Singlet Majorana fermion dark matter: status and prospects

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This work (arXiv:1407.1859) is in collaboration with
Shigeki Matsumoto and Satyanarayan Mukhopadhyay
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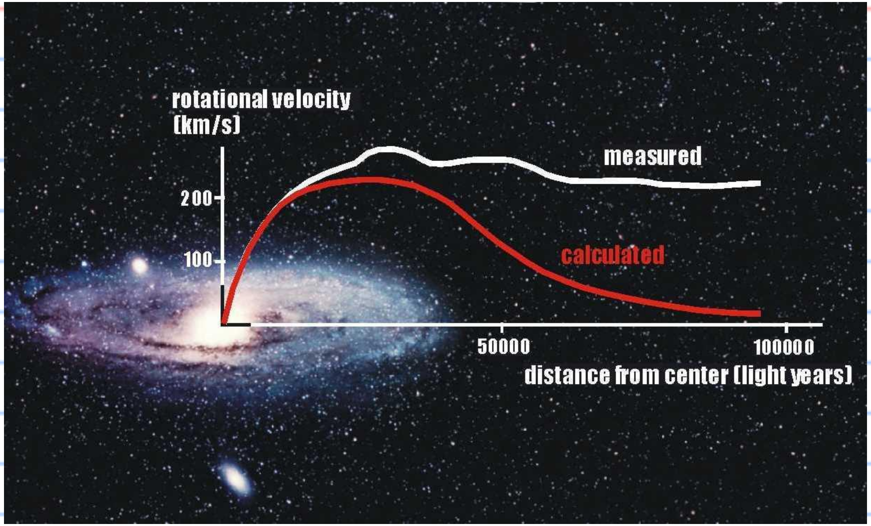
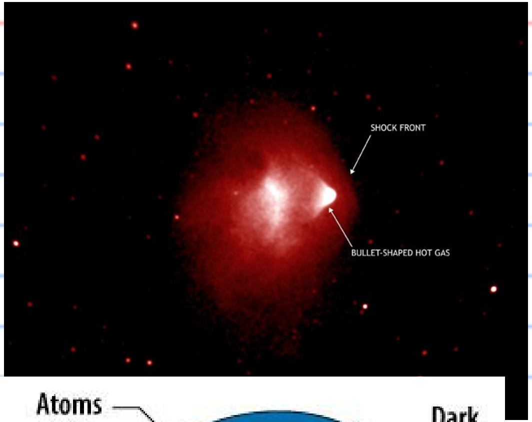
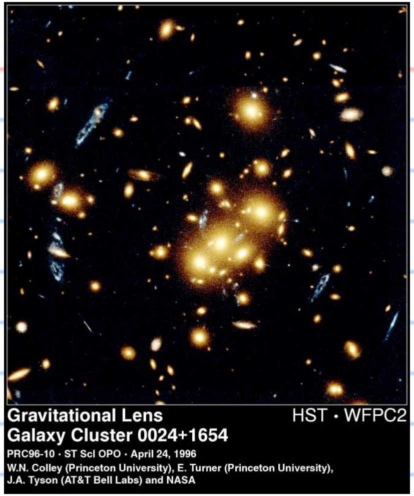
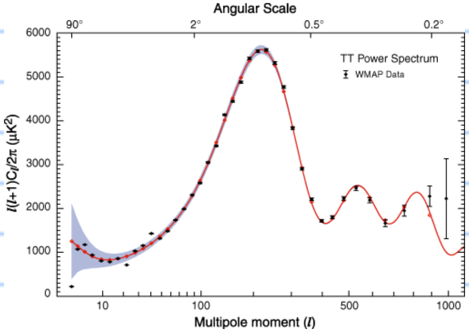
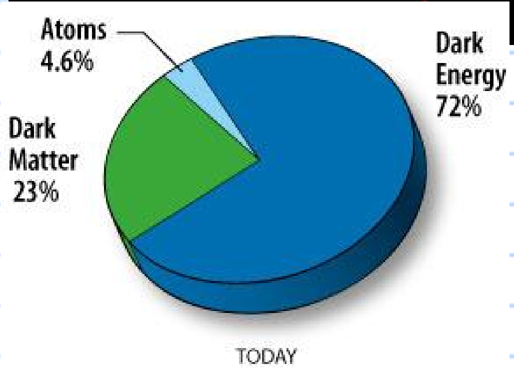
Dark Matter evidence











It will be difficult to explain the universe without dark matter assumption.

