Unexplored regions of WIMP

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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 1611 (2016) 070]
S. M., S. Mukhopadhyay, Y. L. Sming Tsai, [PRD94 (2016) 065034]

Purpose of these studies is

to figure out regions of thermal WIMP which are not explored efficiently so far, by analyzing all WIMP-related data.

WIMP hypothesis

WIMP hypothesis

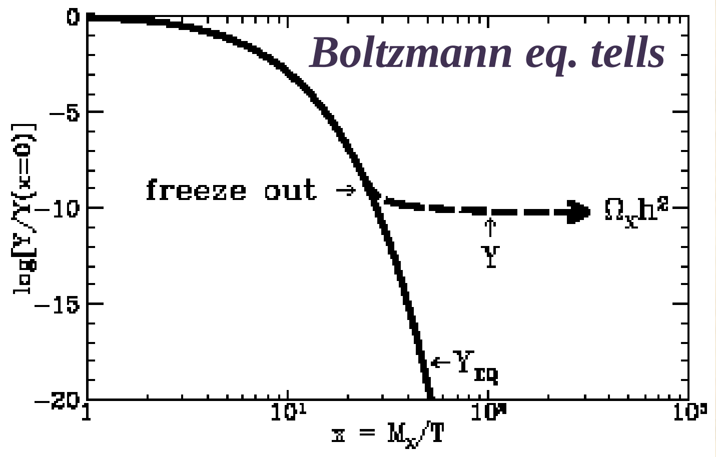
Dark matter is an electromagnetically neutral and stable particle, whose abundance at the present universe is from the freeze-out mechanism.

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

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

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

Freeze-out (reaction vs. expansion) often plays an important role in U.



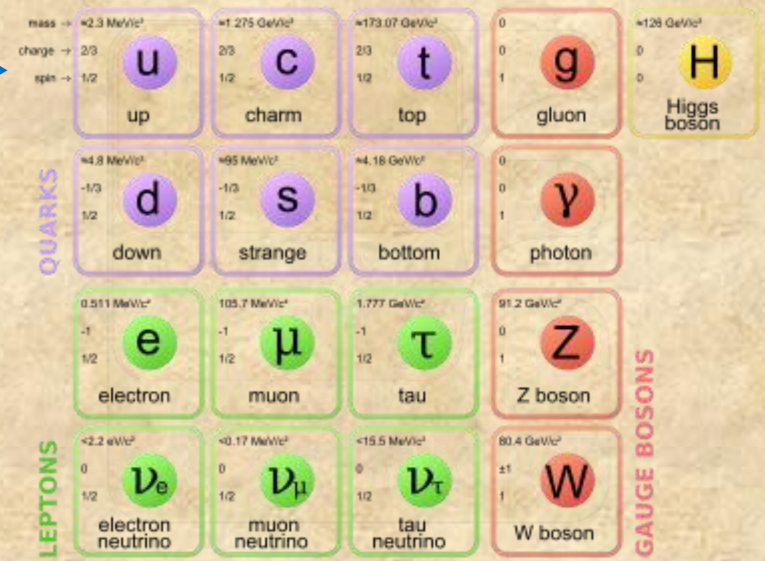
Particle Physicists: The mass of WIMP may have the same origin of the EWSB!

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?

Studying WIMP without prejudice

Which interaction exists between WIMP and SM?

Interaction



Discussing WIMP candidates w/o relying on any specific new physics models!

↓

Classifying WIMPs based on its quantum number is more useful for our purpose.
Weak charge plays an important role!!!

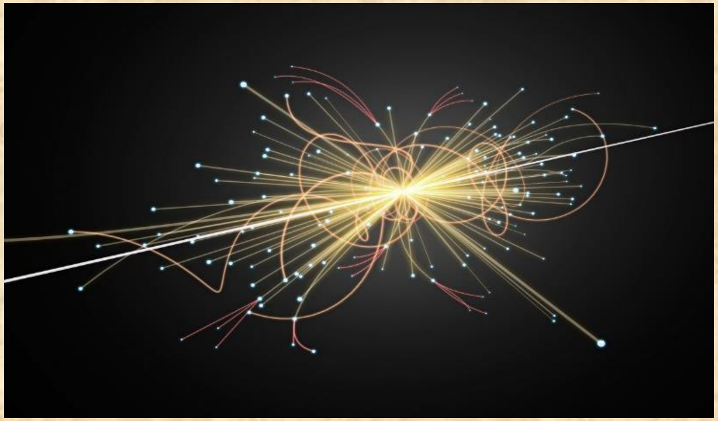
WIMPs can be classified into the following three categories.

- ✓ *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)!

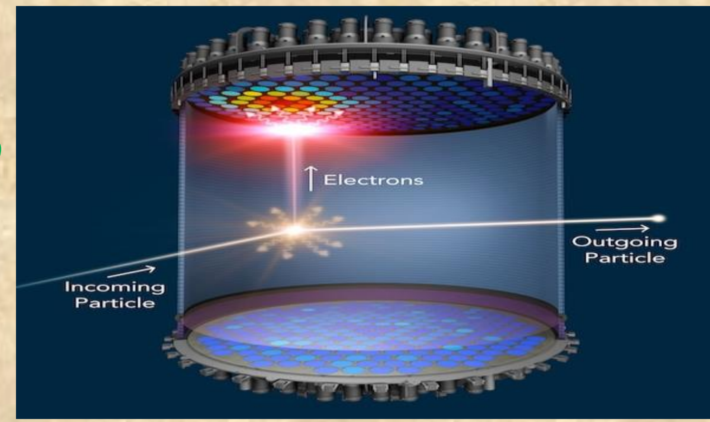
WIMP searches



@ Colliders

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

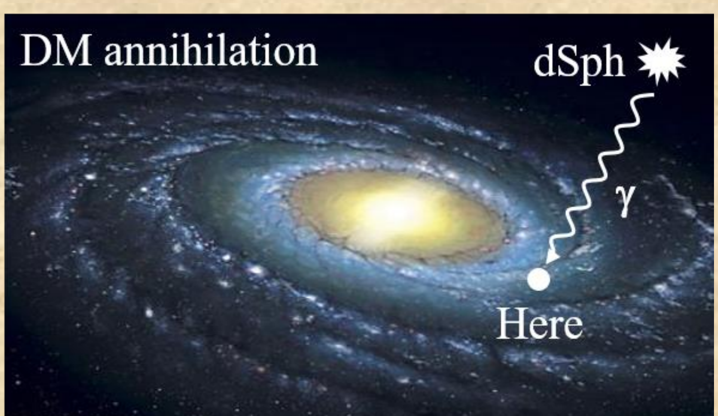
Hadron Collider : Interaction with quarks.
Lepton Collider : Interaction with leptons.



@ 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

Well-tempered WIMP

- The simplest example = Fermionic singlet-doublet WIMP model. Such a WIMP is predicted by some natural SUSY scenarios.

- 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

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

- Parameter space are defined by $[M_S, M_D, y_1 = y\cos\theta, y_2 = y\sin\theta]$. [DM interactions are assumed to preserve the CP symmetry.]

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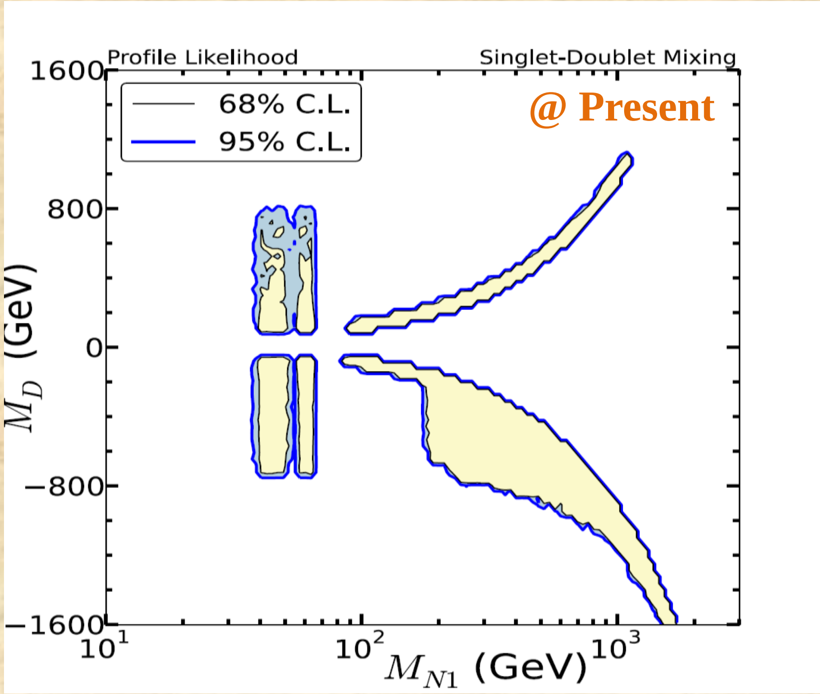
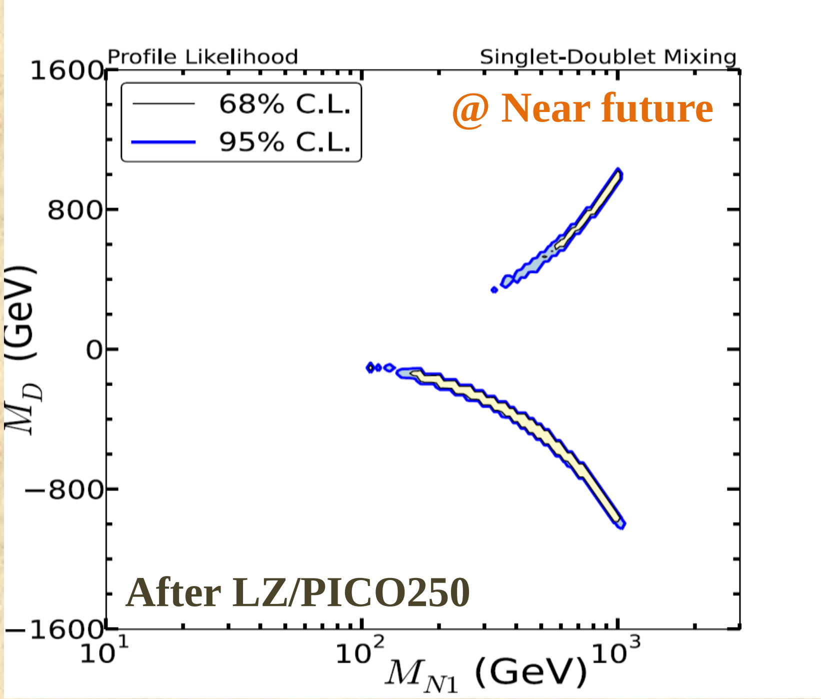
  Scanning parameter space by Likelihood analysis to clarify the current status & future prospects, assuming $|y_i| \leq 1$.

