WIMPダークマター探査の現状と見通し

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Collaborators: Members in IPMU WIMP PROJECT

S. M., S. Mukhopadhyay, Y. L. Sming Tsai, [JHEP 1410 (2014) 155]
S. Banerjee, S. M., K. Mukaida, Y. L. Sming Tsai, [JHEP 16xx (2016) xxx]
S. M., S. Mukhopadhyay, Y. L. Sming Tsai, [PRD94 (2016) 065034]

以下のWIMPに関する3つの問題に焦点を当て、講演します。

What is the current status of the WIMP scenario?
How far can we cover the WIMP scenario in future?
What is the leftover remaining as unexplored regions?

Dark Matter (DM) overview

◆ What we know about DM (∃DM established)

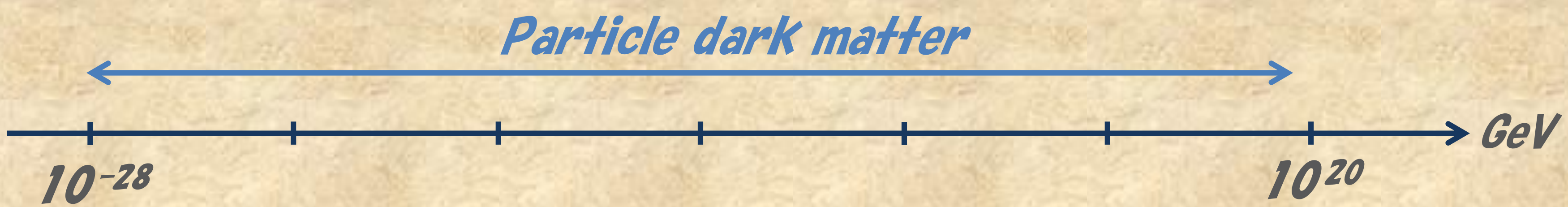
Observations →
- ✓ Neutrality
- ✓ Stability
- ✓ Coldness
- ✓ Abundance

◆ DM candidate in the standard model?

No DM candidate! (Even a single component pBH is excluded.)

→ DM seems some new particle that is not discovered yet.

◆ Mass range of a particle DM



de Broglie length < dSph size
($\lambda = 2\pi/mv$)

Compton length > Schwarzschild radius
($\lambda = 2\pi/m$) ($r = 2m/M_{pl}^2$)

WIMP hypothesis

WIMP hypothesis

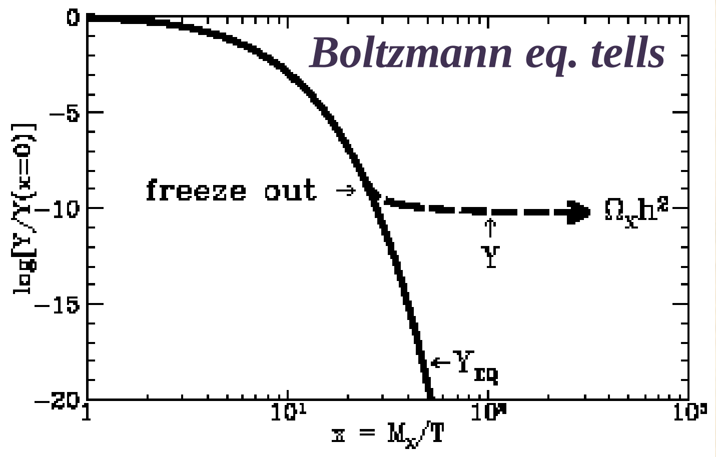
Dark matter is a electromagnetically neutral and stable particle, whose abundance at present is determined by the usual decoupling mechanism.

Solving the Boltzmann equation gives the following behavior of n_{WIMP}/s →

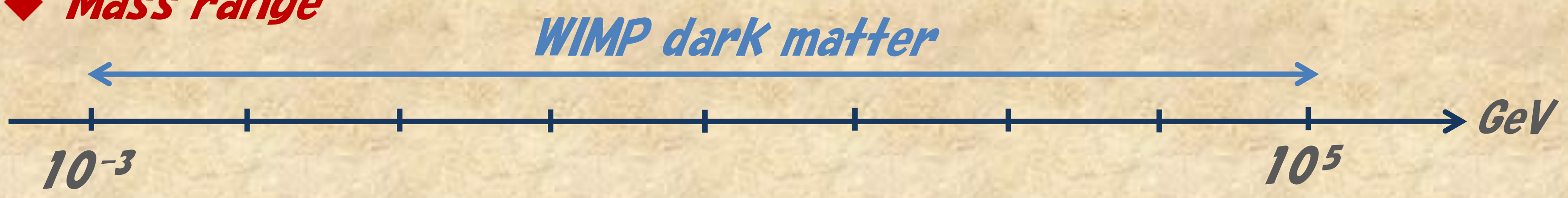
$$\Omega_{TH} h^2 \sim 0.1\ (1\text{pb}/\langle\sigma v\rangle)^2$$