Outline

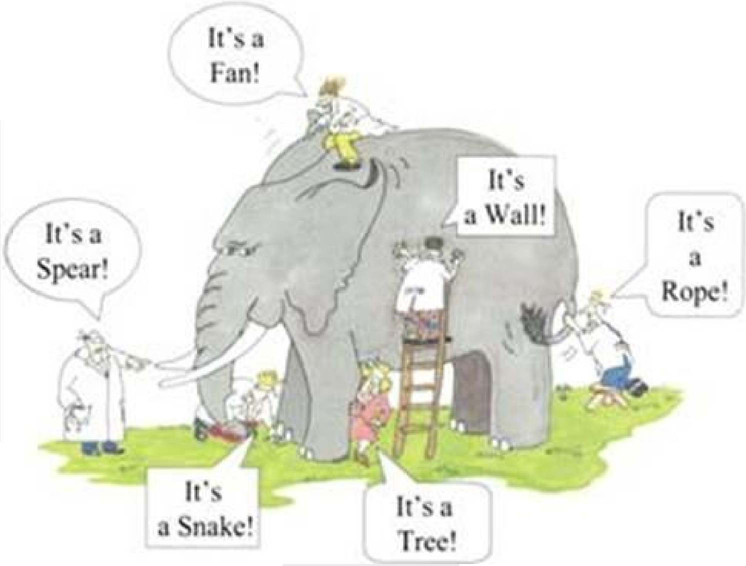
1. Motivation

2. Dark Matter effective operators

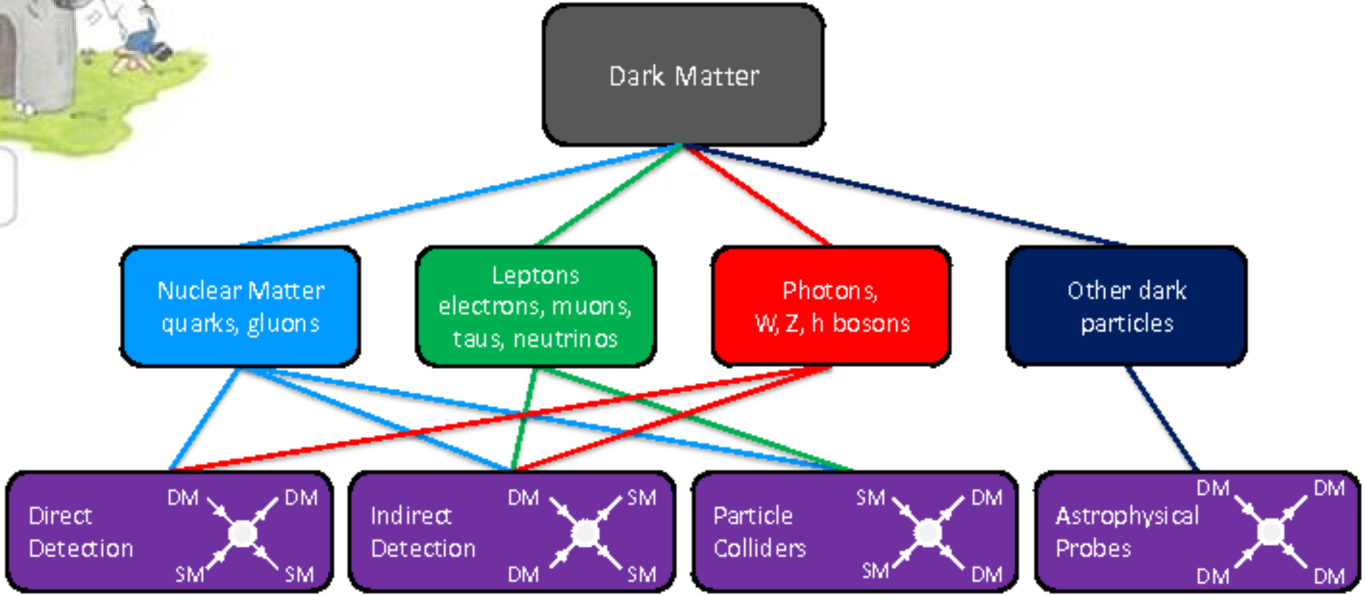
3. Impact of the relic density

4. future prospect

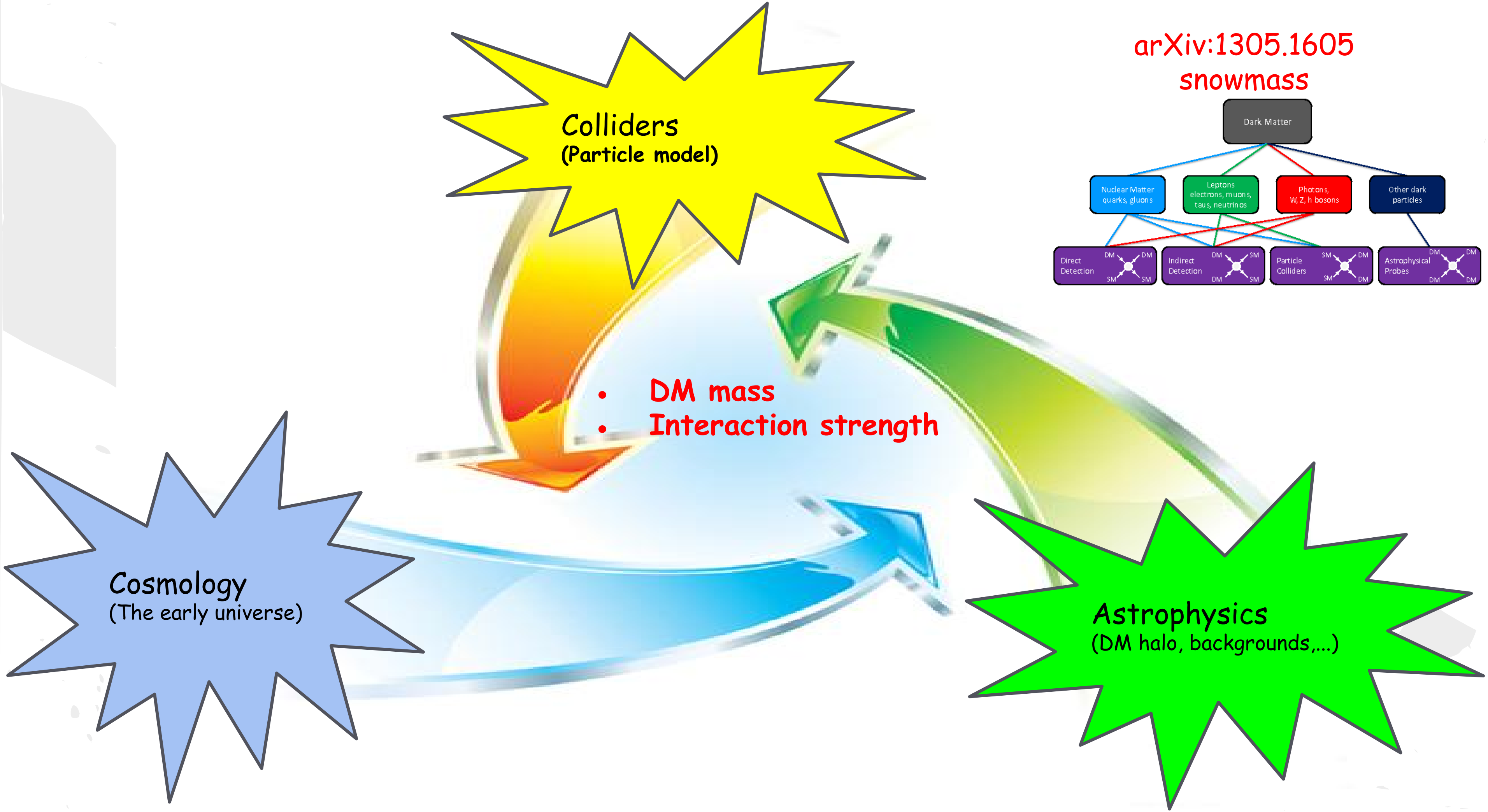
5. Summary



arXiv:1305.1605
snowmass



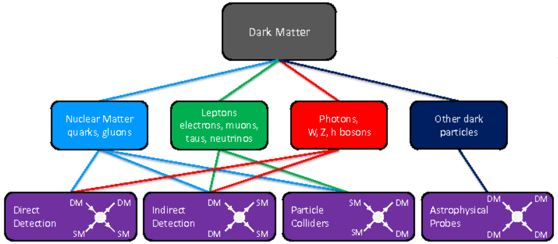
arXiv:1305.1605
snowmass



Credit: CERN Bulletin
http://cds.cern.ch/journal/CERNBulletin/2010/18/News%20Articles/1261775

Colliders
(Particle model)

arXiv:1305.1605
snowmass



- DM mass
- Interaction strength

Cosmology
(The early universe)

Astrophysics
...grounds,...)

Dark Matter studies at one of search are highly with some disadvantages: one can identify part of DM properties.

This will need a confirmation from other two searches.

Dark Matter effective operators


WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
Dark Photon
Asymmetric DM
Light Force Carriers
Sterile Neutrinos
Warm DM
Axion DM
mSUGRA
pMSSM
Dirac DM
R-parity Conserving
Gravitino DM
Q-balls
Supersymmetry
Theories of Dark Matter
?
Soliton DM
Quark Nuggets
T-odd DM
Extra Dimensions
UED DM
6d
5d
RS DM
Warped Extra Dimensions

Could we have a particle model independent DM study?

