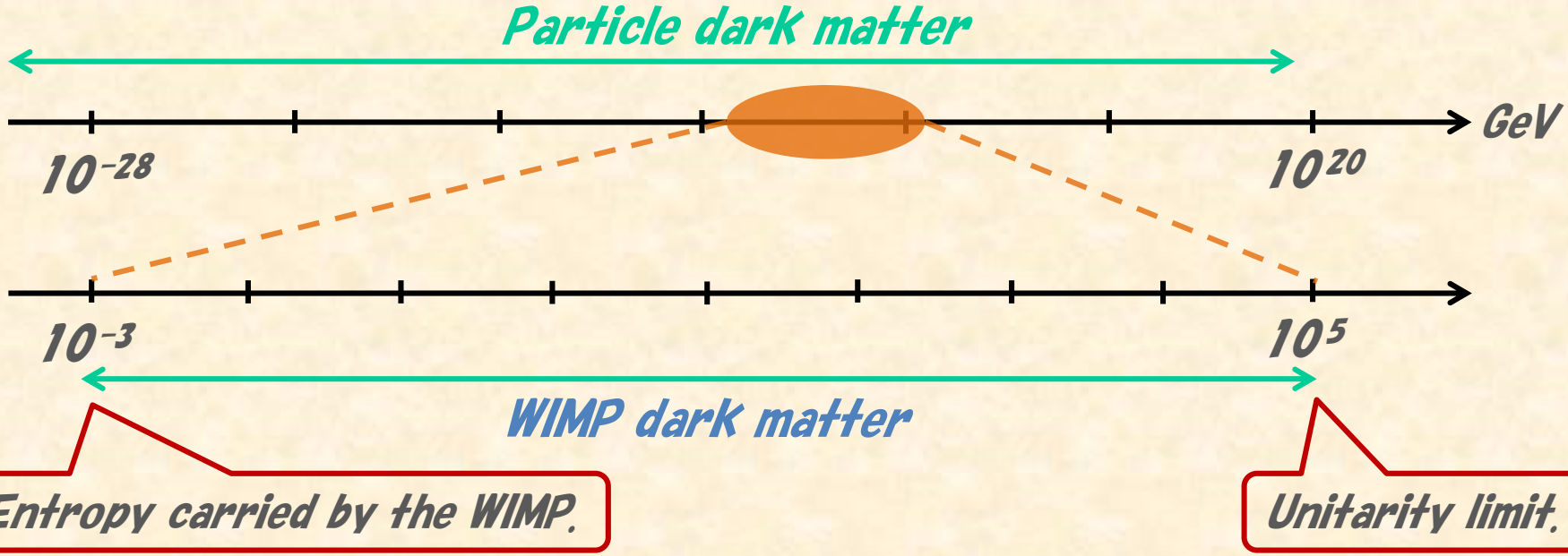
Studying WIMP without prejudice

- *WIMP is involved in various new physics scenarios of the EWSB.*
- *WIMP is predicted to be the lightest particle among new particles.*
- *WIMP can be searched for by not only colliders but also other ones.*

↓

Since the properties of the WIMP is unknown, the study of the WIMP without depending on any specific new physics models is mandatory!

♠ *WIMP mass*



Studying WIMP without prejudice

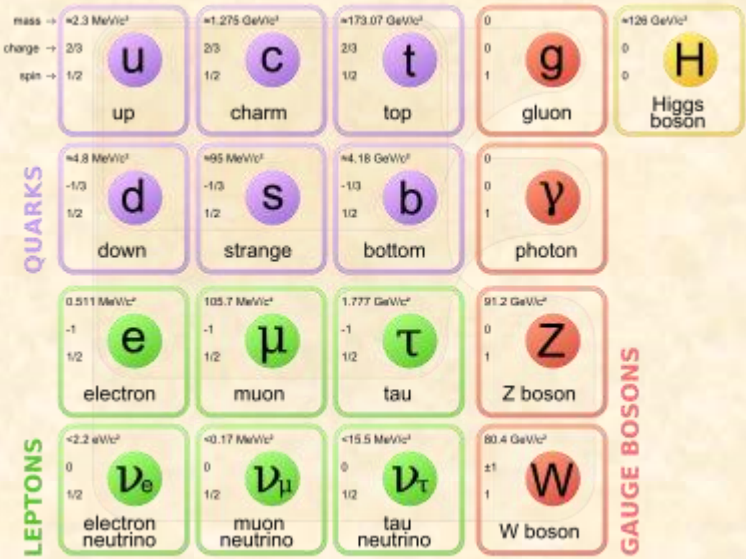
♠ WIMP spin

To have strong enough couplings with SM particles, WIMP is expected to have renormalizable interactions, so that its spin is 0, ½, or 1.

