WIMP暗黒物質探査の現状と将来

Shigeki Matsumoto (Kavli IPMU)

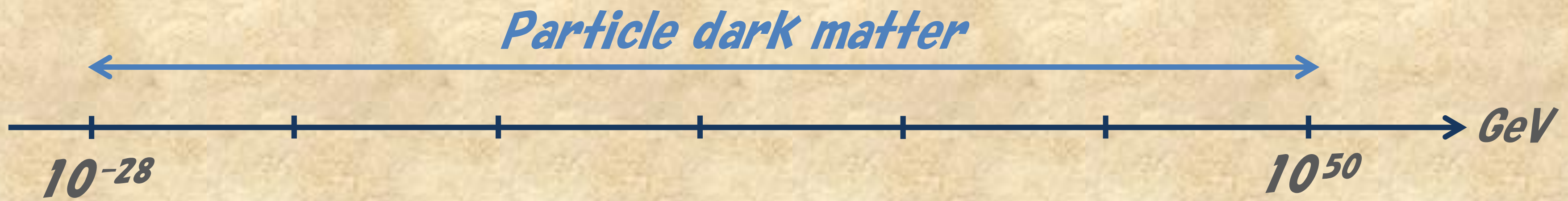
Collaborators: Members in IPMU WIMP PROJECT

S. M., S. Mukhopadhyay, Y. L. Sming Tsai, [JHEP 1410 (2014) 155]
S. Banerjee, S. M., K. Mukaida, Y. L. Sming Tsai, [arXiv:1603.07387]
S. M., S. Mukhopadhyay, Y. L. Sming Tsai, [arXiv:1604.02230]

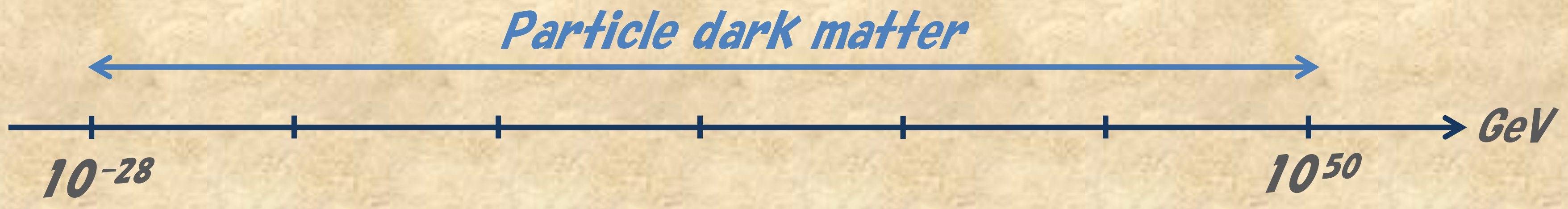
What is the current status of the WIMP paradigm?
How far can we cover the WIMP paradigm in future?
What is the leftover remaining as unexplored regions?

Purpose of the project is to answer these questions without relying on any specific new physics models.

WIMP hypothesis



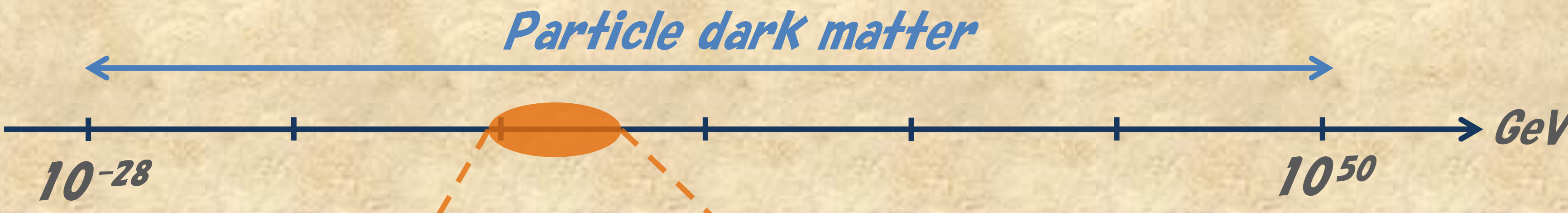
WIMP hypothesis



WIMP hypothesis

Dark matter is a electromagnetically neutral and stable particle with the mass of roughly 100GeV, and it has a usual coupling to SM particles.

WIMP hypothesis



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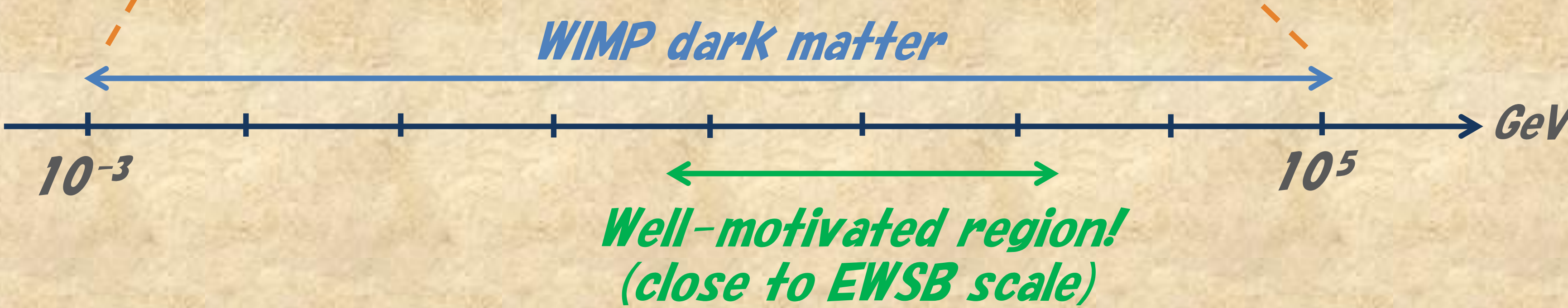


WIMP hypothesis

WIMP hypothesis

Dark matter is a electromagnetically neutral and stable particle with the mass of roughly 100GeV, and it has a usual coupling to SM particles.

- ✓ *Neutrality* ··· *By definition.*
- ✓ *Stability* ··· *By definition. (There must be some symmetry behind it.)*
- ✓ *Coldness* ··· *WIMP decouples from thermal bath when non-relativistic.*
- ✓ *Abundance* ··· *It is predicted to be $\Omega_{DM}h^2 \sim 0.1\ (1\mathrm{pb}/\langle\sigma v\rangle)^2$.* ← *FTFT!*

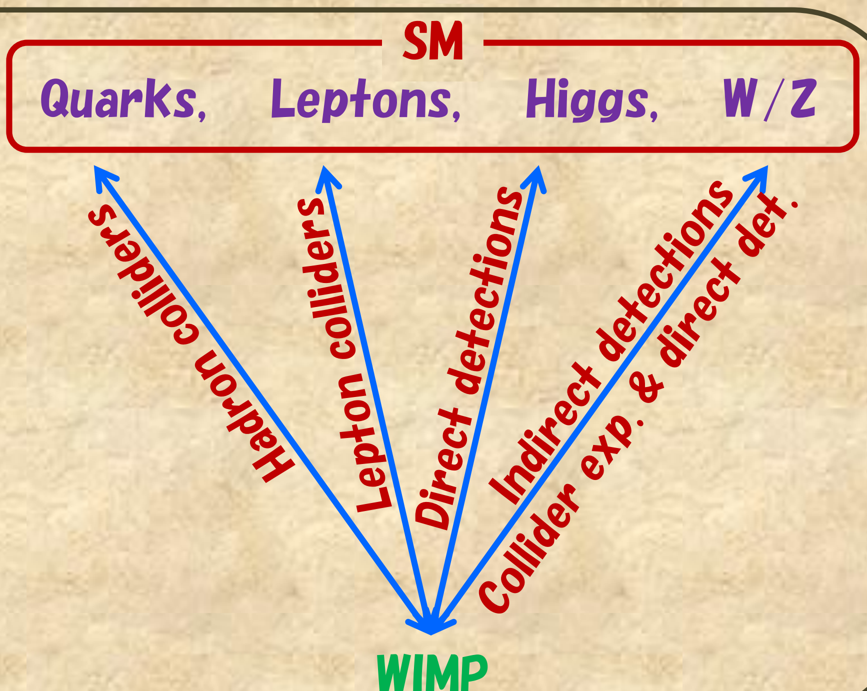
Why is WIMP attractive?

Theoretically, the mass of WIMP and the origin of EWSB can be the same!

Experimentally, there exists a lot of opportunities to detect WIMP, since the coupling between WIMP and SM particles are not suppressed.

↓

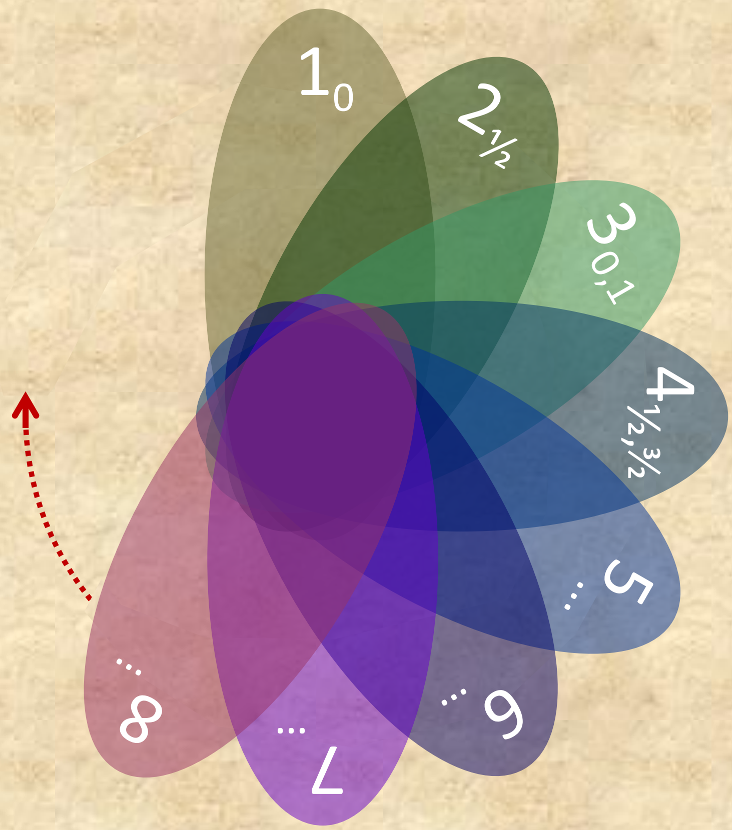
Is there some framework to discuss WIMP detections systematically w/o depending on any specific BSM?



