The lepton asymmetry of the Universe

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based on work with Glenn Starkman and Maik Stuke

Schwarz & Stuke, JCAP 0911 (2009) 025

Stuke, Schwarz & Starkman, JCAP 1203 (2012) 040

Schwarz & Stuke, NJP 15 (2013) 033021

Brussels April 2013

Outline

Introduction

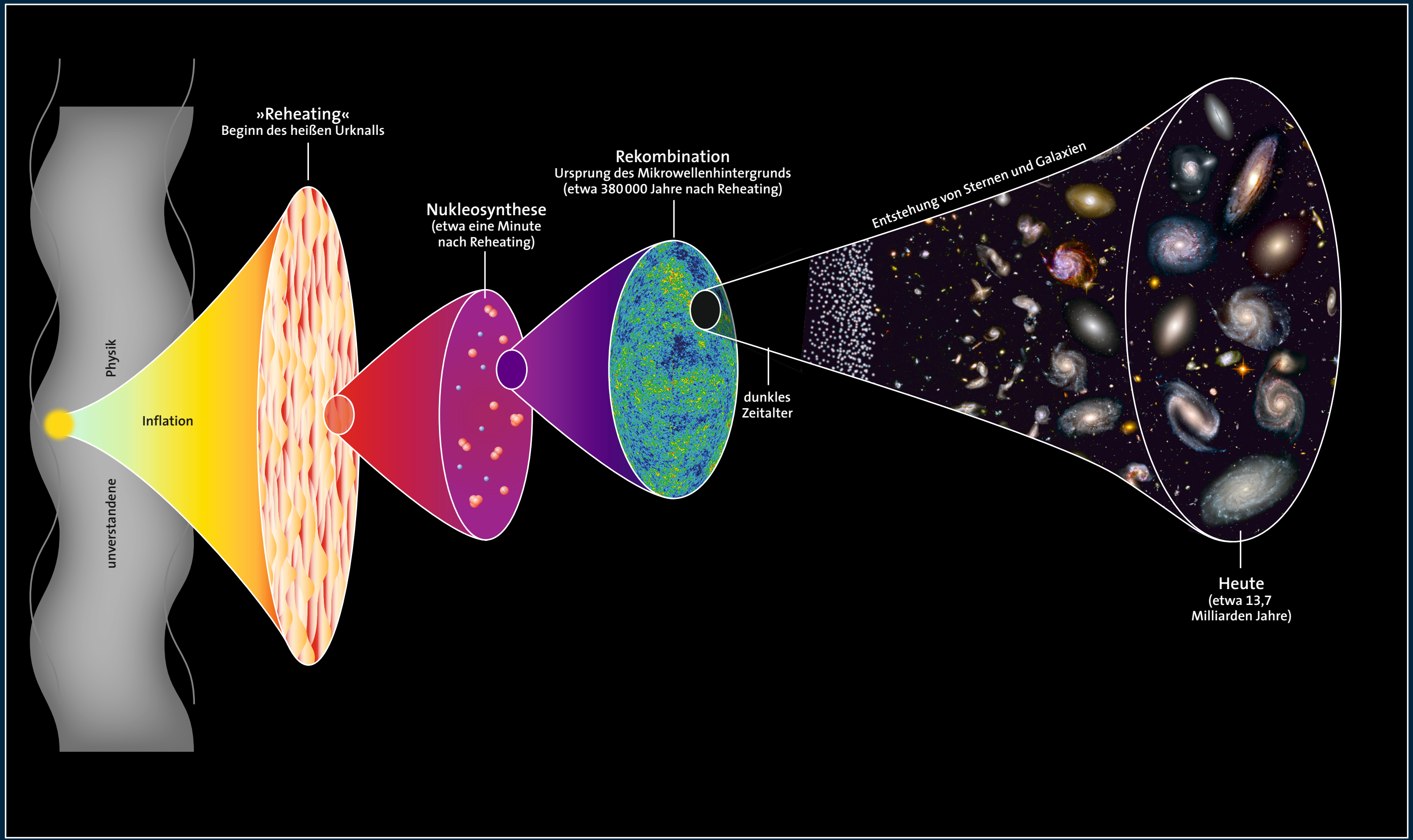
What do we know about l and l_f?

Cosmic evolution of chemical potentials

The cosmic QCD transition and large l and/or l_f

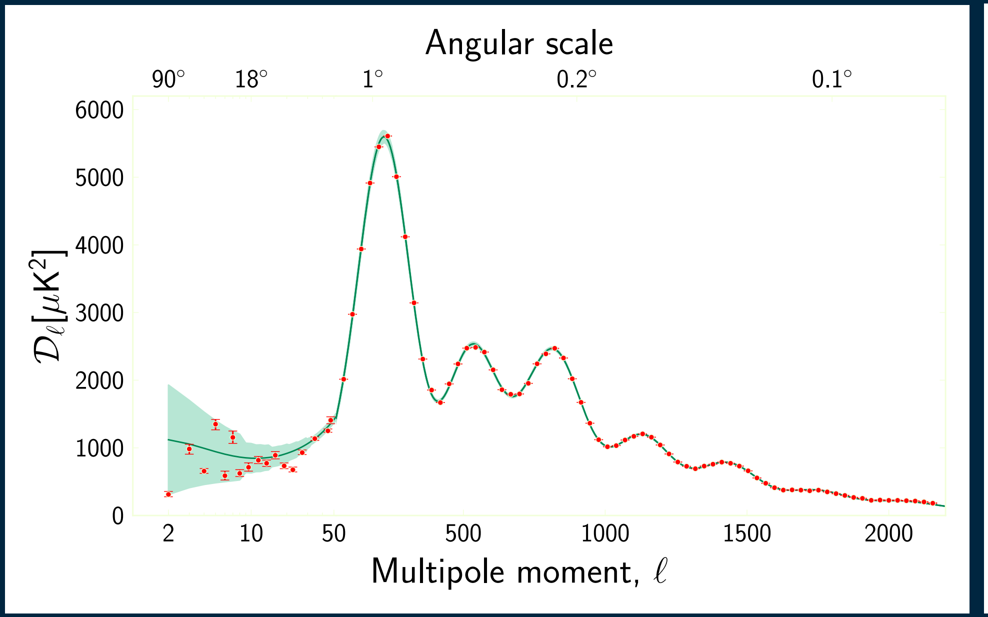
WIMP freeze-out and large l and/or l_f

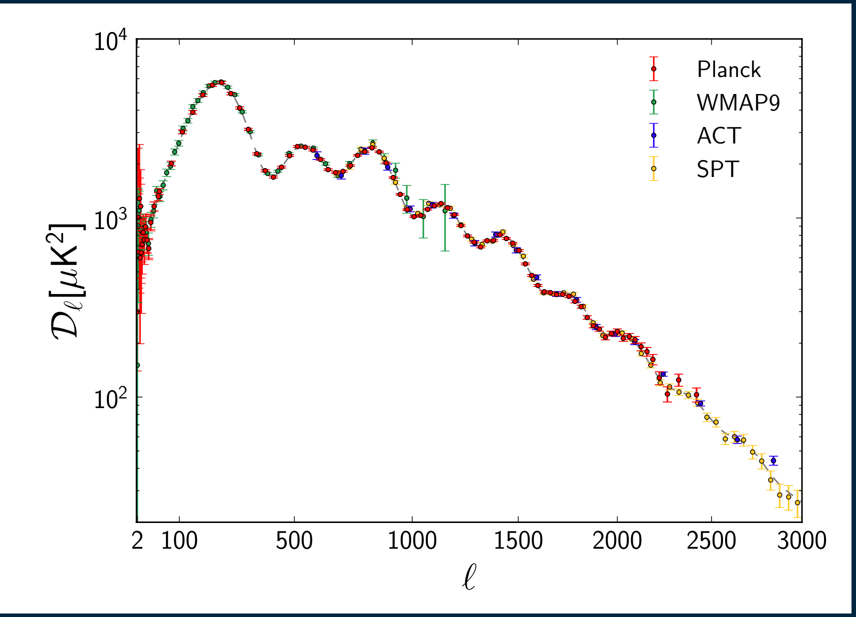
Conclusion



inflation baryo-/leptogenesis ew WIMPs qcd ν-oscillations bbn γ-decoupling structure

Angular power spectra of the cmb





Planck 2013 results. I.

Planck, WMAP, ACT, SPT

The cosmological standard model

inflation:

- isotropic & homogeneous
- spatially flat
- scale invariant structures
- isentropic & gaussian

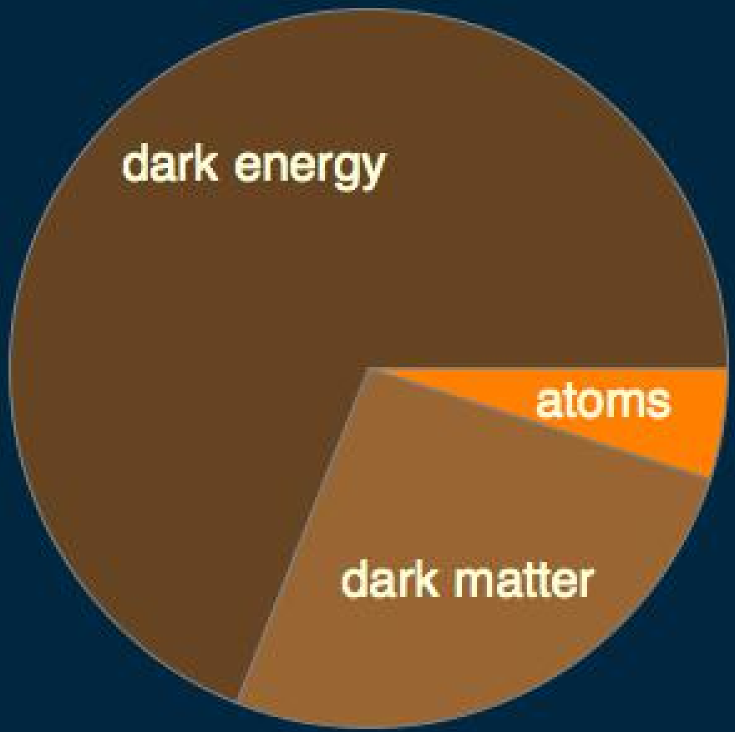
content:

- photons & neutrinos $\leq 1\%$
- baryons & electrons 5%
- cold dark matter 26%
- cosmological constant 69%

flat ΛCDM model

7 (9) parameters

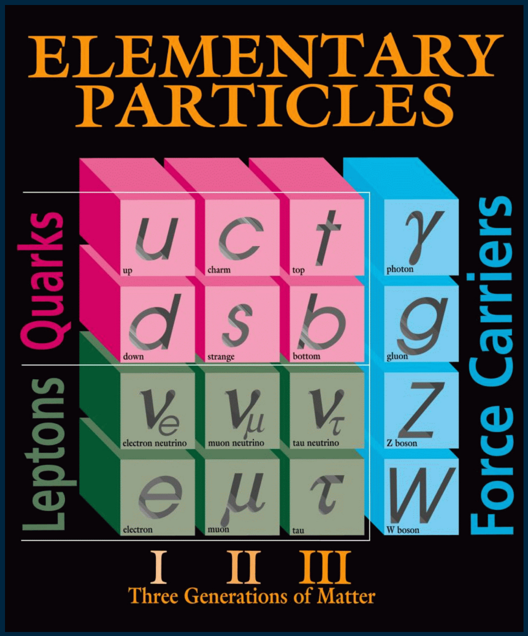
$T_0, \omega_b, \omega_m, h, A, n, \tau, (\omega_\nu, r)$



errors ~ 1 %

Planck 2013 results XVI

What do we know about matter?



