Gravitational particle production and freeze-in at stronger coupling

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– particle production during and after inflation

– Planck-suppressed operators

– non-thermal dark matter

– freeze-in at stronger coupling

– signatures

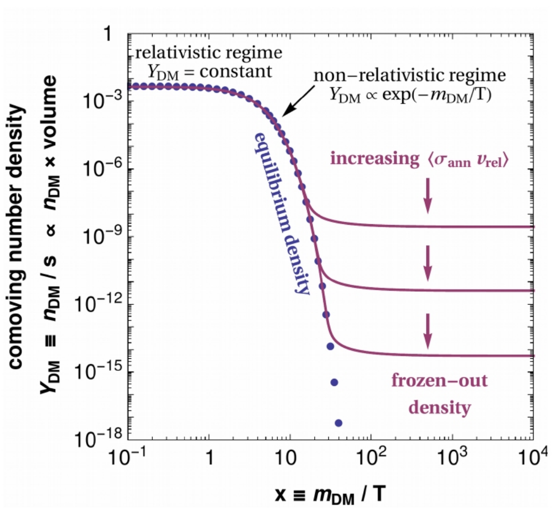
Based on work with Yoon, Cosme, Costa, Koutroulis, Pokorski, Arcadi, Goudelis

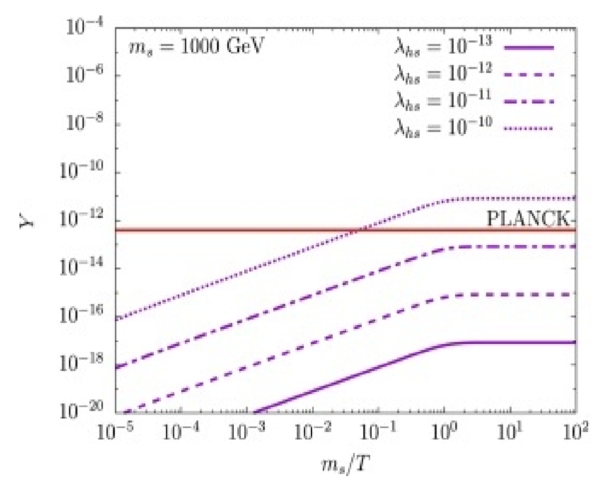
2022 – 2024

Dark Matter Models

thermal

non-thermal





No memory

Memory !

<u>General (philosophical) remarks</u>

– *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)

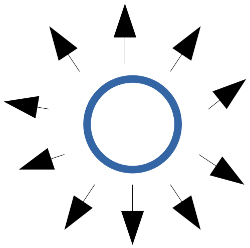
- gravity is always there $\rightarrow$ must prove it's irrelevant

(otherwise there's nothing to talk about)

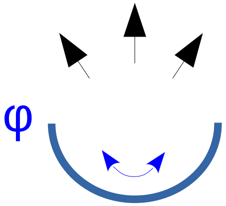
Non-thermal relics / DM have memory !

Production mechanisms (all add up):

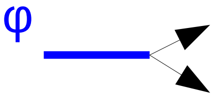
- during inflation



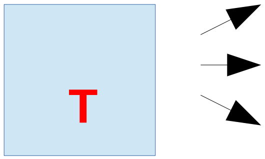
- via inflaton oscillations



- inflaton decay



- thermal emission (freeze-in)



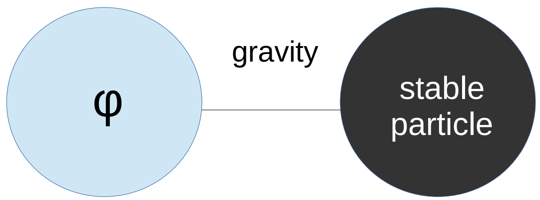
Assume (standard):

- existence of feebly interacting stable particles

- such particles are not super-heavy ($m < H, m_{infl}$)

- large field inflation (φ ~ Planck scale)

- no renormalizable coupling to the inflaton



𝕆bservation:

"small" amount of stable particles can dominate ρ at late times

Focus: inflation + inflaton oscillation epoch (preheating)

Gravitational particle production

Parker, Grib, Mamaev, Starobinsky, Zeldovich,… 1969 - ...

– Bogolyubov method

– de Sitter fluctuations

– perturbative / semiclassical

– lattice simulations

– ...

