Dark matter freeze-in from semi-production

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Freeze-in

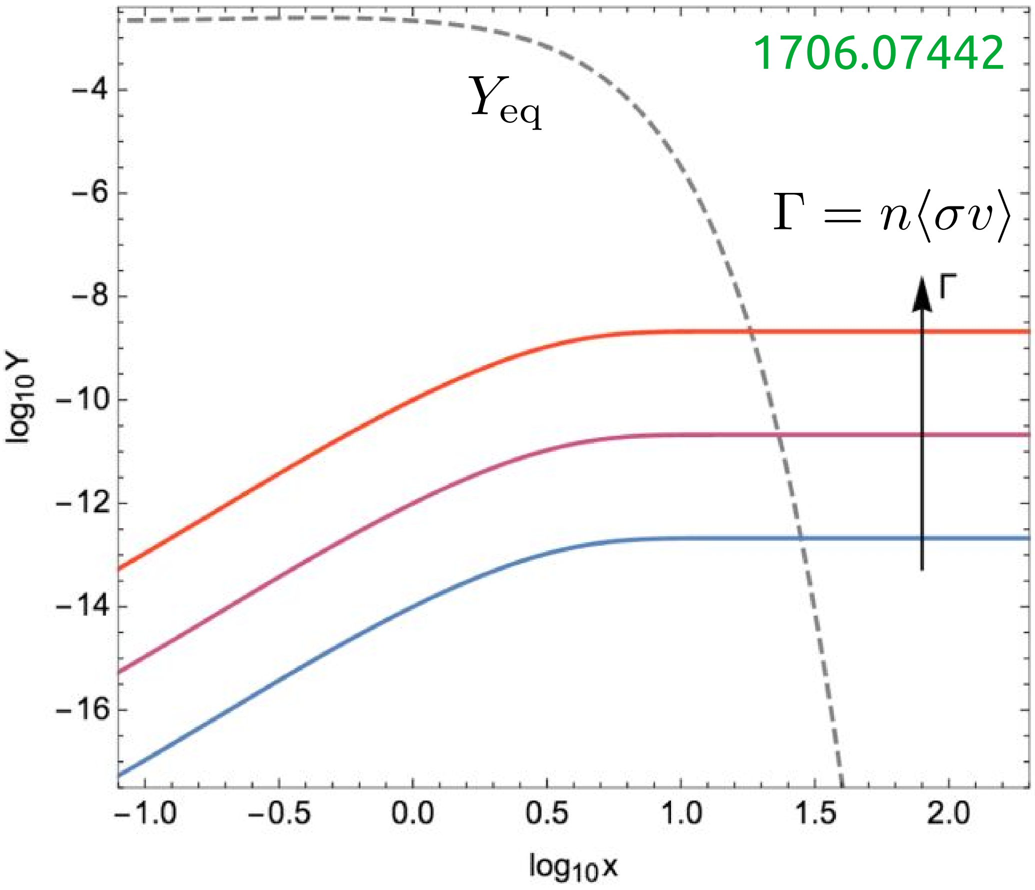
DM interacts feebly with SM and never reaches the thermal equilibrium

