Tiny Flavor Symmetry Breaking Neutrino Mass and Dark Matter

Based on collaboration with Y.Hamada,T.Kobayashi,A.Ogasahara,Y.Omura,D.Yasuhara

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Introduction

Particle Standard Model has been completed by Higgs discovery in 2012.

Our next step is identification of new physics in nature and further fundamental understanding of elementary particles and the interactions beyond SM.

We already have the hints.

Neutrino mass and mixing are experimentally well-established on earth.

Any other hints from cosmology/astrophysics?

Some of primordial quantities in early universe has been well established.

e.g. CMB photon after the decoupling from heat bath.

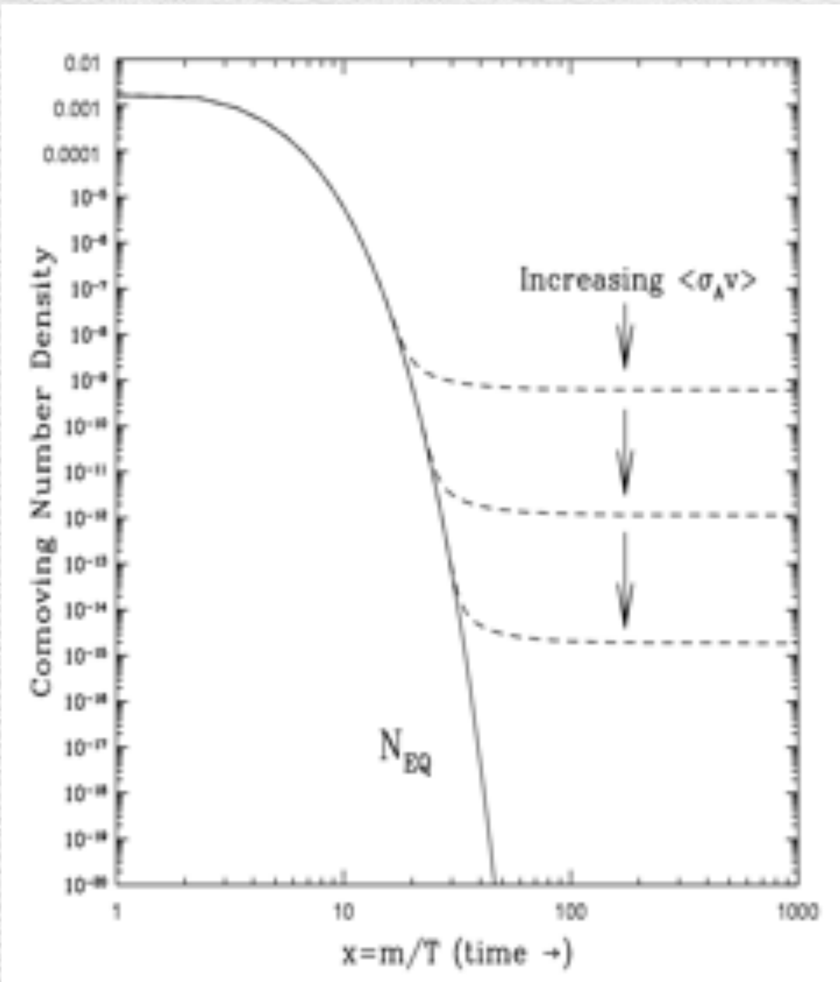
light elements abundances in Big Bang Nucleosynthesis

massless number of freedom → number of (light) neutrinos

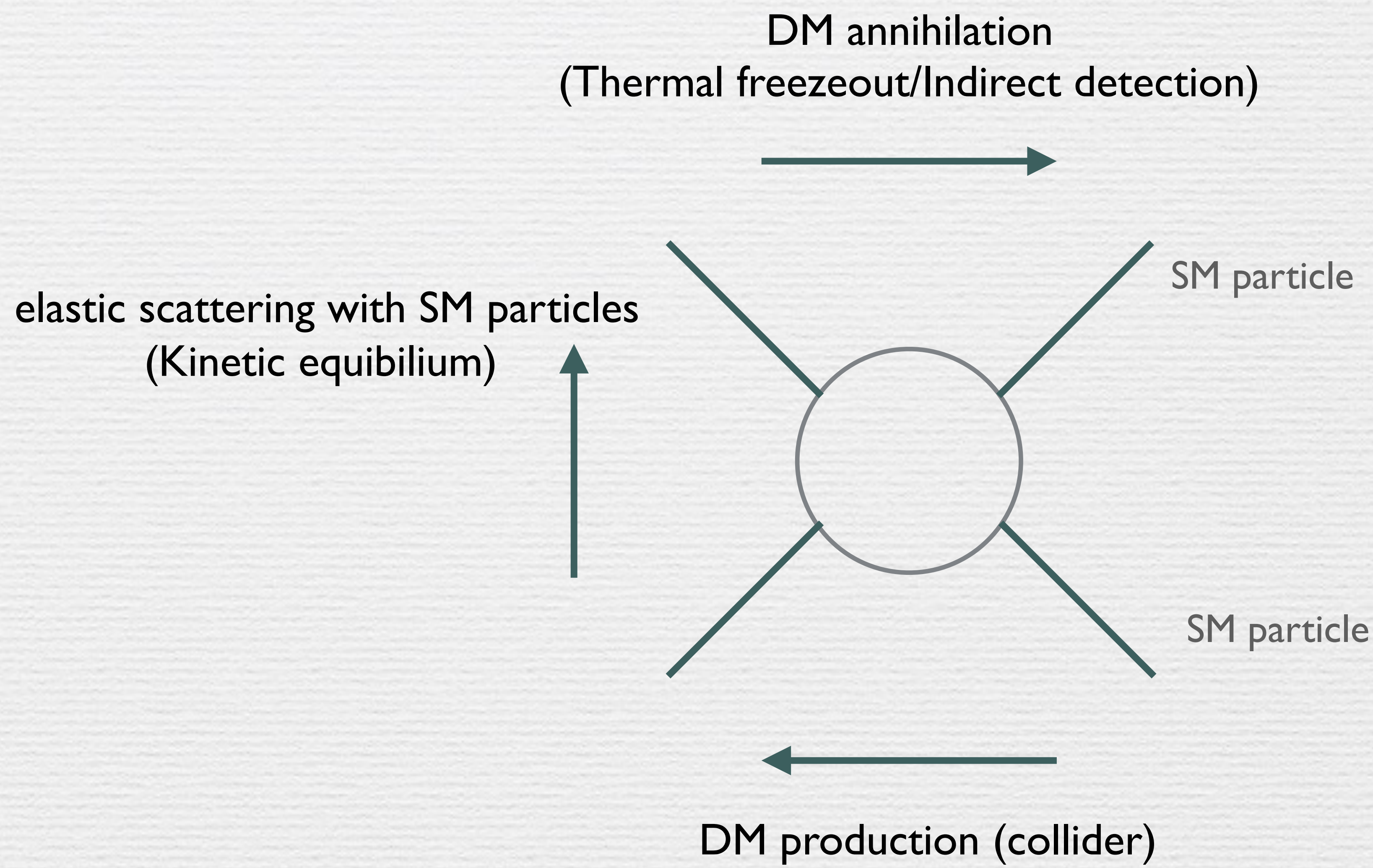
Fortunately these made possible to estimate further primordial values,

e.g. dark matter relic abundance and baryon number

WIMP and the thermal relic: a hint for new physics scale beyond SM



$$\frac{dn_\chi}{dt} + 3H(T)n_\chi = -\langle \sigma v \rangle (n_\chi^2 - n_{\chi,eq}^2),$$

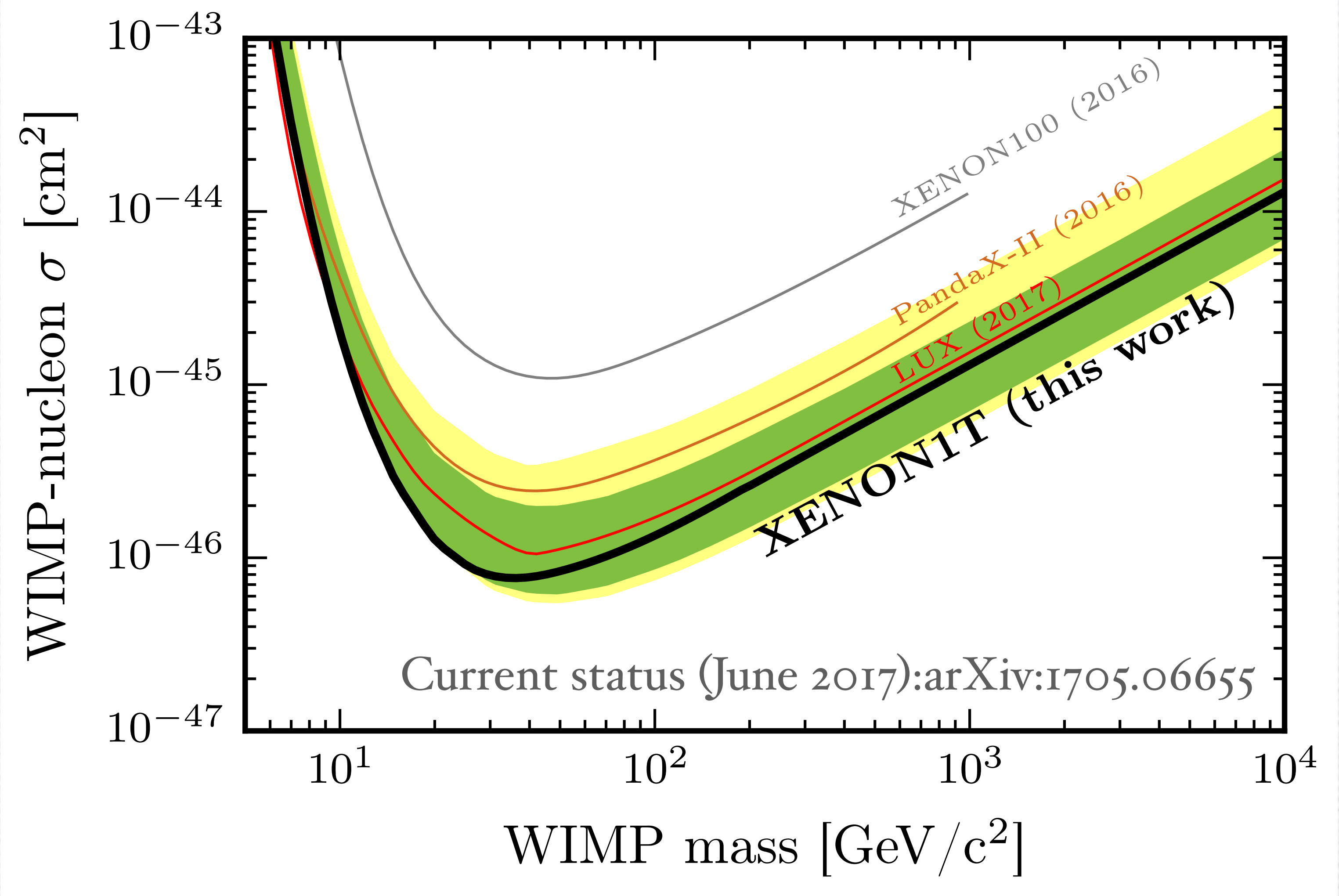


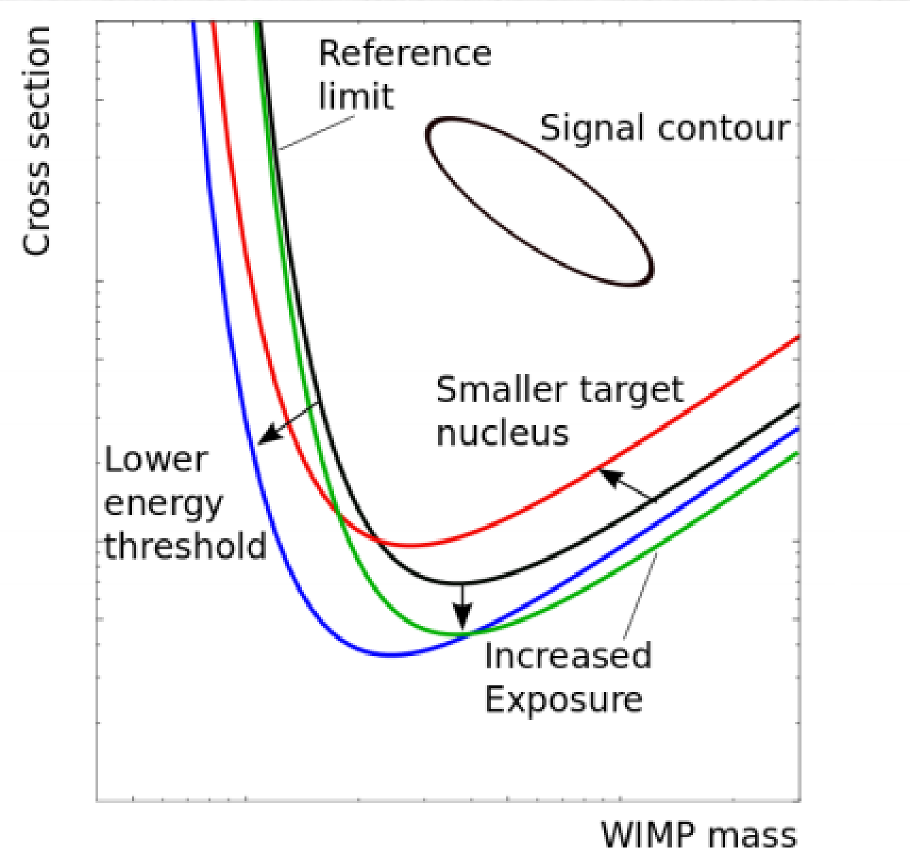
This could allow us to identify new physics scale. <σv>~(α/m)^2~1pb

If DM relic relate to thermal freeze out, DM may become deeper probes for the early universe.

Something unexpected happened after DM relic freeze out can be imprinted as mismatches with the present value.

