Dark Tools 2025

Freeze-in with low reheating temperature

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Freeze-in

Boltzmann equation for the general case :

$$\dot{n}_\chi + 3Hn_\chi = \sum_{A,B} \left(\xi_B - \xi_A\right) \mathcal{N}\left(A \to B\right)$$

Integrated collision term

Sum over all initial and final states containing DM particles

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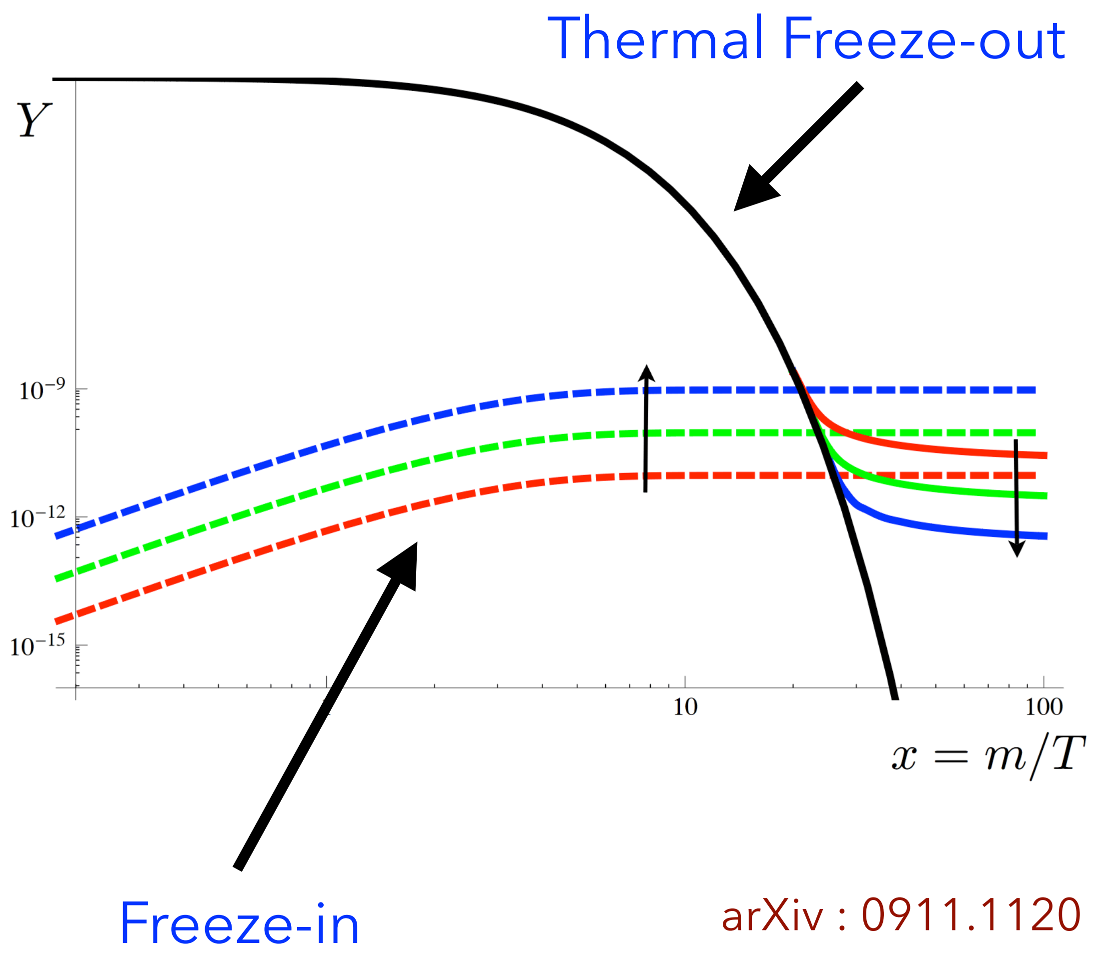
Freeze-in : Initial density is zero and (in principle) feeble DM-SM interactions

