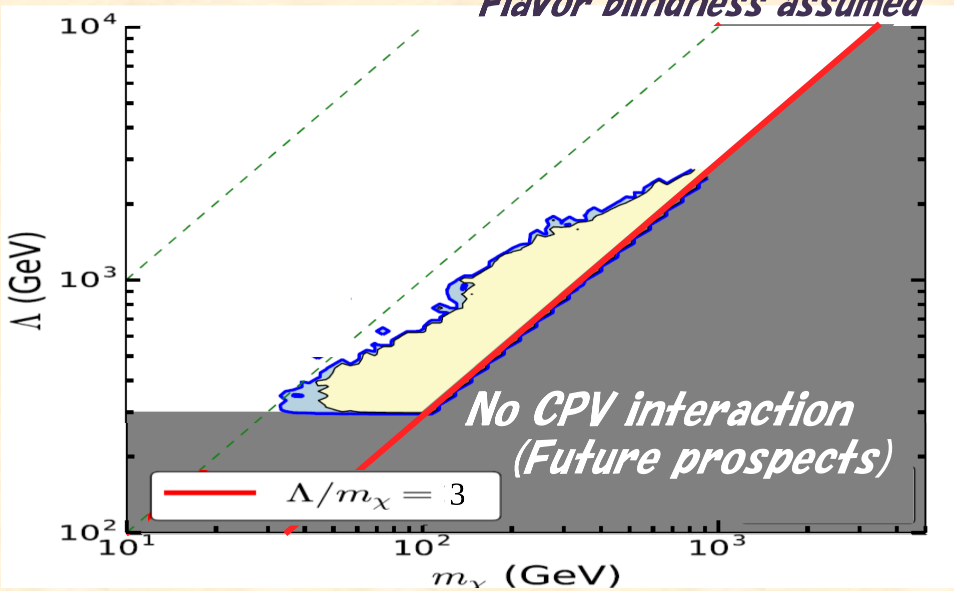

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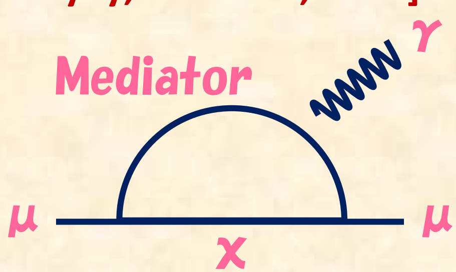

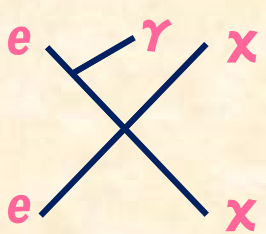

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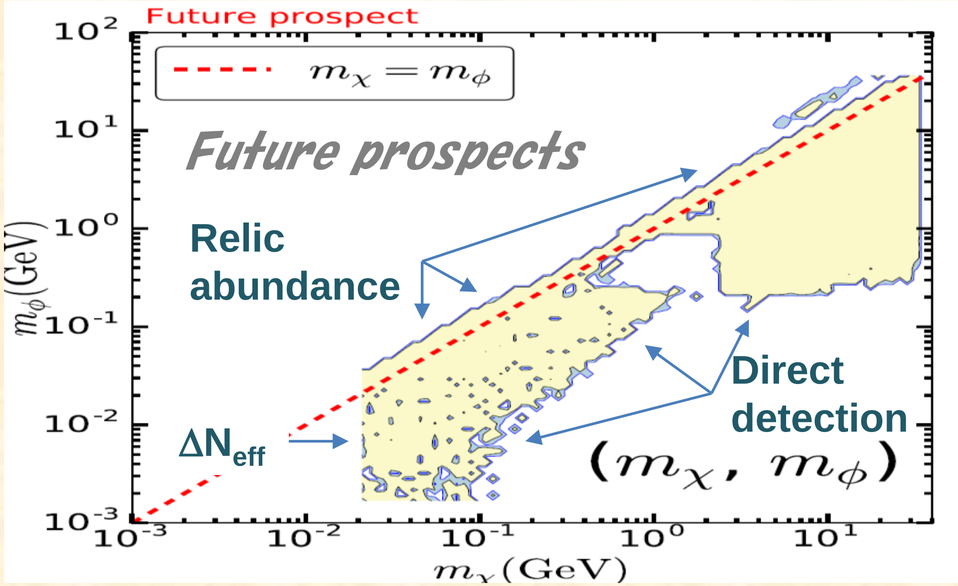

The minimal model for the light fermionic dark matter region requires a bosonic mediator.

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 "$\sin\theta$".