Dark matter searches in underground





G.Arkadi et al arXiv:1703.07364

Future projects: Xenon 1T (1ton), LZ（10ton）

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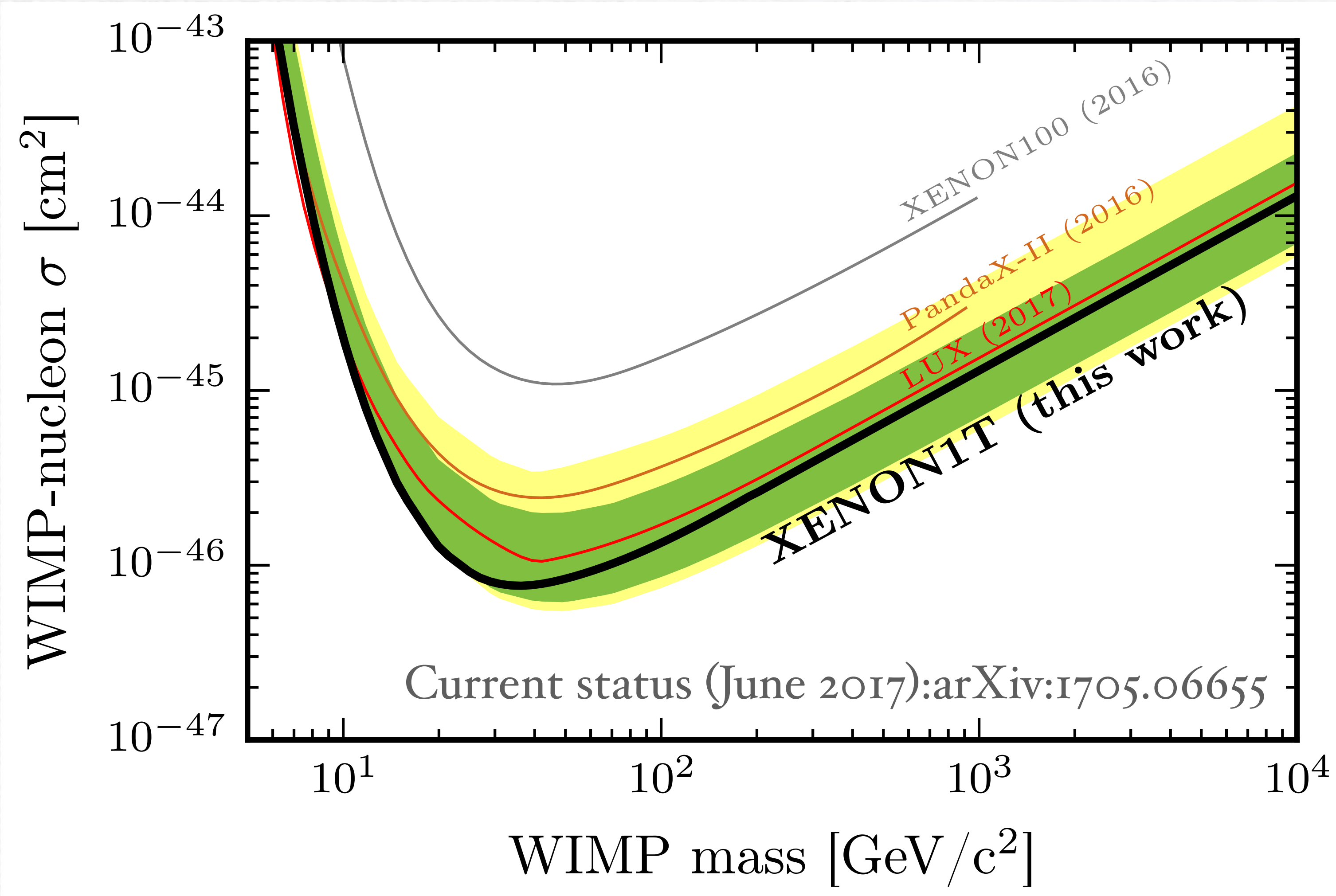

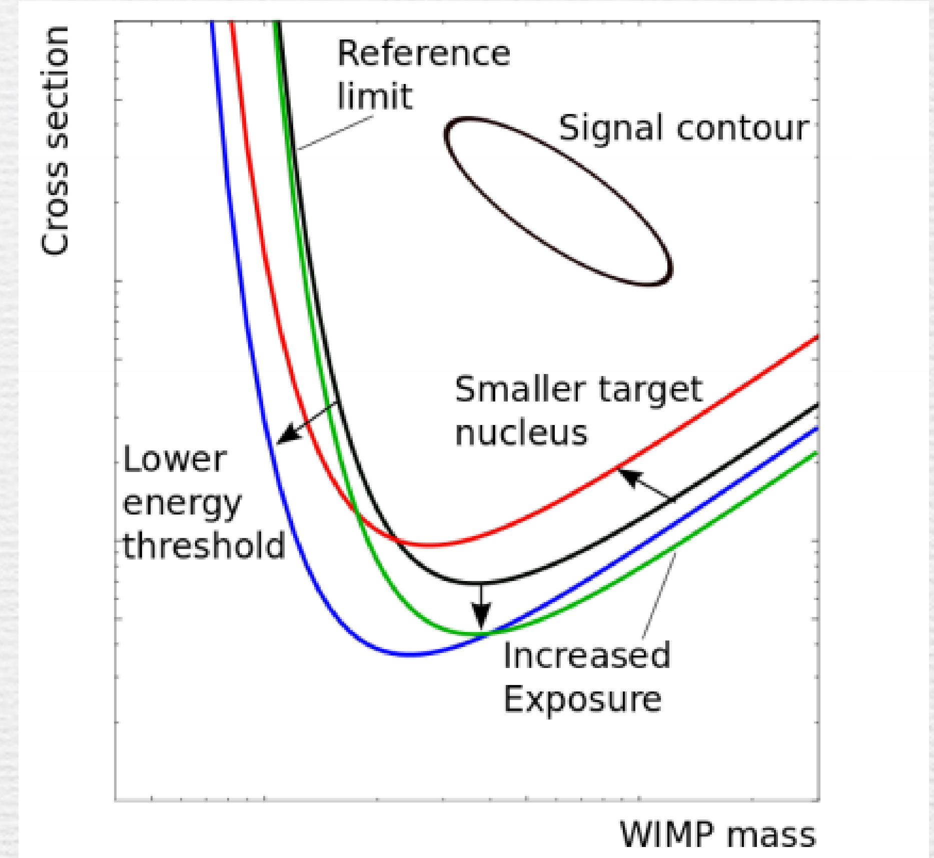

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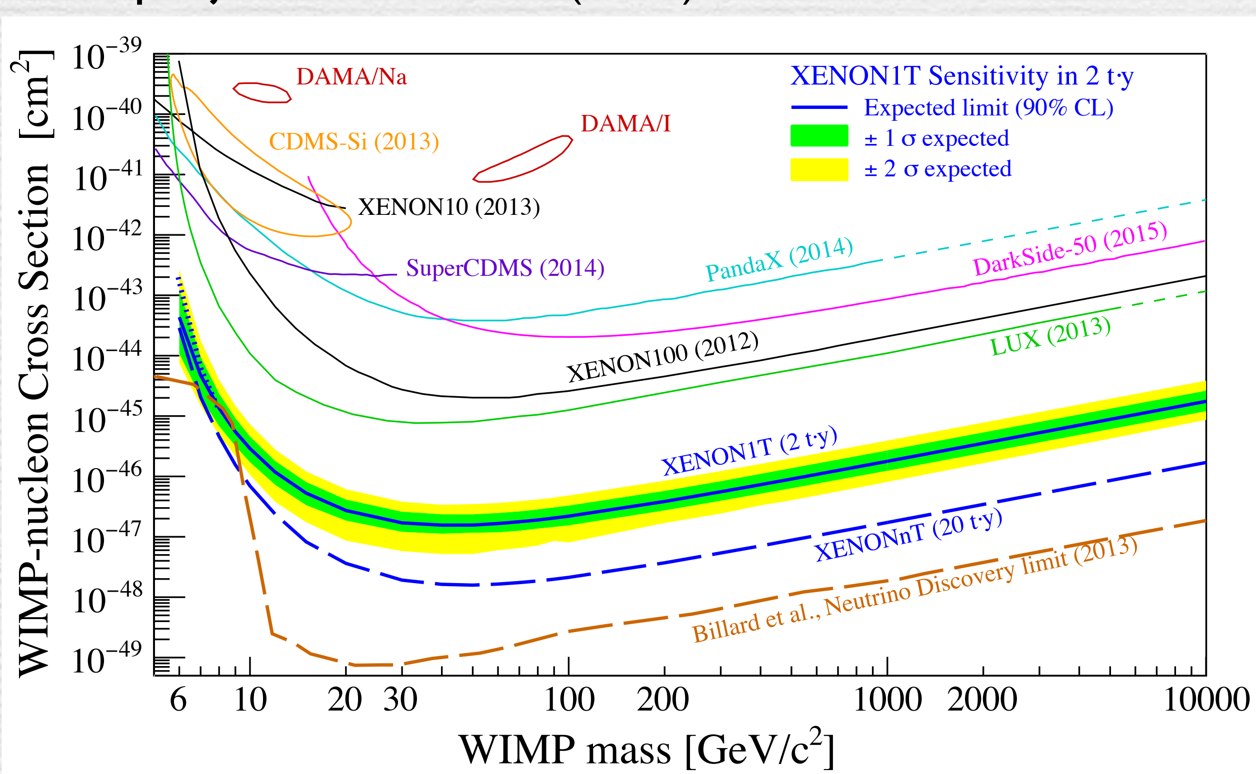

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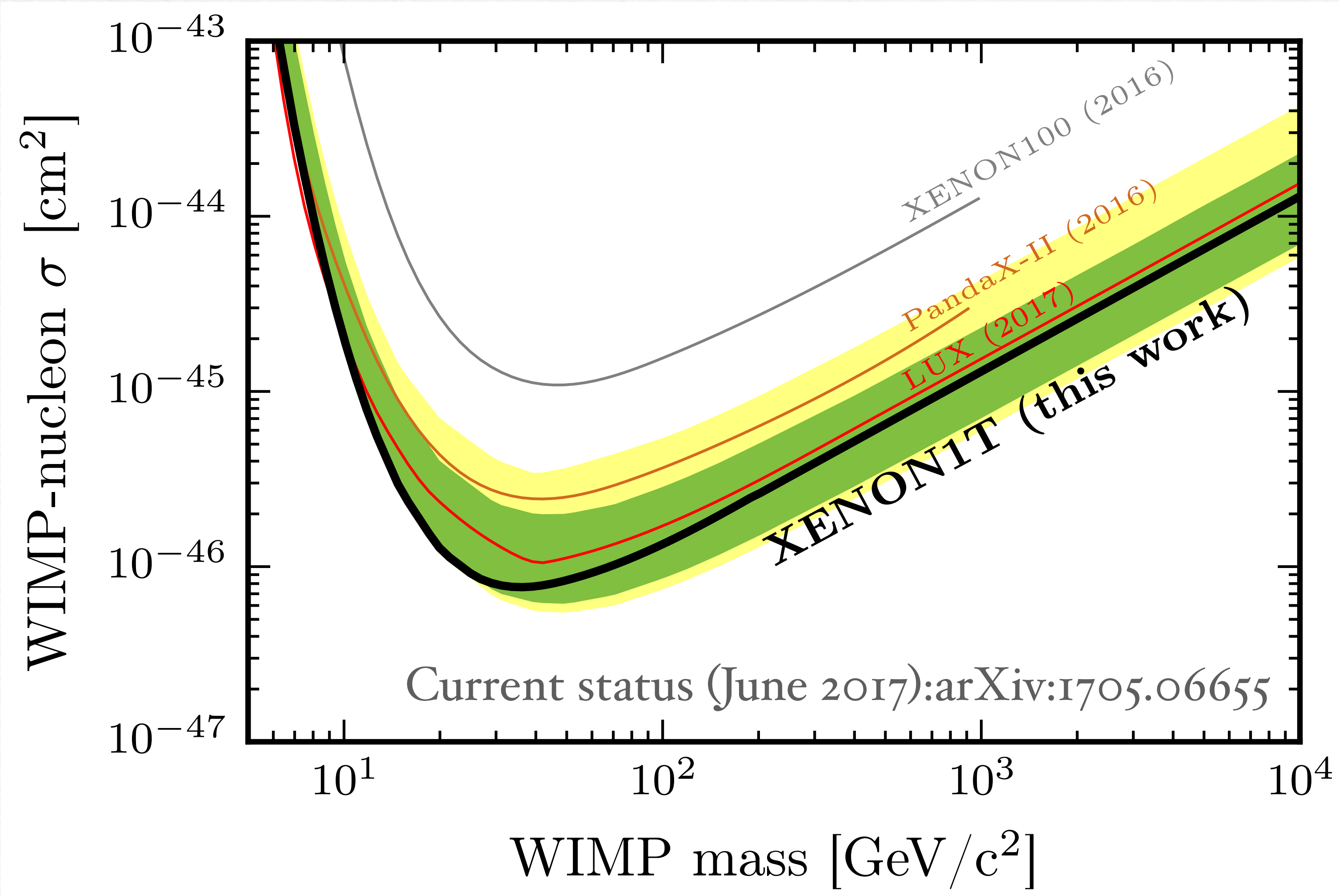

