HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN IN PUBLICA COMMODA SEIT 1737

FREEZE-IN AT STRONGER COUPLING

And the highest temperature of the Universe

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PRD 109, 075038 (2024), 2402.04743, 2405.XXXXX

CATCH22+2

OUTLINE:

INTRO: FREEZE-IN VS FREEZE-OUT

PROBLEMS WITH FREEZE-IN

LOW REHEATING TEMPERATURE

TEMPERATURE EVOLUTION DURING REHEATING

FREEZE-IN AT STRONG COUPLING WITH THE HIGGS PORTAL

CONCLUSIONS

INTRODUCTION

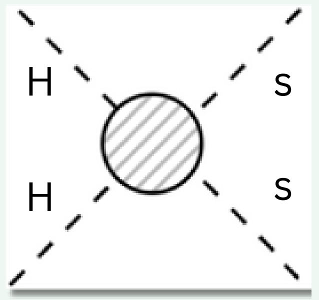
FREEZE-IN VS FREEZE-OUT

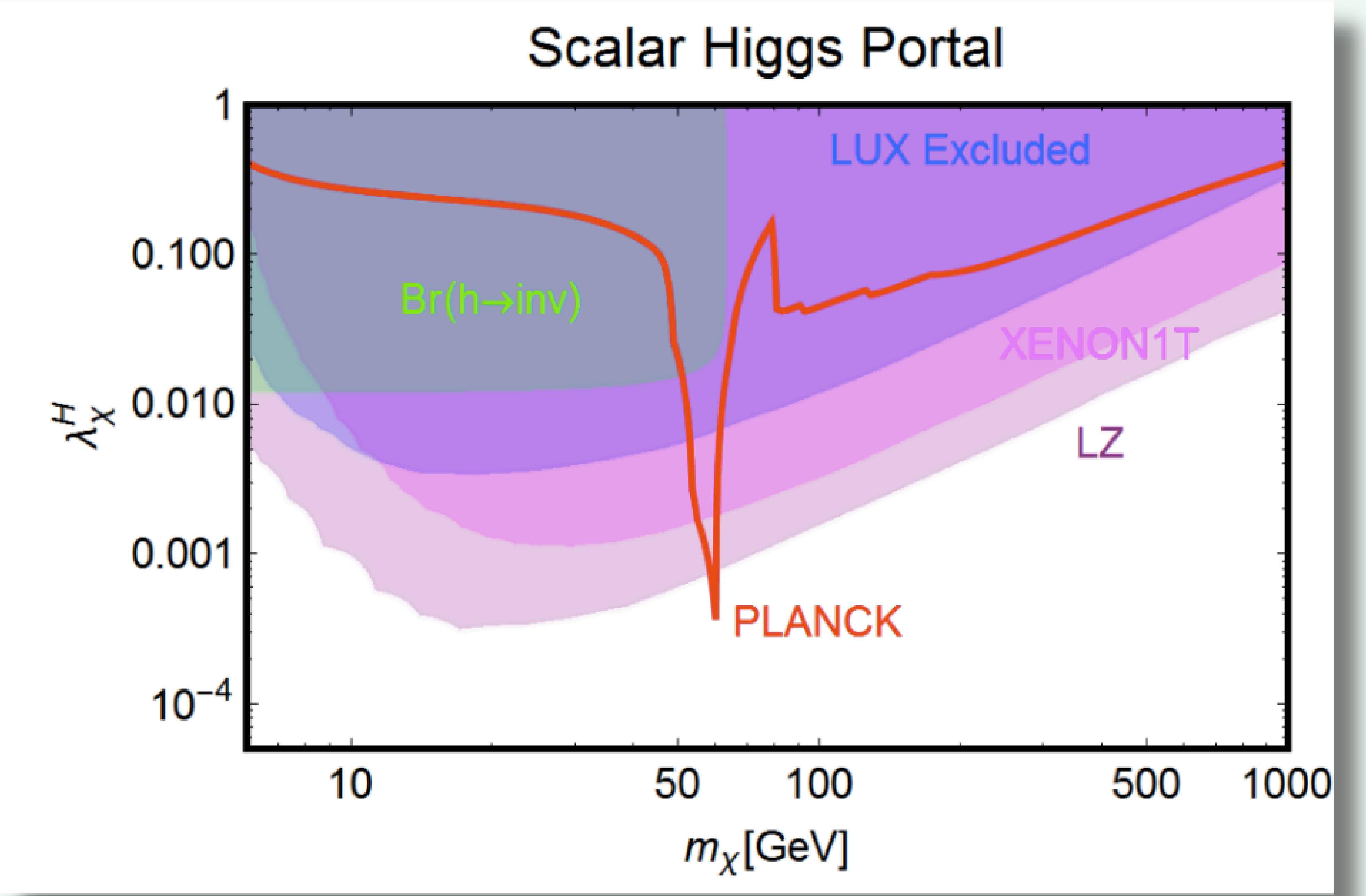
FREEZE-OUT

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

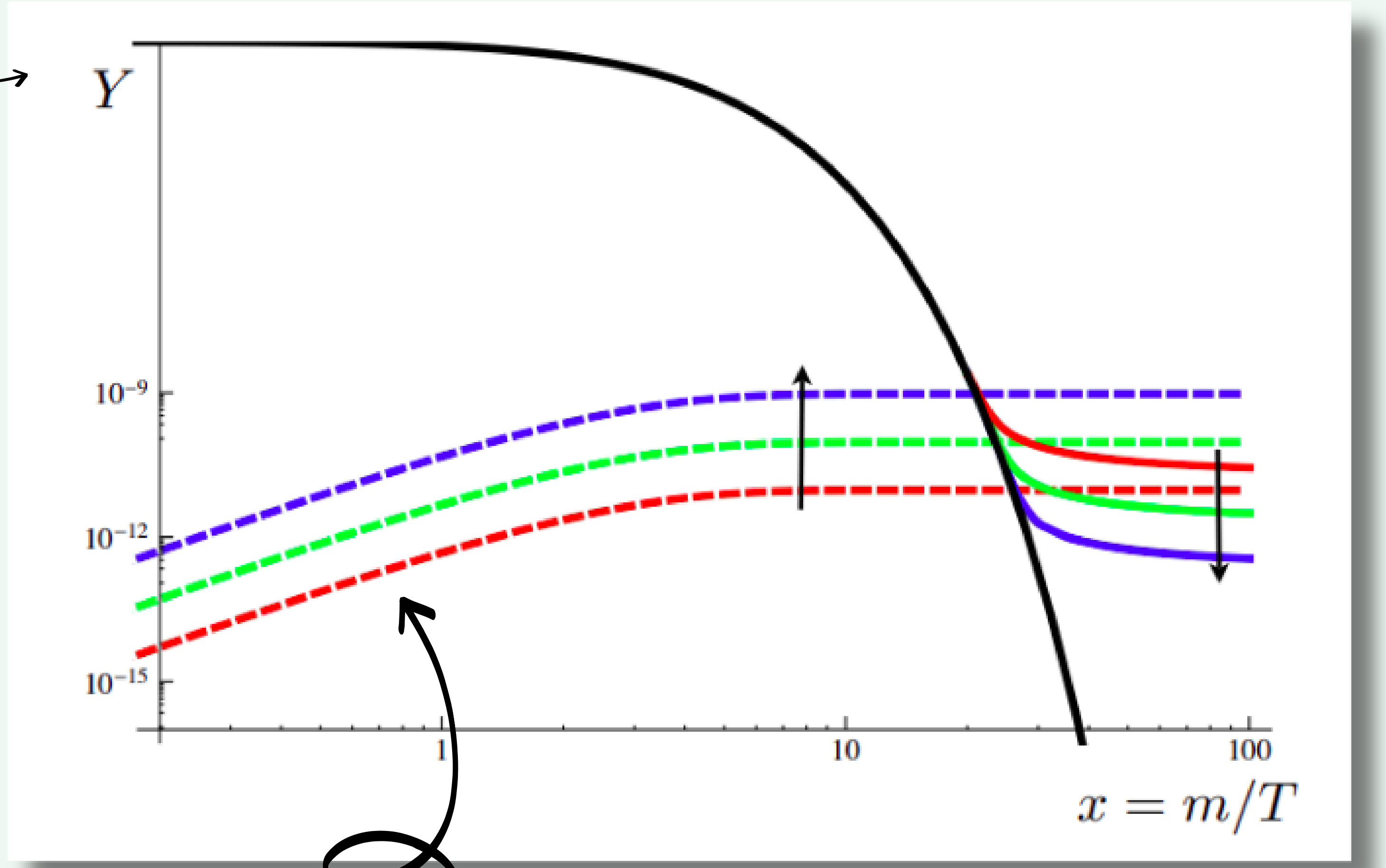
FREEZE-IN

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

➜ We assume a negligible initial abundance

- Very low couplings

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



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

DM abundace grows with the coupling squared

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

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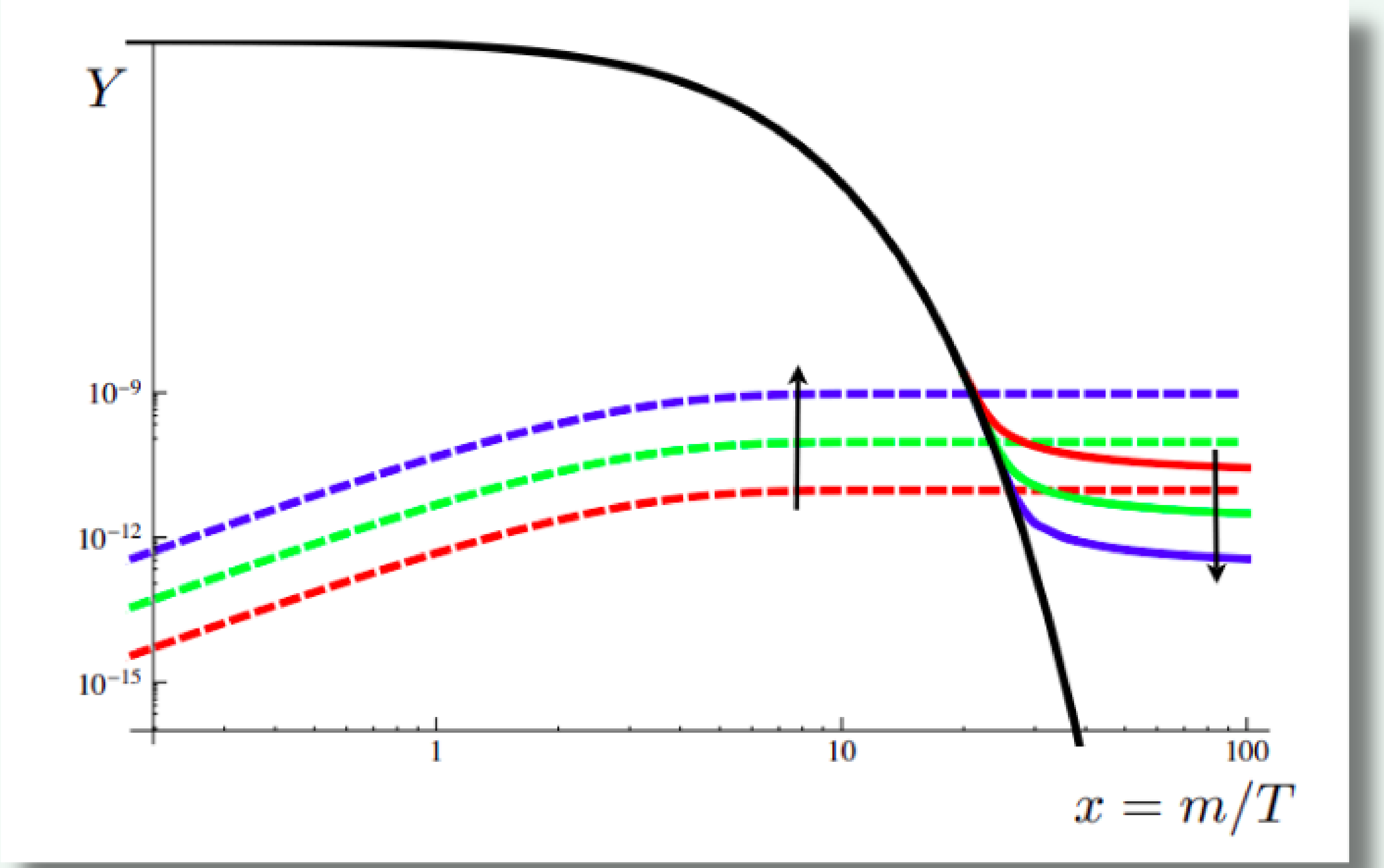
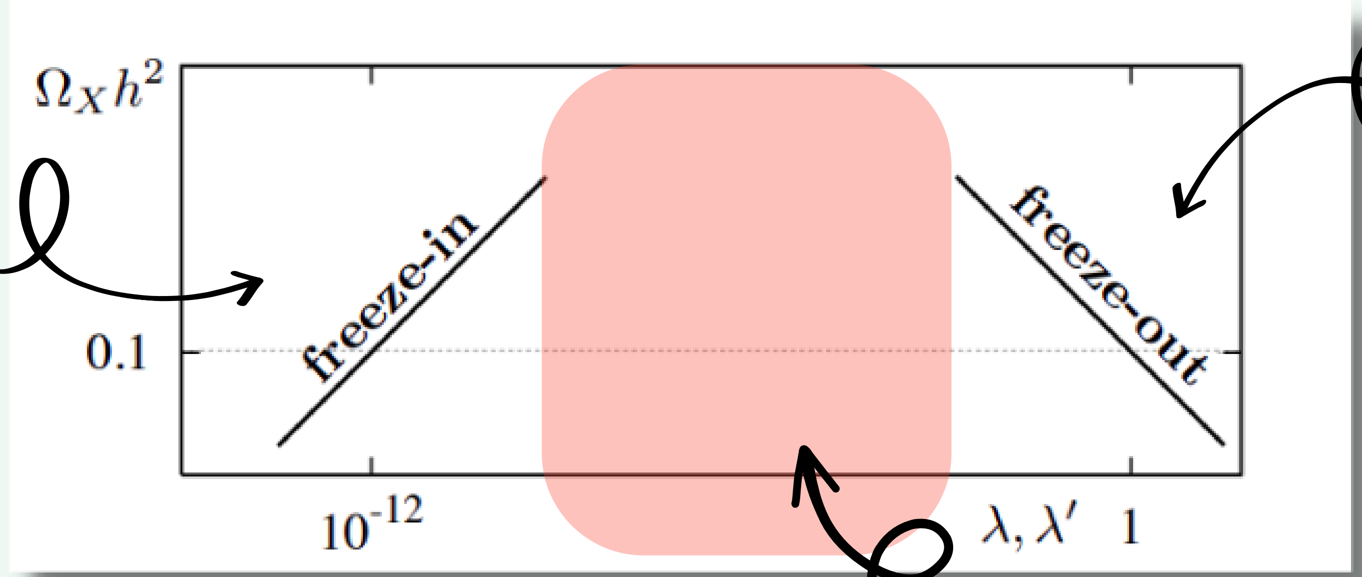


$\Omega h^2 \propto \lambda^2$



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

Overproduction

J. McDonald, hep-ph/0106249

L. J. Hall, K. Jedamzik, J. March-Russell, S. M. West, 0911.1120

FREEZE-IN

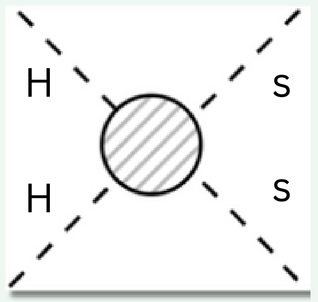
Boltzmann equation for the evolution of the DM number density

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

$\propto n_h^2$

Forward process

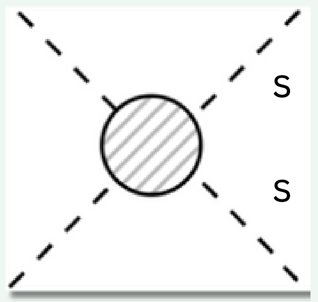
t



$\propto n_s^2$

Back-reaction

t



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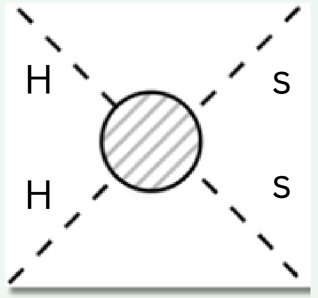
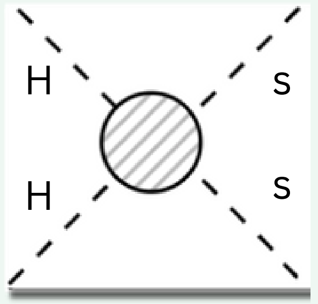


