A Minimal Supersymmetric Cosmological Model

Ewan Stewart

KAIST

22 November 2017
CTPU

S Kim, W-I Park, EDS	arXiv:0807.3607
S E Hong, H-J Lee, Y-J Lee, EDS, H Zoe	arXiv:1503.08938
K Cho, S E Hong, EDS, H Zoe	arXiv:1705.02741
E H Tanin, EDS	arXiv:1708.04865
K Cho, EDS, et al.	in progress

A Minimal Supersymmetric Cosmological Model

Standard model of cosmology

Moduli and gravitinos
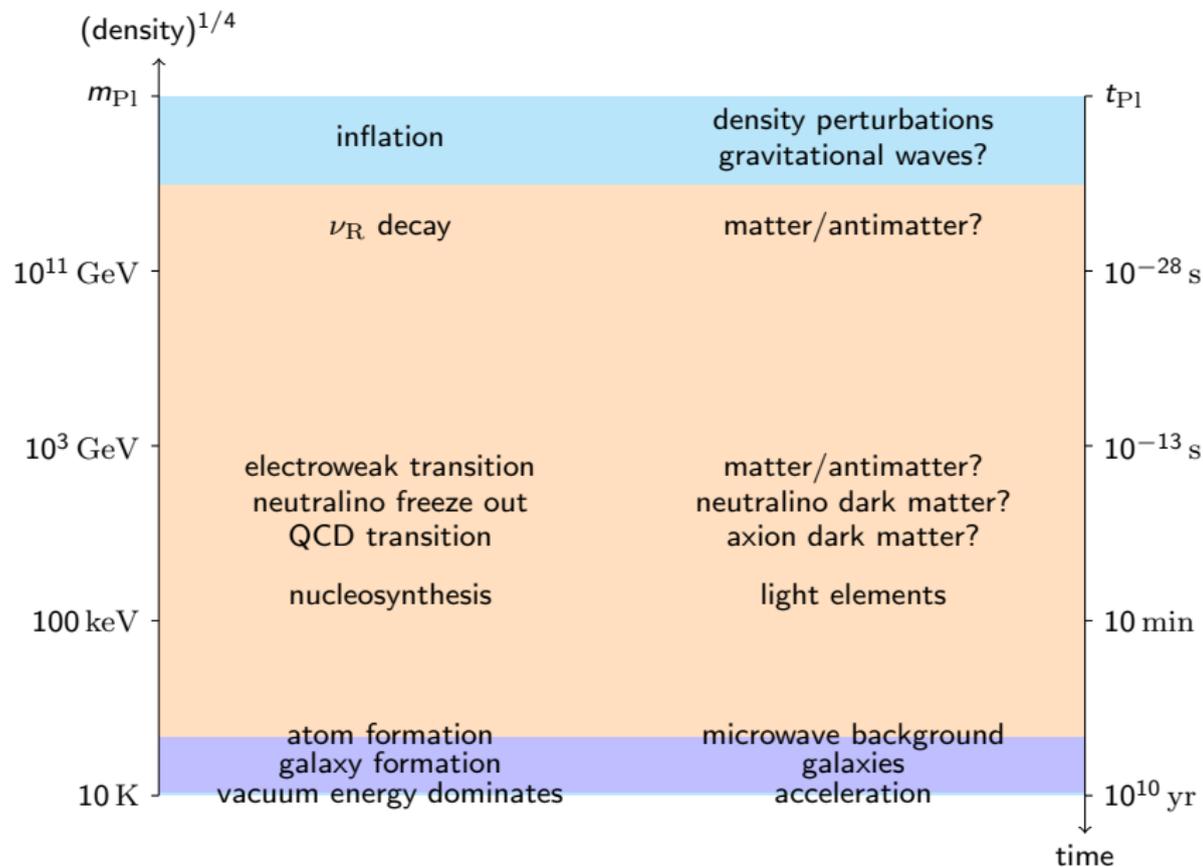
Moduli are cosmologically dangerous. Nucleosynthesis constrains

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

Moduli and gravitinos

Moduli are cosmologically dangerous. Nucleosynthesis constrains

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

In the early universe

$H^2 \left(\Psi - \Psi_1 \right)^2$

Moduli and gravitinos

Moduli are cosmologically dangerous. Nucleosynthesis constrains

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

In the early universe

Moduli and gravitinos

Moduli are cosmologically dangerous. Nucleosynthesis constrains

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

In the early universe

$$\frac{n}{s} \sim 10^7 \qquad m_{\mathrm{susy}}^2 \left(\Psi - \Psi_0\right)^2$$

$$\longleftrightarrow \\ \sim M_{\mathrm{Pl}}$$

Moduli and gravitinos

Moduli are cosmologically dangerous. Nucleosynthesis constrains
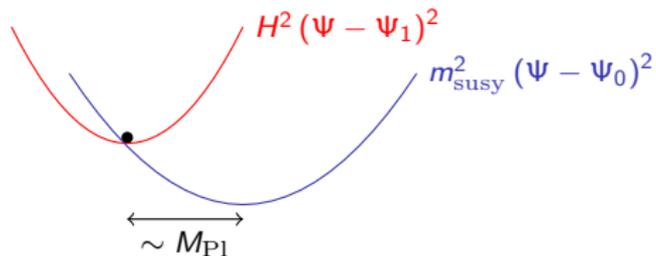
$$\frac{n}{s} \lesssim 10^{-12}$$

In the early universe

$$\frac{n}{s} \sim 10^{7}$$

$$m_{\text{susy}}^2 \left(\Psi - \Psi_0 \right)^2$$

$$\longleftrightarrow \sim M_{\text{Pl}}$$

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

Moduli and gravitinos

Moduli are cosmologically dangerous. Nucleosynthesis constrains
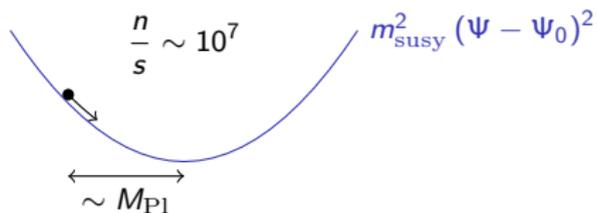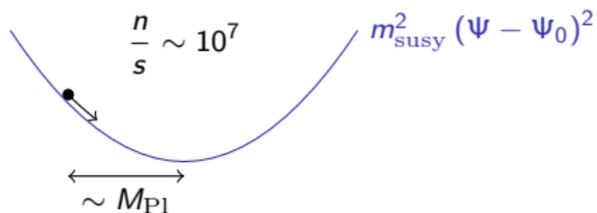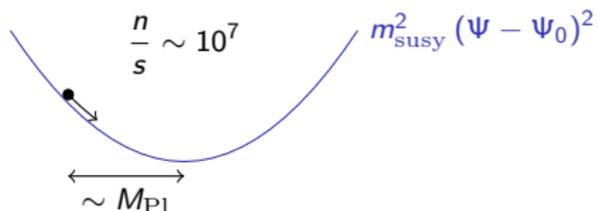
$$\frac{n}{s} \lesssim 10^{-12}$$

In the early universe

$$\frac{n}{s} \sim 10^7 \qquad m_{\mathrm{susy}}^2 \left(\Psi - \Psi_0\right)^2$$

$$\longleftrightarrow \sim M_{\mathrm{Pl}}$$

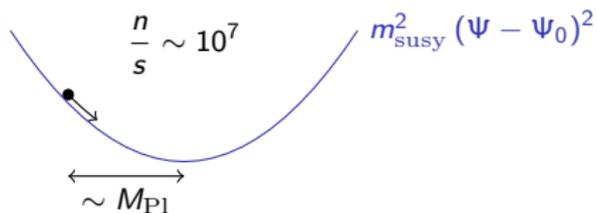Moduli generated: $H \lesssim m_{\mathrm{susy}}$

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

Moduli and gravitinos

Moduli are cosmologically dangerous. Nucleosynthesis constrains

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

In the early universe

$$\frac{n}{s} \sim 10^7 \qquad m_{\text{susy}}^2 \left(\Psi - \Psi_0\right)^2$$

$$\longleftrightarrow \sim M_{\text{Pl}}$$

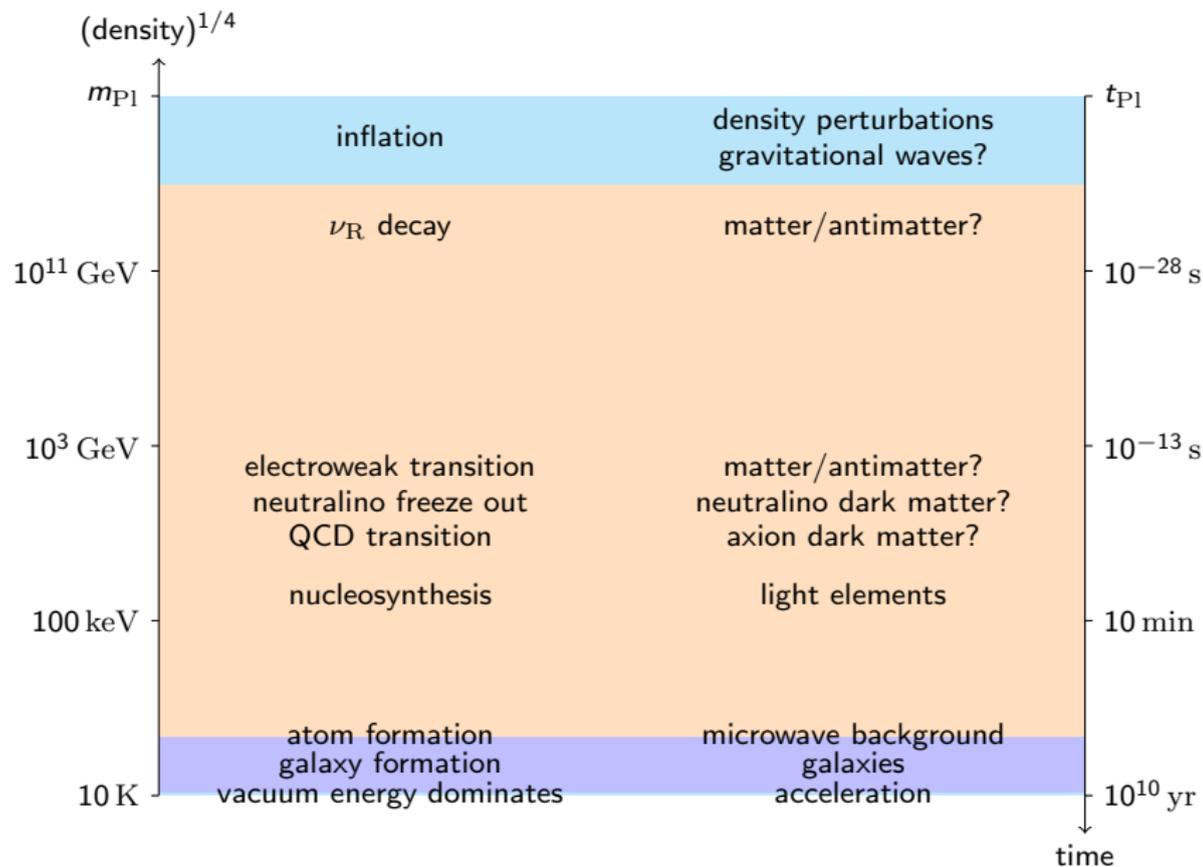Moduli generated: $H \lesssim m_{\text{susy}}$

