

Search for Dark Matter at 240–250 GeV Lepton Colliders

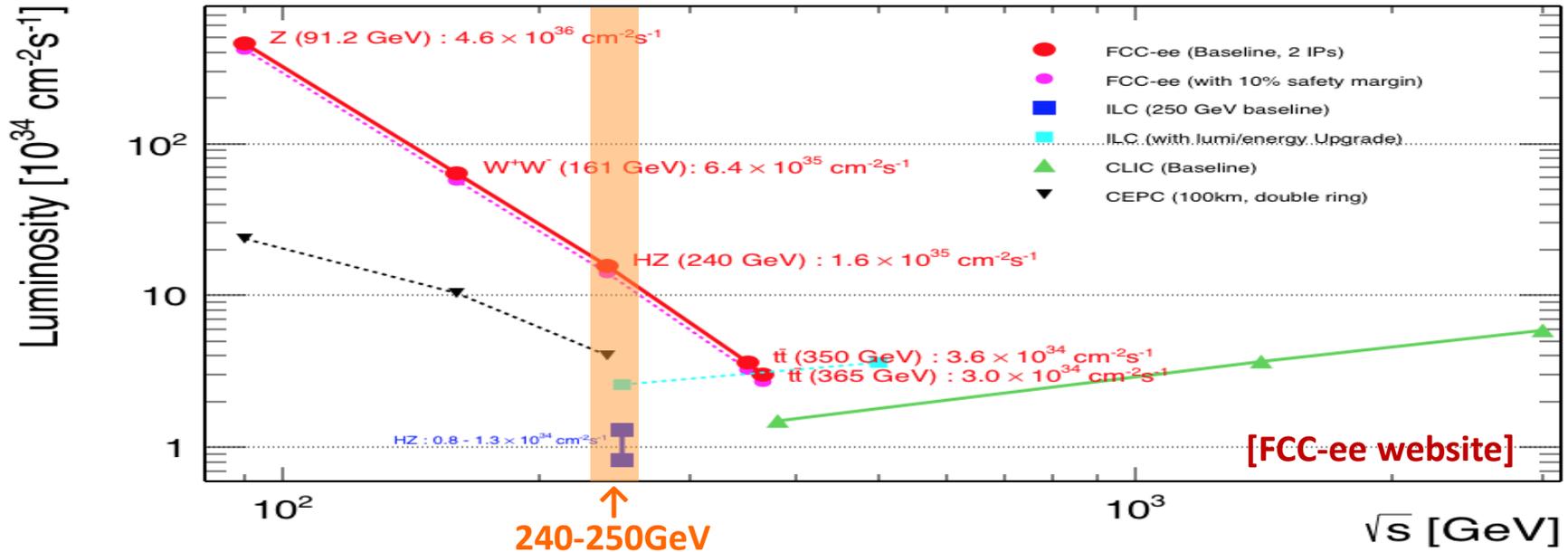
Shigeki Matsumoto (Kavli IPMU)

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

How important is the colliders for dark matter?

The Question

Future lepton colliders

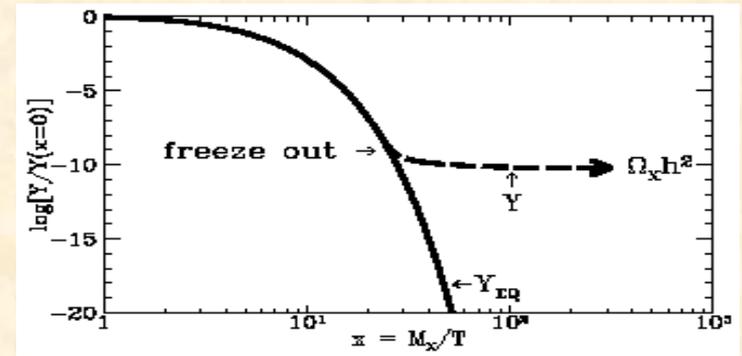


- ✓ *Main goal of the 240–250 GeV lepton colliders is to precisely measure known Higgs couplings to tackle the EWSB problem.*
- ✓ *It is also interesting to discuss whether other new physics signals (in particular dark matter's) can be detected or not.*
- ✓ *Many dark matter experiments already exist 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

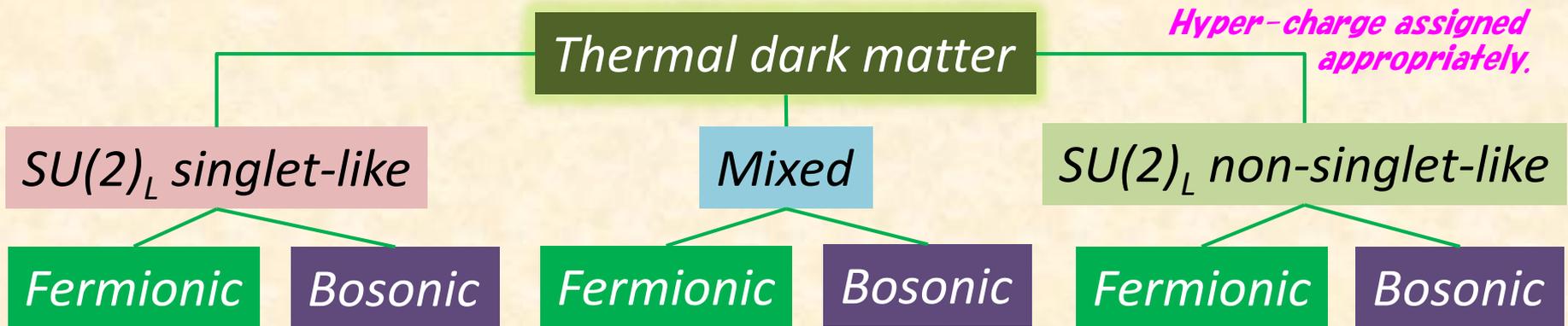
We will focus on the thermal dark matter, where its abundance observed today is determined by the freeze-out mechanism.