$\propto n_s^2$

Back-reaction

t



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

FREEZE-IN PROBLEMS

AND GRAVITATIONAL PARTICLE PRODUCTION

VERY SMALL COUPLINGS

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

GRAVITATIONAL PARTICLE PRODUCTION

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

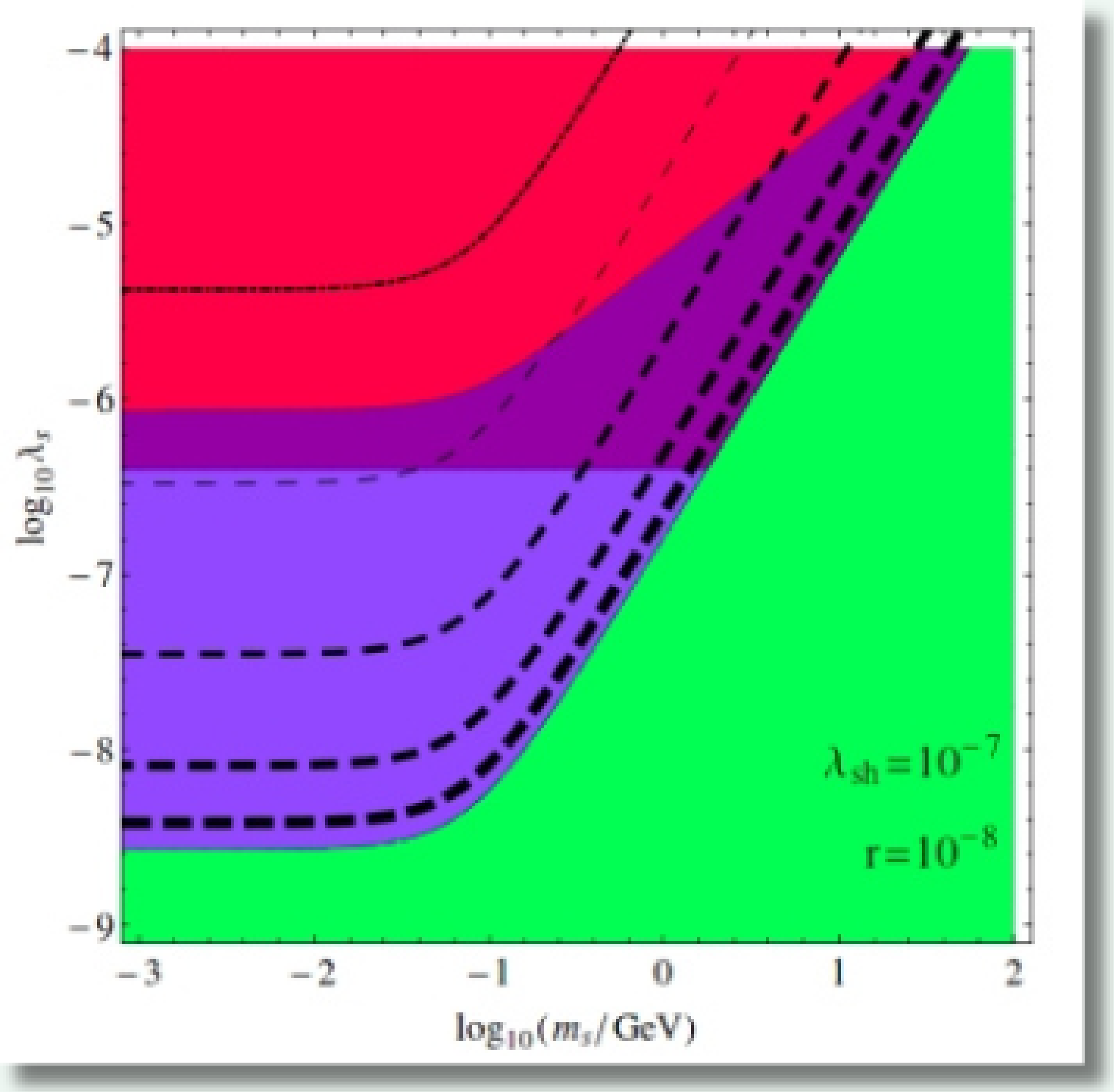
Dark Matter

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).

Thursday talk by Arttu Rajantie



“Spectator DM”

HOW CAN THE FREEZE-IN ASSUMPTION BE SATISFIED?

s is a feebly interacting particle

DILUTION due to early matter dominated epoch

PRODUCTION DURING INFLATON OSCILLATION

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

e.g. $\frac{1}{2}m_\phi^2\phi^2$

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

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 self-coupling

INFLATON OSCILLATION

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

LONG MATTER DOMINATED EPOCH

LOW REHEATING TEMPERATURE

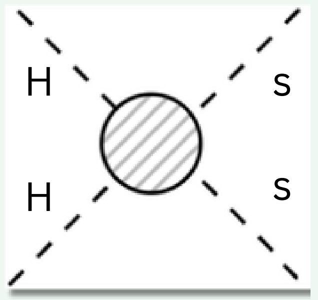
WHAT HAPPENS AT LOW TR?

Example:

Higgs portal

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

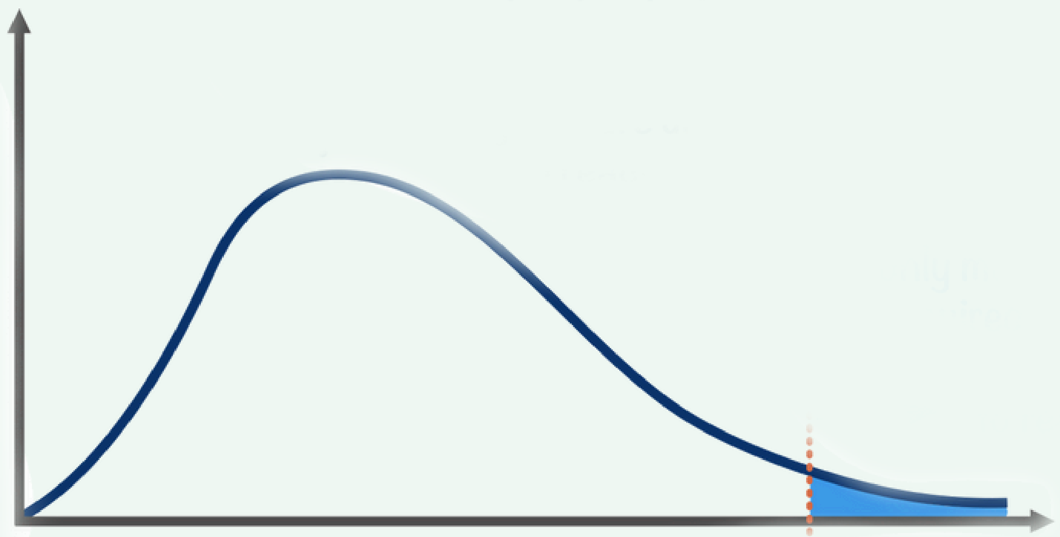
t



Freeze-in

Parameter space:

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



Boltzmann distribution

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

WHAT HAPPENS AT LOW TR?

Example:

Higgs portal

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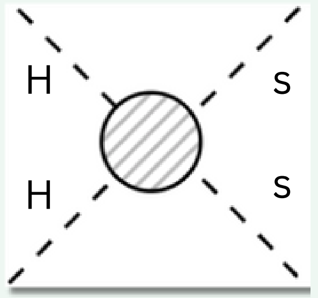
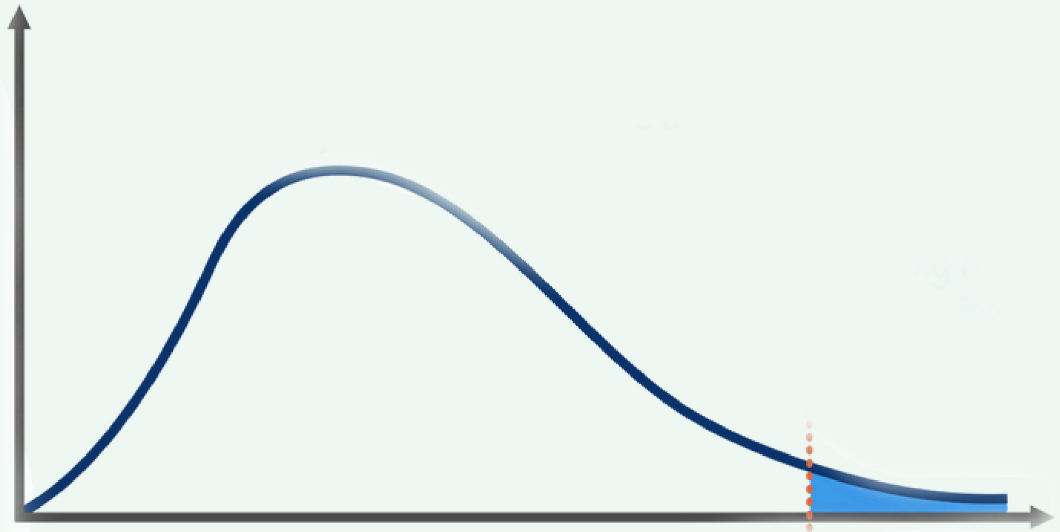


Freeze-in

Parameter space:

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

# of H particles



Energy

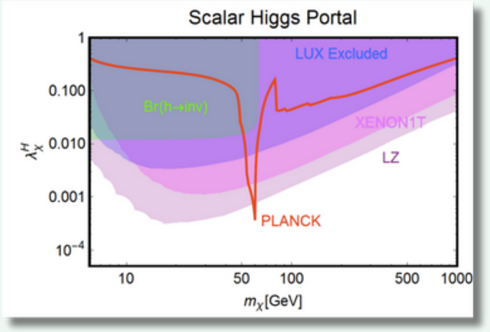
Boltzmann distribution

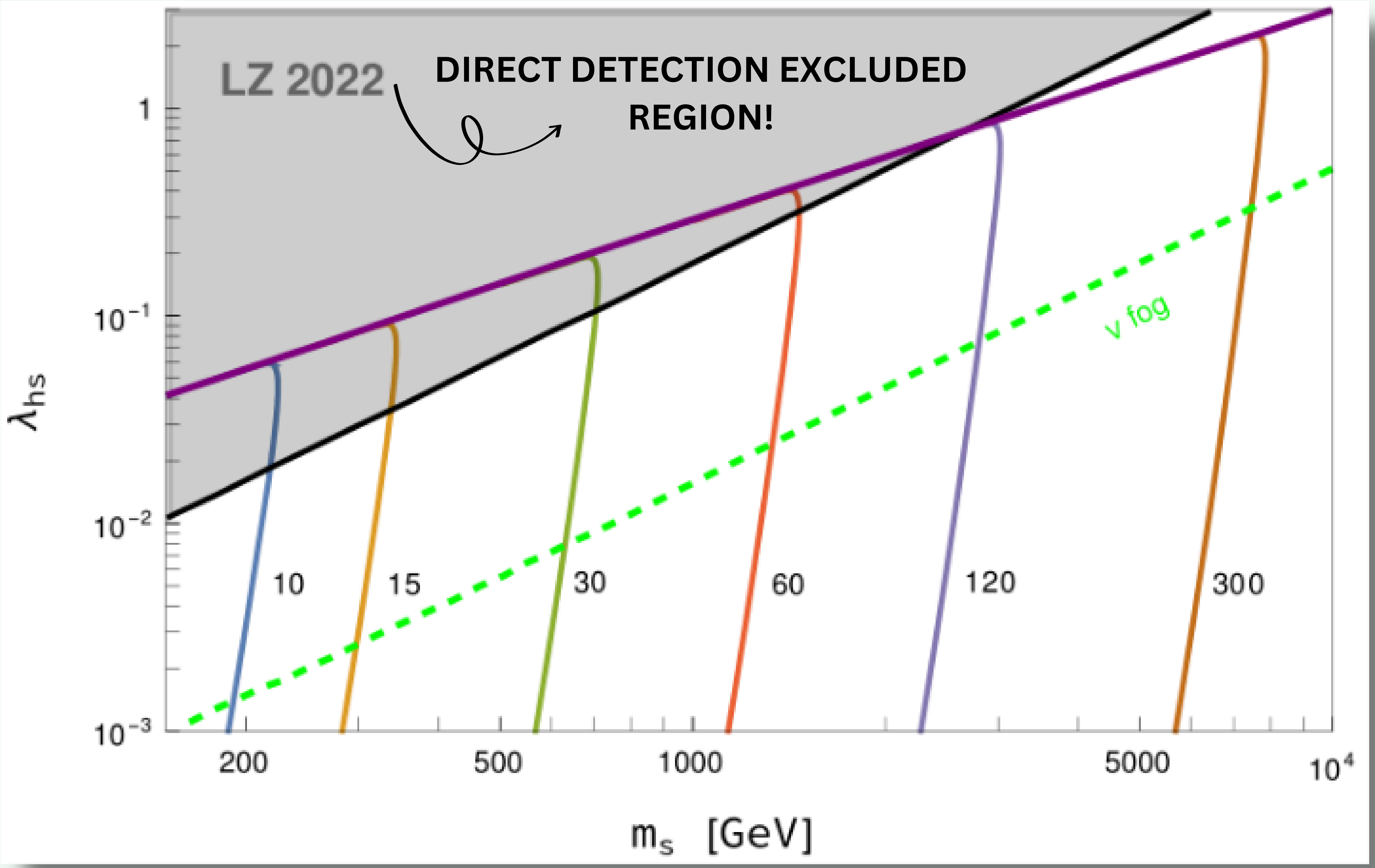
$$\Gamma(h_i h_i \to ss) \simeq \frac{\lambda_{hs}^2 T^3 m_s}{2^7 \pi^4} e^{-2m_s/T}$$

The rate of production is Boltzmann suppressed

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

HIGGS PORTAL TO SCALAR DM





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

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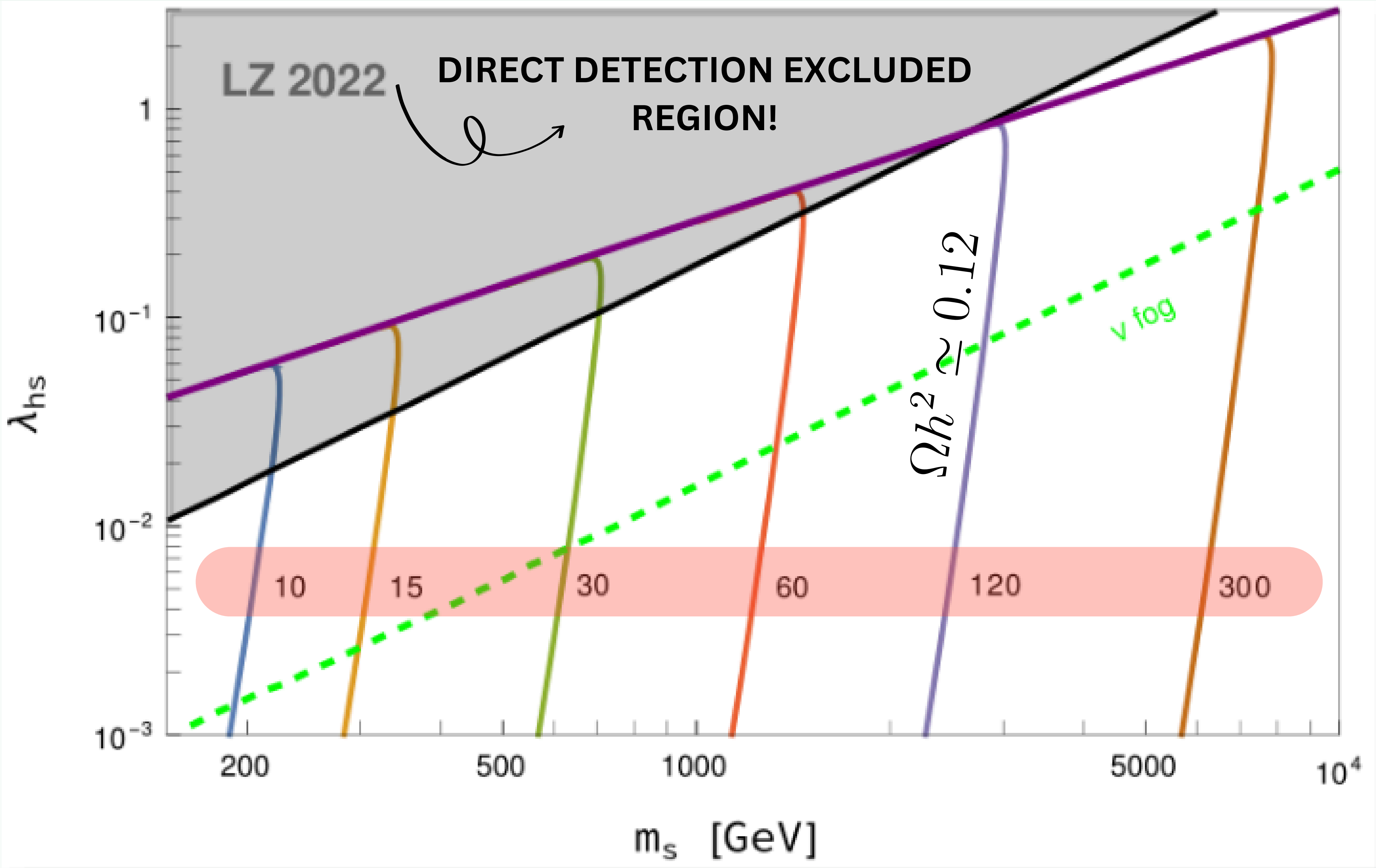


