Pion condensation in the early Universe at nonvanishing lepton flavor asymmetry

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TH Heavy Ion Coffee, CERN

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based on 2009.02309

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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

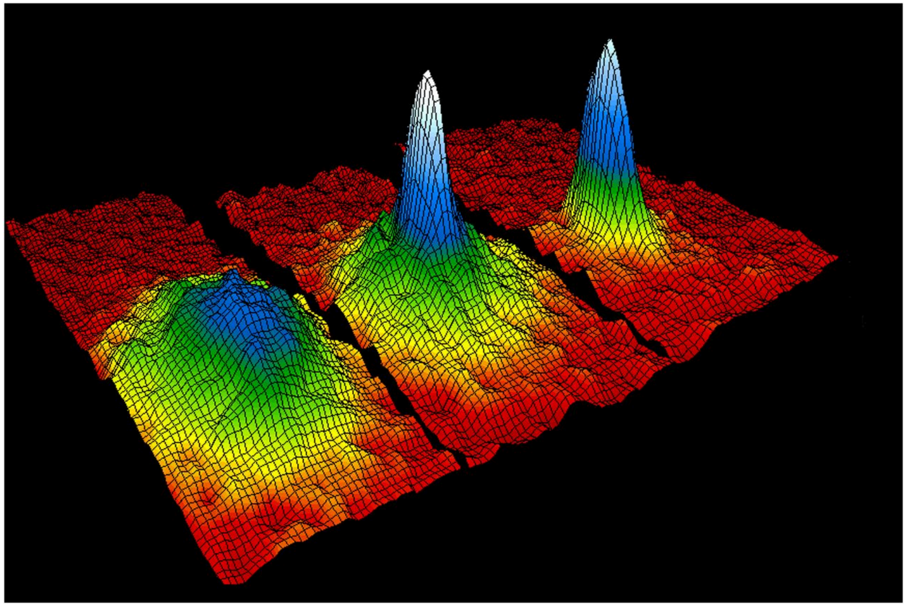
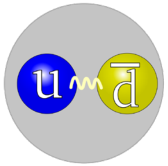


Image courtesy of NIST/JILA/CU-Boulder

Pion condensation

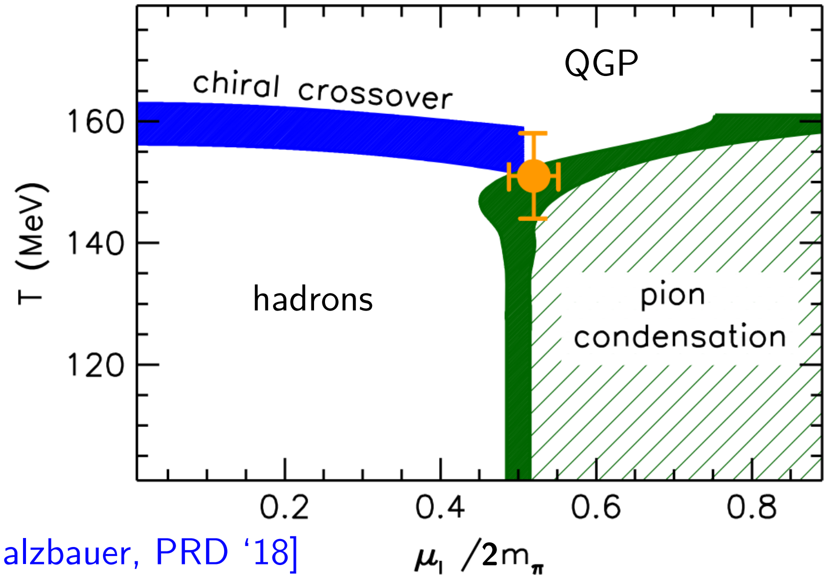
The relevant QCD degrees of freedom at low energies are pions

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



- 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
  - no sign problem at finite μ_I
  - physical quark masses achieved
  - consistent with χPT predictions

