A Minimal Supersymmetric Cosmological Model

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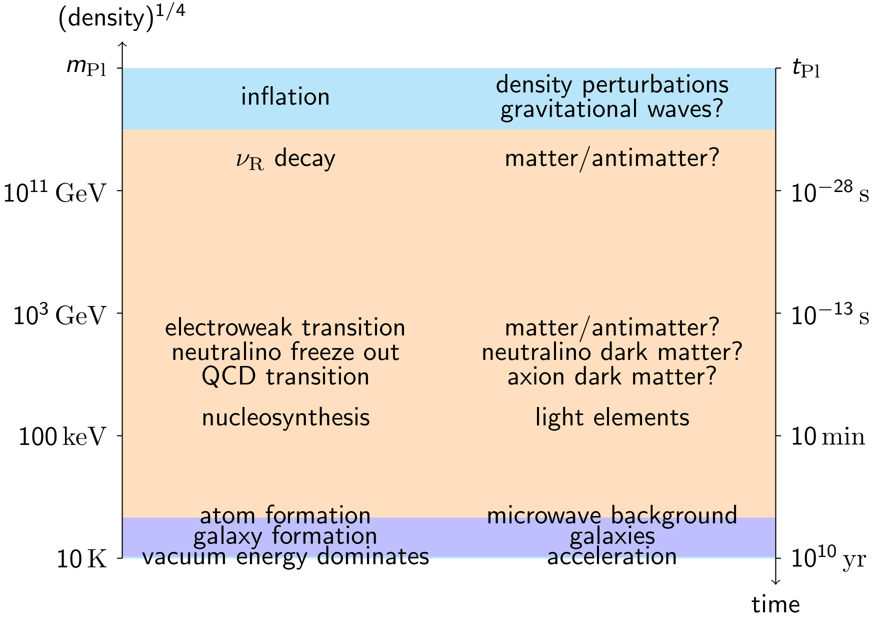
EDS, M Kawasaki, T Yanagida	hep-ph/9603324
D Jeong, K Kadota, W-I Park, EDS	hep-ph/0406136
G N Felder, H Kim, W-I Park, EDS	hep-ph/0703275
R Easther, J T Giblin, E A Lim, W-I Park, EDS	arXiv:0801.4197
S Kim, W-I Park, EDS	arXiv:0807.3607

Standard model of cosmology



Moduli and gravitinos

Moduli are cosmologically dangerous. Nucleosynthesis constrains

$$\frac{n}{s} \lesssim 10^{-12} \text{ to } 10^{-15}$$

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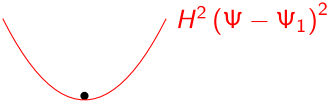
In the early universe



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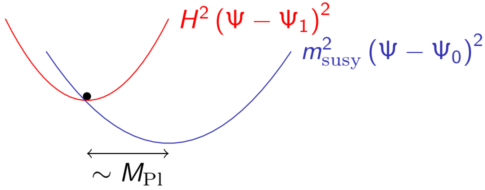

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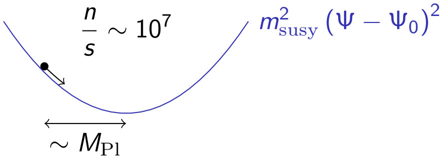

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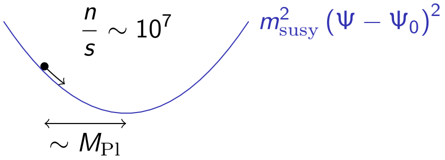

Moduli generated: $H \lesssim m_{\rm susy}$

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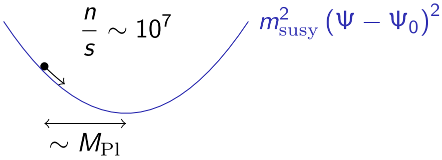

Moduli generated: $H \lesssim m_{\rm susy}$

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

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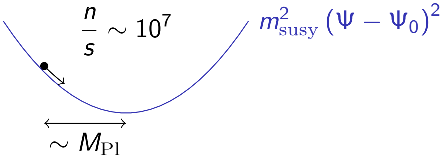
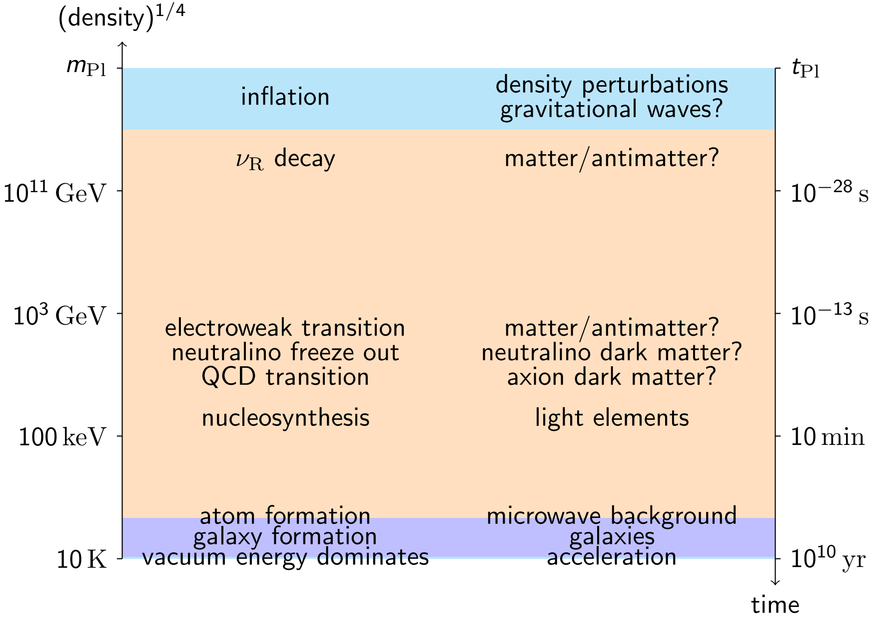


