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Thermal Dark Matter below GeV

Yue-Lin Sming Tsai
(Purple Mountain Observatory)

2024.04.27@NJNU

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Light Fermionic WIMP Dark Matter with Light Scalar Mediator

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

2403.02721

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]

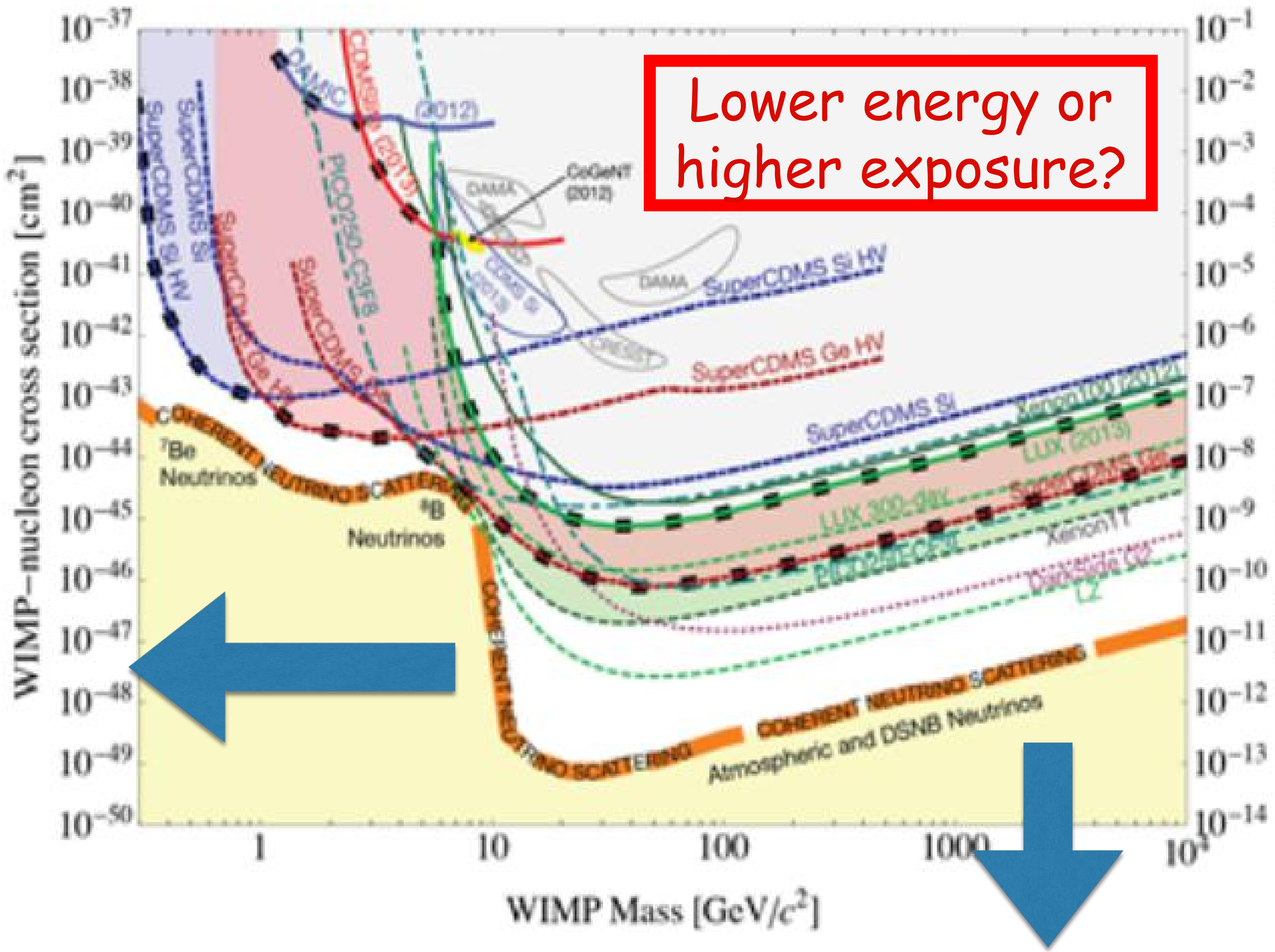
2404.12019

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.



Lower energy or higher exposure?

※ Small coupling gx: a larger exposure is required!

※ Small DM mass: DM mass might be outside the detector range.

※ Small mass splitting between DM and other dark particles.

The light DM mass region

Can we go to the region below GeV?

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Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[a]
Fermi National Accelerator Laboratory,[b] *Batavia, Illinois 60510*

and

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

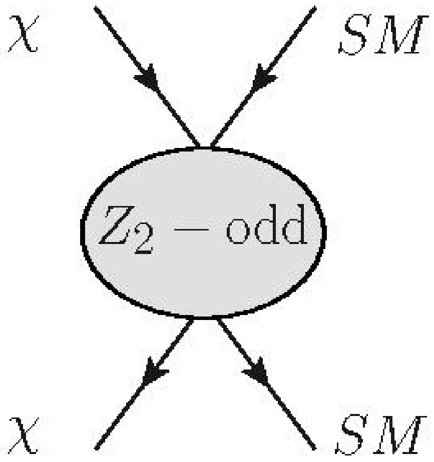
If only a DM introduced...

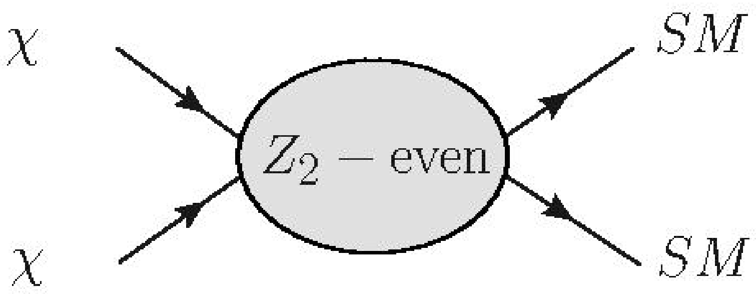
g=Weak coupling

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!

