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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October 17th, 2017


Where the hell is Colombia?
Add a missing place to Google Maps.
Caribbean Sea
Guadeloupe
Dominica
Martinique
St Lucia
St Vincent and the Grenadines
Grenada
Aruba
Punto Fijo
Coro
Trinidad and Tobago
Tapachula
Guatemala
Honduras
Tegucigalpa
El Salvador
Nicaragua
Managua
Costa Rica
Panama City
Panama
Barranquilla
Cartagena
Valledupar
Maracaibo
Caracas
Puerto La Cruz
Barquisimeto
Maturin
Sincelejo
Montería
Merida
Barinas
Guayana City
Apartadó
Cúcuta
San Cristobal
Sierra Imataca
Bucaramanga
Georgetown
Linden
Paramaribo
Medellín
El Caura
Tunja
Parque Nacional Natural El Tuparro
Parque Nacional Canaima
Guyana
Pereira
Bogotá
Villavicencio
Suriname
French Guian
Parc Amazonien de Guyane
Cali
Colombia
Neiva
Popayán
Boa Vista
Parque Nacional Parima Tapirapecó
STATE OF RORAIMA
PARQUE DO TUMUCUMAQUE
RIO PARU DESTE
Pasto
ALTO RIO NEGRO
TROMBETAS/MAPUERA
ZOE
Ibarra
Quito
Isla Isabela
MÉDIO RIO NEGRO I
Barcelos
WAIMIRI-ATROARI
Oriximiná
Monte Alegre
Manta
Ecuador
Salinas
Parque Nacional Natural Río Puré
Parque Nacional do Jaú
Santarém
Parintins
Fonte Boa
Manaus
Itacoatiara
Urucurituba
Cuenca
Tefé
ANDIRÁ-MARAU
Loja
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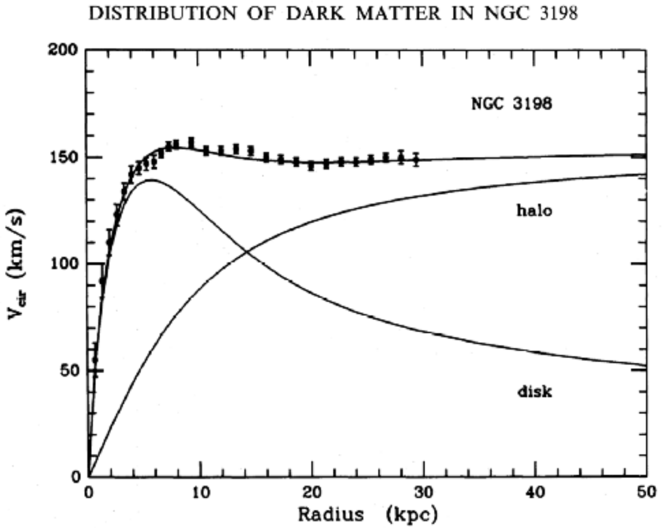
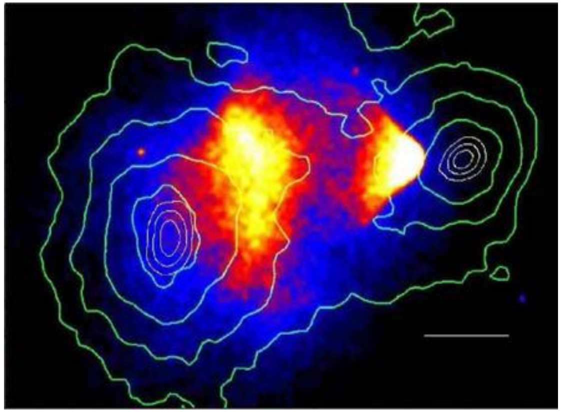
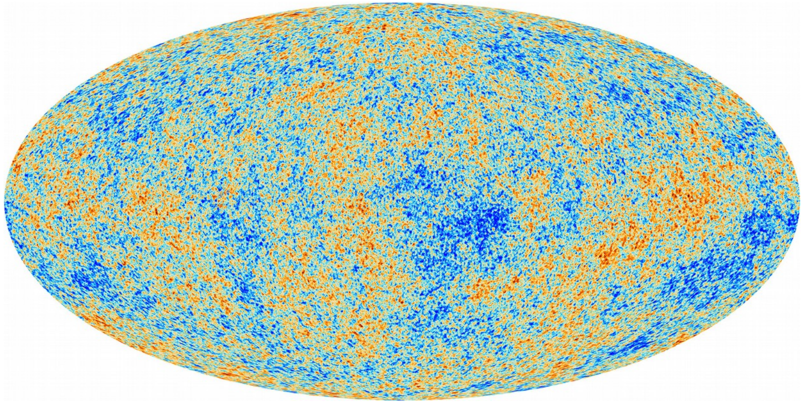
Evidences for Dark Matter

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

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

Dark Matter is there! :-)

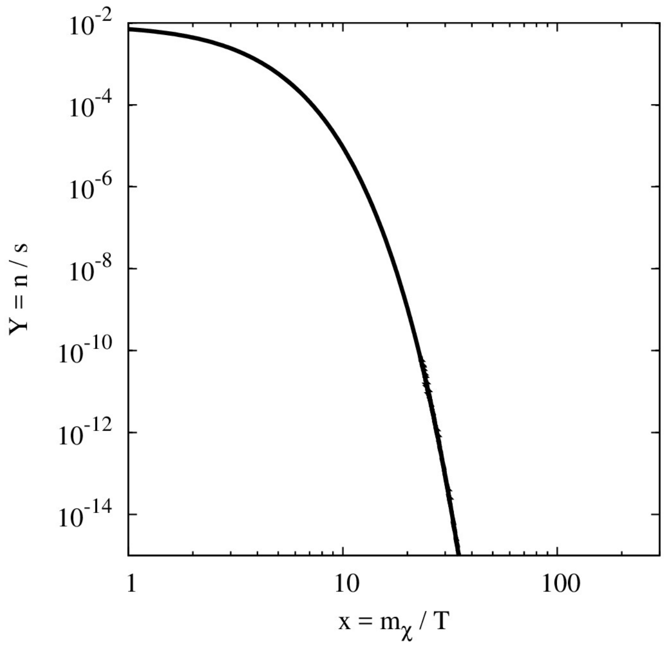
But what is it? :-/

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

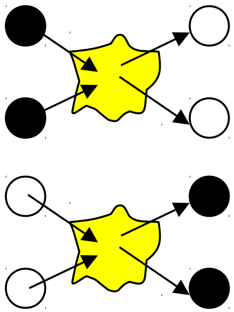
Dark Matter needs
New Physics beyond the Standard Model!

Thermal Collisionless Cold Dark Matter

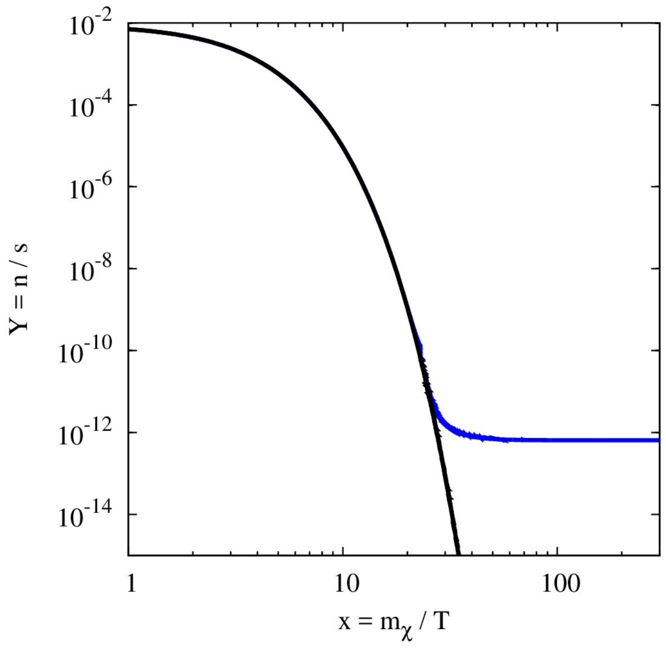
Vanilla WIMP Dark Matter



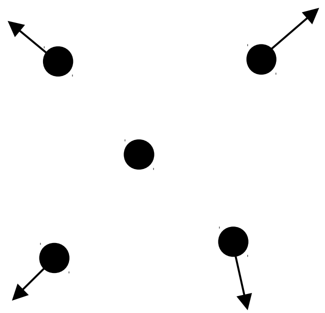
Early Universe:
DM in thermal equilibrium
with the Standard Model.



Vanilla WIMP Dark Matter

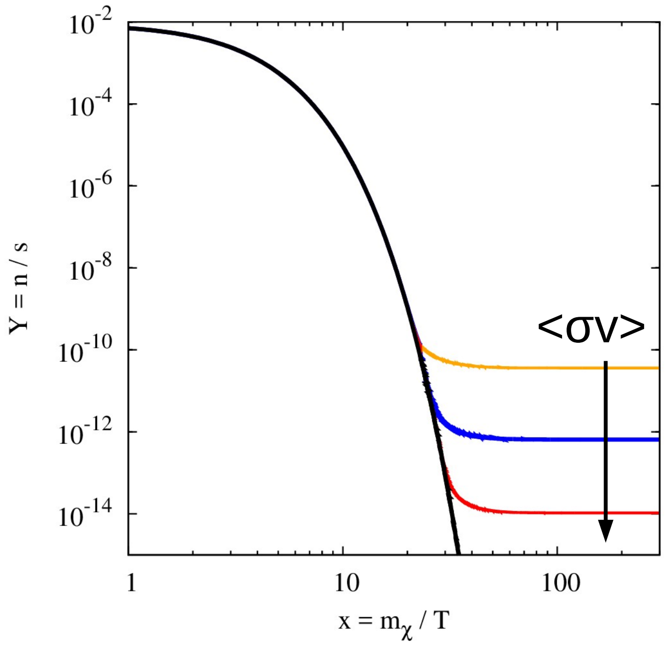


Due to the expansion of the Universe DM particles fall out of equilibrium and cannot annihilate any more.



A Relic Density of DM is obtained which remains constant.

Vanilla WIMP Dark Matter



$\langle \sigma v \rangle \sim 3\times10^{-26}$ cm^3/s

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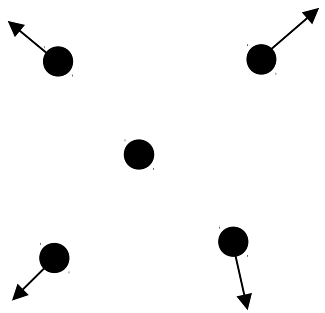
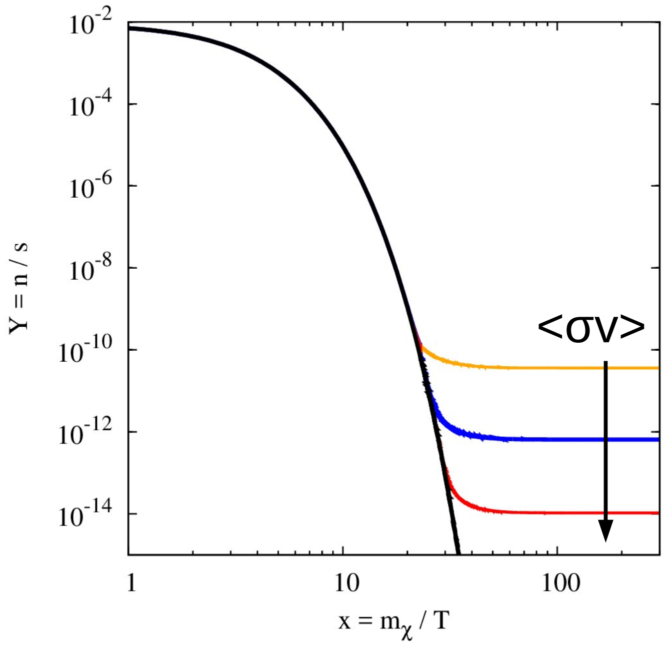


A particle with very weak interactions decouples earlier, having a larger relic density.

A Relic Density of DM is obtained which remains constant.

A particle with stronger interactions keeps in equilibrium for longer, and is more diluted.

Vanilla WIMP Dark Matter



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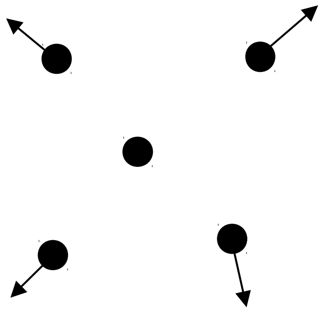

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$\langle\sigma v\rangle \sim 3\times10^{-26}$ cm^3/s

→ ***Collisionless cold*** Dark Matter

Collisionless Dark Matter in Trouble?!

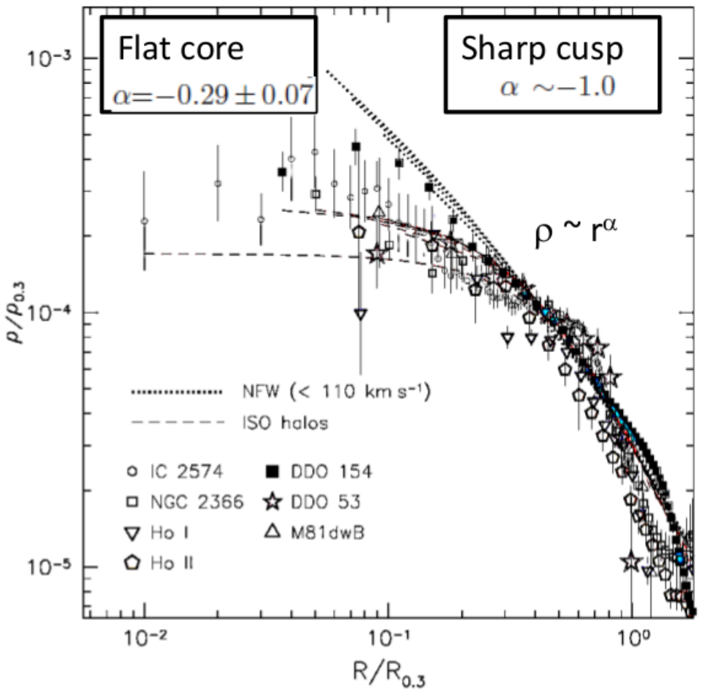
Collisionless cold Dark Matter in Trouble

* Core-vs-cusp problem

Moore '94, Flores & Primack '94

→ Central densities of halos exhibit cores
→ N-body simulations $\rho \sim r^{-1}$

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

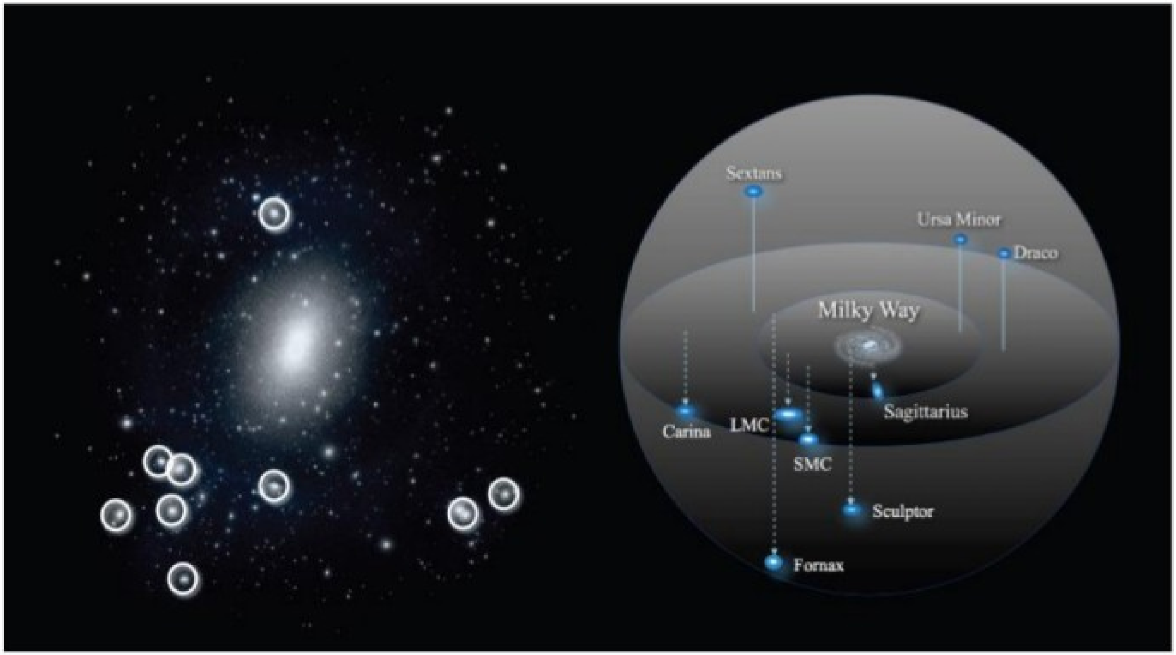


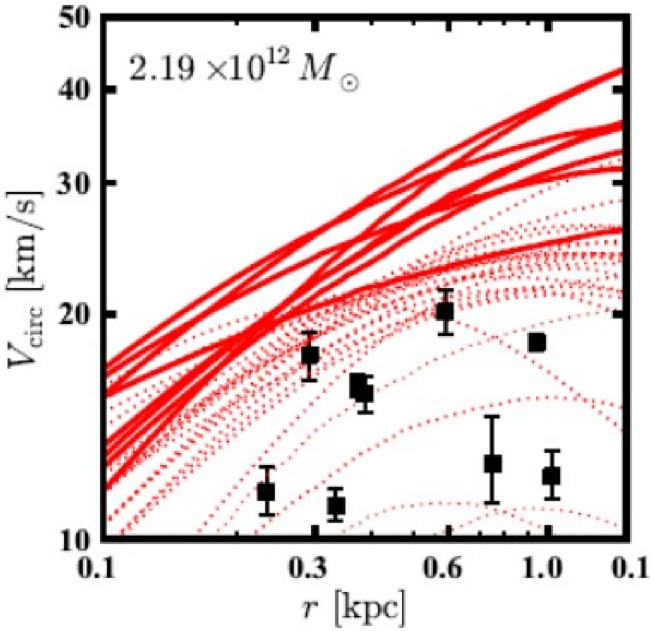
* Field dwarfs
* Satellite dwarfs galaxies
* Low surface brightness galaxies (LSBs)
* Clusters

Collisionless cold Dark Matter in Trouble

* **Too-big-to-fail problem** Boylan-Kolchin, Bullock, Kaplinghat ('11 + '12)

MW galaxy should have ~10 satellite galaxies which are more massive than the most massive dwarf spheroidals





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*

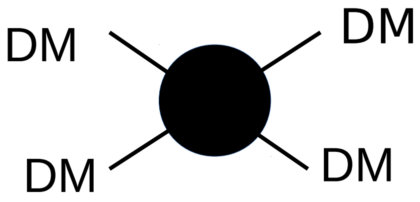
  DM may not be collisionless

Self-interacting Dark Matter

CDM structure problems could be solved if dark matter is **self-interacting**.

Dark matter particles in halos elastically scatter with other dark matter particles.

Spergel & Steinhardt (2000)



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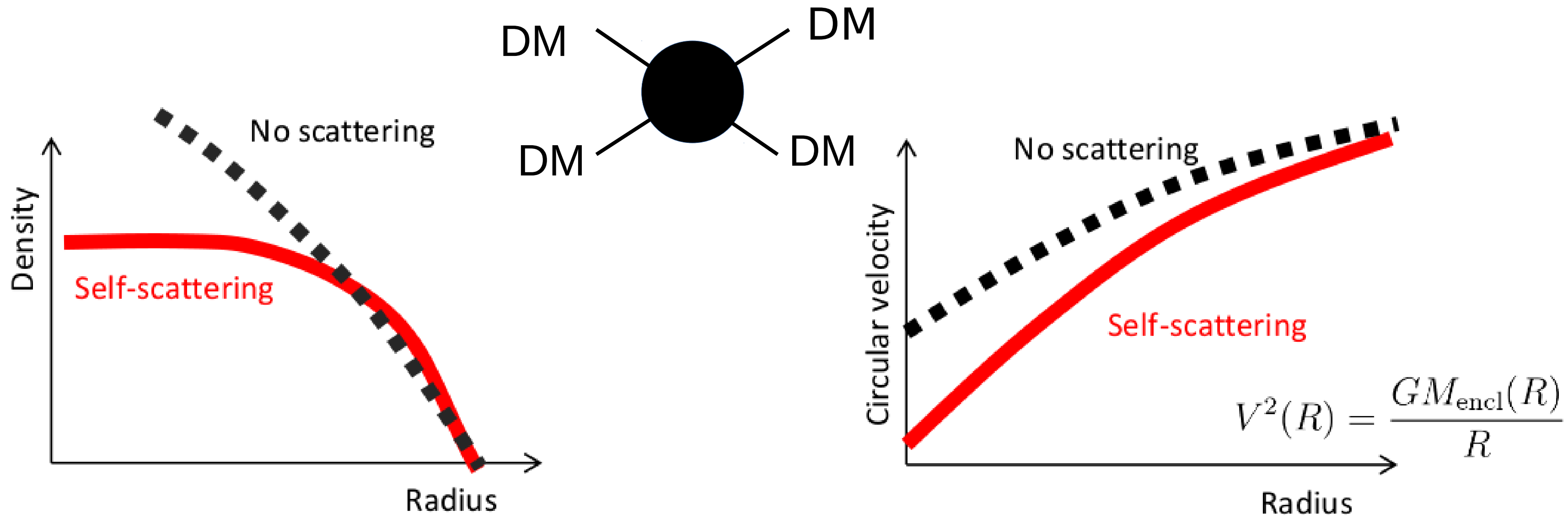

Self-interactions solve core-vs-cusp
Particles get scattered out of dense halo centers

Self-interactions solve too-big-to-fail
Rotation curves reduced (less enclosed mass)
Simulated satellites matched to observations

Small-scale problems → Self-interacting DM

Small-scale problems:

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

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* *Dark Matter*

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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

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

Singlet Scalar DM

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3 free parameters:

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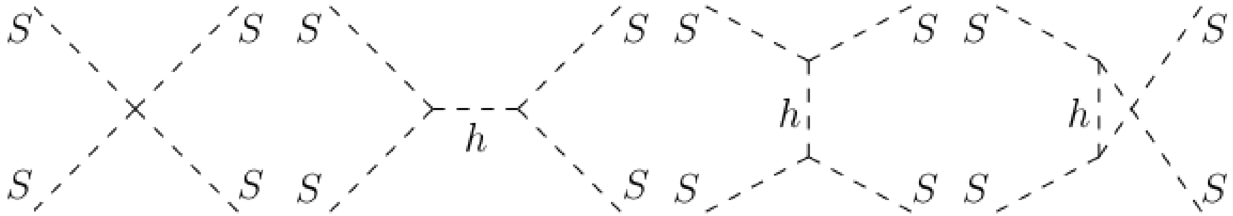
* λ_{HS} Higgs portal

} ← Concentrated on this

* λ_S DM quartic coupling ← ~ Ignored!

Dark Matter Self-Interactions

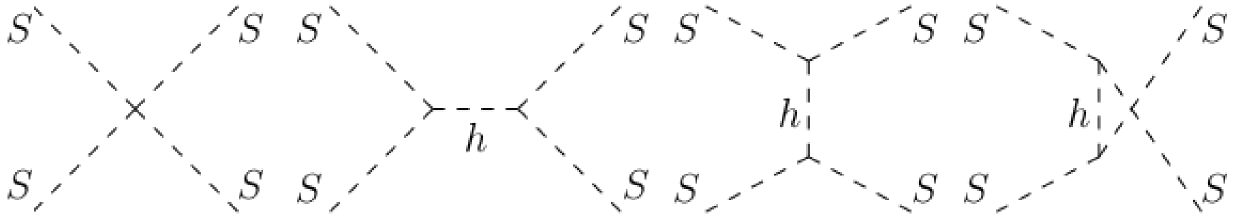


$$\frac{\sigma_{SS}}{m_S} \sim \frac{9}{8\pi} \frac{\lambda_S^2}{m_S^3}$$

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

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

Dark Matter Self-Interactions & Invisible Higgs decay



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

The Higgs tends to annihilate into DM

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

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

How to produce such a Self-Interacting Dark Matter?

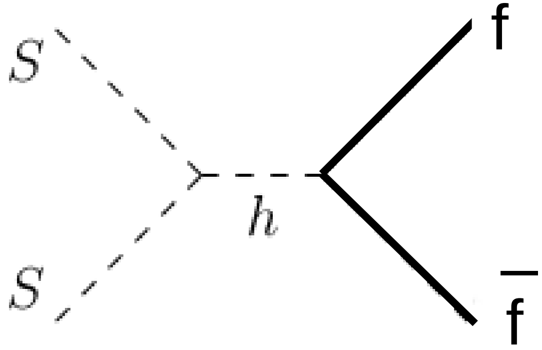
WIMP DM :-/

DM can (only) annihilate into light fermions

other annihilation channels kinematically closed!

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

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



→ Universe overclosed

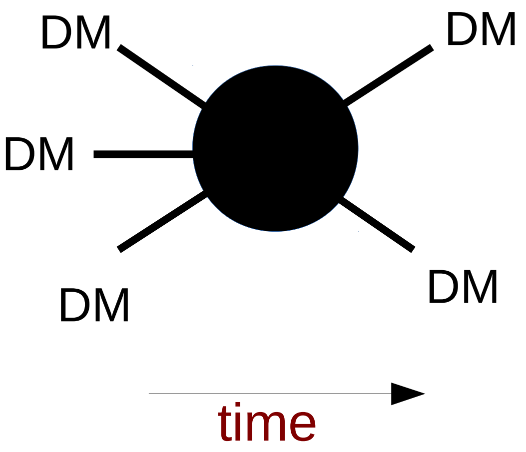
→ SSDM with sizable self-interactions can not be a WIMP

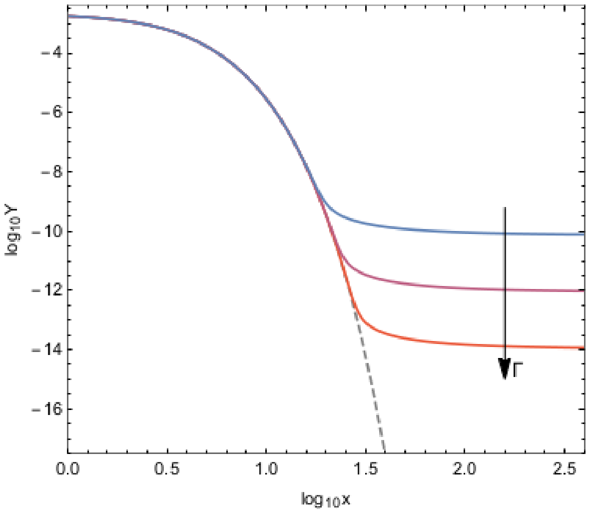
Again: How to produce such a Self-Interacting Dark Matter?

SIMP DM
3→2 annihilations

Hochberg, Kuflik, Volansky & Wacker '14

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





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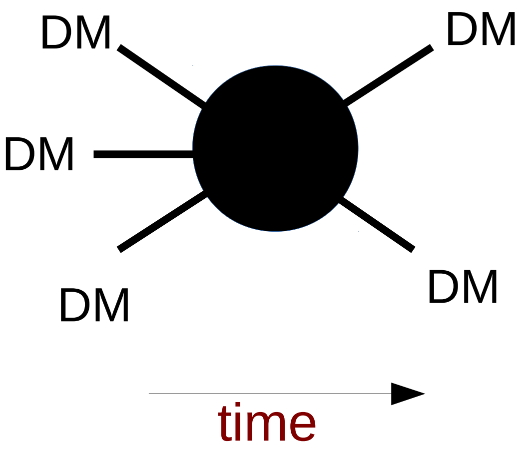

*** DM in the MeV range**

*** Small DM-SM portal**

*** $\lambda_S \sim 1$**

'Strong' Self-interactions
→ SIMP DM

SIMP DM
3→2 annihilations

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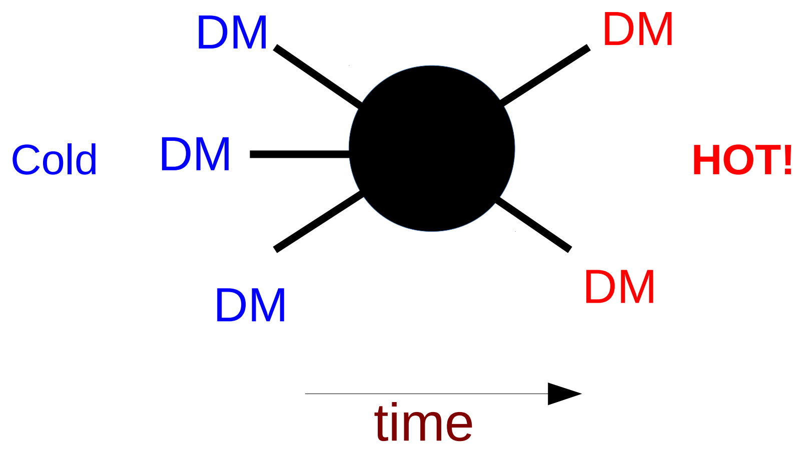
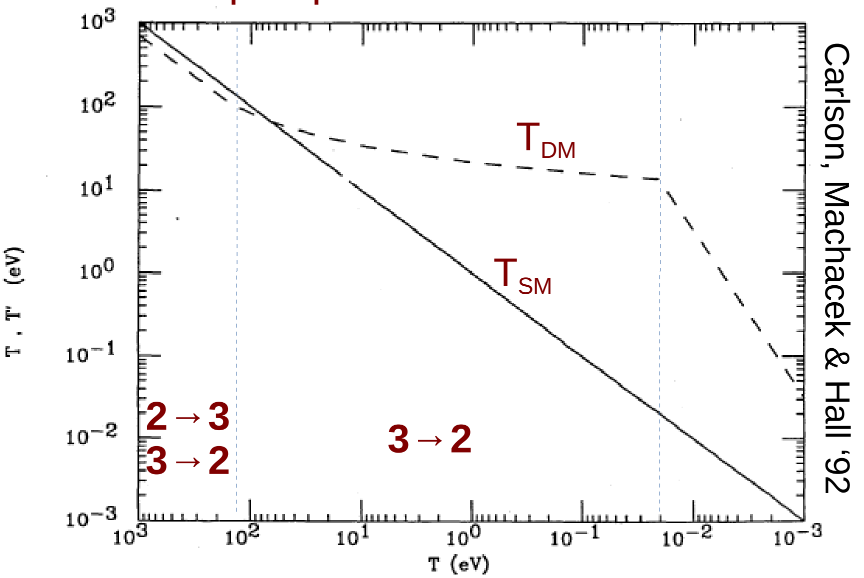
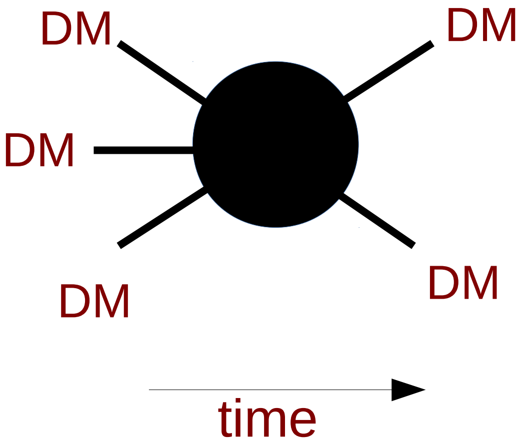


Caveat: 3 → 2 annihilations
pump heat into the dark sector!



SIMP DM
$3\to 2$ annihilations

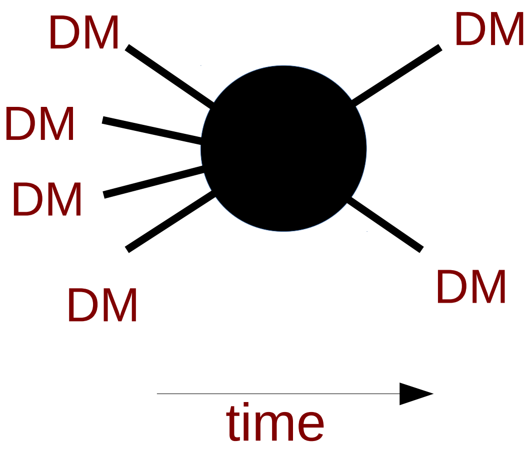
$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v^2\rangle_{3\to 2}\,\left(n^3 - n^2\,n_{\rm eq}\right)$$



However $3\to 2$ 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→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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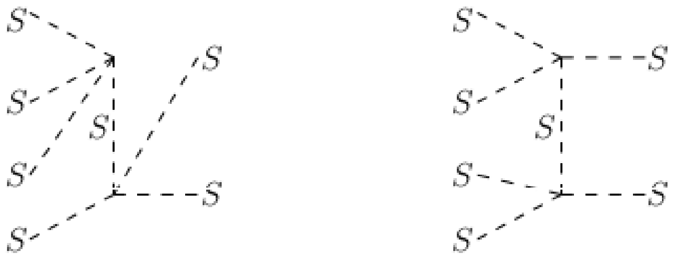
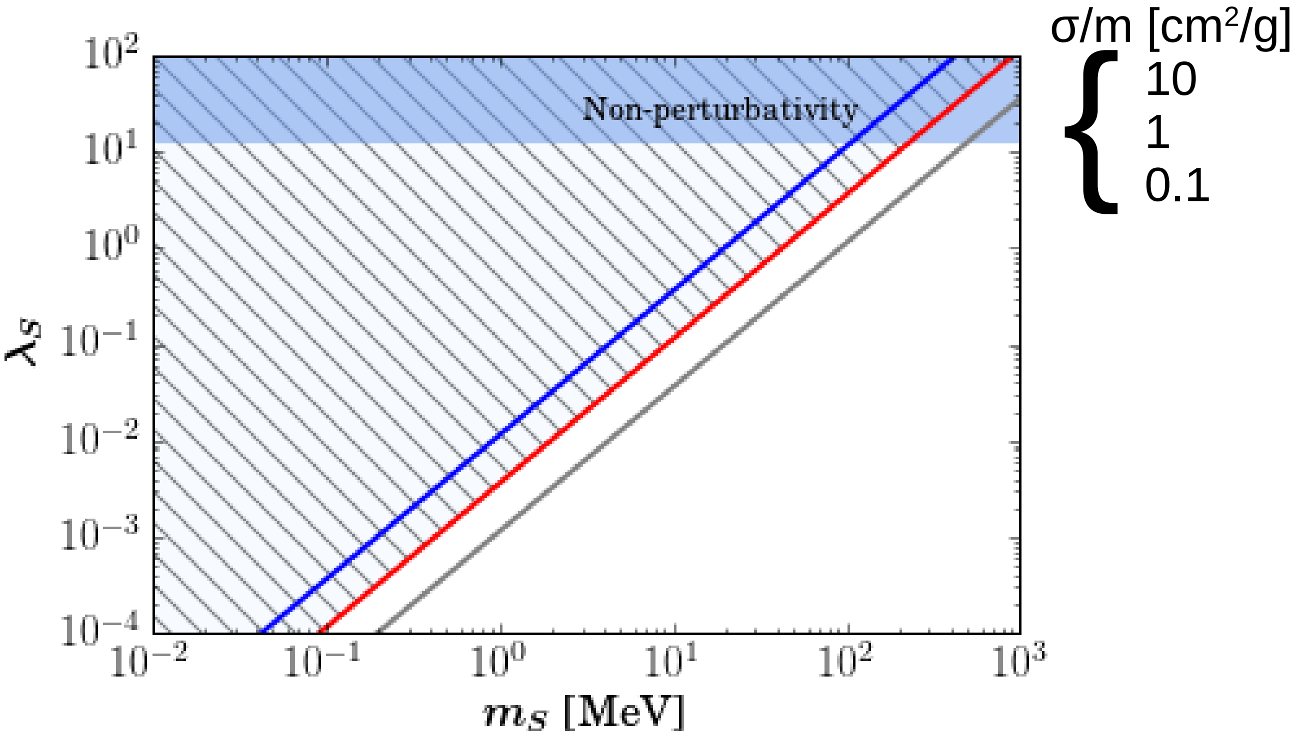


$$\langle\sigma v^3\rangle_{4\to2} \sim \frac{27\sqrt{3}}{8\pi}\,\frac{\lambda_S^4}{m_S^8}$$

Singlet Scalar DM
4→2 annihilations



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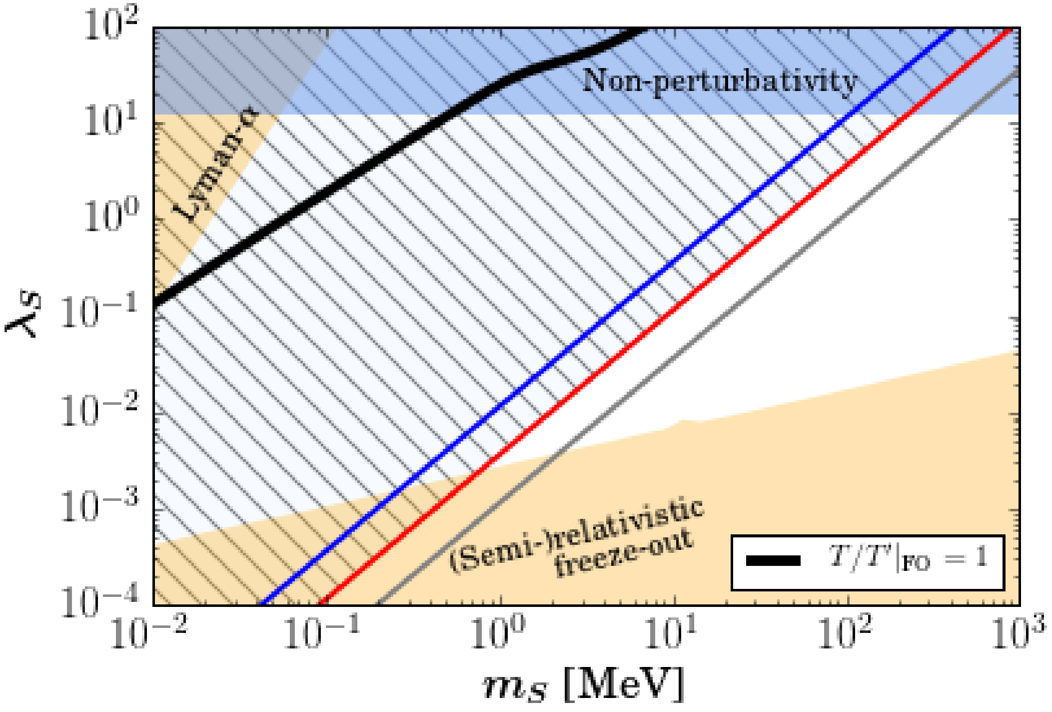
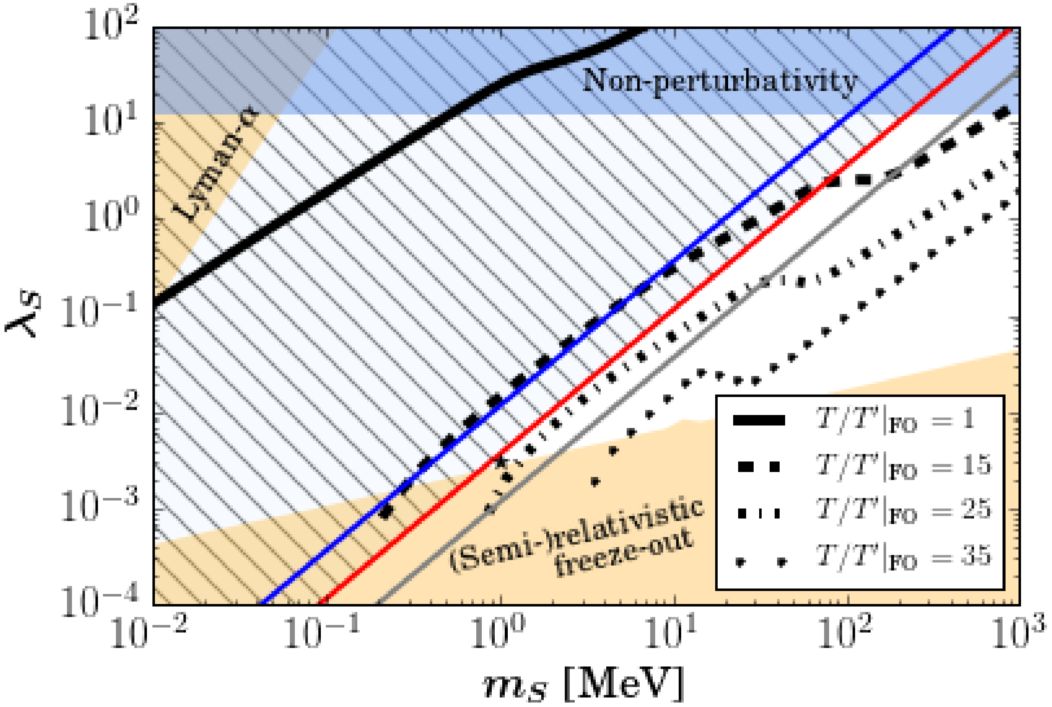


$T_{SM} = T_{DM}$ @ DM freeze-out

Singlet Scalar DM
$4 \to 2$ annihilations



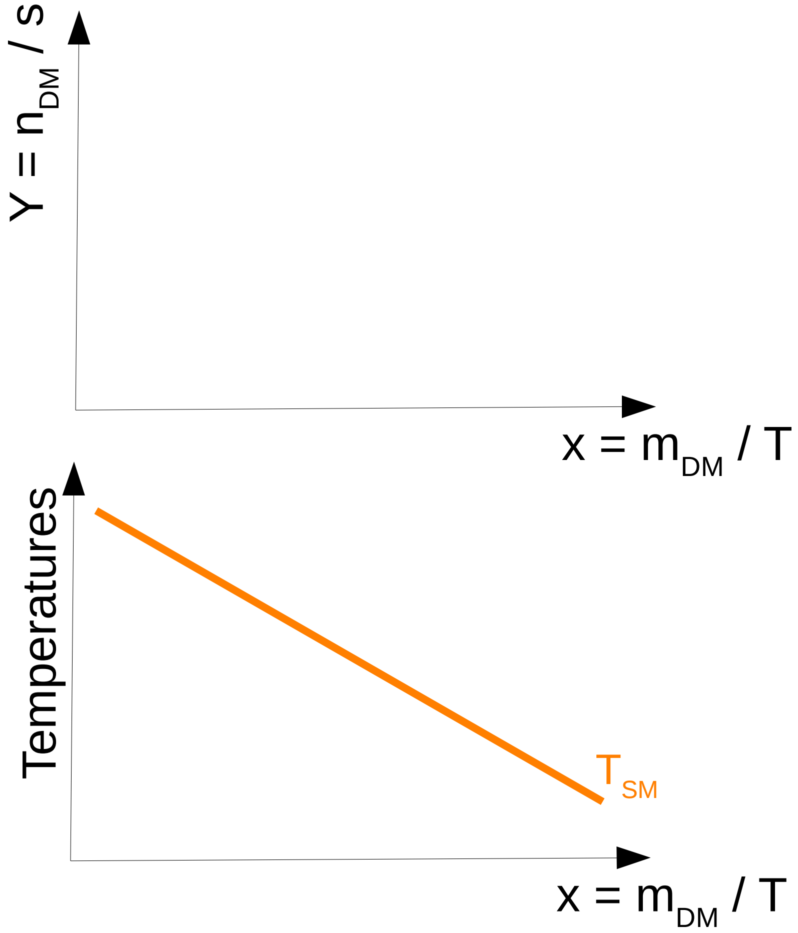
$T_{SM} = T_{DM}$

&

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

How to produce such a difference of temperatures?

(Non-) Thermal evolution of DM



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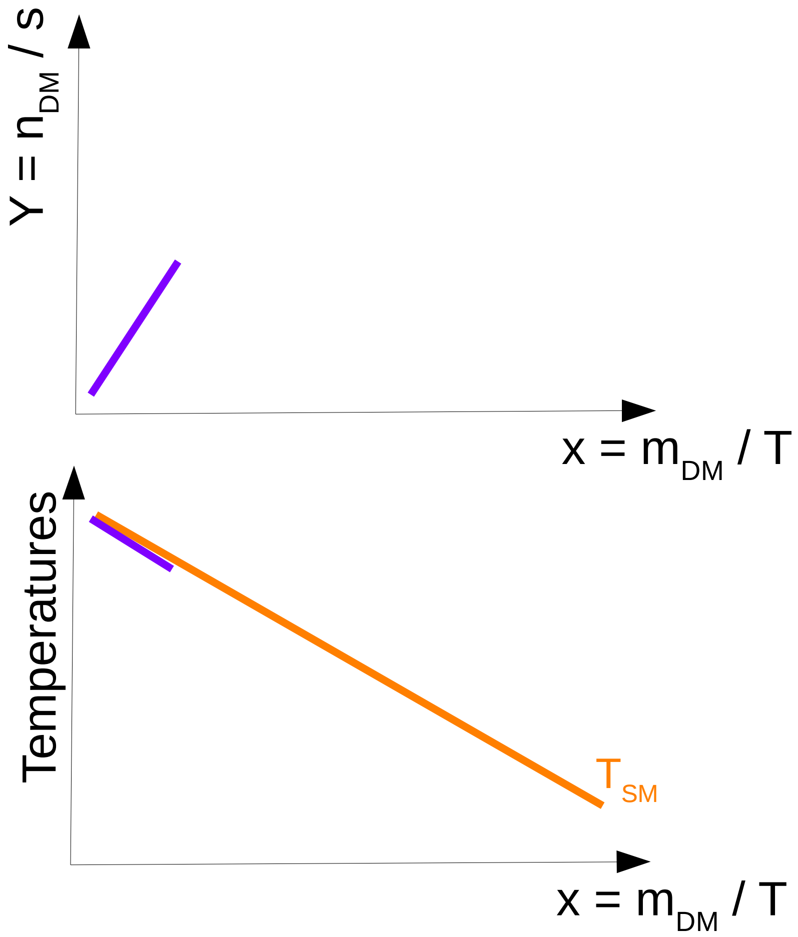
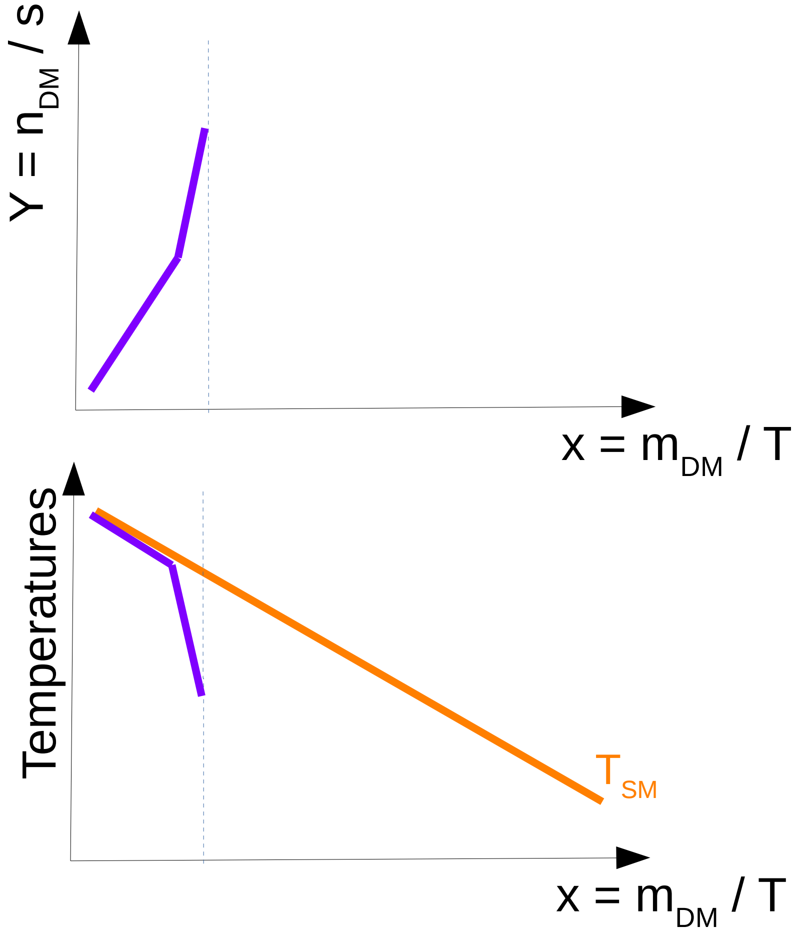


DM Production

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

(Non-) Thermal evolution of DM

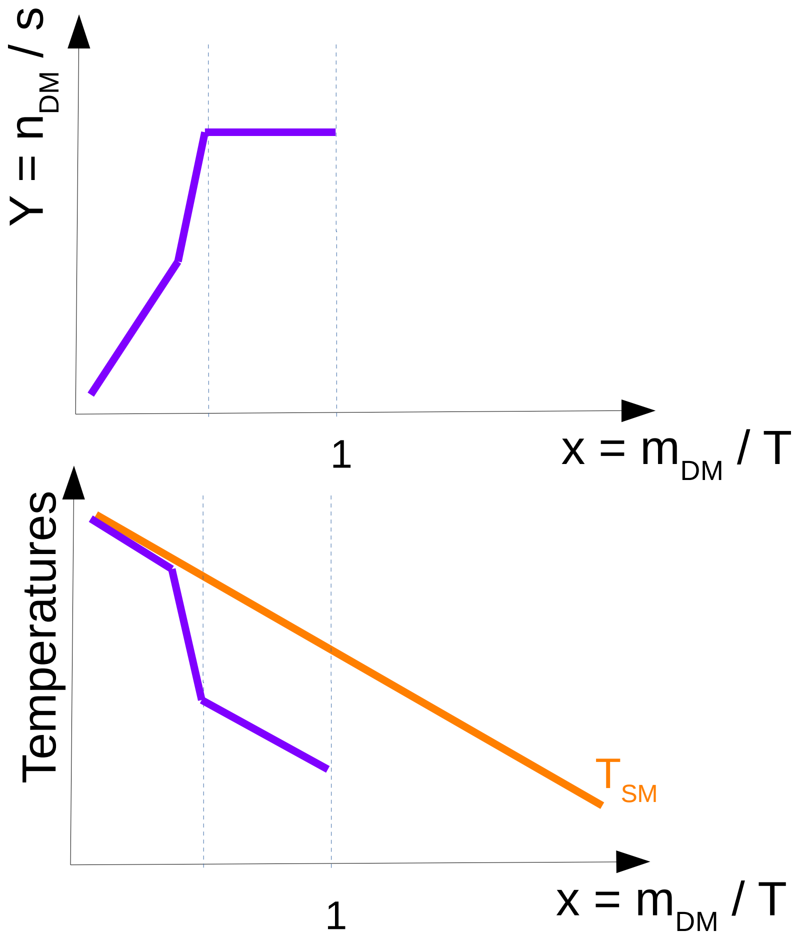


<u>DM Production</u>

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

* 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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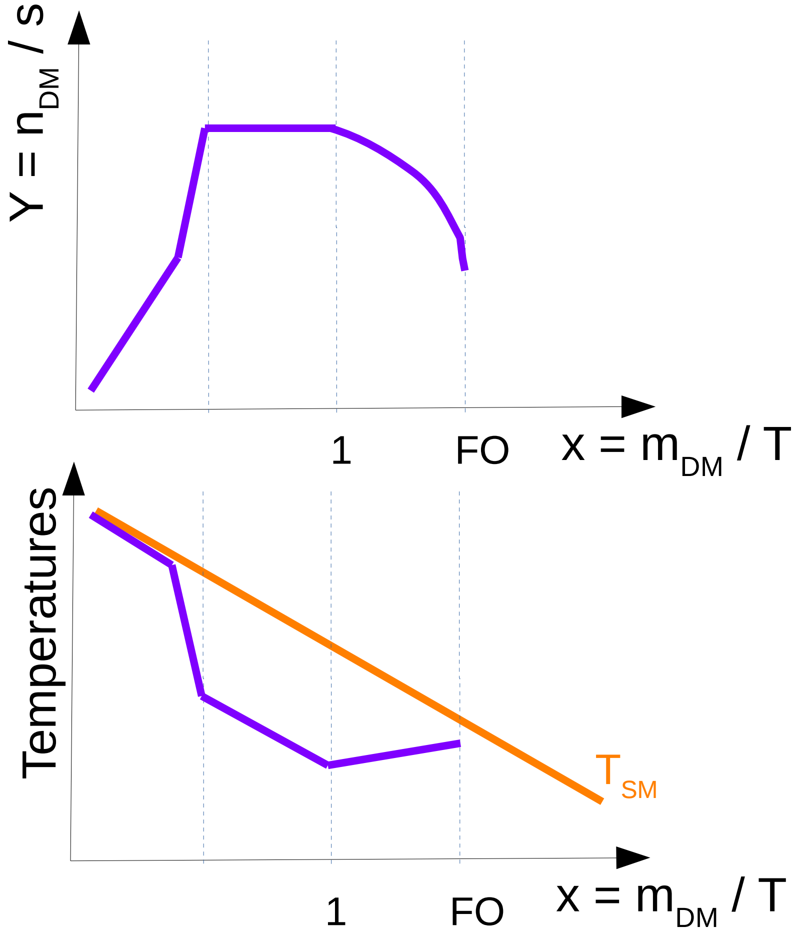
Thermal Equilibrium

* Chemical equilibrium **2** ↔ **4**

(Non-) Thermal evolution of DM



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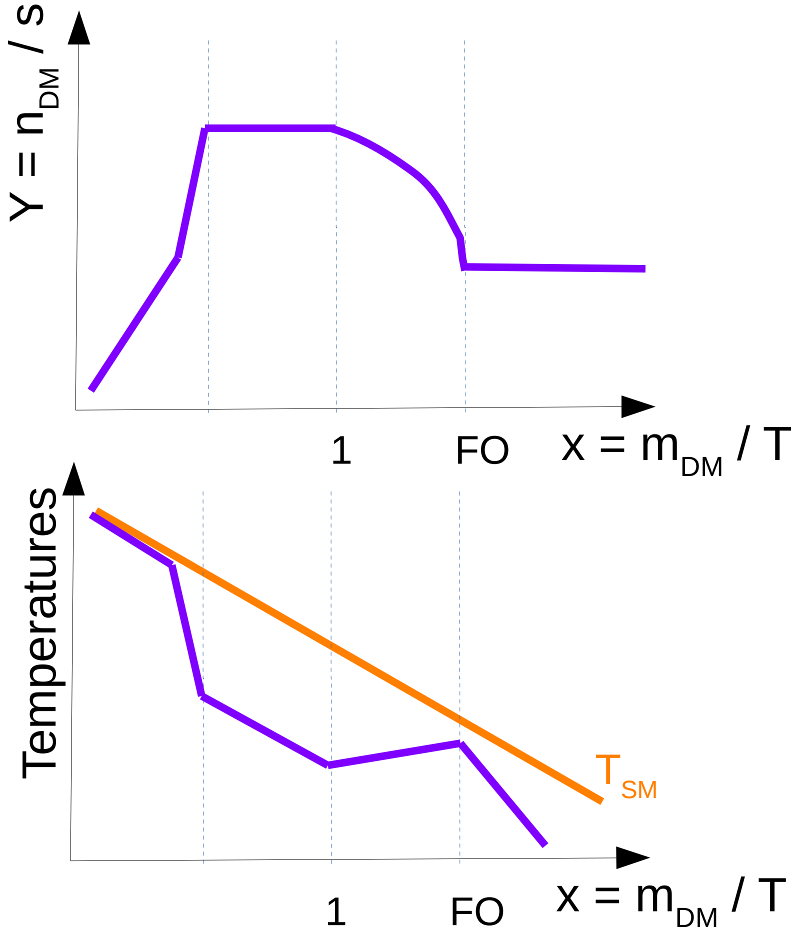
Thermal Equilibrium

* Chemical equilibrium **2**↔**4**

DM Annihilation

* Freeze-out **4**→**2**

(Non-) Thermal evolution of DM



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<u>Thermal Equilibrium</u>

* Chemical equilibrium **2**↔**4**

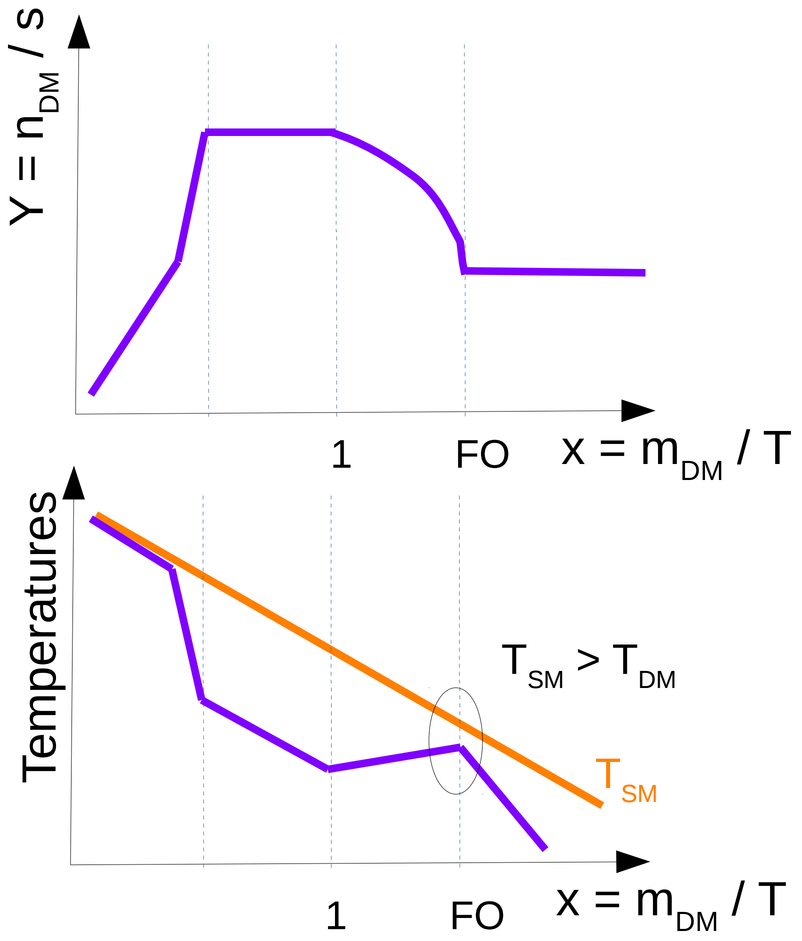
<u>DM Annihilation</u>

* Freeze-out **4**→**2**

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

* Relic abundance
Non-relativistic DM cools down faster

(Non-) Thermal evolution of DM



<u>DM Production</u>

* 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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  Price to pay: Dramatic decrease of T_{DM}

<u>Thermal Equilibrium</u>

* Chemical equilibrium **2** ↔ **4**

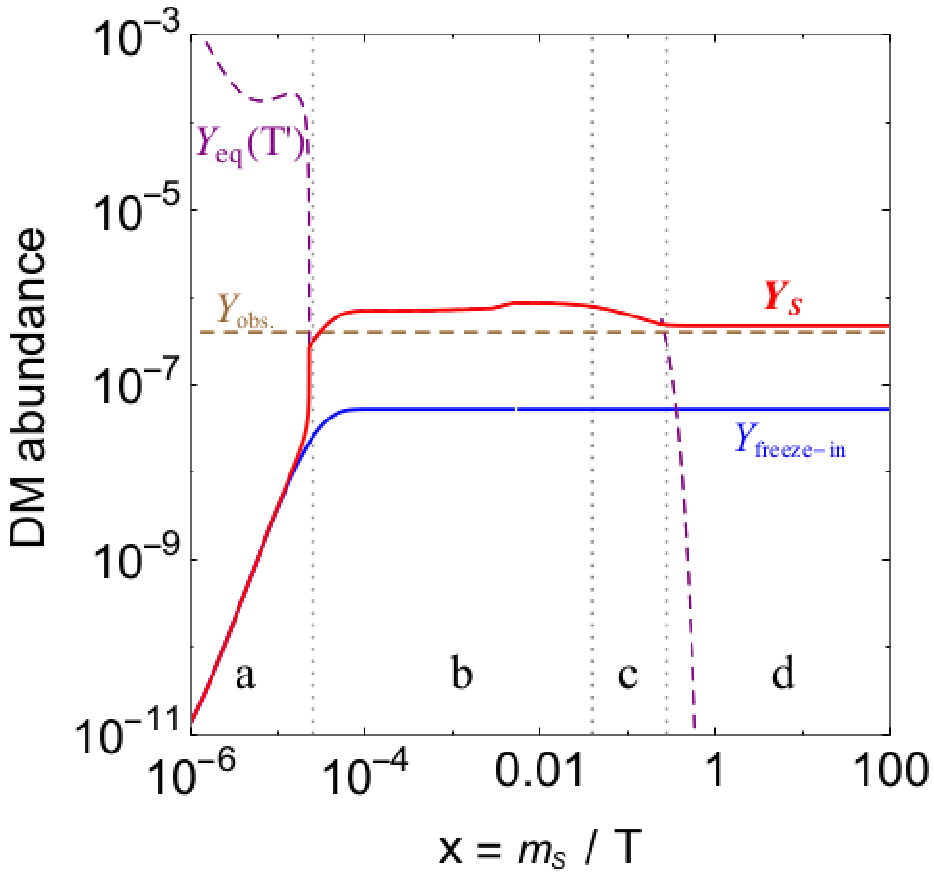
<u>DM Annihilation</u>

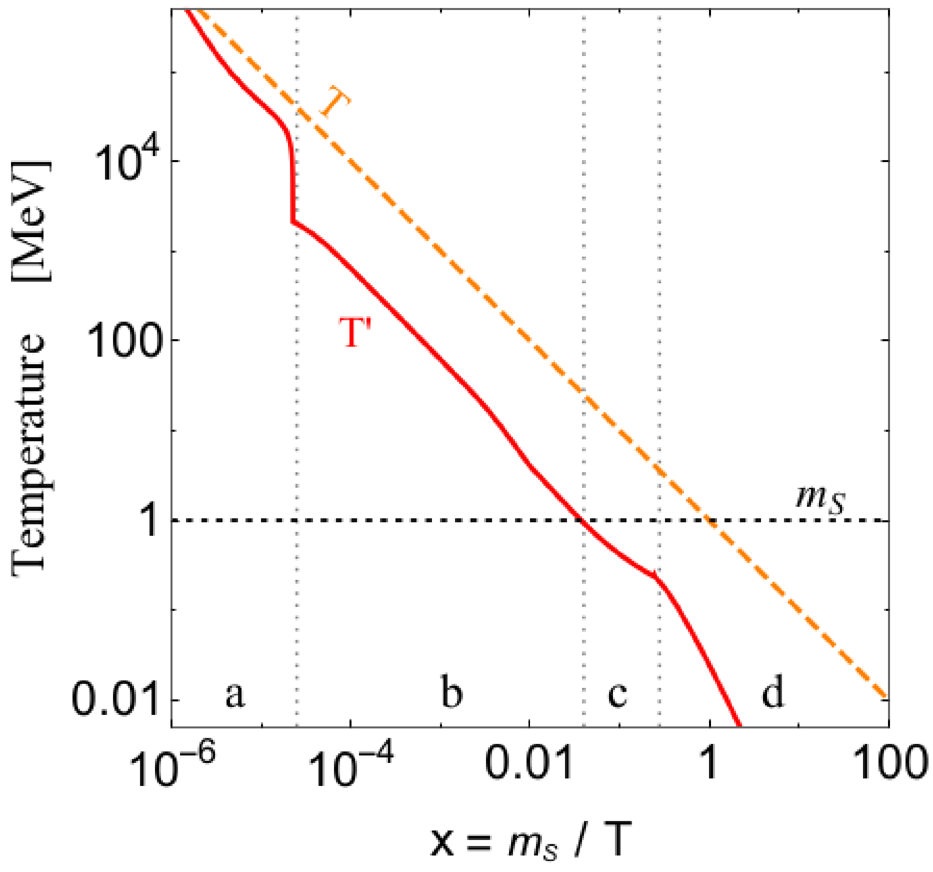
* Freeze-out **4** → **2**

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

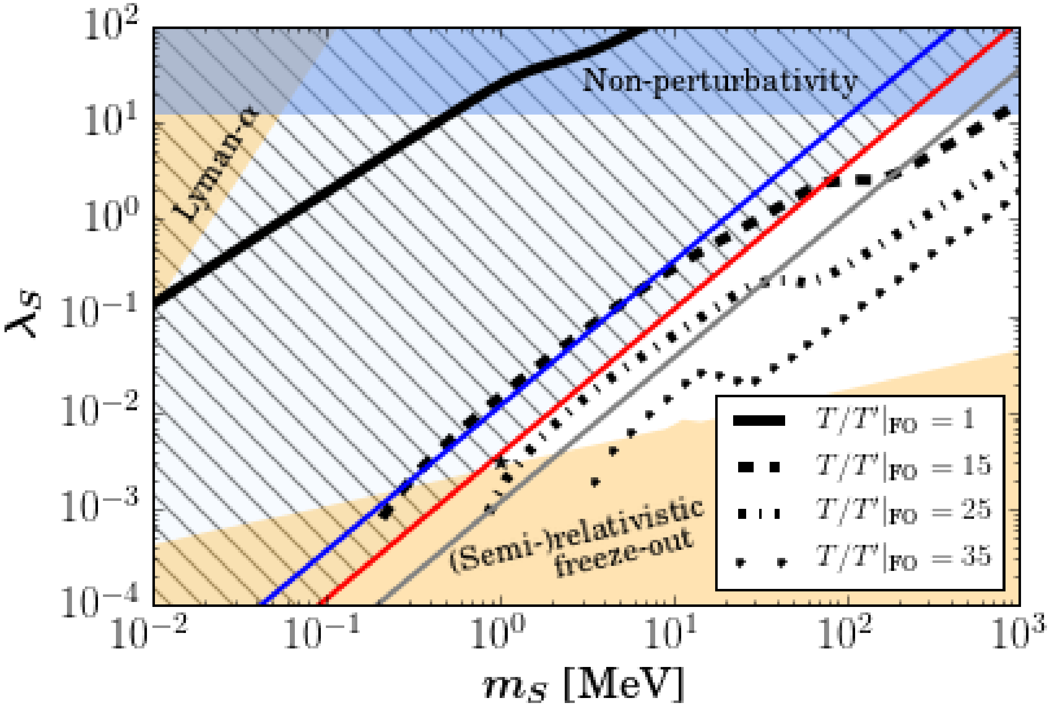
* Relic abundance
  Non-relativistic DM cools down faster

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





Singlet Scalar DM
4→2 annihilations



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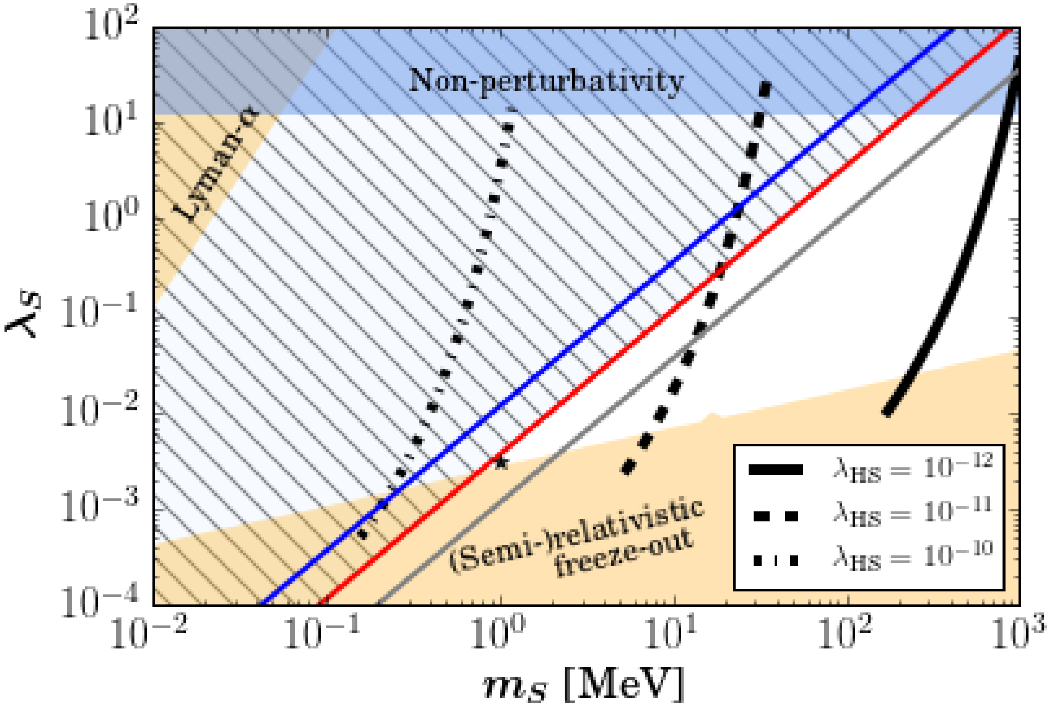

Now let’s Split SIMPs! :-)

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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- 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.

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

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

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

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

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

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Splitting SIMPs: scalars

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

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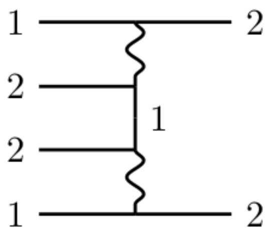
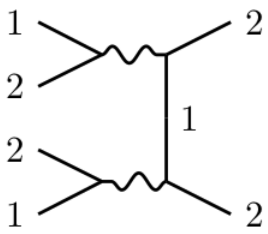
Producing Split SIMPs

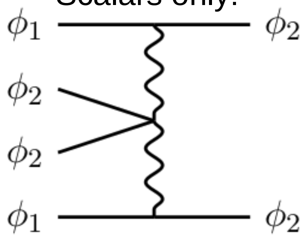
Split SIMPs
4 → 2 annihilations

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





Scalars only!



We take $m_V > m_1 + m_2$

Split SIMPs
4 → 2 annihilations

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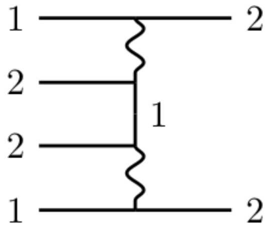

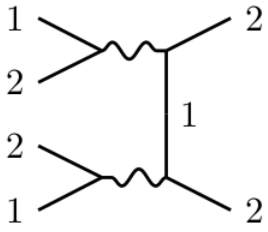

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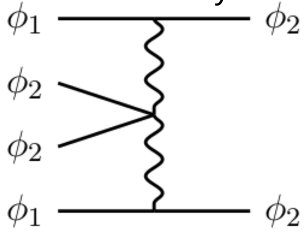


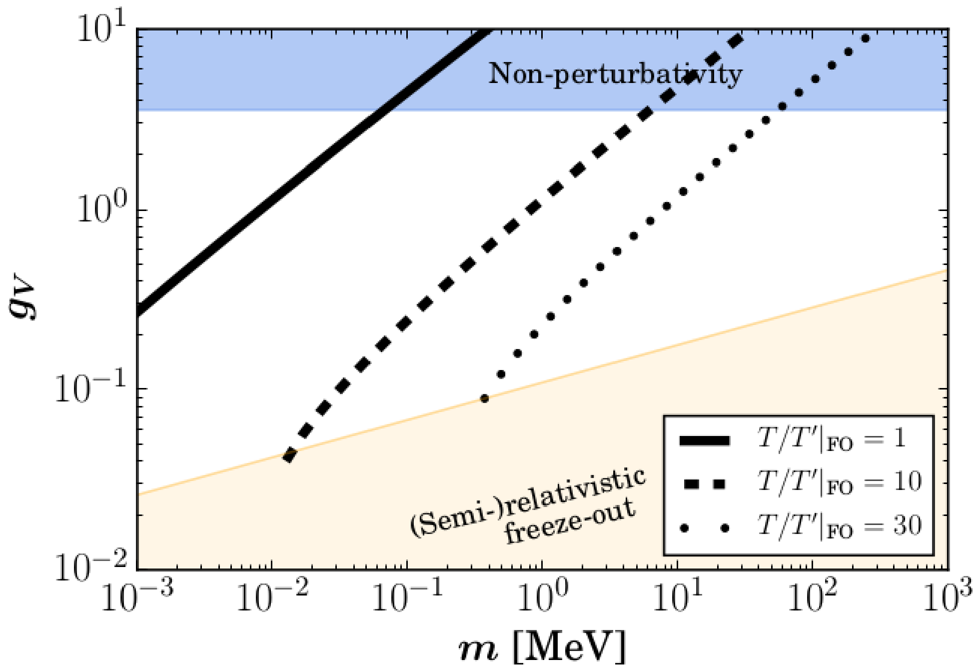
$$\langle\sigma v^3\rangle_{4\to 2} = \left[\langle 1122 \to 22\rangle + \langle 1122 \to 11\rangle\right]\frac{R^2}{(1+R)^4}$$

We take $m_V > m_1 + m_2$

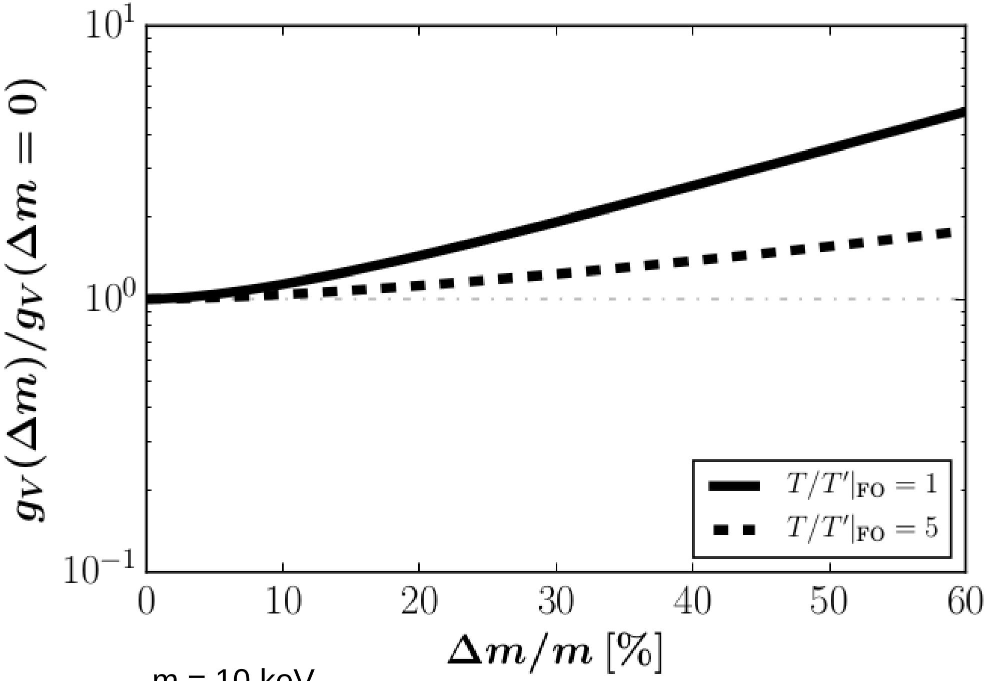
$$\langle 1122 \to 11\rangle = \langle 1122 \to 22\rangle = \frac{27\sqrt{3}\,g_V^8}{32\pi}\,\frac{\left(m_V^4 - 8m^2 m_V^2 - 8m^4\right)^2}{\left(m_V^4 - 2m^2 m_V^2 - 8m^4\right)^4}$$

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

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.

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

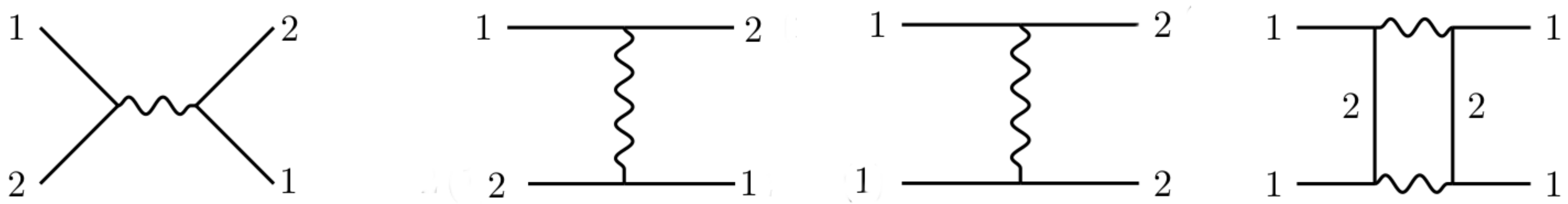
$$\Gamma_{\chi_2\to\chi_1 e^+e^-} \simeq \frac{2\alpha\,\alpha_V\,\kappa^2}{15\pi}\frac{\Delta m^5}{m_V^4} \simeq 2\,H_0 \times \frac{m}{100\ \mathrm{MeV}}\,\frac{\alpha_V}{\alpha}\left(\frac{\kappa}{10^{-10}}\right)^2\left(\frac{\Delta m/m}{10^{-3}}\right)^5\left(\frac{m}{m_V}\right)^4$$

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

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

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

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

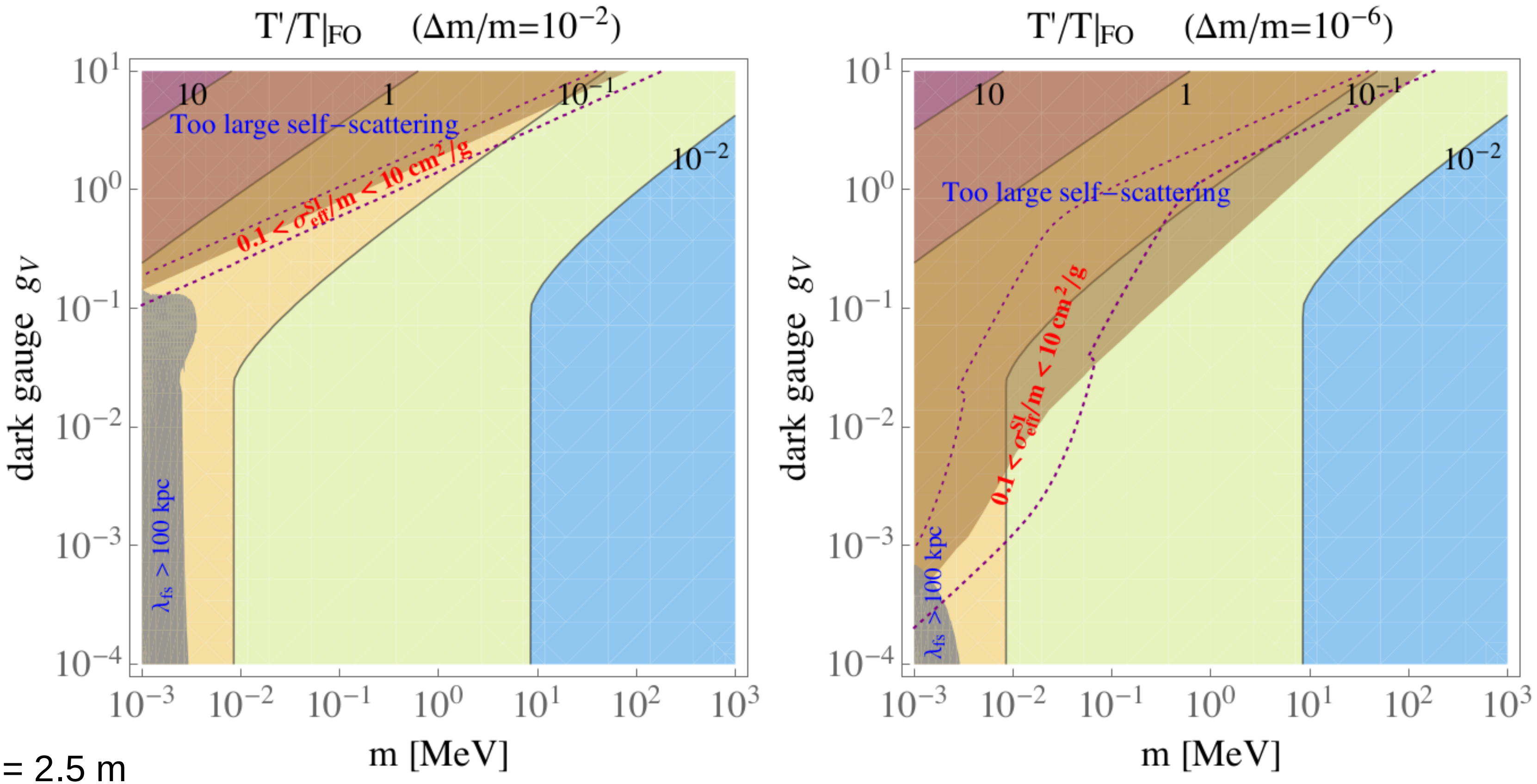
← Versus →

2-to-2
Self-interactions
Decrease the FSL

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

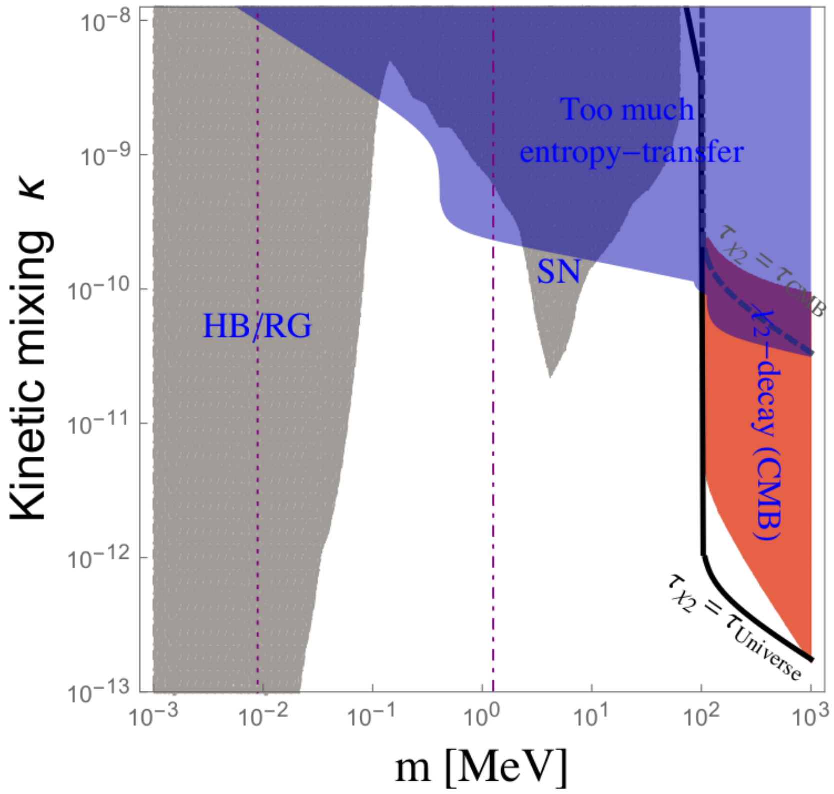
$\lambda_{\rm fs} \lesssim 100~{\rm kpc}$ ← Lyman-α

Astrophysical implications of Split SIMPs



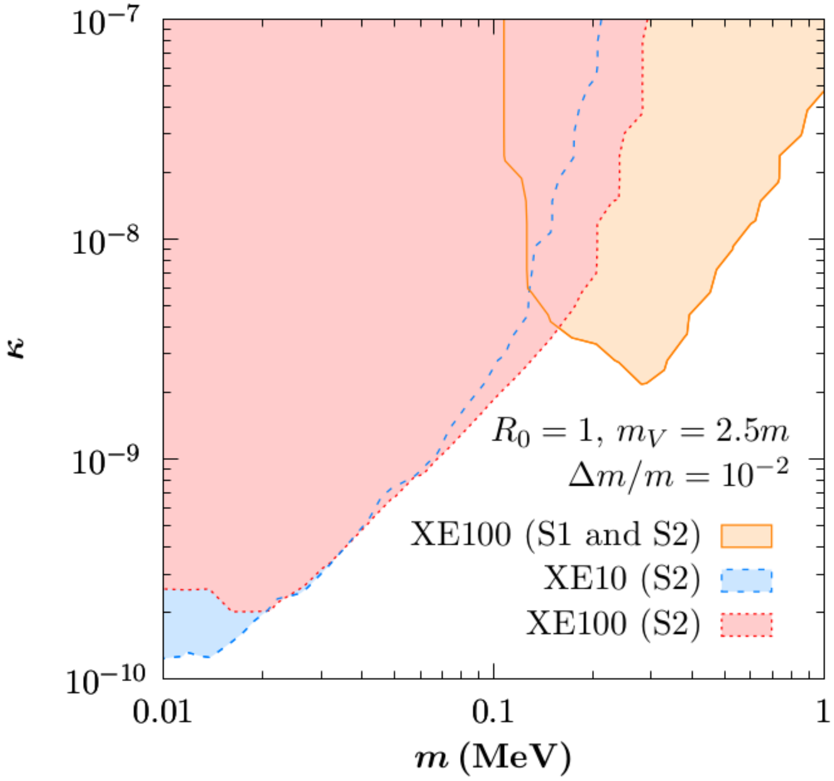
$m_V = 2.5\ m$

Constraints on the Kinetic Mixing Portal

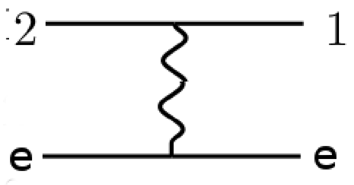


$\Delta m / m = 10^{-2}$
$m_V = 2.5\ m$

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!

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

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Self-Interacting
Dark Matter

$$\frac{\sigma_{SS\to SS}}{m_S} \sim 1\,\mathrm{cm}^2/\mathrm{g}$$

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

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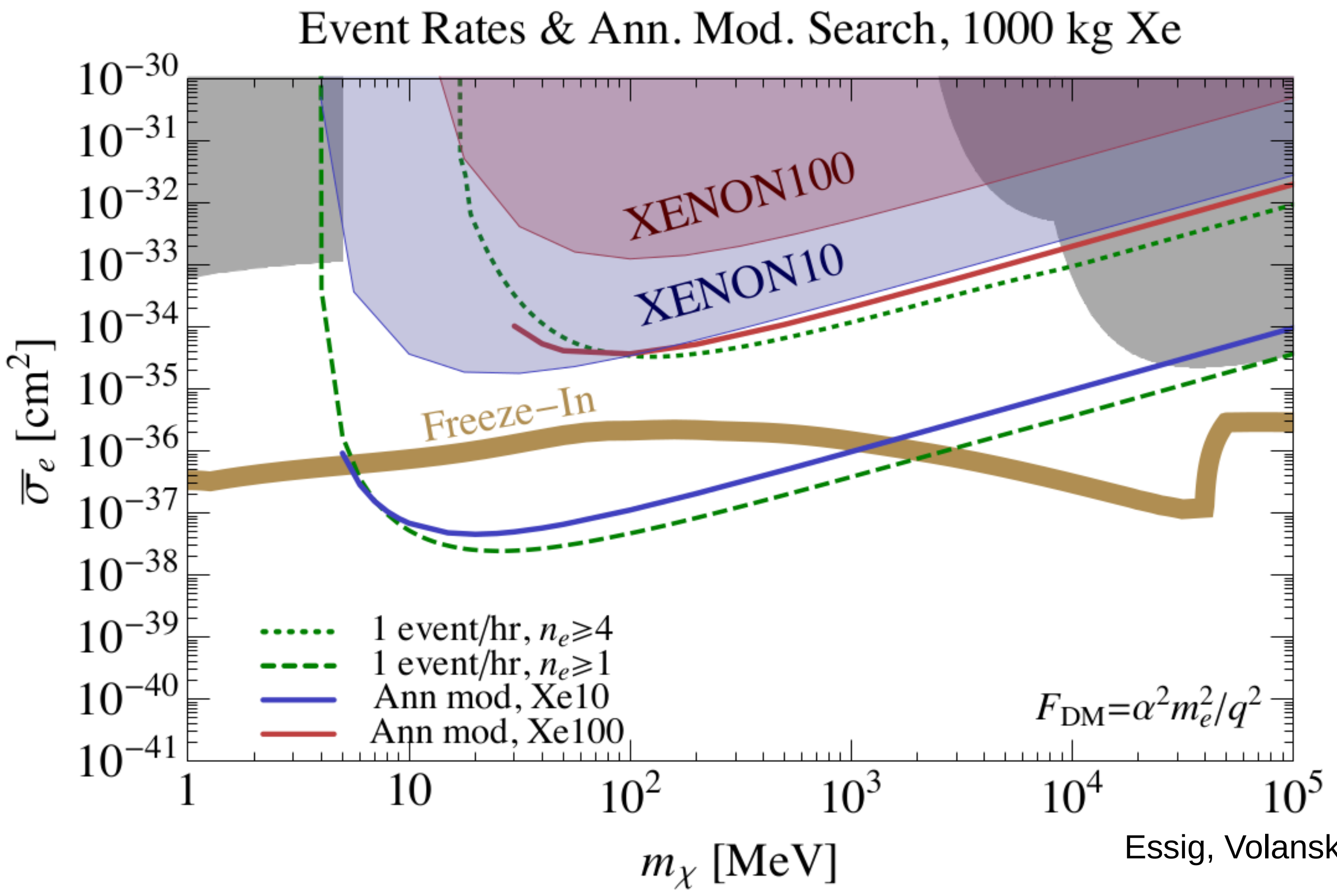
SIMP DM
* dominant N→n
* need to avoid the 'DM reheating'

+ 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
- 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



Essig, Volansky & Yu '17