FREEZE-IN AT STRONGER COUPLING

And the highest temperature of the Universe

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

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Invisible24

Freeze-in at

LOW REHEATING TEMPERATURES

Why? How? Come to see my poster

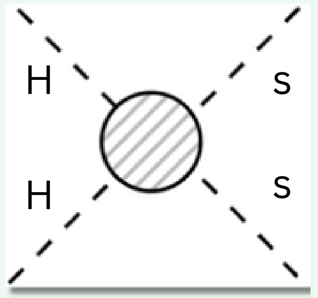
LOW TR FREEZE-IN PRODUCTION

Example:

Higgs portal

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

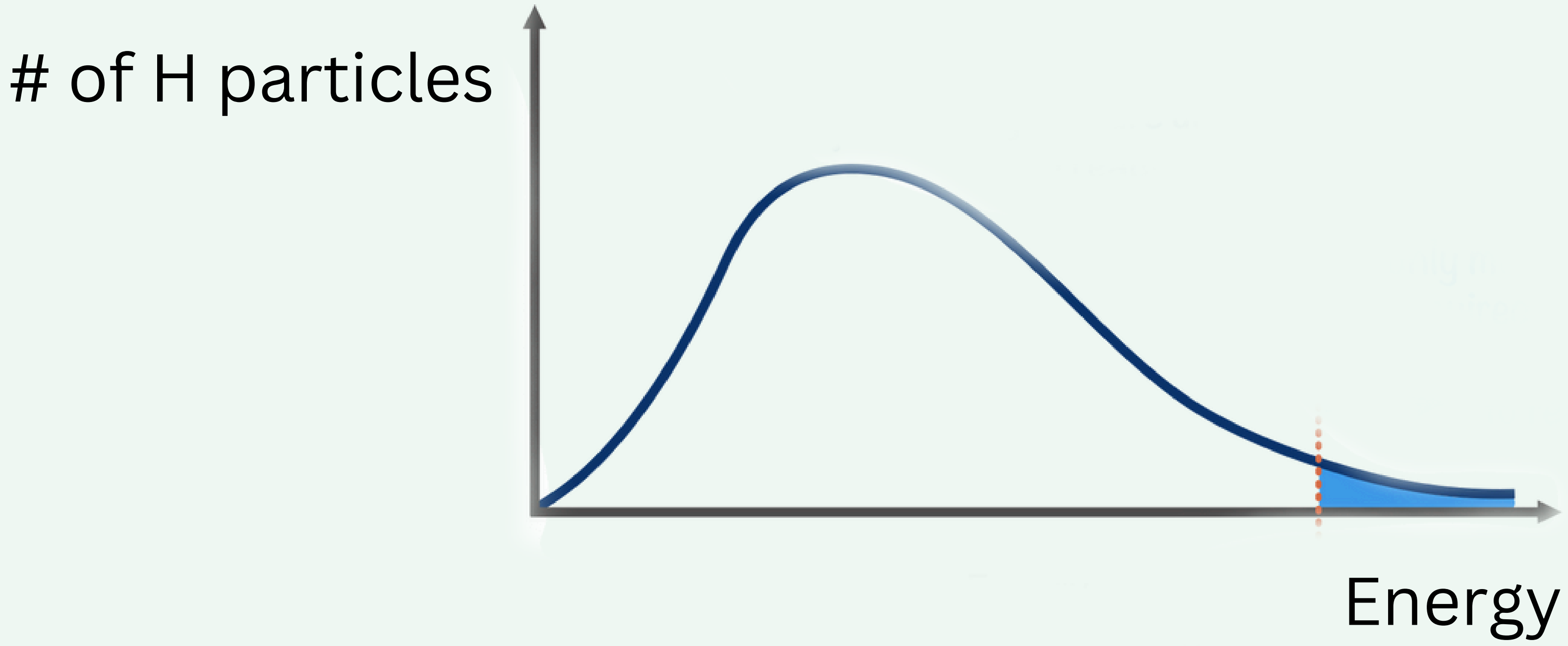
t



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

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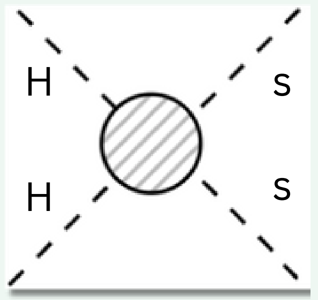

Freeze-in

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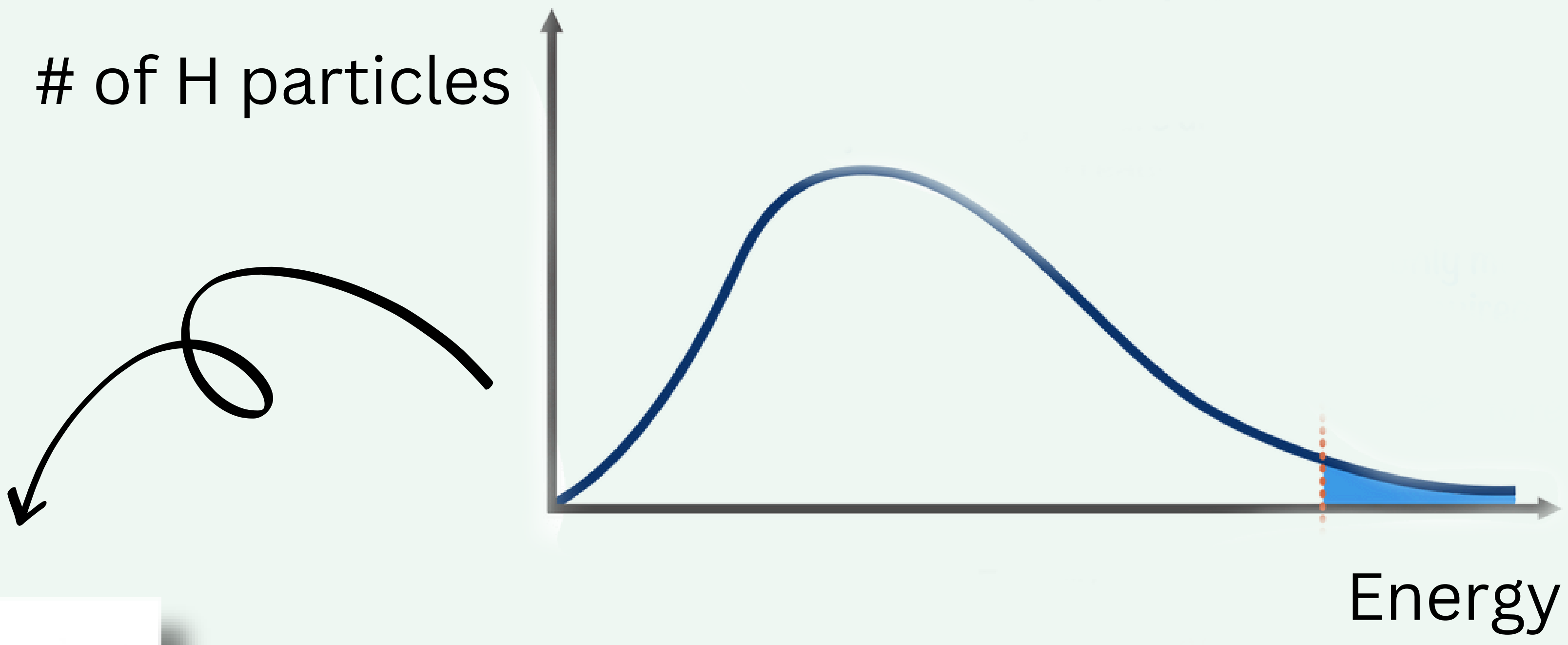

Boltzmann distribution

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

The rate of production is Boltzmann suppressed

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

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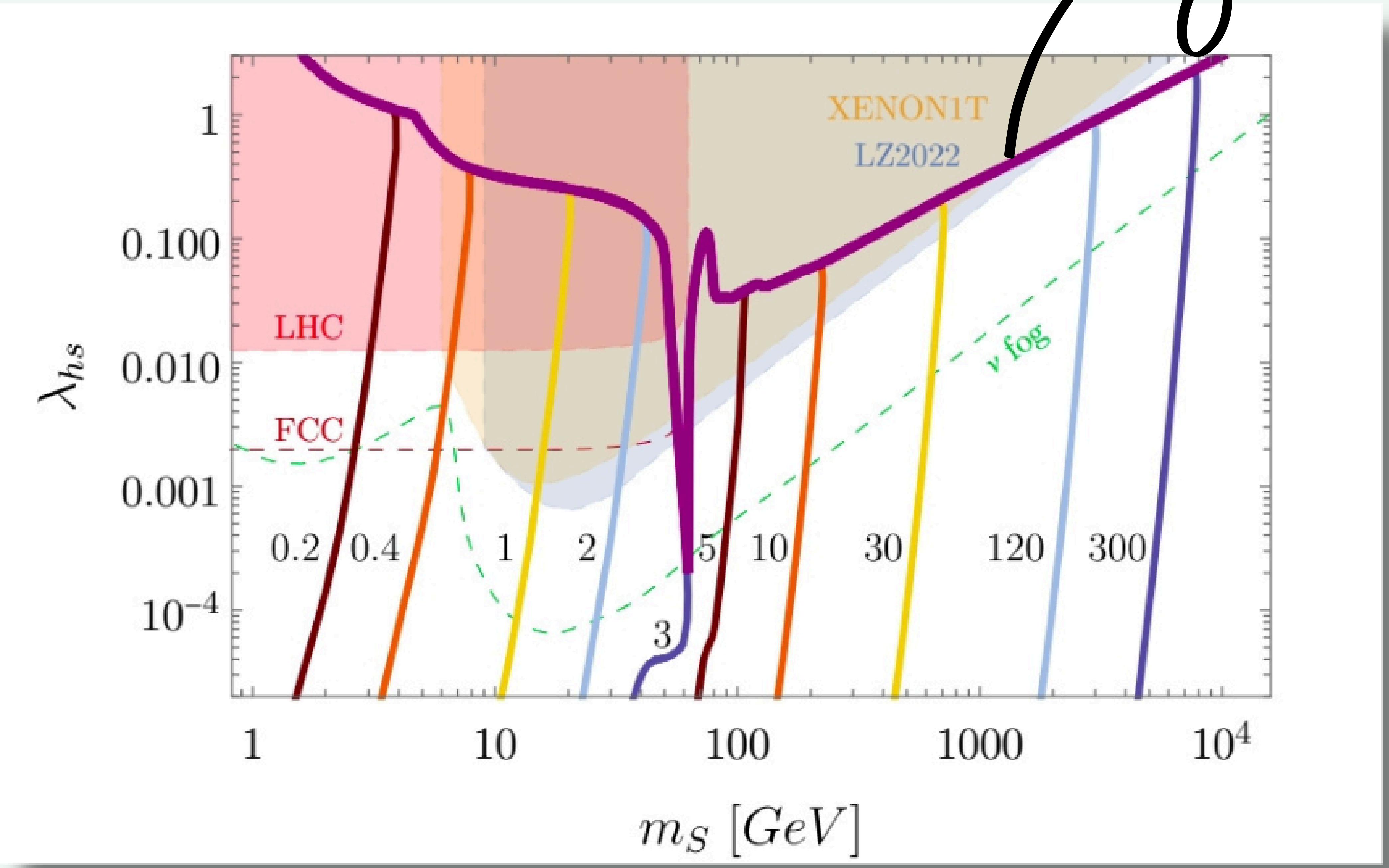
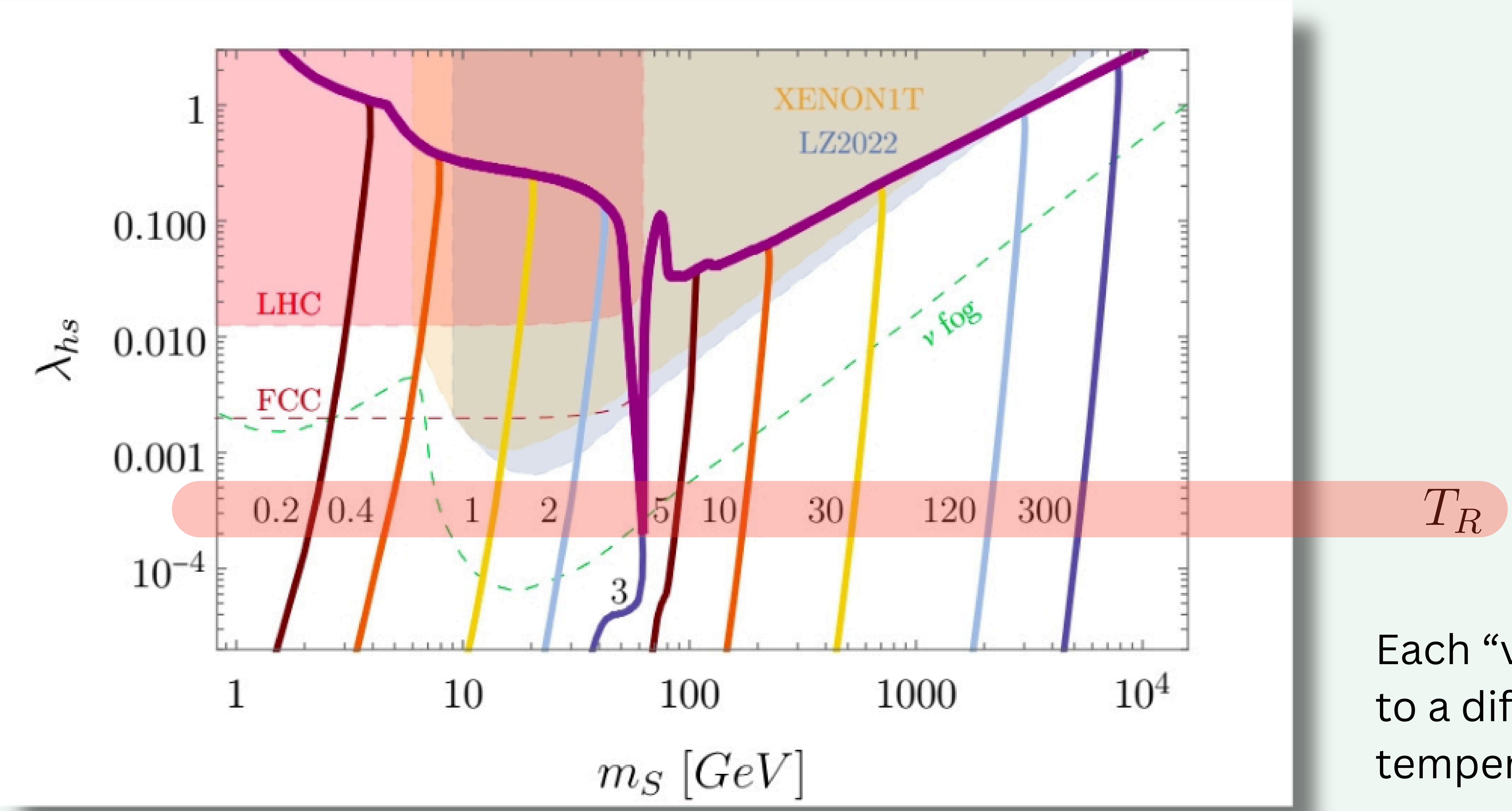
FREEZE-IN AT STRONGER COUPLING



