Current Status and Future Prospects of the WIMP Paradigm

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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, [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.

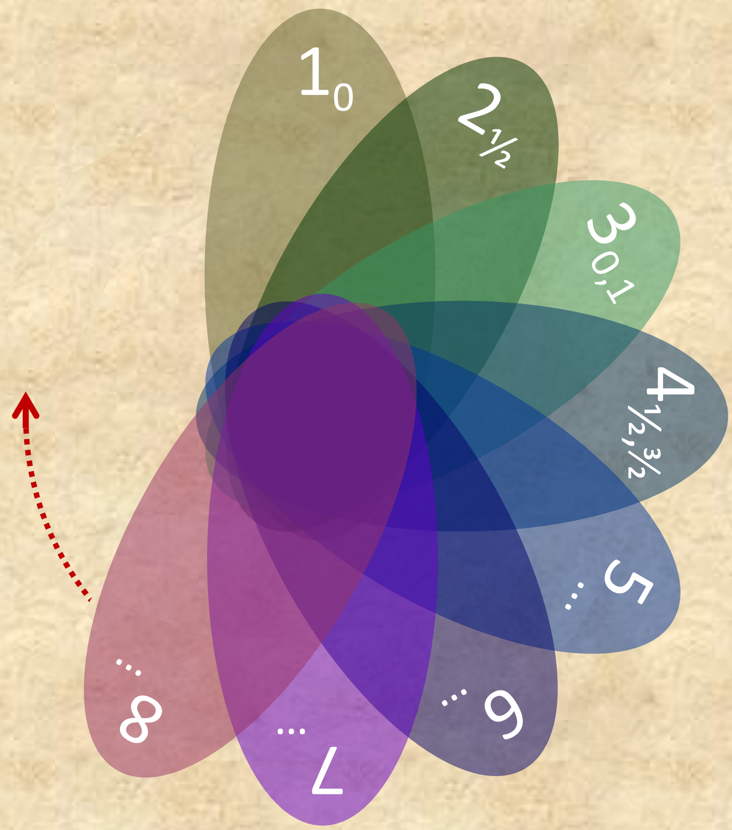
Direct dark matter detections play an important role!

Current@O(100)kg → Near future@O(1)ton → Future@O(10)ton

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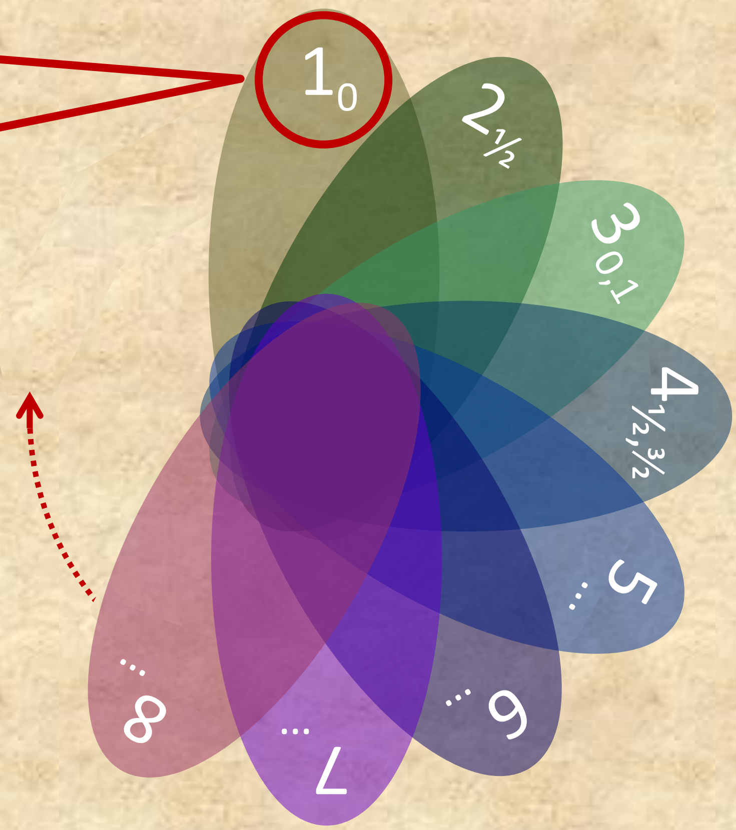
Singlet-like Patch
e.g.
Bino-like in SUSY
KK photon in UED



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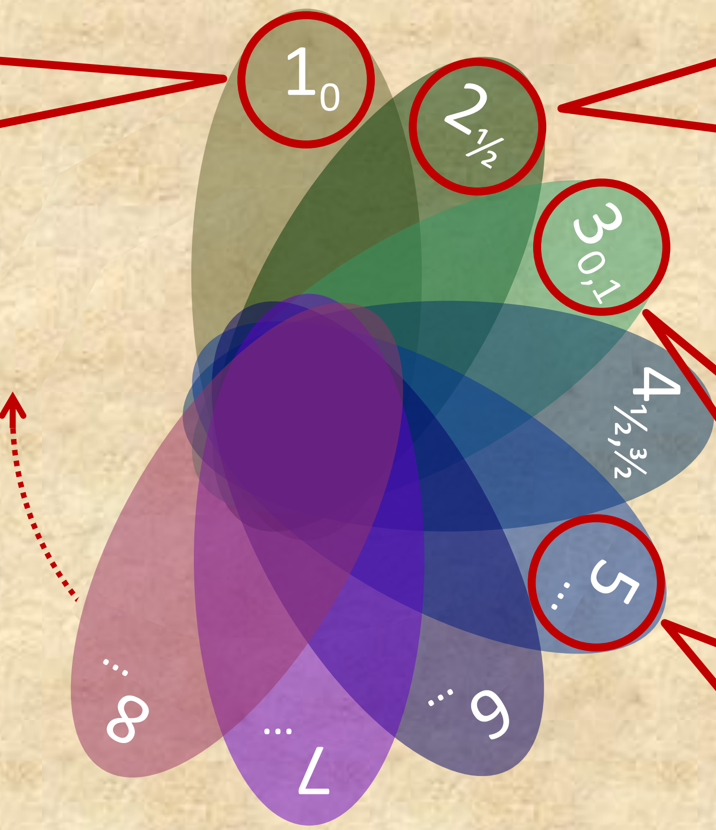
Doublet-like Patch
e.g.
Higgsino-like in SUSY
Inert Higgs in 2HDM



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

Quintet-like Patch
e.g.
Minimal dark matter

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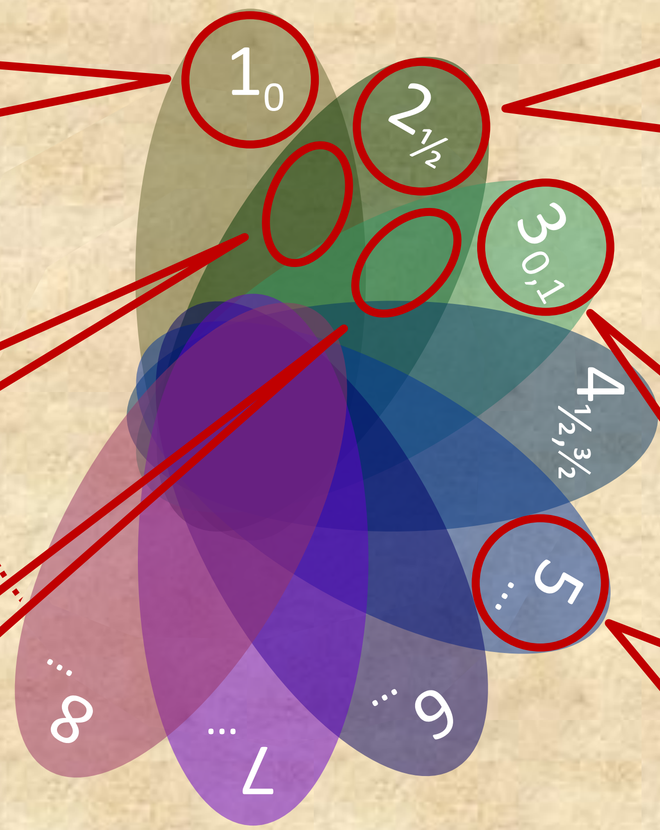
KK photon in UED

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

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



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Higgsino-like in SUSY
Inert Higgs in 2HDM

Triplet-like Patch
e.g.
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Quintet-like Patch
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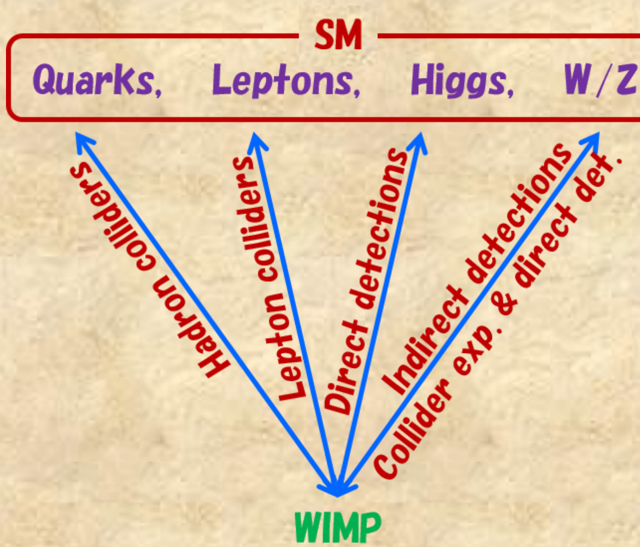
Basic strategy

1. *Constructing the effective Lagrangian with the particle contents as minimal as possible in each patch. It should include all relevant interactions that can be responsible for the freeze-out phenom.*
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 or the Singlet-like patch!!!

