A Minimal Supersymmetric Cosmological Model

Ewan Stewart

KAIST

Prometeo I: LHC Physics and Cosmology
4 March 2009
Dept. of Theoretical Physics, University of Valencia

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Gary N Felder, Hyunbyuk Kim, Wan-Il Park, EDS	hep-ph/0703275
Richard Easther, John T Giblin, Eugene A Lim, Wan-Il Park, EDS	arXiv:0801.4197
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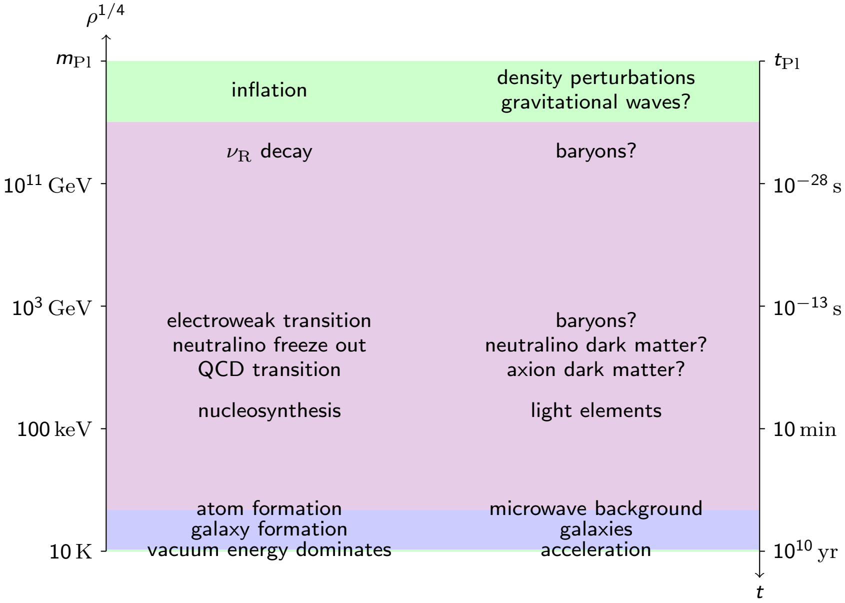
History of the observable universe



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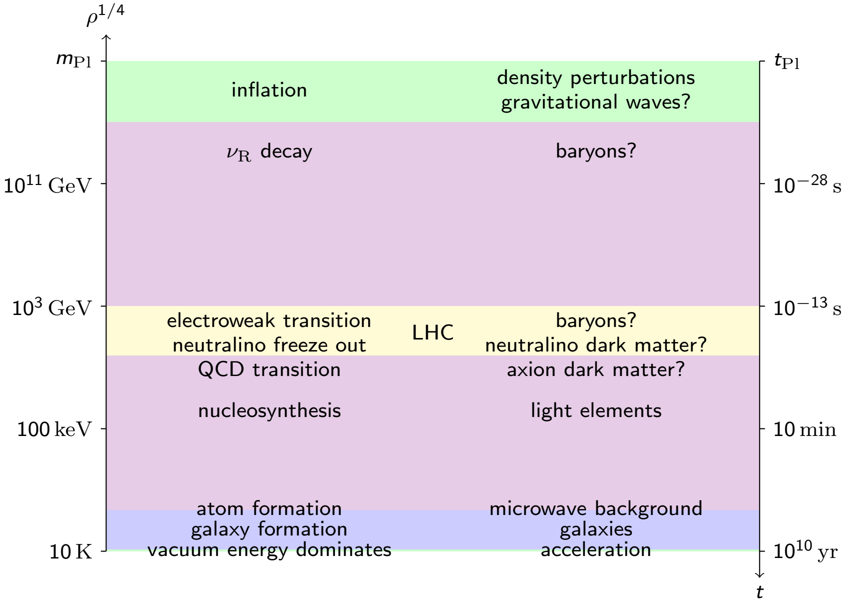

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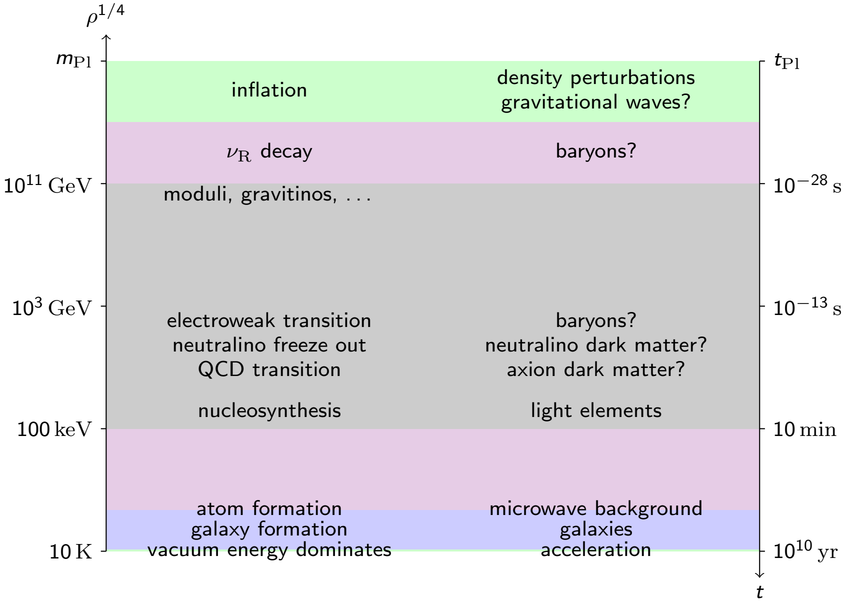

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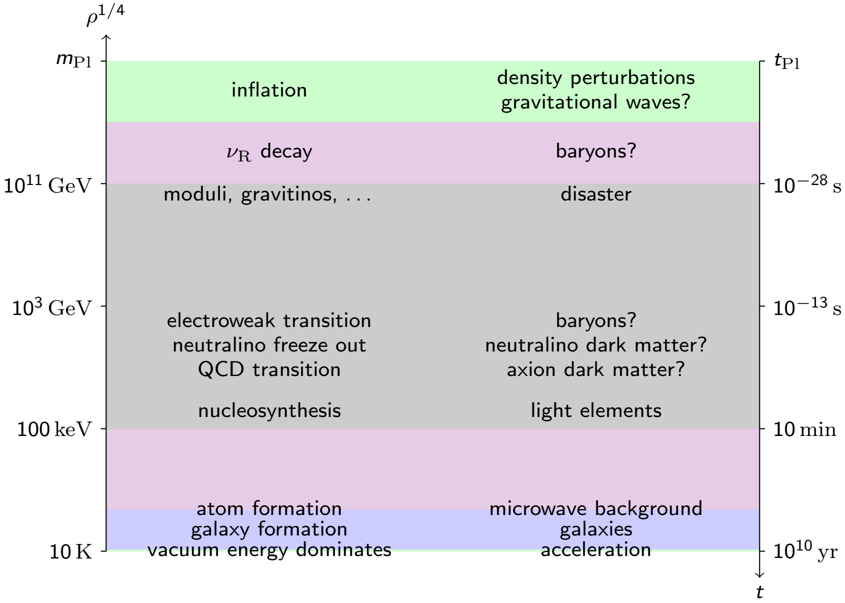

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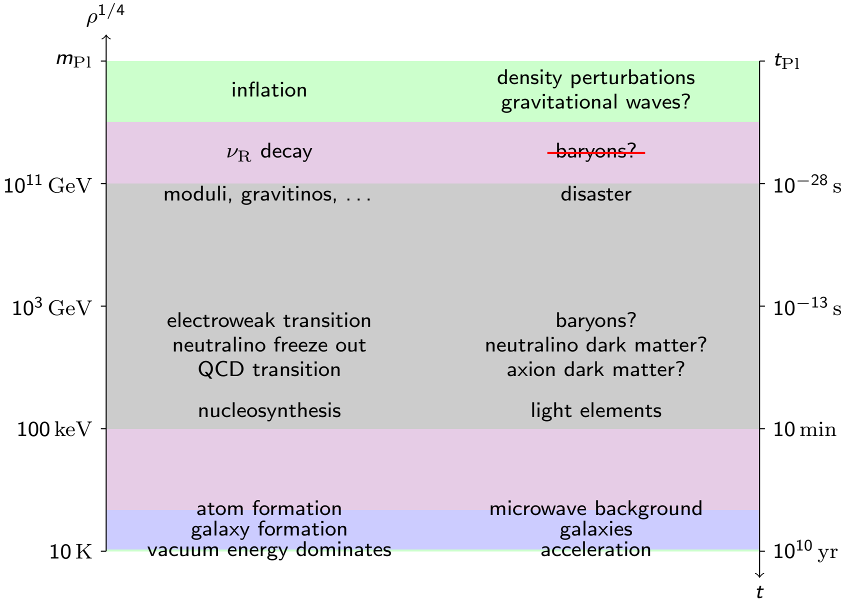

