Thermal Dark Matter in Neutral Naturalness Model

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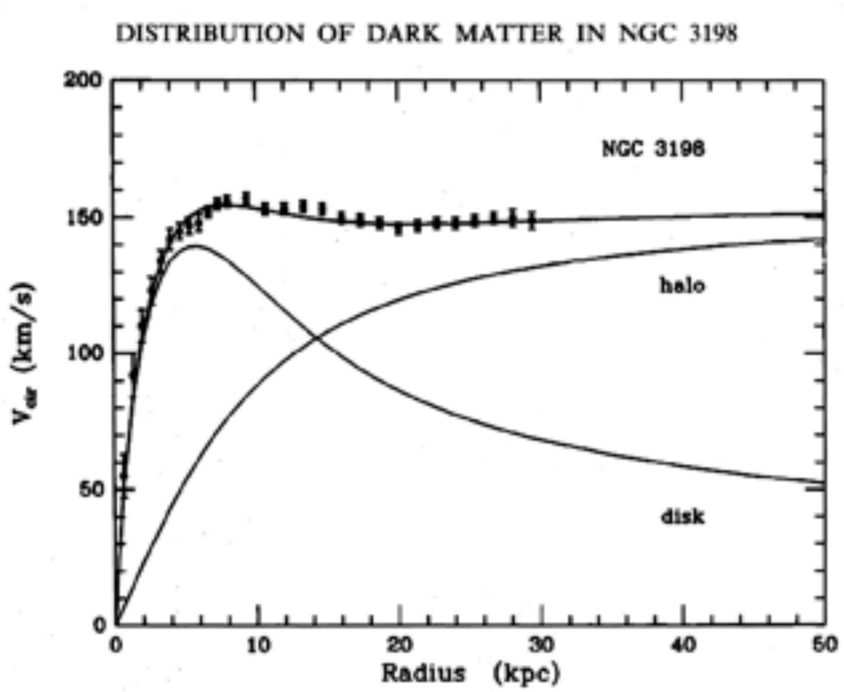
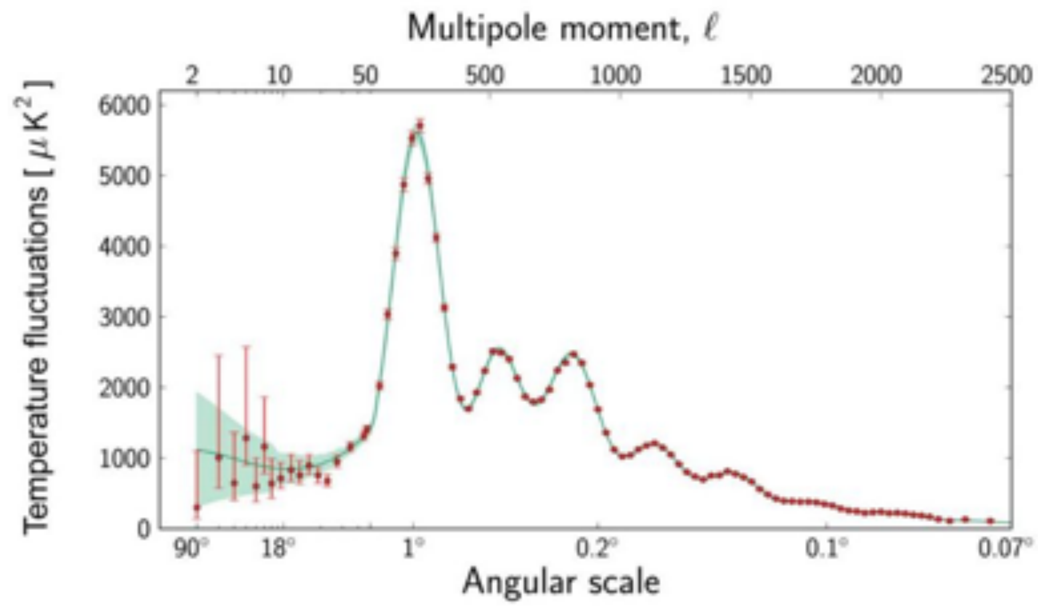
supported by U.S. DEPARTMENT OF ENERGY | Office of Science

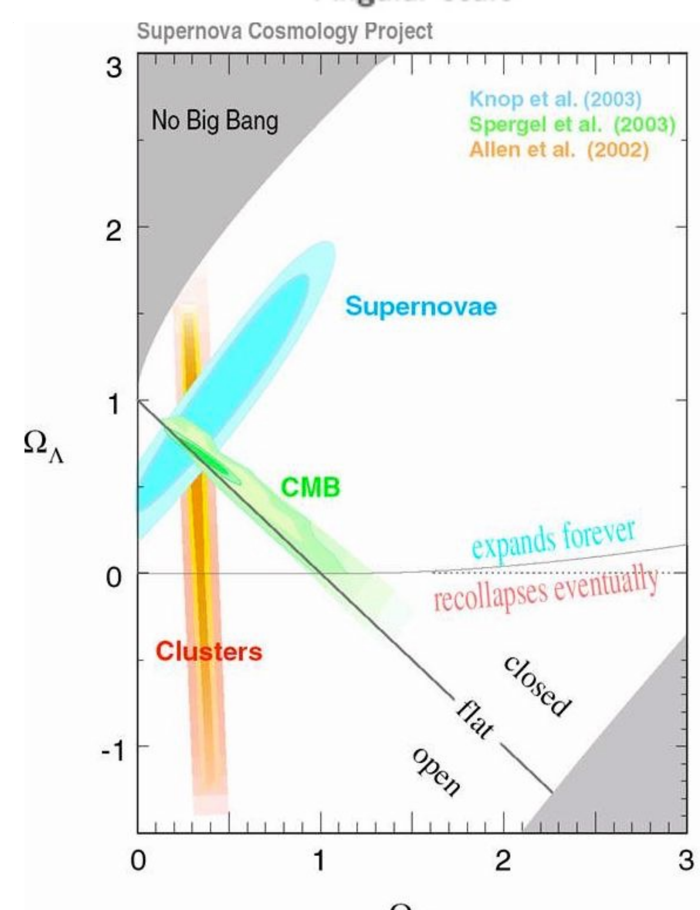
5th International Workshop on Dark Matter, Dark Energy and Matter-Antimatter Asymmetry ,Dec 28-31, 2018

Introduction

The existence of dark matter (DM) in the universe is firmly established, but the nature of the DM is still unknown.





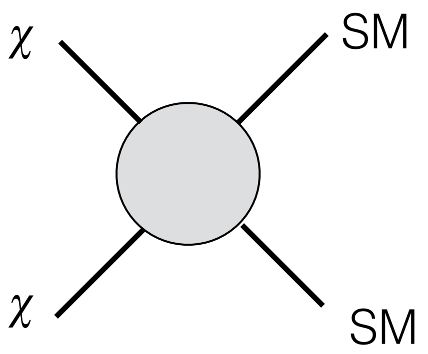


Introduction

There are many viable DM candidates, including axions, primordial blackholes, etc. A most popular and studied scenario is DM being a thermal relic from the Big Bang, which was frozen out in the early universe.

- The observed DM abundance can be naturally given by the thermal relic of a stable weakly interacting particle with a weak scale mass. (WIMP miracle)

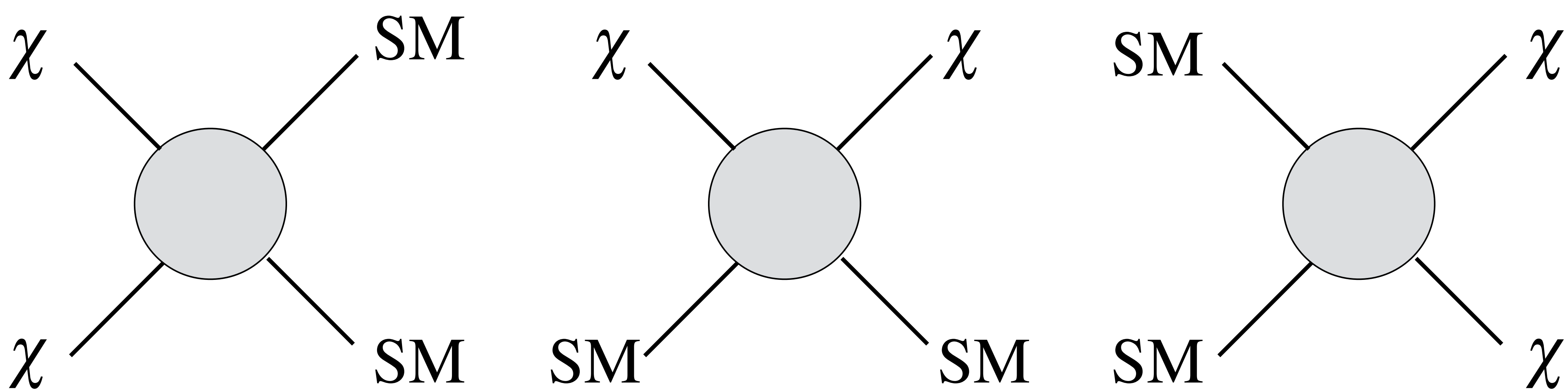
$$\langle \sigma v \rangle \approx 3 \times 10^{-26} \mathrm{cm}^3\, \mathrm{s}^{-1} \approx \frac{\alpha^2}{(200\,\mathrm{GeV})^2}$$



- The proximity with the weak scale may indicate a connection between DM and the hierarchy problem, i.e., DM may belong to the new physics sector which solves the hierarchy problem.

Experimental Tests of WIMP

The interaction responsible for the relic density of WIMP DM also provide ways to test it experimentally.



