Predictive freeze-in

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- gravitational particle production background

- freeze-in with low temperatures

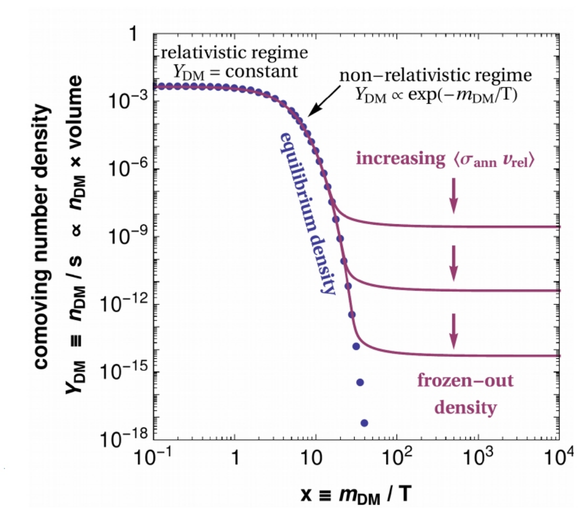
- simplest models (Higgs portal, Z’ , …)

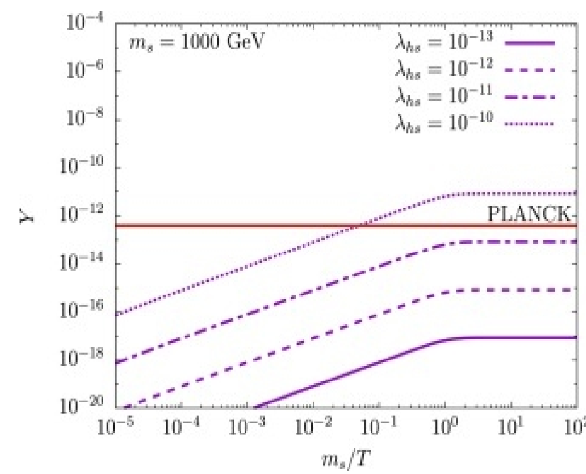
- direct DM detection, invisible Higgs decay

Dark Matter Models

thermal

non-thermal





No memory

(“attractor solution”)

Memory

General remarks

– *psychologically thermal particles are natural:*

we observe ONLY thermal particles in reality (e, gamma, ...)

because we only see particles with gauge interactions

– *freeze-out is real (neutrinos)*

– *non-thermal particles ~ paradigm shift, challenging:*

- **initial conditions are as important as the production mechanism**

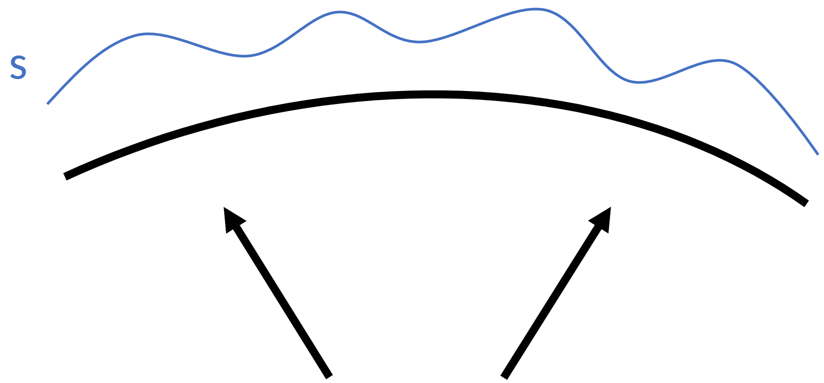
(or prove otherwise)

- **gravity is always there** → must prove it's irrelevant

(otherwise there's nothing to talk about)

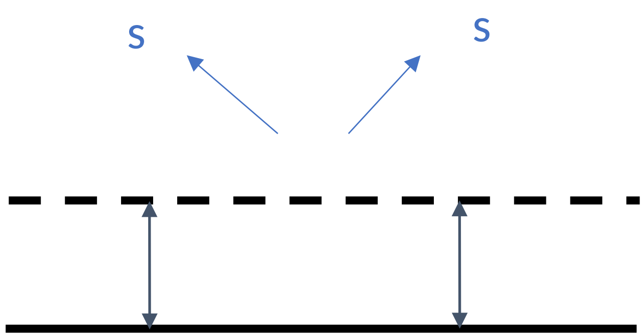
Gravitational particle production

Inflation:



$a \sim e^{Ht}$

After inflation:



$\phi \sim \cos mt$

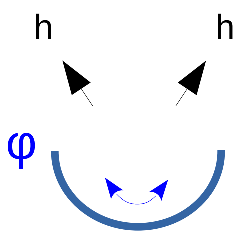
Dolgov, Kirilova ‘90
Traschen, Brandenberger ‘90

Example: perturbative calculation (*no collective effects*)

