Dark Matter in Starobinsky Inflation

Based on:
NB, Javier Rubio and Hardi Veermäe - arXiv:2004.13706 & arXiv:2006.02442

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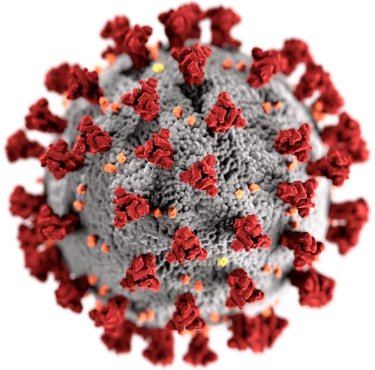
September 24th, 2020



Einstein-Hilbert action

$$S = \frac{M_P^2}{2} \int \mathrm{d}^4x \sqrt{-\tilde{g}} \left[\tilde{R} \qquad\qquad \right] + S_M(\tilde{\varphi}, \tilde{\psi}, \tilde{A}_\mu)$$

R: Ricci scalar

Starobinsky Inflation

A.A. Starobinsky 80’, 81’, 83’

$$S = \frac{M_P^2}{2} \int \mathrm{d}^4x \sqrt{-\tilde{g}} \left[\tilde{R} + \frac{\tilde{R}^2}{6M^2} \right] + S_M(\tilde{\varphi}, \tilde{\psi}, \tilde{A}_\mu)$$

Jordan frame

R: Ricci scalar
M: mass scale

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Jordan frame

Weyl transformation

$$\tilde{g}_{\mu\nu} = \Omega^2\, g_{\mu\nu}$$

$$\Omega^2 = 1 + \frac{\xi\,\Phi^2}{M_P^2} = \exp\left(\sqrt{\frac{2}{3}}\frac{\phi}{M_P}\right)$$

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_P^2}{2}R - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\,\partial_\nu\phi - V(\phi)\right] + S_M(\varphi, \psi, A_\mu)$$

Scalaron frame

$$V(\phi) = \frac{3}{4}M_P^2\,M^2\left[1 - e^{-\sqrt{\frac{2}{3}}\frac{\phi}{M_P}}\right]^2$$

scalaron field $\boldsymbol{\phi}$

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A single free parameter: ***M*** scalaron mass

Starobinsky Inflation: Slow-roll

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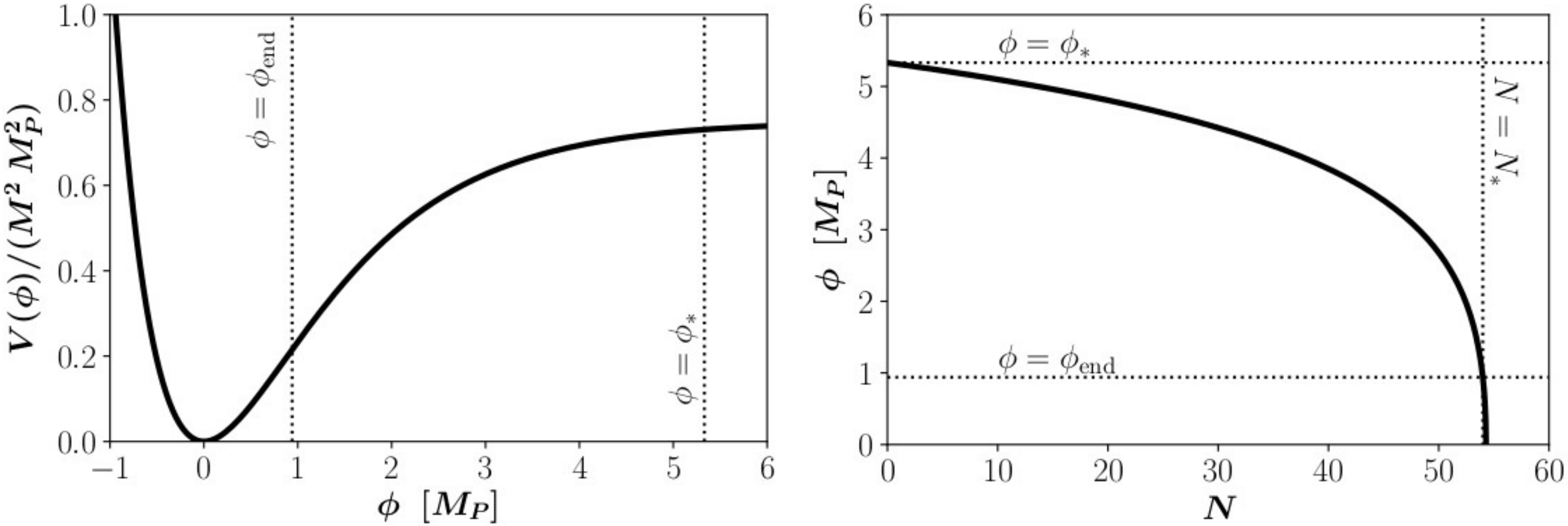


