Four lectures on

COSMOLOGY

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Lecture 1: The large picture

observations, cosmological principle, Friedmann model, Hubble diagram, thermal history

Lecture 2: From quantum to classical

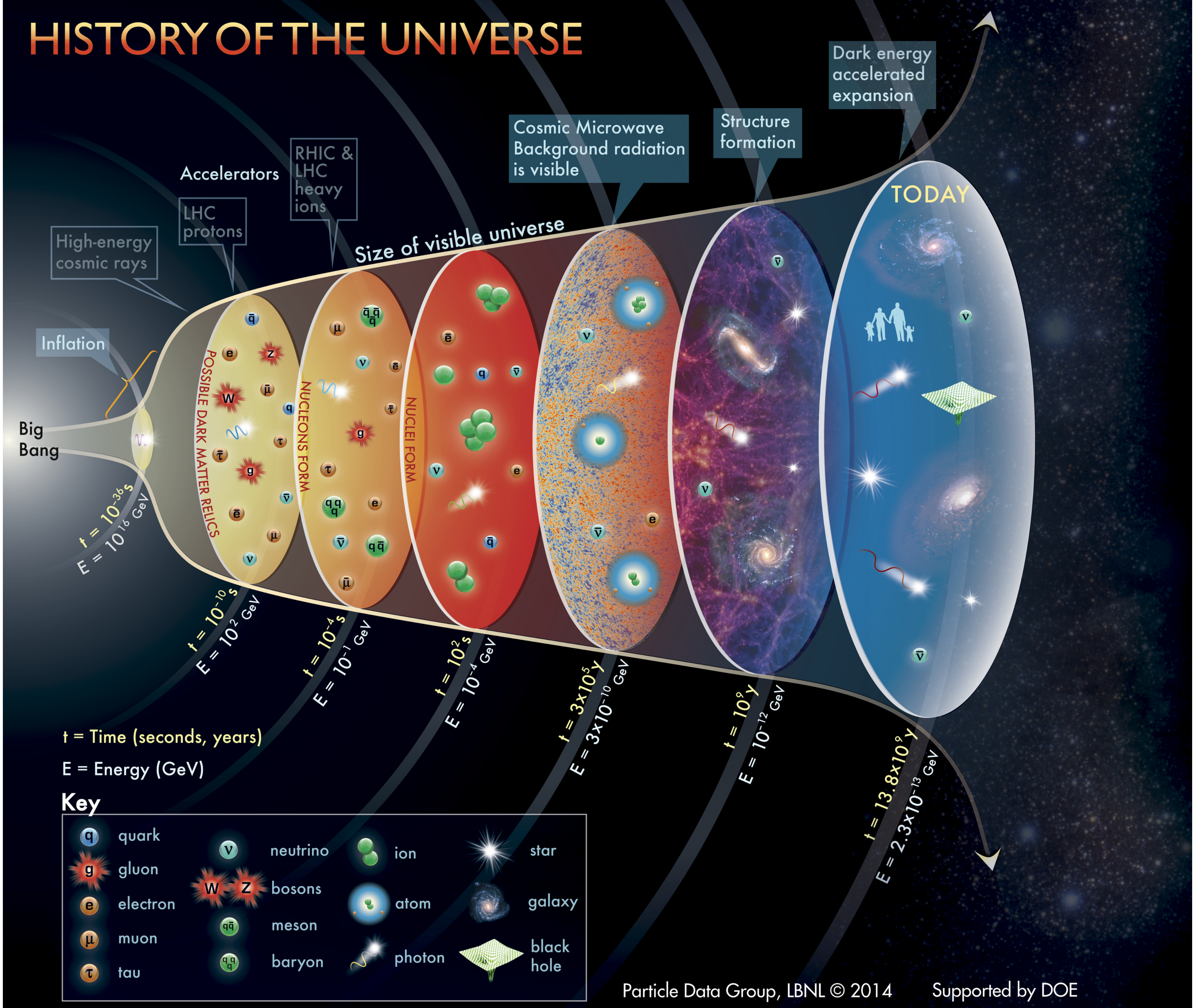
cosmological inflation, isotropy & homogeneity, causality, flatness, metric & matter fluctuations

Lecture 3: Hot big bang

radiation domination, hot phase transitions, relics, nucleosythesis, cosmic microwave radiation

Lecture 4: Cosmic structure

primary and secondary cmb fluctuations, large scale structure, gravitational instability



HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Inflation
Size of visible universe
TODAY
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL © 2014
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End of inflation

- homogeneous & isotropic — Friedmann cosmology
- spatially flat — $\sum_i \Omega_i = 1, \quad i =$ particle species
- empty — all conserved charges are diluted during inflation
- cold — the scalar field oscillates, effectively $p = 0$ cosmology

