Big Bang Nucleosynthesis

George Gamow
(1904-1968)

$$\begin{aligned} n &\leftrightarrow p + e^- + \bar{\nu}_e \\ n + e^+ &\leftrightarrow p + \bar{\nu}_e \\ n + \nu_e &\leftrightarrow p + e^- . \end{aligned}$$

Neutrons-protons inter-converting processes

At the equilibrium: $\left(\frac{n_n}{n_p}\right) \simeq \left(\frac{n_n}{n_p}\right)_{\rm eq} \simeq e^{-\frac{Q_n}{k_B T}}$ $\quad Q_n = (m_n - m_p)\,c^2 \simeq 1.29\,\mathrm{MeV}$

Equilibrium holds until $\Gamma_{n\leftrightarrow p} \simeq G_F^2 T^5 \gtrsim H$ $\Rightarrow$ $T \gtrsim T_{\rm fr} = \frac{\sqrt{2.4}}{g_R^{1/4}}\left(\frac{\rm sec}{t_{\rm fr}}\right)^{1/2} \mathrm{MeV} \simeq 0.85\,\mathrm{MeV}$ Freeze-out temperature

At the freeze-out: $\frac{n_n}{n_p}(T_{\rm fr}) = e^{-\frac{Q_n}{T_{\rm fr}}} \simeq e^{-\frac{1.29}{0.85}} \simeq 0.22$ $\quad t_{\rm fr} \simeq 1.0\,\mathrm{sec}$

After the freeze-out neutrons start to decay prior to nucleosynthesis at $t_{\rm nuc} \simeq 310\,s$

$\tau_n \simeq 885\,\mathrm{s}$ Life time of neutrons

$$\frac{(n_n/n_p)_{\rm nuc}}{(n_n/n_p)_{\rm fr}} = e^{-\frac{t_{\rm nuc}}{\tau}} = e^{-\frac{310}{885}} \simeq 0.7 \Rightarrow (n_n/n_p)_{\rm nuc} \simeq 0.154 \Rightarrow Y_p = 2\,\frac{(n_n/n_p)_{\rm nuc}}{1+(n_n/n_p)_{\rm nuc}} \simeq 0.267$$

