JHEP 07 (2019) 050,
Phys.Rev.D 110 (2024) 6, 063535, and
JHEP 05 (2024) 281

Light thermal dark matter in minimal Higgs portal model Dark Matter

Yue-Lin Sming Tsai
(Purple Mountain Observatory)

2024.12.22@Higgs Potential 2024

JHEP 07 (2019) 050

Light Fermionic WIMP Dark Matter with Light Scalar Mediator

Shigeki Matsumoto[(a)], Yue-Lin Sming Tsai[(b,c)] and Po-Yan Tseng[(a)]

JHEP 05 (2024) 281

Light Thermal Dark Matter Beyond p-Wave Annihilation in Minimal Higgs Portal Model

Yu-Tong Chen[a,b], Shigeki Matsumoto[c],
Tian-Peng Tang[a], Yue-Lin Sming Tsai[a,d], and Lei Wu[b]

Phys.Rev.D 110 (2024) 6, 063535

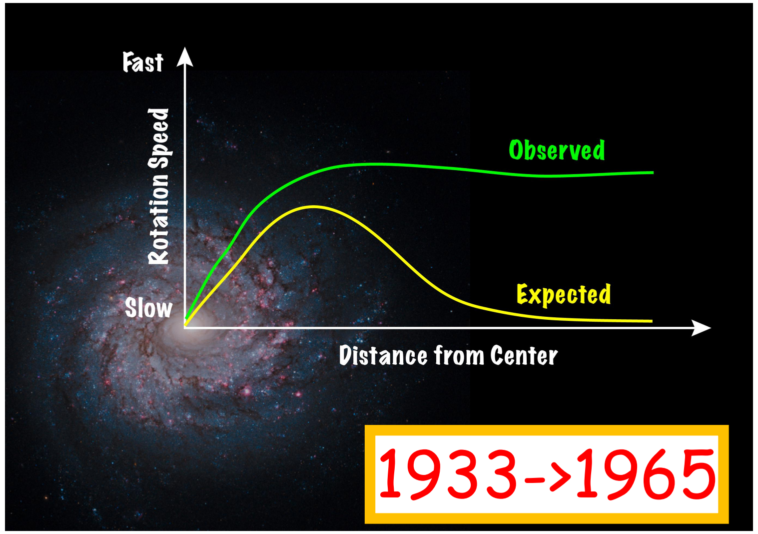
The relic density and temperature evolution of light dark sector

Xin-Chen Duan,[1,2,*] Raymundo Ramos,[3,†] and Yue-Lin Sming Tsai[1,2,‡]

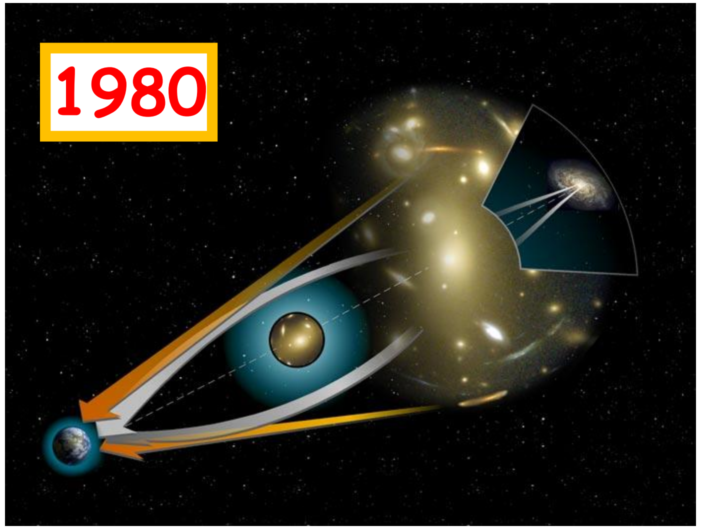
Outline

- [ ] Motivations.
- [ ] Minimal Higgs Portal Model.
- [ ] Parameter space to be detected in gamma-ray telescopes.
- [ ] The relic density of special scenarios.
- [ ] Results and summary.

