Z_2 SIMP Dark Matter

Based on:
NB, C. Garcia-Cely & R. Rosenfeld: arXiv:1501.01973 - JCAP 1504 (2015) 04, 012
NB, X. Chu, C. Garcia-Cely, T. Hambye & B. Zaldivar: arXiv:1510.08063 - JCAP 1603 (2016) 03, 018
NB & X. Chu: arXiv:1510.08527 - JCAP 1601 (2016) 01, 006
NB, J. Pradler & X. Chu: arXiv:1702.04906 - Phys.Rev. D95 (2017) 11, 115023

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UNIVERSIDAD ANTONIO NARIÑO

Self-interacting Mark Matter
Copenhagen
July 31st-August 4th, 2017

The SIMPlest DM model ever:
Singlet Scalar Dark Matter

Singlet Scalar DM

McDonald ‘07

S is a singlet scalar, protected by a Z_2

$$V = \mu_S^2\, S^2 + \lambda_S\, S^4 + \lambda_{HS}\, |H|^2\, S^2$$

3 free parameters:

* m_S DM mass
* λ_{HS} Higgs portal
* λ_S DM quartic coupling

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* m_S DM mass
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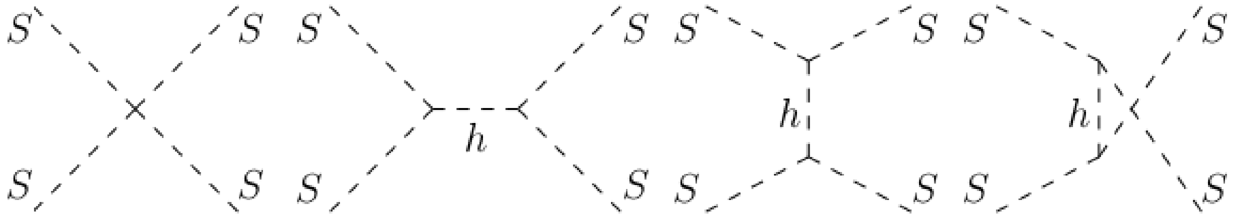
} ← Concentrated on this (m_S, λ_{HS})

← ~ Ignored! (λ_S)

Dark Matter Self-Interactions

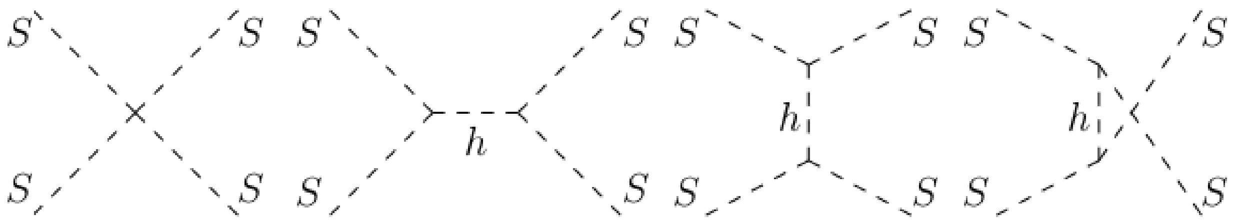


$$\frac{\sigma_{SS}}{m_S} \sim \frac{9}{8\pi}\,\frac{\lambda_S^2}{m_S^3}$$

$$0.1 \lesssim \frac{\sigma_{SS}}{m_S} \lesssim 10\ \mathrm{cm}^2/\mathrm{g}$$

Implies {
- * $\lambda_S \sim 1$
- * $m_S \sim 100$ MeV

Dark Matter Self-Interactions & Invisible Higgs decay



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$$0.1 \lesssim \frac{\sigma_{SS}}{m_S} \lesssim 10\ \mathrm{cm}^2/\mathrm{g}$$

Implies { * λ_S ~ 1
* m_S ~ 100 MeV

The Higgs tends to annihilate into DM
BR(h→ inv.) < 20%

* $\lambda_{HS} < 7\times10^{-3}$

How to produce such a Self-Interacting Dark Matter?

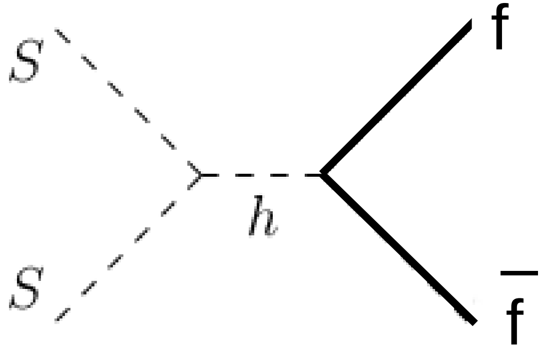
WIMP DM :-/

DM can (only) annihilate into light fermions

other annihilation channels kinematically closed!

$$\langle\sigma_{SS\to f\bar{f}}\, v\rangle \sim \frac{\lambda_{HS}^2}{\pi}\,\frac{m_f^2}{m_h^4}$$

$$\langle\sigma_{SS\to f\bar{f}}\, v\rangle \ll 10^{-26}\,\text{cm}^3/\text{s}$$



→ Universe overclosed

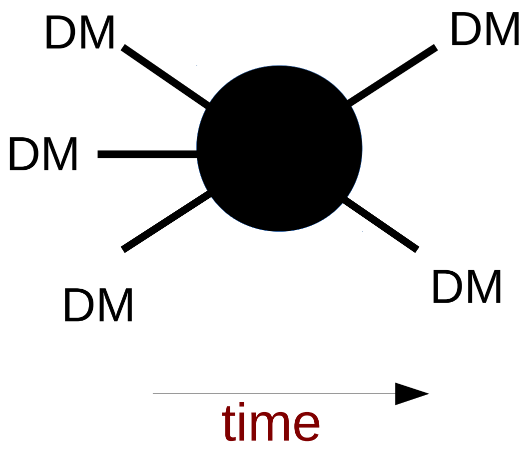
→ SSDM with sizable self-interactions can not be a WIMP

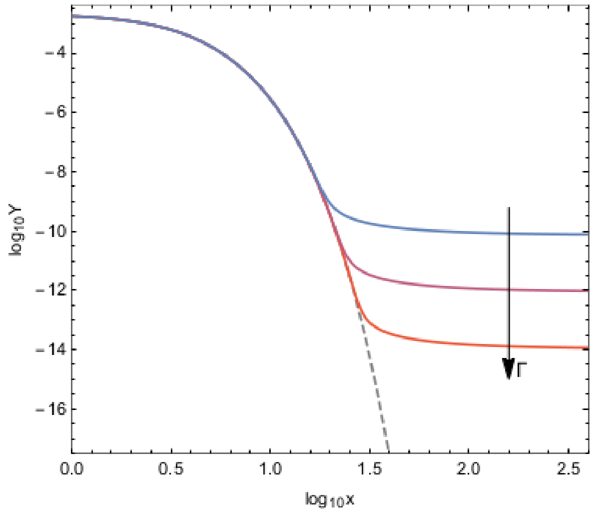
Again:
How to produce such a
Self-Interacting Dark Matter?

SIMP DM
3→2 annihilations

Hochberg, Kuflik, Volansky & Wacker '14

$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v^2\rangle_{3\to2}\,\left(n^3 - n^2\,n_{\rm eq}\right)$$





SIMP DM
3 → 2 annihilations

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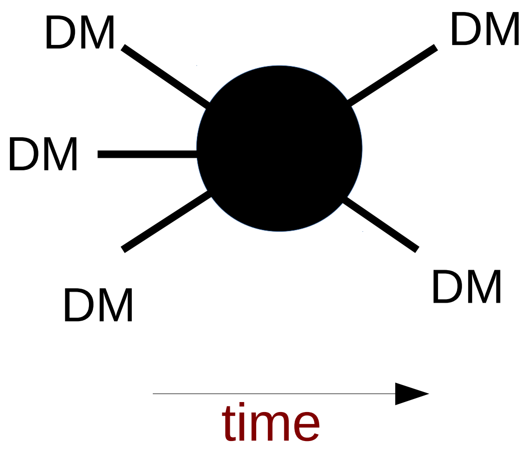

