Heidelberg Physics Graduate Days - 7-10 April 2015

BARYOGENESIS IN THE EARLY UNIVERSE

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invisibles
neutrinos, dark matter & dark energy physics

SEVENTH FRAMEWORK PROGRAMME

MARIE CURIE ACTIONS

OUTLINE

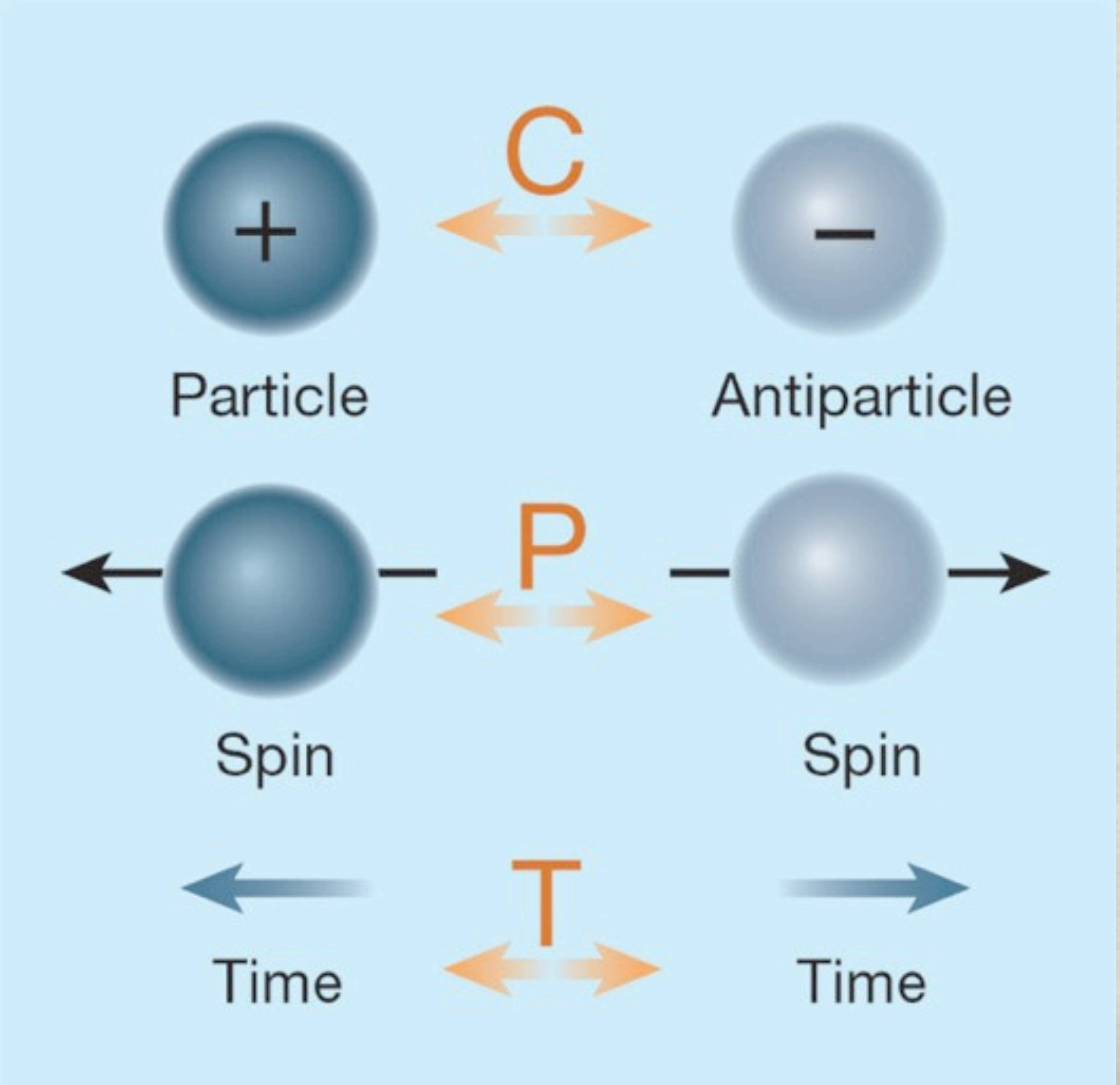
- Lecture I: Basics
- Lecture II: ElectroWeak Baryogenesis
- Lecture III: Leptogenesis
- Lecture IV: Affleck-Dine, etc...
- Outlook

OUTLINE

- Introduction: C,P, T, CP, T Symmetries and CP violation in QFT and SM
- Cosmology and the evidence for the Baryon number of the Universe
- Baryogenesis & the Sakharov conditions
- Outlook

C, P, T & CP SYMMETRIES

C, P, & T SYMMETRIES



C,P,CP,T SYMMETRIES

- Charge conjugation symmetry:

$$u_L \leftrightarrow -i\gamma^2 v_L^*$$

- Parity symmetry: $x, p \to -x, -p$

$$u_L \leftrightarrow u_R$$

- CP symmetry: $x, p \to -x, -p$

$$u_L \leftrightarrow -i\gamma^2 v_R^*$$

- T symmetry: antiunitary ! $t \to -t$

$$u_L, u_R \leftrightarrow u_L^*, u_R^*$$

CPT THEOREM

A Lorentz-invariant QFT with an hermitian Hamiltonian cannot violate the CPT symmetry !

[Lueders & Pauli 1954]

CP violation ↔ T violation

Consequence of CPT theorem and locality:
particle and antiparticle have the same mass !

But not the same decay rate or scattering rate
in the full quantum theory...

CP VIOLATION IS QUANTUM

A theory violates CP if complex couplings are present, i.e.

$$\lambda\, h\bar{q}u + \lambda^*\ h^*\bar{u}q$$

If $\lambda \neq \lambda^*$ particle and antiparticle have to start with different couplings, but since $|\lambda| = |\lambda^*|$ the effect reveals itself only via quantum loops !

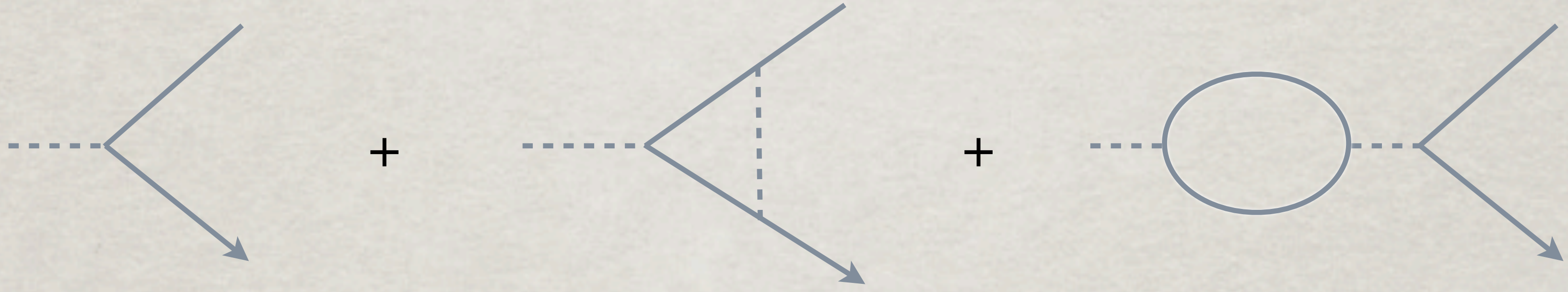
At Born level the matrix element for both decays is

$$\mathcal{M} \propto |\lambda|^2 = |\lambda^*|^2$$

No CP violation at tree level !

CP VIOLATION IS QUANTUM

At one loop level first signs of CP violation can appear, the most dominant usually the interference effect between tree-diagram and one-loop-diagrams



$i\,\lambda$ $\quad$ $i\,\lambda\,i\,\lambda^*i\,\lambda$ $\quad$ $i\,\lambda\;\;i\,\lambda^*\,i\,\lambda$

So we have for particle $\mathcal{M} \propto |\lambda|^2 + 2Re\,[\lambda\lambda^*\lambda\lambda^*\;L(x)] + \ldots$

& antiparticle: $\overline{\mathcal{M}} \propto |\lambda^*|^2 + 2Re\,[\lambda^*\lambda\lambda^*\lambda\;L(x)] + \ldots$

$$\Delta\mathcal{M} \propto 2Re\,[\lambda\lambda^*\lambda\lambda^*\;L(x) - \lambda^*\lambda\lambda^*\lambda\;L(x)] + \ldots$$

$$\Delta\mathcal{M} \propto -4\,Im\,[\lambda\lambda^*\lambda\lambda^*\,]\,Im[L(x)] + \ldots$$

NB: Vanishing for a single coupling, need flavour dependence !