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.
  Such a WIMP is predated by the split-type SUSY (AMSB).

- 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

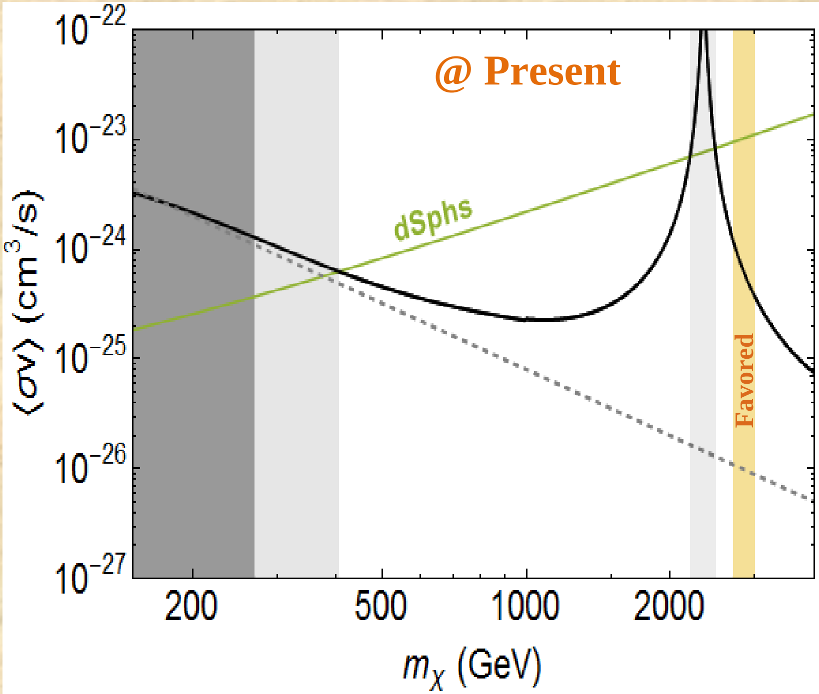
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\bar{T}\left(\not{D} - M_T\right)T$$

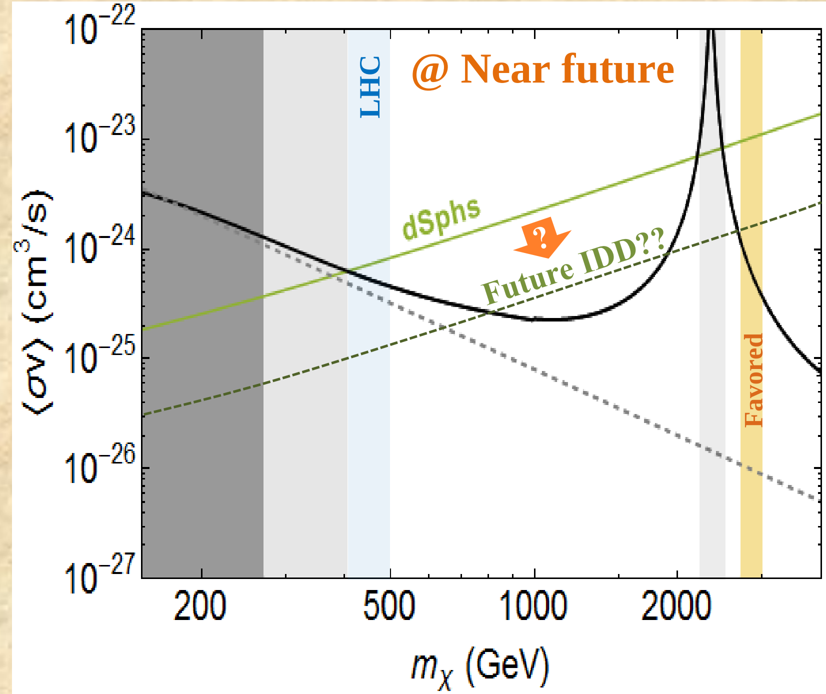
- Parameter space is simply defined by only one parameter M_T.

  ↓

  Scanning parameter space is simple because of one parameter.
  [Small mixing effect can be introduced, but it's less significant.]

EW charged WIMP (EWIMP)





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

LHC will explore the WIMP mass region below 500GeV.

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

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

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

Singlet-like WIMP

- *Such a WIMP is predated in many BSM scenarios of EWSB, etc.*
  However, it cannot interact with SM particles, if it is a fermion

- *Some additional new particle(s) must be introduced connecting WIMP and SM particle. It is called the mediator (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,*

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

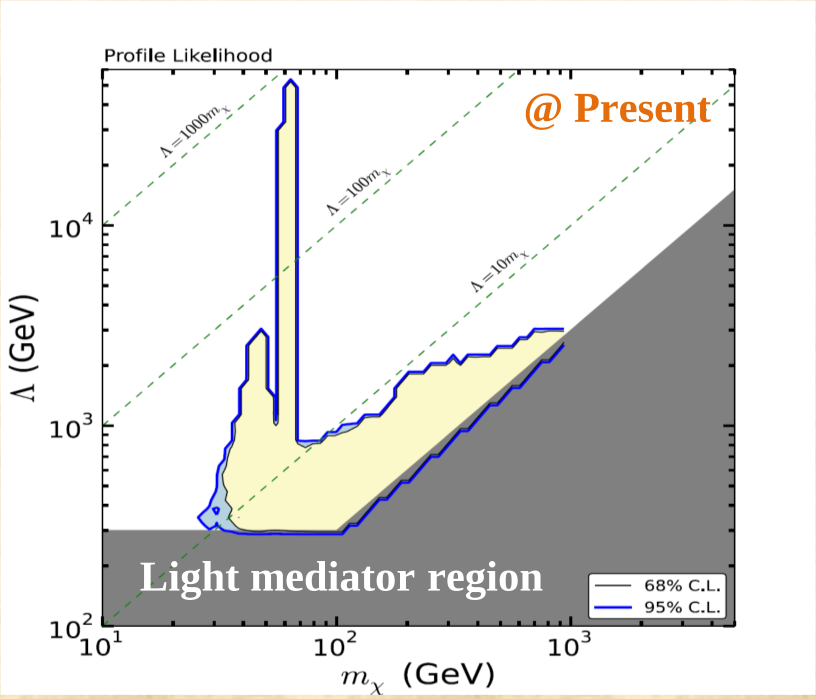
  where Λ represents the typical mass scale of the mediator.
  Some simplified models reproducing the EFT are also utilized.

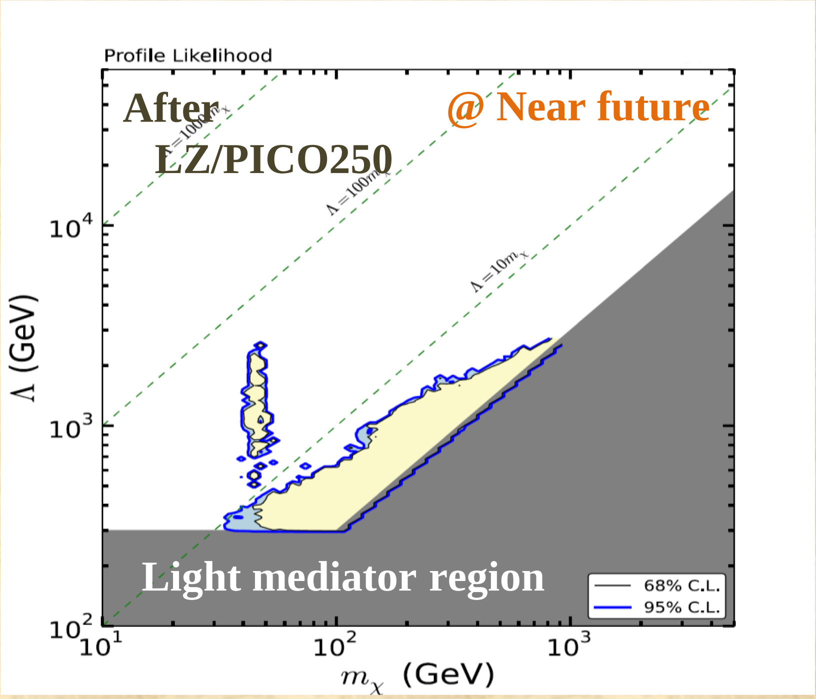
- *Parameter space is very complicated, ∃ around 10 parameters.*

  ↓

  Scanning parameter space using MCMC, assuming CP invariance and the flavor blindness of the WIMP interaction with $|c_i| \lesssim 1$.

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

↓

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 now being reported: Light WIMP in a dark sector, etc.

Studying WIMP without prejudice

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

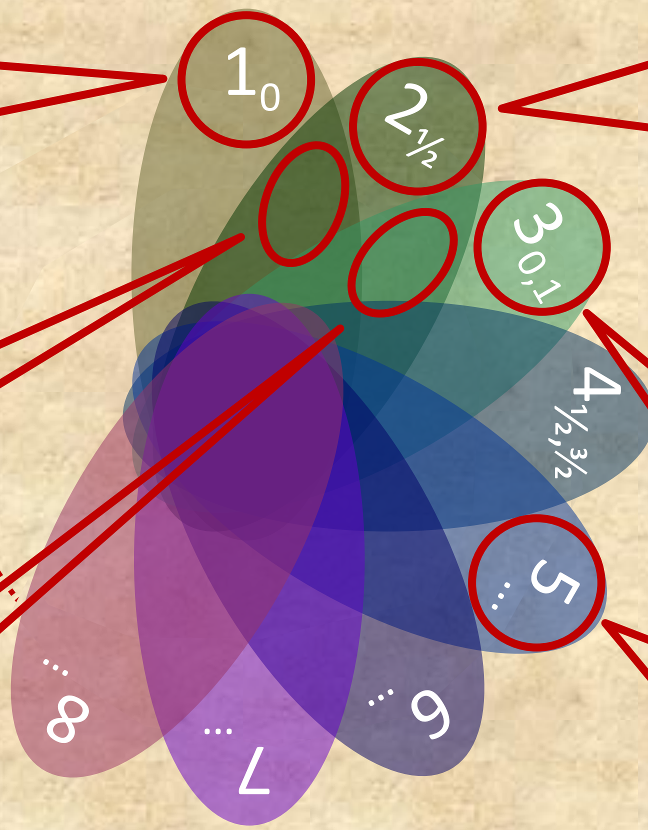
After fixing its spin, the WIMP field is written by a linear combination of colorless rep. of $SU(2)_L \times U(1)_Y$ involving a EM neutral component:

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

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

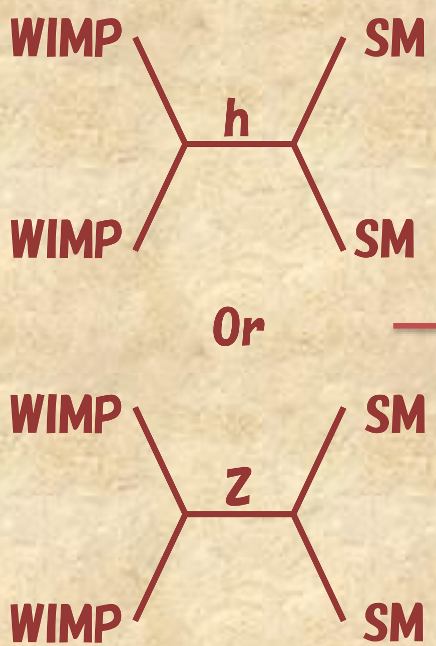


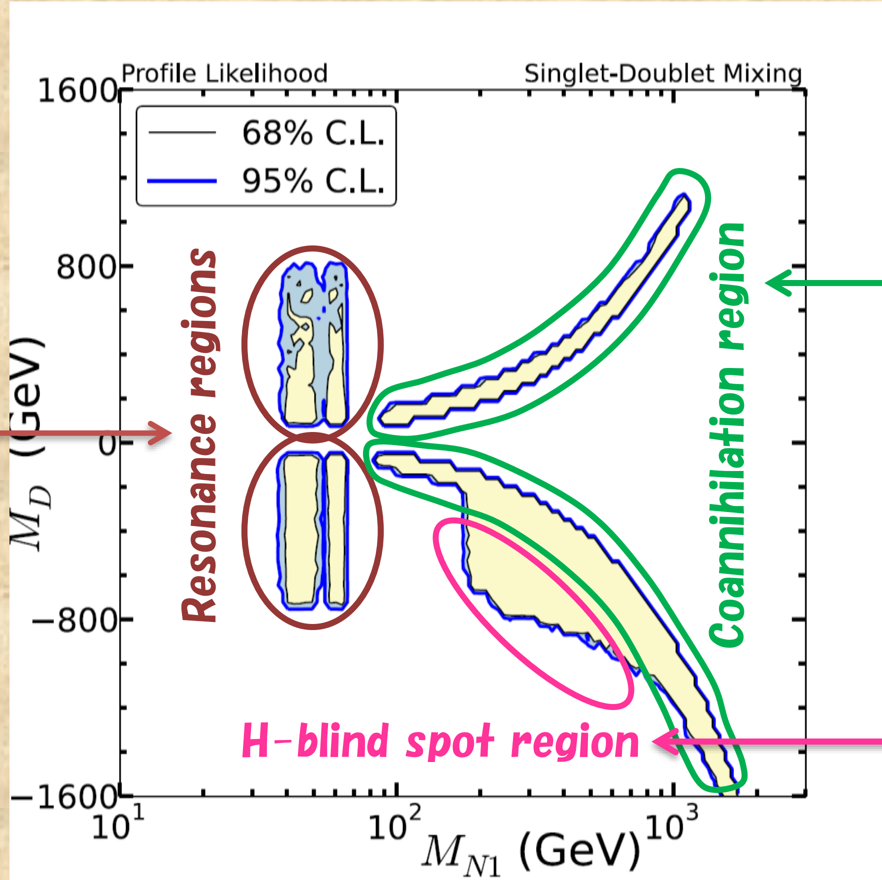
Doublet-like Patch
e.g.
Higgsino-like in SUSY
Inert Higgs in 2HDM

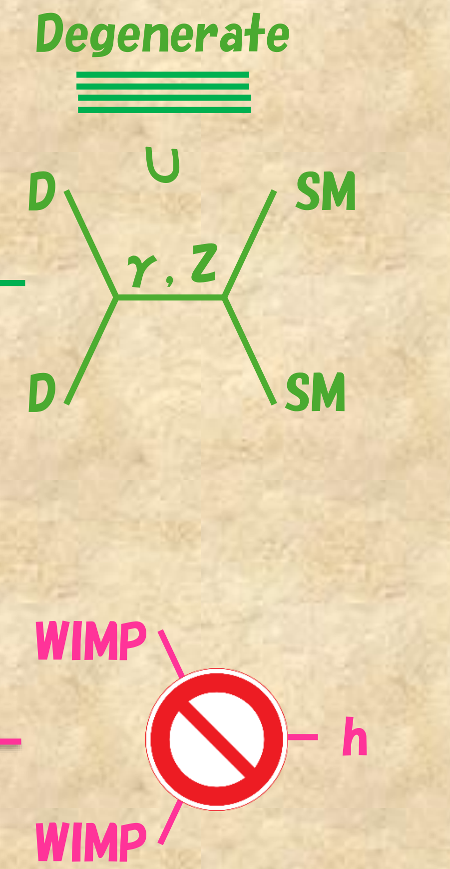
Triplet-like Patch
e.g.
Wino-like in SUSY

Quintet-like Patch
e.g.
Minimal dark matter

Singlet-Doublet mixed WIMP



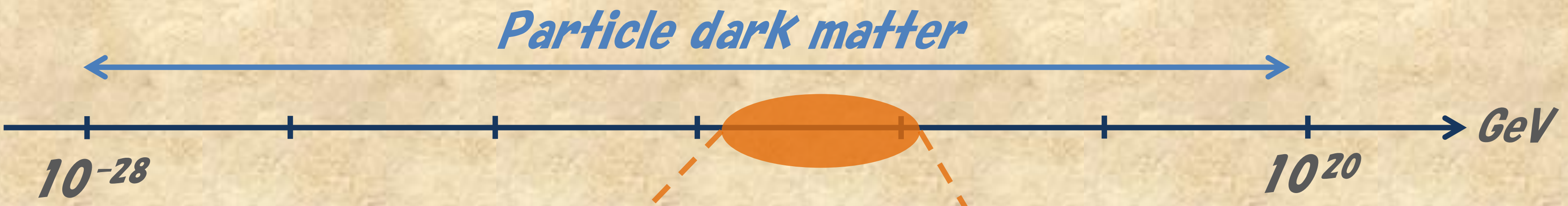




Present status

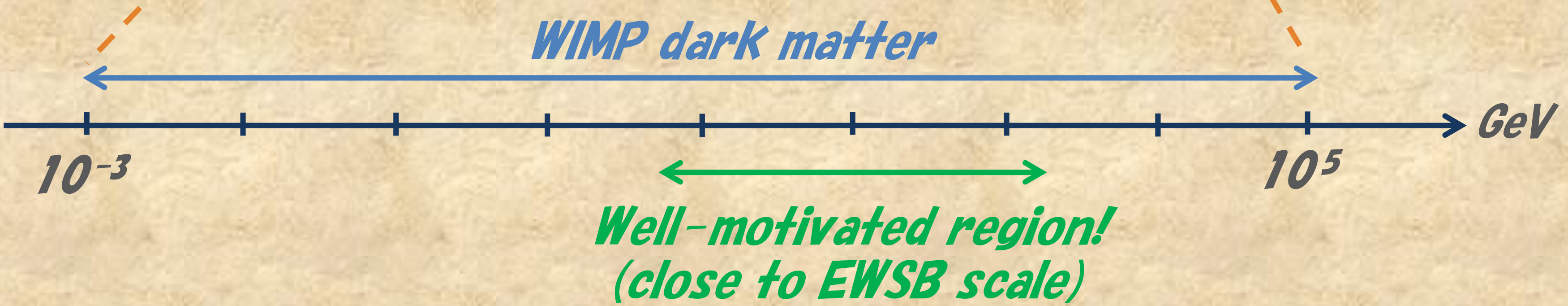
(The likelihood function is now projected onto the (M_{DM}, M_D)-plane.)

WIMP hypothesis

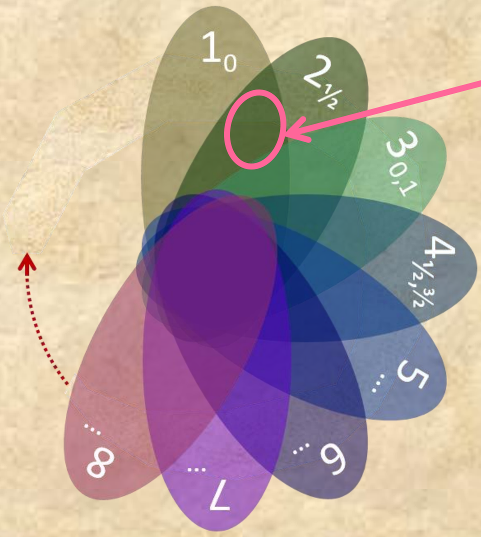


WIMP hypothesis

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 in the S-D mixed patch



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

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

✔ Effective lagrangian for the contents is

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

(Z_2 symmetry is assumed to make WIMP stable.)

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

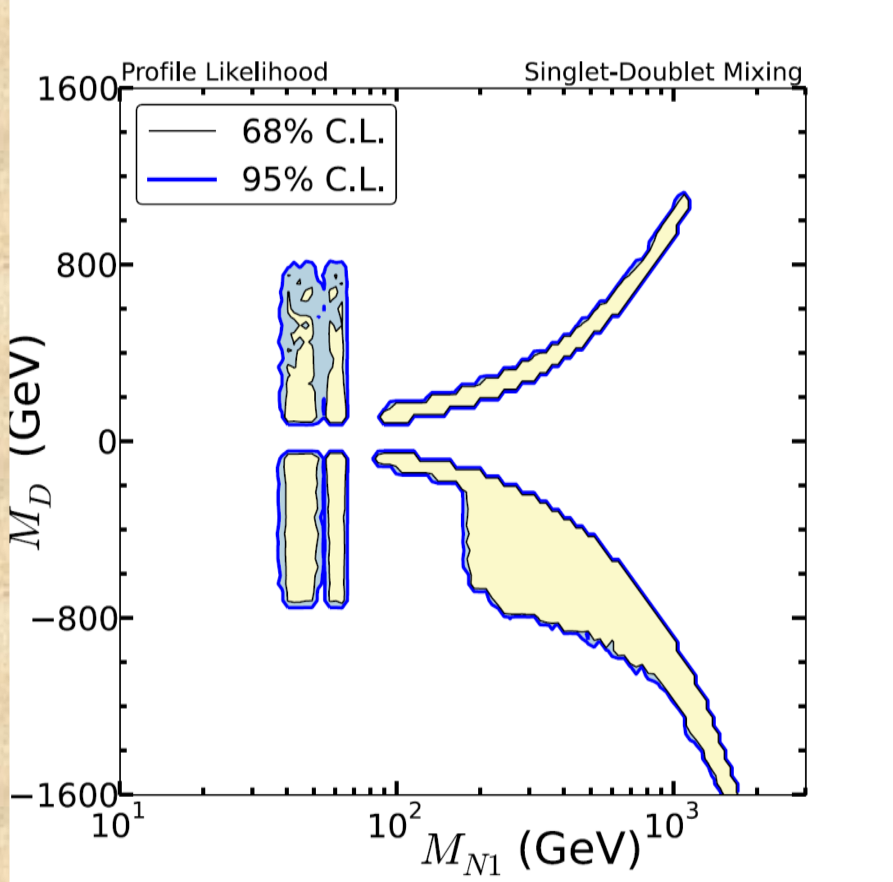
M_S : Singlet mass parameter (Corresponding to M_1 in MSSM)
M_D : Doublet mass parameter (" to μ in ")
$y_1 = y\cos\theta$: U-type Yukawa coupling (" to $y\cos\beta$ in ")
$y_2 = y\sin\theta$: D-type Yukawa coupling (" to $y\sin\beta$ in ")
with y being $y = g' / 2^{1/2}$

✔ 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!