T_R

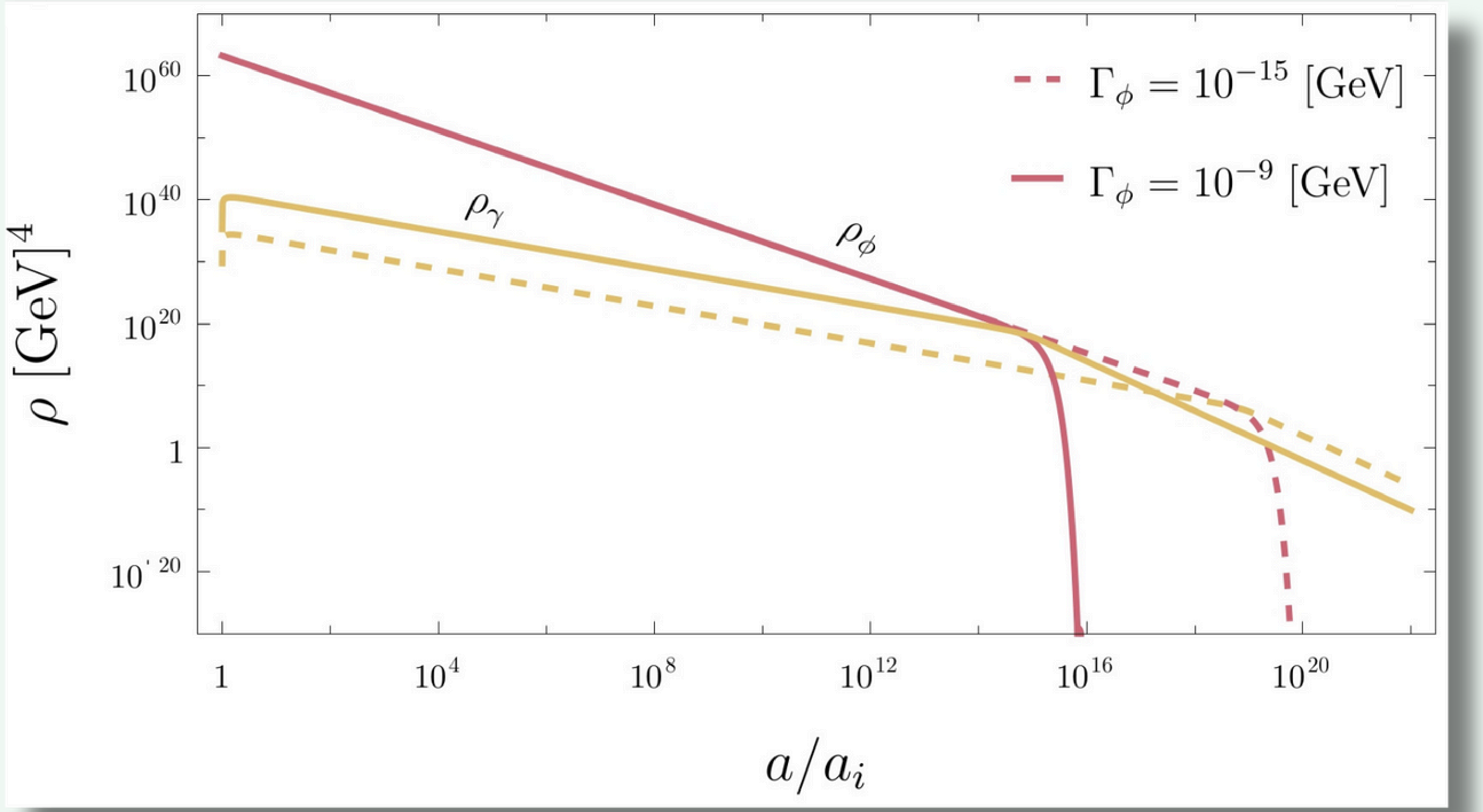
C. Cosme, FC, O. Lebedev, arXiv: 2306.13061

TEMPERATURE EVOLUTION DURING REHEATING

WHAT ABOUT TMAX?

Reheating Boltzmann Equations

$$\dot{\rho}_\phi + 3H\rho_\phi = -\Gamma_\phi \rho_\phi,$$
$$\dot{\rho}_\gamma + 4H\rho_\gamma = \Gamma_\phi \rho_\phi,$$
$$\rho_\phi + \rho_\gamma = 3m_P^2 H^2.$$



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

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

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

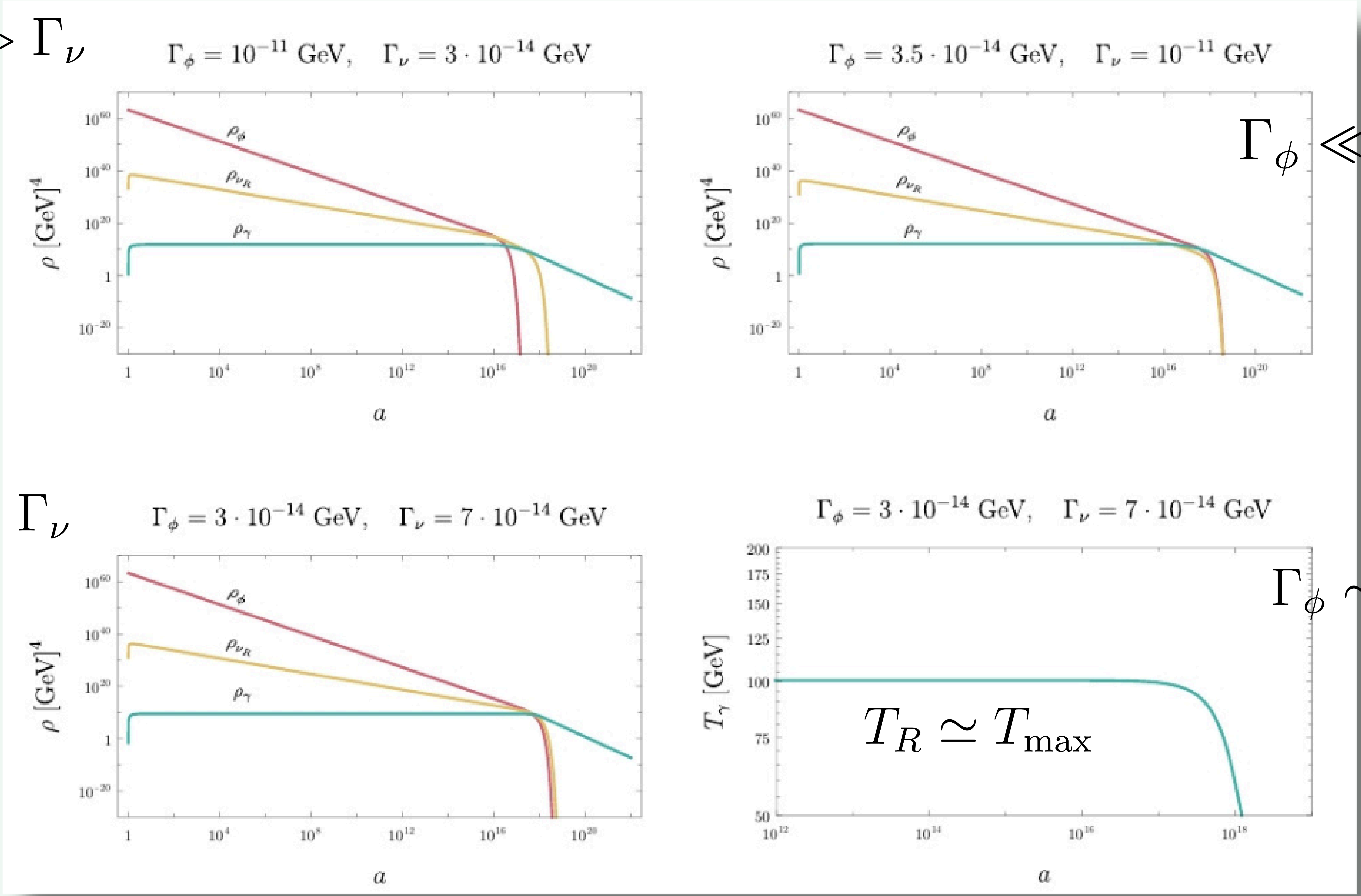
C. Cosme, FC, O. Lebedev, arXiv: 2402.04743

$\Gamma_\phi \gg \Gamma_\nu$

$\Gamma_\phi \ll \Gamma_\nu$

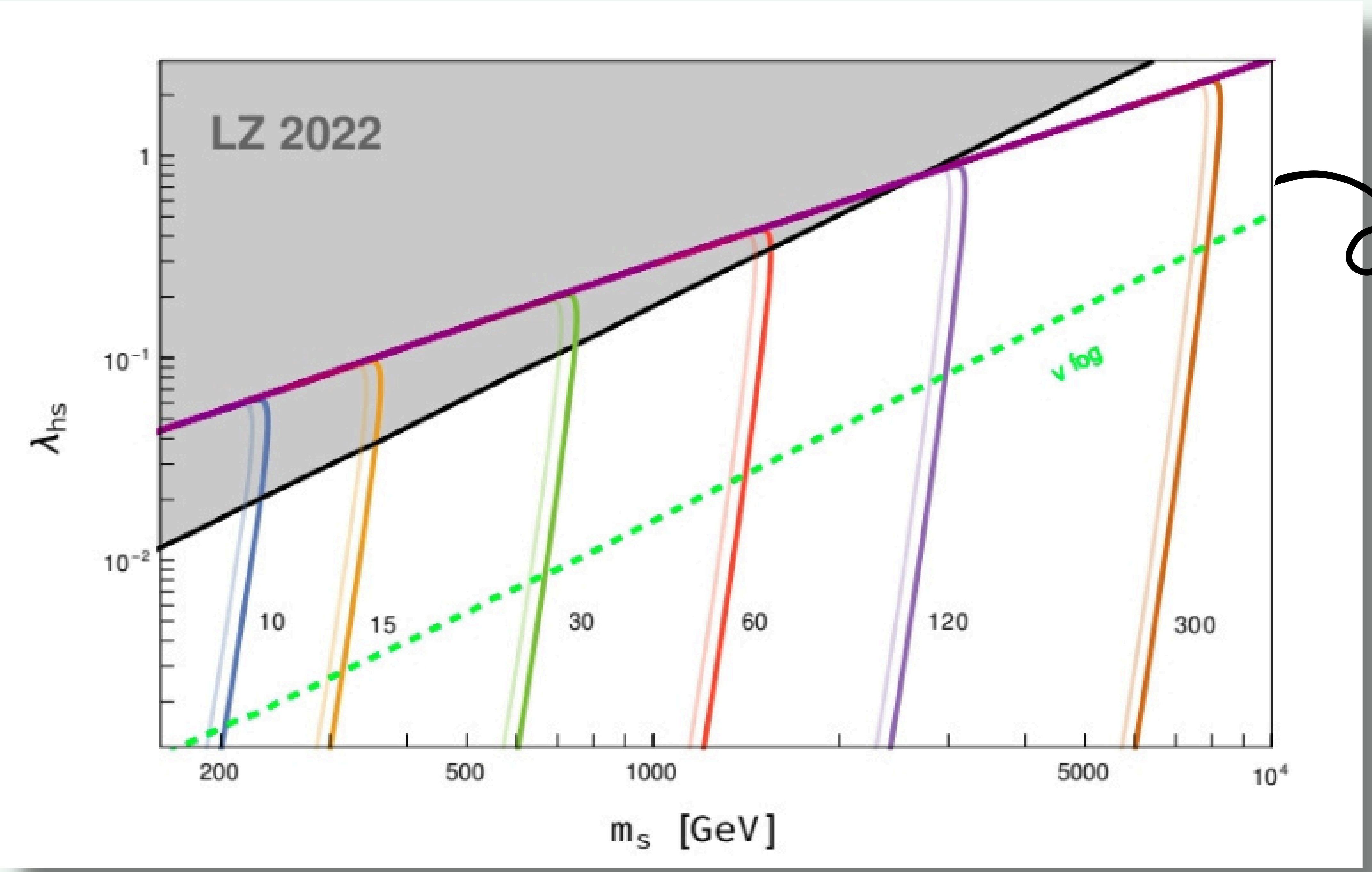
$\Gamma_\phi \sim \Gamma_\nu$

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



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

CORRECTION TO THE DM PRODUCTION



$$T_R \to 0.95 \times T_R$$

5% correction wrt instantaneous reheating approximation

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

HIGGS PORTAL

For different spin DM

HIGGS PORTAL

$$-\Delta\mathcal{L}_{\text{scal}} = \frac{1}{2}\lambda_{hs}H^\dagger H s^2$$

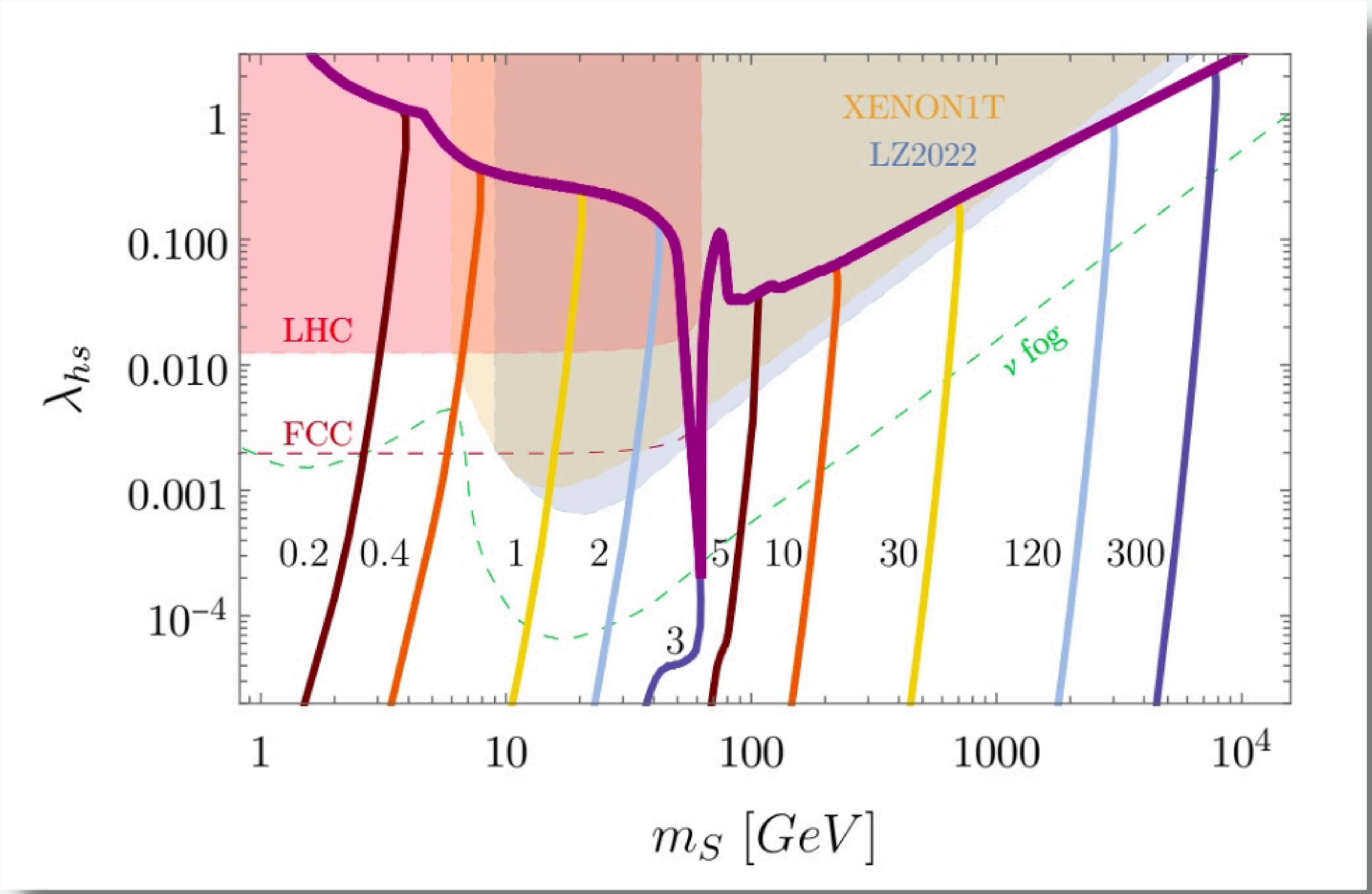
$$-\Delta\mathcal{L}_{\text{ferm}} = \frac{1}{\Lambda}H^\dagger H\bar{\chi}\chi + \frac{1}{\Lambda_5}H^\dagger H\bar{\chi}i\gamma_5\chi$$

$$-\Delta\mathcal{L}_{\text{vect}} = \frac{1}{2}\lambda_{hv}H^\dagger H V_\mu V^\mu$$

