Istituto Nazionale di Fisica Nucleare
Sezione di Roma

# Baryogenesis

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May 27, 2006

# Summary



**Evidence of matter antimatter asymmetry**

**Is the Universe lepton asymmetric ?**

**Ways to a Baryon Asymmetric Universe**

**When the Universe grew up baryons**

**B and CP violations**

**EW phase transition baryogenesis**

**EW phase transition in the MSSM**

**Conclusions**

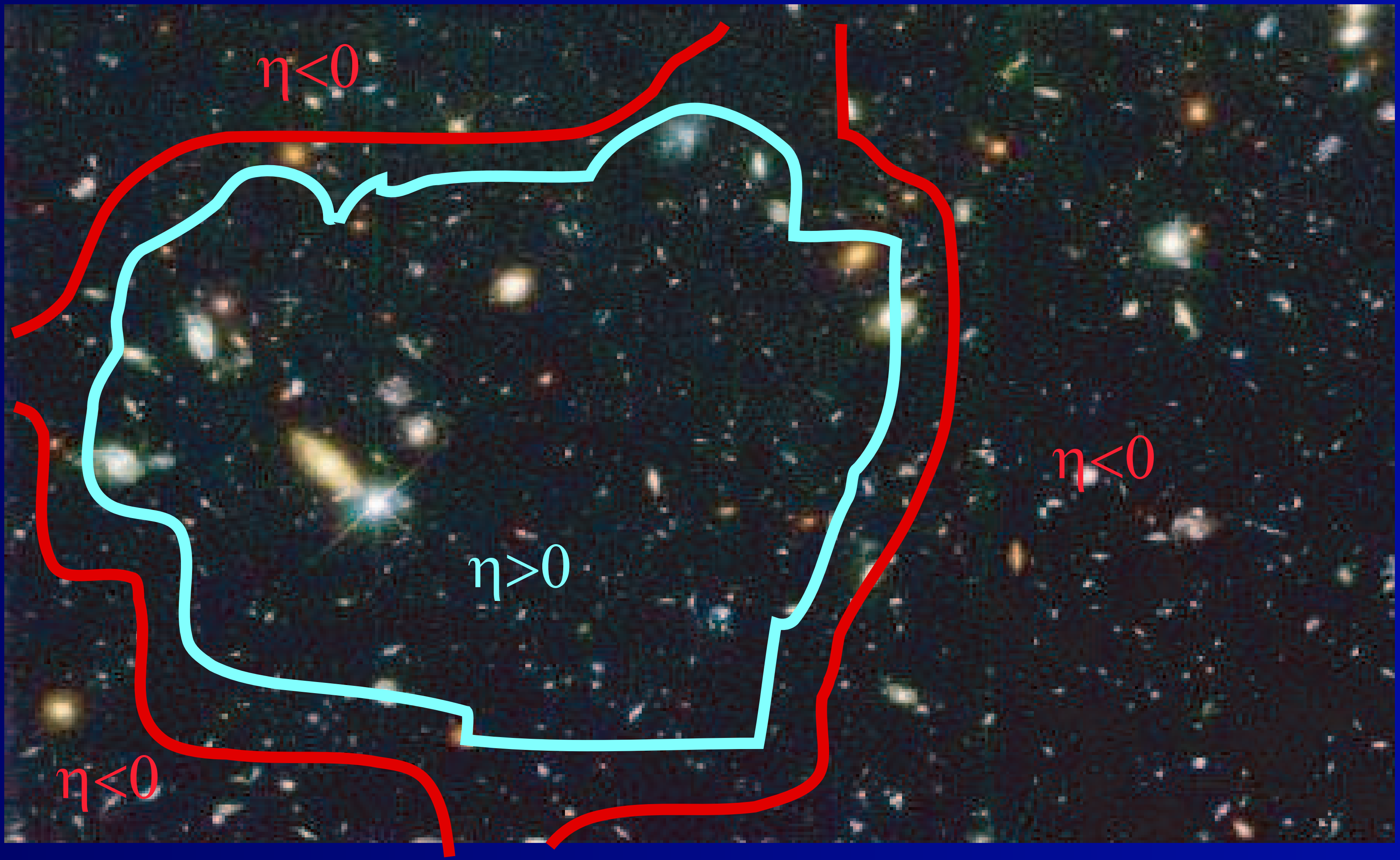
# The Baryon Symmetric Universe




It is possible that far away galaxies could be made of antimatter ...

# The Baryon Symmetric Universe

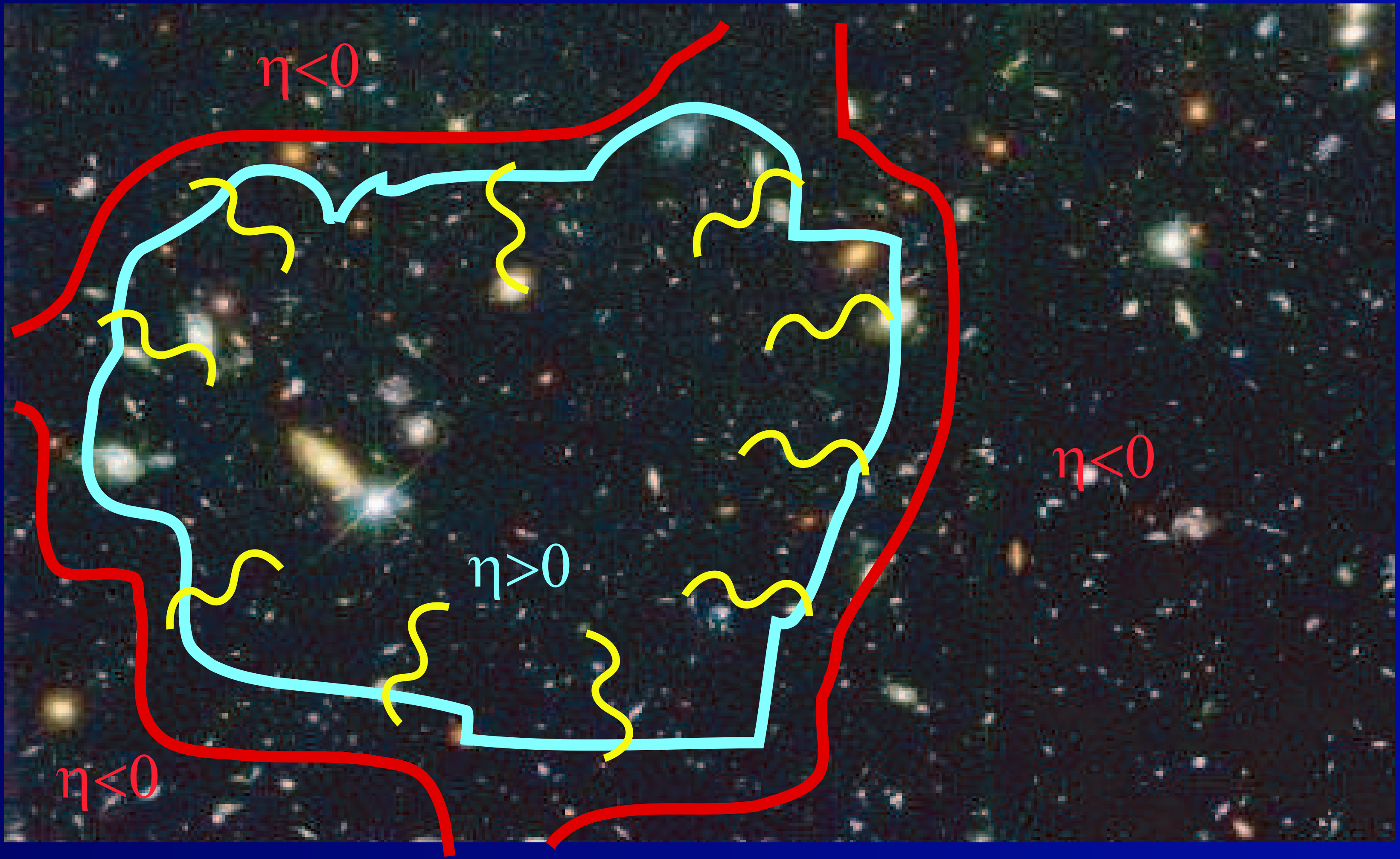





In this case we live in a bubble where the baryon asymmetry is positive...

# The Baryon Symmetric Universe

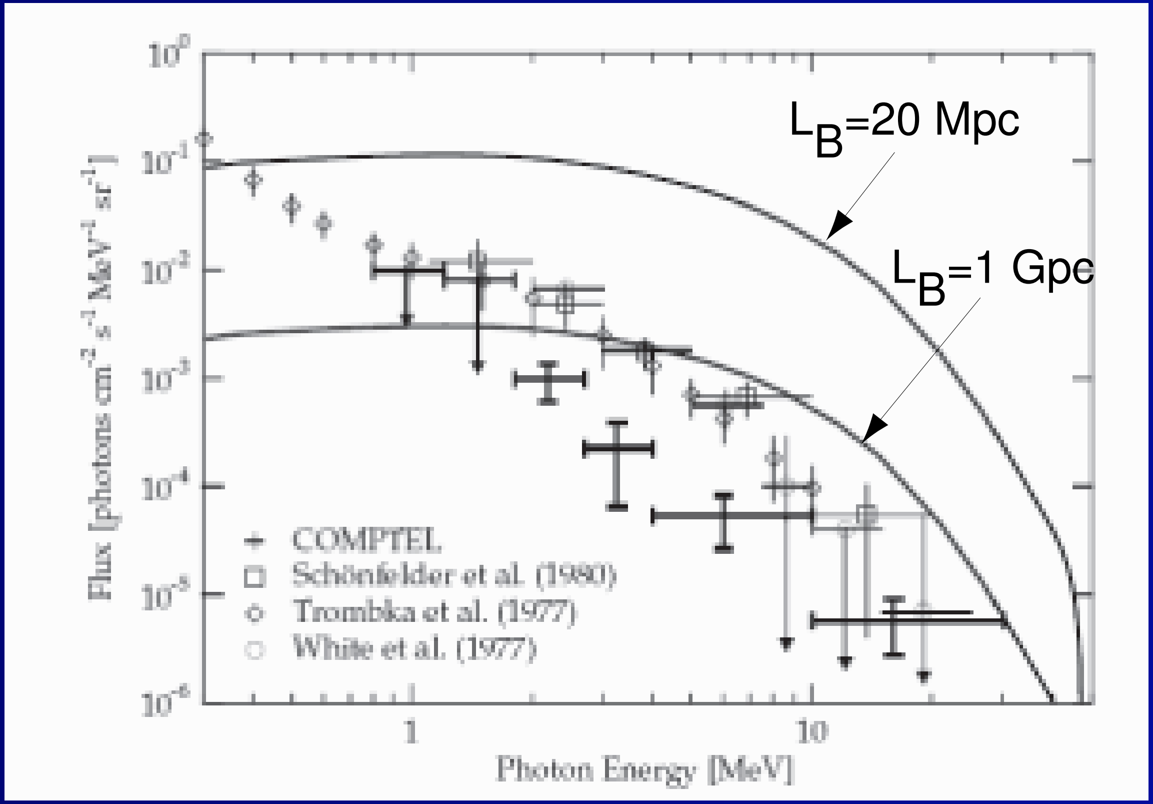





... but annihilation $\gamma$-rays should be produced at the boundary of the bubble.

# Minimum size of matter domains





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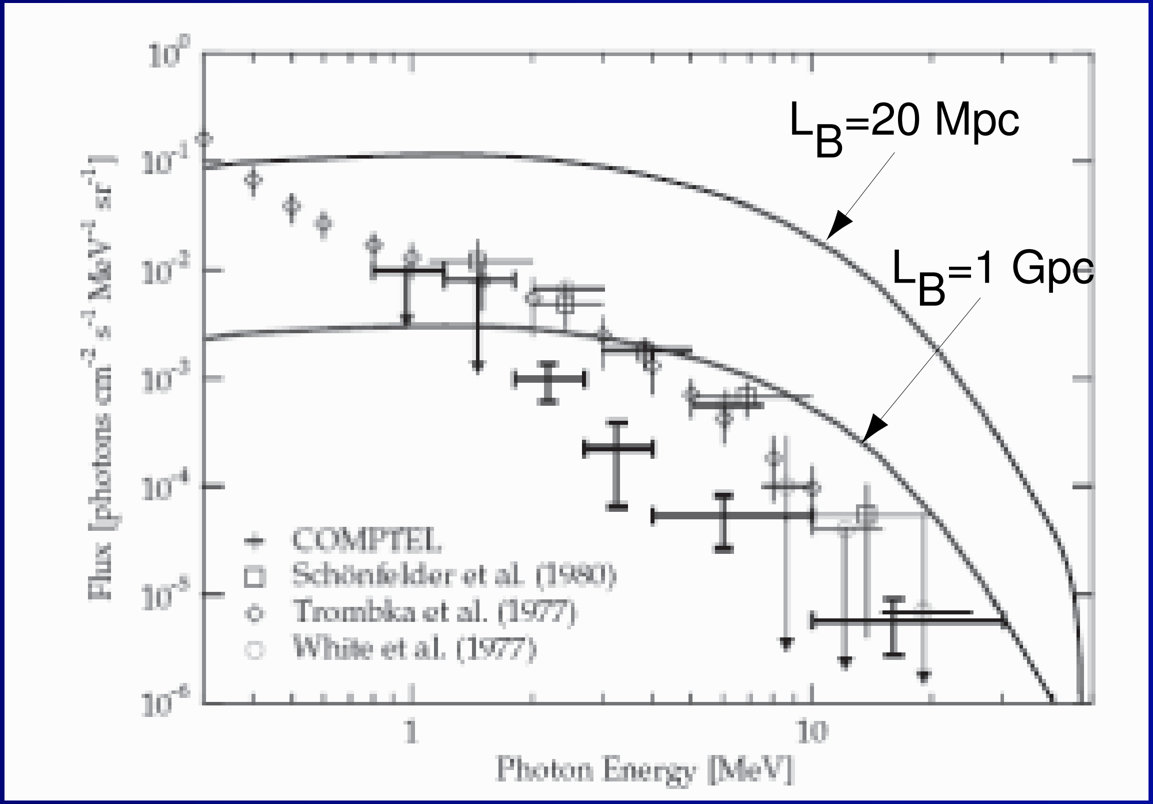


