Predictive freeze-in

or

freezing at low temperatures

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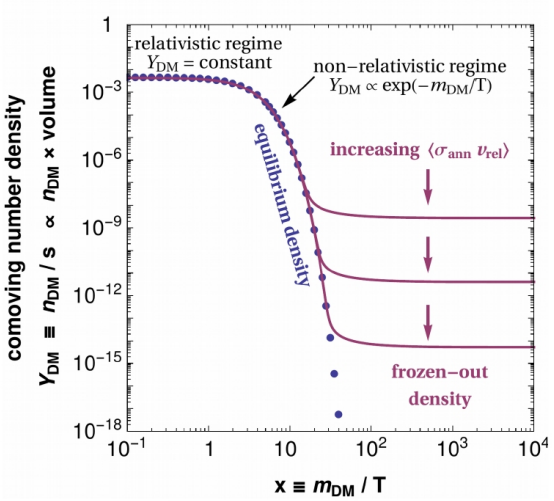
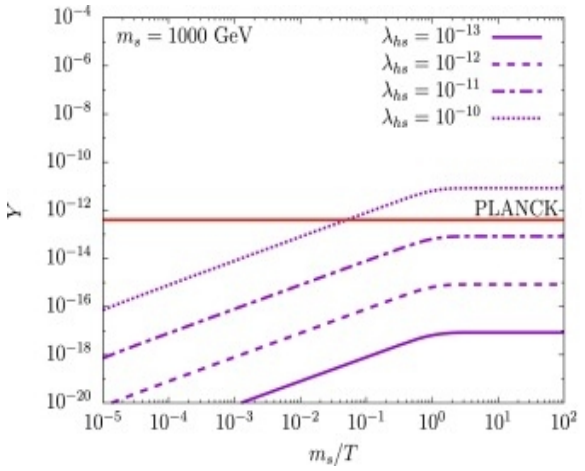
Dark Matter Models

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**

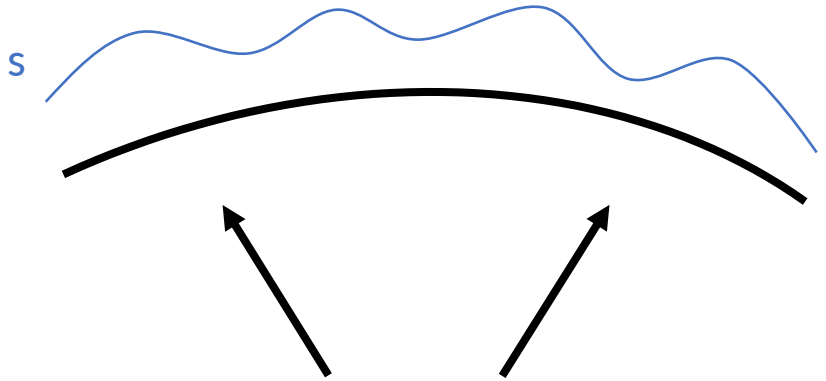
(or prove otherwise)

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

(otherwise there's nothing to talk about)

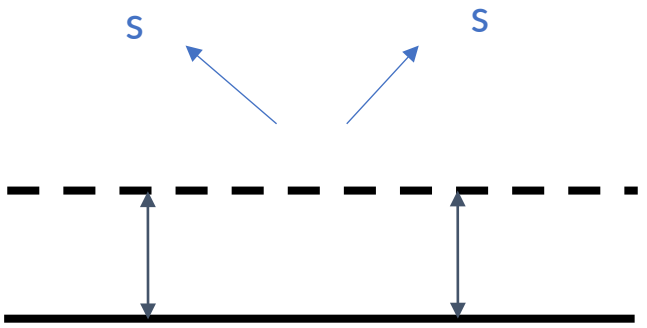
Gravitational particle production

Inflation:



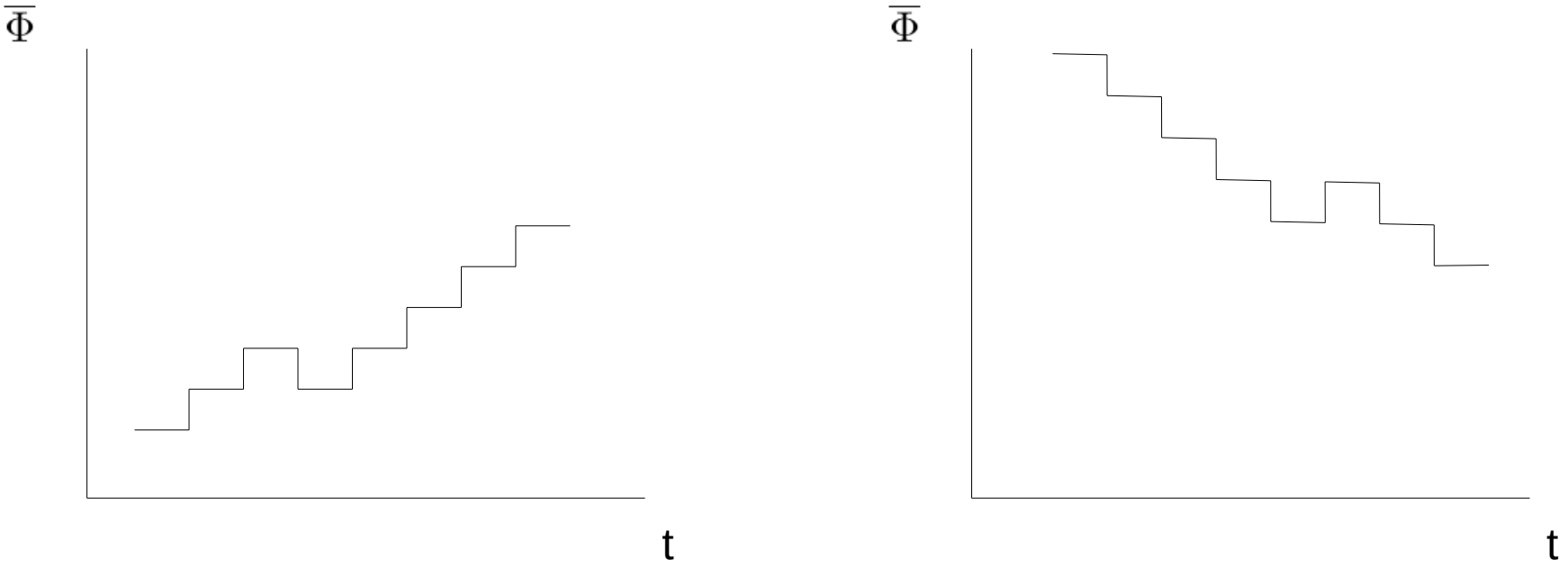
$a \sim e^{Ht}$

After inflation:



$\phi \sim \cos mt$

Starobinsky '86 : **random walk**



Asymptotically,

$$\langle \overline{\Phi}^2 \rangle \to \frac{3}{8\pi^2} \frac{H^4}{m^2}$$

But inflation has a finite duration → average field unknown

OL 2210.02293

Planck-suppressed operators are very efficient in particle production:

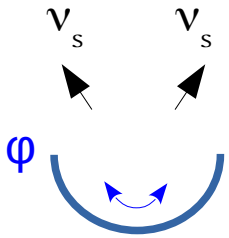
$$\frac{\phi^4 s^2}{M_{\rm Pl}^2} \;, \quad \frac{\phi^6 s^2}{M_{\rm Pl}^4} \;, \quad \frac{\phi^8 s^2}{M_{\rm Pl}^6} \;, \ldots$$

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

OL 2210.02293

– Gravitationally produced relics may be the end of the story

– If not, can get rid of it:

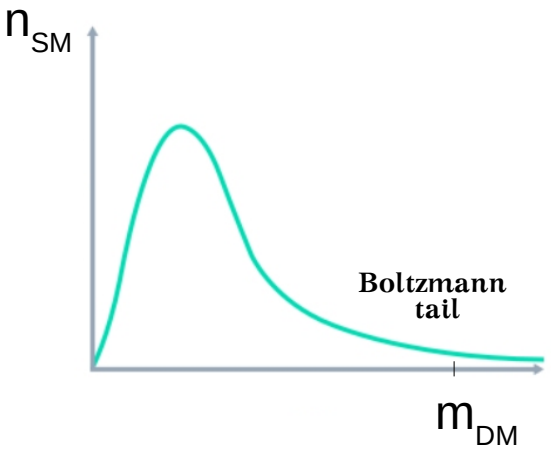
inflaton energy density ~ a^{-3}

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

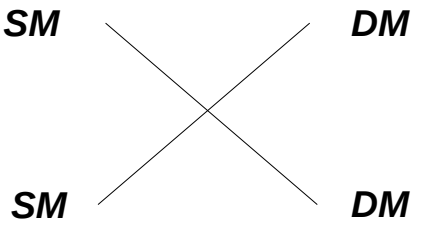
low T_R

What if $T_R < m_{DM}$?

