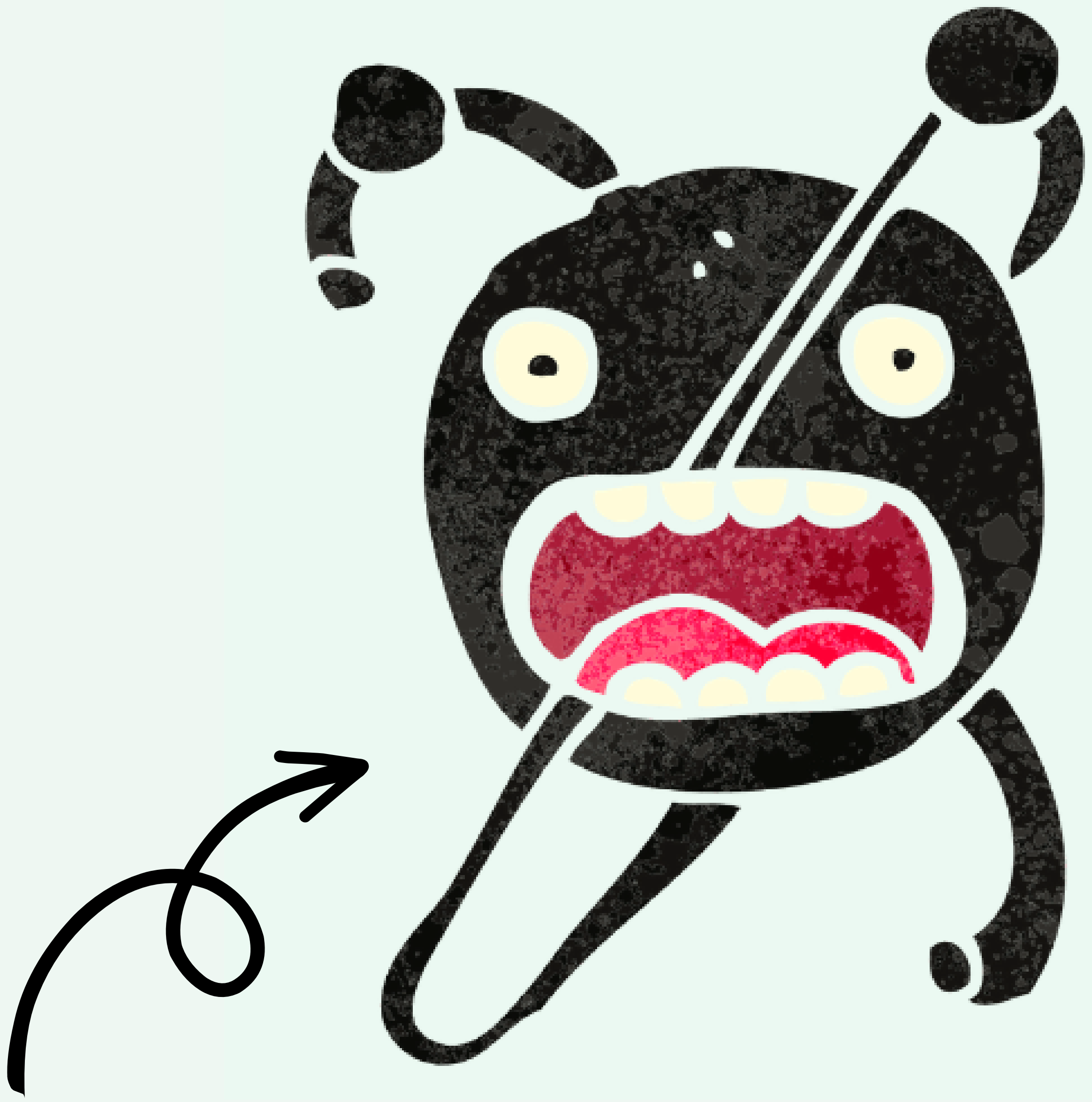
University of Goettingen, Institute for Theoretical Physics

FREEZE-IN:

PROBLEMS AND OPPORTUNITIES

Francesco Costa

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

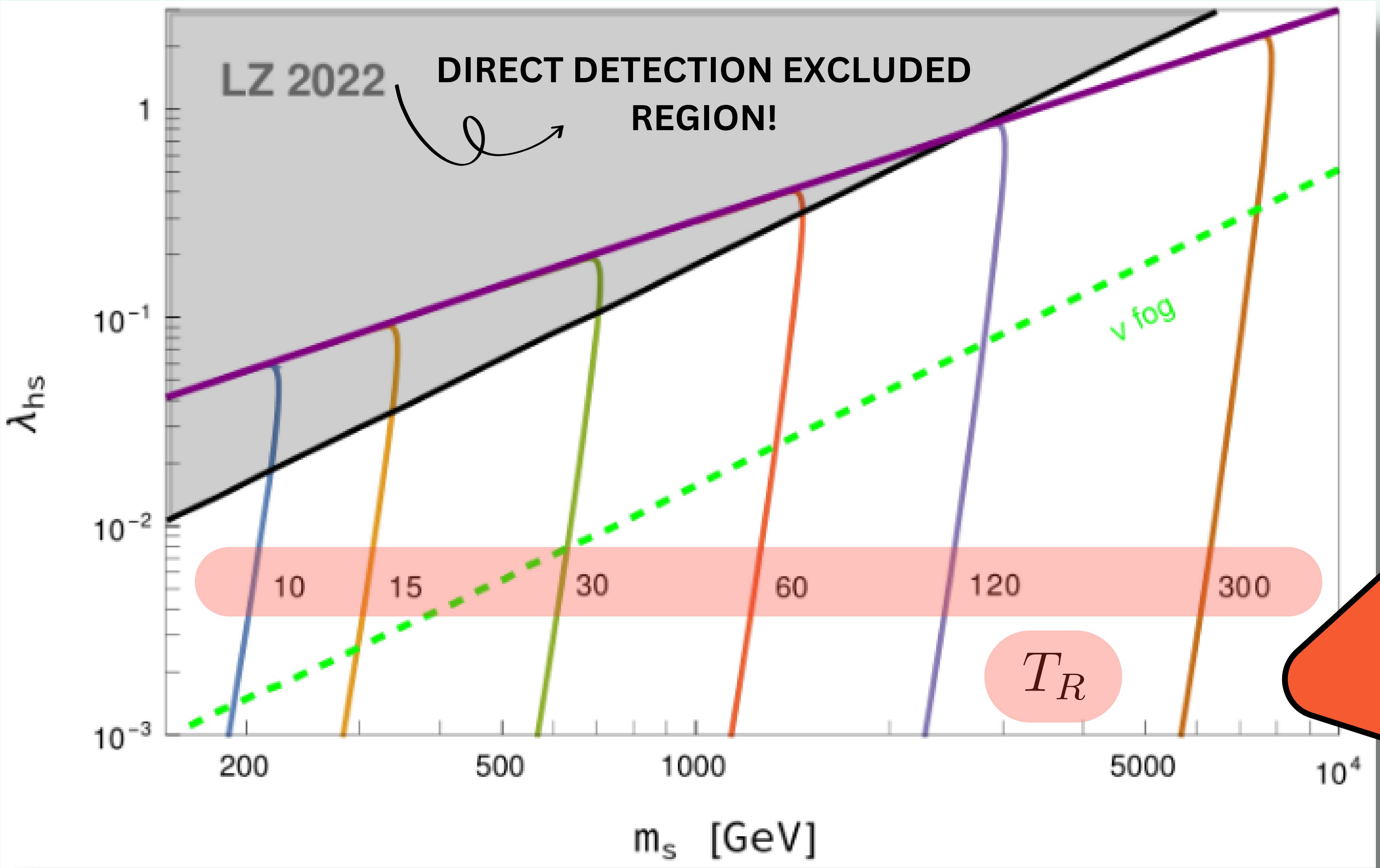


“Artistic” interpretation of
a FIMP dark matter

TeVPA 2023, Napoli

HIGGS PORTAL TO SCALAR DM

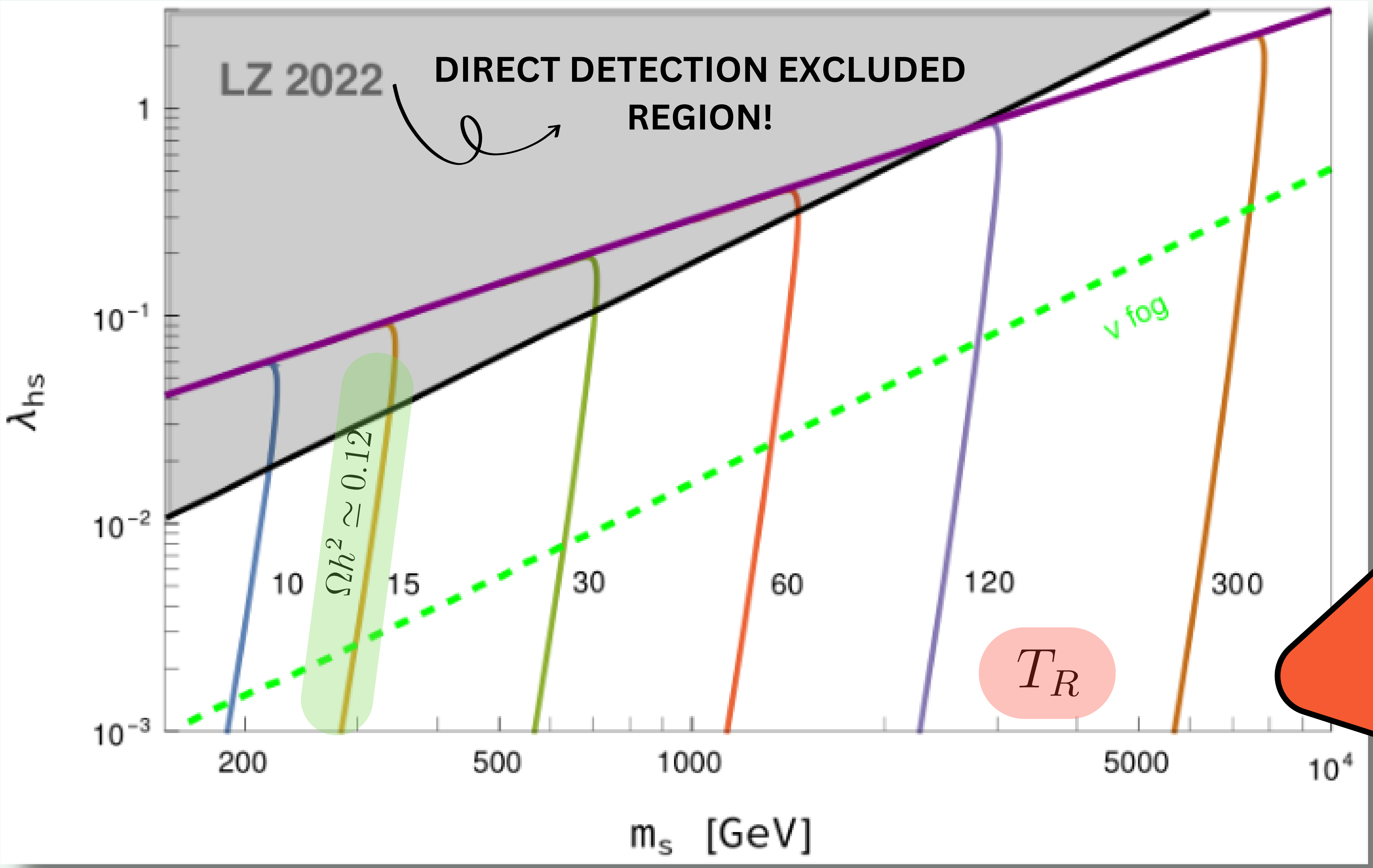
FREEZE-IN



SPOILER ALERT

HIGGS PORTAL TO SCALAR DM

FREEZE-IN



SPOILER ALERT

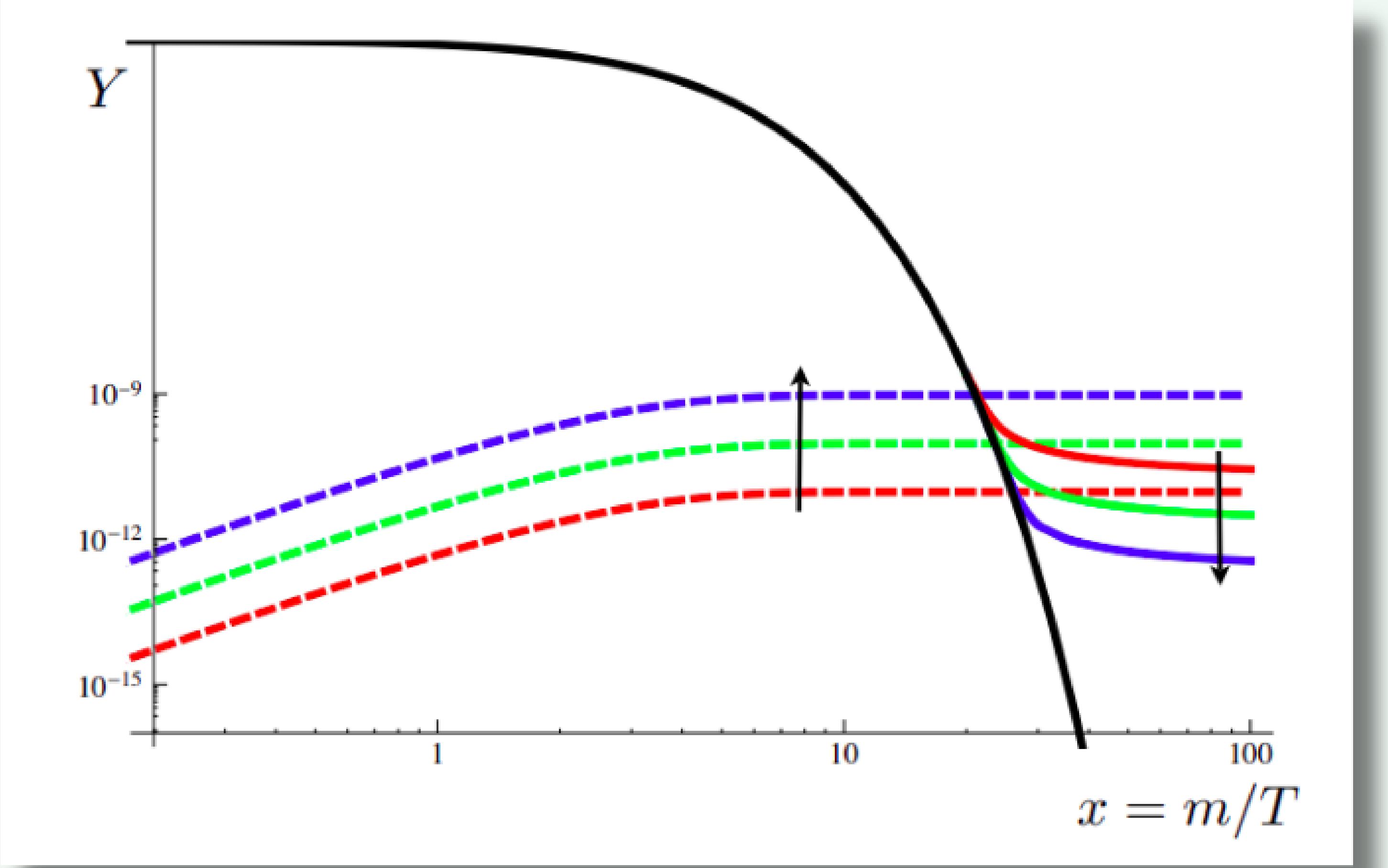
FREEZE-IN

$$\Gamma < H$$

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

  ➜ We assume a negligible initial abundance
- Very low couplings

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



J. McDonald, hep-ph/0106249

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

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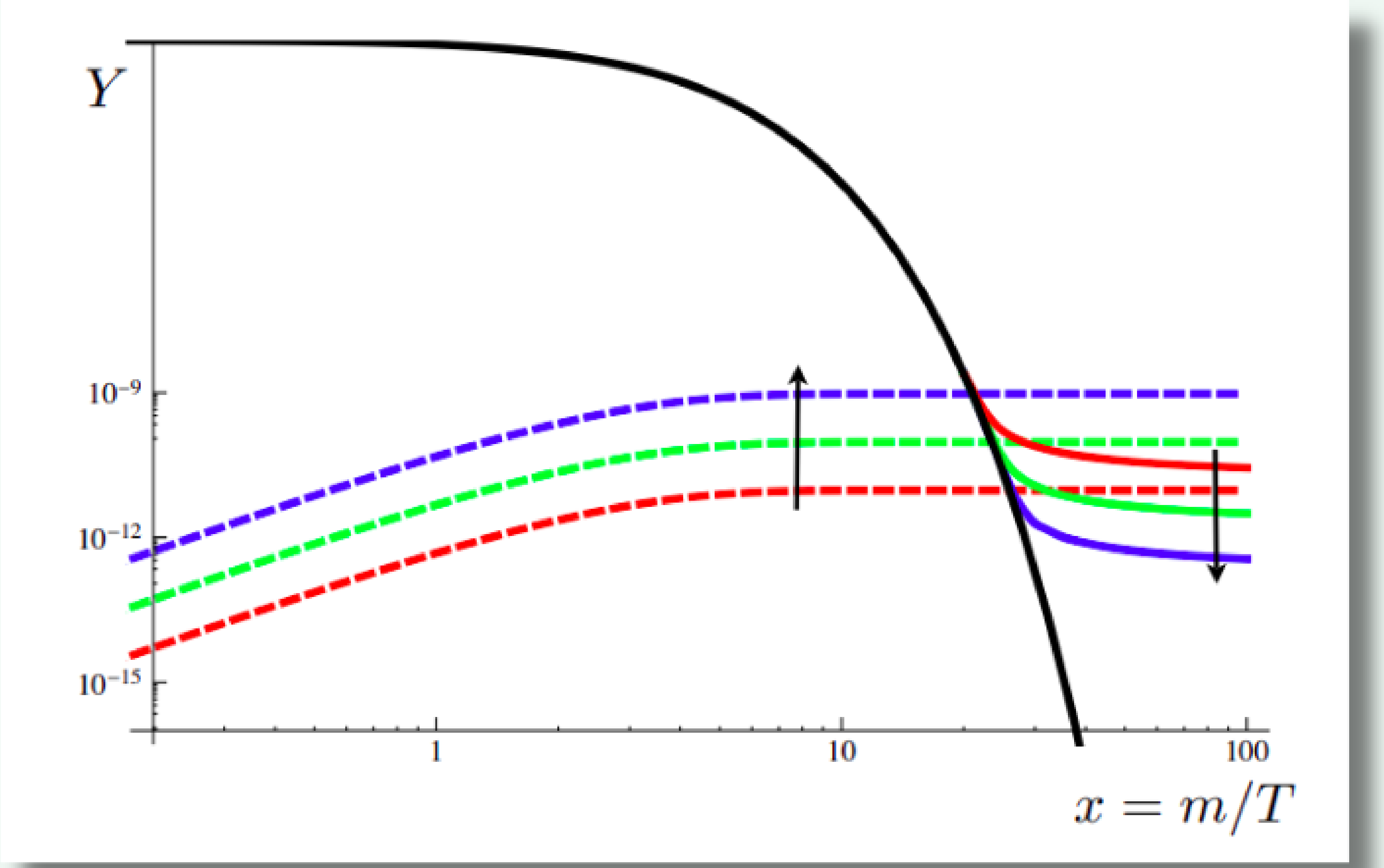

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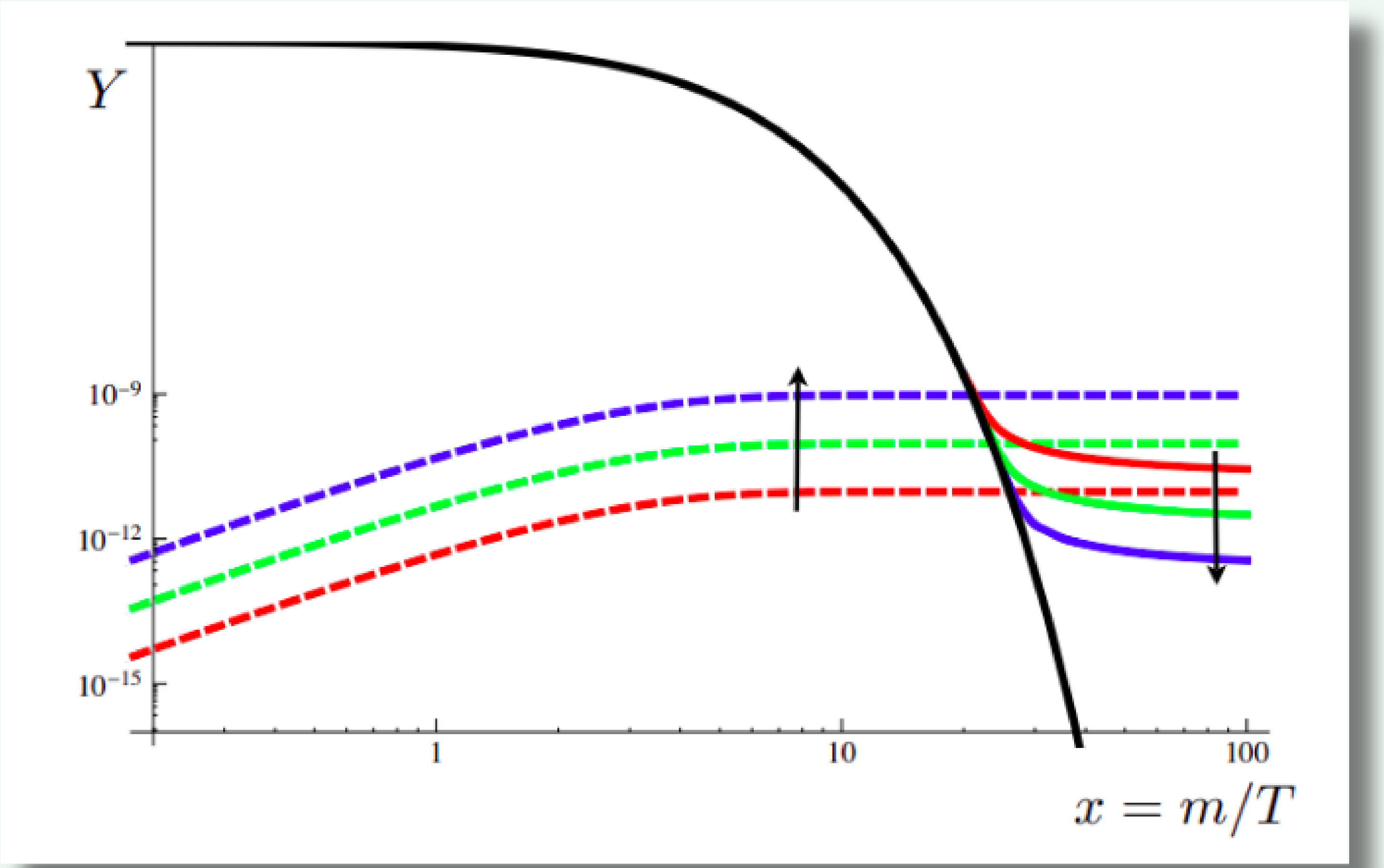