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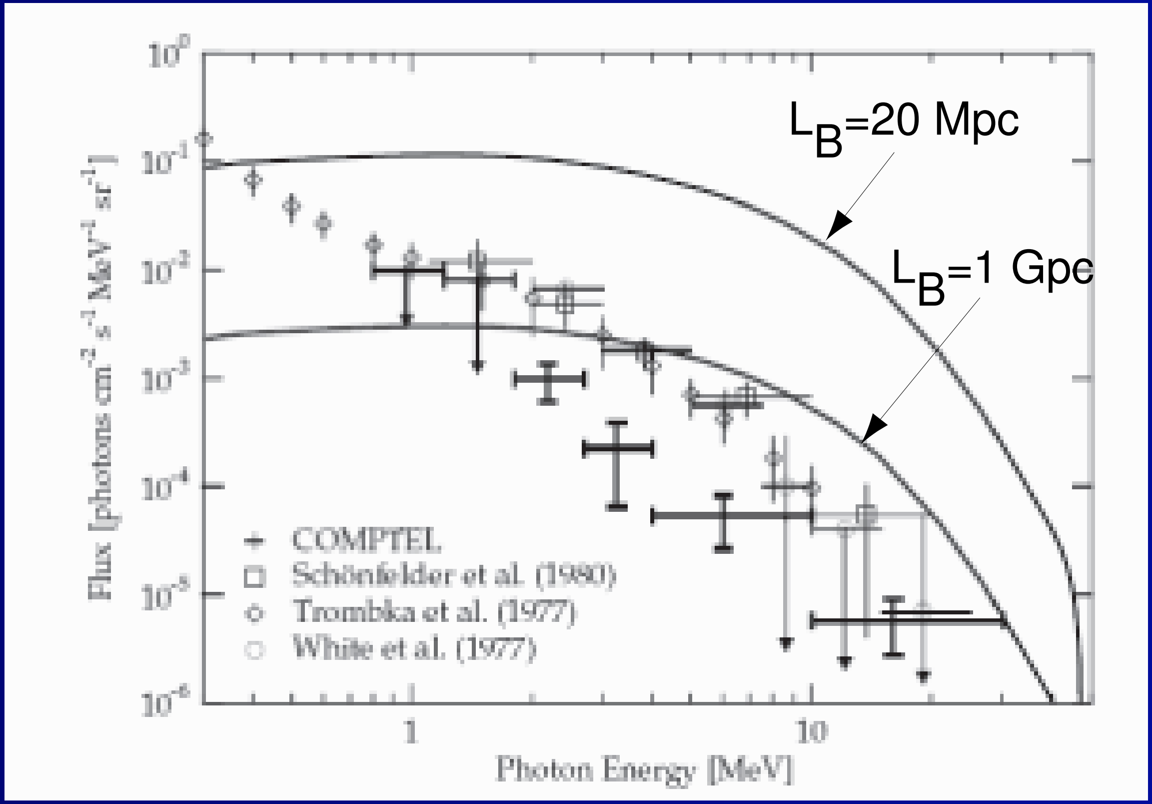


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- Predicted flux is compatible with experimental data points if $\ell_B \geq 1\ \mathrm{Gpc}$.

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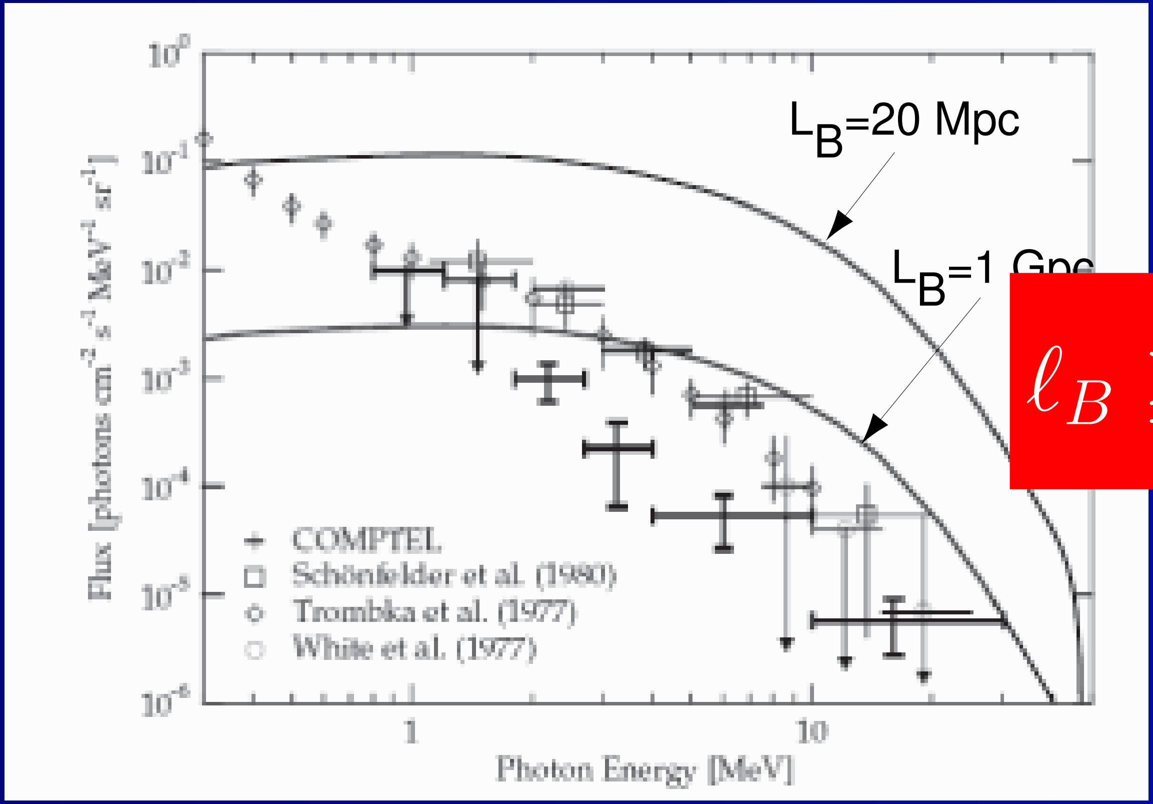


$$\ell_B \geq \frac{1}{4} c t_0$$

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- Predicted flux is compatible with experimental data points if $\ell_B \geq 1\ \mathrm{Gpc}$.

# Census of baryons



| | | | |
|---|---|---|---|
| WMAP fit | | $\Omega_b\, h^2 = 0.0223 \pm 0.0008$ | Spergel *et al.* (2006) |
| SBBN with D/H ratio at $z > 2$ | | $\Omega_b\, h^2 = 0.0214 \pm 0.0020$ | Kirkman *et al.* (2003) |
| Lyman-$\alpha$ forest $z > 2$ | | $\Omega_b\, h^2 \gtrsim 0.018$ | Weinberg *et al.* (1997) |
| Visible baryons $z < 2$ | E+S0 Galaxies | $1.5 \times 10^{-3}$ | Persic & Salucci (2005) |
| | S Galaxies | $0.7 \times 10^{-3}$ | |
| | Gas Clusters | $2.4 \times 10^{-4}\ h^{1.5}$ | |
| | Intragroup gas | $1.8 \times 10^{-4}\ h^{1.5}$ | |
| | Total Visible | $2.2 \times 10^{-3} + 4.2 \times 10^{-4}\ h^{1.5}$ | |
| Lyman-$\alpha$ forest $z < 2$ | | $\Omega_b\, h = 0.015 \pm 0.002$ | Penton *et al.* (2004) |
| Warm-Hot IM $z < 2$ | | $\Omega_b\, h \gtrsim 0.005 \pm 0.002$ | Tripp *et al.* (2000) |

➡ The number density of baryons, producing the Lyman-$\alpha$ forest, detected at redshifts $z > 2$, appear to be more or less consistent with CMBR fluctuations and BBN while the baryonic fraction detected at $z < 2$ add up to just over half (∼55%) of the number seen at $z > 2$, meaning that about 45 percent are 'missing'.

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| WHIM $z < 2$ (CHANDRA) | | $\Omega_b = 0.027^{+0.038}_{-0.019}$ | Nicastro *et al.* (2005) |

New baryonic component detected ! (Nicastro et al. Nature 2005)

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- The visible baryons segregated in stars, galaxies and intracluster gas is about 10-15 % of the total
- Apparently most of the baryons are dispersed in filaments of the warm-hot intergalactic medium with density $n_B \approx (0.5 - 1) \times 10^{-6}\ \mathrm{cm}^{-3}$ and temperature $T \approx 10^5 - 10^7\ {}^\circ\mathrm{K}$, detectable as absorbers of soft X-rays.

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# Measure of baryon asymmetry



- The best estimate of the baryon asymmetry parameter is obtained from WMAP $\Lambda$CDM best fit:

$$\eta_B = \frac{n_B - n_{\overline{B}}}{s} = (4.7 \pm 0.16) \times 10^{-11}$$

consistent with BBN.

- Exception made for periods of the three phase transition that we have described before, a Friedmann-Lemâitre Universe evolves at constant entropy: $S \propto g^*(T)\, T^3\, R^3 = \mathrm{const}$
- The number density of stable particles is $n \propto R^3$ therefore the baryon asymmetry $\eta_B$ is proportional to $1/g^*(T)$.
- Chemical potential of baryons was established by baryogenesis mechanism to be $\frac{\mu_B}{T} \simeq 10^{-12}$ well before $t_{BBN}$

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# Leptonic asymmetry



- Overall charge neutrality of the Universe imposes that the electron asymmetry should be

$$\eta_{L_e} = \eta_B$$

- On the contrary the neutrino asymmetry could be

$$\eta_{L_\nu} \neq \eta_B$$

- Lepton asymmetry implies neutrino degeneracy, because at $T \gtrsim 1 \text{ MeV}$ is

$$\eta_L = \frac{60}{43\pi^2} \sum_i g_i \left[ \frac{\mu_i}{T} + \frac{1}{\pi^2} \left( \frac{\mu_i}{T} \right)^3 \right]$$

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# Limits on lepton asymmetry from BBN



- A neutrino chemical potential modifies the outcome of primordial nucleosynthesis in two different ways:
- The first effect appears only in the $\nu_e$ sector because equilibrium is maintained by the beta process

$$\left\{ \begin{array}{c} p + e^- \rightleftarrows n + \nu_e \\ n + e^+ \rightleftarrows p + \overline{\nu}_e \end{array} \right\} \Rightarrow \quad n/p \propto e^{-\frac{\mu_{\nu_e}}{T}}$$

Therefore $\mu_{\nu_e} > 0$ decreases $Y_p$, the primordial $^4He$ mass fraction, while $\mu_{\nu_e} < 0$ increases it.

- A second effect is an increase of the neutrino energy density for any non-zero $\mu_\nu$ which is

$$\rho_{\nu+\overline{\nu}} = \frac{7\pi^2}{120} T^4 \sum_{i=e,\mu,\tau} \left[ 1 + \frac{30}{7\pi^2} \left( \frac{\mu_{\nu_i}}{T} \right)^2 + \frac{15}{7\pi^2} \left( \frac{\mu_{\nu_i}}{T} \right)^4 \right]$$

That increases the expansion rate of the universe, thus enhancing $Y_p$.

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# Limits on lepton asymmetry from BBN (cont.d)



- However it has been shown (Dolgov *et al*. 2002) that neutrino oscillations mix all the flavors, therefore we may assume that all the chemical potential are equal independent of flavors.
- The BBN limits on the electron neutrino chemical potentials are $\mu_{\nu_e} = 0.03 \pm 0.04$, which converts into a limit to the lepton asymmetry

$$-0.004 \leq \eta_L \leq 0.030 \quad (95\% \text{ C.L.})$$

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# Possible ways to a Baryon Asymmetric Universe



1. Cosmogonical
2. $\eta_B \neq 0$ could be an initial condition:
   (a) Pre-Big Bang in bouncing Universes
   (b) Quantum Gravity at $t_P = 10^{-43}\ s$
   (c) Trans-Planckian Physics at $t_P \leq 10^{-43}\ s$
3. Dynamical Baryogenesis "*à la Sackarov*"
   (a) Out of equilibrium decay
   (b) First order phase transitions
4. Dynamical Baryogenesis via CPT violation
5. Affleck-Dine type of baryonic charge condensate

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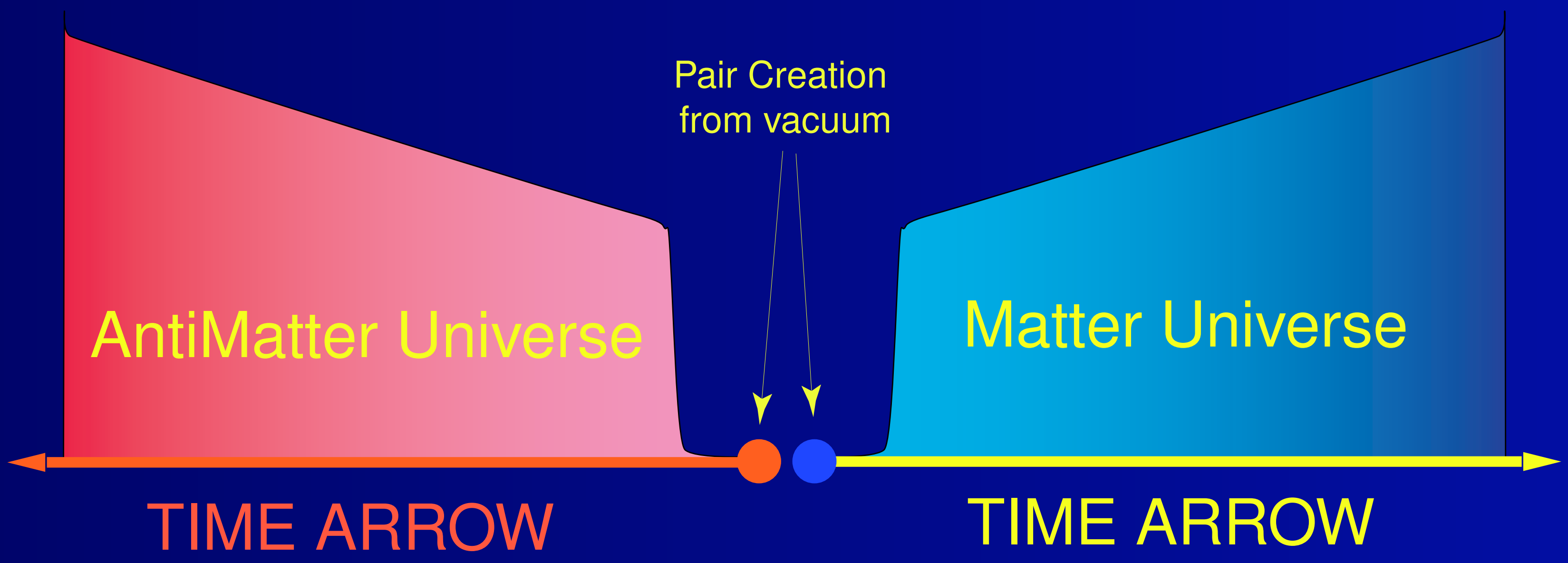


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- Forgotten for a long time this type of speculations had a recent revival in the quite different form of "Parallel Universes"
- In the Goldhaber theory the two universe can coexist spatially, because they are separated in time.