* **DM in the MeV range**
* **Small DM-SM portal**
* **$\lambda_S \sim 1$**

‘Strong’ Self-interactions
→ SIMP DM

SIMP DM
3→2 annihilations

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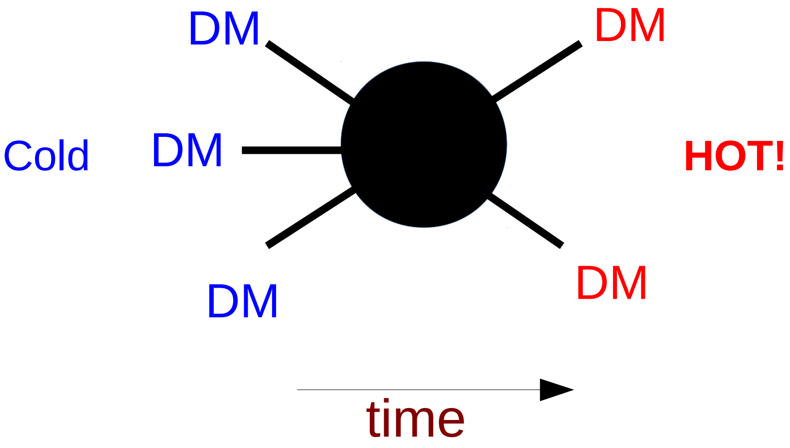
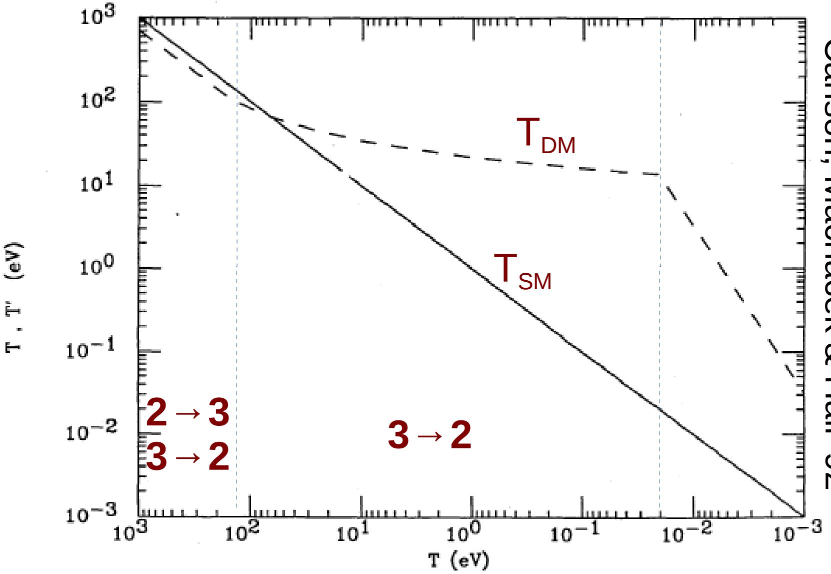


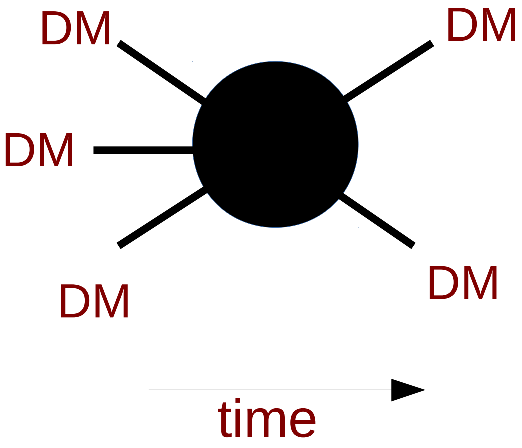
Caveat: 3 → 2 annihilations
pump heat into the dark sector!



Carlson, Machacek & Hall '92

SIMP DM
3→2 annihilations

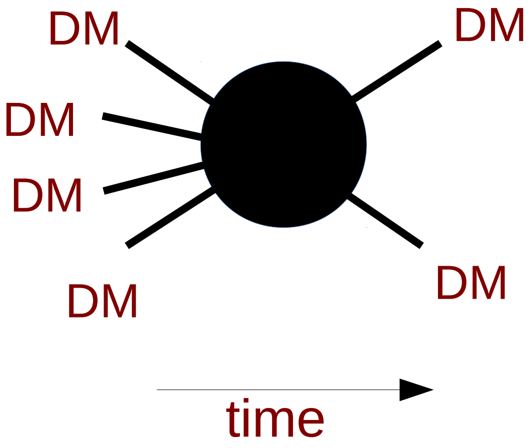
$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v^2\rangle_{3\to 2}\,\left(n^3 - n^2\,n_{\rm eq}\right)$$



However 3→2 reactions are forbidden in most common scenarios where the DM stability is guaranteed by a Z_2 symmetry (R-parity in SUSY, K-parity in Kaluza-Klein…)

SIMP DM
4→2 annihilations

$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v^3\rangle_{4\to2}\,\left(n^4 - n^2\,n_{\rm eq}^2\right)$$



However 3→2 reactions are forbidden in most common scenarios where the DM stability is guaranteed by a Z_2 symmetry (R-parity in SUSY, K-parity in Kaluza-Klein…)

But Z_2 symmetries allow 4→2 annihilations!

Singlet Scalar DM
4 → 2 annihilations

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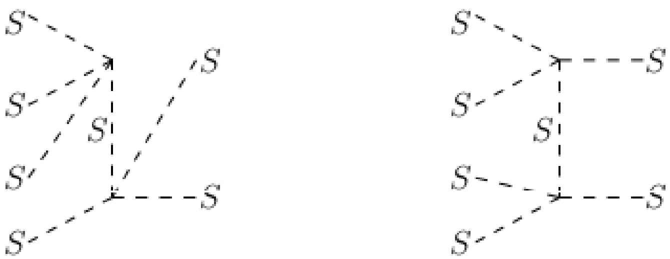
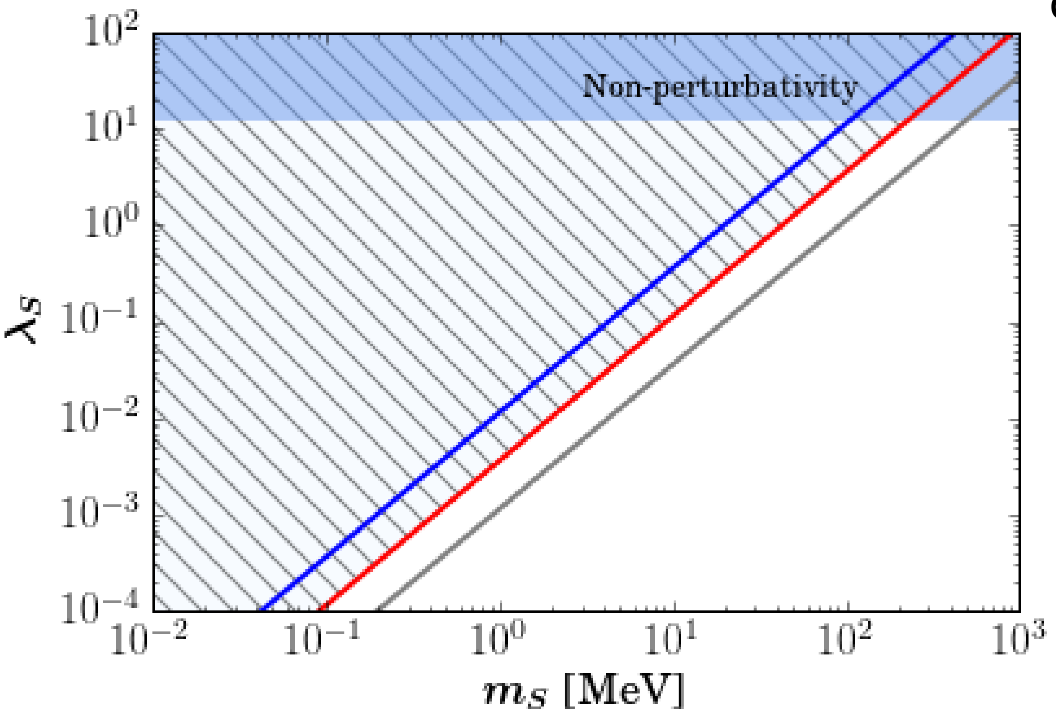


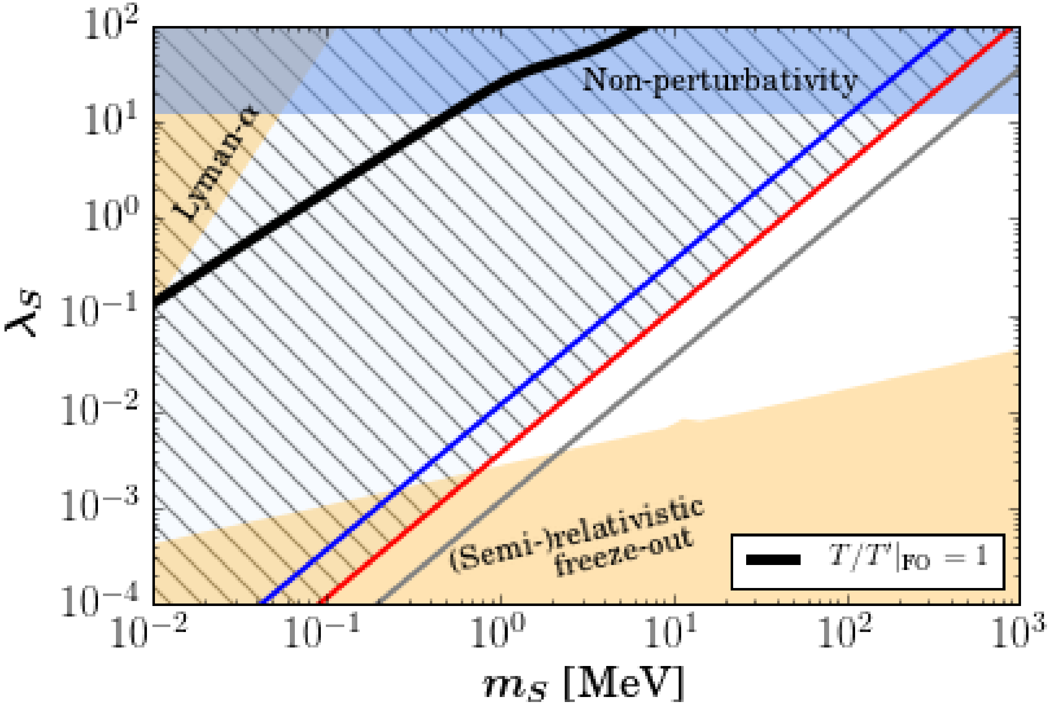
$$\langle\sigma v^3\rangle_{4\to2} \sim \frac{27\sqrt{3}}{8\pi}\,\frac{\lambda_S^4}{m_S^8}$$