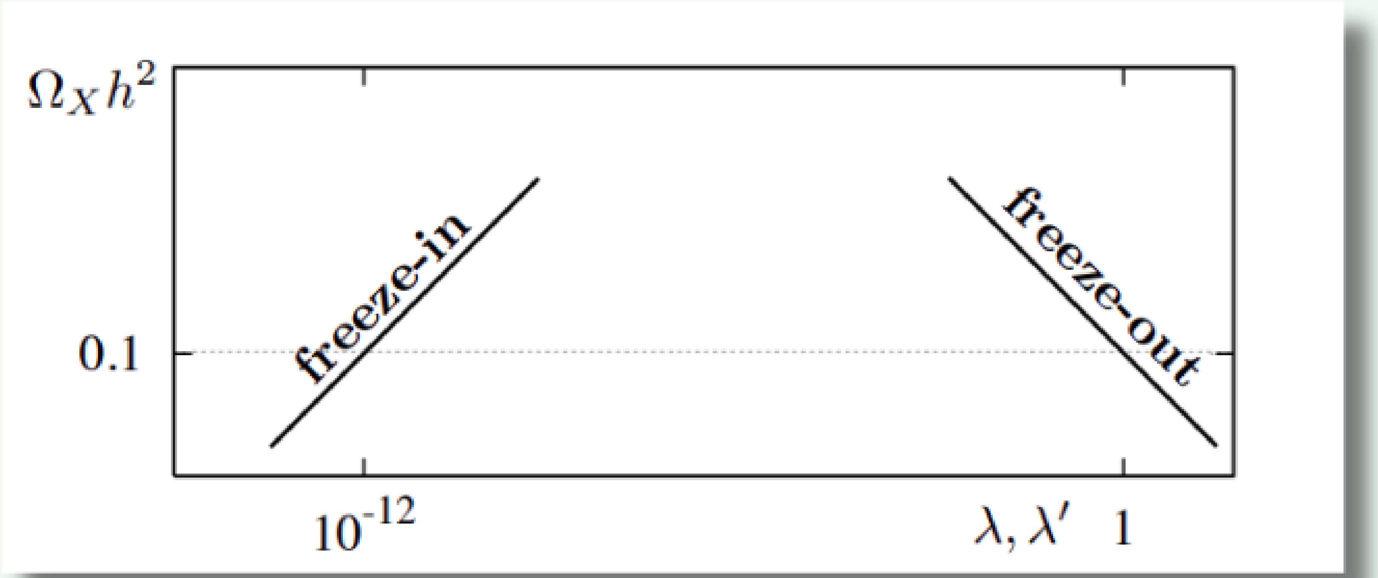

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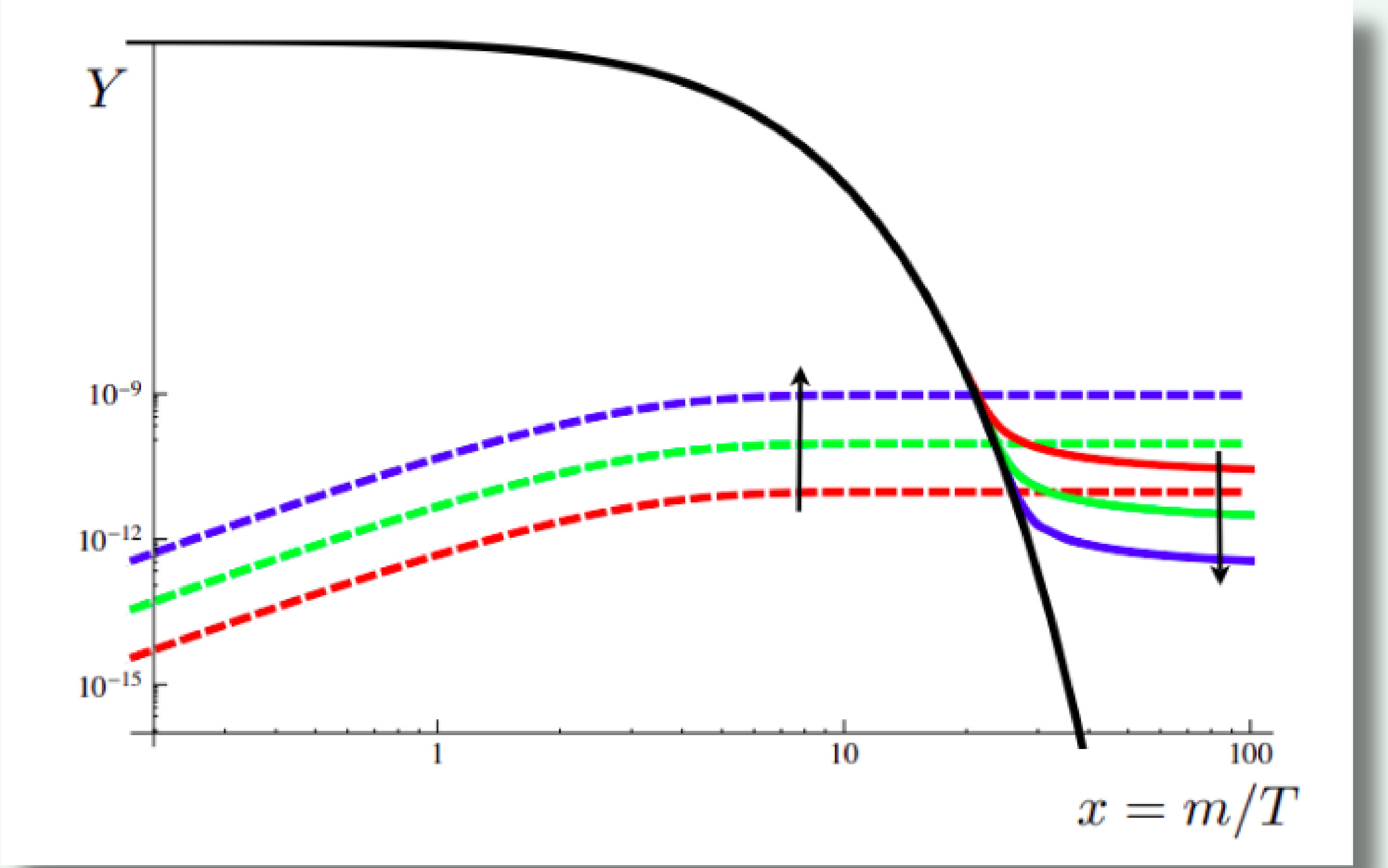

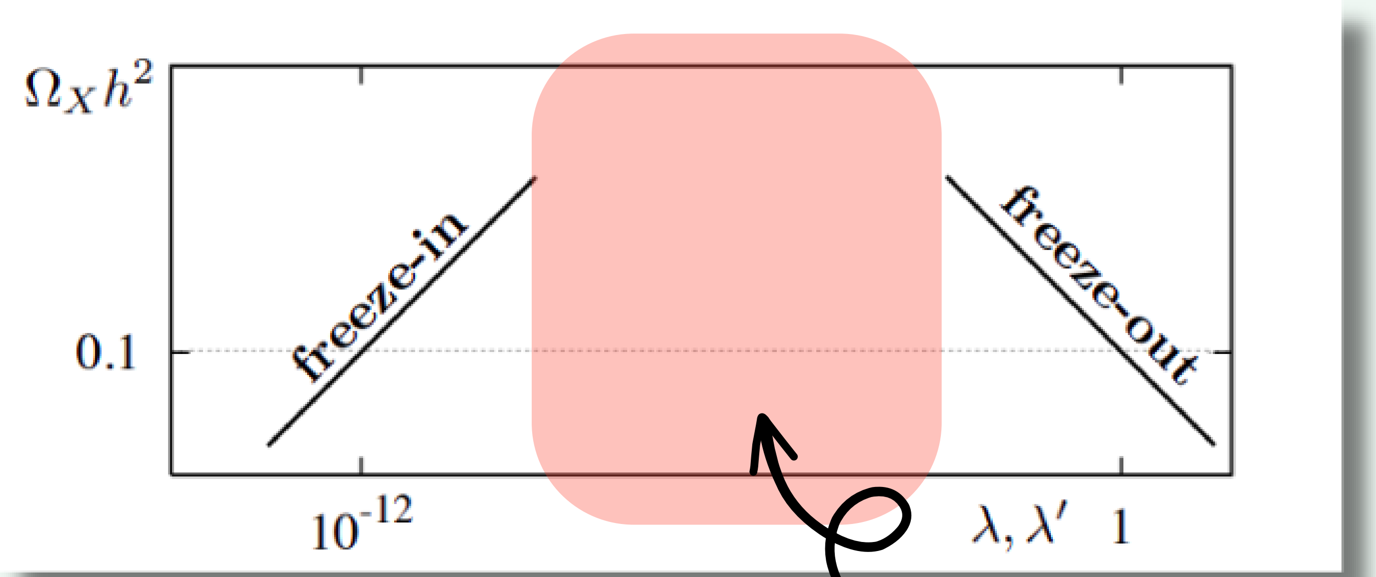

Overproduction

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

GRAVITATIONAL PARTICLE PRODUCTION

INFLATON OSCILLATING AT THE END OF INFLATION → OSCILLATION OF THE SCALE FACTOR

with s is a feebly interacting particle

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

GRAVITATIONAL PARTICLE PRODUCTION

INFLATON OSCILLATING AT THE END OF INFLATION

OSCILLATION OF THE SCALE FACTOR

$$\langle a(t) \rangle = a_0 \left(\frac{t}{t_0} \right)^{\frac{n+2}{3n}}$$

OSCILLATING BACKGROUND METRIC

with s is a feebly interacting particle

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OSCILLATING BACKGROUND METRIC

PARTICLE PRODUCTION

with s is a feebly interacting particle

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GRAVITATIONAL PARTICLE PRODUCTION

s is a feebly interacting particle

PRODUCTION DURING INFLATON OSCILLATION

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GRAVITATIONAL PARTICLE PRODUCTION

s is a feebly interacting particle

PRODUCTION DURING INFLATON OSCILLATION

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

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

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

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

$\Omega_s h^2 \lesssim 0.1$

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

Lower bound on the length matter dominated epoch in order to avoid overproduction of DM

O. Lebedev, 2210.02293
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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

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

QUANTUM GRAVITY

$$C\frac{\phi^4 s^2}{M_{\rm Pl}^2} \rightarrow \Delta_{\rm NR} \gtrsim 10^{17} C^2 \frac{m_s}{\rm GeV}$$

LONG MATTER DOMINATED EPOCH

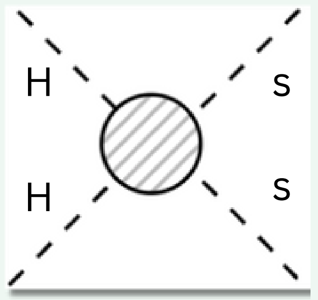
LOW REHEATING TEMPERATURE

WHAT HAPPENS AT LOW TR?

