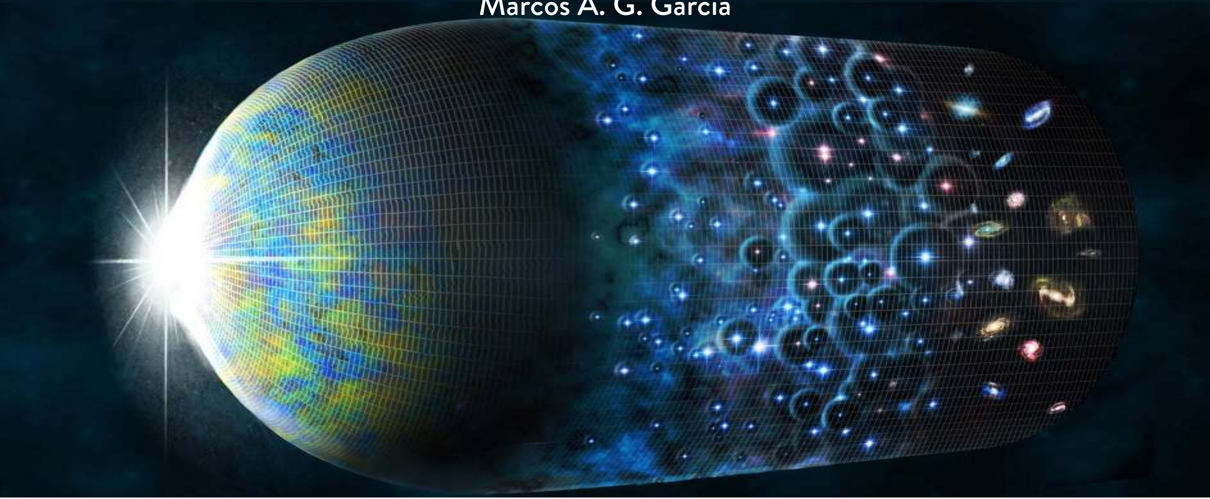
INSTITUTO
DE FÍSICA

Super-Cosmology

Marcos A. G. García

15/10/2021



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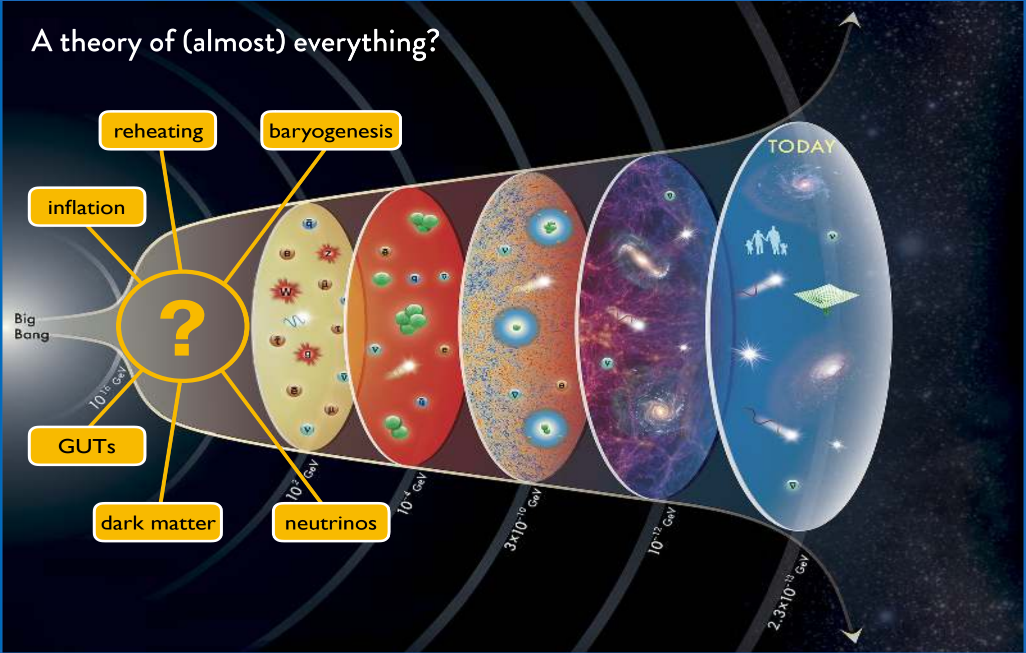
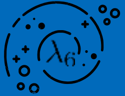
A theory of (almost) everything?

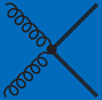


1. No-Scale Inflation

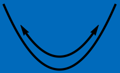
2. Flipped cosmology



3. Heavy gravitinos



4. Preheating



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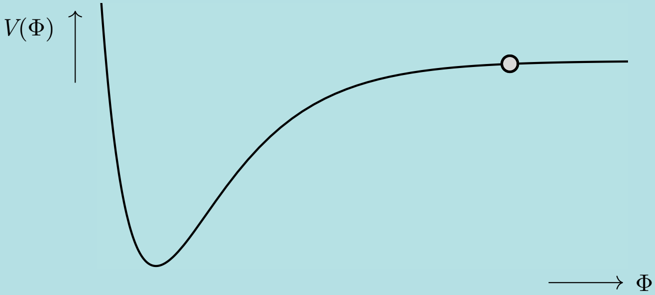
Inflating spacetime

Simplest incarnation: a slowly rolling scalar field in FRW spacetime, $ds^2 = dt^2 - a(t)^2\, d\boldsymbol{x}^2$

$$\begin{aligned} \ddot\Phi + 3H\dot\Phi + V'(\Phi) &= 0 \\ H \equiv \frac{\dot a}{a} &= \left(\frac{\rho_\Phi}{3M_P^2}\right)^{1/2} \end{aligned} \qquad \text{with} \qquad \begin{aligned} \rho_\Phi &= \frac{1}{2}\dot\Phi^2 + V(\Phi) \\ P_\Phi &= \frac{1}{2}\dot\Phi^2 - V(\Phi) \end{aligned}$$



When inflation ends, reheating begins

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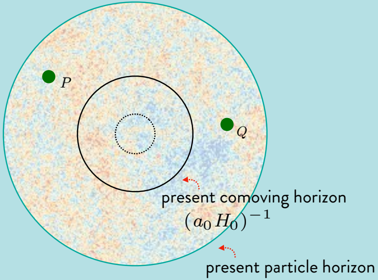
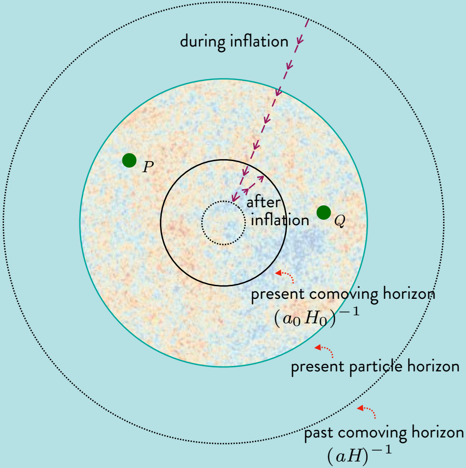
The horizon problem

$\Delta T/T \sim 10^{-5}$ in the CMB

Without inflation



With inflation



Credit: Héctor Ramírez

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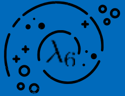

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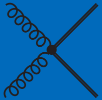

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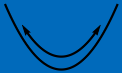
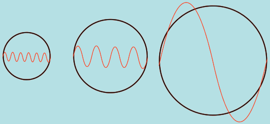
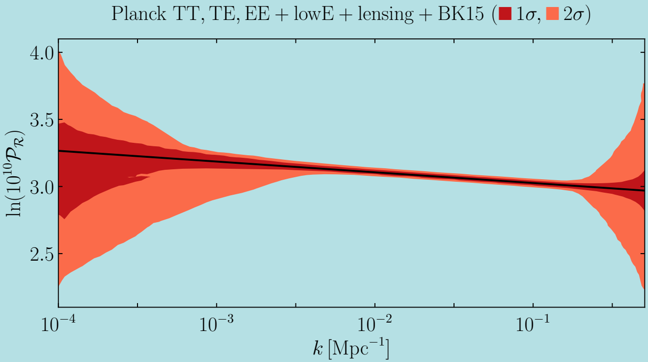


