A Minimal Supersymmetric Cosmological Model

Ewan Stewart

KAIST

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

Donghui Jeong, Kenji Kadota, Wan-II Park, EDS hep-ph/0406136
Gary N Felder, Hyunbyuk Kim, Wan-II Park, EDS hep-ph/0703275
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History of the observable universe

- $\rho^{1/4}$
- $m_{Pl}$
- $t_{Pl}$
- $10^{11}$ GeV
- $10^3$ GeV
- $100$ keV
- $10$ K
- $10^{-28}$ s
- $10^{-13}$ s
- $10$ min
- $10^{10}$ yr

- Inflation
- Density perturbations, gravitational waves?
- $\nu_R$ decay
- Baryons?
- Electroweak transition
- Neutralino freeze out
- QCD transition
- Baryons?
- Neutralino dark matter?
- Axion dark matter?
- Nucleosynthesis
- Light elements
- Atom formation
- Microwave background
- Galaxy formation
- Galaxies
- Vacuum energy dominates
- Acceleration
History of the observable universe

- Inflation
- Density perturbations
- Gravitational waves?

- $\nu_R$ decay
- Baryons?

- Electroweak transition
- Neutralino freeze out
- LHC
- Baryons?
- Neutralino dark matter?
- Axion dark matter?

- QCD transition
- Nucleosynthesis
- Light elements

- Atom formation
- Galaxy formation
- Vacuum energy dominates
- Microwave background
- Galaxies
- Acceleration

- Vacuum energy dominates
- Acceleration
History of the observable universe

- Inflation
- Density perturbations and gravitational waves
- $\nu_R$ decay
- Baryons?
- Moduli, gravitinos, ...
History of the observable universe

- **$\rho^{1/4}$**
- **$m_{\text{Pl}}$**
- **$t_{\text{Pl}}$**

- **10^{11} \text{ GeV}**
  - Inflation
  - Density perturbations
  - Gravitational waves?

- **10^{3} \text{ GeV}**
  - $\nu_R$ decay
  - Baryons?
  - Moduli, gravitinos, ... (Disaster)
  - Electroweak transition
  - Neutralino freeze out
  - QCD transition
  - Baryons?

- **100 \text{ keV}**
  - Nucleosynthesis
  - Light elements

- **10 \text{ K}**
  - Atom formation
  - Microwave background
  - Galaxy formation
  - Galaxies
  - Vacuum energy dominates
  - Acceleration

- **10 \text{ min}**

- **10^{10} \text{ yr}**
History of the observable universe

- $\rho^{1/4}$
- $m_{Pl}$
- $t_{Pl}$

- $10^{11}$ GeV
  - Inflation
  - Density perturbations
  - Gravitational waves?
  - $\nu_R$ decay
  - Baryons?
- $10^3$ GeV
  - Moduli, gravitinos, ...
  - Moduli, gravitinos, ...
  - Disaster
  - Electroweak transition
  - Neutralino freeze-out
  - QCD transition
- $100$ keV
  - Nucleosynthesis
  - Light elements
- $10$ K
  - Atom formation
  - Galaxy formation
  - Vacuum energy dominates
  - Microwave background
  - Galaxies
  - Acceleration
  - Light elements
  - Nucleosynthesis
  - Electroweak transition
  - $\nu_R$ decay
  - Inflation
  - Density perturbations
  - Gravitational waves?
History of the observable universe

- **Vacuum energy dominates**: Acceleration
- **Galaxies**: Formation
- **Microwave background**: Galaxies
- **Atom formation**: Nuclear synthesis
- **Light elements**: Nucleosynthesis
- **QCD transition**: Neutralino freeze out
- **Electroweak transition**: Neutralino dark matter?
- **Moduli, gravitinos, ...**: 
  - Disaster
- **$\nu_R$ decay**: Baryons?
- **Inflation**: Density perturbations, gravitational waves?

$\rho^{1/4}, m_{Pl}, t_{Pl}$

$10^{11}$ GeV

$10^3$ GeV

$100$ keV

$10$ K
History of the observable universe

- Inflation
- Density perturbations gravitational waves?
- $\nu_R$ decay
- Baryons?
- Moduli, gravitinos, ...
- Disaster
- Electroweak transition
- Neutralino freeze out
- QCD transition
- Baryons?
- Neutralino dark matter?
- Axion dark matter?
- Nucleosynthesis
- Light elements
- Atom formation
- Microwave background
- Galaxy formation
- Accretion
- Galaxy galaxies
- Vacuum energy dominates
- Acceleration
History of the observable universe

- $\rho^{1/4}$
- $m_{Pl}$
- $t_{Pl}$
- $10^{11}$ GeV
- $10^3$ GeV
- $100$ keV
- $10$ K
- $10^2$ s
- $10^3$ s
- $10^6$ s
- $10^9$ s
- $10^{10}$ s
- $10^{10}$ yr

- inflation
- density perturbations
- gravitational waves?
- $\nu_R$ decay
- baryons?
- moduli, gravitinos, ...
- disaster
- electroweak transition
- neutralino freeze out
- QCD transition
- baryons?
- neutralino dark matter?
- axion dark matter?
- nucleosynthesis
- light elements
- atom formation
- galaxy formation
- vacuum energy dominates
- microwave background
- galaxies
- acceleration
- baryons?
History of the observable universe

- Inflation
- Density perturbations: gravitational waves?
- $\nu_R$ decay
- Baryons?
- Moduli, gravitinos, ...
- Disaster
- Electroweak transition
- Neutralino freeze-out
- Baryons?
- QCD transition
- Neutralino dark matter?
- Axion dark matter?
- Nucleosynthesis
- Light elements
- Atom formation
- Microwave background
- Vacuum energy dominates
- Galaxy formation
- Galaxies
- Acceleration
- Neutralino dark matter
- $10^{11}$ GeV
- $10^{3}$ GeV
- $100$ keV
- $10$ K
- $10$ min
- $10^{10}$ yr
- $\rho^{1/4}$
- $m_{Pl}$
- $t_{Pl}$
Moduli problem

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

\[ \frac{n\Phi}{s} \lesssim 10^{-12} \]
Moduli problem

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

In the early universe

$$H^2 (\Phi - \Phi_1)^2$$
Moduli problem

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

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In the early universe
Moduli problem

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

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

In the early universe

\[ \frac{n_\Phi}{s} \sim 10^7 \]

\[ m_{\text{susy}}^2 (\Phi - \Phi_0)^2 \]

\[ \sim M_{\text{Pl}} \]
Moduli problem

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

\[
\frac{n\Phi}{s} \lesssim 10^{-12}
\]

