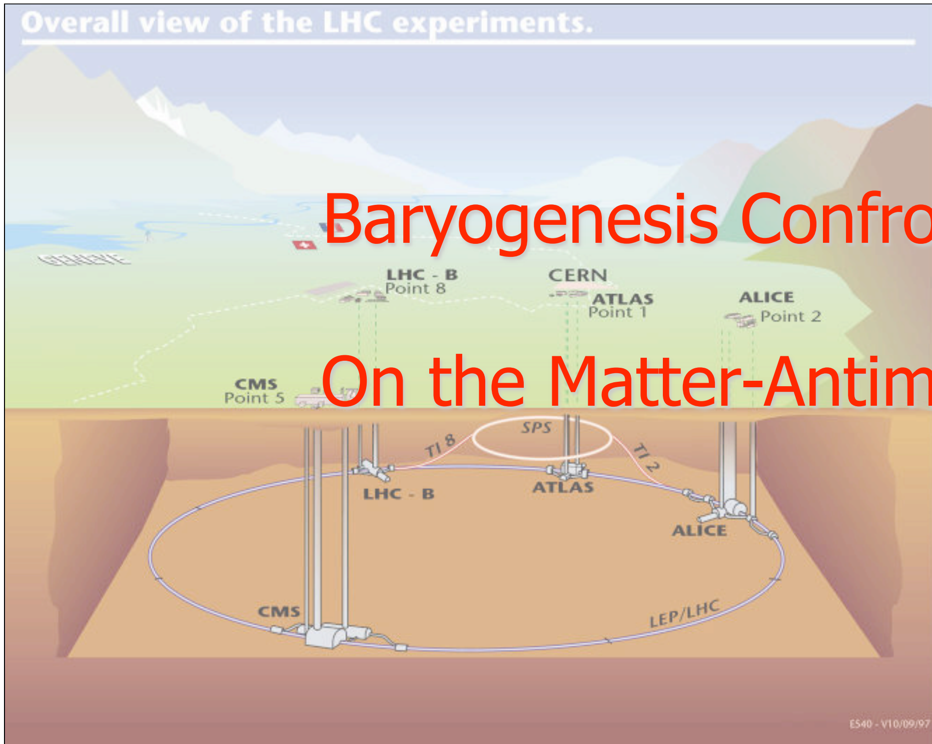
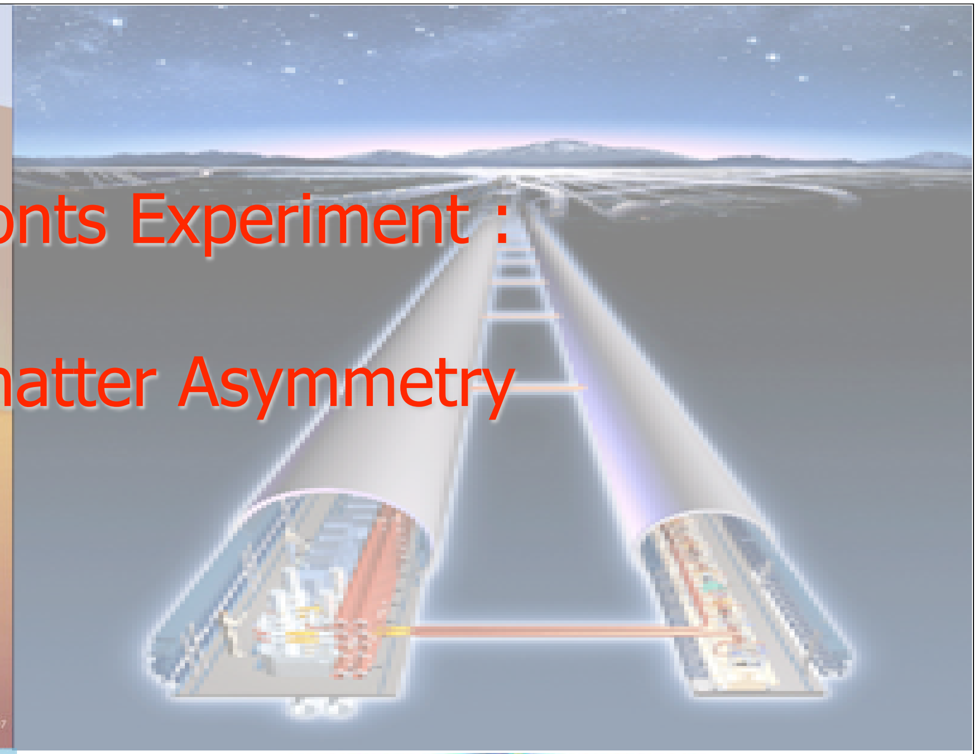
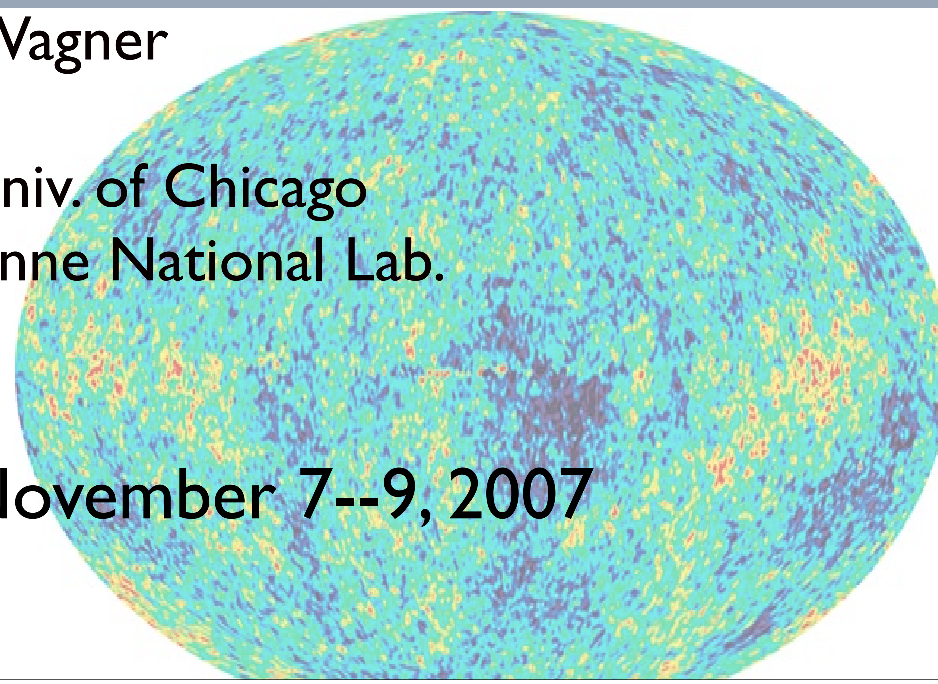