Constraints on the WIMP parameter space

✔ Relic abundance limit:

Thermal + non-thermal productions gives the DM abundance today.

$$\Omega_{WIMP} h^2 \leqq 0.1198$$

✔ Direct DM detection constraints:

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
(with assuming no signals are detected.)

✔ Indirect DM detection constraints:

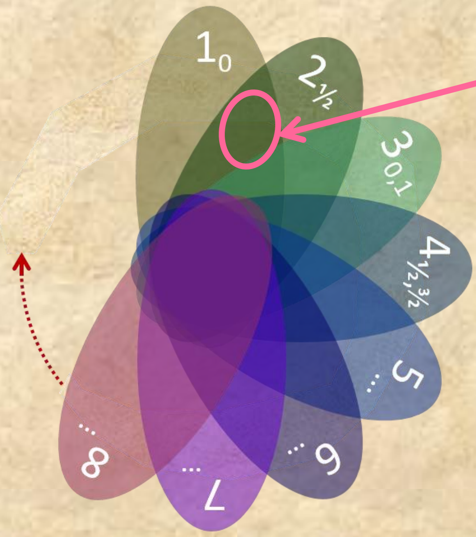
PLANCK (constraining DM annihilation at recombination era)
for other indirect detections have yet large systematic uncertainties.

✔ Constraints from collider experiments:

Invisible Z decay width @ LEP, Mono-j search @ LHC
Invisible H decay width @ LHC/ILC, Mono-g search @ LEP/ILC
Other searches @ 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: 1_0, $2_{½}$, $2_{-½}$ (Anomaly cancel.)

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

✔ **Effective lagrangian for the contents is**

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

(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 M_2	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	")

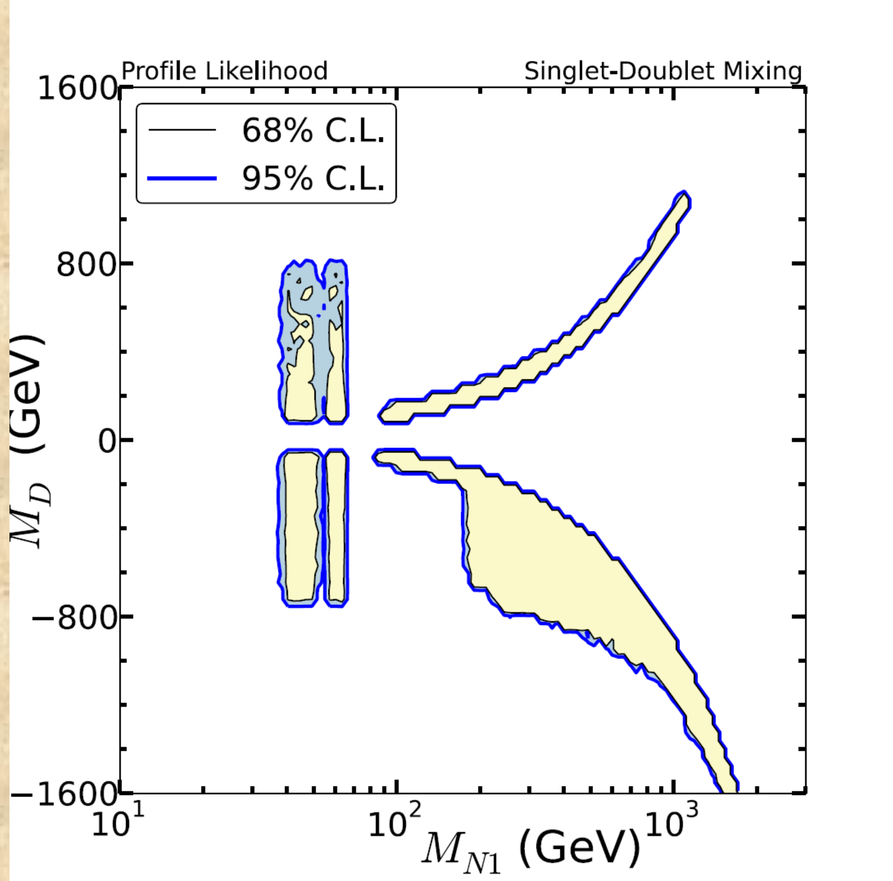
with y being y = g' / $2^{½}$

✔ **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 ≦ 1 is also assumed in our analysis!