♠ WIMP interaction

Which interaction exists between WIMP and SM?

Interaction



Classifying WIMPs by each interaction is not useful due to the consistency of FT.

↓

Classifying WIMPs based on its quantum number is more useful for our purpose.

Weak charge plays an important role!!!

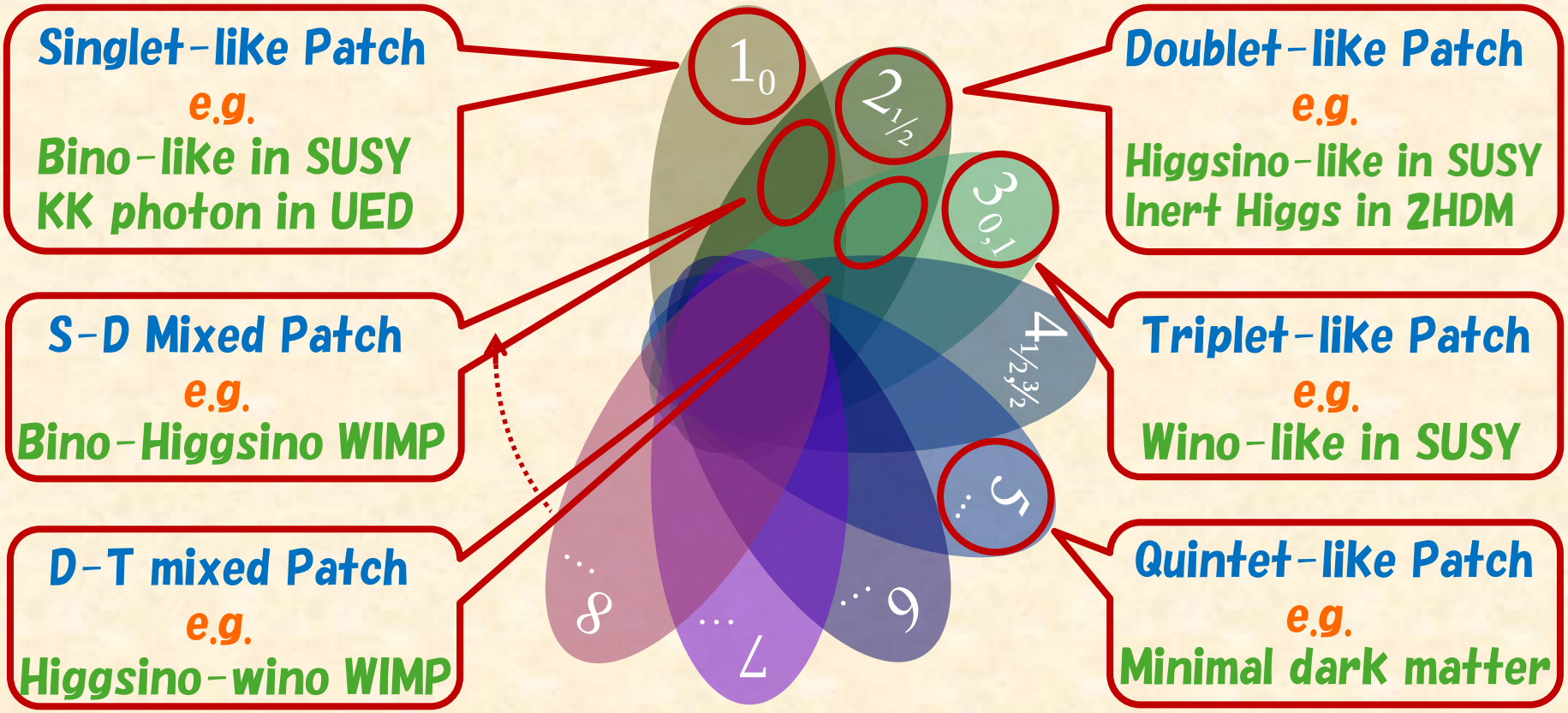
WIMPs can be classified into the following three categories.