Majorana fermion. CP even and fully CP odd case.

2405.XXXXX

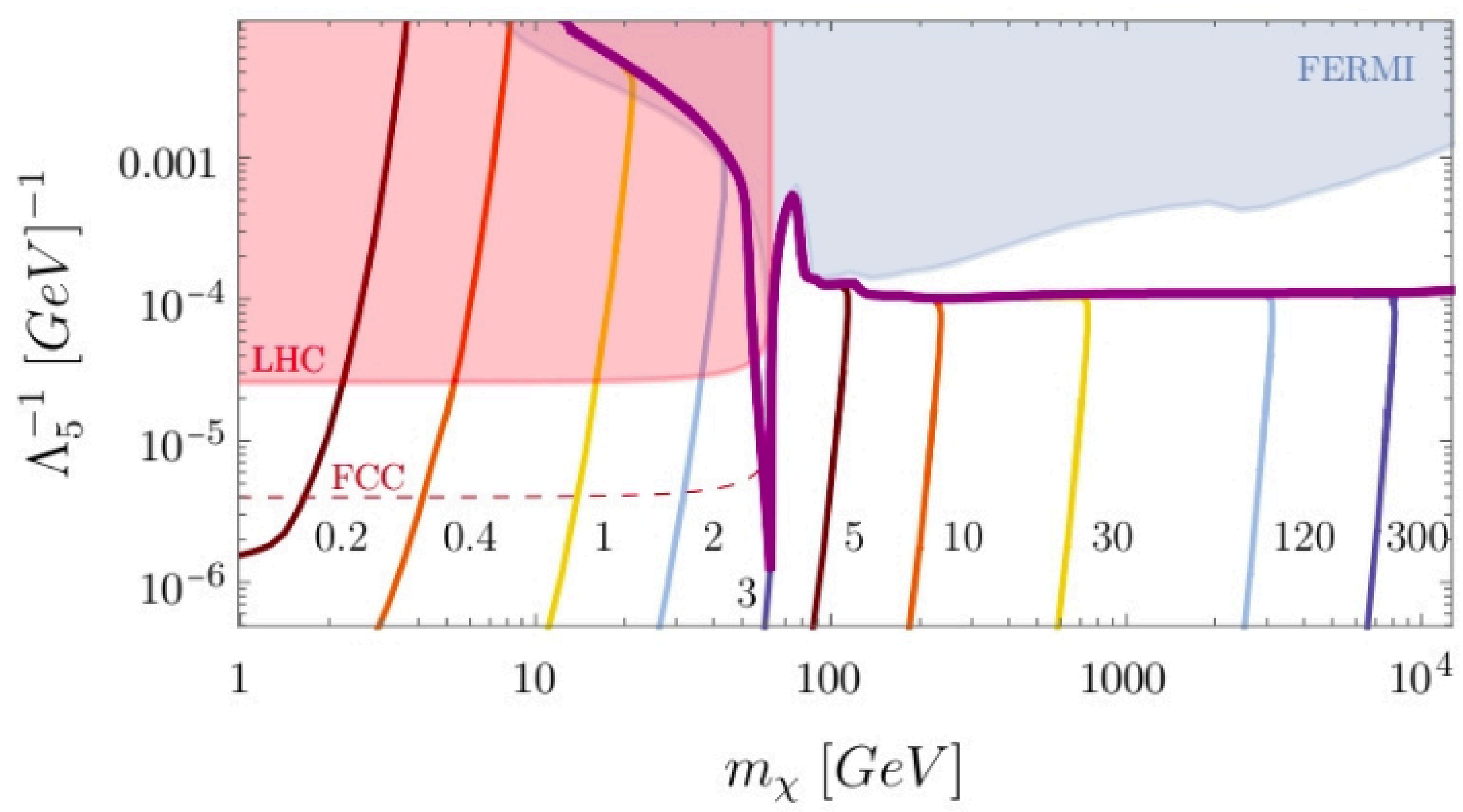
SCALAR DM



High DM mass: DD detection constraint

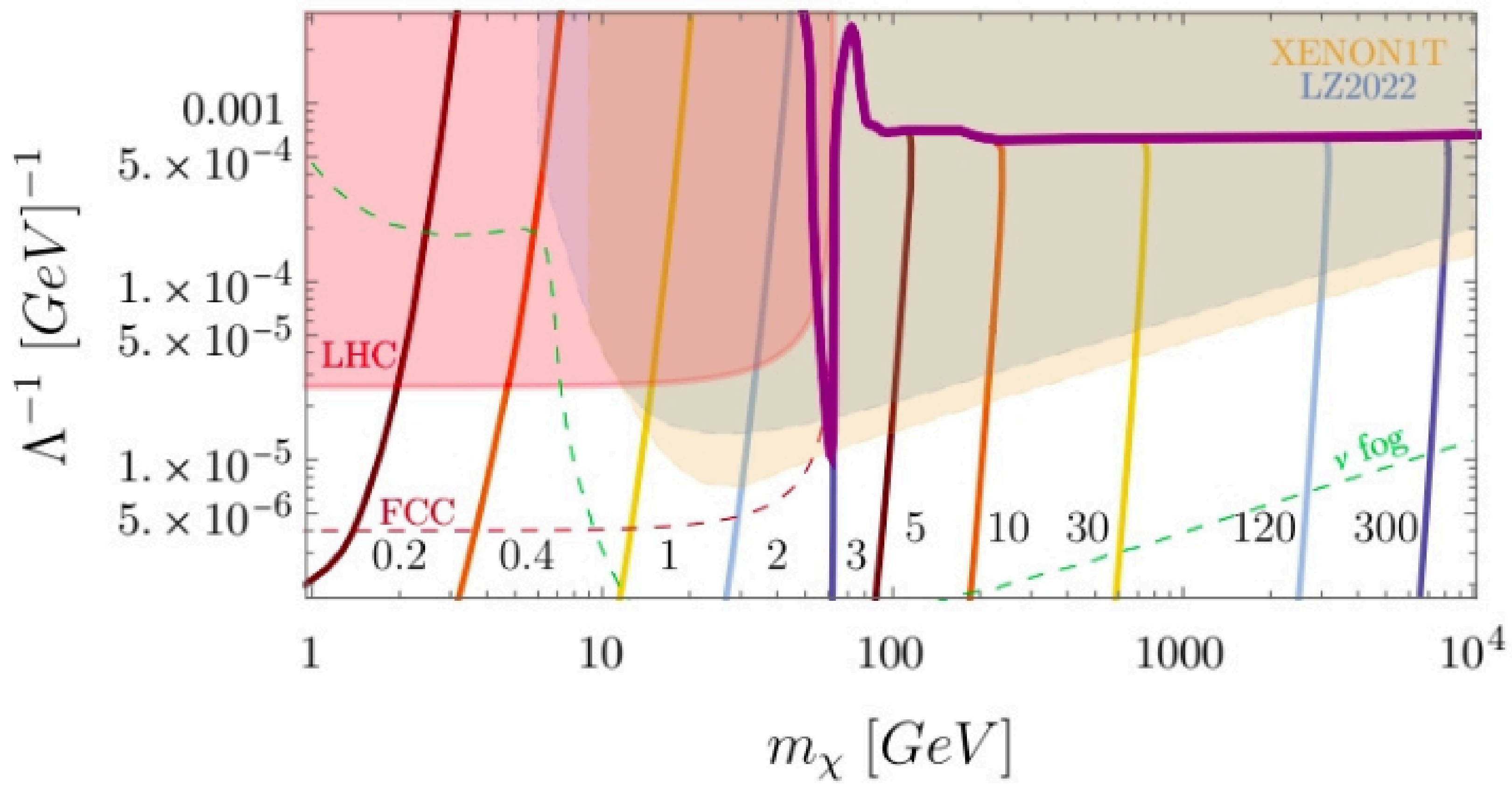
Low DM mass: LHC and future collider constraint

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)



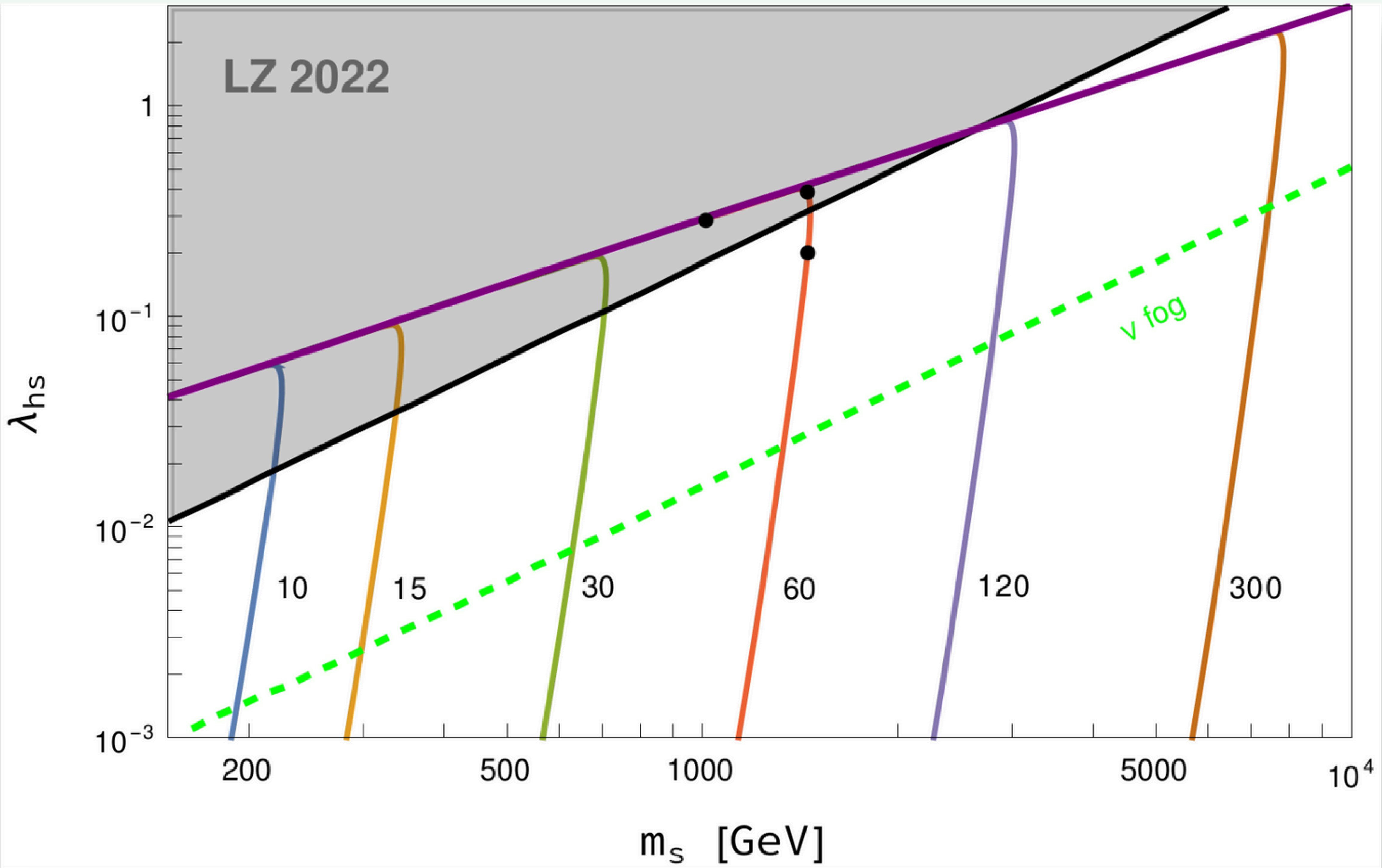
CP EVEN

CONCLUSIONS

Freeze-in is realised with tiny couplings.
Natural? Observable?

Early gravitational particle production can spoil freeze-in DM models.
This issue can be addressed and solved by an early matter dominated epoch, which is long and leads to low reheating temperatures.