Starobinsky Inflation: Slow-roll

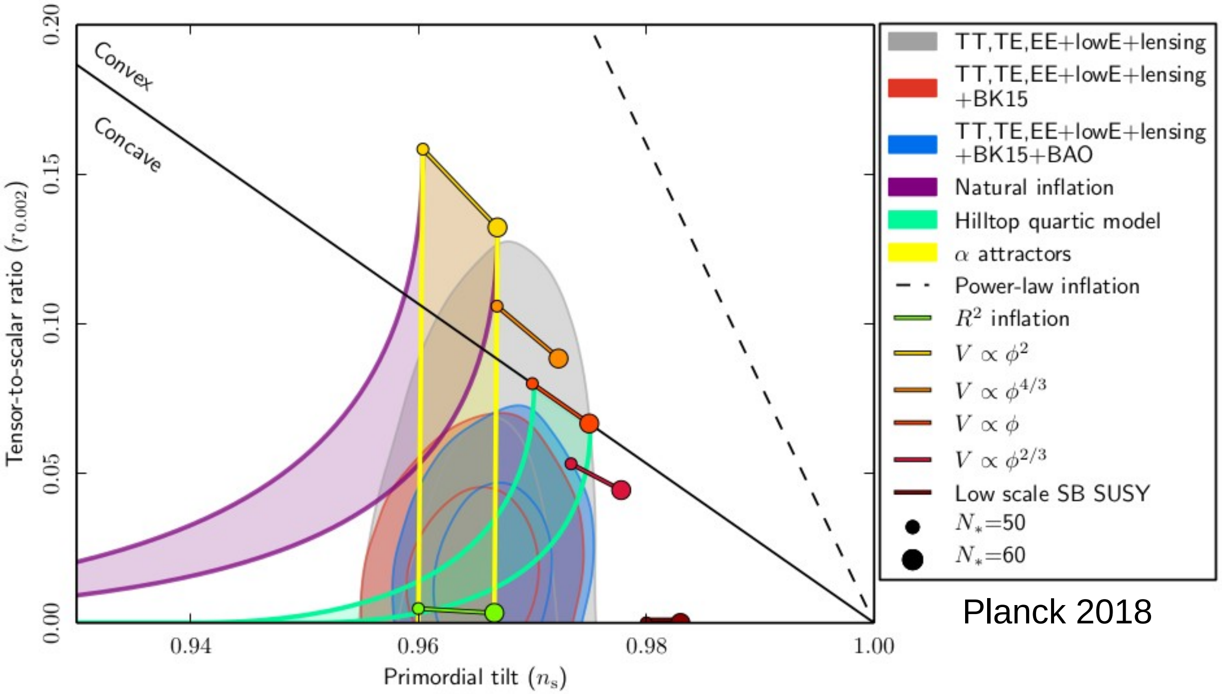
power spectrum of primordial density fluctuations: P and n_s
tensor-to-scalar ratio: r

$$\mathcal{P} = \frac{N_*^2}{24\pi^2}\left(\frac{M}{M_P}\right)^2 , \qquad n_s \simeq 1 - \frac{2}{N_*} , \qquad r \simeq \frac{12}{N_*^2}$$