Singlet Scalar DM
4→2 annihilations



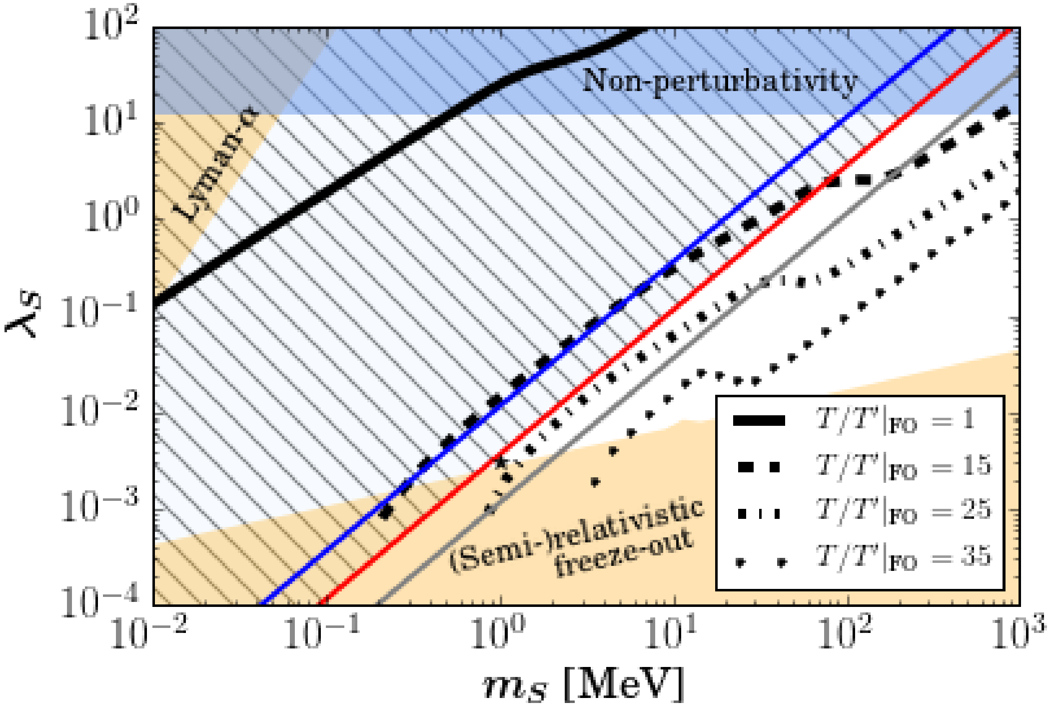
σ/m [cm²/g]
{ 10
1
0.1

Singlet Scalar DM
4→2 annihilations



$T_{SM} = T_{DM}$ @ DM freeze-out

Singlet Scalar DM
4→2 annihilations



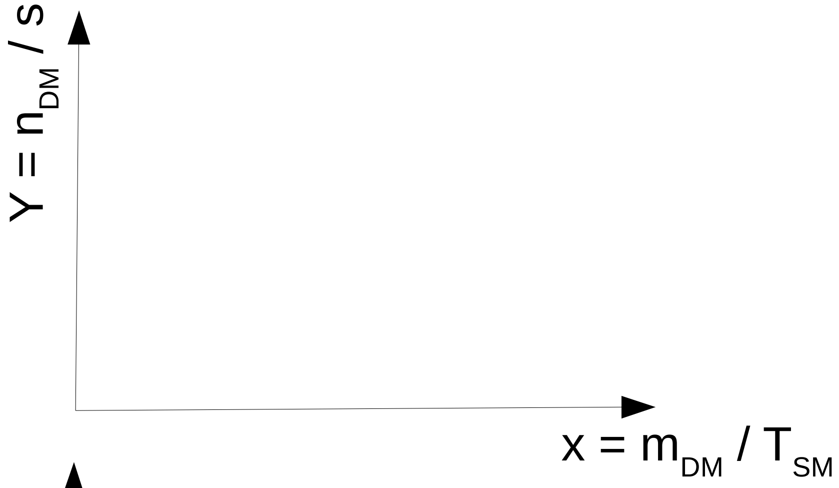
$T_{SM} = T_{DM}$

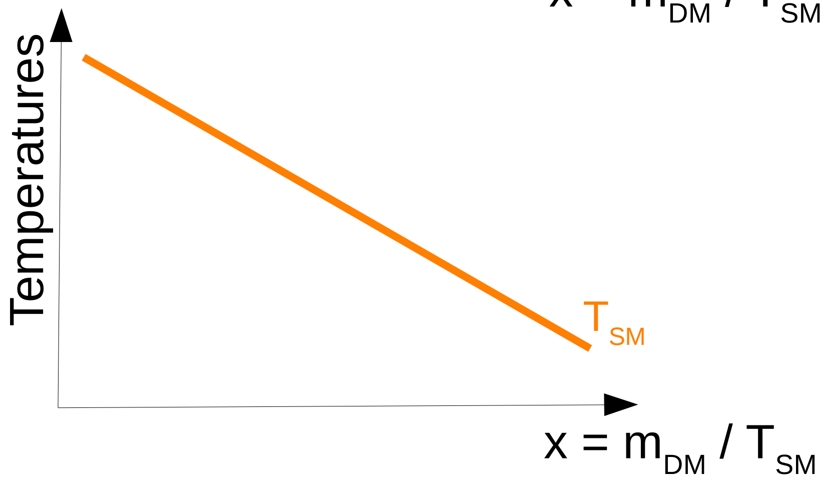
&

$T_{SM} \neq T_{DM}$ @ DM freeze-out

How to produce such a difference of temperatures?

(Non-) Thermal evolution of DM





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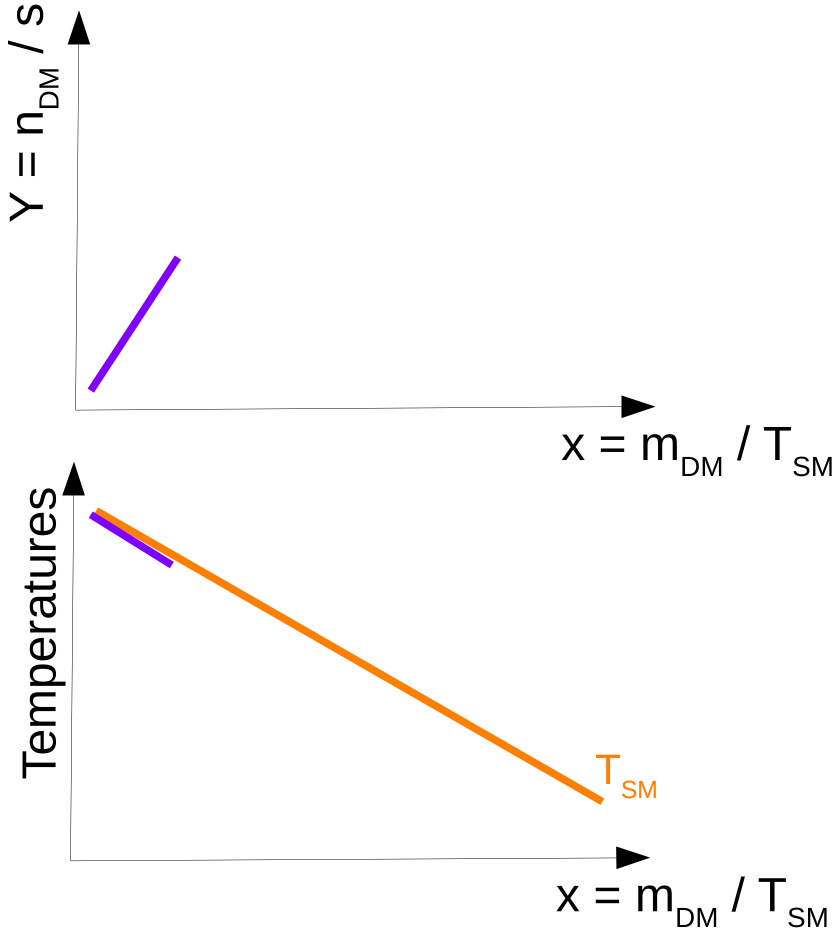

DM Production

* Out-of-equilibrium production à la freeze-in: **h→SS**
  DM in kinetic equilibrium via **2↔2**
  DM inherits SM temperature