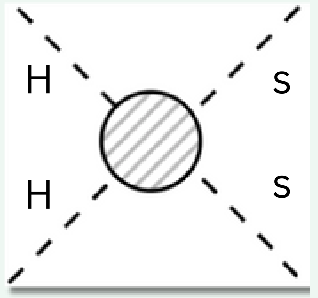
Low reheating freeze-in production is accessible by direct detection experiments and can be a target for future DD experiments

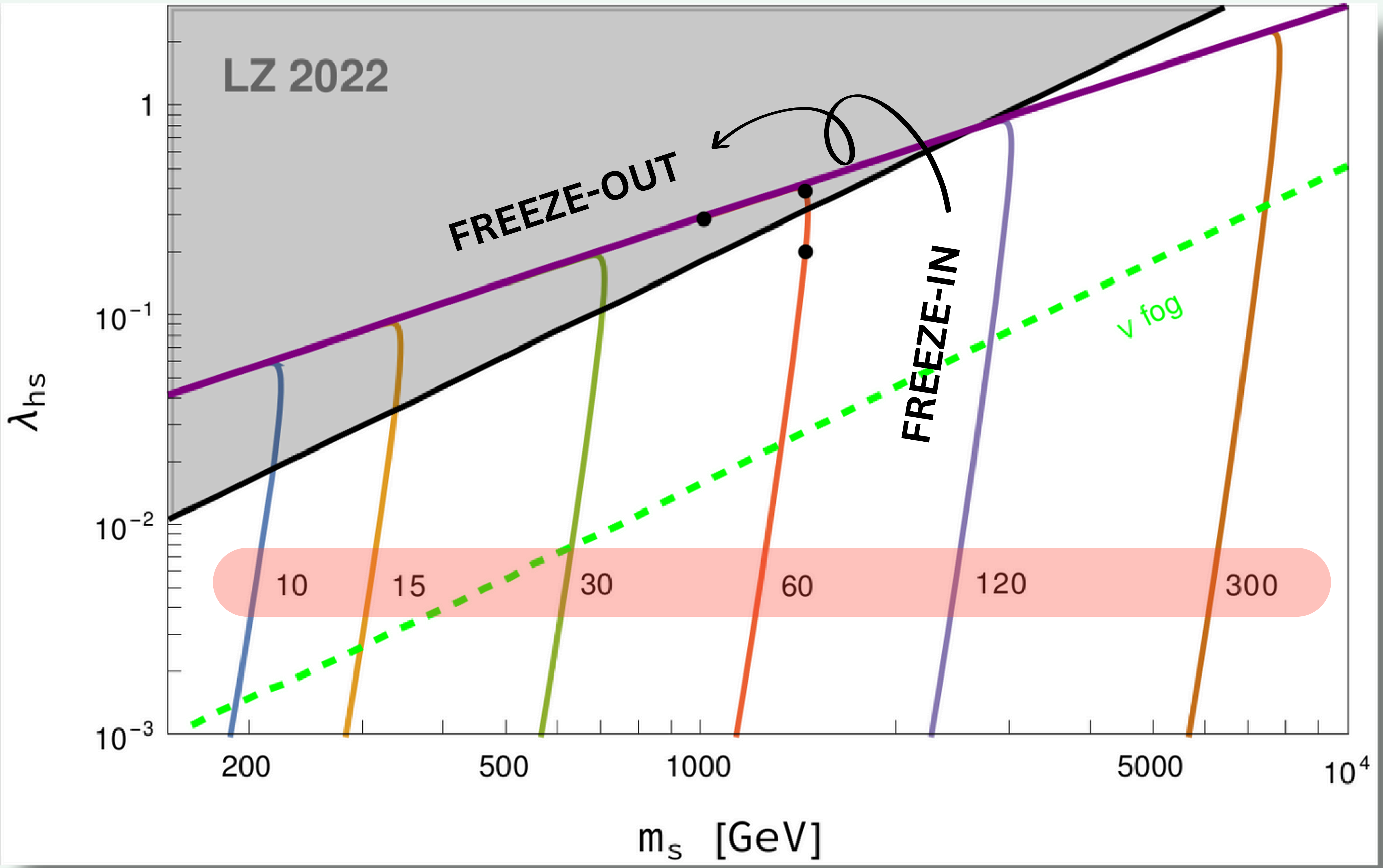


Higgs portal

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

t

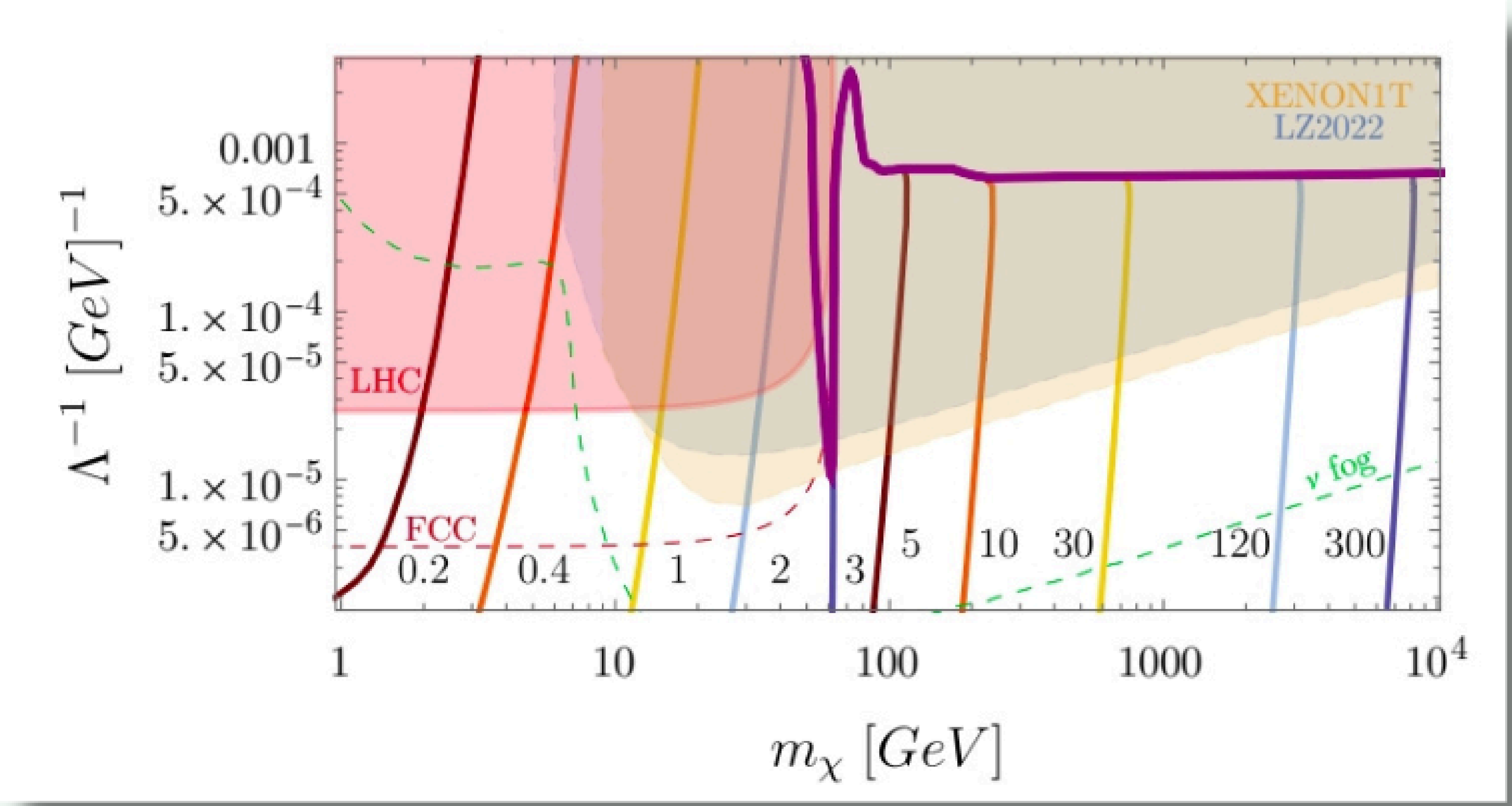




T_R

See also Javier S. Malpartida, N. Bernal, J. Jones-Pérez, R. A. Lineros, arxiv 2306:1493

At low masses LHC probes freeze-in a stronger couplings and future colliders can set bound below the neutrino fog!



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

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HIDDeN Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

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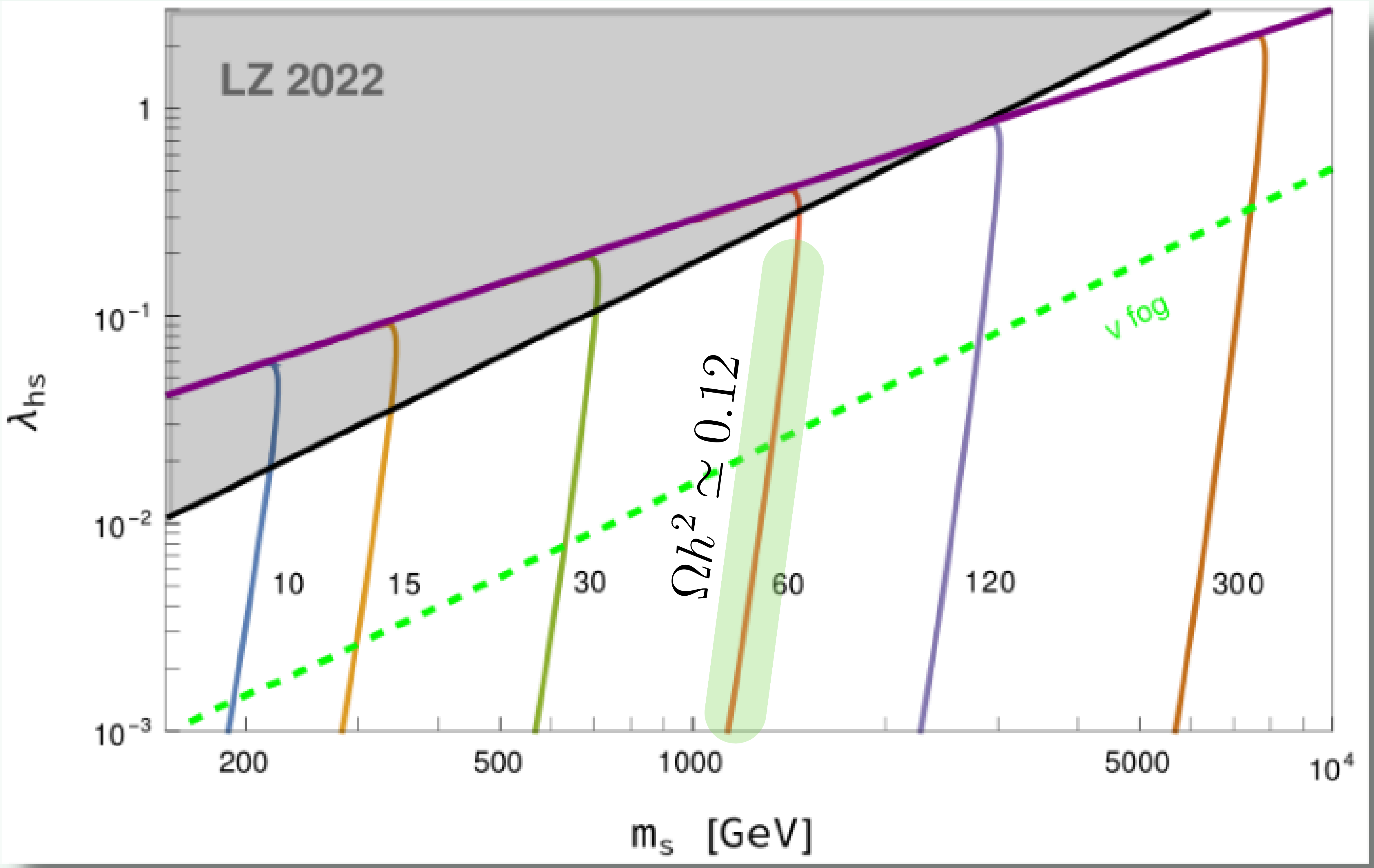
BACK-UP

FREEZE-IN REGIME

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

HIGGS PORTAL TO SCALAR DM

FREEZE-IN



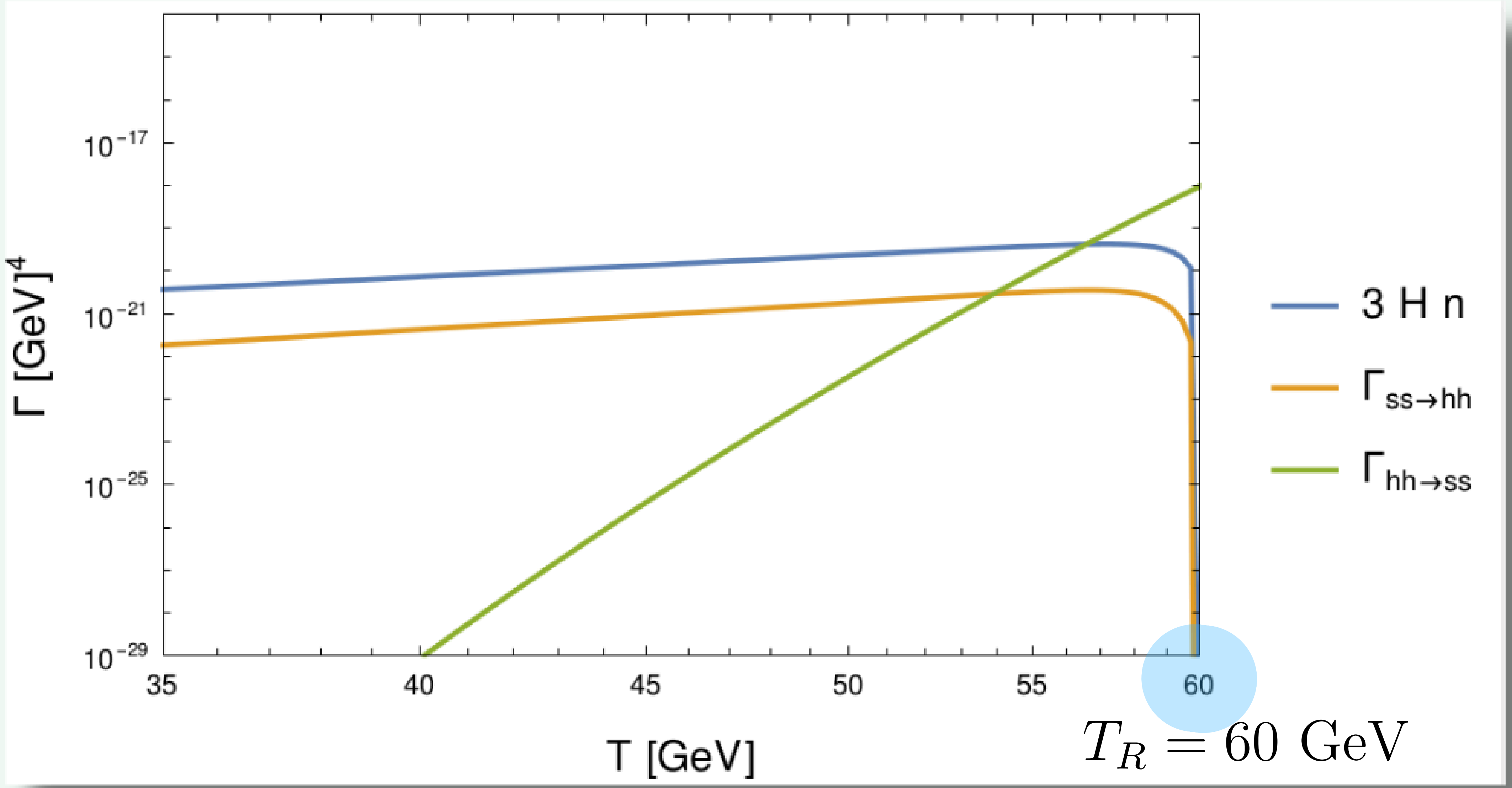
C. Cosme, FC, O. Lebedev, arXiv: 2306.13061

FREEZE-IN REGIME

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

Boltzmann equation

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



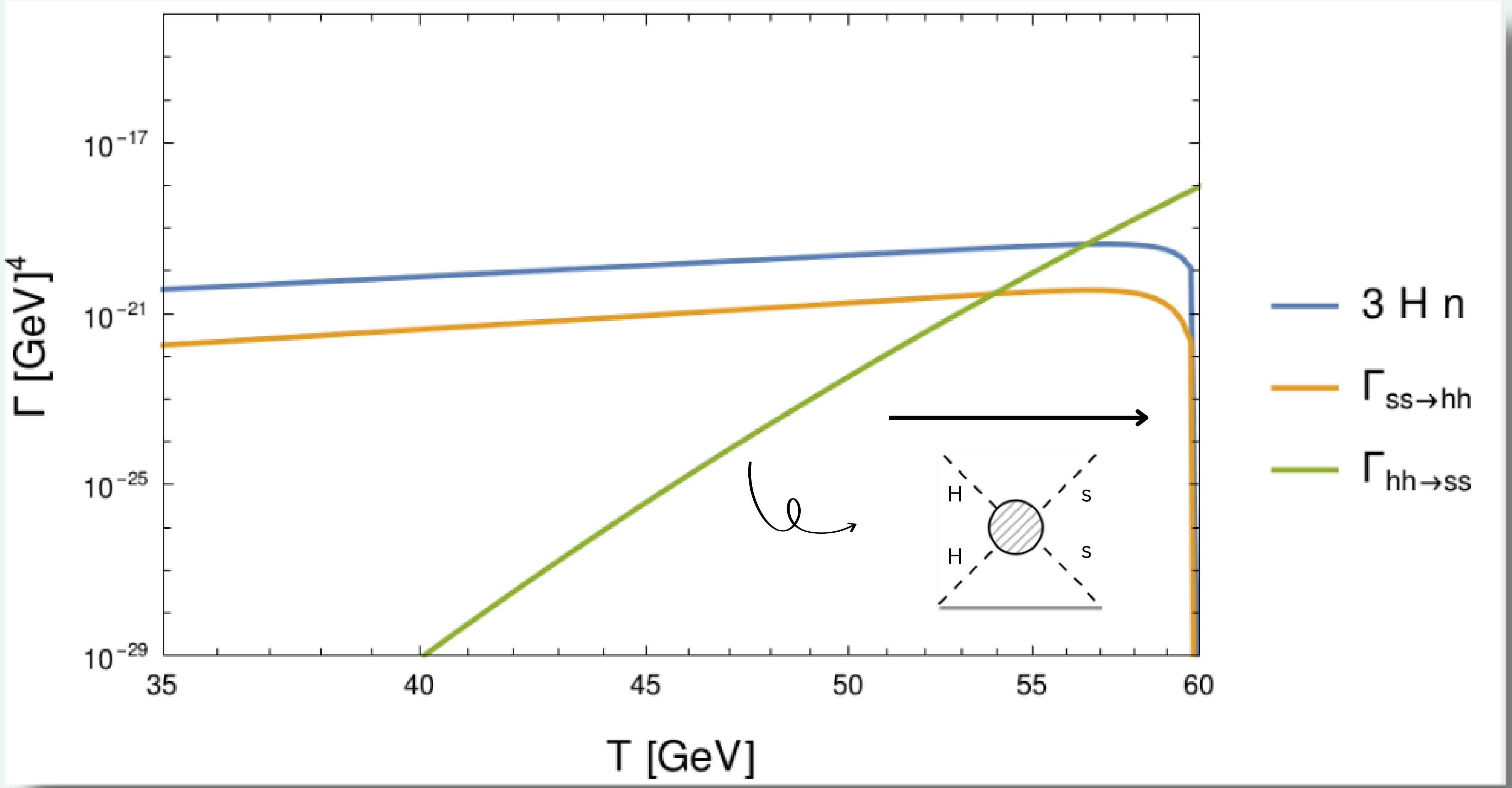
C. Cosme, FC, O. Lebedev, arXiv: 2306.13061