- ✓ *WIMP has a weak charge of (almost) zero. ··· Singlet(-like) WIMP*
- ✓ *WIMP has a weak charge close of (half) integer. ··· EWIMP*
- ✓ *WIMP has a mixed weak charge due to EWSB. ··· Well-tempered WIMP*

Studying WIMP without prejudice

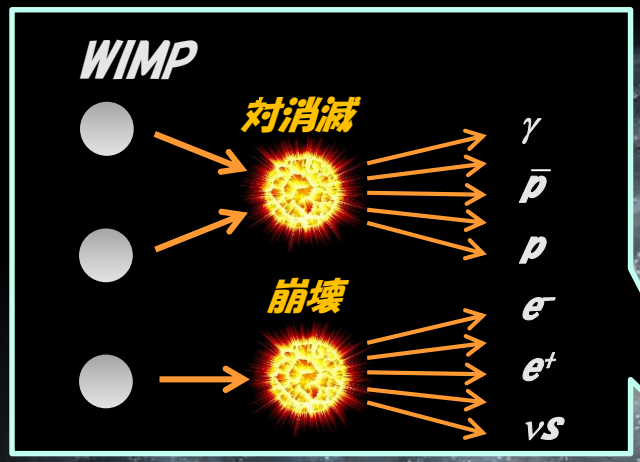
After fixing its spin, the WIMP field is written by a linear combination of colorless rep. of $SU(2)_L \times U(1)_Y$ involving a EM neutral component:

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



WIMP huntings

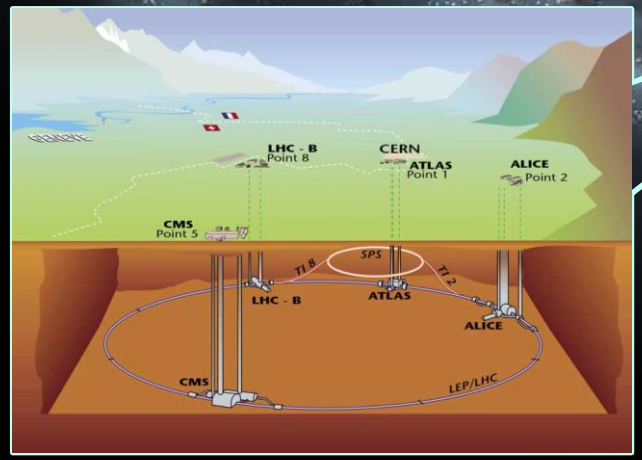
Indirect detection



- Utilizing existent dark matter or producing it.
- The conclusive evidence of DM detection so far.

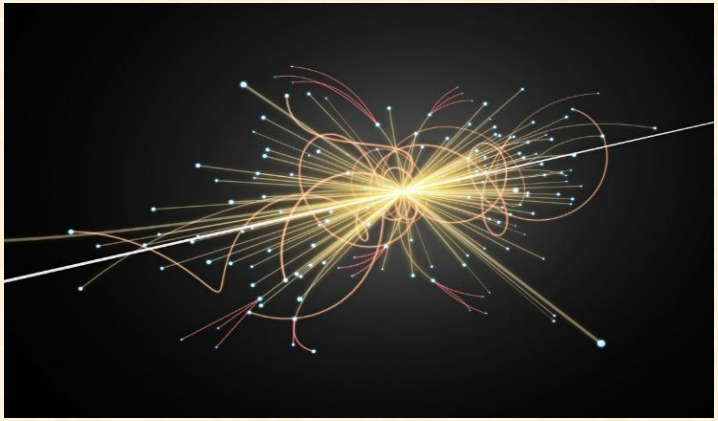
Direct detection

Colliders



[CLARK planetarium website より]

WIMP huntings



@ Colliders

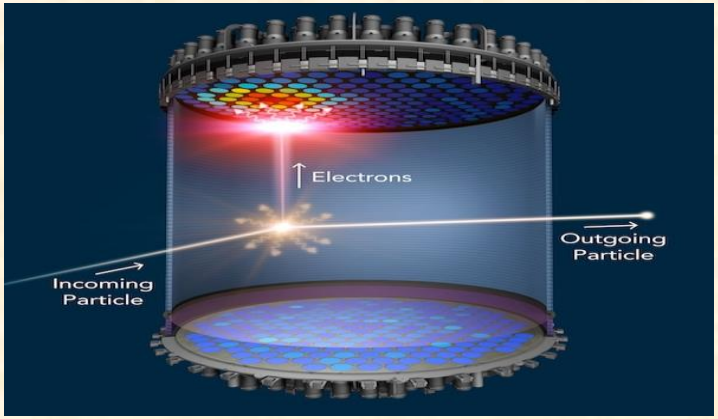
WIMP is expected to be directly produced at colliders, if its energy is high enough.

Hadron Collider: Interaction with quarks.
Lepton Collider: Interaction with leptons.

@ Direct detection

WIMP can be detected by observing release energy by the scattering off a nucleus.

SI scattering: Int. with quarks & Higgs.
SD scattering: Int. with quarks & Z boson.