The scalaron mass M is determined by the COBE normalization $\mathcal{P} = 2.1 \times 10^{-9}$

$$M \simeq 1.3 \times 10^{-5}\left(\frac{54}{N_*}\right) M_P$$

Starobinsky Inflation: Slow-roll



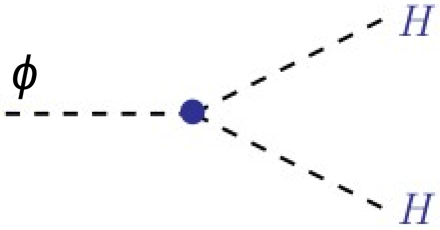
Planck 2018

Starobinsky Inflation: Heating

Reheating proceeds through the gravitational particle production of non-conformally coupled fields.

The scalaron decays into
non-conformally coupled Higgs

$$\Gamma_{\rm SM} \simeq 2.9 \times 10^{-17}(1+6\xi_H)^2\, M_P$$



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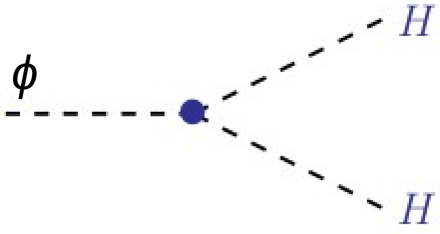


