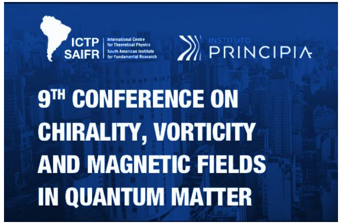
Chiral symmetry breaking and pion condensation in the early universe

Osvaldo Ferreira

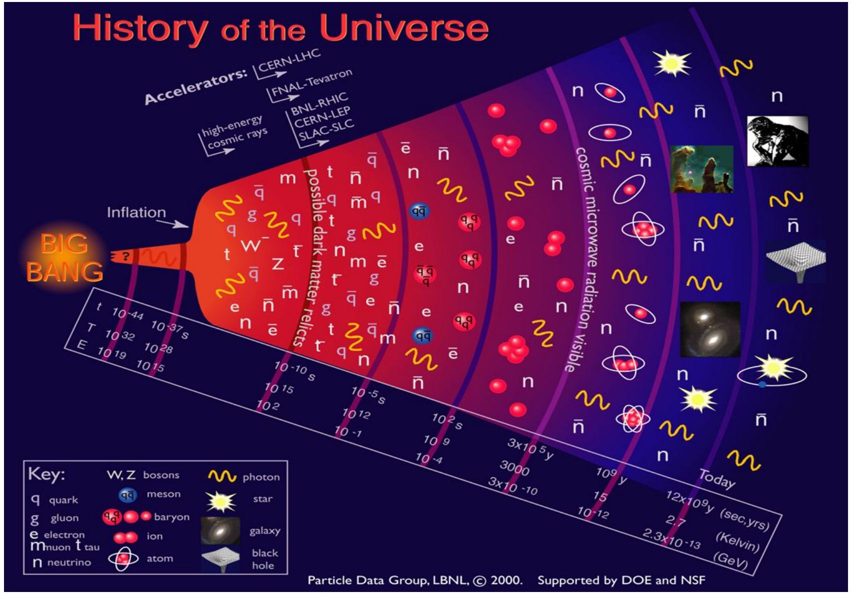
Work done in collaboration with Eduardo S. Fraga, Maurício Hippert and Jürgen Schaffner-Bielich

arXiv:2507.06518



The QCD epoch in the early universe

A simple story



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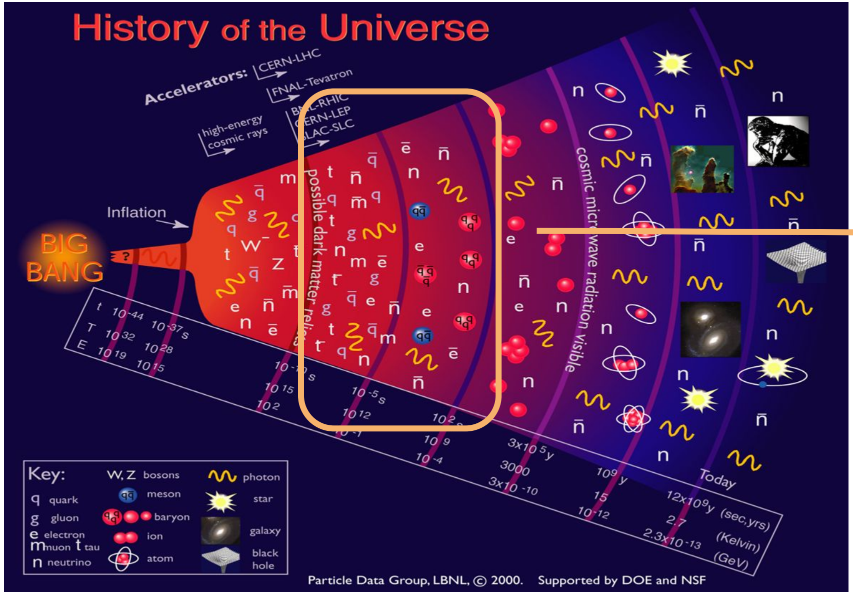

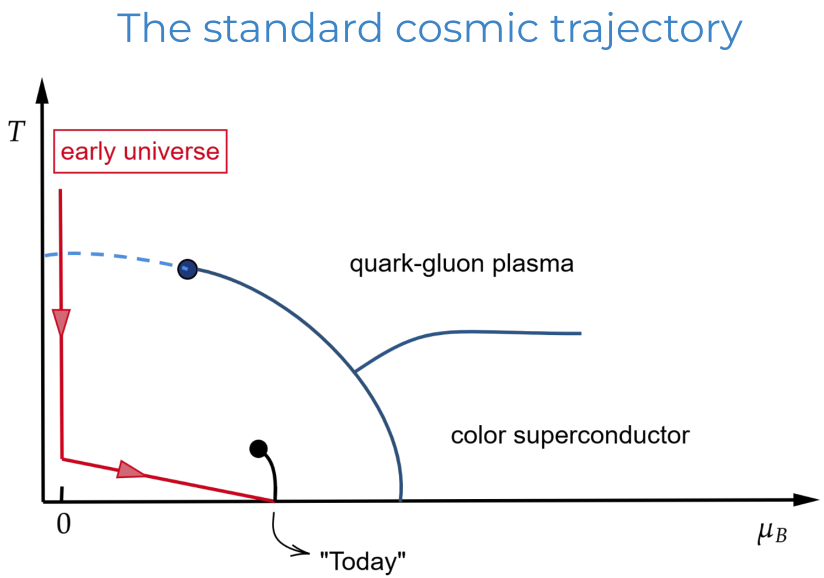

The QCD epoch in the early universe

How do we find this trajectory?

