MultiDark
Multimessenger Approach for Dark Matter Detection

Cosmology with a Master Coupling in Flipped $SU(5) \times U(1)$

Marcos A. G. García

IFT - UAM

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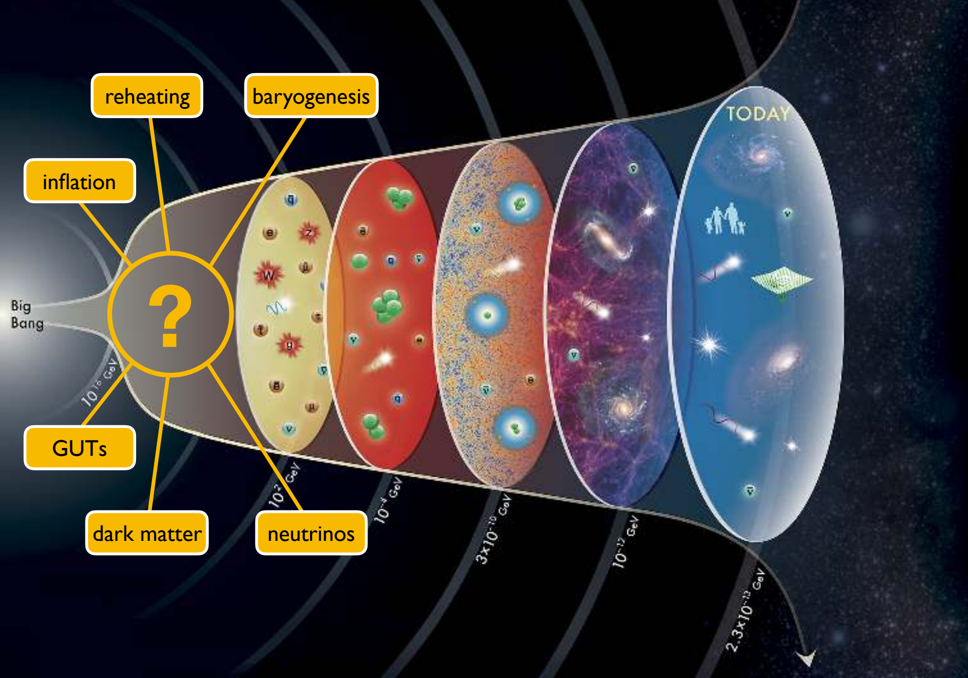
with J. Ellis, D. Nanopoulos, N. Nagata, K. Olive

Instituto de Física Teórica UAM-CSIC

Universidad Autónoma de Madrid

CSIC

Motivation


reheating
baryogenesis
inflation
?
Big
Bang
GUTs
dark matter
neutrinos
TODAY

The GUT of our choice is (supersymmetric) flipped SU(5)×U(1), motivated by strings

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

(Barr, 1982; Derendinger, Kim & Nanopoulos, 1984)

(Antoniadis *et al.*, 1988)

As a susy theory, it is determined by its field content and three functions of chiral (matter) fields:

- The real Kähler potential $K(\Phi, \bar{\Phi})$
- The gauge kinetic function $f_{ab}(\Phi)$
- The holomorphic superpotential $W(\Phi)$

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

$\mathbb{Z}_2$-symmetric $(H \to -H)$ with $\phi_0, \ldots, \phi_3$ singlets.

(Antoniadis, Ellis, Hagelin & Nanopoulos, 1987)

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

- Doublet-triplet SM Higgs splitting: $HHh \xrightarrow{\cancel{\text{GUT}}} \langle \nu_H^c \rangle d_H^c h_3\,;$ not for $h_{u,d}$
- Yukawa unification: $W_{\cancel{\text{GUT}}} = y_u h_u Q \bar{u} + y_\nu h_u L \nu^c - y_d h_d Q \bar{d} - y_e h_d L \bar{e} + \mu h_u h_d$

  $\lambda_2 @ M_{\text{GUT}}$ $\qquad$ $\lambda_7^a \langle \phi_a \rangle$
- Proton decay: $\tau(p \to e^+ \pi^0) = 4.6 \times 10^{35} \times \left(\frac{M_{\text{GUT}}}{10^{16}\,\text{GeV}} \right)^4$ yrs

