Dark matter freeze-in at stronger coupling:

observational prospects

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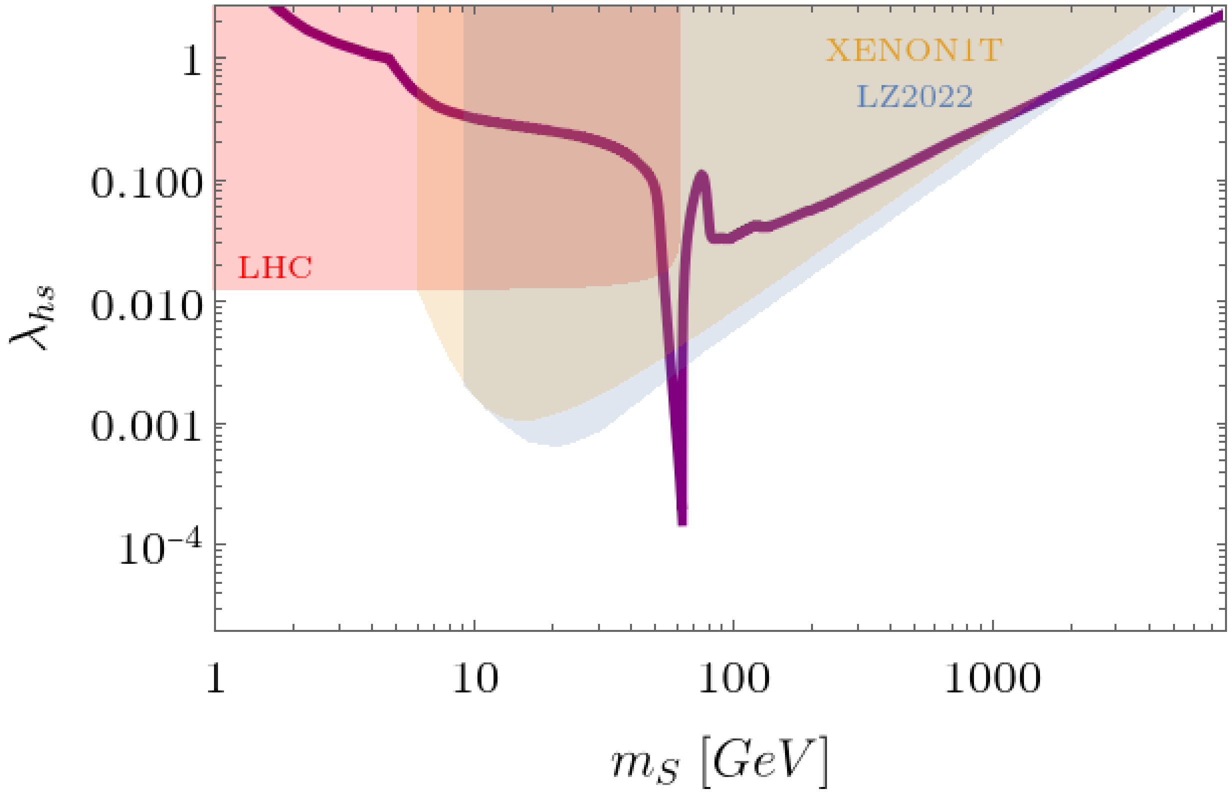
- temperature of the Early Universe

- freeze-in at stronger coupling

- signatures

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

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



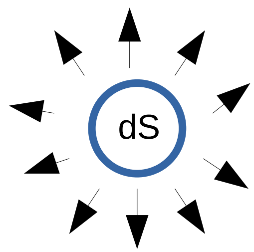
One parameter missing = T_R !

OL ‘22
Feiteira, OL ‘25

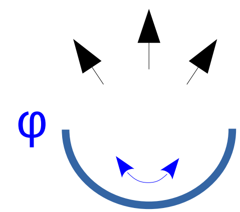
<u>High T_R is a strong assumption</u>:

1. *all we know* $\boxed{T_R > 4\ \text{MeV}}$ (Hannestad’ 04)

2. *problematic for freeze-in*



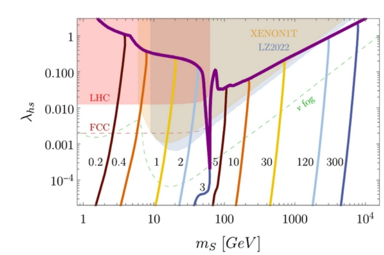
inflation



post-inflation

gravitational particle production background invalidates predictions

<u>**add T_R to any DM plot**</u>



Cosme,Costa,OL '24

Temperature evolution in the Early Universe

General approach:

SM is generated via decay of some primordial field χ

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

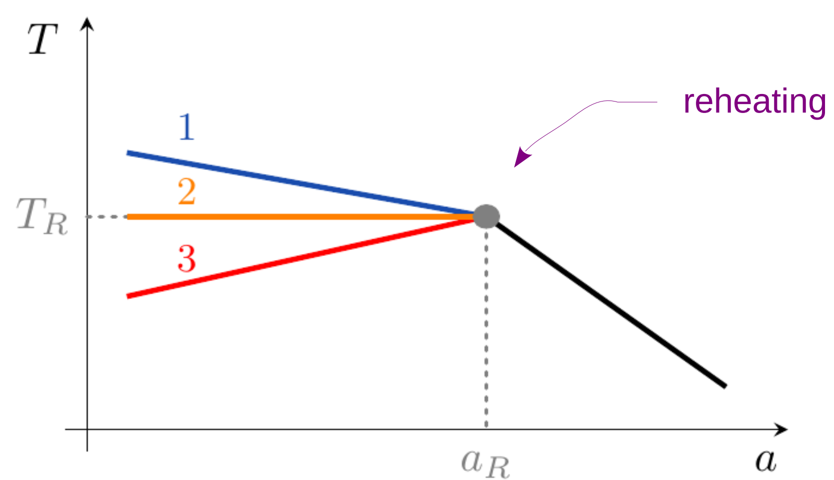
m, n = model-dependent scaling parameters

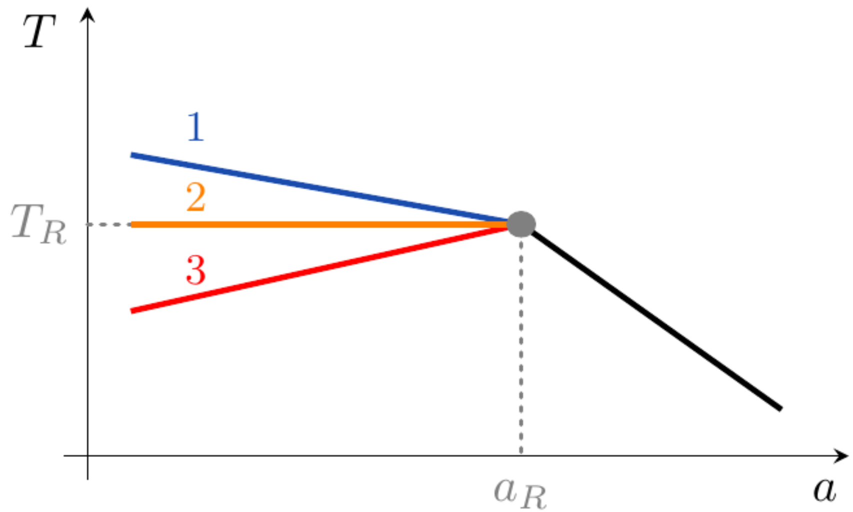
ρ = *SM energy density*

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 !

$$\mathbf{T_R \sim \lambda \longrightarrow 0}$$

Cosme,Costa,OL ‘23

Freeze-in at stronger coupling

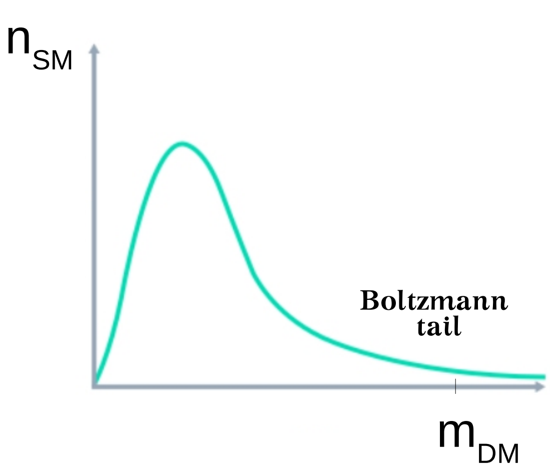
Motivation: dilute the grav. relics

inflaton energy density ~ a^{-3}

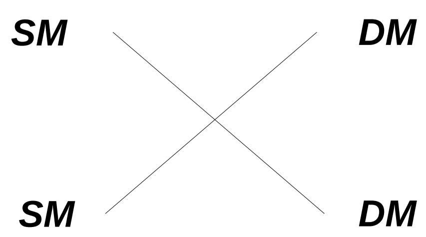
rel. relic energy density ~ a^{-4}

$\boxed{\text{low } T_R}$

What if $T_R < m_{DM}$?