Moduli generated: $H \lesssim m_{\rm susy}$

after

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

Standard model of cosmology



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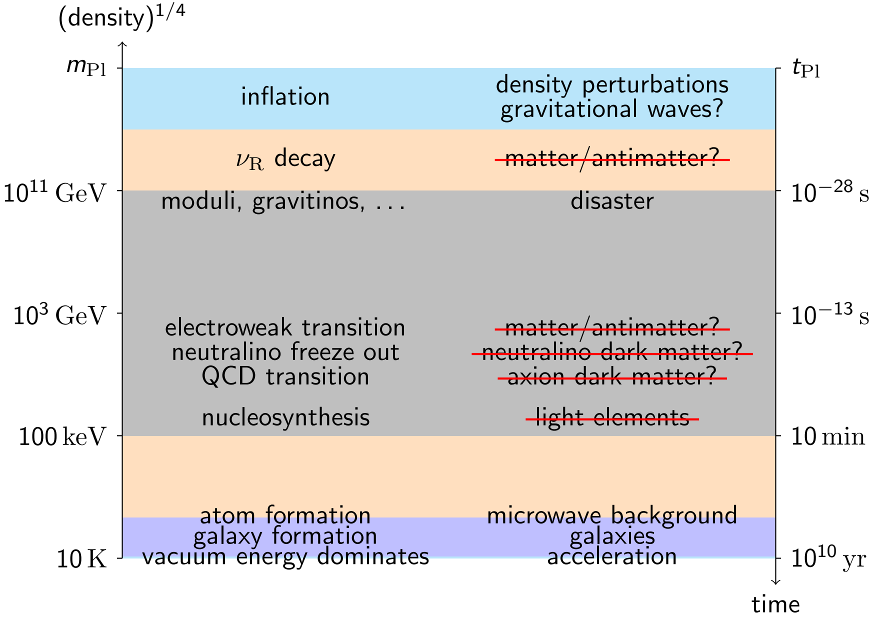

Minimal Supersymmetric Standard Model

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

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But

- μ?
- neutrino masses?
- strong CP?

Minimal Supersymmetric Cosmological Model

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

Minimal Supersymmetric Cosmological Model

MSSM

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

Minimal Supersymmetric Cosmological Model

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Minimal Supersymmetric Cosmological Model

MSSM — neutrino masses — MSSM μ-term

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Minimal Supersymmetric Cosmological Model

MSSM — neutrino masses — MSSM μ-term — drives $m_\phi^2 < 0$

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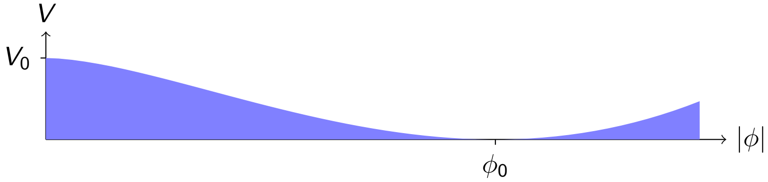

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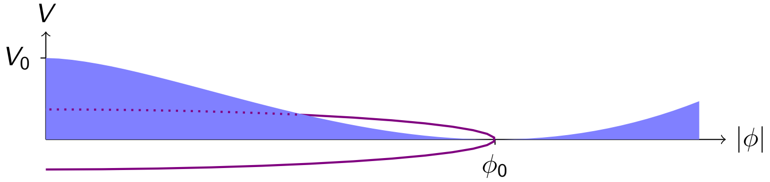
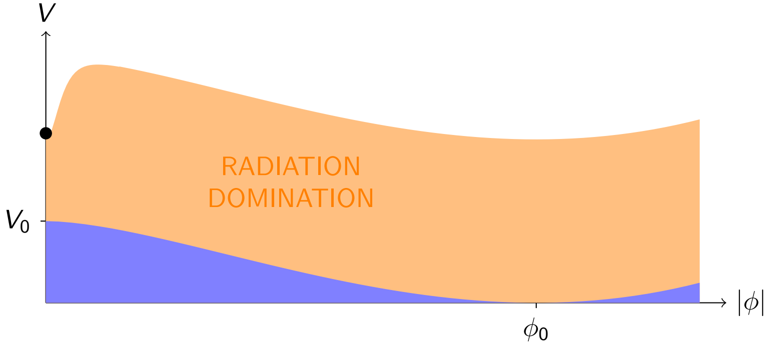