Big Bang Nucleosynthesis

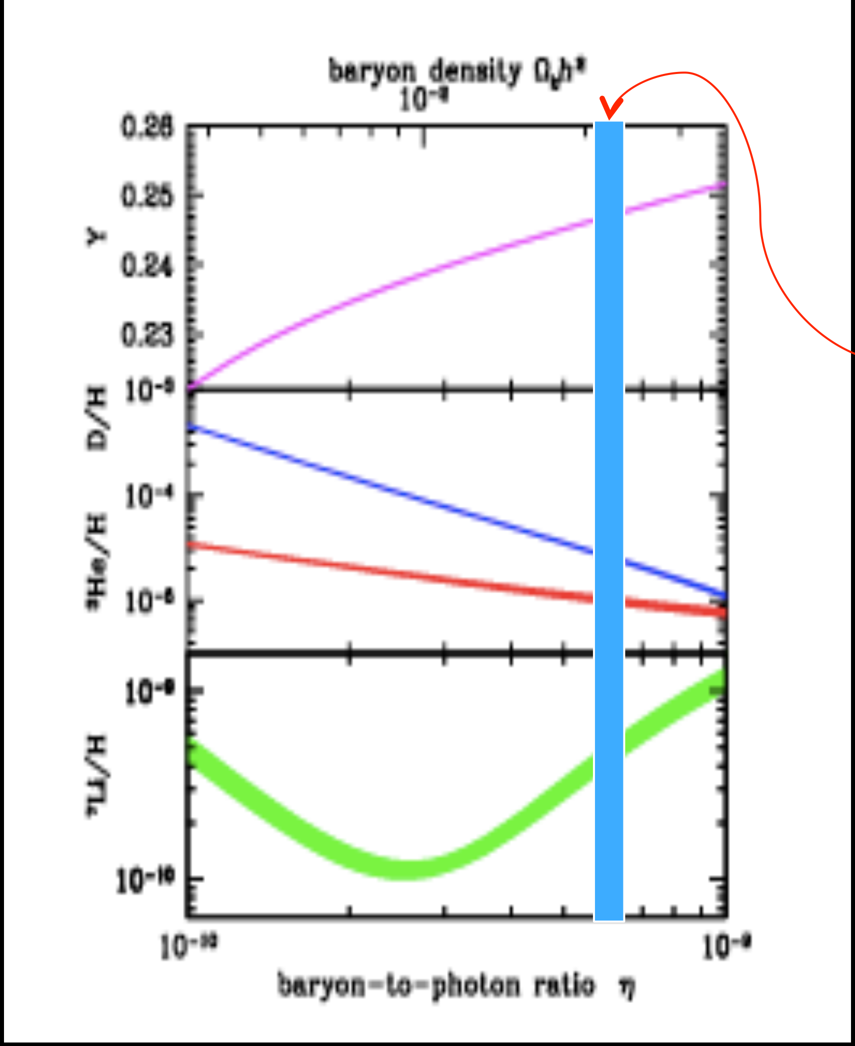
Relevant nuclear processes

$$
\begin{array}{rrcl}
1) & p + n & \leftrightarrow & D + \gamma \\
2) & D + n & \leftrightarrow & T + \gamma \\
3) & {}^3\mathrm{He} + n & \leftrightarrow & {}^4\mathrm{He} + \gamma \\
4) & {}^6\mathrm{Li} + n & \leftrightarrow & {}^7\mathrm{Li} + \gamma \\
5) & {}^3\mathrm{He} + n & \leftrightarrow & T + p \\
6) & {}^7\mathrm{Be} + n & \leftrightarrow & {}^7\mathrm{Li} + p \\
7) & {}^7\mathrm{Li} + n & \leftrightarrow & {}^3\mathrm{He} + {}^4\mathrm{He} \\
8) & {}^7\mathrm{Be} + n & \leftrightarrow & {}^4\mathrm{He} + {}^4\mathrm{He} \\
9) & D + p & \leftrightarrow & {}^3\mathrm{He} + \gamma \\
10) & T + p & \leftrightarrow & {}^4\mathrm{He} + \gamma \\
11) & {}^6\mathrm{Li} + p & \leftrightarrow & {}^7\mathrm{Be} + \gamma \\
12) & {}^7\mathrm{Li} + p & \leftrightarrow & {}^4\mathrm{He} + {}^4\mathrm{He} \\
13) & D + {}^4\mathrm{He} & \leftrightarrow & {}^6\mathrm{Li} + \gamma \\
14) & T + {}^4\mathrm{He} & \leftrightarrow & {}^7\mathrm{Li} + \gamma \\
15) & {}^3\mathrm{He} + {}^4\mathrm{He} & \leftrightarrow & {}^7\mathrm{Be} + \gamma \\
16) & D + D & \leftrightarrow & {}^3\mathrm{He} + n \\
17) & D + D & \leftrightarrow & T + p \\
18) & D + T & \leftrightarrow & {}^4\mathrm{He} + p \\
19) & D + {}^3\mathrm{He} & \leftrightarrow & {}^4\mathrm{He} + n \\
20) & {}^3\mathrm{He} + {}^3\mathrm{He} & \leftrightarrow & {}^4\mathrm{He} + p + p \\
21) & D + {}^7\mathrm{Li} & \leftrightarrow & {}^4\mathrm{He} + {}^4\mathrm{He} + n \\
22) & D + {}^7\mathrm{Be} & \leftrightarrow & {}^4\mathrm{He} + {}^4\mathrm{He} + p
\end{array}
$$

Deuterium bottleneck:
No other element can
Form before Deuterium.
This delays the synthesis
of He-4

Big Bang nucleosynthesis+CMB

(PDB hep-ph/0108182)



(Cyburt, Field, Olive, Yeh 1505.01076)

$$\eta_{B0} \simeq 273.5\,\Omega_{B0} h^2 \times 10^{-10}$$

$$\Rightarrow \eta_{B0}^{(CMB)} = (6.08 \pm 0.06) \times 10^{-10}$$

Using this measurement of η_{B0} from CMB from ^{4}He abundance (Y) one finds:

$$\boxed{N_\nu(t_f = 1s) = 2.9 \pm 0.2}$$

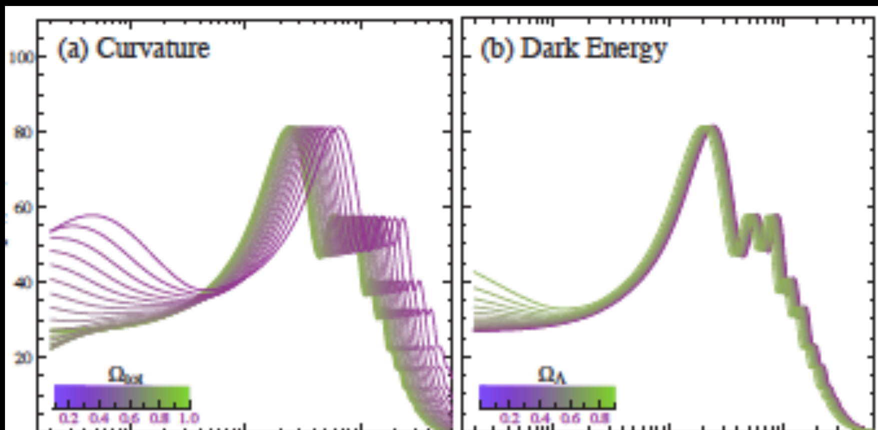
And from Deuterium abundance:

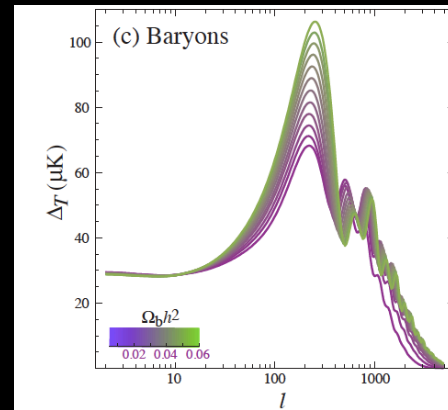
$$\boxed{N_\nu(t_{nuc} \simeq 300s) = 2.8 \pm 0.3}$$

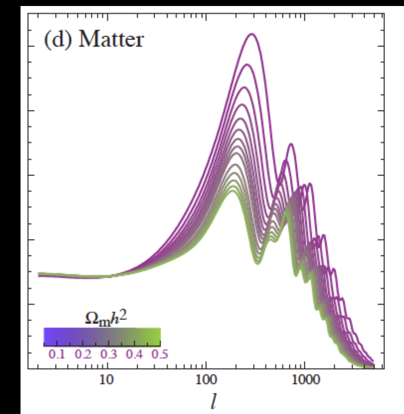
This shows that $T_{RH} \gg T_\nu^{dec} \sim 1$ MeV and again NO DARK RADIATION

Cosmic ingredients

(Hu, Dodelson, astro-ph/0110414)





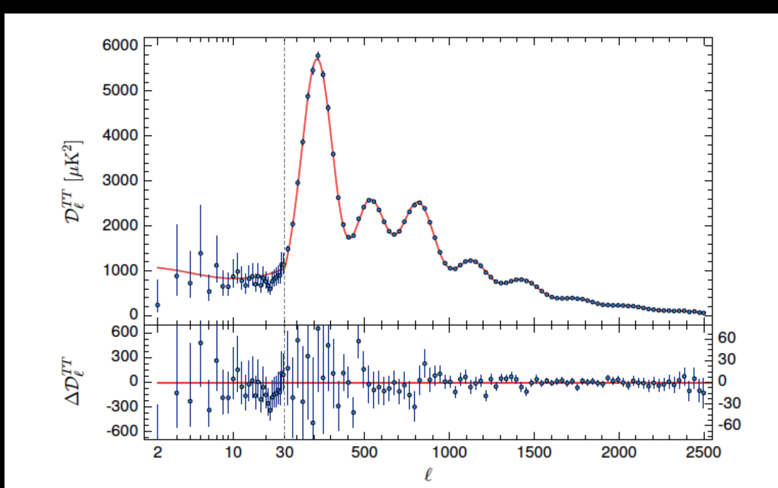


$$\Omega_0 = 1.005 \pm 0.005 \qquad \Omega_{\Lambda 0} = 0.685 \pm 0.013$$

$$\Omega_{B0} h^2 = 0.02222 \pm 0.00023 \qquad \boxed{\Omega_{CDM,0} h^2 = 0.1198 \pm 0.0015 \sim 5\Omega_{B,0} h^2}$$

