Search for Dark Matter at 250 GeV Lepton Colliders

Shigeki Matsumoto (Kavli IPMU)

with members at IPMU WIMP PROJECT for ILC

Physics at 250GeV lepton colliders:

- ✓ Precision Higgs coupling measurements to search for physics behind the electroweak symmetry breaking.
- ✓ Detecting exotic signals to searches for new physics such as dark matter, new force, extra-dimensions, etc.

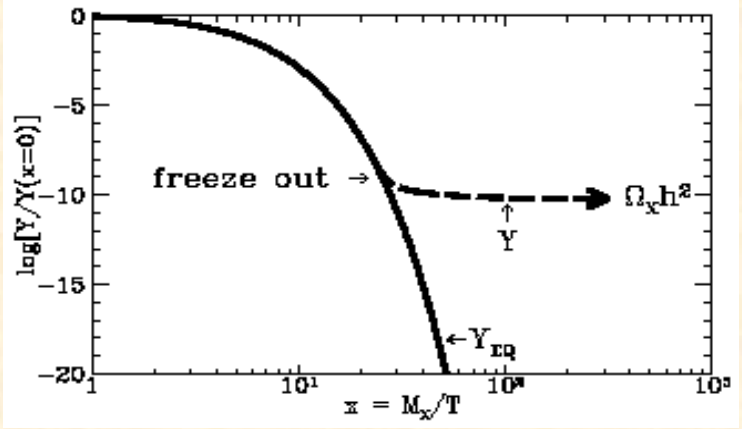
Among various dark matter candidates, I will focus on WIMP (thermal dark matter) in this talk, and discuss what kind of role the lepton colliders play in the detection of the WIMP.

To discuss it quantitatively, it is important to consider synergy, complementarity, competitiveness with other experiments.

WIMP (Thermal Dark Matter) hypothesis

Dark matter was in equilibrium with SM particles in the early universe, and it is eventually decoupled from the thermal bath. This process fixes the abundance of the dark matter at present universe.

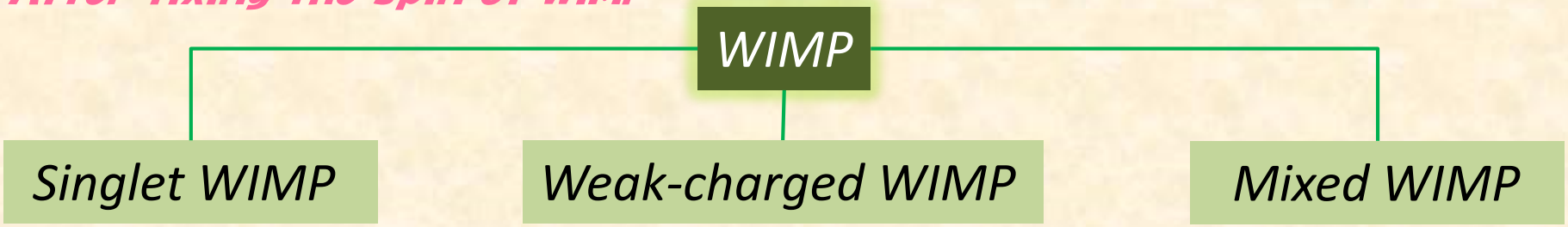
(The same mechanism as BBN/Recombination)



Study of WIMP without depending on any specific new physics models.

→ Classifying WIMP in terms of its quantum number (spin and weak charge) and construct a (minimal) simplified model for the WIMP.

After fixing the spin of WIMP



Since the mixed WIMP can be efficiently searched for at underground experiments, we will focus on singlet and weak-charged WIMP cases.

