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POLAND
grant No. 2018/31/D/ST2/00813

FREEZE-IN OF DARK MATTER:

RECENT DEVELOPMENTS

Andrzej Hryczuk

NATIONAL
CENTRE
FOR NUCLEAR
RESEARCH
ŚWIERK

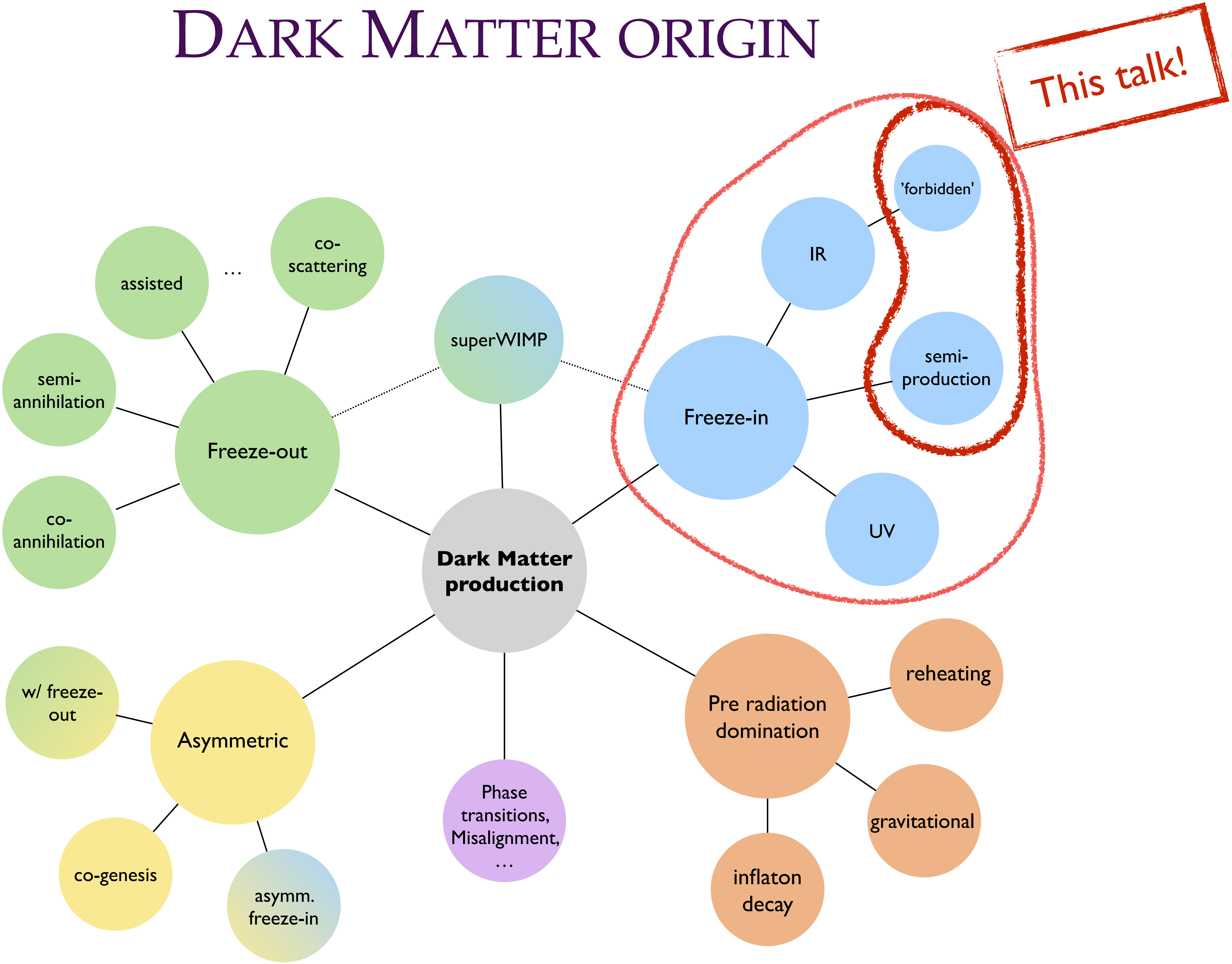
based on: **AH and M. Laletin** 2104.05684
+ a bit on **L. Darmé, AH, D. Karamitros, L. Roszkowski** 1908.05685