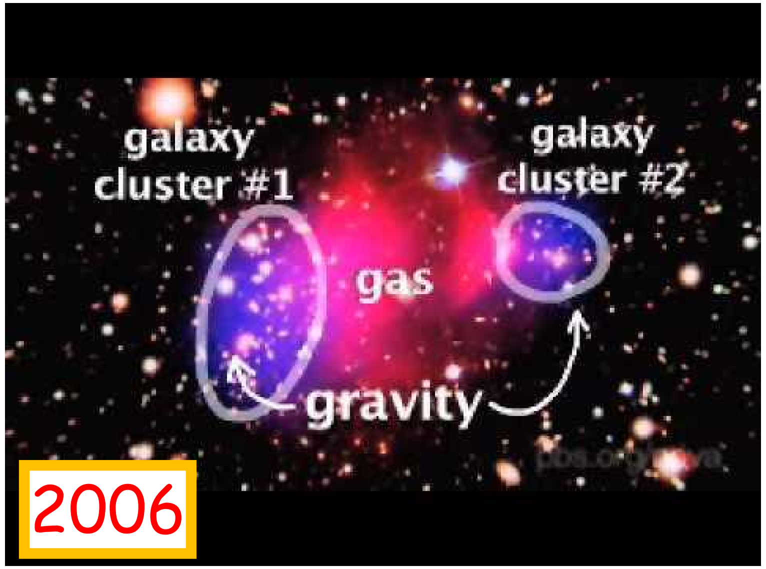
Dark Matter Problems



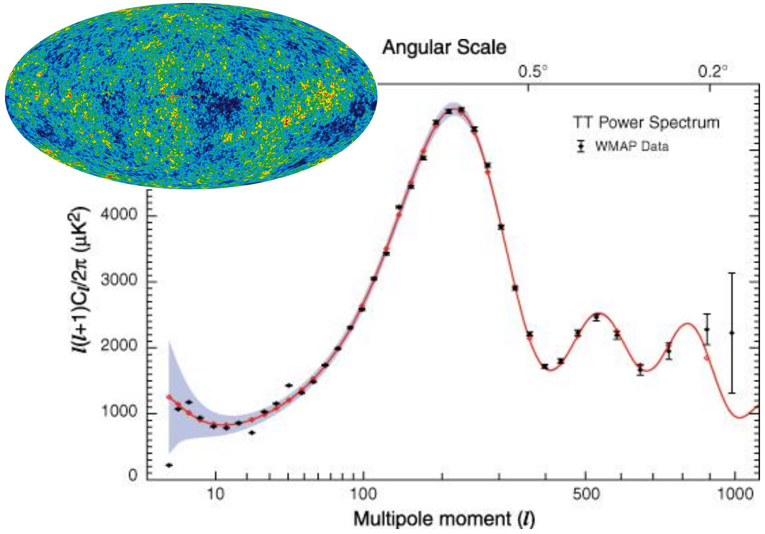
1933->1965



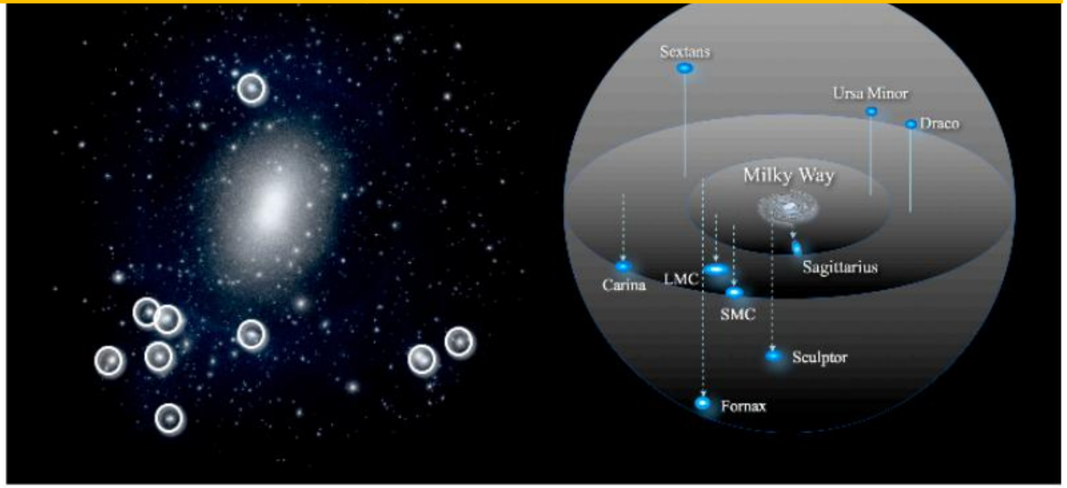
1980



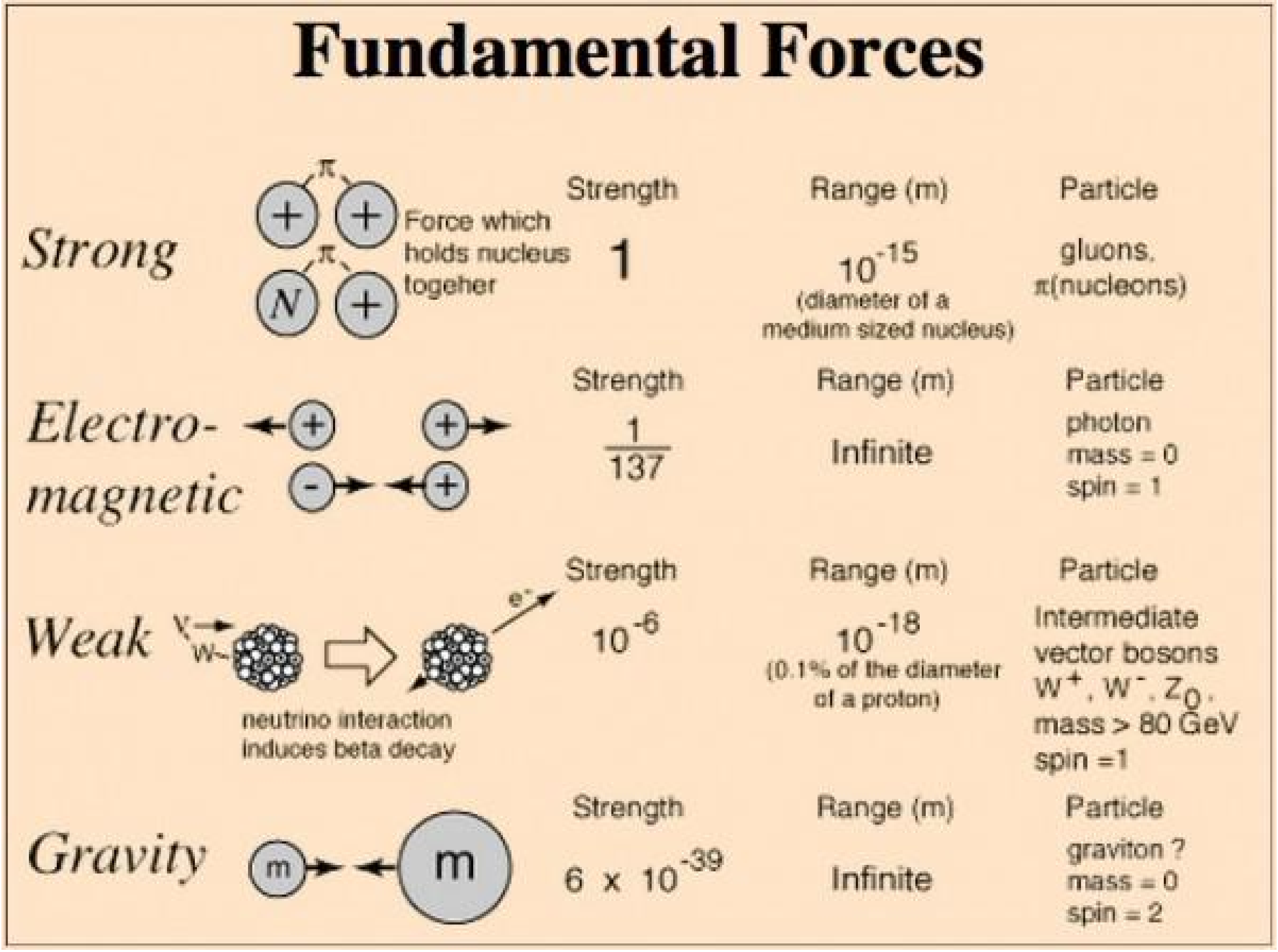
2006



More and more dSphs were found!



IF GR is correct, it will be difficult to explain the universe without DM assumption.



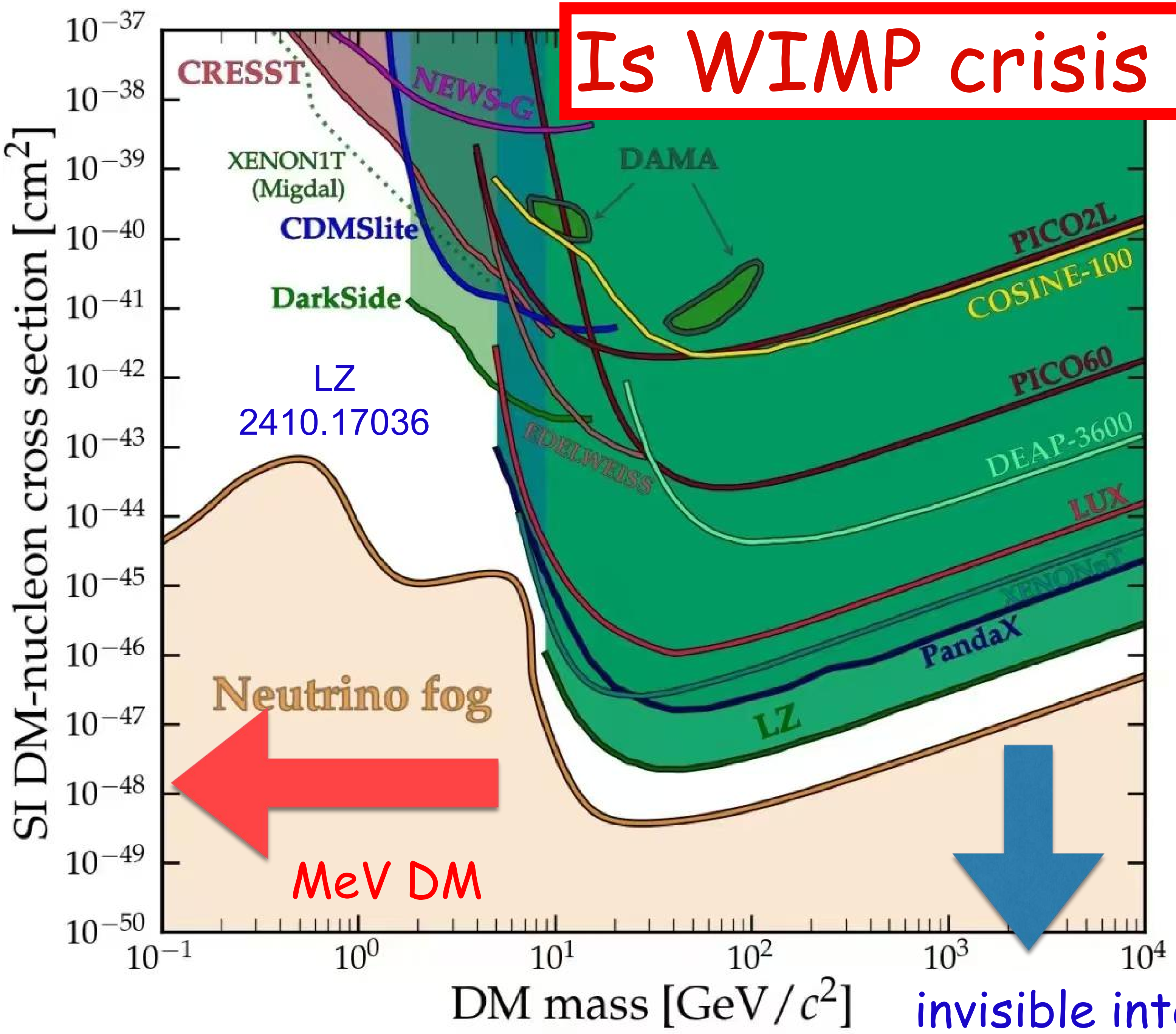
What is the DM-SM interaction strength?

How is possible that no interaction between 1e-6 and 1e-39?

If new interaction greater than Gravity...

Collisional or Collisionless?

Is WIMP crisis or Human panic?



invisible interactions

Lower energy, higher exposure, or wrong DM density?

- p-wave
- Resonance
- Forbidden DM
- Coannihilation
- Secluded DM

Velocity dependent annihilations!

The light DM mass region

Can we go to the region below GeV?

VOLUME 39 25 JULY 1977 NUMBER 4

Cosmological Lower Bound on Heavy-Neutrino Masses

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and

Steven Weinberg[(c)]
Stanford University, Physics Department, Stanford, California 94305
(Received 13 May 1977)

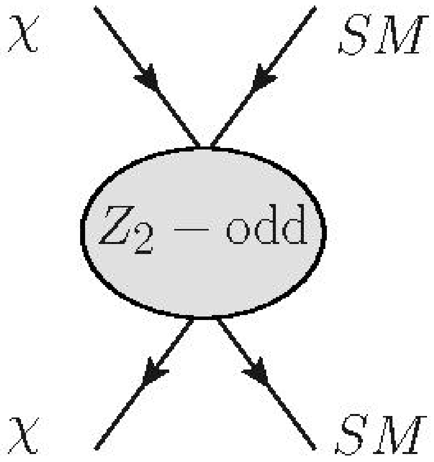
If only a DM introduced...

g=Weak coupling

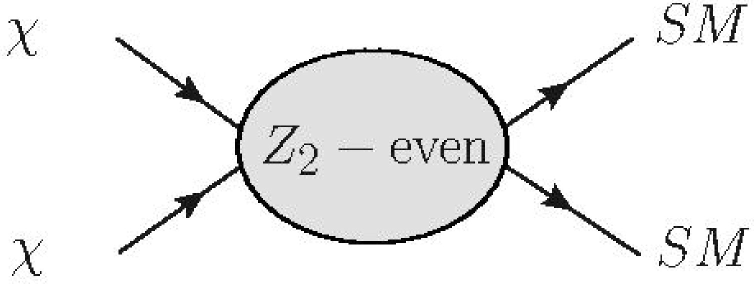
The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

Unless, a new light mediator is introduced!

Simplicity and Light mediator



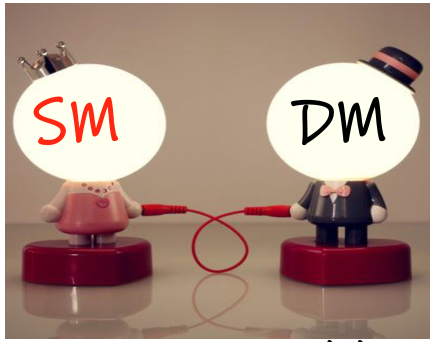
t-channel annihilation



s-channel annihilation

① Z_2 odd scalar mediator (like squark) + SM fermion. LEP mass limit for charged mediator is heavier than 100 GeV.

② Z_2 odd fermion mediator (like Chargino) + SM gauge boson. Invisible decay gives a severe limit.



even odd

Therefore, an MeV mediator of the the DM annihilation to SM pair via t-channel CANNOT be Z_2-odd.

Outline

- Motivations.
- **Minimal Higgs Portal Model.**
- Parameter space to be detected in gamma-ray telescopes.
- The relic density of special scenarios.
- Results and summary.