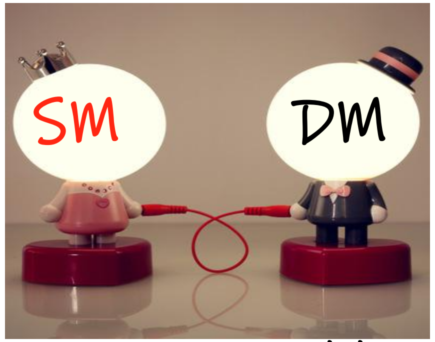
Simplicity and Light mediator





t-channel annihilation

s-channel annihilation

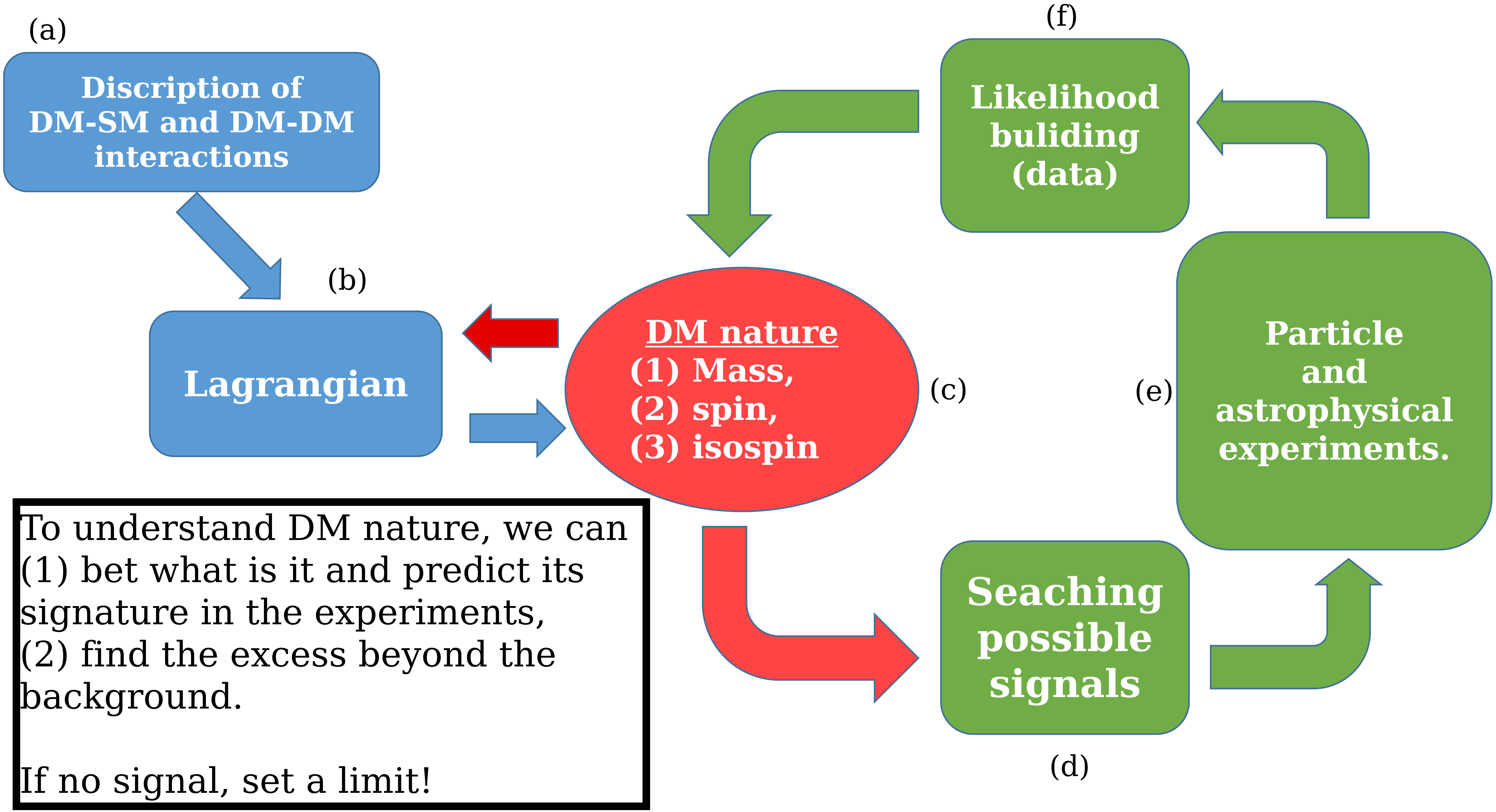


even odd

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

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

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


(a)
Discription of
DM-SM and DM-DM
interactions
(b)
Lagrangian
DM nature
(1) Mass,
(2) spin,
(3) isospin
(c)
(f)
Likelihood
buliding
(data)
(e)
Particle
and
astrophysical
experiments.
Seaching
possible
signals
(d)
To understand DM nature, we can
(1) bet what is it and predict its
signature in the experiments,
(2) find the excess beyond the
background.
If no signal, set a limit!

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Basic and minimum Lagrangian

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

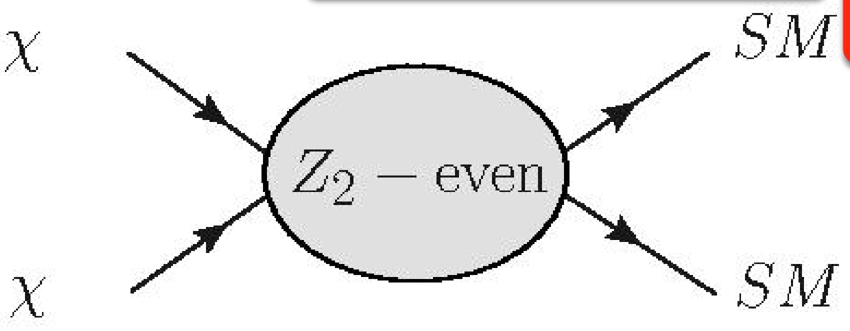
Majorana DM

SM singlet scalar

Scalar interaction

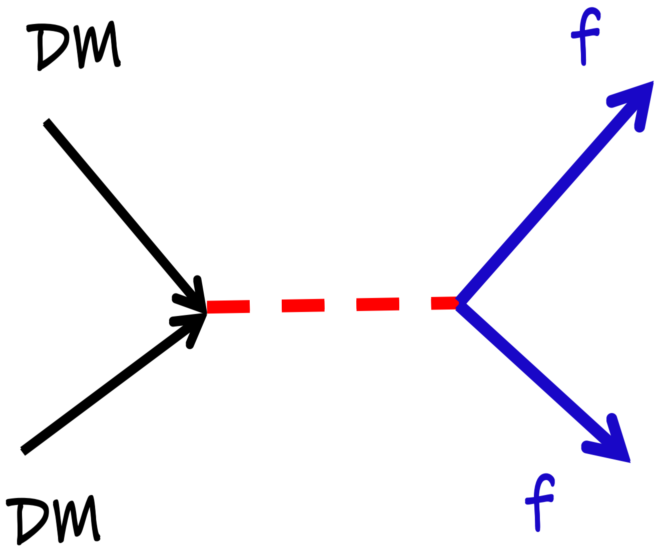
pseudo-scalar interaction

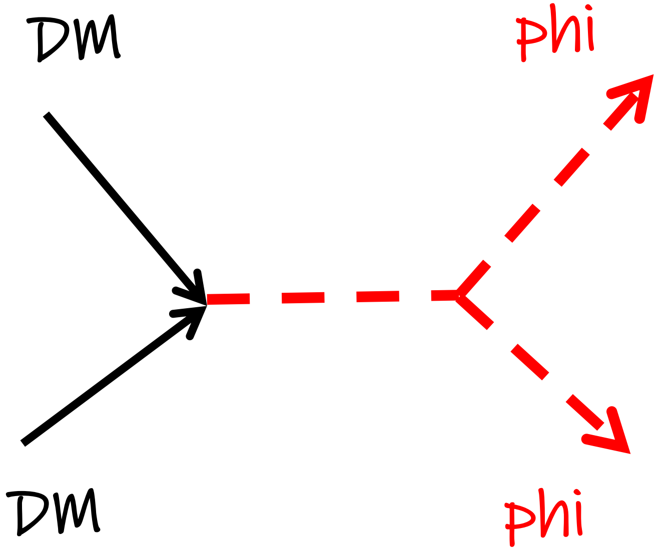
Mixing between New mediator and SM Higgs.