UNITARITY RELATION

We can obtain the same result and the interpretation of the imaginary part of a loop function from the unitarity relation for the scattering matrix & CPT: $S = I - i\,T$

From unitarity: $S^\dagger S = I = I - i(T - T^\dagger) + T^\dagger T$

$$\longrightarrow \quad T = T^\dagger - i\,T^\dagger T$$

Therefore if we square the amplitude we get

$$|T_{fi}|^2 = |T^*_{if}|^2 + 2Im\left[(T^\dagger T)_{fi} T_{if}\right] + |(T^\dagger T)_{fi}|^2$$

From CPT we obtain $T_{if} = T_{\bar{f}\bar{i}}$ and so

$$\boxed{|T_{if}|^2 - |T_{\bar{f}\bar{i}}|^2 = 2\,Im\left[(T^\dagger T)_{fi} T_{if}\right] + |(T^\dagger T)_{fi}|^2}$$

CP VIOLATION IS SMALL

CP violation in particle physics arises as a quantum effect from the interference of tree-level and loop diagrams. For these reasons it is multiply suppressed:

- It is higher order in the couplings, e.g.

  $\Delta\mathcal{M} \propto |\lambda|^4$ compared to $\mathcal{M} \propto |\lambda|^2$

- It contains a loop suppression factor

  $$L(x) \propto \frac{1}{4\pi^2} \sim 0.025$$

- It often needs a non-trivial flavour structure and it is therefore even more suppressed in presence of small mixing between generations.

CP violation in the Standard Model

Yukawa couplings

In the SM the symmetries C and P are violated maximally due to the chiral coupling of the EW interaction. CP is instead violated just by the complex Yukawa matrices, i.e. by the non-diagonal fermion masses:

$$\frac{\lambda_{ij}}{\sqrt{2}}(v_{EW}+h)\bar{u}_{Li}u_{Rj} \qquad \longrightarrow \qquad m_{ij}\;\bar{u}_{Li}u_{Rj}$$

The diagonalization of the mass matrix to obtain the physical masses can be done with two unitary matrices (different for left-handed and right-handed fields !) for up, down and charged leptons (slightly different for neutrinos, see later...)

$$u'_{L/R} = U_{L/R}u_{L/R} \qquad\qquad d'_{L/R} = V_{L/R}d'_{L/R}$$

CP & CHARGED CURRENT

The mixing matrices cancel out for all interactions between the same type fields, even in the coupling with the Higgs, which is diagonalized at the same time as the mass. Therefore no Flavour Changing Neutral Currents exist at tree level in the SM !

$$j^{\mu}_{L/R} = \bar{u}_{L/R}\gamma^{\mu}u_{L/R} \longrightarrow j^{'\mu}_{L/R} = \bar{u}'_{L/R}\gamma^{\mu}u'_{L/R}$$

But the charged current involves both up- and down-quarks (or charged leptons and neutrinos !) therefore a non-trivial mixing matrix remains, due to the mismatch in the unitary matrices U_L and V_L:

$$j^{\mu}_{-} = \bar{u}_{L}\gamma^{\mu}d_{L} \qquad j^{'\mu}_{-} = \bar{u}'_{L}U_{L}V^{\dagger}_{L}\gamma^{\mu}d'_{L} = \bar{u}'_{L}V_{CKM}\gamma^{\mu}d'_{L}$$

No effects of RH rotations in the SM !

CABIBBO KOBAYASHI MASKAWA MATRIX

The CKM matrix is a unitary 3x3 matrix and can in principle contain up to 3 mixing angles and 6 complex phases (recall for nxn: $n(n-1)/2$ angles $n(n+1)/2$ phases), but 5 (2n-1) phases can be reabsorbed in the definition of the fermions, so that only one ($(n-1)(n-2)/2$) phase is physical.

[Wolfenstein 1983]

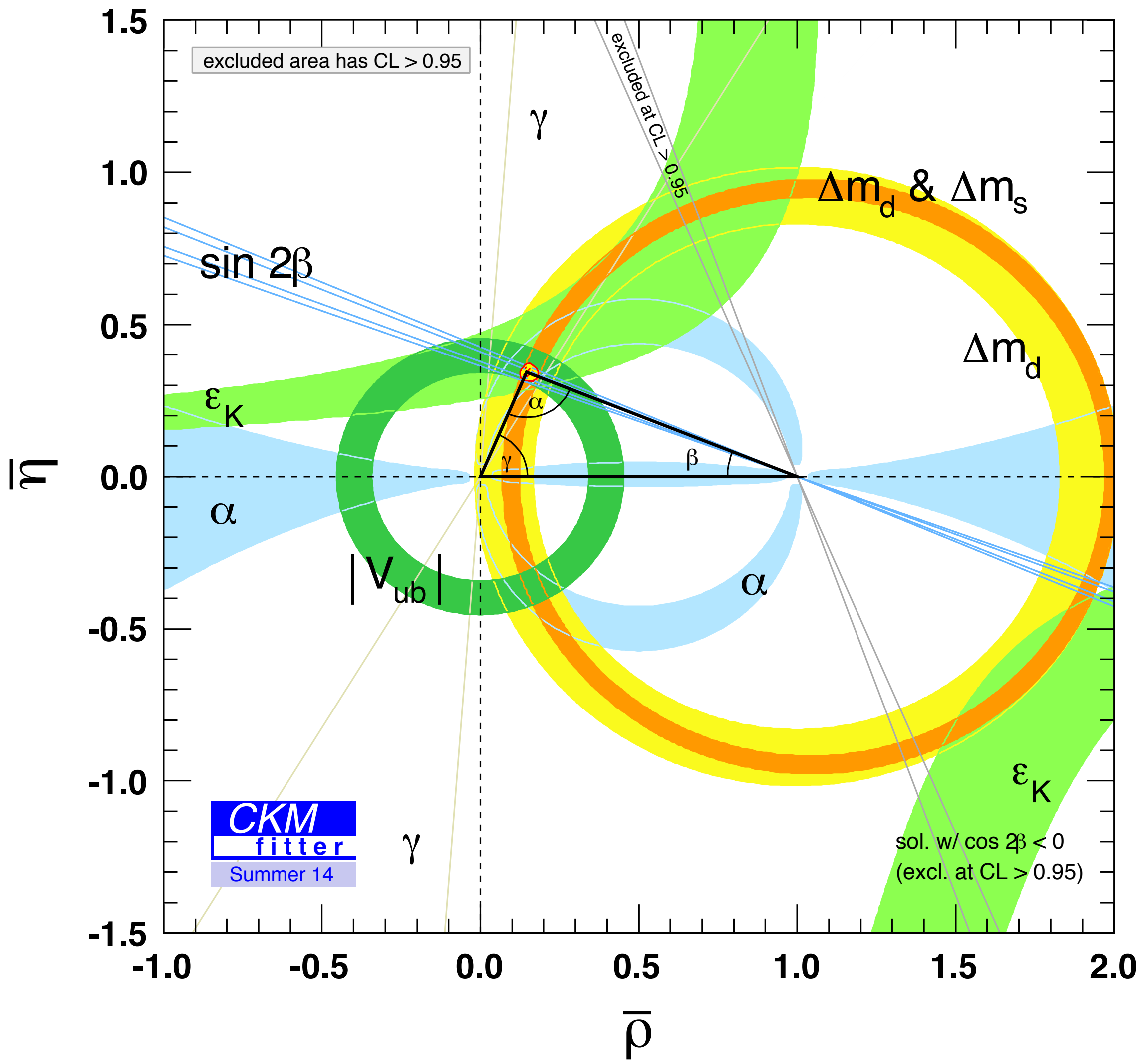
$$V_{CKM} = \begin{pmatrix} 1 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

The parameter η determines the CP violation and in the SM it is not small ! The area of the unitarity triangles is given by the Jarlskog invariant, measured in K/B decays:

$$J \sim \lambda^6 A^2 \eta \sim 10^{-6}$$

UNITARITY TRIANGLE

In the SM the CKM matrix is unitary, i.e. $V^{\dagger}_{CKM}V_{CKM} = I$, so closed triangles correspond to the off-diagonal elements of the unity matrix:



So far all measurements fit with the CKM matrix explanation and one single phase (not so small !)