Basic and minimum Lagrangian

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{2}\bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial\Phi)^2 - \frac{c_s}{2}\Phi\bar{\chi}\chi - \frac{c_p}{2}\Phi\bar{\chi}i\gamma_5\chi - V(\Phi, H),$$

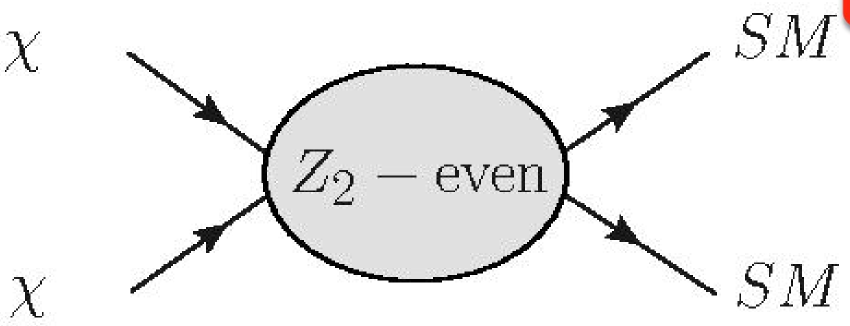
Majorana DM

SM singlet scalar

Scalar interaction

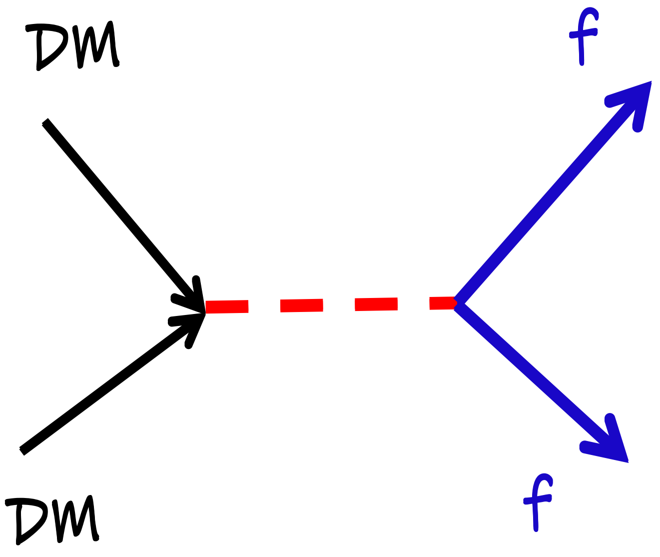
pseudo-scalar interaction

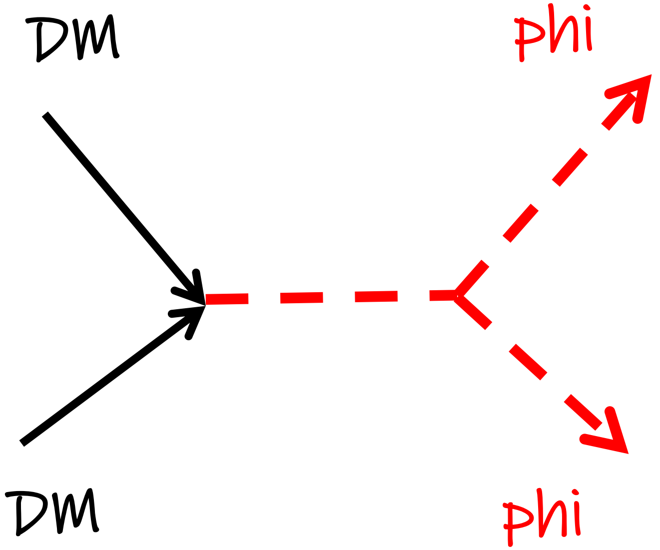
Mixing between New mediator and SM Higgs.



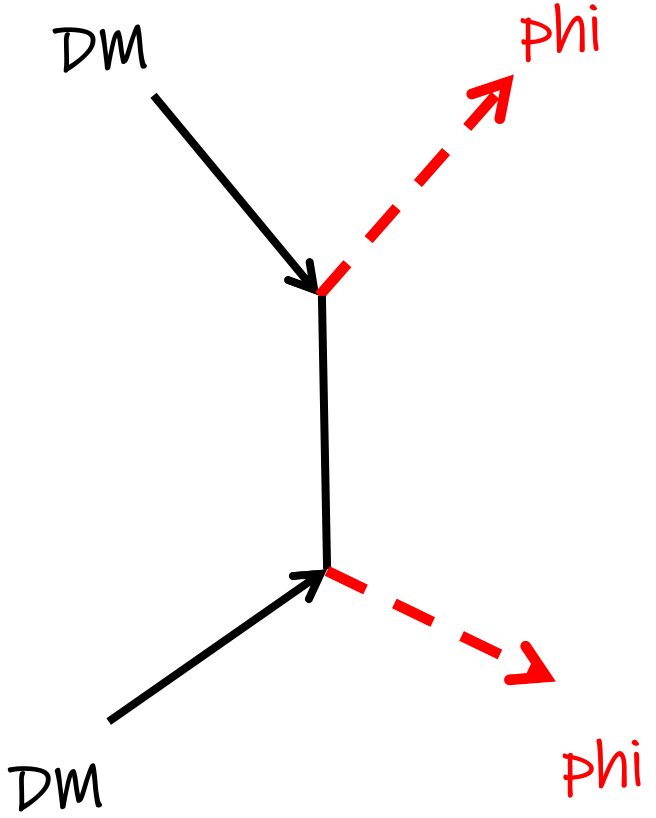
$$\mathscr{L}_{\rm int} \supset -\frac{\cos\theta}{2}(c_s\phi\bar{\chi}\chi + c_p\phi\bar{\chi}i\gamma_5\chi) + \frac{\sin\theta}{2}(c_s h\bar{\chi}\chi + c_p h\bar{\chi}i\gamma_5\chi).$$

A minimum setup:
one SM singlet Majorana DM + one SM singlet scalar mediator.





Z_2 even mediator				
types	Lagrangian	$\langle\sigma v\rangle_{2\mu}$ $\simeq a + bv^2$	$\langle\sigma v\rangle_{4\mu}$ $\simeq a + bv^2$	DD
χ and ϕ	$\mathcal{L}_1 = (g_D\bar\chi\chi + g_f\bar f f)\phi$	$a=0$	$a=0$	Eq. (B1)
	$\mathcal{L}_2 = (g_D\bar\chi\chi + g_f\bar f i\gamma^5 f)\phi$	$a=0$	$a=0$	—
	$\mathcal{L}_3 = (g_D\bar\chi i\gamma^5\chi + g_f\bar f f)\phi$	Case (i)	$a=0$	Eq. (B2)
	$\mathcal{L}_4 = (g_D\bar\chi i\gamma^5\chi + g_f\bar f i\gamma^5 f)\phi$	Case (i)	$a=0$	—
χ and V_μ	$\mathcal{L}_5 = (g_D\bar\chi\gamma^\mu\gamma^5\chi + g_f\bar f\gamma^\mu f)V_\mu$	$a=0$	Case (A)	Eq. (B3)
	$\mathcal{L}_6 = (g_D\bar\chi\gamma^\mu\gamma^5\chi + g_f\bar f\gamma^\mu\gamma^5 f)V_\mu$	Case (ii)	Case (A)	—
	$\mathcal{L}_7 = (g_D\bar\chi\gamma^\mu\chi + g_f\bar f\gamma^\mu f)V_\mu$	Case (i)	Case (C)	Eq. (B4)
	$\mathcal{L}_8 = (g_D\bar\chi\gamma^\mu\chi + g_f\bar f\gamma^\mu\gamma^5 f)V_\mu$	Case (i)	Case (C)	—
S and ϕ	$\mathcal{L}_9 = (M_{D\phi}S^\dagger S + g_f\bar f f)\phi$	Case (i)	Case (B)	Eq. (B5)
	$\mathcal{L}_{10} = (M_{D\phi}S^\dagger S + g_f\bar f i\gamma^5 f)\phi$	Case (i)	Case (B)	—
	$\mathcal{L}_{9'} = (g_D S^\dagger S\phi + g_f\bar f f)\phi$	—	$b=0$	—
	$\mathcal{L}_{10'} = (g_D S^\dagger S\phi + g_f\bar f i\gamma^5 f)\phi$	—	$b=0$	—
S and V_μ	$\mathcal{L}_{11} = (ig_D S^\dagger\overleftrightarrow{\partial_\mu}S + g_D^2 S^\dagger S V_\mu + g_f\bar f\gamma_\mu f)V^\mu$	$a=0$	Case (C)	Eq. (B6)
	$\mathcal{L}_{12} = (ig_D S^\dagger\overleftrightarrow{\partial_\mu}S + g_D^2 S^\dagger S V_\mu + g_f\bar f\gamma_\mu\gamma^5 f)V^\mu$	$a=0$	Case (C)	—
X_μ and ϕ	$\mathcal{L}_{13} = (M_{D\phi}X^\mu X_\mu^\dagger + g_f\bar f f)\phi$	Case (i)	Case (D)	Eq. (B7)
	$\mathcal{L}_{14} = (M_{D\phi}X^\mu X_\mu^\dagger + g_f\bar f i\gamma^5 f)\phi$	Case (i)	Case (D)	—
	$\mathcal{L}_{13'} = (g_D X^\mu X_\mu^\dagger\phi + g_f\bar f f)\phi$	—	$b=0$	—
	$\mathcal{L}_{14'} = (g_D X^\mu X_\mu^\dagger\phi + g_f\bar f i\gamma^5 f)\phi$	—	$b=0$	—
X_μ and V_μ	$\mathcal{L}_{15} = ig_D\{X^{\mu\nu}X_\mu^\dagger V_\nu - X^{\mu\nu\dagger}X_\mu V_\nu + X_\mu X_\nu^\dagger V^{\mu\nu}\}$ $+g_D^2\{X_\mu^\dagger X^\mu V_\nu V^\nu - X_\mu^\dagger V^\mu X_\nu V^\nu\} + g_f\bar f\gamma^\mu f V_\mu$	$a=0$	Case (C)	Eq. (B8)
	$\mathcal{L}_{16} = ig_D\{X^{\mu\nu}X_\mu^\dagger V_\nu - X^{\mu\nu\dagger}X_\mu V_\nu + X_\mu X_\nu^\dagger V^{\mu\nu}\}$ $+g_D^2\{X_\mu^\dagger X^\mu V_\nu V^\nu - X_\mu^\dagger V^\mu X_\nu V^\nu\} + g_f\bar f\gamma^\mu\gamma^5 f V_\mu$	$a=0$	Case (C)	—

