IRN Terascale Montpellier 2025

Freeze-in with low reheating temperature

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Work in progress with A. Goudelis, A. Lessa

Evolution of a particle species

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Matrix elements, contains the particle physics information

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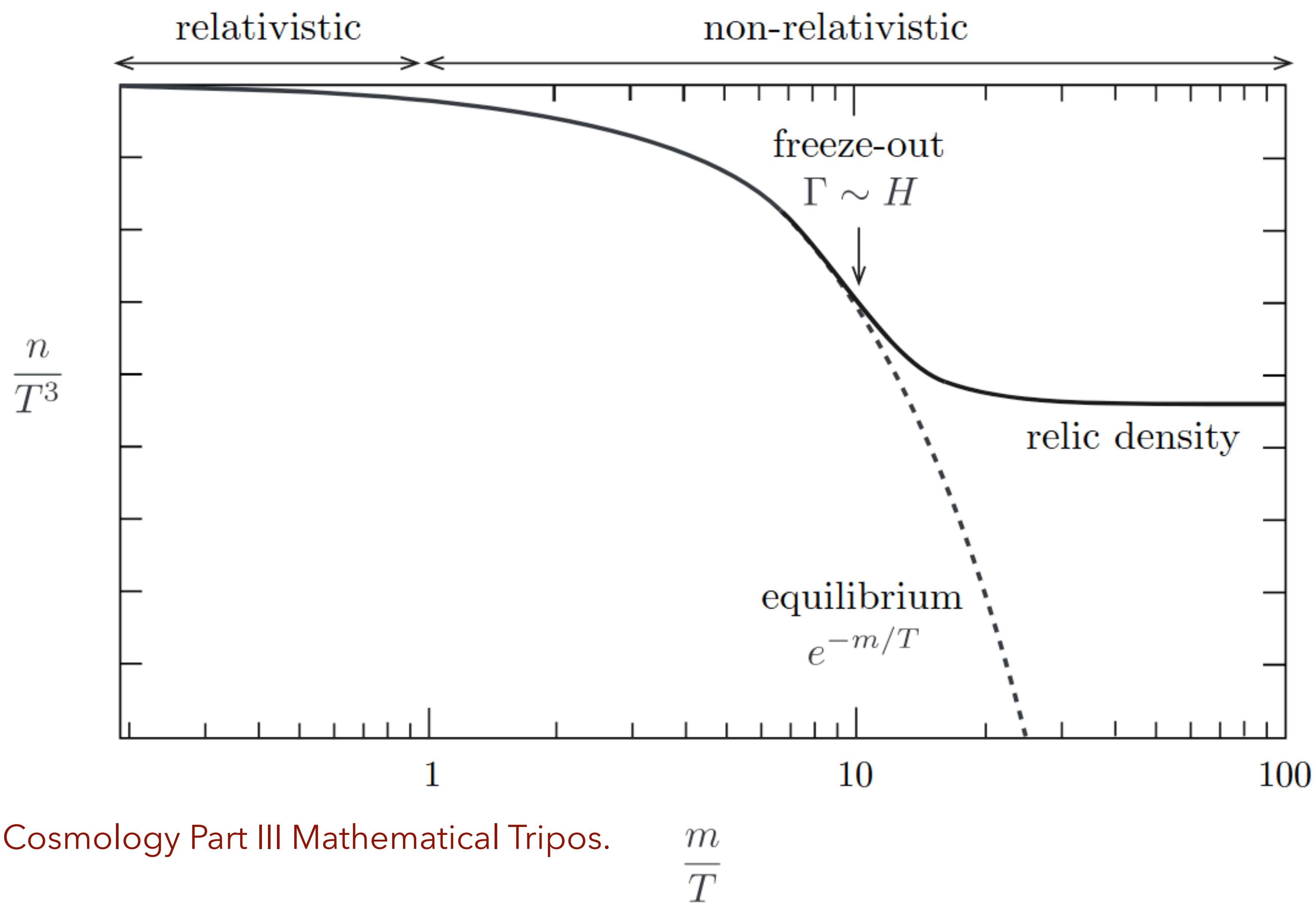
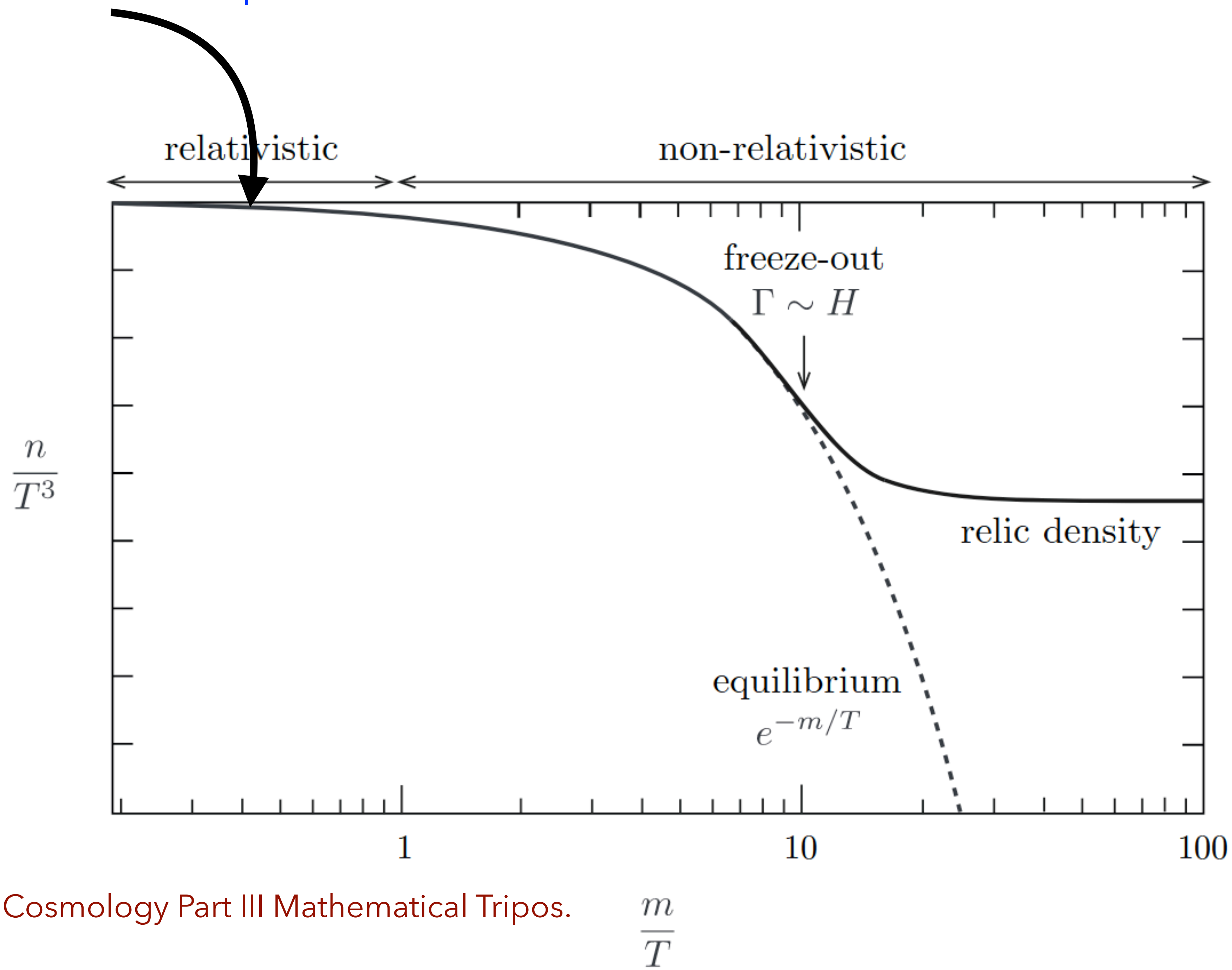


Daniel Baumann. Cosmology Part III Mathematical Tripos.

Freeze-out

χ in equilibrium with the photon bath



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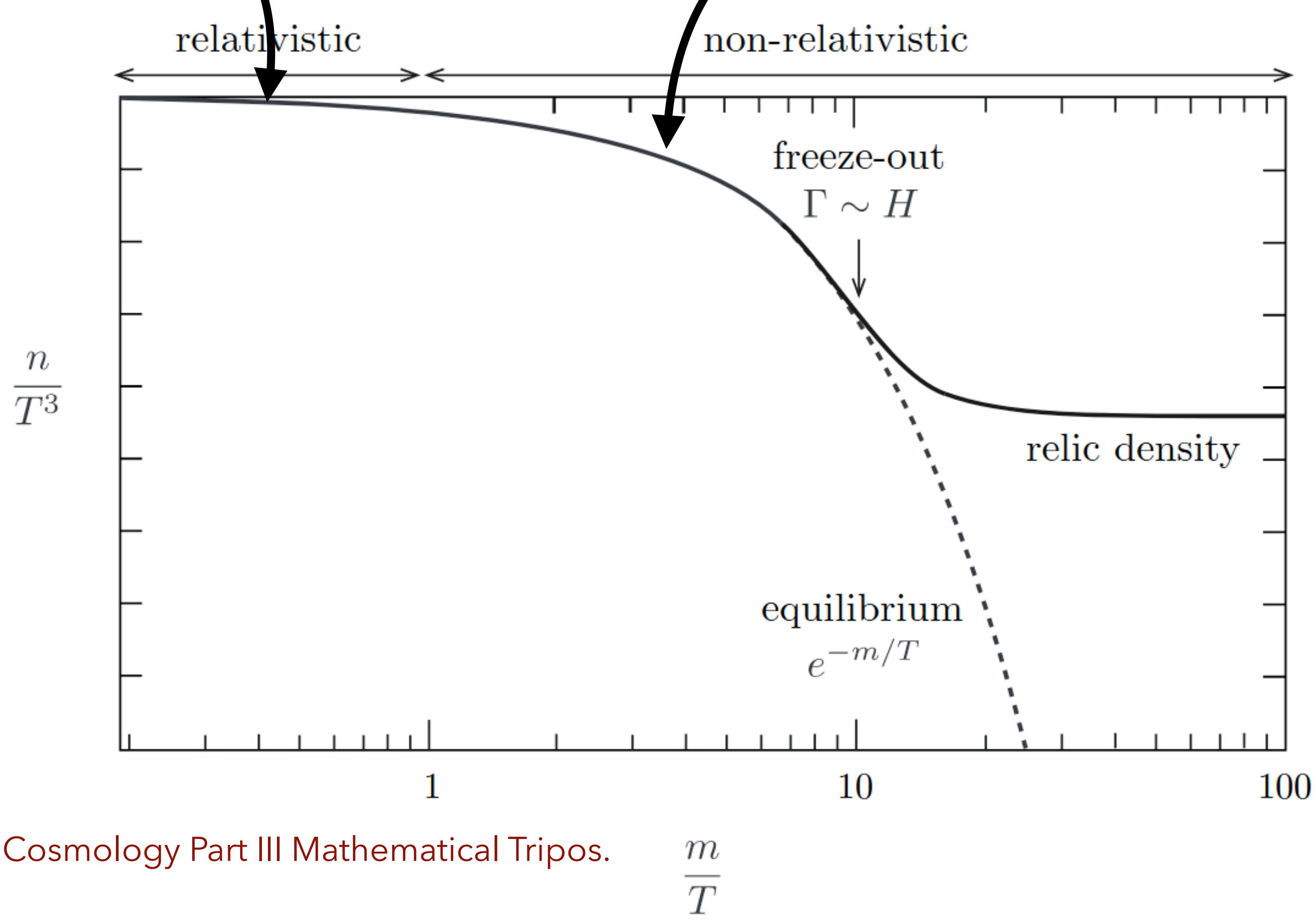