The primordial fluctuations



Quantum fluctuations in Φ, g, are strechted by expansion

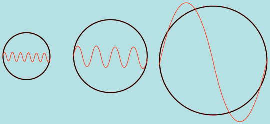


Y. Akrami et al. [Planck], Astron. Astrophys. 641 (2020) A10

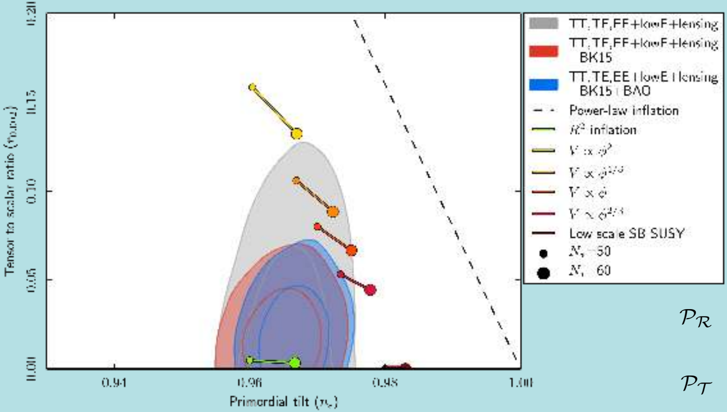
$$\mathcal{P}_\mathcal{R} = \frac{H_*^4}{4\pi^2\dot{\Phi}_*^2}\left(\frac{k}{aH}\right)^{n_s-1}$$

$$\mathcal{P}_\mathcal{T} = \frac{2H_*^2}{\pi^2}\left(\frac{k}{aH}\right)^{n_T}$$

The primordial fluctuations



Quantum fluctuations in Φ, g, are strechted by expansion



$$\mathcal{P}_{\mathcal{R}} = \frac{H_*^4}{4\pi^2\dot{\Phi}_*^2}\left(\frac{k}{aH}\right)^{n_s-1}$$

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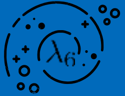

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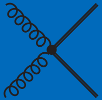

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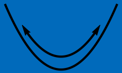


R^2 inflation

Non-minimal GR (singularity-free cosmology)

$$\mathcal{S} \;=\; \frac{1}{2}\int d^4x\sqrt{-g}\left(-R+\frac{R^2}{6m^2}\right)$$

Scalar is hidden! ($\tilde{g} \to \Omega(\phi) g$)

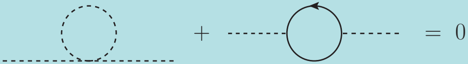
$$\mathcal{S} \;=\; \frac{1}{2}\int d^4x\sqrt{-\tilde{g}}\left[-\tilde{R}+(\partial_\mu\phi)^2-\frac{3}{2}m^2\left(1-e^{\sqrt{2/3}\phi}\right)^2\right]$$

- $\mathcal{P}_\mathcal{R}$ requires $m \simeq 10^{-5}$. What is ϕ then?
- Inflaton traverses trans-Planckian distances: radiative corrections

A cry for supersymmetry?

The only good (super)symmetries are local

- ✓ Supersymmetry → ϕ can be light:



- ✓ Local supersymmetry = supersymmetry + gravity = Supergravity
  - ✓ Couplings determined by just 3 functions!
    - The real Kähler potential $K(\Phi,\bar{\Phi})$
    - The gauge kinetic function $f_{ab}(\Phi)$
    - The holomorphic superpotential $W(\Phi)$
  - ✗ Problems for inflation

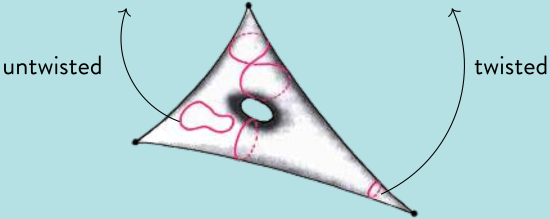
$$V = e^K\left[(K^{-1})_i^j(K^iW+W^i)(K_j\bar{W}+\bar{W}_j)-3|W|^2\right]$$

too steep

$-\mathcal{O}(m_{3/2}^2M_P^2)$ AdS “holes”

No-Scale Inflation

$$K = -3\ln\left[T + \bar{T} - \frac{1}{3}\sum_i |\phi_i|^2\right] + \sum_a \frac{|\varphi_a|^2}{(T + \bar{T})^{n_a}}$$



string orbifold compactification

No-Scale Inflation

$$K = -3\ln\underbrace{\left[T+\bar{T}-\frac{1}{3}\sum_i|\phi_i|^2\right]}_{\text{Pure SU(N,1)/SU(N)}\times\text{U(1)}} + \sum_a \frac{|\varphi_a|^2}{(T+\bar{T})^{n_a}}$$

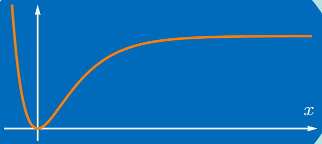
$$W = \sqrt{3}m\phi(T-1/2)$$

$$\mathrm{Re}\ T = \frac{1}{2}e^{\sqrt{2/3}x}$$

$$W = m\left(\frac{\phi^2}{2}-\frac{\phi^3}{3\sqrt{3}}\right)$$

$$\phi = \sqrt{3}\tanh(x/\sqrt{6})$$

$$V = e^{2K/3}|W^i|^2$$



$$W = \sqrt{3}m\phi\left(1+\phi/\sqrt{3}\right)(T-1/2)$$

$$\phi = \sqrt{3}\tanh(x/\sqrt{6})$$

S. Cecotti, PLB 190 (1987), 86

J. Ellis, D. Nanopoulos, K. Olive, PRL 111 (2013) 111301

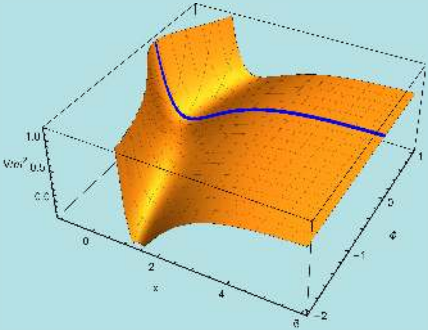
No-Scale Inflation

$$K = \underbrace{-3\ln\left[T+\bar{T}-\frac{1}{3}\sum_i|\phi_i|^2\right]}_{} + \sum_a \frac{|\varphi_a|^2}{(T+\bar{T})^{n_a}}$$

~~Pure~~ SU(N,1)/SU(N)×U(1)

$$W = \sqrt{3}m\phi(T-1/2)$$

$$\mathrm{Re}\ T = \frac{1}{2}e^{\sqrt{2/3}x}$$



need for moduli stabilization

S. Cecotti, PLB 190 (1987), 86

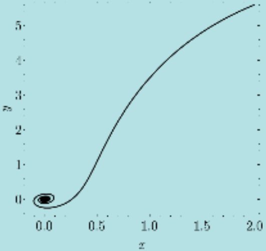
J. Ellis, D. Nanopoulos, K. Olive, PRL 111 (2013) 111301

