Pion Condensation in the Early Universe

Volodymyr Vovchenko

LBNL NSD Staff Meeting

January 26, 2021

In collaboration with:

B. Brandt, G. Endrödi (Bielefeld U.)

F. Cuteri, F. Hajkarim, J. Schaffner-Bielich (Frankfurt U.)

based on Phys. Rev. Lett. 126, 012701 (2021)

BERKELEY LAB

Unterstützt von / Supported by

Alexander von Humboldt
Stiftung / Foundation

Bose-Einstein condensation

$$n(E_p) = \frac{1}{e^{(E_p-\mu)/T} - 1}$$

S.N. Bose, A. Einstein, 1924

BEC at $T < T_c$, $\quad T_c \approx 3.31 \frac{n^{2/3}}{m}$, $\quad \frac{n_0}{n} = 1 - \left(\frac{T}{T_c}\right)^{3/2}$ for non-rel. Bose gas

Velocity-distribution data for a gas of rubidium atoms confirming the discovery of BEC in 1995

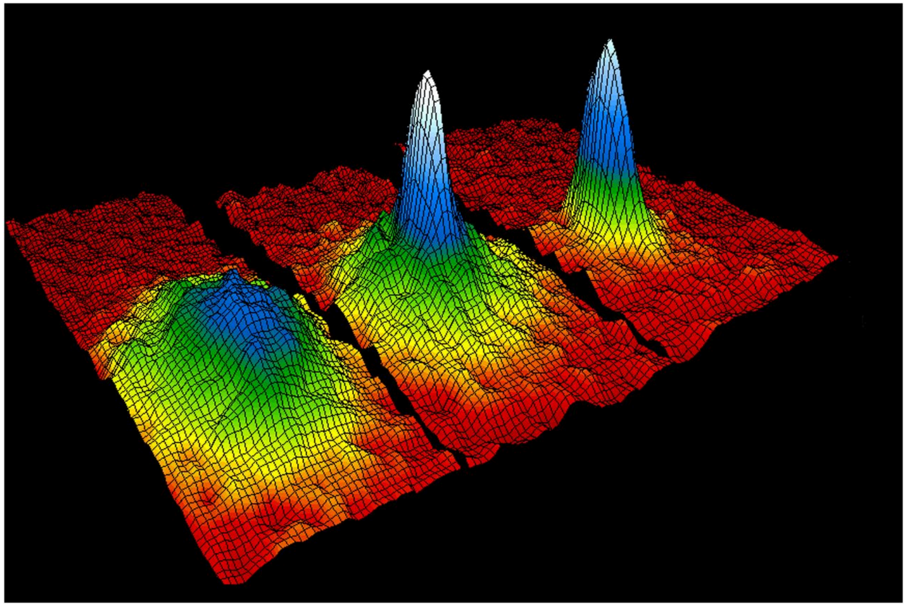


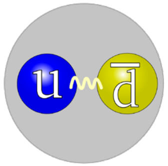
Image courtesy of NIST/JILA/CU-Boulder

Pion condensation

The relevant QCD degrees of freedom at low energies are pions

$$\mu_{\pi^\pm} = \pm\mu_I, \qquad n_I = (n_u - n_d)/2$$

isospin

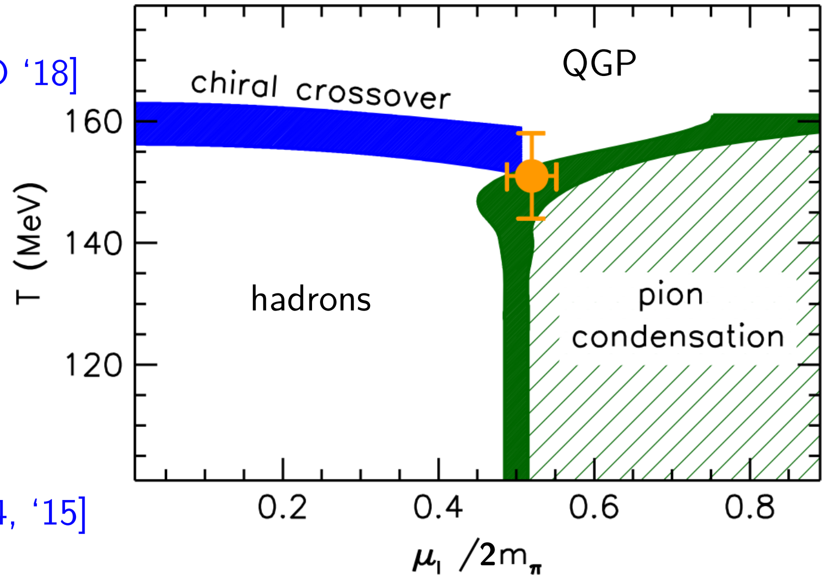


- chiral perturbation theory (T=0) [D.T. Son, M. Stephanov, PRL '01]
  - vacuum at $\mu_{\pi^\pm} < m_\pi$
  - pion BEC at $\mu_{\pi^\pm} \geq m_\pi$ (2nd order phase transition)