The area of the triangle is related to

$$J \sim \lambda^6 A^2 \eta \sim 10^{-6}$$

NEUTRINO MASSES

The neutrinos are neutral and do not carry a conserved (local) charge, therefore in their case we can also write down a Majorana mass term in addition to the Dirac mass term.

e.g. dimension 5 Weinberg operator:

$$\frac{y}{M_P} H^* \bar{\ell}^c H \ell \quad \longrightarrow \quad \frac{y v_{EW}^2}{2 M_P} \bar{\nu}_L^c \nu_L$$

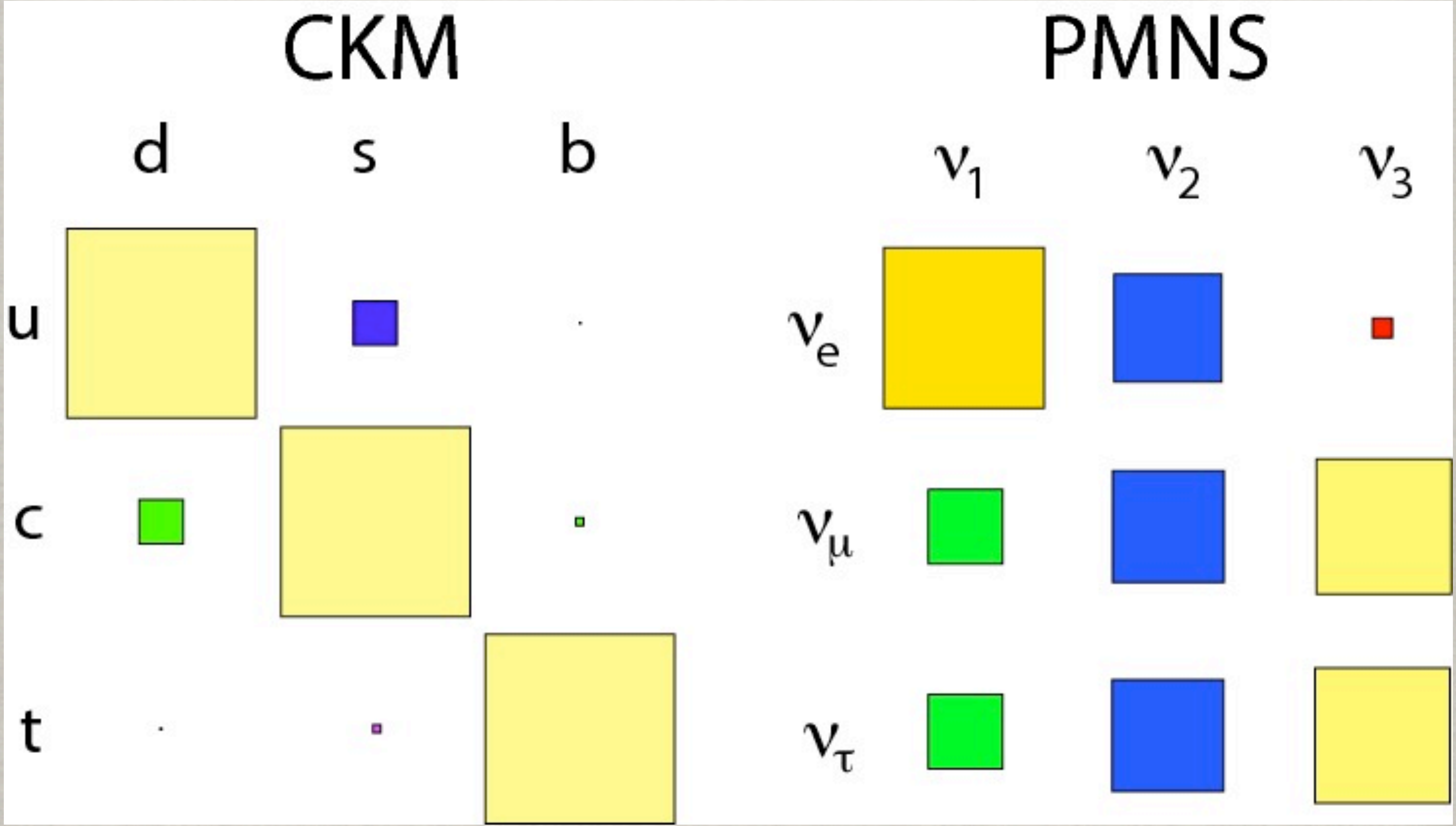
A Majorana mass matrix is symmetric and can be diagonalized by an orthogonal rotation, leaving more physical phases !

Pontecorvo-Maki-Nakagawa-Sakata mixing matrix with one Dirac phase δ and two Majorana phases α, β:

$$U_{PMNS} = P \begin{pmatrix} c_{13}c_{12} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

with P = $\mathrm{diag}(e^{i\alpha}, e^{i\beta}, 1)$ $\qquad s_{ij}, c_{ij} = \sin\theta_{ij}, \cos\theta_{ij}$

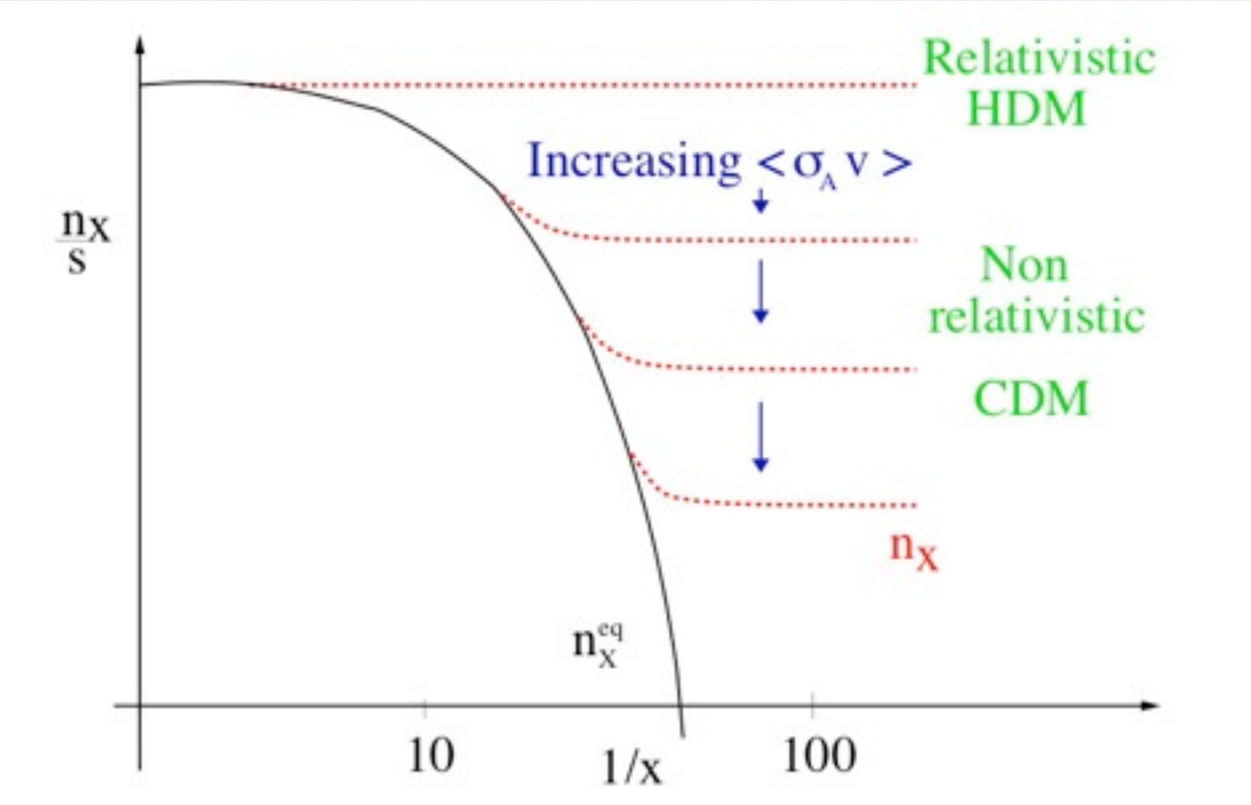
CKM vs PMNS



COSMOLOGY AND THE BAU

BARYONIC MATTER

Baryons annihilate very strongly so that the symmetric Baryonic component is erased very efficiently to leave only $\Omega_B \sim 10^{-10}$.



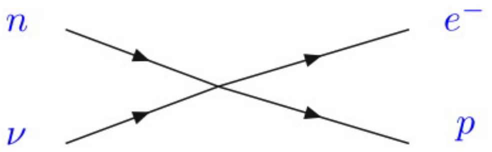
Moreover, how to "segregate" it ?

If an asymmetric baryon component is already present, it survives the freeze-out process !

