A Minimal Supersymmetric Cosmological Model

Ewan Stewart

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Beyond the Standard Models of
Particle Physics, Cosmology and Astrophysics
2 February 2010
Cape Town, South Africa

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Gary N Felder, Hyunbyuk Kim, Wan-Il Park, EDS	hep-ph/0703275
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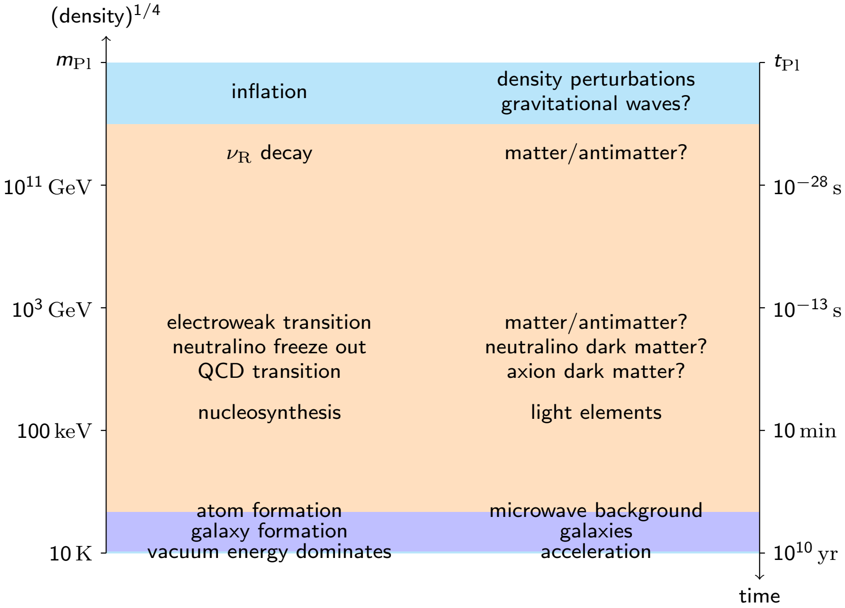
Standard model of cosmology



Moduli and gravitinos

Moduli are cosmologically dangerous. Nucleosynthesis constrains

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

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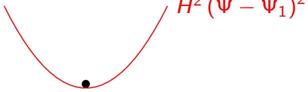
In the early universe



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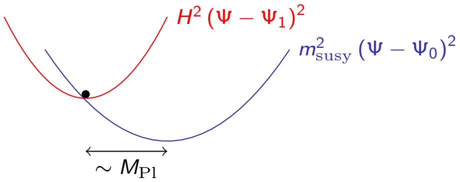

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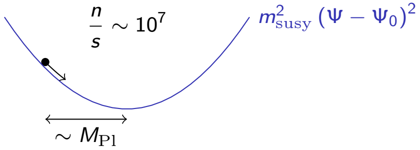

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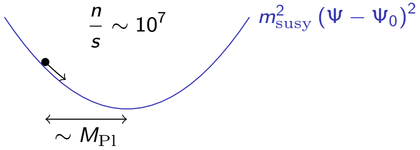

Moduli generated: $H \lesssim m_{\rm susy}$

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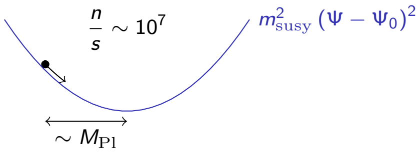

Moduli generated: $H \lesssim m_{\rm susy}$

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

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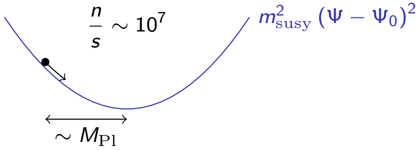

Moduli generated: $H \lesssim m_{\rm susy}$

after

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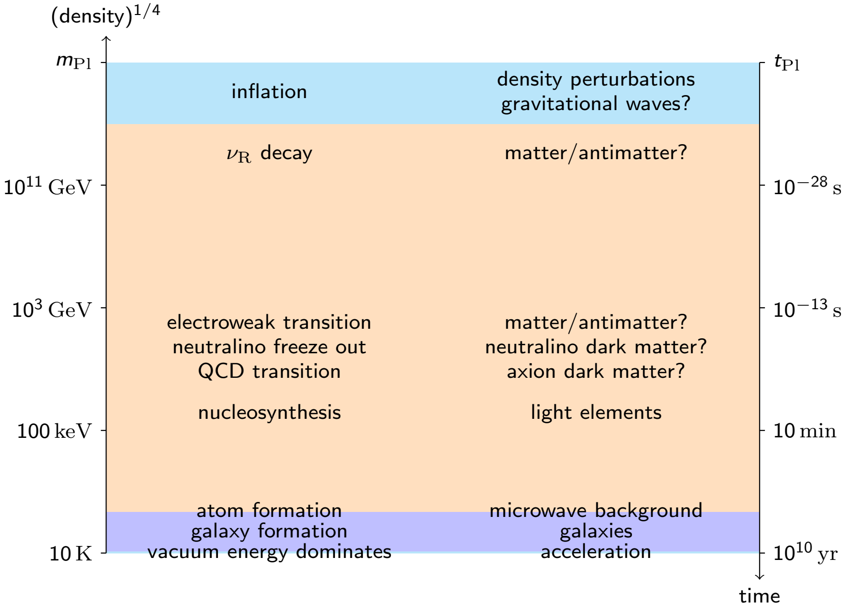