Baryogenesis Confronts Experiment :

On the Matter-Antimatter Asymmetry



C.E.M. Wagner

KICP and EFI, Univ. of Chicago
HEP Division, Argonne National Lab.

KICP Workshop, November 7--9, 2007

High Energy Physics and Cosmology Today

- There has been impressive progress in both particle physics and cosmology in the last 30 years

- Laboratory and satellite based experiments complemented with theories of the dynamics of the cosmos and the micro-cosmos have led to what are today known as Standard Models in both fields

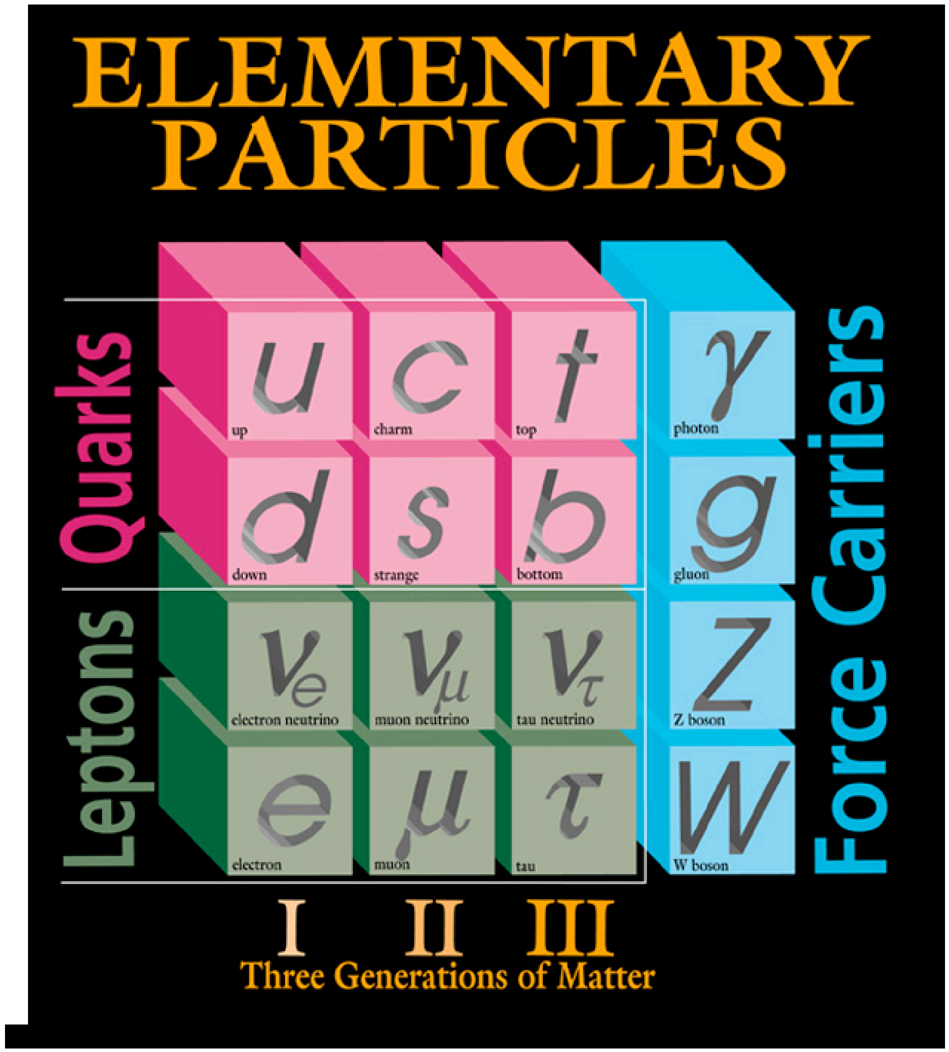
- All experimental observations are consistent with the predictions of these models

