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The lepton asymmetry of the Universe

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Based on work with
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Outline

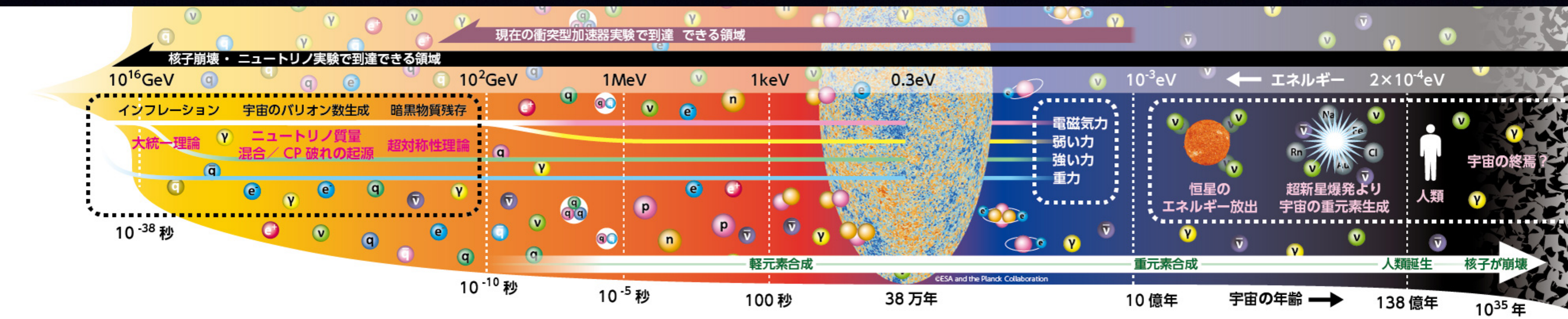


Image: Hyper Kamiokande

1. What do we know about the net charge densities of the Universe?

Lepton asymmetry is the least constrained matter asymmetry

2. What does that tell us on the genesis of matter?

Measurement of lepton asymmetry would constrain matter genesis scenario

3. Cosmological consequences of a large lepton asymmetry?

Evolution at QCD epoch

Dark matter abundance

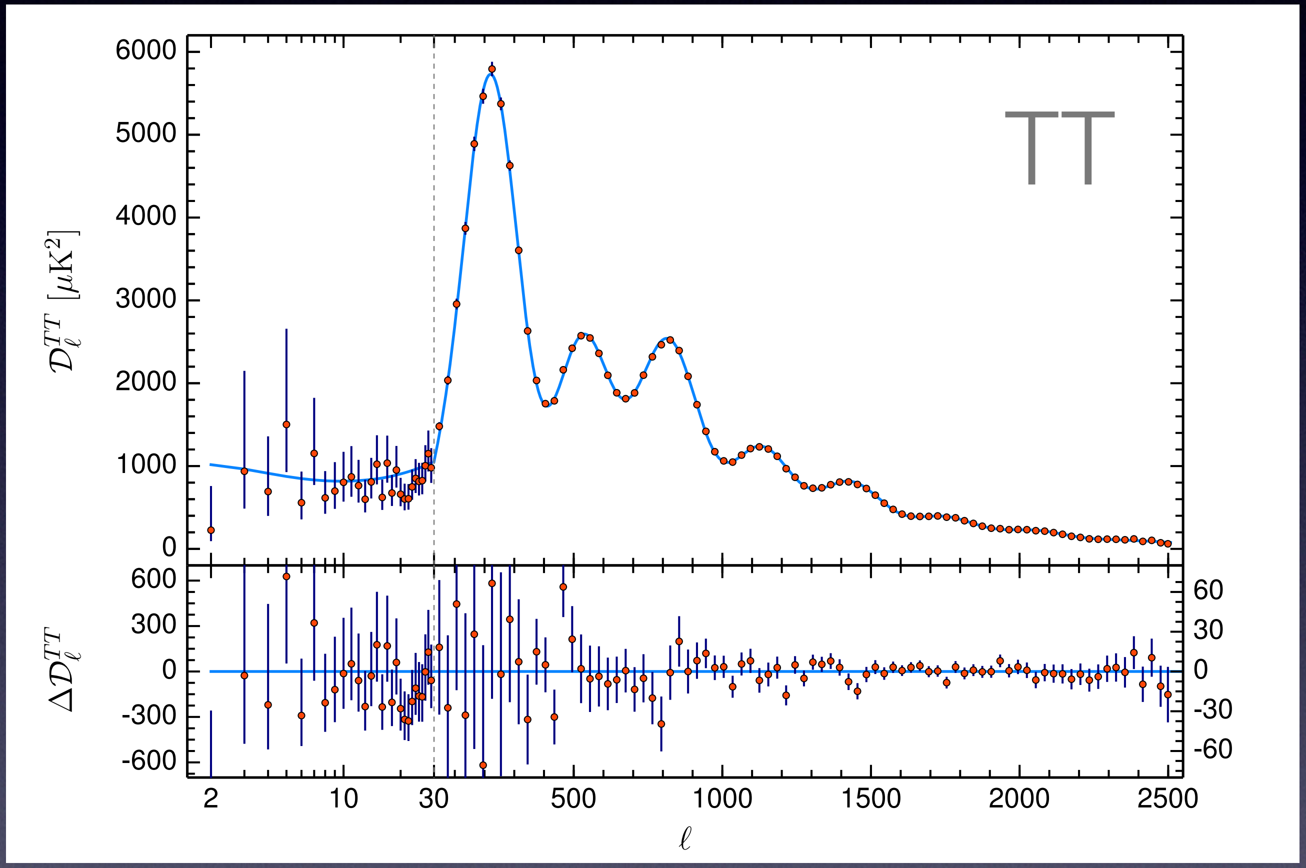
What do we know?