t →

Higgs portal

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



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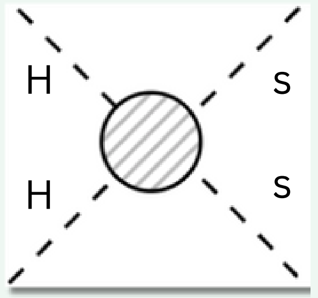
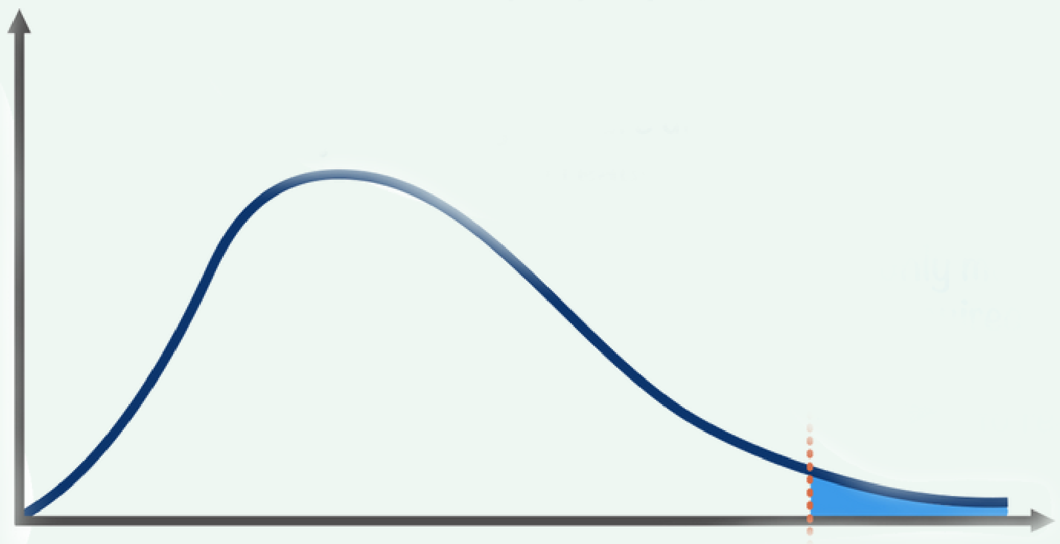


Freeze-in

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

# of H particles



Energy

Boltzmann distribution

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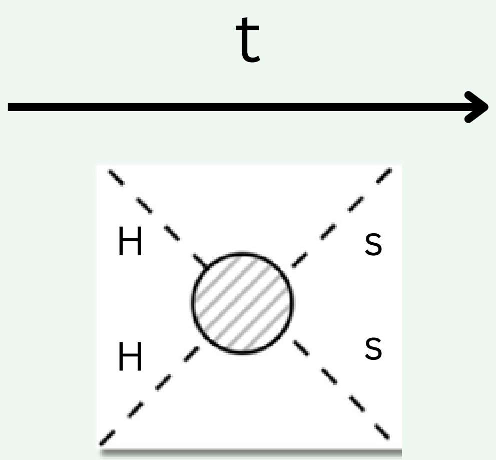

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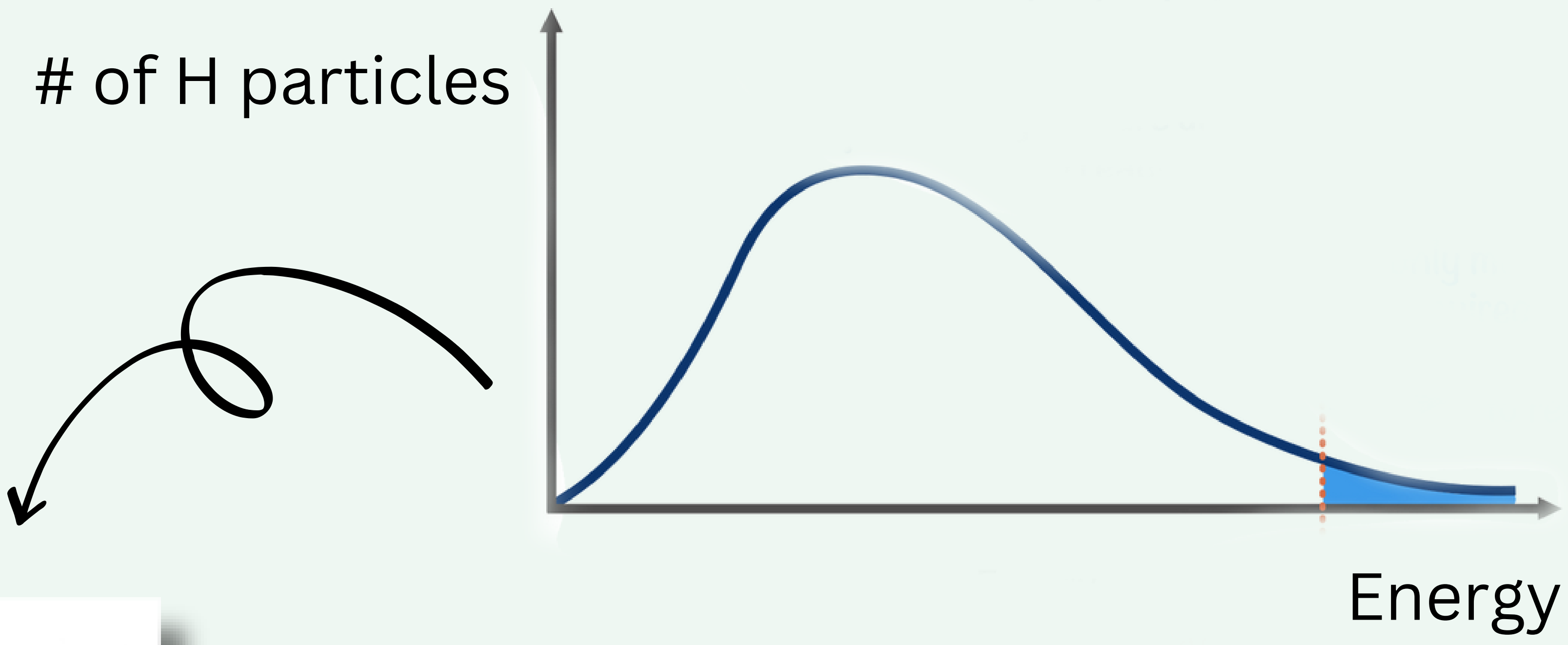

Boltzmann distribution

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

The rate of production is Boltzmann suppressed

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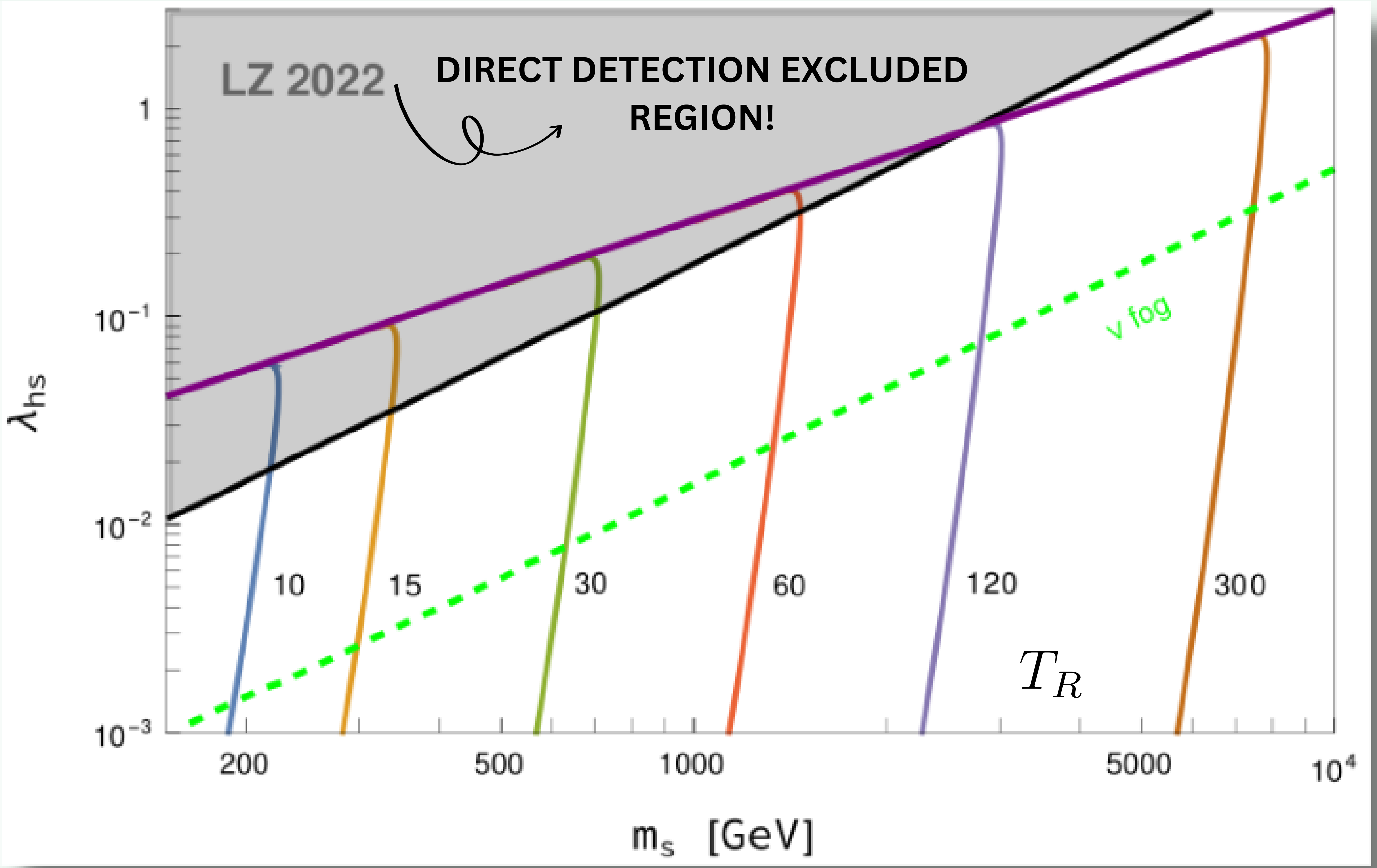
HIGGS PORTAL TO SCALAR DM