Take

$$\Delta V = \frac{1}{4}\lambda_{\phi h}\phi^2 h^2$$

$$\phi^2(t) = \sum_{n=-\infty}^{\infty} \zeta_n e^{-in\omega t}$$



Transition amplitude $|0\rangle \to |p,q\rangle$

$$-i\int_{-\infty}^{\infty} dt \langle f|V(t)|i\rangle = -i\,\frac{\lambda_{\phi h}}{2}\,(2\pi)^4\delta(\mathbf{p}+\mathbf{q})\sum_{n=1}^{\infty}\zeta_n\delta(E_p+E_q-n\omega)$$

Reaction rate per unit volume

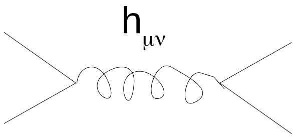
$$\Gamma = \sum_{n=1}^{\infty}\Gamma_n = \sum_{n=1}^{\infty}\frac{1}{2}\int|\mathcal{M}_n|^2 d\Pi_n = \frac{\lambda_{\phi h}^2}{64\pi}\sum_{n=1}^{\infty}|\zeta_n|^2\sqrt{1-\left(\frac{2m_h}{n\omega}\right)^2}\;\theta(n\omega-2m_h)$$

Same applies to Planck-suppressed op-s, e.g.

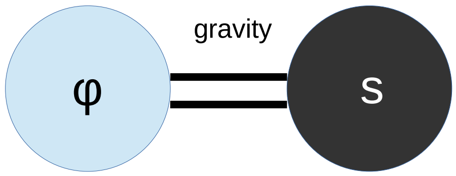
$$\frac{1}{M_{\rm Pl}^2}\,\phi^4 s^2$$

Note: ***gravity is not classical at high energies***

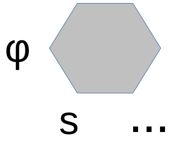
one-graviton exchange ***inadequate***



Need



E.g. n-point fuction in strings



OL 2210.02293

Planck-suppressed operators are very efficient in particle production:

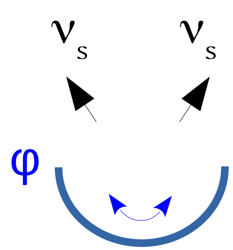
$$\frac{\phi^4 s^2}{M_{\rm Pl}^2}\ ,\quad \frac{\phi^6 s^2}{M_{\rm Pl}^4}\ ,\quad \frac{\phi^8 s^2}{M_{\rm Pl}^6}\ ,\ldots$$

coefficients unknown! *(quantum gravity)*

Koutroulis, OL, Pokorski ‘24

Fermions :

$$\frac{\mathcal{C}}{M_{\rm Pl}}\,\phi^2\,\bar\Psi\Psi \quad ,\ldots$$



produces viable ***COLD keV sterile neutrino DM*** *(C ~ 0.1)*

Freeze-in models suffer from the gravitational background ➡ not predictive

- Gravitationally produced relics may be the end of the story

- If not, can get rid of it:

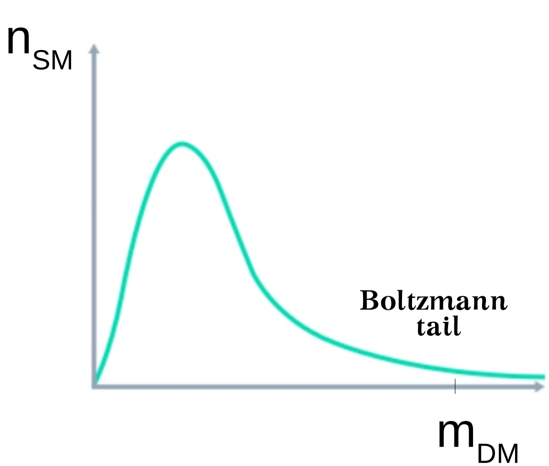
inflaton energy density ~ a^{-3}

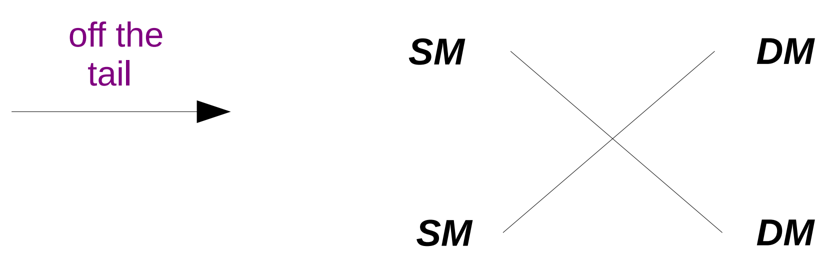
rel. relic energy density ~ a^{-4}

low T_R

What if $T_R < m_{DM}$?

Cosme,Costa,OL '23





Logic:

All we know T_R > 4 MeV (*Hannestad 2004*)

High T_R = strong assumption !