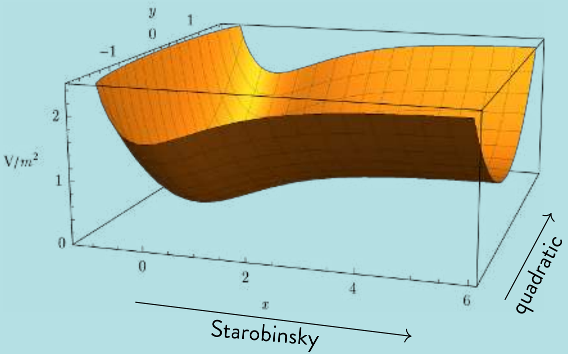
No-Scale Inflation

$$K = -3\ln\left[T + \bar{T} - \frac{1}{3}\sum_i |\phi_i|^2\right] + \underbrace{\sum_a \frac{|\varphi_a|^2}{(T+\bar{T})^{n_a}}}_{n_a \,=\, 3 \text{ twisted matter}}$$

$$W = \sqrt{3}m\varphi(T - 1/2)$$

$$\mathrm{Re}\;T = \frac{1}{2}e^{\sqrt{2/3}x} + \frac{i}{\sqrt{6}}y$$





Starobinsky

quadratic

J. Ellis, MG, D. Nanopoulos and K. Olive, JCAP 08 (2014), 044; JCAP 01 (2015), 010

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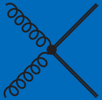

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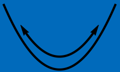

String-inspired GUT embeddings: flipped SU(5)×U(1)

'Regular' SU(5)	Flipped SU(5)×U(1)
$\Psi_i = \mathbf{10}_i \quad \ni \{u^c, Q, e^c\}_i$ $\Phi_i = \bar{\mathbf{5}}_i \quad \ni \{d^c, L\}_i$ $\nu^c_i = \mathbf{1}_i$ $\Sigma = \mathbf{24}$ $h = \mathbf{5}$ $\bar{h} = \bar{\mathbf{5}}$	$F_i = (\mathbf{10}, 1)_i \quad \ni \{d^c, Q, \nu^c\}_i \,,$ $\bar{f}_i = (\bar{\mathbf{5}}, -3)_i \quad \ni \{u^c, L\}_i \,,$ $\ell^c_i = (\mathbf{1}, 5)_i \quad \ni \{e^c\}_i \,,$ $H = (\mathbf{10}, 1) \,,$ $\bar{H} = (\overline{\mathbf{10}}, -1) \,,$ $h = (\mathbf{5}, -2) \,,$ $\bar{h} = (\bar{\mathbf{5}}, 2)$
$SU(5) \xrightarrow{\Sigma} SU(3)_C \times SU(2)_L \times U(1)_Y$ $\xrightarrow{h} SU(3)_C \times U(1)_{\rm EM}$	$SU(5) \times U(1)_X \xrightarrow{H} SU(3)_C \times SU(2)_L \times U(1)_Y$ $\xrightarrow{h} SU(3)_C \times U(1)_{\rm EM}$
$Y = T_{24} = \frac{1}{\sqrt{60}} {\rm diag}(2,2,2,-3,-3)$	$Y = \frac{1}{\sqrt{15}} T_{24} + \frac{1}{5} Q_X$

S. Barr, PLB 112 (1982) 219; J. Derendinger, J. Kim, D. Nanopoulos, PLB 139 (1984) 170

I. Antoniadis, J. Ellis, J. Hagelin, D. Nanopoulos, PLB 208 (1988) 209

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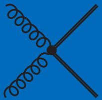

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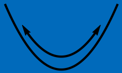

Flipped phenomenology

Superpotential

$$W = \lambda_1^{ij} F_i F_j h + \lambda_2^{ij} F_i \bar{f}_j \bar{h} + \lambda_3^{ij} \bar{f}_i \ell_j^c h + \lambda_4 H H h + \lambda_5 \bar{H}\bar{H}\bar{h}$$
$$+ \lambda_6^{ia} F_i \bar{H} \phi_a + \lambda_7^a h \bar{h} \phi_a + \lambda_8^{abc} \phi_a \phi_b \phi_c + \mu^{ab} \phi_a \phi_b$$

(Partial) Yukawa unification / μ-term

$$W_{\cancel{\text{GUT}}} = y_u h_u Q \bar{u} + y_\nu h_u L \nu^c - y_d h_d Q \bar{d} - y_e h_d L \bar{e} + \mu h_u h_d$$

$\nwarrow \quad \nearrow$ $\qquad\qquad\qquad\qquad\qquad \uparrow$

$\lambda_2 @ M_{\text{GUT}}$ $\qquad\qquad\qquad\qquad\qquad \lambda_7^a \langle \phi_a \rangle$

$\mathbb{Z}_2$ in H: doublet-triplet Higgs splitting

$$HHh \xrightarrow{\cancel{\text{GUT}}} \langle \nu_H^c \rangle d_H^c h_3 \,; \qquad \text{not for } h_{u,d}$$

J. Ellis, MG, N. Nagata, D. Nanopoulos, K. Olive, JCAP 07 (2017), 006; PLB 797 (2019), 134864; JCAP 04 (2019), 009

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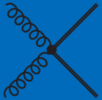

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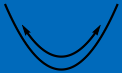
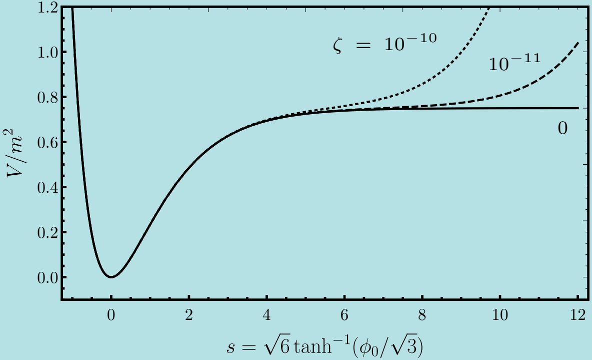


Flipped No-Scale Inflation

Strongly segregated inflaton sector, $\lambda_8^{0ij} \lesssim \mu^{ij}$

$$V = \frac{3}{4}m^2\left(1 - e^{-\sqrt{2/3}s}\right)^2 + \frac{81}{16}\zeta m e^{\sqrt{2/3}s}, \qquad \zeta = \sum_i \mu_{ii}^{-1}(\lambda_8^{00i})^2 + \text{h.c.}$$



1. **No-Scale Inflation**

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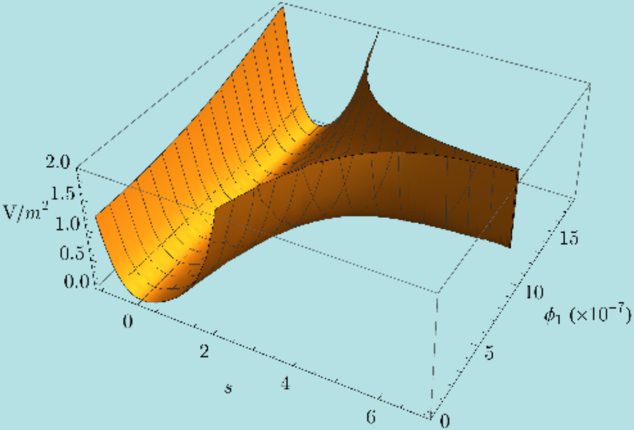
Flipped No-Scale Inflation

Random parameter scan $\mu^{ij} \sim (0.1 - 0.8) M_{\mathrm{GUT}},\ \lambda_8^{0ij}, \lambda_8^{ijk} \sim \pm(0.1 - 1)$



Inflation OK, but mixing during reheating

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The GUT phase transition

SU(5)× U(1) must be broken *after* inflation

$$V = \left(\frac{3g_5^2}{10} + \frac{g_X^2}{80}\right) \underbrace{\left(|\tilde{\nu}^c_H|^2 - |\tilde{\nu}^c_{\bar{H}}|^2\right)^2}_{\substack{\text{GUT broken along flat-direction} \\ \langle \tilde{\nu}^c_H \rangle = \langle \tilde{\nu}^c_{\bar{H}} \rangle \equiv \Phi}} + \frac{1}{8} m^2 e^{\sqrt{2/3}s} |\tilde{\nu}^c_{\bar{H}}|^2 + \cdots$$