Covering WIMP Theory Space by the Patches

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

Once the spin of WIMP is fixed, the WIMP field can always be written as a linear combination of colorless representations of the SM gauge group, viz. $SU(2)_L \times U(1)_Y$, which must involve EM neutral components:



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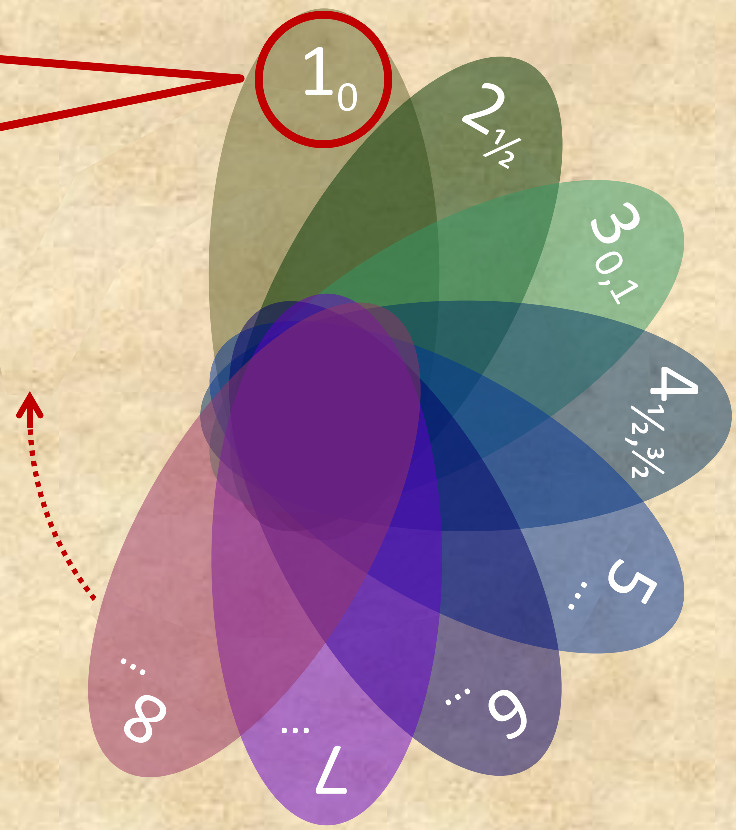
Singlet-like Patch

e.g.

Bino-like in SUSY

KK photon in UED



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

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

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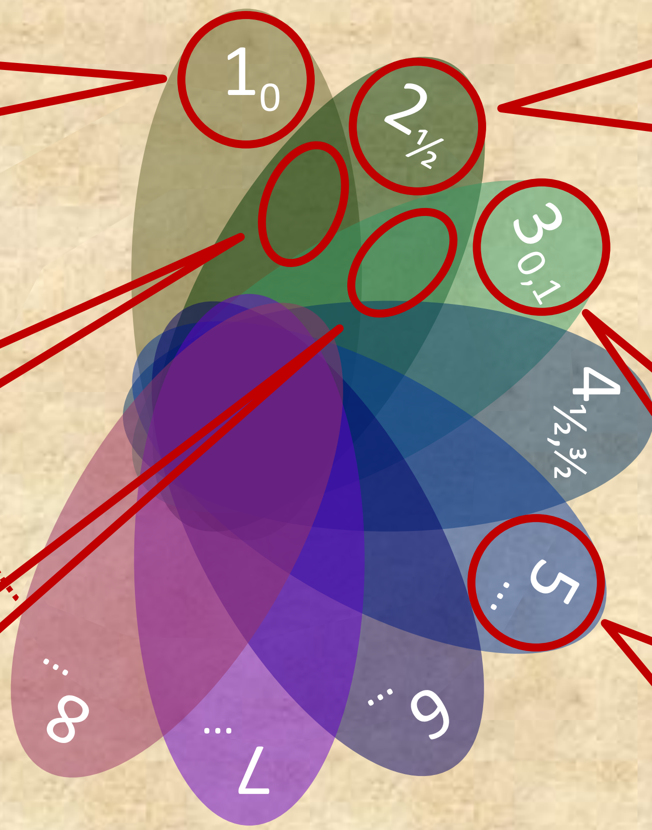
Singlet-like Patch
e.g.
Bino-like in SUSY
KK photon in UED

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

Basic strategy

1. Constructing the effective Lagrangian in each patch, with particle contents as minimal as possible. It should include all interactions that can be responsible for the relic abundance calculation.
2. Considering various constraints from WIMP searches as well as the relic abundance limit to figure out viable parameter space.

WIMP search results
Giving upper limits on the WIMP interactions.

↔

Relic abundance limit
Giving lower limits on the WIMP interactions.

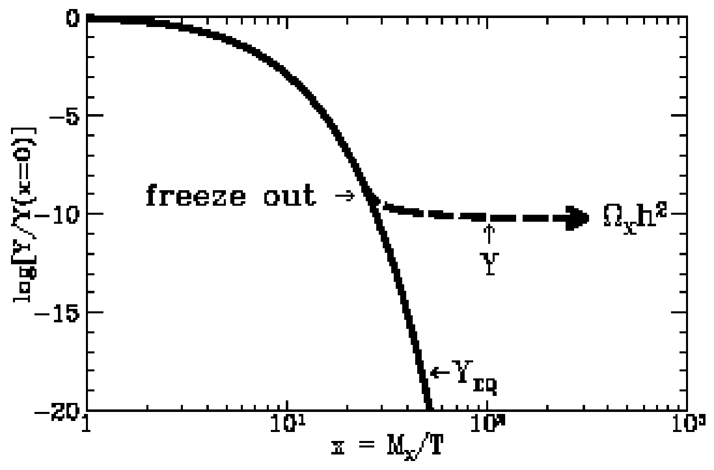
These opposite requirements make the WIMP parameter space finite!

In this talk, we will focus on a fermionic WIMP in the S-D mixed & the Singlet-like patches!

light WIMPs!

Constraints on the WIMP parameter space

DM relic abundance limit

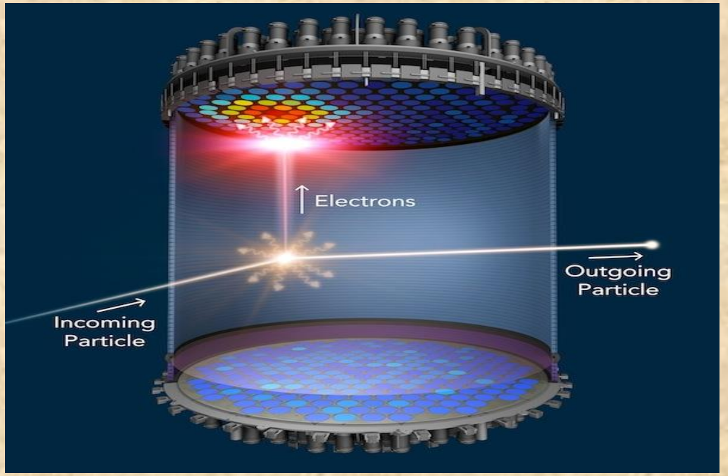


Putting a (lower) limit on dark matter inclusive annihilation cross section.

$$\Omega_{WIMP} h^2 = 0.12 \ (\Omega_{WIMP} h^2 \leq 0.12)$$

The dark matter abundance today is assumed to be determined by thermal (+ a non-thermal) production.

Direct DM detection constraints



Putting upper limits on the scattering cross section between DM and nucleon.

Present status:

LUX for SI/SD_n and PICO-60 for SD_p

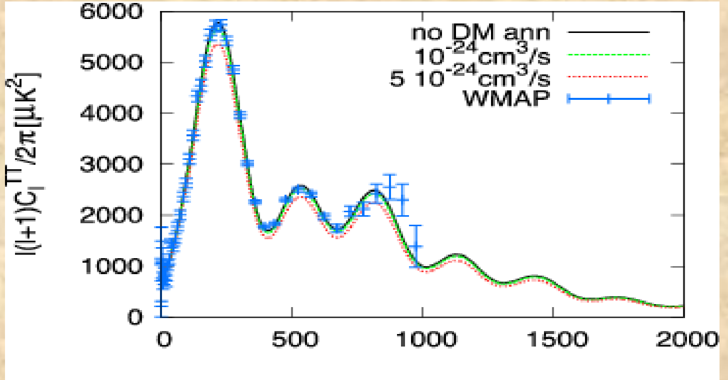
Future prospects:

LZ for SI/SD_n and PICO250 for SD_p

(assuming no signals detected.)

Constraints on the WIMP parameter space

Indirect DM detection constraints

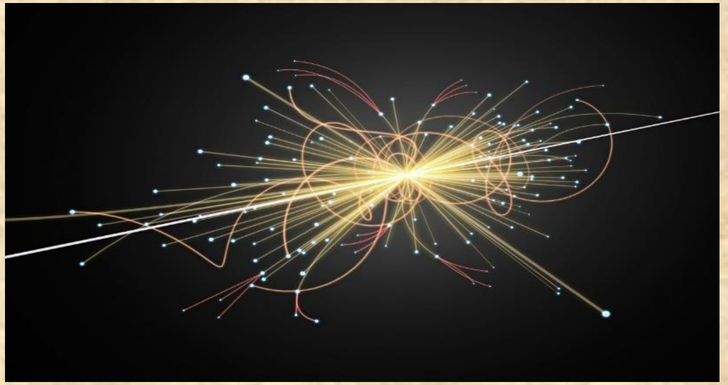


Putting an upper limit on dark matter (semi-inclusive) annihilation X-section.

PLANCK (DM ann. @ recombination era)

Other indirect detections have yet large systematic uncertainties.

Constraints from collider experiments

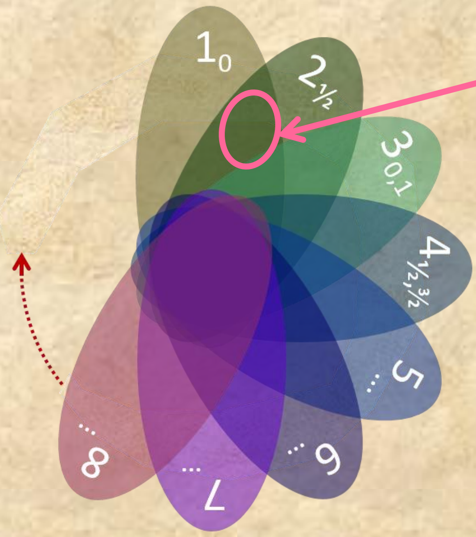


Putting upper limits on the production cross section of the DM particle.

Invisible Z decay (LEP), Mono-jet (LHC)
Invisible H decay (LHC/ILC),
Mono-γ (LEP/ILC), Others (LHC)
(electroweakino, multi-jets, etc.)

All these constraints are taken into account in the likelihood analysis based on the Markov Chain Monte Carlo (MultiNest Sampling) method.