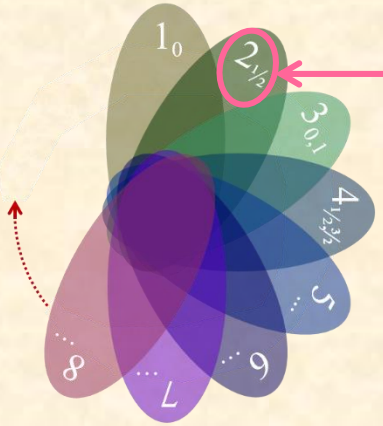


@ Indirect detection

WIMP could be searched for by observing annihilation products produced at DM halo.

Gamma ray: Int. with all the SM particles
Cosmic ray: Int. with all the SM particles

Well-tempered WIMP



Simplest example = (Fermionic) singlet-doublet WIMP

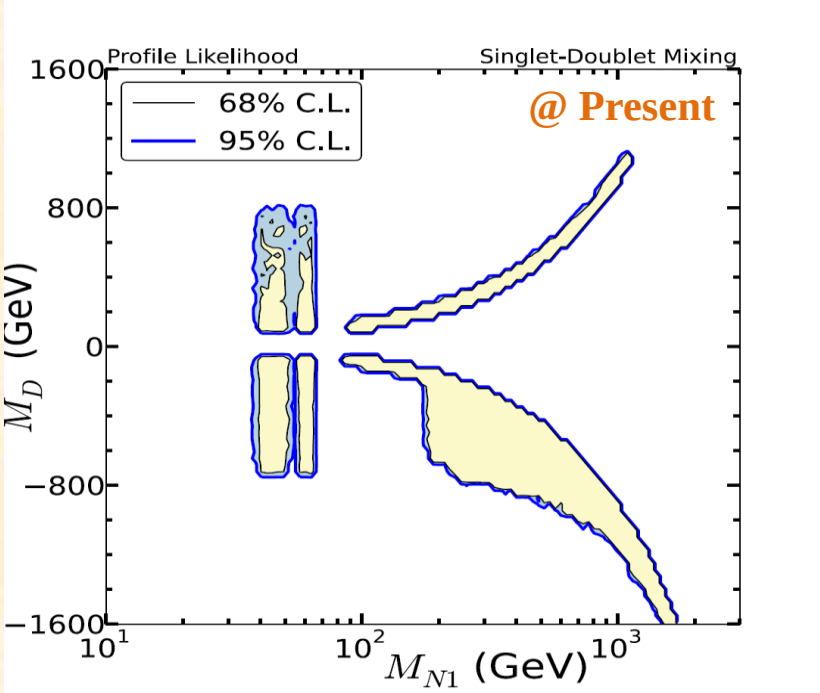
- ✓ **Typical WIMP in the traditional natural SUSY.**
- ✓ **Minimal contents: 1_0, $2_{1/2}$, $2_{-1/2}$ (Anomaly cancel.)**
- ✓ **3 neutral Majorana and 1 charged Dirac fermions.**

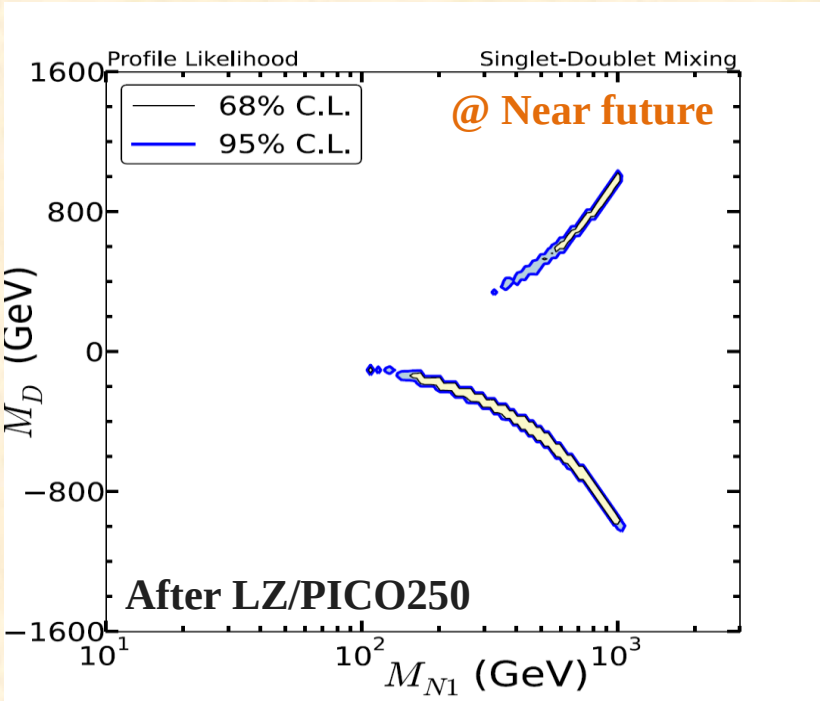
- **Lagrangian assuming Z_2 symmetry making the WIMP stable is**