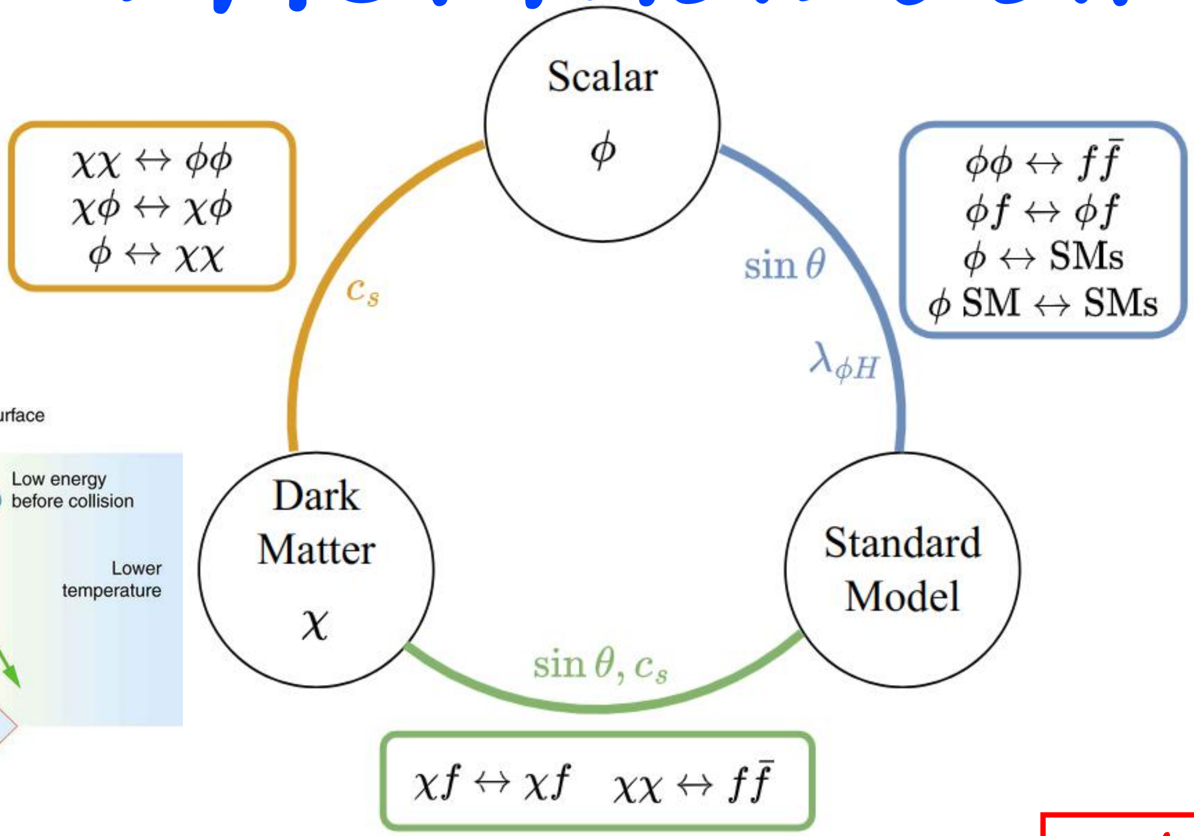


$$\mathscr{L}_{\rm int} \supset -\frac{\cos\theta}{2}(c_s\phi\bar\chi\chi + c_p\phi\bar\chi i\gamma_5\chi) + \frac{\sin\theta}{2}(c_s h\bar\chi\chi + c_p h\bar\chi i\gamma_5\chi).$$

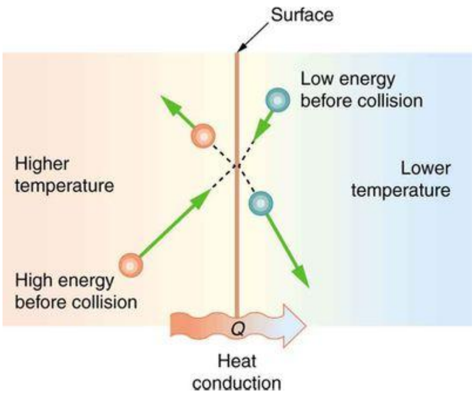
Abdughani, Fan, Lu, Tang and Tsai, JHEP 07 (2022), 127

The joint contribution of $|c_s| \approx |c_p|$ leads to s-wave annihilation of $\chi\chi \to \phi\phi$

Thermal dark matter



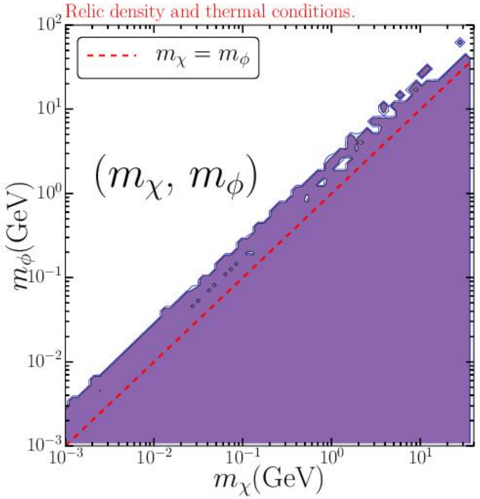
	Likelihood	Constraints
Relic abundance	Gaussian	$\Omega_\chi^{\rm exp} h^2 = 0.1193 \pm 0.0014$ [90]; $\sigma_{\rm sys} = 10\% \times \Omega_\chi^{\rm th} h^2$.
Equilibrium	Conditions	either $(\Gamma_{\chi \rm SM}^{\rm FO} \geq H_{\rm FO})$, or $(\Gamma_{\phi \rm SM}^{\rm FO} \geq H_{\rm FO}$ and $\Gamma_{\chi\phi}^{\rm FO} \geq H_{\rm FO})$
DM direct detection	Half Gaussian	$9\,\rm GeV < m_\phi < 10\,\rm TeV$ (LZ [91]), $3.5\,\rm GeV < m_\phi < 9\,\rm GeV$ (PANDAX-4T [16]), $60\,\rm MeV < m_\phi < 5\,\rm GeV$ (DarkSide [92]).
$\triangle N_{\rm eff}$	Half Gaussian	$\triangle N_{\rm eff} < 0.17$ for 95% C.L. [90]
BBN	Conditions	if $(m_\phi \geq 2m_\pi)$ then $\tau_\phi \leq 1$ s [93], if $(m_\phi \leq 2m_\pi)$ then $\tau_\phi \leq 10^5$ s [94].



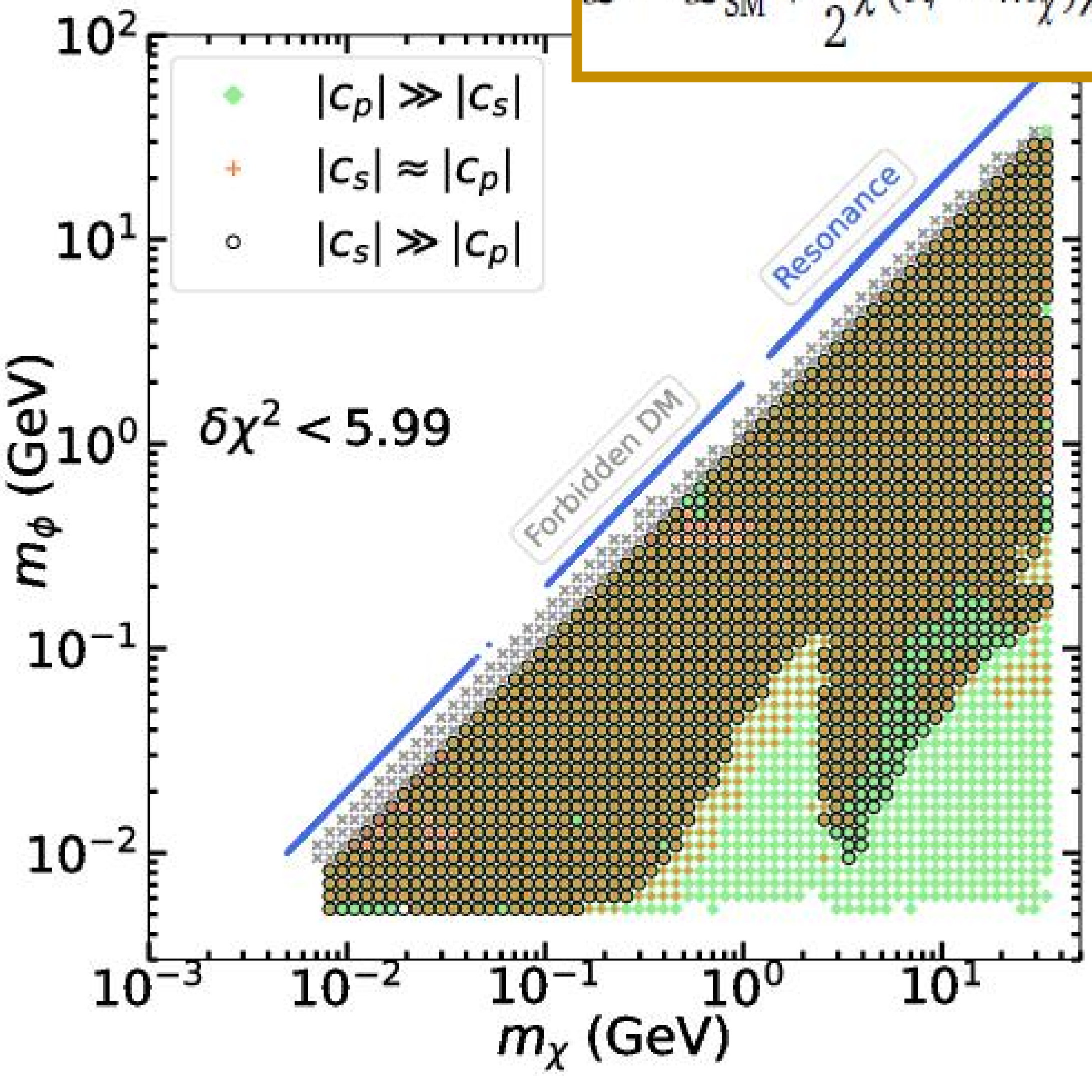
Heat transfer can be via the green or orange+blue.