WIMP in the S-D mixed patch



Minimal contents: $\mathbf{1_0}$, $\mathbf{2_{1/2}}$, $\mathbf{2_{-1/2}}$ (Anomaly cancel.)

Patch coverage: $|z_S|^2 < 0.95$ & $|z_D|^2 < 0.95$

✔ **Effective lagrangian for the contents is**

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

(Z_2 symmetry is assumed to make WIMP stable.)

✔ **Model parameters are** (3 neutral Majorana + 1 charged Dirac)

M_S : Singlet mass parameter (Corresponding to M_1 in MSSM)

M_D : Doublet mass parameter (" to μ in ")

$y_1 = y\cos\theta$: U-type Yukawa coupling (" to $y\cos\beta$ in ")

$y_2 = y\sin\theta$: D-type Yukawa coupling (" to $y\sin\beta$ in ")

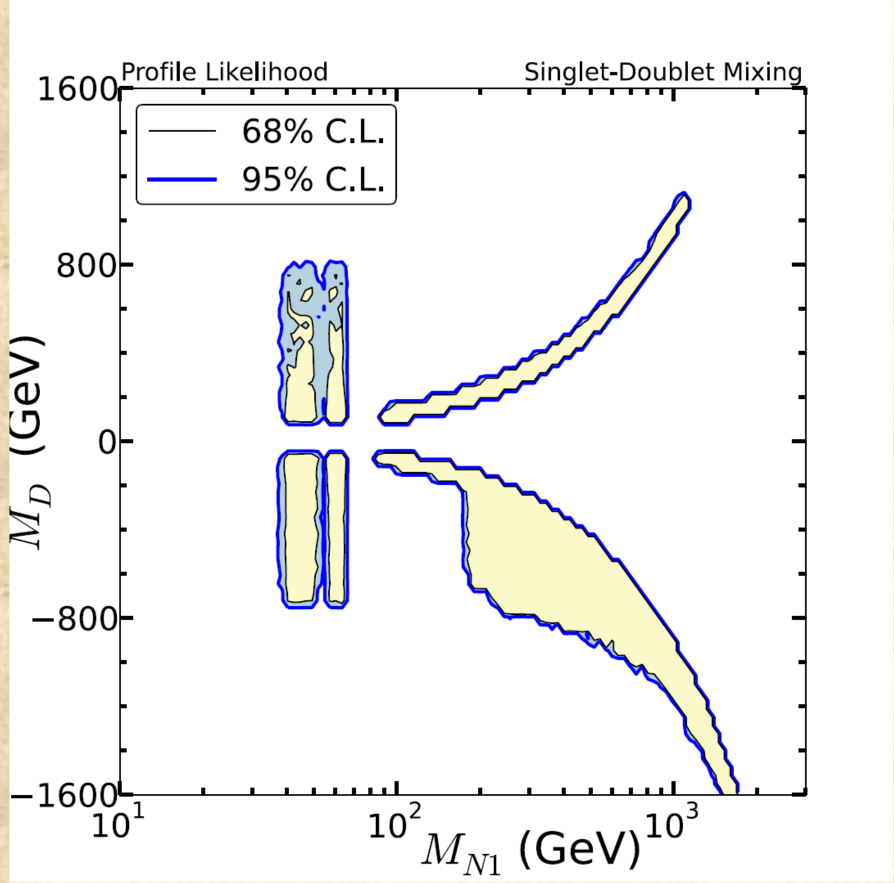
with y being $y = g' / 2^{1/2}$

✔ **Model parameter space is**

$$M_S \geqslant 0,\ M_D,\ y \geqslant 0 \text{ and } \pi/4 \leqslant \theta \leqslant \pi/2\ (\tan\theta \geqslant 1 \text{ or } 0 \leqslant \cot\theta \leqslant 1)$$

CP invariance is assumed. $y \leqq 1$ is also assumed in our analysis!

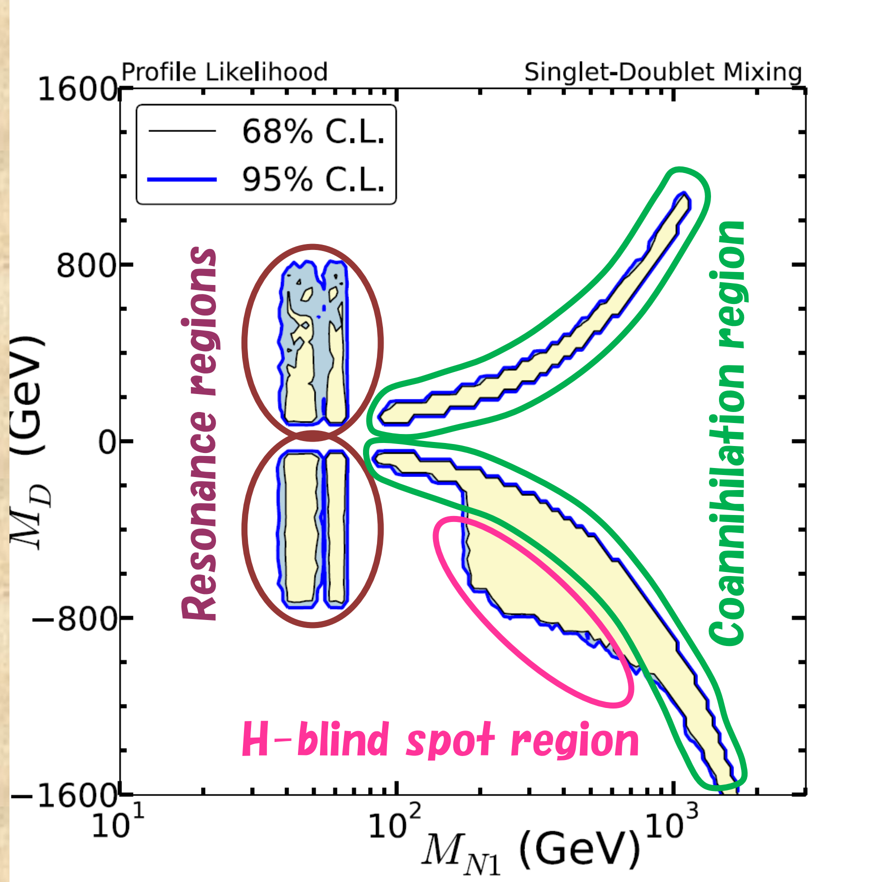
Present status in the S-D mixed patch



Present status

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

Present status in the S-D mixed patch



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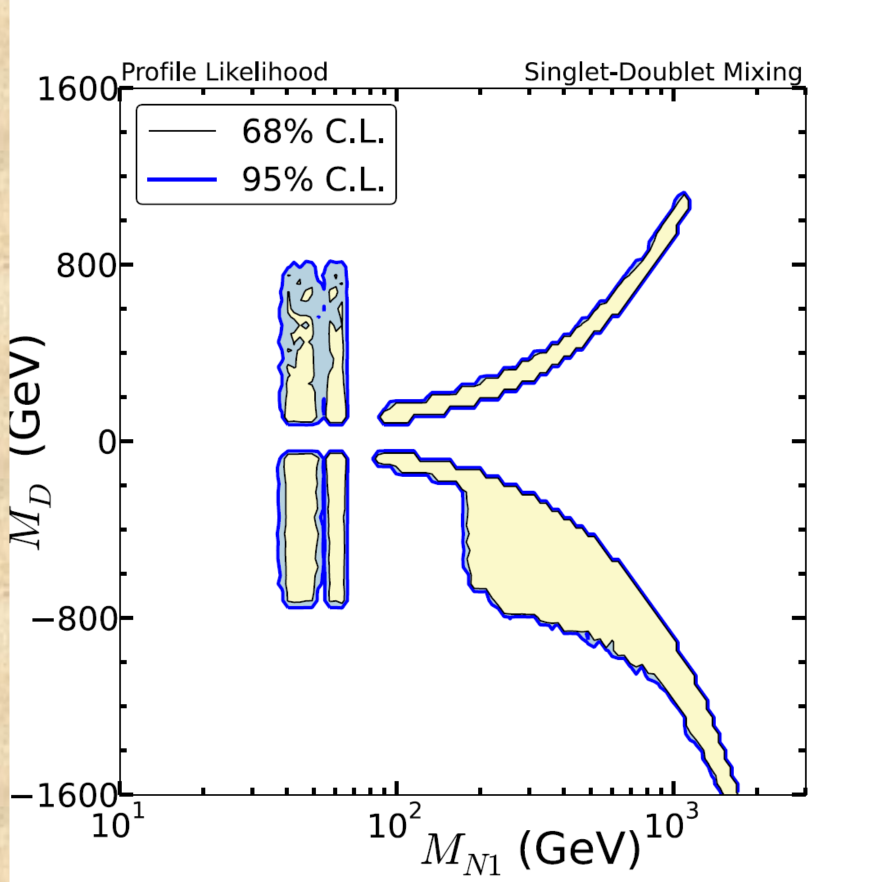
Future prospects in the S-D mixed patch



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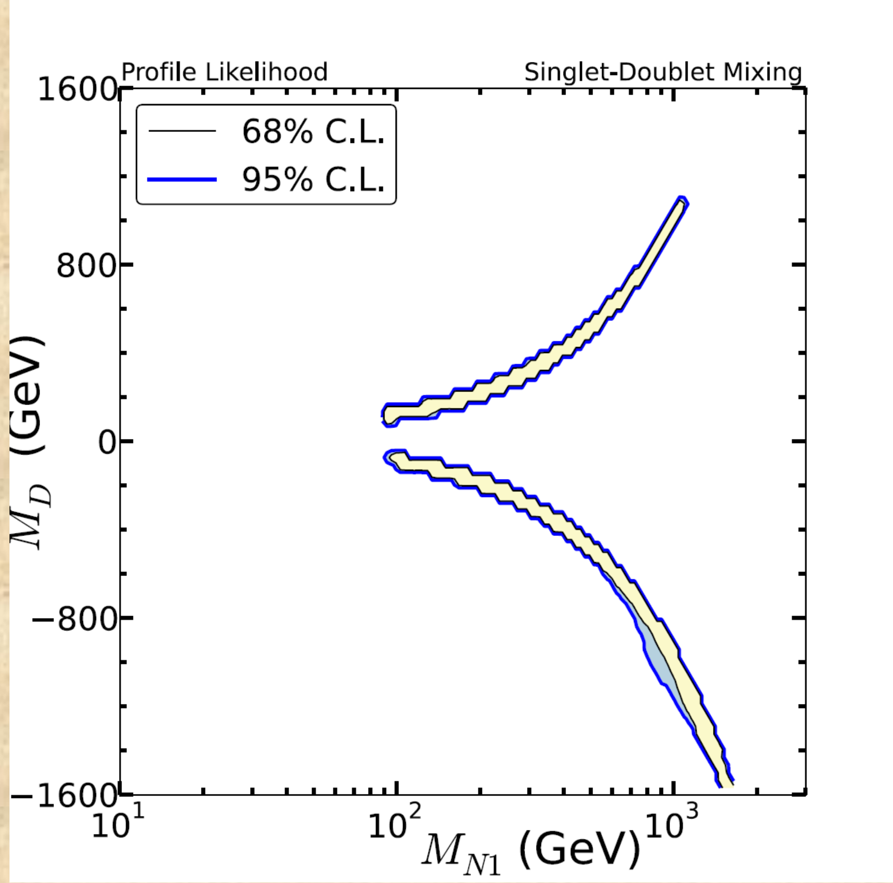