+ Higgs boson

dark matter and dark energy (we don't know what it is)

known matter characterized by quantum numbers
charge Q, baryon number B, lepton (flavour) number L_f

Specific quantum numbers of the Universe

specific quantum number $\equiv$ quantum number per entropy

entropy conservation is an excellent approximation,

if radiation dominates and $t \gg 1/\Gamma$, i.e. below $T_{\rm gut}$

charge asymmetry: $q = 0$ or extremely tiny

baryon asymmetry: $b \equiv (n_B - n_{\bar{B}})/s \simeq 10^{-10}$ measured!

before νs can oscillate:

lepton flavour asymmetries: $l_f \equiv (n_{L_f} - n_{\bar{L}_f})/s = ?$ $\quad l = \sum_f l_f$

once ν-oscillation happens:

lepton asymmetry: $l \equiv (n_L - n_{\bar{L}})/s = ?$ unless neutrinos are Majorana particles

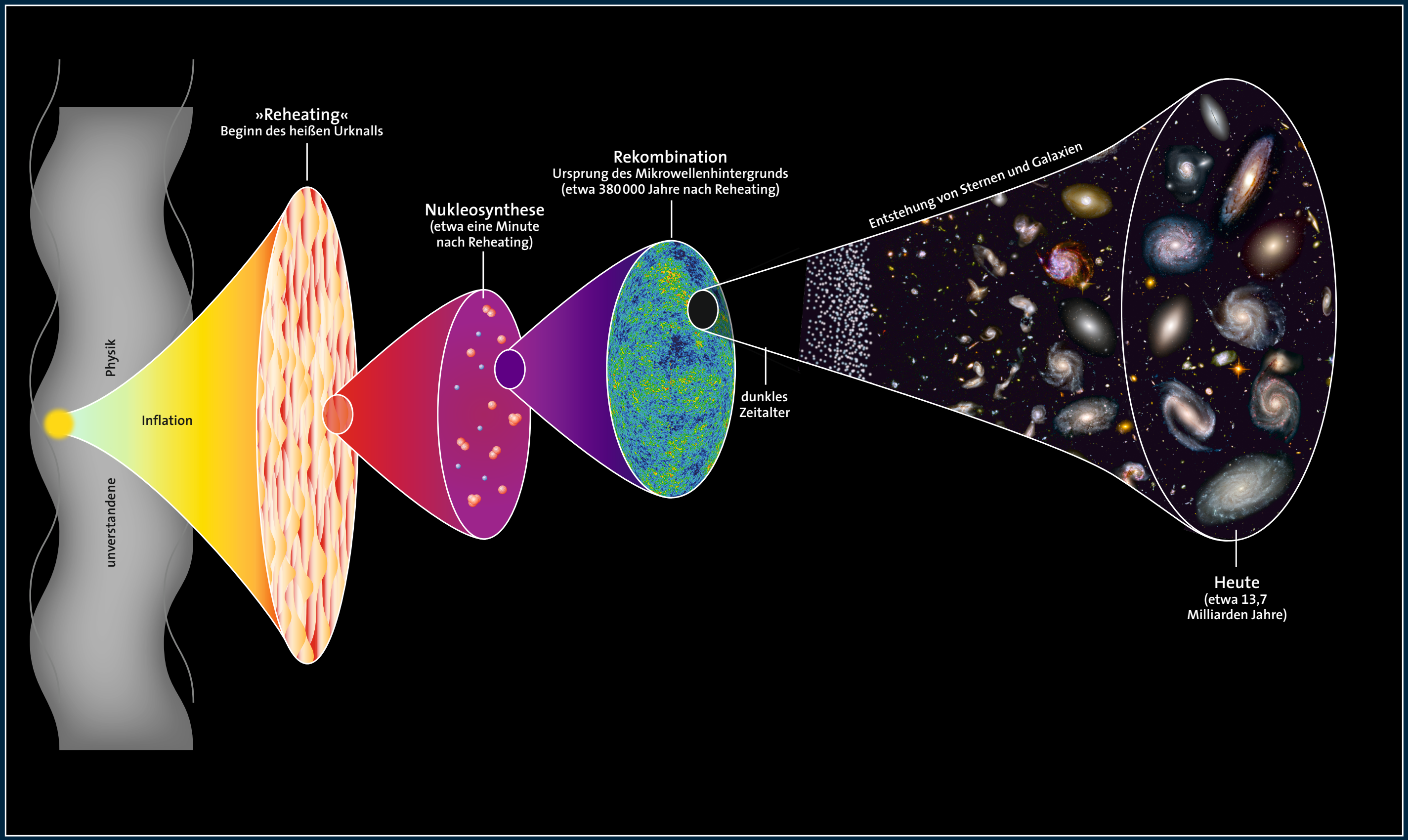
Baryo-/Leptogenesis

generate baryon and/or lepton number after end of inflation

three conditions:
B or/and L violation
C and CP violation
departure form equilibrium

many proposals exist at and well above electroweak scale
only B-L conserved above T_{ew} — sphaleron processes

if baryo-/leptogenesis well before electroweak transition
and if sphaleron processes are efficient: $l = \mathcal{O}(b)$



inflation baryo-/leptogenesis ew WIMPs qcd ν-oscillations bbn γ-decoupling structure

Constraints on lepton asymmetry from the CMB

lepton asymmetry increases the effective number of neutrinos, $N_{\text{eff}} = 3 + \Delta N$

$$\Delta N = \frac{15}{7} \sum_f \left[\left(\frac{\xi_f}{\pi} \right)^2 + \frac{1}{2} \left(\frac{\xi_f}{\pi} \right)^4 \right], \qquad \xi_f \equiv \frac{\mu_f}{T}$$

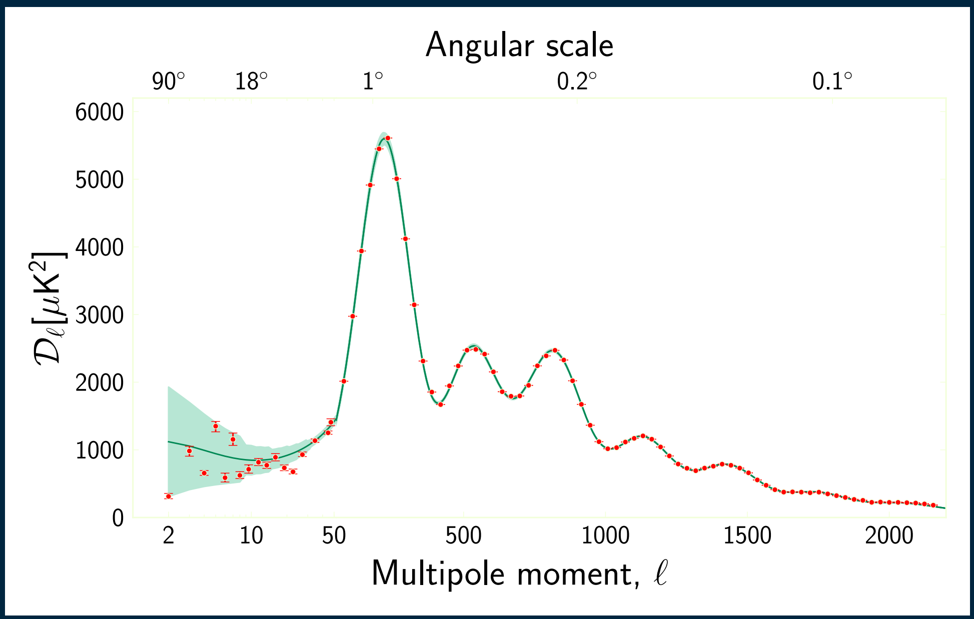
neutrino oscillations wash out lepton flavour well before BBN,

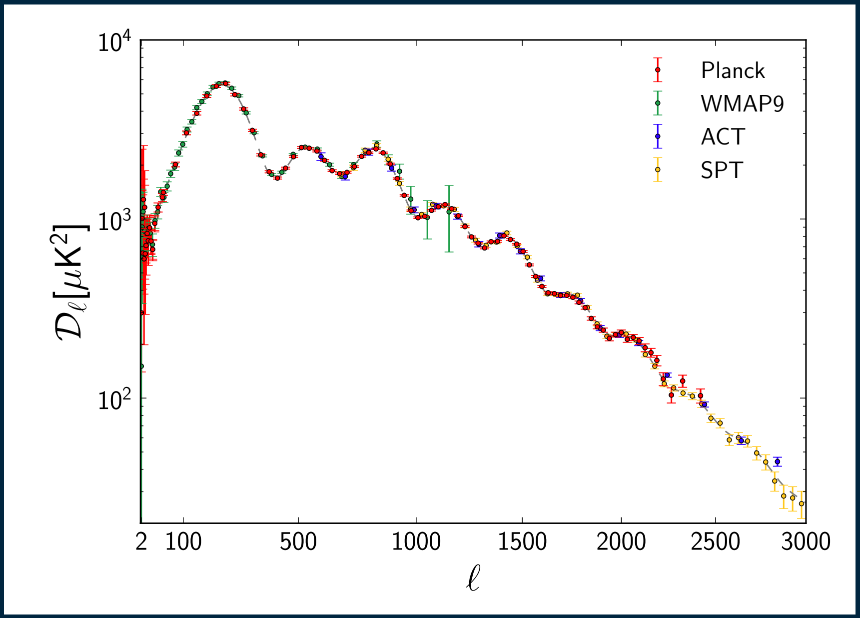
thus $\xi_f = \xi$

for three light neutrinos:

$$l = \frac{45}{43\pi^2} \frac{\xi[1 + (\xi/\pi)^2]}{[1 + 45/86(\xi/\pi)^2]}, \qquad m_\nu/3 < T_\nu < T_{\text{e}^\pm}$$