The GUT phase transition

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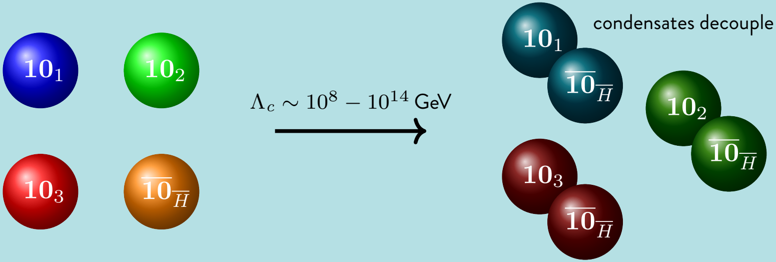
$$V = \left(\frac{3g_5^2}{10} + \frac{g_X^2}{80}\right) \underbrace{\left(|\tilde{\nu}^c_H|^2 - |\tilde{\nu}^c_{\bar{H}}|^2\right)^2}_{\substack{\text{GUT broken along flat-direction} \\ \langle \tilde{\nu}^c_H \rangle = \langle \tilde{\nu}^c_{\bar{H}} \rangle \equiv \Phi}} + \frac{1}{8} m^2 e^{\sqrt{2/3}s} |\tilde{\nu}^c_{\bar{H}}|^2 + \cdots$$

Asymptotic freedom of SU(5) takes care of this! $g^2(\Lambda_c)(C_c - C_1 - C_2) \simeq 4$



condensates decouple

$\Lambda_c \sim 10^8 - 10^{14}$ GeV

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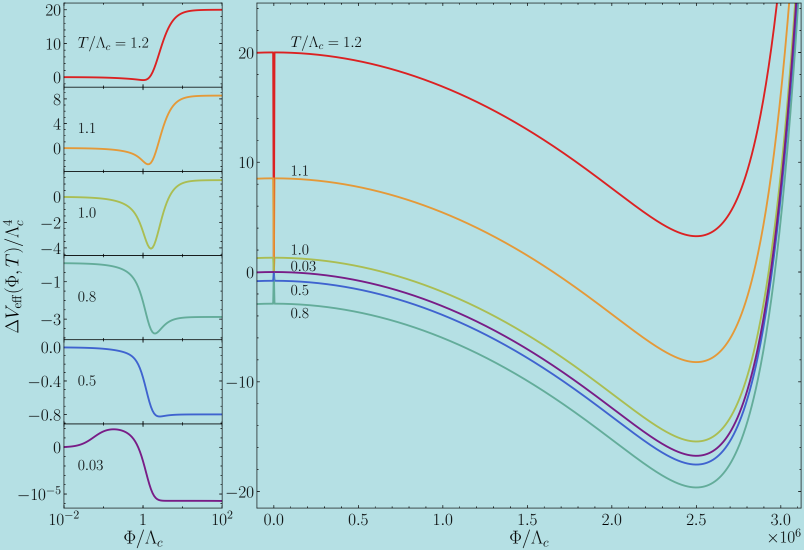

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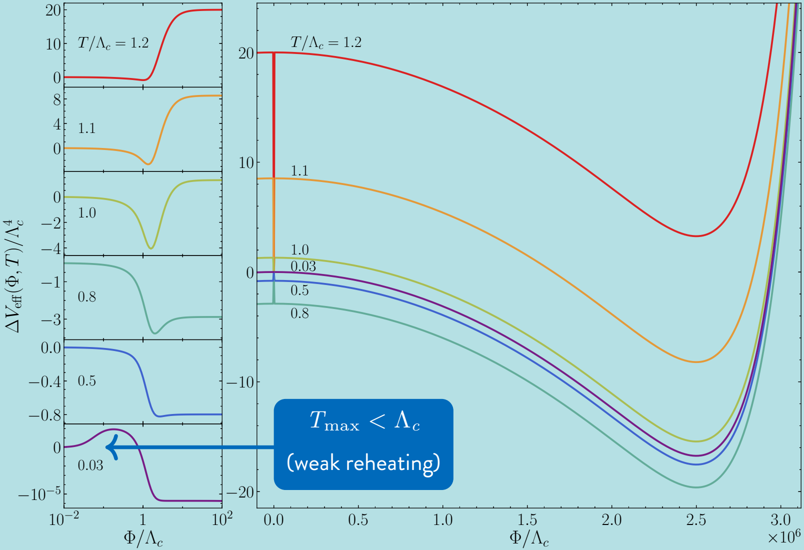

$T_{\rm max} < \Lambda_c$

(weak reheating)

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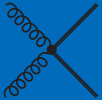

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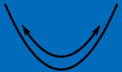
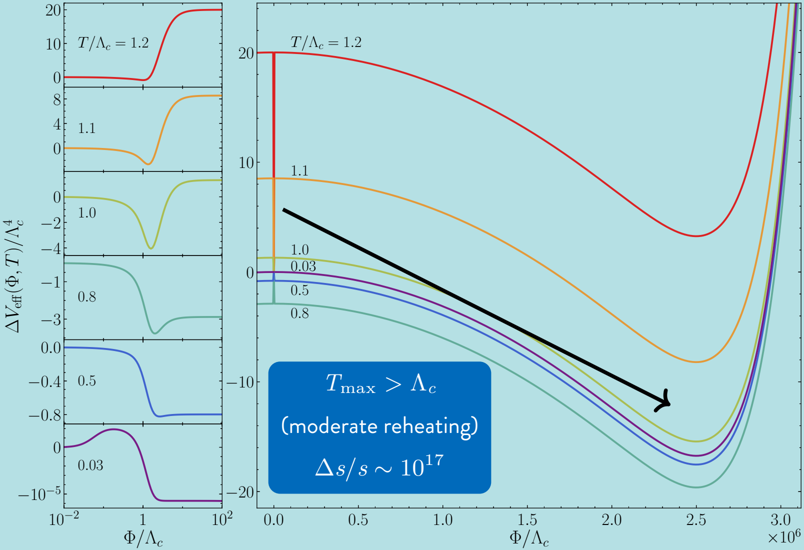


The GUT phase transition



$T_{\rm max} > \Lambda_c$

(moderate reheating)

$\Delta s/s \sim 10^{17}$

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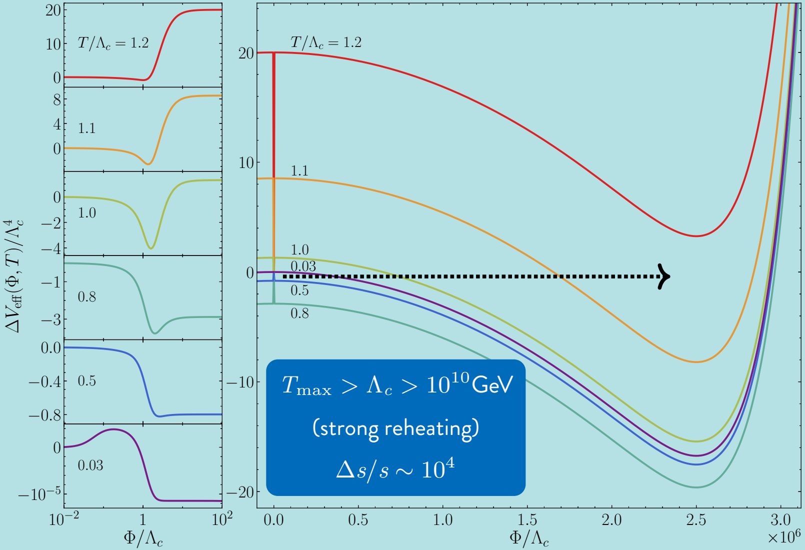
The GUT phase transition



$T_{\rm max} > \Lambda_c > 10^{10}$GeV

(strong reheating)