At $t \lesssim 1\ \mathrm{s},\ \Gamma \gg H \Longrightarrow$ Thermal equilibrium

Baryon number conservation

$$\frac{n_B\left(T, \mu_B, \mu_Q\right)}{s\left(T, \mu_B, \mu_Q, \{\mu_\alpha\}\right)} = b,$$

Electric charge conservation

$$\frac{n_Q\left(T, \mu_B, \mu_Q, \{\mu_\alpha\}\right)}{s\left(T, \mu_B, \mu_Q, \{\mu_\alpha\}\right)} = 0,$$

Lepton number conservation

$$\frac{n_{L_\alpha}\left(T, \mu_Q, \{\mu_\alpha\}\right)}{s\left(T, \mu_B, \mu_Q, \{\mu_\alpha\}\right)} = l_\alpha, \quad \alpha \in e, \mu, \tau.$$

"Cosmic point": $\left(T, \mu_B, \mu_Q, \{\mu_\alpha\}\right)$

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"Cosmic point": $\left(T, \mu_B, \mu_Q, \{\mu_\alpha\}\right)$

Standard assumption:

If sphaleron processes are efficient enough, the SM predicts:

$$l = -\frac{51}{28} b \sim 10^{-11}$$

with

$$l = \sum_\alpha \frac{n_{L_\alpha}}{s}$$

and

$$n_{L_\alpha} = n_\alpha + n_{\nu_\alpha}$$

$$\Downarrow$$

$$\mu_Q, \mu_B, \mu_{L_\alpha} \approx 0$$

The QCD epoch in the early universe: nonzero Lepton asymmetries

Alternative scenarios?

However, this standard picture **cannot** be complete since:

- ➔ The SM does not explain the observed value for the baryon asymmetry;
- ➔ Poor understanding of the neutrino sector: e.g., neutrinos have masses!

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Can something from the lepton sector help? **Leptogênesis**

Many Leptogenesis models predict a relic nonzero lepton asymmetries

M. Flanz, E. A. Paschos, and U. Sarkar, Phys. Lett. B 345, 248 (1995)

W. Buchmuller, R. D. Peccei, and T. Yanagida, Ann. Rev. Nucl. Part. Sci. 55, 311 (2005)

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Can a nonzero lepton asymmetry affect the QCD epoch?

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The QCD epoch in the early universe: nonzero Lepton asymmetries

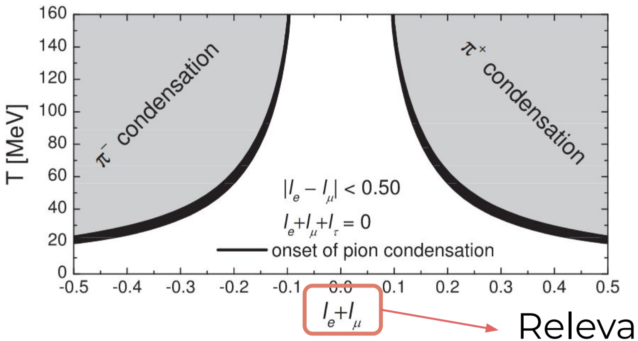
What QCD phenomena are allowed in this scenario?

Unequal lepton asymmetries could lead to **pion condensation** at the QCD epoch.

Wygas et al, Phys. Rev. Lett. 121, 201302, 2018

Wygas et al, Phys. Rev. D 105, 123533, 2022

Quasi-particle model for pion number density:



$$l_e + l_\mu + l_\tau = 0$$

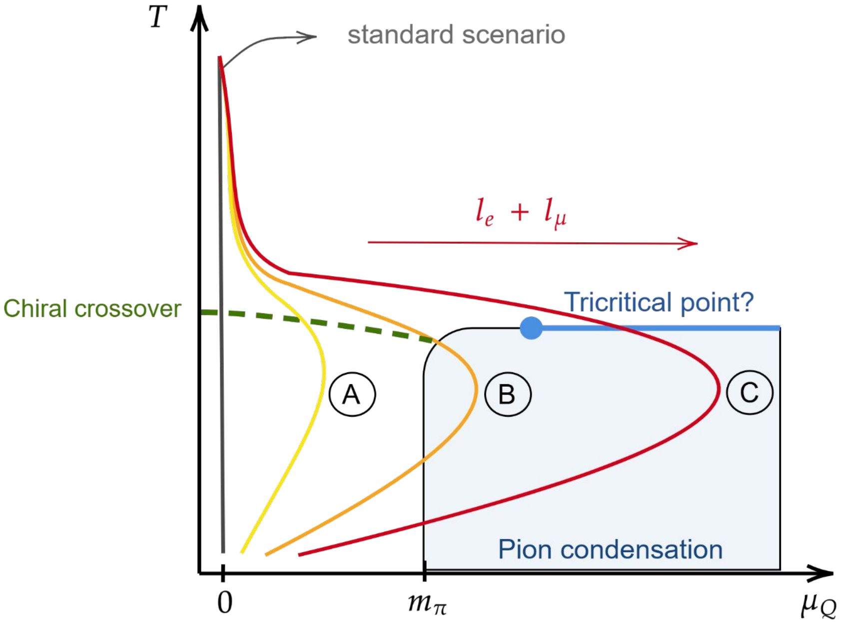
$$l_\tau = -(l_e + l_\mu)$$

Vovchenko et al, Phys. Rev. Lett. 126, 012701, 2021

Relevant quantity for pion condensation

The QCD epoch in the early universe: nonzero Lepton asymmetries

- ➔ What can we tell about the transitions when entering and leaving the pion condensation phase?
- ➔ How do the order parameters, speed of sound and trace anomaly behave?
- ➔ What are the implications of such transitions?