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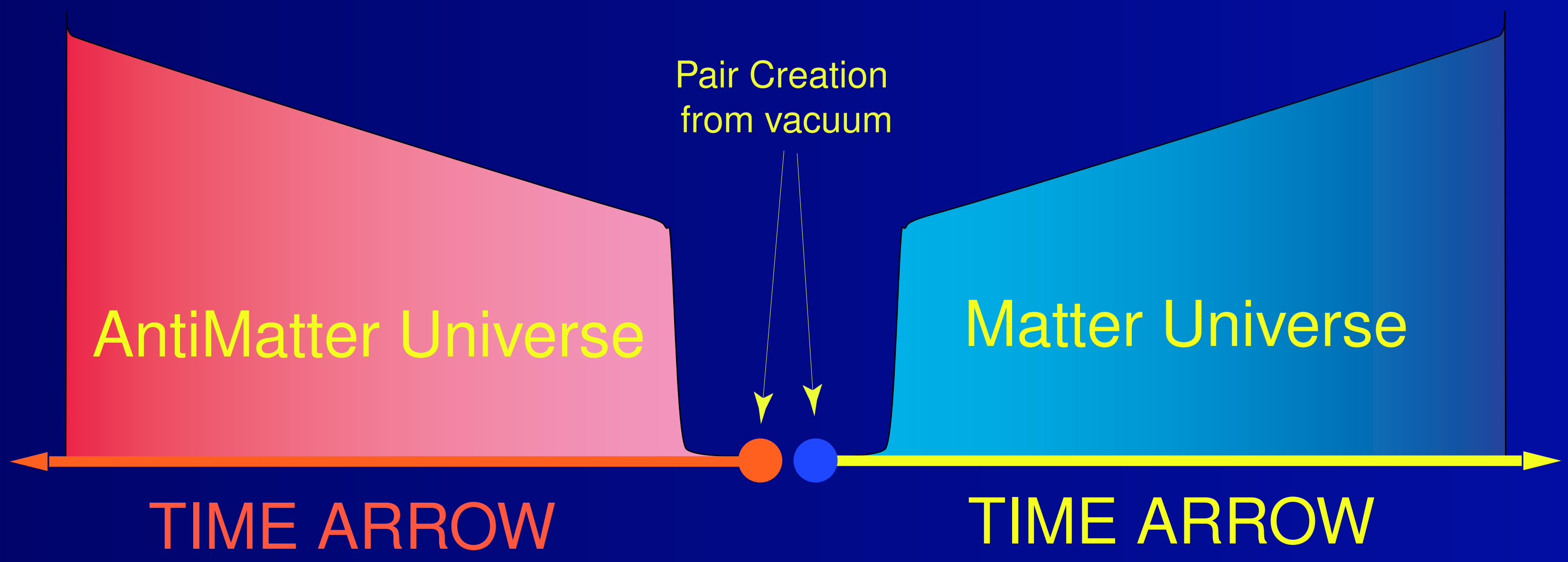


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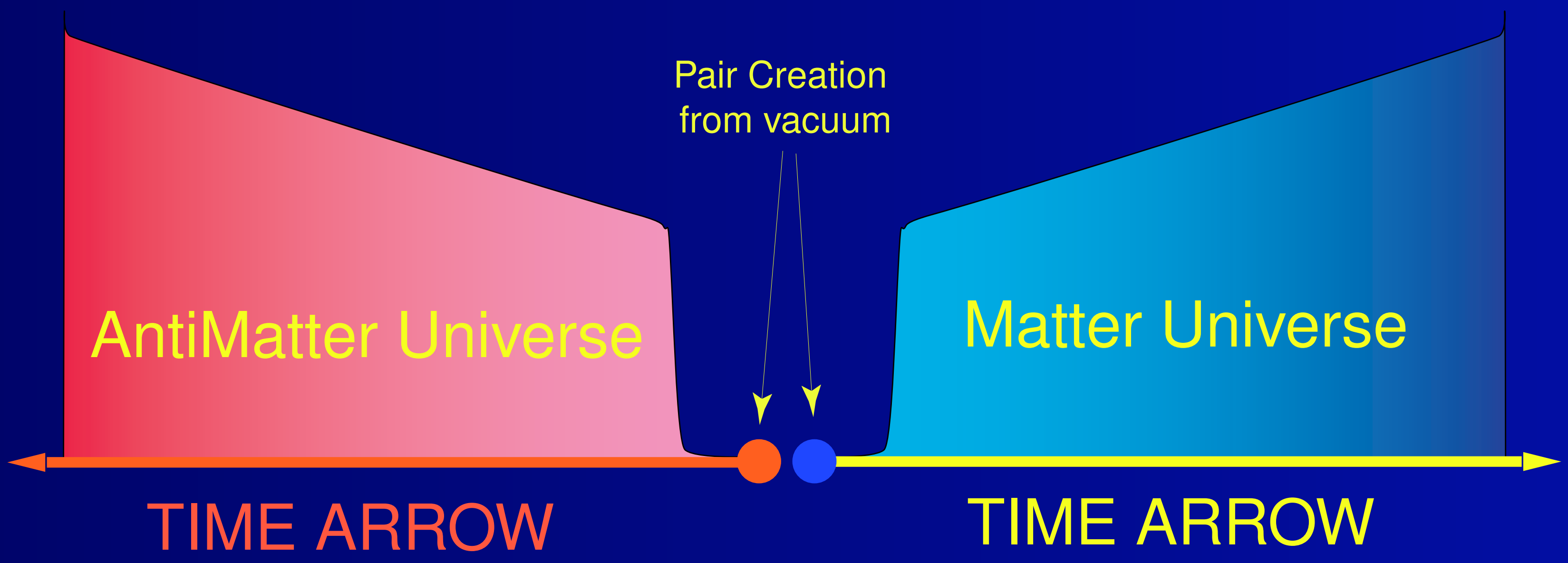


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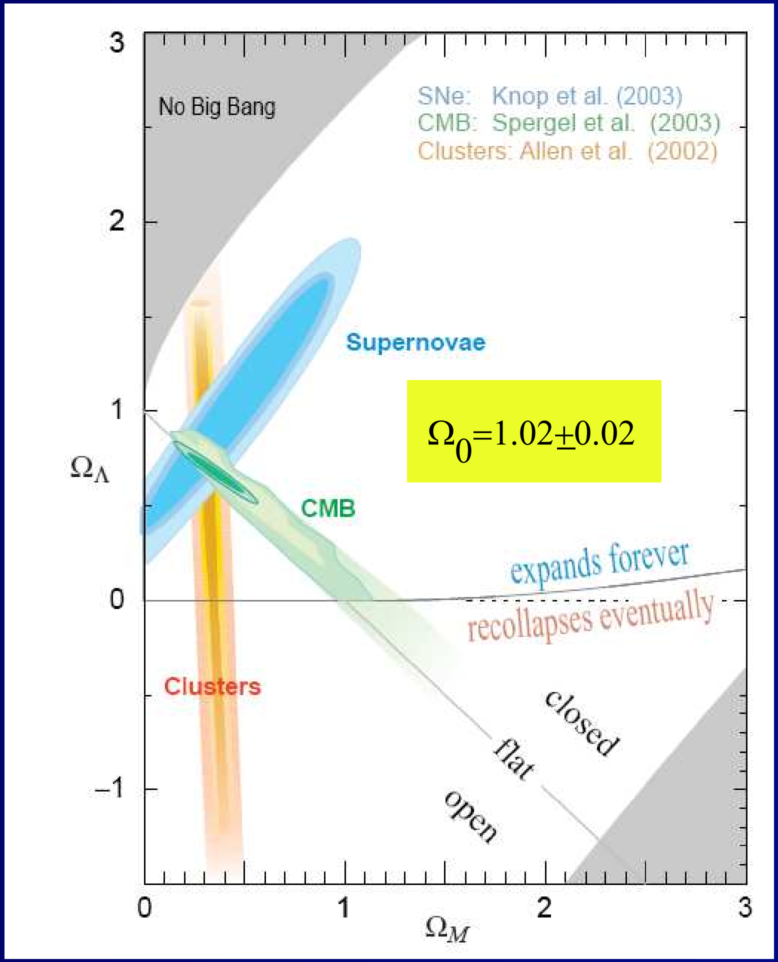
# Difficulties with any preinflationary scenario






- The initial condition $B \neq 0$ is confronted with a formidable difficulty, because after WMAP is impossible to avoid inflation.
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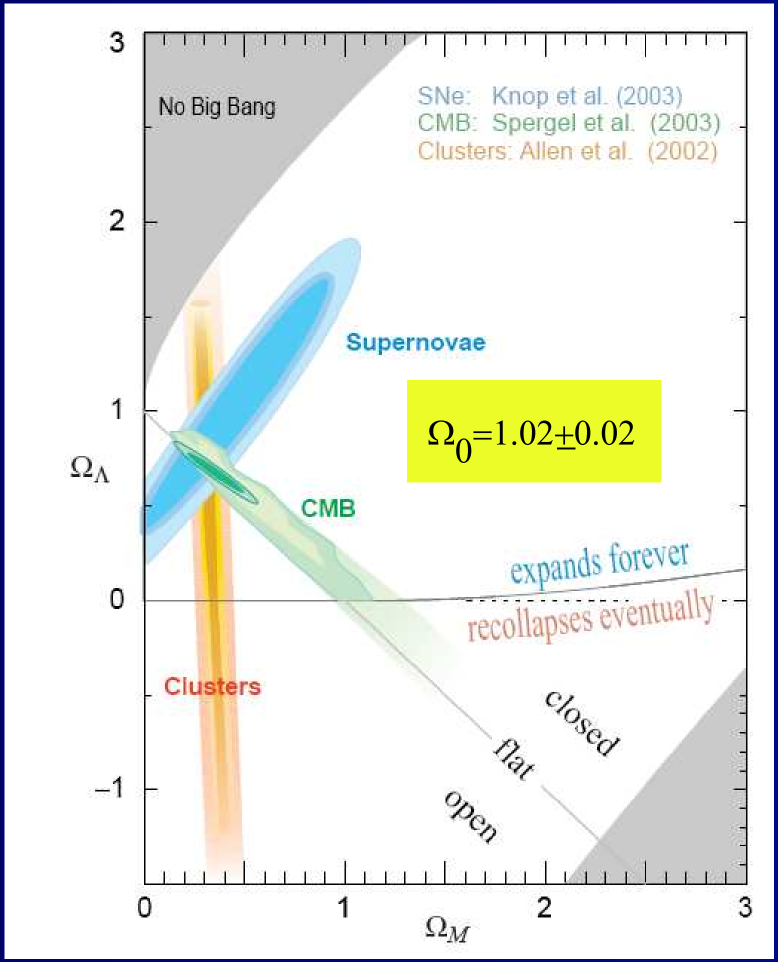


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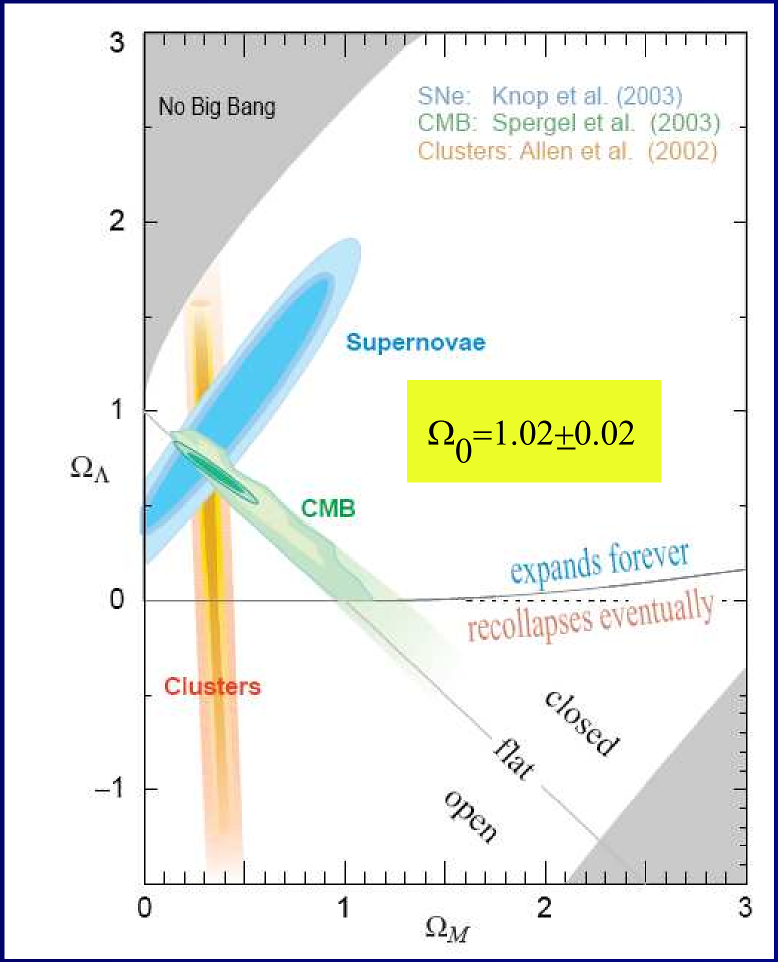


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# Sakharov dynamical scenario



Assuming that the universe started with a complete matter-antimatter symmetry in a standard big bang picture, one can obtain matter-antimatter asymmetry in the universe provided that the following three conditions are satisfied (Sakharov 1967):

