Neutrinos Meet SIMP

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Energy Frontier in Particle Physics: LHC and Future Colliders

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"A Radiative Neutrino Mass Model with SIMP Dark Matter"

In collaboration with Shu-Yu Ho (Caltech), Takashi Toma (TUM)

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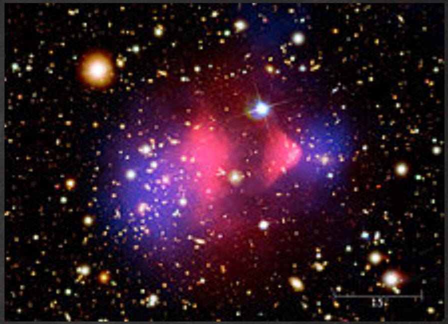
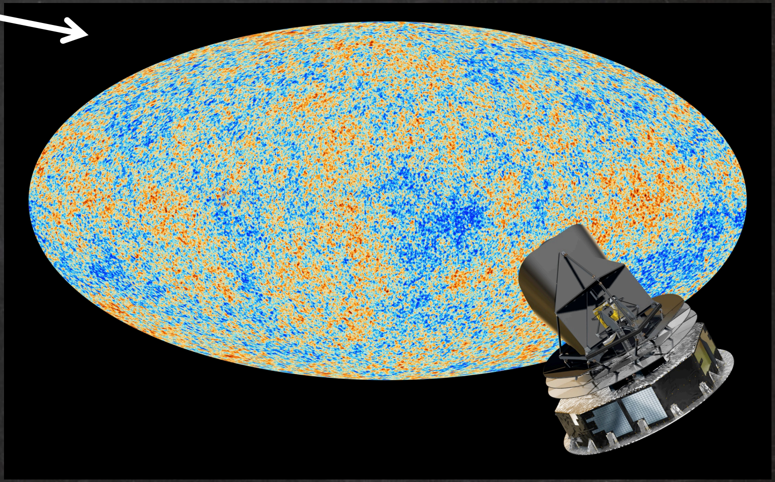
Dark Matter

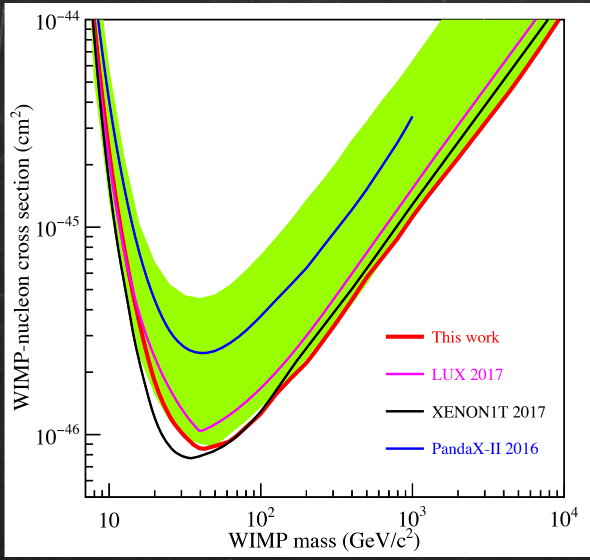
Dark Matter

Many Evidences for DM

- Galaxy Rotation Curve
- Velocity Dispersion of Galaxies
- Galaxy Clusters and Gravitational Lensing
- Sky surveys and baryon acoustic oscillations
- Cosmic Microwave Background (CMB)
- Type Ia supernovae distance measurements
- Lyman-Alpha Forest
- Structure Formation





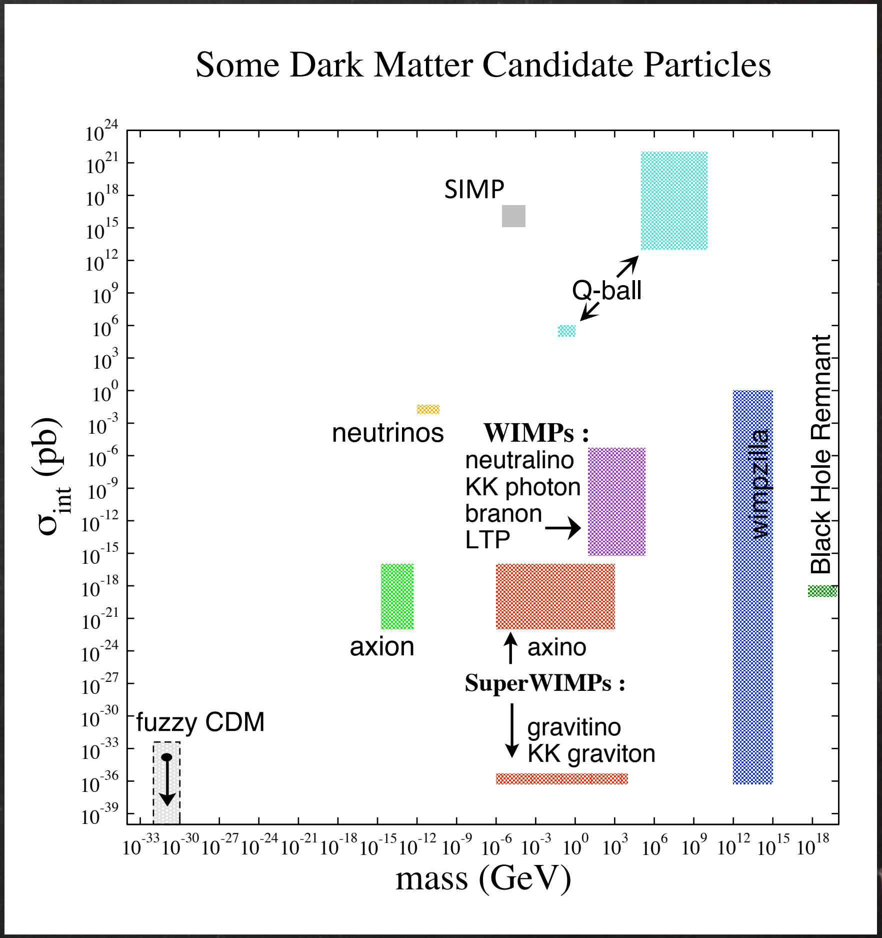


Need DM

Dark Matter

Many Candidates for DM

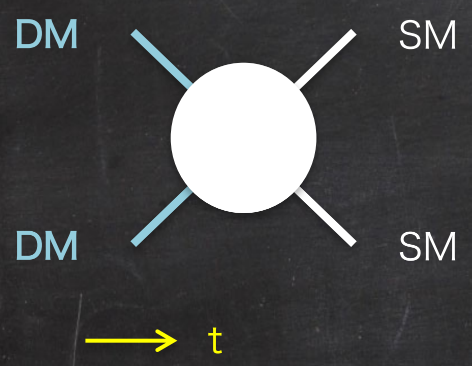
- Primordial Black Hole
- ~~Neutrino (Hot)~~
- **WIMP** [Weakly Interacting Massive Particle]
- **SIMP** [Strongly Interacting Massive Particle]
- Axion, Axion cluster
- Soliton (Q-ball, B-ball, …)
- Super Massive Relic (WIMPzilla, …)
- …