In the early universe

\[
\frac{n\Phi}{s} \sim 10^7
\]

\[
m_{\text{susy}}^2 (\Phi - \Phi_0)^2
\]

\[
\sim M_{\text{Pl}}
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Moduli generated: \( H \lesssim m_{\text{susy}} \)
Moduli problem

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

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

In the early universe

$$m_{\text{susy}}^2 (\Phi - \Phi_0)^2 \sim 10^7$$

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

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

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

\[ \frac{n\Phi}{s} \lesssim 10^{-12} \]

In the early universe

\[ \frac{n\Phi}{s} \sim 10^7 \]

\[ m^{2}_{\text{susy}} (\Phi - \Phi_0)^2 \sim M_{\text{Pl}} \]

Moduli generated: \( H \lesssim m_{\text{susy}} \)

after

slow-roll inflation: \( H \gtrsim m_{\text{inflaton}} \gtrsim m_{\text{susy}} \)
Thermal inflation

\[ V = V_0 - m^2 |\phi|^2 + \ldots \]
Thermal inflation

\[ V = V_0 + g^2 T^2 |\phi|^2 - m^2 |\phi|^2 + \ldots \]
Thermal inflation

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

Inflation for

\[ V_0^{1/4} \gtrsim T \gtrsim m \]
Thermal inflation

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

Inflation for

\[ V^{1/4}_0 \gtrsim T \gtrsim m \]

\[ T \propto e^{-N} \text{ so few e-folds} \]

\[ N \sim \ln \frac{V^{1/4}_0}{m} \]
Thermal inflation

If

\[ V_0^{1/4} \sim 10^6 \text{ to } 10^7 \text{ GeV} \]

which for \( V_0 \sim m^2 \phi_0^2 \) corresponds to

\[ \phi_0 \sim 10^{10} \text{ to } 10^{12} \text{ GeV} \]

then

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

Inflation for

\[ V_0^{1/4} \gtrsim T \gtrsim m \]

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

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Thermal inflation

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then

\textbf{dilution factor} \sim 10^{20}: \text{ pre-existing moduli sufficiently diluted,}

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

\text{Inflation for}
\[ V_0^{1/4} \gtrsim T \gtrsim m \]

\[ T \propto e^{-N} \text{ so few e-folds} \]

\[ N \sim \ln \left( \frac{V_0^{1/4}}{m} \right) \]
Thermal inflation

If
\[ V_0^{1/4} \sim 10^6 \text{ to } 10^7 \text{ GeV} \]
which for \( V_0 \sim m^2 \phi_0^2 \) corresponds to
\[ \phi_0 \sim 10^{10} \text{ to } 10^{12} \text{ GeV} \]
then
- dilution factor \( \sim 10^{20} \): pre-existing moduli sufficiently diluted,
- \( H \sim 10^{-8} m \): moduli regenerated with sufficiently small abundance,

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

Inflation for
\[ V_0^{1/4} \gtrsim T \gtrsim m \]
\[ T \propto e^{-N} \] so few e-folds
\[ N \sim \ln \frac{V_0^{1/4}}{m} \]

\( H \sim 10^{-8} m \): primordial gravitational waves wiped out on solar system scales.
Thermal inflation

If

\[ V_0^{1/4} \sim 10^6 \text{ to } 10^7 \text{ GeV} \]

which for \( V_0 \sim m^2 \phi_0^2 \) corresponds to

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

Inflation for

\[ V_0^{1/4} \gtrsim T \gtrsim m \]

\[ T \propto e^{-N} \text{ so few e-folds} \]

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

\text{dilution factor} \sim 10^{20}: \text{ pre-existing moduli sufficiently diluted,}

\[ H \sim 10^{-8} m: \text{ moduli regenerated with sufficiently small abundance,} \]

\[ N \sim 10: \text{ primordial perturbations from slow-roll inflation preserved on large scales,} \]
Thermal inflation

If
\[ V_{1/4} \sim 10^6 \text{ to } 10^7 \text{ GeV} \]
which for \( V_0 \sim m^2 \phi_0^2 \) corresponds to
\[ \phi_0 \sim 10^{10} \text{ to } 10^{12} \text{ GeV} \]
then

- 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,
- \( H \sim 1 \text{ to } 10 \text{ keV} \): primordial gravitational waves wiped out on solar system scales.

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

Inflation for
\[ V_0^{1/4} \gtrsim T \gtrsim m \]
\[ T \propto e^{-N} \] so few e-folds
\[ N \sim \ln \frac{V_0^{1/4}}{m} \]
First order phase transition since $\phi_0 \gg T_c \sim m$. 

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$V$ 

$V_0$ 

$|\phi|$ 

$\phi_0$ 

$\Omega_{GW} \sim 10^{-20}$ 

$\Omega_{GW} \sim 10^{-20}$ 

$\Gamma \sim 10^{-3}$ to $10^{-5}$ 

$H \sim 10^5$ to $10^3$ 

$\dot{\Gamma} \sim 10^4$ 

$\frac{V}{V_0} \sim 10^{6.5}$ GeV 

$\frac{\dot{\Gamma}}{H} \sim 10^{4}$ 

$\frac{T}{m} \sim 10^{1/3}$ 

$\frac{\rho d}{a^3 c} \sim 10^{1/3}$
First order phase transition since $\phi_0 \gg T_c \sim m$. Typical bubble size

$$\frac{\Gamma}{\Gamma} \sim (10^{-3} \text{ to } 10^{-5}) \frac{1}{H} \sim (10^5 \text{ to } 10^3) \frac{1}{m}$$
First order phase transition

First order phase transition since \( \phi_0 \gg T_c \sim m \). Typical bubble size

\[
\frac{\Gamma}{\dot{\Gamma}} \sim (10^{-3} \text{ to } 10^{-5}) \frac{1}{H} \sim (10^5 \text{ to } 10^3) \frac{1}{m}
\]

Gravitational waves generated with frequency

\[
f \sim 10 \text{ Hz} \left( \frac{\dot{\Gamma}/H\Gamma}{10^4} \right) \left( \frac{V_0^{1/4}}{10^{6.5} \text{ GeV}} \right)^{2/3} \left( \frac{T_d}{10 \text{ GeV}} \right)^{1/3} \left( \frac{V_0 a_c^3/\rho_d a_d^3}{10} \right)^{1/3}
\]
First order phase transition since $\phi_0 \gg T_c \sim m$. Typical bubble size

\[
\frac{\Gamma}{\dot{\Gamma}} \sim (10^{-3} \text{ to } 10^{-5}) \frac{1}{H} \sim (10^5 \text{ to } 10^3) \frac{1}{m}
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Gravitational waves generated with frequency