Consider no-scale SU(N,1)/SU(N)× U(1) supergravity

$$K = -3\ln\left(T + \overline{T} - \frac{1}{3}\sum_i |\Phi_i|^2\right)$$

- It is the EFT of orbifold compactifications of strings (Witten, 1985)
- Global-like potential, $V = e^{2K/3}|W^i|^2$. Minimum at $V = 0$.
- With cubic W, no-scale inflation $\rightarrow$ Starobinsky-like inflation (Ellis *et al.*, 2013)

(Cremmer, Ferrara, Kounnas & Nanopoulos, 1983)

Consider no-scale SU(N,1)/SU(N) × U(1) supergravity

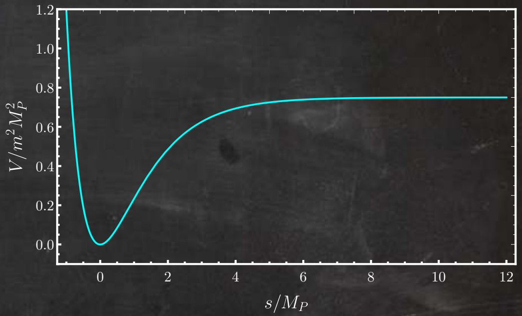
$$K = -3\ln\left(T + \bar{T} - \frac{1}{3}\sum_i |\Phi_i|^2\right)$$

Diagonal μ, λ_8,

$$\mu^{00} = \frac{m}{2}\,, \qquad \lambda_8^{000} = -\frac{m}{3\sqrt{3}M_P}$$

then with
$s \equiv \sqrt{6}M_P \tanh^{-1}(\phi_0/\sqrt{3}M_P)$

$$V = \frac{3}{4}m^2 M_P^2\left(1 - e^{-\sqrt{2/3}s/M_P}\right)^2$$



$m \simeq 3 \times 10^{13}$ GeV

Consider no-scale SU(N,1)/SU(N) $\times$ U(1) supergravity

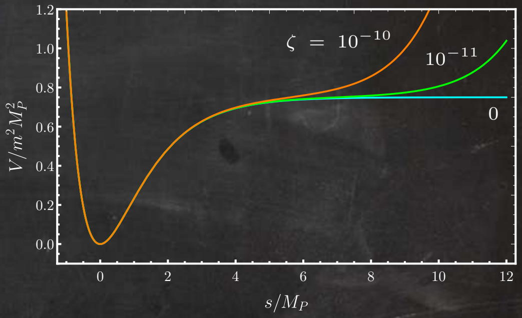
$$K = -3\ln\left(T+\overline{T}-\frac{1}{3}\sum_i|\Phi_i|^2\right)$$

Non-diagonal μ, λ_8,

$$\mu^{00}=\frac{m}{2}\,,\qquad \lambda_8^{000}=-\frac{m}{3\sqrt{3}M_P}$$

then with
$s\equiv\sqrt{6}M_P\tanh^{-1}(\phi_0/\sqrt{3}M_P)$

$$V=\frac{3}{4}m^2M_P^2\left(1-e^{-\sqrt{2/3}s/M_P}\right)^2+\frac{81}{16}\zeta mM_P^3e^{\sqrt{2/3}s/M_P}$$



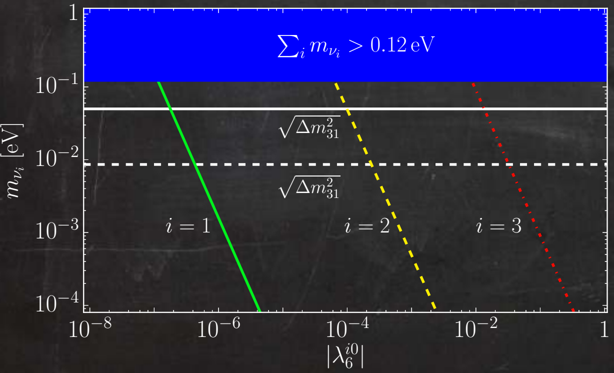
$$\zeta = \sum_i(M_P/\mu_{ii})(\lambda_8^{00i})^2+\text{h.c.}$$