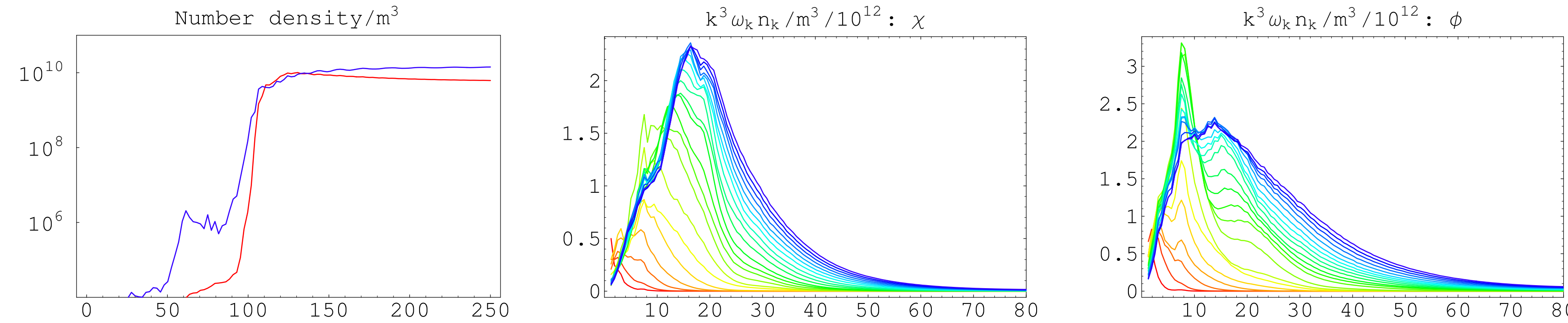
need to heat up and generate matter-antimatter asymmetry

Preheating and thermalisation

coherent oscillations of inflaton ϕ — $V = \frac{1}{2}m^2\phi^2 + \frac{1}{2}g^2\phi^2\chi^2$

decay into ϕ and χ "particles" — $m = 10^{-6}M_\text{P}$

thermalise later on — $g^2 = 2.5 \times 10^{-7}$



time in units of $1/m$ — Felder & Kofman 2007

$T_\text{rh} < 10^{16}$GeV — from $H_\text{end inf} < 10^{-5}M_\text{P}$, instantaneous heating, $g(T_\text{rh}) = 10^2$

Radiation-dominated Universe

maximal $T_{\rm rh} \sim$ GUT scale

below GUT scale all interaction rates $\Gamma \gg H \Rightarrow$ local thermal equilibrium

$\Gamma/H \sim \alpha_{\rm GUT} M_{\rm P}/(g^{1/2}T) \sim 10^{15}{\rm GeV}/T$

Friedmann equations (flat Universe):

$$H^2 = \frac{8\pi G}{3}\epsilon\,, \qquad \dot{\epsilon} = -3H(\epsilon + p)$$

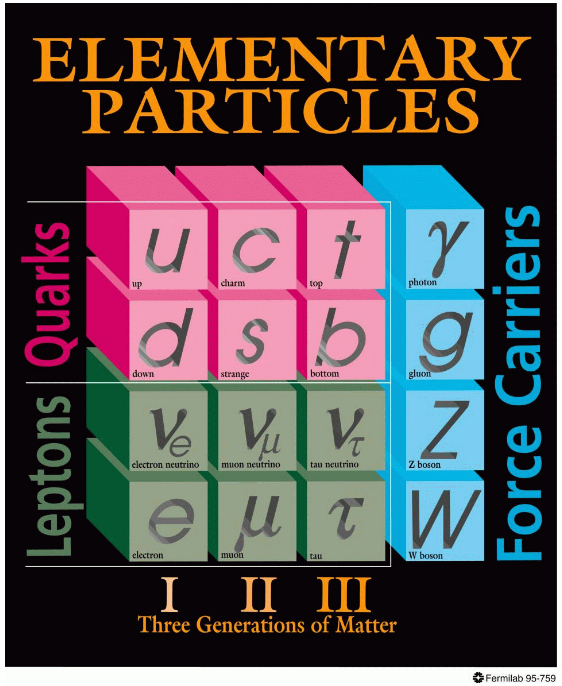
for ultrarelativistic particles ($T \gg m$)