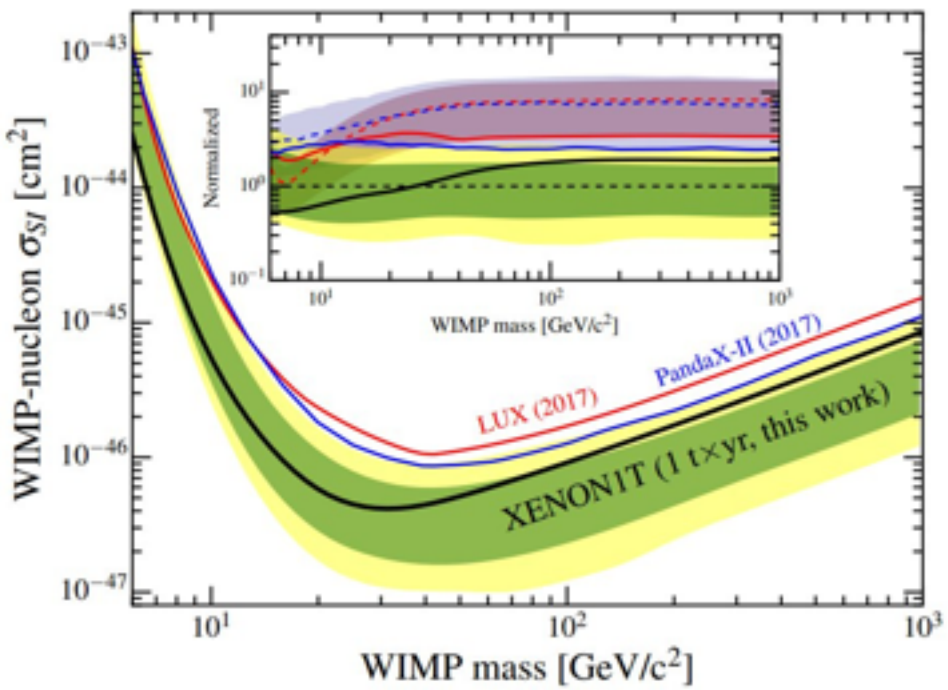
Indirect detection

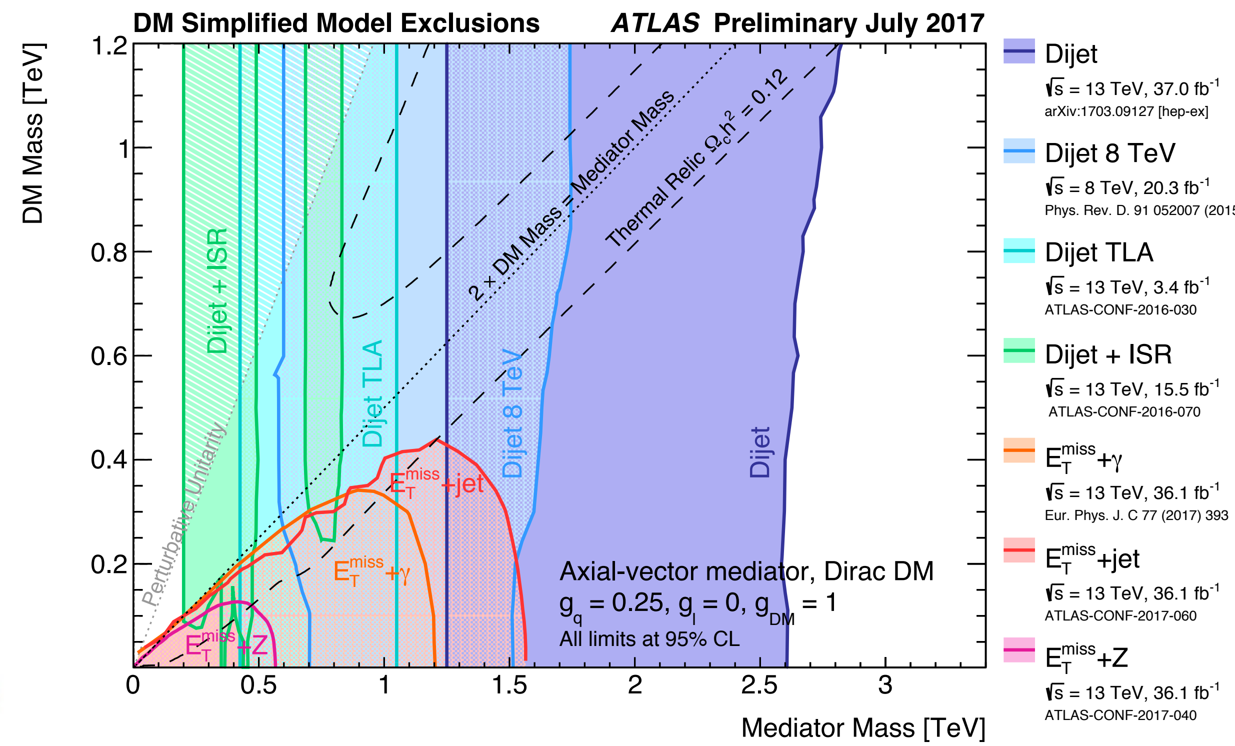
Direct detection

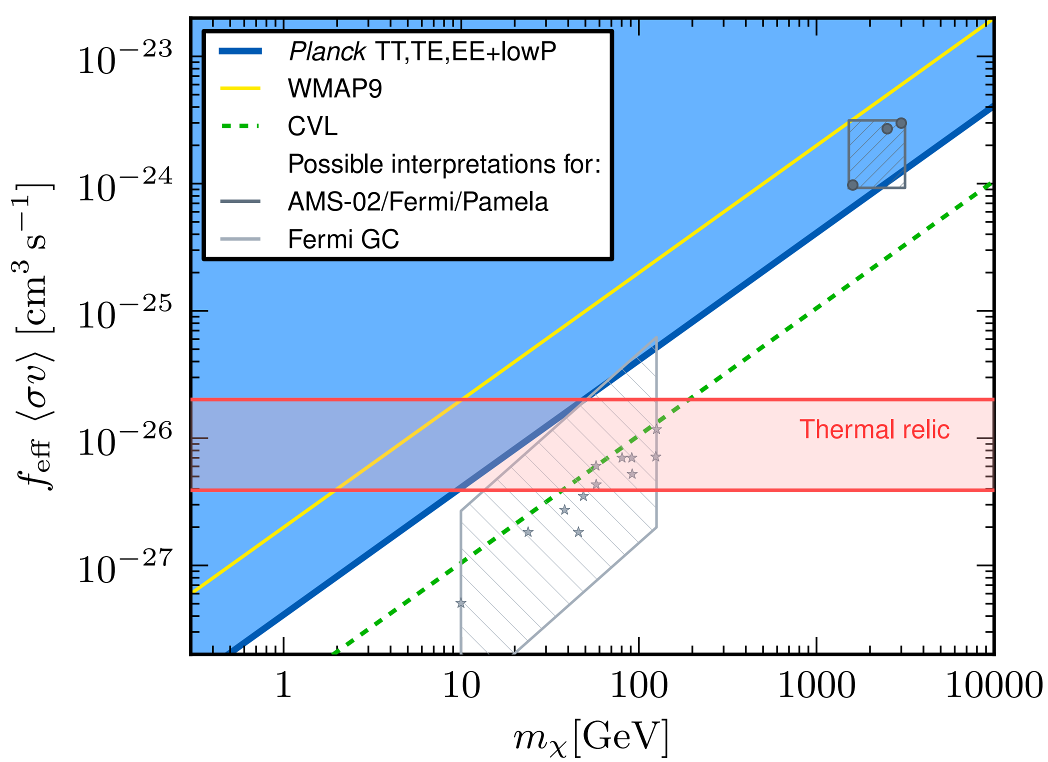
Collider production

Dark Matter Searches

Unfortunately, DM hasn't been found in any of these experiments.