Big Bang Nucleosynthesis

After the QCD phase transition at $T \sim 200$ MeV the baryonic matter are $p, n, \pi^0, \pi^\pm, \Lambda, \ldots,$ but at $T \simeq 1$ MeV only the stable one p and the very long-lived n survive. Their number density is not suppressed by $e^{-m/T} \simeq e^{-10^3}$ due to the presence of a chemical potential related to baryon number μ_B. Proton and neutron have the same chemical potential and are still in equilibrium via the reactions

$n + \nu \leftrightarrow p + e^-$ $\qquad$ $p + \bar{\nu} \leftrightarrow n + e^+$



$$G_F = \frac{\pi \alpha_w}{\sqrt{2} M_W^2}$$

So the chemical equilibrium gives

$$\frac{n_n^{eq}}{n_p^{eq}} = \exp\left(-\frac{\Delta m + \mu_\nu - \mu_e}{T}\right) \simeq e^{-\frac{\Delta m}{T}} \qquad \text{where} \quad \Delta m \sim 1.29 \text{ MeV}$$

How long do neutrons track equilibrium ??? As long as

$$\langle \sigma(n\nu \to pe) v \rangle \sim \# G_F^2 T^5 \qquad \geq \qquad H = \sqrt{\frac{8\pi G \rho_{rad}}{3}} \sim 1 s^{-1} \left(\frac{T}{1\text{MeV}}\right)^2$$

So freeze-out happens at $T_* \simeq 0.84$ MeV $\qquad \Rightarrow n_n^{eq} \simeq 0.21\, n_p^{eq}.$

BIG BANG NUCLEOSYNTHESIS

Abundances of light elements

After freeze-out the neutrons start to decay with $\tau = 886$ s, i.e. $n_n(t) = n_n(t_*)e^{-t/\tau}$. The lightest composite nucleus is Deuterium, that can be produced in the reaction $p + n \leftrightarrow D + \gamma$

Unfortunately the bounding energy for D is very low $B_D \sim 2.23$ MeV and the number of photons in the Universe above such energy still very large: very easy to dissociate Deuterium !

$$\frac{n_D^{eq}}{n_\gamma} \sim \eta_B X_D \left(\frac{T}{B_D}\right)^2 e^{B_D/T}$$

"Deuterium Bottleneck"

where $\eta_B = n_B/n_\gamma$. So D's abundance start to grow only after $T \leq 0.06$ MeV, i.e. $t \geq 300$ s.

The equilibrium densities of the other light elements are not reached until after this time, since they are all produced starting from D:

$$D + D \leftrightarrow^3 He + n \qquad {}^3He + D \leftrightarrow^4 He + p$$

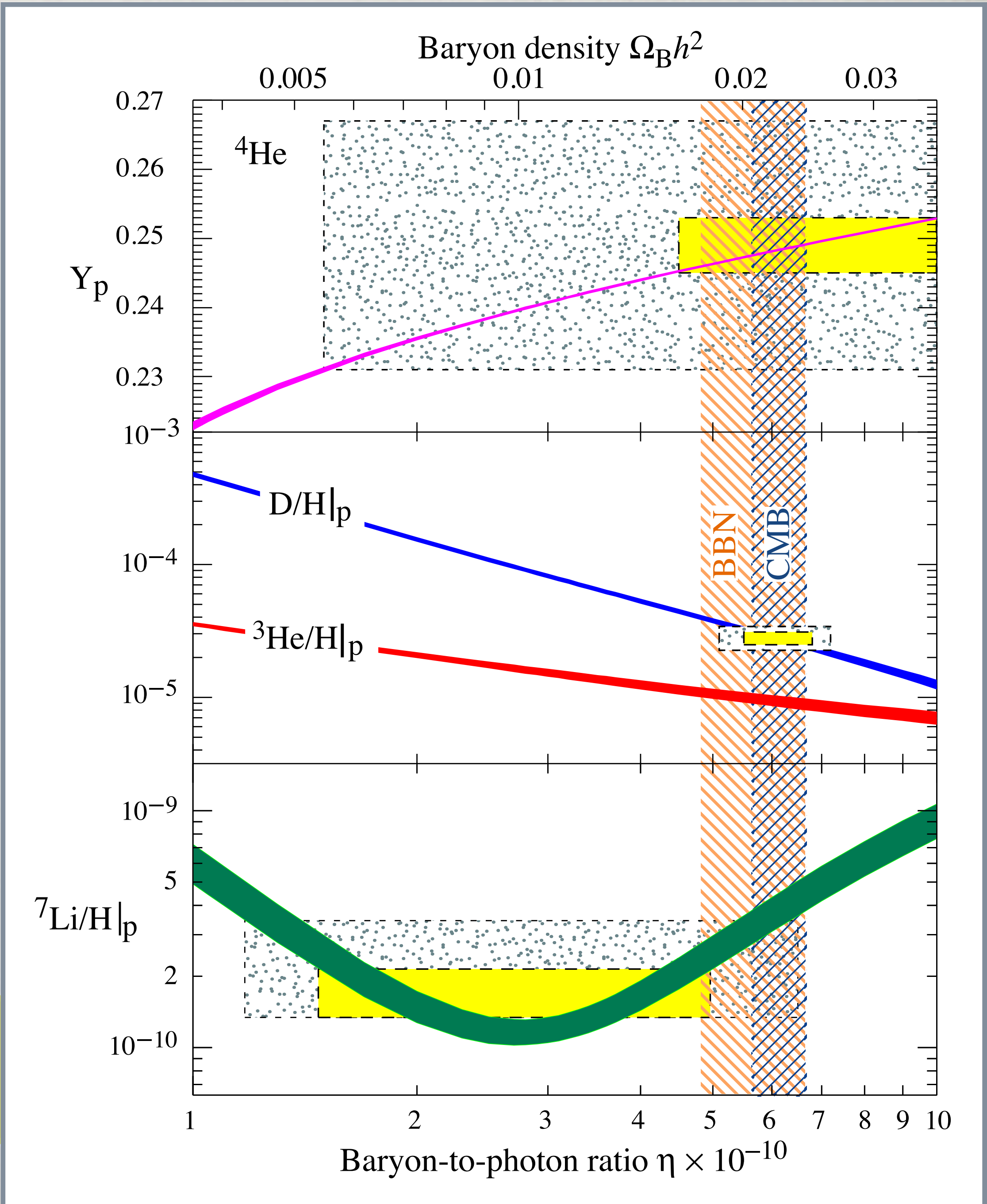
$$D + D \leftrightarrow^3 H + p \qquad {}^3H + D \leftrightarrow^4 He + n$$

$$D + D \leftrightarrow^4 He + \gamma$$

Most of the neutrons end up in ${}^4He$ that is the more strongly bound nucleus, but there remains also a small fraction of Deuterium and ${}^3He$ and some ${}^7Li$ formed from Helium.

BIG BANG NUCLEOSYNTHESIS

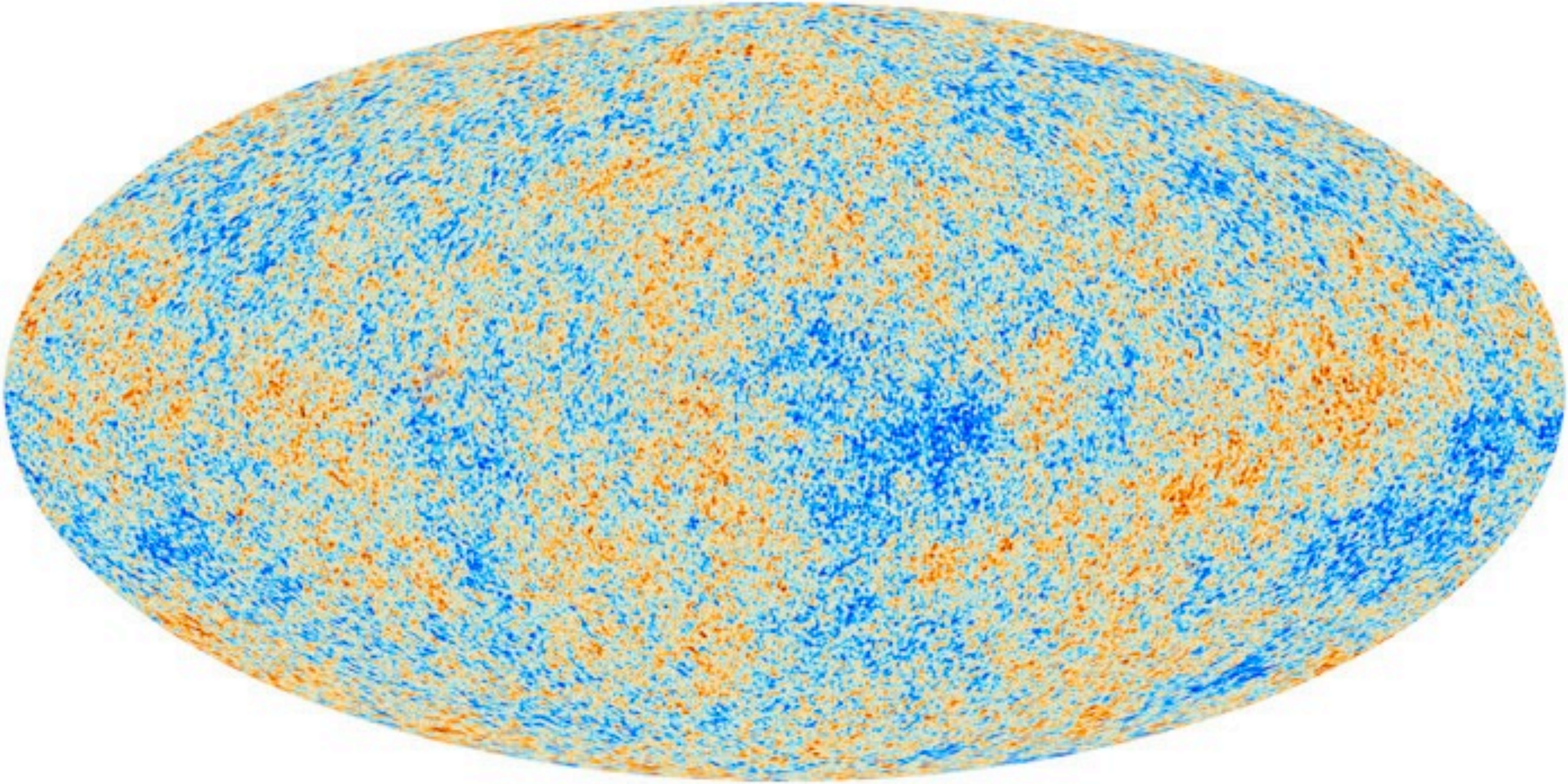
[Fields & Sarkar PDG 07]



