The WIMP Hypothesis Today

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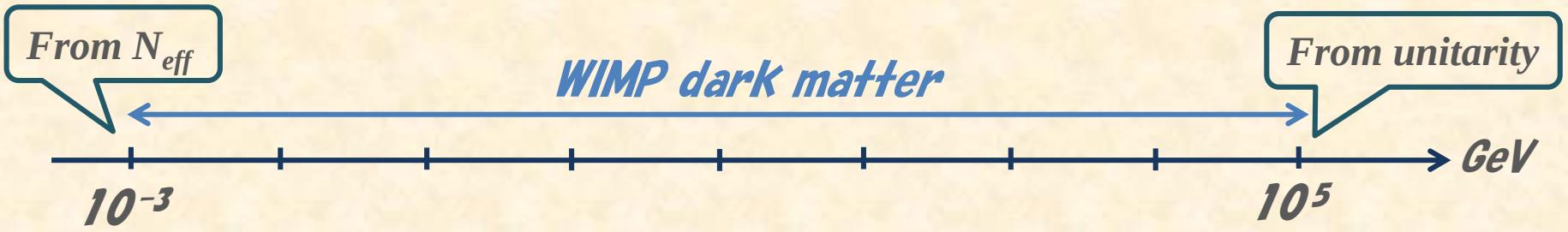
Collaborators: Members in IPMU WIMP PROJECT

The WIMP hypothesis is now efficiently being tested by the direct DM detection at under ground experiments.

- ✔ What kind of WIMP is now being ruled out?
- ✔ What kind of WIMP will be explored in near future?
- ✔ What kind of WIMP remain explored even in future?

The WIMP hypothesis

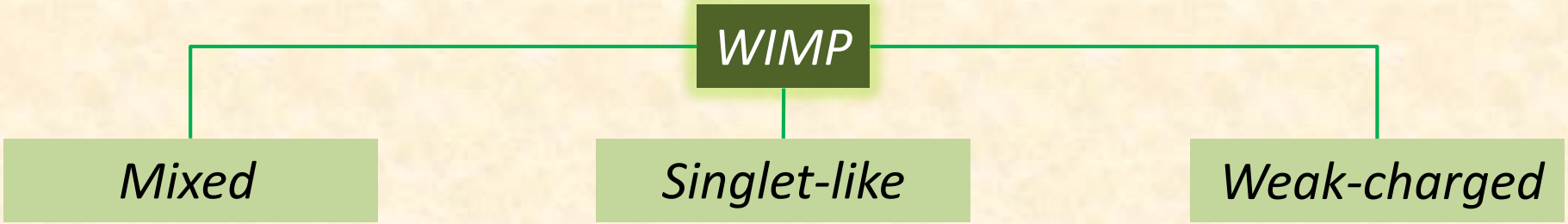
"Dark matter is a massive, stable and electrically neutral particle, and was in a thermal equilibrium with SM particles in the early universe."



There are many types of WIMP, depending on those quantum numbers.

→ Classification of WIMP in terms of its spin and isospin!

After the WIMP spin fixed,



We focus on fermionic WIMPs, for it is predicted in SUSY models!

Research strategy

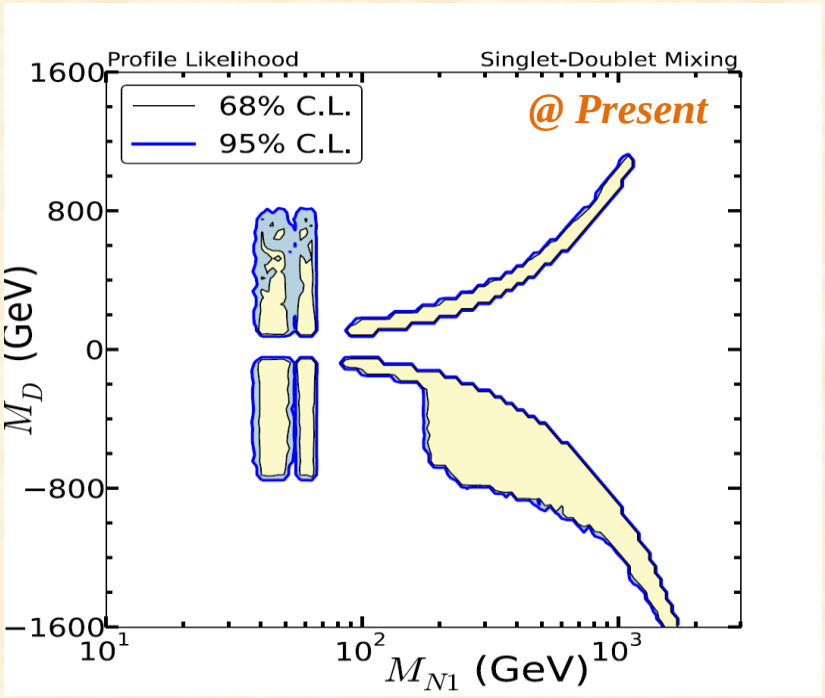
1. Constructing the minimal model in each WIMP quantum number(s).
   The renormalizable one involving the least number of new fields.
2. Imposing all constraints on it & clarifying its present status.
   From direct/indirect detections and lepton/hadron colliders.
   MCMC scanning & Projecting the result on a appropriate plane.
3. Imposing near future-expected direct detection constraints.
   2^{nd} generation direct detections (LZ experiment) imposed.
   Showing the result on the same plane as before for comparison.
4. Figuring out parameter regions not covered even in the future.
   Judging whether or not the remaining regions are attractive.
   Start considering what kind of experiments we need to cover it.