Amount of energetic SM states is exponentially supressed → freeze in

The stronger the coupling → the larger the relic density

If governed by pair-annihilation

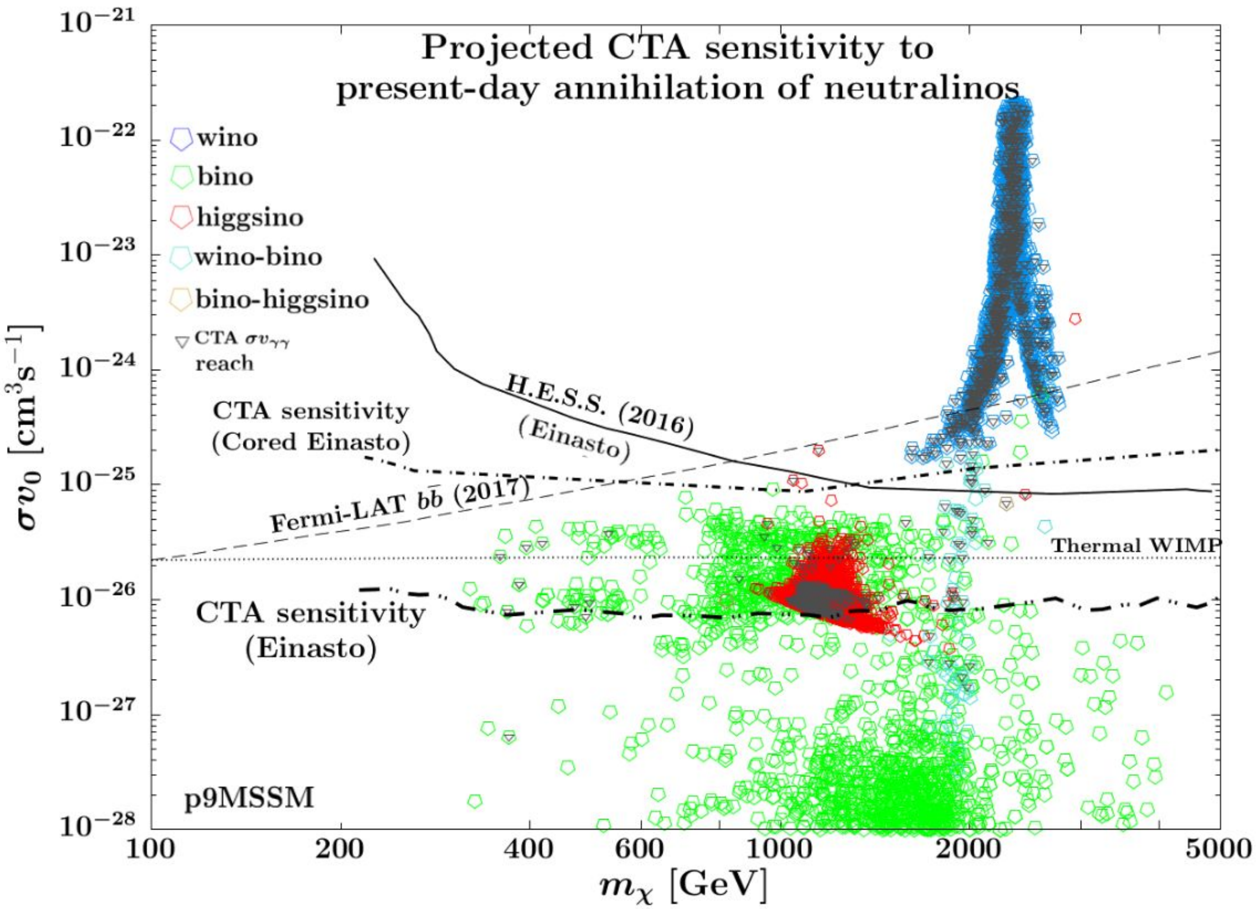
$$\langle \sigma v \rangle \lesssim 10^{-40} \mathrm{cm}^3/\mathrm{s}$$