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

- **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 $|y_i| \leq 1$.**

Well-tempered WIMP





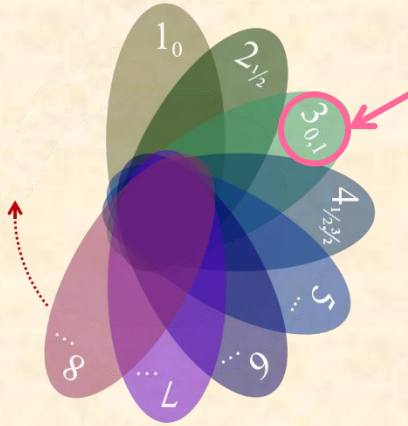
Direct detection is very powerful to explore the well-tempered WIMP!

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

The same conclusion is obtained for the most of well-tempered WIMPs, for the origin of the mixing and DM-DM-h(Z) couplings are the same.

Big direct dark matter detection will be playing an important role!!!!!

EW charged WIMP (EWIMP)



Simplest example = (Fermionic) triplet-like WIMP

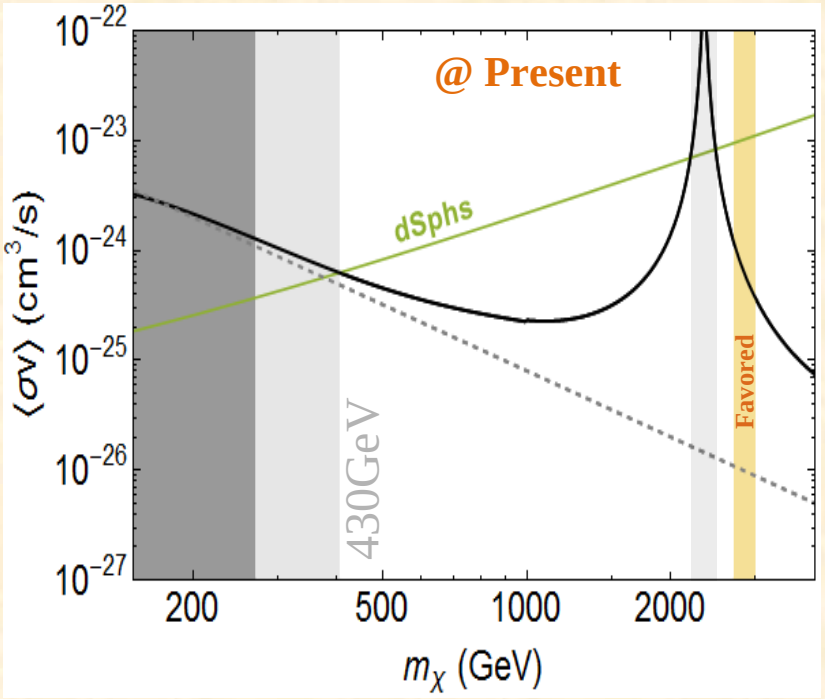
- ✓ **Predicted in High-scale SUSY and MPP scenarios.**
- ✓ **Minimal contents: 3_0. (Just one representation.)**
- ✓ **1 neutral Majorana and 1 charged Dirac fermions.**

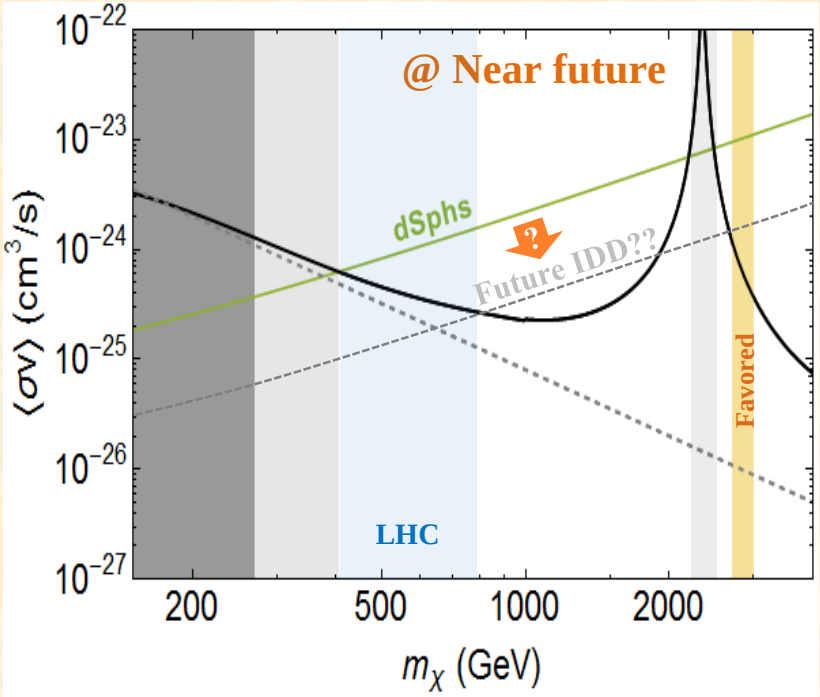
- ➢ **Lagrangian assuming Z_2 symmetry making the WIMP stable is**

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

- ➢ **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.**

EW charged WIMP (EWIMP)





The WIMP seems difficult to be detected at DD searches in near future.

