The Origin of Matter

Ewan Stewart

KAIST

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Dept. of Physics, KAIST

The Origin of Matter

The Standard Model

Beyond the Standard Model

Big Bang cosmology

A theory for the origin of matter

The Origin of Matter

Ordinary matter

atom $=$ electrons $+$ nucleus

Ordinary matter

$$\text{atom} \quad = \quad \text{electrons} \overset{\text{photons}}{+} \text{nucleus}$$

Ordinary matter

$$\begin{aligned} \text{atom} &= \text{electrons} \overset{\text{photons}}{+} \text{nucleus} \\ \text{nucleus} &= \text{protons} + \text{neutrons} \end{aligned}$$

Particle spectrum

neutron
proton

electron

photon

graviton

Quarks

proton	=	up quark	+	up quark	+	down quark
neutron	=	up quark	+	down quark	+	down quark

Quarks

$$\text{proton} = \text{up quark} \overset{\text{gluons}}{+} \text{up quark} \overset{\text{gluons}}{+} \text{down quark}$$

$$\text{neutron} = \text{up quark} \overset{\text{gluons}}{+} \text{down quark} \overset{\text{gluons}}{+} \text{down quark}$$

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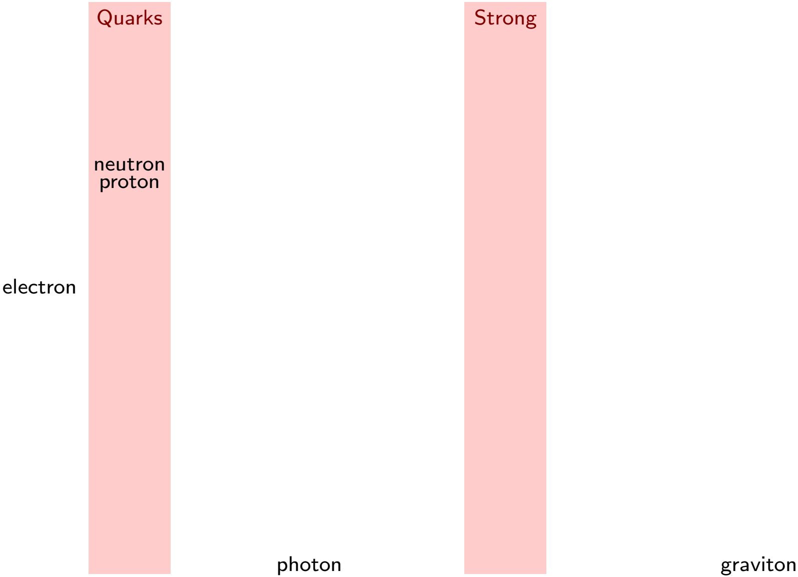
Particle spectrum



Particle spectrum

Quarks

Strong

gluon

down
up

electron

photon

graviton

Particle spectrum

Quarks

top

bottom
charm
strange

down
up

electron

Strong

gluon

photon

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Neutrinos

In the Sun

$$\text{proton} + \text{proton} \longrightarrow \text{deuterium} + \text{antielectron} + \text{neutrino}$$

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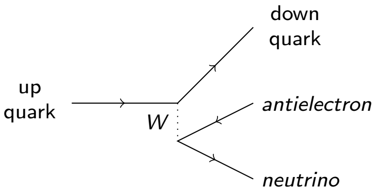
The weak nuclear force is mediated by the W and Z bosons



The W and Z bosons are massive and hence do not give rise to a long range force.

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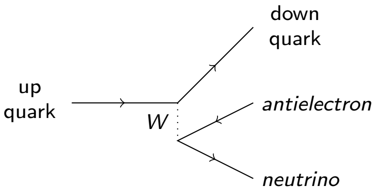

The W and Z bosons are massive and hence do not give rise to a long range force.
The electromagnetic and weak nuclear forces are unified into the electroweak force.

Particle spectrum

Quarks

top

bottom
charm
strange

down
up

electron

Strong

gluon

photon

graviton

Particle spectrum

Quarks

top

bottom
charm

strange

down
up

electron

neutrinos

Strong

gluon

photon

graviton

Particle spectrum

Leptons | Quarks | Electroweak | Strong

top

bottom
charm
strange

gluon

down
up

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neutrinos

photon

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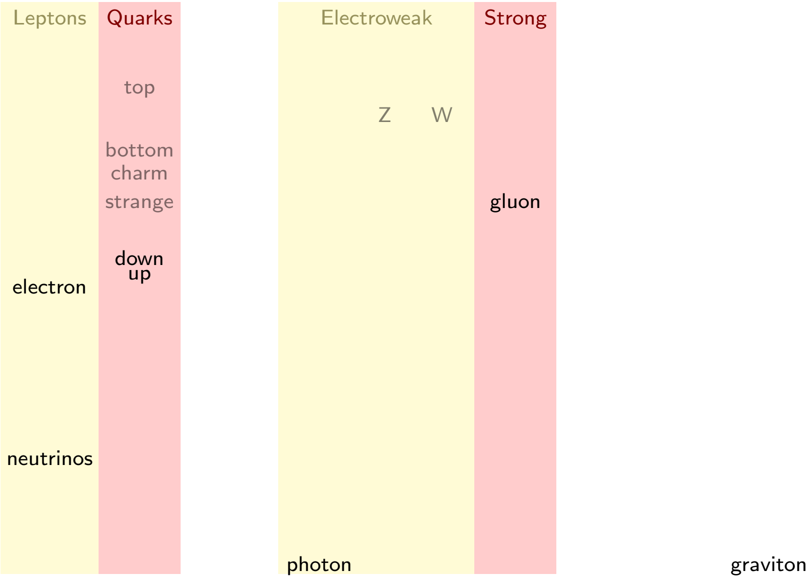
Particle spectrum



Particle spectrum

Higgs boson

The Higgs boson couples to the quarks and leptons in the Standard Model

$$\lambda_u Q H \bar{u} + \lambda_d Q \bar{H} \bar{d} + \lambda_e L \bar{H} \bar{e}$$

where

$$Q = \begin{pmatrix} u \\ d \end{pmatrix} \quad , \quad L = \begin{pmatrix} \nu \\ e \end{pmatrix}$$

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$$\lambda_u Q H \bar{u} + \lambda_d Q \bar{H} \bar{d} + \lambda_e L \bar{H} \bar{e} \quad \rightarrow \quad m_u u \bar{u} + m_d d \bar{d} + m_e e \bar{e}$$

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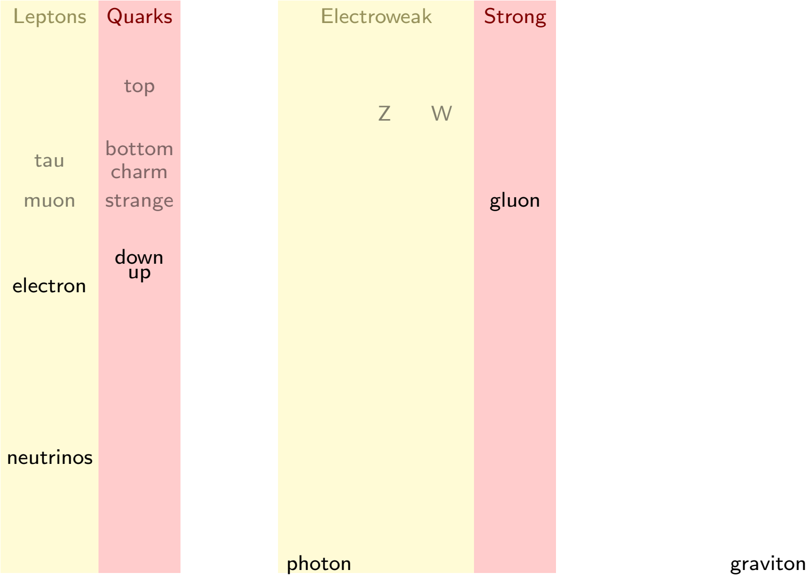
It similarly gives masses to the W and Z bosons.

Particle spectrum



Particle spectrum

The Origin of Matter

Neutrino masses

Neutrinos have no mass in the Standard Model. However, in reality one expects higher order couplings including

$$\frac{1}{2}\lambda_\nu \left(LH\right)^2$$

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$$\frac{1}{2}\lambda_\nu \, (LH)^2 \quad \rightarrow \quad \frac{1}{2} m_\nu \nu^2$$

where

$$L = \begin{pmatrix} \nu \\ e \end{pmatrix} \qquad , \qquad H \rightarrow \begin{pmatrix} 0 \\ h \end{pmatrix}$$

When the Higgs boson acquires a non-zero value, it gives small masses to the neutrinos

$$m_\nu = \lambda_\nu h^2$$

in agreement with observations.

Particle spectrum

Supersymmetry

Supersymmetry is a symmetry between bosons and fermions

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In a supersymmetric field theory, fields are replaced by superfields, which contain both bosons and fermions

$$\text{field} \longrightarrow \text{superfield} = \begin{pmatrix} \text{boson} \\ \text{fermion} \end{pmatrix}$$

The Minimal Supersymmetric Standard Model

MSSM = Standard Model + supersymmetry

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

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There are new superparticles for each of the Standard Model particles. For example

$$\text{quark} \rightarrow \begin{pmatrix} \text{squark} \\ \text{quark} \end{pmatrix} \begin{array}{l} \text{spin } 0 \\ \text{spin } \frac{1}{2} \end{array} \qquad , \qquad \text{photon} \rightarrow \begin{pmatrix} \text{photino} \\ \text{photon} \end{pmatrix} \begin{array}{l} \text{spin } \frac{1}{2} \\ \text{spin } 1 \end{array}$$

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For these reasons, supersymmetry, in the form of the MSSM, is expected to be discovered next year!