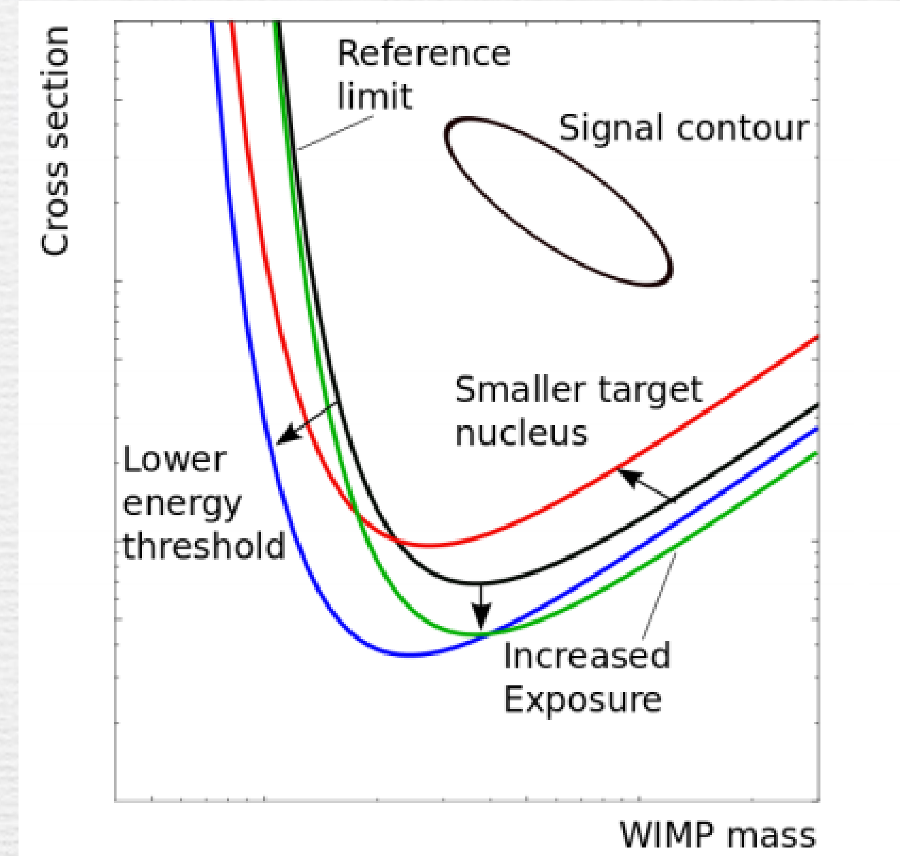

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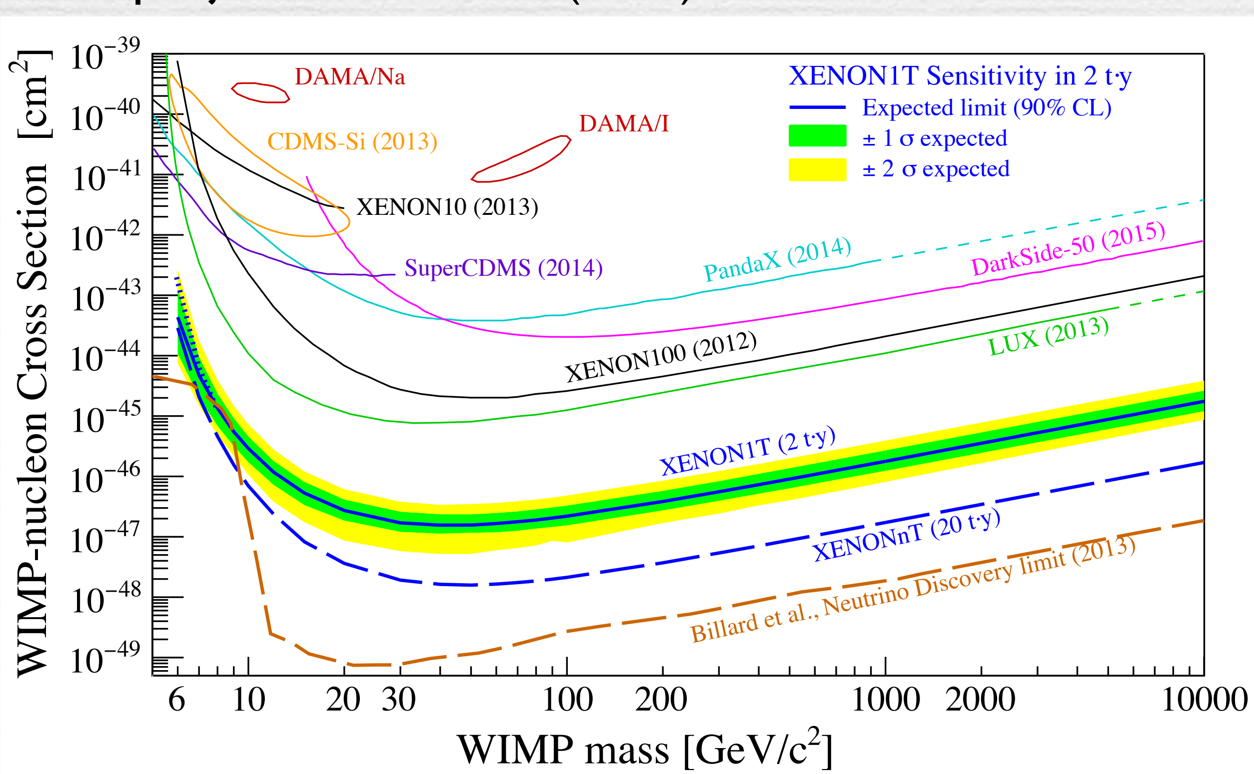
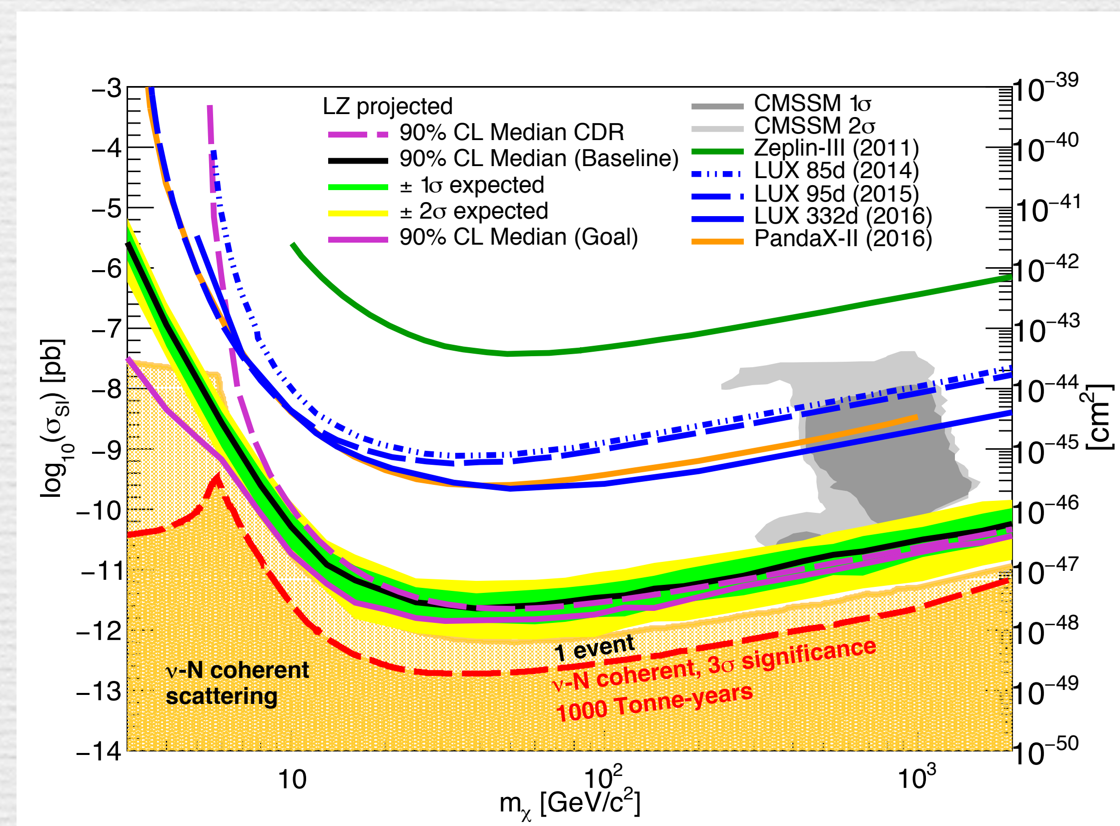




The dark matter coupling with quarks has been searched for .

If Dark Matter is fermion,

the expected coupling with SM particles in UV theory might be yukawa couplings

→ another parity odd new particle (messenger particle) is required.

LHC is searching for heavy messenger particle with missing energy in the decay and getting sever constraints.

If Dark Matter has couplings only with EW particles, collider bound can be weaken.

The both SI and SD couplings with nuclei is highly constrained in underground experiments.

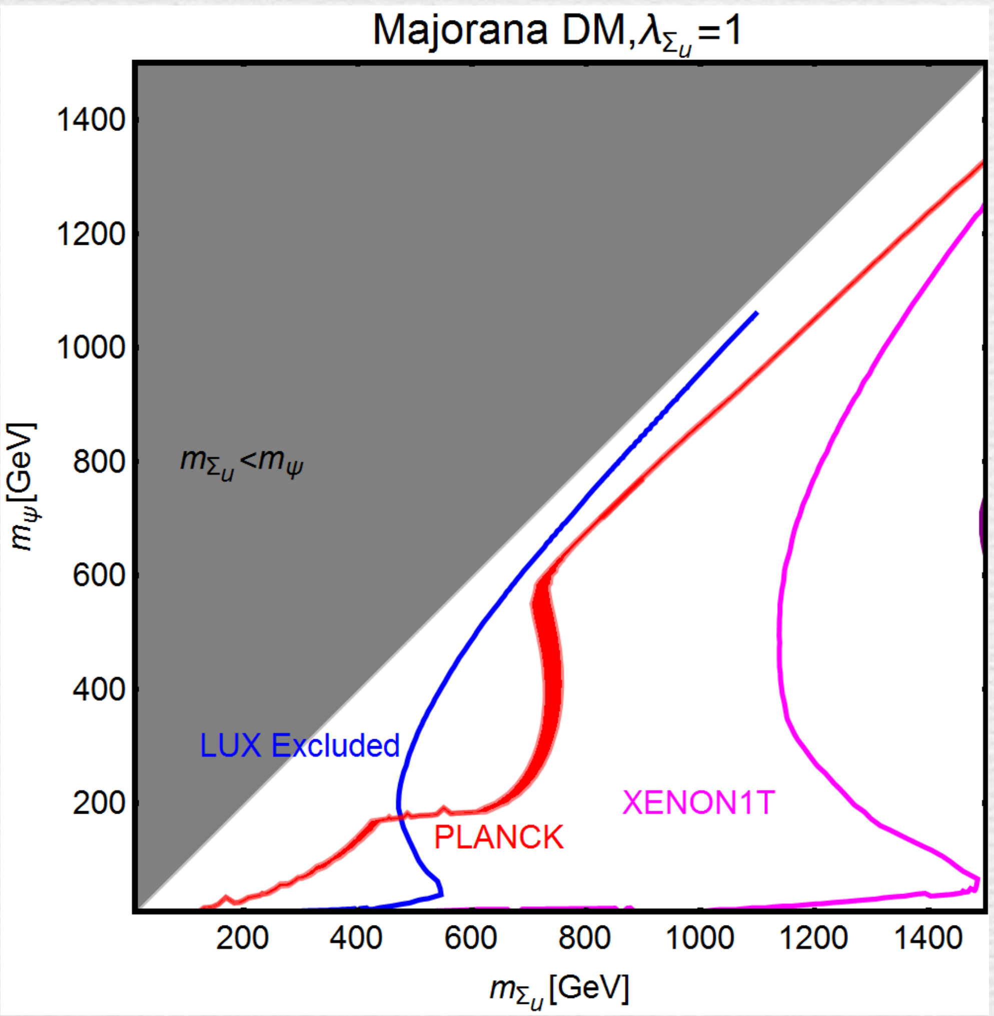
→ The possibility that Dark Matter is EW charged particle is highly constrained.

(Inelastic nature for DM direct detection may save some of scenarios.)

Direct dark matter searches for t-channel messenger scenario

singlet DM and t-channel mediator

$$\mathcal{L} = \lambda_{\Psi_q}\overline{\Psi}_q \chi q_R + h.c. \quad \text{or} \quad \mathcal{L} = \lambda_{\Sigma_q}\overline{\psi}\Sigma_q q_R + h.c., \quad q = u \text{ or } d.$$



Ignoring quark yukawa, Majorana DM escape severe SI bound at tree level

But the large part for DM coupling with quarks is excluded.

Leptophilic nature of Dark Matter might be plausible.

G.Arcadi et al, arXiv:1703.07364

Neutrino mass: another hint for new scale beyond SM

If majorana mass term describes observed neutrino masses,

Neutrino mass appears in dim 5 operator in SM which is the lowest higher dim operator.

The Leading contribution due to UV theory?

If lepton number is approximate good symmetry in low energy,
the effects due to higher operators could be plausible.

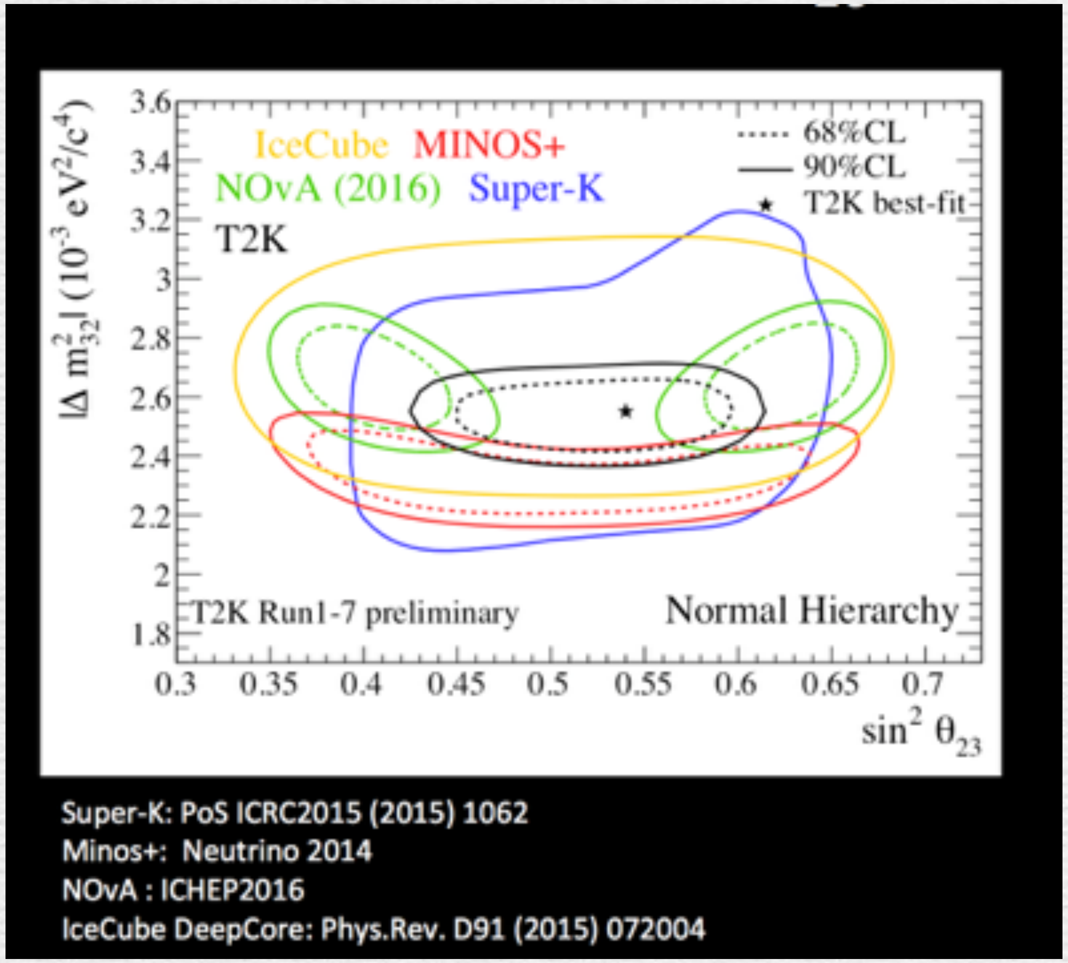
The UV completion is one of the most important subject in particle physics.

The degree of freedom of dim 5 operator is :

Three masses and the following mixing matrix

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$
$$\times \, \mathrm{diag}(1,\ e^{i\frac{\alpha_{21}}{2}},\ e^{i\frac{\alpha_{31}}{2}})\ .$$

Neutrino: from long-baseline experiments



All mixing angles within 3 neutrino scheme has been determined up to the ambiguities of CP and mass ordering.

The structure of mixing angles:

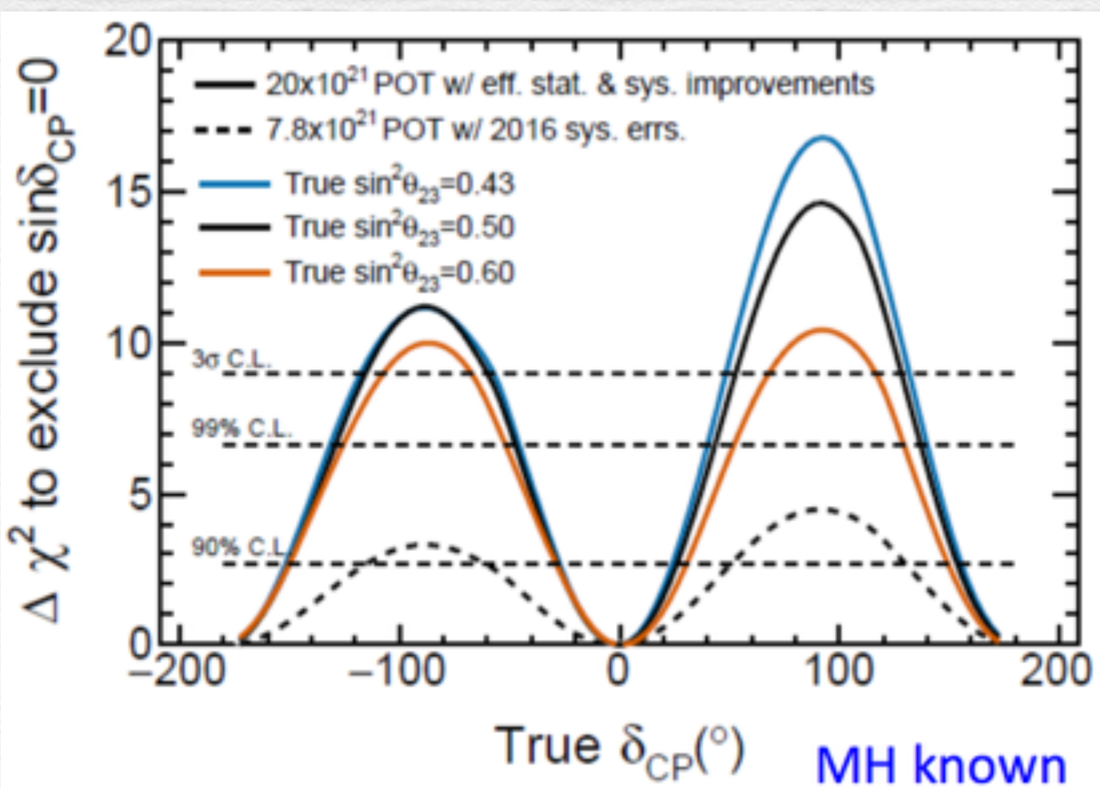
The origin of two large mixings,

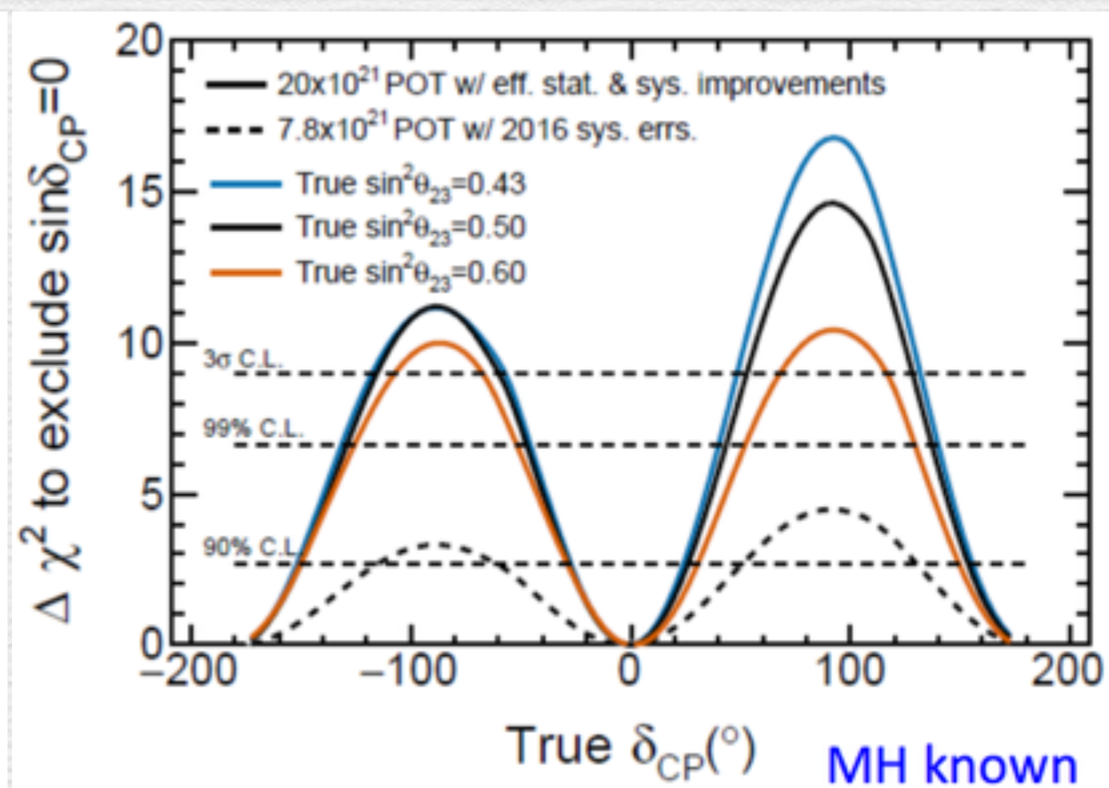
The possible deviation from maximal mixing

The origin of leptonic CP phase

→ Further hint for the detail of underlying UV theory

Near future experiments has the sensitivity to CP phases.