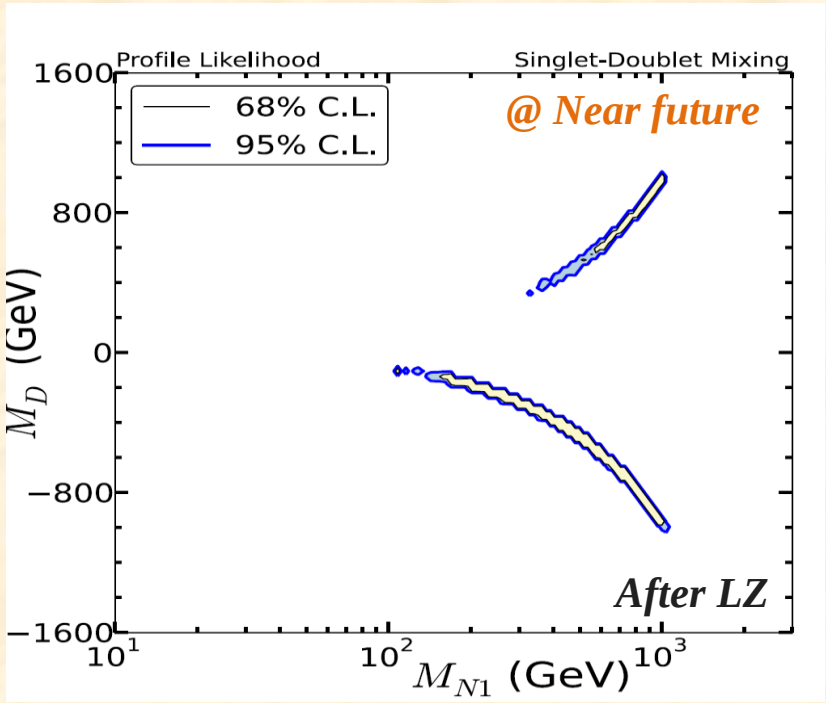
Case mixed: Singlet-Doublets model

$$\mathcal{L}_{SD} = \mathcal{L}_{kin} - \left[\frac{1}{2}M_S SS + M_D D_1 \cdot D_2 + y_1 SD_1 \cdot \tilde{H} + y_2 SD_2 \cdot H + \text{H.c.}\right]$$

[Z_2 symmetry imposed]

Typical WIMP in CMSSM





[S. Banergee, S.M., K. Mukaida, Y-L Sming Tsai, JHEP (2016)]

Mixed WIMP ← Yukawa interactions → DM-DM-h(Z) couplings

The same conclusion holds for the most of mixed WIMPs.

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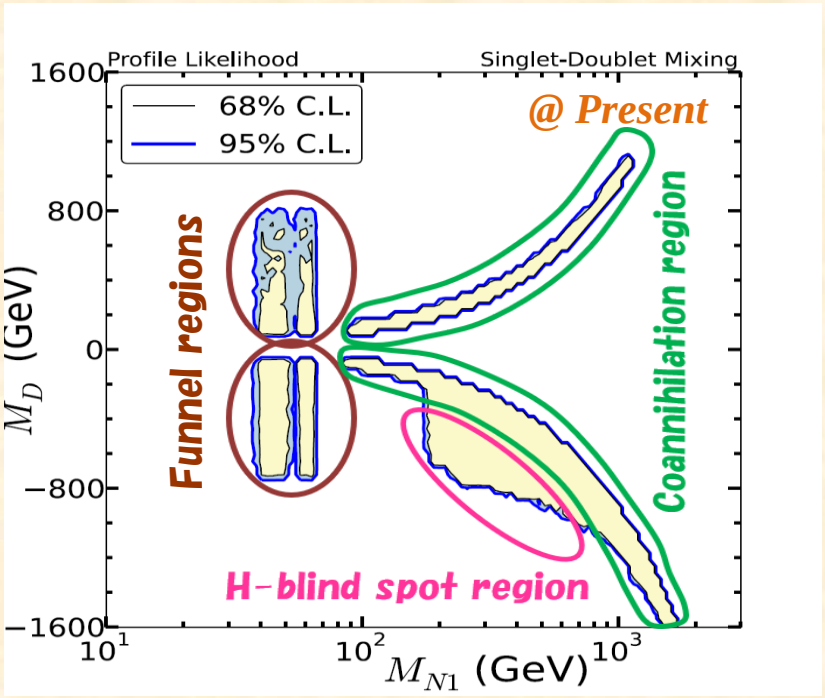