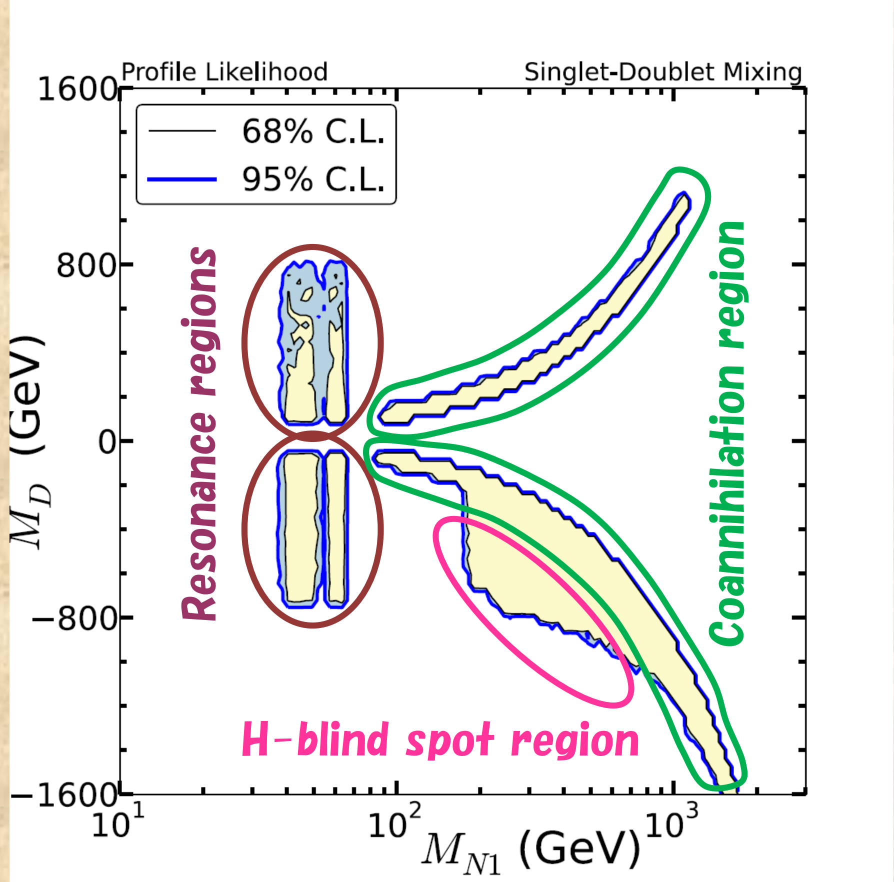
Present status in the S-D mixed patch



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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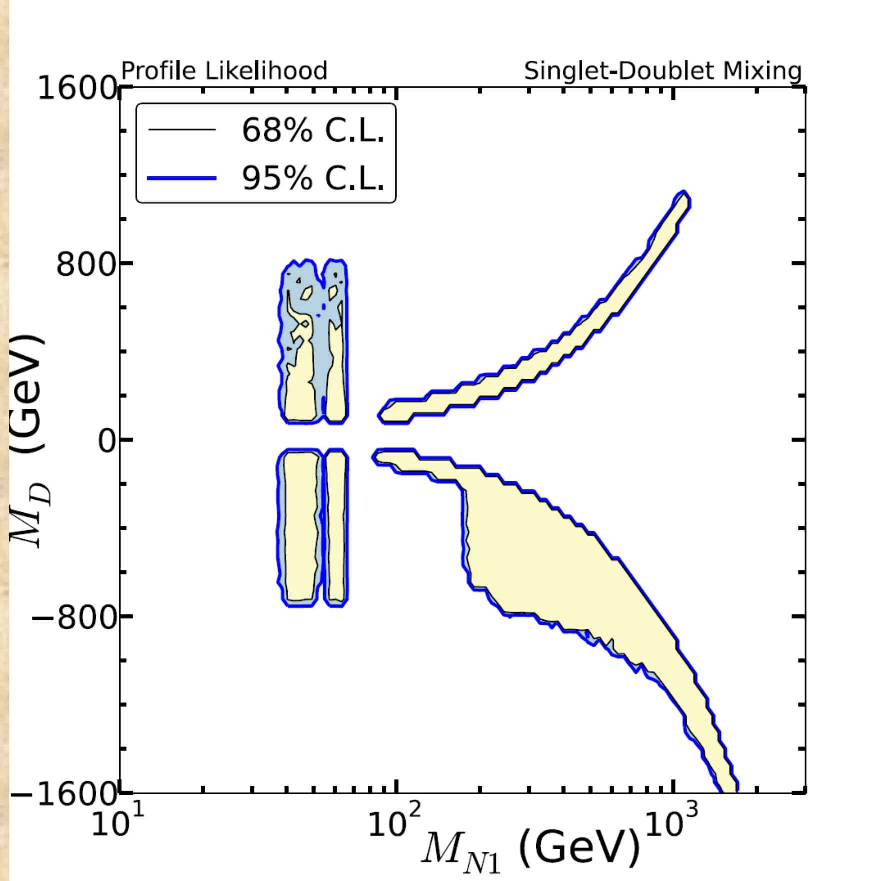
Future prospects in the S-D mixed patch



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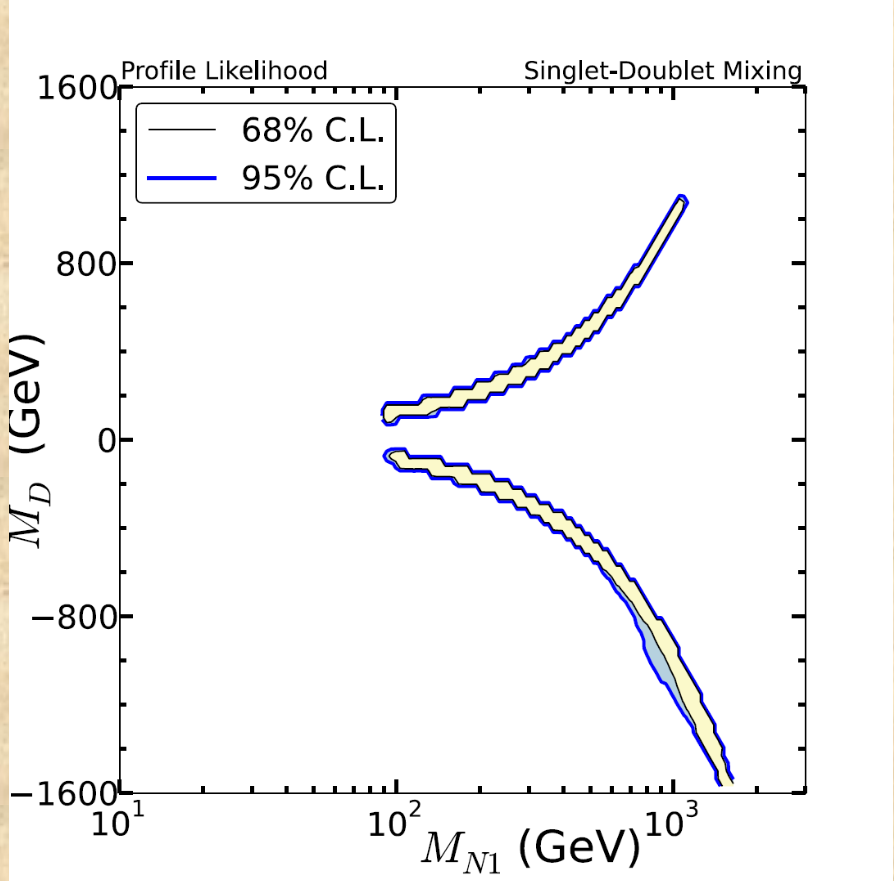
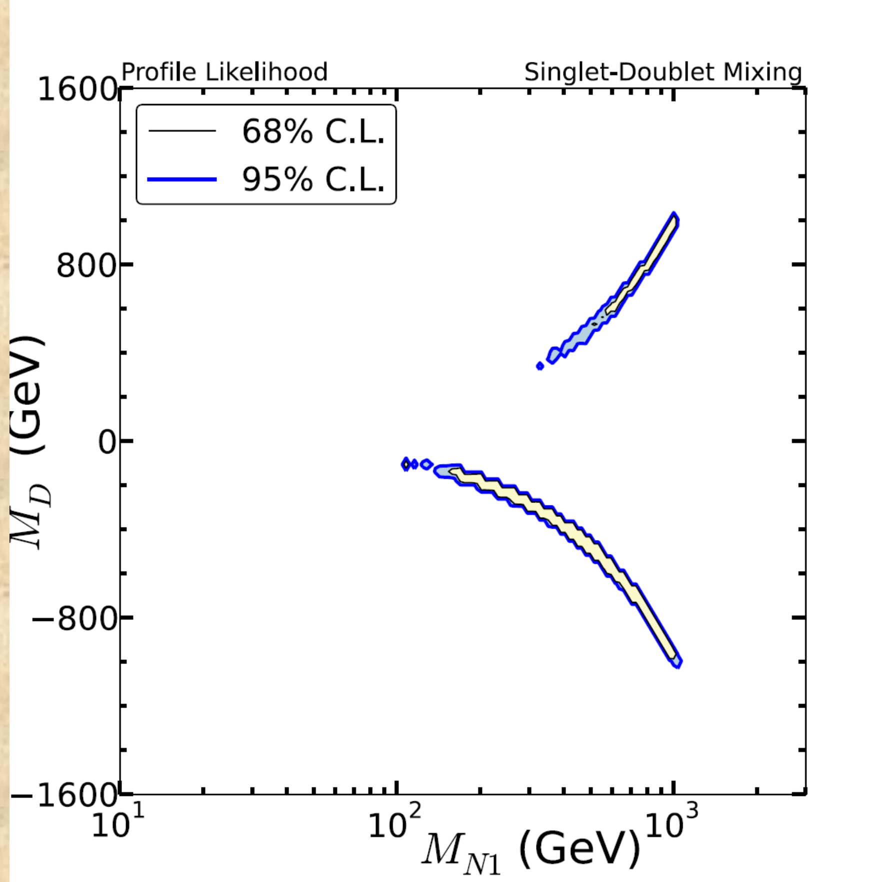