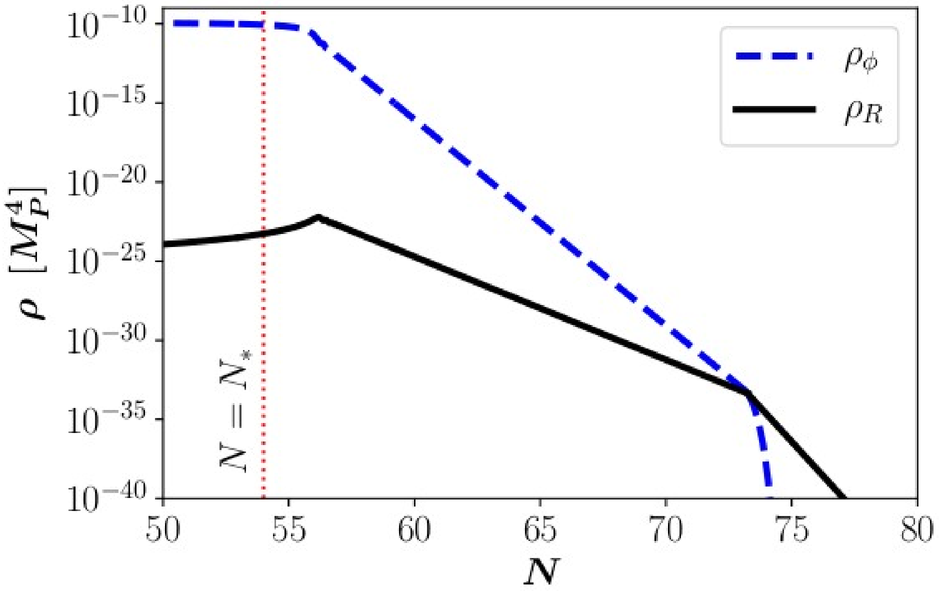
Evolution of the field and SM radiation

$$\ddot{\phi} + (3H + \Gamma_{\rm SM})\,\dot{\phi} + V_{,\phi} = 0$$

$$\dot{\rho}_R + 4H\,\rho_R = \Gamma_{\rm SM}\,\dot{\phi}^2$$

$$H^2 = \frac{\rho_\phi + \rho_R}{3M_P^2}$$

Starobinsky Inflation: Heating



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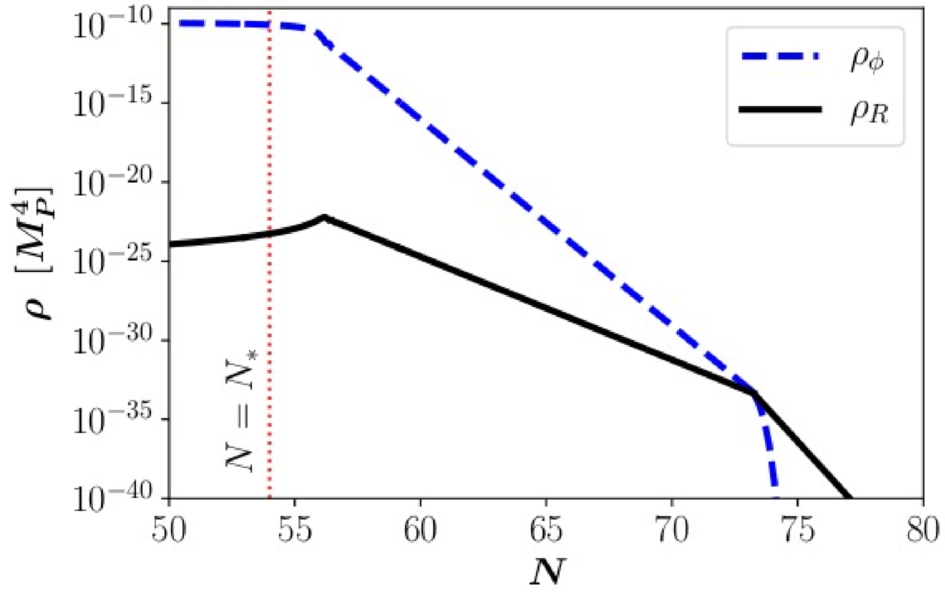

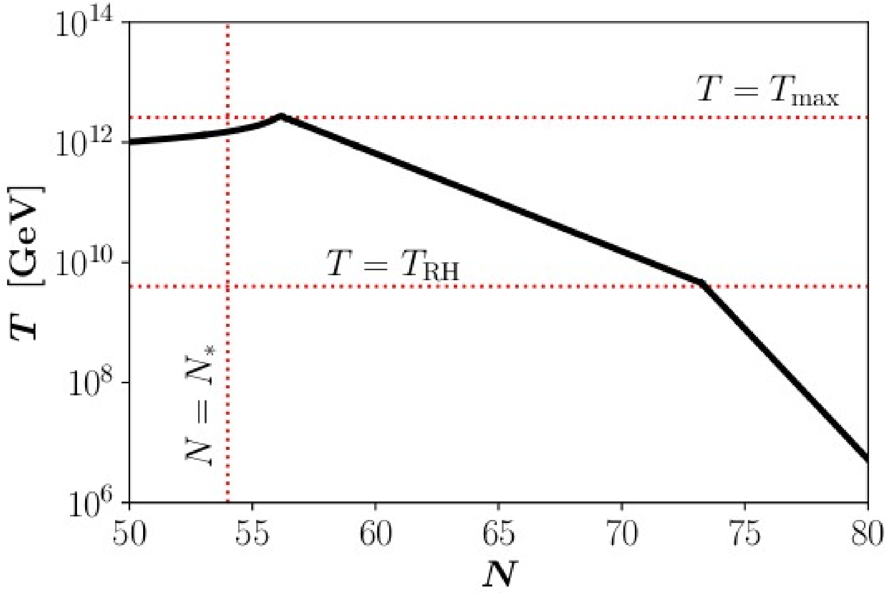

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$$T_{\rm RH} \simeq 4.2 \times 10^9\ \mathrm{GeV}$$

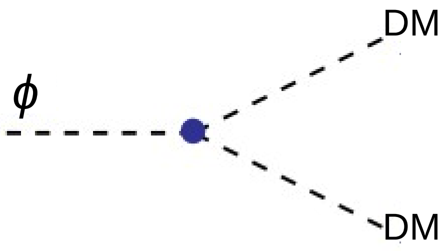
$$T_{\max} \simeq 2 \times 10^{12}\ \mathrm{GeV}$$

Starobinsky Inflation: Dark Matter production

All type of non Weyl-invariant states can be generated by perturbative gravitational particle production.