     after

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

Standard model of cosmology

Standard model of cosmology

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

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

But

- μ?
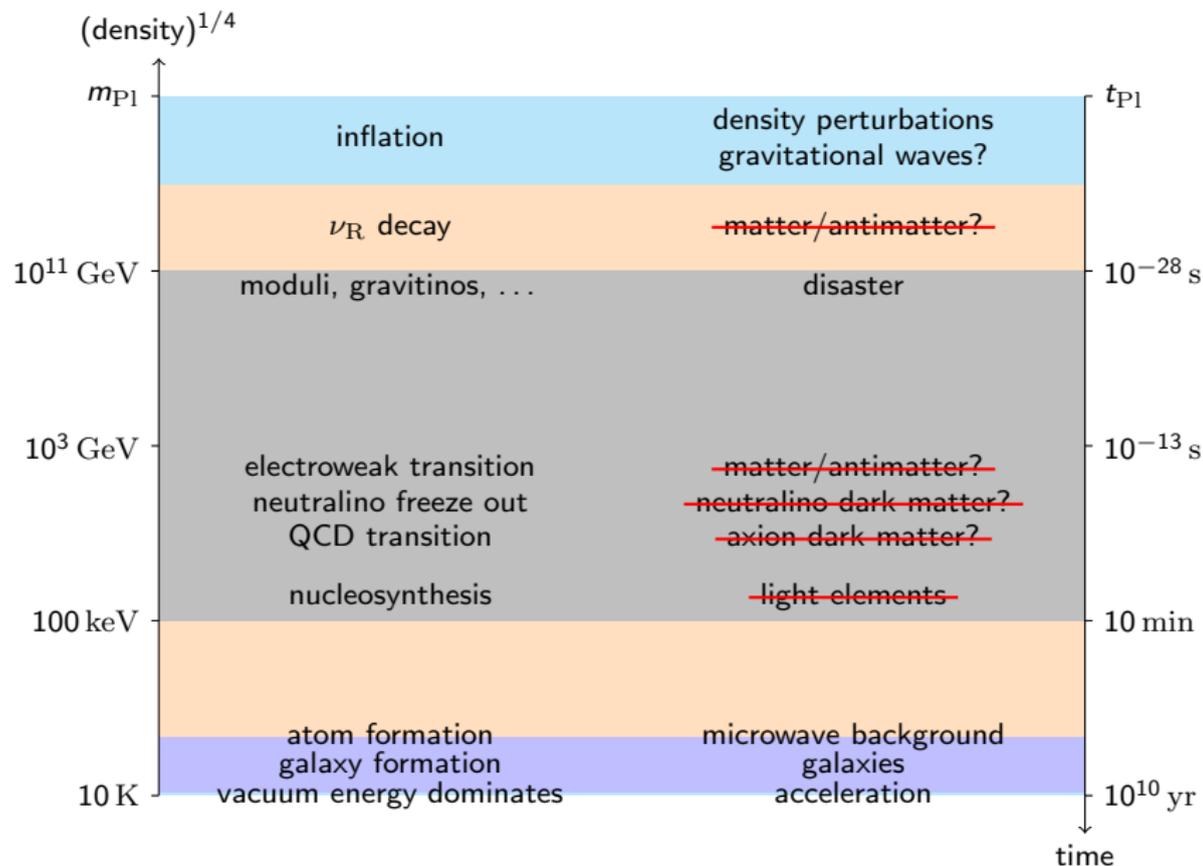
Minimal Supersymmetric Standard Model

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

But

- μ?
- neutrino masses?

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

But

- μ?
- neutrino masses?
- strong CP?

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

Minimal Supersymmetric Cosmological Model

MSSM

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

Minimal Supersymmetric Cosmological Model

MSSM

neutrino masses

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

Minimal Supersymmetric Cosmological Model

MSSM

neutrino masses

MSSM μ-term

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

$$\mu = \kappa_\mu \phi_0^2$$

Minimal Supersymmetric Cosmological Model
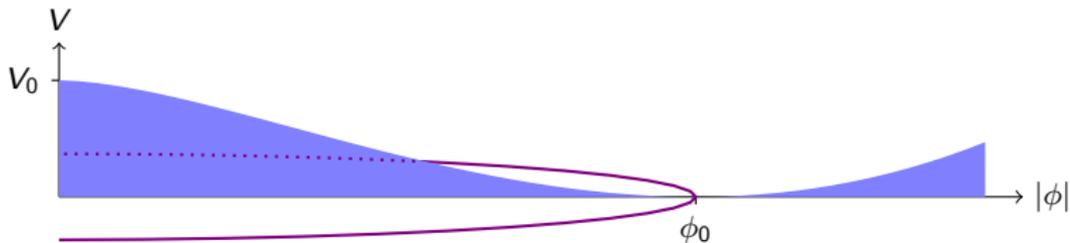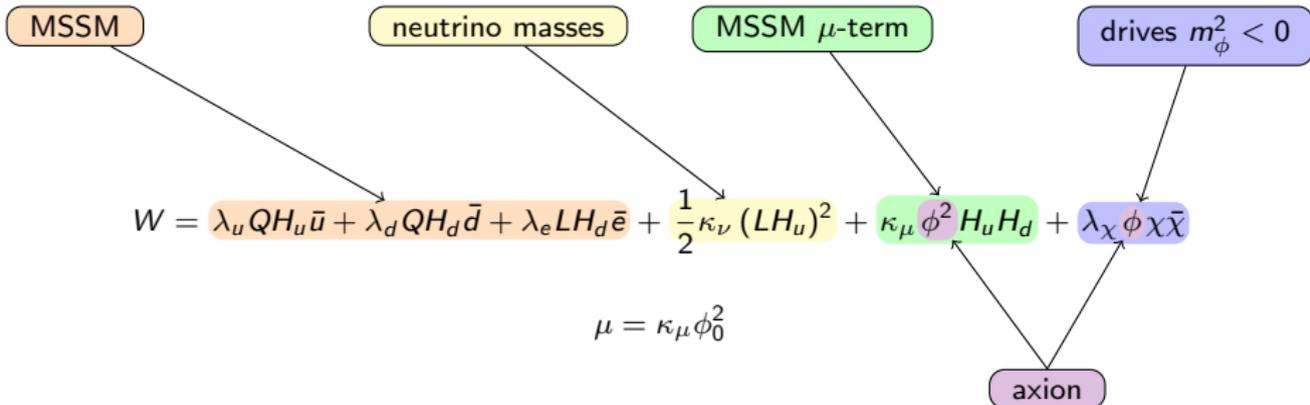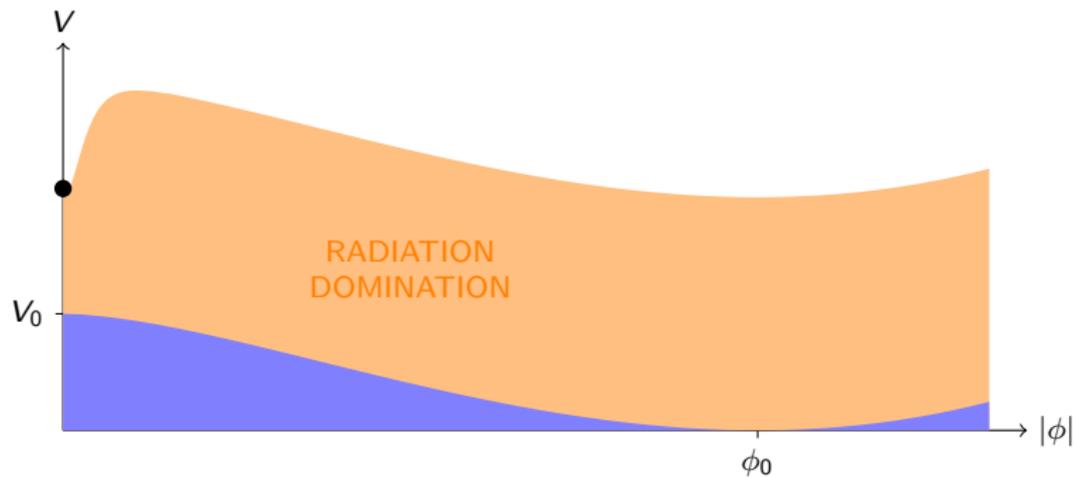
Minimal Supersymmetric Cosmological Model