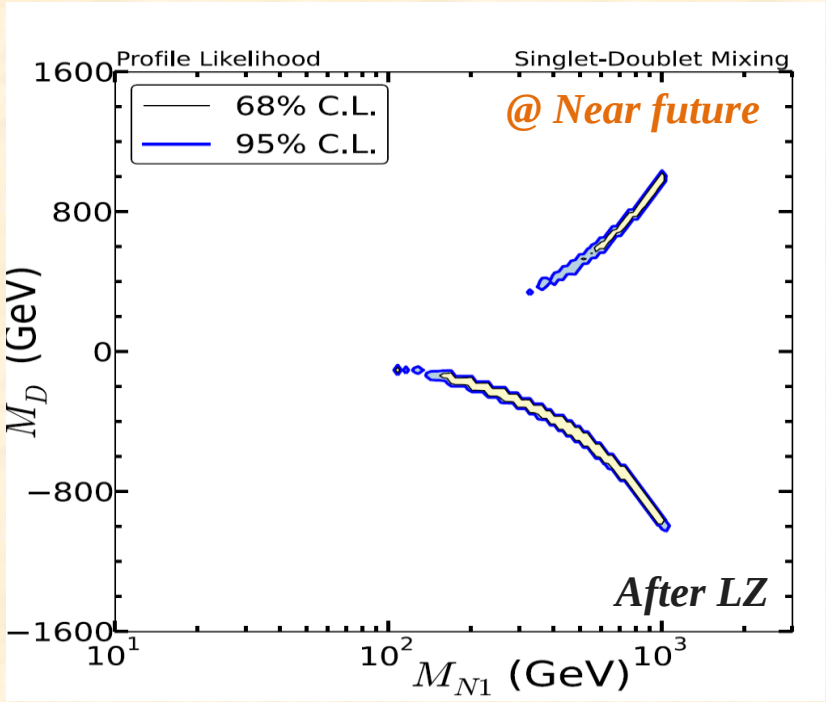

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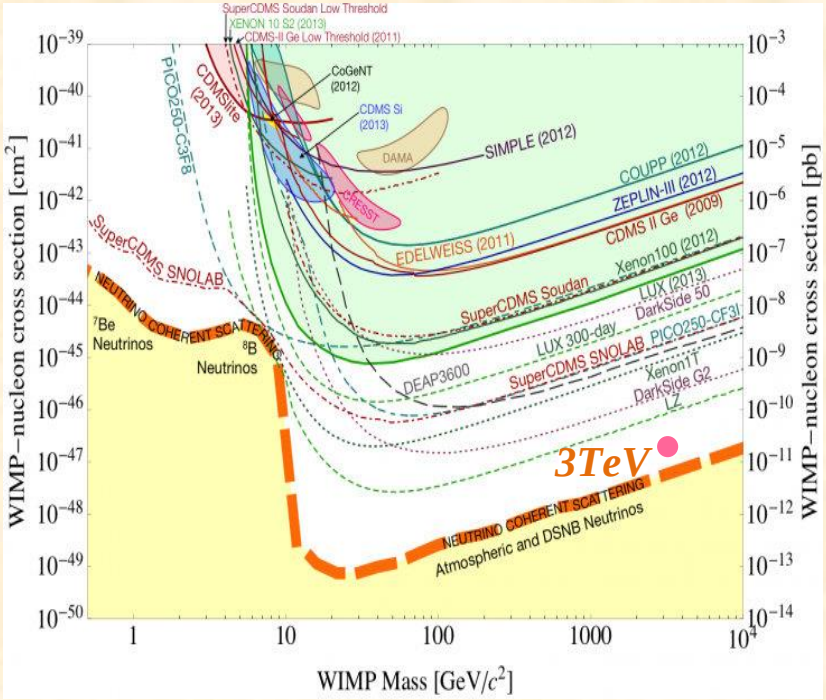
Case weak-charged: Triplet model

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

[Z_2 symmetry imposed]

WIMP in the AMSB
One of minimal DMs



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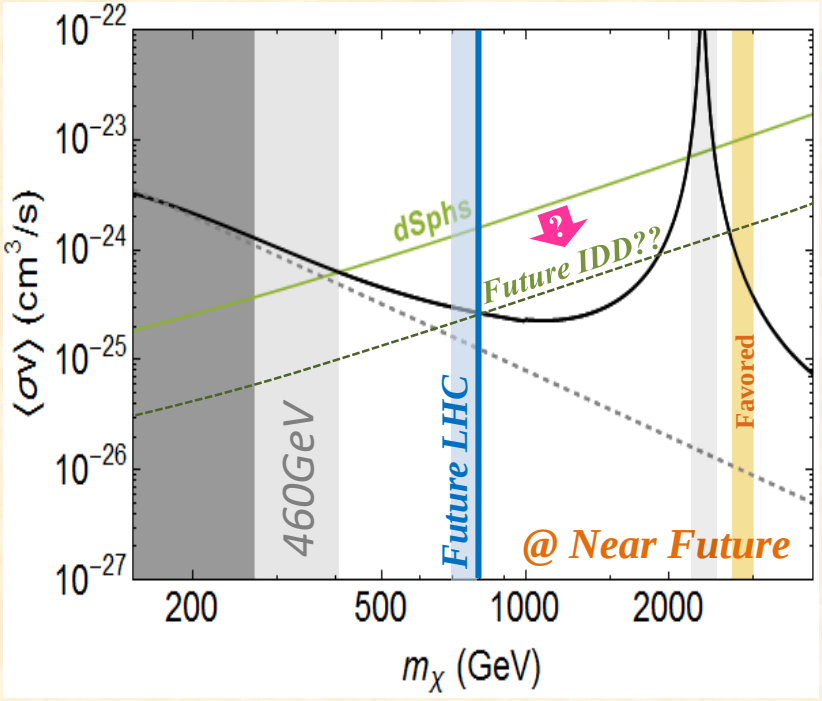


[Sommerfeld effect: J. Hisano, S.M., M. Nojiri (2005-2017)]

Only indirect detection is possible to explore this DM in near future.

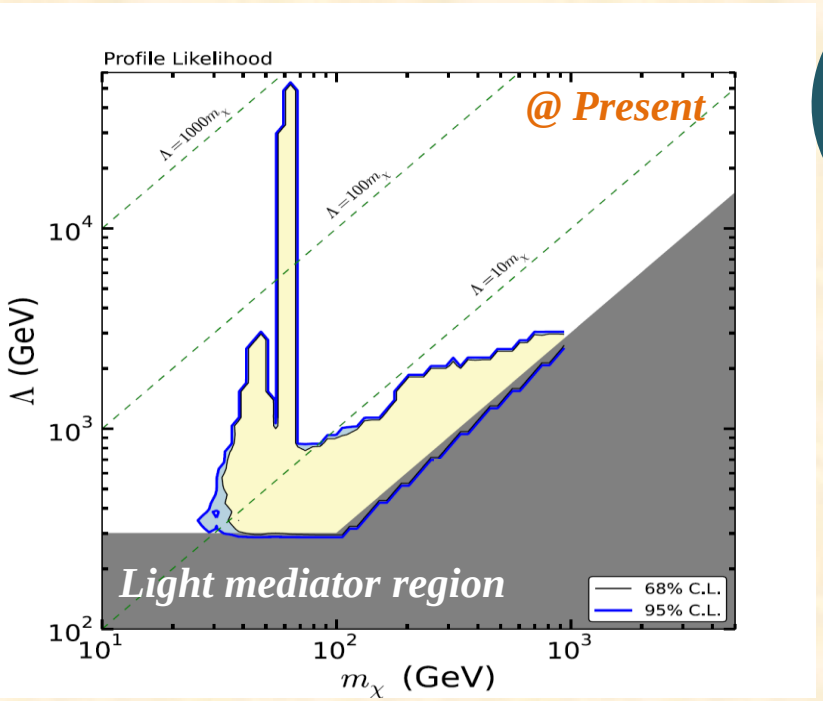
Refinement of the detection is required by updated astronomical data.