Decoupled scalar production during inflation

Scalar “s” with

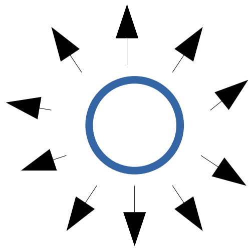
$$V(s) = \frac{1}{2} m_s^2 \, s^2 + \frac{1}{4} \lambda_s \, s^4$$

$$\lambda_s \ll 1 \quad , \quad m_s \ll H$$

Starobinsky-Yokoyama equilibrium distribution of de Sitter fluctuations:

$$P(s) \propto \exp\left[-8\pi^2 V(s)/(3H^4)\right]$$

$$\langle s^2 \rangle \simeq 0.1 \times \frac{H_{\rm end}^2}{\sqrt{\lambda_s}}$$



Mean field:

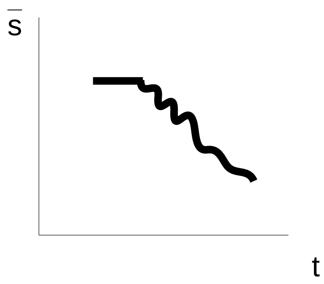
$$\bar{s} \equiv \sqrt{\langle s^2 \rangle}$$

Peebles, Vilenkin ‘99
Markkanen, Rajantie, Tenkanen ‘18

Effective mass:

$$m_{\text{eff}}^2 = m_s^2 + 3\lambda_s \bar{s}^2$$

Evolution:



$$\bar{s}_{\text{end}} \xrightarrow{a^0} \bar{s}_{\text{osc}} \xrightarrow{a^{-1}} \bar{s}_{\text{dust}}$$

frozen → oscillates in s^4 potential → oscillates in s^2 potential

$H > m_{\text{eff}}$ **$H \sim m_{\text{eff}}$** **$m_s \sim m_{\text{eff}}$**

Relic number density (*non-rel.*) = energy density / particle mass :

$$n \simeq m_s^3 / \lambda_s$$

Constraints

Require

$$Y \leq 4.4 \times 10^{-10} \, \frac{\mathrm{GeV}}{m_s}$$

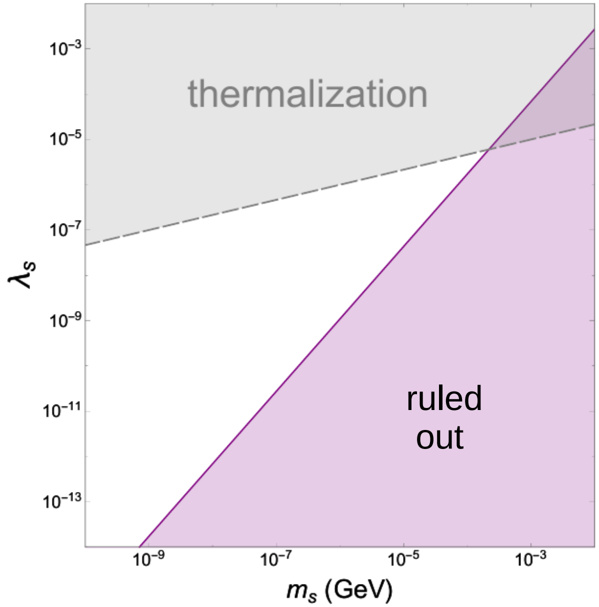
instant reheating
or φ^4

$$m_s \, \lambda_s^{-5/8} \lesssim 10^{-7} \left(\frac{M_{\mathrm{Pl}}}{H_{\mathrm{end}}} \right)^{3/2} \, \mathrm{GeV}$$

Hubble rate at the end of inflation

Very strong constraint :

2210.02293



Starobinsky-Yokoyama
fluctuations

$$H_{\mathrm{end}} \sim 10^{14} \; \mathrm{GeV}$$

$$\Delta_{\mathrm{NR}} = 1$$

In general, the abundance depends on duration of the ***non-relativistic*** expansion period (φ^2 pot.):

$$H_{\rm end} \xrightarrow{a^{-3/2}} H_{\rm reh} \qquad \Delta_{\rm NR} \equiv \left(\frac{H_{\rm end}}{H_{\rm reh}}\right)^{1/2} > 1$$

Dilutes the energy in the condensate → weaker constraint

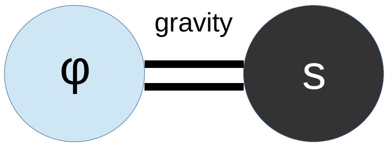
$$m_s\,\lambda_s^{-3/4} \lesssim 10^{-7}\,\Delta_{\rm NR}\left(\frac{M_{\rm Pl}}{H_{\rm end}}\right)^{3/2}\,{\rm GeV}$$

