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Freeze-in dark matter production from semi-annihilations

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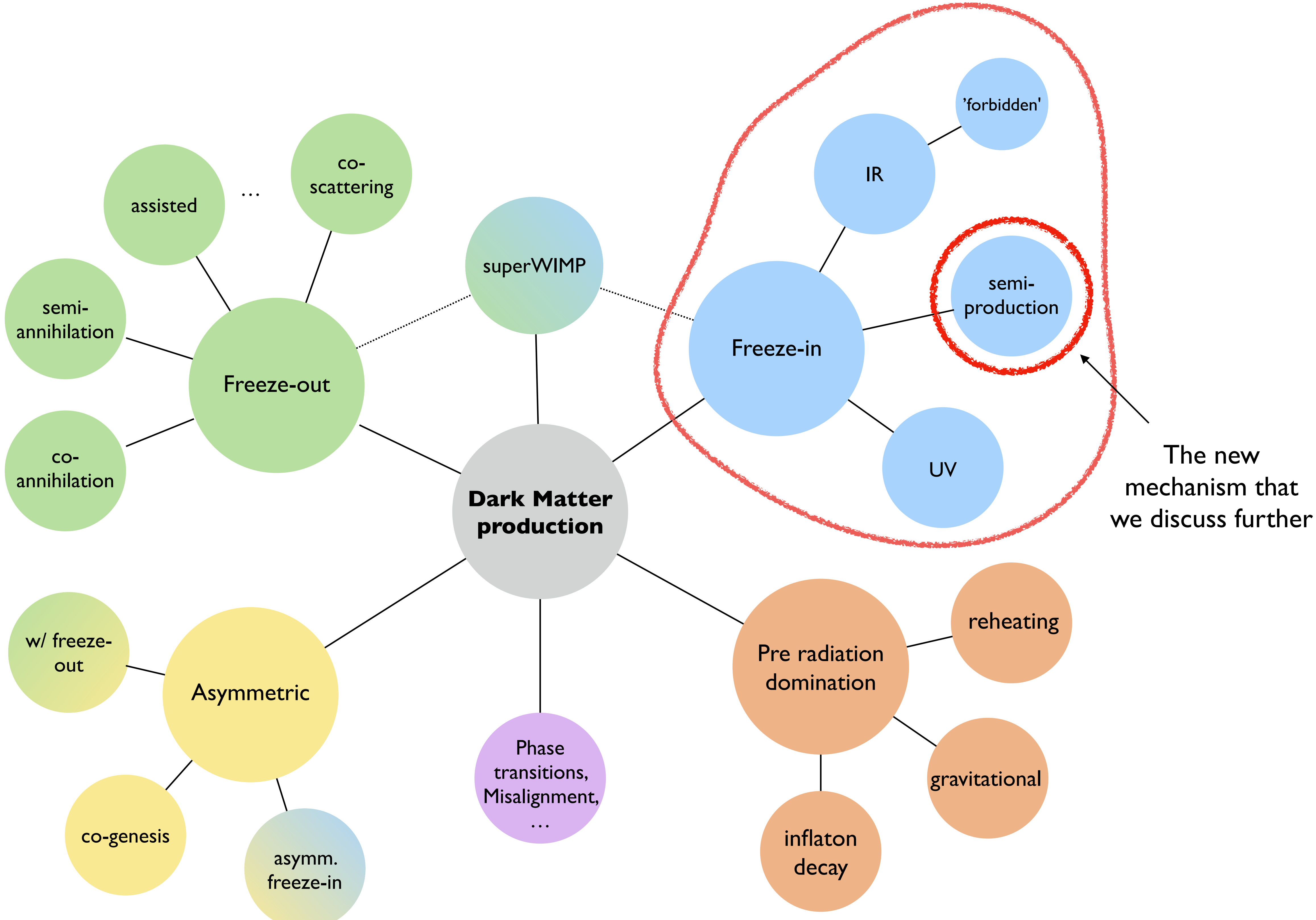
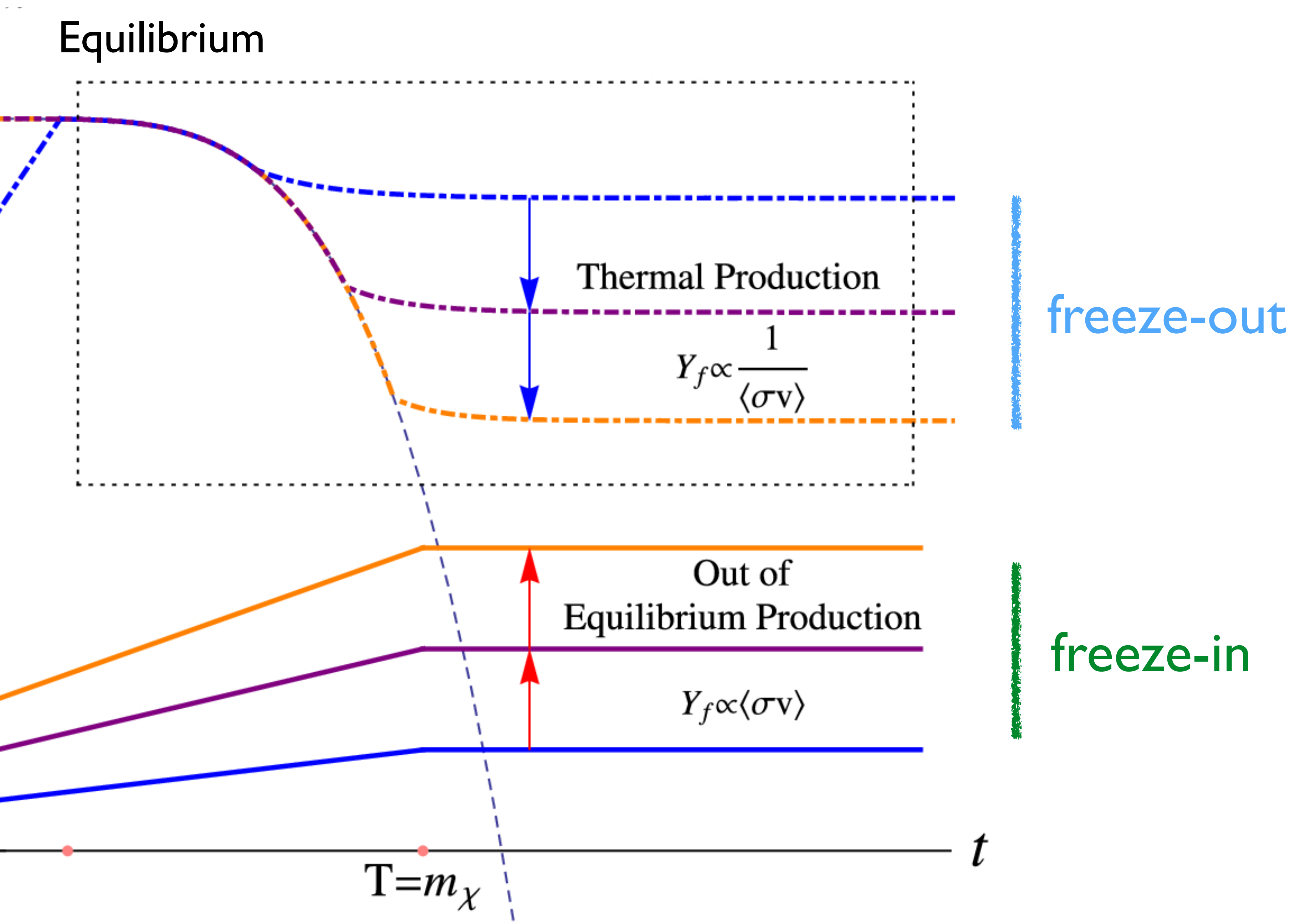
DARK MATTER PRODUCTION