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



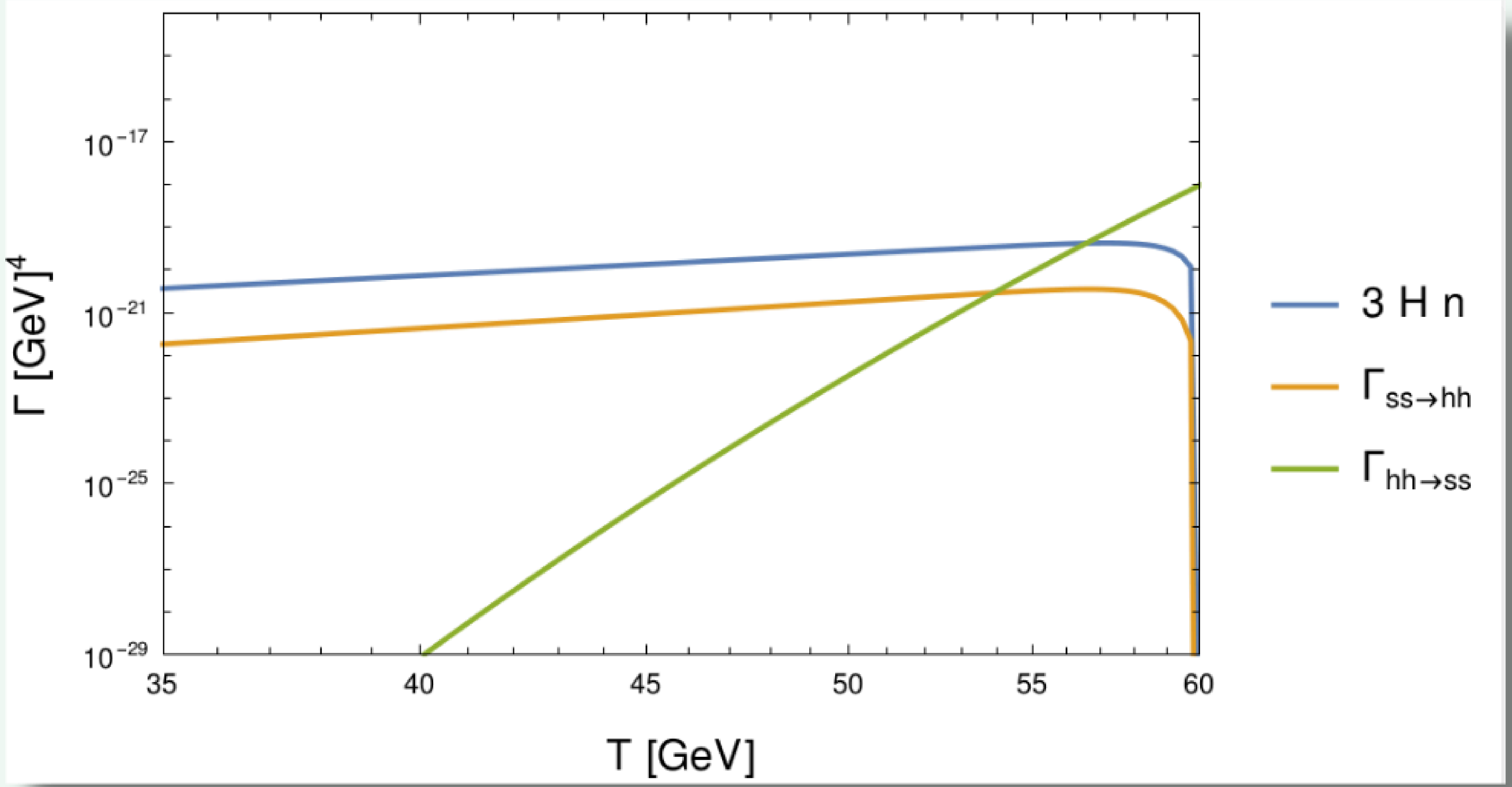
TIME

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

FREEZE-IN REGIME

But

$$\Gamma > 3Hn$$

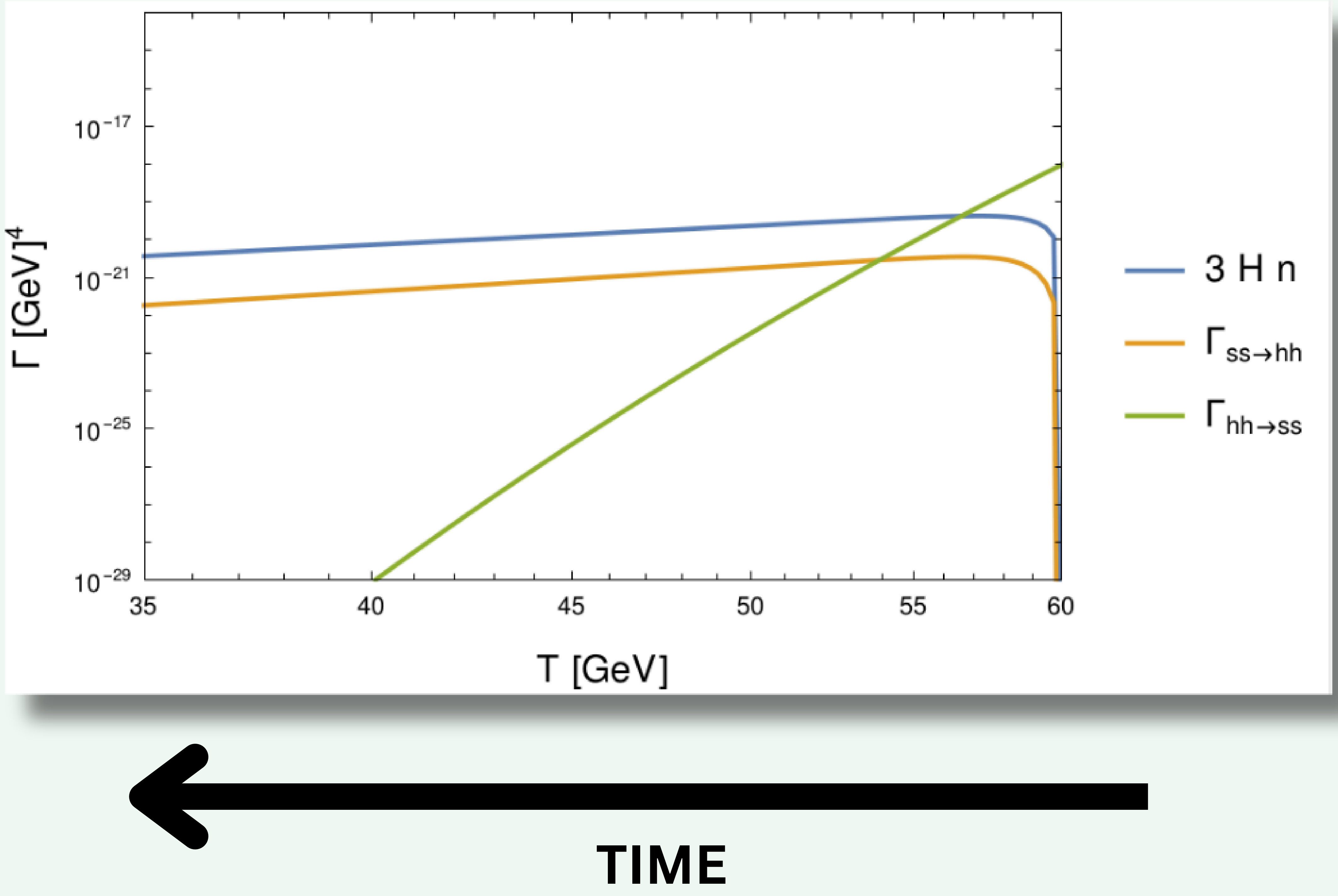


C. Cosme, FC, O. Lebedev, arXiv: 2306.13061

FREEZE-IN REGIME

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

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

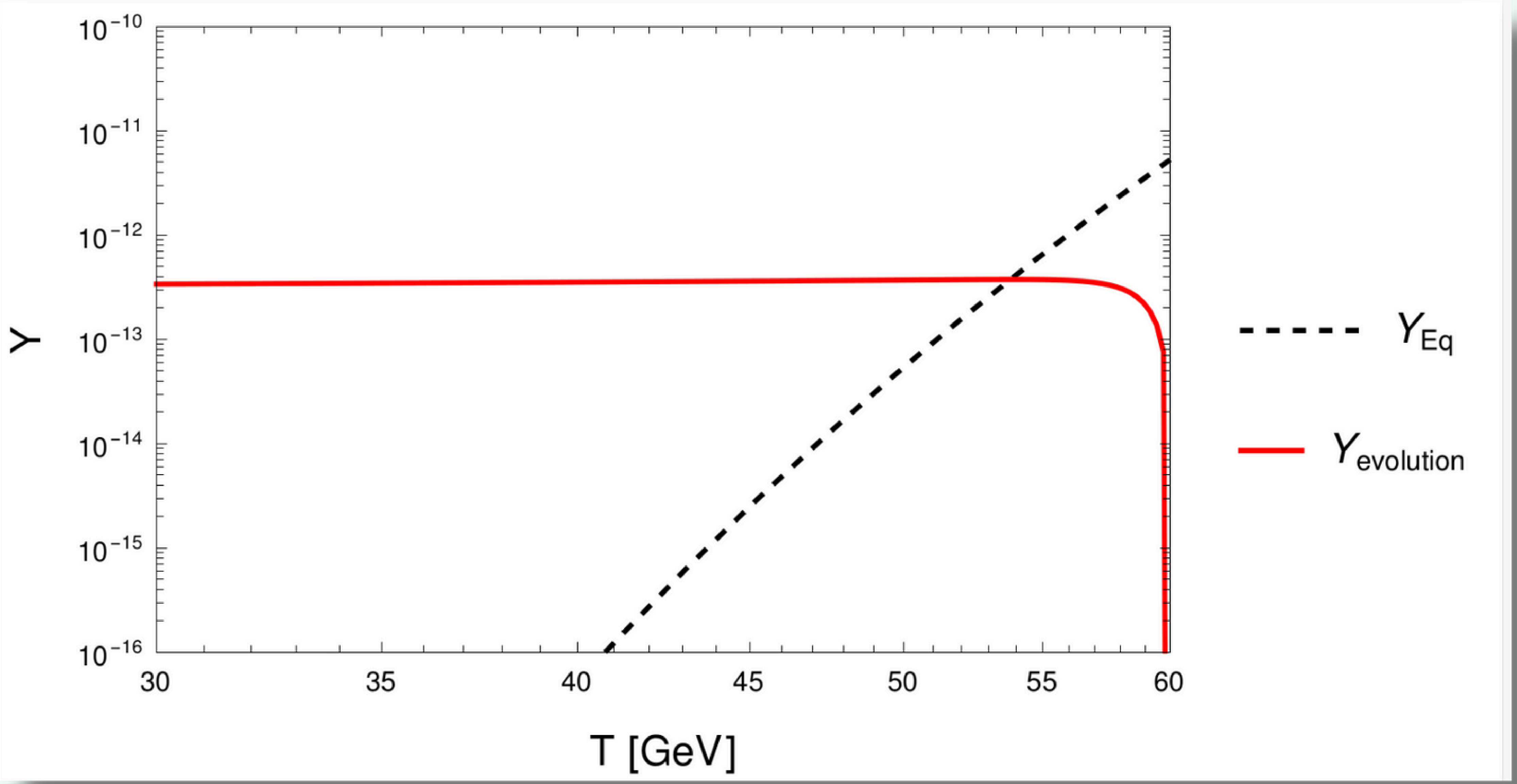


C. Cosme, FC, O. Lebedev, arXiv: 2306.13061

In fact the number density does not follow the equilibrium curve

OUT OF EQUILIBRIUM

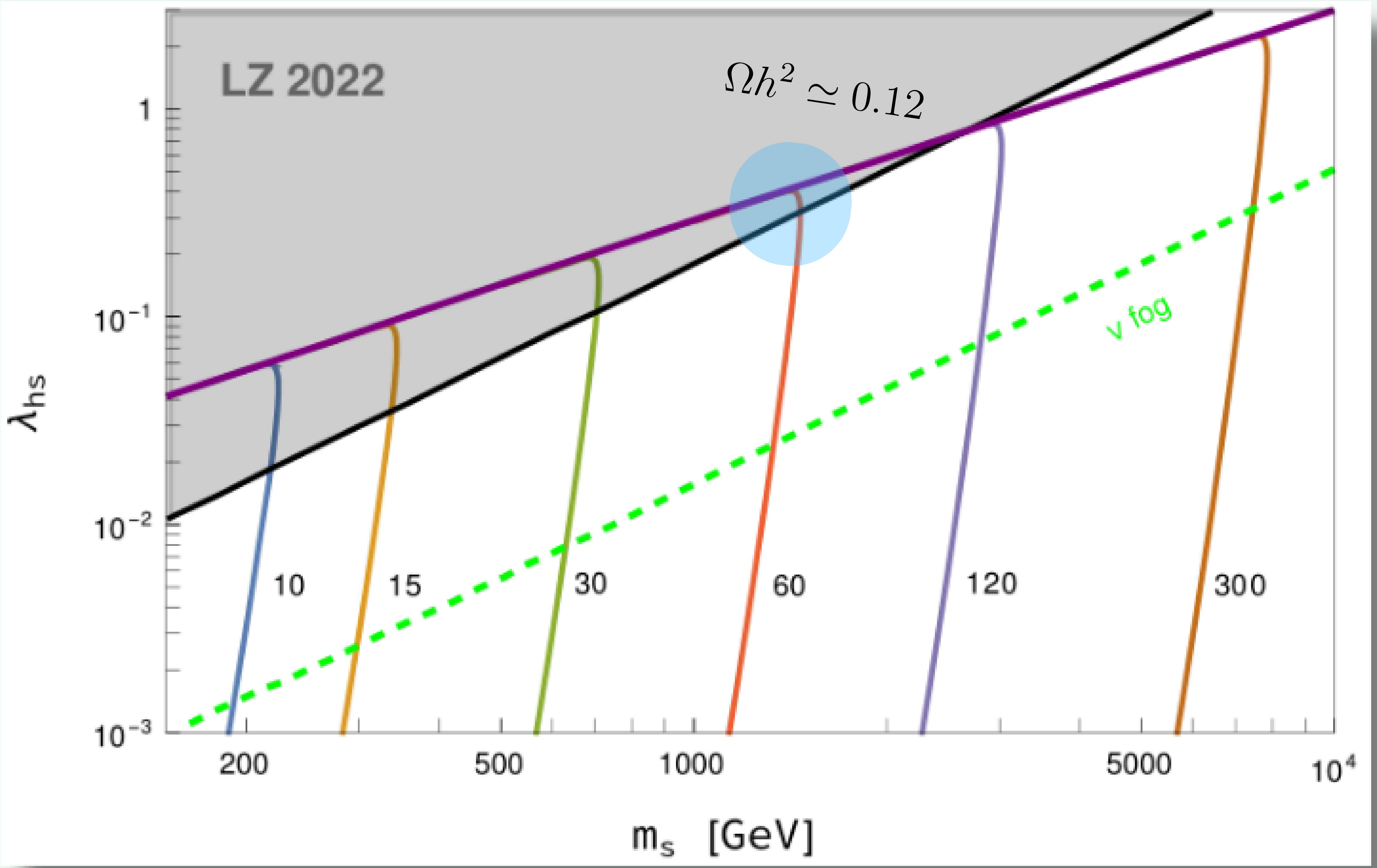
Looks like a UV freeze-in production, peaked at the reheating temperature