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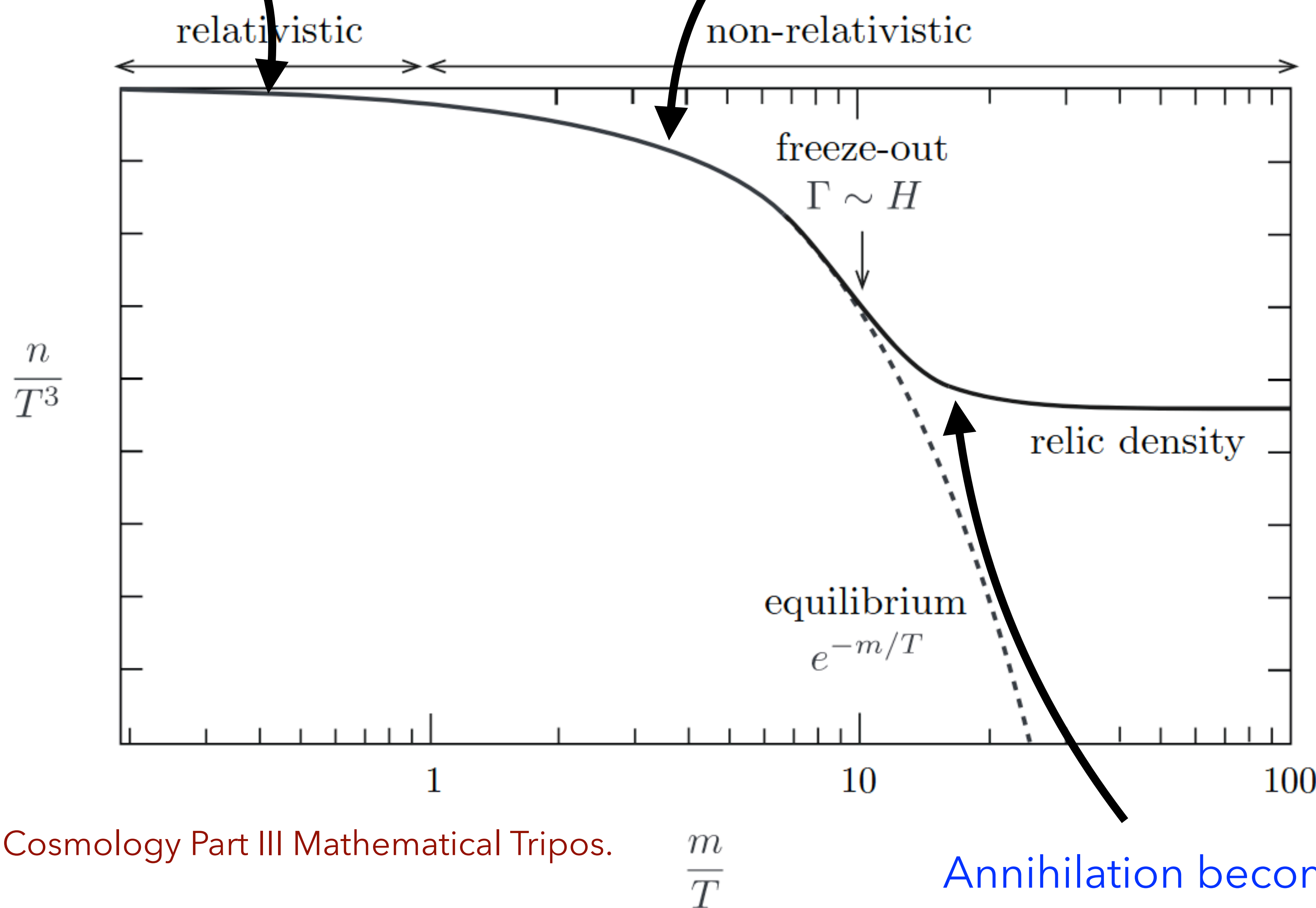

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Annihilation becomes inefficient compared to the expansion rate of the universe, χ freeze-out

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Two different assumptions :

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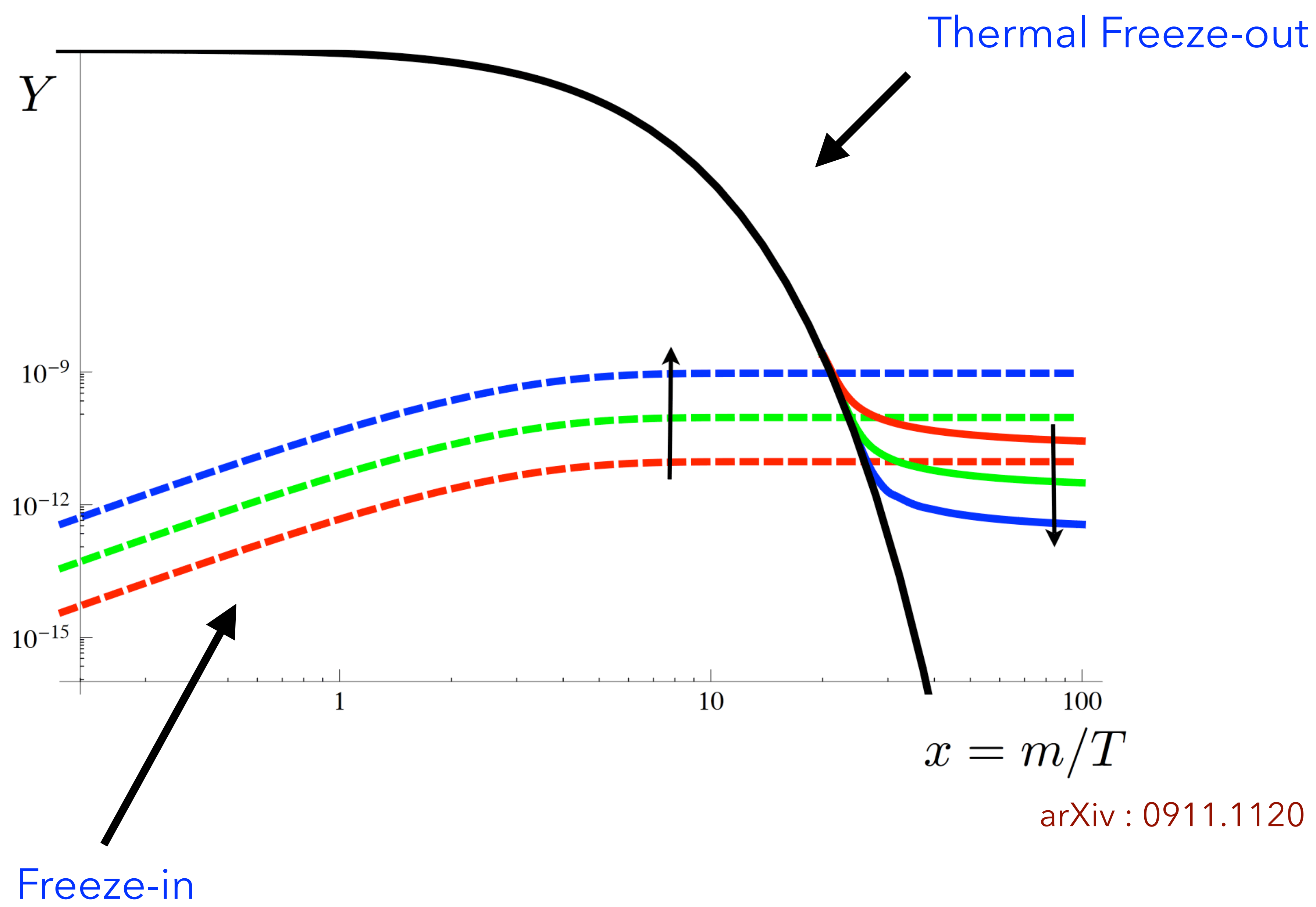

Thermal Freeze-out
Y
10^-9
10^-12
10^-15
1
10
100
x = m/T
arXiv : 0911.1120
Freeze-in

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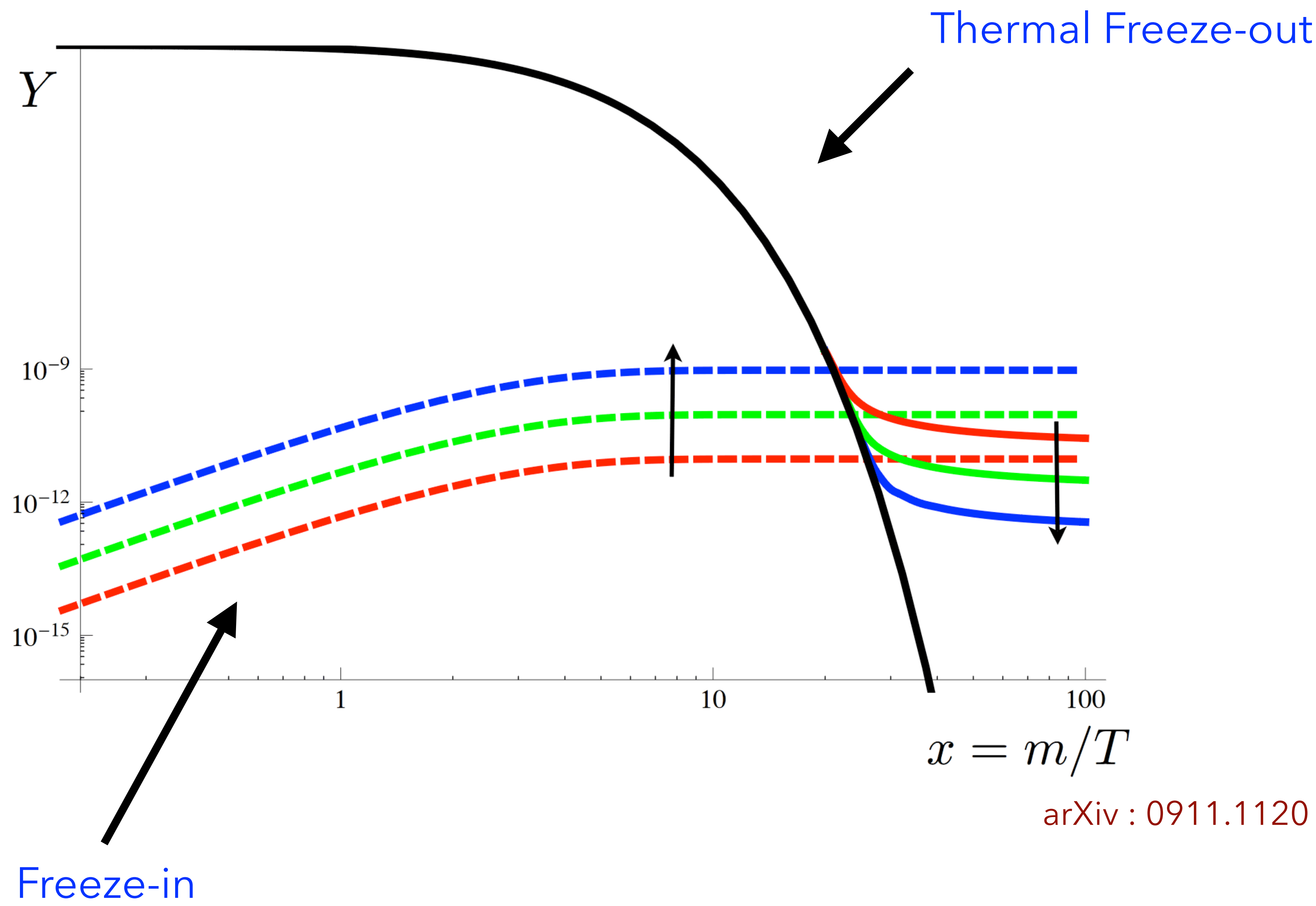

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Usually, $T_{rh} \to \infty$