1. Underlying theory should allow reactions with $\Delta B \neq 0$.
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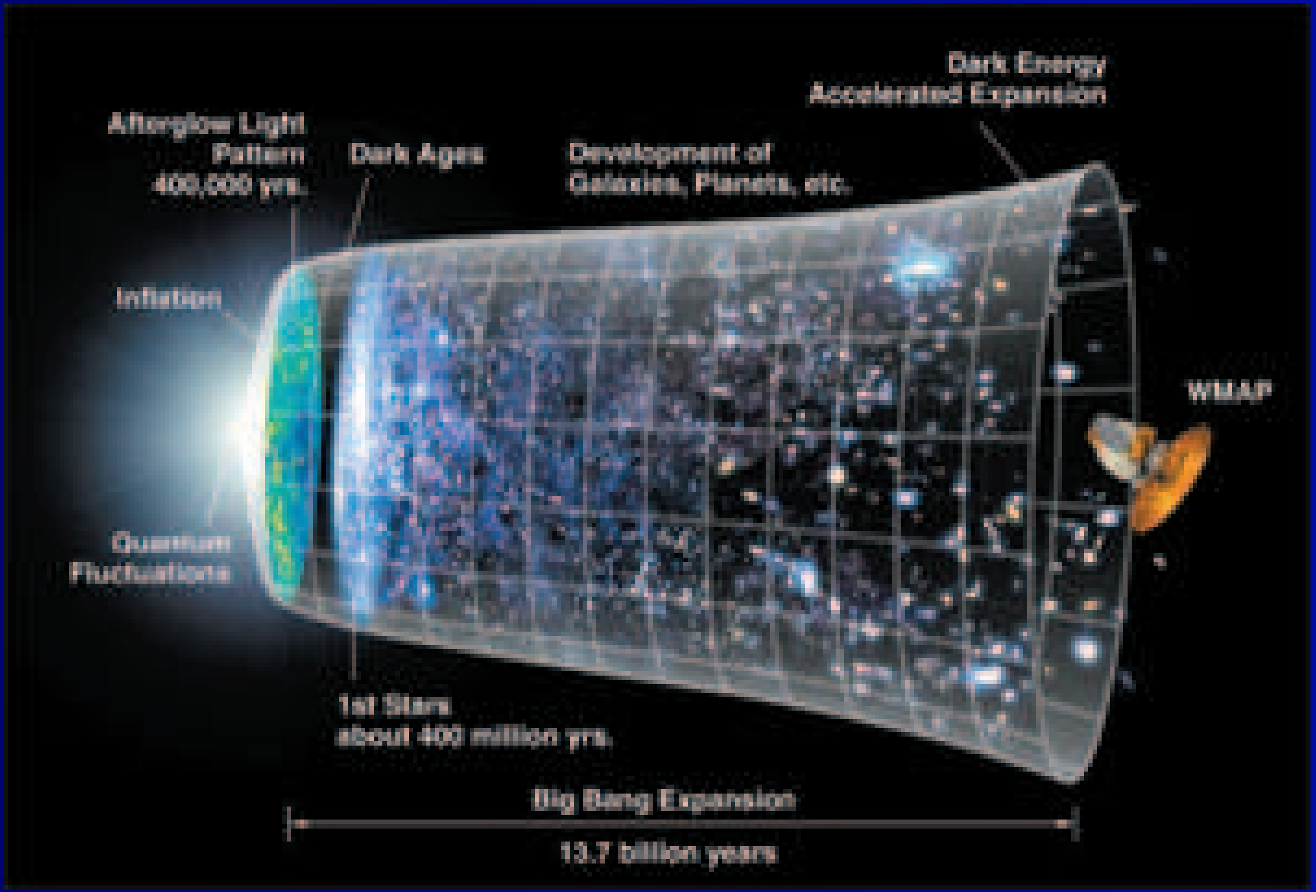
# The evolution of the Universe: The astronomer's view





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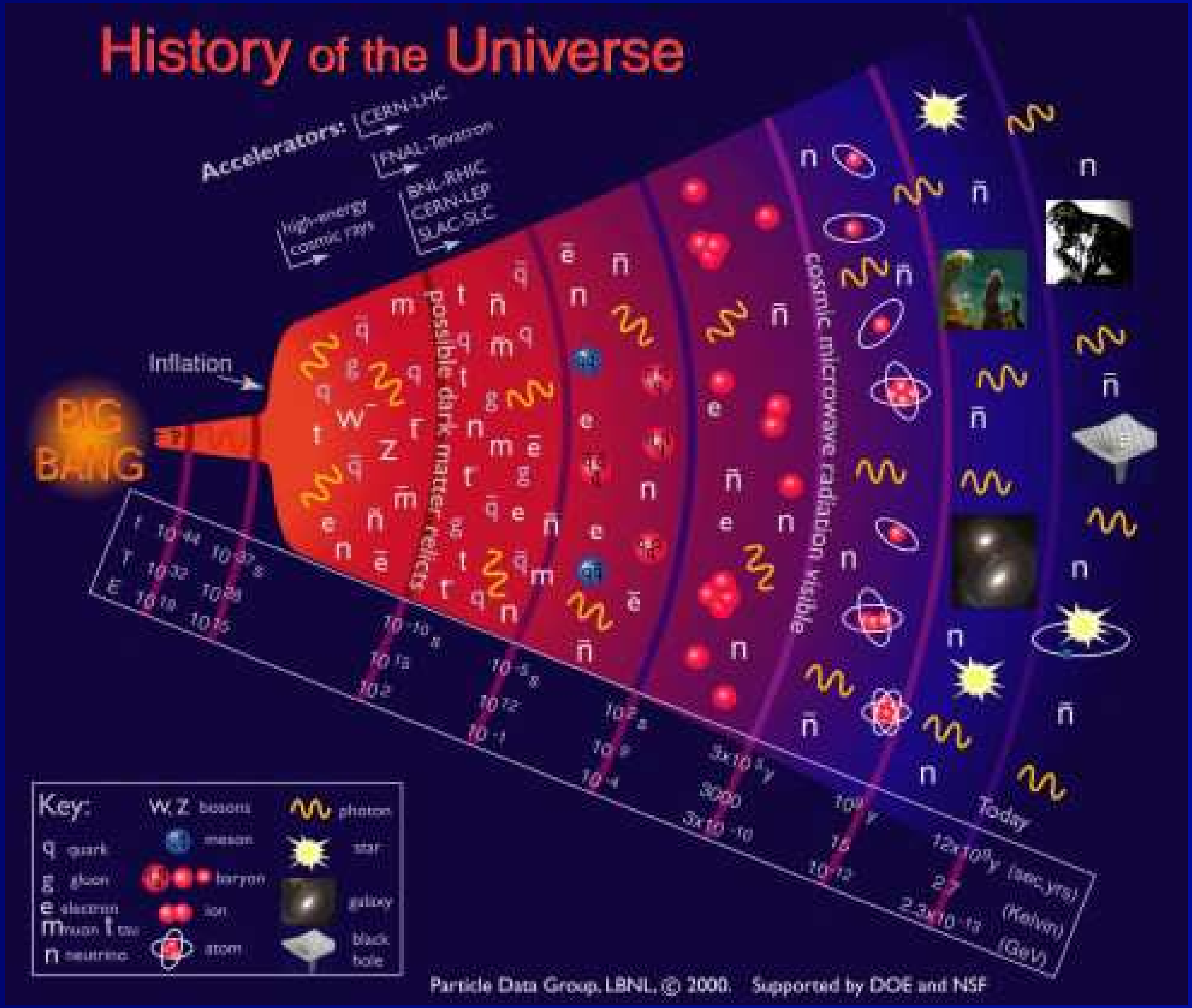
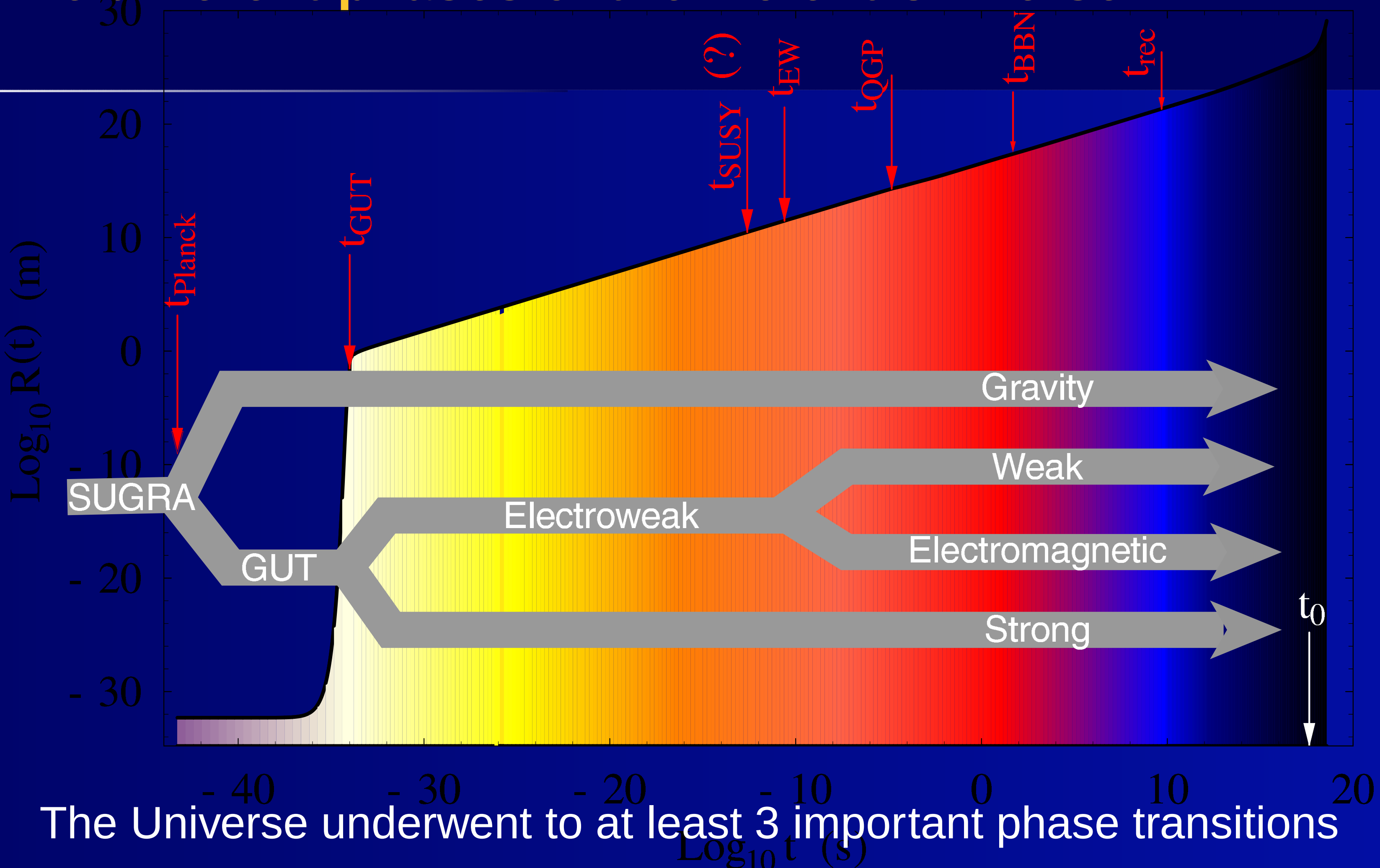


# The different phases of the violent Universe




The Universe underwent to at least 3 important phase transitions

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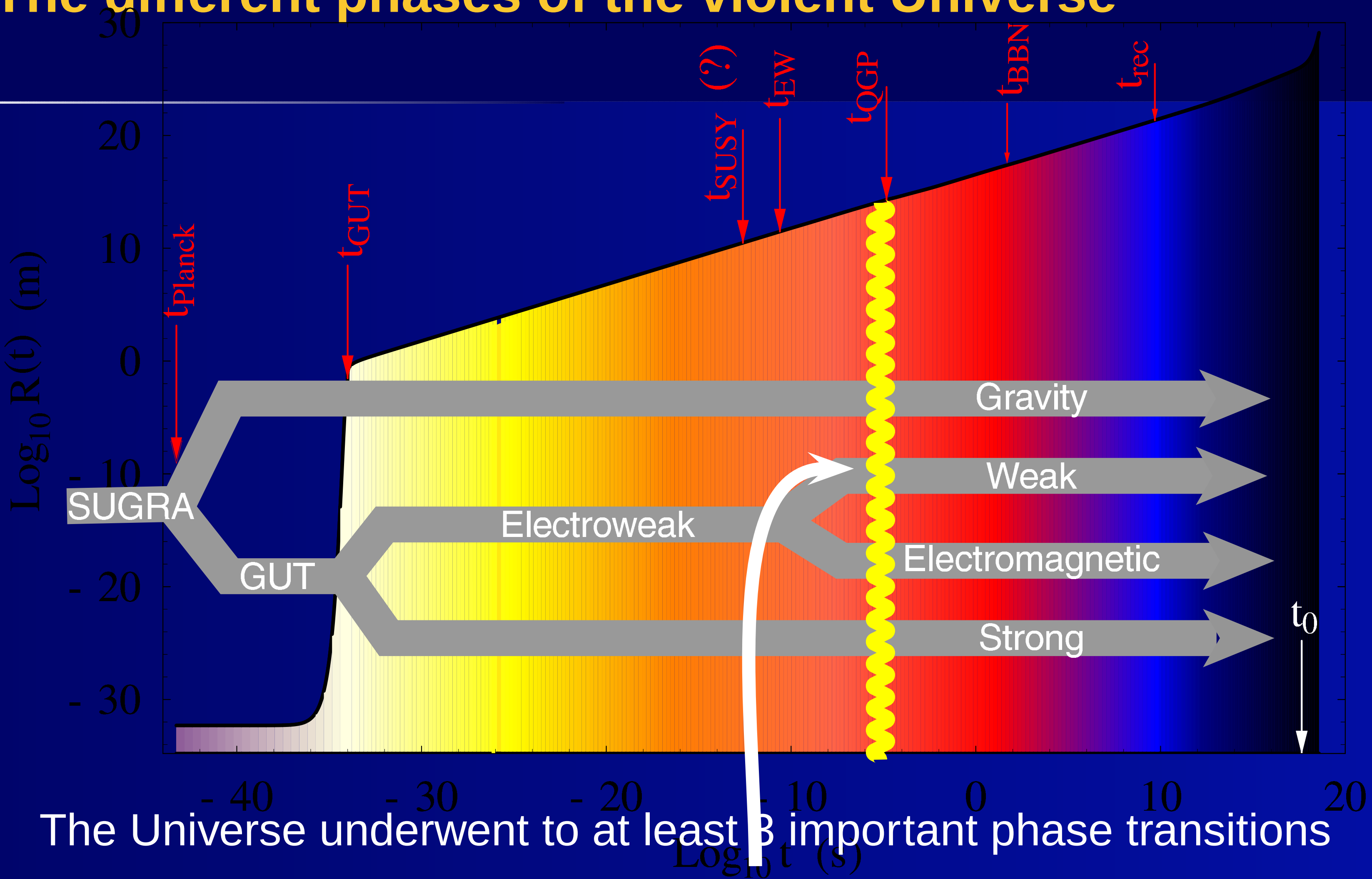