INTERMEDIATE REGIME

HIGGS PORTAL TO SCALAR DM

BACKREACTION



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

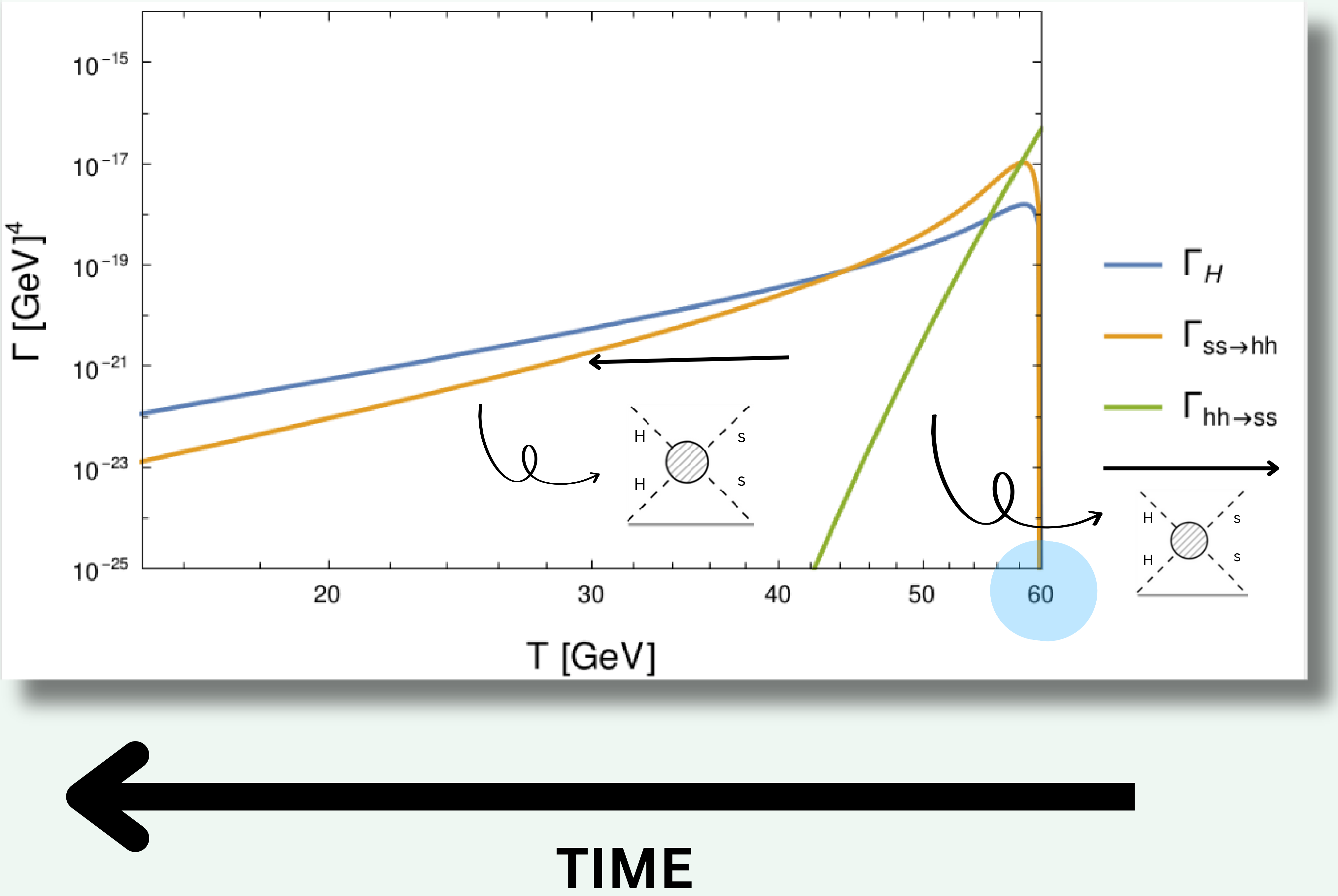
ANNIHILIATION BECOMES IMPORTANT

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

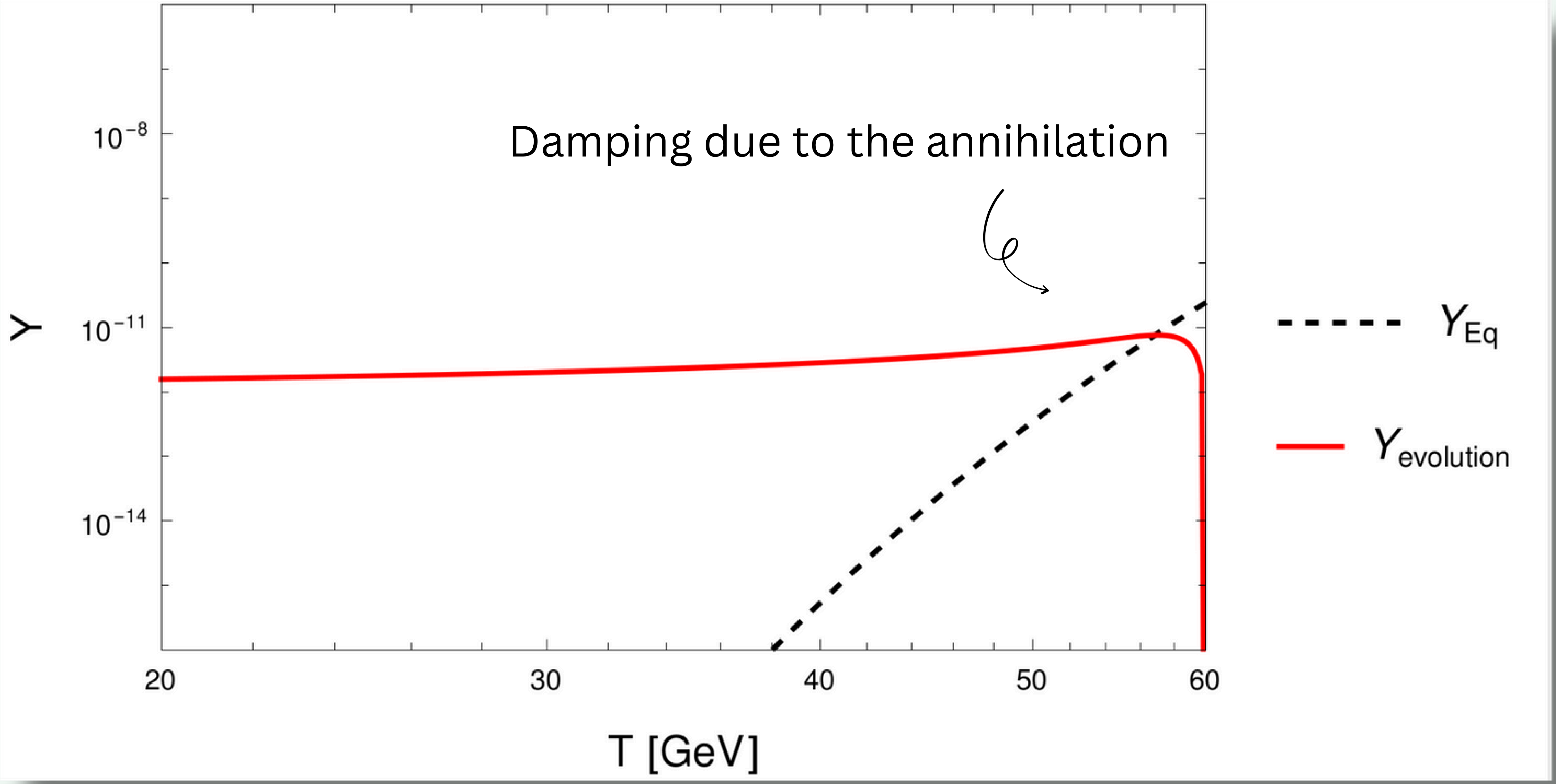
$$m_s = 1451 \text{ GeV} \quad \lambda_{hs} = 0.39$$