Cosme,Costa,OL '23



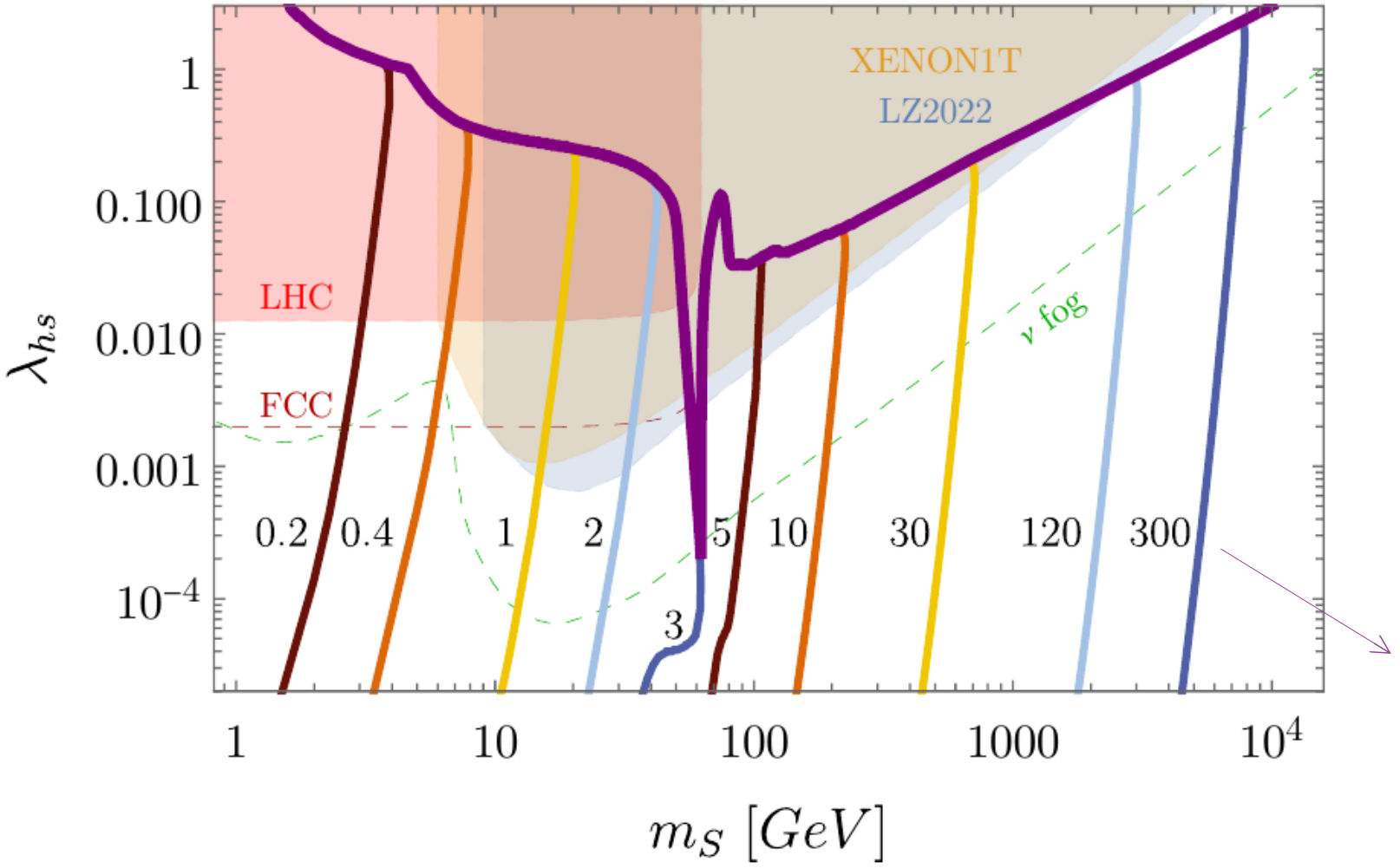
off the tail



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



freeze-out

↑

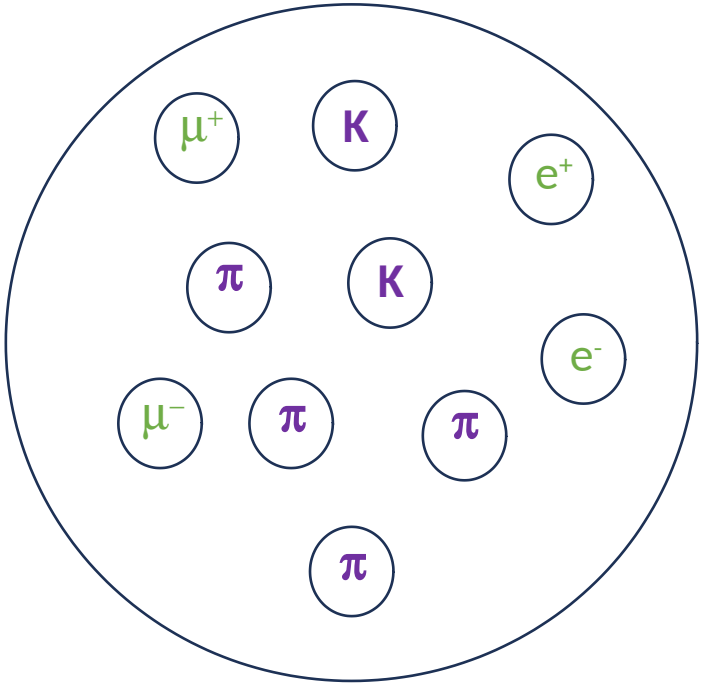
freeze-in