1. Must be frequent momentum exchange!
2. Number density can be discribed by n~exp(-m/T)!

Possible parameter space



$$-1 \leq c_p \leq 1,$$
$$-1 \leq c_s \leq 1,$$
$$1 \text{ MeV} \leq m_\phi \leq 60\,\text{GeV},$$
$$-\pi/6 \leq \theta \leq \pi/6,$$
$$-1\,\text{TeV}^2 \leq \mu_\Phi^2 \leq 1\,\text{TeV}^2,$$
$$-1\,\text{TeV} \leq \mu_3 \leq 1\,\text{TeV},$$
$$-1 \leq \lambda_\Phi \leq 1.$$

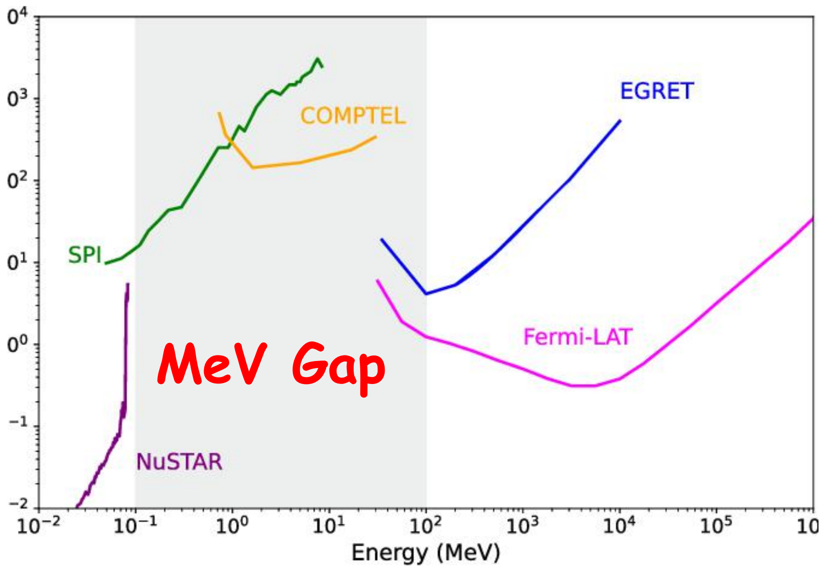


$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{2}\bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial\Phi)^2 - \frac{c_s}{2}\Phi\bar{\chi}\chi - \frac{c_p}{2}\Phi\bar{\chi}i\gamma_5\chi - V(\Phi, H),$$

The unitarity, stability, and perturbative constraints.

	ϕ signature	Constraints
Higgs decay	Prompt*	See the upper limits of BR$(h \to \phi\phi)$BR$(\phi \to ll)^2$ from Fig. 12 of Ref. [99] and Fig. 7 of Ref. [100].
	Displaced*	See Ref. [101, 102]
	Long-lived*	BR$(h \to \text{inv.})_{\rm BSM} \leq 0.145$ [103]
B decay	Prompt	BR$(B^\pm \to K^\pm\mu^-\mu^+) \lesssim 3 \times 10^{-7}$ [104]
	Displaced	(1) $\sin^2\theta \gtrsim 2 \times 10^{-8}$ for the region $0.5 < m_\phi/\,\text{GeV} < 1.5$ and $1 < c\tau_\phi/\text{cm} < 20$ [105] (2) See Fig. 5 of Ref. [106] for details.
	Long-lived*	P_p BR$(B^\pm \to K^\pm\nu\bar{\nu}) = (2.3 \pm 0.7) \times 10^{-5}$ [107]
Kaon decay	Prompt	(1) BR$(K^+ \to \pi^+\mu^-\mu^+) \leq 4 \times 10^{-8}$ [108] (2) BR$(K_L \to \pi^0 e^- e^+) \lesssim 2.8 \times 10^{-10}$ [109] (3) BR$(K_L \to \pi^0\mu^-\mu^+) \lesssim 3 \times 10^{-10}$ [110]
	Displaced	CHARM detected events $\gtrsim 2.3$ [111]
	Long-lived*	(1) BR$(K_L \to \pi^0\nu\bar{\nu}) \leq 3.0 \times 10^{-9}$[112] (2) See BR$(K^+ \to \pi^+\nu\bar{\nu})$ limits from Fig. 18 of Ref. [113] and Fig. 4 of Ref. [114] for details.

Outline



- ☐ Motivations.
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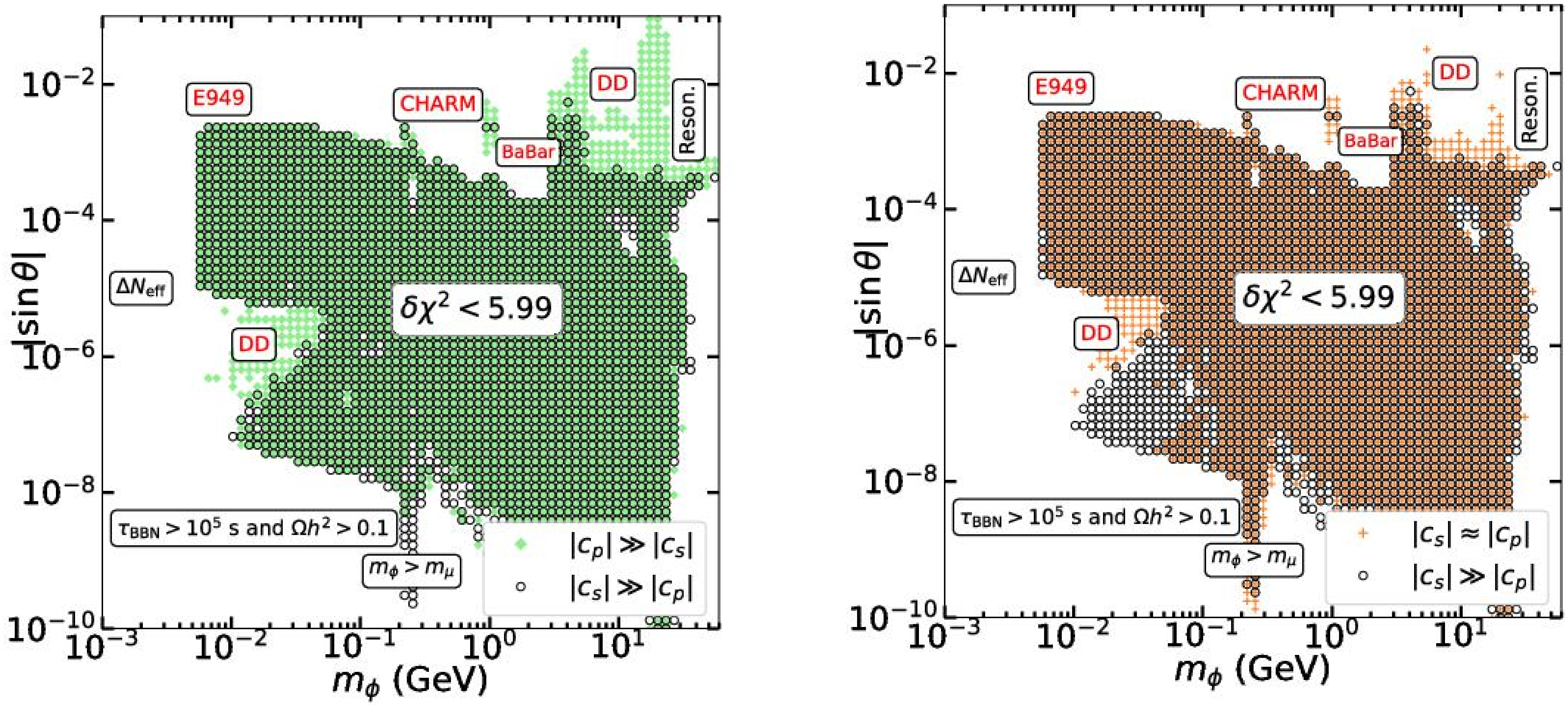
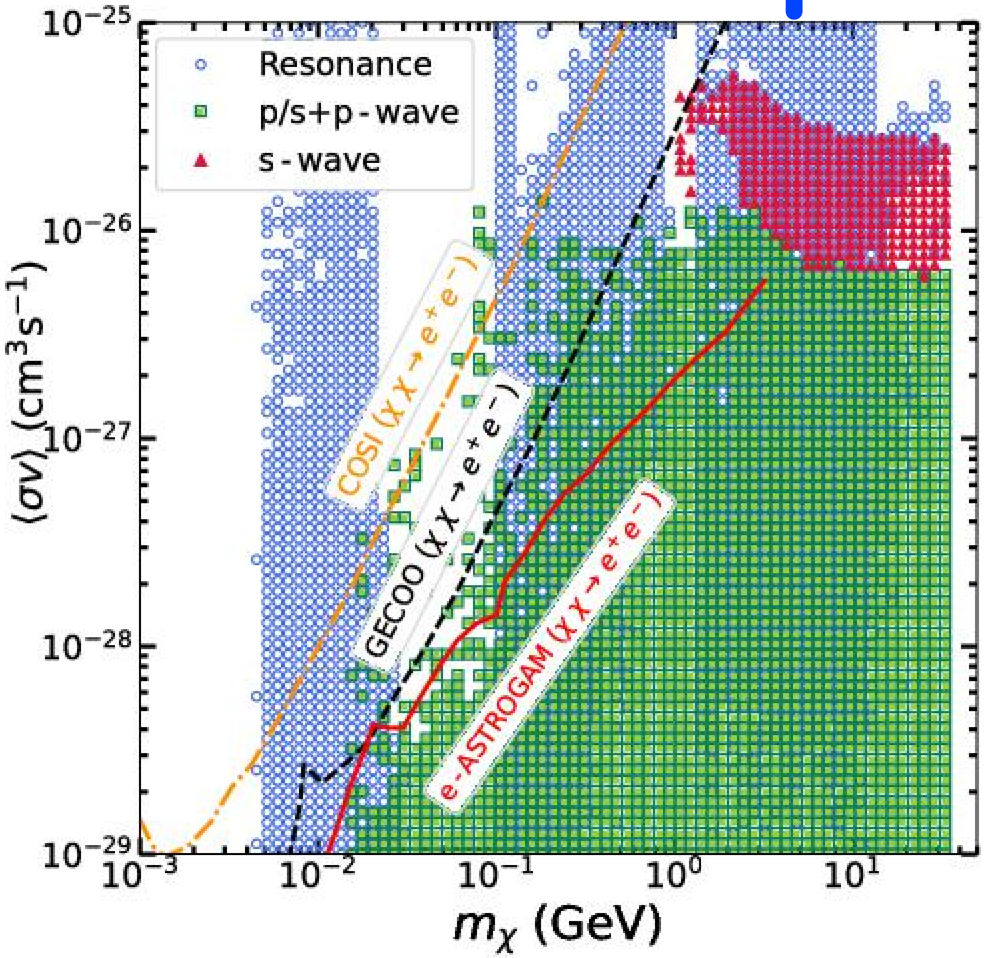
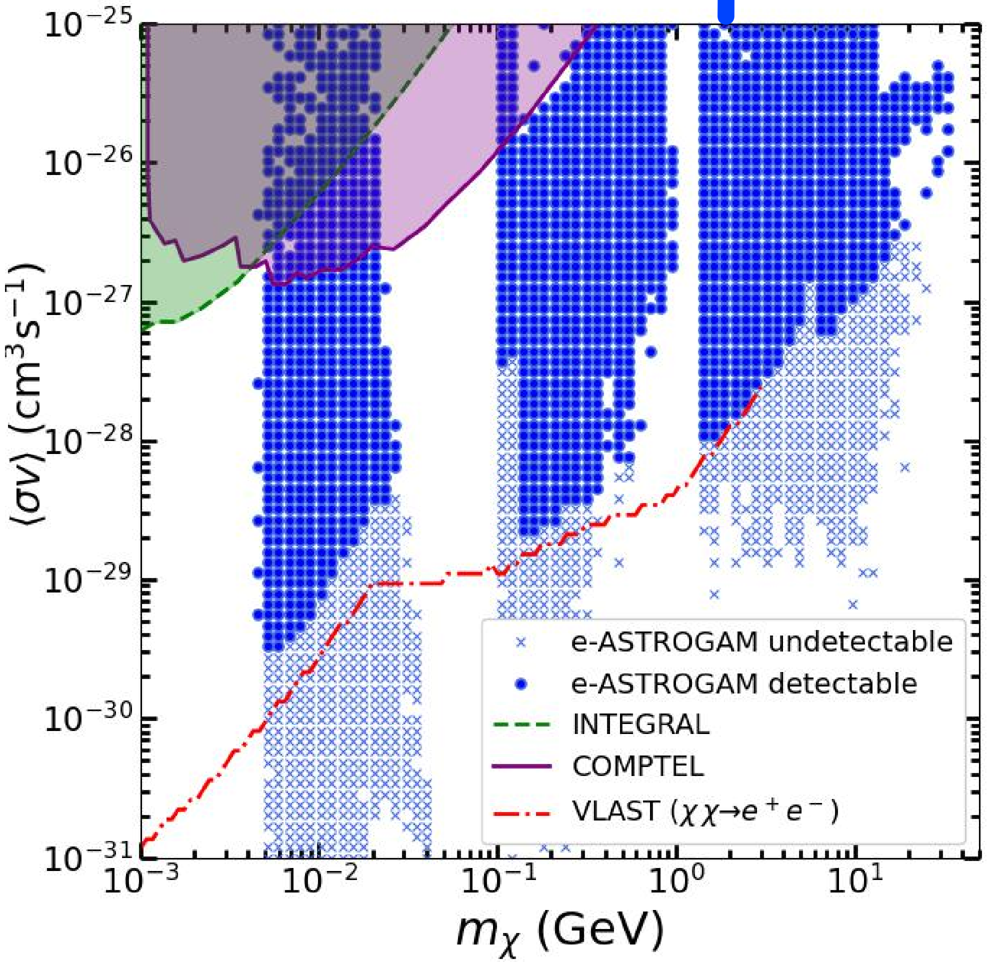
Possible parameter space