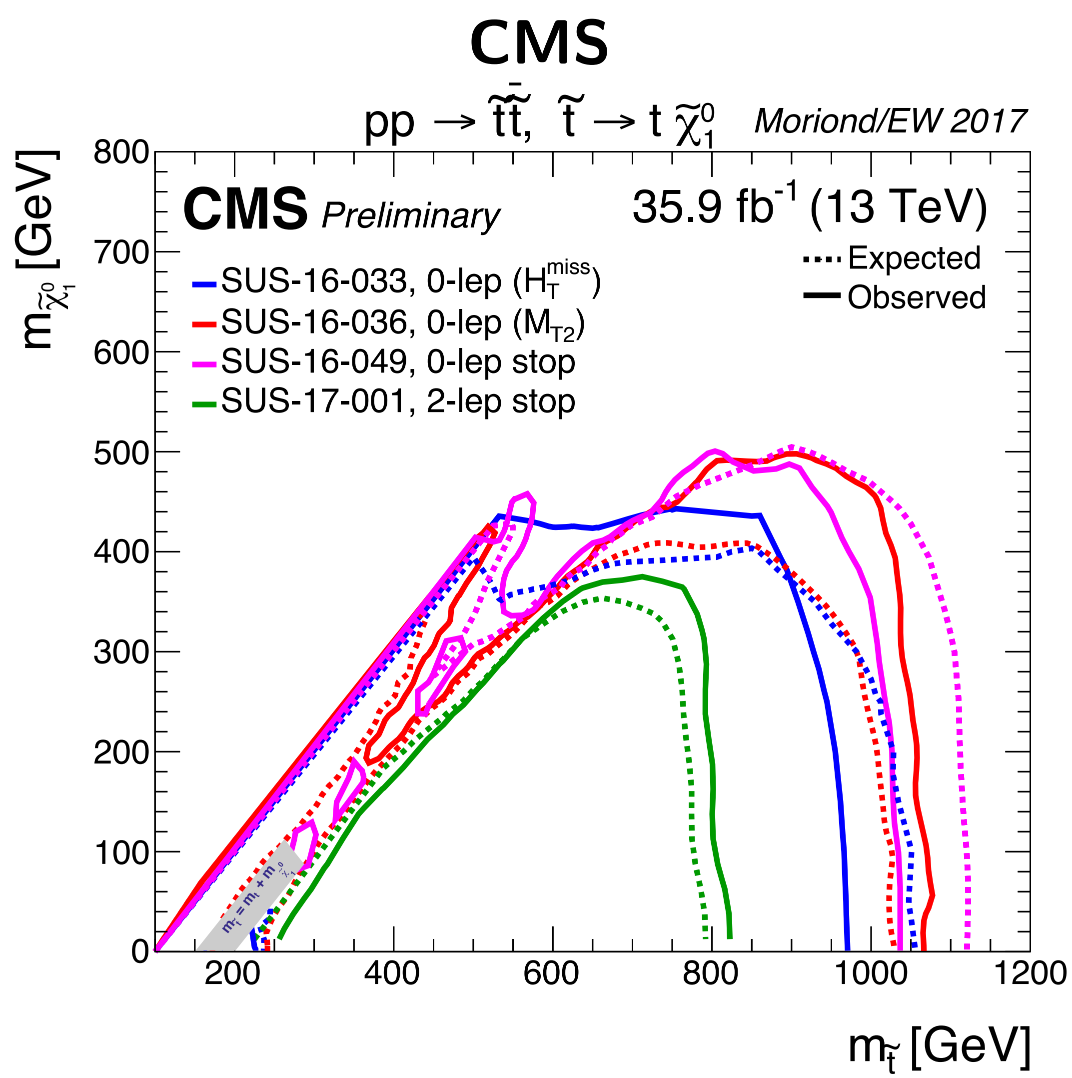


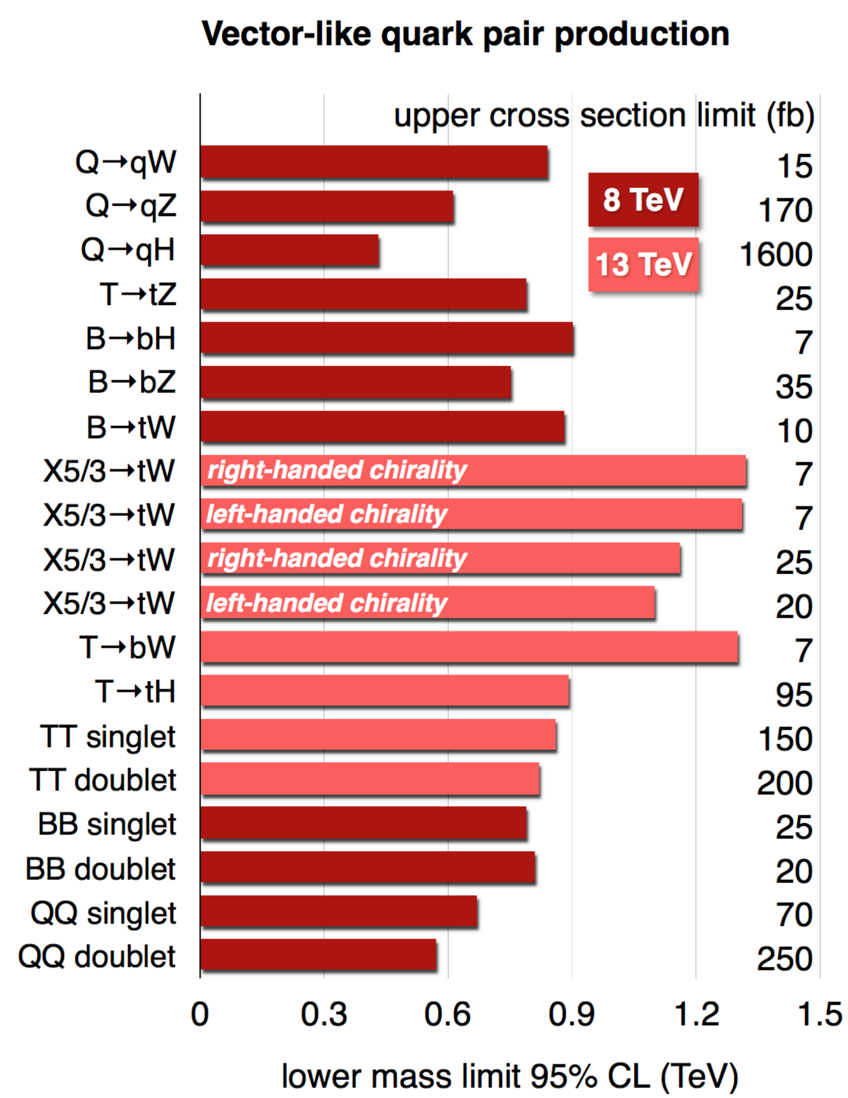


Slatyer, TASI 2016
1710.05137

Collider Searches for New Physics

LHC hasn't found new particles which cut off the quadratic contributions from the SM particles to the Higgs potential either. The constraints on colored partners are quite strong.





Neutral Naturalness

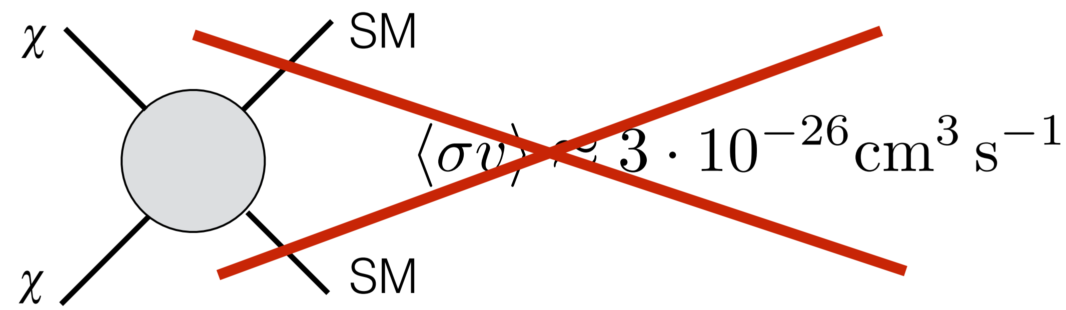
The new physics responsible for the hierarchy problem and DM may be stealthier than we thought.

Ex. Neutral naturalness models for the hierarchy problem.

	Scalar Top Partner	Fermion Top Partner
All SM Charges	SUSY	pNGB Higgs
EW charges	Folded SUSY	Quirky Little Higgs
No SM Charges	Tripled Top/ Hyperbolic Higgs	Twin Higgs

Exceptions to DM Relic Calculation

To evade the detection, one may want to suppress the DM-SM interactions (at the present time).



3 well-known exceptions of the WIMP dark matter calculation (Griest Seckel, PRD'91)

- Coannihilation: annihilation with other states close in mass
- Forbidden channel: annihilation to heavier states
- Annihilation near a resonance

Nontraditional DM Models

Many new mechanisms for the DM freeze-out have been proposed recently. They can obtain the correct DM thermal relic abundance while potentially evading current experimental searches.

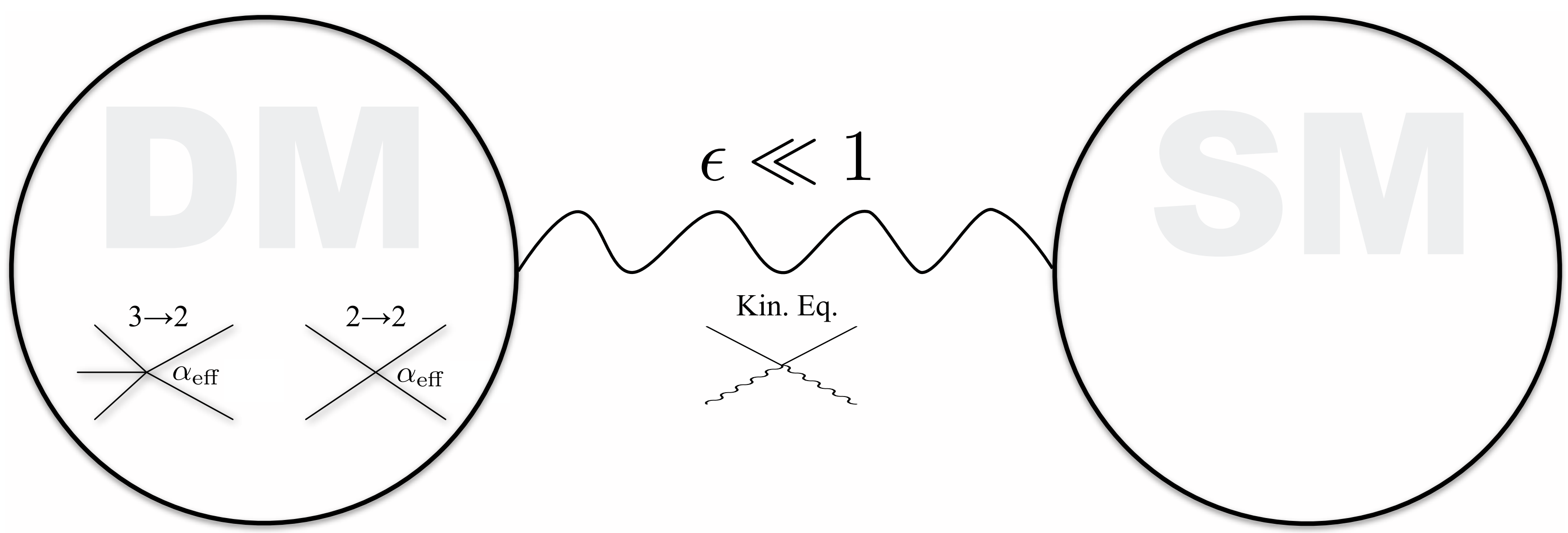
- Strongly interacting massive particles (SIMP) (Hochberg, et al, 1402.5143)
- Elastically decoupling relic DM (ELDER) (Kuflik, et al,1512.04545)
- Coscattering DM (D'Agnolo, et al, 1705.08450)
- Codecaying DM (Dror, et al,1607.03110)
- …

They are often proposed as ad hoc models. However, some of them can be naturally incorporated in neutral naturalness models, providing a connection to the hierarchy problem.

