Light Self-interacting Dark Matter

Based on:
NB, C. Garcia-Cely & R. Rosenfeld: JCAP 1504 (2015) 04, 012
NB, X. Chu, C. Garcia-Cely, T. Hambye & B. Zaldivar: JCAP 1603 (2016) 03, 018
NB & X. Chu: JCAP 1601 (2016) 01, 006
NB, J. Pradler & X. Chu: PRD95 (2017) 11, 115023

Nicolás BERNAL

UAN
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ANTONIO NARIÑO

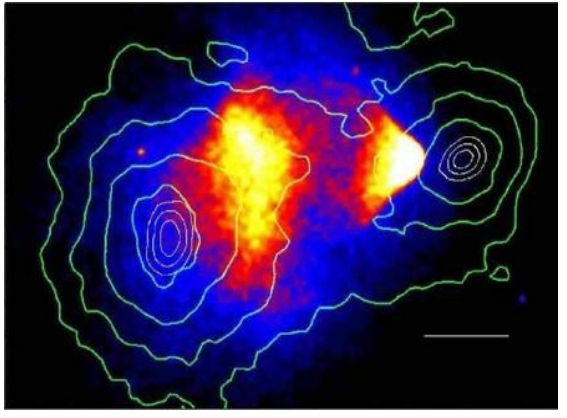
8th KIAS workshop on particle physics and cosmology
November 2nd, 2018

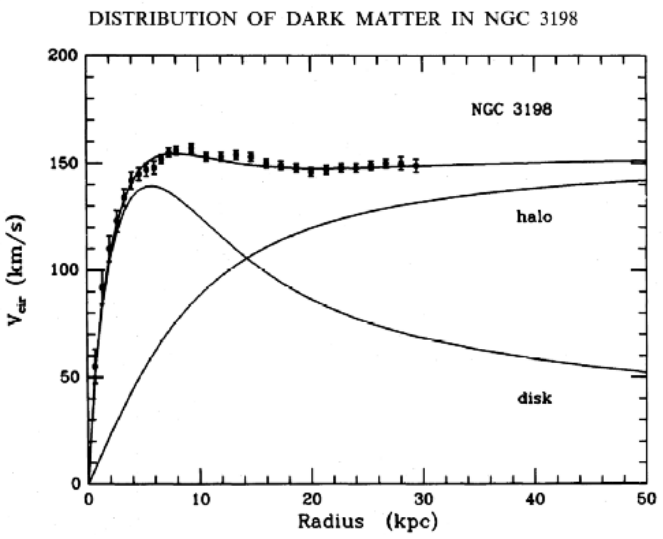
Evidences for Dark Matter

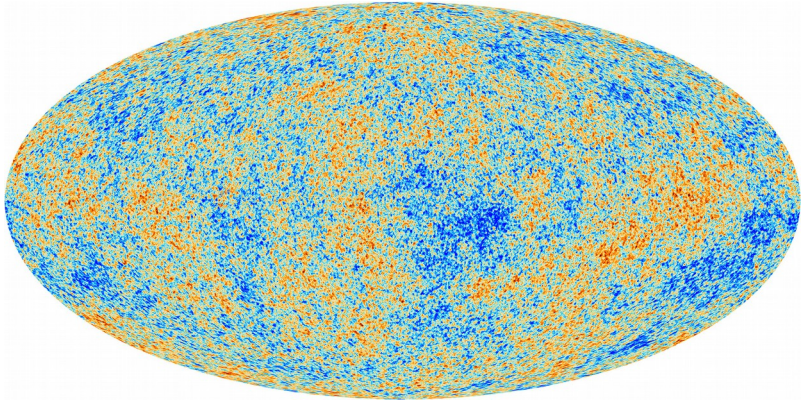
Several observations indicate the existence of non-luminous Dark Matter (missing force) at very different scales!

* Galactic rotation curves
* RC in Clusters of galaxies
* Clusters of galaxies
* CMB anisotropies









Evidences for Dark Matter

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Dark Matter is there! :-)

But what is it? :-/

* Neutral
* Massive enough
* ‘Weak’ interactions
* Stable or long-lived

Dark Matter needs
New Physics beyond the Standard Model!

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Collisionless WIMP DM?

Dark Matter needs
New Physics beyond the Standard Model!

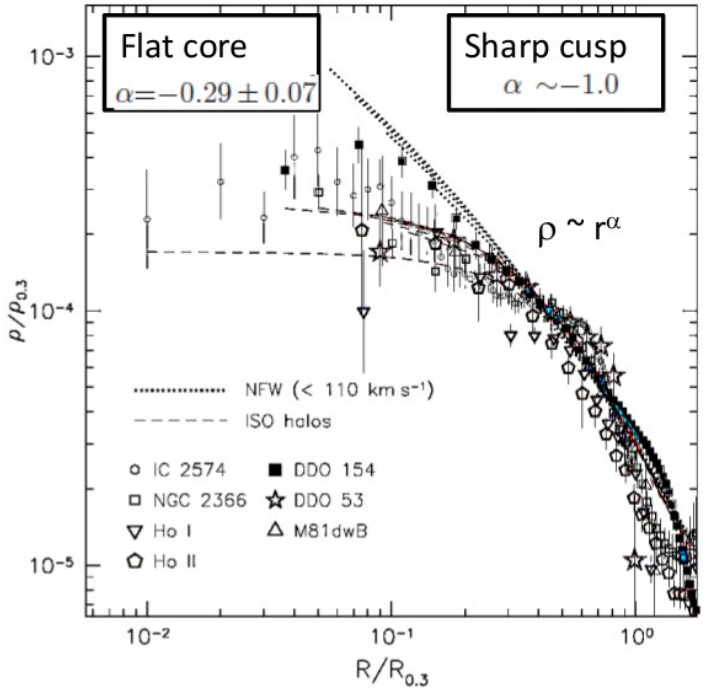
Collisionless Cold Dark Matter Paradigm in Troubles?!

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Collisionless Cold Dark Matter in Troubles?

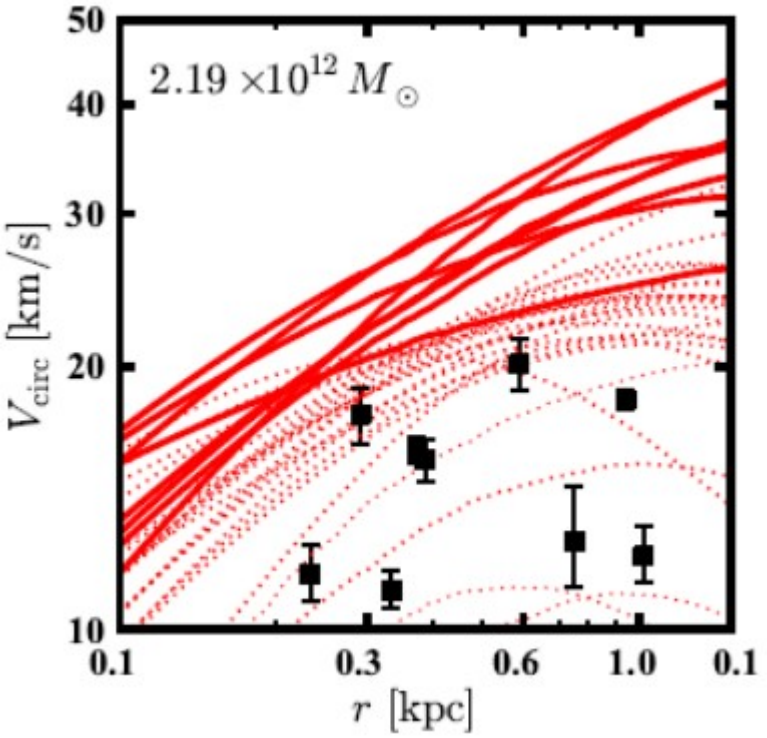
Core-vs-cusp problem

THINGS (dwarf galaxy survey) - Oh et al. (2011)



Too-big-to-fail problem

Talk by Hai-Bo Yu



Small-scale problems → Self-interacting DM

Small-scale problems:

* Core-vs-cusp
* Too-big-to-fail

Possible solutions:

* Baryonic physics
  - Can't use DM-only simulations to model real DM+baryon Universe
  - Astrophysical observations not being modeled correctly

  (Suppressed gas cooling efficiency, low star-formation efficiency, supernova feedback, large velocity anisotropy…)

* *Dark Matter*

  DM may not be collisionless

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$$\left(\frac{\sigma_{\rm scatter}}{m_\chi}\right)_{\rm obs} = (0.1 - 10)\ {\rm cm}^2/{\rm g}$$

~ few barns/GeV

$$\frac{\sigma_{\rm scatter}}{m_X} \lesssim 1\ {\rm cm}^2/{\rm g}\,.$$

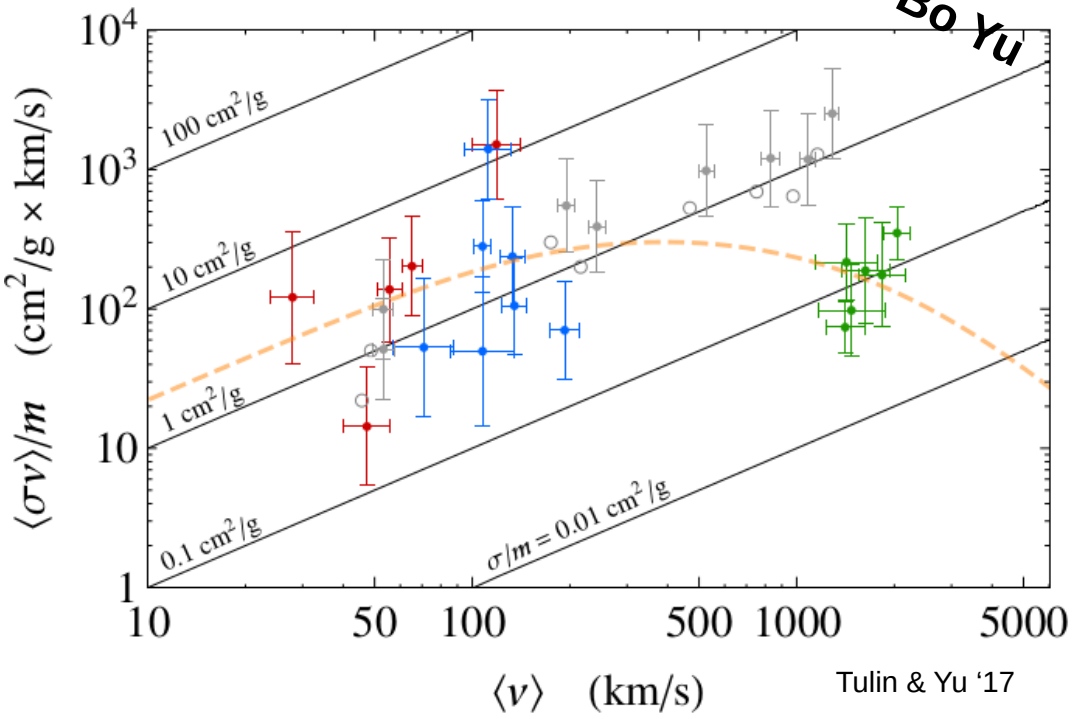
From the Bullet Cluster

Small-scale problems → Self-interacting DM

Talk by Hai-Bo Yu

However, observations tend to favor velocity dependent cross-sections:

* Light mediator
* Resonance



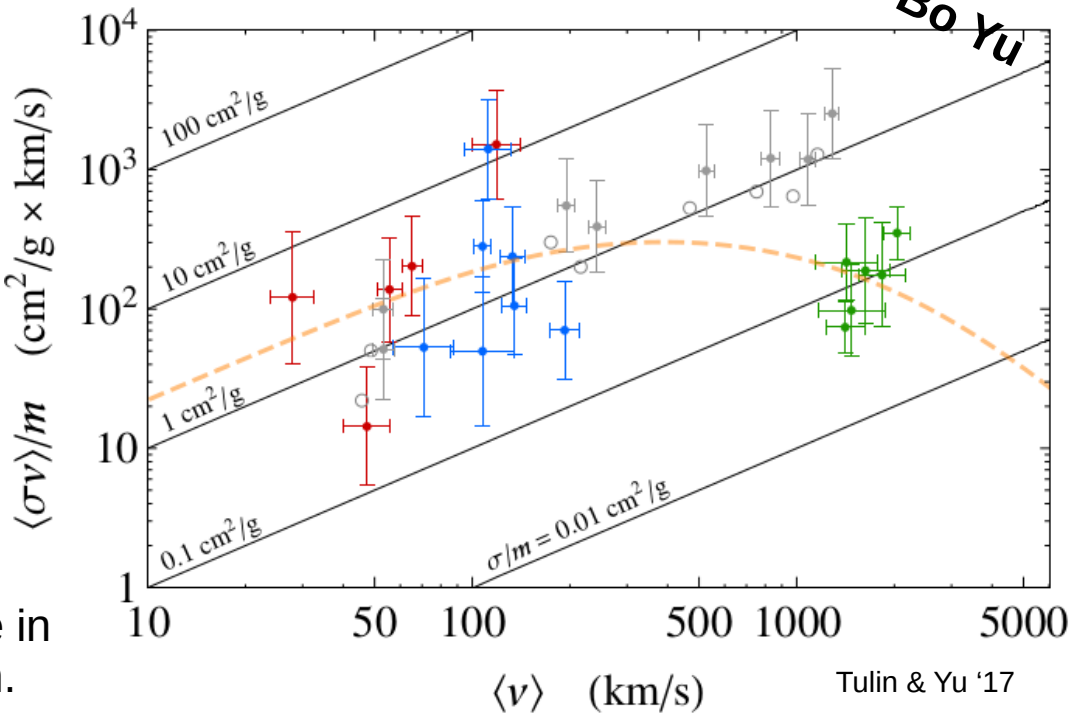
Tulin & Yu '17

Small-scale problems → Self-interacting DM

Talk by Hai-Bo Yu

However, observations tend to favor velocity dependent cross-sections:

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Tulin & Yu '17

My personal view:

I'm completely *agnostic* about DM playing a role in the solution of the small-scale structure problem.

Let's make this an opportunity to explore regions of the parameter space largely overlooked!

The SIMPlest DM model ever: Singlet Scalar Dark Matter

Nicolás BERNAL - UAN

Singlet Scalar DM

McDonald '07

S is a real 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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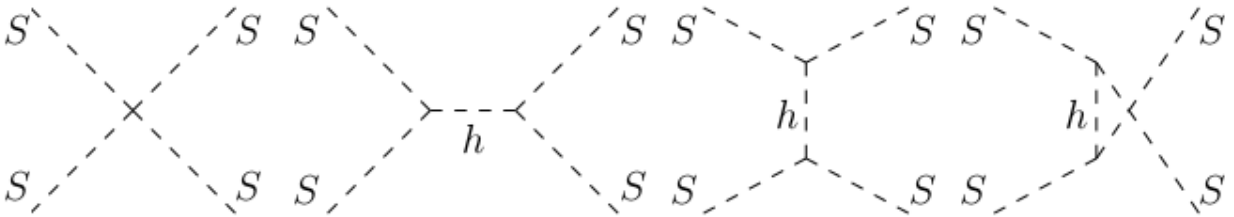
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} ← Concentrated on this

← ~ Ignored!

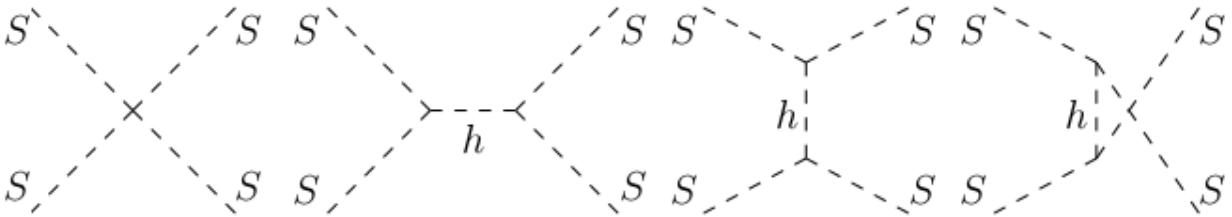
Dark Matter Self-interactions



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

$\frac{\sigma_{SS}}{m_S} \sim$ $O(1)$ cm^2/g Implies { * $\lambda_S \sim 1$ * $m_S \sim 100$ MeV

Dark Matter Self-interactions & Invisible Higgs decay



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

$\frac{\sigma_{SS}}{m_S} \sim$ $O(1)$ cm^2/g Implies { * $\lambda_S \sim 1$; * $m_S \sim 100$ MeV

The Higgs tends to annihilate into DM

BR($h \rightarrow$ inv.) < 20%

* $\lambda_{HS} < 10^{-3}$

How to produce such a Self-interacting Dark Matter?

Nicolás BERNAL - UAN

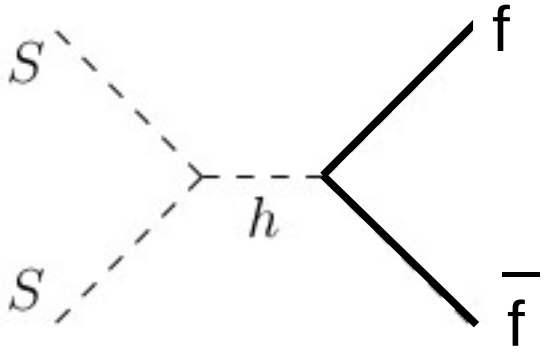
WIMP DM :-/

DM can (only) annihilate into light fermions

other annihilation channels kinematically closed!

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

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



→ Universe overclosed

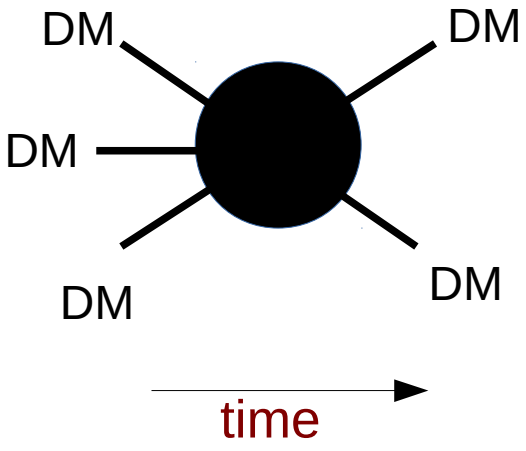
→ SSDM with sizable self-interactions can not be a WIMP

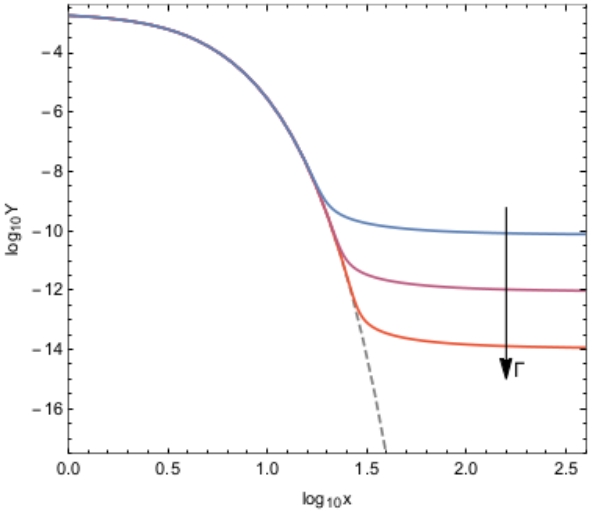
Again:
How to produce such a Self-Interacting Dark Matter?

SIMP DM
$3 \to 2$ annihilations

Hochberg, Kuflik, Volansky & Wacker '14

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

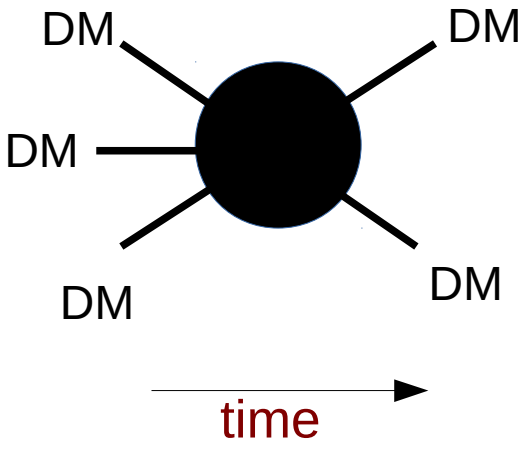




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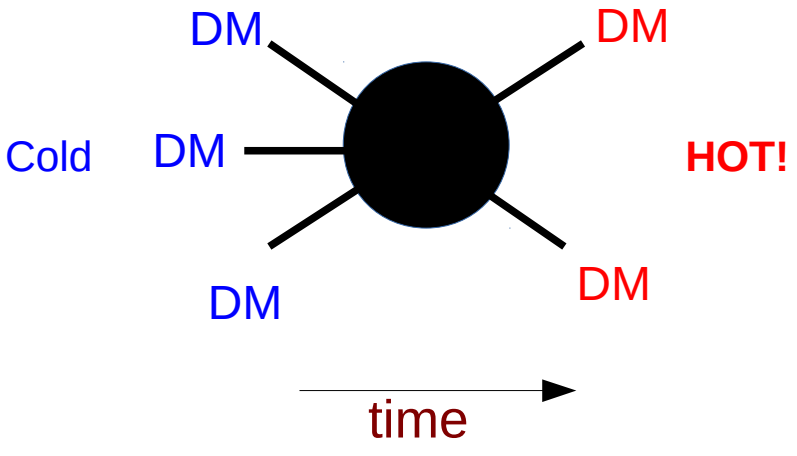
*** DM in the MeV range**

*** Suppressed DM-SM portal λ_{HS}**

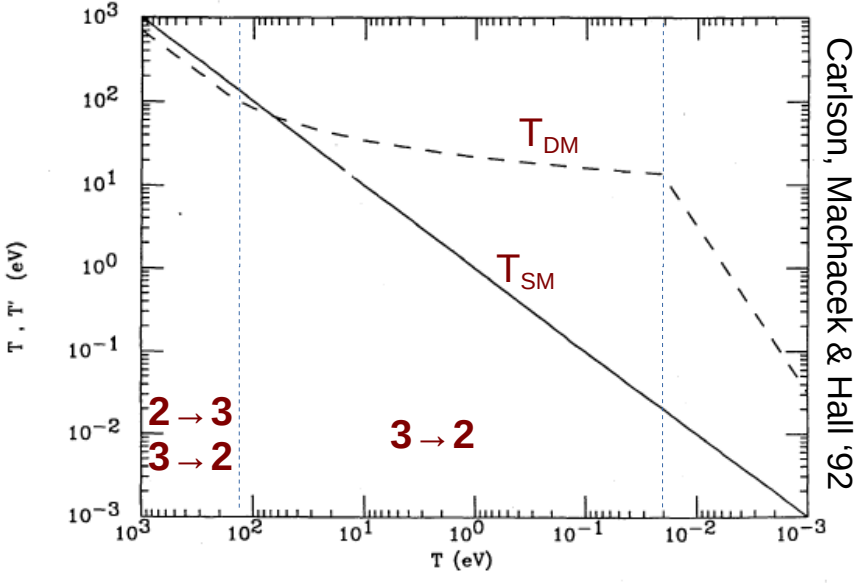
*** $\lambda_S \sim 1$**
'Strong' Self-interactions
→ SIMP DM

SIMP DM
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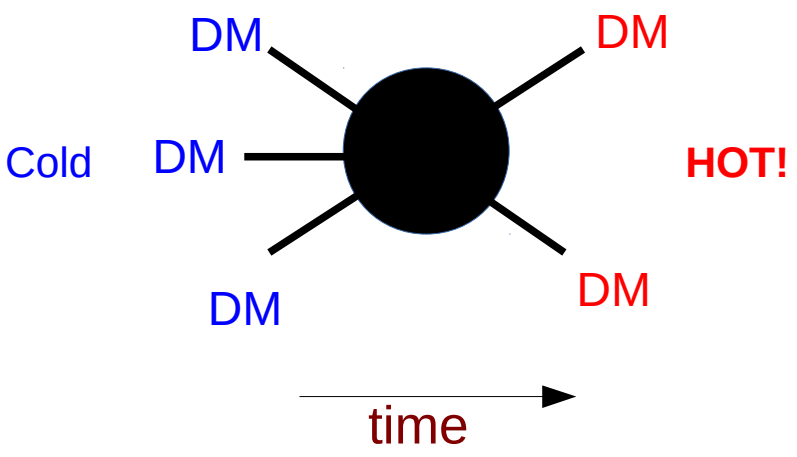


Caveat: $3 \to 2$ annihilations pump heat into the dark sector!