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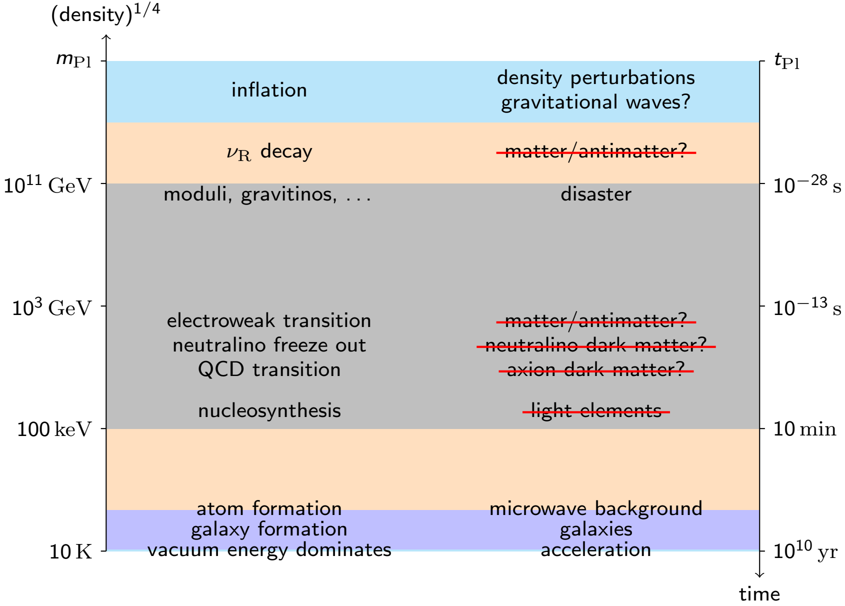

Minimal Supersymmetric Standard Model

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

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- strong CP?

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Minimal Supersymmetric Cosmological Model

MSSM

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MSSM

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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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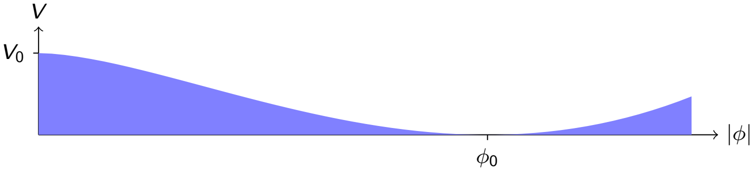

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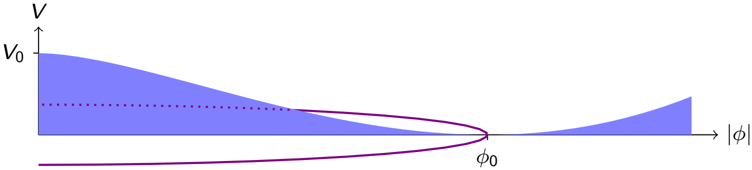
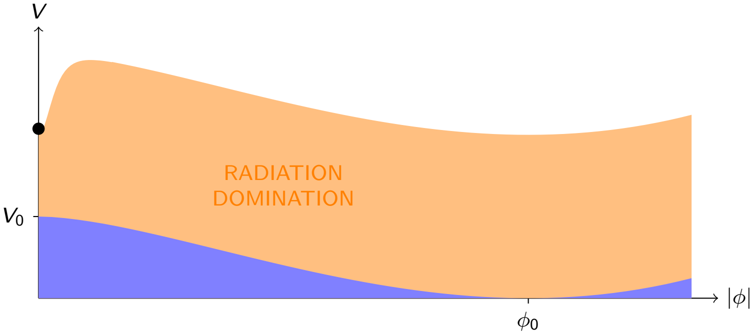