Angular power spectra of the cmb

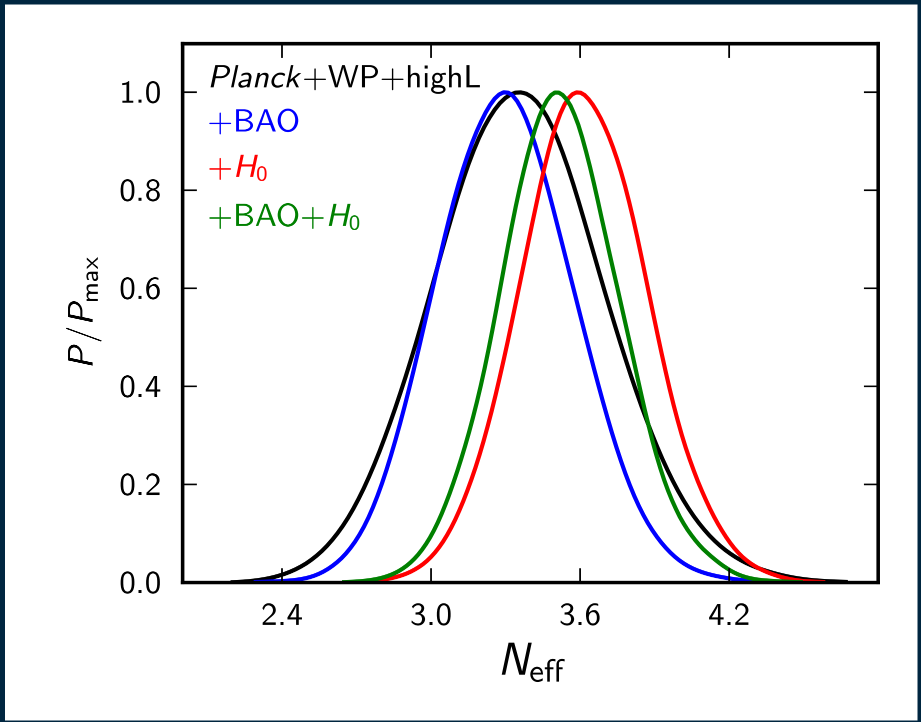


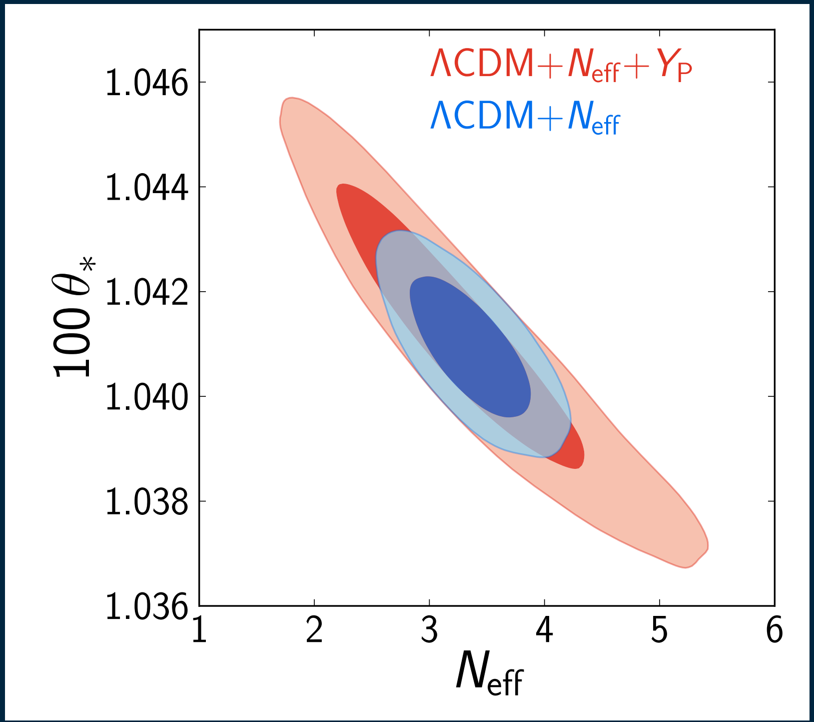


Planck 2013 results. I.

Planck, WMAP, ACT, SPT

Effective number of neutrino degrees of freedom (CMB)





$N_{\mathrm{eff}} = 5.3 \pm 1.3$

$N_{\mathrm{eff}} = 3.85 \pm 0.62$

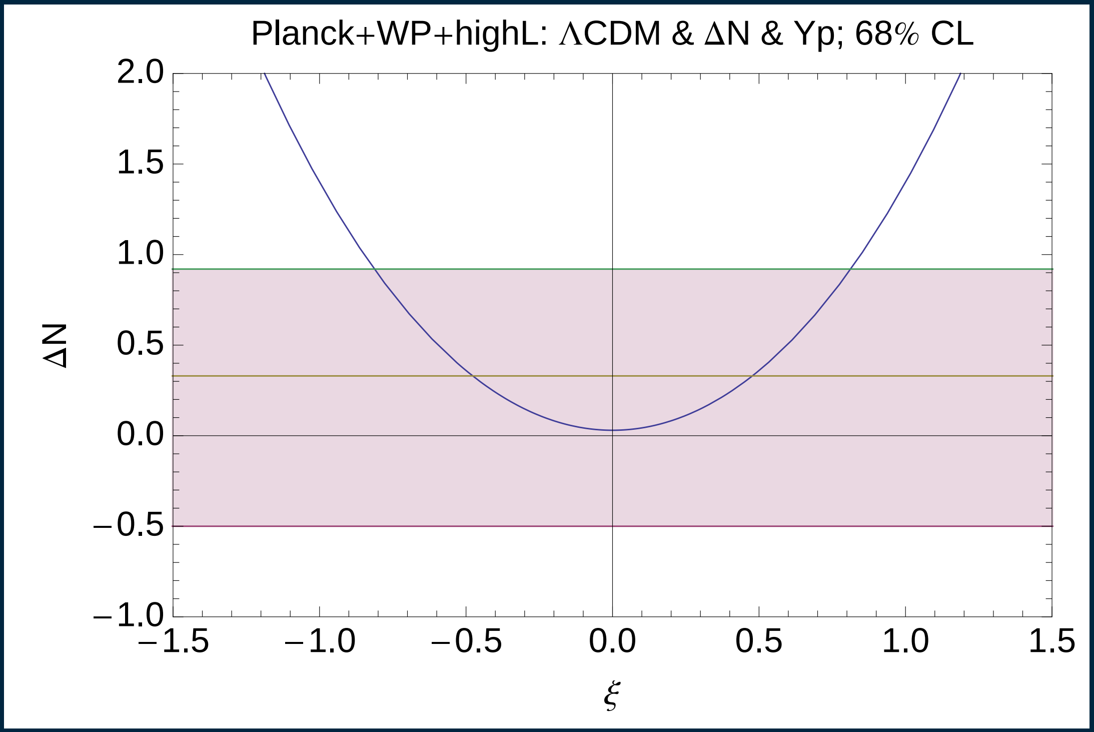
$N_{\mathrm{eff}} = 3.36^{+0.68}_{-0.64}$

ACT: Dunkley et al. 2010

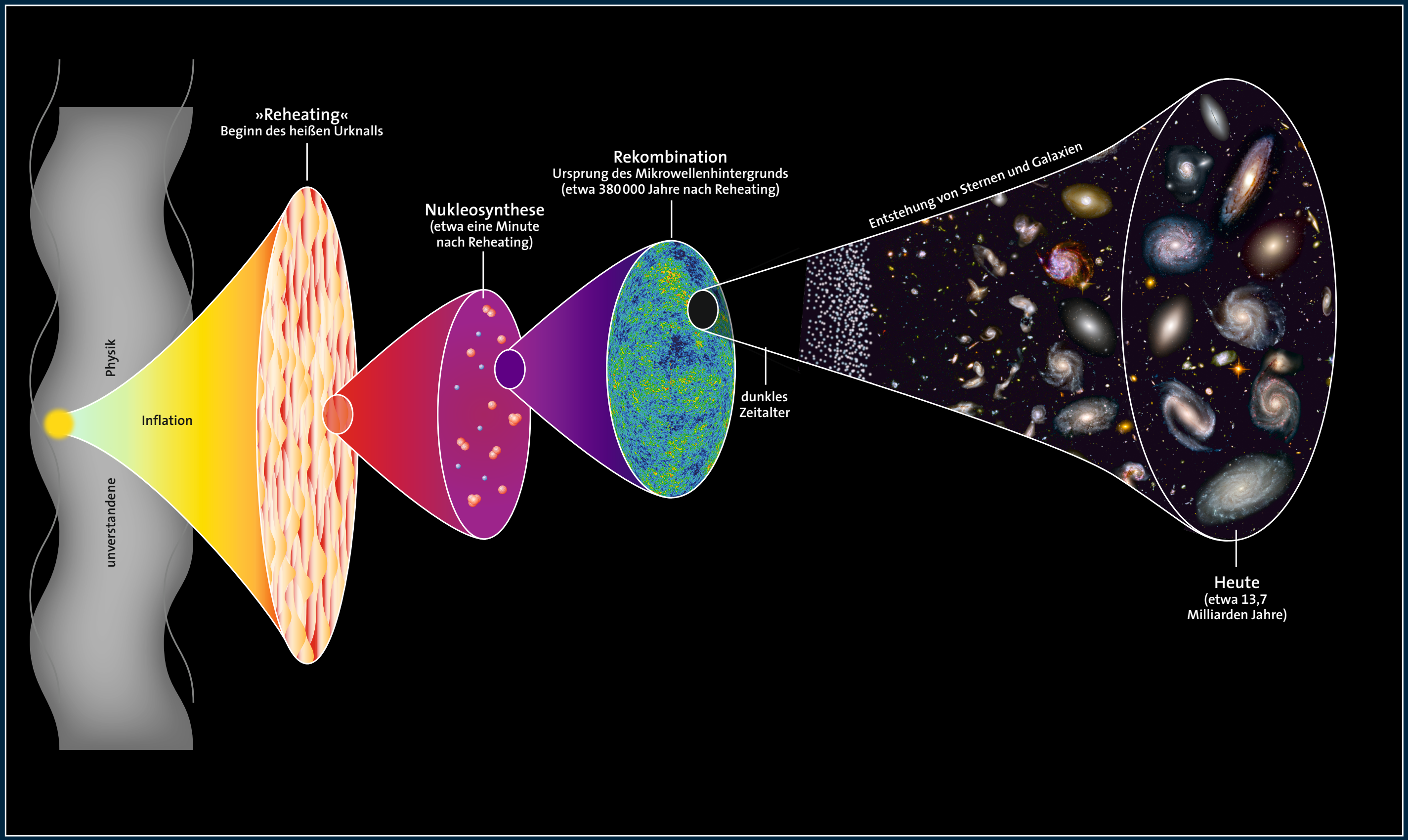
SPT: Keisler et al. 2011

Planck 2013 results. XVI.

