Five lectures on

PARTICLE 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

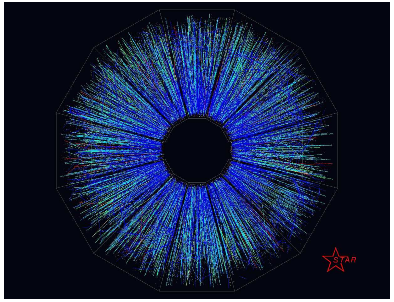
Lecture 5: Cosmic substratum

evidence and candidates for dark matter and dark energy, direct and indirect dm searches

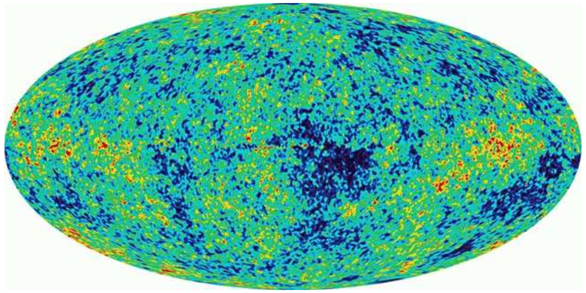
History of the Universe

LHC dipole

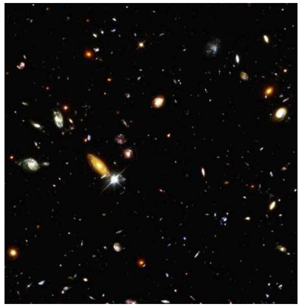
RHIC-event (STAR)

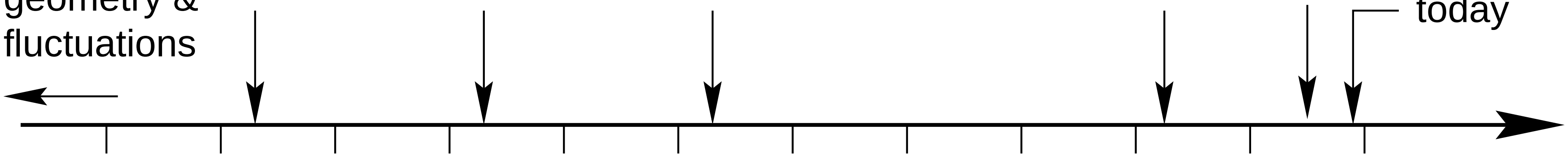


Sky from WMAP



Hubble Deep Field





geometry &
fluctuations

masses

hadrons

nucleosynthesis

3K radiation

galaxies

today

10^{-12} s

10^{-6} s

10^{0} s

10^{6} s

10^{12} s

10^{18} s

inflation

radiation

matter

?

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

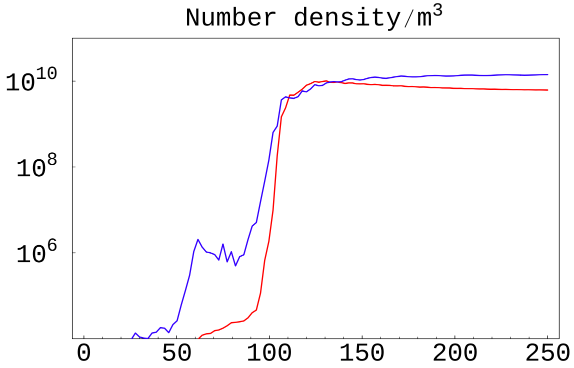
need to heat up and generate matter-antimatter asymmetry

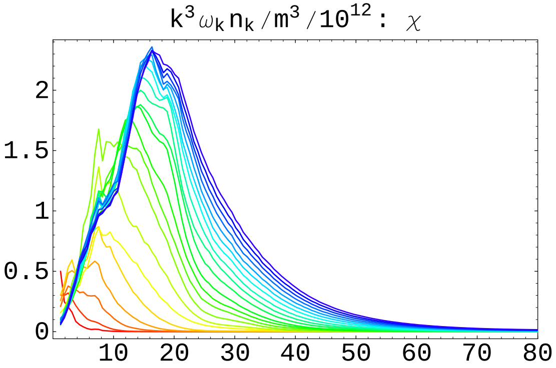
Preheating and thermalisation

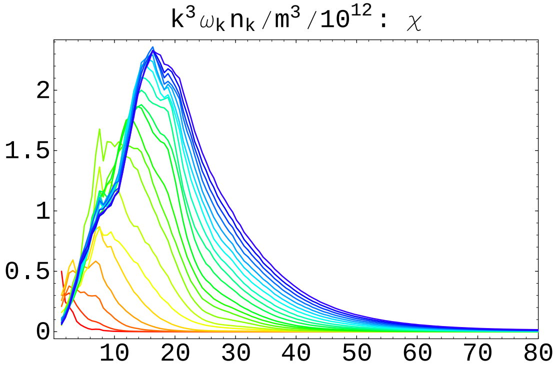
coherent oscillations of inflaton ϕ $$V = \frac{1}{2}m^2\phi^2 + \frac{1}{2}g^2\phi^2\chi^2$$

decay into ϕ and χ “particles” $$m = 10^{-6}M_{\mathrm{P}}$$

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







time in units of $1/m$

Felder & Kofman 2007

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

Radiation-dominated Universe

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

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

$\Gamma/H \sim \alpha_{\mathrm{GUT}} M_{\mathrm{P}}/(g^{1/2}T) \sim 10^{16}\mathrm{GeV}/T$