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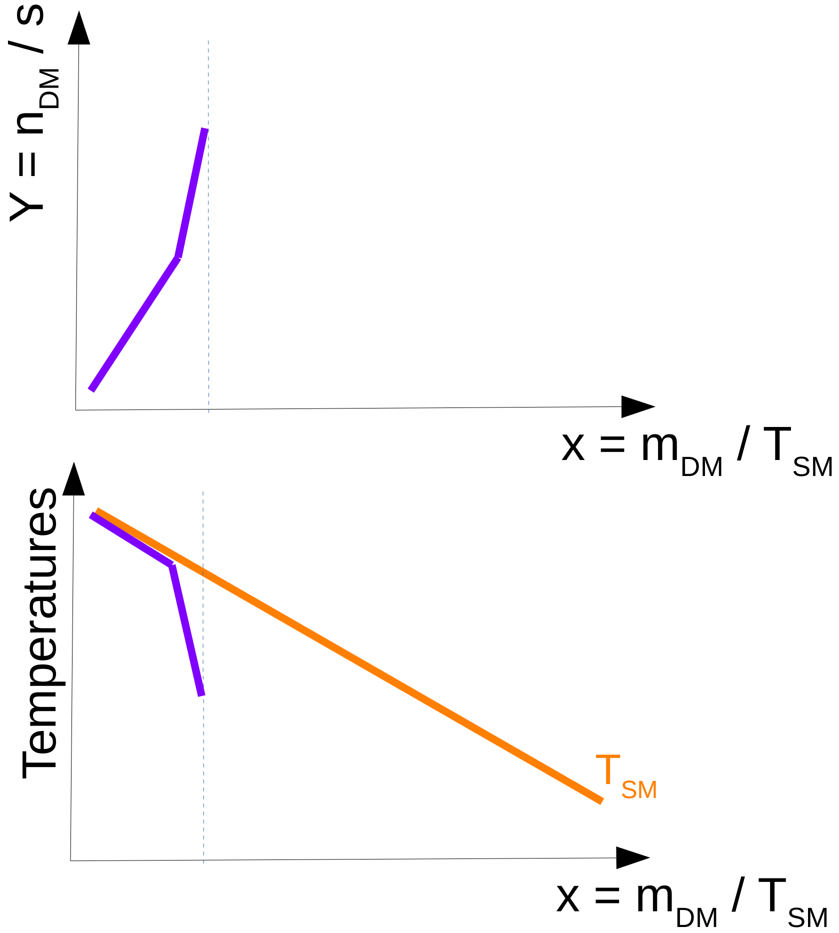

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* DM populates rapidly via out-of-equilibrium **2→4**.
  Price to pay: Dramatic decrease of T_{DM}

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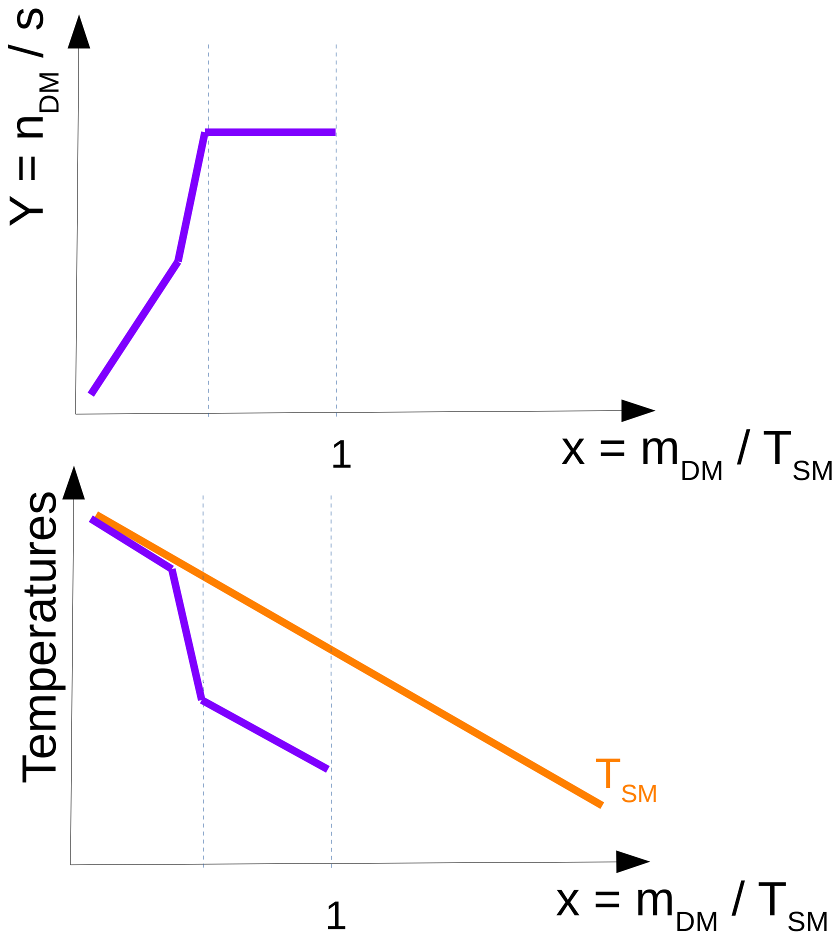

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<u>Thermal Equilibrium</u>

* Chemical equilibrium **2** ↔ **4**

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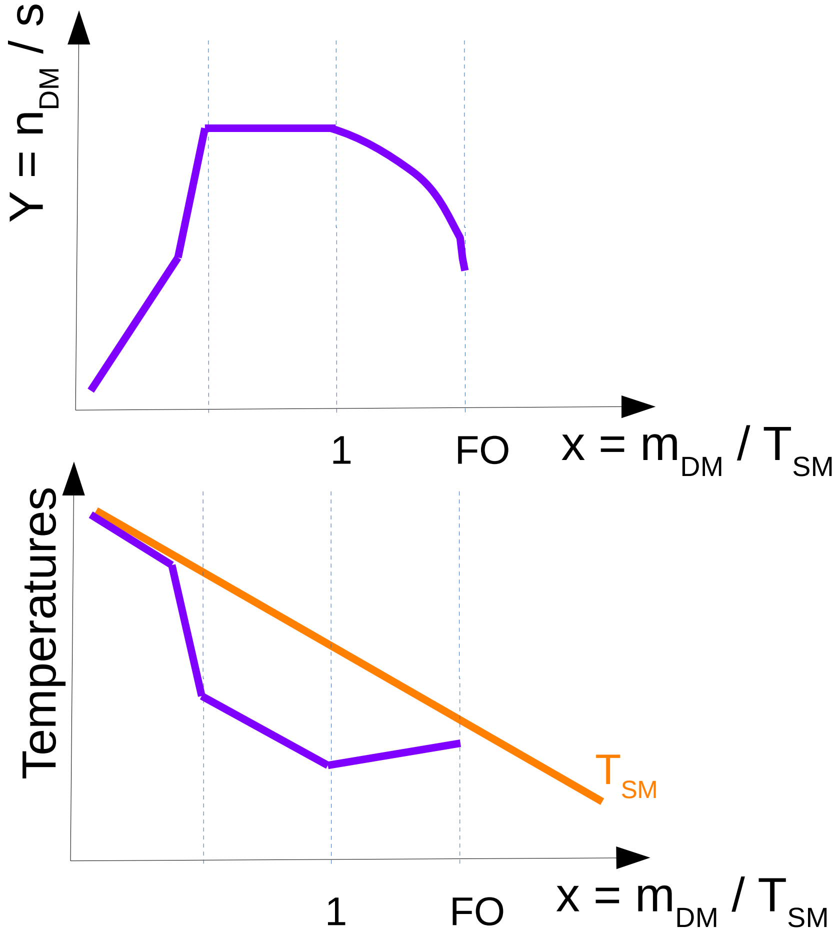