RADIATION
DOMINATION
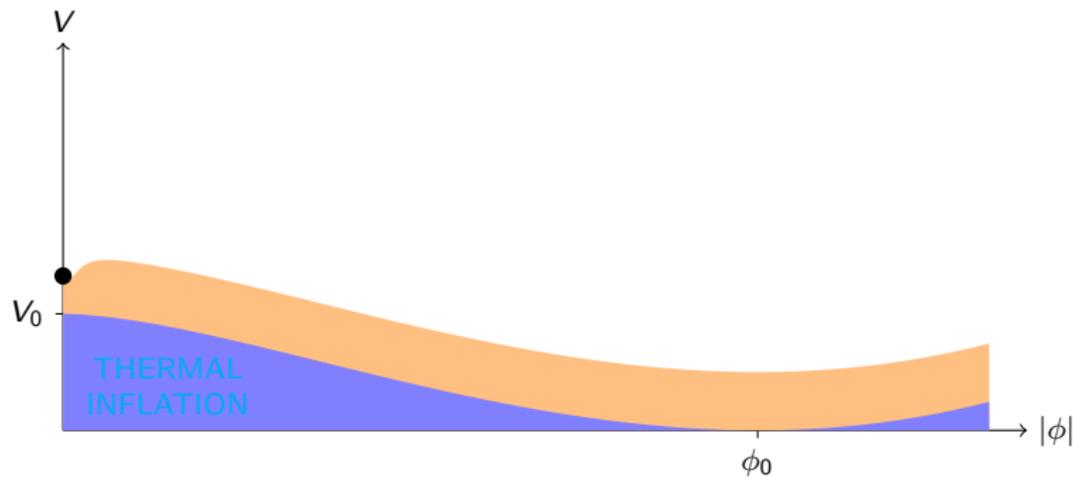
Thermal inflation
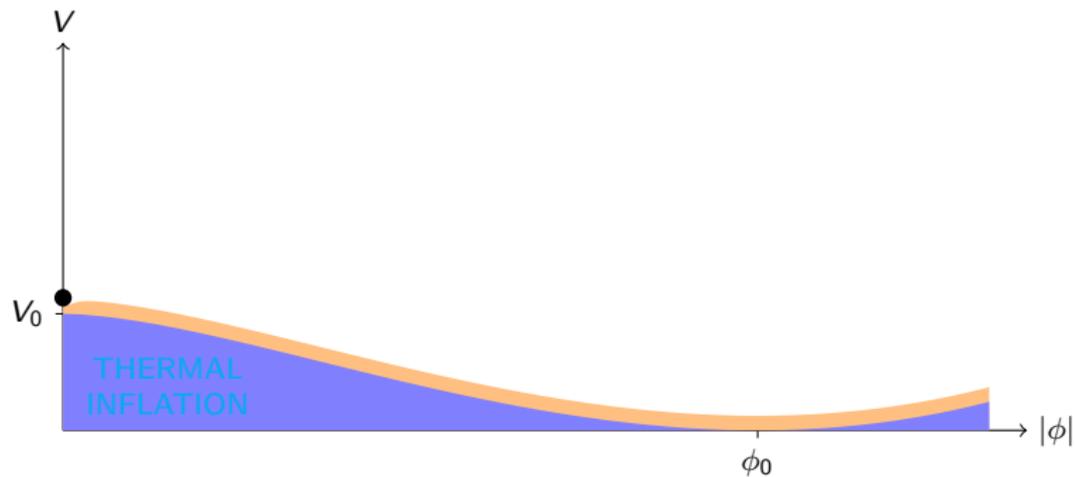
Thermal inflation
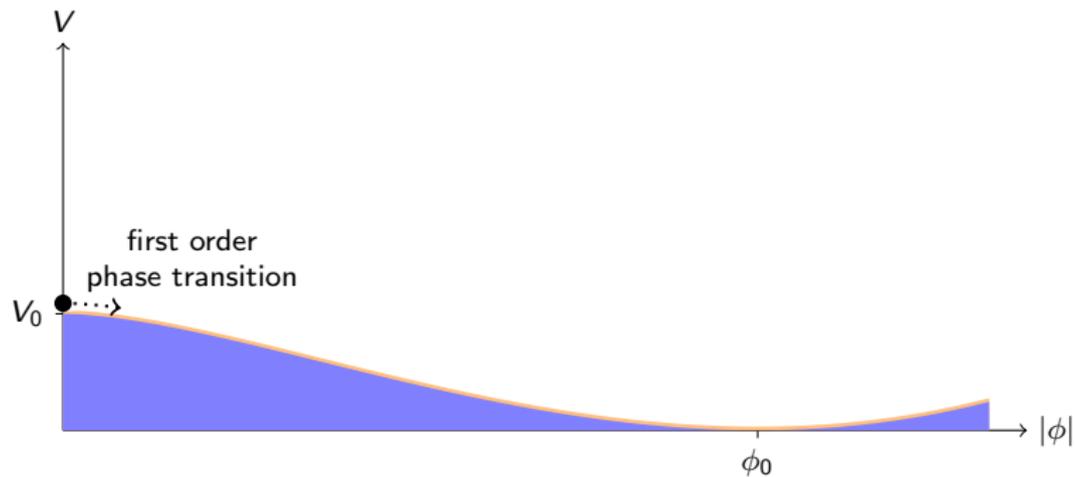
Thermal inflation
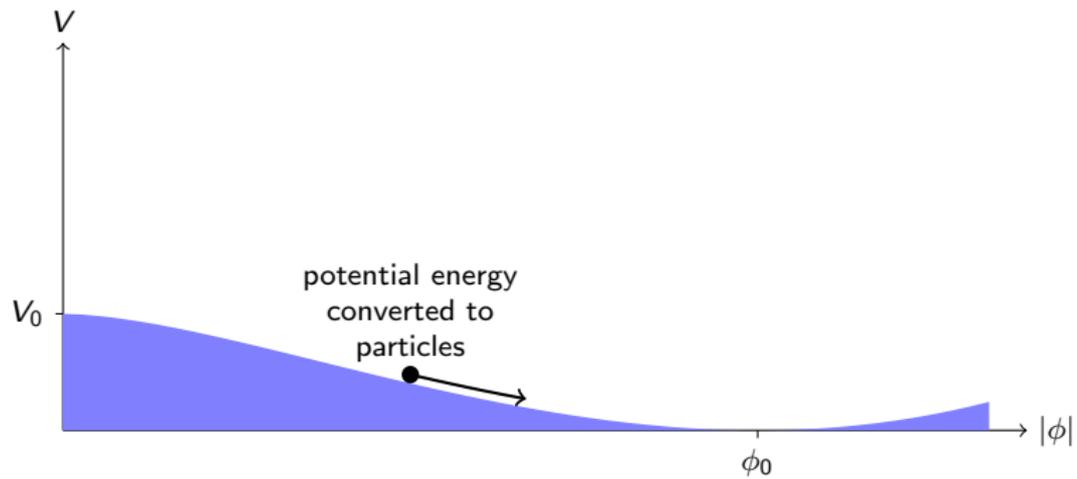
Thermal inflation
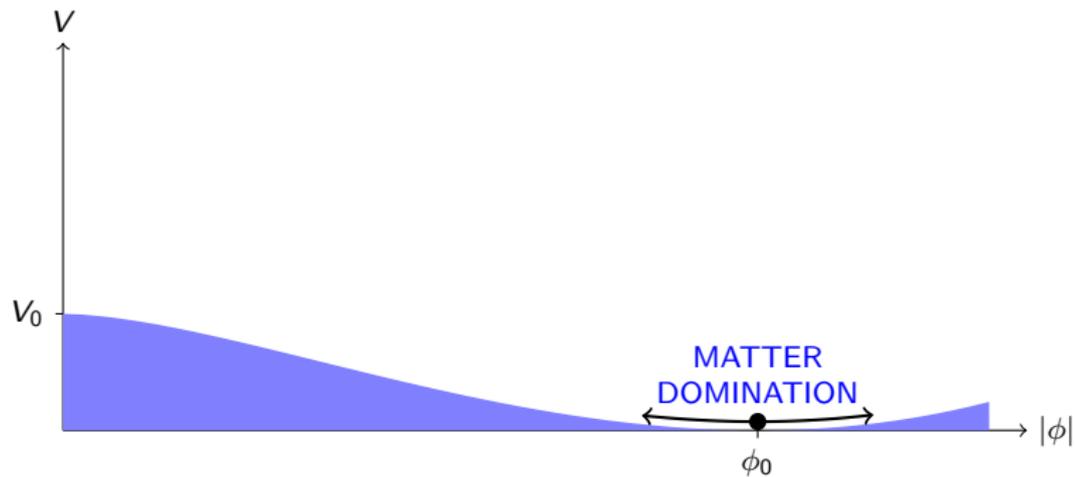
Thermal inflation

Key properties of thermal inflation

For

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

Key properties of thermal inflation

For

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

Large dilution

$$\Delta \sim 10^{20} \quad \implies \quad \text{pre-existing moduli sufficiently diluted}$$

Key properties of thermal inflation

For

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

Large dilution

$$\Delta \sim 10^{20} \quad \Longrightarrow \quad \text{pre-existing moduli sufficiently diluted}$$

Short duration

$$N \sim 10 \quad \Longrightarrow \quad \begin{array}{c} \text{primordial perturbations} \\ \text{from slow-roll inflation} \\ \text{preserved on large scales} \end{array}$$

Key properties of thermal inflation

For

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

Large dilution

$$\Delta \sim 10^{20} \quad \Longrightarrow \quad \text{pre-existing moduli sufficiently diluted}$$