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

A. Acadi, **FC**, A. Goudelis, O. Lebedev, arxiv: 2405.03760

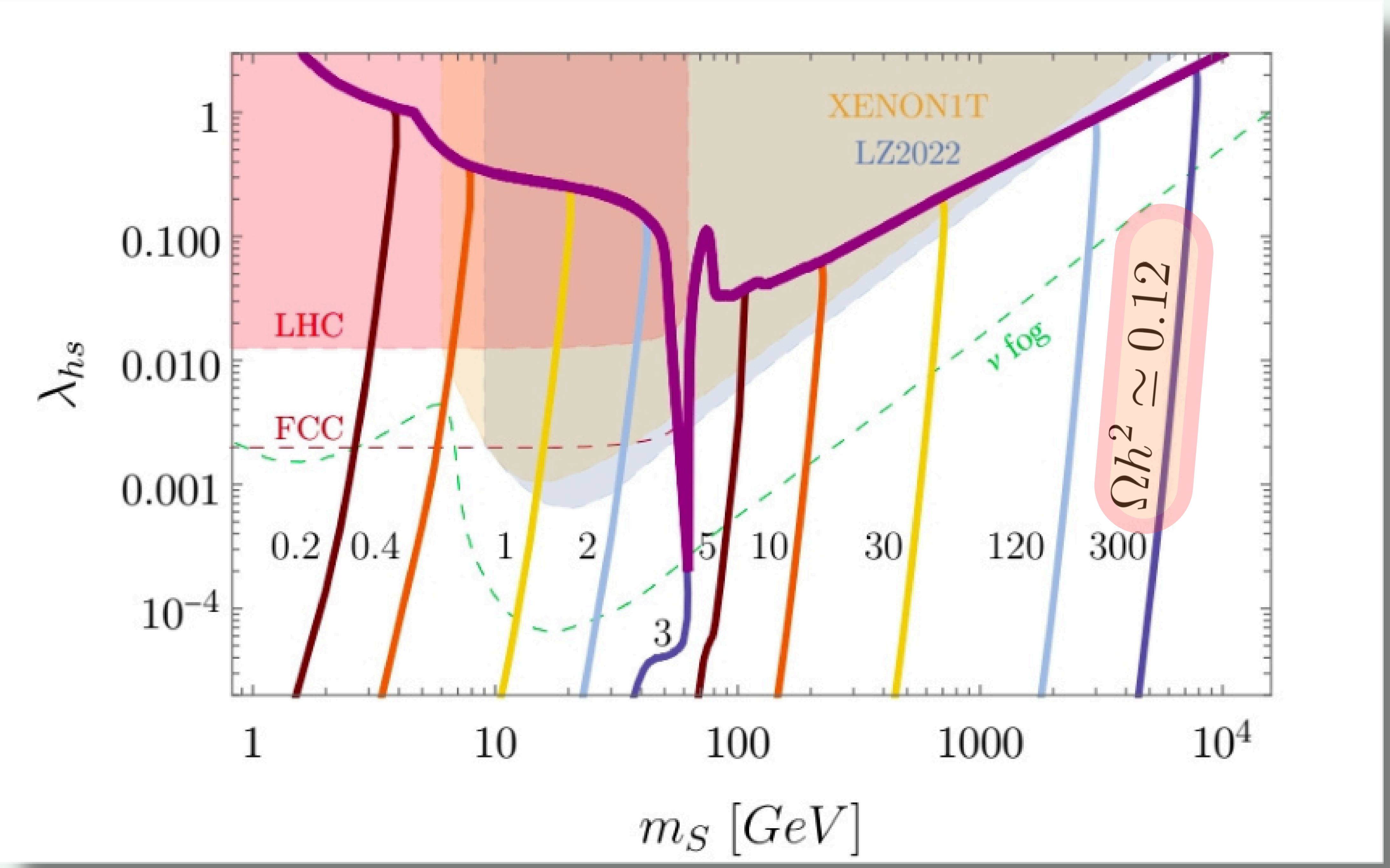
FREEZE-IN AT STRONGER COUPLING



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

A. Acadi, **FC**, A. Goudelis, O. Lebedev, arxiv: 2405.03760

FREEZE-IN AT STRONGER COUPLING



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

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

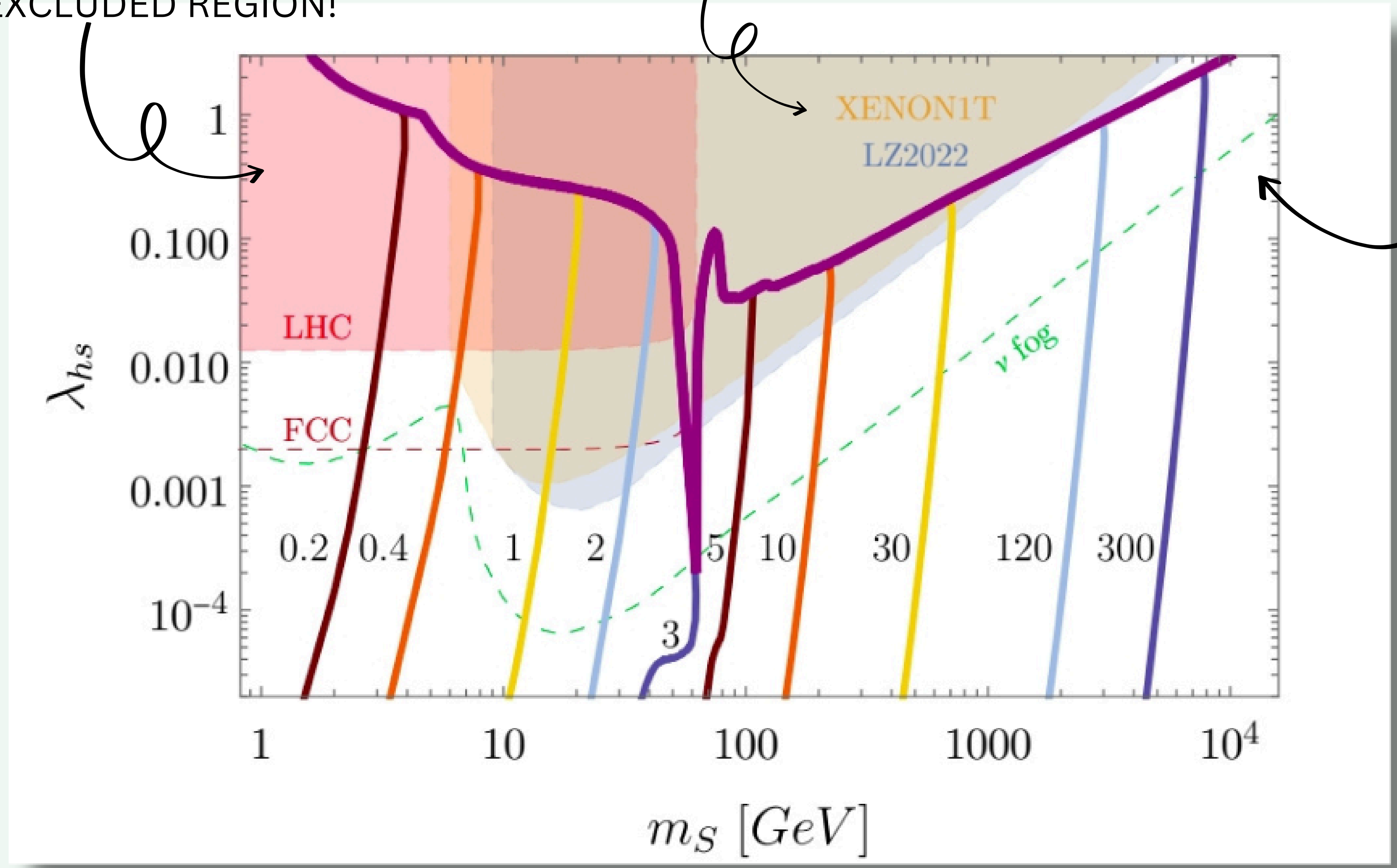
A. Acadi, **FC**, A. Goudelis, O. Lebedev, arxiv: 2405.03760

FREEZE-IN AT STRONGER COUPLING

DIRECT DETECTION EXCLUDED REGION!

INVISIBLE HIGGS DECAY EXCLUDED REGION!

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



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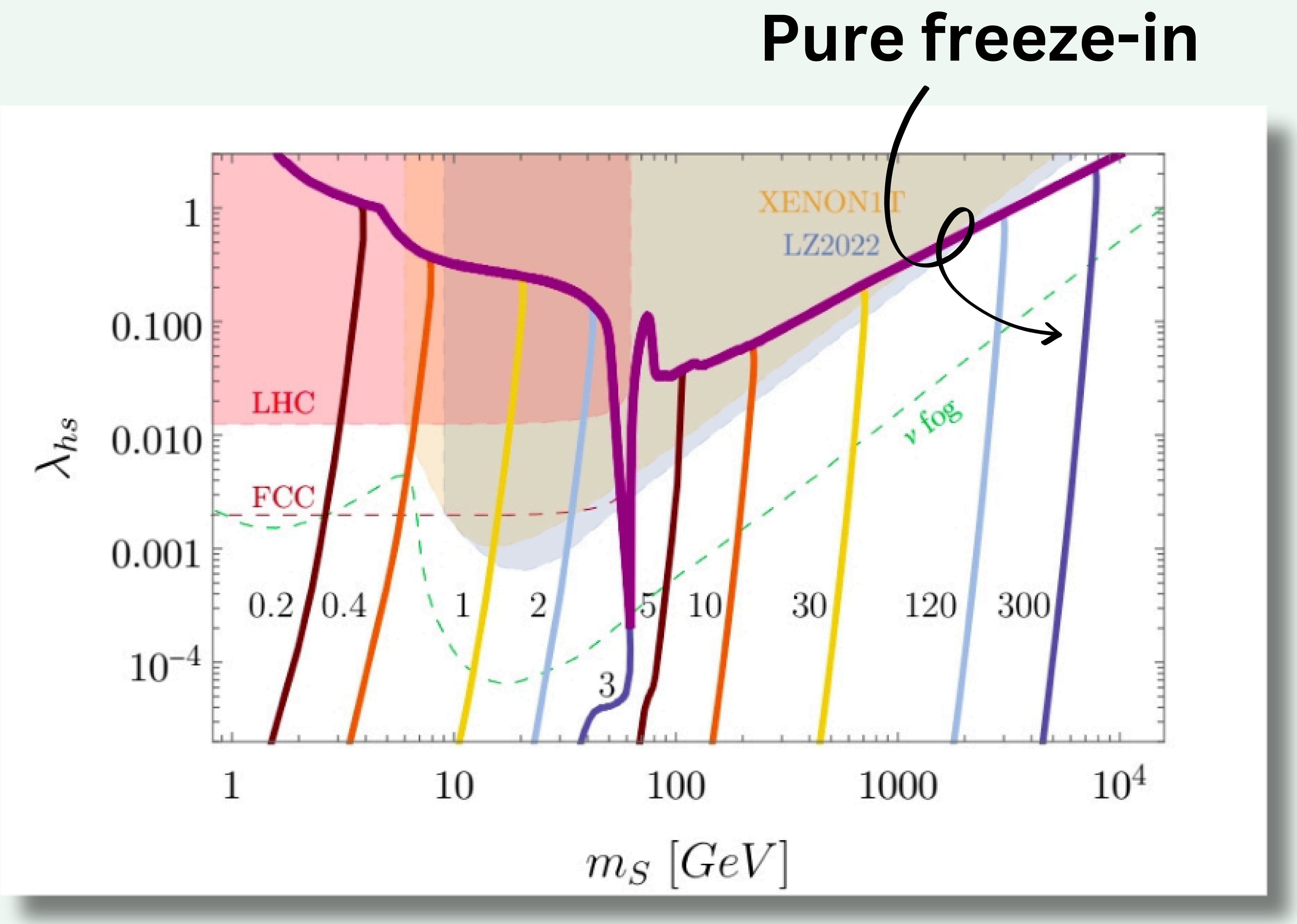