$$p = \frac{\pi^2}{90} g(T) T^4 \quad \text{in thermodynamic equilibrium}$$

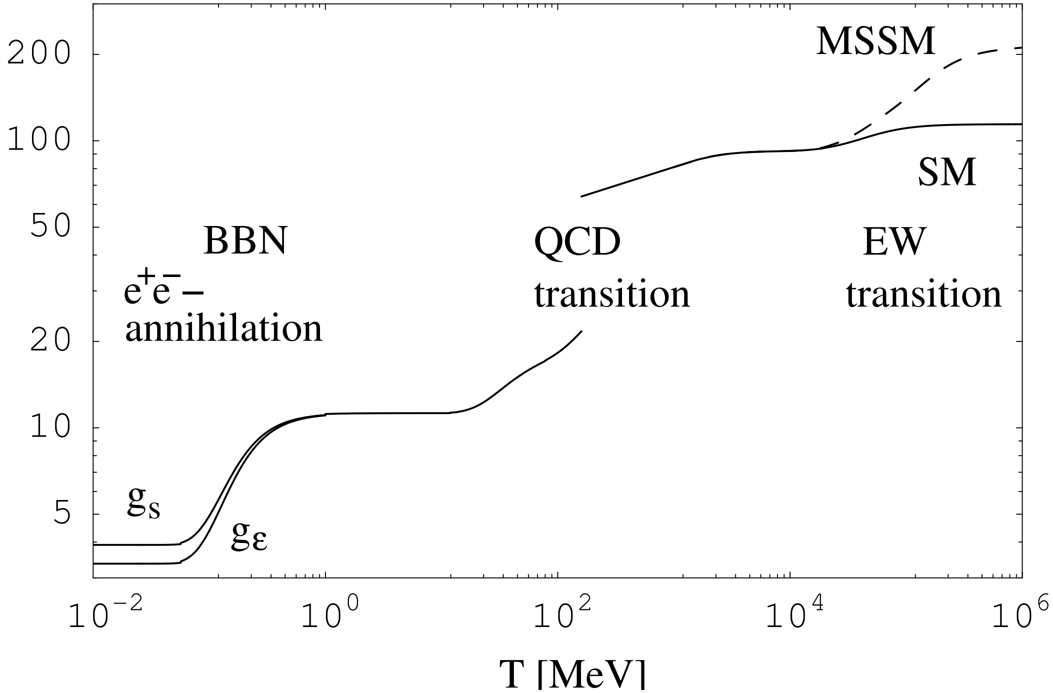
g(T) effective relativistic number of spin degrees of freedom

$\sum_i \Omega_i = 1$; $\omega_i = \Omega_i h^2$ ($i =$ b, ν, cdm, . . .)

