FREEZE-IN AT STRONGER COUPLING

And the highest temperature of the Universe

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University of Goettingen, Institute for Theoretical Physics

Collaborators: G. Arcadi, C. Cosme, L. Covi, A. Goudelis, O. Lebedev

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OUTLINE:

INTRO: FREEZE-IN VS FREEZE-OUT

PROBLEMS WITH FREEZE-IN

LOW REHEATING TEMPERATURE

TEMPERATURE EVOLUTION DURING REHEATING

CONCLUSIONS

INTRODUCTION

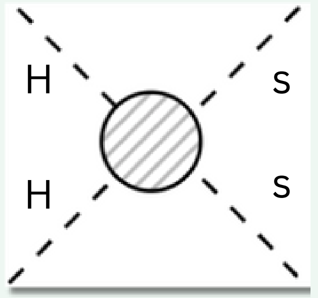
FREEZE-IN VS FREEZE-OUT

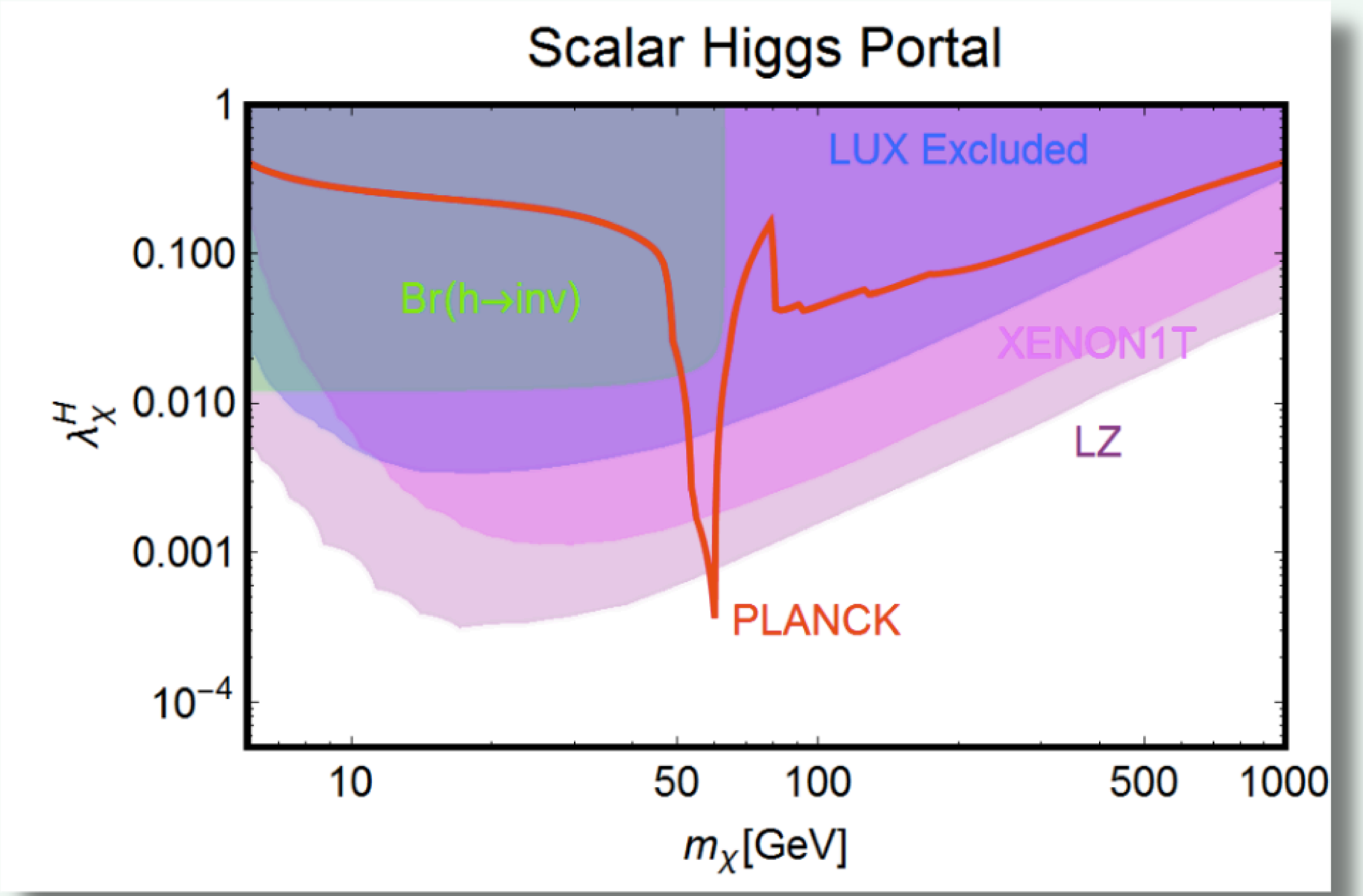
FREEZE-OUT

Higgs portal

$$\mathcal{L} \supset \frac{1}{2}\lambda_{hs} s^2 H^\dagger H$$

t





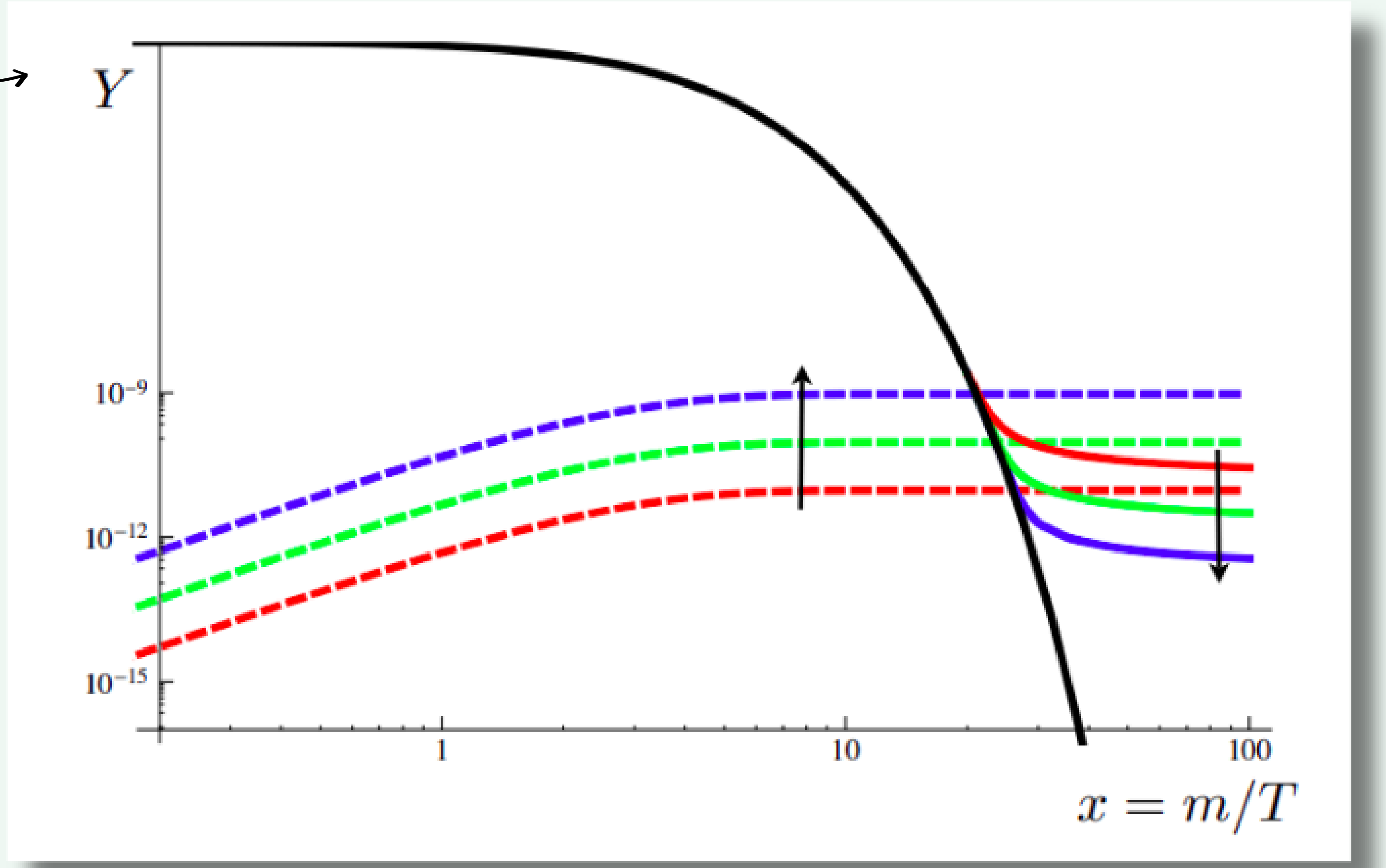
"Vanilla" WIMP models are very constrained or already excluded

G. Arcadi et al. 1703.07364

DM yield $Y = \frac{n_s}{S}$

FREEZE-IN

- Out-of-equilibrium
- Dependence on the initial conditions



J. McDonald, hep-ph/0106249
L. J. Hall, K. Jedamzik, J. March-Russell, S. M. West, 0911.1120

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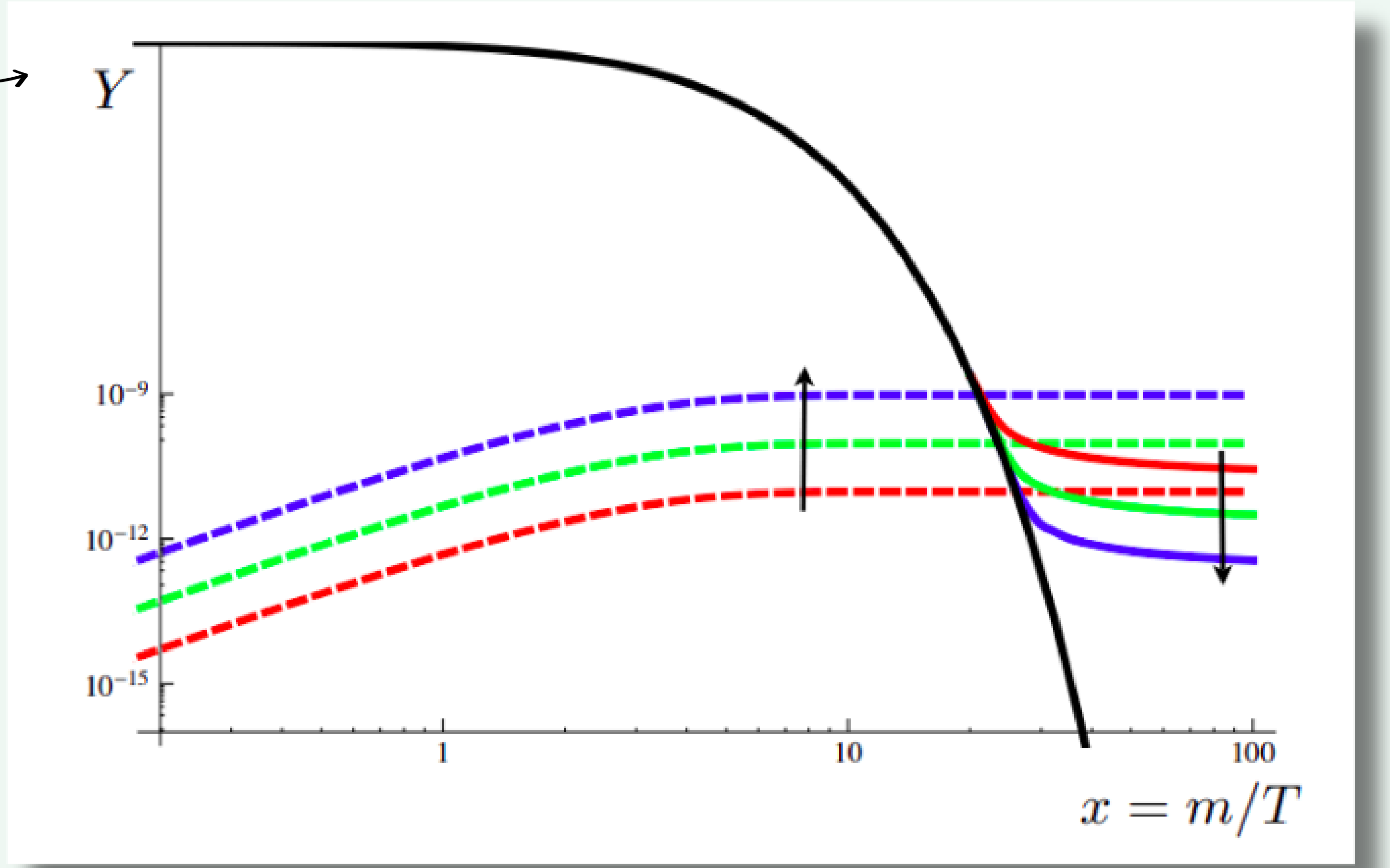
➜ We assume a negligible initial abundance



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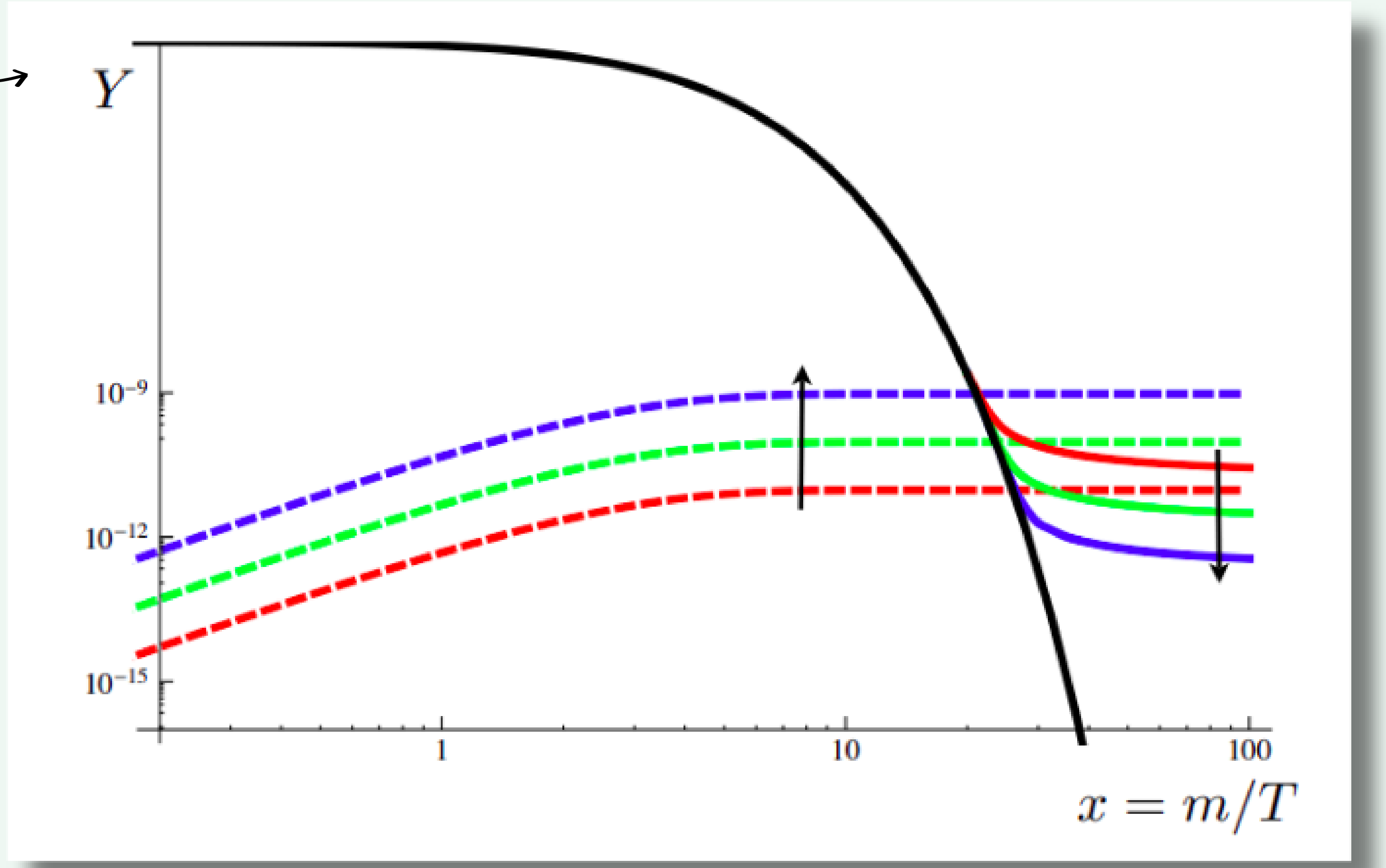
$$\lambda \sim \mathcal{O}(10^{-10})$$



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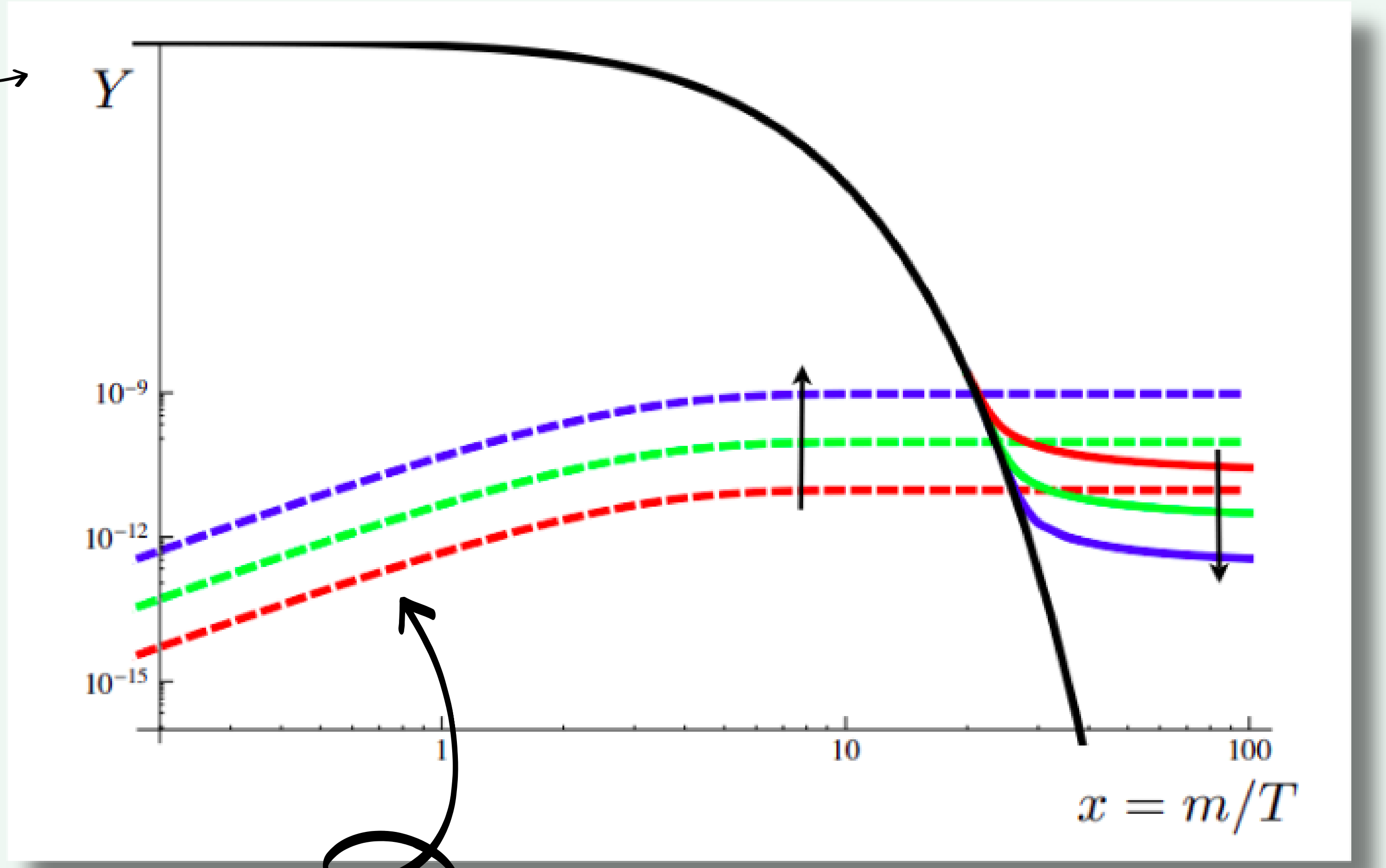