$$Y_0 \simeq \frac{3}{2}\frac{g_\star}{g_{\star s}}\frac{T_{\rm RH}}{M}{\rm Br}_{\rm DM}$$

$${\rm Br}_{\rm DM} \leq 3\times 10^{-9}\left(\frac{1~{\rm TeV}}{m_{\rm DM}}\right)\left(\frac{54}{N_*}\right)\left(\frac{2.8\times 10^9~{\rm GeV}}{T_{\rm RH}}\right)$$



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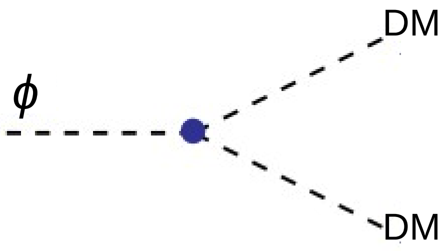

Spin-0 DM

$\mathrm{Br}_{\mathrm{DM}}$ ~ 1/5

Only viable for
m_{DM} ~ 10 keV

Spin-1/2 DM

$$\Gamma_{1/2} = \frac{1}{48\pi} \frac{m_{\rm DM}^2}{M^2} \frac{M^3}{M_P^2} \left(1 - \frac{4\, m_{\rm DM}^2}{M^2}\right)^{3/2}$$

Only viable for:
m_{DM} ~ 10^7 GeV

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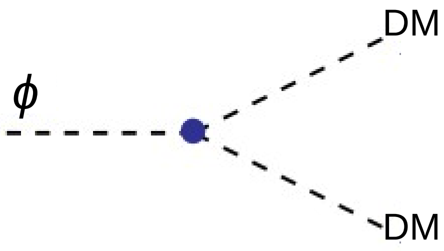

Spin-0 DM

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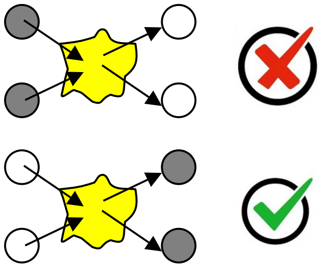
$m_{\mathrm{DM}} \sim 10^7$ GeV

Is there a way to produce DM with other masses and spins?

Dark Matter production: UV freeze-in

Talk by
B. Barman

$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v\rangle\left(n^2 - n_{\rm eq}^2\right)$$



* chemical equilibrium never reached
* non-renormalizable operators
* $\Lambda > T_{RH}$
* $T_{FI} \sim T_{RH}$

$$\langle\sigma v\rangle = \frac{T^n}{\Lambda^{2+n}}$$

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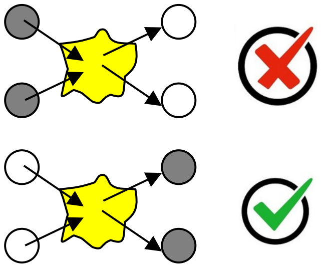

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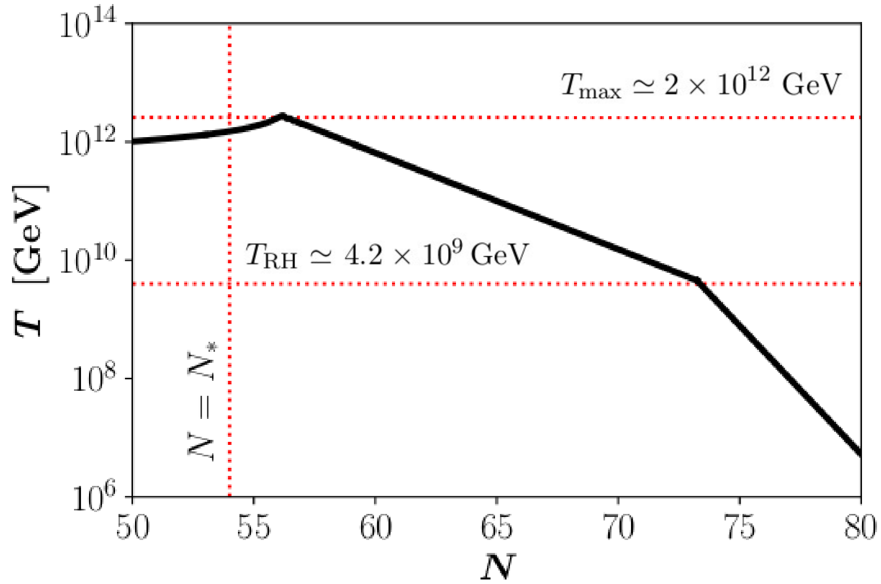