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

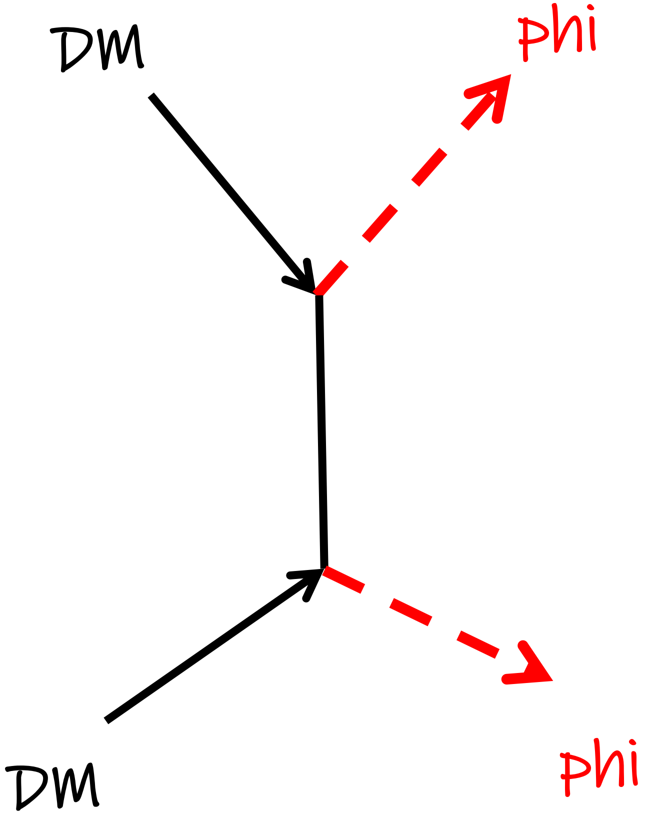
A minimum setup:
one SM singlet Majorana DM + one SM singlet scalar mediator.



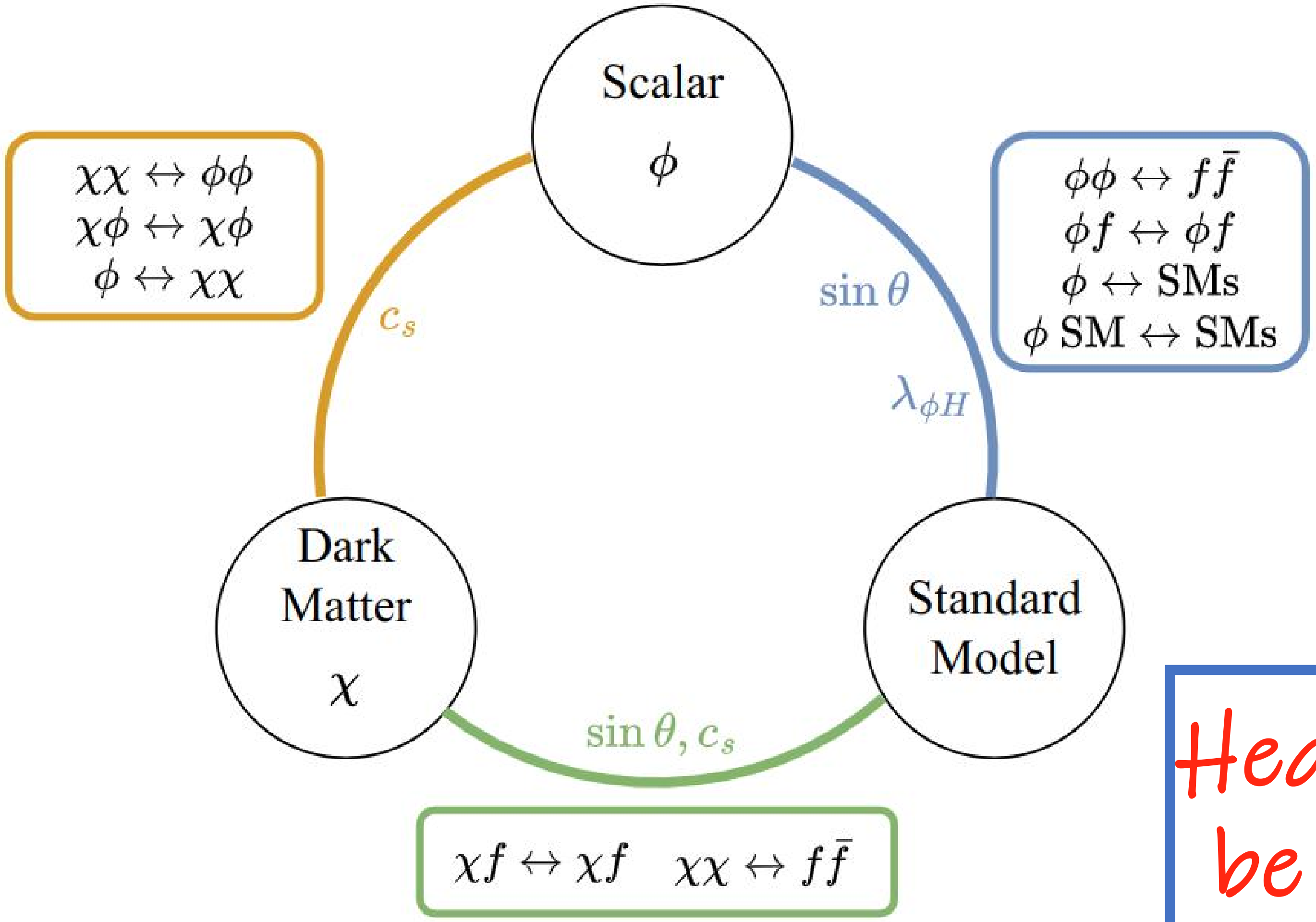


Z_2 even mediator

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)	—



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 $(\Gamma^{\rm FO}_{\chi{\rm SM}} \geq H_{\rm FO})$, or $(\Gamma^{\rm FO}_{\phi{\rm SM}} \geq H_{\rm FO}$ and $\Gamma^{\rm FO}_{\chi\phi} \geq H_{\rm FO})$
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 red+blue.