$H_{\rm end} \sim 10^{14}\ {\rm GeV}$ ➡ $m_s \ll \Delta_{\rm NR}\ {\rm GeV}$

*Only particles **far below** the **GeV** scale are allowed for* $\Delta_{\rm NR} = 1$

Quantum gravity effects

Induce gauge invariant operators
(*with unknown coefficients)*



Dim-6 gravity-induced couplings:

Also induced by ***classical*** gravity!

$$\Delta\mathcal{L}_6 = \frac{C_1}{M_{\rm Pl}^2}\,(\partial_\mu\phi)^2 s^2 + \frac{C_2}{M_{\rm Pl}^2}\,(\phi\partial_\mu\phi)(s\partial^\mu s) + \frac{C_3}{M_{\rm Pl}^2}\,(\partial_\mu s)^2\phi^2 - \frac{C_4}{M_{\rm Pl}^2}\,\phi^4 s^2 - \frac{C_5}{M_{\rm Pl}^2}\,\phi^2 s^4$$

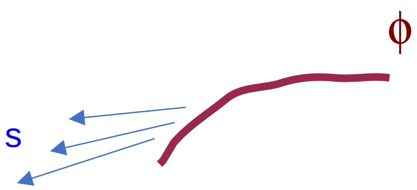
Main operators for on-shell fields contributing to s-pair production:

$$\mathcal{O}_3 = \frac{1}{M_{\rm Pl}^2}\,(\partial_\mu s)^2\phi^2 \quad , \quad \mathcal{O}_4 = \frac{1}{M_{\rm Pl}^2}\,\phi^4 s^2$$

(supplemented with dim-4 $\mathcal{O}_{\rm renorm} = \frac{m_\phi^2}{M_{\rm Pl}^2}\,\phi^2 s^2$ and 4-DM op $\frac{C_5}{M_{\rm Pl}^2}\,\phi^2 s^4$)

Particle production:

$\mathcal{O}_4$ dominates



$$\Gamma = \frac{C_4^2}{4\pi M_{\rm Pl}^4} \sum_{n=1}^{\infty} |\hat{\zeta}_n|^2$$

initial inflaton value^8

$$\dot{n} + 3Hn = 2\Gamma$$

2210.02293

$$\Delta_{\rm NR} \equiv \left(\frac{H_{\rm end}}{H_{\rm reh}}\right)^{1/2}$$

$$|C_4| < 10^{-3}\, \Delta_{\rm NR}^{1/2}\, \frac{H_{\rm end}^{5/4}\, M_{\rm Pl}^{11/4}}{\phi_0^4} \sqrt{\frac{\rm GeV}{m_s}}$$

$$\phi_0 \sim M_{\rm Pl} \text{ and } H_{\rm end} \sim 10^{14}\ \rm GeV$$

$$|C_4| < \text{few} \times 10^{-9}\, \Delta_{\rm NR}^{1/2} \sqrt{\frac{\rm GeV}{m_s}}$$

$$|C_3| \lesssim 10^{-1}\, \Delta_{\rm NR}^{1/2} \sqrt{\frac{\rm GeV}{m_s}}$$

Higher dim operators:

$$\mathcal{O}^{(p)} = \frac{\phi^p s^2}{M_{\rm Pl}^{p-2}}$$

$$|C^{(p)}| < 10^{-3}\, \Delta_{\rm NR}^{1/2}\, \frac{H_{\rm end}^{5/4}\, M_{\rm Pl}^{p-5/4}}{\phi_0^p} \sqrt{\frac{\rm GeV}{m_s}}$$

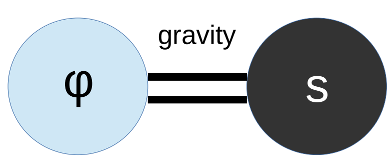
Planck-suppressed operators are very efficient in particle production!

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

<u>Main observation</u> :

Planck—suppressed ("gravity--induced") operators
with <u>small</u> Wilson coefficients
can account for all of the dark matter !