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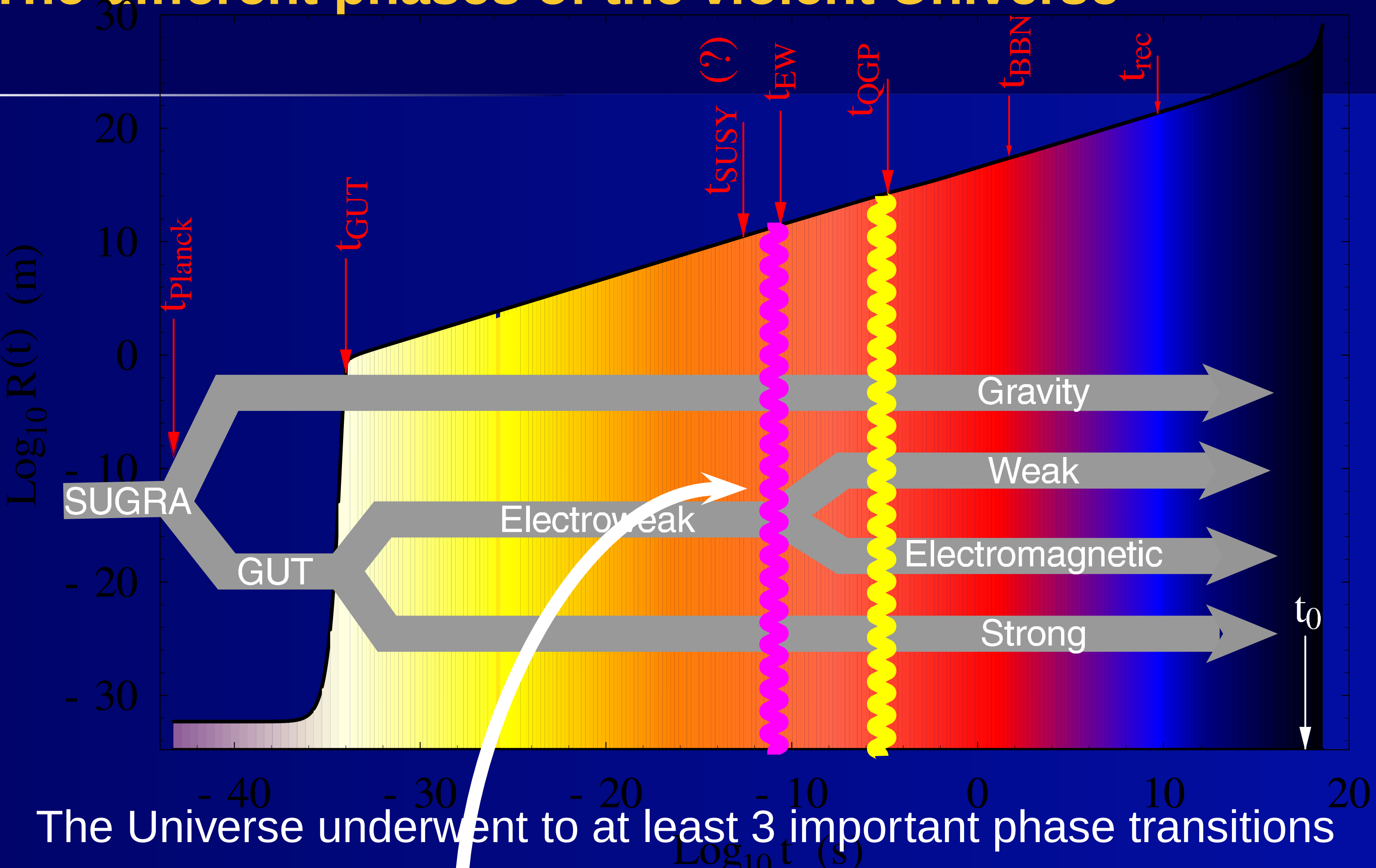


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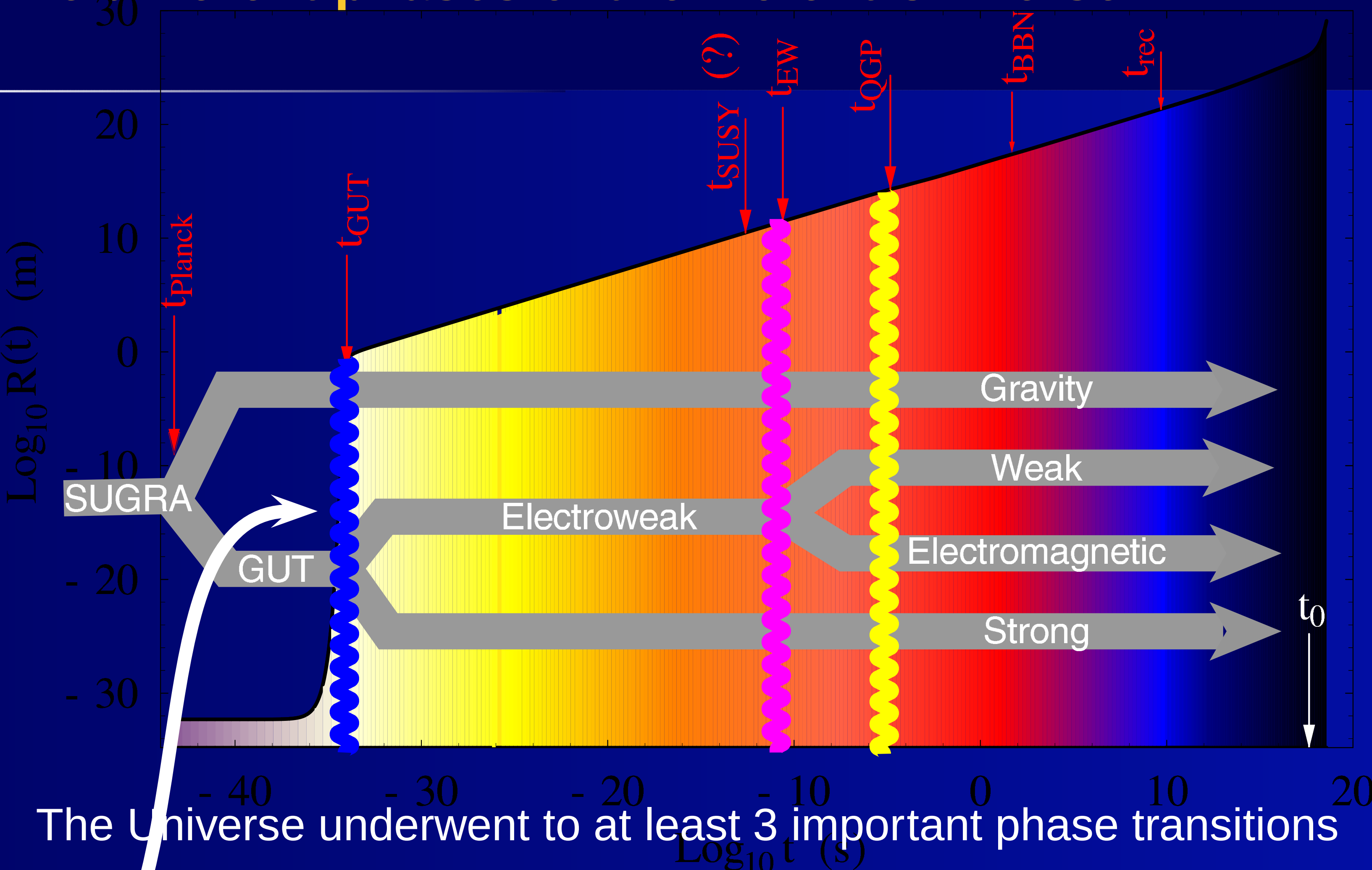


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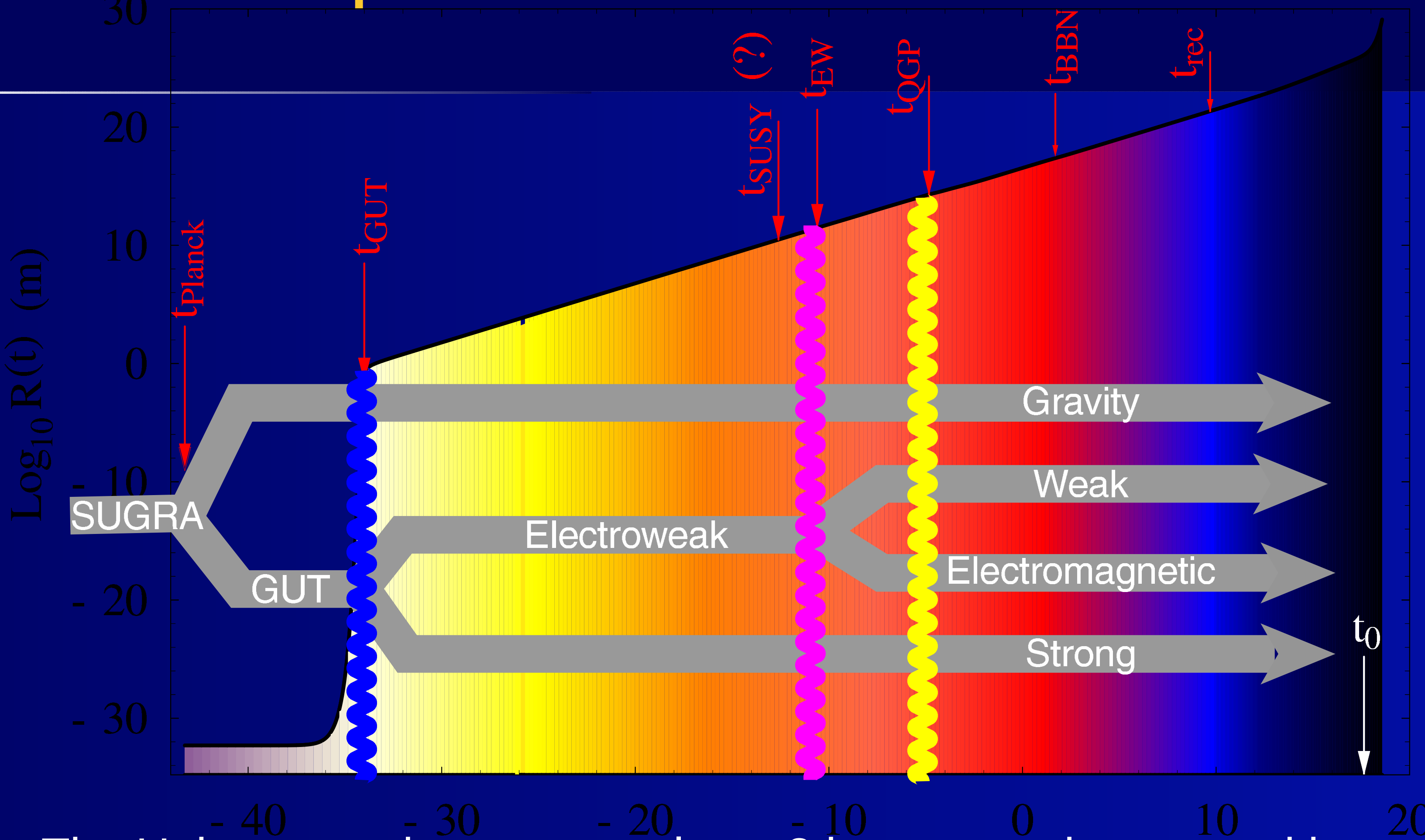


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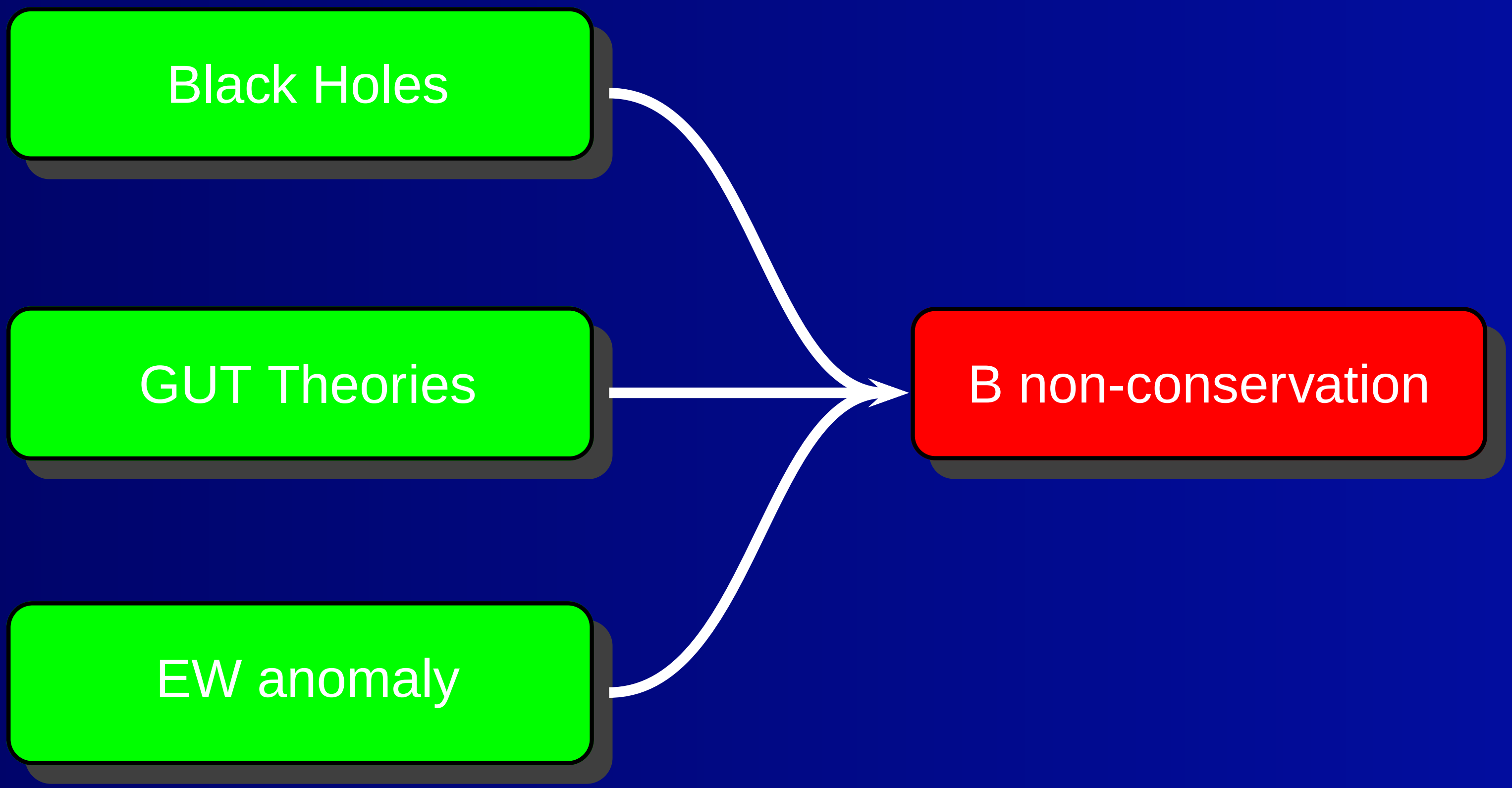