Outline

- [ ] Motivations.
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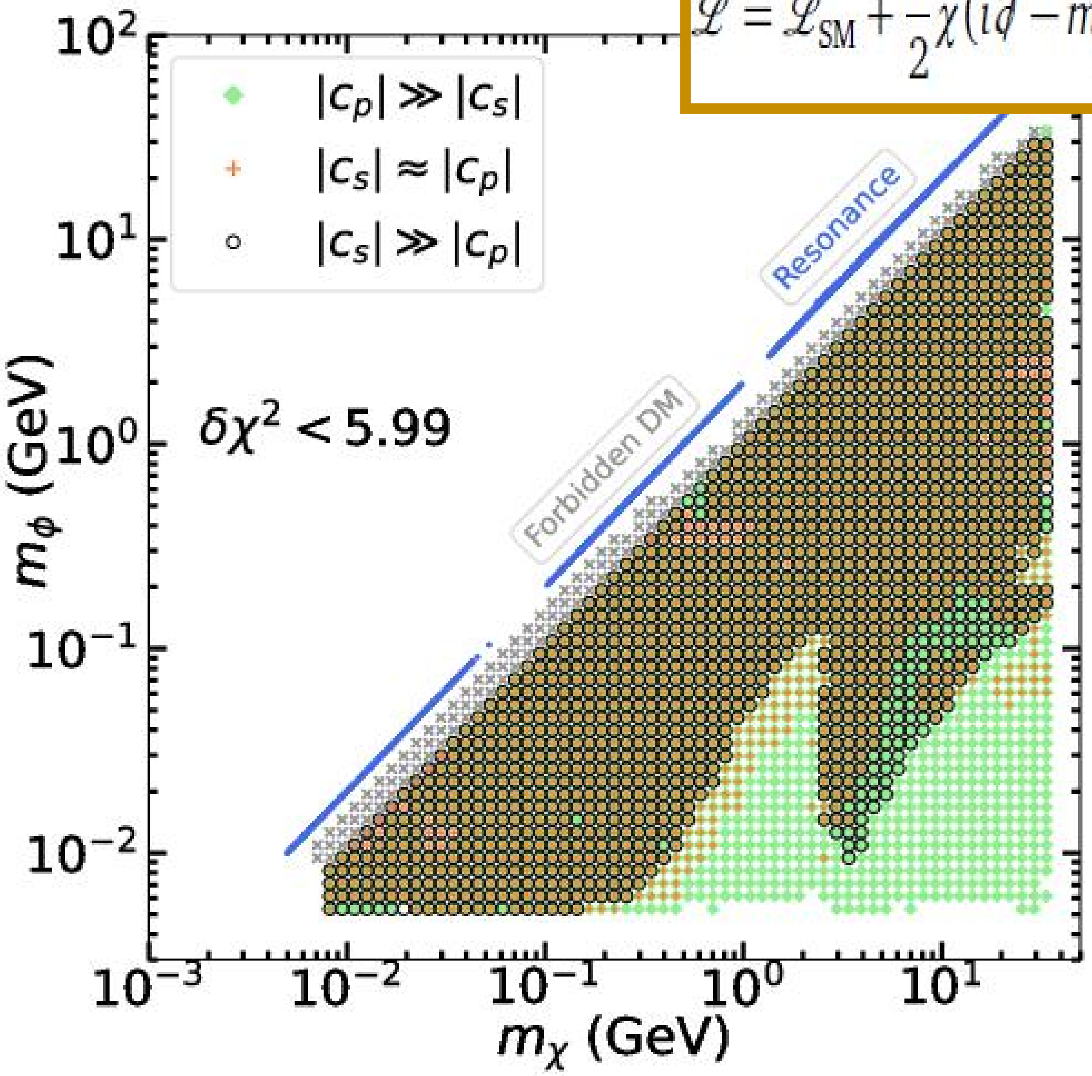
Possible parameter space

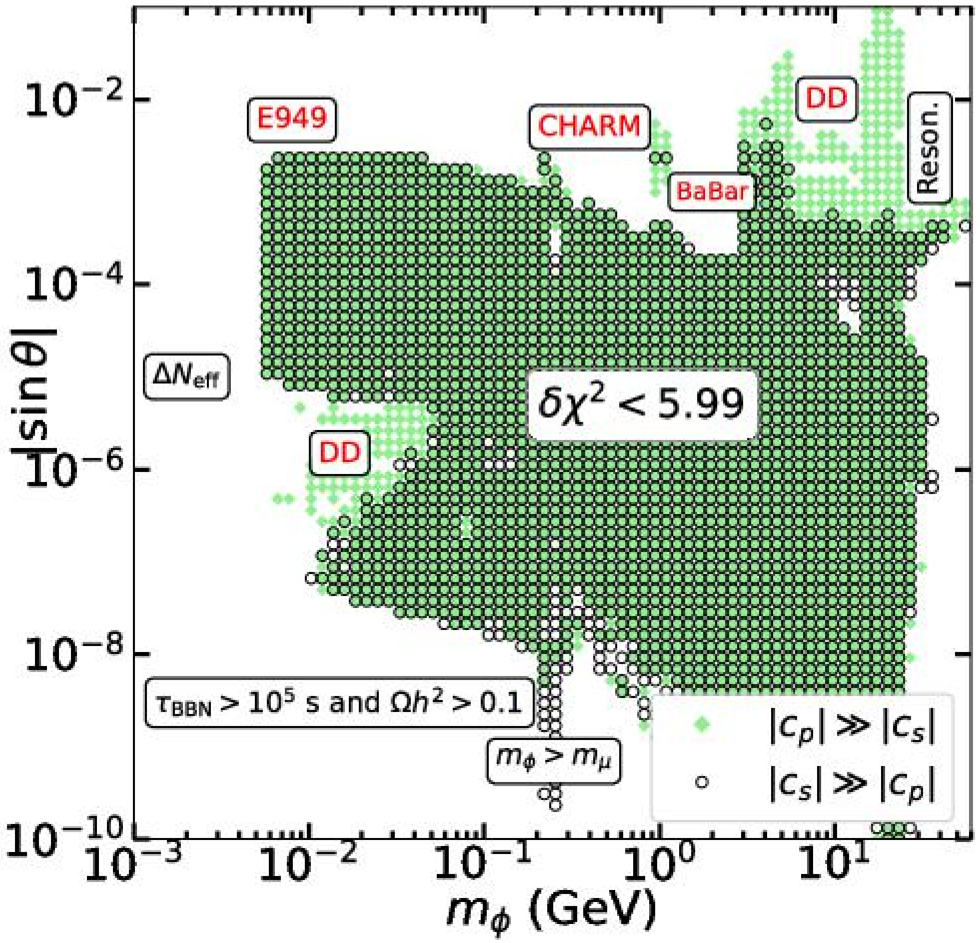
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial\Phi)^2 - \frac{c_s}{2}\Phi\bar{\chi}\chi - \frac{c_p}{2}\Phi\bar{\chi}i\gamma_5\chi - V(\Phi,H),$$

