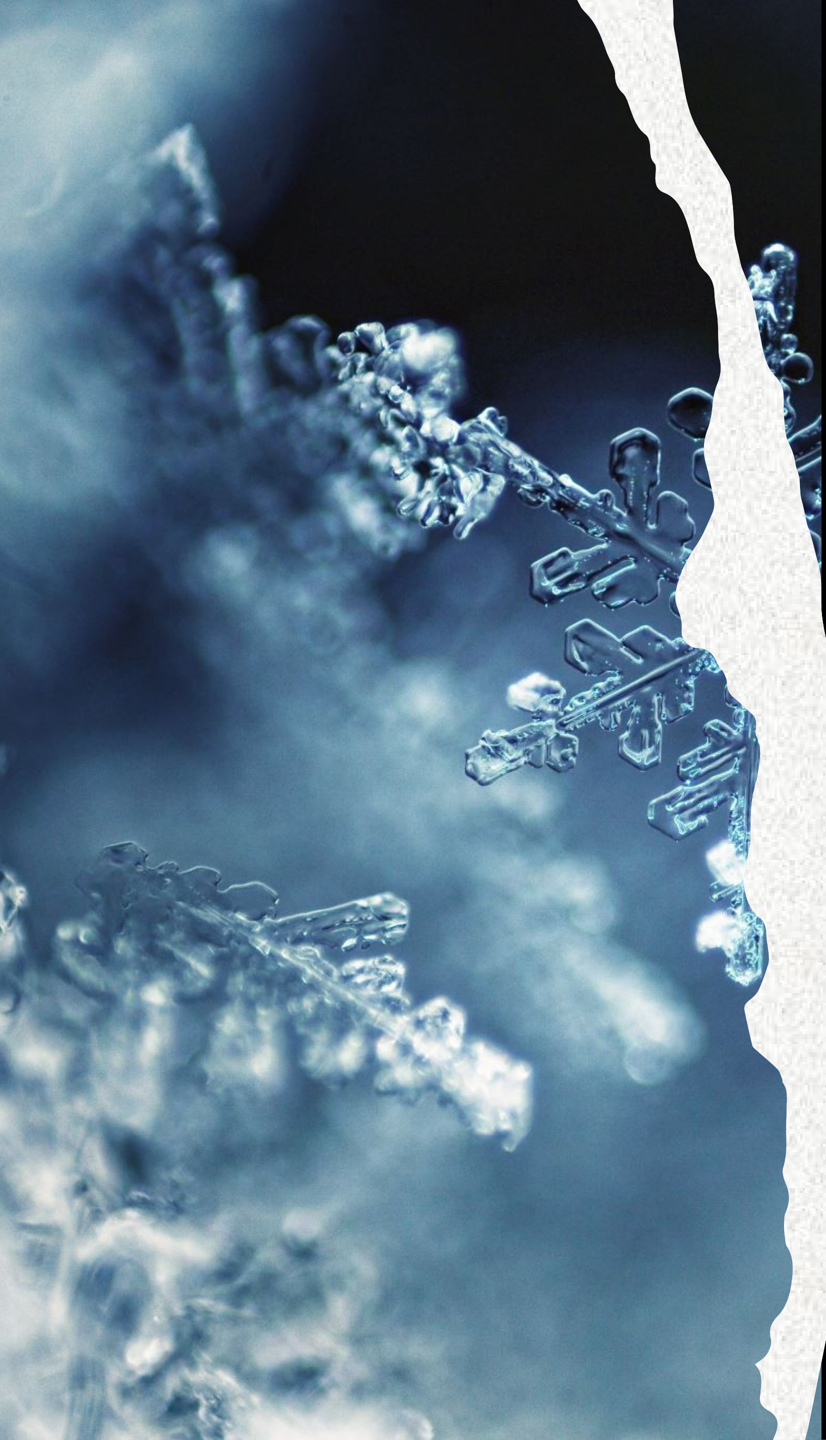


Simplified Models for freeze-in at stronger coupling

Giorgio Arcadi

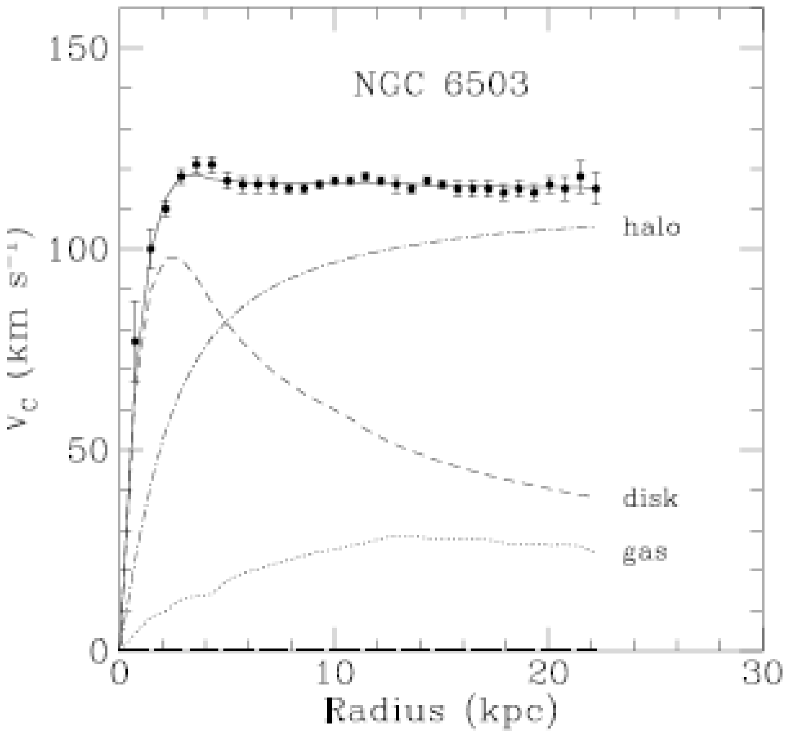
University of Messina

Based on

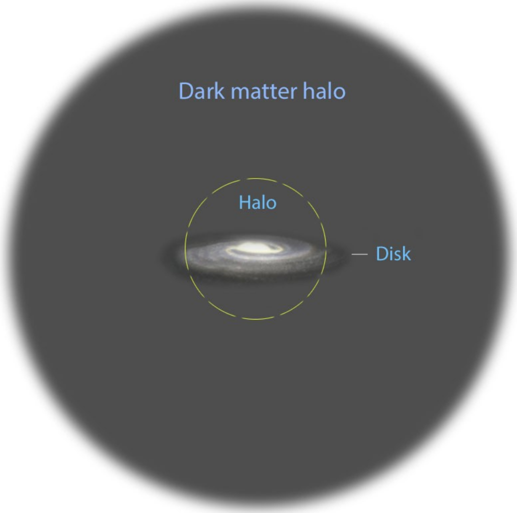
G.A., F. Costa, A. Goudelis, O. Lebedev JHEP 07 (2024) 044

G.A. , D. Cabo-Almeida, O. Lebedev, arXiv:2409.02191

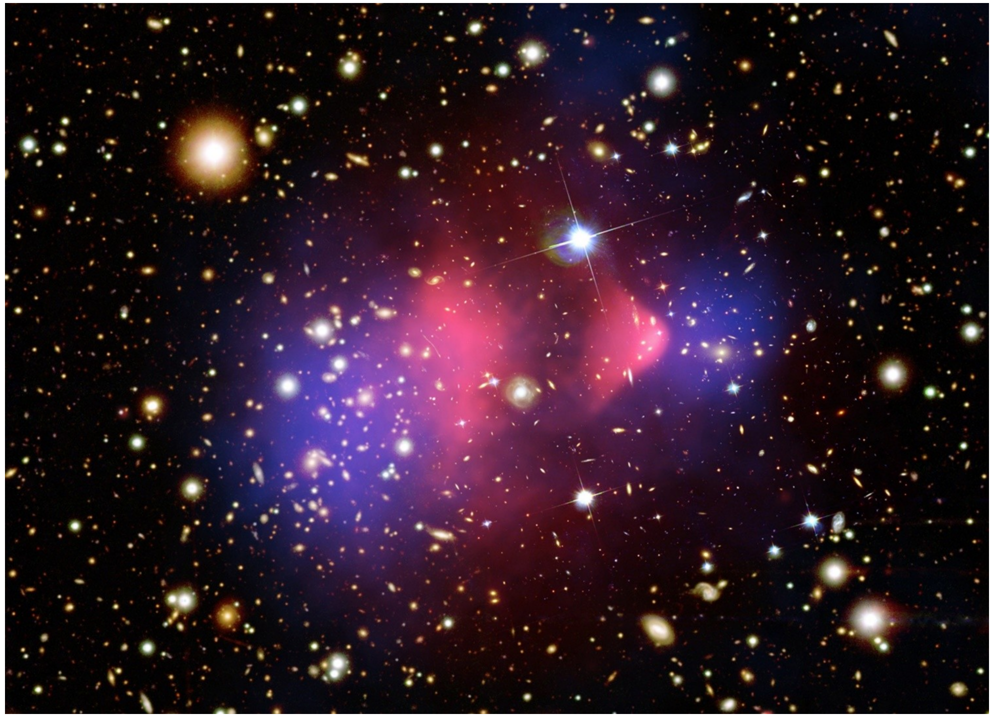
nvincing astrophysical evidence of a Dark Matter Component of the Unive



Galactic rotation curves: Data show a flat profile for the velocity well outside visible size of the galaxy



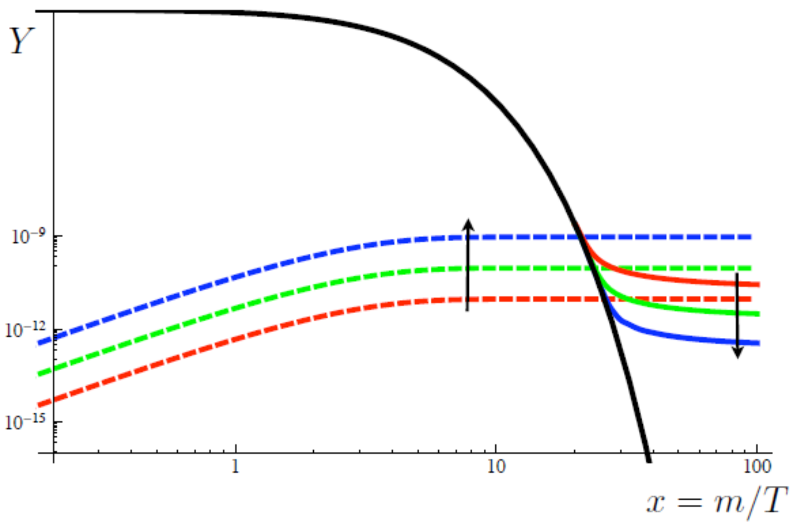
Milky Way model



Explanation:

The galaxy is immersed into a dark matter halo with suitable mass density.

