Thermal inflation, gravitational waves, baryogenesis and dark matter

Wan-Il Park

KAIST

27 October 2008, Fermi National Laboratory

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Gary N Felder, Hyunbyuk Kim, WIP, Ewan Stewart	hep-ph/0703275
Richard Easther, John T Giblin, Eugene A Lim, WIP, Ewan Stewart	arXiv:0801.4197
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Moduli (fields with Planckian expectation values) are cosmologically dangerous. For example, nucleosynthesis constrains

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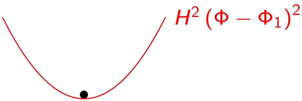

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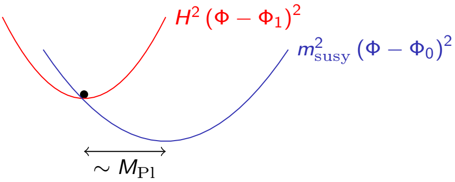

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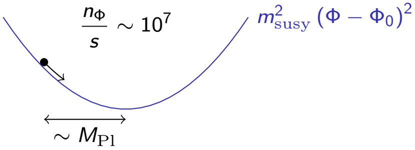

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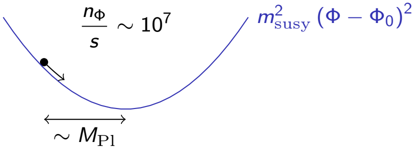

Moduli generated: $H \lesssim m_{\mathrm{susy}}$

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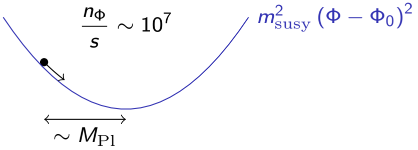

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slow-roll inflation: $H \gtrsim m_{\rm inflaton} \gtrsim m_{\rm susy}$

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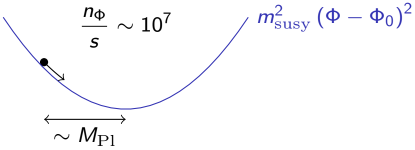
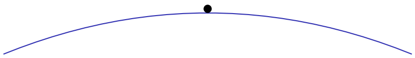


Moduli generated: $H \lesssim m_{\rm susy}$

after

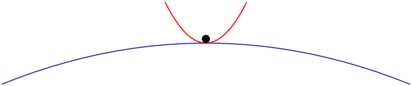
slow-roll inflation: $H \gtrsim m_{\rm inflaton} \gtrsim m_{\rm susy}$

Thermal inflation



$$V = V_0 \qquad - m^2|\phi|^2 + \ldots$$

Thermal inflation



$$V = V_0 + g^2 T^2 |\phi|^2 - m^2 |\phi|^2 + \dots$$

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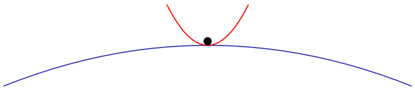

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Inflation for

$$V_0^{1/4} \gtrsim T \gtrsim m$$

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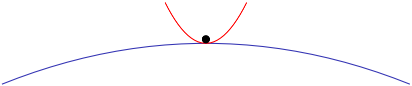

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$T \propto e^{-N}$ so few e-folds

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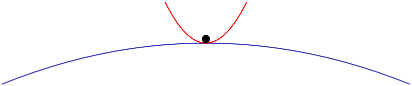

If

$$V_0^{1/4} \sim 10^6 \text{ to } 10^7\,\mathrm{GeV}$$

which for $V_0 \sim m^2\phi_0^2$ corresponds to

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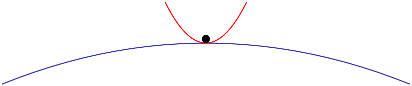

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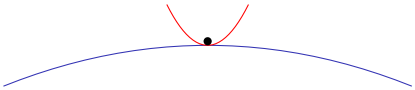

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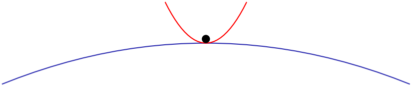

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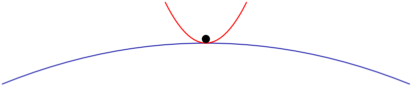

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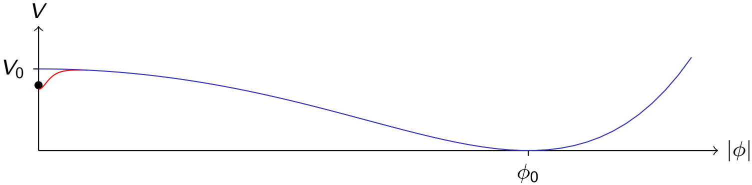
- dilution factor $\sim 10^{20}$: pre-existing moduli sufficiently diluted,
- $H \sim 10^{-8} m$: moduli regenerated with sufficiently small abundance,
- $N \sim 10$: primordial perturbations from slow-roll inflation preserved on large scales,
- $H \sim 1 \text{ to } 10\,\mathrm{keV}$: primordial gravitational waves wiped out on solar system scales.

First order phase transition



First order phase transition since $\phi_0 \gg T_\mathrm{c} \sim m$.

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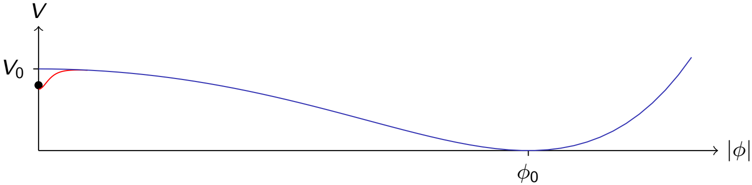

First order phase transition since $\phi_0 \gg T_\mathrm{c} \sim m$. Typical bubble size

$$\frac{\Gamma}{\dot{\Gamma}} \sim \left(10^{-3} \text{ to } 10^{-5}\right) \frac{1}{H} \sim \left(10^{5} \text{ to } 10^{3}\right) \frac{1}{m}$$

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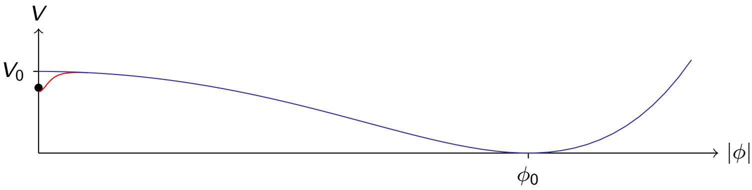

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Gravitational waves generated with frequency

$$f \sim 10\,\mathrm{Hz} \left(\frac{\dot{\Gamma}/H\Gamma}{10^4}\right) \left(\frac{V_0^{1/4}}{10^{6.5}\,\mathrm{GeV}}\right)^{2/3} \left(\frac{T_\mathrm{d}}{10\,\mathrm{GeV}}\right)^{1/3} \left(\frac{V_0 a_\mathrm{c}^3/\rho_\mathrm{d} a_\mathrm{d}^3}{10}\right)^{1/3}$$

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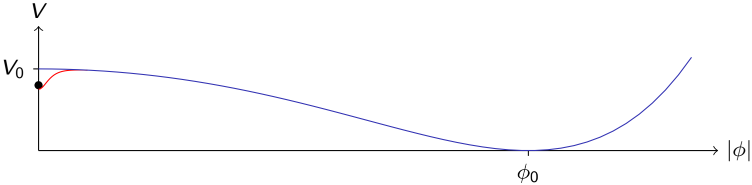