After XENON1T

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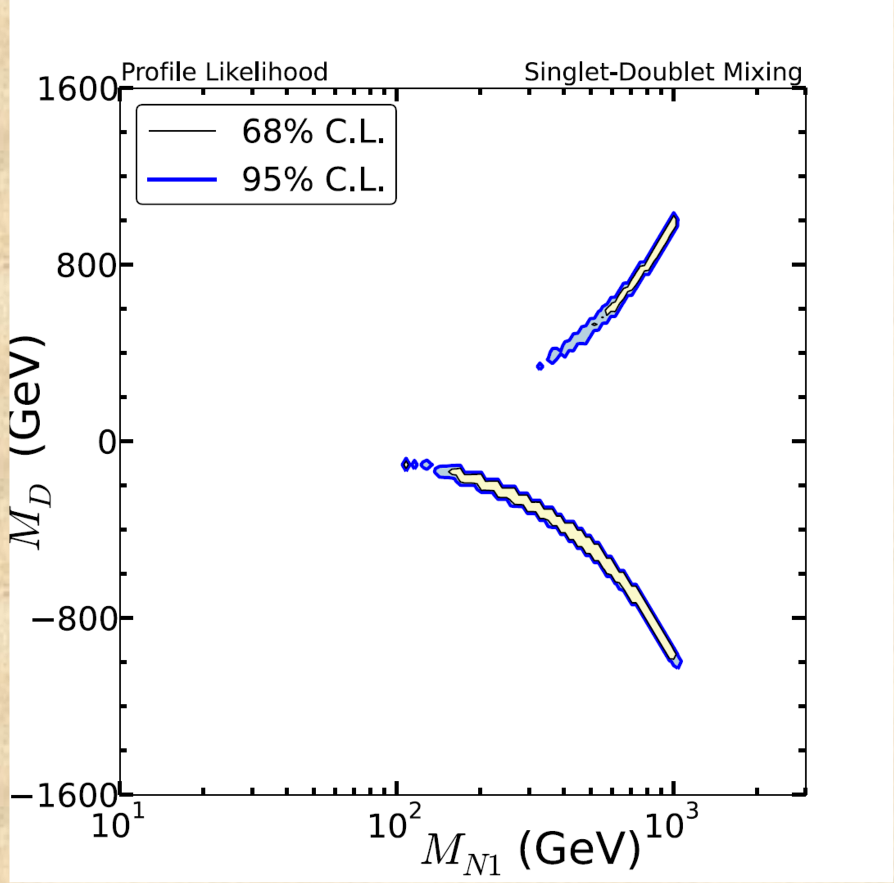
Future prospects in the S-D mixed patch



After LZ/PICO250

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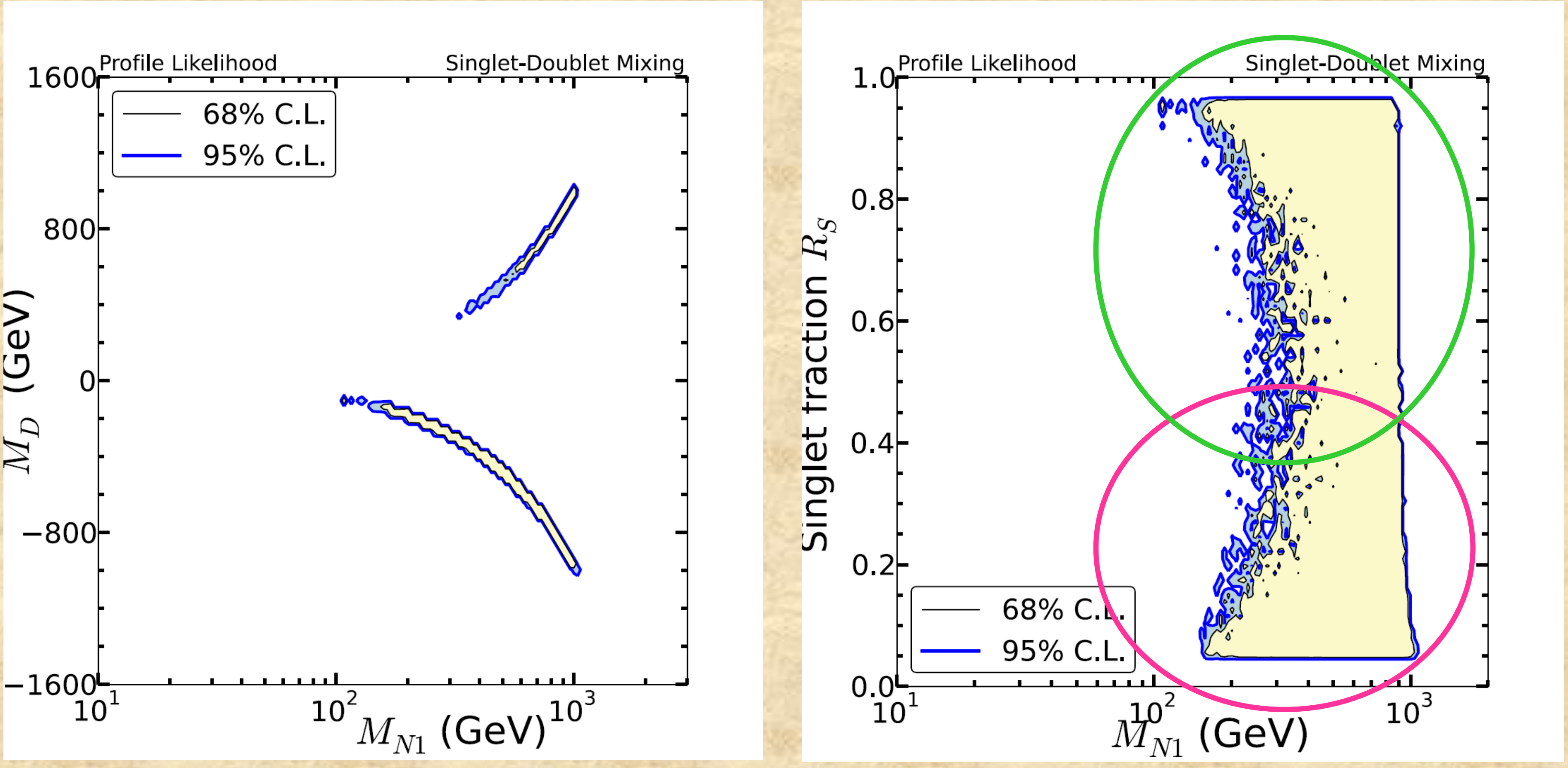
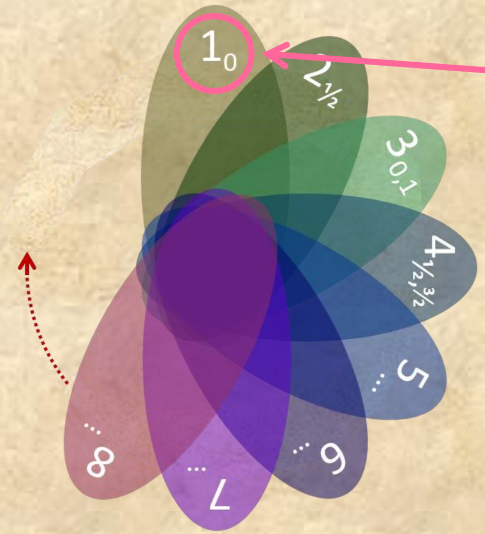


Only coannihilation regions survives after O(1)ton level experiments!

When R_s is suppressed, indirect DM detections will be very important.
(Controlling systematic errors of the experiments will be mandatory.)

When R_s is not suppressed, future e^+e^- colliders will be very important.
(To cover entire region, TeV-scale lepton colliders will be mandatory.)

WIMP in the Singlet-like patch



Minimal content: 1_0 (One Majorana fermion)

Singlet WIMP cannot interact with SM particles by alone because of the Z_2 symmetry making the WIMP stable, so that some other new particles must be introduced. Assuming those are heavy enough, we introduce higher dim. operators. Small mixing effects are automatically involved i.

Patch coverage: $1 - O(v^2/\Lambda^2) < |z_S|^2 < 1$

(v is the VEV of Higgs field.)

✔ Effective lagrangian for the content is

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

✔ Many model parameters, so that we impose simplifying assumptions:

- Common suppression scale ($\Lambda_i = \Lambda$) with $\Lambda >$ [$3\,m_{DM}$, 300 GeV].
- All coupling constants c_i are smaller than one.
- Flavor blindness ($[c_f]_{ij} = c_f$) and CP invariance ($c_P = 0$).

WIMP in the Singlet-like patch

The EFT description is of limited applicability to discuss WIMP signals at energetic colliders, so that we consider a general simplified model which reproduces the EFT at large intermediate particle mass limits.

