Cosmic QCD epoch
at large lepton flavour asymmetries

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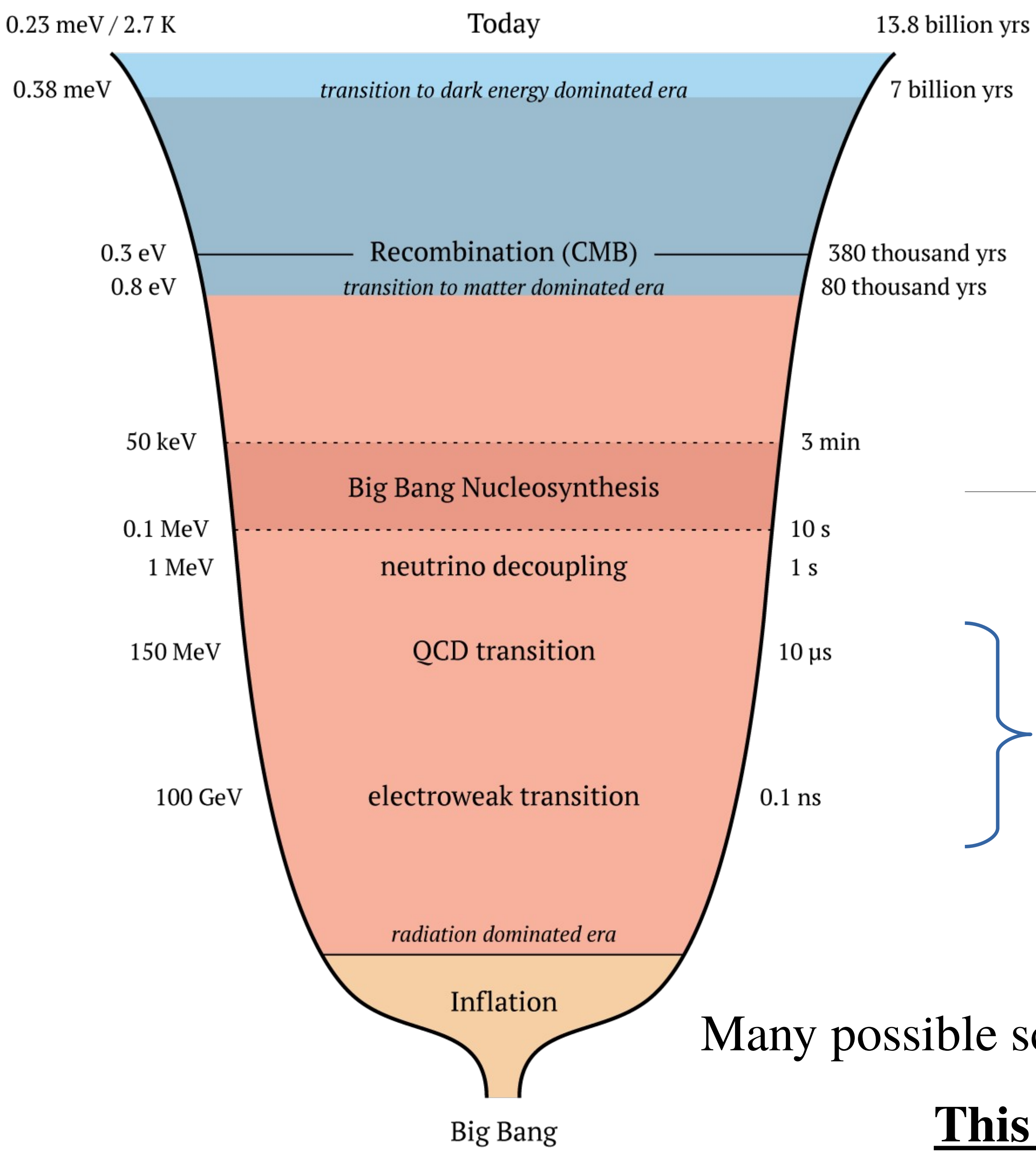
based on: *arXiv: 2106.11991, 2009.00036, 1807.10815*