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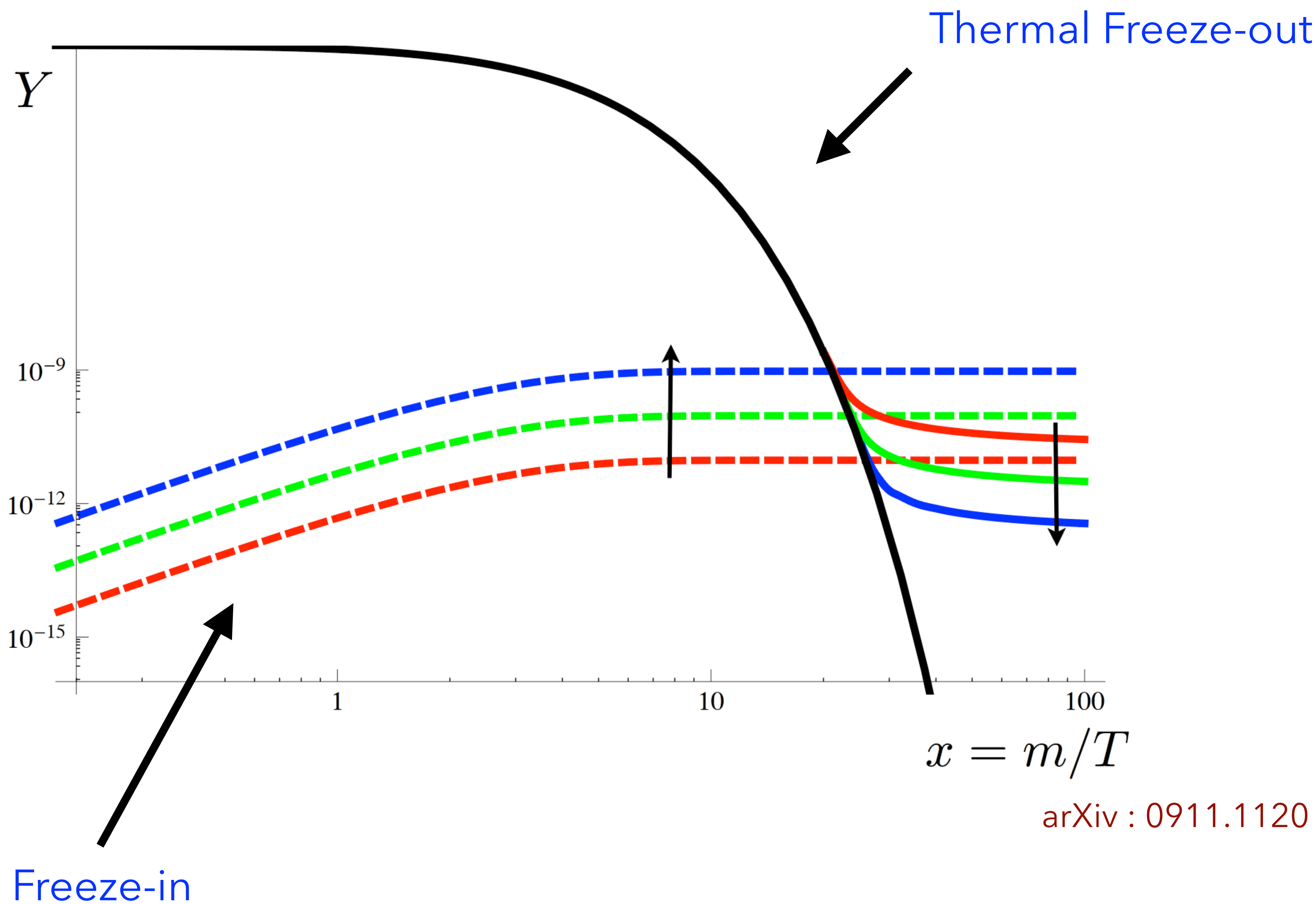

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What happens if one considers low T_{rh} ?

Case study : a charged parent model

Consider a real scalar singlet s, 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 the lightest state is stable.

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We will focus on the case in which F is color-neutral and carries hypercharge (Vector-like « lepton »)

Contributions to the relic density

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

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

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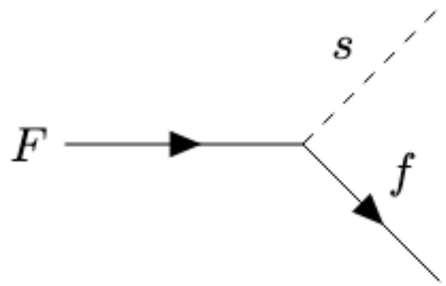
Production from the decay of
F into s and SM fermion



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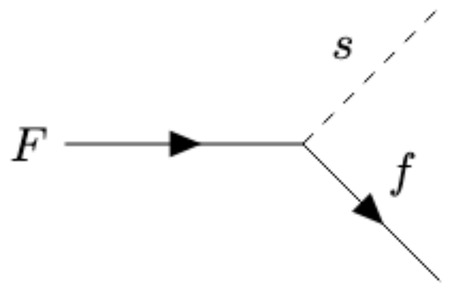
Pair-production of two s from two SM fermions (+ subleading contributions)



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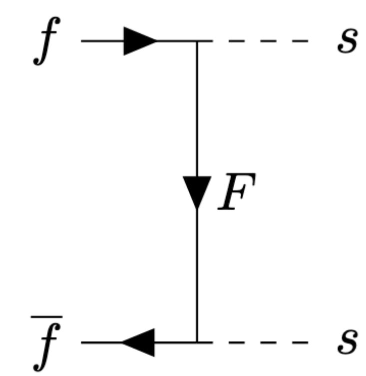

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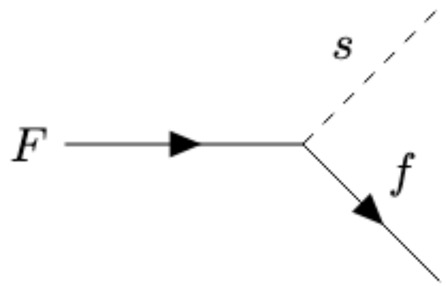

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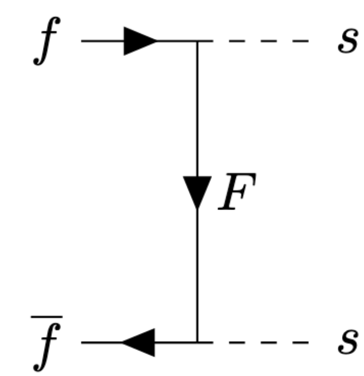

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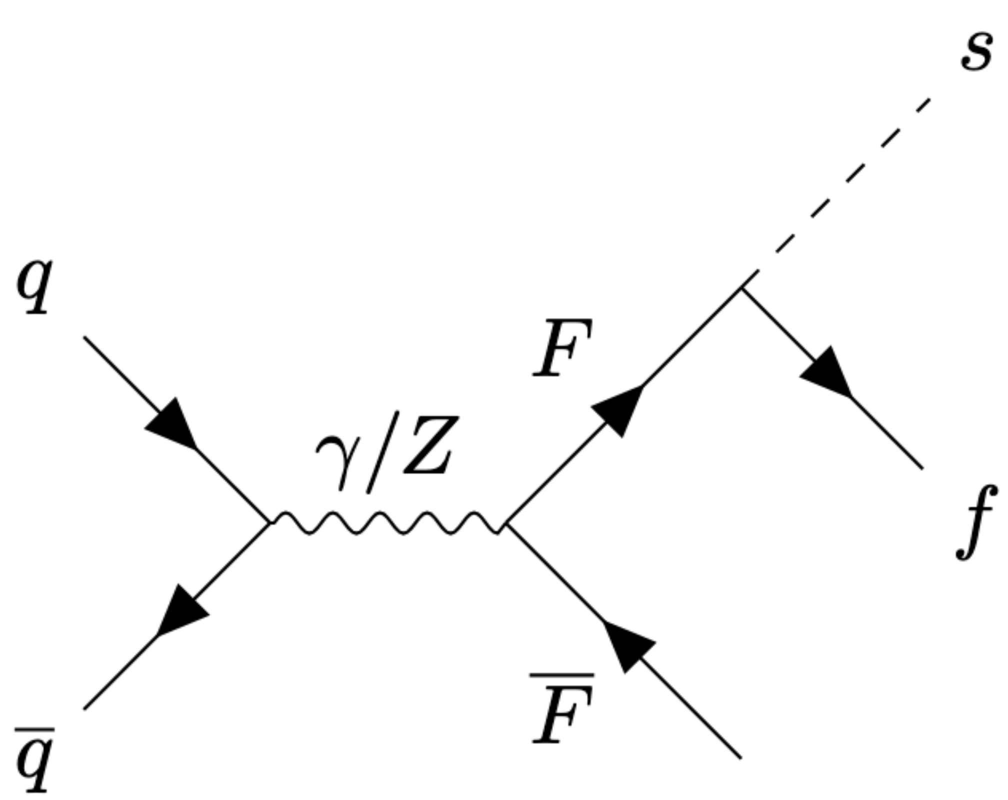
There are also additional contributions to the relic density such as the « super-WIMP » contribution (ie. mediator decay after its freeze-out) if $T_{rh} > T_{FO}$.

In the case $T_{rh} < T_{FO}$, the decay of frozen-in F's

Constraints form LHC searches

For LHC searches, we focus on the detection of the mediator particle : F

→ F produced through Drell-Yan process



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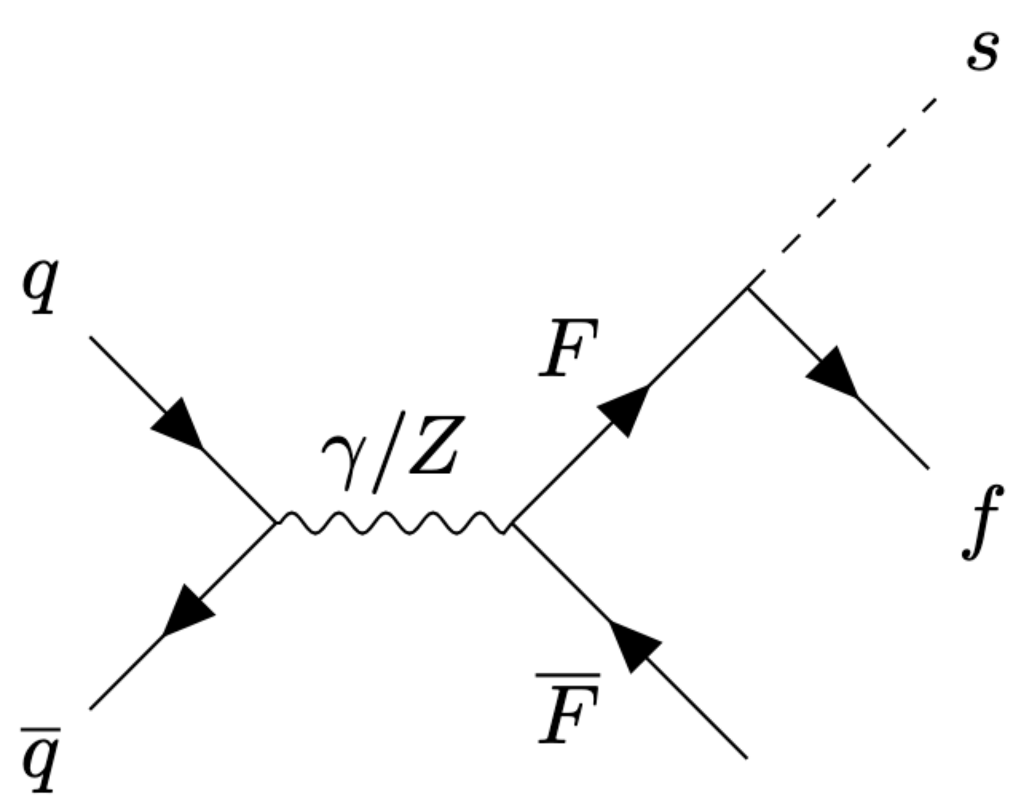

In high T_{rh} freeze-in, this model predicts a very longed-lived F in order to saturate the relic density constraint