[$\sigma_{SI} \sim 2\ 10^{-11}$ pb, and, in addition, it may be cancelled by BSM contributions.]

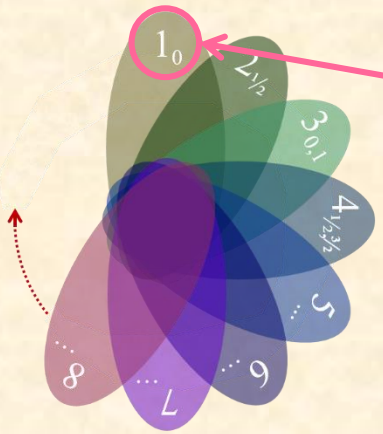
LHC will explore the WIMP mass region below 500GeV. Can it go more?

IDD searches are promising, for the WIMP's annihilation is enhanced!!!

[The enhancement is from the Sommerfeld effect, Hisano, S.M., Nojiri, 2014.]

γ-ray obs. (Fermi, CTA) → IDD (γ from dSphs) ← DM dist. (PSC, PFS)

Singlet-like WIMP (Heavy 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).***

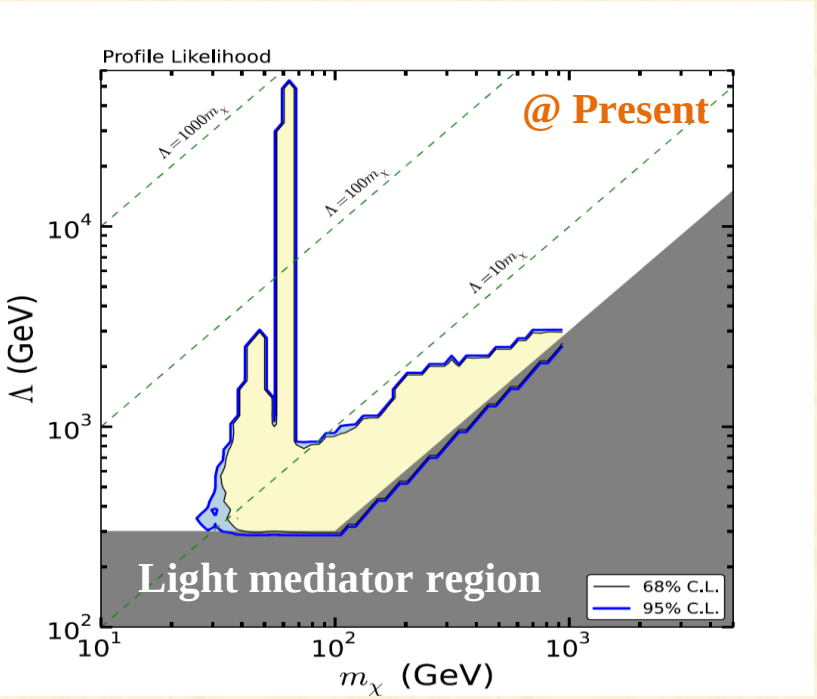
- ***When the mediator is heavier enough than the WIMP and the EW scale, the phenomenology is effectively described by the EFT,***

