Lecture #2
Baryogenesis in the early Universe

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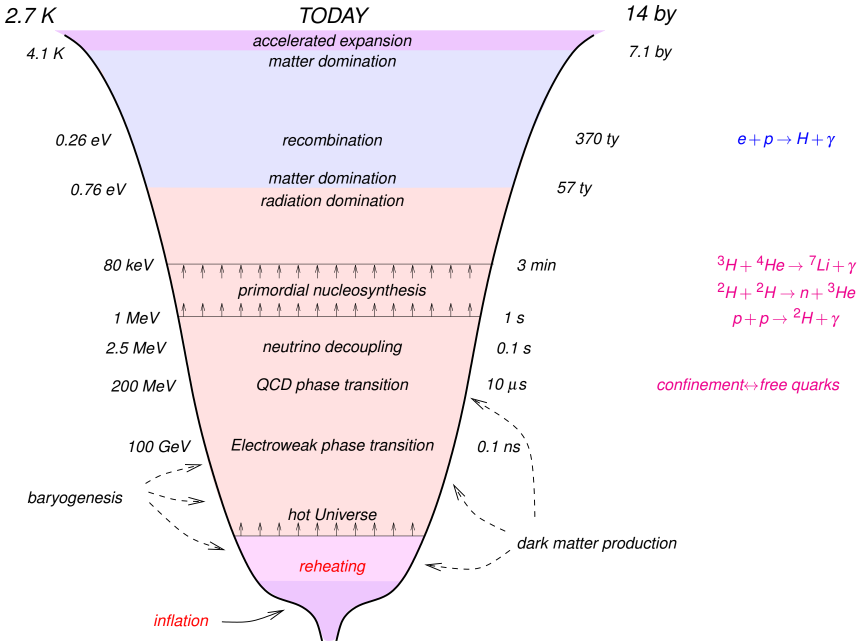
Outline

The only 'direct cosmological evidence' for new particle physics

$$\eta_B = \frac{n_B}{n_\gamma} = 0.6 \times 10^{-9}\,, \quad \frac{n_q - n_{\bar{q}}}{n_q + n_{\bar{q}}}\,, \quad \mu_B$$

must produce adiabatic perturbations δ_B


2.7 K
TODAY
14 by
accelerated expansion
4.1 K
matter domination
7.1 by
0.26 eV
recombination
370 ty
$e + p \to H + \gamma$
matter domination
0.76 eV
radiation domination
57 ty
80 keV
3 min
$^3H + {}^4He \to {}^7Li + \gamma$
primordial nucleosynthesis
$^2H + {}^2H \to n + {}^3He$
1 MeV
1 s
$p + p \to {}^2H + \gamma$
2.5 MeV
neutrino decoupling
0.1 s
200 MeV
QCD phase transition
10 μs
confinement↔free quarks
100 GeV
Electroweak phase transition
0.1 ns
baryogenesis
hot Universe
dark matter production
reheating
inflation

Electroweak sphalerons: $B-L$

$$\partial^\mu j_\mu{}^{\mathrm{B}} = 3\,\frac{g^2}{16\pi^2}\,V^{a\;\mu\nu}\,\tilde{V}^a{}_{\mu\nu}\,,$$

$$\partial^\mu j_\mu{}^{\mathrm{L}n} = \frac{g^2}{16\pi^2}\,V^{a\;\mu\nu}\,\tilde{V}^a{}_{\mu\nu}\,,\quad n=1,2,3\,,$$

$V^a{}_{\mu\nu} = \partial_\mu V^a_\nu - \partial_\nu V^a_\mu + g\varepsilon^{abc}V^b_\mu V^c_\nu$ refer to $SU(2)_{\mathrm{W}}$, $\tilde{V}^a{}_{\mu\nu} = \frac{1}{2}\varepsilon_{\mu\nu\lambda\rho}V^{a\;\lambda\rho}$
Anomaly: only left fermions couple to fields V^a_μ.
For nontrivial gauge fields in vacuum or plasma

$$\Delta B = B(t_f) - B(t_i) = \int_{t_i}^{t_f} dt \int d^3\mathbf{x}\,\partial^\mu j^{\mathrm{B}}_\mu = 3\int_{t_i}^{t_f} d^4x\,\frac{g^2}{16\pi^2}\,V^{a\;\mu\nu}\,\tilde{V}^a{}_{\mu\nu}\,,$$