$\Delta s/s \sim 10^4$

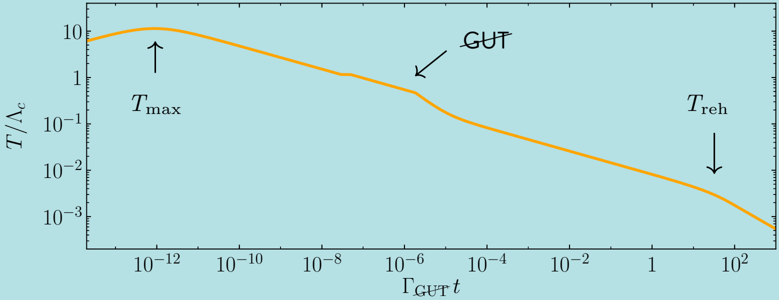
Flipped reheating

Unbroken SU(5)× U(1):

$$\Gamma\left(\phi_0 \to F_i \overline{H}\right) \simeq 10 \times \frac{|\lambda_6^{i0}|^2}{8\pi}\left(1-\frac{\Phi^2}{m^2}\right) m$$

Broken SU(5)×U(1):

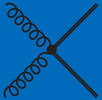
$$\Gamma\left(\phi_0 \to \nu_i^c \Phi\right) \simeq \frac{|\lambda_6^{i0}|^2}{16\pi} m$$



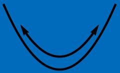
1. No-Scale Inflation

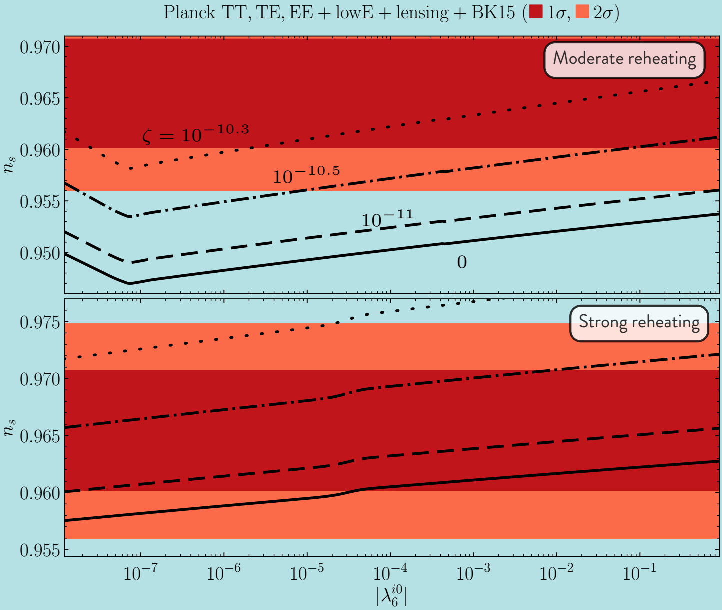
2. Flipped cosmology

3. Heavy gravitinos



4. Preheating





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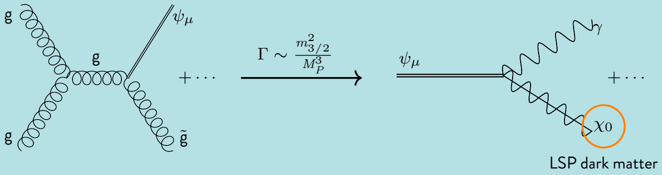
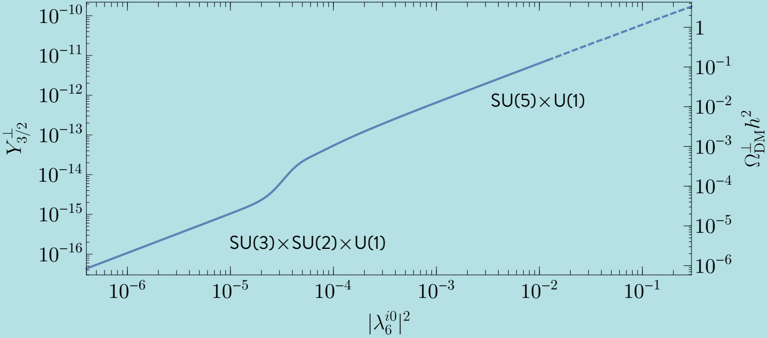
Flipped gravitinos





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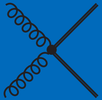

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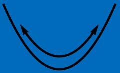

λ_6 also controls neutrino masses...

$$\mathcal{L}_{\rm mass}^{(\nu)} = -\frac{1}{2}\begin{pmatrix}\nu_i & \nu_i^c & \tilde{\phi}_i\end{pmatrix}\begin{pmatrix}0 & \lambda_2^{ij}\langle\bar{h}_0\rangle & 0\\ \lambda_2^{Tij}\langle\bar{h}_0\rangle & 0 & \lambda_6^{ij}\langle\tilde{\nu}^c_{\bar{H}}\rangle \\ 0 & \lambda_6^{Tij}\langle\tilde{\nu}^c_{\bar{H}}\rangle & 2\mu^{ij}\end{pmatrix}\begin{pmatrix}\nu_j\\ \nu_j^c\\ \tilde{\phi}_j\end{pmatrix} + \text{h.c.}$$

$$\Big\Downarrow\ \tilde{\phi}_i = \tilde{\phi}_0$$

$$m_{\nu_i} \simeq \frac{m\,|\lambda_2^{ii}\langle\bar{h}_0\rangle|^2}{|\lambda_6^{i0}\langle\tilde{\nu}^c_{\bar{H}}\rangle|^2} \simeq \frac{m\,m^2_{u,c,t}}{|\lambda_6^{i0}|^2\,M^2_{\mathsf{GUT}}}$$

Random parameter scan $10^{-4} < |\lambda_6^{10}| < 1$

	Normal Ordering		Inverted Ordering	
	Best fit	3σ range	Best fit	3σ range
Δm^2_{21} $[10^{-5}$ eV$^2]$	7.39	6.79 – 8.01	7.39	6.79 – 8.01
$\Delta m^2_{3\ell}$ $[10^{-3}$ eV$^2]$	2.525	2.431–2.622	−2.512	−(2.413–2.606)

1. No-Scale Inflation

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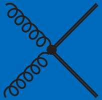

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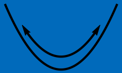
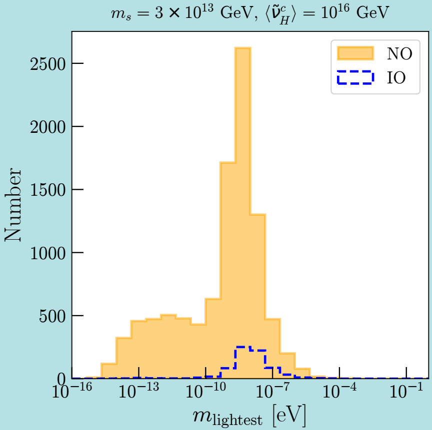
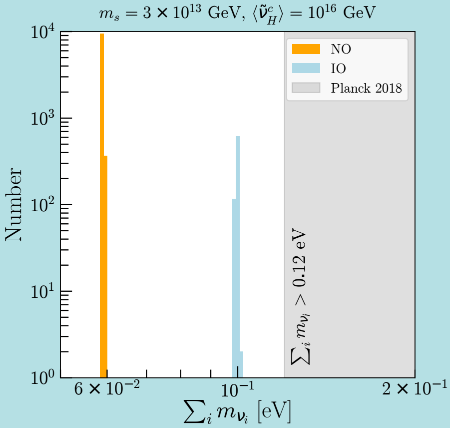


