Light Fermionic WIMP with light scalar mediator

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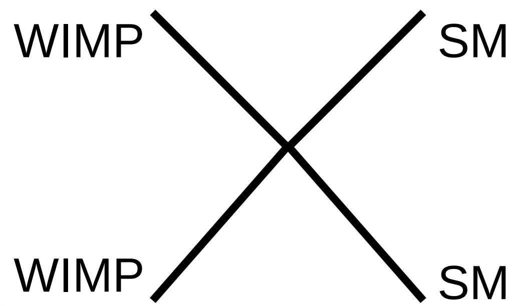
outline

- Introduction
- The minimal WIMP model
- Constraints
- Summary

Introduction

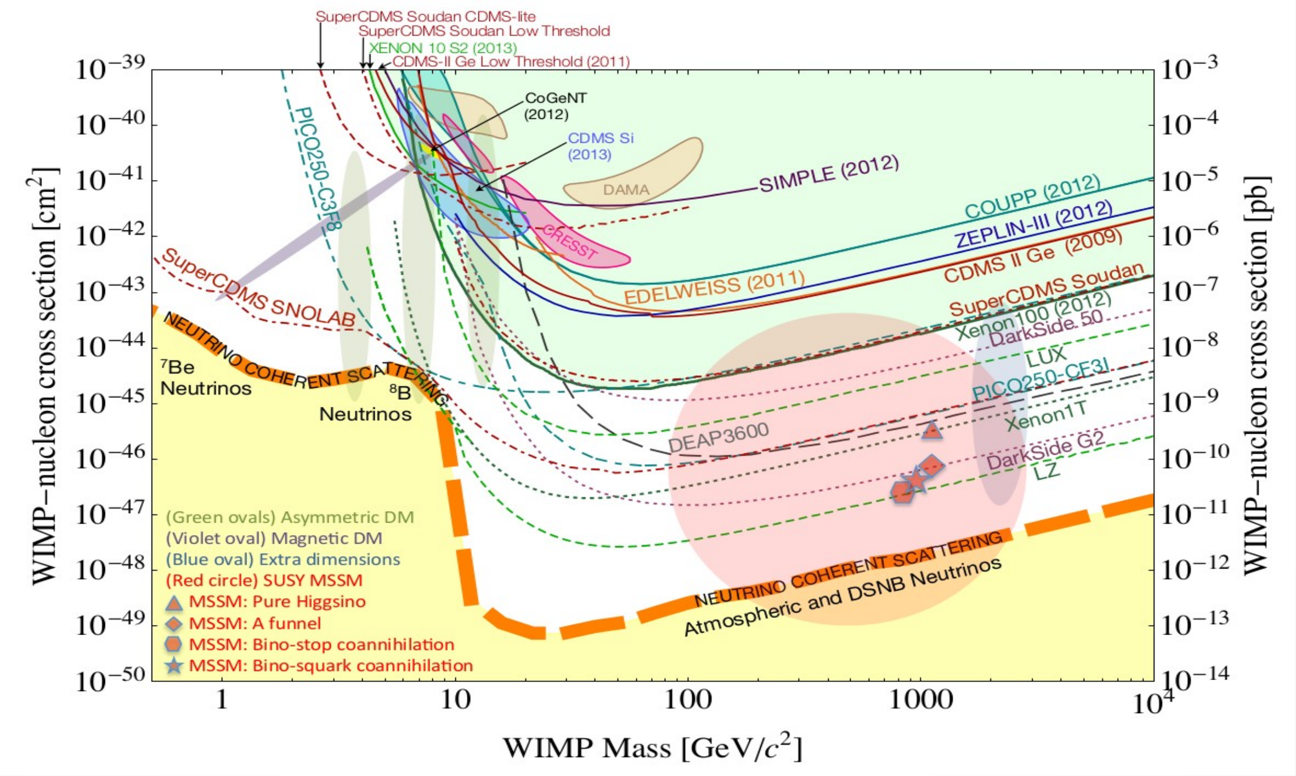
- Sub-GeV thermal produced WIMP.
- Lee-Weinberg limit. Require thermal DM mass larger than GeV. PRL. 39(1977), 165.



- With mediator, Sub-GeV WIMP can thermally produced.

Introduction

- Direct detection for WIMP.



arXiv:1310.8327v2

Introduction

- Sub-GeV singlet Majorana WIMP, χ . Weak-isospin singlet.
- Singlet scalar mediator, Φ . A Z_2-even mediator.
- The mediator mass is around the WIMP mass, in order to give correct relic density.
- Vector mediator case for future work.

Minimal WIMP model

- The Lagrangian with renormalizable interactions is

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

- The scalar potential of the model is

$$\begin{aligned} V_H(H) &= \mu_H^2 H^\dagger H + \frac{\lambda_H}{2}(H^\dagger H)^2, \\ V_\Phi(\Phi) &= \mu_1^3\Phi + \frac{\mu_\Phi^2}{2}\Phi^2 + \frac{\mu_3}{3!}\Phi^3 + \frac{\lambda_\Phi}{4!}\Phi^4, \\ V_{\Phi H}(\Phi, H) &= A_{\Phi H}\Phi H^\dagger H + \frac{\lambda_{\Phi H}}{2}\Phi^2 H^\dagger H. \end{aligned}$$

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V_{\Phi H}(\Phi, H) &= A_{\Phi H}\Phi H^\dagger H + \frac{\lambda_{\Phi H}}{2}\Phi^2 H^\dagger H.
\end{aligned}$$

Minimal WIMP model

- The $A_{\Phi H}\Phi H^{\dagger}H$ allowed the mixing between Higgs doublet and scalar singlet, where the expressed are