SIMP DM
$3 \to 2$ annihilations

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Solutions:

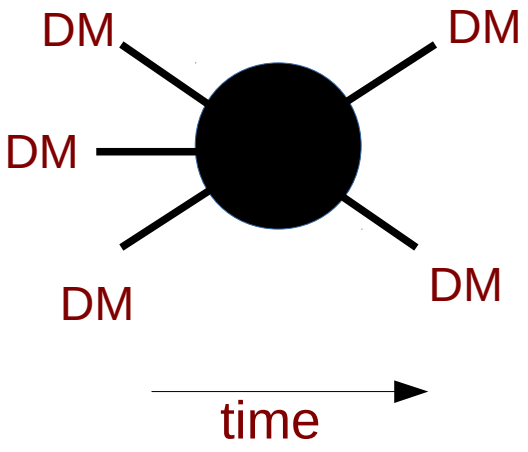
* kinetic equilibrium between SM and DM

* Extended dark sector with relativistic particles at DM FO

* DM and SM always out of kinetic equilibrium *à la freeze-in*

SIMP DM
$3 \to 2$ annihilations

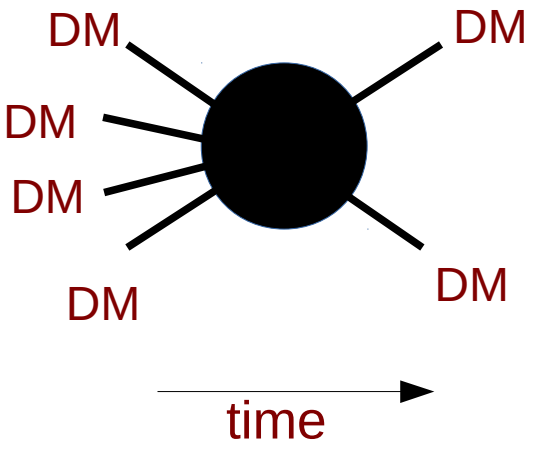
$$\frac{dn}{dt} + 3\,H\,n = -\langle \sigma v^2 \rangle_{3\to 2}\,\left(n^3 - n^2\,n_{\rm eq}\right)$$



$3 \to 2$ 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
$4 \to 2$ annihilations

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

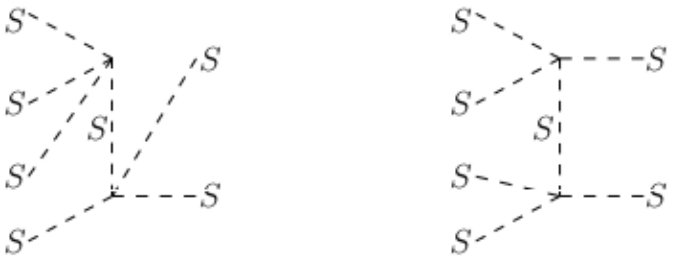


$3 \to 2$ reactions are forbidden in most common scenarios, where the DM stability is guaranteed by a Z_2 symmetry (*R*-parity in SUSY, *K*-parity in Kaluza-Klein…)

But Z_2 symmetries allow $4 \to 2$ annihilations!

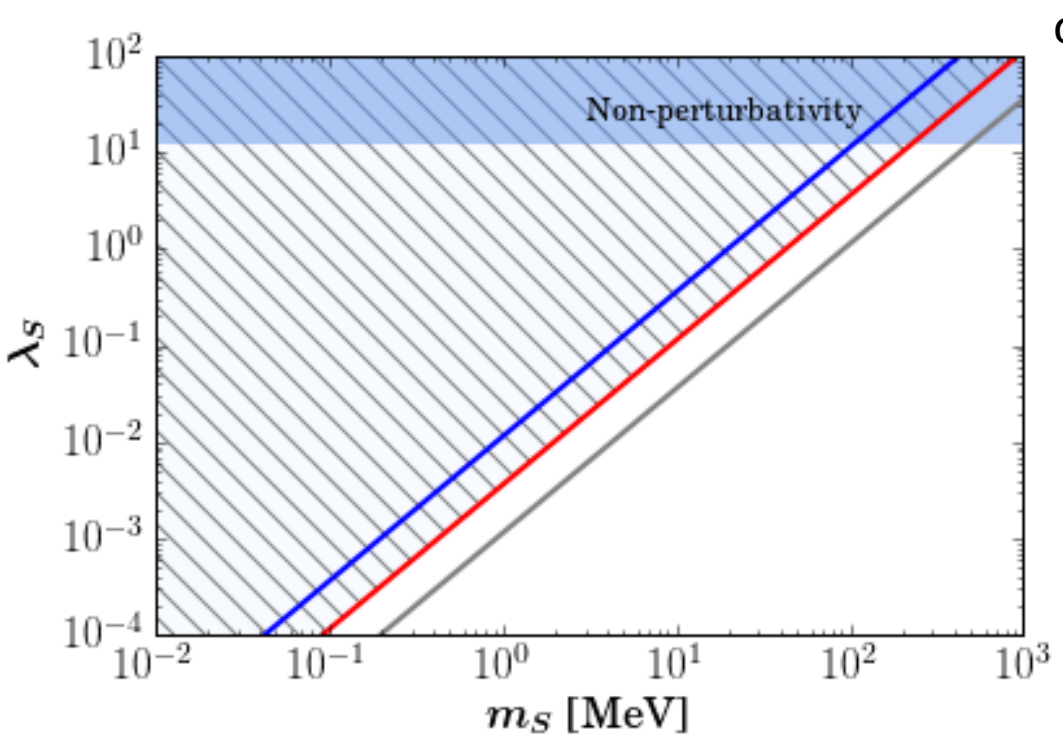
Singlet Scalar DM
$4 \to 2$ annihilations

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$$\langle \sigma v^3 \rangle_{4\to 2} \sim \frac{27\sqrt{3}}{8\pi}\,\frac{\lambda_S^4}{m_S^8}$$

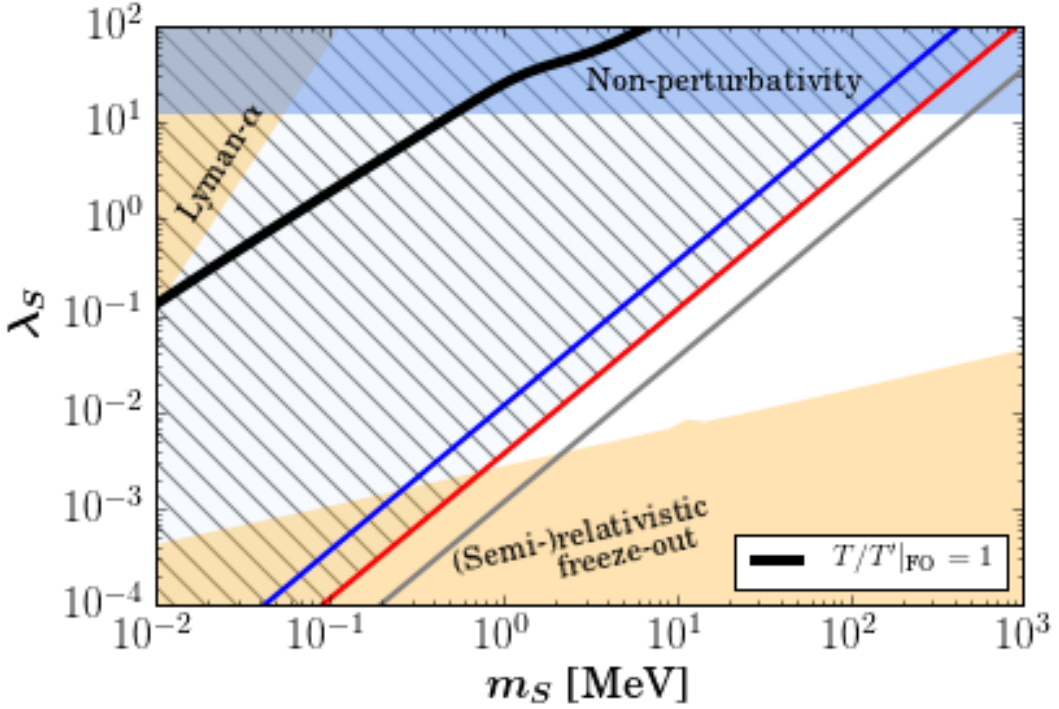
Singlet Scalar DM
$4 \to 2$ annihilations



σ/m [cm²/g]

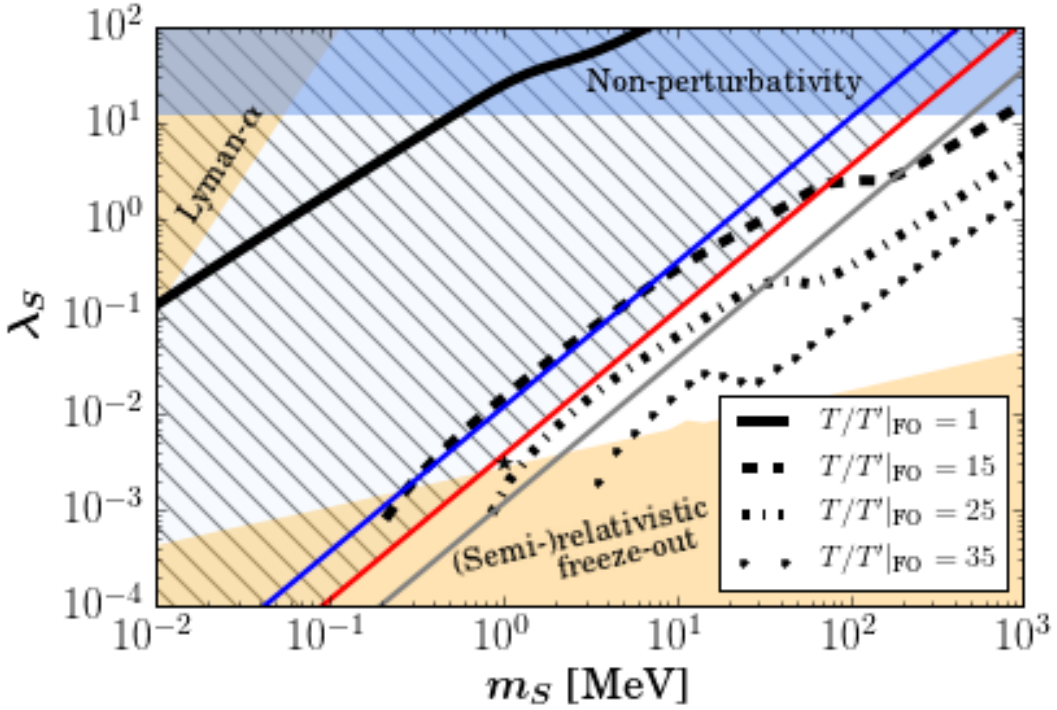
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Singlet Scalar DM
$4 \to 2$ annihilations