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f \sim 10 \text{ Hz} \left( \frac{\dot{\Gamma}/H\Gamma}{10^4} \right) \left( \frac{V_0^{1/4}}{10^{6.5} \text{ GeV}} \right)^{2/3} \left( \frac{T_d}{10 \text{ GeV}} \right)^{1/3} \left( \frac{V_0 a_c^3/\rho_d a_d^3}{10} \right)^{1/3}
\]

and density

\[
\Omega_{GW} \sim 10^{-20} \left( \frac{10^4}{\dot{\Gamma}/H\Gamma} \right)^2 \left( \frac{10^{6.5} \text{ GeV}}{V_0^{1/4}} \right)^{4/3} \left( \frac{T_d}{10 \text{ GeV}} \right)^{4/3} \left( \frac{V_0 a_c^3/\rho_d a_d^3}{10} \right)^{4/3}
\]
Gravitational waves

\[ \Omega_{GW} \]

![Graph showing gravitational waves across different frequencies and amplitudes](image-url)
Gravitational waves

- Primordial Inflation
- Thermal Inflation
- Preheating
- ultimate array
- DECIGO

Graph showing the energy density of gravitational waves, $\Omega_{GW}$, as a function of frequency, $f$, with different regions labeled for different inflationary eras.
MSCM superpotential

\[ W = \lambda_u QH_u \bar{u} + \lambda_d QH_d \bar{d} + \lambda_e LH_d \bar{e} + \mu H_u H_d \]
MSCM superpotential

\[ W = \lambda_u QH_u \bar{u} + \lambda_d QH_d \bar{d} + \lambda_e LH_d \bar{\ell} + \mu H_u H_d + \frac{1}{2} \lambda_{\nu} (LH_u)^2 \]
MSCM superpotential

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

\[ \mu = \lambda_\mu \phi_0^2 \]
MSCM superpotential

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

\[
\mu = \lambda \mu \phi_0^2
\]
MSCM superpotential

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

\[ \mu = \lambda_\mu \phi_0^2 \]

\[ m_\phi^2 < 0 \]
MSCM superpotential

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

\[ \mu = \lambda_\mu \phi_0^2 \]

\[ m^2_\phi < 0 \]
Key assumption

\[ m_{LH_u}^2 = \frac{1}{2} (m_L^2 + m_{H_u}^2) < 0 \]
Key assumption

\[ m_{LH_u}^2 = \frac{1}{2} (m_L^2 + m_{H_u}^2) < 0 \]

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

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

eliminating the \( \mu \)-term contribution to \( LH_u \)'s mass squared.
Reduction

For simplicity, reduce to a single generation

\[
L = \begin{pmatrix}
      \\
\end{pmatrix}
, \quad
H_u = \begin{pmatrix}
      \\
\end{pmatrix}
, \quad
H_d = \begin{pmatrix}
      \\
\end{pmatrix}
, \quad
\bar{e} = \begin{pmatrix}
      \\
\end{pmatrix}

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

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

For simplicity, reduce to a single generation

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

\[ \bar{u} = ( \quad ) , \quad Q = \begin{pmatrix} \end{pmatrix} , \quad \bar{d} = ( \quad ) \]

\[ \phi = \phi , \quad \chi = , \quad \bar{\chi} = \]
Reduction

For simplicity, reduce to a single generation

\[ L = \begin{pmatrix} \end{pmatrix}, \quad H_u = \begin{pmatrix} h_u \\ 0 \end{pmatrix}, \quad H_d = \begin{pmatrix} 0 \end{pmatrix}, \quad \bar{e} = \begin{pmatrix} \end{pmatrix} \]

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

\[ \phi = \phi, \quad \chi = 0, \quad \bar{\chi} = 0 \]
Reduction

For simplicity, reduce to a single generation

\[ L = \begin{pmatrix} 1 \\ \end{pmatrix}, \quad H_u = \begin{pmatrix} h_u \\ 0 \end{pmatrix}, \quad H_d = \begin{pmatrix} 0 \\ h_d \end{pmatrix}, \quad \tilde{e} = \begin{pmatrix} e/\sqrt{2} \end{pmatrix} \]

\[ \tilde{u} = \begin{pmatrix} 0 & 0 & 0 \end{pmatrix}, \quad Q = \begin{pmatrix} 0 & 0 & 0 \end{pmatrix}, \quad \tilde{d} = \begin{pmatrix} d/\sqrt{2} & 0 & 0 \end{pmatrix} \]

\[ \phi = \phi, \quad \chi = 0, \quad \tilde{\chi} = 0 \]
Reduction

For simplicity, reduce to a single generation

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

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

\[ \phi = \phi, \quad \chi = 0, \quad \bar{\chi} = 0 \]
Reduction

For simplicity, reduce to a single generation

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

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

\[ \phi = \phi, \quad \chi = 0, \quad \bar{\chi} = 0 \]

The superpotential reduces to

\[ W = \frac{1}{2} \lambda_d h_d d^2 + \frac{1}{2} \lambda_e h_d e^2 + \lambda_{\mu} \phi^2 h_u h_d + \frac{1}{2} \lambda_{\nu} (lh_u)^2 \]

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

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

\[ V = V_0 + m^2_l |l|^2 - m^2_{H_u} |h_u|^2 + m^2_{H_d} |h_d|^2 - m^2_\phi |\phi|^2 \]

\[ + \frac{1}{2} (m^2_Q + m^2_d) |d|^2 + \frac{1}{2} (m^2_L + m^2_e) |e|^2 \]

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

\[ + |\lambda_{\nu} l h_u^2|^2 + |\lambda_{\nu} l^2 h_u + \lambda_{\mu} \phi^2 h_d|^2 + |\lambda_{\mu} \phi^2 h_u + \frac{1}{2} \lambda_d d^2 + \frac{1}{2} \lambda_e e^2|^2 \]

\[ + |\lambda_d h_d d|^2 + |\lambda_e h_d e|^2 + |2 \lambda_{\mu} \phi h_u h_d|^2 \]