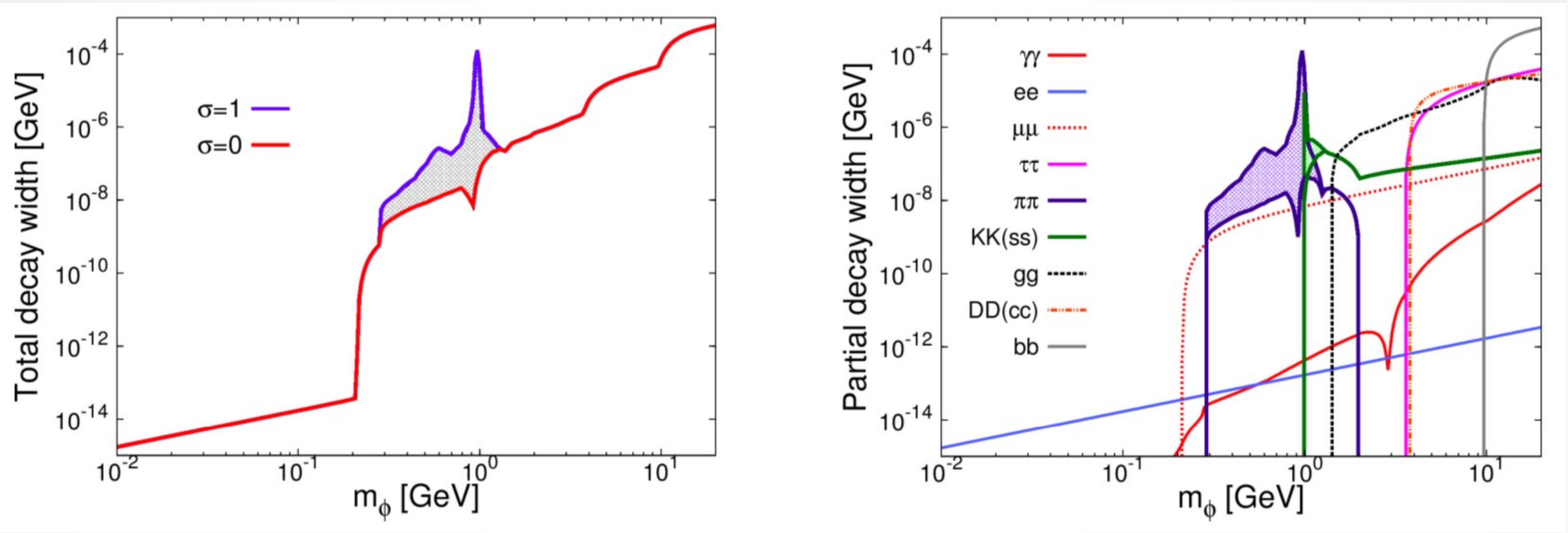
$$H = [0, (v_H + h')/\sqrt{2}]^T \text{ and } \Phi = v_\Phi + \phi'$$

- The mixing is

$$\begin{pmatrix} h \\ \phi \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h' \\ \phi' \end{pmatrix}$$

Minimal WIMP model

- Mediator width and branching ratio:



Minimal WIMP model

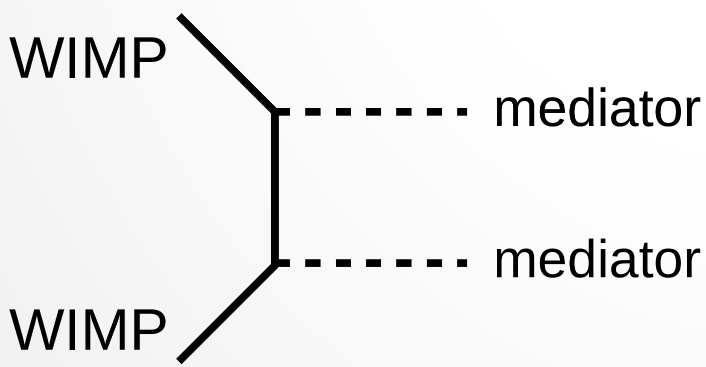
- 125 GeV Higgs decay:

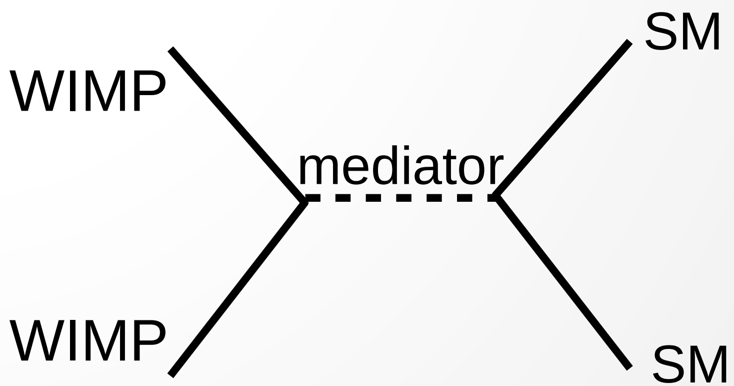
$$\Gamma(h \to \mathrm{SMs}) = \cos^2\theta \times \Gamma(h_{\mathrm{SM}} \to \mathrm{SMs}),$$

- Because of the constraint from Higgs precision measurements, we take $-0.35 < \sin\theta < 0.35$.