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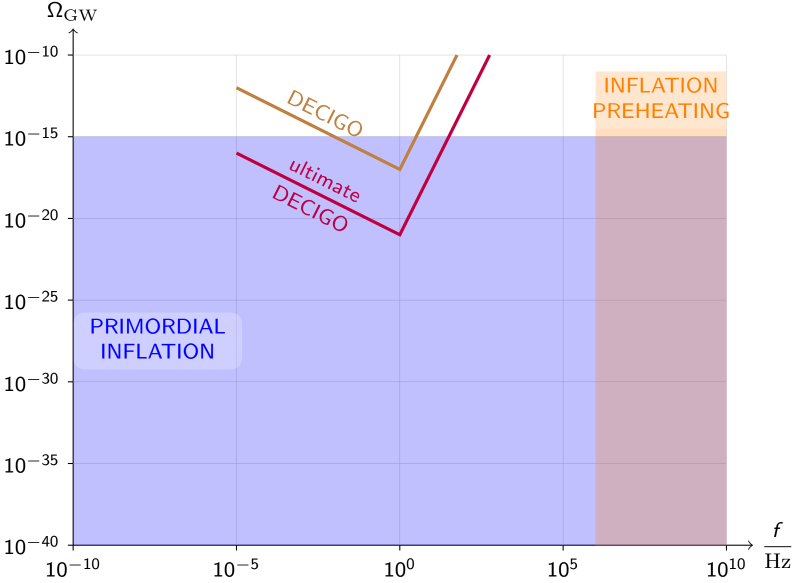
and density

$$\Omega_\mathrm{GW} \sim 10^{-20} \left(\frac{10^4}{\dot{\Gamma}/H\Gamma}\right)^2 \left(\frac{10^{6.5}\,\mathrm{GeV}}{V_0^{1/4}}\right)^{4/3} \left(\frac{T_\mathrm{d}}{10\,\mathrm{GeV}}\right)^{4/3} \left(\frac{V_0 a_\mathrm{c}^3/\rho_\mathrm{d} a_\mathrm{d}^3}{10}\right)^{4/3}$$

Gravitational waves



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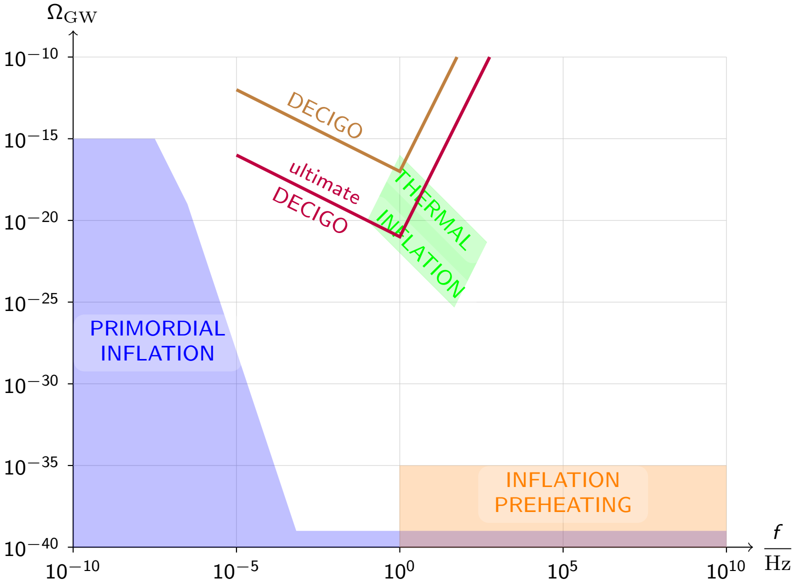

zoom in

Superpotential

$$W = \lambda_u Q H_u \bar{u} + \lambda_d Q H_d \bar{d} + \lambda_e L H_d \bar{e} + \mu H_u H_d$$

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$$\mu = \lambda_\mu \phi_0^2$$

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$$m_\phi^2 < 0$$

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Key assumption

$$m^2_{LH_u} = \frac{1}{2}\left(m^2_L + m^2_{H_u}\right) < 0$$

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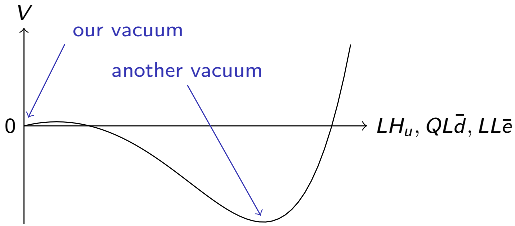
$$m_{LH_u}^2 = \frac{1}{2}\left(m_L^2 + m_{H_u}^2\right) < 0$$

Implies a dangerous non-MSSM vacuum with $LH_u \sim (10^9\mathrm{GeV})^2$ and

$$\lambda_d QL\bar{d} + \lambda_e LL\bar{e} = -\mu LH_u$$

eliminating the μ-term contribution to LH_u's mass squared.



Reduction

For simplicity, reduce to a single generation

$$L = \begin{pmatrix} \\ \\ \end{pmatrix} \quad , \quad H_u = \begin{pmatrix} \\ \\ \end{pmatrix} \quad , \quad H_d = \begin{pmatrix} \\ \\ \end{pmatrix} \quad , \quad \bar{e} = (\qquad)$$

$$\bar{u} = (\qquad) \quad , \quad Q = \begin{pmatrix} \\ \\ \end{pmatrix} \quad , \quad \bar{d} = (\qquad)$$

$$\phi = \qquad , \quad \chi = \qquad , \quad \bar{\chi} =$$

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$$\bar{u} = \begin{pmatrix} 0 & 0 & 0 \end{pmatrix} \quad , \quad Q = \begin{pmatrix} & & \\ 0 & 0 & 0 \end{pmatrix} \quad , \quad \bar{d} = \begin{pmatrix} & & \end{pmatrix}$$

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$$\phi = \phi \quad , \quad \chi = 0 \quad , \quad \bar{\chi} = 0$$

The superpotential reduces to

$$W = \frac{1}{2}\lambda_d h_d d^2 + \frac{1}{2}\lambda_e h_d e^2 + \lambda_\mu \phi^2 h_u h_d + \frac{1}{2}\lambda_\nu \left(l h_u \right)^2$$

with the remaining D-term constraint

$$D = |h_u|^2 - |h_d|^2 - |l|^2 + \frac{1}{2}|d|^2 + \frac{1}{2}|e|^2 = 0$$

Potential

$$
\begin{aligned}
V \quad = \quad & V_0 + m_L^2|l|^2 - m_{H_u}^2|h_u|^2 + m_{H_d}^2|h_d|^2 - m_\phi^2|\phi|^2 \\
& + \frac{1}{2}\left(m_Q^2 + m_d^2\right)|d|^2 + \frac{1}{2}\left(m_L^2 + m_e^2\right)|e|^2 \\
& + \left[\frac{1}{2}A_\nu\lambda_\nu l^2 h_u^2 + A_\mu\lambda_\mu\phi^2 h_u h_d + \frac{1}{2}A_d\lambda_d h_d d^2 + \frac{1}{2}A_e\lambda_e h_d e^2 + \text{c.c.}\right] \\
& + \left|\lambda_\nu l h_u^2\right|^2 + \left|\lambda_\nu l^2 h_u + \lambda_\mu\phi^2 h_d\right|^2 + \left|\lambda_\mu\phi^2 h_u + \frac{1}{2}\lambda_d d^2 + \frac{1}{2}\lambda_e e^2\right|^2 \\
& + |\lambda_d h_d d|^2 + |\lambda_e h_d e|^2 + |2\lambda_\mu\phi h_u h_d|^2 \\
& + \frac{1}{2}g^2\left(|h_u|^2 - |h_d|^2 - |l|^2 + \frac{1}{2}|d|^2 + \frac{1}{2}|e|^2\right)^2
\end{aligned}
$$