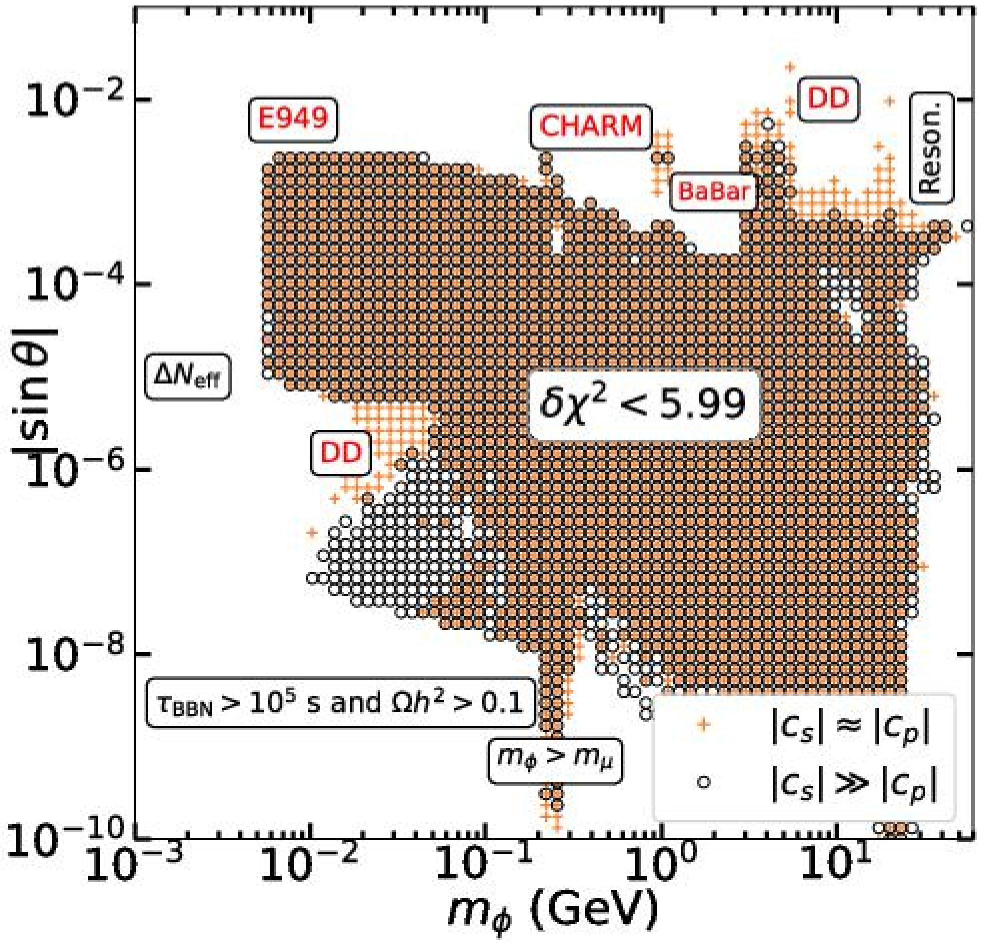
$$\begin{aligned} 1\ \text{MeV} \le\ & m_\chi \le 30\,\text{GeV}, \\ -1 \le\ & c_p \le 1, \\ -1 \le\ & c_s \le 1, \\ 1\ \text{MeV} \le\ & m_\phi \le 60\,\text{GeV}, \\ -\pi/6 \le\ & \theta \le \pi/6, \\ -1\,\text{TeV}^2 \le\ & \mu_\Phi^2 \le 1\,\text{TeV}^2, \\ -1\,\text{TeV} \le\ & \mu_3 \le 1\,\text{TeV}, \\ -1 \le\ & \lambda_\Phi \le 1. \end{aligned}$$



	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($h \to$ inv.)$_{\rm BSM} \le 0.145$ [103]
B decay	Prompt	BR($B^\pm \to K^\pm\mu^-\mu^+) \lesssim 3\times10^{-7}$ [104]
	Displaced	(1) $\sin^2\theta \gtrsim 2\times10^{-8}$ 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($B^\pm \to K^\pm\nu\bar{\nu}) = (2.3\pm0.7)\times10^{-5}$ [107]
Kaon decay	Prompt	(1) BR($K^+ \to \pi^+\mu^-\mu^+) \le 4\times10^{-8}$ [108] (2) BR($K_L \to \pi^0 e^- e^+) \le 2.8\times10^{-10}$ [109] (3) BR($K_L \to \pi^0\mu^-\mu^+) \le 3\times10^{-10}$ [110]
	Displaced	CHARM detected events $\gtrsim 2.3$ [111]
	Long-lived*	(1) BR($K_L \to \pi^0\nu\bar{\nu}) \le 3.0\times10^{-9}$[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.