FUW, Particle Physics and Cosmology Seminar
Warsaw, 25th November 2021

The Soar (Llanfaethlu) Stone

ANY GOOD THEORY
OF DARK MATTER
HAS TO EXPLAIN ITS
<u>ORIGIN</u>

DARK MATTER ORIGIN



FREEZE-IN *VS.* FREEZE-OUT

Freeze-in is in a sense the 'opposite' of freeze-out

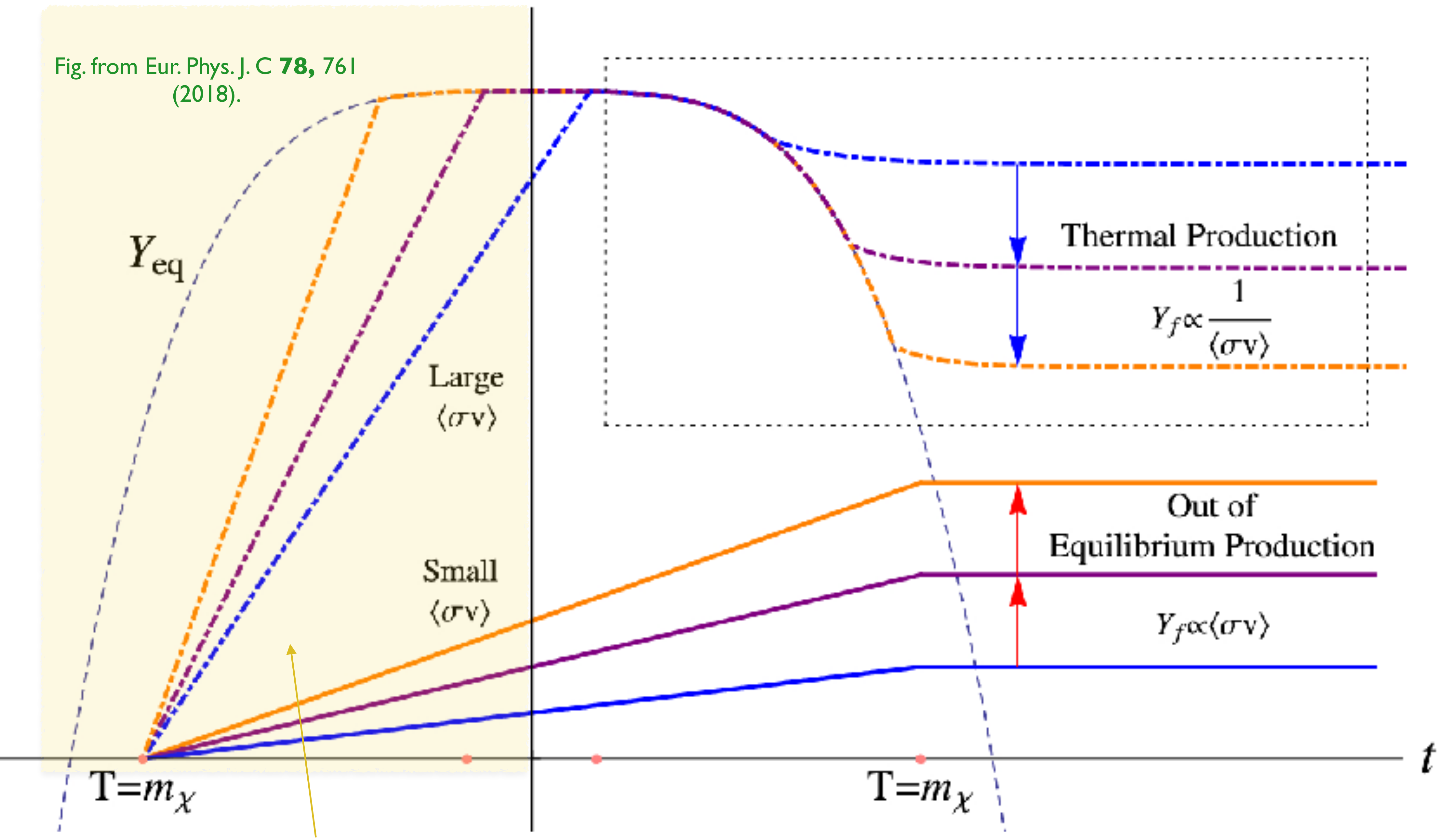


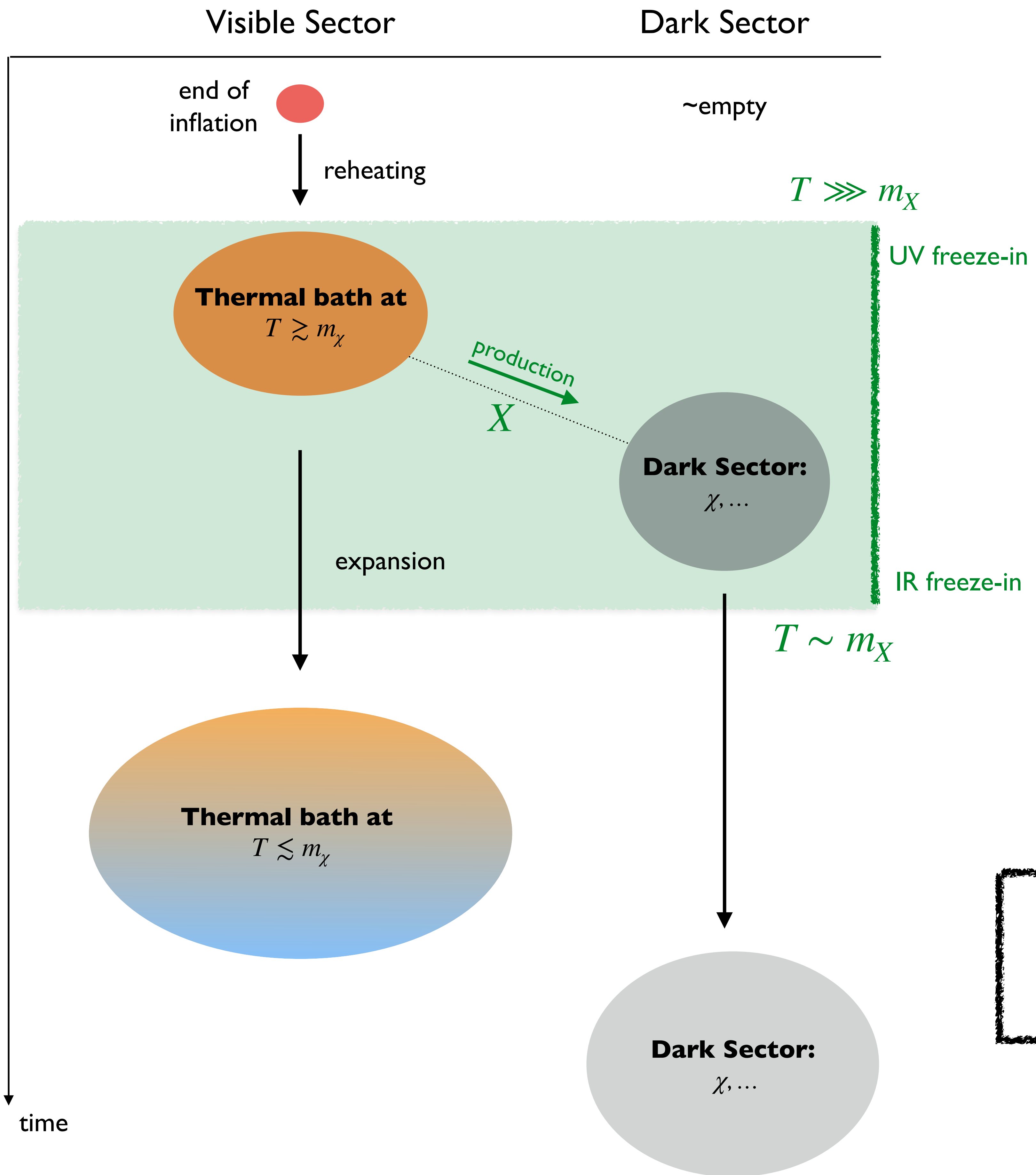
Fig. from Eur. Phys. J. C **78,** 761 (2018).

freeze-out

freeze-in

note: this part is often not shown, but conceptually worth highlighting…

WHAT IS FREEZE-IN?



Visible Sector

Dark Sector

end of inflation

~empty

reheating

$T \ggg m_X$

UV freeze-in

Thermal bath at
$T \gtrsim m_\chi$

production

X

Dark Sector:
$\chi, \dots$

expansion

IR freeze-in

$T \sim m_X$

Thermal bath at
$T \lesssim m_\chi$

Dark Sector:
$\chi, \dots$

time

Freeze-in defined like this is a (very) old idea:

this is a standard production mechanism for e.g. sterile neutrino, gravitino, axino,…

however, old works focused on what now people call UV freeze-in

i.e. dominated by non-renormalizable operators and dependent on $T_{\rm RH}$

Freeze-in = the above mechanism through renormalizable operators (IR freeze-in)

FREEZE-IN…

THE GOOD

simple

predictive

(relatively) generic

THE BAD

very small couplings
&
hard to detect

& THE UGLY

couplings not of O(1)
(by any stretch of imagination)

requires special
initial condition

FREEZE-OUT *VS.* FREEZE-IN

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

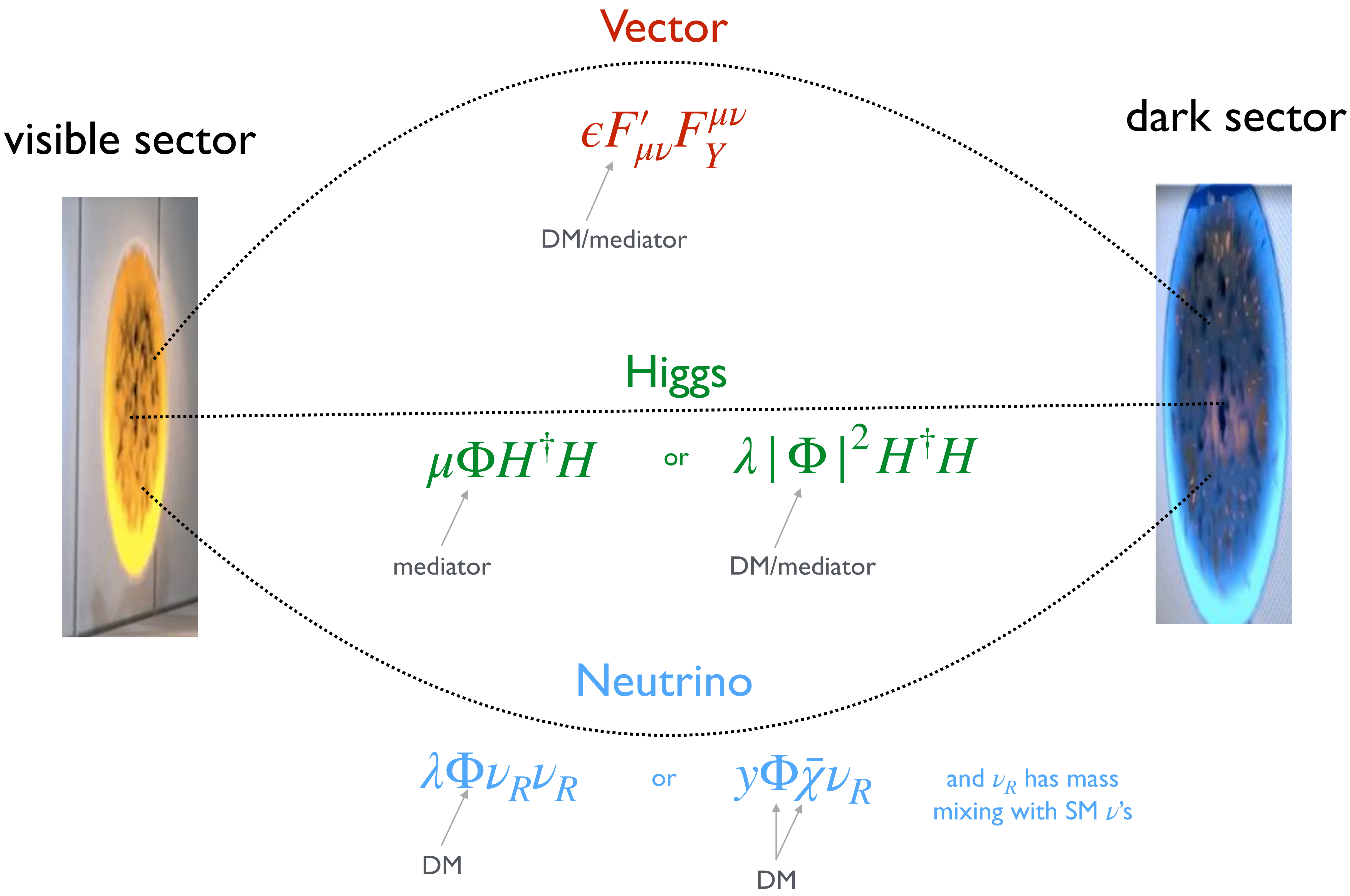
$$\langle \sigma v \rangle \lesssim 10^{-40}\ \mathrm{cm}^3/s$$