Particle spectrum

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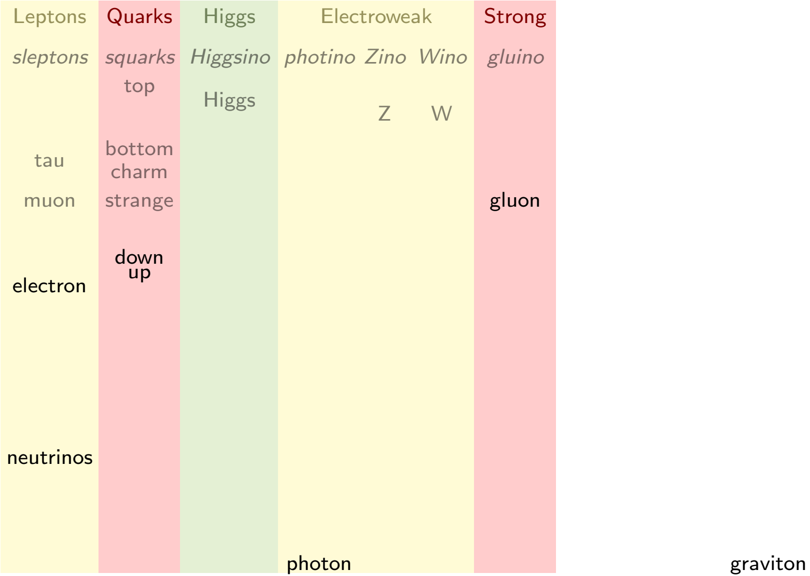

Particle spectrum

The strong CP problem

The strong interactions would be expected to contain a CP violating term

$$\theta F \wedge F$$

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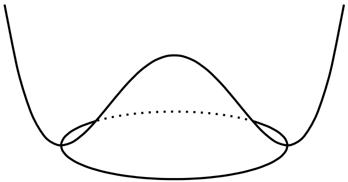
$$\theta F \wedge F$$

where F is the gluon field strength. However, experimental constraints on the electric dipole moment of the neutron require

$$\theta \lesssim 10^{-10}$$

Axions

The strong CP problem can be solved by introducing a complex scalar field ϕ with a rotationally symmetric classical potential



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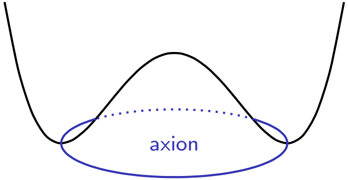

The angular part of the field is the axion

$$\phi = \phi_0 \exp\left(\frac{i a}{\sqrt{2}\,\phi_0}\right)$$

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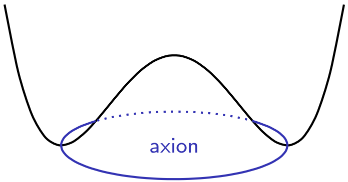

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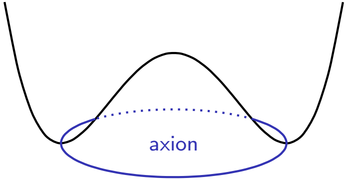

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$$\theta F \wedge F \to \left(\theta - \frac{N a}{\sqrt{2}\,\phi_0}\right) F \wedge F$$

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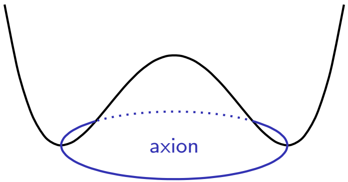

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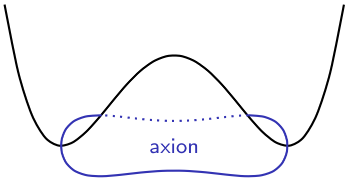

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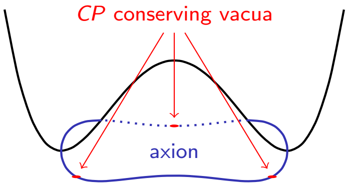

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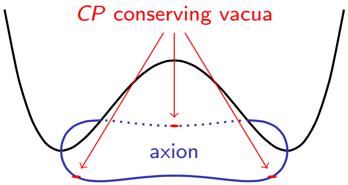

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$$\cancel{\left(\theta - \frac{N a}{\sqrt{2}\,\phi_0}\right) F \wedge F}$$

and quantum mechanics generates a potential for the axion. The minima of the axion potential are automatically CP conserving, cancelling off the problematic term.

Particle spectrum

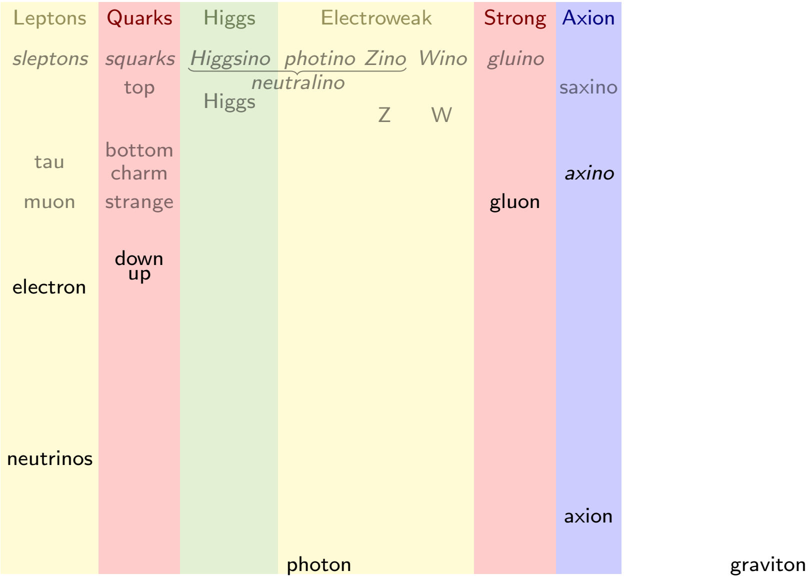
Particle spectrum

Particle spectrum

Gravitinos

$$\text{graviton} \rightarrow \begin{pmatrix} \text{gravitino} \\ \text{graviton} \end{pmatrix} \begin{matrix} \text{spin } \frac{3}{2} \\ \text{spin } 2 \end{matrix}$$

Particle spectrum



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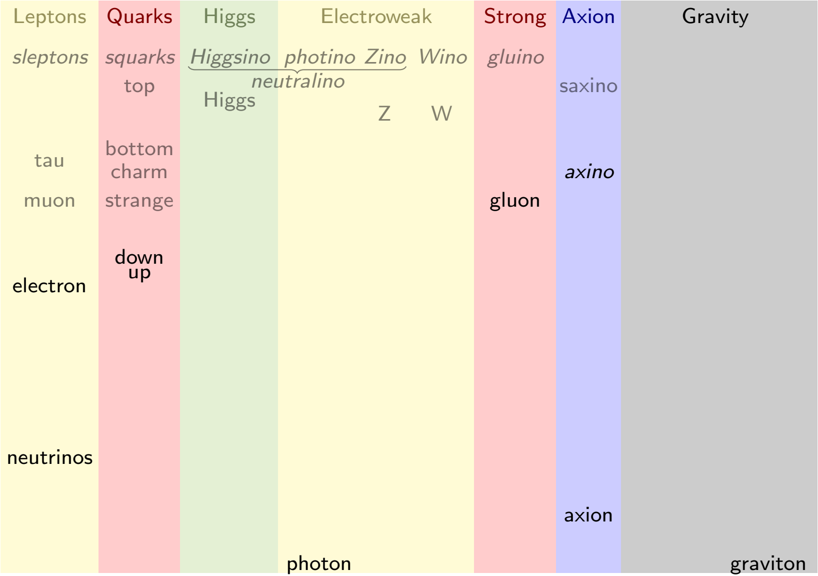

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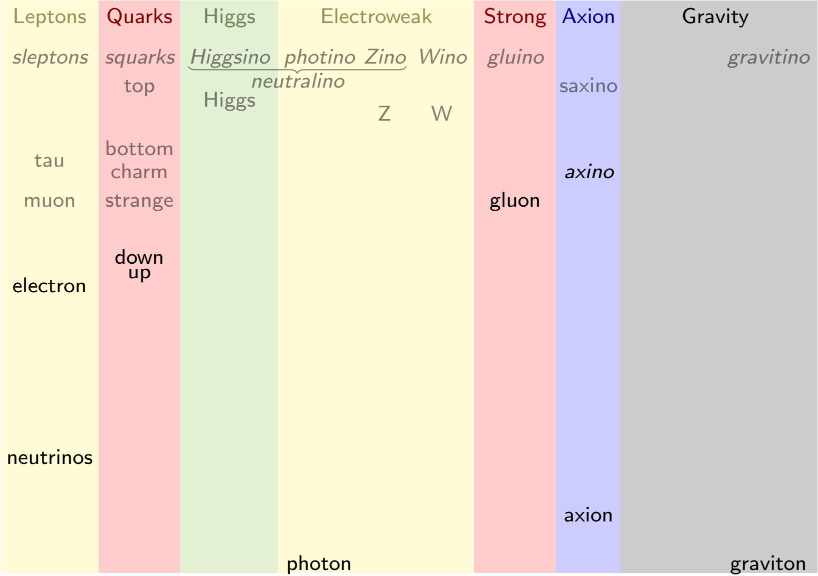

Moduli

field theories	$\longrightarrow$	many arbitrary parameters
string theory	$\longrightarrow$	no parameters

Moduli

field theories	$\longrightarrow$	many arbitrary parameters
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moduli vacuum values $\longrightarrow$ low energy parameters

Moduli

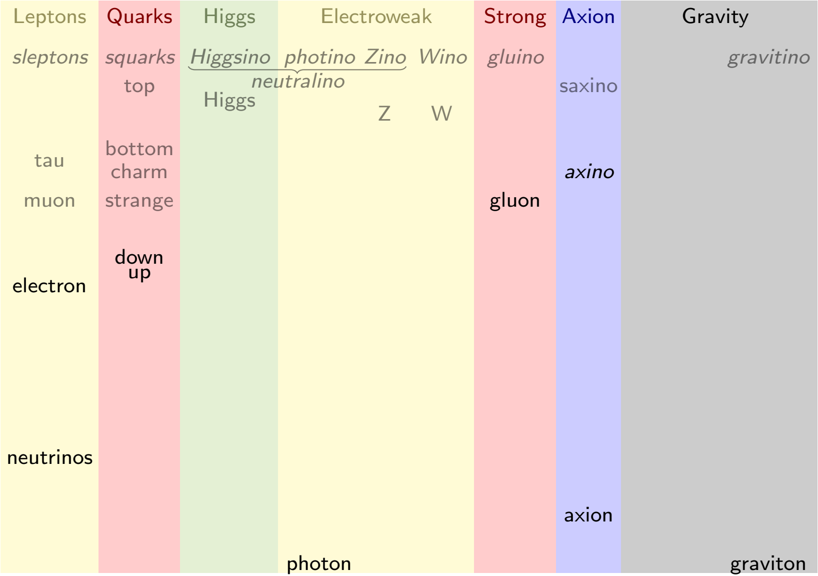
$$\begin{aligned} \text{field theories} \quad &\longrightarrow \quad \text{many arbitrary parameters} \\ \text{string theory} \quad &\longrightarrow \quad \text{many scalar fields (moduli)} \end{aligned}$$

$$\text{moduli vacuum values} \quad \longrightarrow \quad \text{low energy parameters}$$