DM annihilation can be ignored



arXiv : 0911.1120

Boltzmann equation for freeze-in :

$$Y_\chi = \int_{T_0}^{T_{rh}} \frac{dT}{T\overline{H}(T)s(T)} \sum_{A,B} \xi_B \mathcal{N}(A \to B)$$

Where only B contains DM particle

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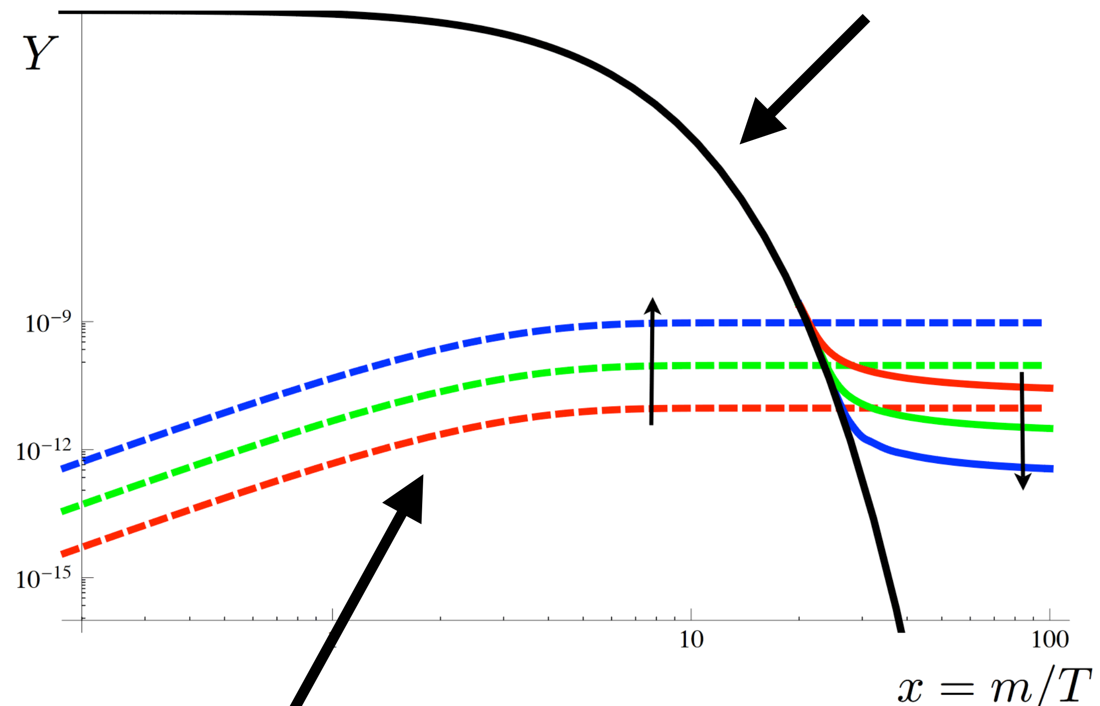
Thermal Freeze-out



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Where only B contains DM particle

Production is dependent on T_{rh} which is poorly constrained.

Usually, $T_{rh} \to \infty$

What happens if one considers low T_{rh} ?

Case study : a charged parent model

Consider a scalar singlet s_0, not charged under the SM gauge groups, and a vector-like fermion F ,singlet under $SU(2)$. Both are odd under a $\mathbf{Z}_2$ symmetry to ensure s stability.

arXiv : 1811.05478

Assumed to be zero

$$\mathscr{L} = \mathscr{L}_{SM} + \partial_\mu s_0 \, \partial^\mu s_0 - \frac{\mu_s^2}{2} s_0^2 + \frac{\lambda_s}{4} s_0^4 + \lambda_{sh} \, s_0^2 \left(H^\dagger H\right)$$

$$+ \bar{F} \, (i\not{D}) \, F - m_F \bar{F} F - \sum_f y_s^f \left(s_0 \bar{F} \left(\frac{1+\gamma^5}{2} \right) f + h.c. \right)$$