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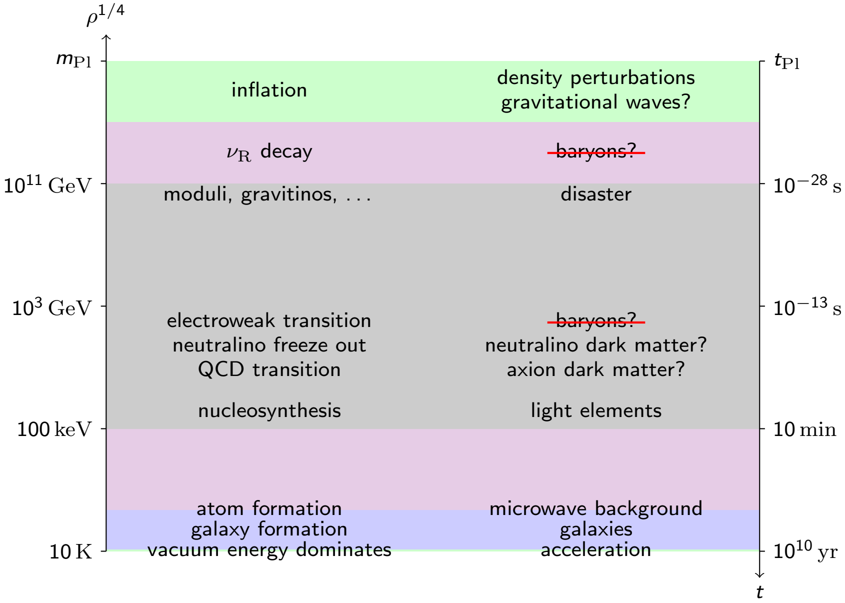

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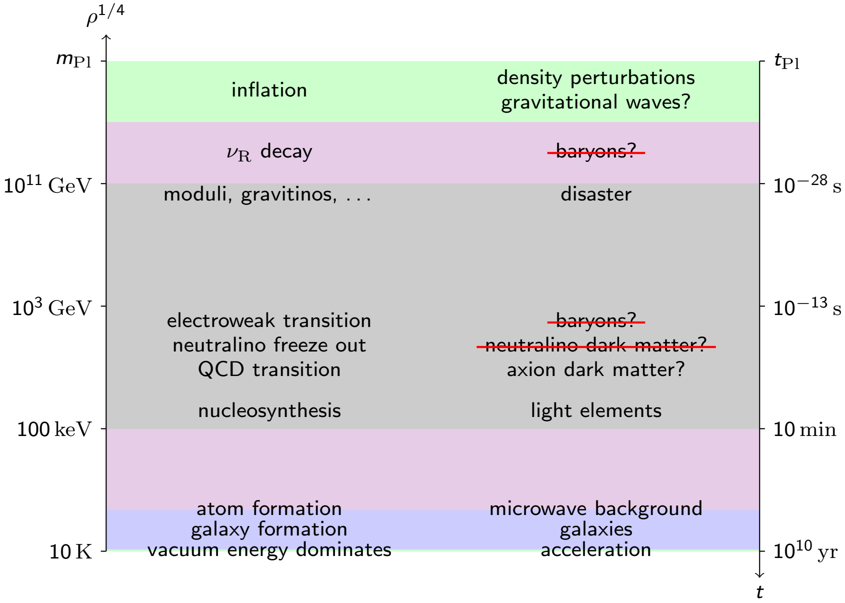

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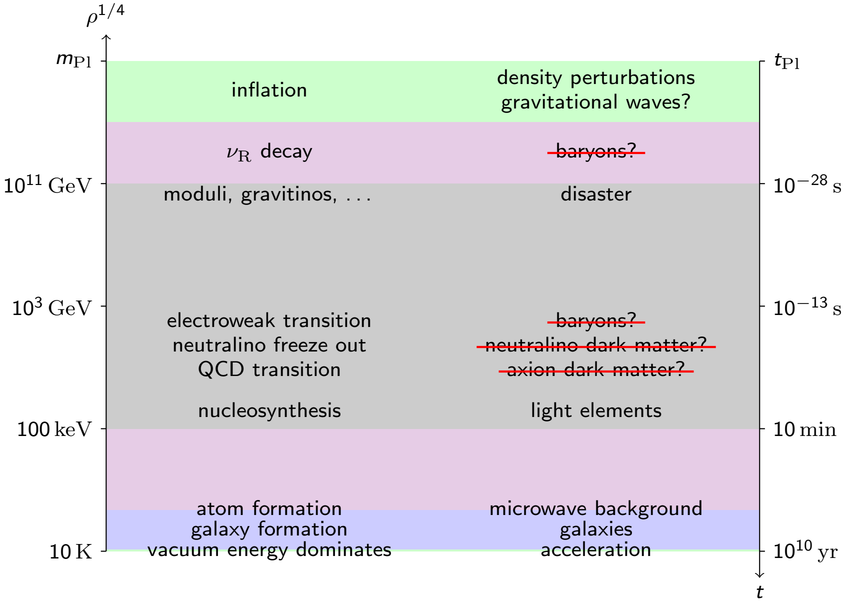

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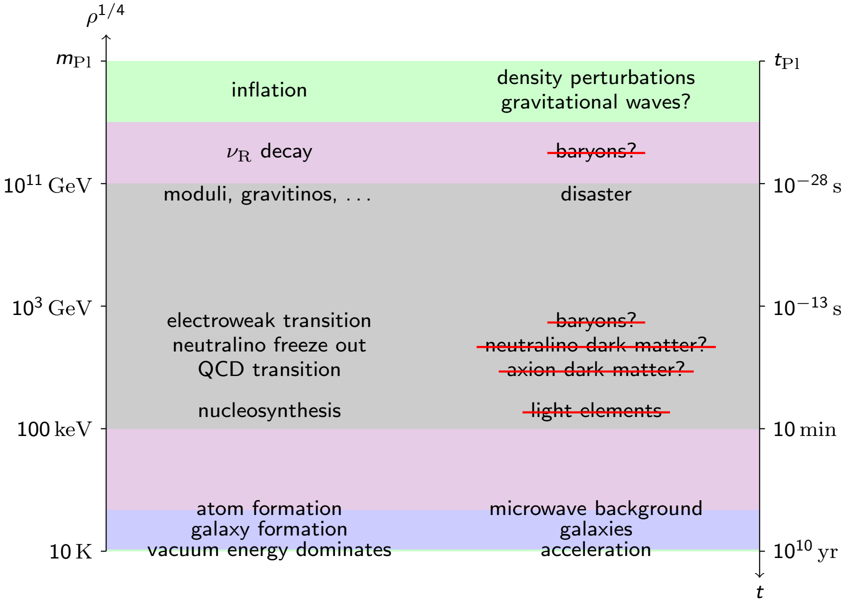

Moduli problem

Moduli (fields with Planckian expectation values) are cosmologically dangerous. For example, nucleosynthesis constrains

$$\frac{n_\Phi}{s} \lesssim 10^{-12}$$

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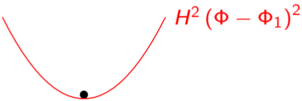

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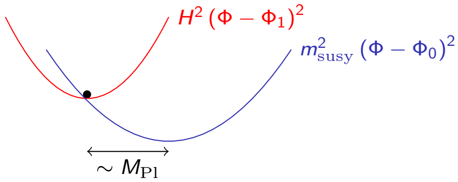

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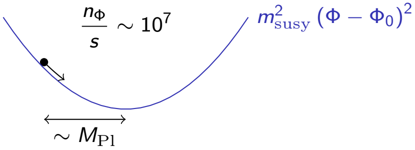

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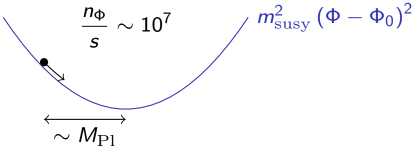

Moduli generated: $H \lesssim m_{\rm susy}$

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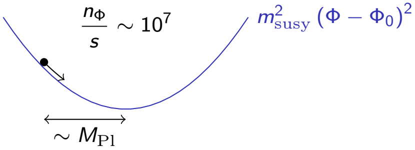