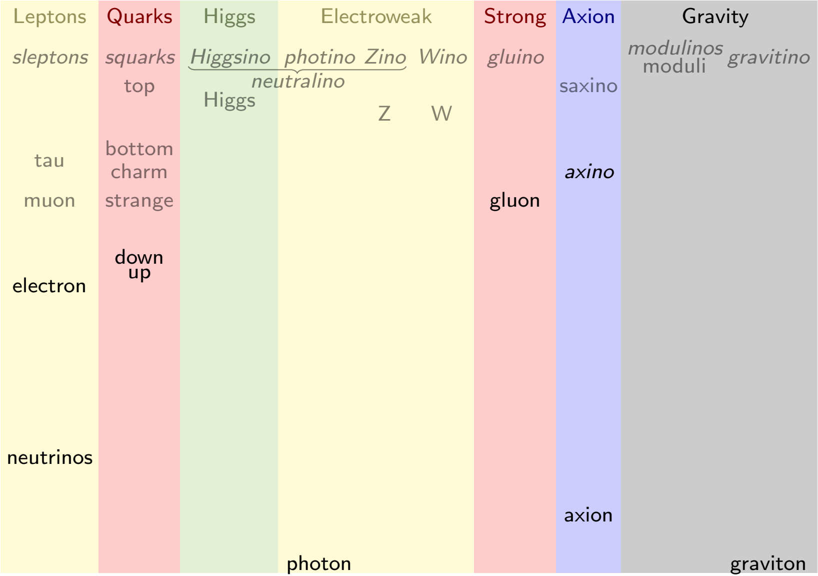
Typically moduli have Planckian values and so gravitational strength interactions. This makes them relatively long lived

$$\text{moduli half-life} \sim \text{minutes}$$

Particle spectrum



Particle spectrum



Particle spectrum

neutron
proton

electron

photon

graviton

Particle spectrum

Quarks

top

bottom
charm
strange

down
up

electron

Strong

gluon

photon

graviton

Particle spectrum

Leptons

tau

muon

electron

neutrinos

Quarks

top

bottom

charm

strange

down

up

Electroweak

Z W

photon

Strong

gluon

graviton

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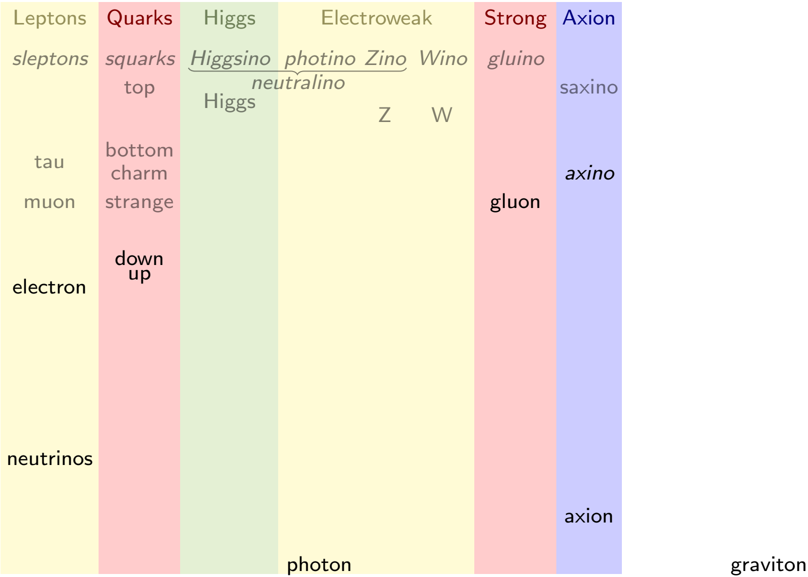

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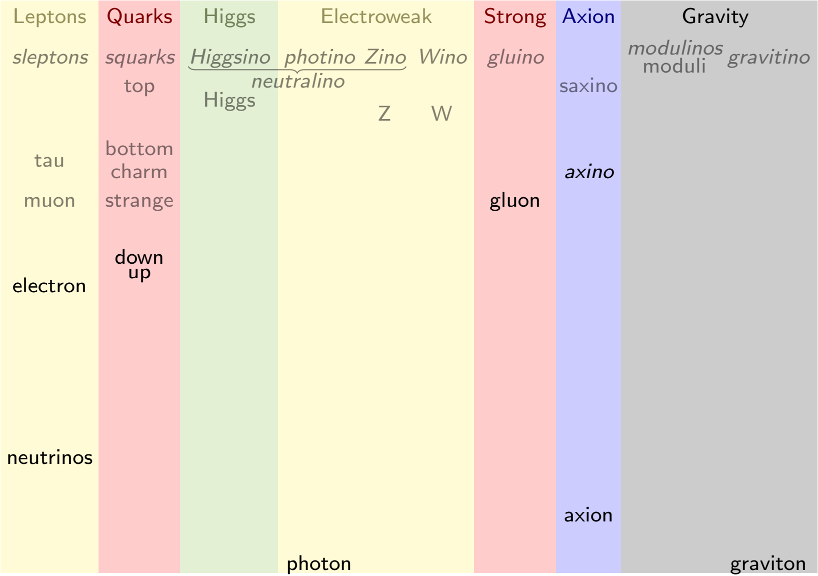

The Origin of Matter

The hot Big Bang

Big Bang $=$ hot dense universe expands and cools

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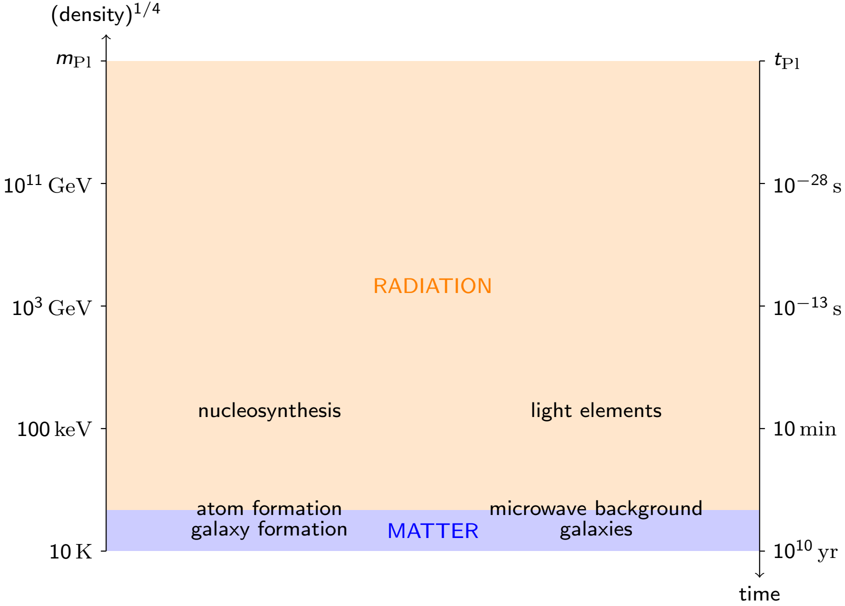
Galaxy formation $T \sim 1\,\mathrm{eV}$

$$\text{radiation domination} \longrightarrow \text{matter domination}$$

$T \lesssim 1\,\mathrm{eV}$

$$\text{density perturbations} \longrightarrow \text{galaxies} \ldots$$

History of the observable universe



Vacuum energy

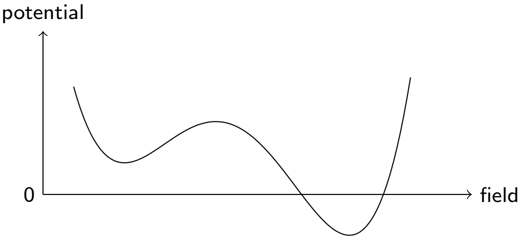
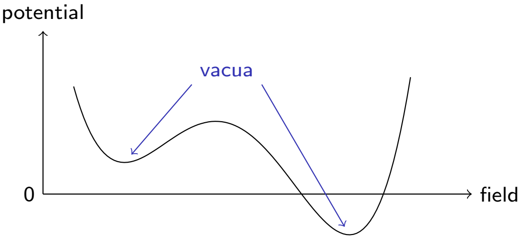


Figure: What is a vacuum?

Vacuum energy



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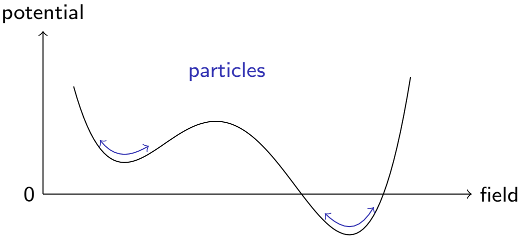

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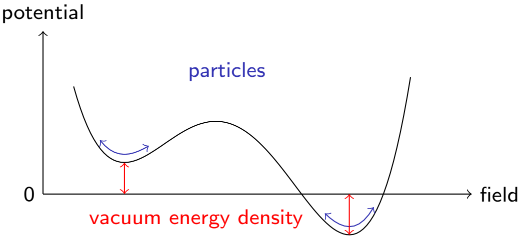

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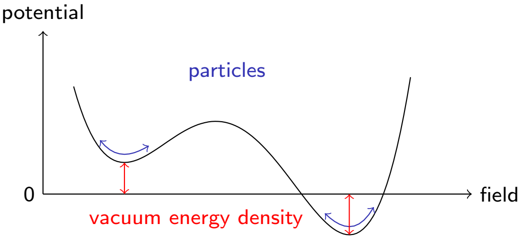

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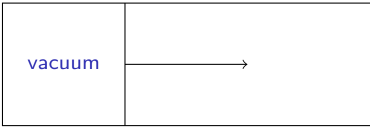

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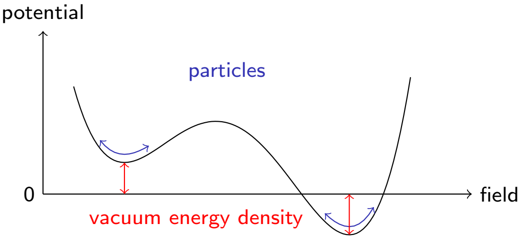

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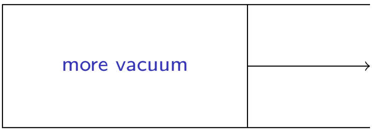

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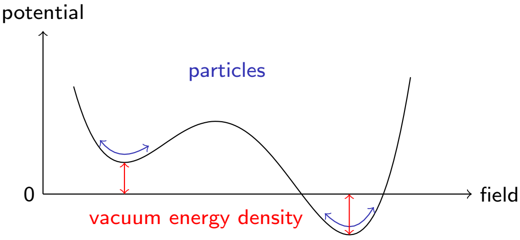

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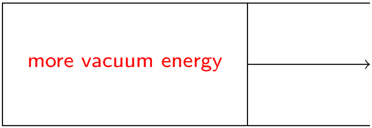

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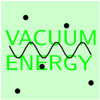

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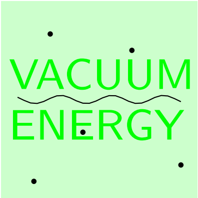

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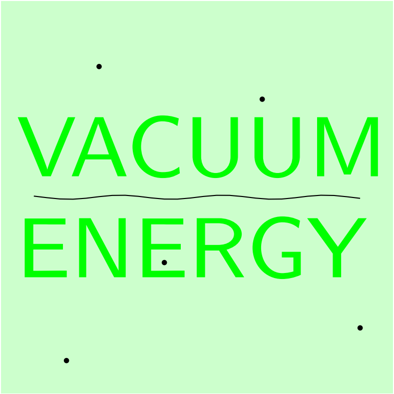