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

Requires

~no initial abundance

PORTALS



visible sector

dark sector

Vector

$\epsilon F'_{\mu\nu} F^{\mu\nu}_{Y}$

DM/mediator

Higgs

$\mu \Phi H^{\dagger} H$ or $\lambda |\Phi|^{2} H^{\dagger} H$

mediator

DM/mediator

Neutrino

$\lambda \Phi \nu_R \nu_R$ or $y \Phi \bar{\chi} \nu_R$

DM

DM

and ν_R has mass mixing with SM ν's

*portal mediator can also be non-reonoramlizable or composite (for more complex dark sector)

FREEZE-IN CALCULATION

Boltzmann equation for $f_\chi(p)$:

$$E\left(\partial_t - H\vec{p}\cdot\nabla_{\vec{p}}\right) f_\chi = \mathcal{C}[f_\chi]$$

with initial condition:

$$f_\chi(p, t = 0) = 0$$

The collision term:

$$C[f_\chi] \sim \int d\Pi_{ij\ldots\to ab}(2\pi)^4\delta^4(\ldots)\,|M|^2\left[f_i f_j\ldots(1\pm f_\chi)(1\pm f_a)(1\pm f_b)\ldots - f_\chi f_a f_b\ldots(1\pm f_i)(1\pm f_j)\ldots\right]$$

„gain" term
(the simple one, describes production)

„loss" term
(the difficult one, usually neglected in freeze-in!)

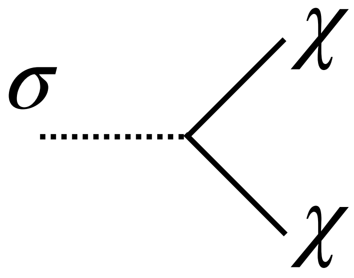
The collision term can also contain:

decays, annihilations, cannibalizations, …

Note: to first approximation freeze-in production is much easier to determine than freeze-out!

FREEZE-IN CALCULATION

<u>Example</u>: freeze-in from decay of σ in equilibrium



$$\frac{x}{Y_\sigma^{\mathrm{eq}}}\frac{\mathrm{d}Y}{\mathrm{d}x} = \underbrace{2\,\frac{\Gamma_{\sigma\to\chi\chi}}{H}\,\frac{K_1(x)}{K_2(x)}}_{Y = n/s \quad \text{independent!}} \quad \Rightarrow \quad \Omega_\chi h^2 \simeq 4.48\times 10^8\,\frac{g_\sigma}{g_{*s}\sqrt{g_*}}\,\frac{m_\chi}{\mathrm{GeV}}\,\frac{M_{\mathrm{P}}\,\Gamma_{\sigma\to\chi\chi}}{m_\sigma^2}$$

$$\Rightarrow \quad y \simeq 10^{-12}\left(\frac{\Omega_\chi h^2}{0.12}\right)^{1/2}\left(\frac{g_*}{100}\right)^{3/4}\left(\frac{m_\sigma}{m_\chi}\right)^{1/2}$$

Why is this IR dominated?

time vs. temperature: $t \sim M_P/T^2$

$$\Rightarrow \quad \frac{t(T=0.1\mathrm{GeV}) - t(T=1\mathrm{GeV})}{t(T=1\mathrm{GeV}) - t(T=T_{\mathrm{RH}})} \sim 100$$

and produced DM ∝ time × rate: $\dfrac{n_\chi}{T^3} \simeq t\,\Gamma_{\sigma\to\chi\chi}$

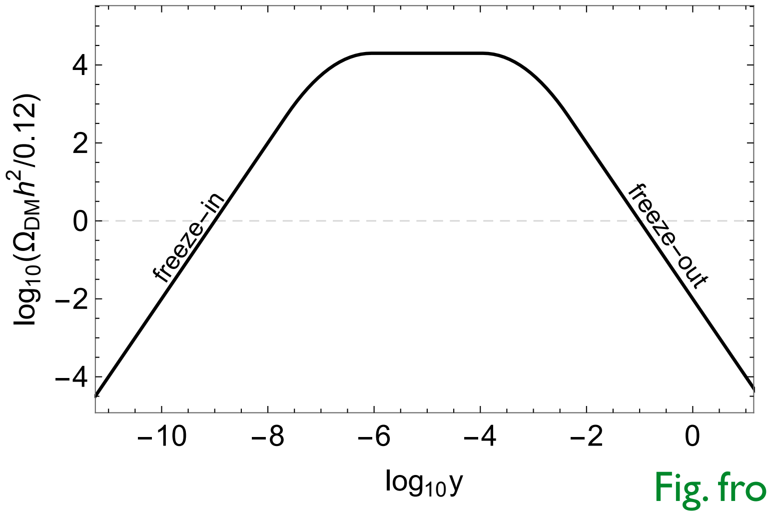


Fig. from 1706.07442

All this is pretty standard, so let's go now for newer developments…

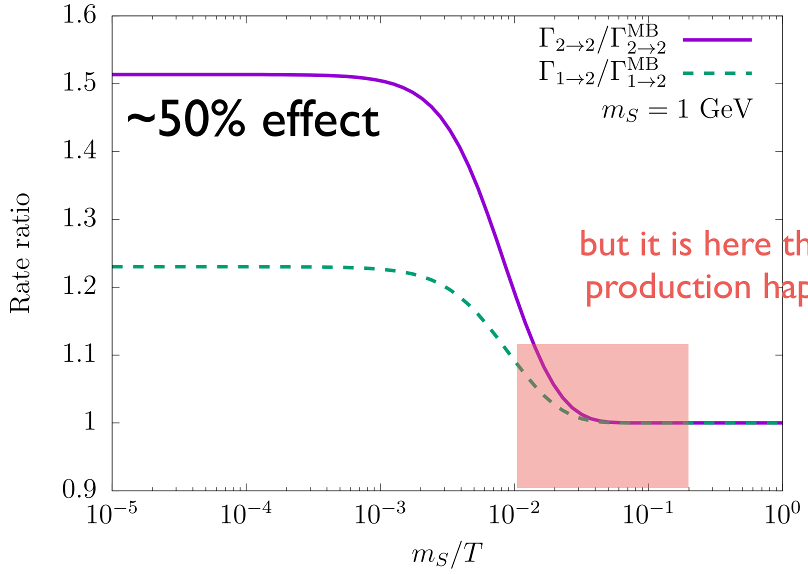
Relativistic or Not?

Relativistic reaction rate:

$$\Gamma_{a\to b} = \int \left(\prod_{i\in a} \frac{d^3\mathbf{p}_i}{(2\pi)^3 2E_i} \underline{f(p_i)} \right) \left(\prod_{j\in b} \frac{d^3\mathbf{p}_j}{(2\pi)^3 2E_j} \underline{(1+f(p_j))} \right) |\mathcal{M}_{a\to b}|^2 \, (2\pi)^4 \delta^4(p_a - p_b).$$

I) In freeze-out one (typically) takes Maxwell-Boltzmann distribution, should one use here:

$$f(p) = \frac{1}{e^{\frac{u\cdot p}{T}} - 1}$$ instead?



~50% effect

but it is here that most production happens…

Lebedev, Toma 1908.05491 & subsequent works

II) when relativistic, not obvious if $(1 \pm f) \approx 1$ which poses a question of the feedback of DM distribution to the production rate