Potentially feeble coupling

Depends on the gauge charges of F

In high T_{rh} freeze-in, this model leads to long-lived particle signatures in collider experiments

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1.05478

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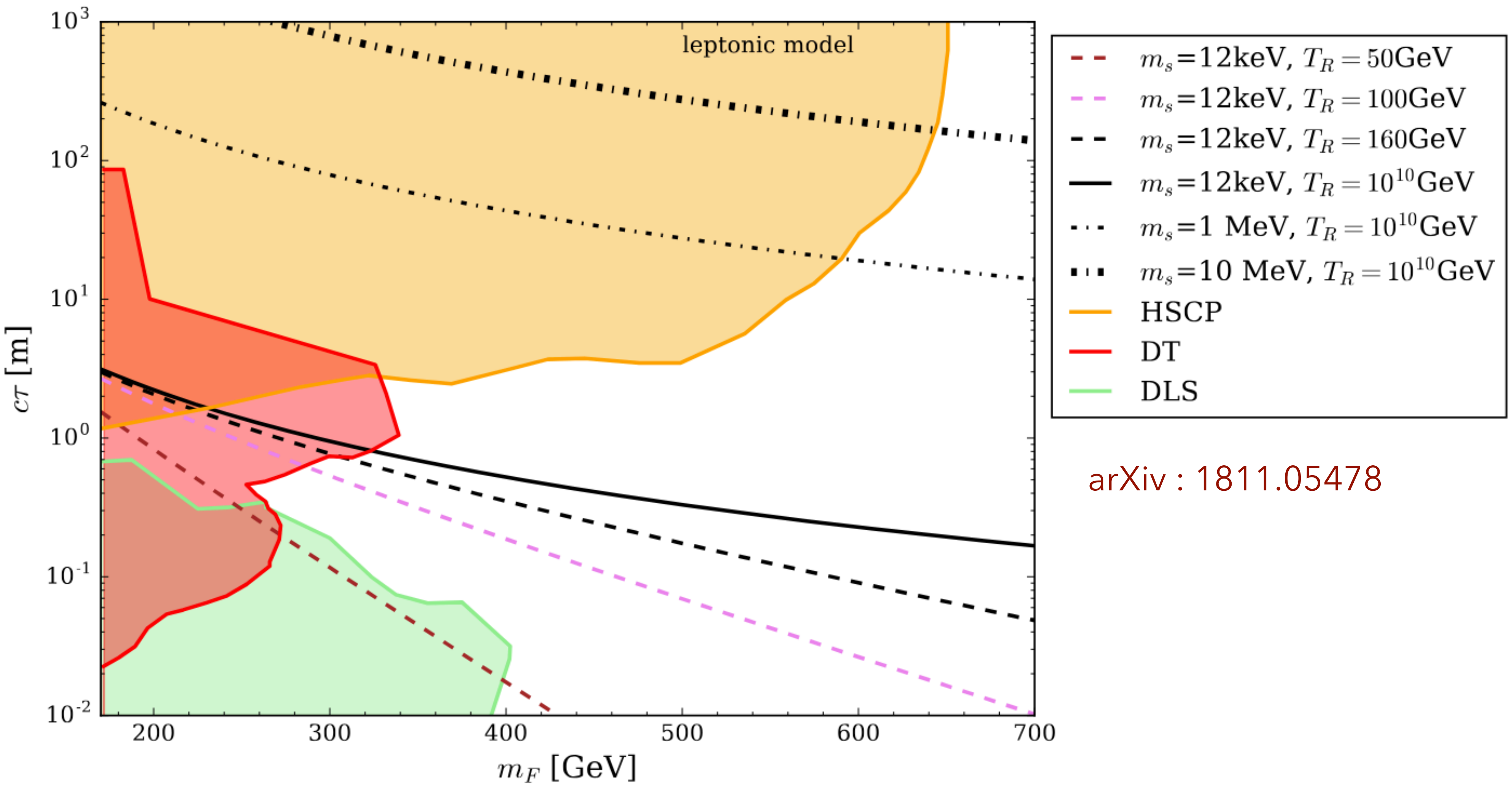