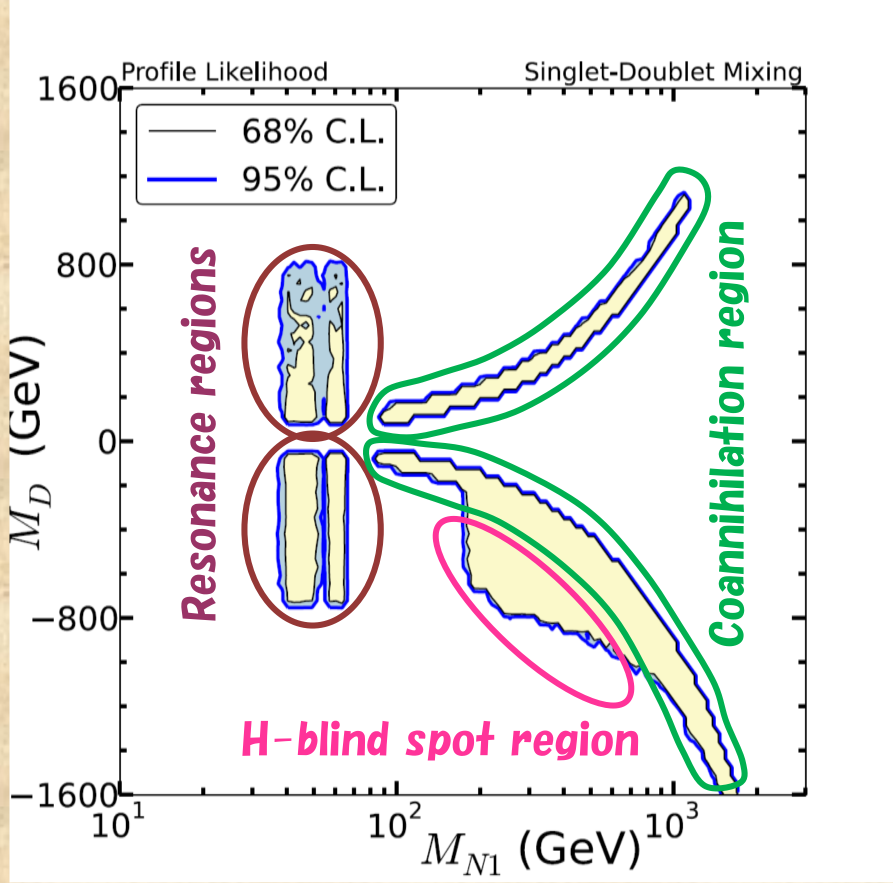
Present status in the S-D mixed patch



Present status

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

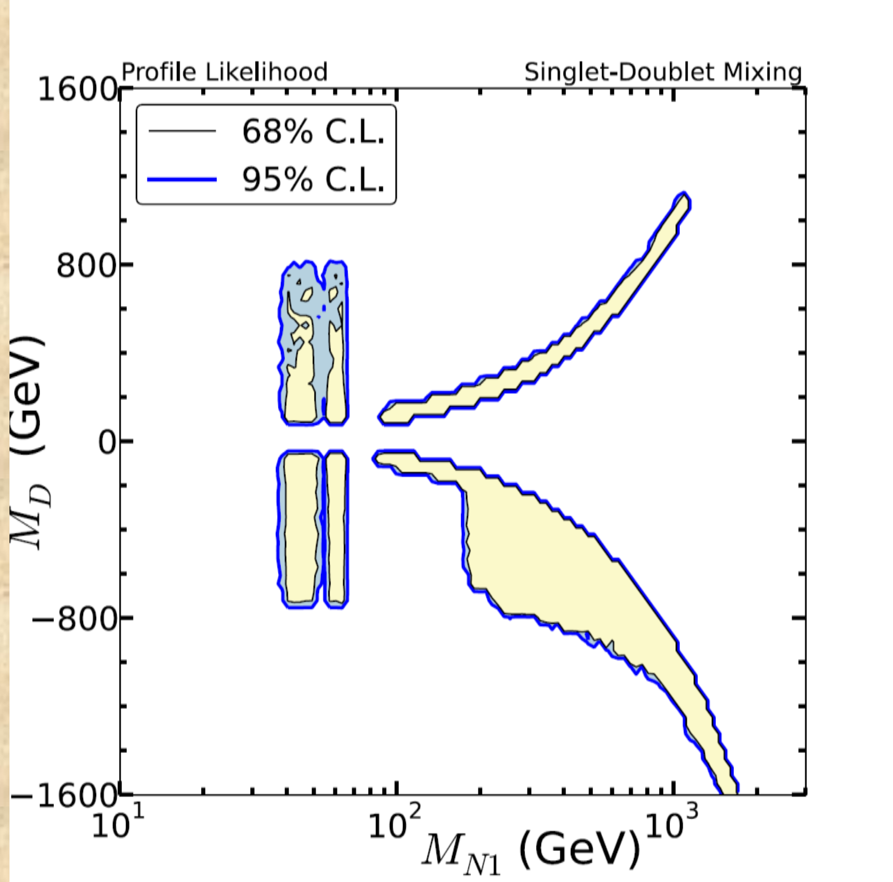
Present status in the S-D mixed patch



Present status

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

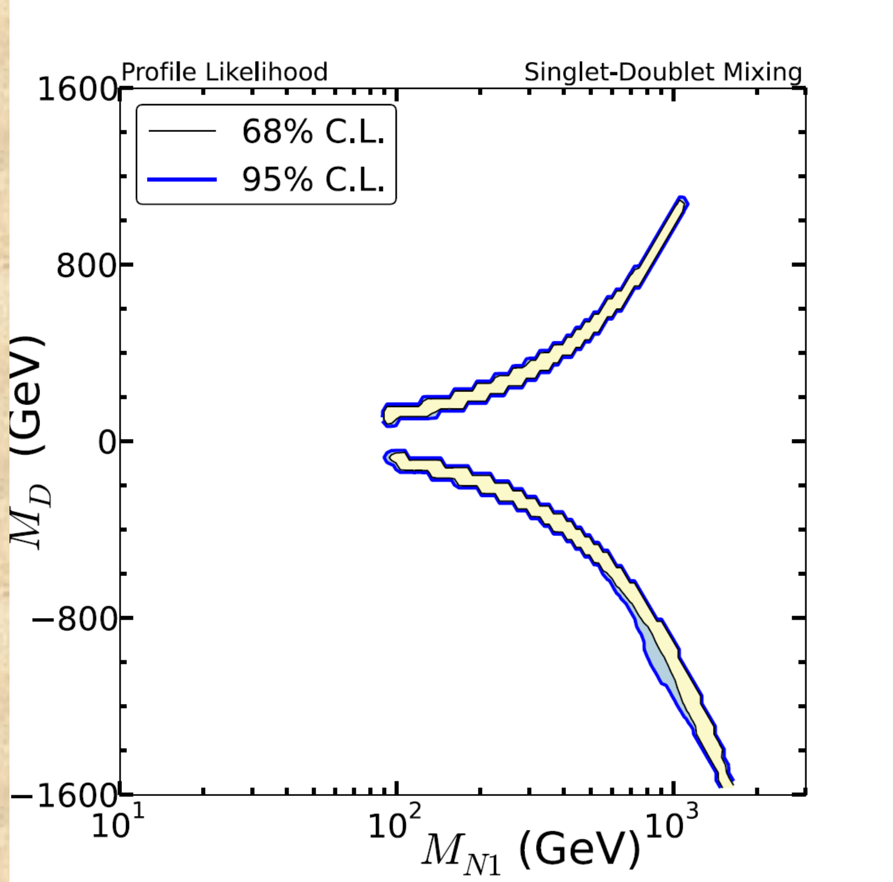
Future prospects in the S-D mixed patch



Present status

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

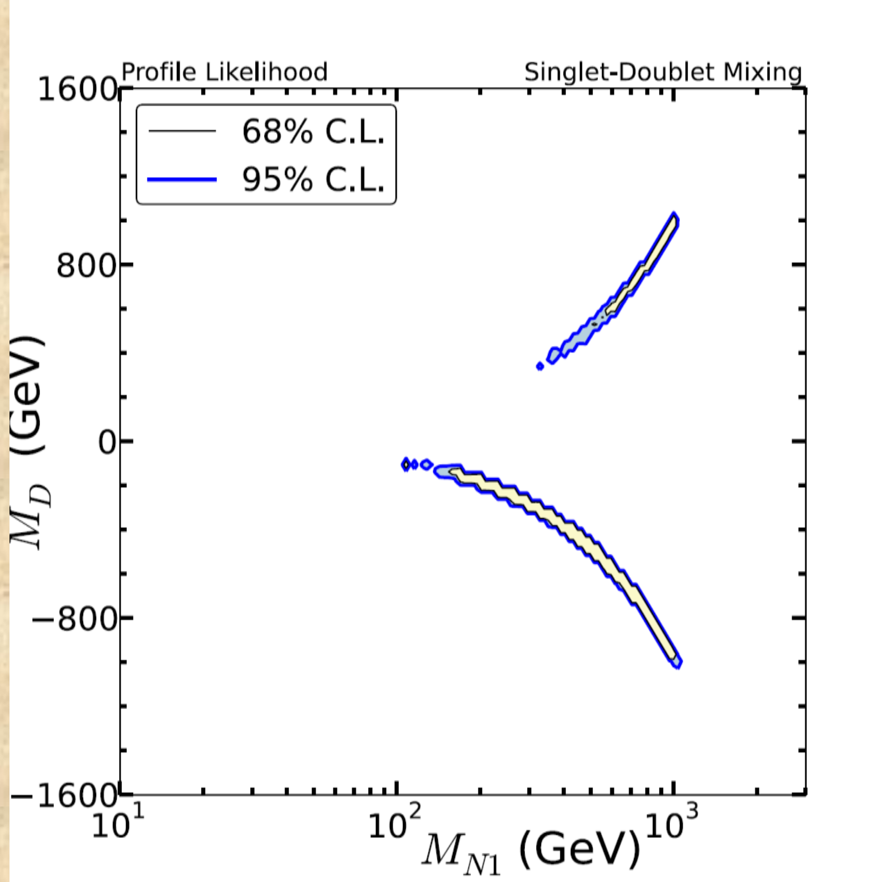
Future prospects in the S-D mixed patch



After XENON1T

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

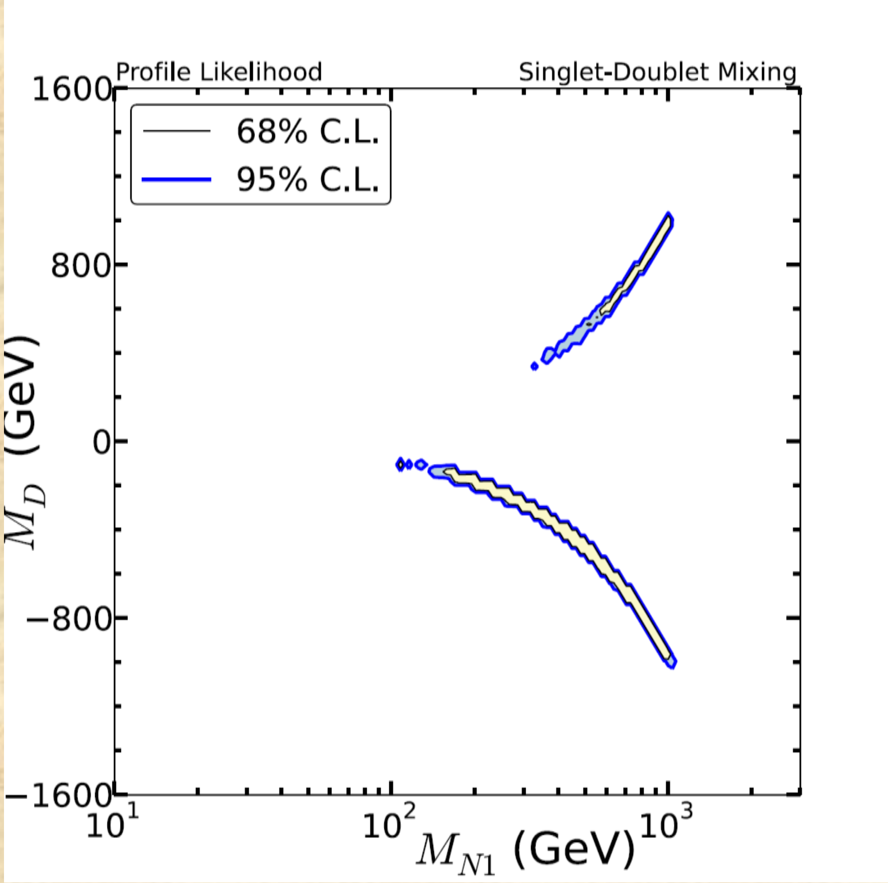
Future prospects in the S-D mixed patch

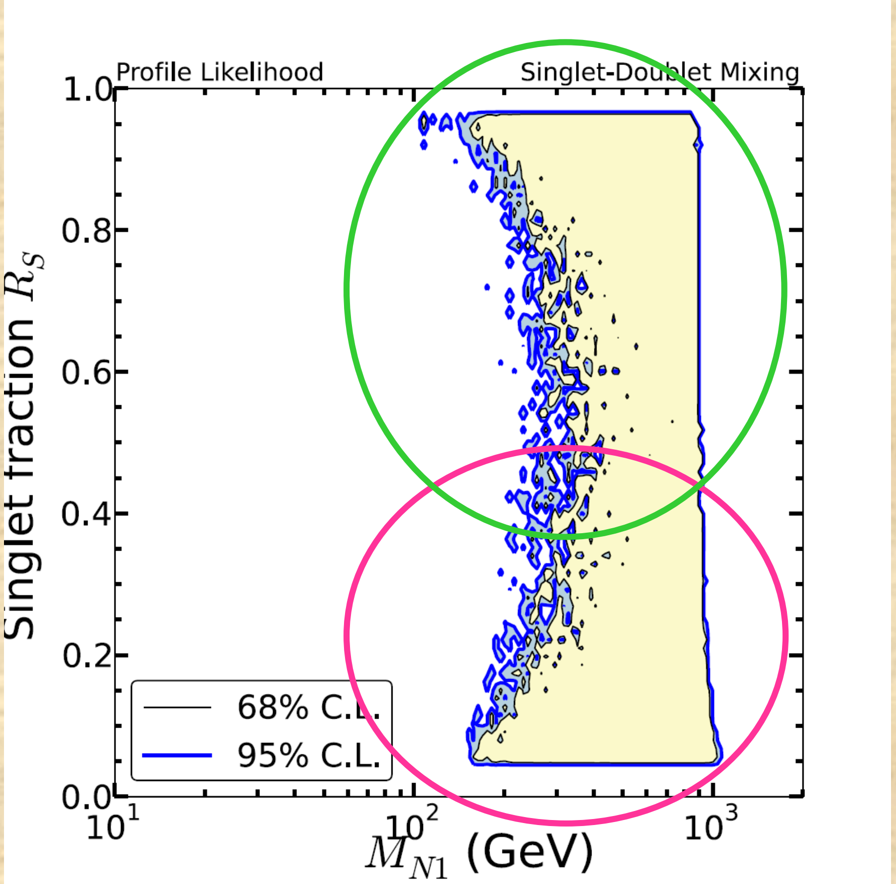


After LZ/PICO250

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

Future prospects in the S-D mixed patch





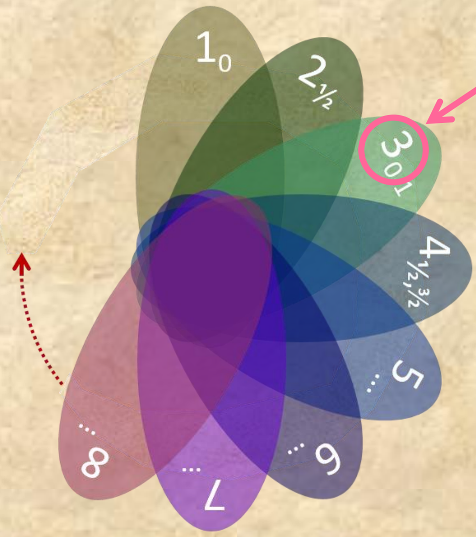
Only coannihilation regions survives after O(1)ton level experiments.

Indirect DM detections will be very important for $R_S << 1$ region.

Future e^+e^- colliders will be very important for $R_S \sim 1$ region.

Direct detection are very powerful to study mixed WIMPs in general!

WIMP in the Triplet -like patch