Strongly Interacting Massive Particles

Hochberg, Kuflik, Volansky, Wacker, 1402.5143

- DM has strong self-interaction. After annihilation to SM particles decouples, it goes through 3→2 annihilation process. The relic density is determined when the 3→2 process freezes out.



$$m_{\rm DM} \sim \alpha_{\rm eff} \left(T_{\rm eq}^2 M_{\rm Pl}\right)^{1/3} \sim 100 \text{ MeV}\,, \quad \textbf{SIMP}$$

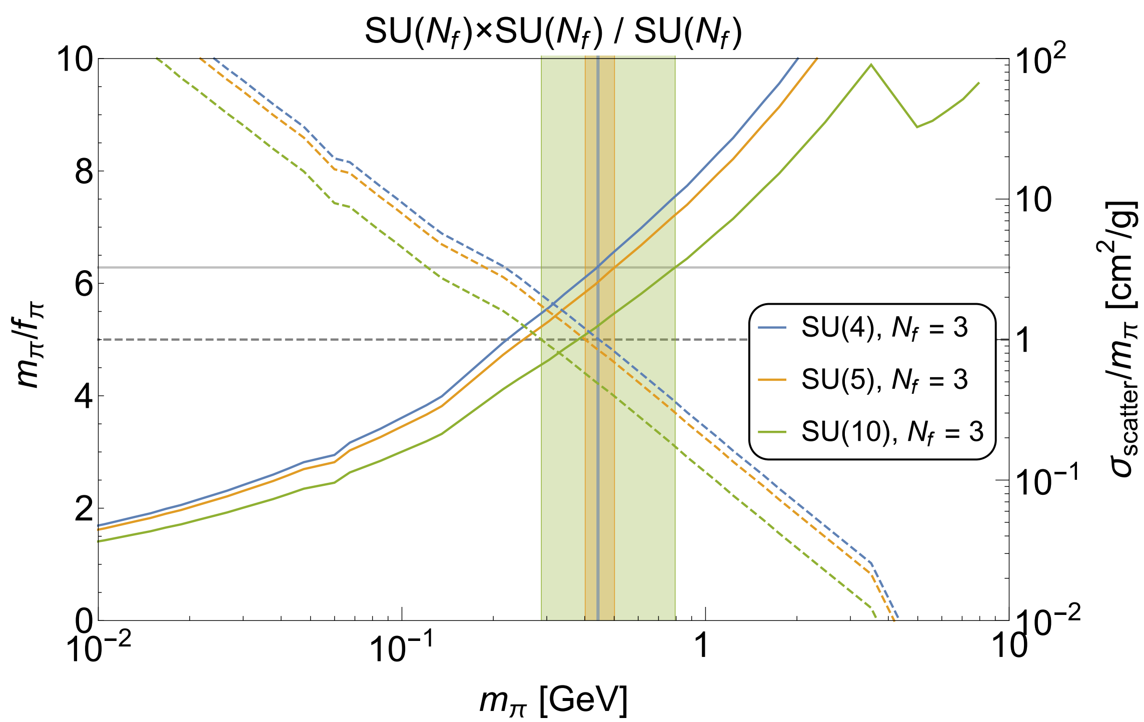
$$\textbf{Cf.} \quad m_{\rm DM} \sim \alpha_{\rm ann} \left(T_{\rm eq} M_{\rm Pl}\right)^{1/2} \sim \text{ TeV} \quad \textbf{for WIMP}$$

Strongly Interacting Massive Particles

Hochberg, Kuflik, Volansky, Murayama, Wacker, 1411.3727

- A natural SIMP DM can be pions from a hidden QCD, with the Wess-Zumino-Witten (WZW) term giving the 3→2 interactions.

$$\mathcal{L}_{\mathrm{WZW}} = \frac{2N_c}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}\left[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi\right]$$



- A more accurate calculation should include vector meson exchange. (Choi, Lee, Ko, Natale, 1801.07726)

SIMP in Neutral Naturalness Models

- A hidden QCD is ubiquitous in neutral naturalness models.
  - In twin Higgs model, if one imposes an exact $SU(2)_f$ symmetry to the two light generations of twin quarks, the twin pions are stable and can be SIMP DM. (Hochberg, Kuflik, Volansky, 1805.09345)
  - In a variant of the tripled top model (HC, Li, Salvioni, Verhaaren, 1803.03651), a Z_2 symmetry is a natural requirement for the hidden sector fields, which implies the isospin symmetry for the dark pions.

Twin Higgs Models

Chacko, Goh, Harnik, hep-ph/0506256

- There is a "mirror" or "twin" sector related to SM by an (approximate) Z_2 symmetry.
- The SM Higgs doublet and twin Higgs doublet have an approximate SU(4) invariant potential, due to the Z_2 symmetry.

$$V(H) = -m^2|H|^2 + \lambda|H|^4 \qquad H = \begin{pmatrix} H_A \\ H_B \end{pmatrix} \begin{matrix} \leftarrow SU(2)_A \\ \leftarrow SU(2)_B \end{matrix}$$

- SU(4) is spontaneously broken by H VEV down to SU(3), producing 7 Goldstone modes.

$$|\langle H \rangle|^2 = \frac{m^2}{2\lambda} \equiv \frac{f^2}{2}$$

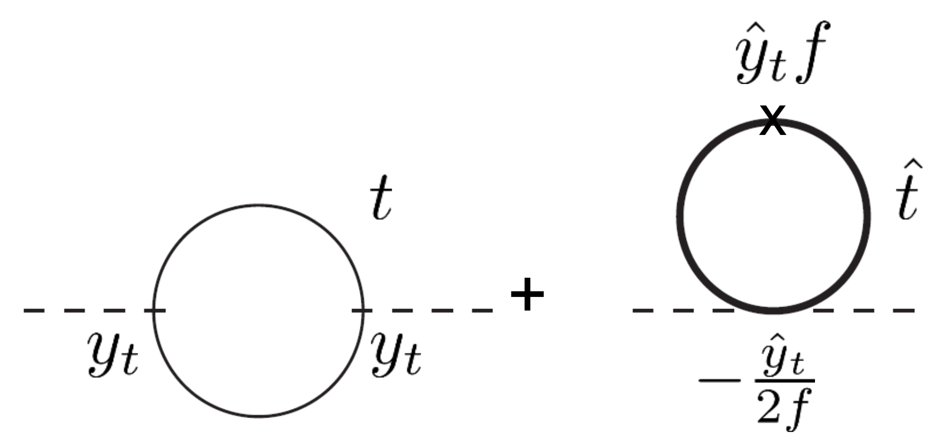
Twin Higgs Models

- In a realistic model, a soft Z_2 breaking term is needed to make the twin Higgs VEV larger than the SM Higgs VEV,

$$\mu^2 H_A^\dagger H_A \;\Rightarrow \langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \\ 0 \\ f\sqrt{1 - v^2/f^2} \end{pmatrix} \;,\; f/v \sim 3-5$$

- 6 of 7 Goldstones are eaten by SM W/Z and twin W/Z, leaving one as the observed light Higgs boson.

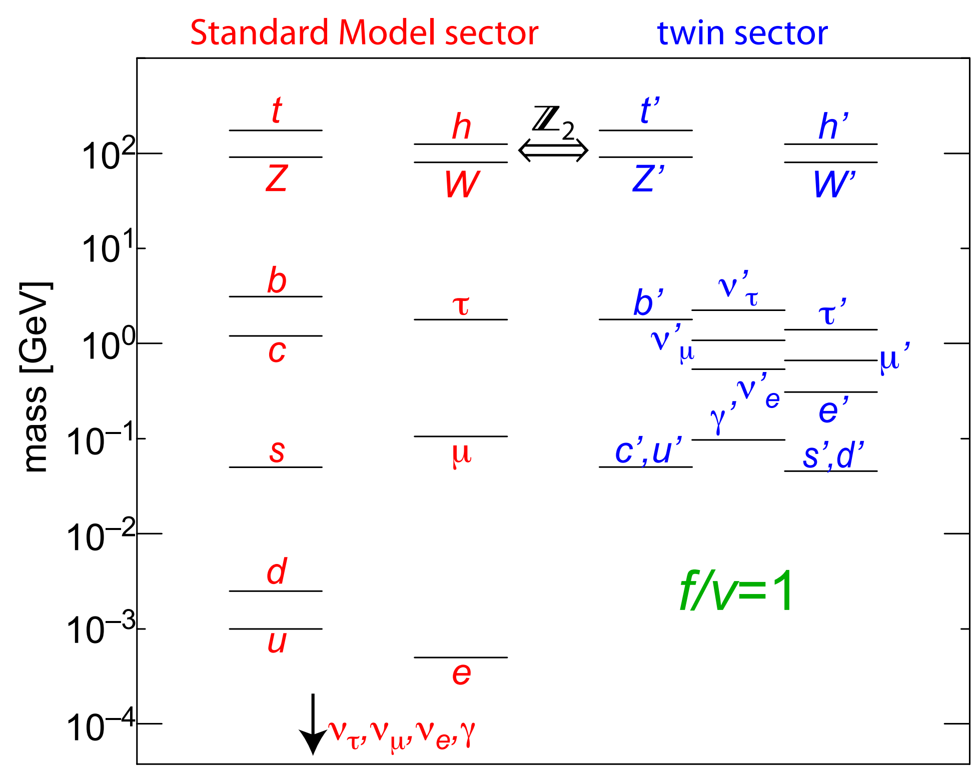
- Cancelation of the quadratic divergence in the Higgs mass from the top loop:



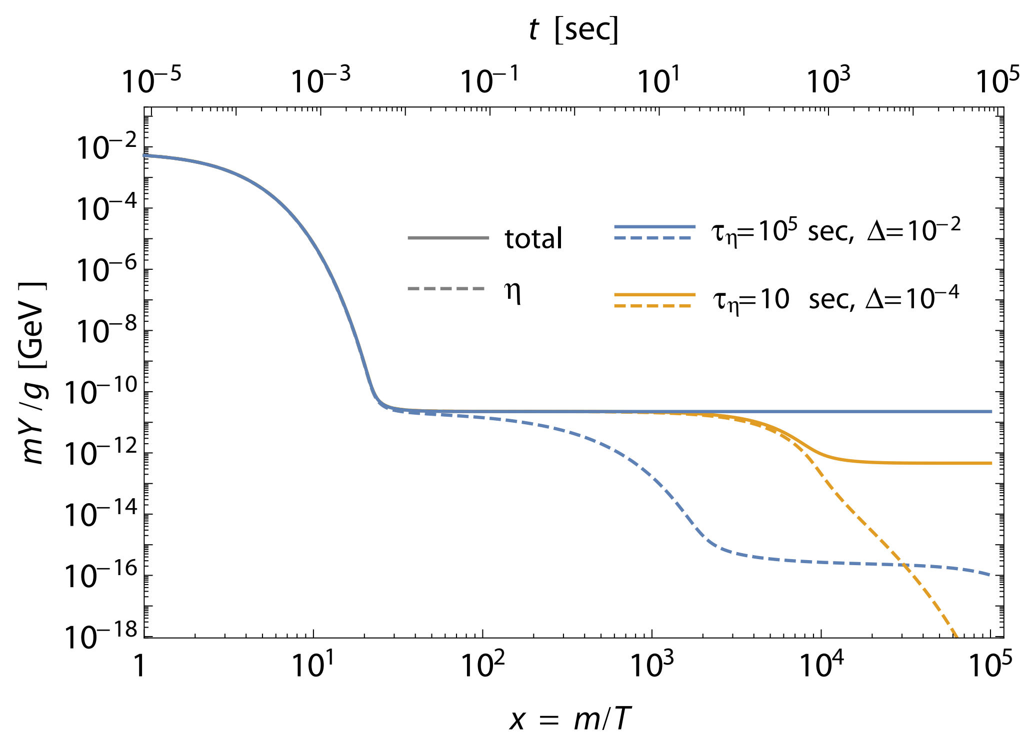
Twin SIMPs

Hochberg, Kuflik, Murayama, 1805.09345

- Impose an exact SU(2)f symmetry on the first two generations of the twin quarks, so that twin "pions" are stable, serving as the SIMP DM.