$$Y = n/s \qquad x = m/T$$

Testing freeze-in

1905.00315



Coupling too small to be probed by near-future indirect detection searches*

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

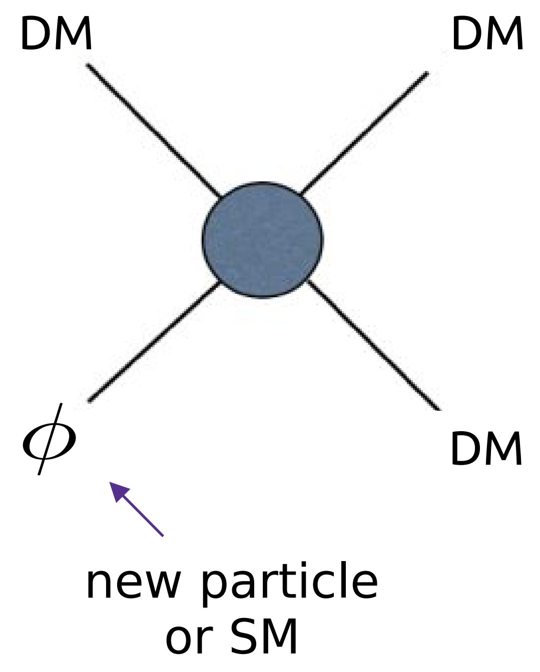
* and direct detection too

Semi-production

Semi-production can appear from symmetry larger than Z_2

Production rate is proportional to the DM density:

Smaller initial abundance → larger cross section to reproduce Ωh^2



If $m_\varphi < m_{DM}$ and the DM kinetic equilibrium isn't maintained (well), semi-production cools DM down →

affects the rate → affects the relic density

Toy model

Scalar real singlet φ + Z3 scalar complex DM

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

- φ is in full thermal equilibrium with SM
- χ has a tiny initial abundance (e.g. from gravitational production)
- No elastic scatterings for χ → $T_\chi \neq T_{\rm SM}$
- Assume that T_χ evolution is known and vary it as a parameter

Calculation of the relic abundance

Solve the Boltzmann equation for the number density (nBE)

(neglecting the backreaction and quantum corrections)

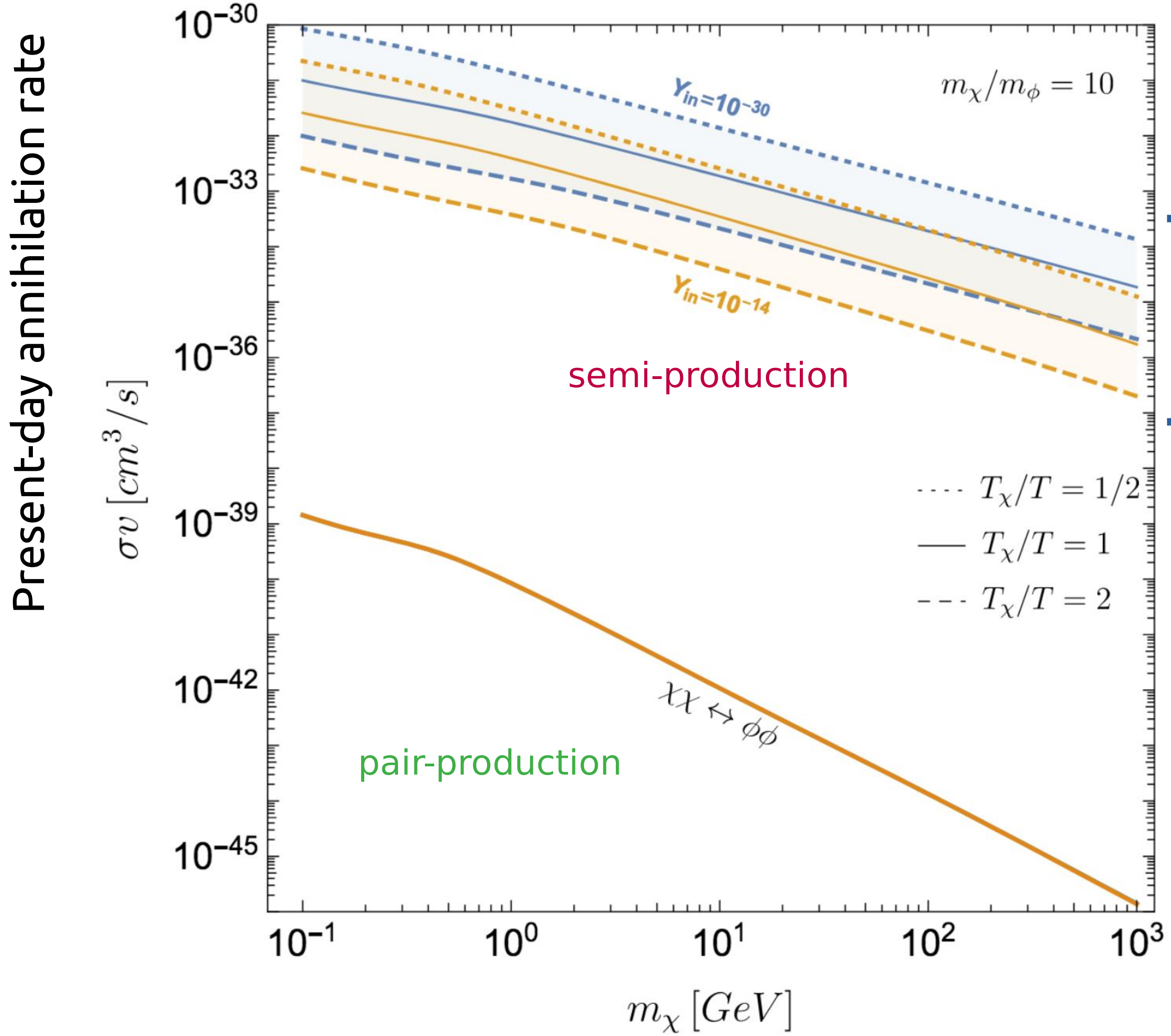
$$\frac{dY}{dx} = \frac{\Gamma_\chi(T_{\rm SM}, T_\chi)}{xsH} Y \qquad \Gamma_\chi = n_\phi \langle \sigma v \rangle$$