Short duration

$$N \sim 10 \quad \Longrightarrow \quad \begin{array}{c} \text{primordial perturbations} \\ \text{from slow-roll inflation} \\ \text{preserved on large scales} \end{array}$$

Low energy scale

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

Baryogenesis

Key assumption

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

Baryogenesis

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.
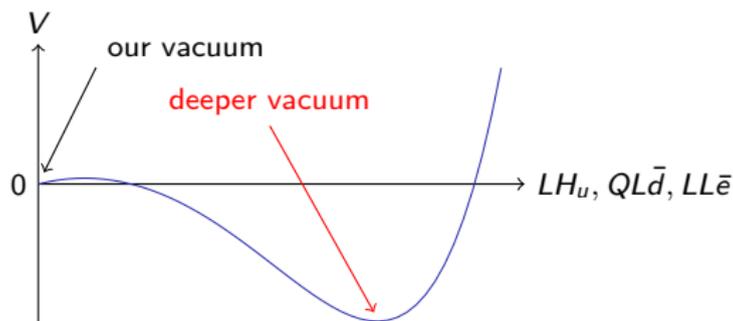
Reduction

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

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

$$L = \left(\begin{array}{c} l \\ e/\sqrt{2} \end{array} \right) \quad , \quad H_u = \left(\begin{array}{c} 0 \\ h_u \end{array} \right) \quad , \quad H_d = \left(\begin{array}{c} h_d \\ 0 \end{array} \right) \quad , \quad \bar{e} = \left(\begin{array}{c} e/\sqrt{2} \end{array} \right)$$

$$\bar{u} = \left(\begin{array}{ccc} 0 & 0 & 0 \end{array} \right) \quad , \quad Q = \left(\begin{array}{ccc} 0 & 0 & 0 \\ d/\sqrt{2} & 0 & 0 \end{array} \right) \quad , \quad \bar{d} = \left(\begin{array}{ccc} d/\sqrt{2} & 0 & 0 \end{array} \right)$$

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

Potential

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

drives thermal inflation

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

Potential

drives thermal inflation

lh_u rolls away

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

Potential

drives thermal inflation lh_u rolls away

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

lh_u stabilized with fixed phase

Potential

drives thermal inflation · lh_u rolls away · ϕ rolls away

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

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

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

Potential

drives thermal inflation

lh_u rolls away

ϕ rolls away

h_d forced out

lh_u stabilized with fixed phase

d and e held at origin

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

Potential

drives thermal inflation

lh_u rolls away

ϕ rolls away

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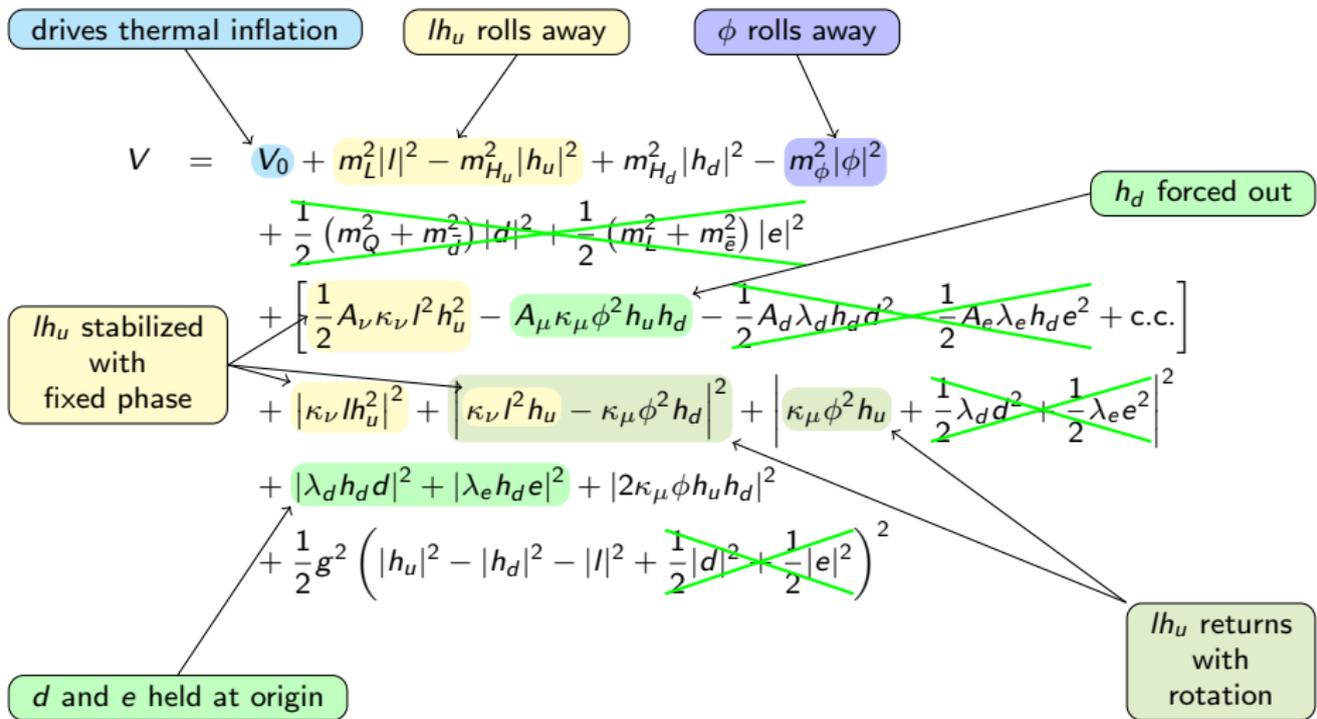& + \left| \kappa_\nu l h_u^2 \right|^2 + \left| \kappa_\nu l^2 h_u - \kappa_\mu \phi^2 h_d \right|^2 + \left| \kappa_\mu \phi^2 h_u + \frac{1}{2}\lambda_d d^2 + \frac{1}{2}\lambda_e e^2 \right|^2 \\
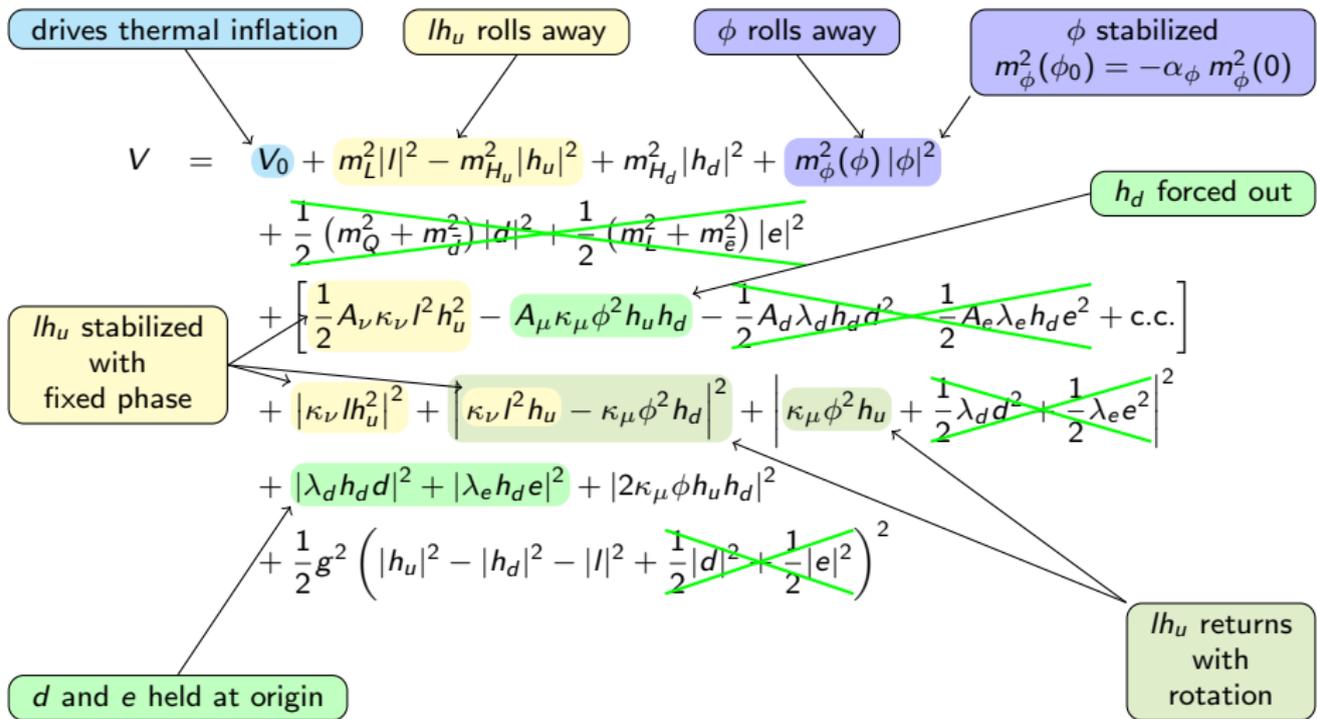& + |\lambda_d h_d d|^2 + |\lambda_e h_d e|^2 + |2\kappa_\mu \phi h_u h_d|^2 \\
& + \frac{1}{2} g^2 \left(|h_u|^2 - |h_d|^2 - |l|^2 + \frac{1}{2}|d|^2 + \frac{1}{2}|e|^2 \right)^2
\end{aligned}
$$

h_d forced out

lh_u stabilized with fixed phase

d and e held at origin

lh_u returns with rotation

Potential

The slide shows labeled boxes with arrows pointing to terms in the potential:

- drives thermal inflation
- lh_u rolls away
- ϕ rolls away
- ϕ stabilized $\quad m_\phi^2(\phi_0) = -\alpha_\phi\, m_\phi^2(0)$
- h_d forced out
- lh_u stabilized with fixed phase
- d and e held at origin
- lh_u returns with rotation