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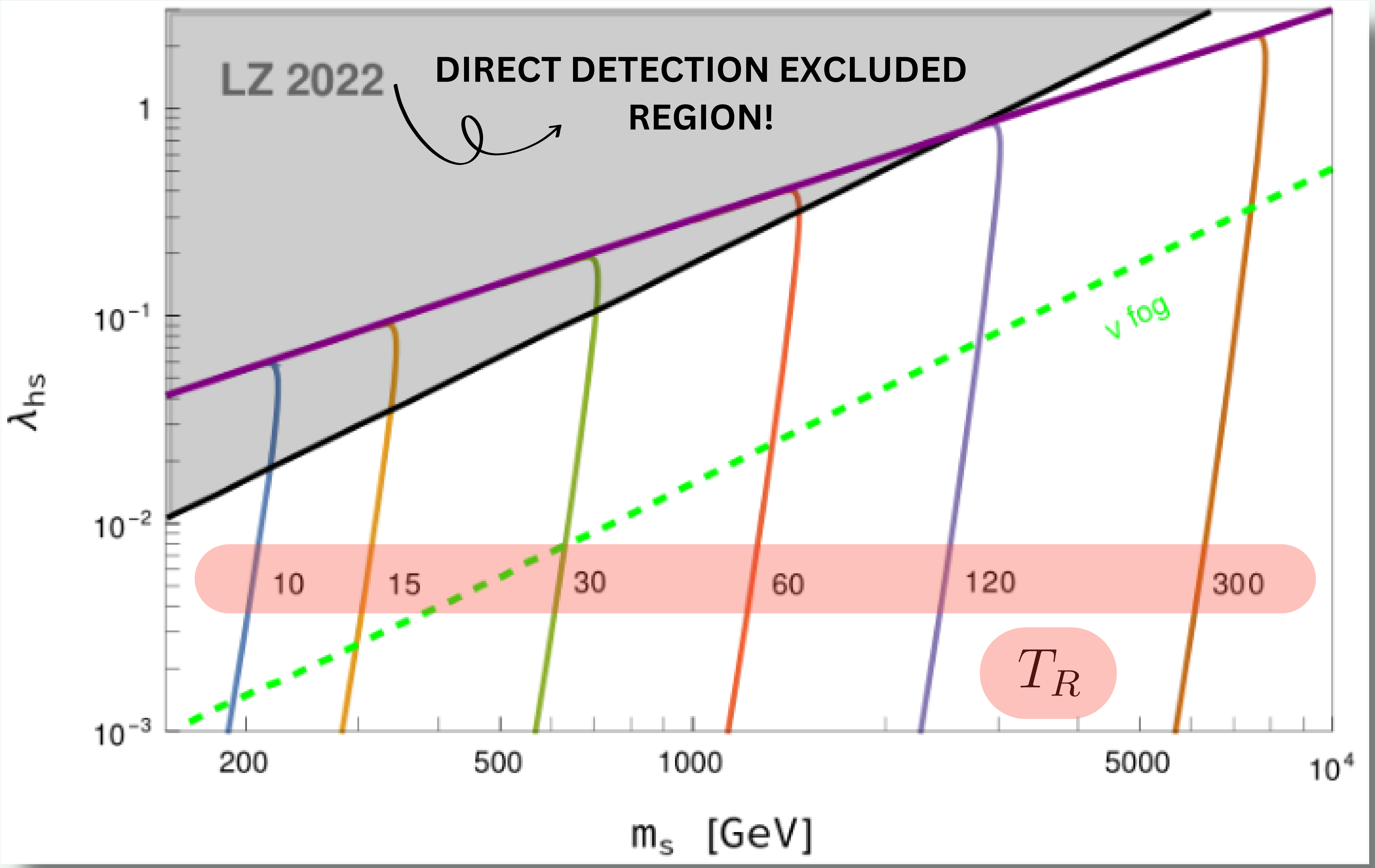

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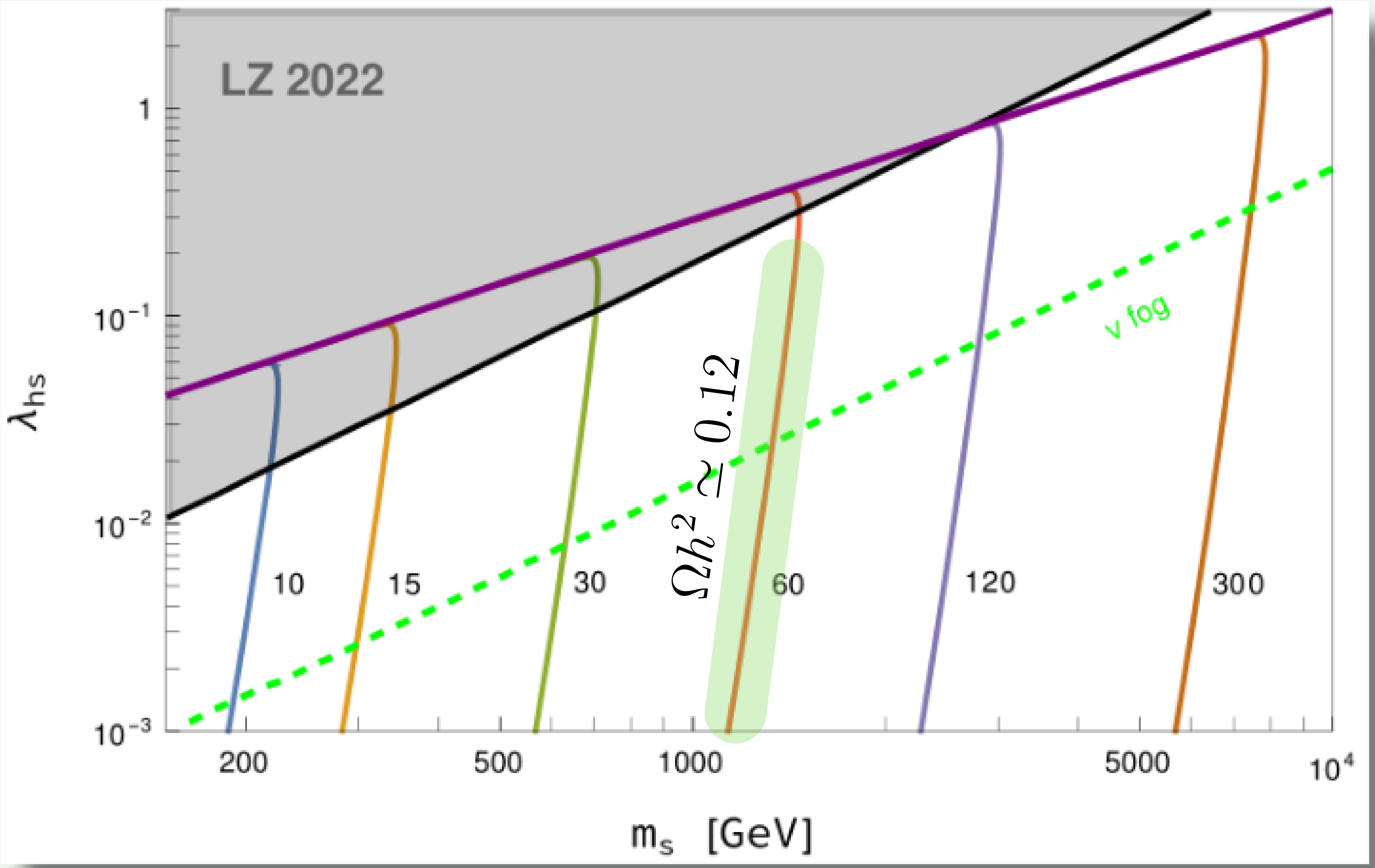

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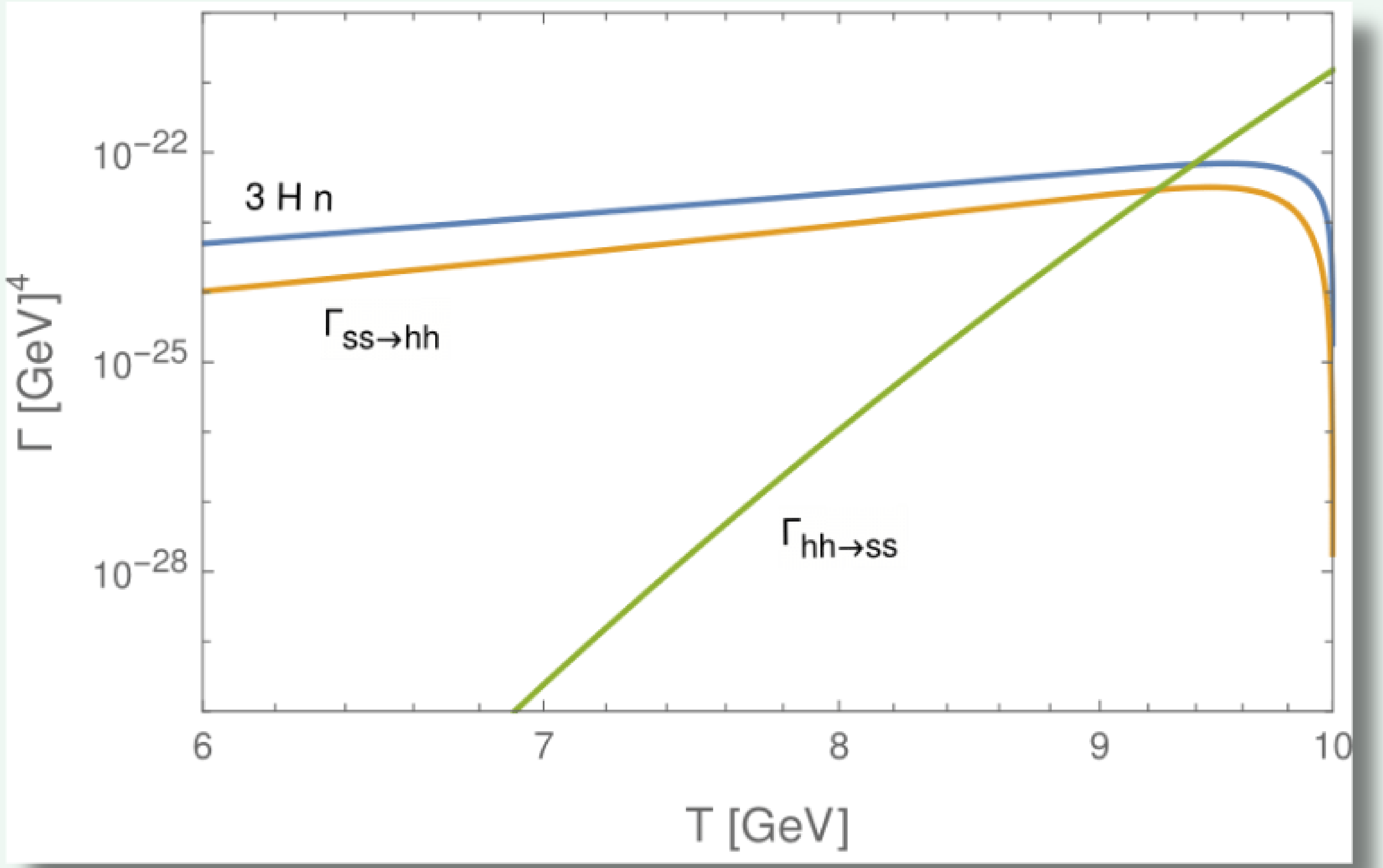
FREEZE-IN REGIME