analytically

$$Y(x) = Y_{\rm in} \exp\left(- \int dx \, \frac{\Gamma_\chi(T_{\rm SM}, T_\chi)}{xsH} \right)$$

$$\langle \sigma v \rangle = \frac{1}{n_\chi^{\rm eq}(T_\chi)} \int \frac{d^3p}{(2\pi)^3} \int \frac{d^3k}{(2\pi)^3} \, \sigma_{\phi\chi\to\chi\chi} v \; f_\phi^{\rm eq}(T_{\rm SM}) f_\chi^{\rm eq}(T_\chi)$$

Results for the toy model



Different initial conditions and temperature assumptions

If φ is also out of equilibrium → even larger cross sections

Realistic model

We expand $\mathcal{L}_{\phi-\mathrm{SM}}$ and add $\phi^2(\chi^*\chi)$ term

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 + elastic scatterings

- $m_\phi < 3m_\chi$
- φ doesn't get a VEV
- Freezes-in before DM

Full Boltzmann equation

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

Assume that $f_\chi = \frac{n_\chi}{n_\chi^{\rm eq}}\, f_\chi^{\rm eq}(E, T_\chi)$ $\qquad T_{\rm DM} \neq T_{\rm SM}$

Self-scatterings maintain local equilibrium

$$\frac{g_i}{s}\int \frac{d^3p_i}{(2\pi)^3} f_i = Y$$

→ 0th moment (density equation)

$$\frac{g_i}{3n_i}\int \frac{d^3p}{(2\pi)^3}\,\frac{p_i^2}{E_i}\exp(-E_i/T) = T$$

→ 2nd moment (temperature equation)

cBE – couple system of Boltzmann equations

We get a system of coupled Boltzmann equations for density and temperature of DM

$$\frac{Y'}{Y} = \frac{m_\chi}{x\tilde{H}} C_0 \,,$$
$$\frac{y'}{y} = \frac{m_\chi}{x\tilde{H}} C_2 - \frac{Y'}{Y} + \frac{H}{x\tilde{H}} \frac{\langle p^4/E^3 \rangle}{3T_\chi}$$