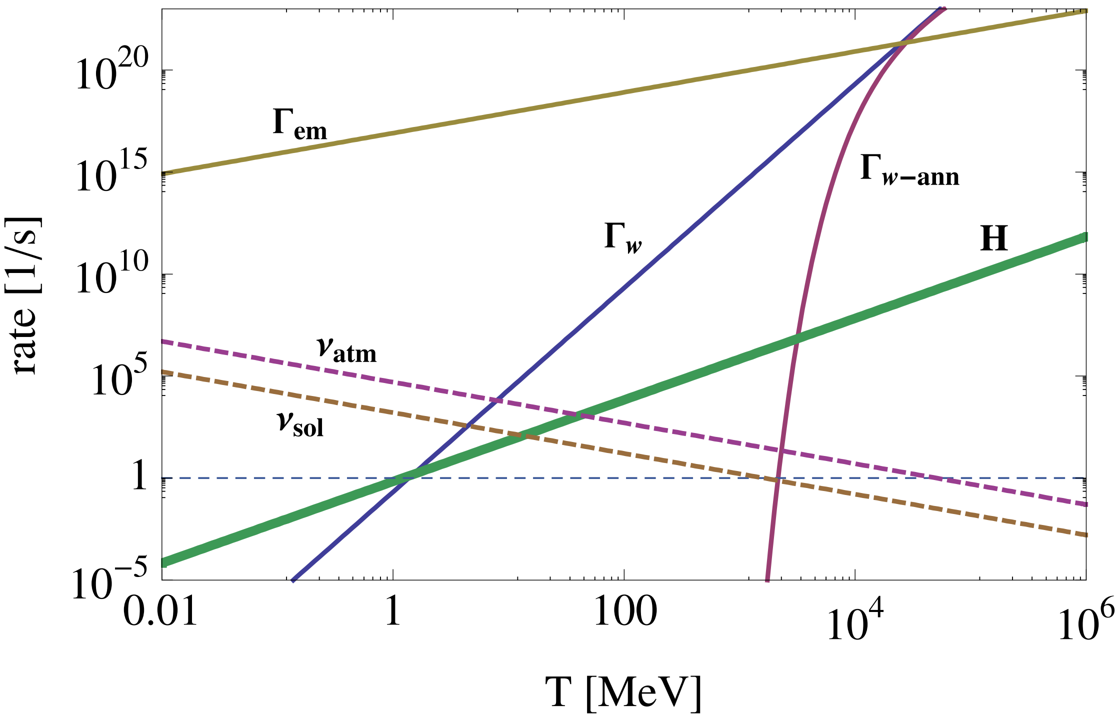
Relativistic degrees of freedom



+ H



Interaction rates



History of the early Universe

...	cosmological inflation
...	grand unification (?), baryogenesis (?)
10^{-11} s	electroweak transition
10^{-5} s	QCD transition
1 s	decoupling of neutrinos and neutrons
100 s	nucleosynthesis & $e^{\pm}$-annihilation
10^{11} s	radiation-matter equality
10^{13} s	atom formation & photon decoupling
...	structure formation

age of the Universe $\sim 10^{17}$ s

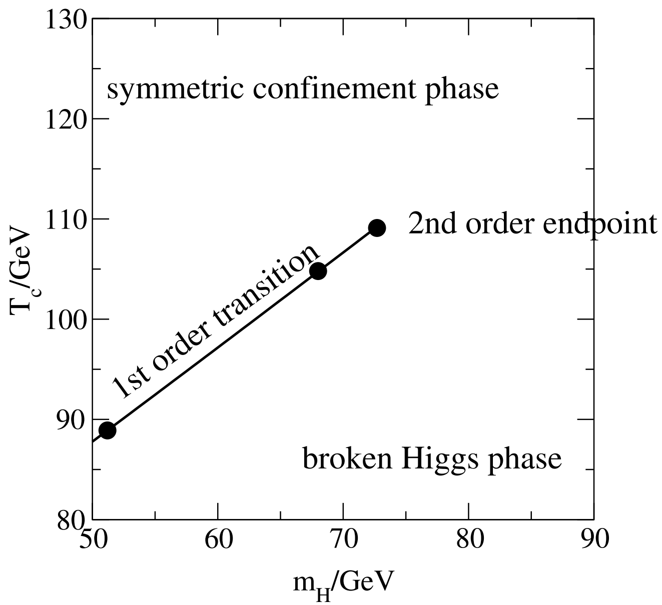
Baryo-/Leptogenesis

Sakharov's conditions (1967):

- baryon/lepton number violation — create baryonic charge
- C and CP violation — distinguish matter from anti-matter
- out of equilibrium — provide a time arrow

standard model of particle physics:
conserves $B - L$, but allows for $B + L$ violation at high temperatures
violates C and CP (but only weakly)
electroweak baryogenesis ? — Kuzmin, Rubakhov & Shaposhnikov 1985

Electroweak transition ($t \sim 10$ ps)



particles obtain masses

scales: $T_{\rm ew} \sim 100$ GeV, $d_{\rm H} \sim 10$ mm

Laine 2000

LHC: $m_H = 126$GeV

no electroweak SM baryogenesis

need to go beyond SM!

Cosmic QCD transition ($t \sim 10$ μs)

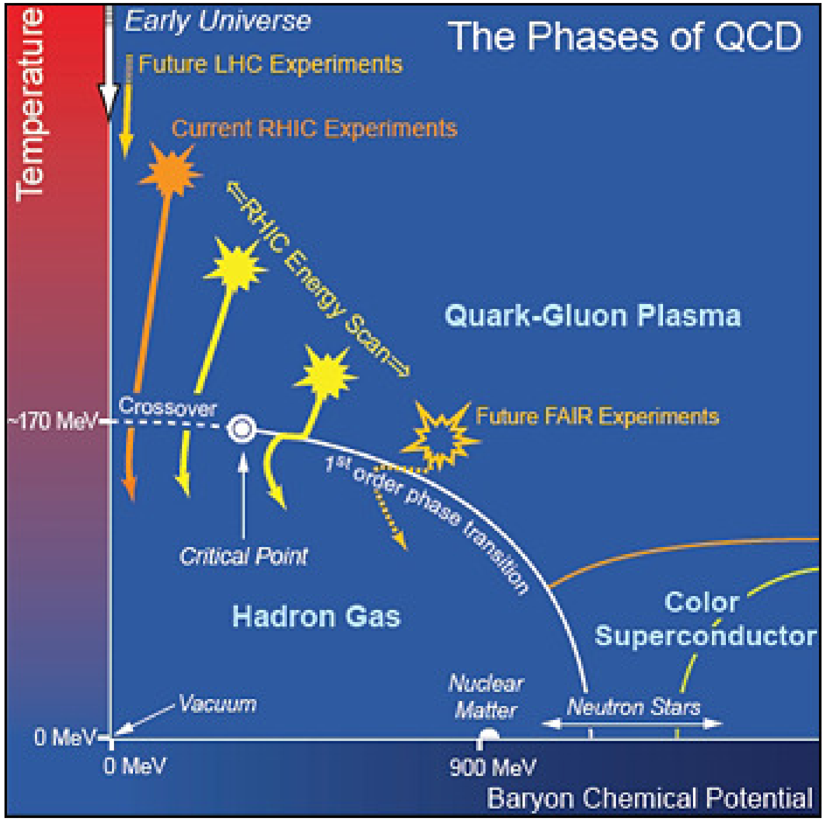
scales: $T \simeq 160$ MeV, $d_{\mathrm{H}} \simeq 10$ km

