Cosmic QCD epoch at large lepton flavour asymmetries

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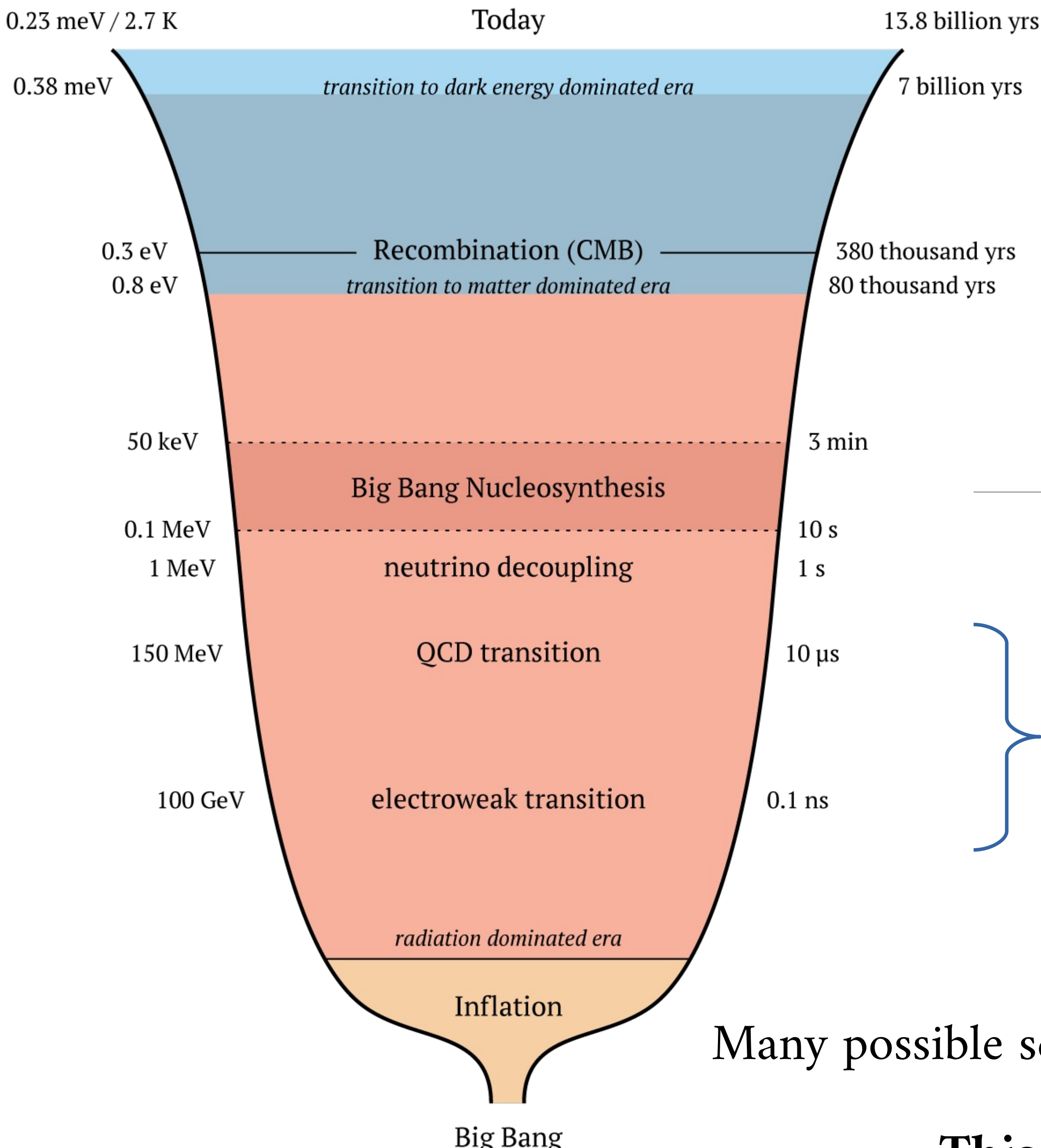
based on: *arXiv: 2309.00672, 2106.11991, 2011.07283, 2009.00036, 1807.10815*

with D. Bödeker, F. Gao, J. Harz, C. Hati, F. Kühnel, M. Middeldorf-Wygas, Y. Lu, D. J. Schwarz, G. White