- No thermalisation = pure freeze-in production
- Coupling up to order 1!
- Freeze-in tested at **DIRECT DETECTION** and **COLLIDER** (Invisible Higgs decay)
- We move freely in the parameter space from FIMP to WIMP, no overproduction region

A. Acadi, **FC**, A. Goudelis, O. Lebedev, arxiv: 2405.03760

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 and we have

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

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

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

UNDERLING APPROXIMATION

INSTANTANEOUS REHEATING

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

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

THE 'STANDARD' STORY OF REHEATING

Inflaton decays directly into the SM $\phi \to \mathrm{SM}$

Reheating Boltzmann Equations

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

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

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

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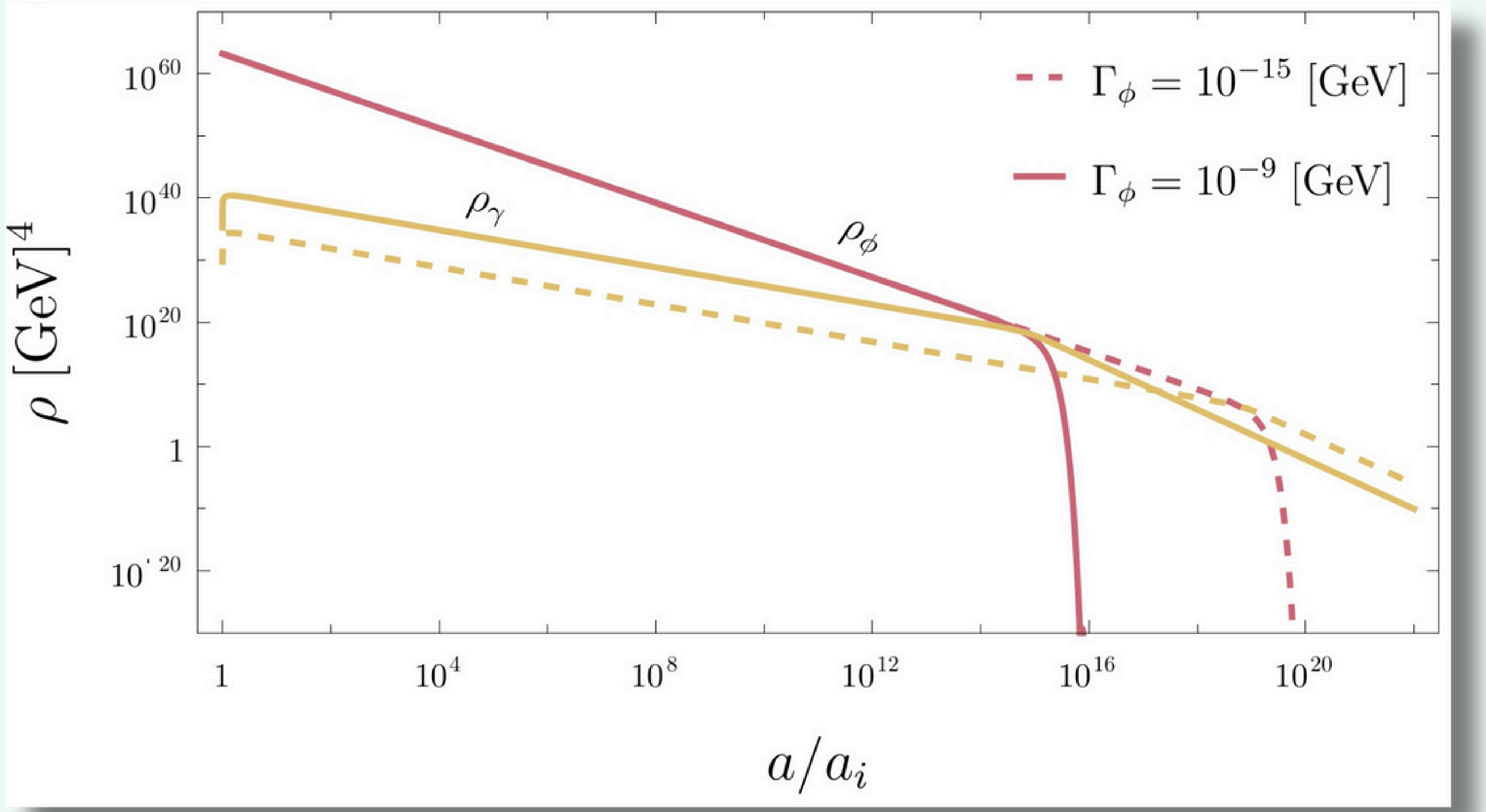


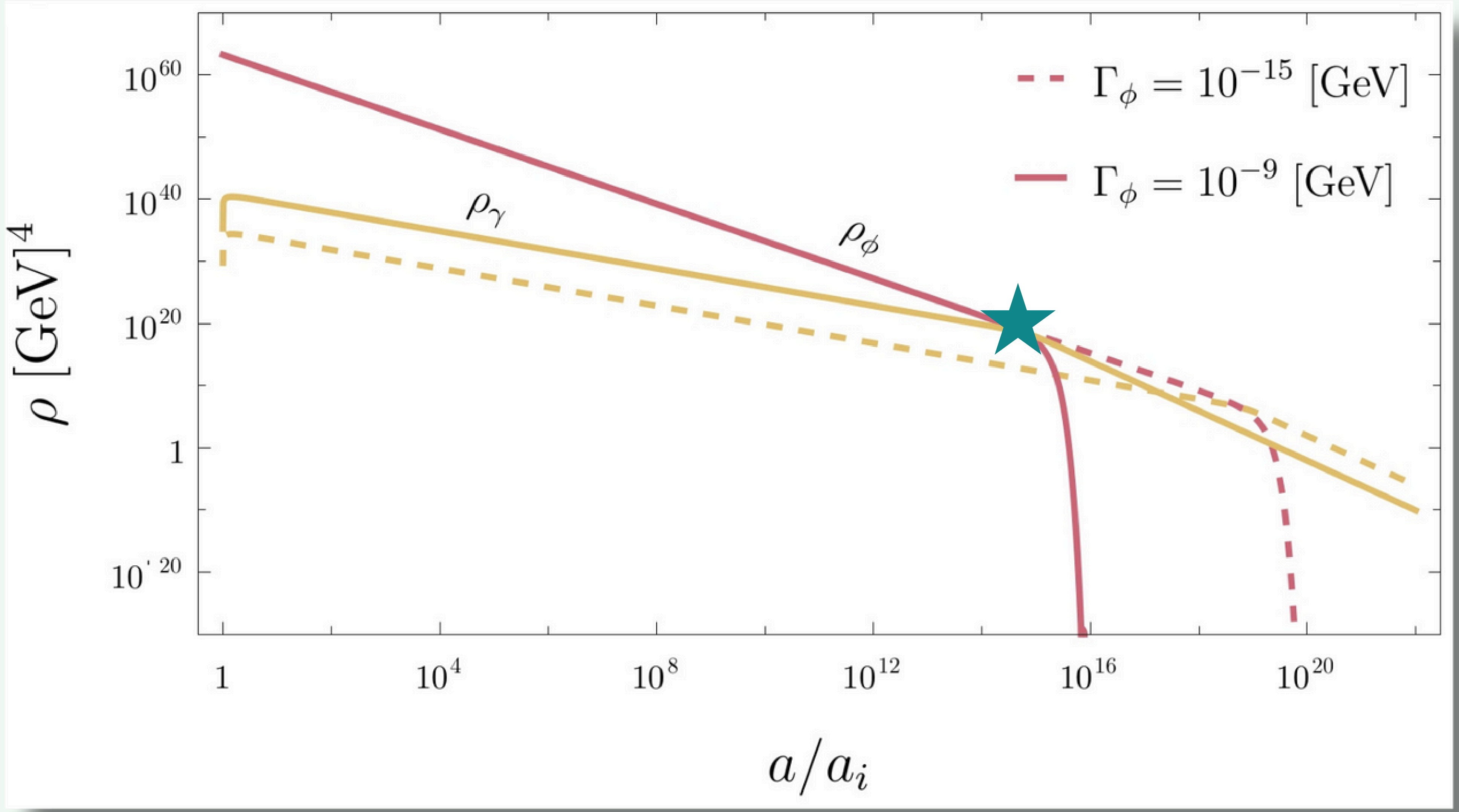
THE 'STANDARD' STORY OF REHEATING

Inflaton decays directly into the SM $\phi \to \mathrm{SM}$

Reheating moment: ★

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

Temperature of the SM bath at this moment is T_R



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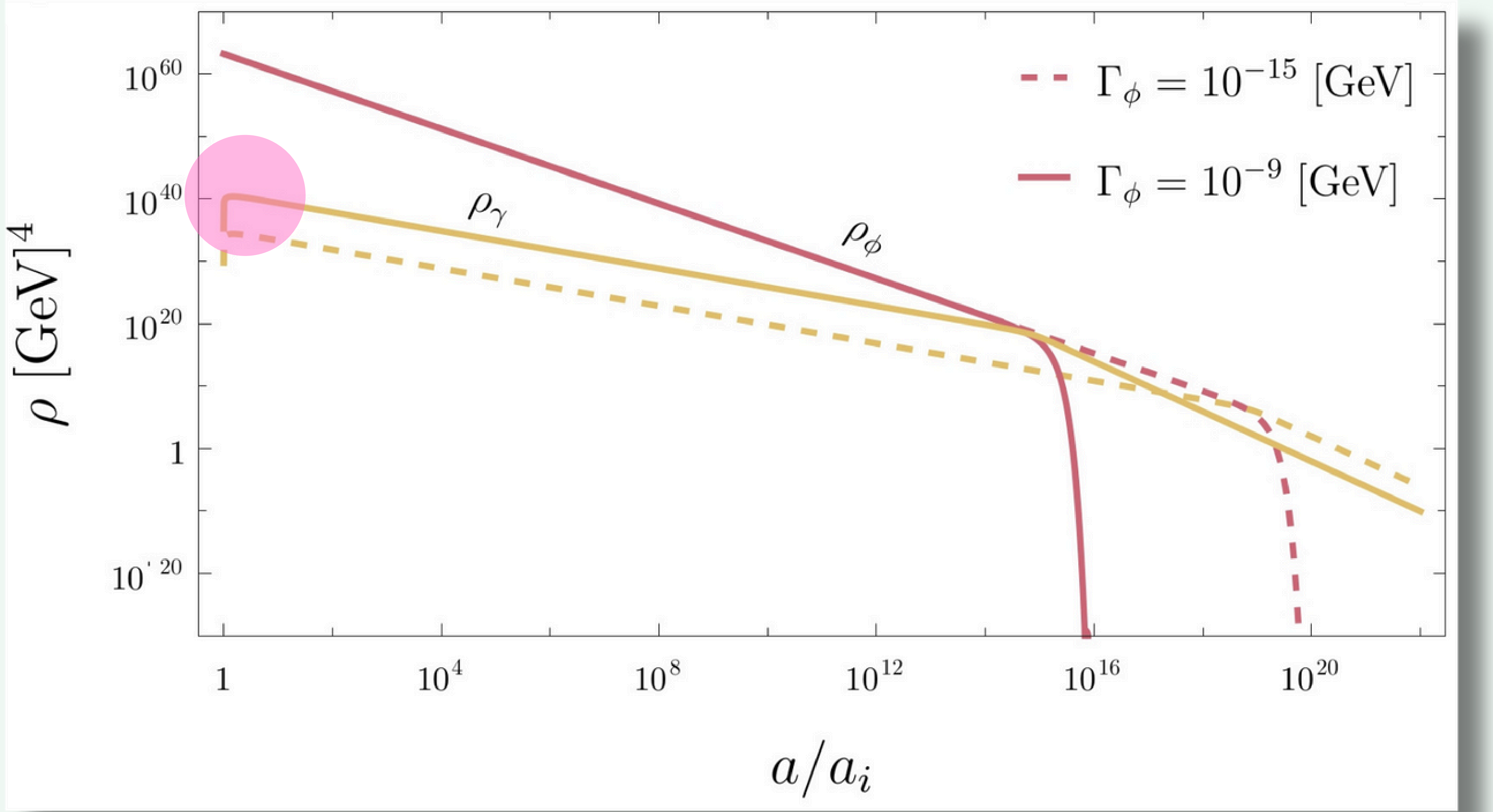