The quark-meson model at finite temperature, charge and baryon chemical potentials

The simplest model with the right symmetries

$$\mu_I = \frac{\mu_Q}{2} \qquad \mu_q = \frac{\mu_B}{3}$$

$$\begin{aligned}\mathcal{L}_{\mathrm{QM}} =& \mathcal{L}_M + \bar{\psi}\left(\not{\partial} + \gamma_0 \hat{\mu} + ig\left(\sigma + i\gamma_5 \vec{\tau}\cdot\vec{\pi}\right)\right)\psi + \\ & - 2\mu_I\left(\pi_1\left(\partial_0\pi_2\right) - \pi_2\left(\partial_0\pi_1\right)\right) - 2\mu_I^2\left(\pi_1^2 + \pi_2^2\right)\end{aligned}$$

$$\hat{\mu} = \begin{pmatrix} \mu_q + \mu_I & 0 \\ 0 & \mu_q - \mu_I \end{pmatrix}$$

$$\mathcal{L}_M = \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma + \frac{1}{2}\partial_\mu\vec{\pi}\cdot\partial^\mu\vec{\pi} + U\left(\sigma, \vec{\pi}, \mu_I\right), \quad U\left(\sigma, \vec{\pi}, \mu_I\right) = \frac{\lambda}{4}\left(\sigma^2 + \pi^2 - v^2\right)^2 - h\sigma - 2{\mu_I}^2\pi^2.$$

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At mean field this leads to:

$$\begin{aligned}\Omega_{QM} = \Omega_{vac} - 2N_c T \int \frac{d^3p}{(2\pi)^3} & \Big[\ln\left(1 + e^{-(E_\Delta^- + \mu_q)/T}\right) + \ln\left(1 + e^{-(E_\Delta^- - \mu_q)/T}\right) \\ & + \ln\left(1 + e^{-(E_\Delta^+ + \mu_q)/T}\right) + \ln\left(1 + e^{-(E_\Delta^+ - \mu_q)/T}\right)\Big] \\ & + U\left(\sigma_0, \pi_0, \mu_I\right) ,\end{aligned}$$

Dropped here, but may be relevant

$$\boxed{\Omega_{vac} = -2N_c \int \frac{d^3p}{(2\pi)^3}\left(E_\Delta^+ + E_\Delta^-\right)}$$

$$E_\Delta^\pm = \sqrt{\left(E_p \pm \mu_I\right)^2 + \Delta^2}$$

The QCD epoch in the early universe

Back to the conditions in the early universe

At $t \lesssim 1\ \mathrm{s},\ \Gamma \gg H \Longrightarrow$ Thermal equilibrium

Baryon number conservation

$$\frac{n_B\left(T,\mu_B,\mu_Q\right)}{s\left(T,\mu_B,\mu_Q,\{\mu_\alpha\}\right)}=b,$$

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+

Gap equations:

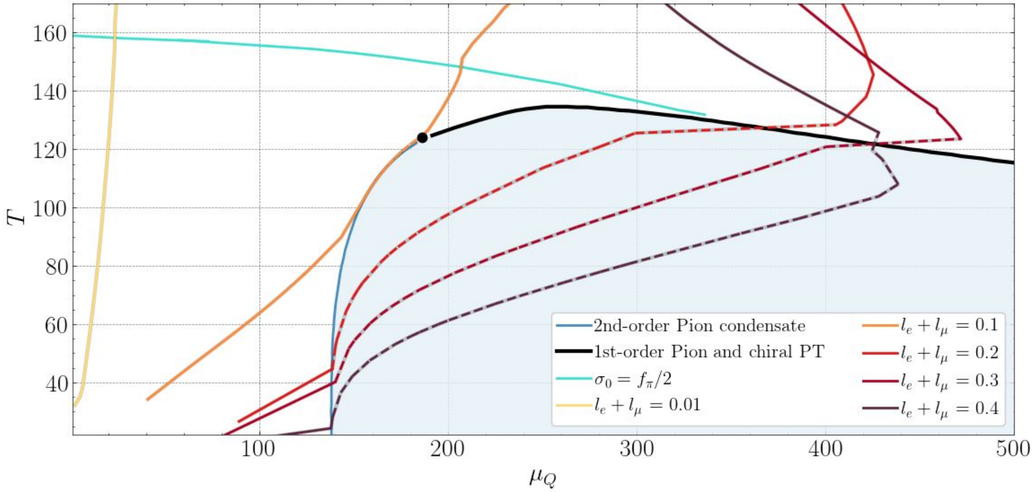
$$\frac{\partial\Omega_{QM}}{\partial\pi_0}=0$$