Standard Model of Particle Physics

- Gauge Theory Based on the group

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

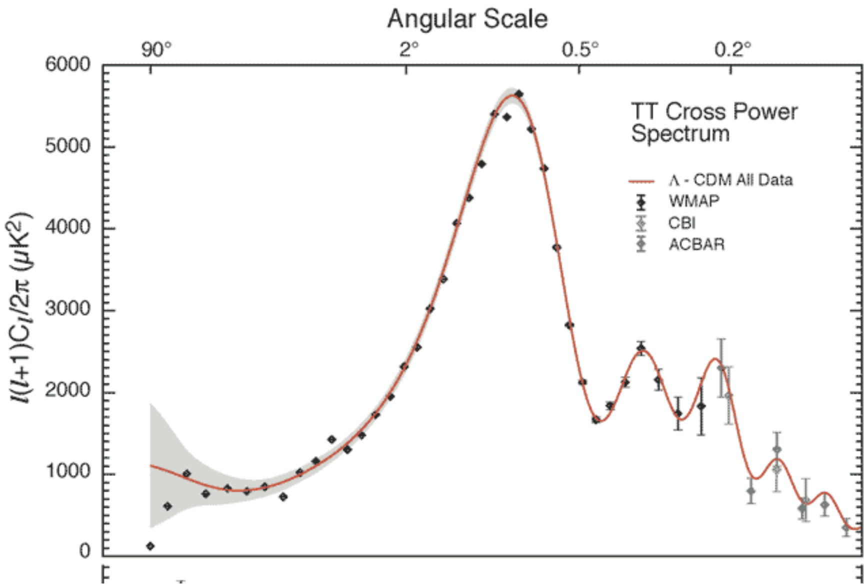
- All particle interactions of the three families of quarks, charged leptons and neutrinos well described by the Standard Model (SM)
- Excellent description of all experimental observables
- Includes heavy particles, like the top quark and the weak gauge bosons, as well as the almost massless neutrinos.


ELEMENTARY PARTICLES
Quarks
Leptons
Force Carriers
u up
c charm
t top
d down
s strange
b bottom
ν_e electron neutrino
ν_μ muon neutrino
ν_τ tau neutrino
e electron
μ muon
τ tau
γ photon
g gluon
Z Z boson
W W boson
I II III
Three Generations of Matter

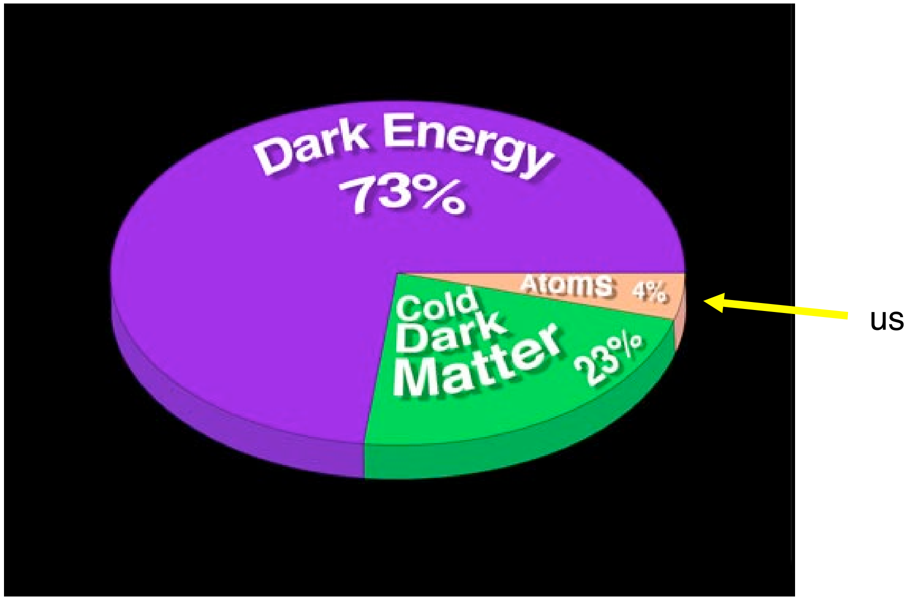
Standard Cosmological Model

Universe density	$\Omega_0 = 1.02 \pm 0.02$
Dark energy density	$\Omega_\Lambda = 0.73 \pm 0.04$
Total matter density	$\Omega_M = 0.27 \pm 0.05$
Baryon matter density	$\Omega_b = 0.044 \pm 0.004$

→ Dark matter is non-baryonic



Our Universe:



Open Questions in Particle Physics and Cosmology

- Origin of Mass of fundamental particles
- Nature of Dark Matter
- Source of Dark Energy
- Quantum Gravity and the Unification of Forces

Missing Question

- The four percent of ordinary matter present in the Universe does not seem to introduce any challenge to our understanding of the Universe
- This naive impression is wrong. Two very puzzling questions remain:
- Why is anti-matter absent in the observable Universe ?
- What explains the smallness of the baryon number density when compared to photons or neutrinos ?

The Puzzle of the Matter-Antimatter asymmetry

- Anti-matter is governed by the same interactions as matter.
- Observable Universe is composed of matter.
- Anti-matter is only seen in cosmic rays and particle physics accelerators
- The rate observed in cosmic rays consistent with secondary emission of antiprotons

$$\frac{n_{\bar{P}}}{n_P} \approx 10^{-4}$$

Baryons and Leptons

- Ordinary matter is composed of baryons (protons and neutrons) and leptons (electrons and neutrinos)
- One can associate an experimentally conserved number to baryons and leptons. Baryons and leptons carry one unit of these numbers, and antibaryons and anti-leptons carry a negative unit.
- The predominance of matter over antimatter is equivalent to the existence of a net baryon number
- To estimate their number, baryons should be treated as stable thermal relics of the Big Bang