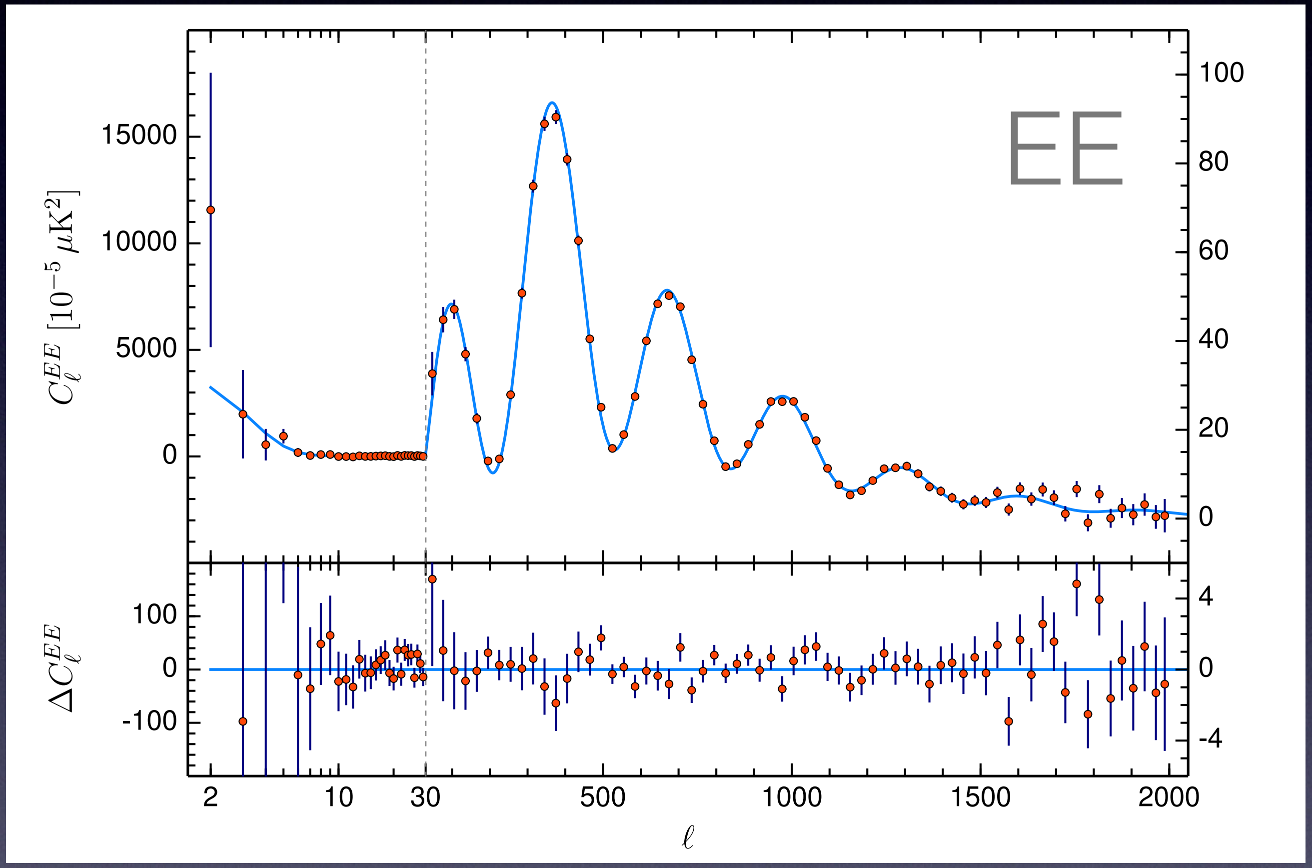
Conserved numbers in the present Universe

- electric charge Q
- baryon number B
- lepton number L
- perhaps dark matter particle number (asymmetric dark matter) ?

Express as net charge densities n_Q, n_B, n_L, …

Cosmic Microwave Background





Planck collaboration 2018

Fluctuations in temperature and polarisation allow to extract all parameters of cosmological standard model
(five of them are determined at precision better than 1 per cent)

Charge asymmetry

Universe is almost perfect conductor ⇒

no electric fields, homogeneous charge distribution

magnetohydrodynamic limit: Gauss law relates charge density to vorticity and magnetic fields

CMB provides upper limits on primordial magnetic field strength and vorticity ⇒

$q = n_Q/s < 10^{-36}$

Caprini & Ferreira 2005

Baryon asymmetry
Cosmic Microwave Background

Planck spectrum $T_0 = 2.7255 \pm 0.0006$ K Fixsen et al. 2009

fixes entropy density at photon decoupling

$s = (4\pi^2/45)[1 + (7/8)(4/11)\, N_{eff}]\, (T_0)^3$ SM: $N_{eff} = 3.046$

angular power spectrum: Planck collaboration 2018

baryonic matter density:

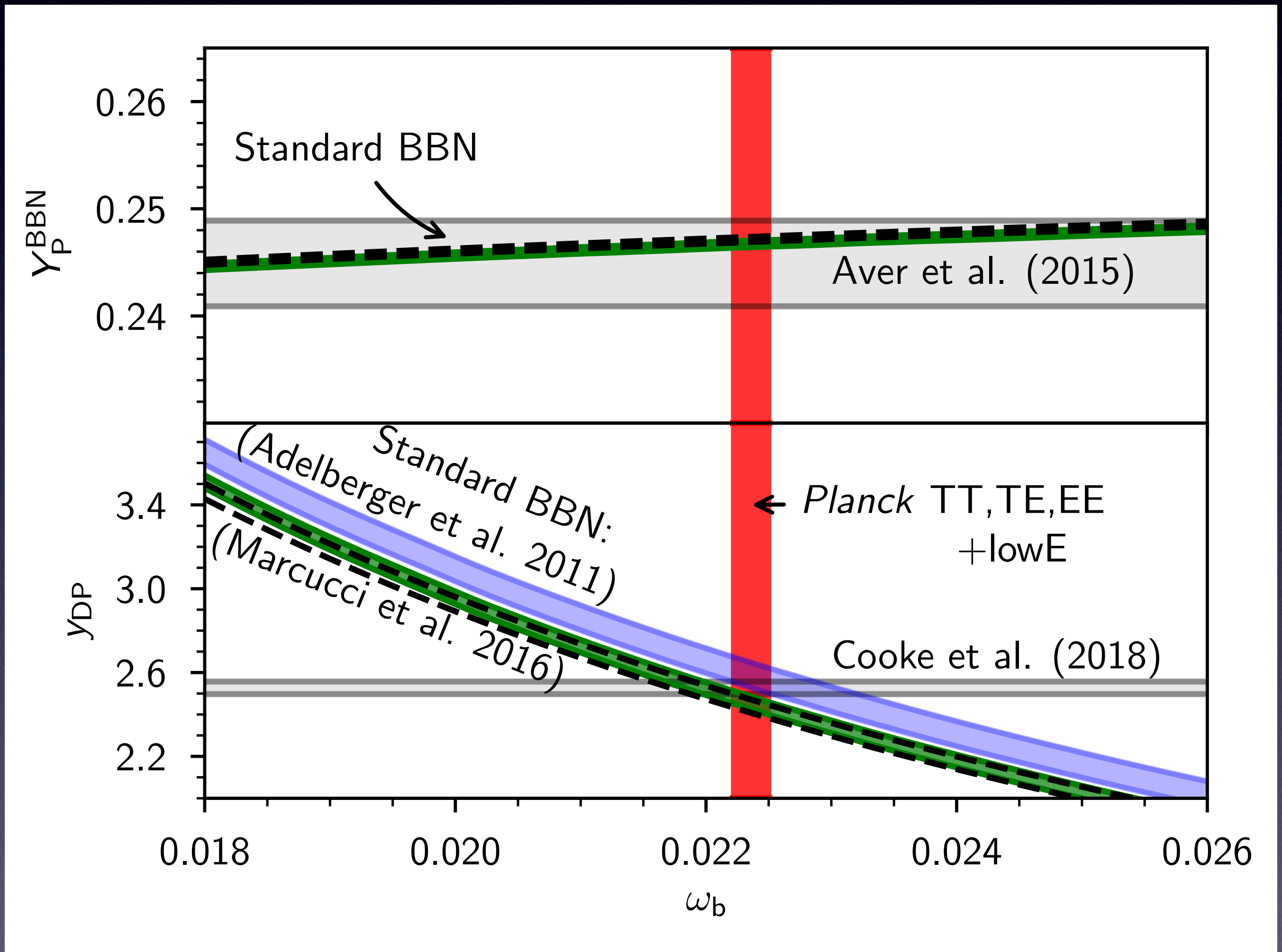
$\omega_b = 0.02236 \pm 0.00029$ (95% Planck TT, TE, EE, low E)