- Light elements abundances obtained as a function of a single parameter $\Omega_B h^2$
- Perfect agreement with WMAP determination
- Some trouble with Lithium 6/7

$$\Omega_B h^2 = 0.02 < \Omega_{DM} h^2$$

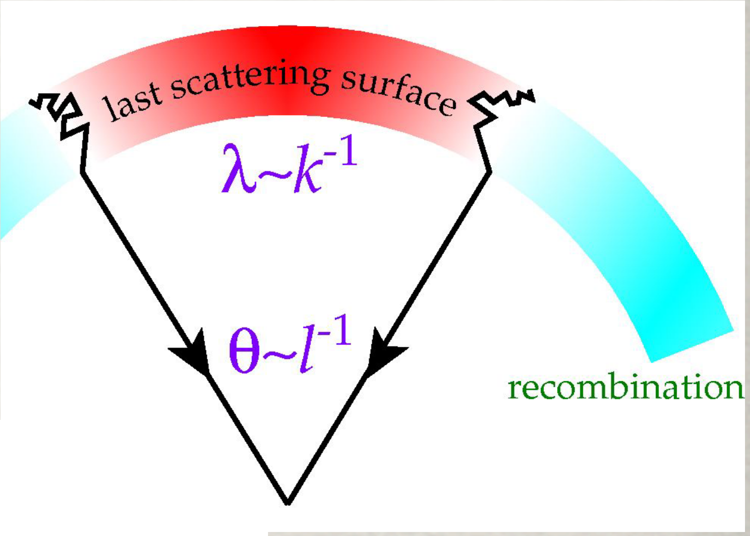
MORE EVIDENCE OF BAU IN CMB FROM WMAP/PLANCK



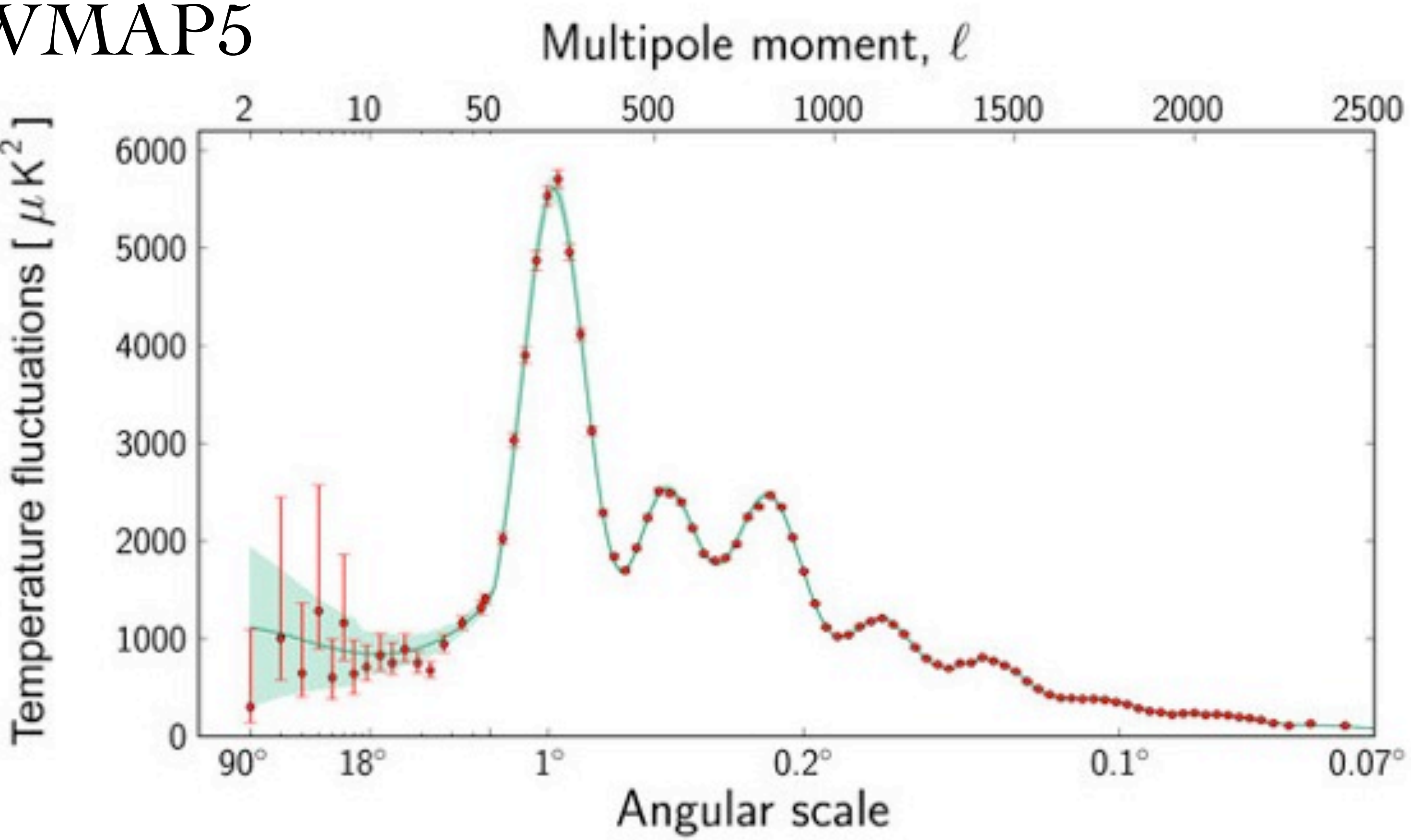
$$\langle T(\theta)T(0)\rangle = \sum_{\ell,m} a_{\ell m} Y^{\ell}_{m}(\theta)$$