Potential

drives thermal inflation

$$
\begin{aligned}
V \;=\;& \boxed{V_0} + m_L^2|l|^2 - m_{H_u}^2|h_u|^2 + m_{H_d}^2|h_d|^2 - m_\phi^2|\phi|^2 \\
&+ \frac{1}{2}\left(m_Q^2 + m_d^2\right)|d|^2 + \frac{1}{2}\left(m_L^2 + m_e^2\right)|e|^2 \\
&+ \left[\frac{1}{2}A_\nu\lambda_\nu l^2 h_u^2 + A_\mu\lambda_\mu\phi^2 h_u h_d + \frac{1}{2}A_d\lambda_d h_d d^2 + \frac{1}{2}A_e\lambda_e h_d e^2 + \text{c.c.}\right] \\
&+ \left|\lambda_\nu l h_u^2\right|^2 + \left|\lambda_\nu l^2 h_u + \lambda_\mu\phi^2 h_d\right|^2 + \left|\lambda_\mu\phi^2 h_u + \frac{1}{2}\lambda_d d^2 + \frac{1}{2}\lambda_e e^2\right|^2 \\
&+ |\lambda_d h_d d|^2 + |\lambda_e h_d e|^2 + |2\lambda_\mu\phi h_u h_d|^2 \\
&+ \frac{1}{2}g^2\left(|h_u|^2 - |h_d|^2 - |l|^2 + \frac{1}{2}|d|^2 + \frac{1}{2}|e|^2\right)^2
\end{aligned}
$$

Potential

drives thermal inflation

lh_u rolls away

$$
\begin{aligned}
V \quad = \quad & V_0 + m_L^2|l|^2 - m_{H_u}^2|h_u|^2 + m_{H_d}^2|h_d|^2 - m_\phi^2|\phi|^2 \\
& + \frac{1}{2}\left(m_Q^2 + m_d^2\right)|d|^2 + \frac{1}{2}\left(m_L^2 + m_e^2\right)|e|^2 \\
& + \left[\frac{1}{2}A_\nu\lambda_\nu l^2 h_u^2 + A_\mu\lambda_\mu\phi^2 h_u h_d + \frac{1}{2}A_d\lambda_d h_d d^2 + \frac{1}{2}A_e\lambda_e h_d e^2 + \text{c.c.}\right] \\
& + \left|\lambda_\nu l h_u^2\right|^2 + \left|\lambda_\nu l^2 h_u + \lambda_\mu\phi^2 h_d\right|^2 + \left|\lambda_\mu\phi^2 h_u + \frac{1}{2}\lambda_d d^2 + \frac{1}{2}\lambda_e e^2\right|^2 \\
& + |\lambda_d h_d d|^2 + |\lambda_e h_d e|^2 + |2\lambda_\mu\phi h_u h_d|^2 \\
& + \frac{1}{2}g^2\left(|h_u|^2 - |h_d|^2 - |l|^2 + \frac{1}{2}|d|^2 + \frac{1}{2}|e|^2\right)^2
\end{aligned}
$$

Potential

drives thermal inflation

lh_u rolls away

lh_u stabilized with fixed phase

$$
\begin{aligned}
V \quad = \quad & V_0 + m_L^2|l|^2 - m_{H_u}^2|h_u|^2 + m_{H_d}^2|h_d|^2 - m_\phi^2|\phi|^2 \\
& + \frac{1}{2}\left(m_Q^2 + m_d^2\right)|d|^2 + \frac{1}{2}\left(m_L^2 + m_e^2\right)|e|^2 \\
& + \left[\frac{1}{2}A_\nu\lambda_\nu l^2 h_u^2 + A_\mu\lambda_\mu\phi^2 h_u h_d + \frac{1}{2}A_d\lambda_d h_d d^2 + \frac{1}{2}A_e\lambda_e h_d e^2 + \text{c.c.}\right] \\
& + \left|\lambda_\nu l h_u^2\right|^2 + \left|\lambda_\nu l^2 h_u + \lambda_\mu\phi^2 h_d\right|^2 + \left|\lambda_\mu\phi^2 h_u + \frac{1}{2}\lambda_d d^2 + \frac{1}{2}\lambda_e e^2\right|^2 \\
& + |\lambda_d h_d d|^2 + |\lambda_e h_d e|^2 + |2\lambda_\mu\phi h_u h_d|^2 \\
& + \frac{1}{2}g^2\left(|h_u|^2 - |h_d|^2 - |l|^2 + \frac{1}{2}|d|^2 + \frac{1}{2}|e|^2\right)^2
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Potential

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&+ \frac{1}{2}\left(m_Q^2 + m_d^2\right)|d|^2 + \frac{1}{2}\left(m_L^2 + m_e^2\right)|e|^2 \\
&+ \left[\frac{1}{2}A_\nu\lambda_\nu l^2 h_u^2 + A_\mu\lambda_\mu\phi^2 h_u h_d + \frac{1}{2}A_d\lambda_d h_d d^2 + \frac{1}{2}A_e\lambda_e h_d e^2 + \text{c.c.}\right] \\
&+ \left|\lambda_\nu l h_u^2\right|^2 + \left|\lambda_\nu l^2 h_u + \lambda_\mu\phi^2 h_d\right|^2 + \left|\lambda_\mu\phi^2 h_u + \frac{1}{2}\lambda_d d^2 + \frac{1}{2}\lambda_e e^2\right|^2 \\
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&+ \frac{1}{2}g^2\left(|h_u|^2 - |h_d|^2 - |l|^2 + \frac{1}{2}|d|^2 + \frac{1}{2}|e|^2\right)^2
\end{aligned}
$$

lh_u stabilized with fixed phase

Potential

drives thermal inflation

lh_u rolls away

ϕ rolls away

h_d forced out

lh_u stabilized with fixed phase

$$
\begin{aligned}
V \;=\;& V_0 + m_L^2|l|^2 - m_{H_u}^2|h_u|^2 + m_{H_d}^2|h_d|^2 - m_\phi^2|\phi|^2 \\
&+ \frac{1}{2}\left(m_Q^2 + m_d^2\right)|d|^2 + \frac{1}{2}\left(m_L^2 + m_e^2\right)|e|^2 \\
&+ \left[\frac{1}{2}A_\nu\lambda_\nu l^2 h_u^2 + A_\mu\lambda_\mu\phi^2 h_u h_d + \frac{1}{2}A_d\lambda_d h_d d^2 + \frac{1}{2}A_e\lambda_e h_d e^2 + \text{c.c.}\right] \\
&+ \left|\lambda_\nu l h_u^2\right|^2 + \left|\lambda_\nu l^2 h_u + \lambda_\mu\phi^2 h_d\right|^2 + \left|\lambda_\mu\phi^2 h_u + \frac{1}{2}\lambda_d d^2 + \frac{1}{2}\lambda_e e^2\right|^2 \\
&+ |\lambda_d h_d d|^2 + |\lambda_e h_d e|^2 + |2\lambda_\mu\phi h_u h_d|^2 \\
&+ \frac{1}{2}g^2\left(|h_u|^2 - |h_d|^2 - |l|^2 + \frac{1}{2}|d|^2 + \frac{1}{2}|e|^2\right)^2
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Potential