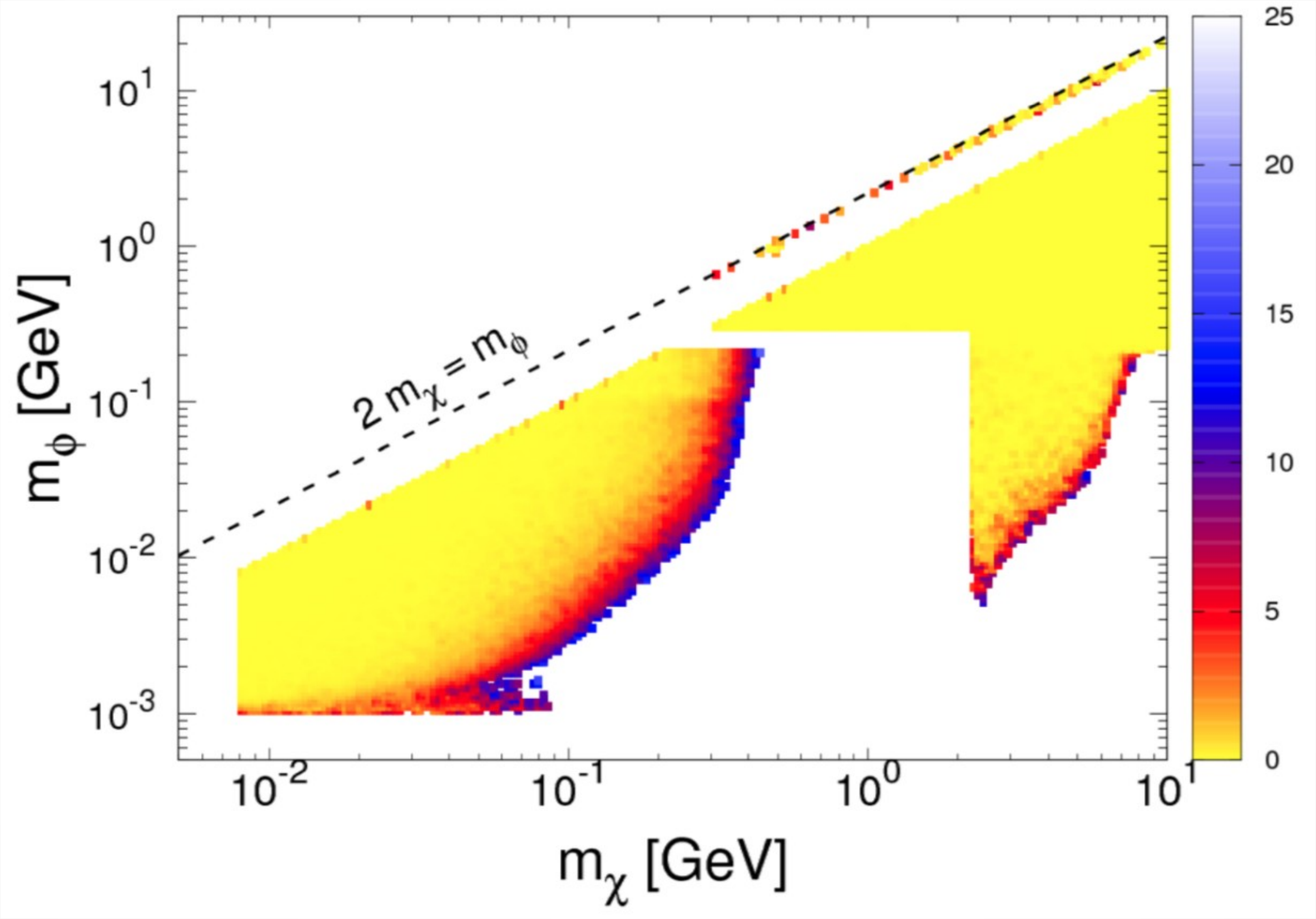
Constraints

- Relic abundance and thermal equilibrium.
- When $m_\chi \geq m_\phi$, t-channel WIMP annihilate into a pair of mediators.
- When $m_\chi \leq m_\phi$, s-channel WIMP annihilate into a pair of SM. The resonance enhancement $m_\chi \sim m_\phi/2$.