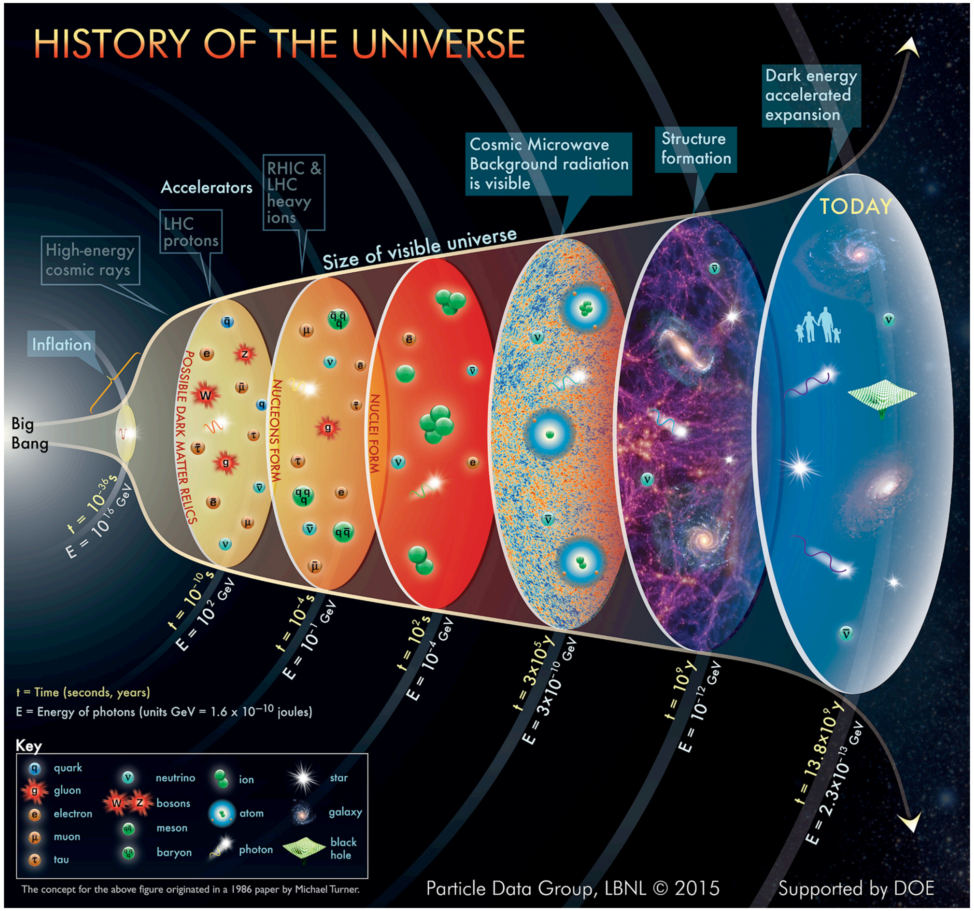
- Lattice QCD [Brandt, Endrodi, Schmalzbauer, PRD '18]
  - no sign problem at finite μ_I
  - physical quark masses achieved
  - consistent with χPT predictions

- Heavy-ion collisions(?)
  - Low-pT pion enhancement

[Begun, Florkowski, Rybczynski, PRC '14, '15]



Early Universe



QCD epoch: $\sim$10 MeV $< T <$ $\sim$100 GeV $\qquad$ $\sim 10^{-11}$ s $< t <$ 1 s

Cosmic trajectories

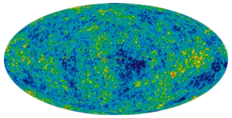
- conservation equations for isentropic expansion

$$\frac{n_B}{s} = b, \quad \frac{n_Q}{s} = 0, \quad \frac{n_{L_\alpha}}{s} = l_\alpha \quad (\alpha \in \{e, \mu, \tau\})$$

- trajectory is a line in 6-dim space of temperature and chemical potentials

$$T, \quad \mu_B, \quad \mu_Q, \quad \mu_{L_\alpha}$$

- empirical constraints (CMB anisotropies)



$$b = (8.60 \pm 0.06) \cdot 10^{-11}$$

[Planck collab., 1502.01589]

$$|l_e + l_\mu + l_\tau| < 0.012$$

[Oldengott, Schwarz, 1706.01705]

- equation of state (QCD epoch)

$$p \approx p_{\text{QCD}} + p_{\text{leptons}} + p_{\text{photons}}$$

Cosmic trajectories

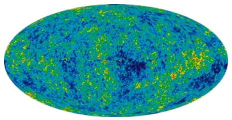
- conservation equations for isentropic expansion

$$\frac{n_B}{s} = b, \quad \frac{n_Q}{s} = 0, \quad \frac{n_{L_\alpha}}{s} = l_\alpha \quad (\alpha \in \{e, \mu, \tau\})$$

- trajectory is a line in 6-dim space of temperature and chemical potentials

$$T, \quad \mu_B, \quad \mu_Q, \quad \mu_{L_\alpha}$$

- empirical constraints (CMB anisotropies)



$$b = (8.60 \pm 0.06) \cdot 10^{-11}$$

[Planck collab., 1502.01589]

$$|l_e + l_\mu + l_\tau| < 0.012$$

[Oldengott, Schwarz, 1706.01705]