Strong fields are needed: $V^a{}_{\mu\nu} \propto \frac{1}{g}$, (integral is natural number!). Energies of such configurations $\propto \frac{1}{g^2}$.

$$\Delta B = 3\,\Delta L_e = 3\,\Delta L_\mu = 3\,\Delta L_\tau$$

At temperatures 100 GeV $\lesssim T \lesssim 10^{12}$ GeV only 3 linear combinations survive, e.g.

$$B-L\,,\quad L_e - L_\mu\,,\quad L_e - L_\tau$$

where $$L \equiv L_e + L_\mu + L_\tau$$

Baryogenesis

Sakharov conditions of successful baryogenesis

- B-violation $(\Delta B \neq 0)\ XY \dots \to X'Y' \dots B$
- C- & CP-violation $(\Delta C \neq 0,\ \Delta CP \neq 0)\ \bar{X}\bar{Y} \dots \to \bar{X}'\bar{Y}' \dots \bar{B}$
- processes above are out of equilibrium $X'Y' \dots B \to XY \dots$

At 100 GeV$\lesssim T \lesssim 10^{12}$ GeV nonperturbative processes (EW-sphalerons) violate B, L_α, so that only three charges are conserved out of four, e.g.

$$B - L\,, \quad L_e - L_\mu\,, \quad L_e - L_\tau$$

and $B = \alpha \times (B - L)$, $L = (\alpha - 1) \times (B - L)$

Leptogenesis: Baryogenesis from lepton asymmetry of the Universe ... due to sterile neutrinos

Why $\Omega_B \sim \Omega_{DM}$? antropic principle?

Lepton asymmetry from sterile neutrino decays

Most general renormalizable lagrangian with Majorana neutrinos N_I, $I, \alpha = 1, 2, 3$.

$$\mathscr{L}_{SM} + \overline{N}_I i \partial\!\!\!/ N_I - y_{I\alpha} \bar{L}_\alpha \widetilde{H} N_I - \frac{M_I}{2} \overline{N}_I^c N_I + \text{h.c.}$$

where $\widetilde{H}_i = \varepsilon_{ij} H_j^*$, $i, j = 1, 2$; complex Yukawas, Majorana mass: $\Delta L \neq 0$ lepton number violating processes ($N = N^c$!):

$$N_I \to h l_\alpha \,, \quad N_I \to h \bar{l}_\alpha \,,$$
$$h l_\alpha \to h \bar{l}_\beta$$

- neutrino oscillations are explained
- BAU via leptogenesis (decays for $M_I > 10^9$ GeV or oscillations for light neutrinos, even $M_I \gtrsim 100$ MeV
- dark matter with $M_I \sim$ 1-100 keV

Electroweak transition might help with baryogenesis

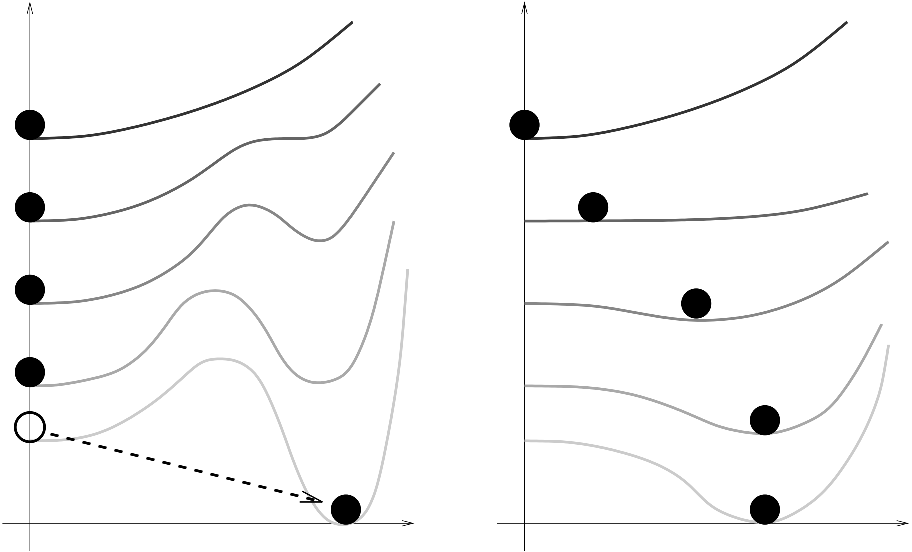
Sakharov's condition of a successful baryogenesis