drives thermal inflation

lh_u rolls away

ϕ rolls away

$$
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V \;=\;& V_0 + m_L^2|l|^2 - m_{H_u}^2|h_u|^2 + m_{H_d}^2|h_d|^2 - m_\phi^2|\phi|^2 \\
&+ \cancel{\frac{1}{2}\left(m_Q^2 + m_d^2\right)|d|^2 + \frac{1}{2}\left(m_L^2 + m_e^2\right)|e|^2} \\
&+ \left[\frac{1}{2}A_\nu\lambda_\nu l^2 h_u^2 + A_\mu\lambda_\mu\phi^2 h_u h_d + \cancel{\frac{1}{2}A_d\lambda_d h_d d^2 + \frac{1}{2}A_e\lambda_e h_d e^2} + \text{c.c.}\right] \\
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&+ |\lambda_d h_d d|^2 + |\lambda_e h_d e|^2 + |2\lambda_\mu\phi h_u h_d|^2 \\
&+ \frac{1}{2}g^2\left(|h_u|^2 - |h_d|^2 - |l|^2 + \cancel{\frac{1}{2}|d|^2 + \frac{1}{2}|e|^2}\right)^2
\end{aligned}
$$

h_d forced out

lh_u stabilized with fixed phase

d and e held at origin

Potential

drives thermal inflation

lh_u rolls away

ϕ rolls away

h_d forced out

lh_u stabilized with fixed phase

$$
\begin{aligned}
V \;=\;& V_0 + m_L^2|l|^2 - m_{H_u}^2|h_u|^2 + m_{H_d}^2|h_d|^2 - m_\phi^2|\phi|^2 \\
&+ \cancel{\frac{1}{2}\left(m_Q^2 + m_d^2\right)|d|^2 + \frac{1}{2}\left(m_L^2 + m_e^2\right)|e|^2} \\
&+ \left[\frac{1}{2}A_\nu\lambda_\nu l^2 h_u^2 + A_\mu\lambda_\mu\phi^2 h_u h_d + \cancel{\frac{1}{2}A_d\lambda_d h_d d^2 + \frac{1}{2}A_e\lambda_e h_d e^2} + \text{c.c.}\right] \\
&+ \left|\lambda_\nu l h_u^2\right|^2 + \left|\lambda_\nu l^2 h_u + \lambda_\mu\phi^2 h_d\right|^2 + \left|\lambda_\mu\phi^2 h_u + \cancel{\frac{1}{2}\lambda_d d^2 + \frac{1}{2}\lambda_e e^2}\right|^2 \\
&+ |\lambda_d h_d d|^2 + |\lambda_e h_d e|^2 + |2\lambda_\mu\phi h_u h_d|^2 \\
&+ \frac{1}{2}g^2\left(|h_u|^2 - |h_d|^2 - |l|^2 + \cancel{\frac{1}{2}|d|^2 + \frac{1}{2}|e|^2}\right)^2
\end{aligned}
$$

d and e held at origin

lh_u returns with rotation

Potential

drives thermal inflation

lh_u rolls away

ϕ rolls away

ϕ stabilized
$m_\phi^2(\phi_0) = -\alpha_\phi \, m_\phi^2(0)$

$$
\begin{aligned}
V \;=\;& V_0 + m_L^2|l|^2 - m_{H_u}^2|h_u|^2 + m_{H_d}^2|h_d|^2 + m_\phi^2(\phi)\,|\phi|^2 \\
&+ \cancel{\frac{1}{2}\left(m_Q^2 + m_d^2\right)|d|^2 + \frac{1}{2}\left(m_L^2 + m_e^2\right)|e|^2} \\
&+ \left[\frac{1}{2}A_\nu\lambda_\nu l^2 h_u^2 + A_\mu\lambda_\mu\phi^2 h_u h_d + \cancel{\frac{1}{2}A_d\lambda_d h_d d^2 + \frac{1}{2}A_e\lambda_e h_d e^2} + \text{c.c.}\right] \\
&+ \left|\lambda_\nu l h_u^2\right|^2 + \left|\lambda_\nu l^2 h_u + \lambda_\mu\phi^2 h_d\right|^2 + \left|\lambda_\mu\phi^2 h_u + \cancel{\frac{1}{2}\lambda_d d^2 + \frac{1}{2}\lambda_e e^2}\right|^2 \\
&+ |\lambda_d h_d d|^2 + |\lambda_e h_d e|^2 + |2\lambda_\mu\phi h_u h_d|^2 \\
&+ \frac{1}{2}g^2\left(|h_u|^2 - |h_d|^2 - |l|^2 + \cancel{\frac{1}{2}|d|^2 + \frac{1}{2}|e|^2}\right)^2
\end{aligned}
$$

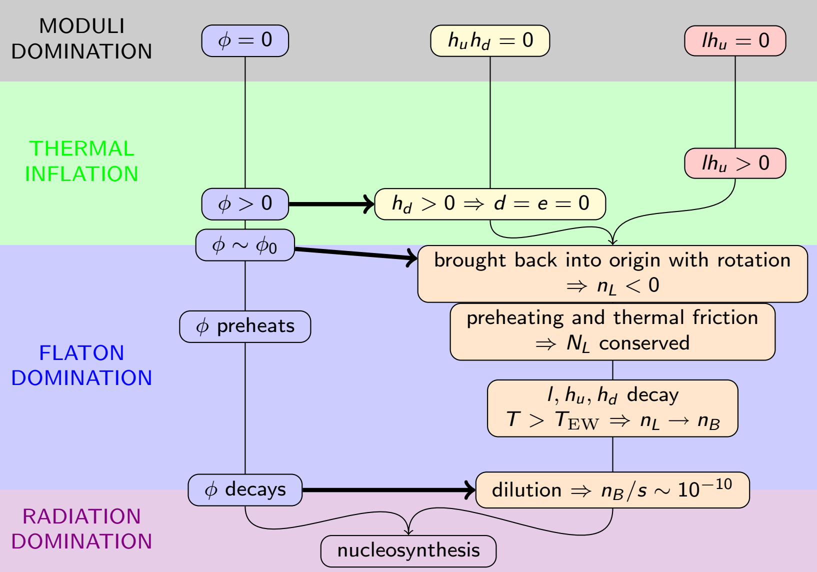
h_d forced out

lh_u stabilized with fixed phase

lh_u returns with rotation

d and e held at origin

Cosmology


MODULI DOMINATION
THERMAL INFLATION
FLATON DOMINATION
RADIATION DOMINATION
$\phi = 0$
$h_u h_d = 0$
$l h_u = 0$
$l h_u > 0$
$\phi > 0$
$h_d > 0 \Rightarrow d = e = 0$
$\phi \sim \phi_0$
brought back into origin with rotation $\Rightarrow n_L < 0$
ϕ preheats
preheating and thermal friction $\Rightarrow N_L$ conserved
l, h_u, h_d decay
$T > T_{\mathrm{EW}} \Rightarrow n_L \rightarrow n_B$
ϕ decays
dilution $\Rightarrow n_B/s \sim 10^{-10}$
nucleosynthesis

Simulation

Lattice 128^3, box size $= 200m^{-1}$, Fourier modes $0.033m \leq k \leq 3.5m$.