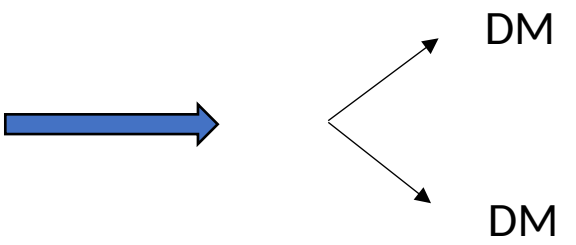
T_R

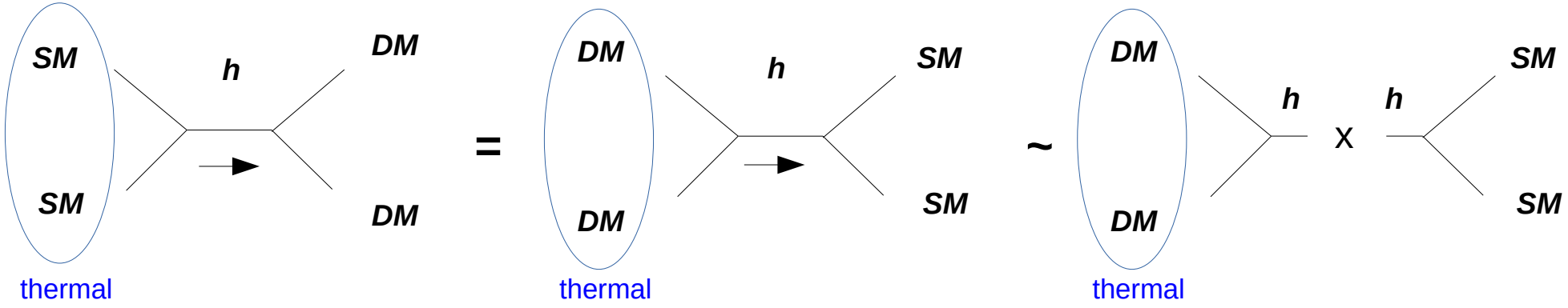
New input: treat ***unknown*** T_R as a free parameter ➡ direct detection + invisible Higgs decay

Very low T :