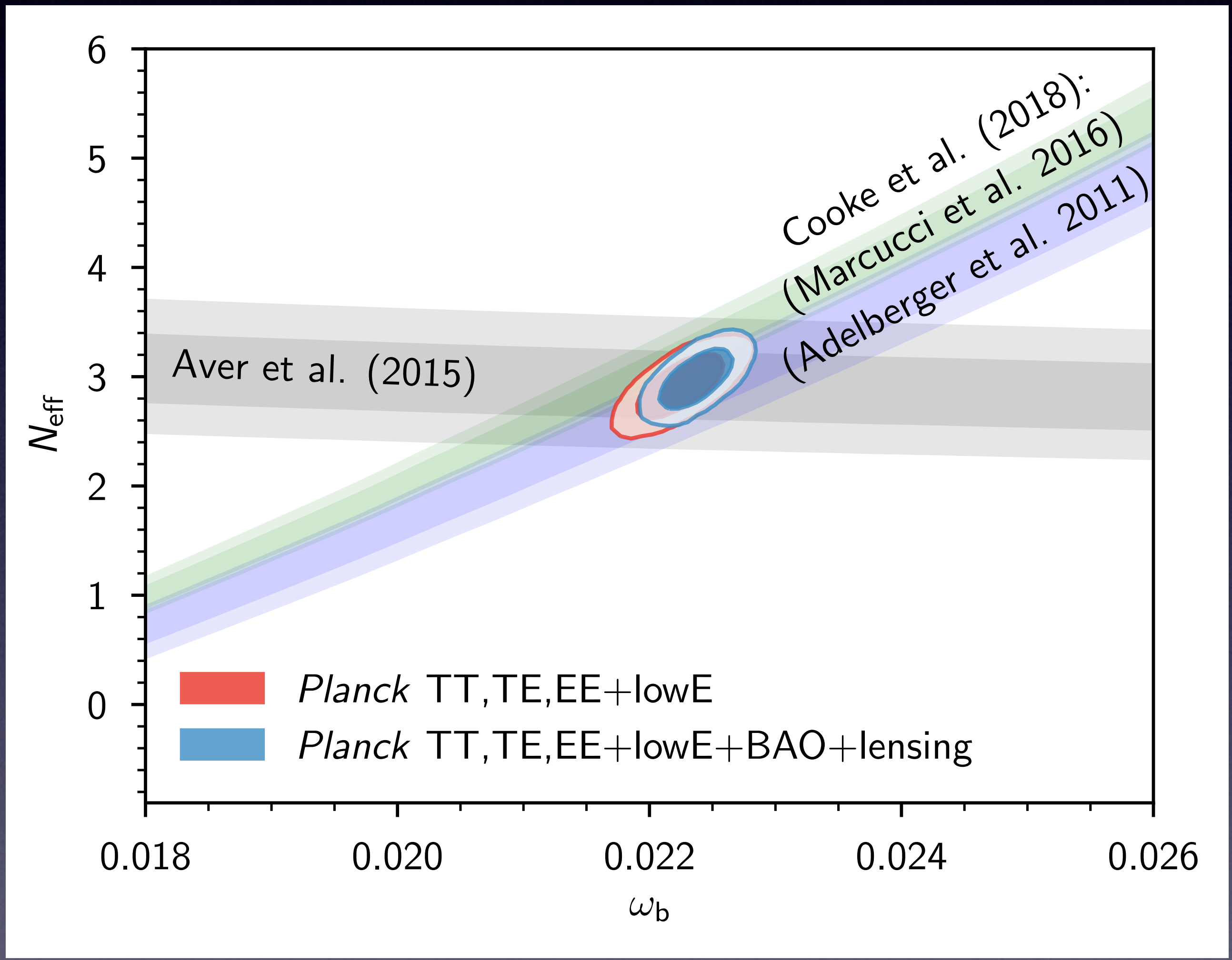
number of thermal neutrino flavours:

$N_{eff} = 2.99 \pm 0.34$ (95% Planck TT, TE, EE, low E, lensing, BAO)

$b = n_B / s = (8.60 \pm 0.06) \times 10^{-11}$

Baryon asymmetry
Primordial nucleosynthesis





Planck collaboration 2018

Measurements are consistent with observed light element abundance and primordial nucleosynthesis

(systematic nuclear physics and BBN code errors exceed observational errors on D/H)