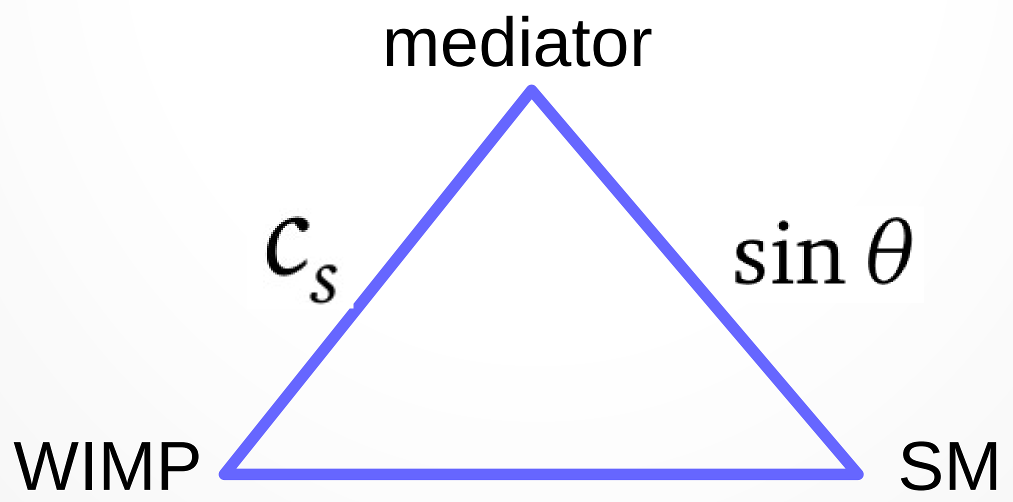


Constraints



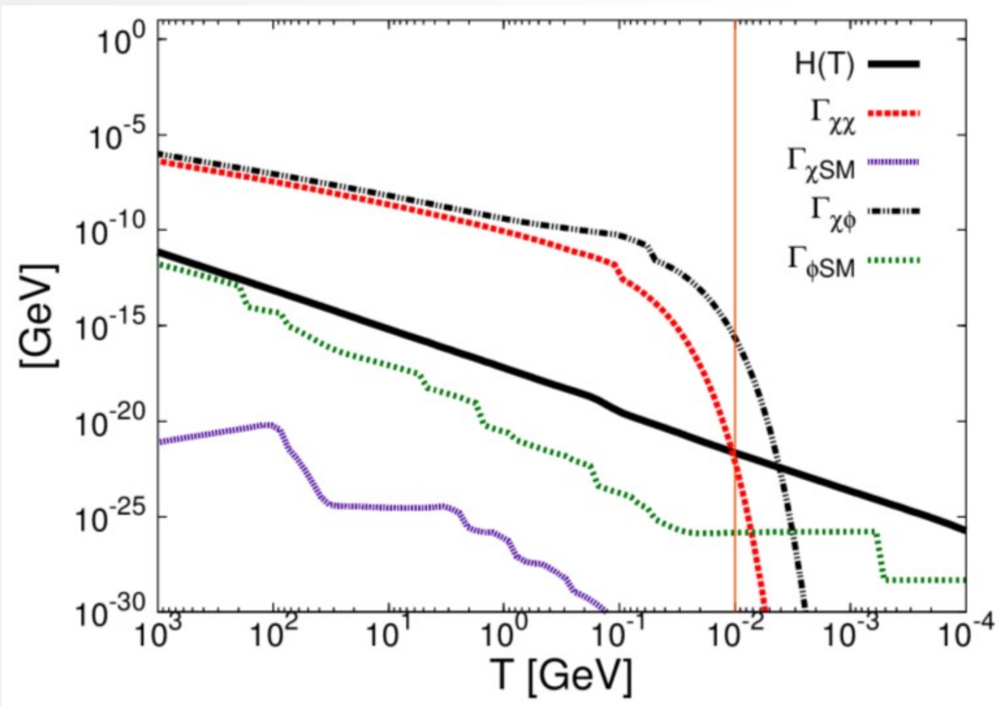
Constraints

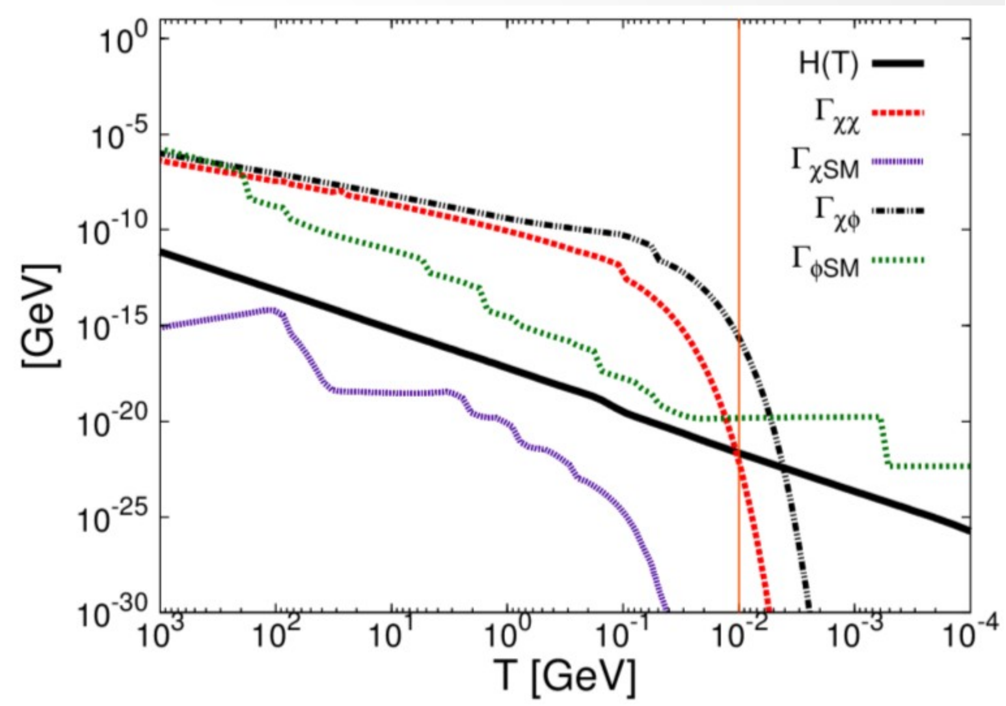
- Relic abundance and thermal equilibrium.
- WIMP and SM particles need to be in kinetic equilibrium during the freeze-out.
- WIMP ↔ mediator ↔ SM.



Constraints

WIMP ↔ mediator ↔ SM.





$$(m_\chi, c_s, m_\phi, \sin\theta, \mu_3) =$$

$$(200\text{MeV}, 0.022, 100\text{MeV}, 10^{-6}, 10\text{MeV})$$

$$(200\text{MeV}, 0.1, 50\text{MeV}, 10^{-3}, 10\text{MeV})$$

Constraints

- Cosmology constraints.
- BBN → the life time of mediator less than 1 sec.
- The ΔN_{eff} , require the WIMP mass > 6.4 MeV. (WIMP inject entropy into SM during freeze-out, and neutrino decouples at T~2.3 MeV.)
- CMB constraint → , $c_p = 0$,

  WIMP annihilation is P-wave.

$$\langle \sigma v \rangle_{\rm CMB}/m_\chi \lesssim 3 \times 10^{-28} {\rm cm}^3\,{\rm s}^{-1}\,{\rm GeV}^{-1}$$

Constraints

- Collider constraints.
- K, B-meson, Upsilon decays:

$$\mathrm{Br}(K^+ \to \pi^+ s) < 5\times 10^{-10} \sim 10^{-8} \text{ at 90\% CL for } m_s \subset [0, 240\ \mathrm{MeV}],\ \text{E949}$$

$$\mathrm{Br}(B^+ \to K^+ \nu\bar{\nu}) < 1.4\times 10^{-5} \text{ at 90\% CL, Belle [41],}$$

$$\mathrm{Br}(B^+ \to K^+ \nu\bar{\nu}) < 1.3\times 10^{-5} \text{ at 90\% CL, BABAR [36, 41],}$$