In our freeze-in at stronger coupling analysis we need to replace $T_R \to T_{\max}$

This could spoil the assumption

$$m_s < T_R$$

If Tmax is very large

AN ALTERNATIVE: 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

AN ALTERNATIVE: REHEATING VIA RH NEUTRINOS

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

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

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

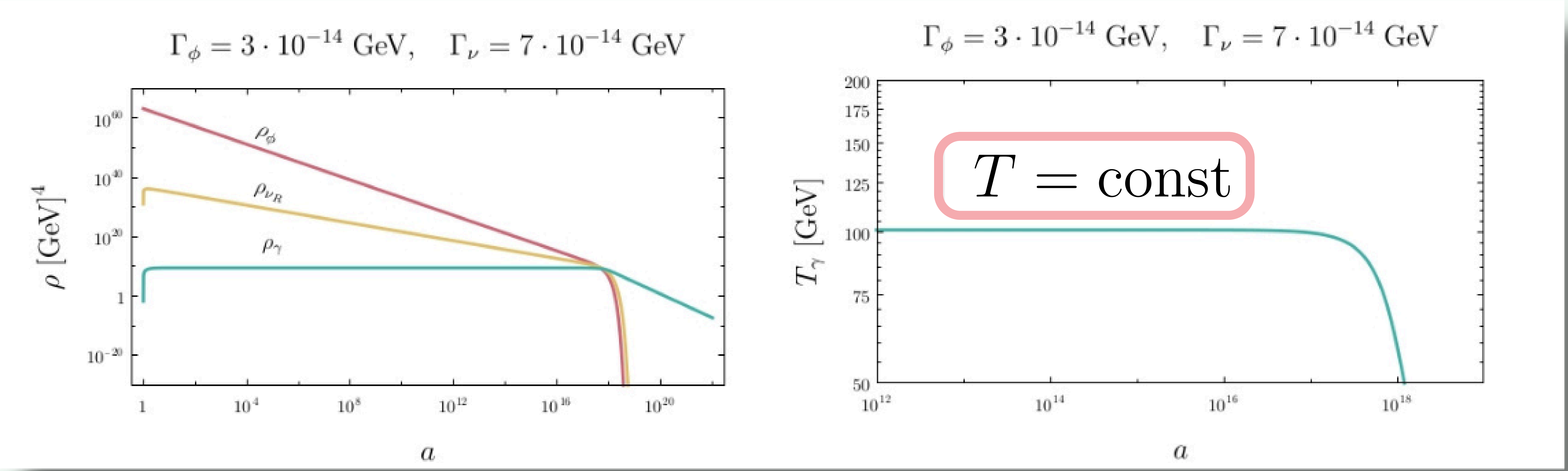
Reheating Boltzmann Equations

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

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

AN ALTERNATIVE: REHEATING VIA RH NEUTRINOS

One choice: $\Gamma_\phi \sim \Gamma_\nu$



Constant temperature before rehating

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

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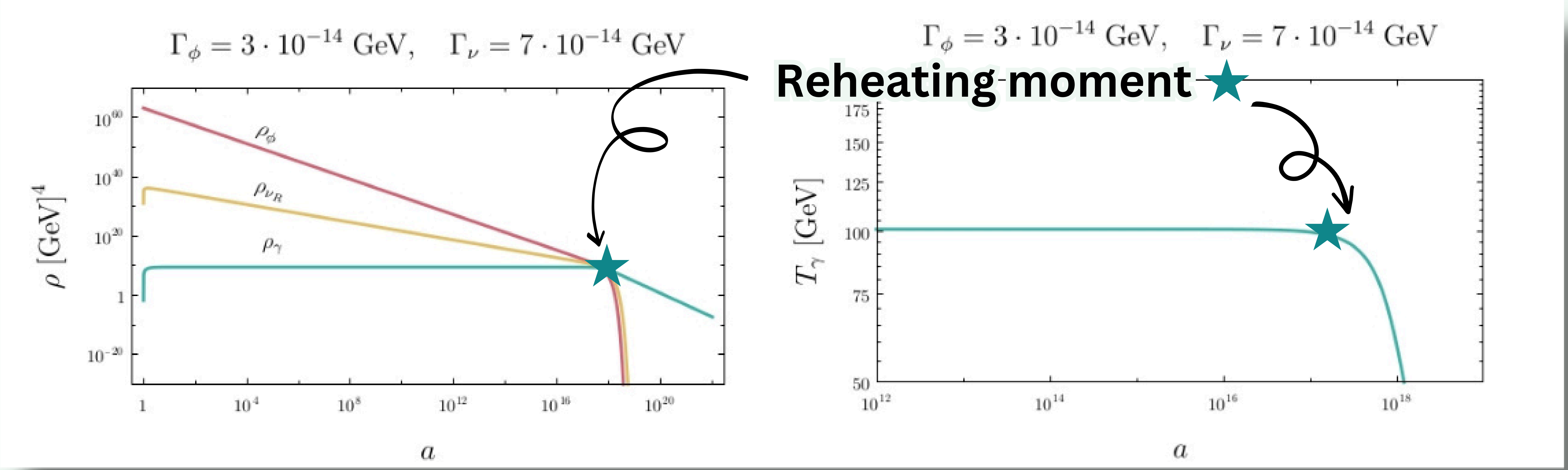

Constant temperature before rehating

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AN ALTERNATIVE: REHEATING VIA RH NEUTRINOS

$$T_R \to 0.95 \times T_R$$

5% correction with respect to the instantaneous reheating approximation

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

You can find different reheating histories here

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

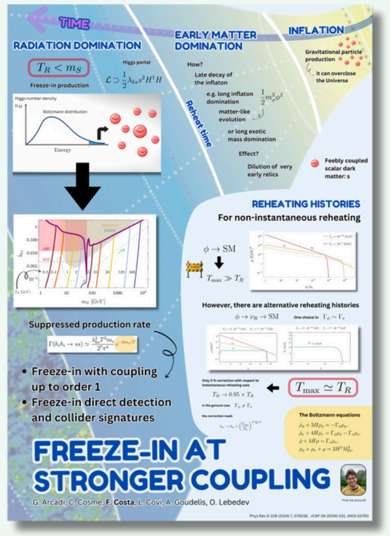
TAKE HOME MESSAGE

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 **DIRECT DETECTION AND COLLIDER SIGNATURES!**
- **NO OVERPRODUCTION GAP** BETWEEN FREEZE-OUT AND FREEZE-IN AT LOW REHEATING TEMPERATURES
- **5% CORRECTION ON TR** ACCOUNTING FOR THE REHEATING HISTORY WHEN

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



More info at the poster session

THANK YOU

Francesco Costa

Institute for Theoretical Physics,
University of Goettingen

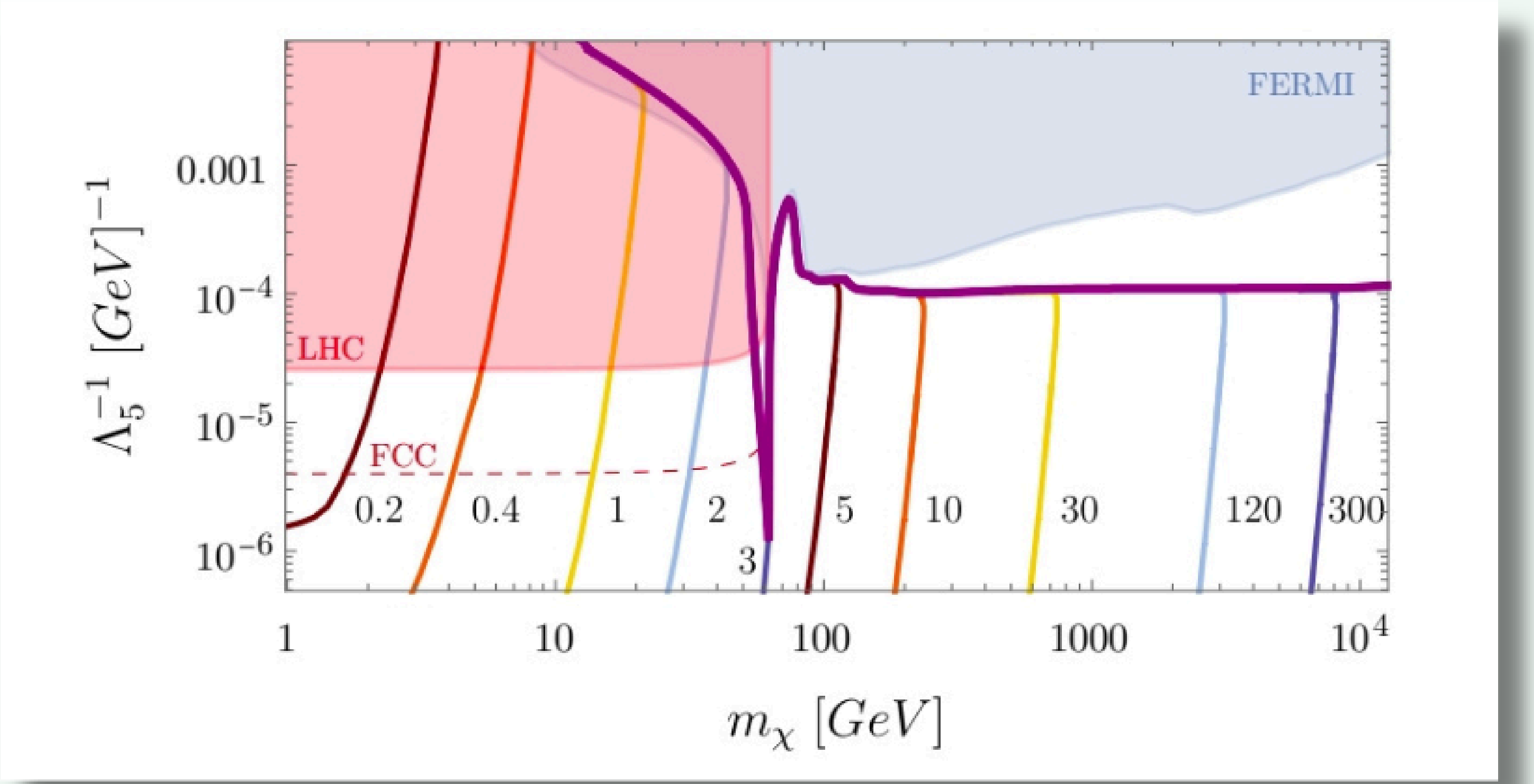
HIDDeN Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN IN PUBLICA COMMODA SEIT 1737

This project has received funding/support from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 860881-HIDDeN

BACK-UP

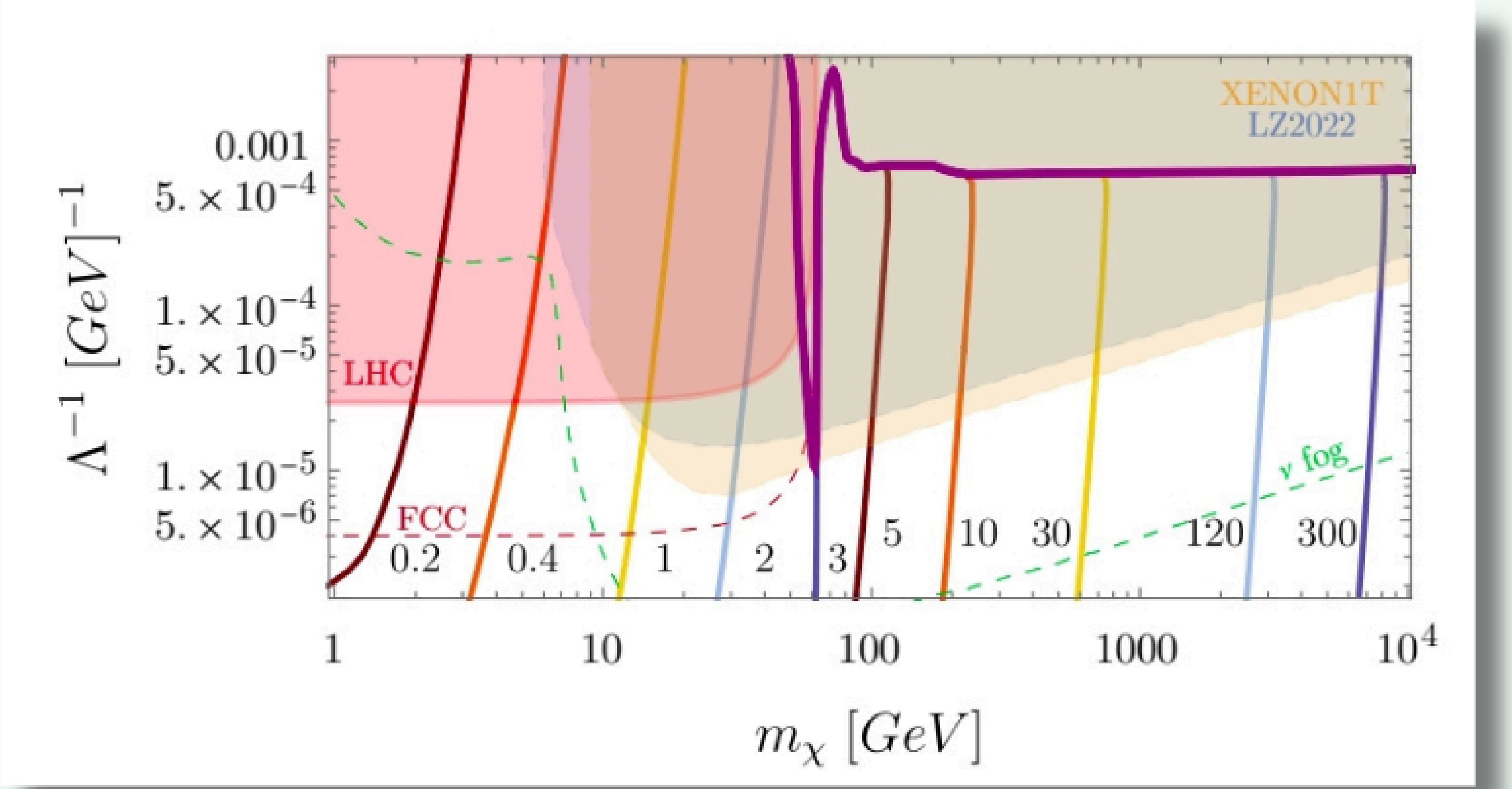
CP ODD



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)