Effective number of neutrino degrees of freedom (CMB)

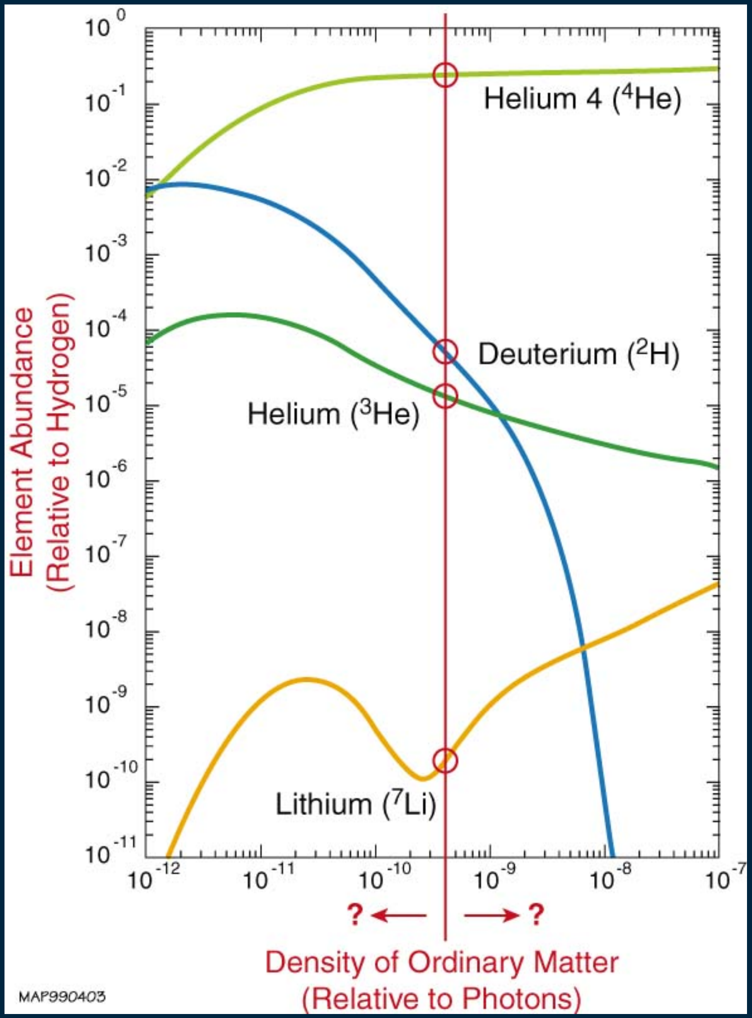


$|\xi| < 1.1$ and $|l| < 0.12$ at 95% C.L.



inflation baryo-/leptogenesis ew WIMPs qcd ν-oscillations bbn γ-decoupling structure

Abundance of light elements



primordial nucleosynthesis

$N_{\text{eff}} = 3 + \Delta N$ and chemical potential of ν_e (BBN)

primordial nucleosynthesis measures

• Hubble expansion rate against τ_n and nuclear reaction rates:

$$\Delta t/t = -\Delta H/H = -\tfrac{1}{2}\Delta\epsilon/\epsilon = -\tfrac{7}{86}\Delta N$$

• n/p at decoupling of weak forces ($T \simeq 1$ MeV):

$n/p = \exp(-\Delta m/T - \xi_e)$ with $\xi_e \equiv \mu_{\nu_e}/T$

$\Delta N > 0 \Rightarrow \Delta Y_{\text{p}} > 0$ and $\xi_e > 0 \Rightarrow \Delta Y_{\text{p}} < 0$

Constraints on ξ_f from BBN and CMB

$$\Delta N = \frac{15}{7} \sum_f \left[\left(\frac{\xi_f}{\pi} \right)^2 + \frac{1}{2} \left(\frac{\xi_f}{\pi} \right)^4 \right]$$

from BBN: $-0.14 < \xi_e < 0.12$ Krauss, Lunardini & Smith 2010

without ACT, SPT and Planck data!

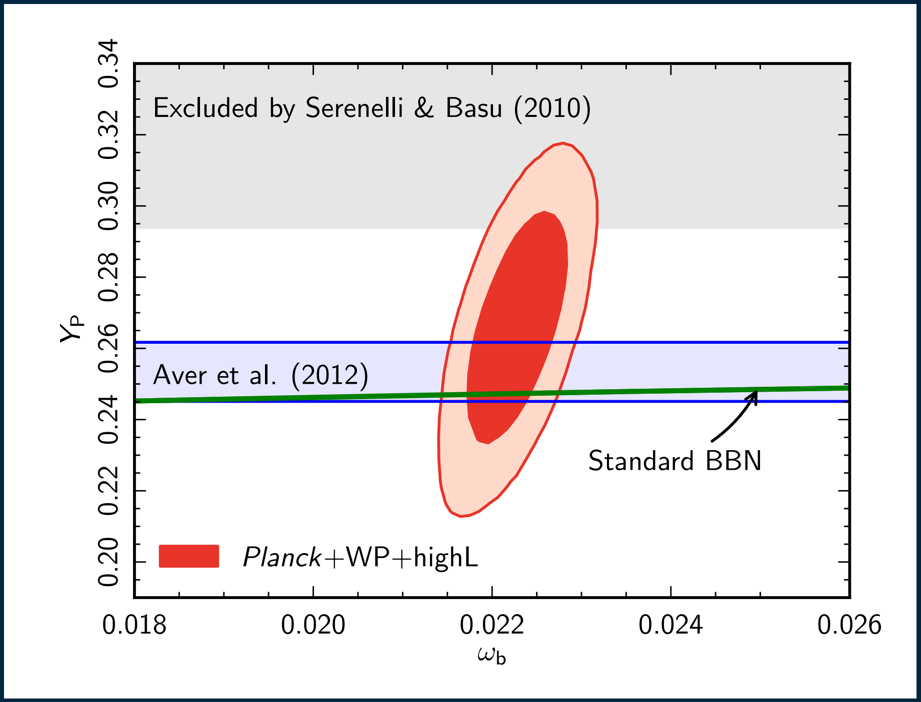
from BBN & CMB: $|\xi_f| <$ few $(f = \mu, \tau)$

$$l = \frac{T^3}{6s} \sum_f \left[\frac{\xi_f}{\pi} + \left(\frac{\xi_f}{\pi} \right)^3 \right]$$

$\Rightarrow l \sim \xi/\pi \Rightarrow |l| < 1$

more precise limit needs a detailed study of μ-equilibration due to ν-oscillations

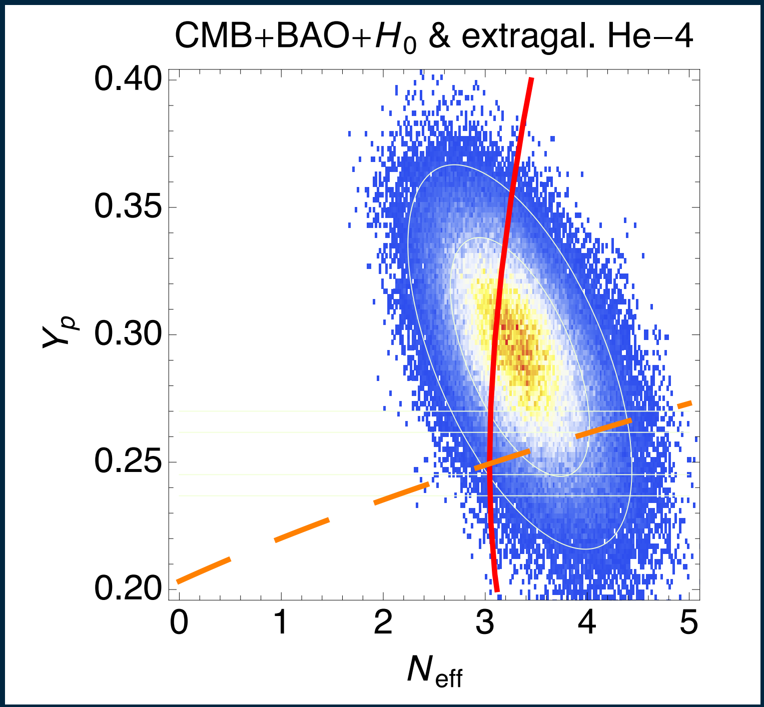
Helium abundance (CMB)

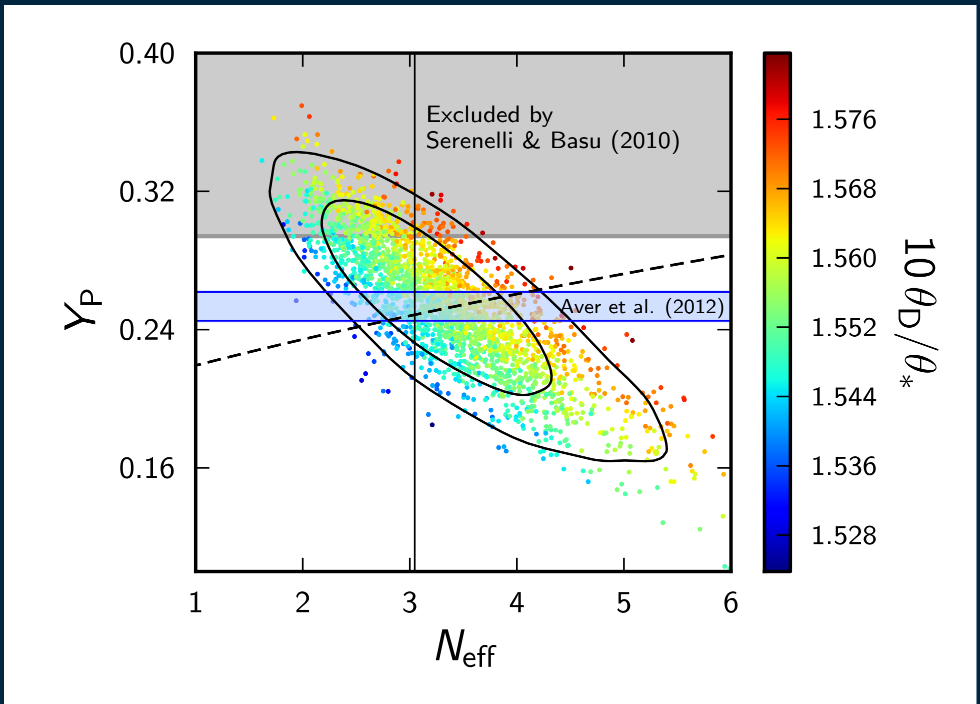


$Y_p = 0.305 \pm 0.024$ SPT12+WMAP7+BAO+H0: Hou et al. 2012

$Y_p = 0.266 \pm 0.021$ Planck release 2013. XVI

Helium abundance and N_{eff} (CMB)