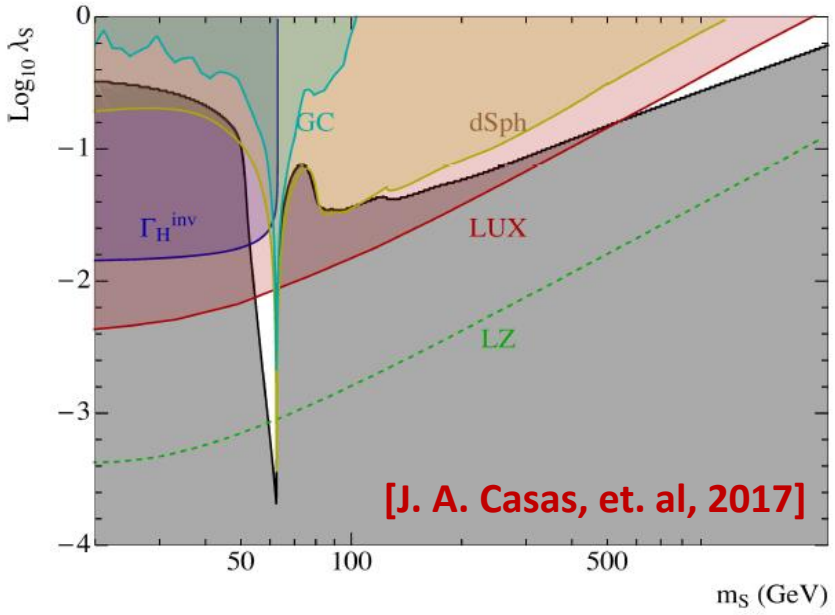
Search for Singlet WIMP(I)

Bosonic (Scalar) case:

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

Z_2 symmetry

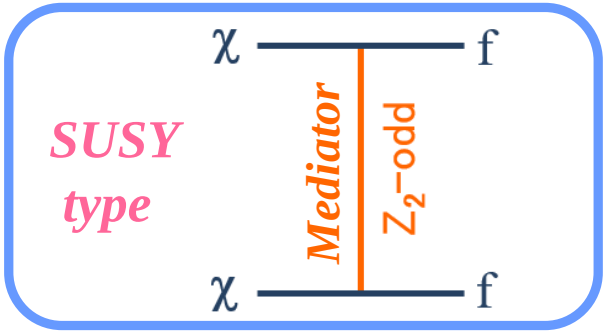
The WIMP is almost excluded by direct dark matter detections. It is further updated in future.



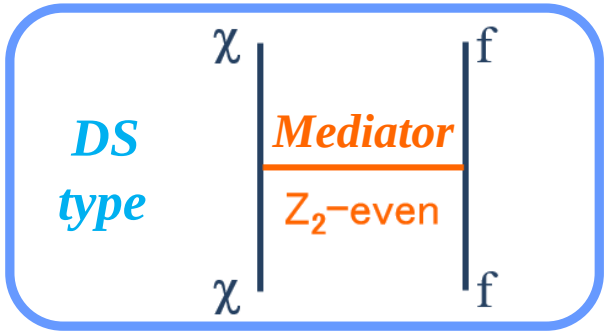
Fermionic case:

No renormalizable interactions at SM + WIMP system due to symmetry.

→ New particle called Mediator must be introduced in addition to WIMP.



Or



Search for Singlet WIMP (ii)

When the mediator is heavier enough than WIMP & EW scale,

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

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CP conservation ***Flavor-blind assumption***

The CP invariance and flavor blindness of interactions between WIMP and SM particles are assumed in the analysis.

[S.M., S. Mukhopadhyay, Y-L Sming Tsai, 2014, 2016]

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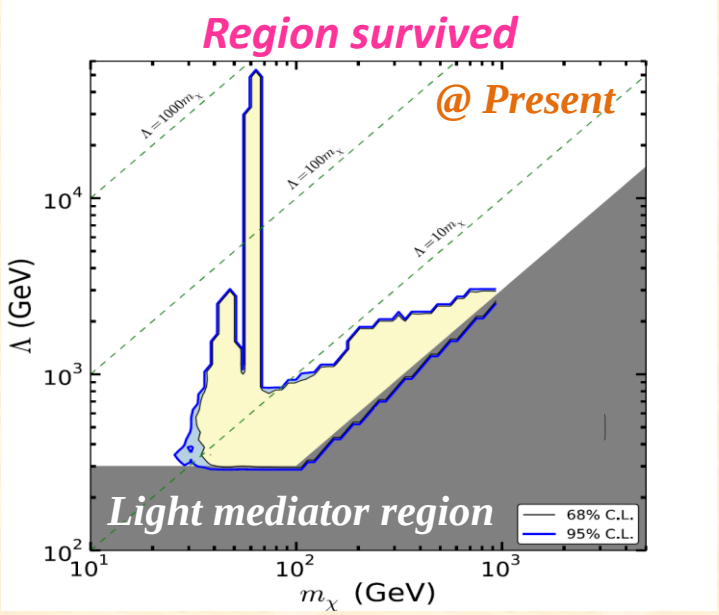

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Multidimensional parameter space was scanned with various constraints from cosmology (relic abundance), colliders (LEP, LHC), direct and indirect dark matter detections within $|c_i| \leqq 1$.