- equation of state (QCD epoch)

$$p \approx p_{\text{QCD}} + p_{\text{leptons}} + p_{\text{photons}}$$

Pion condensation may occur if $|\mu_Q| > m_\pi$ at $T < 160$ MeV

As pointed out in [M. Wygas et al., PRL '18]

Modeling the cosmic equation of state

$$p \approx p_{\mathrm{QCD}} + p_{\mathrm{leptons}} + p_{\mathrm{photons}}$$

- leptons

$$p_{\mathrm{leptons}}(T, \mu_Q, \mu_{L_\alpha}) = \sum_{\alpha \in \{e, \mu, \tau\}} \left[p_\alpha^{\mathrm{id}}(T, \mu_Q, \mu_{L_\alpha}) + p_{\nu_\alpha}^{\mathrm{id}}(T, \mu_{L_\alpha}) \right] \; + \; \text{antiparticles}$$

- photons

$$p_\gamma(T) = \frac{\pi^2}{45} T^4$$

- QCD?

Modeling the cosmic equation of state

$$p \approx p_{\text{QCD}} + p_{\text{leptons}} + p_{\text{photons}}$$

- leptons

$$p_{\text{leptons}}(T, \mu_Q, \mu_{L_\alpha}) = \sum_{\alpha \in \{e,\mu,\tau\}} \left[p_\alpha^{\text{id}}(T, \mu_Q, \mu_{L_\alpha}) + p_{\nu_\alpha}^{\text{id}}(T, \mu_{L_\alpha}) \right] \; + \; \text{antiparticles}$$

- photons

$$p_\gamma(T) = \frac{\pi^2}{45} T^4$$

- QCD?

The typical model of choice for hadronic matter is hadron resonance gas (HRG)

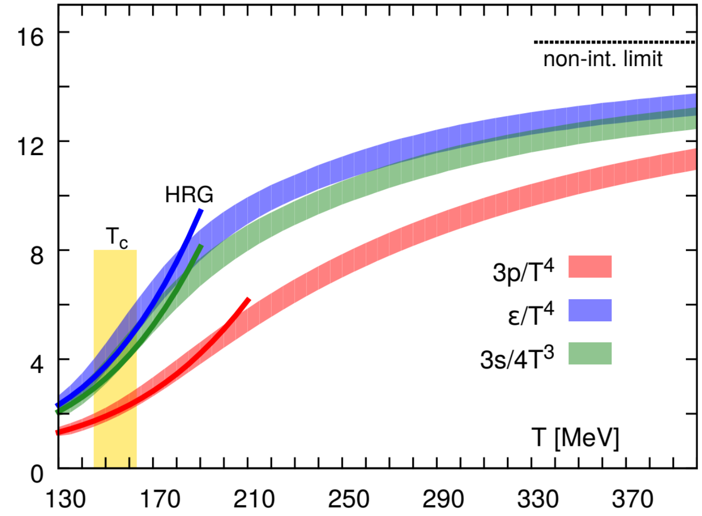


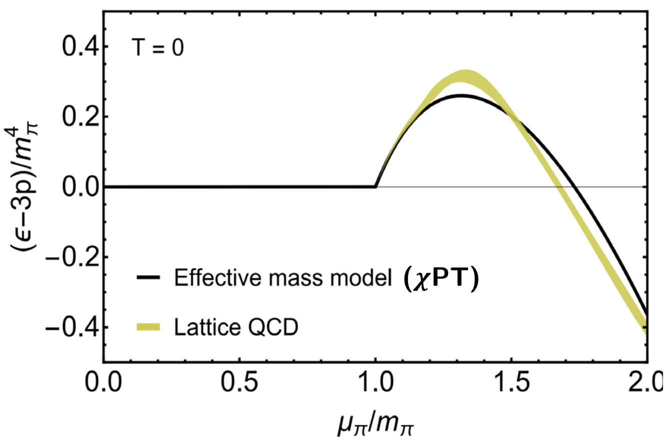
Figure from HotQCD coll., PRD '14

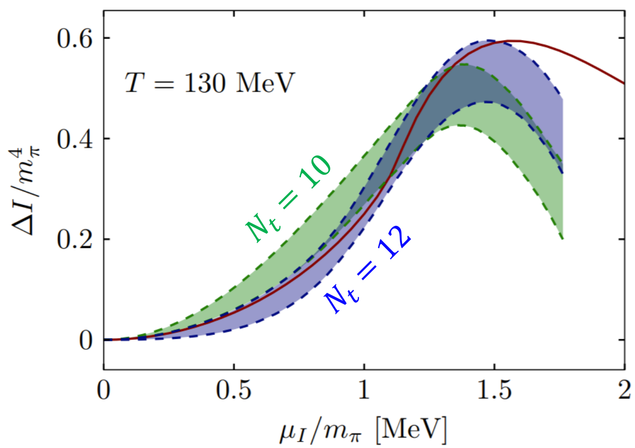
Strategy: Implement pion-pion interactions into the HRG model to account for the pion-condensed phase