$$Y_{FI} \sim \lambda^2 \left(\frac{M_{Pl}}{m} \right)$$

DM abundace grows with the coupling squared

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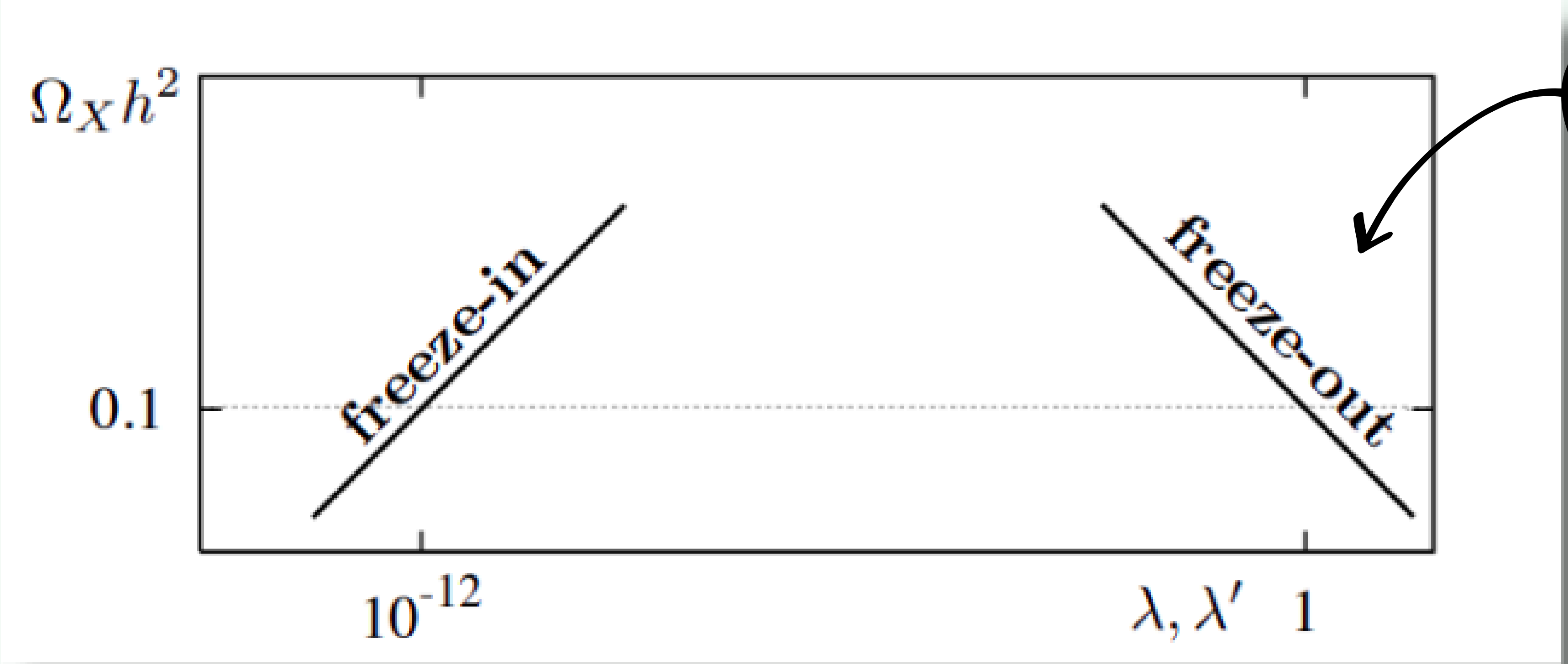
FREEZE-IN VS FREEZE-OUT



$$\Omega h^2 \propto \frac{1}{<\sigma v>} \sim \frac{1}{\lambda^2}$$

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FREEZE-IN VS FREEZE-OUT

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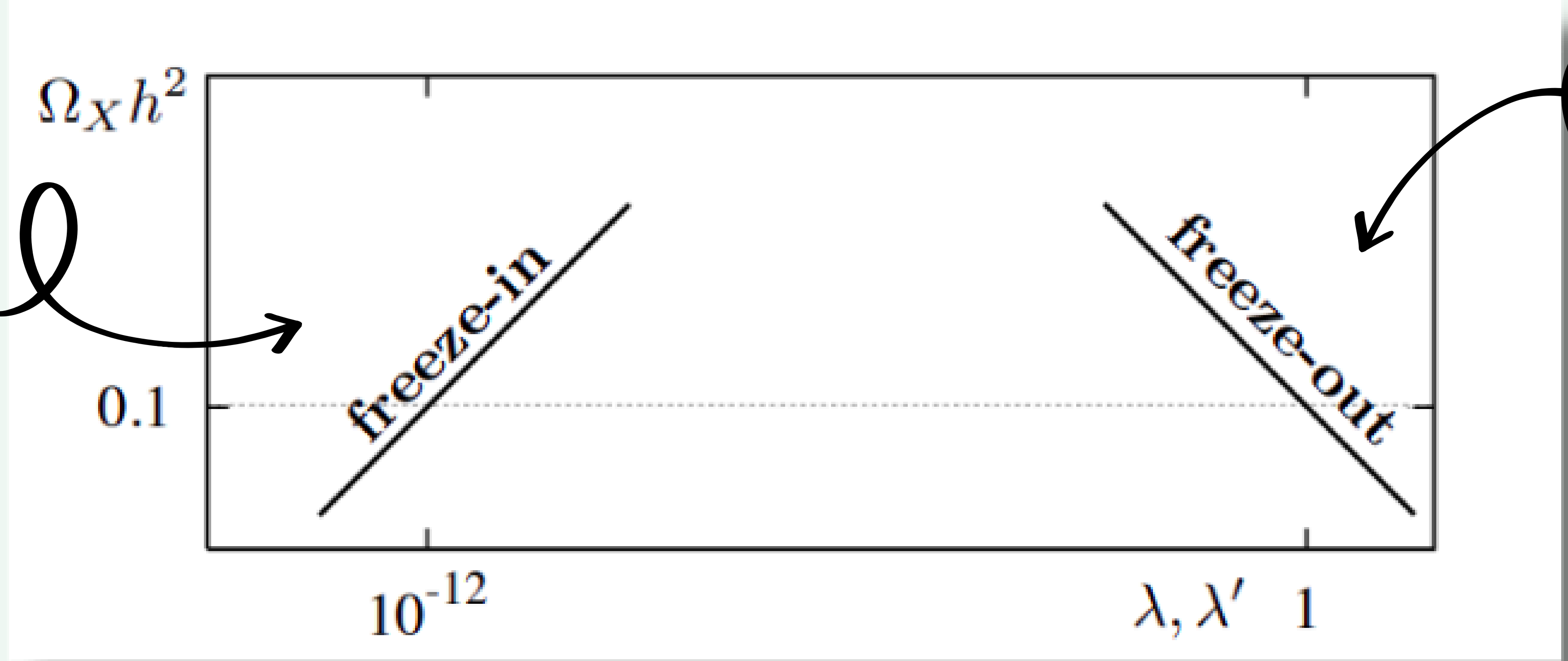

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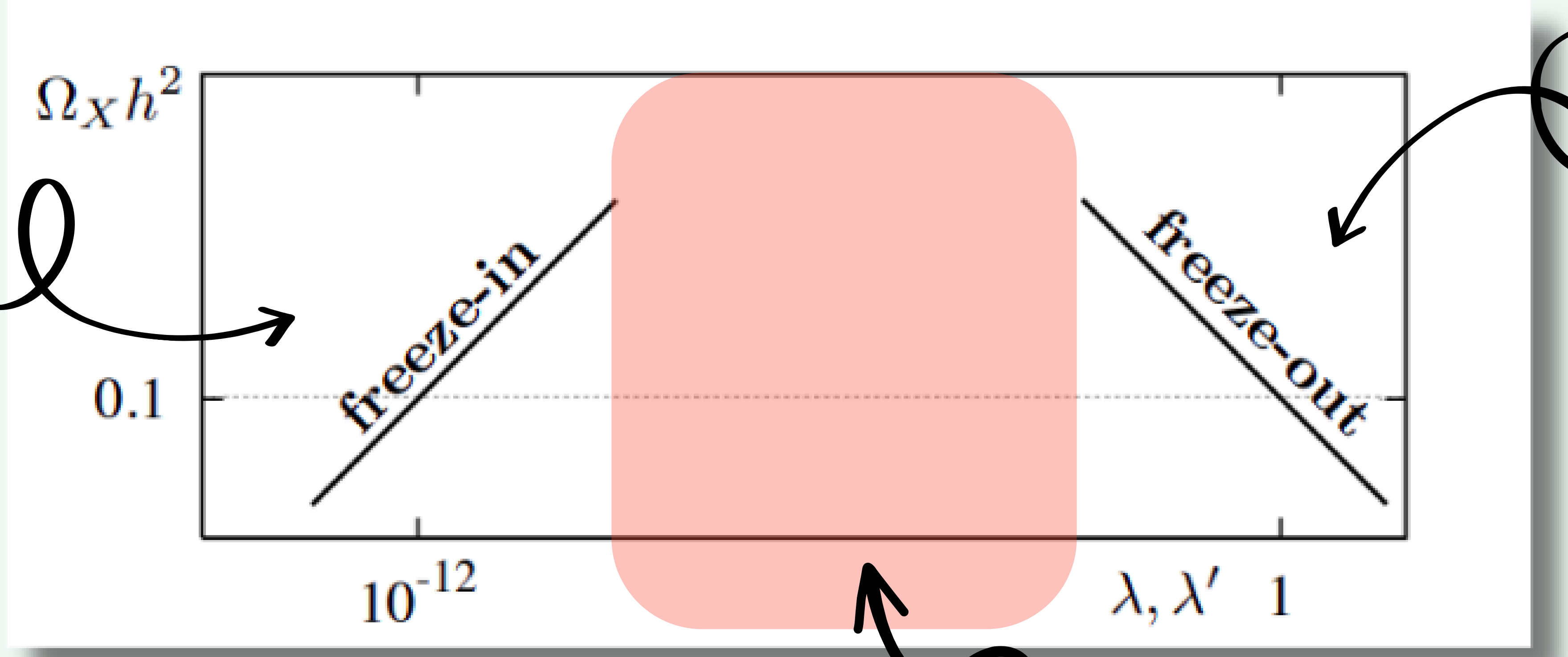

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Overproduction

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Higgs portal

$$\mathcal{L} \supset \frac{1}{2}\lambda_{hs} s^2 H^\dagger H$$

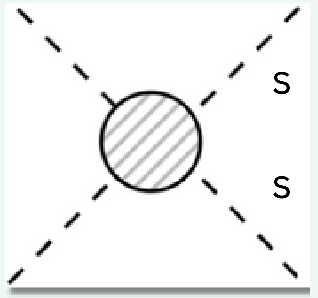
FREEZE-IN PRODUCTION

Boltzmann equation for the evolution of the DM number density

$$\dot{n}_s + 3Hn_s = \Gamma\left(h_i h_i \to ss\right) - \Gamma\left(ss \to h_i h_i\right)$$

Back-reaction

t

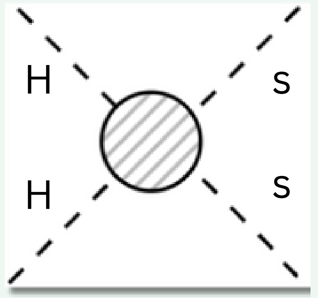


$\propto n_h^2$

$\propto n_s^2$

Forward process

t



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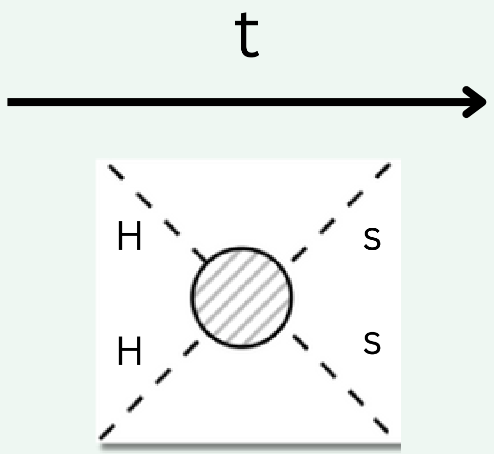

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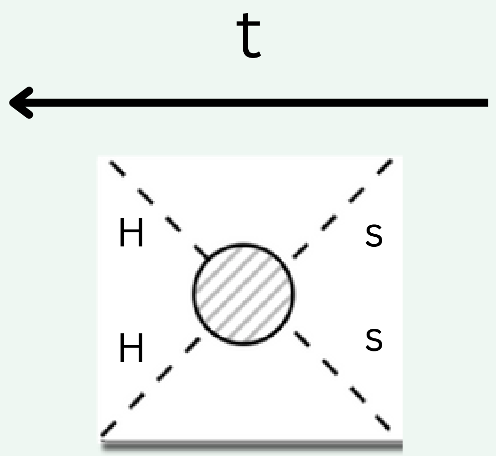

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FREEZE-IN PROBLEMS

AND GRAVITATIONAL PARTICLE PRODUCTION

VERY SMALL COUPLINGS

$$\lambda \sim \mathcal{O}(10^{-10})$$

GRAVITATIONAL PARTICLE PRODUCTION

During inflation and inflaton oscillations

S. G. Mamaev, V. M. Mostepanenko and A. A. Starobinsky, Zh. Eksp. Teor. Fiz. 70, 1577-1591 (1976),
L. Parker, Phys. Rev. 183, 1057-1068 (1969),
A. A. Grib, S. G. Mamaev and V. M. Mostepanenko, Gen. Rel. Grav. 7, 535-547 (1976).
L. H. Ford, Phys. Rev. D 35, 2955 (1987)
Y. Ema, R. Jinno, K. Mukaida, K. Nakayama, 1502.02475
O. Lebedev, 2210.02293

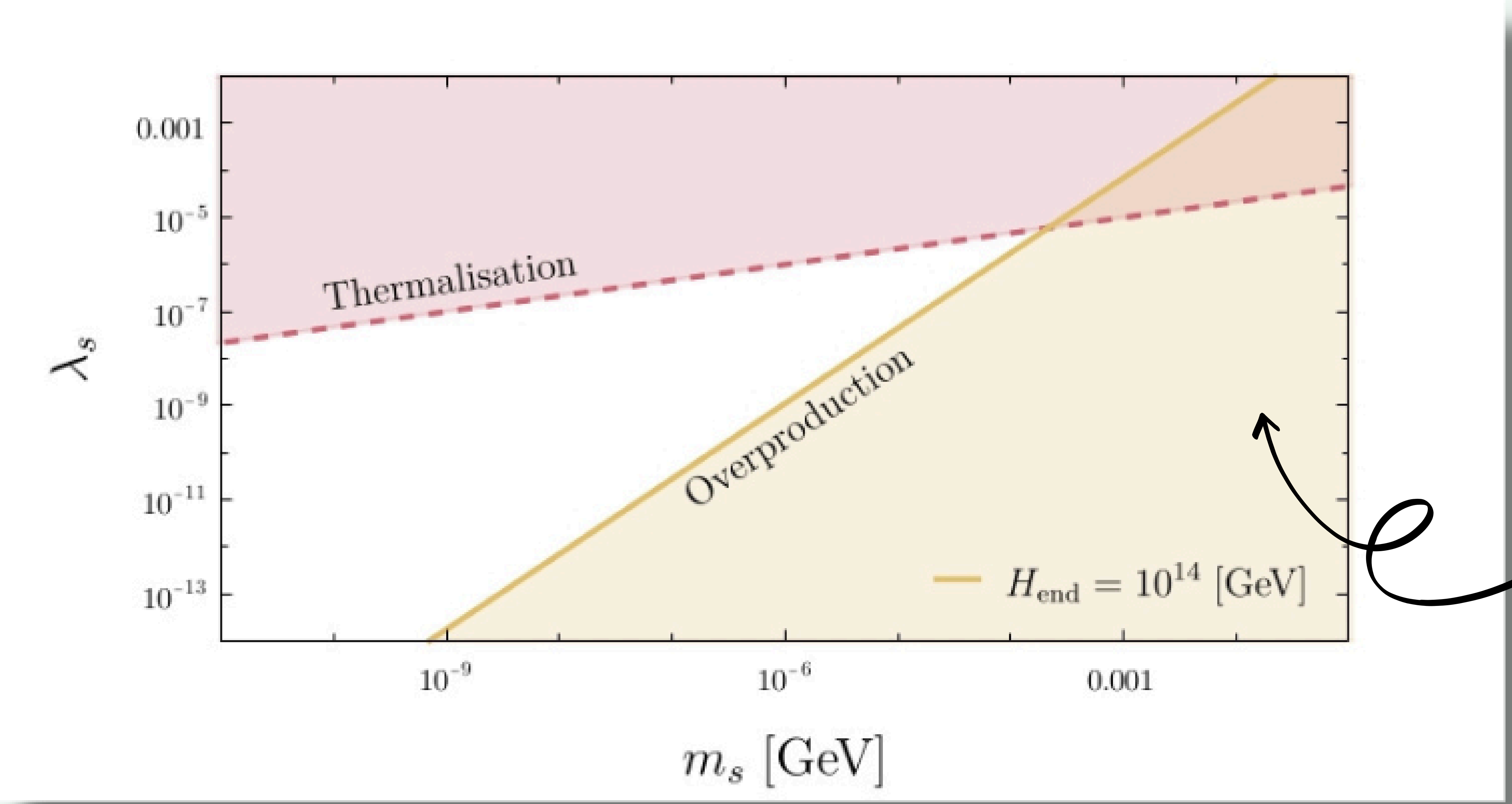
Dark Matter produced only via gravitational productiuon

P. J. E. Peebles and A. Vilenkin, Phys. Rev. D 60, 103506 (1999),
S. Nurmi, T. Tenkanen and K. Tuominen, JCAP 11, 001 (2015),
T. Markkanen, A. Rajantie and T. Tenkanen, Phys. Rev. D 98, no.12, 123532 (2018)

Starobinsky Yokoyama statistichal method

A. A. Starobinsky and J. Yokoyama, Phys. Rev. D 50, 6357-6368 (1994).

OVERPRODUCTION VIA GRAVITY



Unavoidable DM production from gravitational interaction even if the scalar does not interact with the inflaton directly.

Orange area leads to overproduction

Here we assumed the absence of any matter dominated epoch after inflation

O. Lebedev, 2210.02293

RESCUING THE FREEZE-IN

s is a feebly interacting particle

DILUTION due to early matter dominated epoch

STRONGLY PRODUCED
GRAVITATIONALLY

e.g massive inflaton oscillating around its minimum, with potential $\frac{1}{2}m_\phi^2\phi^2$

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$$\Delta_{\text{NR}} \equiv \left(\frac{H_{\text{end}}}{H_{\text{reh}}} \right)^{1/2}$$

RESCUING THE FREEZE-IN

To avoid overproduction we obtain the bounds on $\Delta_{\rm NR}$

$(\,\Omega h^2 \lesssim 0.12\,)$

During inflation

$$\Delta_{\rm NR} \gtrsim 10^7 \lambda_s^{-3/4} \left(\frac{H_{\rm end}}{M_{\rm Pl}}\right)^{3/2} \left(\frac{m_s}{\rm GeV}\right)$$

← λ_s is the inflaton self-coupling

O. Lebedev, 2210.02293
Y. Ema, R. Jinno, K. Mukaida, K. Nakayama, 1502.02475
C. Cosme, FC, O. Lebedev, arXiv: 2306.13061

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e.g for $H_{\rm end} \sim 10^{14}$ GeV,
$m_s \sim 100$ GeV and
$\lambda_s \sim 10^{-10}$

→ $\Delta_{\rm NR} \sim 10^{10}$

O. Lebedev, 2210.02293
Y. Ema, R. Jinno, K. Mukaida, K. Nakayama, 1502.02475
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Inflaton oscillation

$$\Delta_{\rm NR} \gtrsim 10^6 \left(\frac{H_{\rm end}}{M_{\rm Pl}}\right)^{3/2} \left(\frac{m_s}{\rm GeV}\right)$$

O. Lebedev, 2210.02293
Y. Ema, R. Jinno, K. Mukaida, K. Nakayama, 1502.02475
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LONG MATTER DOMINATED EPOCH

$$H_{\text{reh}} \leftrightarrow T_R$$

LOW REHEATING TEMPERATURE

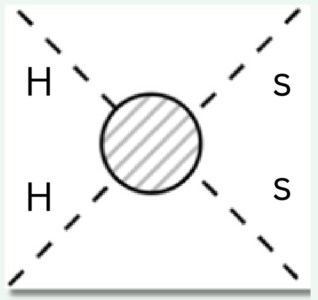
WHAT HAPPENS AT LOW TR?