Thermal inflation



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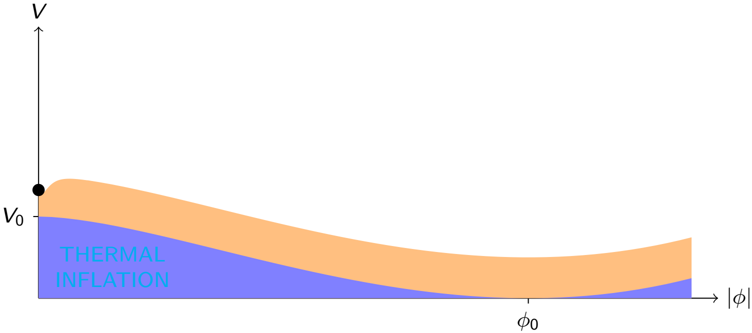

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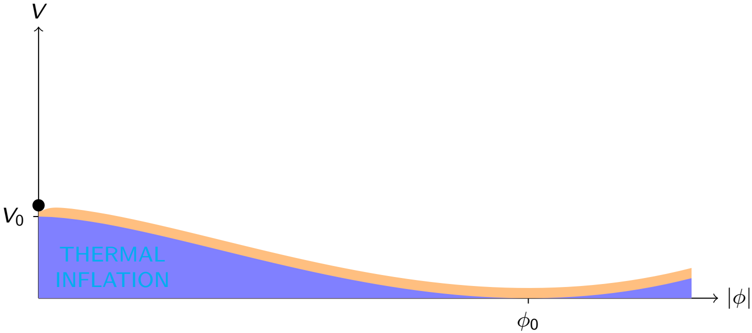

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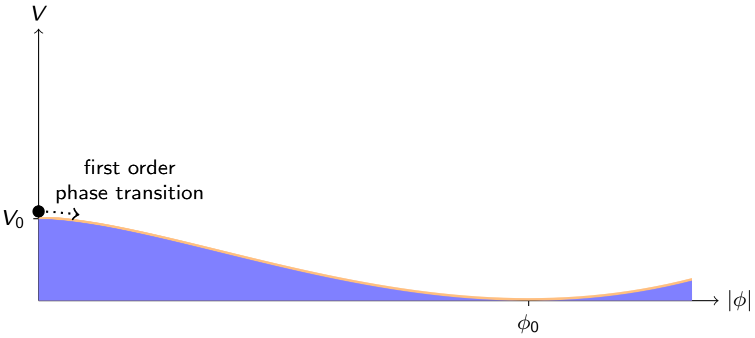

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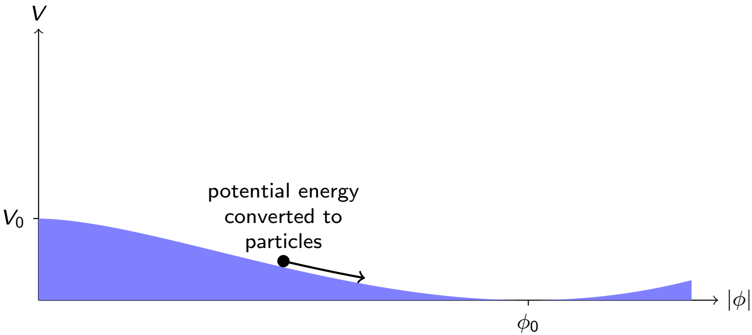

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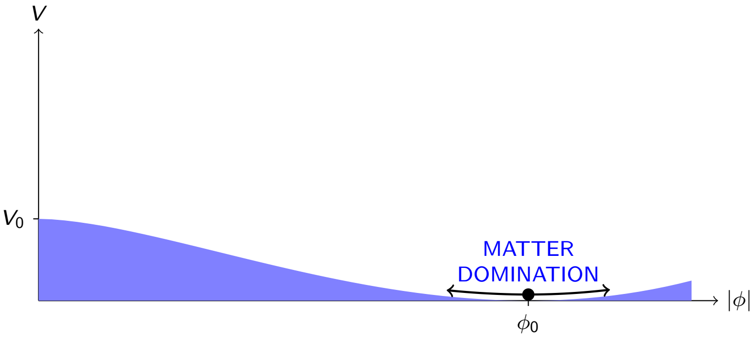