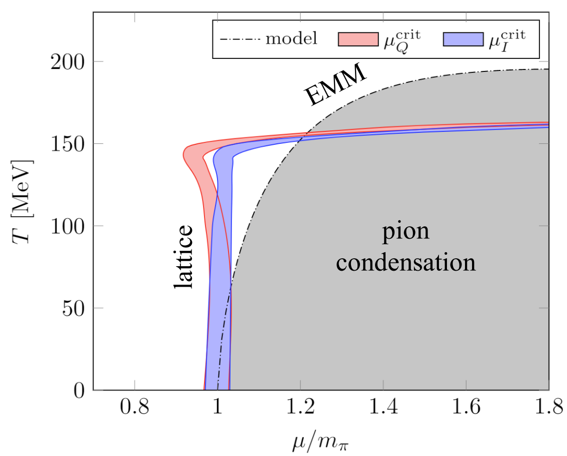
HRG model with pion interactions

$$p_{\mathrm{QCD}}(T,\mu_B,\mu_Q) \approx \underbrace{\sum_{i\in\pi^\pm,\pi^0} p_i^{\mathrm{EMM}}(T,\mu_i)}_{\textit{interacting pions}} + \underbrace{\sum_j p_j^{\mathrm{id}}(T,\mu_j)}_{\textit{free hadrons and resonances}}$$

- Pion interactions via effective mass $m_i^*(T,\mu_Q)$ matched to χPT at T $= 0$
- Validate the model using lattice QCD data for $\Delta I = I(T,\mu_I) - I(T,0), \quad I \equiv \varepsilon - 3p$





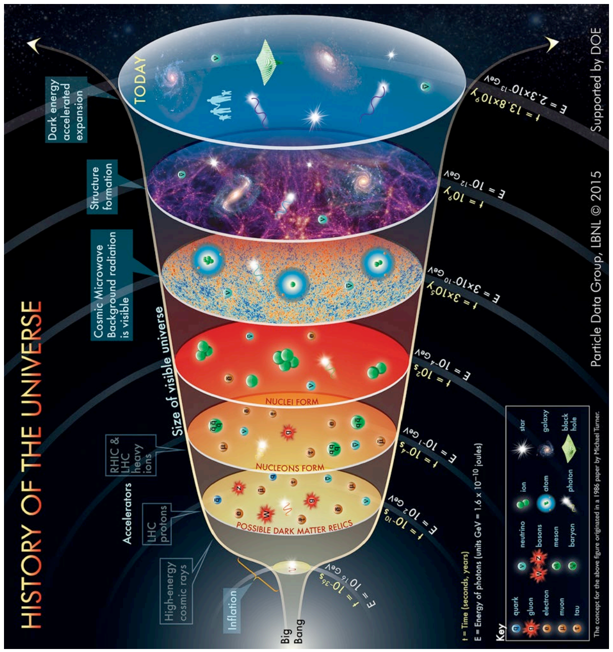


- Validity range of the model: $T \lesssim 160$ MeV, $\mu_I \lesssim 1.5\, m_\pi$

The lattice data and comparison details: VV, Brandt, Cuteri, Endrodi, Hajkarim, Schaffner-Bielich, 2009.02309

Calculating the cosmic trajectories

Early universe



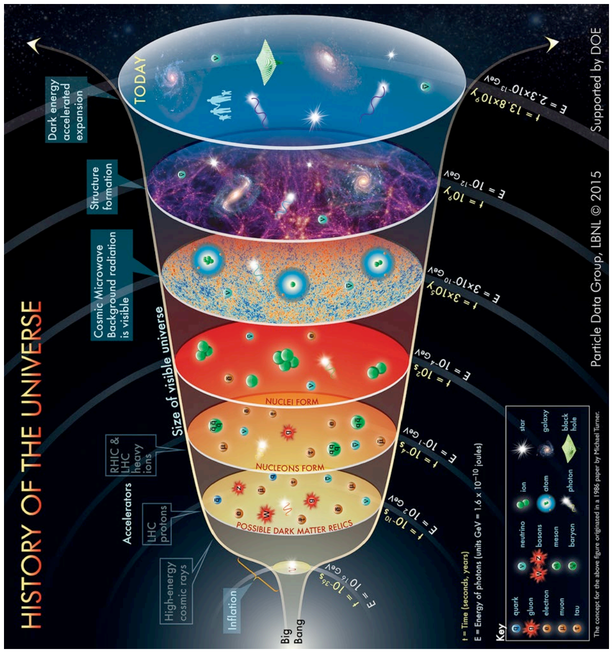
PDG

$$\frac{n_B}{s} = b, \quad \frac{n_Q}{s} = 0, \quad \frac{n_{L_\alpha}}{s} = l_\alpha$$