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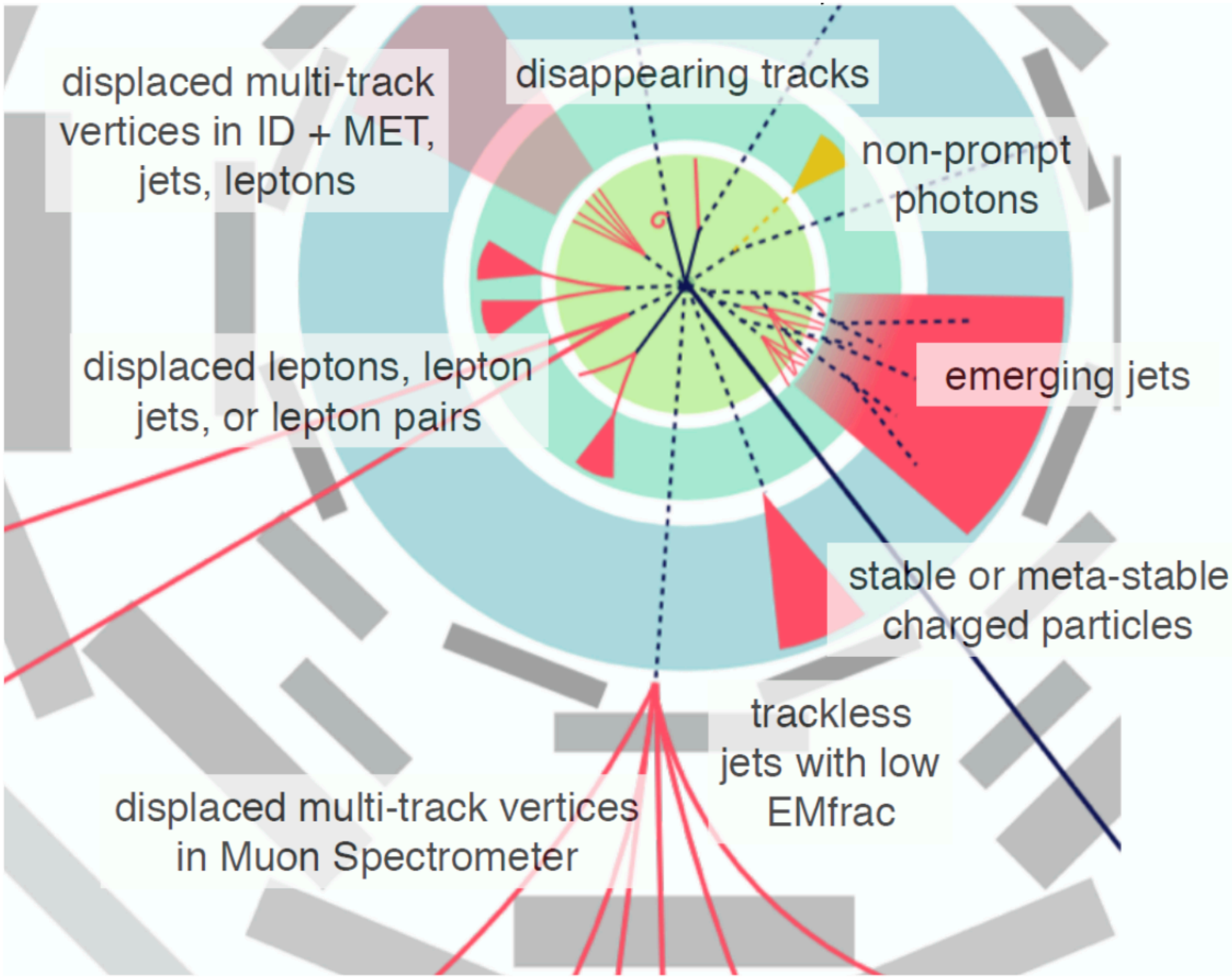
Depending on the lifetime of F, we can have different types of signatures in colliders



Graphic credits : Heather Russel

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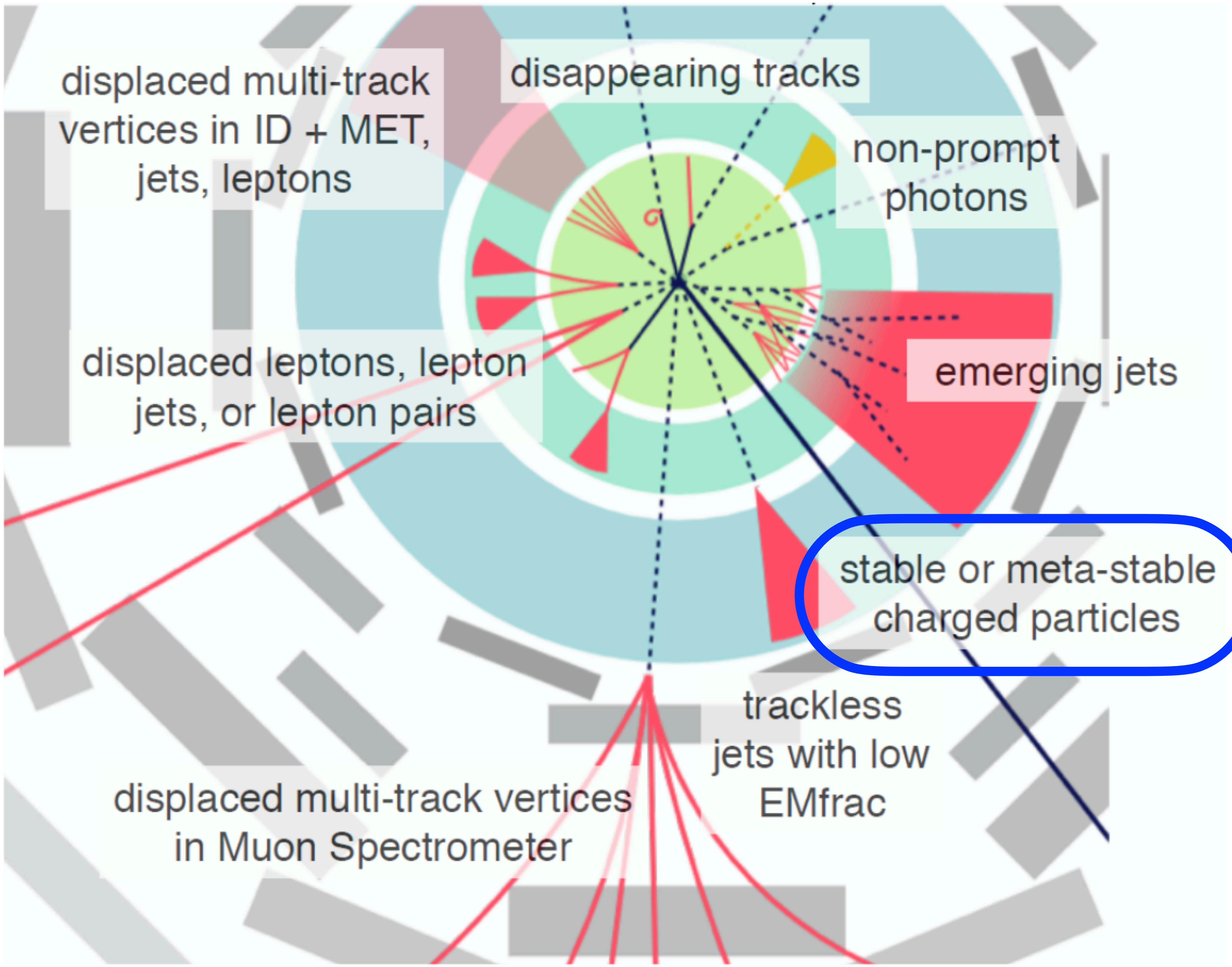

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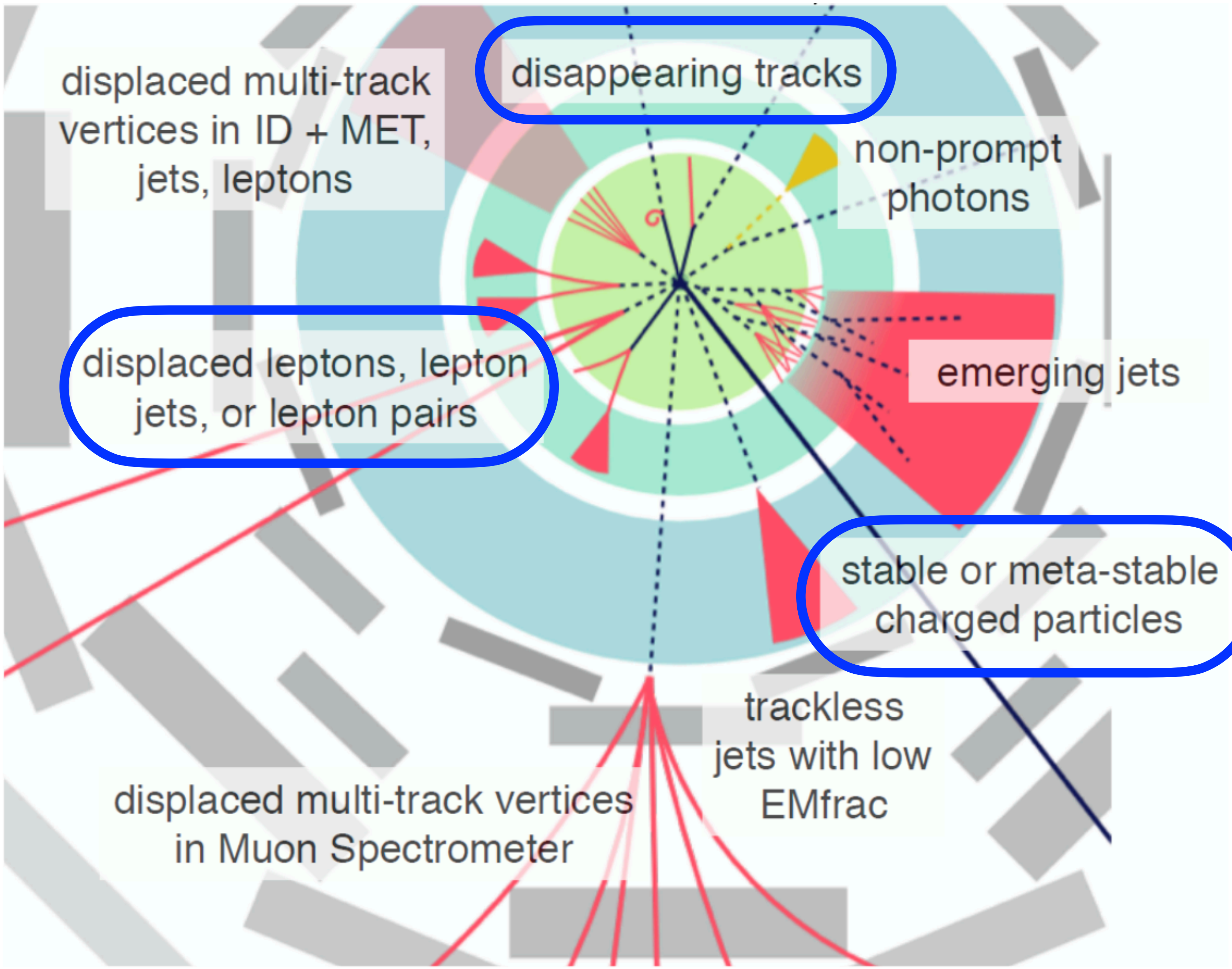

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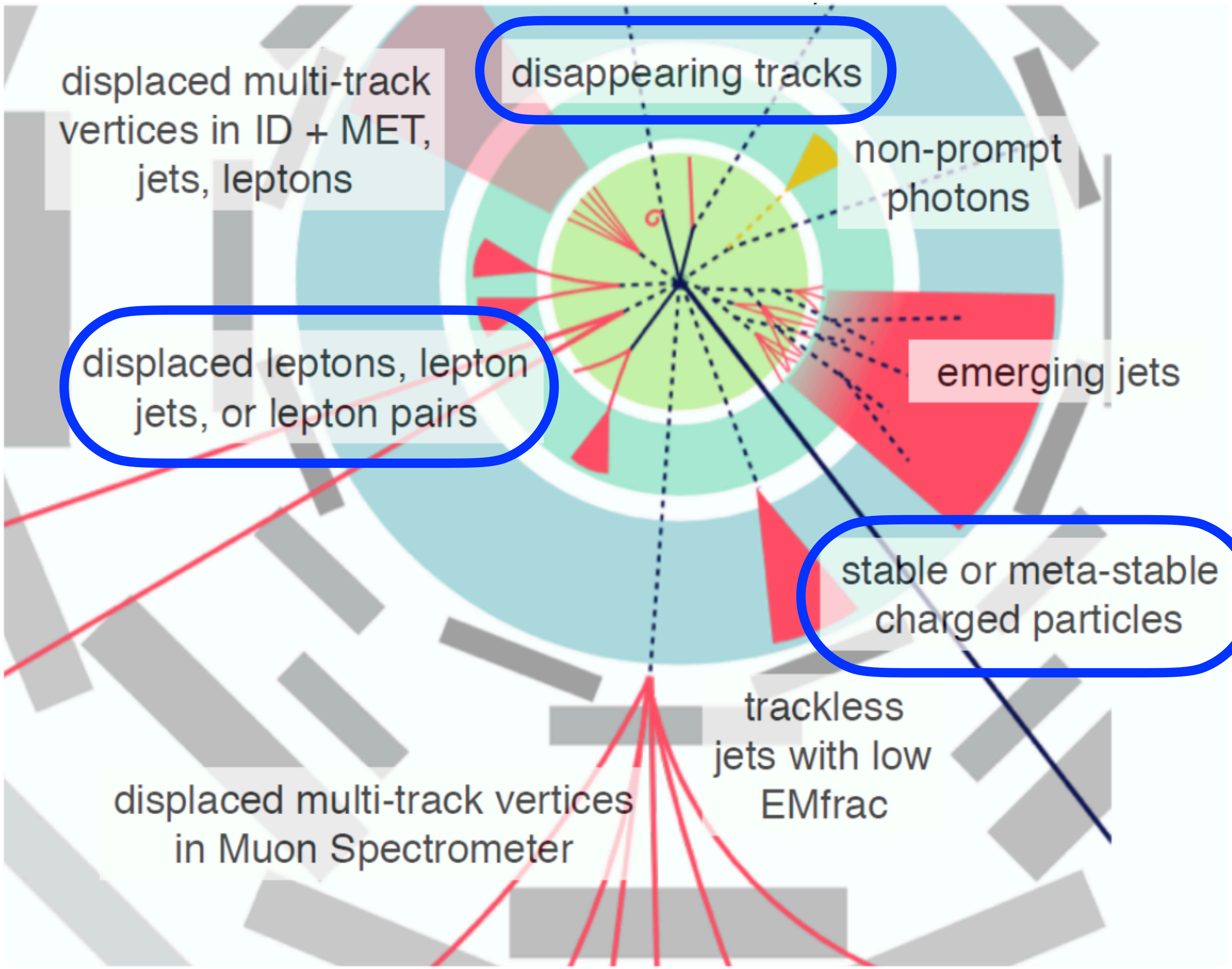