with M. Middeldorf-Wygas, F. Gao, D. Bödeker, D. J. Schwarz



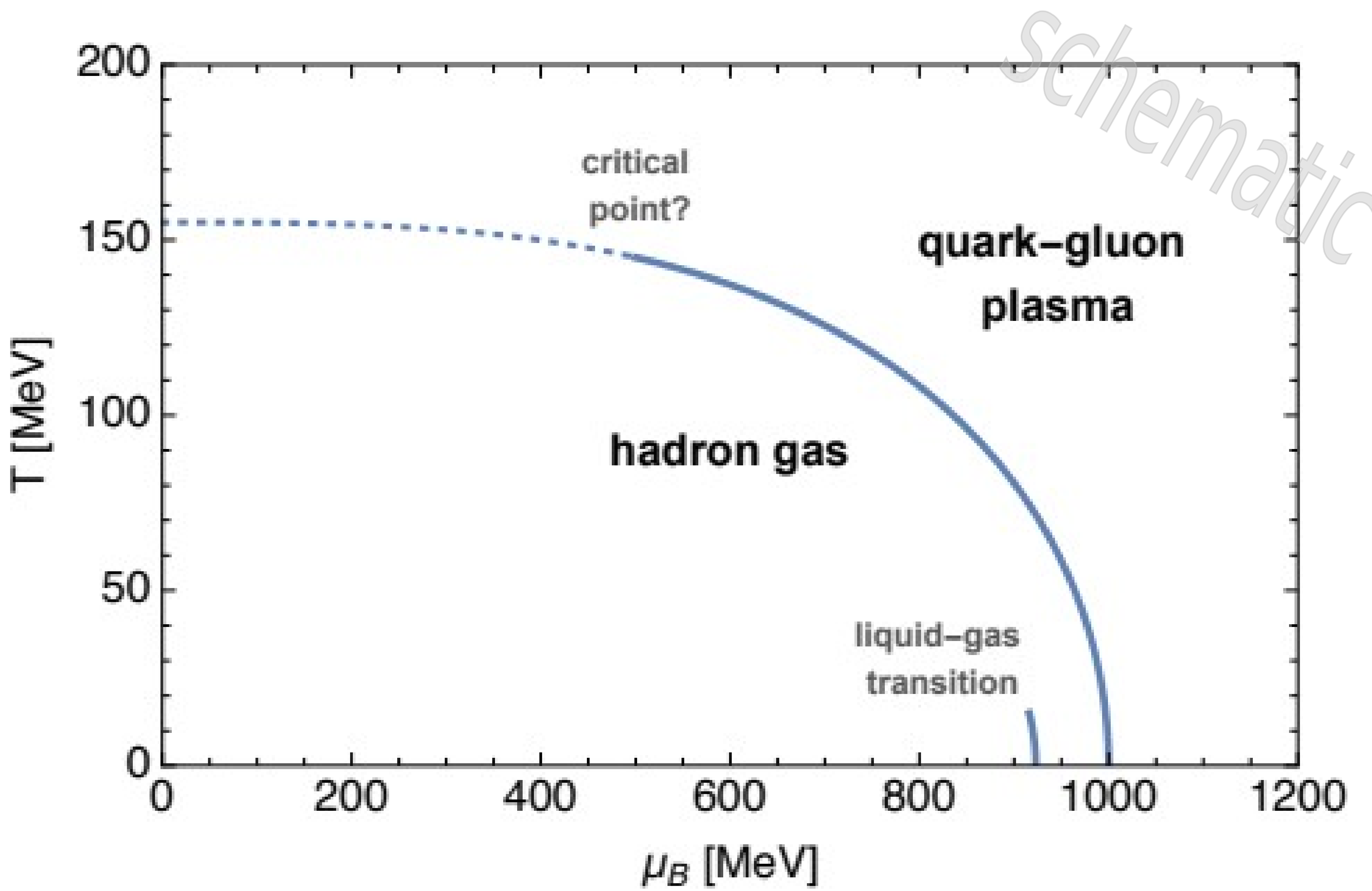
Very well measured

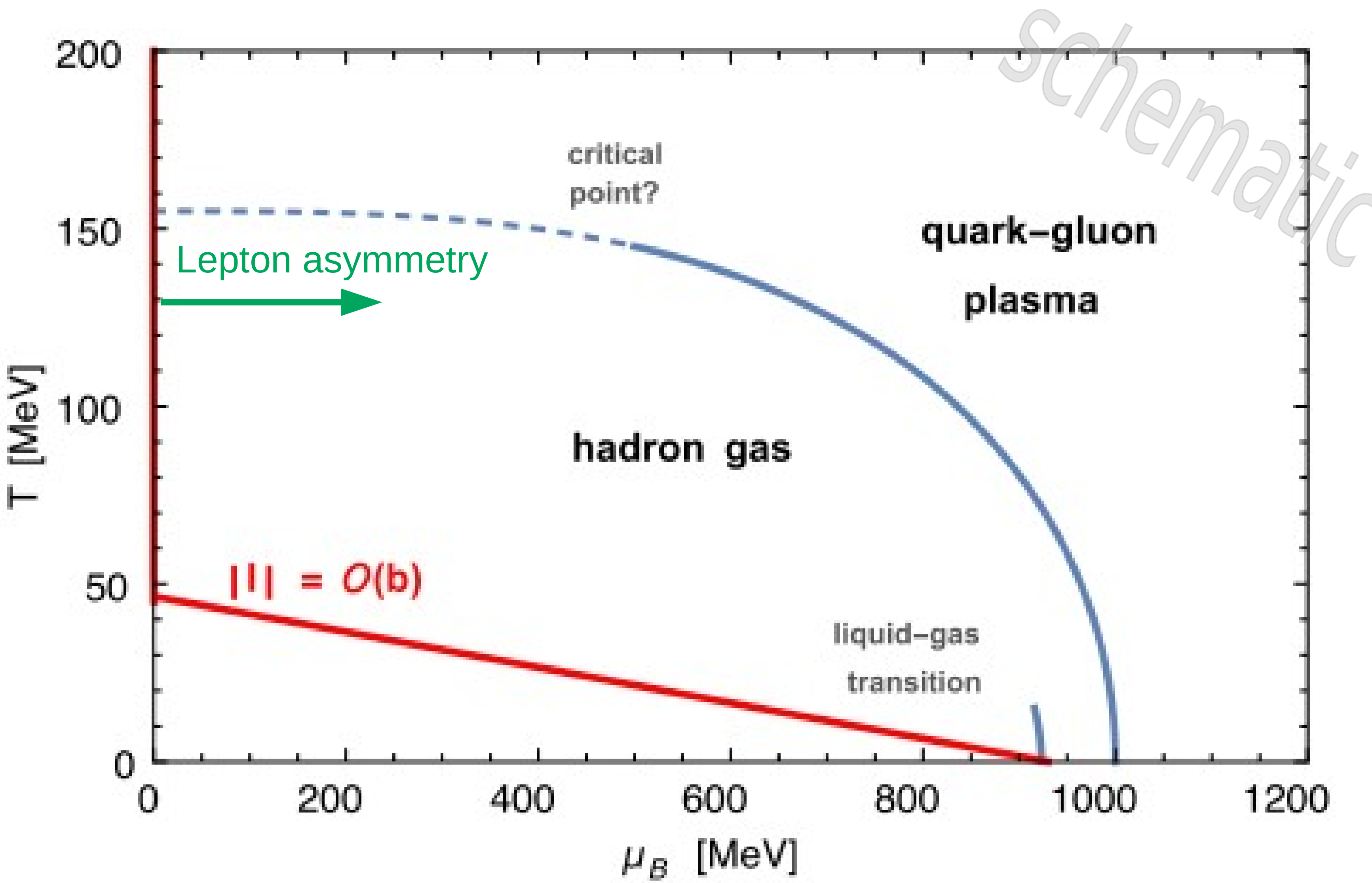
Well measured, earliest epoch we can probe so far

GW era gives hope to obtain insight about those eras

Many possible scenarios → 1st order EW transition

<u>This work: QCD transition</u>


schematic
critical point?
quark–gluon plasma
hadron gas
liquid–gas transition
T [MeV]
μ_B [MeV]
200
150
100
50
0
0
200
400
600
800
1000
1200



M. Stuke, D. Schwarz (2009)

Baryon asymmetry of Universe : $b = \frac{n_{\mathrm{B}}}{s} = (8.70 \pm 0.06) \times 10^{-11}$ *(Planck 2018)*

$\rightarrow$ well measured, but poorly understood...

Tiny, but why so big?

$\rightarrow$ Baryogenesis, Leptogenesis

Leptogenesis: 1.) Mechanism for creation of lepton asymmetry
2.) Sphaleron processes transfer lepton asymmetry to baryon asymmetry

$\rightarrow$ standard assumption:
lepton asymmetry ≈ baryon asymmetry (i. e. tiny)

Possible caveats?

- sphaleron processes experimentally not confirmed
- suppress sphaleron processes? *(S. Eijima, M. Shaposhnikov 2017; G. Barenboim, W. Park 2017;...)*
- create large lepton asymmetry at later times, when sphaleron processes are inefficient *(Drewes et al. 2021; Canetti et al. 2012; Affleck-Dine mechanism; Barbieri & Dolgov 1991; ...)*

Lepton asymmetry = key parameter for origin of matter-antimatter asymmetry

What do we know about the lepton asymmetry of our Universe?

charge neutrality:

$\rightarrow$ possibly hidden in cosmic neutrino background

$\rightarrow$ no direct measurement possible $(T_\nu = 1.9\,\mathrm{K})$

Any observational constraints?

At CMB and BBN:

$$\boxed{\eta_l = \sum_{\alpha=e,\mu,\tau} \eta_\alpha \approx \sum_{\alpha=e,\mu,\tau} \frac{n_{\nu,\alpha} - n_{\bar{\nu},\alpha}}{n_\gamma} = \frac{1}{12\zeta(3)} \sum_{\alpha=e,\mu,\tau} \left(\frac{T_{\nu,\alpha}}{T_\gamma}\right)^3 (\pi^2 \xi_\alpha + \xi_\alpha^3)}$$

Fermi-Dirac

chemical potentials: $\frac{\mu_\alpha}{T_{\nu,\alpha}}$

Alternative definition: $l = \sum_{\alpha=e,\mu,\tau} \frac{n_{\nu,\alpha} - n_{\bar{\nu},\alpha}}{s}$

Observational constraints?

I) increased relativistic energy density:

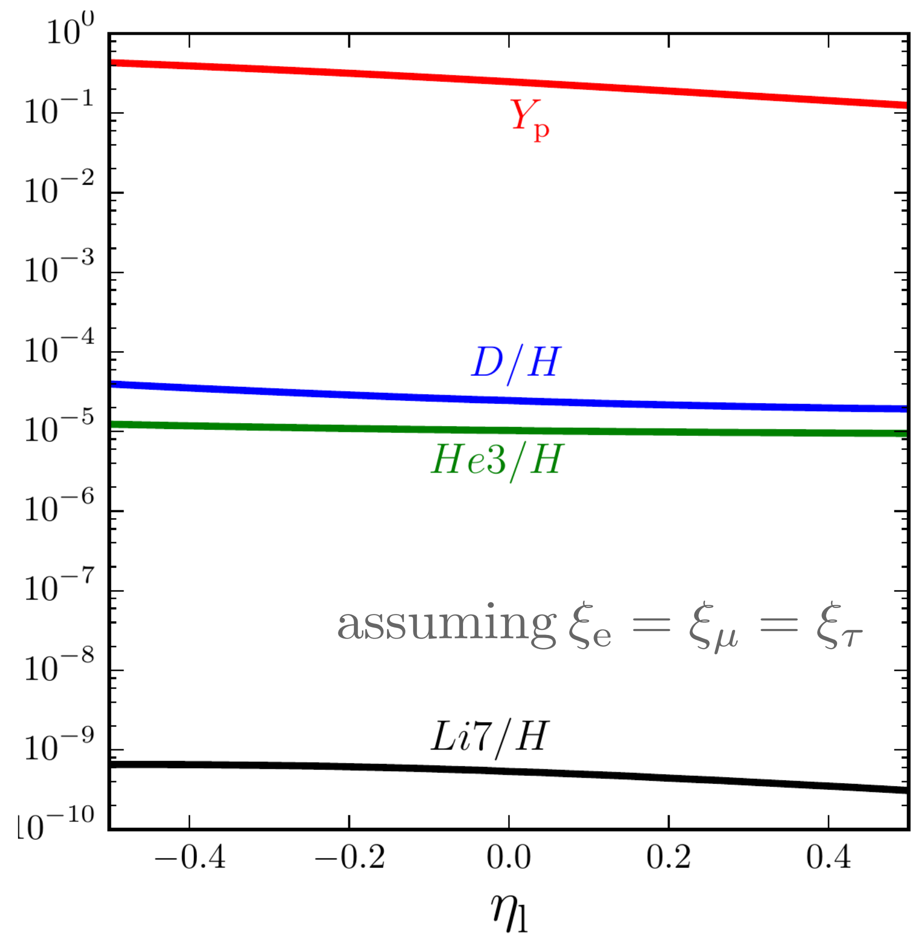
$$N_{\mathrm{eff}} = 3.046 + \frac{15}{7}\sum_{\alpha} \underbrace{\left(\frac{\xi_\alpha}{\pi}\right)^2 \left[2 + \left(\frac{\xi_\alpha}{\pi}\right)^2\right]}_{\geq 0}$$

