

Probing mixed complex scalar WIMP dark matter

Akiteru Santa (Univ. of Toyama)

M. Kakizaki, E.-K. Park, J.-h. Park, A. Santa, PLB 749, 44 (2015)

M. Kakizaki, A. Santa, O. Seto, arXiv: 1609.06555

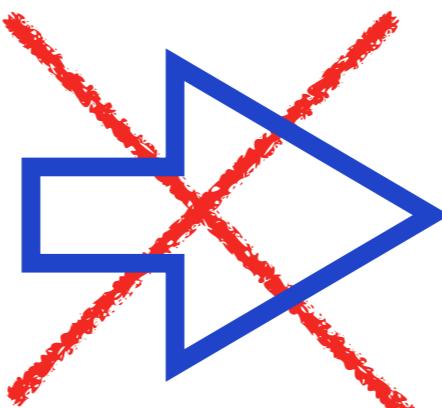
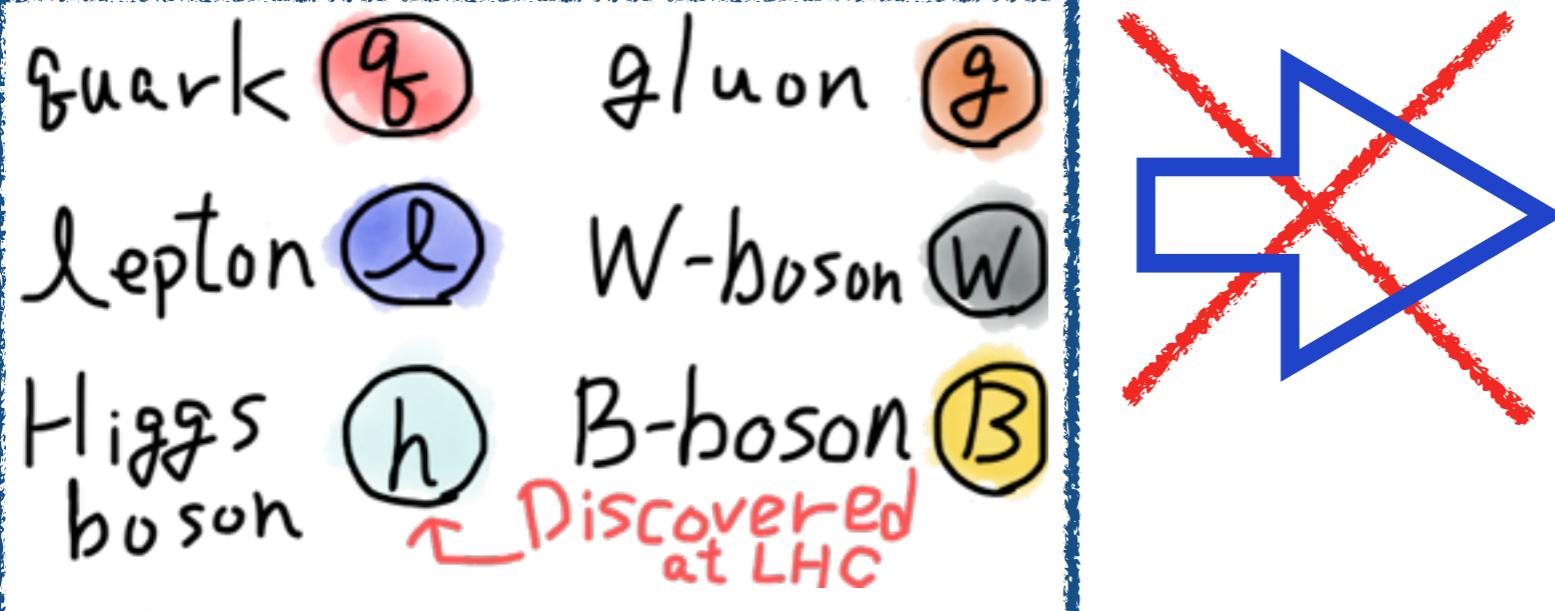
Dec. 1, 2016, CosPA 2016, Univ. of Sydney

Motivation

The Standard Model

cannot solve

Problems

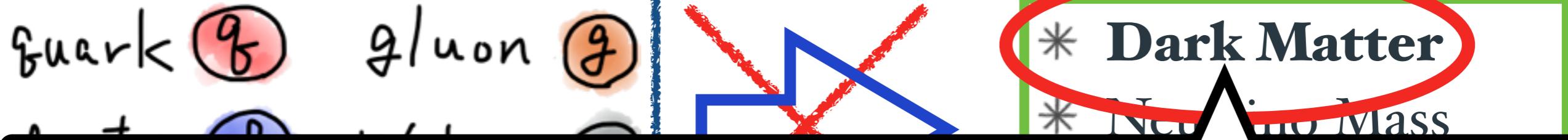


- * Dark Matter
- * Neutrino Mass
- * Baryon Asymmetry
- * Inflation
- * Hierarchy Problem
- etc.

We should extend the standard model
and solve such problems !

Motivation

The Standard Model cannot solve Problems

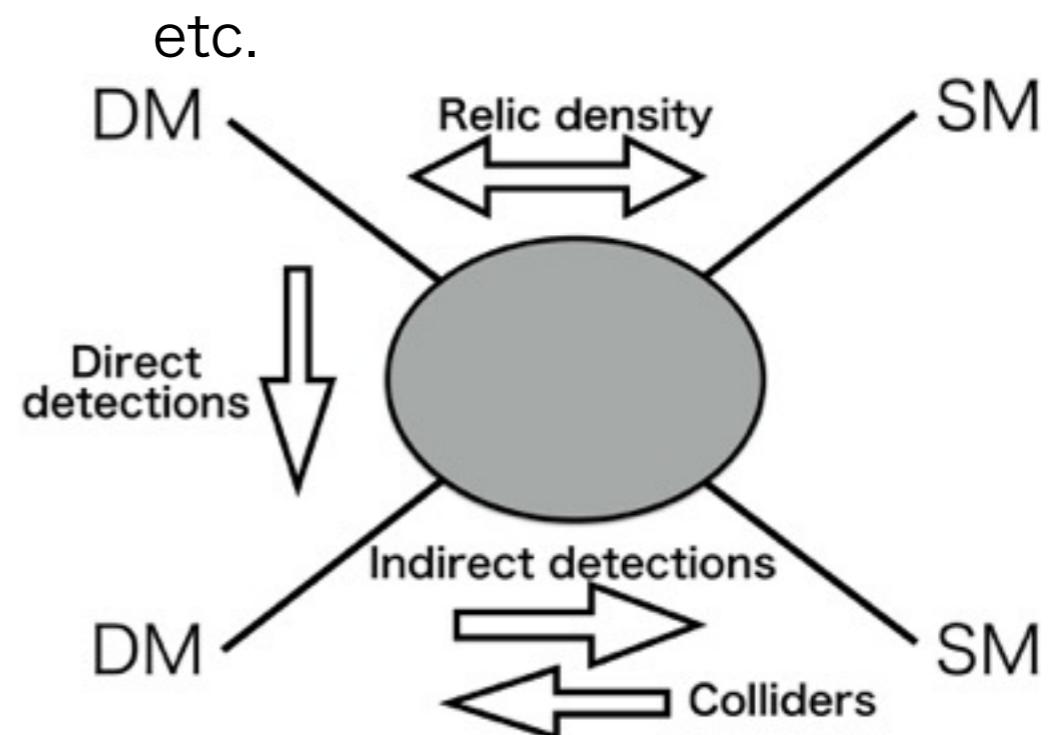


Evidences

- Rotational curve of galaxies
- Collision of clusters
- Relic density: $\Omega h^2 \approx 0.11$

However, the SM does not contain a DM candidate

Many experiments are searching for DM =>



What is property of DM χ ?

- Real scalar

- Majorana fermion

=> WIMP

- Complex scalar

- Dirac fermion

=> WIMP, Asymmetric Dark Matter

$m_{\text{WIMP}} \sim 1 \text{ GeV} - 1 \text{ TeV}$

$m_{\text{ADM}} \sim 1 \text{ GeV} - 10 \text{ GeV}$

Final Goal: Examination for possibility
to distinguish **WIMP** and **ADM** scenarios

This Talk: Analysis of
GeV-mass complex scalar WIMP scenarios

Mixed sneutrino WIMP scenarios

Arkani-Hamed, Hall, Murayama, Smith and Weiner (2001),
Kakizaki, Park, Park, Santa (2015), etc.

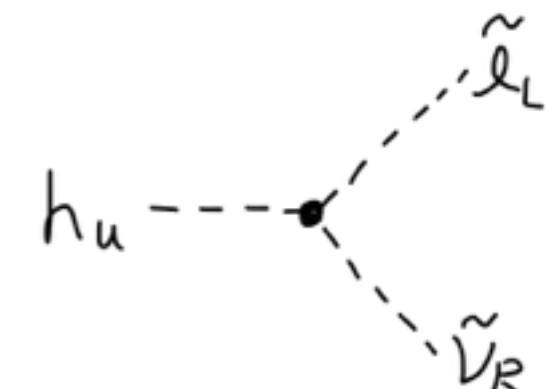
Example of GeV-mass WIMP scenarios

Lagrangian:

$$\mathcal{L} \sim (\mathcal{L}_{\text{SM}} + \mathcal{L}_{\nu_R}) \times \text{SUSY} + \mathcal{L}_{\text{SUSY breaking}}$$

Scalar Trilinear Coupling :

$$\mathcal{L}_{\text{SUSY breaking}} \supset -A_{\tilde{\nu}} h_u \cdot \tilde{l}_L \tilde{\nu}_R^c + \text{h.c.}$$



=> Off-diagonal components of sneutrino mass matrix

$$-\mathcal{L}_{\text{mass}} = (\tilde{\nu}_L^*, \tilde{\nu}_R^*) \begin{pmatrix} m_{\tilde{L}}^2 + \frac{1}{2}m_Z^2 \cos 2\beta & \frac{v}{\sqrt{2}} A_{\tilde{\nu}} \sin \beta \\ \frac{v}{\sqrt{2}} A_{\tilde{\nu}} \sin \beta & m_{\tilde{N}}^2 \end{pmatrix} \begin{pmatrix} \tilde{\nu}_L \\ \tilde{\nu}_R \end{pmatrix}$$

=> Left- and right-handed sneutrios mix:

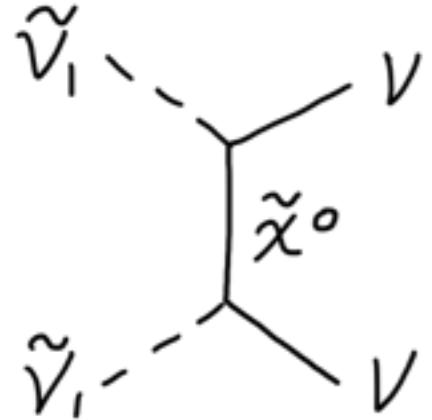
$$\begin{pmatrix} \cos \theta_{\tilde{\nu}} & -\sin \theta_{\tilde{\nu}} \\ \sin \theta_{\tilde{\nu}} & \cos \theta_{\tilde{\nu}} \end{pmatrix} \begin{pmatrix} \tilde{\nu}_R \\ \tilde{\nu}_L \end{pmatrix} = \begin{pmatrix} \tilde{\nu}_1 \\ \tilde{\nu}_2 \end{pmatrix}$$