Friedmann equations (flat Universe):

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

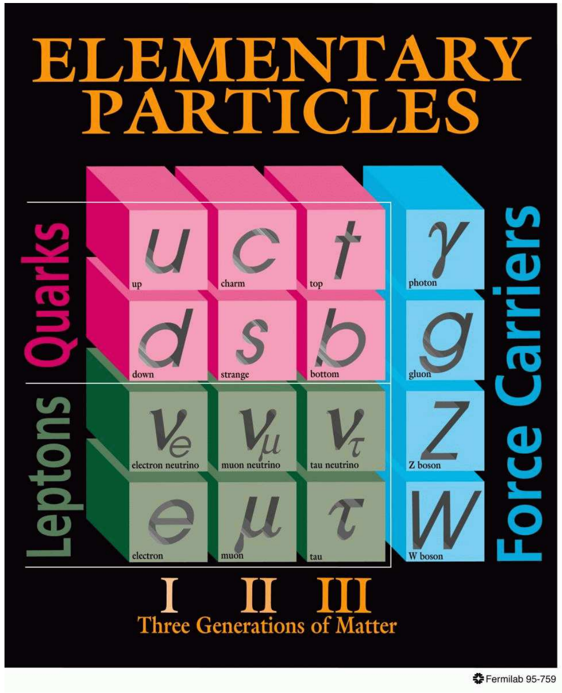
for ultrarelativistic particles ($T \gg m$)

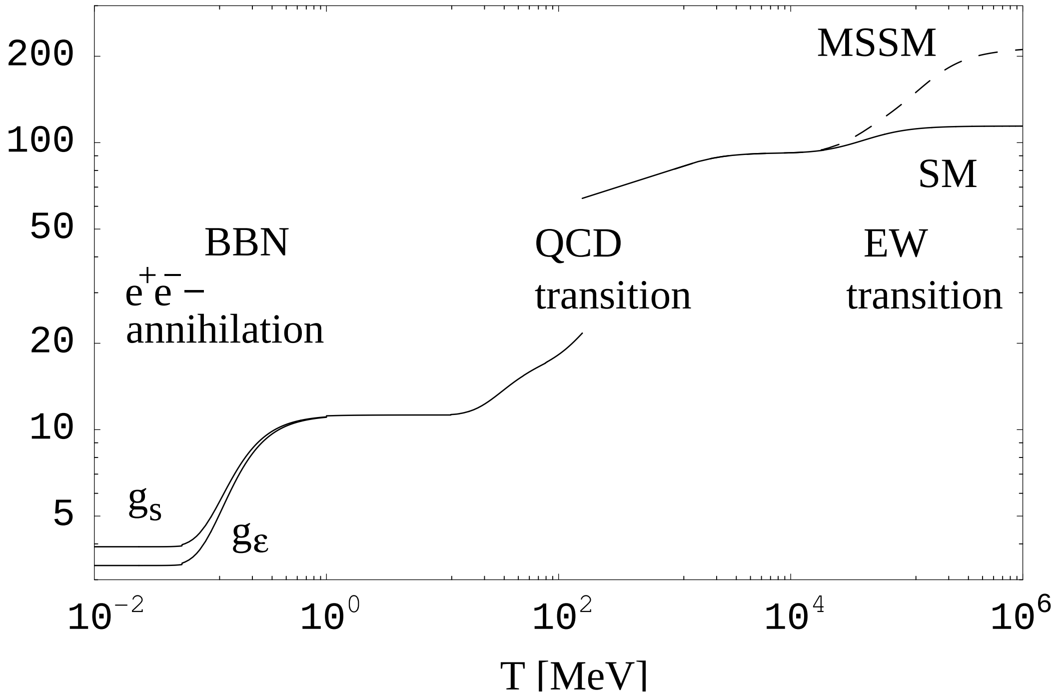
$$p = \frac{\pi^2}{90} g(T) T^4 \quad \text{in thermodynamic equilibrium}$$