***CP* phase**

$$\arg\left(-B^* A_\nu\right) = \begin{cases} \pi - \frac{\pi}{20} & CP+ \\ \pi & CP0 \\ \pi + \frac{\pi}{20} & CP- \end{cases}$$

Initial conditions

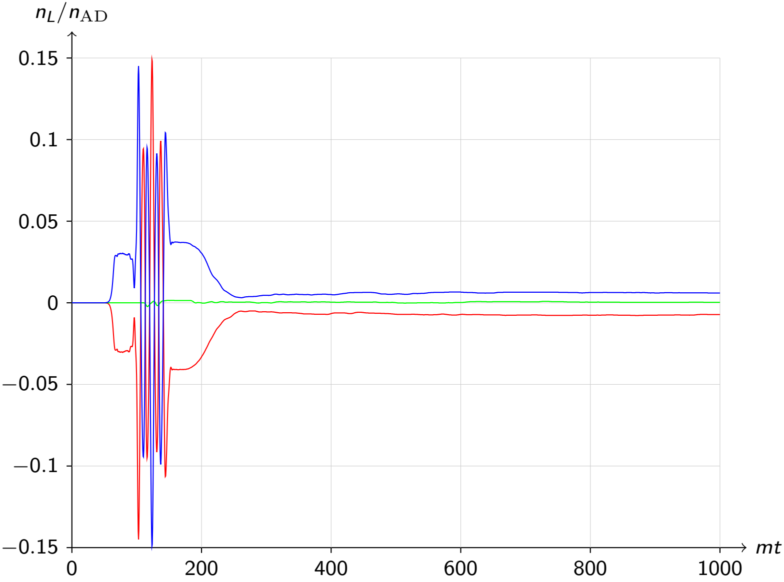
$$\begin{aligned} \phi &= 4m + \delta\phi \\ l &= l_0 + \delta l \\ h_d &= \delta h_d \end{aligned}$$

Constraints

$$\begin{aligned} D &= \epsilon^2 \qquad \text{with } \epsilon = 4.8 \times 10^{-3} l_0 \\ j_0 &= 0 \end{aligned}$$

Algorithm Adaptive constrained gauge invariant leapfrog type algorithm. Exactly conserves the constraints and charges, and has good energy conservation.

Lepton number



Baryon asymmetry

$$\frac{n_B}{s} \sim \frac{n_L}{n_{\mathrm{AD}}} \frac{n_{\mathrm{AD}}}{n_\phi} \frac{T_{\mathrm{d}}}{m_\phi(\phi_0)}$$

Baryon asymmetry

$$\frac{n_B}{s} \sim \frac{n_L}{n_{\rm AD}} \frac{n_{\rm AD}}{n_\phi} \frac{T_{\rm d}}{m_\phi(\phi_0)}$$

Using $n_\phi \sim m_\phi(\phi_0)\,\phi_0^2$ and $m_\phi^2(\phi_0) \sim \alpha_\phi\, m_\phi^2(0)$, and $n_{\rm AD} \sim m_{LH_u} l_0^2$ and

$$l_0 \sim 100\,{\rm GeV}\sqrt{\frac{m_{LH_u}}{m_\nu}}$$

gives

$$\frac{n_B}{s} \sim 10^{-10}\left(\frac{n_L/n_{\rm AD}}{10^{-2}}\right)\left(\frac{10^{12}\,{\rm GeV}}{\phi_0}\right)^2\left(\frac{T_{\rm d}}{1\,{\rm GeV}}\right)\left(\frac{10^{-1}}{\alpha_\phi}\right)\left(\frac{10^{-2}\,{\rm eV}}{m_\nu}\right)\left(\frac{m_{LH_u}}{m_\phi(0)}\right)^2$$

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and using

$$T_{\rm d} \sim 1\,{\rm GeV} \left(\frac{10^{12}\,{\rm GeV}}{\phi_0}\right) \left(\frac{|\mu|}{10^3\,{\rm GeV}}\right)^2$$

gives

$$\frac{n_B}{s} \sim 10^{-10} \left(\frac{n_L/n_{\rm AD}}{10^{-2}}\right) \left(\frac{10^{12}\,{\rm GeV}}{\phi_0}\right)^3 \left(\frac{|\mu|}{10^3\,{\rm GeV}}\right)^2 \left(\frac{10^{-1}}{\alpha_\phi}\right) \left(\frac{10^{-2}\,{\rm eV}}{m_\nu}\right) \left(\frac{m_{LH_u}}{m_\phi(0)}\right)^2$$

Dark matter candidates

Peccei-Quinn symmetry

$$W = \lambda_u Q H_u \bar{u} + \lambda_d Q H_d \bar{d} + \lambda_e L H_d \bar{e} + \frac{1}{2}\lambda_\nu (L H_u)^2 + \lambda_\mu \phi^2 H_u H_d + \lambda_\chi \phi \chi \bar{\chi}$$

Dark matter candidates

Peccei-Quinn symmetry

DFSZ axion

$$W = \lambda_u Q H_u \bar{u} + \lambda_d Q H_d \bar{d} + \lambda_e L H_d \bar{e} + \frac{1}{2}\lambda_\nu (LH_u)^2 + \lambda_\mu \phi^2 H_u H_d + \lambda_\chi \phi \chi \bar{\chi}$$

Dark matter candidates

Peccei-Quinn symmetry

$$W = \lambda_u Q H_u \bar{u} + \lambda_d Q H_d \bar{d} + \lambda_e L H_d \bar{e} + \frac{1}{2}\lambda_\nu \left(L H_u\right)^2 + \overbrace{\lambda_\mu \phi^2 H_u H_d}^{\text{DFSZ axion}} + \overbrace{\lambda_\chi \phi \chi \bar{\chi}}^{\text{KSVZ axion}}$$

Dark matter candidates

Peccei-Quinn symmetry

$$W = \lambda_u Q H_u \bar{u} + \lambda_d Q H_d \bar{d} + \lambda_e L H_d \bar{e} + \frac{1}{2}\lambda_\nu (L H_u)^2 + \overbrace{\lambda_\mu \phi^2 H_u H_d}^{\text{DFSZ axion}} + \overbrace{\lambda_\chi \phi \chi \bar{\chi}}^{\text{KSVZ axion}}$$

Axion

$$\begin{aligned} m_a &= \frac{\Lambda^2_{\mathrm{QCD}}}{2\pi f_a} \qquad \text{where } f_a = \frac{\sqrt{2}\,\phi_0}{N} \\ &\simeq 6 \times 10^{-5}\,\mathrm{eV}\left(\frac{10^{11}\,\mathrm{GeV}}{f_a}\right) \end{aligned}$$

Dark matter candidates

Peccei-Quinn symmetry

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Axino

$$\begin{aligned} m_{\tilde{a}} &= \frac{1}{16\pi^2} \sum_\chi \lambda_\chi^2 A_\chi \\ &\sim 1 \text{ to } 10\,\mathrm{GeV} \end{aligned}$$

Dark matter abundance

Axion

Axino

Dark matter abundance

Axion Misalignment

$$\Omega_a \sim 0.1 \left(\frac{\sqrt{6}}{N}\right)^{1.2} \left(\frac{\phi_0}{10^{11}\,\mathrm{GeV}}\right)^{1.2}$$

Axino

Dark matter abundance

Axion Misalignment

$$\Omega_a \sim 0.1 \left(\frac{\sqrt{6}}{N}\right)^{1.2} \left(\frac{\phi_0}{10^{11}\,\mathrm{GeV}}\right)^{1.2}$$