WIMP candidate

Allowed GeV-mass WIMP region

M. Kakizaki, E.-K. Park, J.-h. Park, A. Santa, PLB 749, 44 (2015)

Dominant ann. mode



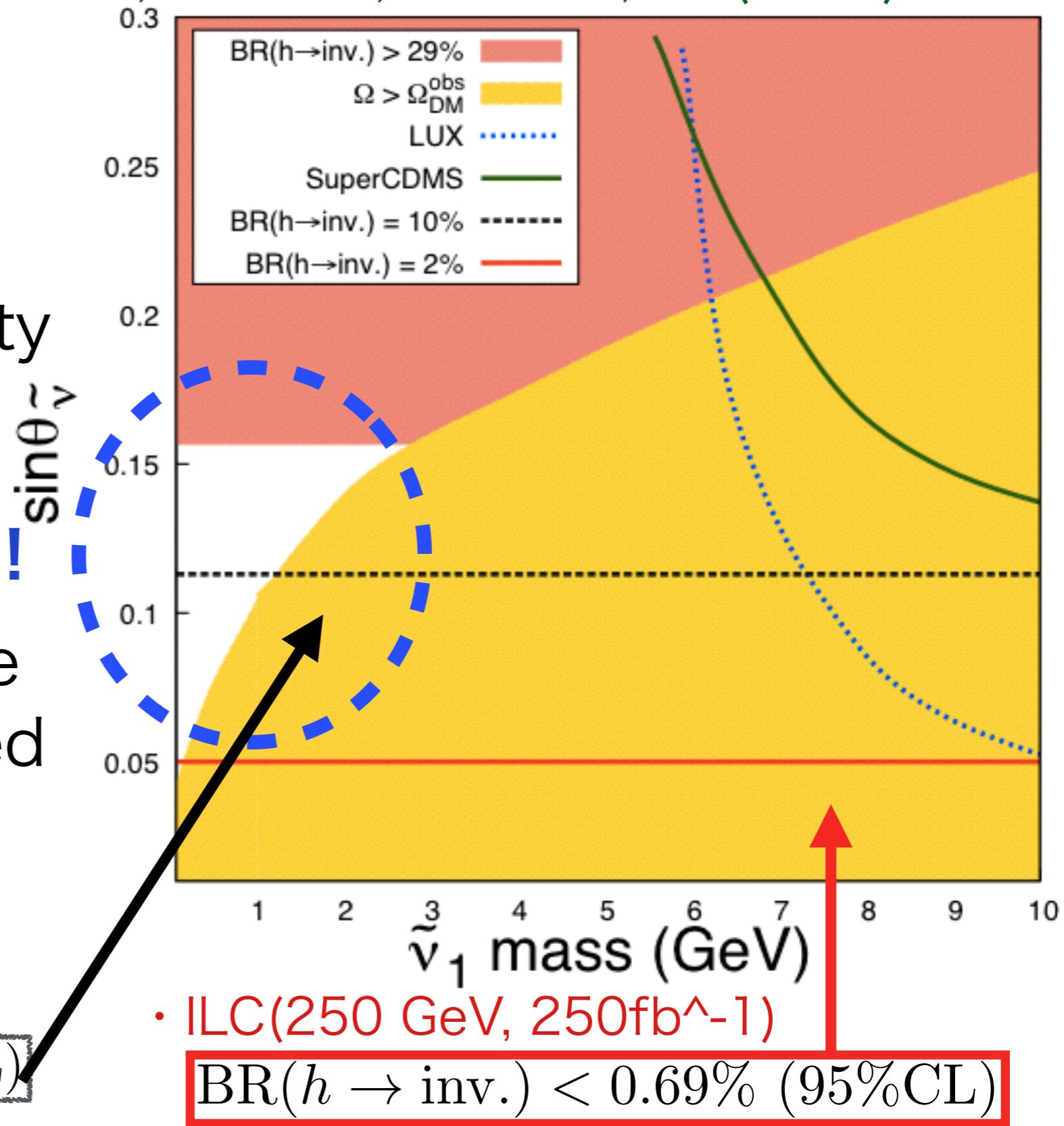
→ Correct
relic density

Consistent region!

The mass region above
0.1 GeV can be covered
at future colliders !!

- LHC(14 TeV, 3000 fb⁻¹)

$\boxed{\text{BR}(h \rightarrow \text{inv}) < 8.0\% \text{ (95\% CL)}}$



Mixed Complex Scalar Model

M. Kakizaki, A. Santa, O. Seto, arXiv: 1609.06555

The non-SUSY effective theory of the sneutrino model

Particle contents

New global symmetry

		$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
Left-handed lepton	L_i	1	2	-1/2	+1
Right-handed lepton	e_i	1	1	-1	+1
SM Higgs doublet	H	1	2	+1/2	0
Inert scalar doublet	η	1	2	+1/2	-1
Inert scalar singlet	s	1	1	0	-1
Majorana fermion	ψ	1	1	0	0

New particles

Yukawa coupling

$$-\Delta\mathcal{L}_{\text{Yukawa}} = Y(\bar{L}\psi \cdot \eta + h.c.)$$

Scalar potential

$$\begin{aligned} V = & \mu_H^2 (H^\dagger H) + \frac{\lambda_1}{2} (H^\dagger H)^2 \\ & + \mu_\eta^2 (\eta^\dagger \eta) + \frac{\lambda_2}{2} (\eta^\dagger \eta)^2 + \lambda_3 (H^\dagger H)(\eta^\dagger \eta) + \lambda_4 (H^\dagger \eta)(\eta^\dagger H) \\ & + \mu_s^2 (s^* s) + \frac{\lambda_s}{2} (s^* s)^2 + \lambda_{Hs} (H^\dagger H)(s^* s) + \lambda_{\eta s} (\eta^\dagger \eta)(s^* s) \\ & + A(H^\dagger \eta s^* + h.c.) \end{aligned}$$

Inert doublet and singlet mixing

Mixed Complex Scalar Model

M. Kakizaki, A. Santa, O. Seto, arXiv: 1609.06555

The non-SUSY effective theory of the sneutrino model

Particle contents

New global symmetry

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
ν_e	1	1	1	1

Mixed Inert Scalar WIMP Scenarios

Mass matrix of neutral inert scalars

$$-\mathcal{L}_{\text{mass}} = (\eta^{0*}, s^*) \begin{pmatrix} \mu_\eta^2 + \frac{v^2}{2}\lambda & \frac{v}{\sqrt{2}}A \\ \frac{v}{\sqrt{2}}A & \mu_s^2 + \frac{v^2}{2}\lambda_{Hs} \end{pmatrix} \begin{pmatrix} \eta^0 \\ s \end{pmatrix} \quad \lambda \equiv \lambda_3 + \lambda_4$$

→ off-diagonal elements trigger the scalar mixing

$$\begin{pmatrix} \cos \theta_\chi & \sin \theta_\chi \\ -\sin \theta_\chi & \cos \theta_\chi \end{pmatrix} \begin{pmatrix} \eta^0 \\ s \end{pmatrix} = \begin{pmatrix} \chi_2 \\ \chi_1 \end{pmatrix}$$

WIMP candidate

$$+\mu_s^2(s^*s) + \frac{\lambda_s}{2}(s^*s)^2 + \lambda_{Hs}(H^\dagger H)(s^*s) + \lambda_{\eta s}(\eta^\dagger \eta)(s^*s)$$

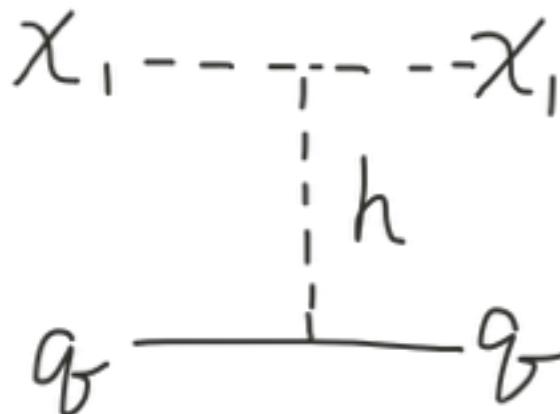
$$+A(H^\dagger \eta s^* + h.c.)$$

Inert doublet and singlet mixing

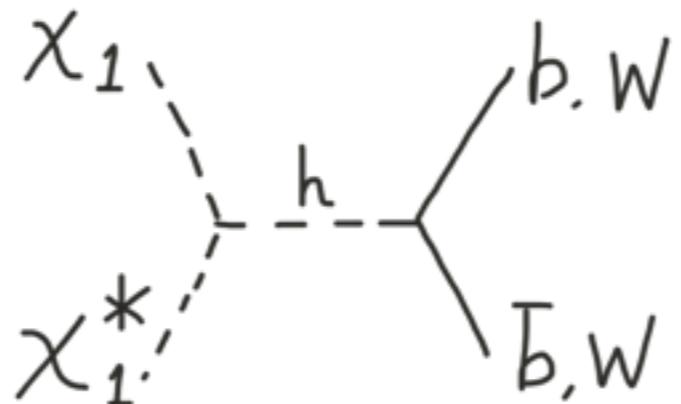
χ_1 interactions

$$\mathcal{L} \rightarrow \left[-v\lambda \sin^2 \theta_\chi - v\lambda_{Hs} \cos^2 \theta_\chi + \frac{A}{\sqrt{2}} \sin 2\theta_\chi \right] h \chi_1 \chi_1^* + \frac{Y}{2} \sin \theta_\chi [\bar{\nu}(1 - \gamma_5)\psi \chi_1^* + h.c.] + \dots$$

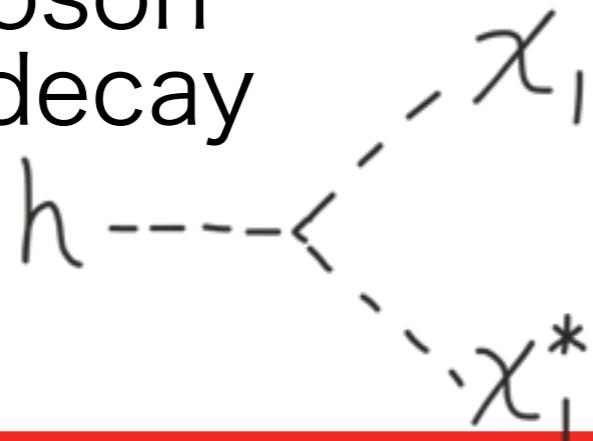
WIMP-nucleon scattering



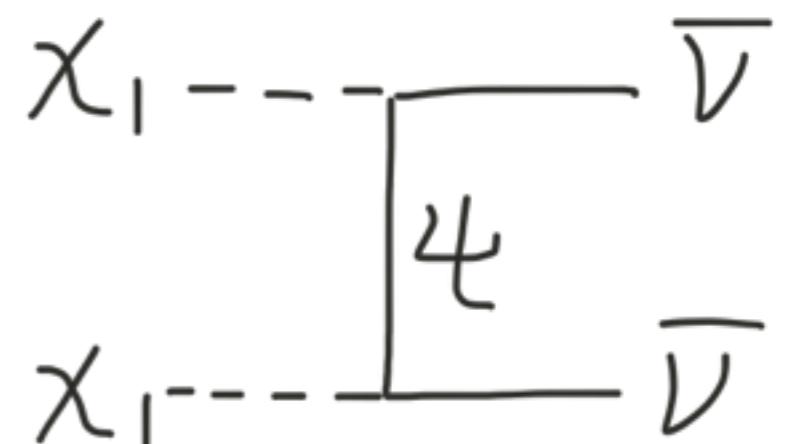
Annihilation



Higgs boson invisible decay



Annihilation of GeV-mass WIMP



Parameter set

Parameter	Scan bound / Reference value
m_{χ_1}	[10 MeV, 1.5 TeV]
m_{χ_2}	[100 GeV, 16.5 TeV]
$\sin \theta_\chi$	[0.001, 1]
m_ψ	[10 MeV, 10 GeV]
λ	-0.14
λ_{Hs}	0