After XENON1T

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

Future prospects in the S-D mixed patch



After LZ/PICO250

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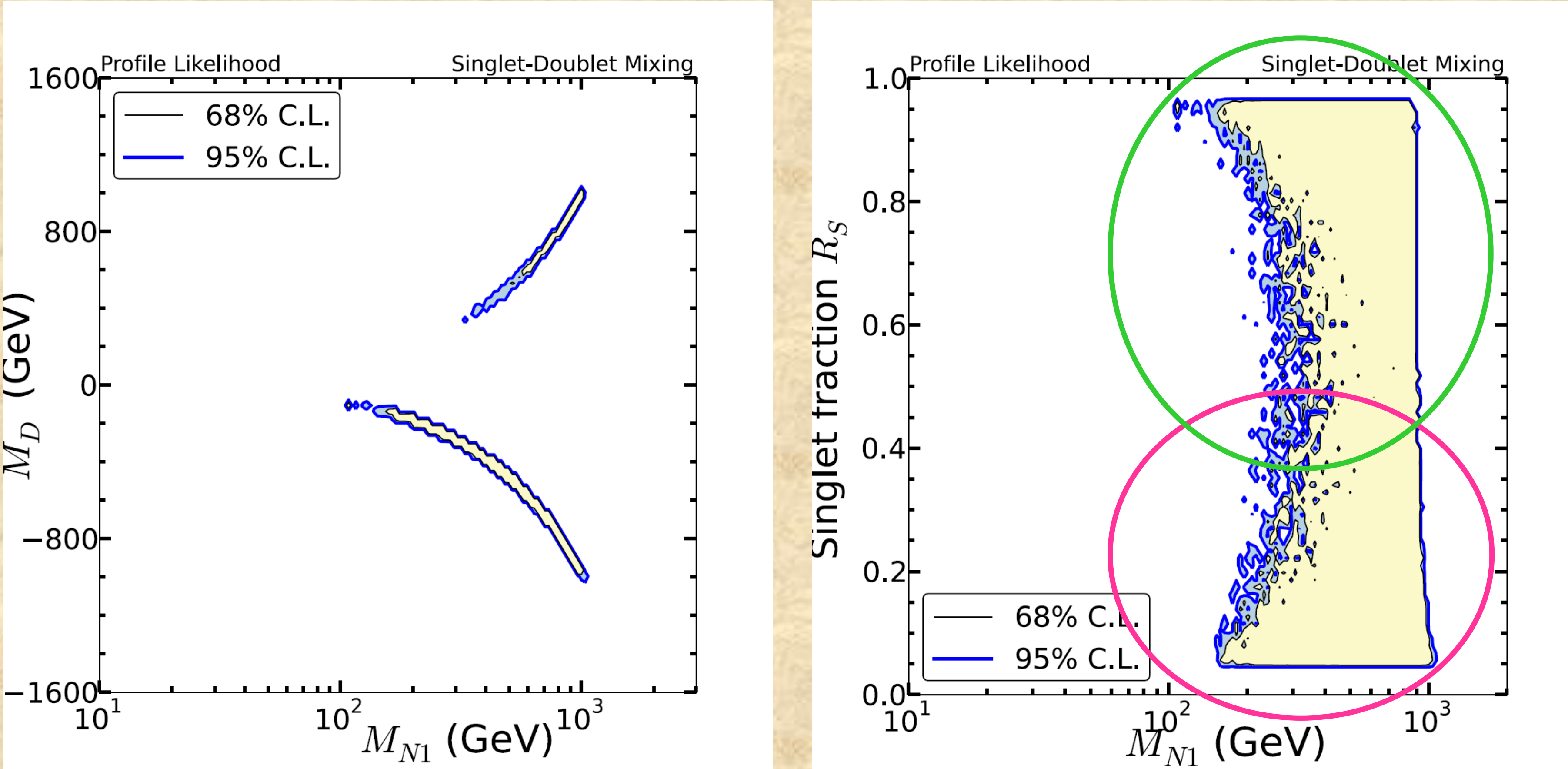
Future prospects in the S-D mixed patch

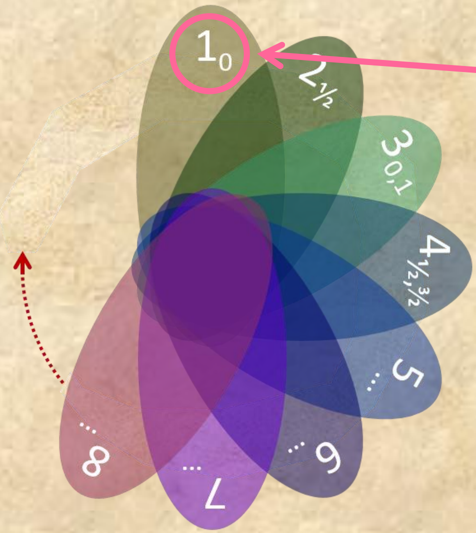


Only coannihilation regions survives after O(1)top level experiments!

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)

In order to describe not only a pure singlet WIMP but also a singlet-like WIMP, we introduce higher dimensional operators. Small mixing effects (e.g. between 1_0 & $2_{1/2}$) are involved in the operators.

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

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

There is no renormalizable interaction between WIMP and SM particles, because of the Z_2 symmetry which is assumed to make the WIMP stable.

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

- Common suppression scale ($\Lambda_i = \Lambda$) with $\Lambda > [3\,m_{DM}, 300\,\mathrm{GeV}]$.
- 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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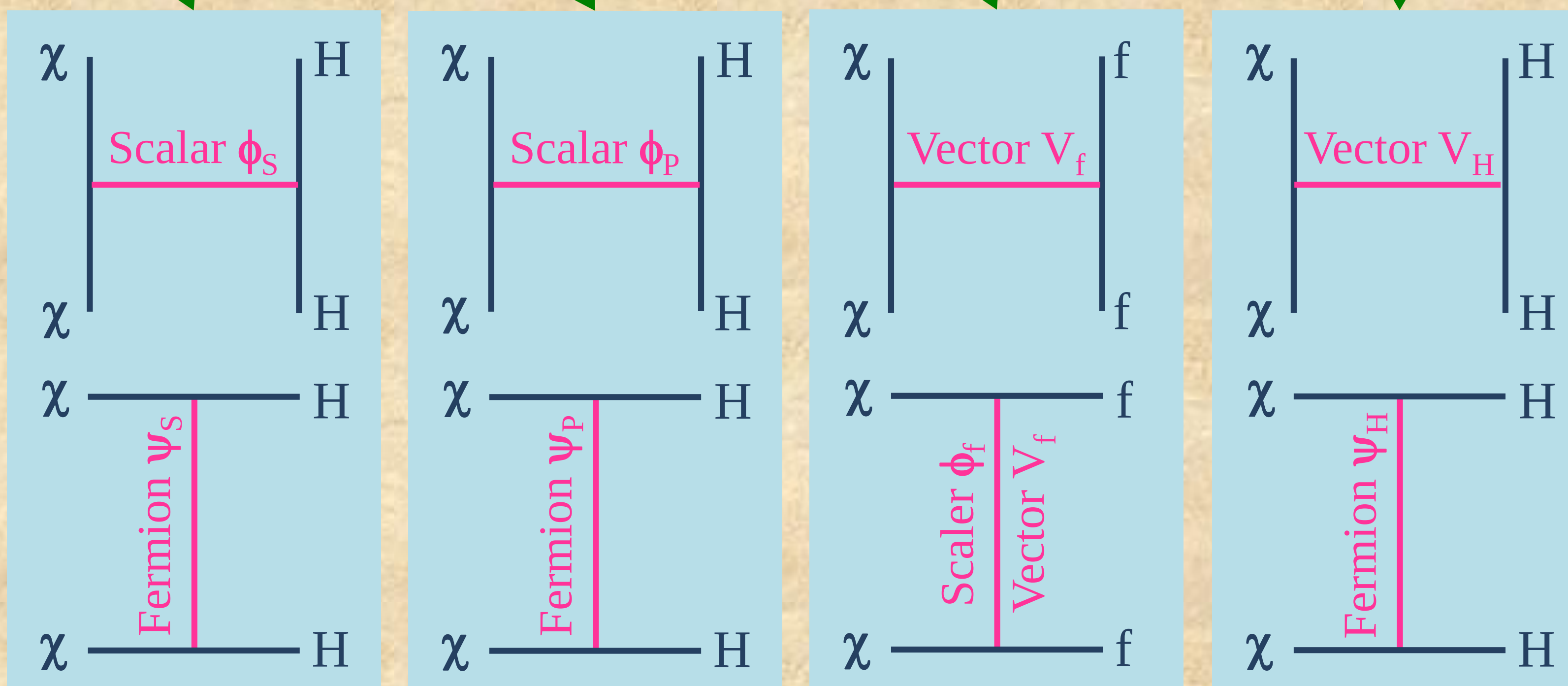