Axino Flaton decay

$$\Omega_{\tilde{a}} \simeq 0.4 \left(\frac{\alpha_{\tilde{a}}}{10^{-1}}\right)^2 \left(\frac{m_{\tilde{a}}}{1\,\mathrm{GeV}}\right)^3 \left(\frac{10\,\mathrm{GeV}}{T_{\mathrm{d}}}\right) \left(\frac{10^{11}\,\mathrm{GeV}}{\phi_0}\right)^2$$

Dark matter abundance

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Thermal NLSP decay

$$\Omega_{\tilde{a}} \sim 10^3 \left(\frac{m_{\tilde{a}}}{1\,\mathrm{GeV}}\right) \left(\frac{10^{11}\,\mathrm{GeV}}{\phi_0}\right)^2$$

Dark matter abundance

Flaton decays late

$$T_{\rm d} \sim 10\,\mathrm{GeV} \left(\frac{|\mu|}{10^3\,\mathrm{GeV}}\right)^2 \left(\frac{10^{11}\,\mathrm{GeV}}{\phi_0}\right)$$

Axion Misalignment

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Axion Misalignment

$$\Omega_a \sim 0.1 \left(\frac{\sqrt{6}}{N} \right)^{1.2} \left(\frac{\phi_0}{10^{11}\,\mathrm{GeV}} \right)^{1.2} \times \begin{cases} 1 & \text{for } T_\mathrm{d} \gg 1\,\mathrm{GeV} \\ \left(\frac{T_\mathrm{d}}{1\,\mathrm{GeV}} \right)^2 & \text{for } T_\mathrm{d} \ll 1\,\mathrm{GeV} \end{cases}$$

Axino Flaton decay

$$\Omega_{\tilde{a}} \simeq 0.4 \left(\frac{\alpha_{\tilde{a}}}{10^{-1}} \right)^2 \left(\frac{m_{\tilde{a}}}{1\,\mathrm{GeV}} \right)^3 \left(\frac{10\,\mathrm{GeV}}{T_\mathrm{d}} \right) \left(\frac{10^{11}\,\mathrm{GeV}}{\phi_0} \right)^2$$

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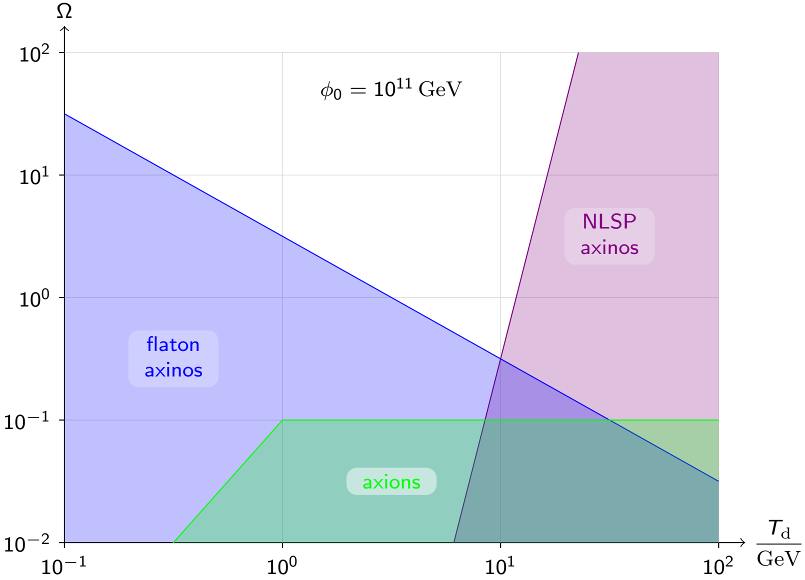
Axino Flaton decay

$$\Omega_{\tilde{a}} \simeq 0.4\left(\frac{\alpha_{\tilde{a}}}{10^{-1}}\right)^2\left(\frac{m_{\tilde{a}}}{1\,{\rm GeV}}\right)^3\left(\frac{10\,{\rm GeV}}{T_{\rm d}}\right)\left(\frac{10^{11}\,{\rm GeV}}{\phi_0}\right)^2$$

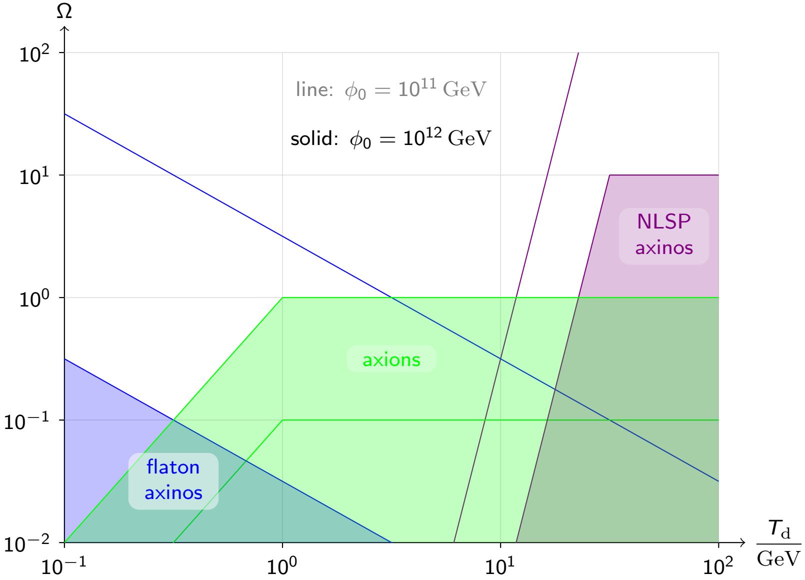
Thermal NLSP decay

$$\Omega_{\tilde{a}} \sim 10^3\left(\frac{m_{\tilde{a}}}{1\,{\rm GeV}}\right)\left(\frac{10^{11}\,{\rm GeV}}{\phi_0}\right)^2\times\begin{cases} 1 & \text{for } T_{\rm d} \gg \dfrac{m_N}{7} \\ \left(\dfrac{7\,T_{\rm d}}{m_N}\right)^7 & \text{for } T_{\rm d} \ll \dfrac{m_N}{7}\end{cases}$$