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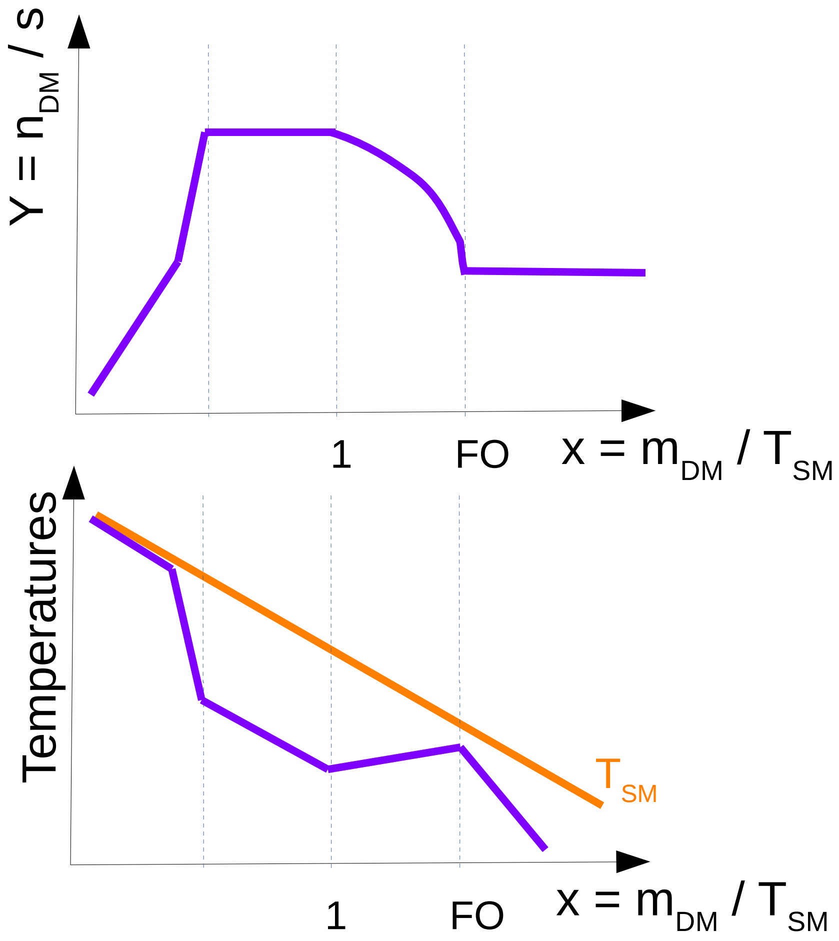
Thermal Equilibrium

* Chemical equilibrium **2↔4**

DM Annihilation

* Freeze-out **4→2**

(Non-) Thermal evolution of DM



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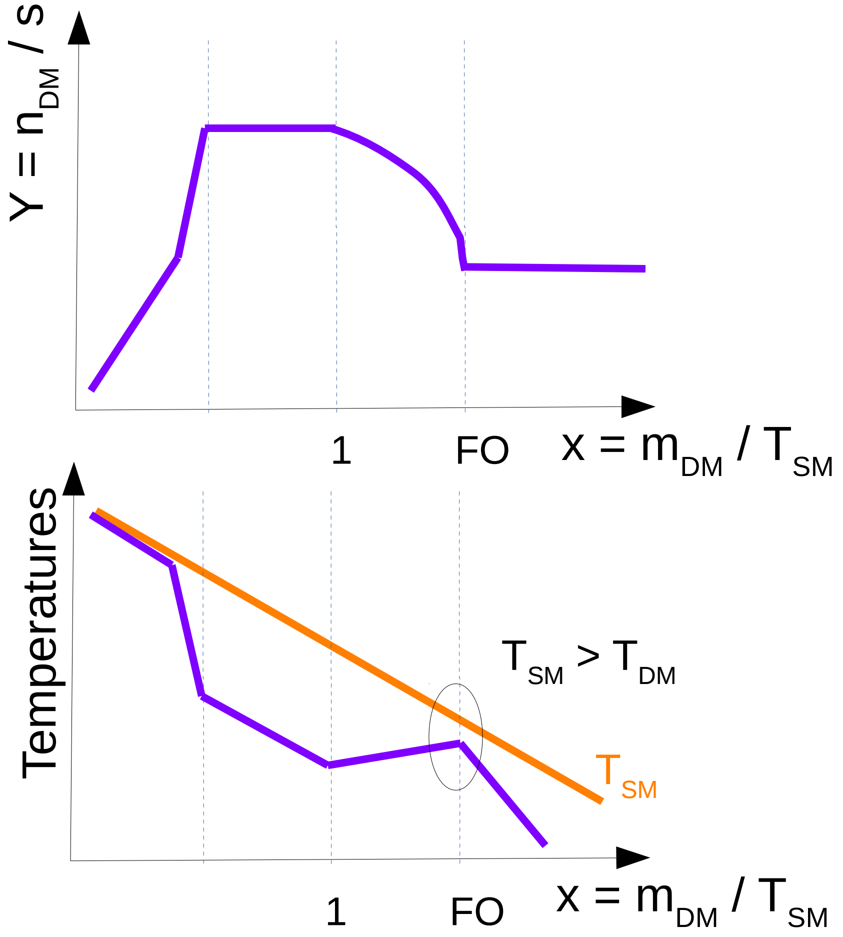
<u>DM Annihilation</u>

* Freeze-out **4 → 2**

<u>After the Freeze-out</u>

* Relic abundance
  Non-relativistic DM cools down faster

(Non-) Thermal evolution of DM



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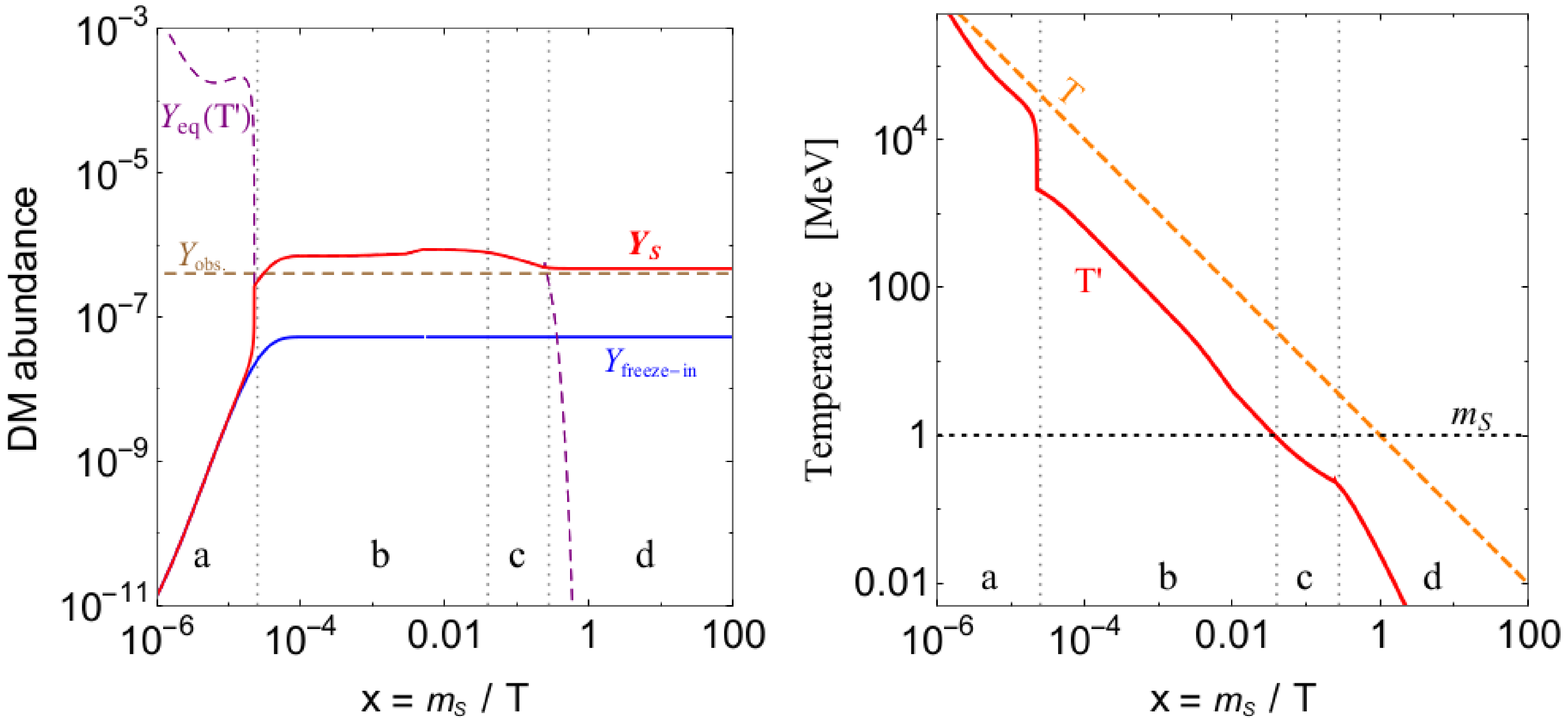
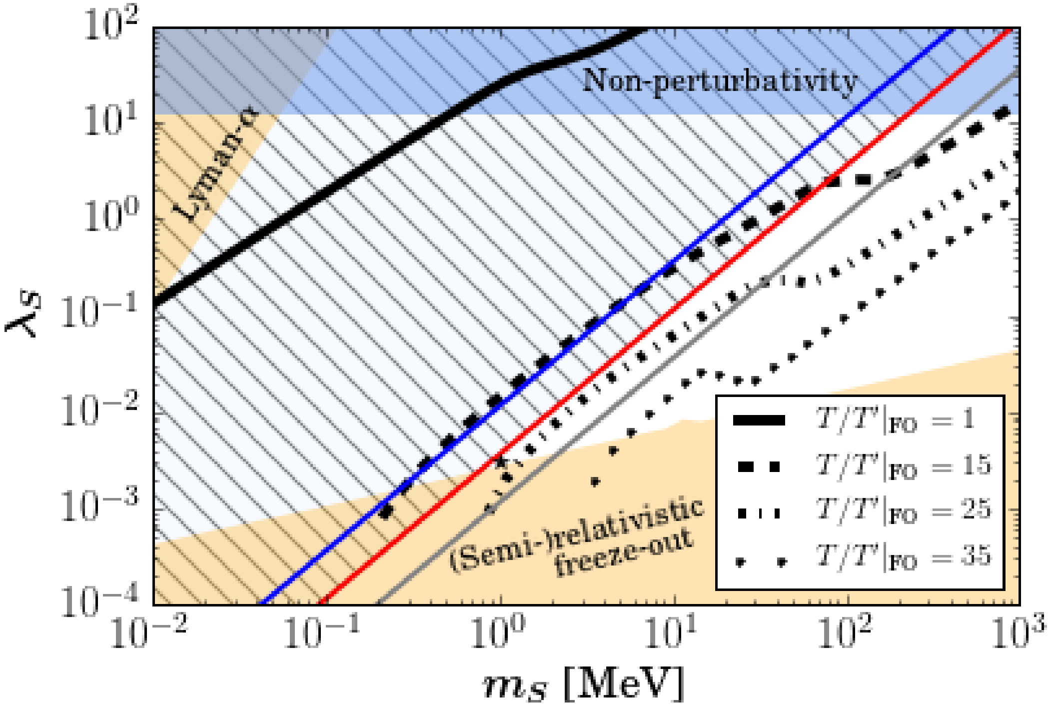
Generating $T_{DM} < T_{SM}$ via the Higgs Portal