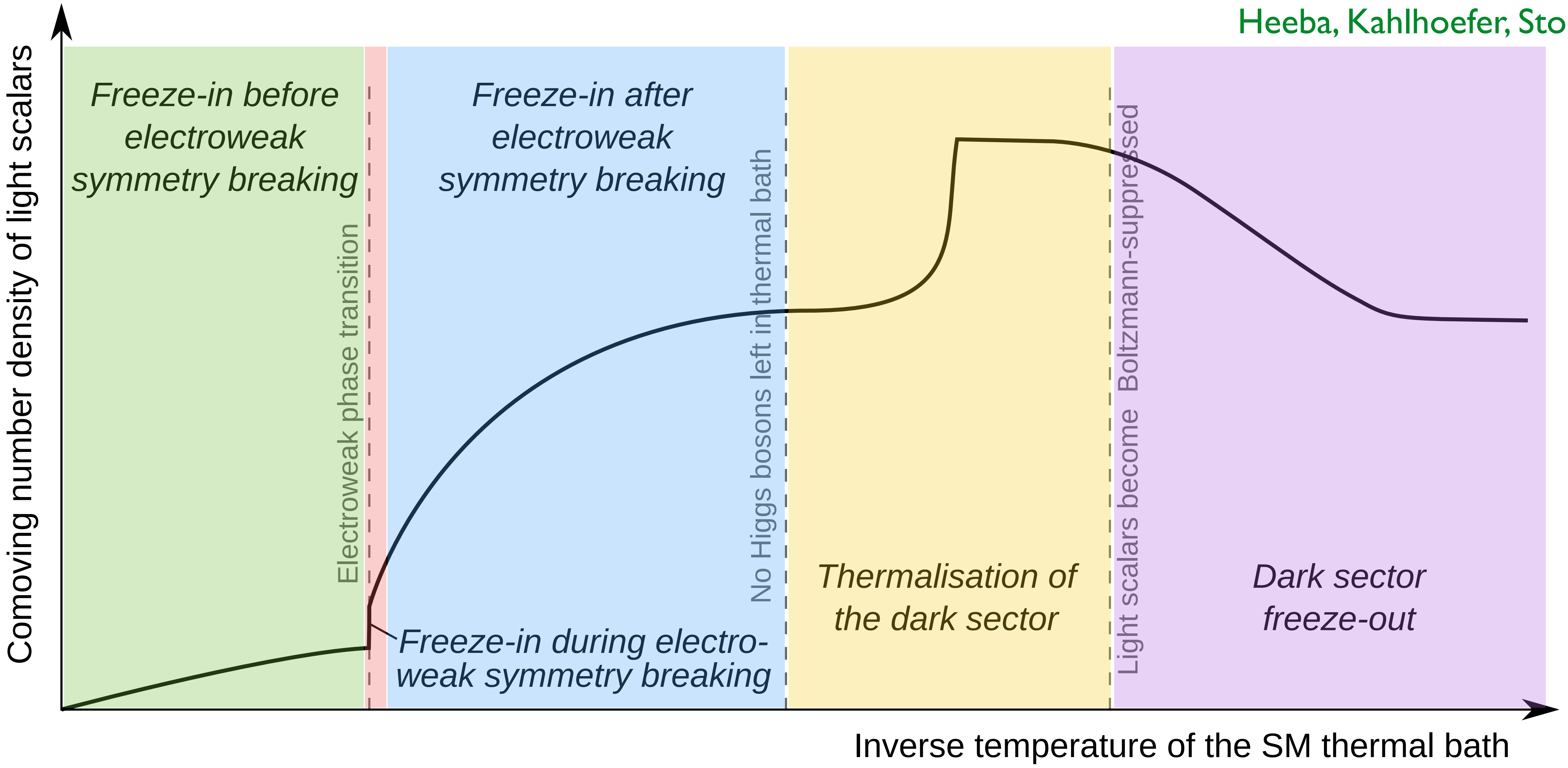
At early stages of evolution DM is very diluted allowing for such approx.

but when $T \sim m$ this is less obvious…

MORE COMPLETE PICTURE

Illustration for production through Higgs portal:

Heeba, Kahlhoefer, Stocker 1809.04849



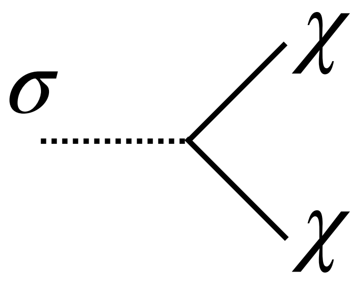
One should be careful to include such (potentially relevant) effects!

NEVER FORGET THAT EARLY UNIVERSE WAS REALLY HOT!

TDungiven Stone

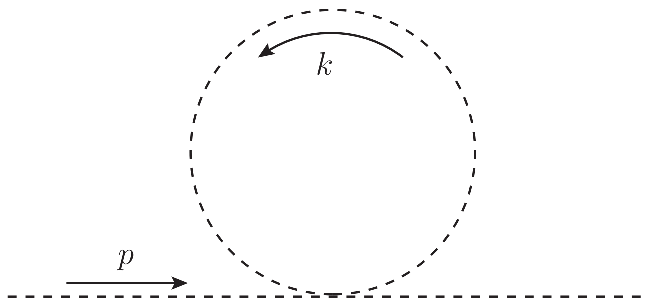
MODIFICATIONS DUE TO $T \neq 0$

Let's come back to the simple example:



$$\boxed{\text{Is condition } m_\sigma > 2m_\chi \text{ necessary?}}$$

Thermal mass of σ in $\lambda\sigma^4$ theory:



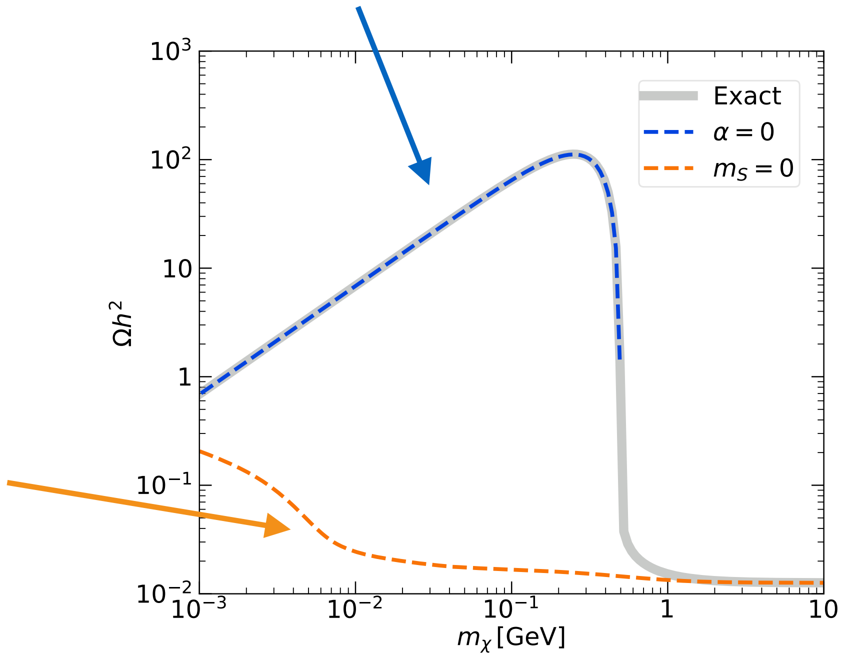
$$\Pi_S = i\frac{\lambda}{2}\int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2 - m_S{}^2 + i\epsilon} + \frac{\lambda}{2}\int \frac{d^3\vec{k}}{(2\pi)^3}\frac{f_B(\omega_k)}{\omega_k} \quad \Rightarrow \quad \boxed{m_{S,T}{}^2 \approx \Pi_S^{(T)} = \frac{\lambda_S}{24}T^2}$$

Following the freeze-in calculation as discussed before:

$$m_S^2 = \alpha T^2 \quad \Rightarrow \quad m_\chi Y_0 \sim \alpha^4 y_\chi^2 K_1(\alpha)$$

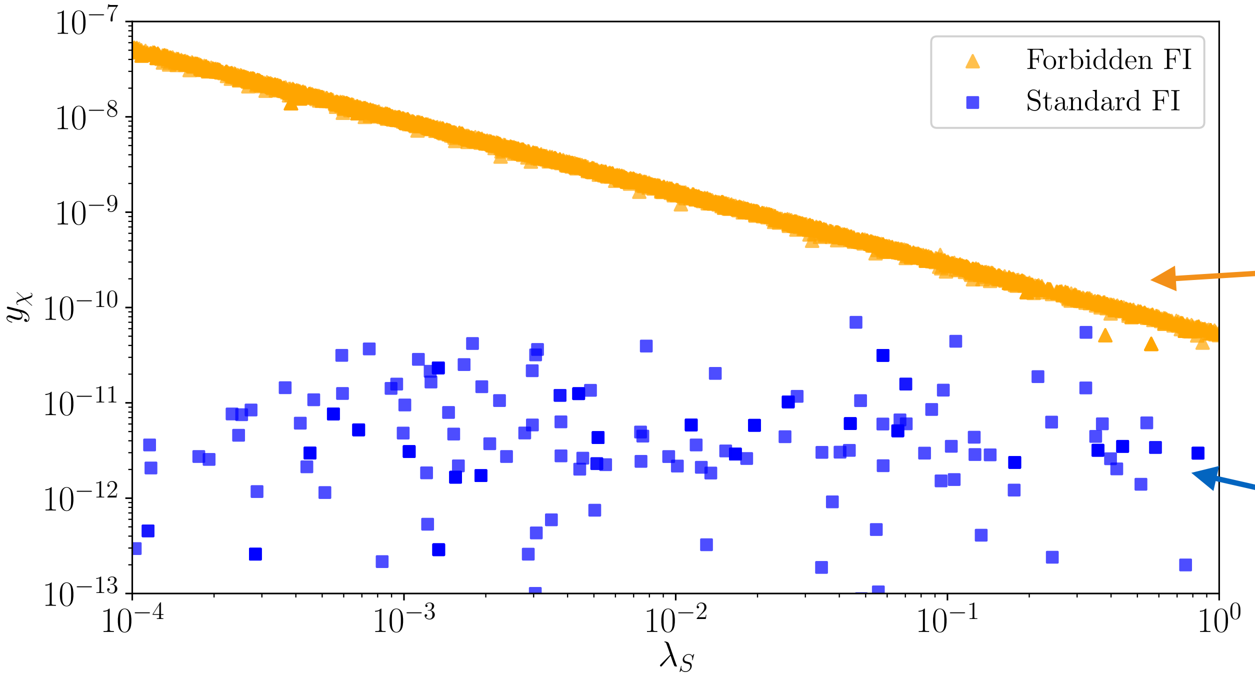
$$\Rightarrow \quad \Omega h^2 \text{ nearly independent of } m_\chi$$