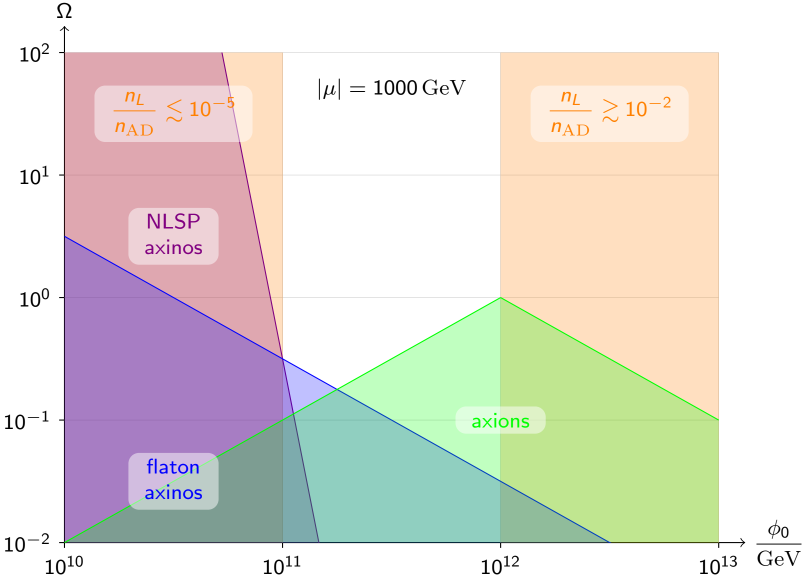
Dark matter composition



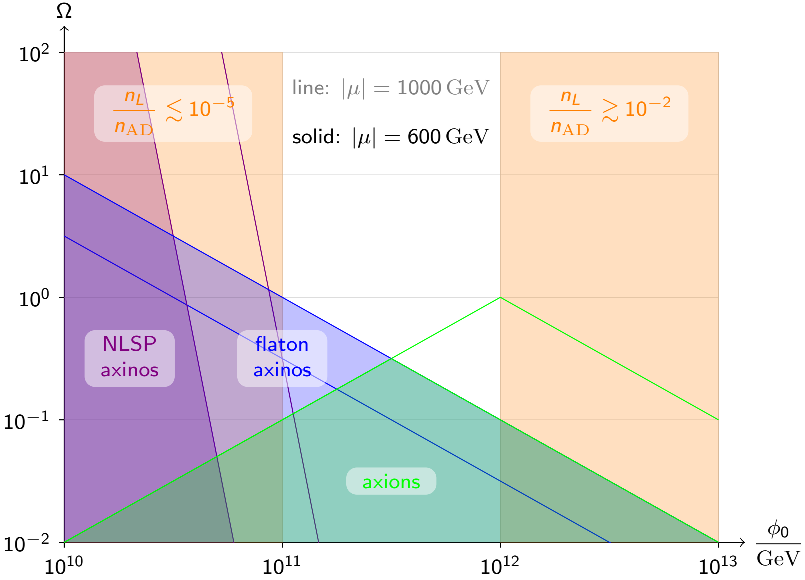
Dark matter composition



Dark matter composition



Dark matter composition



Simple model

$$W = \lambda_u Q H_u \bar{u} + \lambda_d Q H_d \bar{d} + \lambda_e L H_d \bar{e} + \frac{1}{2}\lambda_\nu (L H_u)^2 + \lambda_\mu \phi^2 H_u H_d + \lambda_\chi \phi \chi \bar{\chi}$$

Simple model

MSSM

$$W = \boxed{\lambda_u Q H_u \bar{u} + \lambda_d Q H_d \bar{d} + \lambda_e L H_d \bar{e}} + \frac{1}{2}\lambda_\nu (L H_u)^2 + \lambda_\mu \phi^2 H_u H_d + \lambda_\chi \phi \chi \bar{\chi}$$

Simple model

MSSM

neutrino masses

$$W = \underbrace{\lambda_u Q H_u \bar{u} + \lambda_d Q H_d \bar{d} + \lambda_e L H_d \bar{e}}_{\text{MSSM}} + \underbrace{\frac{1}{2}\lambda_\nu (L H_u)^2}_{\text{neutrino masses}} + \lambda_\mu \phi^2 H_u H_d + \lambda_\chi \phi \chi \bar{\chi}$$

Simple model

MSSM

neutrino masses

MSSM μ-term

$$W = \lambda_u Q H_u \bar{u} + \lambda_d Q H_d \bar{d} + \lambda_e L H_d \bar{e} + \frac{1}{2}\lambda_\nu (L H_u)^2 + \lambda_\mu \phi^2 H_u H_d + \lambda_\chi \phi \chi \bar{\chi}$$

Simple model

MSSM

neutrino masses

MSSM μ-term

$$W = \lambda_u Q H_u \bar{u} + \lambda_d Q H_d \bar{d} + \lambda_e L H_d \bar{e} + \frac{1}{2}\lambda_\nu (L H_u)^2 + \lambda_\mu \phi^2 H_u H_d + \lambda_\chi \phi \chi \bar{\chi}$$

drives $m_\phi^2 < 0$

Simple model

MSSM

neutrino masses

MSSM μ-term
DFSZ axion

$$W = \lambda_u Q H_u \bar{u} + \lambda_d Q H_d \bar{d} + \lambda_e L H_d \bar{e} + \frac{1}{2}\lambda_\nu (L H_u)^2 + \lambda_\mu \phi^2 H_u H_d + \lambda_\chi \phi \chi \bar{\chi}$$

drives $m_\phi^2 < 0$

Simple model

MSSM

neutrino masses

MSSM μ-term
DFSZ axion

$$W = \lambda_u Q H_u \bar{u} + \lambda_d Q H_d \bar{d} + \lambda_e L H_d \bar{e} + \frac{1}{2}\lambda_\nu (LH_u)^2 + \lambda_\mu \phi^2 H_u H_d + \lambda_\chi \phi \chi \bar{\chi}$$

drives $m_\phi^2 < 0$
KSVZ axion

Simple model

MSSM

neutrino masses

MSSM μ-term
DFSZ axion

$$W = \lambda_u Q H_u \bar{u} + \lambda_d Q H_d \bar{d} + \lambda_e L H_d \bar{e} + \frac{1}{2}\lambda_\nu (L H_u)^2 + \lambda_\mu \phi^2 H_u H_d + \lambda_\chi \phi \chi \bar{\chi}$$

drives $m_\phi^2 < 0$
KSVZ axion
thermal inflation

Simple model

MSSM

neutrino masses

MSSM μ-term
DFSZ axion

$$W = \lambda_u Q H_u \bar{u} + \lambda_d Q H_d \bar{d} + \lambda_e L H_d \bar{e} + \frac{1}{2}\lambda_\nu (L H_u)^2 + \lambda_\mu \phi^2 H_u H_d + \lambda_\chi \phi \chi \bar{\chi}$$

drives $m^2_{LH_u} < 0$

drives $m^2_\phi < 0$
KSVZ axion
thermal inflation

Simple model

MSSM

neutrino masses
stabilizes LH_u

MSSM μ-term
DFSZ axion

$$W = \lambda_u Q H_u \bar{u} + \lambda_d Q H_d \bar{d} + \lambda_e L H_d \bar{e} + \frac{1}{2}\lambda_\nu (LH_u)^2 + \lambda_\mu \phi^2 H_u H_d + \lambda_\chi \phi \chi \bar{\chi}$$

drives $m^2_{LH_u} < 0$

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Simple model

MSSM

neutrino masses
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$$W = \lambda_u Q H_u \bar{u} + \lambda_d Q H_d \bar{d} + \lambda_e L H_d \bar{e} + \frac{1}{2}\lambda_\nu (L H_u)^2 + \lambda_\mu \phi^2 H_u H_d + \lambda_\chi \phi \chi \bar{\chi}$$

drives $m^2_{LH_u} < 0$

drives $m^2_\phi < 0$
KSVZ axion
thermal inflation
releases ϕ

Simple model

MSSM

neutrino masses
stabilizes LH_u

MSSM μ-term
DFSZ axion
forces $H_d > 0$

$$W = \lambda_u Q H_u \bar{u} + \lambda_d Q H_d \bar{d} + \lambda_e L H_d \bar{e} + \frac{1}{2}\lambda_\nu (LH_u)^2 + \lambda_\mu \phi^2 H_u H_d + \lambda_\chi \phi \chi \bar{\chi}$$

drives $m^2_{LH_u} < 0$

drives $m^2_\phi < 0$
KSVZ axion
thermal inflation
releases ϕ

Simple model

MSSM

neutrino masses
stabilizes LH_u

MSSM μ-term
DFSZ axion
forces $H_d > 0$

$$W = \lambda_u Q H_u \bar{u} + \lambda_d Q H_d \bar{d} + \lambda_e L H_d \bar{e} + \frac{1}{2}\lambda_\nu (LH_u)^2 + \lambda_\mu \phi^2 H_u H_d + \lambda_\chi \phi \chi \bar{\chi}$$