$T_R < T_{QCD}$

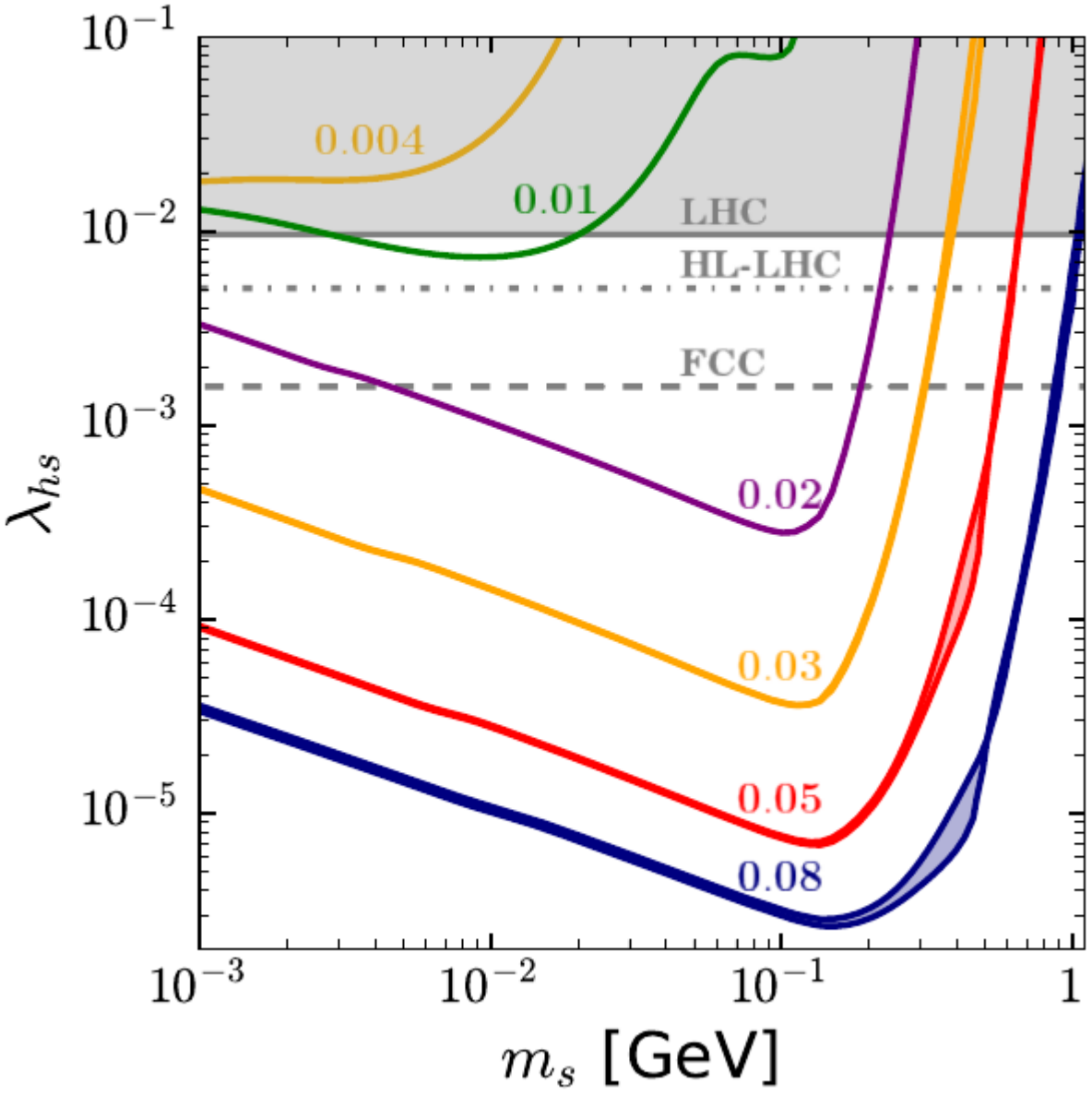






$$\Gamma_{\mathrm{SM}\to SS} = \Gamma^{\mathrm{th}}_{SS\to\mathrm{SM}} = \frac{T}{2^5\pi^4 m_h^4}\int_{4m_s^2}^{\infty} ds\,\sqrt{s(s-4m_s^2)}\,K_1\left(\sqrt{s}/T\right)\,\Gamma_h\left(m_h=\sqrt{s}\right)\,|\mathcal{M}_{SS\to h}|^2$$

OL,Morais,Oliveira,Pasechnik ‘24



***pion**-dominated production*

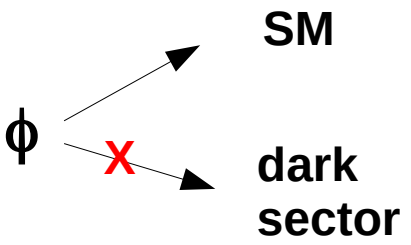
Reheating vs Maximal temperature

Not much is known if any ... Textbook ($\phi \rightarrow$ SM) :

