UNIVERSITY OF MICHIGAN

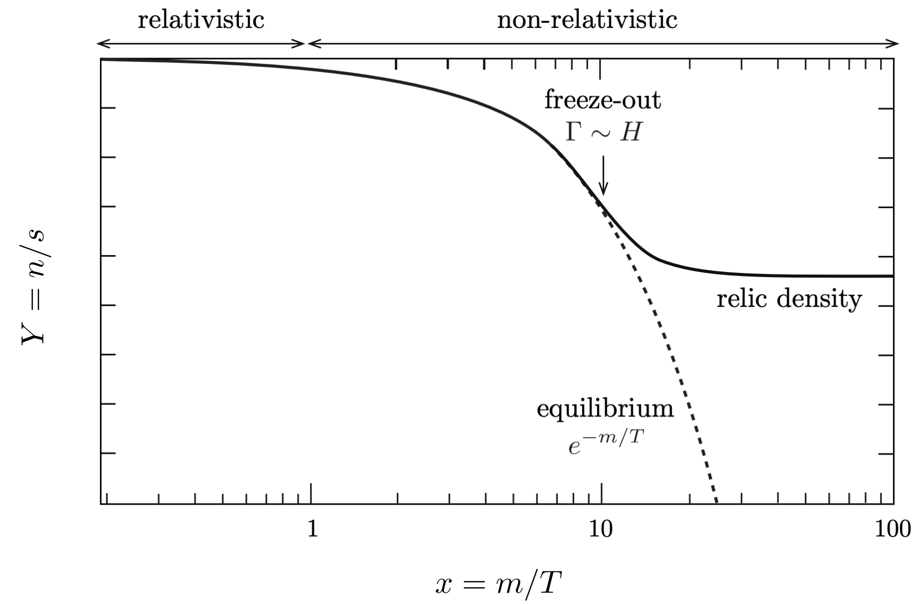
LEINWEBER INSTITUTE FOR THEORETICAL PHYSICS

Singlet Doublet Dark Matter Outside of Chemical Equilibrium

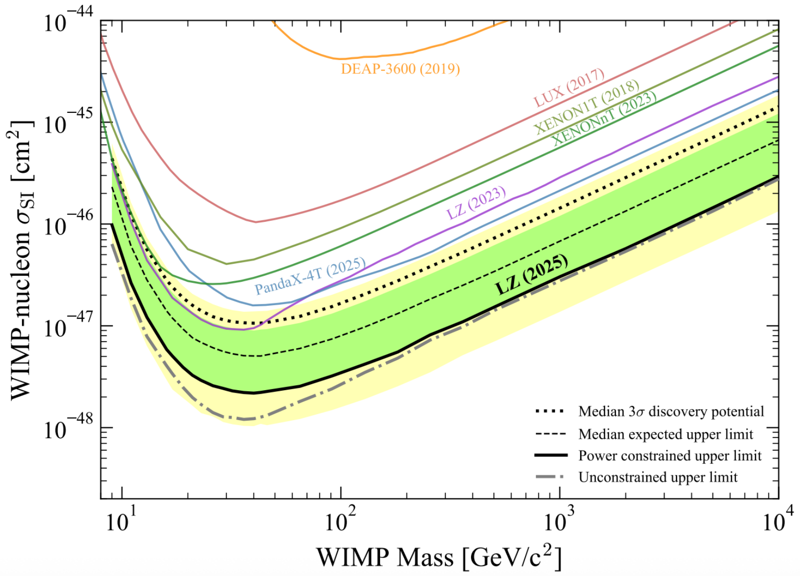
Prudhvi Bhattiprolu, Evan Petrosky, Aaron Pierce
Alexander Takla

April 25th, 2026

WIMP Dark Matter

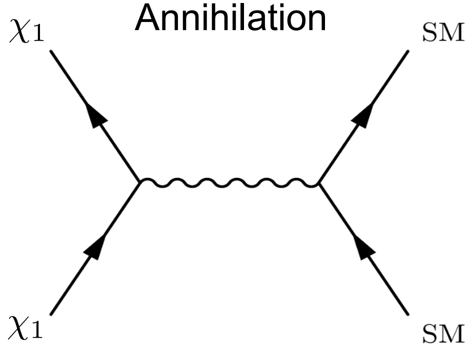


Daniel D. Baumann,
Lecture notes on Cosmology

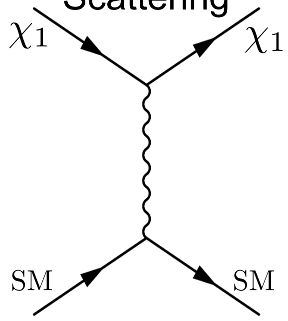


Phys. Rev. Lett. 135, 011802 (2025),
LZ collaboration

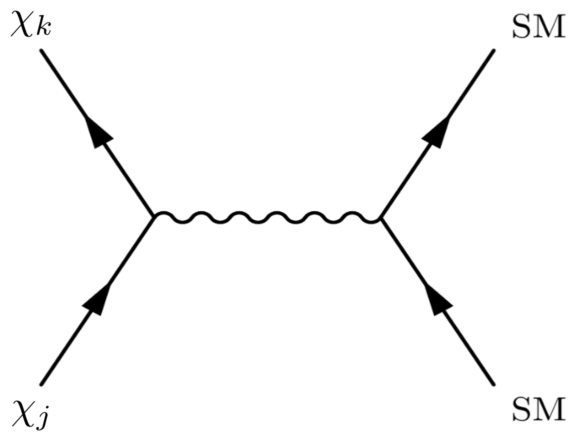
Annihilation



Scattering

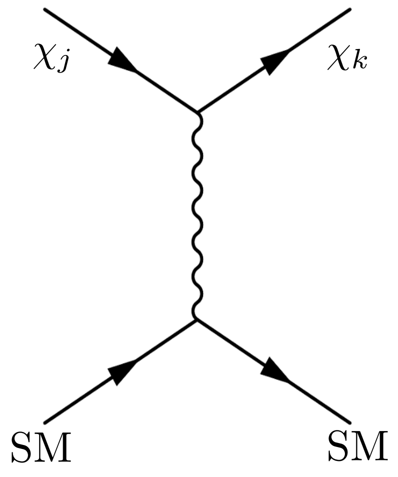


Dark Sectors



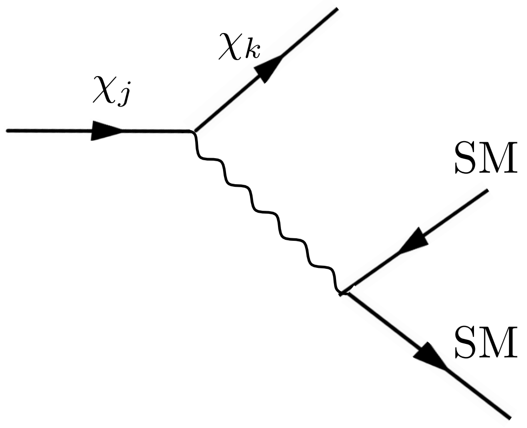
Coannihilation

Phys. Rev. D 43, 3191
Griest, Seckel



Coscattering

SciPost Phys. 13, 124
Alguero, Belanger, Kraml, Pukhov



Decays

Notions of equilibrium

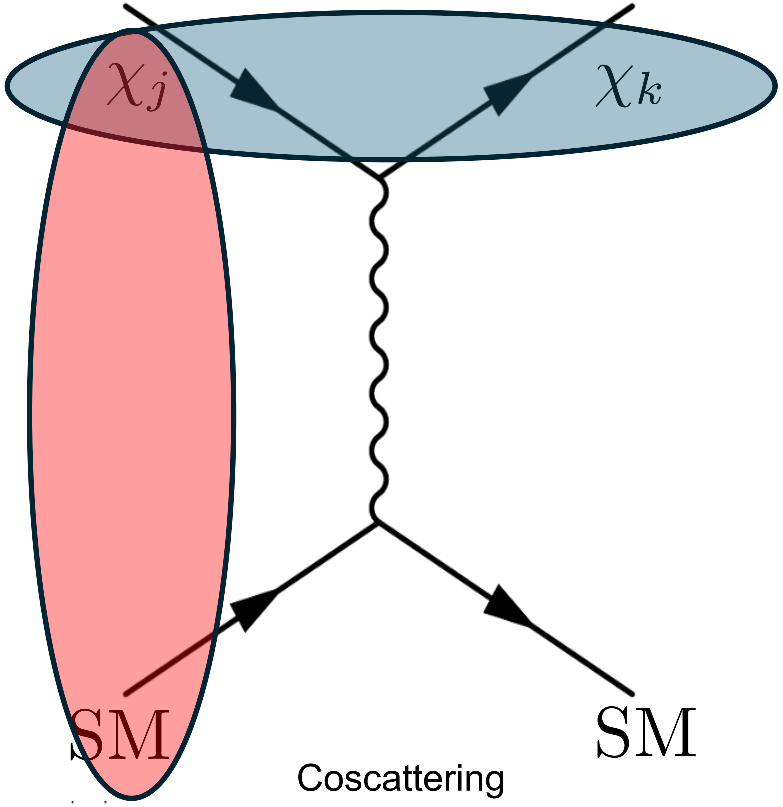
Chemical Equilibrium

Maintained through scattering between j and k

Kinetic Equilibrium

Maintained through scattering off SM particles.
Phase space distribution follows SM temperature

$$\frac{\Gamma_{j\to k}}{H} \sim O(1)$$



Singlet Doublet Model

$$\mathcal{L}_{SDM} = \mathcal{L}_{gauge} + \mathcal{L}_{mix}$$

$$\mathcal{L}_{gauge} = iS^\dagger \bar{\sigma}^\mu \partial_\mu S + iD^\dagger \bar{\sigma}^\mu \nabla_\mu D + i\bar{D}^\dagger \bar{\sigma}^\mu \nabla_\mu \bar{D}$$

$$\mathcal{L}_{mix} = -\frac{1}{2} M_s S^2 - M_D D\bar{D} - y_1 DHS - y_2 H^\dagger \bar{D} S + \text{h.c.}$$

$$S_{(\mathbf{1},\mathbf{1},0)} \xrightarrow{\text{SUSY}} \tilde{B}$$

$$D = \begin{pmatrix} N \\ C \end{pmatrix}_{(\mathbf{1},\mathbf{2},-1/2)} \longrightarrow \tilde{H}_u$$

$$\bar{D} = \begin{pmatrix} \bar{C} \\ \bar{N} \end{pmatrix}_{(\mathbf{1},\mathbf{2},1/2)} \longrightarrow \tilde{H}_d$$

$$\mathcal{M}_N = \begin{pmatrix} M_S & \frac{y_1 v}{\sqrt{2}} & \frac{y_2 v}{\sqrt{2}} \\ \frac{y_1 v}{\sqrt{2}} & 0 & M_D \\ \frac{y_2 v}{\sqrt{2}} & M_D & 0 \end{pmatrix}$$

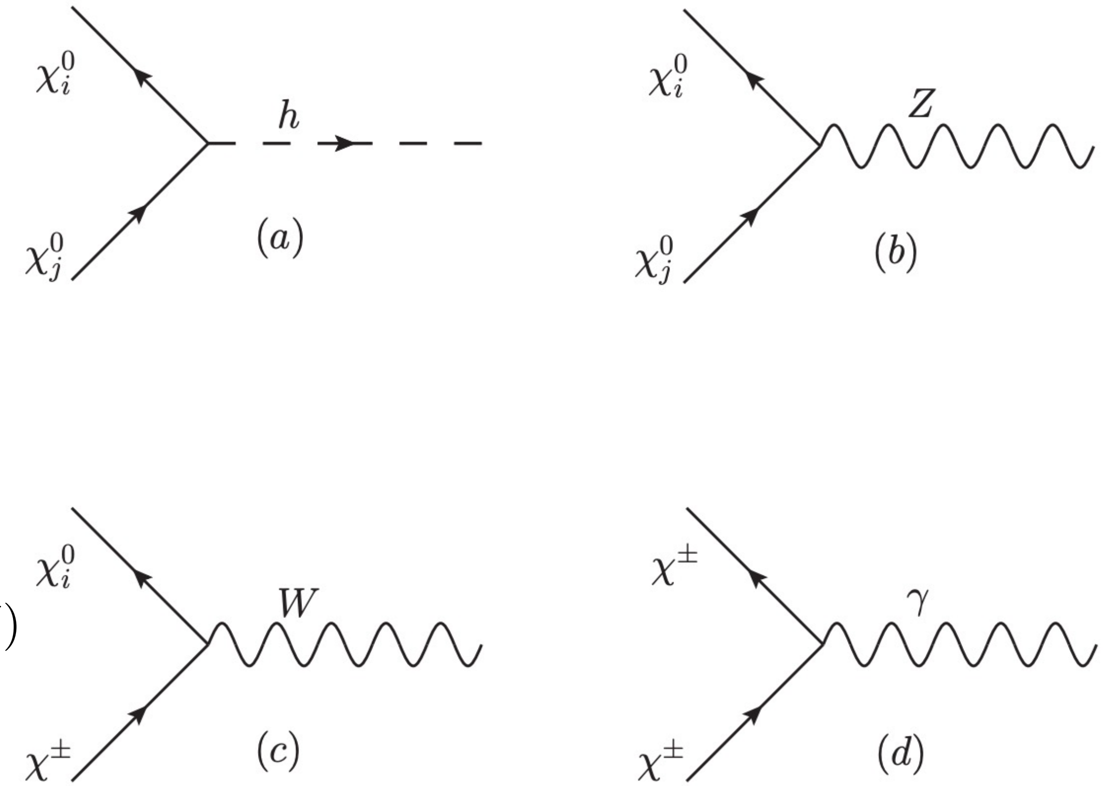
Phys. Rev. D 85, 075003
Cohen, Kearney, Pierce, Tucker-Smith

Mass spectrum and vertices

M_D — $\chi^{\pm}$, $\chi_{3,2} \sim \dfrac{\bar{N} \pm N}{\sqrt{2}}$

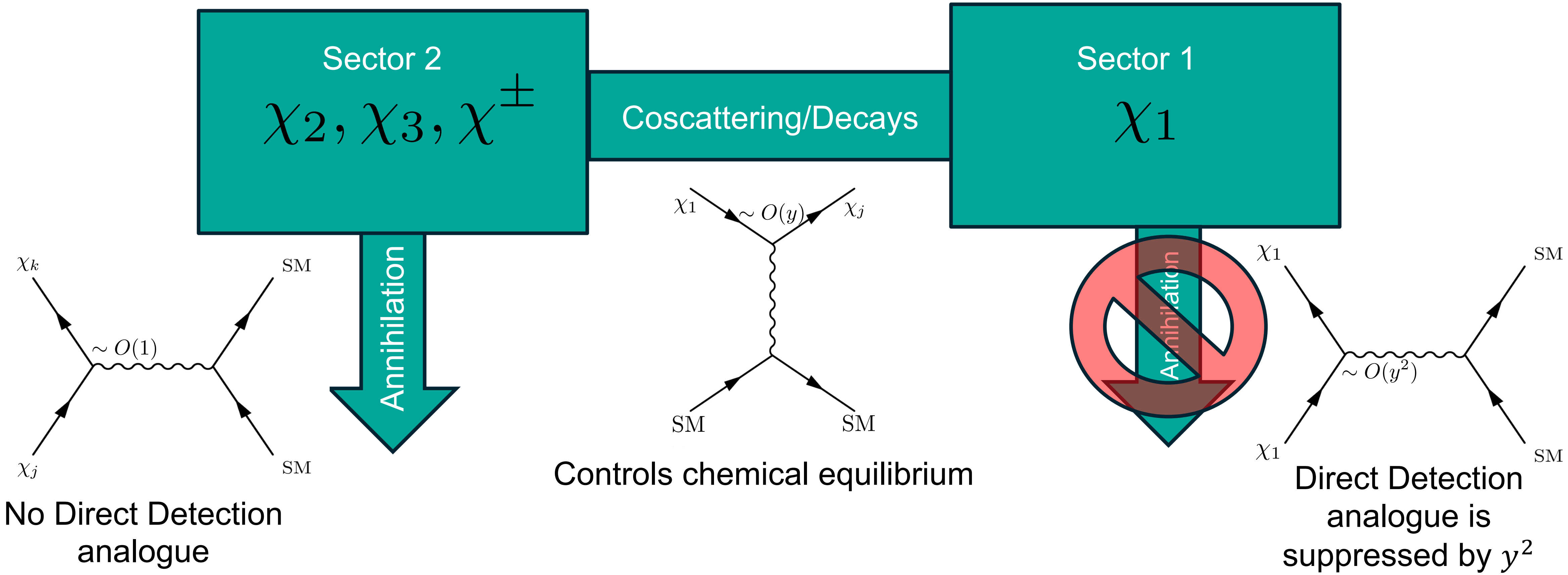
$$M_S \lesssim M_D$$
$$y_1, y_2 \ll 1$$

M_s — $\chi_1 \sim S + O(y)(N + \bar{N})$



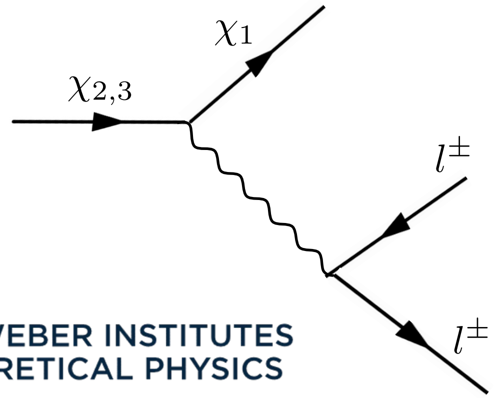
arXiv:2505.11607
Bhattiprolu, Petrosky, Pierce

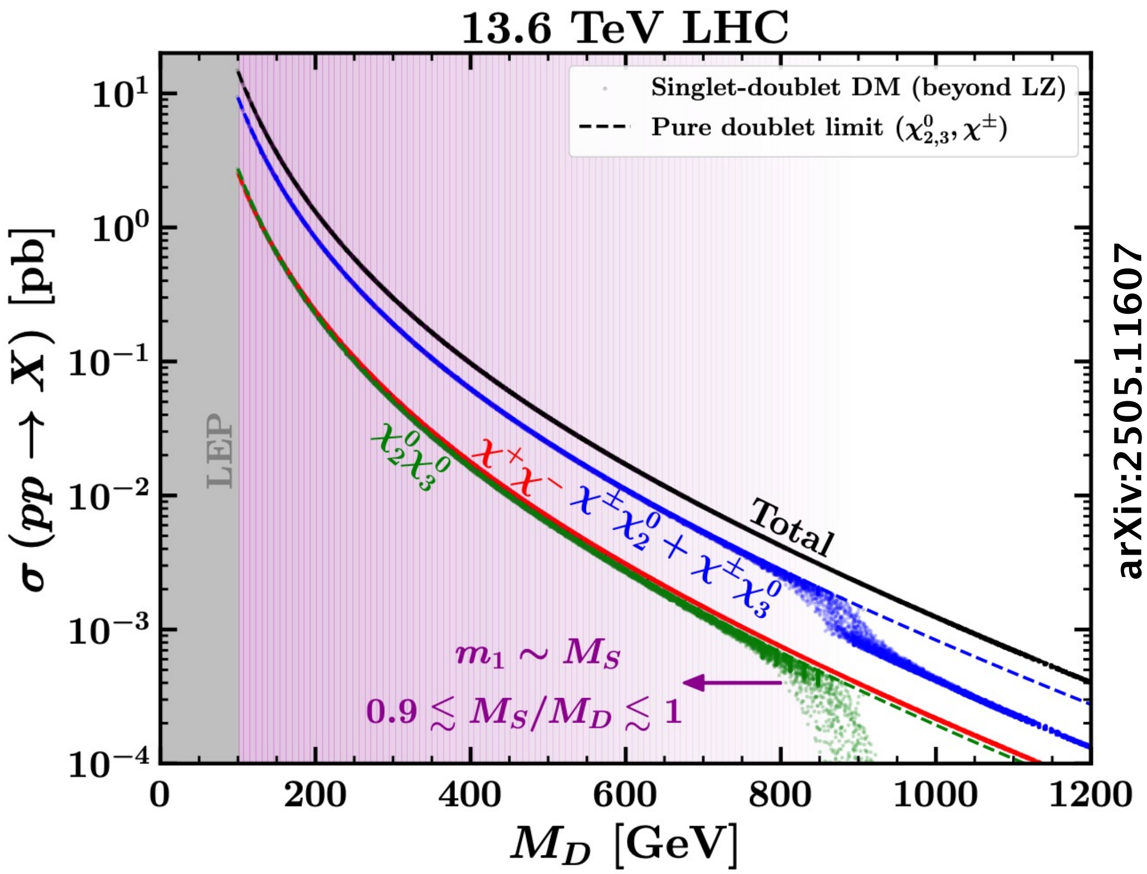
Early universe story



How to test the model

Method	Possibility
Direct Detection	X
Indirect Detection	X
Collider	✓ Larger Yukawas prompt decays to soft leptons Smaller Yukawas we have displaced vertices and long-lived particles The $\chi^{\pm}$ promptly decay to $\chi_{2,3}$ via 2-body pion decays





arXiv:2505.11607
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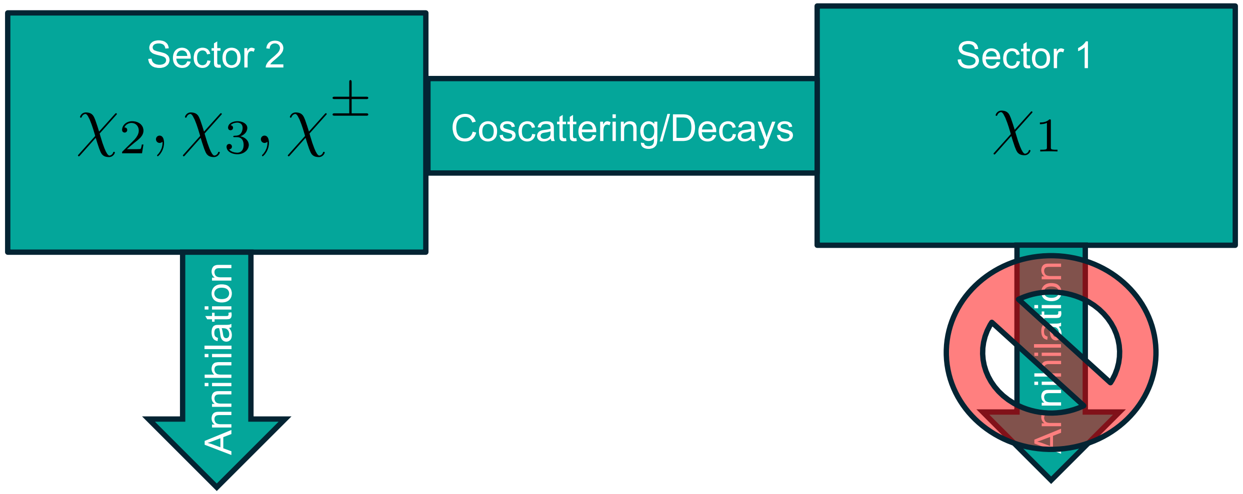
Goal of this work

- Study the Singlet Doublet Model in/out of chemical and kinetic equilibrium
- Explore the parameter space M_s, M_D, y_1, y_2 and determine what mechanisms are dominant in determining the relic abundance



Boltzmann equation

Chemical equilibrium between sector 1 and sector 2

$$\frac{dY}{dx} = -\frac{s}{Hx}\langle\sigma v_{\rm eff}\rangle(Y^2 - Y^{eq2})$$

$$\boxed{\langle\sigma v_{\rm eff}\rangle = \langle\sigma v_{2200}\rangle\frac{Y_2^{eq2}}{Y^{eq2}}}$$

$$Y = Y_1 + Y_2$$

Chemical equilibrium loss

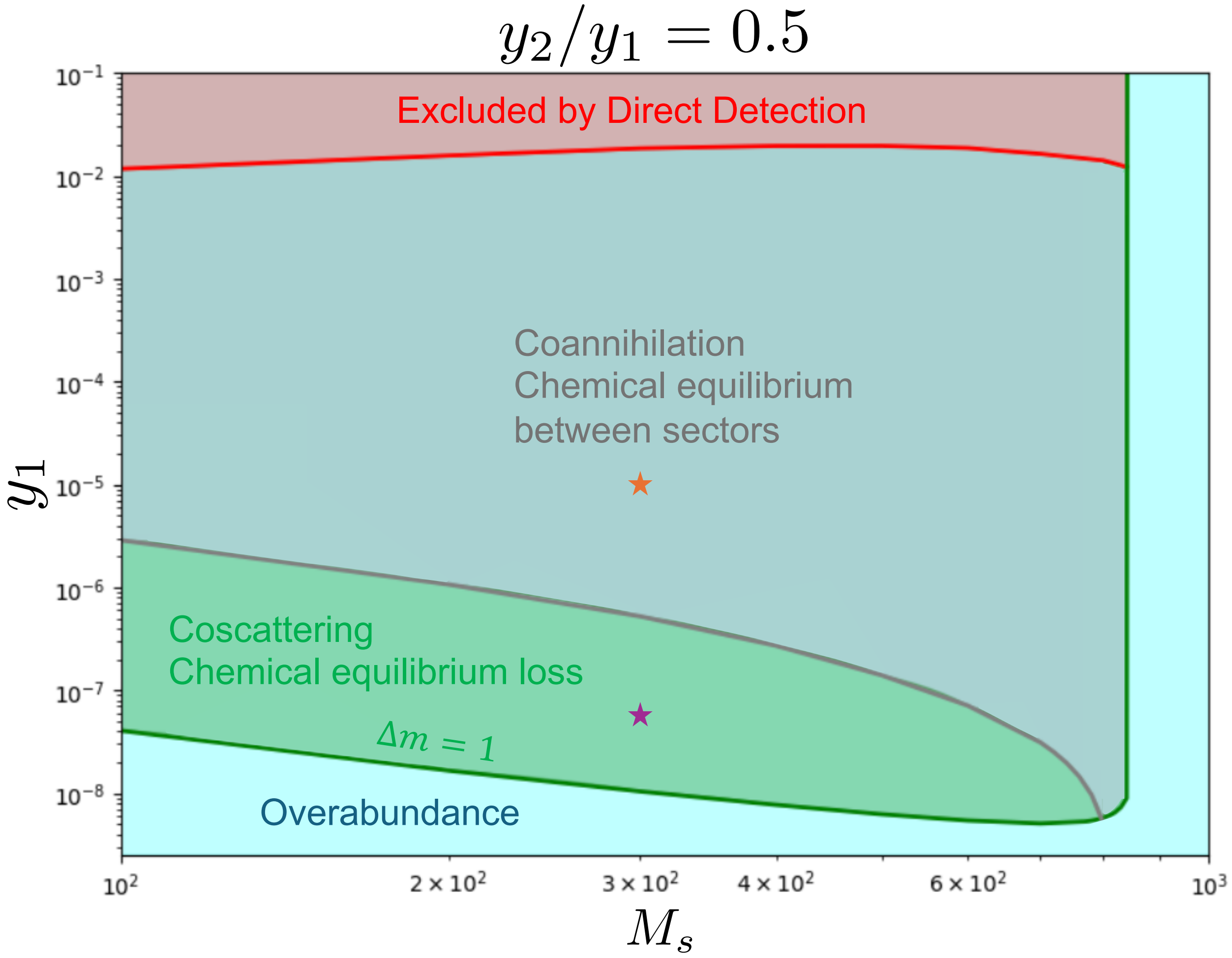
$$\frac{dY_1}{dx} = \frac{\Gamma_{2\to1}}{Hx}\left(Y_2 - Y_1\frac{Y_2^{eq}}{Y_1^{eq}}\right)$$

$$\boxed{\Gamma_{2\to1} = \frac{\sum\limits_{a\in2}\Gamma_{a\to1,0}g_a m_a^2 K_1(\frac{m_a}{T})}{\sum\limits_{a\in2} g_a m_a^2 K_2(\frac{m_a}{T})} + \langle\sigma v_{2010}\rangle n_0^{eq}}$$

$$\frac{dY_2}{dx} = -\frac{s}{Hx}\left[\langle\sigma v_{2200}\rangle(Y_2^2 - Y_2^{eq2}) + \frac{\Gamma_{2\to1}}{s}\left(Y_2 - Y_1\frac{Y_2^{eq}}{Y_1^{eq}}\right)\right]$$

$$\frac{\Gamma_{2\to1}}{H} \sim O(1)$$

Results(1)



Preliminary
Bhattiprolu, Petrosky, Pierce, AT
(to appear)

Borders of these regions shift downwards (upwards) when y_2/y_1 approaches 1 (-1)

Shapes of curves are roughly independent of y_2/y_1

★ $\mathrm{m}, \mathrm{M}, y_1, y_2$ =(300,316.7,1e-5,5e-6)
★ $\mathrm{m}, \mathrm{M}, y_1, y_2$ =(300,305,6e-8,3e-8)

Preliminary results suggest that kinetic equilibrium effects are small

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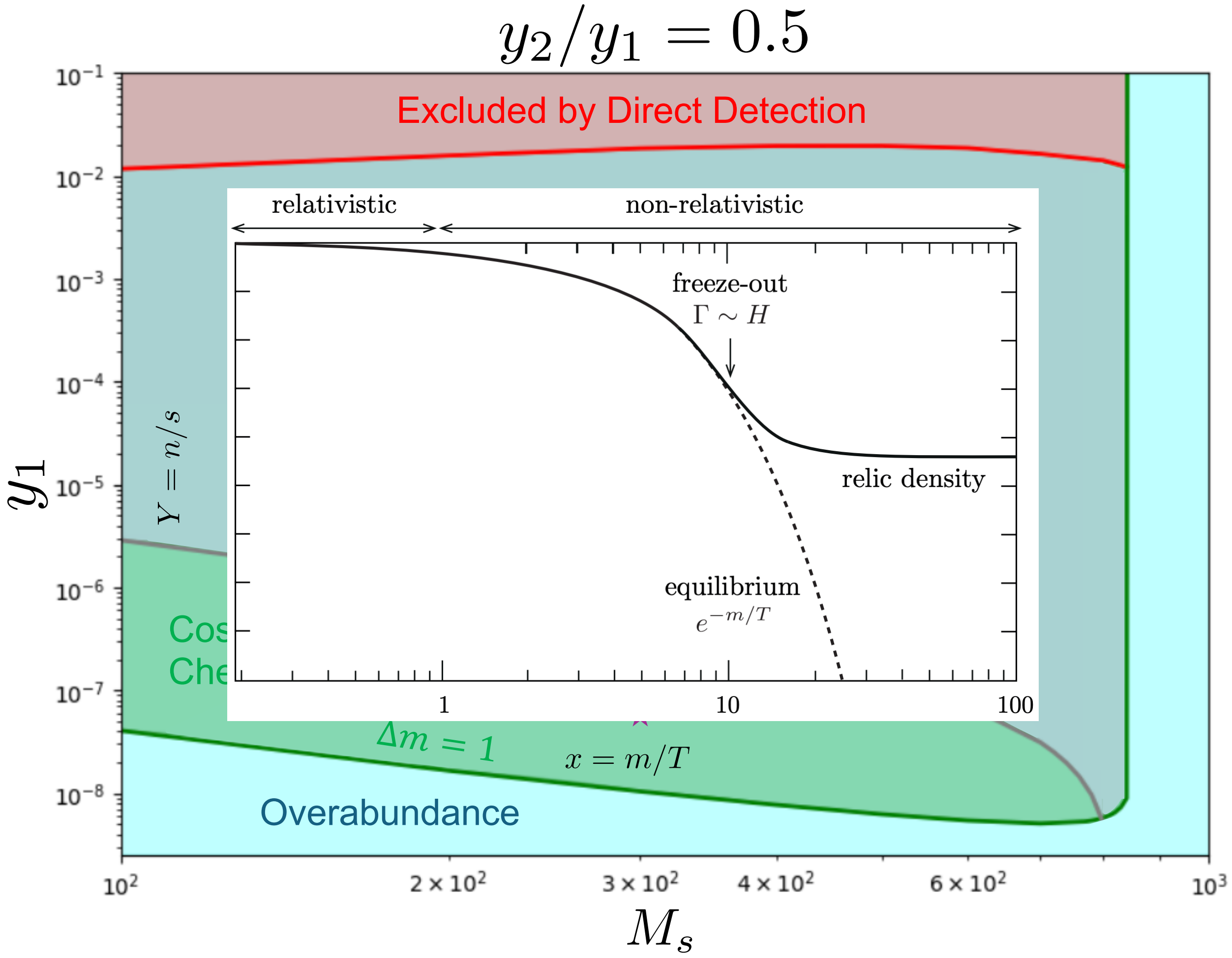

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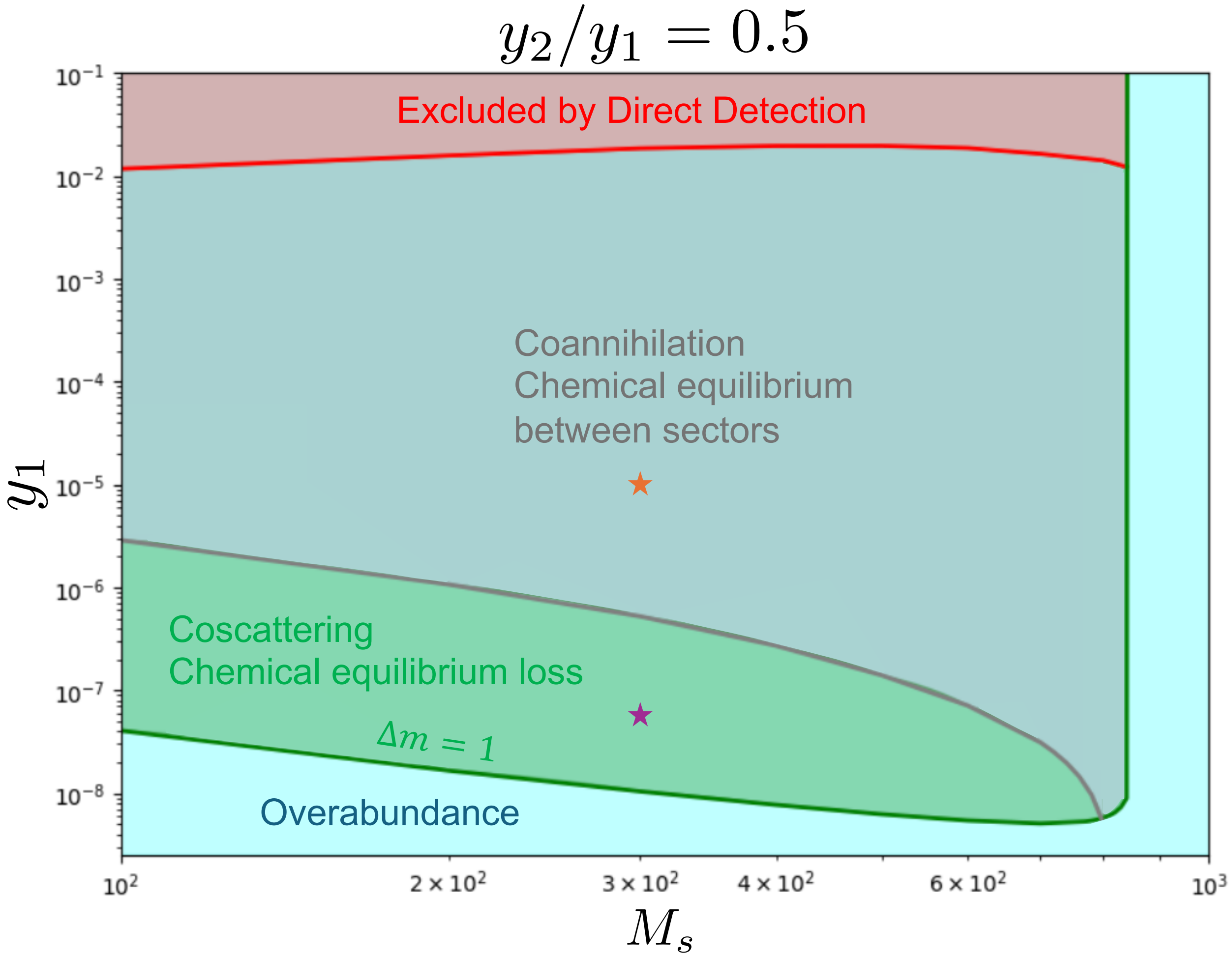

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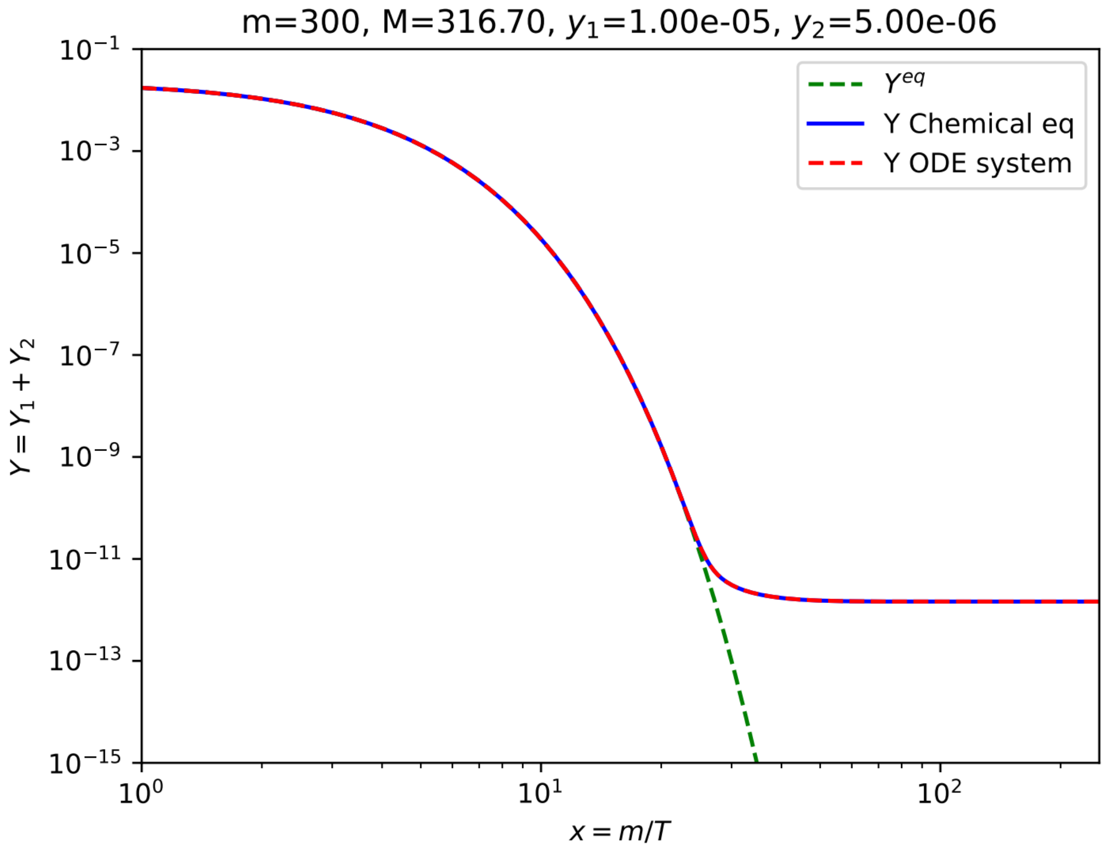
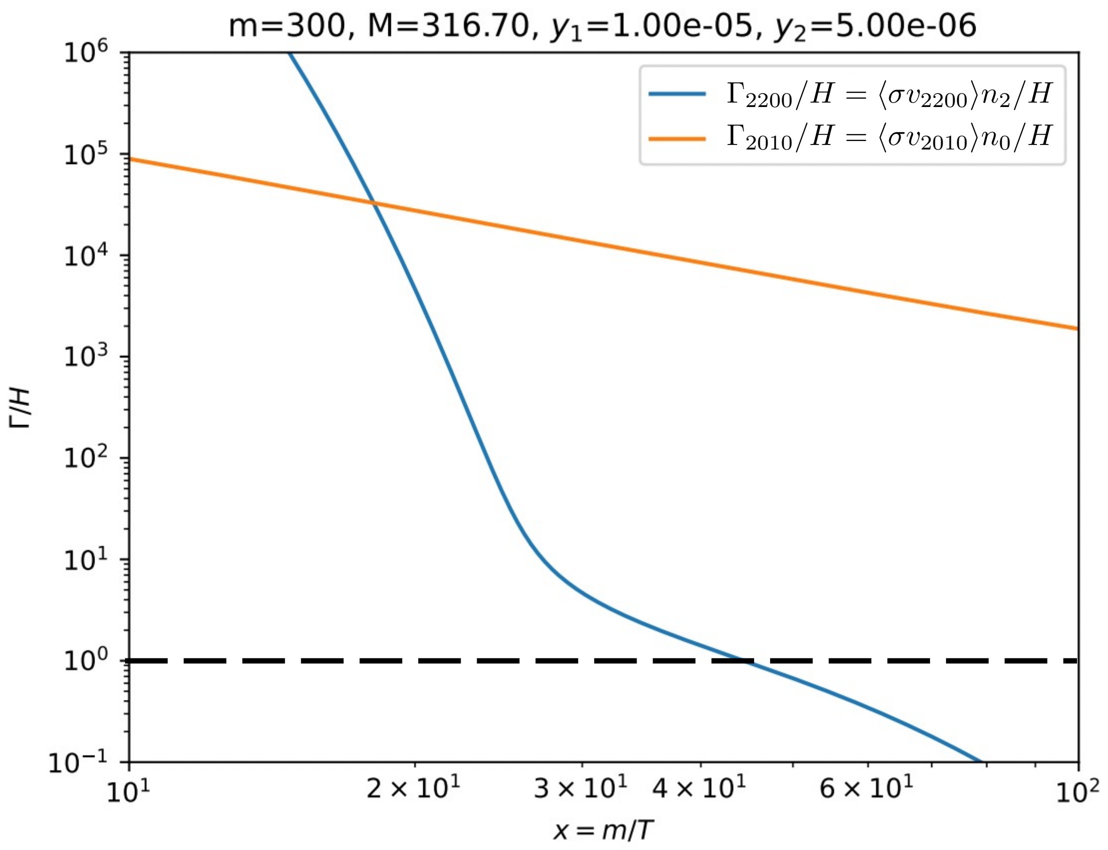
Results(2)

★ $\mathrm{m}, \mathrm{M}, y_1, y_2$ =(300,316.7,1e-5,5e-6)





Preliminary
Bhattiprolu, Petrosky, Pierce, AT
(to appear)

Results(3)

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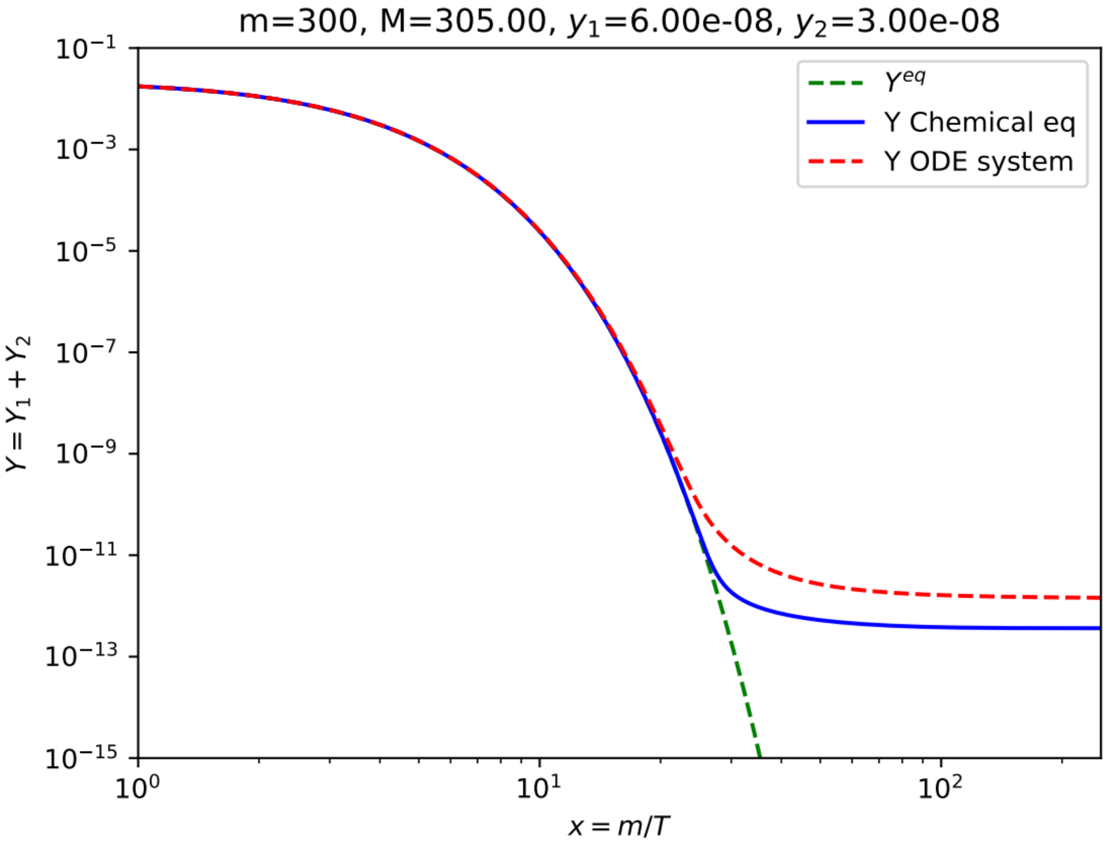

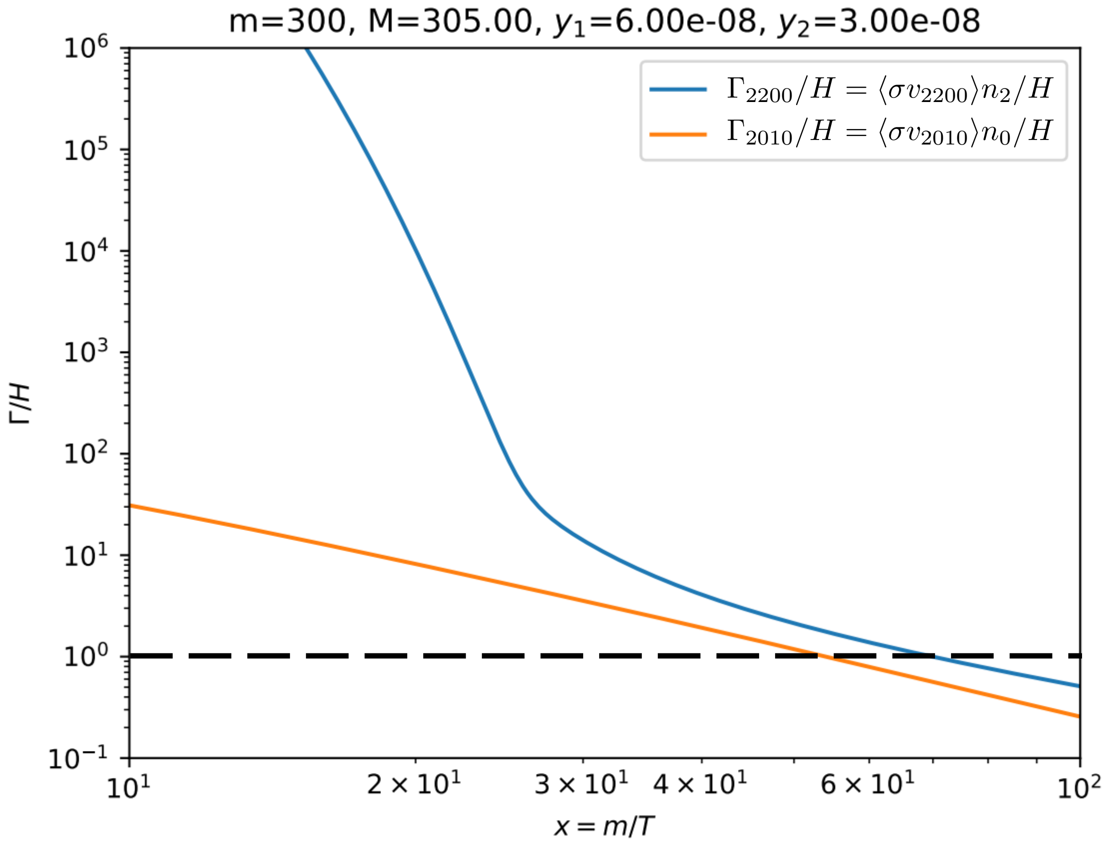

Preliminary
Bhattiprolu, Petrosky, Pierce, AT
(to appear)

Future Work

- Generalize our code as a tool for studying dark sectors outside of chemical and kinetic equilibrium
- Probe the freeze-in/superWIMP regime of the Singlet Doublet Model

JHEP 03 (2010) 080
Hall, Jedamzikb ,March-Russellc, West
Phys. Rev. D 98, 095031 (2018)
Garny, Heisig