Key properties of thermal inflation

For

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

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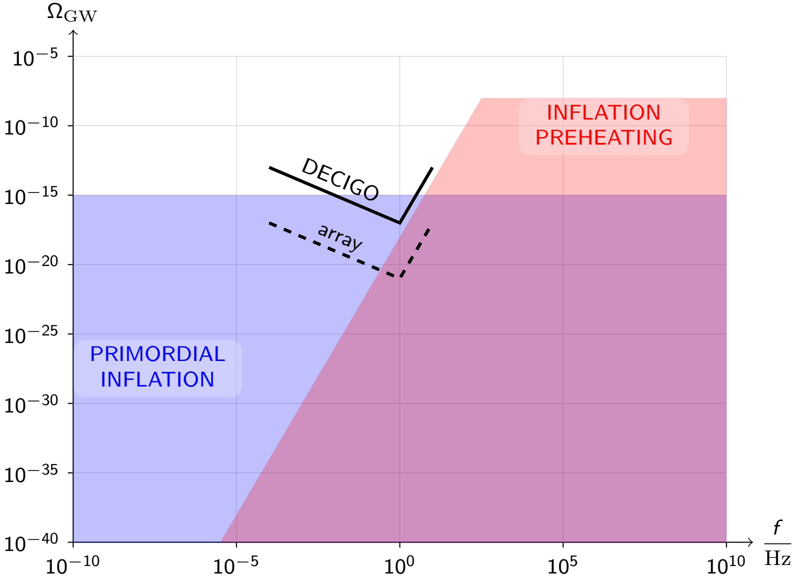
Low energy scale

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

Gravitational waves



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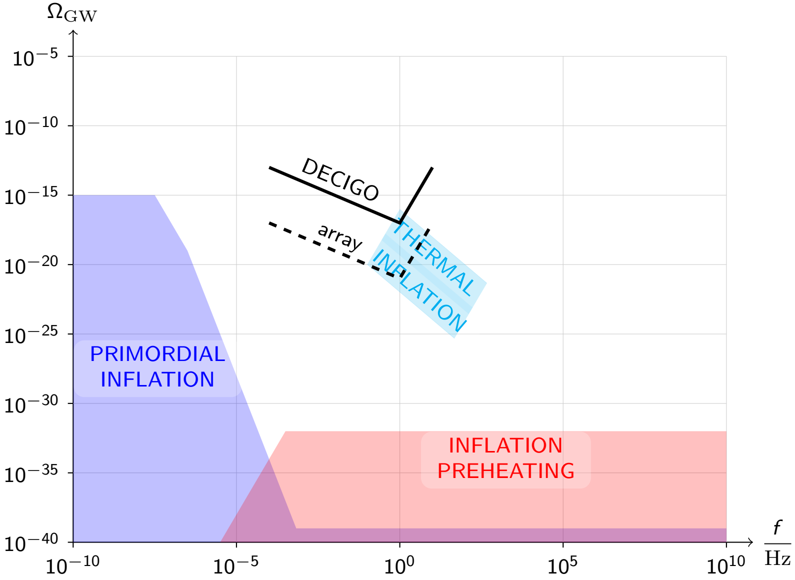

Baryogenesis

Key assumption

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

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

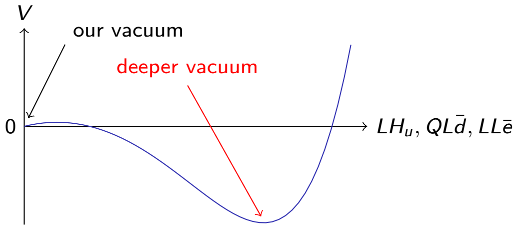
Implies a dangerous non-MSSM vacuum with

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

and

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

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



Reduction

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

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

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

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

Potential

$$
\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

drives thermal inflation

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lh_u rolls away

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h_d forced out

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\end{aligned}
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lh_u stabilized with fixed phase