Freeze-in vs. Freeze-out



(more info in the next slide…)

Freeze-in vs. Freeze-out

WIMPs
(Weakly Interacting Massive Particles)

DM starts in equilibrium with the SM bath

The role of the interaction with SM is to suppress DM from its huge initial population

If through annihilation typical value required

$$\langle \sigma v \rangle \sim 10^{-26}\ \mathrm{cm}^3/s$$

Relic abundance decreases with $\langle \sigma v \rangle$

Requires
$T_{\mathrm{RH}} \gtrsim m_\chi$

FIMPs
(Feebly Interacting Massive Particles)

DM never in equilibrium with the SM bath

The role of the interaction with SM is to produce DM

If through annihilation typical value required

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

Relic abundance increases with $\langle \sigma v \rangle$

Requires
~no initial abundance

Typical annihilation cross section for freeze-in

$$\langle \sigma v \rangle \lesssim 10^{-40}\ \text{cm}^3/s$$

This is too weak for a near-future direct or indirect detection

Is it possible to have an observable signal from freeze-in?

SEMI-PRODUCTION

Consider process of production that is the inverse of semi-annihilation:

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

DM — mediator or a SM state

What is different (from the decay/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

EXAMPLE TOY MODEL

We start the investigation with a simple two-scalar toy model:

Z_3 symmetry

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

DM

A. Assume that ϕ is in equilibrium with SM and for now simply take χ to have some tiny initial abundance (e.g. from reheating or UV pair production)

B. For now also neglect any other potential interaction terms in the Lagrangian

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 Y

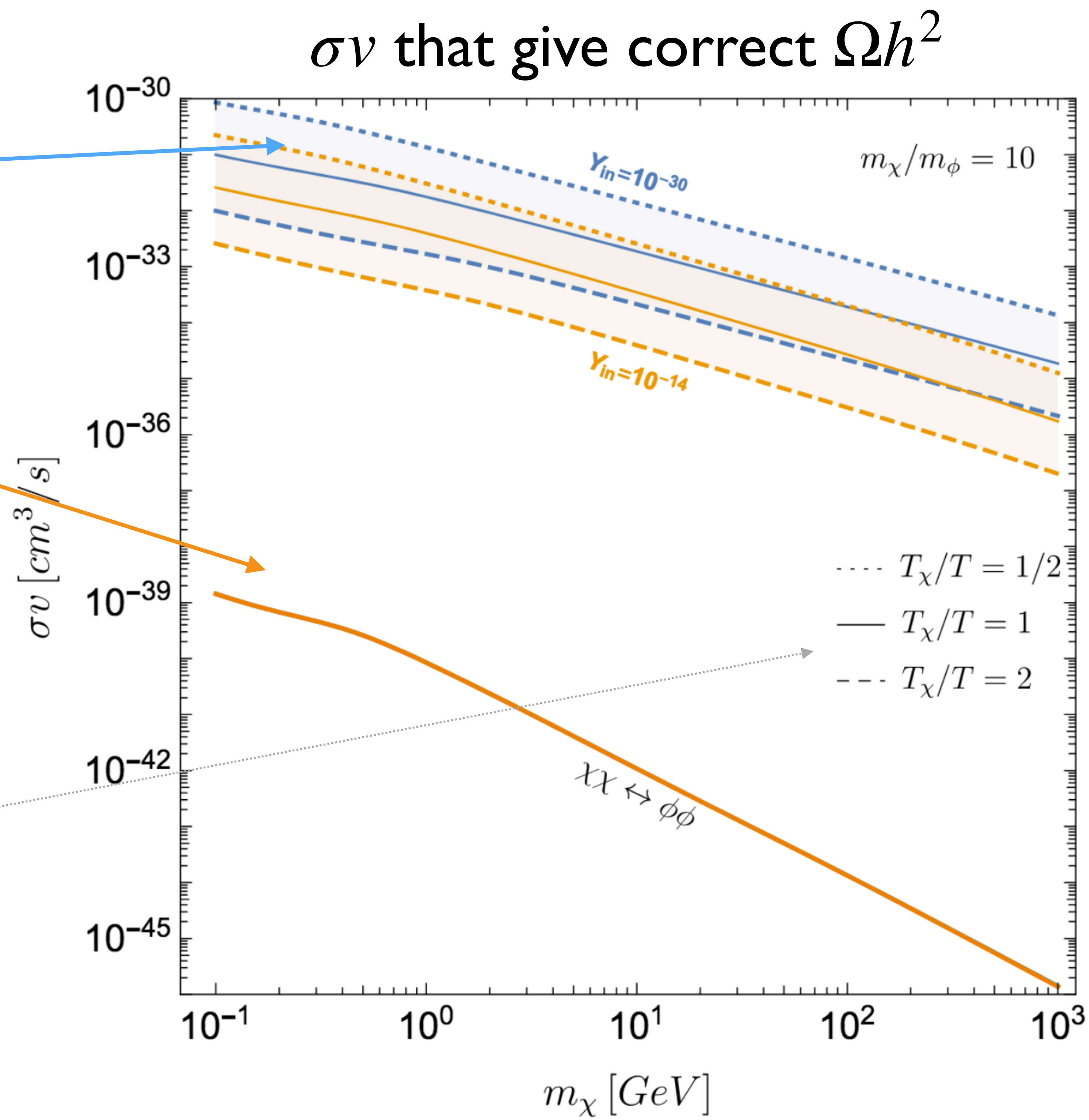
$$\frac{dY}{dx} = \frac{\langle\sigma v\rangle(T_\chi, T_\phi)}{xsH}Y$$