Relax it and **reanalyze**

– Higgs portal

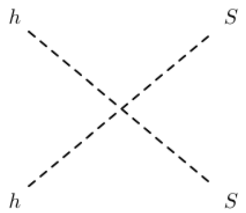
– Z' extension

– ν_R + scalar extension

⇒ **direct DM detection + invisble Higgs decay**

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:

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

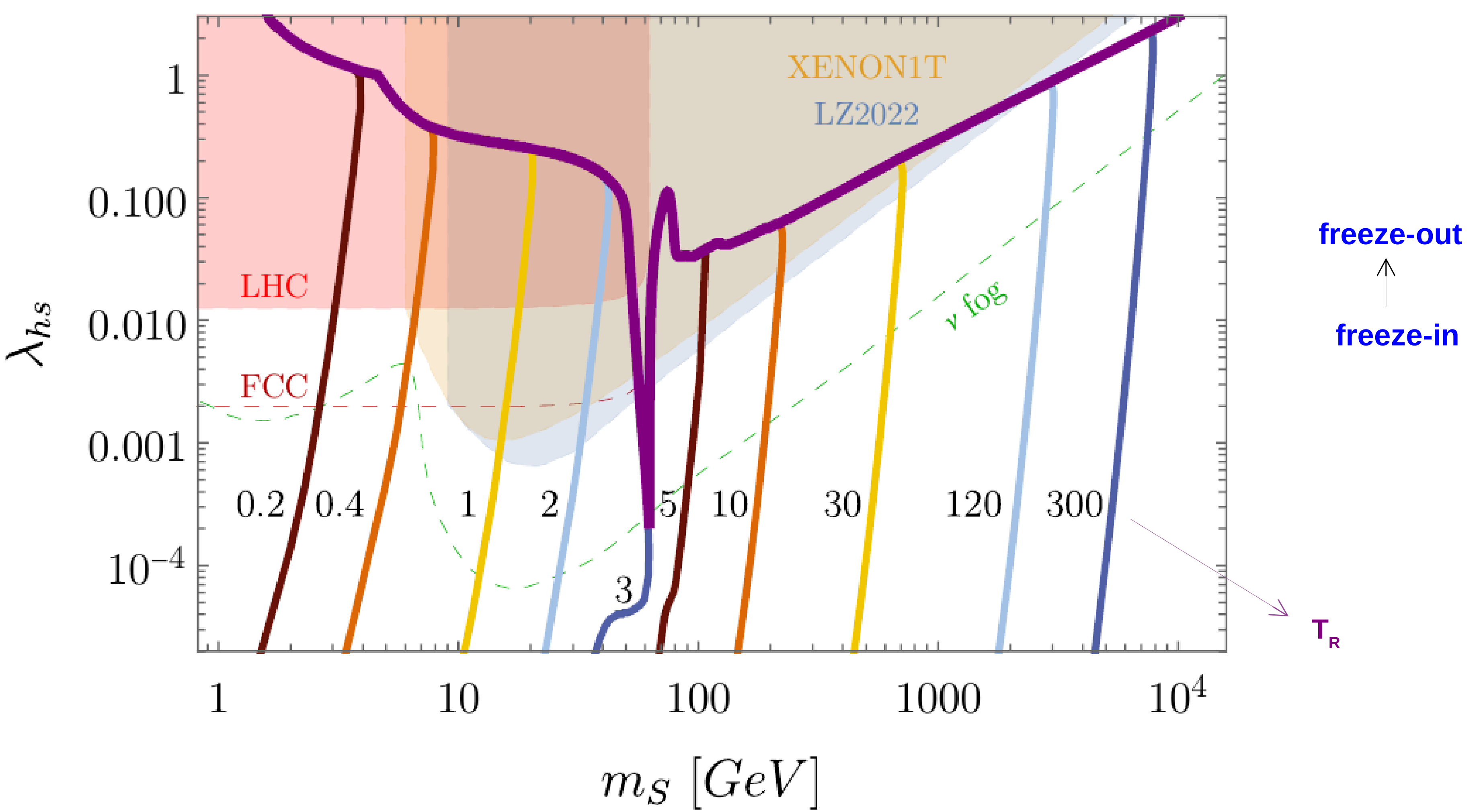
No thermalization:

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

Scalar Higgs portal DM :