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quantum
vacuum
fluctuations

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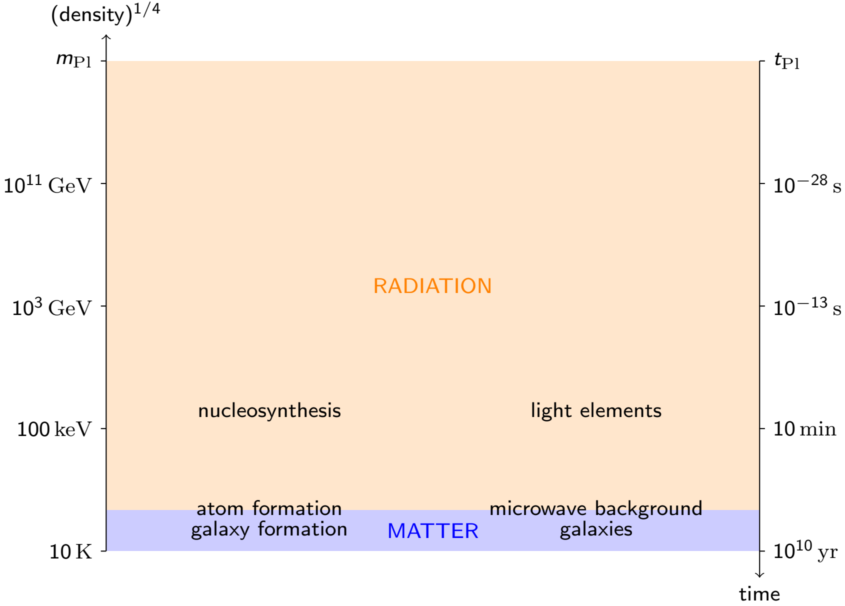

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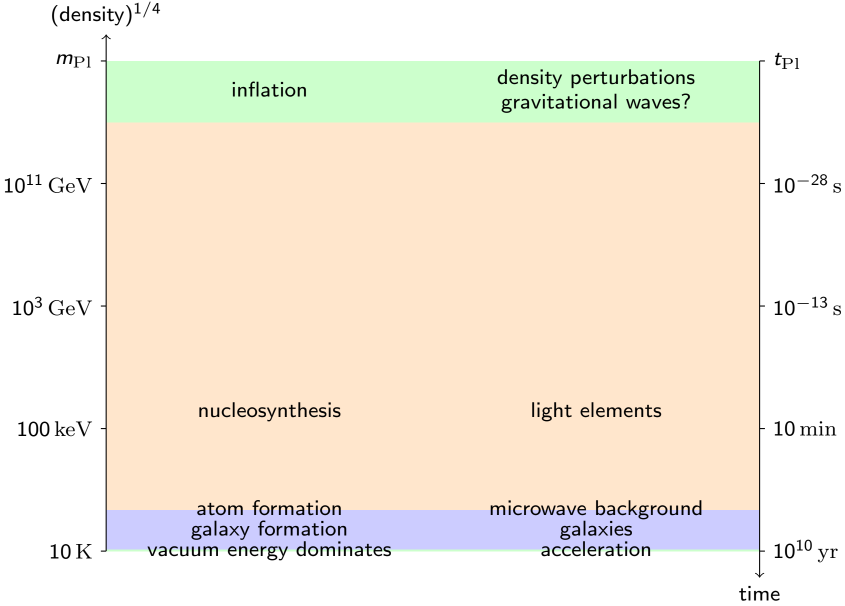

Matter and antimatter

Every particle has an antiparticle with equal mass and opposite charges

$$\begin{array}{rcl} \text{electron} & \leftrightarrow & \text{antielectron} \\ \text{quark} & \leftrightarrow & \text{antiquark} \\ \text{photon} & \leftrightarrow & \text{photon} \end{array}$$

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If a small matter/antimatter asymmetry, with slightly more matter than antimatter, can be generated (baryogenesis) then

$$\begin{array}{c} \text{matter/antimatter} \\ \text{asymmetry} \end{array} \xrightarrow{\text{annihilation}} \text{matter}$$

Baryogenesis mechanisms

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Particle decay

$$\begin{array}{c}\text{heavy particles}\\ \text{out of equilibrium}\end{array} \xrightarrow{\text{decay}} \begin{array}{c}\text{matter/antimatter}\\ \text{asymmetry}\end{array}$$

Best example is decay of right-handed neutrinos.

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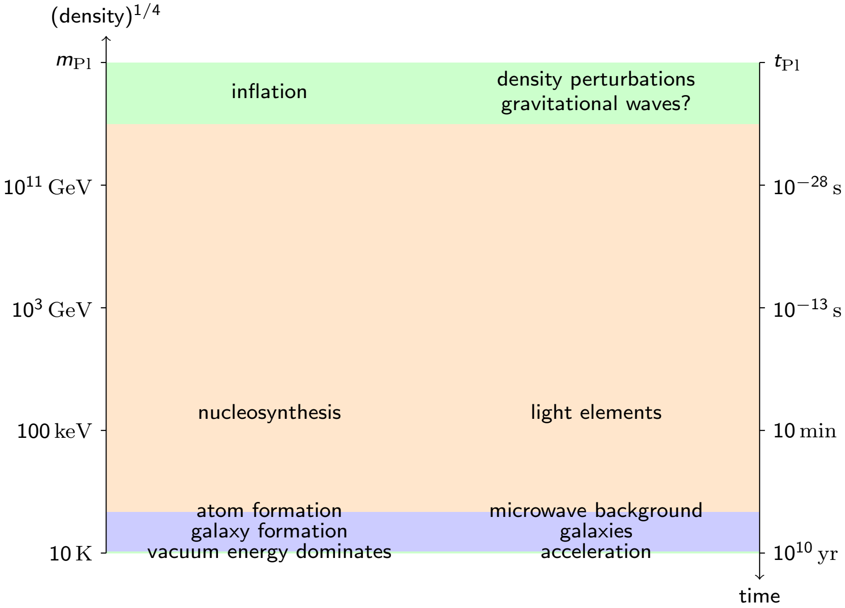
Affleck-Dine baryogenesis

$$\begin{array}{c}\text{angular momentum}\\ \text{in field space}\end{array} = \begin{array}{c}\text{matter/antimatter}\\ \text{asymmetry}\end{array}$$

History of the observable universe



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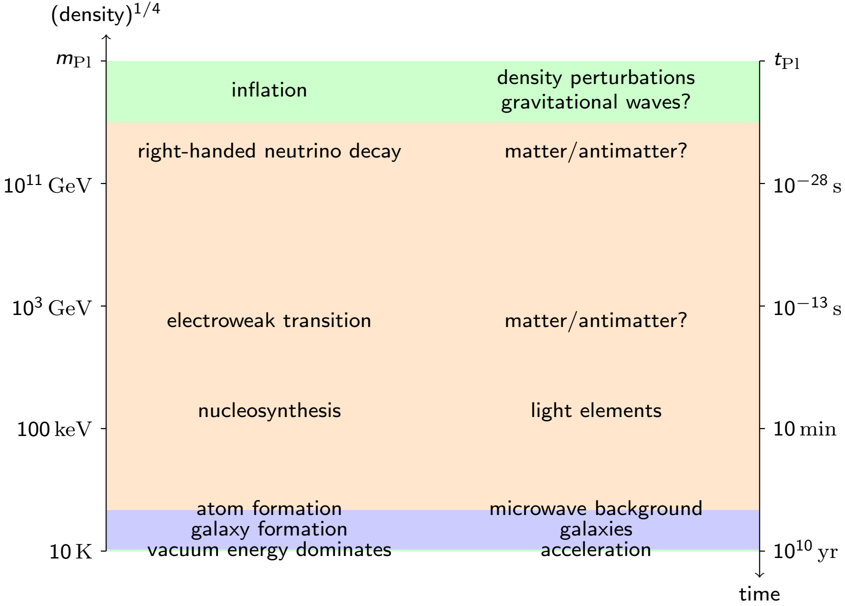

Dark matter

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Axion Generated in coherent oscillations when the axion potential turns on during the QCD phase transition (when the strong nuclear force becomes strong).

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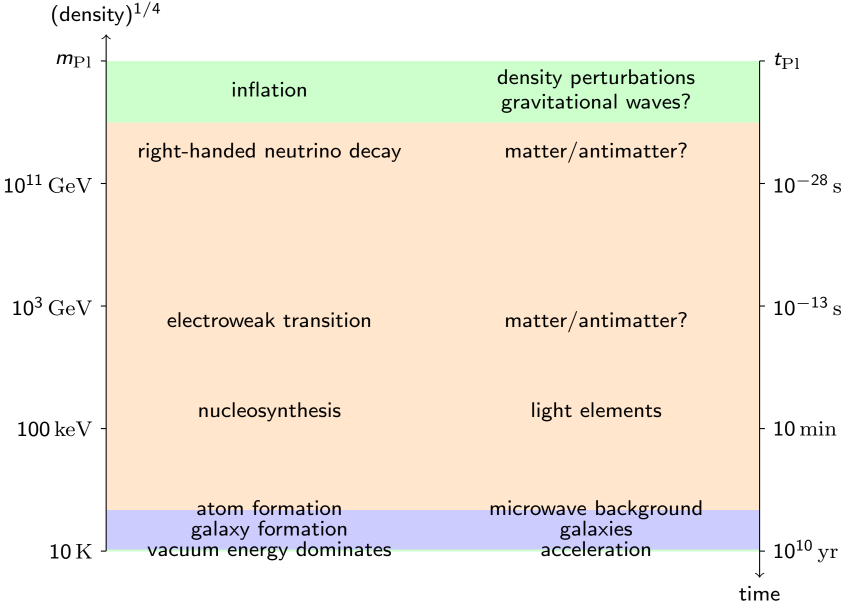

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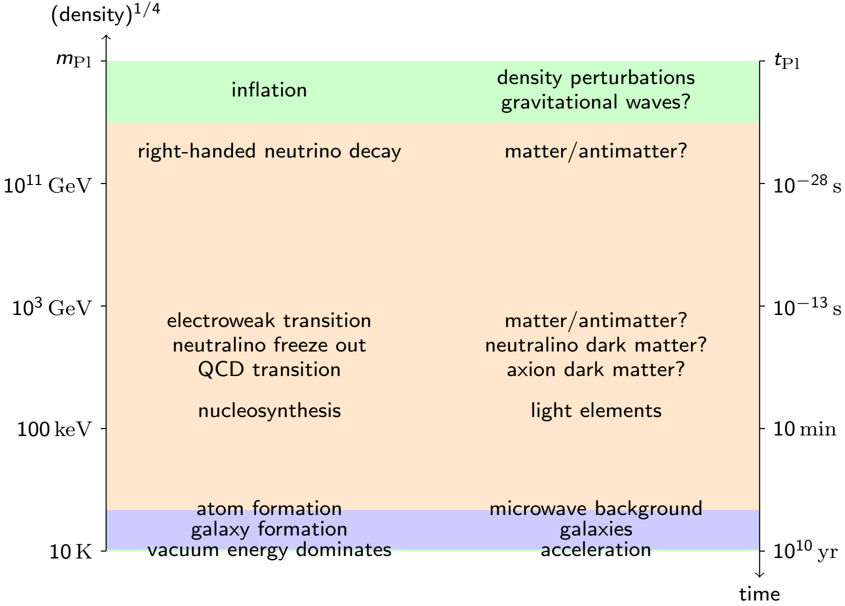

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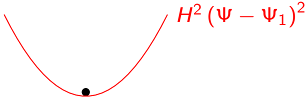

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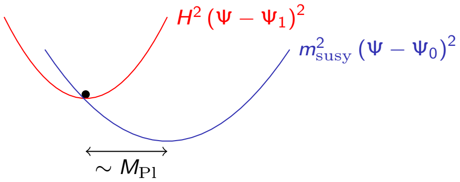

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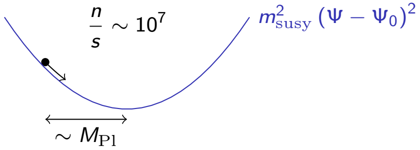

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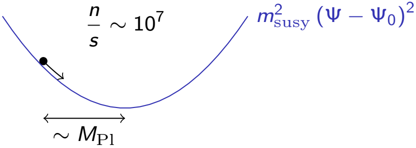

Gravitinos are thermally produced in the early universe, leading to a similar, though less severe, problem.