$$h \equiv \frac{H_0}{100 km\, s^{-1}\ Mpc^{-1}} = 0.67 \pm 0.1$$

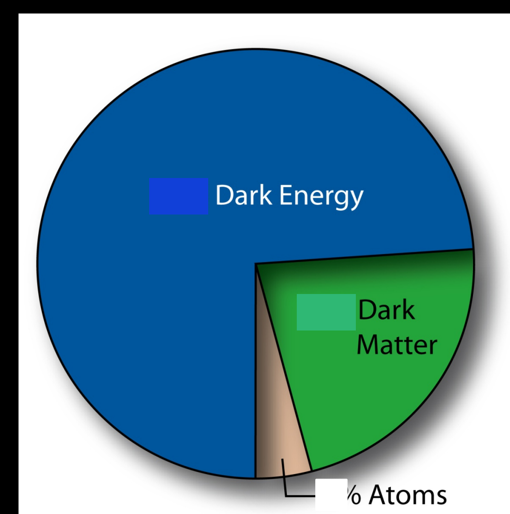
(Planck 2015, 1502.01589)



$$\Omega_{B0} \simeq 0.048$$

$$\Omega_{CDM,0} \simeq 0.26$$

$$\Omega_{M,0} \simeq 0.308$$



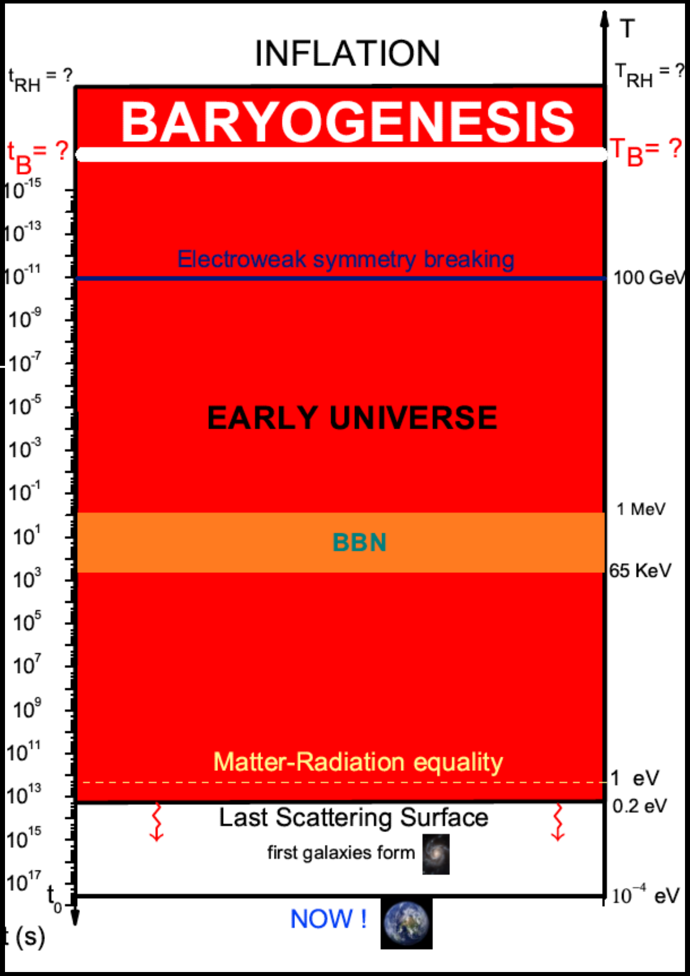
Number of ultra-relativistic degrees of freedom vs. T