d and e held at origin

Potential

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

drives thermal inflation

lh_u rolls away

ϕ rolls away

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

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

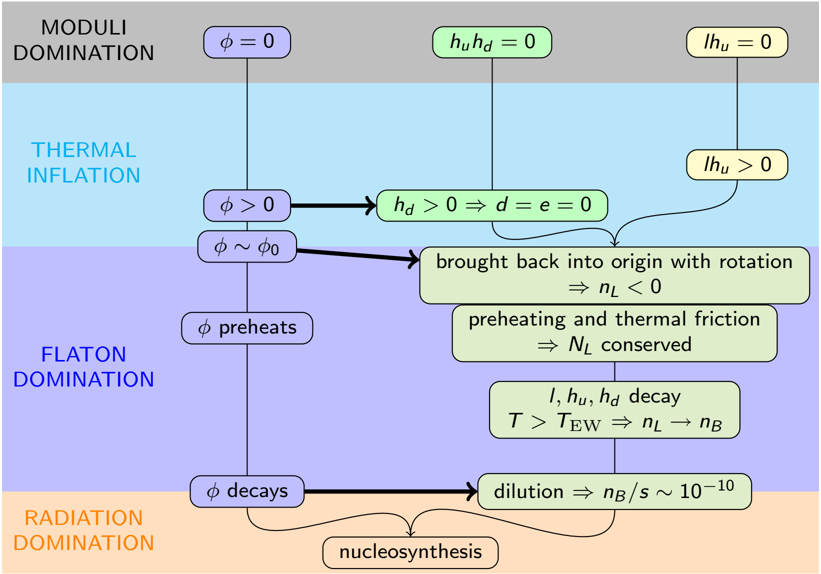
h_d forced out

lh_u stabilized with fixed phase

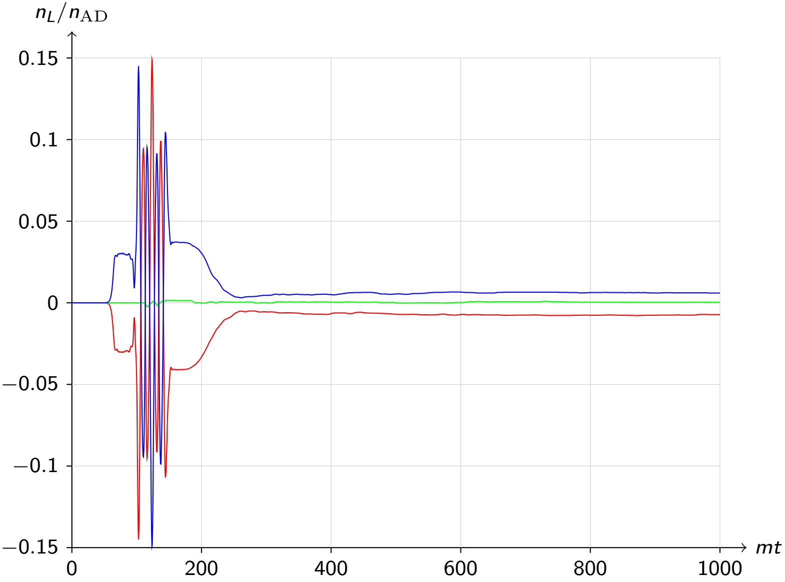
lh_u returns with rotation

d and e held at origin

Baryogenesis



Numerical simulation



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

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Using

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

$$l_0 \sim 10^9\,\mathrm{GeV}\sqrt{\left(\frac{10^{-2}\,\mathrm{eV}}{m_\nu}\right)\left(\frac{m_{LH_u}}{10^3\,\mathrm{GeV}}\right)}$$

and

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

gives

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

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

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

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which suggests

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

Dark matter candidates

Peccei-Quinn symmetry

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

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

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

Dark matter candidates

Peccei-Quinn symmetry

DFSZ axion KSVZ axion

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

Axion

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

$$\simeq 6.2 \times 10^{-6}\,\text{eV}\left(\frac{10^{12}\,\text{GeV}}{f_a}\right)$$

Dark matter candidates

Peccei-Quinn symmetry

DFSZ axion — KSVZ axion

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

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$$\simeq 6.2 \times 10^{-6}\,\mathrm{eV}\left(\frac{10^{12}\,\mathrm{GeV}}{f_a}\right)$$

Axino

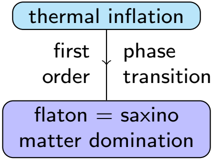
$$m_{\tilde{a}} = \frac{1}{16\pi^2}\sum_\chi \lambda_\chi^2 A_\chi$$