- *B*-violation
- *C*-, *CP*-violation
- departure from thermal equilibrium

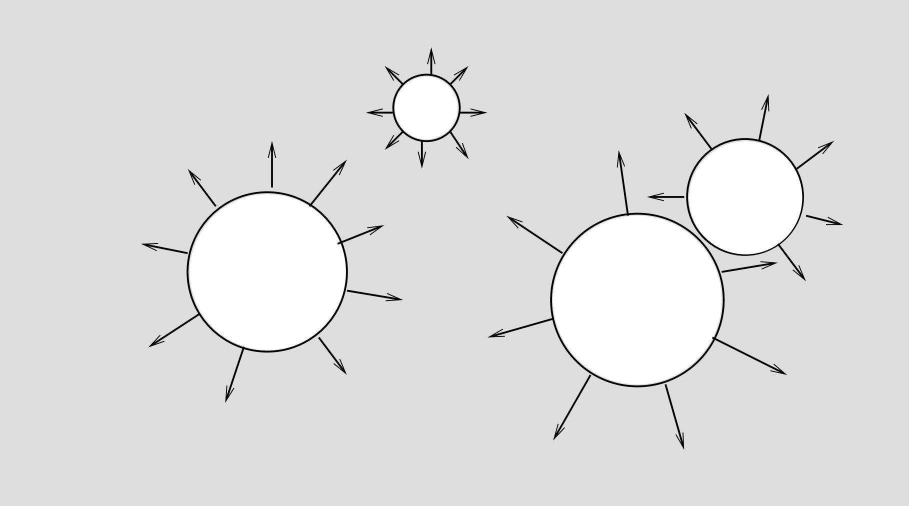
I order phase transition
due to bubble percollation

would happen for $m_h \lesssim 40$ GeV

Phase transitions of the I and II orders



Baryons are produced on the bubble walls



Minimal extension with one real scalar

$$\Delta V = \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4 + \frac{1}{2}\lambda_{HS} S^2 H^\dagger H$$

- EW phase transition of the strongly I order
- Gravitational waves production by the new phase bubbles

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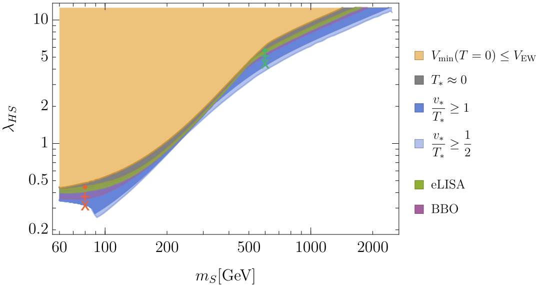
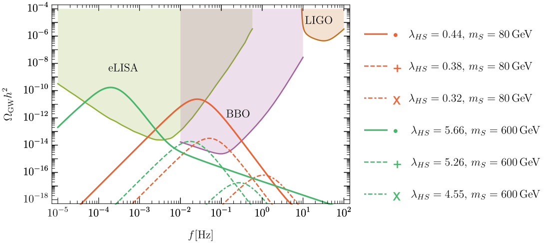




Split SUSY: heavy sfermions, light gauginos $M_{\tilde{Q}} \gg M_\lambda$

Is it possible in SUSY?