C_0, C_2 – the corresponding moments of the collision term

$$T_\chi = y s^{2/3}/m_\chi$$

$$\langle p^4/E^3 \rangle \equiv n_\chi^{-1} \; g_\chi \int \frac{d^3p}{(2\pi)^3} \frac{\mathbf{p}^4}{E^3} f_\chi(\mathbf{p})$$

DM relic abundance beyond kinetic equilibrium

Solves nBE, cBE and fBE for pair-annihilation freeze-out

DRAKE

Dark matter Relic Abundance beyond Kinetic Equilibrium

https://drake.hepforge.org

[written in *Wolfram Language*, lightweight, modular and simple to use code for calculating relic abundance]

Binder, Bringmann, Hryczuk, Gustafsson 2103.01944

We use parts of the DRAKE code

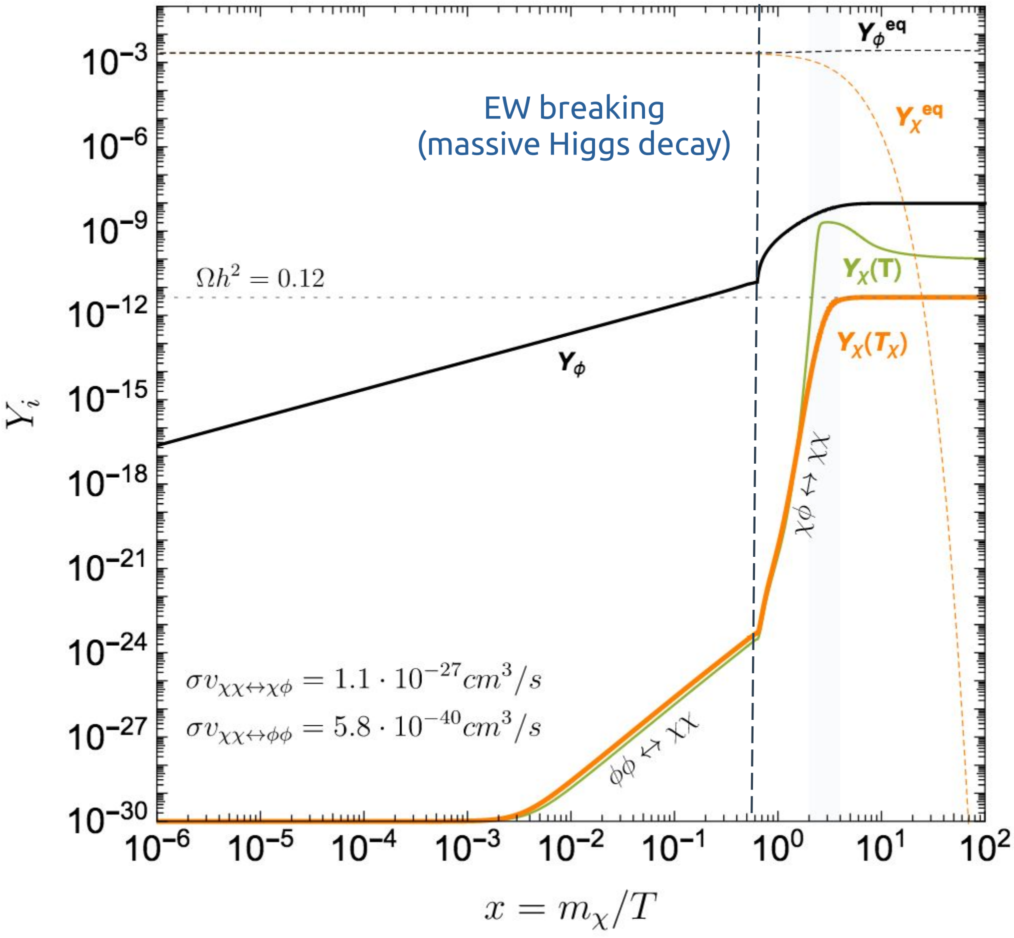
+ decays

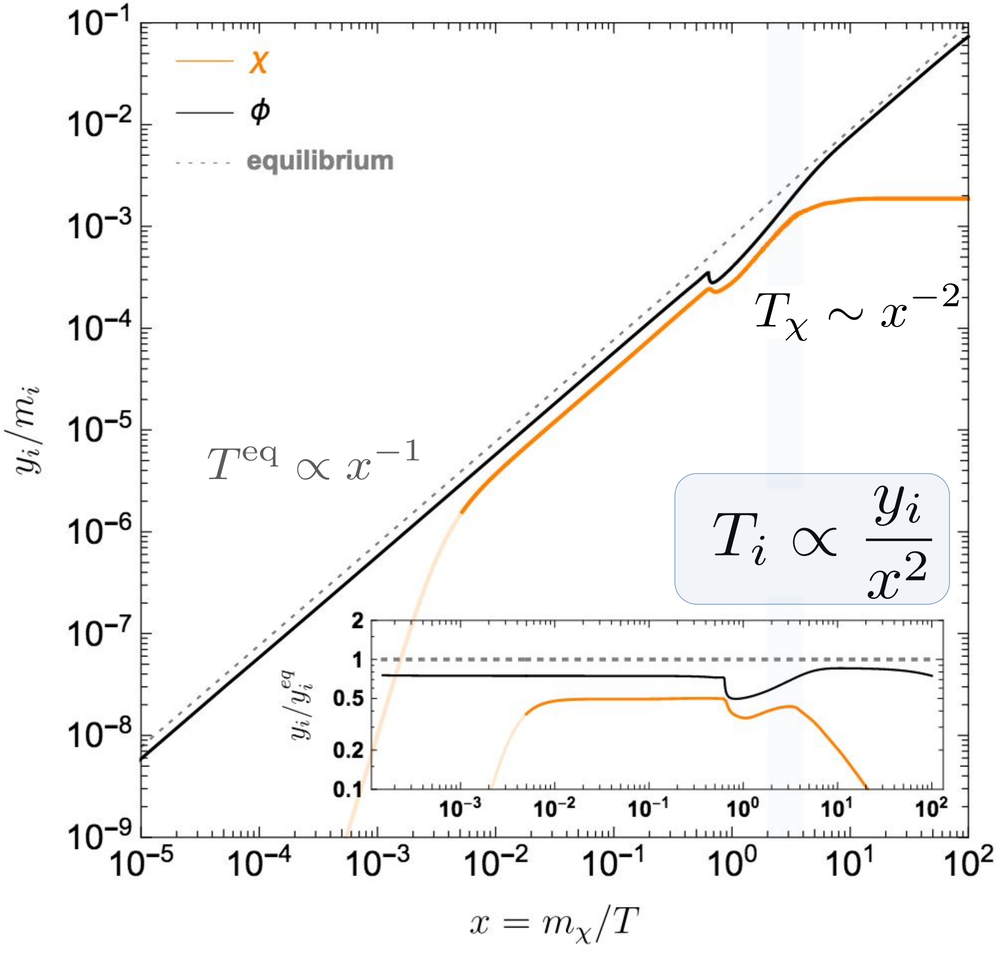
+ semi-annihilation terms

+ freeze-in

(not yet available in the public version)