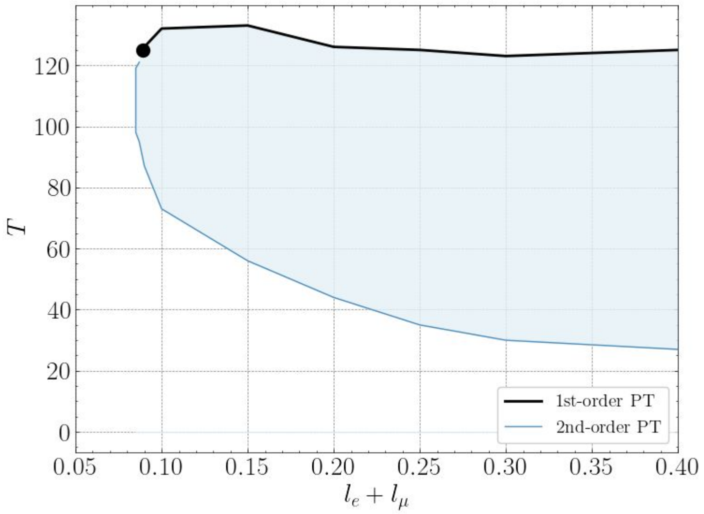
$$\frac{\partial\Omega_{QM}}{\partial\sigma_0}=0$$

"Cosmic point": $\left(T,\mu_Q,\mu_B,\{\mu_{L_\alpha}\},\boxed{\pi_0,\sigma_0}\right)$

Results: cosmic trajectories in the QCD phase diagram

First-order PT when entering the pion condensation phase?

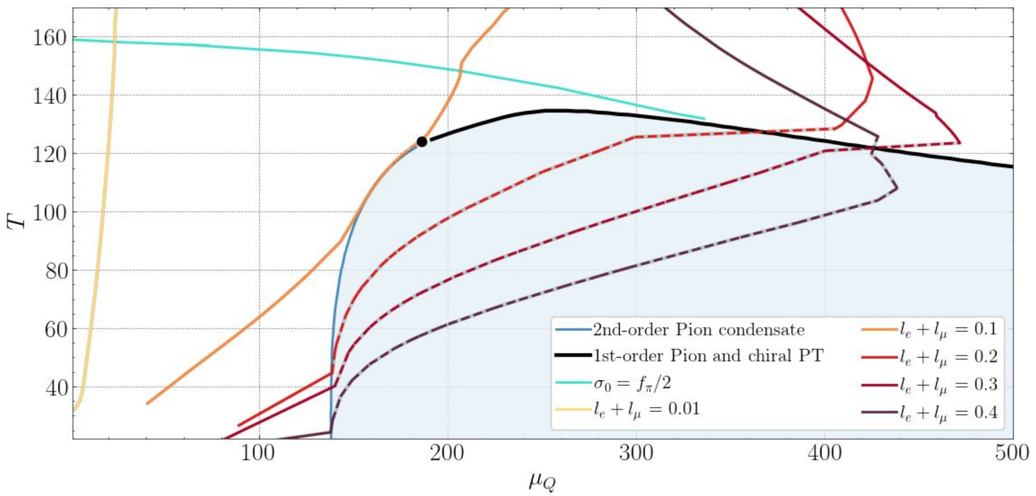


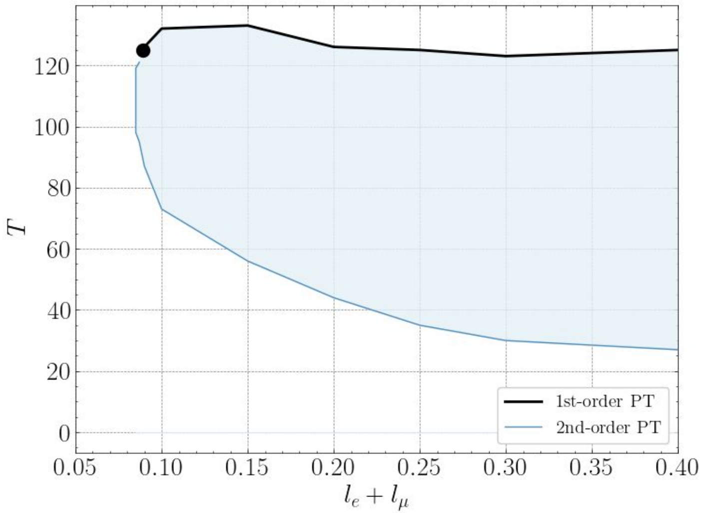


➔ For high enough ($\gtrsim 0.1$) imbalances the universe may enter the pion condensate.

Results: cosmic trajectories in the QCD phase diagram

First-order PT when entering the pion condensation phase?