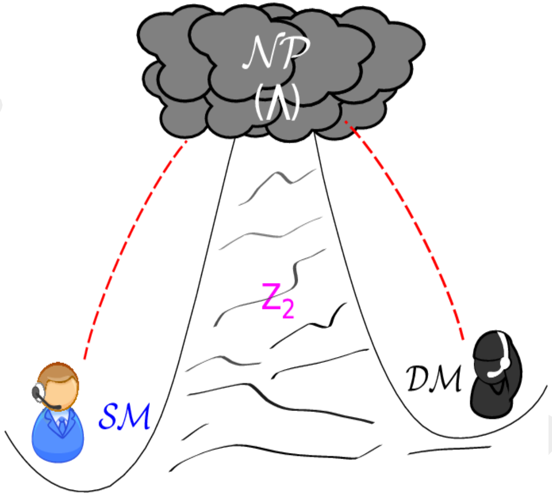
Phenomenological WIMP DM models

Scientific name	Popular name	Spin	$SU(2)_L$	$U(1)_Y$
Singlet scalar	The simplest DM	0	0	0
Doublet scalar	Inert Higgs DM	0	½	½
Triplet scalar		0	1	0
Triplet scalar II		0	1	1
…	…	…	…	…
Singlet fermion	Bino / Singlino	½	0	0
Doublet fermion	Higgsino	½	½	½
Triplet fermion	Wino	½	1	0
Triplet fermion II		½	1	1
…	…			
Singlet vector	Little Higgs DM	1	0	0
Doublet vector		1	½	½
Triplet vector		1	1	0
Triplet vector II		1	1	1
…	…			

Credit: Shigeki Matsumoto

DM still leaves a lot unknown:

- Spin
- Electroweak charge
- Real/Majorana or Complex/Dirac



Credit: Qing-Hong Cao, Chuan-Ren Chen, Chong Sheng Li, Hao Zhang (0912.4511)

The effective Model to start with

The simplest settings:

- Majorana fermion
- Singlet
- Z2-symmetry
- WIMP
- dimension<7

The DM in this class:

- Bino neutralino
- Singlino neutralino
- Sterile neutrino

EFT requirements:
(Heavy mediator)

- **lambda>2 mx**
- **lambda>10 mx**

Minimal requirement of not producing mediator particle on shell in a process.

EFT calculation of annihilation rate accurate to O(8%) when compared to s-channel UV completions

SM particles. An EFT description in this case boils down to replacing by a constant mass scale the product of couplings of X to the DM-pair ($g_X^{\rm DM}$) and to the SM-pair ($g_X^{\rm SM}$), and its propagator denominator:

$$\frac{g_X^{\rm DM} g_X^{\rm SM}}{s - m_X^2} \to \frac{-g_X^{\rm DM} g_X^{\rm SM}}{m_X^2} \left(1 + \frac{s}{m_X^2} + \mathcal{O}(\frac{s}{m_X^2})^2\right) . \tag{13}$$

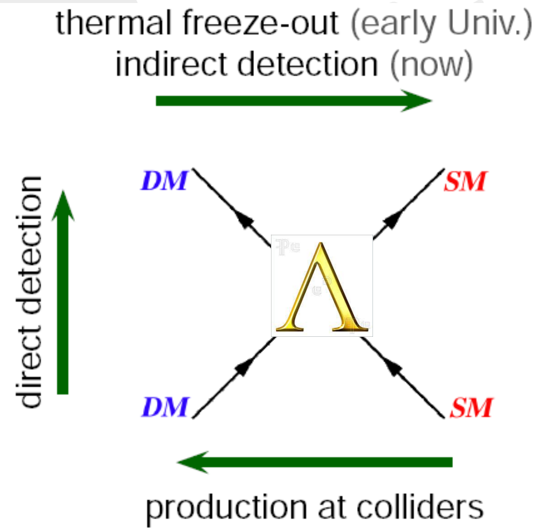
In an weakly coupled underlying theory, $g_X^{\rm DM} \sim g_X^{\rm SM} \sim \mathcal{O}(1)$, and henceforth we shall assume this to be the case. Therefore, when matching the UV theory to the EFT, we obtain the relation $\Lambda = m_X$ for $g_X^{\rm DM} \times g_X^{\rm SM} = 1$. Now, consider the pair annihilation rate of χ in the early universe, which is relevant for determining its current abundance. In this case, if v is the relative velocity between the DM particles, then the centre of mass energy squared is given by

$$s = 4m_\chi^2 + m_\chi^2 v^2 + \mathcal{O}(v^4). \tag{14}$$

Therefore, the 2nd term in the propagator expansion in Eq. 13 now reads

$$\frac{-s}{m_X^4} \simeq \frac{-4m_\chi^2}{m_X^4} - \frac{m_\chi^2 v^2}{m_X^4}. \tag{15}$$

DM effective operators



$$\mathcal{L}_{\rm D5} = \frac{g_S}{\Lambda}\bar{\chi}\chi H^\dagger H$$

$$\mathcal{L}_{\rm D6}^{\rm Higgs} = \frac{g_D}{\Lambda^2}(\bar{\chi}\gamma_\mu\gamma_5\chi)(H^\dagger i D^\mu H)$$

$$\mathcal{L}_{\rm D6}^{Lepton} = \sum_{i=1}^{3}\frac{1}{\Lambda^2}(\bar{\chi}\gamma_\mu\gamma_5\chi)(g_{LL}\bar{L}^i\gamma^\mu L^i + g_{RE}\bar{E}_R^i\gamma^\mu E_R^i)$$

$$\mathcal{L}_5^{\rm CPV} = \frac{g_{PS}}{\Lambda}\overline{\chi}i\gamma_5\chi H^\dagger H.$$

$$\mathcal{L}_{\rm D6}^{Quark} = \sum_{i=1}^{3}\frac{1}{\Lambda^2}(\bar{\chi}\gamma_\mu\gamma_5\chi)(g_{LQ}\bar{Q}^i\gamma^\mu Q^i + g_{Ru}\bar{U}^i\gamma^\mu U^i + g_{Rd}\bar{D}^i\gamma^\mu D^i)$$

Why all operators?

$$O_1 = \sum_f \frac{C_1^f}{\Lambda_1^2} (\bar{\chi}\gamma^\mu\chi)(\bar{f}\gamma_\mu f) \ ,$$

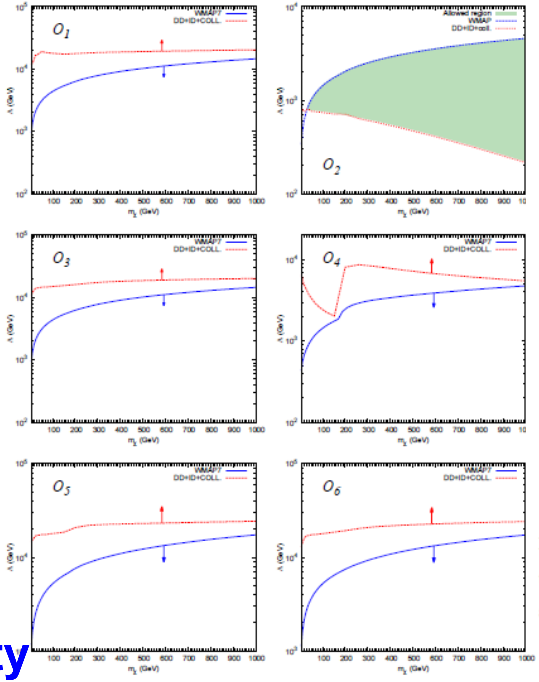
$$O_2 = \sum_f \frac{C_2^f}{\Lambda_2^2} (\bar{\chi}\gamma^\mu\gamma^5\chi)(\bar{f}\gamma_\mu f) \ ,$$

$$O_3 = \sum_f \frac{C_3^f}{\Lambda_3^2} (\bar{\chi}\gamma^\mu\chi)(\bar{f}\gamma_\mu\gamma^5 f) \ ,$$

$$O_4 = \sum_f \frac{C_4^f}{\Lambda_4^2} (\bar{\chi}\gamma^\mu\gamma^5\chi)(\bar{f}\gamma_\mu\gamma^5 f) \ ,$$

$$O_5 = \sum_f \frac{C_5^f}{\Lambda_5^2} (\bar{\chi}\sigma^{\mu\nu}\chi)(\bar{f}\sigma_{\mu\nu} f) \ ,$$

$$O_6 = \sum_f \frac{C_6^f}{\Lambda_6^2} (\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi)(\bar{f}\sigma_{\mu\nu} f) \ ,$$