Thermal inflation



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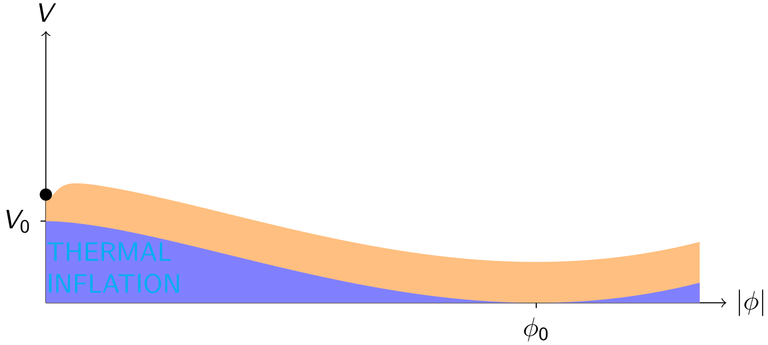

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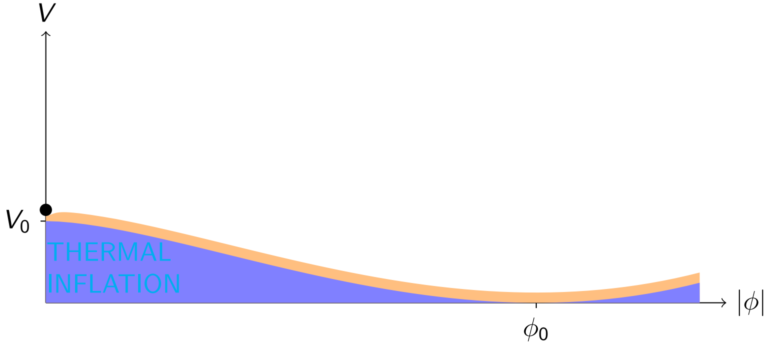

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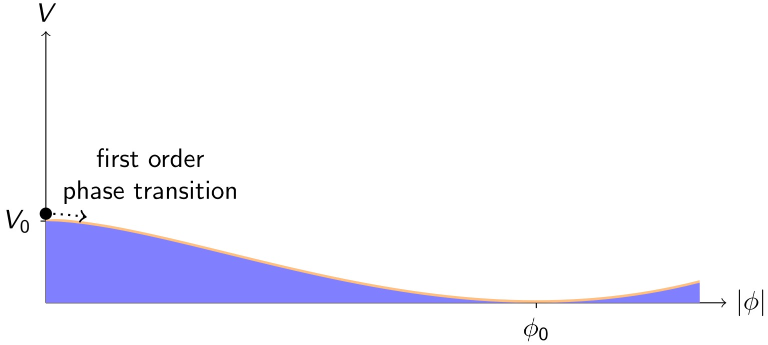

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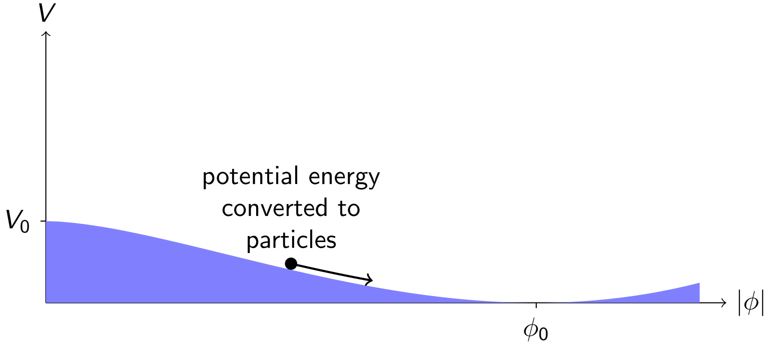

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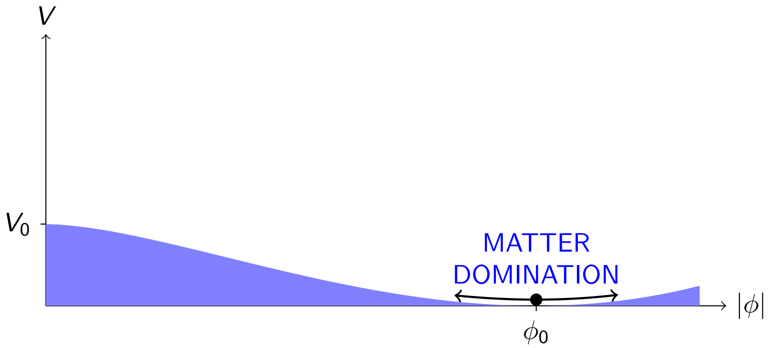