Parameter space is finite and we may be able to probe them ALL!

Possible parameter space





Future DM indirect detection (like VLAST) can probe resonance DM.

Outline

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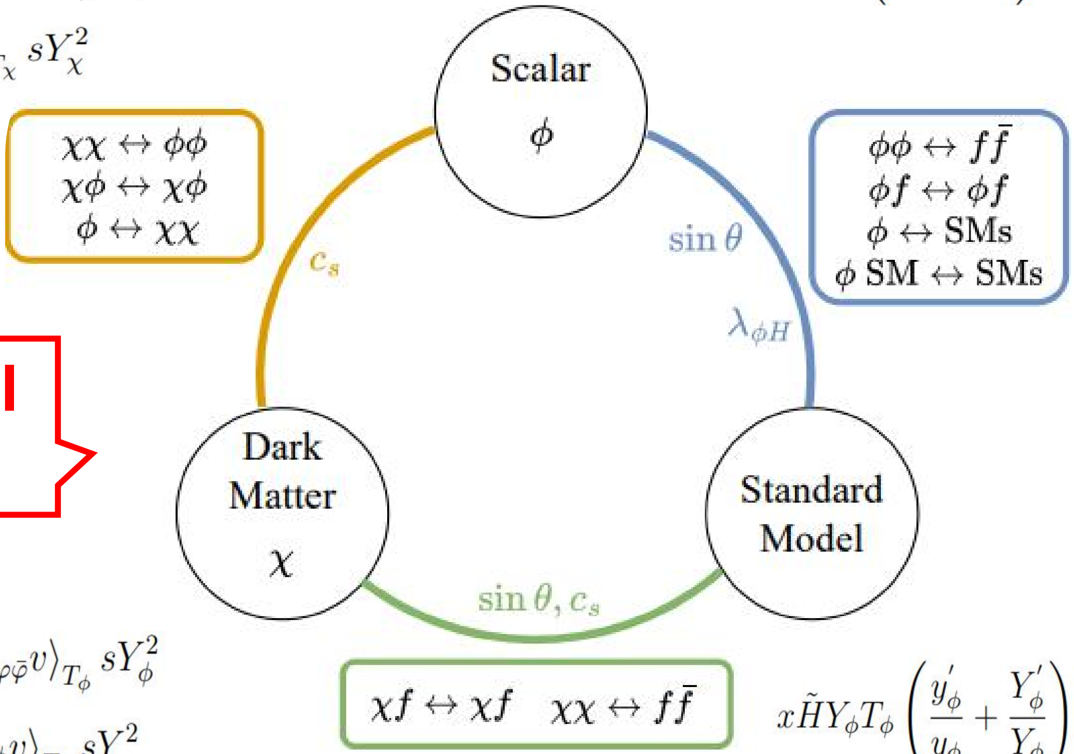
Thermal Dark Matter evolution.

$$
\begin{aligned}
x\tilde{H}Y_\chi' = &\langle\sigma_{\varphi\bar{\varphi}\to\chi\chi}v\rangle_T\, sY_{\varphi,\mathrm{eq}}^2 - \langle\sigma_{\chi\chi\to\varphi\bar{\varphi}}v\rangle_{T_\chi}\, sY_\chi^2 \\
&- \langle\sigma_{\chi\chi\to\phi\phi}v\rangle_{T_\chi}\, sY_\chi^2 + \langle\sigma_{\phi\phi\to\chi\chi}v\rangle_{T_\phi}\, sY_\phi^2 \\
&+ \langle\Gamma_{\phi\to\chi\chi}\rangle_{T_\phi}\, Y_\phi - \langle\sigma_{\chi\chi\to\phi}v\rangle_{T_\chi}\, sY_\chi^2
\end{aligned}
$$

$$
\begin{aligned}
x\tilde{H}Y_\chi T_\chi\left(\frac{y_\chi'}{y_\chi}+\frac{Y_\chi'}{Y_\chi}\right) = &\frac{H}{3}\left\langle\frac{\mathbf{p}_\chi^4}{E_\chi^3}\right\rangle Y_\chi + \langle T_\chi\sigma_{\varphi\bar{\varphi}\to\chi\chi}v\rangle_T\, sY_{\varphi,\mathrm{eq}}^2 - \langle T_\chi\sigma_{\chi\chi\to\varphi\bar{\varphi}}v\rangle_{T_\chi}\, sY_\chi^2 \\
&- \langle T_\chi\sigma_{\chi\chi\to\phi\phi}v\rangle_{T_\chi}\, sY_\chi^2 + \langle T_\chi\sigma_{\phi\phi\to\chi\chi}v\rangle_{T_\phi}\, sY_\phi^2 \\
&+ \langle T_\chi\Gamma_{\phi\to\chi\chi}\rangle_{T_\phi}\, Y_\phi - \langle T_\chi\sigma_{\chi\chi\to\phi}v\rangle_{T_\chi}\, sY_\chi^2 \\
&+ \mathcal{S}_{\chi\phi}(T_\chi,T_\phi)sY_\chi Y_\phi + \mathcal{S}_{\chi\varphi}(T_\chi,T)sY_\chi Y_{\varphi,\mathrm{eq}}
\end{aligned}
$$