Boltzmann equation

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



TIME

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

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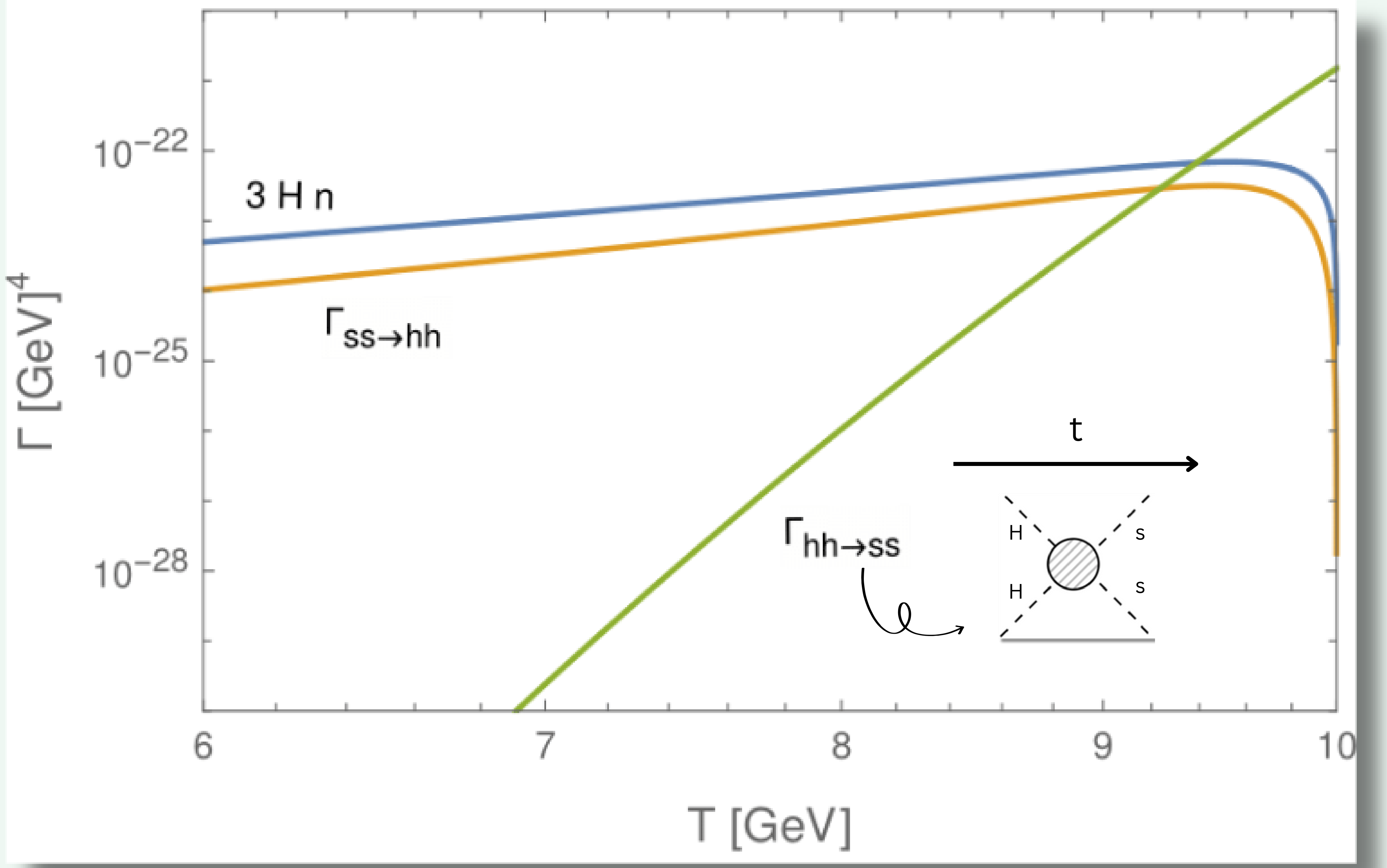

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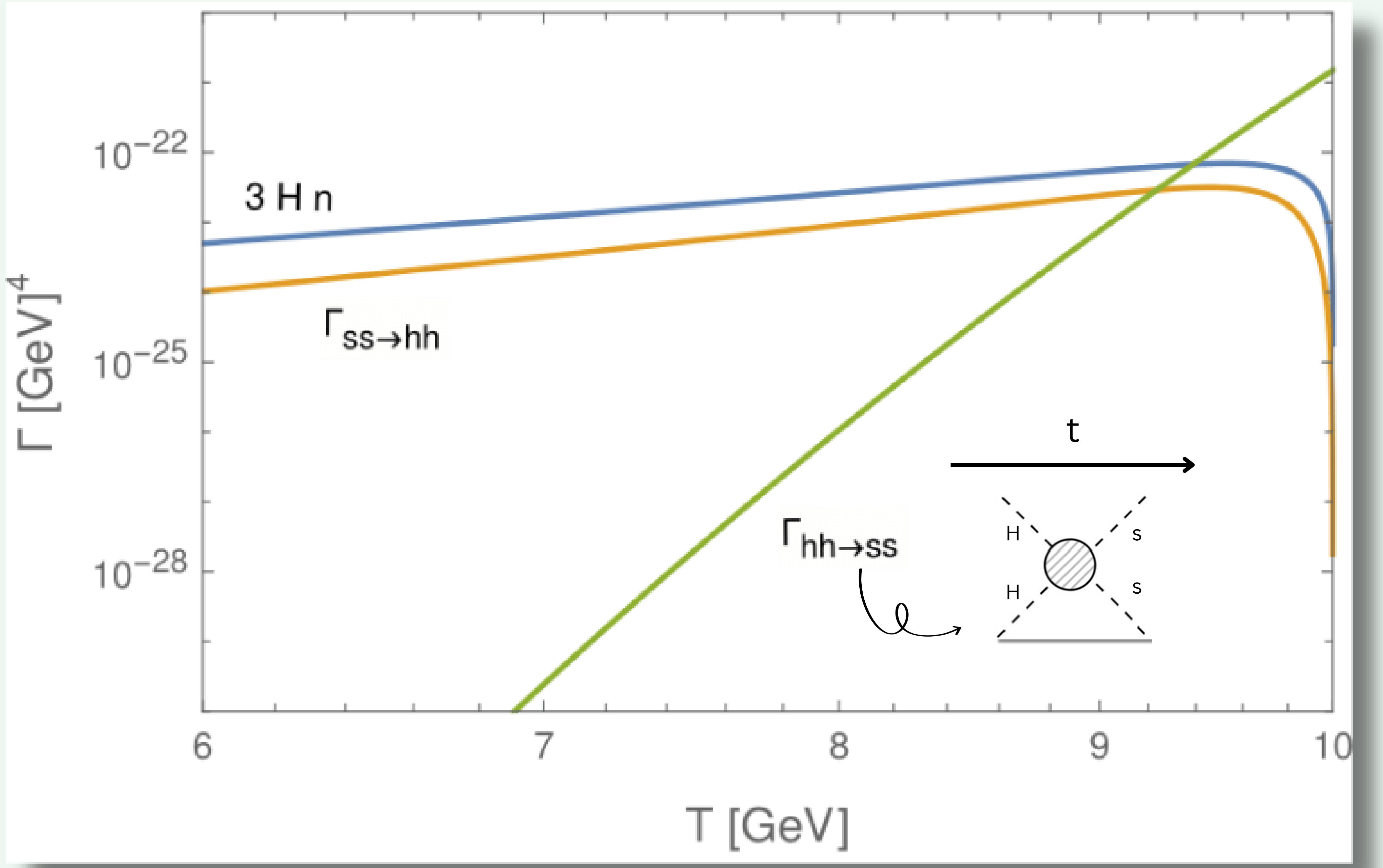
FREEZE-IN REGIME

Boltzmann equation

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

But

$$\Gamma > 3Hn$$



TIME

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FREEZE-IN REGIME

Boltzmann equation

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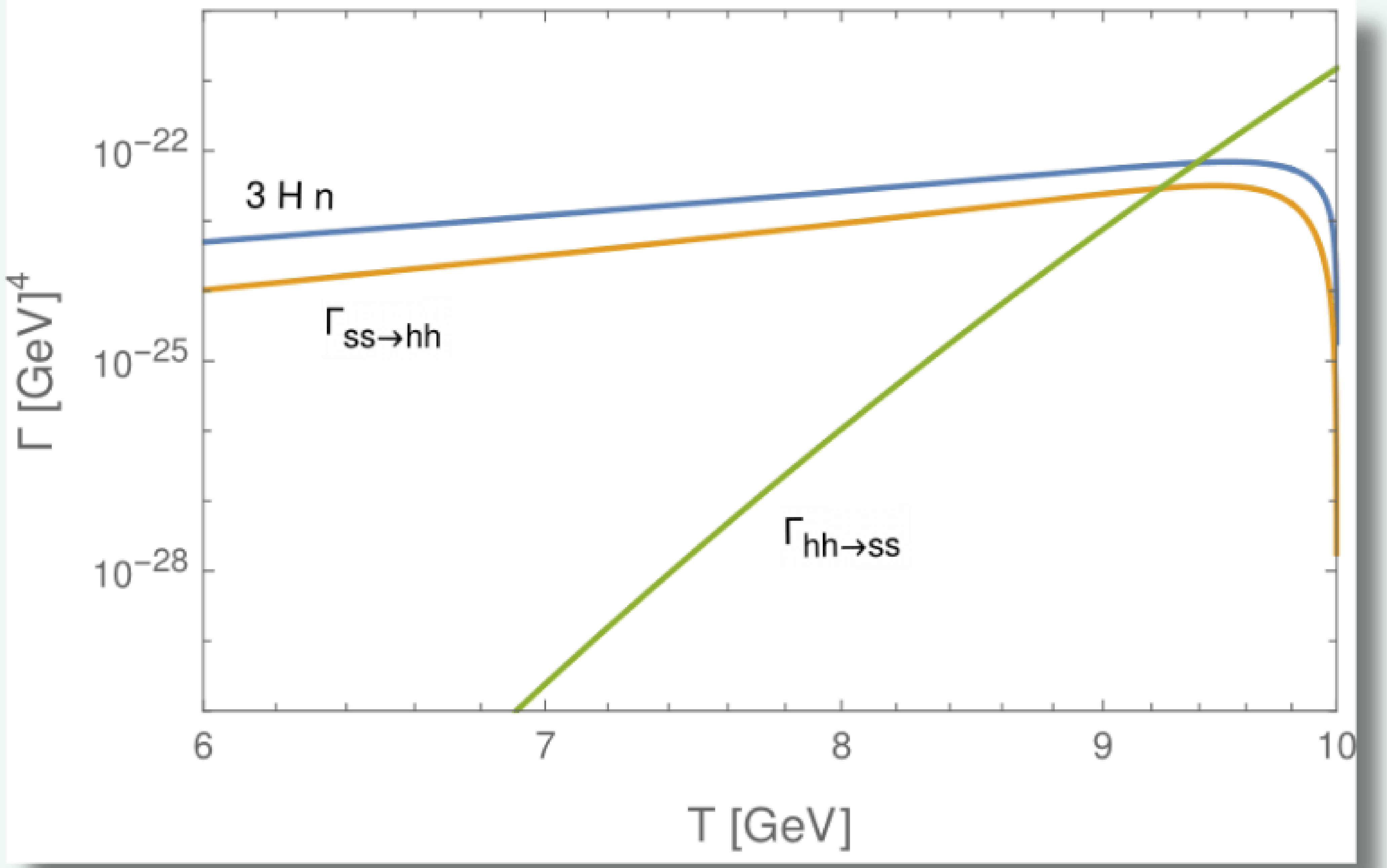
$$\Gamma\left(h_i h_i \to ss\right) > 3Hn \not\Longrightarrow \text{Thermalisation}$$