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

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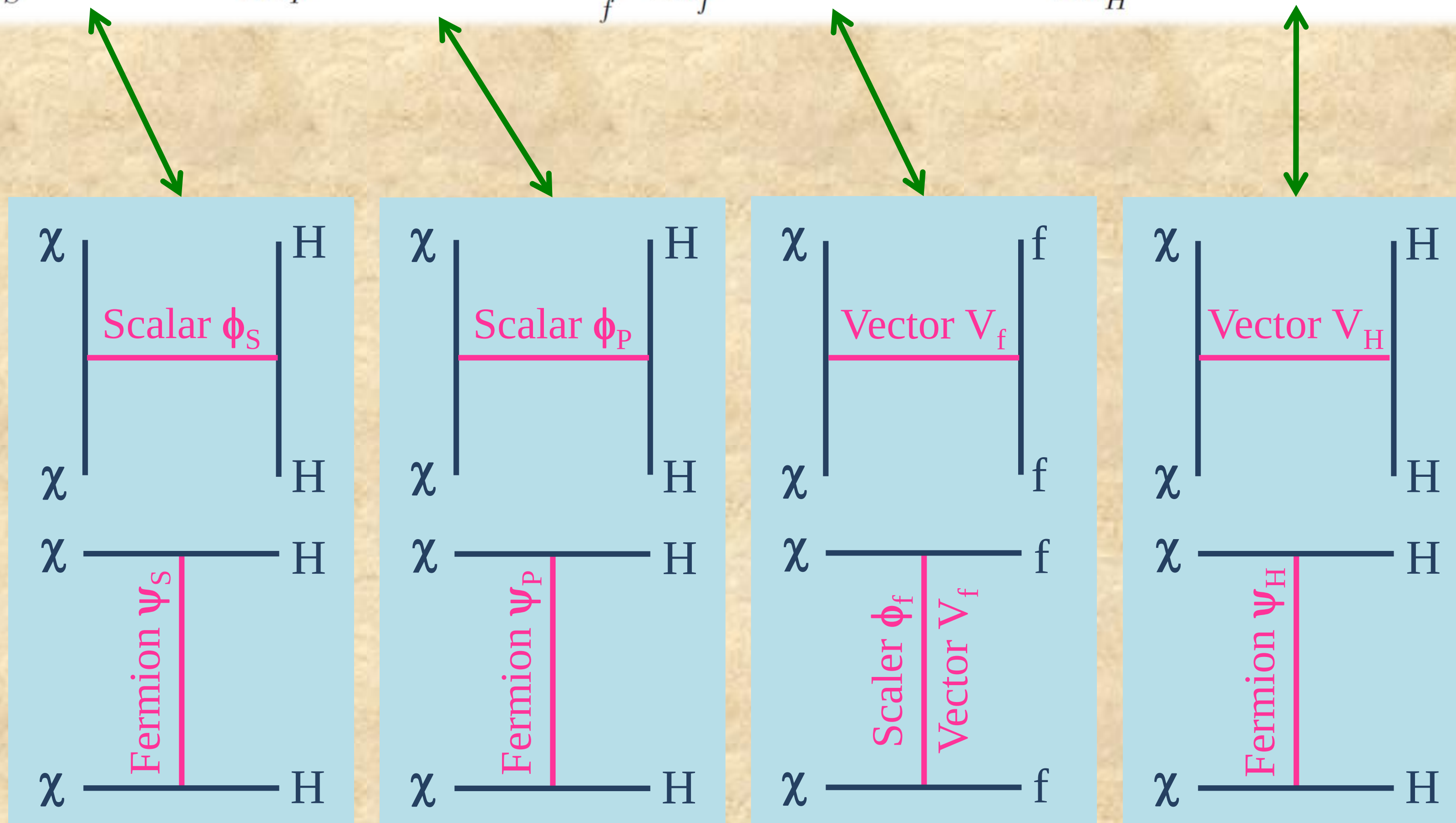

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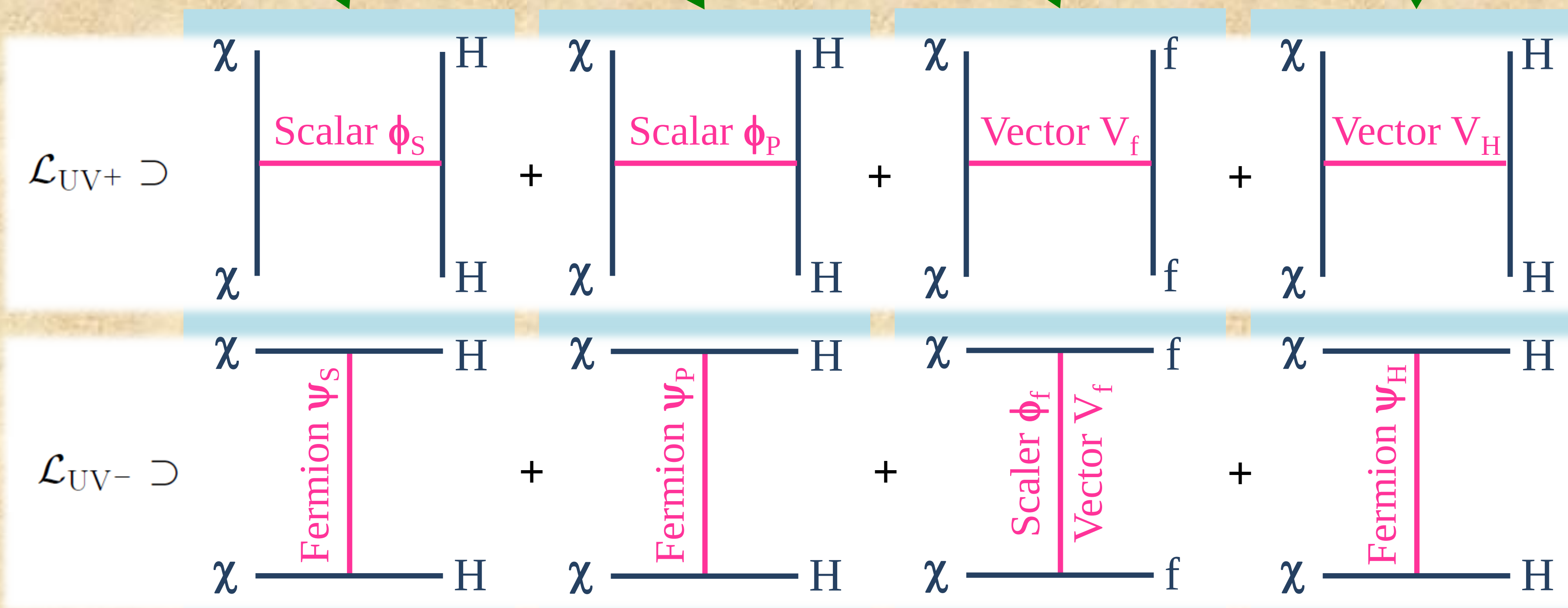
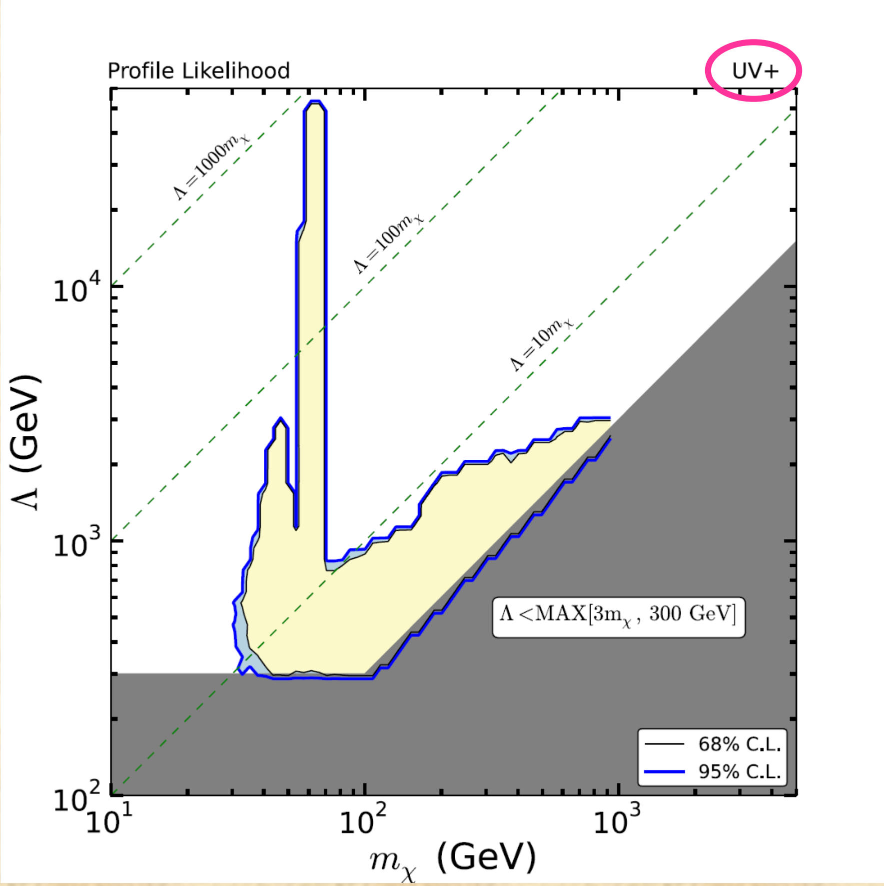
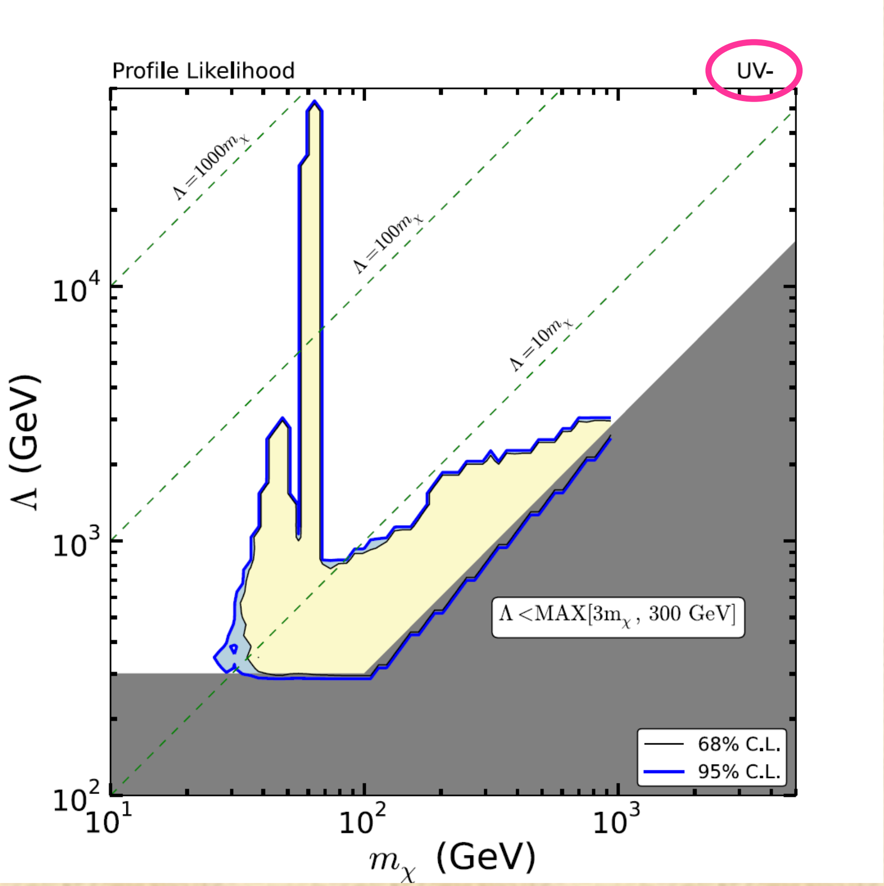
Using these simplified models to take collider constraints into account!