Key properties of thermal inflation

For

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

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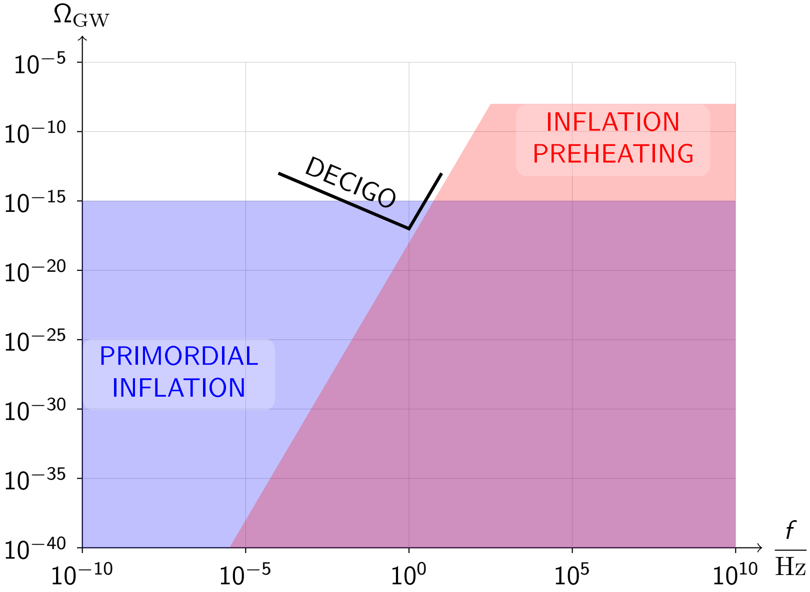
Low energy scale

$$V_0^{1/4} \sim 10^6 \text{ to } 10^7\,\mathrm{GeV} \quad \Longrightarrow \quad \begin{array}{c}\text{moduli regenerated with}\\ \text{sufficiently small abundance}\end{array}$$

Gravitational waves



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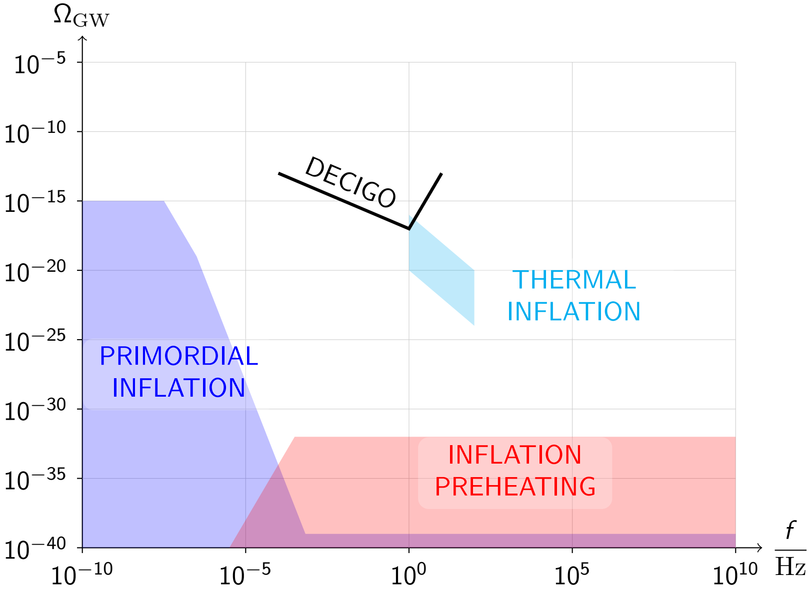

Baryogenesis

Key assumption

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

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Key assumption

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

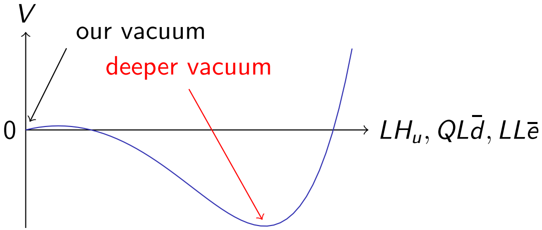
Implies a dangerous non-MSSM vacuum with

$$LH_u \sim (10^9 \mathrm{GeV})^2$$

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

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

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$$L = \begin{pmatrix} l \\ e/\sqrt{2} \end{pmatrix} \quad , \quad H_u = \begin{pmatrix} 0 \\ h_u \end{pmatrix} \quad , \quad H_d = \begin{pmatrix} h_d \\ 0 \end{pmatrix} \quad , \quad \bar{e} = \begin{pmatrix} e/\sqrt{2} \end{pmatrix}$$

$$\bar{u} = \begin{pmatrix} 0 & 0 & 0 \end{pmatrix} \quad , \quad Q = \begin{pmatrix} 0 & 0 & 0 \\ d/\sqrt{2} & 0 & 0 \end{pmatrix} \quad , \quad \bar{d} = \begin{pmatrix} d/\sqrt{2} & 0 & 0 \end{pmatrix}$$