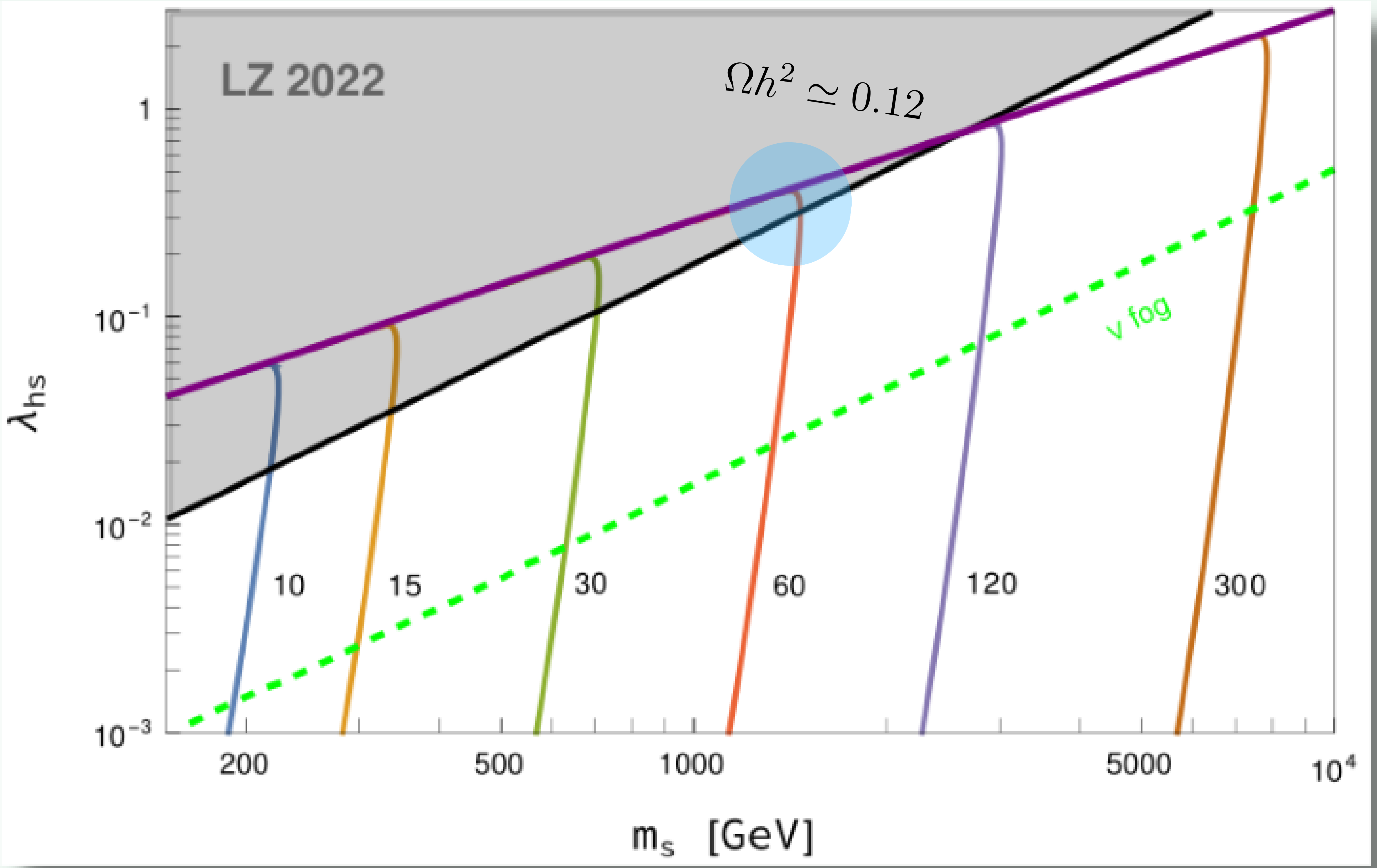
$$\Gamma\left(h_i h_i \to ss\right) = \Gamma\left(ss \to h_i h_i\right) \Longrightarrow \text{Thermalisation}$$



TIME

HIGGS PORTAL TO SCALAR DM

BACKREACTION



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ANNIHILIATION BECOMES IMPORTANT

Boltzmann equation

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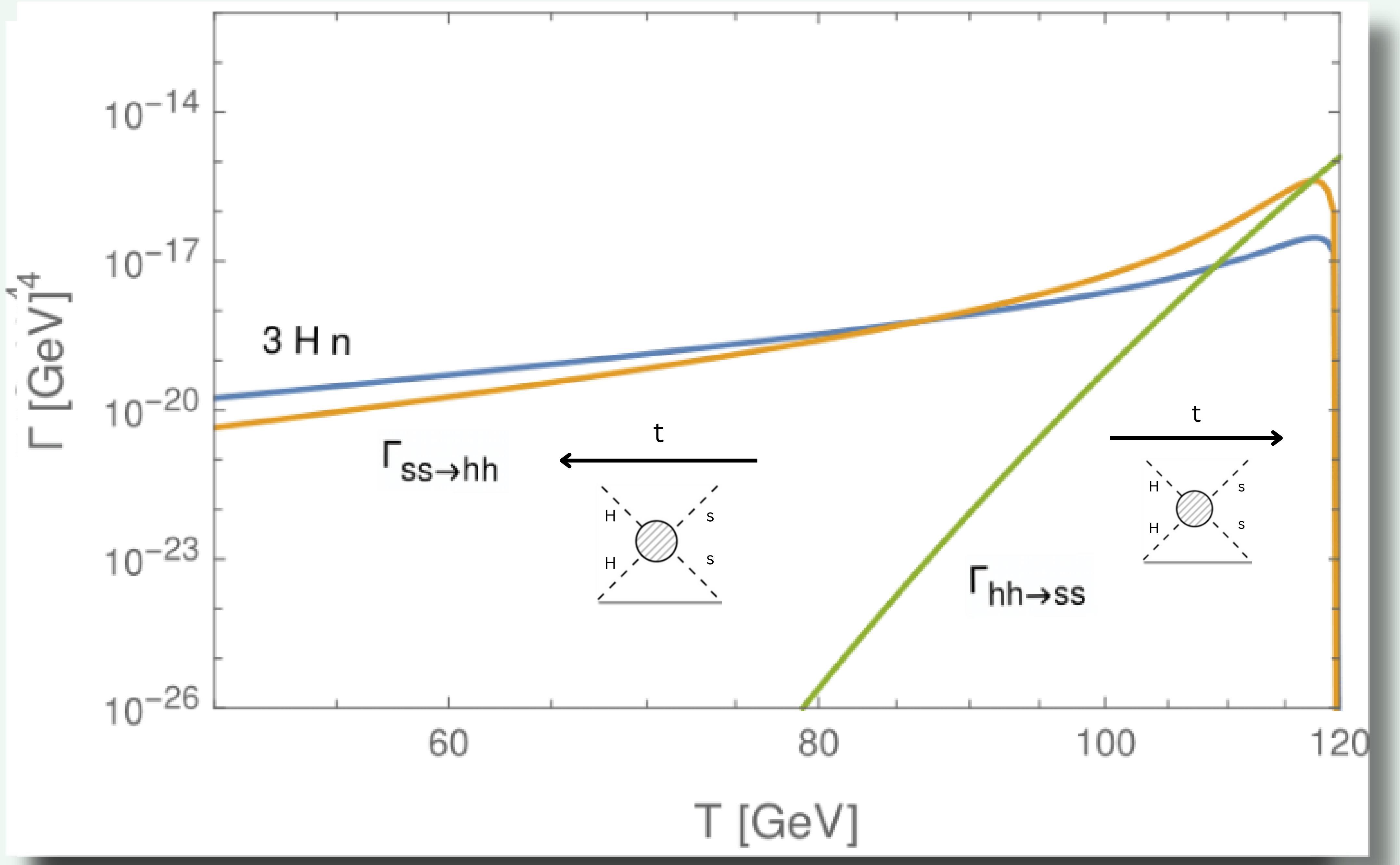
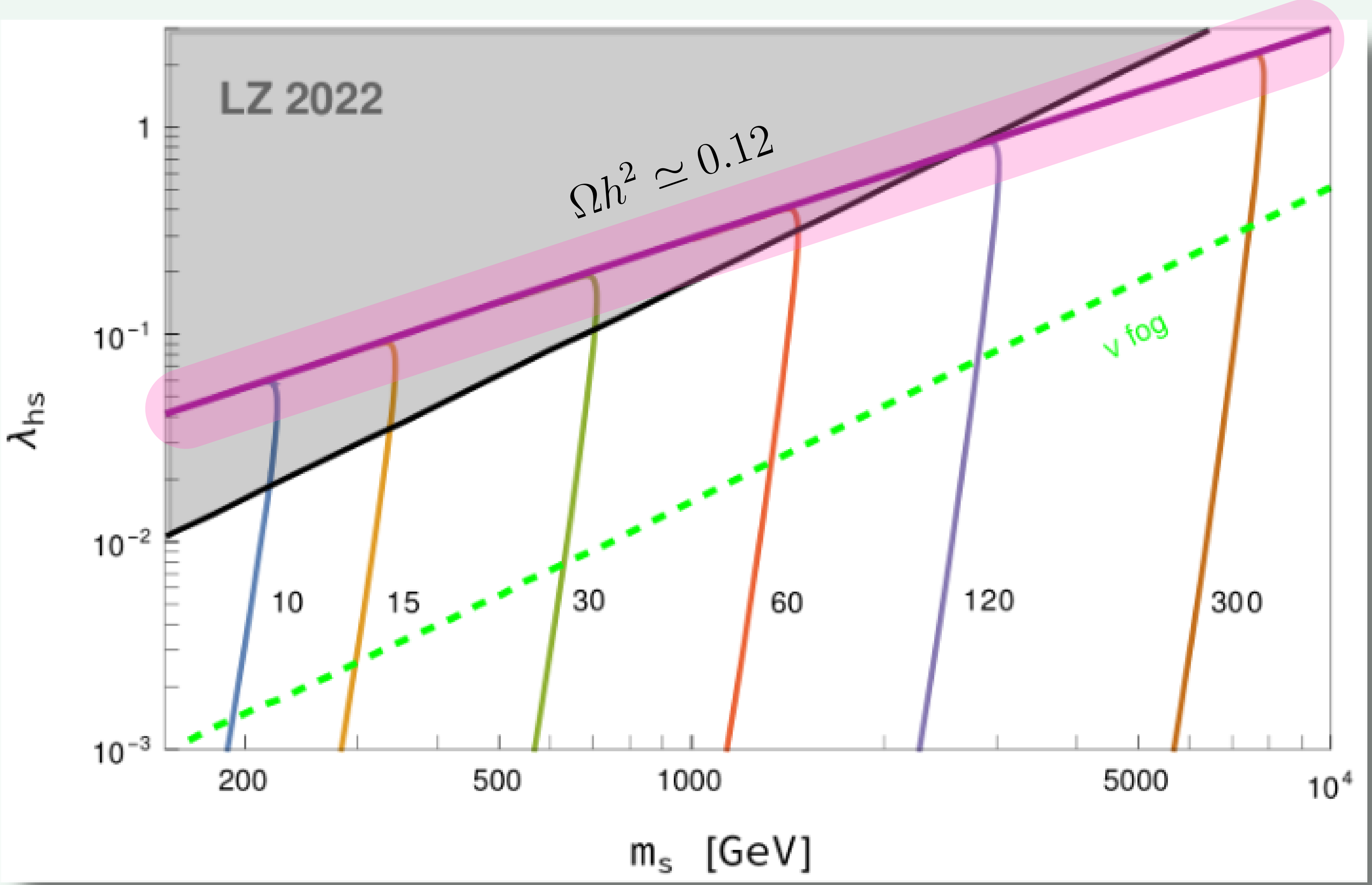