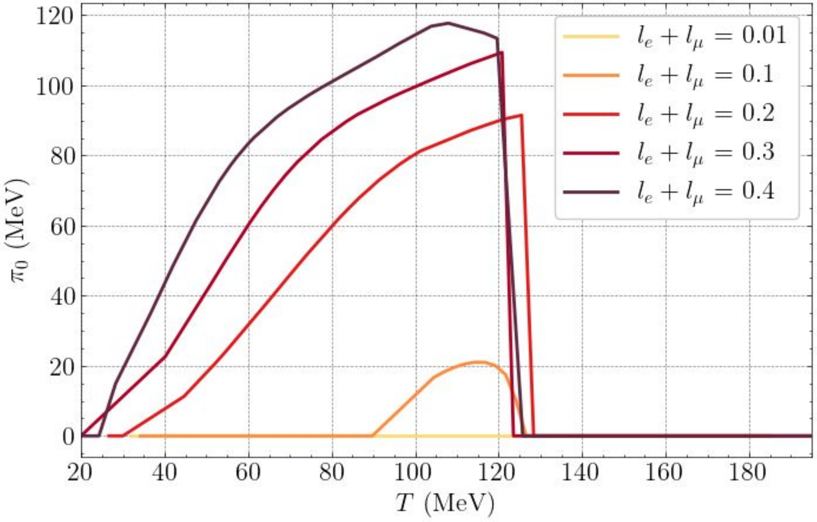


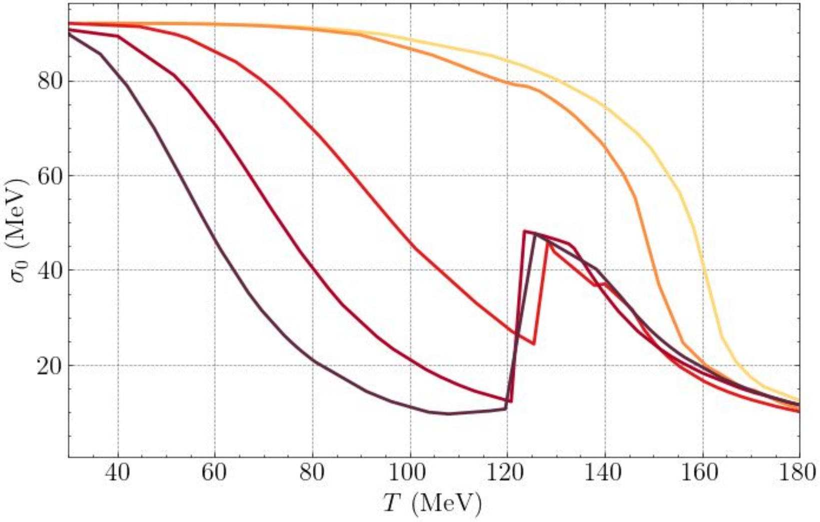


➔ As the universe cools, most trajectories enter the pion condensate through a first-order PT followed by a second-order phase transition when exiting it.

Results: cosmic trajectories in the QCD phase diagram

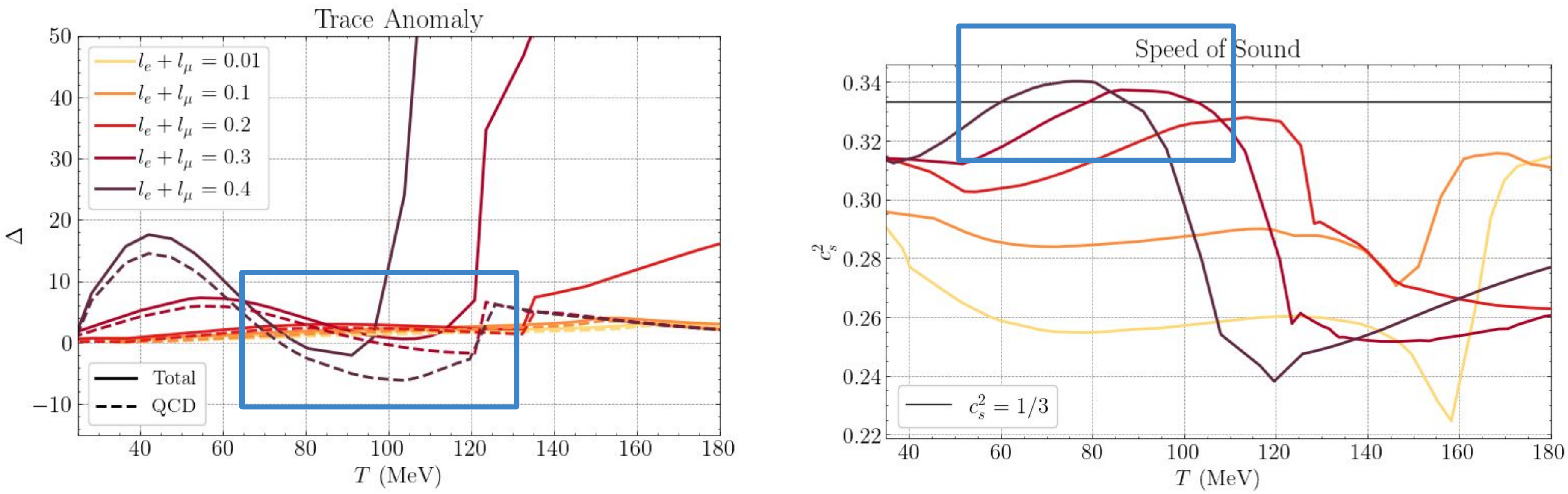
Trace anomaly and speed of sound





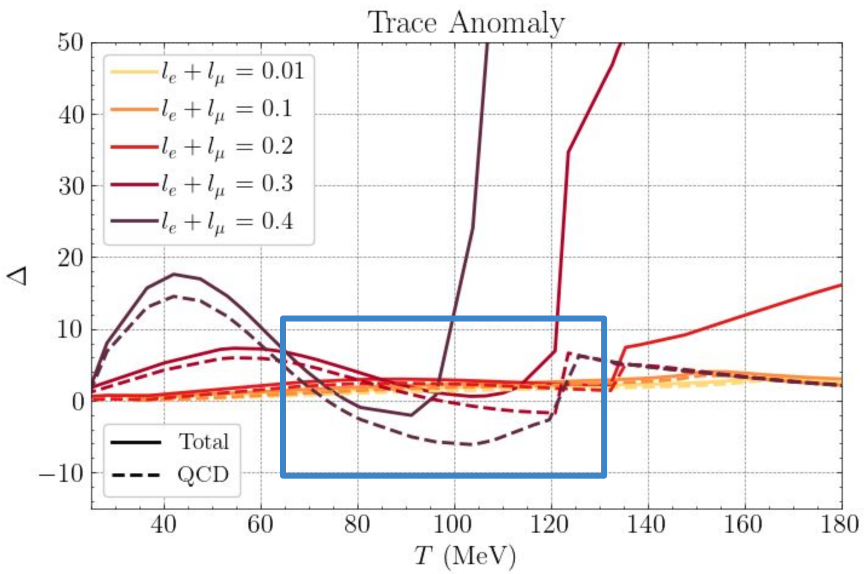
➔ Jumps on the condensates signaling the first-order PTs.