λ_6 also controls neutrino masses…





J. Ellis, MG, N. Nagata, D. Nanopoulos, K. Olive, JCAP 01 (2020), 035; JHEP 05 (2020), 021

1. No-Scale Inflation

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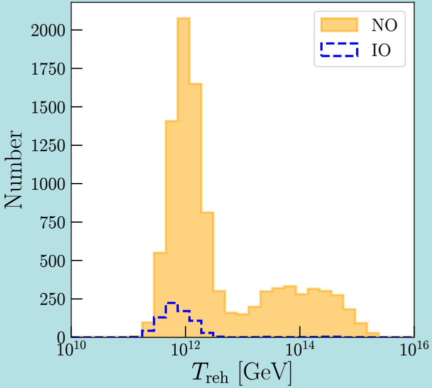
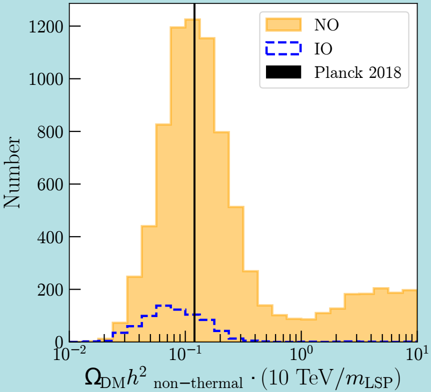
… the dark matter abundance …



$m_s = 3 \times 10^{13}$ GeV, $\langle \tilde{\nu}^c_H \rangle = 10^{16}$ GeV, $\Delta = 10^4$



1. No-Scale Inflation

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… the matter-antimatter asymmetry …

Out of equilibrium decay of ν_i^c

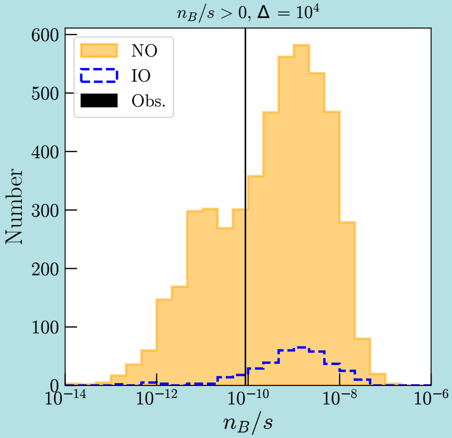
sphaleron conversion

in equilibrium at $T_{\rm reh}$

$$\frac{n_B}{s} = -\frac{28}{79}\left(\frac{s}{\Delta s}\right)\frac{135\zeta(3)}{4\pi^4 g_{\rm reh}}\sum_{i=1,2,3}\epsilon_i$$

Φ-dilution

$$\epsilon_i = \frac{\sum_{j\neq i}\mathrm{Im}\left[\left(U^\dagger_{\nu^c}(\lambda_2^D)^2\,U_{\nu^c}\right)^2_{ji}\right]}{2\pi\left[U^\dagger_{\nu^c}(\lambda_2^D)^2\,U_{\nu^c}\right]_{ii}}\,g\!\left(\frac{m^2_{\nu^c_j}}{m^2_{\nu^c_i}}\right)$$



1. No-Scale Inflation
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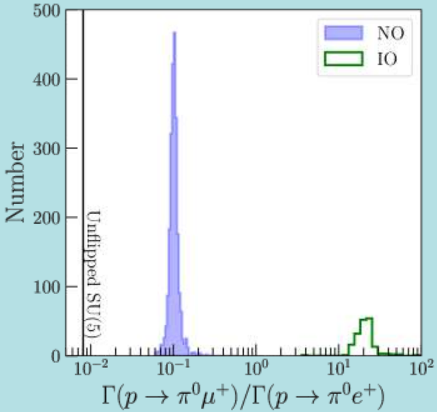
… and proton decay

$$\frac{\Gamma(p \to \pi^0 \mu^+)_{\text{flipped}}}{\Gamma(p \to \pi^0 e^+)_{\text{flipped}}} = \frac{\left(\langle \pi^0 | (ud)_R u_L | p \rangle_\mu\right)^2 |(U_l)_{21}|^2}{\left(\langle \pi^0 | (ud)_R u_L | p \rangle_e\right)^2 |(U_l)_{11}|^2}$$



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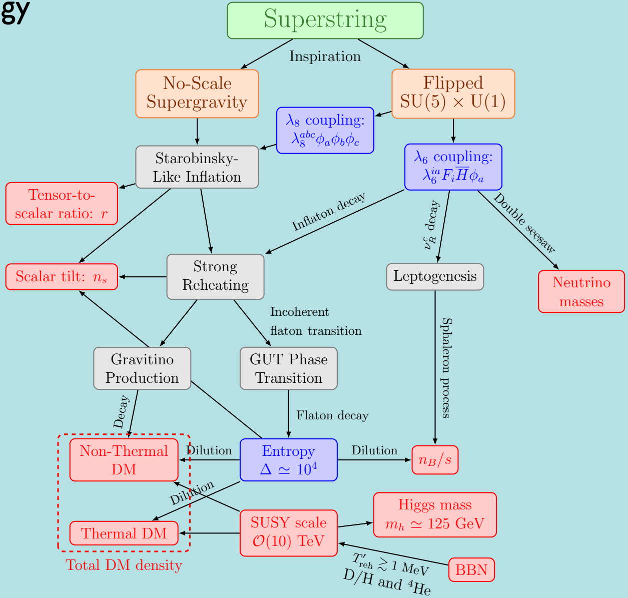
Supercosmology



Superstring

Inspiration

No-Scale Supergravity

Flipped SU(5) × U(1)

λ_8 coupling: $\lambda_8^{abc}\phi_a\phi_b\phi_c$

λ_6 coupling: $\lambda_6^{ia}F_i\overline{H}\phi_a$

Starobinsky-Like Inflation

Tensor-to-scalar ratio: r

Inflaton decay

ν_R^c decay

Double seesaw

Scalar tilt: n_s

Strong Reheating

Leptogenesis

Neutrino masses

Incoherent flaton transition

Sphaleron process

Gravitino Production

GUT Phase Transition

Decay

Flaton decay

Non-Thermal DM

Dilution

Entropy $\Delta \simeq 10^4$

Dilution

n_B/s

Dilution

Thermal DM

SUSY scale $\mathcal{O}(10)$ TeV

Higgs mass $m_h \simeq 125$ GeV

Total DM density

$T'_{\rm reh} \gtrsim 1$ MeV

D/H and ^{4}He

BBN

1. No-Scale Inflation

2. Flipped cosmology

3. Heavy gravitinos

4. Preheating

No-Scale susy breaking

Untwisted gravity mediation

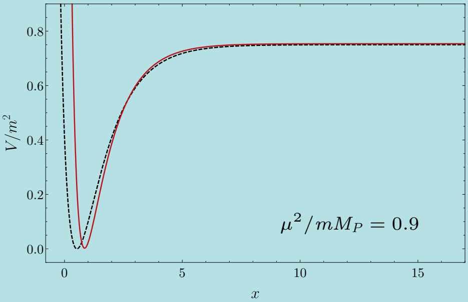
$$K \;=\; -3\ln\left[T+\overline{T}-\frac{1}{3}\sum_i|\phi_i|^2-\frac{1}{3}|z|^2+\frac{|z|^4}{\Lambda^2}\right]$$

Twisted gravity mediation

$$K \;=\; -3\ln\left[T+\overline{T}-\frac{1}{3}\sum_i|\phi_i|^2\right]+|z|^2-\frac{|z|^4}{\Lambda^2}$$

Featuring T-inflation

$$W \;=\; \sqrt{3}m\phi(T-1/2)+\mu^2(z+b)$$



$$\langle z\rangle \propto \Lambda^2\,,\qquad m_{3/2}\;\simeq\;\frac{\mu^2}{\sqrt{3}M_P}\sim \mathrm{EeV}$$

J. Ellis, MG, D. V. Nanopoulos, K. A. Olive, JCAP 10 (2015), 003

E. Dudas, T. Gherghetta, Y. Mambrini, K. A. Olive, PRD 96 (2017), 115032

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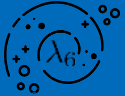