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

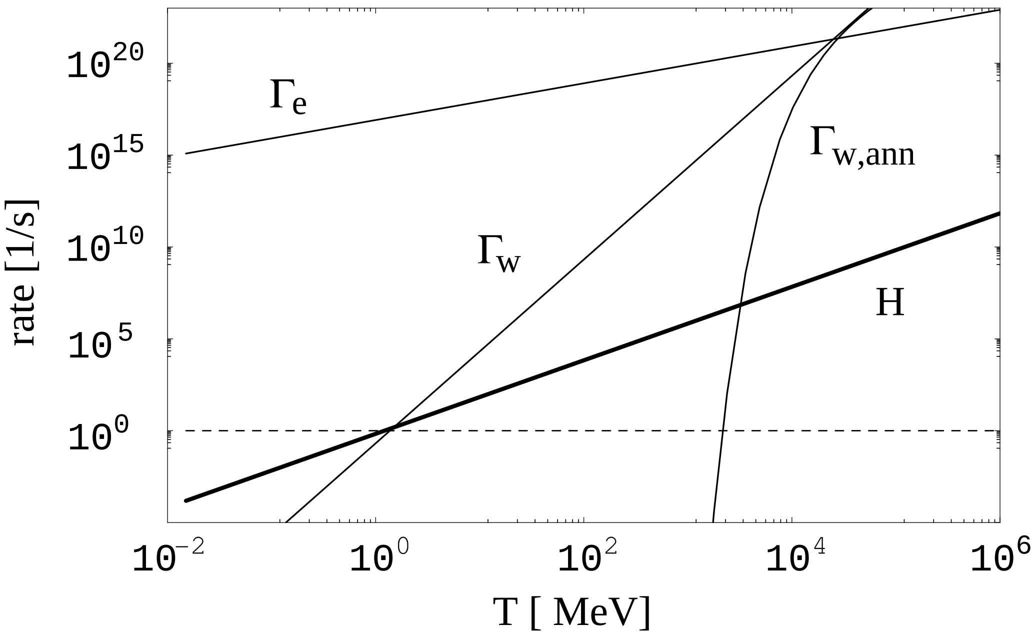
$\sum_i \Omega_i = 1$; $\omega_i = \Omega_i h^2$ ($i =$ b, ν, cdm, ...)

Relativistic degrees of freedom





Interaction rates

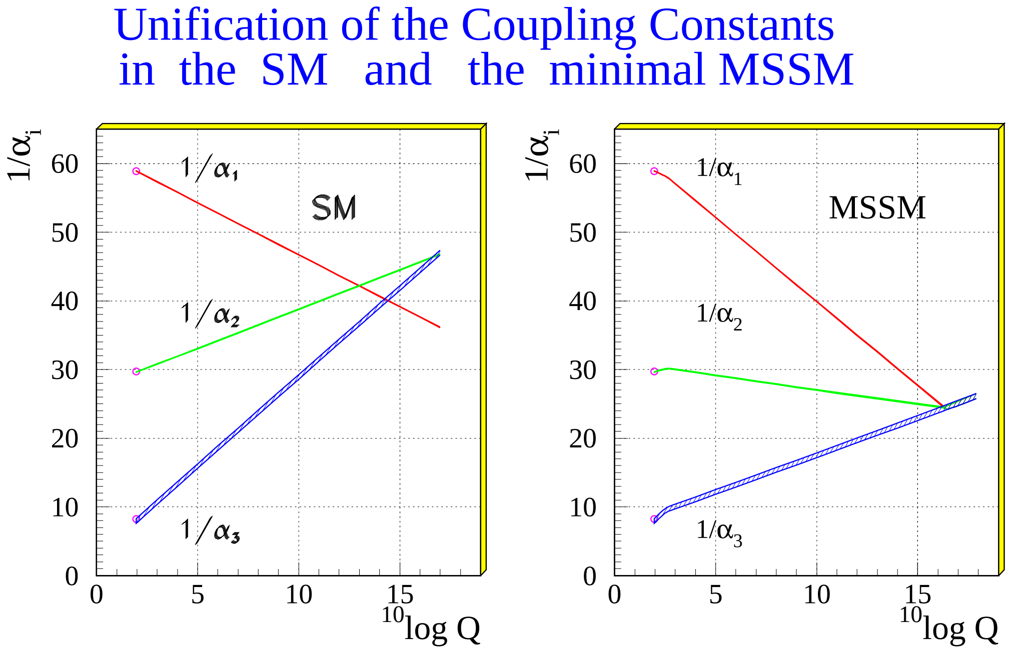


History of the early Universe

. . .	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

Grand unification



Unification of the Coupling Constants
in the SM and the minimal MSSM

scale Q in GeV Kazakov 2000

Is T_{rh} high enough to realise unification in the early Universe?