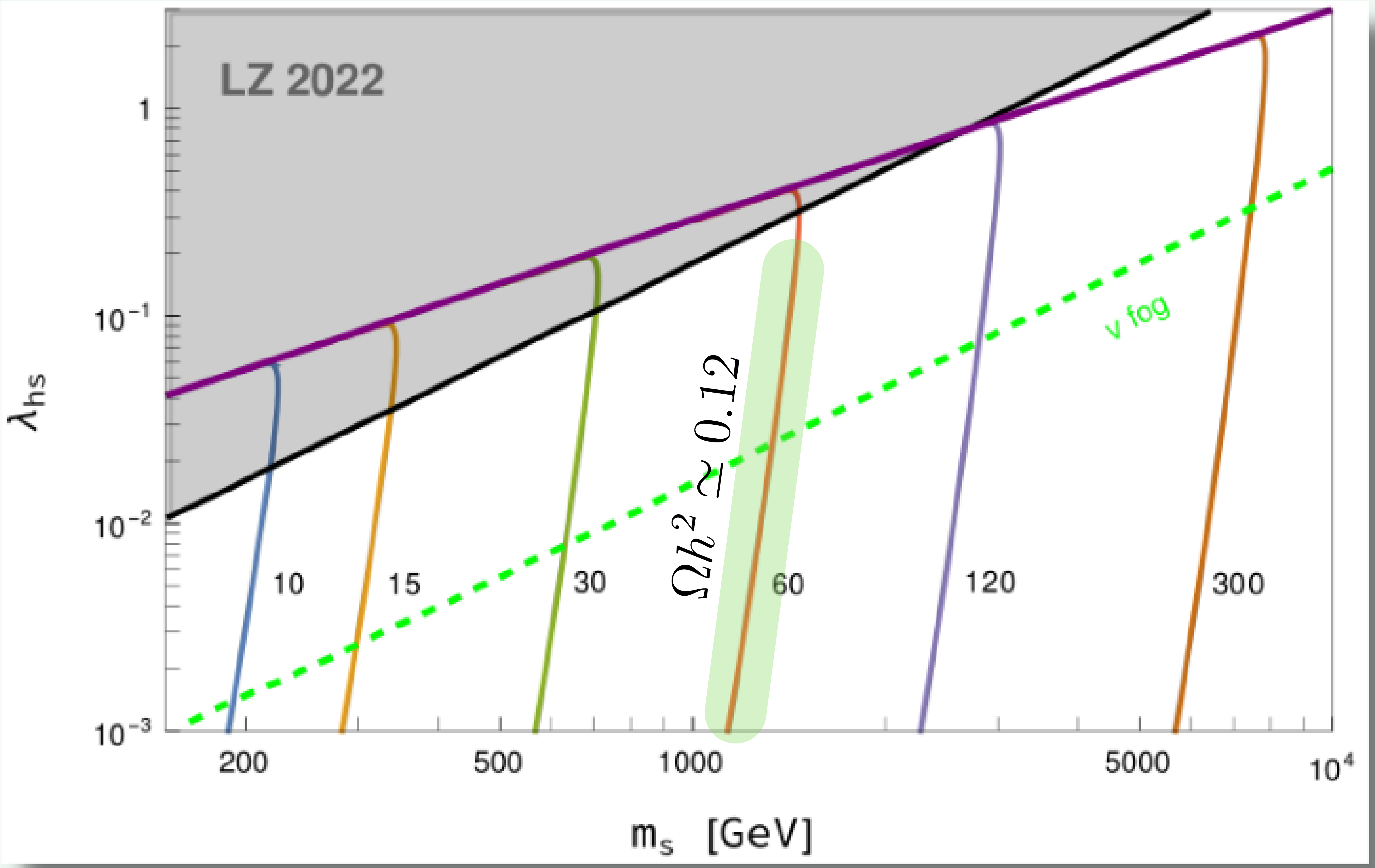
CP EVEN



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

FREEZE-IN REGIME

FREEZE-IN



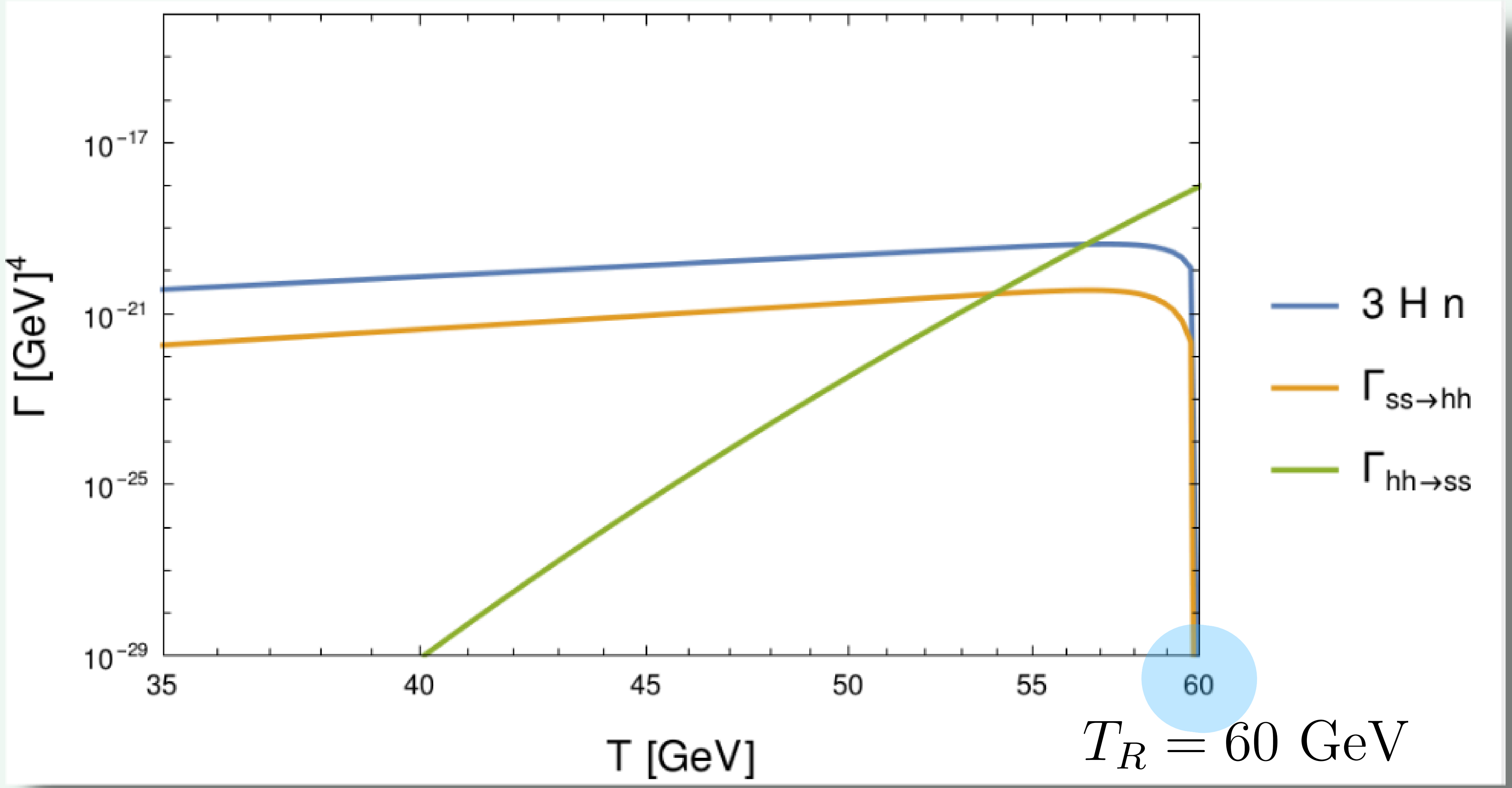
C. Cosme, FC, O. Lebedev, arXiv: 2306.13061

FREEZE-IN REGIME

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

Boltzmann equation

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



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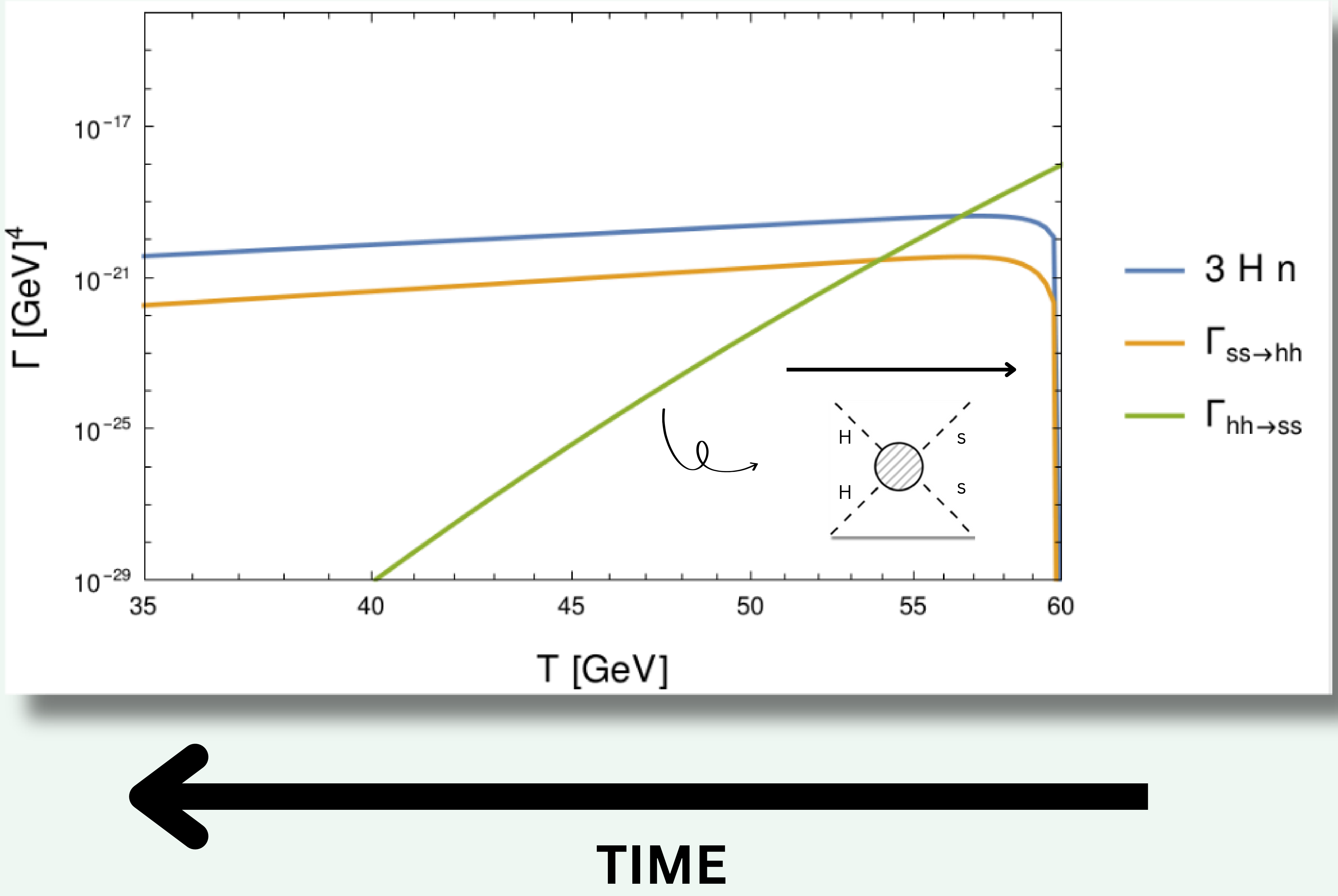
FREEZE-IN REGIME