Three singlets couple to neutrino sector

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

Three singlets couple to neutrino sector

$$\mathcal{L}^{(\nu)}_{\rm mass} = -\frac{1}{2}\begin{pmatrix}\nu_i & \nu_i^c & \tilde{\phi}_0\end{pmatrix}\begin{pmatrix} 0 & \lambda_2^{ii}\langle\bar{h}_0\rangle & 0 \\ \lambda_2^{ii}\langle\bar{h}_0\rangle & 0 & \lambda_6^{i0}\langle\tilde{\nu}^c_{\bar{H}}\rangle \\ 0 & \lambda_6^{i0}\langle\tilde{\nu}^c_{\bar{H}}\rangle & m \end{pmatrix}\begin{pmatrix}\nu_i \\ \nu_i^c \\ \tilde{\phi}_0\end{pmatrix} + \text{h.c.}$$



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

Potential for H singlets

$$V = \left(\frac{3g_5^2}{10} + \frac{g_X^2}{80}\right) \underbrace{\left(|\tilde{\nu}^c_H|^2 - |\tilde{\nu}^c_{\bar{H}}|^2\right)^2}_{\text{GUT broken along flat-direction}}$$

GUT broken along flat-direction

$$\langle \tilde{\nu}^c_H \rangle = \langle \tilde{\nu}^c_{\bar{H}} \rangle \equiv \Phi$$

Potential for H singlets

$$V = \left(\frac{3g_5^2}{10} + \frac{g_X^2}{80}\right) \underbrace{\left(|\tilde{\nu}_H^c|^2 - |\tilde{\nu}_{\bar{H}}^c|^2\right)^2}_{} + \frac{1}{8} m^2 e^{\sqrt{2/3}s} |\tilde{\nu}_{\bar{H}}^c|^2 + \cdots$$

GUT broken along flat-direction

$$\langle \tilde{\nu}_H^c \rangle = \langle \tilde{\nu}_{\bar{H}}^c \rangle \equiv \Phi$$

$\Rightarrow$ SU(5)$\times$ U(1) broken *after* inflation

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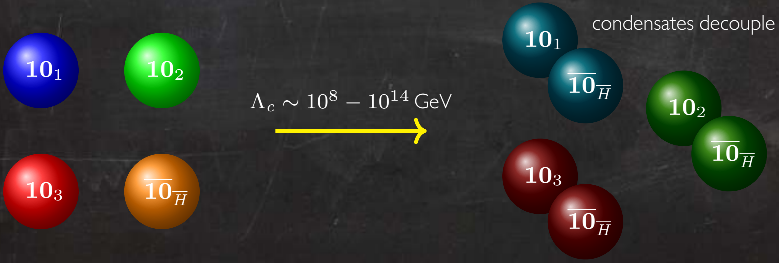
GUT broken along flat-direction

$$\langle \tilde{\nu}_H^c \rangle = \langle \tilde{\nu}_{\overline{H}}^c \rangle \equiv \Phi$$

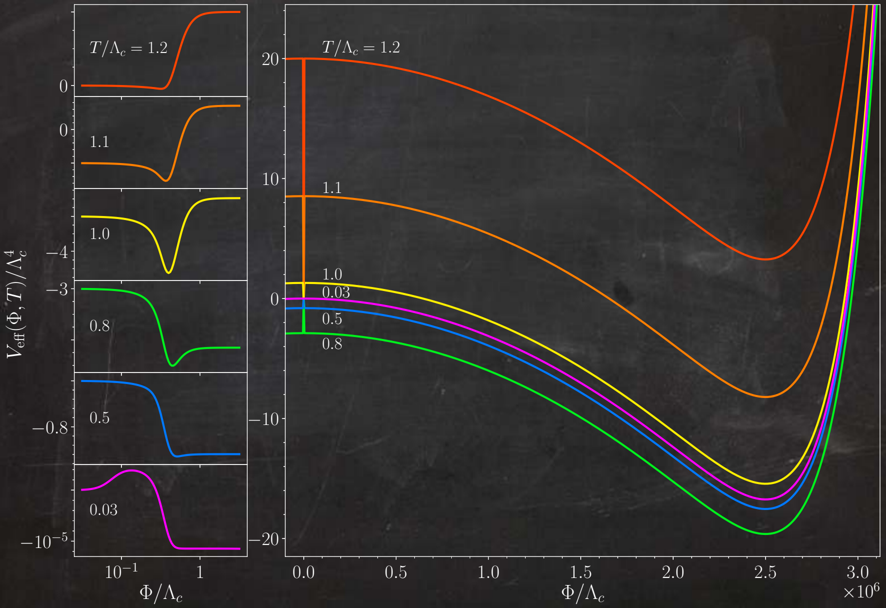
$\Rightarrow$ SU(5)× U(1) broken *after* inflation