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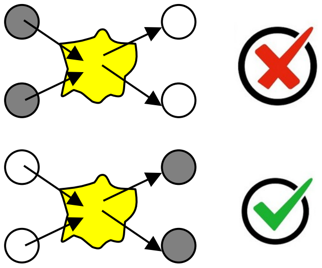

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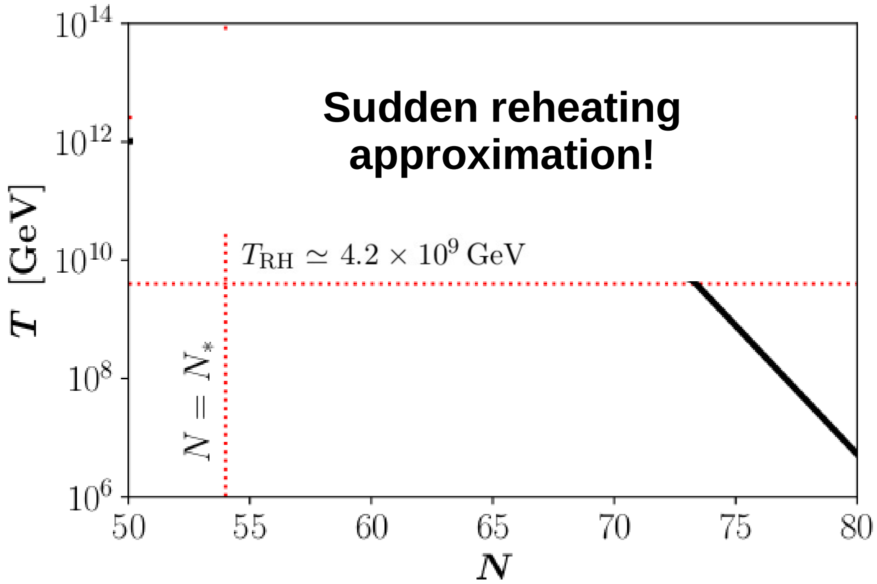

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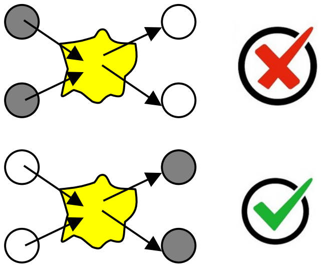

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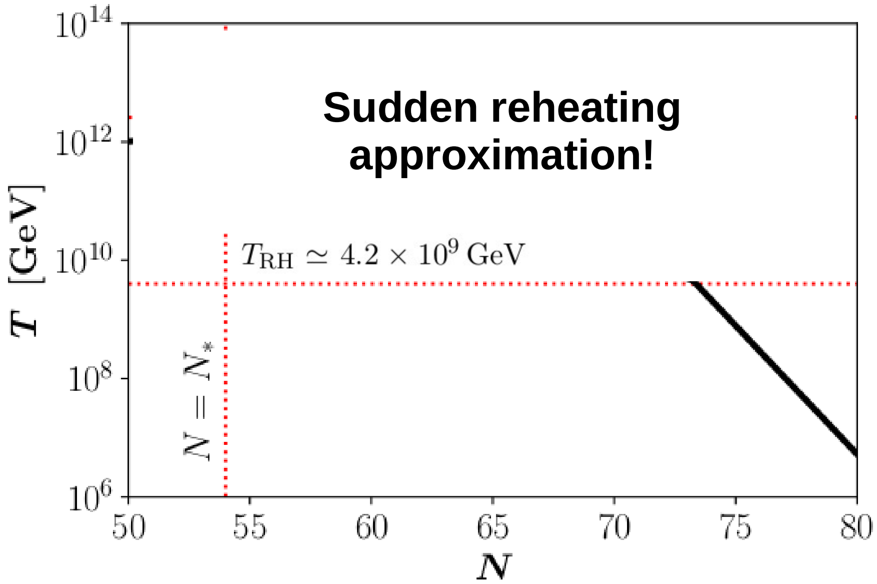