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

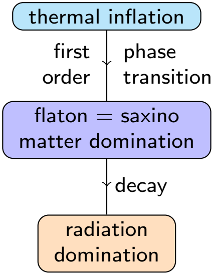
Dark matter genesis

thermal inflation

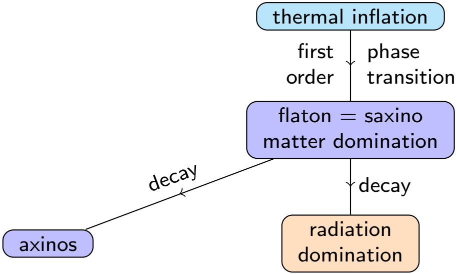
Dark matter genesis



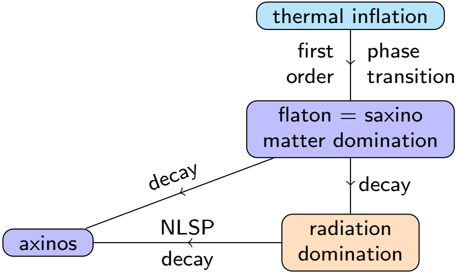
Dark matter genesis



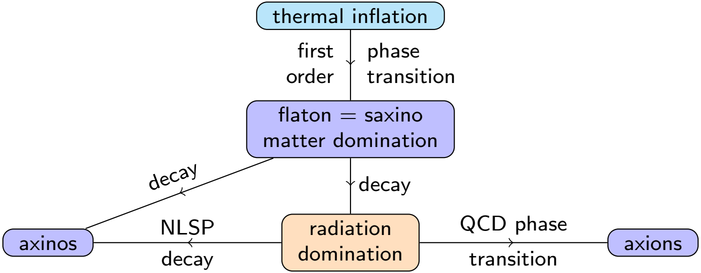
Dark matter genesis



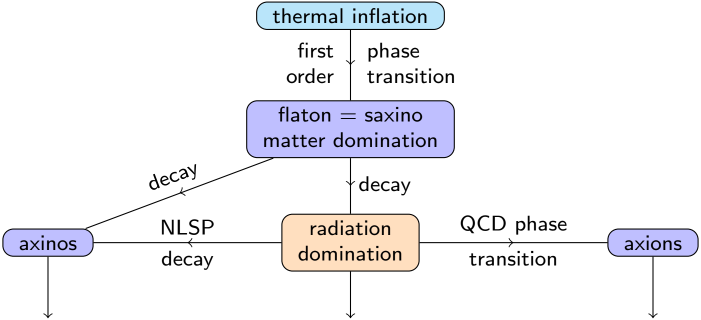
Dark matter genesis



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

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

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

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

Axion Misalignment

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Axion Misalignment

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

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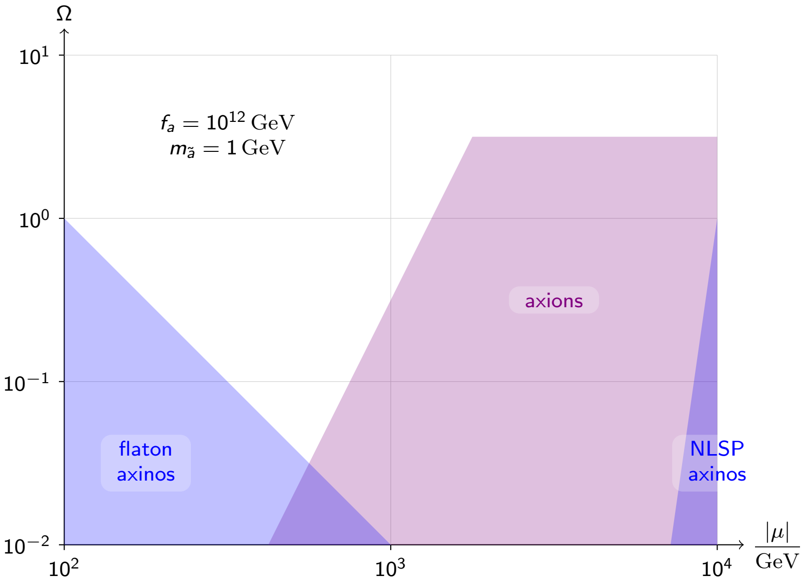
Thermal NLSP decay

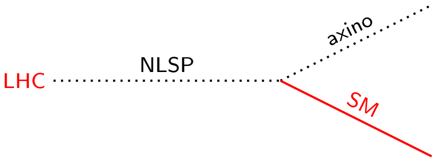
$$\Omega_{\tilde a} \sim 10\left(\frac{m_{\tilde a}}{1\,{\rm GeV}}\right)\left(\frac{10^{12}\,{\rm GeV}}{\phi_0}\right)^2 \times \begin{cases} 1 & \text{for } T_{\rm d} \gg \frac{m_N}{7} \\ \left(\frac{7\,T_{\rm d}}{m_N}\right)^7 & \text{for } T_{\rm d} \ll \frac{m_N}{7} \end{cases}$$

Dark matter composition



Axino LHC signal

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



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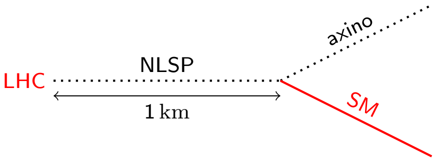

with a decay length

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

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 $m_\phi^2 < 0$

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

axion

Simple model

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neutrino masses

MSSM μ-term

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axion

thermal inflation

Simple model

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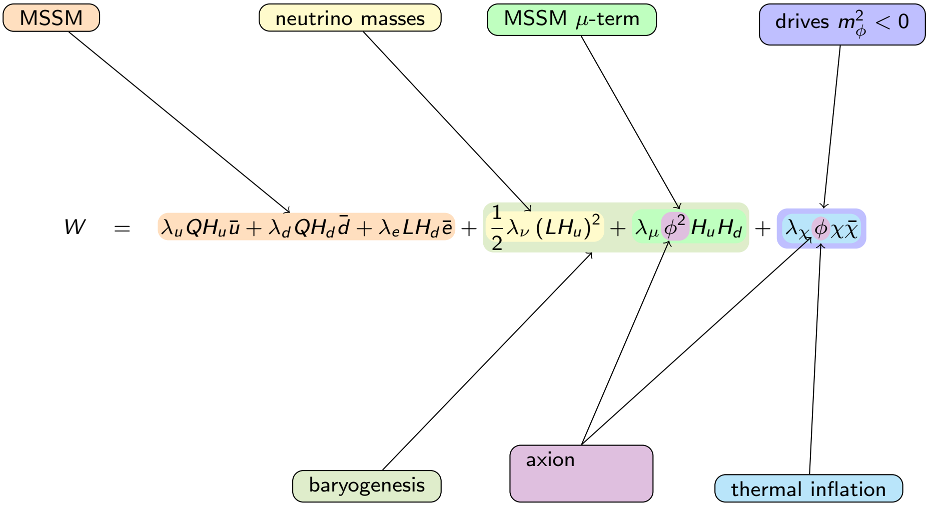