$$p \approx p_{\text{QCD}} + p_{\text{leptons}} + p_{\text{photons}}$$

Calculating the cosmic trajectories

Early universe

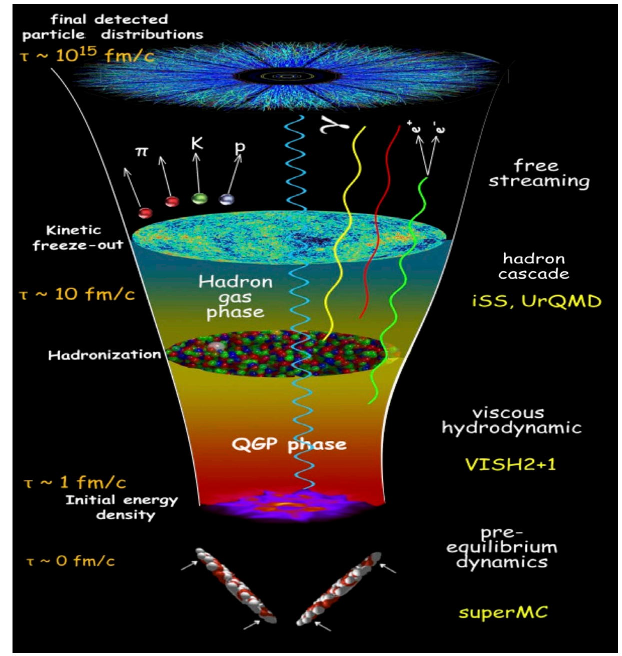


PDG

$$\frac{n_B}{s} = b, \quad \frac{n_Q}{s} = 0, \quad \frac{n_{L_\alpha}}{s} = l_\alpha$$

$$p \approx p_{\text{QCD}} + p_{\text{leptons}} + p_{\text{photons}}$$

Heavy-ion collision



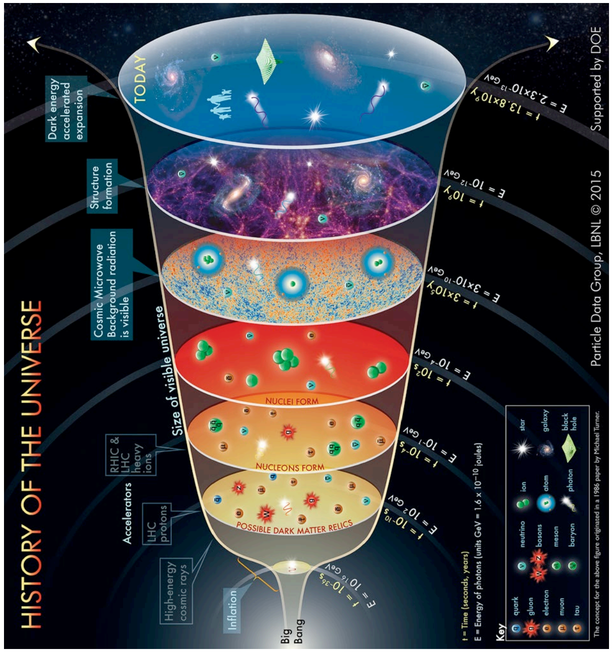
C. Shen, Ohio State U.

$$\frac{n_B}{s} = b, \quad \frac{n_Q}{s} = q, \quad \frac{n_S}{s} = 0$$

$$p = p_{\text{QCD}}$$

Calculating the cosmic trajectories

Early universe

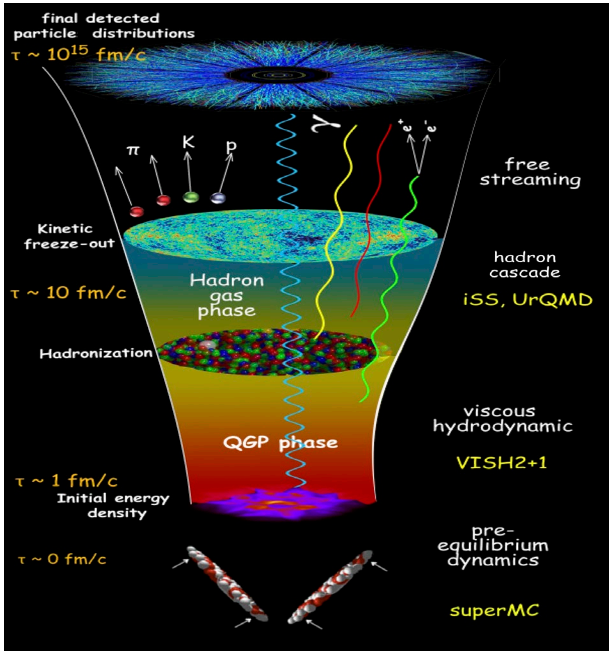


PDG

$$\frac{n_B}{s} = b, \quad \frac{n_Q}{s} = 0, \quad \frac{n_{L_\alpha}}{s} = l_\alpha$$