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

The number density still does not follow the equilibrium curve

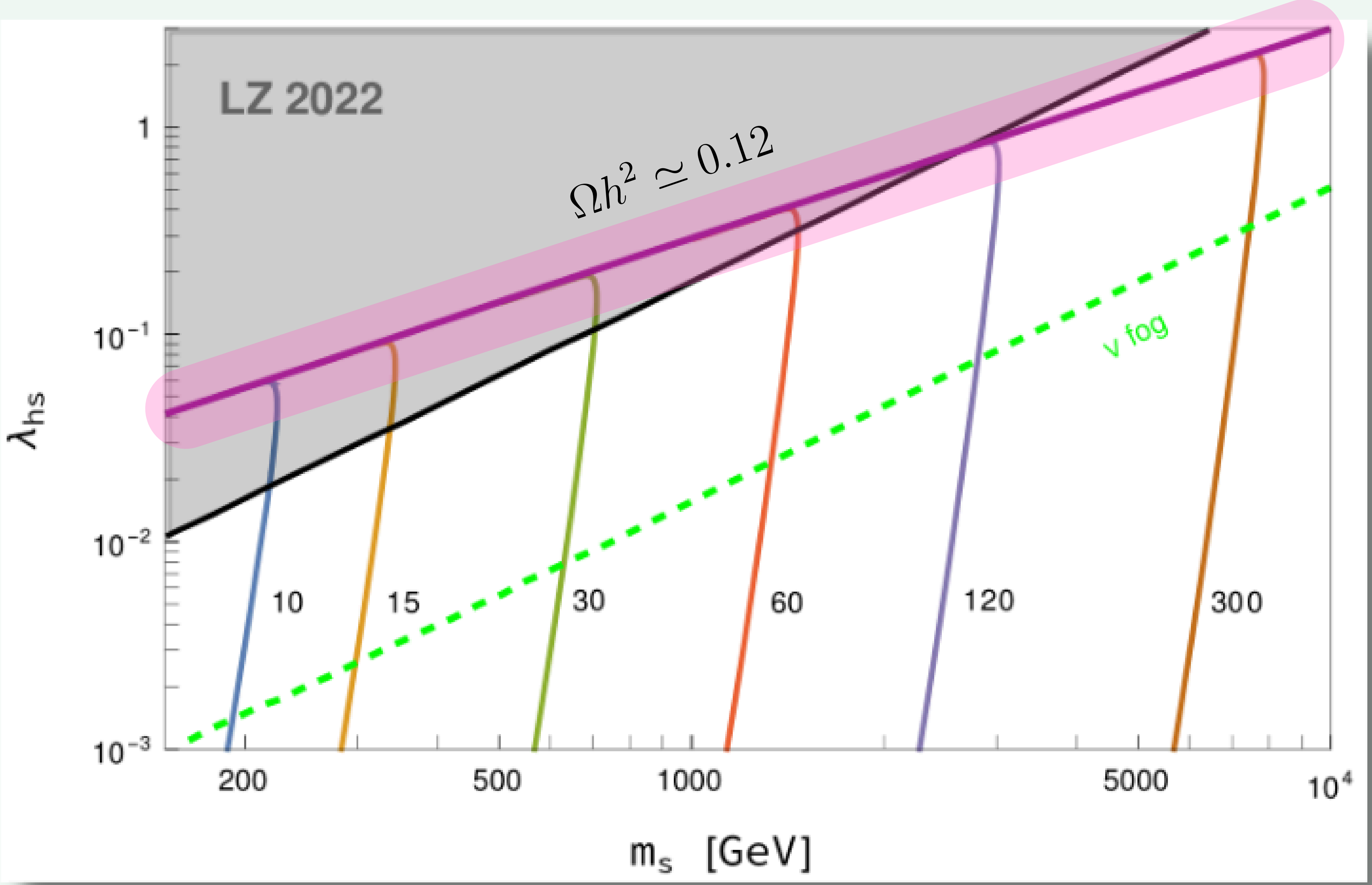
OUT OF EQUILIBRIUM



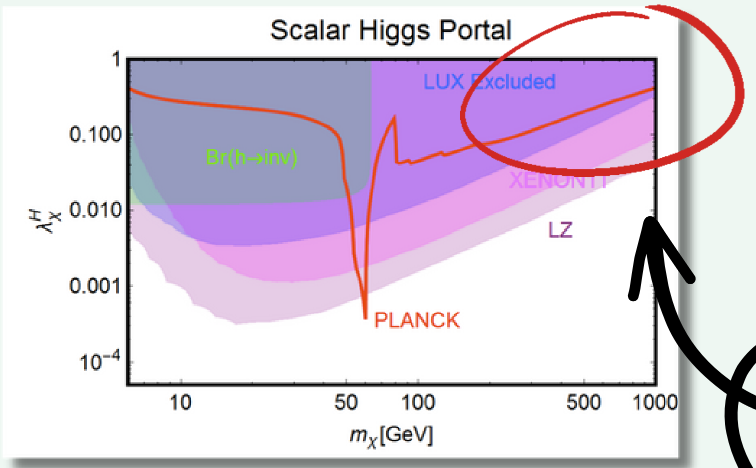
FREEZE-OUT REGIME

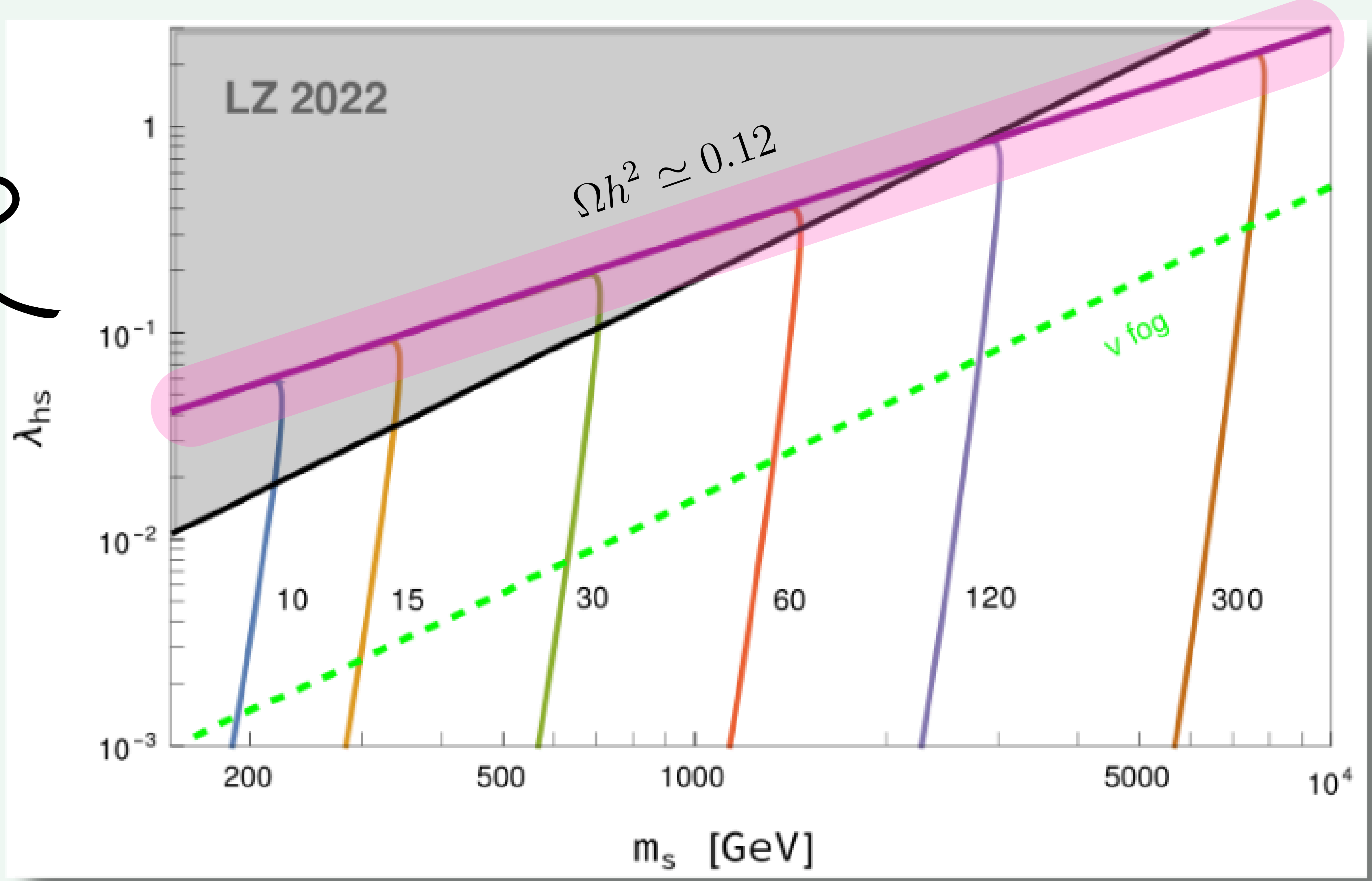
HIGGS PORTAL TO SCALAR DM

FREEZE-OUT



HIGGS PORTAL TO SCALAR DM





FREEZE-OUT

FREEZE-OUT REGIME

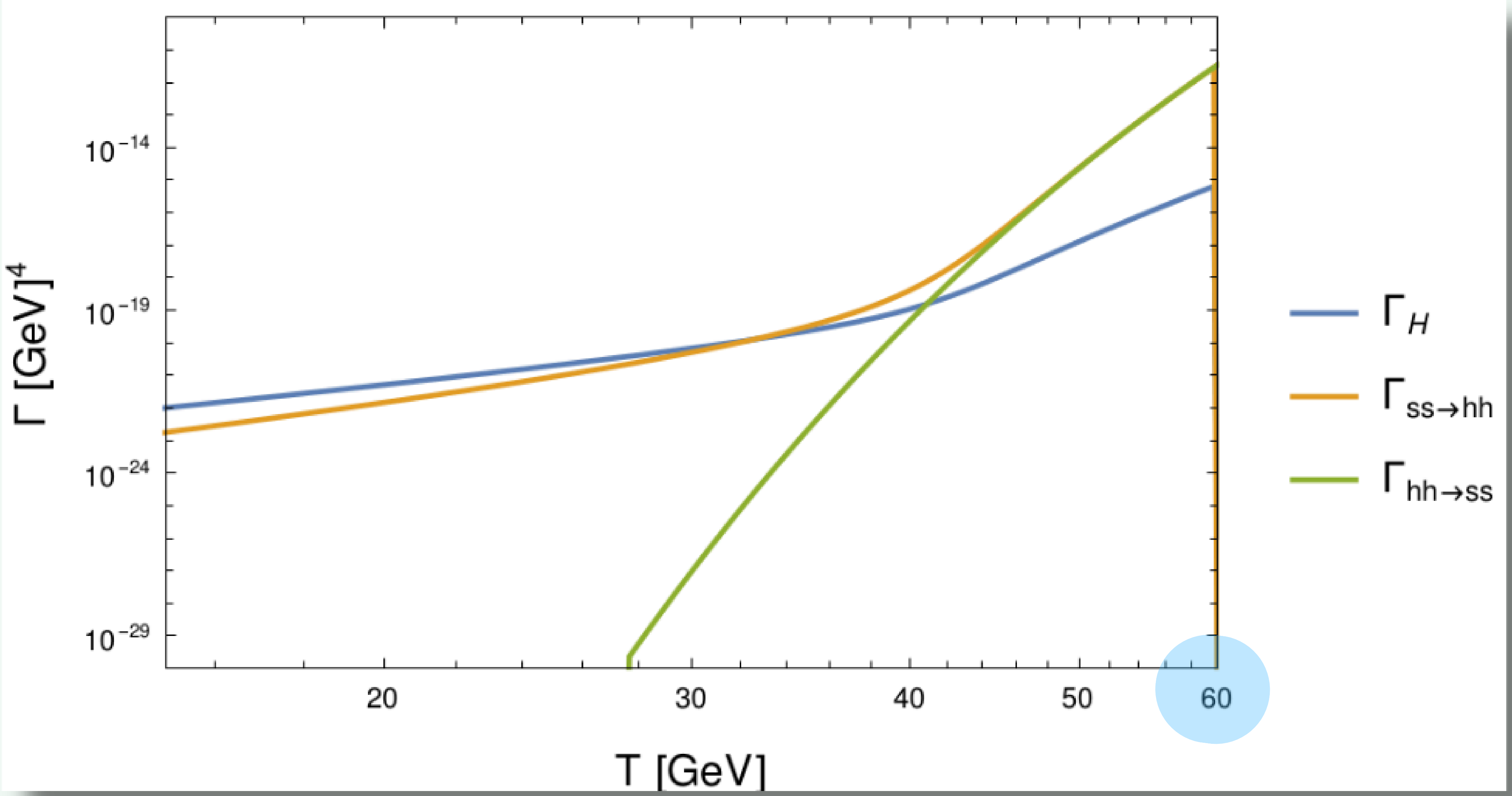
$$m_s = 1012 \text{ GeV} \qquad \lambda_{hs} = 0.29$$

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

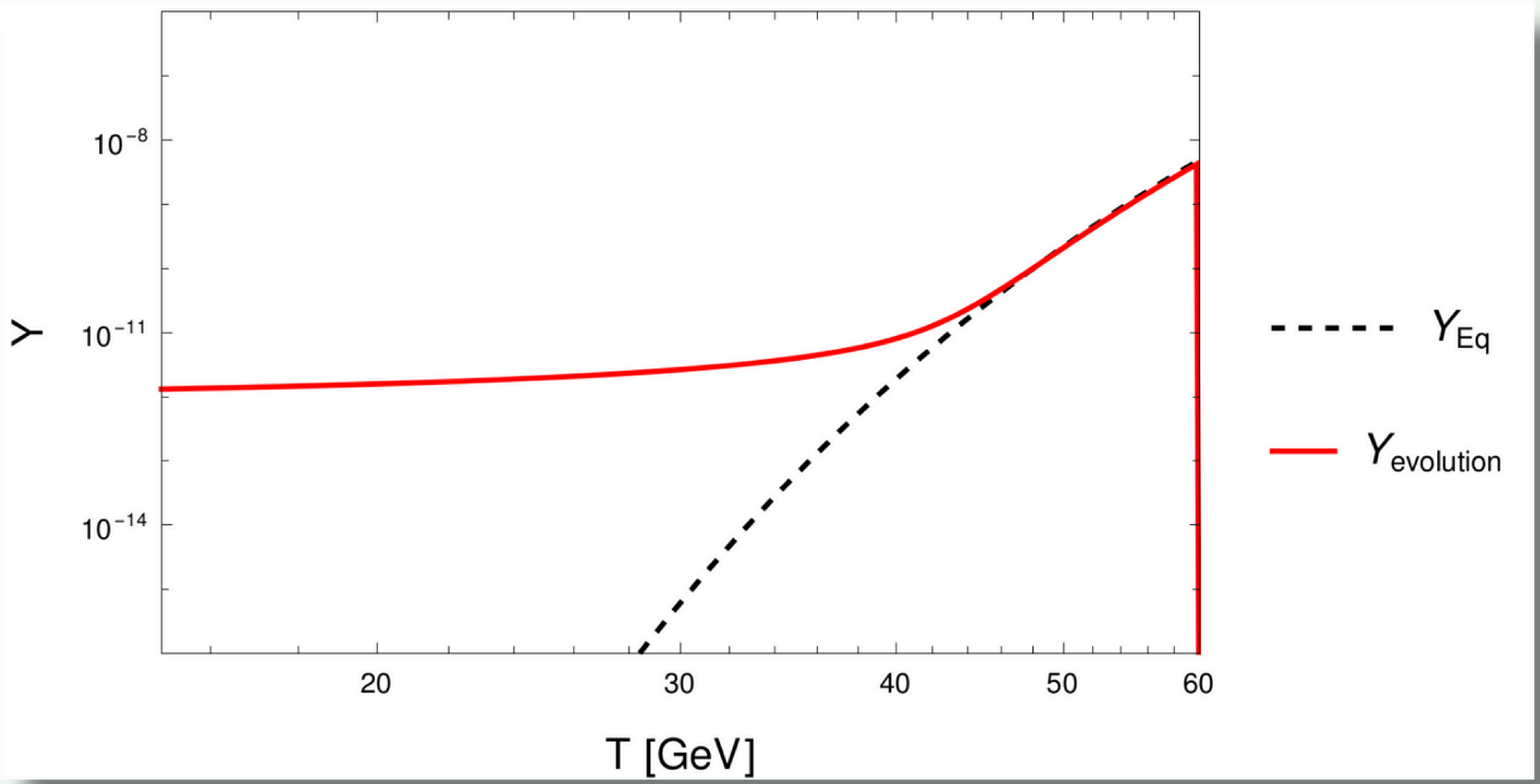
$$\Gamma\left(h_i h_i \to ss\right) = \Gamma\left(ss \to h_i h_i\right)$$



TIME

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

IN EQUILIBIRIUM

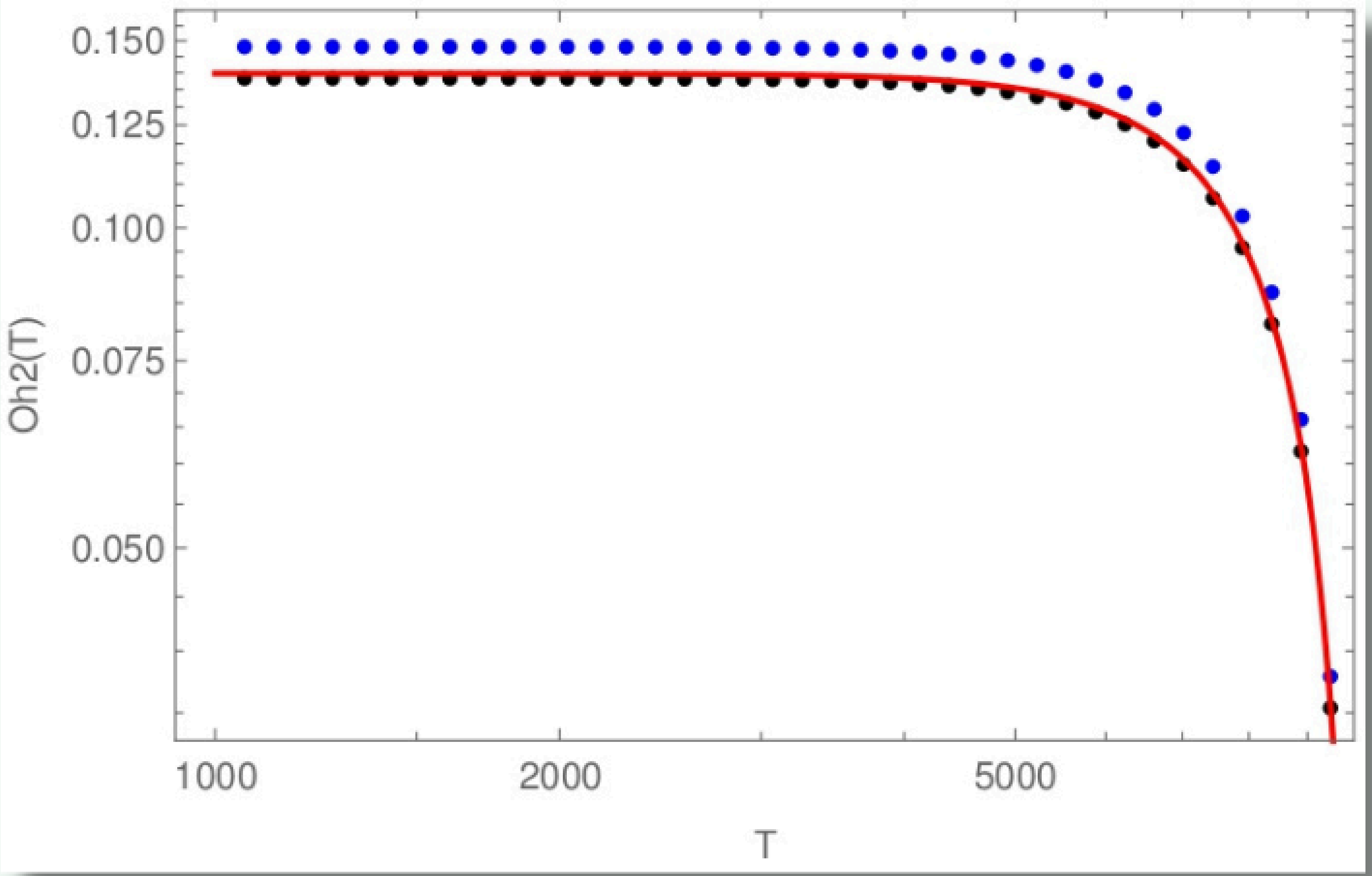


TIME

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

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Non-Standard Cosmology

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

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

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

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

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

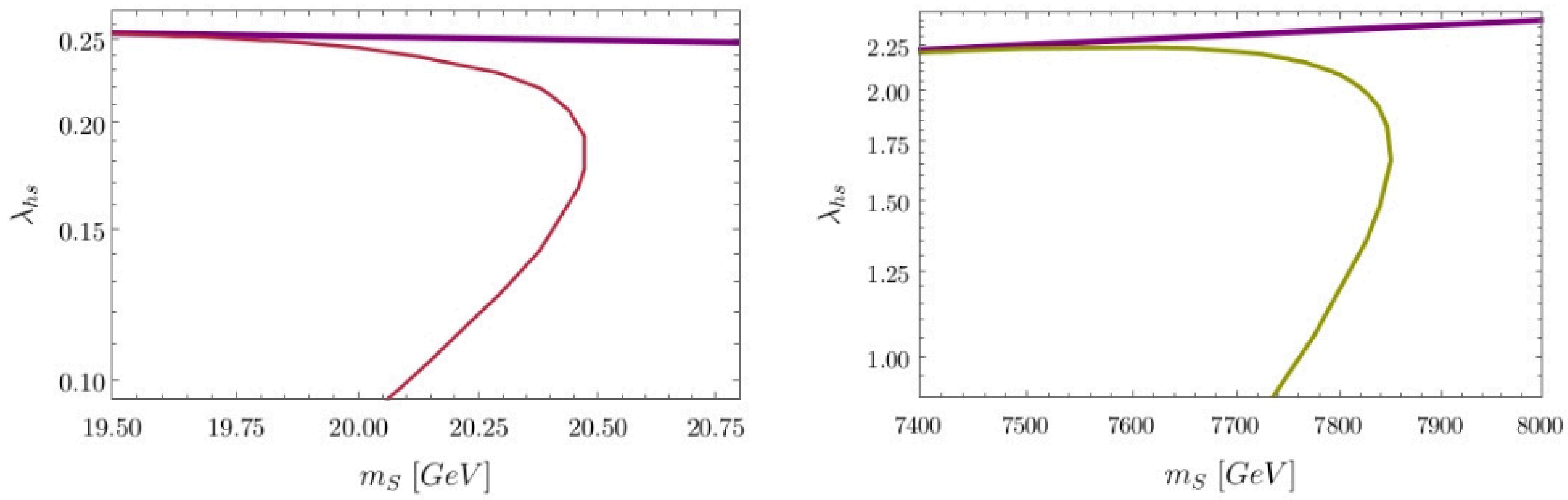

Figure 4: Freeze-in to freeze-out transition at low and high temperatures. The purple line corresponds to thermal DM as in Fig. 2. *Left:* $T_R = 1$ GeV. *Right:* $T_R = 300$ GeV.