Lepton asymmetry l

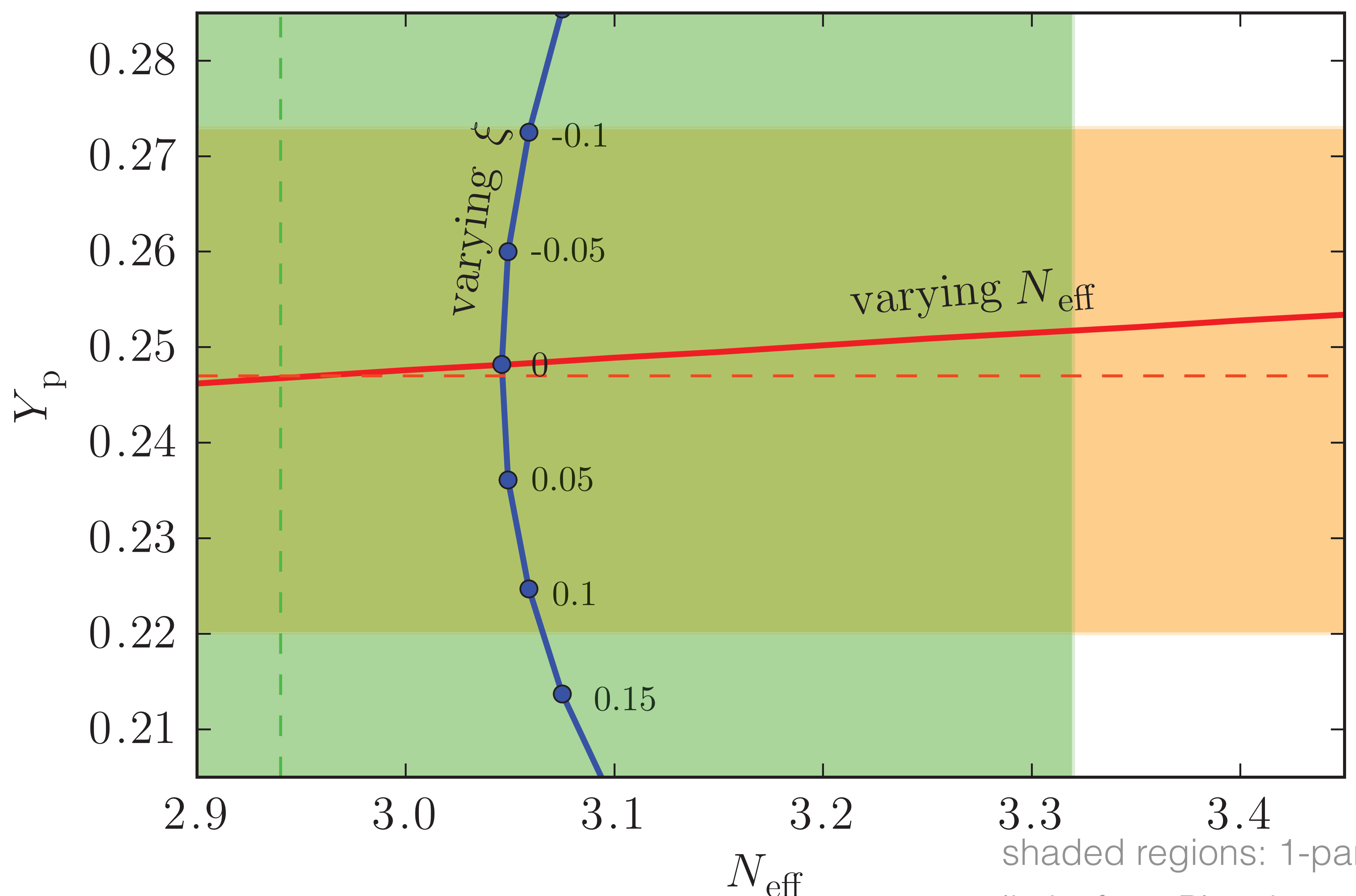
- before onset of neutrino oscillations at T~10 MeV lepton flavour is effectively conserved
- neutrino flavour chemical potentials equilibrate once neutrino oscillations start in the early Universe
- neutrinos decouple at T ~1 MeV
- after electron-positron annihilation (at $T \sim m_e/3$) electron density fixed by proton density, fixed by b and Y_P
  lepton asymmetry l turns into a neutrino asymmetry
- neutrino asymmetry described by neutrino degeneracy parameter ξ
  neutrino momentum distribution function becomes
  $f(p;T,\xi) = [\exp(p/T - \xi) + 1]^{-1}$

Lepton asymmetry II

- $N_{eff} = 3[1 + (30/7)(\xi/\pi)^2 + (15/7)(\xi/\pi)^4]$
  $\Rightarrow$ lepton asymmetry increases the expansion rate

- $n_n/n_p = \exp[-(m_n - m_p)/T - \xi]$ (an excess in electron neutrinos leads to induced neutron decay and thus less neutrons)
  $\Rightarrow$ positive lepton asymmetry reduces Y_P