The region with $\Lambda < 3m_\chi$ and $\Lambda < 300$ GeV is painted by grey color, because the above effective theory can not be applied to describe the WIMP physics.

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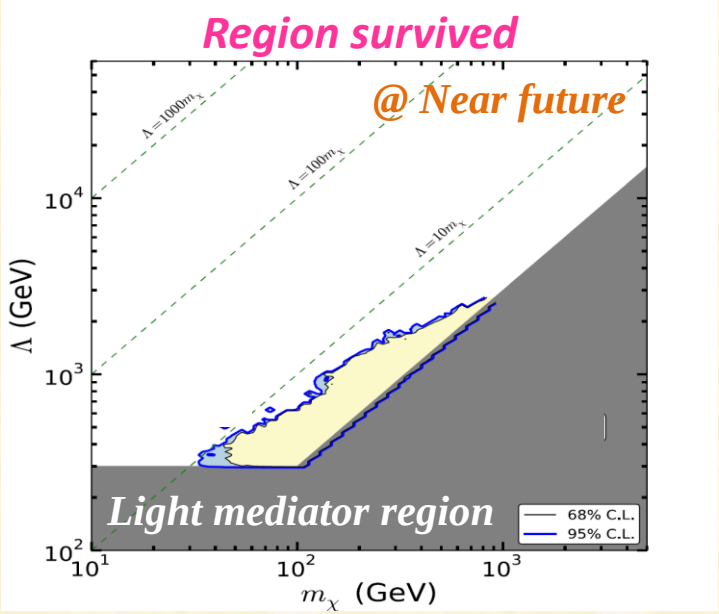

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The allowed parameter region will be shrieked, if no signal is detected at near future underground experiments, namely 2nd generation direct dark matter detection experiments such as LZ, and the LHC experiment before HL-LHC.

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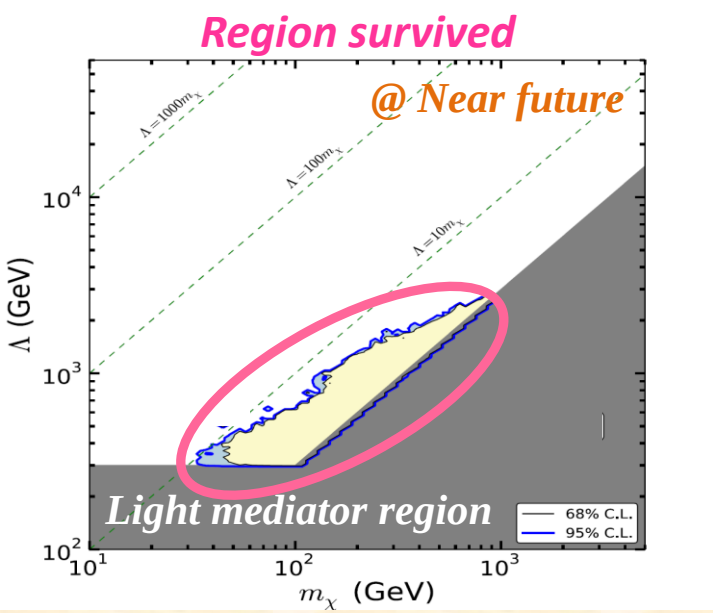