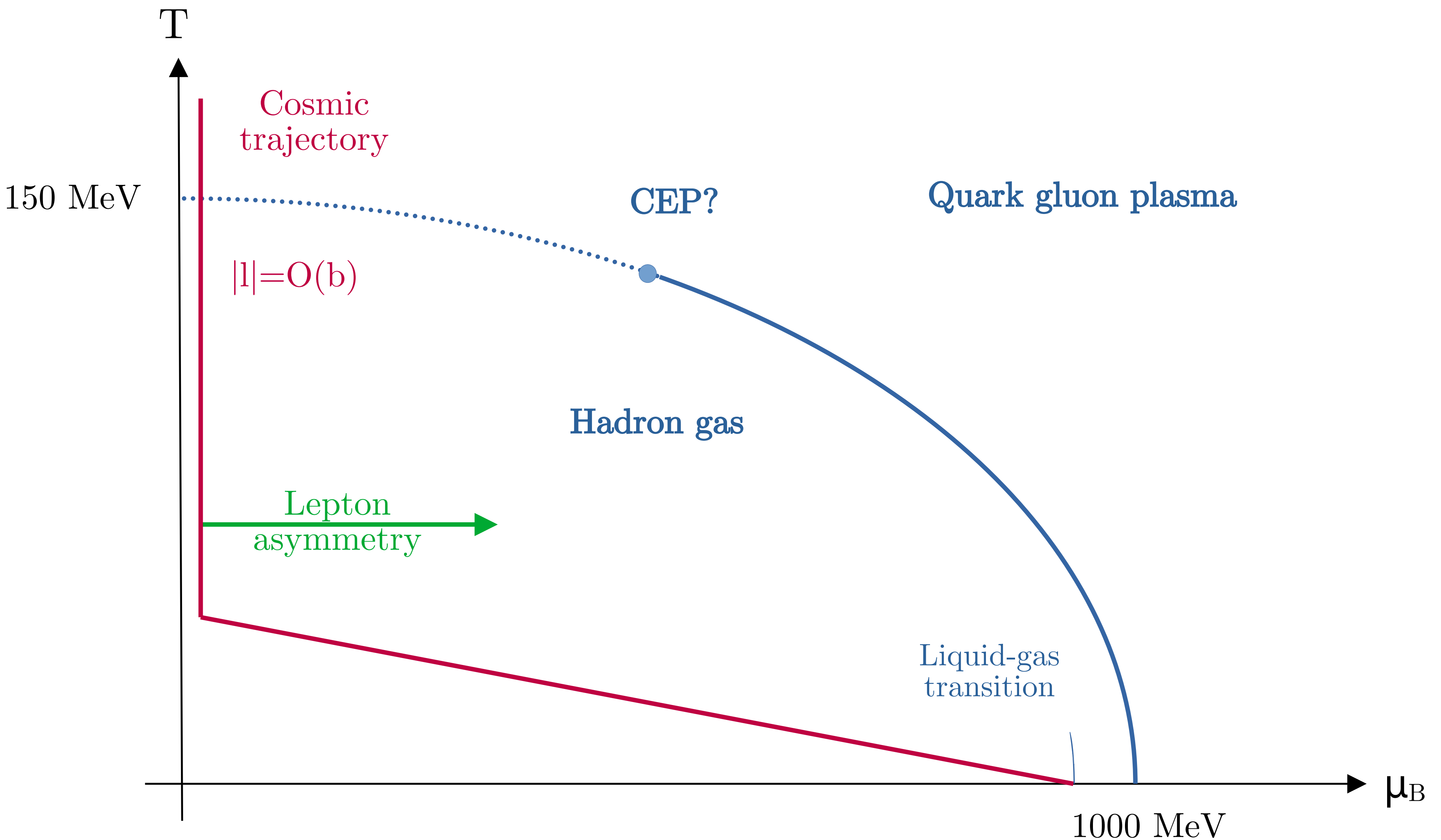
→ Very well measured

→ 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>



M. Stuke, D. Schwarz (2009), *K. Zarembo* (2000)

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

→ well measured, but poorly understood...

Tiny, but why so big?

→ Baryogenesis, Leptogenesis

Leptogenesis: 1.) Mechanism for creation of lepton asymmetry

2.) Sphaleron processes transfer lepton asymmetry to baryon asymmetry

→ standard assumption:

lepton asymmetry ≈ baryon asymmetry (i. e. tiny)

Possible caveats?

- sphaleron processes experimentally not confirmed
- suppress sphaleron processes? (*G. Barenboim, W. Park* 2017; ***C. Hati et al. arXiv:2309.00672 → later***)
- 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:

→ possibly **hidden** in cosmic neutrino background $(T_\nu = 1.9\,\mathrm{K})$

→ no direct measurement possible

Any observational constraints?

At CMB and BBN:

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

Fermi-Dirac

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

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

Impact on cosmological observables?