Example:

t

Higgs portal

$$\mathcal{L} \supset \frac{1}{2}\lambda_{hs} s^2 H^\dagger H$$

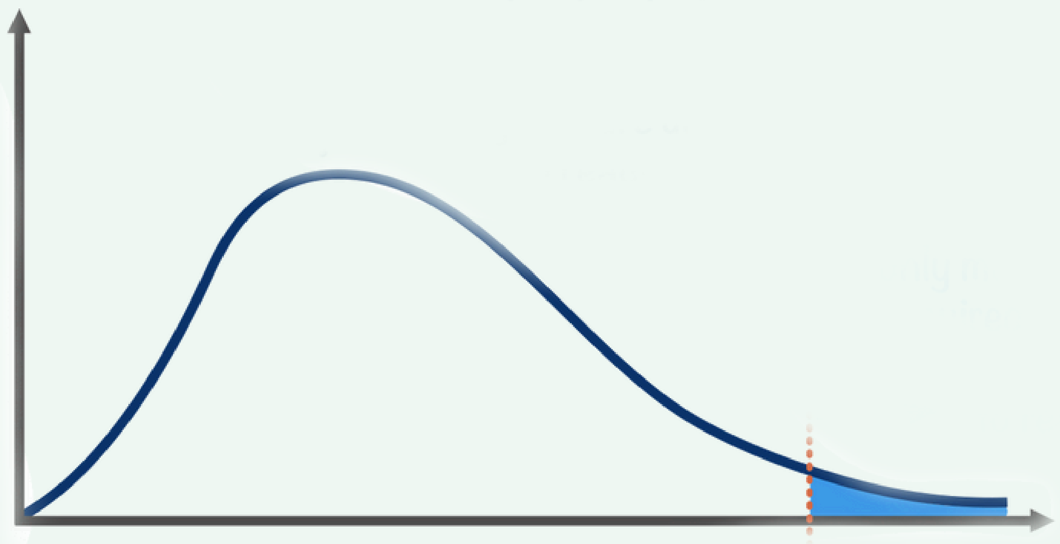


Freeze-in

Parameter space:

$$m_H < m_s \;\; \& \;\; T_R < m_s$$

# of H particles



Energy

Boltzmann distribution

C. Cosme, FC, O. Lebedev, arXiv: 2306.13061
FC, L. Covi, to appear soon

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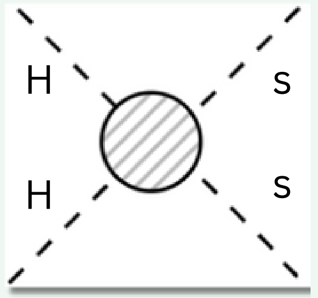

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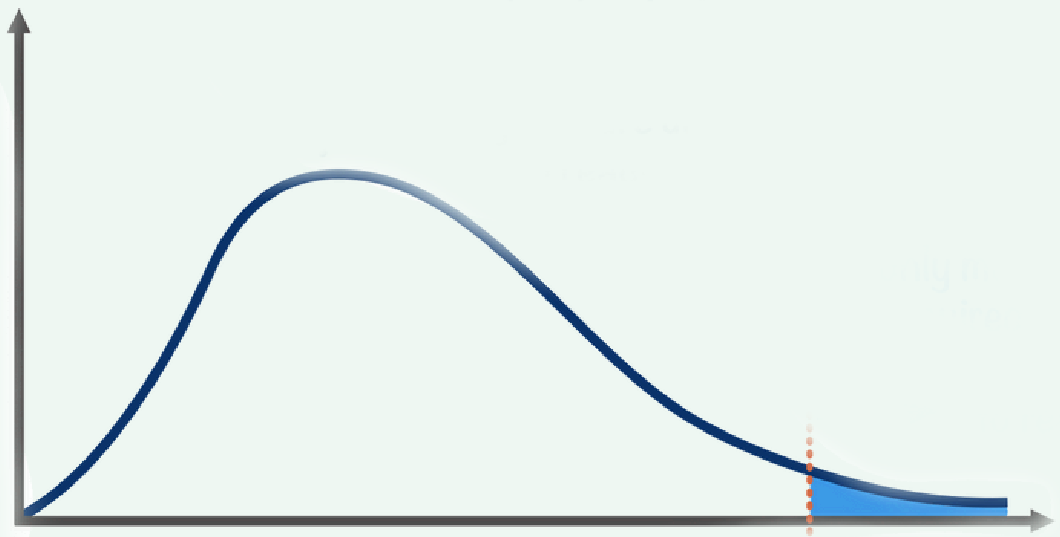


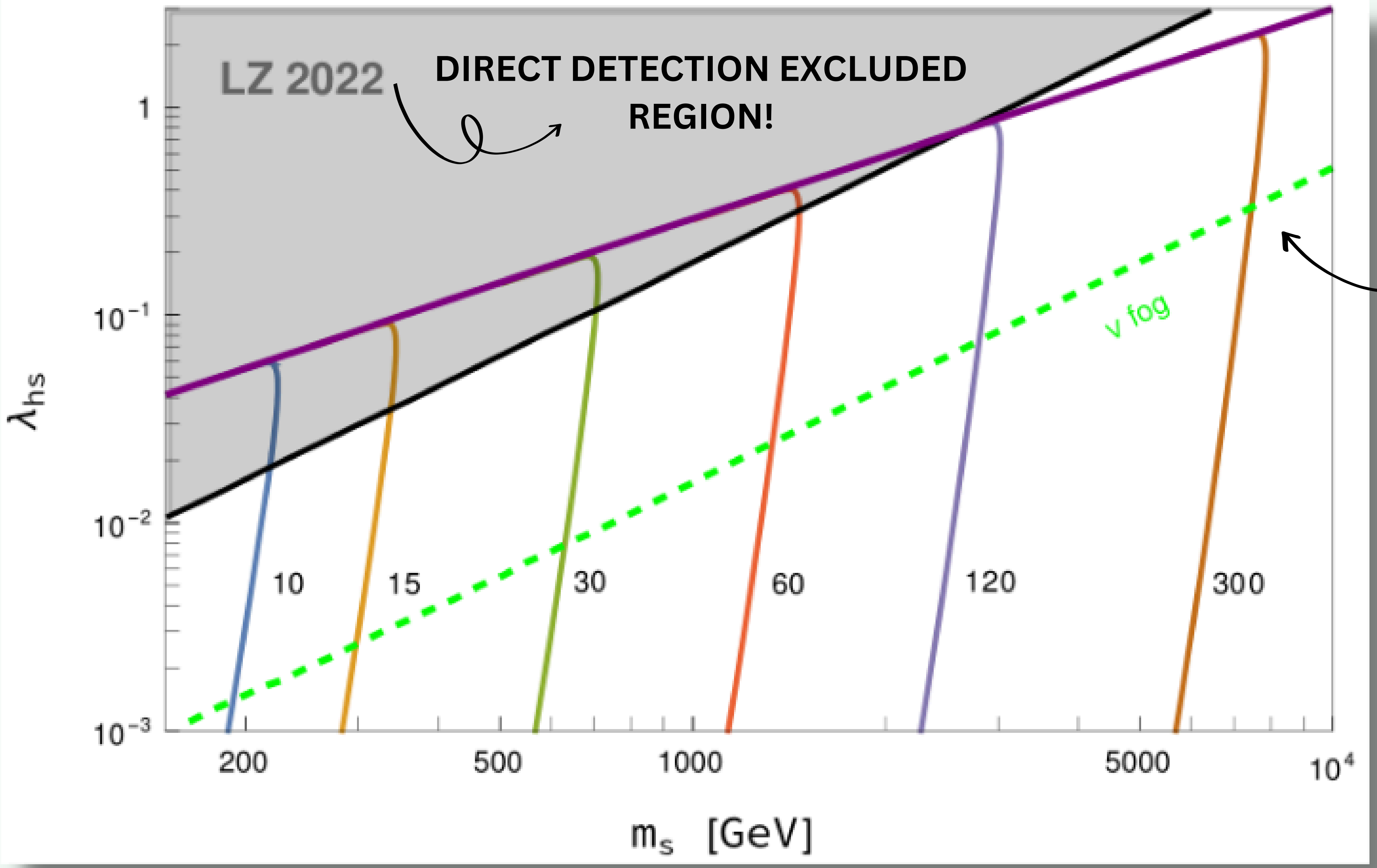
Boltzmann distribution

$$\Gamma(h_i h_i \to ss) \simeq \frac{\lambda_{hs}^2 T^3 m_s}{2^7 \pi^4}\, e^{-2m_s/T}$$

The rate of production is Boltzmann suppressed

C. Cosme, FC, O. Lebedev, arXiv: 2306.13061
FC, L. Covi, to appear soon

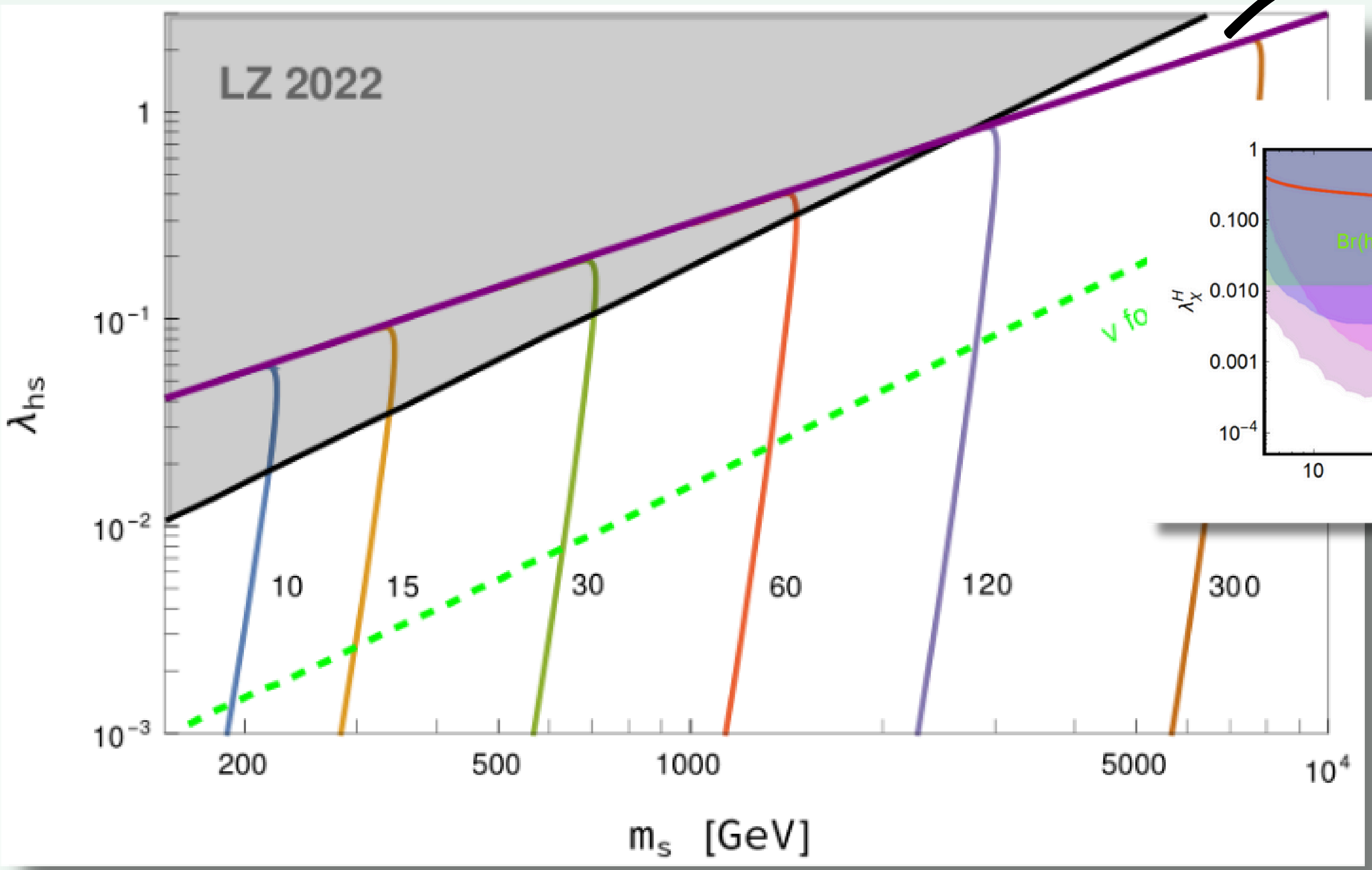
FREEZE-IN AT STRONGER COUPLING

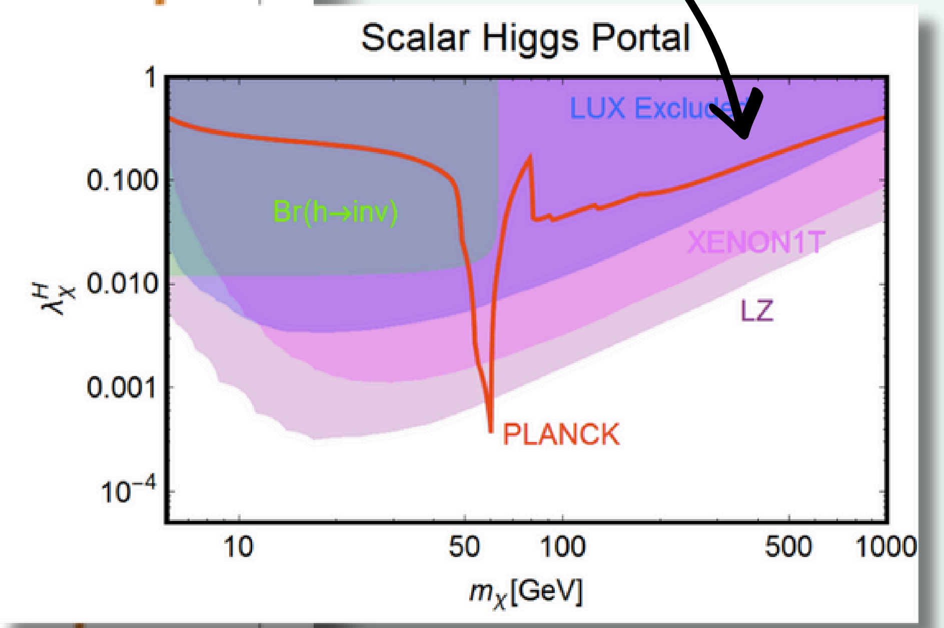


Neutrino fog line. Future direct detection will set constains at this level

C. Cosme, FC, O. Lebedev, arXiv: 2306.13061

FREEZE-IN AT STRONGER COUPLING

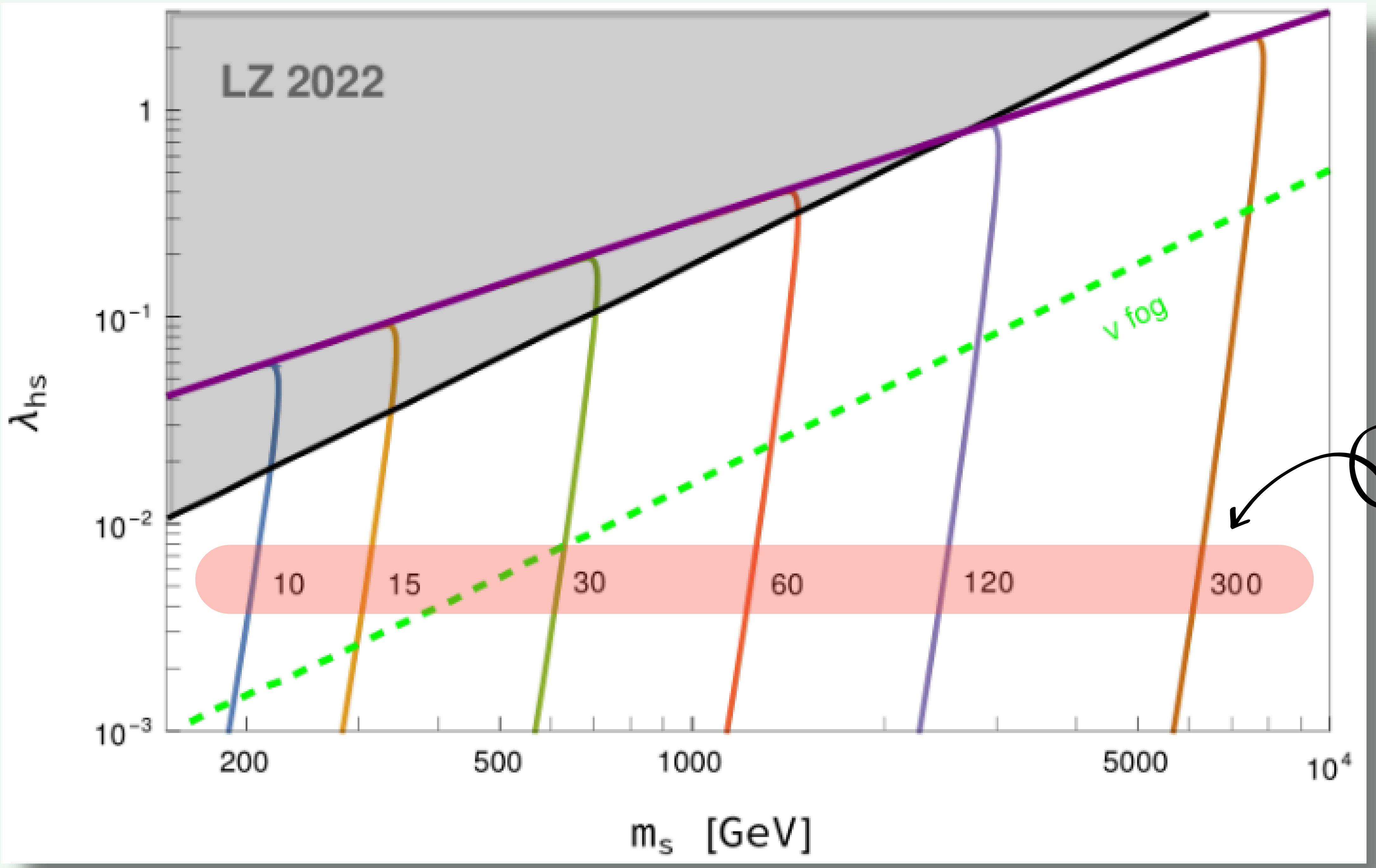




The purple line is the freeze-out line, from there and above the DM is thermalised and the relic abundance is set by freeze-out

C. Cosme, FC, O. Lebedev, arXiv: 2306.13061

FREEZE-IN AT STRONGER COUPLING

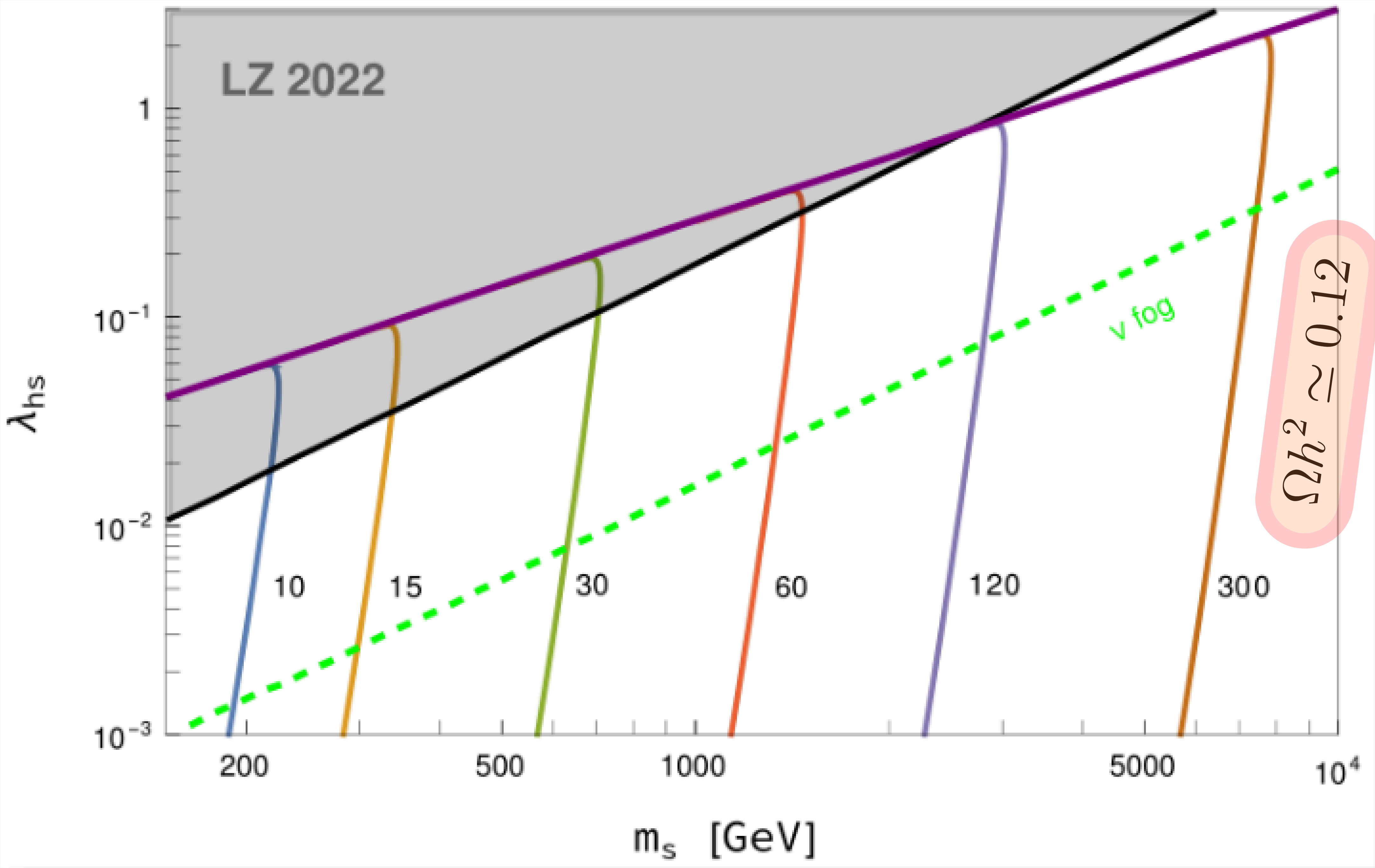


T_R

Each "vertical" line corresponds to a different reheating temperature (in GeV) ...

C. Cosme, FC, O. Lebedev, arXiv: 2306.13061

FREEZE-IN AT STRONGER COUPLING



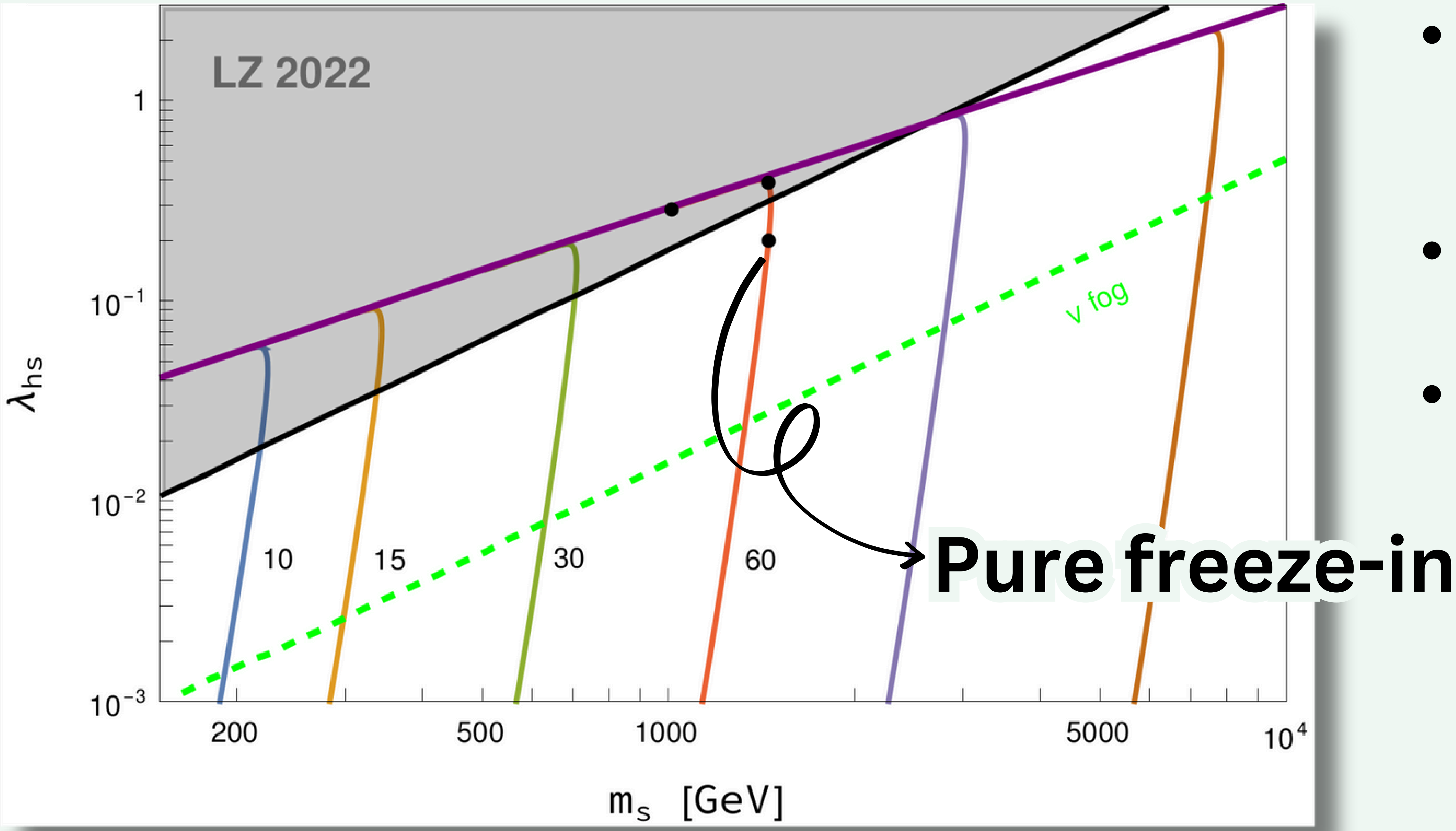
Each "vertical" line corresponds to a different reheating temperature (in GeV) ...