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

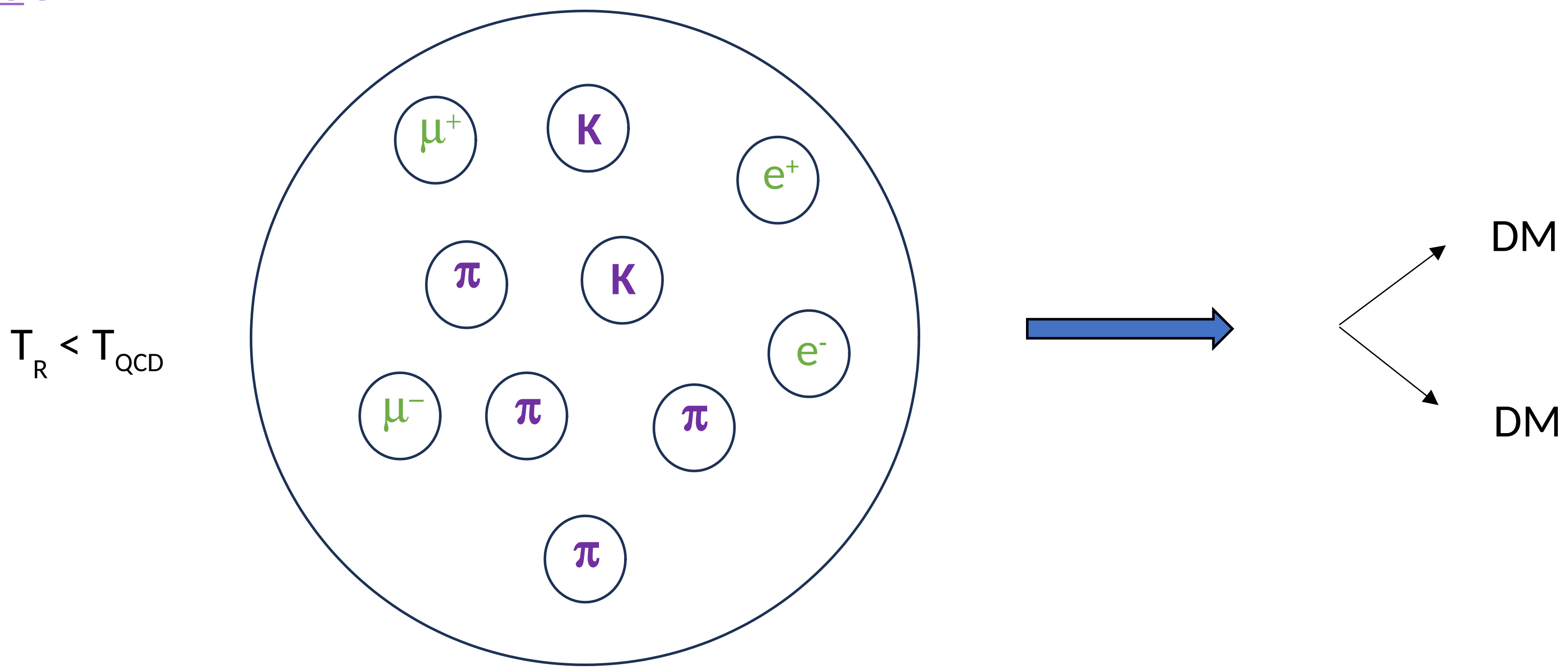
Arcadi,Costa,Goudelis,OL '24

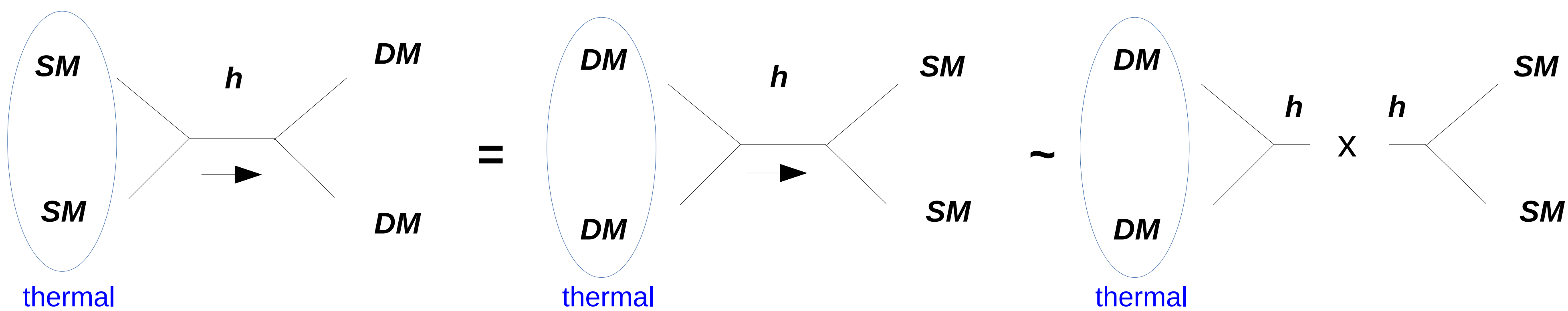


New input: treat ***unknown*** T_R as a free parameter ➡ direct detection + invisible Higgs decay