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+ eventually prompt searches for short lifetimes

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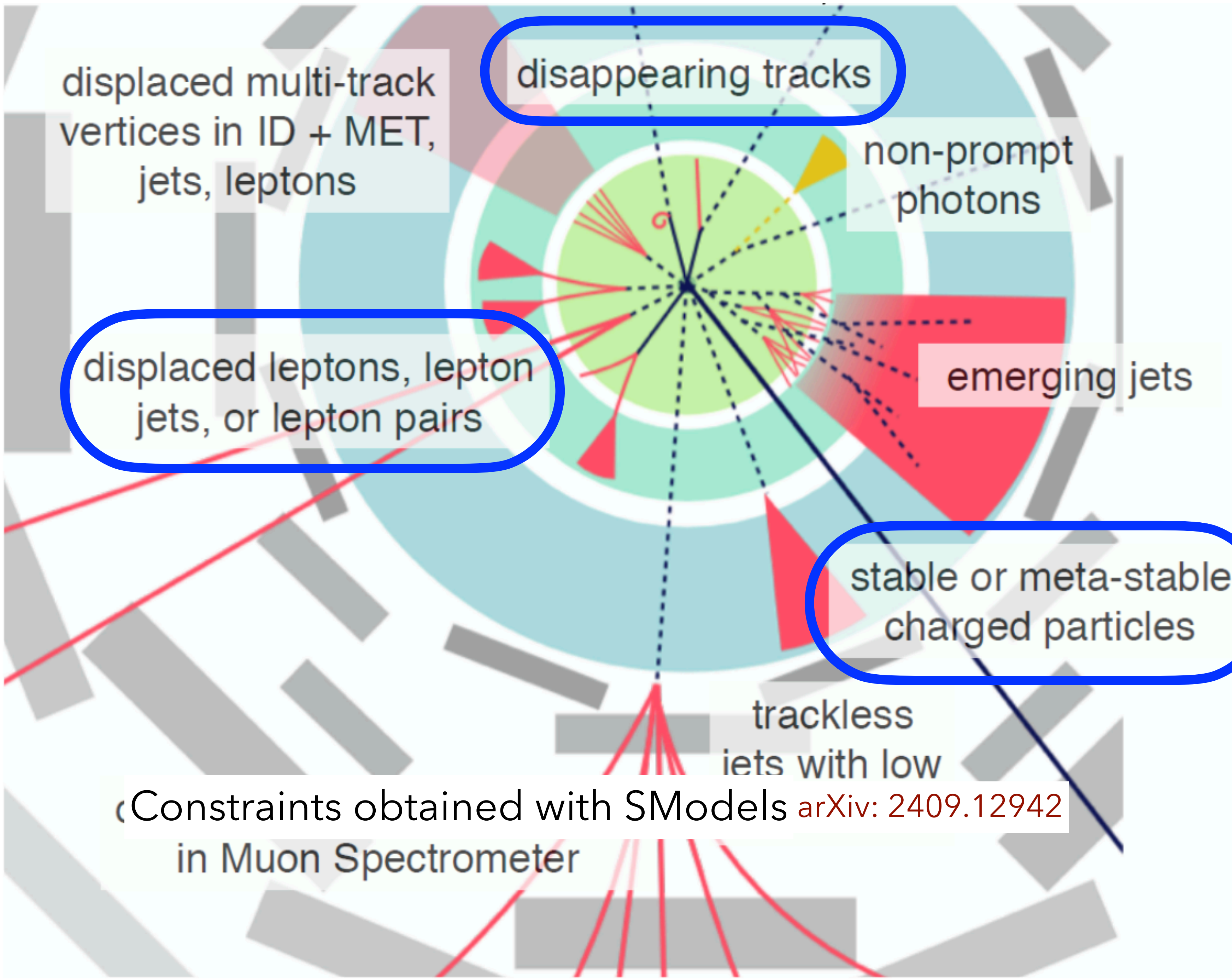

Constraints obtained with SModels arXiv: 2409.12942

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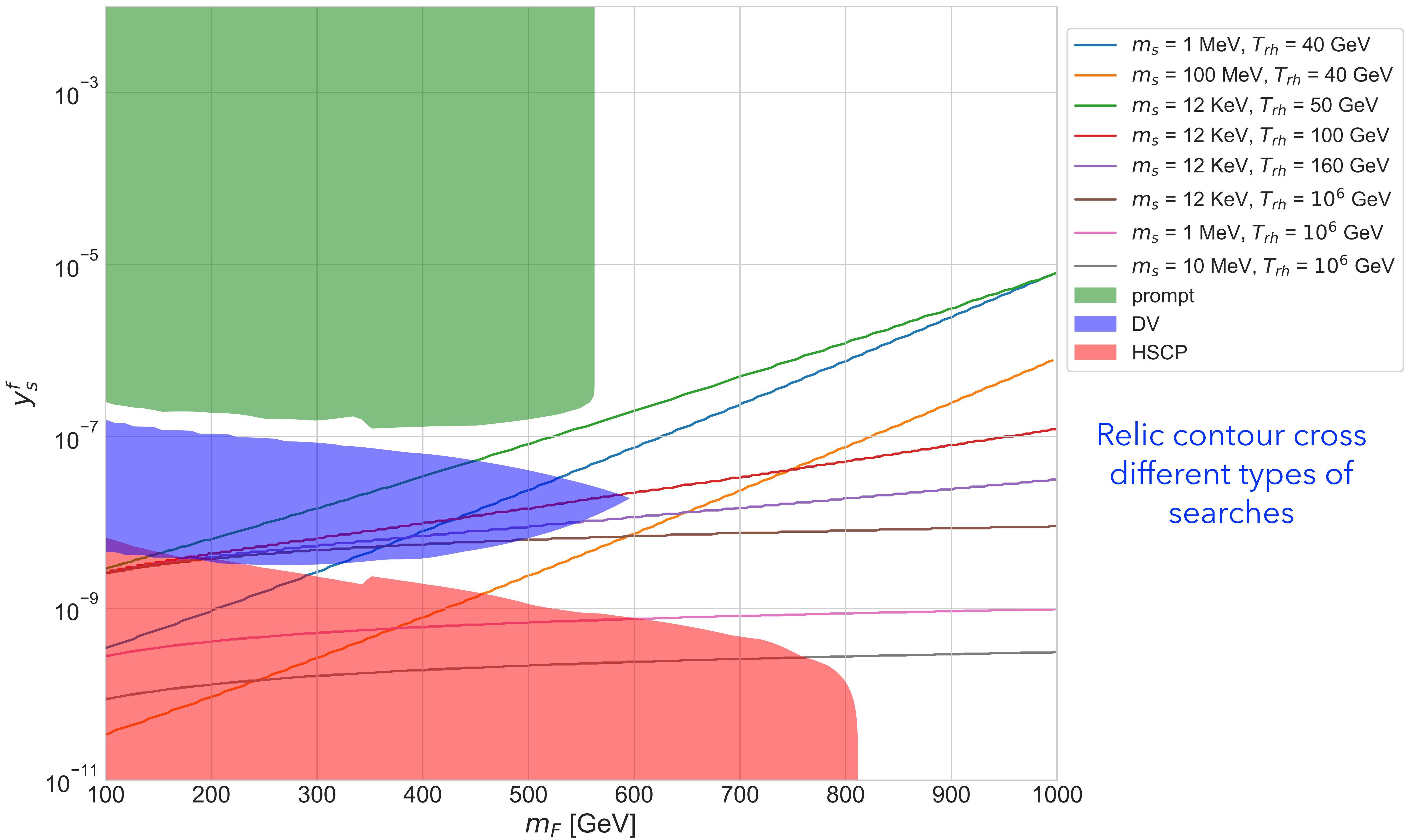
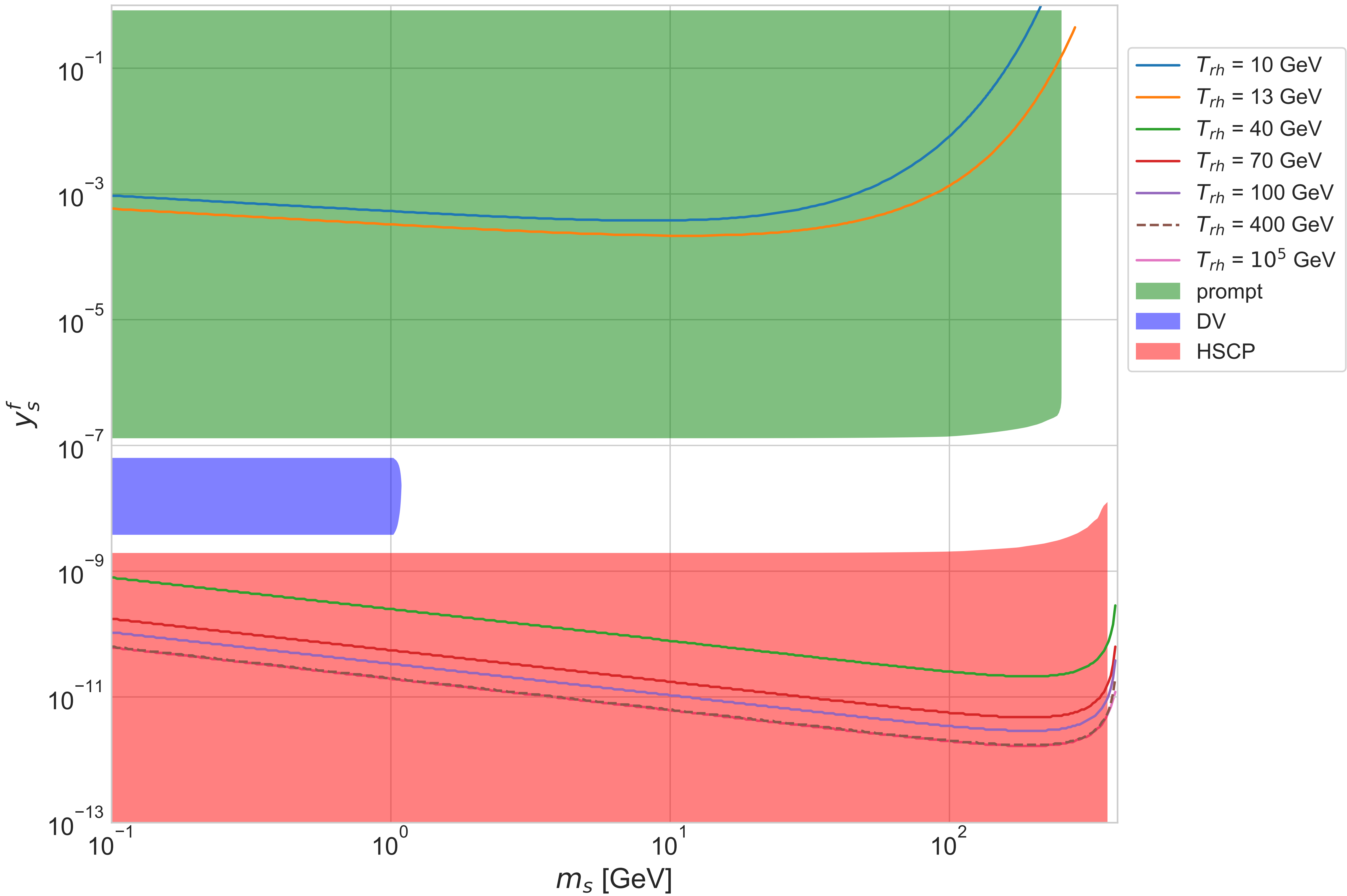
y_s^f vs m_F