PLANCK ANGULAR POWER SPECTRUM

$$C_\ell = \frac{1}{2\ell+1}\sum_m |a_{\ell m}|^2$$

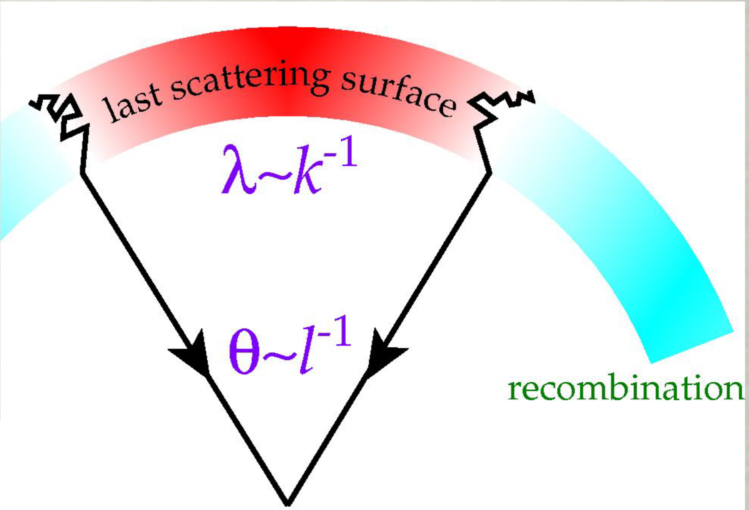


WMAP5

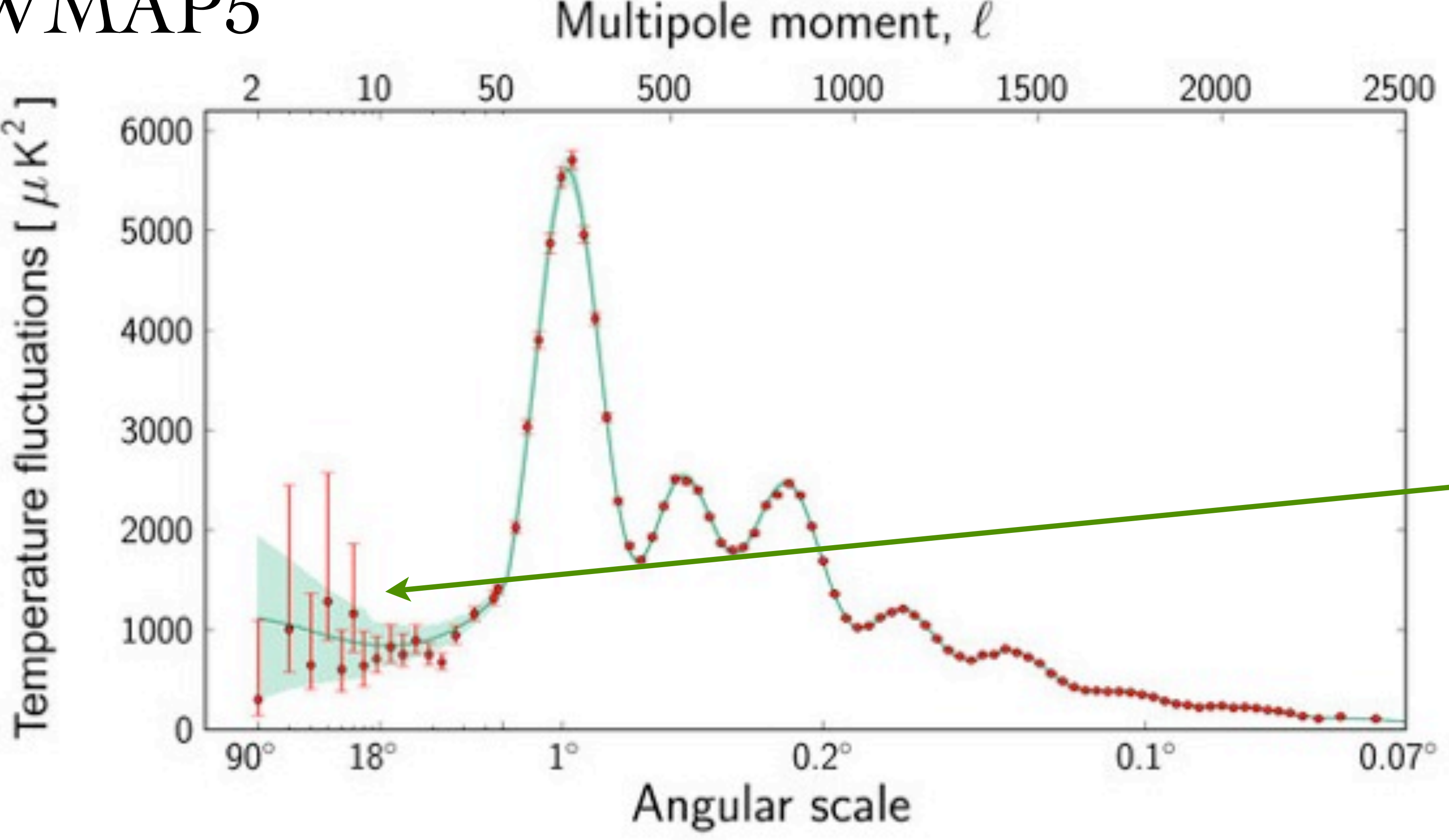


PLANCK ANGULAR POWER SPECTRUM

$$C_\ell = \frac{1}{2\ell + 1} \sum_m |a_{\ell m}|^2$$



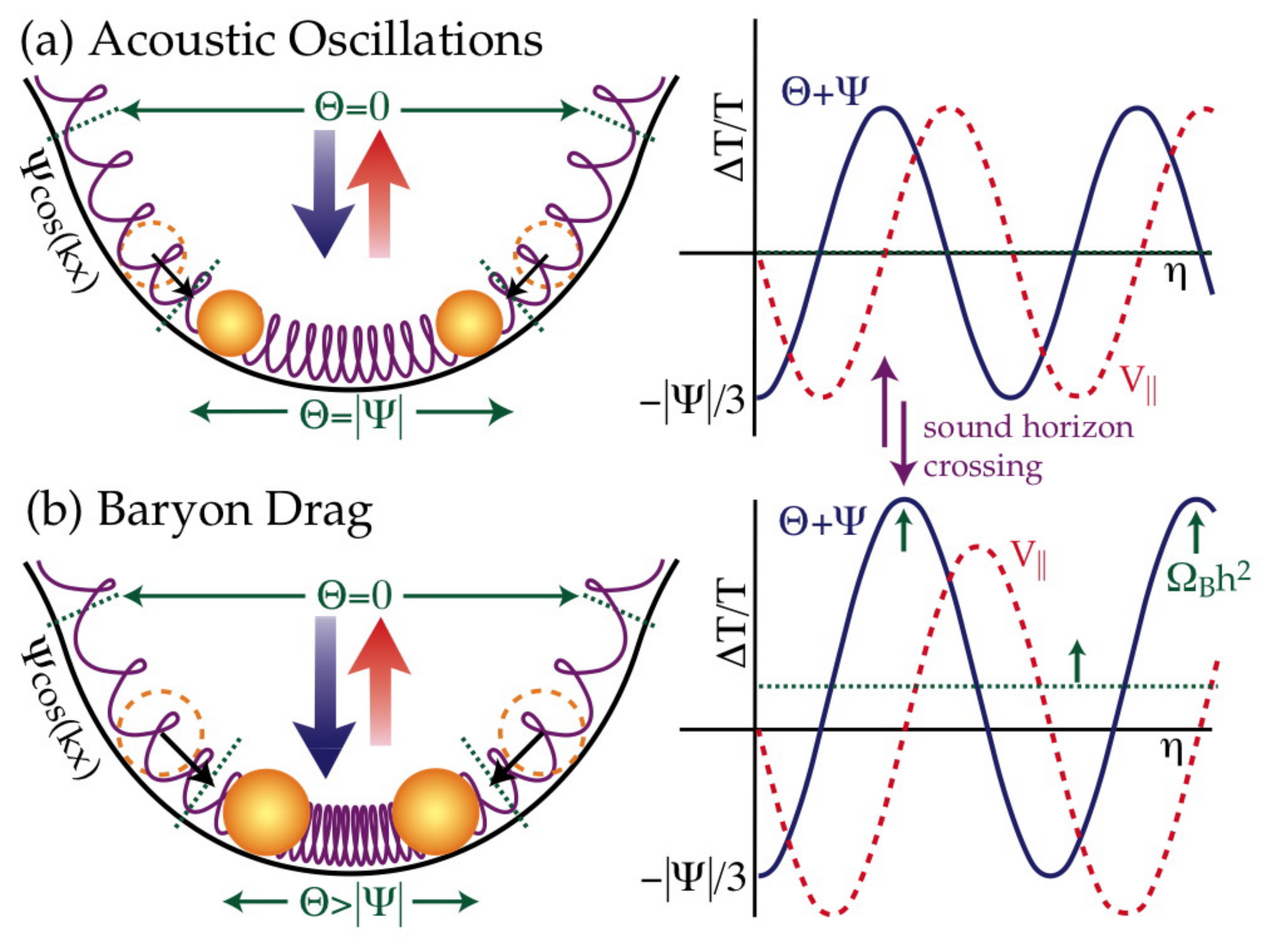
WMAP5



Cosmic variance

CMB PRIMER

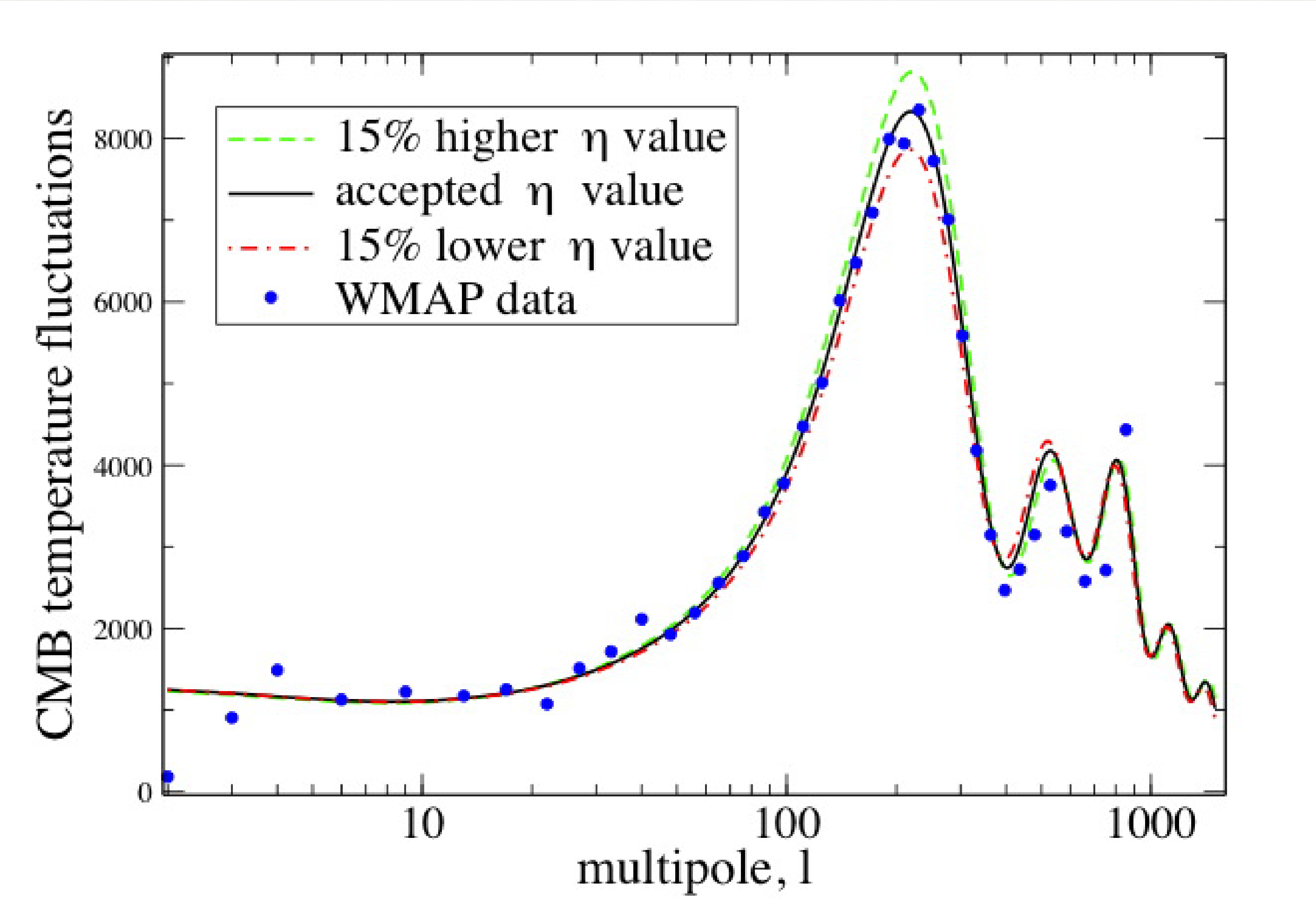
[Wayne Hu's CMB primer at http://background.uchicago.edu/~whu/]