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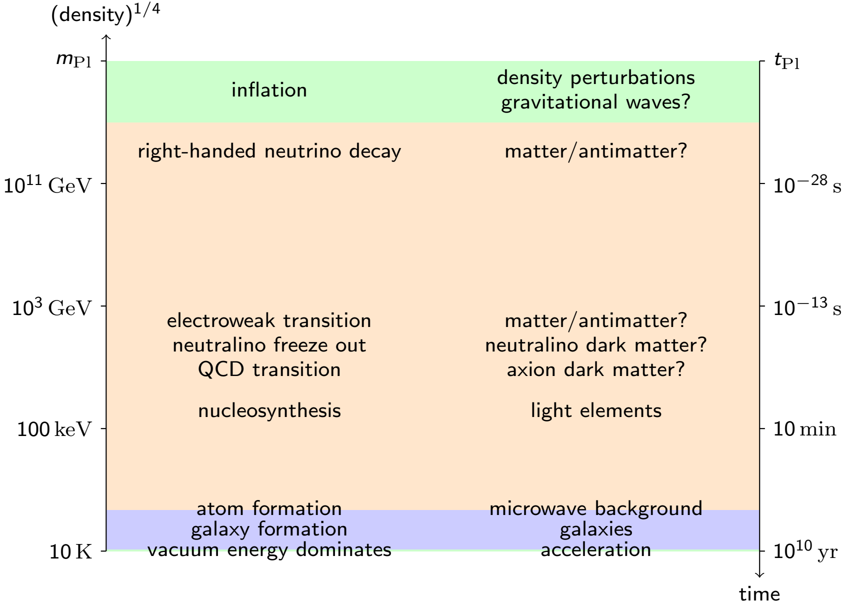

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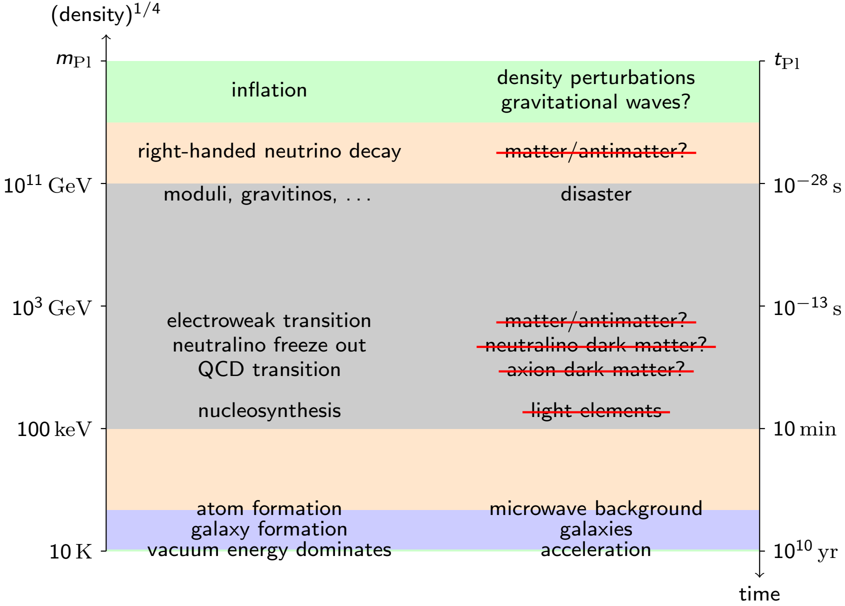

The Origin of Matter

A Minimal Supersymmetric Cosmological Model

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

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MSSM

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MSSM μ-term

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MSSM

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Thermal inflation

The superpotential term

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generates a potential

$$V = V_0 - m_\phi^2 |\phi|^2 + m_\chi^2 |\chi|^2 + m_{\bar{\chi}}^2 |\bar{\chi}|^2 + [A_\chi \lambda_\chi \phi \chi \bar{\chi} + \text{c.c.}] + |\lambda_\chi \chi \phi|^2 + |\lambda_\chi \bar{\chi} \phi|^2 + |\lambda_\chi \chi \bar{\chi}|^2$$

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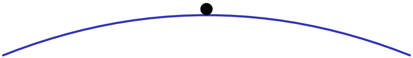
$$V(\phi) = V_0 \qquad -m_\phi^2 |\phi|^2 + \ldots$$



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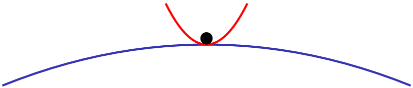
At finite temperature

$$V(\phi) = V_0 + g^2 T^2 |\phi|^2 - m_\phi^2 |\phi|^2 + \dots$$



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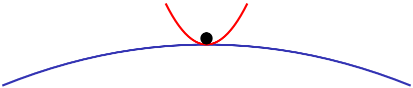

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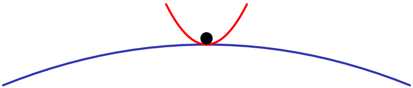

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$$T^4 \lesssim V_0 \quad \Longrightarrow \quad \text{inflation}$$

Thermal inflation

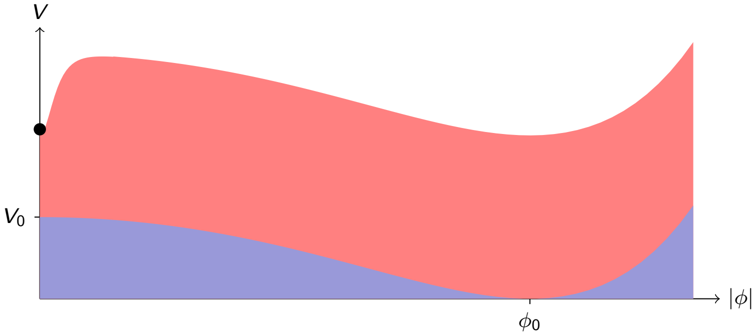

Figure: Radiation domination

Thermal inflation

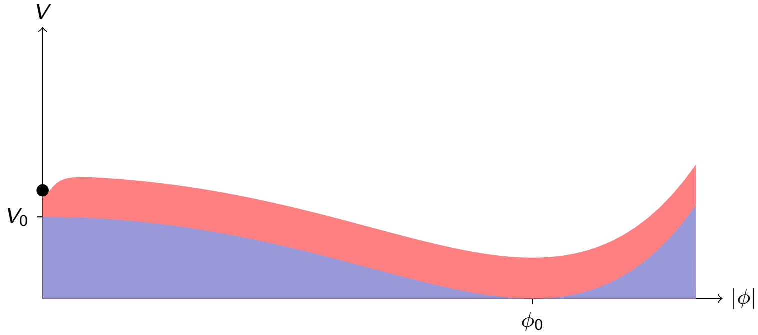

Figure: Thermal inflation

Thermal inflation

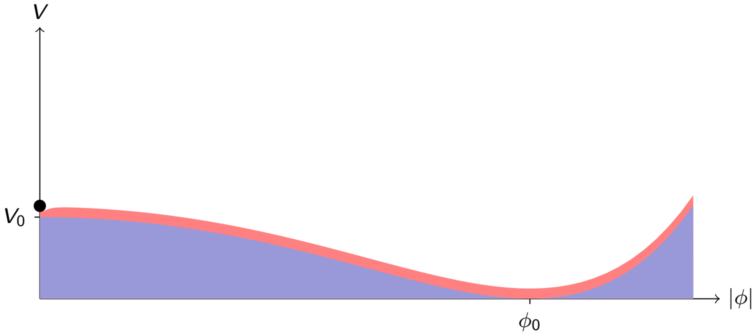

Figure: Thermal inflation

Thermal inflation

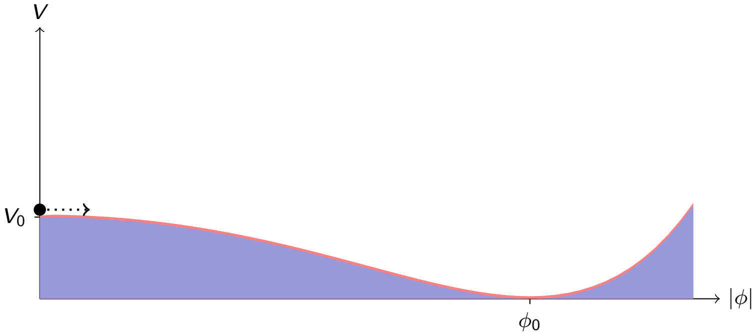

Figure: First order phase transition

Thermal inflation

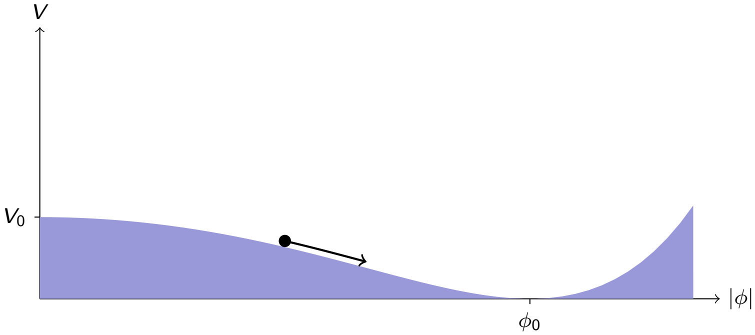

Figure: Potential energy converted to particles

Thermal inflation

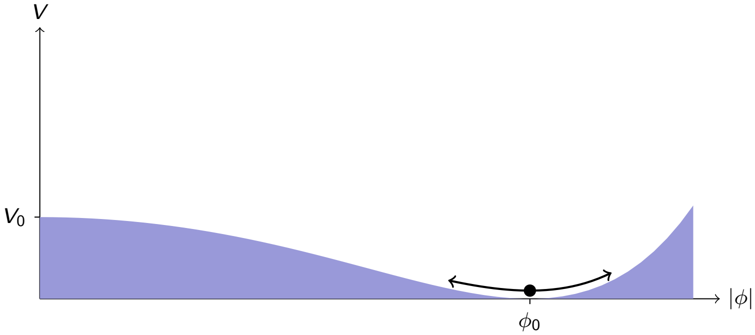

Figure: Matter domination

Key properties of thermal inflation

For

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

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Dilution factor (10^{20}): pre-existing moduli sufficiently diluted.