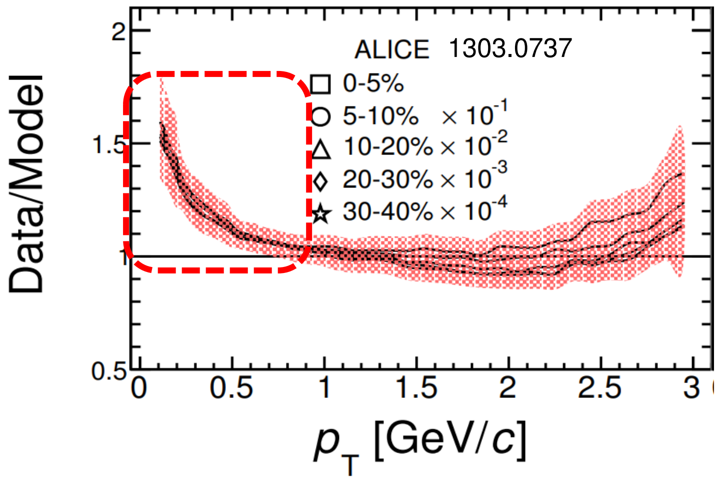


[Brandt, Endrodi, Schmalzbauer, PRD '18]

Pion condensation and heavy-ion collisions

- Low-p_T enhancement of pions produced in Pb-Pb collisions at LHC energies relative to hydro predictions

Figure from Devetak et al., JHEP '20



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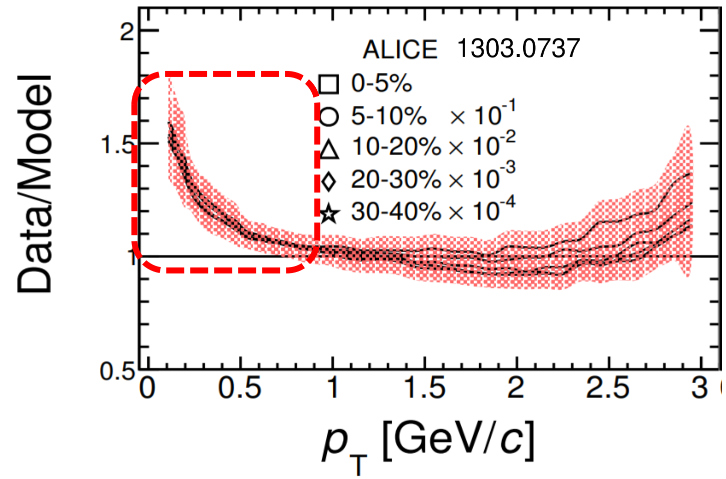
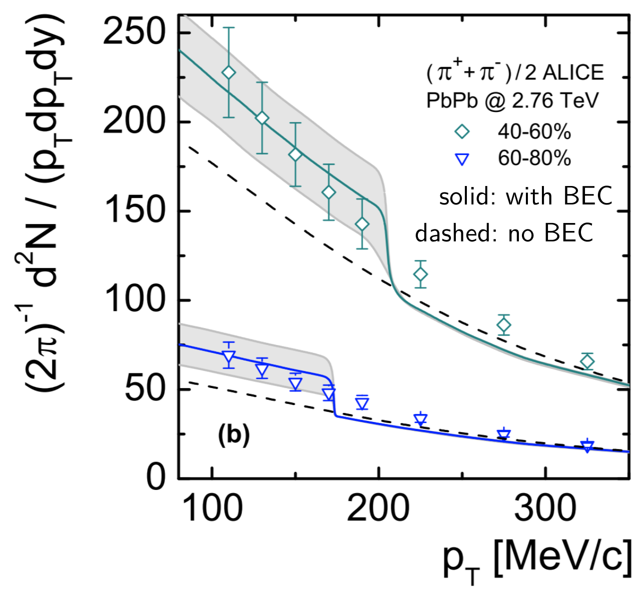