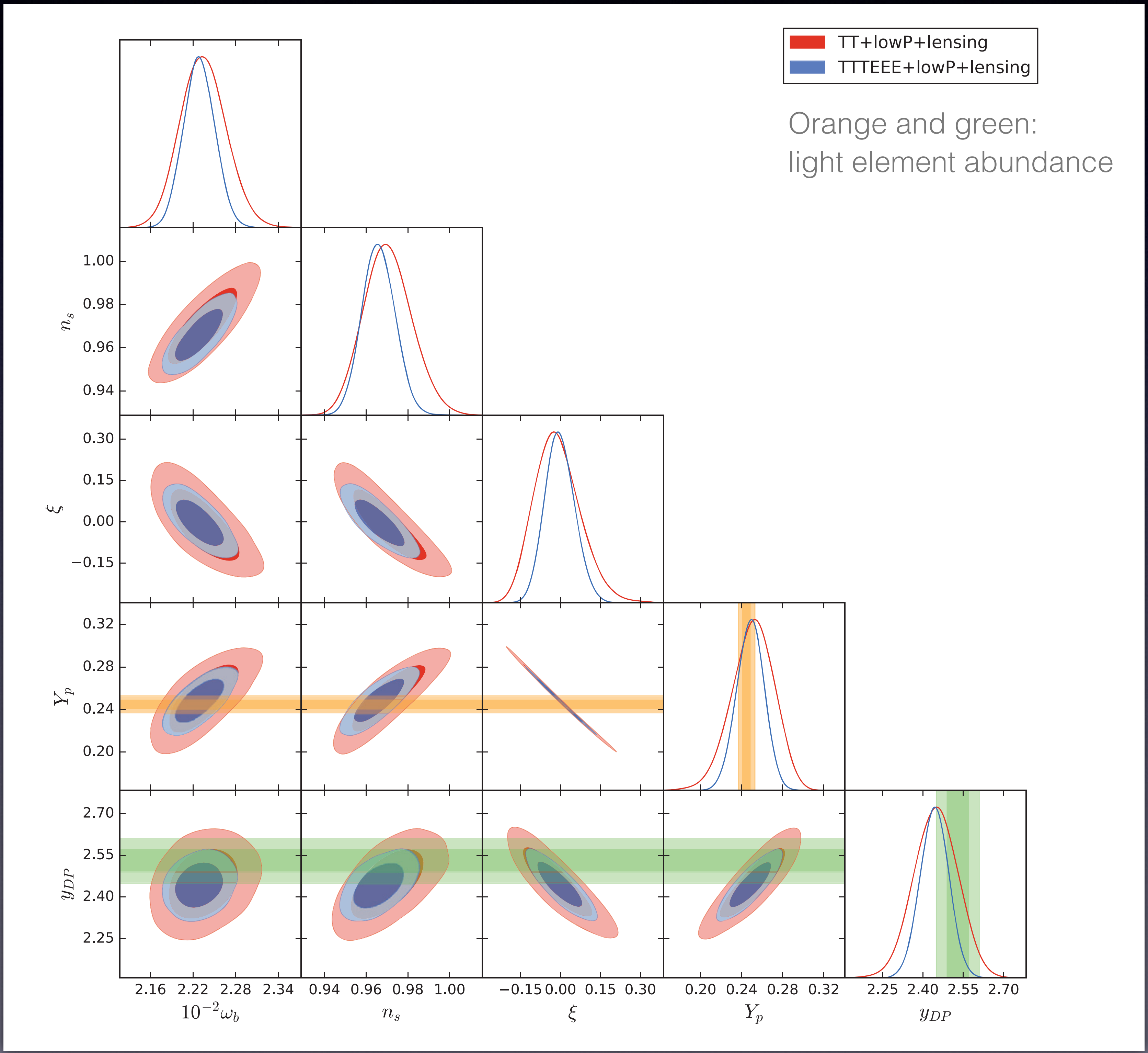
Lepton asymmetry III



shaded regions: 1-parameter limits from Planck 2016

Oldengott & Schwarz 2017

Lepton asymmetry
Cosmic Microwave Background



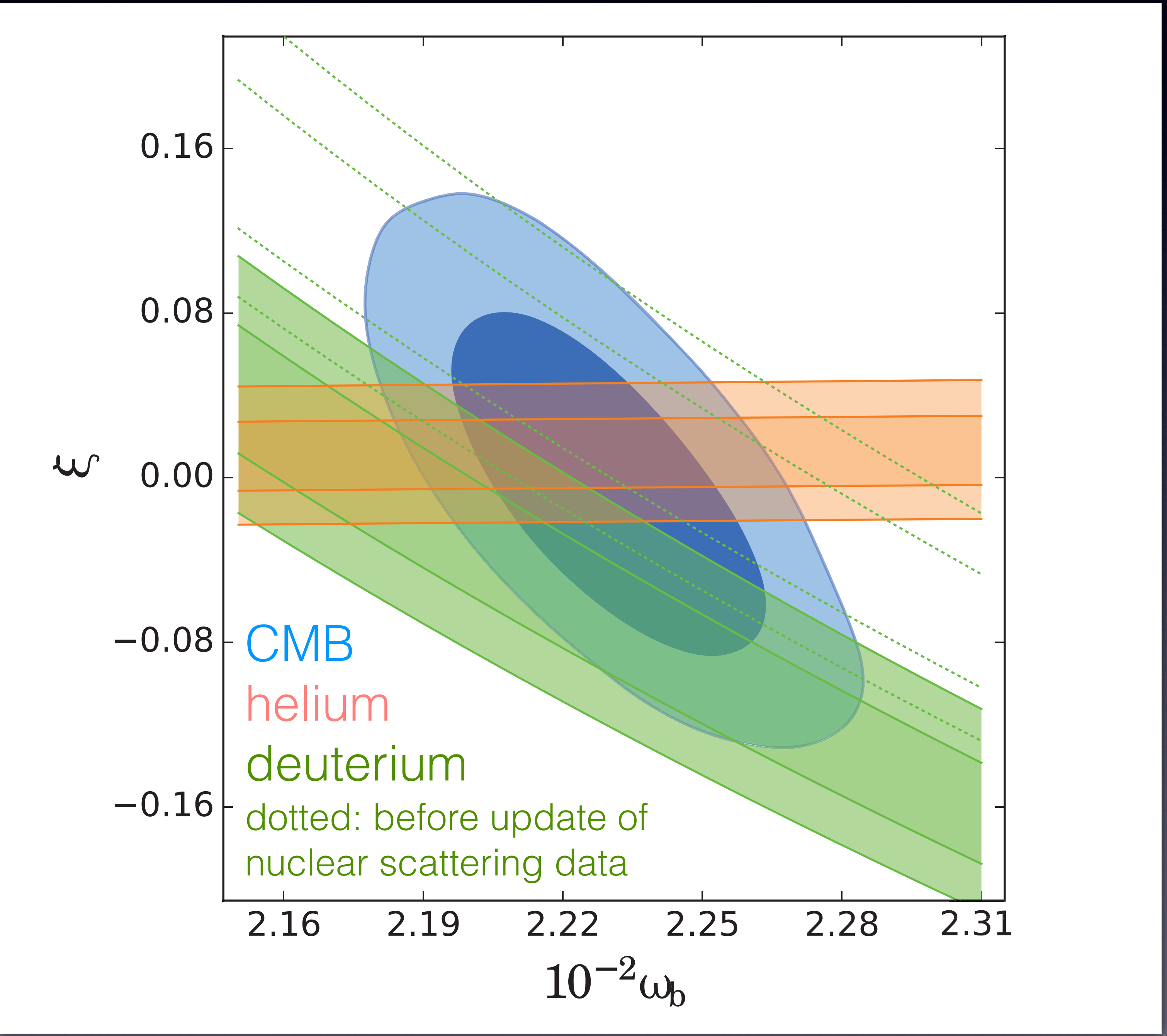
$- 0.113 < \xi < + 0.112$ (95% CL)

$l = n_L/s$:

$- 0.012 < l < + 0.012$

Oldengott & Schwarz 2017

Lepton asymmetry
Primordial Nucleosynthesis



light element abundance:
helium is leptometer
deuterium is barometer

obtain formally tighter limits based on light element abundance, but systematic errors dominate

CMB constraints are robust (unlike BBN)

potential to improve significantly

Oldengott & Schwarz 2017

What does it tell us?

$q = 0$
$b = 10^{-10}$??
$|\,l\,| < 10^{-2}$

tiny baryon asymmetry —
lepton asymmetry could be much larger

Cosmological Inflation

- Evidence in favour of cosmological inflation:
  1. Spatial flatness
  2. Coherent fluctuations
  3. Gaussian fluctuations
  4. Almost scale-invariant power spectrum
- Exponential dilution of all charge densities and entropy density by inflation e.g. $n_C(t_{end}) = n_C(t_{initial}) \exp(- N)$, $N > 50$
- Suppression of $c = n_C/s$ by massive entropy production during reheating after end of inflation

Matter-Antimatter asymmetry

- Need either exponentially fine tuned initial conditions before inflation, or
- Generate asymmetry at or after reheating ⇒ matter genesis
- Requires three conditions Sakharov 1967:
  1. Violation of respective quantum number (e.g. B or L)
  2. Violation of C and CP
  3. Out-of-equilibrium situation

Many scenarios

- baryogenesis
- leptogenesis
- electric charge, baryon and lepton number are conserved at LHC (so far)
- lowest possible matter genesis energy scale above $T_{ew} \sim 100$ GeV and/or $E_{LHC} \sim 10$ TeV

Sphaleron process

- non-perturbative, $E_S \sim 10$ TeV, conserves B - L, but not B + L
  Klinkhamer & Manton 1984
- take place if Universe thermal above T_{ew} and $|l| < 10^{-2}$ McDonald 1999
- vanilla scenarios (inflation scale » 10 TeV, rapid reheating, and small matter asymmetry) predict relation between b and l. For the particle content of the standard model Harvey & Turner 1990:
  l = - (51/28) b = - (1.6 ± 0.1) 10^{-10} (tiny antineutrino excess today)
- Scenarios of late leptogenesis or with inefficient sphaleron processes can give rise to $|l| \gg b$
- Sphaleron processes do not equilibrate flavour asymmetries