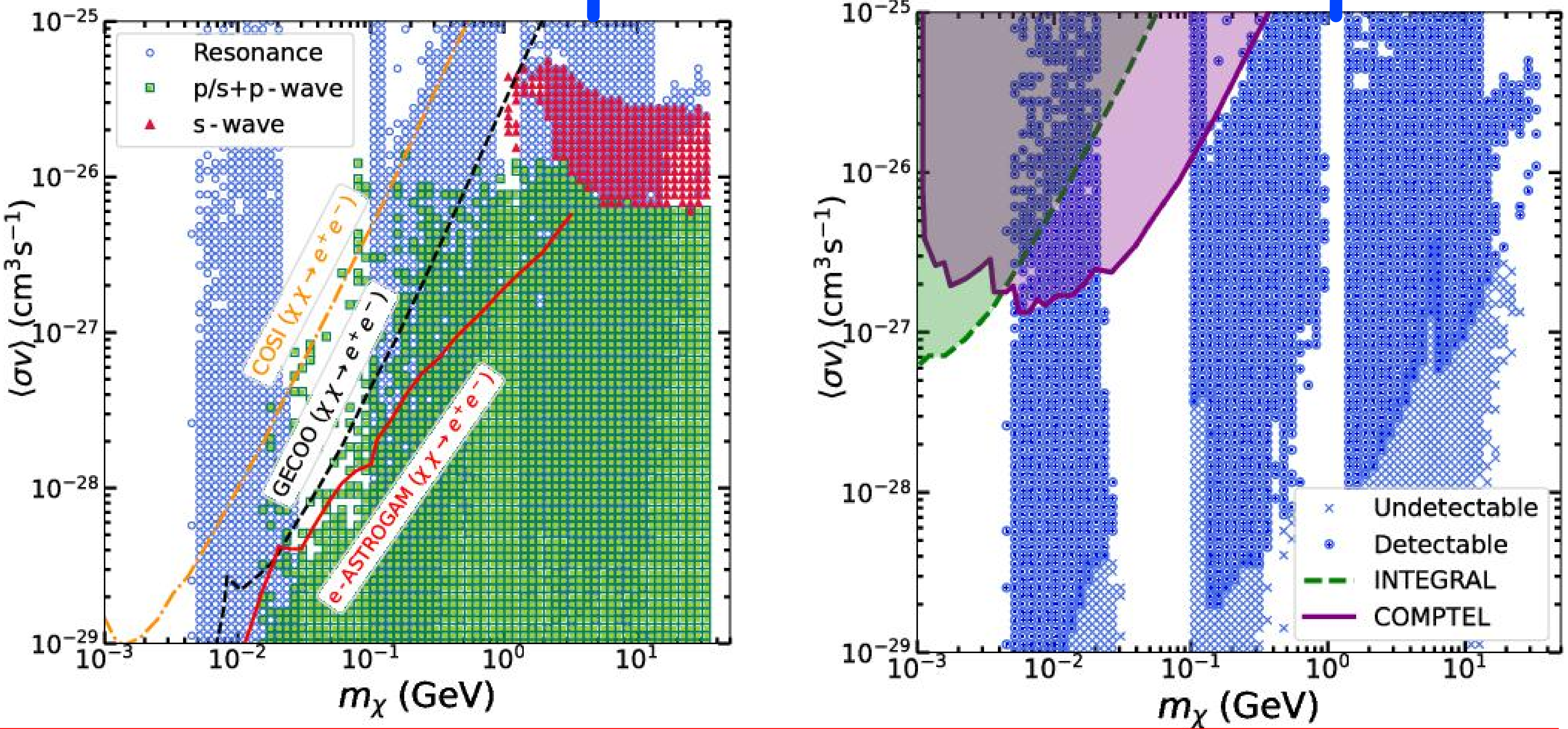
Possible parameter space





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

Possible parameter space



Future DM indirect detection can probe resonance DM

Outline

- Motivations.
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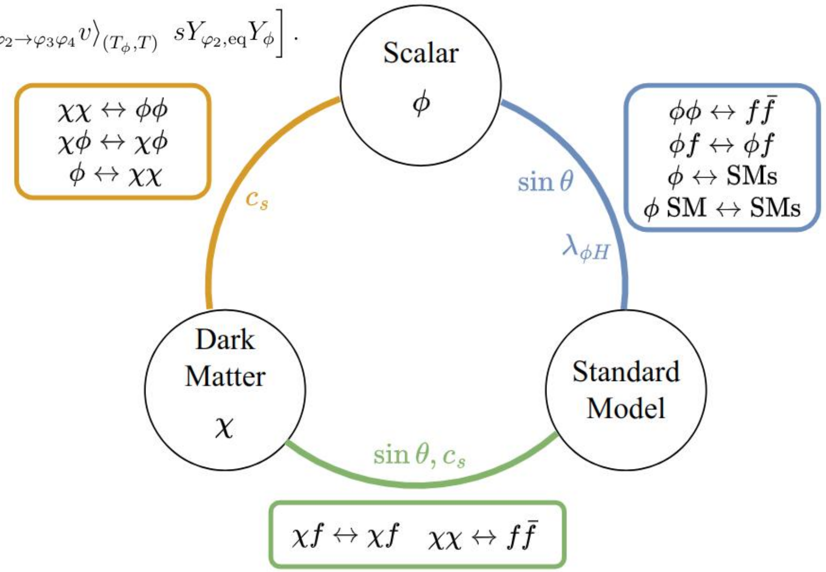
The evolution equations of the comoving number density and temperature

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

and

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

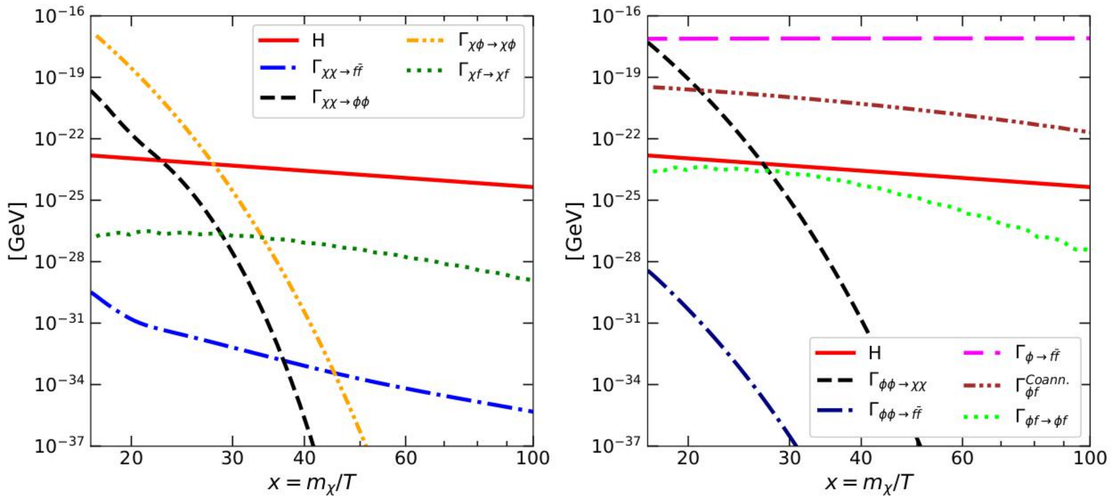


$$
\begin{aligned}
x\tilde{H}Y_\chi T_\chi\left(\frac{y_\chi'}{y_\chi}+\frac{Y_\chi'}{Y_\chi}\right) = {} & \frac{H}{3}\left\langle\frac{\mathbf{p}_\chi^4}{E_\chi^3}\right\rangle Y_\chi + \langle T_\chi\sigma_{\varphi\bar\varphi\to\chi\chi}v\rangle_T\, sY_{\varphi,\mathrm{eq}}^2 - \langle T_\chi\sigma_{\chi\chi\to\varphi\bar\varphi}v\rangle_{T_\chi}\,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