... and lead to the correct relic abundance $\Omega h^2 \simeq 0.12$

C. Cosme, FC, O. Lebedev, arXiv: 2306.13061

$$\dot{n}_s + 3Hn_s = \Gamma\left(h_i h_i \to ss\right) - \Gamma\left(ss \to h_i h_i\right)$$

THREE REGIMES OF DM PRODUCTION



- No thermalisation = pure freeze-in production
- Coupling up to order 1!
- Freeze-in tested at DIRECT DETECTION!

C. Cosme, FC, O. Lebedev, arXiv: 2306.13061

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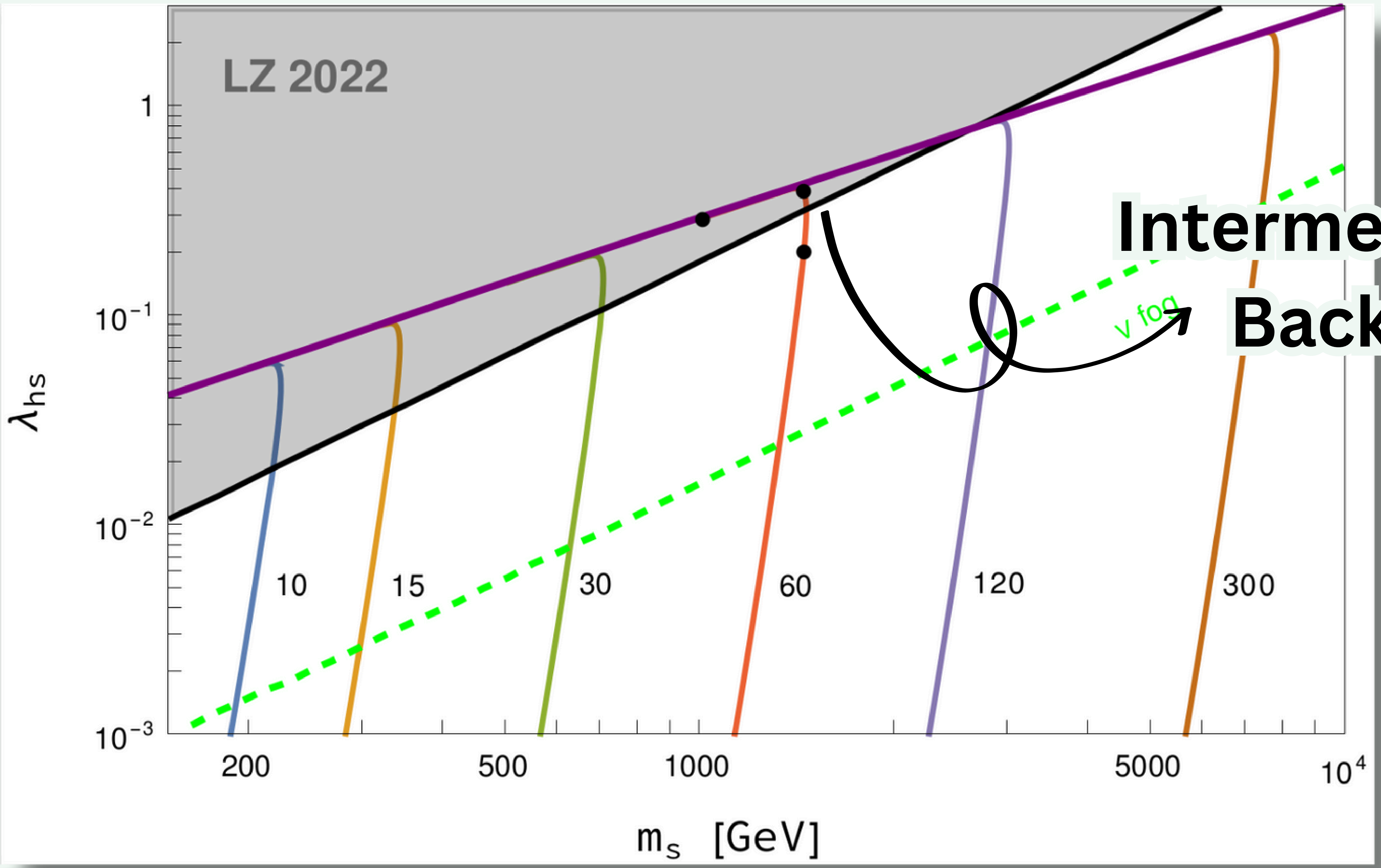

Intermediate region

Backreaction

- DM annihilation is important!
- DM is still no thermalised

C. Cosme, FC, O. Lebedev, arXiv: 2306.13061

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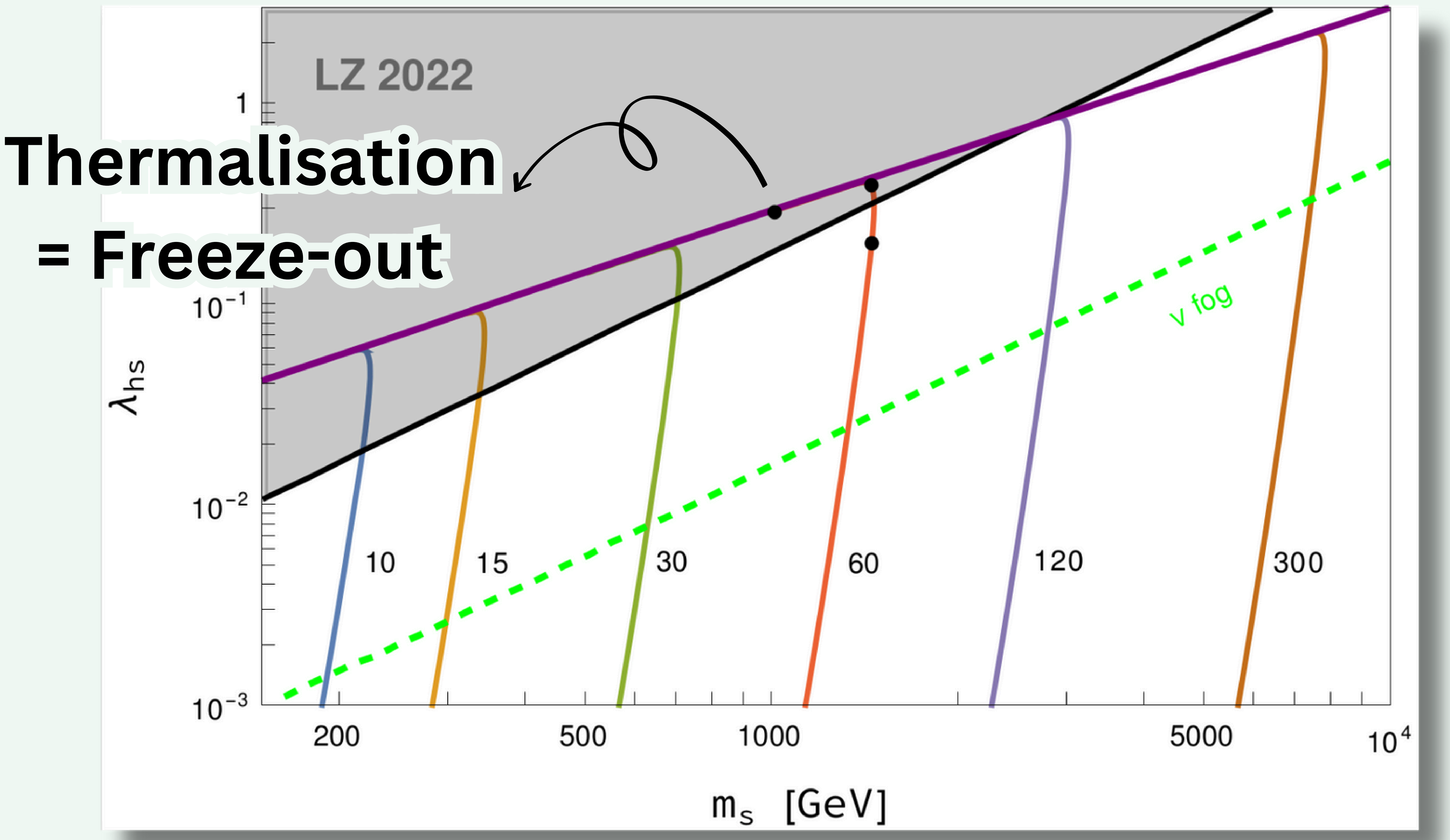
THREE REGIMES OF DM PRODUCTION



- The two rates are equal and DM is in equilibrium
- The relic abundance is set by freeze-out
- We move freely in the parameter space from FIMP to WIMP, no overproduction region

C. Cosme, FC, O. Lebedev, arXiv: 2306.13061

CONCLUSIONS

TAKE HOME MESSAGE

EARLY UNIVERSE: EFFICIENT **GRAVITATIONAL PRODUCTION** OF FEEBLY COUPLED PARTICLES

NEED FOR A "LONG" MATTER DOMINATED EPOCH AND THEREFORE **LOW REHEATING TEMPERATURE** TO AVOID OVEPRODUCTION

- **BOLTZMANN SUPPRESSED** PRODUCTION RATE AND POSSIBLE **DIRECT DETECTION AND COLLIDER SIGNATURES!**
- **NO OVERPRODUCTION GAP** BETWEEN FREEZE-OUT AND FREEZE-IN AT LOW REHEATING TEMPERATURES

THANK YOU

Francesco Costa

Institute for Theoretical Physics,
University of Goettingen

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN IN PUBLICA COMMODA SEIT 1737

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BACK-UP

UNDERLING APPROXIMATION

REHEATING VIA RH NEUTRINOS

If the SM is produced by a subdominant component during reheating we can have

$$T_R \simeq T_{\max}$$

C. Cosme, FC, O. Lebedev, arXiv: 2402.04743

REHEATING VIA RH NEUTRINOS

$$\phi \to \nu_R \to \mathrm{SM}$$

If the SM is produced by a subdominant component during reheating we can have

$$T_R \simeq T_{\max}$$

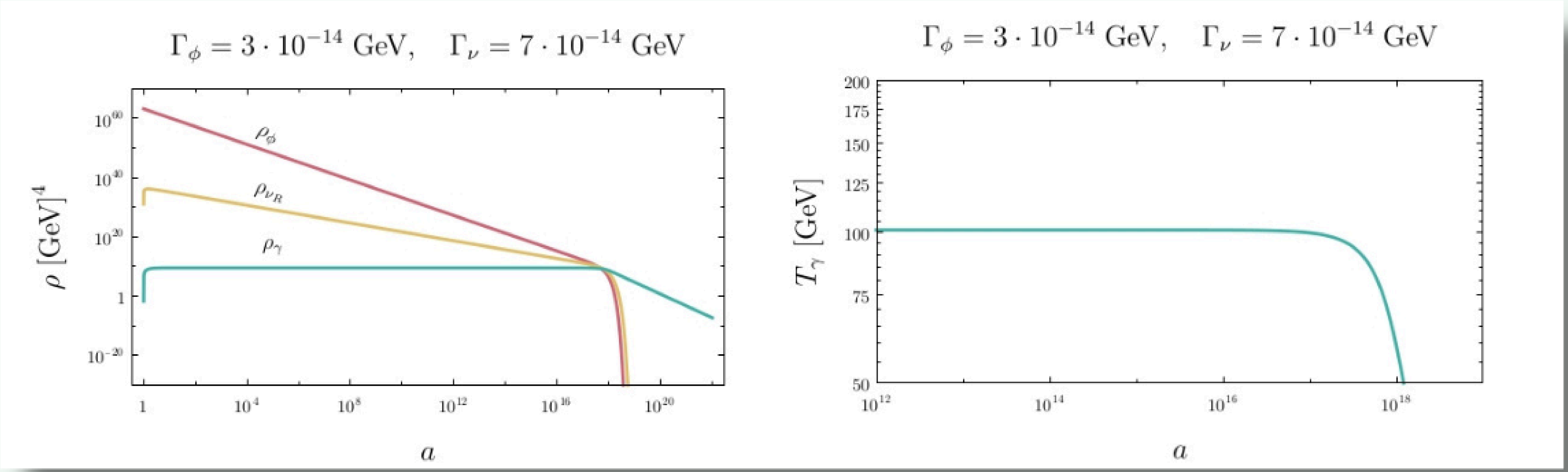
Reheating Boltzmann Equations

$$\begin{aligned}
\dot{\rho}_\phi + 3H\rho_\phi &= -\Gamma_\phi \rho_\phi, \\
\dot{\rho}_\nu + 4H\rho_\nu &= \Gamma_\phi \rho_\phi - \Gamma_\nu \rho_\nu, \\
\dot{\rho}_\gamma + 4H\rho_\gamma &= \Gamma_\nu \rho_\nu, \\
\rho_\phi + \rho_\nu + \rho_\gamma &= 3H^2 m_P^2,
\end{aligned}$$

C. Cosme, FC, O. Lebedev, arXiv: 2402.04743

TEMPERATURE EVOLUTION

$$\Gamma_\phi \sim \Gamma_\nu$$



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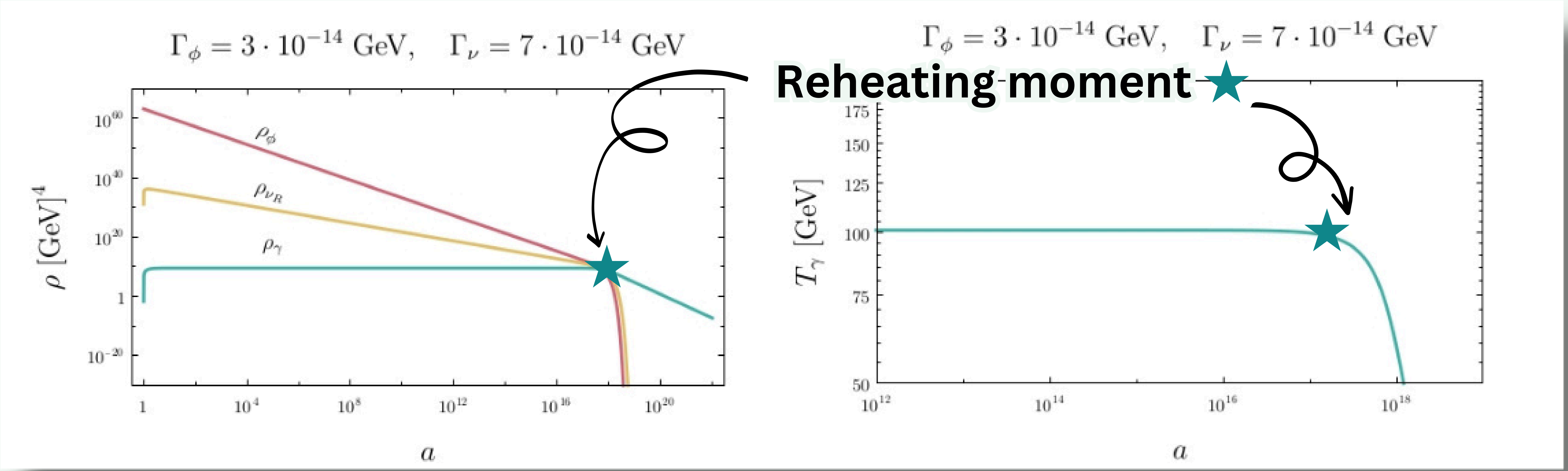

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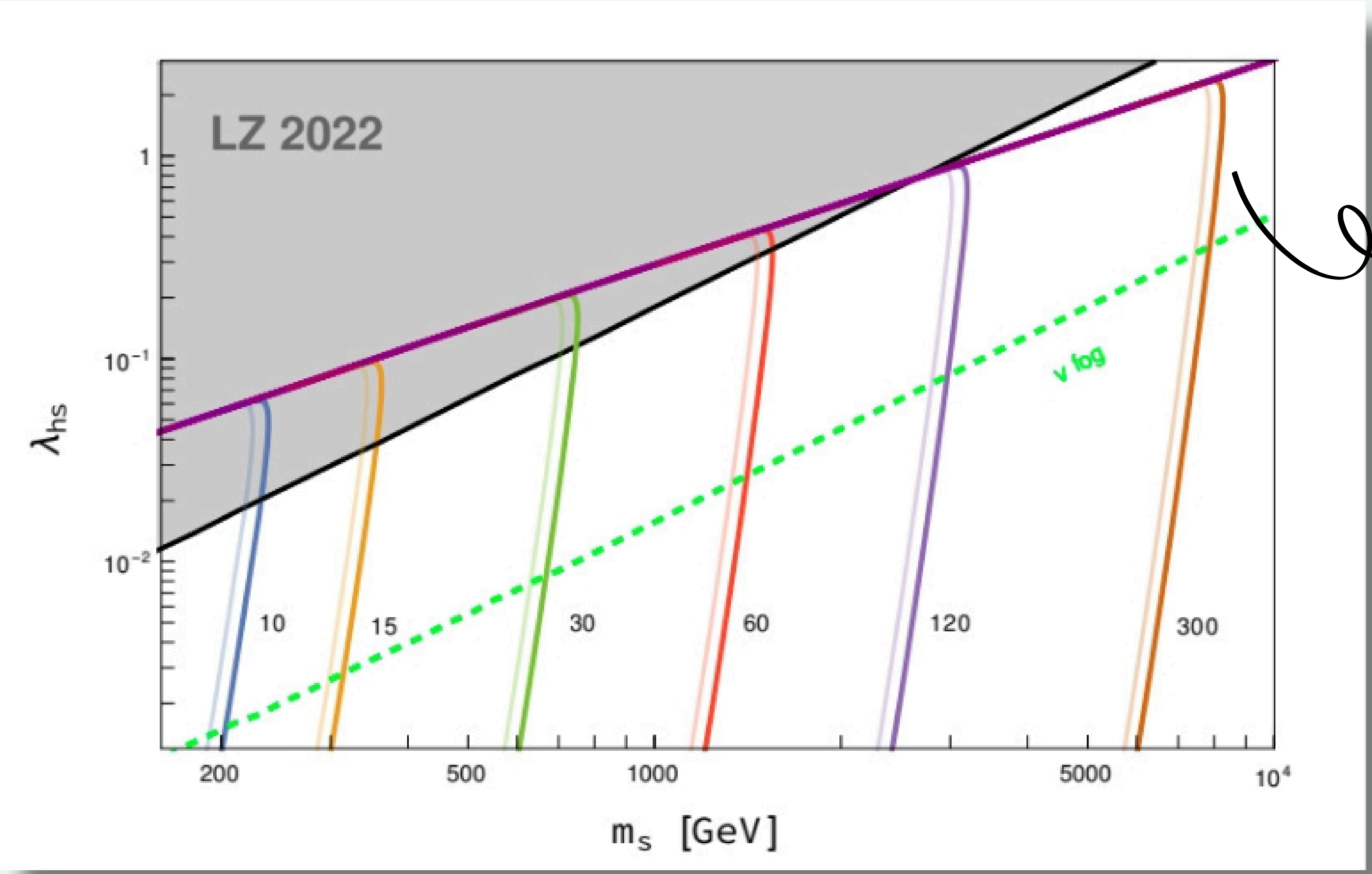
CORRECTION TO THE DM PRODUCTION



$$T_R \to 0.95 \times T_R$$

5% correction wrt instantaneous reheating approximation

Faint lines: instantaneous reheating

Thick lines: non-instantaneous reheating with $\Gamma_\phi \sim \Gamma_\nu$

C. Cosme, FC, O. Lebedev, arXiv: 2402.04743

UNDERLING ASSUMPTION

INSTANTANEOUS REHEATING

When the inflaton decay becomes active: $\Gamma_\phi \simeq H$

The inflaton decays instantaneously into the SM particles and create a thermal bath

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When the inflaton decay becomes active: $\Gamma_\phi \simeq H$

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"Standard" choice $T_R \sim 10^{14} - 10^{15}\ \mathrm{GeV}$