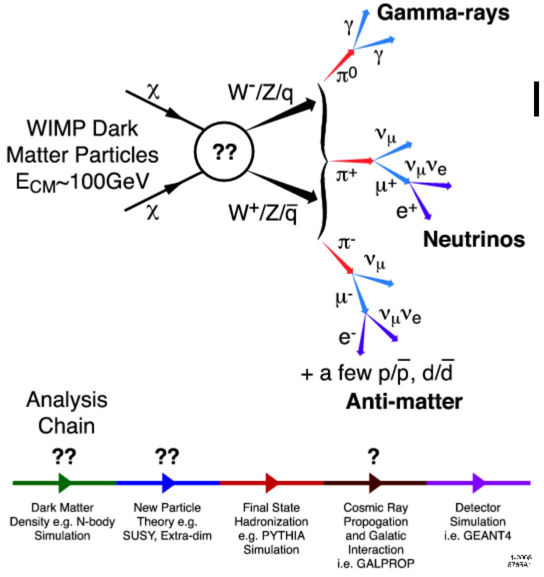
Gravitational lensing (Bullet cluster)

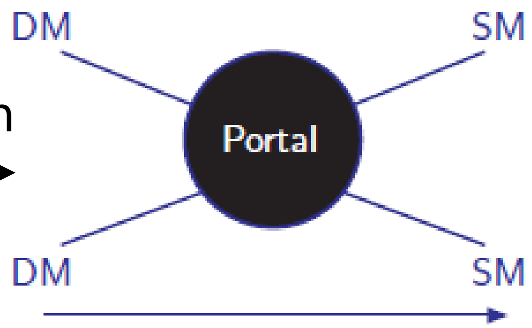


Interest in particle candidates with production mechanism connected to experimental observables

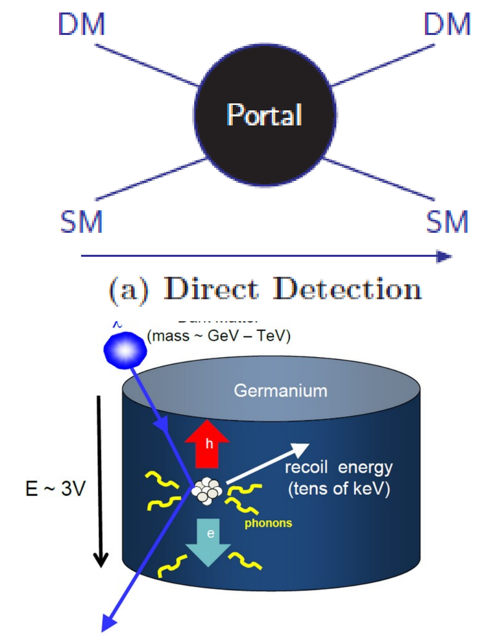
Relic Density

Indirect Detection

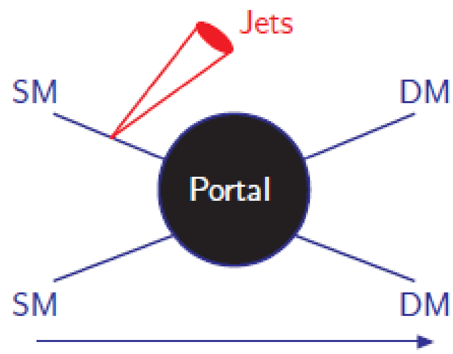




(b) Indirect Detection

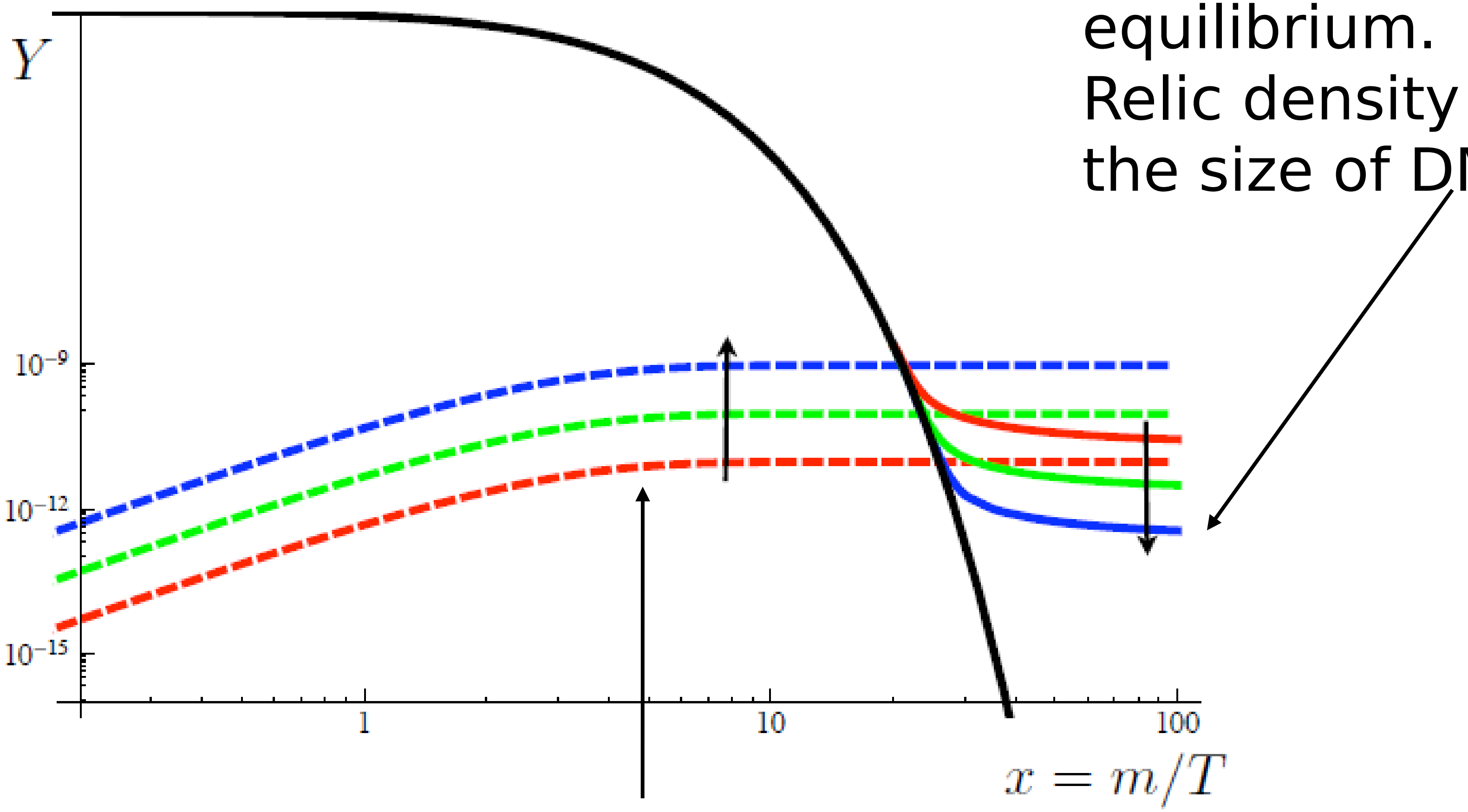


(a) Direct Detection



(c) Collider Detection

Freeze-out: DM initially in thermal equilibrium.
Relic density inversely proportional to the size of DM interactions.

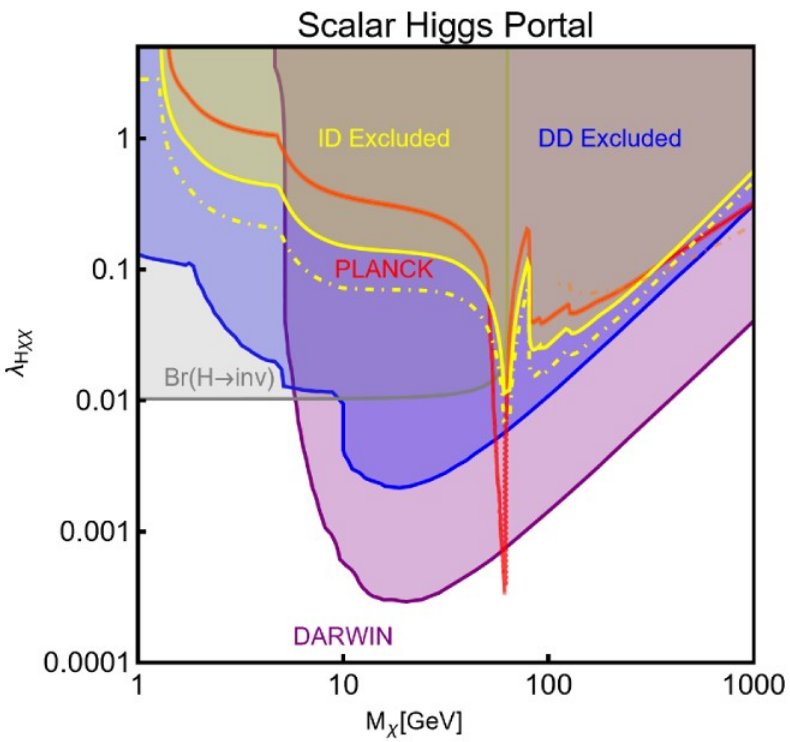


Freeze-in: DM has initially negligible adundance. DM never in thermal equilibrium and continuosly produced out from thermal bath particles. Relic density proportional to size of DM interactions.