II) modified weak interactions:

$$\left(\frac{n}{p}\right)_{\xi_{\mathrm{e}}} \approx \left(\frac{n}{p}\right)_{\xi_{\mathrm{e}}=0} \times \begin{cases} e^{-\xi_{\mathrm{e}}} & \text{for } \xi_{\mathrm{e}} < 0 \\ e^{-1.2\xi_{\mathrm{e}}} & \text{for } \xi_{\mathrm{e}} > 0 \end{cases}$$

G. Beaudet, P. Goret, 1976

→ BBN codes, e.g. AlterBBN *(A. Arbey)*



→ Constraints on lepton asymmetry from observations of:

- Primordial element abundances *e.g. Pitrou et al. (2018), arXiv: 1801.08023*
- CMB anisotropies *e.g. IMO, D. Schwarz (2017), arXiv: 1706.01705*

$$\boxed{\eta_l \leq \mathcal{O}(0.01)}$$

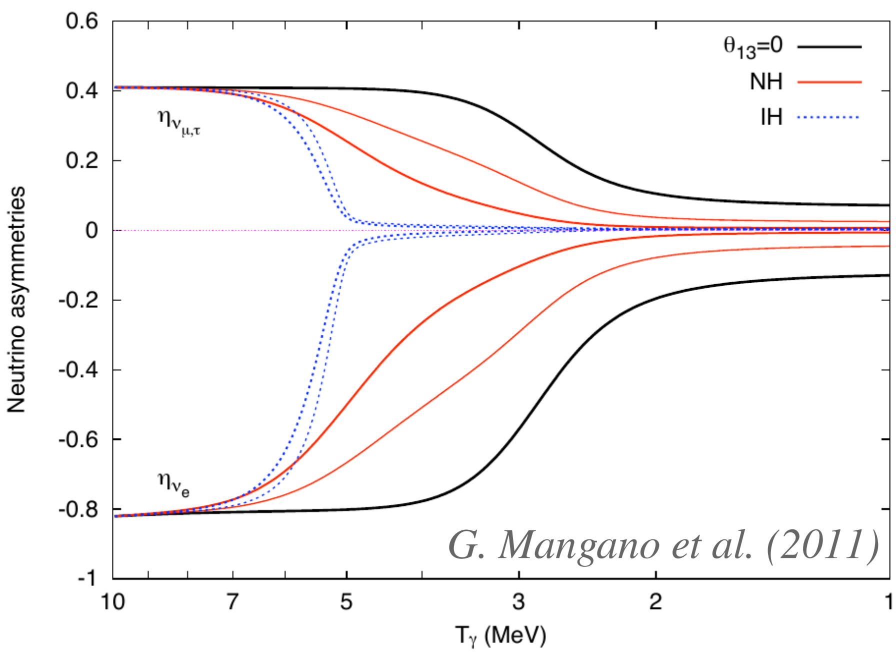
→ very weak

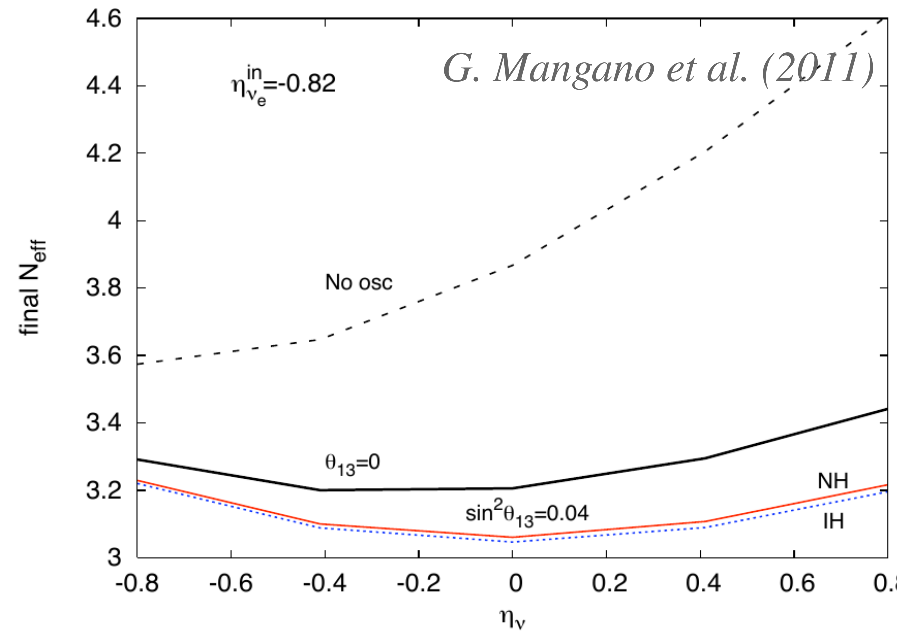
Only total asymmetry constrained by BBN and CMB:

(A. D. Dolgov et al. (2002), arXiv: 0201287; Y.YY. Wong (2002), arXiv: 0203180;

G. Mangano et al. (2011), arXiv: 1110.4335)

Neutrino oscillations at **T~10 MeV** $\rightarrow$ **Equilibration** of lepton flavour asymmetries:





$$\eta_\alpha\big|_{\mathrm{BBN,CMB}} \approx \frac{\eta_l}{3}$$

But equilibration probably only partial...

(G. Barenboim et al. arXiv: 1609.01584)

However, individual lepton flavour asymmetries before 10 MeV almost unconstrained

Agnostic point of view: lepton asymmetries = free parameters for cosmology

QCD epoch: How to compute the cosmic trajectory

Some new-physics's scale where lepton asymmetry gets produced

Conservation laws (at $10 \text{ MeV} < T < T_{BSM}$) :

Free input parameters

1.) Lepton number: $l_\alpha s = n_\alpha + n_{\nu_\alpha}, \; \alpha = e, \mu, \tau$

2.) Baryon number: $bs = \sum_i B_i n_i$ $\quad b = 8.7 \times 10^{-11}$

3.) Electric charge: $qs = \sum_i Q_i n_i$ $\quad q = 0$ (charge neutral)

+ relations for chemical pot.:

$\mu_u = \mu_c, \; \mu_e - \mu_{\nu_e} = \mu_\mu - \mu_{\nu_\mu}, \; etc.$

$$\mu_{L_\alpha} = \mu_{\nu_\alpha},$$
$$\mu_B = \mu_u + 2\mu_d,$$
$$\mu_Q = \mu_u - \mu_d,$$

3 input parameters,
5 equations,
5 variables
$\mu_{\mathrm{L}_e}, \mu_{\mathrm{L}_\mu}, \mu_{\mathrm{L}_\tau}, \mu_{\mathrm{B}}, \mu_{\mathrm{Q}}$

$\downarrow$

Cosmic trajectory
= solution for different temperatures T

Why should large lepton asymmetries induce large baryon chemical potentials?

$$l_\alpha = \frac{n_\alpha + n_{\nu_\alpha}}{s}$$ ➡ large l_e induce large electron asymmetry (→ large μ_e)

$$q = 0 = \sum_i \frac{Q_i n_i}{s}$$ ➡ needs to be compensated by asymmetry in quark sector (→ large μ_u)

➡ $\mu_B = \mu_u + 2\mu_d$ **large baryon chemical potential**

How to compute the cosmic trajectory:

$$l_\alpha = \frac{n_\alpha + n_{\nu_\alpha}}{s}$$

$$q = -\sum_{\alpha=e,\mu,\tau} \frac{n_\alpha}{s} + \boxed{\sum_{i=baryons} \frac{Q_i n_i}{s}}$$

$$b = \boxed{\sum_{i=baryons} \frac{B_i n_i}{s}}$$

Leptonic sector "easy":
Fermi-Dirac distributions

Baryonic sector:
That's where it becomes complicated…

→ two different methods

- **Method I: Lattice QCD** *Middeldorf-Wygas, IMO, Schwarz, Bödeker (2018 + 2020), Phys.Rev.Lett. 121 (2018) 20, 201302, arXiv: 1807.10815; arXiv: 2009.00036*

