Temperature of the Early Universe and freeze-in

Oleg Lebedev



University of Helsinki

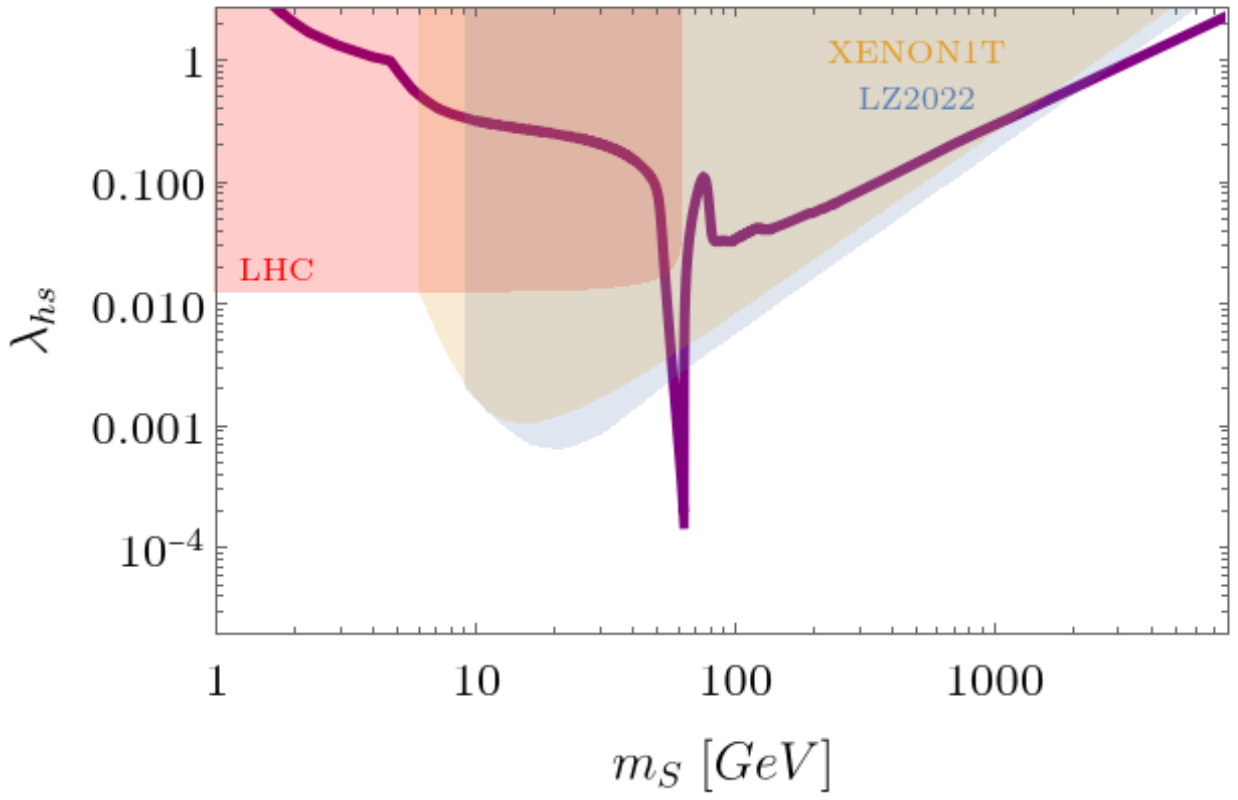
– temperature of the Early Universe

– freeze-in at stronger coupling

– signatures

Singlet scalar dark matter (Silveira, Zee '85) :

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



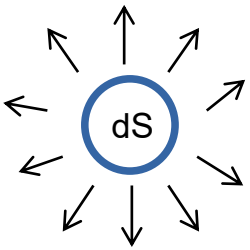
One parameter missing = T_R !

OL '22
Feiteira, OL '25

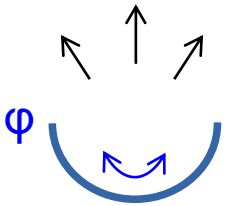
High T_R is a strong assumption:

1. *all we know* **$T_R > 4$ MeV** (Hannestad' 04)

2. *problematic for freeze-in*



inflation

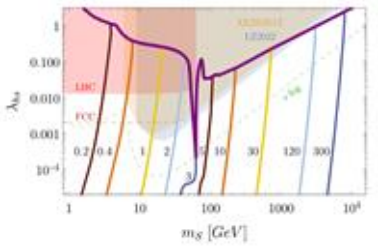


post-inflation

$$\frac{\varphi^4 \Phi^2}{M_{\rm Pl}^2}$$

Gravitational particle production background invalidates predictions !