Case singlet-like with Heavy mediator

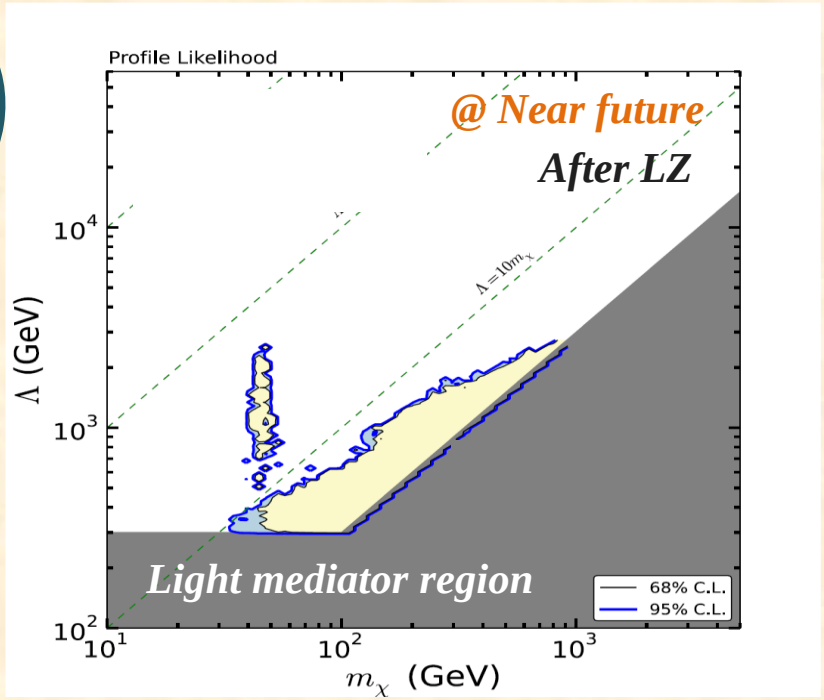
Mediator particle must be introduced!

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

[Simplified model involving all possible interactions reproducing above EFT is used.]



Bino in MSSM



$c_P = 0$ & flavor blind 4-Fermi int. [S.M., S. Mukhopadhyay, Y-L Sming Tsai, (2014, 2016)]

Z-portal and leptophilic regions will remain unexplored in near future.

SD direct detection & lepton collider experiment play important role!

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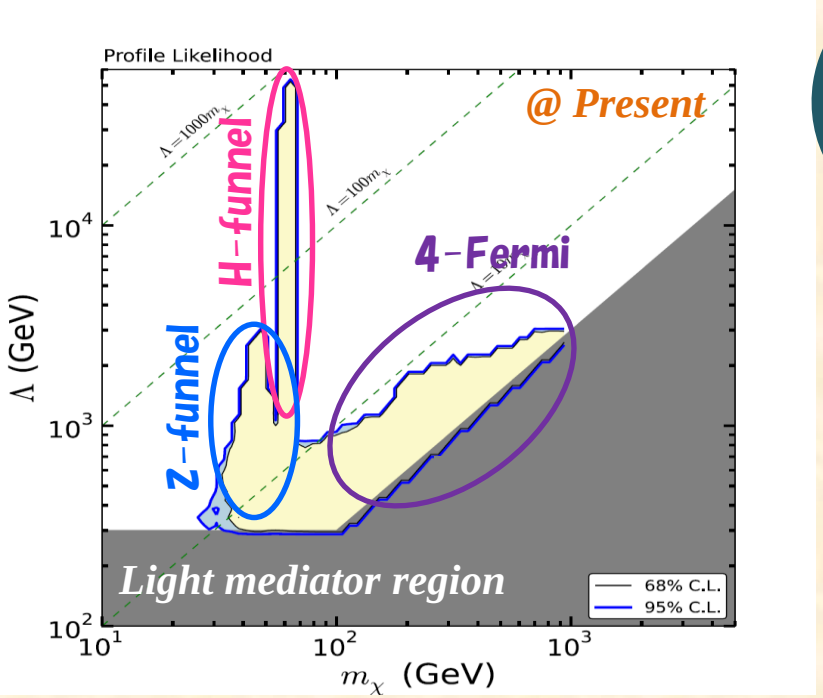

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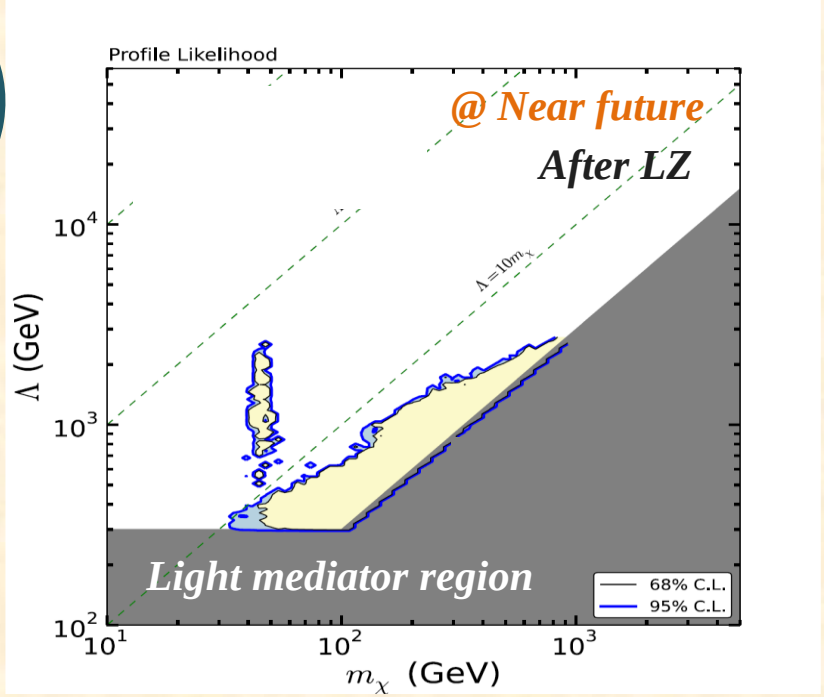

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Z-portal and leptophilic regions will remain unexplored in near future.