We referred to mixed sneutrino model for λ, λ_{Hs}

M. Kakizaki, E.-K. Park, J.-h. Park, A. Santa, PLB 749, 44 (2015), etc.

Experimental Constraints

Relic abundance Planck(2013) $\Omega h^2 \leq 0.1258$ (95%CL)

Direct / indirect detections

m_{χ_1}	~ 1 GeV	$\sim m_h/2$	> 100 GeV
Direct detection	CDMSlite (2015) SNOLAB (2018?)	LUX (2016) XENON1T (2016?)	LUX (2016) XENON1T (2016?)
Direct detection	$\chi_1\chi_1 \rightarrow \bar{\nu}\bar{\nu}$ \Rightarrow SuperK (2015)	$\chi_1\chi_1^* \rightarrow b\bar{b}$ \Rightarrow FermiLAT (2014)	$\chi_1\chi_1^* \rightarrow W^+W^-$ \Rightarrow FermiLAT (2014)

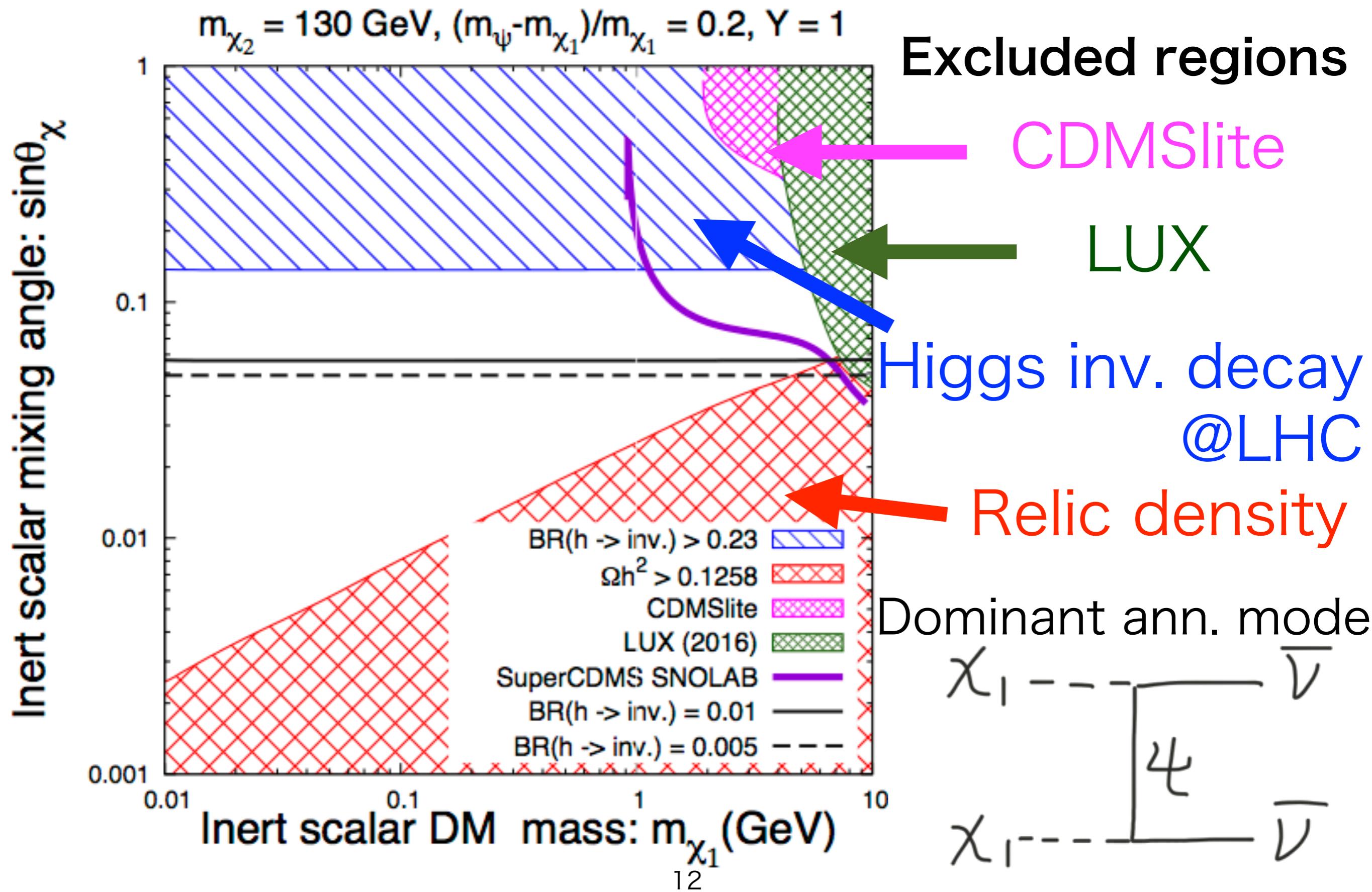
Collider experiments

Charged scalar mass $m_{\eta^\pm} > 93.1$ GeV (95% CL) ATLAS(2014)

Higgs boson invisible decay

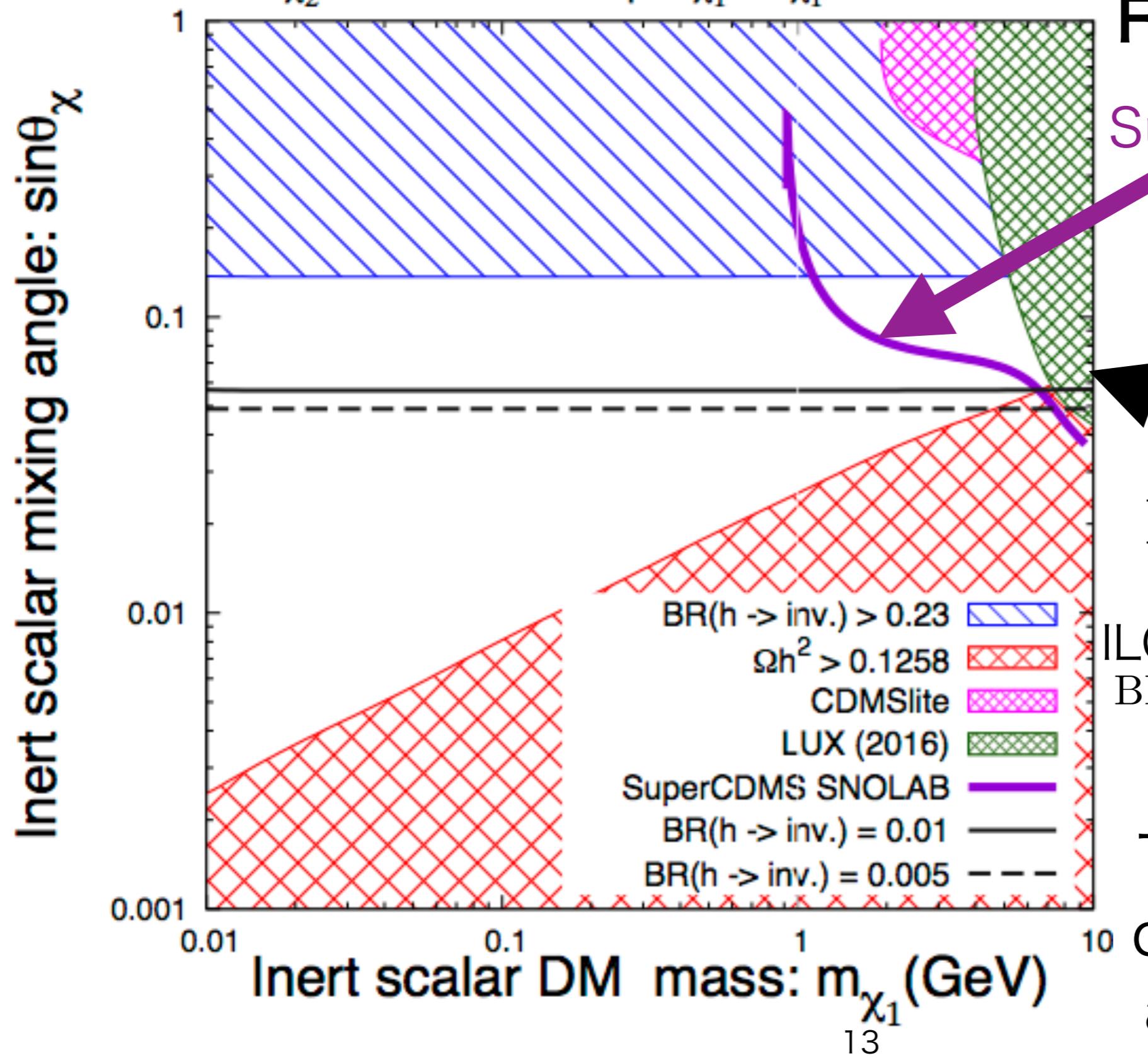
$\text{BR}(h \rightarrow \text{inv.}) < 0.29$ (95% CL) for $m_{\chi_1} < m_h/2$ ATLAS(2015)

Result of mixed complex scalar model



Result of mixed complex scalar model

$$m_{\chi_2} = 130 \text{ GeV}, (m_\psi - m_{\chi_1})/m_{\chi_1} = 0.2, Y = 1$$



Future prospects

SuperCDMS SNOLAB

$\text{BR}(h \rightarrow \text{inv.}) = 1\%$

ILC(250 GeV, 250 fb^{-1})
 $\text{BR}(h \rightarrow \text{inv.}) < 0.69\% \text{ (95\%CL)}$

Ishikawa (LCWS14)

The allowed region
can be constrained
at future colliders!

Summary

Final Goal: Examination for possibility
to distinguish **WIMP** and **ADM** scenarios

This Talk: Analysis of
GeV-mass complex scalar WIMP scenarios

Mixed sneutrino model

- Annihilation mode via neutralino contributes dominantly to relic density of GeV-mass WIMP
- Allowed GeV-mass region can be reached at future colliders

Mixed complex scalar model

- The model is effective theory of mixed sneutrino ones
- GeV-mass consistent region can be tested by Higgs boson invisible decay searches at future experiments

Back up

Mixed Sneutrino DM Scenarios 1/2

Earlier Works

Arkani-Hamed,Hall,Murayama,Smith and Weiner (2001)

G. Belanger, M. Kakizaki, E. K. Park, S. Kraml and A. Pukhov (2010)

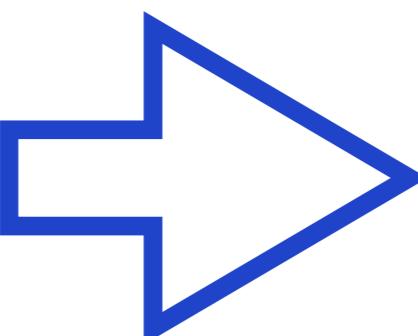
B. Dumont, G. Belanger, S. Fichet, S. Kraml and T. Schwetz (2012) etc.