UNDERLING APPROXIMATION

INSTANTANEOUS REHEATING

“Standard“ choice $T_R \sim 10^{14} - 10^{15}\ \mathrm{GeV}$

Strongest experimental bound is BBN $T_R \gtrsim \text{few eV}$

NON-INSTANTANEOUS REHEATING

Reheating Boltzmann Equations

$$\dot{\rho}_\phi + 3H\rho_\phi = -\Gamma_\phi \rho_\phi,$$

$$\dot{\rho}_\gamma + 4H\rho_\gamma = \Gamma_\phi \rho_\phi,$$

$$\rho_\phi + \rho_\gamma = 3m_P^2 H^2.$$

Inflaton decays directly into the SM

NON-INSTANTANEOUS REHEATING

Reheating Boltzmann Equations

$$\dot{\rho}_\phi + 3H\rho_\phi = -\Gamma_\phi \rho_\phi,$$
$$\dot{\rho}_\gamma + 4H\rho_\gamma = \Gamma_\phi \rho_\phi,$$
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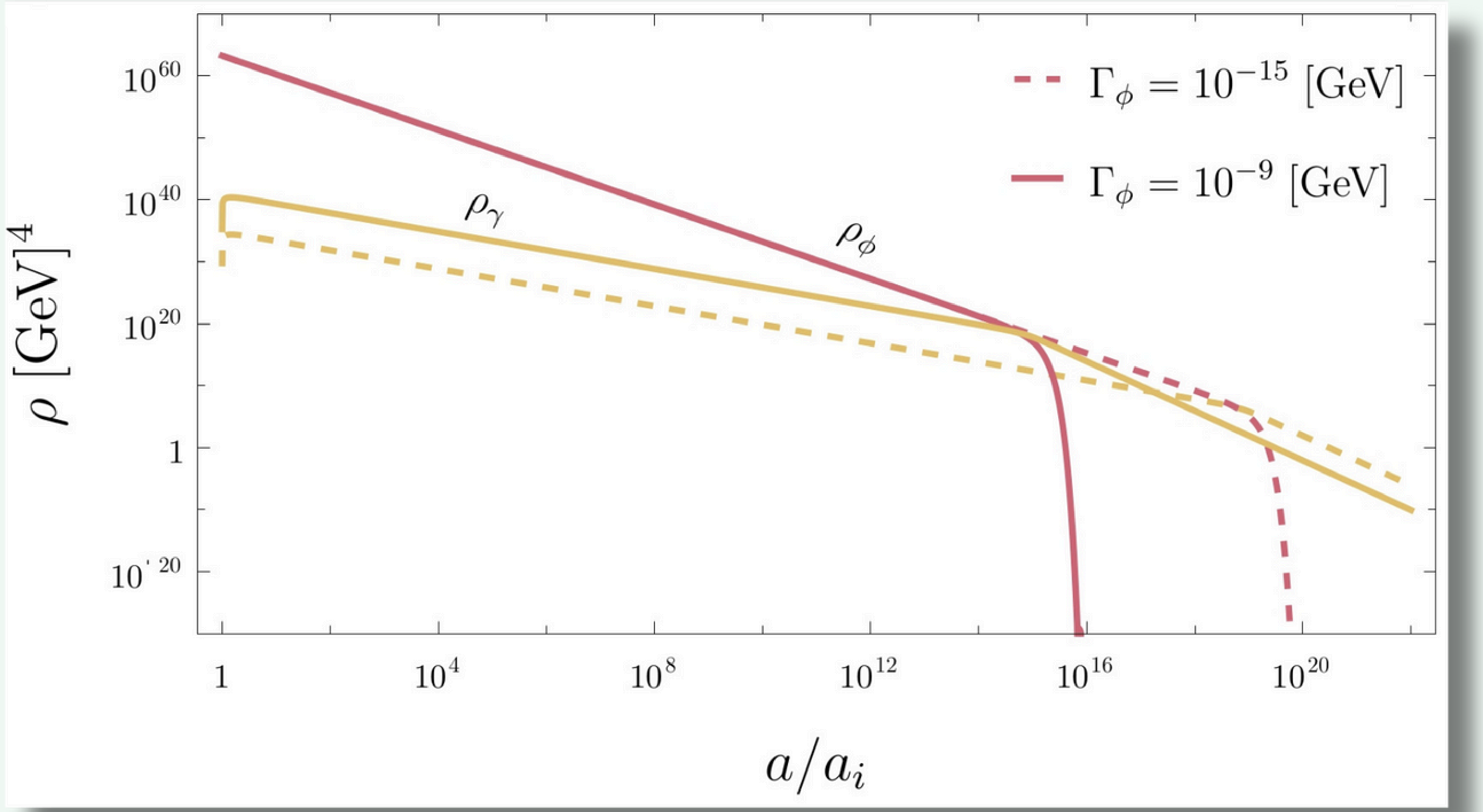


In our freeze-in at stronger coupling analysis we need to replace $T_R \to T_{\max}$

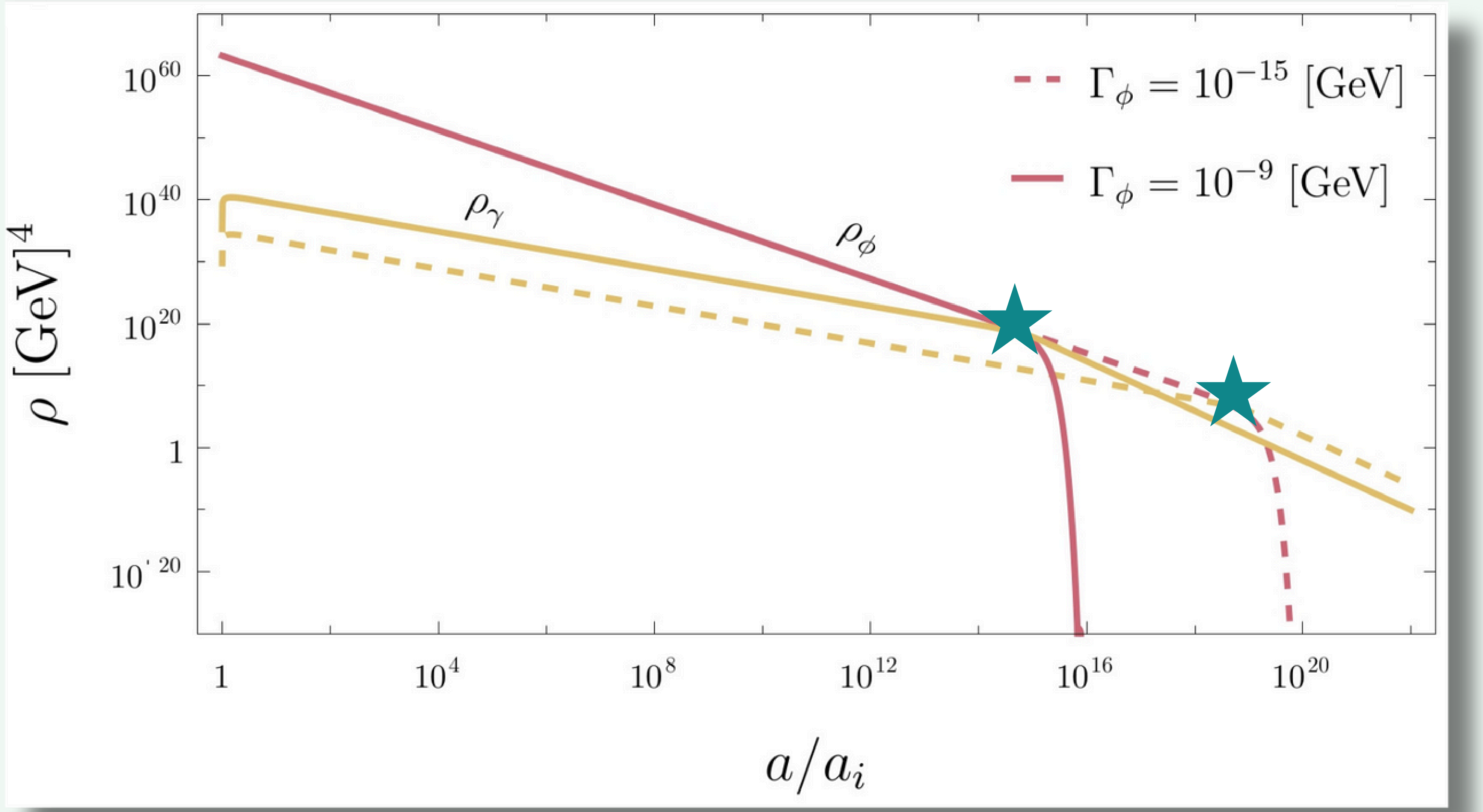
NON-INSTANTANEOUS REHEATING

Reheating moment: ★

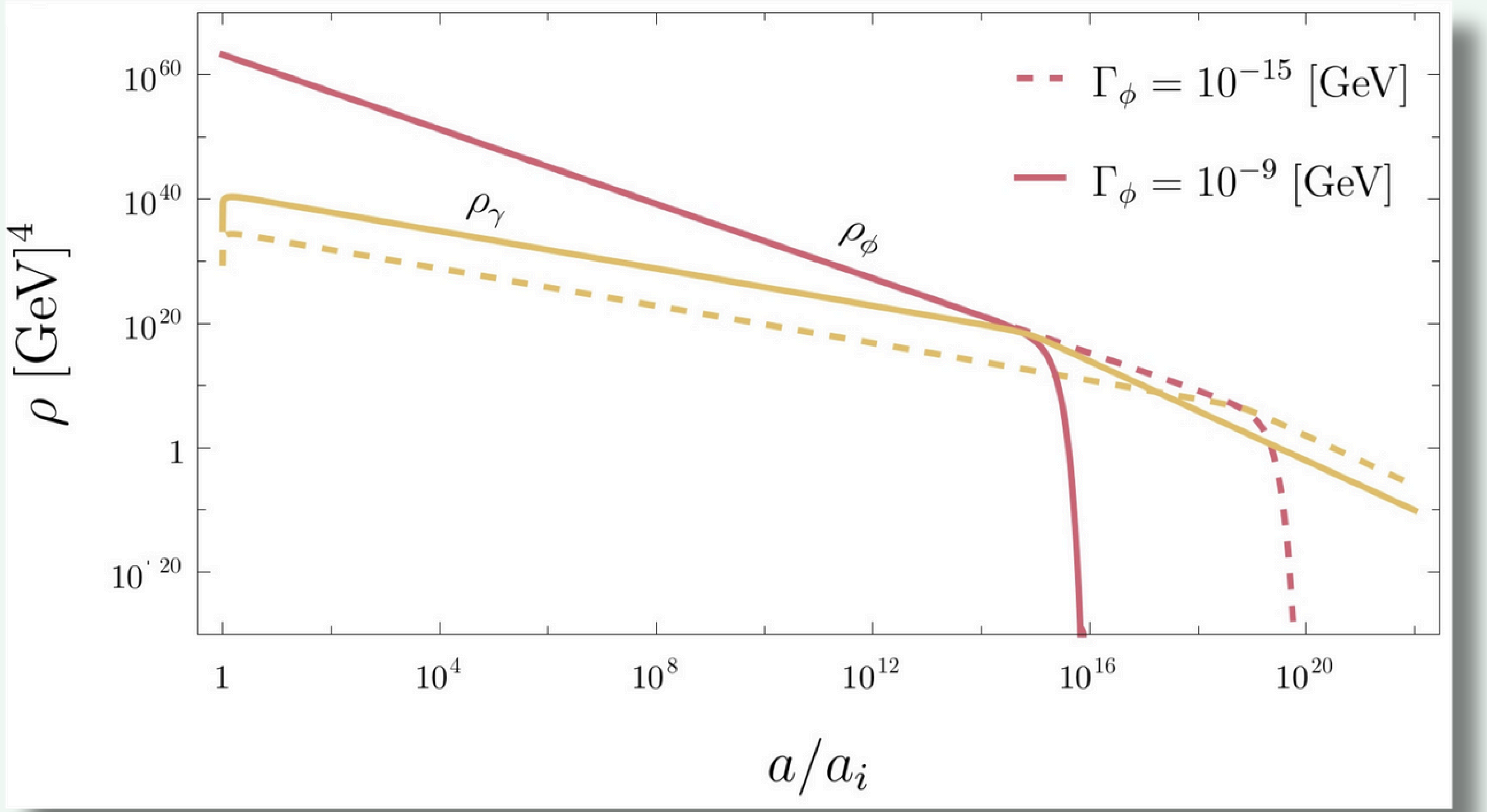
$$\rho_\phi \simeq \rho_\gamma$$

Temperature of the SM bath at this moment is

$$T_R$$



NON-INSTANTANEOUS REHEATING



In our freeze-in at stronger coupling analysis we need to replace

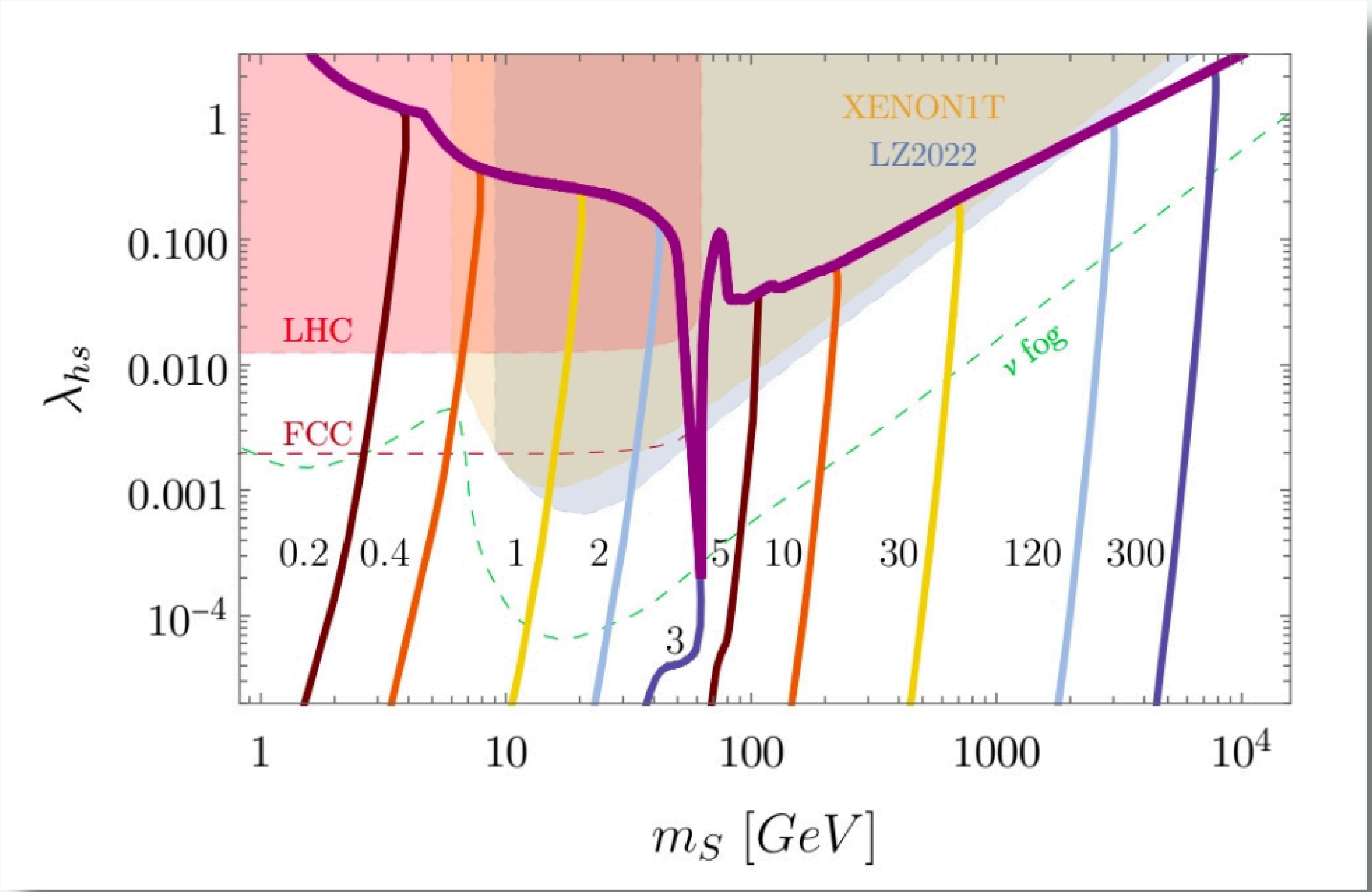
$$T_R \to T_{\max}$$

This could spoil the assumption

$$m_s < T_R$$

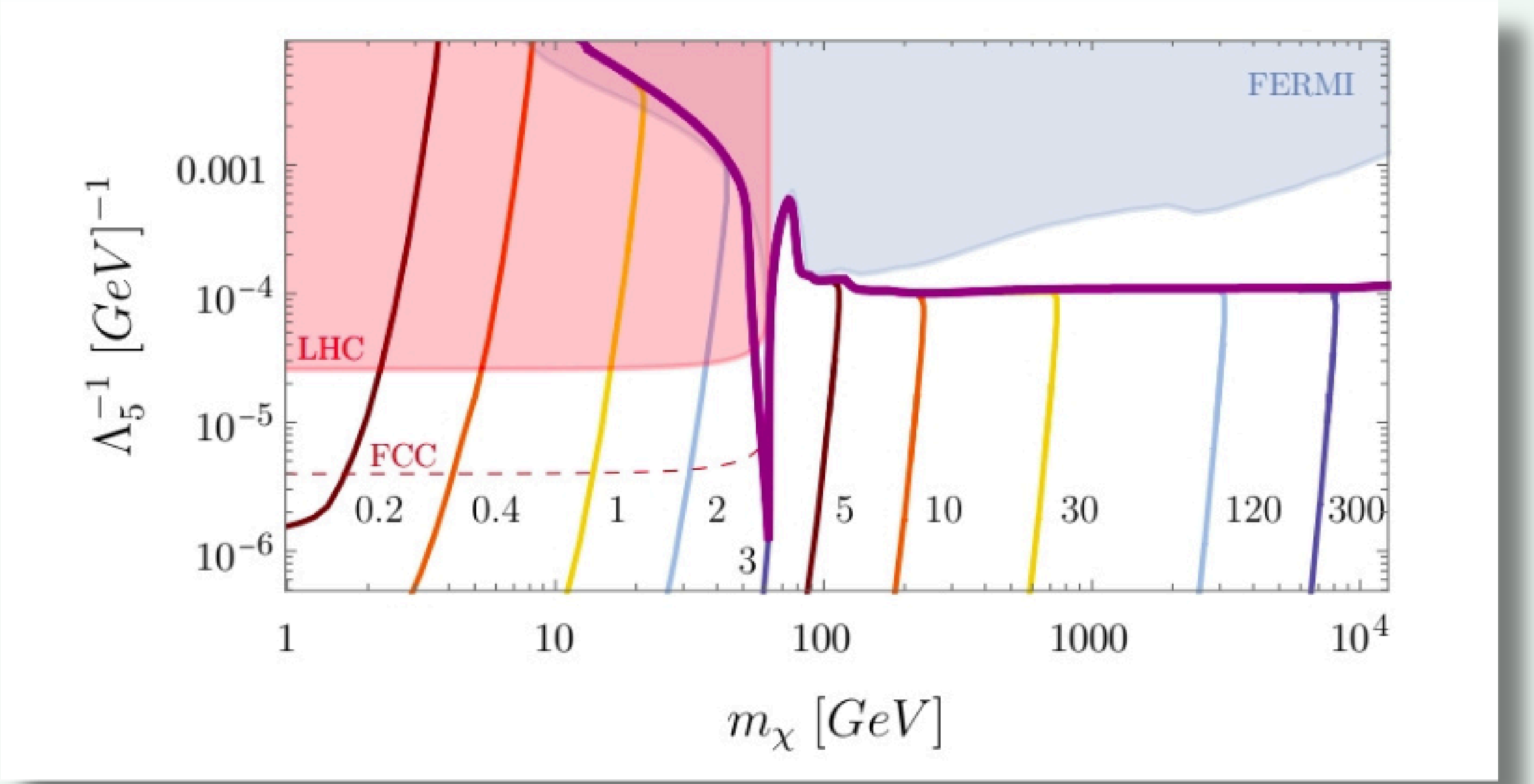
If Tmax is very large

SCALAR DM



High DM mass: DD detection constraint

Low DM mass: LHC and future collider constraint

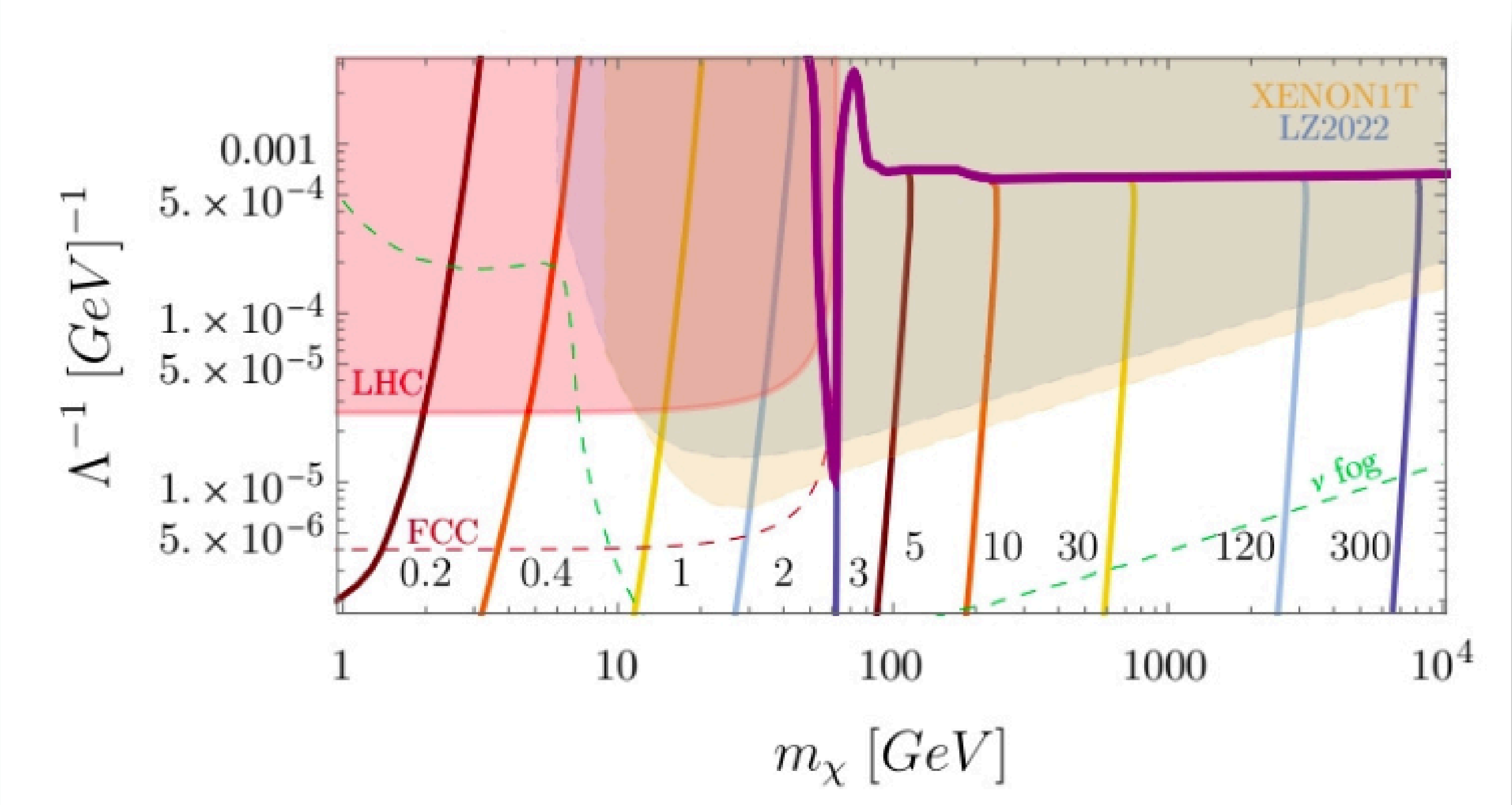


CP ODD

New parameter space opened up at low DM masses and testable at collider!