I) High temperatures:

Ideal quark gas (equilibrium distributions)

II) around the QCD transition

Taylor expansion + lattice QCD susceptibilities:

Only applicable at small chemical potentials...

$$p^{\mathrm{QCD}}(T,\mu) = p^{\mathrm{QCD}}(T,0) + \frac{1}{2}\mu_a \chi_{ab}(T)\mu_b + \mathcal{O}(\mu^4)$$

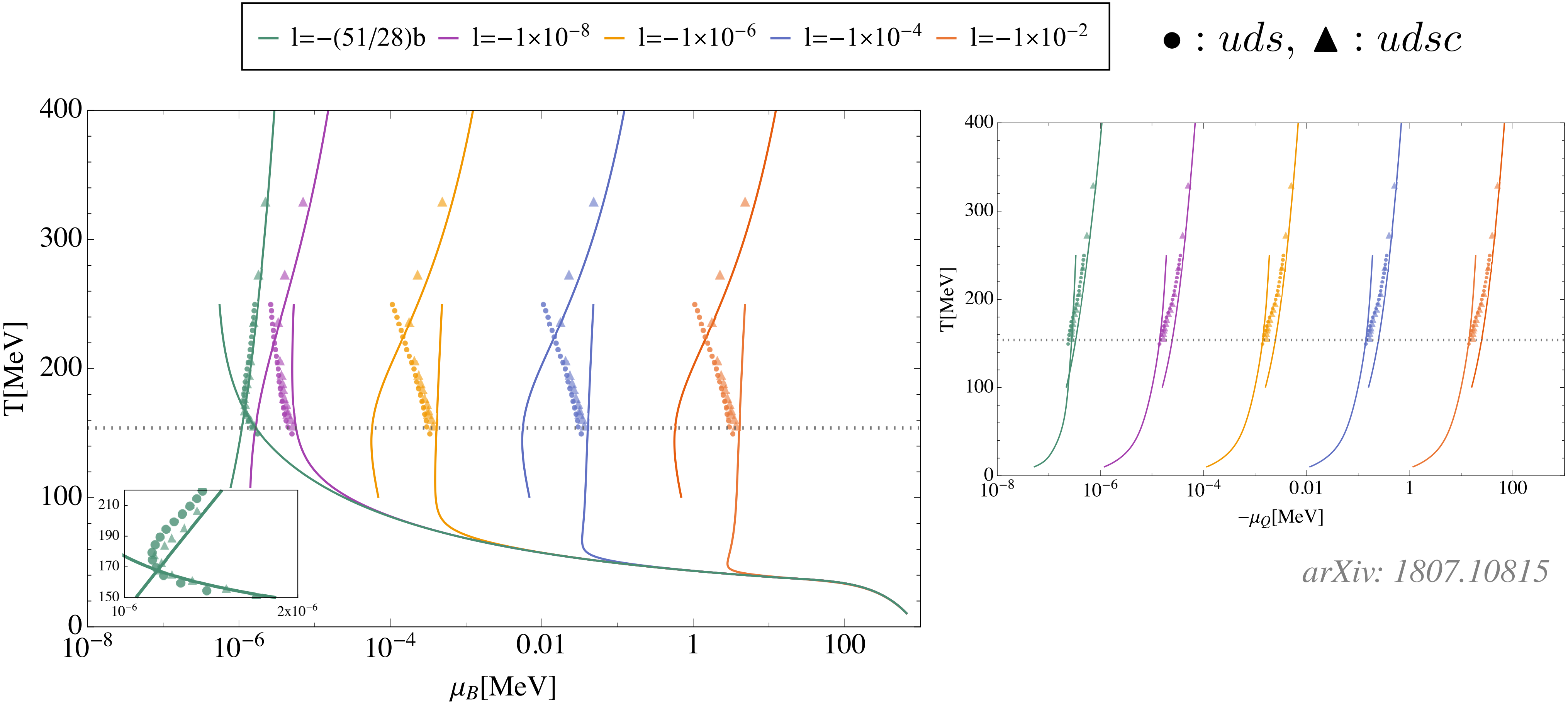
$$n_a(T,\mu) = \frac{\partial p^{\mathrm{QCD}}(T,\mu)}{\partial \mu_a} = \chi_{ab}\mu_b + \mathcal{O}(\mu^3)$$

(Hot QCD coll. 2012 & 2014)

III) Low temperatures:

Hadron resonance gas (equilbrium distributions for hadrons)