$$\Omega_{OB} h^2 \sim 0.12 \pm 0.0015$$

Decoupling (reaction vs. expansion) often plays an important role in U.



◆ Mass range

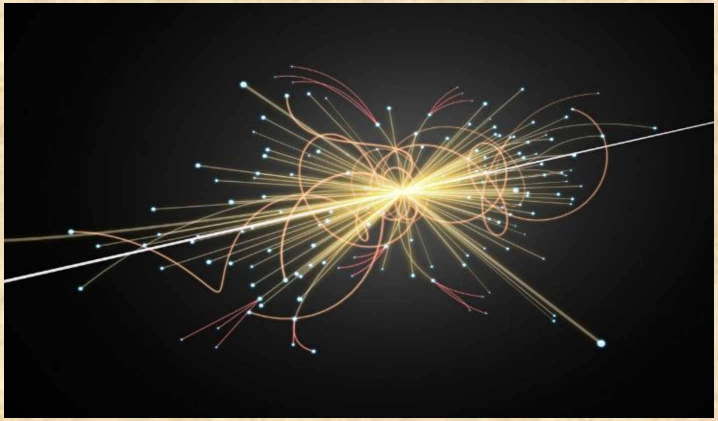


Particle Physicists: The mass of WIMP may have the same origin of the EWSB!

Experimenters: WIMP must have some interactions with SM particles, so that there exists a lot of opportunities to detect WIMP!

Which SM particle(s) does the WIMP interact with?

WIMP searches



@ Colliders

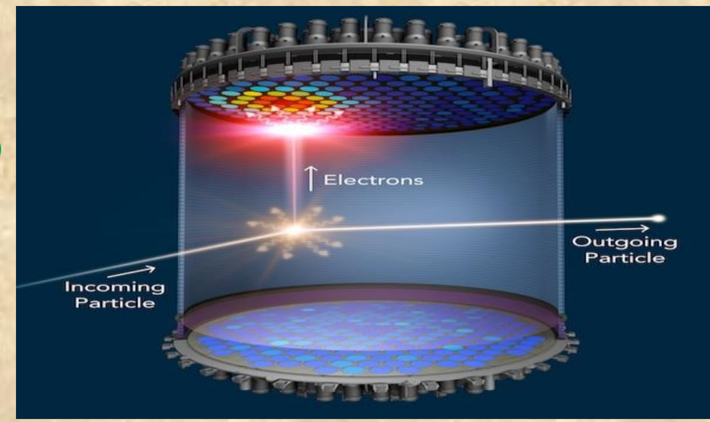
WIMP is expected to be directly produced at colliders, if its energy is high enough.

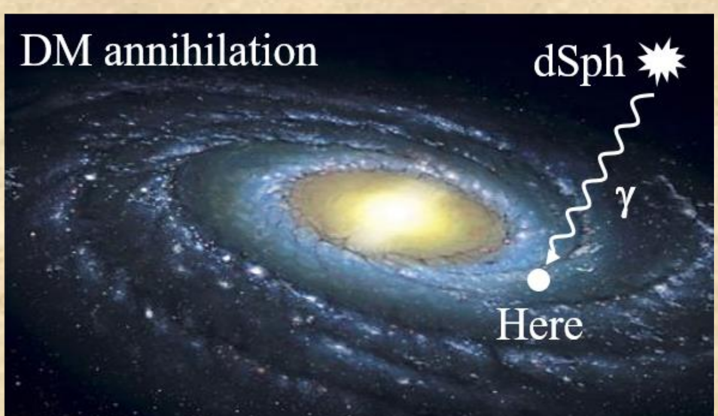
Hadron Collider: Interaction with quarks.
Lepton Collider: Interaction with leptons.