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

\[ V = V_0 + m_L^2 |l|^2 - m_{H_u}^2 |h_u|^2 + m_{H_d}^2 |h_d|^2 - m_{\phi}^2 |\phi|^2 \]

\[ + \frac{1}{2} (m_Q^2 + m_d^2) |d|^2 + \frac{1}{2} (m_L^2 + m_e^2) |e|^2 \]

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

\[ + |\lambda_\nu l^2 h_u|^2 + |\lambda_\nu l^2 h_u + \lambda_\mu \phi^2 h_d|^2 + |\lambda_\mu \phi^2 h_u + \frac{1}{2} \lambda_d d^2 + \frac{1}{2} \lambda_e e^2|^2 \]

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

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

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

- \text{drives thermal inflation}
- \text{\(lh_u\) rolls away}
- \text{\(\phi\) rolls away}

\text{\(lh_u\) stabilized with fixed phase}
Potential

\[ V = V_0 + m_L^2 |l|^2 - m_{H_u}^2 |h_u|^2 + m_{H_d}^2 |h_d|^2 - m_{\phi}^2 |\phi|^2 \]

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

- \text{drives thermal inflation}
- \text{\(lh_u\) rolls away}
- \text{\(\phi\) rolls away}
- \text{\(lh_u\) stabilized with fixed phase}
- \(h_d\) forced out

\(lh_u\) returns with rotation \(\phi\) stabilized
\(m_2 \phi \phi (0) = -\alpha \phi m_2 \phi (0)\)
Potential

\[ V = V_0 + \left( m_L^2 |l|^2 - m_{H_u}^2 |h_u|^2 \right) + m_{H_d}^2 |h_d|^2 - m_{\phi}^2 |\phi|^2 \]

\[ + \frac{1}{2} (m_Q^2 + m_{d}^2) |d|^2 \quad + \frac{1}{2} (m_i^2 + m_e^2) |e|^2 \]

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

\[ + |\lambda_{\nu} l h_u^2|^2 \quad + |\lambda_{\nu} l^2 h_u | + |\lambda_{\mu} \phi^2 h_d|^2 \quad + |\lambda_{\mu} \phi^2 h_u + \frac{1}{2} \lambda_{d} d^2 + \frac{1}{2} \lambda_{e} e^2|^2 \]

\[ + |\lambda_{d} h_d d|^2 \quad + |\lambda_{e} h_d e|^2 \quad + |2 \lambda_{\mu} \phi h_u h_d|^2 \]

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

- \( lh_u \) stabilizes with fixed phase
- \( lh_u \) rolls away
- \( \phi \) rolls away
- \( d \) and \( e \) held at origin
- \( h_d \) forced out

\( lh_u \) drives thermal inflation
Potential

$$V = V_0 + m_L^2 |l|^2 - m_{H_u}^2 |h_u|^2 + m_{H_d}^2 |h_d|^2 - m_{\phi}^2 |\phi|^2$$

$$+ \frac{1}{2} (m_Q^2 + m_d^2) |\alpha|^2 + \frac{1}{2} (m_i^2 + m_e^2) |e|^2$$

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

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

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

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

- Drives thermal inflation
- $lh_u$ rolls away
- $\phi$ rolls away

$lh_u$ stabilized with fixed phase

$d$ and $e$ held at origin

$h_d$ forced out

$lh_u$ returns with rotation
Potential

\[
V = V_0 + m_L^2 |l|^2 - m_{H_u}^2 |h_u|^2 + m_{H_d}^2 |h_d|^2 + m_{\phi}^2(\phi) |\phi|^2
\]

\[
+ \frac{1}{2} (m_Q^2 + m_d^2) |\phi'|^2 + \frac{1}{2} (m_i^2 + m_e^2) |e|^2
\]

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

\[
+ |\lambda_{\nu} l h_u^2|^2 + |\lambda_{\nu} l l h_u + \lambda_{\mu} \phi^2 h_d|^2 + |\lambda_{\mu} \phi^2 h_u + \frac{1}{2} \lambda_d d^2 + \frac{1}{2} \lambda_e e^2|^2
\]

\[
+ |\lambda_{d} h_d d|^2 + |\lambda_{e} h_d e|^2 + |2 \lambda_{\mu} \phi h_u h_d|^2
\]

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

\[
\phi \text{ stabilized } \Rightarrow m_{\phi}^2(\phi_0) = -\alpha_{\phi} m_{\phi}^2(0)
\]

\[
lh_u \text{ stabilized with fixed phase}
\]

\[
lh_u \text{ rolls away}
\]

\[
lh_u \text{ returns with rotation}
\]

\[
d \text{ and } e \text{ held at origin}
\]

\[
h_d \text{ forced out}
\]
Cosmology

**Moduli Domination**
- $\phi = 0$
- $h_u h_d = 0$
- $l h_u = 0$

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

**Flaton Domination**
- $\phi$ preheats
- $\phi$ decays

**Radiation Domination**
- $\phi$ decays

nucleosynthesis
Simulation

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

CP phase

\[
\text{arg} (-B^* A_\nu) = \begin{cases} 
\pi - \frac{\pi}{20} & \text{CP+} \\
\pi & \text{CP0} \\
\pi + \frac{\pi}{20} & \text{CP-}
\end{cases}
\]

Initial conditions

\[
\begin{align*}
\phi &= 4m + \delta \phi \\
l &= l_0 + \delta l \\
h_d &= \delta h_d
\end{align*}
\]

Constraints

\[
\begin{align*}
D &= \epsilon^2 \quad \text{with } \epsilon = 4.8 \times 10^{-3} l_0 \\
\dot{j}_0 &= 0
\end{align*}
\]

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

$n_L/n_{AD}$

$mt$
Baryon asymmetry

\[
\frac{n_B}{s} \sim \frac{n_L}{n_{AD}} \frac{n_{AD}}{n_\phi} \frac{T_d}{m_\phi(\phi_0)}
\]
Baryon asymmetry

\[ \frac{n_B}{s} \sim \frac{n_L}{n_{AD}} \frac{n_{AD}}{n_\phi} \frac{T_d}{m_\phi(\phi_0)} \]

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 \( n_{AD} \sim m_{LH_u} l_0^2 \) and

\[ l_0 \sim 100 \text{ GeV} \sqrt{\frac{m_{LH_u}}{m_\nu}} \]

gives

\[ \frac{n_B}{s} \sim 10^{-10} \left( \frac{n_L/n_{AD}}{10^{-2}} \right) \left( \frac{10^{12} \text{ GeV}}{\phi_0} \right)^2 \left( \frac{T_d}{1 \text{ GeV}} \right) \left( \frac{10^{-1}}{\alpha_\phi} \right) \left( \frac{10^{-2} \text{ eV}}{m_\nu} \right) \left( \frac{m_{LH_u}}{m_\phi(0)} \right)^2 \]
Baryon asymmetry

\[
\frac{n_B}{s} \sim \frac{n_L}{n_{AD}} \frac{n_{AD}}{n_\phi} \frac{T_d}{m_\phi(\phi_0)}
\]