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Depends on charges of F

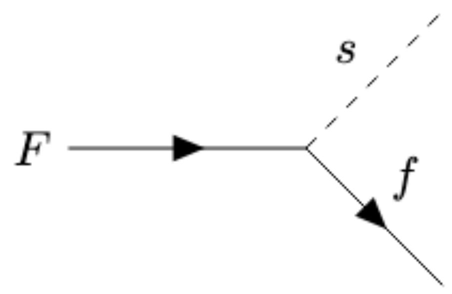
With infinite T_{rh} this model produces long-lived particle signatures in collider experiments

Effect of a low reheating temperature

There are usually two kind of process contributing to the relic density

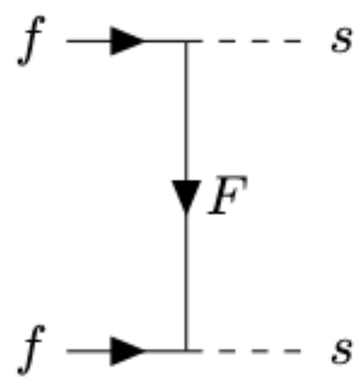
$$Y_{s_0} = \int_{T_0}^{T_{rh}} \frac{dT}{T\overline{H}(T)s(T)} \left(\mathcal{N}(F \to s_0, f) + 2\mathcal{N}(f, f \to s_0, s_0)\right)$$

Production from the decay of F into s and SM fermion



$\mathcal{N}(F \to s, f) \propto n_F(T)\Gamma$

Pair-production of two s from two SM fermions (+ subleading contributions)