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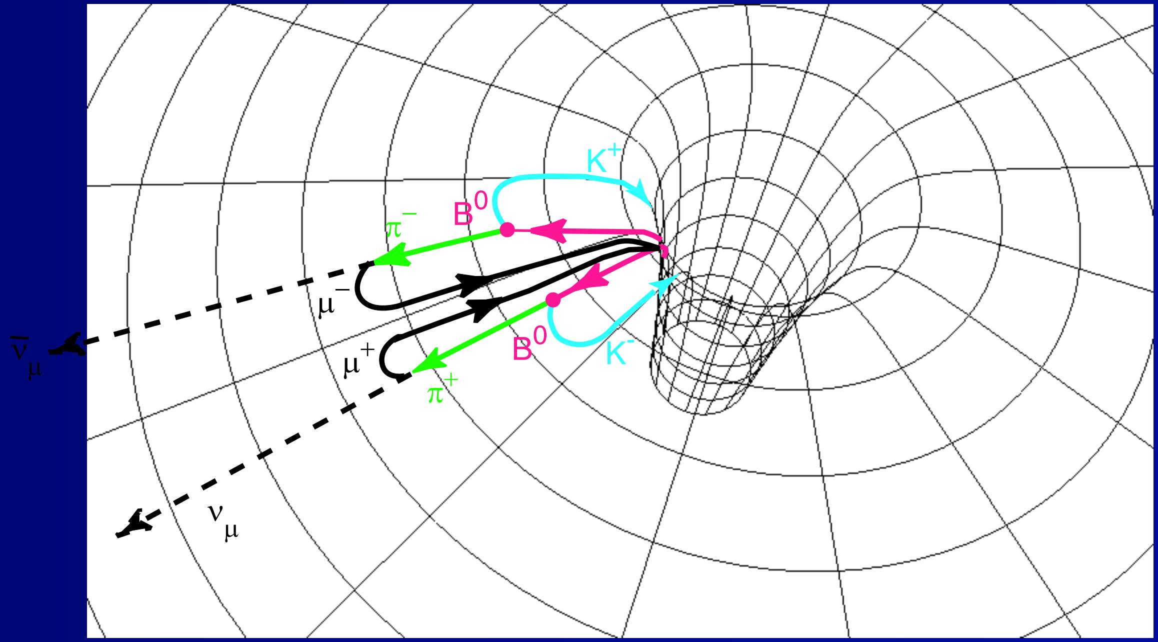


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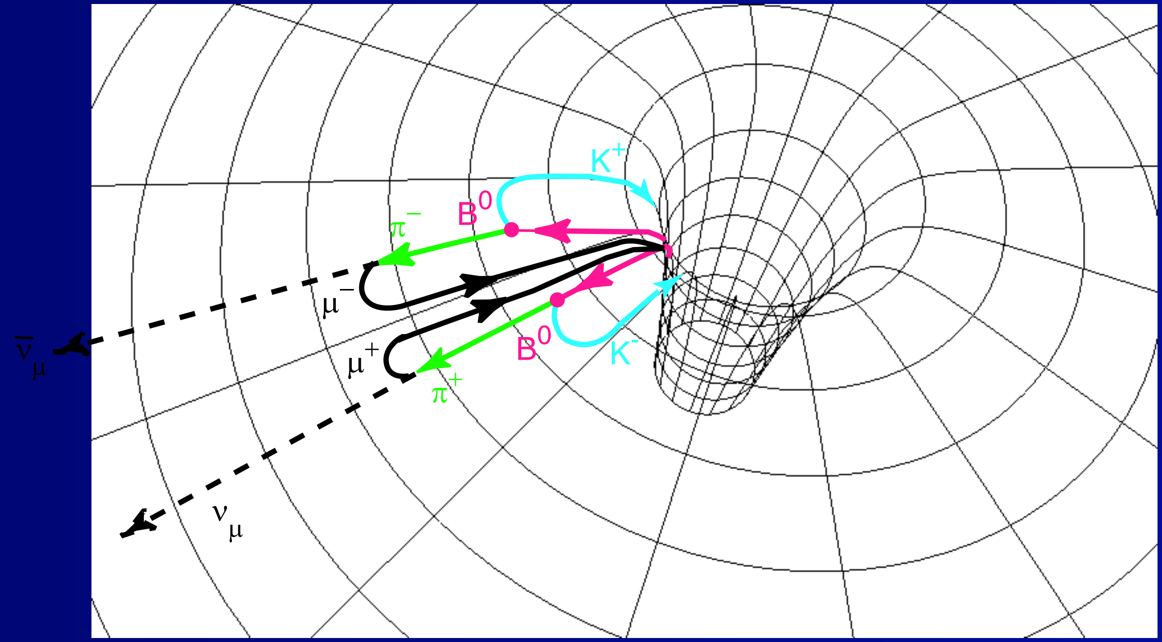


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$$\frac{n_{K^+\pi^-} - n_{K^-\pi^+}}{n_{K^+\pi^-} + n_{K^-\pi^+}} = 0.133 \pm 0.030(\mathrm{stat}) \pm 0.009(\mathrm{syst})$$

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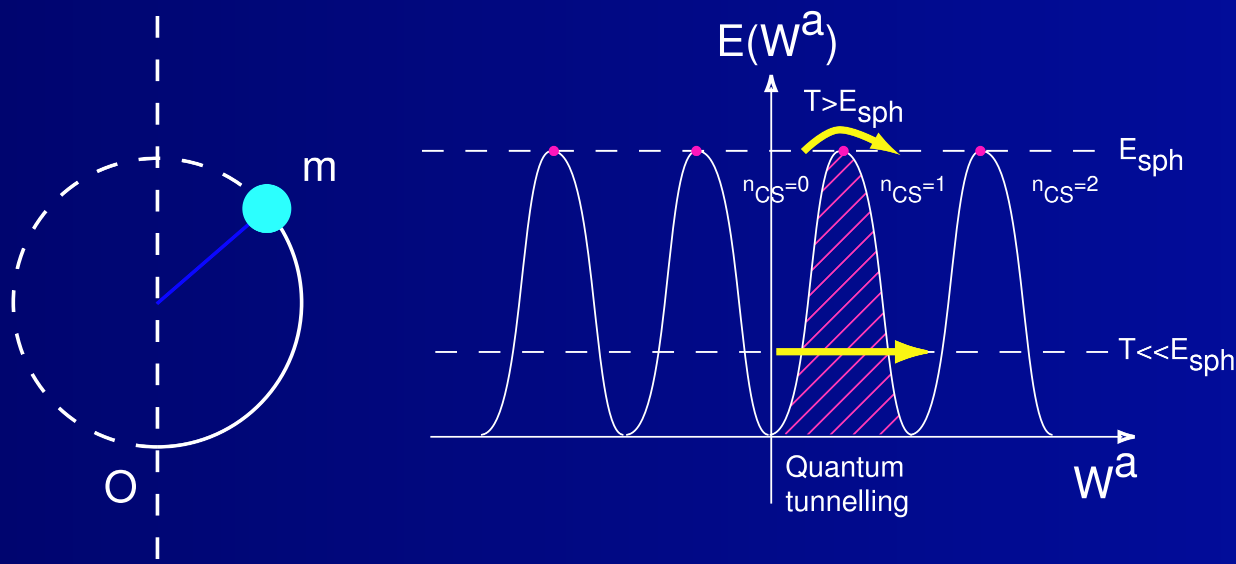
- In the SM baryon number violations follows from the axial anomaly (t'Hooft 1976), a subtle non-perturbative effect, completely negligible for particle reactions in the laboratory.

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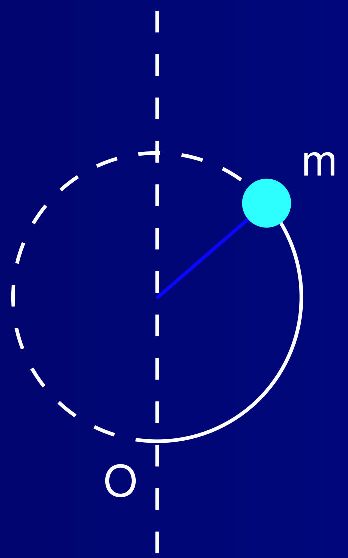


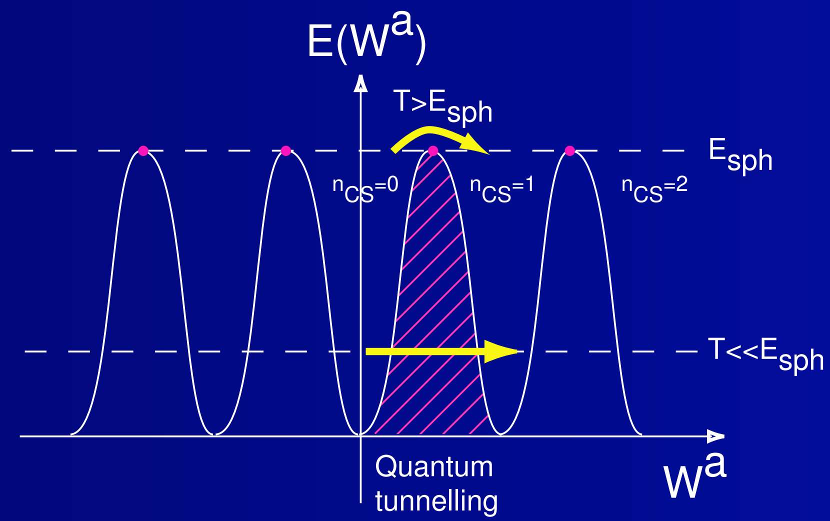


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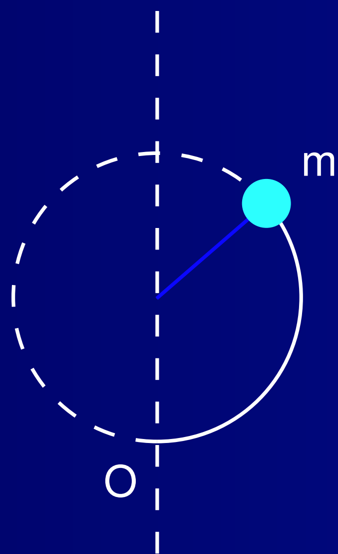


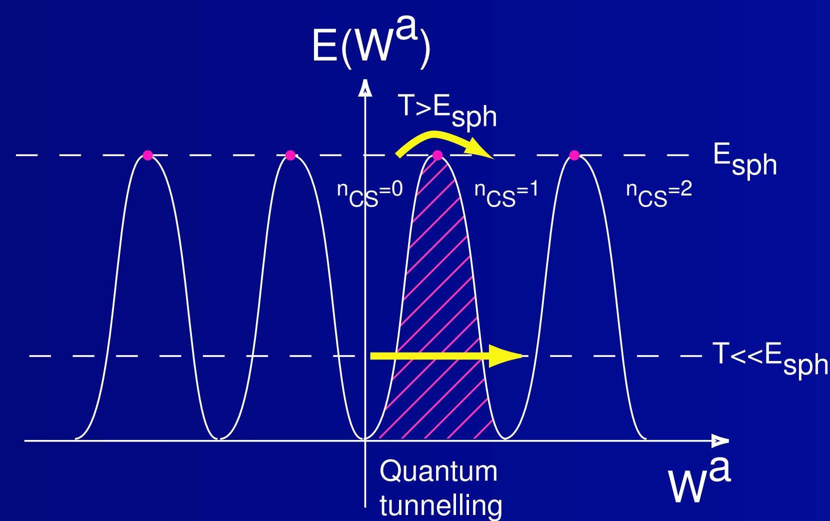


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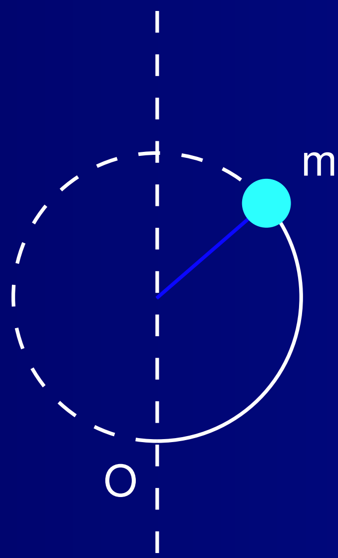