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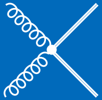

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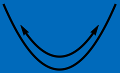
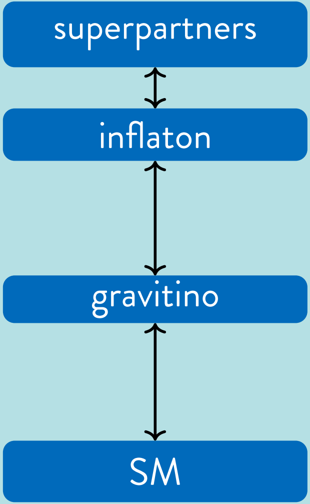


High scale susy breaking



superpartners

inflaton

gravitino

SM

$$M_{\rm susy} = \frac{F}{\Lambda_{\rm mess}} \,, \quad \Lambda_{\rm mess} \geq M_{\rm susy}$$

$$m_{3/2} = \frac{F}{\sqrt{3} M_P} \gtrsim 0.1\,\mathrm{EeV}$$

E. Dudas, Y. Mambrini, K. Olive, PRL 119 (2017), 051801

K. Benakli, Y. Chen, E. Dudas, Y. Mambrini, PRD 95 (2017), 095002

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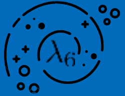

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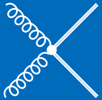

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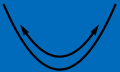
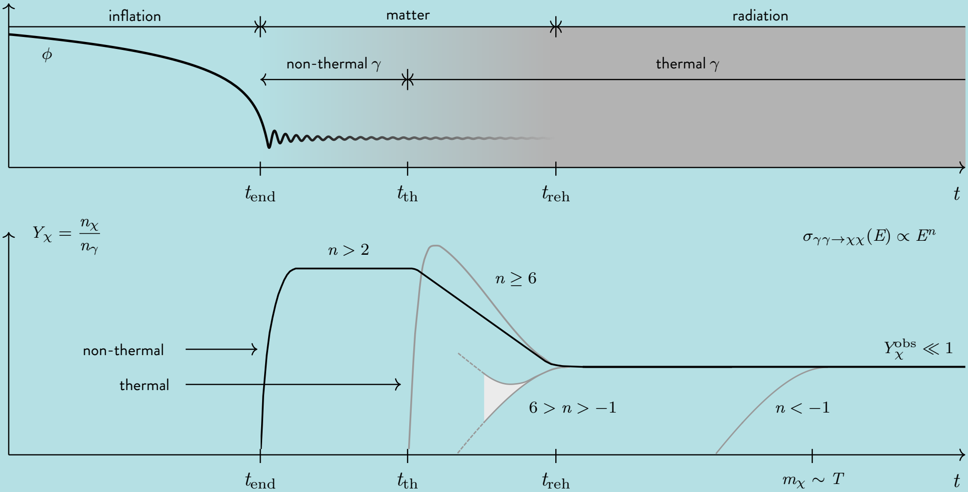


Out-of-equilibrium Dark Matter Production



MG and M. Amin, PRD 98 (2018), 103504

1. **No-Scale Inflation**

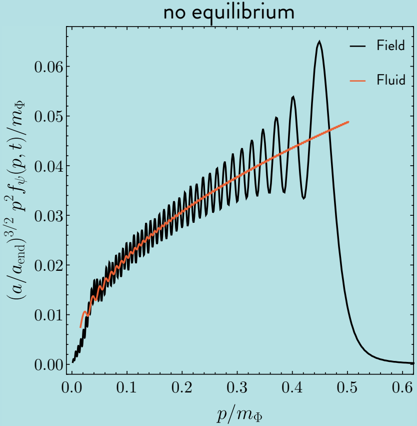
2. **Flipped cosmology**

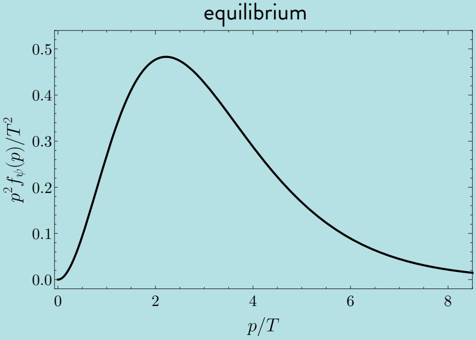
3. **Heavy gravitinos**

4. **Preheating**

The phase space distribution for $\phi \to \bar{\psi}\psi$

$$n_\psi = \int \frac{d^3\boldsymbol{p}}{(2\pi)^3} f_\psi(p,t)$$





1. No-Scale Inflation

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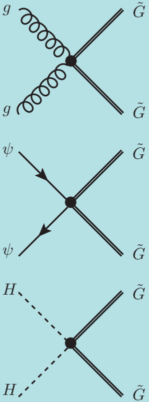
4. Preheating

A heavy gravitino

Leading-order universal Goldstino-matter interactions ($F = \sqrt{3} m_{3/2} M_P$):

$$\mathcal{L}_{2G} = \frac{i}{2F^2}\left(G\sigma^\mu\partial^\nu\bar{G} - \partial^\nu G\sigma^\mu\bar{G}\right)T_{\mu\nu}$$



$$(F_\mu^{\lambda a}F^a_{\nu\lambda})$$

$$(\bar{\psi}\bar{\sigma}_\mu\partial_\nu\psi + \cdots)$$

$$(\partial_\mu H\partial_\nu H^\dagger + \text{h.c.})$$

$$\langle\sigma v\rangle_{\text{NT}} = \frac{154 m_\phi^6}{5(64)^2F^4}$$

$$\langle\sigma v\rangle_{\text{T}} = \frac{6400\pi^{11}T^6}{(945)^2\zeta(3)^2F^4}$$

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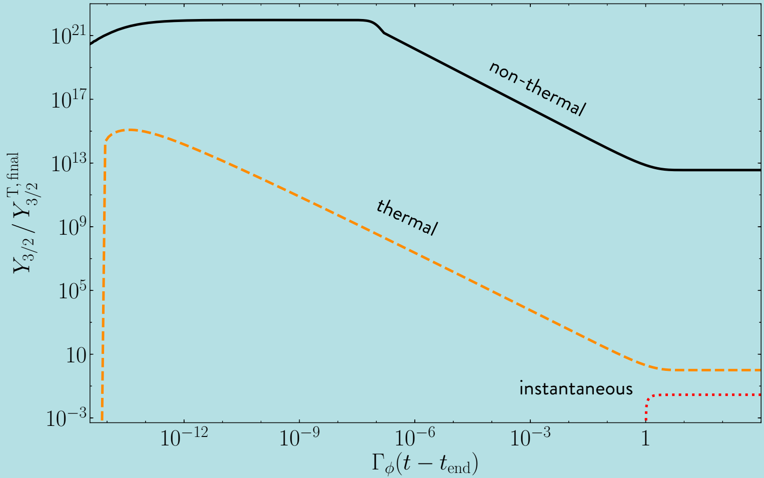
4. Preheating

A heavy gravitino



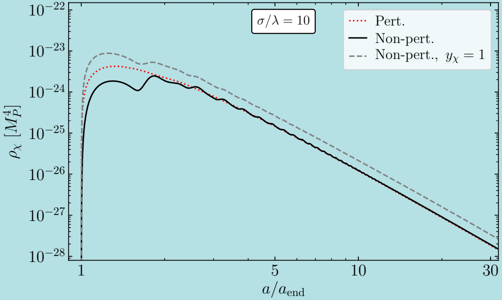
Freeze-in from preheating

Sensitivity to early times = sensitivity to *non-perturbative* dynamics

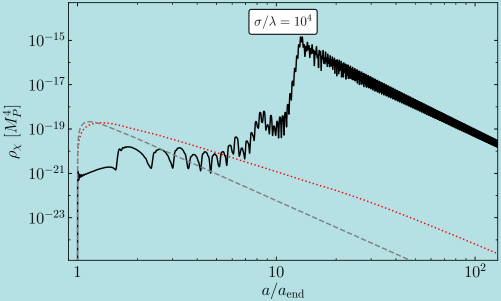
Scalar preheating

$$\mathcal{L} = \frac{1}{2}\sigma\phi^2\chi^2\,, \qquad \Gamma_\chi = \frac{y_\chi^2}{8\pi}m_\chi$$

weak



strong



MG, K. Kaneta, Y. Mambrini, K. Olive, S. Verner, arXiv: 2109.13280 [hep-ph]