Consider the simplest Higgs portal $\Delta L_{Scalar,DM} = \frac{1}{2}\lambda_{hs} H^\dagger H s^2$

Freeze out: Correct relic density matched for

Very constrained scenario



G.A. et al, 2403.15860

Freeze-in: Correct relic density matched for

$$\sigma^{SI}_{DM,p} \simeq \frac{\mu^2_{DM,p}}{\pi} ¿ f_N|^2 \frac{\lambda^2_{hs,Fi}}{M_h^4} \approx 1.5 \times 10^{-59}\, cm^2$$

These scenarios implicitly assume .

Freeze-in at stronger coupling

Consider . DM produced by interactions with primordial plasma (a-la-freeze-in). Al the interactions are Boltzmann suppressed because of the low temperature.

$$\lambda_{hs,FI} \rightarrow \overline{\lambda}_{hs,FI} e^{-2m_{DM}/T_R}$$

Correct relic density potentially matched for

↓

w current limits but potential benchmark for next generation experiments


Higgs Portal

$$\Delta L_{Scalar,DM} = \frac{1}{2} \lambda_{hs} H^{\dagger} H s^2$$

$$\Delta L_{Fermion,DM} = \frac{1}{\Lambda} H^{\dagger} H \bar{\chi} \chi + \frac{1}{\Lambda_5} i H^{\dagger} H \bar{\chi} \gamma_5 \chi$$

$$\Delta L_{Vector,DM} = \frac{1}{2} \lambda_{hv} H^{\dagger} H V^{\mu} V_{\mu}$$

$$\dot{n}_h + 3 H n_h = \Gamma_{\bar{f} f \to h} - \Gamma_{h \to \bar{f} f}$$

Approximate rule of thumb

$$3 H n_h \lesssim \Gamma_{\bar{f} f \to h}, \Gamma_{h \to \bar{f} f}$$

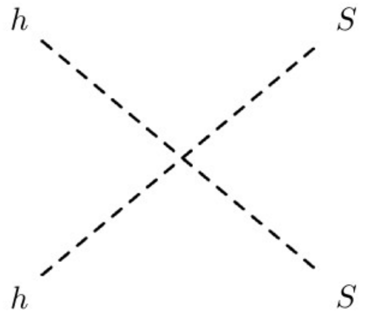
$$n_h = \left(\frac{m_h T}{2\pi}\right)^{3/2} e^{-m_h/T}$$

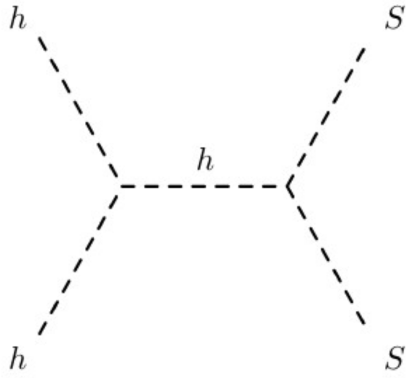
$$\Gamma_{\bar{f} f \to h} = \int \left(\prod_i \frac{d^3 p_i}{(2\pi)^3 2E_f} f(p_i) \right) \frac{d^3 p_f}{(2\pi)^3 2E_f} |M_{2\to 1}|^2 (2\pi)^4 \delta^{(4)}\left(\sum p_i - p_f\right) \simeq 10^{-2} \times y_f^2 m_h^{\frac{5}{2}} T^{\frac{3}{2}} e^{-m_h/T}$$

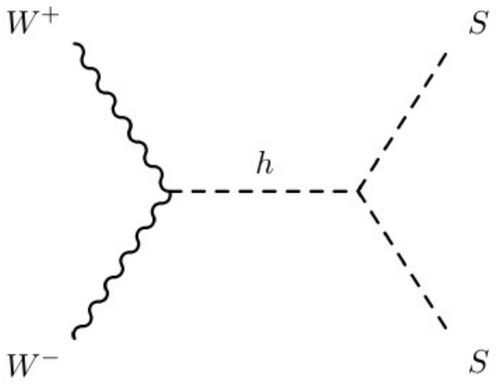
$y_f \sqrt{m_h M_{Pl}} \gtrsim T$ Always satisfied above the QCD phase transition

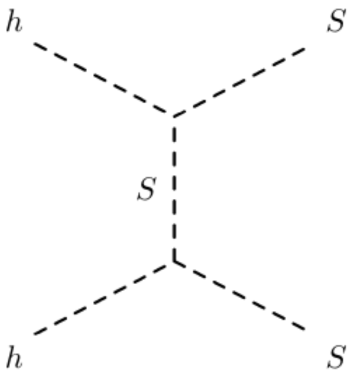
Detailed case of study: Scalar DM

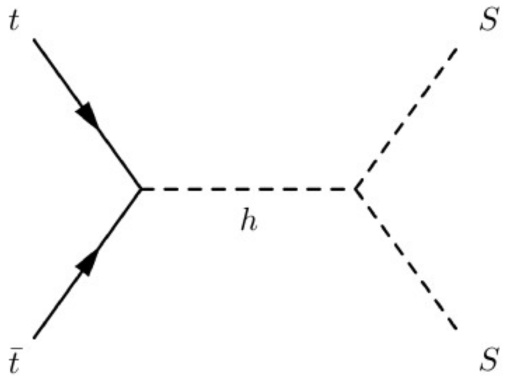
$$\dot{n}_s + 3 H n_s = 2\Gamma(SM \rightarrow ss) - 2\Gamma(ss \rightarrow SM)$$











Heavy DM regime: . DM production dominated by (inverse) annihilations into Higgs bosons.

$$\Gamma(hh \to ss) = \frac{1}{(2\pi)^6} \int \tilde{\sigma} v_r e^{-(E¿¿1+E_2)/T d^3 p_1 d^3 p_2 = \frac{2\pi^2 T}{(2\pi)^6} \int_{4m_s^2}^{+\infty} ds\, \tilde{\sigma}(s)(s-4m_h^2)\sqrt{s} K_1(\sqrt{s}/T)} ¿$$

$$\tilde{\sigma} = \frac{\lambda_{hs}^2}{16\pi s} \sqrt{\frac{s-4m_s^2}{s-4m_h^2}}$$

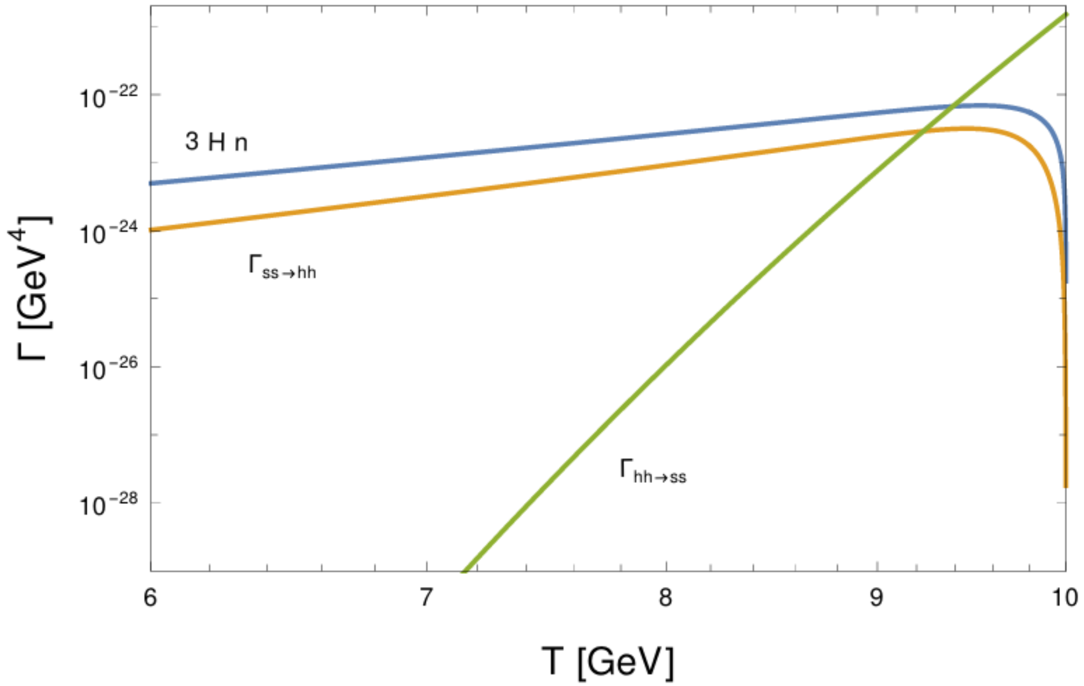
$$\Gamma(hh \to ss) \simeq \frac{\lambda_{hs}^2 T^3 m_s}{256\pi^4} e^{-2m_s/T}$$