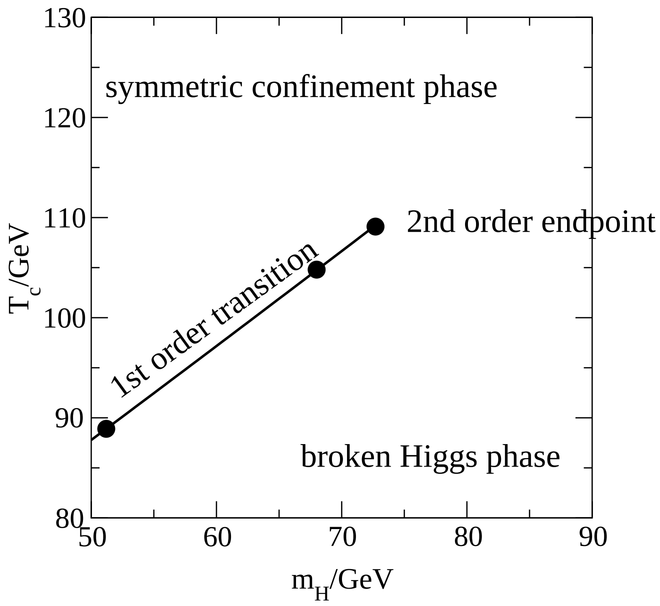
Baryogenesis

Sakharov's conditions (1967):

- baryon 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: $T_{\mathrm{ew}} \sim 100$ GeV, $d_{\mathrm{H}} \sim 10$ mm

Laine 2000

LEP: $m_H \geq 115$GeV

no electroweak SM baryogenesis

MSSM parameter space allows 1st order transition and baryogenesis

Cosmic QCD transition ($t \sim 10\ \mu$s)

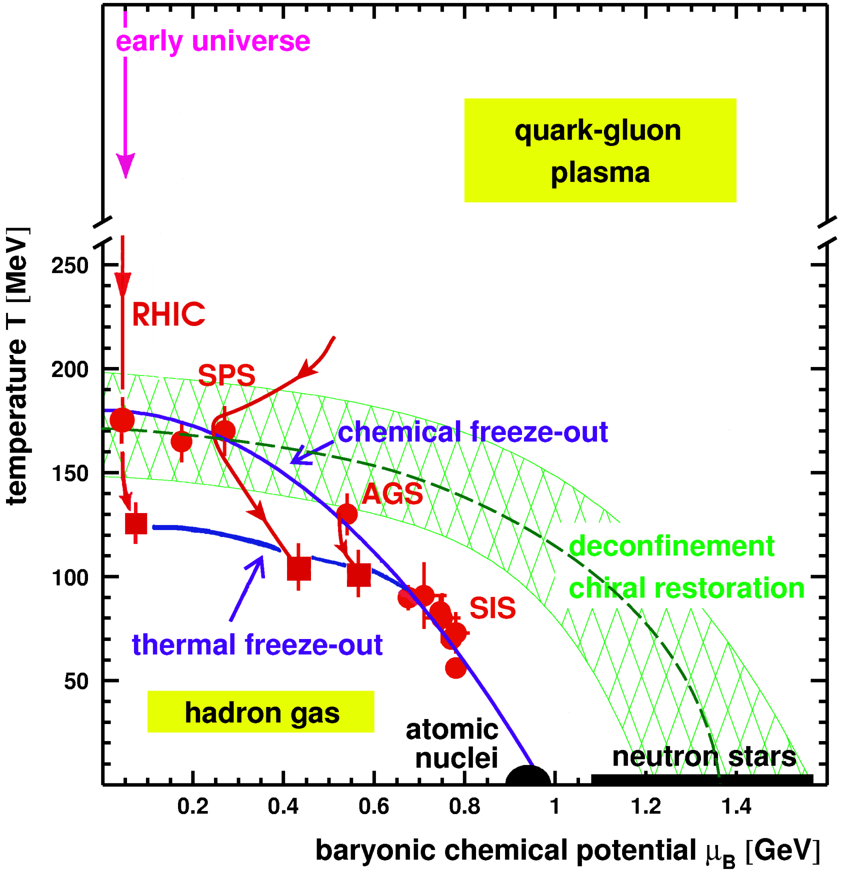
scales: $T \simeq 160$ MeV, $d_{\mathrm{H}} \simeq 10$ km

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

initial conditions for primordial nucleosynthesis (homogeneous?)