Present status in the Singlet-like patch





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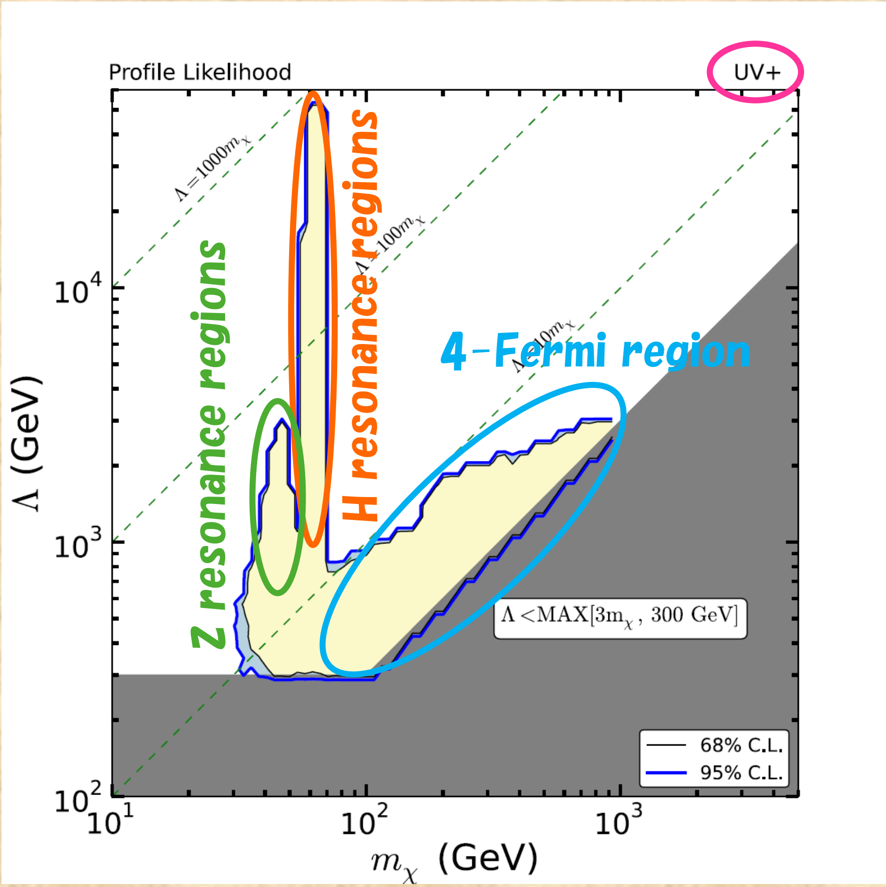

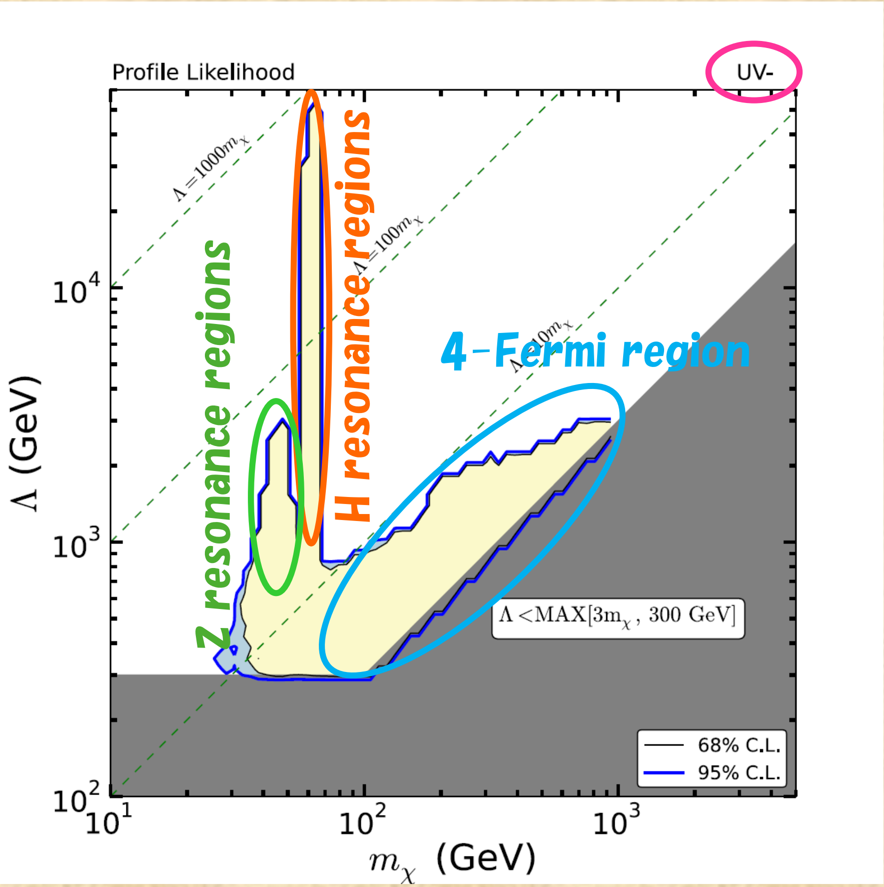

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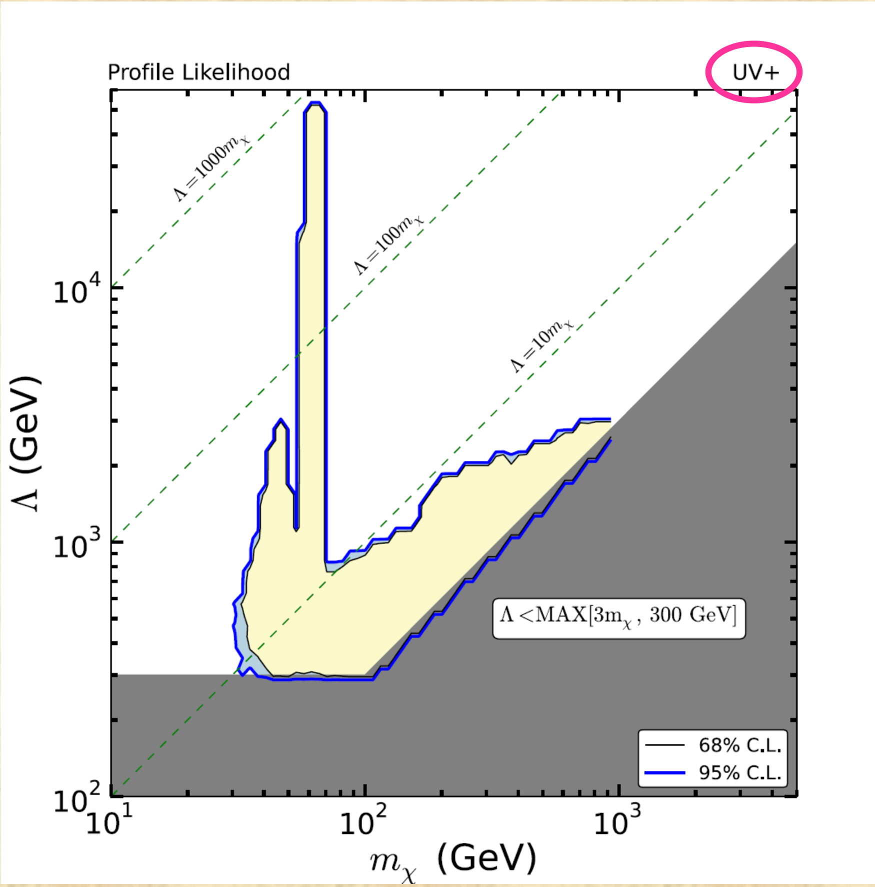
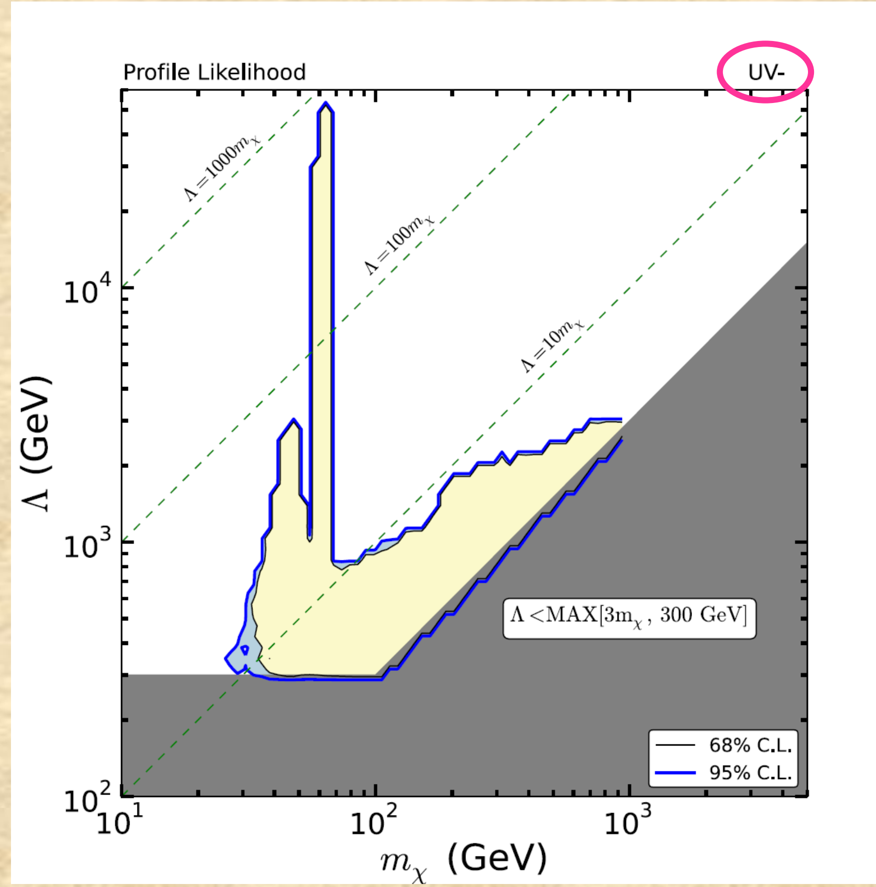
Future prospects in the Singlet-like patch