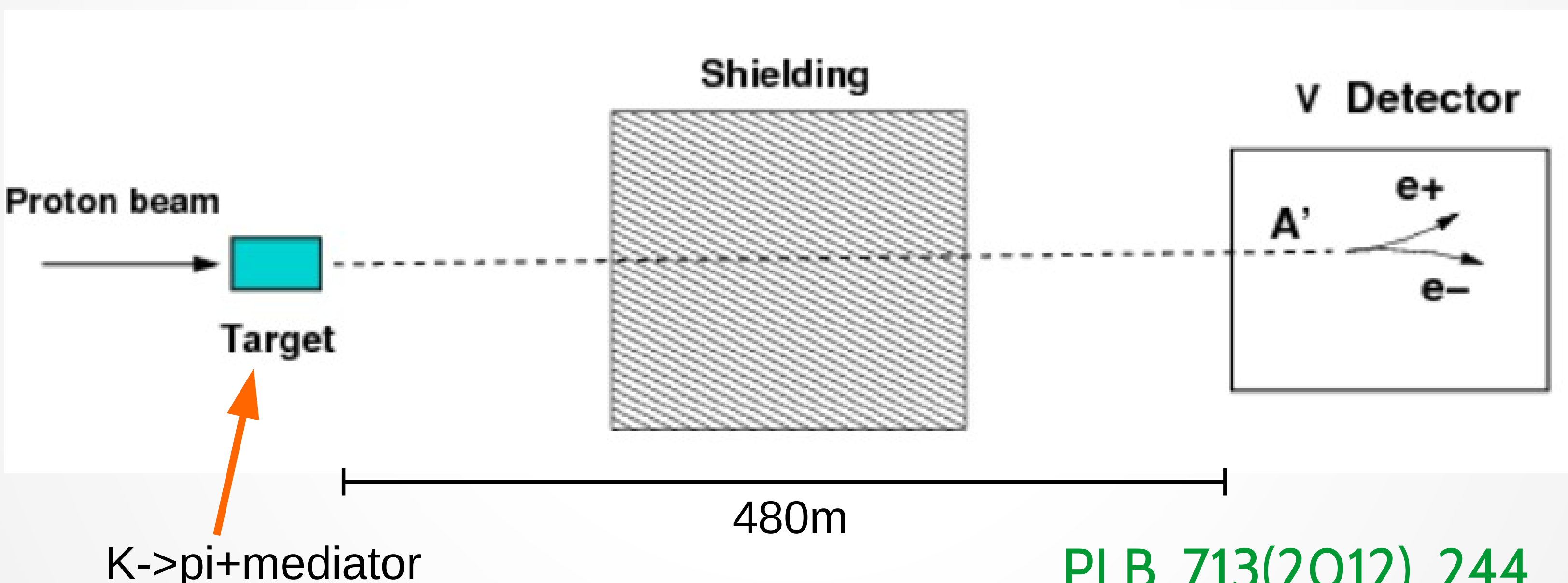
$$\mathrm{Br}(B^+ \to K^+ \mu^+\mu^-) = (4.36 \pm 0.15 \pm 0.18)\times 10^{-7}, \quad \text{LHCb[34]}$$

$$\mathrm{Br}(B^+ \to K^+ \mu^+\mu^-) = (5.3^{+0.8}_{-0.7} \pm 0.3)\times 10^{-7}, \quad \text{Belle[35]}$$

- CHARM: proton beam dump experiment.

Constraints

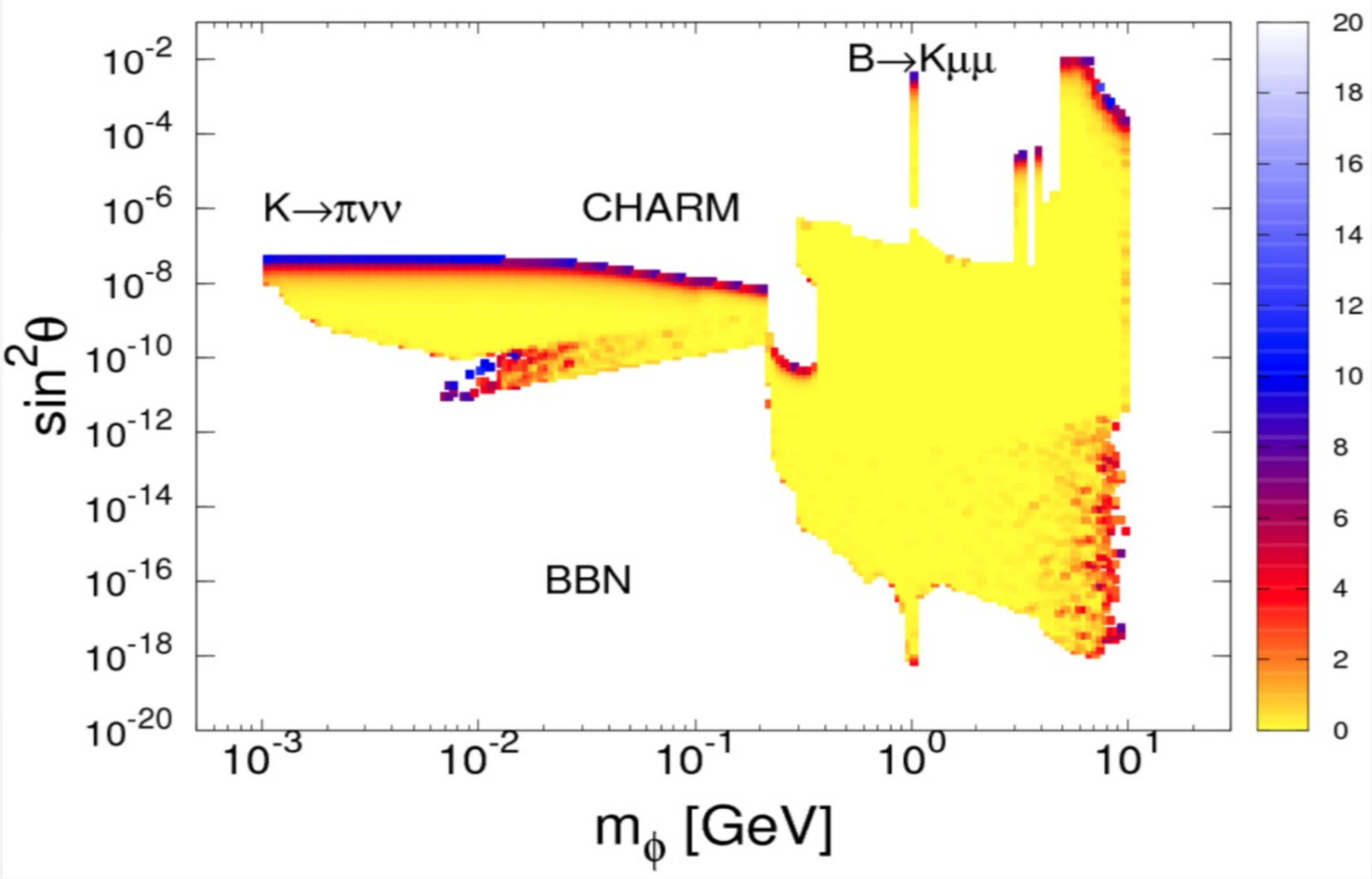
- Collider constraints.
- CHARM: proton beam dump experiment.



PLB. 713(2012), 244.