drives $m^2_{LH_u} < 0$

stabilizes d and e

drives $m^2_\phi < 0$
KSVZ axion
thermal inflation
releases ϕ

Simple model

MSSM

neutrino masses
stabilizes LH_u

MSSM μ-term
DFSZ axion
forces $H_d > 0$
$m^2_{LH_u} + \frac{1}{2}|\mu|^2 > 0$

$$W = \lambda_u QH_u\bar{u} + \lambda_d QH_d\bar{d} + \lambda_e LH_d\bar{e} + \frac{1}{2}\lambda_\nu (LH_u)^2 + \lambda_\mu \phi^2 H_u H_d + \lambda_\chi \phi \chi \bar{\chi}$$

drives $m^2_{LH_u} < 0$

stabilizes d and e

drives $m^2_\phi < 0$
KSVZ axion
thermal inflation
releases ϕ

Simple model

MSSM

neutrino masses
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MSSM μ-term
DFSZ axion
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drives $m^2_{LH_u} < 0$

stabilizes d and e

leptogenesis

drives $m^2_\phi < 0$
KSVZ axion
thermal inflation
releases ϕ

Simple model

MSSM

neutrino masses
stabilizes LH_u

MSSM μ-term
DFSZ axion
forces $H_d > 0$
$m^2_{LH_u} + \frac{1}{2}|\mu|^2 > 0$
efficient ϕ decay

$$W = \lambda_u Q H_u \bar{u} + \lambda_d Q H_d \bar{d} + \lambda_e L H_d \bar{e} + \frac{1}{2}\lambda_\nu (LH_u)^2 + \lambda_\mu \phi^2 H_u H_d + \lambda_\chi \phi \chi \bar{\chi}$$

drives $m^2_{LH_u} < 0$

stabilizes d and e

leptogenesis

drives $m^2_\phi < 0$
KSVZ axion
thermal inflation
releases ϕ

Simple model

MSSM

neutrino masses
stabilizes LH_u

MSSM μ-term
DFSZ axion
forces $H_d > 0$
$m^2_{LH_u} + \frac{1}{2}|\mu|^2 > 0$
efficient ϕ decay

dark matter

$$W = \lambda_u Q H_u \bar{u} + \lambda_d Q H_d \bar{d} + \lambda_e L H_d \bar{e} + \frac{1}{2}\lambda_\nu (LH_u)^2 + \lambda_\mu \phi^2 H_u H_d + \lambda_\chi \phi \chi \bar{\chi}$$

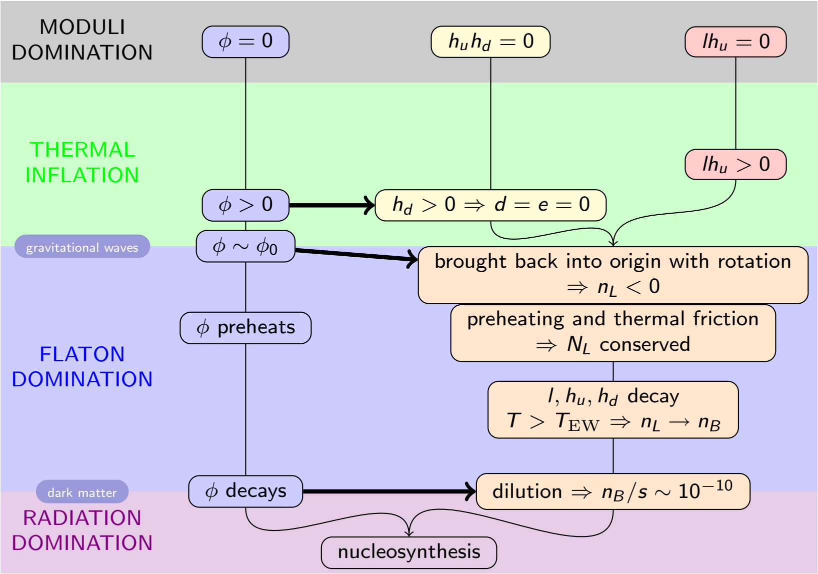
drives $m^2_{LH_u} < 0$

stabilizes d and e

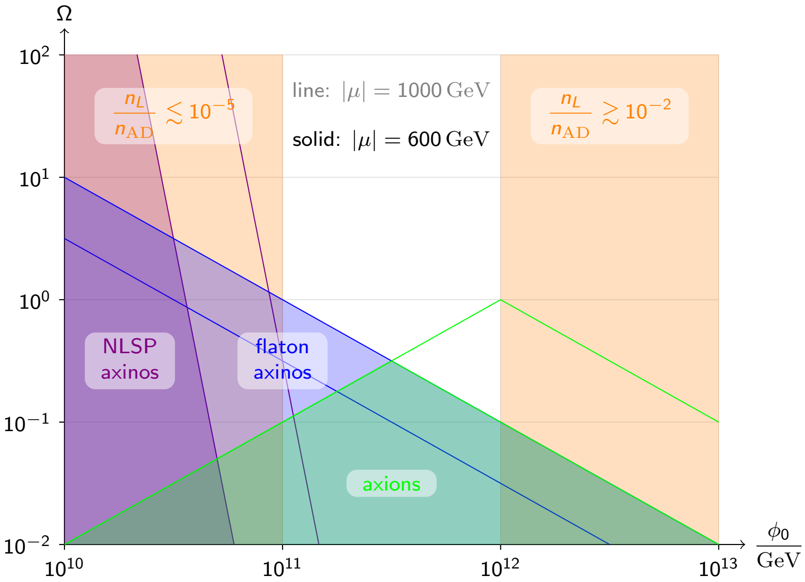
leptogenesis

drives $m^2_\phi < 0$
KSVZ axion
thermal inflation
releases ϕ

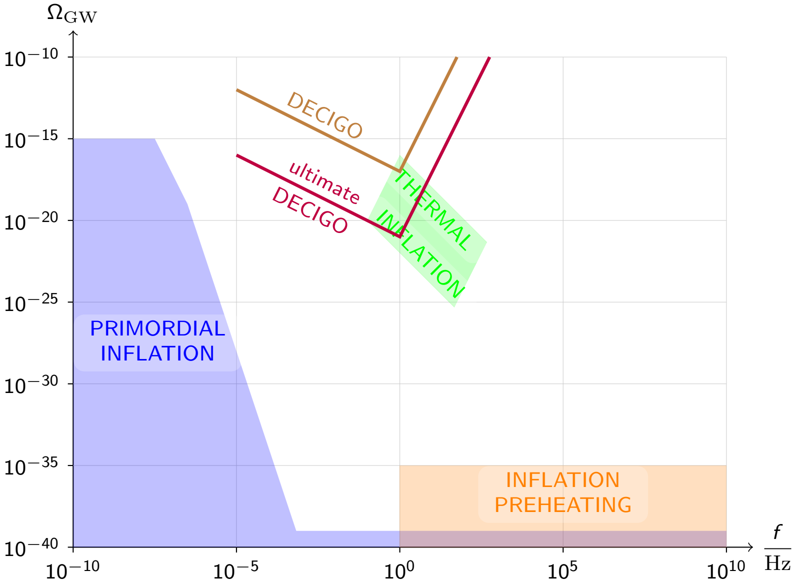
Rich cosmology



Dark matter composition



Gravitational waves



Gravitational waves