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

Potential

$$V_0 + m_L^2|l|^2 - m_{H_u}^2|h_u|^2 + m_{H_d}^2|h_d|^2 + m_d^2|d|^2 + m_e^2|e|^2 - m_\phi^2|\phi|^2$$

$$+ \left[\frac{1}{2}A_\nu\lambda_\nu l^2 h_u^2 - \frac{1}{2}A_d\lambda_d h_d d^2 - \frac{1}{2}A_e\lambda_e h_d e^2 - A_\mu\lambda_\mu\phi^2 h_u h_d + \text{c.c.} \right]$$

$$+ \left|\lambda_\nu l h_u^2\right|^2 + \left|\lambda_\nu l^2 h_u - \lambda_\mu\phi^2 h_d\right|^2 + \left|\lambda_\mu\phi^2 h_u + \frac{1}{2}\lambda_d d^2 + \frac{1}{2}\lambda_e e^2\right|^2$$

$$+ |\lambda_d h_d d|^2 + |\lambda_e h_d e|^2 + |2\lambda_\mu\phi h_u h_d|^2$$

$$+ \frac{1}{2}g^2\left(|h_u|^2 - |h_d|^2 - |l|^2 + \frac{1}{2}|d|^2 + \frac{1}{2}|e|^2\right)^2$$

Potential

drives thermal inflation

$$
\begin{aligned}
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lh_u rolls away

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lh_u stabilized with fixed phase

Potential

drives thermal inflation

lh_u rolls away

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lh_u stabilized with fixed phase

h_d forced out

Potential

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lh_u stabilized with fixed phase

d and e held at origin

h_d forced out

Potential

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lh_u rolls away

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lh_u stabilized with fixed phase