if no thermal mass



'FORBIDDEN' FREEZE-IN

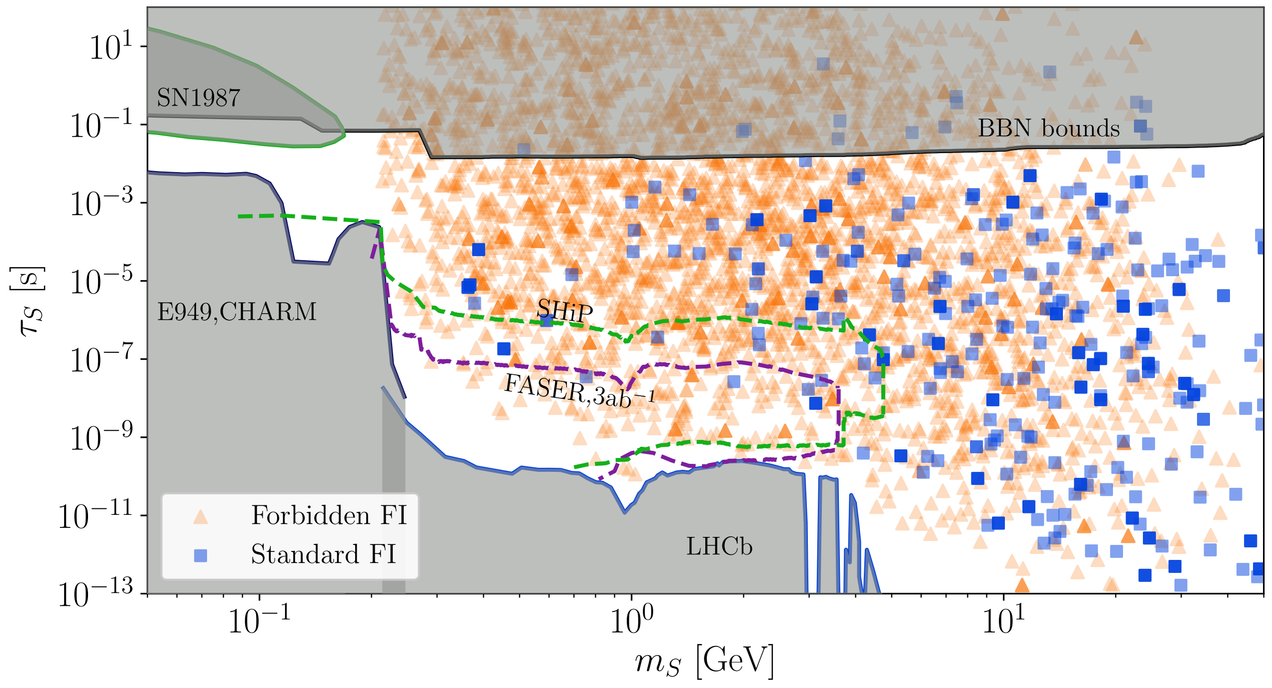
Darme, AH, Karamitros, Roszkowski 1908.05685



Required coupling to get correct Ωh^2:

forbidden freeze-in

standard freeze-in



Experimental limits on the example Higgs portal model

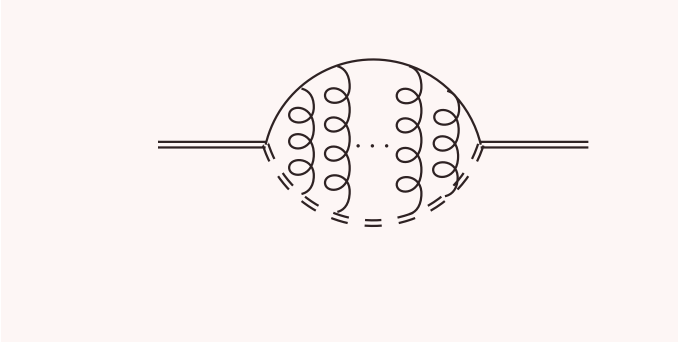
points: Bayesian scan results

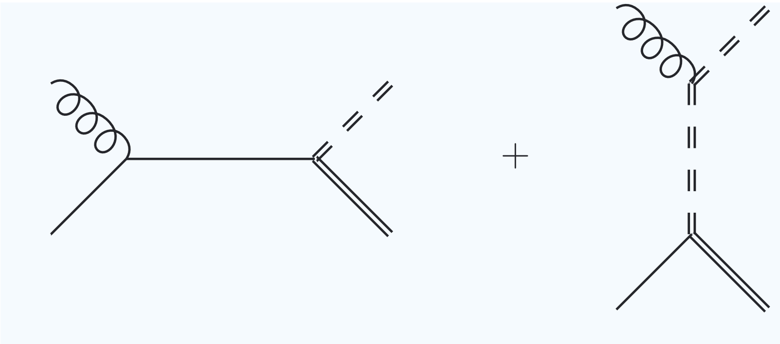
Note that <u>more points</u> found in the forbidden freeze-in regime

MODIFICATIONS DUE TO $T \neq 0$ CTD.

Biondini, Ghighlieri 2012.09083

Multiple soft and 2-2 scatterings at $T \gg m_{\rm DM}$:





not only thermal masses, but also scatterings can be very important - even for renormalizable interactions!

- Before: in renormalizable models bulk DM population produced at $T \sim M$
- Our work: this is not always the case
  high-temperature $1 \leftrightarrow 2$, $2 \rightarrow 2$ can give $\mathcal{O}(1)$ contribution

S. Biondini, talk at HECA seminar, March 2021

FREEZE-IN FROM OTHER PROCESSES

Until now we discussed freeze-in from decays.
What about other production channels? E.g:

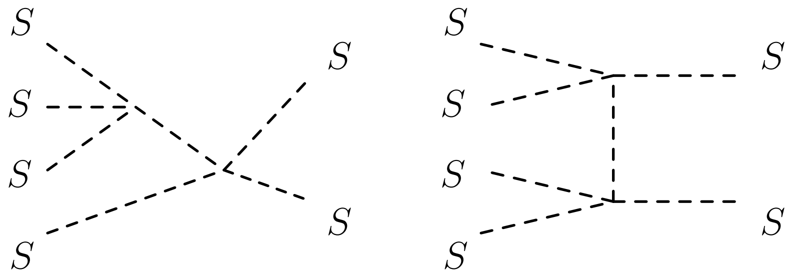
annihilations and scatterings → possible, but typically more suppressed and UV sensitive

very large literature, see e.g. 1706.07442 for a review

sequential → DM connected to SM through mediator that undergoes freeze-in

Belanger *et al.* 2005.06294

boosting freeze-in by (inverse) cannibalization etc. →



see e.g. Bernal 2005.08988

Our motivation:

IS THERE ANY OTHER PROCESS POSSIBLE LEADING TO BETTER DETECTION PROSPECTS?

The Kerloas Menhir

YOU CAN'T LOOK FOR FREEZE-IN DARK MATTER IN DIRECT & INDIRECT DETECTION

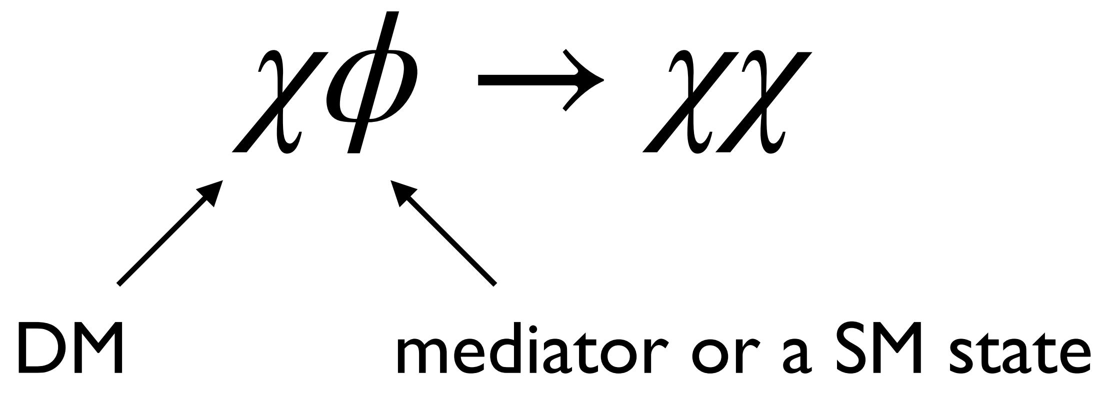
...are we sure about that one

?!