→ **add T_R to any DM plot**



Temperature evolution in the Early Universe

General approach:

SM is generated via decay of some primordial field χ

$$\dot{\rho} + 4H\rho = \Gamma_\chi \rho_\chi \,,$$
$$H = H_0/a^m \,,$$
$$\rho_\chi = \rho_\chi^0/a^n \,.$$

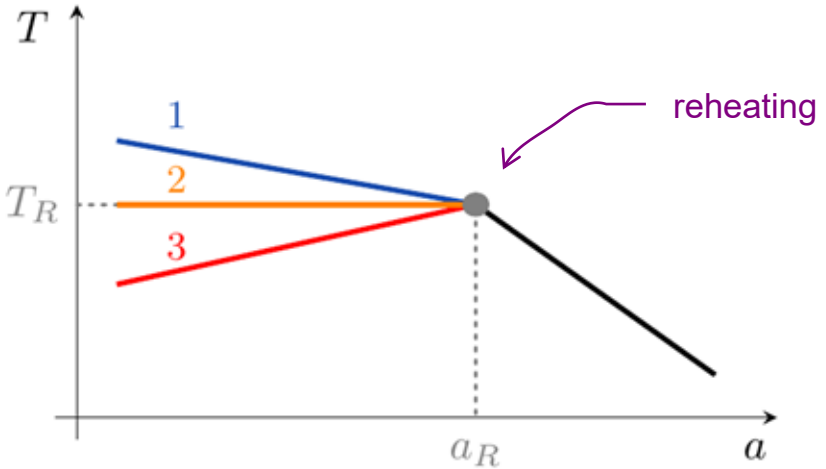
m, n = model-dependent scaling parameters

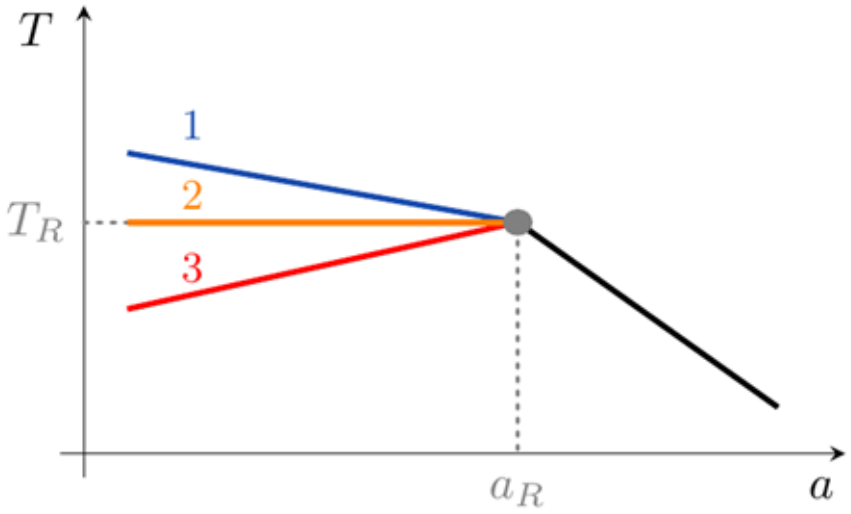
ρ = *SM energy density*

Solution:

$$\rho(a) = \frac{\Gamma_\chi \rho_\chi^0}{(4-n+m)H_0}\left[\frac{1}{a^{n-m}} - \frac{1}{a^4}\right] \;\rightarrow\; \frac{\Gamma_\chi \rho_\chi^0}{(4-n+m)H_0}\frac{1}{a^{n-m}}$$

$$T_{\rm SM} \simeq \left(\frac{30}{g_*\pi^2}\right)^{1/4} \rho^{1/4} \;\propto\; a^{-\frac{n-m}{4}}$$





1. n-m > 0 : textbook (inflaton decay)
2. n-m = 0 : SM via cascade decay (R-neutrino decay)
3. n-m < 0 : "instant reheating"-like