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 \(n_{AD} \sim m_{LH_u} l_0^2\) and

\[
l_0 \sim 100 \text{ GeV} \sqrt{\frac{m_{LH_u}}{m_\nu}}
\]
gives

\[
\frac{n_B}{s} \sim 10^{-10} \left( \frac{n_L/n_{AD}}{10^{-2}} \right) \left( \frac{10^{12} \text{ GeV}}{\phi_0} \right)^2 \left( \frac{T_d}{1 \text{ GeV}} \right) \left( \frac{10^{-1}}{\alpha_\phi} \right) \left( \frac{10^{-2} \text{ eV}}{m_\nu} \right) \left( \frac{m_{LH_u}}{m_\phi(0)} \right)^2
\]

and using

\[
T_d \sim 1 \text{ GeV} \left( \frac{10^{12} \text{ GeV}}{\phi_0} \right) \left( \frac{|\mu|}{10^3 \text{ GeV}} \right)^2
\]
gives

\[
\frac{n_B}{s} \sim 10^{-10} \left( \frac{n_L/n_{AD}}{10^{-2}} \right) \left( \frac{10^{12} \text{ GeV}}{\phi_0} \right)^3 \left( \frac{|\mu|}{10^3 \text{ GeV}} \right)^2 \left( \frac{10^{-1}}{\alpha_\phi} \right) \left( \frac{10^{-2} \text{ eV}}{m_\nu} \right) \left( \frac{m_{LH_u}}{m_\phi(0)} \right)^2
\]
Dark matter candidates

Peccei-Quinn symmetry

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

Peccei-Quinn symmetry

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

Peccei-Quinn symmetry

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

DFSZ axion

KSVZ axion

Axion

\[ m_a \sim \Lambda_{QCD} \]

\[ f_a = \sqrt{2} \phi_0 N \approx 6 \times 10^{-5} \text{eV} \left(10^{11} \text{GeV} f_a \right) \]

Axino

\[ m_{\tilde{a}} = \frac{1}{16} \pi^2 \sum \lambda \chi^2 A \chi \sim 1 \text{to} 10 \text{GeV} \]
Dark matter candidates

Peccei-Quinn symmetry

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

Axion

\[ m_a \sim \frac{\Lambda_{QCD}^2}{f_a} \quad \text{where} \quad f_a = \frac{\sqrt{2} \phi_0}{N} \]

\[ \simeq 6.2 \times 10^{-5} \text{eV} \left( \frac{10^{11} \text{GeV}}{f_a} \right) \]
Dark matter candidates

Peccei-Quinn symmetry

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

Axion

\[ m_a \sim \frac{\Lambda_{\text{QCD}}^2}{f_a} \quad \text{where} \quad f_a = \frac{\sqrt{2} \phi_0}{N} \]

\[ \sim 6.2 \times 10^{-5} \text{eV} \left( \frac{10^{11} \text{GeV}}{f_a} \right) \]

Axino

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

\[ \sim 1 \text{ to } 10 \text{ GeV} \]
Dark matter abundance

Axion

Axino
Axion Misalignment

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

Axino
Dark matter abundance

**Axion** Misalignment

\[ \Omega_a \sim 0.1 \left( \frac{\sqrt{6}}{N} \right)^{1.2} \left( \frac{\phi_0}{10^{11} \text{ GeV}} \right)^{1.2} \]

**Axino** Flaton decay

\[ \Omega_{\tilde{a}} \sim 0.4 \left( \frac{\alpha_{\tilde{a}}}{10^{-1}} \right)^2 \left( \frac{m_{\tilde{a}}}{1 \text{ GeV}} \right)^3 \left( \frac{10 \text{ GeV}}{T_d} \right) \left( \frac{10^{11} \text{ GeV}}{\phi_0} \right)^2 \]
Dark matter abundance

**Axion** Misalignment

\[ \Omega_a \sim 0.1 \left( \frac{\sqrt{6}}{N} \right)^{1.2} \left( \frac{\phi_0}{10^{11} \text{ GeV}} \right)^{1.2} \]

**Axino** Flaton decay

\[ \Omega_{\tilde{a}} \sim 0.4 \left( \frac{\alpha_{\tilde{a}}}{10^{-1}} \right)^2 \left( \frac{m_{\tilde{a}}}{1 \text{ GeV}} \right)^3 \left( \frac{10 \text{ GeV}}{T_d} \right) \left( \frac{10^{11} \text{ GeV}}{\phi_0} \right)^2 \]

**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

\[ T_d \sim 10 \text{ GeV} \left( \frac{|\mu|}{10^3 \text{ GeV}} \right)^2 \left( \frac{10^{11} \text{ GeV}}{\phi_0} \right) \]

Axion Misalignment

\[ \Omega_a \sim 0.1 \left( \frac{\sqrt{6}}{N} \right)^{1.2} \left( \frac{\phi_0}{10^{11} \text{ GeV}} \right)^{1.2} \]

Axino Flaton decay

\[ \Omega_{\tilde{a}} \sim 0.4 \left( \frac{\alpha_{\tilde{a}}}{10^{-1}} \right)^2 \left( \frac{m_{\tilde{a}}}{1 \text{ GeV}} \right)^3 \left( \frac{10 \text{ GeV}}{T_d} \right) \left( \frac{10^{11} \text{ GeV}}{\phi_0} \right)^2 \]

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

\[ T_d \sim 10 \text{ GeV}\left(\frac{|\mu|}{10^3 \text{ GeV}}\right)^2 \left(\frac{10^{11} \text{ GeV}}{\phi_0}\right) \]

Axion Misalignment

\[ \Omega_a \sim 0.1 \left(\frac{\sqrt{6}}{N}\right)^{1.2} \left(\frac{\phi_0}{10^{11} \text{ GeV}}\right)^{1.2} \times \begin{cases} 1 & \text{for } T_d \gg 1 \text{ GeV} \\ \left(\frac{T_d}{1 \text{ GeV}}\right)^2 & \text{for } T_d \ll 1 \text{ GeV} \end{cases} \]