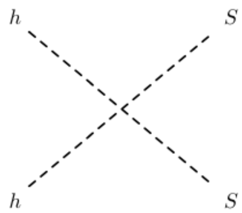
off the tail $\longrightarrow$



2306.13061 [hep-ph] Cosme, Costa, OL

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:

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

With annihilation:

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

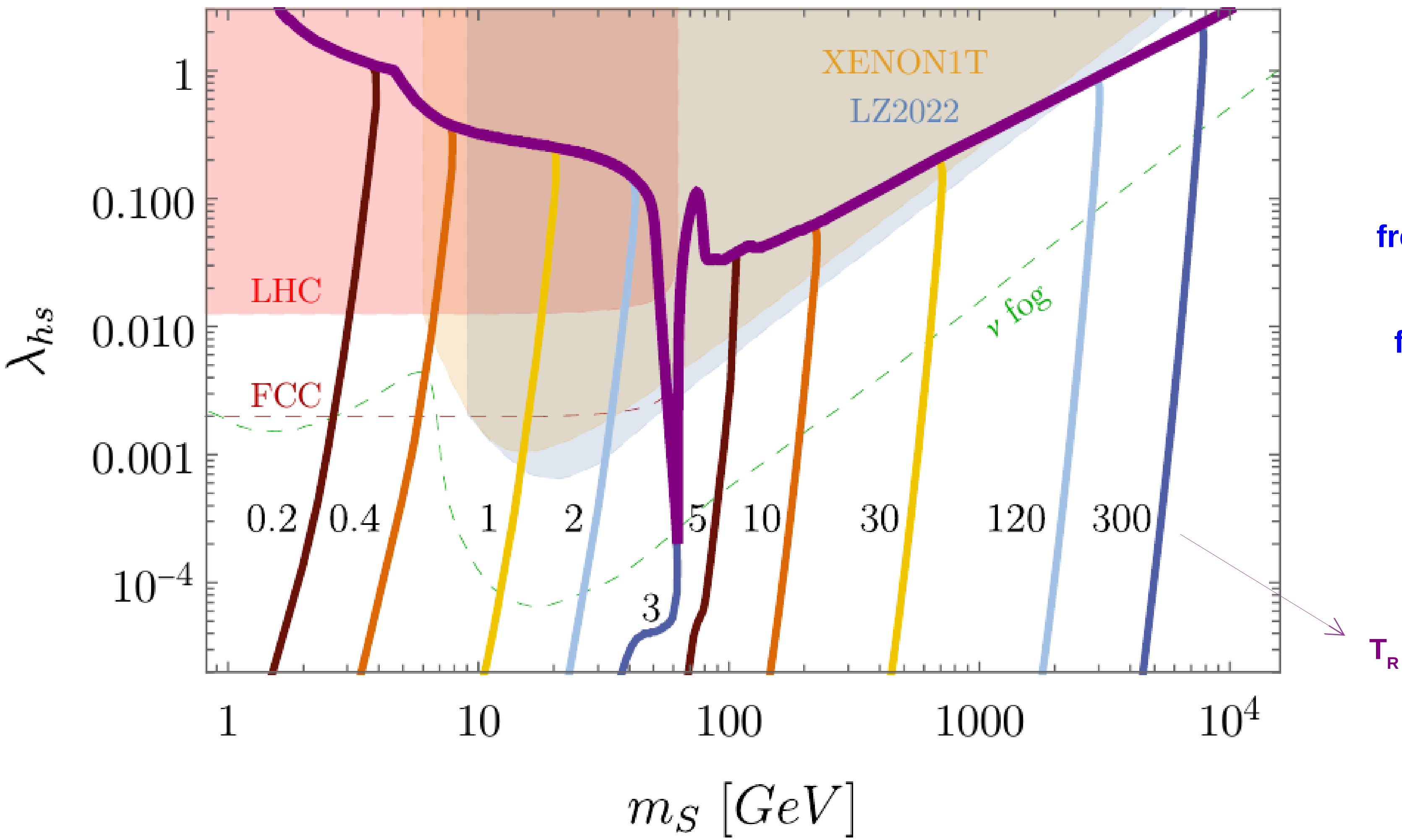
No thermalization:

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

Scalar Higgs portal DM :