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

Baryogenesis

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

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

Using

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

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

and

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

gives

$$\frac{n_B}{s} \sim 10^{-10} \left(\frac{n_L/n_{\mathrm{AD}}}{10^{-5}}\right) \left(\frac{10^{11}\,\mathrm{GeV}}{\phi_0}\right)^3 \left(\frac{10^{-2}\,\mathrm{eV}}{m_\nu}\right) \left(\frac{|\mu|}{10^3\,\mathrm{GeV}}\right)^2 \left(\frac{10^{-1}}{\alpha_\phi}\right) \left(\frac{m_{LH_u}}{m_\phi(0)}\right)^2$$

Baryon asymmetry

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

Using

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

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

and

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

gives

$$\frac{n_B}{s} \sim 10^{-10}\left(\frac{n_L/n_{\mathrm{AD}}}{10^{-5}}\right)\left(\frac{10^{11}\,\mathrm{GeV}}{\phi_0}\right)^3\left(\frac{10^{-2}\,\mathrm{eV}}{m_\nu}\right)\left(\frac{|\mu|}{10^3\,\mathrm{GeV}}\right)^2\left(\frac{10^{-1}}{\alpha_\phi}\right)\left(\frac{m_{LH_u}}{m_\phi(0)}\right)^2$$

which suggests

$$\phi_0 \sim 10^{11}\,\mathrm{GeV}$$

Dark matter candidates

Peccei-Quinn symmetry

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

Dark matter candidates

Peccei-Quinn symmetry

DFSZ axion

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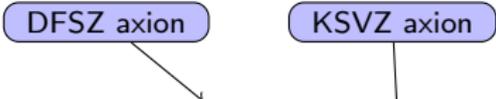
Dark matter candidates

Peccei-Quinn symmetry

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

DFSZ axion

KSVZ axion

Dark matter candidates

Peccei-Quinn symmetry

DFSZ axion   KSVZ axion

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

Axion

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

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

Dark matter candidates

Peccei-Quinn symmetry

DFSZ axion   KSVZ axion

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

Axion

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

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

Axino

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

$$\sim 0.1 \text{ to } 10 \, \mathrm{GeV}$$

Dark matter genesis

thermal inflation

Dark matter genesis
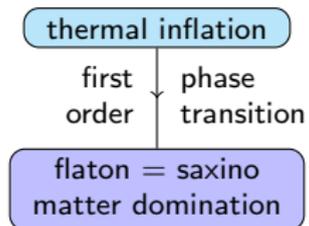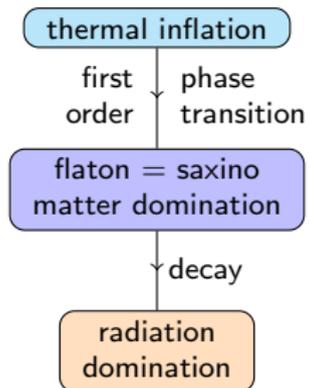
thermal inflation

first order | phase transition

flaton = saxino
matter domination

Dark matter genesis

Dark matter genesis

thermal inflation

first order / phase transition

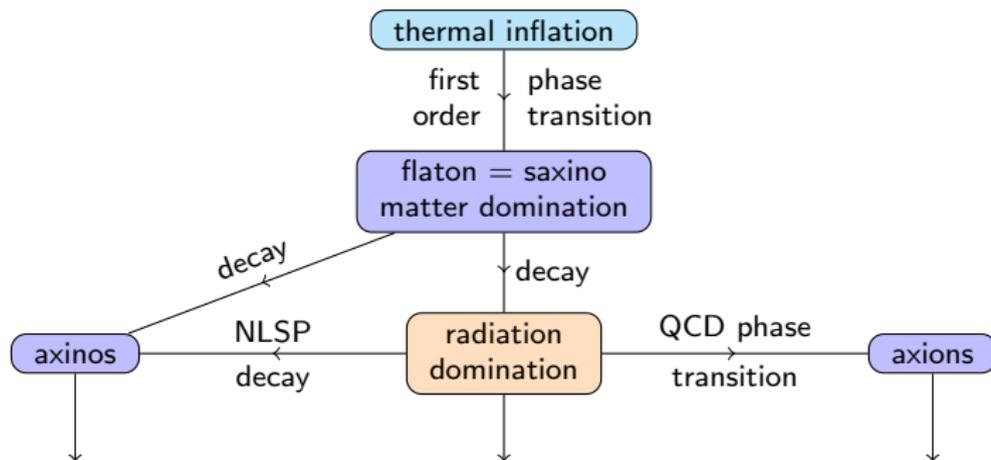flaton = saxino
matter domination

decay

axinos

decay

radiation
domination
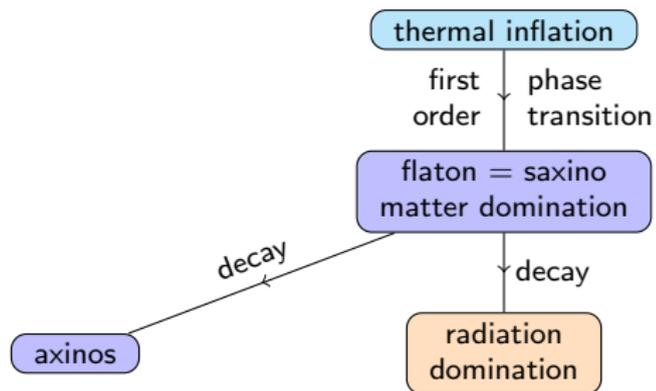
Dark matter genesis
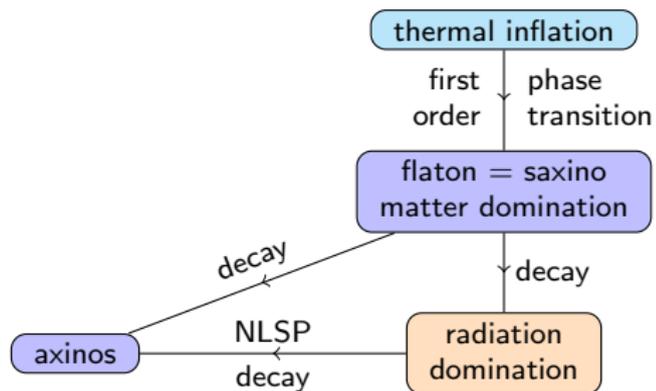
Dark matter genesis
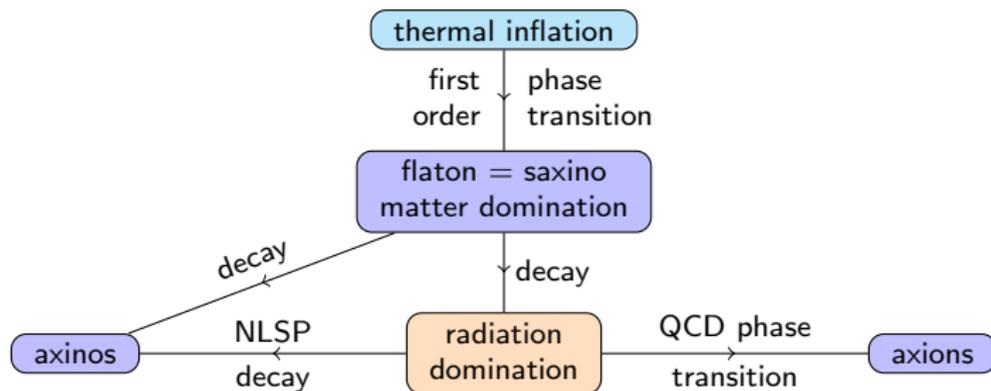
Dark matter genesis

Dark matter abundance

Axion

Axino

Dark matter abundance

Axion Misalignment

$$\Omega_a \sim 0.2 \left(\frac{\phi_0}{10^{11}\,\text{GeV}} \right)^{1.2}$$

Axino

Dark matter abundance

Axion Misalignment

$$\Omega_a \sim 0.2 \left(\frac{\phi_0}{10^{11}\,\mathrm{GeV}} \right)^{1.2}$$

Axino Flaton decay

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

Dark matter abundance

Axion Misalignment

$$\Omega_a \sim 0.2 \left(\frac{\phi_0}{10^{11} \, \text{GeV}} \right)^{1.2}$$

Axino Flaton decay

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

Thermal NLSP decay

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

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

$$\Omega_a \sim 0.2 \left(\frac{\phi_0}{10^{11} \, \mathrm{GeV}} \right)^{1.2}$$

Axino Flaton decay

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

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

$$\Omega_a \sim 0.2 \left(\frac{\phi_0}{10^{11}\,{\rm GeV}} \right)^{1.2} \times \left\{ \begin{array}{cl} 1 & \text{for } T_{\rm d} \gg 1\,{\rm GeV} \\[2ex] \left(\dfrac{T_{\rm d}}{1\,{\rm GeV}} \right)^2 & \text{for } T_{\rm d} \ll 1\,{\rm GeV} \end{array} \right.$$

Axino Flaton decay

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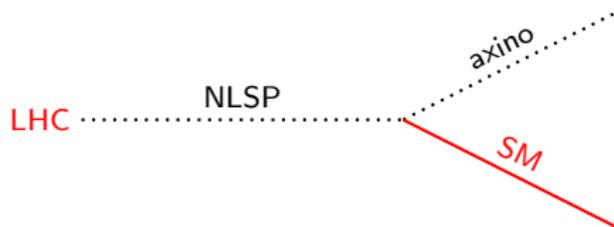
Thermal NLSP decay

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

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

$$\Omega_a \sim 0.2 \left(\frac{\phi_0}{10^{11}\,{\rm GeV}}\right)^{1.2} \times \left\{ \begin{array}{cc} 1 & \text{for } T_{\rm d} \gg 1\,{\rm GeV} \\ \\ \left(\frac{T_{\rm d}}{1\,{\rm GeV}}\right)^2 & \text{for } T_{\rm d} \ll 1\,{\rm GeV} \end{array} \right.$$