meson M	particle content	$m_M^2 \propto$	m_M
$\theta^0(\mathbf{3},\mathbf{1})$	$u'\bar{c}',\, c'\bar{u}',\, \frac{1}{\sqrt{2}}(u'\bar{u}' - c'\bar{c}')$	$2m_{u'}$	$m_\pi(1+\Delta)$
$D^+(\mathbf{2},\mathbf{2})$	$u'\bar{d}',\, c'\bar{d}',\, u'\bar{s}',\, c'\bar{s}'$	$m_{u'} + m_{d'}$	$m_\pi(1+\frac{\Delta}{2})$
$D^-(\mathbf{2},\mathbf{2})$	$d'\bar{u}',\, s'\bar{u}',\, d'\bar{c}',\, s'\bar{c}'$	$m_{u'} + m_{d'}$	$m_\pi(1+\frac{\Delta}{2})$
$\eta^0(\mathbf{1},\mathbf{1})$	$\frac{1}{2}(d'\bar{d}' + s'\bar{s}' - u'\bar{u}' - c'\bar{c}')$	$m_{u'} + m_{d'}$	$m_\pi(1+\frac{\Delta}{2})$
$\pi^0(\mathbf{1},\mathbf{3})$	$d'\bar{s}',\, s'\bar{d}',\, \frac{1}{\sqrt{2}}(d'\bar{d}' - s'\bar{s}')$	$2m_{d'}$	m_π



SIMP in a Variant of Tripled Top Model

- $SU(3)^2 \times SU(2) \times U(1)$ SUSY extension of the SM

$$W = y_t Q_A H u^c_A + y_t Q_B H u^c_B + y_t Q_C H u^c_C + \omega(u^c_B u'_B + u^c_C u'_C) + M(Q_B Q'^c_B + Q_C Q'^c_C)$$

B,C sector quarks carry a hidden QCD color but not SM color. Their EW quantum numbers are

$$Q_{B,C} = \begin{pmatrix} t_{B,C} \\ b_{B,C} \end{pmatrix} \sim \mathbf{2}_{-1/2}, \qquad Q'^c_{B,C} = \begin{pmatrix} b'^c_{B,C} \\ t'^c_{B,C} \end{pmatrix} \sim \mathbf{2}_{1/2} \qquad u^c_{B,C},\, u'_{B,C} \sim \mathbf{1}_0$$

M ~ a few TeV, $\omega < \Lambda_{\mathrm{B,C}} \ll M$

The leading soft SUSY breaking takes the form

$$V_s = \tilde{m}^2(|\tilde{Q}_A|^2 + |\tilde{u}^c_A|^2) - \tilde{m}^2(|\tilde{Q}_B|^2 + |\tilde{Q}_C|^2)$$

$$\widetilde{m} \approx M \qquad \Delta = \sqrt{M^2 - \widetilde{m}^2} \sim \text{few hundred GeV}$$

Tripled Top Model

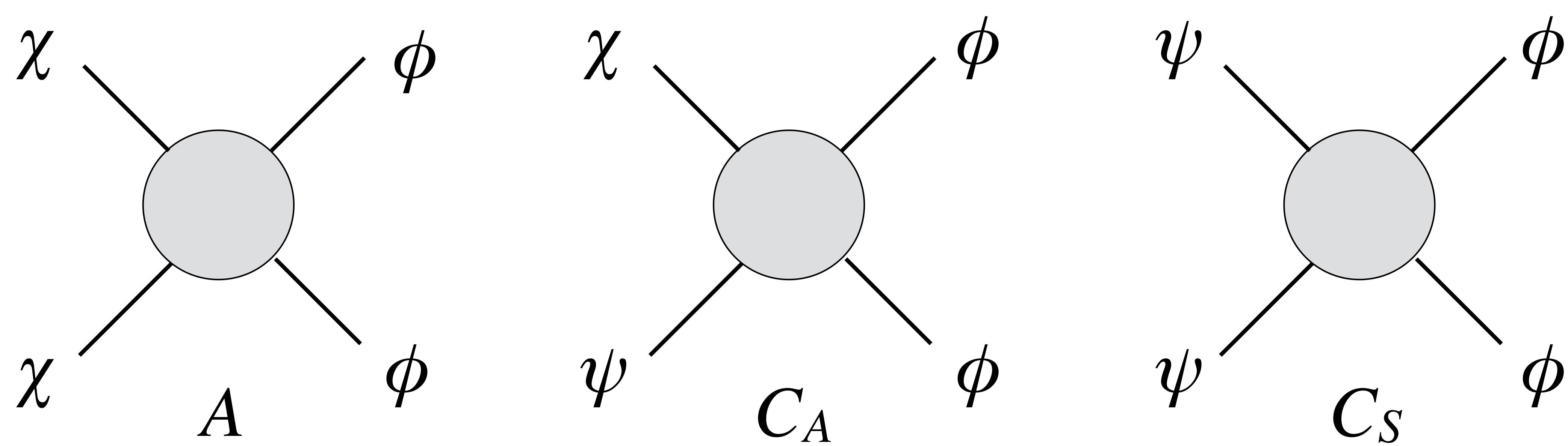
- Top Yukawas respect a Z_3 symmetry, which is softly broken to Z_2 by mass terms
- The SM colored stops are raised to multi-TeV by soft SUSY breaking mass.
- $\tilde{Q}_B, \tilde{Q}_C$ masses are reduced to Δ~ few hundred GeV. They play the roles of top partners, cutting off the quadratic top loop contribution to the Higgs mass.
- This model is natural from a bottom-up point of view, though the special soft masses require a UV explanation.
- The hidden QCD has two light flavors with a Z_2 symmetry, which keeps dark pions stable. They can be the SIMP DM candidate.

Coscattering Dark Matter

D'Agnolo, Pappadopulo, Ruderman, 1705.08450, Garny et al, 1705.09292

- Coscattering DM is closely relate to coannihilation.
  - χ : DM particle
  - ψ : Coannihilation partner
  - ϕ : SM particles or new particles which decay to SM particles.

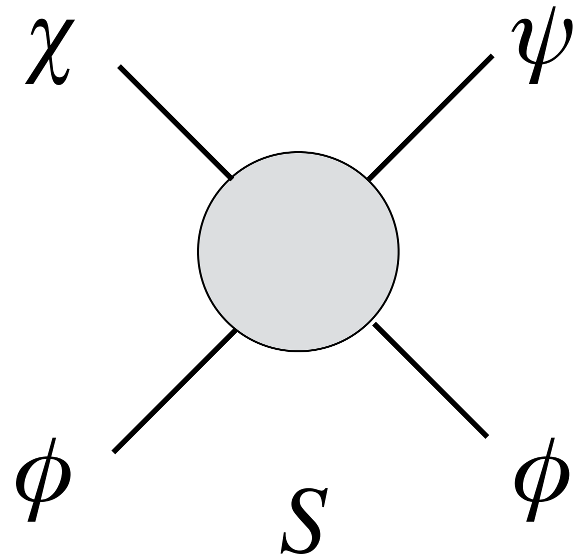
$$m_\psi \gtrsim m_\chi > m_\phi$$



In coannihilation, freeze out is decided by weighted average of the above annihilation processes.

Coscattering Dark Matter

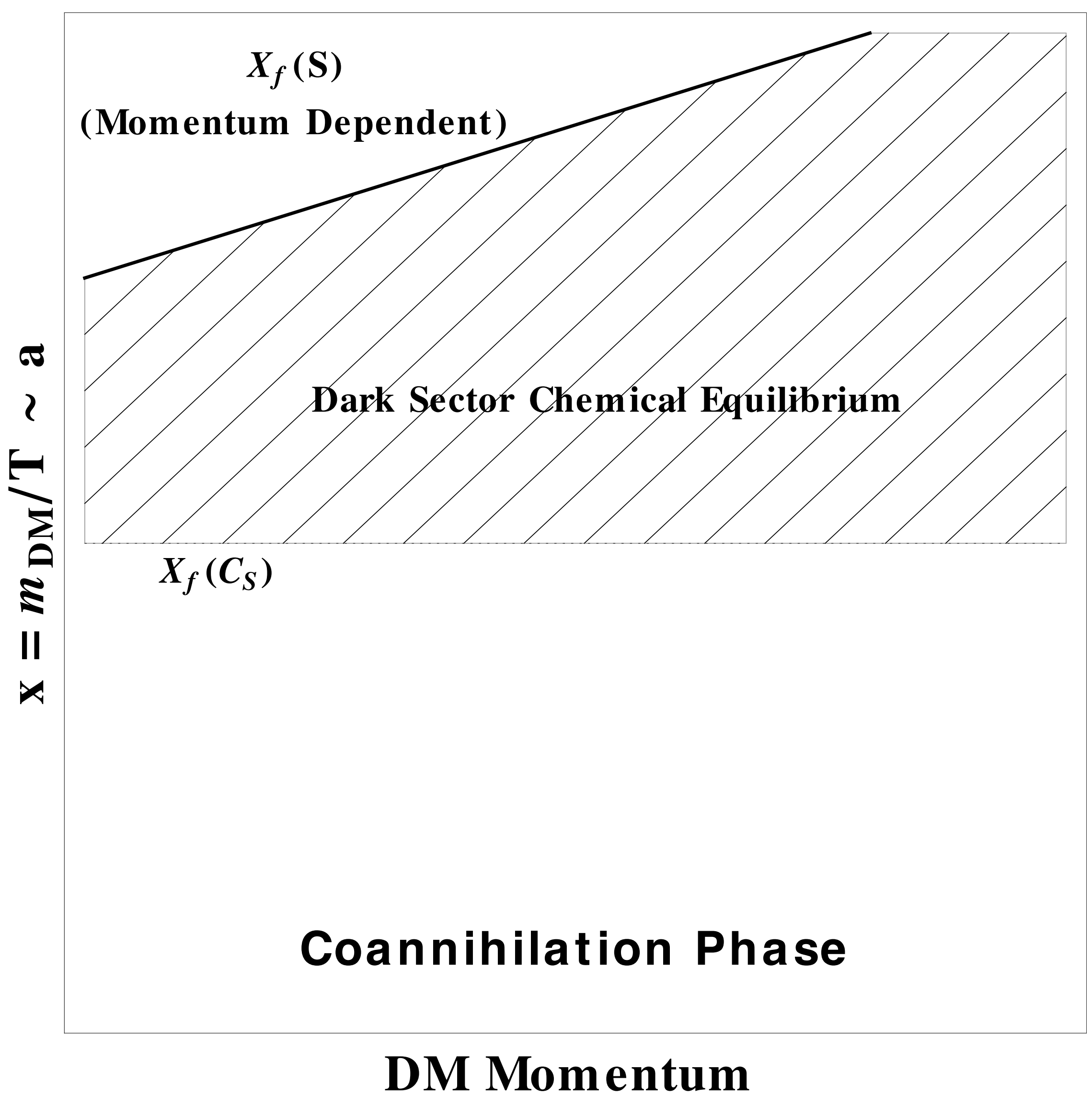
- ψ and χ are kept in thermal equilibrium by the scattering process.