Evolution of density and temperature

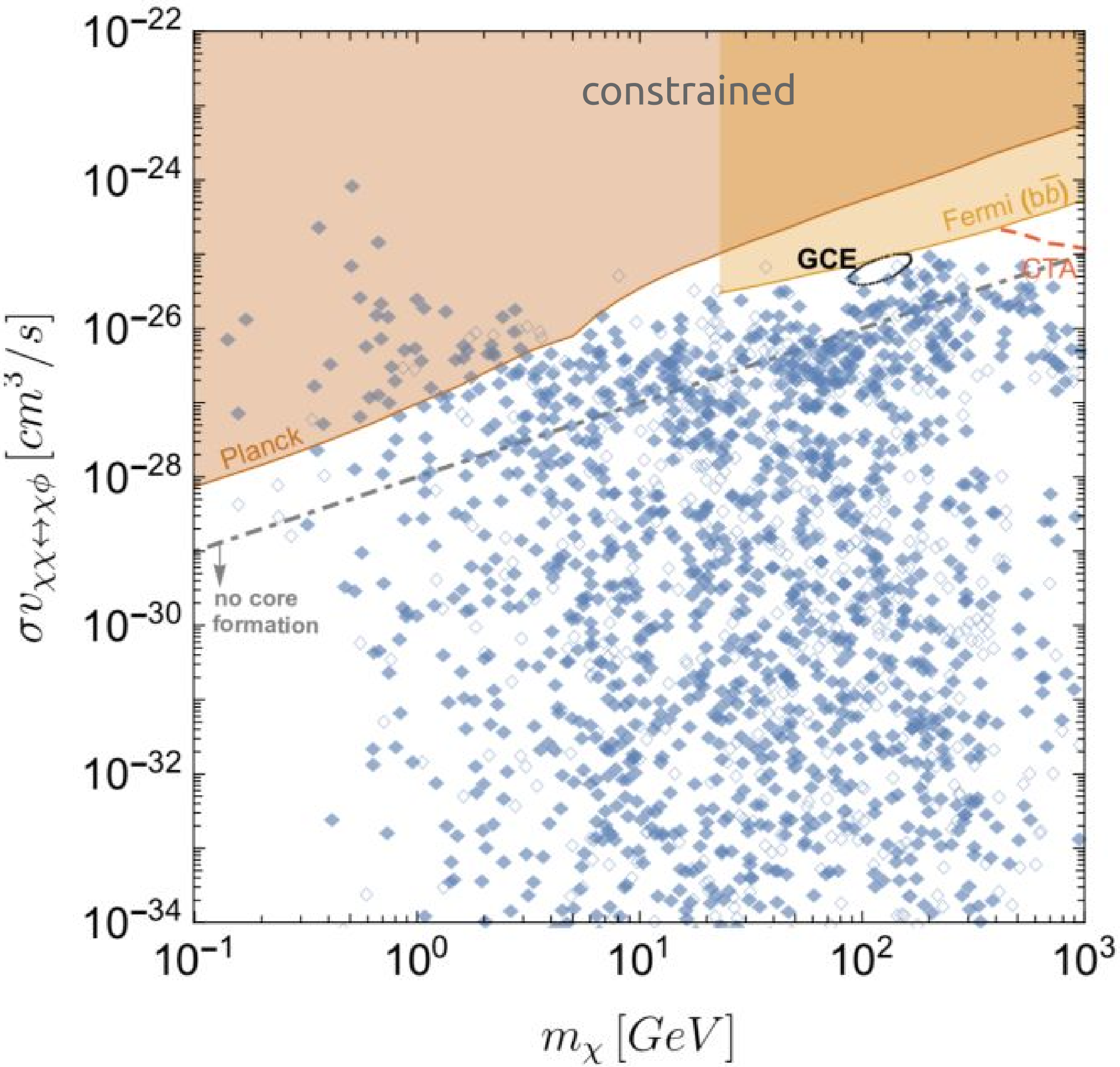




$$T_i \propto \frac{y_i}{x^2}$$

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

Indirect detection constraints and predictions



The results of the scan:

DM production **dominated** by semi-annihilation

Blue squares → within the reach of the future searches for φ

Potentially explain the galactic center excess (GCE)

1603.08228

Above the grey dot-dashed line → potentially explain the core formation in dSph

1803.09762

Conclusion

Freeze-in from semi-production is a novel mechanism that can emerge or be incorporated into different particle physics models