Minimal content: 3_0 (1 Majorana + 1 Dirac)

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

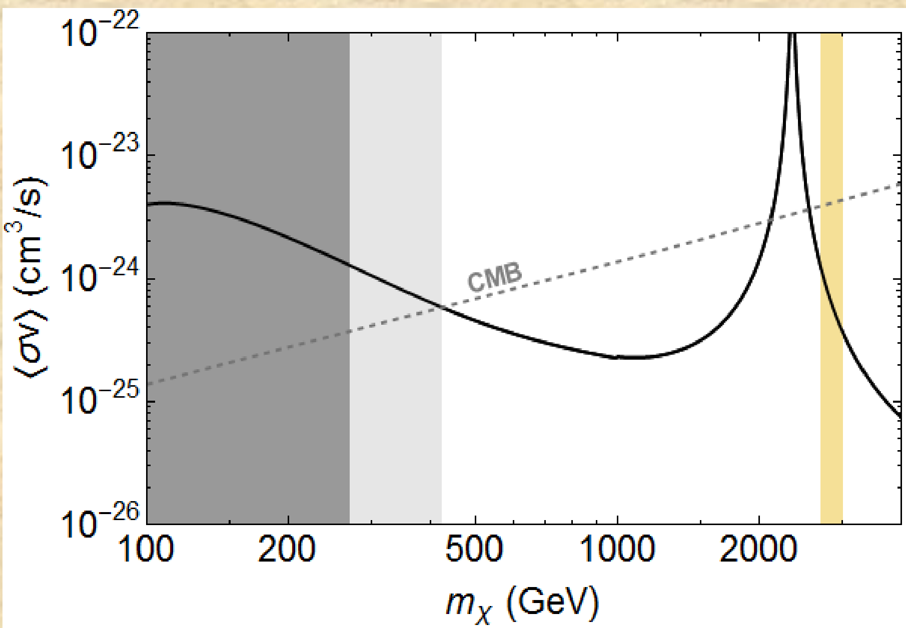
(Small mixing effects from high-dim operators.)

✔ Effective lagrangian for the content is

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\bar{T}\,(\not{D} - M_T)\,T + ({\rm High-dim\ operators})$$

(Z_2 symmetry is assumed to make WIMP stable.)

✔ There is only one model parameter M_T.



Relic abundance limit → $M_T \sim 3$TeV

[Hisano, Matsumoto, Nagai, Saito, Senami, 2007]

Direct detection → $\sigma_{SI} \sim 10^{-11}$pb

[LUX; Hisano, Ishiwata, Nagata, 2015]

Collider (LHC) limit → $M_T >$ 270GeV

[ATLAS; CMS; Ibe, Matsumoto and Sato, 2013]

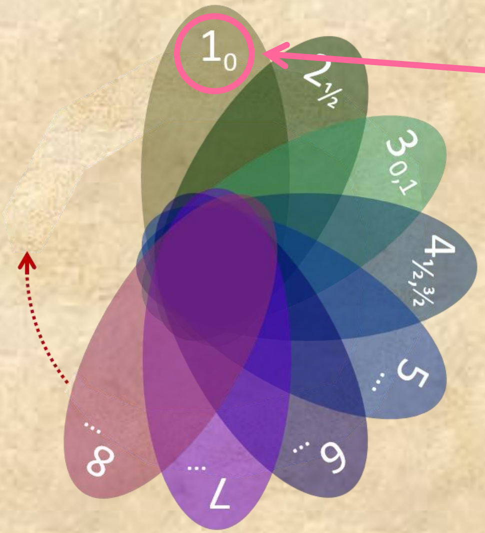
Indirect detection → $M_T >$ 410GeV

Wino annihilation is highly boosted!

[Hisano, Matsumoto, Nojiri, Saito, 2004]

Using γ-ray from dSphs in future!

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 particle(s) must be introduced. Assuming those are heavy enough, we introduce higher dim. operators.

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

Small mixing effects are automatically involved because of the higher-dimensional operators.