d and e held at origin

lh_u returns with rotation

h_d forced out

Potential

drives thermal inflation

lh_u rolls away

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

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

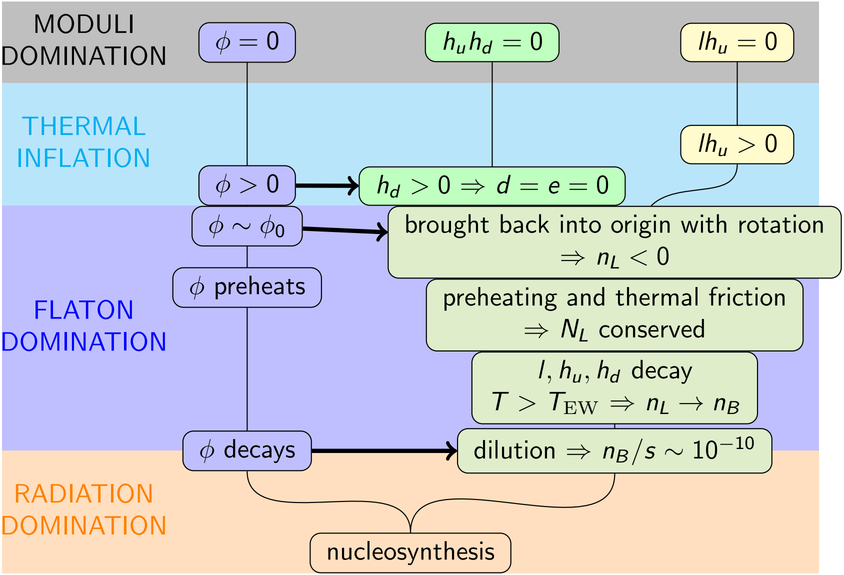
lh_u stabilized with fixed phase

d and e held at origin

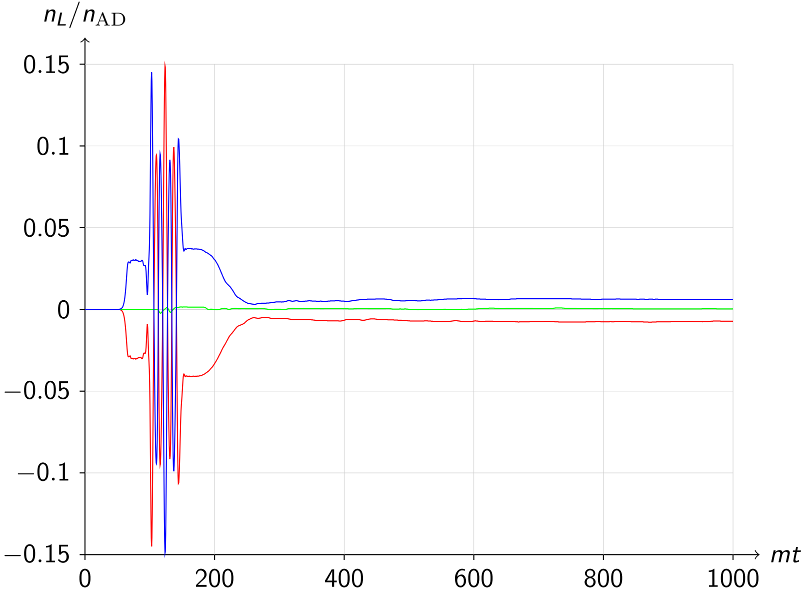
lh_u returns with rotation

h_d forced out

Baryogenesis



Numerical simulation



Baryon asymmetry

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

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Using

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

$$l_0 \sim 10^9\,{\rm GeV} \sqrt{\left(\frac{10^{-2}\,{\rm eV}}{m_\nu}\right) \left(\frac{m_{LH_u}}{\rm TeV}\right)}$$

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

gives

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

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which suggests

$$\phi_0 \sim 10^{12}\,{\rm GeV}$$

Dark matter candidates

Peccei-Quinn symmetry

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

Dark matter candidates

Peccei-Quinn symmetry

DFSZ axion

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Peccei-Quinn symmetry

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Axion

$$\begin{aligned} m_a &\sim \frac{\Lambda_{\rm QCD}^2}{f_a} \qquad \text{where } f_a = \frac{\sqrt{2}\,\phi_0}{N} \\ &\simeq 6.2 \times 10^{-6}\,{\rm eV} \left(\frac{10^{12}\,{\rm GeV}}{f_a}\right) \end{aligned}$$

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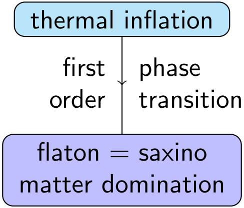
Axino

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

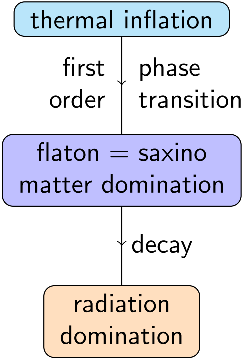
Dark matter genesis

thermal inflation

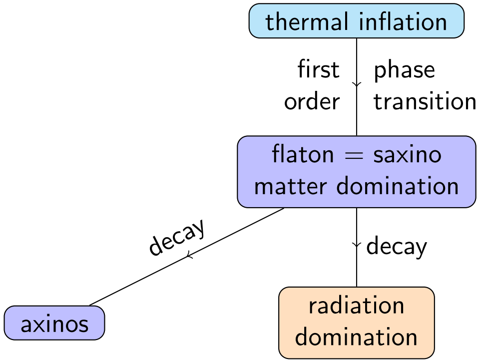
Dark matter genesis



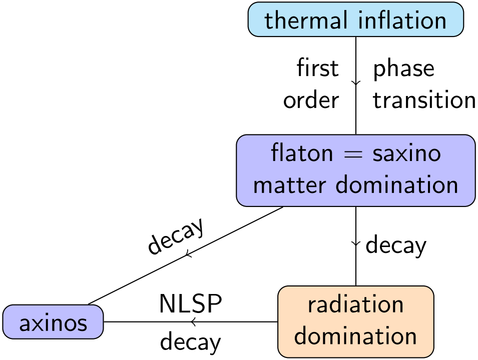
Dark matter genesis



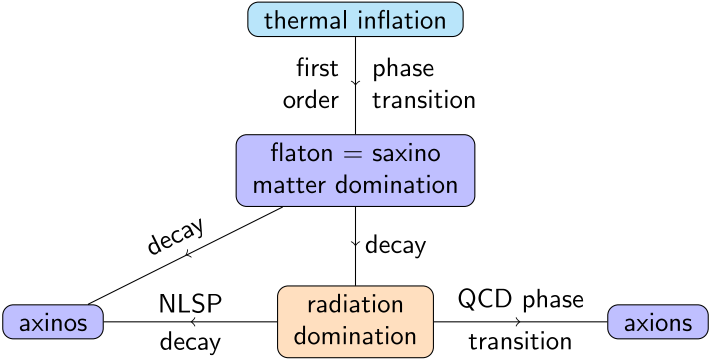
Dark matter genesis



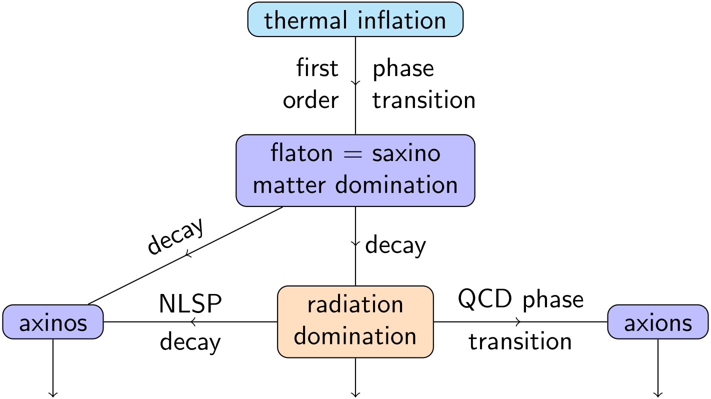
Dark matter genesis



Dark matter genesis



Dark matter genesis



Dark matter abundance

Axion

Axino

Dark matter abundance

Axion Misalignment

$$\Omega_a \sim 3 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}} \right)^{1.2}$$