TIME

HIGGS PORTAL TO SCALAR DM

FREEZE-OUT



FREEZE-OUT REGIME

Boltzmann equation

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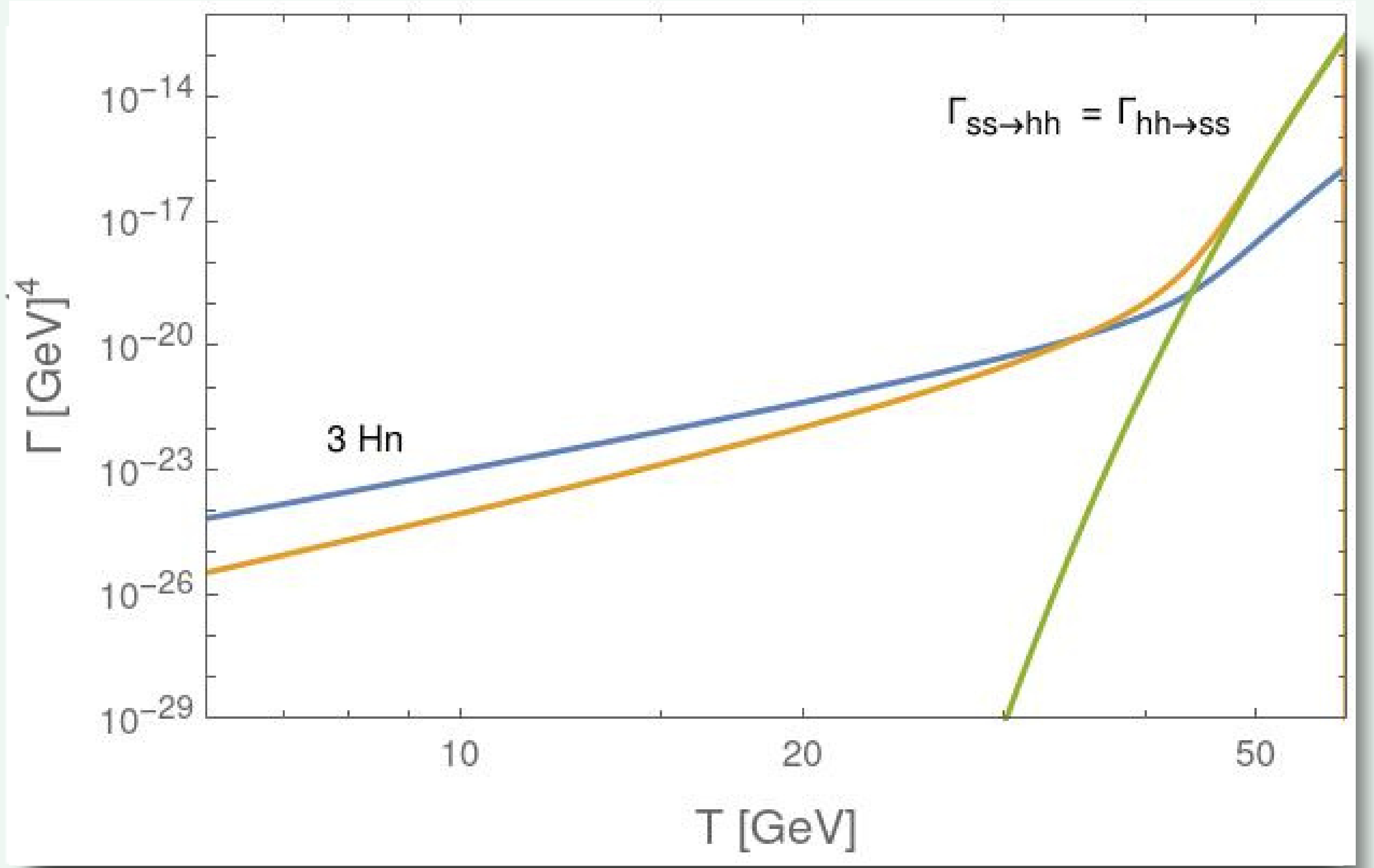
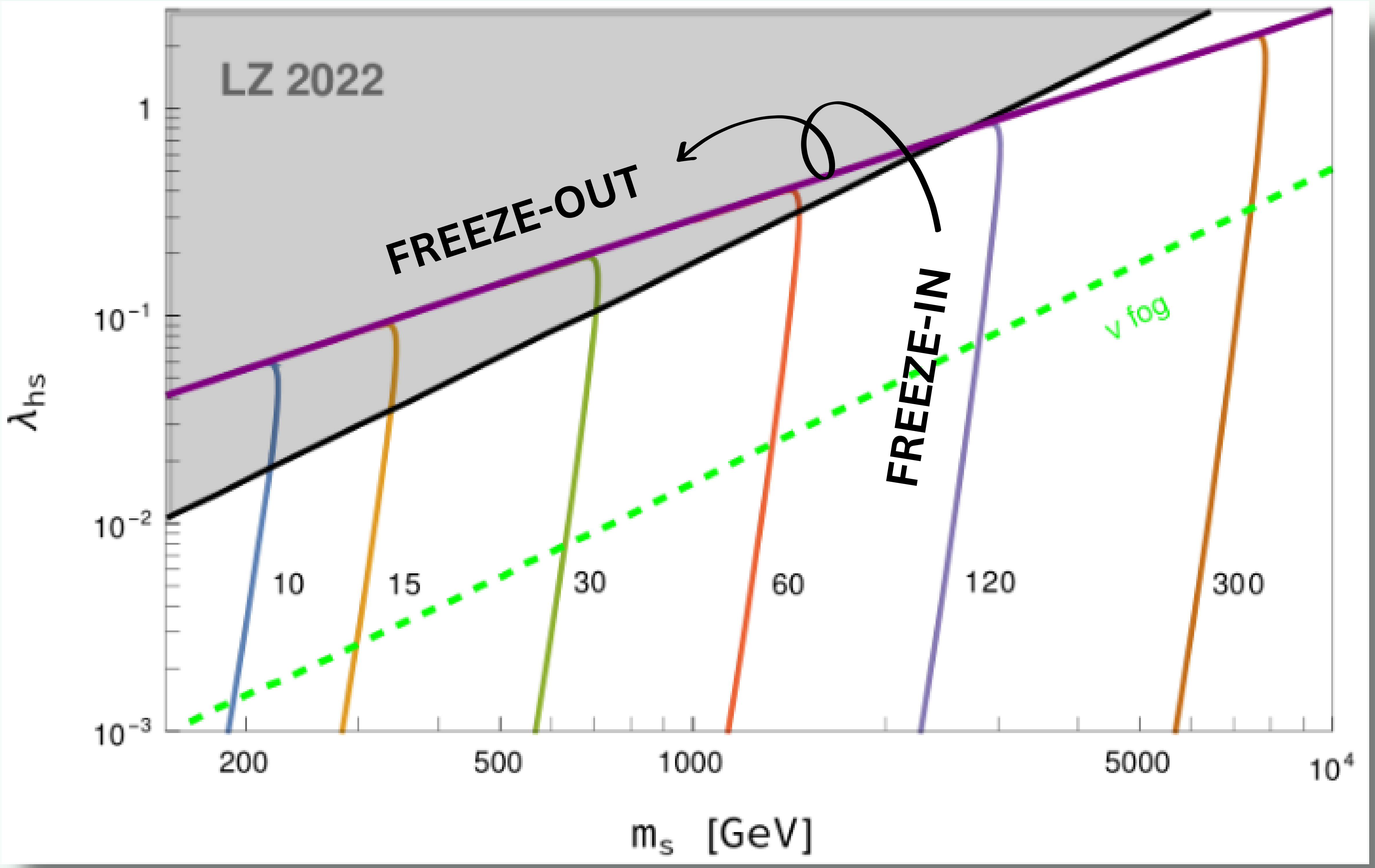
Freeze-out

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



TIME

HIGGS PORTAL TO SCALAR DM



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

TAKE HOME MESSAGE

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

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

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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

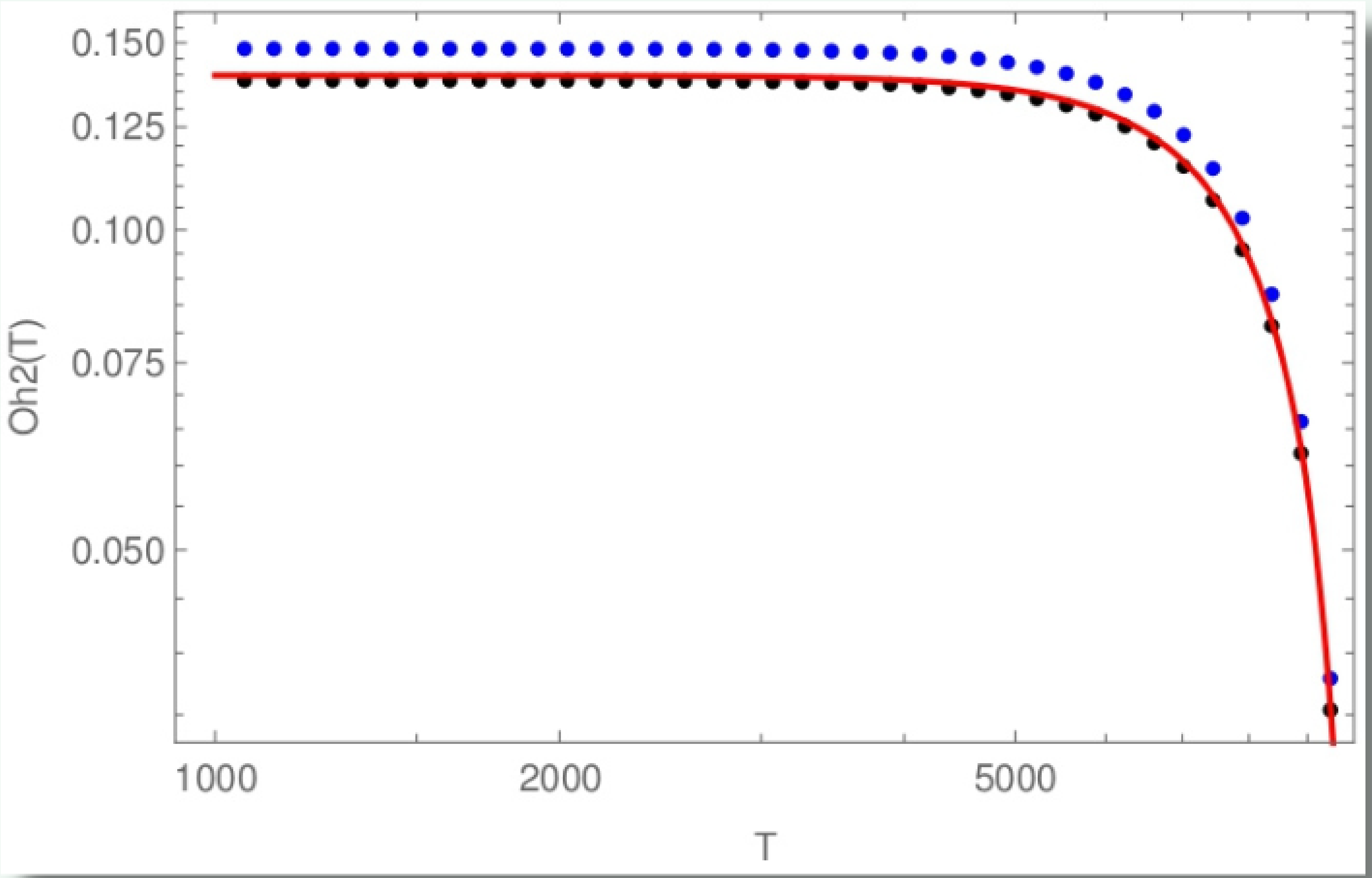
This project has received funding/support from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 860881-HIDDeN

BACK-UP

Non-instantaneous reheating

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

Relativistic effect



BOLTZMANN SUPPRESSION

Scalar potential

$$V(s) = \frac{1}{2}\lambda_{hs} s^2 H^\dagger H + \frac{1}{2} m_s^2 s^2$$

Boltzmann equation

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

Freeze-in rate

$$\Gamma\left(h_i h_i \to ss\right) = \left\langle \sigma\left(h_i h_i \to ss\right) v_r \right\rangle n_h^2 = \frac{2\pi^2 T}{(2\pi)^6} \int_{4m_s^2}^{\infty} d\,\mathrm{s}\sigma\left(\mathrm{s} - 4m_h^2\right) \sqrt{\mathrm{s}} K_1(\sqrt{\mathrm{s}}/T)$$

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

$$\lambda_{hs} \simeq 3 \times 10^{-11}\, e^{m_s/T_R} \sqrt{\frac{T_R}{m_s}}$$

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

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