T	g_R	Particle content
$m_e\, c^2/2 \simeq 0.25\,\mathrm{MeV} \gg T \geq T_0$	3.36	$\gamma + 3$ massless $\nu' s$
$m_\mu\, c^2/2 \simeq 50\,\mathrm{MeV} \gg T \gg m_e\, c^2/2$	$43/4 = 10.75$	$\ldots + e^\pm$
$m_\pi\, c^2/2 \simeq 75\,\mathrm{MeV} \gg T \gg m_\mu\, c^2/2$	$57/4 = 14.25$	$\ldots + \mu^\pm$
$T_{\mathrm{qh}} \simeq 150\,\mathrm{MeV} \gg T \gg m_\pi\, c^2/2$	$69/4 = 17.25$	$\ldots + \pi^0, \pi^\pm$
$m_\tau\, c^2/2 \gtrsim m_{\mathrm{c}}\, c^2/2 \simeq 0.65\,\mathrm{GeV} \gg T \gtrsim T_{\mathrm{qh}}$	61.75	$\ldots +$ u,d,s quarks + 8 gluons
$m_{\mathrm{b}}\, c^2/2 \simeq 2\,\mathrm{GeV} \gg T \gg m_\tau\, c^2/2$	75.75	$\ldots + \tau^\pm +$ c quark
$m_{W,Z,H^0}\, c^2/2 \simeq 40\,\mathrm{GeV} \gg T \gg m_{\mathrm{b}}\, c^2/2$	86.25	$\ldots +$ b quark
$m_{\mathrm{t}}\, c^2/2 \simeq 90\,\mathrm{GeV} \gg T \gg m_{W,Z,H^0}\, c^2/2$	96.25	$\ldots + W^\pm,\ Z^0,\ H^0$ bosons
$T \gg m_{\mathrm{t}}\, c^2/2$	106.75	$\ldots +$ top quark

TABLE 13.1 Dependence of g_R on temperature in the standard model.

Cosmological puzzles

dark
matter
production

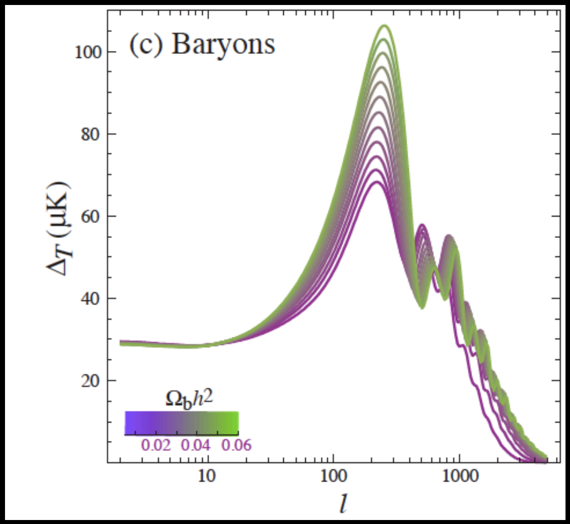


It is reasonable to think that the same extension of the SM necessary to explain neutrino masses and mixing might also address the cosmological puzzles:

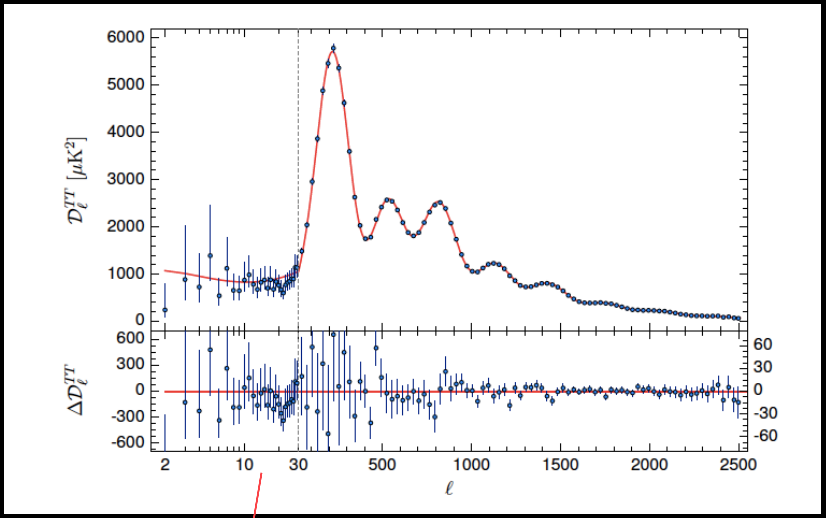
- Leptogenesis,
- RH neutrino as Dark matter

The baryon asymmetry of the Universe

(Hu, Dodelson, astro-ph/0110414)



(Planck 2015, 1502.10589)



$$\Omega_{B0} h^2 = 0.02230 \pm 0.00014$$

$$\boxed{\eta_{B0} \equiv \frac{n_{B0} - \bar{n}_{B0}}{n_{\gamma 0}} \simeq \frac{n_{B0}}{n_{\gamma 0}} \simeq 273.5\,\Omega_{B0} h^2 \times 10^{-10} = (6.10 \pm 0.04) \times 10^{-10}}$$

- Consistent with (older) BBN determination but more precise and accurate

Matter-antimatter asymmetry of the Universe

- A relic abundance of matter and antimatter would be incredibly small. Something should have segregated them prior to annihilations
- Symmetric Universe with matter- anti matter domains ?