relics? (strangelets, magnetic fields, primordial black holes, . . .)

initial conditions for primordial nucleosynthesis (homogeneous?)

influence on cosmological perturbations

Phases of strongly interacting matter



$\mu_B = 0$:
crossover transition
at $T = 155(9)$ MeV
Bhattacharya et al. 2014

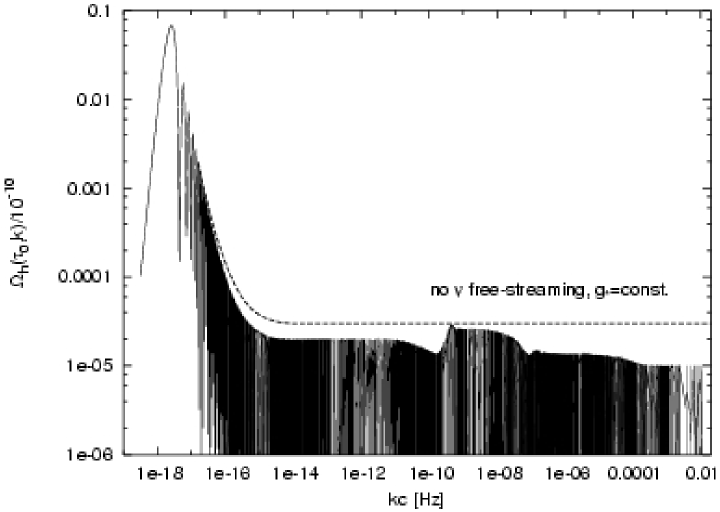
μ_B large enough:
1st order transition

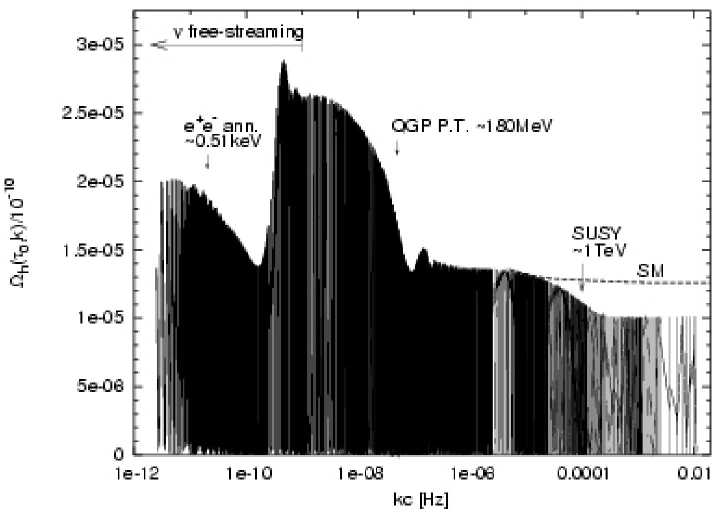
Consequences of QCD transition

• probably no relics (strangelets, magnetic fields, black holes)