Axino

Dark matter abundance

Axion Misalignment

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Axino Flaton decay

$$\Omega_{\tilde{a}} \simeq 0.04 \left(\frac{\alpha_{\tilde{a}}}{10^{-1}} \right)^2 \left(\frac{m_{\tilde{a}}}{1\,\mathrm{GeV}} \right)^3 \left(\frac{10^{12}\,\mathrm{GeV}}{\phi_0} \right)^2 \left(\frac{1\,\mathrm{GeV}}{T_\mathrm{d}} \right)$$

Dark matter abundance

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Thermal NLSP decay

$$\Omega_{\tilde{a}} \sim 10 \left(\frac{m_{\tilde{a}}}{1\,\mathrm{GeV}} \right) \left(\frac{10^{12}\,\mathrm{GeV}}{\phi_0} \right)^2$$

Dark matter abundance

Flaton decays late

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

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Axion Misalignment

$$\Omega_a \sim 3\left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{1.2} \times \begin{cases} 1 & \text{for } T_{\mathrm{d}} \gg 1\,\mathrm{GeV} \\ \left(\frac{T_{\mathrm{d}}}{1\,\mathrm{GeV}}\right)^2 & \text{for } T_{\mathrm{d}} \ll 1\,\mathrm{GeV} \end{cases}$$

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Thermal NLSP decay

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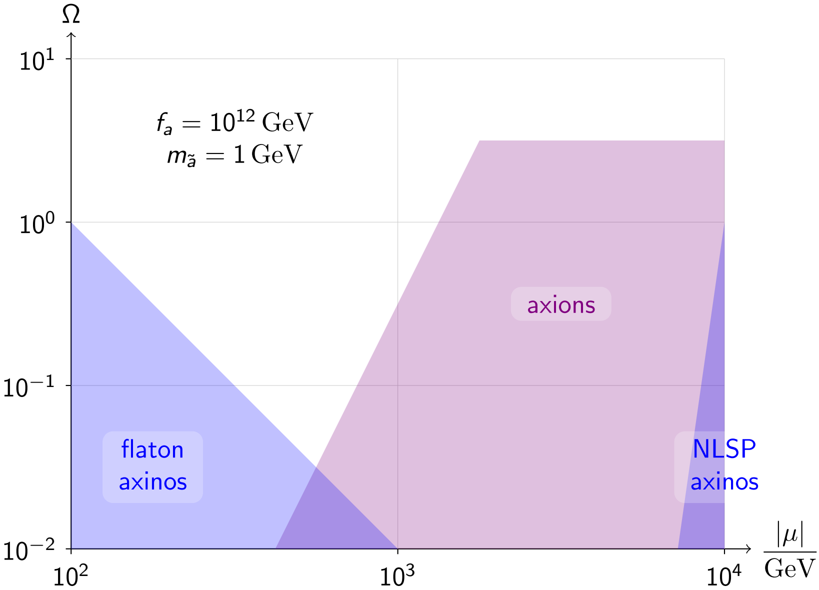
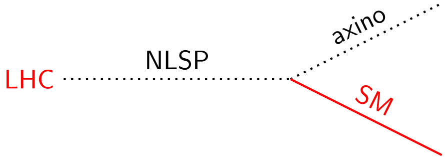
Dark matter composition



Axino LHC signal

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



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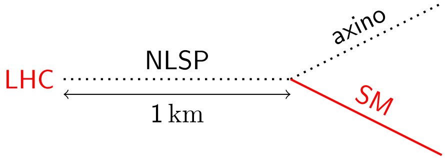

with a decay length

$$\frac{1}{\Gamma_{N \to \tilde{a}}} \sim \frac{16\pi\phi_0^2}{m_N^3} \sim 1\,\mathrm{km}\left(\frac{200\,\mathrm{GeV}}{m_N}\right)^3 \left(\frac{\phi_0}{10^{12}\,\mathrm{GeV}}\right)^2$$