$$m_s \gg T$$

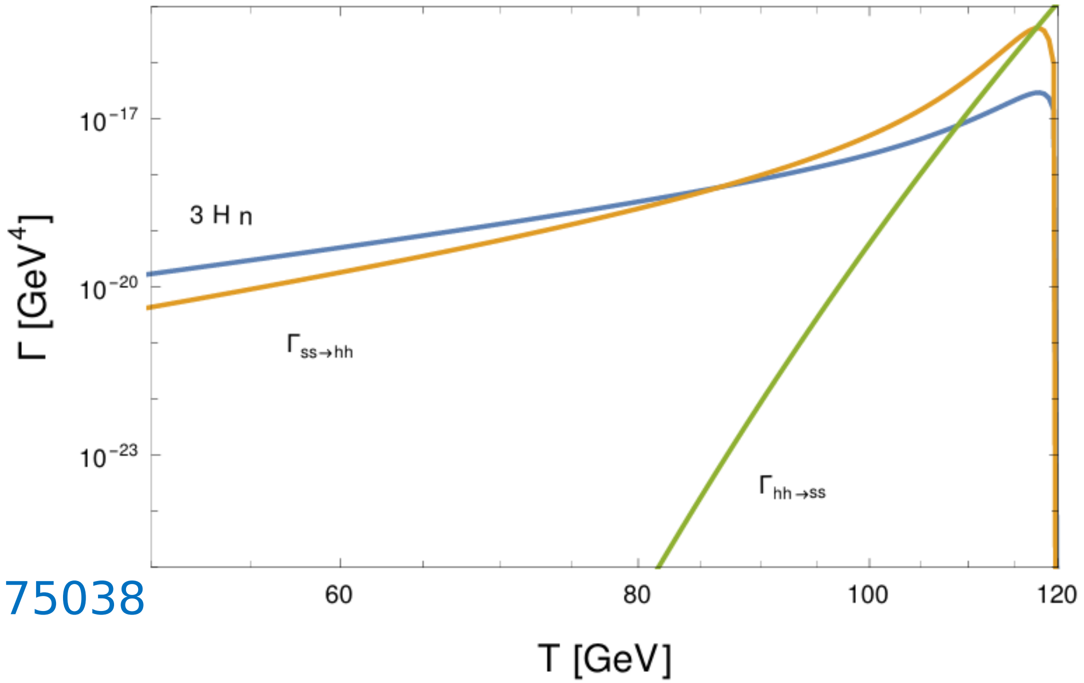
annihilation rate is computed in the hyphothesis of kinetic equilibrium

$$\Gamma(ss \to hh) = \sigma(ss \to hh) v_r n_{DM}^2$$

$$\sigma(ss \to hh) v_r = \frac{\lambda_{hs}^2}{16 \pi m_s^2}$$



$$T_R = 10\, GeV, m_s = 223.5\, GeV, \lambda_{hs} = 0.05$$



$$T_R = 120\, GeV, m_s = 2.81\, TeV, \lambda_{hs} = 0.82$$

Cosme, F. Costa and O. Lebedev *Phys.Rev.D* 109 (2024) 7, 075038

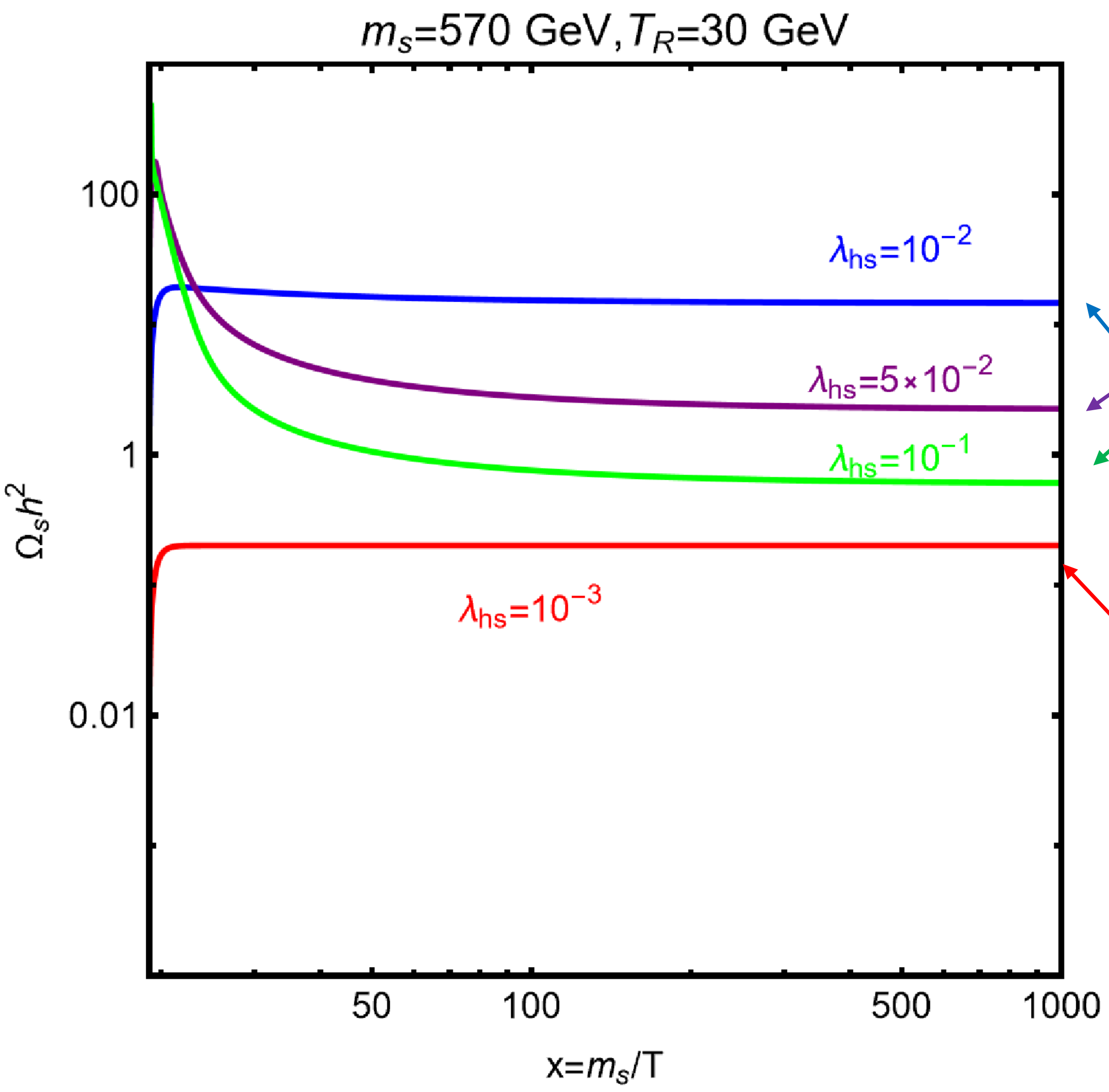
For small enough couplings one can neglect (pure freeze-in regime)

$$\frac{dY_{DM}}{dT} = -2\frac{\Gamma(hh \to ss)}{HT\, s_{SM}} \qquad s_{SM} = \frac{2\pi^2}{45} g_* T^3 \qquad H = 1.66\sqrt{g_*}\frac{T^2}{M_{Pl}}$$

$$\longrightarrow \quad Y_{DM} \approx 2.5 \times 10^{-7} \frac{\lambda_{hs}^2 M_{Pl}}{T_R} e^{-2 m_s/T_R}$$

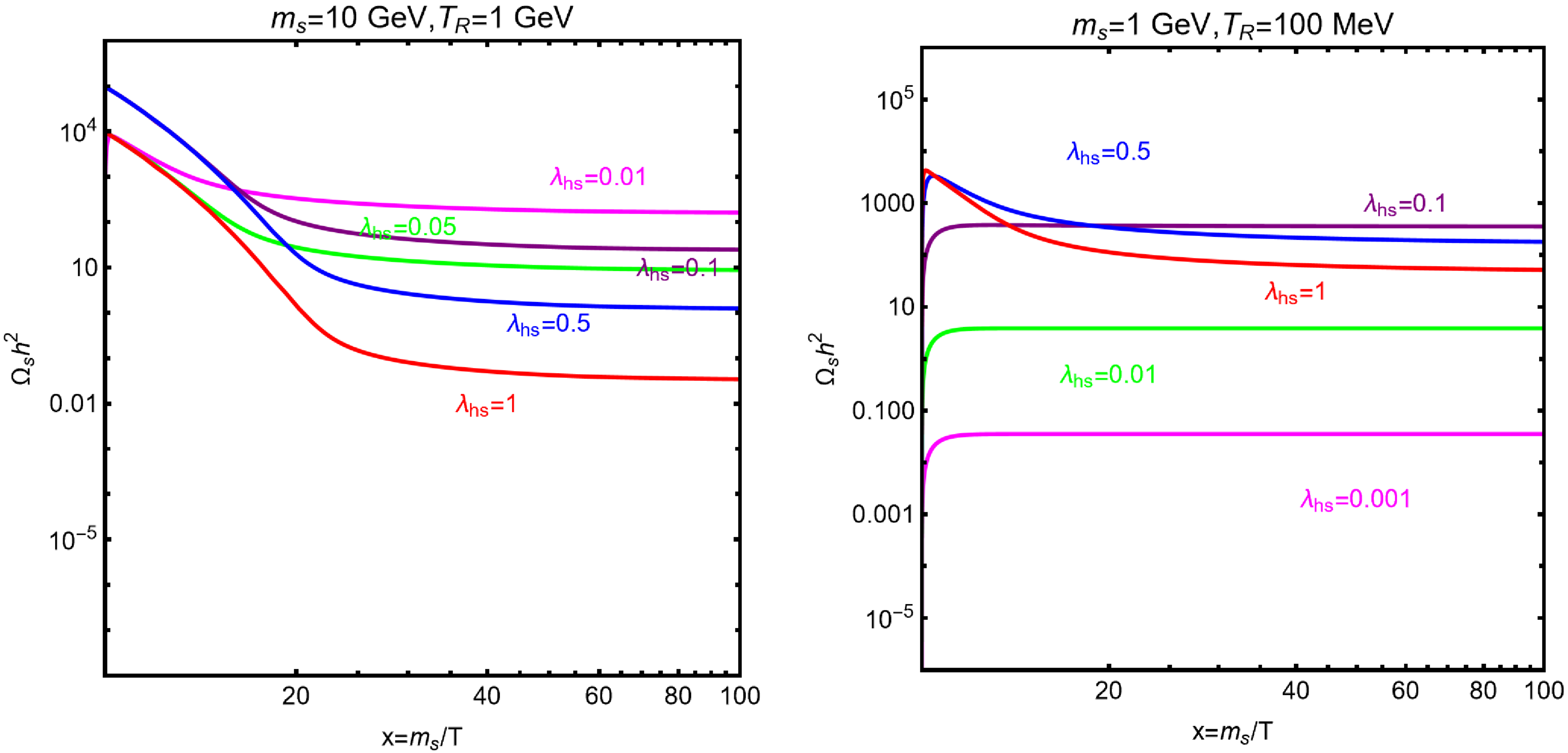
Correct relic density achieved for:

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



Higher coupling: DM production is efficient enough to activate annihilation processes. The relic density decreases with the coupling.