I) increased relativistic energy density →

impact on Hubble expansion rate

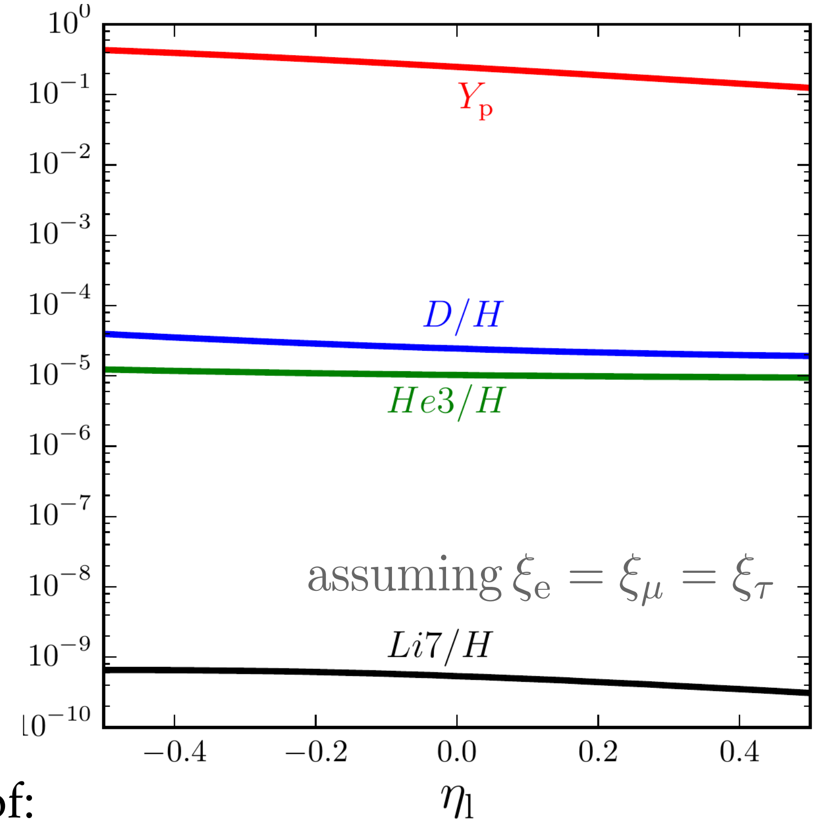
$$N_{\text{eff}} = 3.046 + \frac{15}{7}\sum_{\alpha} \underbrace{\left(\frac{\xi_\alpha}{\pi}\right)^2 \left[2 + \left(\frac{\xi_\alpha}{\pi}\right)^2\right]}_{\geq 0}$$

II) modified neutron-to-proton-ratio:

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

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

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

→ very weak

Hint towards positive lepton asymmetry???

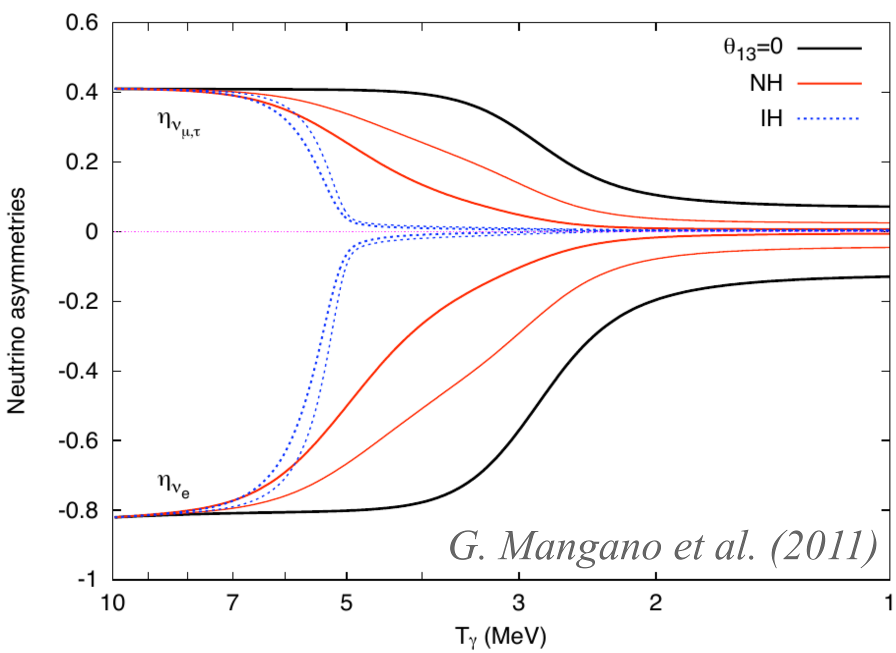
(Escudero et al. 2022, Burns et 1l. 2022)

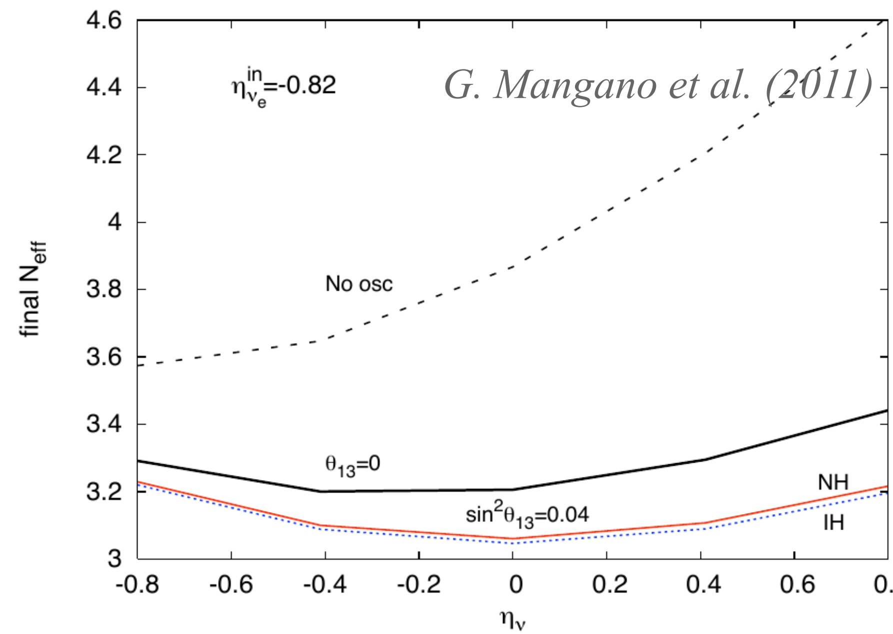
Recent He4 measurements (EMPRESS survey) → $\eta_l = 0.011 \pm 0.008\ (95\%\text{CL})$