Baryons increase the mass in the plasma and the drag force...

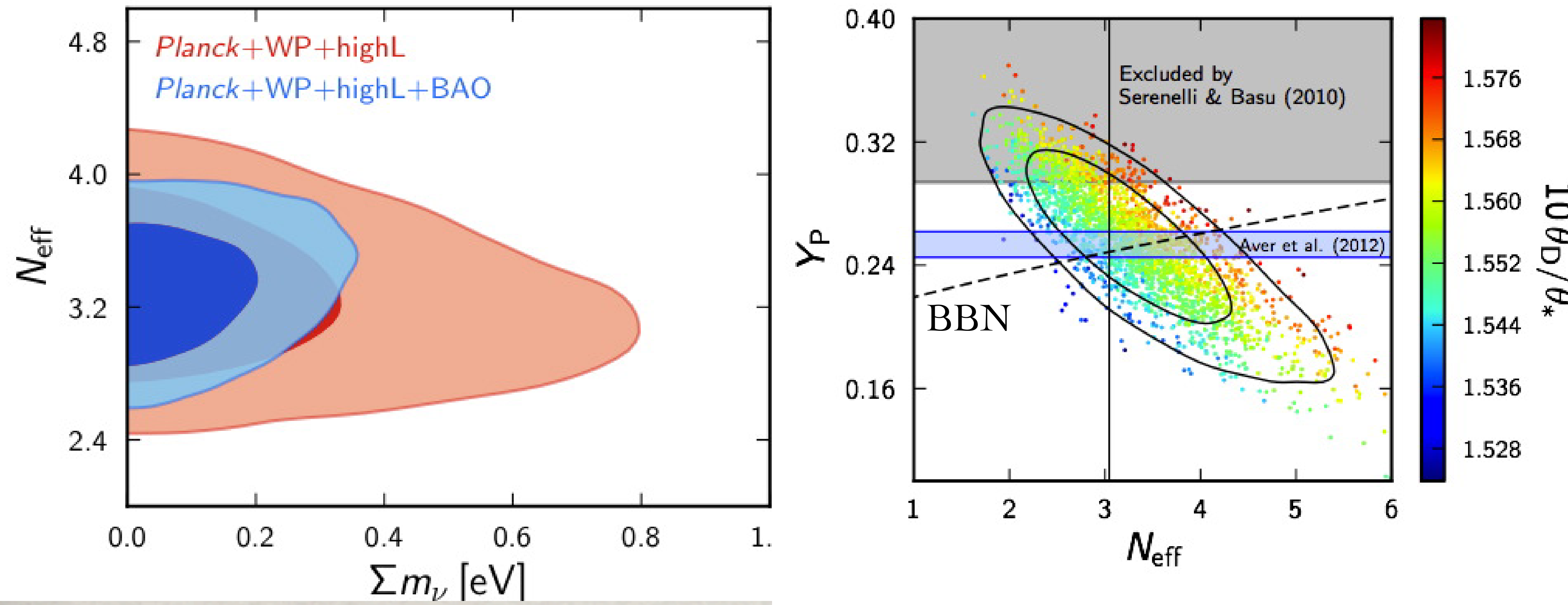
BARYONIC MATTER EVIDENCE

The relative height between the odd (compression) and the even (rarefaction) peaks in the CMB power spectrum depends on the amount of baryons since the mass of the plasma is due to the baryons and DM is decoupled from the photon gas...



PLANCK: DARK RADIATION

[Planck coll. 1303.5076]

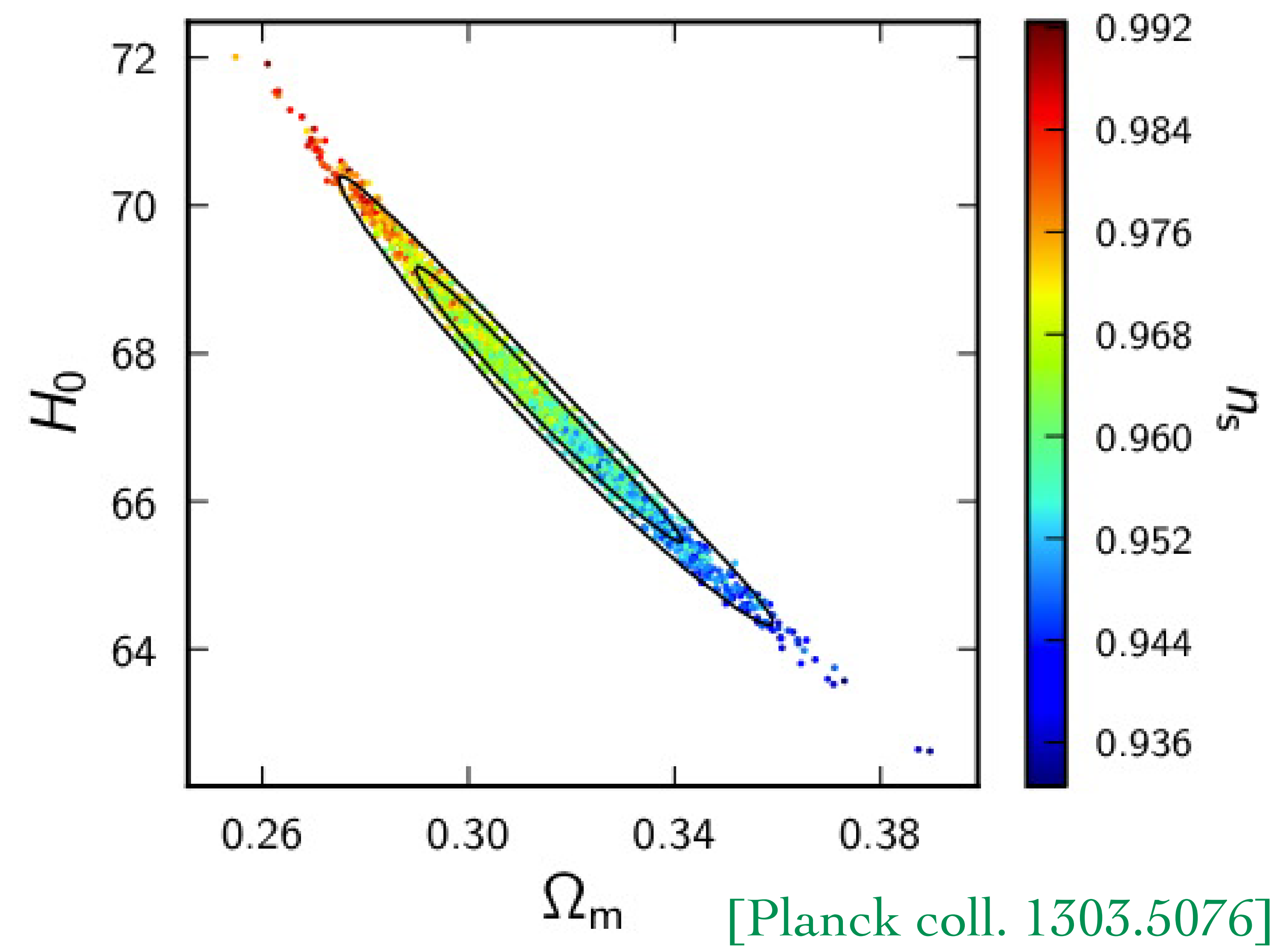


No evidence for dark radiation, Neff =3.046 is within 1 σ.