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

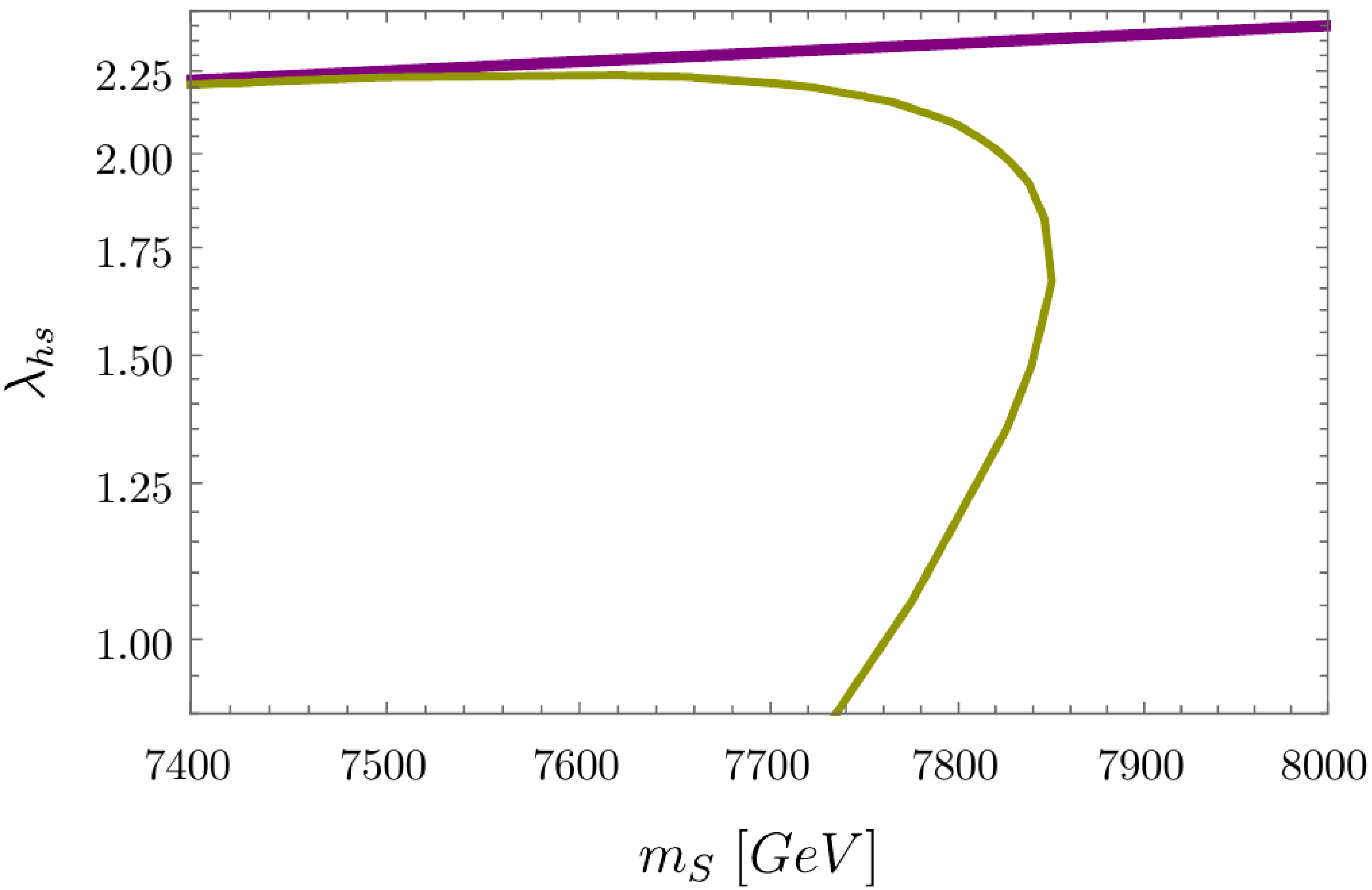
Arcadi,Costa,Goudelis,OL '24



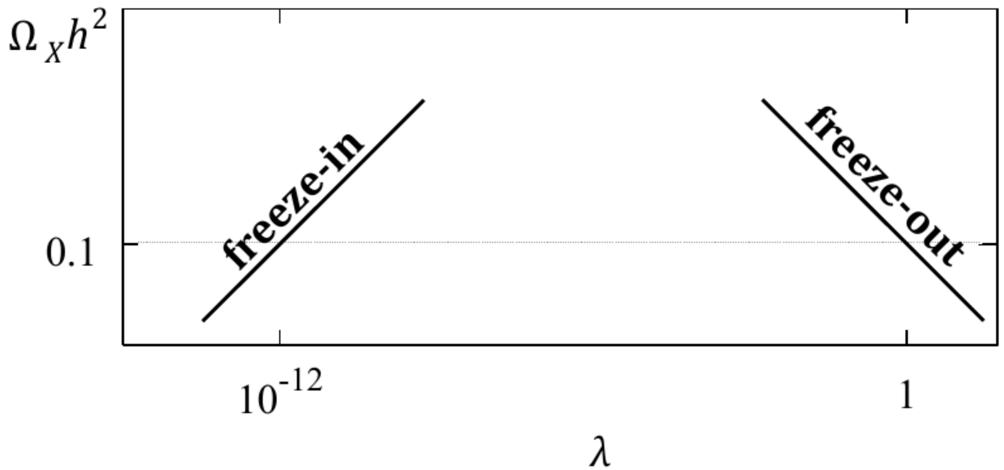
New input: treat ***unknown*** T_R as a free parameter ➡ direct detection + invisible Higgs decay