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

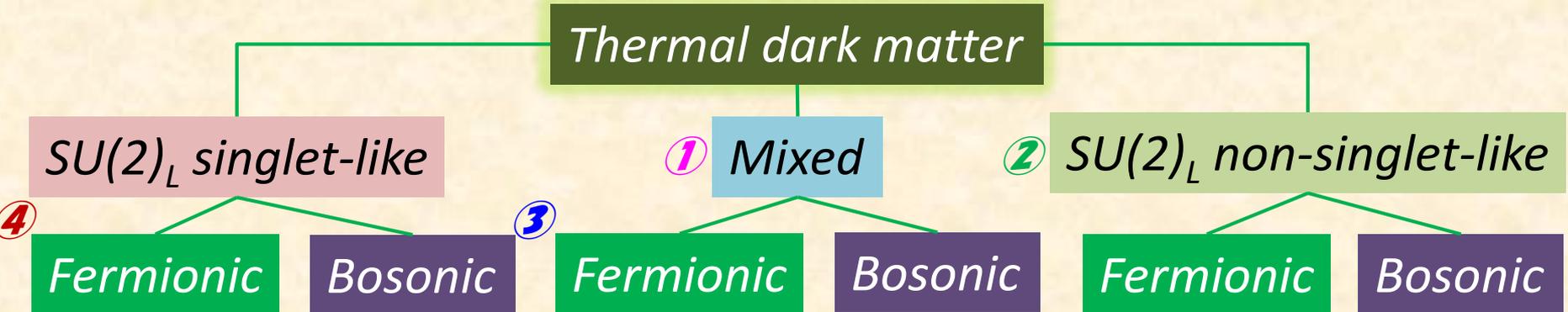


To systematically study the DM, we take the following strategy.

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.



Thermal Dark Matter Hypothesis



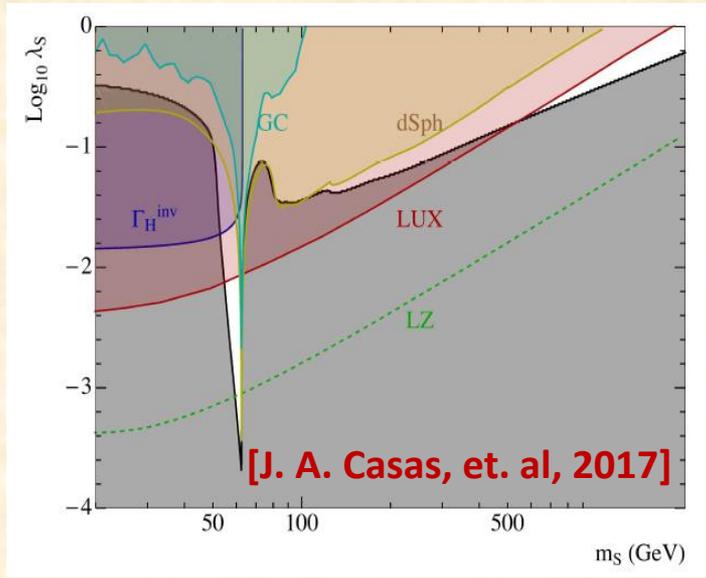
- ① *The dark matter always has interactions DM-DM-H and DM-DM-Z, so that it is efficiently detected by direct dark matter detection.*
- ② *The mass of the dark matter is predicted to be in the TeV region.*
- ③ *The minimal model for the dark matter is the so-called Higgs portal DM model,*

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

Z₂ 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

Heavy mediator

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

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

Light mediator

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

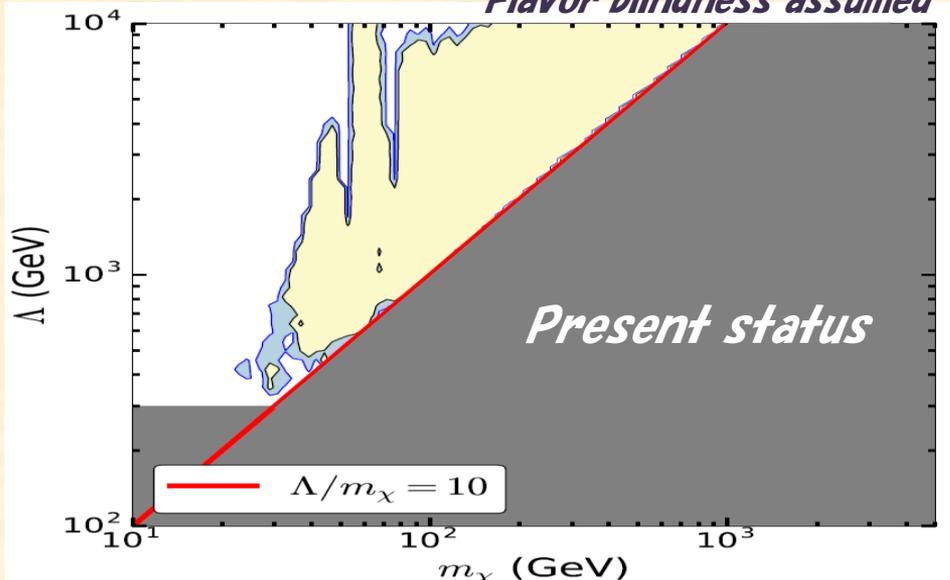
Indeed, many cases are now being studied as so-called simplified models, assuming various types (quantum numbers) of the mediator.