influence on cosmological perturbations

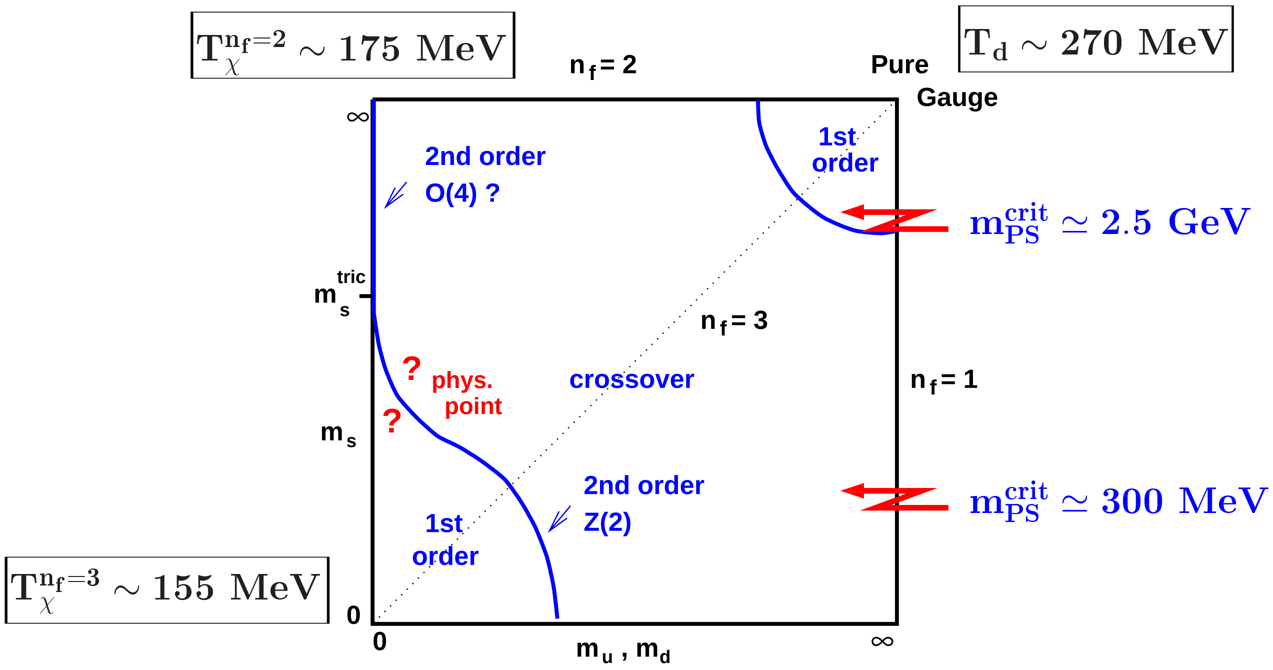
Sketch of the QCD phase diagram



Heinz 2001

Lessons from lattice QCD

3-flavour phase diagram



$\boxed{T_\chi^{n_f=2} \sim 175 \text{ MeV}}$

$\boxed{T_d \sim 270 \text{ MeV}}$

$\boxed{T_\chi^{n_f=3} \sim 155 \text{ MeV}}$

$m_{PS}^{crit} \simeq 2.5$ GeV

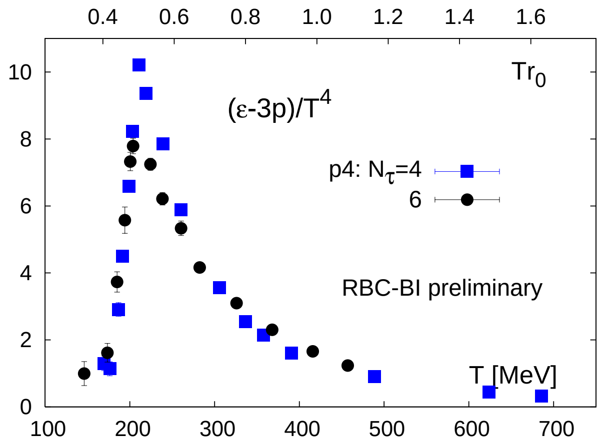
$m_{PS}^{crit} \simeq 300$ MeV

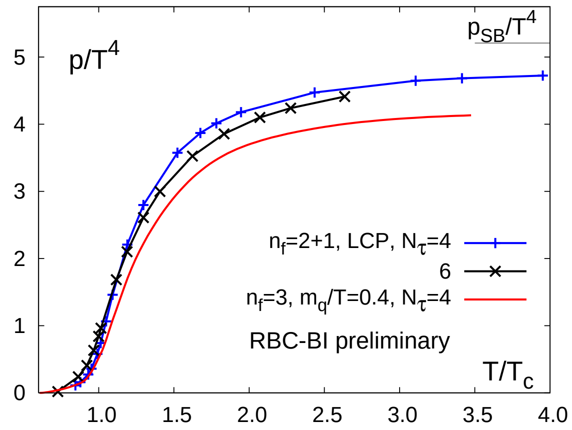
Karsch 2001

Order of the transition, T_{QCD} and equation of state

lattice QCD indicates for physical quark masses that transition is crossover

transition temperature $T_{\mathrm{QCD}} = 192(7)(4)$ MeV Cheng et al. 2006, but $T_{\mathrm{QCD}} = 151(3)(3)$ MeV Aoki et al. 2006