$\mathcal{N}(f, f \to s, s) \propto n_f^2 \langle \sigma v \rangle$

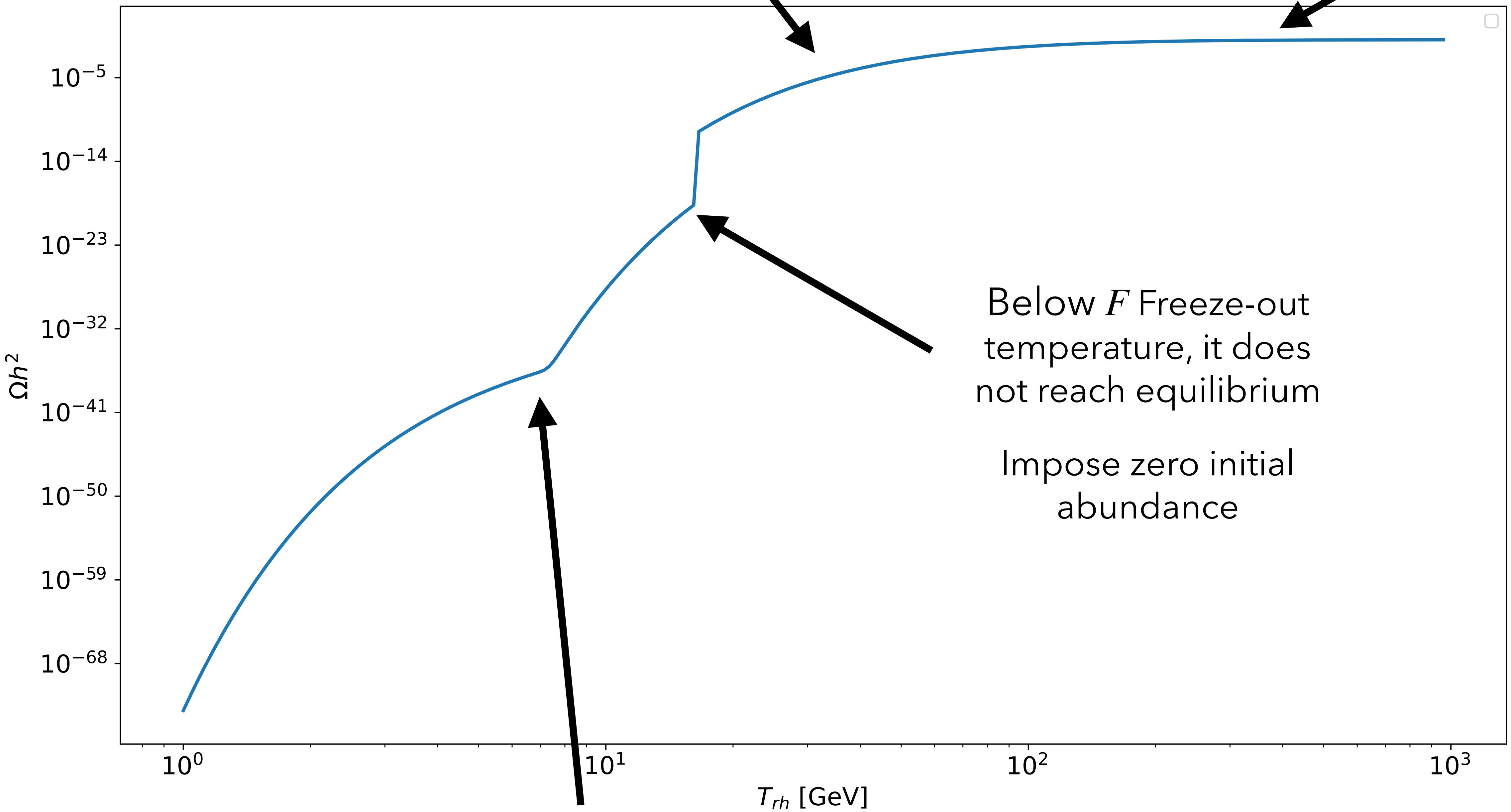
For effectively infinite reheating temperature, the production is dominated by the decay of F

Lower T_{rh} → F Boltzmann suppressed + Smaller fraction of the plasma can produce DM → Stronger DM-SM coupling

Effect of the reheating temperature on the relic density

F Boltzmann suppressed

Effectively infinite reheating temperature



Below F Freeze-out temperature, it does not reach equilibrium

Impose zero initial abundance

Pair production becomes dominant

s_0 is Boltzmann suppressed

with $m_F = 500\text{GeV}, m_{s0} = 50\text{GeV}$ and $y_s^f = 3.16 \times 10^{-12}$