- ✓ 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.

Singlet Fermion DM with Heavy Mediator (Case 1)

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

Flavor blindness assumed

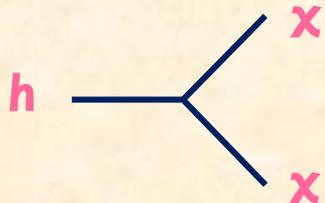


Scanning multi-dim parameter space via MCMC and cast the result onto the (m_χ, Λ) -plane.

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]

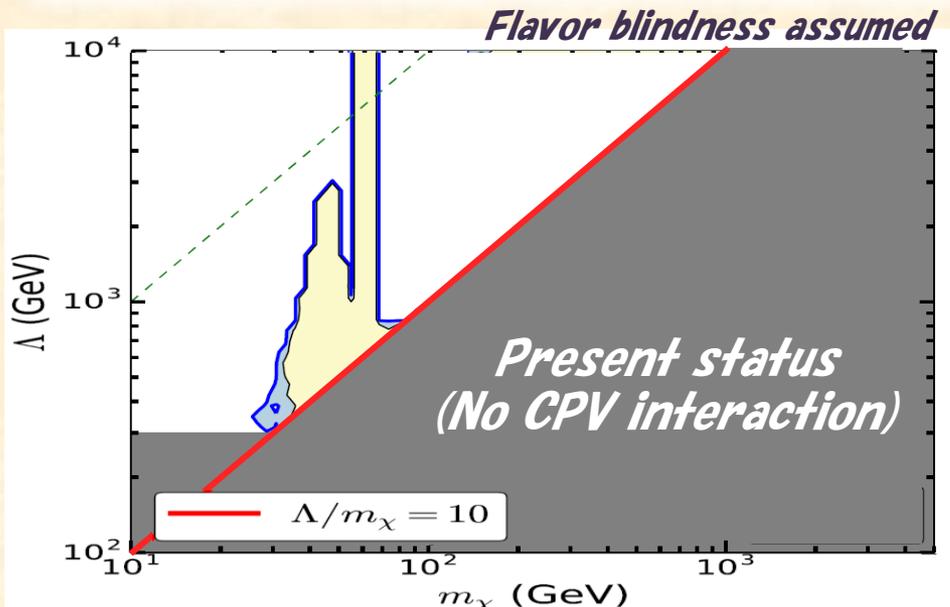
This CPV H-portal dark matter is known to be the simplest model to explain the GeV gamma-ray excess from G.C. when its mass is about 50GeV, though the excess is likely to be from ... [Fermi-LAT, arXiv:1704.03910]



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

Singlet Fermion DM with Heavy Mediator (Case 1)

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

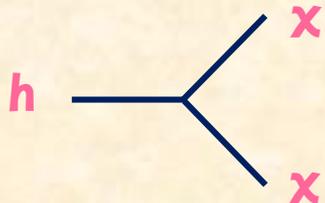


Scanning multi-dim parameter space via MCMC and cast the result onto the (m_χ, Λ) -plane.

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]

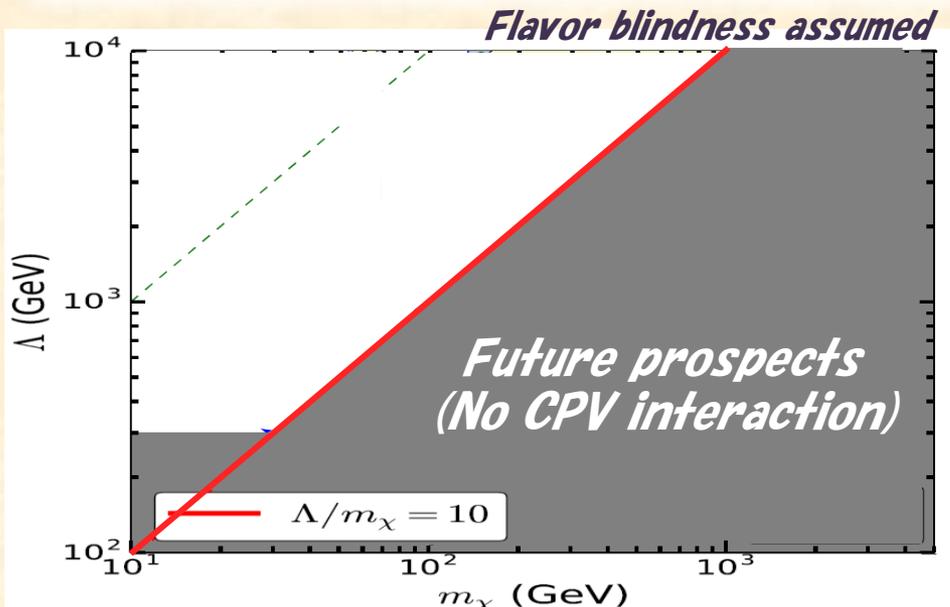
This CPV H-portal dark matter is known to be the simplest model to explain the GeV gamma-ray excess from G.C. when its mass is about 50GeV, though the excess is likely to be from ... [Fermi-LAT, arXiv:1704.03910]