HOW ABOUT SEMI-PRODUCTION?

AH, Laletin 2104.05684
(see also Bringmann et al. 2103.16572)

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

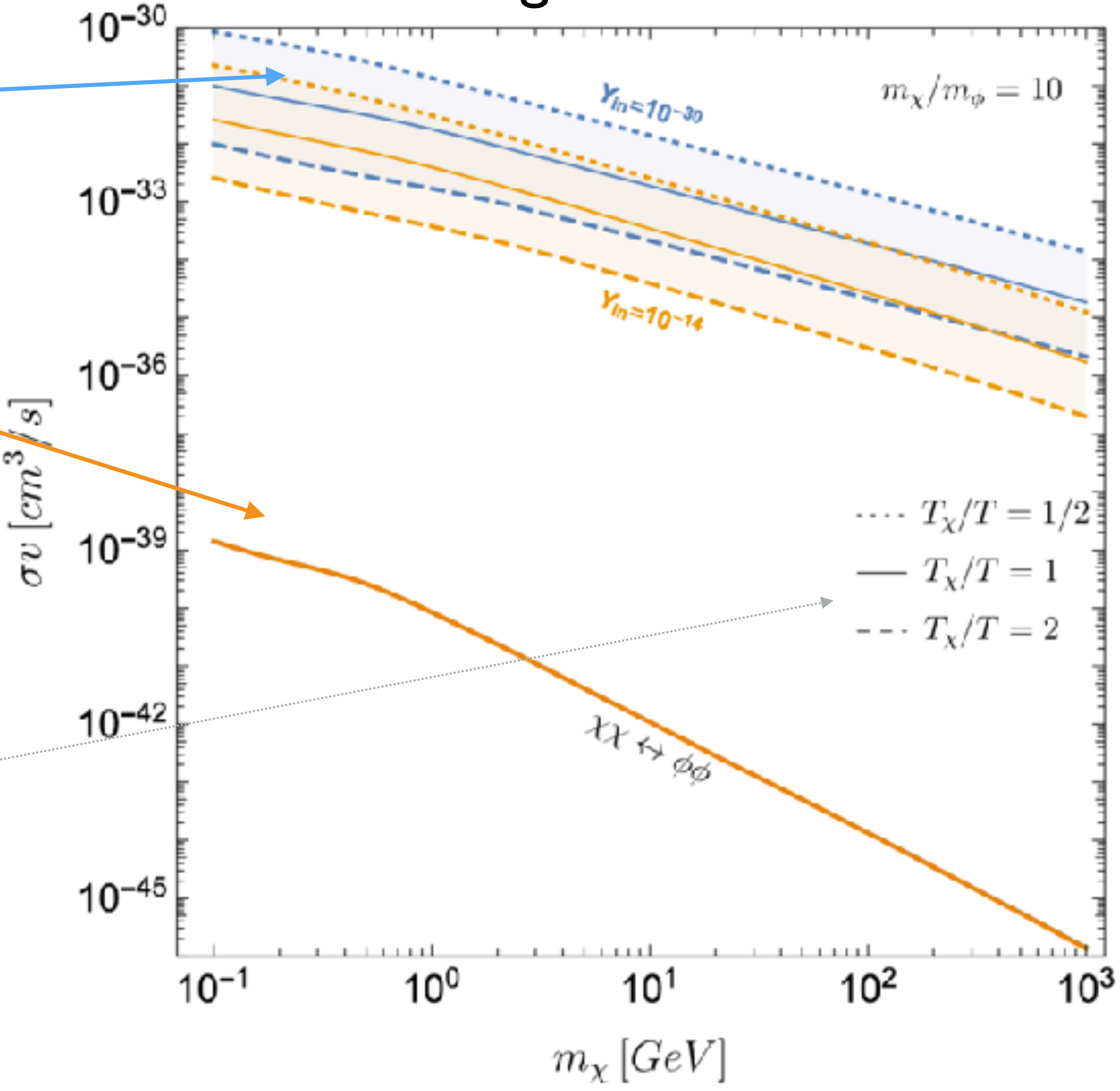
A. Assume that ϕ is in equilibrium with SM and for now simply take χ to have some tiny initial abundance (e.g. from reheating or UV pair production)

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

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

σv that give correct Ωh^2



→ T_χ can be quite relevant!

System of BEs for Y_χ and T_χ

This we obtain through equations for the 0th and 2nd moment of the BE:

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

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

where $y \equiv \frac{m_\chi T_\chi}{s^{2/3}}$ is a parameter that describes the DM temperature $T_\chi \equiv \frac{g_\chi}{3n_\chi} \int \frac{\mathrm{d}^3p}{(2\pi)^3} \frac{p^2}{E} f_\chi(p)$

The collision term is also given by its moments:

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

Now, there is a technical difficulty for semi-annihilation…

- the collision term contains term $\propto f_\chi(T_\chi) f_\phi(T)$
- and the distribution functions break LI… so one needs to work in plasma frame

REALISTIC MODEL

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

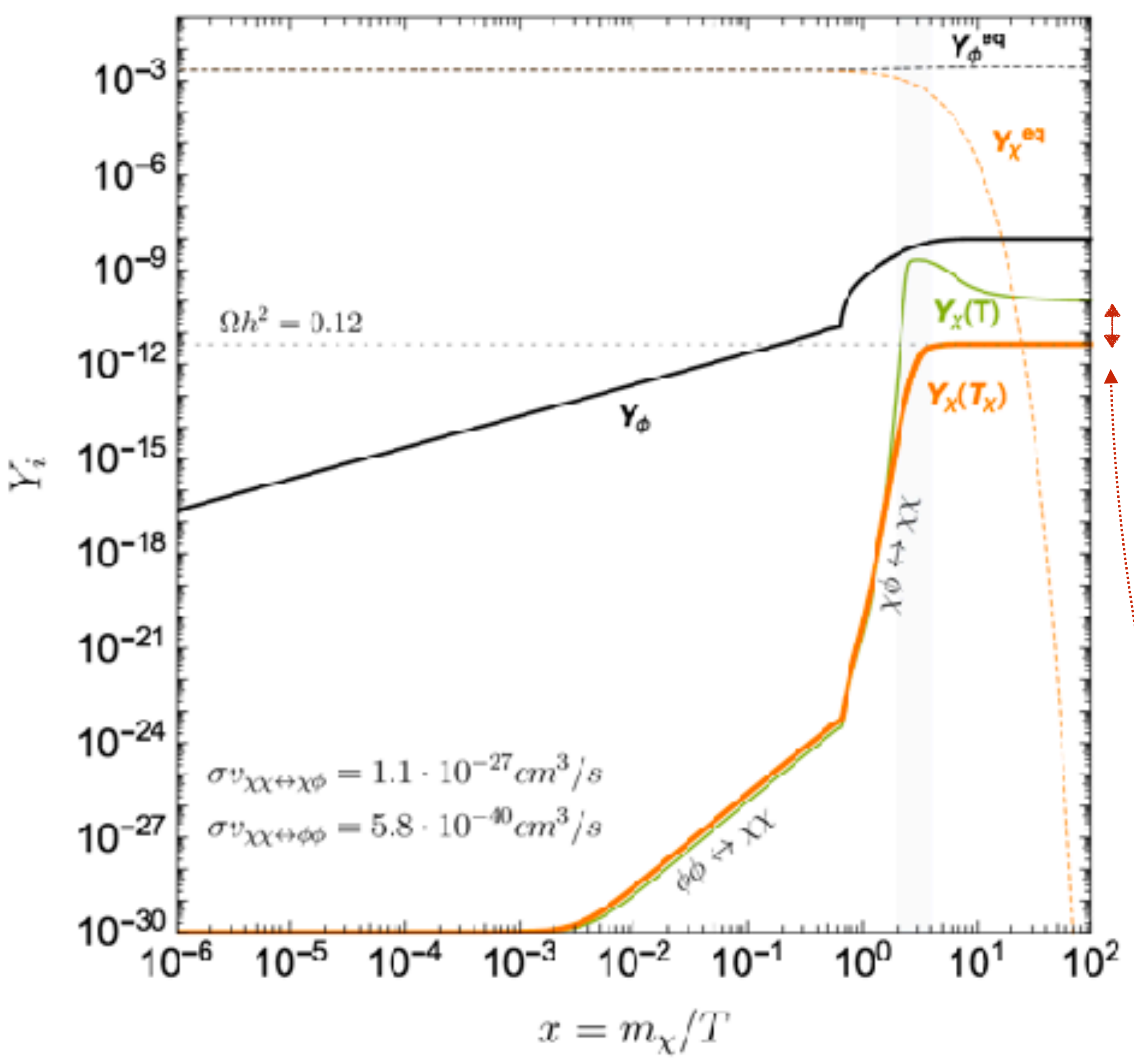
$$
\begin{aligned}
\mathcal{L}_{\phi-SM} &= \overbrace{A\phi H^\dagger H + \frac{\lambda_{h\phi}}{2}\phi^2 H^\dagger H}^{\text{Higgs portal interactions}} - \mu_h^2 H^\dagger H + \frac{\lambda_h}{2}(H^\dagger H)^2 \\
\mathcal{L}_{DS} &= \frac{\mu_\phi^2}{2}\phi^2 + \frac{\mu_3^2}{3!}\phi^3 + \frac{\lambda_\phi}{4!}\phi^4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