Relic density for $m_F = 500\text{GeV}$

Effectively Infinite reheating temperature

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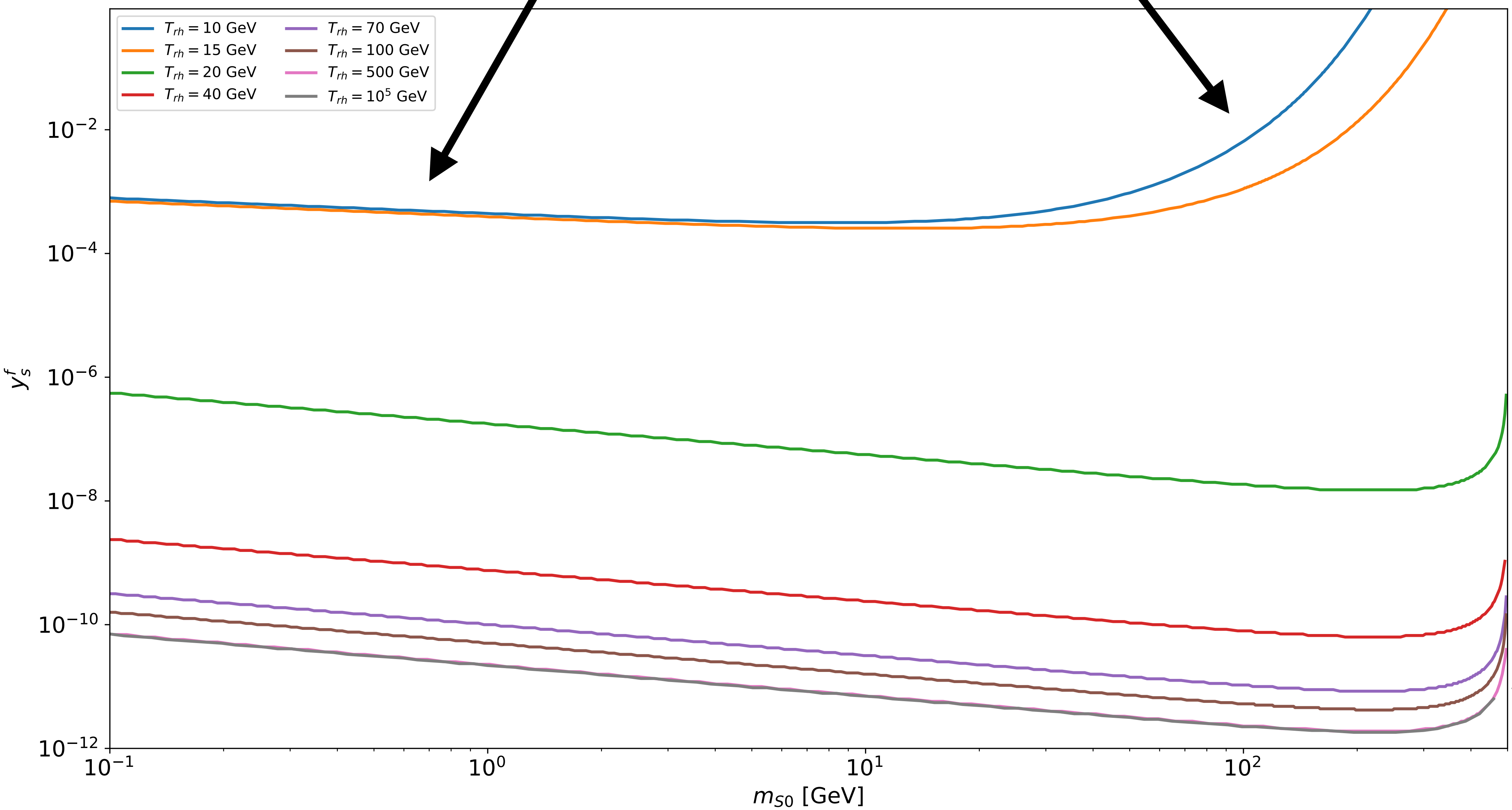