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slow-roll inflation: $H \gtrsim m_{\rm inflaton} \gtrsim m_{\rm susy}$

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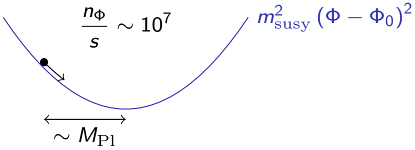
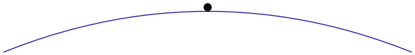


Moduli generated: $H \lesssim m_{\mathrm{susy}}$

after

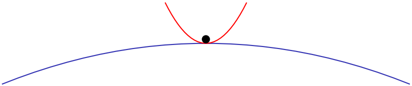
slow-roll inflation: $H \gtrsim m_{\mathrm{inflaton}} \gtrsim m_{\mathrm{susy}}$

Thermal inflation



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

Thermal inflation



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

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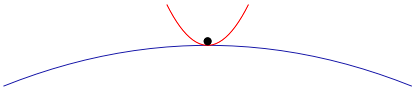

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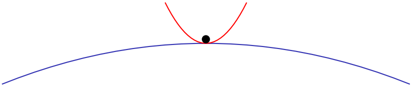
Inflation for

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

Thermal inflation



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

$$N \sim \ln \frac{V_0^{1/4}}{m}$$

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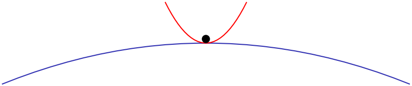

If

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

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

$$\phi_0 \sim 10^{10} \text{ to } 10^{12}\,\mathrm{GeV}$$

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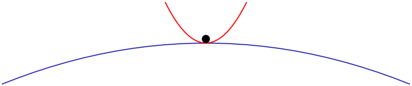

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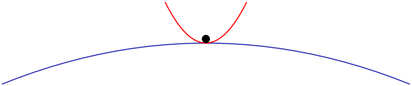

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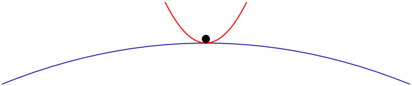

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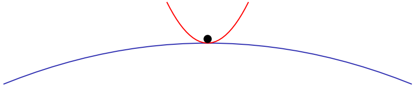

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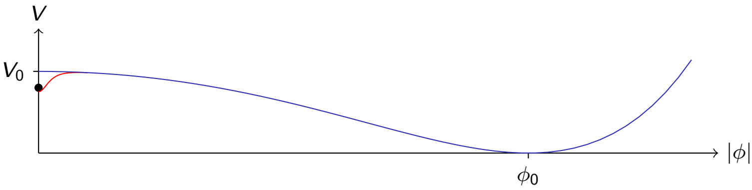
- dilution factor $\sim 10^{20}$: pre-existing moduli sufficiently diluted,
- $H \sim 10^{-8} m$: moduli regenerated with sufficiently small abundance,
- $N \sim 10$: primordial perturbations from slow-roll inflation preserved on large scales,
- $H \sim 1 \text{ to } 10 \,\mathrm{keV}$: primordial gravitational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

First order phase transition



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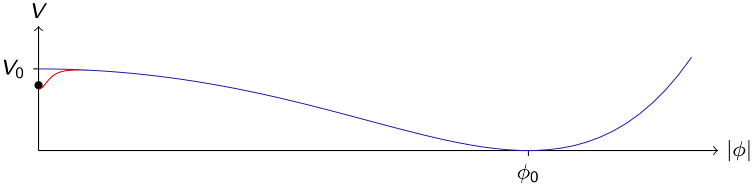

First order phase transition since $\phi_0 \gg T_\mathrm{c} \sim m$. Typical bubble size

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

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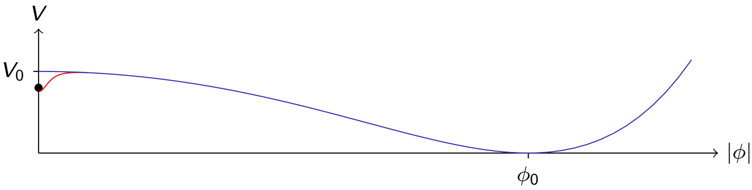

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Gravitational waves generated with frequency

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

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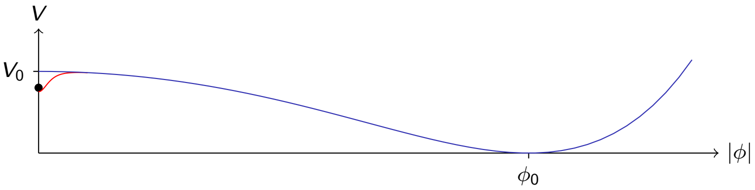

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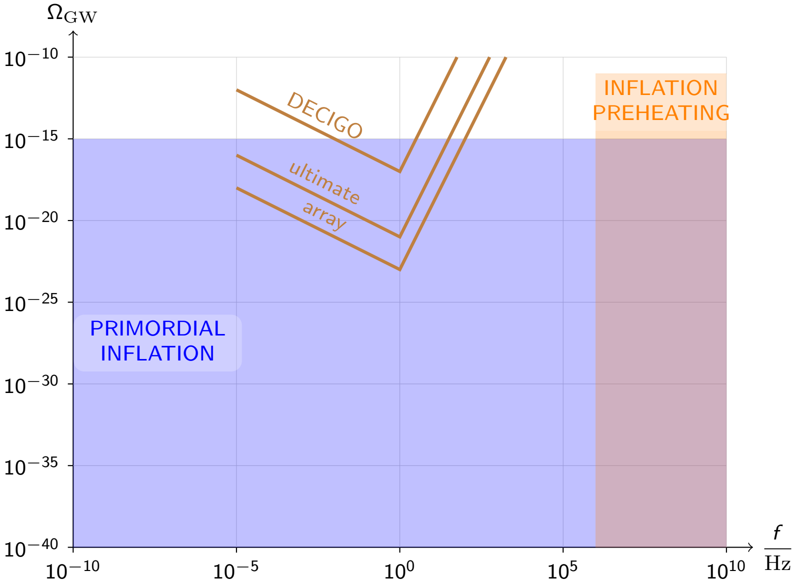
and density

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

Gravitational waves



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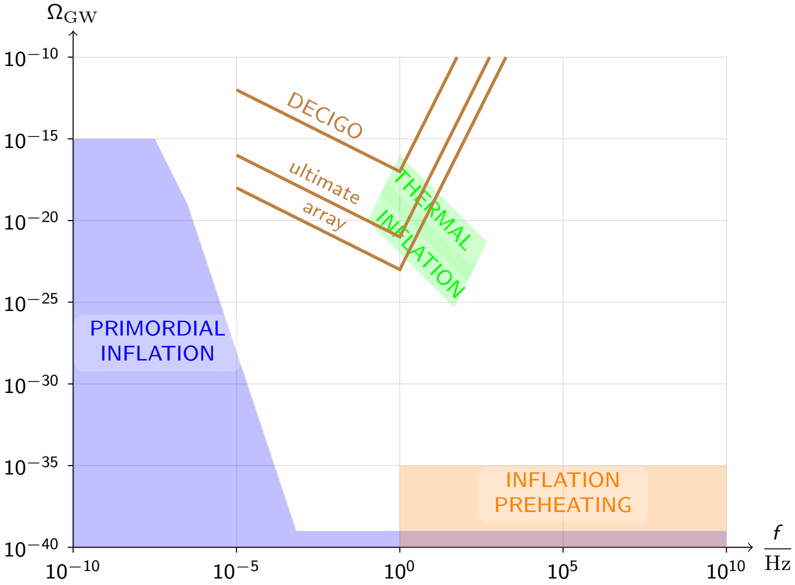

MSCM superpotential

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

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$$m_\phi^2 < 0$$

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Key assumption

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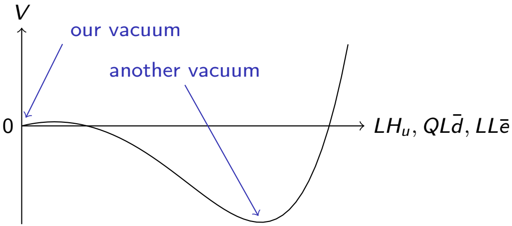
Implies a dangerous non-MSSM vacuum with $LH_u \sim (10^9\mathrm{GeV})^2$ and

$$\lambda_d Q L \bar{d} + \lambda_e L L \bar{e} = -\mu L H_u$$

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



Reduction

For simplicity, reduce to a single generation

$$L = \left(\quad \right) \quad , \quad H_u = \left(\quad \right) \quad , \quad H_d = \left(\quad \right) \quad , \quad \bar{e} = (\quad)$$

$$\bar{u} = (\quad) \quad , \quad Q = \left(\quad \right) \quad , \quad \bar{d} = (\quad)$$