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

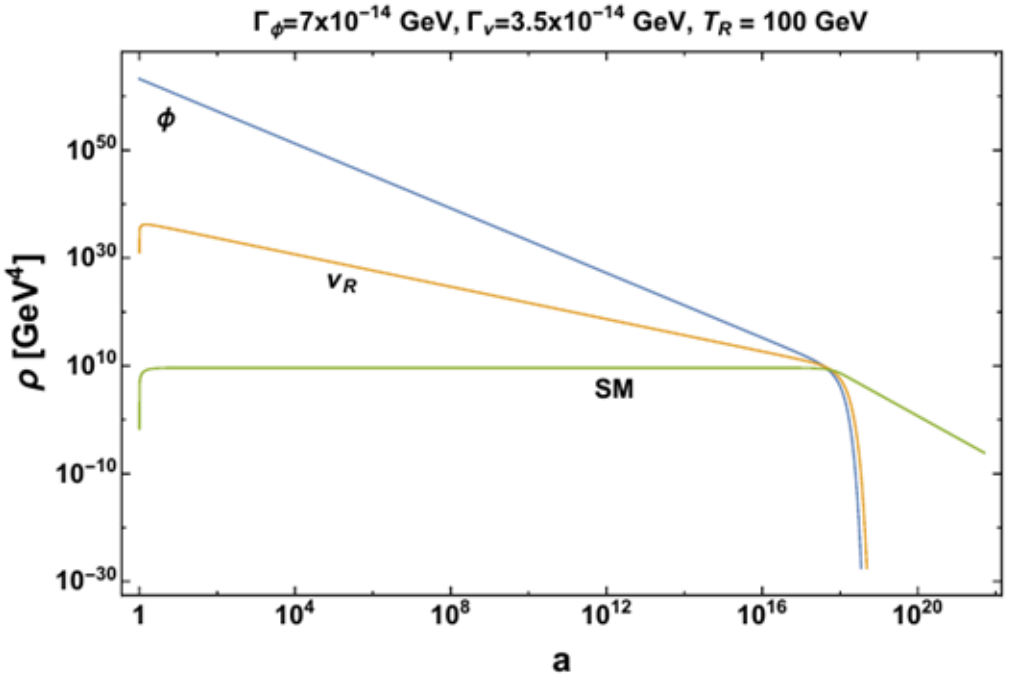
SM bath temperature may have never been high !

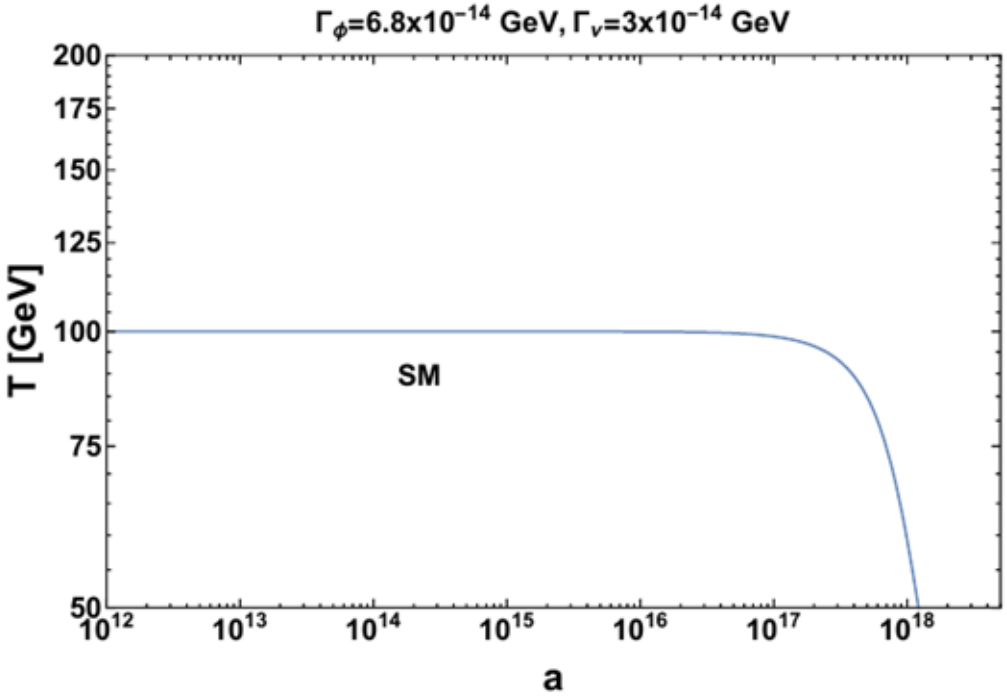
$$T_R \sim \lambda \rightarrow 0$$

Example: ***reheating via neutrinos*** ($\phi \nu_R \nu_R$ + lepton symmetry)