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

Singlet Fermion DM with Heavy Mediator (Case 1)

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

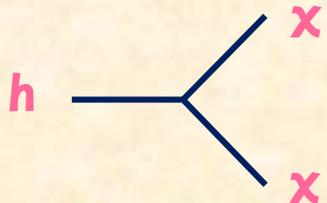


Scanning multi-dim parameter space via MCMC and cast the result onto the (m_χ, Λ) -plane.

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]

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]

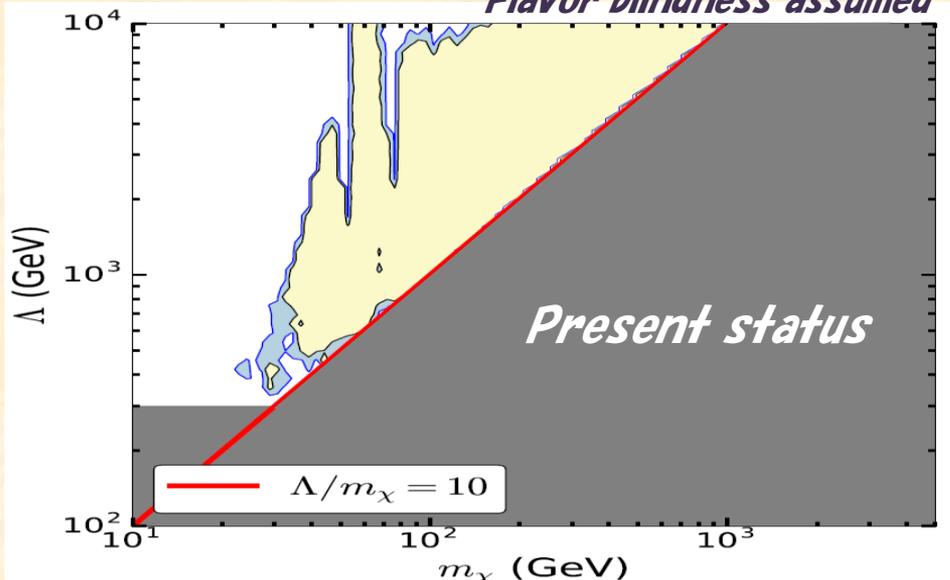


The interesting DM mass is below half a Higgs mass, it is thus efficiently searched for at the invisible H width search at future lepton colliders: $Br(h \rightarrow \chi\chi) < 0.004!$

Singlet Fermion DM with Heavy Mediator (Case 1)

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

Flavor blindness assumed

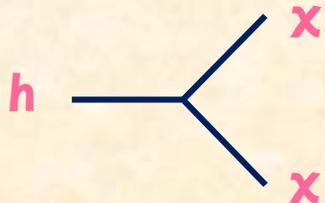


Scanning multi-dim parameter space via MCMC and cast the result onto the (m_χ, Λ) -plane.

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]

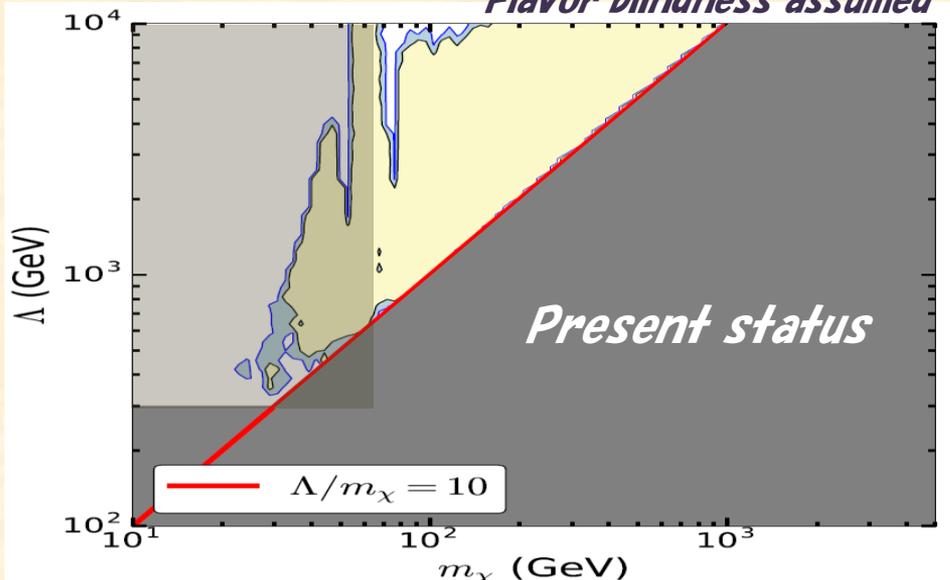


The interesting DM mass is below half a Higgs mass, it is thus efficiently searched for at the invisible H width search at future lepton colliders: $Br(h \rightarrow \chi\chi) < 0.004!$

Singlet Fermion DM with Heavy Mediator (Case 1)

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

Flavor blindness assumed

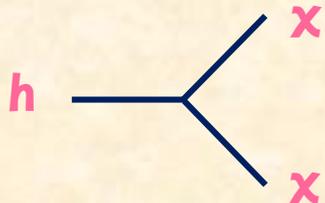


Scanning multi-dim parameter space via MCMC and cast the result onto the (m_χ, Λ) -plane.