Mixed Sneutrino DM Scenarios

can solve

Problems

- SM particles t, b, l, h, g, W, B
- Right-handed neutrino ν_R
- SUSY particles
 - ex. sneutrinos $\tilde{\nu}_L, \tilde{\nu}_R$
 - bino \tilde{B}
 - wino \tilde{W}
 - higgsino \tilde{h}
 - neutralino $\tilde{\chi}^0$
 - chargino $\tilde{\chi}^\pm$



- * Dark Matter
- * Neutrino Mass
- * Hierarchy Problem

These problems are related through one supermultiplet

$$\bar{N}_R = \tilde{\nu}_R^c + \sqrt{2} \nu_R^c \theta + F_{\nu_R^c} \theta^2$$

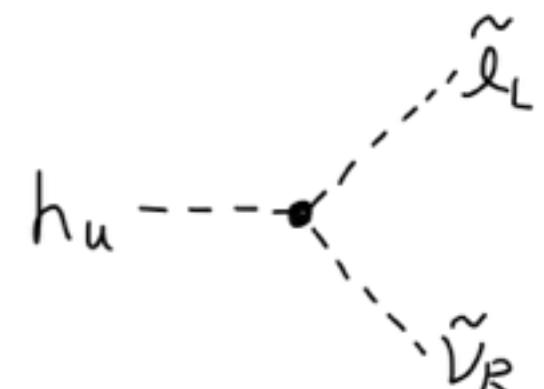
Mixed Sneutrino DM Scenarios 2/2

Lagrangian:

$$\mathcal{L} \sim (\mathcal{L}_{\text{SM}} + \mathcal{L}_{\nu_R}) \times \text{SUSY} + \mathcal{L}_{\text{SUSY breaking}}$$

Sneutrino Trilinear Coupling :

$$\mathcal{L}_{\text{SUSY breaking}} \supset -A_{\tilde{\nu}} h_u \cdot \tilde{l}_L \tilde{\nu}_R^c + \text{h.c.}$$



=> Off-diagonal components of sneutrino mass matrix

$$-\mathcal{L}_{\text{mass}} = (\tilde{\nu}_L^*, \tilde{\nu}_R^*) \begin{pmatrix} m_{\tilde{L}}^2 + \frac{1}{2}m_Z^2 \cos 2\beta & \frac{v}{\sqrt{2}} A_{\tilde{\nu}} \sin \beta \\ \frac{v}{\sqrt{2}} A_{\tilde{\nu}} \sin \beta & m_{\tilde{N}}^2 \end{pmatrix} \begin{pmatrix} \tilde{\nu}_L \\ \tilde{\nu}_R \end{pmatrix}$$

=> Left- and right-handed sneutrios mix:

$$\begin{pmatrix} \cos \theta_{\tilde{\nu}} & -\sin \theta_{\tilde{\nu}} \\ \sin \theta_{\tilde{\nu}} & \cos \theta_{\tilde{\nu}} \end{pmatrix} \begin{pmatrix} \tilde{\nu}_R \\ \tilde{\nu}_L \end{pmatrix} = \begin{pmatrix} \tilde{\nu}_1 \\ \tilde{\nu}_2 \end{pmatrix} \quad \text{WIMP candidate}$$

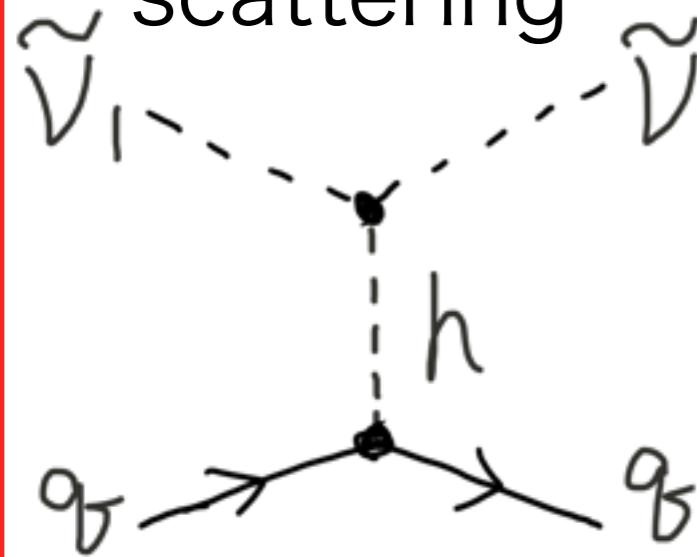
$\tilde{\nu}_1$ interactions

$$\mathcal{L} \rightarrow \left[-\frac{m_Z^2}{v} \cos 2\beta \sin^2 \theta_{\tilde{\nu}} + \frac{A_\nu}{\sqrt{2}} \sin \beta \sin 2\theta_{\tilde{\nu}} \right] h \tilde{\nu}_1^* \tilde{\nu}_1$$

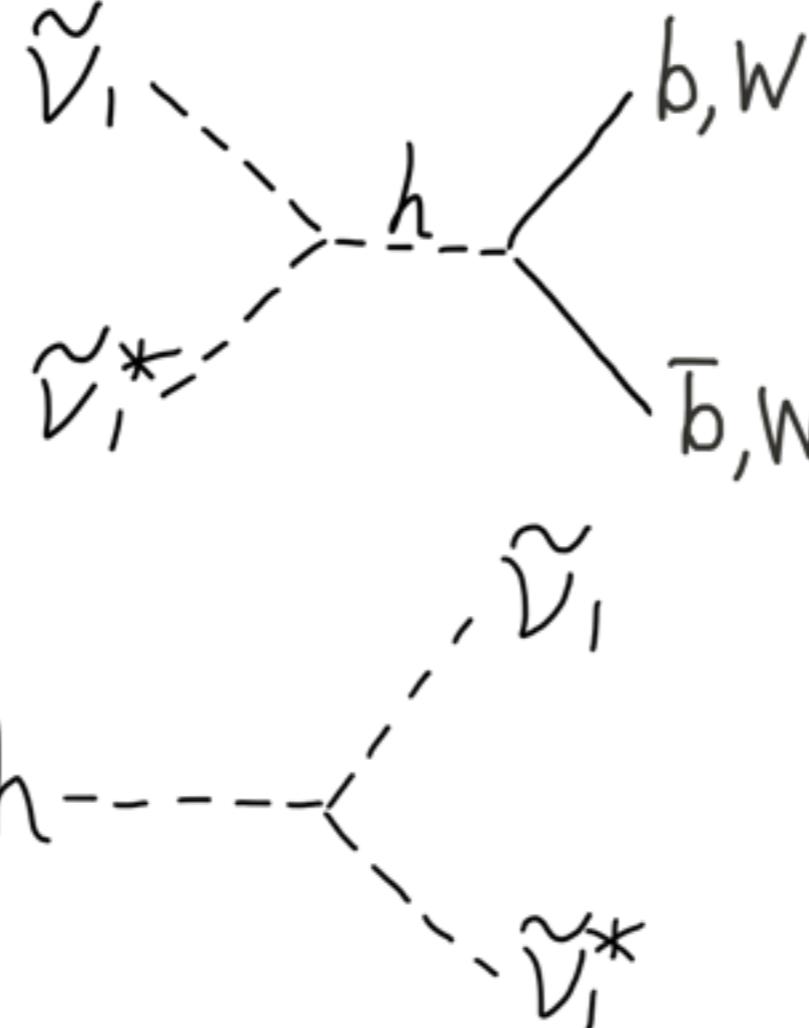
$$-\frac{e}{\sqrt{2} \sin 2\theta_W} \sin \theta_{\tilde{\nu}} (\cos \theta_W N_{i2} - \sin \theta_W N_{i1}) [\bar{\nu}_\tau (1 - \gamma_5) \tilde{\chi}_i^0 \tilde{\nu}_1 + h.c.] + \dots$$

$(\beta - \alpha \rightarrow \pi/2)$

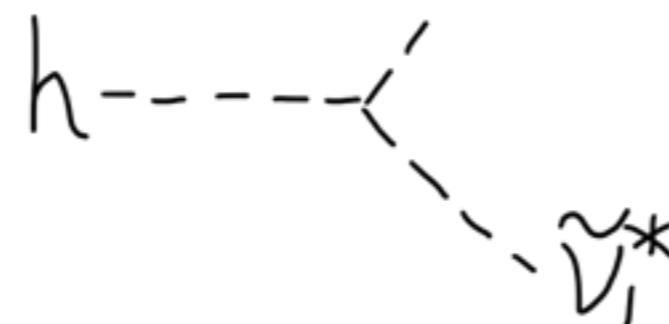
WIMP-nucleon scattering



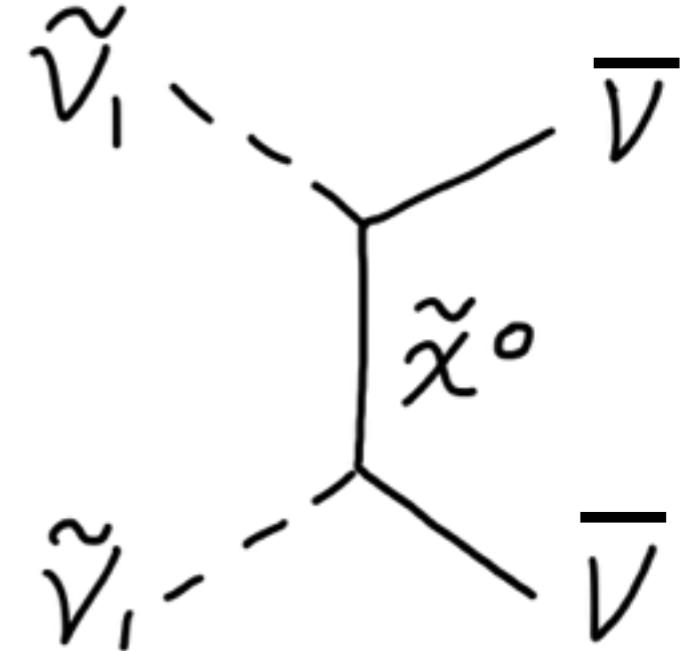
annihilation



Higgs boson invisible decay



annihilation of GeV-mass case

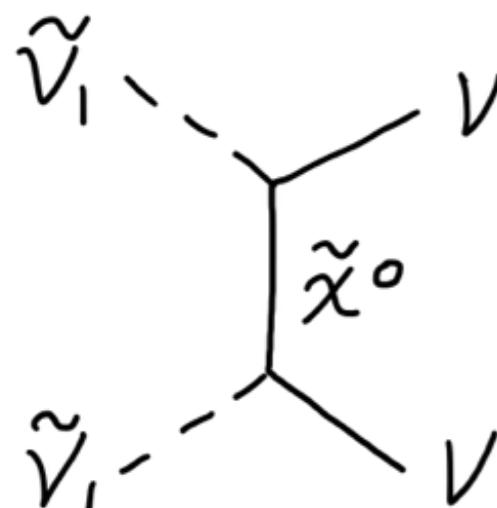


Analysis of GeV-mass sneutrino WIMP

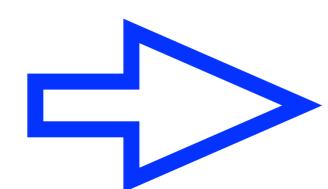
M. Kakizaki, E.-K. Park, J.-h. Park, A. Santa, PLB 749, 44 (2015)

Relic density of GeV-mass WIMP

dominant ann. mode

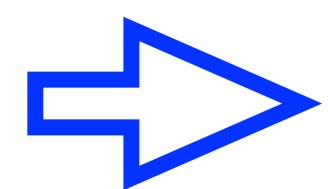


$$6M_{\tilde{B}} = 3M_{\widetilde{W}} = M_{\widetilde{g}}$$



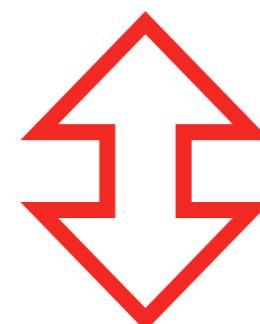
$$\Omega h^2 \sim 0.1 \times \left(\frac{m_{\tilde{\chi}_1^0}}{100 \text{ GeV}} \right)^2 (\sin \theta_{\tilde{\nu}})^{-4}$$

$$6M_{\tilde{B}} \neq 3M_{\widetilde{W}} \neq M_{\widetilde{g}}$$



$$\Omega h^2 \sim 0.1 \times \left(\frac{m_{\tilde{\chi}_1^0}}{1 \text{ GeV}} \right)^2 \left(\frac{\sin \theta_{\tilde{\nu}}}{0.1} \right)^{-4}$$

Consistent !