OL,Morais,Oliveira,Pasechnik ‘24

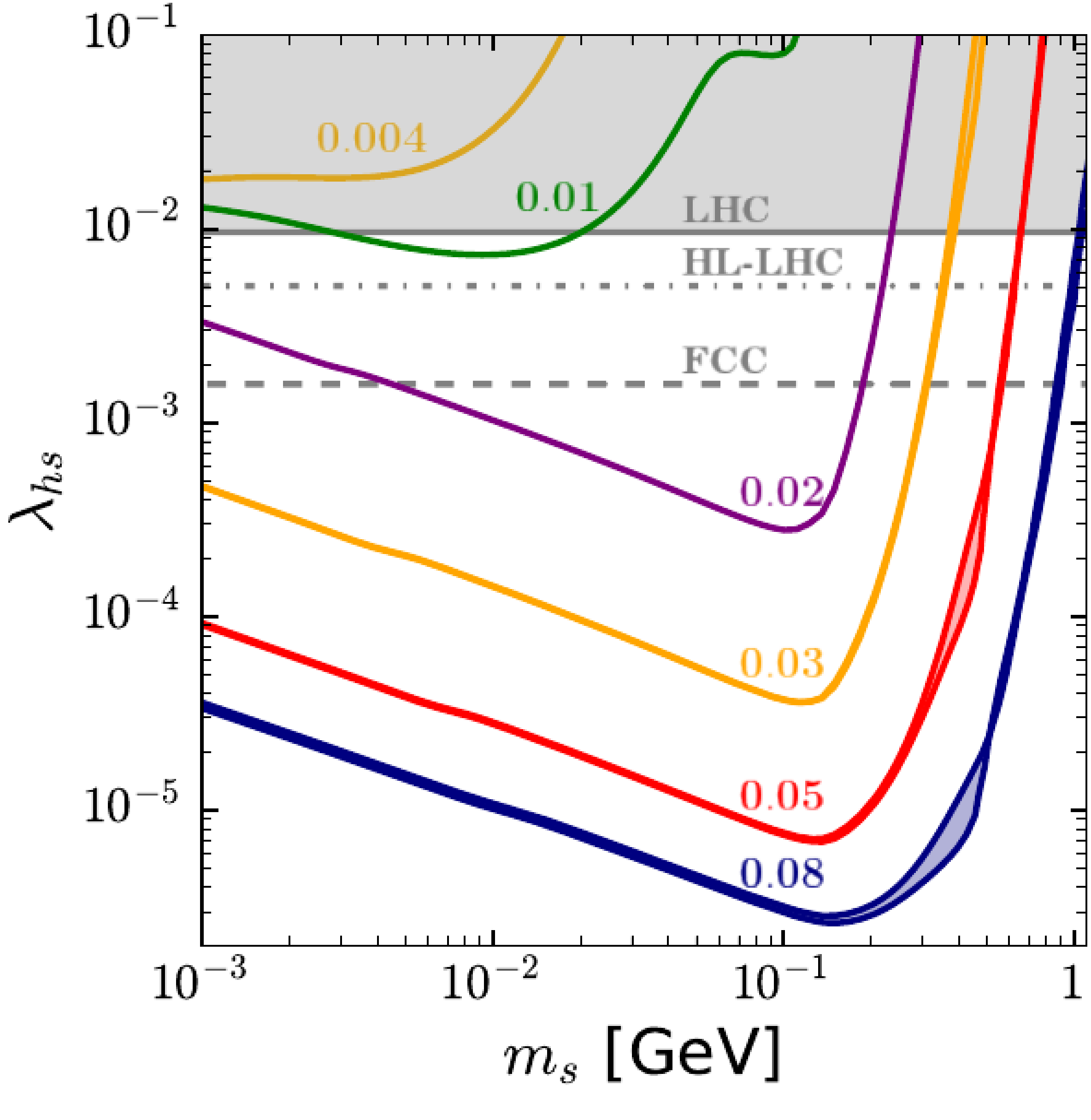
Very low T :



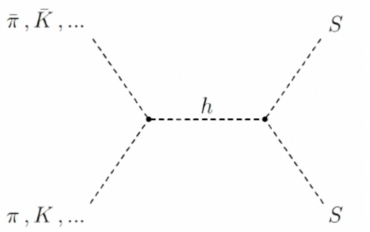


$$\Gamma_{\mathrm{SM}\to SS} = \Gamma^{\mathrm{th}}_{SS\to\mathrm{SM}} = \frac{T}{2^5\pi^4 m_h^4}\int_{4m_s^2}^{\infty} ds\,\sqrt{s(s-4m_s^2)}\,K_1\left(\sqrt{s}/T\right)\,\Gamma_h\left(m_h=\sqrt{s}\right)\,\left|\mathcal{M}_{SS\to h}\right|^2$$