$$p \approx p_{\rm QCD} + p_{\rm leptons} + p_{\rm photons}$$

Heavy-ion collision



C. Shen, Ohio State U.

$$\frac{n_B}{s} = b, \quad \frac{n_Q}{s} = q, \quad \frac{n_S}{s} = 0$$

$$p = p_{\rm QCD}$$

Cosmic trajectories implemented within (extended) **Thermal-FIST** package 

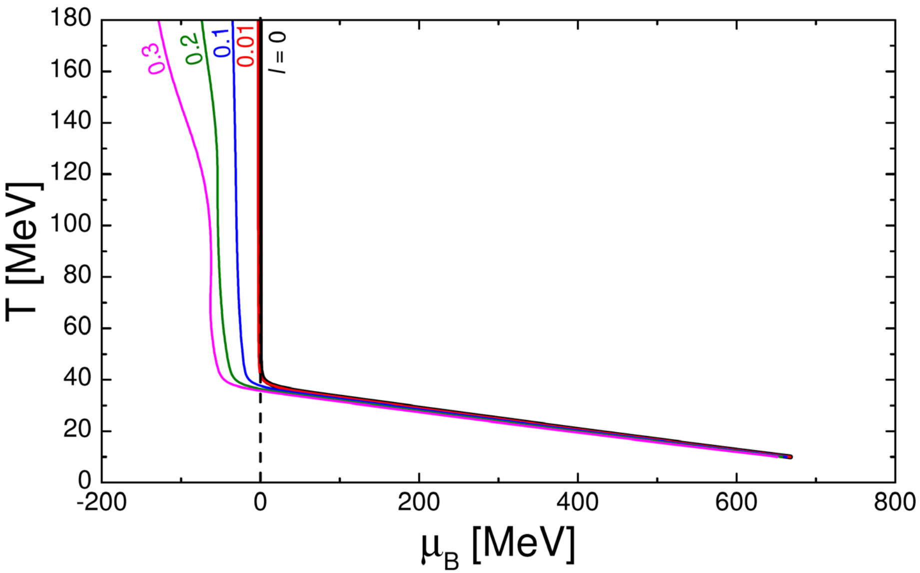
[**V.V.**, H. Stoecker, *Computer Physics Communications* ***244,*** *295 (2019); on* github]