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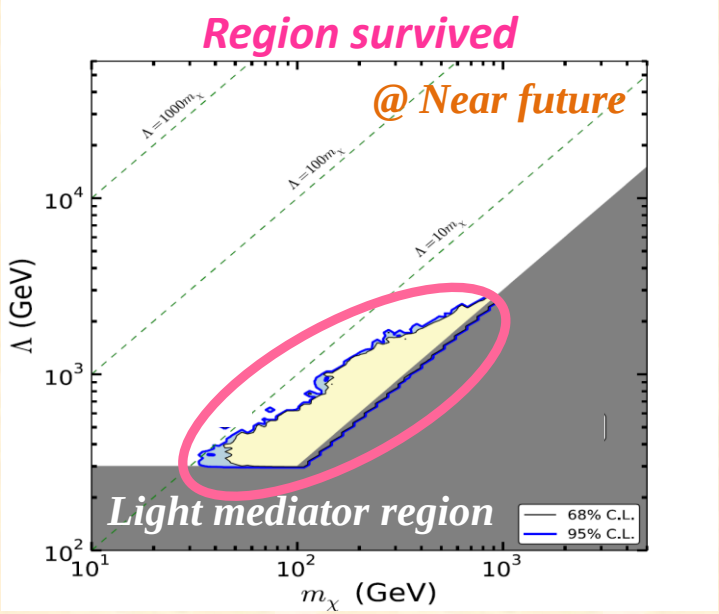
CP conservation — Flavor-blind assumption



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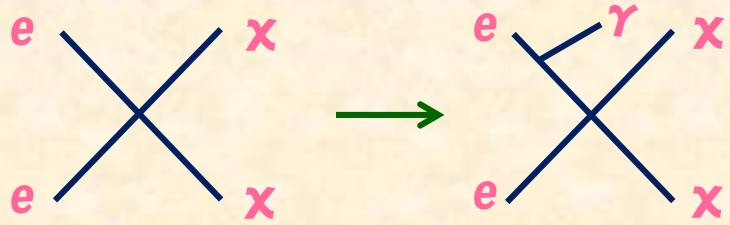
If the mediator is SUSY-type (Z_2-odd), this region is known to be the one where the so-called muon anomalous $g_\mu - 2$ can be explained. [L. Calibbi, et. al, arXiv:1804.00009]



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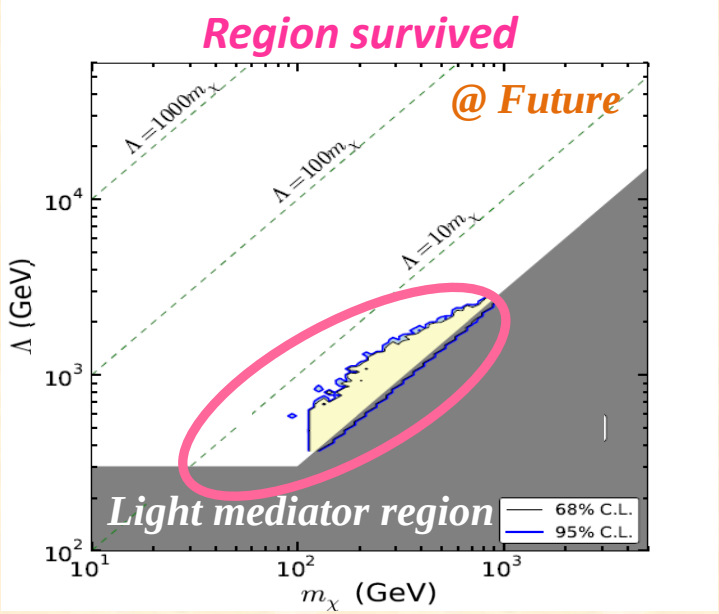

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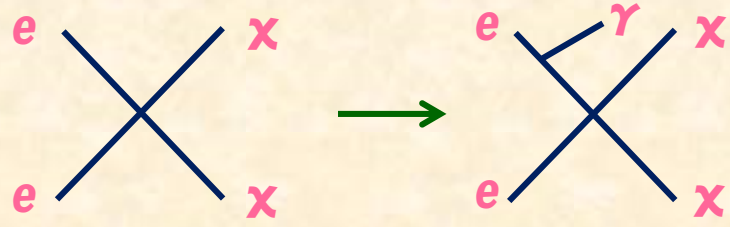