Impact of neutrino oscillations:

(A. D. Dolgov et al. (2002), Y.Y.Y. Wong (2002), G. Mangano et al. (2011), L. Johns et al. (2016), G. Barenboim et al. (2016), J. Froustey & C. Pitrou (2022))

Neutrino oscillations at **T~10 MeV** → **Equilibration** of lepton flavour asymmetries:





➡ $\eta_\alpha\big|_{\mathrm{BBN,CMB}} \approx \frac{\eta_l}{3}$ → **CMB and BBN only sensitive to total lepton asymmetry**

But equilibration probably only partial… *(Froustey and Pitrou (2022), arXiv: 2110.11889)*

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 $10\ \mathrm{MeV} < T < T_{BSM}$) :

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

$\mu_{\mathrm{L}_e}, \mu_{\mathrm{L}_\mu}, \mu_{\mathrm{L}_\tau}, \mu_{\mathrm{B}}, \mu_{\mathrm{Q}}$

↓

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:

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

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

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

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)

I) High temperatures:

Perturbative QCD *(Laine & Schröder 2006)*

II) around the QCD transition

Only applicable at small chemical potentials…

Taylor expansion + lattice QCD susceptibilities:

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

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

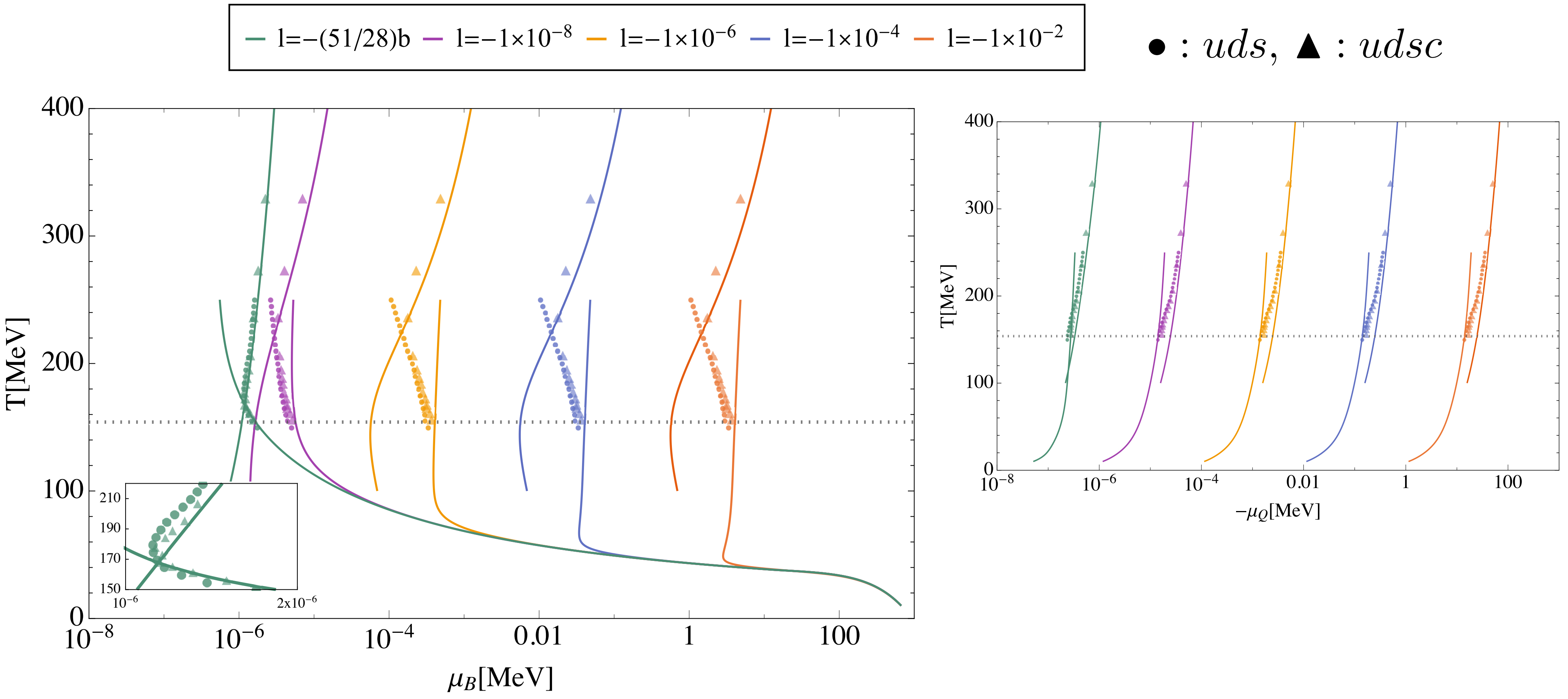
(Hot QCD coll. 2012 & 2014)

III) Low temperatures:

Hadron resonance gas (equilbrium distributions for hadrons)