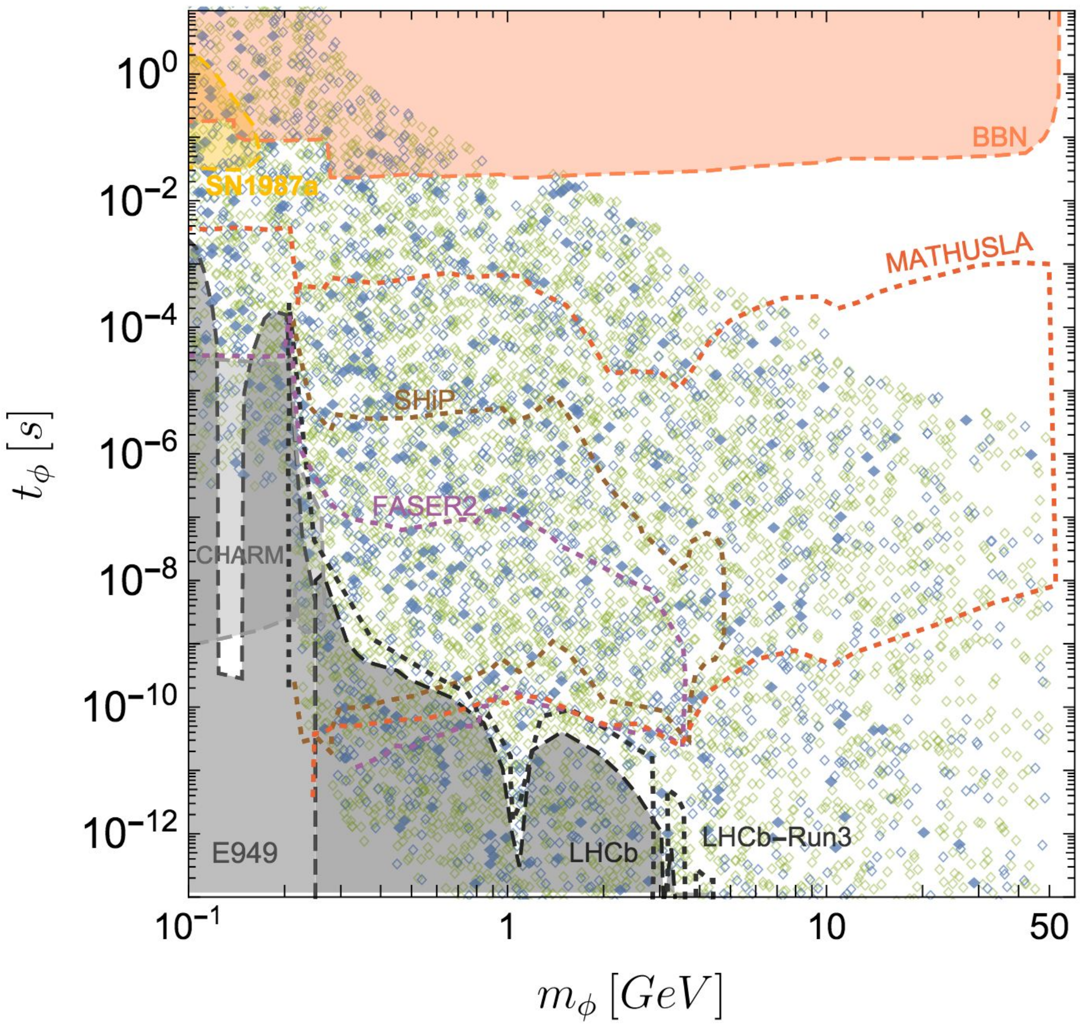
Semi-production can cool down the DM population → important for the relic density calculation

Can be tested via indirect DM searches and by searching for long-lived particles at colliders

Thank you for attention!

Backup slides

Long-lived particle searches



Constraints on the properties of the mediator φ and the prospects for its detection.

Blue points → DM production dominated by semi-annihilation

Green points → pair-annihilation