CMB consistent with BBN even fitting both N_{eff} & Y_p .

Note the degeneracy between these two parameters !

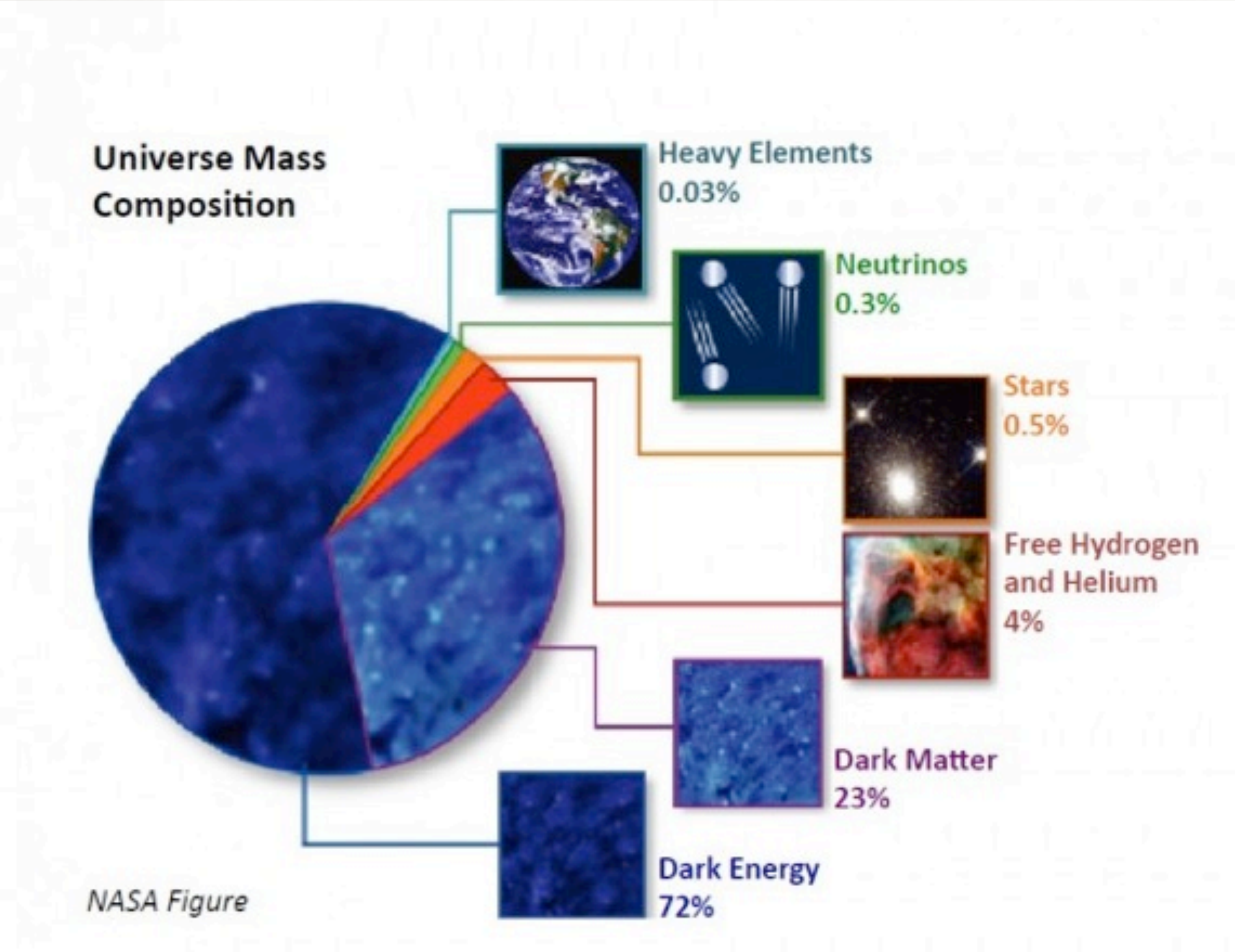
PLANCK COSMO PARAMETERS



[Planck coll. 1303.5076]

Degeneracy in the plane H_0 vs Ω_m depending on n_s.

UNIVERSE COMPOSITION



$$\Omega_{DM} \sim 5\, \Omega_B$$

Why so many components with similar densities ???

BARYOGENESIS & SAKHAROV CONDITIONS

BARYOGENESIS

- The CMB data and BBN both require $\Omega_B \sim 0.05$
- Can it be a relic of thermal decoupling from a symmetric state ? NO ! Decoupling "a la WIMP" give a value $\Omega_B \sim 10^{-10}$, way too small...
- Are we living in a matter patch ??? No evidence of boundaries between matter/antimatter in gammas or antinuclei in cosmic rays... Our patch is as large as the observable Universe !
- No mechanism know can create such separation... The Universe is asymmetric !

SAKHAROV CONDITIONS

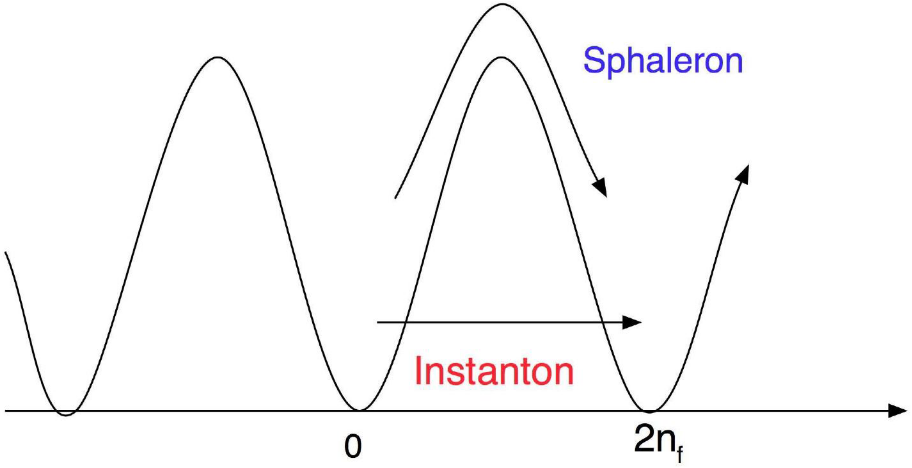
Sakharov studied already in 1967 the necessary conditions for generating a baryon asymmetry from a symmetric state:

- B violation: trivial condition since otherwise B remains zero...
- C and CP violation: otherwise matter and antimatter would still be annihilated/created at the same rate
- Departure from thermal equilibrium: the maximal entropy state is for B = 0, or for conserved CPT, no B generated without time-arrow...

SPHALERON PROCESSES

$B+L$ violation in the Standard Model

In the SM the global $U(1)_{B+L}$ is anomalous. This is related to the complex vacuum structure of the theory, which contains vacua with different configurations of the gauge fields and different topological number. Non-perturbative transitions between the vacua change $B+L$ by $2n_f$.



– $T=0$: tunneling and is suppressed by $e^{-\frac{4\pi}{\alpha_W}} \ll 1$

$\rightarrow B$ & L practically conserved!

– $T>0$: the transition can happen via a sphaleron

with rate $\Gamma_{sph}(T) \sim \left(\frac{M_W}{\alpha_W T}\right)^3 M_W^4 e^{-E_{sph}/T}$

So at temperatures $T \geq 100$ GeV sphaleronic transitions are in equilibrium in the Universe $\rightarrow B+L$ erased if $B-L=0$, otherwise

$$B = \frac{8n_f + 4n_H}{22n_f + 13n_H}(B-L)$$

A $B-L$ number is reprocessed into B number !

SAKHAROV CONDITIONS II

For the Standard Model actually we have instead:

- B-L violation: B+L violation by the chiral anomaly

$$\partial_\mu J^\mu_{B+L} = 2n_f \frac{g^2}{32\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- C and CP violation: present in the CKM matrix, but unfortunately quite small ! Possibly also additional phases needed...
- Departure from thermal equilibrium: phase-transition or particle out of equilibrium ?

BARYOGENESIS MECHANISMS

Again need to go beyond the Standard Model :

- EW baryogenesis in extensions of the SM with: more scalars, more CP violations...
  This is possible in Supersymmetry, but also without.

- Leptogenesis: generate first L via decay of heavy Majorana neutrinos -> connection to the see-saw mechanism and neutrino masses.

- Affleck-Dine baryogenesis: store baryon number in a scalar condensates and transfer it to particles when the condensate decays. Mostly studied in SUSY !

CONCLUSIONS & OUTLOOK

- The baryon asymmetry of the Universe is jet an unsolved puzzle !
- Different mechanisms can explain it, MOSTLY based on physics beyond the Standard Model !
- Basic ingredient for baryogenesis: deviation from thermal equilibrium, therefore not easy to make computations...
- Few mechanisms are connected to the EW scale/ phase transition and are being tested at the LHC, in particular SUSY EW baryogenesis.