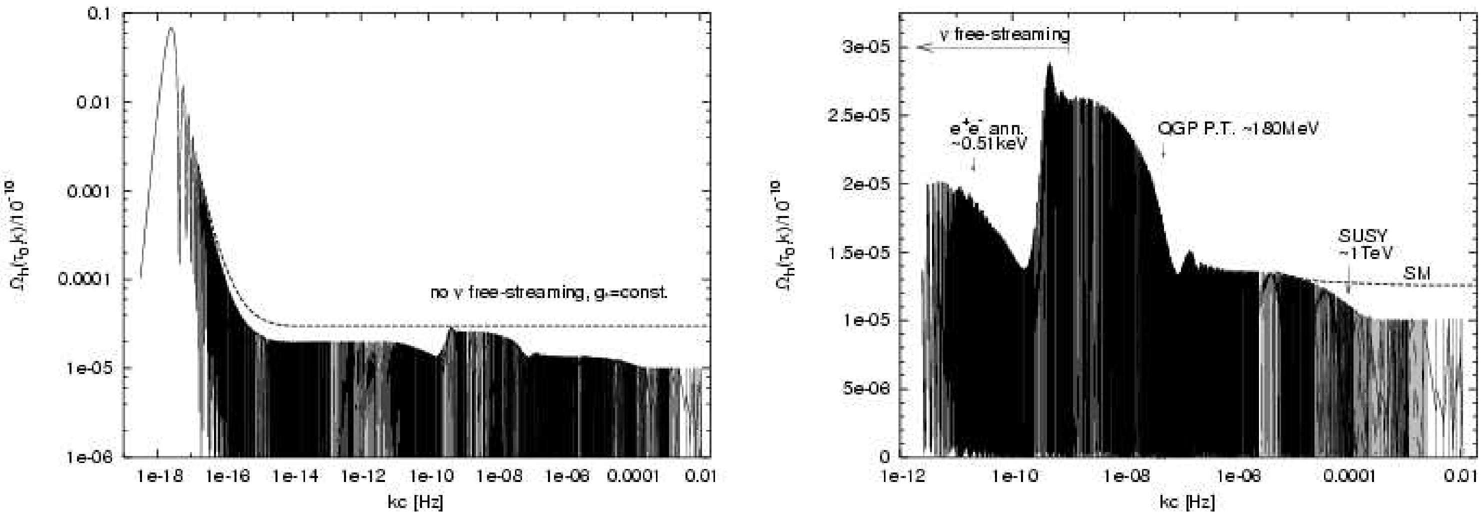
Karsch 2006

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

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

Initial conditions for nucleosynthesis

no isentropic density perturbations for $M < 10^{-6} M_\odot$ or $l < 10^4$ km

$M_\mathrm{H} \simeq 0.1 M_\odot$ or $d_\mathrm{H} \simeq 4 \times 10^5$ km at $T = 1$ MeV

nucleon diffusion

$l_{\mathrm{N-diff}} \simeq 200$ m at $T = 1$ MeV

$\simeq 2$ m at $T = 100$ MeV

no fluctuations in

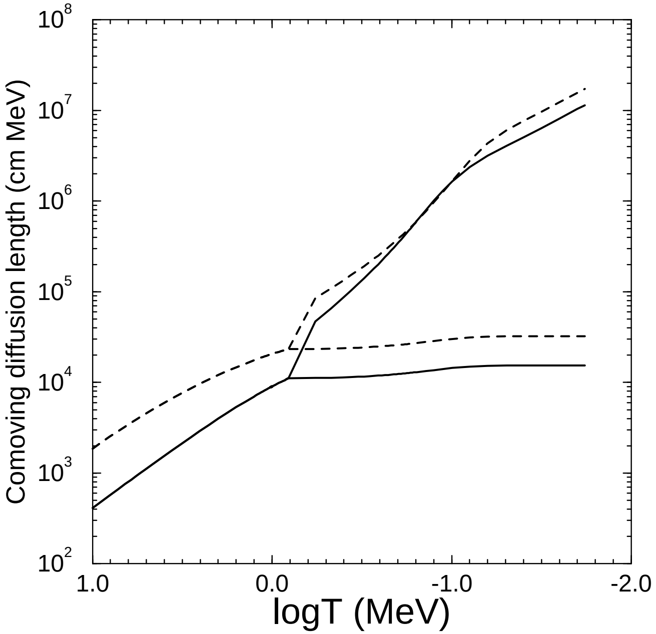
$\eta \equiv n_\mathrm{B}/n_\gamma$ and $X_n \equiv n_n/n_p$

for $l < l_{\mathrm{N-diff}}$

allowed range for entropy perturbations

in n_p/n_γ: > 0.2 km,

in n_n/n_γ: > 10 km



Shu & Mathews 1998

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

$N_\nu = 3$ & homogeneity

deuteron binding energy 1.2 MeV

small baryon density

$\omega_\mathrm{b} = 3.66 \times 10^7 \eta$, $\eta \equiv n_\mathrm{b}/n_\gamma \simeq 6.1 \times 10^{-10}$