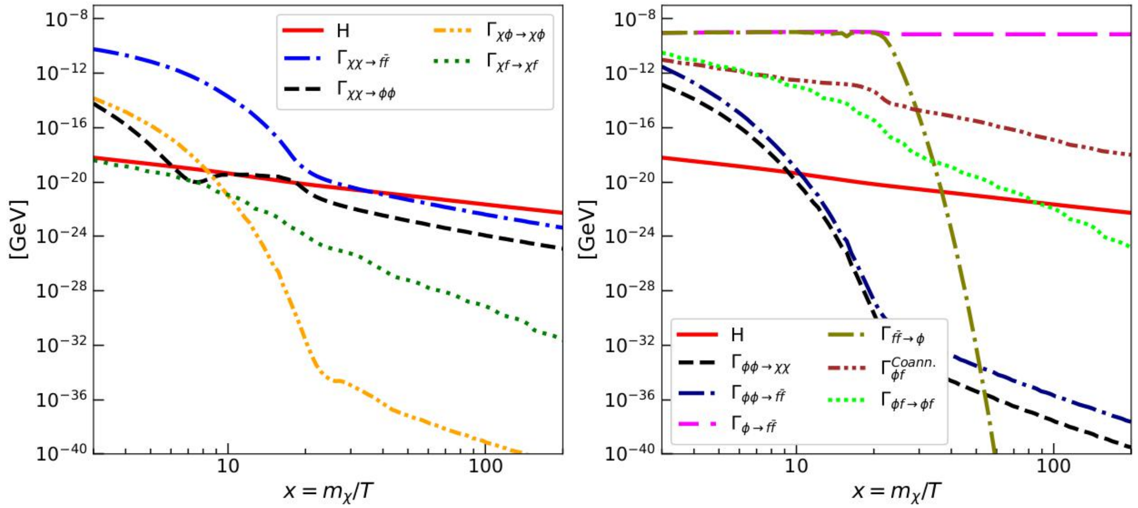
$$
\begin{aligned}
x\tilde{H}Y_\phi T_\phi\left(\frac{y_\phi'}{y_\phi}+\frac{Y_\phi'}{Y_\phi}\right) = {} & \frac{H}{3}\left\langle\frac{\mathbf{p}_\phi^4}{E_\phi^3}\right\rangle Y_\phi + \langle T_\phi\sigma_{\varphi\bar\varphi\to\phi\phi}v\rangle_T\, sY_{\varphi,\mathrm{eq}}^2 - \langle T_\phi\sigma_{\phi\phi\to\varphi\bar\varphi}v\rangle_{T_\phi}\,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

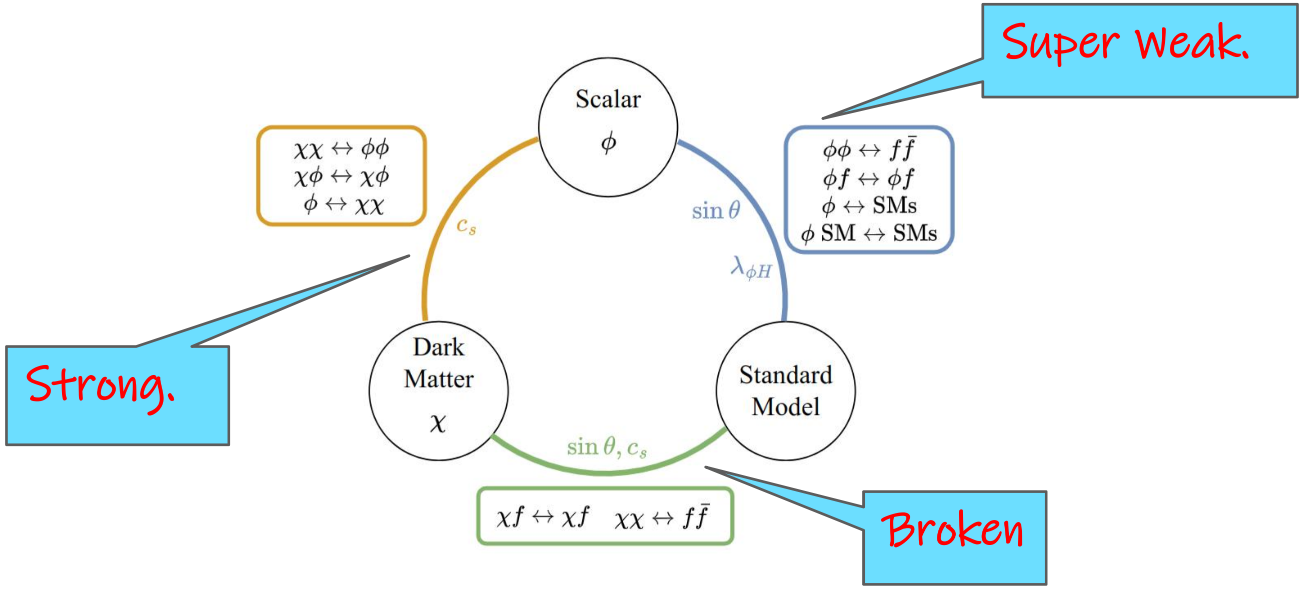
Interaction rates

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

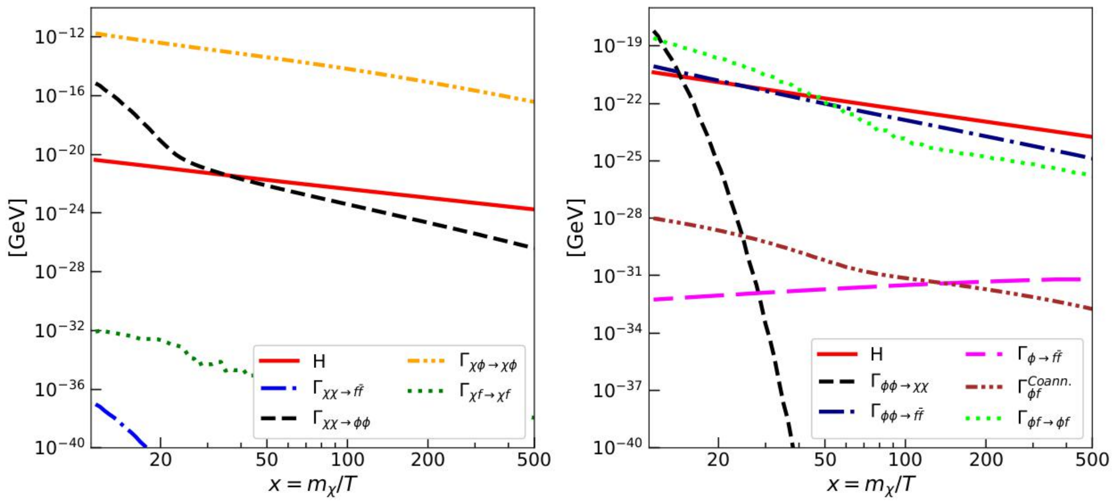


Resonance DM : $m_\chi = 2.2$ Gev, $m_\phi = 4.7$ GeV, $\sin\theta = 0.01$, $c_s = 10^{-3}$ and $\lambda_{\phi H} = 1.0$