Axino Flaton decay

\[ \Omega_{\tilde{a}} \sim 0.4 \left(\frac{\alpha_{\tilde{a}}}{10^{-1}}\right)^2 \left(\frac{m_{\tilde{a}}}{1 \text{ GeV}}\right)^3 \left(\frac{10 \text{ GeV}}{T_d}\right) \left(\frac{10^{11} \text{ GeV}}{\phi_0}\right)^2 \]

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

\[ T_d \sim 10 \text{ GeV} \left( \frac{|\mu|}{10^3 \text{ GeV}} \right)^2 \left( \frac{10^{11} \text{ GeV}}{\phi_0} \right) \]

Axion Misalignment
\[ \Omega_a \sim 0.1 \left( \frac{\sqrt{6}}{N} \right)^{1.2} \left( \frac{\phi_0}{10^{11} \text{ GeV}} \right)^{1.2} \times \begin{cases} 1 & \text{for } T_d \gg 1 \text{ GeV} \\ \left( \frac{T_d}{1 \text{ GeV}} \right)^2 & \text{for } T_d \ll 1 \text{ GeV} \end{cases} \]

Axino Flaton decay
\[ \Omega_{\tilde{a}} \sim 0.4 \left( \frac{\alpha_{\tilde{a}}}{10^{-1}} \right)^2 \left( \frac{m_{\tilde{a}}}{1 \text{ GeV}} \right)^3 \left( \frac{10 \text{ GeV}}{T_d} \right) \left( \frac{10^{11} \text{ GeV}}{\phi_0} \right)^2 \]

Thermal NLSP decay
\[ \Omega_{\tilde{a}} \sim 10^3 \left( \frac{m_{\tilde{a}}}{1 \text{ GeV}} \right) \left( \frac{10^{11} \text{ GeV}}{\phi_0} \right)^2 \times \begin{cases} 1 & \text{for } T_d \gg \frac{m_N}{7} \\ \left( \frac{7T_d}{m_N} \right)^7 & \text{for } T_d \ll \frac{m_N}{7} \end{cases} \]
Dark matter composition

\[ \phi_0 = 2 \times 10^{11} \text{ GeV} \]

\[ \phi_0 = 10^{12} \text{ GeV} \]

\[ T_d \]

\[ \Omega \]

- flaton axinos
- NLSP axinos
- axions
Dark matter composition

\[ \phi_0 = 10^{12} \text{ GeV} \]

\[ \phi_0 = 2 \times 10^{11} \text{ GeV} \]
Dark matter composition

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

$\frac{n_L}{n_{AD}} \lesssim 10^{-5}$

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

$\frac{n_L}{n_{AD}} \gtrsim 10^{-2}$
Dark matter composition

\[ |\mu| = 600 \text{ GeV} \]

\[ \frac{n_L}{n_{AD}} \lesssim 10^{-5} \]

\[ \frac{n_L}{n_{AD}} \gtrsim 10^{-2} \]

\[ |\mu| = 1300 \text{ GeV} \]

- NLSP axinos
- flaton axinos
- axions
NLSPs produced by the LHC decay to axinos plus Standard Model particles

Axino LHC signal

\[ \Gamma_N \rightarrow \tilde{a} \sim 16 \pi \phi^2_0 m^3_N \sim 100 m (200 \text{ GeV} m_N)^3 (\phi_0^3 \times 10^{11} \text{ GeV})^2 \]

and well constrained parameters

\[ 10^{11} \text{ GeV} \lesssim \phi_0 \lesssim 10^{12} \text{ GeV} \]

\[ m_{\tilde{a}} \approx 1 \text{ GeV} \]
Axino LHC signal

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

with a decay length

\[
\frac{1}{\Gamma_{N \rightarrow \tilde{a}}} \sim \frac{16\pi \phi_0^2}{m_N^3} \sim 100 \text{ m} \left( \frac{200 \text{ GeV}}{m_N} \right)^3 \left( \frac{\phi_0}{3 \times 10^{11} \text{ GeV}} \right)^2
\]

and well constrained parameters

\[
10^{11} \text{ GeV} \lesssim \phi_0 \lesssim 10^{12} \text{ GeV}
\]

\[
m_{\tilde{a}} \simeq 1 \text{ GeV}
\]
Simple model

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

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

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

MSSM

neutrino masses

\text{MSSM} \quad \text{neutrino masses}
Simple model

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

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

drives \( m_\phi^2 < 0 \)
Simple model

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

- **MSSM**
- **neutrino masses**
- **MSSM \( \mu \)-term**
- **DFSZ axion**

- Drives \( m_\phi^2 < 0 \)
Simple model

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

drives \( m_\phi^2 < 0 \)

KSVZ axion

MSSM

neutrino masses

MSSM \( \mu \)-term

DFSZ axion

MSSM \( \mu \)-term

DFSZ axion

KSVZ axion
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
- MSSM $\mu$-term
- DFSZ axion
- Drives $m_\phi^2 < 0$
- KSVZ axion
- Thermal inflation
- Leptogenesis
- Dark matter
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

MSSM $\mu$-term DFSZ axion

drives $m_{LH_u}^2 < 0$

drives $m_\phi^2 < 0$

KSVZ axion thermal inflation

stabilizes LH

stabilizes d and e leptogenesis
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 stabilize** \( LH_u \)
- **MSSM \( \mu \)-term**
- **DFSZ axion**

- **drives** \( m_{LH_u}^2 < 0 \)

- **drives** \( m_\phi^2 < 0 \)
- **KSVZ axion thermal inflation**

**Leptogenesis**

**Dark matter**
Simple model

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

- MSSM
- MSSM $\mu$-term DFSZ axion
- neutrino masses stabilizes $LH_u$
- drives $m_{LH_u}^2 < 0$
- drives $m_\phi^2 < 0$
- KSVZ axion thermal inflation releases $\phi$
Simple model

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

- **MSSM**: drives \( m_{LH_u}^2 < 0 \)
- Neutrino masses stabilize \( LH_u \)
- **MSSM \( \mu \)-term DFSZ axion forces \( H_d > 0 \)
- Drives \( m_\phi^2 < 0 \)
- KSVZ axion thermal inflation releases \( \phi \)
- Leptogenesis dark matter
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**
  - Drives \( m_{LH_{u}}^{2} < 0 \)
  - Stabilizes \( d \) and \( e \)

- **MSSM \( \mu \)-term**
  - DFSZ axion forces \( H_{d} > 0 \)

- **Neutrino masses**
  - Stabilizes \( LH_{u} \)