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]



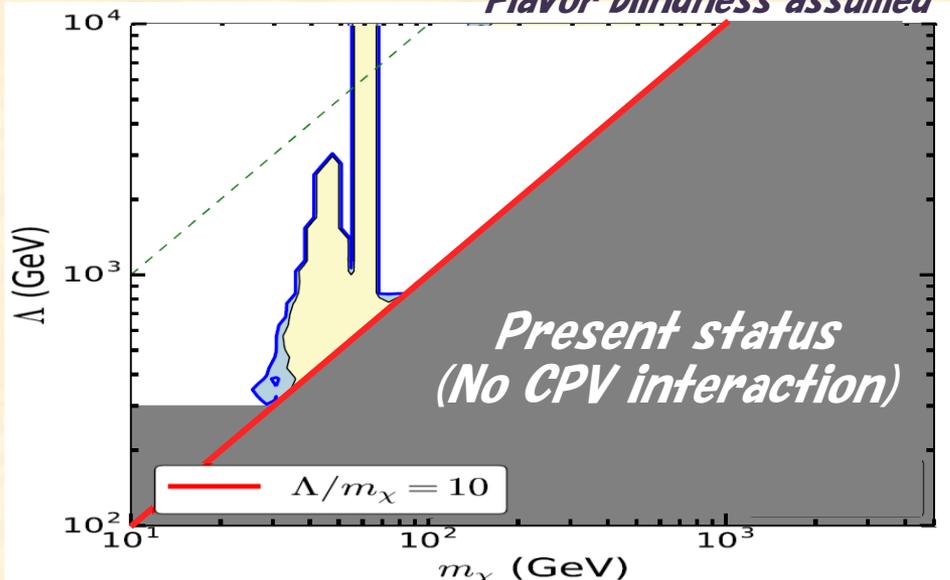
The interesting DM mass is below half a Higgs mass, it is thus efficiently searched for at the invisible H width search at future lepton colliders: $Br(h \rightarrow \chi\chi) < 0.004!$

Singlet Fermion DM with (Heavy) Mediator (Case 2)

The other interesting DM candidate is...

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

Flavor blindness assumed

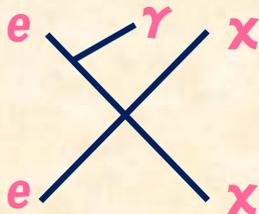
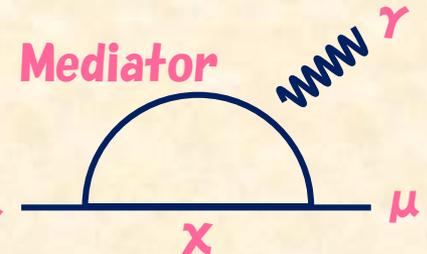


When we look into the region, $3 < \Lambda/m_\chi < 10$, there exists a allowed region even in future.

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

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

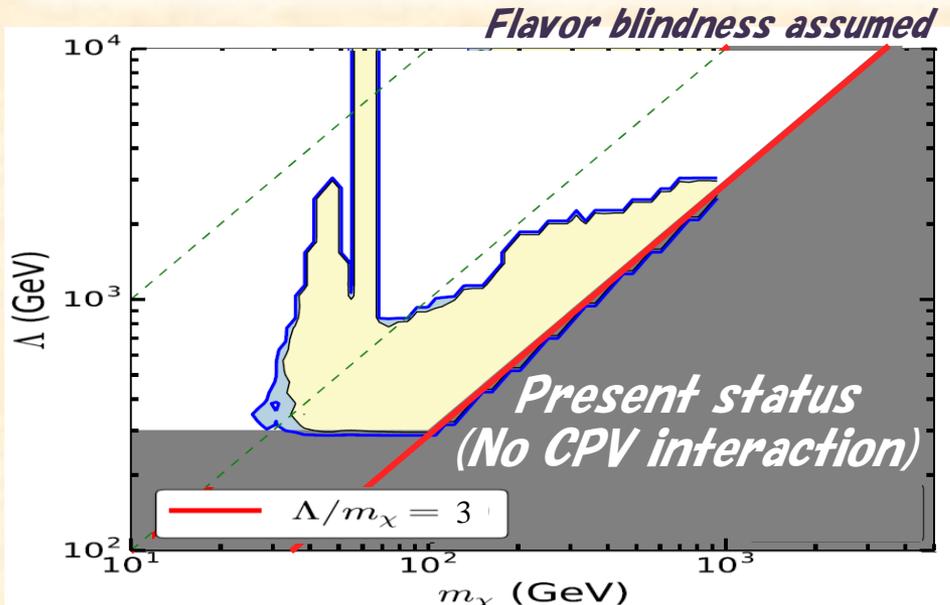
This leptophilic dark matter is known to be one of the models for explaining the muon anomalous magnetic moment, $g_\mu - 2$. [L. Calibbi, et. al, arXiv:1804.00009]