Since the leptophilic WIMP has interactions with leptons with a certain strength, it is efficiently searched for by mono-γ signals. $\sigma(ee \to \chi\chi\gamma) < O(1)$fb at 250GeV leads to …

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When the mediator is heavier enough than WIMP & EW scale,

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

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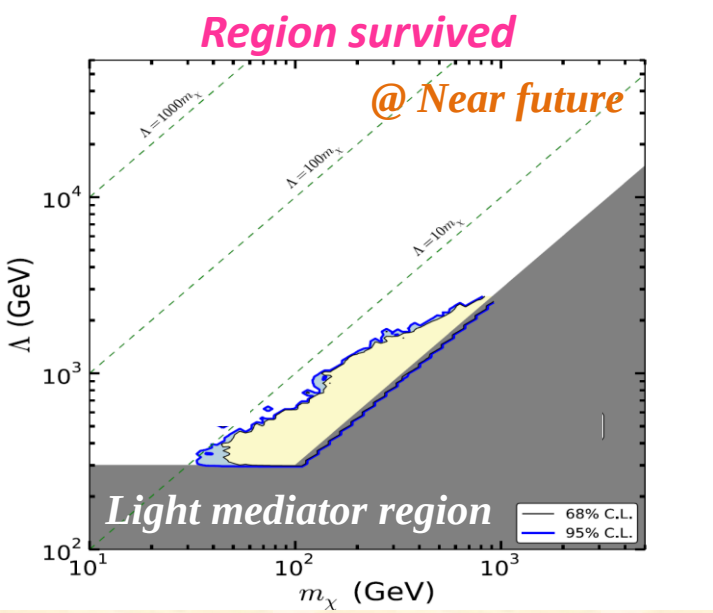

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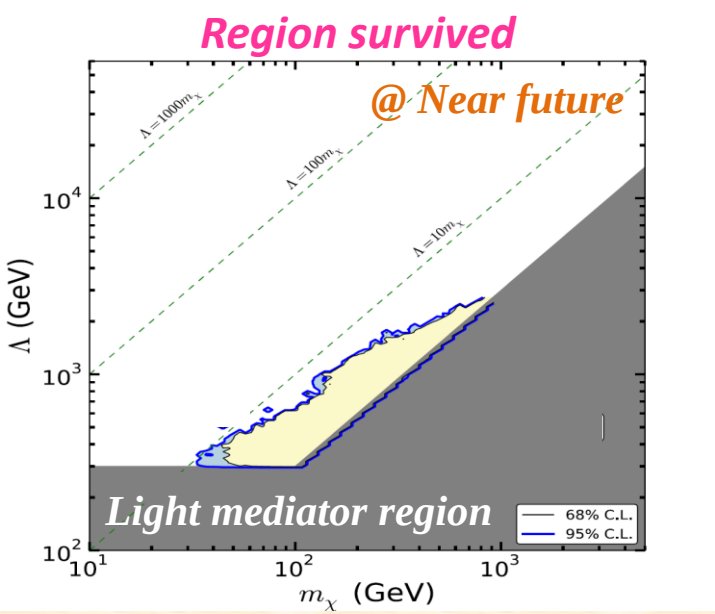

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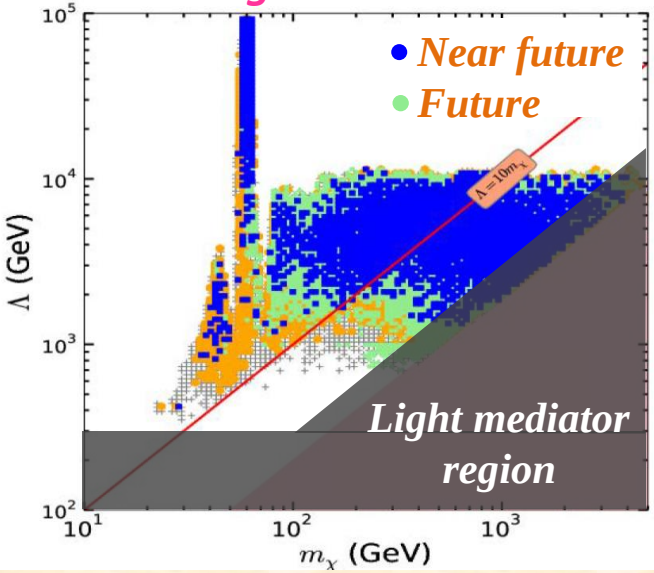
Flavor-blind assumption

Region survived



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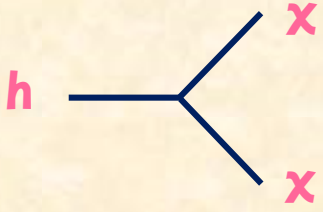
Dark matter abundance is fixed by this interaction, so the region can be called "CP violating H-funnel WIMP region"!