Singlet Scalar DM
4→2 annihilations



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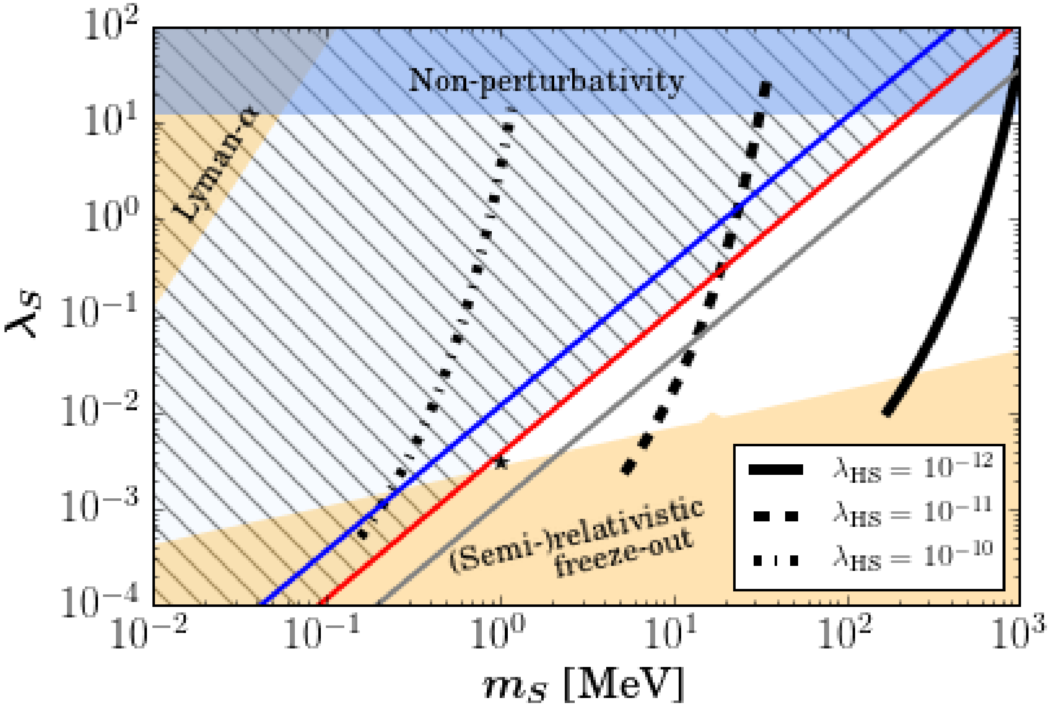

Now let’s Split SIMPs!

Splitting SIMPs: fermions

- Fermionic DM:
  Dirac fermion Ψ split by small Majorana masses m_L and m_R.

$$\mathcal{L}_\Psi = \bar{\Psi}\left(i\not{D} - M_D\right)\Psi - \frac{m_L}{2}\left(\bar{\Psi}^c P_L \Psi + h.c.\right) - \frac{m_R}{2}\left(\bar{\Psi}^c P_R \Psi + h.c.\right)$$

$$\chi_1 \simeq \frac{i}{\sqrt{2}}(\Psi - \Psi^c)\,, \quad \chi_2 \simeq \frac{1}{\sqrt{2}}(\Psi + \Psi^c)$$

$$\text{Pseudo-Dirac } \chi_{1,2}: \quad m_{1,2} \simeq M_D \mp \frac{m_L + m_R}{2} + O(\delta)\,,$$

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$$\text{Pseudo-Dirac } \chi_{1,2}: \quad m_{1,2} \simeq M_D \mp \frac{m_L + m_R}{2} + O(\delta)\,,$$

- The gauged dark U(1) symmetry explicitly broken by Δm
  → the interaction with DM proceeds off-diagonally!

$$\mathcal{L}_{\text{int},\,\chi} = i g_V \bar{\chi}_1 \gamma^\mu \chi_2 V_\mu + O(\delta)$$

- The dark gauge boson:

$$\mathcal{L}_V = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{m_V^2}{2}V^2 - \kappa\, V_\mu J^\mu_{\text{SM}}$$

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Free parameters:
m, Δm, m_V, g_V and κ.

Splitting SIMPs: scalars

- Scalar DM:
  Complex scalar Φ split by a mass-squared parameter m^2_φ.

$$\mathcal{L}_\Phi = |D_\mu \Phi|^2 + M^2 |\Phi|^2 + (m_\phi^2\, \Phi^2 + h.c.) - V_\Phi$$

$$V_\Phi = \lambda_\Phi |\Phi|^4 + \frac{\lambda'_\Phi}{2}(\Phi^4 + h.c.) + \lambda_m |\Phi|^2 |H|^2 + (\lambda'_m \Phi^2 + h.c.)|H|^2$$

$$\Phi = \frac{1}{\sqrt{2}}(\phi_1 + i\,\phi_2)$$

$$\text{Scalar } \phi_{1,2}: \quad m^2_{1,2} = M^2 \mp m^2_\phi$$

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  → the interaction with DM proceeds off-diagonally!

$$\mathcal{L}_{\text{int},\phi} = g_V\,(\phi_1 \partial^\mu \phi_2 - \phi_2 \partial_\mu \phi_1)\, V_\mu + \frac{1}{2} g_V^2 \left(\phi_1^2 + \phi_2^2\right) V^2 - V_\Phi(\phi_1,\, \phi_2)$$

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Splitting SIMPs: scalars

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Producing Split SIMPs

Split SIMPs
$4 \rightarrow 2$ annihilations

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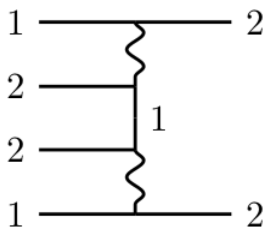
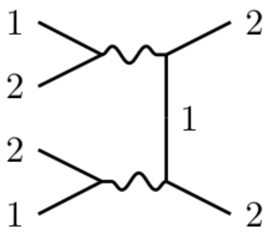
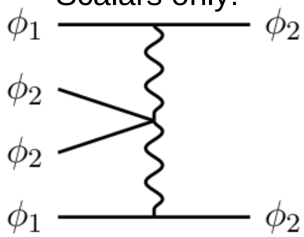




Scalars only!



We take $m_V > m_1 + m_2$

Split SIMPs
4 → 2 annihilations

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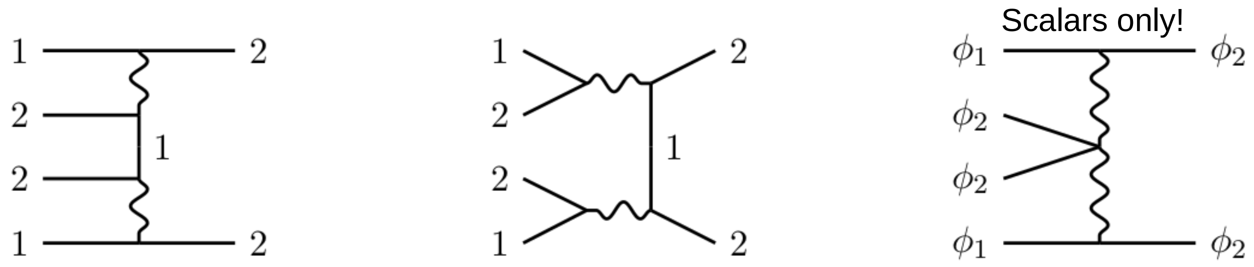