OL,Morais,Oliveira,Pasechnik '24



***pion*-dominated production**

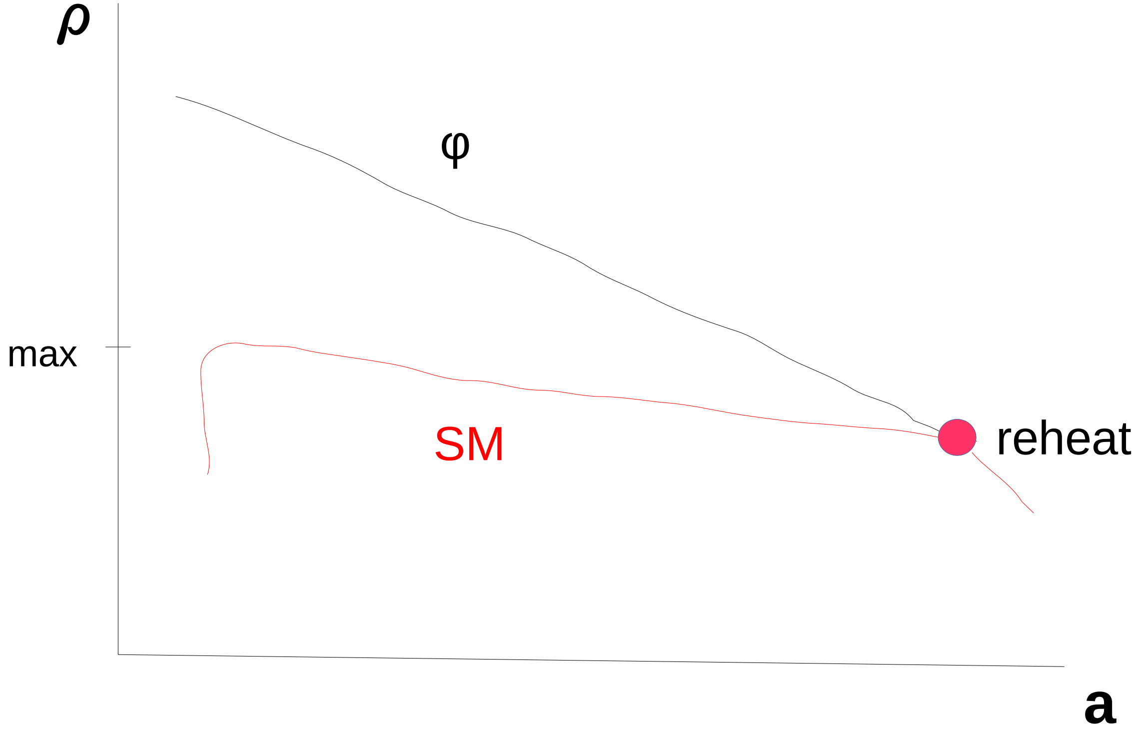


Detour: *Reheating vs Maximal temperature*

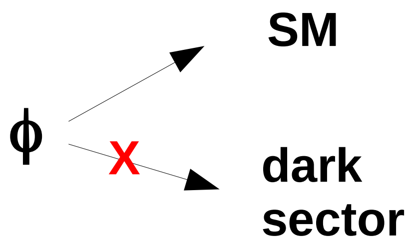
Not much is known if any ...

Textbook ($\phi \rightarrow$ SM) :

$$T^2_{max} \sim M_{pl} \, (\Gamma_\phi \, H_0)^{1/2}$$

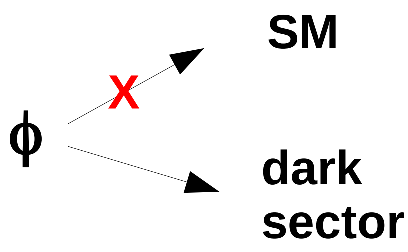


Closer look at "freeze-in" paradigm:



2 tiny couplings: *DM-SM and DM-inflaton* !

Logical extension:



⇒ **T_{max} changes completely!**

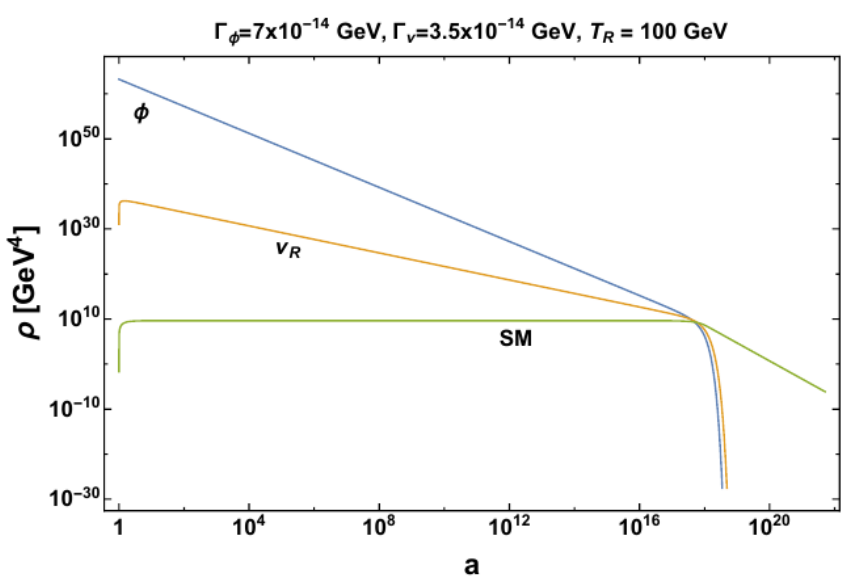
SM ρ produced via "spectator" χ decay:

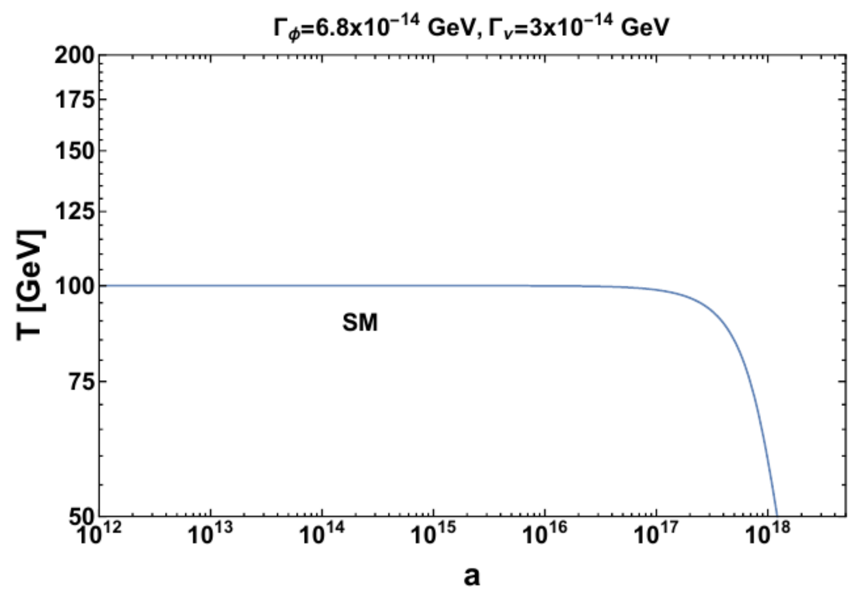
$$\dot{\rho} + 4H\rho = \Gamma_\chi \rho_\chi$$
$$H = H_0/a^m \ ,$$
$$\rho_\chi = \rho_\chi^0/a^n \ ,$$

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

Example:

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





$T_R \sim T_{max}$

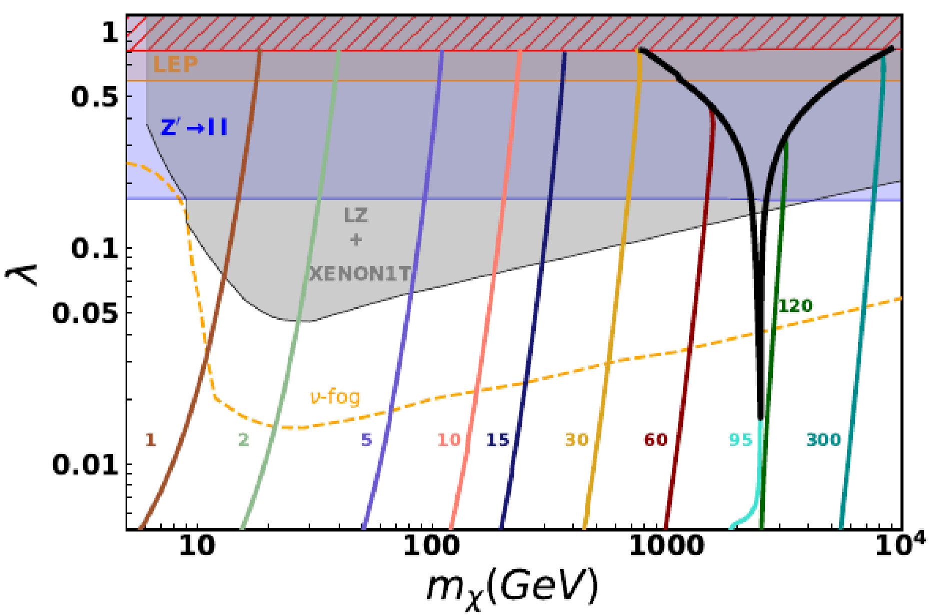
Z' extension

$$\mathcal{L} \supset -m_\chi \bar{\chi}\chi - \frac{1}{2} M_{Z'}^2 Z'_\mu Z'^\mu + \bar{\chi}\gamma^\mu \left(V_\chi - A_\chi \gamma_5\right) \chi \; Z'_\mu + \sum_f \bar{f}\gamma^\mu \left(V_f - A_f \gamma_5\right) f \; Z'_\mu$$