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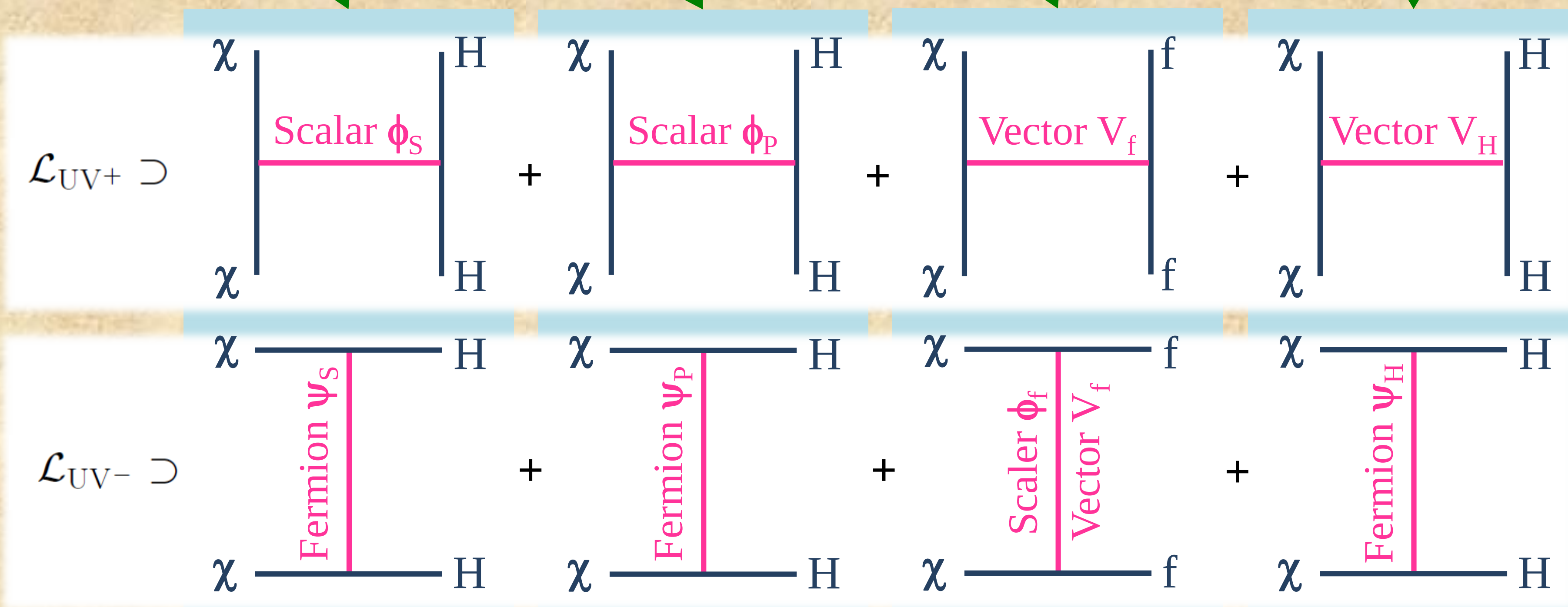
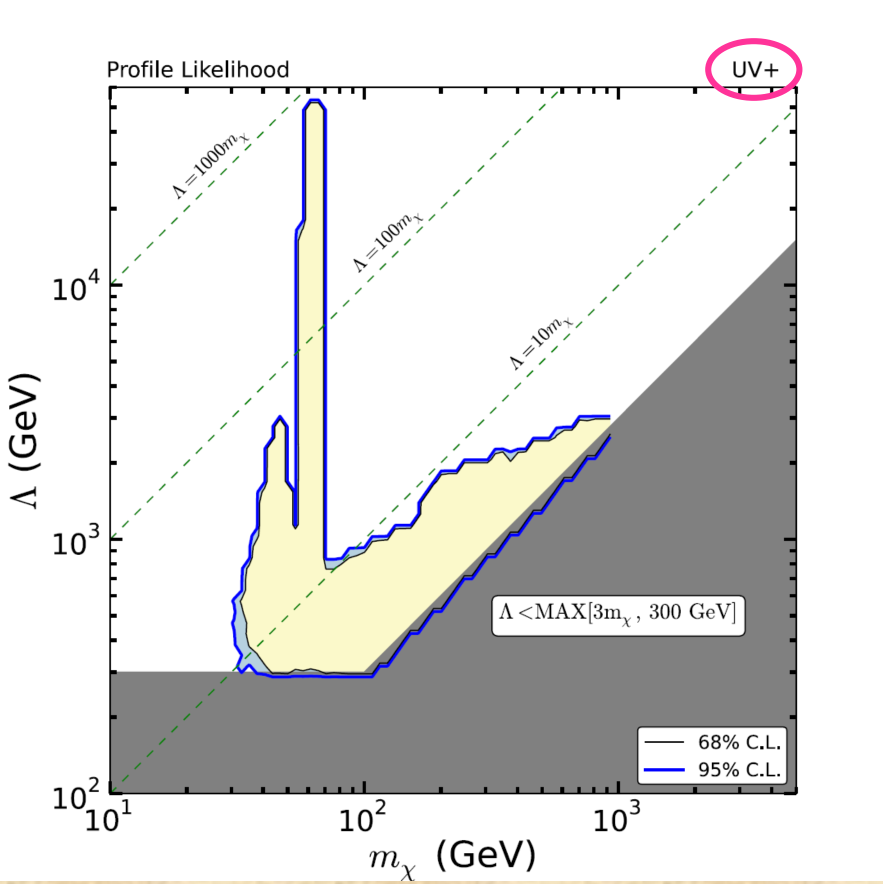
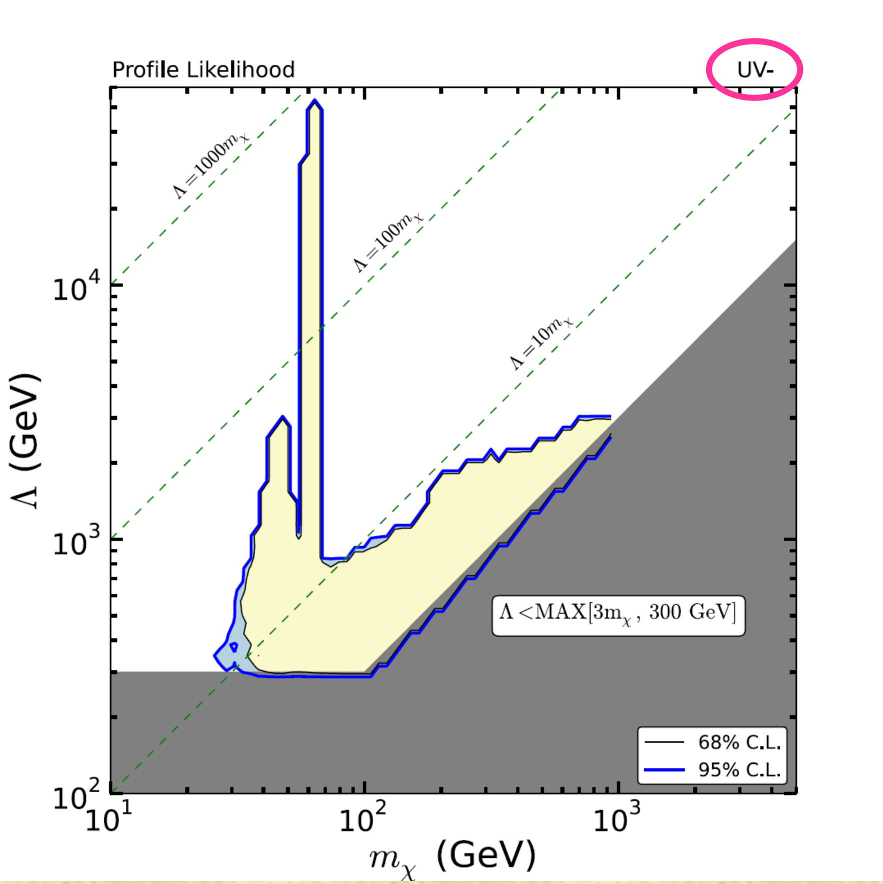
Using these simplified models to take collider constraints into account!



Present status in the Singlet-like patch





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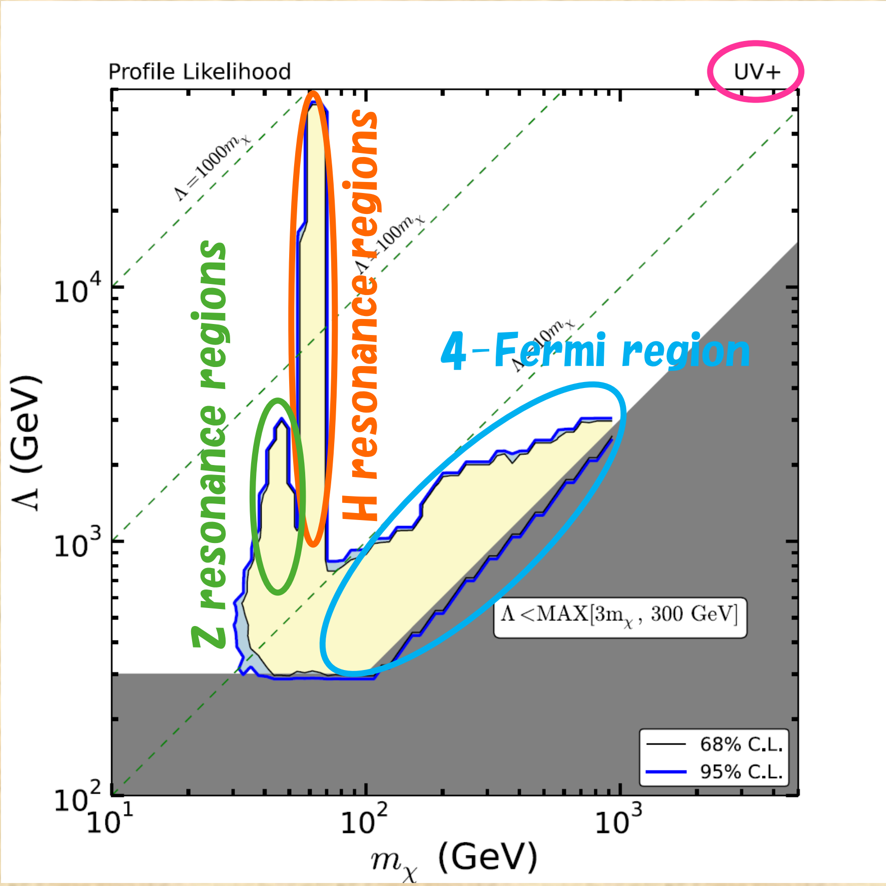