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

Reduction

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$$L = \begin{pmatrix} \\ l \end{pmatrix} \quad , \quad H_u = \begin{pmatrix} h_u \\ 0 \end{pmatrix} \quad , \quad H_d = \begin{pmatrix} \\ \end{pmatrix} \quad , \quad \bar{e} = (\qquad)$$

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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

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

Potential

drives thermal inflation

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

Potential

drives thermal inflation

lh_u rolls away

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

Potential

drives thermal inflation

lh_u rolls away

lh_u stabilized with fixed phase

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

Potential

drives thermal inflation → V_0

lh_u rolls away → $m_L^2|l|^2 - m_{H_u}^2|h_u|^2$

ϕ rolls away → $m_\phi^2|\phi|^2$

lh_u stabilized with fixed phase → $\frac{1}{2}A_\nu\lambda_\nu l^2 h_u^2$, $|\lambda_\nu l h_u^2|^2$, $\lambda_\nu l^2 h_u$

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

Potential

drives thermal inflation

lh_u rolls away

ϕ rolls away

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

h_d forced out

lh_u stabilized with fixed phase

Potential

drives thermal inflation

lh_u rolls away

ϕ rolls away

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

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

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

h_d forced out

lh_u stabilized with fixed phase

lh_u returns with rotation

d and e held at origin

Potential

drives thermal inflation

lh_u rolls away

ϕ rolls away

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

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

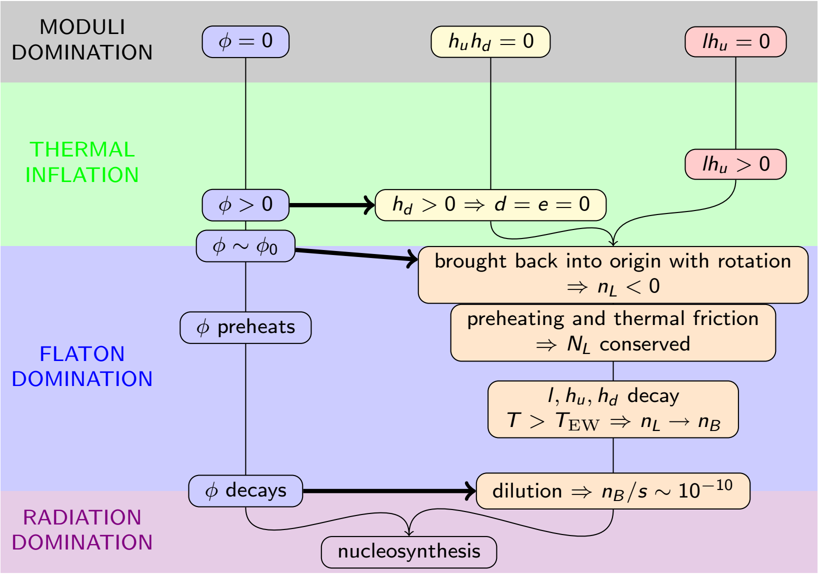
h_d forced out

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
$\phi = 0$
$h_u h_d = 0$
$lh_u = 0$
$lh_u > 0$
$\phi > 0$
$h_d > 0 \Rightarrow d = e = 0$
$\phi \sim \phi_0$
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 $T > T_{\mathrm{EW}} \Rightarrow n_L \to n_B$
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

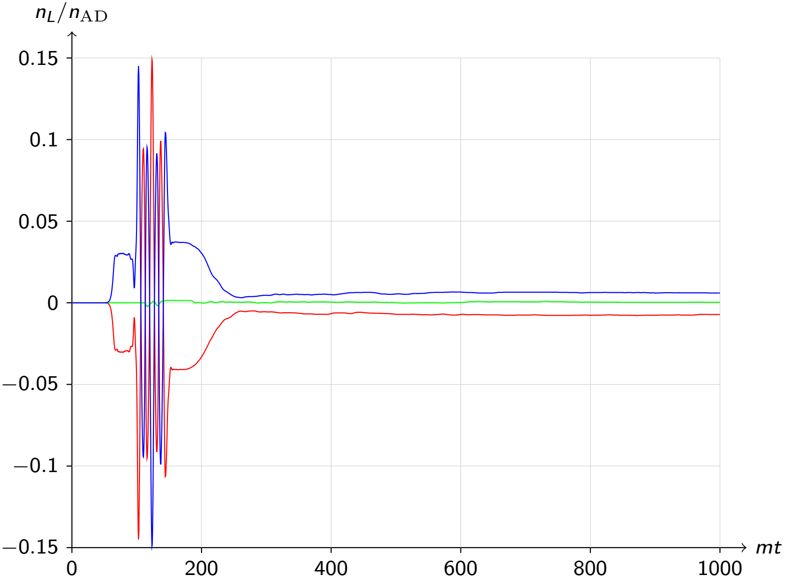
$$\begin{aligned} \phi &= 4m + \delta\phi \\ l &= l_0 + \delta l \\ h_d &= \delta h_d \end{aligned}$$

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

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

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

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

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

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

Dark matter candidates

Peccei-Quinn symmetry

DFSZ axion

KSVZ axion

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

Dark matter candidates

Peccei-Quinn symmetry

DFSZ axion → $\lambda_\mu \phi^2 H_u H_d$; KSVZ axion → $\lambda_\chi \phi \chi \bar{\chi}$

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

Axion

$$m_a \sim \frac{\Lambda^2_{\rm QCD}}{f_a} \qquad \text{where } f_a = \frac{\sqrt{2}\,\phi_0}{N}$$

$$\simeq 6.2 \times 10^{-5}\,\mathrm{eV} \left(\frac{10^{11}\,\mathrm{GeV}}{f_a}\right)$$

Dark matter candidates

Peccei-Quinn symmetry

DFSZ axion

KSVZ axion

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

Axion

$$m_a \sim \frac{\Lambda^2_{\rm QCD}}{f_a} \qquad \text{where } f_a = \frac{\sqrt{2}\,\phi_0}{N}$$

$$\simeq 6.2 \times 10^{-5}\,\mathrm{eV}\left(\frac{10^{11}\,\mathrm{GeV}}{f_a}\right)$$