Relic contour cross different types of searches

y_s^f vs m_s with $m_F = 400\,\mathrm{GeV}$



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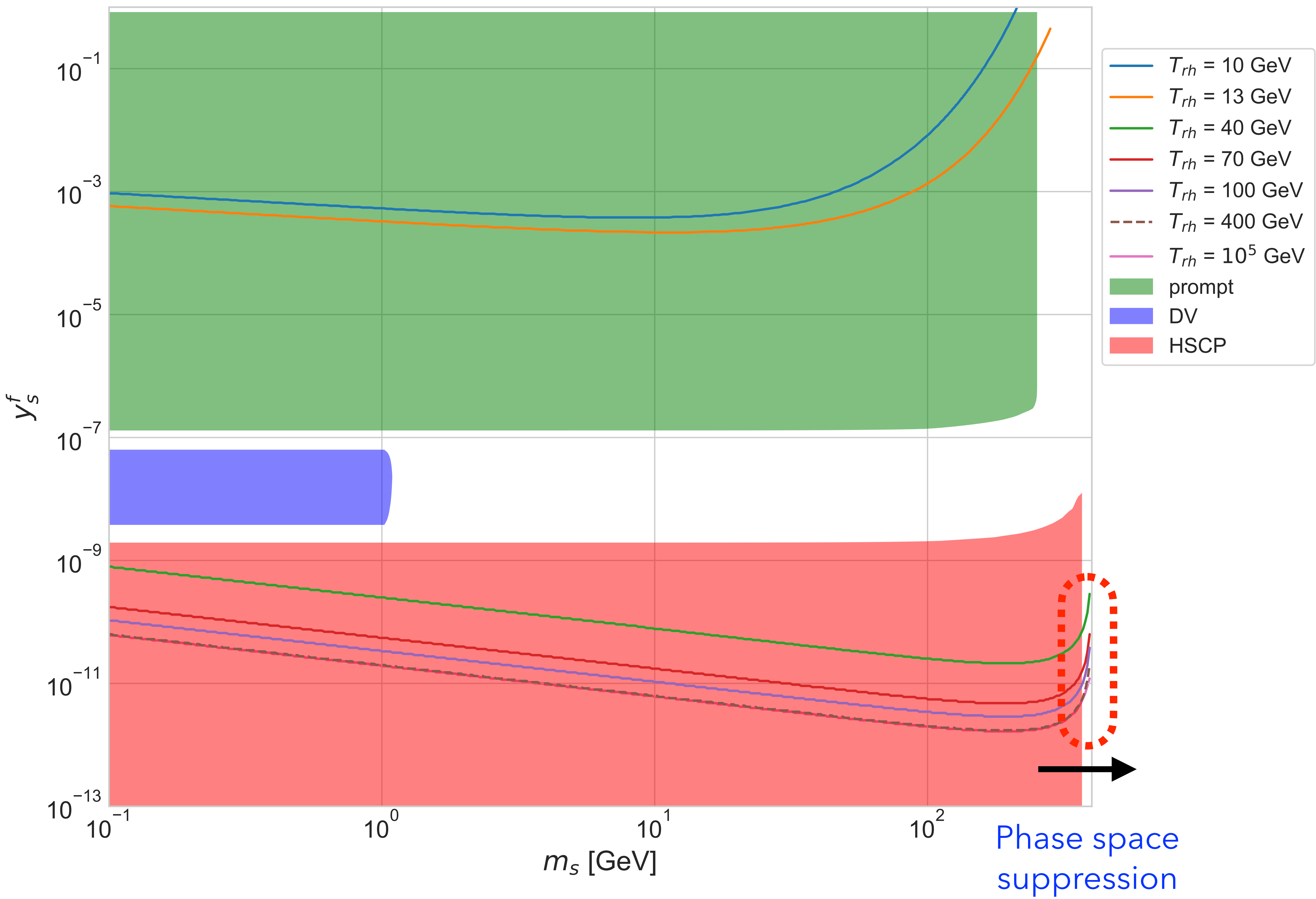

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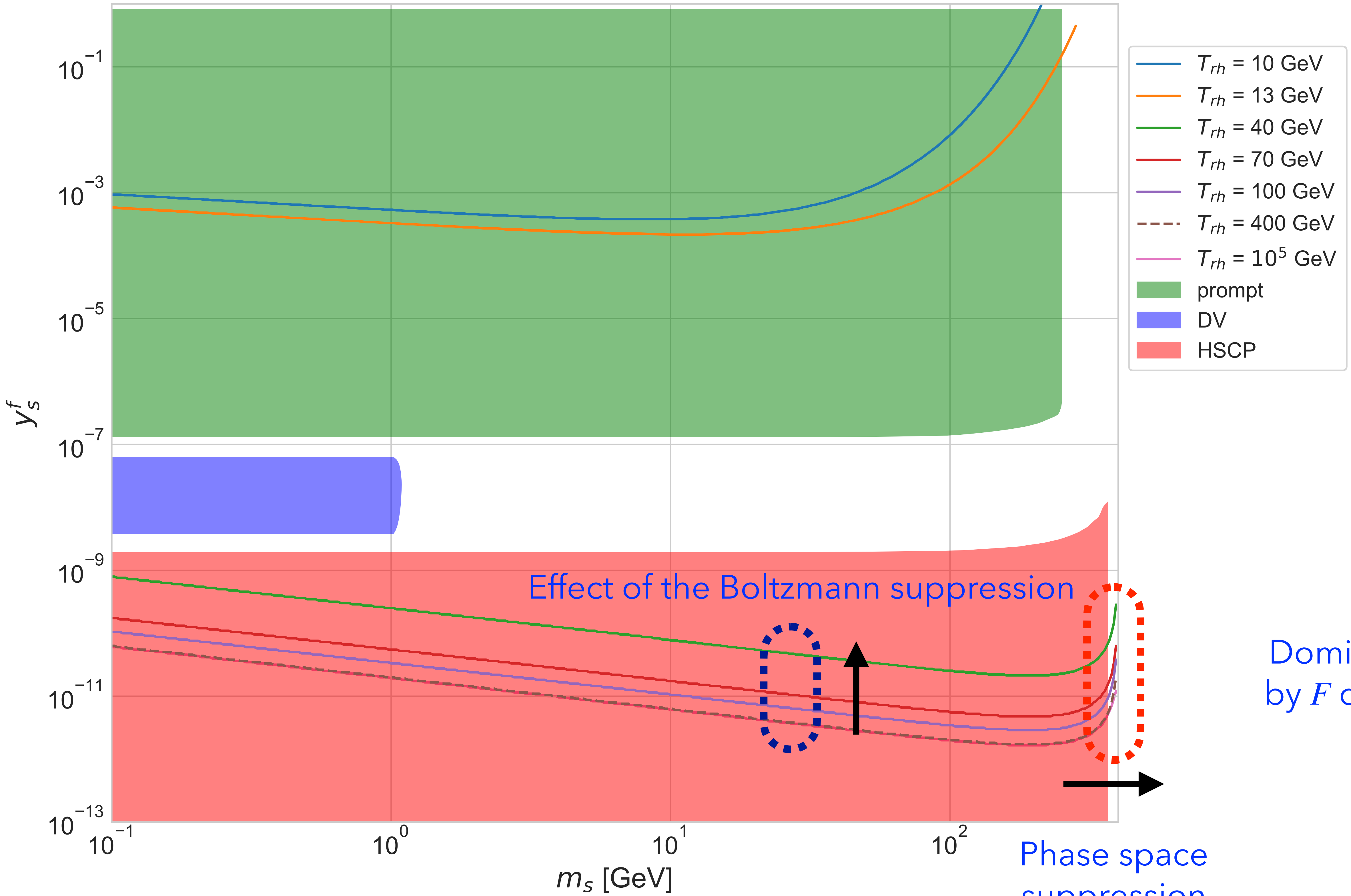