crossover, scales too small — Boyanovsky, de Vega & Schwarz 2007

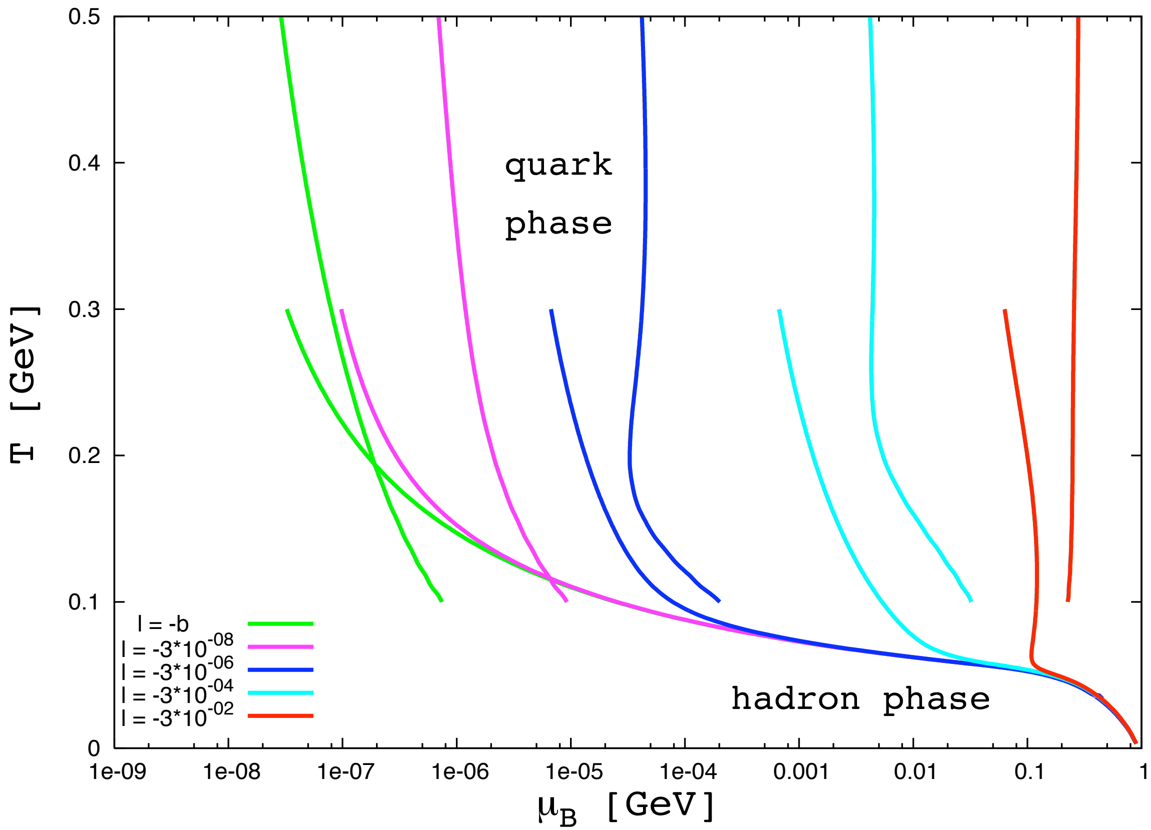
• feature in primordial gravitational wave spectrum — Schwarz 1998





Watanabe & Komatsu 2006

An alternative scenario: large lepton asymmetry



needs further consideration

Schwarz & Stuke 2009

Neutrino decoupling ($t \sim 1$ s)

radiation fluid at $T \sim 1$ MeV: $\gamma, e, \nu_e, \nu_\mu, \nu_\tau$

ν_μ, ν_τ neutral current interactions $\Gamma_{\mu,\tau} = 0.06 G_\mathrm{F}^2 T^5$

ν_e charged and neutral current interactions $\Gamma_e = 0.3 G_\mathrm{F}^2 T^5$

ν decouple at $H \sim \Gamma \Rightarrow T_{\nu_e} = 2.2$ MeV   Hannestad 2007

collisional damping of density perturbations $\delta \equiv \delta\epsilon/\epsilon$

$$\ddot{\delta} + \frac{\eta_\mathrm{visc}}{\epsilon} k_\mathrm{ph}^2 \dot{\delta} + c_s^2 k_\mathrm{ph}^2 \delta = 0 \qquad \text{for} \quad k_\mathrm{ph} \gg H$$

primordial fluctuations are washed out $M \equiv (4\pi/3)\rho_\mathrm{cdm}(\pi/k_\mathrm{ph})^3$