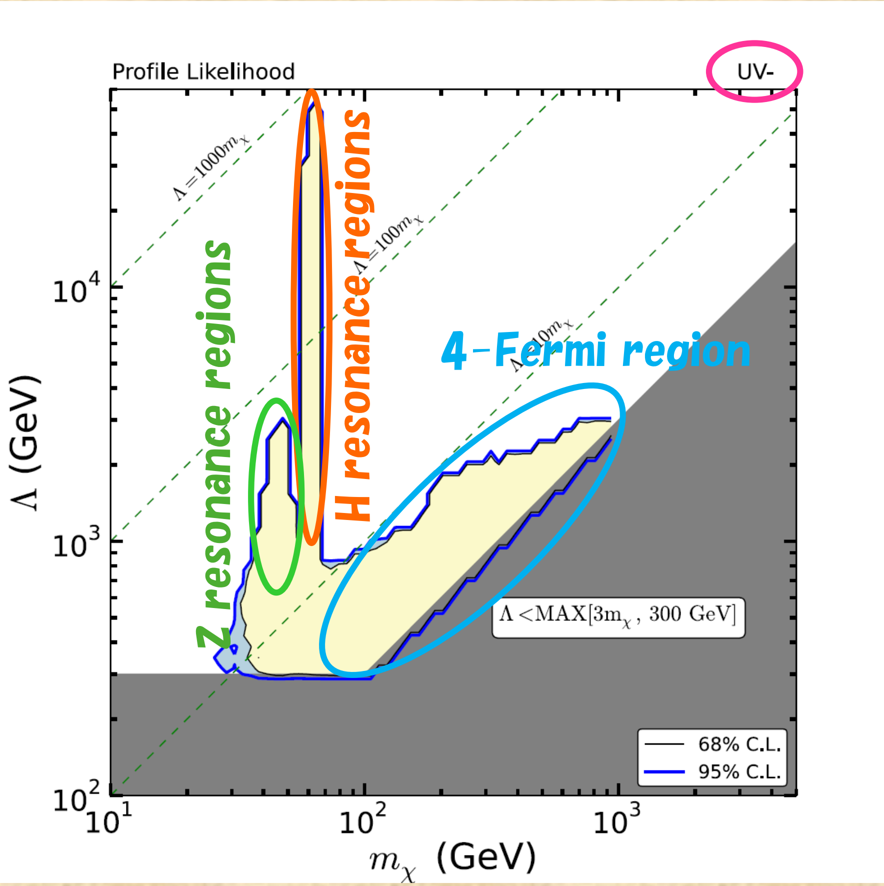

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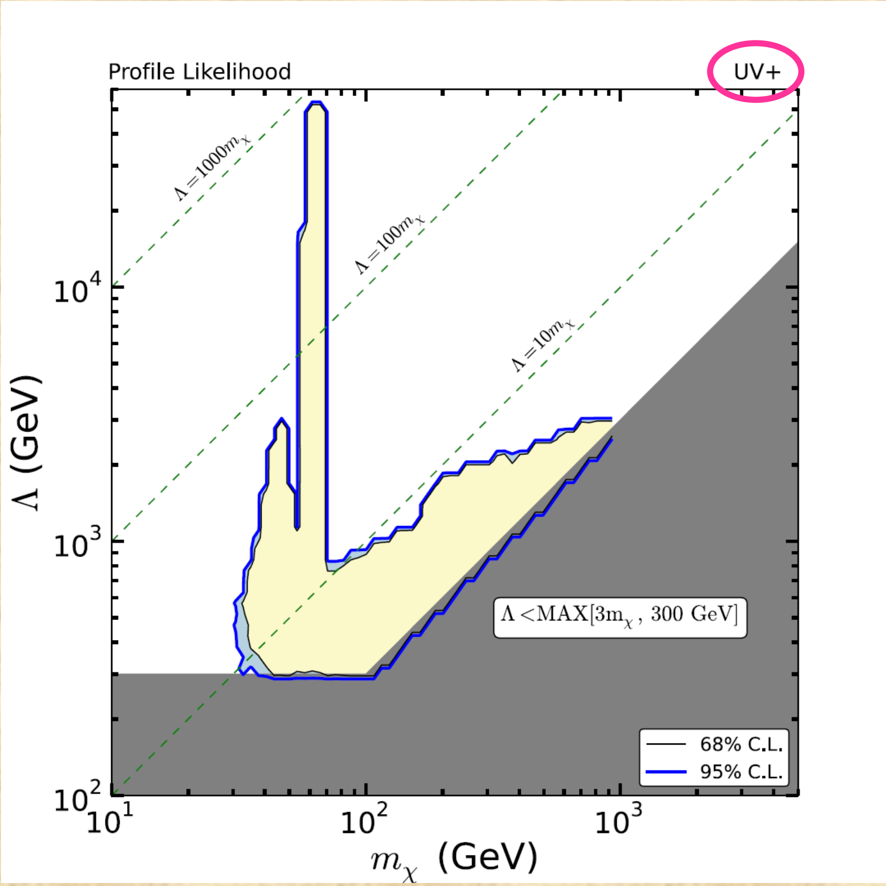
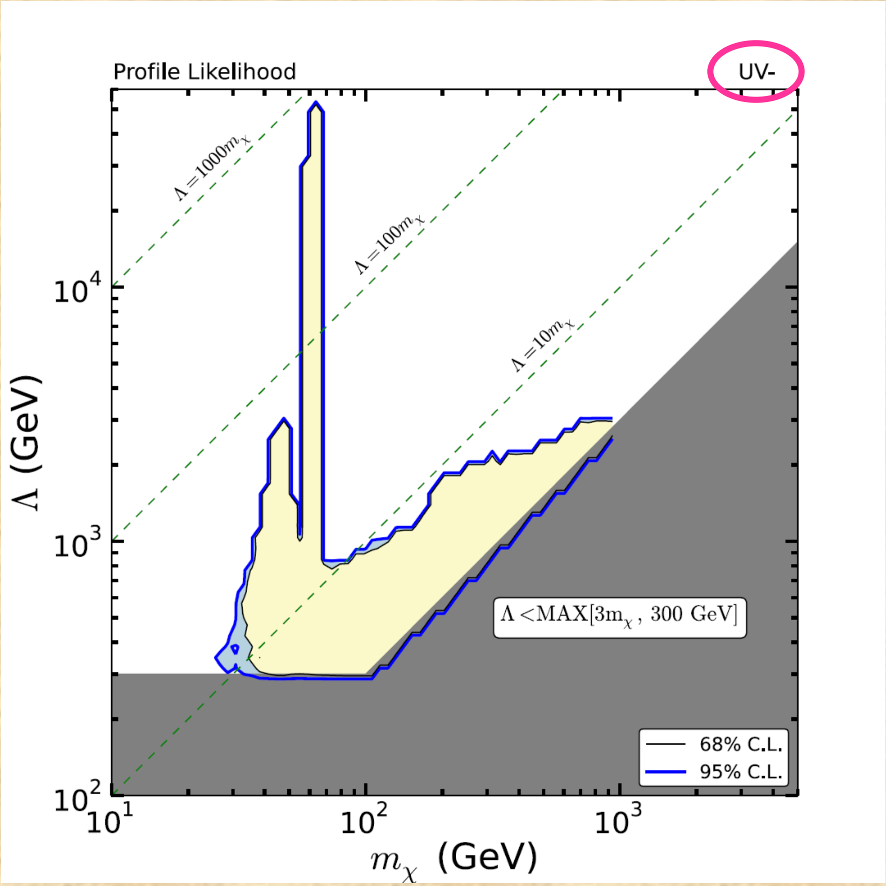
Future prospects in the Singlet-like patch