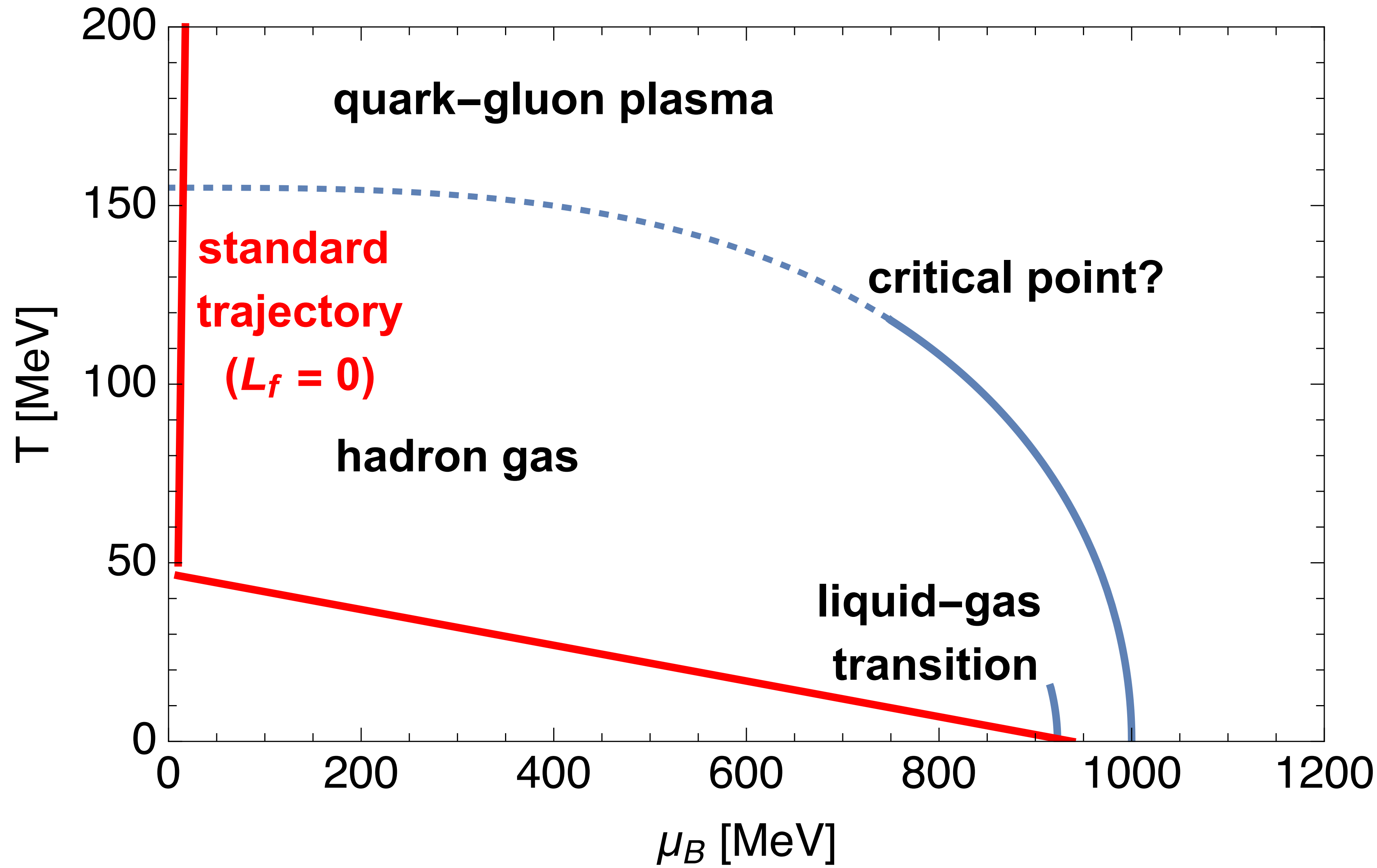
Large lepton asymmetry would indicate low energy scale or a delayed mechanism of matter genesis (close to ew scale)

What is the finger print of large lepton asymmetry ?

Lepton flavour number

- L_e, L_μ, L_τ are effectively conserved before Universe is old enough for neutrino oscillations
- **all scenarios allow large lepton flavour asymmetries, if a suitable flavour violating matter genesis mechanism is at work, e.g. $l_e = l = -1.6 \times 10^{-10}$ and $l_\mu = -l_\tau$ of order unity**

QCD epoch

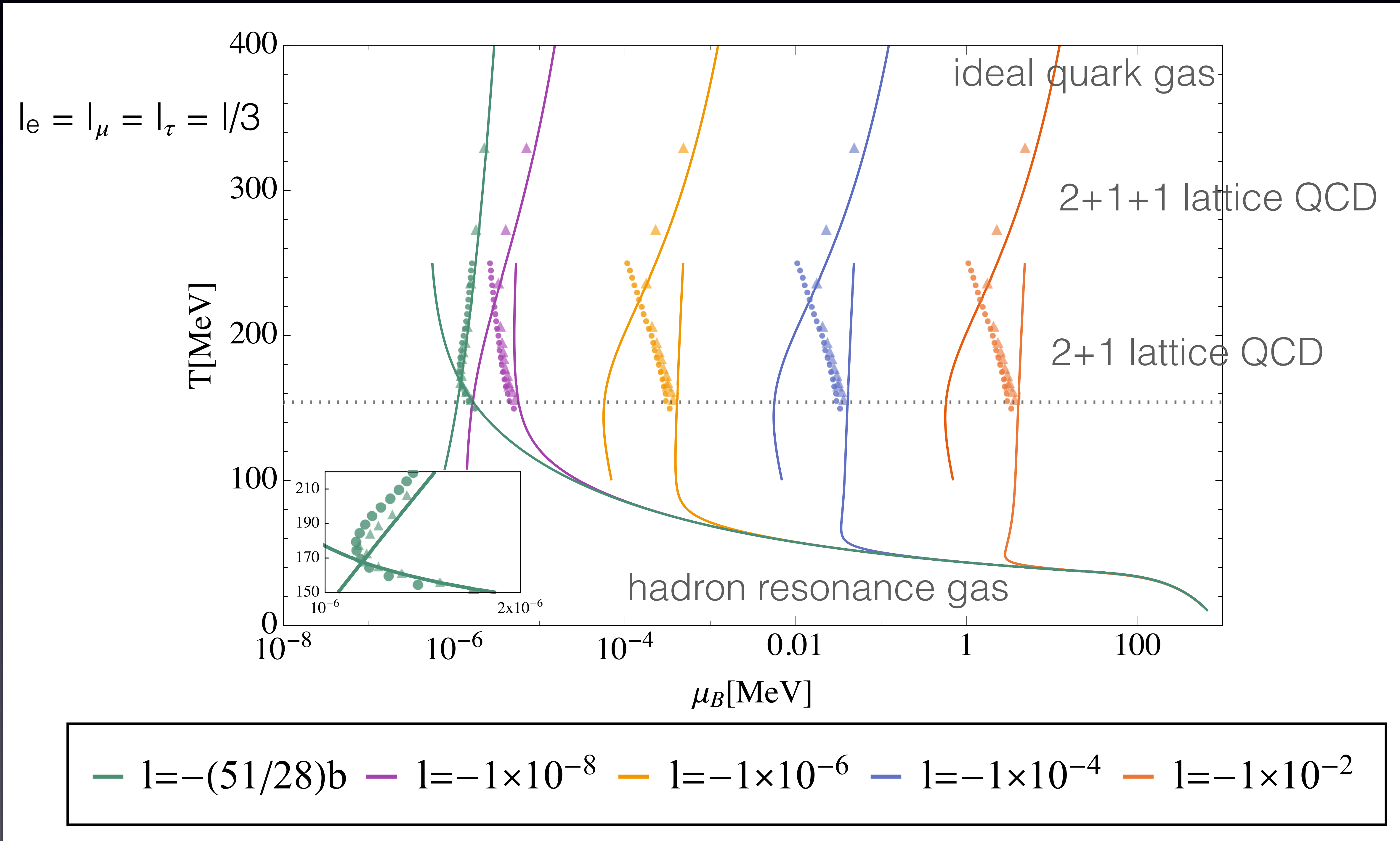


quark–gluon plasma
standard
trajectory
(L_f = 0)
critical point?
hadron gas
liquid–gas
transition
T [MeV]
μ_B [MeV]
200
150
100
50
0
0
200
400
600
800
1000
1200