Blue: relic density

Red: Coll+DD+ID

FIG The combined analysis for O_1, O_2, O_3, O_4, O_5 and O_6. In each panel, the WMAP7 data requires the area below the blue curve (indicated by the blue arrow) while all the other data requires the area above the red curve (indicated by the red arrow). The allowed region is shaded for O_2.

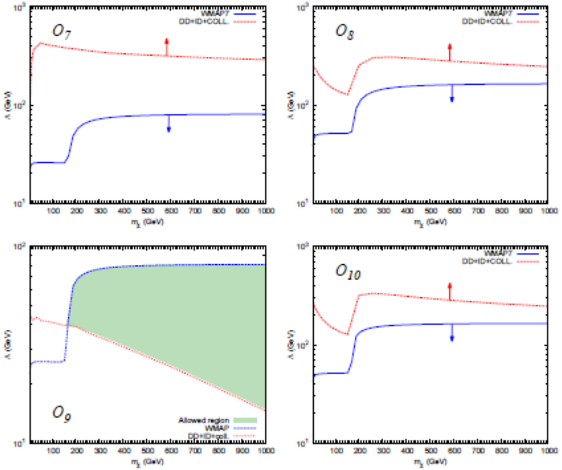


FIG. 8. The combined analysis for O_7, O_8, O_9 and O_{10}. In each pa the area below the blue curve (indicated by the blue arrow) while area above the red curve (indicated by the red arrow). The allowe

$$O_7 = \sum_f \frac{C_7^f m_f}{\Lambda_7^3} (\bar{\chi}\chi)(\bar{f}f) \ ,$$

$$O_8 = \sum_f \frac{iC_8^f m_f}{\Lambda_8^3} (\bar{\chi}\gamma^5\chi)(\bar{f}f) \ ,$$

$$O_9 = \sum_f \frac{iC_9^f m_f}{\Lambda_9^3} (\bar{\chi}\chi)(\bar{f}\gamma^5 f) \ ,$$

$$O_{10} = \sum_f \frac{C_{10}^f m_f}{\Lambda_{10}^3} (\bar{\chi}\gamma^5\chi)(\bar{f}\gamma^5 f) \ .$$

The Model to start with

$$\mathcal{L}_{D5} = \frac{g_S}{\Lambda}\bar{\chi}\chi H^\dagger H$$

$$\mathcal{L}_{D6}^{\text{Higgs}} = \frac{g_D}{\Lambda^2}(\bar{\chi}\gamma_\mu\gamma_5\chi)(H^\dagger iD^\mu H)$$

$$\mathcal{L}_5^{\text{CPV}} = \frac{g_{PS}}{\Lambda}\bar{\chi}i\gamma_5\chi H^\dagger H.$$

Family universality

$$\mathcal{L}_{D6}^{\text{Lepton}} = \sum_{i=1}^{3}\frac{1}{\Lambda^2}(\bar{\chi}\gamma_\mu\gamma_5\chi)(g_{LL}\bar{L}^i\gamma^\mu L^i + g_{RE}\bar{E}_R^i\gamma^\mu E_R^i)$$

$$\mathcal{L}_{D6}^{\text{Quark}} = \sum_{i=1}^{3}\frac{1}{\Lambda^2}(\bar{\chi}\gamma_\mu\gamma_5\chi)(g_{LQ}\bar{Q}^i\gamma^\mu Q^i + g_{Ru}\bar{U}^i\gamma^\mu U^i + g_{Rd}\bar{D}^i\gamma^\mu D^i)$$

Constraints	PLANCK (relic)	LUX (SI)	X100 (SD)	gamma-ray	Mono-jet	Mono-photon	inv. Z	inv. H
constrained couplings	ALL	gS	Quark, gD	ALL	Quark, gD	Lepton, gD	gD	gS, gPS

We included all the opertaors together!

The global study of Singlet Majorana DM

Measurement	Central Value	Error (1σ)	Distribution	Ref.
Relic density	0.1199	0.0027	Gaussian	[19]
BR($h \to$ invisible)	0.0	$\frac{24\%}{1.64}$	Gaussian	[40]
$\Gamma(Z \to$ invisible)(MeV)	0.0	$\frac{2.0}{1.64}$	Gaussian	[24]
XENON100 $\sigma_n^{\rm SD}$ (2012)	Appendix A	Appendix A	Gaussian+Poisson	[21]
LUX $\sigma_p^{\rm SI}$ (2013)	Appendix A	Appendix A	Gaussian	[20]
Monojet (CMS, 8 TeV, 19.5 fb^{-1})	Appendix B	Appendix B	Gaussian+Poisson	[26]
Mono-photon (LEP, 650 pb^{-1})	Sec. 3.5.2	Sec. 3.5.2	Gaussian+Poisson	[25]
Fermi dSphs (5-yrs)	Ref. [37]	Ref. [37]	Gaussian+Poisson	[22]
IceCube-79	Sec. 3.4.2	Sec. 3.4.2	hard cut	[23]

Table 1: *The experimental constraints employed in our analysis, along with their central values, 1σ experimental uncertainties, and functional form of the likelihood functions. The details of most of the constraints are provided in the relevant sections referred to above.*

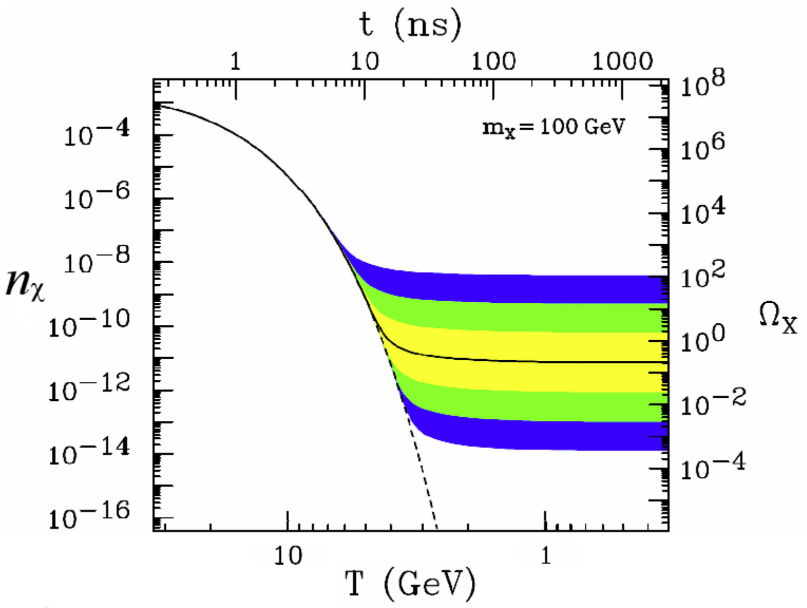
$$10\ \text{GeV} \le m_\chi \le 5\ \text{TeV}$$
$$2m_\chi \le \Lambda \le 100\ \text{TeV}$$
$$-1 \le g_i \le 1.$$