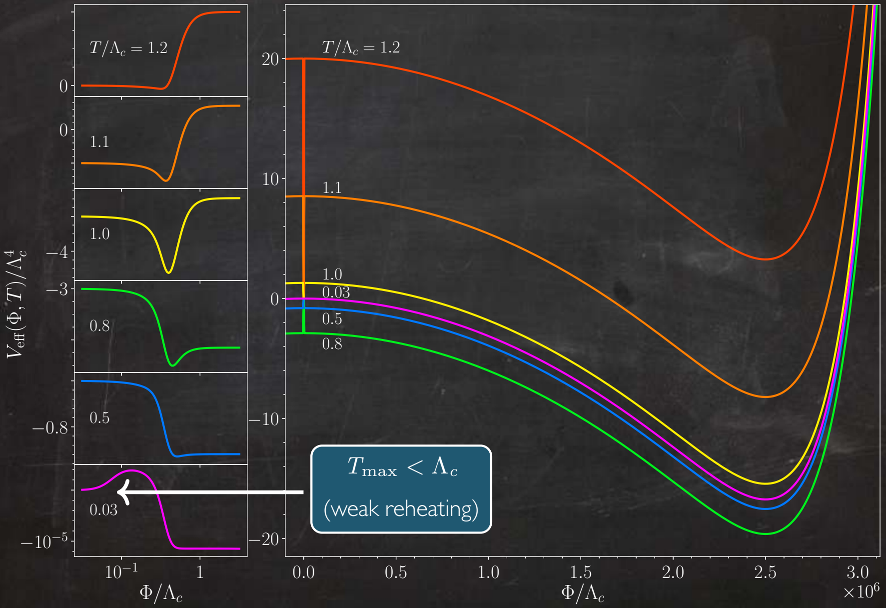
Asymptotic freedom of SU(5) takes care of this! $g^2(\Lambda_c)(C_c - C_1 - C_2) \simeq 4$



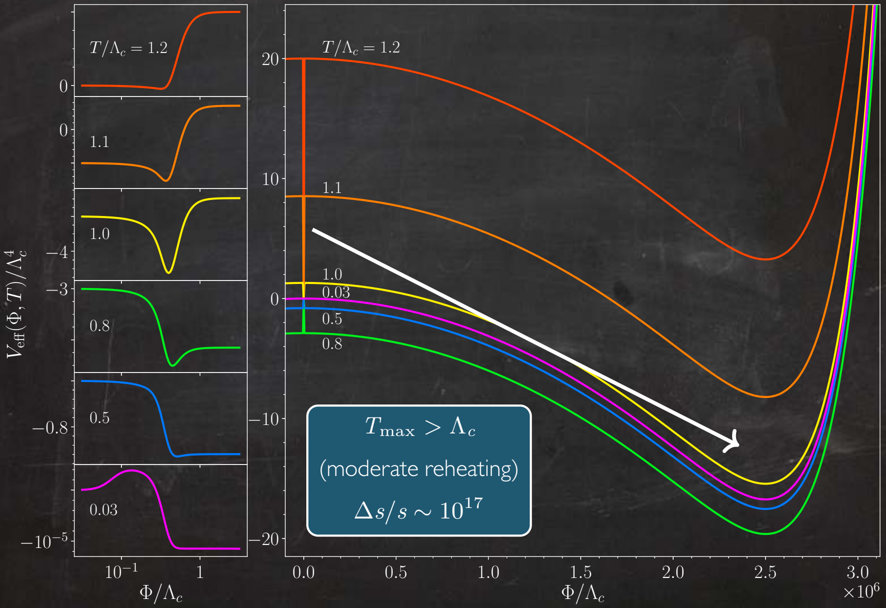
(Kogut, 1983; Campbell, Ellis, Hagelin, Nanopoulos & Olive, 1987)