@ 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

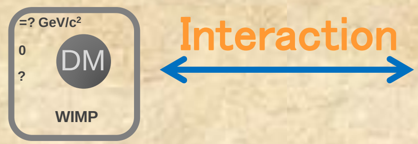
WIMP could be searched for by observing annihilation products produced at DM halo.

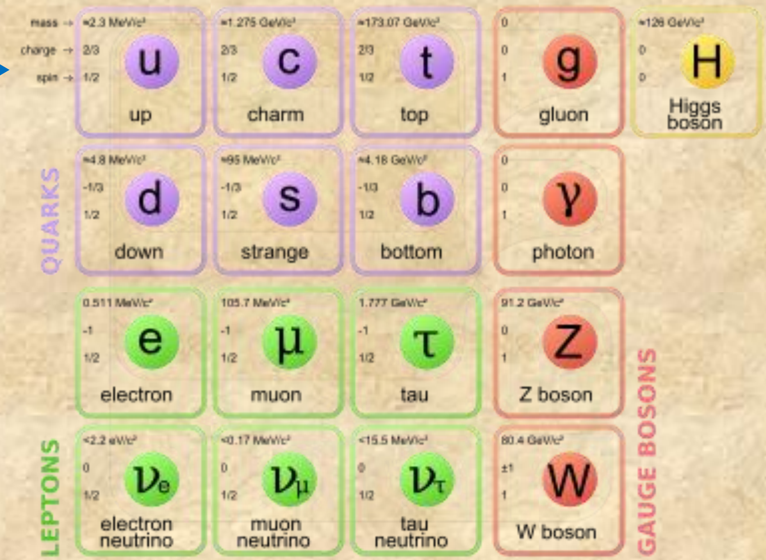
Gamma ray: Int. with all the SM particles
Cosmic ray: Int. with all the SM particles

Studying WIMP without prejudice

Discussing WIMP without relying on any specific new physics models!
[New physics viewpoint is used to support the region found in the above discussion.]

Which interaction exists between WIMP and SM?





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*

Let us discuss each WIMP using the simplest example to see what kind of strategy is (expected to be) taken to detect it at present (future).