WIMP with about 40GeV mass in the region is known to be the simplest dark matter candidate to explain the GeV γ-ray excess from G.C. [Fermi-LAT, arXiv:1704.03910]



Since the interesting mass region is below half a Higgs mass, the WIMP is efficiently searched for at invisible H width searches.
Br($h \to \chi\chi$) < 0.004 at ILC leads to …

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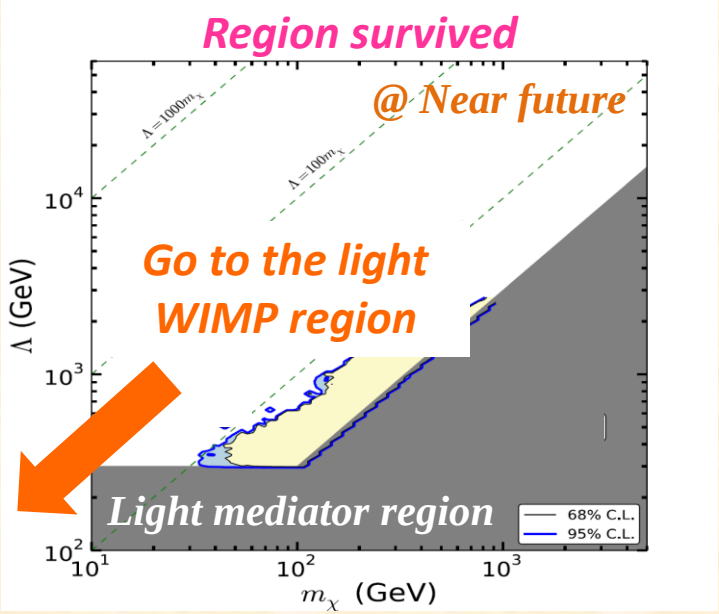

Since the effective theory can not be used in this region, the WIMP should be discussed by a renormalizable theory. The mediator is then required to be DS type, and hence bosonic and SM singlet.

Search for Singlet WIMP (iv)

Minimal model for the light WIMP with a scalar mediator:

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

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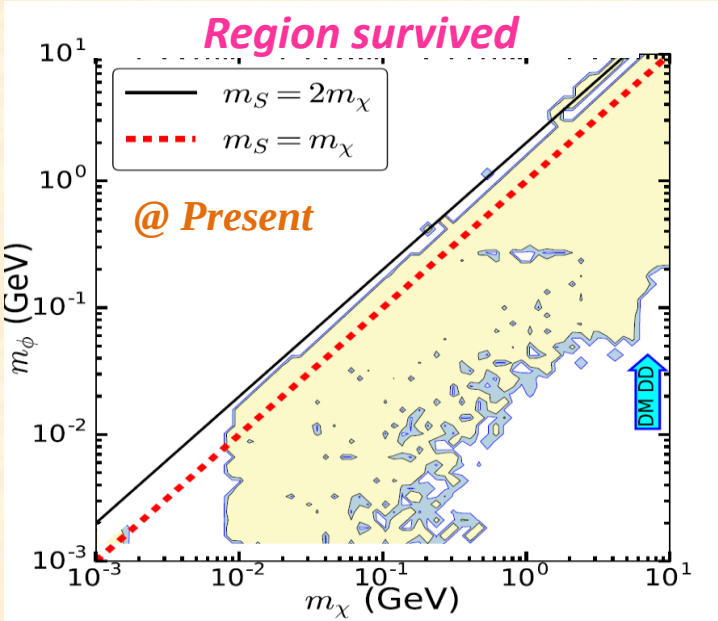