Cosmic trajectory

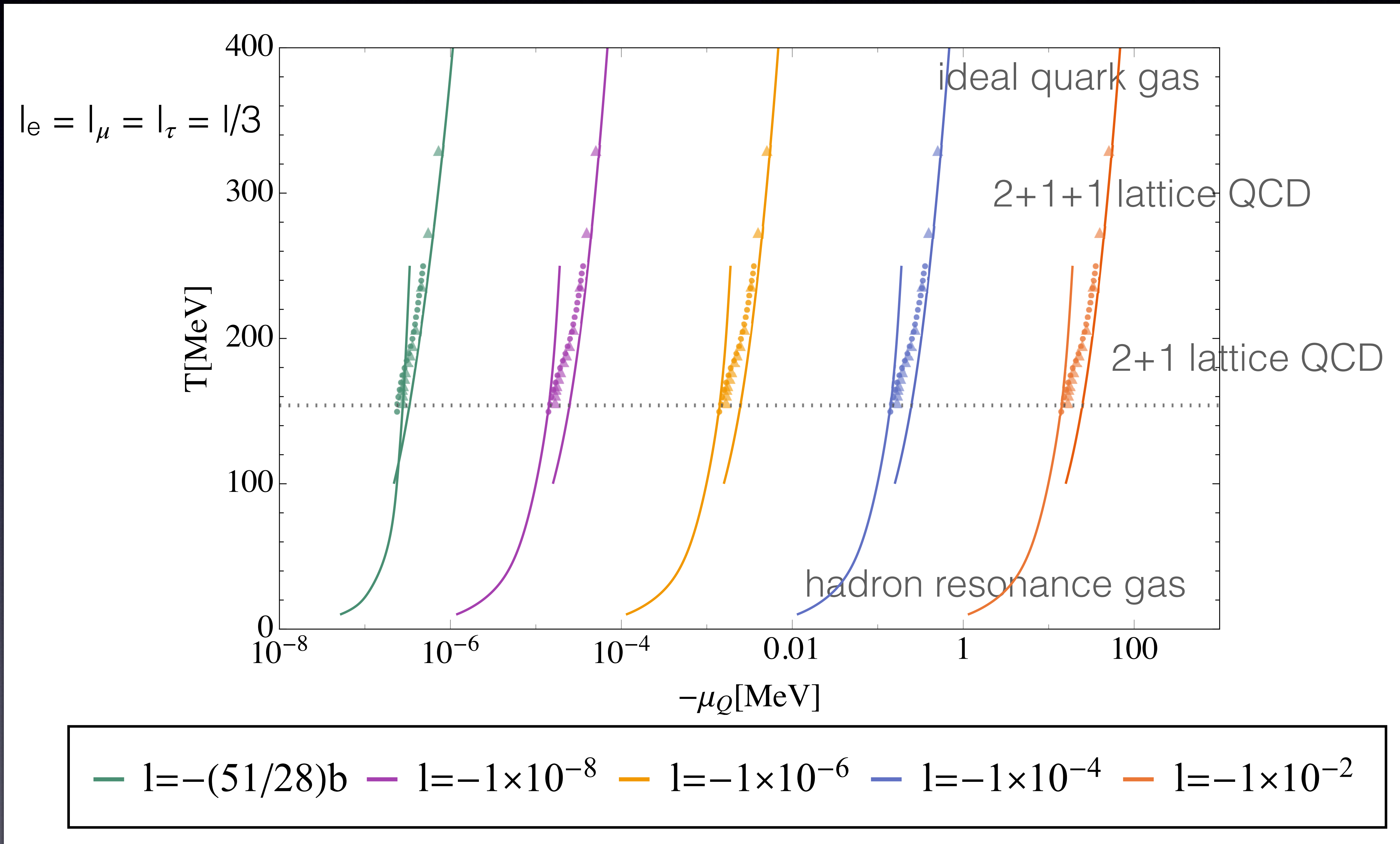
- five conservation equations: q, b, l_e, l_μ, l_τ
- weak interactions in equilibrium, i.e. $\mu_u = \mu_d + \mu_e - \mu_\nu$
- high T: ideal quark gas $\mu_B = \mu_u + 2\mu_d$, $\mu_Q = \mu_u - \mu_d$, $\mu_L = \mu_\nu$
- low T: hadron resonance gas $\mu_B = \mu_n$, $\mu_Q = \mu_\pi = \mu_p - \mu_n$, $\mu_L = \mu_\nu$
- T~ Λ_{QCD}: susceptibilities from lattice QCD at μ=0, analytic for ideal lepton gas, $n_B(T,\mu) = \chi_{BB}\, \mu_B + \chi_{BQ}\, \mu_Q$, etc.