Dominated by F decays

Phase space suppression

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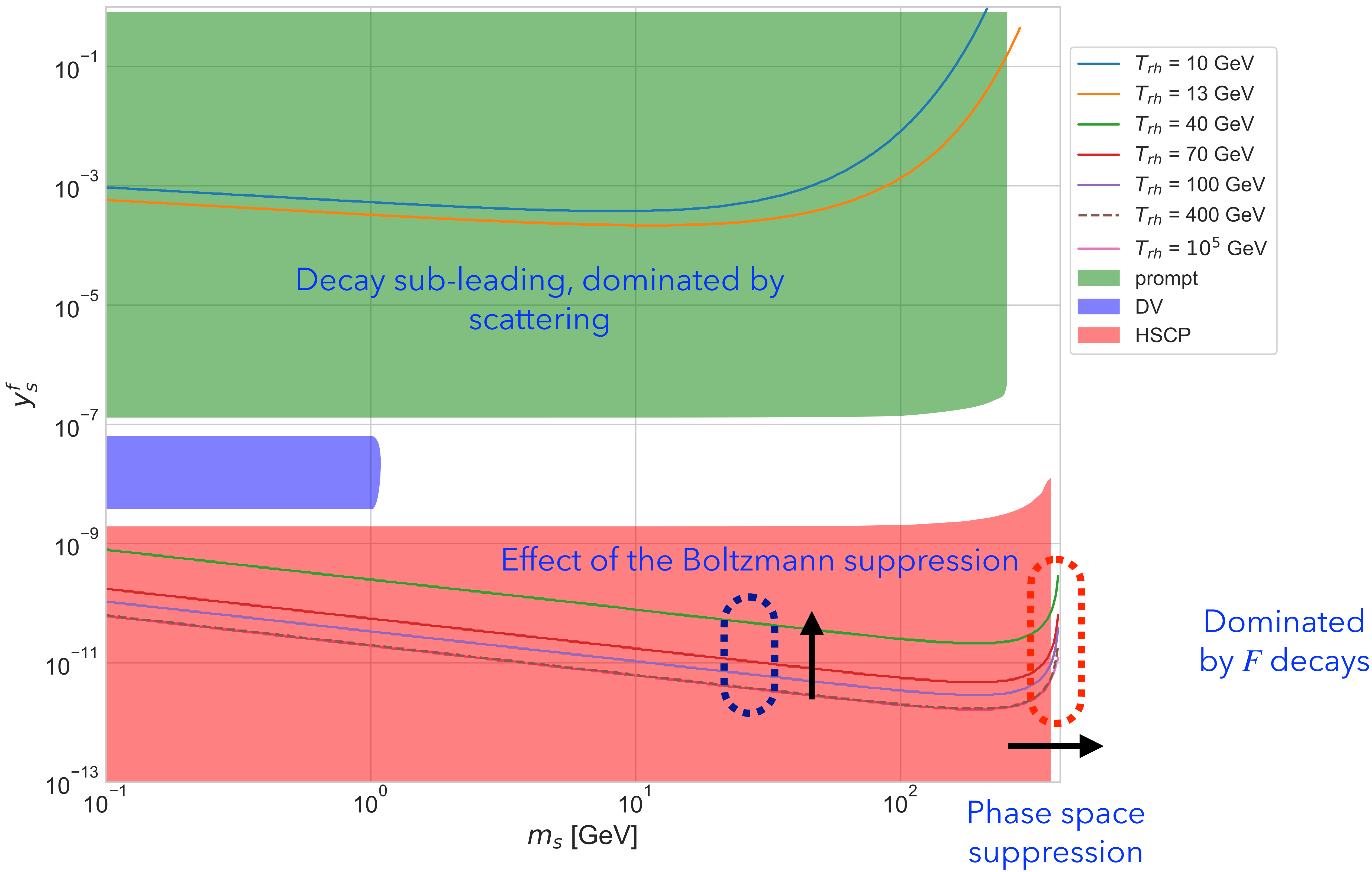
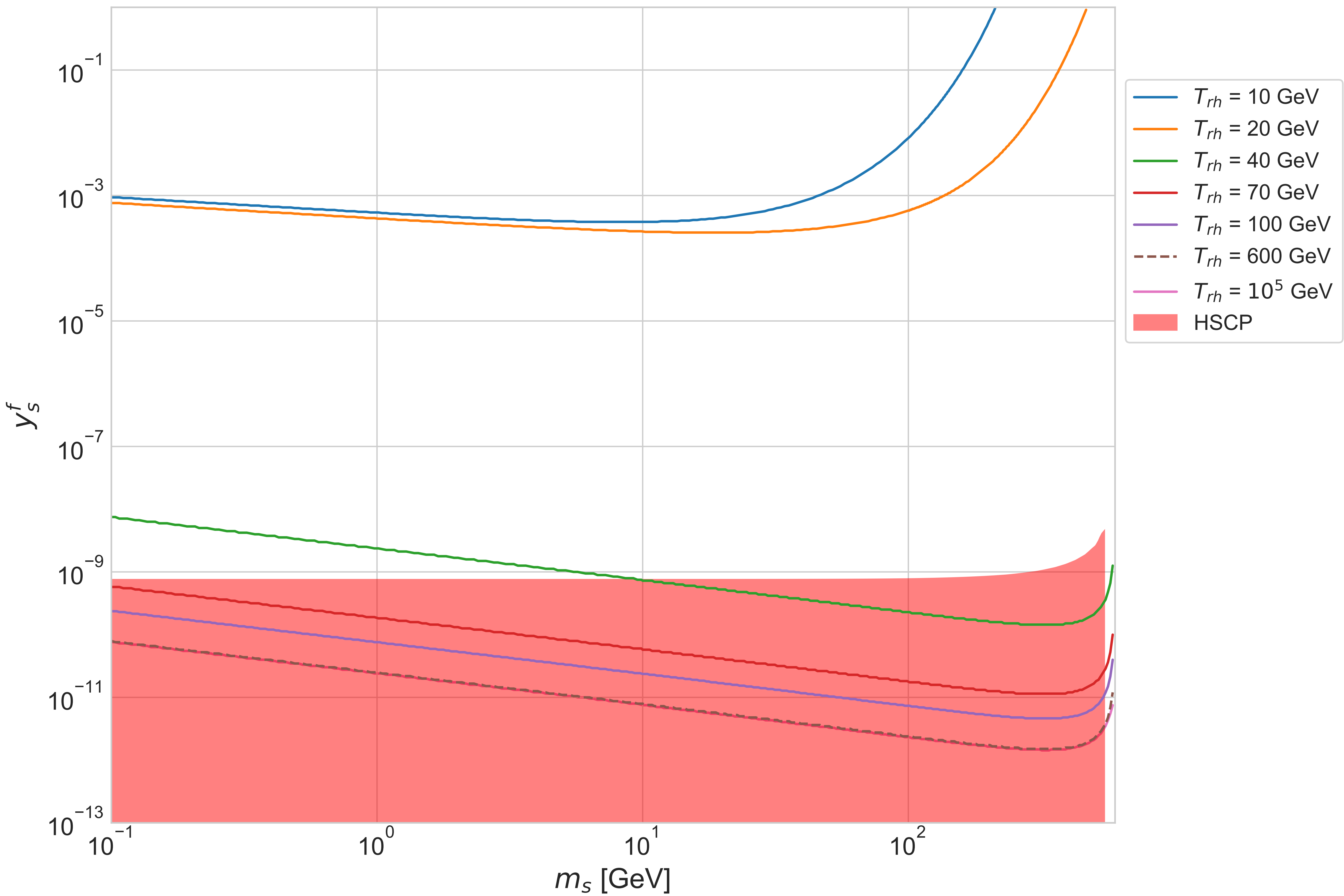


y_s^f vs m_s with $m_F = 600\,\text{GeV}$



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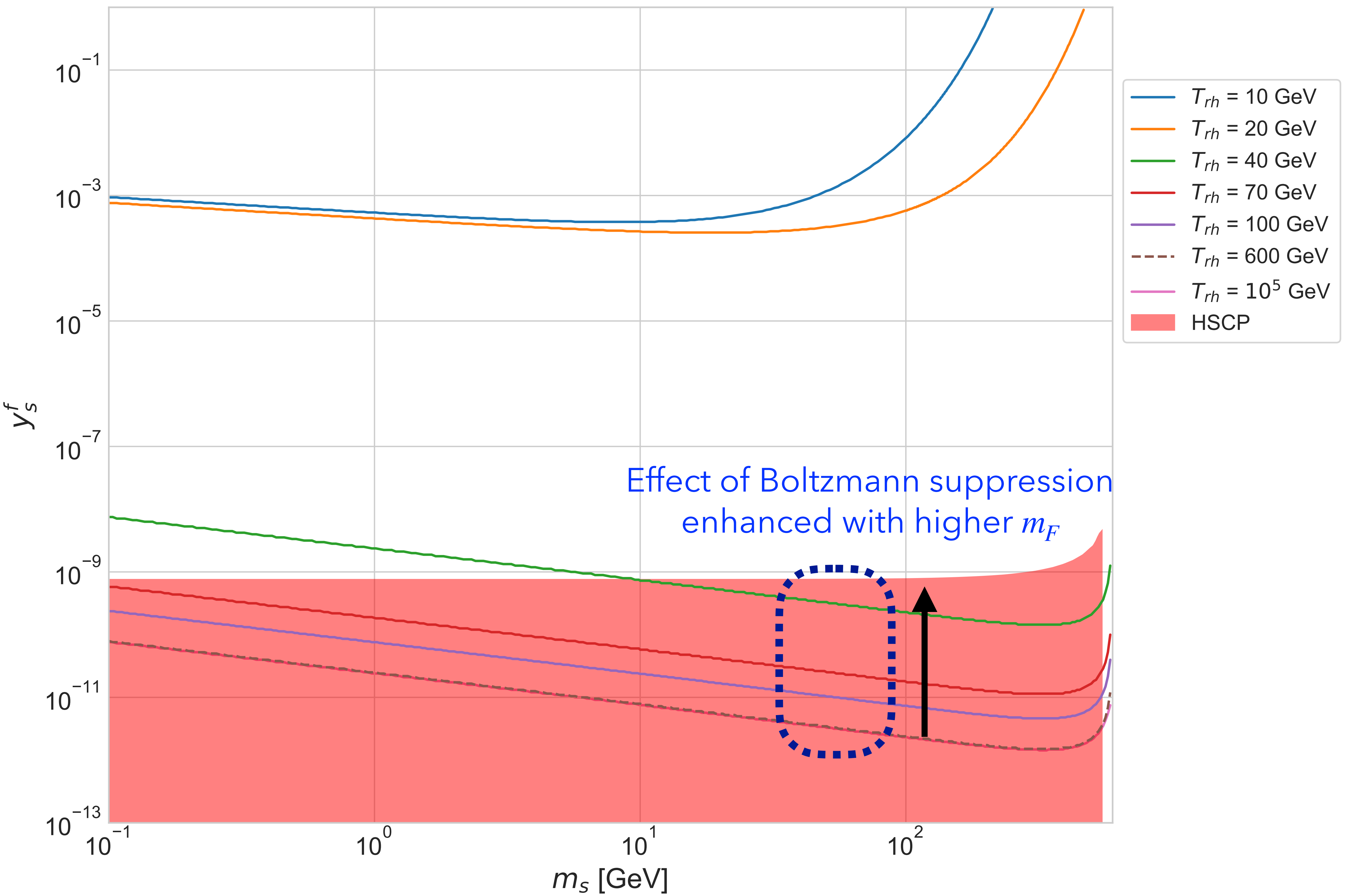
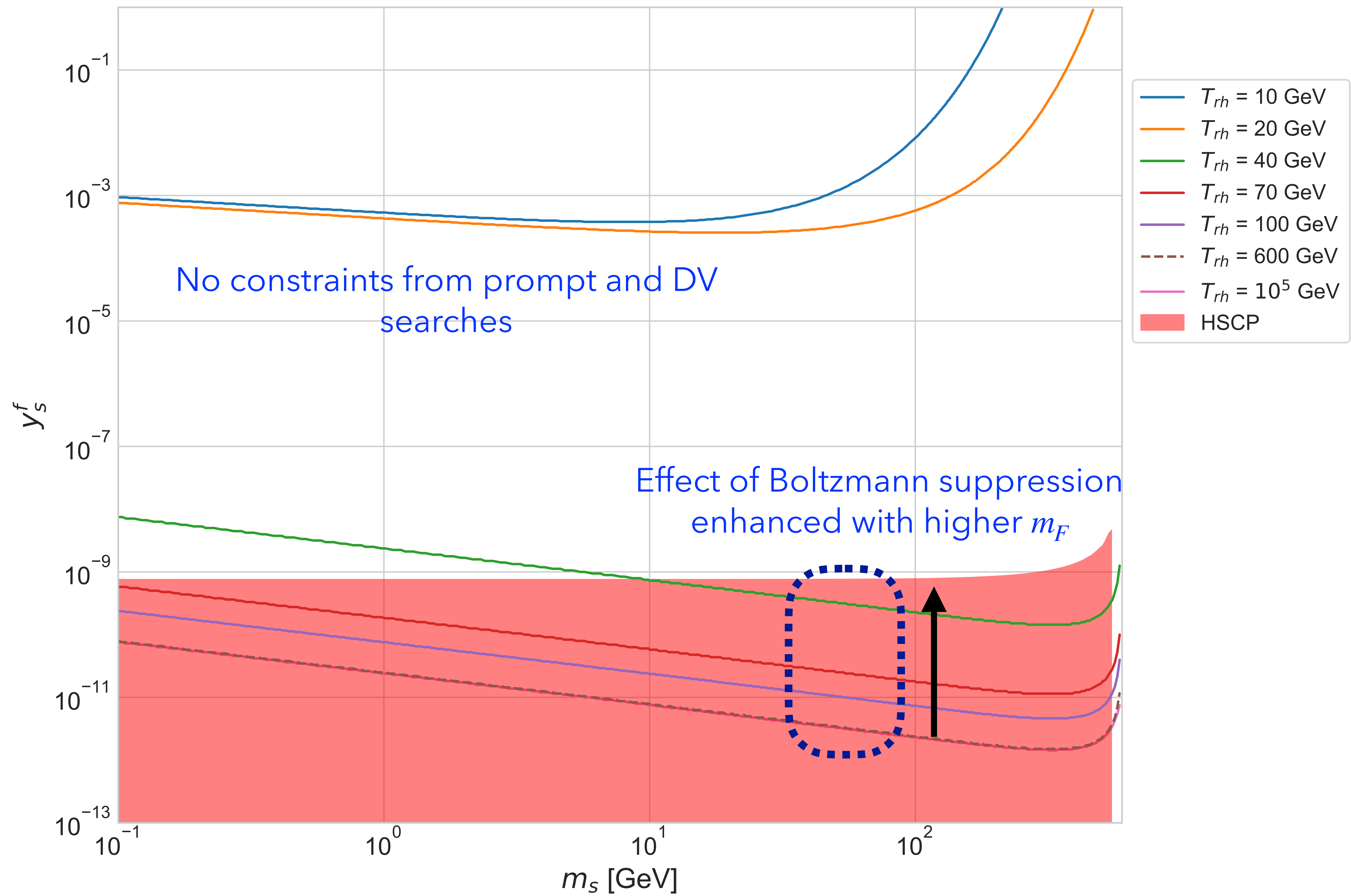
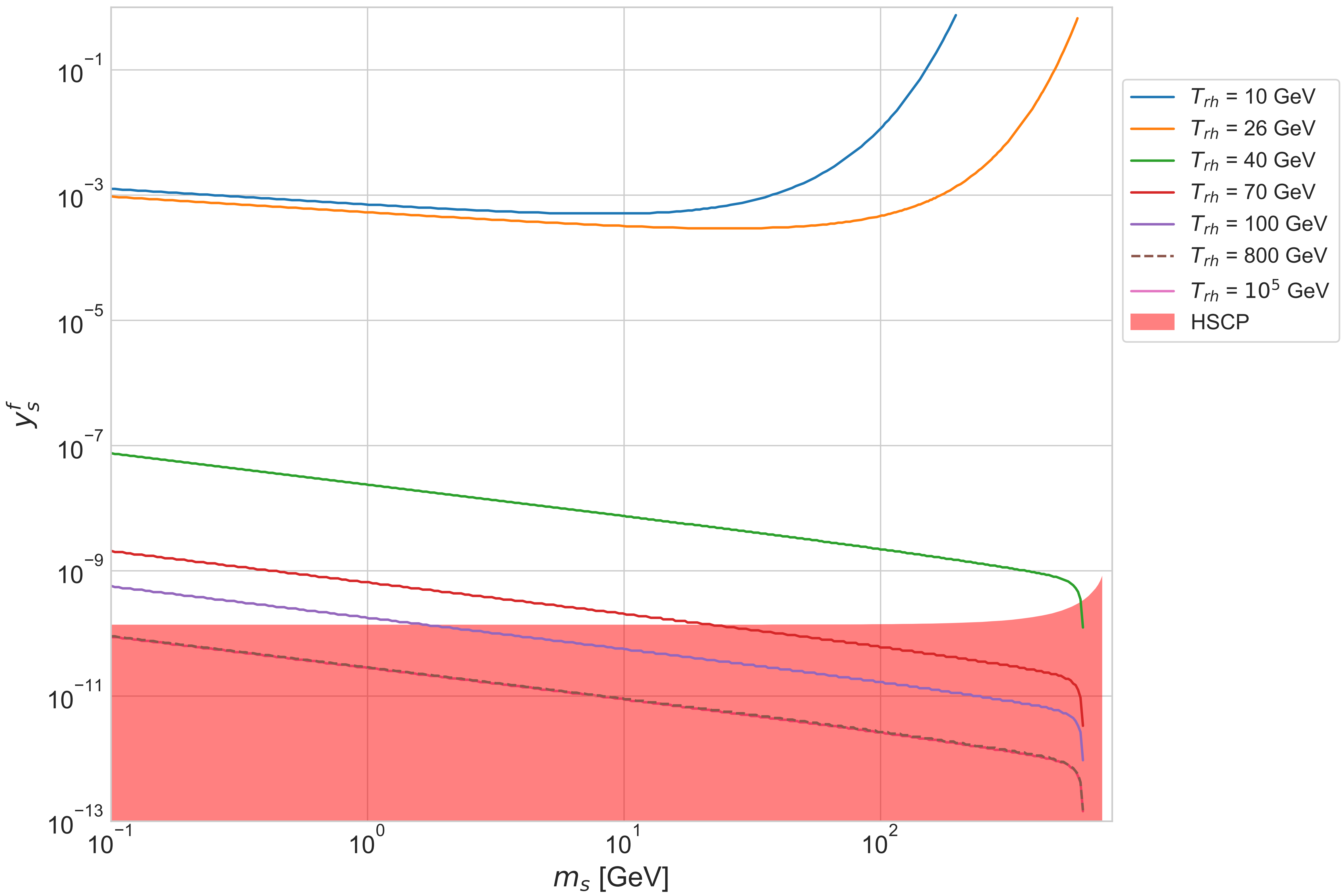