  Excluded by CMB + cosmic rays
- Pre-existing ? It conflicts with inflation ! (Dolgov '97)
- **dynamical generation at the end or after inflation is necessary (baryogenesis)** (Sakharov '67)
- A Standard Model baryogenesis ? $\eta_B^{SM} <<< \eta_B^{CMB}$
- **New Physics is needed!**

Models of Baryogenesis

- From phase transitions:

  - ELECTROWEAK BARYOGENESIS (EWBG)

  * in the SM
  * in the MSSM
  * in the nMSSM
  * in the NMSSM
  * in the 2 Higgs model
  * ....

- Affleck-Dine:

  - at preheating
    - Q-balls
  - ....

- From Black Hole evaporation
- Spontaneous Baryogenesis
- ....
- From heavy particle decays:

  - GUT Baryogenesis
  - LEPTOGENESIS

Baryogenesis in the SM ?

All 3 Sakharov conditions are fulfilled in the SM:

1. baryon number violation if T ~ 100 GeV,
2. CP violation in the quark CKM matrix,
3. departure from thermal equilibrium (an arrow of time)

from the expansion of the Universe

Baryon Number Violation at finite T

('t Hooft '76)

Even though at T= 0 baryon number violating processes are inhibited, at finite T:

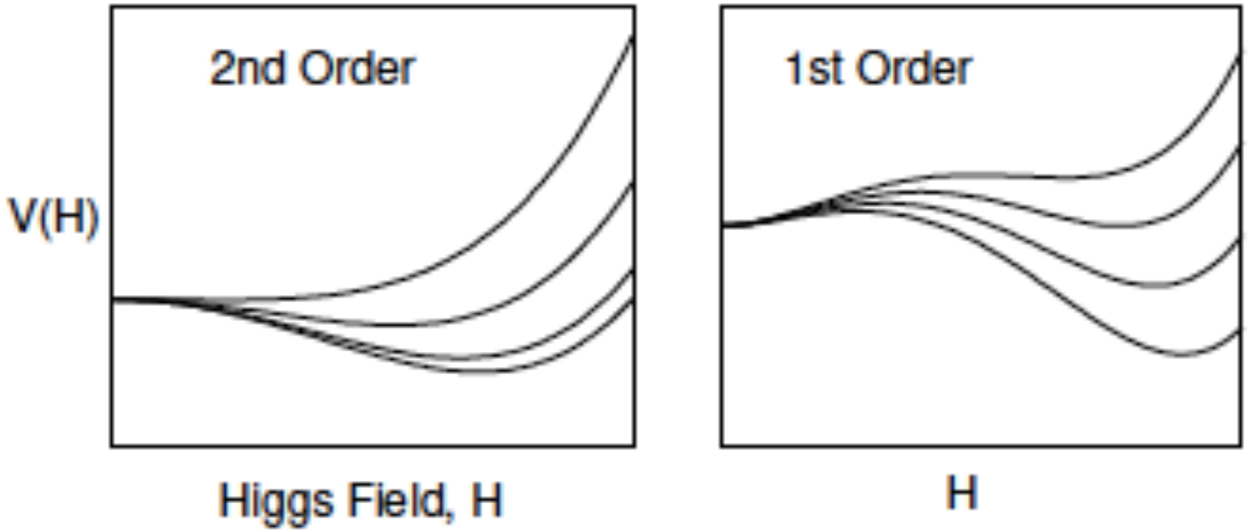
$$\Gamma(\Delta B \neq 0) \propto T^4 \exp\left[-\kappa \frac{v(T)}{T}\right]$$

$$v \equiv \langle \Phi \rangle = \begin{cases} 0 \text{ for } T \gtrsim T_c \text{ (unbroken phase)} \\ v(T_c) \text{ for } T \lesssim T_c \text{ (broken phase)} \end{cases}$$

- Baryon number violating processes are unsuppressed at $T \lesssim T_c \simeq 100$ GeV
- Anomalous processes violate lepton number as well but preserve B-L !