Limit from Higgs invisible decay searches:

$$\sin \theta_{\tilde{\nu}} < 0.16 \text{ for } m_{\tilde{\nu}_1} \leq m_h/2$$

Collider experiments

LEP2(2006), ATLAS(2014, 2015), CMS(2014)

Invisible decay searches

$$\Delta\Gamma(Z \rightarrow \text{inv}) < 2.0 \text{ MeV (95% CL)} \Rightarrow \sin\theta_{\tilde{\nu}} < 0.4$$

$$\text{BR}(h \rightarrow \text{inv}) < 0.29 \quad (95\% \text{ CL}) \Rightarrow \sin\theta_{\tilde{\nu}} < 0.16$$

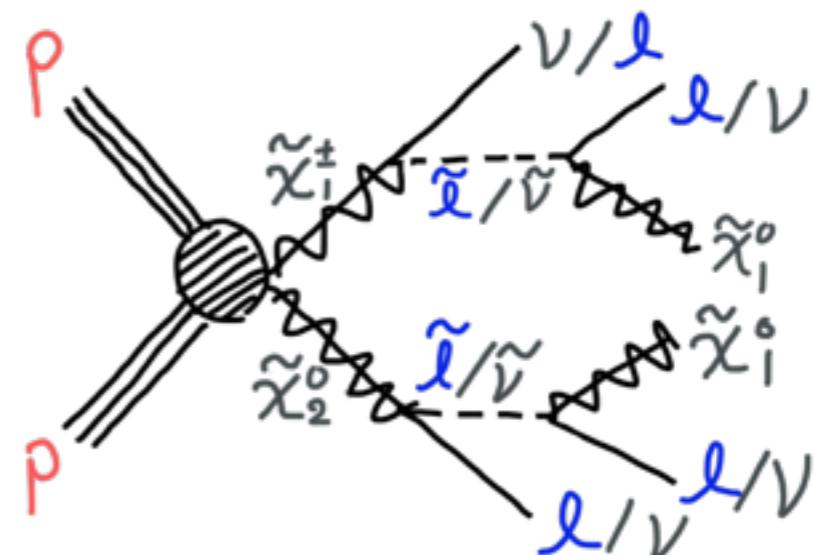
for $m_{\tilde{\nu}_2} > m_h - m_{\tilde{\nu}_1}$, $\mu \geq 500 \text{ GeV}$

Superparticle searches

example:

$$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp, \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow 2\tau, 3\tau \text{ searches}$$

$$\Rightarrow m_{\tilde{\chi}_1^\pm} > 420 \text{ GeV}$$



Mono-photon searches

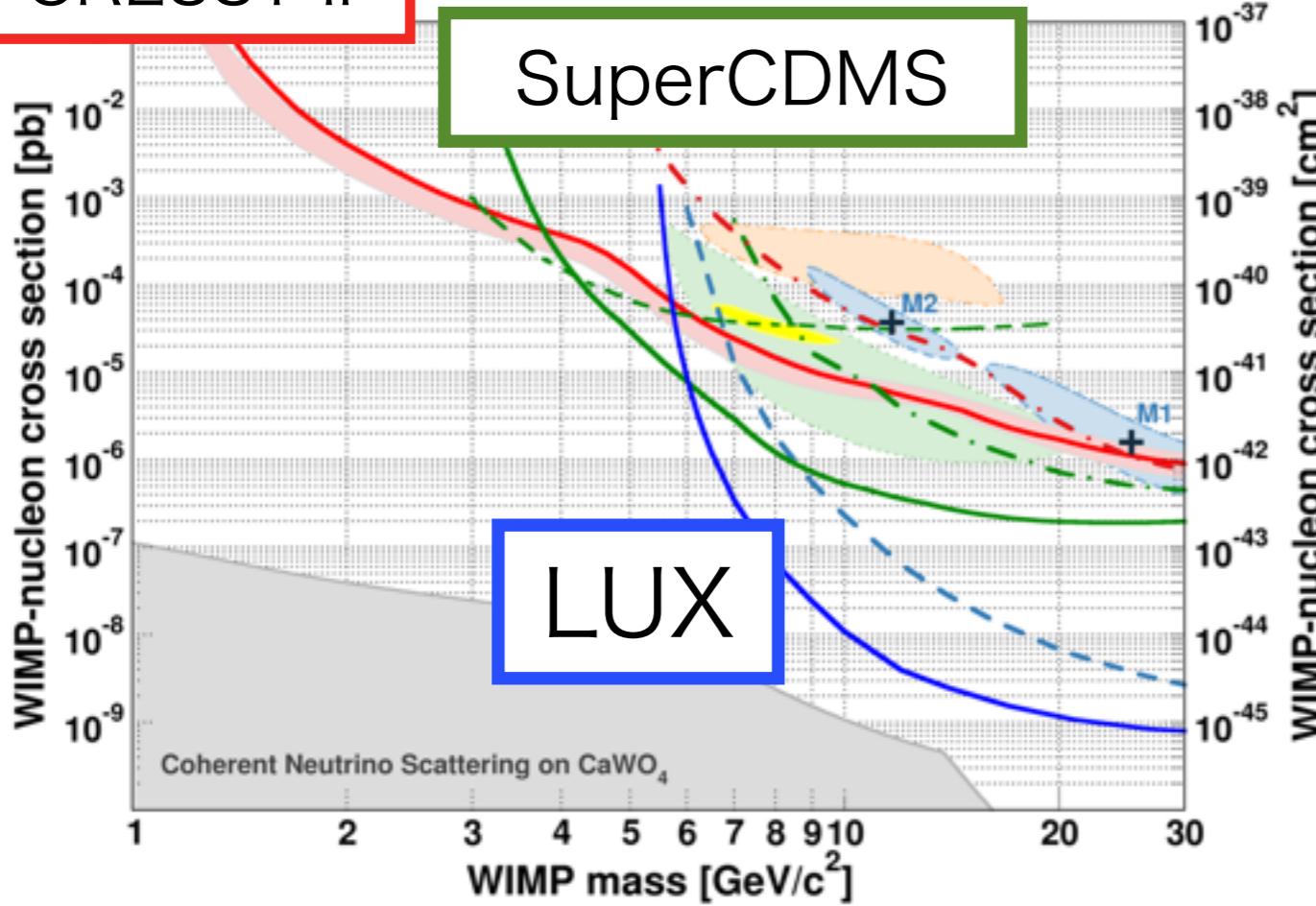
$$\sigma_n \lesssim \mathcal{O}(10^{-37}) \text{ cm}^2$$

for mediator mass : $m_V \sim 100 \text{ GeV}$,

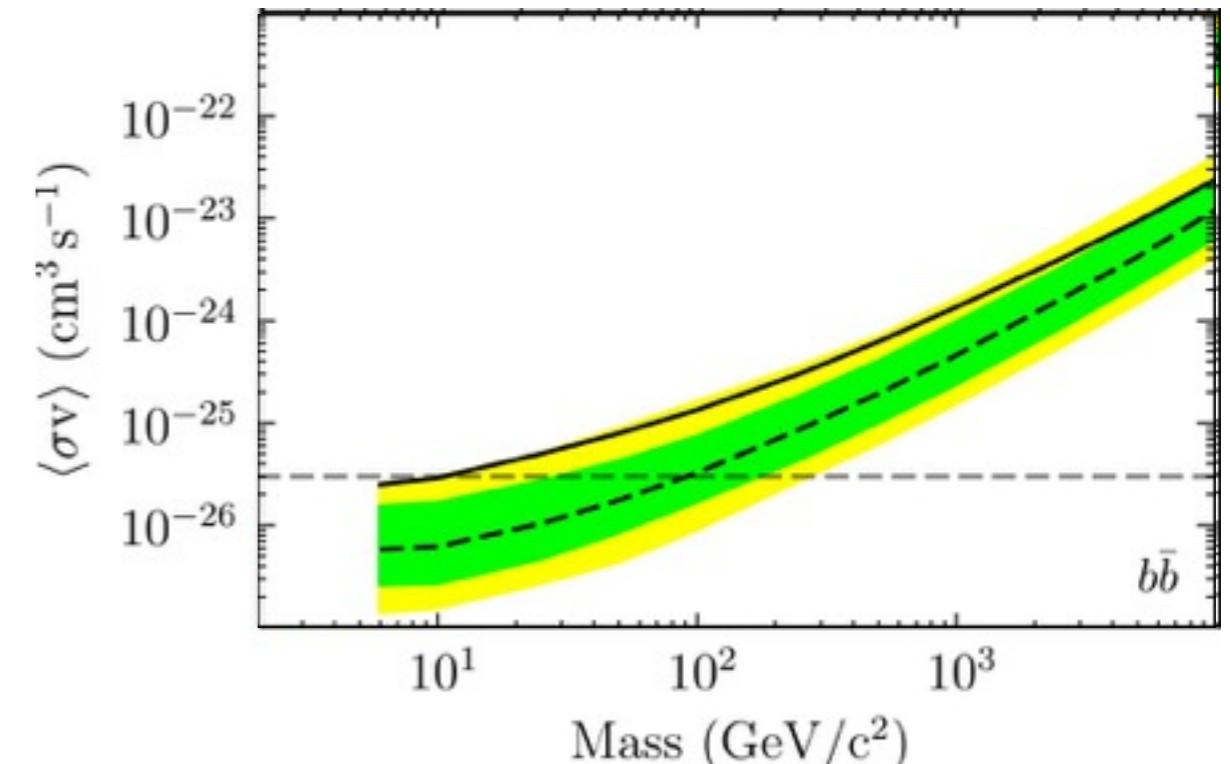
DM mass : $m_\chi \lesssim 50 \text{ GeV}$

Direct, indirect detections

CRESST II



CRESST II (2014)



FermiLAT (2014)

$m_{\tilde{\nu}_1}$	1 GeV	10 GeV
Direct Detection	Energy threshold =>Insensitive	LUX(2014) SuperCDMS(2014)
Indirect Detection	$\tilde{\nu}\tilde{\nu} \rightarrow \nu\nu$ is dominant =>Insensitive	$\tilde{\nu}\tilde{\nu}^* \rightarrow b\bar{b}$ is dominant =>FermiLAT(2014)