The GUT phase transition

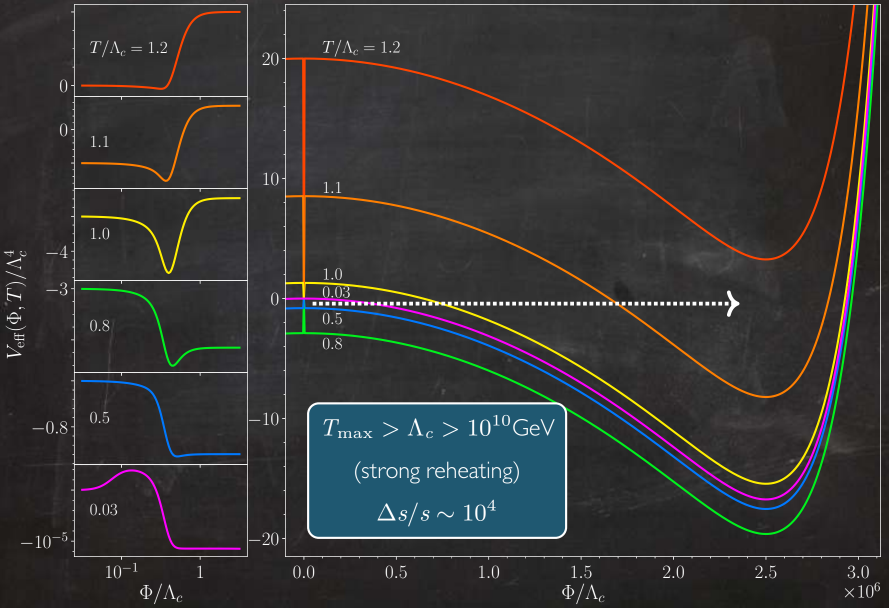




$V_{\rm eff}(\Phi,T)/\Lambda_c^4$
$T/\Lambda_c = 1.2$
1.1
1.0
0.8
0.5
0.03
0.03
0
0
-4
-3
-0.8
-10^{-5}
10^{-1}
1
Φ/Λ_c
20
10
0
-10
-20
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$\times 10^6$
Φ/Λ_c
$T_{\rm max} < \Lambda_c$
(weak reheating)



$T/\Lambda_c = 1.2$
1.1
1.0
0.8
0.5
0.03
$V_{\rm eff}(\Phi,T)/\Lambda_c^4$
0
0
-4
-3
-0.8
-10^{-5}
10^{-1}
1
Φ/Λ_c
$T/\Lambda_c = 1.2$
1.1
1.0
0.03
0.5
0.8
20
10
0
-10
-20
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$\times 10^6$
Φ/Λ_c
$T_{\rm max} > \Lambda_c$
(moderate reheating)
$\Delta s/s \sim 10^{17}$



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

(strong reheating)

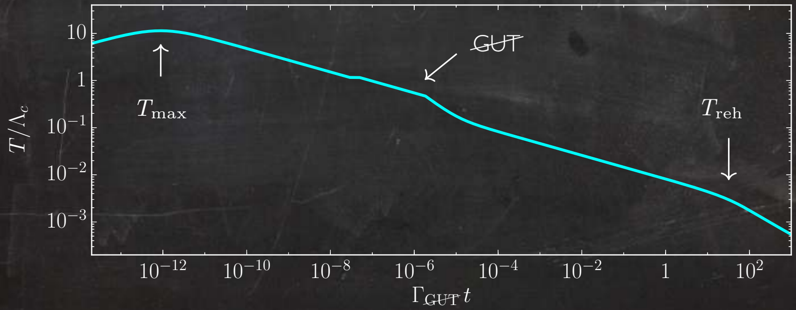
$\Delta s/s \sim 10^4$

Unbroken SU(5)× U(1):