Non-thermal DM model building is highly **UV sensitive** :



– abundance is additive ("memory")

– need to control quantum gravity

– **predictivity ?**

Fermion production

(1) Via inflation

$$\left(i\gamma^\mu \partial_\mu - a(\eta)M\right)\Psi = 0$$

$$Y \simeq 4.5 \times 10^{-3} \left(\frac{M}{M_{\rm Pl}}\right)^{3/2}$$

➡ *too small*

(2) Via inflaton oscillations

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

Koutroulis, OL, Pokorski '24

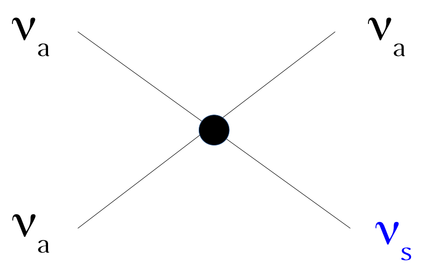
$$Y = 10^{-1}\,\mathcal{C}^2\,\frac{H_e^{3/2}\,M_{\rm Pl}^{1/2}}{\Delta_{\rm NR}\,m_\phi^2}$$

➡ *large*

Can produce all of dark matter, e.g. ***keV sterile neutrinos (!) :***

$$\mathcal{C}(M \sim {\rm keV}) \simeq 10^{-2} \qquad (\Delta_{\rm NR} \sim 1)$$

Dodelson-Widrow ‘93 :

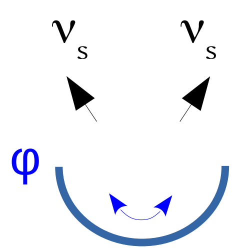


warm keV neutrino DM
via
freeze-in

Assumes zero initial abundance. ***Ruled out****.*

Koutroulis, OL, Pokorski ‘24

Gravity-induced ops:



cold keV neutrino DM

$E_\nu \sim m_\phi << V^{1/4}$

Viable!

Irreducible gravity background for ***<u>Freeze-in</u>*** **:**

inflation | preheating | reheating

De Sitter fluctuations

metric oscillations + QG ops

$\phi^4 s^2 / M^2_{Pl}$

smaller corrections

The problem is not to produce DM, but to get rid of it !

- 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}

⬇

dilution: at late reheating, relics are insignificant

$$\Delta_{\rm NR} \simeq T_R^{\rm inst}/T_R \gg 1$$

E.g. $Y = 10^{-1}\, \mathcal{C}^2\, \frac{H_e^{3/2}\, M_{\rm Pl}^{1/2}}{\Delta_{\rm NR}\, m_\phi^2}$

Low T_R !

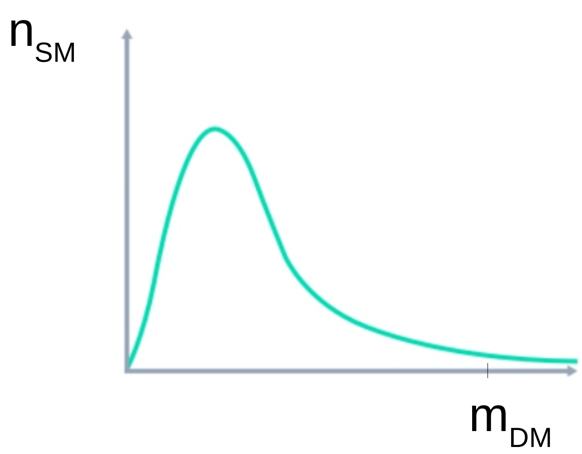
Freeze-in at stronger coupling

Need to get rid of the gravitational background → matter dominated expansion

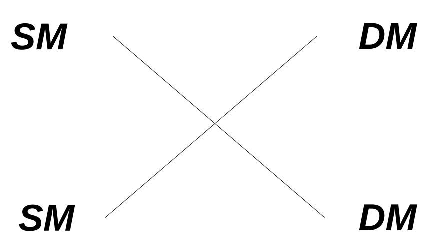
φ^2 local inflaton potential

relics are diluted , low reheating temperature T_R

What if $T_R < m_{DM}$?



off the tail →



Boltzmann-suppressed DM production requires a stronger coupling → observable !