$$\phi \to \nu_R \nu_R \quad , \quad \nu_R \to \mathrm{SM}$$

n=3/2 , m=3/2 ➡ n-m=0 ➡ *flat temperature profile*





$T_R \sim T_{max}$

Freeze-in at stronger coupling

Motivation: *dilute gravitationally-produced relics*

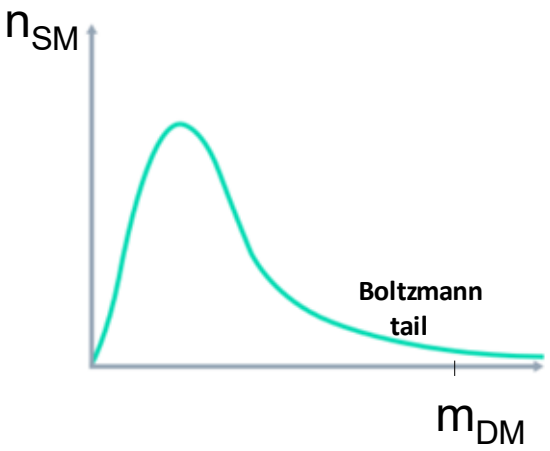
inflaton energy density ~ a^{-3}

rel. relic energy density ~ a^{-4}



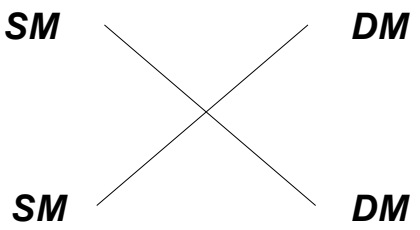
low T_R

What if $T_R < m_{DM}$?



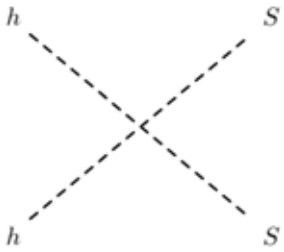
off the tail





Simplest model = Higgs portal DM

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



Boltzmann equation:

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

No annihilation:

$$\Gamma(h_i h_i \to ss) \simeq \frac{\lambda_{hs}^2 T^3 m_s}{2^7 \pi^4} e^{-2m_s/T} \quad \Rightarrow \quad \lambda_{hs} \simeq 3 \times 10^{-11}\, e^{m_s/T_R} \sqrt{\frac{T_R}{m_s}}$$

With annihilation:

$$\Gamma(ss \to h_i h_i) = \sigma(ss \to h_i h_i) v_r\, n^2 \quad , \quad \sigma(ss \to h_i h_i) v_r = 4 \times \frac{\lambda_{hs}^2}{64\pi m_s^2}$$