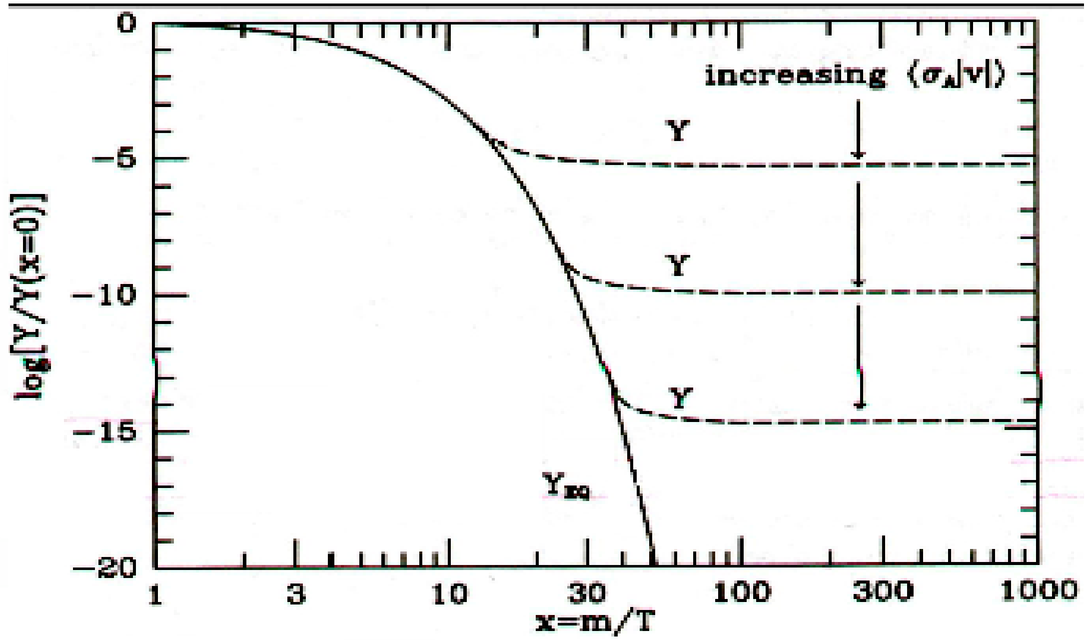
Evolution of Thermal Relic Density

$$\frac{dn}{dt} = -3Hn - <\sigma_{eff} v>(n^2 - n_{eq}^2), \qquad n_{eq} \approx \exp(-m/T)$$

$< \sigma_{eff} v >$ Thermal average of (co-)annihilation cross section

$$Y = \frac{n}{s}$$

$$s \approx g_* T^3$$



At present $s \simeq 7\, n_\gamma$

Numerical Estimate

- Baryons annihilate with antibaryons via strong interactions mediated by pions

- This is a very efficient annihilation channel and the equilibrium density is

$$\frac{n_{\bar{B}}}{n_\gamma} = \frac{n_B}{n_\gamma} \simeq 10^{-20}$$

- The first problem is the equality of baryon and antibaryon number density. Even obviating this problem, how does this compare to experiment ?

Baryon Abundance

- Information on the baryon abundance comes from two main sources:
- Abundance of primordial elements. When combined with Big Bang Nucleosynthesis tell us

$$\eta = \frac{n_B}{n_\gamma} \quad , \qquad n_\gamma = \frac{421}{cm^3}$$

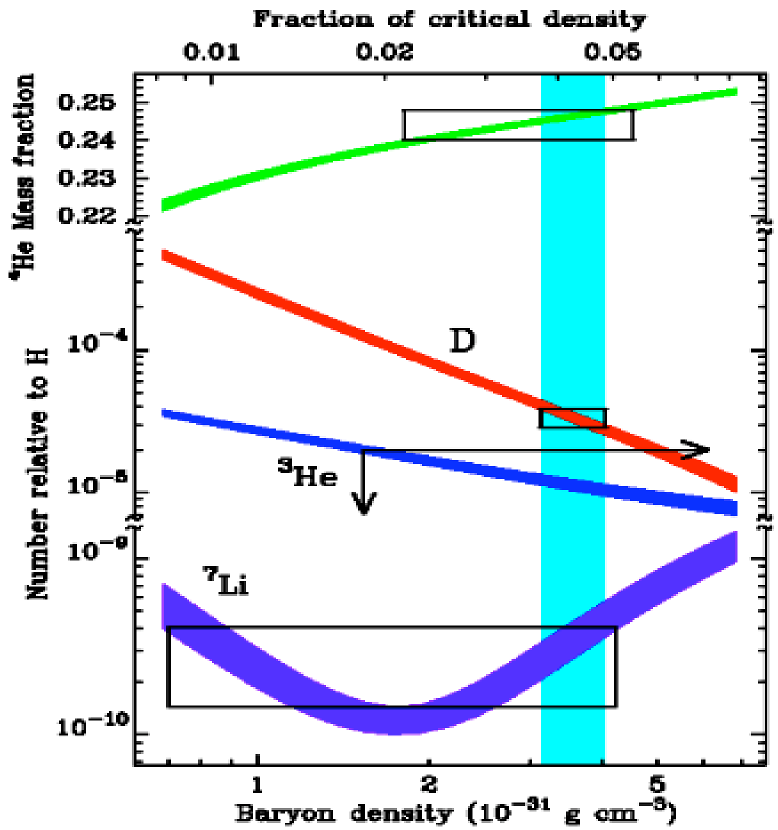
- CMBR, tell us ratio

$$\frac{\rho_B}{\rho_c} \equiv \Omega_B , \qquad \rho_c \approx 10^{-5} h^2 \frac{GeV}{cm^3}$$