Equal lepton flavour asymmetries

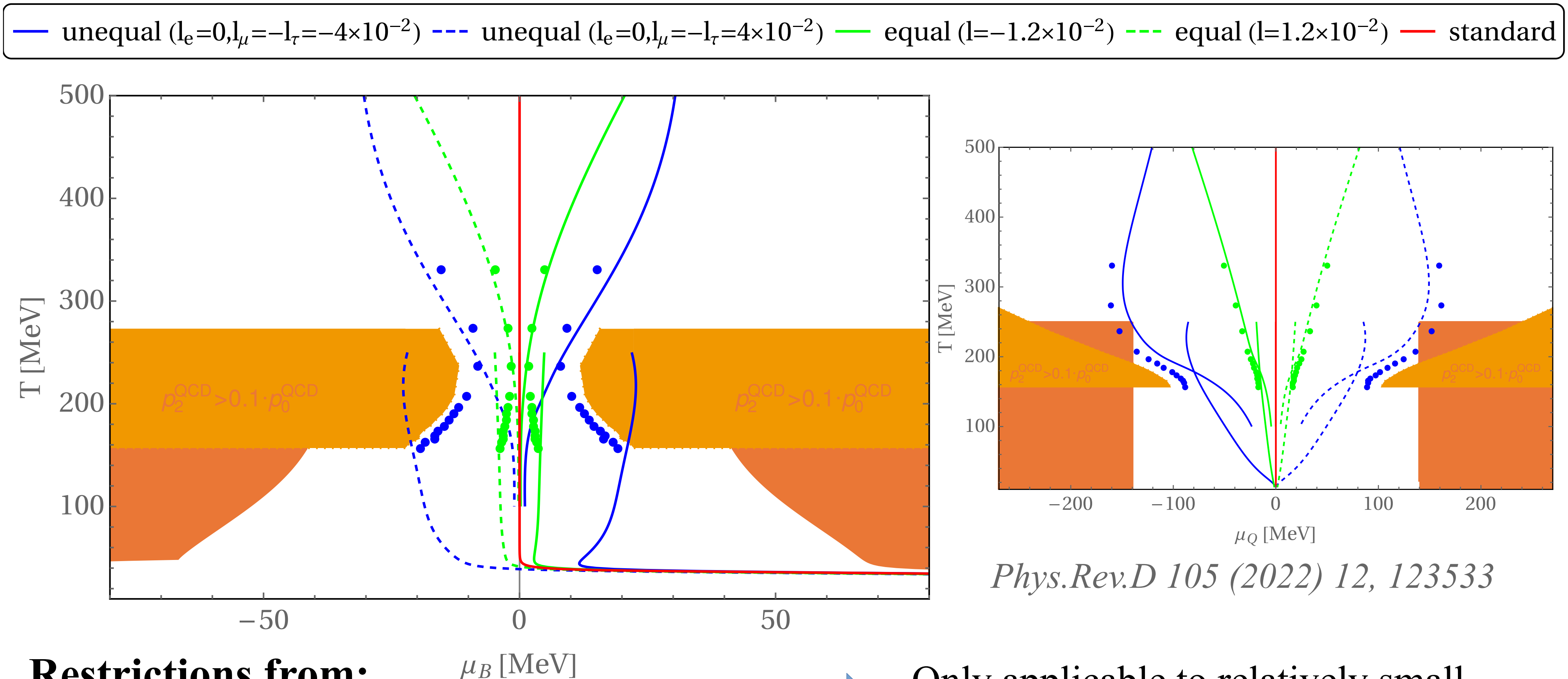
*M. M. Wygas, **IMO**, D. Bödeker, D. J. Schwarz, arXiv:1807.10815*



→ Lepton asymmetry induces large baryon and charge chemical potentials.

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

<u>Unequal lepton flavour asymmetries</u>



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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