New! Allowed Region

Scan bounds

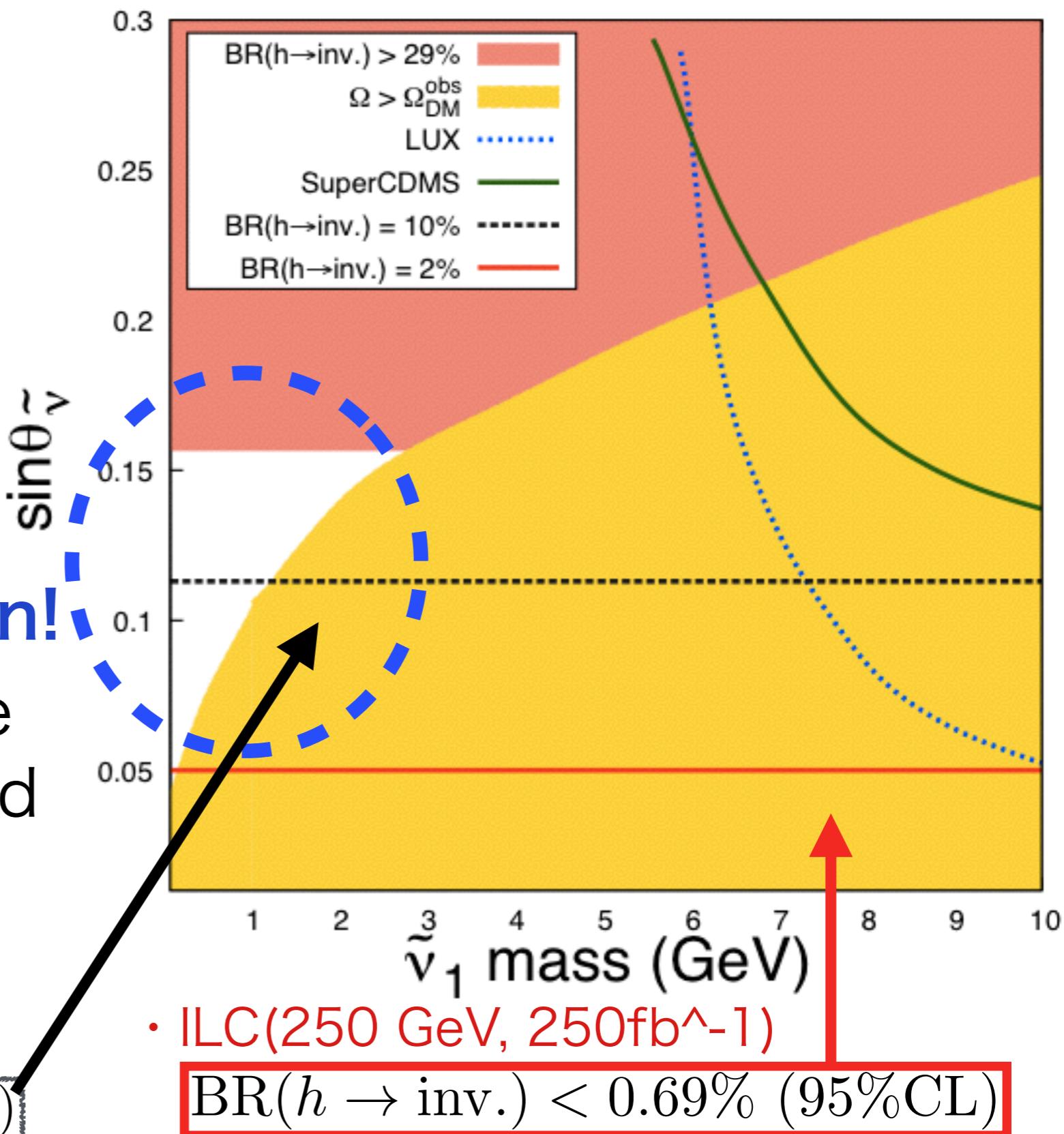
Parameter	Reference value/ Scan bound
μ	500 GeV
$\tan \beta$	10
$m_{\tilde{\nu}_1}$	[0.1 GeV, 10 GeV]
$m_{\tilde{\nu}_2}$	126 GeV
$\sin \theta_{\tilde{\nu}}$	[0.01, 0.3]
$M_{\tilde{B}}$	[0.1 GeV, 20 GeV]

Consistent region!

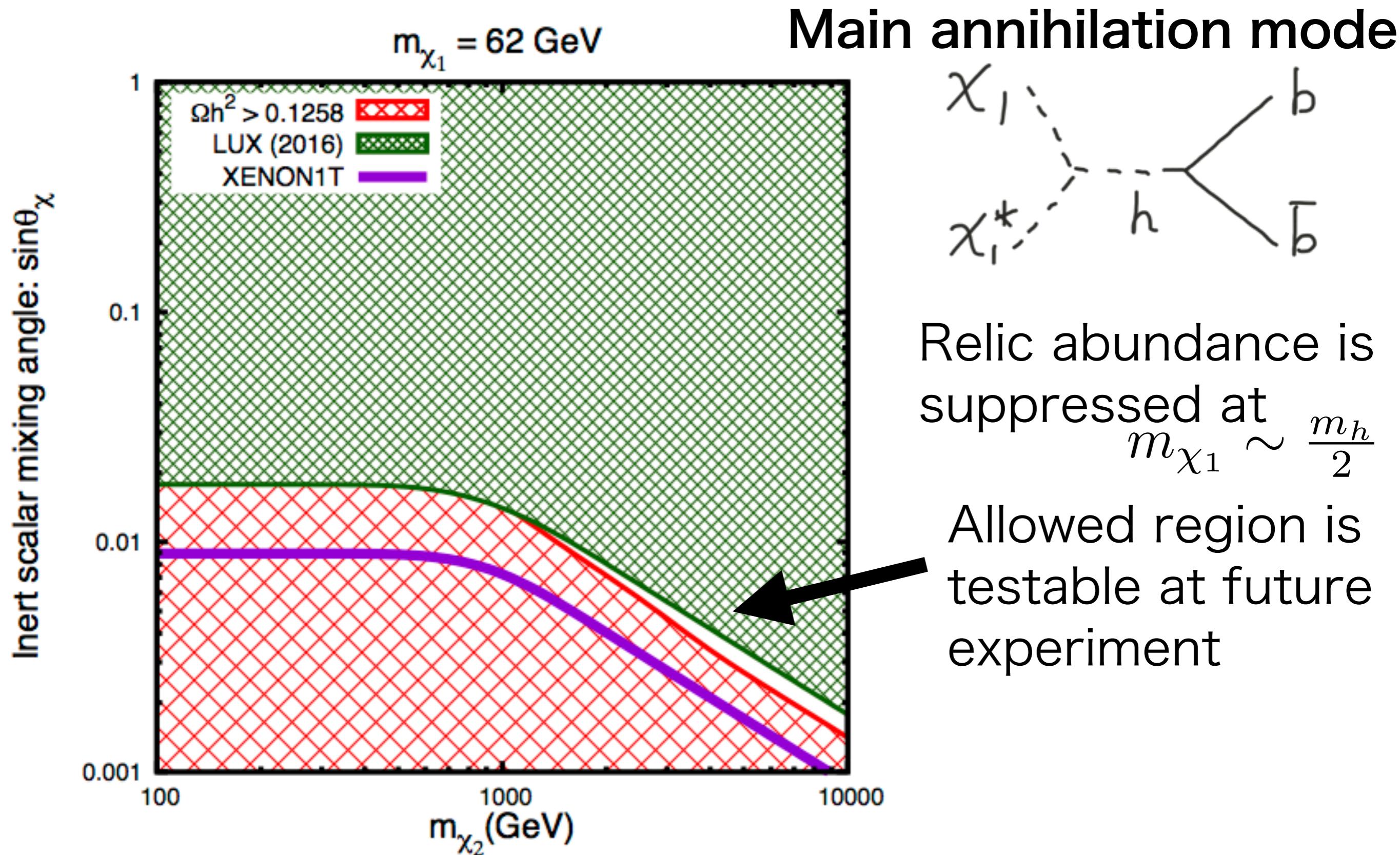
The mass region above 0.1 GeV can be covered at future colliders !!

- **Future experiments**
 - LHC(14 TeV, 3000 fb $^{-1}$)

$\boxed{\text{BR}(h \rightarrow \text{inv}) < 8.0\% \text{ (95\% CL)}}$



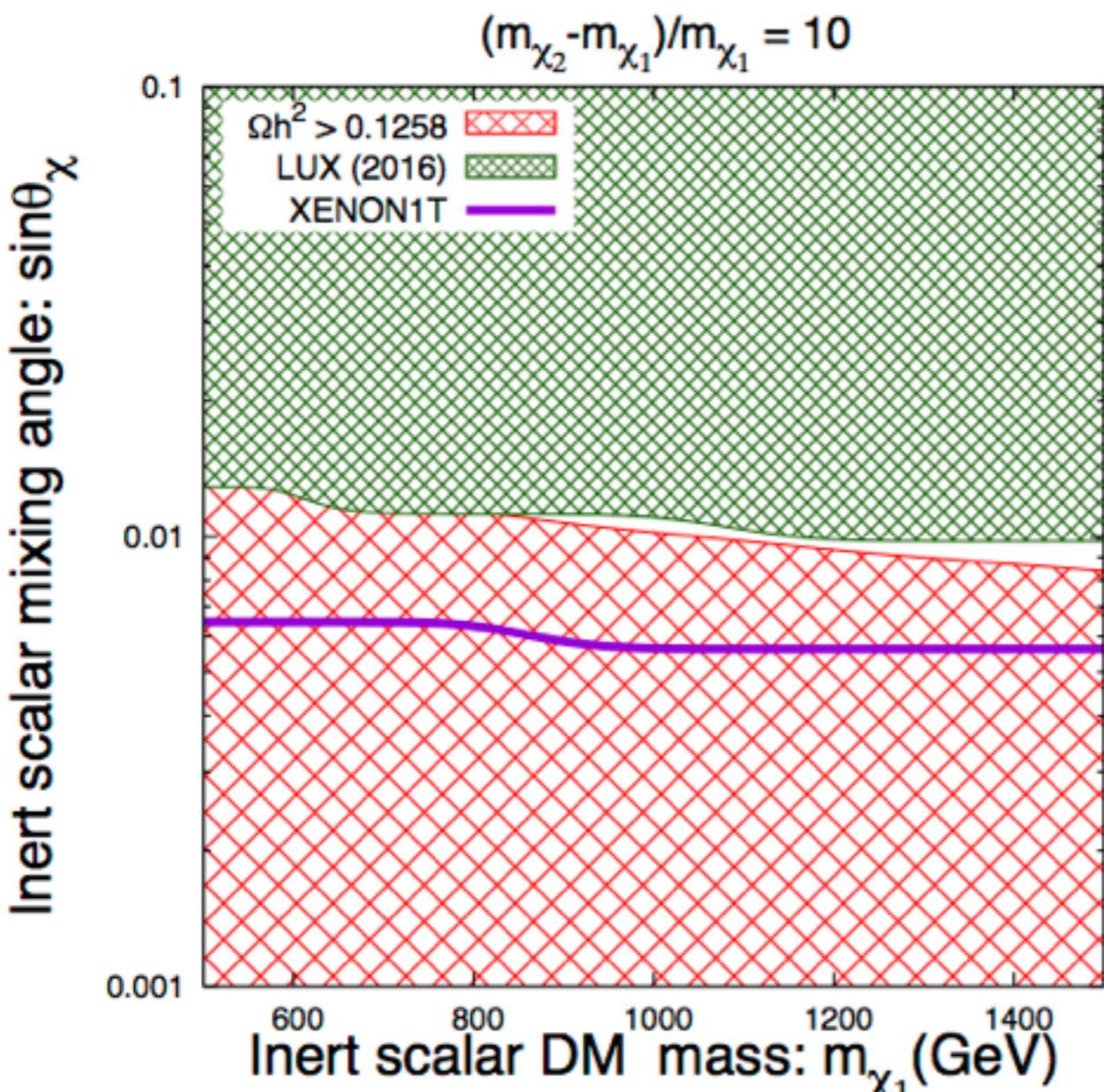
Allowed region at $m_{\chi_1} \sim \frac{m_h}{2}$