Low couplings, pure freeze-in regime. The relic density increases with the coupling.

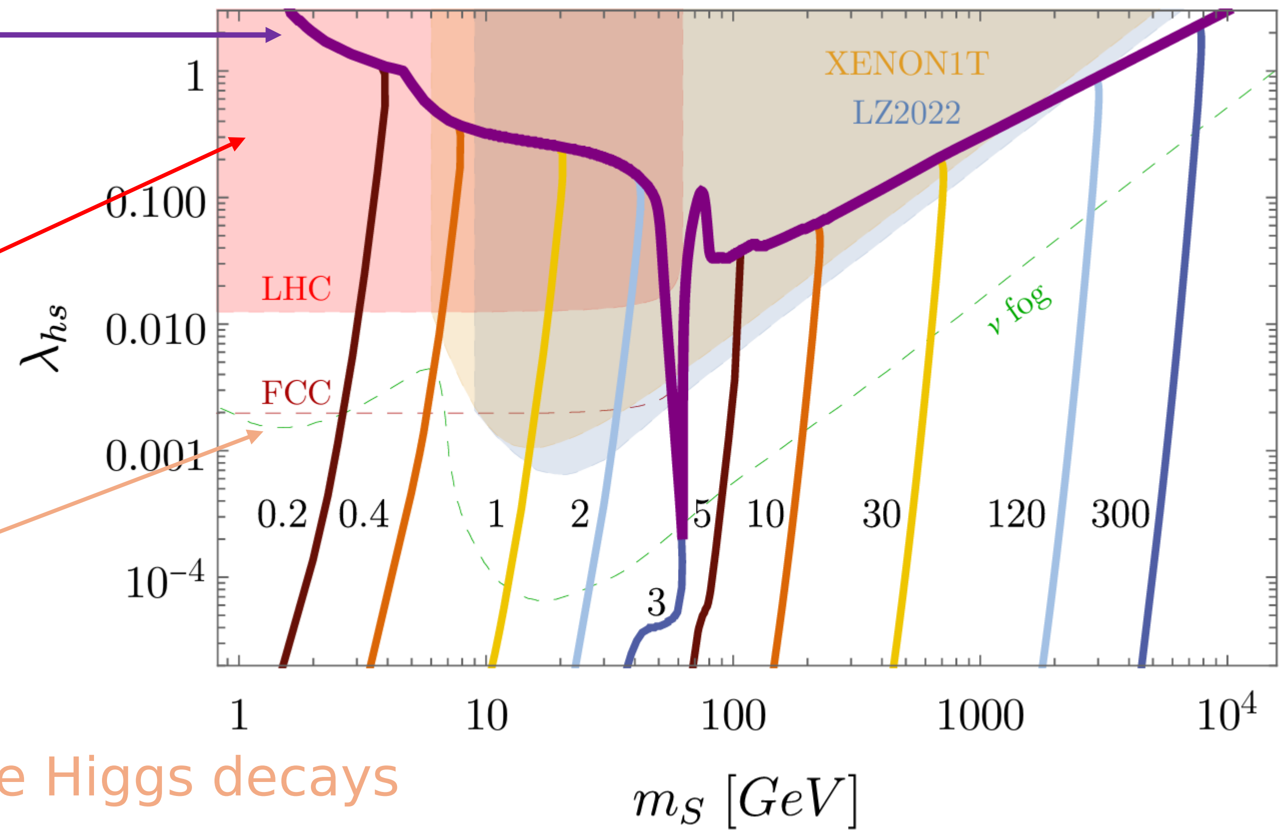

m_s=10 GeV, T_R=1 GeV
λ_{hs}=0.01
λ_{hs}=0.05
λ_{hs}=0.1
λ_{hs}=0.5
λ_{hs}=1
10^4
10
0.01
10^{-5}
$\Omega_s h^2$
20
40
60
80
100
x=m_s/T
m_s=1 GeV, T_R=100 MeV
λ_{hs}=0.5
λ_{hs}=0.1
λ_{hs}=1
λ_{hs}=0.01
λ_{hs}=0.001
10^5
1000
10
0.100
0.001
10^{-5}
$\Omega_s h^2$
20
40
60
80
100
x=m_s/T

Scalar Higgs Portal

Standard F.O.

Limit on Invisible Higgs width

Projected sensitivity of FCC to invisible Higgs decays



Fermionic Higgs Portal

$$\frac{1}{\Lambda} i \bar{\chi} \chi H^\dagger H$$

$$\frac{1}{\Lambda_5} i \bar{\chi} \gamma_5 \chi H^\dagger H$$

$$\Gamma(hh \to \chi\chi) \simeq \frac{3}{16\pi^4} \frac{m_\chi^2 T^4}{\Lambda^2} e^{-\frac{2 m_\chi}{T}}$$

$$\Gamma(hh \to \chi\chi) \simeq \frac{1}{8\pi} \frac{m_\chi^3 T^3}{\Lambda_5^2} e^{-\frac{2 m_\chi}{T}}$$

$$Y \simeq 1.2 \times 10^{-5} \frac{m_\chi M_{Pl}}{\Lambda^2} e^{-\frac{2 m_\chi}{T_R}}$$

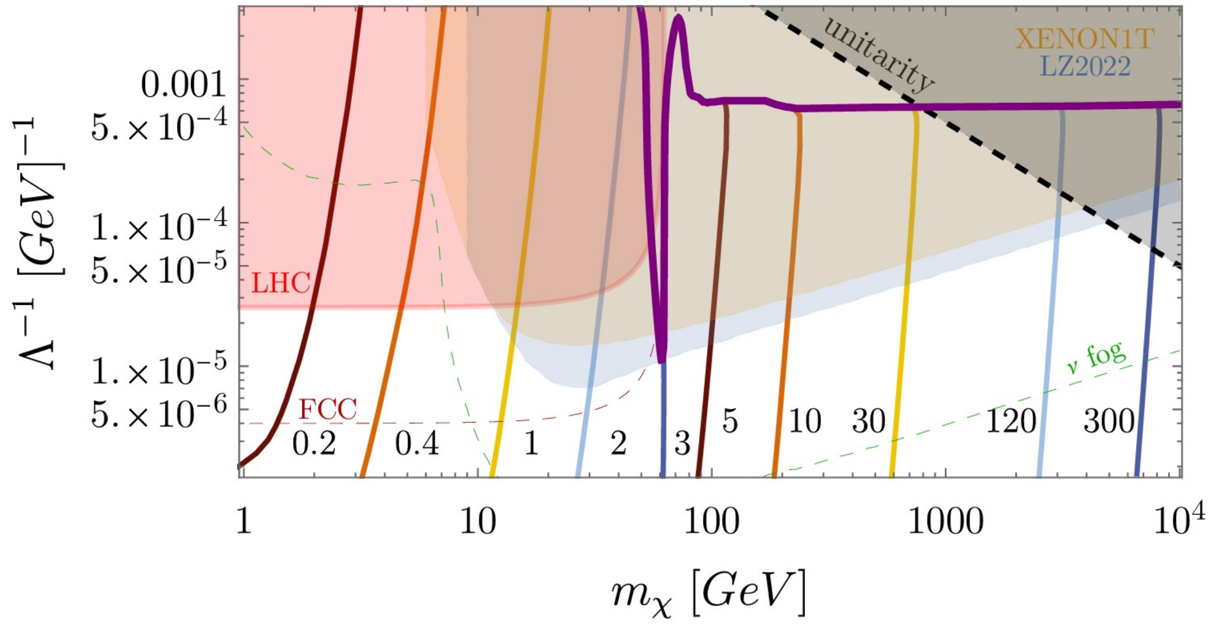
$$Y \simeq 8 \times 10^{-6} \frac{m_\chi^2 M_{Pl}}{\Lambda_5^2 T_R} e^{-\frac{2 m_\chi}{T_R}}$$