Arcadi,Costa,Goudelis,OL '24

Freeze-in ➡ Freeze-out



Generic DM models



freeze-in at stronger coupling

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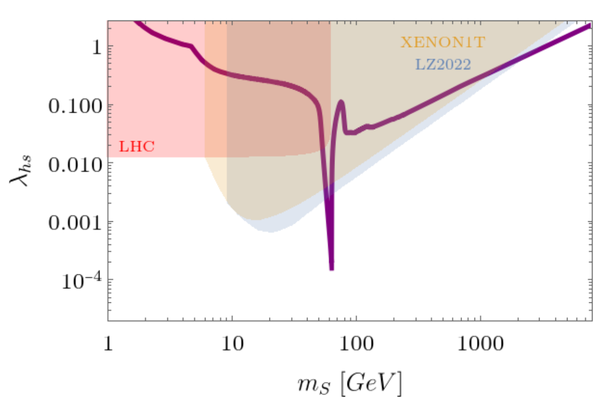
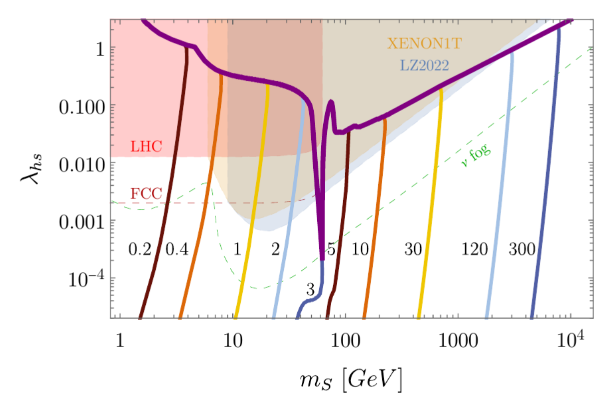
"excluded"