N.Arkani-Hamed, S.Dimopoulos (2004)

Yes, moreover, someones argued natural

- In many (simple) models where SUSY is broken spontaneously gauginos are light (massless), that was the problem
- the hierarchy $M_{\tilde{Q}} \gg M_\lambda$ is stable with respect to quantum corrections (RG-evolution)

$$\frac{dM_{\lambda_i}}{d\log Q^2} \propto \alpha_i M_{\lambda_i} \qquad\qquad + \alpha_i y^2 A$$

$$\frac{dM^2_{\tilde{Q}}}{d\log Q^2} \propto y^2 M^2_{\tilde{Q}} + \cdots + \alpha_i M^2_{\lambda_i}$$

$$\frac{dA_i}{d\log Q^2} \propto y^2 A_i + \cdots + \alpha_i M_{\lambda_i}$$

Split SUSY: $M_{\tilde{Q}} \gg M_\lambda$

@ 1 TeV: gauginos + higgsinos + SM-like Higgs boson

- dark matter (natural)
- gauge coupling unification (feature of Split MSSM)
- no FCNC (natural)
- stability of gauge hierarchy (LOST)
  - Though...in MSSM is lost (to some extent) as well: $(100\text{ GeV})^2 \ll (1\text{ TeV})^2$
  - Splitting scale is not very high in fact

out of LHC reach though

Why NMSSM ? Adding 4 d.o.f. to 230...

- μ-problem : $\mu^2\left(H_U^\dagger H_U + H_D^\dagger H_D\right)$

  MSSM: $\hat{W} = \mu \hat{H}_u \hat{H}_d$ NMSSM: $\hat{W} = \hat{N} \hat{H}_u \hat{H}_d$
- mechanism of baryogenesis within the Split SUSY:

  NMSSM: Electroweak

EWB does not work in MSSM:
the Higgs sector mimics SM, no EW phase transition of the I order

MSSM: new sources of *CP*-violation
NMSSM: + the strongly first order phase transition

Electroweak baryogenesis is attractive:
both ingredients can be directly tested

S.Demidov, D.G. (2007)

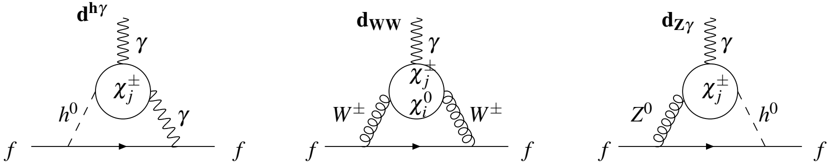
Electric dipole moments of electron and neutron

CP-source: the same contributions to EDMs as in Split MSSM
but here one has generally two additional phases,

$$\phi_1 = \arg(\tilde{g}_u{}^* \tilde{g}_d{}^* M_2 \tilde{\mu})\,, \quad \phi_2 = \arg\left(\kappa k^* \lambda_u \lambda_d (\tilde{\mu}^*)^{-2}\right)\,, \quad \phi_3 = \arg(\lambda_u \lambda_d^* \tilde{g}_u^* \tilde{g}_d)$$

$$\tilde{\mu} = \mu + \kappa(v_s + i v_P)/\sqrt{2}$$

$$d_f = d_{h\gamma} + d_{WW} + d_{hZ}$$



Other ideas...

– in equilibrium...

$$\mathscr{L} \propto J^B_\mu \partial_\mu (R, \phi, etc) \quad \to \quad \mu_B$$

– Affleck–Dine variants (SUSY?)

$$V = m^2|\phi|^2 + \lambda|\phi|^4 + \lambda'\phi^4 + \lambda'\phi^{*4}$$

– even at inflation

$$(\mu_1 \mathrm{Re}(\phi) + \mu_1 \mathrm{Im}(\phi)) \times F(inflaton)$$

Observation: why $\rho_B \sim \rho_{DM}$?

1. coincidence

   all well-motivated (hence, natural) models (WIMPs, axions, sterile neutrinos) imply this answer

2. partly coincidence, because:
   - if $\rho_{DM} \ll \rho_B$ then DM is unobservable
     DM can be formed by several specia, only one of which dominates
   - if $\rho_{DM} \gg \rho_B$ then what ?

   (anthropic arguments. . . ?)