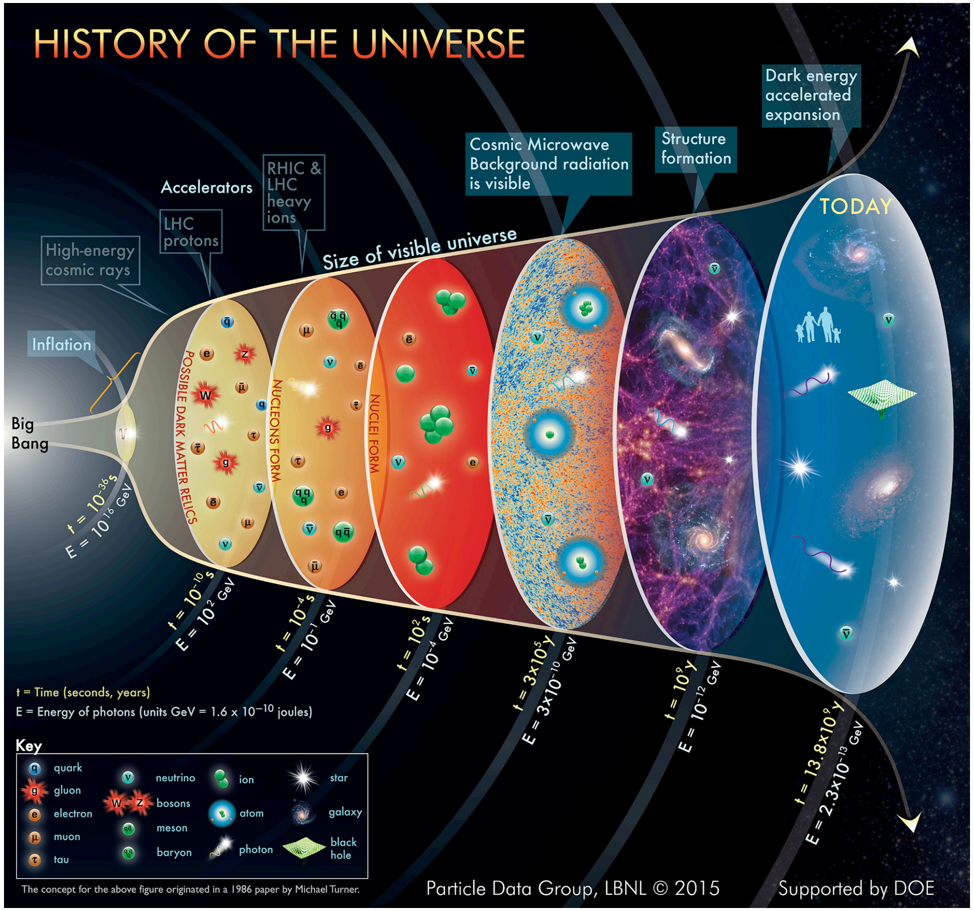
- Formation of a pion condensate may explain the data?
  [Begun, Florkowski, Rybczynski, PRC '14, '15]

- But requires a large non-equilibrium pion chemical potential, e.g. an off-equilibrium hadronization of quark-gluon plasma
  [Rafelski, Letessier, et al., EPJA '08, PRC '13]

Figure from Begun, Florkowski, PRC '14



Early Universe



QCD epoch: $\sim$10 MeV $< T <$ $\sim$100 GeV $\sim 10^{-11}$ 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)

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

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

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

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

- 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?

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- QCD?

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

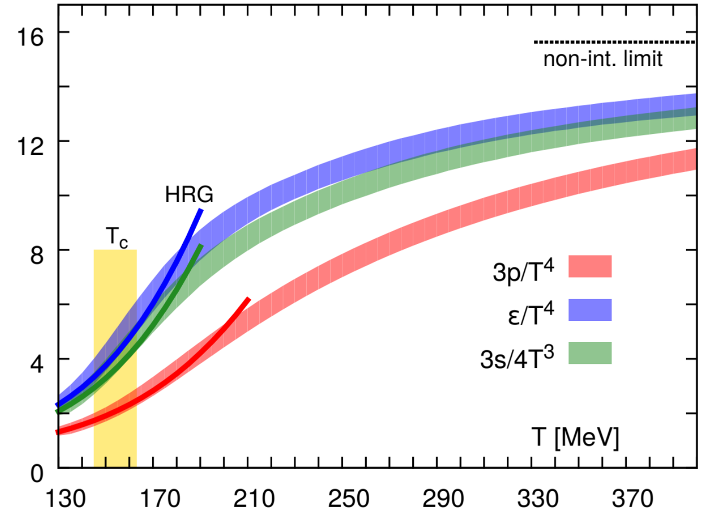

Figure from HotQCD coll., PRD ‘14

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

Effective mass model for pion condensation

- **A quasiparticle picture:** pion interactions are driven by effective mass:

$$p_\pi^{\mathrm{EM}}(T, \mu_\pi; m^*) = p_\pi^{\mathrm{id}}(T, \mu_\pi; m^*) + p_f(m^*)$$

rearrangement term

$m^*(T, \mu_\pi)$ from gap equation, $\frac{\delta p_\pi}{\delta m^*} = 0$: $\quad p_f'(m^*) = n_\sigma^{\mathrm{id}}(T, \mu_\pi; m^*)$

scalar density

more details: [Barz et al., Phys. Rev. D 40 (1989) 157; Savchuk et al., Phys. Rev. C 102 (2020) 035202]

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scalar density

- Onset of pion condensation takes place when chemical potential becomes equal to the effective mass, $\mu_\pi = m^*$. This gives the Bose-Einstein condensation line:

$$T_{\text{cond}}(\mu_\pi) : \qquad p_f'(\mu_\pi) = n_\sigma^{\text{id}}[T_{\text{cond}}(\mu_\pi),\mu_\pi;m^* = \mu_\pi]$$

- $T < T_{cond}$: a fraction of pions forms a Bose-Einstein condensate, $n_\pi = n_\pi^{\text{th}} + n_\pi^{\text{BEC}}$

$$n_\pi^{\text{th}} = n^{\text{id}}(T,\mu_\pi;m^* = \mu_\pi) \qquad n_\pi^{\text{BEC}} = p_f'(\mu_\pi) - n_\sigma^{\text{id}}(T,\mu_\pi;m^* = \mu_\pi)$$

thermal pions *condensed pions*

The specific form of the rearrangement term $p_f(m^*)$ defines the model

more details: [Barz et al., Phys. Rev. D 40 (1989) 157; Savchuk et al., Phys. Rev. C 102 (2020) 035202]

Effective mass model: $T = 0$

No thermal excitations at $T = 0$, only condensed pions at $\mu_\pi > m_\pi$

$$n_\pi^{\mathrm{EM}}(T=0,\mu_\pi) = p_f'(\mu_\pi)\,\theta(\mu_\pi - m_\pi)$$

χPT: $$n_{\chi\mathrm{PT}}(T=0,\mu_\pi) = \frac{\mu_\pi f_\pi^2}{2}\left[1 - \frac{m_\pi^4}{\mu_\pi^4}\right]\theta(\mu_\pi - m_\pi)$$

[D.T. Son, M. Stephanov, PRL '01]

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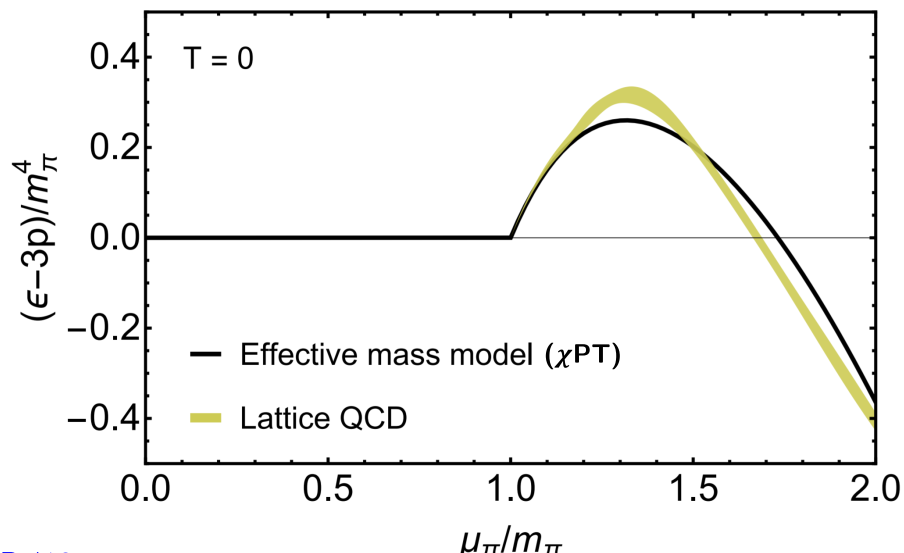
[D.T. Son, M. Stephanov, PRL '01]

