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Relaxing Lyman-α bounds by self-cooling Dark Sectors

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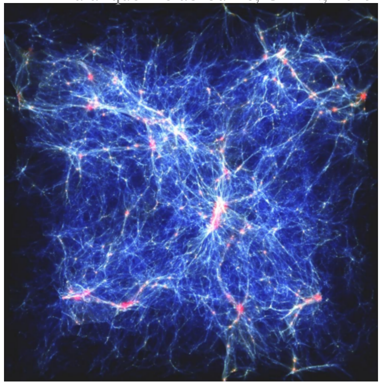
[publication in preparation]

Lyman-α constraints on light Dark Matter

Palanque-Delabrouille, CERN, 2019



- Lyman-α observations dictate an upper bound on the free-streaming scale of dark matter.

- "Warm Dark Matter" hydro-simulations:

$$m_{\mathrm{WDM}}^{\mathrm{Ly}\text{-}\alpha} \geq \mathbf{5.3\ keV}$$ [J. Lesgourgues et al., 2020]

(1.6 keV for conservative estimates) [A. Boyarsky et al., 2020]

These bounds must be carefully translated for other DM models!

→ e.g.: map $f_\chi(p,T)$ to WDM via its **velocity dispersion**:

$$\boxed{m_\chi^{\mathrm{Ly}\text{-}\alpha} \sim m_{\mathrm{WDM}}^{\mathrm{Ly}\text{-}\alpha} \times \sqrt{\langle p_\chi^2 \rangle} \sim \sqrt{\frac{1}{n_\chi} \times \int_p p^2\, f_\chi(p)}}$$

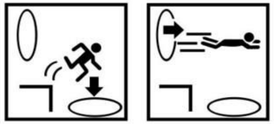
Freeze-In

superWIMP

more sophisticated methods exist:

Probe	NCDM test	$m_{\mathrm{FI}}^{\mathrm{lim}}$ [keV]	$m_{\mathrm{SW}}^{\mathrm{lim}}$ [keV]
Lyman-α	Velocity dispersion, Sec. 3.1.1	16	3.8
	Fits to transfer function, see Sec. 3.1.2	15	3.9
	Area criterion, see Sec. 3.1.3	15	3.8

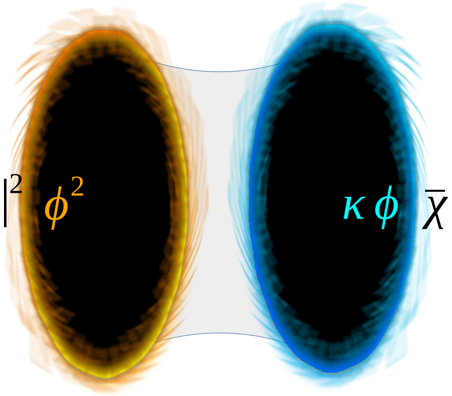
[Heisig et al., 2021]



Simple Scalar Toy Model

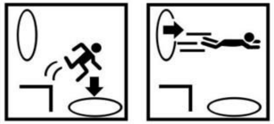
$$\mathscr{L} \supset \frac{g_h}{2}|H|^2 \phi^2 + \kappa \phi \bar{\chi} \chi$$

$\mathcal{SM} \longrightarrow \frac{g_h}{2}|H|^2 \phi^2$



$\kappa \phi \bar{\chi} \chi \longrightarrow \mathcal{DM}$

Problem: (co-moving) momentum conservation



Simple Scalar Toy Model

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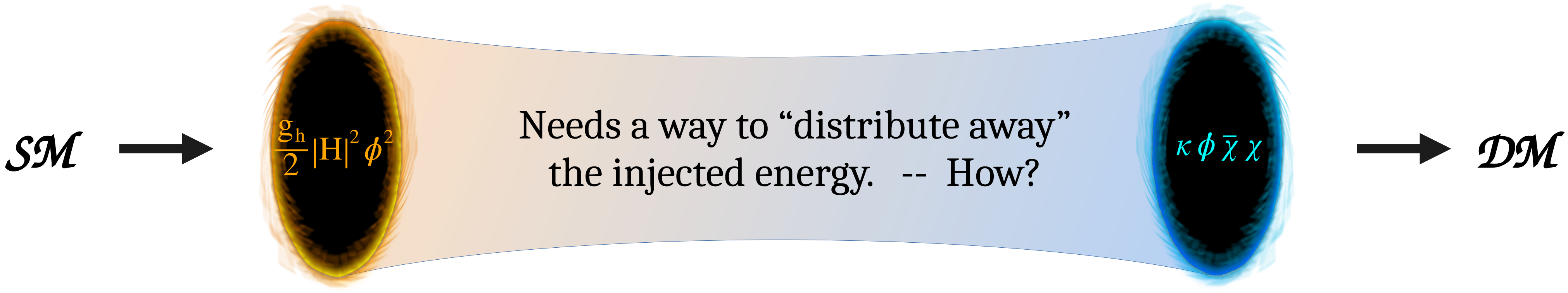
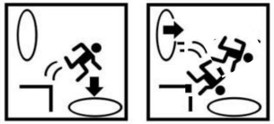
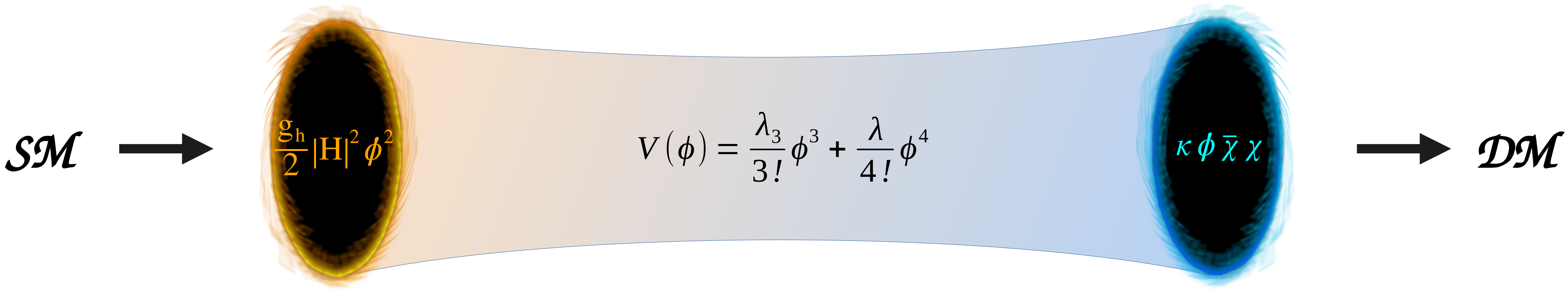
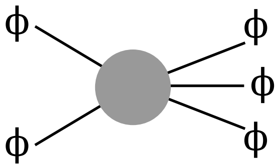


Simple Scalar Toy Model



$$\mathscr{L} \supset \frac{g_h}{2}|H|^2\phi^2 + \frac{\lambda_3}{3!}\phi^3 + \frac{\lambda}{4!}\phi^4 + \kappa\,\phi\,\bar{\chi}\,\chi$$





→ 2-to-3 translate kinetic energy to rest mass.

(reverse) "cannibal process"

Boltzmann equations

- assume ***kinetic equilibrium***: $f_\phi(p, T_\phi) \sim e^{-\omega_p/T_\phi}$

- Solve coupled BME up to **second** moment: $n_\phi(x)$ & $T_\phi(x)$

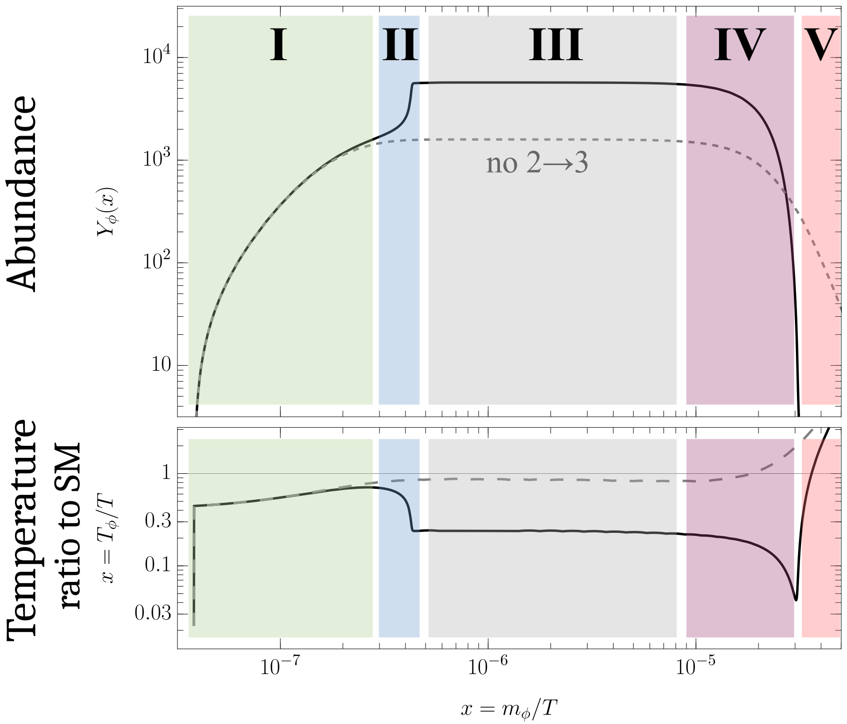
Abundance Y=n/s: $$x H \frac{d Y_\phi}{d x} = + 2 \Gamma_{H\to\phi\phi} Y_H^{eq} + \langle\sigma v\rangle_{2\to 3}\, s Y_\phi \left(Y_\phi - Y_\phi^{eq}\right) - \Gamma_{\phi\to\bar\chi\chi} Y_\phi$$

Temperature: $$\frac{d T_\phi}{d x} = \ldots$$

- Simplify model: $\lambda_3 \sim \lambda^{1/2} \;\rightarrow\; (\sigma v)_{2\to 3} \sim \lambda^3$

Dark sector evolution

$$x\,H\,\frac{d\,Y_\phi}{d\,x} = 2\,\Gamma_{H\to\phi\phi}\times Y_H^{eq} + \langle\sigma\,v\rangle_{2\to 3}\,s Y_\phi\times\left(Y_\phi - Y_\phi^{eq}\right) - \Gamma_{\phi\to\bar{\chi}\chi}\times Y_\phi$$



Inverse temperature (~time)

I. Freeze-in

II. Thermalization of ϕ

III. (Redshifting in equilibrium)

IV. Decay in thermal equilibrium

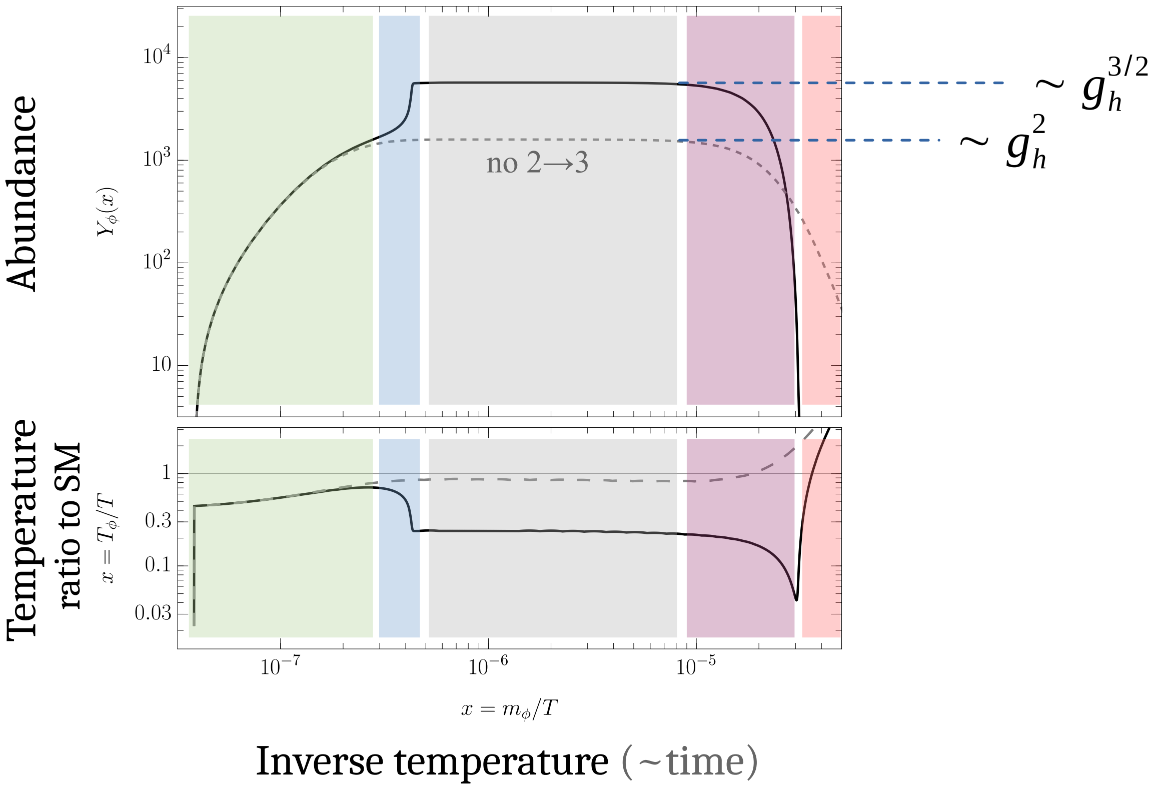
V. Decay:

a) in kinetic equilibrium

b) after kinetic decoupling

Dark sector evolution

$$x H \frac{d Y_\phi}{d x} = 2\Gamma_{H\to\phi\phi} \times Y_H^{eq} + \langle \sigma v \rangle_{2\to3}\, s Y_\phi \times \left(Y_\phi - Y_\phi^{eq} \right) - \Gamma_{\phi\to\bar{\chi}\chi} \times Y_\phi$$



➢ Change in abundance from self-thermalization: $\sim g_h^{-1/2}$

$$\rho^{FI} = \rho^{eq}$$

$$n_\phi^{eq}\Big|_{T_\phi \gg m_\phi} \approx \sqrt[4]{\pi^2 n_\phi^{FI} {T_\phi^{FI}}^3}$$

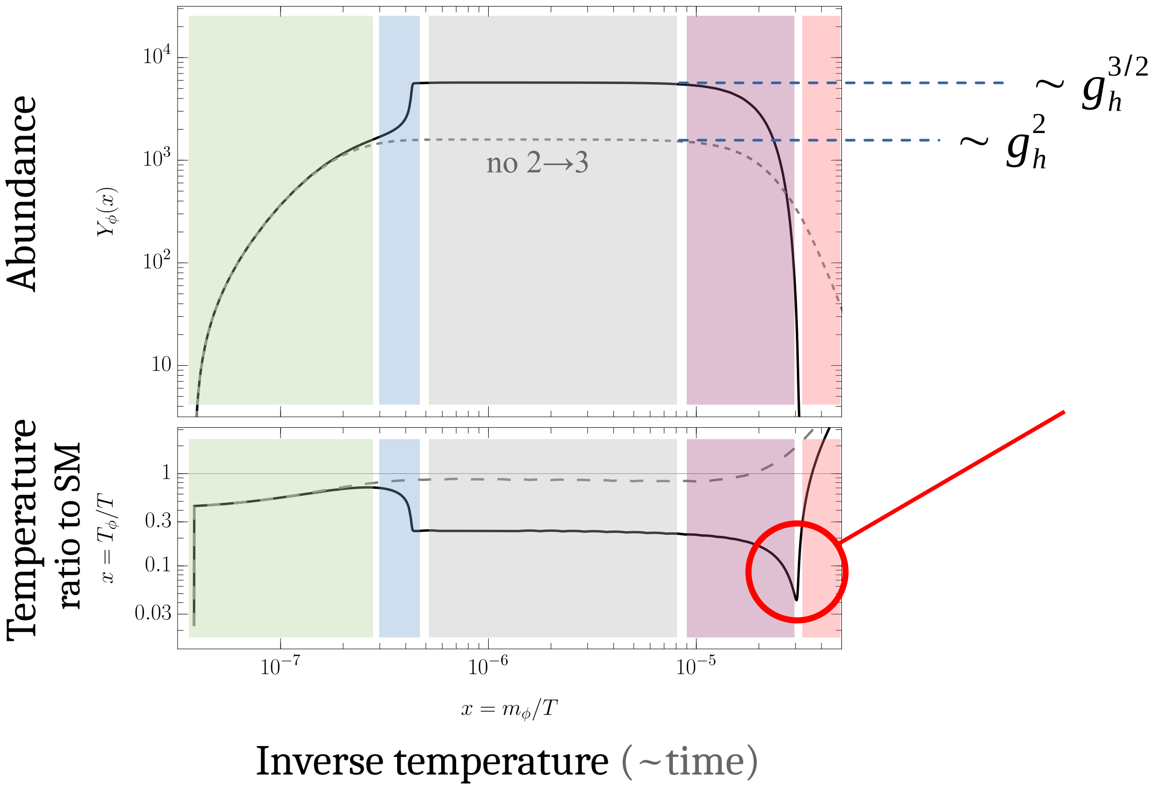
$$n_\phi^{FI} \sim \Gamma_{h\to\phi\phi} \sim g_h^2$$

$$T_\phi^{FI} \approx T_\phi^{FI}\left(\frac{m_h}{m_\phi}\right)$$

$$n_\phi^{FI} / n_\phi^{eq} \sim \sqrt{g_h}$$

Dark sector evolution

$$x\,H\,\frac{d\,Y_\phi}{d\,x} = 2\,\Gamma_{H\to\phi\phi}\times Y_H^{eq} + \langle\sigma v\rangle_{2\to3}\, s Y_\phi \times \left(Y_\phi - Y_\phi^{eq}\right) - \Gamma_{\phi\to\bar\chi\chi}\times Y_\phi$$



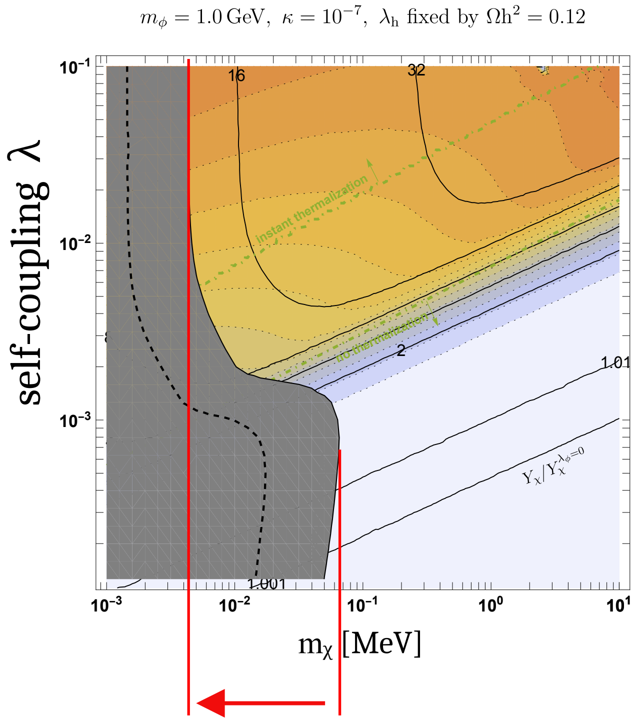
- Change in abundance from self-thermalization: $\sim g_h^{-1/2}$

- Decay starts *during* efficient $2 \leftrightarrow 3$: decaying modes are rapidly replenished. $\longrightarrow$ strong secondary cooling.

Lyman-α exclusion bounds

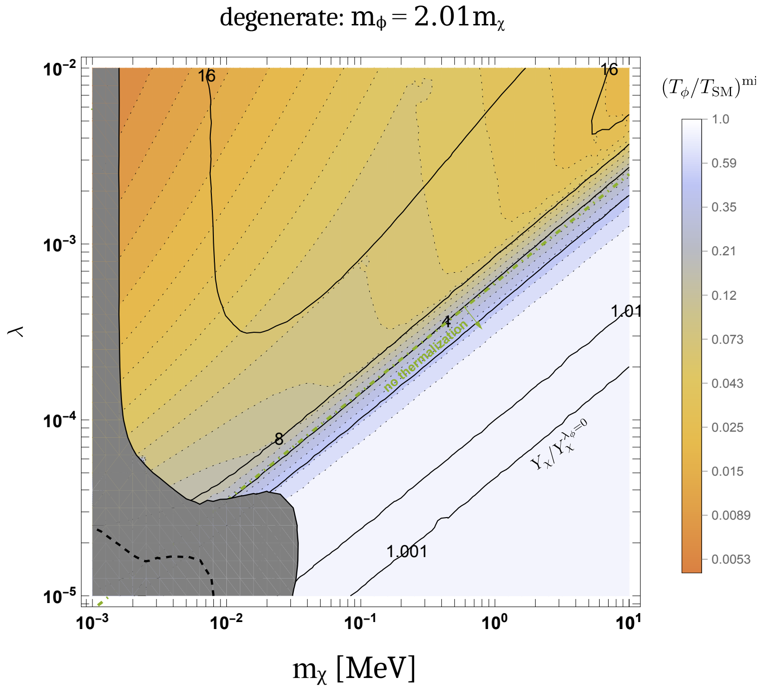
procedure

- Pick mass-scale (m_ϕ)
- Fix decay time (κ)
- match $\Omega h^2 = 0.12$ (g_h)
- Plot Lyman-α exclusion bounds in λ and m_χ.



DS self-cooling for $\lambda \gtrsim 0.001$

$\rightarrow (\lambda_3 \gtrsim 0.03)$

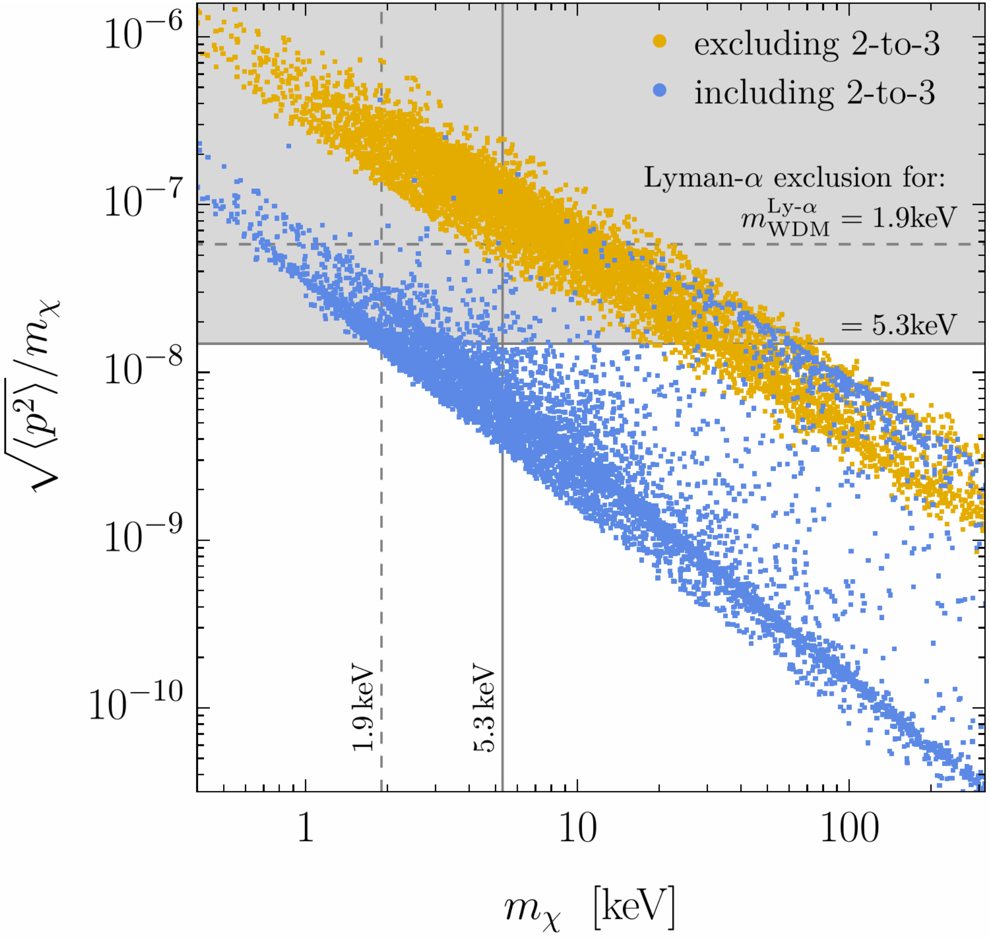


Model Exploration via MCMC

MCMC results for 5D-scan (still ongoing)

- 2-to-3 reactions **included**
- 2-to-3 reactions **disregarded**

- DS-Cooling reduces $<v_\chi^2>$ in a given model



Model Exploration via MCMC

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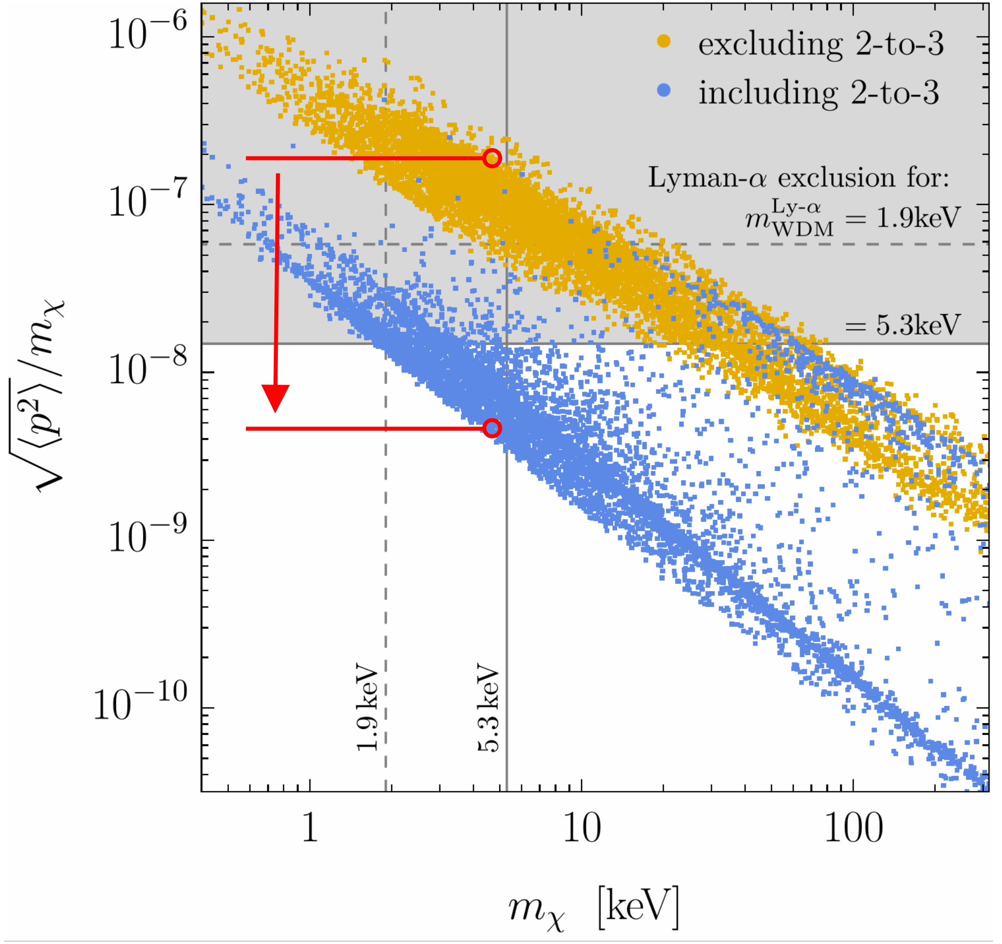

Model Exploration via MCMC

MCMC results for 5D-scan (still ongoing)

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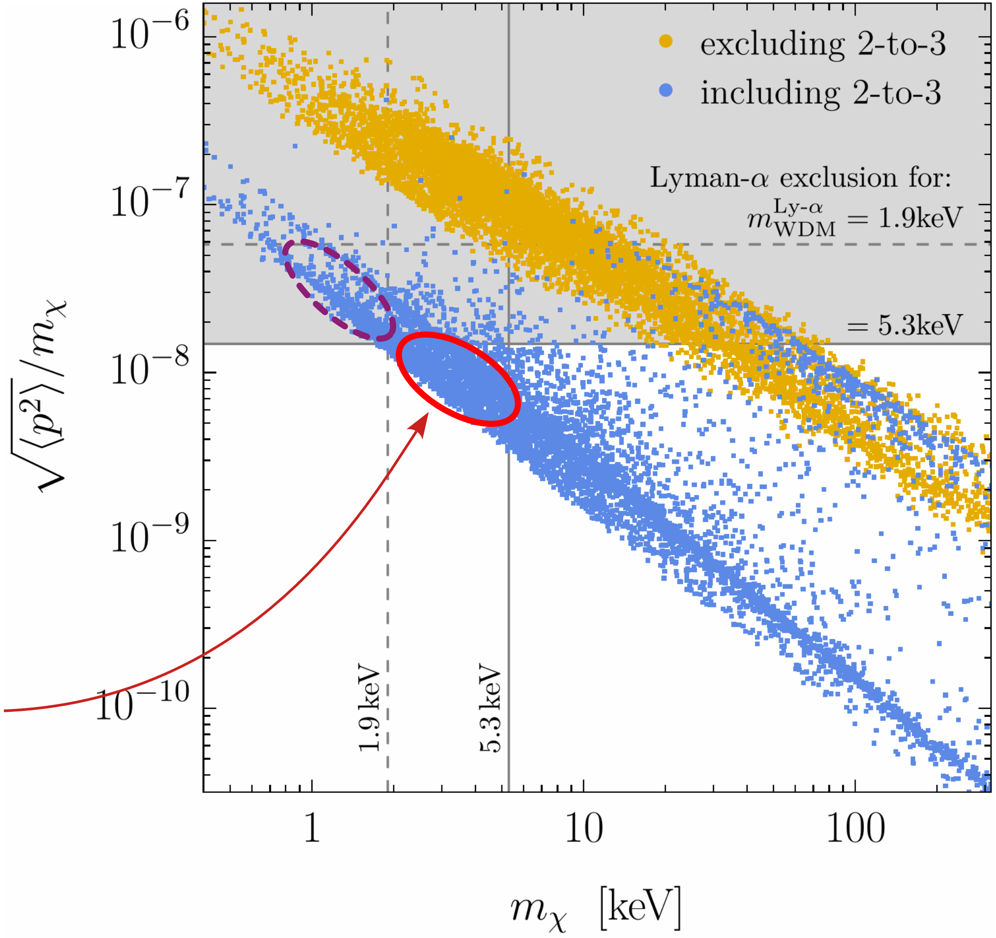
Models allowed but below the WDM limit.



Model Exploration via MCMC

preliminary

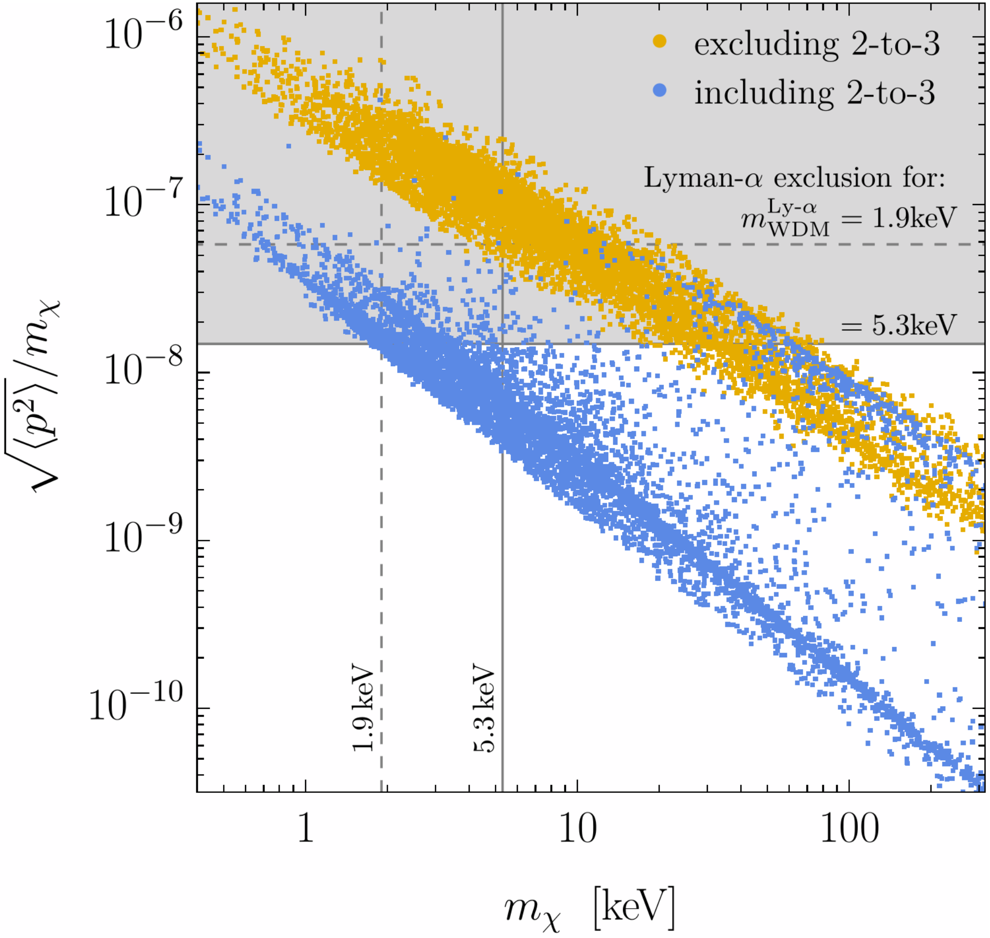
MCMC results for 5D-scan (still ongoing)

- 2-to-3 reactions **included**
- 2-to-3 reactions **disregarded**
- DS-Cooling reduces $\langle v_\chi^2 \rangle$ in a given model

  - ➢ lowest m_χ = **1.7keV** (m_{WDM} = 5.3keV)
  - ➢ Lyman-α corrections as large as **O(10²)**

    → decay-cooling is also large!

  - ➢ Cooling present even at **low λ** ~ O(10⁻⁴) !



Summary

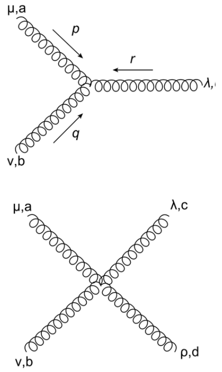
<u>Already for the simplest toy model:</u>

- Self-cooling non-thermal dark sectors allow for $\mathbf{m_\chi \approx 1keV}$.
- Already for small self-interactions ($\sim 10^{-2}$).
- Cooling during decay-onset important.

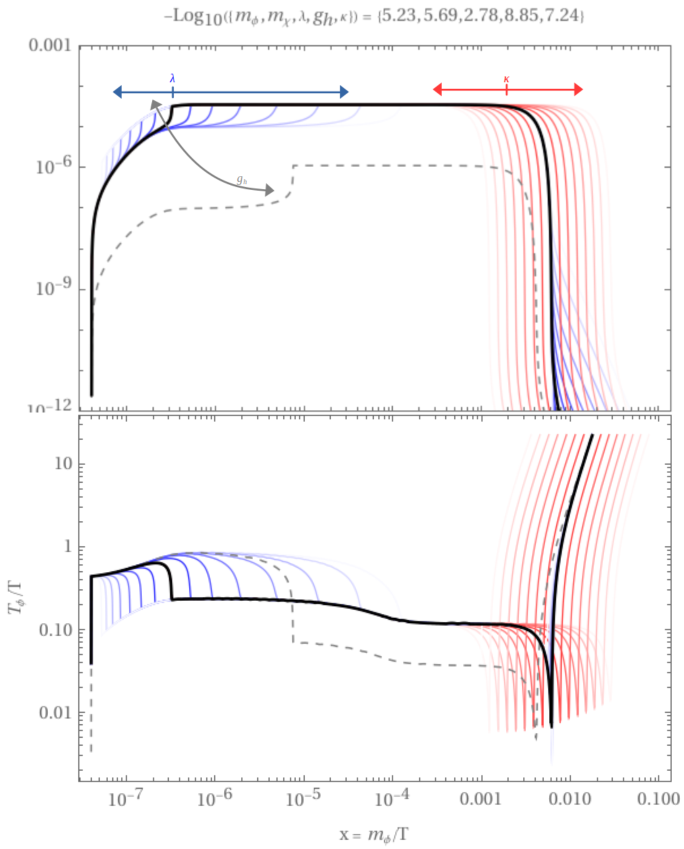
<u>*Outlook:*</u>

- Mechanism also possible in (broken) $\mathbf{SU(N)_d}$ models: $\phi \to A_{\mu,a}$

(→ momentum dependent vertices. Qualitatively identical results)



Parameter dependence of DS evolution



Lyman-α-bounds shift vs. self-coupling

MCMC-scan of parameter space. (8240 points converged to Ωh^2=0.12)