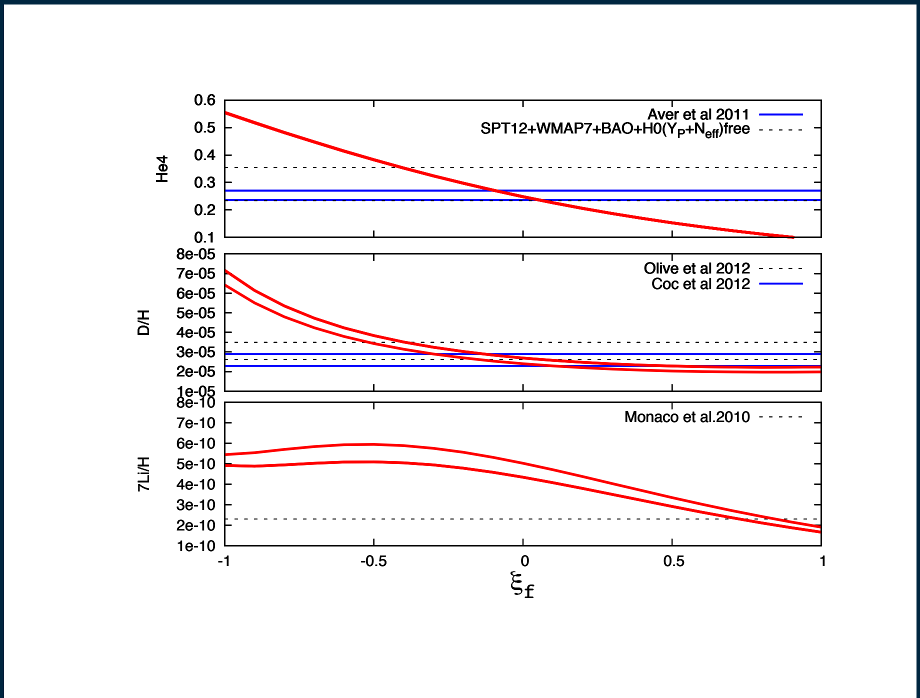


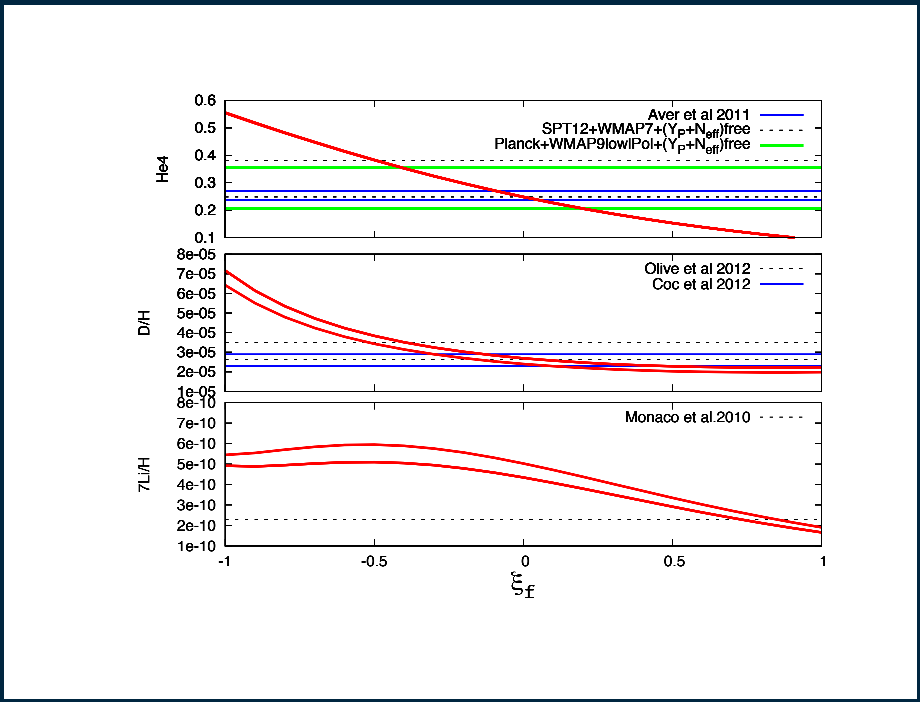


Schwarz & Stuke 2013 (SPT: Hou et al. 2012)

Planck 2013 results. XVI.

Neutrino chemical potential and BBN





Schwarz & Stuke 2013

Stuke preliminary 2013

Summary on observational constraints

from CMB alone $|\xi| < 1$ and $|l| < 0.1$,
which translates into $|\xi_f| < 1$ for all flavours

future CMB data will allow to fix two BBN parameters $(\omega_{\rm b}, \xi_e)$,
use light element abundance as a check of validity of model

from He4 (CMB) $-0.4 < \xi < 0.06$ without Planck

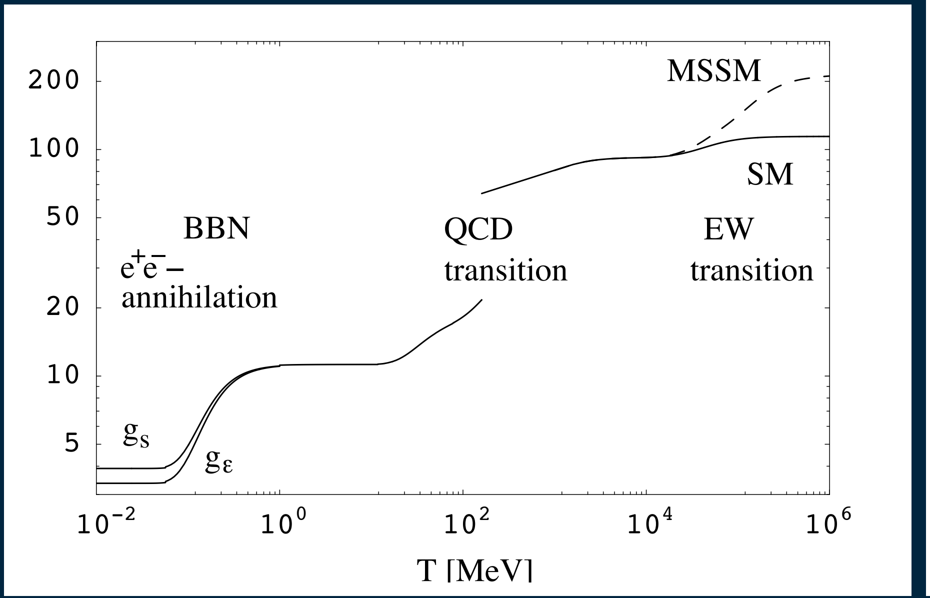
from He4 (extragalactic HII regions) $-0.1 < \xi < 0.05$

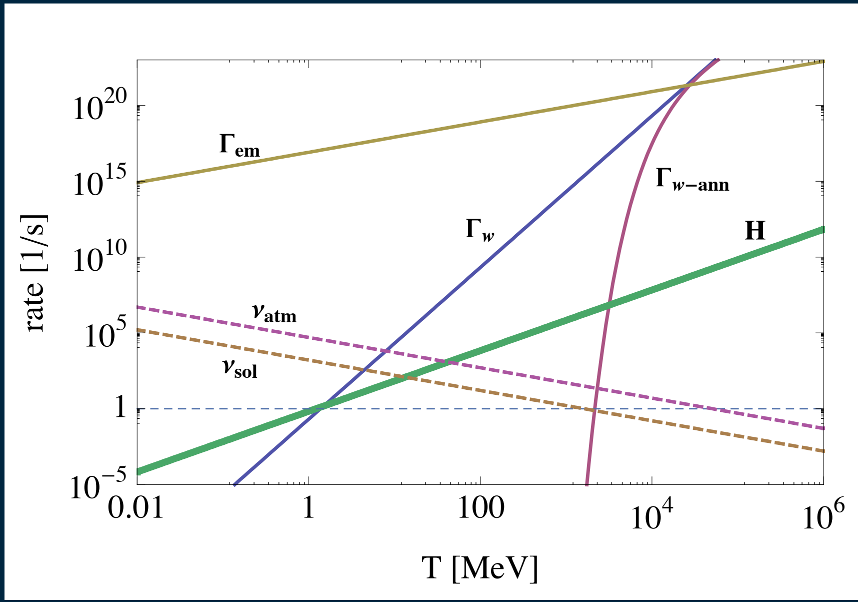
best fit at $\xi < 0 \Rightarrow$ excess of anti-neutrinos

He-4 abundance can be used as a leptometer

CMB & BBN: $-0.01 < l < 0.005$, thus $|l| \gg b = 10^{-10}$ is allowed

The hot Universe





Evolution of chemical potentials

in thermal and chemical equilibrium:

$\mu_{\bar{i}} = -\mu_i$ for all particles
$\mu_d + \mu_f = \mu_u + \mu_{\nu_f}$, for $f = e, \mu, \tau$
$\mu_u = \mu_c (= \mu_t)$
$\mu_d = \mu_s = \mu_b$

$\Rightarrow \mu_u, \mu_d, \mu_{\nu_f}$; five independent chemical potentials before $t_{\nu-\text{osc}}$
use μ_p, μ_n instead of μ_u, μ_d after QCD transition and
$\mu_\nu = \mu_{\nu_f}$ for $f = e, \mu, \tau$; three after $t_{\nu-\text{osc}}$

Evolution of chemical potentials

net particle densities

$$n_i = \frac{g_i}{2\pi^2} \int_{m_i}^{\infty} E(E^2 - m_i^2)^{1/2} \left[f_i(E) - f_{\bar{i}}(E)\right] \mathrm{d}E$$

five conservation laws (quark phase):

$0 = -\sum_f n_f + \frac{2}{3} \sum_u n_u - \frac{1}{3} \sum_d n_d$ electric charge density

$bs = \frac{1}{3} \sum n_q$ baryon number density

$l_f s = n_f + n_{\nu_f}$ lepton flavour number density

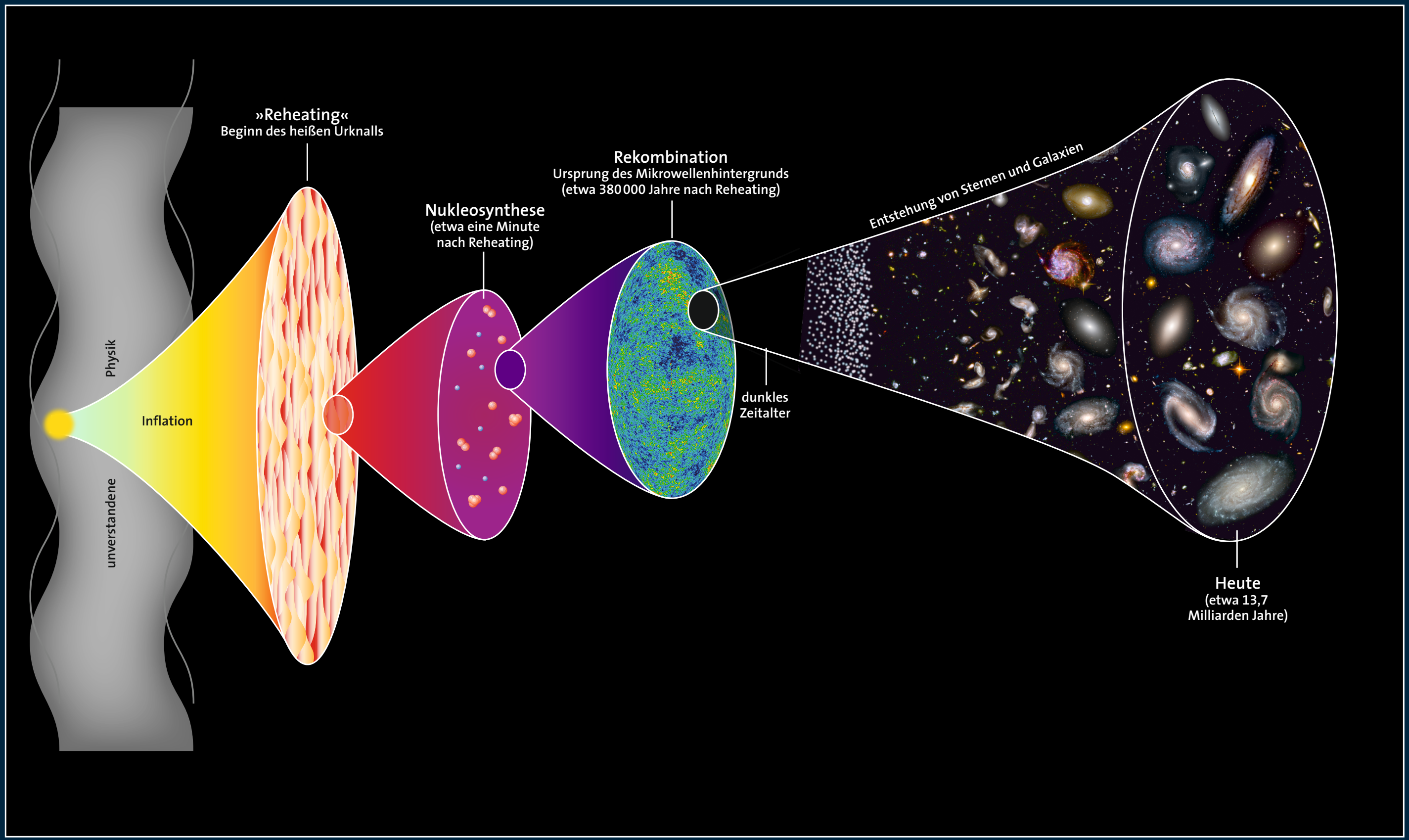
$\Rightarrow \mu_i = \mu_i(T; b, l_e, l_\mu, l_\tau)$ numerical solution of set of coupled integral equations