Axino

$$m_{\tilde{a}} = \frac{1}{16\pi^2}\sum_\chi \lambda_\chi^2 A_\chi$$

$$\sim 1 \text{ to } 10\,\mathrm{GeV}$$

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

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

Axion Misalignment

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

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

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

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

Axino Flaton decay

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

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

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

Axion Misalignment

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

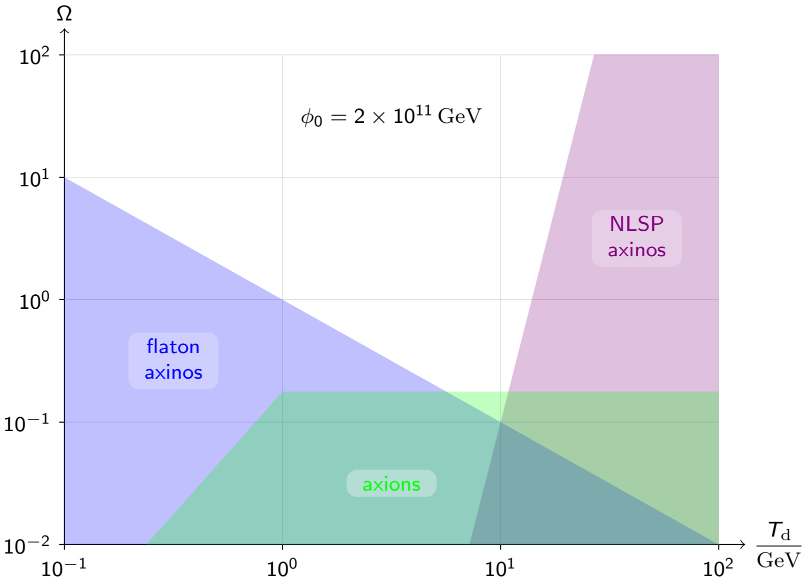
Axino Flaton decay

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

Thermal NLSP decay

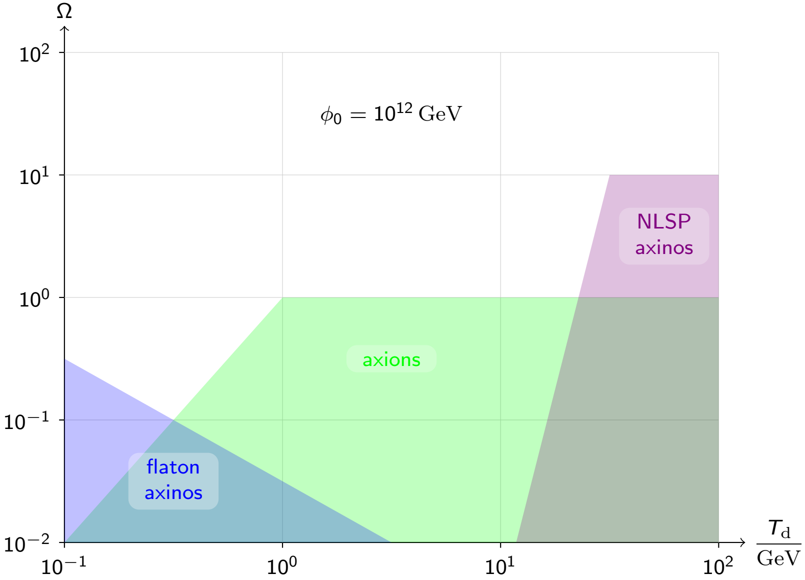
$$\Omega_{\tilde a} \sim 10^3\left(\frac{m_{\tilde a}}{1\,{\rm GeV}}\right)\left(\frac{10^{11}\,{\rm GeV}}{\phi_0}\right)^2\times\begin{cases} 1 & \text{for } T_{\rm d} \gg \frac{m_N}{7} \\ \left(\frac{7\,T_{\rm d}}{m_N}\right)^7 & \text{for } T_{\rm d} \ll \frac{m_N}{7}\end{cases}$$

Dark matter composition



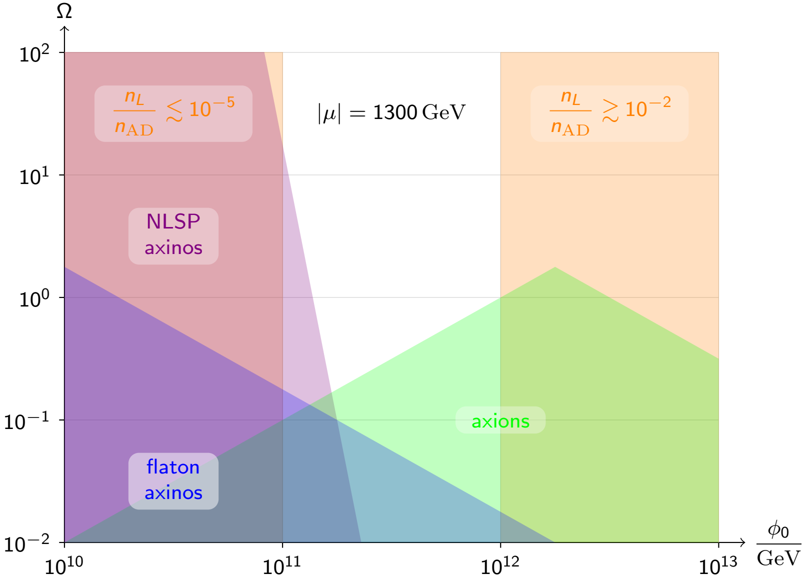
$\phi_0 = 10^{12}$ GeV

Dark matter composition



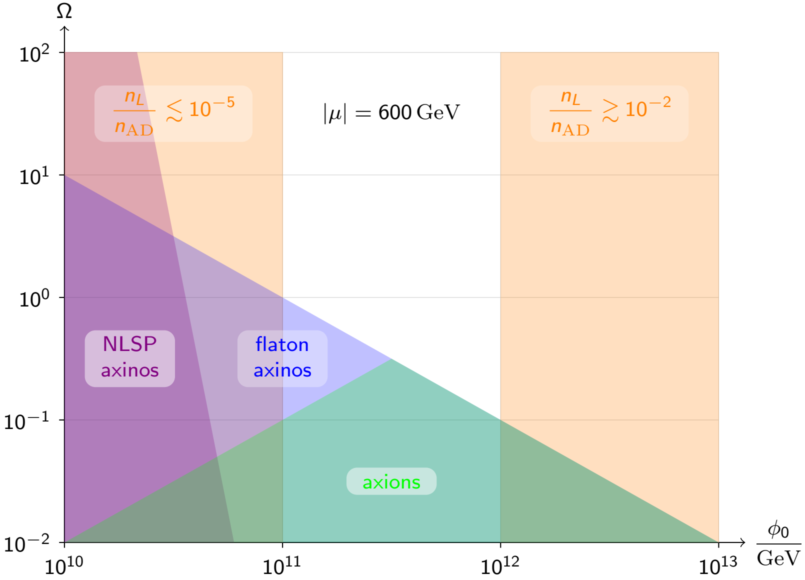
$\phi_0 = 2 \times 10^{11}$ GeV

Dark matter composition



$|\mu| = 600\ \mathrm{GeV}$

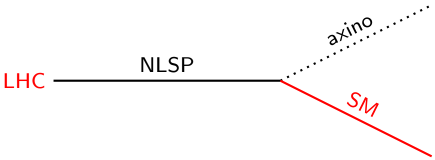
Dark matter composition



$|\mu| = 1300\ \mathrm{GeV}$

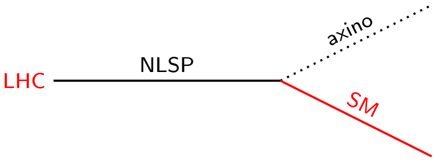
Axino LHC signal

NLSPs produced by the LHC decay to axinos plus Standard Model particles



Axino LHC signal

NLSPs produced by the LHC decay to axinos plus Standard Model particles



with a decay length

$$\frac{1}{\Gamma_{N\to\tilde{a}}} \sim \frac{16\pi\phi_0^2}{m_N^3} \sim 100\,\mathrm{m}\left(\frac{200\,\mathrm{GeV}}{m_N}\right)^3\left(\frac{\phi_0}{3\times 10^{11}\,\mathrm{GeV}}\right)^2$$

and well constrained parameters

$$10^{11}\,\mathrm{GeV} \lesssim \phi_0 \lesssim 10^{12}\,\mathrm{GeV}$$

$$m_{\tilde{a}} \simeq 1\,\mathrm{GeV}$$

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

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

Simple model

MSSM

neutrino masses

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

Simple model

MSSM

neutrino masses

MSSM μ-term

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

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

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

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Simple model

MSSM

neutrino masses

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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

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 $m_{LH_u}^2 < 0$

drives $m_\phi^2 < 0$
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 $m_{LH_u}^2 < 0$

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Simple model

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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 $m^2_{LH_u} < 0$

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

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

MSSM

neutrino masses
stabilizes LH_u

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

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

stabilizes d and e

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

Simple model

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

MSSM ($\lambda_u Q H_u \bar{u} + \lambda_d Q H_d \bar{d} + \lambda_e L H_d \bar{e}$)

neutrino masses
stabilizes LH_u ($\frac{1}{2}\lambda_\nu (L H_u)^2$)

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

drives $m^2_{LH_u} < 0$ ($\lambda_u Q H_u \bar{u}$)

stabilizes d and e ($\lambda_d Q H_d \bar{d} + \lambda_e L H_d \bar{e}$)

leptogenesis ($\frac{1}{2}\lambda_\nu (L H_u)^2 + \lambda_\mu \phi^2 H_u H_d$)

drives $m^2_\phi < 0$
KSVZ axion
thermal inflation
releases ϕ ($\lambda_\chi \phi \chi \bar{\chi}$)