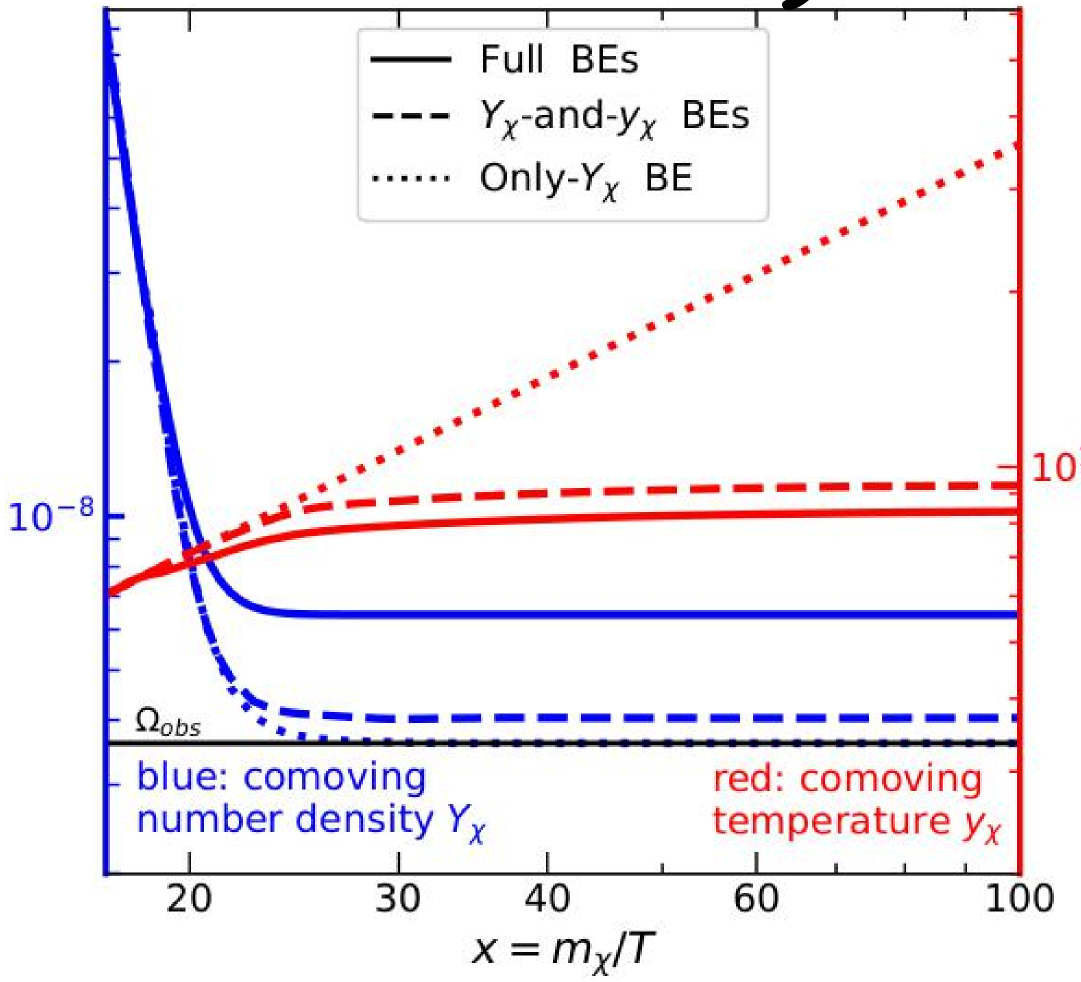


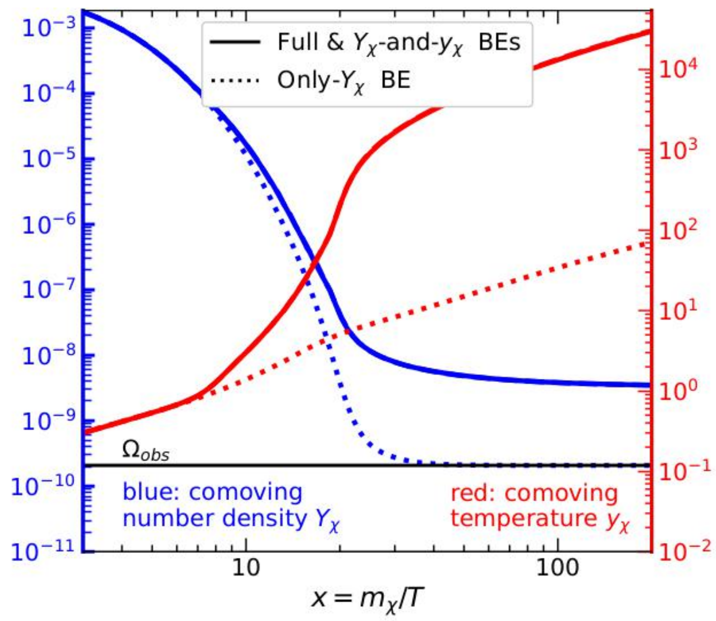


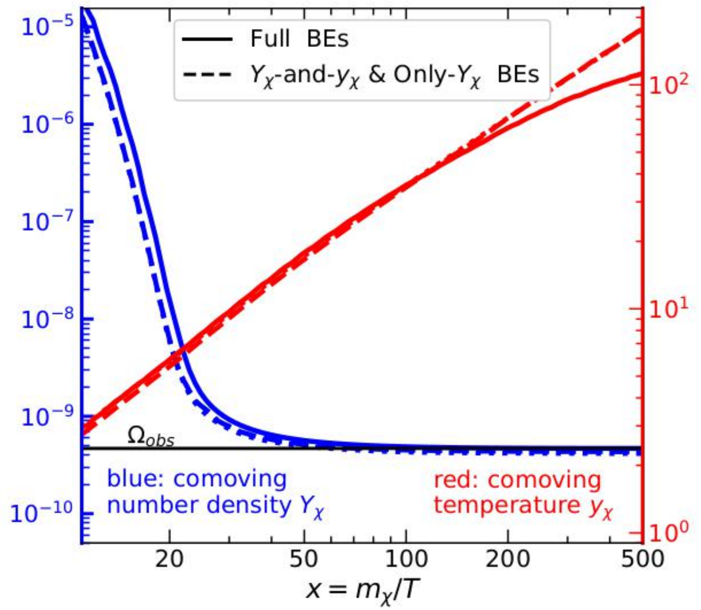
Secluded DM : $m_\chi = 1.0$ Gev, $m_\phi = 0.01$ GeV, $\sin\theta = 10^{-9}$, $c_s = 0.045$ and $\lambda_{\phi H} = 0.1$



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!