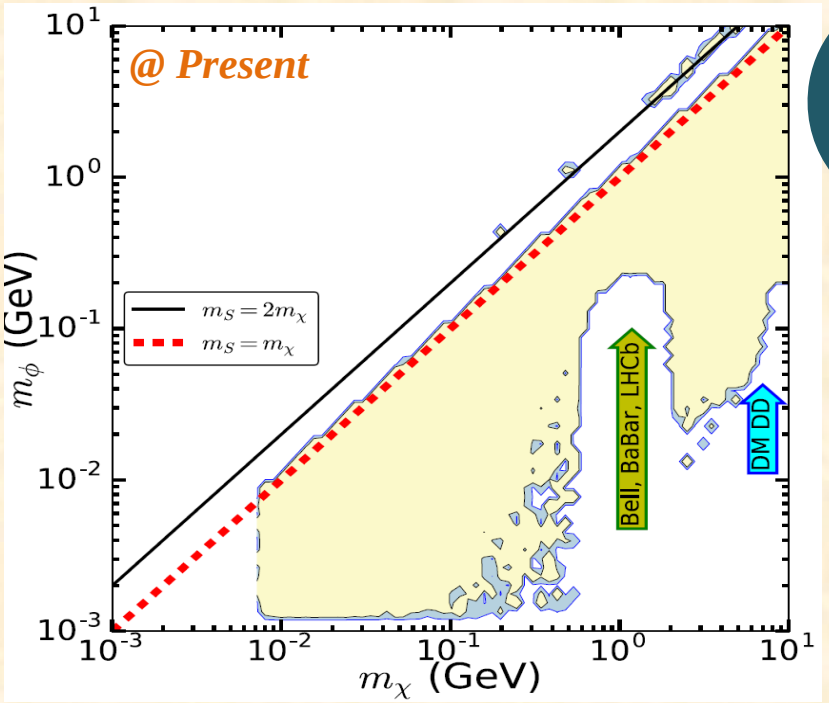
SD direct detection & lepton collider experiment play important role!

Case singlet-like with Light mediator

Light WIMP region!

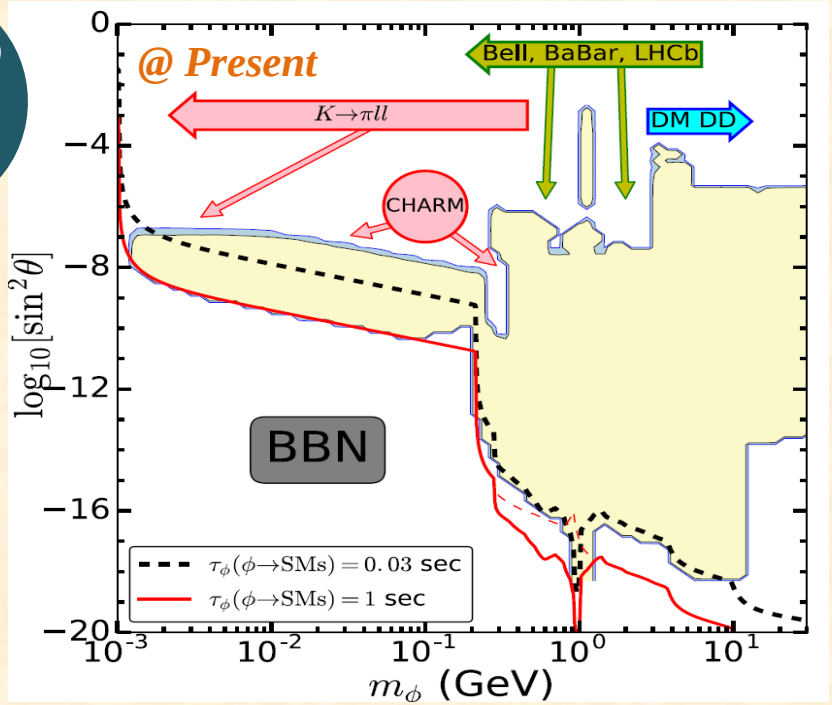
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial\phi)^2 - \frac{c_s}{2}\phi\bar{\chi}\chi - \frac{c_p}{2}i\phi\bar{\chi}\gamma^5\chi - V(\phi, H),$$

[Scalar mediator case]