F cannot reach the equilibrium density

$T_{FO} < T_{RH}$

F Boltzmann suppressed but decays still dominate

Phase space suppression, need stronger coupling

Relic density for $m_F = 500\text{GeV}$: Impact of LHC searches

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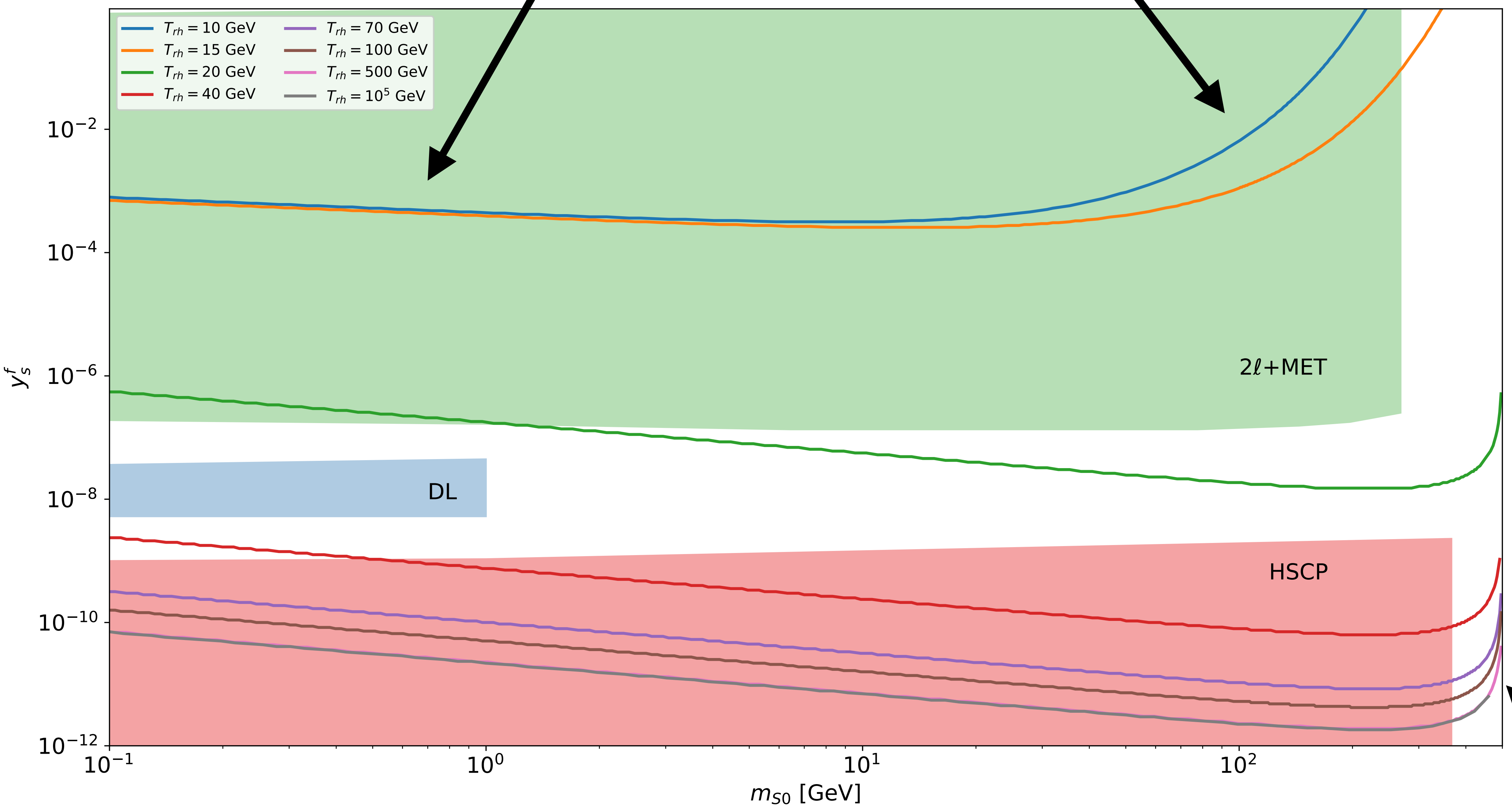

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Summary

- In the freeze-in mechanism, dark matter production depends on the reheating temperature which is poorly constrained.
- Usually taken to be effectively infinite, reducing this parameter leads to significant change in both the dark matter production and the phenomenology of the model
- When $T_{RH} < m_F$ its number density is Boltzmann suppressed larger coupling are needed to produce the observed relic density
- Lowering the reheating temperature even further, F cannot reach reach the equilibrium density and the decay contribution becomes sub-dominant
- As long as the VLL remains kinematically within LHC reach, the model is highly constrained by LLP + prompt searches
- To appear : extended parameters coverage, monojets, potentially alternative cosmological history

Thank you for your attention !!