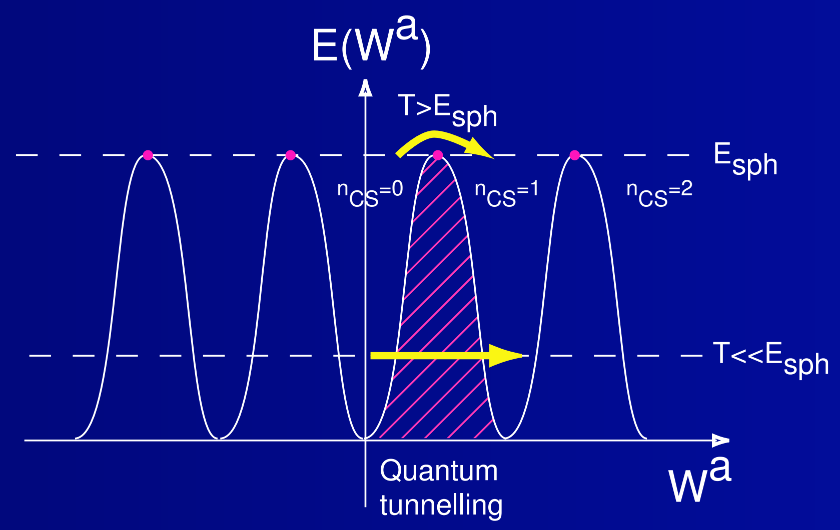


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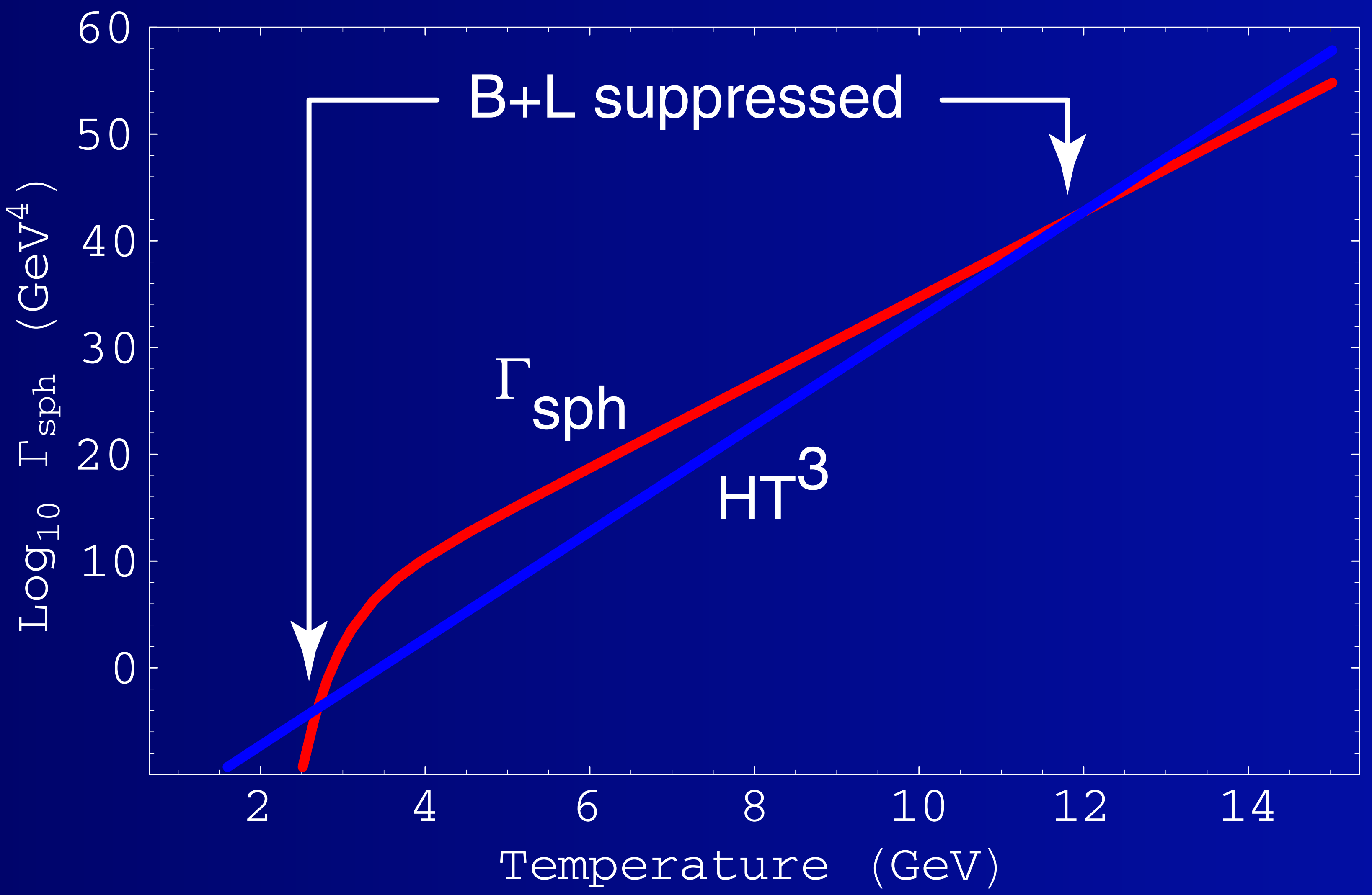

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Exact calculation change this coefficients to $\frac{4}{11}$ and this to $\frac{7}{11}$

# CP violations



- CP violations are a well established experimental fact since 1964 when in the Cronin-Fitch experiment (Christenson et al., 1964) observed 45 CP-violating decays $K_L^0 \rightarrow 2\pi$ over about 20,000 $K_L^0$ produced.
- After the discovery several interpretation has been given to the origin of the CP-Violations.
- There are 3 possible mechanism to violate CP:
  1. In the Yukawa interaction between fermions and the Higgs boson (CKM mechanism);
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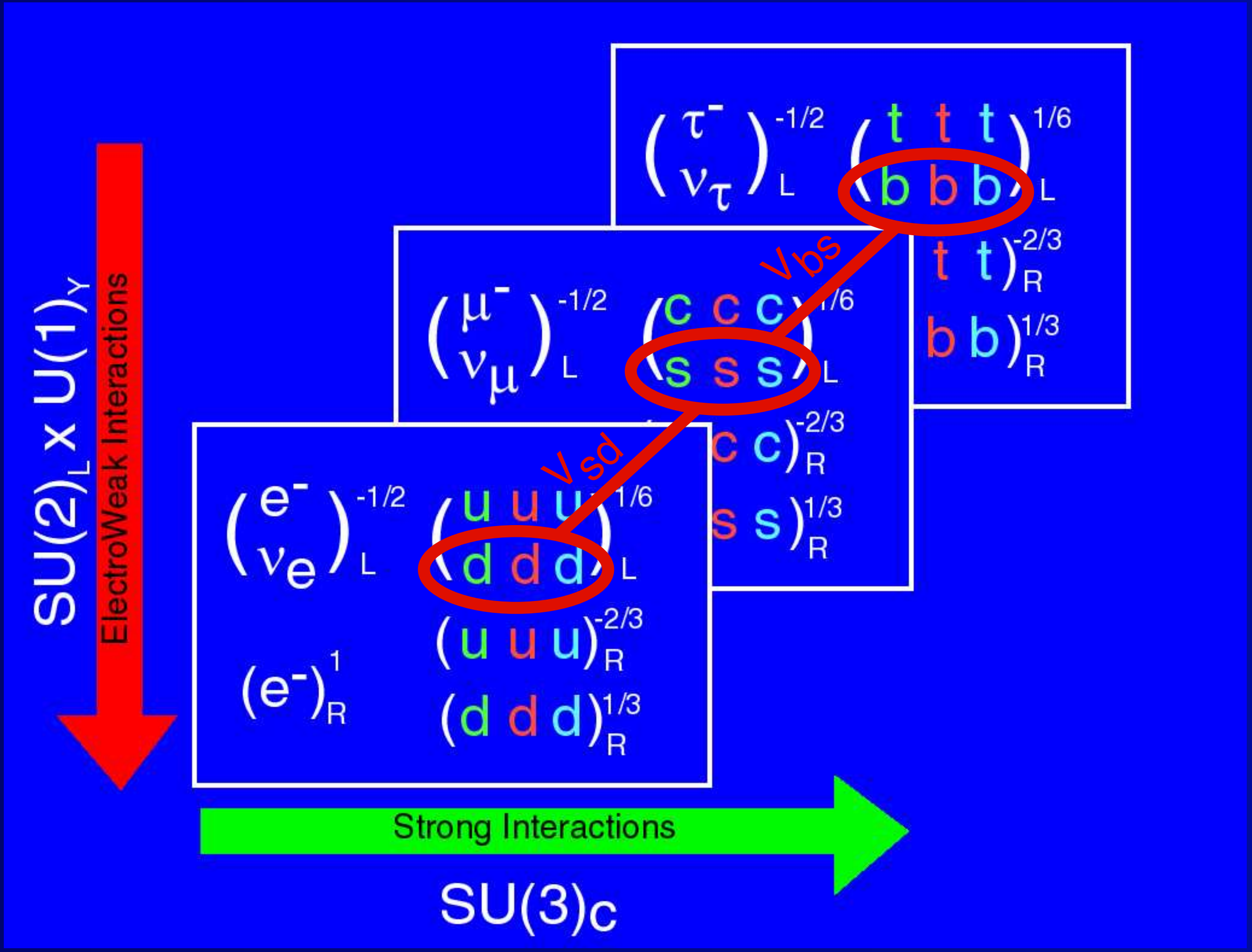
# CKM CP-violation mechanism






Mass eigenstates $\neq$ Weak Interactions (*i.e.* flavor's) eigenstates

# CP-violations in the Standard Model



- All the observed CP violations up to now are consistent with the CKM paradigm, proposed by Kobayashy & Maskawa in 1973, originated from complex Yukawa coupling of the quarks with the Higgs field. For three generation of quarks there is only one phase $\delta_{CP} = 70° \pm 6°$
- Masses of quarks are generated by the Yukawa coupling of the Higgs boson, respect to which $D_j$ type quarks are also mixed. Therefore if any 2 of the $D_j$ or of the $U_i$ have the same mass the matrix $V_{jk}$ must be real and there are no CP-violations.
- Suppression factor should be (Jarlskog 1985):

$$\epsilon_{CP} \propto (m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)\, J_{CP}$$

  with $J_{CP} \simeq 10^{-5}$ and $T$ is the temperature.
- Common wisdom (with few exception see e.g. Berkooz, Nir & Volansky 2004) is that $\epsilon_{CP} \to 0$ when $T \to T_{EW}$, because at $T \geq T_{EW}$ symmetry is restored and all quark's masses $\to 0$.

# CP-violations in the Standard Model



- All the observed CP violations up to now are consistent with the CKM paradigm, proposed by Kobayashy & Maskawa in 1973, originated from complex Yukawa coupling of the quarks with the Higgs field. For three generation of quarks there is only one phase $\delta_{CP} = 70^\circ \pm 6^\circ$
- Masses of quarks are generated by the Yukawa coupling of the Higgs boson, respect to which $D_j$ type quarks are also mixed. Therefore if any 2 of the $D_j$ or of the $U_i$ have the same mass the matrix $V_{jk}$ must be real and there are no CP-violations.
- Suppression factor should be (Jarlskog 1985):

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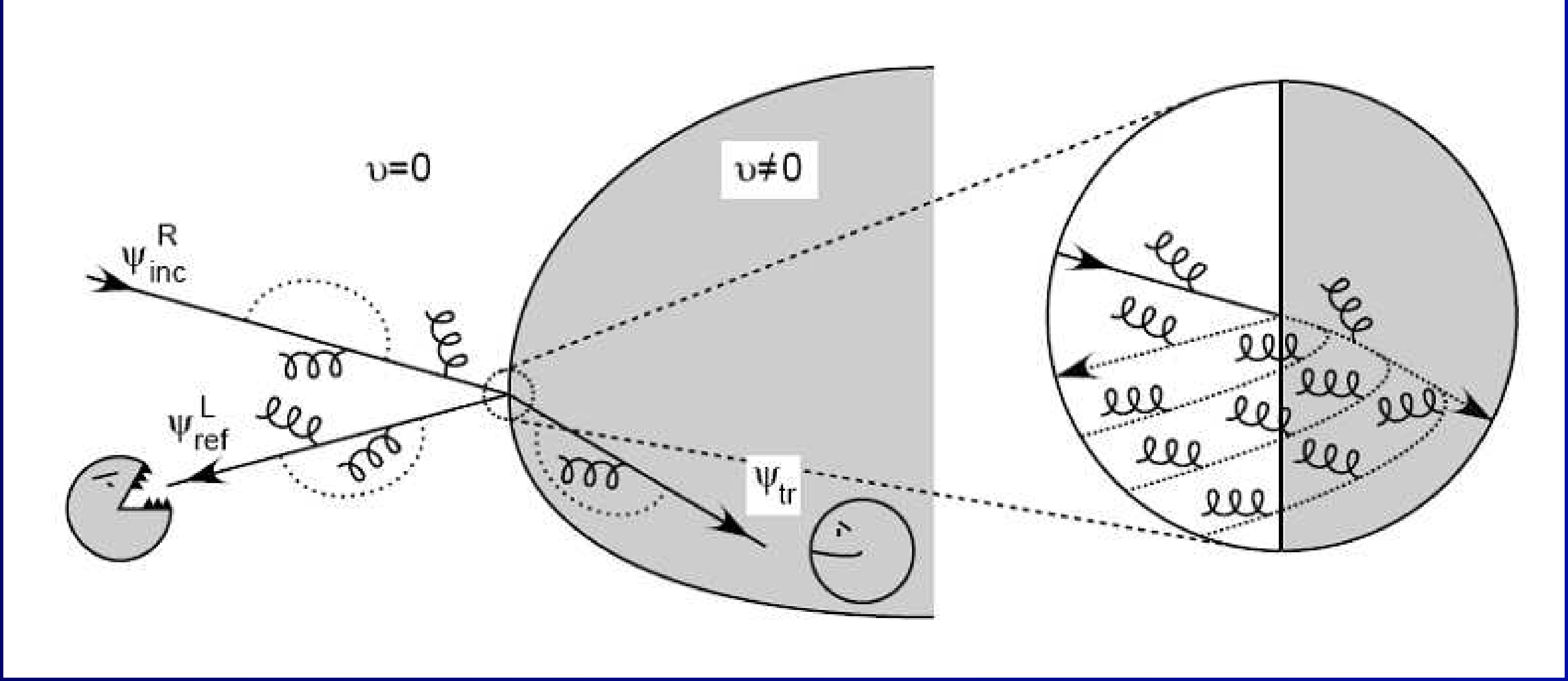


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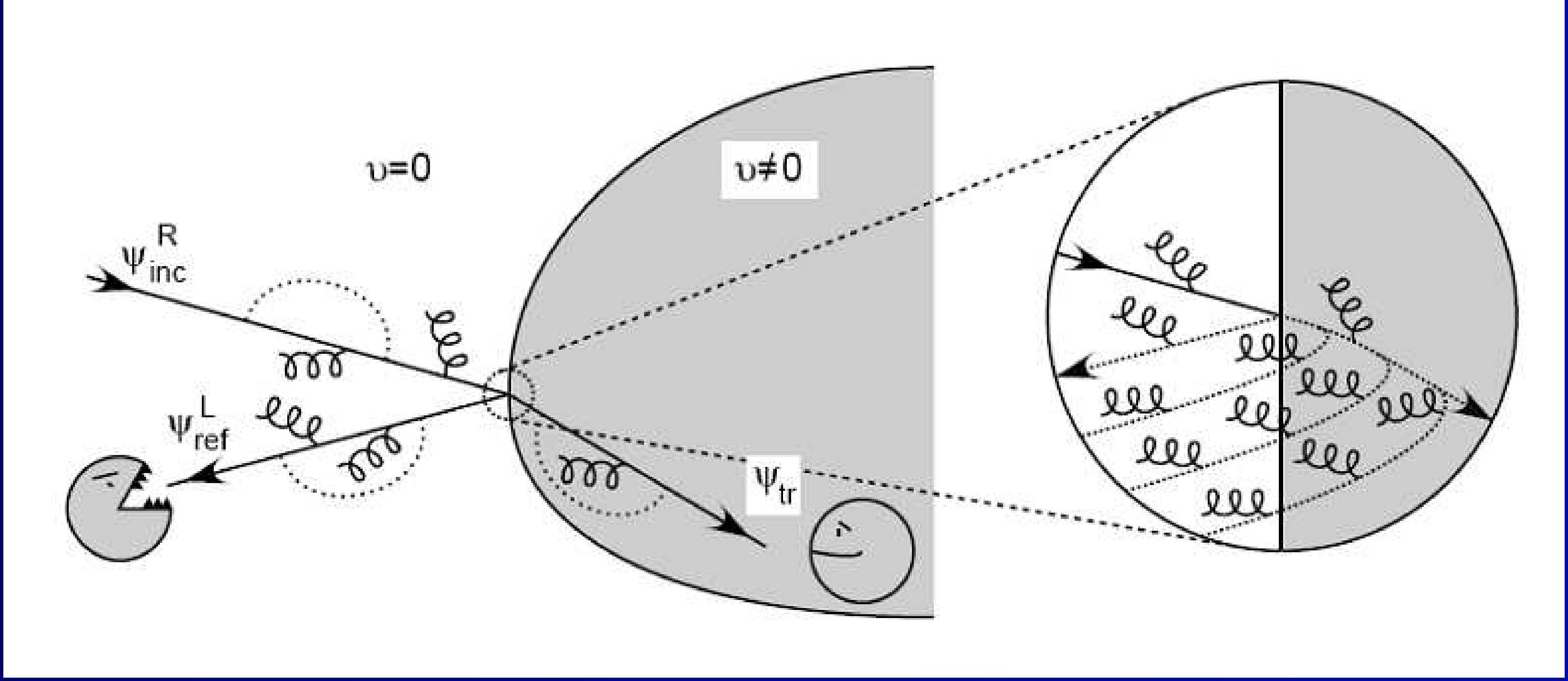