- **KSVZ axion**
  - Drives \( m_{\phi}^{2} < 0 \)
  - Thermal inflation releases \( \phi \)
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**: drives \( m_{LH_u}^2 < 0 \)
- **neutrino masses stabilizes \( LH_u \)**
- **MSSM \( \mu \)-term DFSZ axion forces \( H_d > 0 \)
  \( m_{LH_u}^2 + \frac{1}{2} |\mu|^2 > 0 \)
- **drives \( m_{\phi}^2 < 0 \)**
  KSVZ axion thermal inflation releases \( \phi \)
- **stabilizes \( d \) and \( e \)**
Simple model

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

- **MSSM**
  - Neutrino masses stabilize \( L H_u \)
  - MSSM \( \mu \)-term
  - DFSZ axion forces \( H_d > 0 \)
  - \( m_{LH_u}^2 + \frac{1}{2} |\mu|^2 > 0 \)

- Drives \( m_{LH_u}^2 < 0 \)
- Stabilizes \( d \) and \( e \)
- Leptogenesis

- Drives \( m_\phi^2 < 0 \)
- KSVZ axion
- Thermal inflation
- Releases \( \phi \)
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**
  - Drives \( m_{LH_u}^2 < 0 \)
  - Stabilizes \( L H_u \)

- **neutrino masses stabilizes \( L H_u \)**

- **MSSM \( \mu \)-term**
  - DFSZ axion forces \( H_d > 0 \)
  - \( m_{LH_u}^2 + \frac{1}{2} |\mu|^2 > 0 \)
  - Efficient \( \phi \) decay

- **leptogenesis**
  - Drives \( m_{\phi}^2 < 0 \)
  - KSVZ axion thermal inflation releases \( \phi \)
Simple model

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

- **MSSM**
  - drives \( m_{LH_u}^2 < 0 \)
  - stabilizes \( LH_u \)

- **neutrino masses stabilizes \( LH_u \)**

- **MSSM \( \mu \)-term**
  - DFSZ axion forces \( H_d > 0 \)
  - \( m_{LH_u}^2 + \frac{1}{2} |\mu|^2 > 0 \)
  - efficient \( \phi \) decay

- **dark matter**
  - drives \( m_{\phi}^2 < 0 \)
  - KSVZ axion thermal inflation releases \( \phi \)

- **stabilizes \( d \) and \( e \)**

- **leptogenesis**
Rich cosmology

**MODULI DOMINATION**

- $\phi = 0$
- $h_u h_d = 0$
- $lh_u = 0$

**THERMAL INFLATION**

- $\phi > 0$
- $h_d > 0 \Rightarrow d = e = 0$
- $lh_d > 0$

- $\phi \sim \phi_0$
- $\phi$ preheats

- $l, h_u, h_d$ decay
- $T > T_{EW} \Rightarrow n_L \rightarrow n_B$

**FLATON DOMINATION**

- $\phi$ preheats
- $\phi$ decays
- $\phi$ decays
- $d = e = 0$

- $lh_u > 0$

**RADIATION DOMINATION**

- $lh_u > 0$

- brought back into origin with rotation
  - $\Rightarrow n_L < 0$
- preheating and thermal friction
  - $\Rightarrow N_L$ conserved
- $l, h_u, h_d$ decay
- $T > T_{EW} \Rightarrow n_L \rightarrow n_B$

- dilution
  - $\Rightarrow n_B/s \sim 10^{-10}$

- nucleosynthesis

- gravitational waves

- dark matter

- nucleosynthesis
History of the observable universe

- inflation
- density perturbations
- gravitational waves?
- $\nu_R$ decay
- baryons?
- moduli, gravitinos, ...
- disaster
- electroweak transition
- neutralino freeze out
- QCD transition
- baryons?
- neutralino dark matter?
- axion dark matter?
- nucleosynthesis
- light elements
- atom formation
- galaxy formation
- microwave background
- galaxies
- vacuum energy dominates
- acceleration
- $10^{11}$ GeV
- $10^3$ GeV
- 100 keV
- 10 K
- $10^{10}$ yr
- $10^{-28}$ s
- $10^{-13}$ s
- 10 min
- $m_{\text{Pl}}$
- $\rho^{1/4}$
- $t_{\text{Pl}}$
History of the observable universe

- **Inflation**
  - Density perturbations, gravitational waves?
  - \( \rho^{1/4} \)
  - \( m_{Pl} \)
  - \( t_{Pl} \)
  - \( 10^{11} \text{ GeV} \)
  - \( 10^{-28} \text{ s} \)

- **\( \nu_R \) decay**
  - Baryons?
  - Moduli, gravitinos, ...
  - Thermal inflation
  - \( 10^3 \text{ GeV} \)
  - \( 10^{-13} \text{ s} \)

- **QCD transition**
  - Nucleosynthesis
  - Light elements
  - \( 100 \text{ keV} \)
  - \( 10 \text{ min} \)

- **Atom formation**
  - Microwave background
  - Galaxy formation
  - Vacuum energy dominates
  - \( 10 \text{ K} \)
  - \( 10^{10} \text{ yr} \)
  - \( t \)
History of the observable universe

- Vacuum energy dominates
- galaxy formation
- microwave background
- galaxies
- acceleration
- nucleosynthesis
- light elements
- QCD transition
- thermal inflation
- $\nu_R$ decay
- moduli, gravitinos, ...
- inflation
- density perturbations
- gravitational waves?
- $t_{\text{Pl}}$:
  - $10^{-28}$ s
- $m_{\text{Pl}}$:
  - $10^{11}$ GeV
- $\rho^{1/4}$:
  - $10^3$ GeV
- $\nu_R$ decay:
  - baryons?
- moduli, gravitinos, ...
  - disaster
- inflation:
  - density perturbations
  - gravitational waves?
History of the observable universe

- $\rho^{1/4}$
- $m_{Pl}$
- $t_{Pl}$
- $10^{10}$ yr
- $10^{10}$ min
- $10^{-28}$ s
- $10^{-13}$ s
- $10^{3}$ GeV
- $10^{11}$ GeV
- $10^3$ GeV
- $100$ keV
- $10$ K

**Density Perturbations and Gravitational Waves?**

- Inflation
- Moduli, gravitinos, ...
- $\nu_R$ decay
- Thermal inflation
- $LH_u \rightarrow 0$
- QCD transition
- Nucleosynthesis
- Light elements
- Atom formation
- Microwave background
- Vacuum energy dominates
- Galaxy formation
- Galaxies
- Acceleration
History of the observable universe