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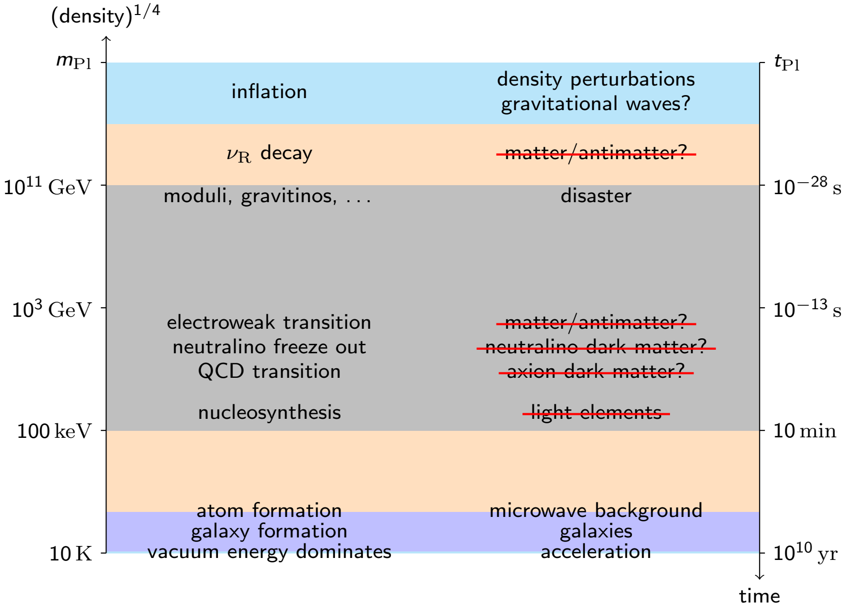
baryogenesis