T2K Moriond2017

Neutrino mass from SeeSaw: three types for new scale physics beyond SM

The most famous UV completion for neutrino mass is to include

$$m_\nu = y_\nu^2 \frac{v_\eta^2}{M_R}$$

$$y_l \bar{L} H e_R + \mathrm{h.c}$$

$$y_\nu \bar{L} \eta \nu_R + M_R \overline{\nu_R^c} \nu_R + \mathrm{h.c}$$

$1. M_R \sim M_{\mathrm{pl}} \gg m_{\mathrm{EW}}$ $\quad \eta = H \quad y_\nu \sim O(1)$

$2. y_\nu \ll 1$ $\quad \eta = H \quad M_R < O(\mathrm{TeV})$

$\boxed{3. v_\eta \ll m_{\mathrm{EW}} \quad \text{TeV scale } \nu_R \text{ and } y_\nu \sim O(1)}$

leptophilic new $SU(2)_L$ doublet bosons required!

The new physics scale in the third possibility may coincide with the scale required in DM thermal relic.

Tiny EW symmetry breaking VEV: scenario I : R parity violating SSM

L.Hall, M.Suzuki(1984)

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Neutralino(e.g Bino)

3. $v_\eta \ll m_{\mathrm{EW}}$ $\quad$ TeV scale ν_R and $y_\nu \sim O(1)$

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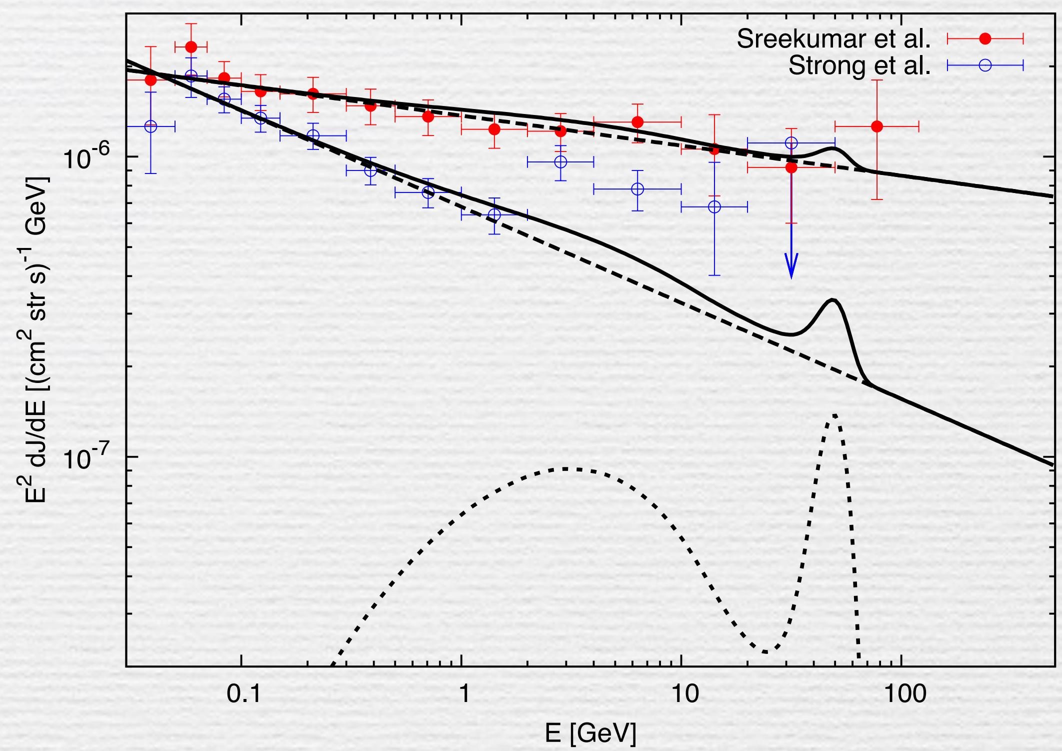
SM EW weak gauge couplings



W.Buchmuller,A.Ibarra,T.Shindou,D.Tran,F.Takayama(2010)

The breaking field for SU(2)L and lepton number might be sneutrino.

Bilinear terms of sneutrino-higgs are induced and develop sneutrino vev in EW symmetry breaking.

We could avoid NLSP late decay after BBN era

Once sneutrinos get their vev, R-parity is broken and we lose the candidate of "stable" dark matter.

On the other hand, gravitino has lifetime longer than age of the universe → dark matter candidate.

M.Yamaguchi, F.Takayama(2000) W.Buchmuller, L.Covi, K.Hamaguchi, A.Ibarra, T.Yanagida(2006)

We lose coincidence of scales for DM/neutrino But busy breaking connect it again.

→Dark matter decays open up another possibility on indirect DM detection in sky.

e.g in MSSM ,A.Ibarra, D.Tran(2006),K.Ishiwata, S.Matsumoto,T.Moroi(2006),L.Covi,M.Grefe,A.Ibarra,D.Tran(2008)

in μν

In general, TeV new physics faces flavor problem.

Underlying flavor symmetry may play some role in the problem.

If the flavor symmetry breaking is tiny,
low energy physics can be almost flavor symmetric.

→ After integration of heavy new particles,
the couplings of the given higher dim operators in SM are controlled by the symmetry.

The flavor symmetry symmetric LFV operators in SM may be constrained by experiments.

If the tiny breaking related to EW symmetry breaking VEV,
we could learn the observed symmetry breaking effects in neutrino masses.

Flavor symmetry breaking may leave a remnant symmetry.

Tiny EW symmetry breaking VEV: scenario II

Flavored dark matter

$$m_\nu = y_\nu^2 \frac{v_\eta^2}{M_R}$$

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Remember the thermal scenario for DM relic. Only the third possibility could realize it.

VEV of flavored SU(2)L doublets could be the origin of both neutrino masses and Flavor symmetry breaking

↓

Small VEV (and residual symmetry Z2) $\qquad$ TeV scale right handed neutrinos

↓

Very small Flavor symmetry breaking $\quad \dfrac{v_\eta}{M_R}, \dfrac{v_\eta}{m_\eta} \sim O(10^{-6})$

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TeV scale νR DM ←→ Flavor symmetry symmetric LFV

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A Flavoerd DM Concrete Model

$A_4 \to Z_2$: odd states(ν_{R2}, ν_{R3}) can be dark matter.

Along with this line, let's consider the following model.

Lepton flavor symmetry=Non-Abelian discrete symmetry

	L_e	L_μ	L_τ	e_R	μ_R	τ_R	$\nu_R = (\nu_R^1, \nu_R^2, \nu_R^3)$	N_4	h	$\eta = (\eta_1, \eta_2, \eta_3)$
$\mathrm{SU(2)_L}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$
A_4	$\mathbf{1}$	$\mathbf{1'}$	$\mathbf{1''}$	$\mathbf{1}$	$\mathbf{1''}$	$\mathbf{1'}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$

Scalar DM: M.Hirch et al (2011)

Right handed neutrino DM: F.Takayama et al (2014)

Z3 symmetry in charged lepton sector

$$\mathcal{L}_{\rm Yukawa} = y_e \overline{L}_e e_R h + y_\mu \overline{L}_\mu \mu_R h + y_\tau \overline{L}_\tau \tau_R h$$
$$+ y_\nu^e \overline{L}_e (\nu_R \tilde{\eta})_1 + y_\nu^\mu \overline{L}_\mu (\nu_R \tilde{\eta})_{1''} + y_\nu^\tau \overline{L}_\tau (\nu_R \tilde{\eta})_{1'}$$
$$+ Y_4 \overline{L}_e N_4 \tilde{h} + M_N \overline{\nu_R^c} \nu_R + M_4 \overline{N_4^c} N_4 + \text{h.c..}$$

$$\begin{aligned}
(ab)_{\mathbf{1}} &= a_1 b_1 + a_2 b_2 + a_3 b_3, \\
(ab)_{\mathbf{1'}} &= a_1 b_1 + \omega a_2 b_2 + \omega^2 a_3 b_3, \\
(ab)_{\mathbf{1''}} &= a_1 b_1 + \omega^2 a_2 b_2 + \omega a_3 b_3, \\
(ab)_{\mathbf{3}_1} &= \begin{pmatrix} a_2 b_3 \\ a_3 b_1 \\ a_1 b_2 \end{pmatrix}, \quad (ab)_{\mathbf{3}_2} = \begin{pmatrix} a_3 b_2 \\ a_1 b_3 \\ a_2 b_1 \end{pmatrix}.
\end{aligned}$$

$$\mathbf{1'} \otimes \mathbf{1'} = \mathbf{1''}, \quad \mathbf{1''} \otimes \mathbf{1''} = \mathbf{1'}, \quad \mathbf{1'} \otimes \mathbf{1''} = \mathbf{1},$$
$$\mathbf{3} \otimes \mathbf{3} = \mathbf{3}_1 \oplus \mathbf{3}_2 \oplus \mathbf{1} \oplus \mathbf{1'} \oplus \mathbf{1''}.$$

$$\begin{aligned}
V(h,\eta) = {} & m_\eta^2 \eta^\dagger \eta + m_h^2 h^\dagger h - m_{h\eta_1}^2 \eta_1^\dagger h + \text{h.c.}, \\
& + \lambda_1 (h^\dagger h)^2 + \lambda_2 [\eta^\dagger \eta]_1^2 + \lambda_3 [\eta^\dagger \eta]_{1'} [\eta^\dagger \eta]_{1''} \\
& + \lambda_4 ([\eta^\dagger \eta^\dagger]_{1'} [\eta\eta]_{1''} + [\eta^\dagger \eta^\dagger]_{1''} [\eta\eta]_{1'}) + \lambda_5 [\eta^\dagger \eta^\dagger]_1 [\eta\eta]_1 \\
& + \lambda_6 ([\eta^\dagger \eta]_{3_1} [\eta^\dagger \eta]_{3_1} + [\eta^\dagger \eta]_{3_2} [\eta^\dagger \eta]_{3_2}) + \lambda_7 [\eta^\dagger \eta]_{3_1} [\eta^\dagger \eta]_{3_2} + \lambda_8 [\eta^\dagger \eta^\dagger]_{3_1} [\eta\eta]_{3_1} \\
& + \lambda_9 [\eta^\dagger \eta]_1 (h^\dagger h) + \lambda_{10} [\eta^\dagger h]_3 [h^\dagger \eta]_3 + \lambda_{11} ([\eta^\dagger \eta^\dagger]_1 hh + h^\dagger h^\dagger [\eta\eta]_1) \\
& \cancel{+ \lambda_{12} ([\eta^\dagger \eta^\dagger]_{3_1} [\eta h]_3 + [h^\dagger \eta^\dagger]_3 [\eta\eta]_{3_2}) + \lambda_{13} ([\eta^\dagger \eta^\dagger]_{3_2} [\eta h]_3 + [h^\dagger \eta^\dagger]_3 [\eta\eta]_{3_1})} \\
& \cancel{+ \lambda_{14} ([\eta^\dagger \eta]_{3_1} [\eta^\dagger h]_3 + [h^\dagger \eta]_3 [\eta^\dagger \eta]_{3_2}) + \lambda_{15} ([\eta^\dagger \eta]_{3_2} [\eta^\dagger h]_3 + [h^\dagger \eta]_3 [\eta^\dagger \eta]_{3_1}).}
\end{aligned}$$

$\Delta\eta=1$ terms are set to zero except for bilinear soft term.

$\Delta\eta=2$ breaking term $M_4 \gg M_N$, tiny λ_{11} is assumed.

Neutrino masses/PMNS mixing matrix

We take CP inv mulit-higgs potential here,
but we could introduce CP phase in this model.

In this model, the degree of freedom in neutrino mass matrix is 5 (+relative signs).

$$m_\nu = \begin{pmatrix} a^2 + X_A & ab & ac \\ ab & b^2 & bc + X_B \\ ac & bc + X_B & c^2 \end{pmatrix}. \qquad \frac{(m_\nu)_{12}^2}{(m_\nu)_{22}} = \frac{(m_\nu)_{13}^2}{(m_\nu)_{33}}.$$

Physical degree of freedom of neutrino mass matrix=3(masses)+3(mixings)+1(CP)+2(Majorana Phase)

Experiments have fixed 5 observables in neutrino mass matrix(+1(CP)+mee).

Parameter	3σ range	best fit value
Δm^2_{21} (10^{-5}eV^2)	$6.99 - 8.18$	7.54
$\lvert\Delta m^2\rvert$ (10^{-3}eV^2)	$2.19 - 2.62(2.17 - 2.61)$	2.43(2.42)
$\sin^2\theta_{12}$	$0.259 - 0.359$	0.307
$\sin^2\theta_{23}$	$0.331 - 0.637(0.335 - 0.663)$	0.386(0.392)
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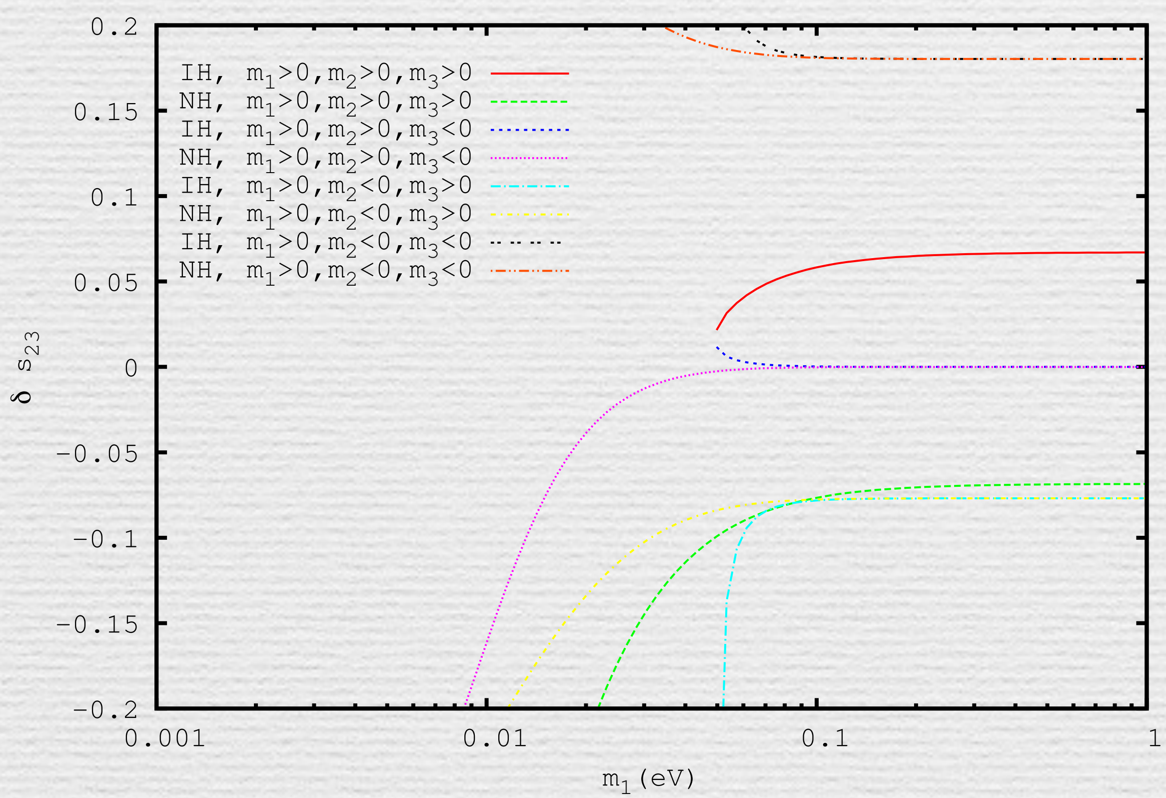