Charge, baryon and lepton (flavour) potentials

$$\mu_Q n_Q + \mu_B n_B + \sum_f \mu_{L_f} n_{L_f} =$$

$$\sum_q \mu_q n_q + \sum_l \mu_l n_l + \sum_g \mu_g n_g \text{ (quark phase)}$$

$$\sum_b \mu_b n_b + \sum_m \mu_m n_m + \sum_l \mu_l n_l \text{ (hadron phase)}$$



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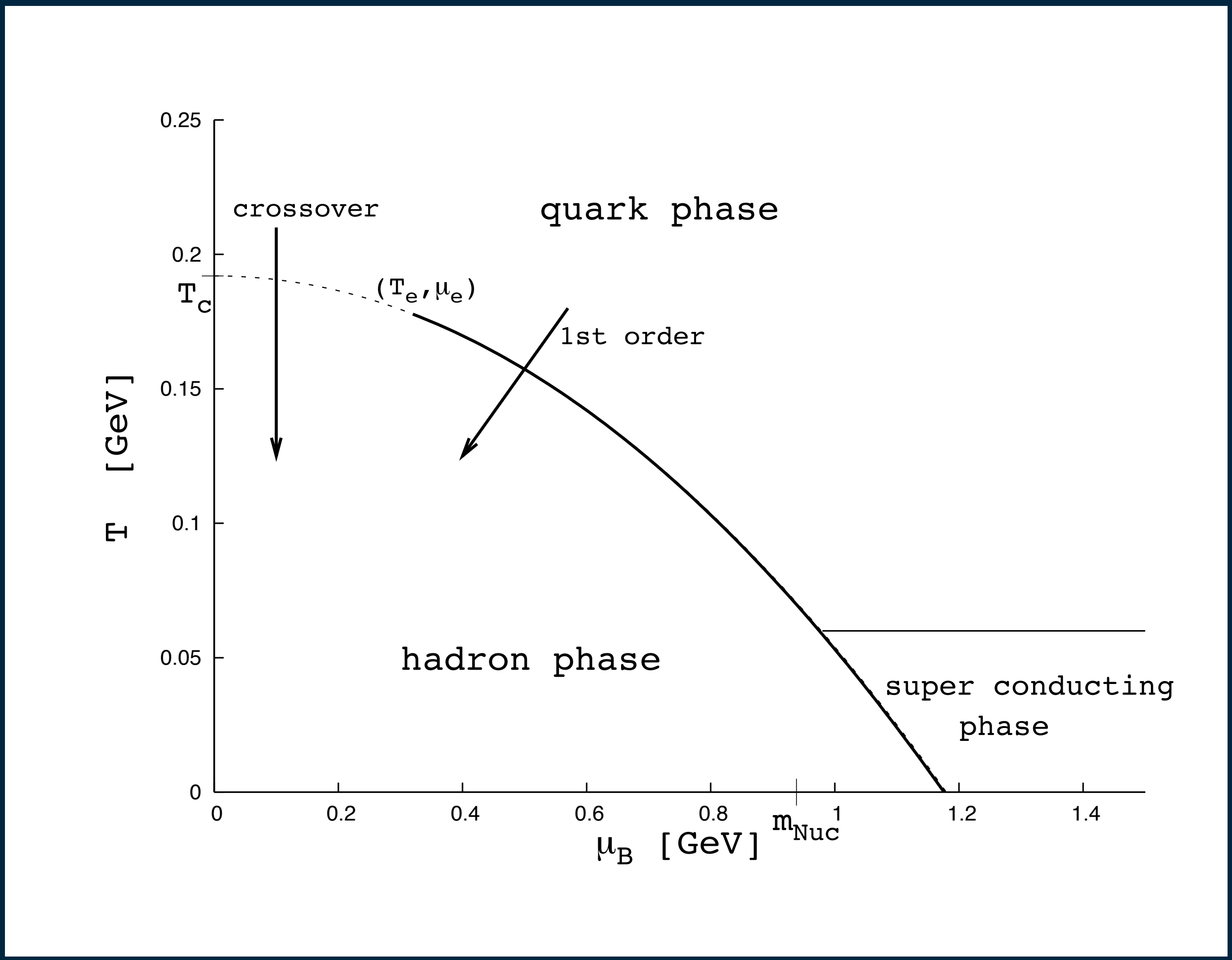
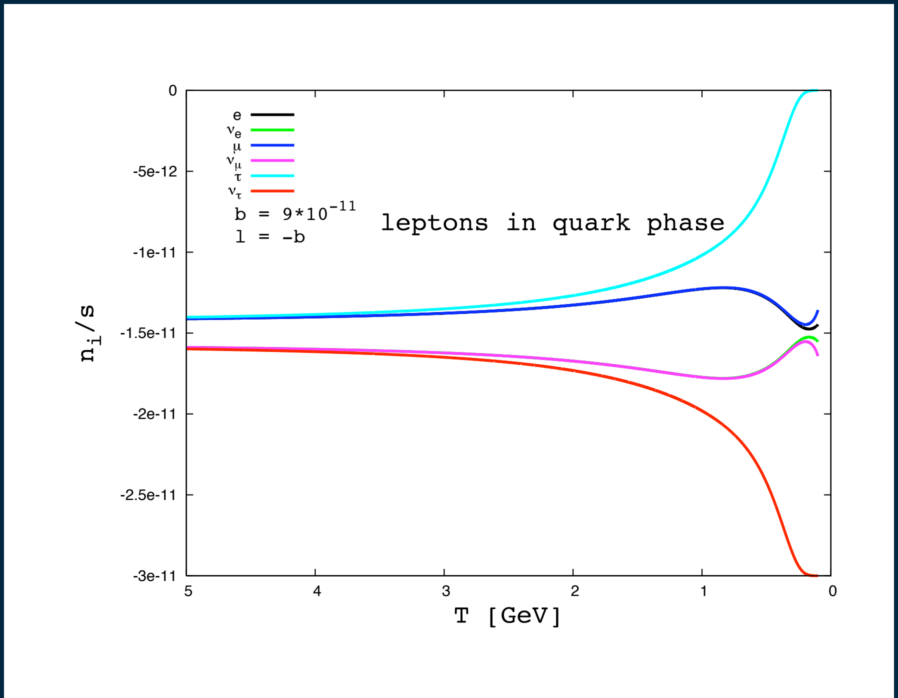
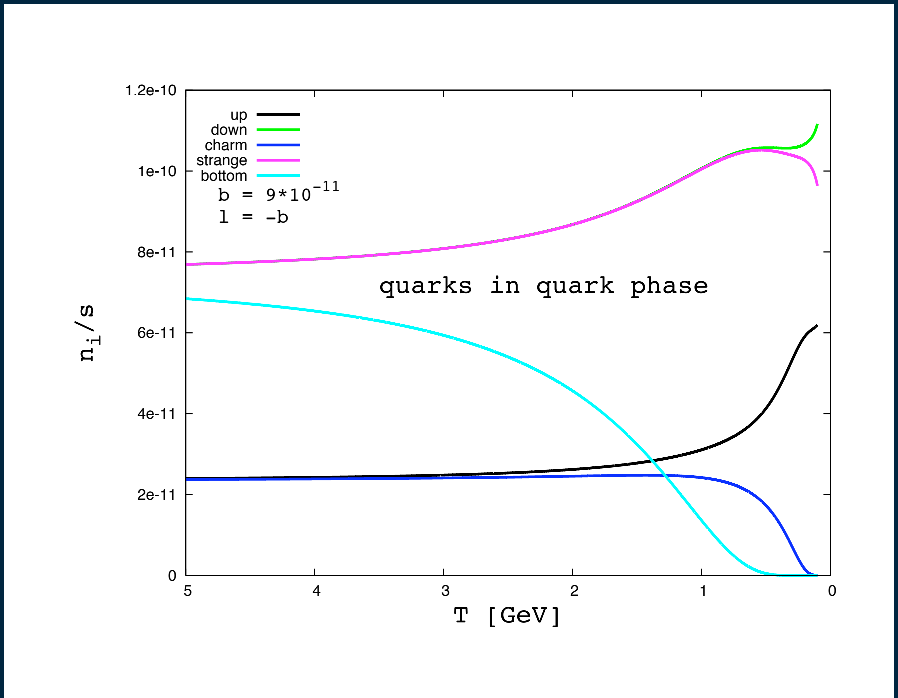
Cosmic QCD transition