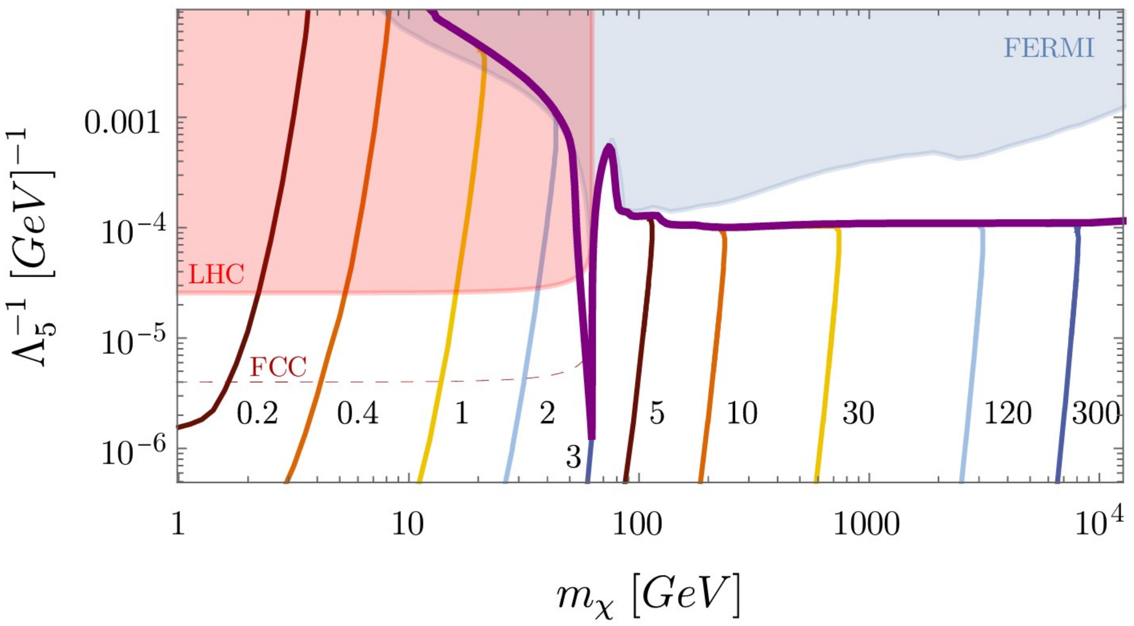
Correct Relic Density for:

$$\frac{m_\chi}{\Lambda} e^{-m_\chi/T_R} \simeq 4 \times 10^{-12}$$

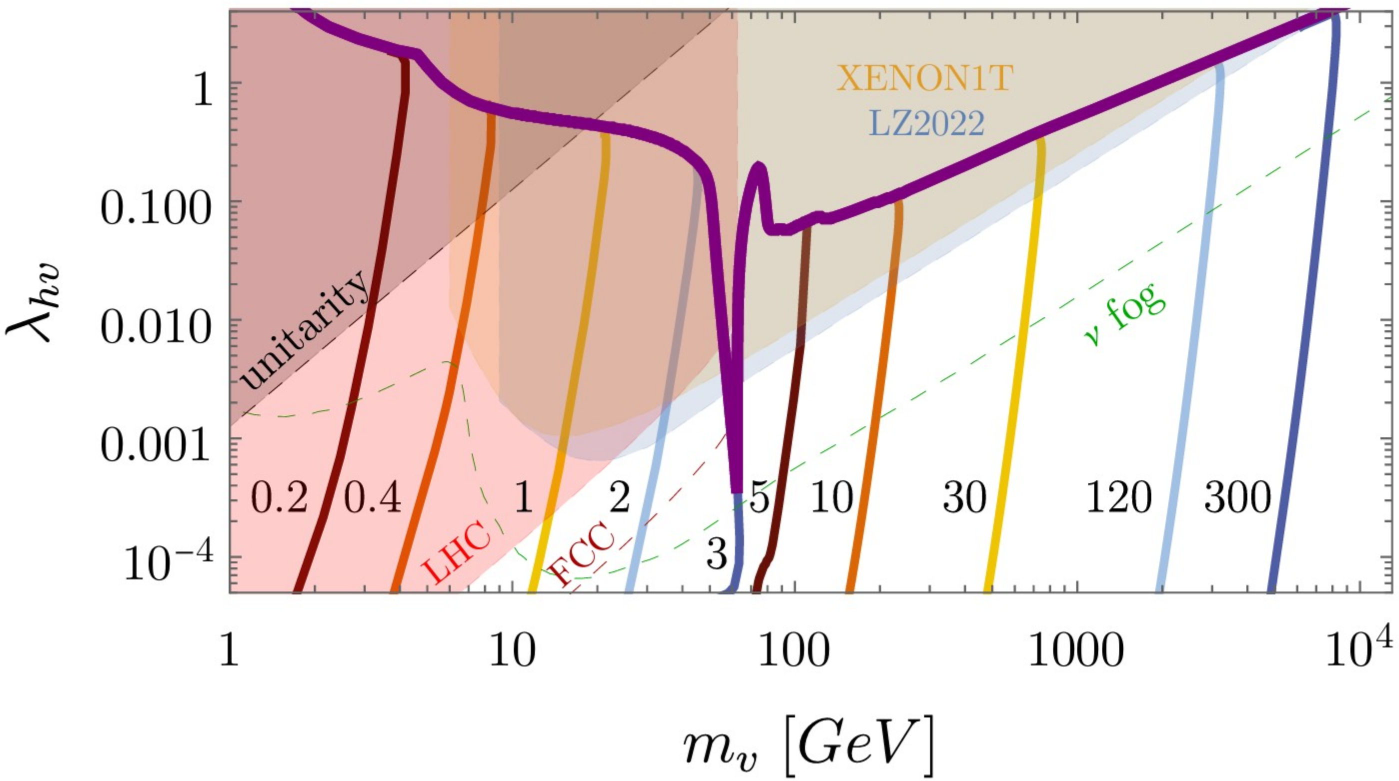
Correct Relic Density for:

$$\frac{m_\chi^{3/2}}{\Lambda_5 T_R^{1/2}} e^{-m_\chi/T_R} \simeq 5 \times 10^{-12}$$

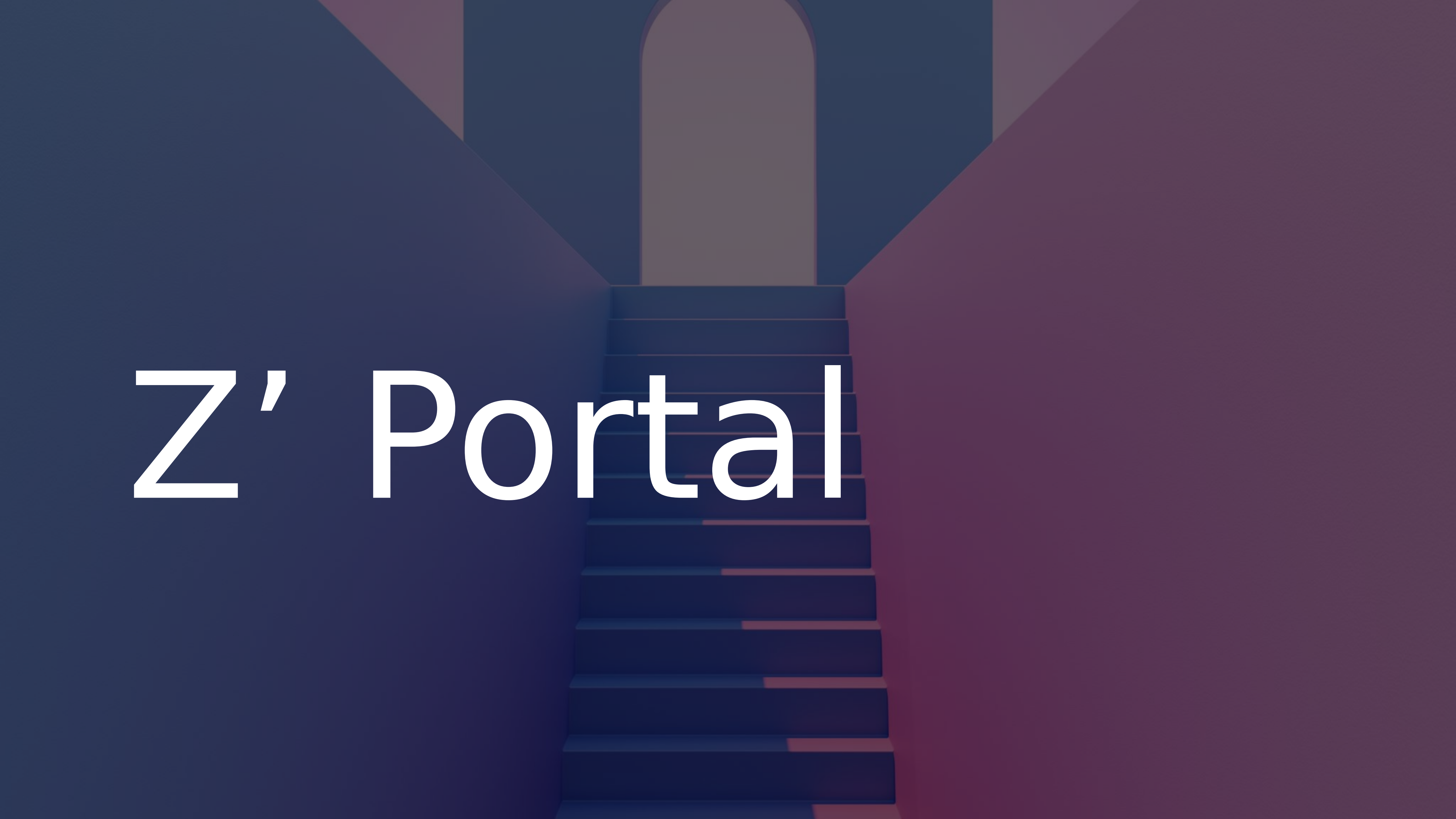

unitarity
XENON1T
LZ2022
LHC
FCC
ν fog
0.2
0.4
1
2
3
5
10
30
120
300
$\Lambda^{-1}\ [GeV]^{-1}$
$m_\chi\ [GeV]$


FERMI
LHC
FCC
0.2
0.4
1
2
3
5
10
30
120
300
$\Lambda_5^{-1}\ [GeV]^{-1}$
$m_\chi\ [GeV]$

Vector Higgs Portal



Z’ Portal



$$\dot{n}_\chi + 3Hn_\chi = 2\Gamma(\bar{f} f \to \bar{\chi}\chi) - 2\Gamma(\bar{\chi}\chi \to \bar{f} f)$$

nly vectorial couplings pure freeze-in regime

$$\Gamma(\bar{f} f \to \bar{\chi}\chi) = \frac{V_f^2 V_\chi^2 m_\chi^5 T^3}{2\pi^4 M_{Z'}^4} e^{-2m_\chi/T_R}$$