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This can be a SIDM for the small scale structure problem. [F. Kahlhoefer, et. al, 2017]

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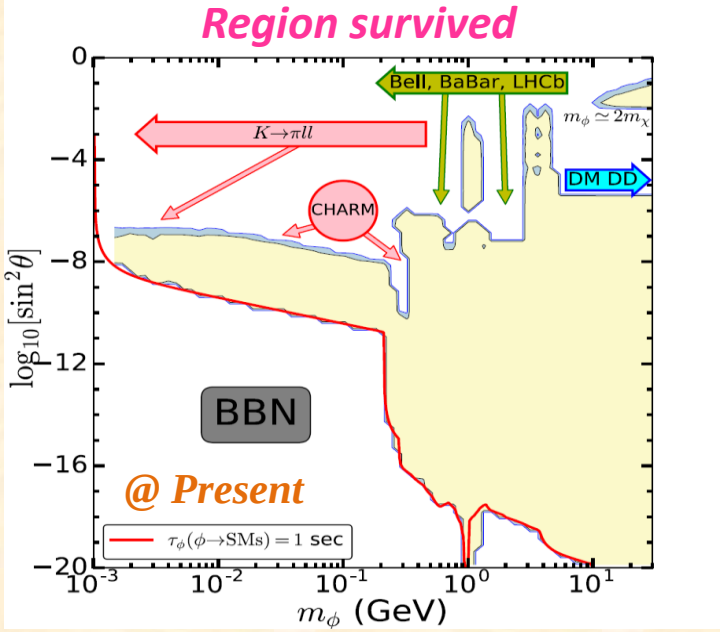

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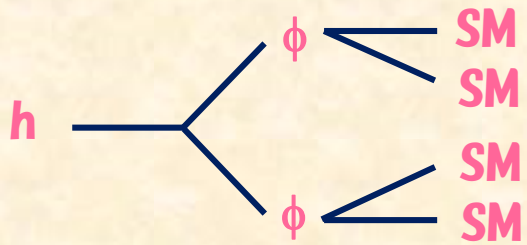
Light WIMP region is explored through the search for the mediator indirectly, It interacts with SM particles via the ϕ-h mixing & ϕ-ϕ-h interaction.



Exotic H decays search for the mediator efficiently based the ϕ-ϕ-h interaction, which are difficult at other experiments.

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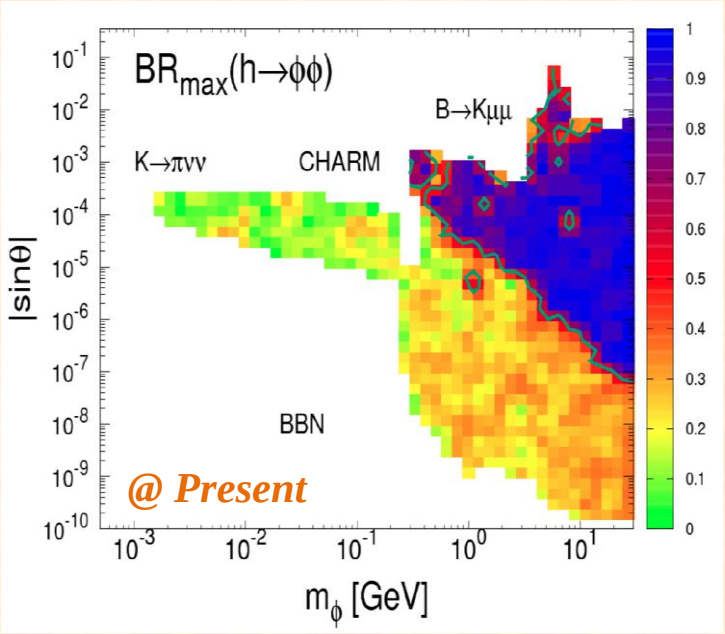