✔ 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:

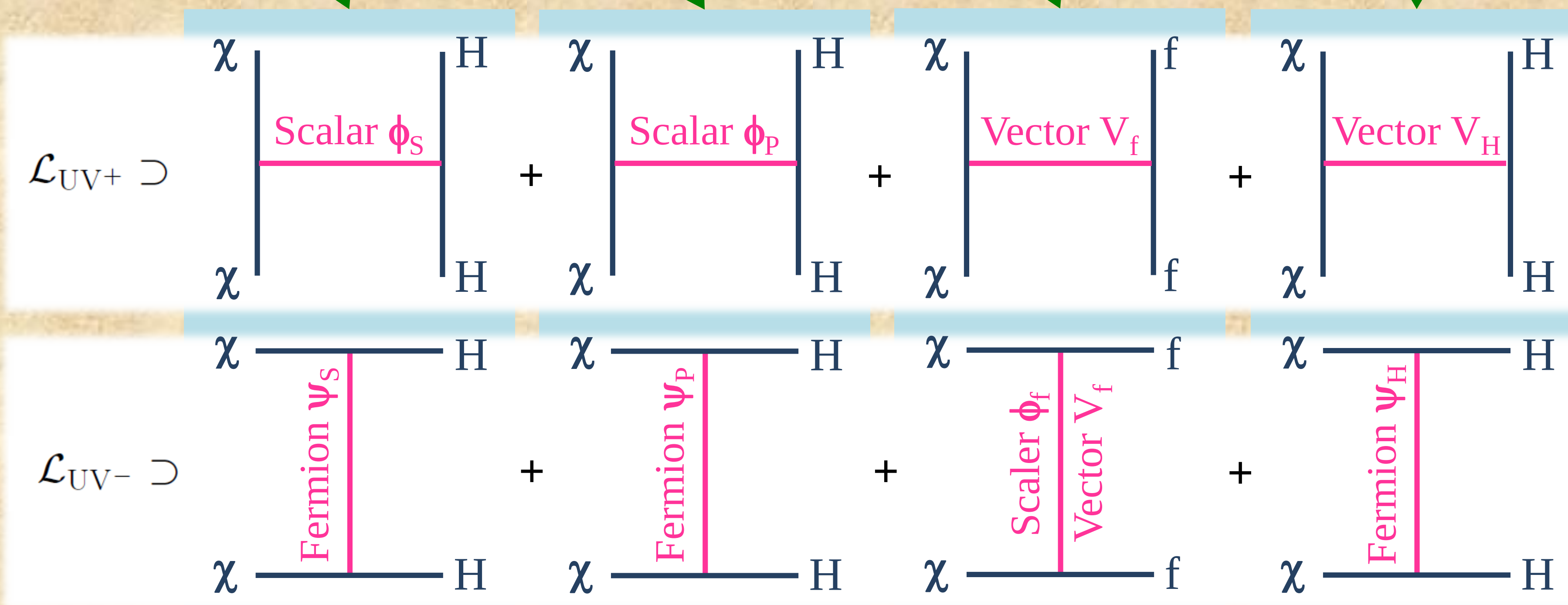
- Common suppression scale ($\Lambda_i = \Lambda$) with $\Lambda > [3\, m_{DM}, 300\,\mathrm{GeV}]$.
- All coupling constants c_i are smaller than one.
- Flavor blindness ($[c_f]_{ij} = c_f$) and CP invariance ($c_P = 0$).

WIMP in the Singlet-like patch

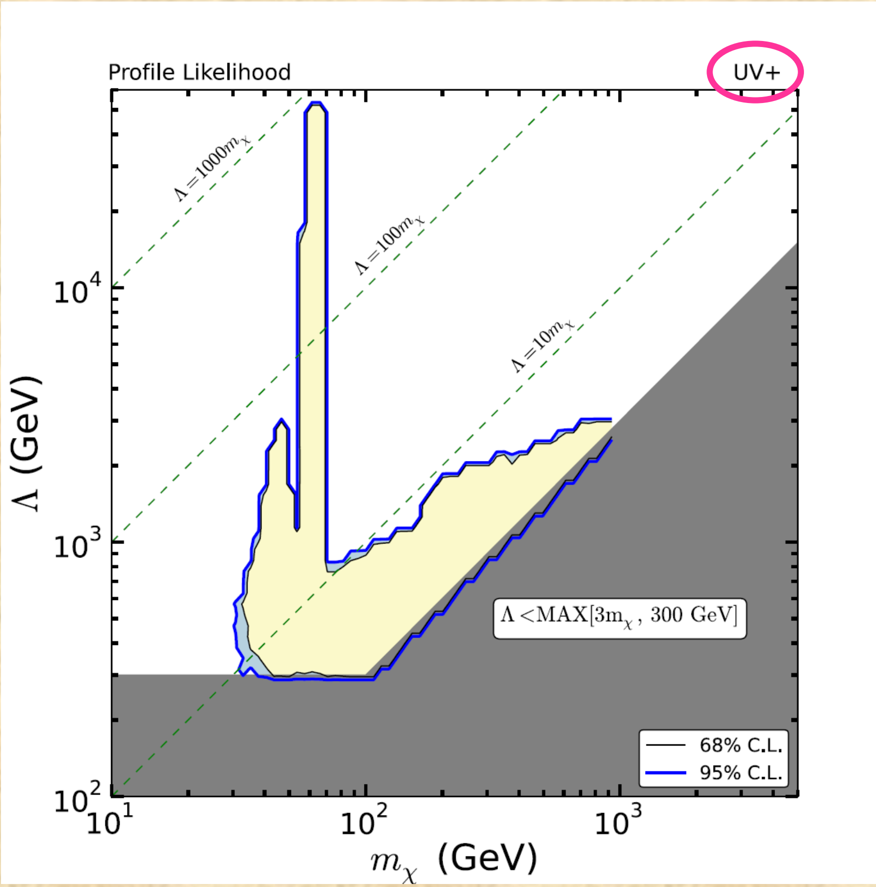
The EFT description is of limited applicability to discuss WIMP signals at energetic colliders, so that we consider a general simplified model which reproduces the EFT at large intermediate particle mass limits.

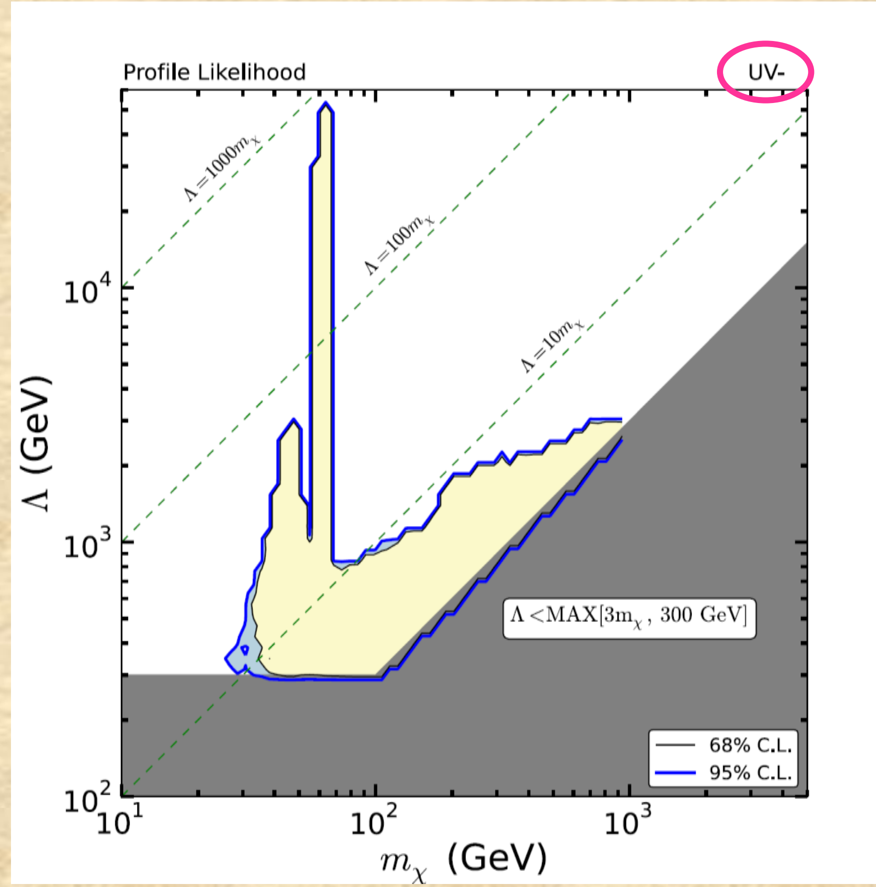
$$\mathcal{L}_{\rm EFT} \supset \frac{c_S}{2\Lambda_S}(\bar{\chi}\chi)|H|^2 + \frac{c_P}{2\Lambda_P}(\bar{\chi}i\gamma_5\chi)|H|^2 + \sum_f \frac{c_f}{2\Lambda_f^2}(\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{f}\gamma_\mu f) + \frac{c_H}{2\Lambda_H^2}(\bar{\chi}\gamma^\mu\gamma_5\chi)(H^\dagger i\overleftrightarrow{D}_\mu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

Using these simplified models to take collider constraints into account!