- Inflation
- Density perturbations gravitational waves?
- $\nu_R$ decay
- Baryons?
- Moduli, gravitinos, …
- Disasters
- Thermal inflation
- $LH_u \rightarrow 0$
- Baryons
- QCD transition
- Nucleosynthesis
- Light elements
- Atom formation
- Microwave background
- Galaxies
- Vacuum energy dominates
- Galaxy formation
- Microwave background
- Galaxies
- Acceleration
- 10 K
- Vacuum energy dominates
- 10 min
- 10 K
- Galaxy formation
- 10 min
- Galaxy formation
- 10 min
- Atom formation
- Microwave background
- 10 min
- Atom formation
- Microwave background
- 10 min
History of the observable universe

- Inflation
- Density perturbations, gravitational waves?
- $\nu_R$ decay
- Baryons?
- Moduli, gravitinos, ...
- Thermal inflation
- $LH_u \rightarrow 0$
- Baryons
- Flaton decay
- Axino dark matter
- QCD transition
- Nucleosynthesis
- Light elements
- Atom formation
- Microwave background
- Vacuum energy dominates
- Galaxy formation
- Galaxies
- Acceleration
- 10 K
- 100 keV
- $10^{11}$ GeV
- $10^{10}$ yr
- $10^{-13}$ s
- $10^{-28}$ s
- $t_{Pl}$
- $m_{Pl}$
- $\rho^{1/4}$
History of the observable universe

- $\rho^{1/4}$
- $\frac{1}{4}$
- $m_{\text{Pl}}$
- $t_{\text{Pl}}$
- $10^{11}$ GeV
- $10^{10}$ GeV
- $100$ keV
- $10$ K
- $10^{-28}$ s
- $10^{-13}$ s
- $10$ min
- $10^{10}$ yr

- Inflation
- Density perturbations gravitational waves?
- $\nu_R$ decay
- Baryons?
- Moduli, gravitinos, ...
- Disaster
- Thermal inflation
- $LH_u \rightarrow 0$
- Baryons
- Flaton decay
- Axino dark matter
- QCD transition
- Axion dark matter
- Nucleosynthesis
- Light elements
- Atom formation
- Microwave background
- Vacuum energy dominates
- Galaxy formation
- Galaxies
- Acceleration
History of the observable universe

- **Vacuum energy dominates** (today)
- **Galaxy formation**
- **Microwave background**
- **Galaxies**
- **Accretion**
- **Nucleosynthesis**
- **Light elements**
- **QCD transition**
- **Axino dark matter**
- **Axion dark matter**
- **Flaton decay**
- **Thermal inflation**
- **Moduli, gravitinos, ...**
- **$\nu_R$ decay**
- **Inflation**
- **Density perturbations, gravitational waves?**

**Timelines:**
- $10^{-28}$ s
- $10^{-13}$ s
- 10 min
- $10^{10}$ yr
- $10^{11}$ GeV
- $10^3$ GeV
- 100 keV
- 10 K
History of the observable universe

- Inflation
- \( \rho^{1/4} \)
- \( m_{\text{Pl}} \)
- \( t_{\text{Pl}} \)
- \( 10^{11} \text{ GeV} \)
- \( 10^{3} \text{ GeV} \)
- \( 100 \text{ keV} \)
- \( 10 \text{ K} \)
- \( 10^{10} \text{ yr} \)
- \( 10^{10} \text{ min} \)
- \( 10^{-28} \text{ s} \)
- \( 10^{-13} \text{ s} \)
- \( \nu_R \) decay
- Moduli, gravitinos, ...
- Thermal inflation
- Gravitational waves
- Flaton decay
- QCD transition
- Nucleosynthesis
- Light elements
- Atom formation
- Galaxy formation
- Vacuum energy dominates
- Microwave background
-Galaxies
- Acceleration
History of the observable universe

Vacuum energy dominates
- galaxy formation
- atom formation

10 K
- peak of nucleosynthesis
- QCD transition
- flaton decay
- thermal inflation

$10^3$ GeV
- LHC
- flaton decay
- $LH_u \rightarrow 0$

$10^1$ GeV
- inflation
- density perturbations
- gravitational waves?

$t_{Pl}$
- $10^{-28}$ s
- $10^{-13}$ s
- $10^{10}$ yr
- $10$ min
- $10^3$ s
Introduction
  History of the observable universe

Thermal inflation and gravitational waves
  Moduli problem
  Thermal inflation
  First order phase transition
  Gravitational waves

Baryogenesis
  Superpotential
  Key assumption
  Reduction
  Potential
  Cosmology
  Numerical simulation
  Lepton number
  Baryon asymmetry

Dark matter
  Candidates
  Abundance
  Composition
  LHC signal

Summary
  Simple model
  Rich cosmology
  History of the observable universe
Gravitational waves

\[ \Omega_{GW} \]

\[ f \quad \text{Hz} \]

- **PRIMORDIAL INFLATION**
- **THERMAL INFLATION**
- **INFLATION PREHEATING**
- **DECIGO**
- **ultimate array**
Dark matter composition

\[ \frac{n_L}{n_{AD}} \lesssim 10^{-5} \]

\[ |\mu| = 1300 \text{ GeV} \]

\[ \frac{n_L}{n_{AD}} \gtrsim 10^{-2} \]

NLSP
axinos

|\mu| = 600 \text{ GeV}

flaton
axinos

axions
$|\mu| = 600 \text{ GeV}$}

$\frac{n_L}{n_{AD}} \lesssim 10^{-5}$

$\frac{n_L}{n_{AD}} \gtrsim 10^{-2}$
Key assumption

\[ m_{LH_u}^2 = \frac{1}{2} (m_L^2 + m_{H_u}^2) < 0 \]

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

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

eliminating the \( \mu \)-term contribution to \( LH_u \)'s mass squared.
Axino LHC signal

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

\[ \frac{1}{\Gamma_{N \rightarrow \tilde{a}}} \sim \frac{16\pi \phi_0^2}{m_N^3} \sim 100 \text{ m} \left( \frac{200 \text{ GeV}}{m_N} \right)^3 \left( \frac{\phi_0}{3 \times 10^{11} \text{ GeV}} \right)^2 \]

with a decay length

and well constrained parameters

\[ 10^{11} \text{ GeV} \lesssim \phi_0 \lesssim 10^{12} \text{ GeV} \]

\[ m_{\tilde{a}} \simeq 1 \text{ GeV} \]