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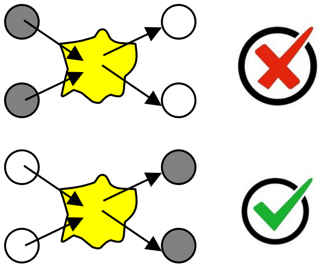

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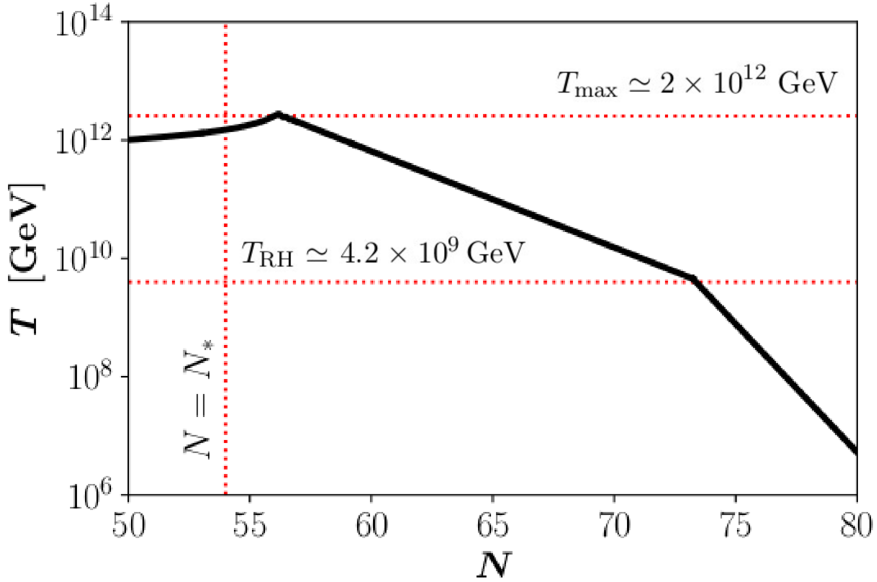

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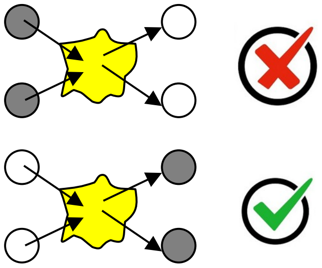

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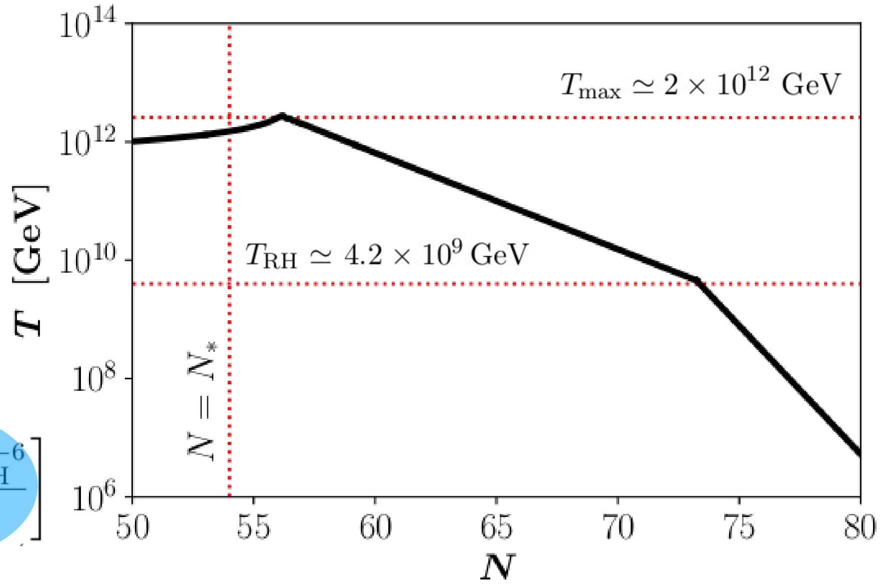