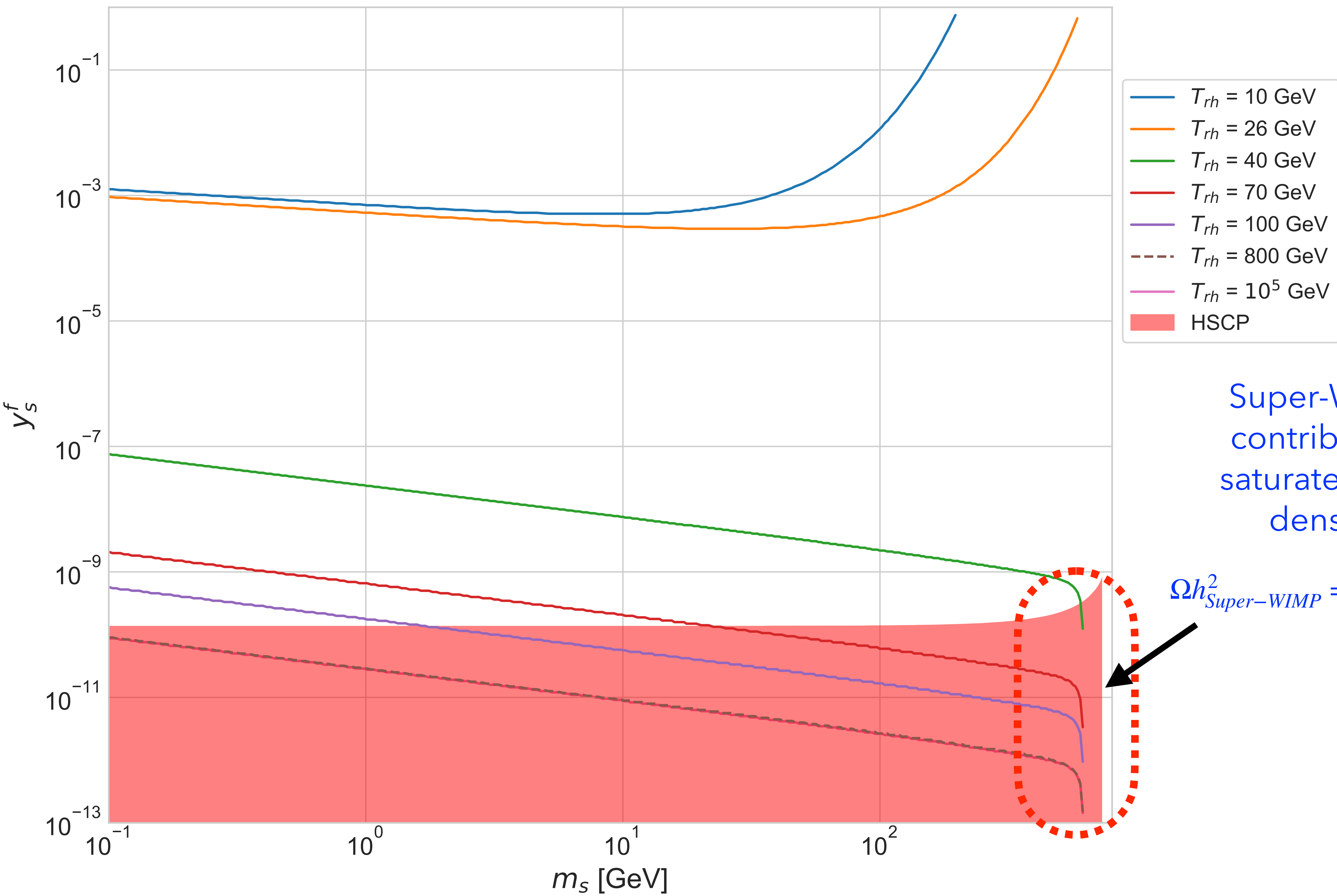
y_s^f vs m_s with $m_F = 600\,\text{GeV}$



y_s^f vs m_s with $m_F = 800\,\text{GeV}$



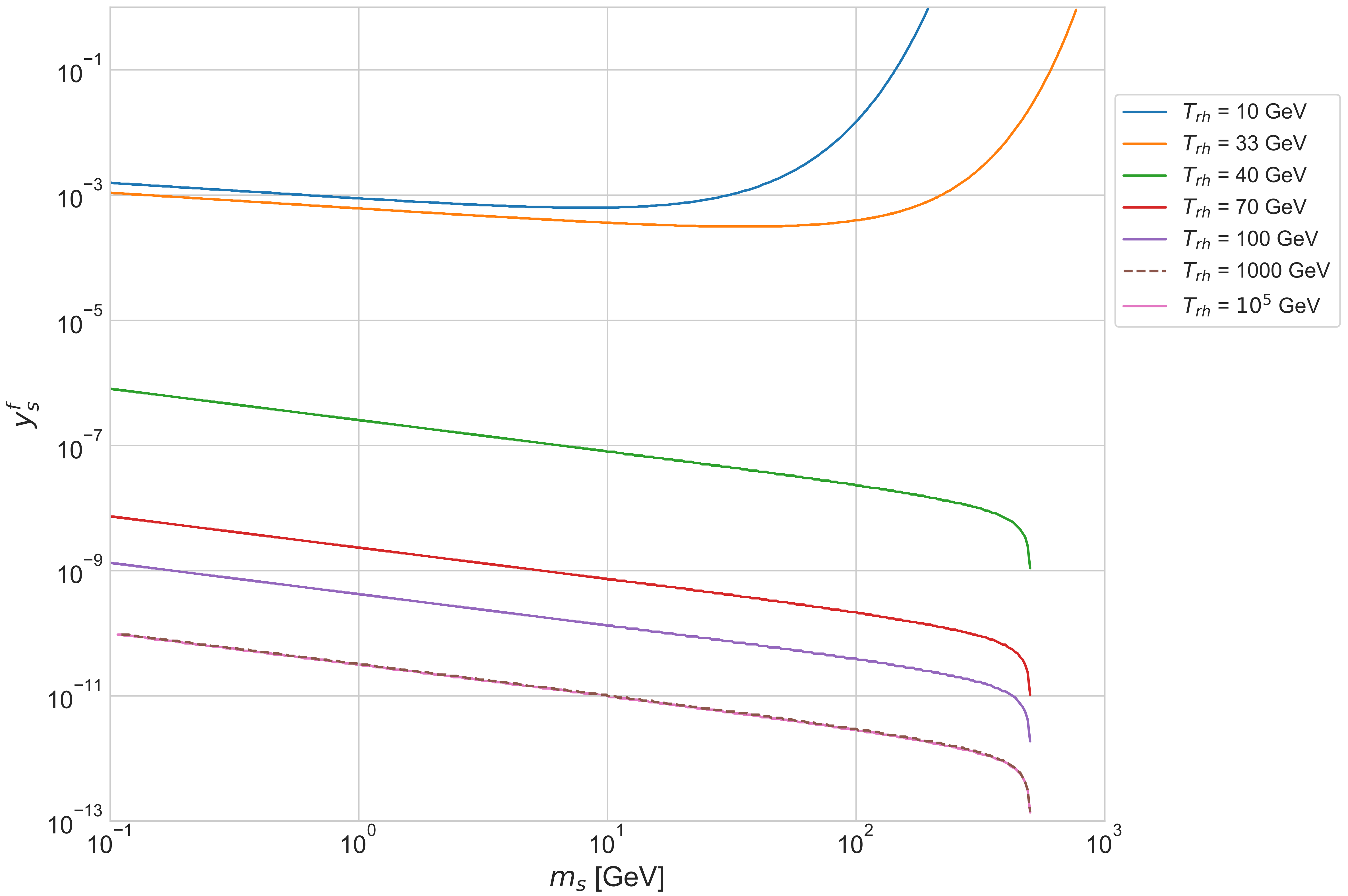
y_s^f vs m_s with $m_F = 800\,\text{GeV}$



Super-WIMP contribution saturates relic density

$$\Omega h^2_{Super-WIMP} = \Omega h^2_F \times \frac{m_s}{m_F}$$

y_s^f vs m_s with $m_F = 1000\,\mathrm{GeV}$



Conclusion and outlook

- In the freeze-in mechanism, dark matter production depends on the reheating temperature which is poorly constrained.
- Usually taken to be effectively infinite, reducing its value leads to stronger coupling in order to reproduce the observed dark matter abundance in the universe
- Different contributions enter the predicted dark matter density (F decays, SM particle annihilation, Super-WIMP contribution) and become dominant in different regions of parameter space and for different reheating temperatures

$\longrightarrow$ The phenomenology of freeze-in models can be drastically modified

- Modified cosmological assumptions can lead to different phenomenological signatures for freeze-in models
- To appear : $\mu \to e\gamma$ + direct detection constraints, consider alternative coupling patterns