WIMP Paradigm

A promising candidate for **Thermal** DM

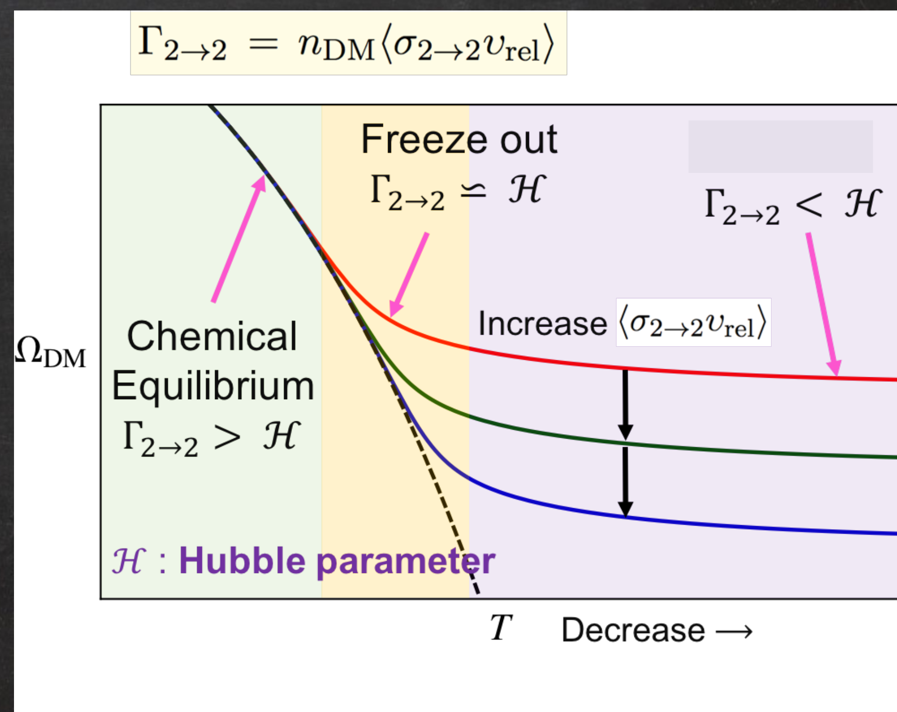
Annihilation



$$\dot{n} + 3Hn = -(n^2 - n_{eq}^2)\langle \sigma_{2\to2} v_{rel} \rangle$$

$$\langle \sigma_{2\to2} v_{rel} \rangle \equiv \frac{\alpha_{2\to2}^2}{M_{DM}^2}$$

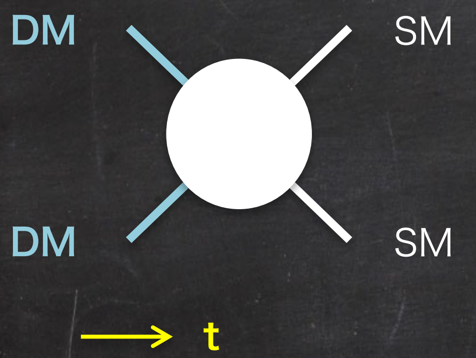
$$\Omega_{DM} \simeq \frac{0.1\mathrm{pb}}{\langle \sigma_{2\to2} v_{rel} \rangle}$$



WIMP Miracle

A promising candidate for Thermal DM

Annihilation



$$\langle \sigma_{2\to 2} v_{\rm rel} \rangle \equiv \frac{\alpha_{2\to 2}^2}{M_{\rm DM}^2}$$

$$\Omega_{\rm DM} \simeq \frac{0.1{\rm pb}}{\langle \sigma_{2\to 2} v_{\rm rel} \rangle} \sim \frac{0.12}{h^2}$$

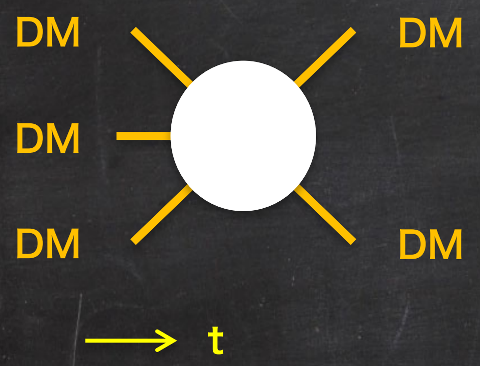
$$M_{\rm DM} \simeq \left(\frac{\alpha_{2\to 2}}{1/30} \right) \times 1\,{\rm TeV}$$

Weak int. + TeV (WIMP Miracle)

SIMP Paradigm

New promising candidate for Thermal DM

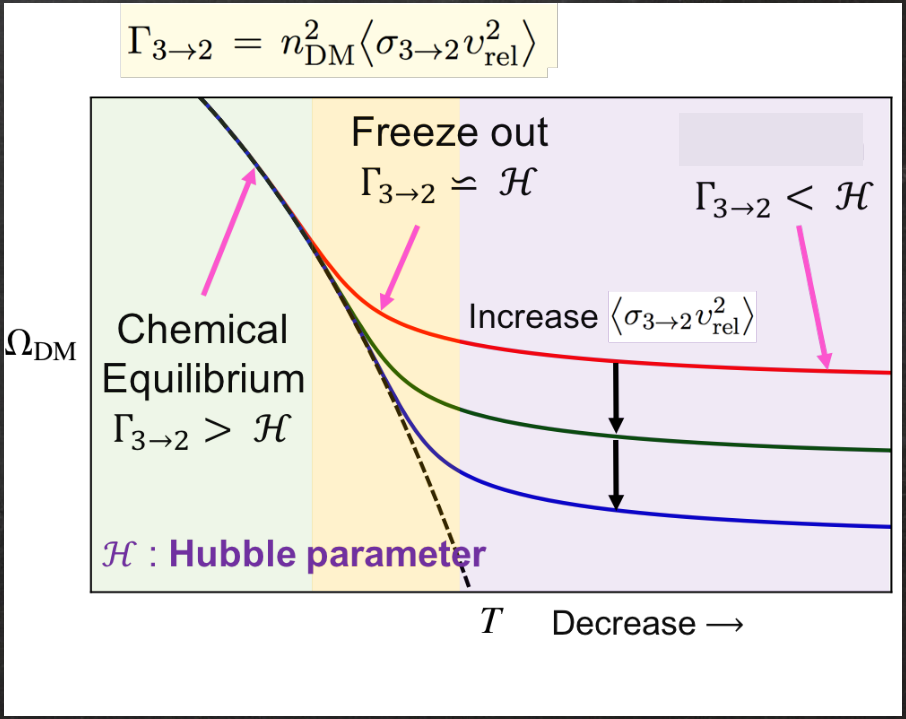
Annihilation



$$\dot{n} + 3Hn = -(n^3 - n^2 n_{\rm eq})\langle \sigma_{3\to 2} v_{\rm rel} \rangle$$