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



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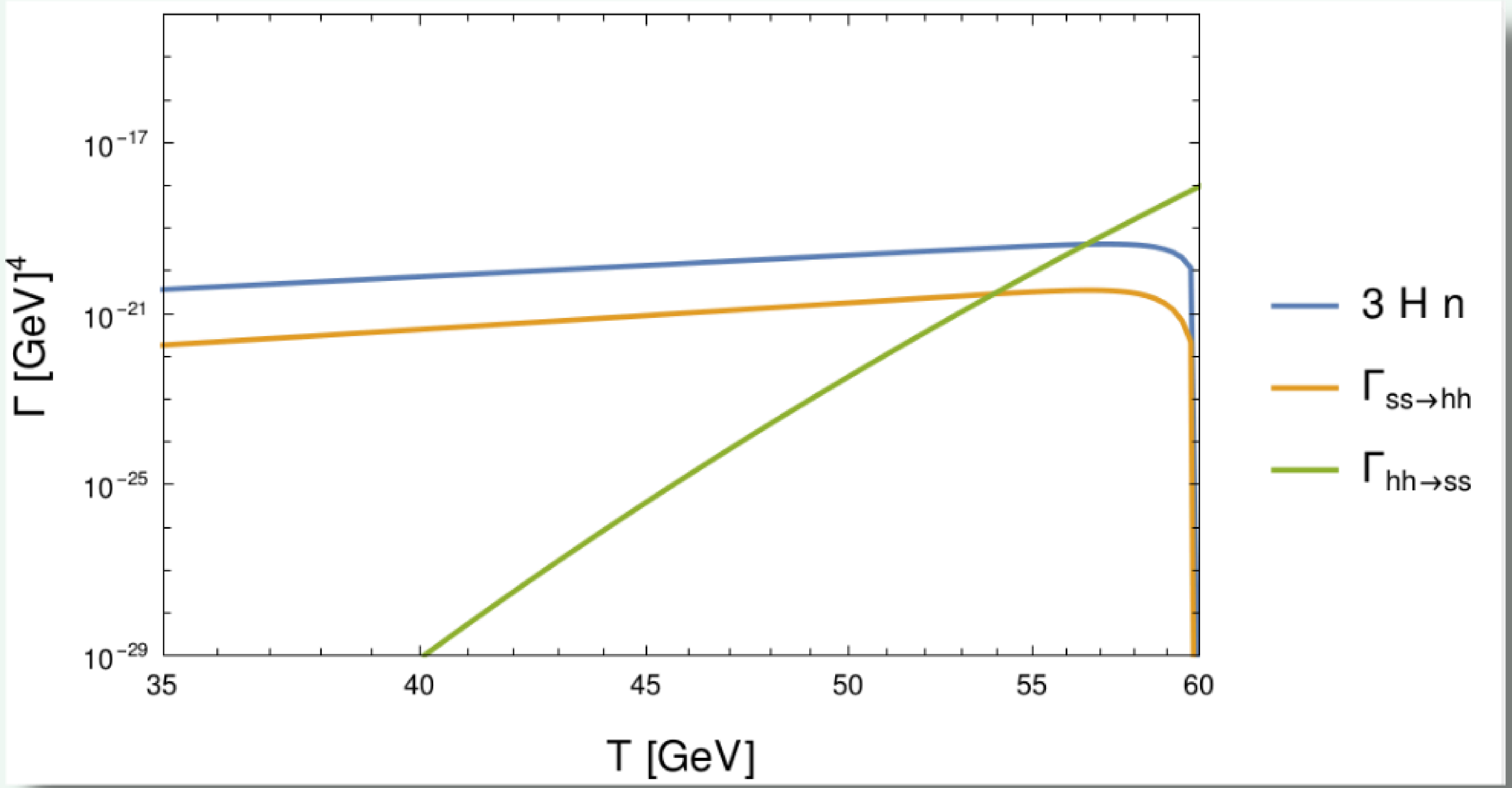
FREEZE-IN REGIME

But

$$\Gamma > 3Hn$$



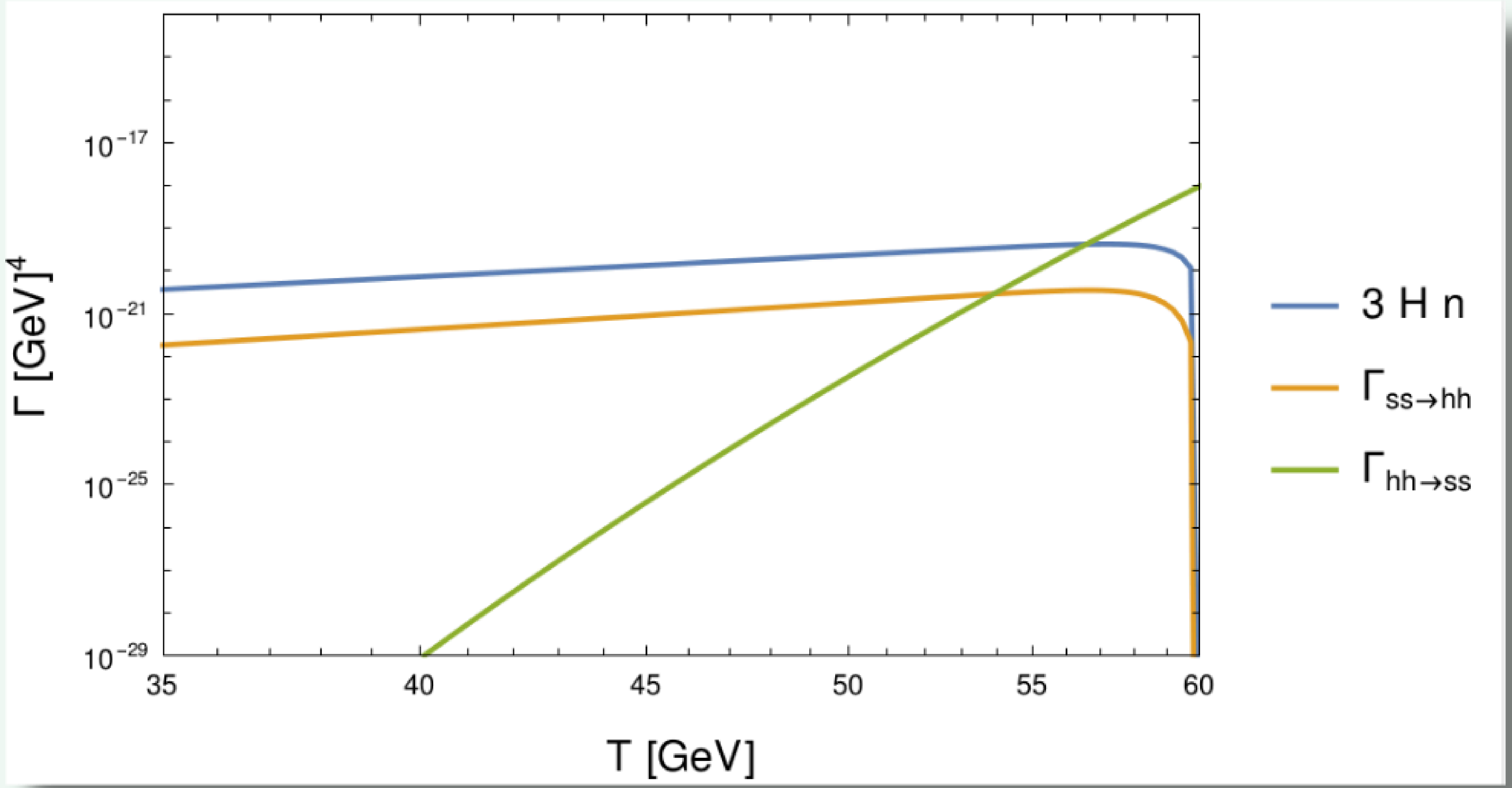
TIME

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

FREEZE-IN REGIME

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

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



TIME

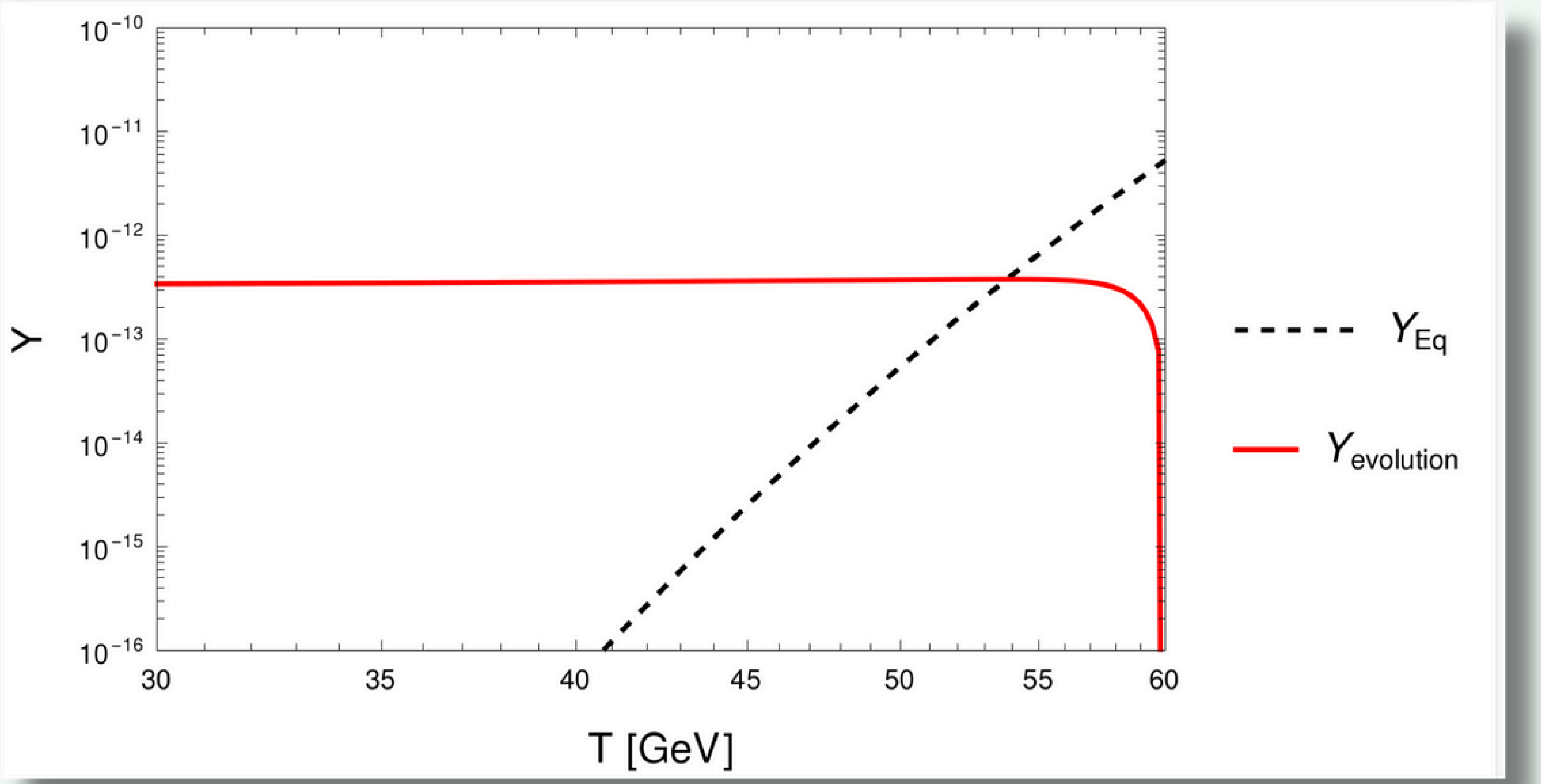
C. Cosme, FC, O. Lebedev, arXiv: 2306.13061