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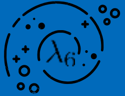
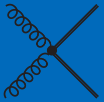


3. **Heavy gravitinos**



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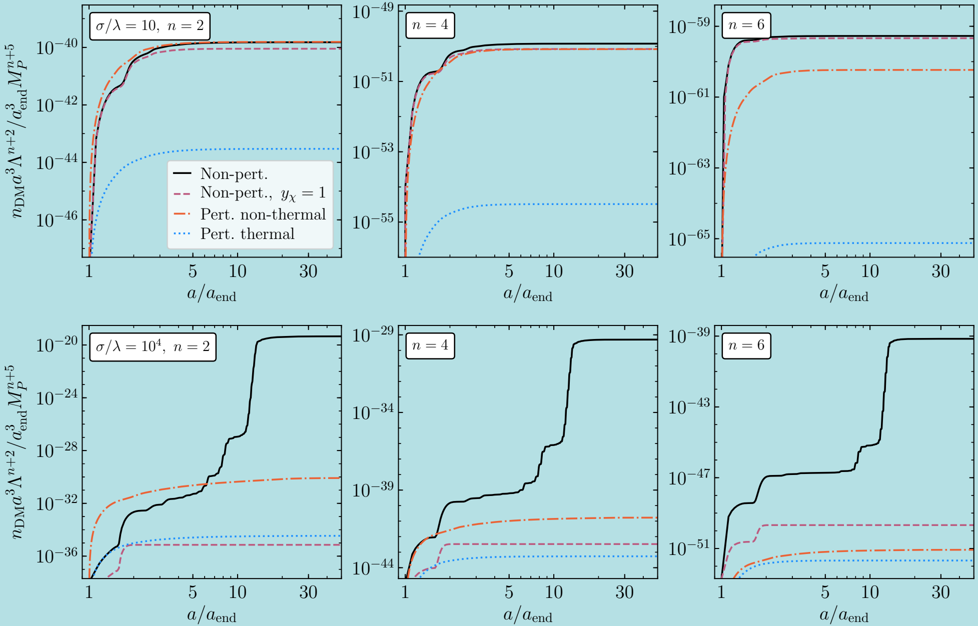

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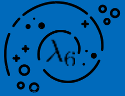

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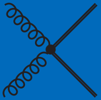


4. Preheating

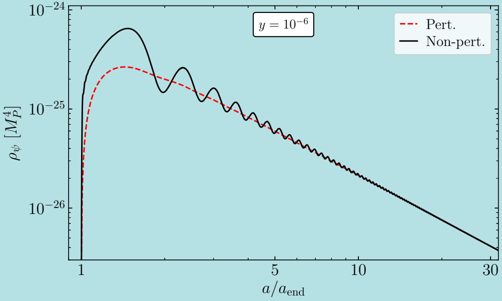
Freeze-in from preheating

Sensitivity to early times = sensitivity to *non-perturbative* dynamics

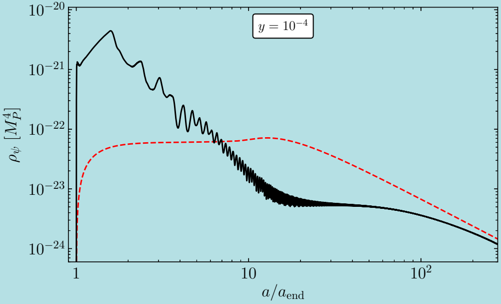
Fermion preheating

$$\mathcal{L} = y\phi\bar{\psi}\psi$$

weak



strong



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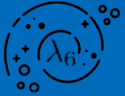

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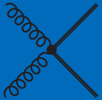

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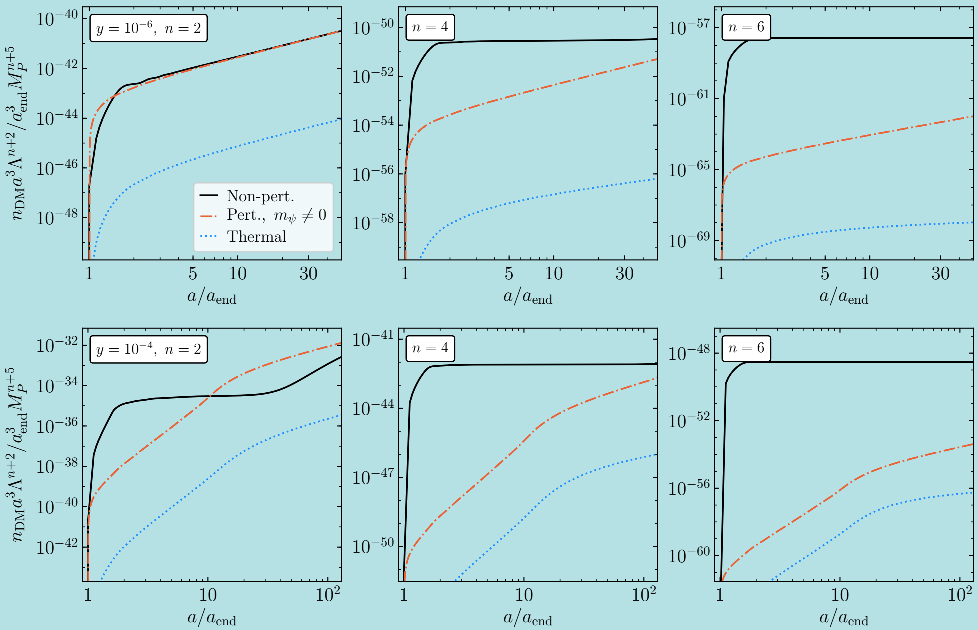

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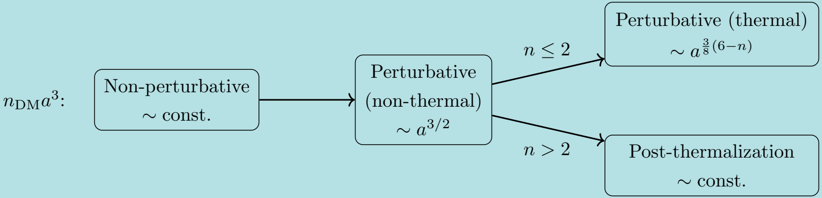
Dark matter from fermion preheating



$n_{\rm DM}a^3$:

Non-perturbative $\sim$ const.

Perturbative (non-thermal) $\sim a^{3/2}$

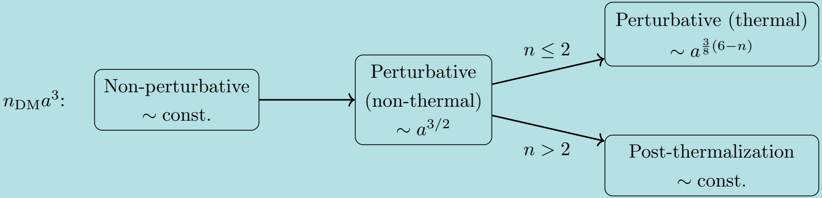
$n \leq 2$

Perturbative (thermal) $\sim a^{\frac{3}{8}(6-n)}$

$n > 2$

Post-thermalization $\sim$ const.

Dark matter from fermion preheating



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¡Gracias!