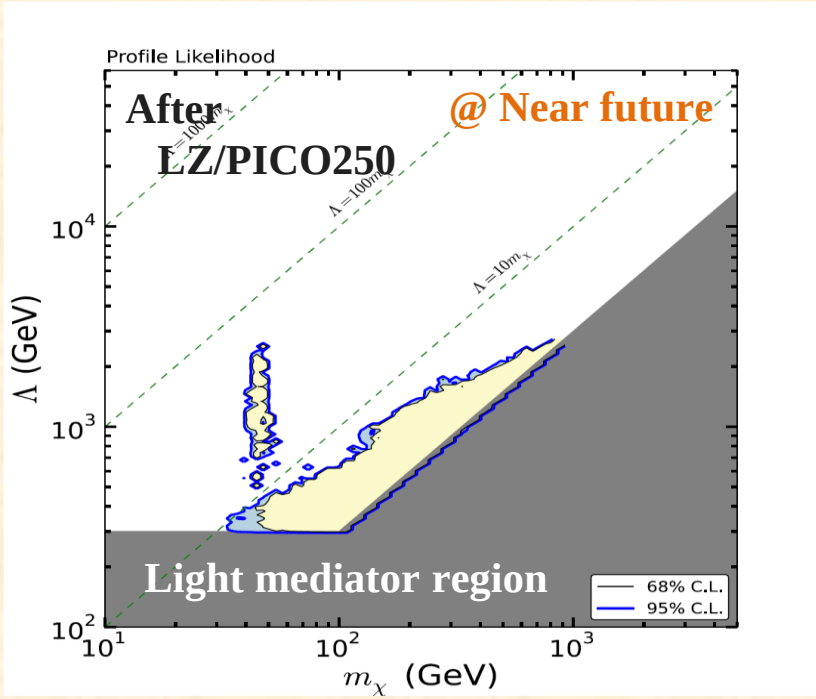
$$\mathcal{L}_{\rm EFT} \supset \frac{c_S}{2\Lambda}(\bar{\chi}\chi)|H|^2 + \frac{c_P}{2\Lambda}(\bar{\chi}i\gamma_5\chi)|H|^2 + \sum_f \frac{c_f}{2\Lambda^2}(\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{f}\gamma_\mu f) + \frac{c_H}{2\Lambda^2}(\bar{\chi}\gamma^\mu\gamma_5\chi)(H^\dagger i\overleftrightarrow{D}_\mu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

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 $|c_i| \leqq 1$.***

Singlet-like WIMP (Heavy mediator)





Direct detection is powerful to explore the H- & Z-resonance regions.

The four Fermi interactions governs the other region with $\Lambda < 10m_{DM}$,
[This region is not so much searched for at DD and LHC exps in near future!]

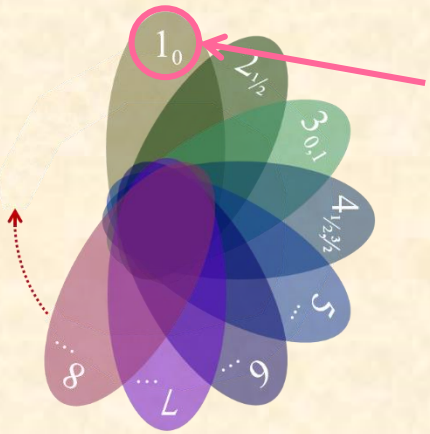
LHC results → The four Fermi region ← DD (LZ, PICO250) results

↓

Leptophilic or Z-portal WIMP!

[It is governed mainly by the interactions with leptons or Z-boson.]

Light singlet WIMP (Light 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！

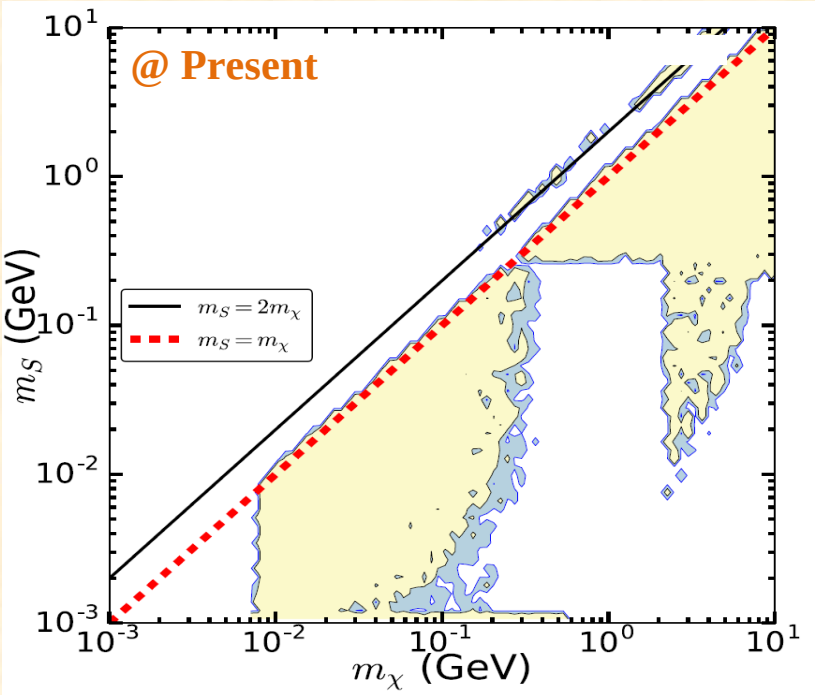
Let us consider the case of a light singlet WIMP + a scalar mediator!