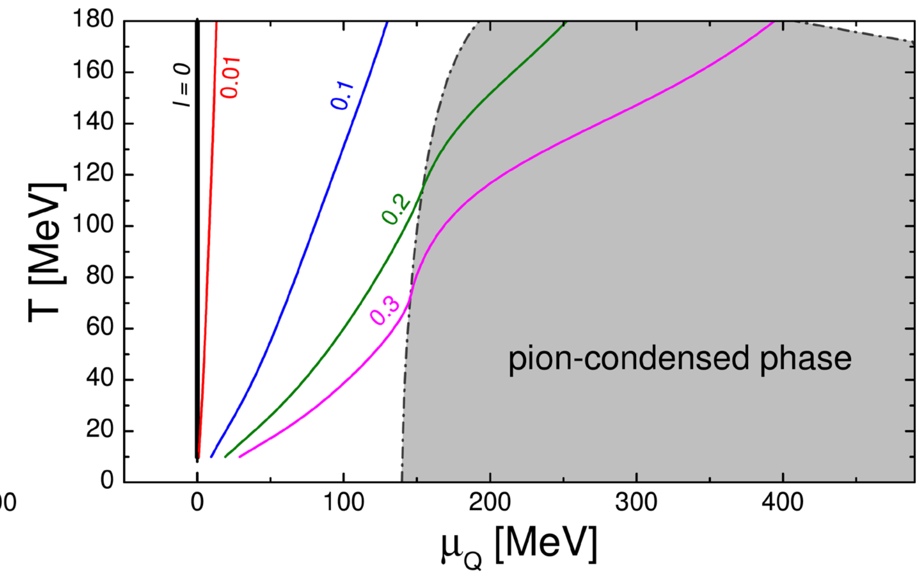
Using a heavy-ion tool in cosmology

Trajectories: Lepton-flavor symmetric case

Fix $b = 8.6 \cdot 10^{-11}$ and do a parametric scan in lepton asymmetries

First consider $l_e = l_\mu = l_\tau = l/3$

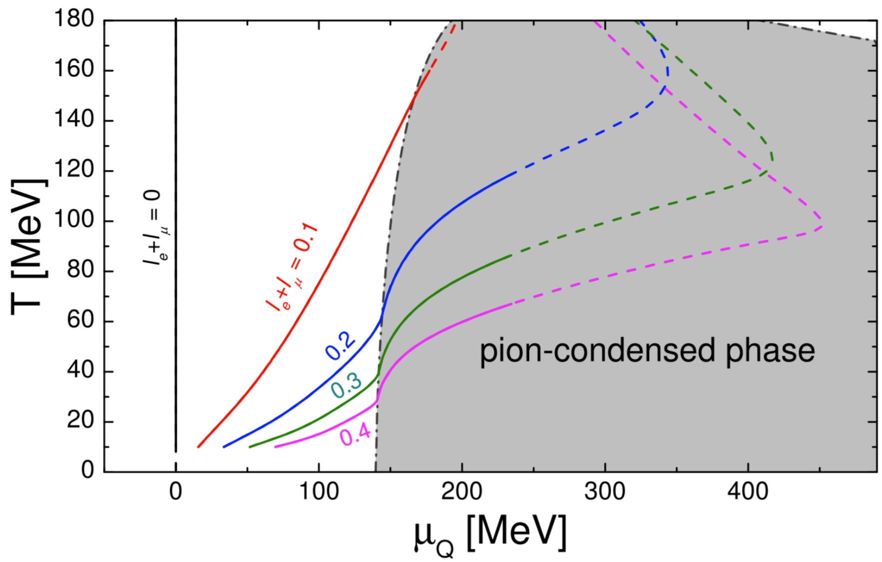


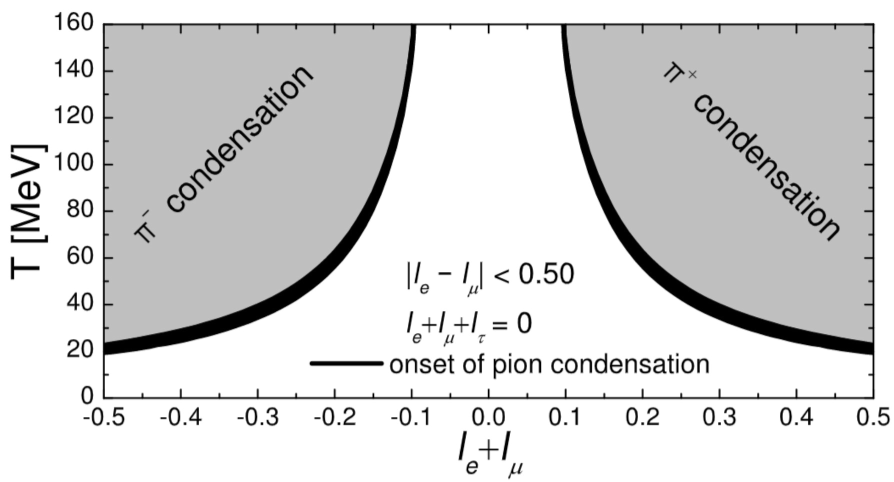


- Pion condensation in the symmetric scenario occurs if $|l| > \sim 0.15$
- However, this violates the empirical constraint $|l| < 0.012$

Outside pion-condensed region reproduces HRG model results of [M. Wygas et al., PRL '18; 2009.00036]

Trajectories: Lepton-flavor asymmetric case





- Individual lepton flavor asymmetries are much less constrained

- Set total lepton asymmetry to zero but vary individual flavor ones

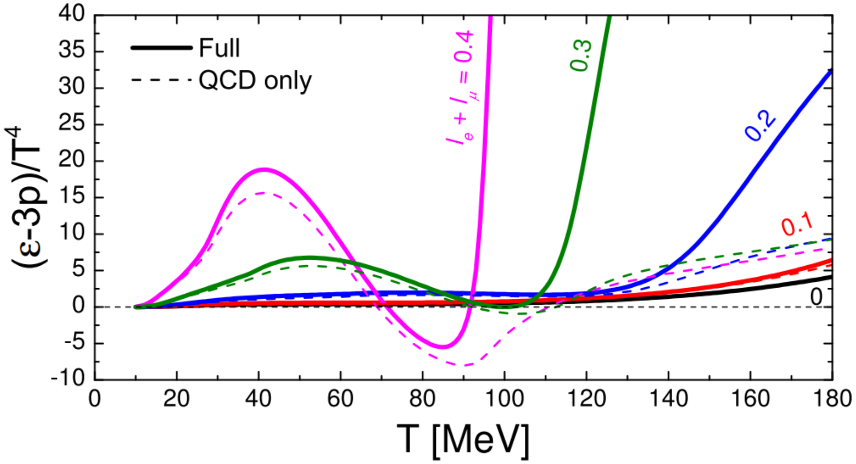
  $l_e + l_\mu + l_\tau = 0$ but $l_e \neq l_\mu \neq l_\tau$