Equal lepton flavour asymmetries



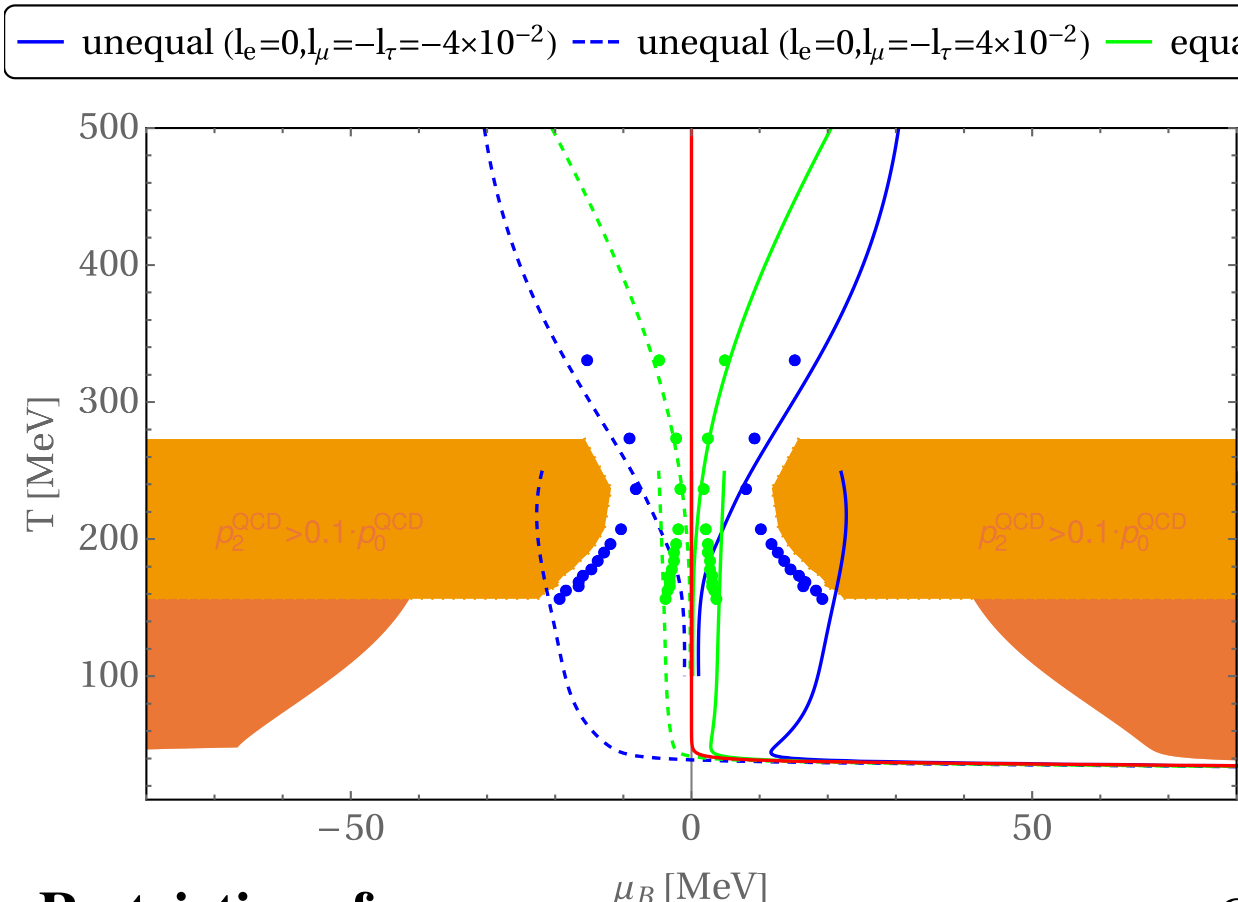
arXiv: 1807.10815

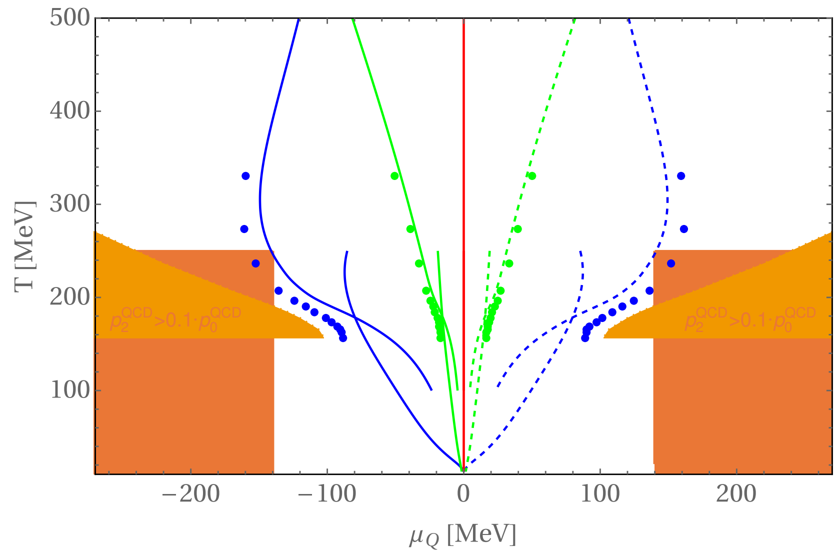
→ Lepton asymmetry induces large baryon and charge chemical potentials.

→ Need to include charm quark in order to smoothly connect different phases.

Modifications of equation of state: Impact on primordial black hole formation *(D. Bödeker, F. Kühnel, IMO, D. Schwarz ,arXiv: 2011.07283)*

Unequal lepton flavour asymmetries





arXiv: 2009.00036

Restrictions from:

1) Reliability from Taylor expansion

2) Formation of a pion condensate

→ **cosmological consequences:**

V. Vovchenko et al. (2020), arXiv:2009.02309

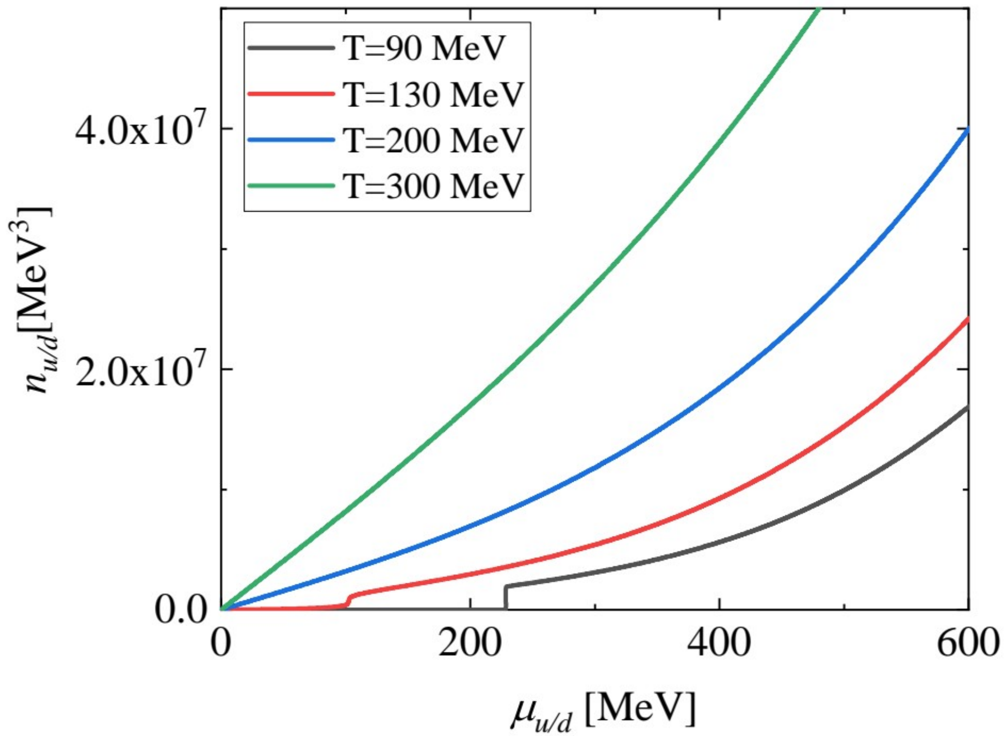
Only applicable to relatively small lepton asymmetries

Can large lepton flavour asymmetries induce a 1st order cosmic QCD transition???

Method II: Functional QCD

(F. Gao, IMO (2021), Phys.Rev.Lett. 128 (2022) 13, 131301, arXiv: 2106.11991)

Thermodynamic quantities derived from Dyson-Schwinger equations in the rainbow-ladder(RL) truncation:

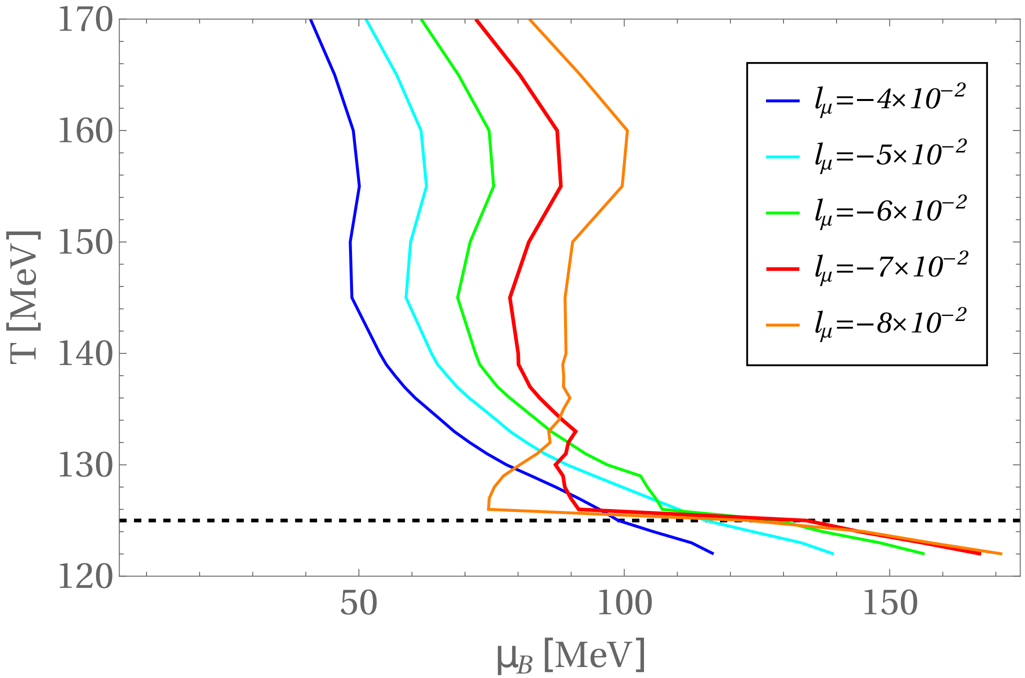


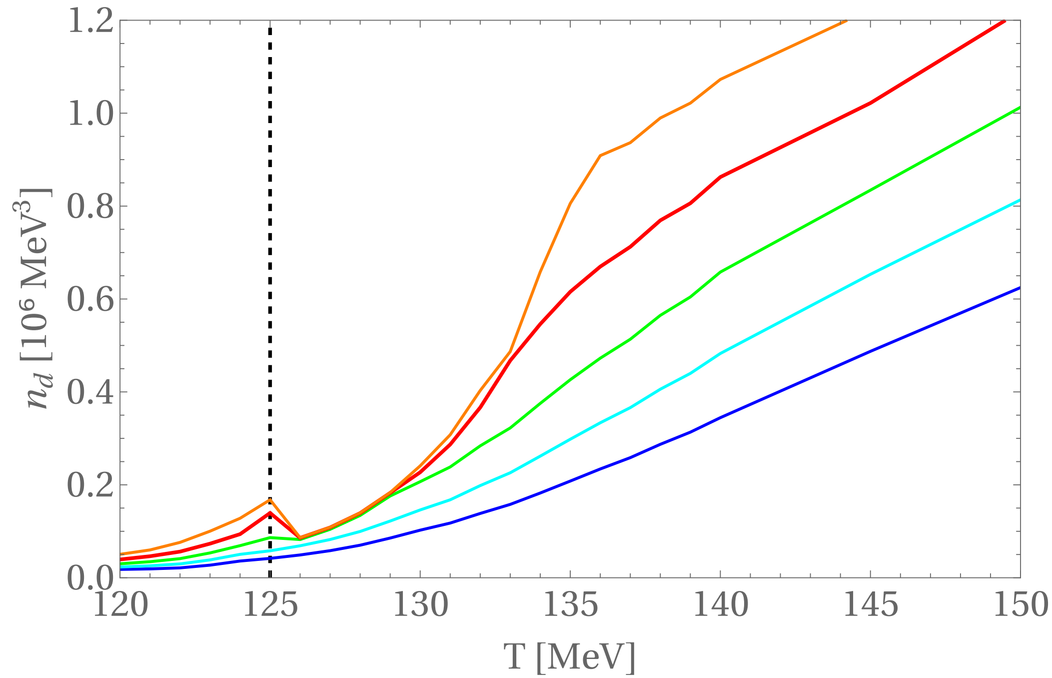
F. Gao, J. Chen, Y.-X. Liu, S.-X. Qin, C. D. Roberts, S. M. Schmidt (2015), arXiv:1507.00875

$$\Rightarrow (T_{\mathrm{CEP}}, \mu_{\mathrm{CEP}})_{u/d} = (125, 111)\ \mathrm{MeV}$$

Include thermodynamic quantities into calculation of cosmic trajectory:

Consider here: l_e=0, l_μ = -l_τ ◄—— fullfils CMB/BBN requirement l=0





Discontinuity between l_μ=-0.06 and l_μ=-0.07

→ 1st order transition !

To predict when a first-order transition happens add as an additional constraint to system of equations:

$$\mu_{u/d} \geq \mu_{CEP} \quad \text{at} \quad T = T_{CEP}$$

$\rightarrow$ 6 equations, eliminates one degree of freedom

(i) $l_e = l_\mu = l_\tau = \frac{l}{3}$

(ii) $l_e = 0, l_\mu = -l_\tau$

(iii) $l_e = -l_\tau, l_\mu = 0$

(iv) $l_e = -l_\mu, l_\tau = 0$

(v) $l_e = l_\mu, l_\tau = -2l_e$

(vi) $l_e = l_\tau, l_\mu = -2l_e$

(vii) $l_e = -2l_\mu, l_\mu = l_\tau$

described by 1 dof $\rightarrow$ no further input

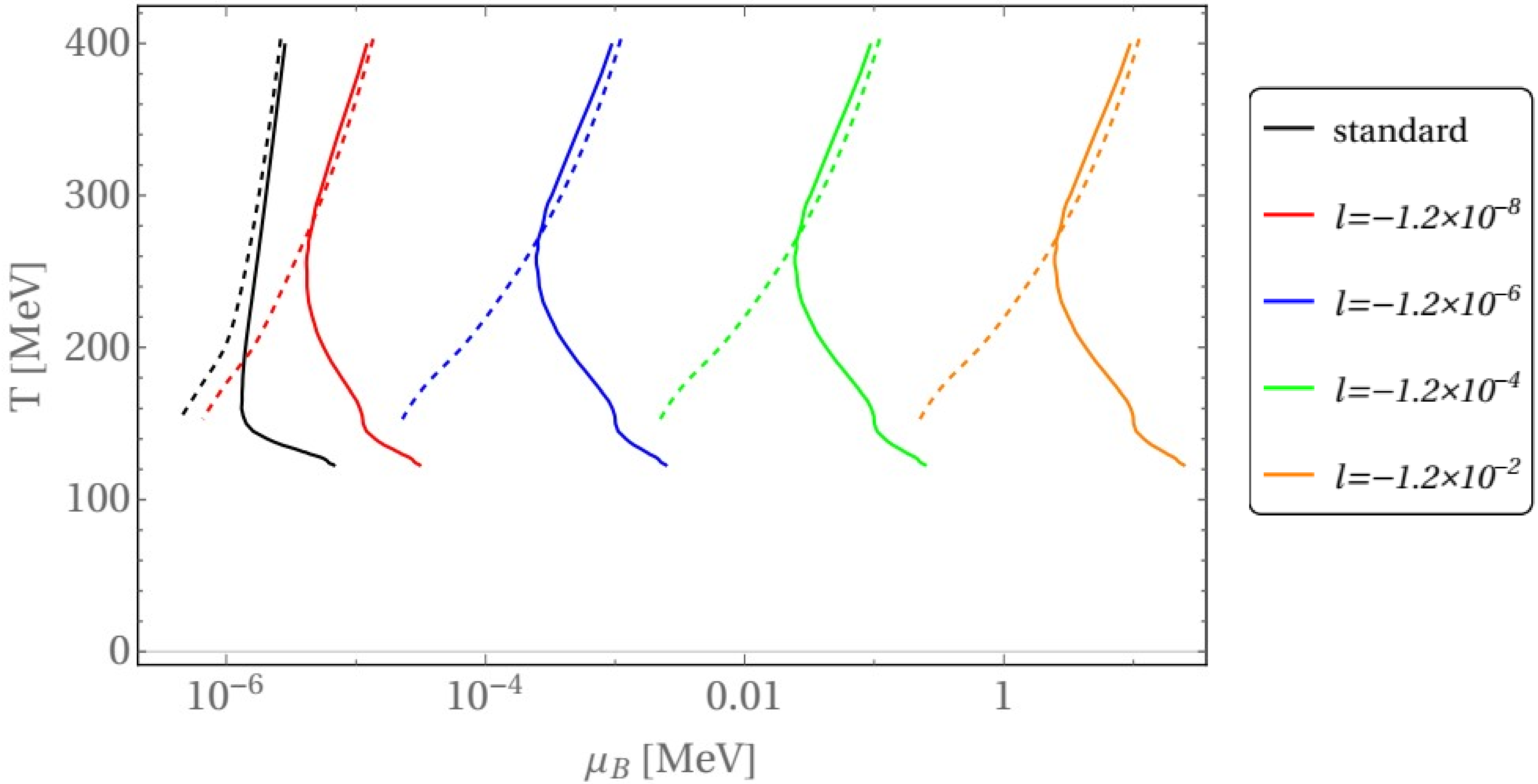
solutions $\Rightarrow$

	$\mu_u \geq 111$ MeV	$\mu_d \geq 111$ MeV
(i)	$l \geq 1.10 \times 10^{-1}$	$l \leq -1.03 \times 10^{-1}$
(ii)	$l_\mu \geq 7.43 \times 10^{-2}$	$l_\mu \leq -6.85 \times 10^{-2}$
(iii)	$l_e \geq 7.14 \times 10^{-2}$	$l_e \leq -6.59 \times 10^{-2}$
(iv)	$l_e \geq 1.36 \times 10^{-3}$	no solution
(v)	$l_e \geq 3.46 \times 10^{-2}$	$l_e \leq -3.23 \times 10^{-2}$
(vi)	$l_e \leq -1.20 \times 10^{-1}$	$l_e \geq 1.02 \times 10^{-1}$
(vii)	$l_e \leq -1.14 \times 10^{-1}$	$l_e \geq 9.43 \times 10^{-2}$

- **Confirms interpretation of 1st order transition.**
- **(i) is already excluded by CMB/BBN constraints, all others are unconstrained observationally.**