FREEZE-IN REGIME

In fact the number density does not follow the equilibrium curve

OUT OF EQUILIBRIUM

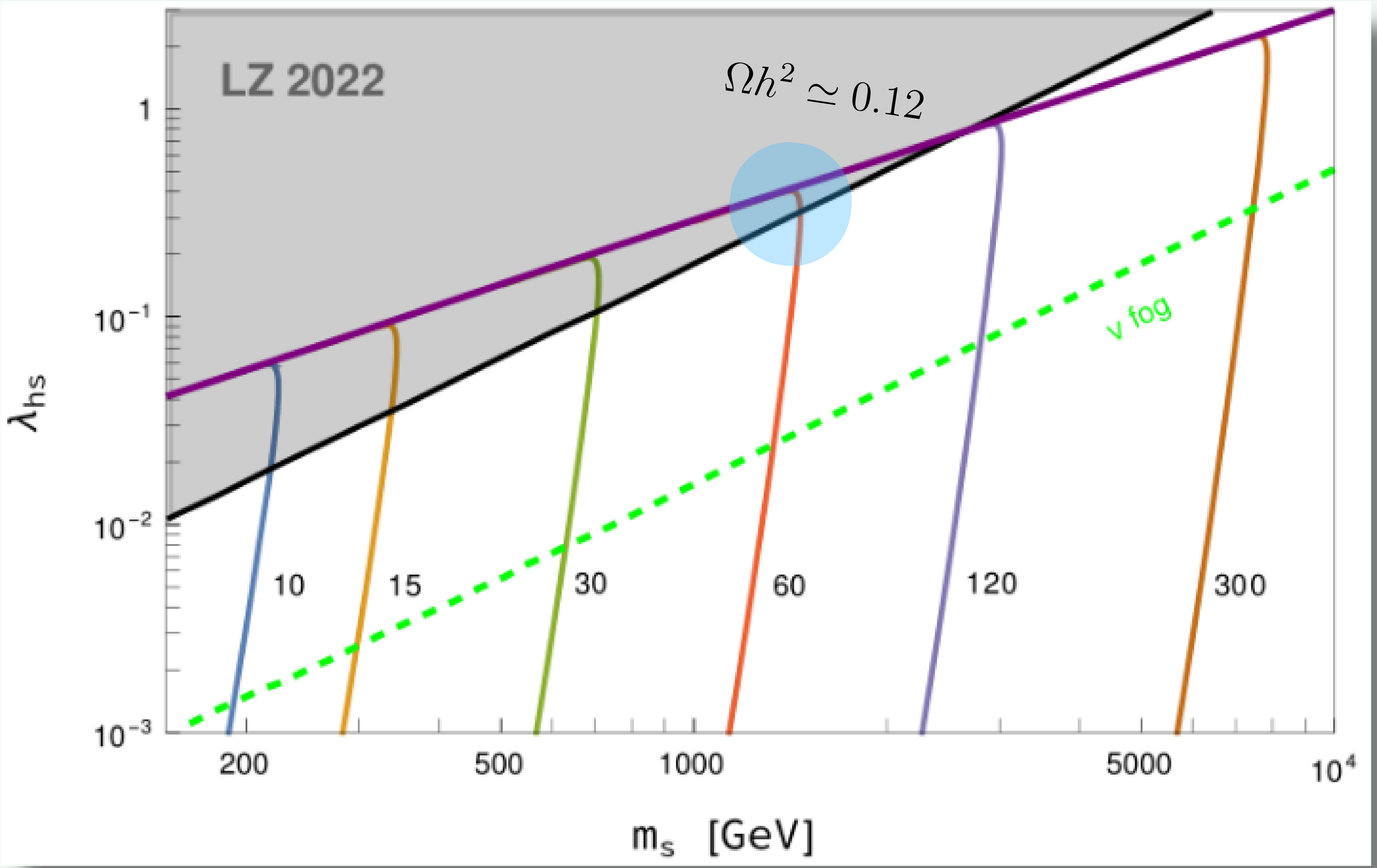
Looks like a UV freeze-in production, peaked at the reheating temperature



TIME

ANNIHILIATION BECOMES IMPORTANT

BACKREACTION



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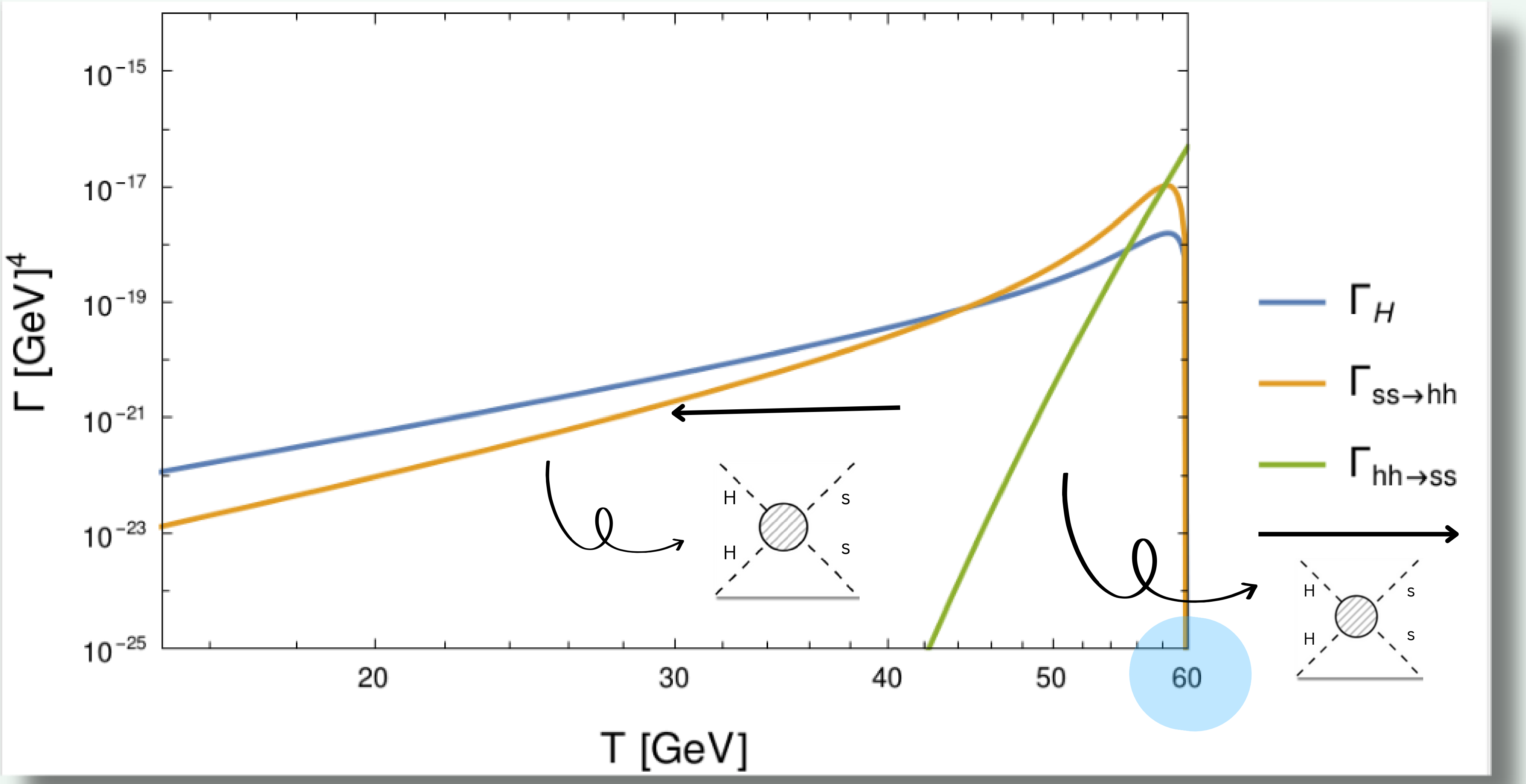
ANNIHILIATION BECOMES IMPORTANT

Boltzmann equation

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

Here the backreaction is not negligible anymore

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



TIME

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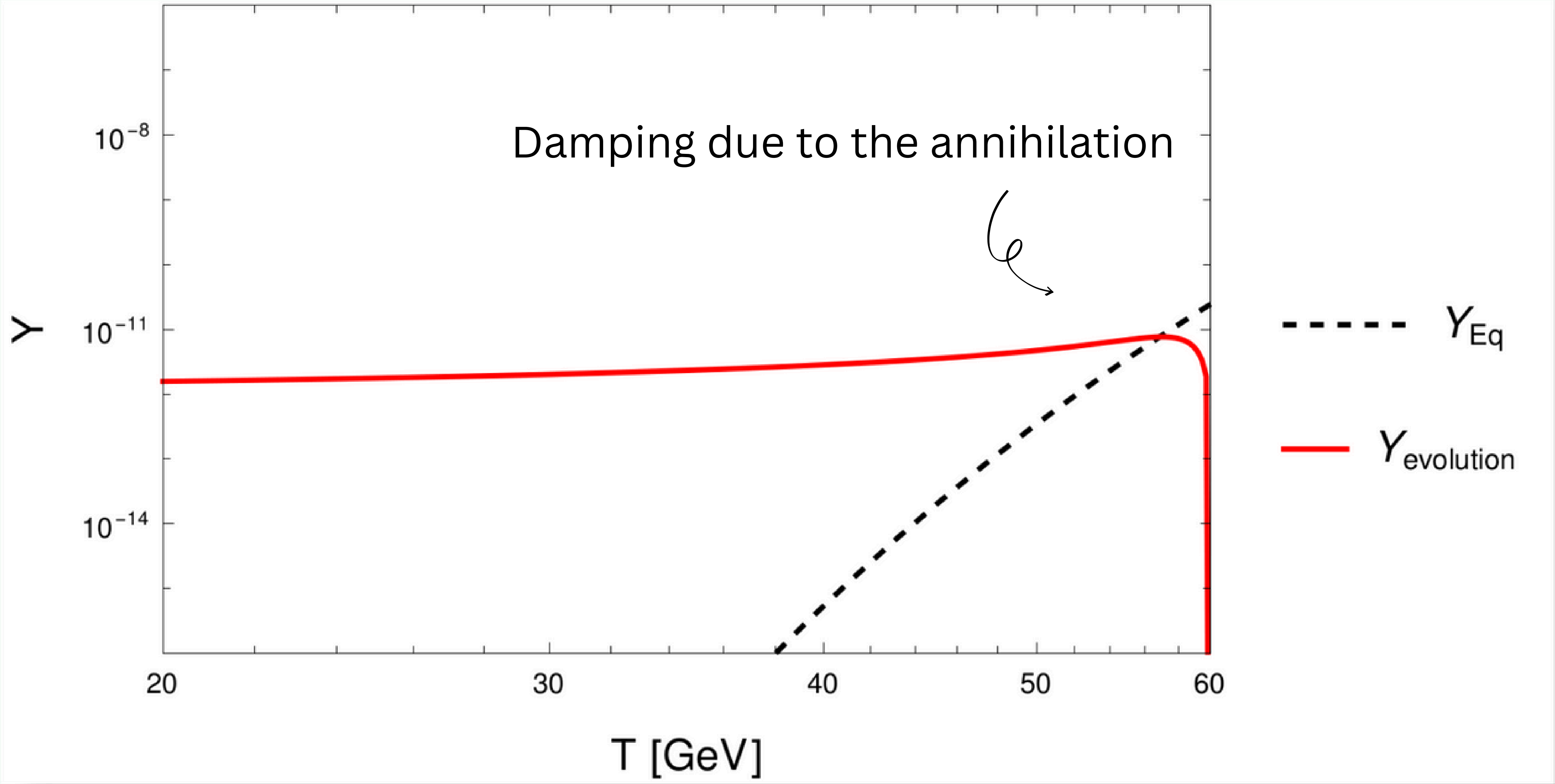
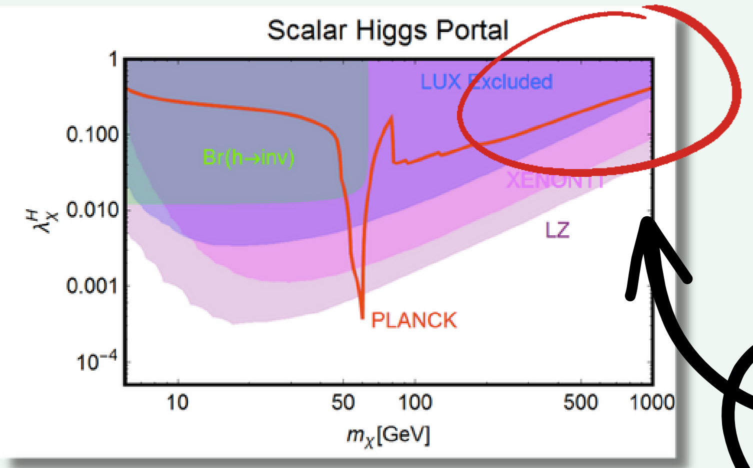
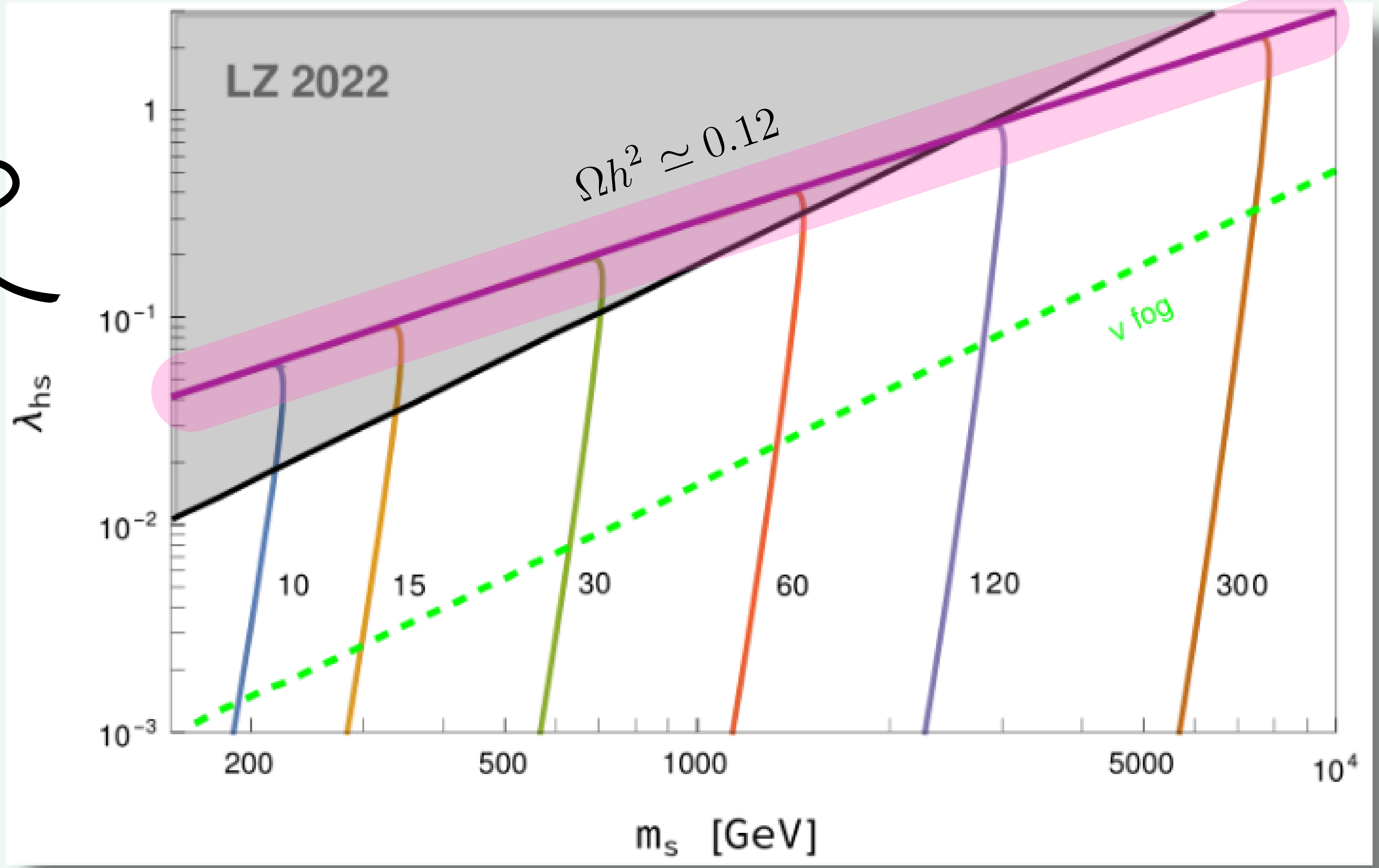