- There is a simple relation between these two quantities

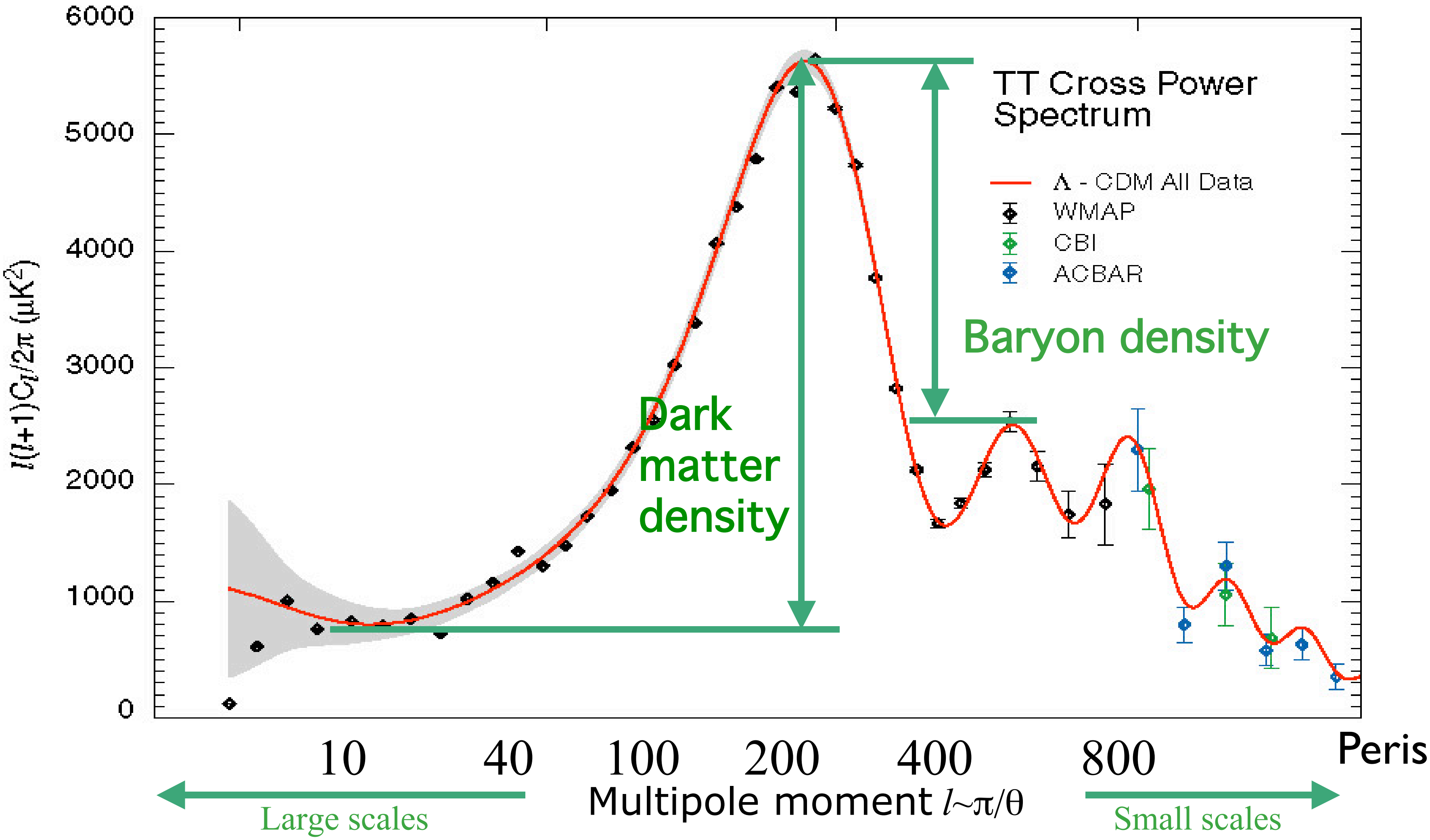
$$\eta = 2.68 \; 10^{-8} \Omega_B h^2$$

Element Abundance and Big-Bang Nucleosynthesis predictions



$1\,\text{GeV} \approx 1.6\ 10^{-24}\ \text{g}$

Information coming from the CMBR



Experimental evidence

- Baryon Number abundance is only a tiny fraction of other relativistic species

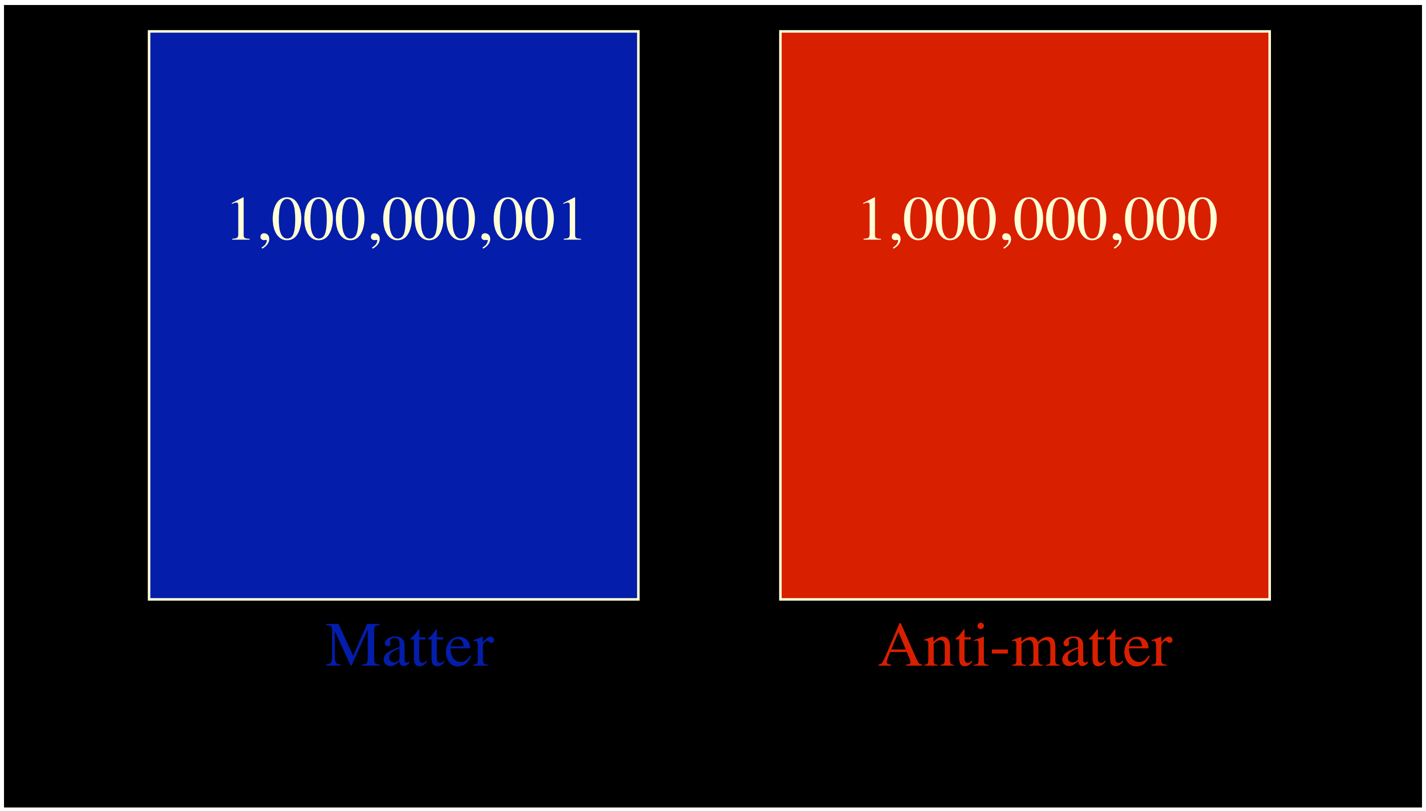
$$\frac{n_B}{n_\gamma} \approx 6\ 10^{-10}$$

- Still, it is much larger than what the situation of equality of baryon and anti-baryon number densities would suggest

- Why is $\Omega_\Lambda \simeq \Omega_{\mathrm{CDM}} \simeq \Omega_b$?

- What generated the small observed baryon-antibaryon asymmetry ?

Small Asymmetry must be generated primordially



Murayama

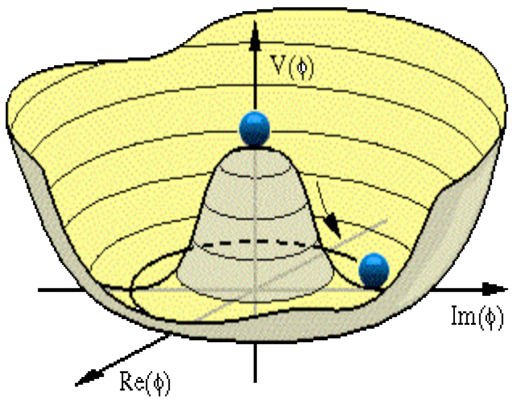
Annihilation will occur efficiently and finally the small asymmetry will be the only remaining thing left in the Universe

Baryogenesis

- Under natural assumptions, there are three conditions, enunciated by Sakharov, that need to be fulfilled for baryogenesis. The SM fulfills them :