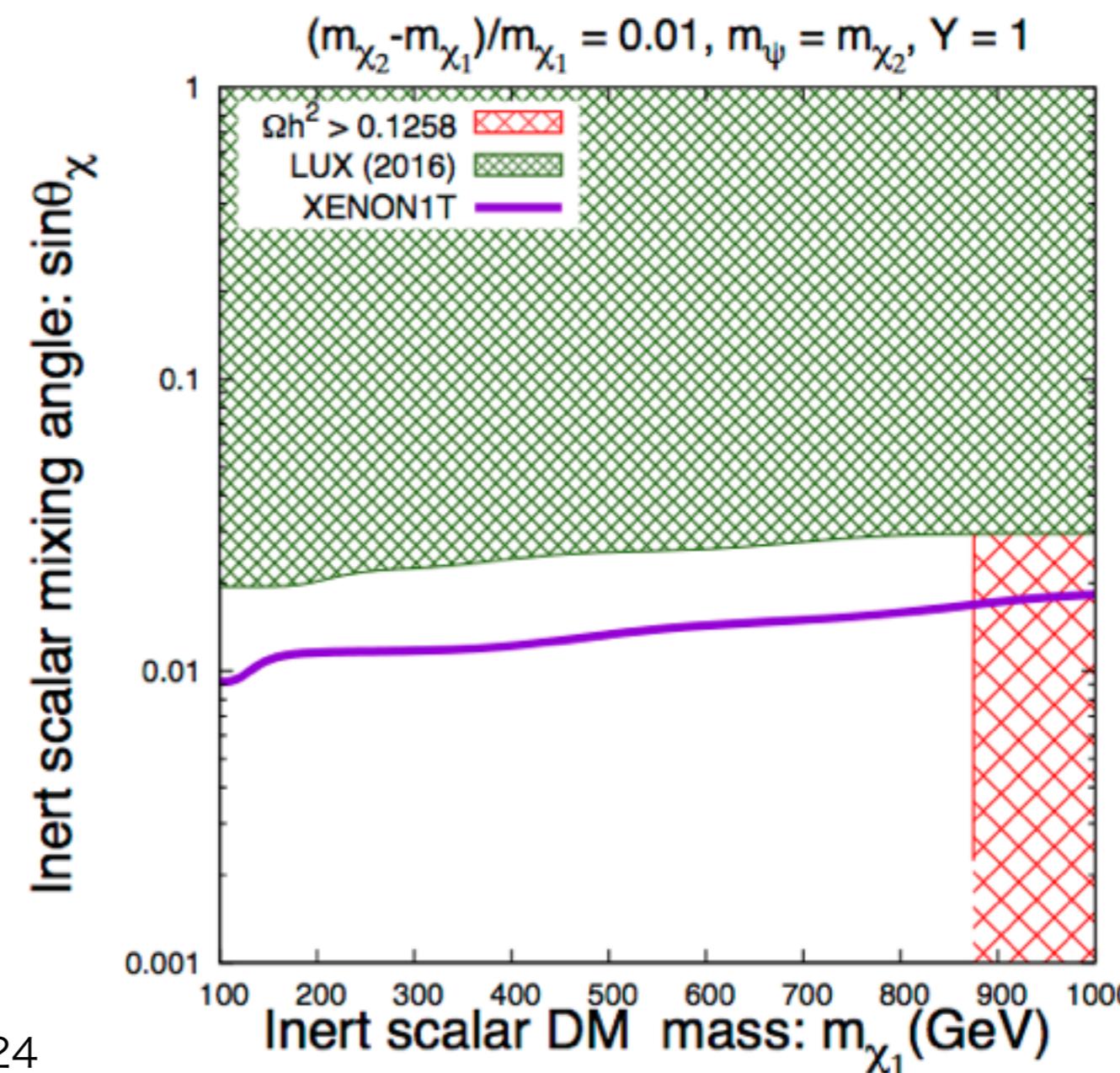
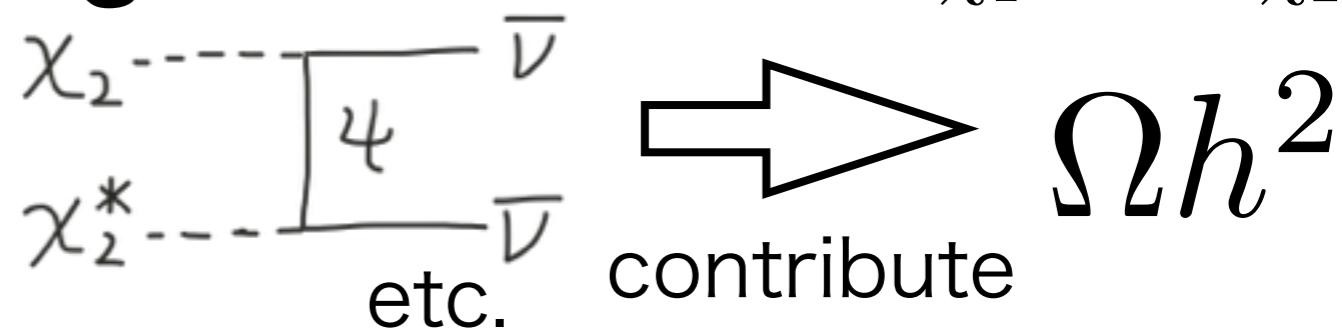
Heavy WIMP case

Splitting case: $m_{\chi_1} \ll m_{\chi_2}$

$$\Omega h^2 \propto A^{-2} = \left[\frac{m_{\chi_2}^2 - m_{\chi_1}^2}{\sqrt{2}v} \sin 2\theta_\chi \right]^{-2}$$



Degenerate case: $m_{\chi_1} \approx m_{\chi_2}$

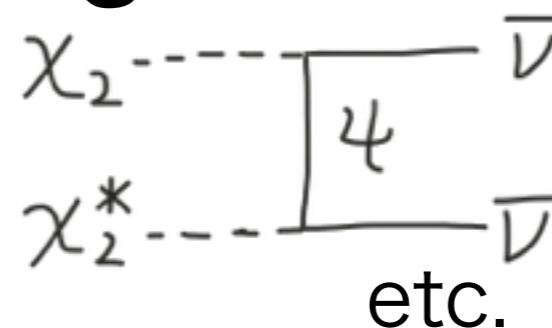


Heavy WIMP case

Splitting case: $m_{\chi_1} \ll m_{\chi_2}$

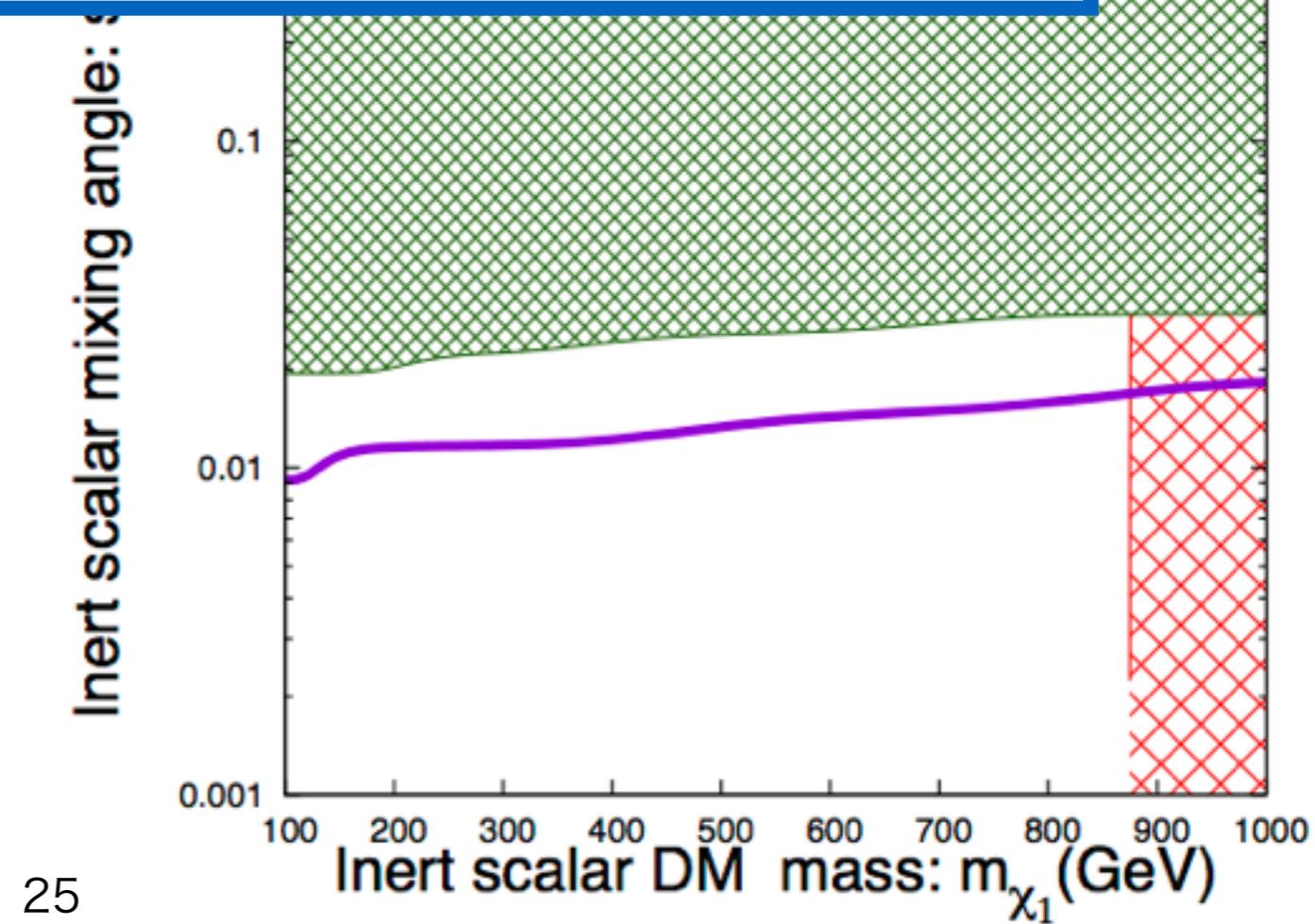
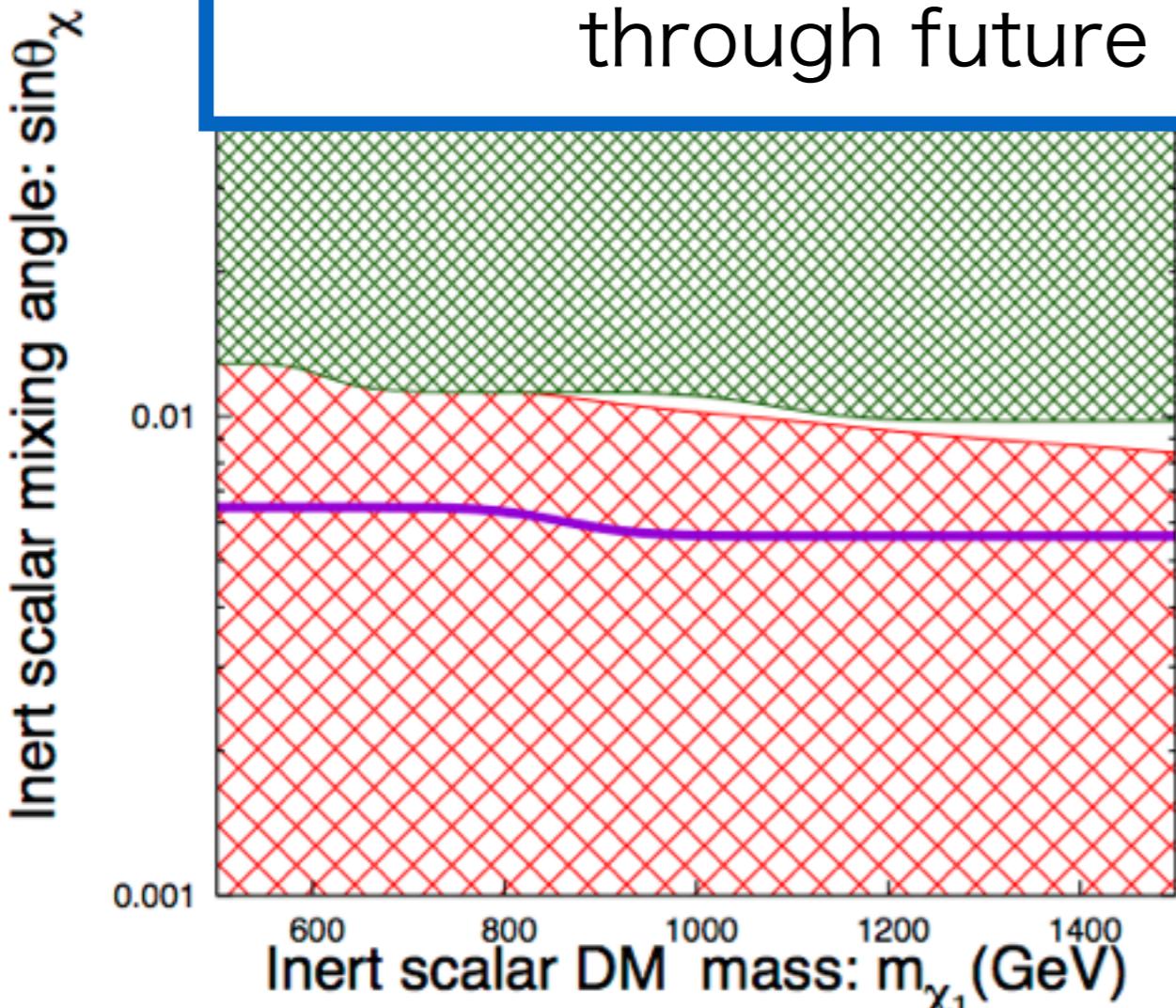
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Degenerate case: $m_{\chi_1} \approx m_{\chi_2}$