FREEZE-OUT REGIME





FREEZE-OUT

FREEZE-OUT REGIME

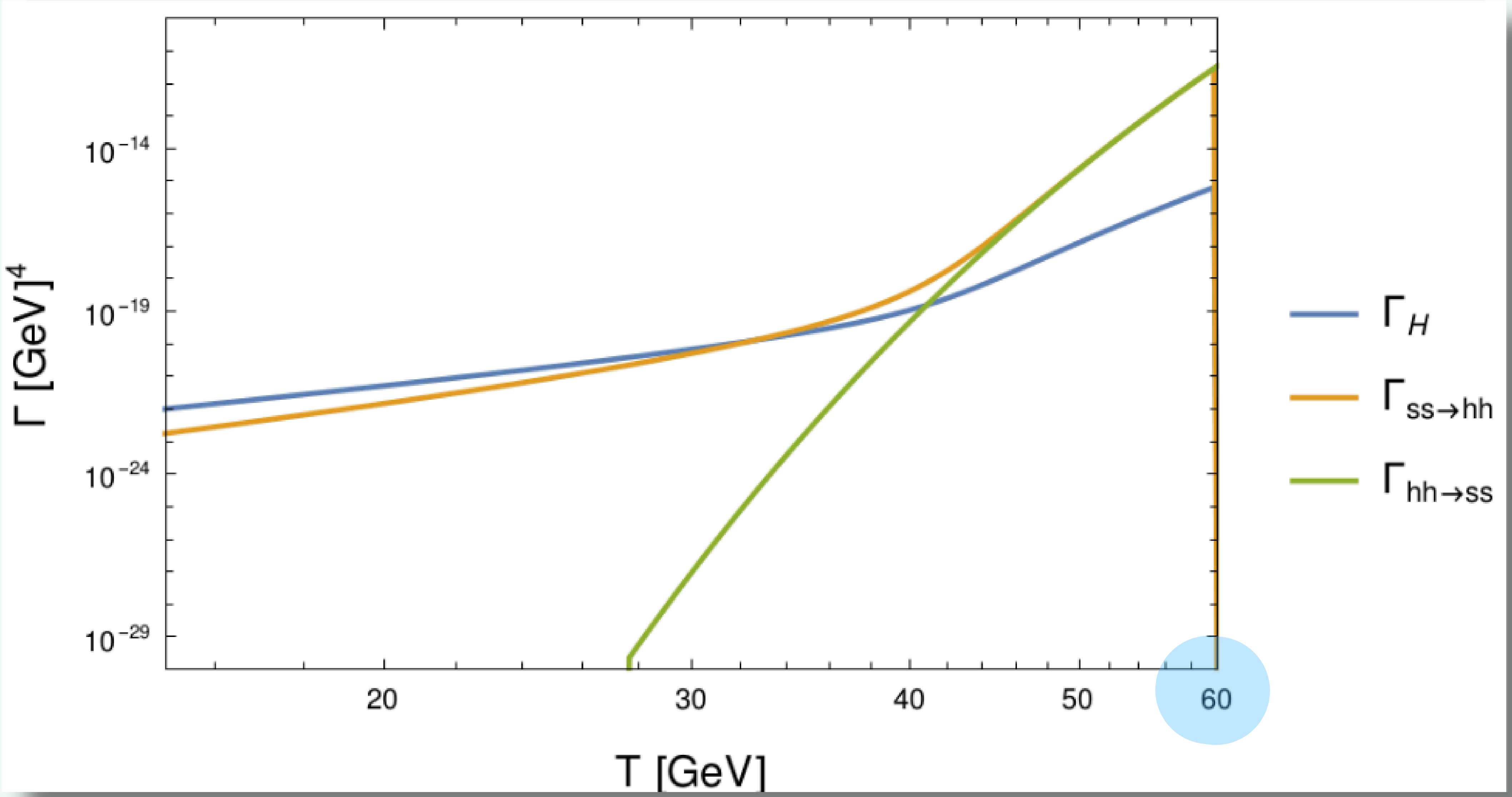
$m_s = 1012\ \text{GeV} \qquad \lambda_{hs} = 0.29$

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

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

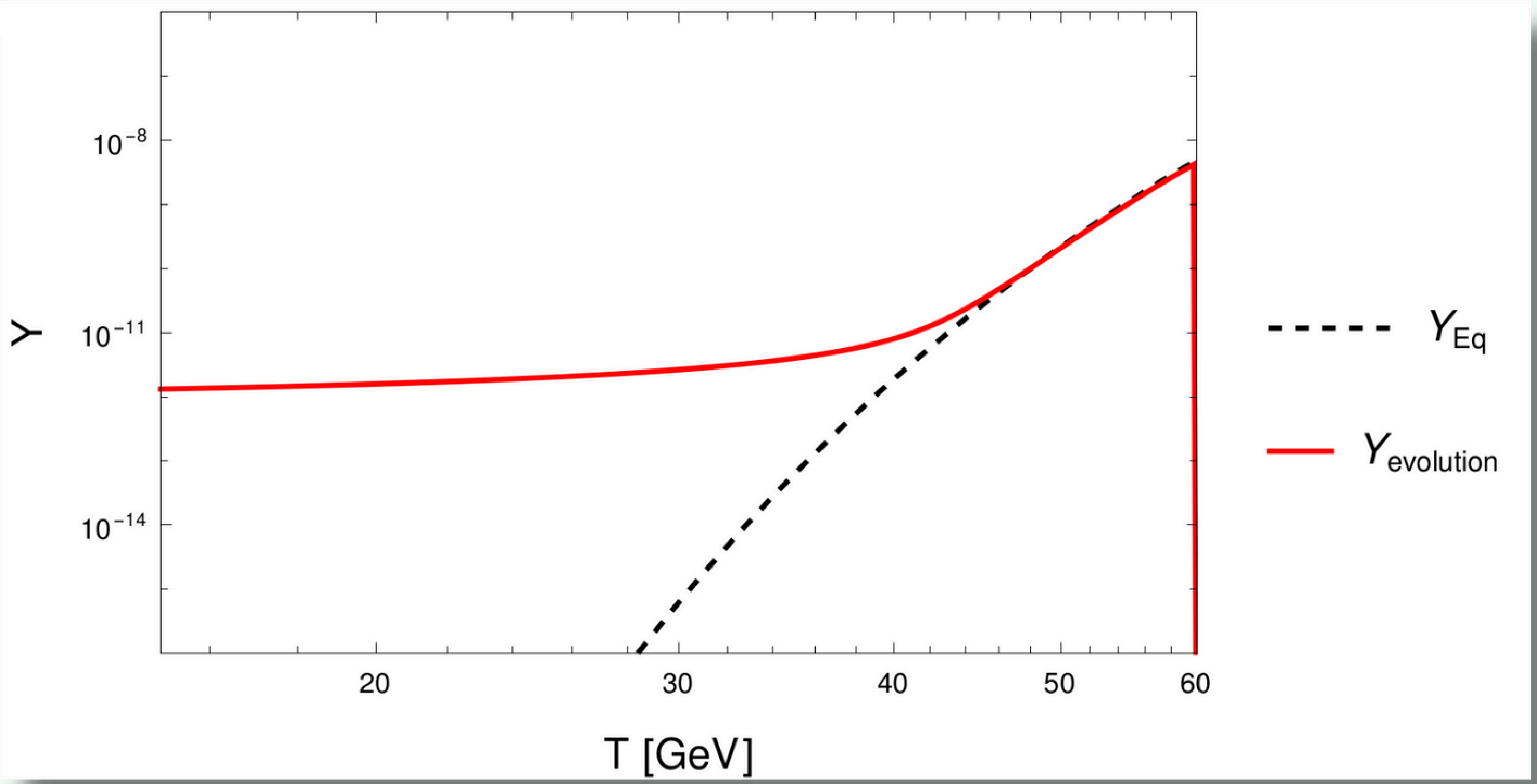


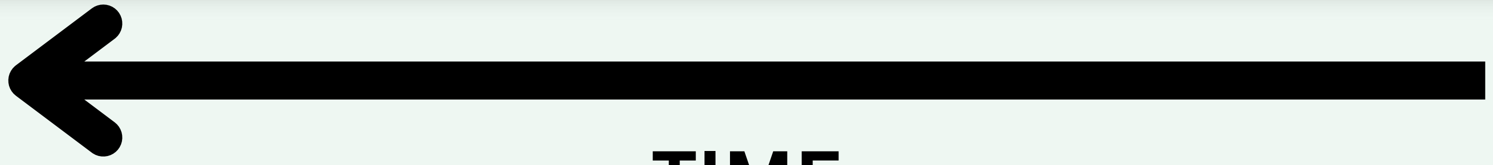
TIME

FREEZE-OUT REGIME

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

IN EQUILIBIRIUM





TIME

FREEZE-IN TO FREEZE-OUT

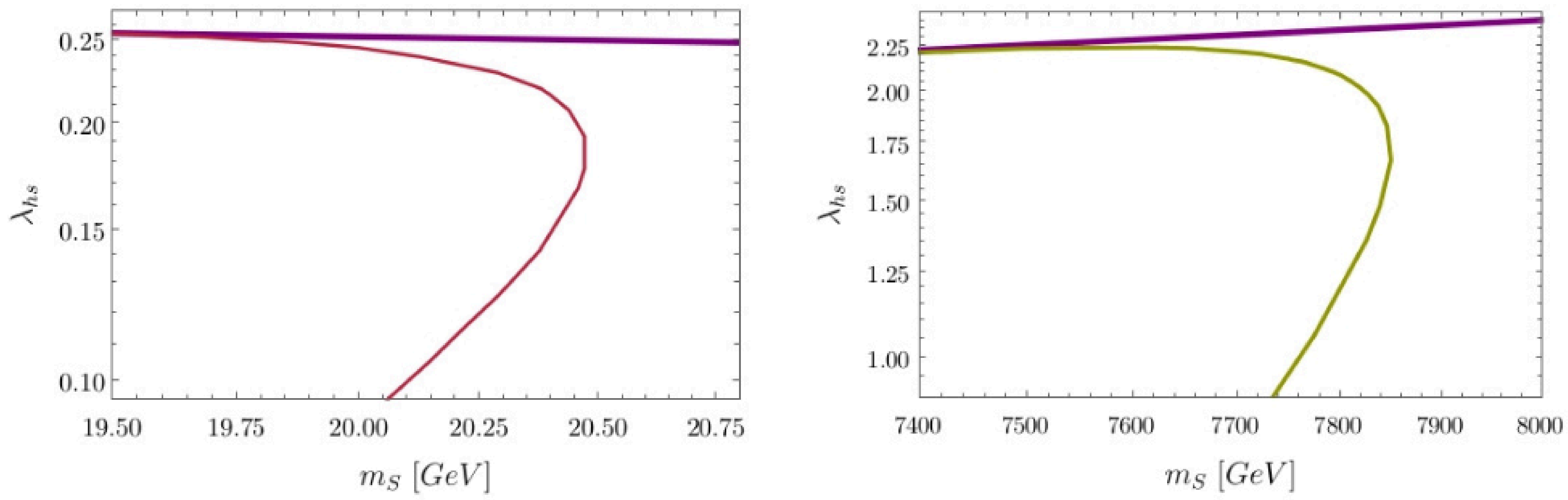


Figure 4: Freeze-in to freeze-out transition at low and high temperatures. The purple line corresponds to thermal DM as in Fig. 2. *Left:* $T_R = 1$ GeV. *Right:* $T_R = 300$ GeV.