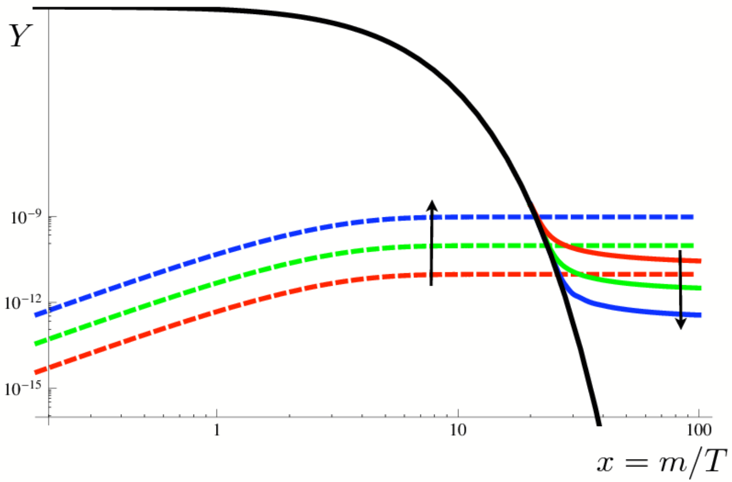
7 or 8 independent couplings

Constraints	PLANCK (relic)	LUX (SI)	X100 (SD)	gamma-ray	Mono-jet	Mono-photon	inv. Z	inv. H
constrained couplings	ALL	gS	Quark, gD	ALL	Quark, gD	Lepton, gD	gD	gS, gPS

Impact of the relic density

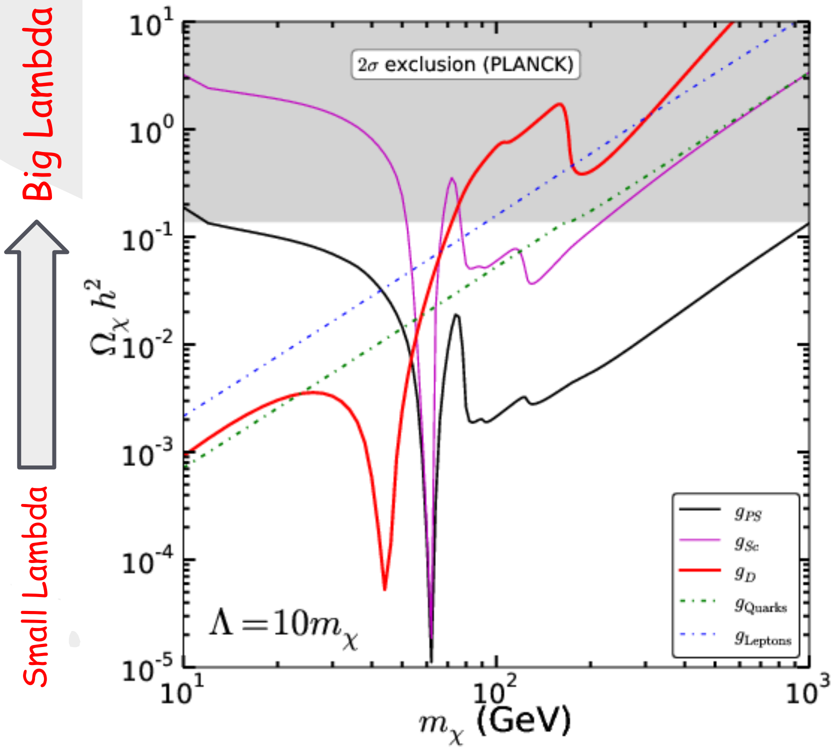
Thermal and Nonthermal





Assumption: DM can be reproduced by late time decay
relic density(thermal+nonthermal)=0.1

Relic density constraint



- We allow the relic density can be reproduced non-thermally, e.g., decay from moduli, gravitino, cosmic string...

$$\Phi_\gamma^{\rm real} \neq \left[\frac{\Omega_{\rm F.O.}}{\Omega_{\rm Now}}\right]^2 \times \Phi_\gamma^{\rm pred.}$$

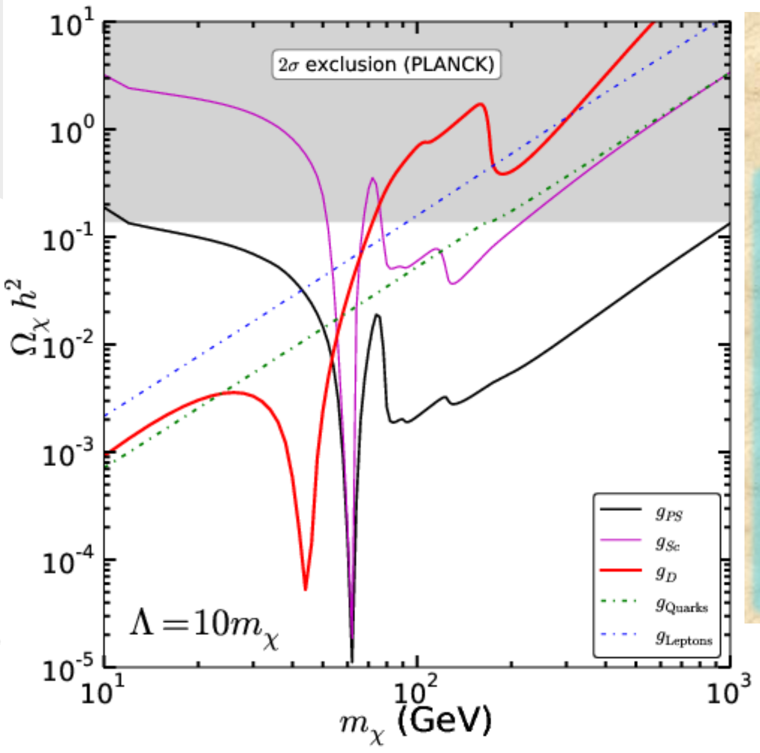
$$\sigma_{\chi p}^{\rm real} \neq \frac{\Omega_{\rm F.O.}}{\Omega_{\rm Now}} \times \sigma_{\chi p}^{\rm pred.}$$