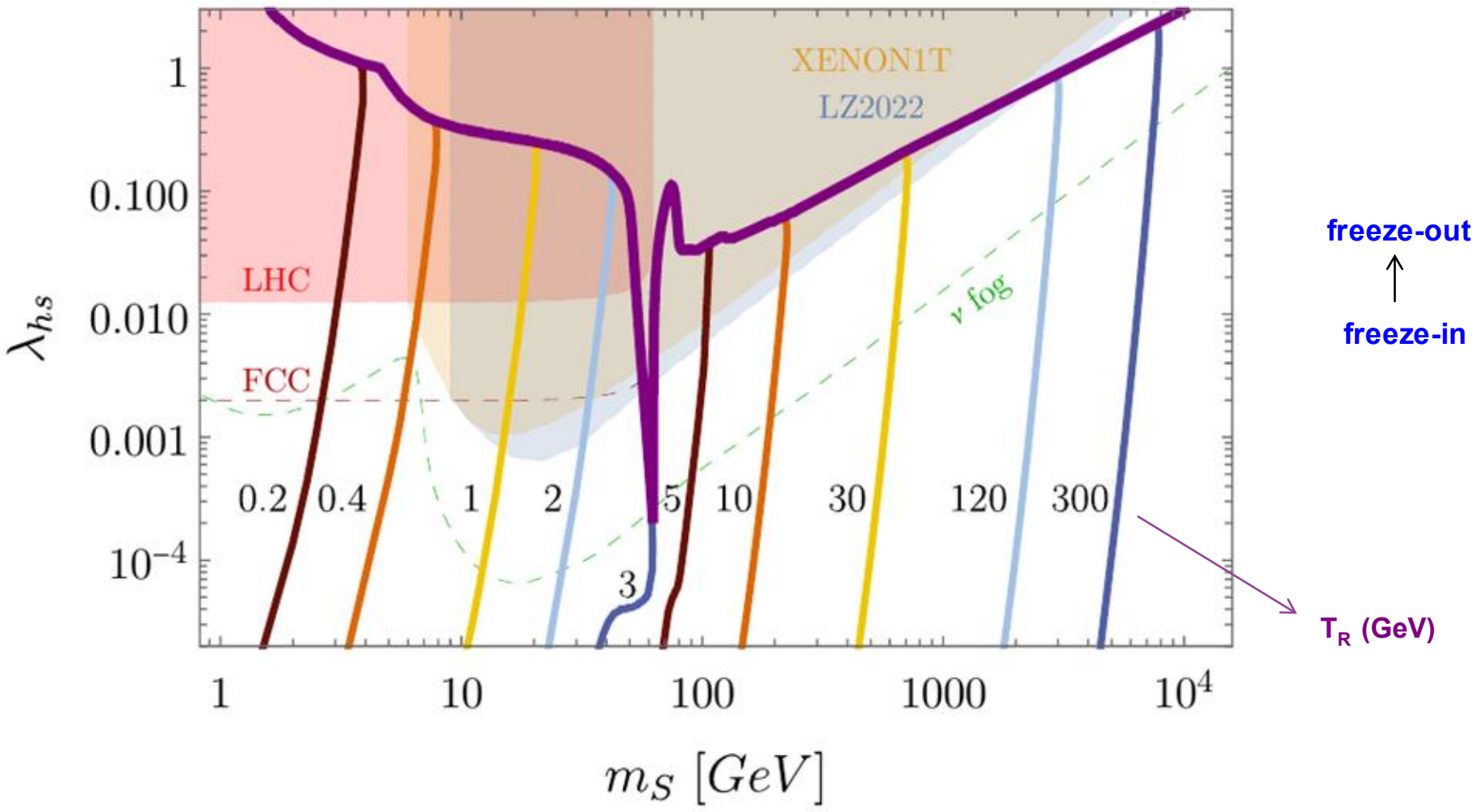
No thermalization:

$$\Gamma(h_i h_i \to ss) \neq \Gamma(ss \to h_i h_i)$$

Scalar Higgs portal DM :