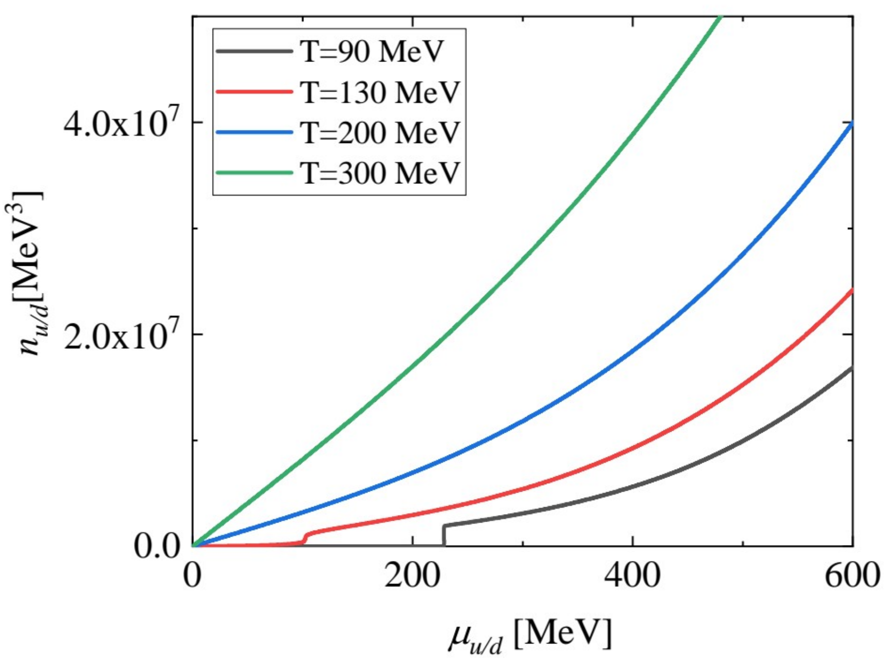
IIa):
(Almost) pure functional QCD

IIb):
functional QCD + Ising paramterization

IIa): Almost pure functional QCD

*(F. Gao & **IMO**, arXiv: 2106.11991)*

Thermodynamic quantities derived from Dyson-Schwinger equations (gap equation for the quark propagator) in the rainbow-ladder (RL) truncation

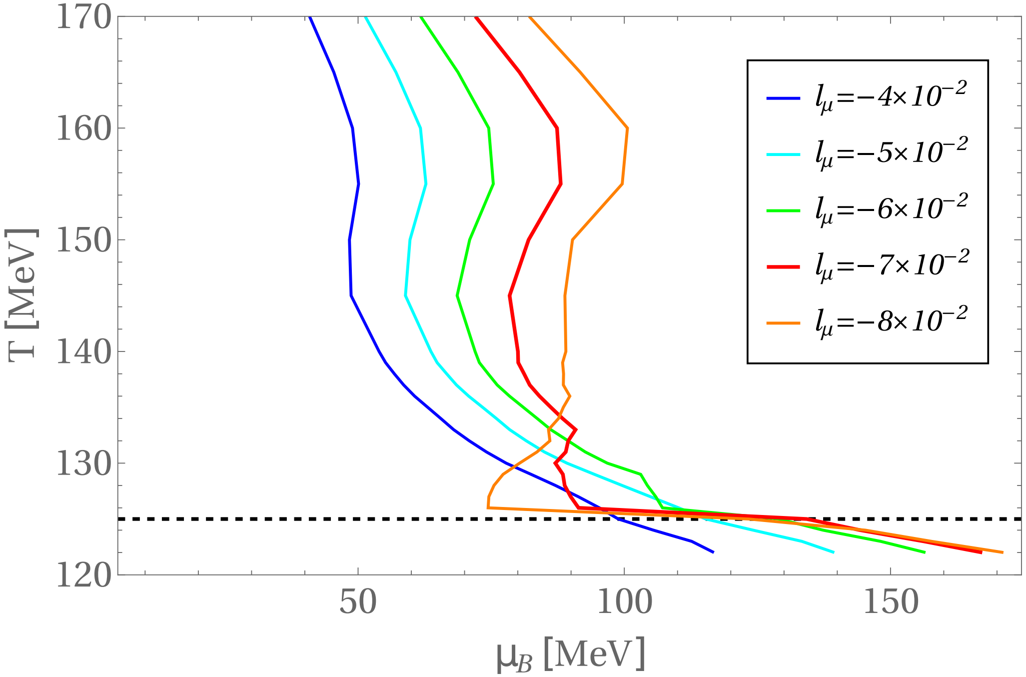


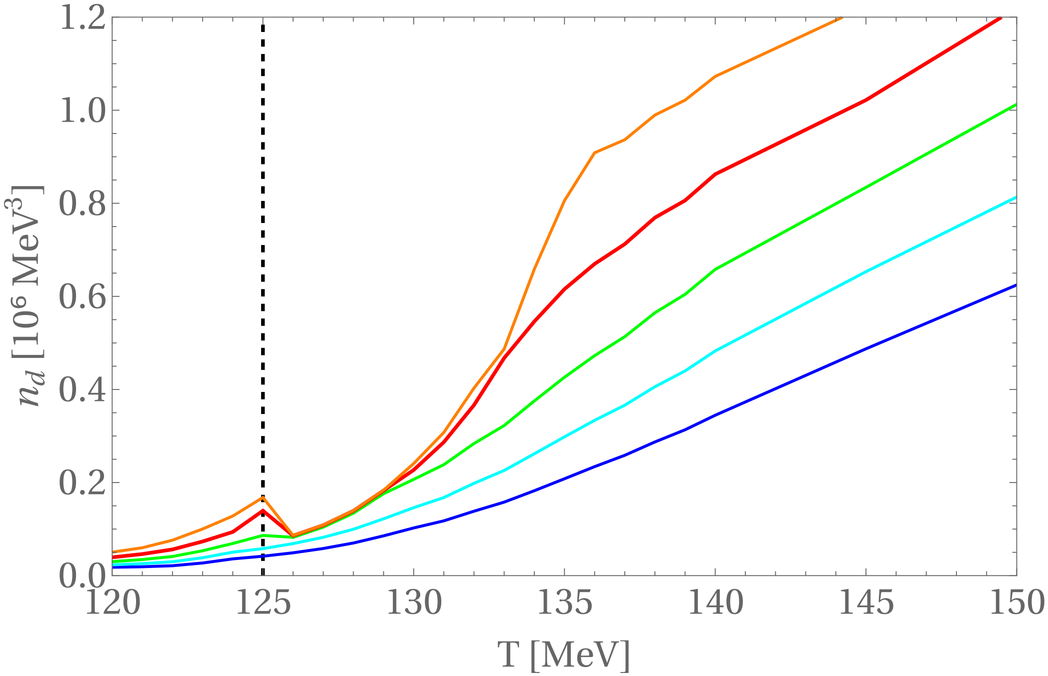
$$\Rightarrow (T_{\mathrm{CEP}}, \mu_{\mathrm{CEP}})_{u/d} = (125, 111)\ \mathrm{MeV}$$