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: $\sigma(ee \rightarrow \chi\chi\gamma) < 0(1)\text{fb!}$

Singlet Fermion DM with (Heavy) Mediator (Case 2)

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

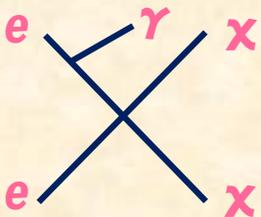
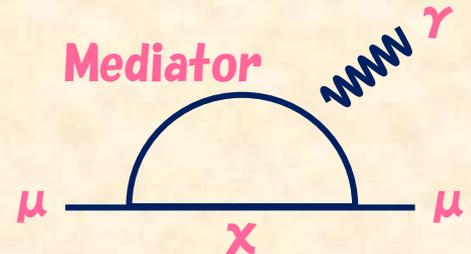


When we look into the region, $3 < \Lambda/m_\chi < 10$, there exists a allowed region even in future.

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

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

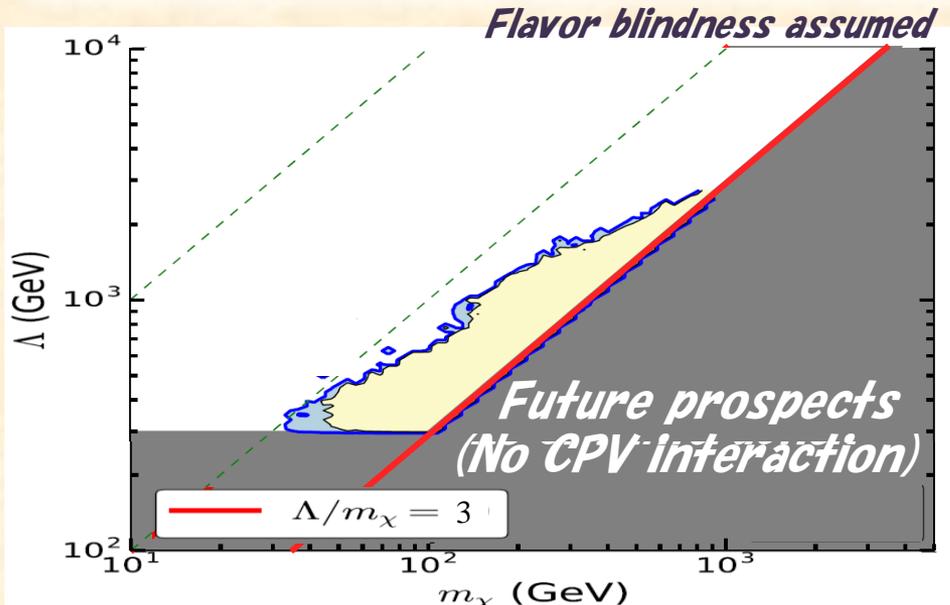
This leptophilic dark matter is known to be one of the models for explaining the muon anomalous magnetic moment, $g_\mu - 2$. [L. Calibbi, et. al, arXiv:1804.00009]



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: $\sigma(ee \rightarrow \chi\chi\gamma) < 0(1)\text{fb!}$

Singlet Fermion DM with (Heavy) Mediator (Case 2)

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

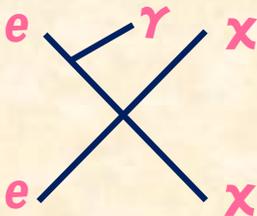
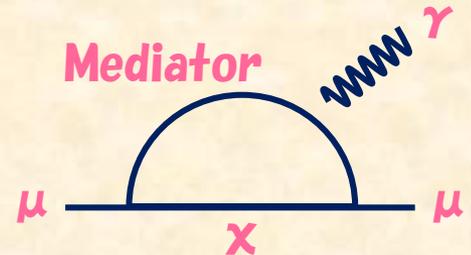


When we look into the region, $3 < \Lambda/m_\chi < 10$, there exists a allowed region even in future.

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

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

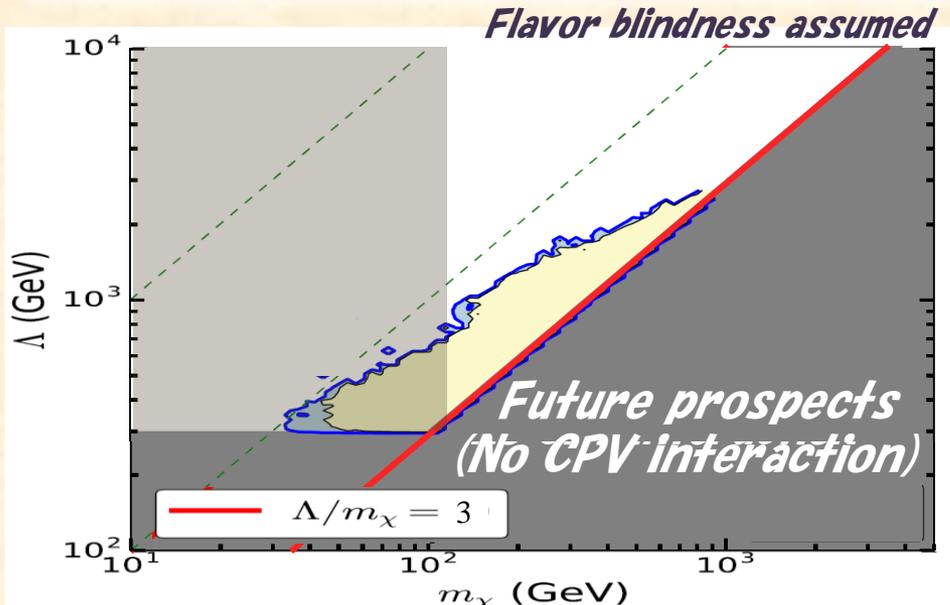
This leptophilic dark matter is known to be one of the models for explaining the muon anomalous magnetic moment, $g_\mu - 2$. [L. Calibbi, et. al, arXiv:1804.00009]