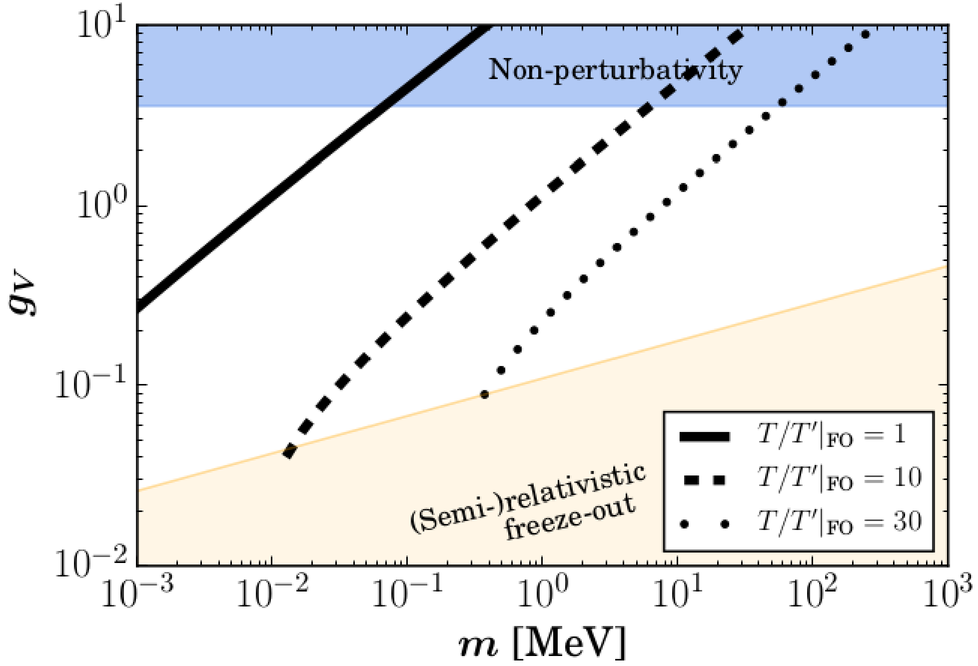
$$\langle\sigma v^3\rangle_{4\to2} = \left[\langle 1122\to22\rangle + \langle1122\to11\rangle\right]\frac{R^2}{(1+R)^4}$$

We take $m_V > m_1 + m_2$

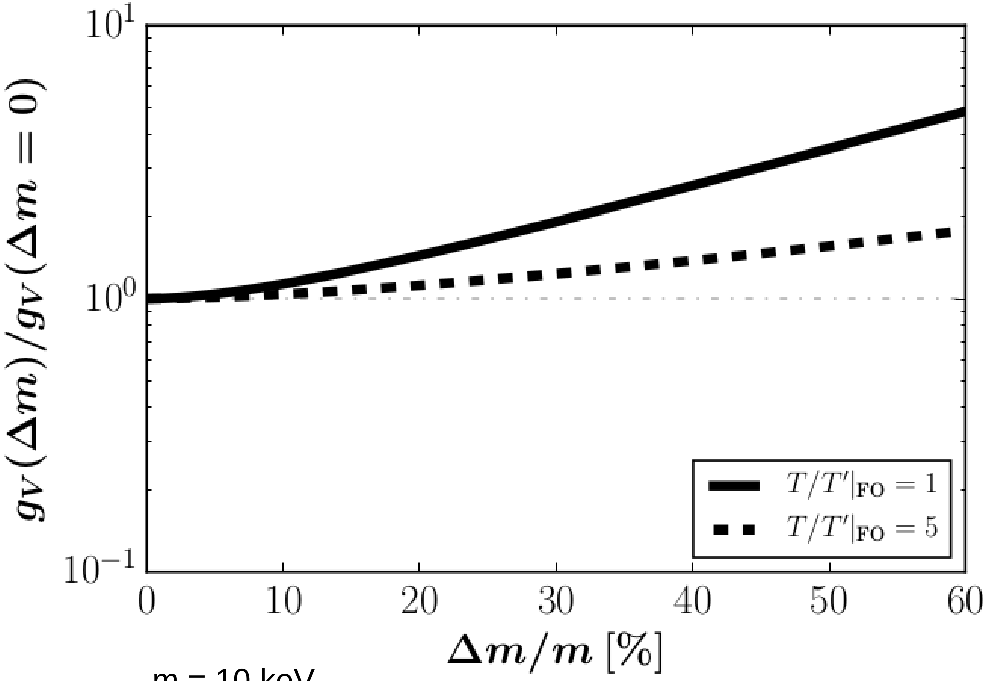
$$\langle1122\to11\rangle = \langle1122\to22\rangle = \frac{27\sqrt{3}\,g_V^8}{32\pi}\,\frac{\left(m_V^4-8m^2m_V^2-8m^4\right)^2}{\left(m_V^4-2m^2m_V^2-8m^4\right)^4}$$

$$R(T')\equiv\frac{n_2(T')}{n_1(T')} = \left(1+\frac{\Delta m}{m}\right)^{3/2} e^{-\frac{\Delta m}{T'}} \simeq e^{-\frac{\Delta m}{T'}}\,.$$

Split SIMPs
4→2 annihilations



Δm = 0
$m_V = 2.5$ m



m = 10 keV
$m_V = 2.5$ m + Δm

Astrophysical Implications of Split SIMPs

(Late) Decay of the State 2

The decay of state 2 into state 1 is accompanied by SM radiation, possibly constrained by BBN and CMB.

$$\chi_2 \to \chi_1 V^* \to \chi_1 e^+ e^-$$

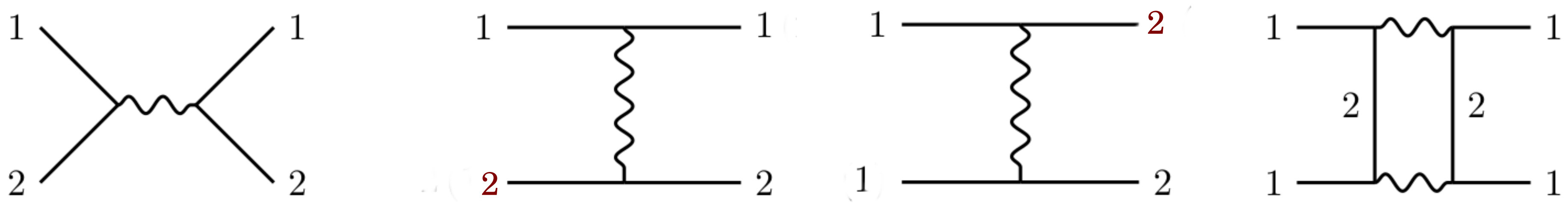
$$\Gamma_{\chi_2 \to \chi_1 e^+ e^-} \simeq \frac{2\alpha\, \alpha_V\, \kappa^2}{15\pi} \frac{\Delta m^5}{m_V^4} \simeq 2\, H_0 \times \frac{m}{100\ \text{MeV}} \frac{\alpha_V}{\alpha} \left(\frac{\kappa}{10^{-10}}\right)^2 \left(\frac{\Delta m/m}{10^{-3}}\right)^5 \left(\frac{m}{m_V}\right)^4$$

$$\chi_2 \to \chi_1 V^* \to \chi_1\, 3\gamma;$$

$$\Gamma_{\chi_2 \to \chi_1 3\gamma} \simeq \Gamma_{\chi_2 \to \chi_1 \nu\bar{\nu}} \times \left.\frac{\Gamma_{V \to 3\gamma}}{\Gamma_{V \to \nu\bar{\nu}}}\right|_{m_V \to \Delta m}$$

$$\simeq H_0 \times \left(\frac{m}{50\,\text{MeV}}\right)^9 \frac{\alpha_V}{\alpha} \left(\frac{\kappa}{10^{-10}}\right)^2 \left(\frac{\Delta m/m}{10^{-2}}\right)^{13} \left(\frac{m}{m_V}\right)^4$$

Self-scatterings



$$\frac{\sigma^{\rm SI}_{\rm eff}}{m} \equiv R_0 \frac{\sigma_{12}}{m} + \frac{\langle \sigma_{\rm en} v \rangle}{m\, v} + \frac{\sigma_{\rm rad}}{m} \lesssim 1~{\rm cm}^2/{\rm g}$$