3➔2 annihilation in DM sector

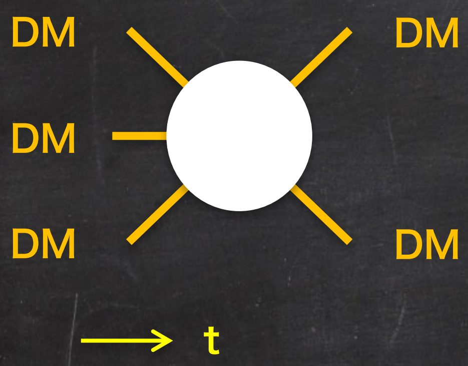
$$\langle \sigma_{3\to 2} v_{\rm rel}^2 \rangle \equiv \frac{\alpha_{3\to 2}^3}{M_{\rm DM}^5}$$



SIMP Miracle

New promising candidate for Thermal DM

Annihilation



3➔2 annihilation in DM sector

$$\langle \sigma_{3\to 2} v_{\rm rel}^2 \rangle \equiv \frac{\alpha_{3\to 2}^3}{M_{\rm DM}^5}$$

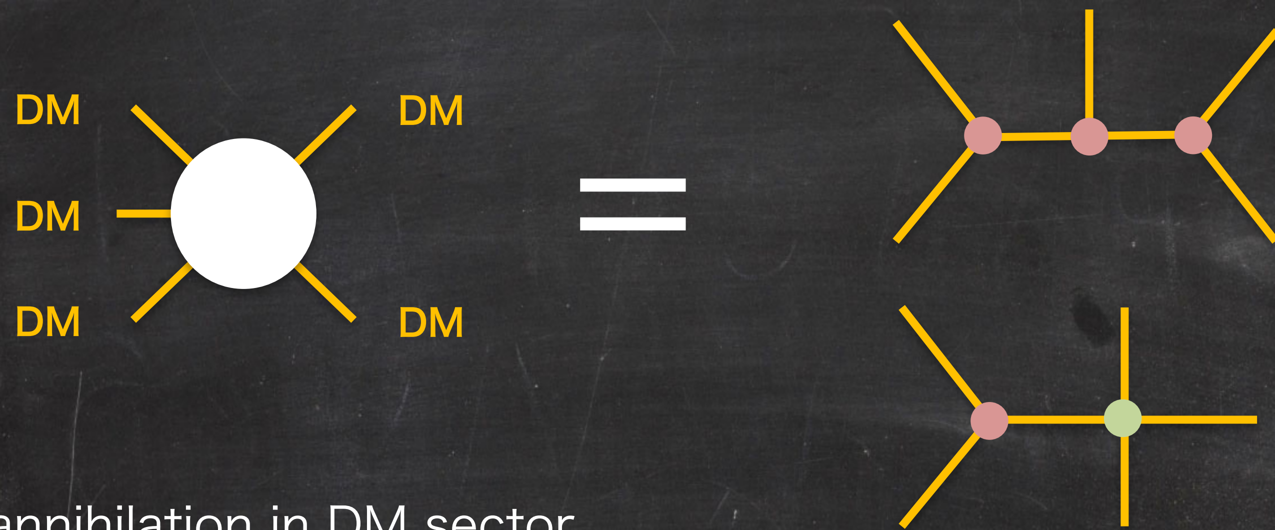
$$M_{\rm DM} \simeq \alpha_{3\to 2} \times 100\,\mathrm{MeV}$$

Strong int. + Λ_{QCD} (SIMP Miracle)

SIMP Stability?

Strong Cubic int.

ex. Z_3 : $\chi \to e^{(2\pi/3)i}\chi$ $\qquad \mathcal{L}_{Z_3} = m^2|\chi|^2 + \kappa(\chi^3 + \mathrm{H.c.}) + \lambda|\chi|^4$



$\sim \dfrac{\kappa^3}{M^4}$

$\sim \dfrac{\kappa\lambda}{M^2}$

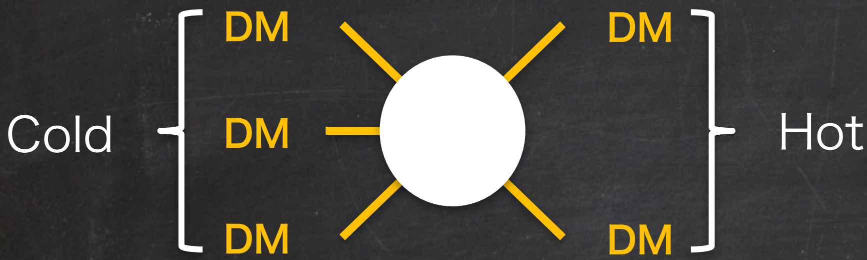
3➔2 annihilation in DM sector

$$\langle \sigma_{3\to 2} v_{\rm rel}^2 \rangle \equiv \frac{\alpha_{3\to 2}^3}{M_{\rm DM}^5}$$

single scale theory

$\kappa \sim g\,M,\ \ \lambda \sim g^2$ ➡ $\mathcal{M} \sim \dfrac{g^3}{M}$

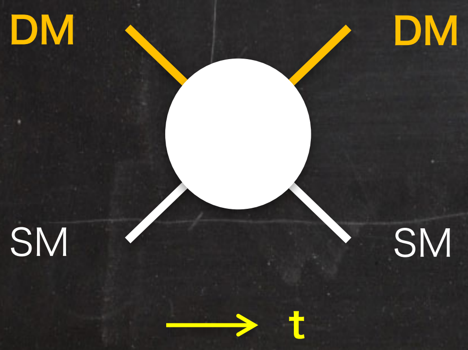
Hot DM ?