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: $\sigma(ee \rightarrow \chi\chi\gamma) < 0(1)\text{fb!}$

Singlet Fermion DM with (Heavy) Mediator (Case 2)

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

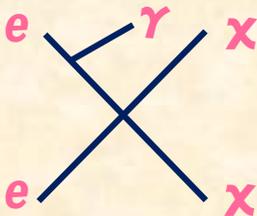
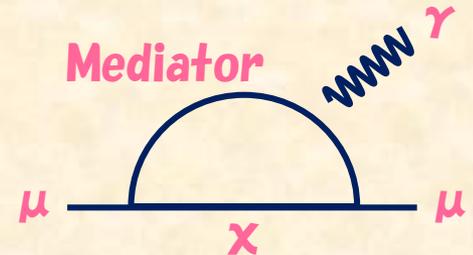


When we look into the region, $3 < \Lambda/m_\chi < 10$, there exists a allowed region even in future.

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

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

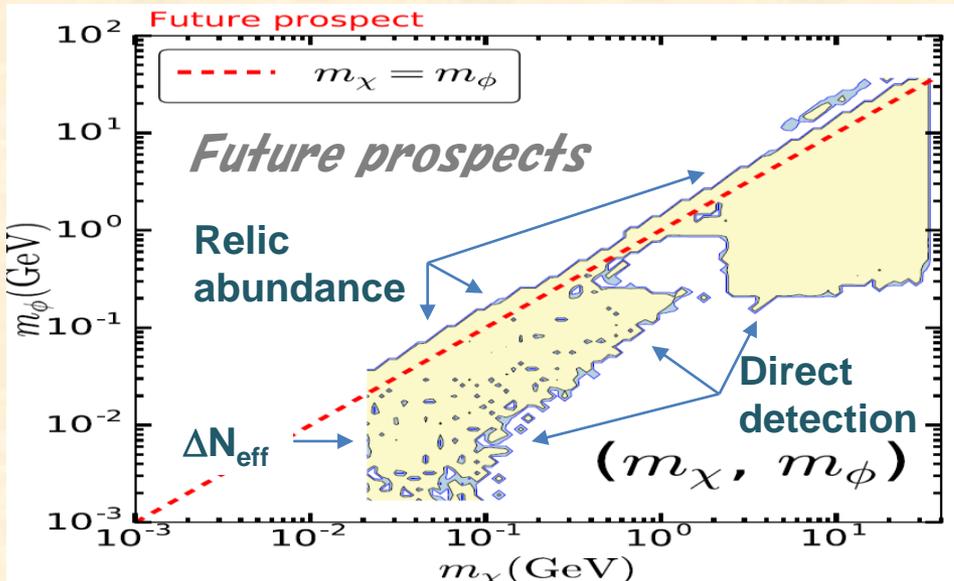
This leptophilic dark matter is known to be one of the models for explaining the muon anomalous magnetic moment, $g_\mu - 2$. [L. Calibbi, et. al, arXiv:1804.00009]



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: $\sigma(ee \rightarrow \chi\chi\gamma) < 0(1)\text{fb!}$

Singlet Fermion DM with Light Mediator

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2} \bar{\chi} (i \not{\partial} - m_{\chi}) \chi + \frac{1}{2} (\partial \phi)^2 - \frac{c_s}{2} \phi \bar{\chi} \chi - \frac{c_p}{2} i \phi \bar{\chi} \gamma^5 \chi - V(\phi, H)$$



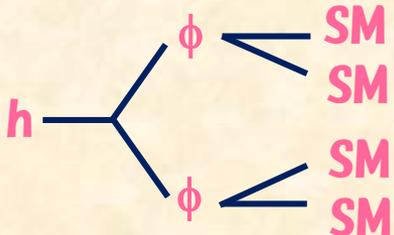
The minimal model for the light fermionic dark matter region requires a bosonic mediator.

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 θ ".

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

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.