Comparison between methods

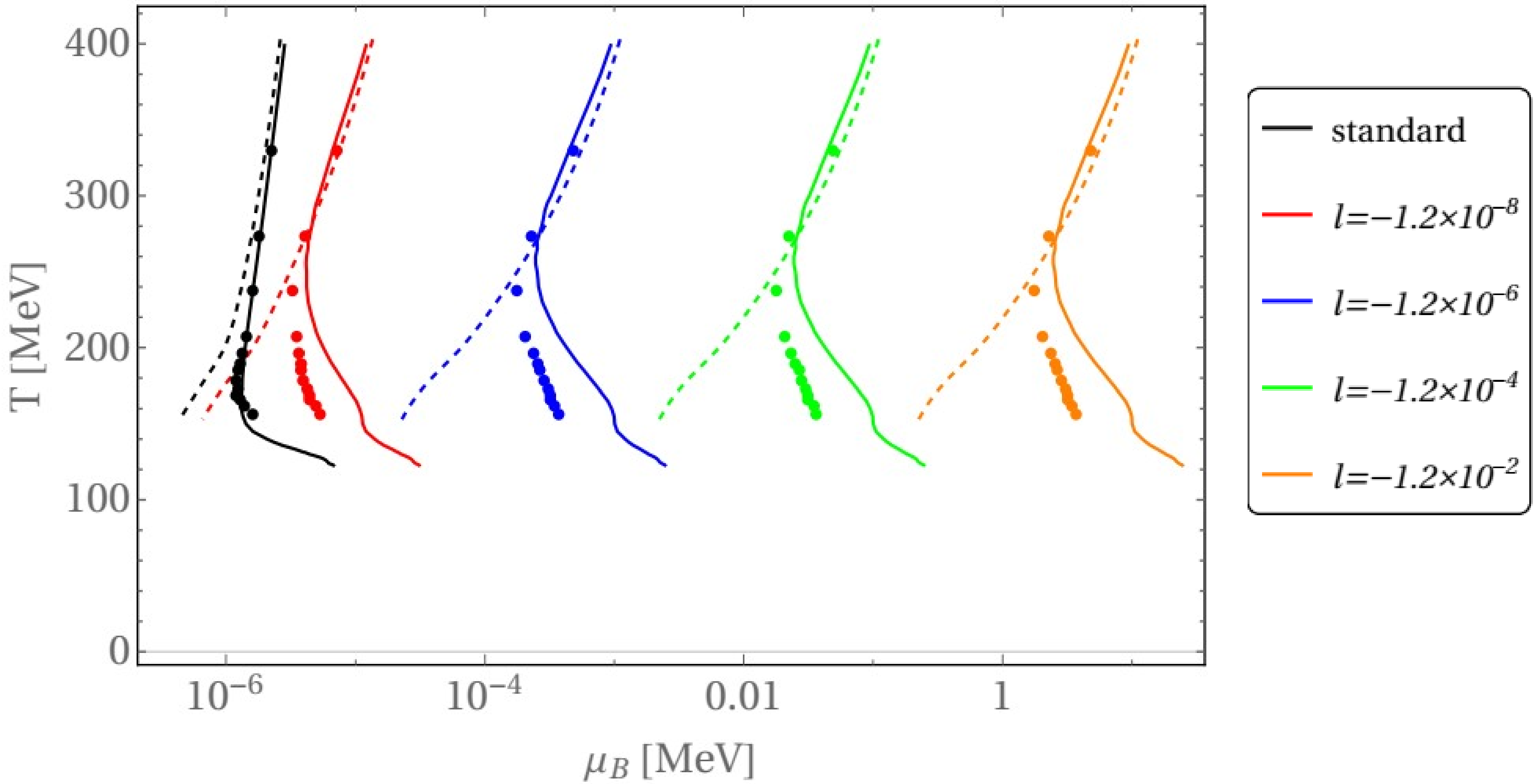
$$(i)\ \ l_e = l_\mu = l_\tau = \frac{l}{3}$$



- **High T**: works quite well

Comparison between methods

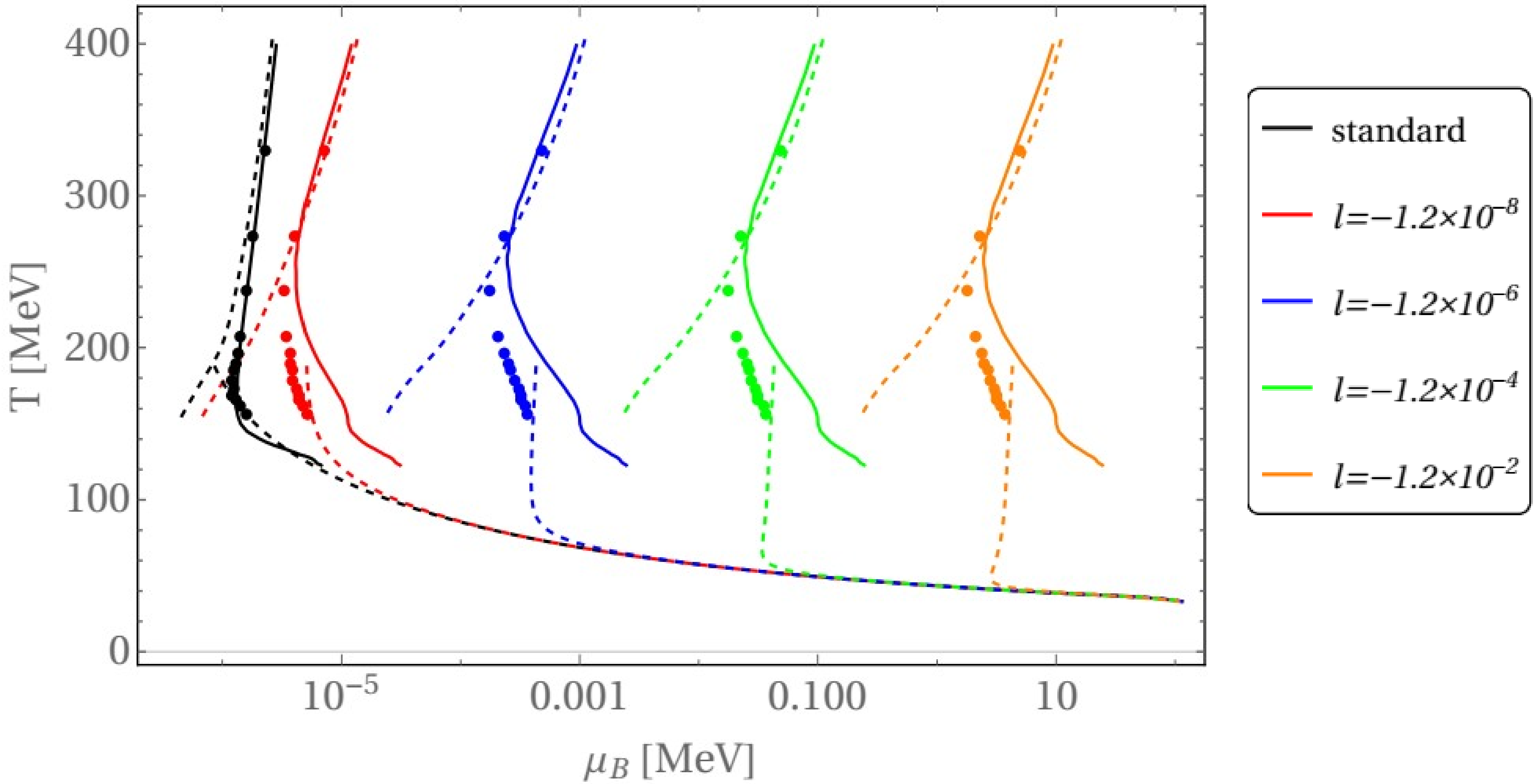
$(i)\ l_e = l_\mu = l_\tau = \dfrac{l}{3}$



- **High T**: works quite well
- **Around T_{QCD}**: same trend but not really matching