→ Excluded by Structure Formation

No SM int. ➔ No Cooling by radiations $T_{DM} \neq T_{SM}$ Carlson, Machacek, Hall (92)

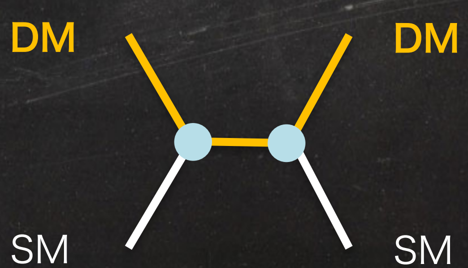
Need connection with SM to keep it in Thermal Equilibrium



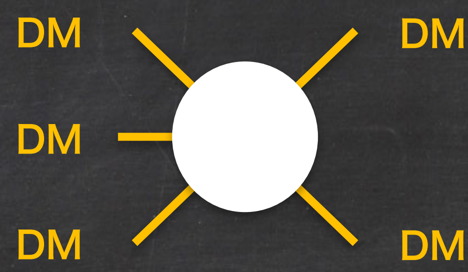
$$\Gamma_{\rm kin} = n_{\rm SM}\langle\sigma_{\rm kin}v\rangle \simeq n_{\rm SM}\langle\sigma_{\rm ann}v\rangle$$

New portal int.

$$\langle\sigma_{\rm ann}v\rangle = \frac{y^2}{M_{\rm DM}^2}$$



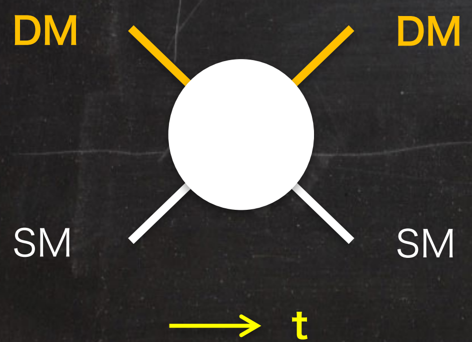
SIMP Condition



Keep SIMP in Thermal Bath

Non WIMP condition

$$\Gamma_{\text{kin}} > \Gamma_{3\to 2}(\sim H_F) > \Gamma_{2\to 2}$$

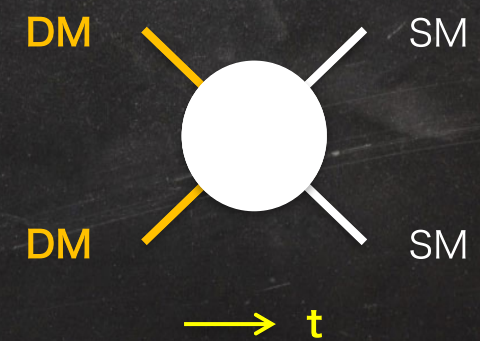


$$\Gamma_{\text{kin}} \simeq n_{\text{SM}} \langle \sigma_{\text{ann}} v \rangle$$

(SIMP Miracle)

$$n_{\text{SM}} \gg n_{\text{DM}}$$

$$\sim T_F^3 \qquad \sim \frac{T_{\text{eq}}}{M_{\text{DM}}} T_F^3$$



$$\Gamma_{2\to 2} \simeq n_{\text{DM}} \langle \sigma_{\text{ann}} v \rangle$$

Neutrino

Neutrino

$$M_\nu <<<<<<< v_{\rm EW} \qquad \mathcal{O}(10^{12})$$

$\sim 0.1\,{\rm eV}$ $\qquad\qquad = 2.46 \times 10^{11}\,{\rm eV}$

$$M_\nu <<< M_e \qquad \mathcal{O}(10^{7})$$

$= 5.11 \times 10^{5}\,{\rm eV}$

$\sim 0.1\,{\rm t}$

$\sim 2.9 \times 10^{12}\,{\rm t}$

Mt. Fuji

(a big mountain)

Seesaw Mechanism

Neutrinos can be **Majorana** Particle

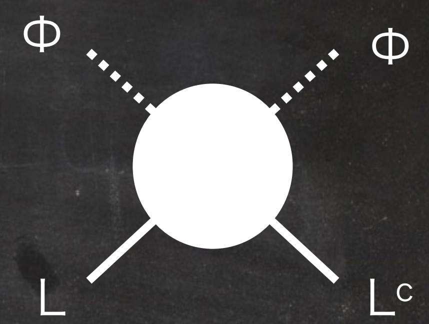
$$\mathcal{L}_M = \frac{1}{2} \underline{m_\nu} \overline{\nu}_L \nu_L^c + \mathrm{H.c}$$

L#V by 2 unit

$$\Rightarrow \frac{1}{\underline{\Lambda}} (\overline{L}\widetilde{\Phi})(\widetilde{\Phi}^T L^c) + \mathrm{H.c}$$

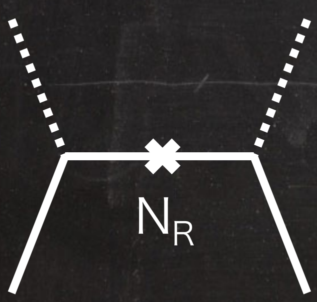
Weinberg (77)

New mass scale (Seesaw!?)



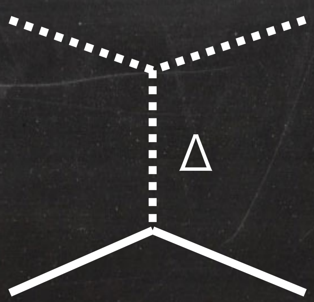
Minkowski (77)

Type-I



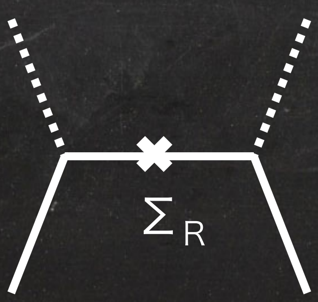
Konetschny, Kumer (77)

Type-II



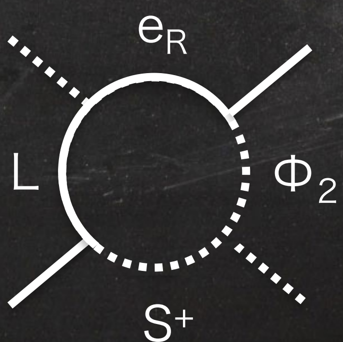
Foot, Lew, He, Joshi (89)

Type-III



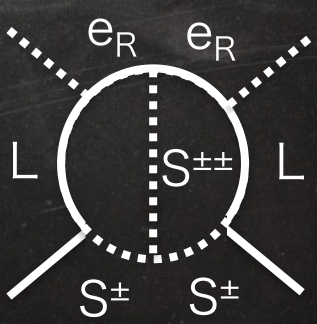
Zee (80)