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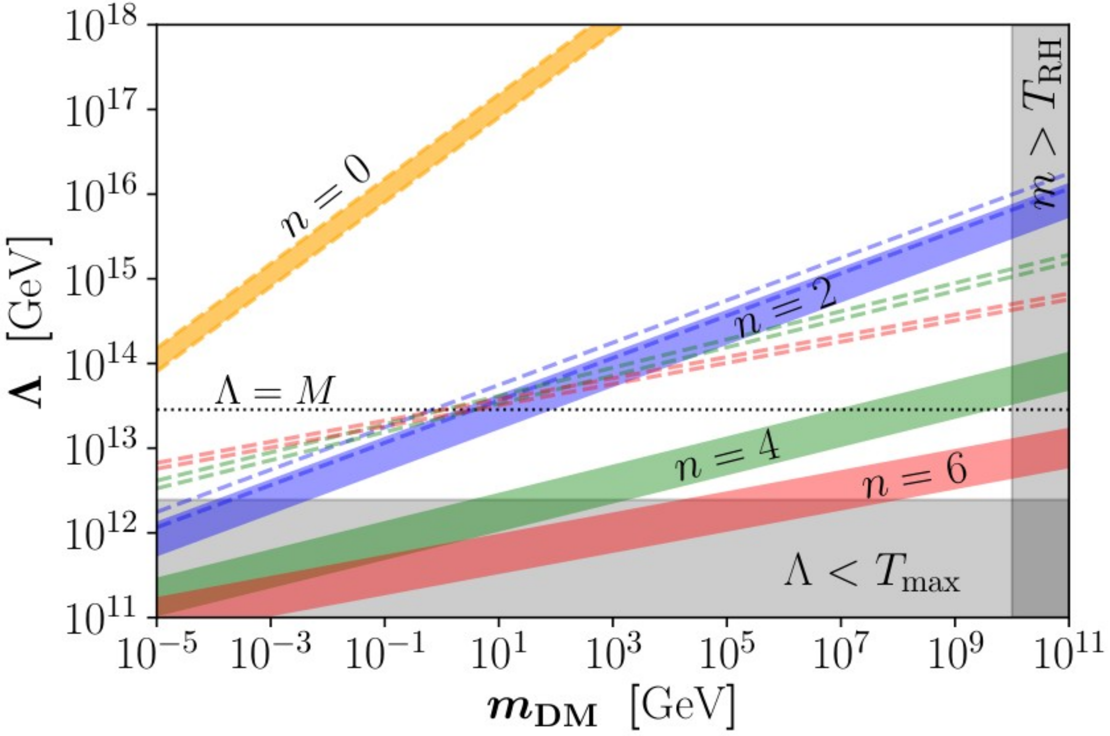

Conclusions

- Starobinsky inflation is in excellent agreement with observations!
- Dark Matter is there: What it is? How was it produced in the Early Universe?
- UV freeze-in is a viable DM production mechanism
- **Strongly depends on the dynamics at the highest temperatures of the Universe**: heating dynamics
- Instantaneous reheating may not be a good approximation
  → miserably fails for $n > n_c$
- Boost factor B

$$B \propto \begin{cases} \mathcal{O}(1) & \text{for } n < n_c \\ \ln\left(\frac{T_{\max}}{T_{\rm rh}}\right) & \text{for } n = n_c \\ \left(\frac{T_{\max}}{T_{\rm rh}}\right)^{n-n_c} & \text{for } n > n_c \end{cases}$$

$$\langle \sigma v \rangle = \frac{T^n}{\Lambda^{2+n}}$$

- For $n > n_c$: Bulk of DM produced near T_{max}
- Big boost factors due to the non-sudden reheating
  → $T_{max} >> T_{rh}$
  → depend on the effective equation of state of the early Universe
  → Bigger boosts for stiffer EoS
  → Bigger boosts if no entropy injection, i.e. no DM dilution

¡Muchas gracias!