3. May be a hint at common origin of dark matter production and baryon asymmetry generation in the early Universe

An example: Hylogenesis

H.Davoudiasi, D.Morrissey, K.Sigurdson, S.Tulin (2010)

Greek: hyle (primordial matter) + genesis (origin)

- New fields:
  1 Dirac fermion Y — $m_Y \sim \mathcal{O}(1)$ GeV
  1 complex scalar Φ — $m_\Phi \sim \mathcal{O}(1)$ GeV
  2 Dirac fermions X_a, $a = 1, 2$ — $m_2 > m_1 \gtrsim 1$ TeV
- Coupling to SM via "neutron portal"

$$-\mathcal{L}_{\text{int}} = \frac{\lambda_a}{M^2}\bar{X}_a d_R \bar{u}^C d_R + \zeta_a \bar{X}_a Y^C \Phi^* + \text{h.c.}$$

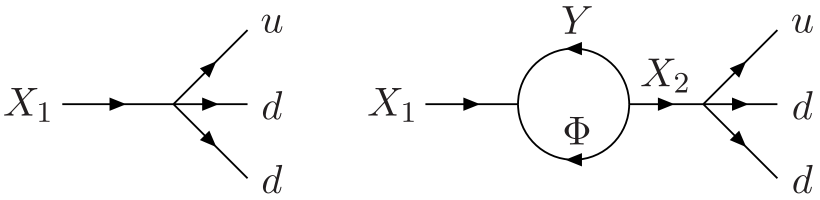
- Baryon charge $B_{X_a} = -(B_Y + B_\Phi) = 1$
- Proton and DM particles (both Y and Φ) are stable if

$$|m_Y - m_\Phi| < m_p + m_e < m_Y + m_\Phi$$

Baryogenesis (asymmetry generation)

Sakharov's conditions

1. B-violation (in visible sector !) $\lambda_a \neq 0$
2. C- & CP-violation $\Im\left(\lambda_1^* \lambda_2 \zeta_1 \zeta_2^*\right) \neq 0$
3. out-of-equilibrium decays of nonrelativistic X_1



Microscopic asymmetry (assuming $X_1 \to \bar{Y}\Phi^*$ dominates and $M_1 \ll M_2$)

$$\varepsilon = \frac{\Gamma(X_1 \to udd) - \Gamma(\bar{X}_1 \to \bar{u}\bar{d}\bar{d})}{\Gamma(X_1 \to \bar{Y}\Phi^*) + \Gamma(\bar{X}_1 \to Y\Phi)} \approx \frac{m_1^5 \Im[\lambda_1^* \lambda_2 \zeta_1 \zeta_2^*]}{256\,\pi^3\,|\zeta_1|^2 M^4 m_2} \Rightarrow \varepsilon/g_* \sim \Delta_B = \frac{n_B}{s} \approx 10^{-10}$$

if $m_2 > 2m_1$, $M > 2m_2$ then $\varepsilon \simeq 2.5 \times 10^{-7} \times \Im[\lambda_1^* \lambda_2 \zeta_1 \zeta_2^*]/|\zeta_1|^2$ seems OK

if $m_2 > 3m_1$, $M > 3m_2$ then $\varepsilon \simeq 6.5 \times 10^{-9} \times \Im[\lambda_1^* \lambda_2 \zeta_1 \zeta_2^*]/|\zeta_1|^2$ needs $|\zeta_1| \ll 1$?

Asymmetric Dark Matter freeze out

To make DM natural:
all CP-symmetric pairs (Y and $\bar{Y}$), (Φ and Φ^*) must annihilate

- CP-asymmetric relics form Dark Matter
  is exactly the counterpart of baryon asymmetry in visible sector
- then baryon number conservation implies $n_Y = n_\Phi = n_B$ and so

$$\frac{\Omega_{DM}}{\Omega_B} = \frac{m_Y + m_\Phi}{m_p}$$

- stability of proton and DM is kinematically guaranteed for

$$1.7\,\text{GeV} \lesssim m_Y, m_\Phi \lesssim 2.9\,\text{GeV}$$

- hence $\Omega_{DM} \sim \Omega_B$ is natural

Tests?

– Direct production of X_a at LHC
– Induced proton decay (HyperK, DUNE)