Cosmic trajectory



Wygas, Oldengott, Bödeker & Schwarz 2018

Cosmic trajectory



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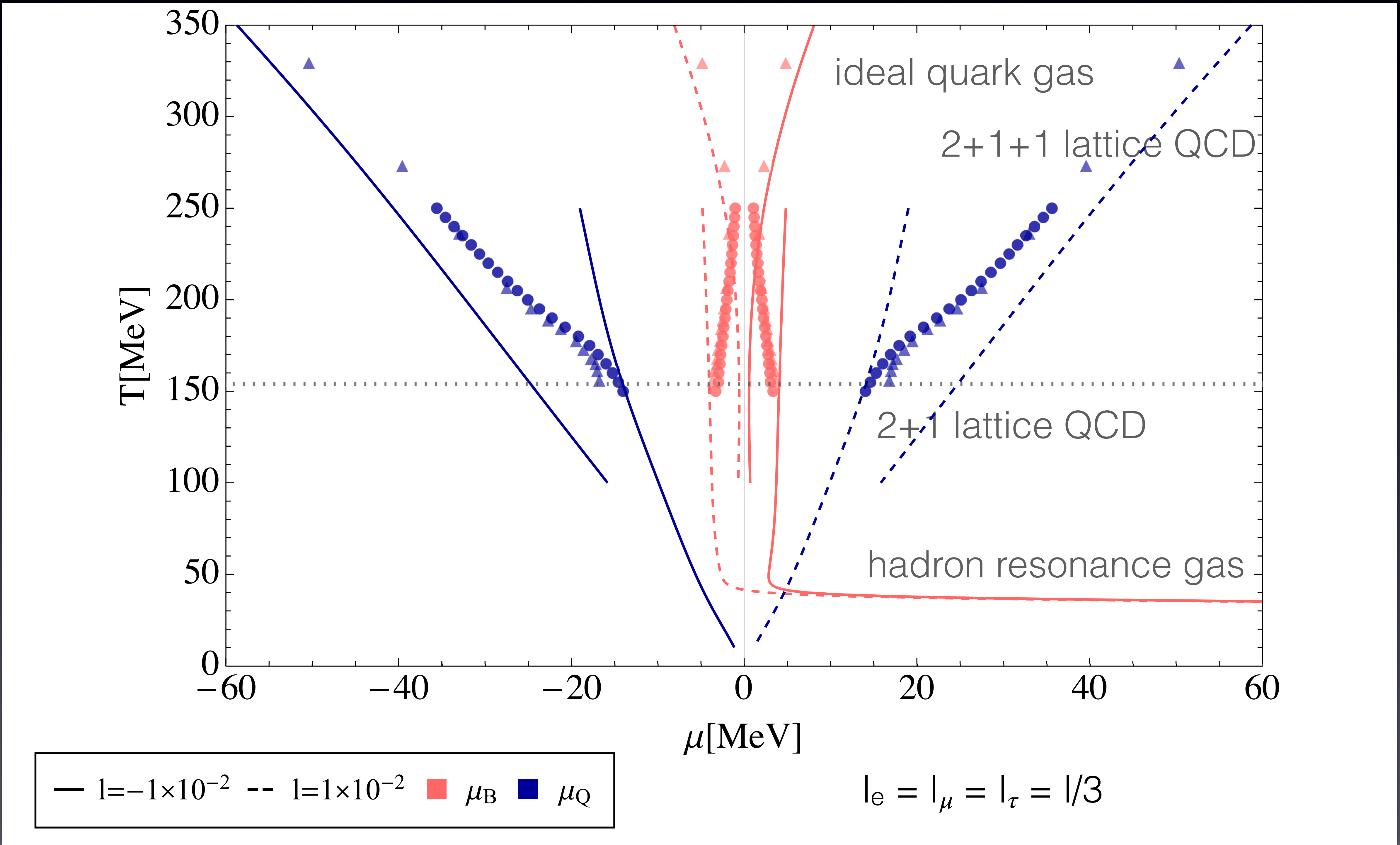
Cosmic trajectory



Wygas, Oldengott, Bödeker & Schwarz 2018

Further consequences?

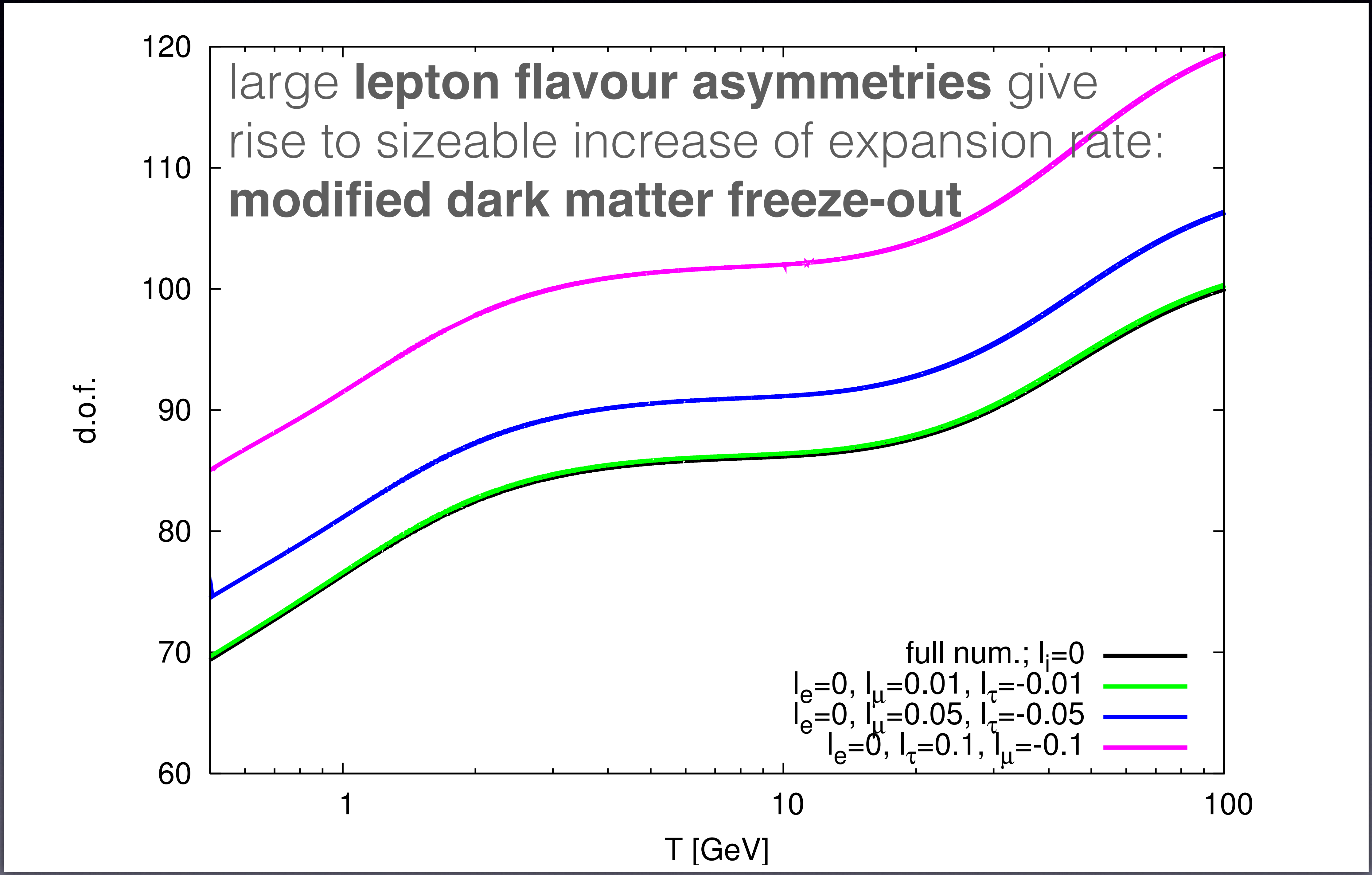
Flavour equilibrium:

- can large lepton asymmetry make the cosmic QCD transition a first order transition? … quite unlikely
- can it give rise to a pion condensate in the early Universe, i.e. is $\mu_Q \sim m_\pi$ possible? … no

No flavour equilibrium:

- Effects can be more extreme … under investigation

Dark matter abundance



Stuke, Schwarz & Starlkman 2012

Conclusion

- lepton asymmetry is most robustly constrained from CMB, $|l| < 0.012$ @ 95%CL, need to improve deuterium prediction
- large lepton asymmetry affects cosmic trajectory in QCD diagram, but no change of nature of transition and no pion condensate
- in very early Universe $|\mu_Q| > \mu_B$, if $|l| > 10^{-8}$
- lepton (flavour) asymmetry affect dark matter abundance
- weaker constraints on l_μ and l_τ dropping assumption on neutrino flavour equilibration … under investigation
- direct determination of l would be possible from CνB, e.g. PTOLEMY