- Baryon number violation: Anomalous Processes
- C and CP violation: Quark CKM mixing
- Non-equilibrium: Possible at the electroweak phase transition.

The Higgs Mechanism and the Origin of Mass

A scalar (Higgs) field is introduced. The Higgs field acquires a nonzero value to minimize its energy



Spontaneous Breakdown of the symmetry :
Vacuum becomes a source of energy = a source of mass

$$< H > = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

A physical state (Higgs boson) appear associated to fluctuations in the radial direction . Goldstone modes: Longitudinal component of massive Gauge fields.

Masses of fermions and gauge bosons proportional to their couplings to the Higgs field:

$$M_W^2 = \frac{g^2 v^2}{2}, \qquad m_{\rm top} = h_{\rm top}\, v \qquad m_H^2 = 2\lambda v^2$$

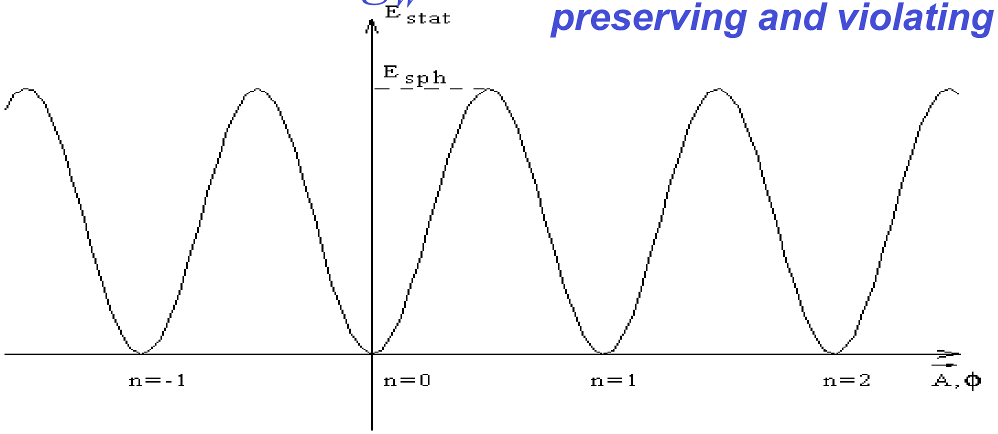
Non-equivalent Vacua and Static Energy in Field Configuration Space

The sphaleron is a static configuration with non-vanishing values of the Higgs and gauge boson fields.