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$\sin^2\theta_{23}$	$0.331 - 0.637(0.335 - 0.663)$	$0.386(0.392)$
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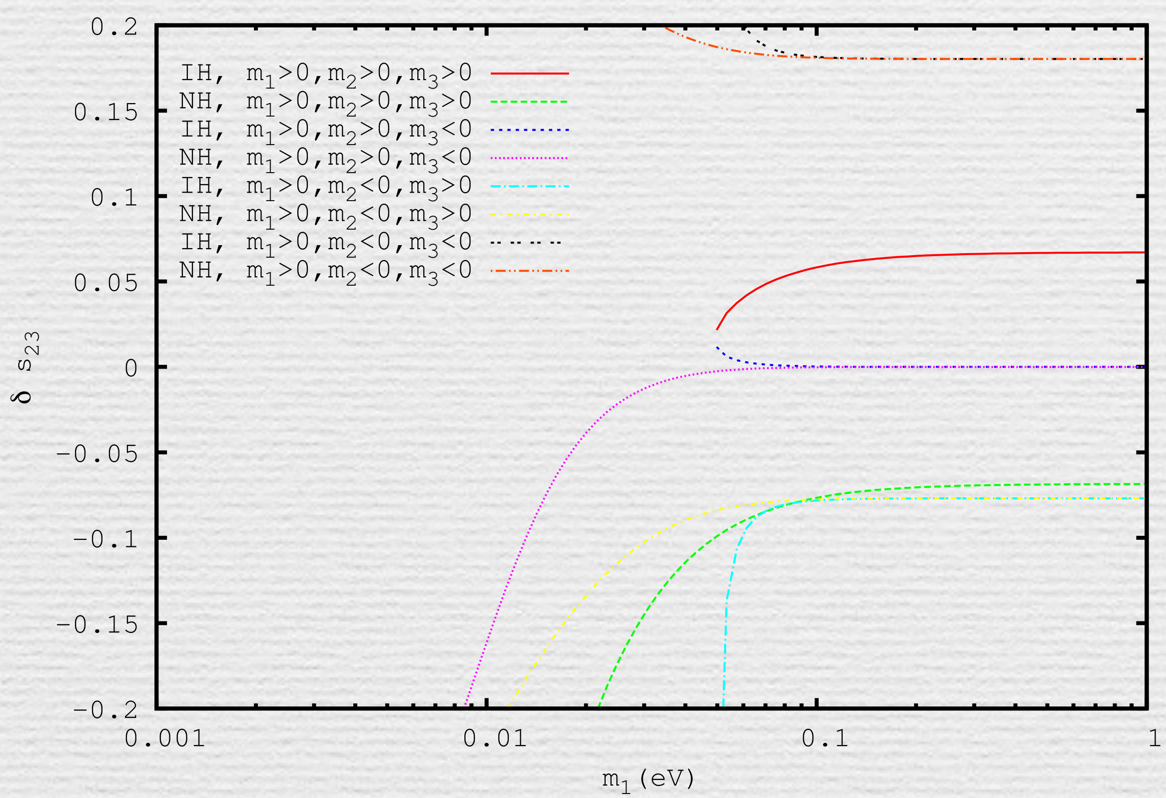
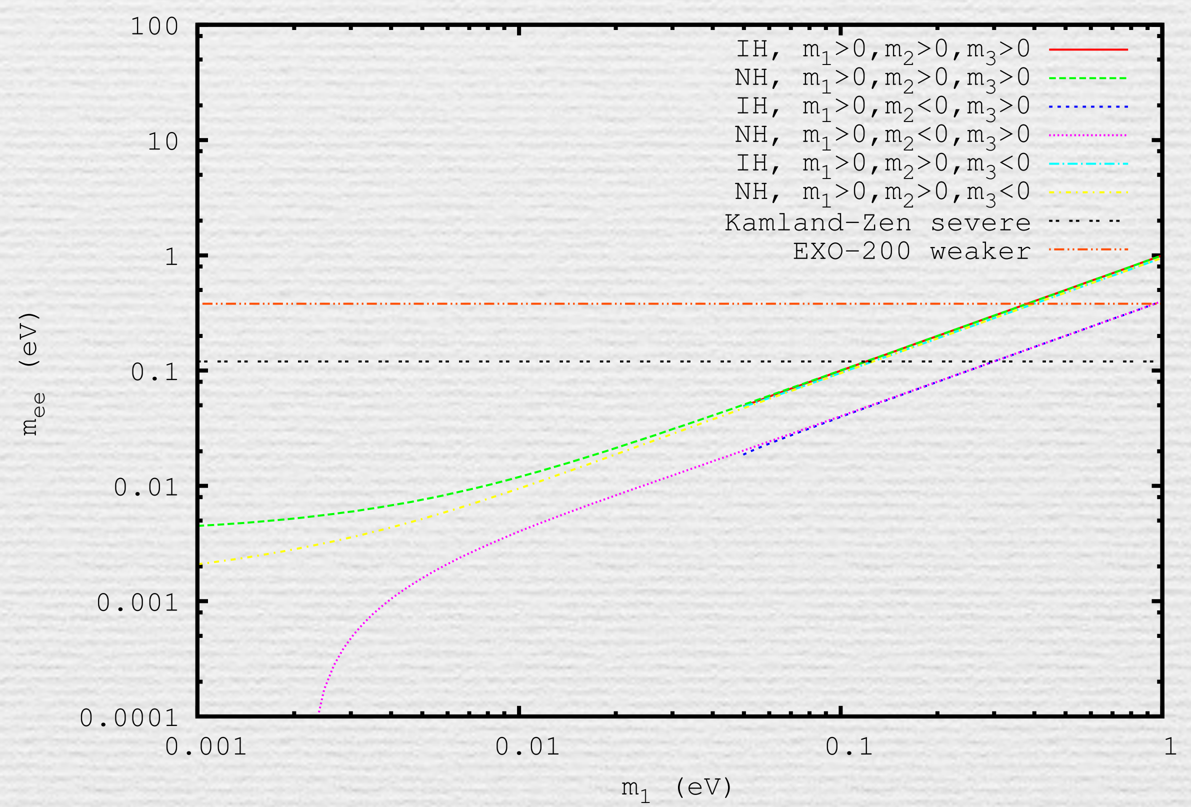




Neutrino masses/PMNS mixing matrix

We take CP inv mulit-higgs potential here,
but we could introduce CP phase in this model.

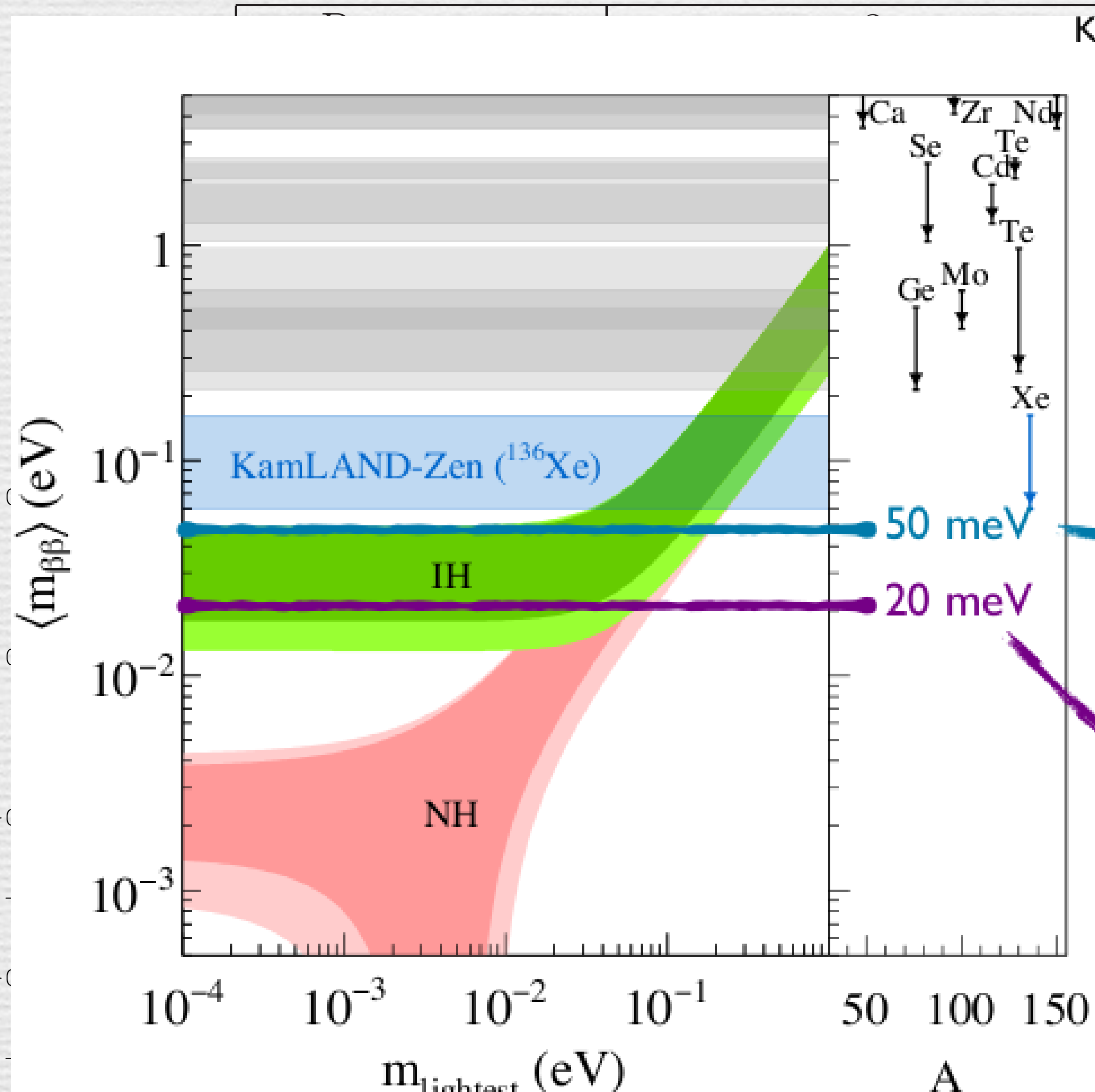
In this model, the degree of freedom in neutrino mass matrix is 5 (+relative signs).

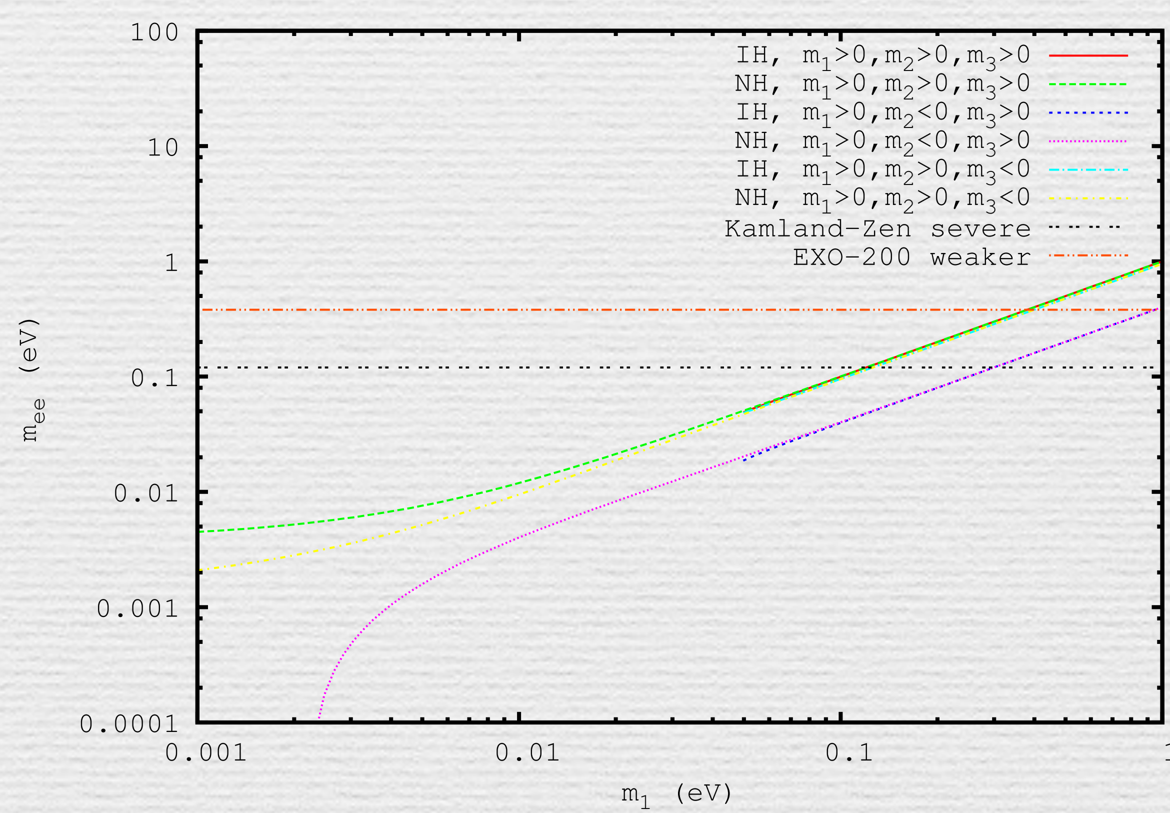
$$m_\nu = \begin{pmatrix} a^2 + X_A & ab & ac \\ ab & b^2 & bc + X_B \\ ac & bc + X_B & c^2 \end{pmatrix}. \qquad \frac{(m_\nu)_{12}^2}{(m_\nu)_{22}} = \frac{(m_\nu)_{13}^2}{(m_\nu)_{33}}.$$

Physical degree of freedom of neutrino mass matrix=3(masses)+3(mixings)+1(CP)+2(Majorana Phase)

Experiments have fixed 5 observables in neutrino mass matrix(+1(CP)+mee).

	best fit value
	7.54
.61)	2.43(2.42)
	0.307
0.663)	0.386(0.392)
- 0.0315)	0.0241(0.0244)