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

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

TOY MODEL RESULTS

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



$\to$ T_χ can be quite relevant!

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

$$\frac{Y_i'}{Y_i} = \frac{m_i}{x\tilde{H}} C_i^0 \,,$$

$$\frac{y_i'}{y_i} = \frac{m_i}{x\tilde{H}} C_i^2 - \frac{Y_i'}{Y_i} + \frac{H}{x\tilde{H}} \frac{\langle p^4/E_i^3 \rangle}{3T_i}$$

$$C_i^0 \equiv \frac{g_i}{m_i n_i} \int \frac{d^3p}{(2\pi)^3 E_i} C[f_i] \,,$$

$$C_i^2 \equiv \frac{g_i}{3 m_i n_i T_i} \int \frac{d^3p}{(2\pi)^3 E_i} \frac{p^2}{E_i} C[f_i]$$

higher moment term

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

We have developed a code (Wolfram & C++) to solve this coupled system with all the relevant processes

Realistic Model

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

Higgs portal interactions

$$\mathcal{L}_{\phi-SM} = A\phi H^\dagger H + \frac{\lambda_{h\phi}}{2}\phi^2 H^\dagger H - \mu_h^2 H^\dagger H + \frac{\lambda_h}{2}(H^\dagger H)^2$$

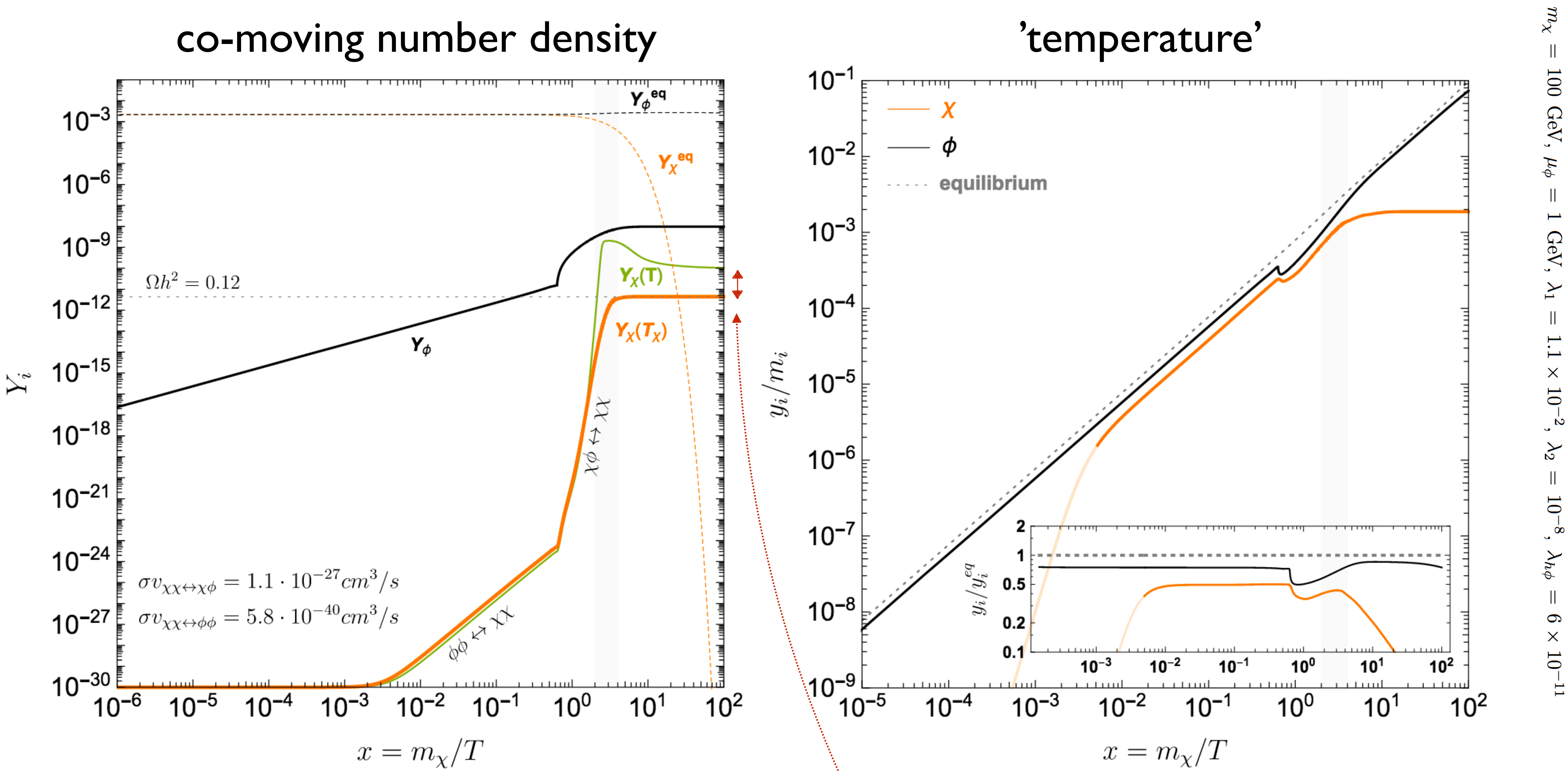
$$\mathcal{L}_{DS} = \frac{\mu_\phi^2}{2}\phi^2 + \frac{\mu_3^2}{3!}\phi^3 + \frac{\lambda_\phi}{4!}\phi^4 + \mu_\chi^2\chi^*\chi + \frac{\lambda_\chi}{4}(\chi^*\chi)^2 + \frac{\lambda_1}{3!}\phi\left(\chi^3 + (\chi^*)^3\right) + \frac{\lambda_2}{2}\phi^2(\chi^*\chi),$$