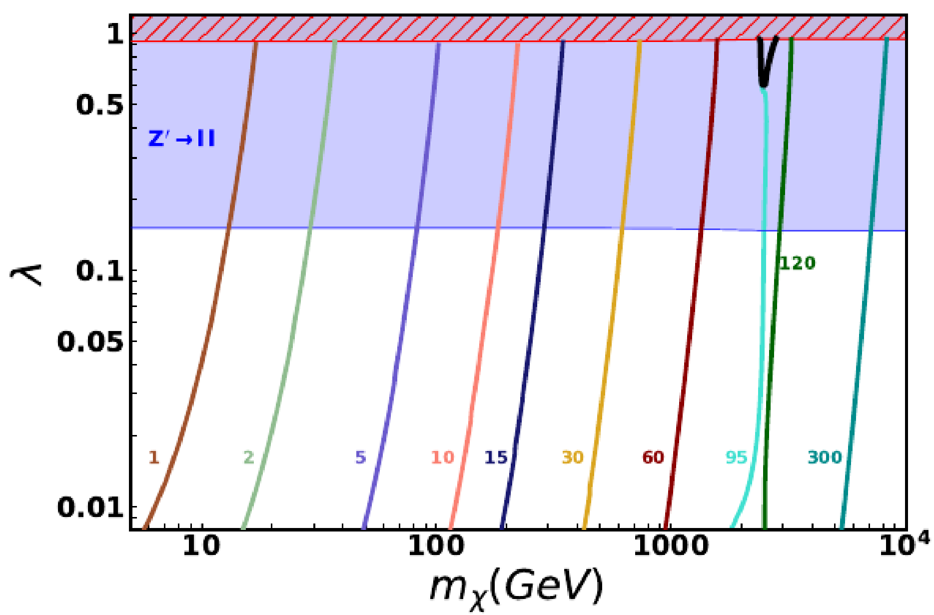
DM

Example: *universal coupling* λ , $M_{Z'} = 5$ TeV

vector



axial

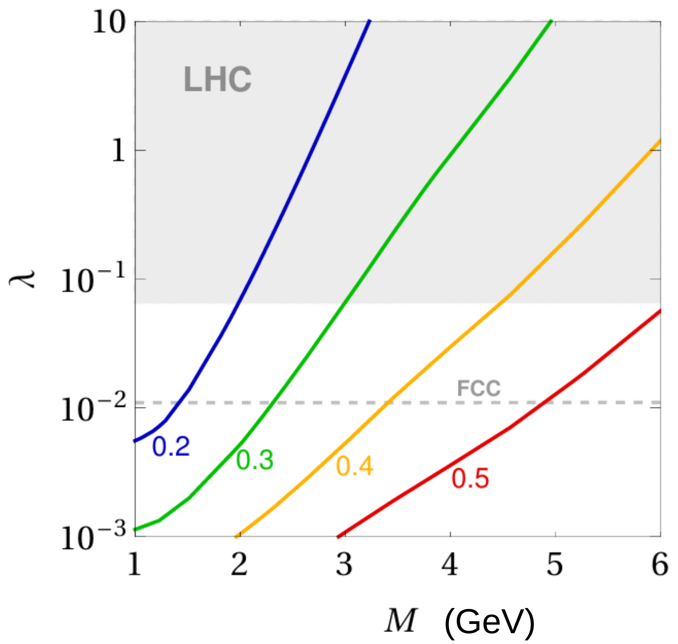


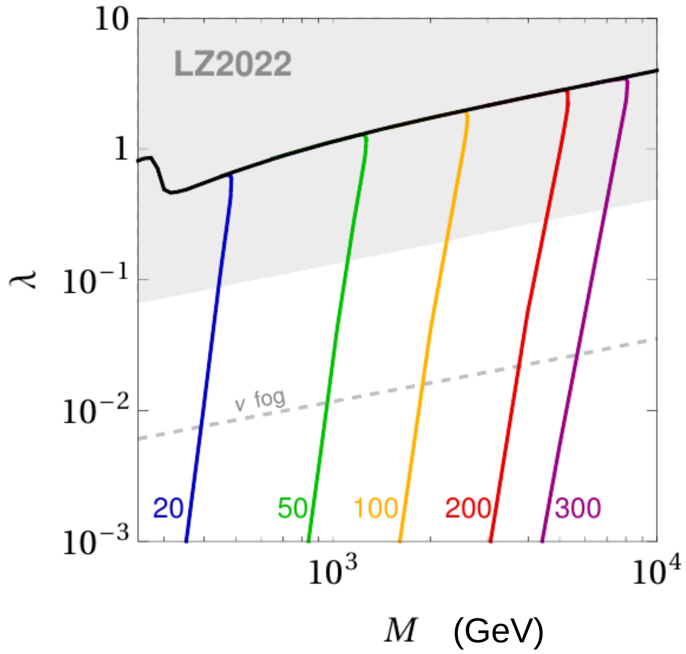
ν_R extension

$$\mathcal{L} \supset \frac{1}{2} M\, \overline{\nu}\nu + \frac{1}{2}\lambda\, S\, \overline{\nu}\nu + \left(y_{\nu,i} \bar{L}_{L,i} \widetilde{H} \nu + \text{h.c.} \right)$$

DM

Example: *scalar mixing = 0.2, heavy scalar mass = 300 GeV*





CONCLUSION

- *dark relics are (over)produced during/after inflation*
- *non-thermal DM is sensitive to (quantum) gravity*
- *motivates freeze-in at stronger coupling (LHC,DD)*