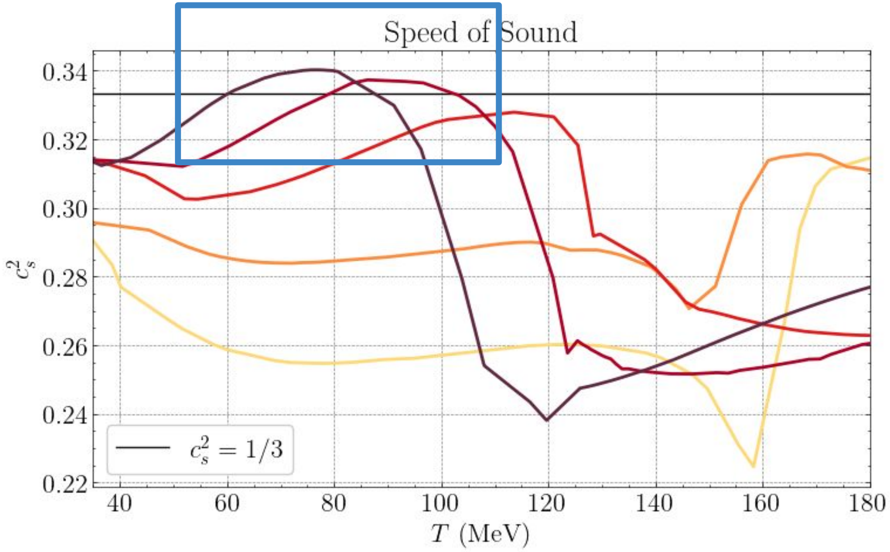
Results: cosmic trajectories in the QCD phase diagram



➔ The trace anomaly becomes negative and the speed of sound exceeds the conformal value when inside the condensate.

Results: cosmic trajectories in the QCD phase diagram





➔ This may have an effect on the evolution of the universe through Friedmann equations.

Implications

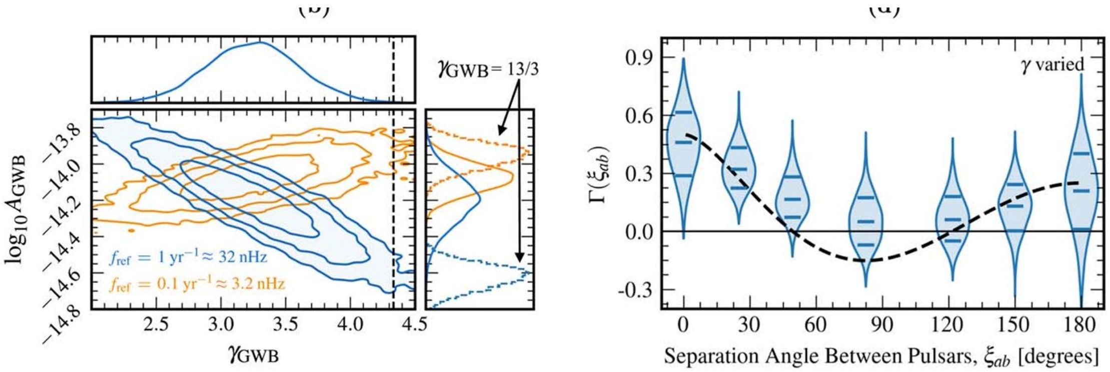
Generation of primordial gravitational waves

First order PTs at temperatures in the QCD epoch (T ~ 150 MeV) can generate nanohertz primordial gravitational waves.

Schwarz, Mod.Phys.Lett.A 13 (1998)

Gosh et al, JCAP 05 (2024)

Can our scenario be an explanation for the NANOGrav observation?



NANOGrav Collaboration, Astrophys.J.Lett. 951 (2023)

Summary

- ➔ Using the quark-meson model as an effective description of QCD, we investigated the consequences of its phase diagram structure on the possible cosmic trajectories of the universe during the QCD epoch;
- ➔ Showed that for large enough lepton asymmetries we may have pion condensation in the early universe;
- ➔ Showed that this phase could be reached through a first-order PT followed by a second order PT.
- ➔ Motivation for searching a first-order PT at high μ_Q in the Lattice.

outlook

- ➔ Many improvements can be implemented in the model: vacuum contributions, 3 flavors, etc…
- ➔ Generation of Gravitational waves;
- ➔ Other implications: spectrum of PBHs, relic density of DM, etc..

arXiv:2507.06518

CMB and BBN constraints on lepton asymmetries

What do observations tell us about the lepton asymmetries?