Present status in the Singlet-like patch

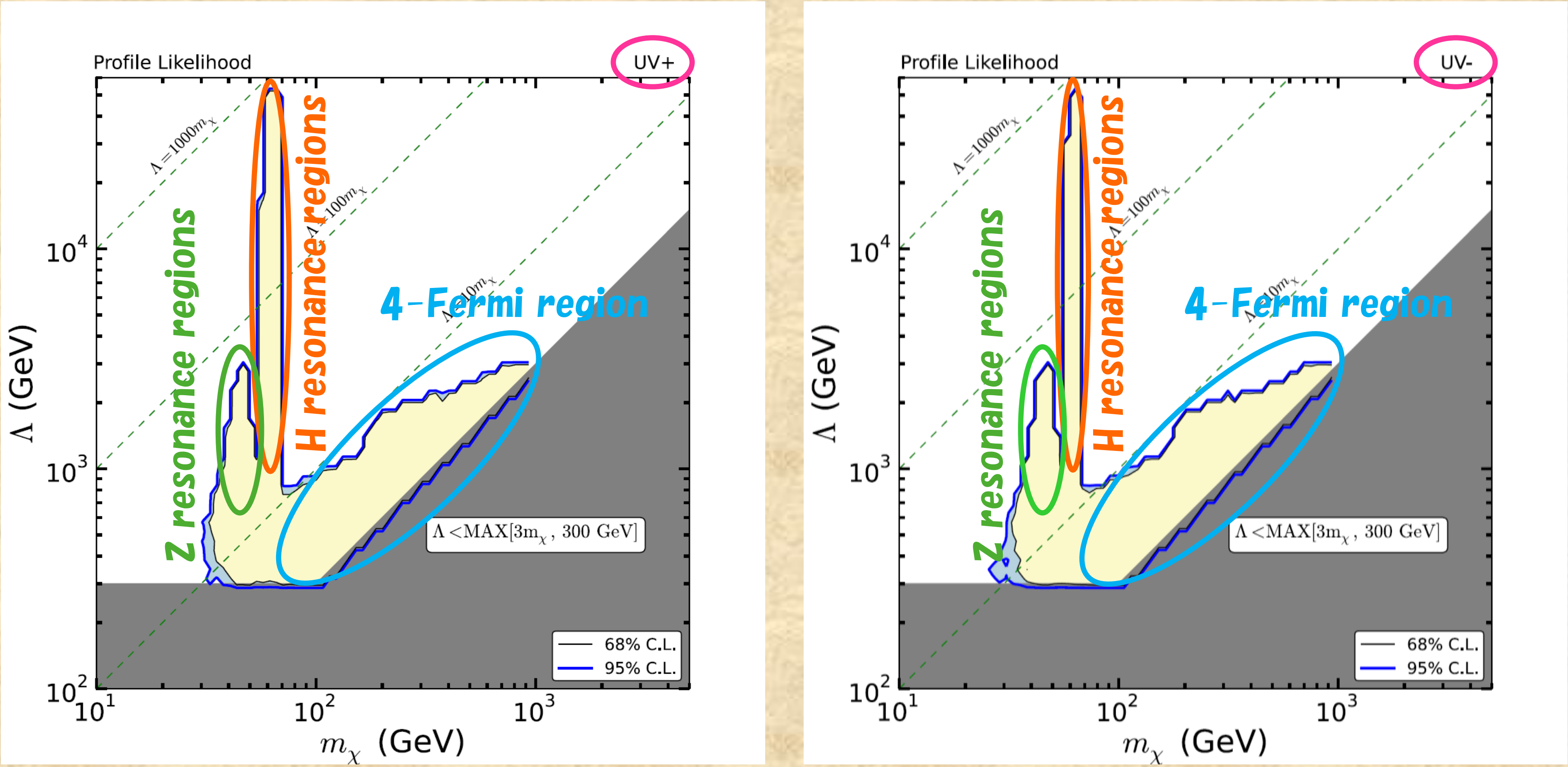




Present status

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

Present status in the Singlet-like patch



Present status

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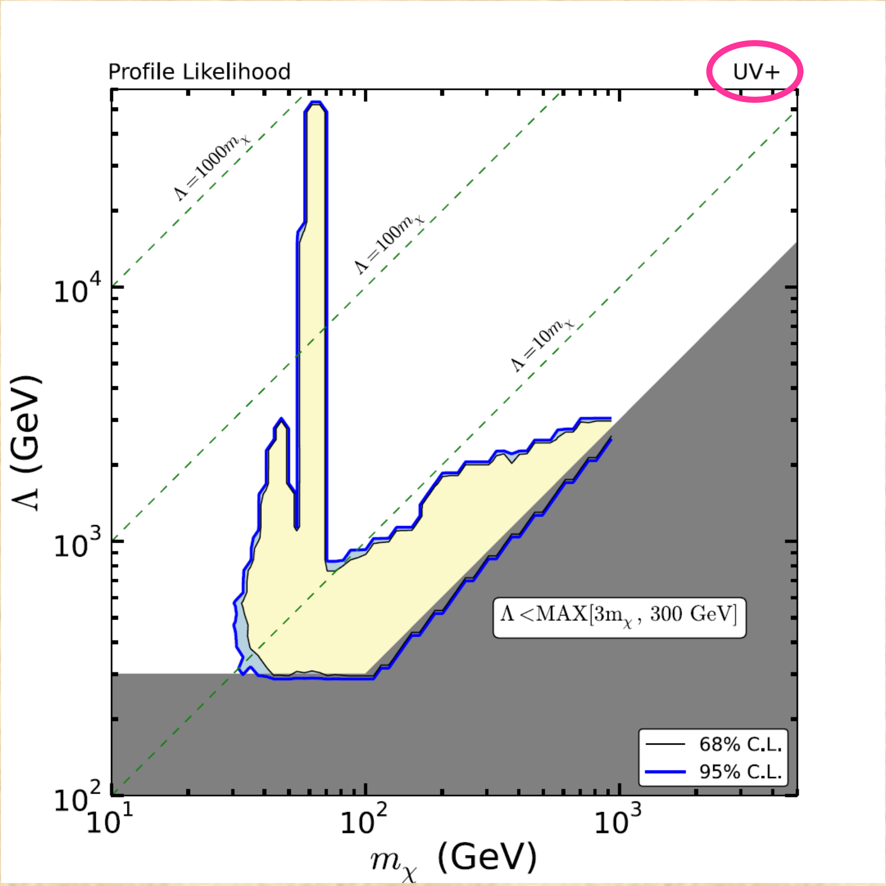
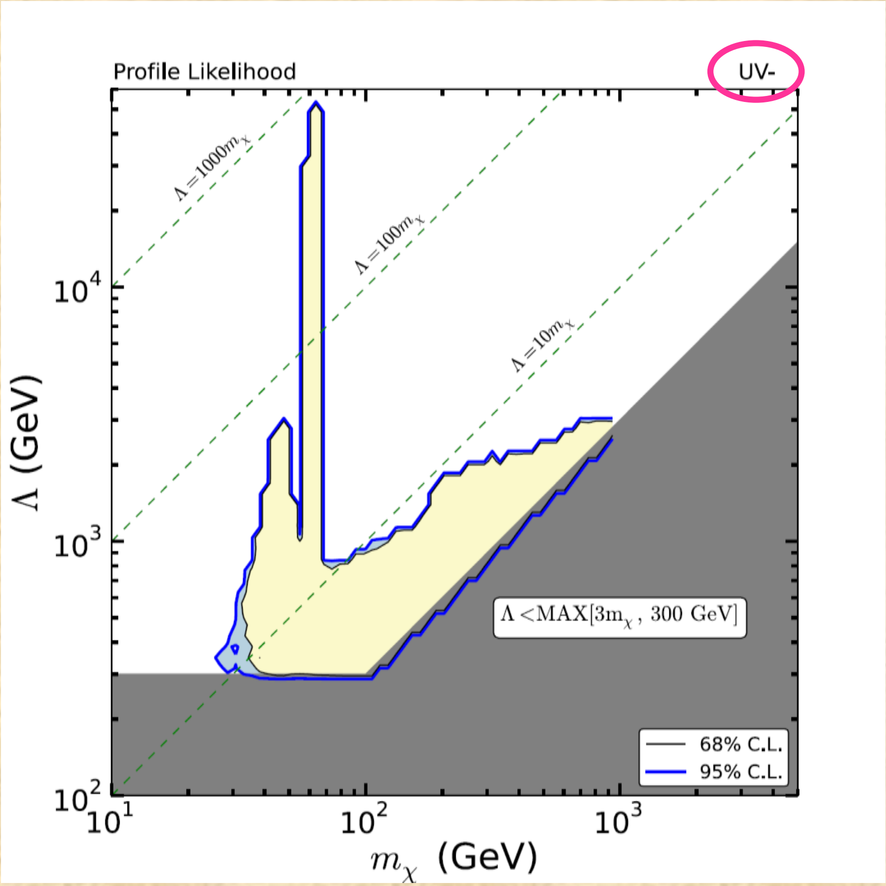
Future prospects in the Singlet-like patch

App 6





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Future prospects in the Singlet-like patch

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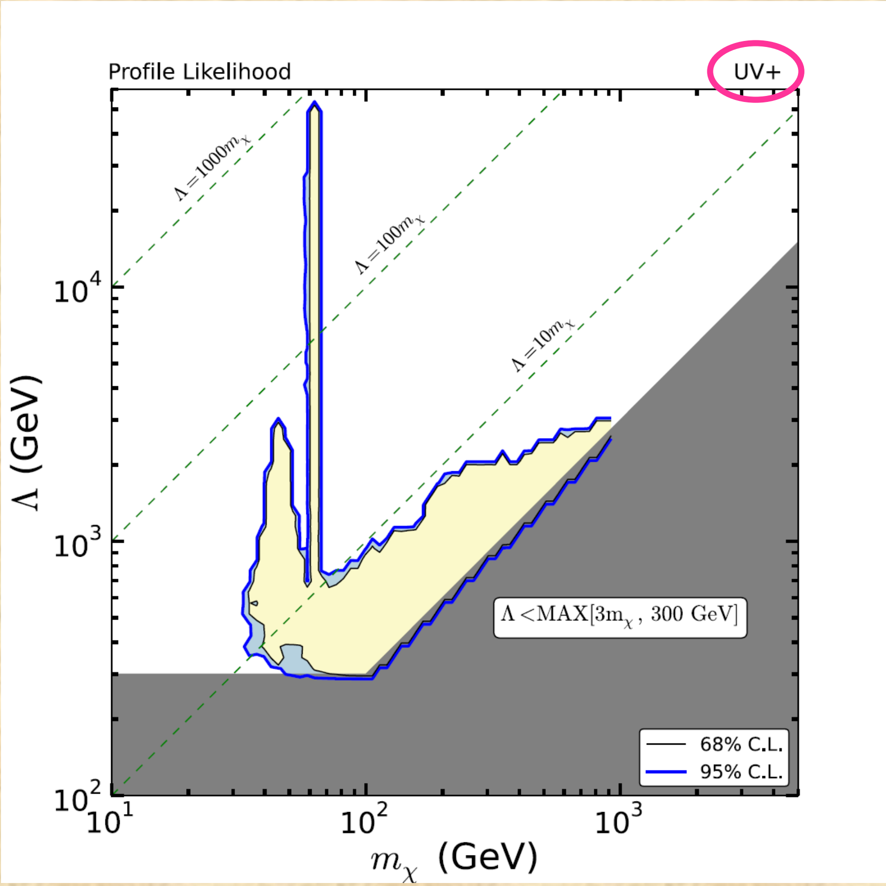