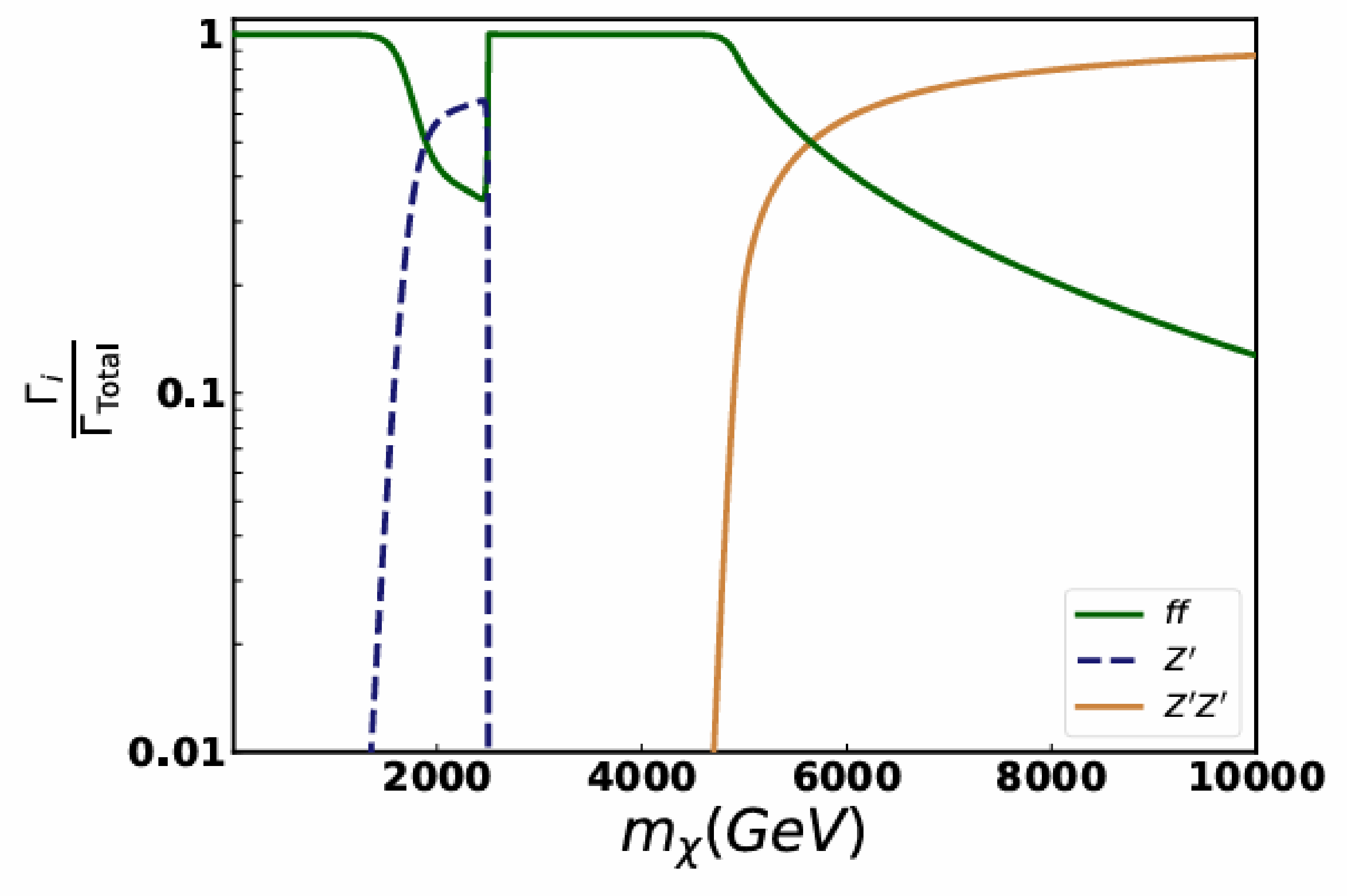
$$\longrightarrow \quad Y_\chi \approx 3.3 \times 10^{-5} \sum_f \frac{V_f^2 V_\chi^2 m_\chi^4}{M_{Z'}^4} \frac{M_{Pl}}{T_R} e^{-2m_\chi/T_R}$$

Assuming $V_\chi = V_f = \lambda$

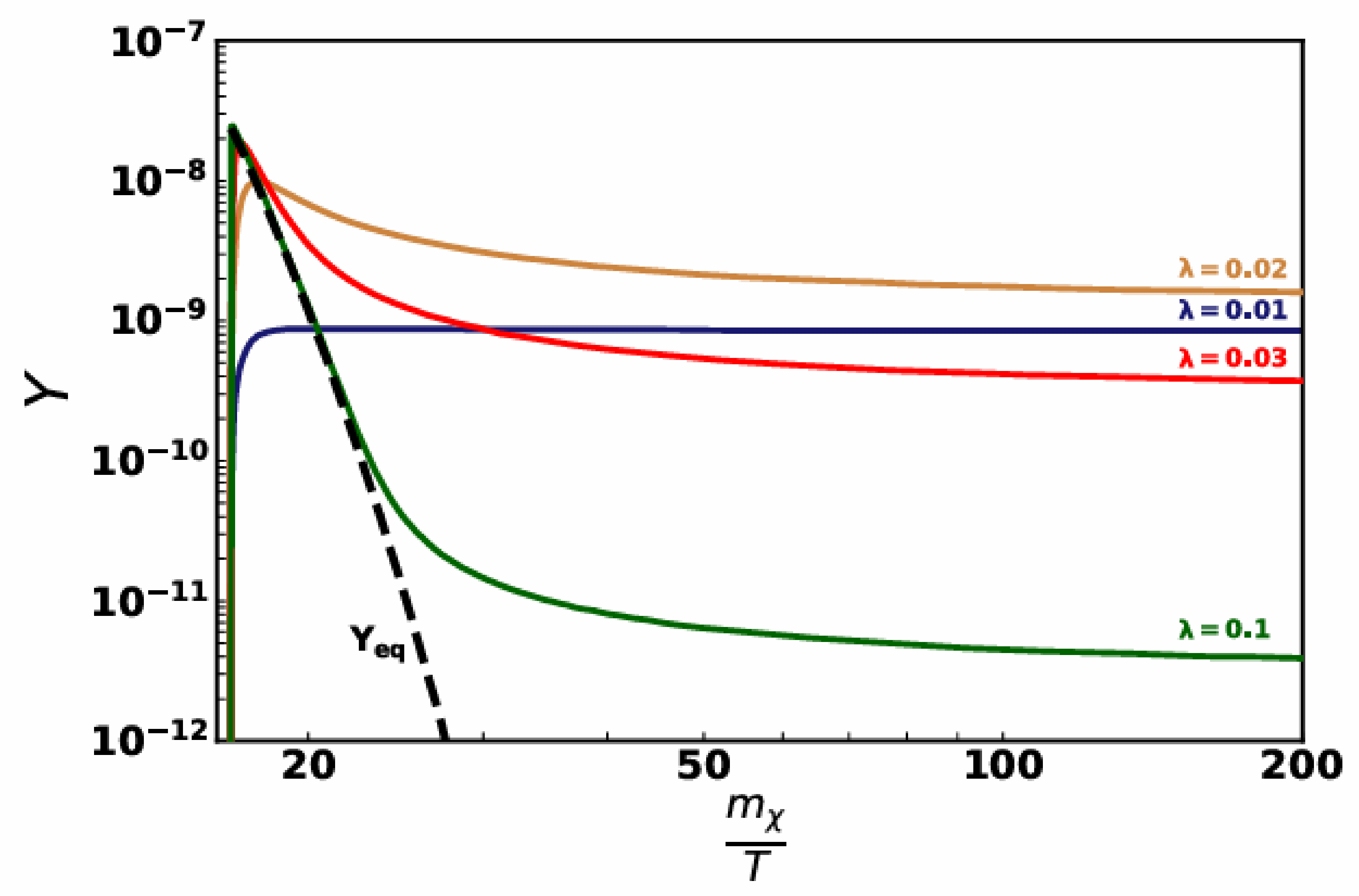
$$Y_{\chi,obs} = 4.4 \times 10^{-10} \left(\frac{GeV}{m_\chi}\right) \quad \longrightarrow \quad \lambda \simeq 10^{-6} \frac{M_{Z'} T_R^{\frac{1}{4}}}{m_\chi^{\frac{5}{4}}} e^{m_\chi/(2T_R)}$$

Analogous result for purely axial couplings.