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

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

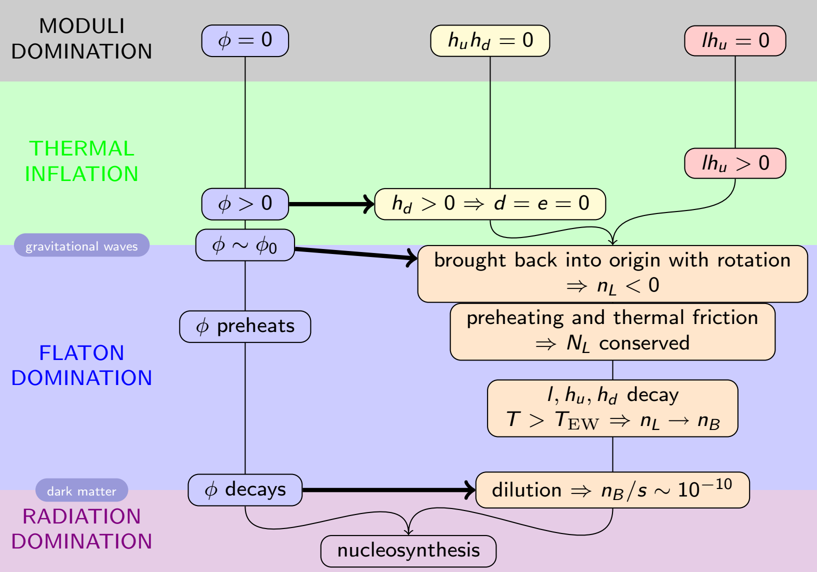
drives $m^2_{LH_u} < 0$

stabilizes d and e

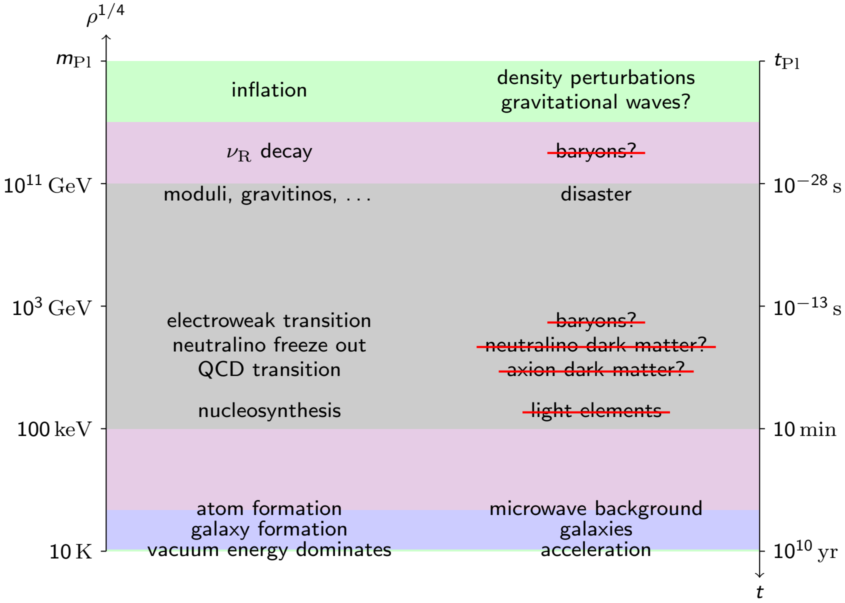
leptogenesis

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

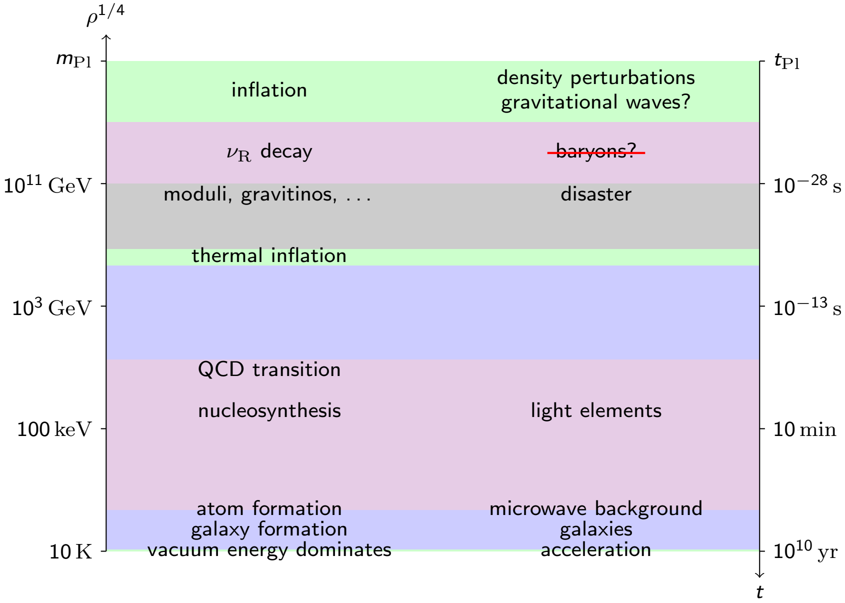
Rich cosmology



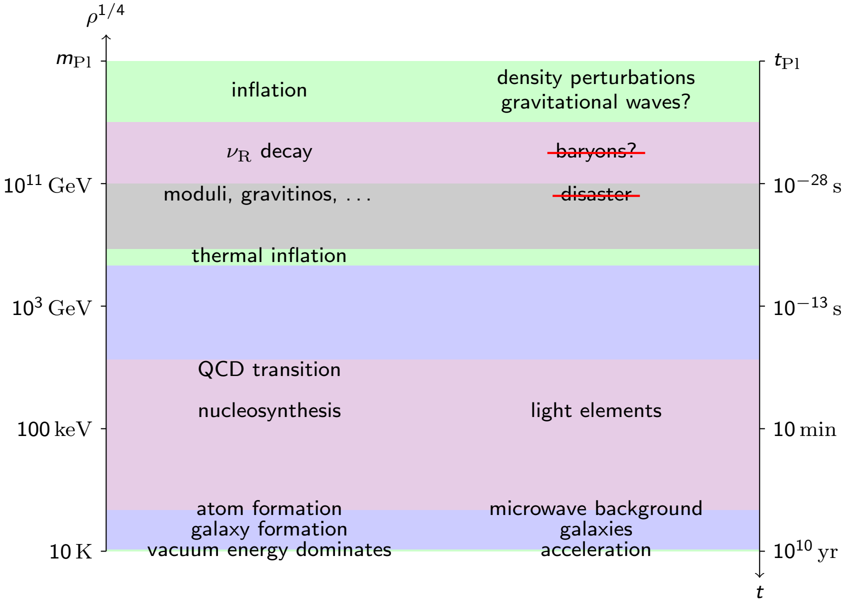
History of the observable universe



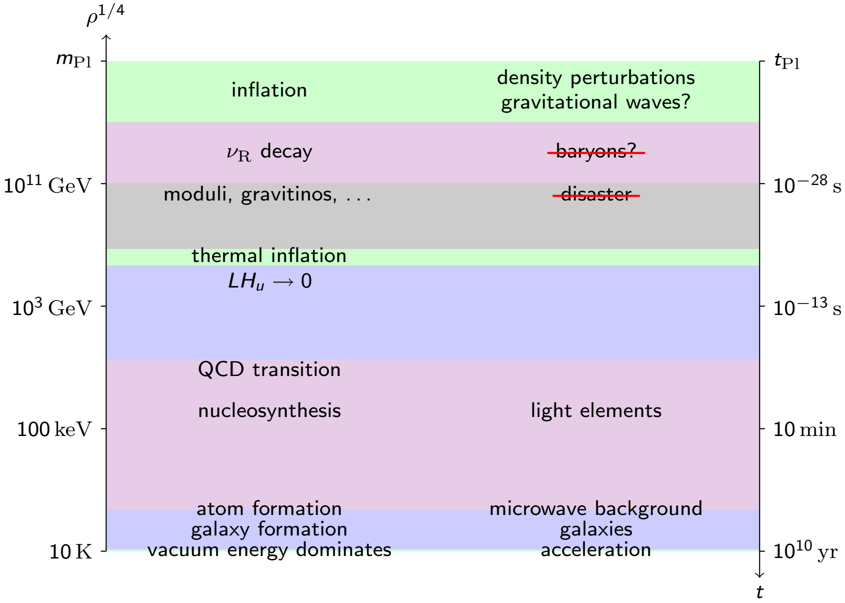
History of the observable universe



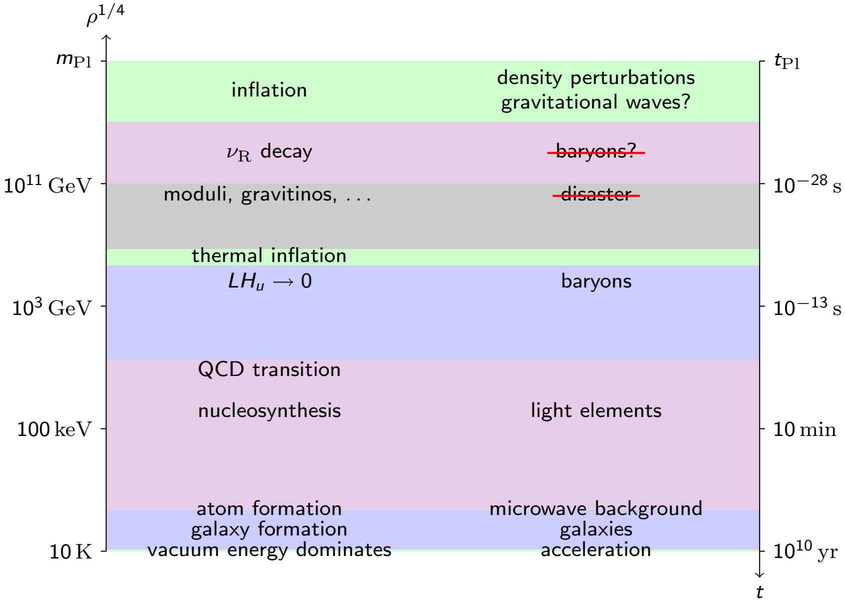
History of the observable universe



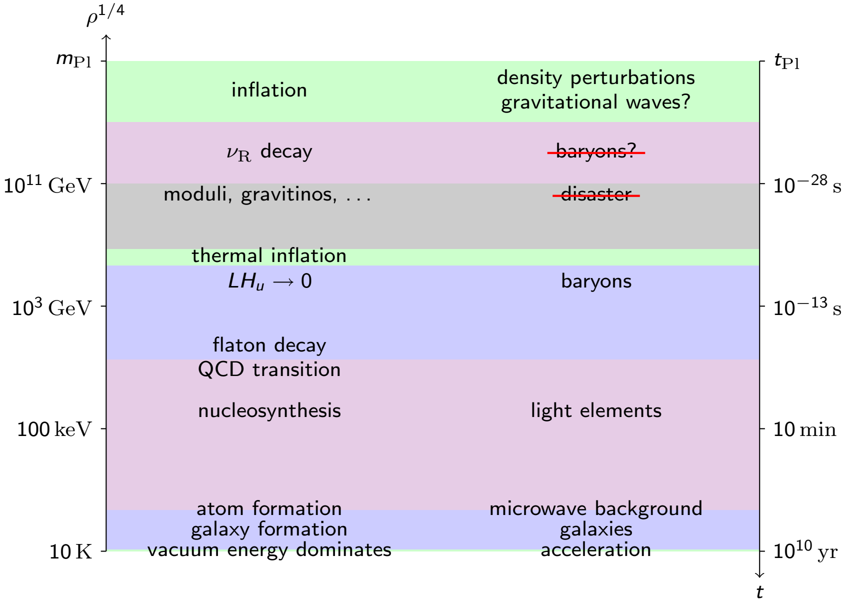
History of the observable universe



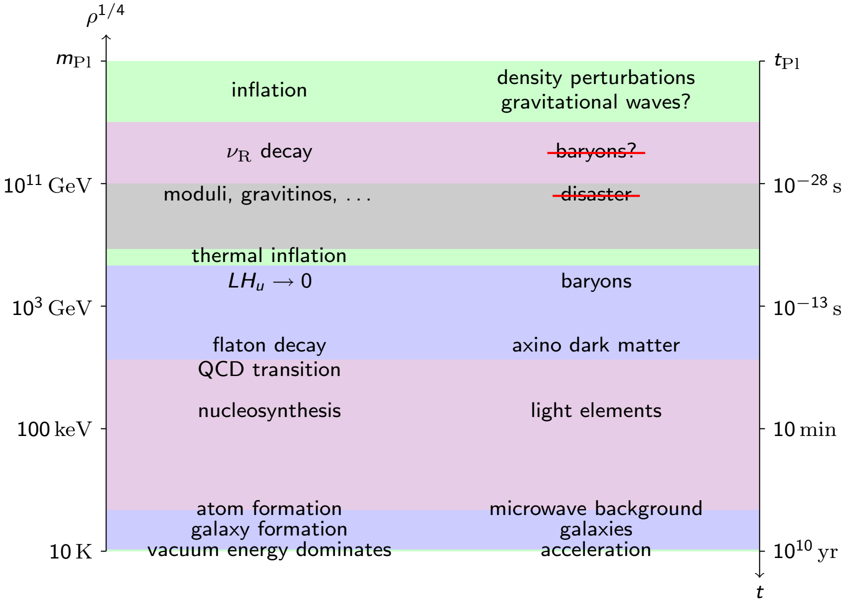