Axino Flaton decay

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

Thermal NLSP decay

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

Dark matter composition
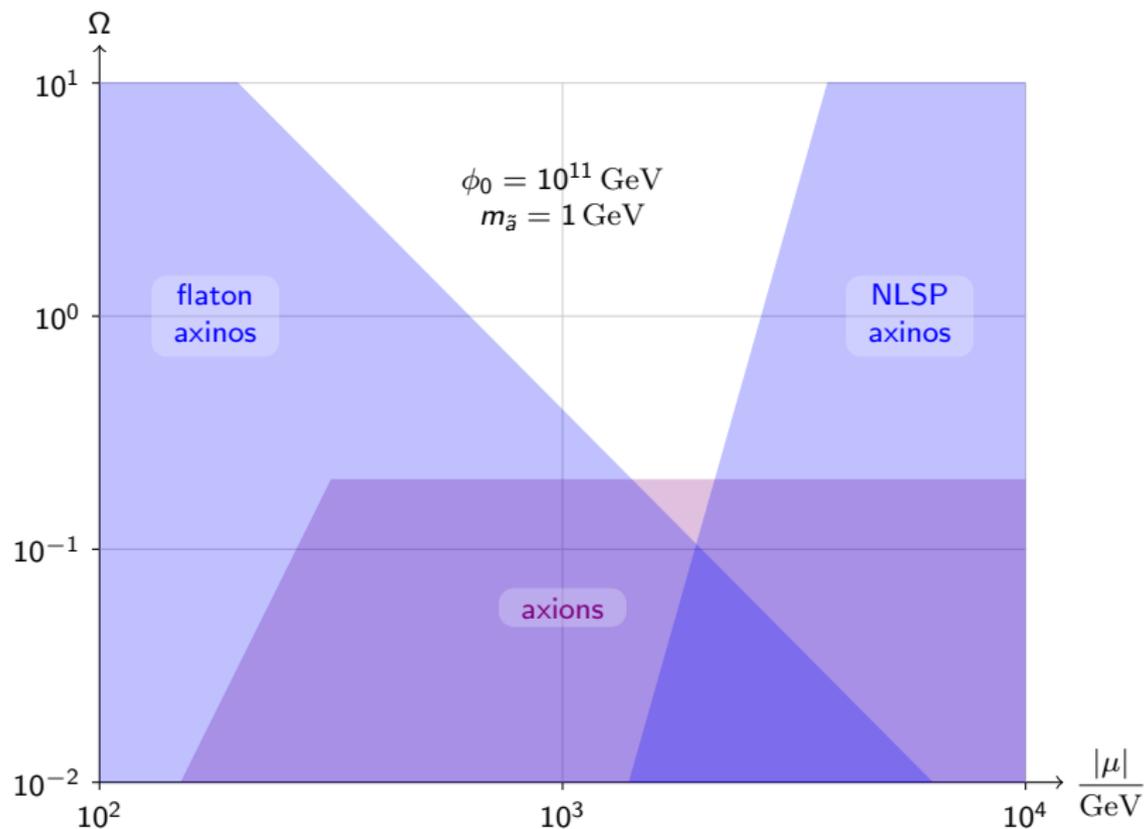
Axino LHC signal

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

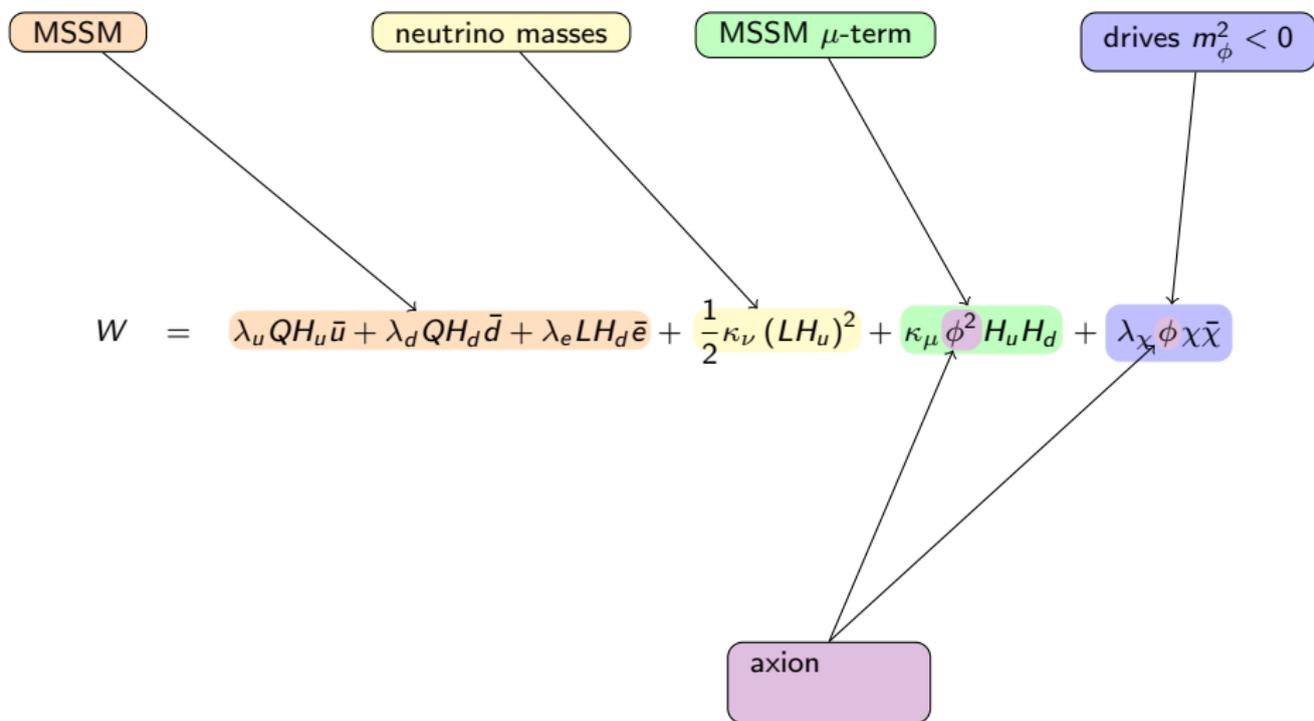NLSPs produced by the LHC decay to axinos plus Standard Model particles
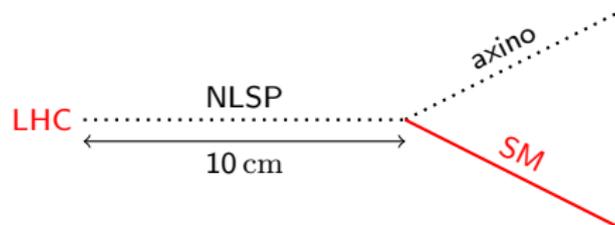
with a decay length

$$\frac{1}{\Gamma_{N \to \tilde{a}}} \sim \frac{16\pi\phi_0^2}{m_N^3} \sim 10\,\text{cm} \left(\frac{1\,\text{TeV}}{m_N}\right)^3 \left(\frac{\phi_0}{10^{11}\,\text{GeV}}\right)^2$$
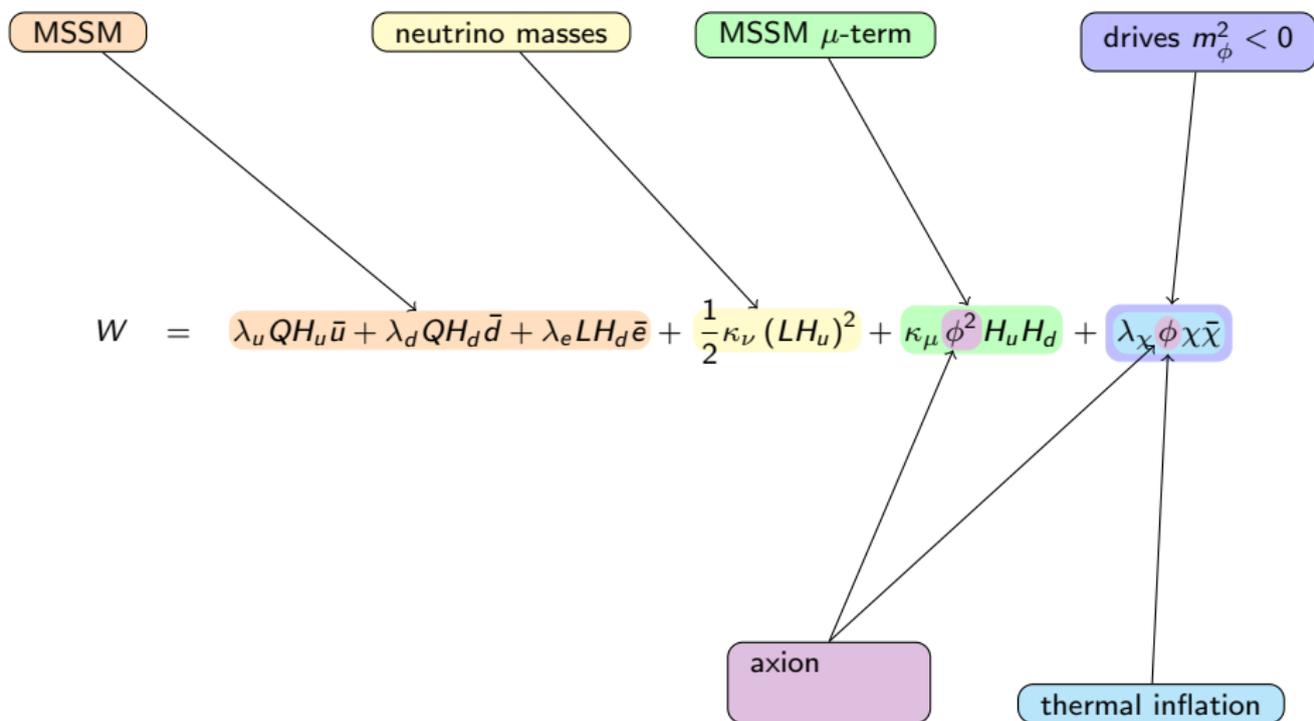
and well constrained parameters