$t < 1$ s: neutrons in β-equilibrium

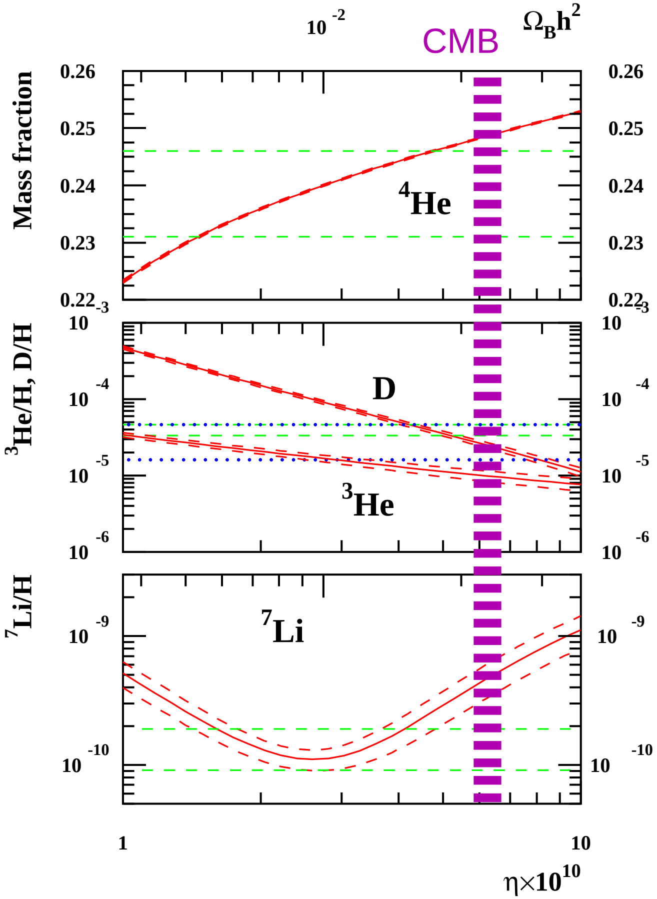
$X_n \equiv n_n/n_p \simeq 1/6$

$t > 100$ s: neutrons decay, $X_n \simeq 1/7$

$t <$ few minutes: nucleosynthesis

$Y_p \equiv \rho_{^4\mathrm{He}}/\rho_\mathrm{b} \simeq 1/4$

CMB	$\omega_\mathrm{b} = 0.02229(73)$	Spergel et al. 2006
D/H	$\omega_\mathrm{b} = 0.0213(13)(4)$	O'Meara et al. 2006
^{7}Li	$\omega_\mathrm{b} = 0.006$–$0.016$	Coc et al. 2001



Coc et al 2001

Bounds on new physics

N_ν effective number of neutrino dof

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

non-trivial agreement of

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

and

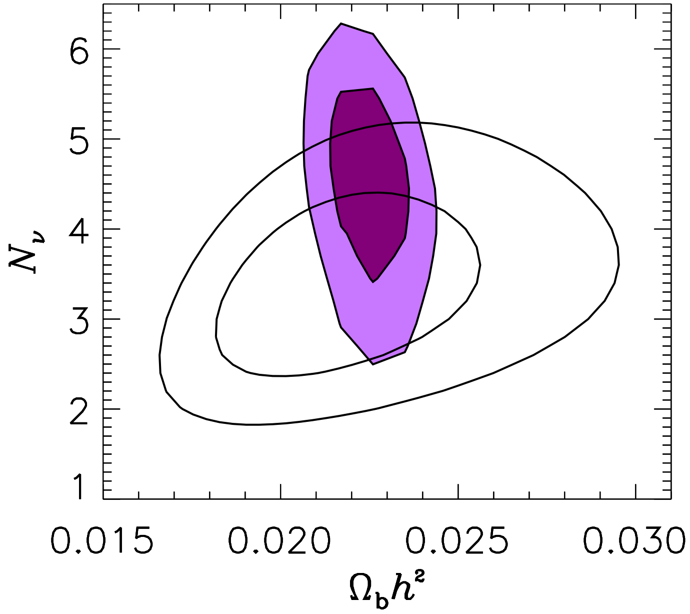
CMB & LSS & SN1a constraint (coloured)

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



Hannestad 2005

Evidence for non-baryonic (non-nuclear) matter

flatness + SN 1a require $\Omega_{\mathrm{m}} \sim 0.3$ or $\omega_{\mathrm{m}} \sim 0.15$ with $h = 0.7$