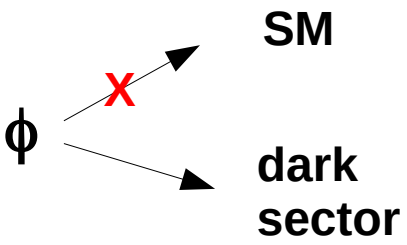
$$T_{max} \sim M_{pl} \, (\Gamma_{\phi} \, H_0)^{1/2}$$

Closer look at "freeze-in" paradigm:

(***2 tiny couplings:*** *DM-SM and DM-inflaton*)



Logical extension:



T_{max} changes completely!

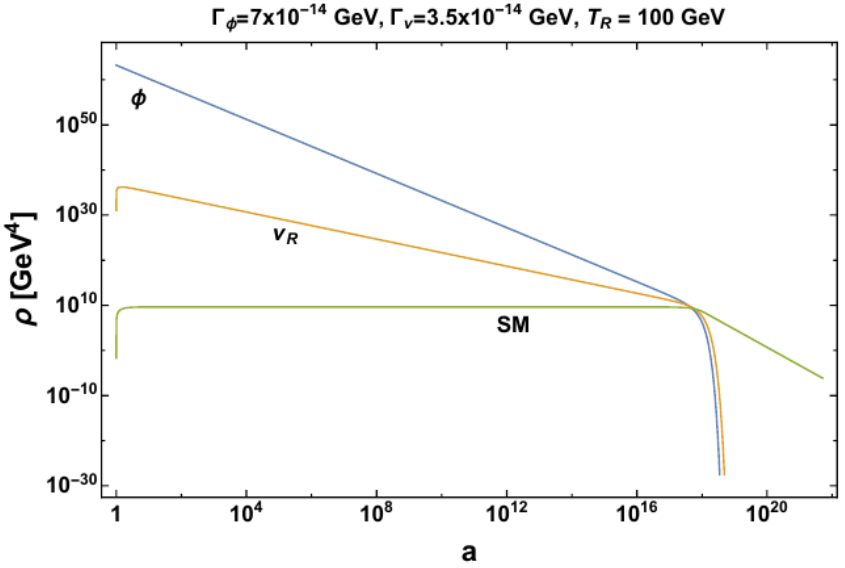
SM ρ produced via "spectator" χ decay:

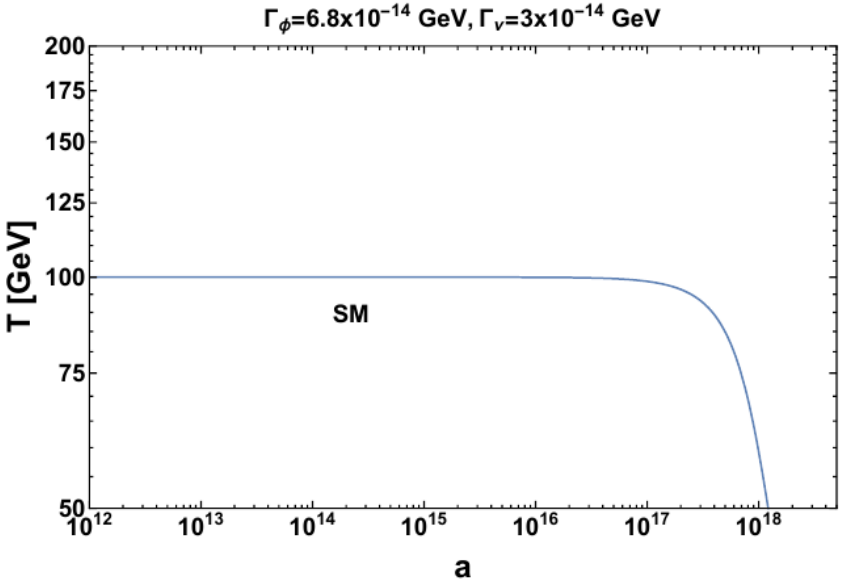
$$\dot{\rho} + 4H\rho = \Gamma_\chi \rho_\chi$$
$$H = H_0/a^m \ ,$$
$$\rho_\chi = \rho_\chi^0/a^n \ ,$$

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

Example:

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





$T_R \sim T_{max}$

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)*