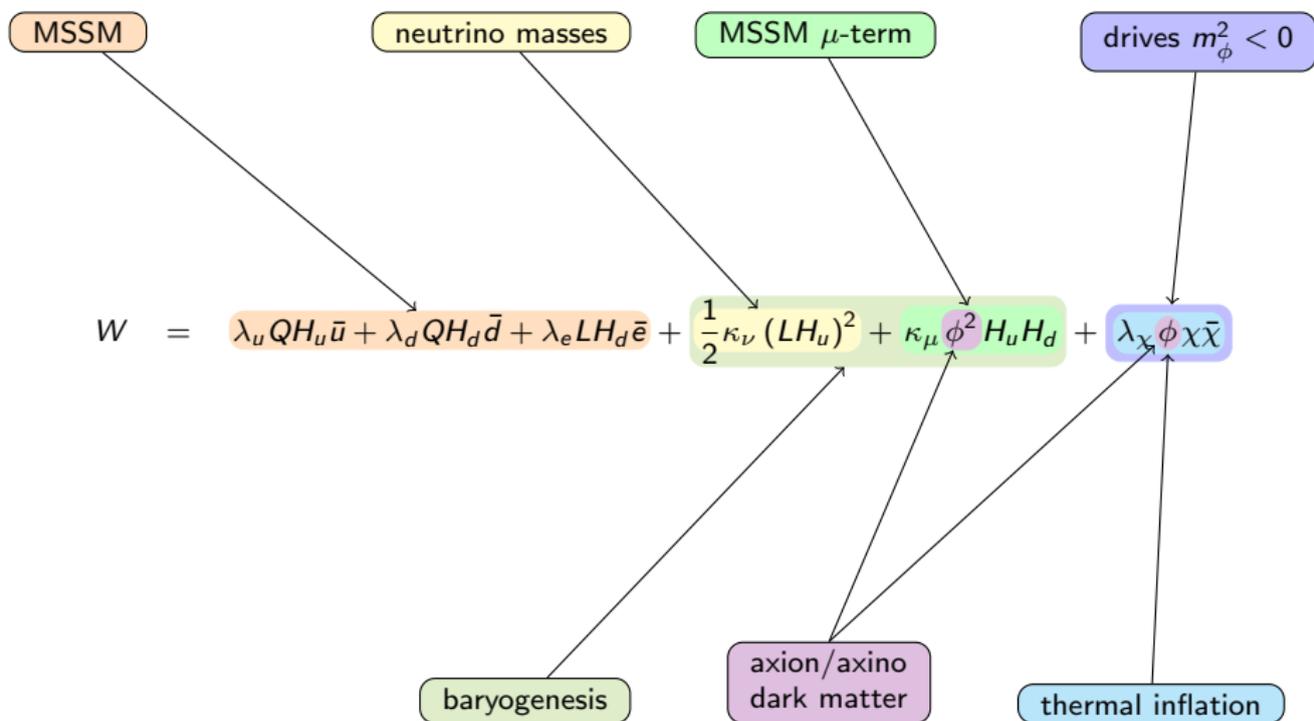$$\phi_0 \sim 10^{11}\,\text{GeV}$$

$$m_{\tilde{a}} \sim 1\,\text{GeV}$$

Simple model

MSSM

neutrino masses

MSSM μ-term

drives $m_\phi^2 < 0$

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

axion

Simple model

MSSM

neutrino masses

MSSM μ-term

drives $m_\phi^2 < 0$

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

axion

thermal inflation

Simple model

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

MSSM

neutrino masses

MSSM μ-term

drives $m_\phi^2 < 0$

baryogenesis

axion

thermal inflation

Simple model

MSSM

neutrino masses

MSSM μ-term

drives $m_\phi^2 < 0$

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

baryogenesis

axion/axino
dark matter

thermal inflation

Rich cosmology

Rich cosmology

Rich cosmology

Rich cosmology

Rich cosmology

Diagram axis: $(\text{density})^{1/4}$ (vertical left), time (horizontal bottom).

Left axis labels: m_{Pl}, $10^{11}\,\text{GeV}$, $10^3\,\text{GeV}$, $100\,\text{keV}$, $10\,\text{K}$

Right axis labels: t_{Pl}, $10^{-28}\,\text{s}$, $10^{-13}\,\text{s}$, $10\,\text{min}$, $10^{10}\,\text{yr}$

inflation — density perturbations, ~~gravitational waves?~~

ν_{R} decay — ~~matter/antimatter?~~

moduli, gravitinos, . . . — ~~disaster~~

thermal inflation — gravitational waves
$LH_u \to 0$ — matter/antimatter

ϕ decay — axino dark matter

QCD transition — axion dark matter

nucleosynthesis — light elements

atom formation — microwave background
galaxy formation — galaxies
vacuum energy dominates — acceleration

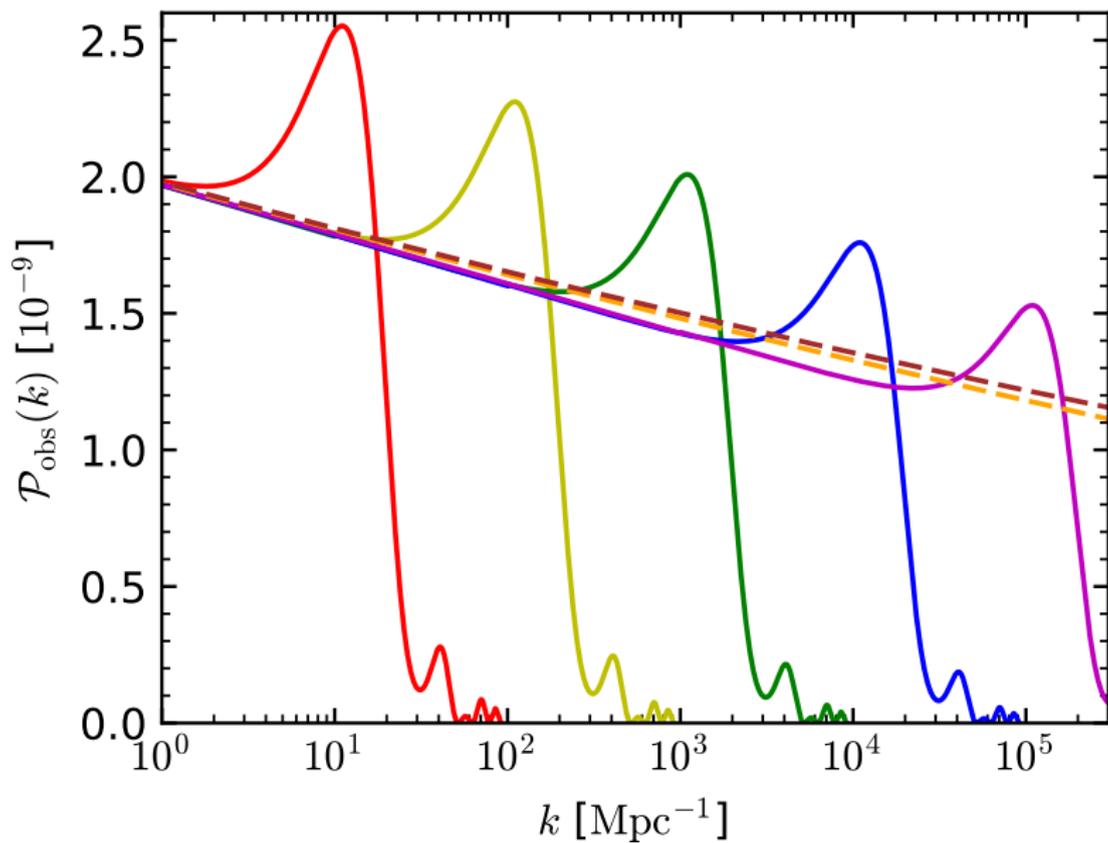# A Minimal Supersymmetric Cosmological Model