Singlino in NMSSM

&



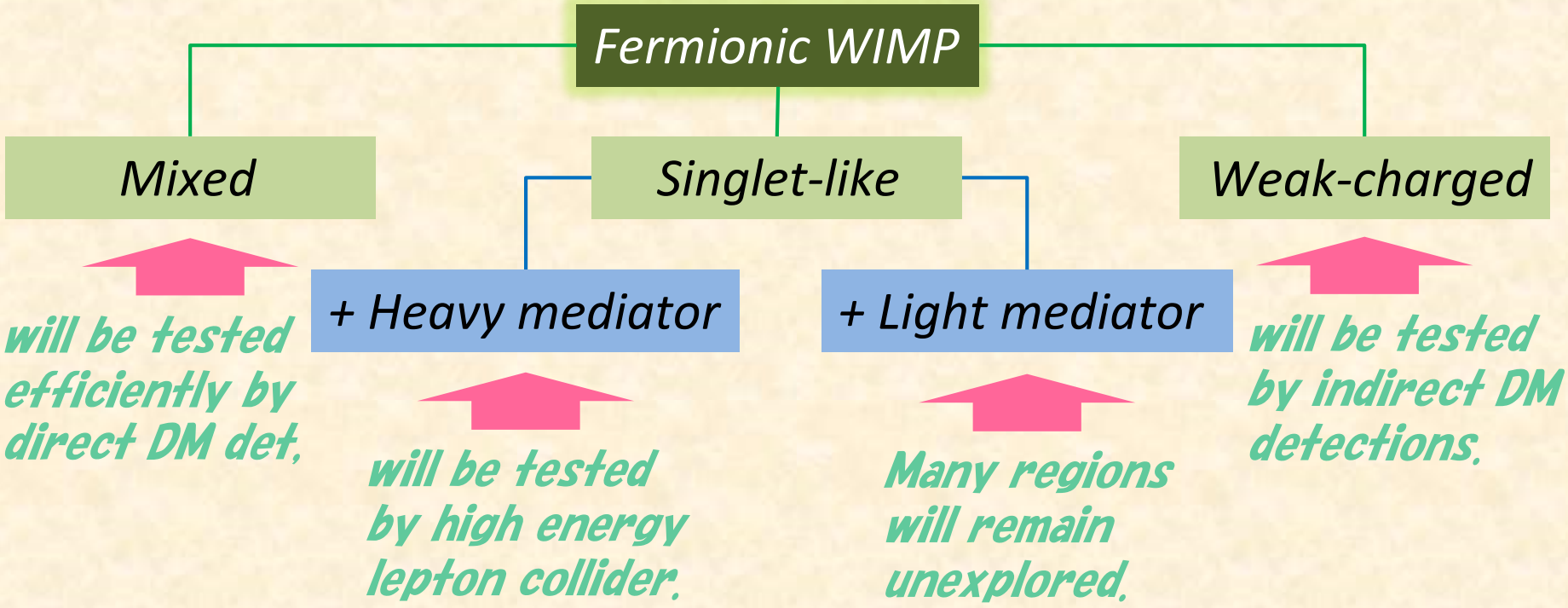
[S.M., Y-L Sming Tsai, Po-Yan Tseng, (2017)]

Testing the scenario ← Light mediator → Physics of dark matter

For more details, go to the talk by Po-Yan Tseng this afternoon!

Summary

Wide parameter regions are still there in all cases & should be explored!



Backup (Classifying WIMPs)

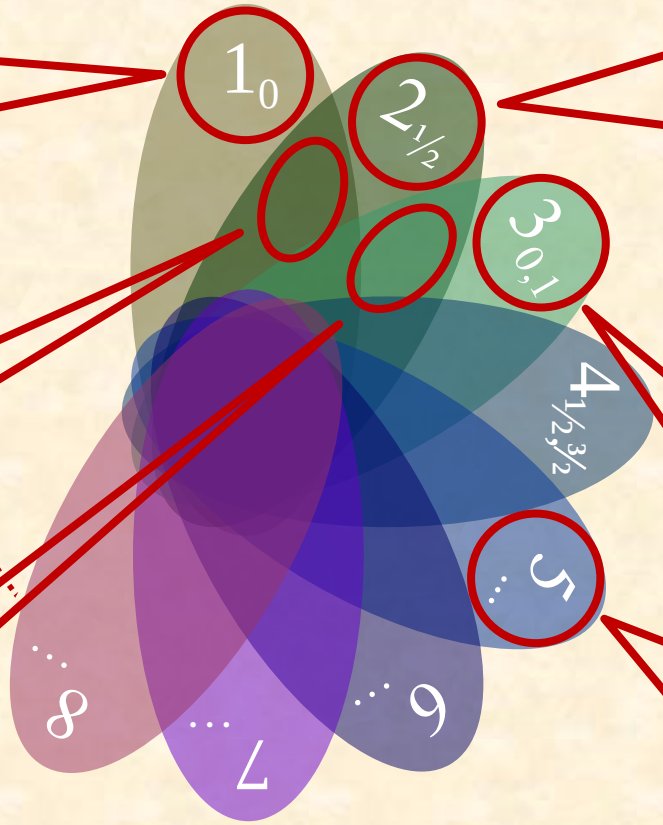
After fixing its spin, the WIMP field is written by a linear combination of colorless rep. of $SU(2)_L \times U(1)_Y$ involving a EM neutral component:

$$\mathrm{WIMP}(x) = \sum_i z_i \left[\chi_i(x)\right]_{\mathrm{N.C.}} \text{ with } \sum_i |z_i|^2 = 1$$

Singlet-like Patch
e.g.
Bino-like in SUSY
KK photon in UED

S-D Mixed Patch
e.g.
Bino-Higgsino WIMP

D-T mixed Patch
e.g.
Higgsino-wino WIMP

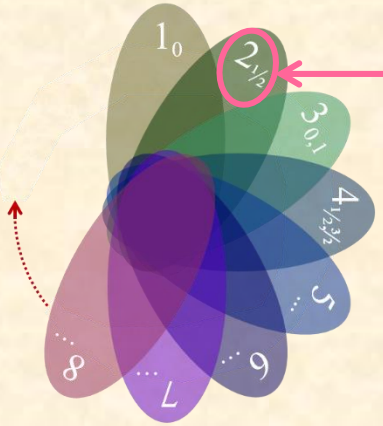


Doublet-like Patch
e.g.
Higgsino-like in SUSY
Inert Higgs in 2HDM

Triplet-like Patch
e.g.
Wino-like in SUSY

Quintet-like Patch
e.g.
Minimal dark matter

Backup (Mixed WIMP)