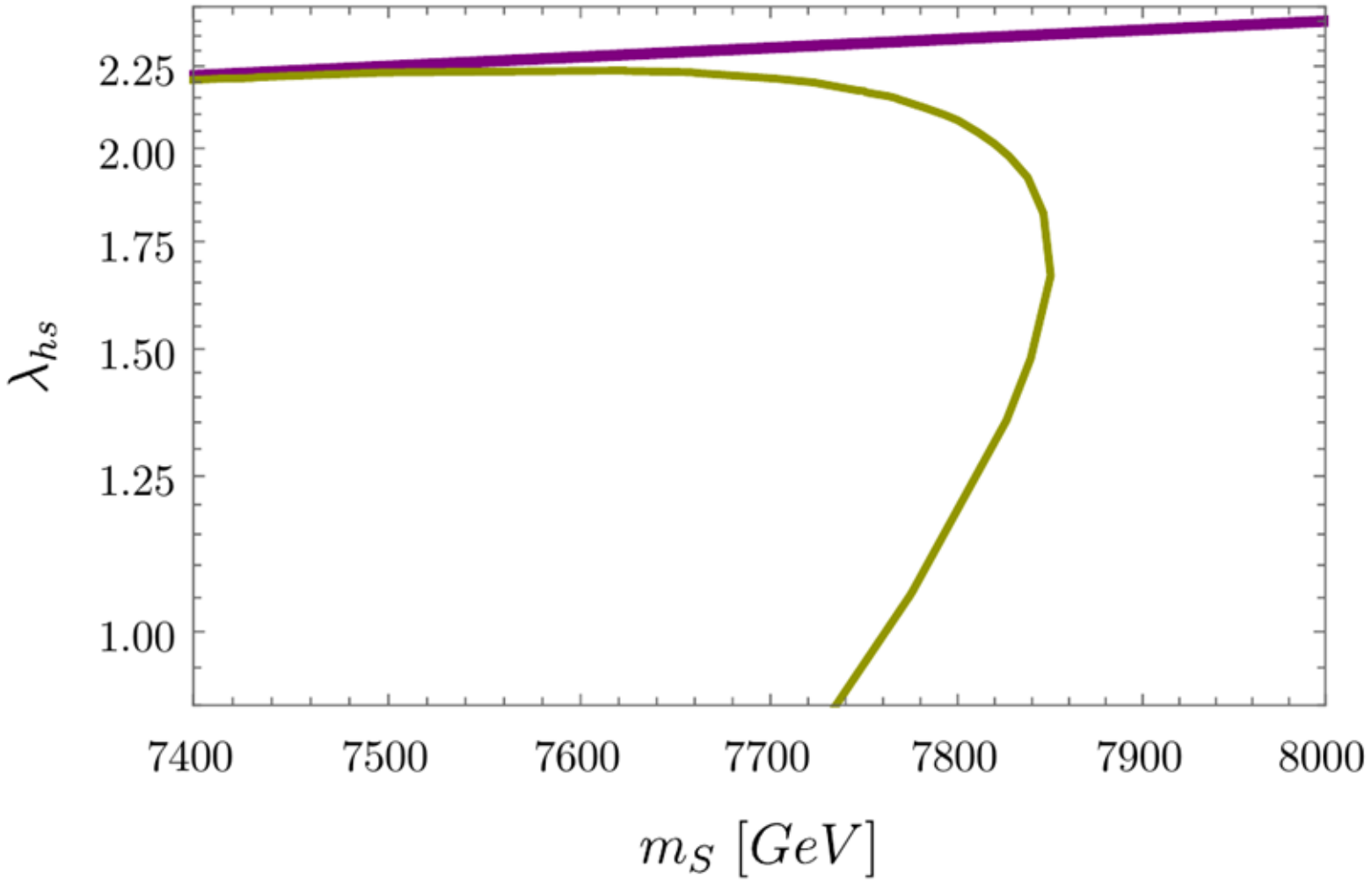
$$V(s) = \frac{1}{2}\lambda_{hs} s^2 H^\dagger H + \frac{1}{2} m_s^2 s^2$$