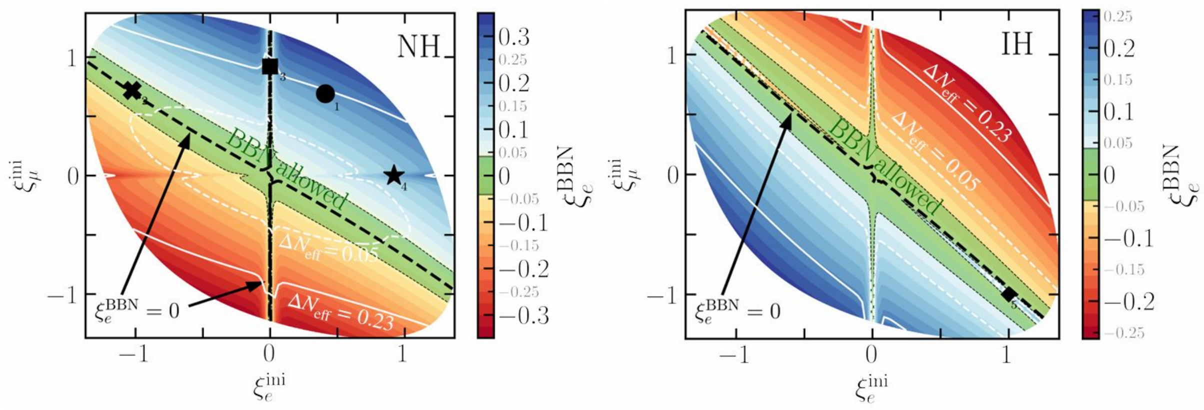


FIG. 1. Asymmetry in the electron neutrino sector at the onset of BBN ($\xi_e^{\rm BBN} = \mu_e/T|_{\rm BBN}$) as a function of the primordial lepton flavor asymmetries $\xi_e^{\rm ini}$ and $\xi_\mu^{\rm ini}$ (with $\Delta n_e^{\rm ini} + \Delta n_\mu^{\rm ini} + \Delta n_\tau^{\rm ini} = 0$) present before the onset of neutrino oscillations at 20 MeV. The green region indicates the region currently allowed by BBN constraints [35] at 95% CL and the black symbols indicate particular parameter points that will be discussed in detail in Sec. III. Almost the entire parameter space shown is compatible with Planck CMB observations ($\Delta N_{\rm eff} < 0.23$). The two panels show our result for normal (left) and inverted (right) neutrino mass hierarchy.

Domcke et al, JHEP 06 (2025) 137, 2025

Unequal lepton asymmetries and neutrino oscillations

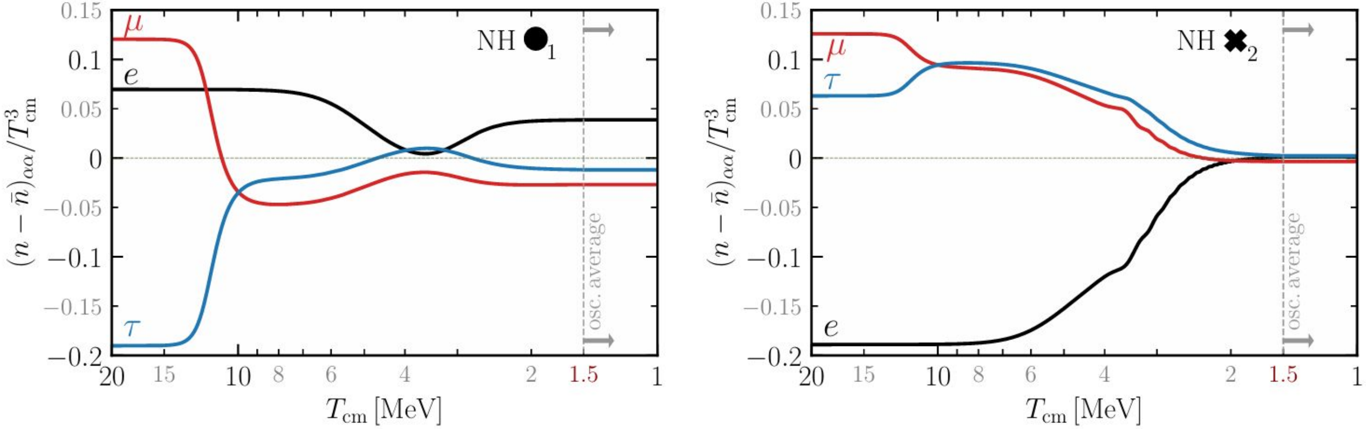


FIG. 3. Typical examples of the time evolution for large amplitude of initial flavor asymmetries in normal hierarchy. In the left (right) plot we choose $A = \sqrt{2}, \phi = \pi/3$ ($A = \sqrt{2}, \phi = \arctan(-3, 2) \simeq 2.55$). The full solution depicted here essentially overlaps with the adiabatic approximation ($V_s = 0$). The symbol in the top right of the plot indicates the positions of this specific initial condition within the contour plots in Figs. 4 and 1.

Domcke et al, JHEP 06 (2025) 137

Vacuum terms in similar models

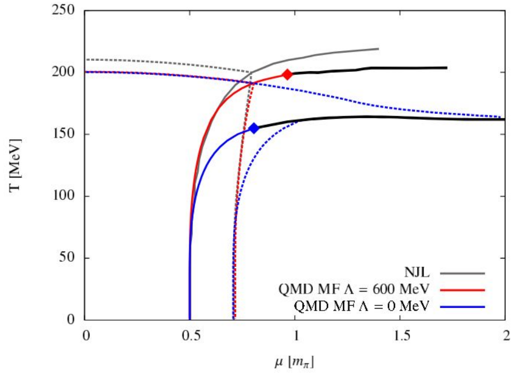


FIG. 4. Mean field phase diagrams: QMD model (with and without vacuum term) vs. NJL model (with parameters from [26]); dashed: chiral crossover; solid: second order transition; thick solid black: first order transition; diamonds: tricritical points as predicted in [9].