Five free model parameters

Three typical annihilation :

a. **Forbidden** : $m_\chi < m_\phi$

b. **Resonance** : $2m_\chi \approx m_\phi$

c. **Secluded** : $m_\chi \gg m_\phi$

$$
\begin{aligned}
x\tilde{H}Y_\phi' = &\langle\sigma_{\varphi\bar{\varphi}\to\phi\phi}v\rangle_T\, sY_{\varphi,\mathrm{eq}}^2 - \langle\sigma_{\phi\phi\to\varphi\bar{\varphi}}v\rangle_{T_\phi}\, sY_\phi^2 \\
&- \langle\sigma_{\phi\phi\to\chi\chi}v\rangle_{T_\phi}\, sY_\phi^2 + \langle\sigma_{\chi\chi\to\phi\phi}v\rangle_{T_\chi}\, sY_\chi^2 \\
&- \langle\Gamma_{\phi\to\varphi\bar{\varphi}}\rangle_{T_\phi}\, Y_\phi + \langle\sigma_{\varphi\bar{\varphi}\to\phi}v\rangle_T\, sY_{\varphi,\mathrm{eq}}^2 \\
&- \langle\Gamma_{\phi\to\chi\chi}\rangle_{T_\phi}\, Y_\phi + \langle\sigma_{\chi\chi\to\phi}v\rangle_{T_\chi}\, sY_\chi^2 \\
&+ \sum_{\varphi_2,\varphi_3,\varphi_4}\left[\langle\sigma_{\varphi_3\varphi_4\to\phi\varphi_2}v\rangle_T\; sY_{\varphi_3,\mathrm{eq}}Y_{\varphi_4,\mathrm{eq}} - \langle\sigma_{\phi\varphi_2\to\varphi_3\varphi_4}v\rangle_{(T_\phi,T)}\; sY_{\varphi_2,\mathrm{eq}}Y_\phi\right]
\end{aligned}
$$

$$
\begin{aligned}
x\tilde{H}Y_\phi T_\phi\left(\frac{y_\phi'}{y_\phi}+\frac{Y_\phi'}{Y_\phi}\right) = &\frac{H}{3}\left\langle\frac{\mathbf{p}_\phi^4}{E_\phi^3}\right\rangle Y_\phi + \langle T_\phi\sigma_{\varphi\bar{\varphi}\to\phi\phi}v\rangle_T\, sY_{\varphi,\mathrm{eq}}^2 - \langle T_\phi\sigma_{\phi\phi\to\varphi\bar{\varphi}}v\rangle_{T_\phi}\, sY_\phi^2 \\
&- \langle T_\phi\sigma_{\phi\phi\to\chi\chi}v\rangle_{T_\phi}\, sY_\phi^2 + \langle T_\phi\sigma_{\chi\chi\to\phi\phi}v\rangle_{T_\chi}\, sY_\chi^2 \\
&- \langle T_\phi\Gamma_\phi\rangle_{T_\phi}\, Y_\phi + \langle T_\phi\sigma_{\chi\chi\to\phi}v\rangle_{T_\chi}\, sY_\chi^2 + \langle T_\phi\sigma_{\varphi\bar{\varphi}\to\phi}v\rangle_T\, sY_{\varphi,\mathrm{eq}}^2 \\
&+ \mathcal{S}_{\phi\chi}(T_\phi,T_\chi)sY_\chi Y_\phi + \mathcal{S}_{\phi\varphi}(T_\phi,T)sY_\phi Y_{\varphi,\mathrm{eq}} \\
&+ \sum_{\varphi_2,\varphi_3,\varphi_4} s\left[\langle T_\phi\sigma_{\varphi_3\varphi_4\to\phi\varphi_2}v\rangle_T\; Y_{\varphi_3,\mathrm{eq}}Y_{\varphi_4,\mathrm{eq}} - \langle T_\phi\sigma_{\phi\varphi_2\to\varphi_3\varphi_4}v\rangle_{(T_\phi,T)}\; Y_{\varphi_2,\mathrm{eq}}Y_\phi\right]
\end{aligned}
$$

Three typical annihilation :

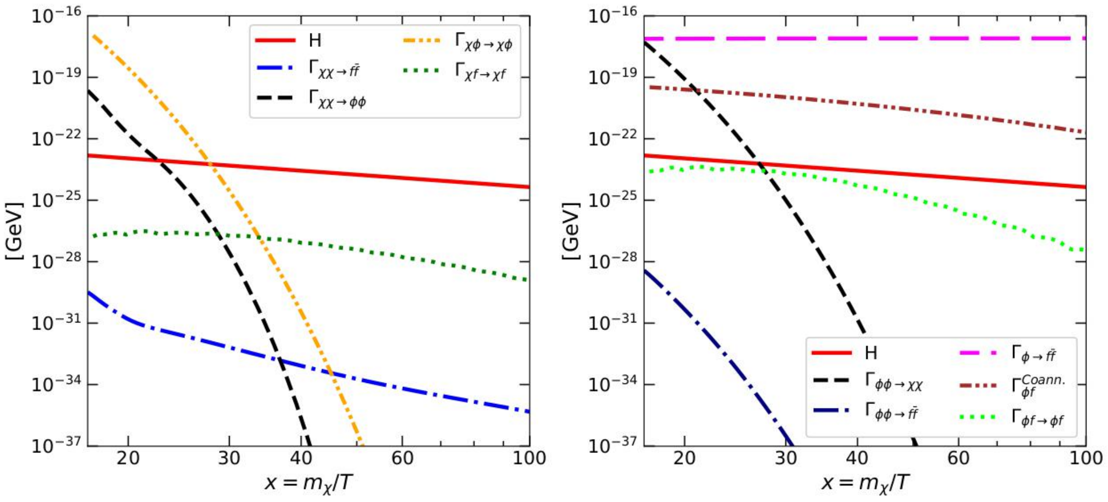
a. **Forbidden** : $m_\chi < m_\phi$

b. **Resonance** : $2m_\chi \approx m_\phi$

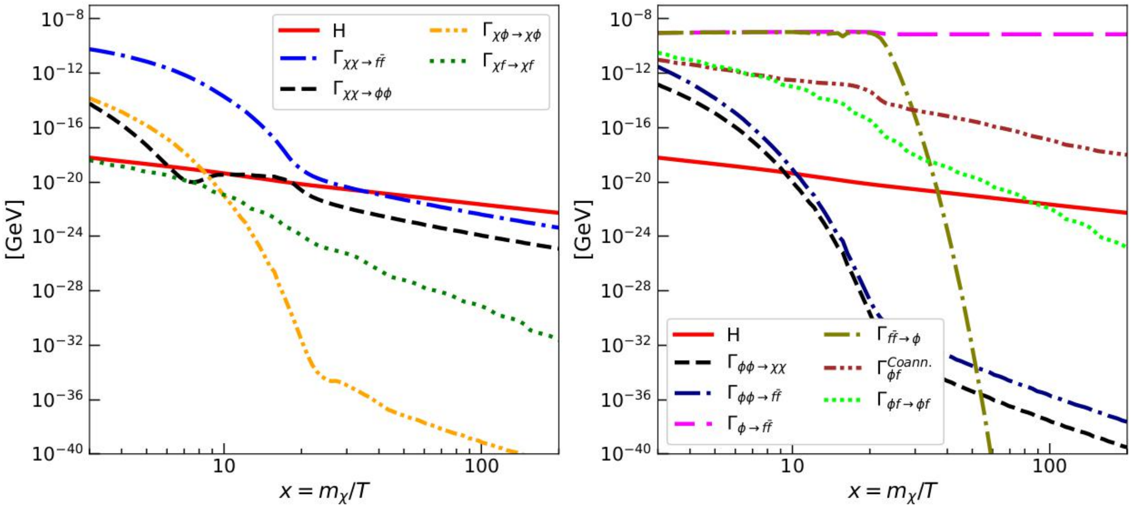
c. **Secluded** : $m_\chi \gg m_\phi$

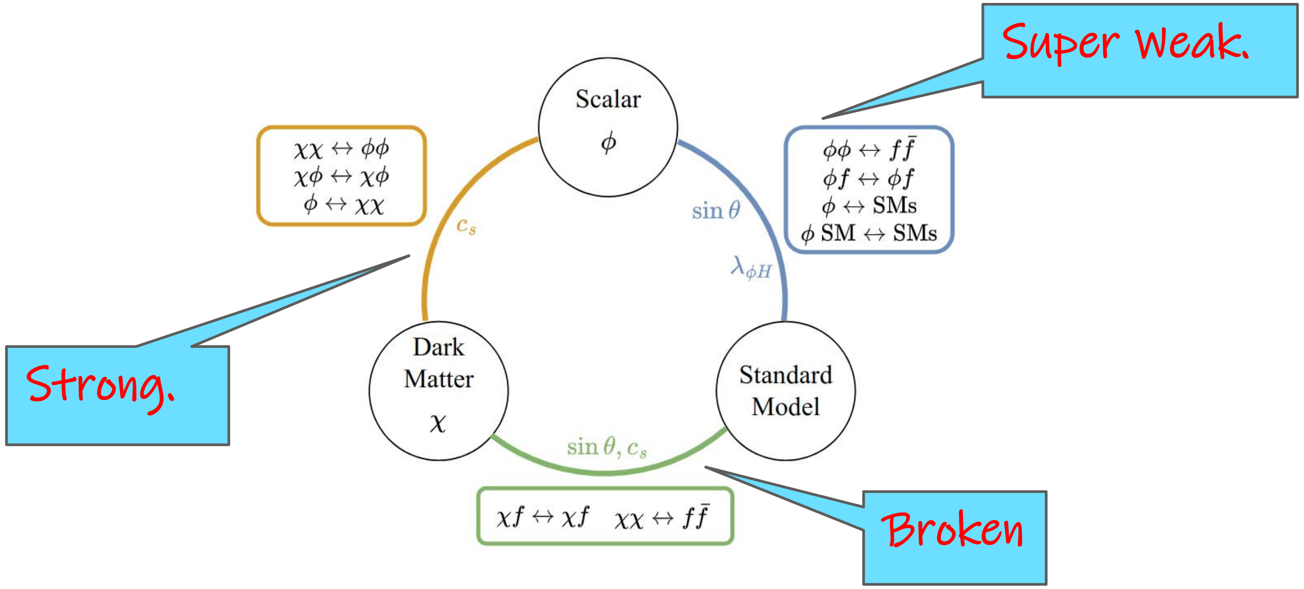
Interaction rates

Forbidden DM : $m_\chi = 0.1$ Gev, $m_\phi = 0.13$ GeV, $\sin\theta = 10^{-3}$, $c_s = 0.1$ and $\lambda_{\phi H} = 1.0$