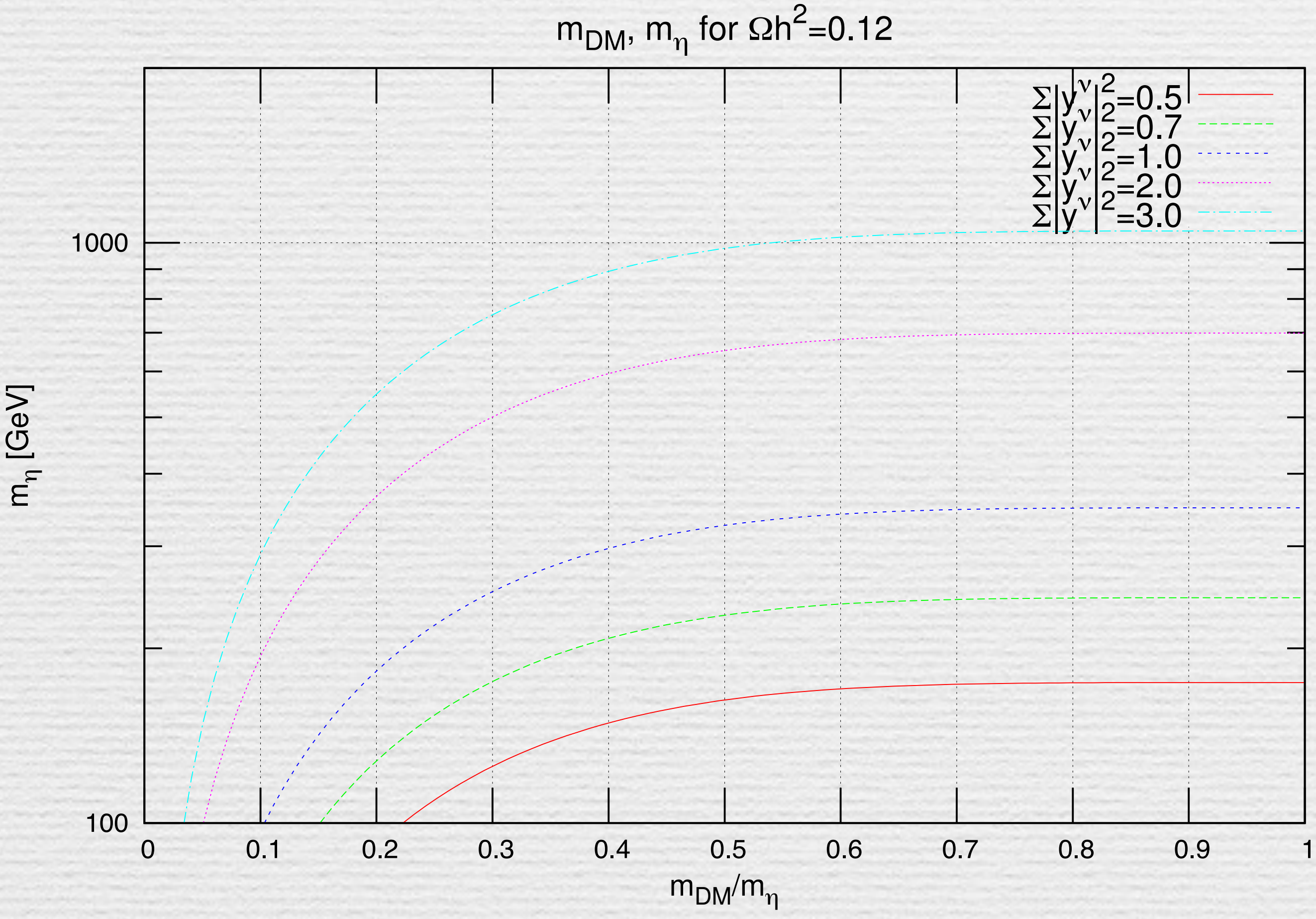




Thermal freeze out and ν_R Dark Matter relic abundance

$$
\begin{aligned}
\sigma_{\rm ann} v_{\rm rel} &\simeq \frac{y_\nu^2}{16\pi}\frac{1}{m_N^2}\frac{1+(m_\eta/m_N)^4}{(1+(m_\eta/m_N)^2)^4}v_{\rm rel}^2, \\
&\sim 2.4\text{pb}\left(\frac{v_{\rm rel}^2}{0.3}\right)\left(\frac{y_\nu^2}{1.0}\right)^2\left(\frac{350\text{GeV}}{m_N}\right)^2\left(\frac{(1+(\frac{m_\eta}{m_N})^4)/(1+(\frac{m_\eta}{m_N})^2)^4}{1/8}\right)
\end{aligned}
$$

$y_\nu^2 = \sum_{i=e,\mu,\tau}(y_\nu^i)^2$



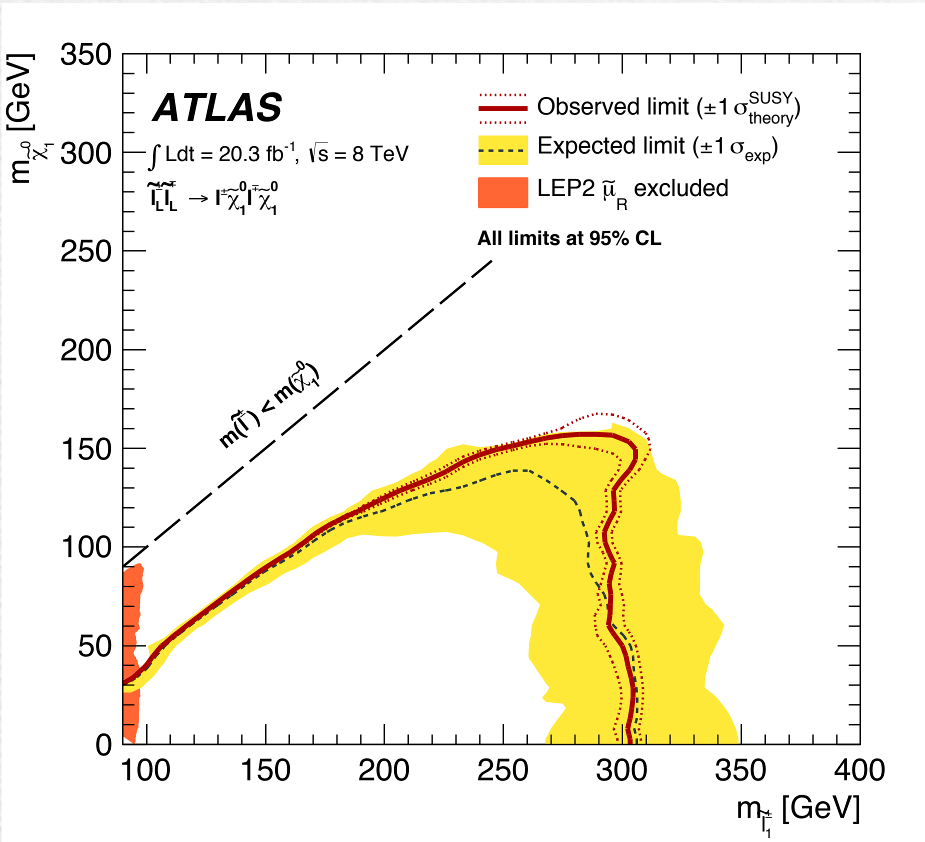
Co-annihilation is not included.

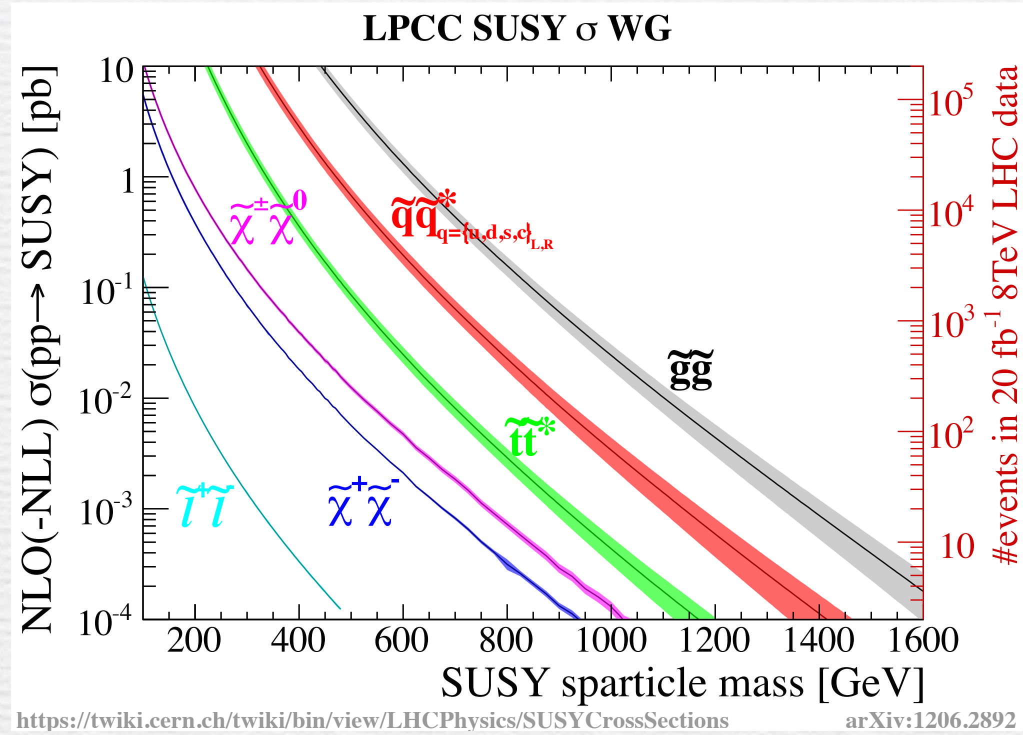
The large regions are accessible at LHC.

However, the region of mass degeneracy would be hard to be probed at LHC.

If dilution happen after the freeze out, e.g by entropy production,
the preferred mass range could be shifted to ν_R heavier mass.

Collider searches



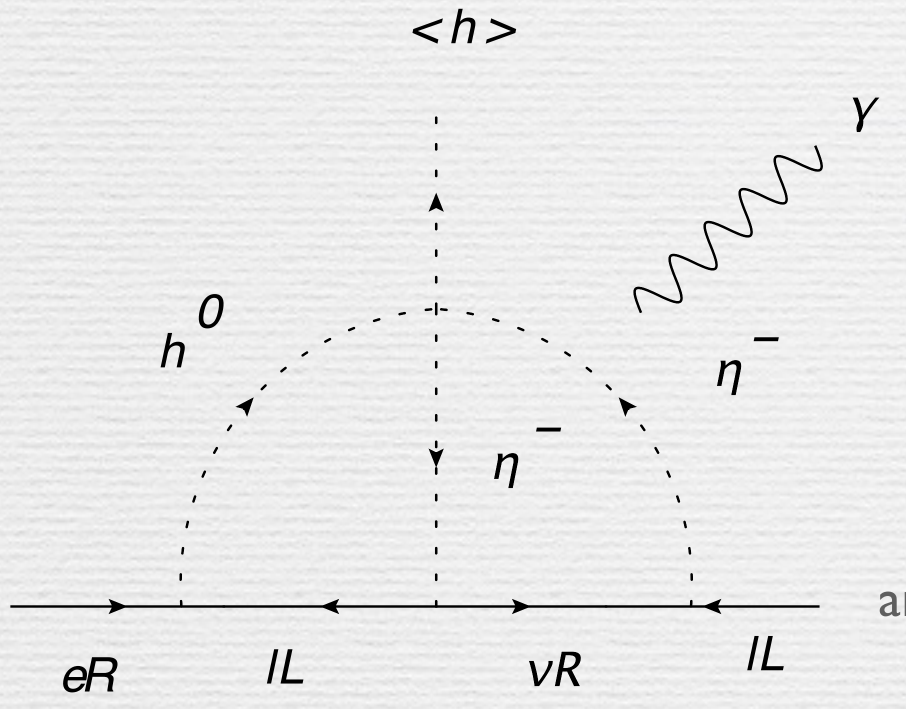


$\sqrt{s}$ = 7, 8 TeV　$\sqrt{s}$ = 13 TeV

EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	36.1	$\tilde{\ell}$ 90-440 GeV
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	36.1	$\tilde{\chi}_1^\pm$ 710 GeV
	$\tilde{\chi}_1^+\tilde{\chi}_1^\mp/\tilde{\chi}_2^0$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$, $\tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^\pm$ 760 GeV
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	36.1	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 1.16 TeV
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	36.1	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 580 GeV
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 270 GeV
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 635 GeV
	GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$	1 $e,\mu+\gamma$	-	Yes	20.3	$\tilde{W}$ 115-370 GeV
	GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$	2 γ	-	Yes	20.3	$\tilde{W}$ 590 GeV

Only degenerate mass region is survived in the interesting cases for thermal scenario of DM relic.

Experimental searches for lepton flavor violation/lepton non-universality



arXiv:1405.3592v1

Residual symmetry forbid LFV processes in transition magnetic moment.

Since SM higgs-new scalar sector is highly suppressed by v_η, Barr-Zee two loop would get minor effects.

The loop structure should be similar to MSSM in the decoupling of sparticles except for multi-bino (lepton non-universal coupling) and left-handed sleptons

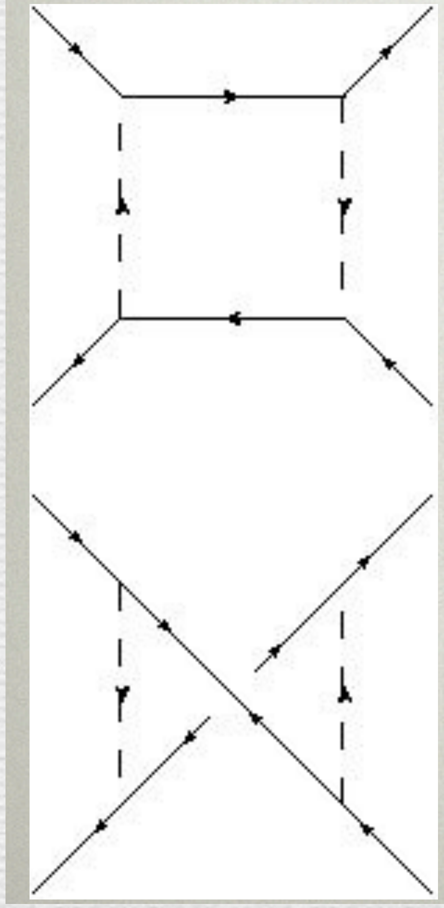
Tests of Flavor symmetry symmetric structure in LFV processes

Lepton non-universality/EW precision

Flavor symmetric structure: The role of Z3 (of A4) in charged lepton sector

Flavor symmetry breaking coupling $\sim v_\eta/v_h \sim O(10^{-6})$

→ Flavor symmetry control LFV!
Flavor symmetry is a good symmetry in low energy processes.



A. Flavor symmetry violating processes are highly suppressed.

Flavor symmetry prohibit $\mu \to e\gamma$, $\mu \to e$ conversion due to Z_3 of A_4,

$$L_{LFV} \sim \frac{c_{ij}}{\Lambda}^2 \overline{L_i} H \sigma_{\mu\nu} (e_R)_j F^{\mu\nu}$$

B. Flavor symmetric processes are unsuppressed.

$$L_{\rm LFV} \sim \frac{c_{ijkl}}{\Lambda^2} (\overline{L_i}\gamma_\mu L_j)(\overline{L_k}\gamma^\mu L_l)$$

$$\Lambda \sim \frac{3}{4}\frac{1}{(4\pi)^2}\frac{1}{m_\eta^2}, \quad c_{ijkl} = y_\nu^i y_\nu^j y_\nu^k y_\nu^l$$

EWPT, lepton rare decay → $m_\eta >$ a few 100GeV $\times (\frac{y_\nu^2}{1.0})$

Neutrino interaction can also be modified but obtain weaker constraints.

Neutrino mass information can fix all neutrino yukawa which results predictions to LFV

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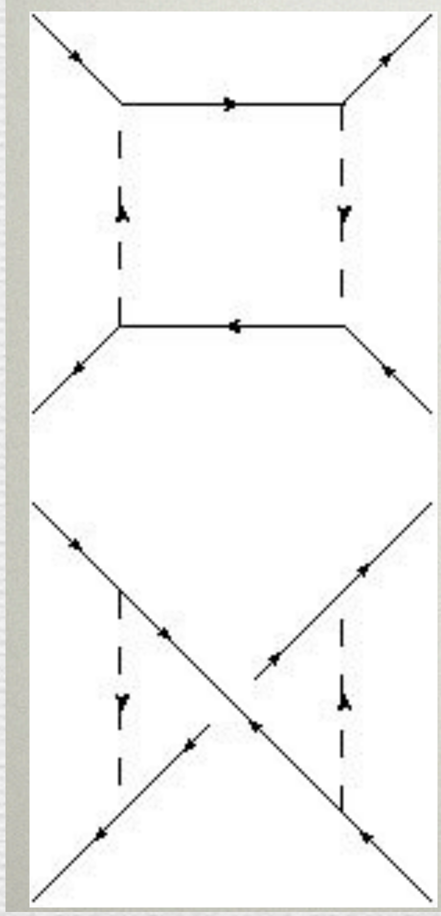

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For the other models, e.g $L = Y_{ij}^k \bar{L}_i H_k e_R^j$ (Direct LFV source in charged lepton sector)

The Z3 structure could work well in similar way.

F.Takayama et al JHEP1510(2015)042

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Table 13: Best published limits on lepton-flavour-violating decays [523–533].