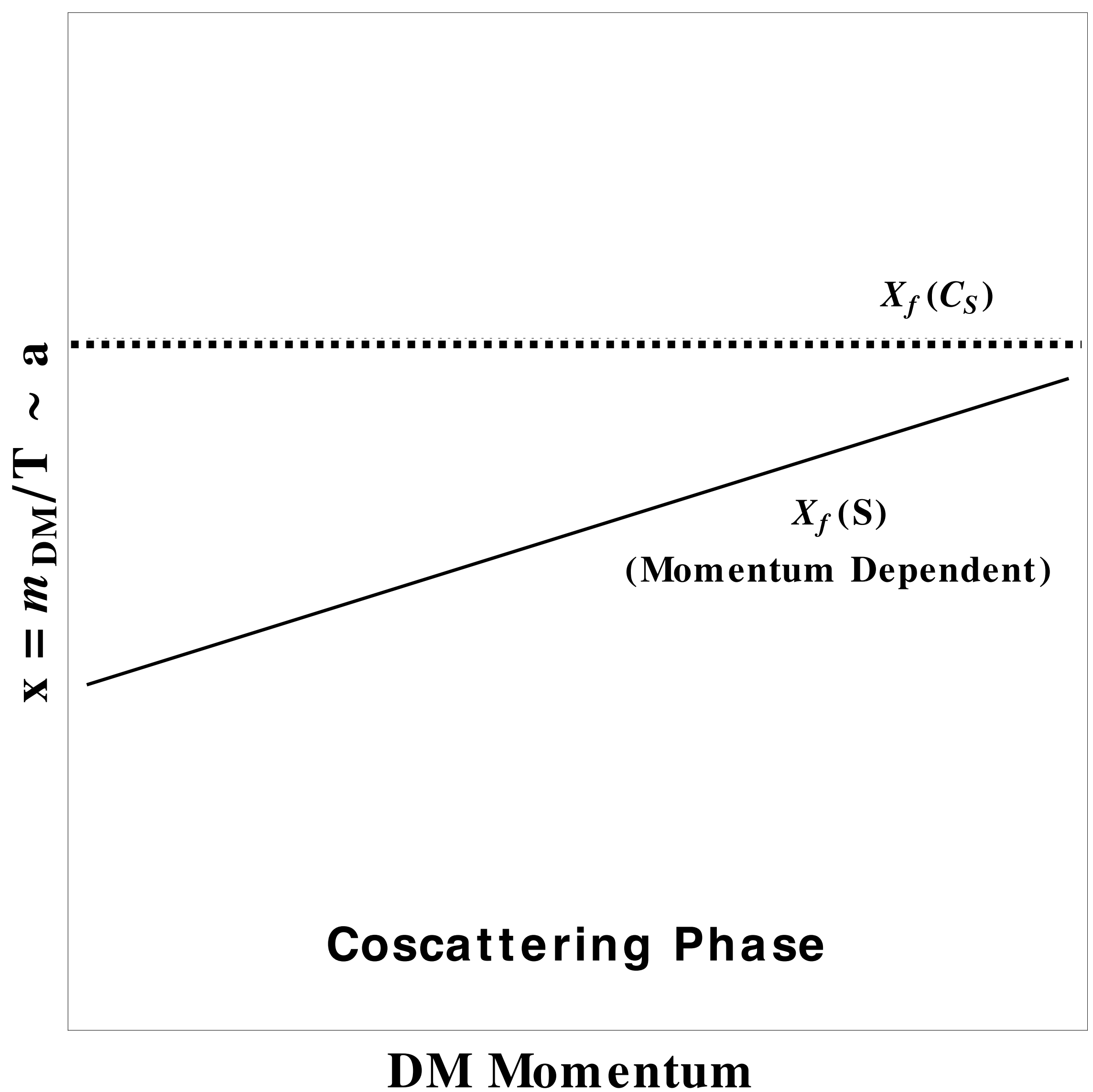
If the scattering S freezes out before the coannihilation C_S, the relic density is determined by the freeze-out temperature of the scattering process, which has strong momentum dependence. The relic density calculation is more complicated, which requires solving unintegrated Boltzmann equations.