1-loop



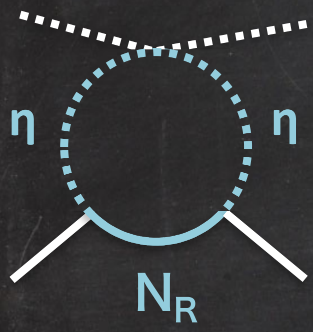
Zee (86)

2-loop



Neutrinos Meet DM

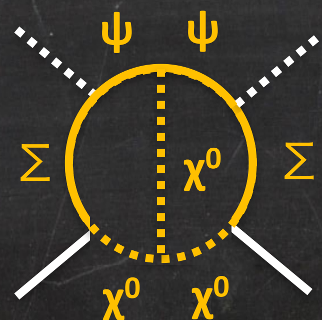
Scoto-genic Model (Scotos = Darkness)



Ma (06) [Ma (98)]

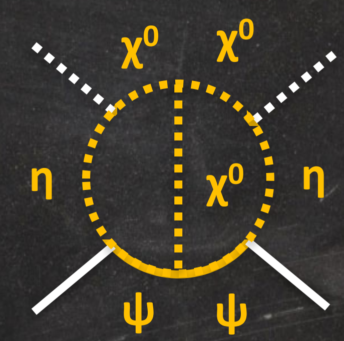
Z_2 odd

Imposed Discrete Sym. ➔ WIMP DM



Z_3 charged

Ma (07)



Can we construct a model with SIMP DM?

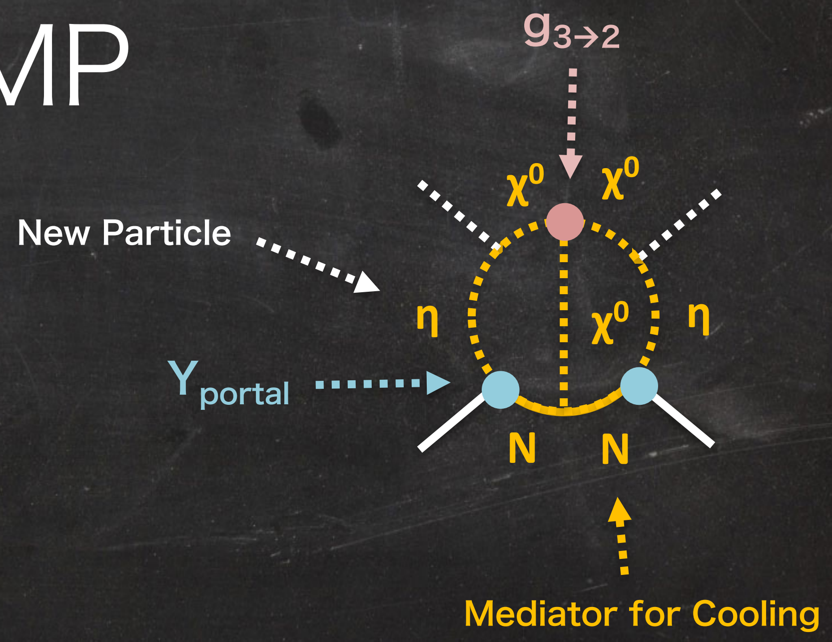
S-Y Ho, T. Toma, KT,JHEP1708, 101 (2017) [arXiv:1705.00592]

“A Radiative Neutrino Mass Model with SIMP Dark Matter”

νSIMP

	E	Φ	N	η	χ
SU(2)	**2**	**2**	**1**	**2**	**1**
$\mathrm{U}(1)_Y$	$-1/2$	$1/2$	0	$1/2$	0
$\mathbb{Z}_3$	1	1	ω	ω	ω

$\omega=\exp(2\pi i/3)$

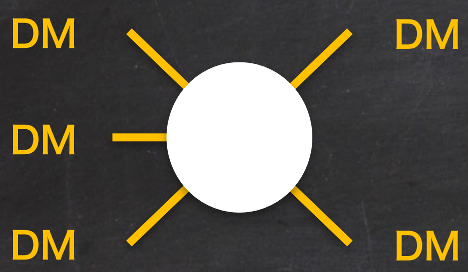


$$M_{\rm DM} \simeq \alpha_{3\to 2} \times 100{\rm MeV}$$

Relic Abundance

$$\kappa_\chi \leftrightarrow g_{3\to 2} M_{\rm DM}$$

$$V_\chi = m_\chi^2 + \frac{1}{6}\kappa_\chi[\chi^3 + (\chi^\star)^3] + \frac{1}{4}\lambda_\chi(\chi^\star\chi)^2$$



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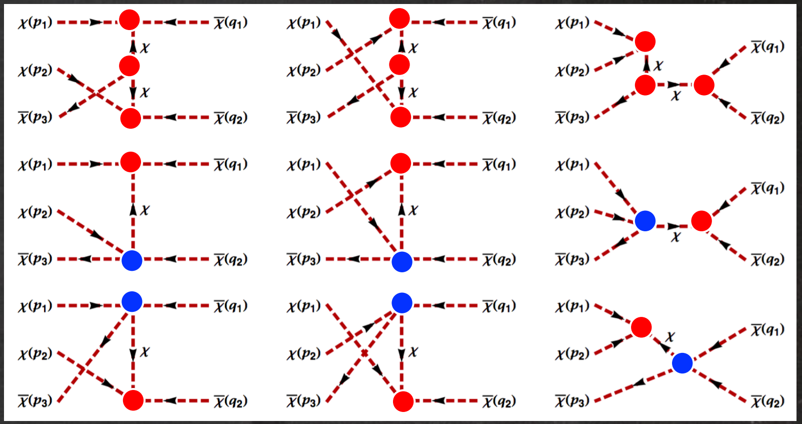
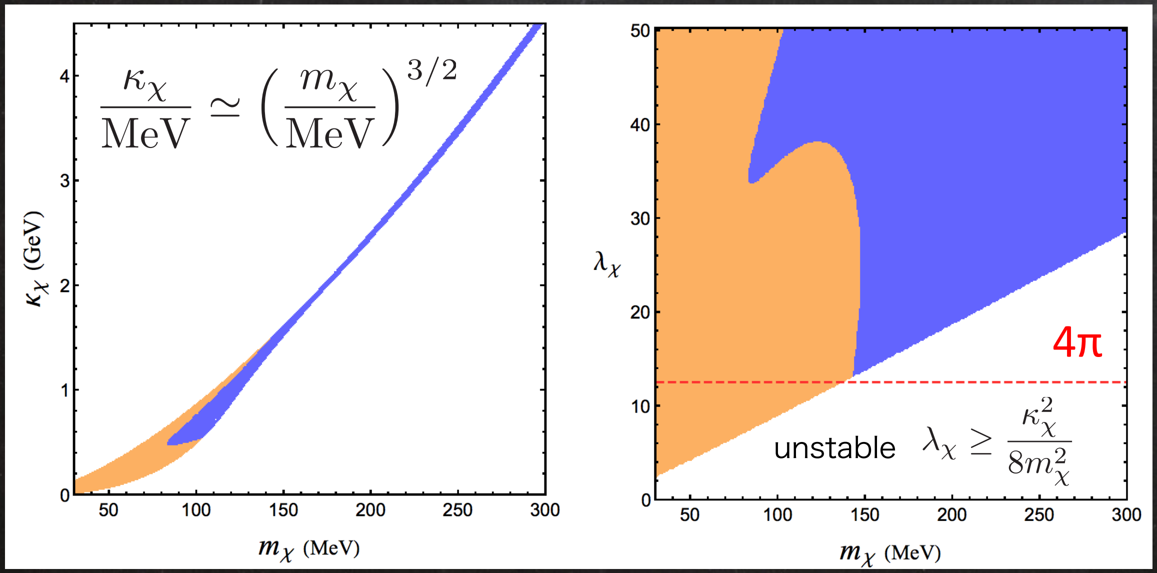
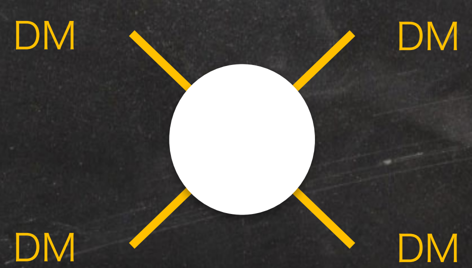