- ϕ gets a VEV, but χ doesn’t

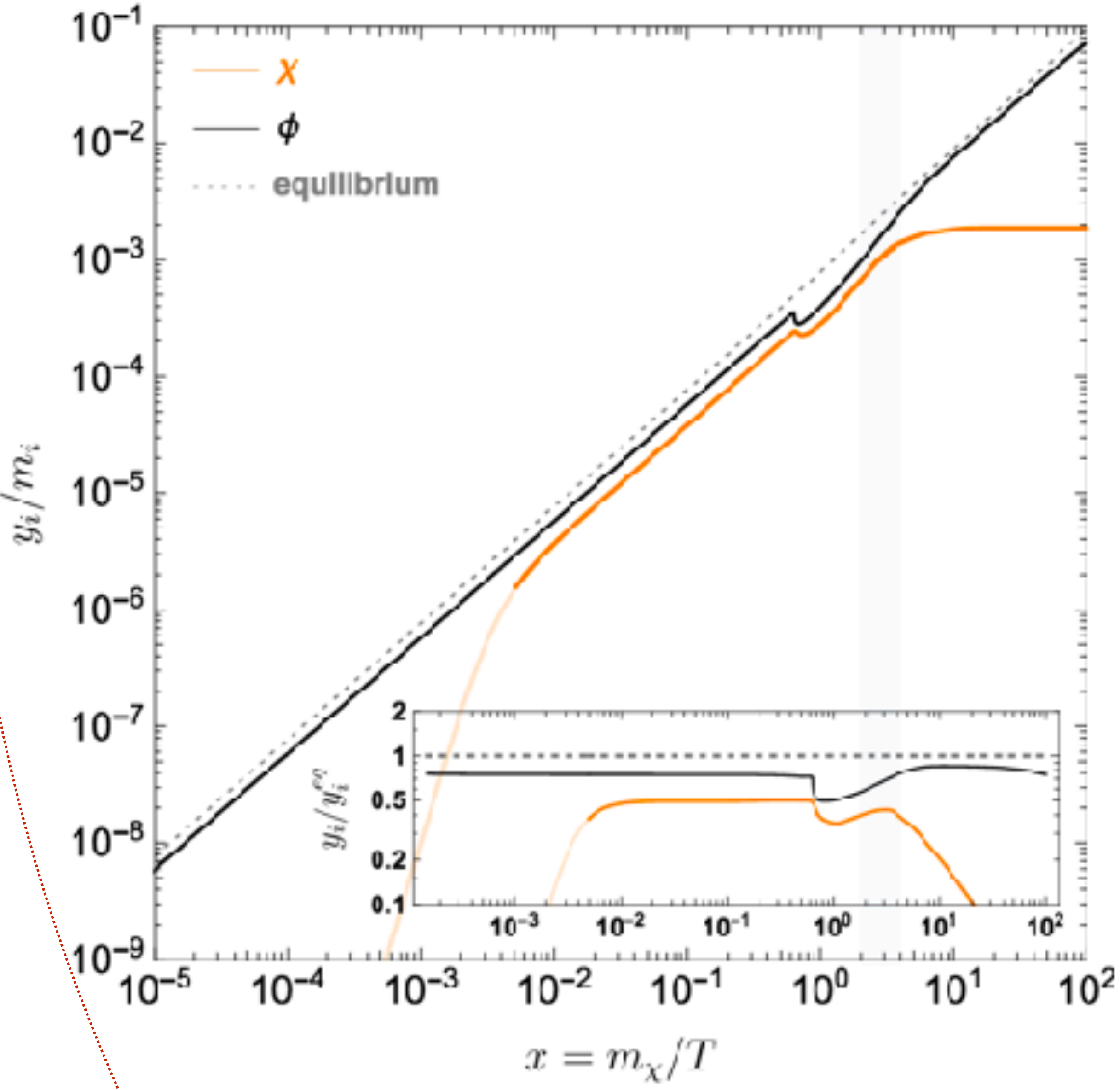
- $m_\phi < 3m_\chi$ → no decays

EVOLUTION

co-moving number density



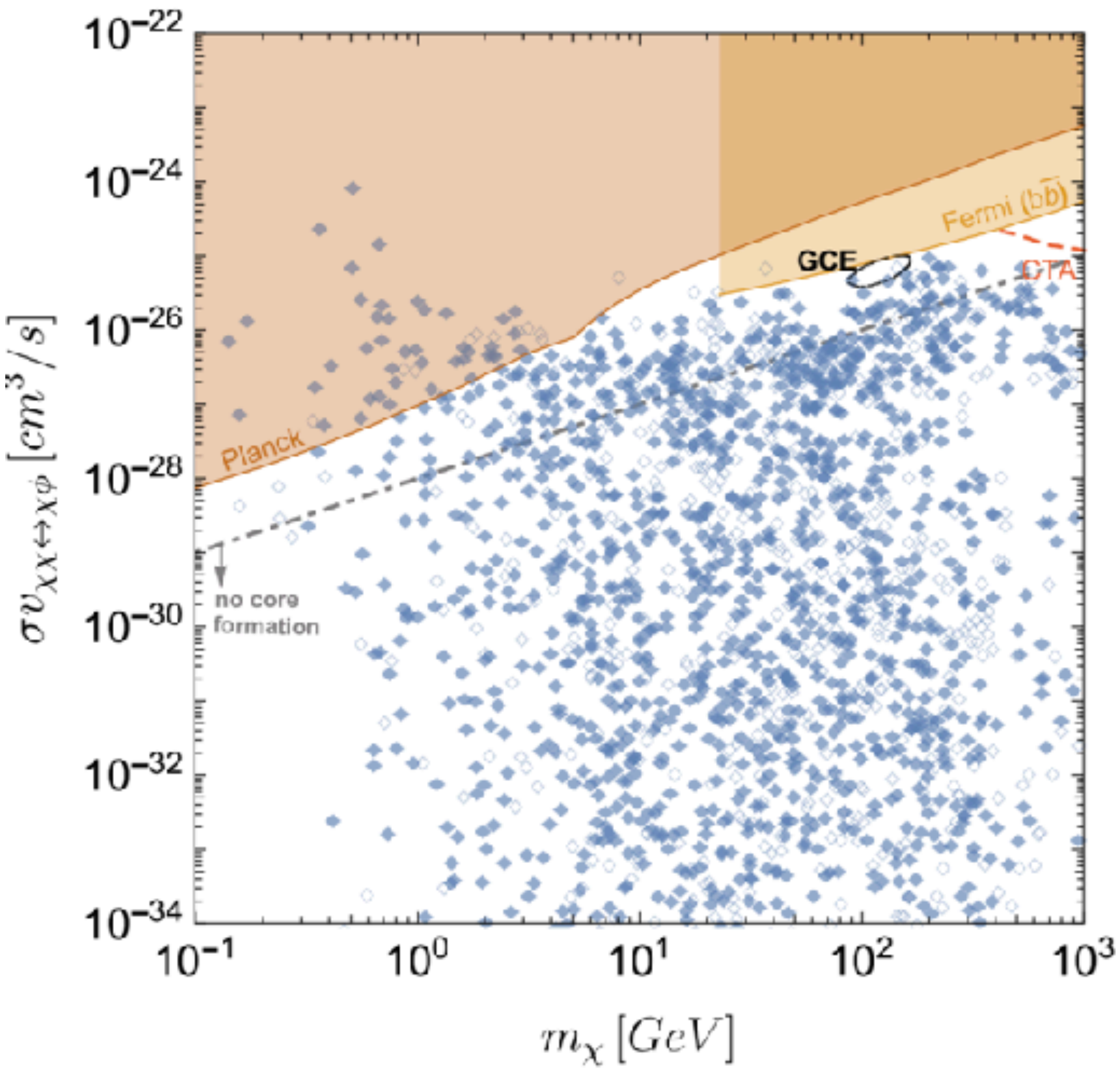
'temperature'



$m_\chi = 100$ GeV, $\mu_\phi = 1$ GeV, $\lambda_1 = 1.1 \times 10^{-3}$, $\lambda_2 = 10^{-8}$, $\lambda_{h\phi} = 6 \times 10^{-11}$