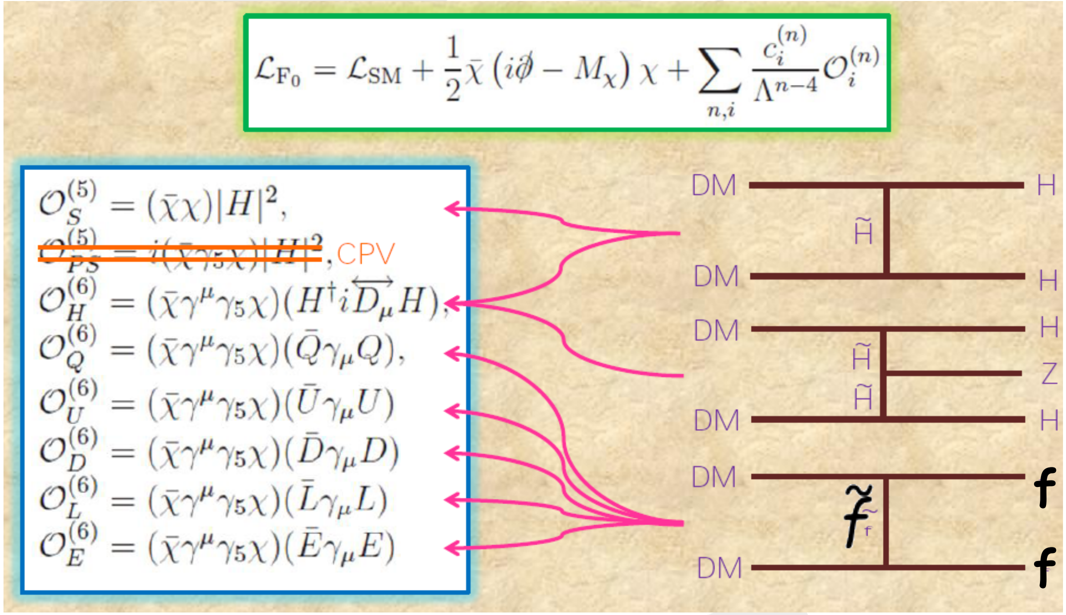
- The EFT validating line limits the lowest relic density.
- Except psudo-scalar coupling, all other couplings are only efficient at mx less than 300 GeV.

Relic density constraint

Big Lambda

Small Lambda

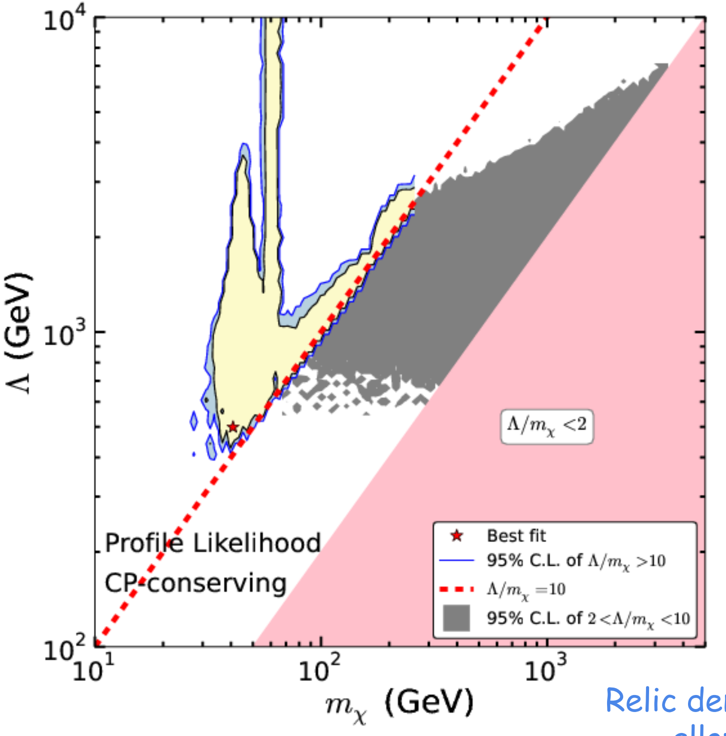




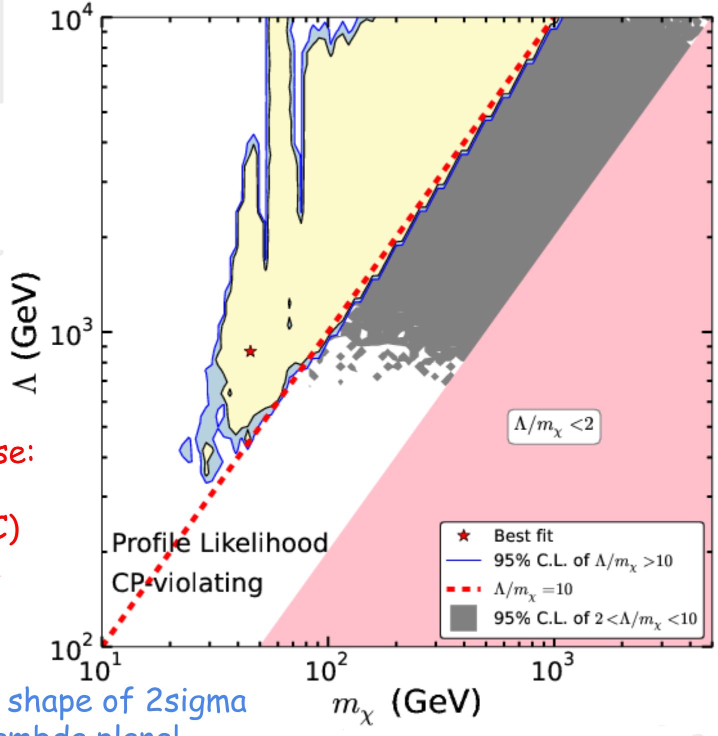
Credit: Shigeki Matsumoto

CP conserving and violating

$$\boxed{\mathcal{L}(\psi_{i=1,\dots,r}) = \max_{m\in\mathbb{R}^{n-r}} \mathcal{L}(m)}$$