Requiring the correct **DM relic abundance**



Strong Self-int. of DM



$$\frac{\sigma_{\rm self}}{M_{\rm DM}} < 1{\rm cm}^2/g$$

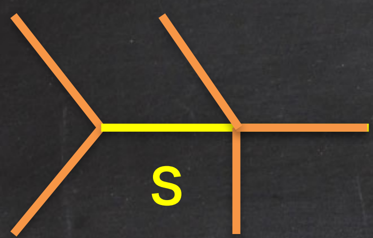
Bullet Cluster

Resonant SIMP

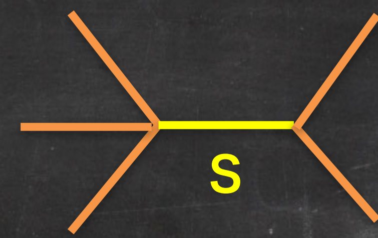
.Choi, Lee '16

Large $\sigma_{3\to2}$ while keeping $\sigma_{2\to2}$ small by **Resonance**

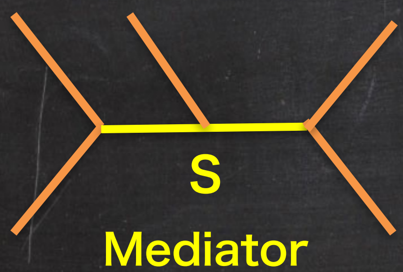
3→2



$$\propto \frac{1}{M_S^2 - 4M_\chi^2}$$



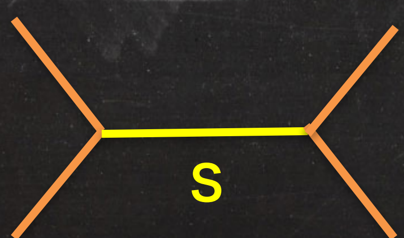
$$\propto \frac{1}{M_S^2 - 9M_\chi^2}$$



$$\propto \frac{1}{M_S^2 - 9M_\chi^2}\frac{1}{M_S^2 - 4M_\chi^2}$$

Resonant Condition : $M_S \simeq 3M_\chi$

2→2

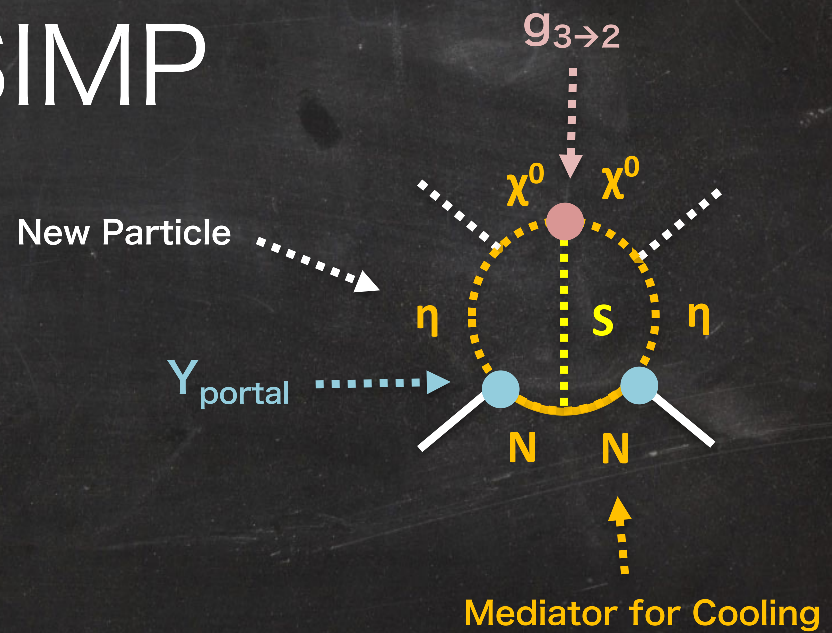


$$\propto \lambda_{H\phi}\frac{1}{M_h^2 - 4M_\chi^2}\lambda_{H\phi}$$

S-Y Ho, T. Toma, KT,JHEP1708, 101 (2017) [arXiv:1705.00592]

“A Radiative Neutrino Mass Model with SIMP Dark Matter”

Z_5 vSIMP



	E	Φ	N	η	χ	S
SU(2)	**2**	**2**	**1**	**2**	**1**	**1**
$U(1)_Y$	$-1/2$	$1/2$	0	$1/2$	0	0
$\mathbb{Z}_5$	1	1	ω	ω	ω	ω^3