$\mathrm{Br}(\mu^- \to \mathrm{X}^-) \cdot 10^{12}$		(90% CL)							
$e^-\gamma$	0.57	$e^-2\gamma$	72	$e^-e^-e^+$	1.0				
$\mathrm{Br}(\tau^- \to \mathrm{X}^-) \cdot 10^{8}$		(90% CL)							
$e^-\gamma$	3.3	$e^-e^+e^-$	2.7	$e^-\mu^+\mu^-$	2.7	$e^-e^-\mu^+$	1.5	$e^-\pi^0$	8.0
$\mu^-\gamma$	4.4	$\mu^-e^+e^-$	1.8	$\mu^-\mu^+\mu^-$	2.1	$\mu^-\mu^-e^+$	1.7	$\mu^-\pi^0$	11
$e^-\eta$	9.2	$e^-\eta'$	16	$e^-\rho^0$	1.8	$e^-\omega$	4.8	$e^-\phi$	3.1
$\mu^-\eta$	6.5	$\mu^-\eta'$	13	$\mu^-\rho^0$	1.2	$\mu^-\omega$	4.7	$\mu^-\phi$	8.4
e^-K_S	2.6	e^-K^{*0}	3.2	$e^-\bar{K}^{*0}$	3.4	$e^-K^+\pi^-$	3.1	$e^-\pi^+K^-$	3.7
μ^-K_S	2.3	μ^-K^{*0}	5.9	$\mu^-\bar{K}^{*0}$	7.0	$\mu^-K^+\pi^-$	4.5	$\mu^-\pi^+K^-$	8.6
$e^-K_SK_S$	7.1	$e^-K^+K^-$	3.4	$e^-\pi^+\pi^-$	2.3				
$\mu^-K_SK_S$	8.0	$\mu^-K^+K^-$	4.4	$\mu^-\pi^+\pi^-$	2.1				
$e^-f_0(980) \to e^-\pi^+\pi^-$			3.2	$\mu^-f_0(980) \to \mu^-\pi^+\pi^-$			3.4		
$\mathrm{Br}(\mathrm{Z} \to \mathrm{X}^0) \cdot 10^{6}$		(95% CL)							
$e^\pm\mu^\mp$	1.7	$e^\pm\tau^\mp$	9.8	$\mu^\pm\tau^\mp$	12				
$\mathrm{Br}(\mathrm{B}^0_{(\mathrm{s})} \to \mathrm{X}^0) \cdot 10^{8}$		(95% CL)							
$B^0 \to e^\pm\mu^\mp$	0.37	$B^0_s \to e^\pm\mu^\mp$	1.4						
$\mathrm{Br}(\mu^- + \mathrm{N} \to \mathrm{e}^- + \mathrm{N}) \cdot 10^{12}$			(90% CL)						
Au	0.7	Ti	4.3	Pb	46				

$0^{-6})$

processes.

y suppressed.

version due to Z_3 of A_4,

$\sim \frac{c_{ij}}{\Lambda}^2 \overline{L_i} H \sigma_{\mu\nu}(e_R)_j F^{\mu\nu}$

$\frac{1}{\eta_\eta^2}, \quad c_{ijkl} = y_\nu^i y_\nu^j y_\nu^k y_\nu^l$

$100\mathrm{GeV} \times (\frac{y_\nu^2}{1.0})$

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Flavored ν_R (leptophilic) Dark Matter signatures

Neutrino line search give factor a few stronger constraint.

Dark Matter accumulation in Sun(SuperK/ANTARES/IceCube)

$$\sigma \sim \frac{1}{\pi}\frac{m_e^2}{(m_\eta^2 - m_\chi^2)^2}$$

$$\sigma_{\chi e}^0 \equiv \frac{G^2 m_e^2}{\pi} = \frac{m_e^2}{\pi\Lambda^4} \approx 3.1\times 10^{-39}\,\mathrm{cm}^2 \left(\frac{\Lambda}{10\,\mathrm{GeV}}\right)^{-4}$$

neutrino-DM scattering can also be large.

Dark Matter direct searches

Some plots/basic discussions from J.Kopp et al (2009,2014)

Loop induced DM couplings with Weak bosons are negligible.

Majorana nature forbids flavor diagonal vector and tensor coupling with vector bosons.

$$\overline{\nu_R}\gamma_\mu\nu_R V_\mu + \mathrm{h.c},\ \overline{\nu_R}\sigma_{\mu\nu}\nu_R F^{\mu\nu}_{(V)} + \mathrm{h.c} \to 0$$

Pseudo-vector couplings are allowed but it's suppressed by multiple cutoff scale and loop factor.

$$\frac{c_A}{\Lambda^2}(\overline{\nu_R}\gamma_5\gamma_\mu\nu_R)\times i(H^\dagger D_\mu H) \qquad c_A \sim O(1)\times\frac{\lambda}{16\pi^2}y_\nu^2$$

$$\boxed{\sigma_p^{\mathrm{SI}} \sim 10^{-47}\mathrm{cm}^2 \times \left(\frac{100\mathrm{GeV}}{m_{\nu_R}}\right)^4\left(\frac{\lambda}{0.1}\right)^2\left(\frac{\sigma_{\mathrm{ann}}v}{1\mathrm{pb}}\right),\ v^2\sim 3\frac{T_f}{m_{\nu_R}}\sim 0.1}$$

The flavor changing couplings are highly suppressed due to small flavor violation. $\frac{v_\eta}{v_h}\sim 10^{-6}$

$$\frac{c_V}{\Lambda^2}[(H^\dagger\eta)_3[\overline{\nu_R}\gamma_\mu\nu_R]_3]_1 V_\mu + \mathrm{h.c},\ \frac{c_T}{\Lambda^2}[(H^\dagger\eta)_3[\overline{\nu_R}\sigma_{\mu\nu}\nu_R]_3]_1 F^{\mu\nu}_{(V)} + \mathrm{h.c}$$

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At dim 5 if CP is violated,

$$\frac{c_{\mathrm{CPV}}}{\Lambda}\overline{\nu_R}\gamma_5\sigma_{\mu\nu}\nu_R F^{\mu\nu}$$

At dim 6 if CP is well-conserved,

$$\frac{c_{\mathrm{CP}}}{\Lambda^2}\overline{\nu_R}\gamma_5\gamma_\mu\nu_R\partial_\nu F^{\mu\nu}$$

This again can contribute to SI process in DM direct search.

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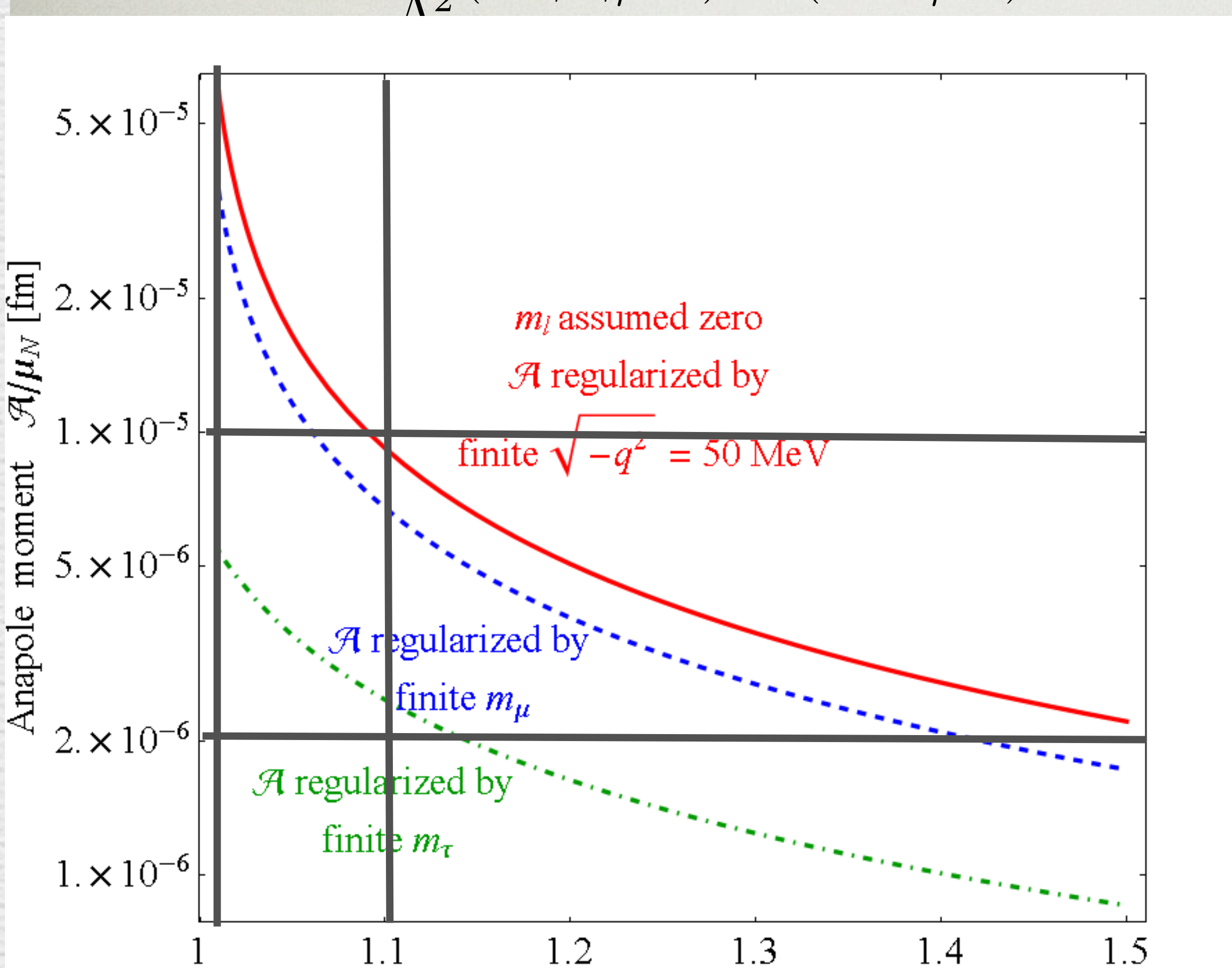

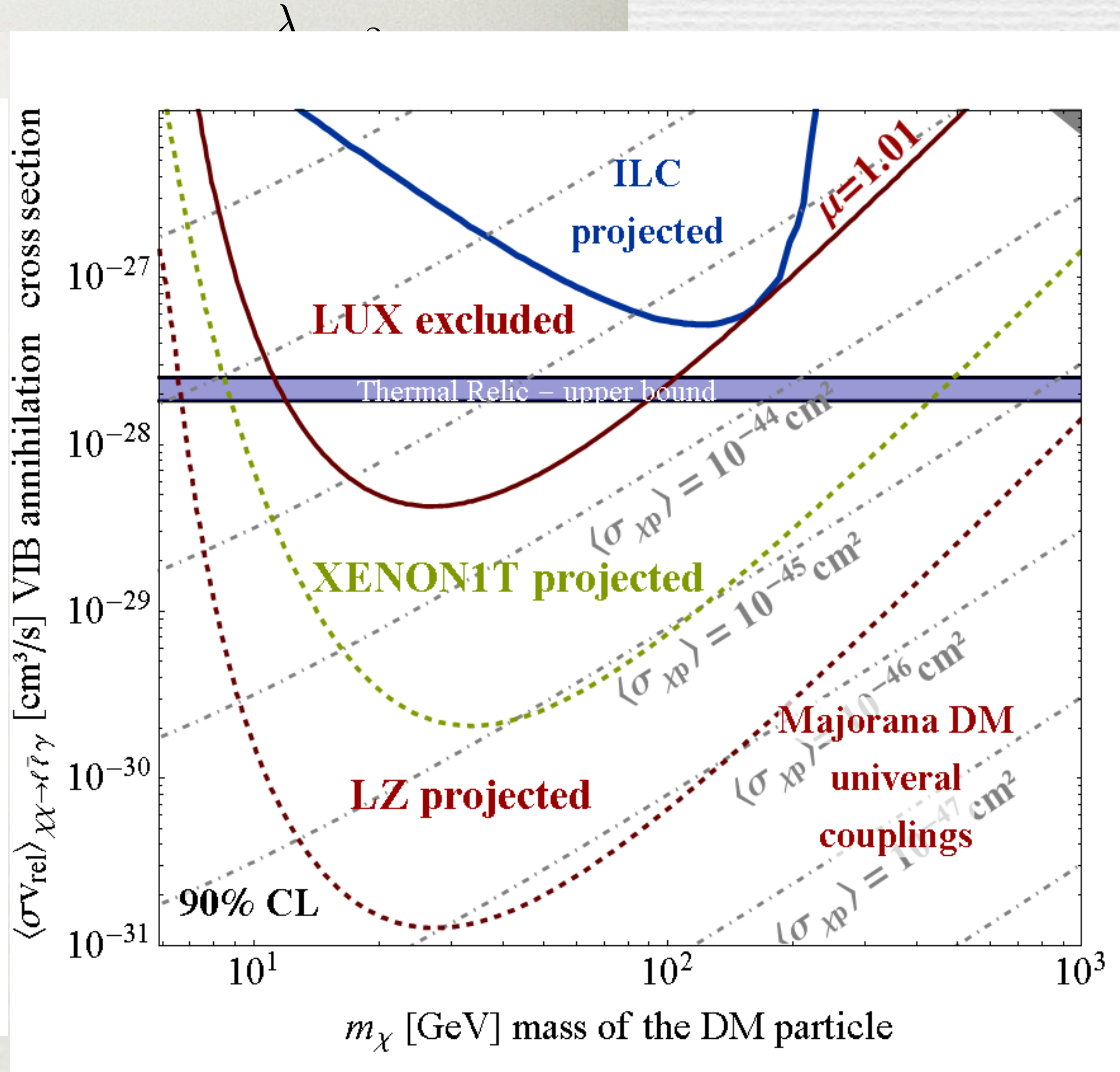

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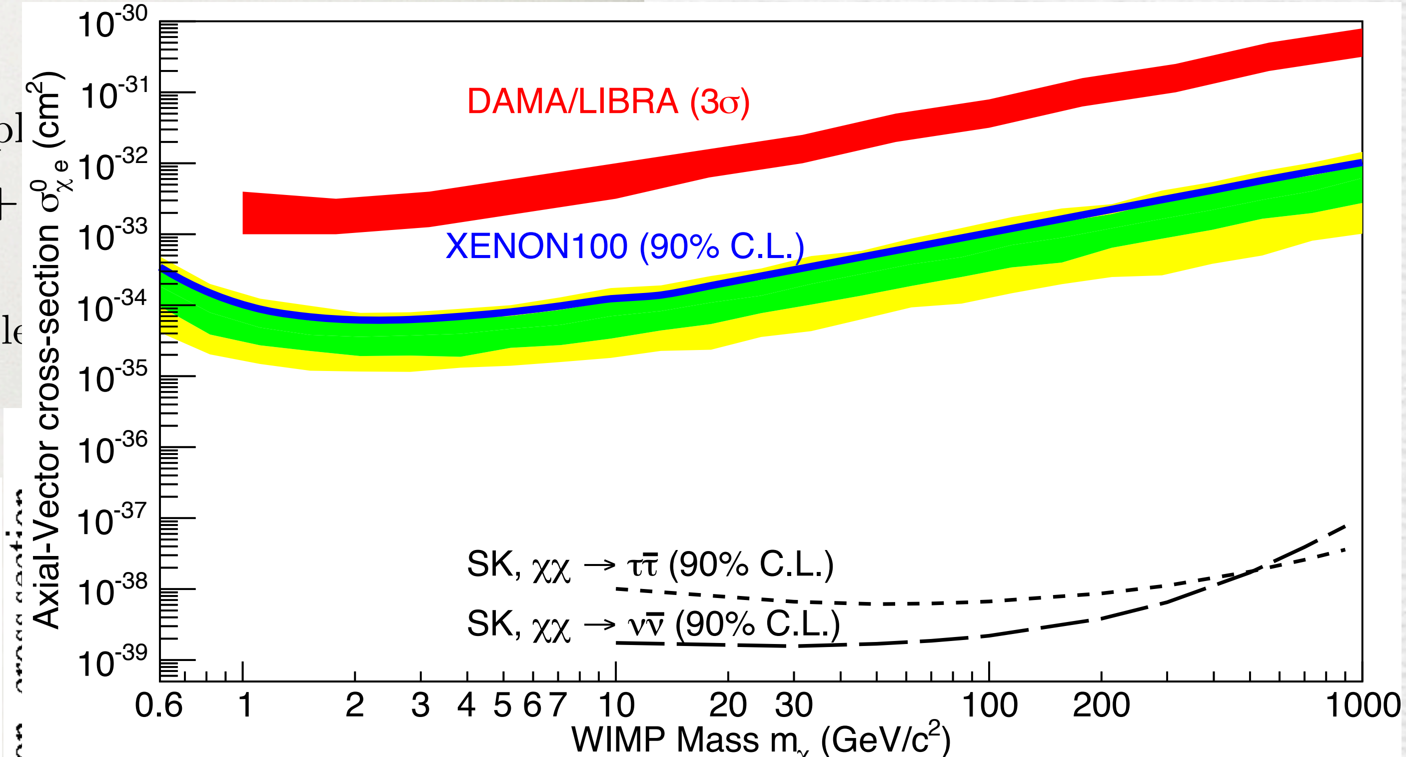