Colliders can test below the reach of DD experiments (below the neutrino fog)

CP EVEN

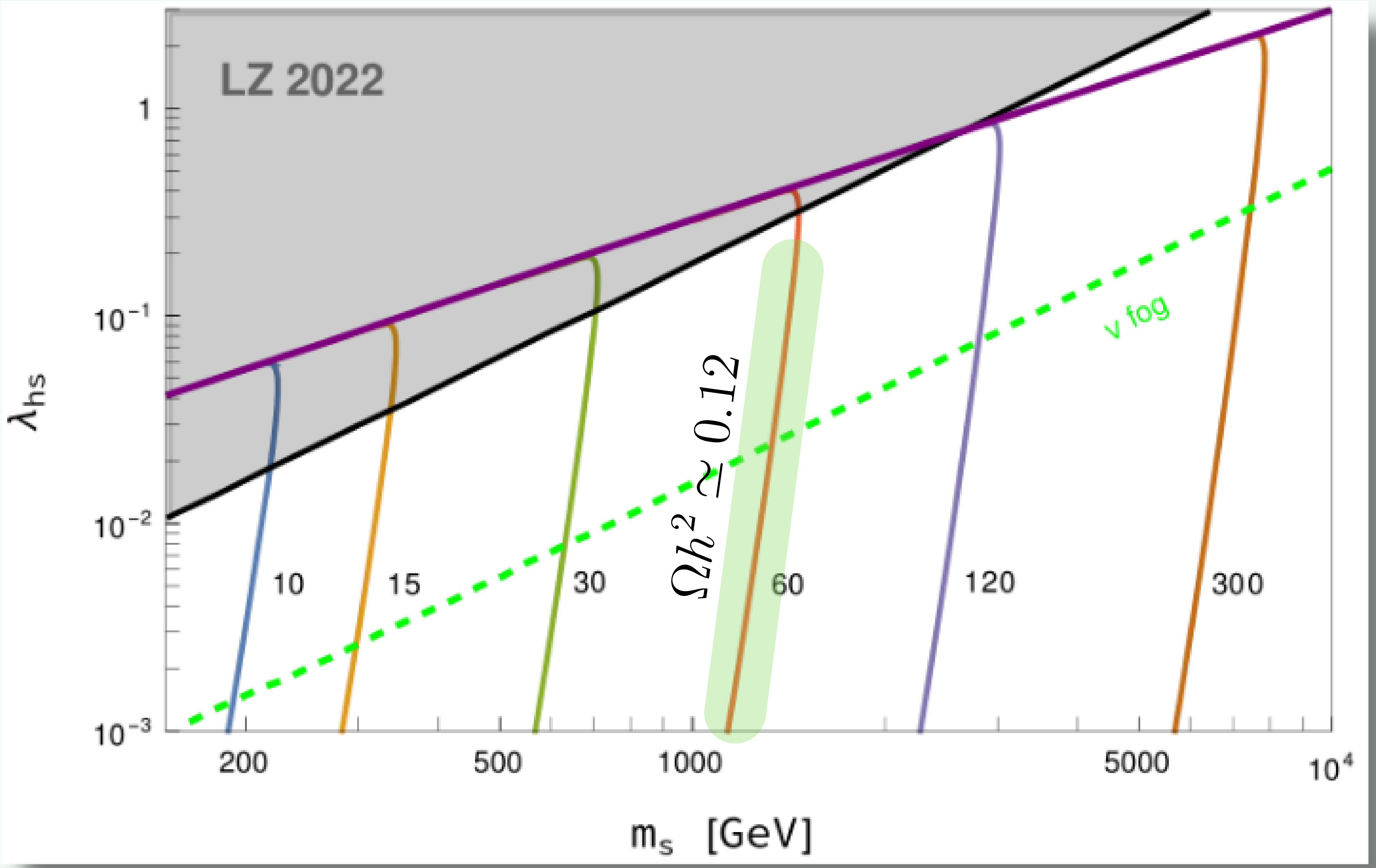


FREEZE-IN REGIME

C. Cosme, FC, O. Lebedev, arXiv: 2306.13061

HIGGS PORTAL TO SCALAR DM

FREEZE-IN



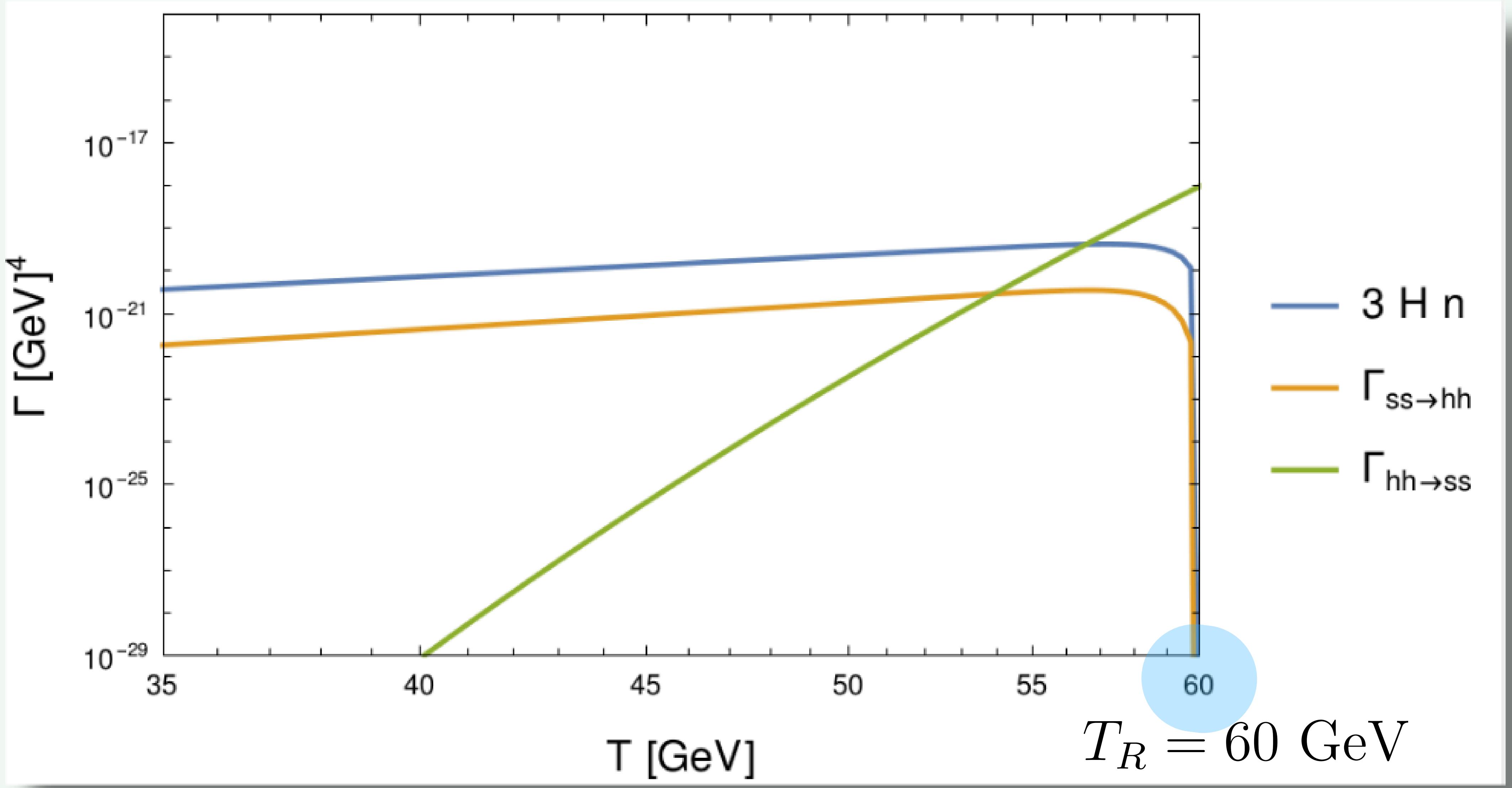
C. Cosme, FC, O. Lebedev, arXiv: 2306.13061

FREEZE-IN REGIME

$$m_s = 1460\ \text{GeV} \quad \lambda_{hs} = 0.10$$

Boltzmann equation

$$\dot{n}_s + 3Hn_s = \Gamma\left(h_i h_i \to ss\right) - \Gamma\left(ss \to h_i h_i\right)$$



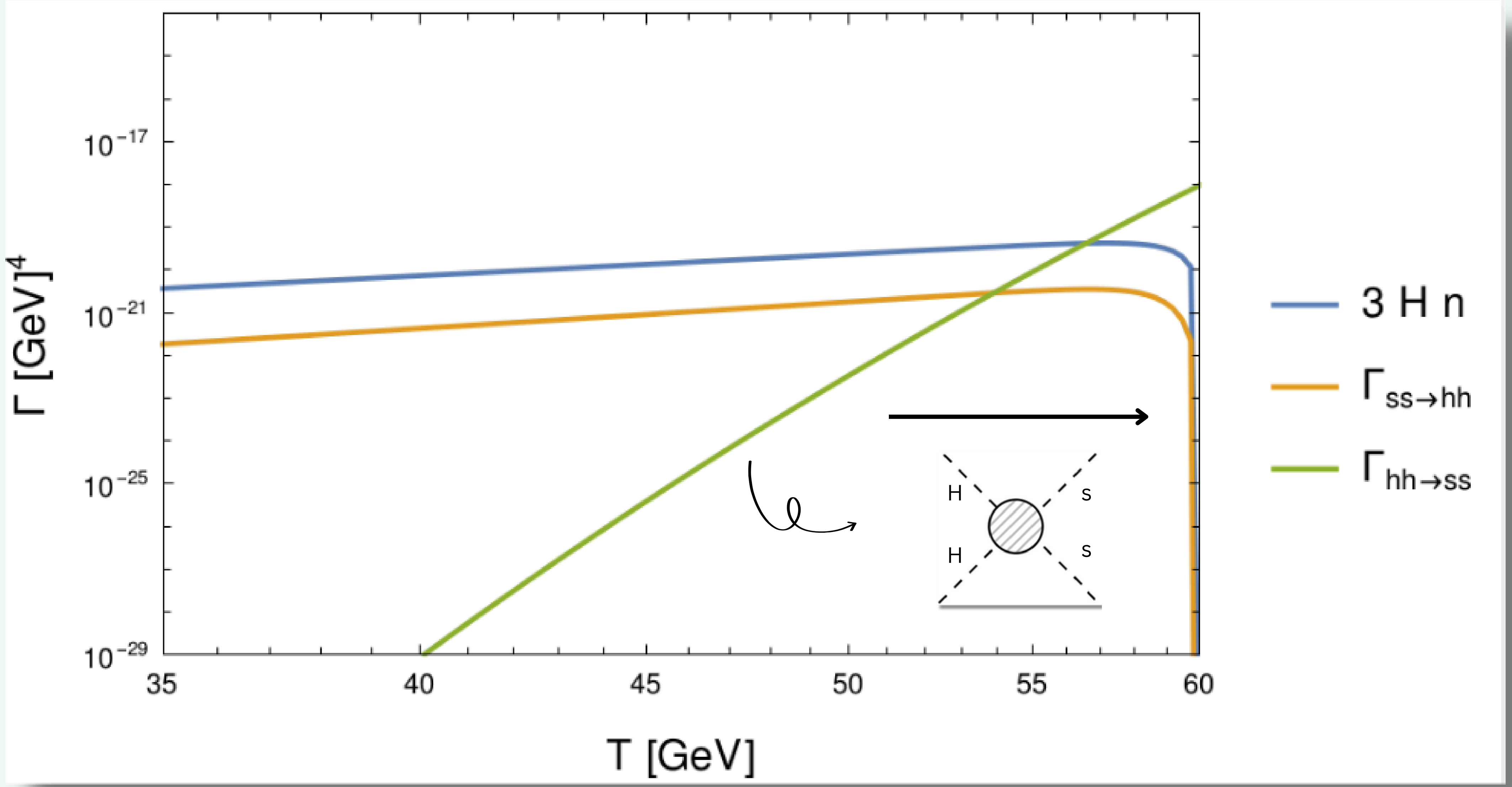
C. Cosme, FC, O. Lebedev, arXiv: 2306.13061

FREEZE-IN REGIME

Boltzmann equation

$$\dot{n}_s + 3Hn_s = \Gamma\left(h_i h_i \to ss\right) - \Gamma\left(ss \to h_i h_i\right)$$

Only the production rate of the freeze-in process is active at ealy times



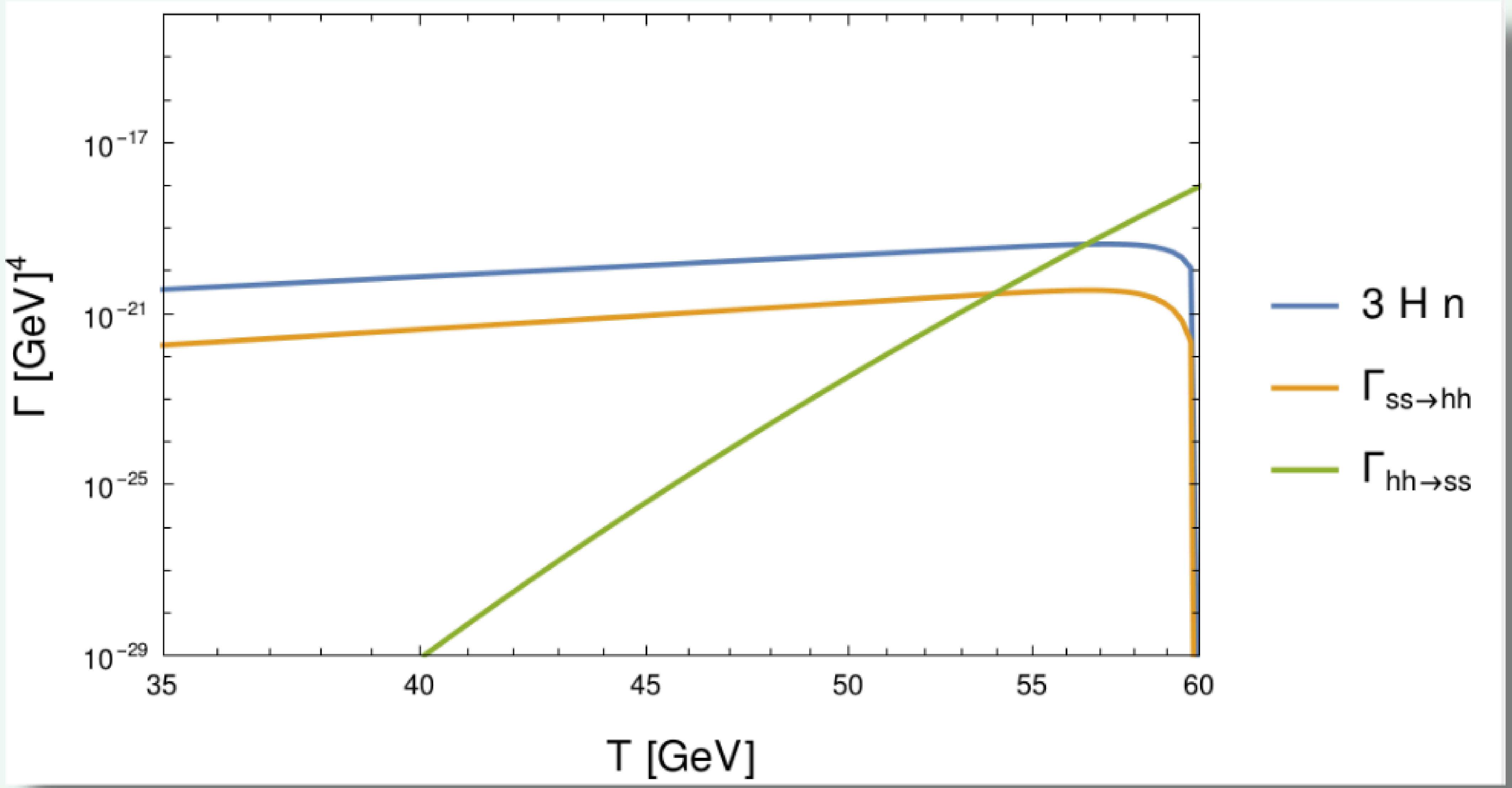
TIME

C. Cosme, FC, O. Lebedev, arXiv: 2306.13061

FREEZE-IN REGIME

But

$$\Gamma > 3Hn$$



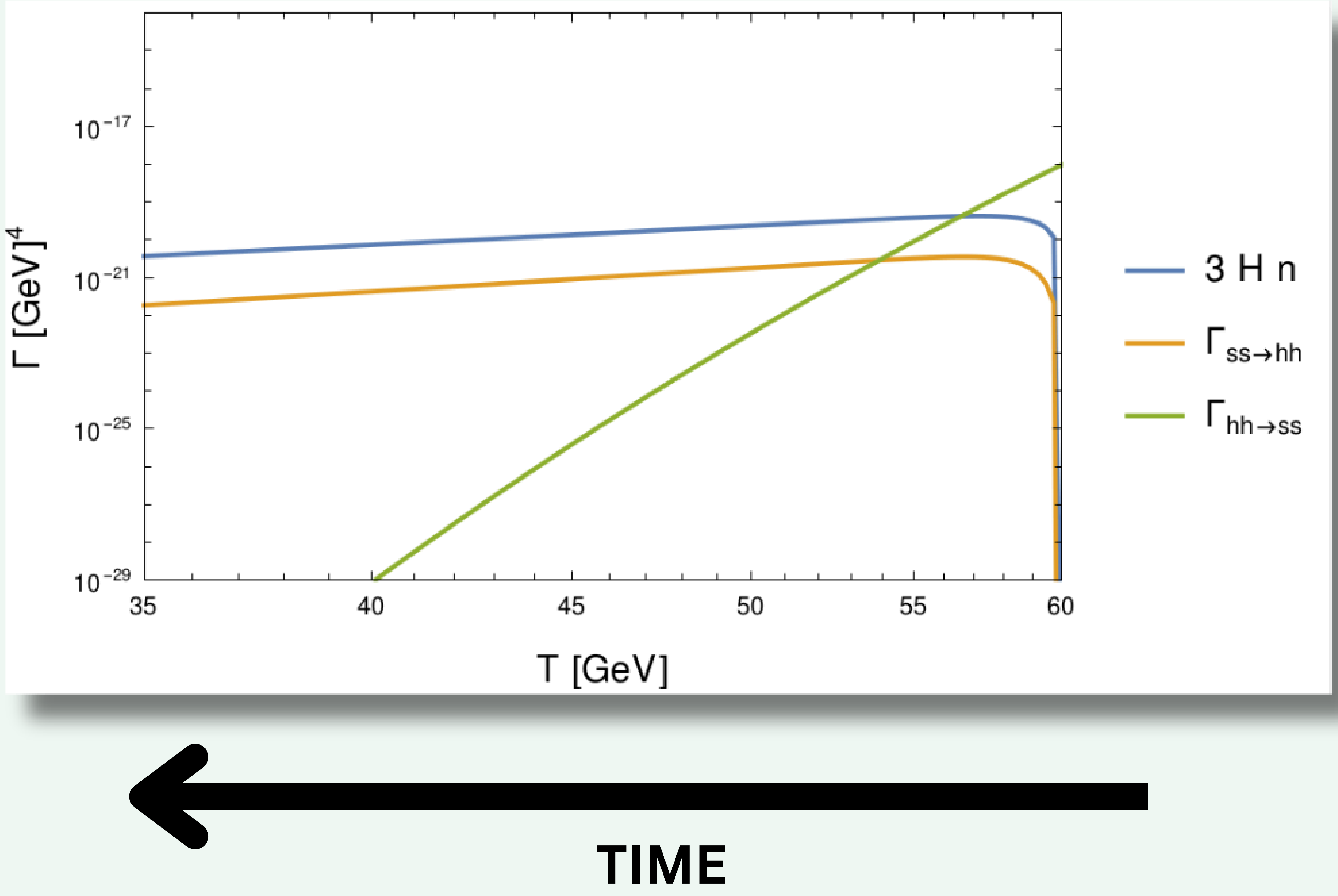
TIME

C. Cosme, FC, O. Lebedev, arXiv: 2306.13061

FREEZE-IN REGIME

$$\Gamma\left(h_i h_i \to ss\right) > 3Hn \not\Longrightarrow \text{ Thermalisation}$$

$$\Gamma\left(h_i h_i \to ss\right) = \Gamma\left(ss \to h_i h_i\right) \implies \text{ Thermalisation}$$