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

Singlet Scalar DM
$4 \to 2$ annihilations



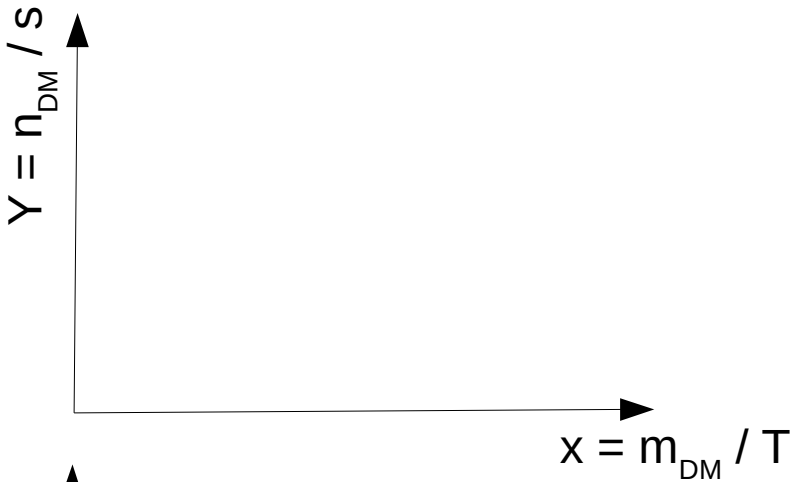
$T_{SM} = T_{DM}$

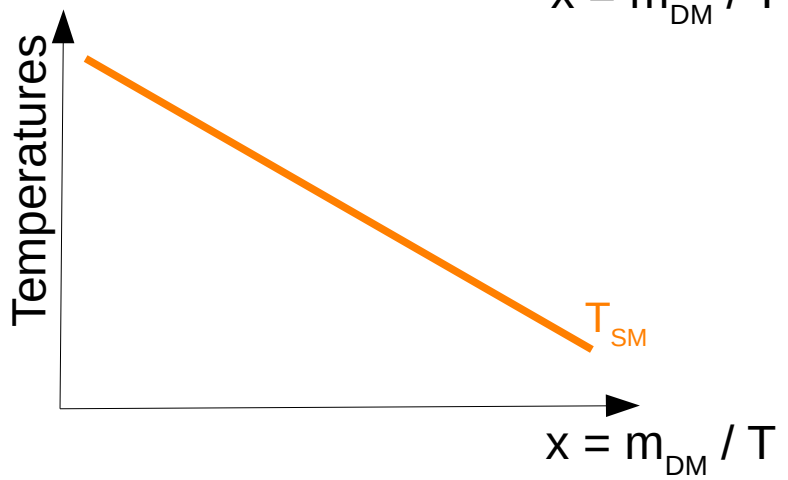
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$T_{SM} \neq T_{DM}$ @ DM freeze-out

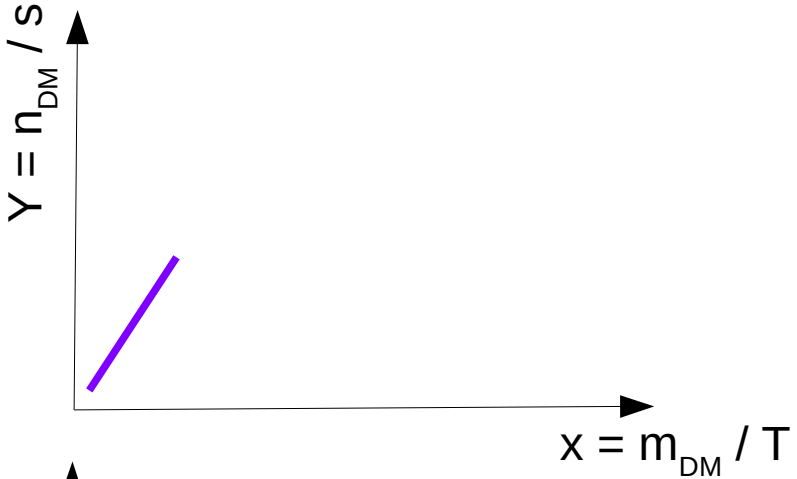
How to dynamically produce such a difference of temperatures?

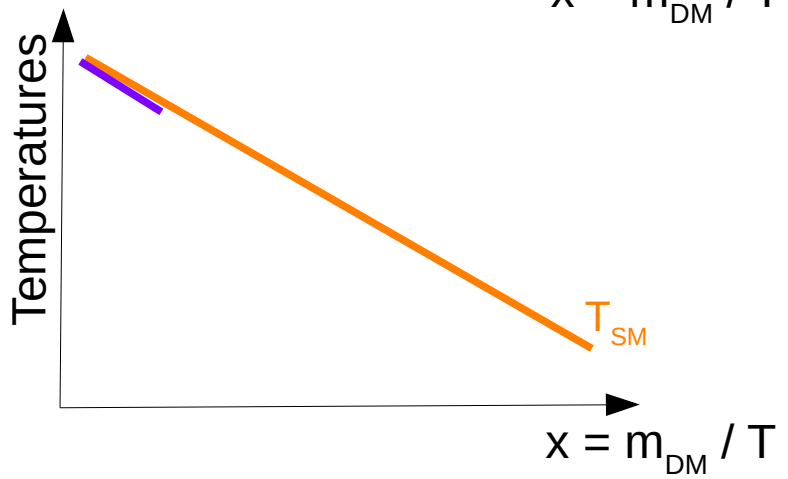
(Non-) Thermal evolution of DM





(Non-) Thermal evolution of DM

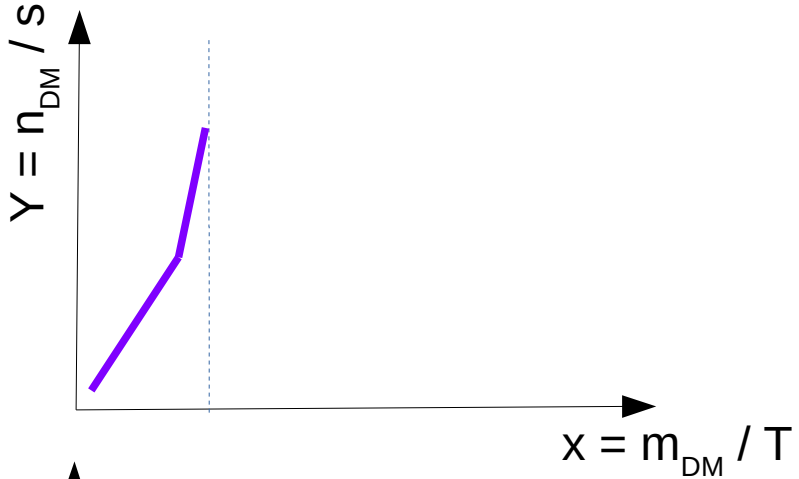


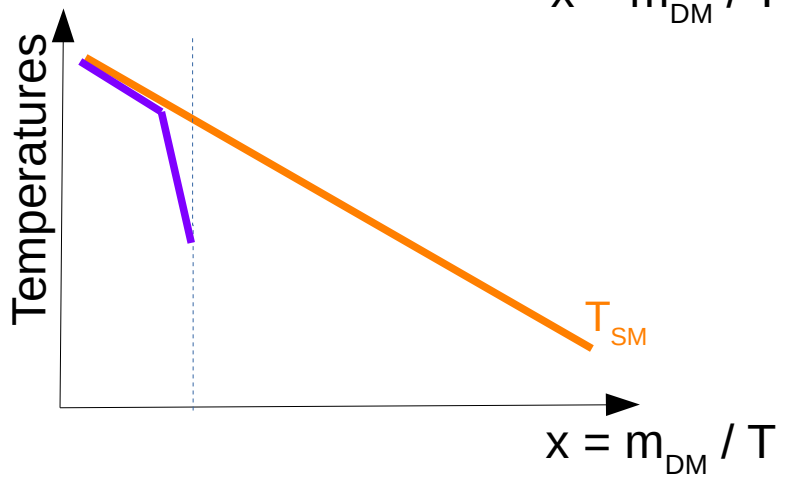


DM Production

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

(Non-) Thermal evolution of DM



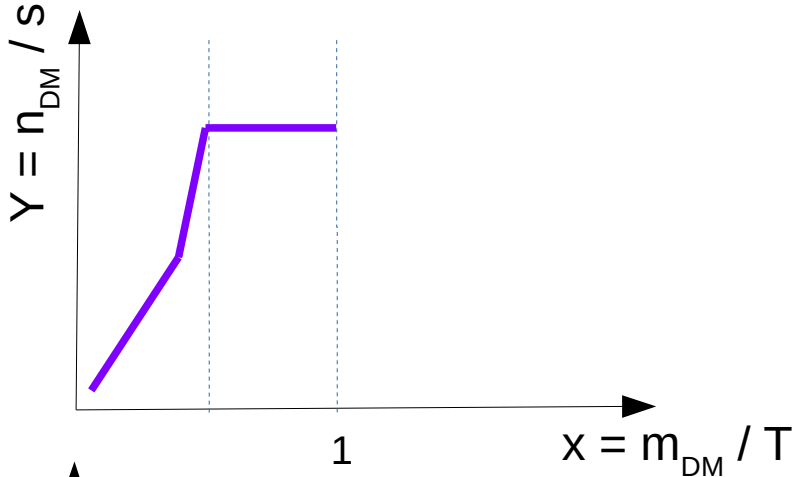


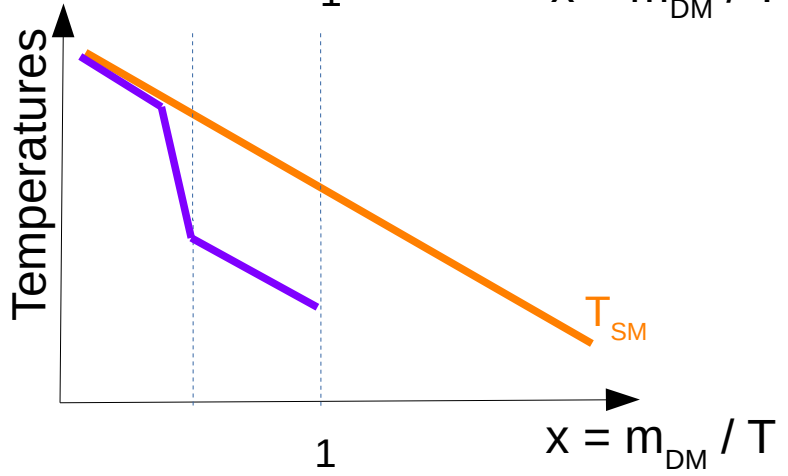
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* DM populates rapidly via out-of-equilibrium **2 → 4**.
  Price to pay: Dramatic decrease of T_{DM}