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

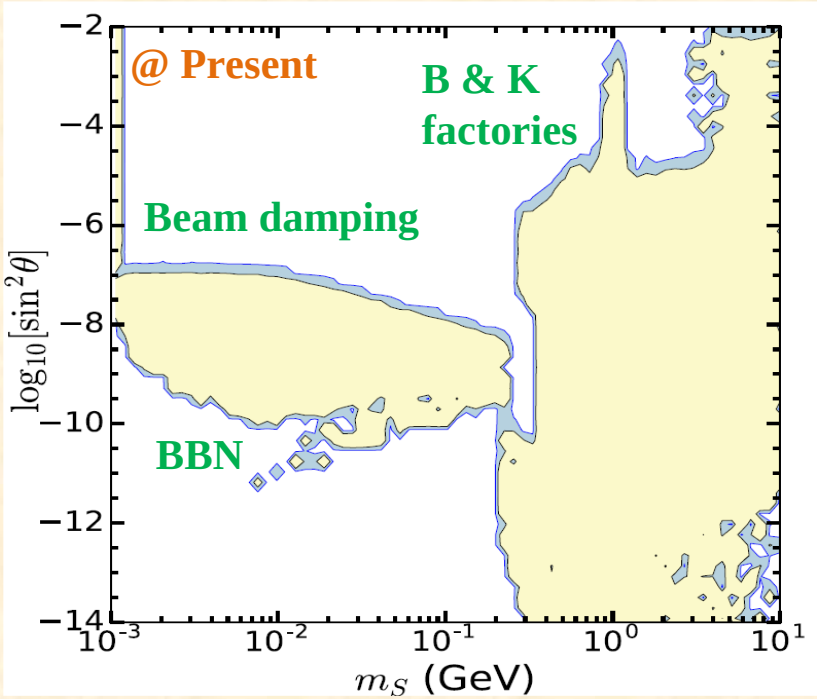
$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{2}\bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial\phi)^2 - \frac{c_s}{2}\phi\bar{\chi}\chi - \frac{c_p}{2}i\phi\bar{\chi}\gamma^5\chi - V(\phi, H),$$

- ***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).***

Light singlet WIMP (Light mediator)



&

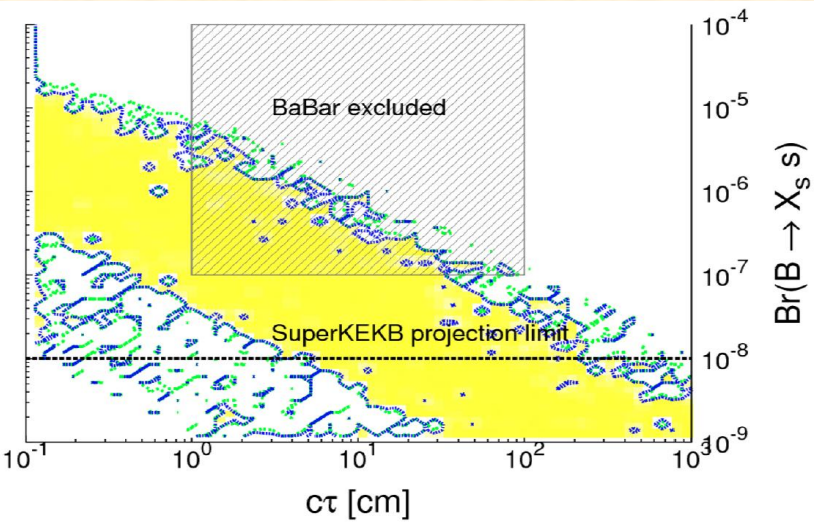


Various experiments will contribute in order to explore the light WIMP.

Search for the light mediator s will play a crucial role in this program.

[An exception is direct DM detection, where the WIMP plays a central role.]

Long-lived particle search @ Belle II →



Summary

- ✓ We have discussed WIMP candidates and new physics of EWSB!
- ✓ Lot of new physics models predict the existence of WIMP:
  - Traditional natural SUSY … Well-tempered WIMP
  - Focus point SUSY scenario … Doublet-like WIMP
  - High-scale SUSY scenario … Triplet-like WIMP
  - Multiple point principle … Triplet-like WIMP
  - Dark sector scenario … Singlet-like WIMP
- ✓ Current status & future prospect to search for the WIMP are
  - Direct detection searches are (and will be) playing a very important role to search for the well-tempered WIMP.
  - Indirect detection searches will be the only way to explore the electroweakly charged WIMP (EWIMP) in near future.
  - Leptophilic and Z-pole regions will remain unexplored for the singlet-like WIMP with heavy Mediator particle(s).
  - Many studies are now on-going for the singlet-like WIMP with light Mediator(s). Among those, the light WIMP region is interest, which will be explored by e.g. Belle II.