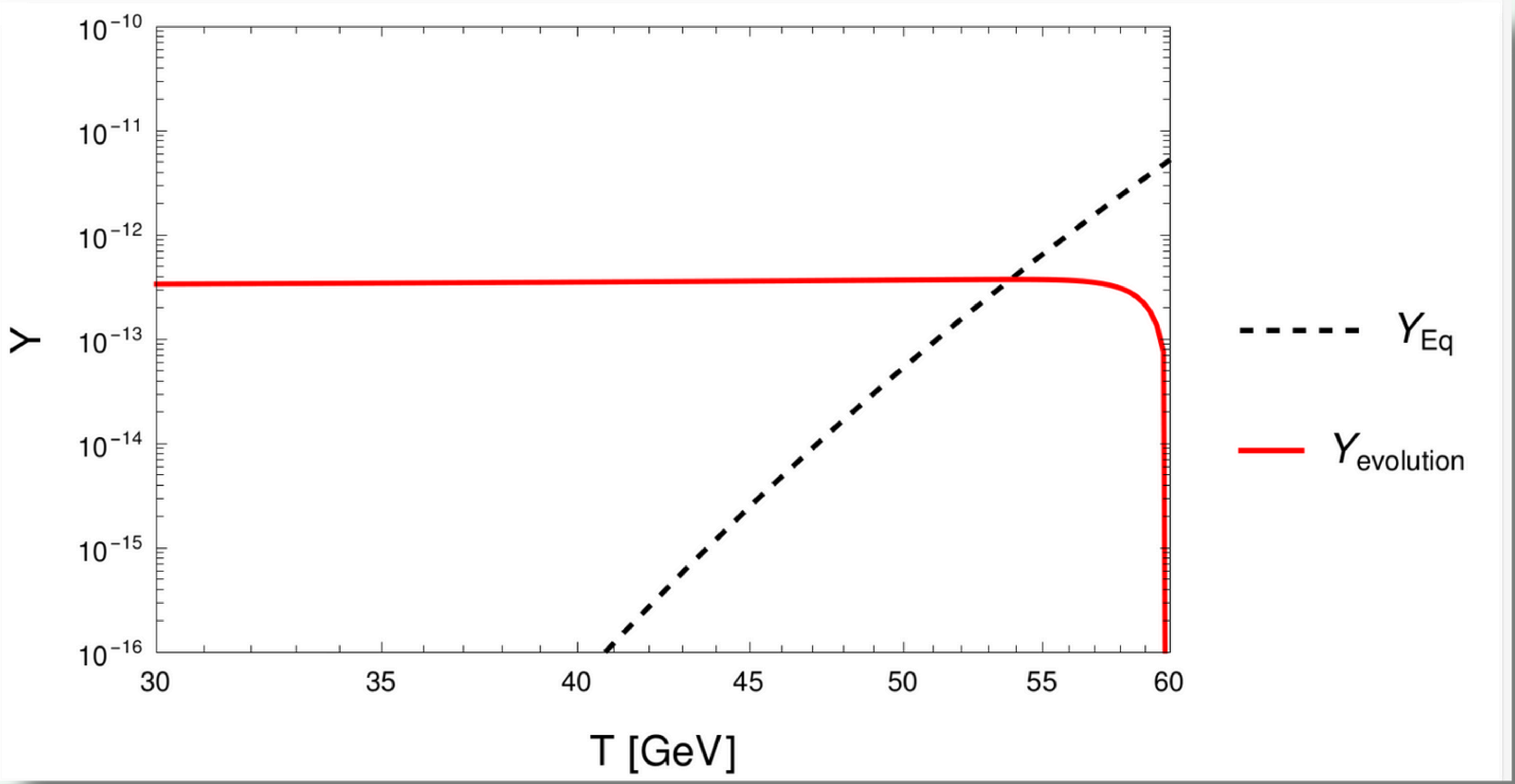


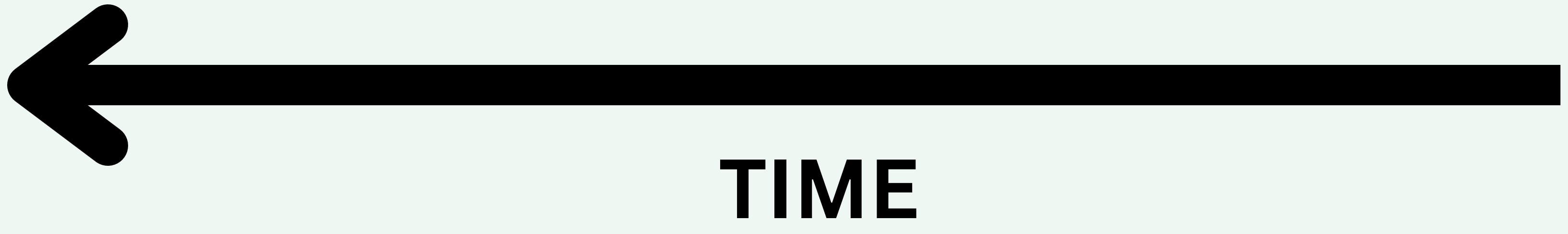
C. Cosme, FC, O. Lebedev, arXiv: 2306.13061

In fact the number density does not follow the equilibrium curve

OUT OF EQUILIBRIUM

Looks like a UV freeze-in production, peaked at the reheating temperature

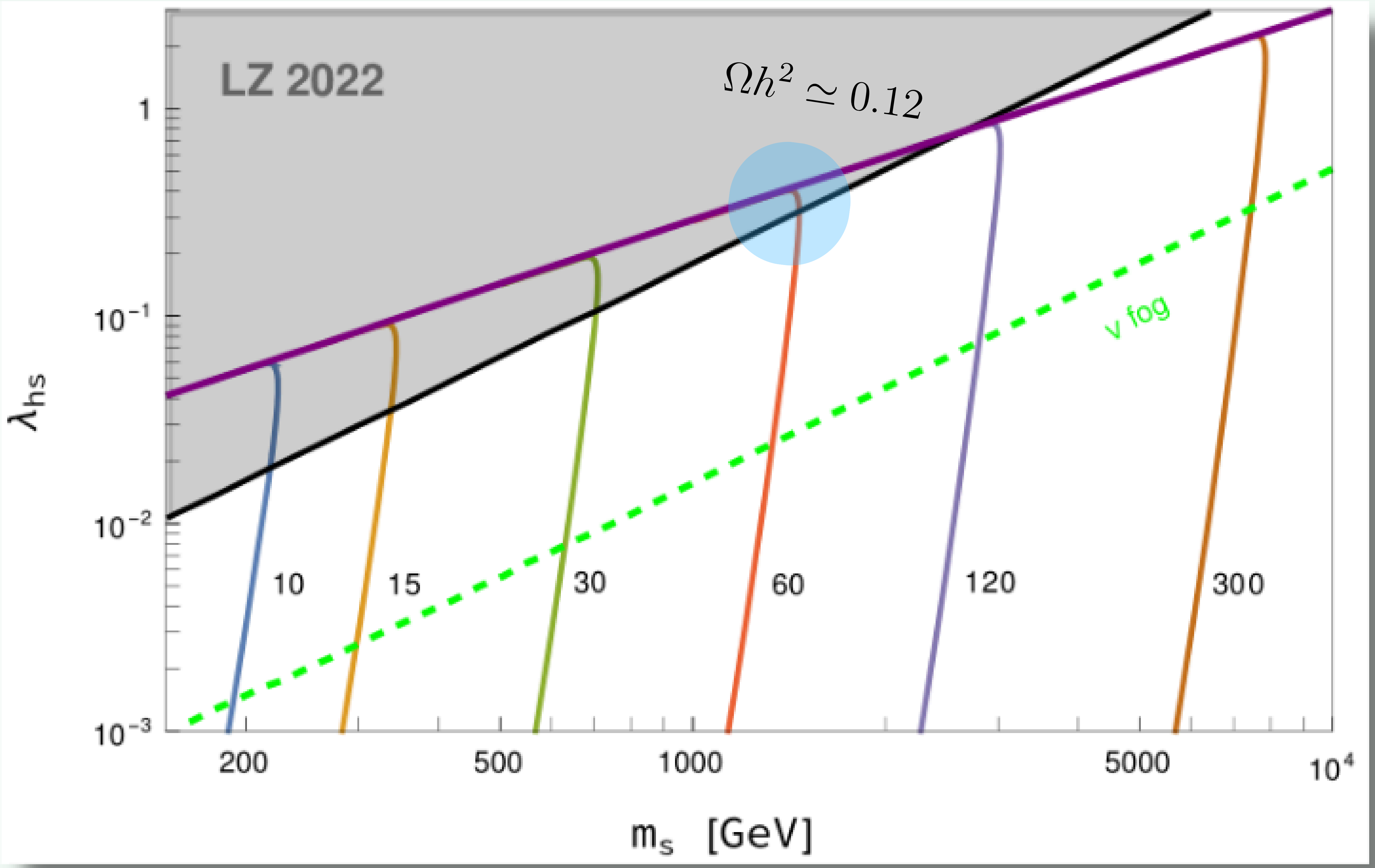




INTERMEDIATE REGIME

HIGGS PORTAL TO SCALAR DM

BACKREACTION



C. Cosme, FC, O. Lebedev, arXiv: 2306.13061

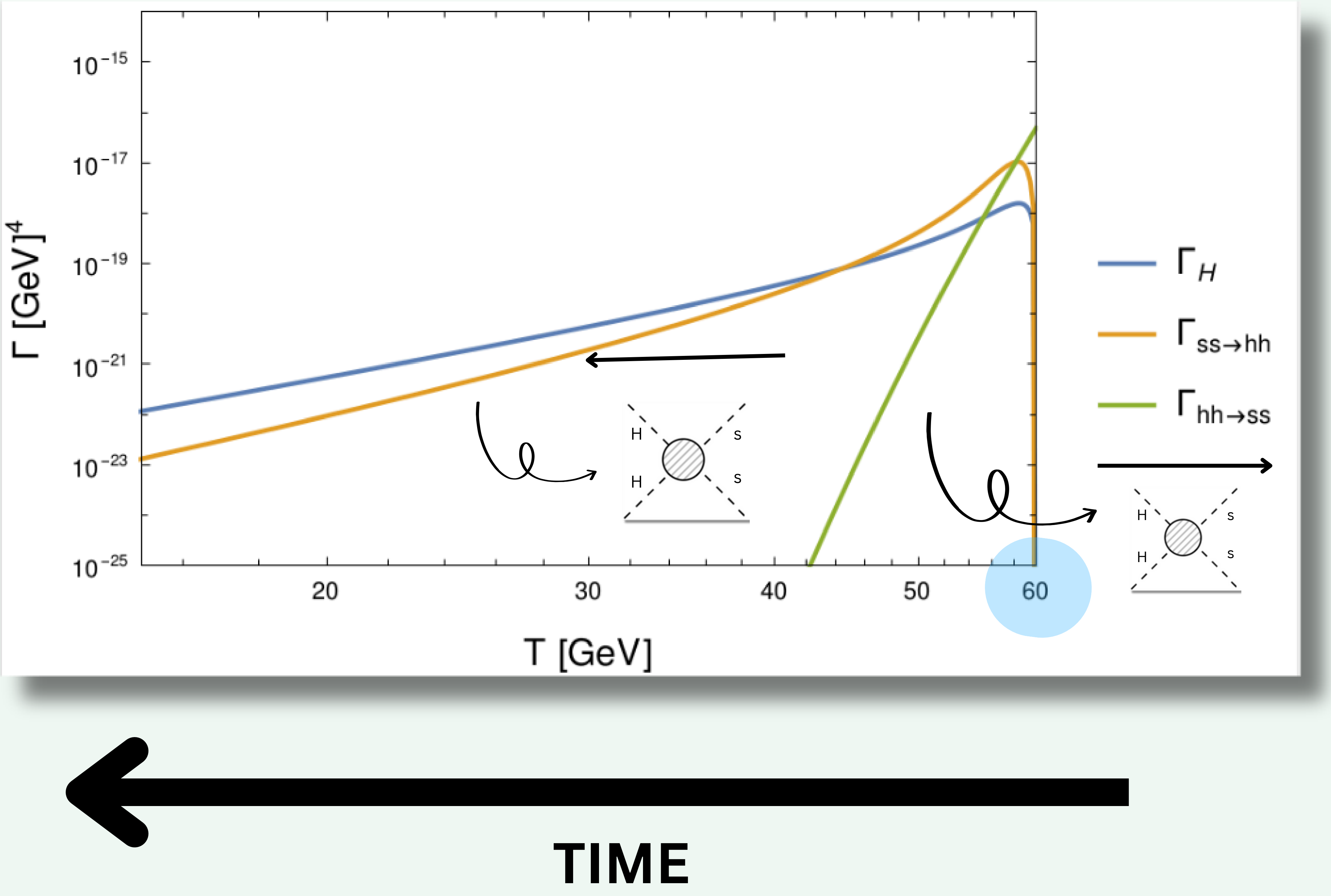
ANNIHILIATION BECOMES IMPORTANT

Boltzmann equation

$$\dot{n}_s + 3Hn_s = \Gamma\left(h_i h_i \to ss\right) - \Gamma\left(ss \to h_i h_i\right)$$

Here the backreaction is not negligible anymore

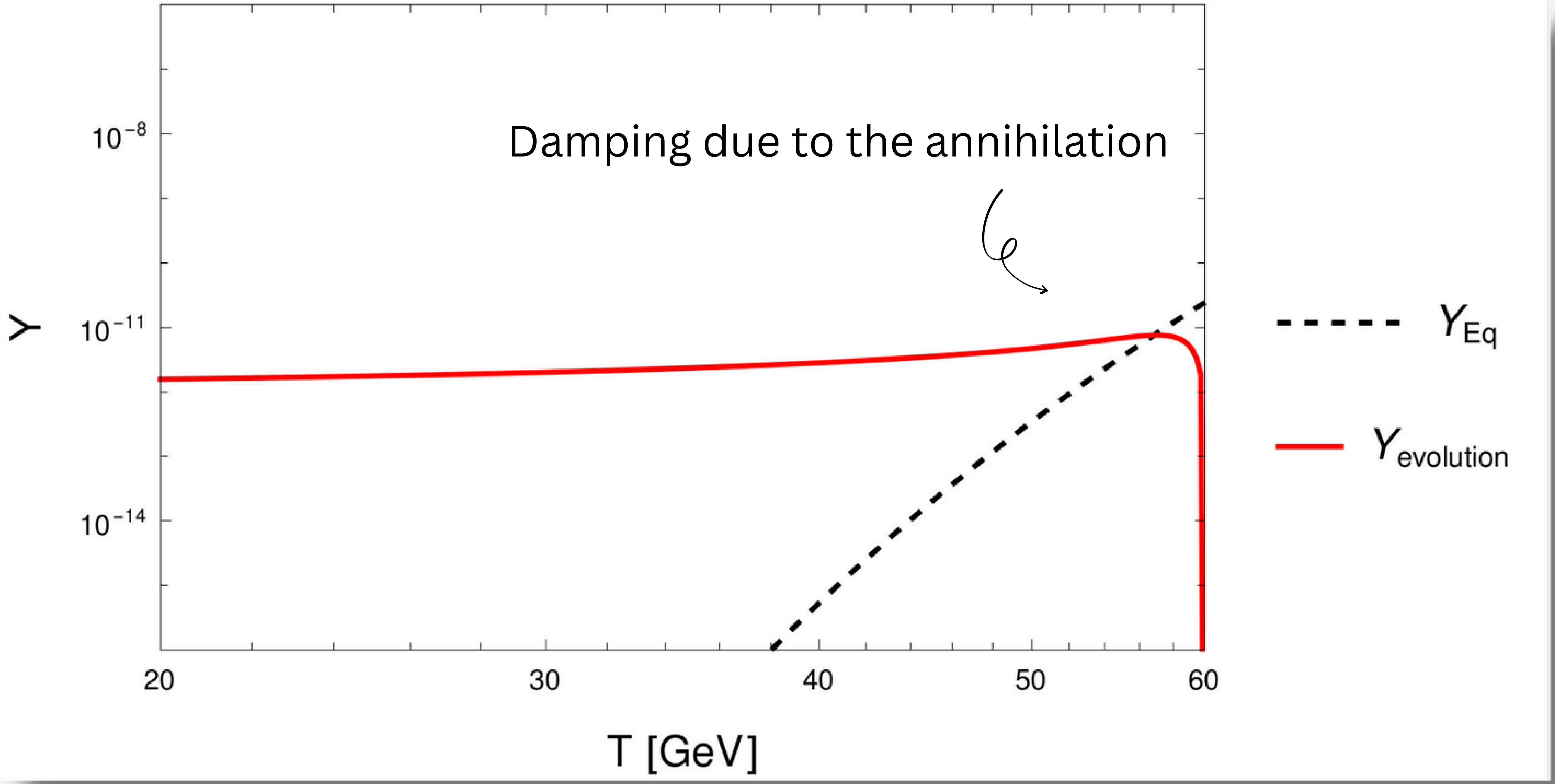
$$m_s = 1451 \text{ GeV} \quad \lambda_{hs} = 0.39$$