(Non-) Thermal evolution of DM





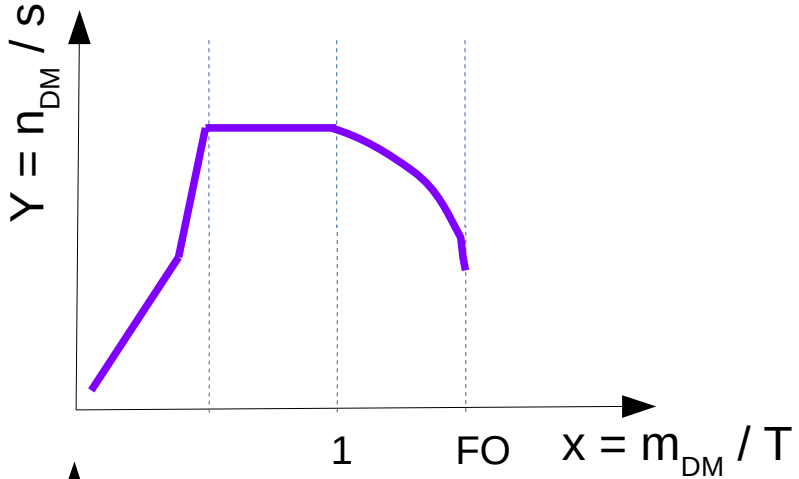
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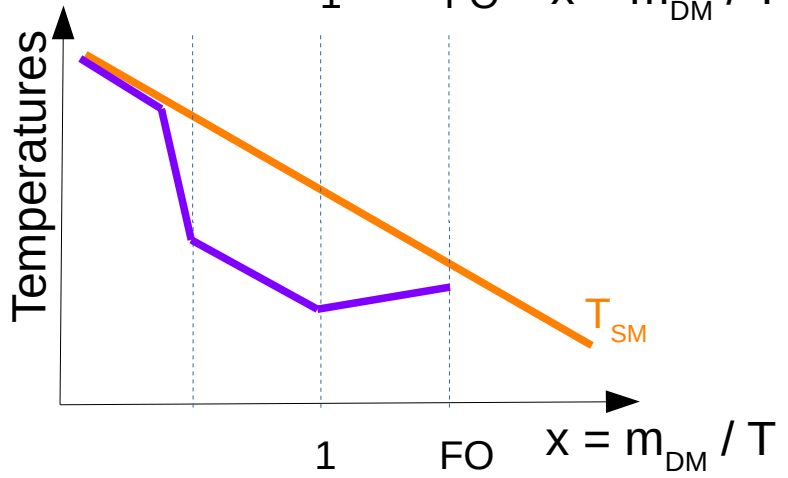
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Thermal Equilibrium

* Chemical equilibrium **2 ↔ 4**

(Non-) Thermal evolution of DM





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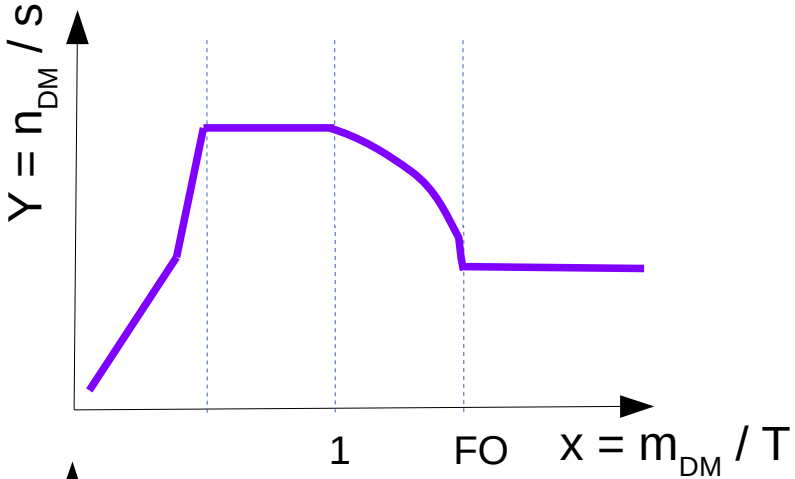
Thermal Equilibrium

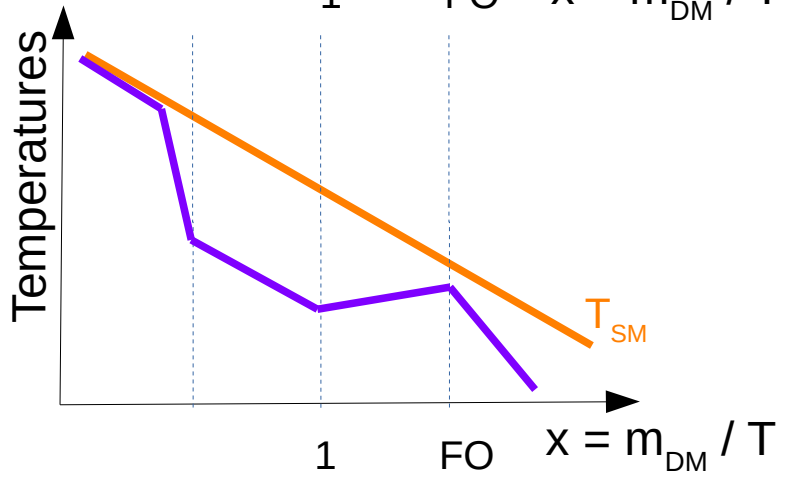
* Chemical equilibrium **2 ↔ 4**

DM Annihilation

* Freeze-out **4 → 2**

(Non-) Thermal evolution of DM





DM Production

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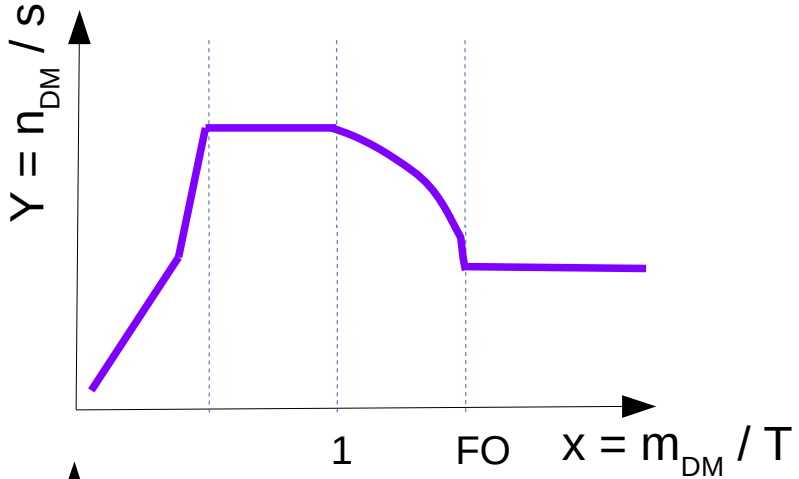
DM Annihilation

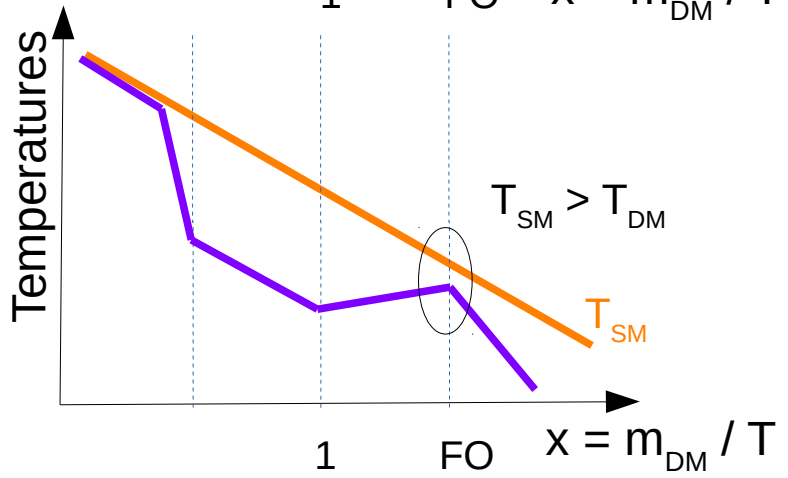
* Freeze-out **4 → 2**

After the Freeze-out

* Relic abundance
  Non-relativistic DM cools down faster

(Non-) Thermal evolution of DM





DM Production

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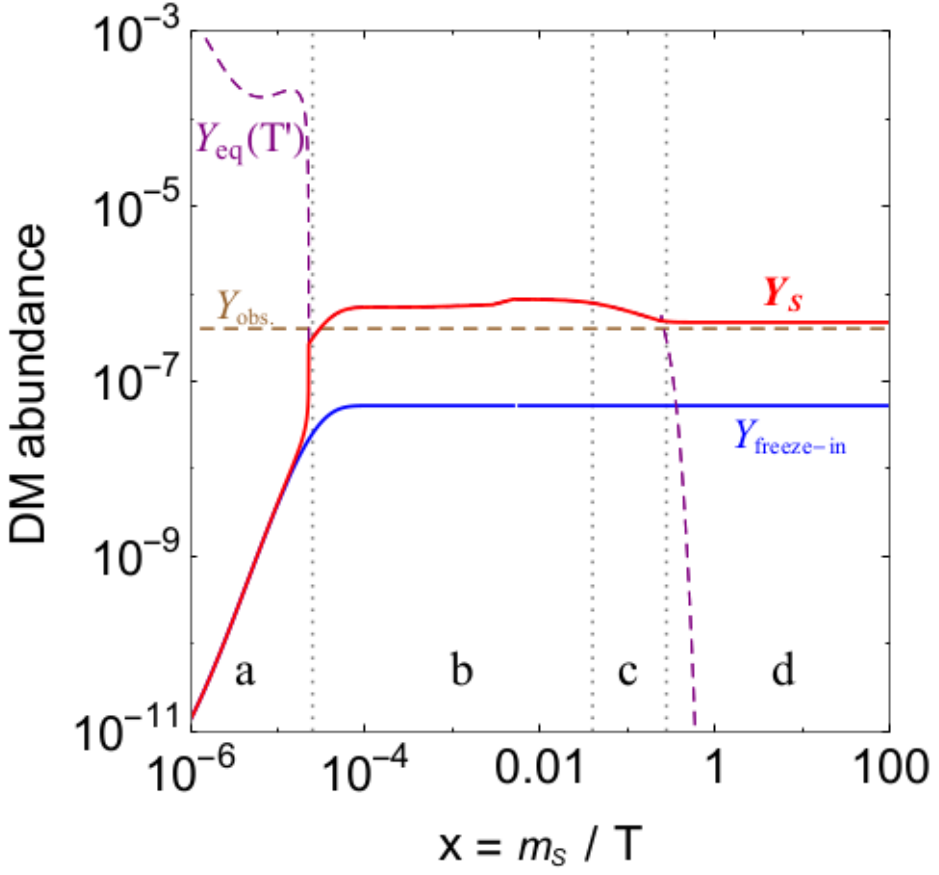
DM Annihilation

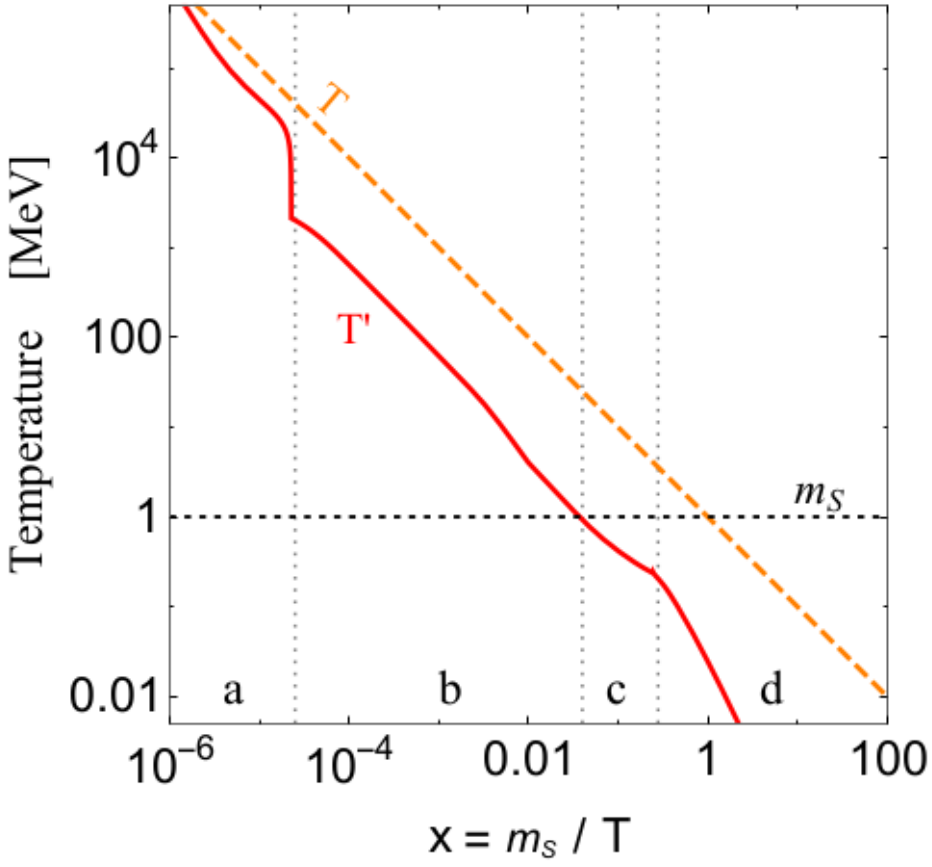
* Freeze-out **4 → 2**

After the Freeze-out

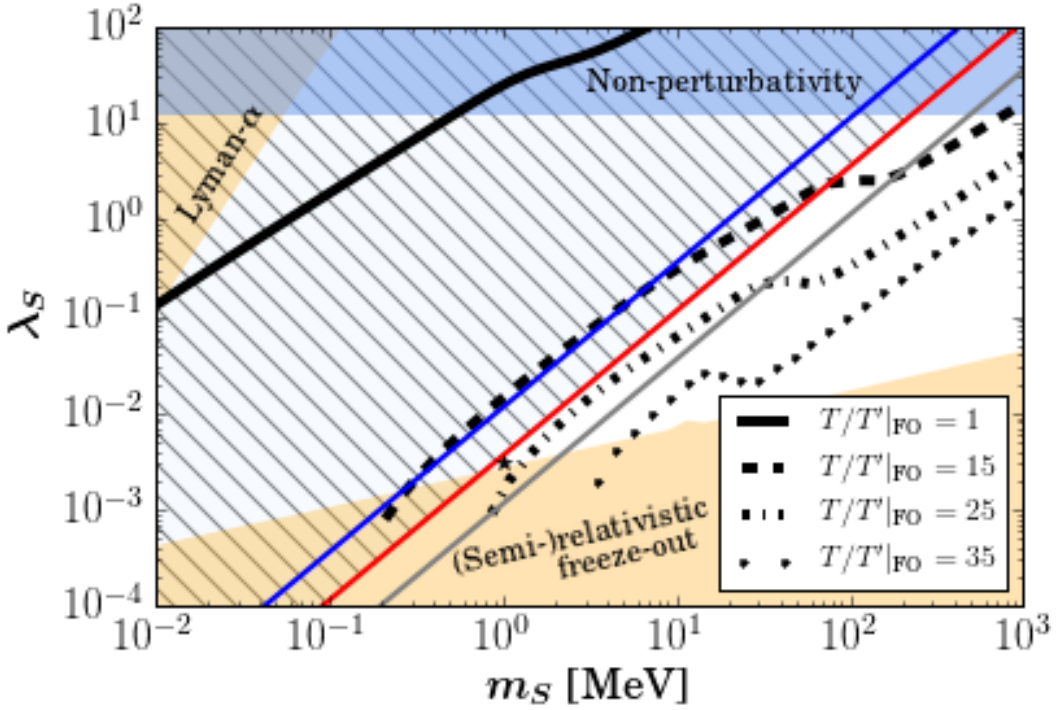
* Relic abundance
  Non-relativistic DM cools down faster

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

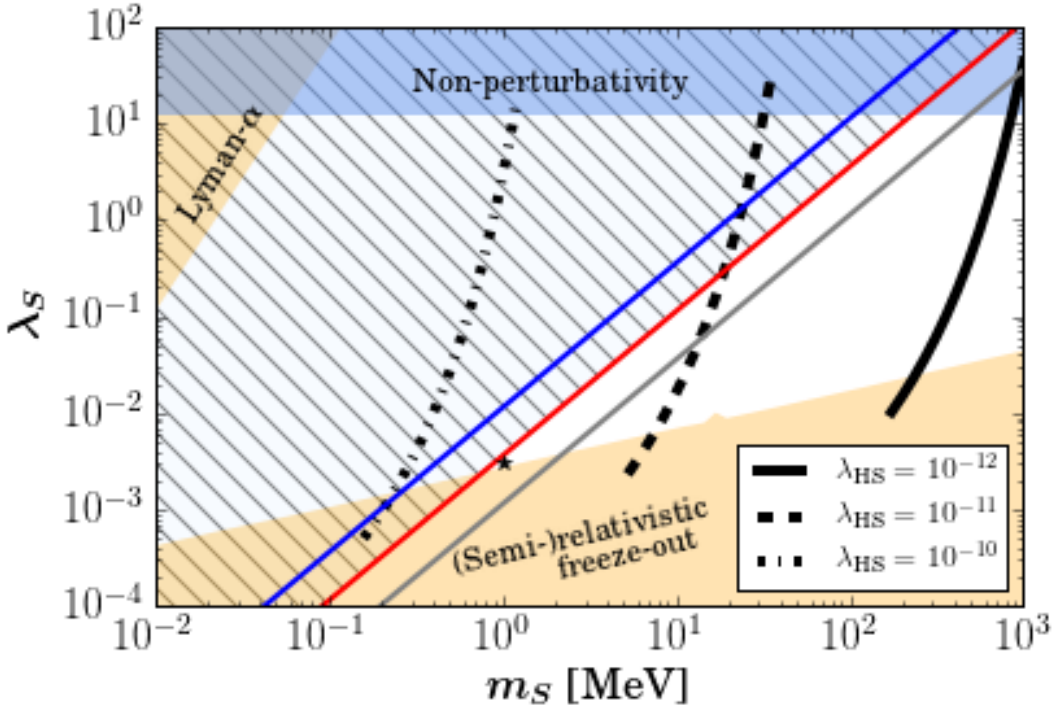




Singlet Scalar DM
$4 \to 2$ annihilations



Singlet Scalar DM
$4 \to 2$ annihilations



$3 \rightarrow 2$ annihilations can also do the job: Hidden Vector Dark Matter

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Hidden Vector DM

T. Hambye '08

$SU(2)_{\rm DM}$ with gauge boson A_μ + φ scalar doublet with no SM charges

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} F'^{\mu\nu} \cdot F'_{\mu\nu} + (D_\mu \phi)^\dagger (D^\mu \phi) - \mu_\phi^2 \, \phi^\dagger \phi - \lambda_\phi \, (\phi^\dagger \phi)^2 - \lambda_m \, \phi^\dagger \phi \, H^\dagger H$$

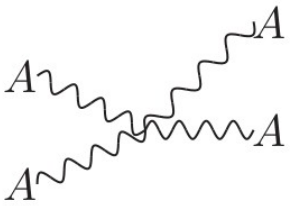
φ spontaneously break the $SU(2)_{\rm DM} \rightarrow$ accidental $SO(3)_{DM}$ symmetry

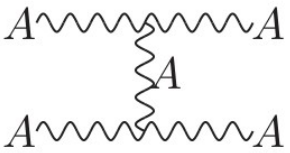
4 free parameters:

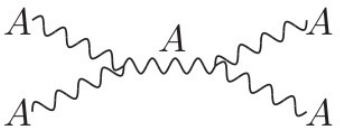
* m_A DM mass
* α_X gauge coupling
* m_φ φ mass
* λ_m Higgs portal

Hidden Vector DM

Self-Interactions







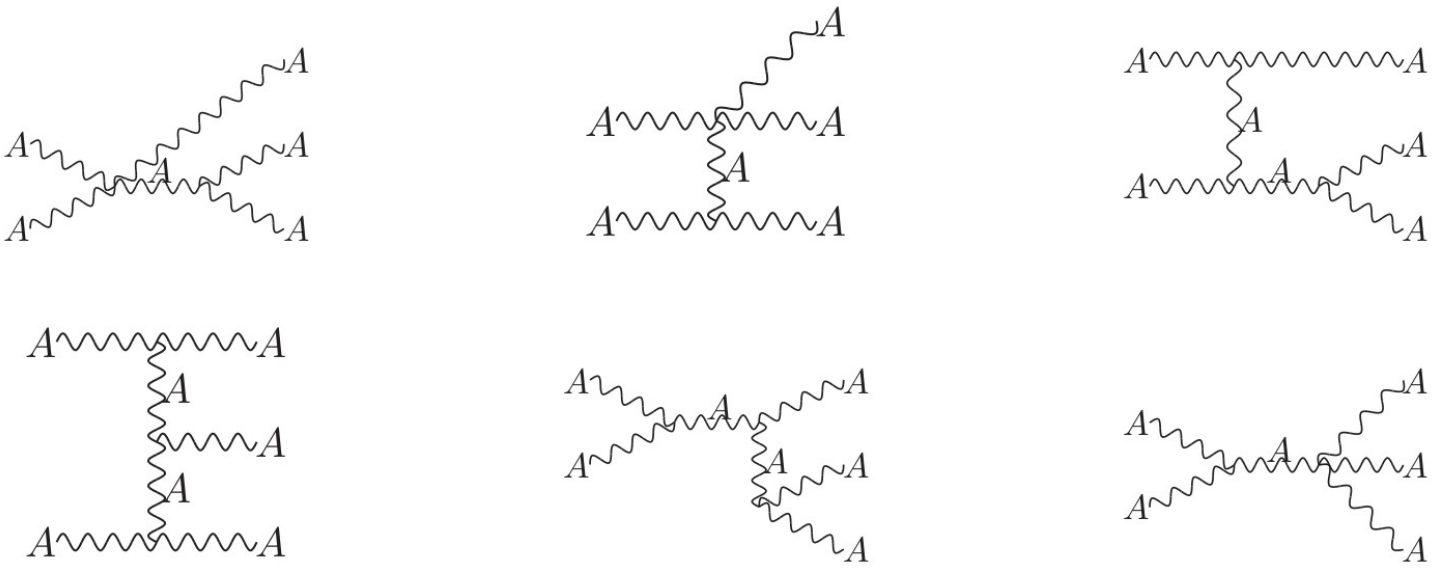
$$\sigma_{AA} = \frac{65}{9}\frac{\alpha_X^2}{m_A^2}\left[1 + \mathcal{O}\left(\frac{m_A^2}{m_\eta^2}\right)\right]$$

$$\frac{\sigma_{SS}}{m_S} \sim O(1)\ \text{cm}^2/\text{g}$$ Implies { * α_X ~ 1 * m_A ~ 100 MeV

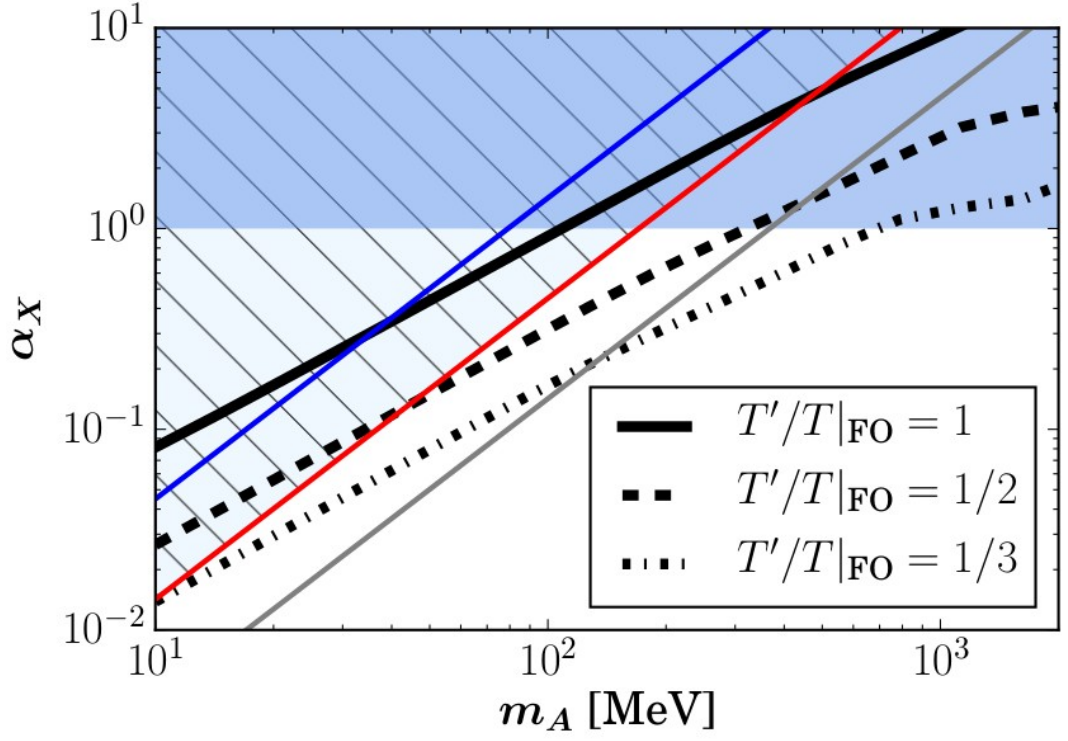
Assuming there's no light mediator! $m_\varphi > m_A$

Hidden Vector DM
$3 \to 2$ annihilations

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



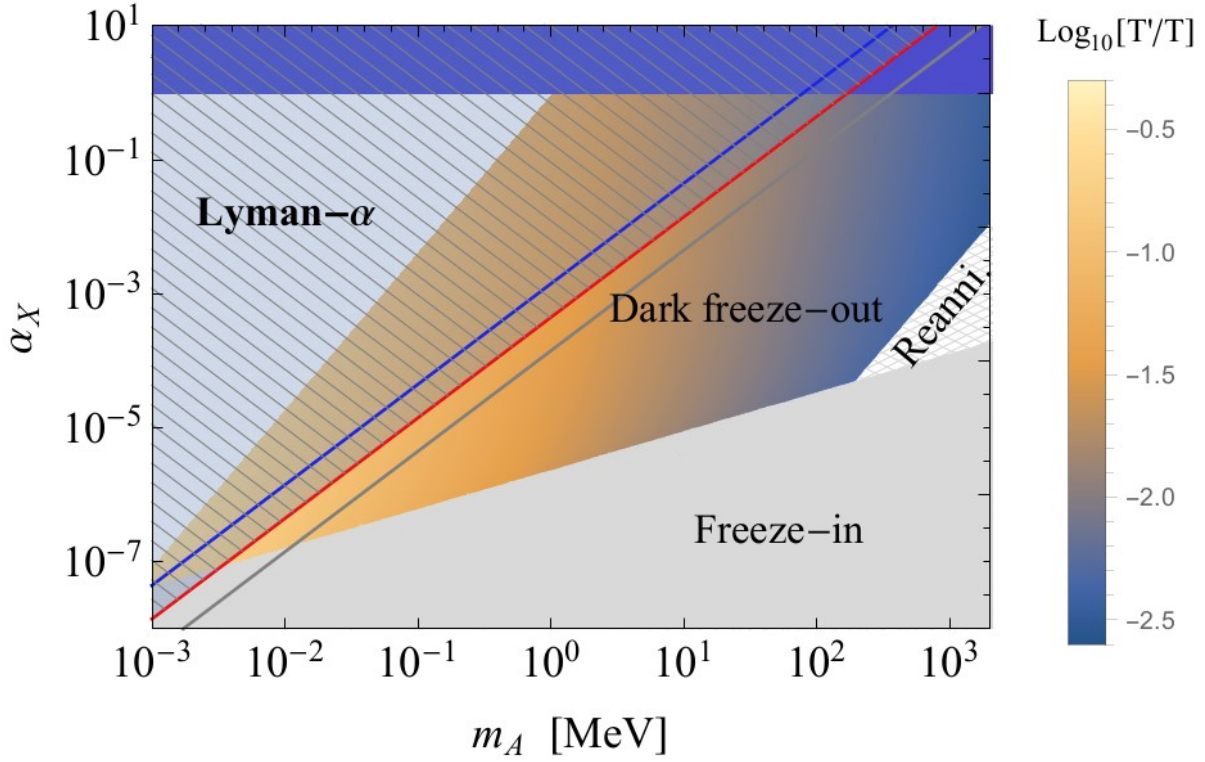
Hidden Vector DM
$3 \to 2$ annihilations



σ/m [cm²/g]

{ 10
1
0.1

Hidden Vector DM
$3 \to 2$ annihilations



Now let’s Split SIMPs! :-)

Splitting SIMPs

- 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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- 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.

Producing Split SIMPs

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Split SIMPs
$4 \to 2$ annihilations

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



We take $m_V > m_1 + m_2$

Split SIMPs
$4 \to 2$ annihilations

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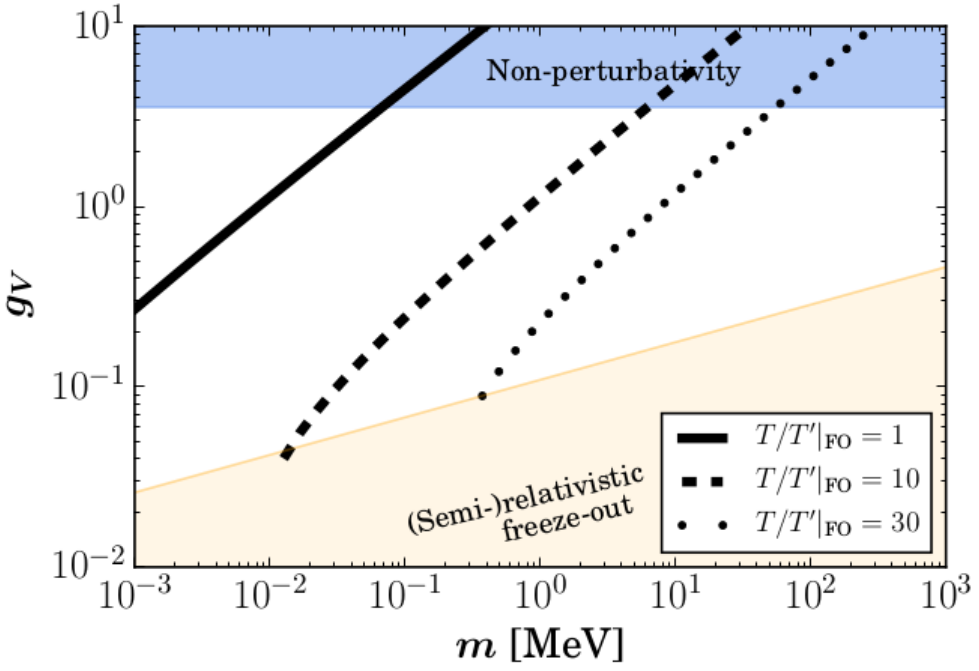
$$\langle \sigma v^3 \rangle_{4\to 2} = \left[\langle 1122 \to 22\rangle + \langle 1122 \to 11\rangle\right]\frac{R^2}{(1+R)^4}$$

$$\langle 1122 \to 11\rangle = \langle 1122 \to 22\rangle = \frac{27\sqrt{3}\,g_V^8}{32\pi}\frac{\left(m_V^4 - 8m^2m_V^2 - 8m^4\right)^2}{\left(m_V^4 - 2m^2m_V^2 - 8m^4\right)^4}$$

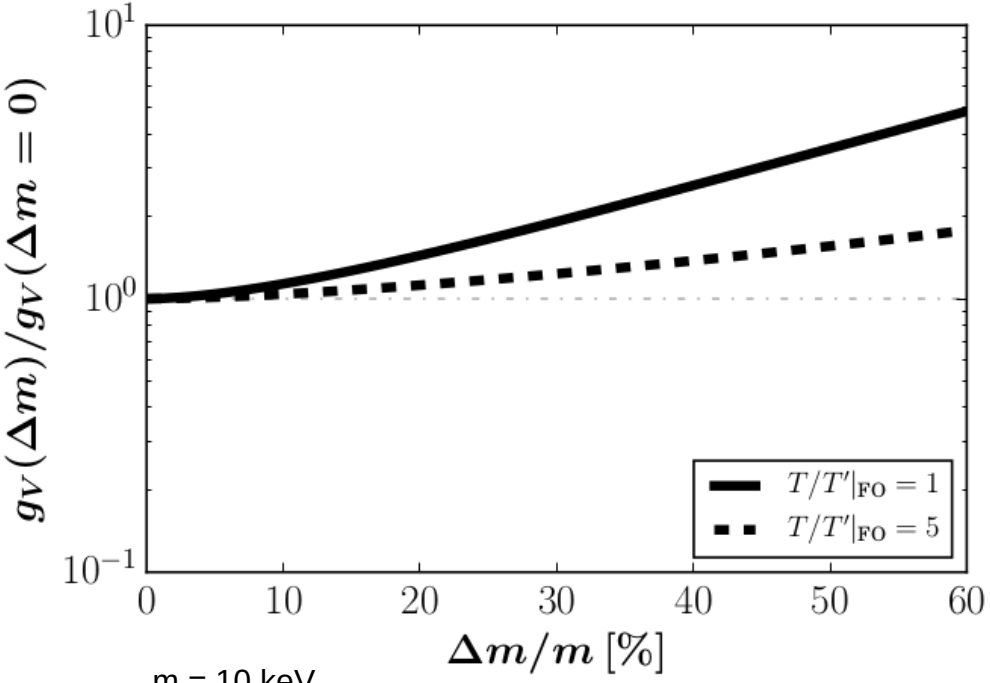
We take $m_V > m_1 + m_2$

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

Split SIMPs
$4 \to 2$ annihilations



Δm = 0
m_V = 2.5 m



m = 10 keV
m_V = 2.5 m + Δm

Astrophysical Implications of Split SIMPs

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(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.

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

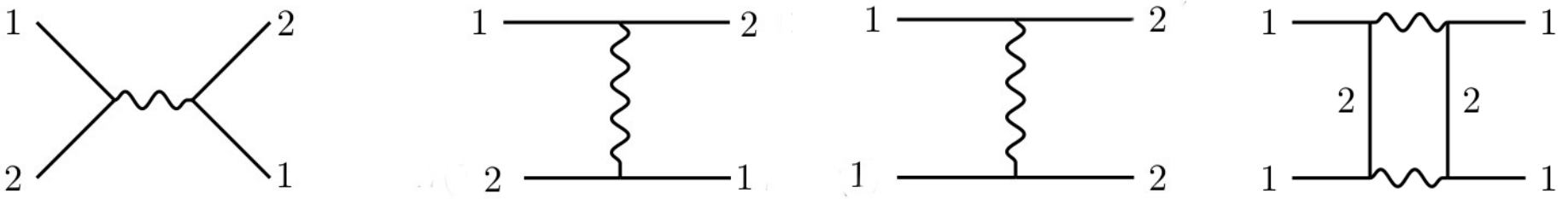
$$\Gamma_{\chi_2\to\chi_1 e^+e^-} \simeq \frac{2\alpha\,\alpha_V\,\kappa^2}{15\pi}\frac{\Delta m^5}{m_V^4} \simeq 2\,H_0 \times \frac{m}{100\ \text{MeV}}\frac{\alpha_V}{\alpha}\left(\frac{\kappa}{10^{-10}}\right)^2\left(\frac{\Delta m/m}{10^{-3}}\right)^5\left(\frac{m}{m_V}\right)^4$$

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

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

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

Self-scatterings



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

Free-streaming Length

4-to-2
'reheat' DM
Increasing the FSL

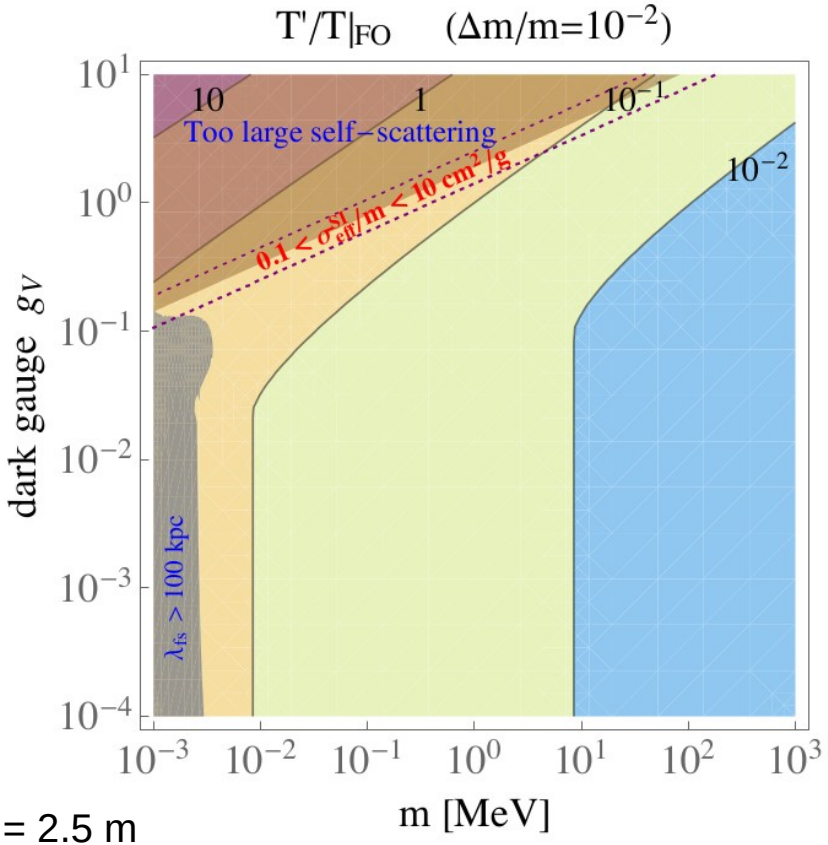
← Versus →

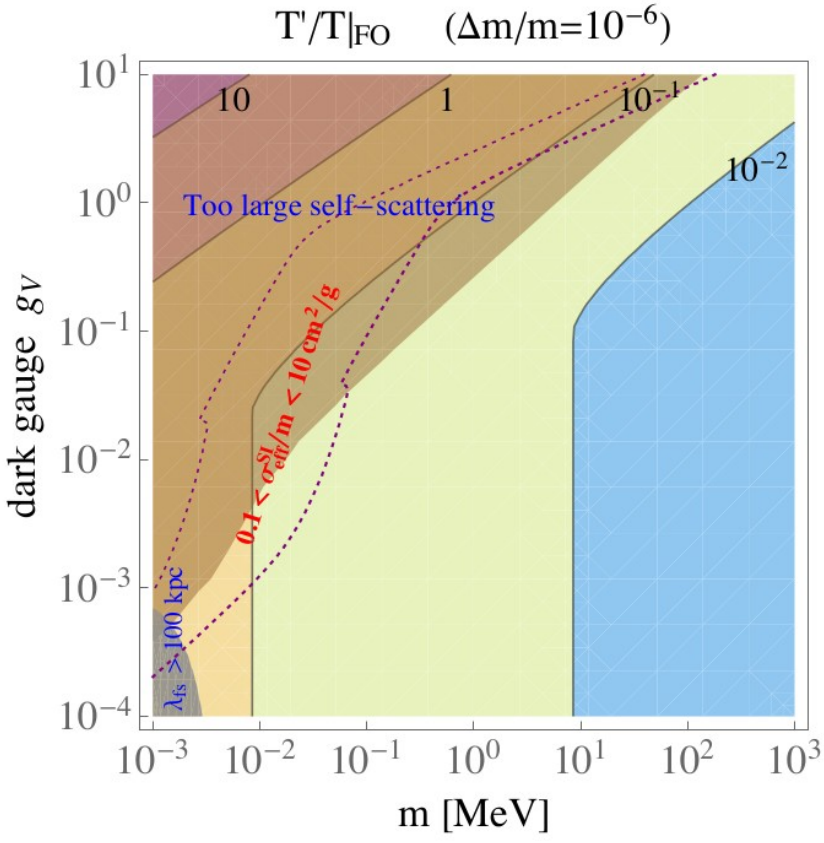
2-to-2
Self-interactions
Decrease the FSL

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

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

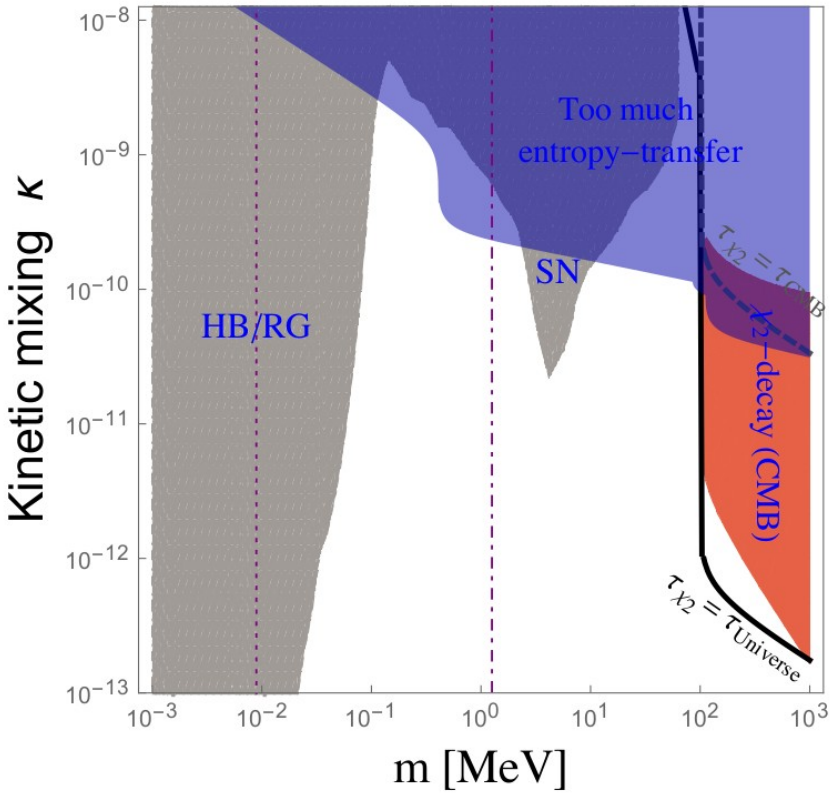
Astrophysical implications of Split SIMPs





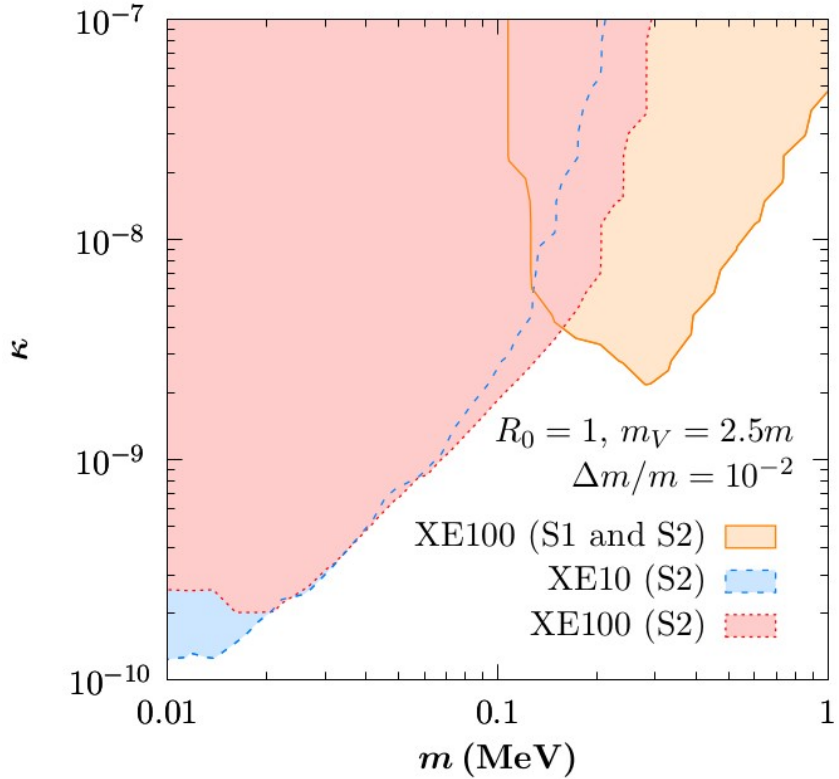
m_V = 2.5 m

Constraints on the Kinetic Mixing Portal

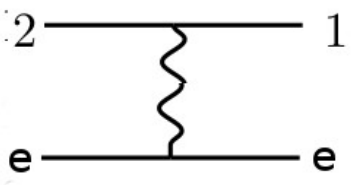


$\Delta m / m = 10^{-2}$
$m_V = 2.5\ m$

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!

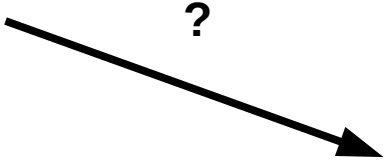
On the verge of being probable with reported data (S1 and S2) from XENON100!

Conclusions

Small-scale anomalies
* Cusp-vs-core
* Too-big-to-fail

Conclusions

Small-scale anomalies
* Cusp-vs-core
* Too-big-to-fail



Self-Interacting
Dark Matter

$\frac{\sigma_{SS}}{m_S} \sim O(1)$ cm^2/g

Conclusions

Small-scale anomalies
* Cusp-vs-core
* Too-big-to-fail

?

Self-Interacting
Dark Matter

$\frac{\sigma_{SS}}{m_S} \sim O(1)$ cm^2/g

$m_S \sim 100$ MeV
$\lambda_S \sim 1$
$\lambda_{HS} < 10^{-3}$

Conclusions

Small-scale anomalies
* Cusp-vs-core
* Too-big-to-fail

?

Self-Interacting
Dark Matter

$\frac{\sigma_{SS}}{m_S} \sim O(1)$ cm^2/g

$m_S \sim 100$ MeV
$\lambda_S \sim 1$
$\lambda_{HS} < 10^{-3}$

SIMP DM
* dominant N → n
* need to avoid the ‘DM reheating’

+ kinetic equilibrium SM ↔ DM
+ dark sector with relativistic particles @ FO
+ SM and DM never in kinetic equilibrium

Conclusions

- Self-interacting DM with no light mediators → SIMP DM
- SIMP DM generated via $3 \to 2$ or $4 \to 2$ annihilations
- DM: MeV ballpark, ‘large’ self-interactions & ‘small’ portal with the SM
- If SM - DM sectors could be naturally out of kinetic equilibrium: difference of temperatures *dynamically* produced via freeze-in.
- *DM Self-interactions can play a mayor role in DM genesis.*
- SIMPs offer a new window to DM: Points to different physical scales beyond the usual WIMP and FIMP paradigms

Muchas gracias!



Nicolás BERNAL - UAN