[S.M., Y. S. Tsai, P. Y. Tsng, 2018(exp)]

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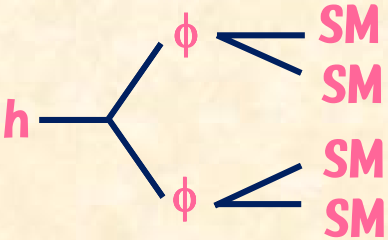

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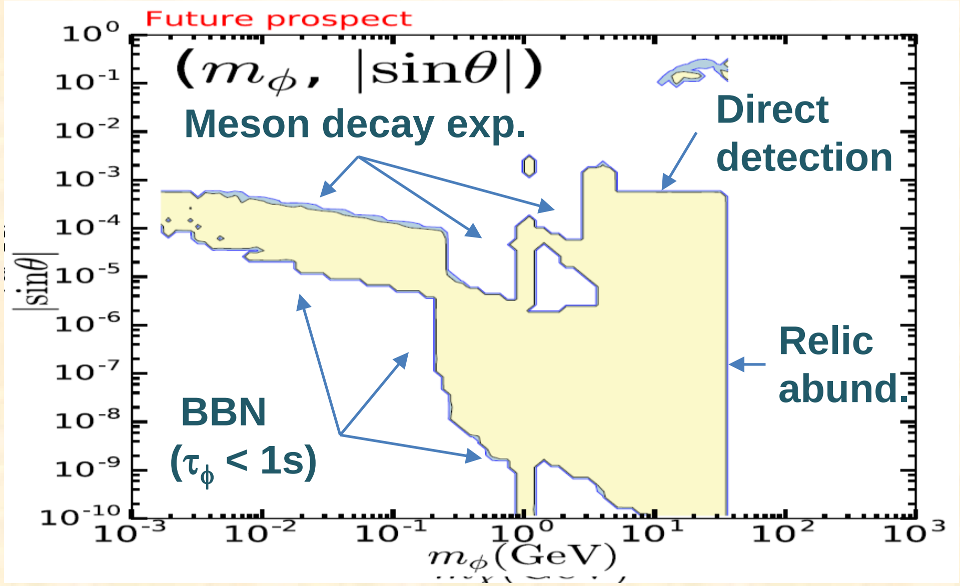

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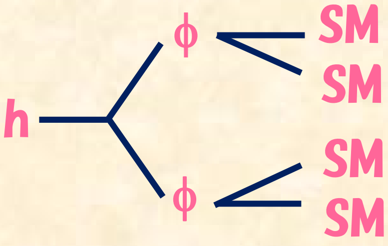

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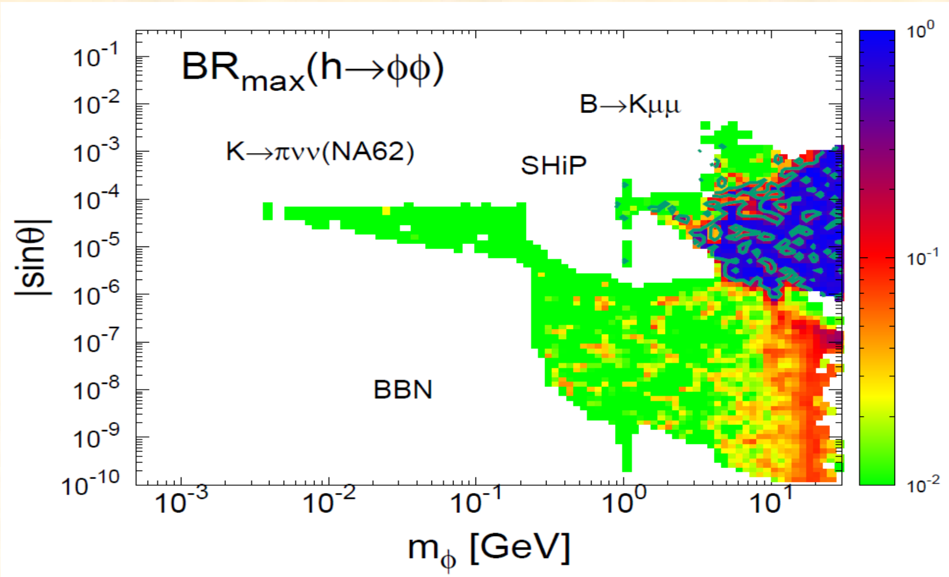

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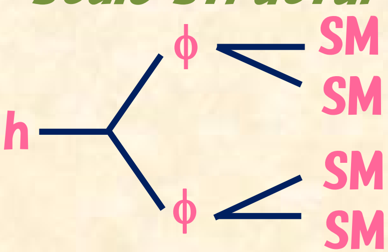

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Summary

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	G.C. γ-ray	Invisible H-decay
✓ Leptophilic DM	g_μ - 2	Mono-γ
✓ Light DM	SSS problem	Exotic H-decay

There would be more thermal dark matter candidates detected mainly by the future lepton colliders, if we relax the flavor-blind condition, consider various types of the mediator, go beyond the minimality.