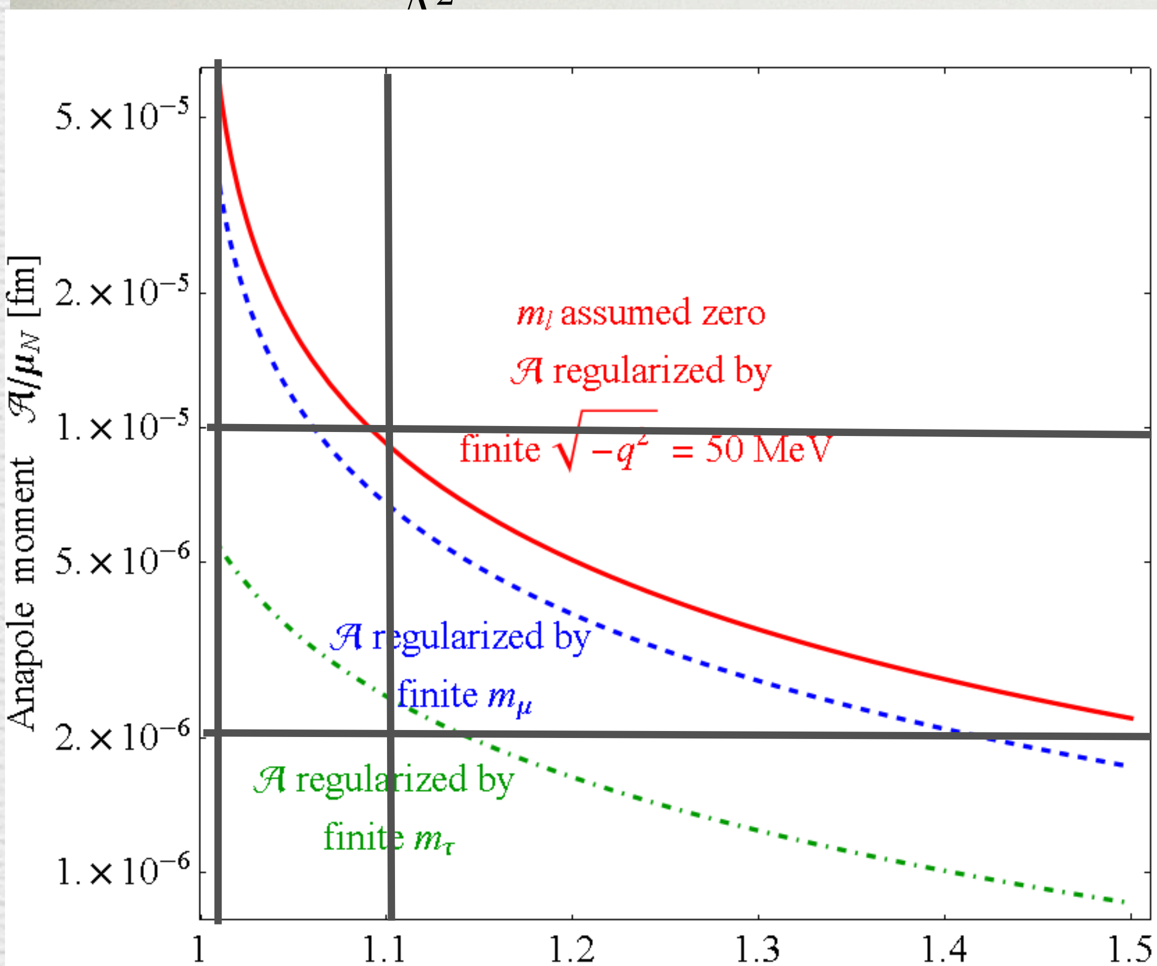

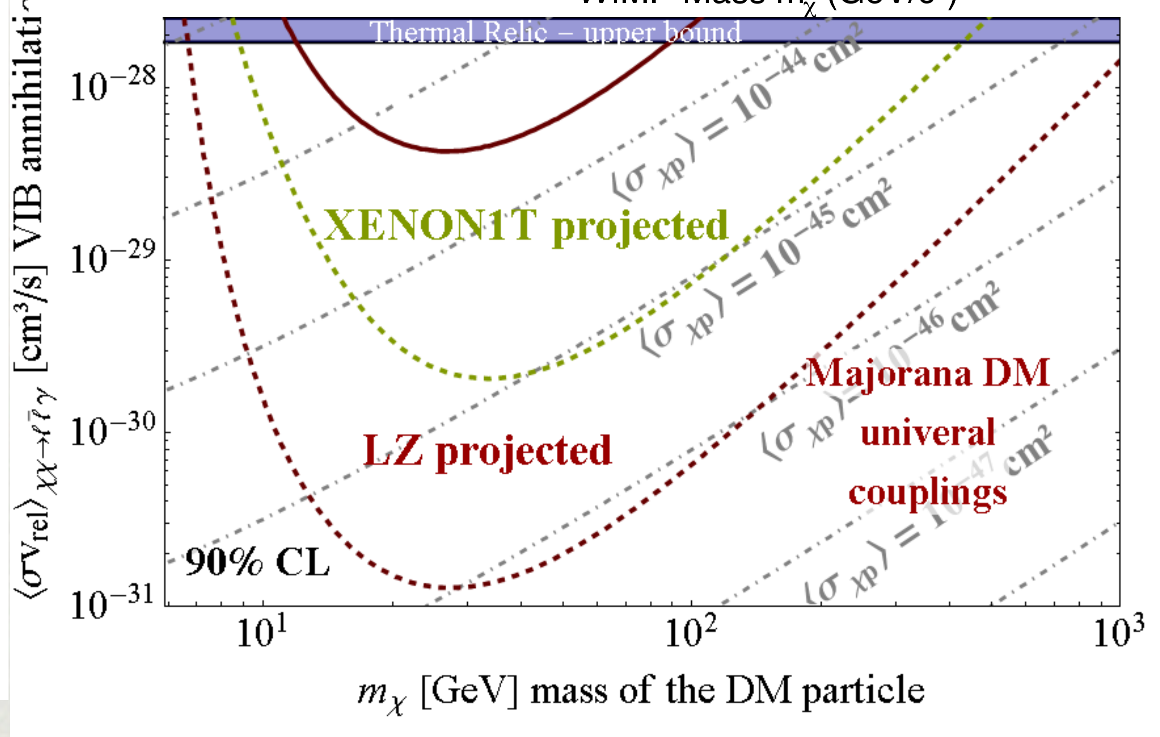

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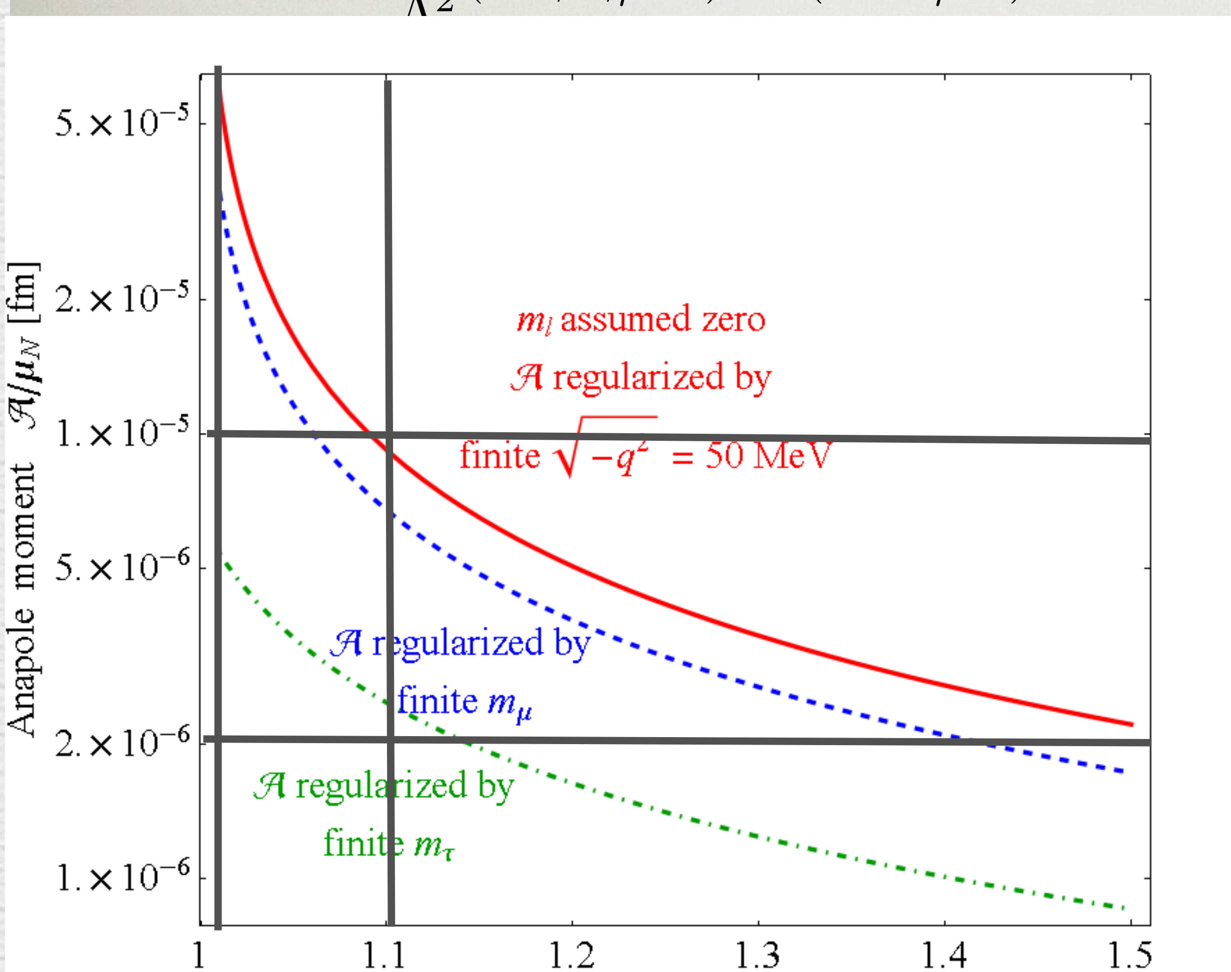

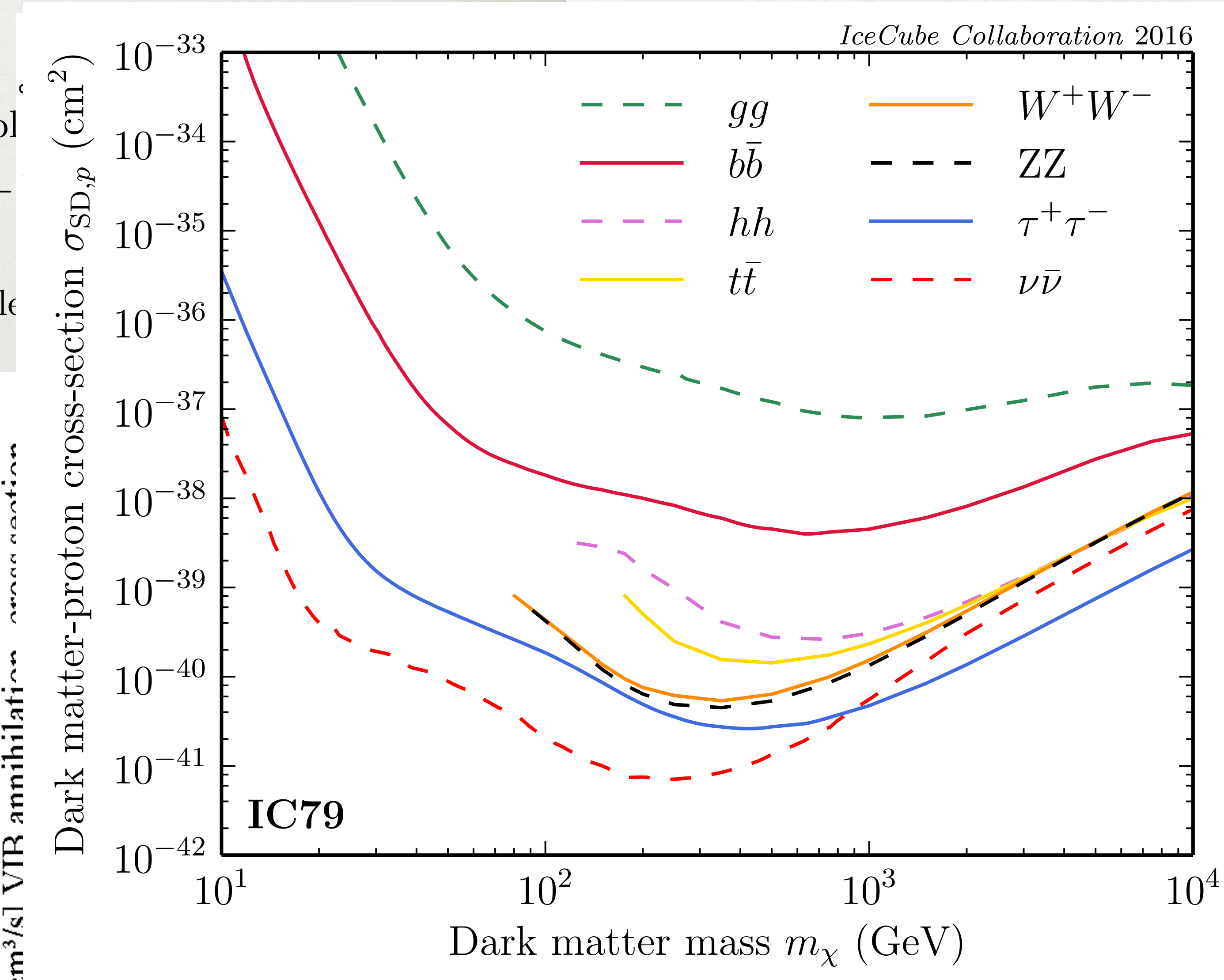

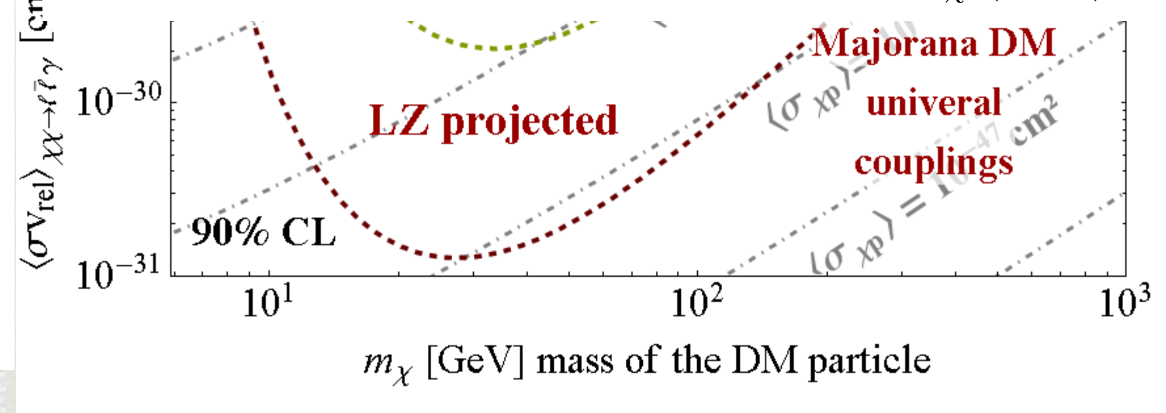

Dark Matter indirect detection

The annihilation into two leptons are P-wave suppressed.

In this kind of cases, the leading contribution may come from 2→3 process.

Two leptons + a photon or Two leptons + a EW boson(W/Z)

T.Bringmann,L.Bergstrom, J.Edsjo(2008)

The mass degeneracy between messenger and DM obtain enhancement in the rate.

P-wave nature of 2→2 process may not always completely hidden in present universe.

If DM velocity dispersion is large e.g nearby BH.

J.Shelton, S.Shapiro, B.D.Fields(2015)

Summary

We discussed the possibility of thermal dark matter in small VEV seesaw scenario.

LHC is putting constraints on this model.

→Moderate degeneracy between DM and messenger particle has been required.

EW precision measurements and rare decay searches also put the constraints for
the possibility of thermal DM.

The detail model building discussions for small flavor symmetry breaking/EW VEV would be required.