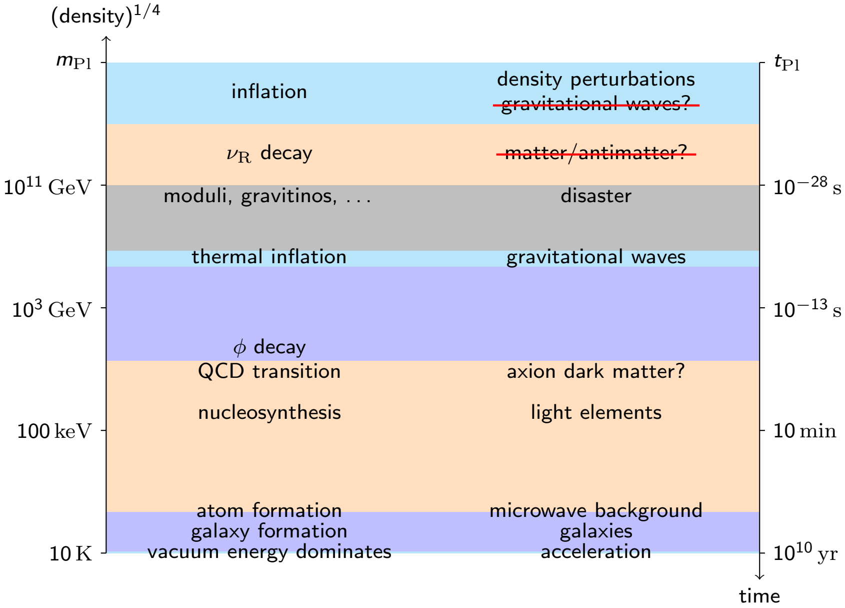
axion/axino dark matter

thermal inflation

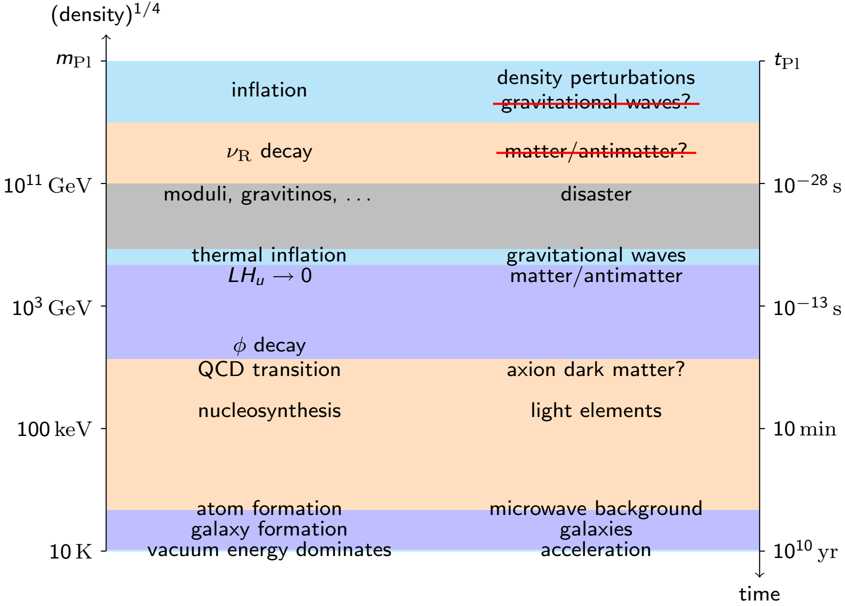
Rich cosmology



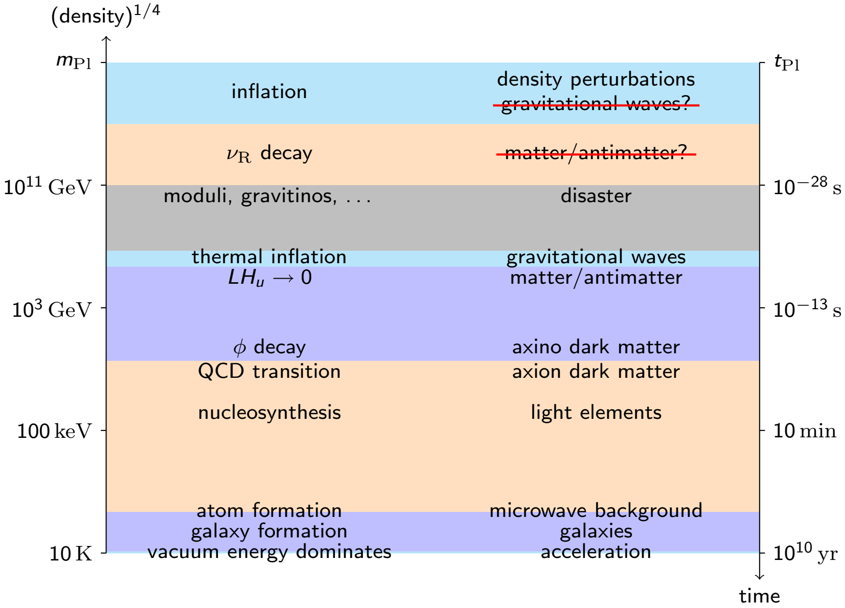
Rich cosmology



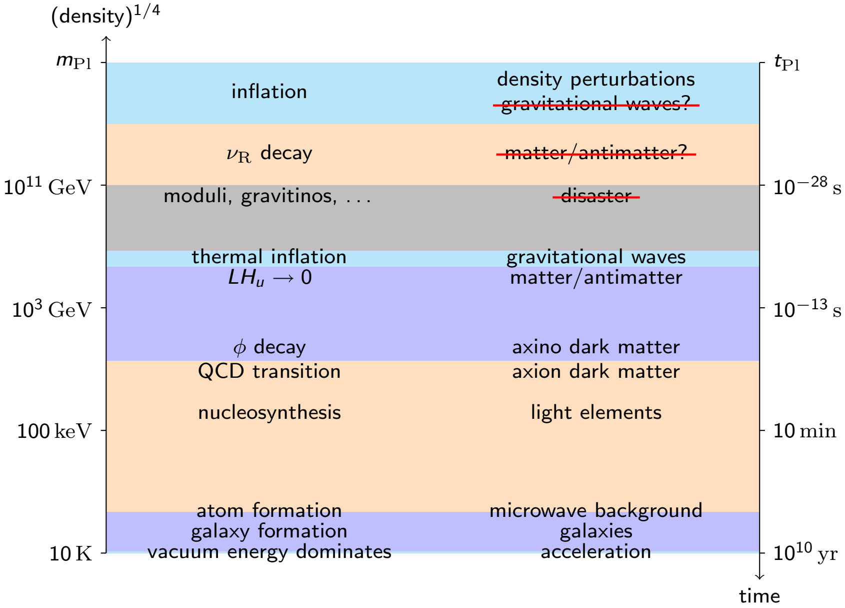
Rich cosmology



Rich cosmology



Rich cosmology



A Minimal Supersymmetric Cosmological Model