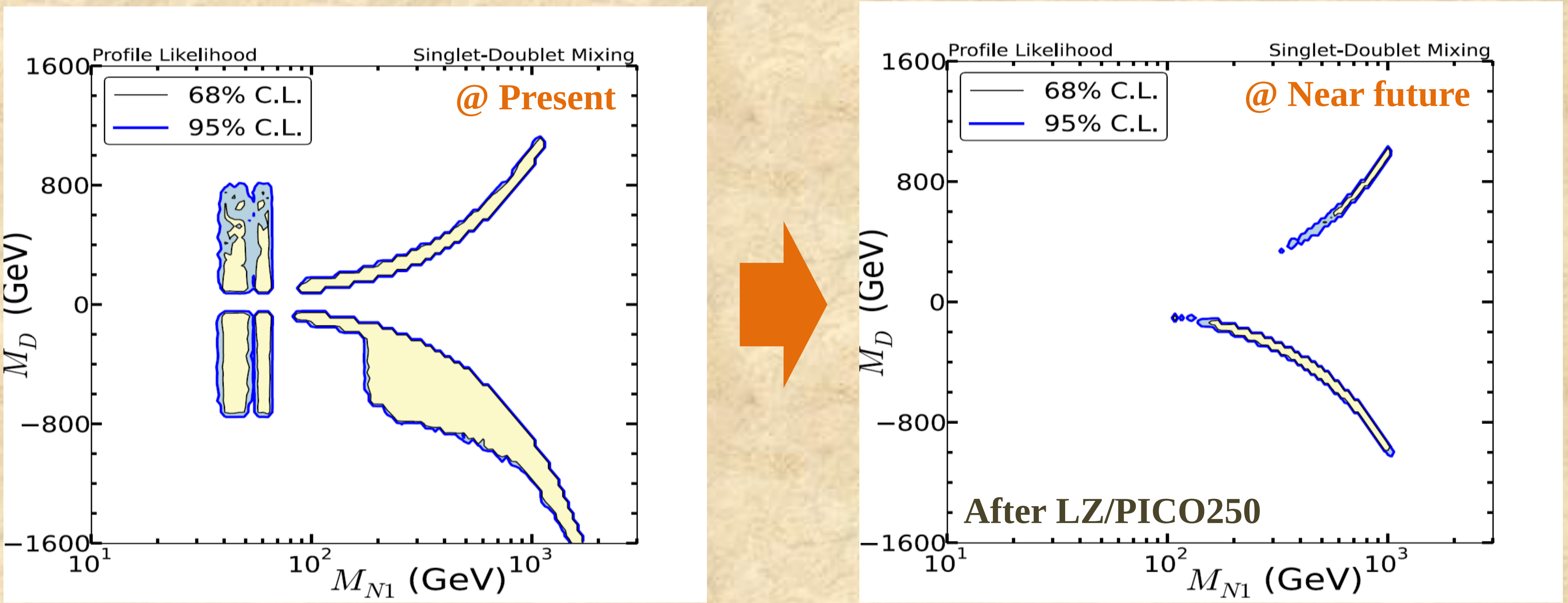
Well-tempered WIMP

- The simplest example = Fermionic singlet-doublet WIMP model.
- Minimal contents are 1_0, $2_{½}$, $2_{-½}$ due to anomaly cancelation.
- 3 neutral Majorana and 1 charged Dirac fermion introduced.
- Lagrangian assuming Z_2 symmetry making the WIMP stable is

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

- 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.]
- Such a WIMP is predicted by some natural SUSY scenarios.
- 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.

What we learn: Just waiting future big direct detection experiments!

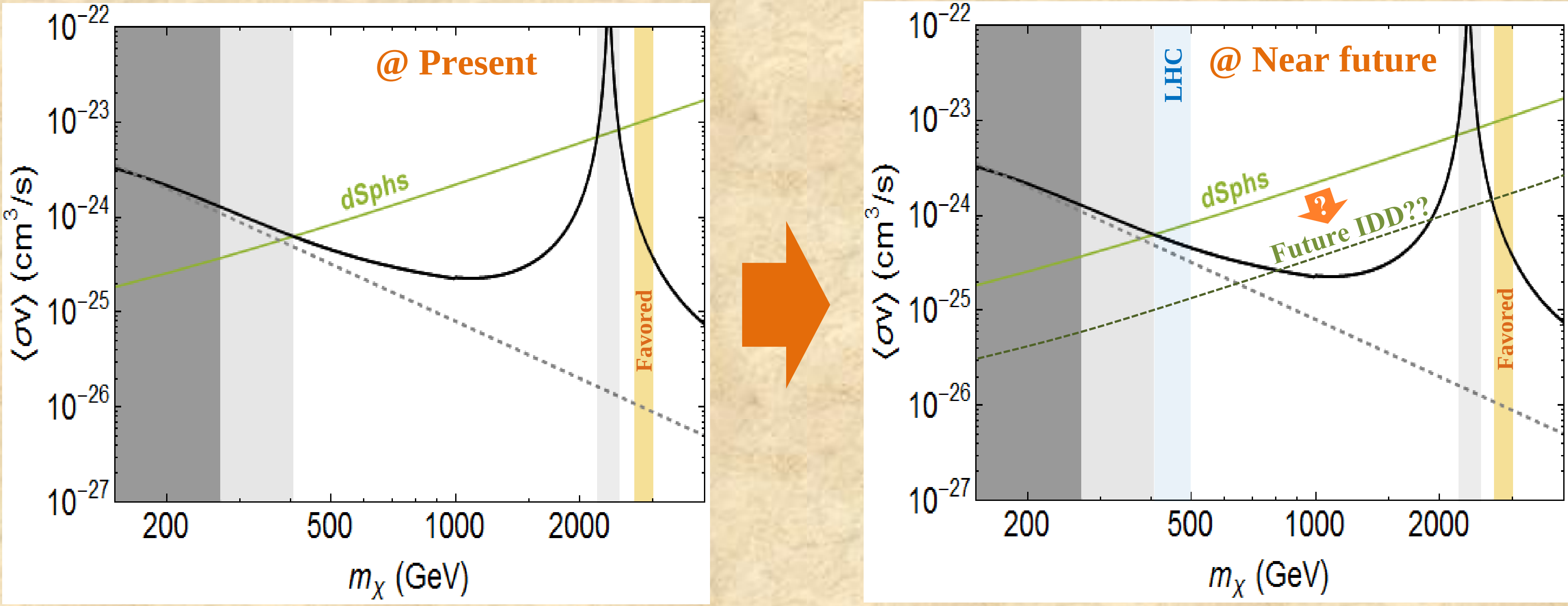
EW charged WIMP (EWIMP)

- The simplest example = Fermionic triplet-like WIMP model.
- Minimal content is 3_0, namely just one representation.
- 1 neutral Majorana and 1 charged Dirac fermion introduced.
- 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.
- Such a WIMP is predated by the AMSB (high-scale) scenarios.
- 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.