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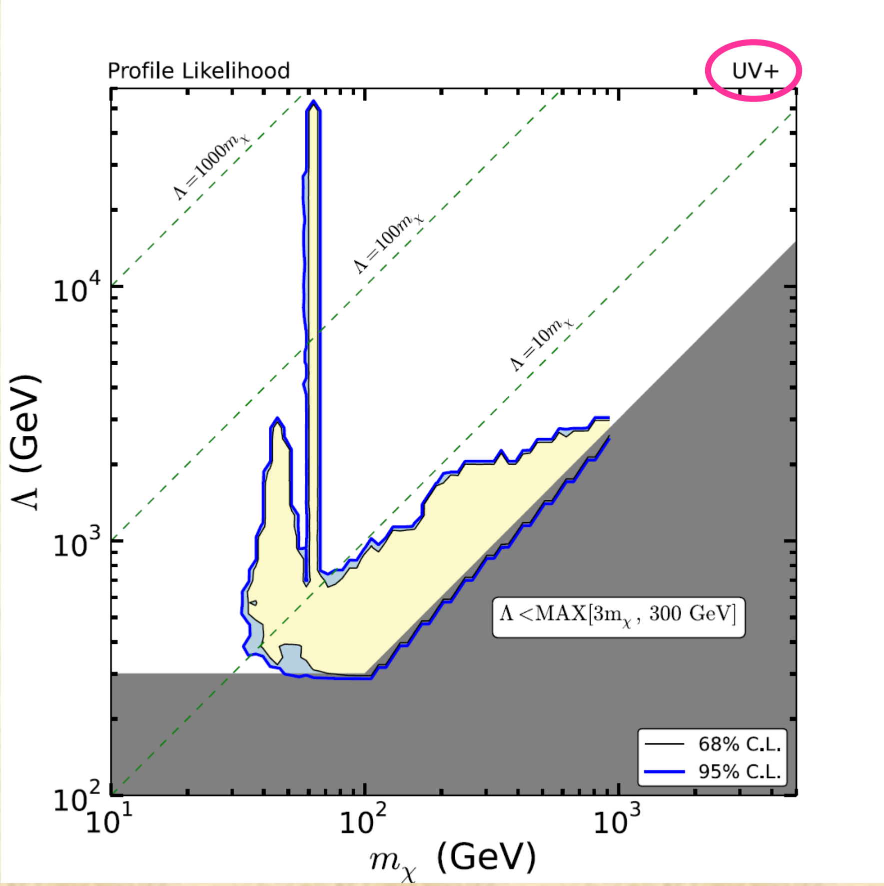

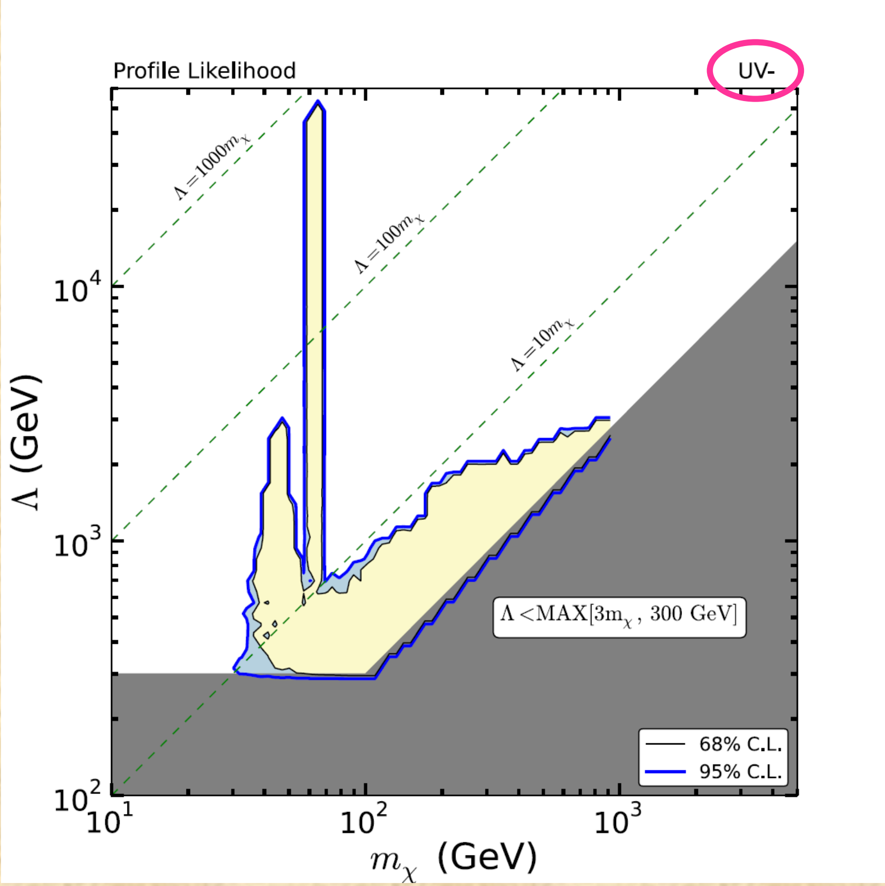

After XENON1T

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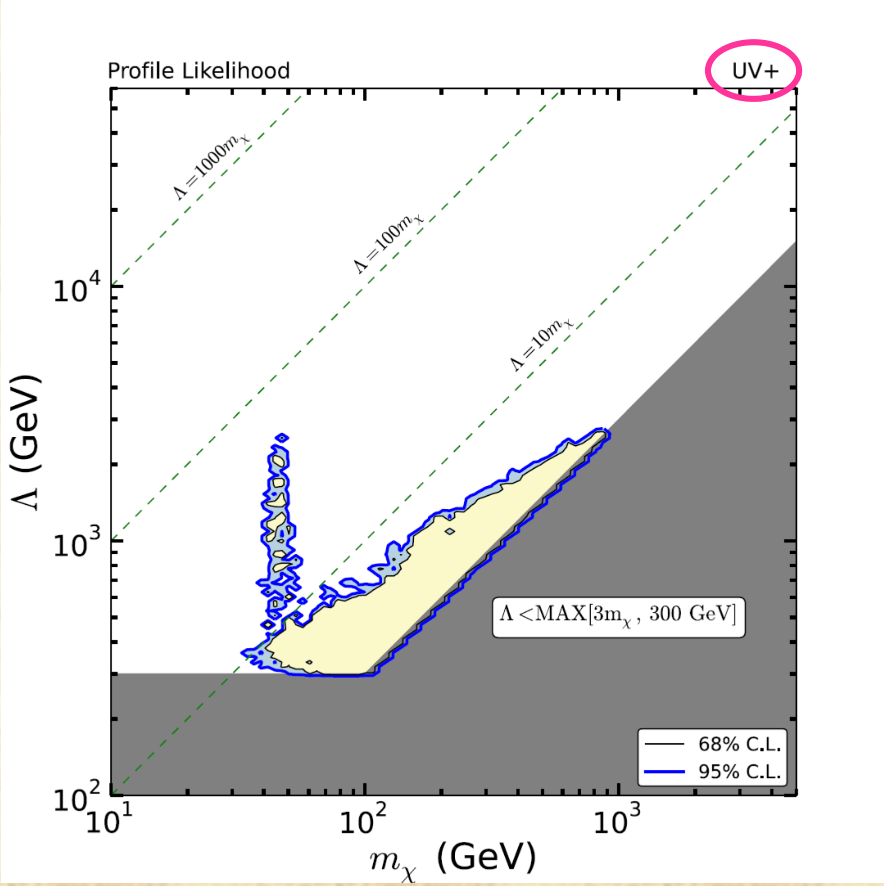