Low energy scale ($H \sim 10^{-8} m$): moduli regenerated with sufficiently small abundance.

Short duration ($N \sim 10$): density perturbations from primordial inflation preserved on large scales.

Gravitational waves from thermal inflation

The comoving length scale of thermal inflation is of order the Earth-Moon system. On these scales:

Gravitational waves from thermal inflation

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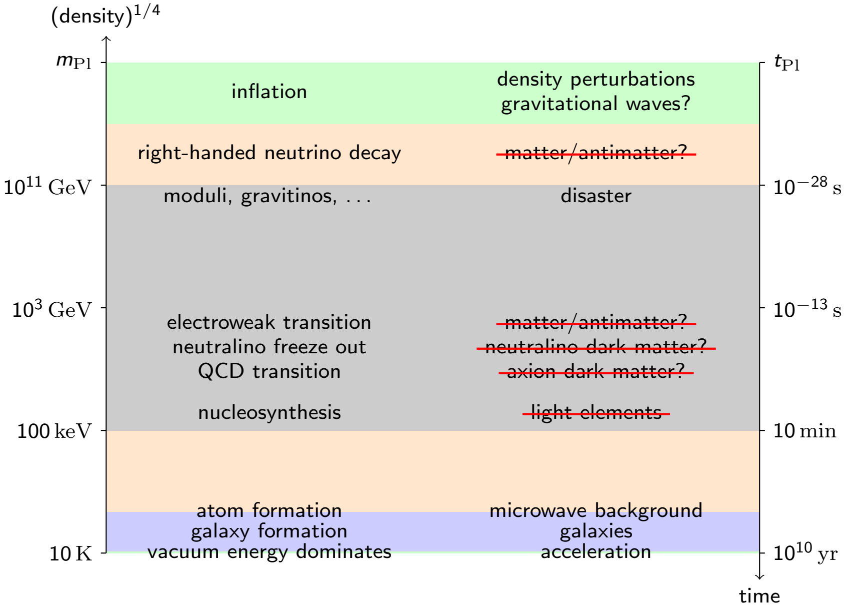
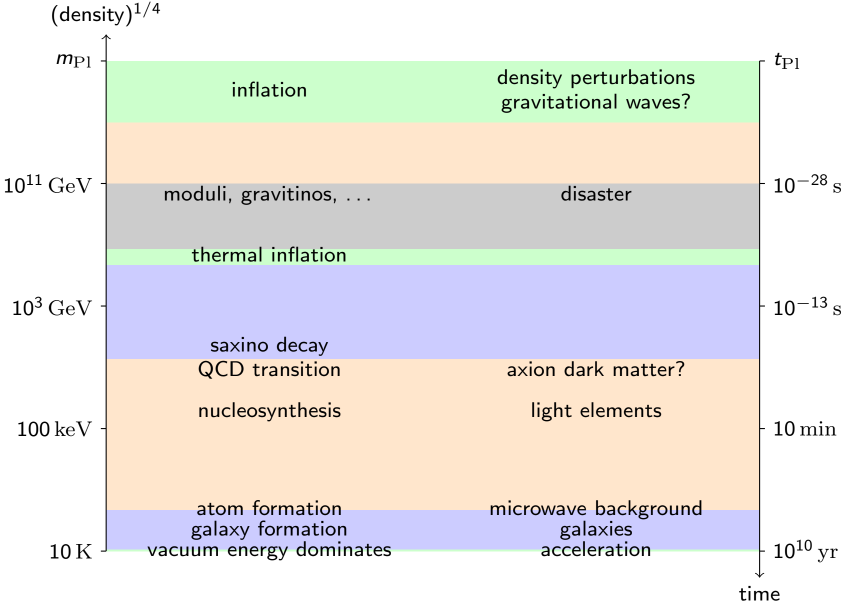
- new gravitational waves generated by the first order phase transition at the end of thermal inflation

May be observable at future space based gravitational wave detectors such as BBO or DECIGO.

History of the observable universe



History of the observable universe



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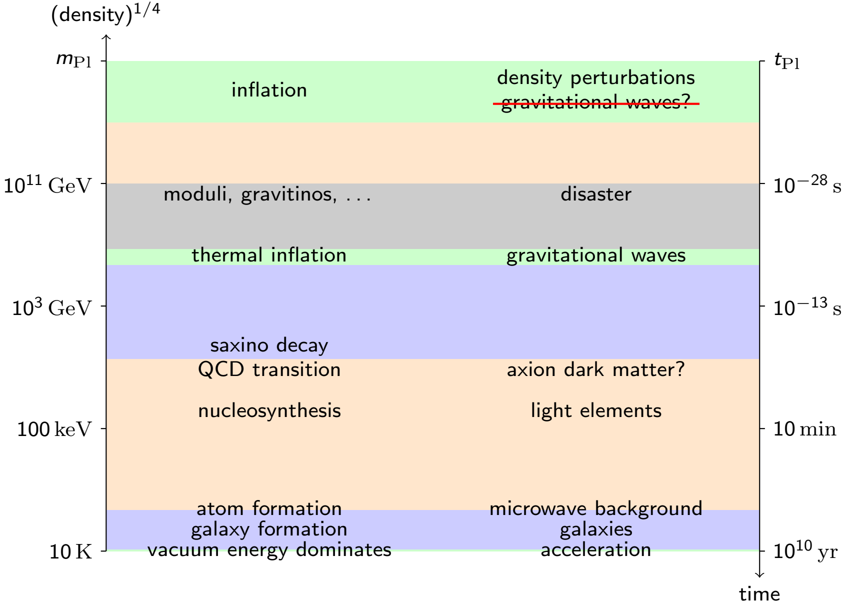

Baryogenesis

Key assumption

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

Baryogenesis

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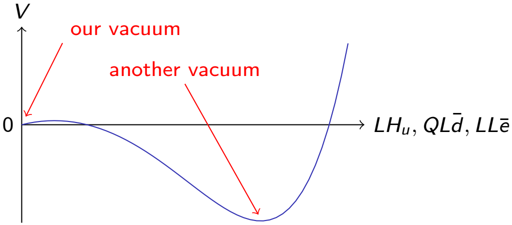
$$m^2_{LH_u} = \frac{1}{2}\left(m^2_L + m^2_{H_u}\right) < 0$$

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

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

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



Reduction

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

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

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

Potential

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

Potential

drives thermal inflation

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

Potential

$$
\begin{aligned}
V \quad = \quad & \underbrace{V_0}_{\text{drives thermal inflation}} + \underbrace{m_L^2|l|^2 - m_{H_u}^2|h_u|^2}_{lh_u \text{ rolls away}} + m_{H_d}^2|h_d|^2 + \frac{1}{2}\left(m_Q^2 + m_d^2\right)|d|^2 - m_\phi^2|\phi|^2 \\
& + \left[\frac{1}{2}A_\nu\lambda_\nu l^2 h_u^2 - \frac{1}{2}A_d\lambda_d h_d d^2 - A_\mu\lambda_\mu\phi^2 h_u h_d + \text{c.c.}\right] \\
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\end{aligned}
$$

Potential

drives thermal inflation

lh_u rolls away

$$
\begin{aligned}
V \;=\;& V_0 + m_L^2|l|^2 - m_{H_u}^2|h_u|^2 + m_{H_d}^2|h_d|^2 + \frac{1}{2}\left(m_Q^2 + m_d^2\right)|d|^2 - m_\phi^2|\phi|^2 \\
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&+ |\lambda_d h_d d|^2 + |2\lambda_\mu\phi h_u h_d|^2 + \frac{1}{2}g^2\left(|h_u|^2 - |h_d|^2 - |l|^2 + \frac{1}{2}|d|^2\right)^2
\end{aligned}
$$

lh_u stabilized with fixed phase

Potential

drives thermal inflation

lh_u rolls away

ϕ rolls away

$$
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V \quad = \quad & V_0 + m_L^2|l|^2 - m_{H_u}^2|h_u|^2 + m_{H_d}^2|h_d|^2 + \frac{1}{2}\left(m_Q^2 + m_d^2\right)|d|^2 - m_\phi^2|\phi|^2 \\
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\end{aligned}
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lh_u stabilized
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fixed phase

h_d forced out

Potential

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lh_u rolls away

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d held at origin

lh_u stabilized with fixed phase

h_d forced out

Potential

drives thermal inflation

lh_u rolls away

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$$
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V \quad = \quad & V_0 + m_L^2|l|^2 - m_{H_u}^2|h_u|^2 + m_{H_d}^2|h_d|^2 + \cancel{\frac{1}{2}\left(m_Q^2 + m_d^2\right)|d|^2} - m_\phi^2|\phi|^2 \\
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\end{aligned}
$$