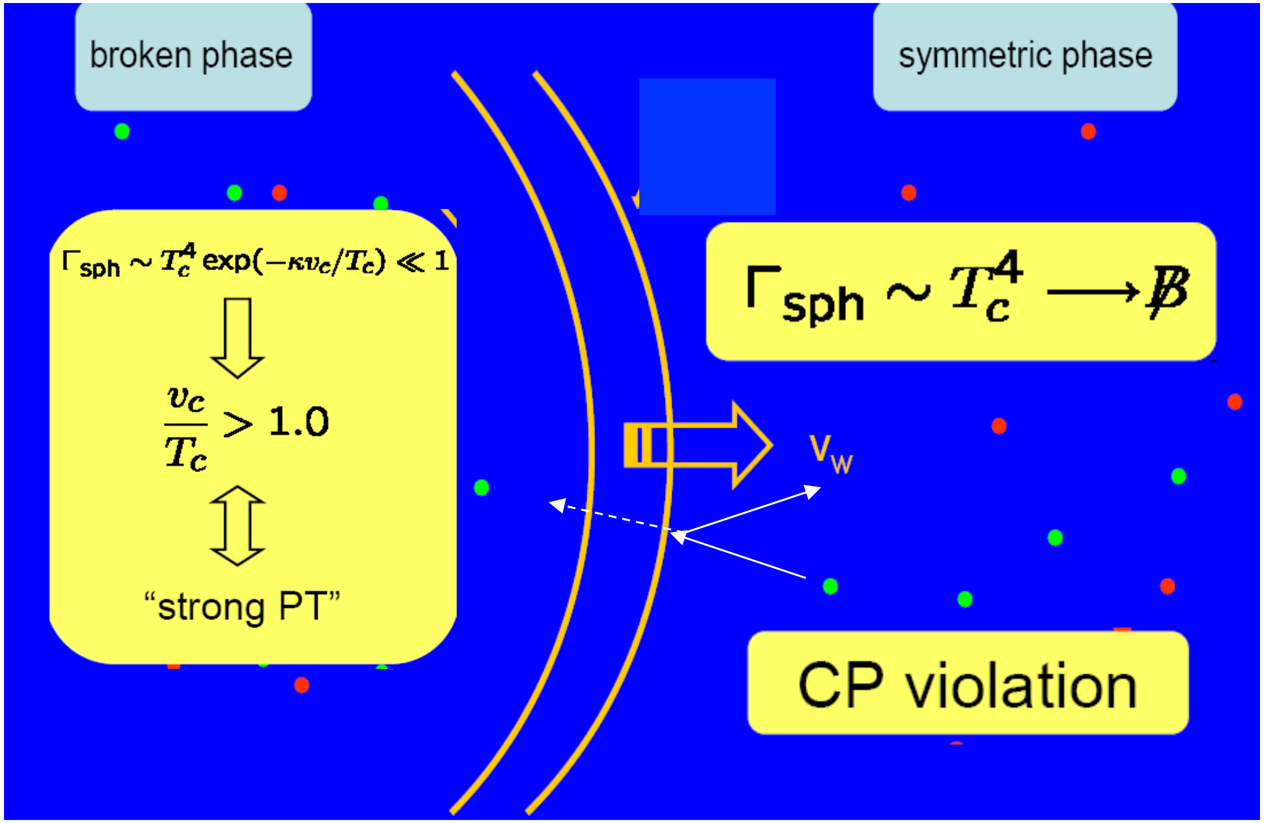
There can be enough departure from thermal equilibrium ?

1st or 2nd order PT?