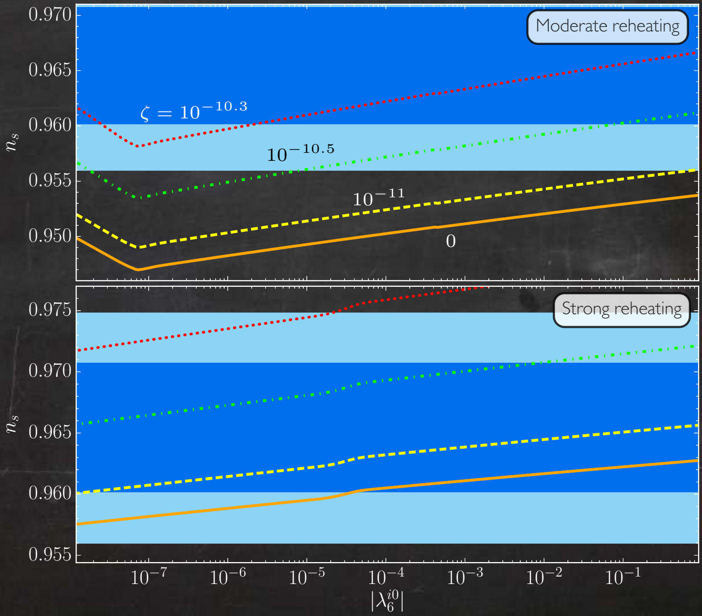
$$\Gamma\left(\phi_0 \to F_i \overline{H}\right) \simeq 10 \times \frac{|\lambda_6^{i0}|^2}{8\pi}\left(1 - \frac{\Phi^2}{m^2}\right) m$$

Broken SU(5)×U(1):

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



(segregated inflaton)


Moderate reheating
Strong reheating
$\zeta = 10^{-10.3}$
$10^{-10.5}$
10^{-11}
0
n_s
0.970
0.965
0.960
0.955
0.950
0.975
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
$|\lambda_6^{i0}|$

For $|\lambda_6^{i0}|^2 \gtrsim 10^{-5}$, SU(5)×U(1) broken after reheating

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

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

For $|\lambda_6^{i0}|^2 \gtrsim 10^{-5}$, SU(5)×U(1) broken after reheating

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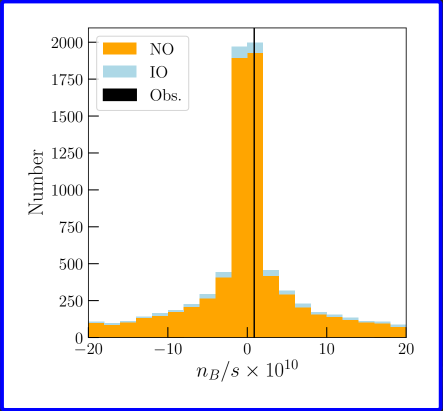
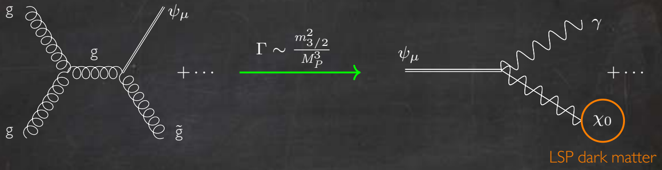
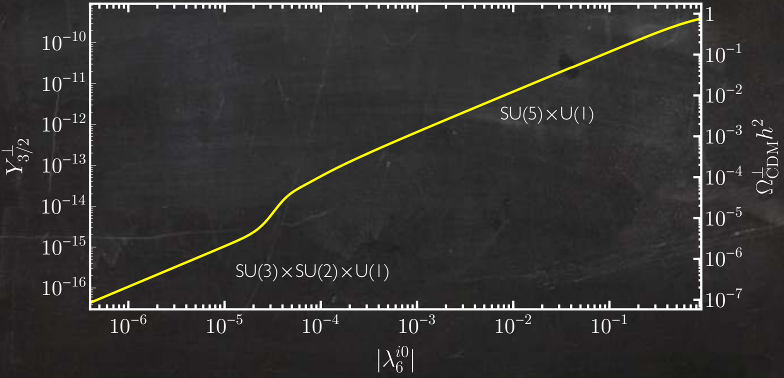
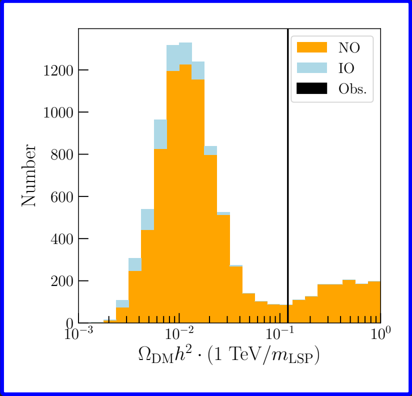