[σ_{SI} ~ 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)***

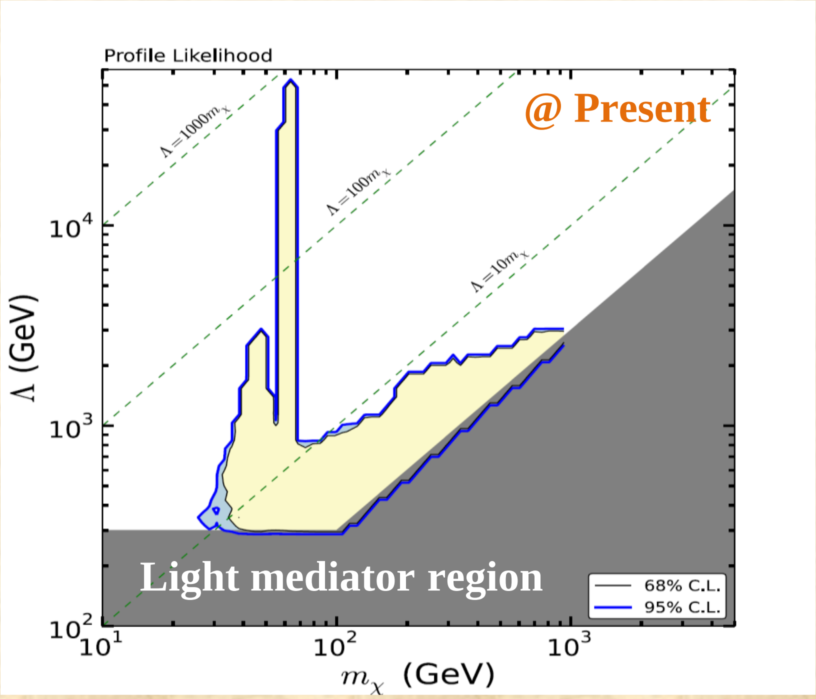
Singlet-like WIMP

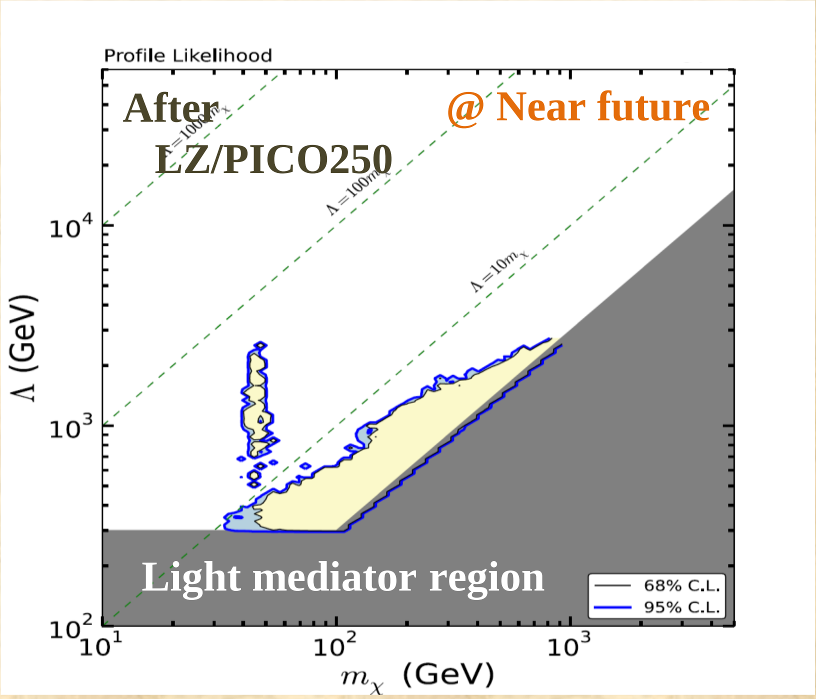
- *The WIMP cannot interact with SM particles by alone due to the SM gauge symmetry and the Z_2 symmetry, if it is a fermion.*
- *Some the other new particle(s) must be introduced WIMP, which is called the mediator connecting WIMP & SM (portal scenario).*
- *Phenomenology of the WIMP depends strongly on the mediator.*
- *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, ∃ around 10 parameters.*
- *The WIMP is predated in many BSMs of EWSB, ν, & dark sector.*
- *Scanning parameter space using MCMC, assuming CP invariance and the flavor blindness of the WIMP interaction with $|c_i| \leq 1$.*

Singlet-like WIMP





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

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Leptophilic WIMP!