Small scale perturbations

- Effects of thermal inflation on small scale density perturbations, S E Hong, H-J Lee, Y-J Lee, EDS and H Zoe, arXiv:1503.08938.
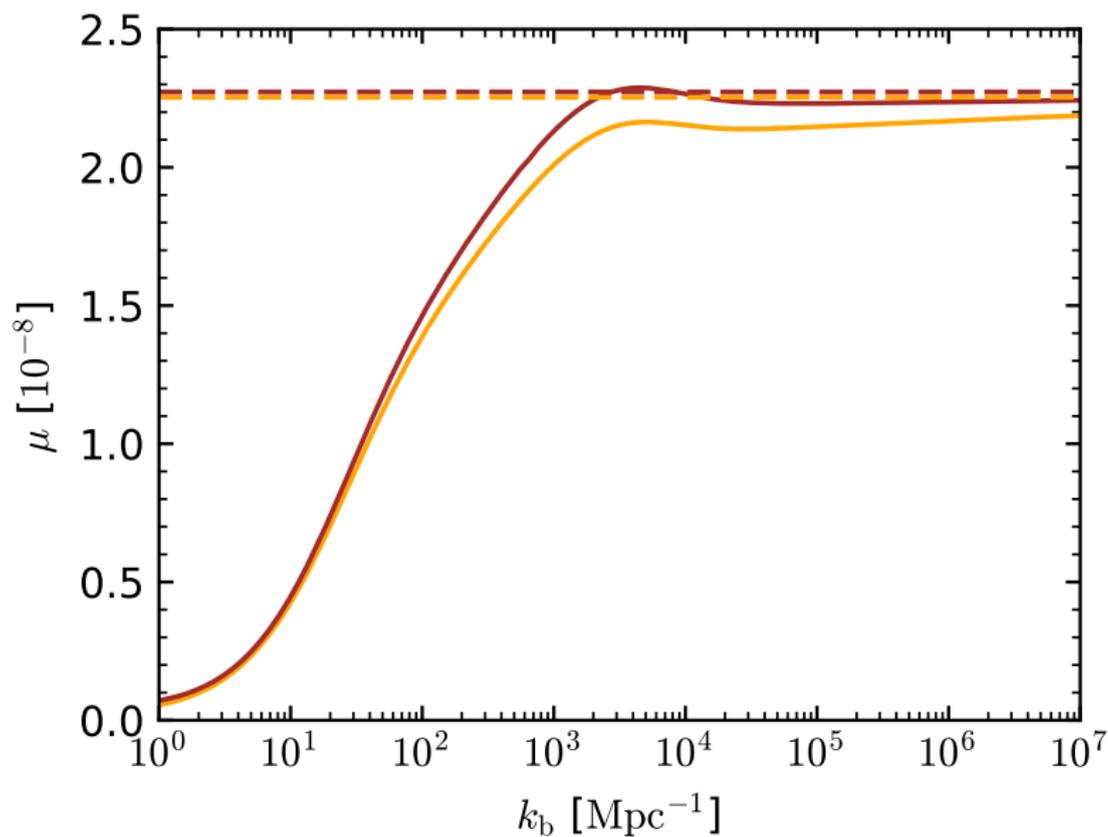- CMB spectral distortion constraints on thermal inflation, K Cho, S E Hong, EDS and H Zoe, arXiv:1705.02741.
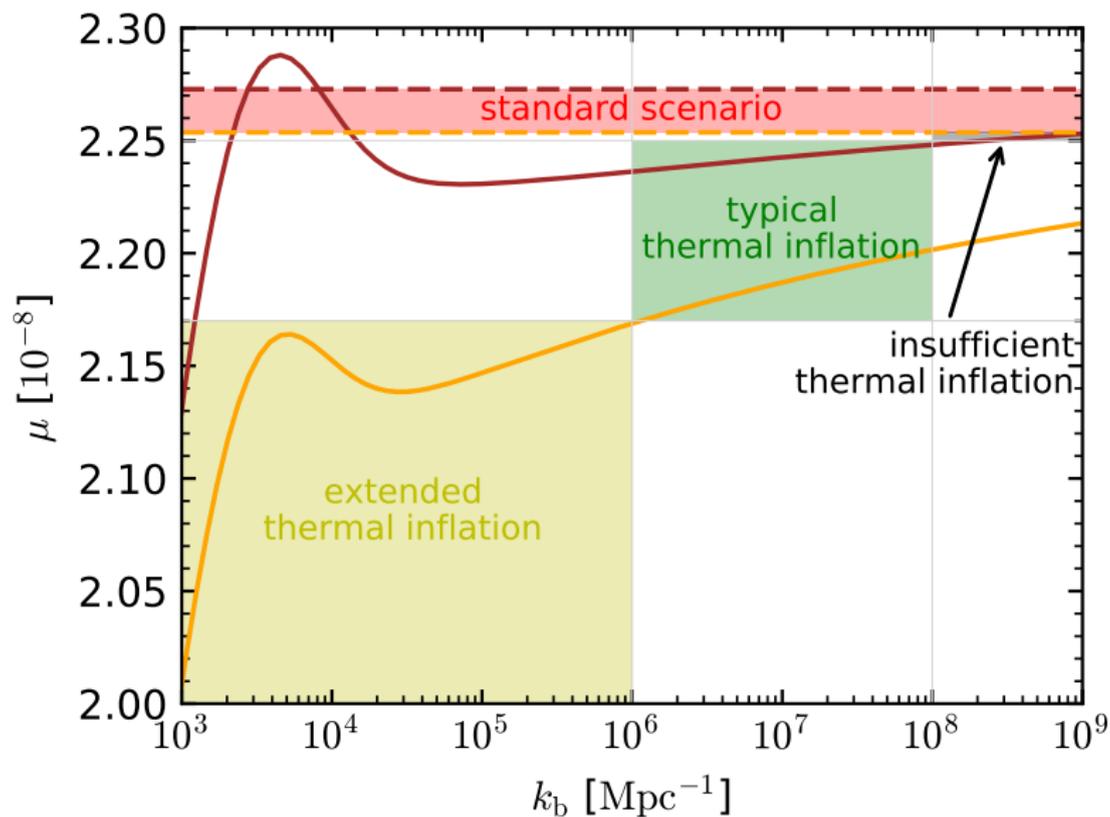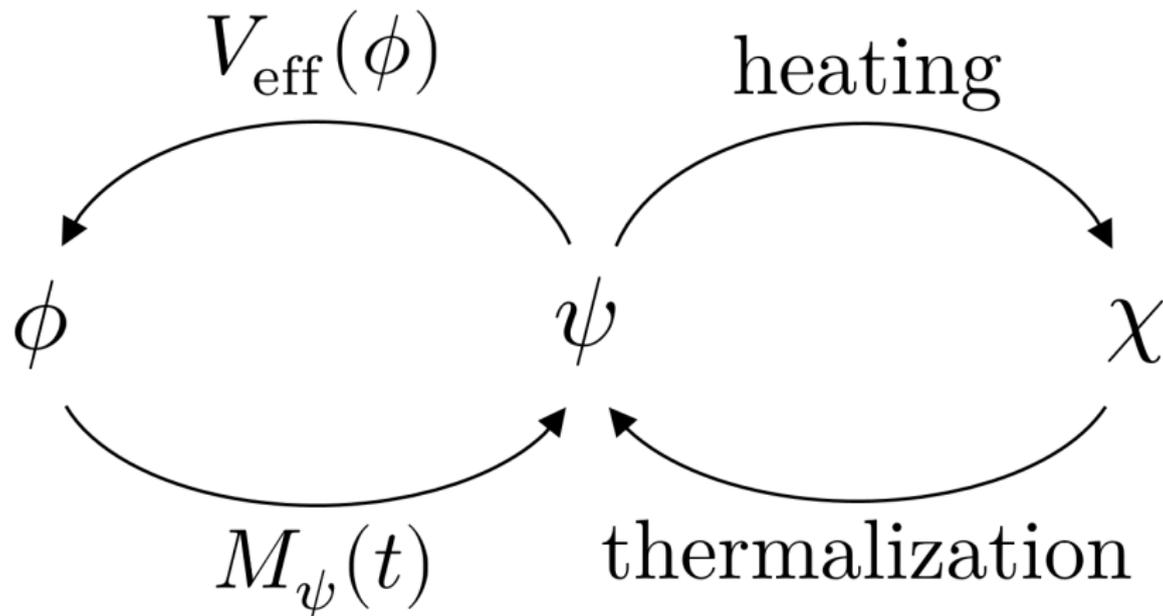
CMB spectral distortions

CMB spectral distortions

- Damping of an oscillating scalar field indirectly coupled to a thermal bath, E H Tanin and EDS, arXiv:1708.04865.

Preheating

bare mass (BM)
$V_{\text{eff}}^{\text{BM}}(\phi) = \frac{1}{2} m_\phi^2 \phi^2$

thermal log (TL)
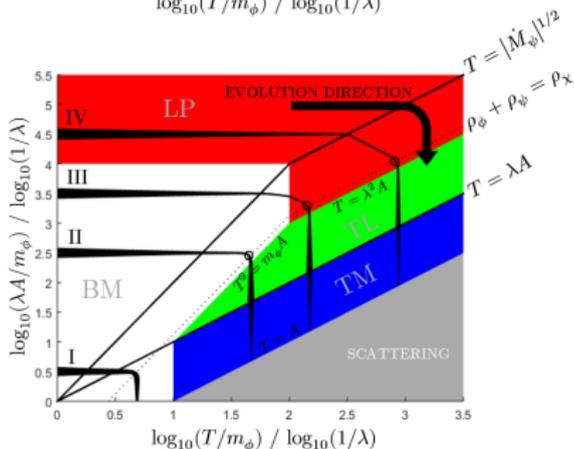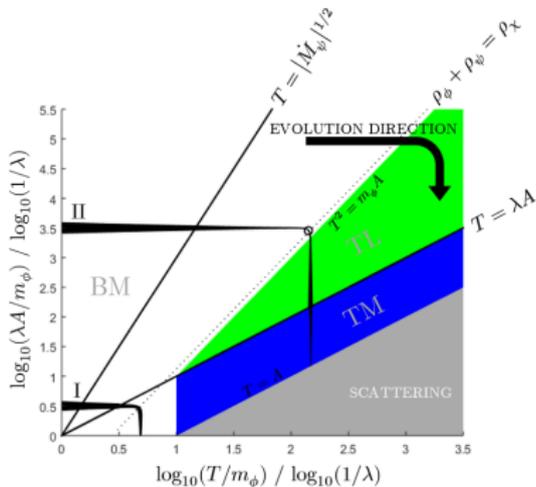$V_{\text{eff}}^{\text{TL}}(\phi) \sim T^4 \ln\left(\frac{\lambda\phi}{T}\right)$

thermal mass (TM)
$V_{\text{eff}}^{\text{TM}}(\phi) \sim \lambda^2 T^2 \phi^2$

linear potential (LP)
$V_{\text{eff}}^{\text{LP}}(\phi) \sim \lambda |\dot{M}_\psi| \max(|\dot{M}_\psi|^{1/2}, T) |\phi|$

Vacuum stability

- K Cho, EDS, et al., in progress.

$v/v_0 = +,\times:1,\ \Diamond,\Box:2;\ \mu = r:1,\ g:2,\ b:4;\ m_{H_d}^2 + \mu^2 = 1,\ m_q = 1,\ 400 < S_\ell < 420$