from CMB: $\omega_{\mathrm{m}} = 0.127^{+0.009}_{-0.007}$ Spergel et al. 2006

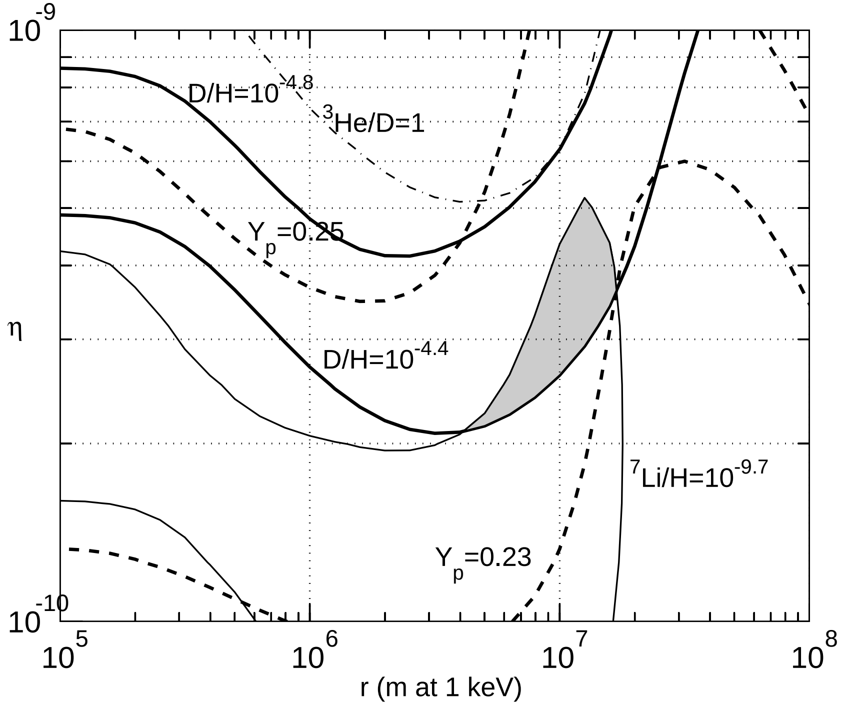
from BBN: $\omega_{\mathrm{b}} = 0.0213(13)(4)$ O'Meara et al. 2006

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

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

Inhomogeneous nucleosynthesis

geometry
typical distances
volume fraction of inhomogeneities
density contrast of baryons



Keihänen 2002

existence of non-nuclear matter robust

$e^{\pm}$ 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/SN1a independently

Photon decoupling — cosmic microwave background

binding energy of H-atom 13.6 eV

2s → 1s forbidden

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

high entropy delays atom formation:

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

fraction of free electrons x_e drops,

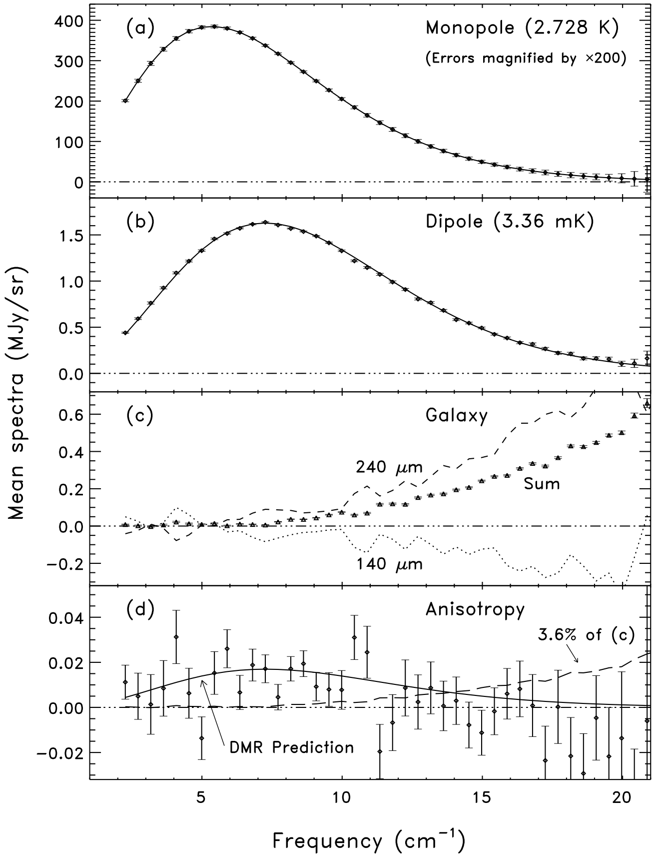
photons decouple:

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

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

Planck spectrum

$T_0 = 2.725 \pm 0.001$ K



Fixsen et al. 1997

Limits on new physics

e.g. decay of massive particles

pseudo-chemical photon potential $|\mu/T_0| < 9 \times 10^{-5}$:
limit on energy release at $10^5 < z < 3 \times 10^6$ (no chemical equilibration)

Compton parameter $|y| \equiv |\int \sigma(T_e - T_\gamma)/m_e \mathrm{d}\tau| < 1.5 \times 10^{-5}$:
limit on energy release at $z < 10^5$ (no thermalisation)
$\mathrm{d}\tau \equiv \sigma x_e n_e \mathrm{d}l_\mathrm{p}$ infitesimal optical depth

COBE/FIRAS

residual ionization $x_e \sim 10^{-5}$

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: $T_{\rm rh}, T_0, \omega_{\rm b}$

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