Arcadi,Costa,Goudelis,OL '24

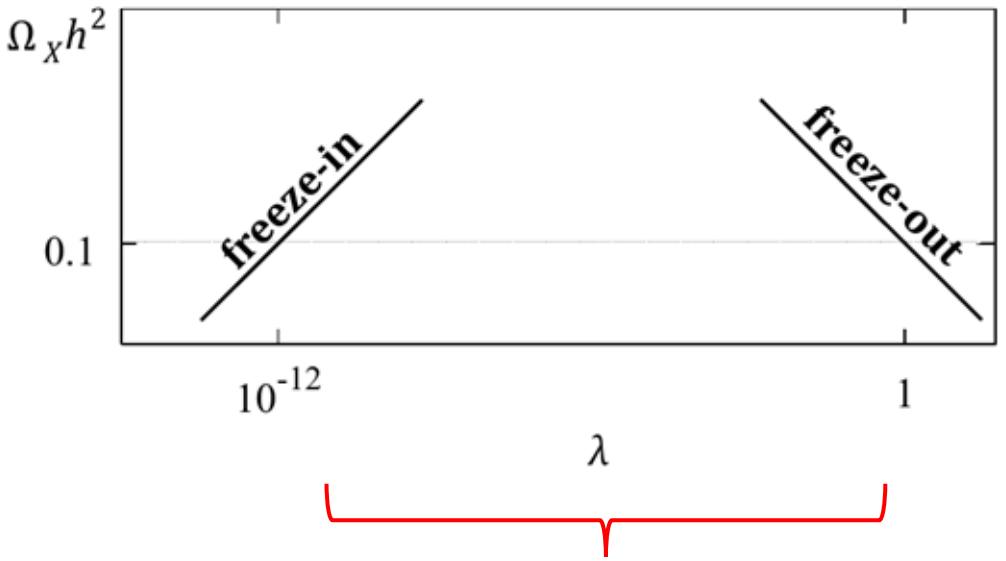


New input: treat ***unknown*** T_R as a free parameter ➡ direct detection + invisible Higgs decay

Freeze-in ➡ Freeze-out

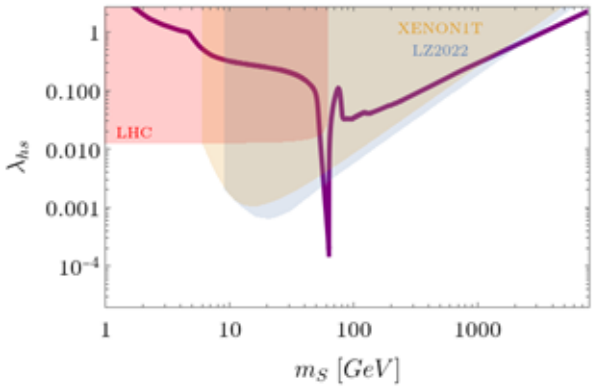


FIMP → WIMP



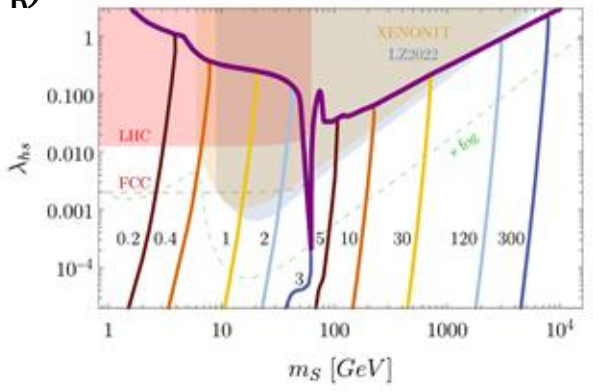
freeze-in at stronger coupling

"excluded"



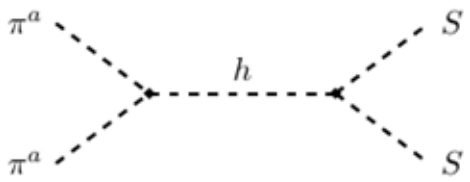
(m, λ) → (m, λ, T_R)