Comparison between methods

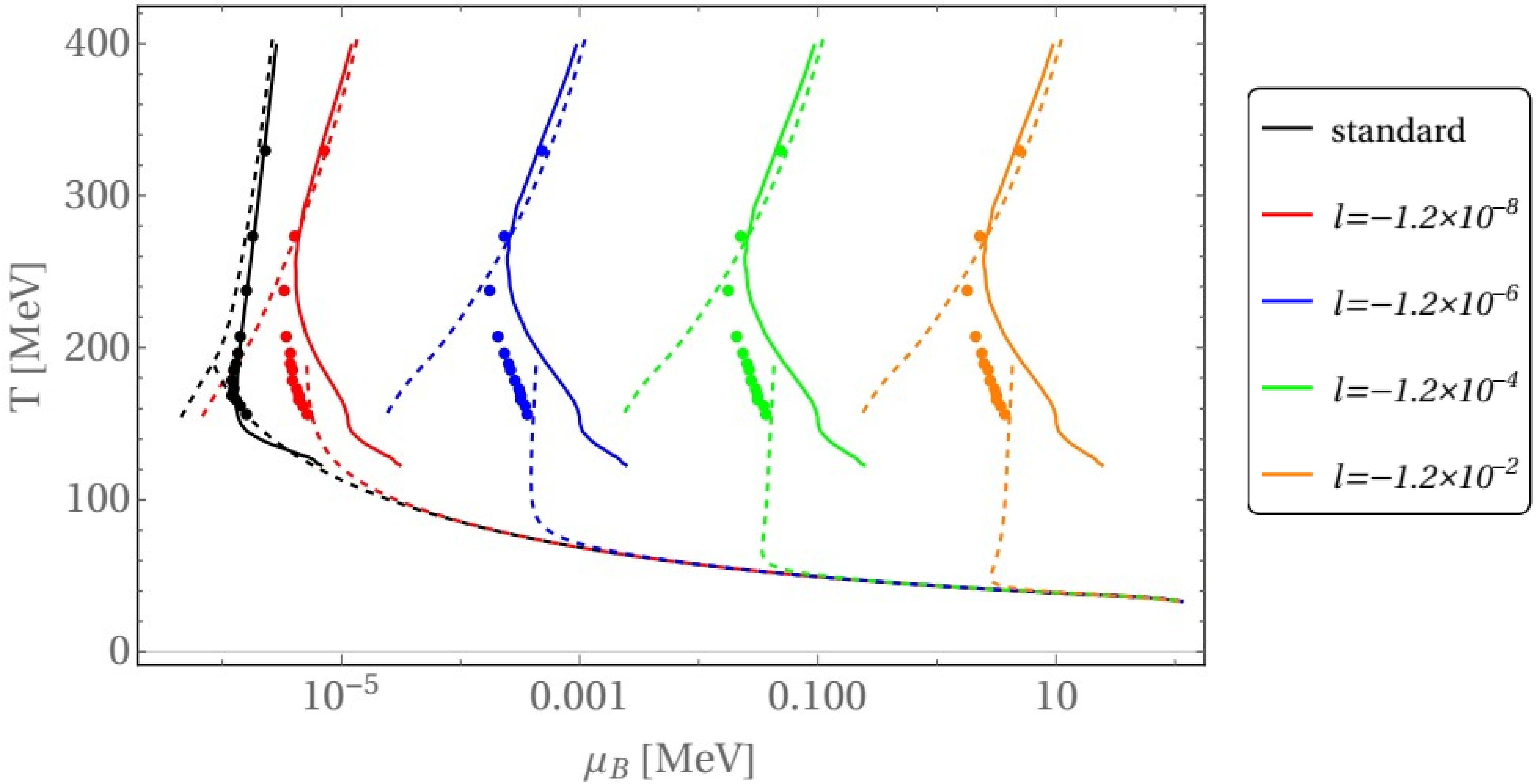
$$(i)\ l_e = l_\mu = l_\tau = \frac{l}{3}$$



- **High T**: works quite well
- **Around $\mathbf{T_{QCD}}$**: same trend but not really matching
- **Low T**: does not really match

Comparison between methods

$(i)\ l_e = l_\mu = l_\tau = \dfrac{l}{3}$



- **High T**: works quite well
- **Around T$_{QCD}$**: same trend but not really matching
- **Low T**: does not really match

Sneak preview (preliminary):

Improved truncation scheme can significantly improve this

- Lepton flavour asymmetries before ~ 10 MeV are almost unconstrained and have an impact on the cosmic trajectory during the QCD epoch.

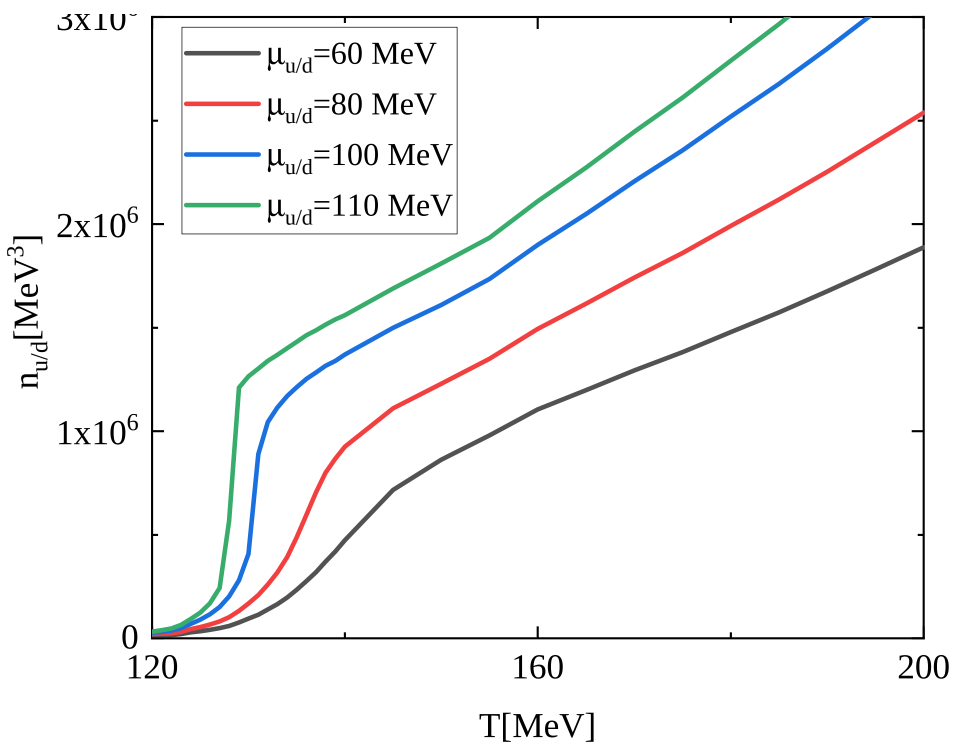
$\rightarrow$ Two different methods to calculate cosmic trajectory:

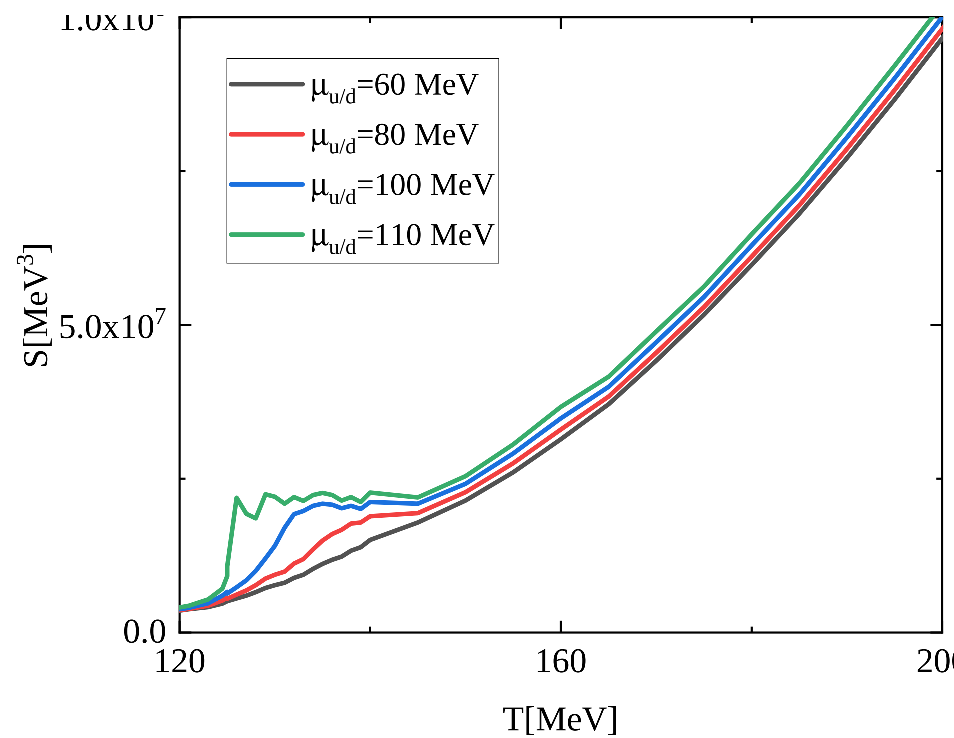
I) Lattice QCD susceptibilities
II) functional QCD

- For small values of the lepton asymmetries method I) is more reliable but cannot be extended to region of 1st order transition $\rightarrow$ method II)

- Method II) reveals that the cosmic QCD transition can be first order IF lepton flavour asymmetries are unequal.

Thank you





$$\delta s(T,\mu) = s(T,\mu) - s(T,\mu=0) = \int_0^{\mu} \frac{\partial n(T,\mu')}{\partial T} d\mu'$$