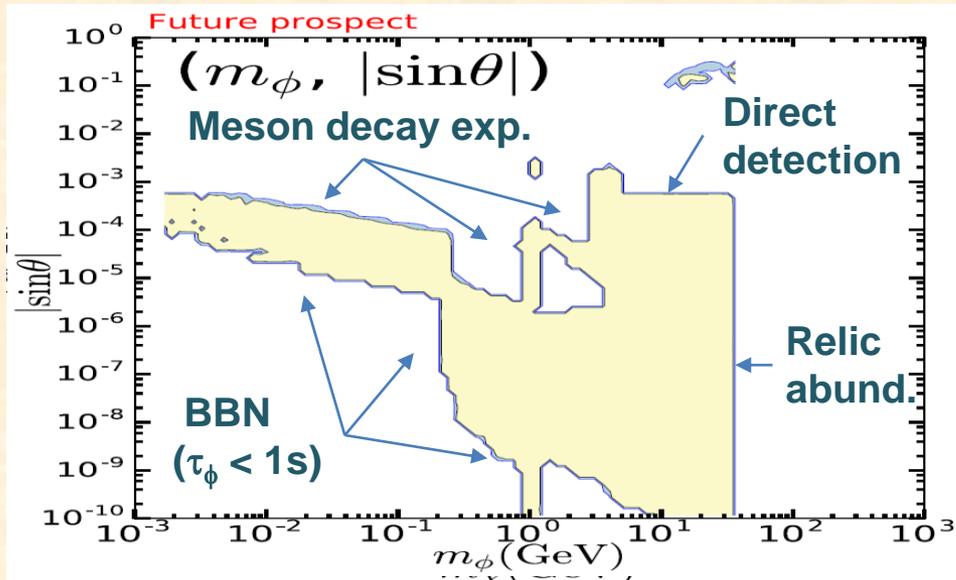
[L. Calibbi, et. al, arXiv:1804.00009]



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

Singlet Fermion DM with Light Mediator

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2} \bar{\chi} (i \not{\partial} - m_{\chi}) \chi + \frac{1}{2} (\partial \phi)^2 - \frac{c_s}{2} \phi \bar{\chi} \chi - \frac{c_p}{2} i \phi \bar{\chi} \gamma^5 \chi - V(\phi, H)$$



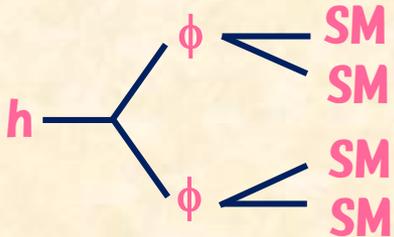
The minimal model for the light fermionic dark matter region requires a bosonic mediator.

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 θ ".

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

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.

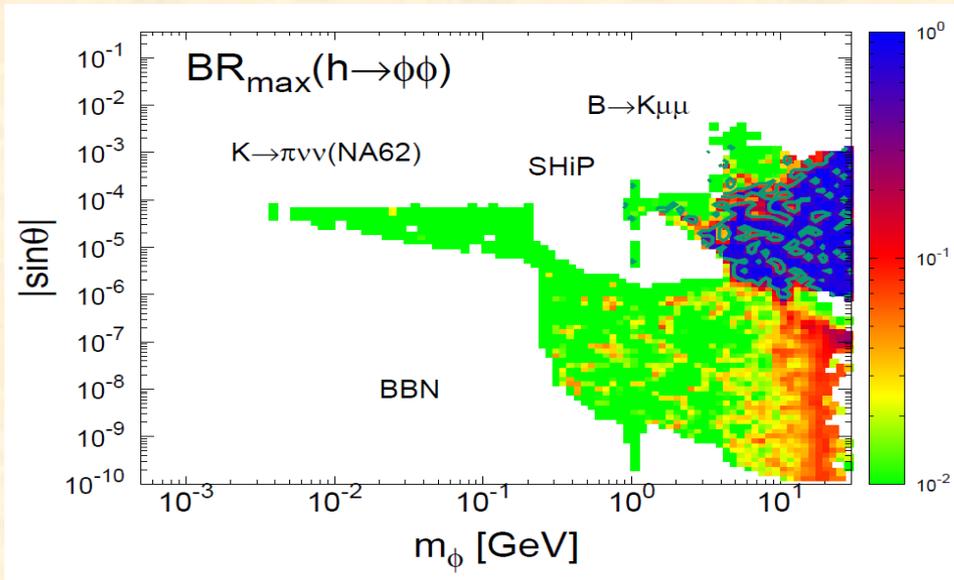
[L. Calibbi, et. al, arXiv:1804.00009]



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

Singlet Fermion DM with Light Mediator

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2} \bar{\chi} (i \not{\partial} - m_{\chi}) \chi + \frac{1}{2} (\partial \phi)^2 - \frac{c_s}{2} \phi \bar{\chi} \chi - \frac{c_p}{2} i \phi \bar{\chi} \gamma^5 \chi - V(\phi, H)$$



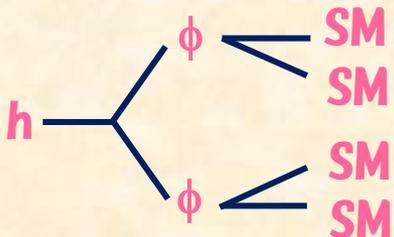
The minimal model for the light fermionic dark matter region requires a bosonic mediator.

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 θ ".

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

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]



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

<i>DM candidates</i>	<i>Motivation</i>	<i>Signal @ Lepton Collides</i>
✓ <i>CPV H-funnel DM</i>	<i>G.C. γ-ray</i>	<i>Invisible H-decay</i>
✓ <i>Leptophilic DM</i>	<i>$g_\mu - 2$</i>	<i>Mono-γ search</i>
✓ <i>Light DM</i>	<i>SSS problem</i>	<i>Exotic H-decays</i>

There would be more thermal dark matter candidates that 240–250 GeV future lepton colliders play an leading role to detect it,

- *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.*