and well constrained parameters

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

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

Simple model

MSSM

neutrino masses

MSSM μ-term

drives $m_\phi^2 < 0$

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

axion

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axion

thermal inflation

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baryogenesis

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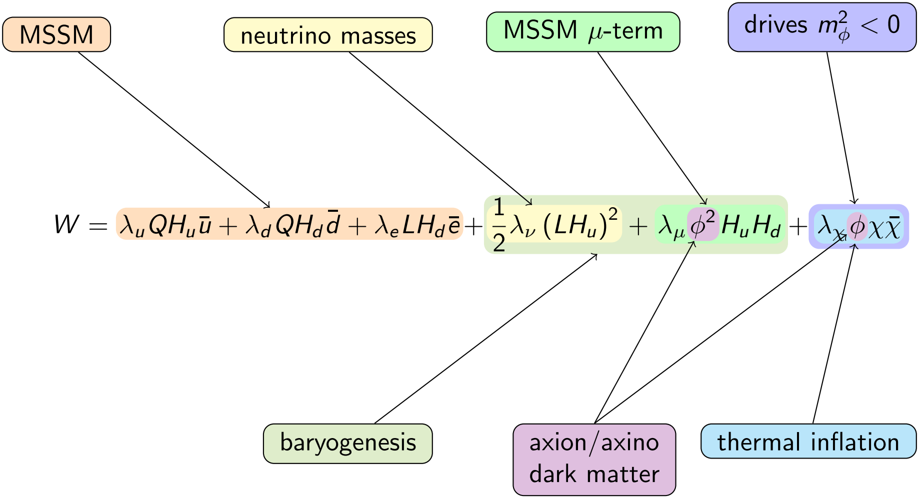
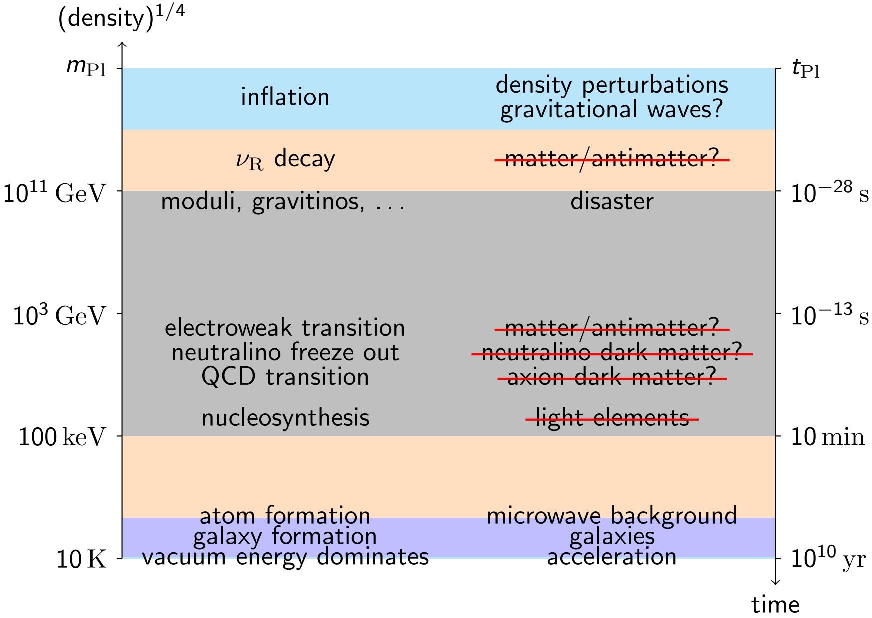


Rich cosmology



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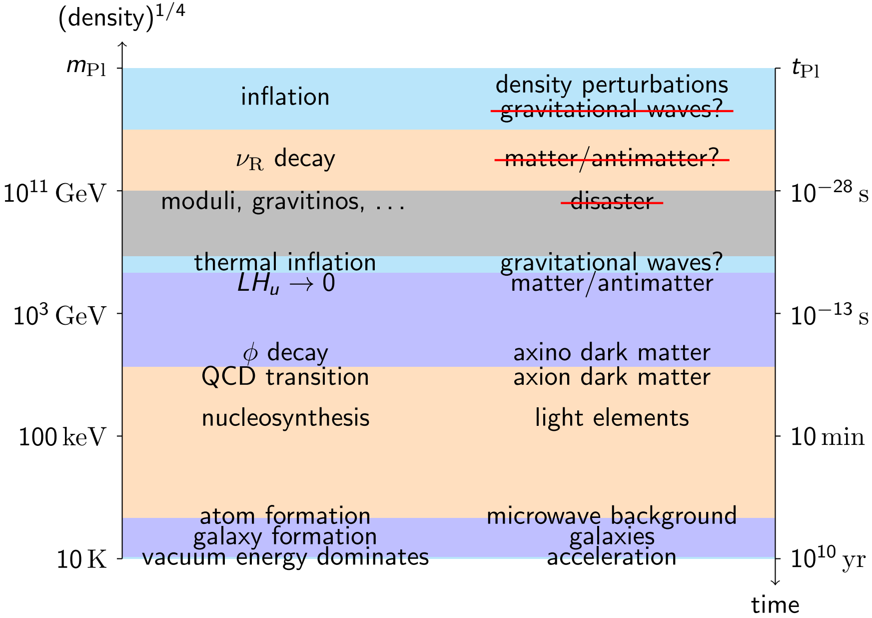

A Minimal Supersymmetric Cosmological Model