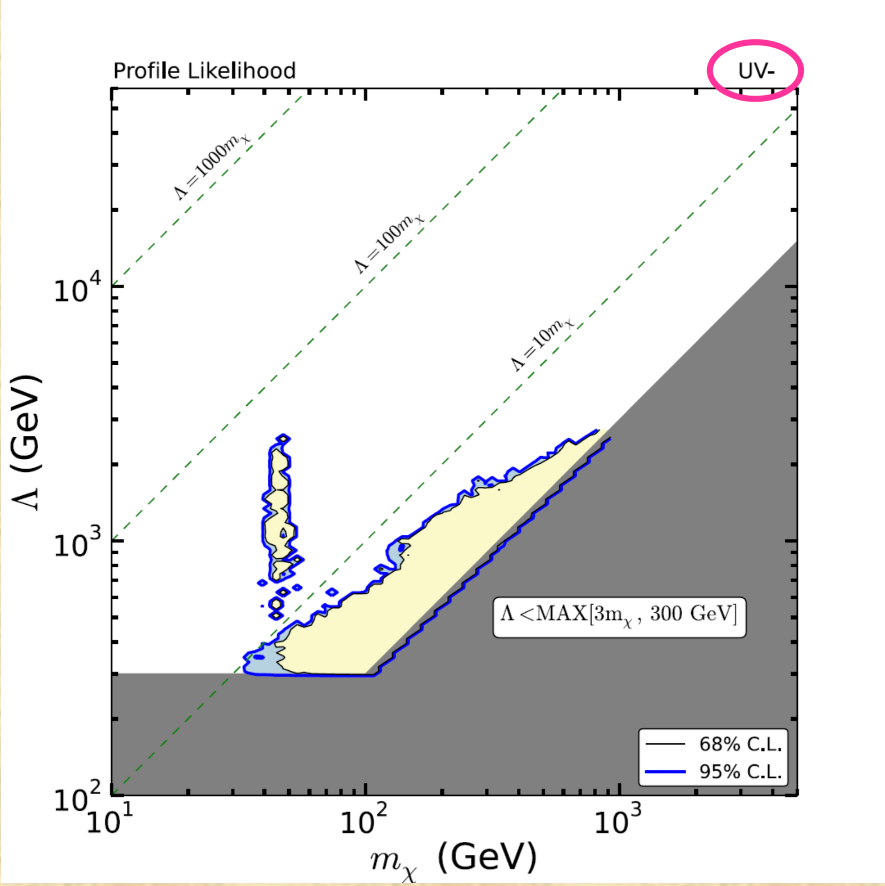

After LZ/PICO250

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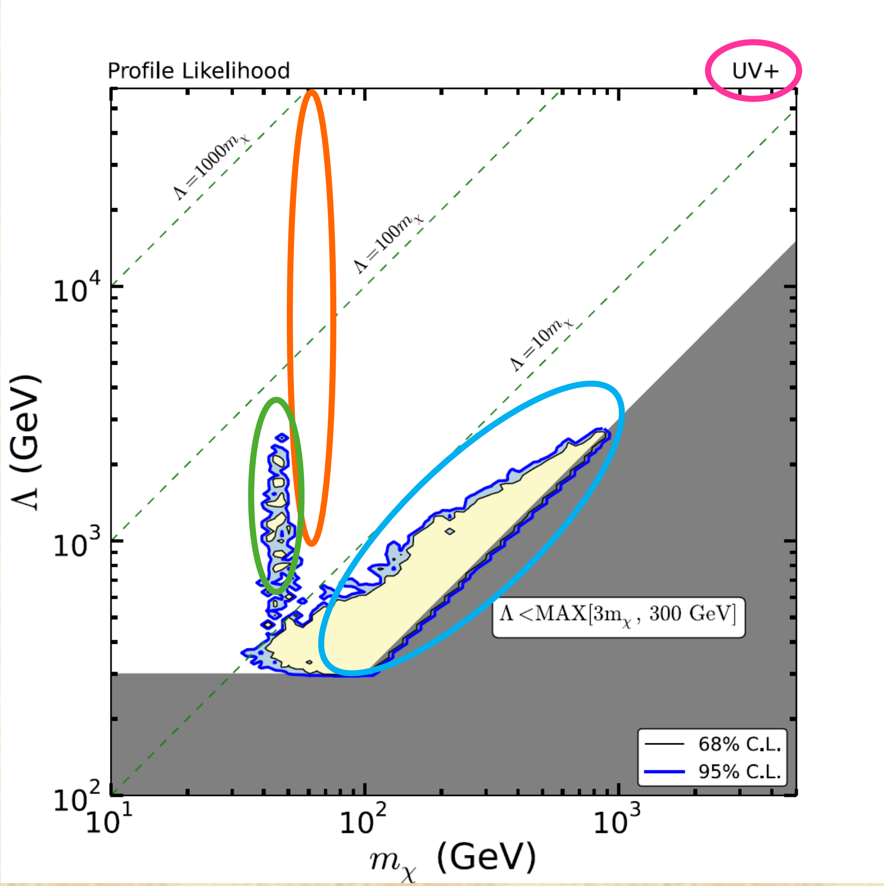
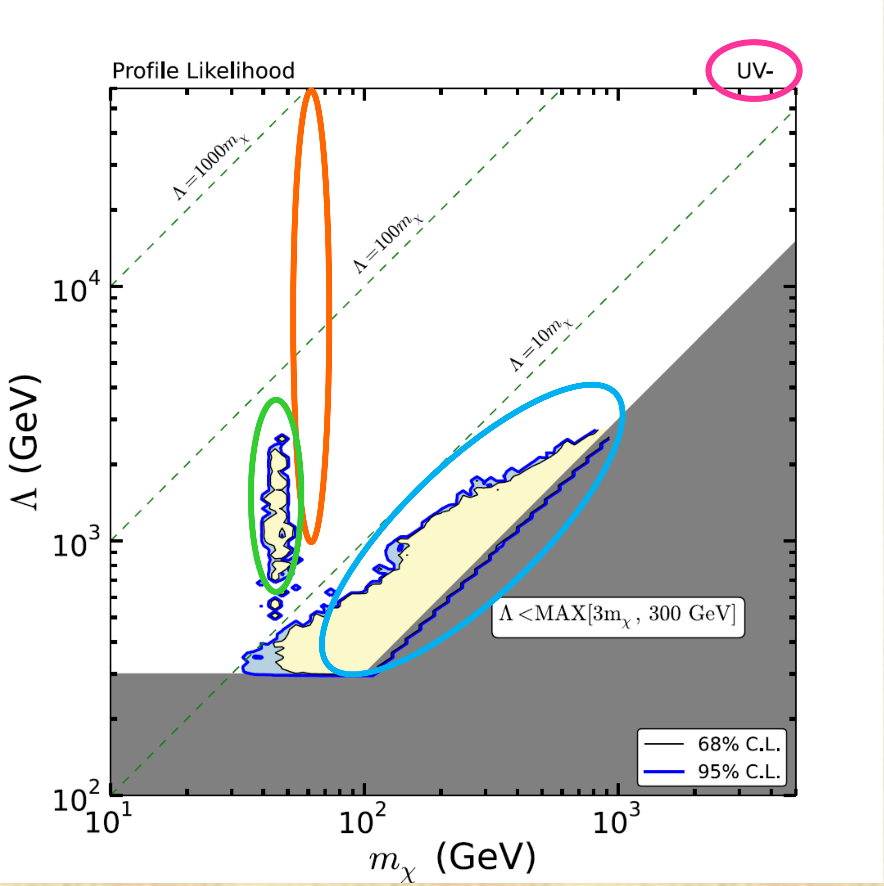
Future prospects in the Singlet-like patch



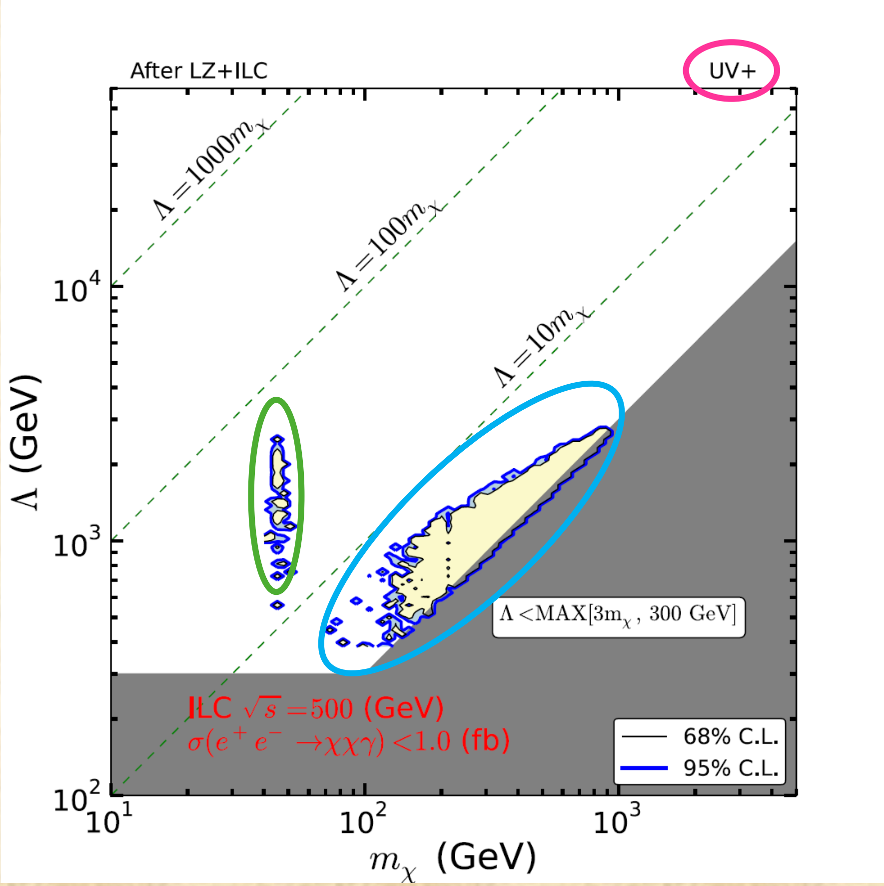


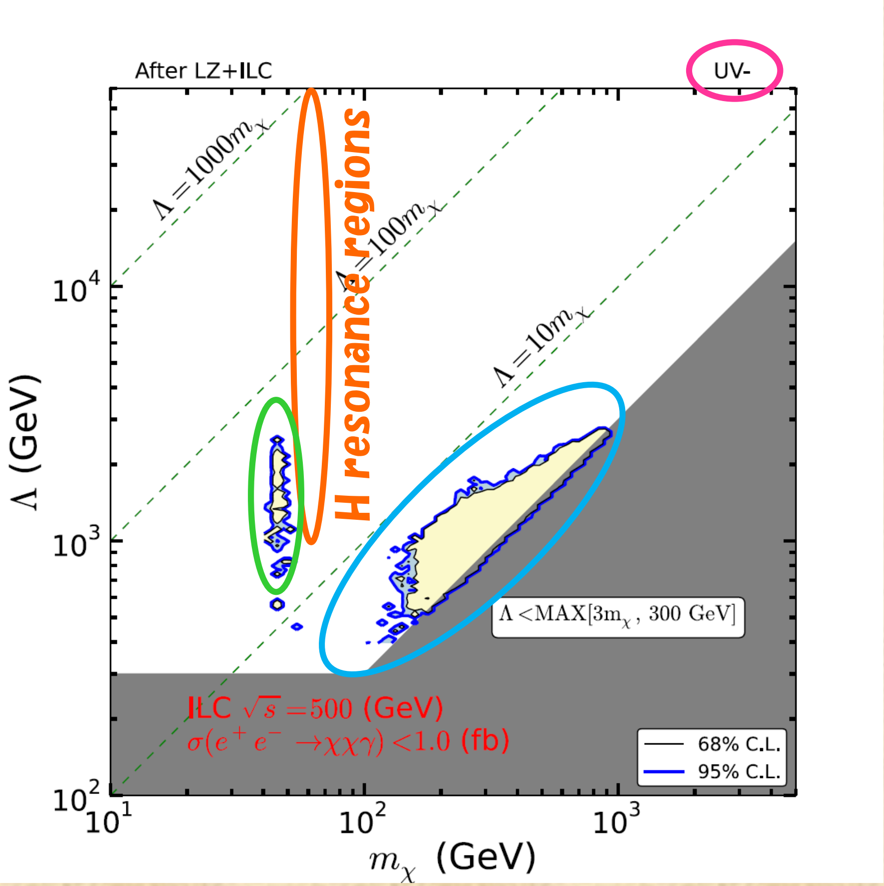
O(10)ton level direct detection cover the H resonance region entirely.

The Z resonance region will be widely covered by SD direct detections.
(Remaining part could be covered by luminous lepton colliders, Giga-Z.)

The 4-Fermi region has already been restricted to be below $\Lambda < 10 m_{DM}$.
(Hadron and Lepton colliders can efficiently cover the remaining part.)

Future prospects in the Singlet-like patch





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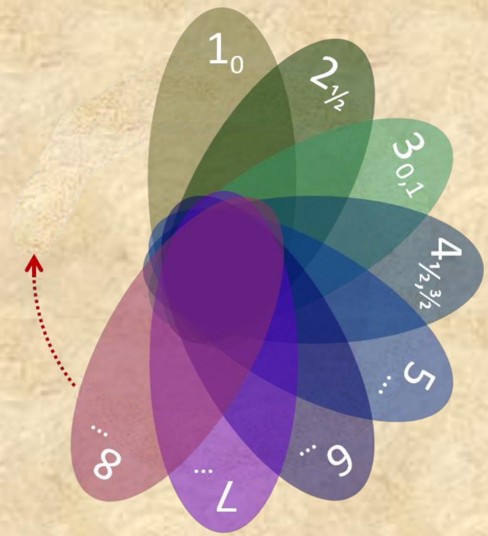
Summary

✓ The era of serious WIMP searches has begun!

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

We have proposed a framework in order to answer these questions without relying on any specific new physics models beyond the SM.

✓ Direct dark matter detections & LHC are playing important roles!



We have focused on a fermionic WIMPs in the S-D mixed & the Singlet-like patches.

- In the S-D mixed patch, the coannihilation region remains after LZ & LHC experiments.
- In the single-like patch, the Z resonance & 4-Fermi (lepton) regions remains after LZ & LHC when a mediator particle is heavy.
- Further studies are needed for the singlet-like WIMP with a light mediator particle.

✓ Experiment probing other WIMP interactions (ILC) will be important.

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.