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

INDIRECT DETECTION

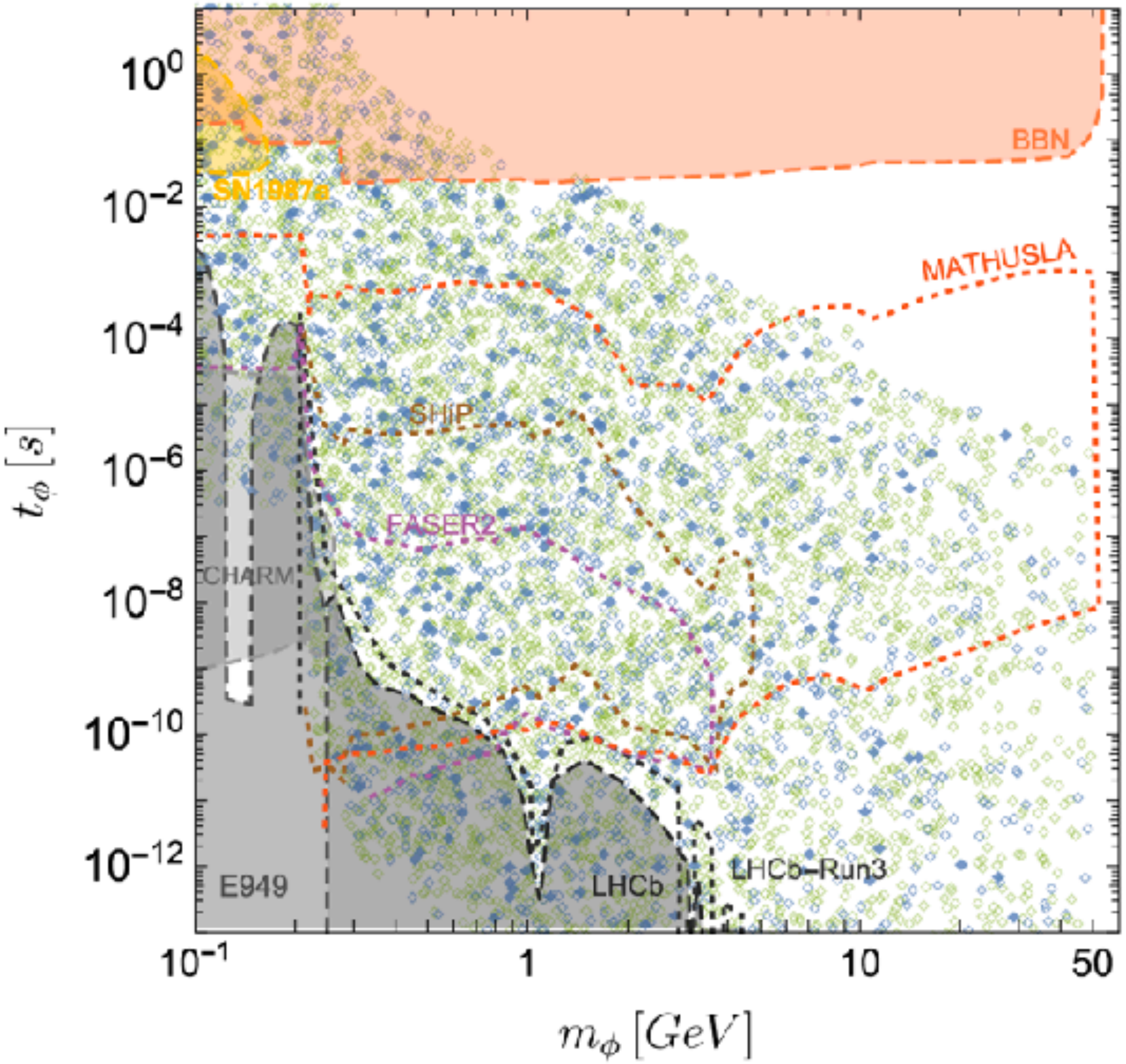


- The results of the scan in the parameter space for the DM production dominated by the semi-annihilation processes.

- 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.

GOING BEYOND KINETIC EQUILIBRIUM

Above we assumed that T_χ can be different than SM bath T but still:

$$f_\chi(p) \propto f^{eq}(p, T_\chi)$$

It is clear however that this need not to be the case, especially in freeze-in where typically there is no efficient equilibration

see e.g.: Belanger *et al.* 2005.06294
Du *et al.* 2111.01267

Work in progress: freeze-in module for

DRAKE

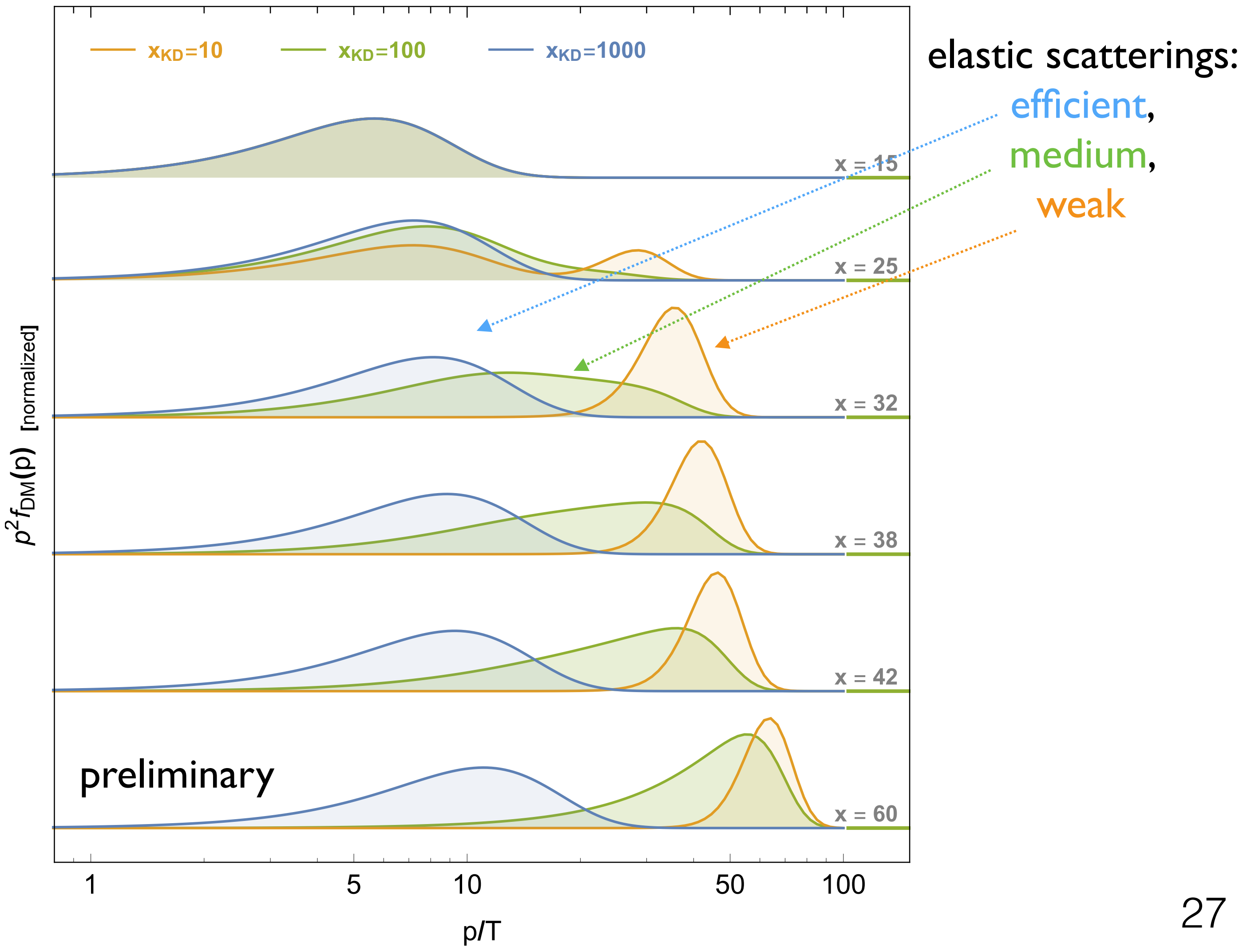
Dark matter Relic Abundance beyond Kinetic Equilibrium

https://drake.hepforge.org

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

Binder, Bringmann, AH, Gustafsson 2103.01944

DM having second component from a decay:



elastic scatterings:
efficient,
medium,
weak

CONCLUSIONS

1. Freeze-in is a well motivated Dark Matter production mechanism. In recent years some interesting developments took place, opening new questions and possibilities.

2. DM produced via freeze-in can lead to detectable signals in indirect searches.

3. Temperature (and momentum distribution) can have a non-trivial impact in such scenarios and a lot left to be studied in this topic.

Thank you!