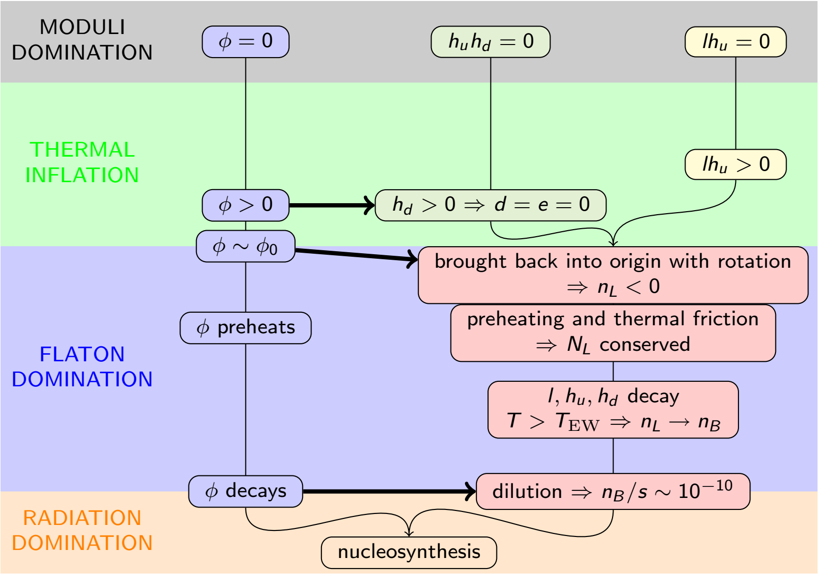
d held at origin

lh_u stabilized with fixed phase

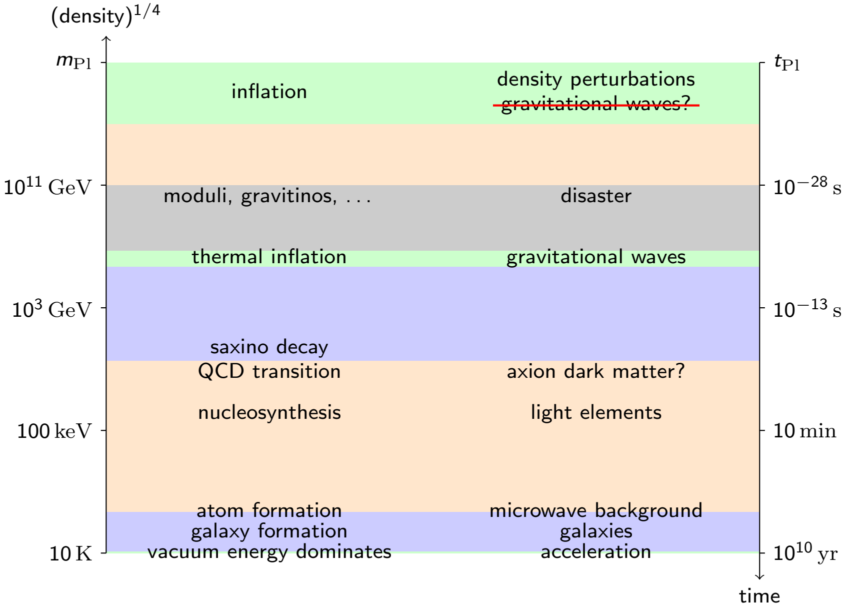
lh_u returns with rotation

h_d forced out

Baryogenesis



History of the observable universe



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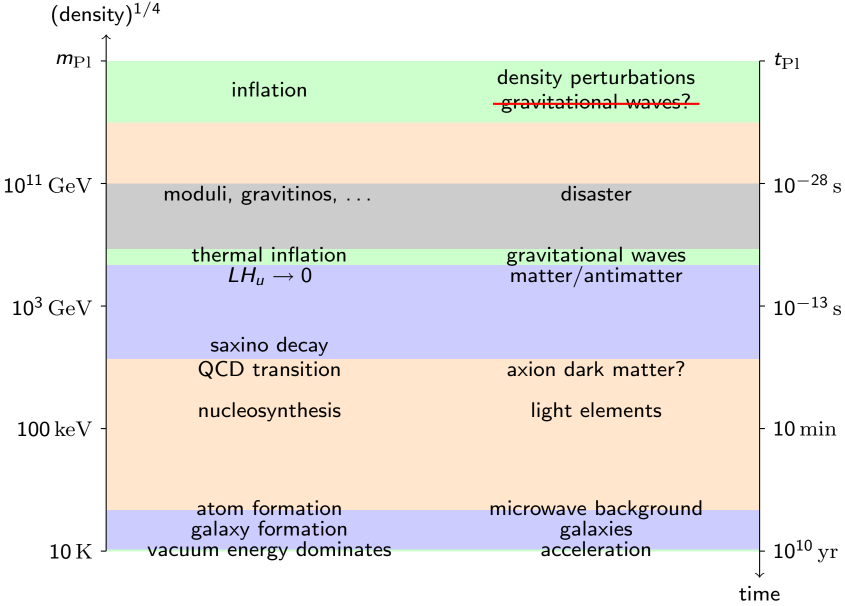
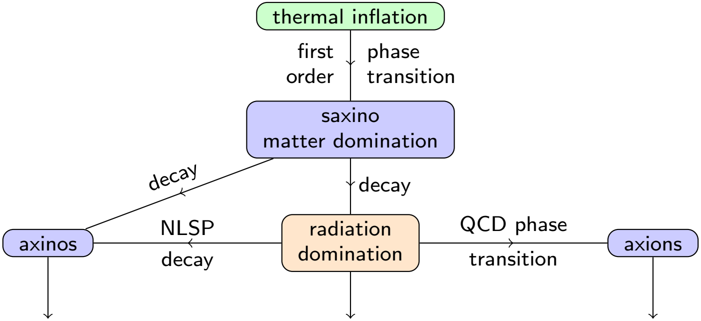


Dark matter

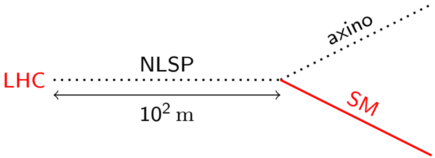
A mixture of

- **Axino** The axino is the lightest superparticle (LSP) and hence stable. It is generated by the decay of the saxino, and by the decay of the next lightest superparticle (NLSP).
- **Axion** As before, generated in coherent oscillations when the axion potential turns on during the QCD phase transition, though may be diluted by the decay of the saxino.



Axino LHC signal

Next lightest superparticles (NLSPs) produced by the Large Hadron Collider (LHC) decay to axinos plus Standard Model particles



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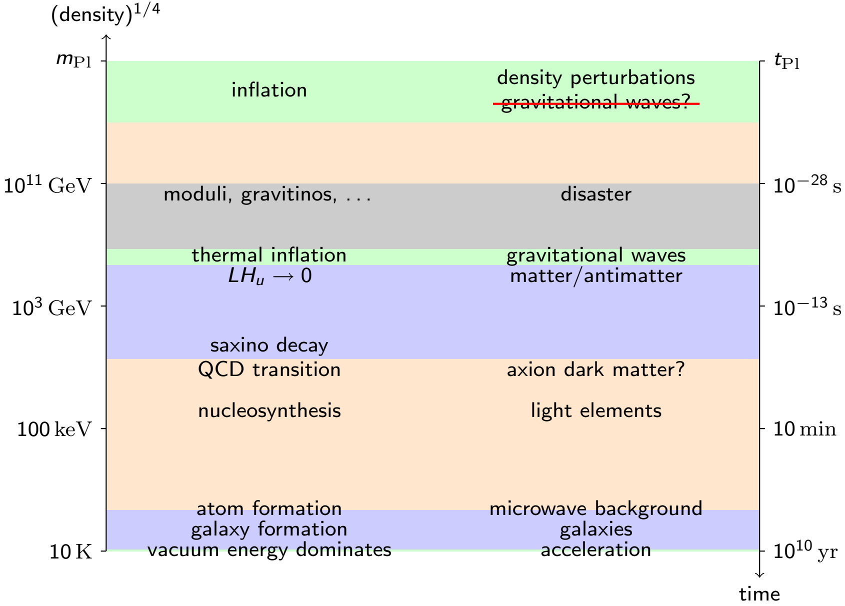

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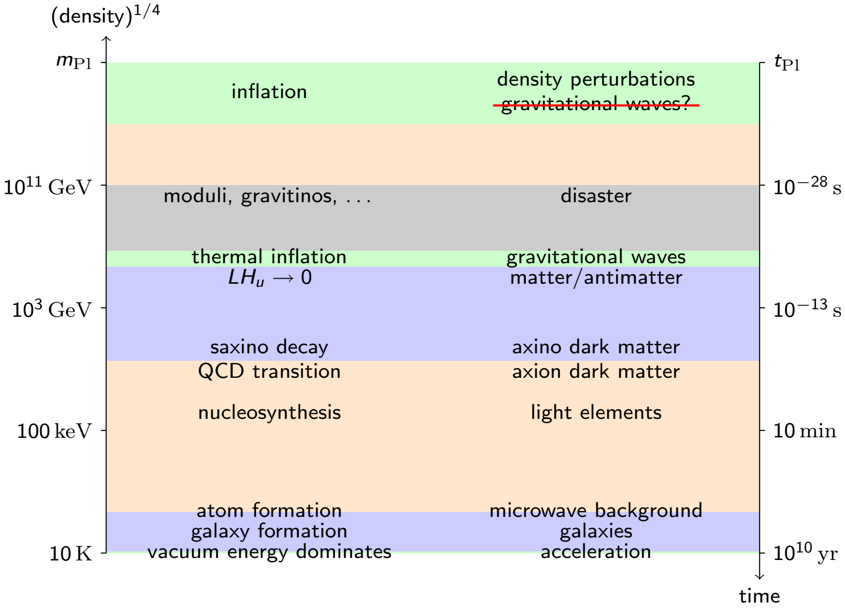

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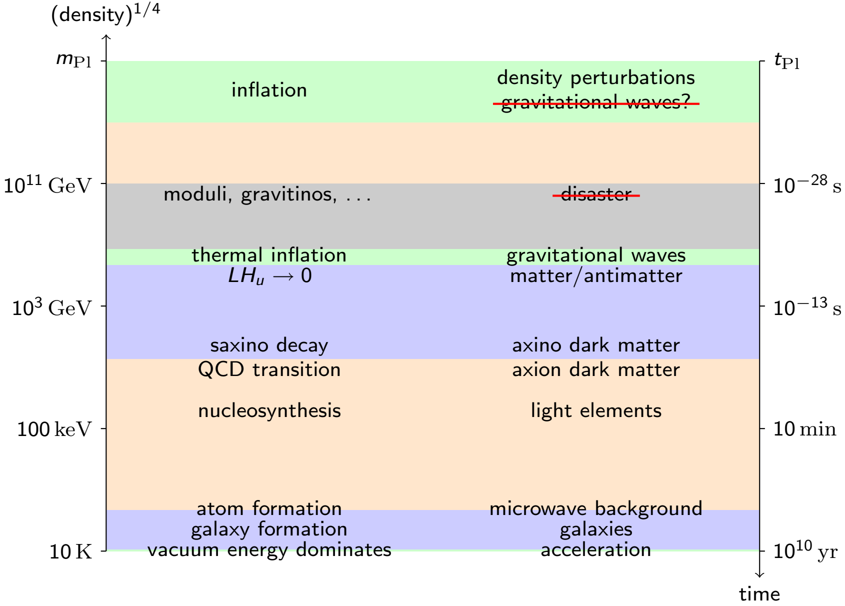

A Minimal Supersymmetric Cosmological Model

MSSM

neutrino masses

MSSM μ-term

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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thermal inflation