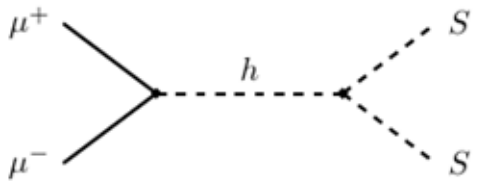
viable

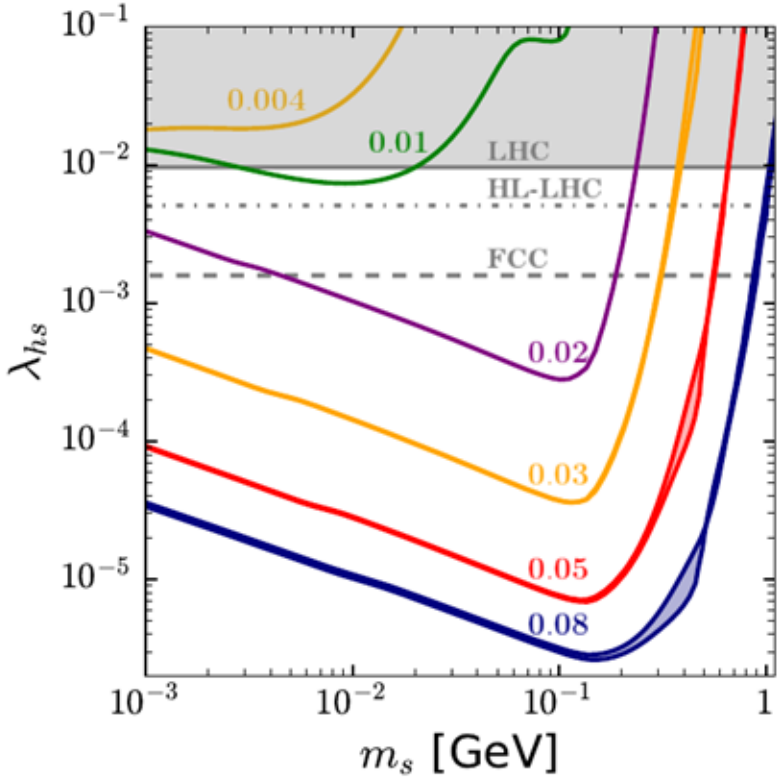


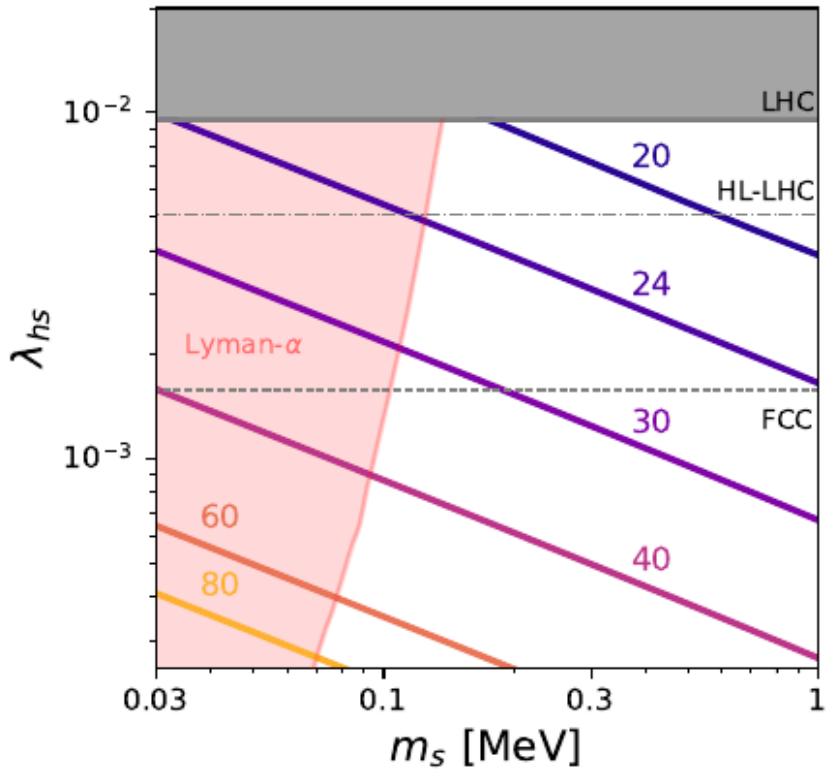
OL,Morais,Oliveira,Pasechnik ‘24
Feiteira, OL, Oliveira ‘26

Low DM mass :





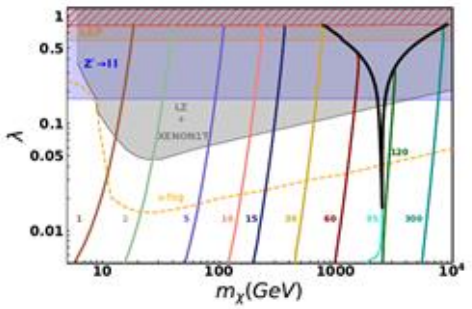




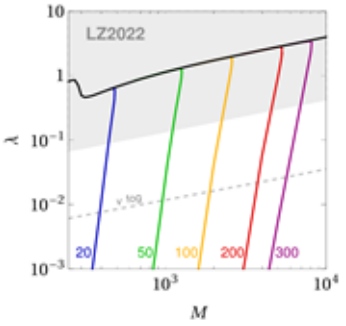
Warm DM: invisible Higgs decay at LHC / FCC

CONCLUSION

- *T_R is an unknown variable*
- *stronger coupling freeze-in: FIMP → WIMP*
- *your favorite model is not ruled out, just cool it*



Z'



ν_R

...