Simplest example = (Fermionic) singlet-doublet WIMP

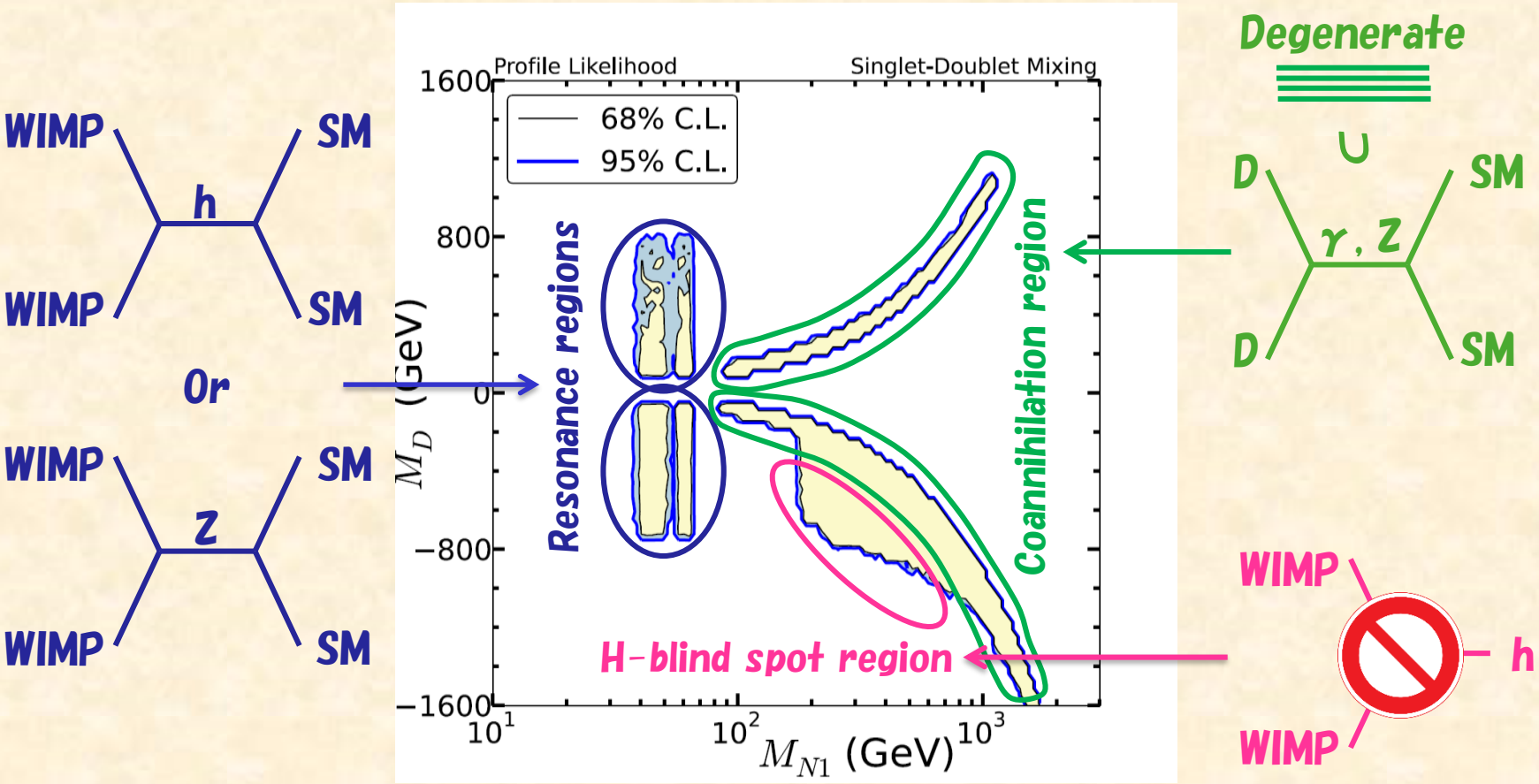
- ✓ **Typical WIMP in the traditional natural SUSY.**
- ✓ **Minimal contents: 1_0, $2_{1/2}$, $2_{-1/2}$ (Anomaly cancel.)**
- ✓ **3 neutral Majorana and 1 charged Dirac fermions.**

- **Lagrangian assuming Z_2 symmetry making the WIMP stable is**

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

- **Parameter space are defined by $[M_S, M_D, y_1 = y\cos\theta, y_2 = y\sin\theta]$, corresponding to $[M_1, \mu, (g'/\sqrt{2})\cos\beta, (g'/\sqrt{2})\sin\beta]$ at the MSSM. [DM interactions are assumed to preserve the CP symmetry.]**
- **Scanning parameter space using MCMC to clarify the current status and future prospects of the WIMP, assuming $|y_i| \leq 1$.**

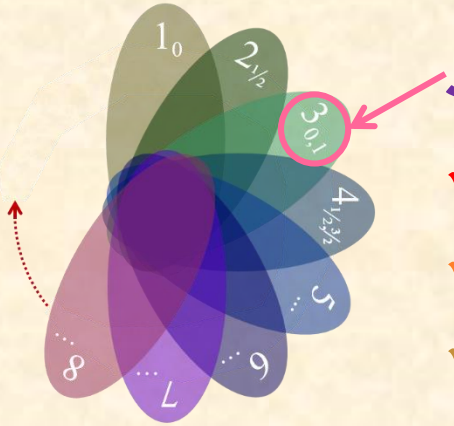
Backup (Mixed WIMP)



Present status

(The likelihood function is now projected onto the (M_{DM}, M_D)-plane.)

Backup (Triplet-like Fermion WIMP)



Simplest example = (Fermionic) triplet-like WIMP

- ✓ **Predicted in High-scale SUSY and MPP scenarios.**
- ✓ **Minimal contents: 3_0. (Just one representation.)**
- ✓ **1 neutral Majorana and 1 charged Dirac fermions.**

- **Lagrangian assuming Z_2 symmetry making the WIMP stable is**

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

- **Parameter space is simply defined by only one parameter M_T.**
- **Scanning parameter space is simple because of one parameter.**
- **It is possible to include higher dimensional operators to take new physics effects beyond the WIMP into account, however, those do not play important roles at WIMP's phenomenology.**

Backup (Triplet-like Fermion WIMP)

Field Theory Lagrangian of WIMP

$$\mathcal{L} = \mathcal{L}_{SM} + \bar{T}\left(i\gamma^{\mu}D_{\mu} - \mathrm{M_T}\right)T$$

↓

Non-relativistic expansion and introducing a 'composite' field describing WIMP 2-body states.