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:

$$\Gamma(h_i h_i \to ss) \simeq \frac{\lambda_{hs}^2 T^3 m_s}{2^7 \pi^4} e^{-2m_s/T}$$

→

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

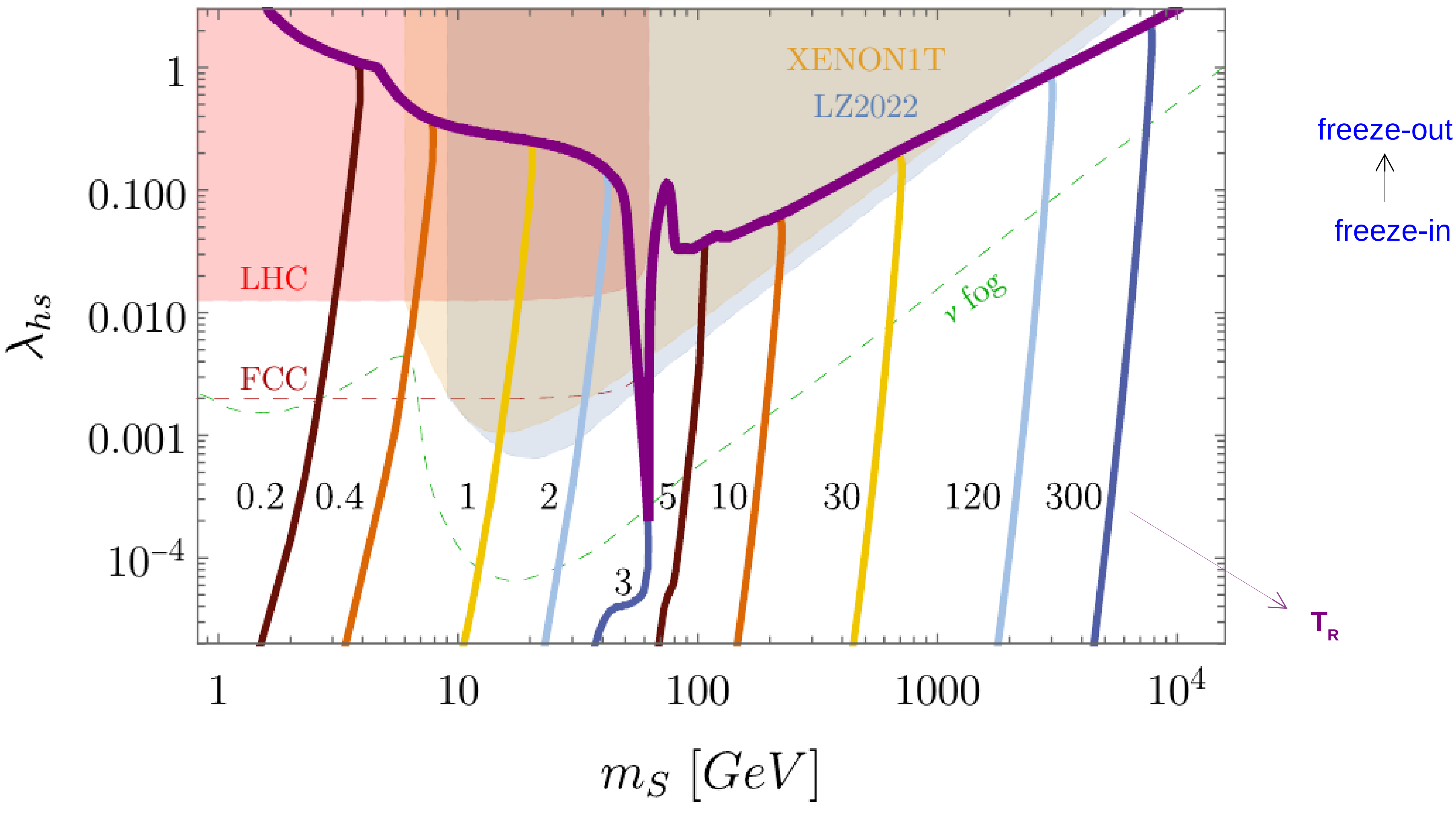
With annihilation:

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

No thermalization (at weak coupling):

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

Scalar dark matter:



Signatures: direct detection + invisible Higgs decay

CONCLUSION

– *dark relics are (over)produced during/after inflation*

– *Planck-suppressed operators are very important*

– *non-thermal DM is sensitive to gravity*

– *low T_R solves the problem → strong coupling freeze-in*

– *freeze-in probed by direct detection and LHC*

Reheating

Only know that $T_R > 4$ MeV

Example of reheating via neutrinos:

$$\Delta\mathcal{L} = y_\phi \, \phi \, \nu_R \nu_R + y_\nu \, H^c \bar{\ell} \nu_R + \text{h.c.}$$

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

$\Rightarrow$ T = const !!