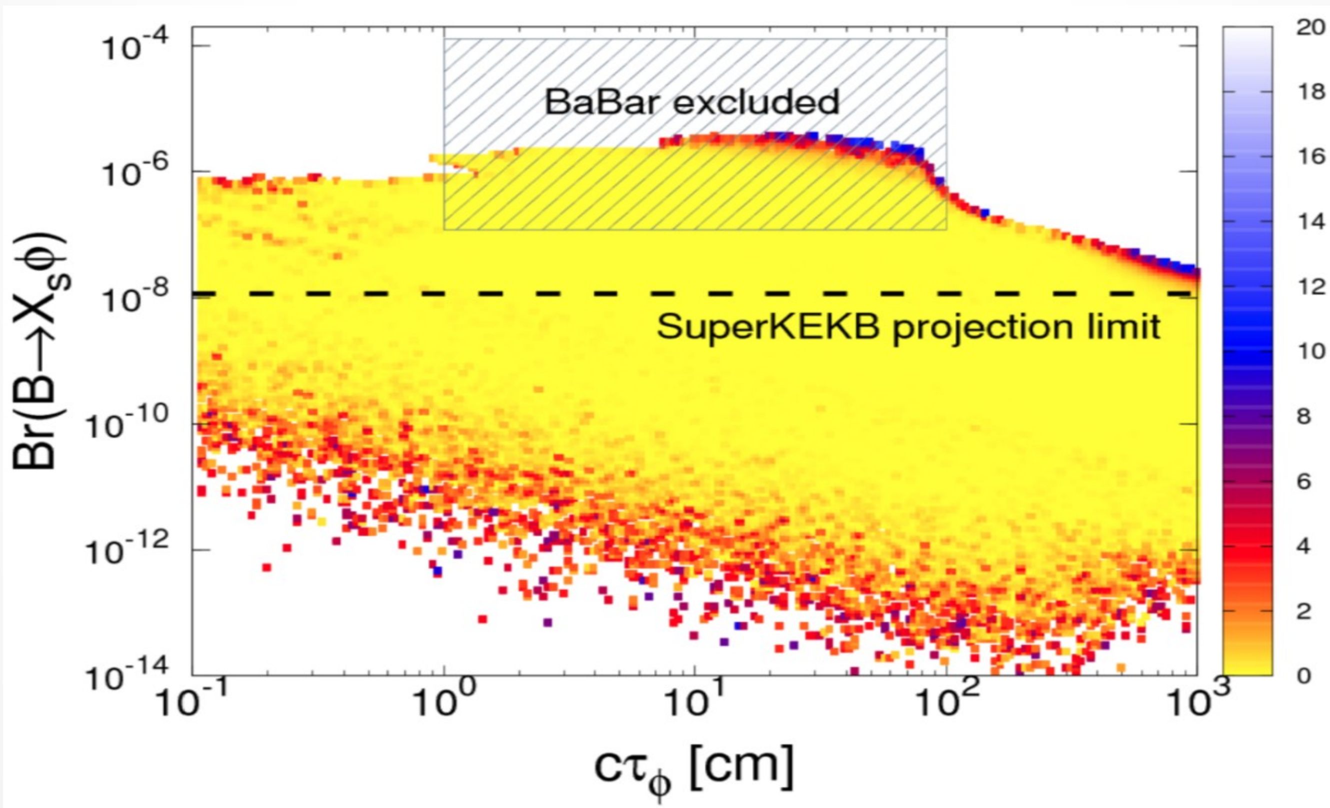
Constraints

- Combine all the constraints:



Constraints

- Future Collider constraints.
- Belle-II (SuperKEKB) with luminosity 50/ab.



Summary

- Consider the minimal sub-GeV WIMP model.
- Mediator mix with SM Higgs.
- Theoretical, cosmology, and collider constraints are take into account.
- The scalar mediator: i).correct relic density. ii).maintain thermal equilibrium between WIMP and SM. iii) provide signal at collider.

Thank you !

Minimal WIMP model

- Mediator decays through the mixing with Higgs:

$$\Gamma(\phi \to e^+e^-) = \sin^2\theta \times \frac{m_e^2 m_\phi}{8\pi v_H^2}\left(1 - \frac{4m_e^2}{m_\phi^2}\right)^{3/2} .$$

- If mediator mass > 0.25 GeV:

$$\Gamma(\phi \to \pi\pi) \equiv \frac{\Gamma_{\pi\pi}}{\Gamma_{\pi\pi} + \Gamma_{KK}}[\sigma\Gamma_+ + (1-\sigma)\Gamma_-],$$

$$\Gamma(\phi \to KK) \equiv \frac{\Gamma_{KK}}{\Gamma_{\pi\pi} + \Gamma_{KK}}[\sigma\Gamma_+ + (1-\sigma)\Gamma_-],$$