Coannihilation vs Coscattering

$T_{C_S} > T_S$

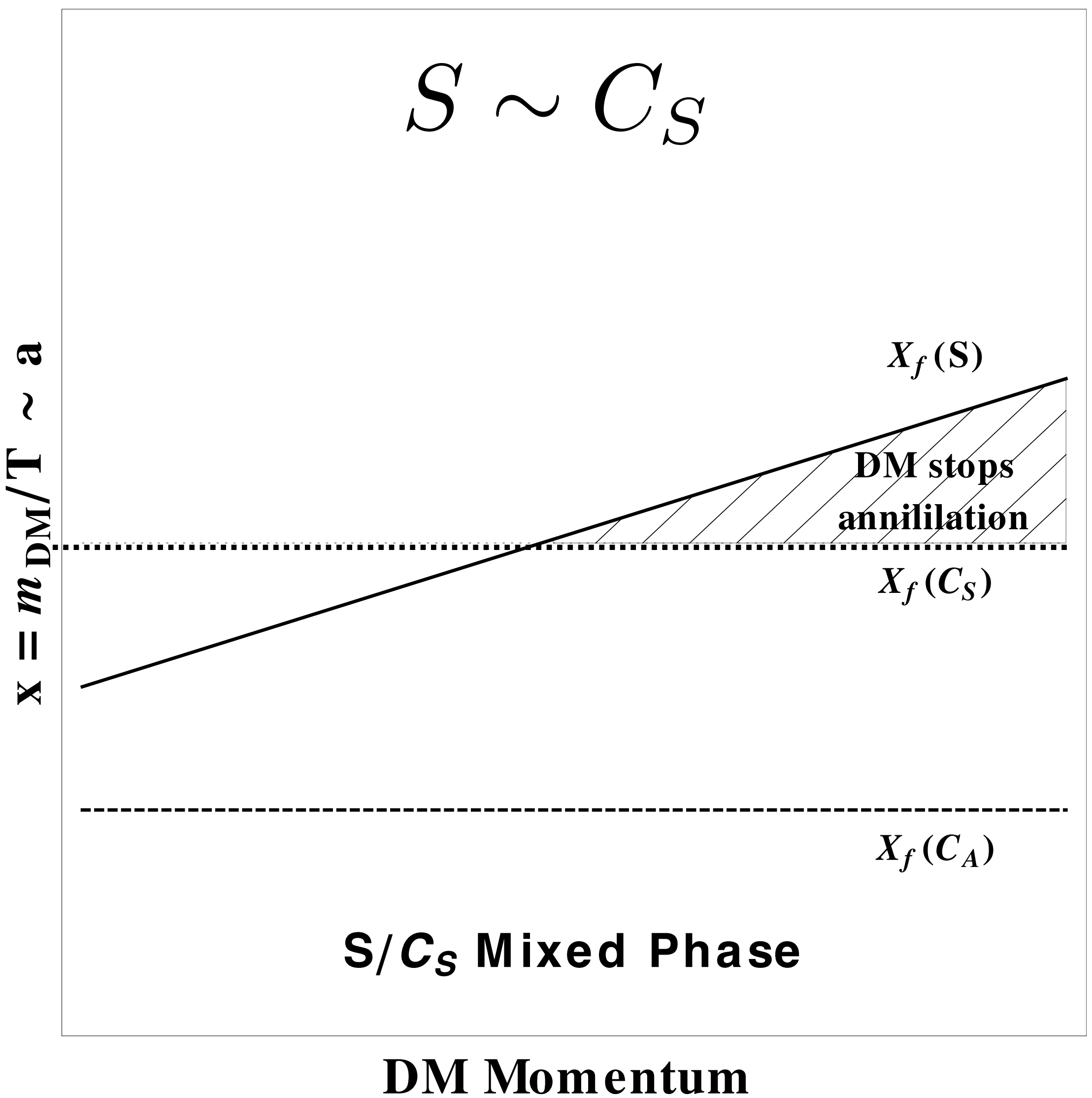


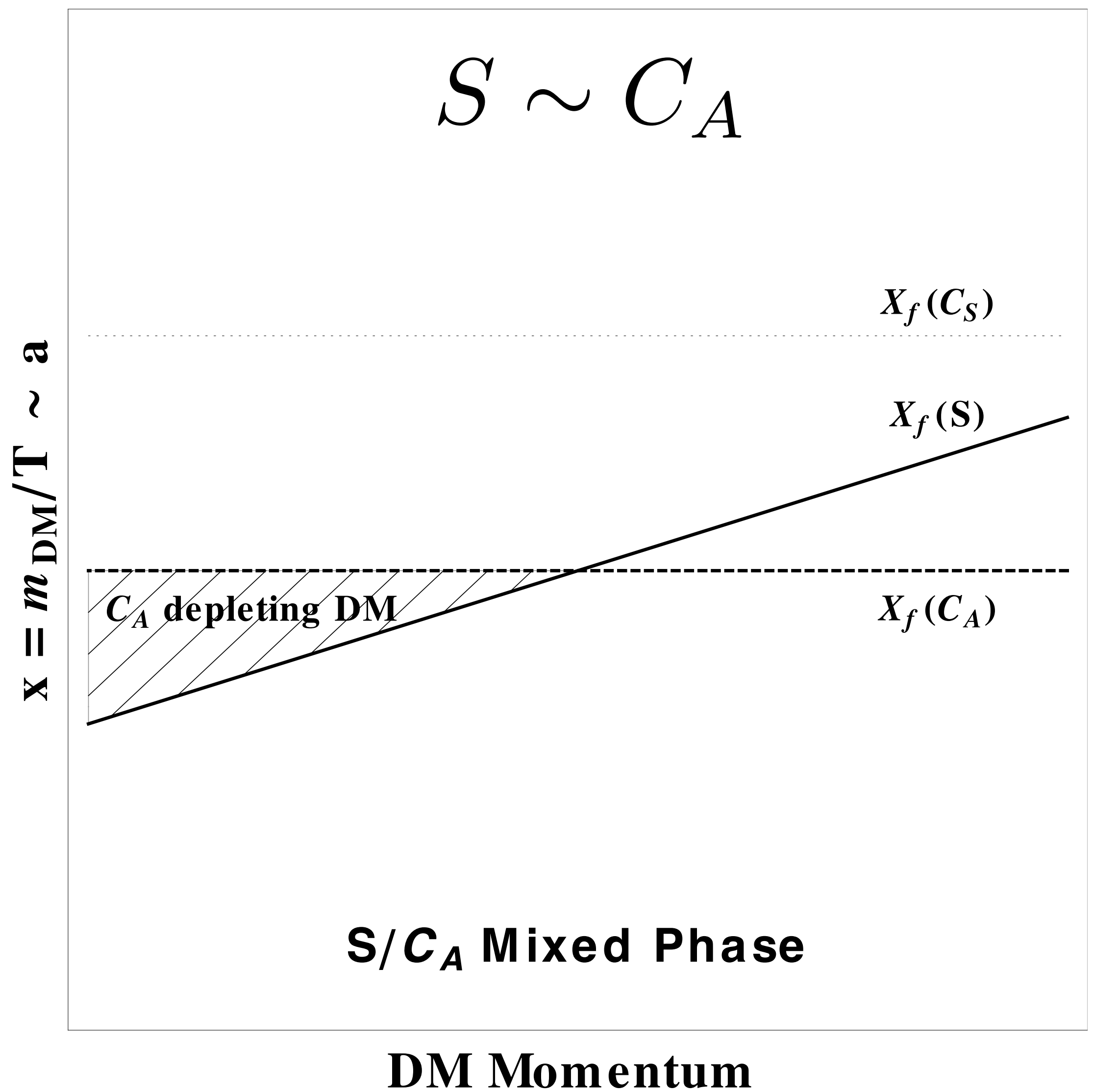
$T_{C_S} < T_S$



Mixed Phases

Due to the momentum dependence of the freeze-out of the scattering process, the relic density may be determined by a combination of coscattering and coannihilation.





Fraternal Twin Higgs (FTH)

Craig, Katz, Strassler, Sundrum, arXiv:1501.05310

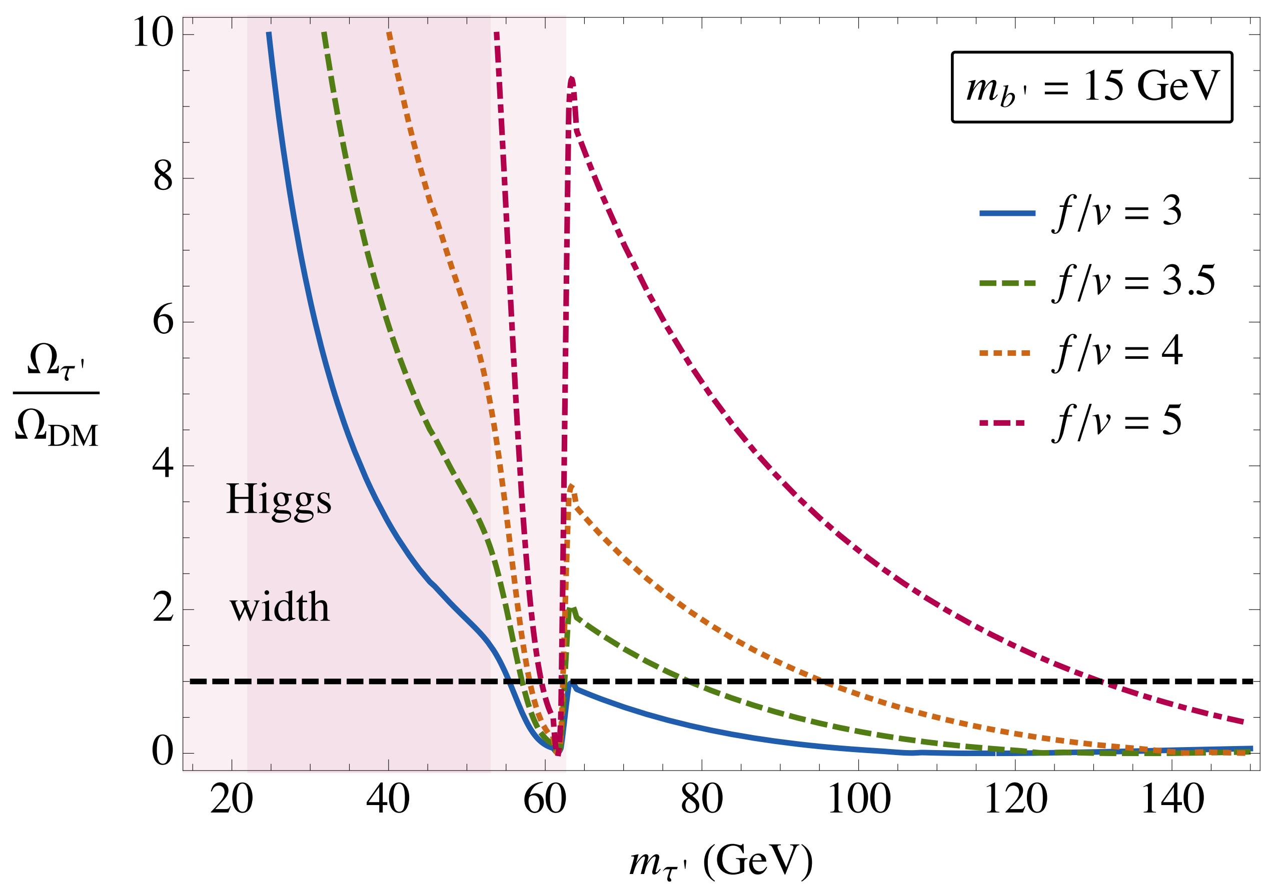
Only particles that have large couplings to the Higgs (e.g., top, W/Z) need to have the Z_2 symmetry to address the naturalness problem.

- The twin sector only contains the 3rd generation twin fermions.
  - Top Yukawas need to respect Z_2.
  - Twin bottom, tau, and neutrino masses are free parameters as long as much lighter than twin top.
- SU(2) and SU(3) gauge couplings of the SM and twin sectors need to be approximately equal.
- Twin U(1) is not needed. (Twin photon can be removed or have a mass.)

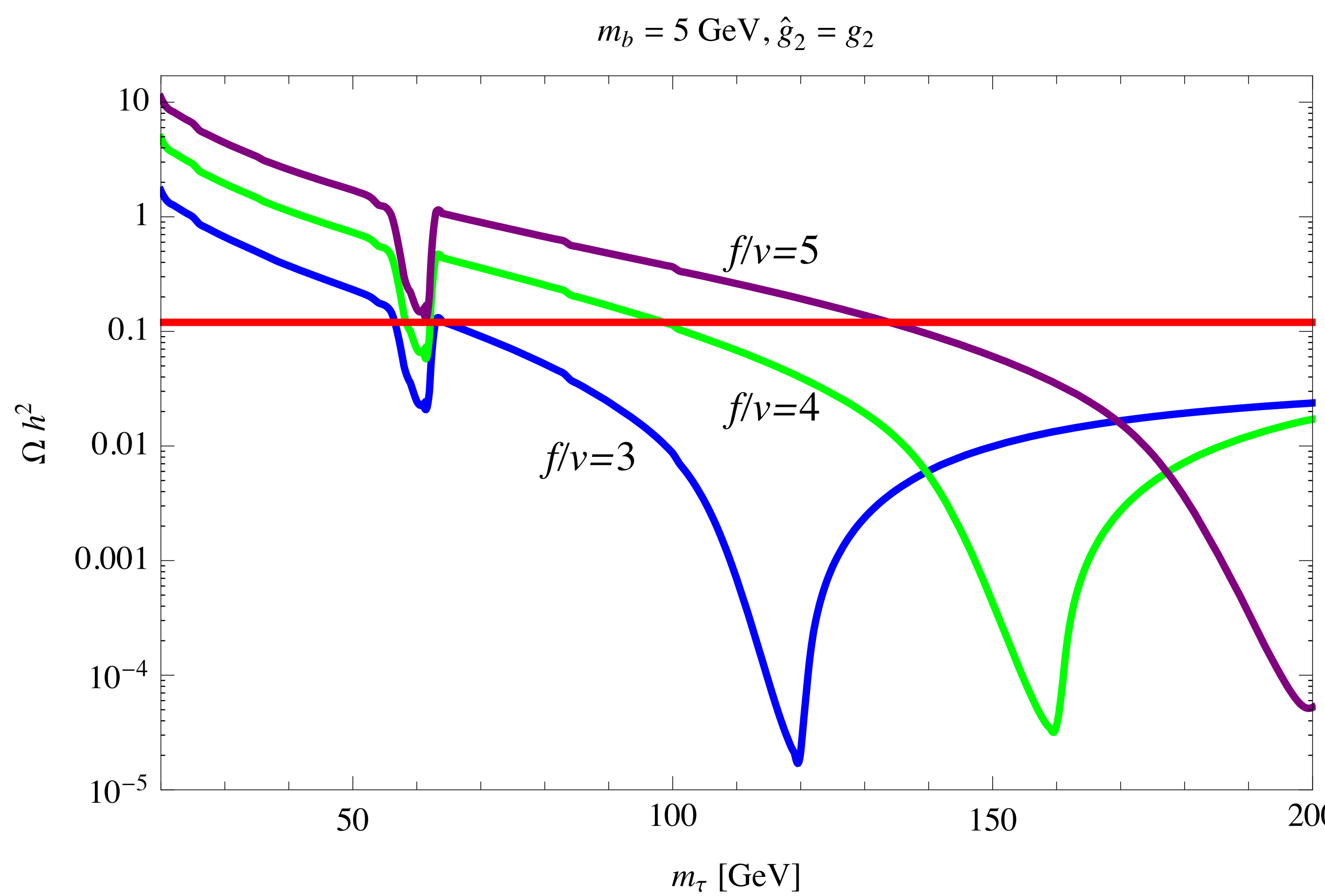
Dark Matter in FTH

Twin tau dark matter

Garcia Garcia, Lasenby, March-Russell, 1505.07109



Craig, Katz, 1505.07113



The recent XENON1T result puts strong constraints on twin tau DM, ruling out most natural parameter space with f/v< 5.