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

Include thermodynamic quantities into calculation of cosmic trajectory:

<u>Consider here:</u> $l_e=0,\ l_\mu = -l_\tau$ fullfils CMB/BBN requirement l=0





Discontinuity between l_μ=-0.06 and l_μ=-0.07 → **1st order transition !**

➔ Have calculated the required lepton asymmetries for several scenarios:
For equal lepton asymmetries a first-order QCD transition is excluded by CMB/BBN

➔ Other scenarios fulfill CMB/BBN bounds and can lead to a first-order QCD transition

Method IIa has provided the **first proof-of-principle** of the possibility of a first-order cosmic QCD transition due to large lepton asymmetries.

But the applied Rainbow-Ladder truncation turns out to be not good enough.

→ **Method IIb: functional QCD + Ising mapping**

*(F. Gao., J. Harz, C. Hati, Y. Lu, **IMO**, G. White, arXiv: 2309.00672, arXiv:2403.XXXX)*

What's new?

1) Apply an improved truncation. *(F. Gao, J. Pawlowski, 2021)*

→ consistent with low-μ results from lattice QCD (cross-over temperature and phase transition line)

→ predicts CEP at $(T_{CEP}, \mu_{CEP})_{u/d}$=(118, 200) MeV (instead of (125, 111) MeV with RL)

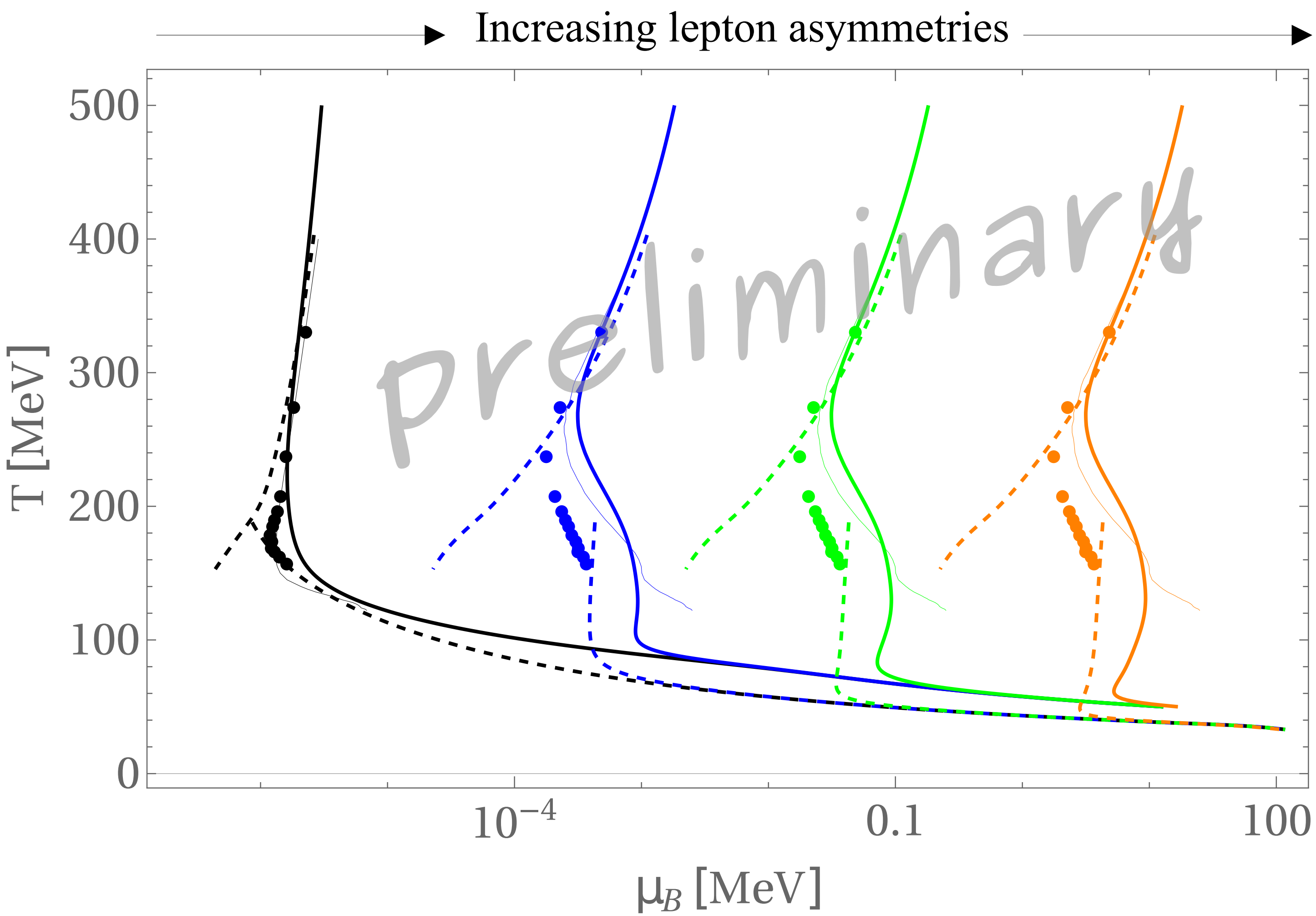
Lepton asymmetries required for 1st order transition were underestimated.