$\omega=\exp(2\pi i/5)$

Radiative M_ν

From SIMP Condition

≈ 100 MeV ≈ 0.1 $\xi \approx 0.05$

≈ 10^{-3}

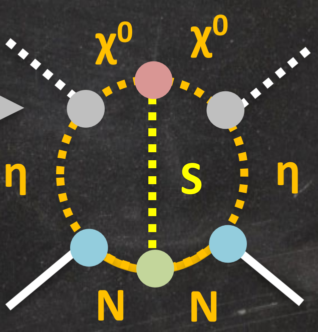
$$\left(M_\nu\right)_{rs} = \frac{\mu_2 \, Y_{rj} Y_{sk} \, s_{2\xi}^2}{4(4\pi)^2} \left(\mathcal{Y}^L_{ji} \mathcal{C}^L_{ji} + \mathcal{Y}^R_{ji} \mathcal{C}^R_{ji} \right)$$

≈ 0.1eV

Loop integrals ≈ 0.1-10

η^0-χ^0 mixing

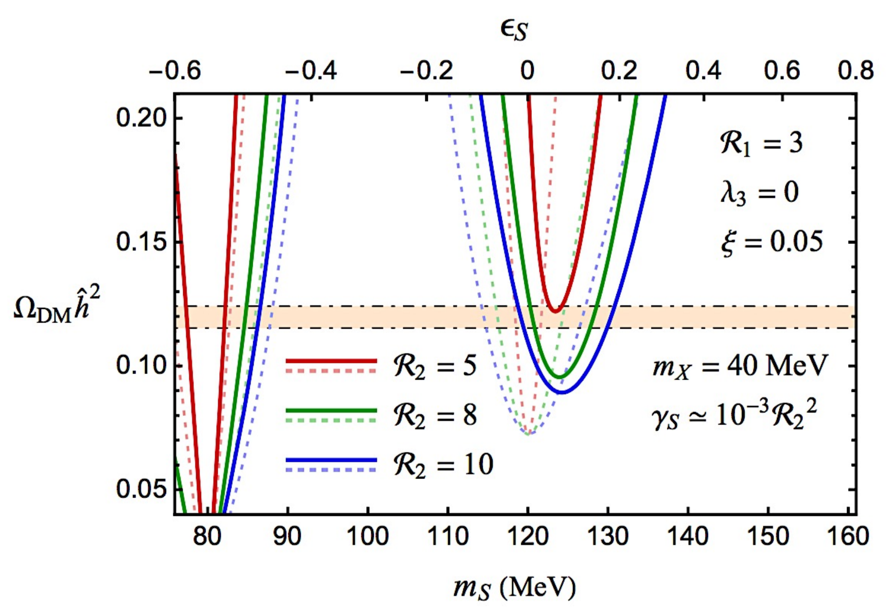
$$s_{2\xi} = \frac{\kappa \, v}{m_\eta^2 - m_\chi^2}$$

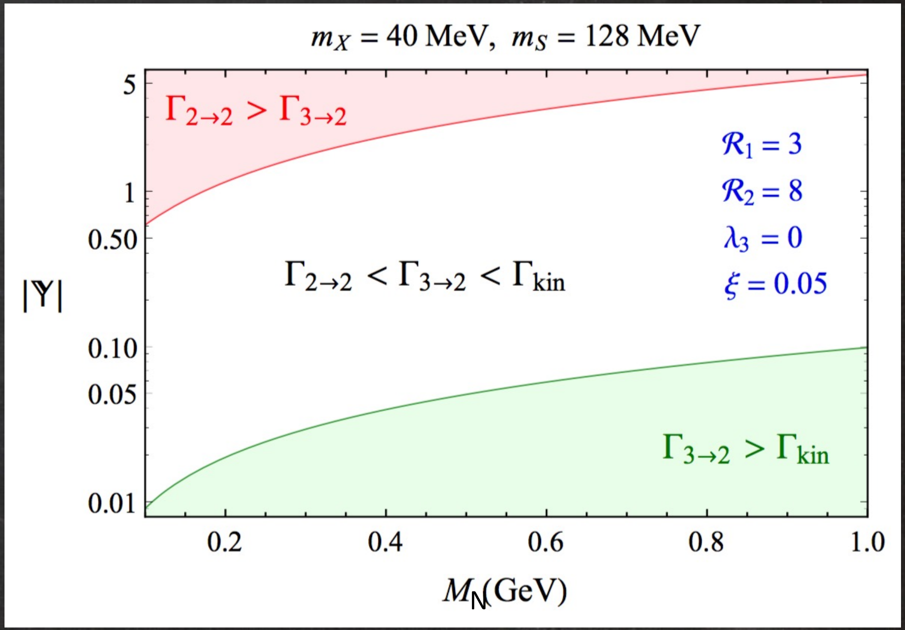


➡
- ✓ Higgs Invisible Decay
- ✓ Direct Search of η

Relic Abundance

SIMP Condition : $\Gamma_{\rm kin} > \Gamma_{3\to2}(\sim H_F) > \Gamma_{2\to2}$





Resonant Mechanism Works

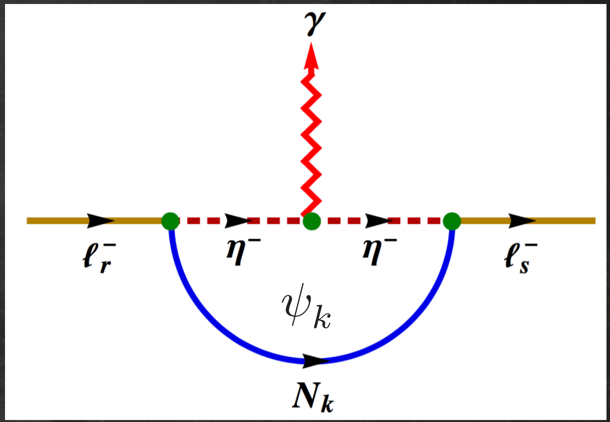
To keep SIMP condition

$$\frac{\mu_2}{(Y\, s_{2\xi})^2} \simeq 1\,\mathrm{TeV}$$

Stability : $\mu_2 \lesssim 100$MeV → $Y\, s_{2\xi} \lesssim 0.01$

Lepton Flavor Violation

$$\mathcal{B}_{\ell_r \to \ell_s \gamma} \approx \frac{\alpha\, \mathcal{B}_{\ell_r \to \ell_s \overline{\nu_s} \nu_r}}{768\pi G_F^2 m_\eta^4} \left| \sum_k \mathcal{Y}_{rk}^\star \mathcal{Y}_{sk} \right|^2$$