Its energy may be identified with the height of the barrier separating vacua with different baryon number

$$E_{sph} = \frac{8\pi \, v}{g_W}$$

The quantity v is the Higgs vacuum expectation value, $\langle H \rangle = v$.
This quantity provides an order parameter which distinguishes the electroweak symmetry preserving and violating phases.



$$\partial^{\mu} j_{\mu}^{B,L} = \frac{N_g}{32\pi^2} Tr(\ \varepsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta}\ )$$

Instanton configurations may be regarded as semiclasical **configurations** *for tunelling effect between vacuum states with different baryon number*

$$S_{inst} = \frac{2\pi}{\alpha_W} \qquad \Gamma_{\Delta B \neq 0} \propto \exp(-S_{inst}\ )$$

Weak interactions: Transition amplitude exponentially small.
No observable baryon number violating effects at T = 0

Baryon Number Violation at finite T

- Anomalous processes violate both baryon and lepton number, but preserve B – L. Relevant for the explanation of the Universe baryon asymmetry.

- At zero T baryon number violating processes highly suppressed

- At finite T, only Boltzman suppression

$$\Gamma(\Delta B \neq 0) = \Gamma(\Delta L \neq 0) \propto AT \exp\left(-\frac{E_{\rm sph}}{T}\right) \qquad \mathbf{E_{sph}} \propto \frac{8\pi\,\mathbf{v}}{\mathbf{g}}$$

Klinkhamer and Manton '85, Arnold and Mc Lerran '88

Baryon Asymmetry Preservation

If Baryon number generated at the electroweak phase transition,

$$\frac{n_B}{s} = \frac{n_B(T_c)}{s} \exp\left(-\frac{10^{16}}{T_c(\mathrm{GeV})}\exp\left(-\frac{E_{sph}(T_c)}{T_c}\right)\right)$$

Kuzmin, Rubakov and Shaposhnikov, '85—'87

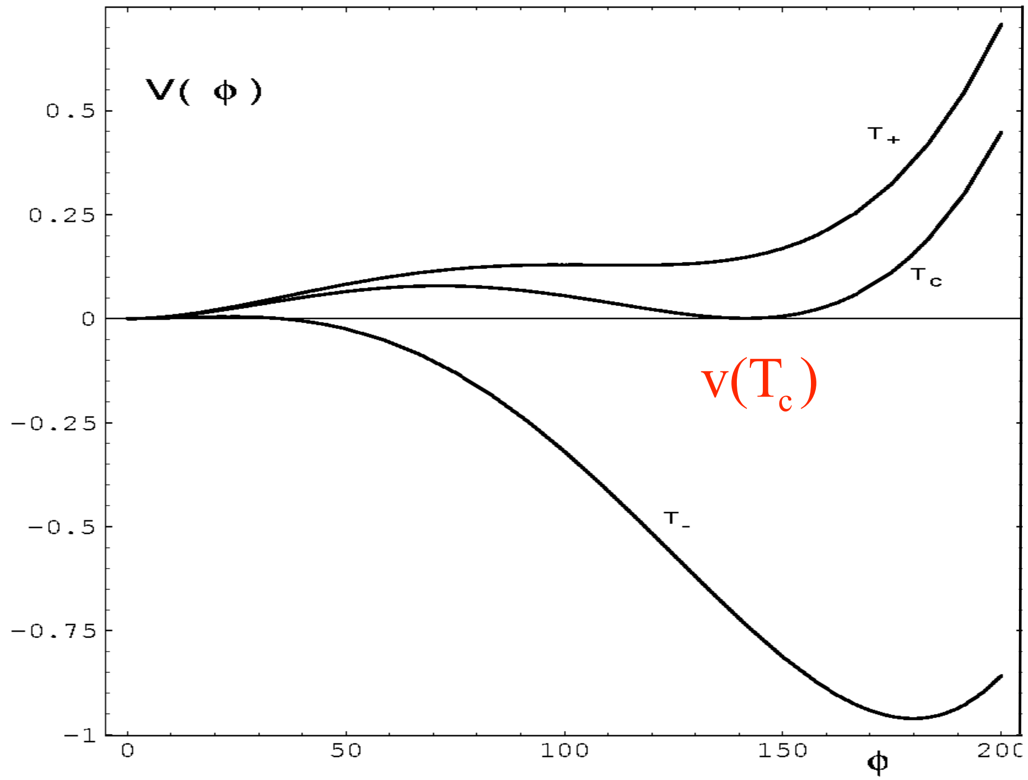
Baryon number erased unless the baryon number violating processes are out of equilibrium in the broken phase.