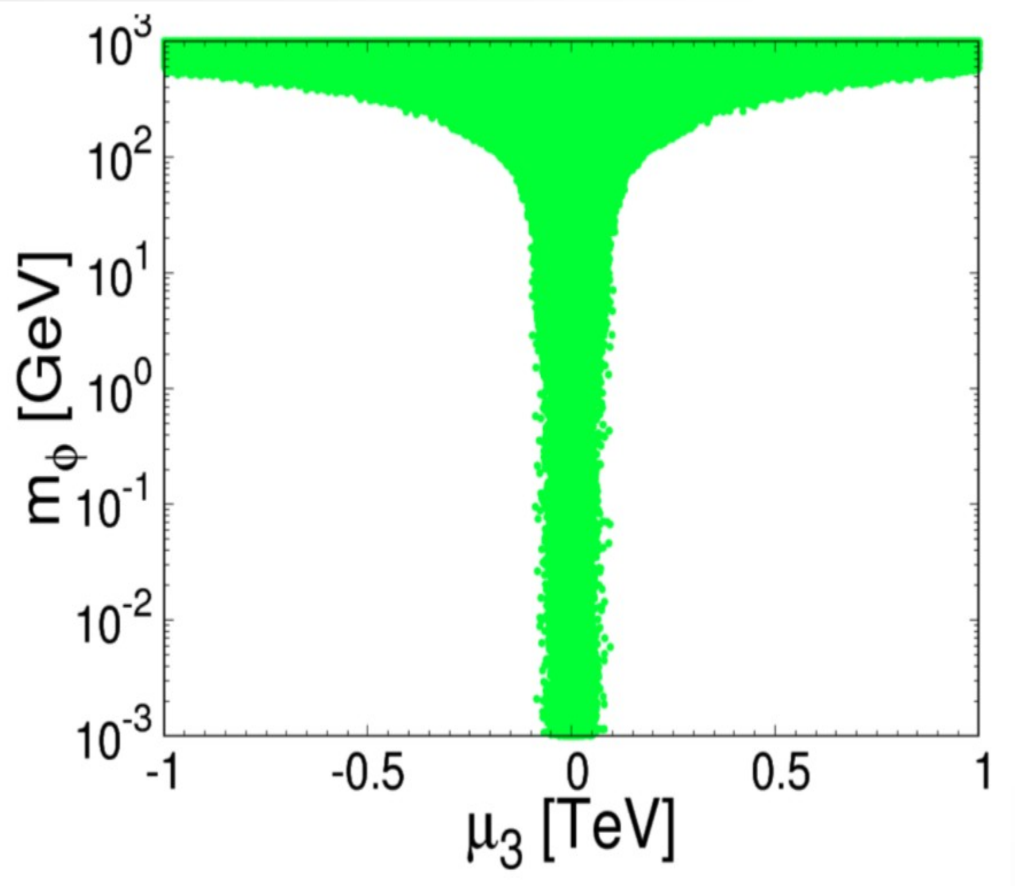
Constraints

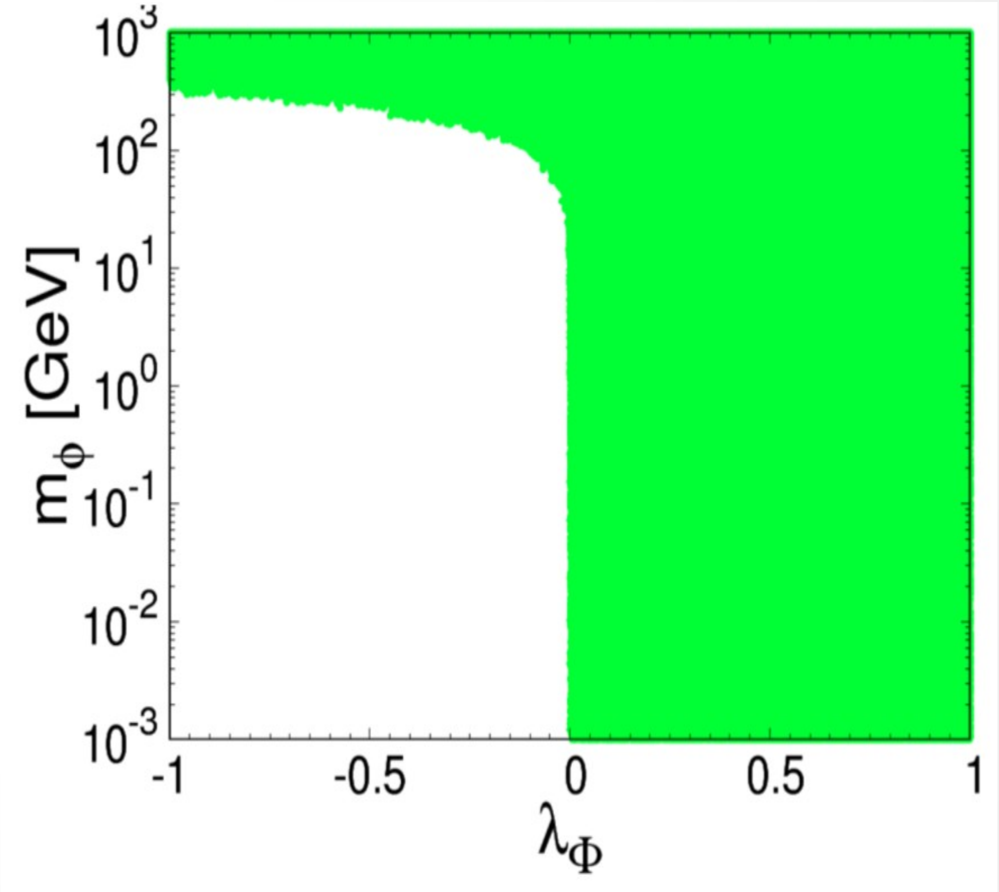
- Vacuum stability condition below 1TeV.
- This minimal WIMP model is an effective model below 1TeV.
- Minimum of potential at (246,0)GeV:

$$V(\eta, \xi) \geq V(v_\Phi, v_H)$$

Constraints

- Vacuum stability constraint





Minimal WIMP model

- The Lagrangian with renormalizable interactions is

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

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Minimal WIMP model

- There are eight parameters:

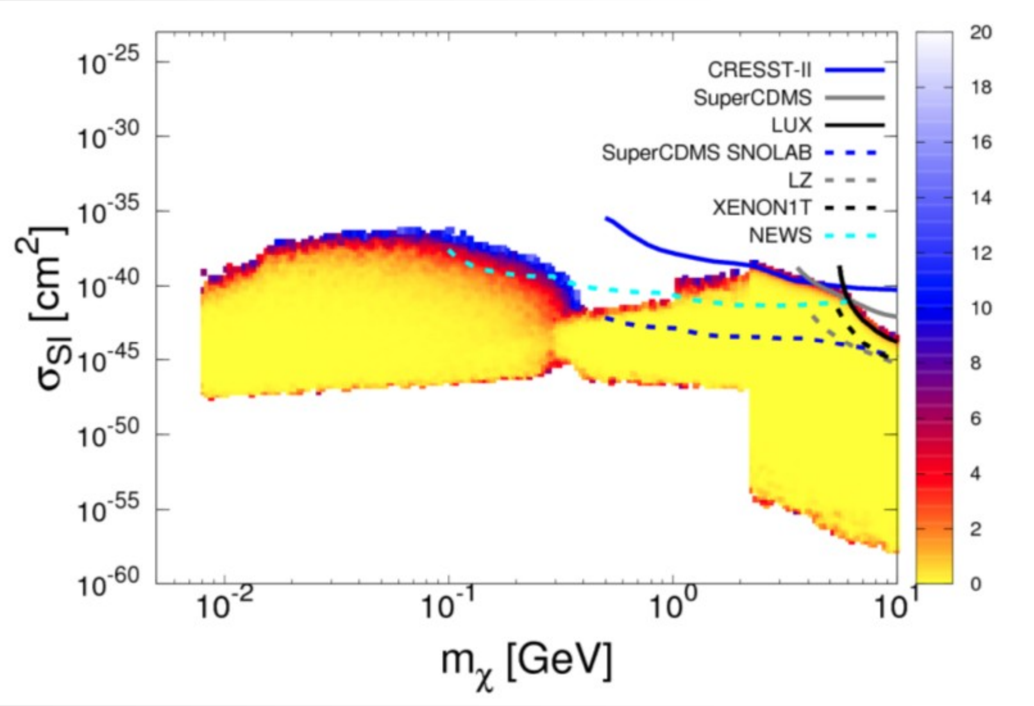
$$m_\chi,\ c_s,\ c_p,\ m_\phi,\ \sin\theta,\ \mu_\phi^2,\ \mu_3 \text{ and } \lambda_\Phi,$$