Evolution of net number densities — quark phase

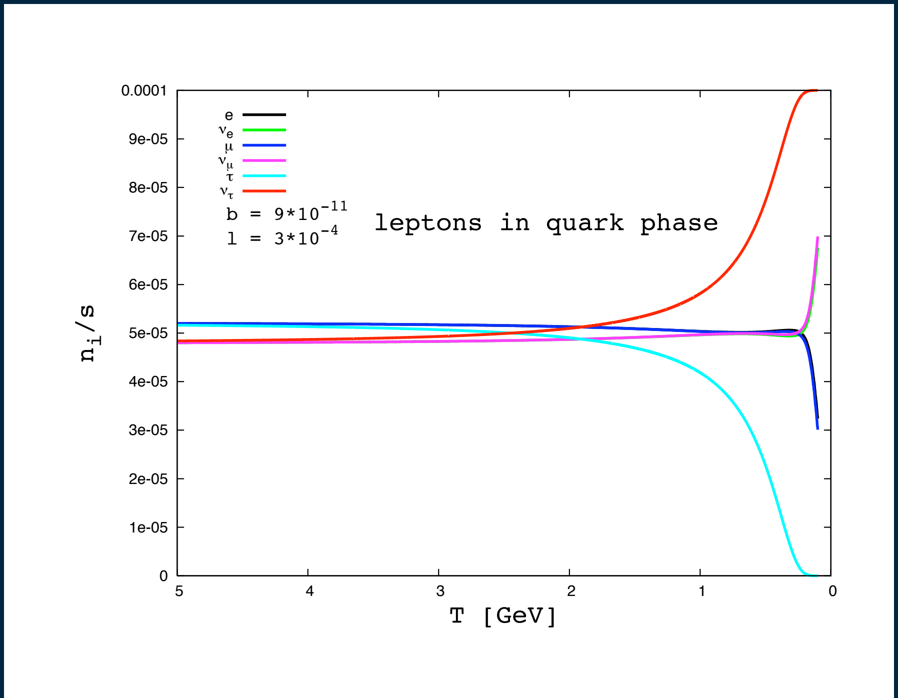


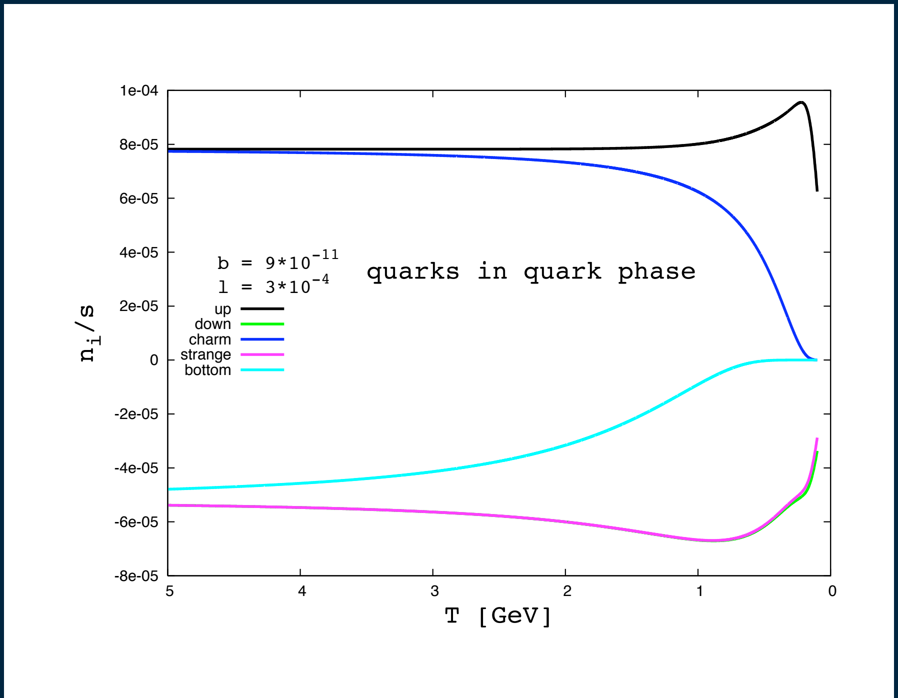


$l_e = l_\mu = l_\tau = -b/3$

numerical solution

Evolution of net number densities — quark phase

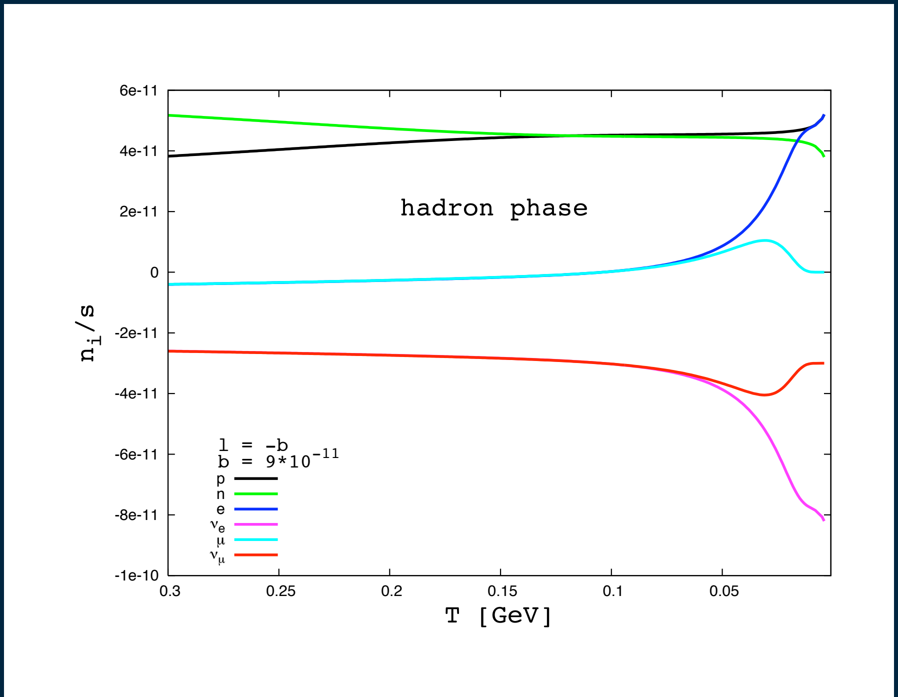


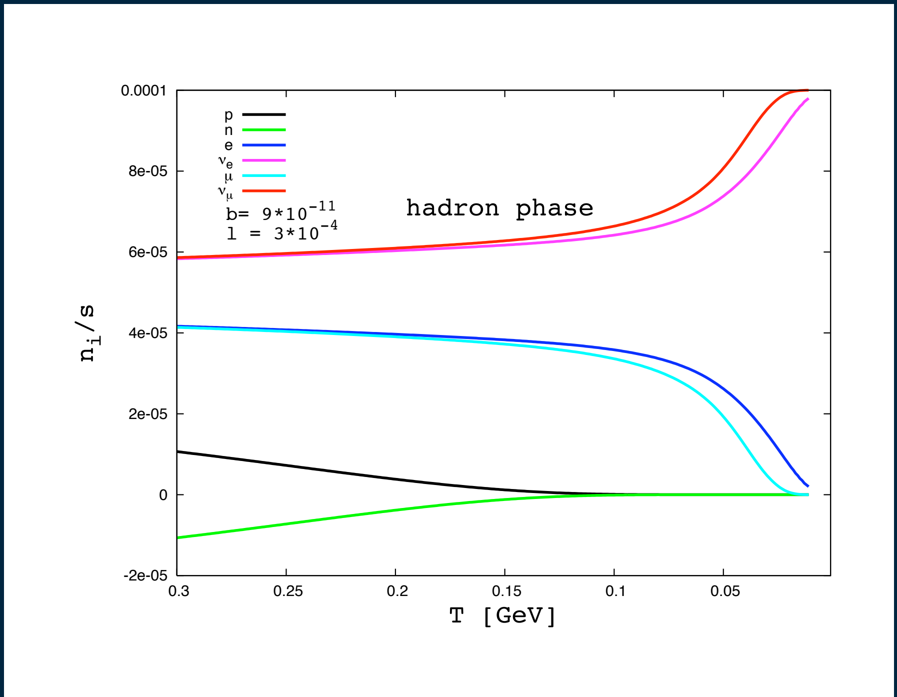


$l_e = l_\mu = l_\tau \gg b$

$l \gg b$ affects quark densities!