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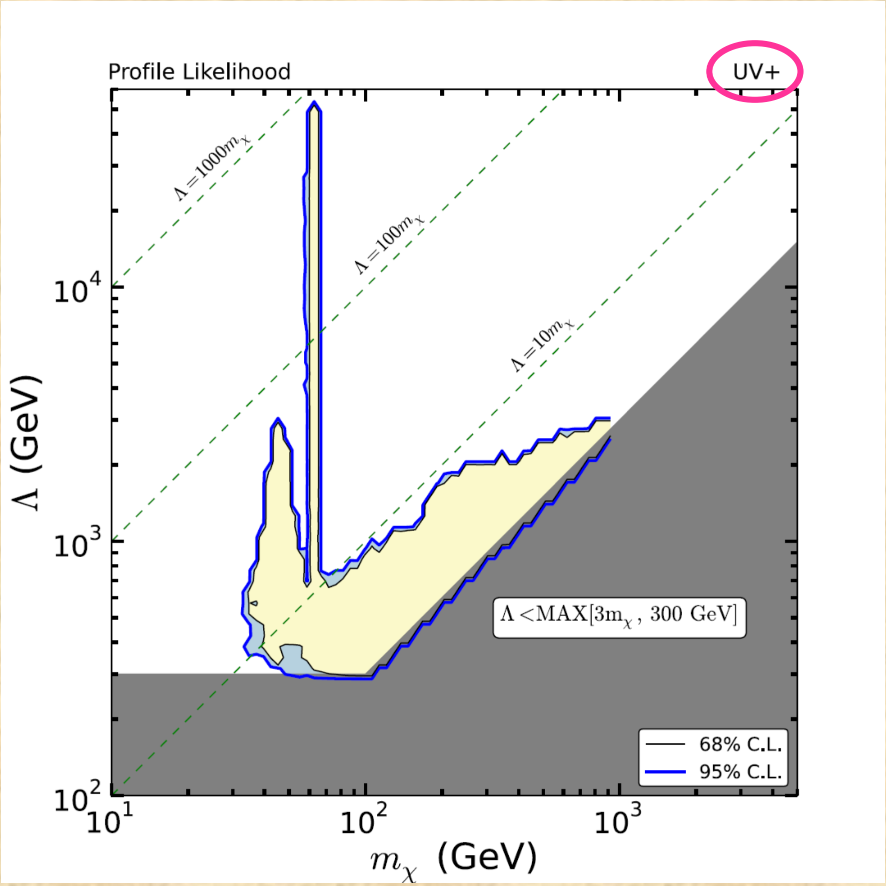

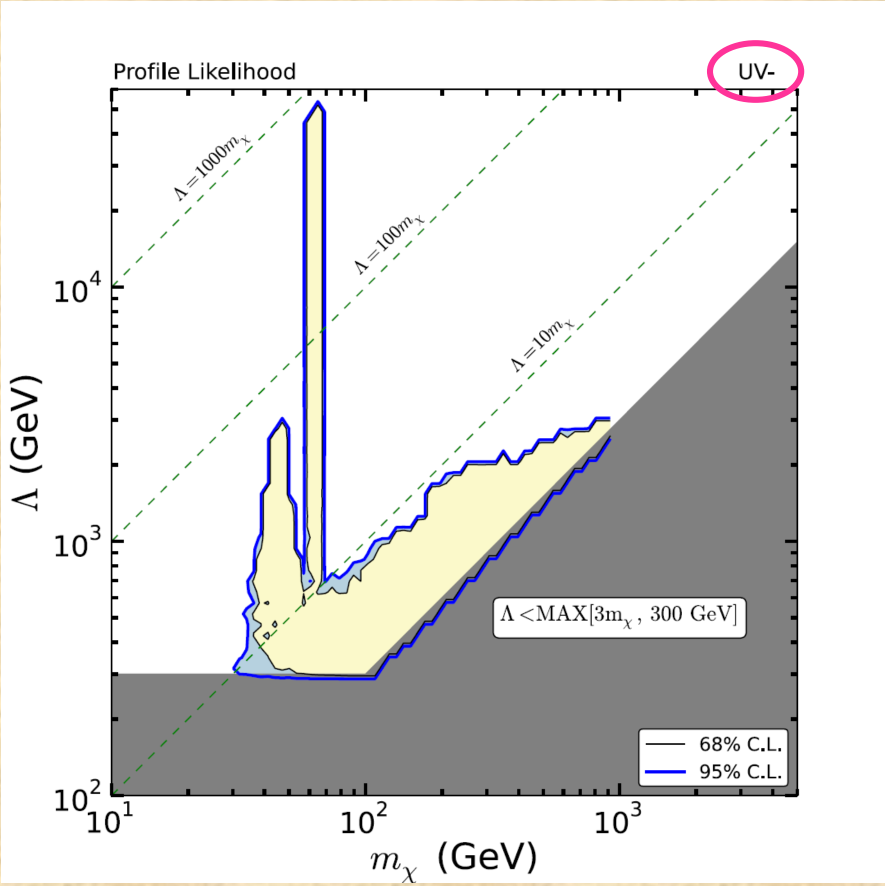

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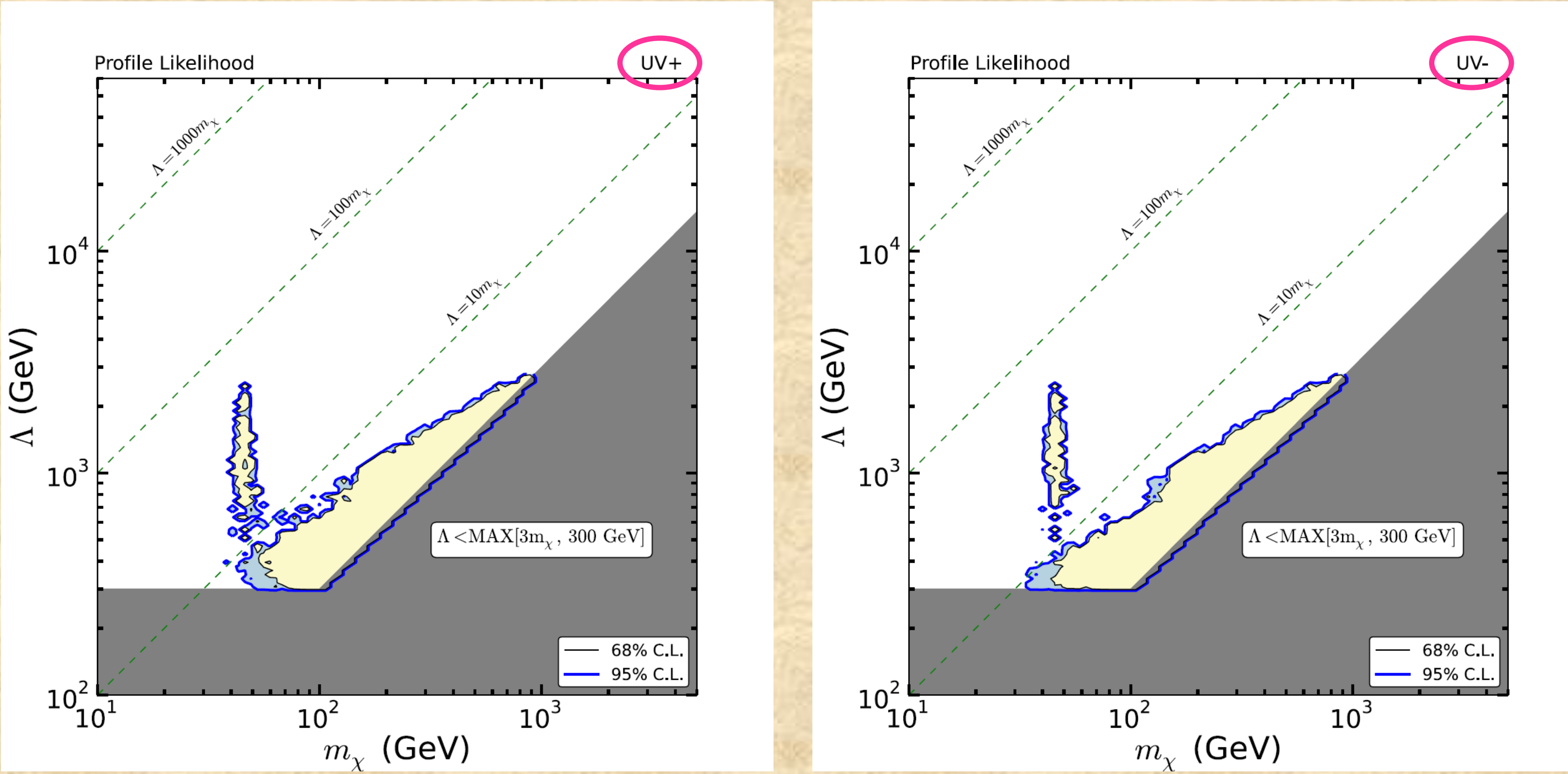