[It is governed mainly by the interactions with leptons.]

Summary

- ✓ We discussed fermionic WIMPs w/o relying on specific BSMs.
- ✓ Well-tempered WIMP:
  Direct detection searches are (and will be) playing a very important role to explore the WIMP. What we should do is to wait for their results in the near future.
- ✓ Electroweakly charged WIMP (EWIMP):
  It seems to be the most motivated WIMP from the particle physics viewpoint. Indirect detection searches will be the only way to explore the WIMP in near future, requiring a precision determination of WIMP distribution near by us.
- ✓ Singlet-like WIMP with heavy Mediator:
  Because of LHC and direct detection searches, leptophilic region will remain unexplored. Experiments sensitive to WIMP-lepton interactions will be very welcome.
- ✓ Singlet-like WIMP with light Mediator:
  Studies are now on-going by many DM people in the world, via simplified models. Among those, interesting regions are reported, such as the light WIMP in the dark sector, etc.

Backup (Constraints from LHC)

We use L_{UV+} & L_{UV-} instead of L_{EFT} to evaluate constraints from colliers.

- ✔ Invisible Higgs decay @ LHC: Sensitive to the scalar type coupling.
- ✔ Invisible Z decay @ LEP: Sensitive to WIMP-Higgs current coupling.
- ✔ Mono-γ search @ LEP: Sensitive to WIMP-Lepton & Higgs couplings.
- ✔ Mono-jet search @ LHC: Sensitive to WIMP-Quark couplings.

Decay widths of mediator particles are fixed as $\Gamma = \Lambda/2$ in the analysis.

Are there some other channels?

- ➢ Radiative corrections (off-shell contributions) from the mediators.
  Mediator particles may contribute to some SM processes (e.g. SM 4-Fermi couplings). The contribution could be, however, alleviated by introducing other new particles coupled only to SM particles.
- ➢ On-shell productions of the mediator particles at the LHC.
  Some single productions (and decays into WIMP) are included.
  For Z_2-even mediators, single productions into 2jets are weaker.
  For Z_2-odd mediators, pair productions give weaker signals.

Studying WIMP without prejudice

Is there a framework to study WIMP w/o relying on any specific BSM?

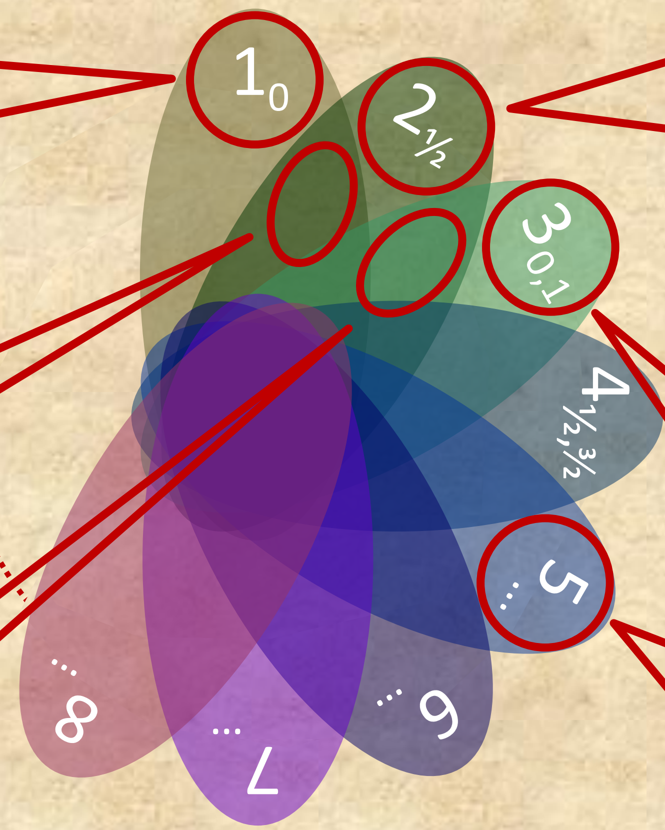
After fixing its spin, the WIMP field is written by a linear combination of colorless rep. of $SU(2)_L \times U(1)_Y$ involving a EM neutral component:

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

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

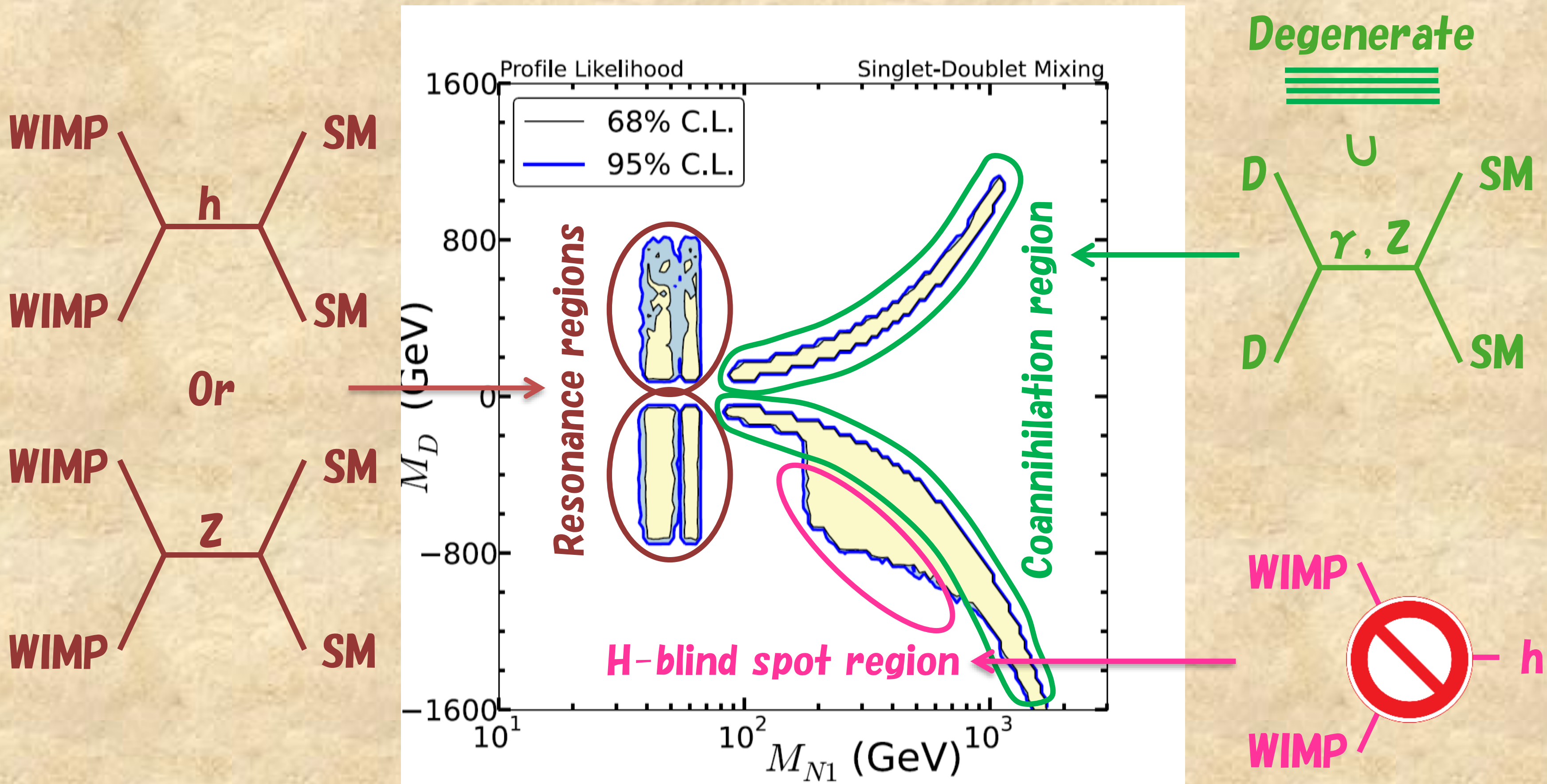


Doublet-like Patch
e.g.
Higgsino-like in SUSY
Inert Higgs in 2HDM

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

Quintet-like Patch
e.g.
Minimal dark matter

Singlet-Doublet mixed WIMP



Present status

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