EWBG in the SM

If the EW phase transition (PT) is 1st order ⇒ **broken phase bubbles nucleate**



In the SM the ratio v_c/T_c is directly related to the Higgs mass and only for $M_h < 40$ GeV one can have a strong PT

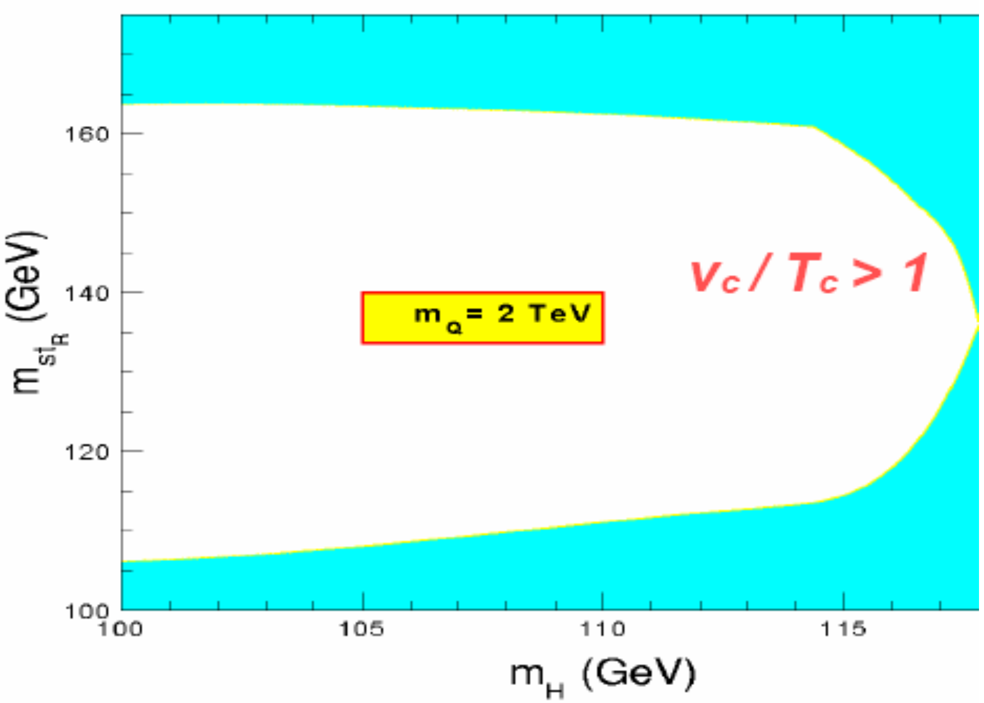
⇒ EW baryogenesis in the SM is ruled out (also not enough CP)

⇒ New Physics is needed!

EWBG in the MSSM

(Carena, Quiros, Wagner '98)

- Additional bosonic degrees of freedom (dominantly the light stop contribution) can make the EW phase transition more strongly first order if :



•With the discovery of Higgs boson with a mass m_H ~126 GeV the EWBG in MSSM is basically dead (D.Curtin et al.arXiv:1203.2932) though very ad hoc loopholes have been found

EWBG in the nMSSM

(Menon, Morissey, Wagner'04; Balazs, Carena, Freitas, Wagner et al. `07)

- The `μ-problem' in the MSSM can be solved introducing a singlet chiral superfield ⇒ the mass of the (CP-even) Higgs boson responsible for EWSB can be easily much higher than the Higgs mass

Discrete symmetries have to be imposed to solve the *domain wall problem*,

Two popular options :

`Next-to-MSSM' (NMSSM) based on Z_3

`nearly-MSSM' (nMSSM) based on Z_5 or Z_7

- The nMSSM is interesting for EWBG because strong first order phase transition does not require too light Higgs and stop masses;
- However chargino and Higgs mass parameters are required to be in the range testable at LHC and ILC
- Constraints from EDM's are still present but weaker than in the MSSM; new experiments will improve current upper bound on the electron EDM and in many scenarios non zero value is expected
- At the same time neutralino is the LSP and can be the Dark Matter for masses about 30-45 GeV

Is EWBG in general still alive ?

(See J.Cline 1704.08911 *"Is EWBG dead?"*, for a review on the status of EWBG)

2 attitudes:

- **Optimistic**: EWBG in the MSSM has strong constraints but these can be relaxed within other frameworks:
  - in the NMSSM
    (Pietroni '92,Davies et al. '96, Huber and Schmidt '01)
  - in the nMSSM
    (Wagner et al. '04)
  - in left-right symmetric models at B-L symmetry breaking
    (Mohapatra and Zhang '92)
  - all these models also start to be strongly constrained!
  - adding a scalar singlet (Choi,Volkas '93, Espinosa et al'15, J.Cline et al '17.)
- **Pessimistic**: Still viable models start to be too *ad hoc* and we need some other mechanism: LEPTOGENESIS!