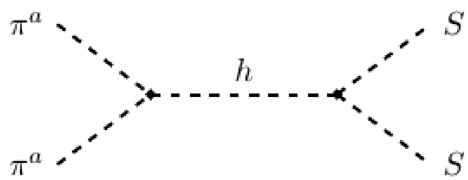


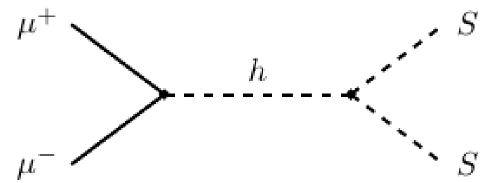
viable

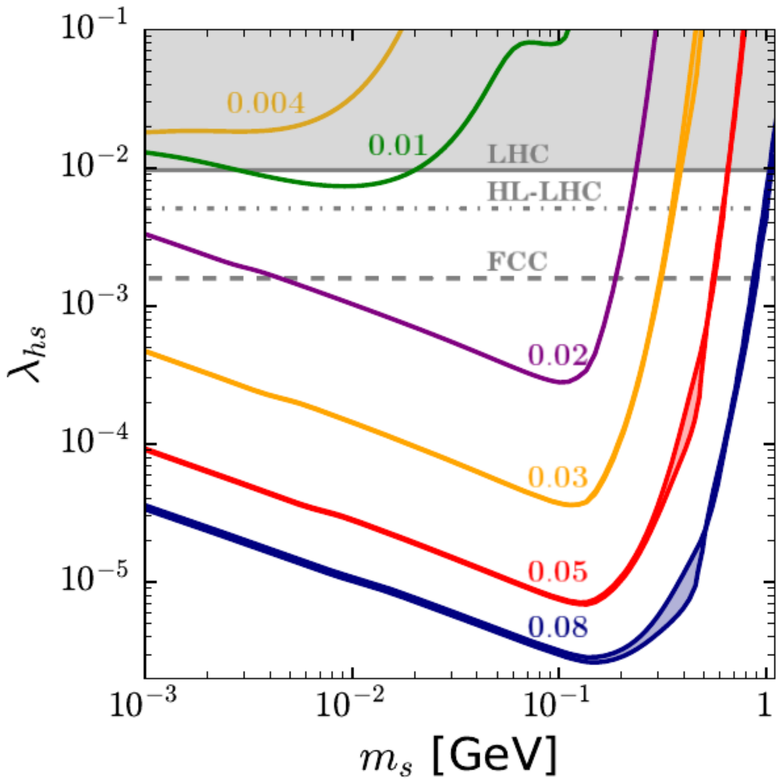


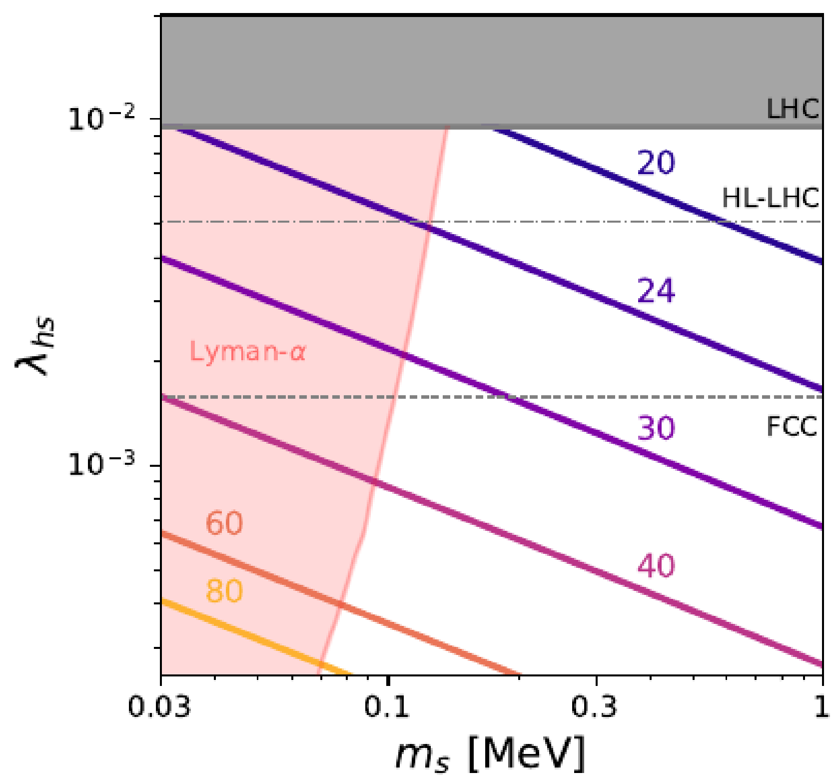
OL,Morais,Oliveira,Pasechnik ‘24
Feiteira,OL, Oliveira ‘26

Low DM mass :









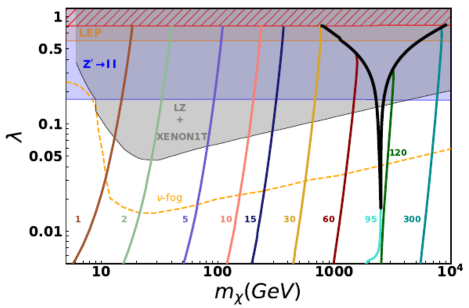
Invisible Higgs decay !

CONCLUSION

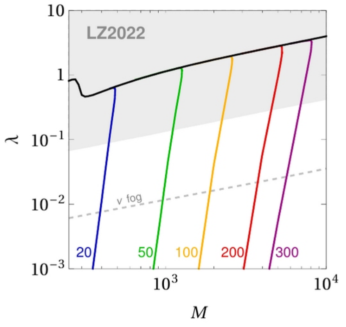
– T_R *is an unknown variable*

– *stronger coupling FI fills the desert between FIMPs and WIMps*

– *your favorite model is not ruled out, just cool it*



Z’



ν_R

...