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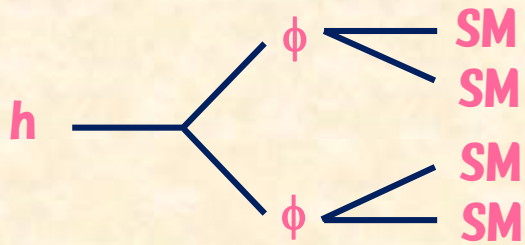
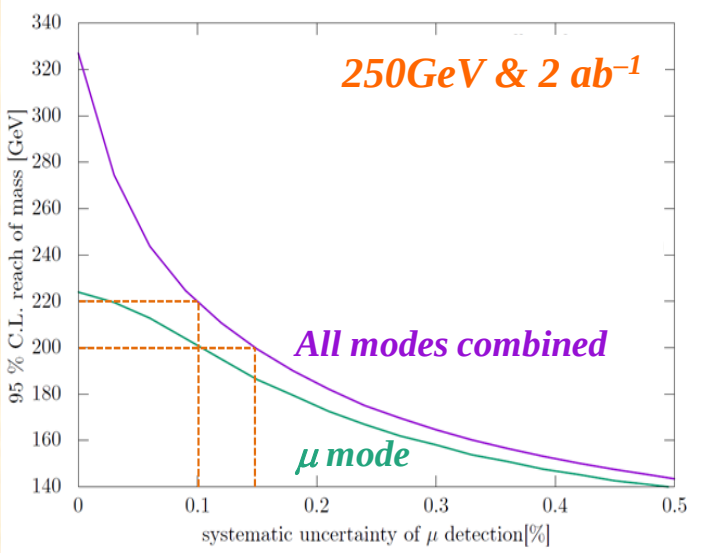


Exotic H decays search for the mediator efficiently based the ϕ-ϕ-h interaction, which are difficult at other experiments. $Br(h \to \phi\phi) < O(10^{-3})$ is reached at ILC.

Search for Weak-charged WIMP

WIMP with a weak-charge of ½:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{\psi}\left(\not{D} - m_{\rm DM}\right)\psi + (\textit{Higher dimensional operators})$$

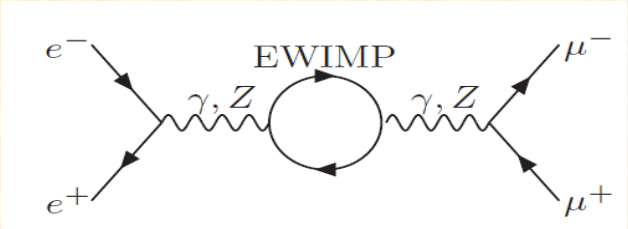


[Harigaya, Ichikawa, Kundu, S. M., Shirai (2015)]

Weak-charged WIMP has O(1) TeV mass due to the relic abundance condition.

The WIMP with the mass below O(1)TeV is also discussed for various reasons. In this case, it is assumed WIMP is also produced non-thermally or composing a part of the density observed today.

The weak-charged WIMP ($2_{\pm 1/2}$) region, whose mass is EW scale, is motivated Very well by the focus-point supersymmetry scenario. [J. Feng, et. al, 1999]



Precise measurements of the EW processes, ee→ff, can be used to search for the WIMP. The WIMP is probed within m < 220GeV.
[*Sys. errors*, μ : e : b : c = 1.5 : 2: 5 : 10]

Summary

We systematically investigated the capability of 250GeV ILC to search for WIMP, based on a minimal model at each WIMP's quantum number.

250GeV lepton colliders play a crucial role for the following WIMPs.

- ✓ Leptophilic WIMP (Muon anomalous magnetic moment, Mono-γ)
- ✓ CP violating H-funnel WIMP (γ-ray anomaly from G.C., Γ_h(invisible))
- ✓ Light WIMP (Small scale structure problem, $\Gamma(h \to \phi\phi)$)
- ✓ EW weak iso-doublet WIMP (Focus-point SUSY, $e^- e^+ \to f \bar{f}$)

Scientific significance of 250GeV lepton colliders (ILC)

☆ Precision Higgs coupling measurements

Those will open a new frontier in our struggle to discover the new fundamental interactions that underlie the Standard Model.

☆ Searching for new physics signals

- ✔ Dark matter … ILC plays crucial roles, as mentioned above.
- ✔ New forces … Gauge-Higgs unification, etc. ($e^- e^+ \to f \bar{f}$)
- ✔ Extra-dim. … 〃