Match the effective mass model to chiral perturbation theory at $T = 0$:

$$p_f(\mu_\pi) = \frac{\mu_\pi^2 f_\pi^2}{4}\left[1-\frac{m_\pi^2}{\mu_\pi^2}\right]^2$$

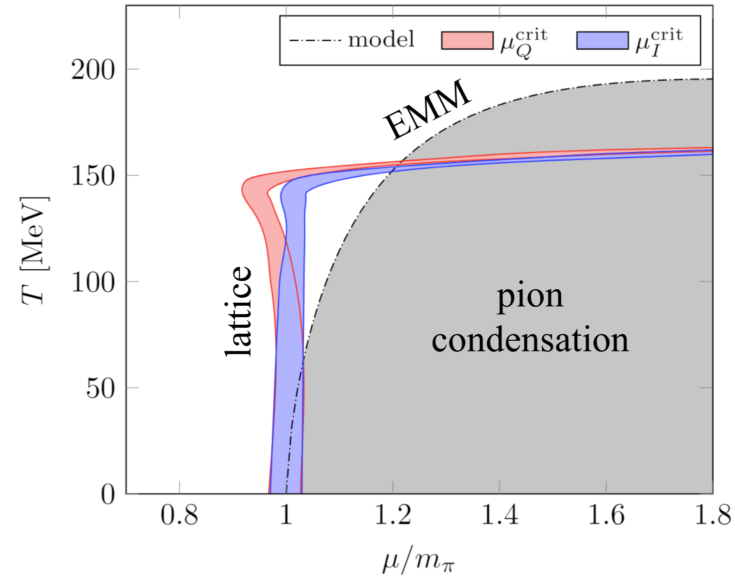
$$f_\pi = 133\ \mathrm{MeV}$$



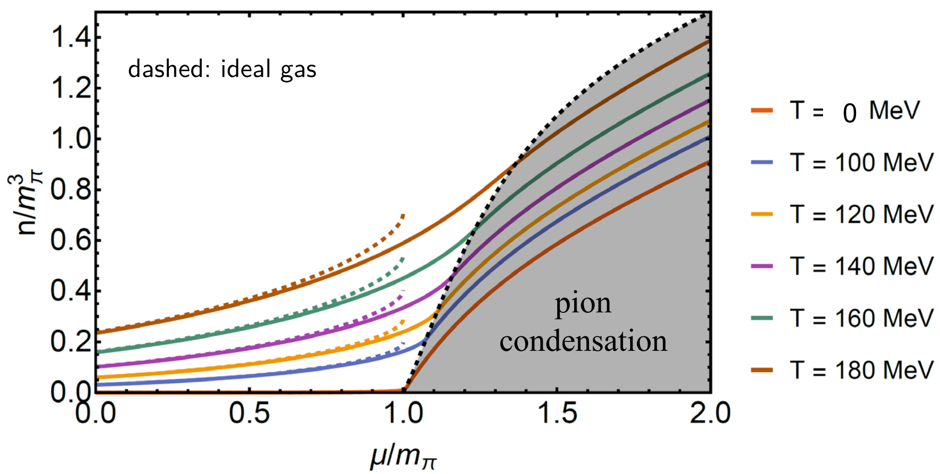
Lattice data from Brandt, Endrodi, et al., 1802.06685, PRD '18

Effective mass model: Phase diagram

- Pion condensation boundary
  - Qualitatively similar to lattice QCD
  - Not as abrupt leveling off as on lattice*
  - Model has no deconfinement, thus not reliable at T > 160 MeV



- Order of the transition
  - Kink in $n_\pi(\mu_\pi)$ at zero temperature → 2nd order phase transition
  - Does not turn 1st order at finite T
  - Consistent with lattice QCD observations



*See PQM type models for a more involved modeling of the transition line e.g. [Adhikari, Andersen, Kneschke, 1805.08599]