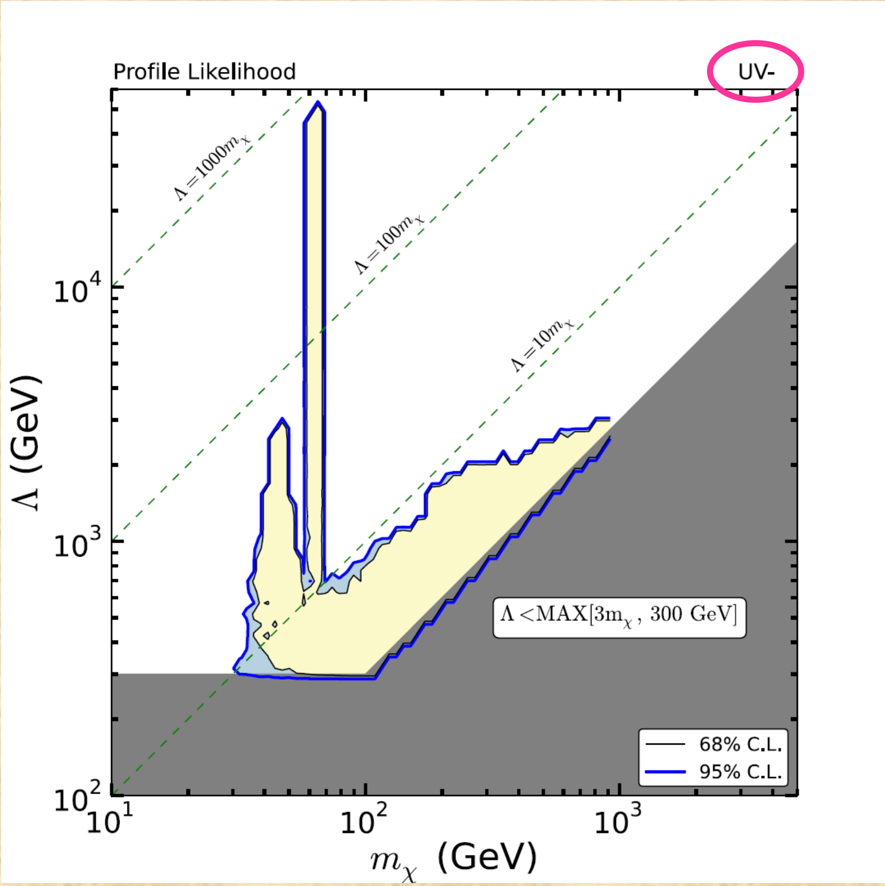

After XENON1T

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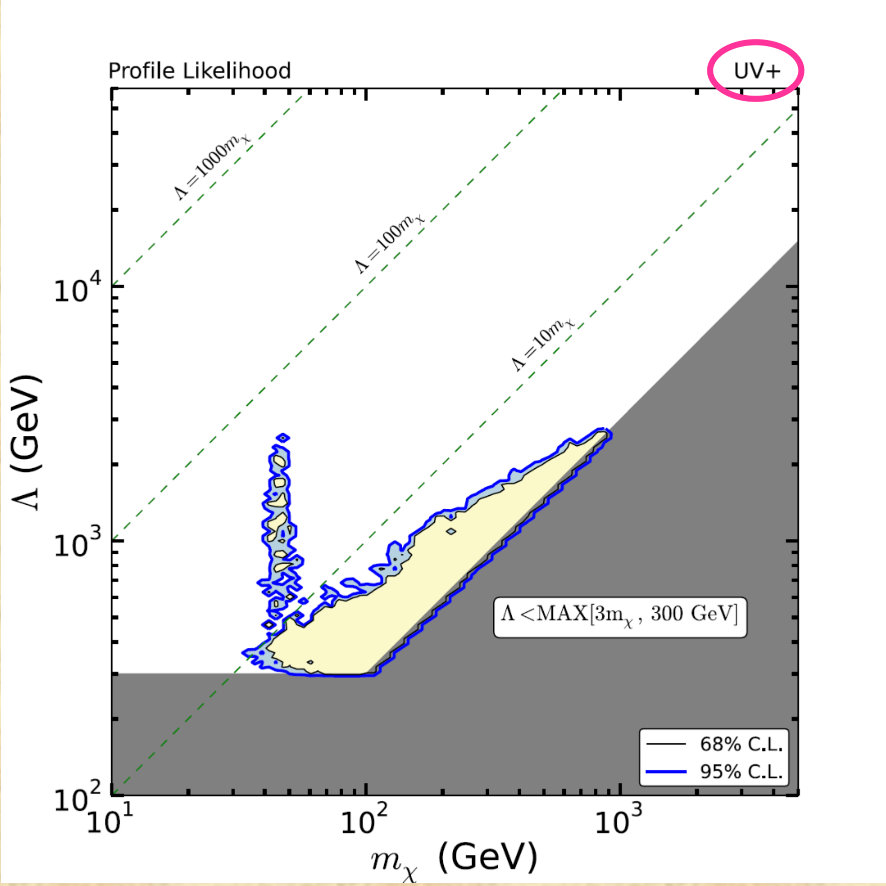
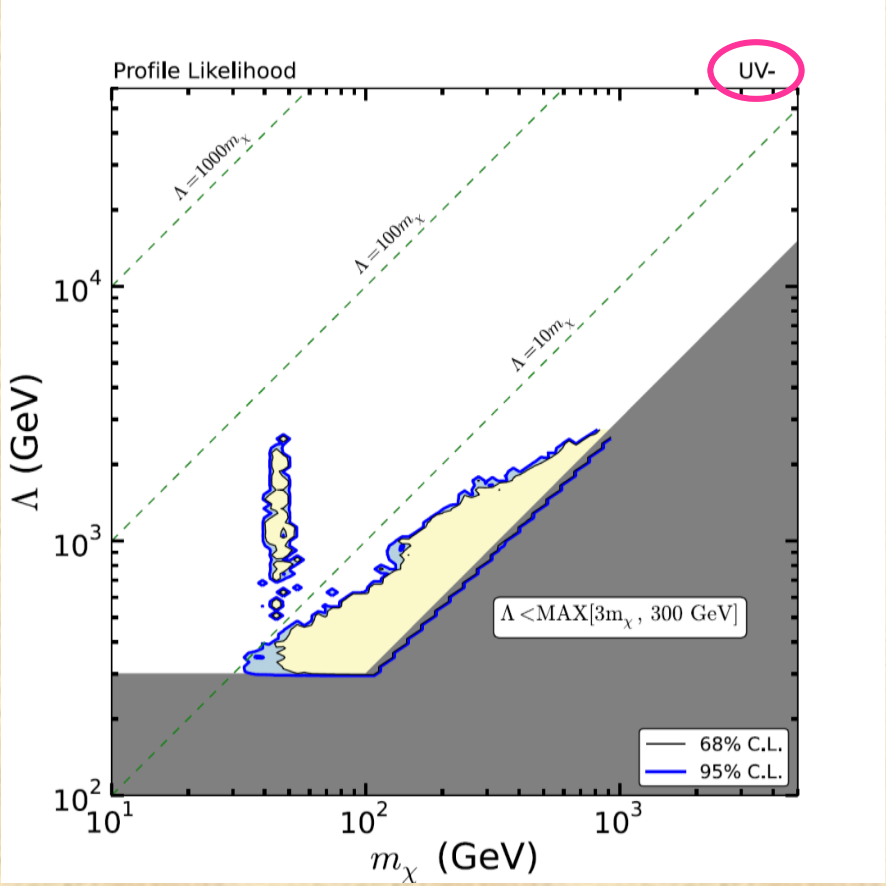
App 6

Future prospects in the Singlet-like patch

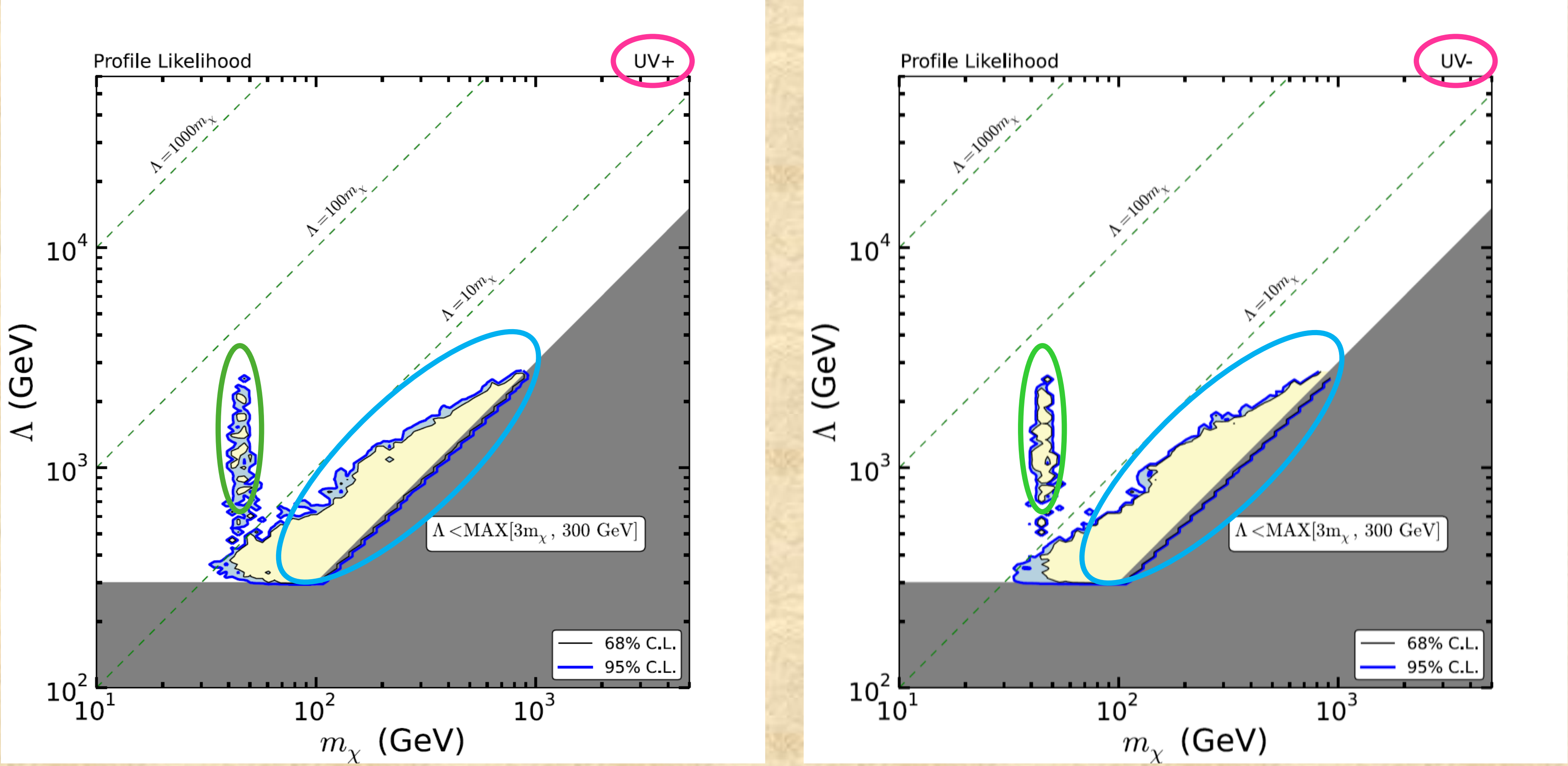




After LZ/PICO250

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

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.

The 4-Fermi region has already been restricted to be below $\Lambda < 10m_{DM}$.

Remaining parameter region is composed mainly of Leptophilic WIMP!