History of the observable universe



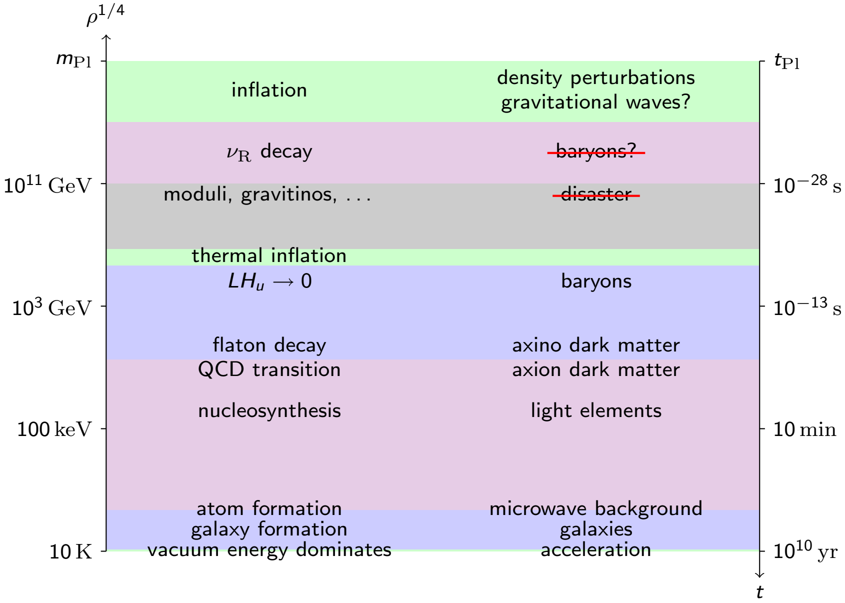
History of the observable universe



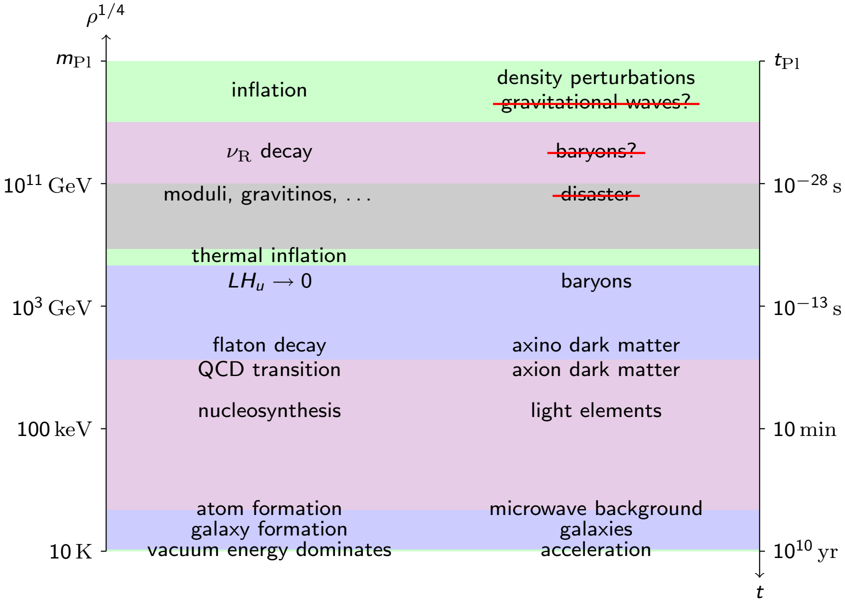
History of the observable universe



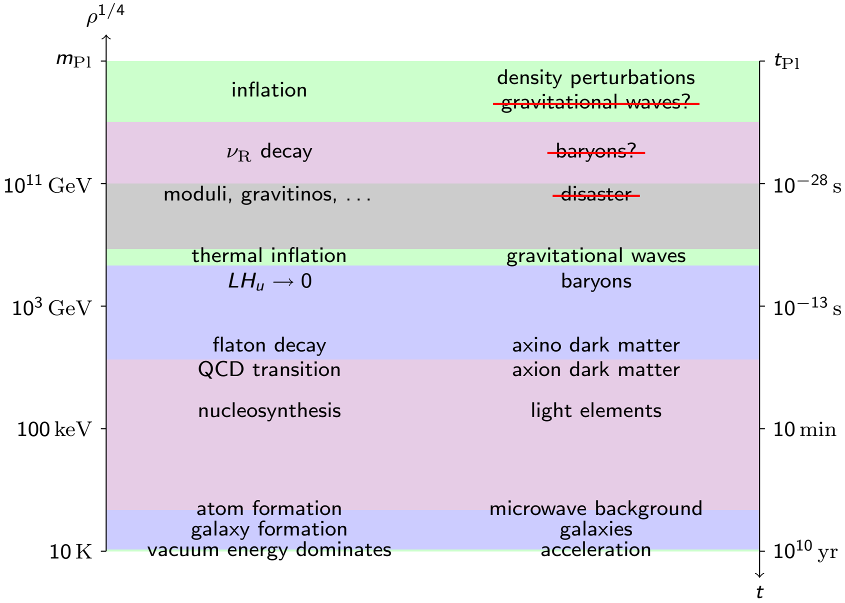
History of the observable universe



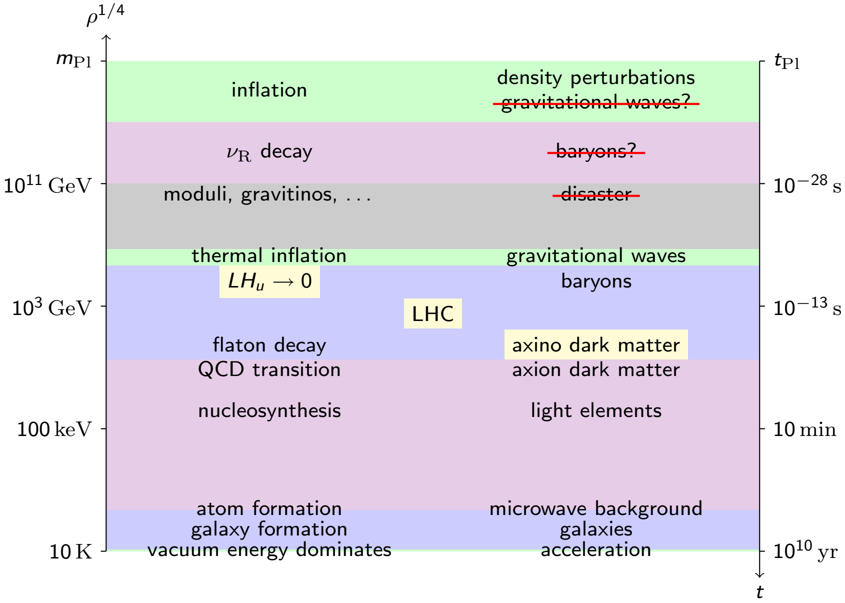
History of the observable universe



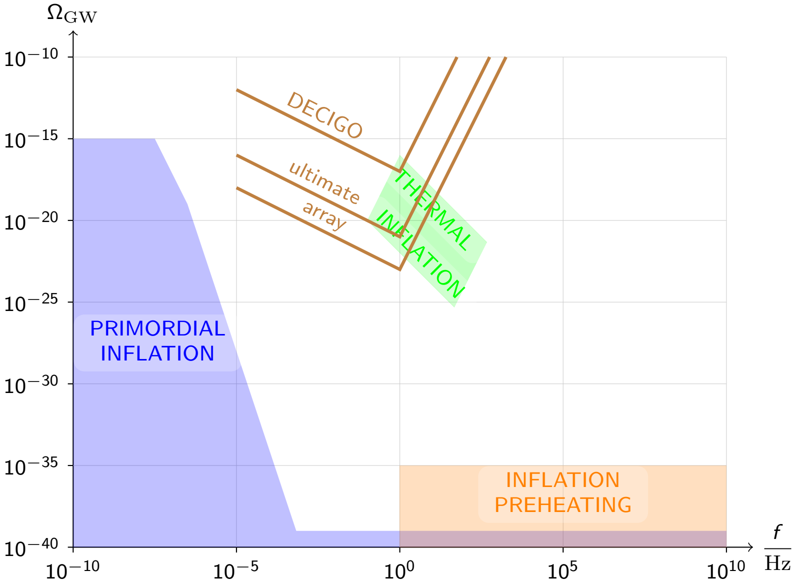
History of the observable universe



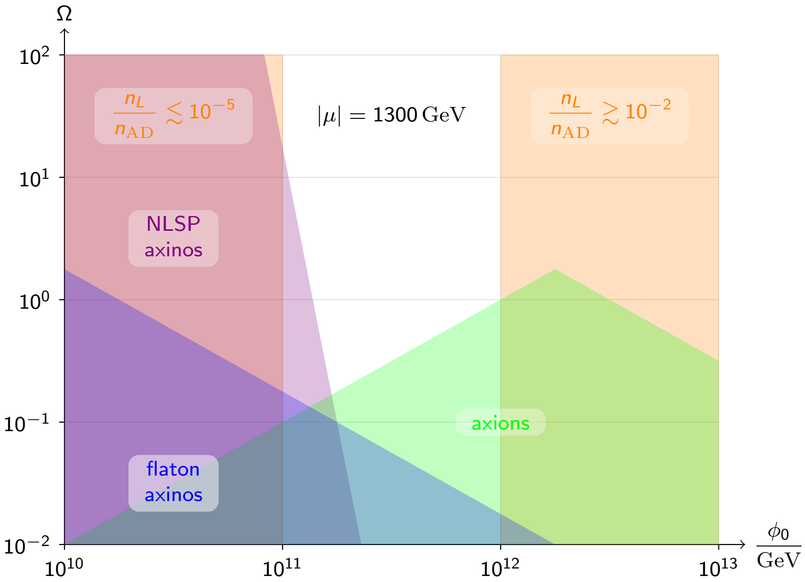
History of the observable universe



Gravitational waves

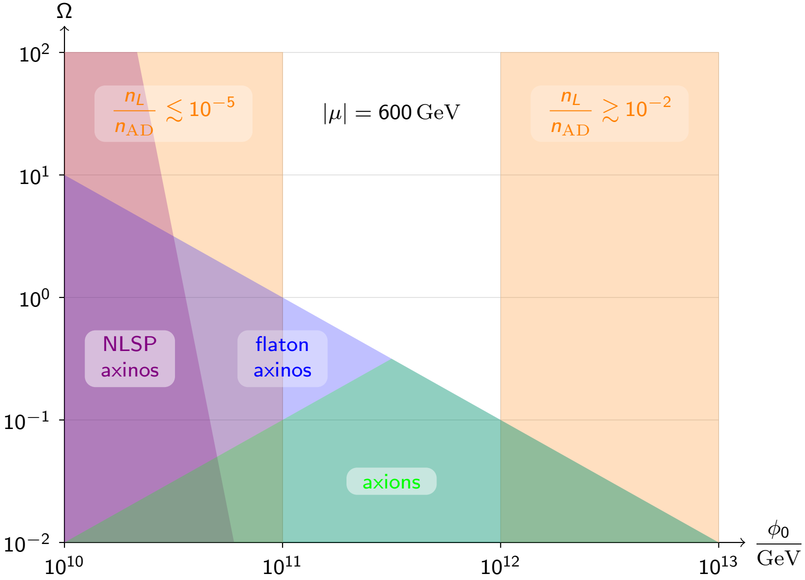


Dark matter composition



$|\mu| = 600$ GeV

Dark matter composition



$|\mu| = 1300$ GeV

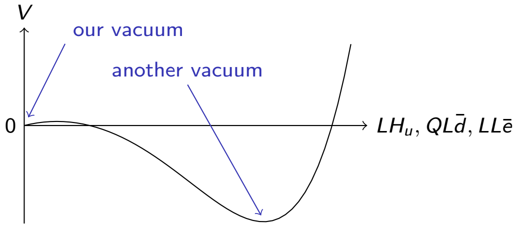
Key assumption

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

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

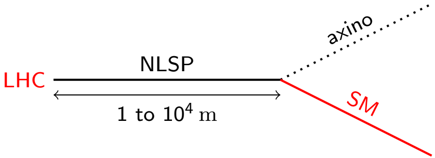
$$\lambda_d QL\bar{d} + \lambda_e LL\bar{e} = -\mu LH_u$$

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



Axino LHC signal

NLSPs produced by the LHC decay to axinos plus Standard Model particles



with a decay length

$$\frac{1}{\Gamma_{N\to\tilde{a}}} \sim \frac{16\pi\phi_0^2}{m_N^3} \sim 100\,\mathrm{m}\left(\frac{200\,\mathrm{GeV}}{m_N}\right)^3\left(\frac{\phi_0}{3\times 10^{11}\,\mathrm{GeV}}\right)^2$$

and well constrained parameters

$$10^{11}\,\mathrm{GeV} \lesssim \phi_0 \lesssim 10^{12}\,\mathrm{GeV}$$

$$m_{\tilde{a}} \simeq 1\,\mathrm{GeV}$$