- The vacuum stability condition give two relations.
- Higgs mass = 125 GeV.
- We consider CP-conservation, $c_p = 0$. Because of the CMB constraint.

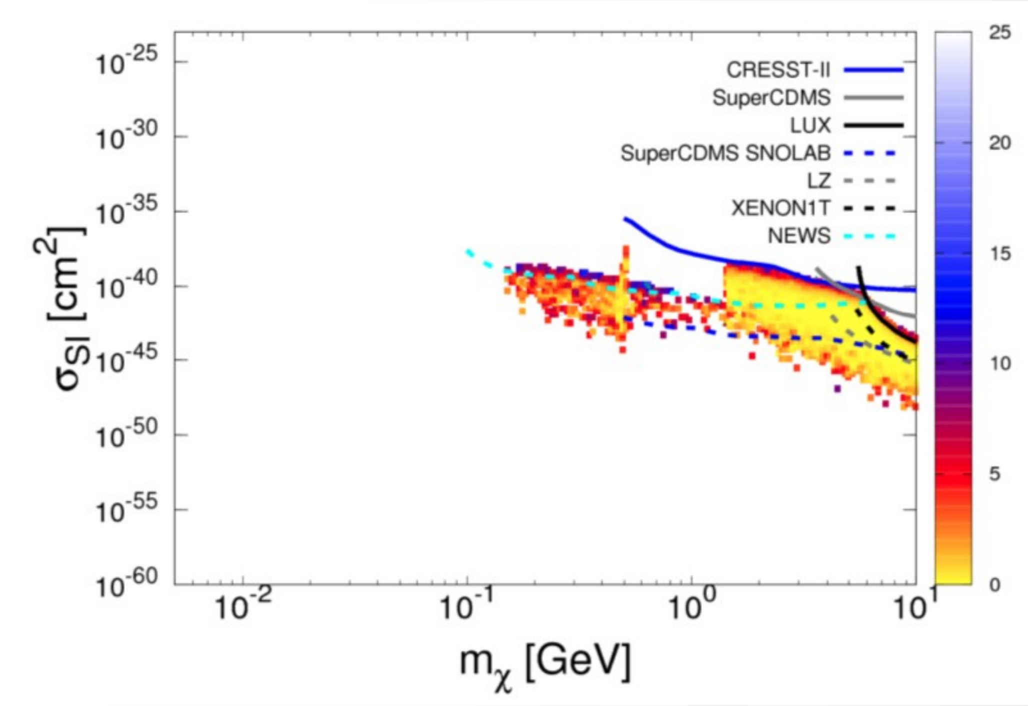
$$\langle\sigma v\rangle_{\rm CMB}/m_\chi \lesssim 3\times 10^{-28}\,{\rm cm^3\,s^{-1}\,GeV^{-1}}$$

Constraints

- Direct direction.



$$m_\chi \geq m_\phi$$



$$m_\chi \leq m_\phi$$

Constraints

- Collider constraints.
- 125GeV Higgs precision measurement:

$$\mathrm{Br}(h \to \mathrm{nonstandard}) < 19\%$$

- 125GeV Higgs decay into a pair of mediators from ATLAS and CMS: prompt and long-live searches.

$$h \to aa \to 4\ell$$

Constraints

- Thermal equilibrium
- Rate of decay width:

$$\Gamma_{\phi\to\mathrm{All}} = \left\langle \frac{1}{\gamma} \right\rangle \Gamma_\phi = \frac{\int_1^\infty d\gamma \, \frac{1}{\gamma} f(\gamma)}{\int_1^\infty d\gamma \, f(\gamma)} \Gamma_\phi$$

- Where $f(\gamma)$ is the thermal distribution of relativistic gas.

$$f(\gamma) = \gamma^2 \sqrt{1 - 1/\gamma^2} \, e^{-\gamma m_\phi / T}$$

Constraints

- Thermal equilibrium
- Relaxation rate of scattering process:

DM<->mediator<->SM

- After DM freeze-out, SM: relativistic
- Mediator: relativistic, non-relativistic
- DM: non-relativistic

Constraints

- Thermal equilibrium
- Relaxation rate:

$$\Gamma_{SE\to \mathrm{All}} = \begin{cases} \sqrt{\frac{3}{8}}\, n_E < \sigma v >_{SE\to \mathrm{All}}, & \text{for } (\frac{m_S}{T} \leq 2, \frac{m_E}{T} \leq 2) \\ \sqrt{\frac{3}{2}}\, \frac{T}{m_E}\, n_E < \sigma v >_{SE\to \mathrm{All}}, & \text{for } (\frac{m_S}{T} < 2, \frac{m_E}{T} > 2) \\ \sqrt{\frac{3}{2}}\, \frac{T}{m_S}\, n_E < \sigma v >_{SE\to \mathrm{All}}, & \text{for } (\frac{m_S}{T} > 2, \frac{m_E}{T} < 2) \\ F_{\mathrm{non-R}}\left(\frac{m_E}{T}, \frac{m_S}{T}\right) n_E < \sigma v >_{SE\to \mathrm{All}}, & \text{for } (\frac{m_S}{T} \geq 2, \frac{m_E}{T} \geq 2), \end{cases}$$

Constraints

- Thermal equilibrium
- Relaxation rate: