Dark matter freeze-in from semi-production

Maxim Laletin

National Centre for Nuclear Research (NCBJ), Poland

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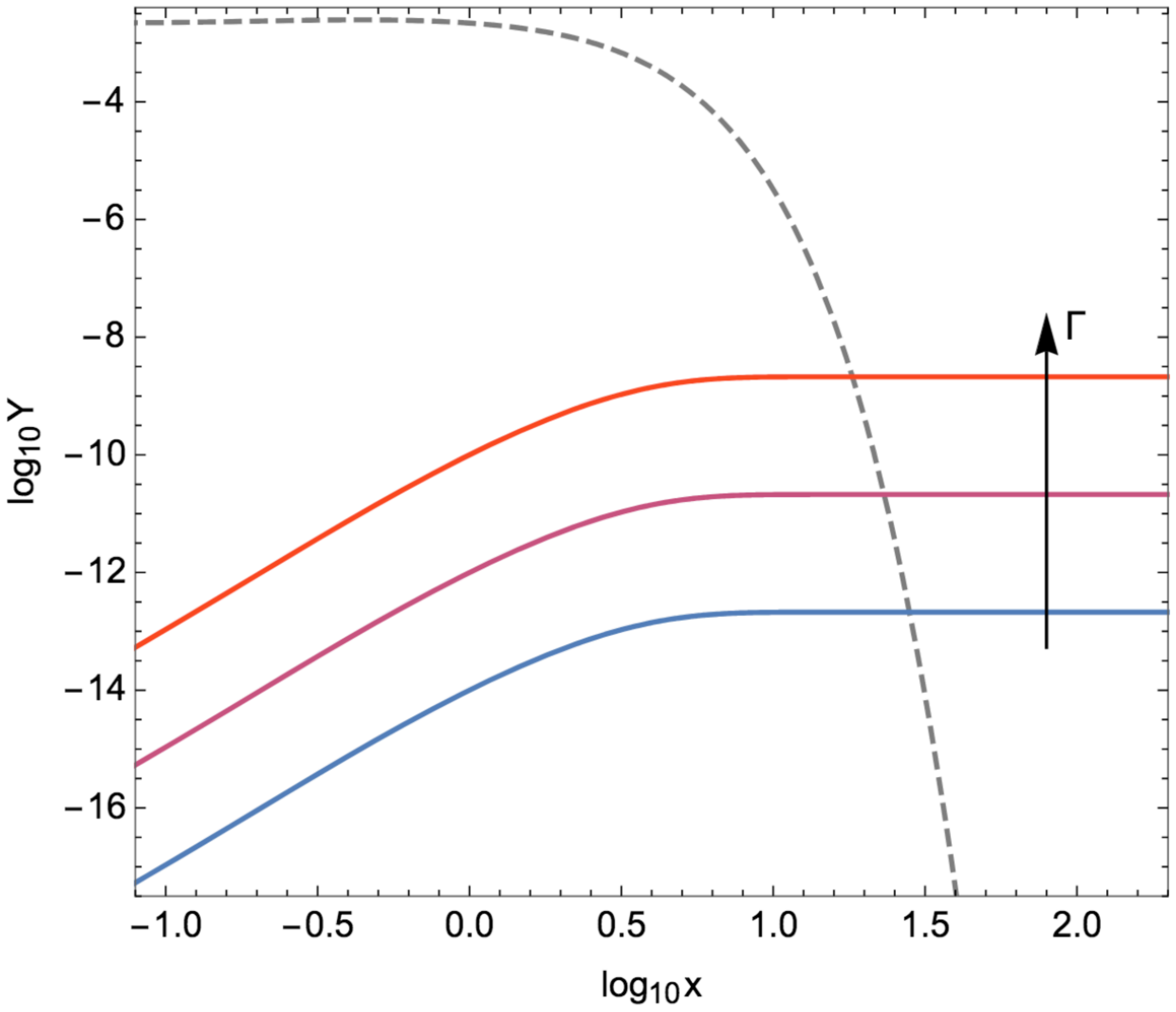
Freeze-in production of DM

From 1706.07442



$$x = \frac{m}{T}$$

- Dark matter interacts feebly with SM (not in equilibirum) and it's initial concentration is tiny
- DM density freezes in when the density of SM is suppressed and the production is inefficient
- The production process can be a decay or annihilation
- Typical annihilation cross section required

$$\sigma v \lesssim 10^{-40}\ \mathrm{cm}^3/s$$

Semi-production

Dark matter

$$\chi\phi \to \chi\chi$$

New particle (mediator) or a SM state

Motivation for study

What is different from the pair-annihilation freeze-in?

- The production rate is proportional to the DM density. Smaller initial abundance → larger cross section
- Semi-production modifies the energy of DM particles in a non-trivial way, so the temperature evolution can affect the relic density

Toy model

We start the investigation with a simple toy model

Z3 symmetry

$$\mathcal{L}_{int} = \mathcal{L}_{SM} + \mathcal{L}_{\phi-SM} + \frac{\lambda}{2}\phi\left(\chi^3 + (\chi^*)^3\right)$$

- Assume that ϕ is in equilibrium with SM and χ has some tiny initial abundance (e.g. from the gravitational production)

- The abundance of χ is determined by the Boltzmann equation (we search for the model parameters that can reproduce the observed relic density of DM)

Boltzmann equation (BE)

$$2E_i\left(\partial_t - H\,p\partial_p\right) f_i(p) = C\left[f_i\right]$$

Hubble rate

Distribution function

Collision term (interactions)

- Integrating over the phase-space of the DM particle (and introducing comoving variables) one gets an equation for the abundance

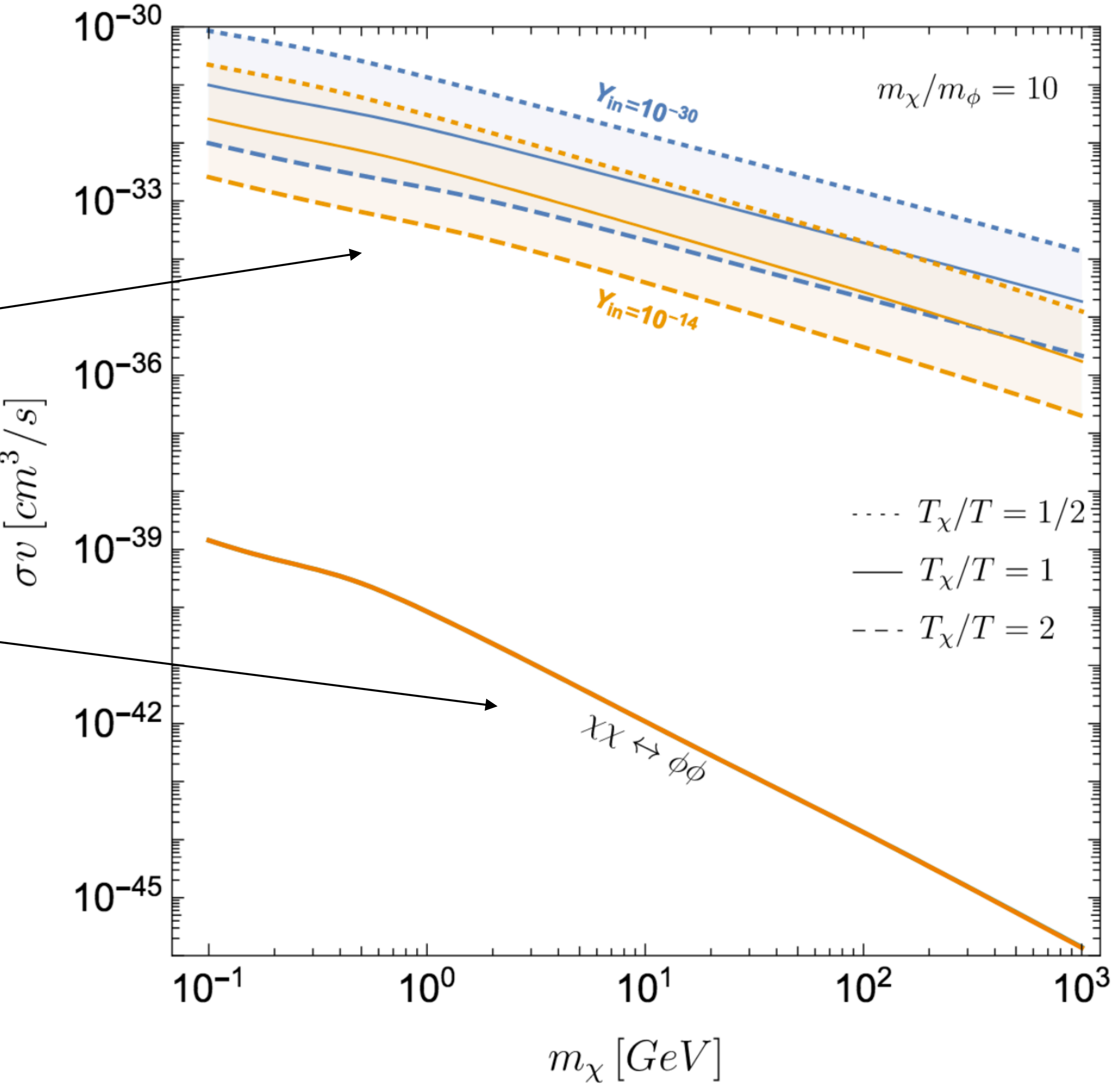
$$\frac{dY}{dx} = \frac{\langle \sigma v\rangle(T_\chi, T_\phi)}{xsH} Y$$

$$x = \frac{m}{T}$$

$$Y = \frac{n_{\rm DM}}{s}$$

Toy model

- Assume that the temperature of χ is known
- Semi-production requires much larger cross sections than pair-production
- If ϕ is out of equilibrium, even larger cross sections are possible



Coupled system of BEs

- In reality we don't know the temperatures of χ and ϕ *apriori*, but they can be important!
- We assume that ϕ and χ are both self-thermalized (have an equilibrium shape) and solve for their density and temperature

$$\frac{Y_i'}{Y_i} = \frac{m_i}{x\tilde{H}} C_i^0 \,, \qquad C_i^0 \equiv \frac{g_i}{m_i n_i} \int \frac{d^3p}{(2\pi)^3 E_i} C[f_i] \,,$$

$$\frac{y_i'}{y_i} = \frac{m_i}{x\tilde{H}} C_i^2 - \frac{Y_i'}{Y_i} + \frac{H}{x\tilde{H}} \frac{\langle p^4/E_i^3 \rangle}{3T_i} \qquad C_i^2 \equiv \frac{g_i}{3 m_i n_i T_i} \int \frac{d^3p}{(2\pi)^3 E_i} \frac{p^2}{E_i} C[f_i]$$

higher moment term

$y_i \equiv m_i T_i / s^{2/3}$ **Temperature parameter**

Setting

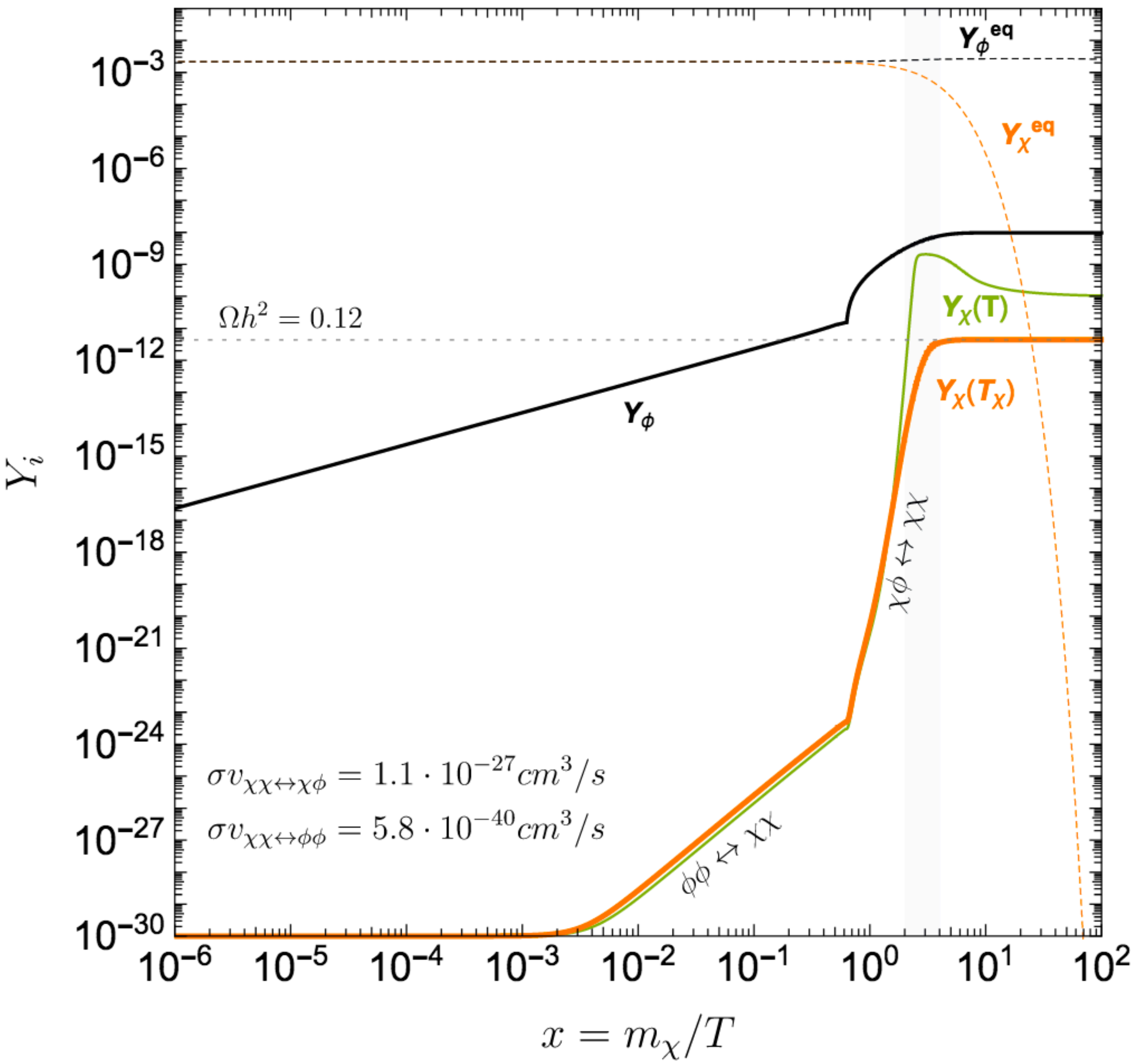
- We now consider a more detailed example model, where ϕ is a scalar singlet coupled to the Higgs doublet

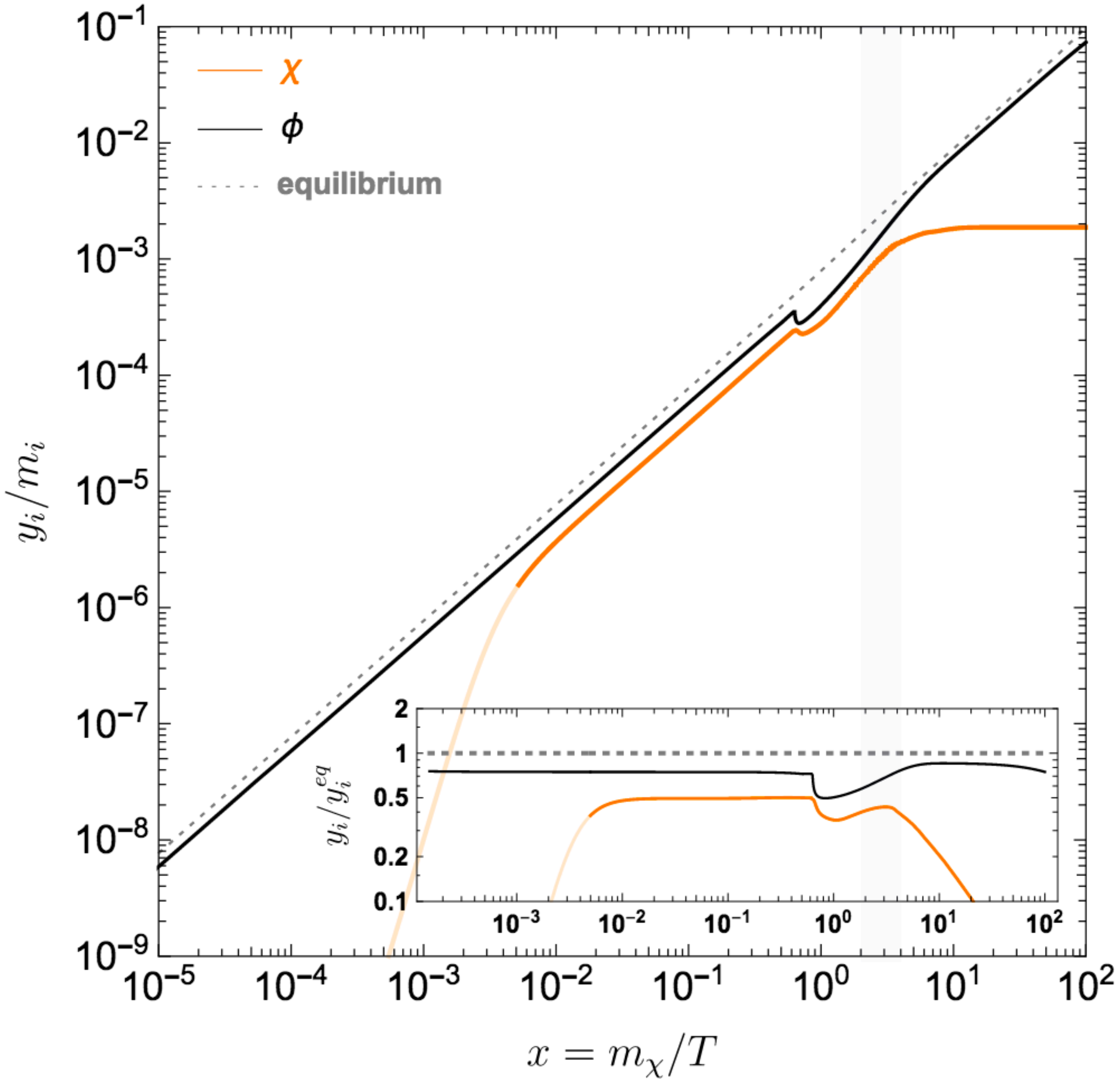
$$
\begin{aligned}
\mathcal{L}_{\phi-SM} &= \overbrace{A\phi H^\dagger H + \frac{\lambda_{h\phi}}{2}\phi^2 H^\dagger H}^{\text{Higgs portal interactions}} - \mu_h^2 H^\dagger H + \frac{\lambda_h}{2}(H^\dagger H)^2 \\
\mathcal{L}_{DS} &= \frac{\mu_\phi^2}{2}\phi^2 + \frac{\mu_3^2}{3!}\phi^3 + \frac{\lambda_\phi}{4!}\phi^4 + \mu_\chi^2 \chi^*\chi + \frac{\lambda_\chi}{4}(\chi^*\chi)^2 \\
&\quad + \underbrace{\frac{\lambda_1}{3!}\phi\left(\chi^3 + (\chi^*)^3\right)}_{\text{semi-production}} + \underbrace{\frac{\lambda_2}{2}\phi^2(\chi^*\chi)}_{\text{pair-production}},
\end{aligned}
$$

- ϕ gets a VEV, but χ doesn’t

- $m_\phi < 3m_\chi$ → no decays

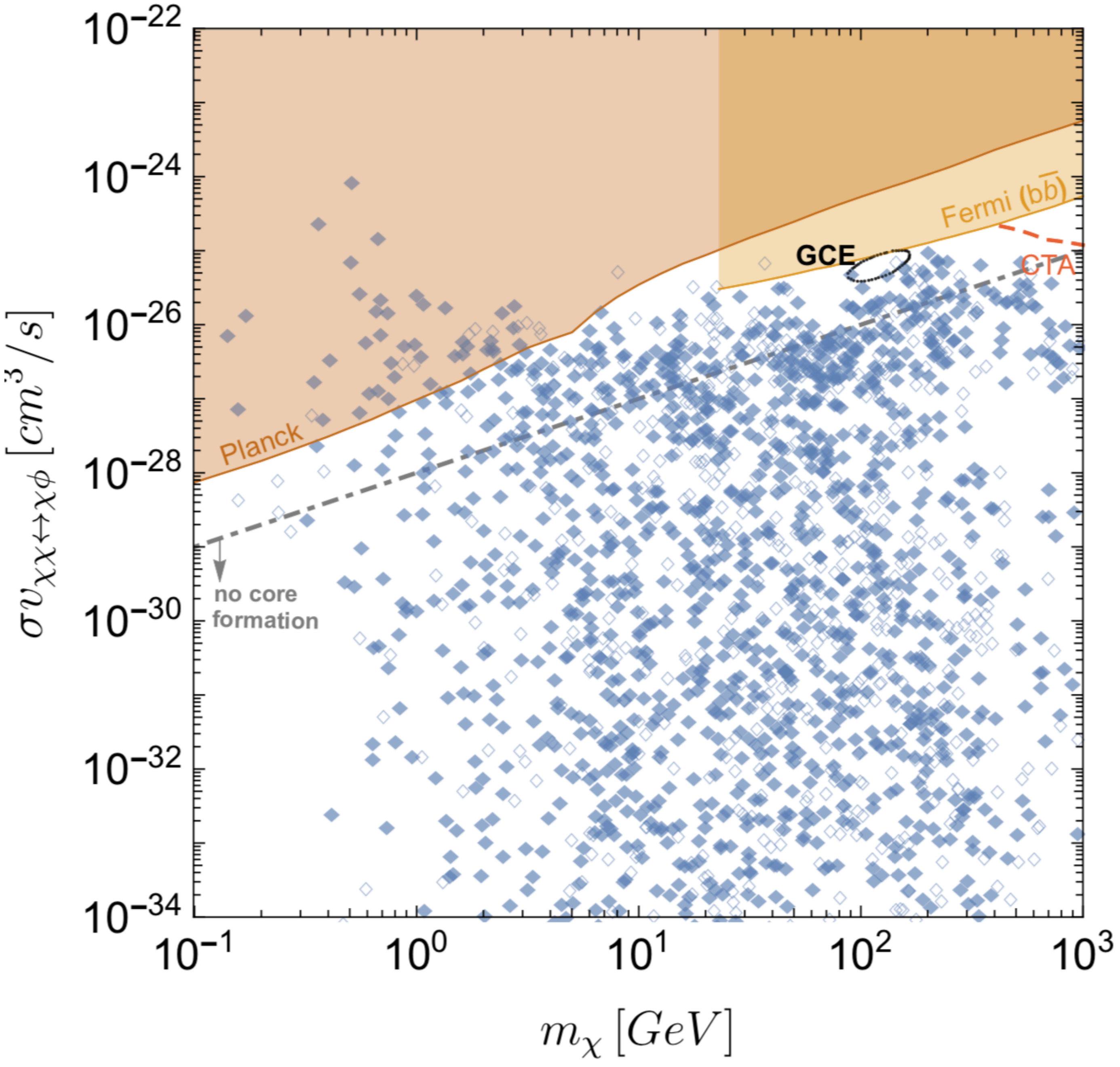
Evolution of density and temperature





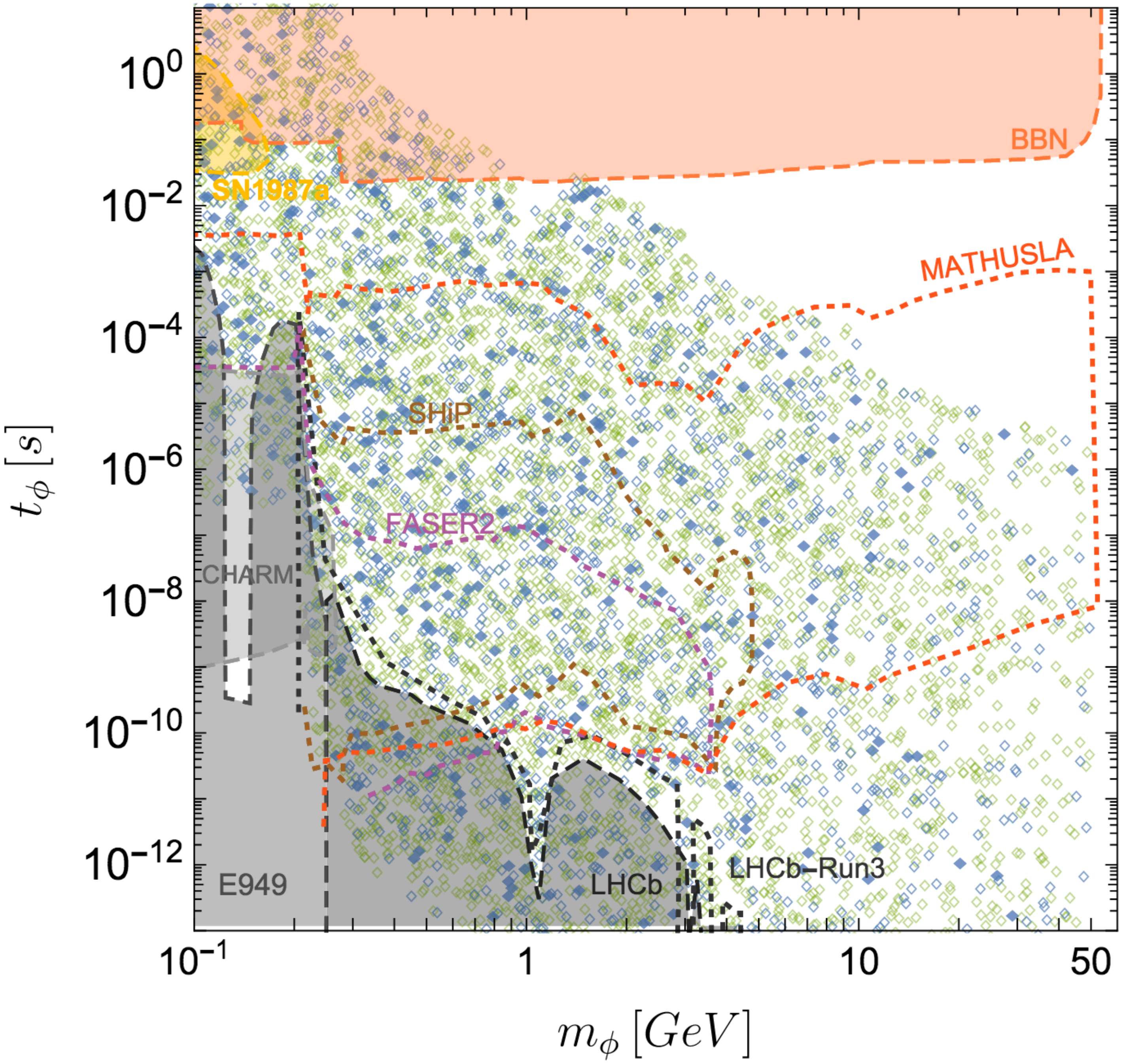
$$m_\chi = 100 \text{ GeV},\ \mu_\phi = 1 \text{ GeV},\ \lambda_1 = 1.1 \times 10^{-2},\ \lambda_2 = 10^{-8},\ \lambda_{h\phi} = 6 \times 10^{-11}$$

Indirect detection constraints and predictions



- The results of the scan in the parameter space for the DM production dominated by the semi-annihilation processes.
- The coloured squares indicate the points, which are within the reach of the future searches for the mediator ϕ and the empty ones are beyond these prospects.
- The points above the grey dot-dashed line can potentially explain the core formation in dSph [1803.09762]

Long-lived particle searches



- The constraints on the properties of the mediator ϕ and the prospects for its detection.

- The blue points correspond to the DM production dominated by the semi-annihilation, while the green ones – by the pair-annihilation.

Conclusion

- We have studied the freeze-in mechanism based on the semi-annihilation process
- Semi-production freeze-in requires larger cross sections than the pair-production freeze-in
- This mechanism can be incorporated in various models and promises an interesting phenomenology that is within the reach of near-future experiments
- Temperature evolution has a significant impact on the relic density

Thank you!