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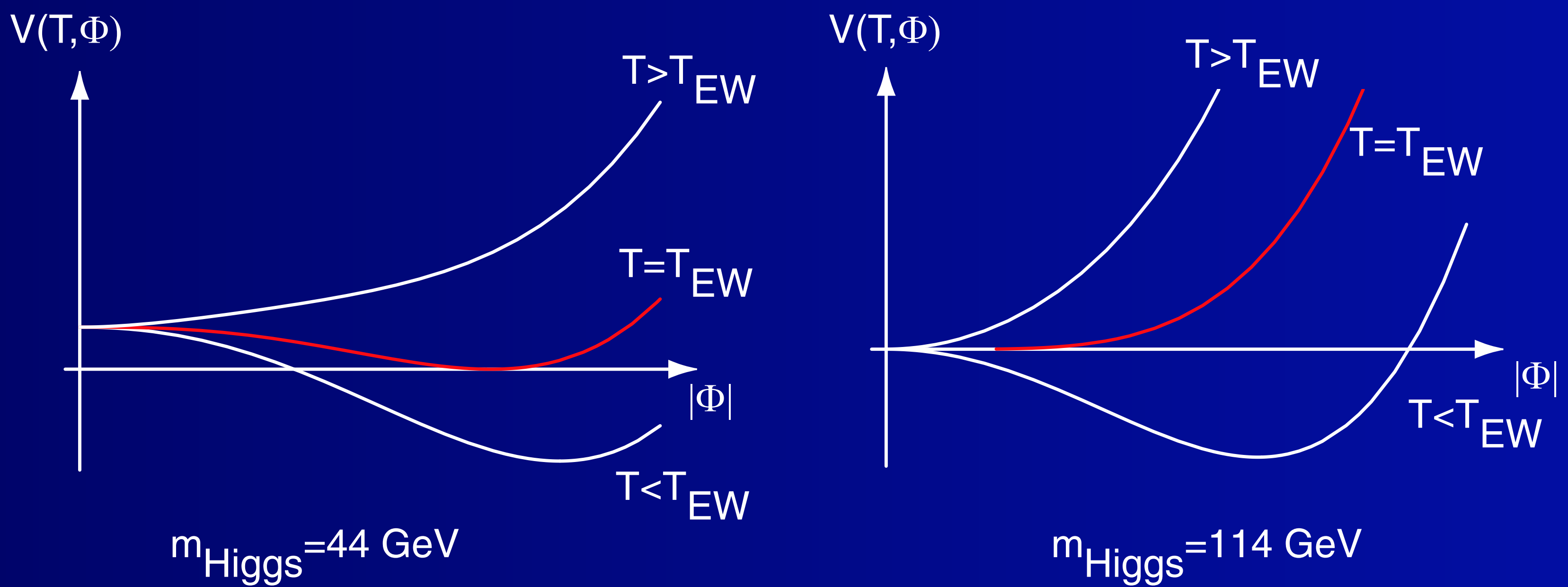


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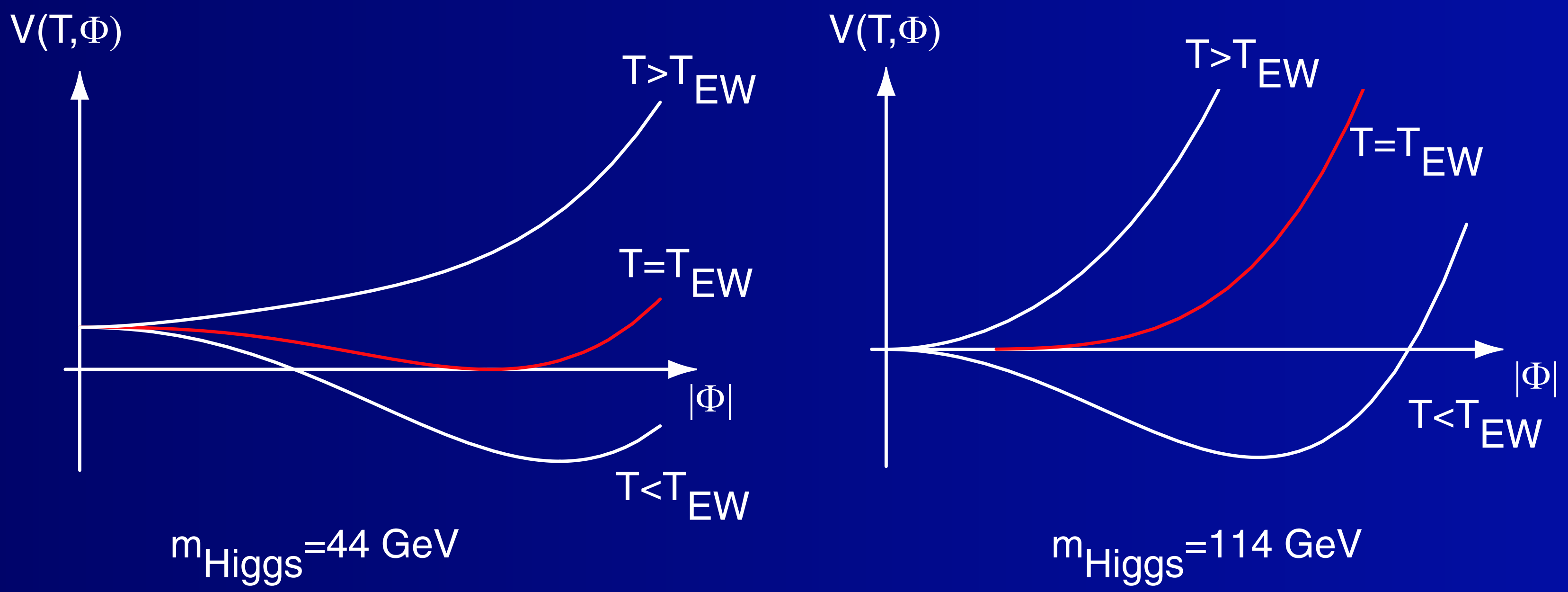


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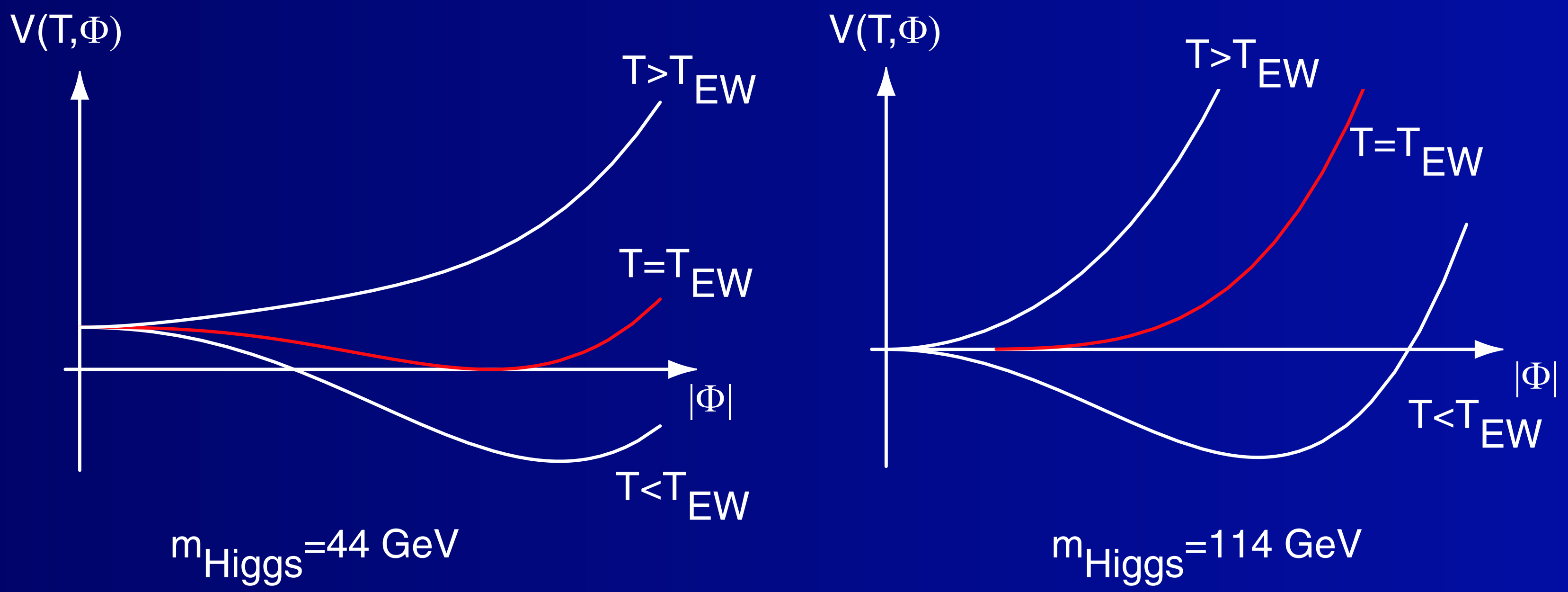


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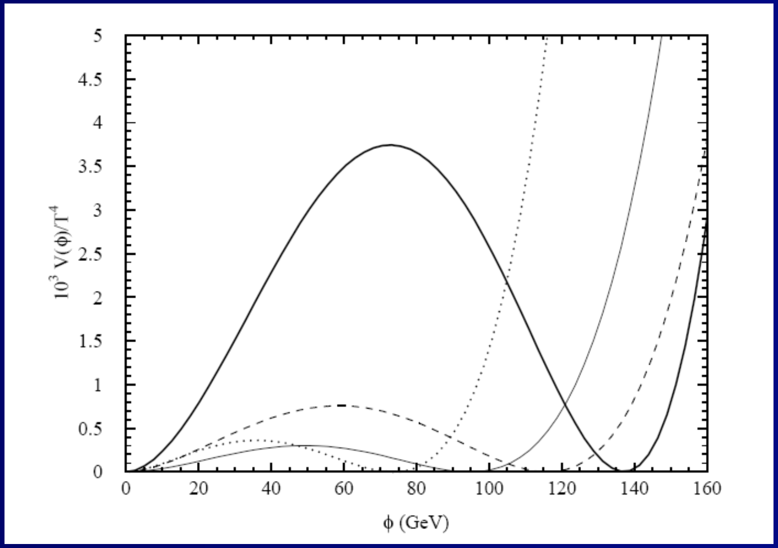
# MSSM EW phase transition






Effective potential in the MSSM under different assumptions (Espinosa 1966)

- The expectations changes drastically in the Minimal Supersymmetric Standard Model (MSSM)
- MSSM contains multiple CP-violating complex phases. This is in marked contrast to the Standard Model which has only one phase in the CKM matrix.
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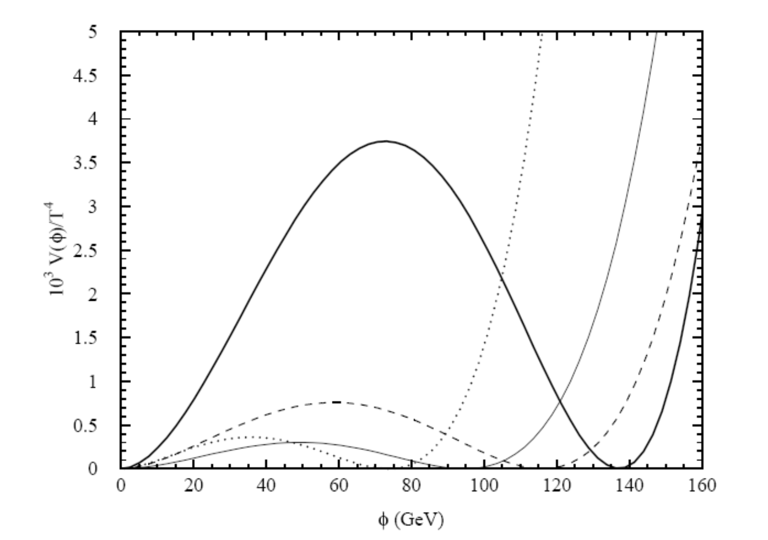


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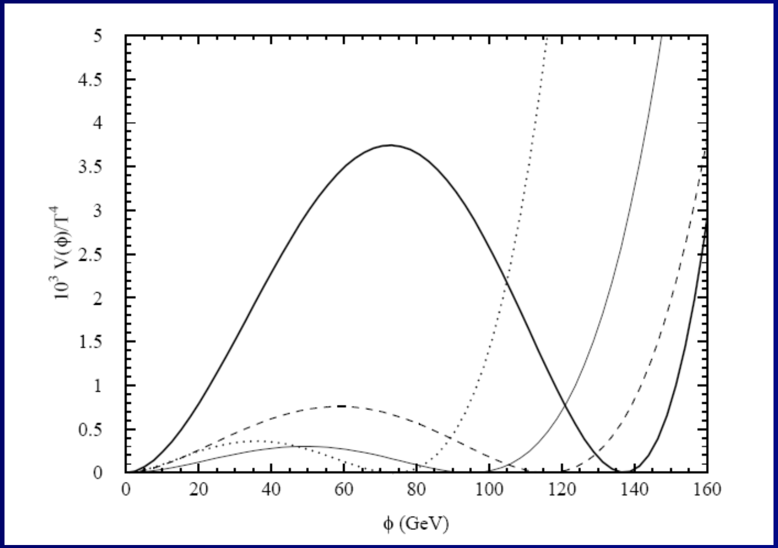


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# Conclusions



- The asymmetry between matter and anti-matter, evident in our neighborhood Universe, has stimulated in the last three quarter of a century a very exciting interplay at the frontier between Astronomy, Cosmology and High Energy Particle physics.
- The study of CMBR, Gamma-ray Astronomy and the success of Big Bang Nucleosynthesis have given increasing evidence that presumably a positive baryon charge is a general feature of the entire visible Universe.
- Standard Model of Particle Physics, well supported by experiments up to now, that includes CP & B violations, suggests that the dynamical build up of the observed matter anti-matter asymmetry, could the viable mechanism.
- However the minimal Standard Model alone fails to reproduce the observed asymmetry for two reasons:
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# Thanks for your attention !