semi-production   pair-production

- ϕ gets a VEV, but χ doesn't

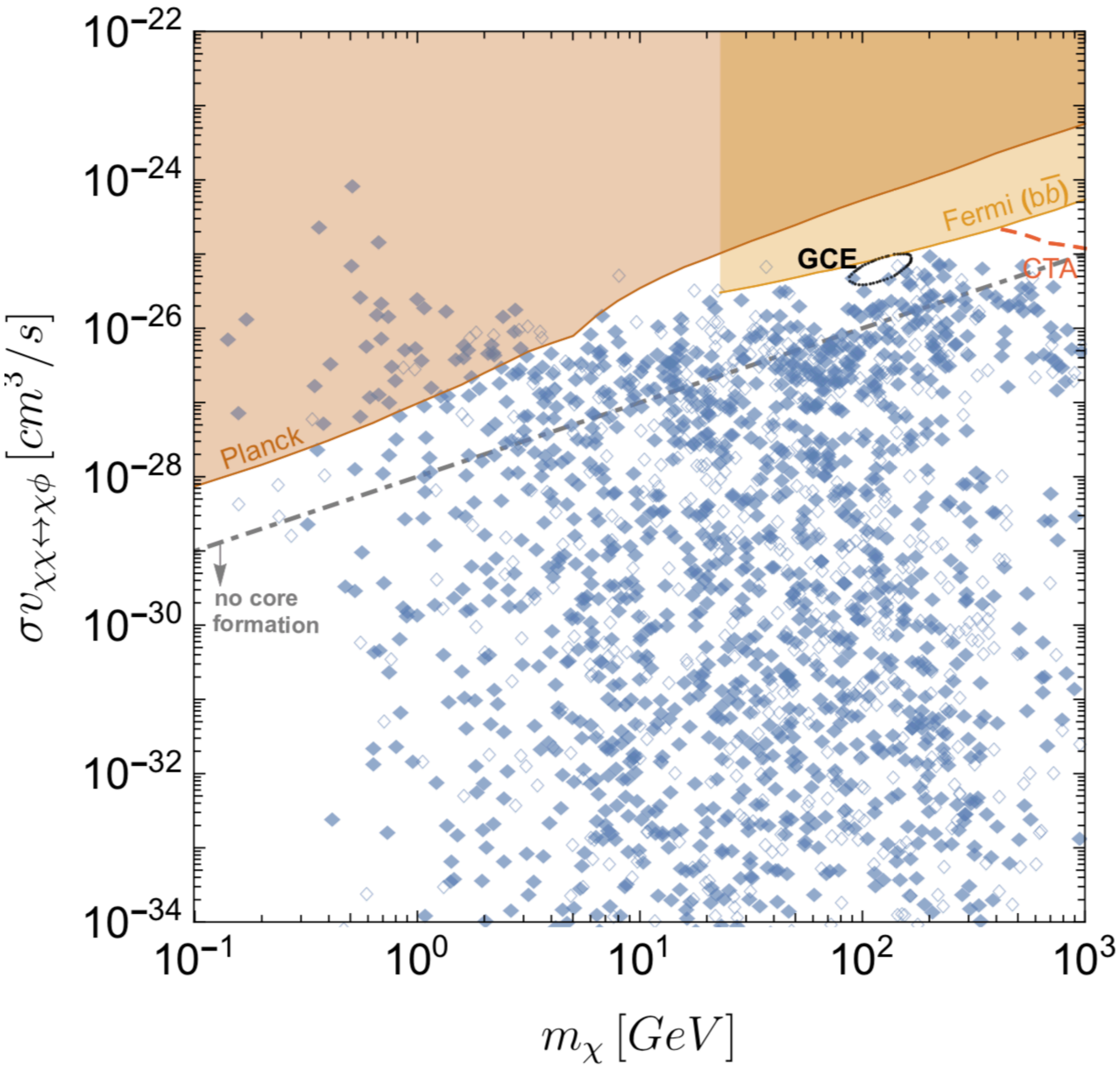
- $m_\phi < 3m_\chi$ → no decays

EVOLUTION



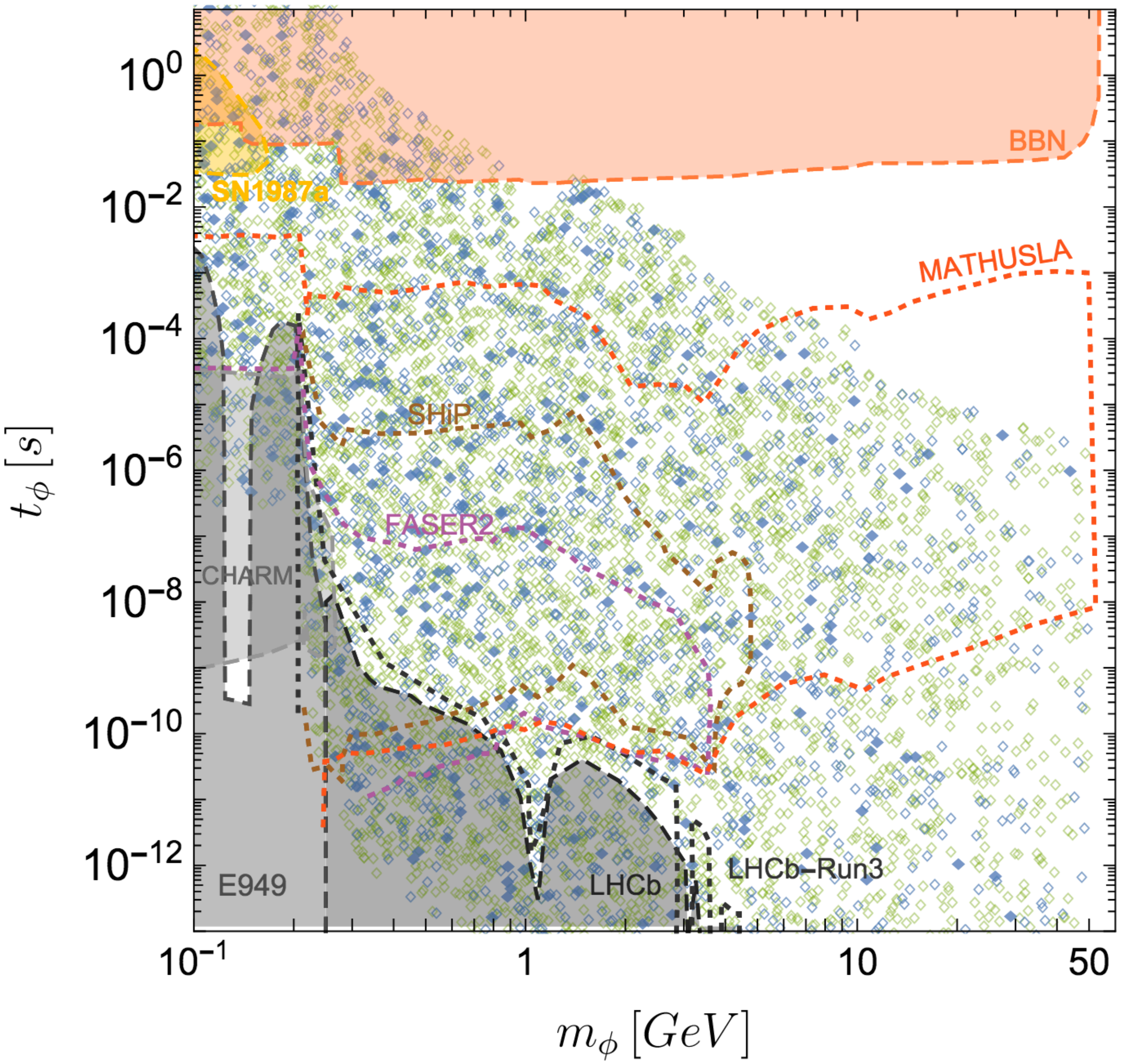
The full calculation compared to one assuming $T_\chi = T$ can differ by more than order of magnitude!

INDIRECT DETECTION



- 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]

LABORATORY 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 novel 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!