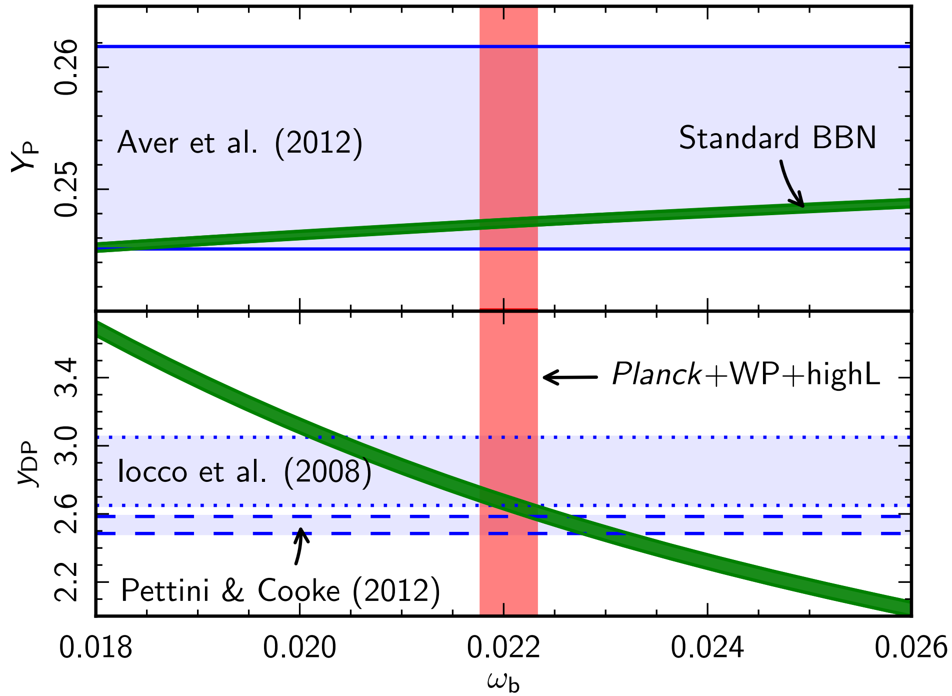
$$\delta \propto \exp\left[-\left(\frac{M_{\nu-\mathrm{dmp}}}{M}\right)^{1/4}\right] \qquad \text{for} \quad M < M_{\nu-\mathrm{dmp}} = 2 \times 10^{-6} M_\odot$$

Schmid, Schwarz & Widerin 1999

Primordial nucleosynthesis (D, ^{3}He, ^{4}He, ^{7}Li)

$N_\nu = 3$ & homogeneity
deuteron binding energy 1.2 MeV
small baryon density
$\omega_b = 3.66 \times 10^7 \eta$, $\eta \equiv n_b/n_\gamma \simeq 6.1 \times 10^{-10}$

$t < 1$ s: neutrons in β-equilibrium
$X_n \equiv n_n/n_p \simeq 1/6$
$t > 100$ s: neutrons decay, $X_n \simeq 1/7$
$t <$ few minutes: nucleosynthesis
$Y_p \equiv \rho_{^4\mathrm{He}}/\rho_b \simeq 1/4$



CMB	$\omega_b = 0.02205(28)$	Planck: Ade et al 2014
D/H	$\omega_b = 0.02202(20)(41)$	Cooke et al 2013
^{7}Li	problem	Coc et al 2001

Planck: Ade et al 2014

Bounds on new physics

N_ν effective number of neutrino dof

$H \simeq 1.66(2 + \frac{7}{4}N_\nu + \ldots)^{1/2} T^2 / M_{\rm P}$

non-trivial agreement of

BBN (^{4}He & D/H) constraint (blue)

and

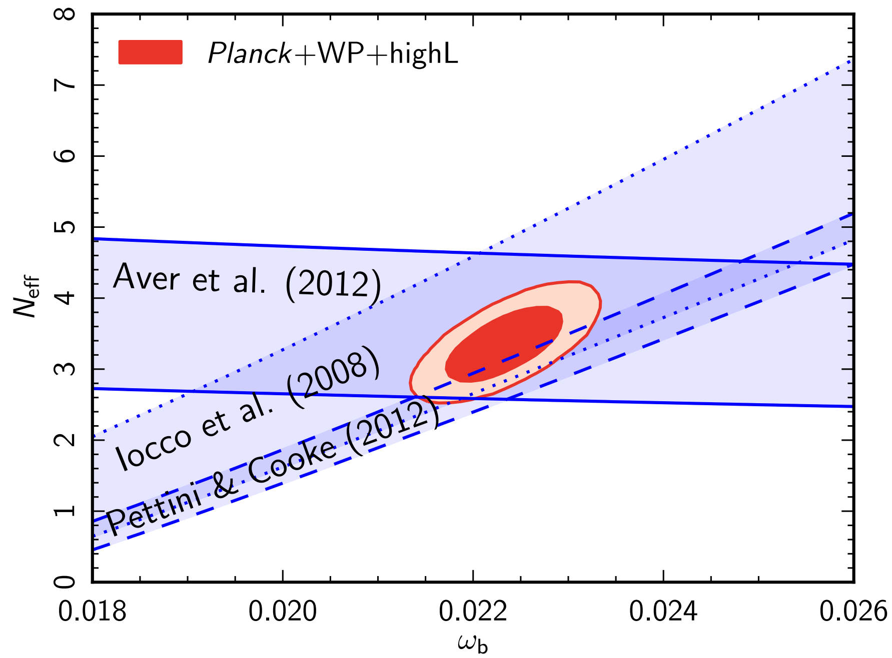
CMB constraint (red)

impressive agreement with LEP:

$N_\nu = 2.994 \pm 0.012$ SM fit

$N_\nu = 2.92 \pm 0.06$ invisible Z width

PDG 2006



Planck: Ade et al 2014

Evidence for non-baryonic (non-nuclear) matter

from CMB: $\omega_{\rm m} = 0.127^{+0.009}_{-0.007}$ Planck collaboration 2014

from BBN: $\omega_{\rm b} = 0.02202(20)(41)$ Cooke et al. 2013

non-baryonic (non-nuclear) component with non-relativistic eos
$\Rightarrow$ cold dark matter (cdm)

caveat: primordial black holes, strangelets, etc.
could carry baryon number, but would not participate in BBN;
thus $\omega_{\rm b} = \omega_{\rm m}$ not excluded, rather $\omega_{\rm nuclei} \sim 0.15\,\omega_{\rm m}$

$e^{\pm}$ annihilation

$e^{\pm}$ annihilation happens at $T \sim m_e/3 \sim 0.2$ MeV

at that time νs are decoupled, T_γ increases relative to T_ν

after $e^{\pm}$ annihilation:

$$T_\nu(t) = \left(\frac{4}{11}\right)^{1/3} T_\gamma(t), \qquad T_\nu(t_0) = 1.946 \pm 0.001 \text{ K}$$

indirect detection: $N_\nu > 0$ from BBN and CMB independently

Photon decoupling — cosmic microwave background

binding energy of H-atom 13.6 eV

2s $\rightarrow$ 1s forbidden

$\eta = \frac{4}{11}\eta_{\rm BBN} \simeq 2 \times 10^{-10}$

high entropy delays atom formation:

$T_{\rm atom} \sim 0.3$ eV

fraction of free electrons x_e drops,

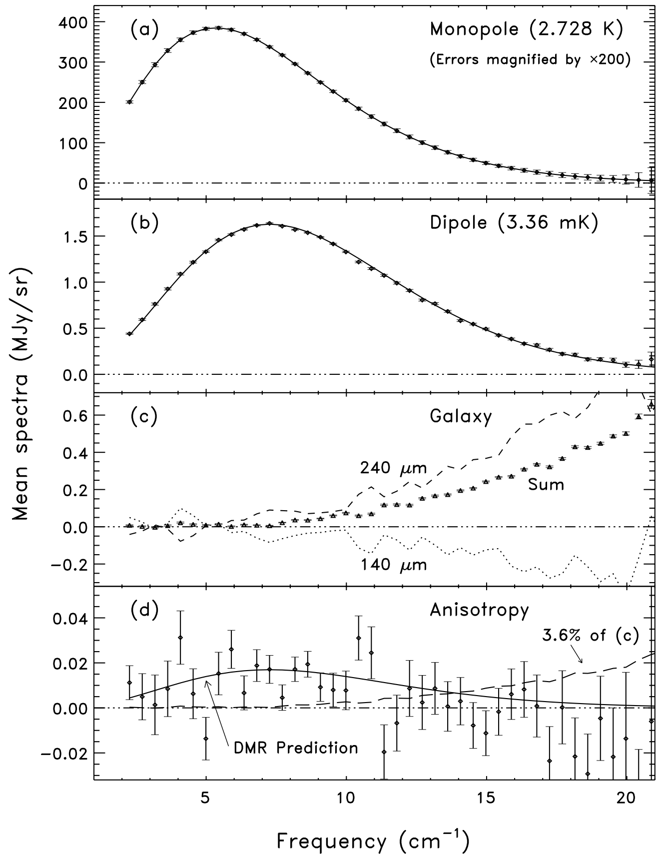
photons decouple:

$T_{\rm dec} \sim 0.2$ eV, $z_{\rm dec} \sim 1100$

$t_{\rm dec} \sim 350,000$ yr

Planck spectrum

$T_0 = 2.7255 \pm 0.0006$ K



Fixsen et al. 1997

Summary of 3rd lecture

heating up after inflation
10^2 GeV (min. scale for baryogenesis) $< T_{\rm rh} < 10^{16}$ GeV

series of (thermal) phase transitions gut, ew, qcd

synthesis of light nuclei: 75% H, 25% ^{4}He, rest metals ($< 1\%$)

formation of atoms and photon decoupling:
cosmic microwave background

physical parameters: $T_{\rm rh}, T_0, \omega_{\rm b}, (l$ or $\mu_\nu)$

what is the mechanism to generate a tiny baryon/lepton excess?
$n_b/s = (8.2 \pm 0.4) \times 10^{-11}$ and how small/big is n_l/s?