↓

The Schrodinger eq. is obtained as EOM of the composite field.

$$[-\nabla^2/m + V(r)]\psi(r) = 0$$

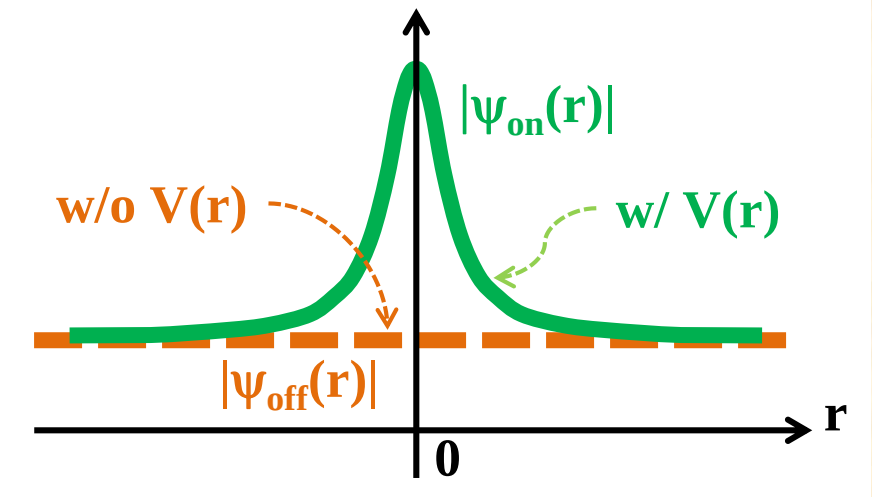
↓

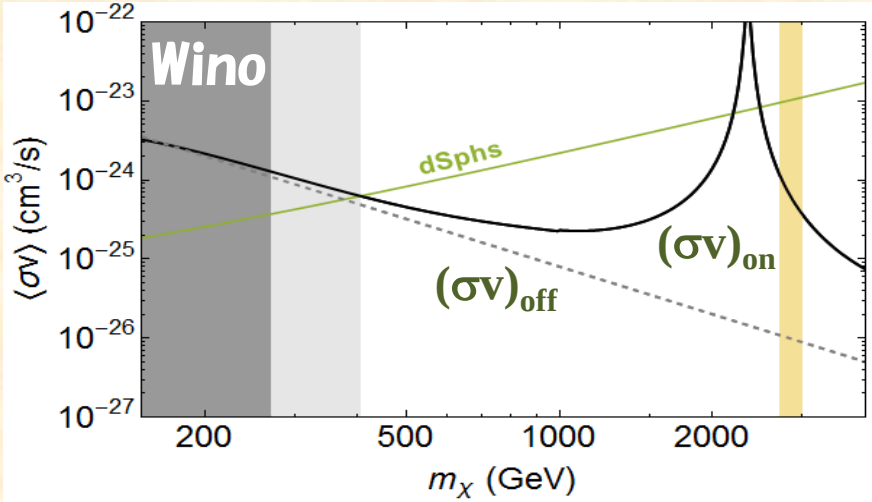
WIMP Annihilation cross section is obtained by the formula:

$$(\sigma v)_{on} = (|\psi_{on}(0)|^2/|\psi_{off}(0)|^2)\,(\sigma v)_{off}$$

↓

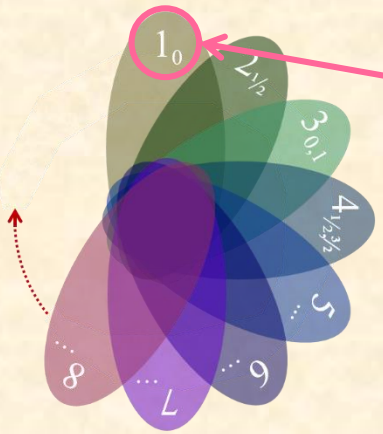
Weak long-range force increase the wave function at origin, for it acts as a attractive force!!!





[J. Hisano, S. M., M. Nagai, M. Nojiri, O. Saito, M. Senami, 2004-2007.]

Backup (S-like F-WIMP w/ H-mediator)



Simplest example = (Fermionic) singlet-like WIMP

- ✓ **Predicted in all of the DS scenarios involving WIMP.**
- ✓ **Minimal contents: 1_0 + Mediator** 大事！
- ✓ **1 neutral Majorana and mediator states(s).**

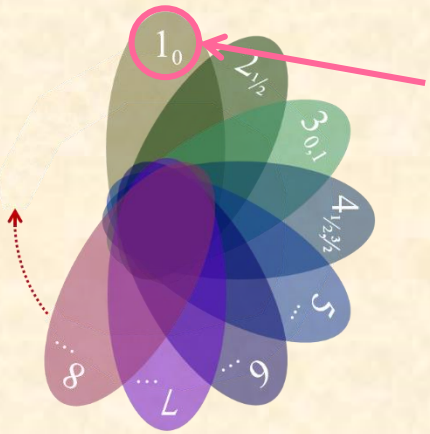
- ➢ **When the mediator is heavier enough than the WIMP and the EW scale, the phenomenology is effectively described by the EFT,**

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

where Λ represents the typical mass scale of the mediator.

- ➢ **Parameter space is very complicated, ∃ about 10 parameters.**
- ➢ **Scanning parameter space using MCMC, assuming CP invariance and the flavor blindness of the WIMP interaction with $|c_i| \leqq 1$.**

Backup (S-like F-WIMP w/ L-mediator)



Simplest example = (Fermionic) singlet-like WIMP

- ✓ ***Predicted in all of the DS scenarios involving WIMP.***
- ✓ ***Minimal contents: 1_0 + Scalar/Vector Mediator.***
- ✓ ***1 neutral Majorana and mediator states.*** ↑ 大事！

Let us consider the case of a light singlet WIMP + a scalar mediator!

- ***Lagrangian involving all possible renormalizable interactions:***

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

- ***Parameter space is again very complicated, ∃ 8 parameters.***
- ***Scanning parameter space using MCMC, assuming CP invariance (c_p = 0) with being |dimension-less(full) coupling| ≦ 1(1TeV).***