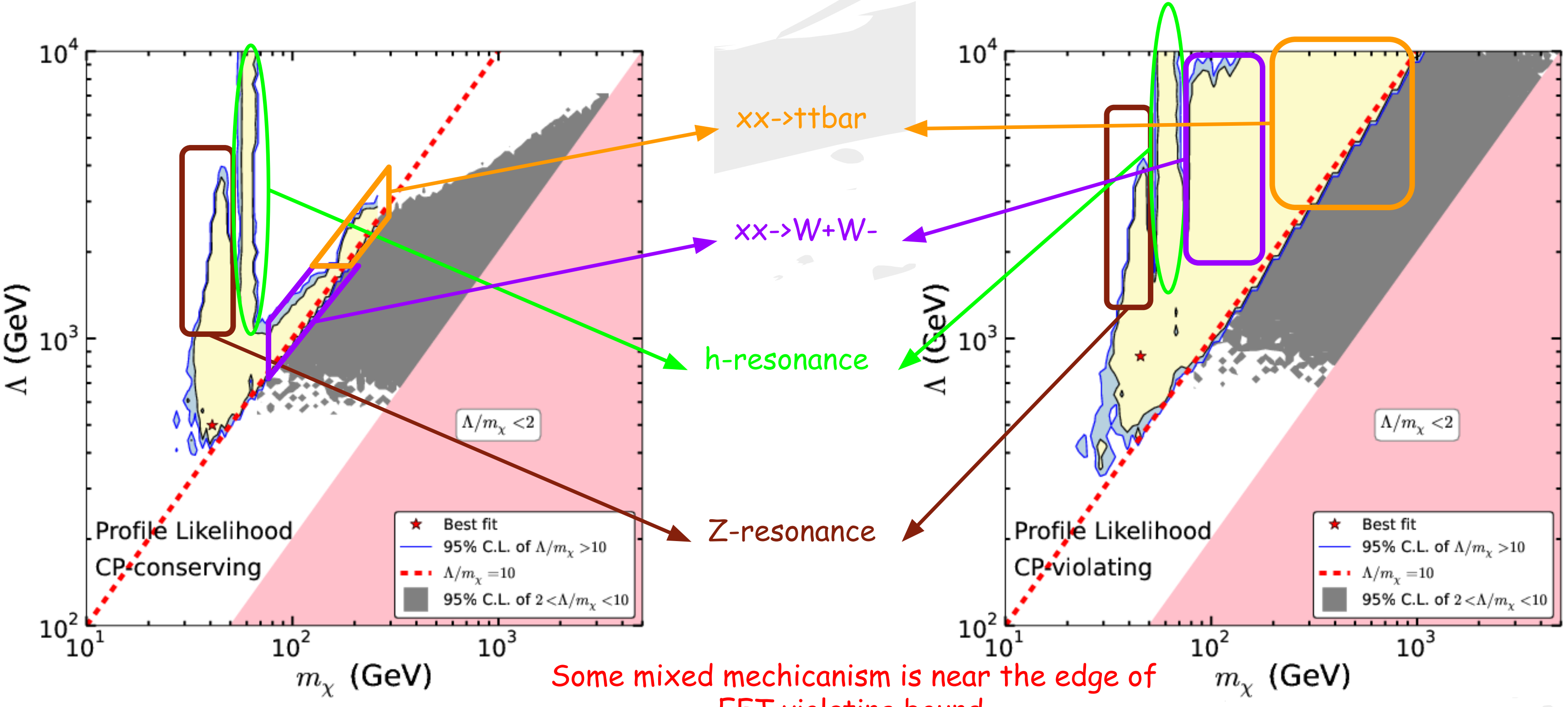


Lambda>10*mx case:
mx>20 GeV
mx<300 GeV (CPC)
mx<1 TeV (CPV).



Relic density dominant the shape of 2sigma allowed region in mx-lambda plane!

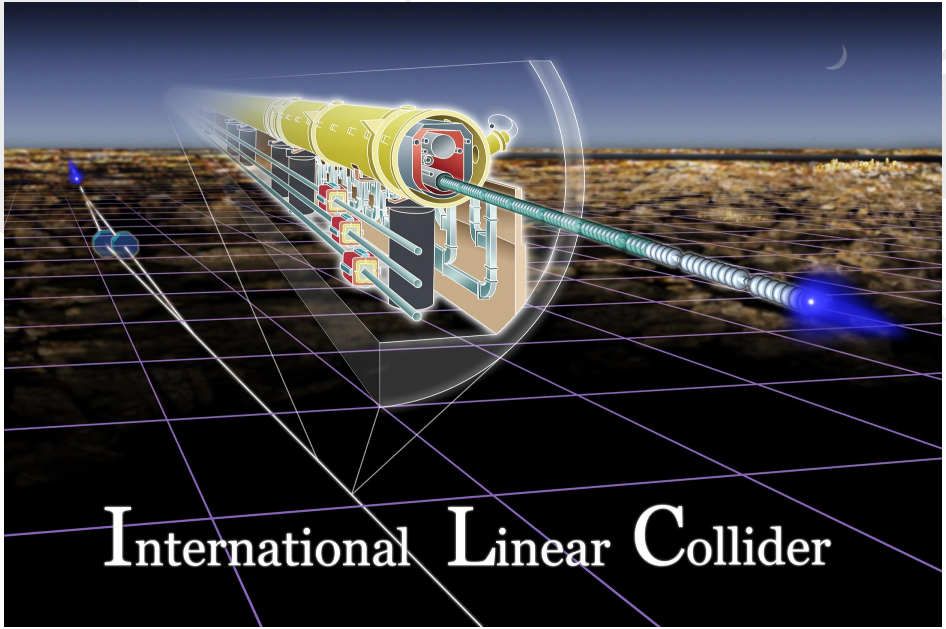
CP conserving and violating

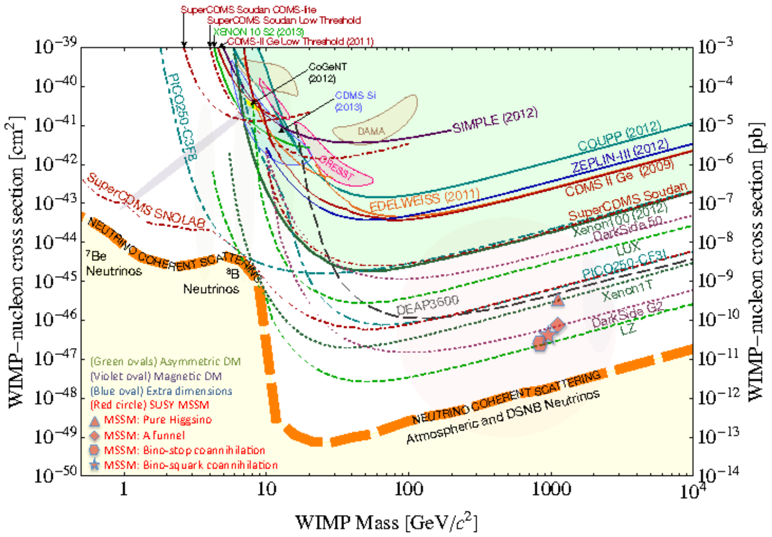


Some mixed mechicanism is near the edge of EFT violating bound.