2) Apply an analytical Ising parameterization for the dynamical quark mass.

→ derive thermodynamic quantities *(Y. Lu et al., arXiv:2310.16345)*

Comparison between different methods

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



Method IIb has improved agreement to hadron resonance gas model significantly.

For small values of the lepton asymmetries method I) (lattice QCD based) is more reliable but cannot be extended to region of 1st order transition.

Method IIa) and IIb) (functional QCD based) reveal that the cosmic QCD transition can be first order IF lepton flavour asymmetries are unequal.

Method IIb) also qualitatively agrees with method I).

↓

Cosmological consequences?

- Pion condensate in the early Universe *(V. Vovchenko et al. (2020), arXiv:2009.02309)*
- Equation of state impacts formation of primordial black holes *(D. Bödeker, **IMO** et al. ArXiv:2011.07283, V. Vovchenko et al. (2020), arXiv:2009.02309)*
- Impact on the primordial GW spectrum *(F. Hajkarim, arXiv:1904.01046)*

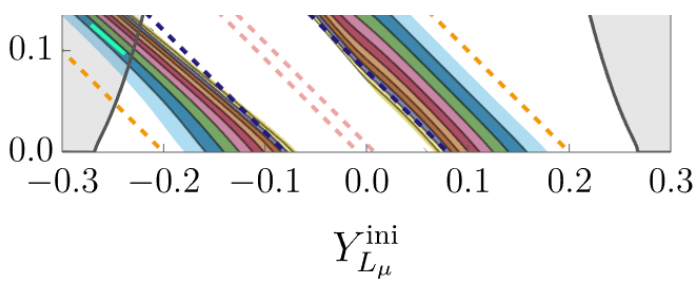
} Independent of the nature of the transition

- First-order QCD transition leads to additional emission of GWs *(F. Gao., J. Harz, C. Hati, Y. Lu, **IMO**, G. White, arXiv: 2309.00672)*

Can lepton asymmetries lead to successful baryogenesis, induce a first-order QCD transition and lead to a detectable GW imprint???

*(F. Gao., J. Harz, C. Hati, Y. Lu, **IMO**, G. White, arXiv: 2309.00672)*

Large lepton asymmetries can lead to a non-restoration of the electroweak symmetry
→ suppress sphaleron rate
→ lead to the right amount of baryon asymmetry, **successful baryogenesis**



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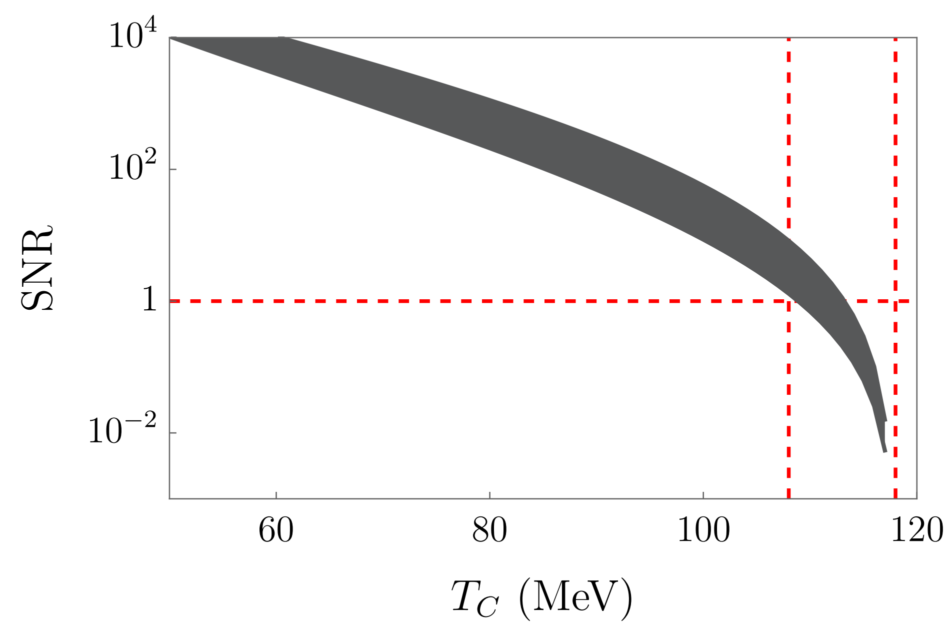

- Lepton flavour asymmetries before ~ 10 MeV are almost unconstrained and have an impact on the cosmic trajectory during the QCD epoch.

→ 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 → method II)

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

Thank you