Quark-meson-diquark model

Strodthoff et al, Phys.Rev.D 85 (2012)

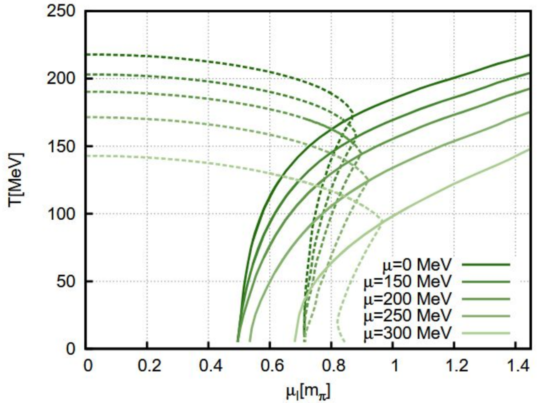


Figure 10: (μ_I, T) slices for different baryon chemical potentials of the three-dimensional FRG phase diagram in Fig. 9. Also shown here are chiral crossover lines (dashed) as the half-value of the chiral condensate.

Quark-meson model with fluctuations

Kamikado et al, Phys.Lett. B718 (2013)

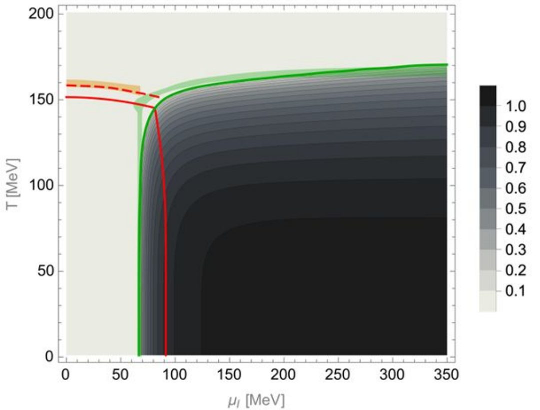
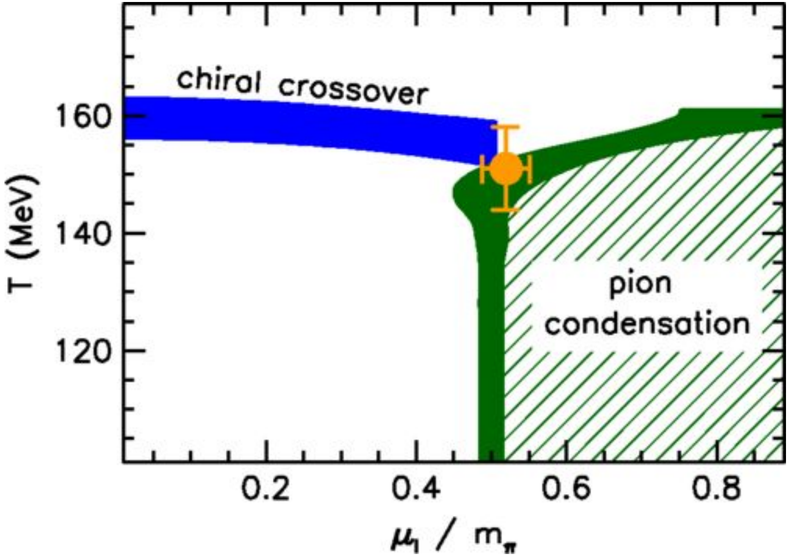


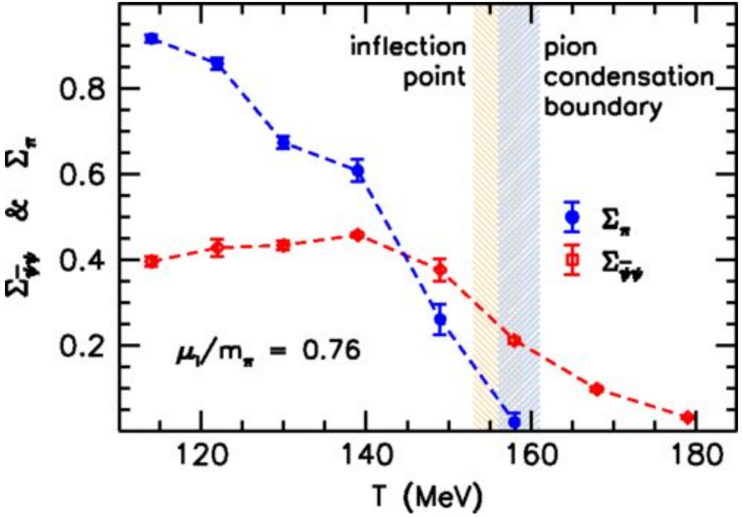
FIG. 5. Phase diagram in the (μ_I, T)-plane from the RG-invariant quark meson model calculation (with M_0 = 350 MeV, m_π = 135 MeV, f_π = 90 MeV and m_σ = 470 MeV): chiral crossover (dashed red), half-value of the chiral order parameter Σ (solid red), and contour plot of the normalized pion condensate Δ/M_0 with second-order phase boundary (solid green), compared to the chiral crossover (light orange band) and pion condensation phase boundary (light green band), as determined on the lattice in Ref. [7].

RG invariant quark-meson model

Brandt et al, arXiv:2502.04025 (2025)

Lattice (μB=0)





Brandt et al, Phys. Rev. D 97 (2018)