Evolution of net number densities — hadron phase

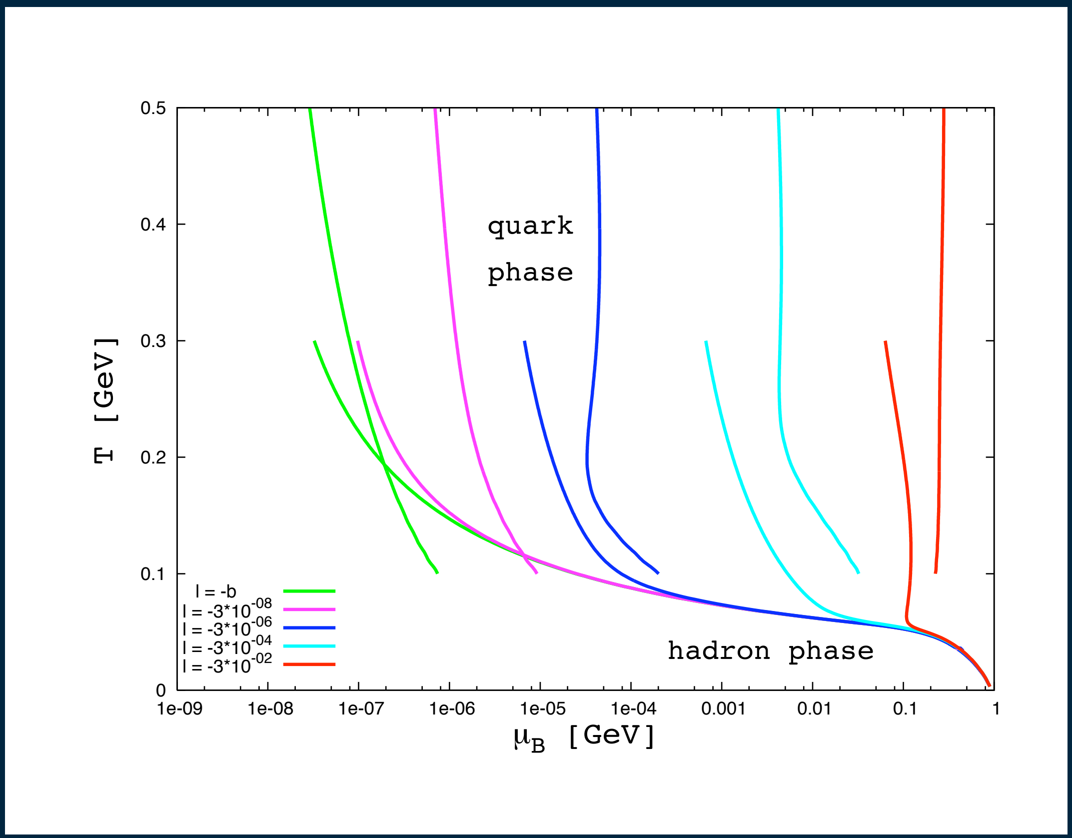




$l = -b$

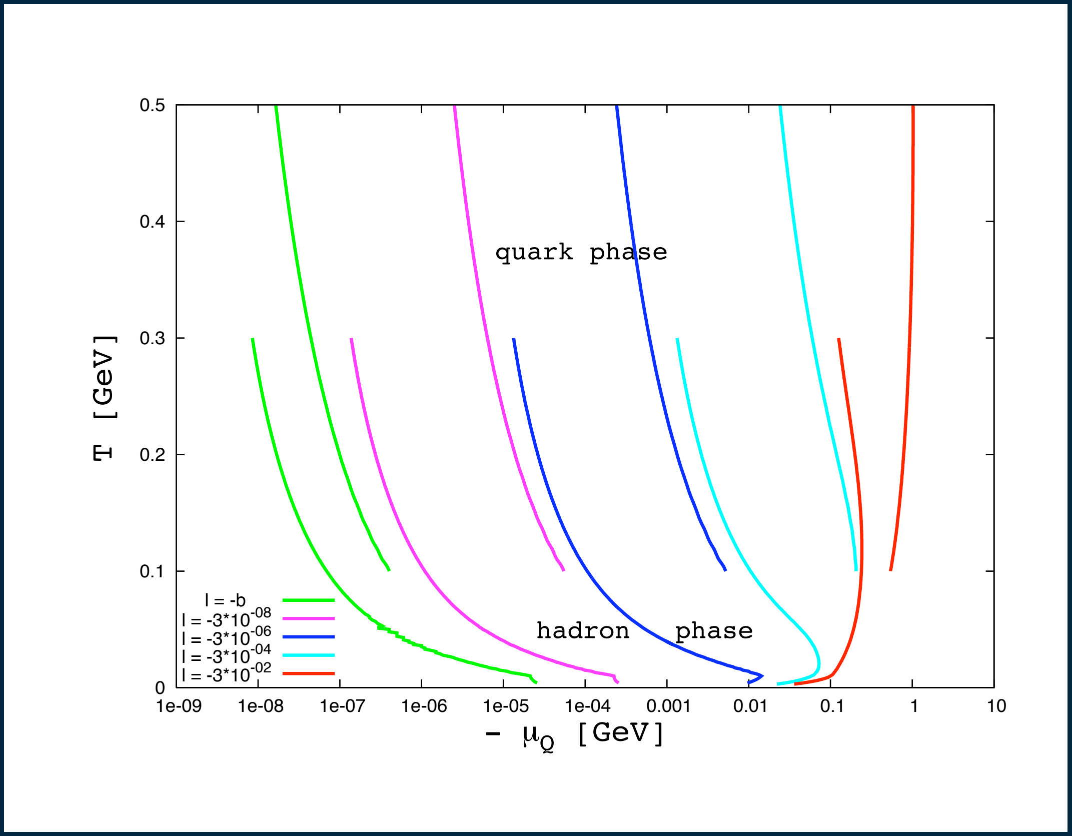
$l \gg b$

Cosmic trajectory in the (μ_B, T) diagram



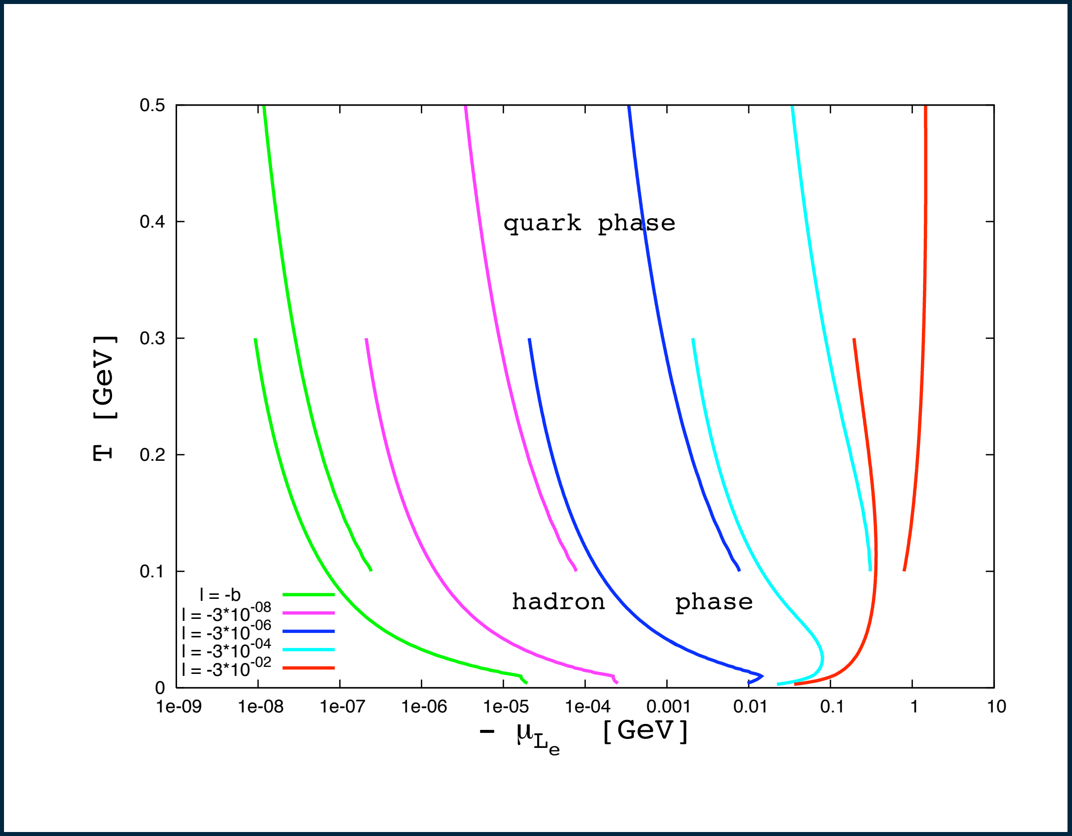
for $b \ll l < 1$ a first order QCD phase transition seems possible

Cosmic trajectory in the (μ_Q, T) diagram



for $b \ll l < 1$ a first order QCD phase transition seems possible

Cosmic trajectory in the (μ_{L_e}, T) diagram



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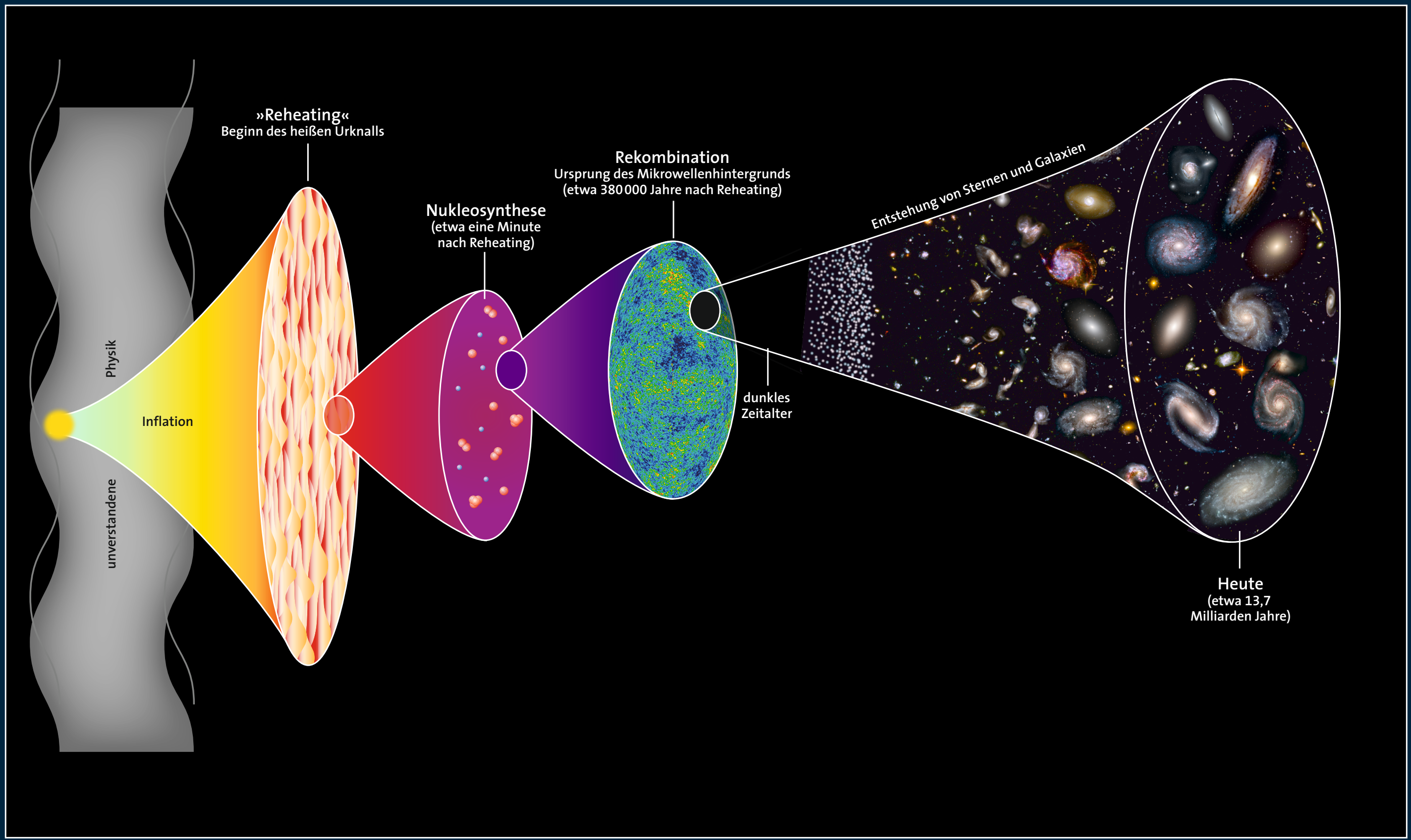

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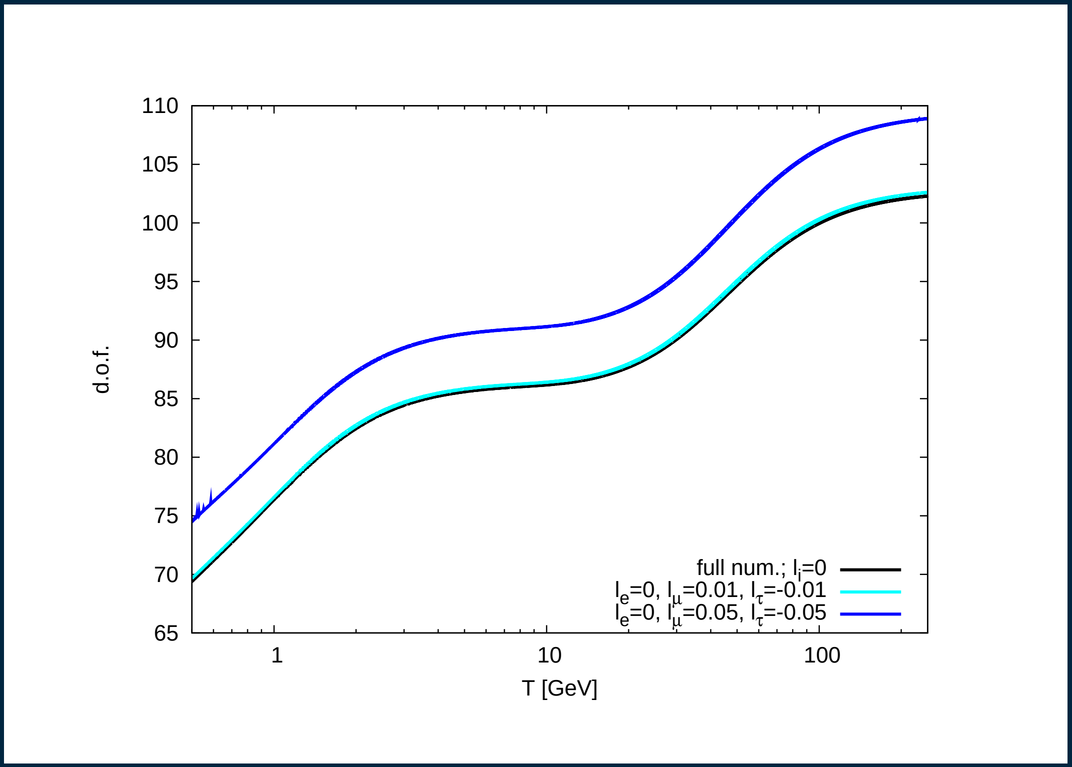
Relativistic helicity degrees of freedom at $T_{\text{qcd}} < T < T_{\text{ew}}$



for $b, l = \mathcal{O}(10^{-10})$, but $l_\mu = -l_\tau \gg b$

WIMP freeze out

dark matter candidate: 100 GeV $< m_X <$ 1 TeV

chemical freeze out of weakly interacting massive particles happens at $T \sim m_X/25$, i.e. 4 GeV $< T <$ 40 GeV

$$\dot{n} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{\rm eq}^2)$$

with $Y_X \equiv n/s$

$$Y \simeq \sqrt{\frac{45}{\pi}} \frac{1}{T_{\rm fo} M_{\rm pl} \langle \sigma v \rangle \sqrt{g_{\rm eff}}}$$

and

$$\Delta\omega_{\rm dm}/\omega_{\rm dm} = -\Delta g_{\rm eff}/2 g_{\rm eff}$$

10% increase of $g_{\rm eff}$, from $l_\mu = -l_\tau = 0.05$ and $l_e = 0$, leads to 5% decrease in $\omega_{\rm dm}$

Conclusions

observational limits on l and l_f are very weak

before ν oscillations: no constraints on flavour asymmetry

$1 \gg |l| \gg b$ affects dynamics of QCD transition (1st order?)

$|l_f| > 10^{-2}$ lead to sizeable corrections to WIMP abundance, even if $l = 0$

Next steps

update limits on l from recent CMB and BBN data (assuming flavour equilibration before BBN)

effects of neutrino oscillations on BBN in case of large l_f

how to explore relevant QCD transition region on lattice?

influence of l and l_f on ew transition?