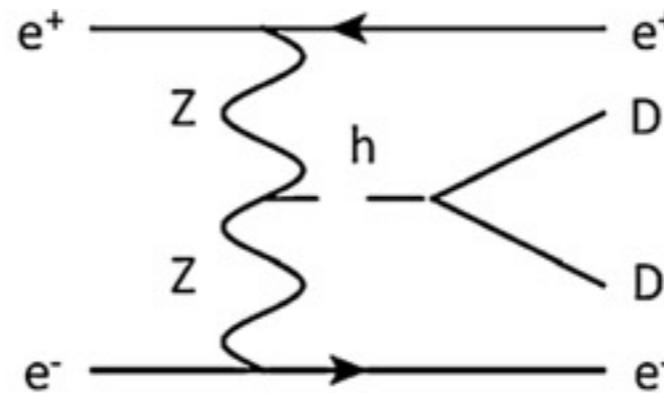
Ωh^2 contribute

Splitting and degenerate cases can be distinguished through future direct detections !!

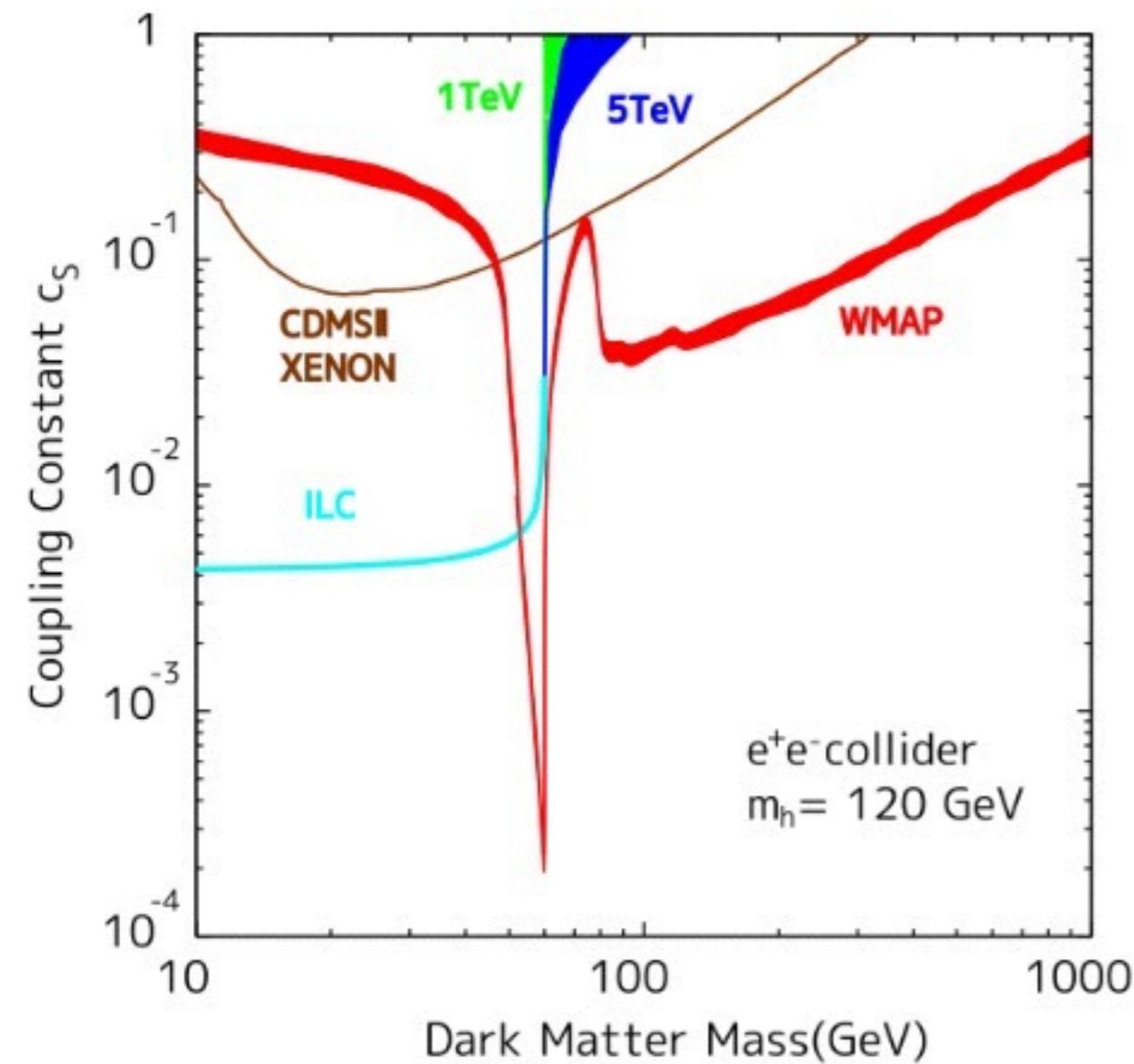


Constraints from Z boson fusion

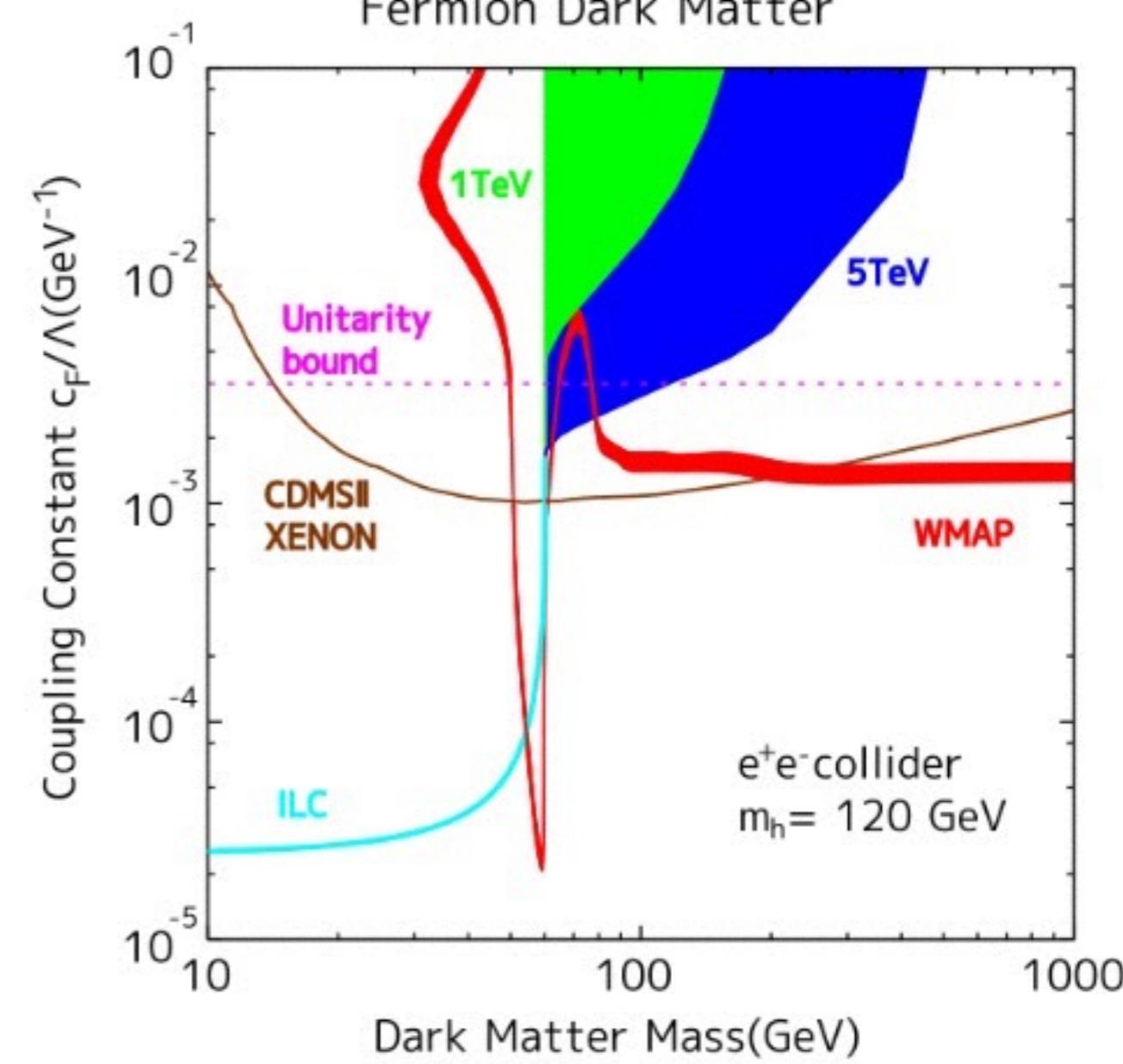
[S. Kanemura, S. Matsumoto, T. Nabeshima, H. Taniguchi, PLB 701(2011)591]



Scalar Dark Matter



Fermion Dark Matter



Direct detections