$M_{Z'} = 5\,TeV$

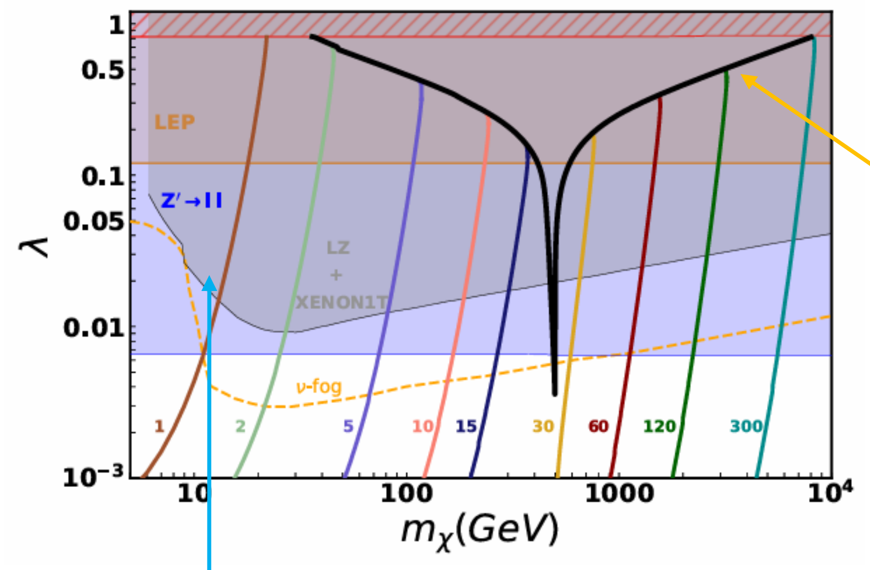


1
0.1
0.01
$\frac{\Gamma_i}{\Gamma_{\rm Total}}$
2000
4000
6000
8000
10000
$m_\chi(GeV)$
ff
Z'
$Z'Z'$

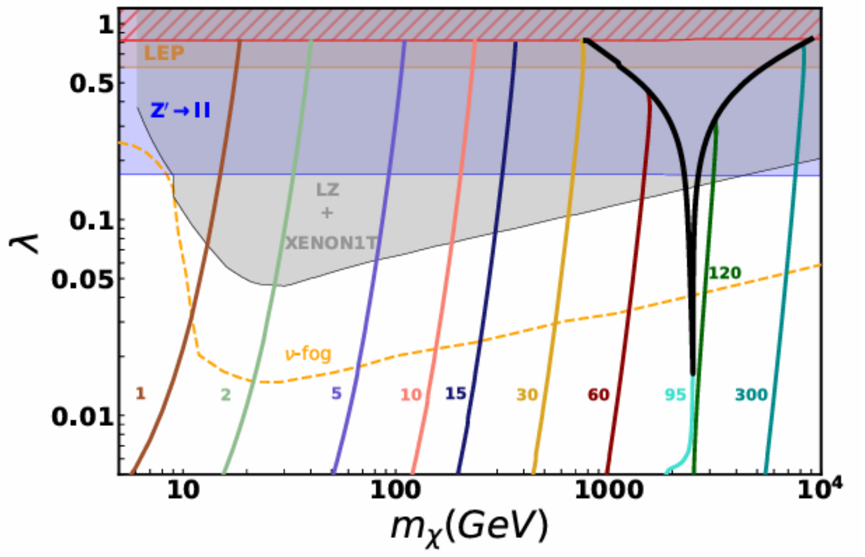

10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
Y
Y_{eq}
$\lambda = 0.02$
$\lambda = 0.01$
$\lambda = 0.03$
$\lambda = 0.1$
20
50
100
200
$\frac{m_\chi}{T}$

Vectorial Couplings

$M_{Z'} = 1\,TeV$

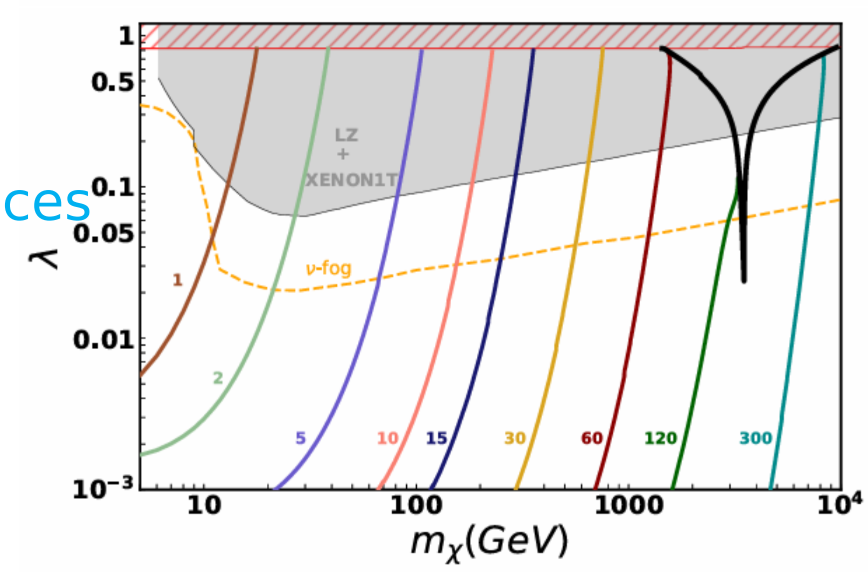


$M_{Z'} = 5\,TeV$



$$\frac{\lambda}{M_{Z'}} < \frac{0.12}{TeV}$$ (LEP)

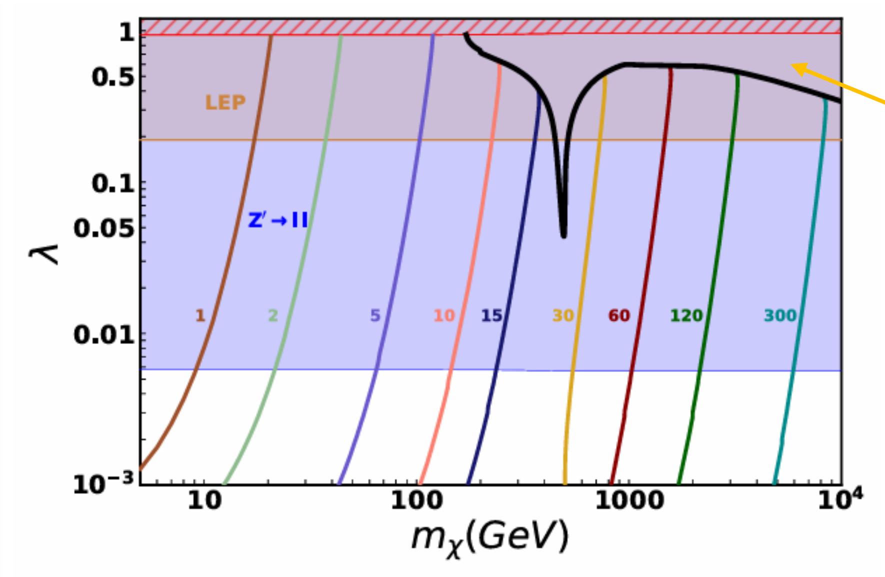
$M_{Z'} = 7\,TeV$



LHC searches of dilepton resonances

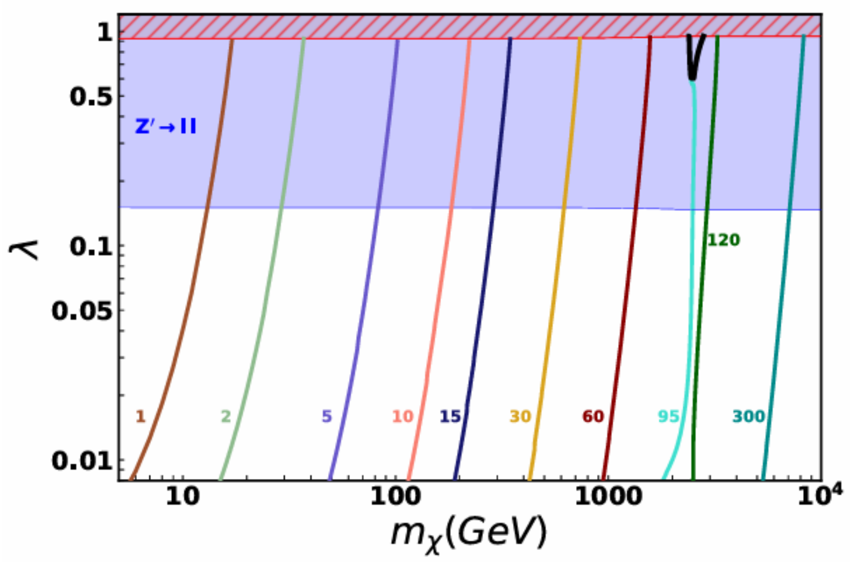
Axial Couplings

$M_{Z'}=1\,TeV$

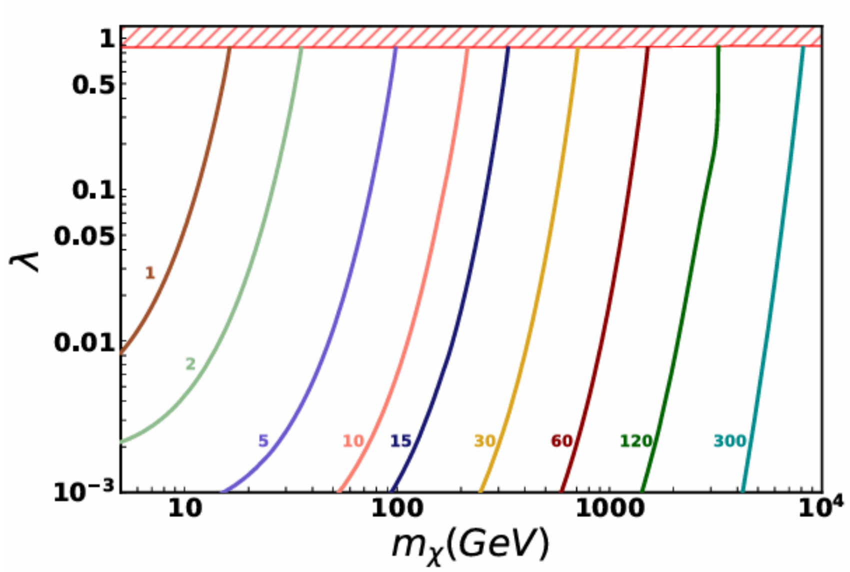


$$\frac{\lambda}{M_{Z'}}<\frac{0.19}{TeV}$$

$M_{Z'}=5\,TeV$



$M_{Z'}=7\,TeV$



Conclusions

We have studied the scenario of «freeze-in at stronger couplings» in the case of Higgs and Z' portals.

Freeze-in at stronger coupling allows to a viable relic density solutions testable at future detectors.

The parameter space is enlarged, with respect to the conventional freeze-out, allowing for light DM masses. In the case of Higgs portals we have benchmarks for future updates in the sensitivity to invisible decays of the Higgs boson.