A Minimal Supersymmetric Cosmological Model

MSSM

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baryogenesis

thermal inflation

A Minimal Supersymmetric Cosmological Model

MSSM

neutrino masses

MSSM μ-term

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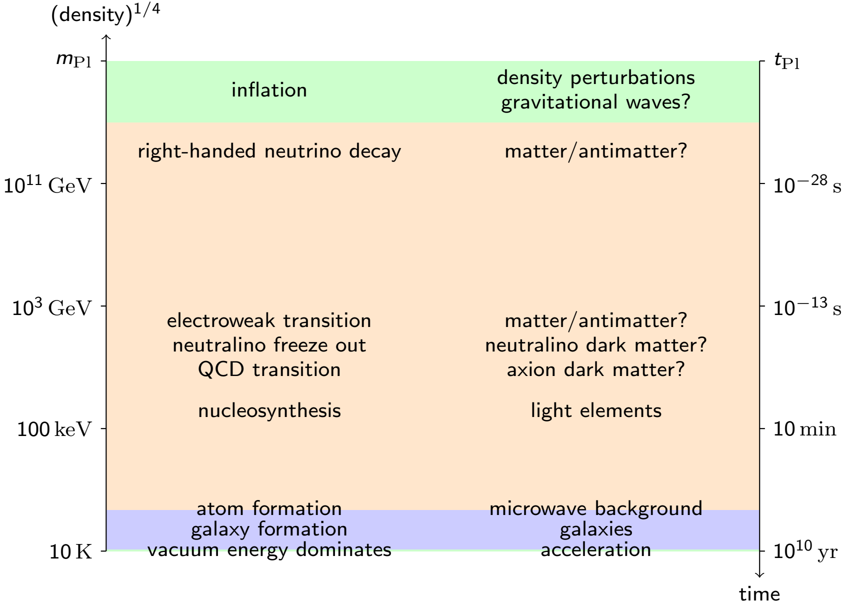
baryogenesis

dark matter

thermal inflation

History of the observable universe



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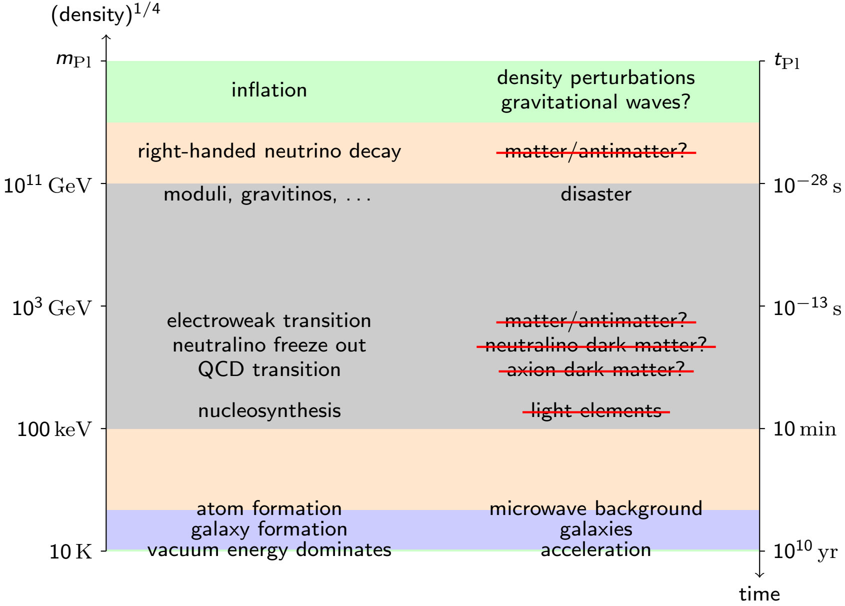
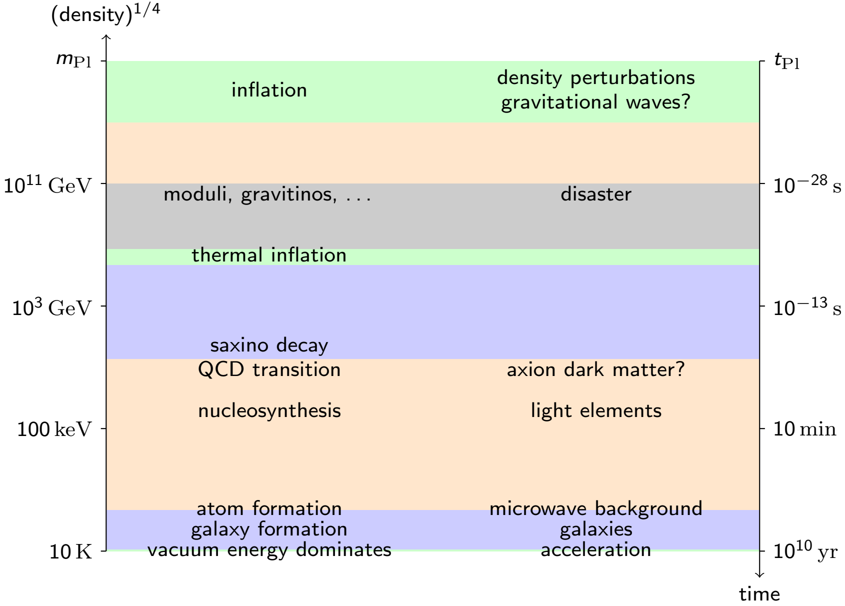


History of the observable universe



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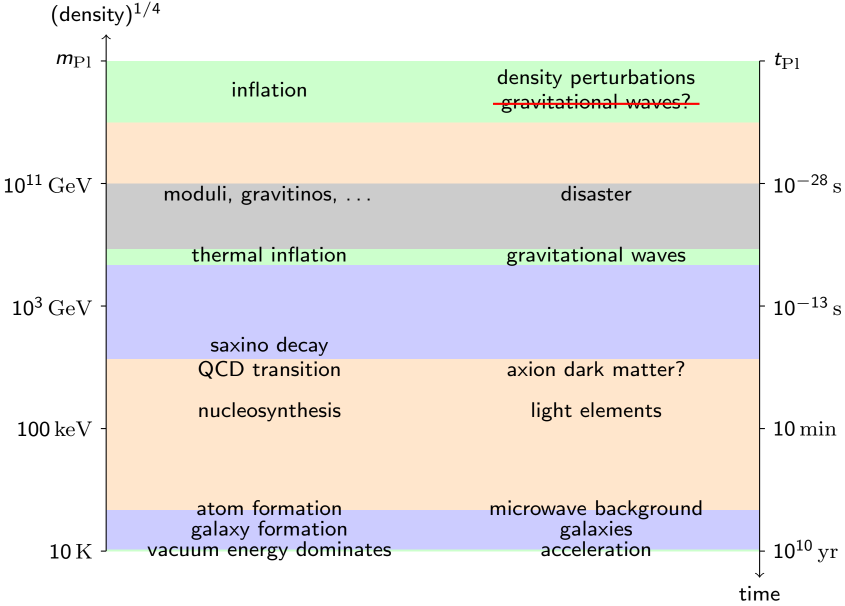

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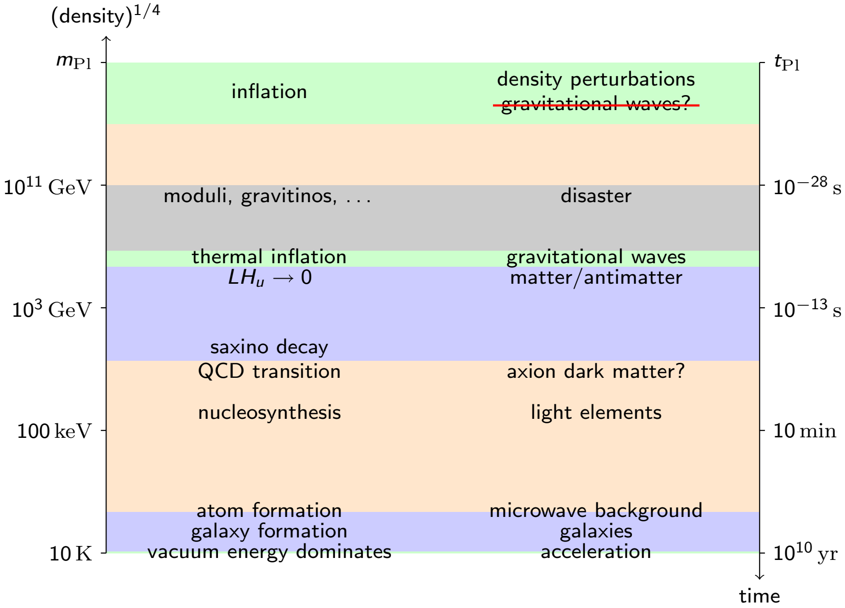

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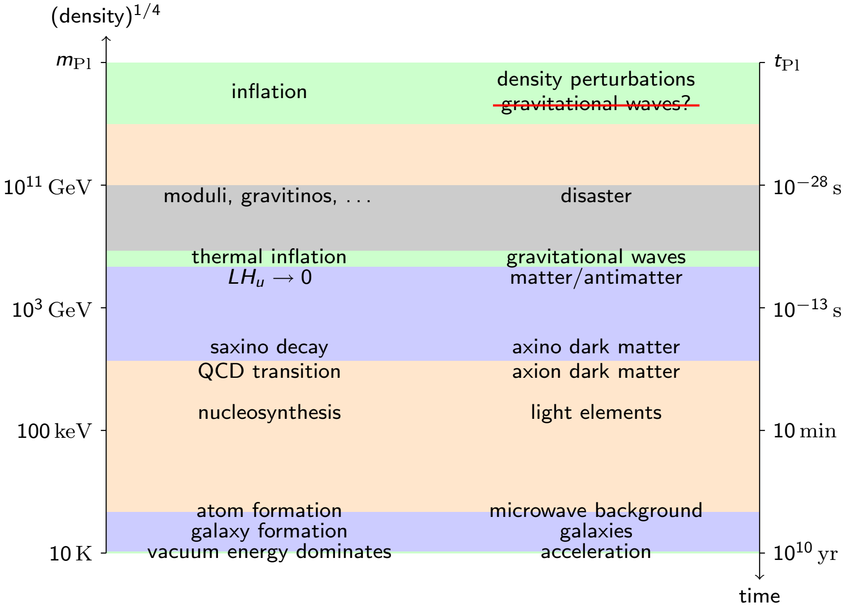

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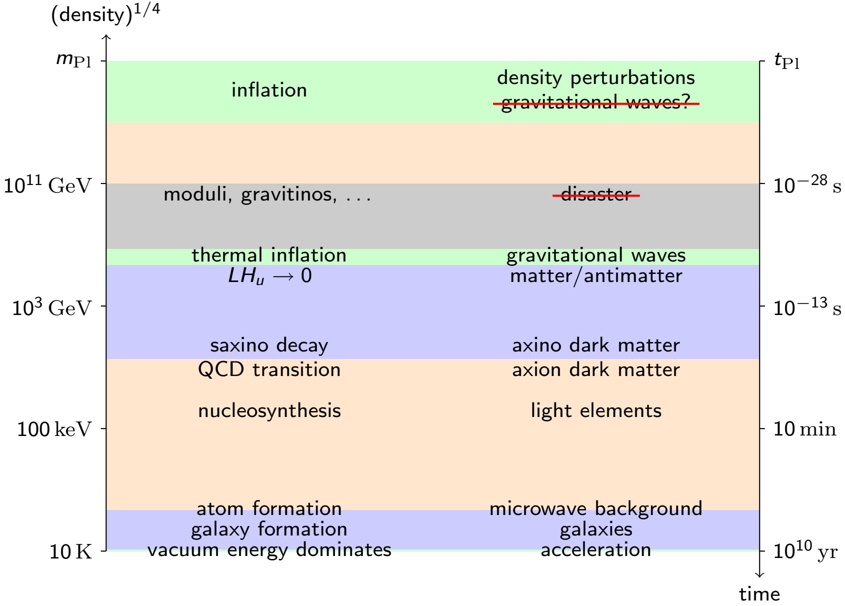

The Origin of Matter