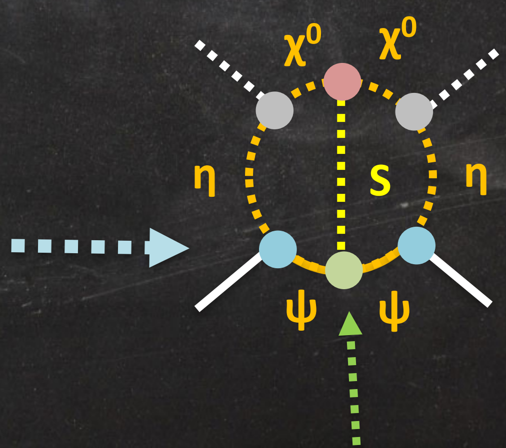
Without considering the specific structure of Yukawa

➡ $$\mathcal{Y}_{rk} \lesssim 0.02 \times \left(\frac{300\,\mathrm{GeV}}{m_\eta}\right)$$

Conflict with SIMP condition

An easy solution :

$$\mathcal{Y} = \begin{pmatrix} Y_{e1} & Y_{e2} & Y_{e3} \\ Y_{\mu 1} & Y_{\mu 2} & Y_{\mu 3} \\ Y_{\tau 1} & Y_{\tau 2} & Y_{\tau 3} \end{pmatrix} \Rightarrow \begin{pmatrix} Y_{e1} & & \\ & Y_{\mu 2} & \\ & & Y_{\tau 3} \end{pmatrix}$$



Structure of M_ν can be adjusted by Y^L, Y^R

Energy/Precision Frontier

Higgs Invisible Decay

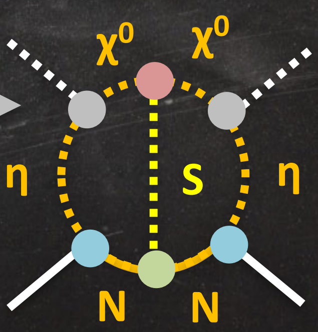
[$h_{125} \to \chi^0\chi^0$] is induced by mixing

$$\mathcal{L}_{\rm eff} = -\frac{1}{2}\kappa\, s_{2\xi}\, h\,(\chi^0)^2 \;\Rightarrow\; \Gamma_{h\to\chi^0\chi^0} \approx \frac{(\kappa s_{2\xi})^2}{64\pi m_h}$$

The latest data : $B(h\to \chi^0\chi^0) < 0.16$

$$|s_{2\xi}| < 0.11 \times \left(\frac{\mathcal{B}^{\rm up}_{\rm inv}}{0.16}\right)^{1/4}\left(\frac{300\,{\rm GeV}}{m_\eta}\right)$$

η^0-χ^0 mixing

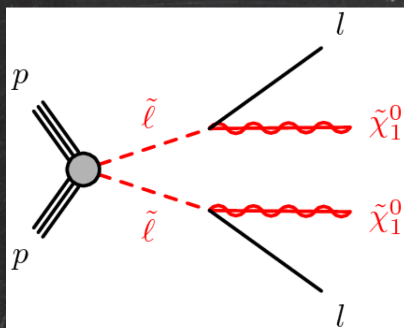


$$s_{2\xi} = \frac{\kappa\, v}{m_\eta^2 - m_\chi^2}$$

SIMP condition → $Y s_{2\xi} \lesssim 0.01$

Slepton Direct Search

η has the same quantum charge with left-handed slepton

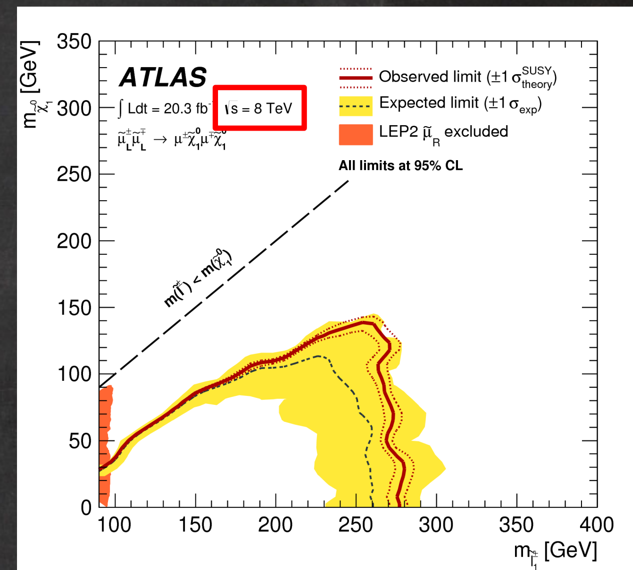


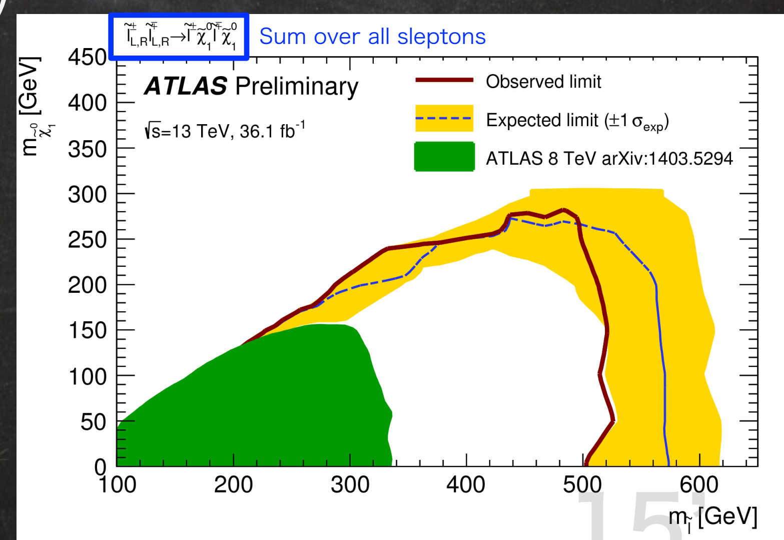
$$|s_{2\xi}| < 0.11 \times \left(\frac{\mathcal{B}^{\rm up}_{\rm inv}}{0.16}\right)^{1/4} \left(\frac{300\,{\rm GeV}}{m_\eta}\right)$$

ILC h→inv.

$$\left(\frac{0.004}{0.16}\right)^{1/4} \approx 0.4$$

SIMP condition → Y $s_{2\xi} \lesssim 0.01$





Summary

- ν & DM are evidences of BSM
- **νSIMP**
  - M_ν may be generated by SIMP
  - SIMP may be thermalized by ν
  - Collider search is powerful probe of νSIMP

	E	Φ	N	η	χ	S
SU(2)	**2**	**2**	**1**	**2**	**1**	**1**
$U(1)_Y$	$-1/2$	$1/2$	0	$1/2$	0	0
$\mathbb{Z}_5$	1	1	ω	ω	ω	ω^3