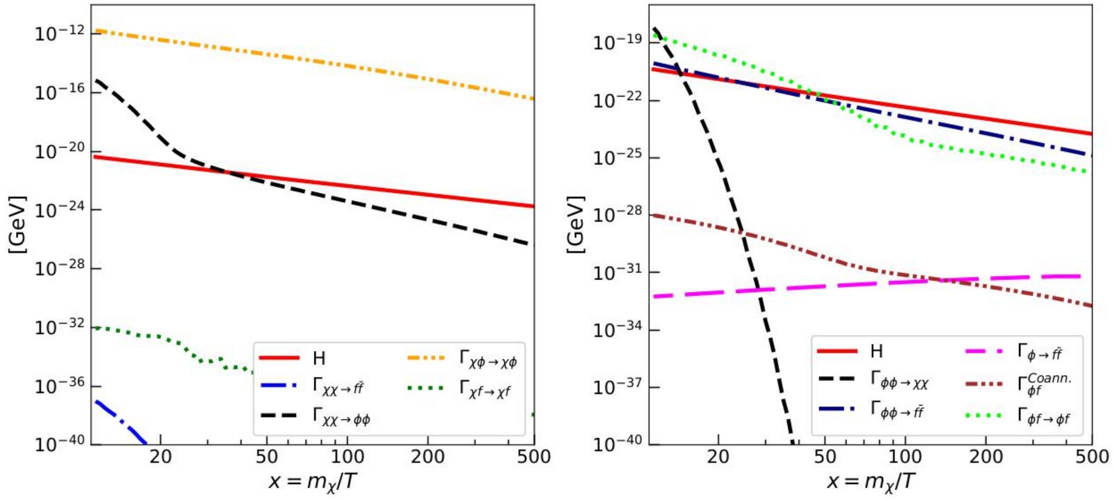


Resonance DM : $m_\chi = 2.2$ Gev, $m_\phi = 4.7$ GeV, $\sin\theta = 0.01$, $c_s = 10^{-3}$ and $\lambda_{\phi H} = 1.0$

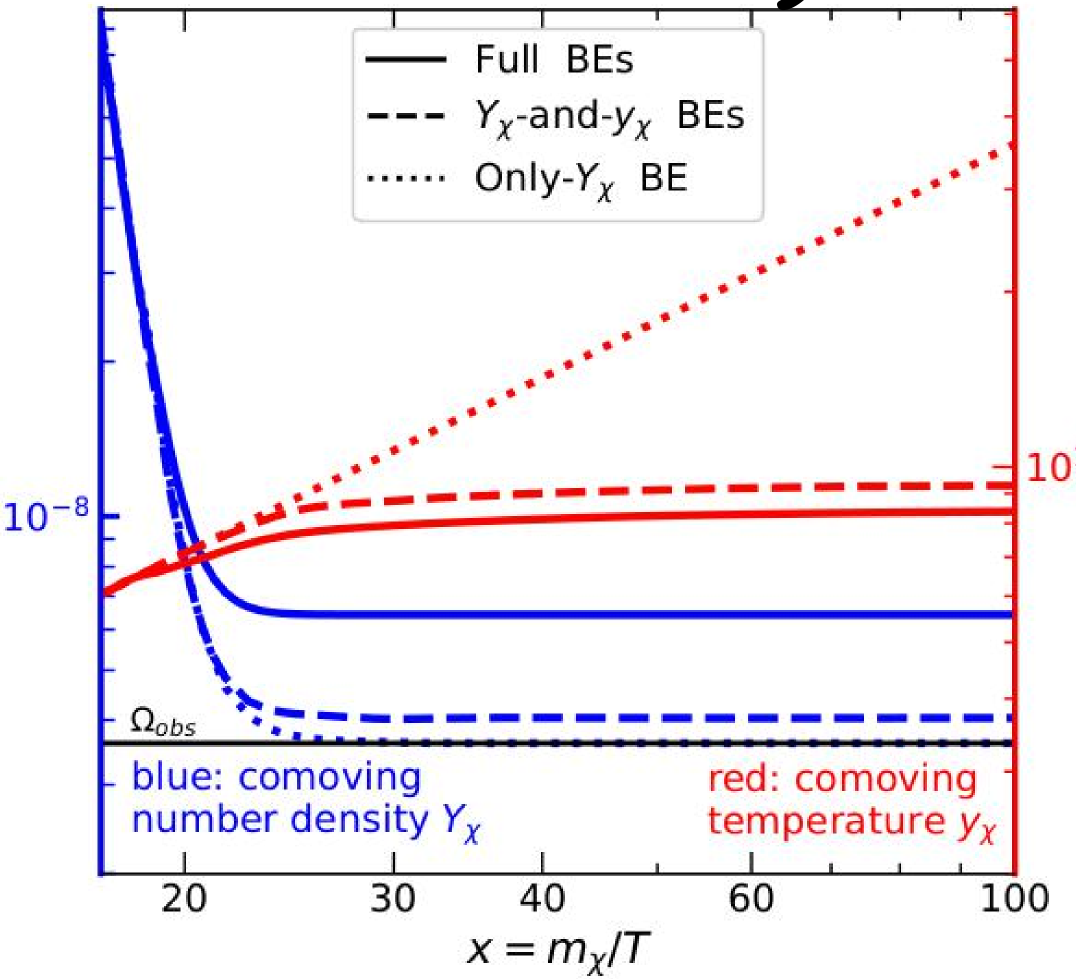


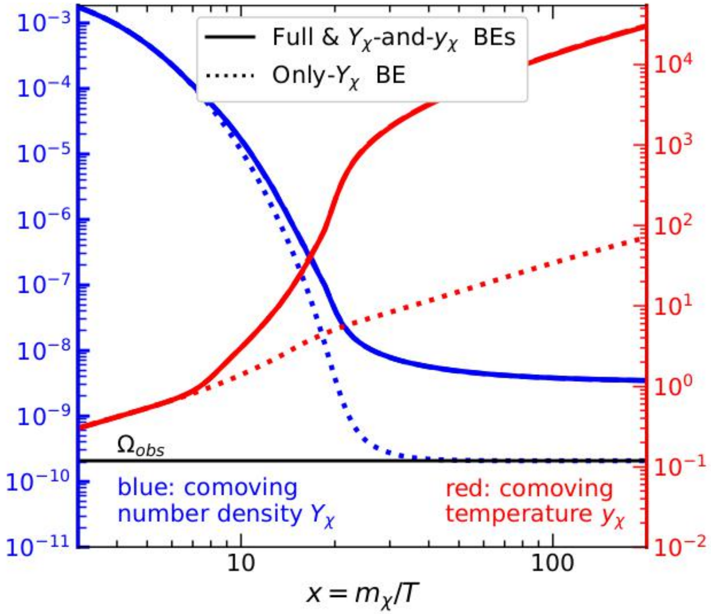


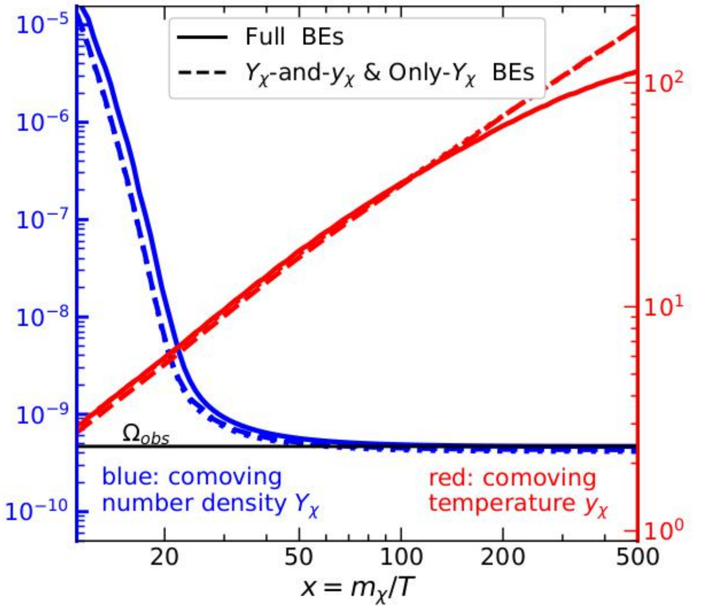
Secluded DM : $m_\chi = 1.0$ Gev, $m_\phi = 0.01$ GeV, $\sin\theta = 10^{-9}$, $c_s = 0.045$ and $\lambda_{\phi H} = 0.1$



The challenge of Relic density computation







Errors to Only-Yx	2 BEs	4 BEs
Forbidden DM	10%	72%
Resonance DM	1000%	1000%
Secluded DM	---	9%

Planck error is around 1%.
(TT+TE+EE+lowE+lensing)

Summary

- The light thermal DM has a lower mass limit around MeV.
- Direct detection can also constrain the low mass mediator mass region, but pseudoscalar can relax this tension.
- Pseudoscalar can generate s-wave annihilation which is testable in indirect detection.
- Considering CMB constraints, most of p-wave annihilation with mass below GeV is excluded, while the resonance is still testable in future MeV gamma ray telescopes.
- For the resonance DM and forbidden DM scenario, the temperature evolution is very important (72% and 1000%), while the Seculded DM shows some impacts from asymmetric elastic scattering between phi and DM (9%).

Thank you for listening and please stay on dark matter!