Twin Neutrino Dark Matter

The FTH can naturally realize the coscattering mechanism: (HC, L. Li, R. Zheng, 1805.12139)

- χ → twin neutrino

- ψ → twin tau

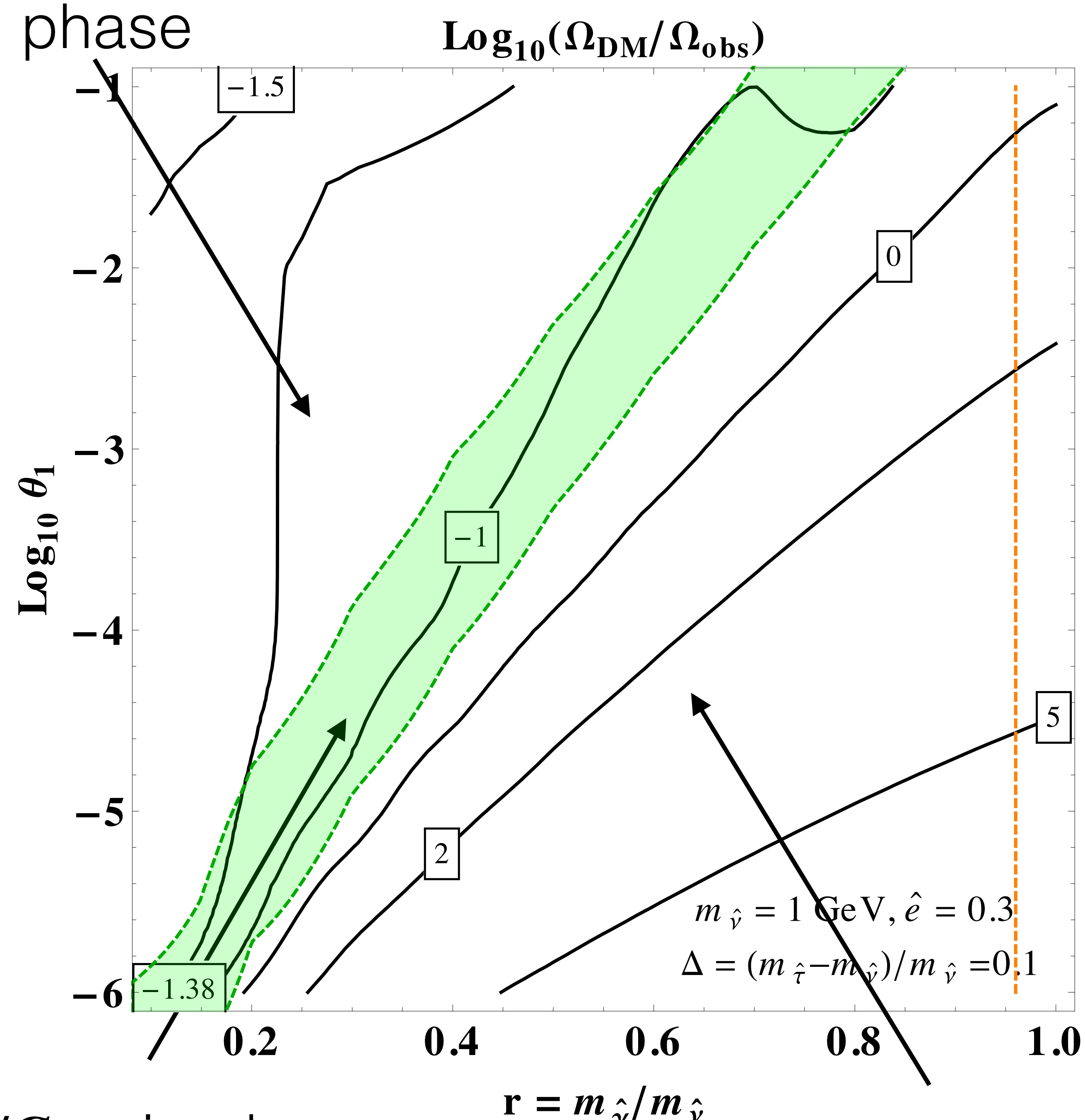
- ϕ → twin photon

- Twin U(1) is broken, twin photon has a mass. Twin tau and twin neutrino can mix by inserting U(1) breaking VEV (spurions), twin neutrino mass eigenstate acquire a small coupling to twin photon.
- A kinetic mixing between the SM photon and the twin photon, $-(\epsilon/2)F_{\mu\nu}\hat{F}^{\mu\nu}$, keeping twin photon in thermal equilibrium during the DM freeze-out ($\varepsilon > 10^{-9}$).

Numerical Results

HC, L. Li, R. Zheng, 1805.12139

Coannihilation phase



S/C$_S$ mixed phase

Coscattering phase

$$m_{\hat{\gamma}} < m_{\hat{\nu}} < m_{\hat{\tau}},$$

(~ 0.01-10 GeV)

$\hat{\nu}$, $\hat{\tau}$ mixing angle:

$\theta_1 \ll 1$

$$r \equiv \frac{m_{\hat{\gamma}}}{m_{\hat{\nu}}}(< 1),$$

$$\Delta \equiv \frac{m_{\hat{\tau}} - m_{\hat{\nu}}}{m_{\hat{\nu}}}(> 0),$$

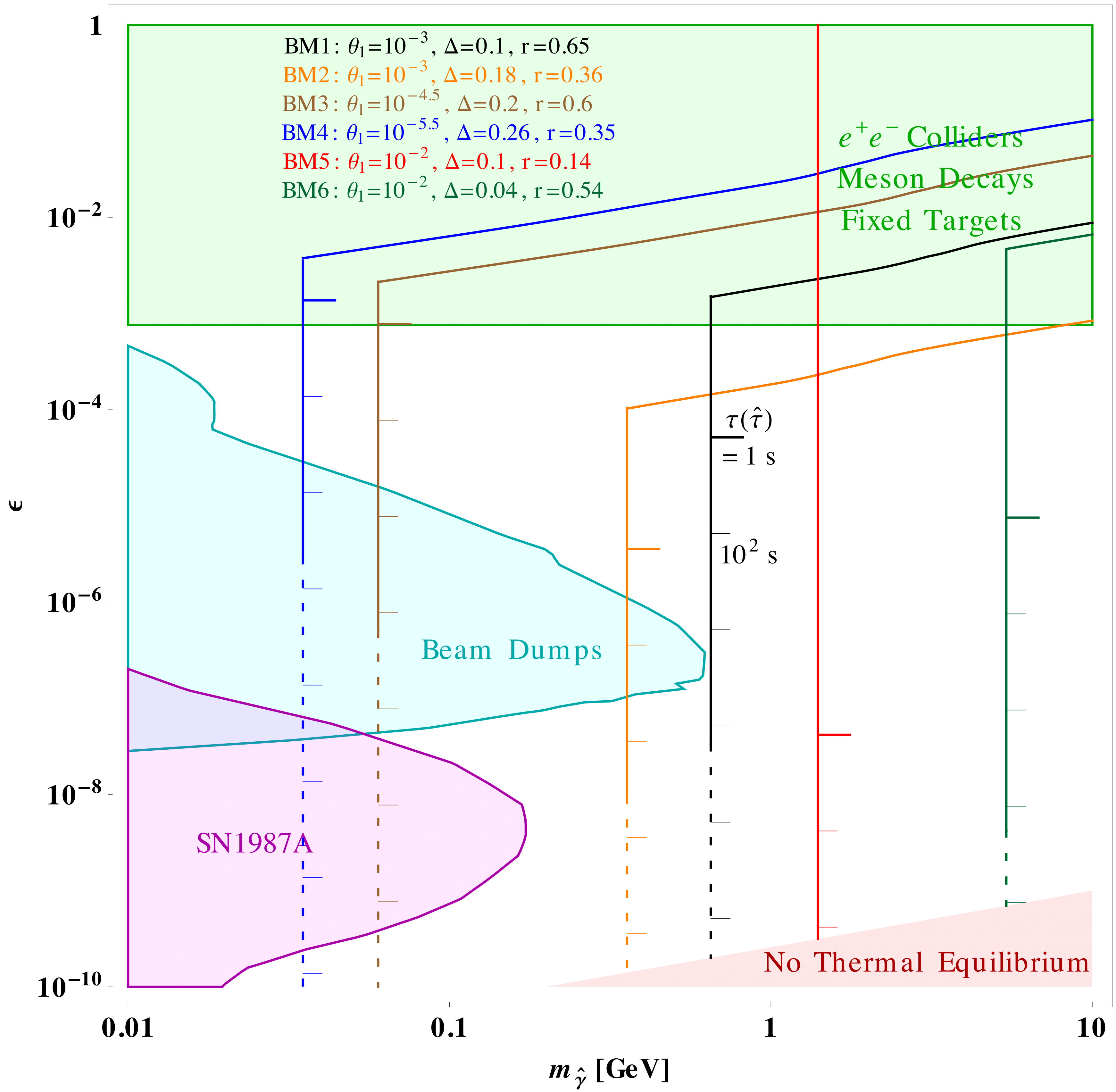
Experimental Constraints

- Direct detection: Experiments based on electron recoiling can probe part of the parameter space with larger mixings.
- Indirect constraints from DM annihilation: CMB observables restrict the net energy deposited from DM annihilation into visible particles during the reionization era. (Liu, et al,1604.02457)
- Dark photon constraints:
  - N_{eff} constrains $m_{\hat{\gamma}} \gtrsim 11\ \mathrm{MeV}$.
  - ε constrained by fixed target, meson decay, and beam dump experiments and SN1987A.
- Twin tau and twin neutrino constraints:
  - Higgs invisible width from future Higgs factory.
  - Long-lived twin tau constrained by BBN.

BM1,3,4,6 in coscattering phase

BM 2 in mixed phase

BM5 in coannihilation phase



Conclusions

- DM in a hidden sector may explain the absence of detections and new physics so far.
- Many new mechanisms for the freeze-out of the DM relic density can find home in neutral naturalness models, providing a link between the DM and the hierarchy problem.
- These new scenarios are typically difficult to cover a single type of experiments. A combination of lab experiments and astro/cosmology observations are needed to constrain their parameter spaces.