Free-streaming Length

4-to-2
‘reheat’ DM
Increasing the FSL

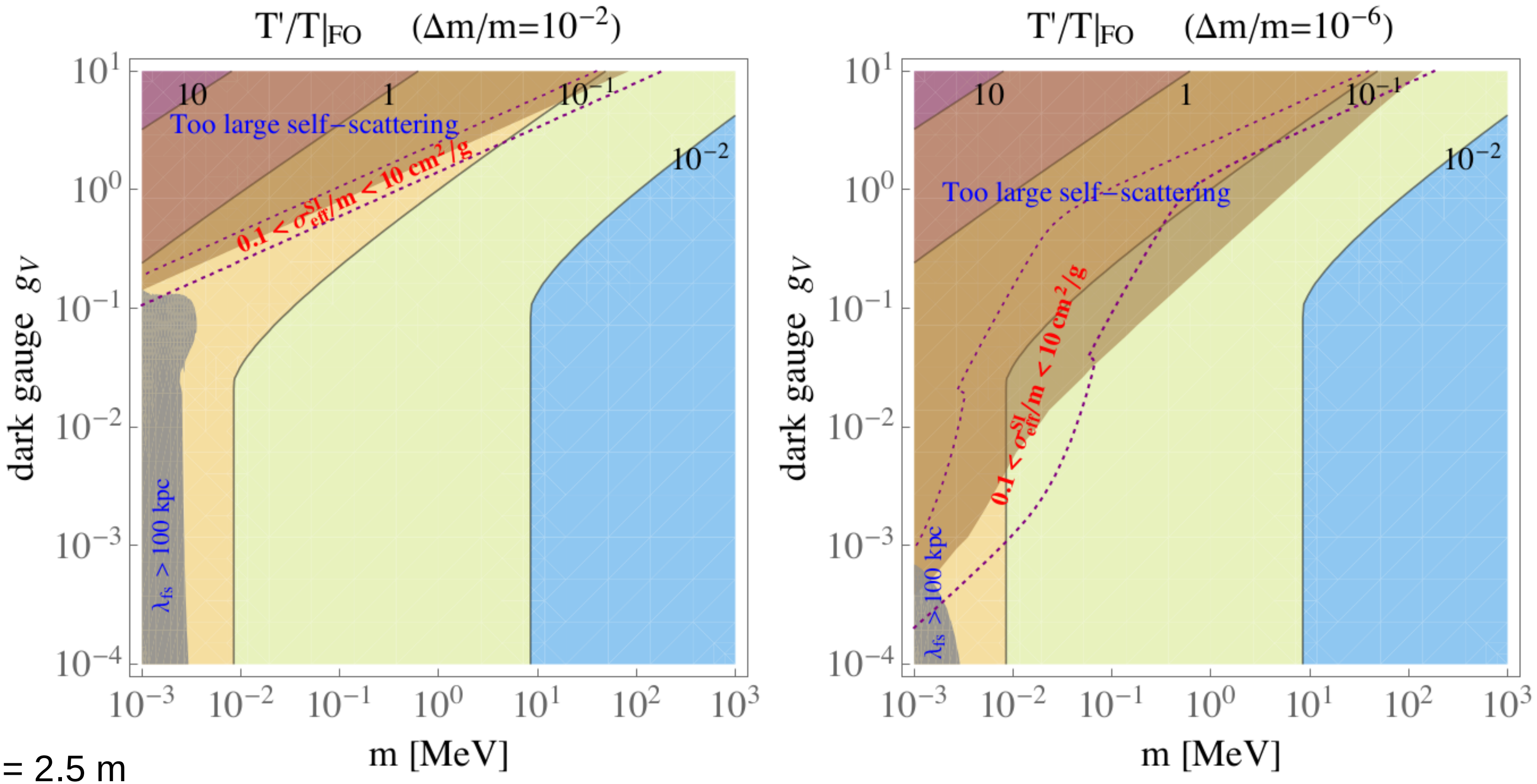
← Versus →

2-to-2
Self-interactions
Decrease the FSL

$$\lambda_{\rm fs} = \int_{t_{\rm k}}^{t_{\rm eq}} \frac{v_\chi(t)}{a(t)} dt \sim \frac{26\,{\rm kpc}}{\sqrt{g_\star(T_k)}} \times \frac{10~{\rm keV}}{\sqrt{T_k\, m}} \left(\frac{T'_{\rm k}}{T_{\rm k}}\right)^{1/2} \log_{10}\left(\frac{T_k}{T_{\rm eq}}\right)$$

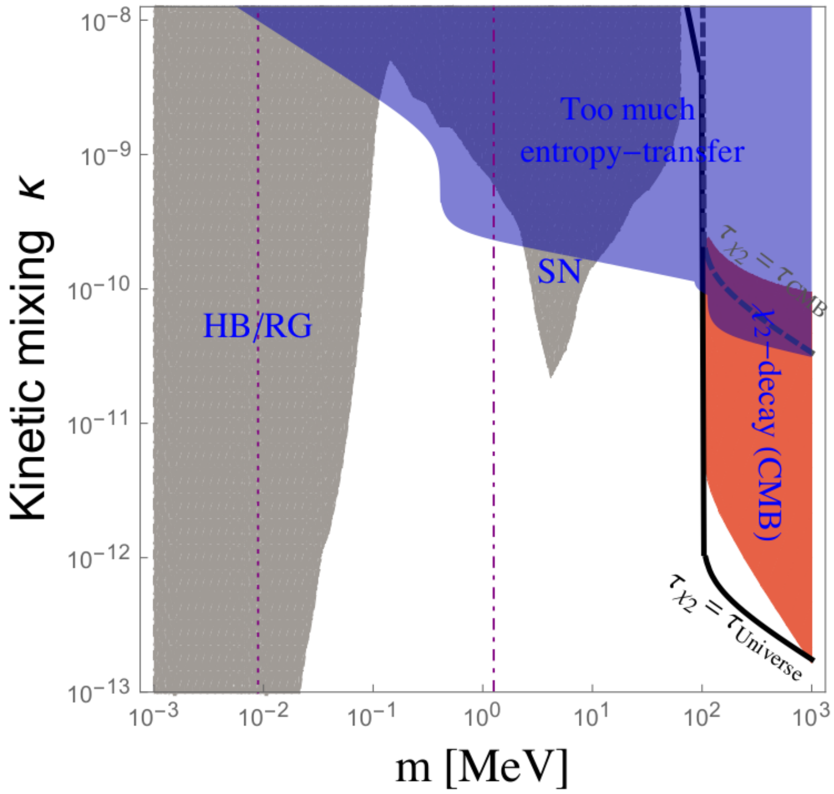
$\lambda_{\rm fs} \lesssim 100~{\rm kpc}$ ← Lyman-α

Astrophysical implications of Split SIMPs



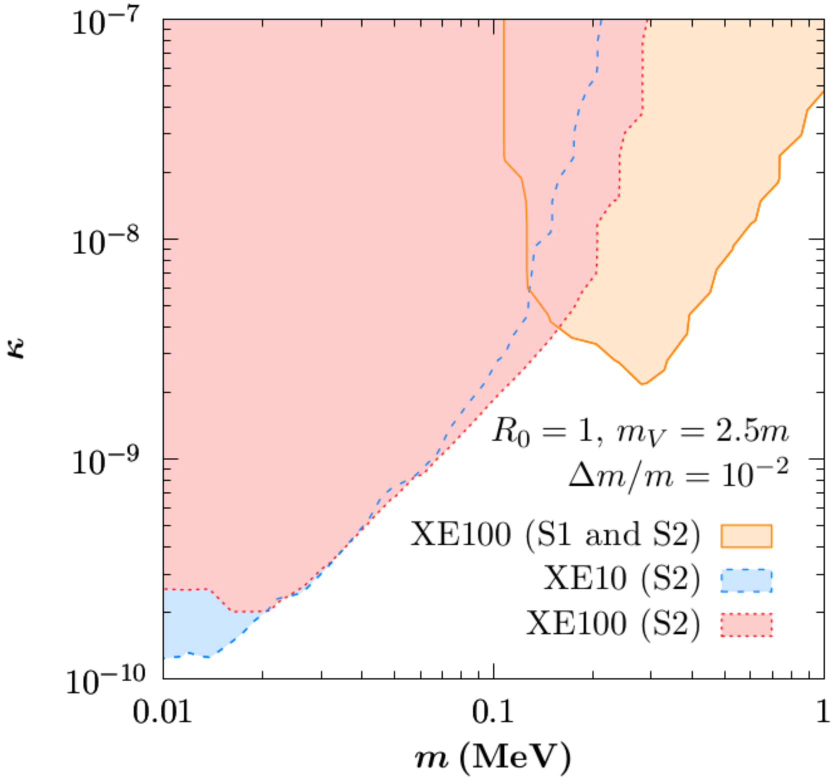
$m_V = 2.5\ m$

Constraints on the Kinetic Mixing Portal

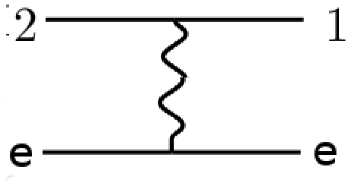


$\Delta m / m = 10^{-2}$
$m_V = 2.5\ m$

Exothermic DM-Electron Scattering



$$\bar{\sigma}_e = a\frac{16\pi\,\alpha\,\alpha_V\,\kappa^2\,\mu_{\chi e}^2}{m_V^4} \simeq 10^{-44}\,\mathrm{cm}^2\,a\frac{\alpha_V}{\alpha}\left(\frac{\kappa}{10^{-10}}\right)^2\left(\frac{m}{100\,\mathrm{keV}}\right)^2\left(\frac{300\,\mathrm{keV}}{m_V}\right)^4$$



~ monochromatic signal!

$$E_{\mathrm{recoil}} \sim \Delta m \frac{\mu_{mA}}{m_A}$$

On the verge of being probable with reported data (S1 and S2) from XENON100!

Conclusions

- Self-interacting DM with no light mediators → SIMP DM
- Z_2 SIMP DM generated via 4→2 annihilations
- DM: MeV ballpark, ‘large’ self-interactions & ‘small’ portal with the SM
- Difference of temperatures *dynamically* produced via freeze-in!
- Self-interactions: small velocity dependence

- SIMPs offer a new window to DM: Points to different physical scales