C. Cosme, FC, O. Lebedev, arXiv: 2306.13061

The number density still does not follow the equilibrium curve

OUT OF EQUILIBRIUM

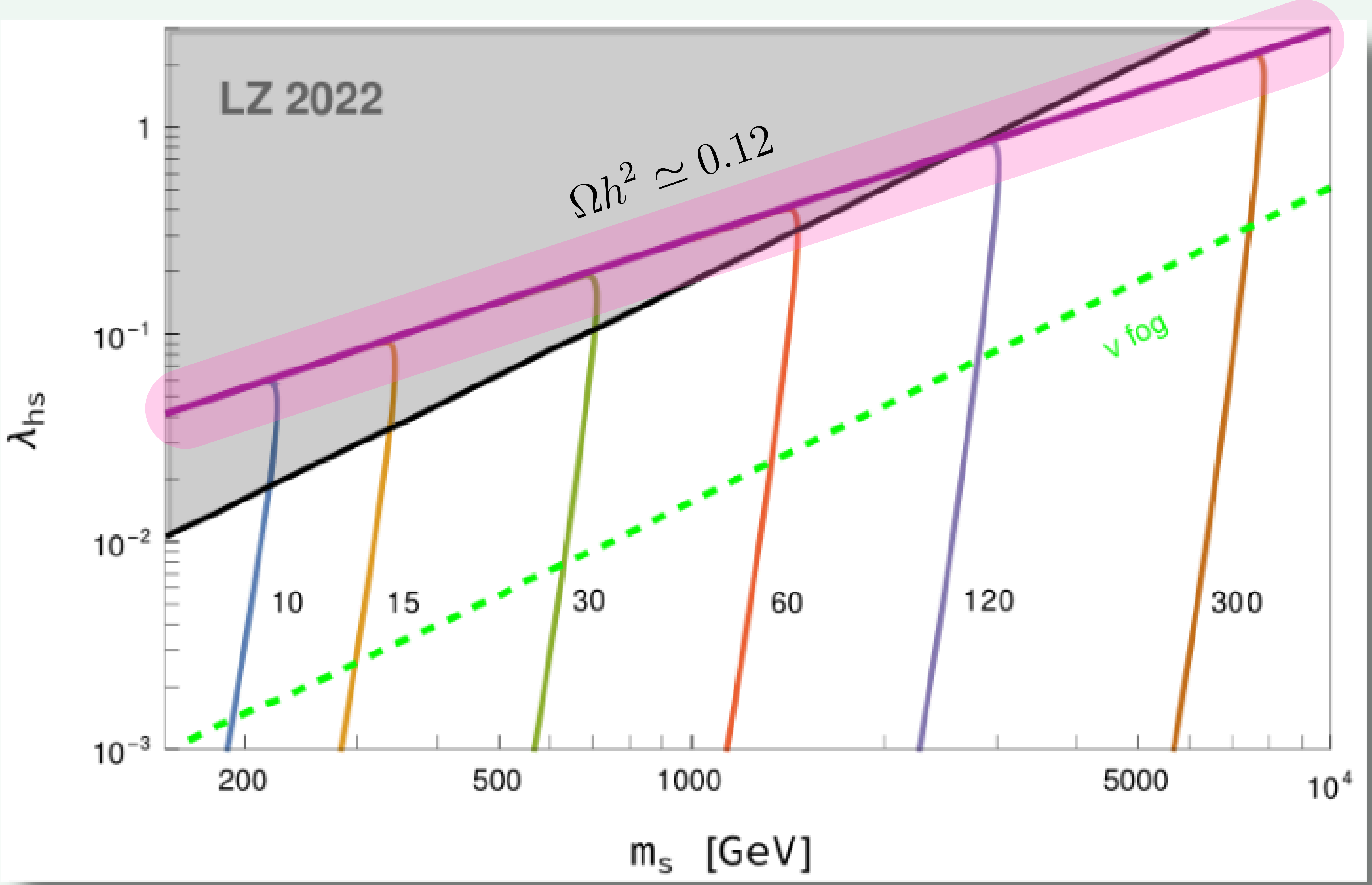


TIME

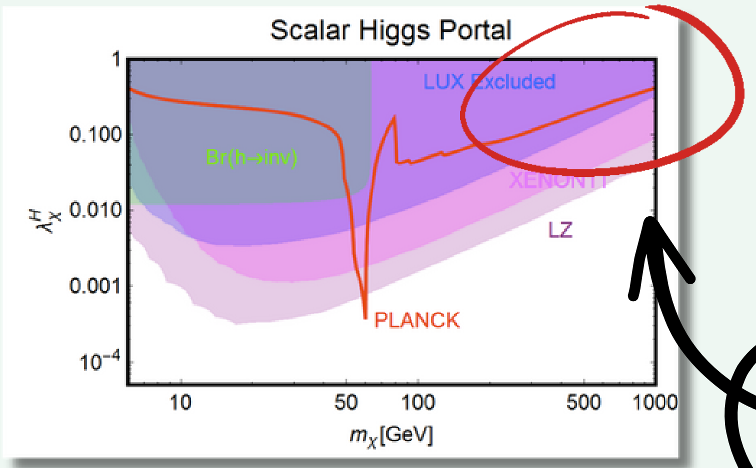
FREEZE-OUT REGIME

HIGGS PORTAL TO SCALAR DM

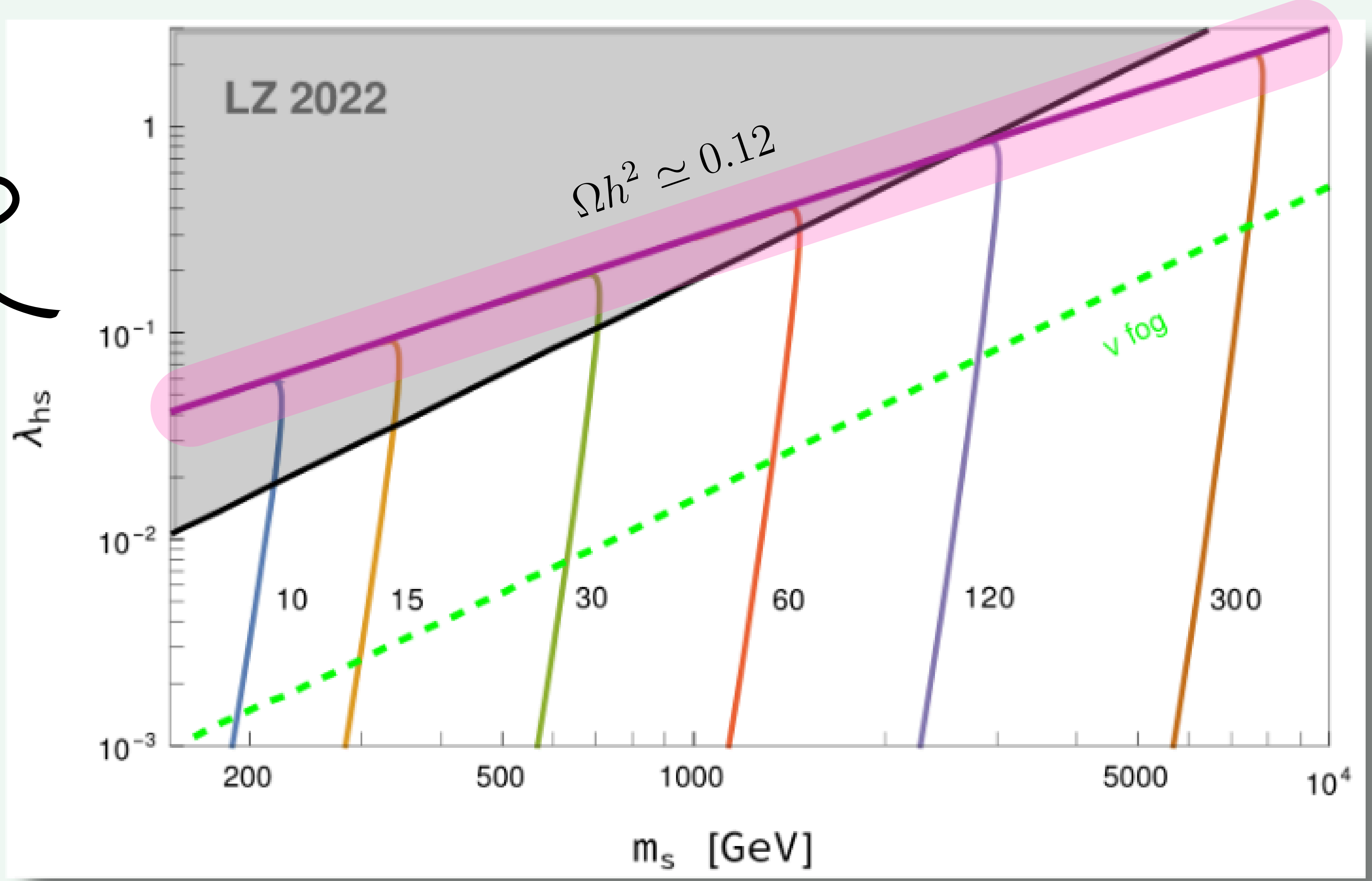
FREEZE-OUT



HIGGS PORTAL TO SCALAR DM



FREEZE-OUT



FREEZE-OUT REGIME

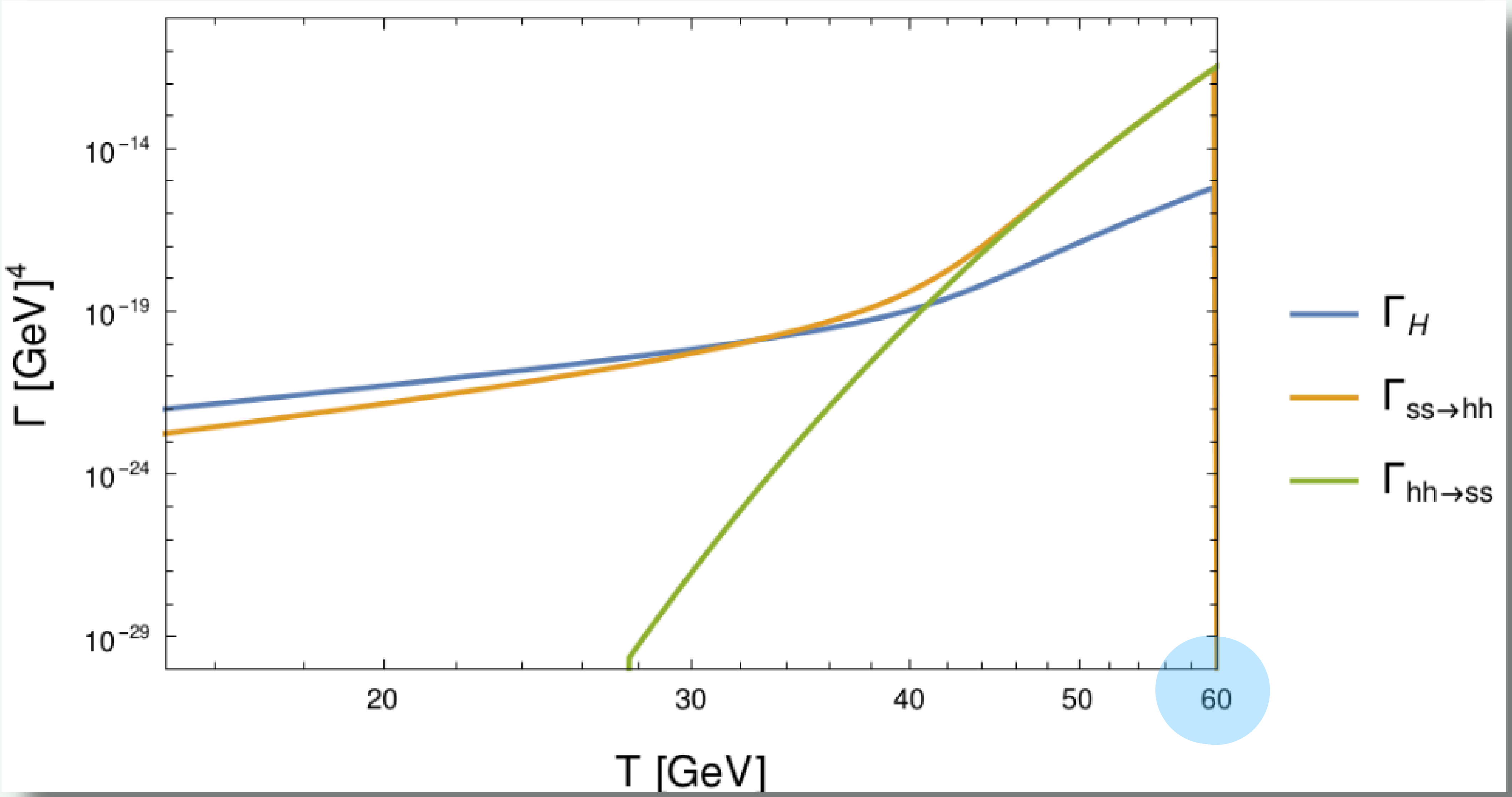
$$m_s = 1012 \text{ GeV} \qquad \lambda_{hs} = 0.29$$

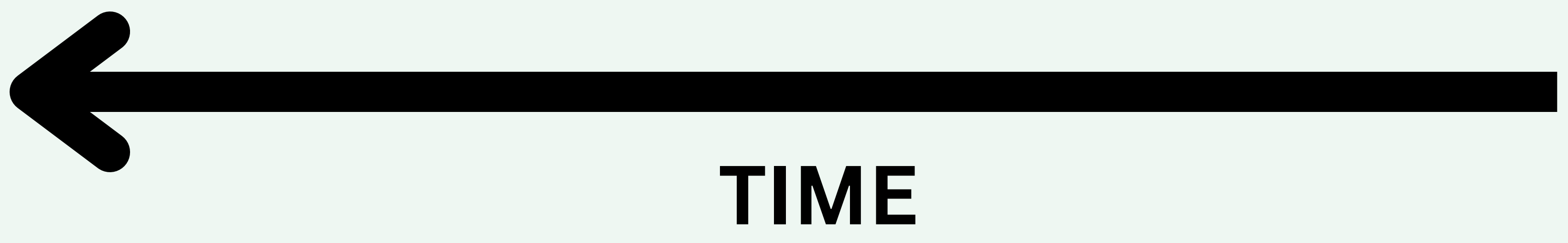
Boltzmann equation

$$\dot{n}_s + 3Hn_s = \Gamma\left(h_i h_i \to ss\right) - \Gamma\left(ss \to h_i h_i\right)$$

Freeze-out

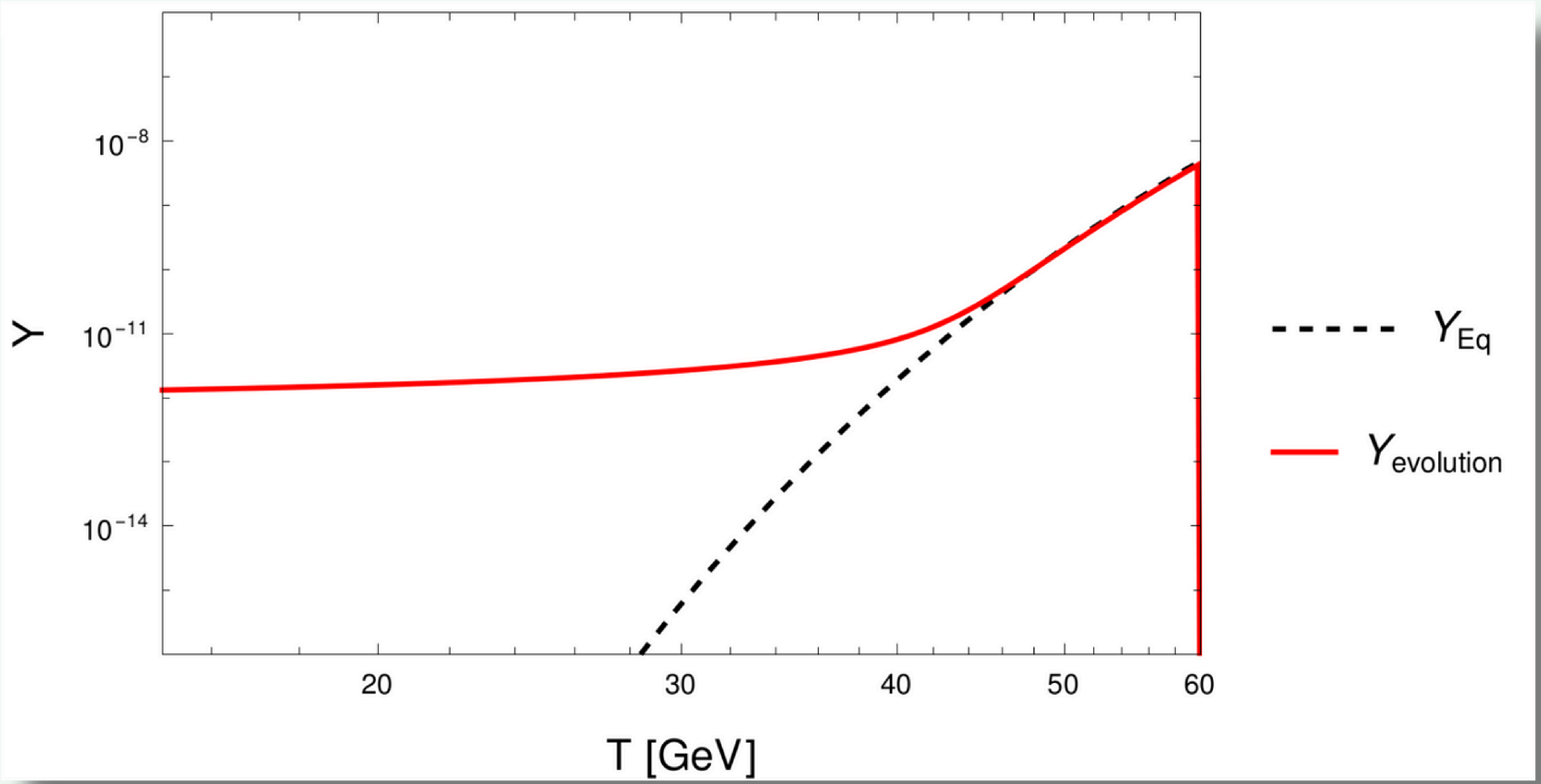
$$\Gamma\left(h_i h_i \to ss\right) = \Gamma\left(ss \to h_i h_i\right)$$

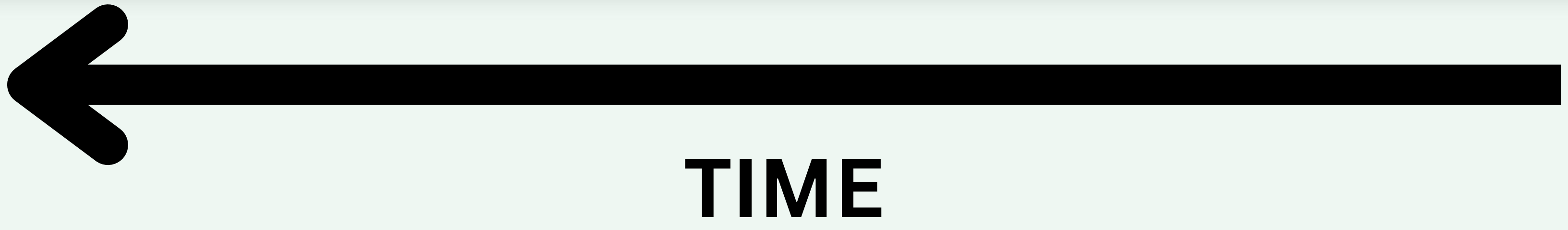




The number density is equal to the equilibrium number density until freeze-out

IN EQUILIBIRIUM

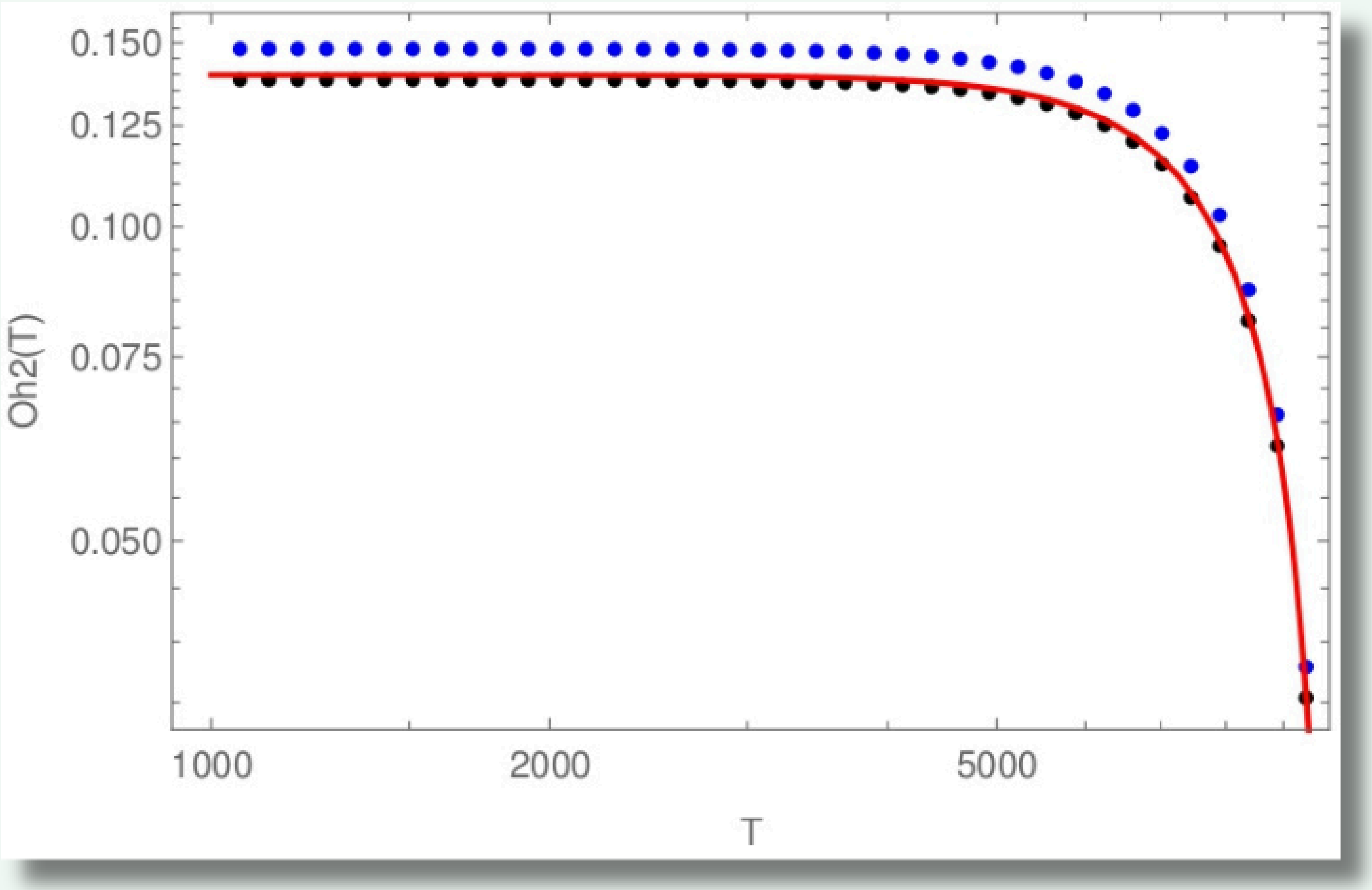




Relativistic effect

Non-instantaneous reheating

$$m_\psi Y = 4 \times m_\psi Y_{inst}$$



DILUTION

Standard Cosmology

RD $a \propto t^{1/2}$

$$n(t) \propto \left(\frac{a_{end}}{a_t}\right)^3 n(t_{end}) \propto \left(\frac{t_{end}}{t}\right)^{3/2} n(t_{end})$$

DILUTION

Standard Cosmology

RD $\quad a \propto t^{1/2}$

$$n(t) \propto \left(\frac{a_{end}}{a_t}\right)^3 n(t_{end}) \propto \left(\frac{t_{end}}{t}\right)^{3/2} n(t_{end})$$

Non-Standard Cosmology

EMD $\quad a \propto t^{2/3}$

$$n(t) \propto \left(\frac{a_{end}}{a_t}\right)^3 n(t_{end}) \propto \left(\frac{t_{end}}{t}\right)^{2} n(t_{end})$$

DILUTION

Standard Cosmology

RD $a \propto t^{1/2}$

$$n(t) \propto \left(\frac{a_{end}}{a_t}\right)^3 n(t_{end}) \propto \left(\frac{t_{end}}{t}\right)^{3/2} n(t_{end})$$

Non-Standard Cosmology

EMD $a \propto t^{2/3}$

$$n(t) \propto \left(\frac{a_{end}}{a_t}\right)^3 n(t_{end}) \propto \left(\frac{t_{end}}{t}\right)^{2} n(t_{end})$$

Extra dilution due to the matter domination

$$\frac{n^{Non-Std}}{n^{Std}} \propto \left(\frac{t_{\text{end}}}{t}\right)^{1/2} \propto \left(\frac{T}{T_{\text{end}}}\right)$$

FREEZE-IN TO FREEZE-OUT

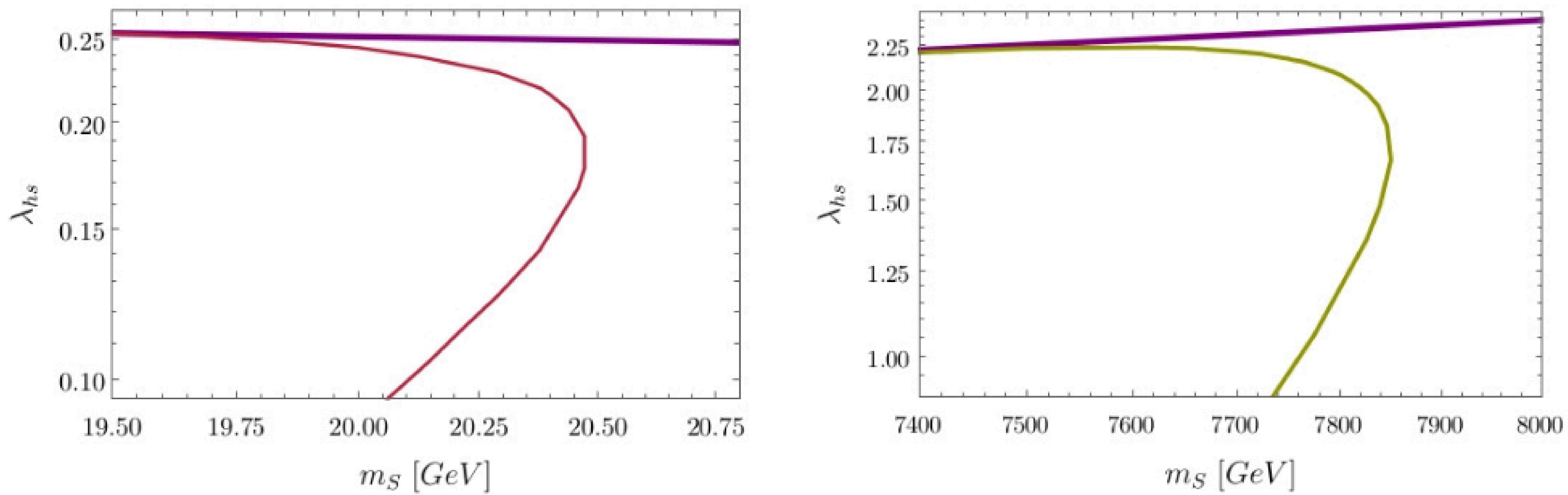


Figure 4: Freeze-in to freeze-out transition at low and high temperatures. The purple line corresponds to thermal DM as in Fig. 2. *Left:* $T_R = 1$ GeV. *Right:* $T_R = 300$ GeV.