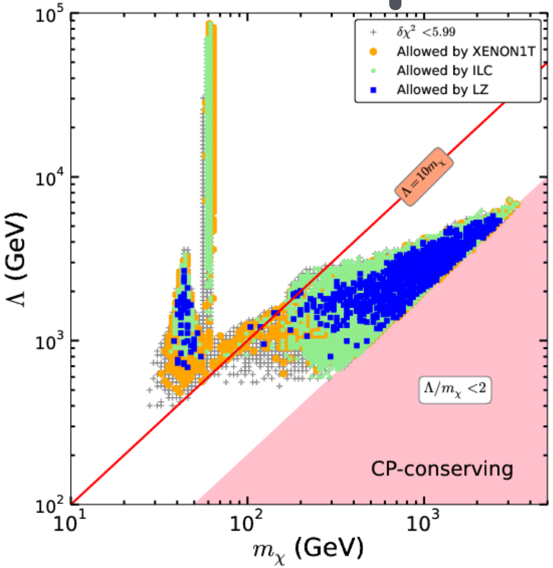
Future prospect

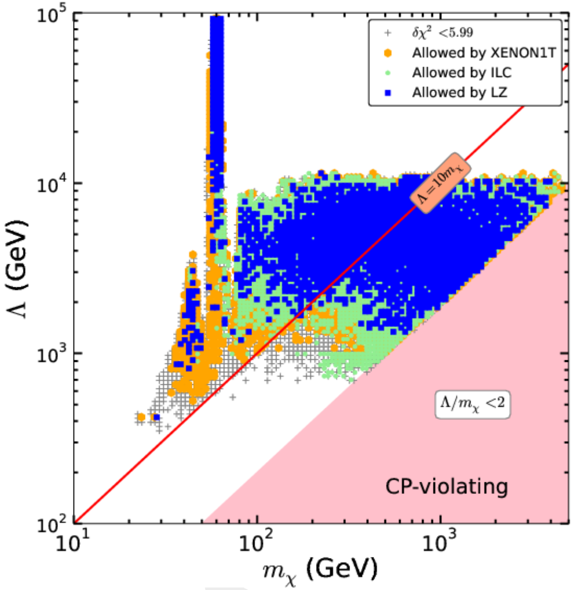
Future powerful experiments





Future prospect



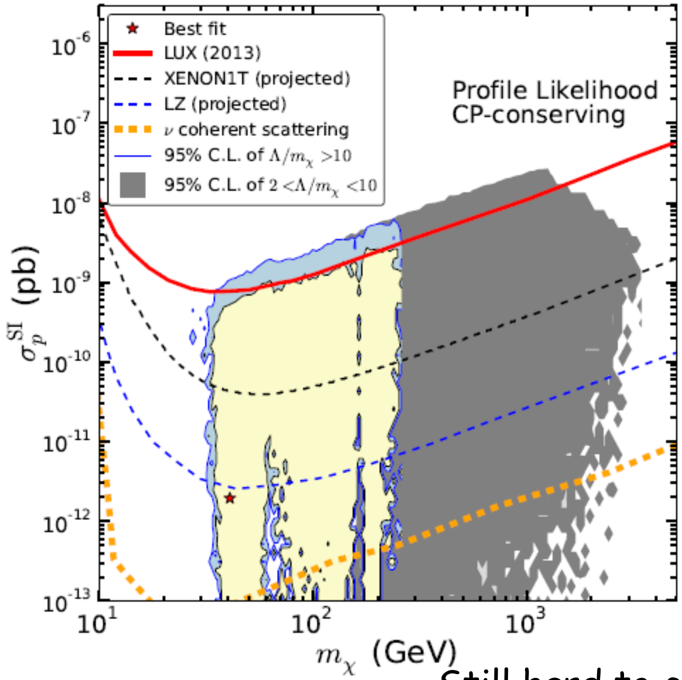


- Future LZ experiment can rule out most of parameter space in CPC scenario, even in Higgs resonance region.
- For the case Lambda>10*mx, only small lambda region near Lambda=10*mx (W+W- and ttbar) or Z-resonance survives.

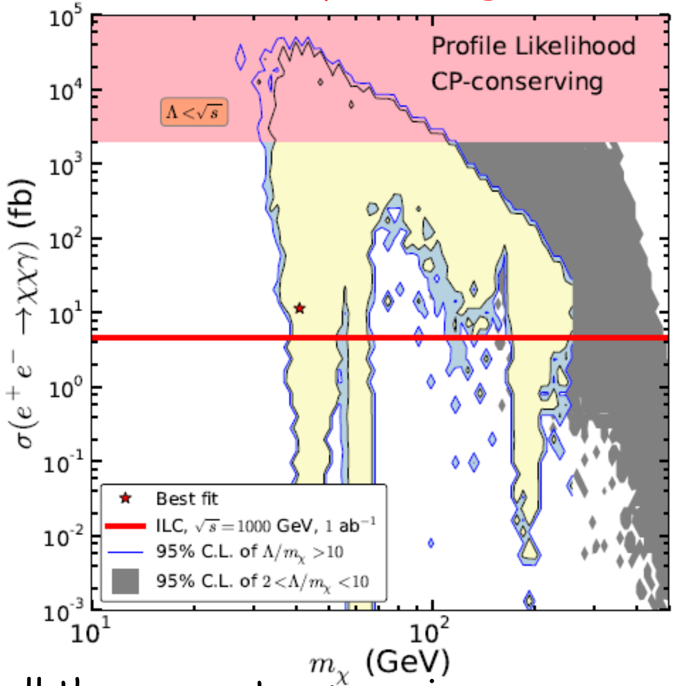
CP-violating term can weaken the future constraint's power.

DM Direct Detection and mono-photon cross section

gS



lepton and gD



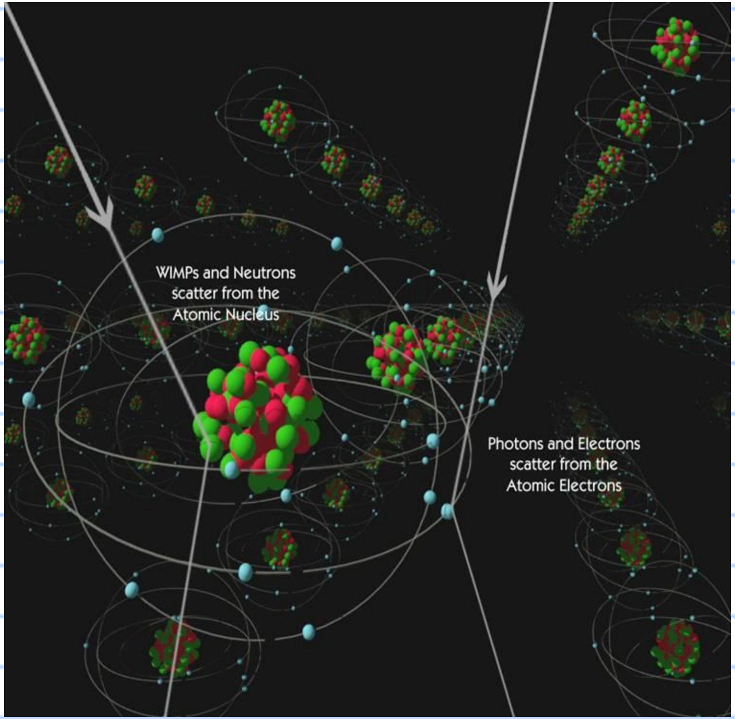
Still hard to cover all the parameter space in near future DM DD experiments and ILC.

Summary and Conclusion

- If mediator is heavy enough, lambda>10 mx, CPC/CPV DM has a limit on the mass, 20<mx/GeV<300/1000.
- In CPC case, even with non-thermal relic constraint, oh2<0.11, only h/Z-resonance and some tiny region at the small lambda is allowed. However, CPV operator can release more parameter space.
- Future LZ can entirely rule out h-resonance but it requires stronger spin-dependant DD and invisible Z-width to test DM-Z coupling.
- As long as the mediator heavier than 2*mx, our limits can be applied to bino/siglino/sterile neutrino dark matter.
- The most robust limits of Majorana fermion DM are given.
- It is testable in the future experiments.

Backup

Detect Dark Matter elastic scattering



Undetermined direct detection parameters:

- Local dark matter density
- Dark matter velocity distribution
- Dark matter mass
- Form Factor
- effective couplings of DM to protons and neutrons.

Large theoretical uncertainties from lattice physics

Astrophysical uncertainties ~2 (1111.0292, 1012.3458)
Form Factor uncertainties ~1.2 (hep-ph/0608035v2)

CDM in trouble

1. Core-vs-cusp problem

- Central densities of dwarf halos exhibit cores

2. Too-big-to-fail problem

- Simulations predict O(10) massive MW satellites more massive than observed MW dSphs

3. Missing satellite problem

- Fewer small MW dSphs than predicted by simulation
- Small enough to fail