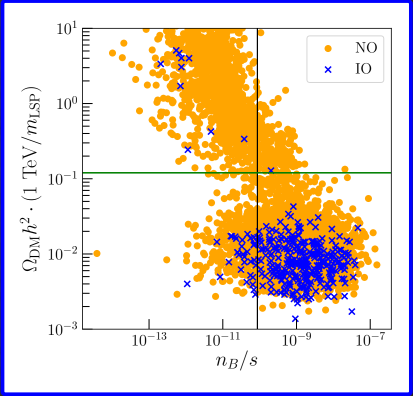
Random parameter scan $10^{-4} < |\lambda_6^{i0}| < 1$

Light gravitino produced in thermalized plasma



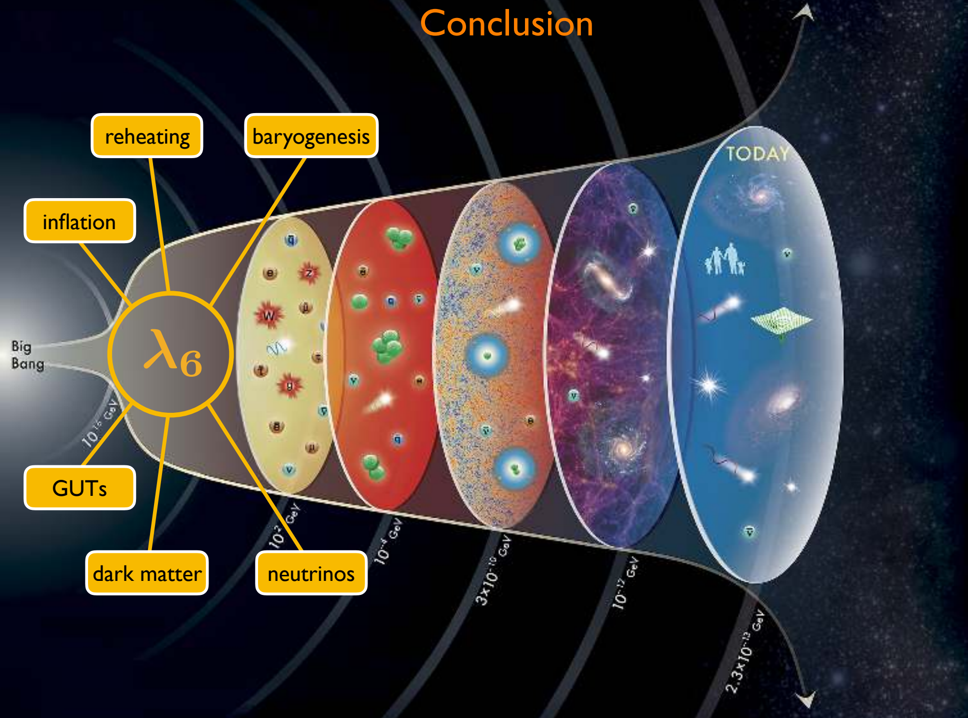






$T_{\rm reh} \sim 10^{12} - 10^{14}$ GeV favoured

Conclusion


reheating
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λ_6
GUTs
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Big Bang
TODAY
10^{16} GeV
10^{2} GeV
10^{-4} GeV
3×10^{-10} GeV
10^{-12} GeV
2.3×10^{-13} GeV