Therefore, to preserve the baryon asymmetry, a strongly first order phase transition is necessary:

$$\frac{v(T_c)}{T_c} > 1$$

Electroweak Phase Transition

Higgs Potential Evolution in the case of a first order Phase Transition



Finite Temperature Higgs Potential

$$V(T) = D(T^2 - T_0^2)\phi^2 - E_B T\phi^3 + \frac{\lambda(T)}{2}\phi^4$$

D receives contributions at one-loop proportional to the sum of the couplings of all bosons and fermions squared, and is responsible for the phenomenon of symmetry restoration

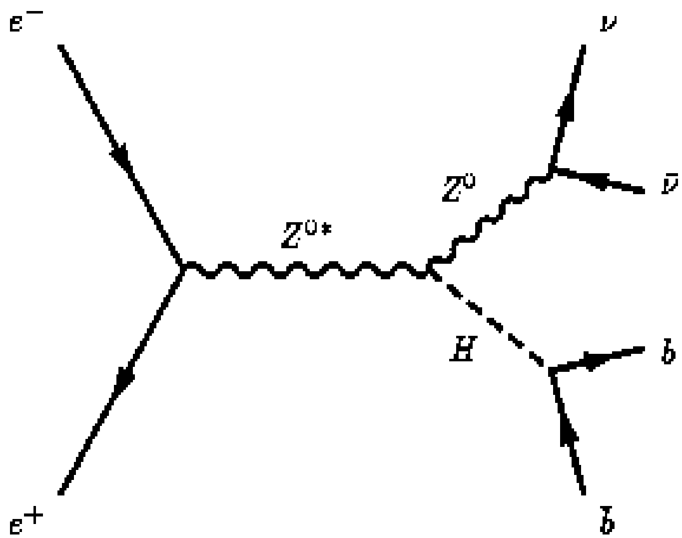
E receives contributions proportional to the sum of the cube of all light boson particle couplings

$$\frac{v(T_c)}{T_c} \approx \frac{E}{\lambda} \quad , \quad \text{with} \quad \lambda \propto \frac{m_H^2}{v^2}$$

Since in the SM the only bosons are the gauge bosons, and the quartic coupling is proportional to the square of the Higgs mass,

$$\frac{v(T_c)}{T_c} > 1 \quad \text{implies} \quad m_H \quad < 40 \text{ GeV.}$$

If the Higgs Boson is created , it will decay rapidly into other particles



At LEP energies mainly into pairs of b quarks

One detects the decay products of the Higgs and the Z bosons

LEP Run is over

- **No Higgs seen with a mass below 114 GeV**
- **But, tantalizing hint of a Higgs with mass about 115 -- 116 GeV (just at the edge of LEP reach)**

Electroweak Baryogenesis in the SM is ruled out

CP-Violation sources

- Another problem for the realization of the SM electroweak baryogenesis scenario:

- Absence of sufficiently strong CP-violating sources

- Even assuming preservation of baryon asymmetry, baryon number generation several order of magnitues lower than required

$$\Delta_{CP}^{max} = \left[\sqrt{\frac{3\pi}{2}\frac{\alpha_W T}{32\sqrt{\alpha_s}}}\right]^3 J\,\frac{(m_t^2-m_c^2)(m_t^2-m_u^2)(m_c^2-m_u^2)}{M_W^6}\,\frac{(m_b^2-m_s^2)(m_s^2-m_d^2)(m_b^2-m_d^2)}{(2\gamma)^9}$$

$$J \equiv \pm Im[K_{li}K_{lj}^* K_{l'j}K_{l'i}^*] = c_1c_2c_3s_1^2s_2s_3s_\delta$$

γ : Quark Damping rate

Gavela, Hernandez, Orloff, Pene and Quimbay'94

Baryogenesis and New Physics

- As Dark Matter and Dark Energy, then Baryogenesis does not have a natural explanation within the Standard Models of particle physics and cosmology
- New mechanisms should be invoked. Many of these mechanism use the baryon and lepton number violation induced by the sphaleron processes.
- New sources of CP-violation are also necessary
- And new processes, going out of equilibrium at some point in the evolution of the Universe

Generic Scenarios: Leptogenesis

- Neutrinos have tiny masses. These can be naturally explained if they proceed from the Yukawa coupling of ordinary neutrinos with heavy Majorana neutrinos

$$M_\nu \simeq Y^T M^{-1} Y \ \mathrm{v}^2$$

- These heavy Majorana neutrinos decay into ordinary leptons through lepton and CP-violating processes induced by the Majorana mass and the complex Yukawa couplings, respectively

- The resulting lepton asymmetry is then converted into a baryon asymmetry via the anomalous processes, which try to erase B+L, and conserve B-L.

- This generic mechanism of generation of baryon number from lepton number is called leptogenesis, and is very attractive since it is tied to the mechanism of neutrino mass generation

Generic Scenarios: Electroweak Baryogenesis

- Like in the Standard Model, assume that baryogenesis is generated by processes occurring at the electroweak phase transition

- Attractive models will be those associated with the new physics responsible for the explanation of electroweak symmetry breaking and the generation of mass (and hopefully dark matter)

- Again, new sources of CP-violation are necessary

- Testable in near future experiments

Alternative Scenarios

- The baryon asymmetry may be generated already in the inflationary period
- Or after sphaleron processes are out of equilibrium.
- Or it may result from a violation of Lorentz or CPT symmetries.
- Or....

Aim of the Workshop

- In this workshop, many different scenarios for the generation of the baryon asymmetry will be presented.

- We hope to get an understanding of the feasibility of each scenario, as well as the what are the observable consequences of these scenarios

- Many talks will be dedicated to variations of leptogenesis (5 talks) and electroweak baryogenesis (6 talks), but a large number of talks (8 talks) will cover other scenarios

- I am quite confident that we will all learn from this excercise !