After LZ/PICO250

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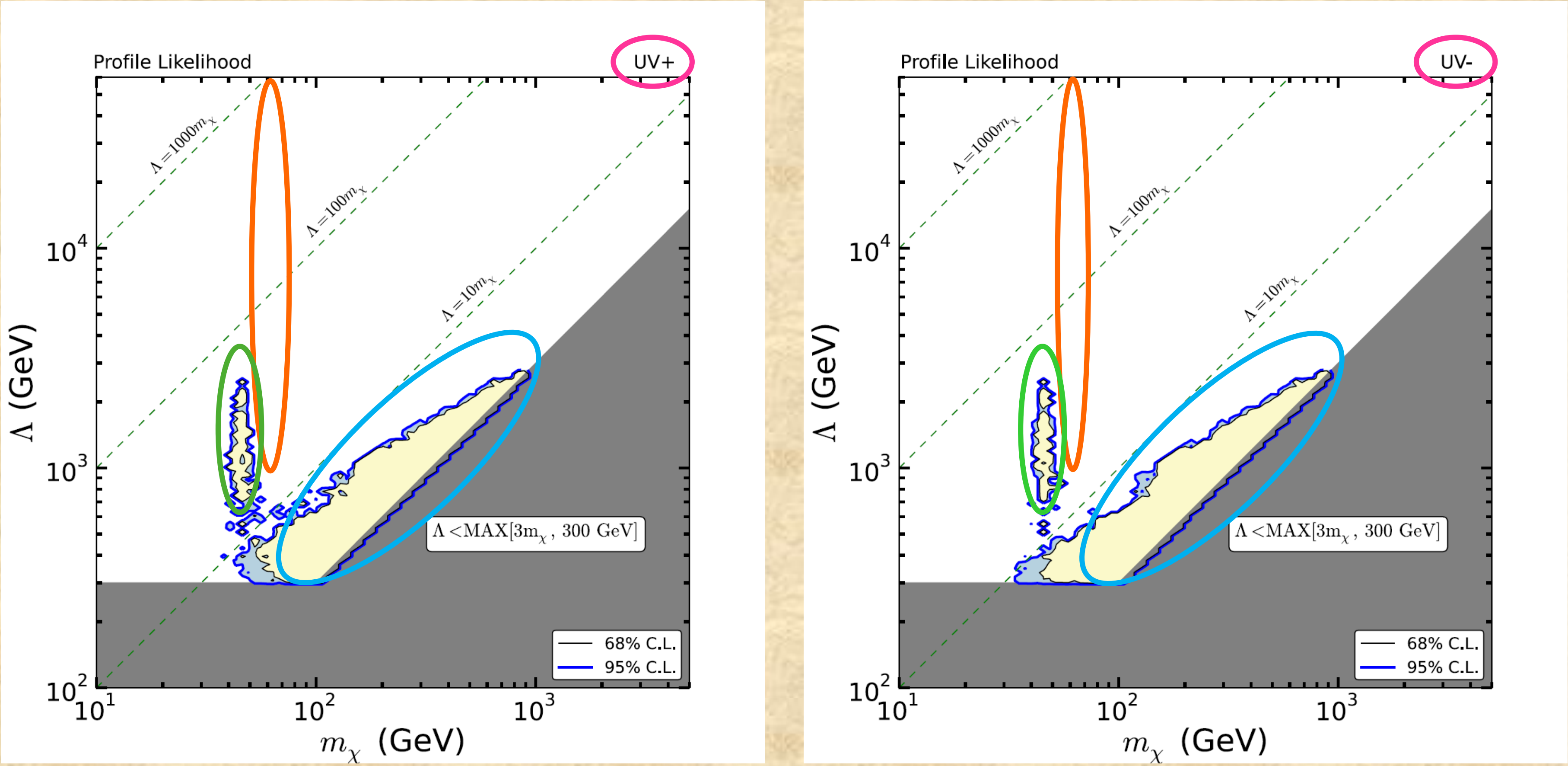
Future prospects in the Singlet-like patch

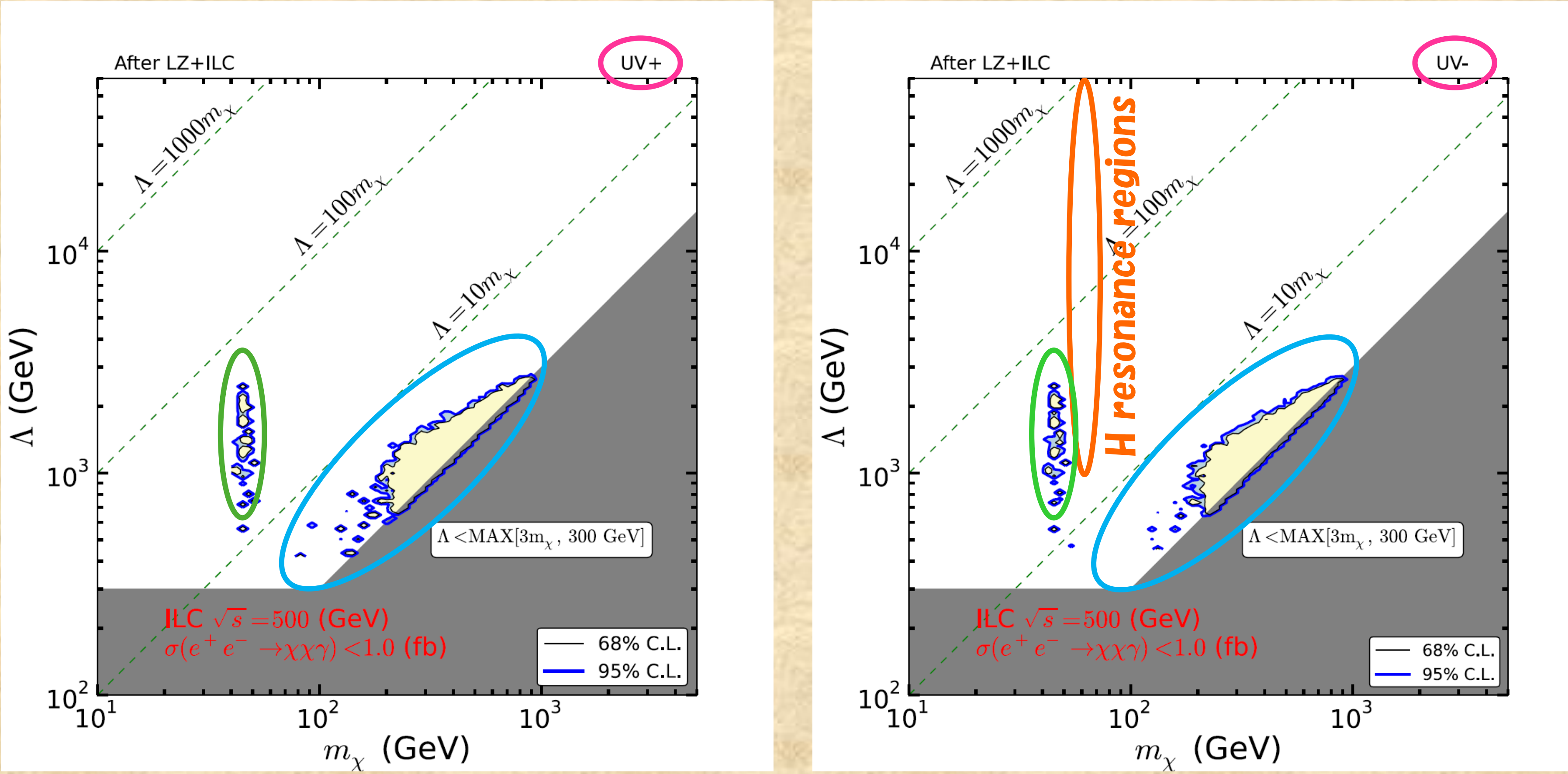


O(10)ton level direct detection cover the H resonance region entirely.

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 $\Lambda < 10m_{DM}$.
(High energy lepton colliders can efficiently cover the remaining part.)

Future prospects in the Singlet-like patch



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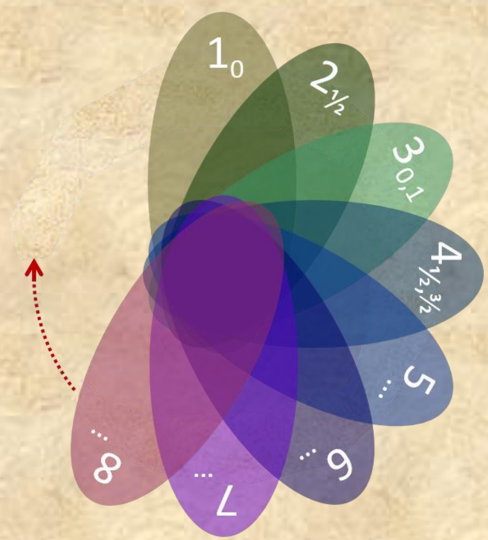
Summary

- ✓ The era of serious WIMP searches has began!

  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 program in order to answer these questions without relying on any specific new physics models beyond the SM.

- ✓ Direct dark matter detections are playing the most important role.



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 level experiments.
- In the single-like patch, the Z resonance & 4-Fermi (lepton) regions remains after LZ.
- In the doublet-like and triple-like patches, the most of regions are know to be survive.

- ✓ Indirect DM detections (Systematic errors must be under control).
- ✓ Future lepton colliders (High energy & high luminosity are needed.)

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.