- 2D scan in $(l_e+l_\mu, l_e - l_\mu)$

Pion condensation occurs if

$$|l_e + l_\mu| \gtrsim 0.1$$

Implications of pion condensation

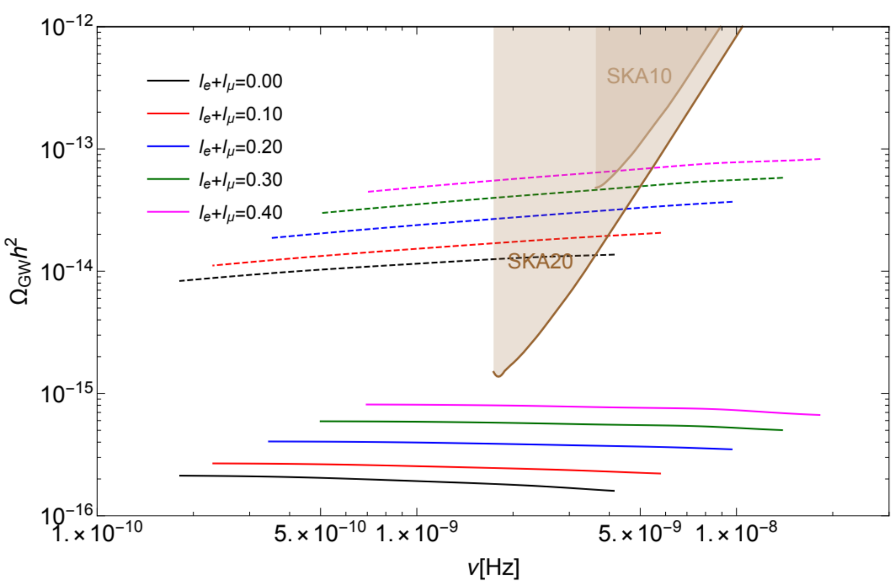


Strong effect on the pre-BBN equation of state

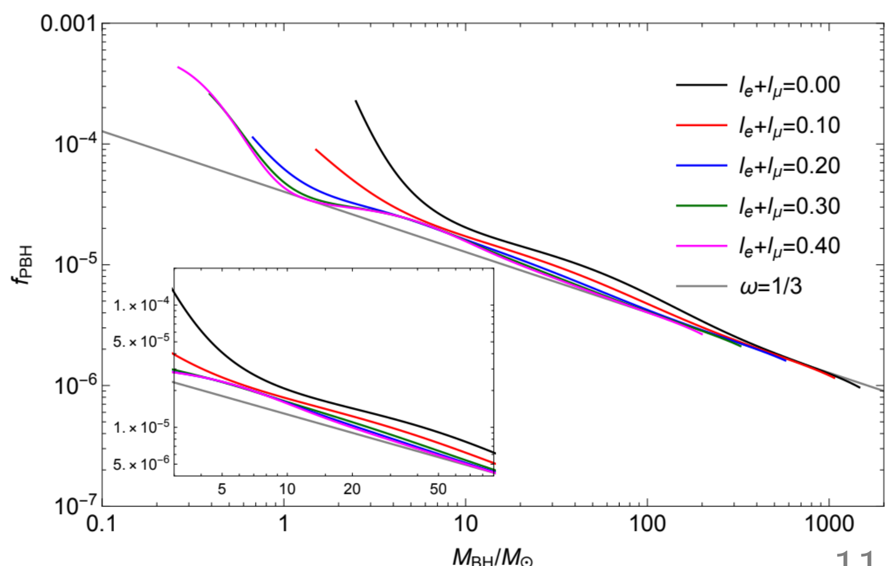
$$s(T)[a(T)]^3 = \text{const} \qquad H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\varepsilon$$

scale factor *Hubble rate*

Primordial gravitational waves



Primordial black holes



Production mechanism for pion stars

- Pion stars are gravitationally bound objects whose main constituent is the Bose-Einstein condensate of charged pions
  [Carignano et al., 1610.06097; Brandt et al., 1802.06685; Andersen, Kneschke, 1807.08951]

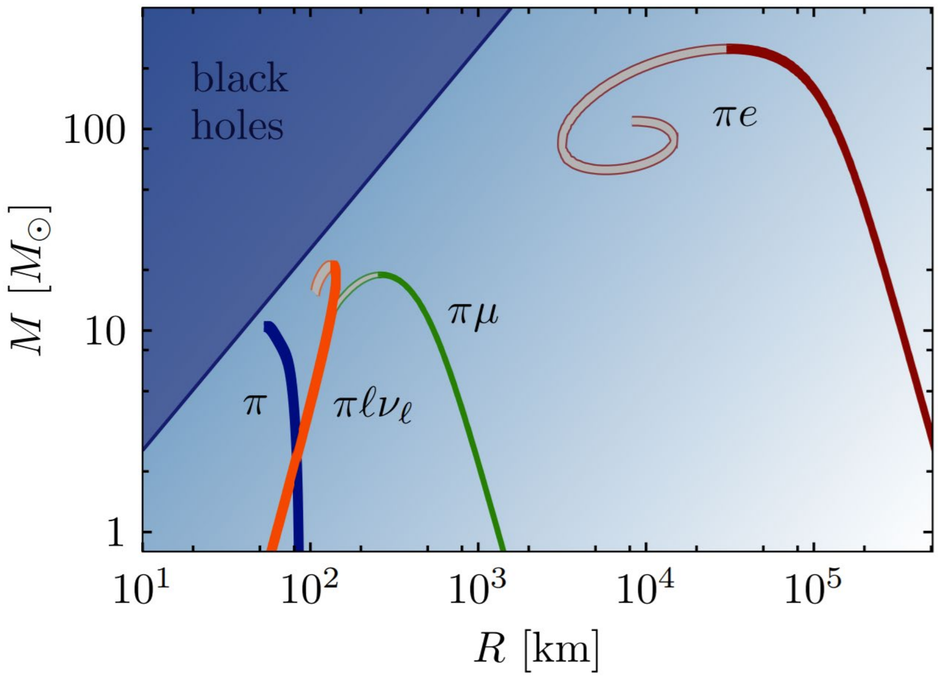


Figure from Brandt et al., 1802.06685

- Pion condensation serves as a primordial production mechanism

- Stabilized by neutrinos

- If pion stars decay around the time of big bang nucleosynthesis, the produced high energy leptons can influence the primordially produced nuclei

Summary

- The early universe passes through a pion-condensed phase if electron and muon lepton asymmetry is sufficiently large:

$$|l_e + l_\mu| > 0.1$$

- **Implications:**
  - Large effect on the pre-BBN equation of state
  - Enhanced relic density of primordial gravitational waves (relative to amplitude at $l_e + l_\mu = 0$)
  - Pion condensation as a source of primordial black holes heavier than $M_\odot$
  - Possible formation and decay of pion stars, effect on big bang nucleosynthesis

Summary

- The early universe passes through a pion-condensed phase if electron and muon lepton asymmetry is sufficiently large:

$$|l_e + l_\mu| > 0.1$$

- **Implications:**
  - Large effect on the pre-BBN equation of state
  - Enhanced relic density of primordial gravitational waves (relative to amplitude at $l_e + l_\mu = 0$)
  - Pion condensation as a source of primordial black holes heavier than $M_\odot$
  - Possible formation and decay of pion stars, effect on big bang nucleosynthesis

Thank you!