HRG model with pion interactions

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

interacting pions *free hadrons and resonances*

HRG model with pion interactions

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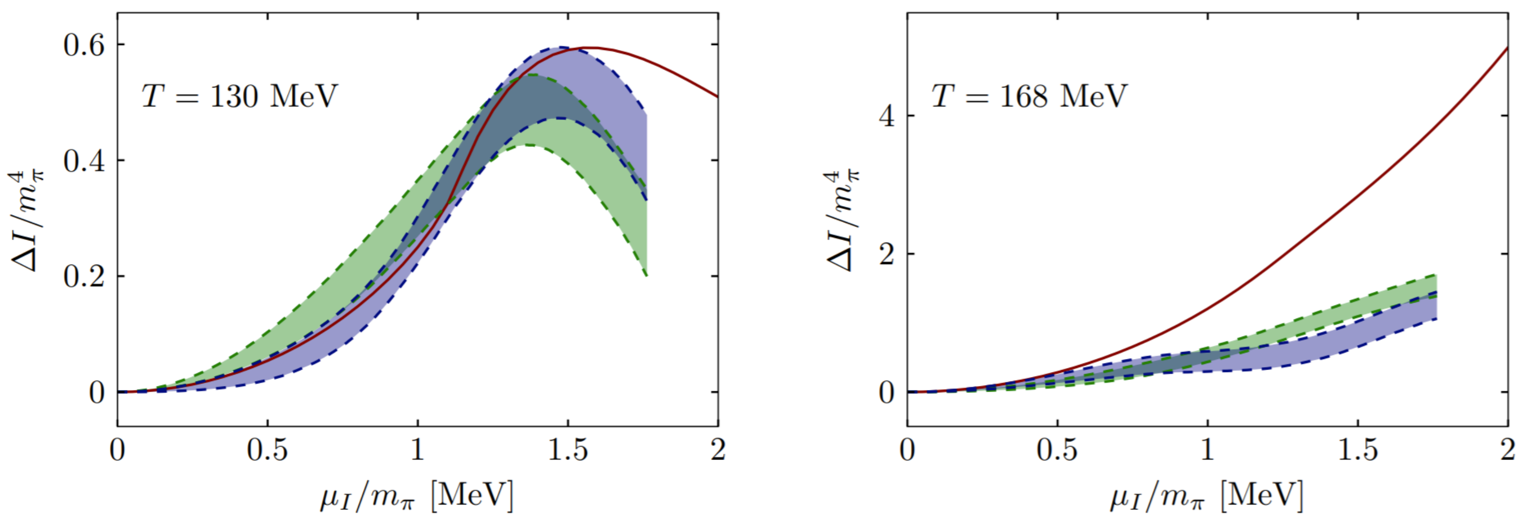
- $\Delta I = I(T, \mu_I) - I(T, 0), \quad I \equiv \varepsilon - 3p$
- Two lattice spacings: $N_t = 10$, $N_t = 12$

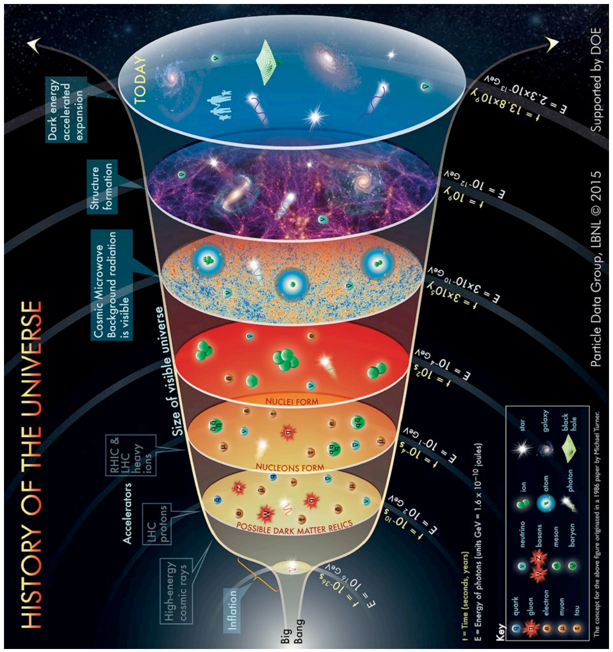


- Validity range of the model: $T \lesssim 160$ MeV, $\mu_I \lesssim 1.5\, m_\pi$

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

Calculating the cosmic trajectories

Early universe



PDG

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

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

Calculating the cosmic trajectories

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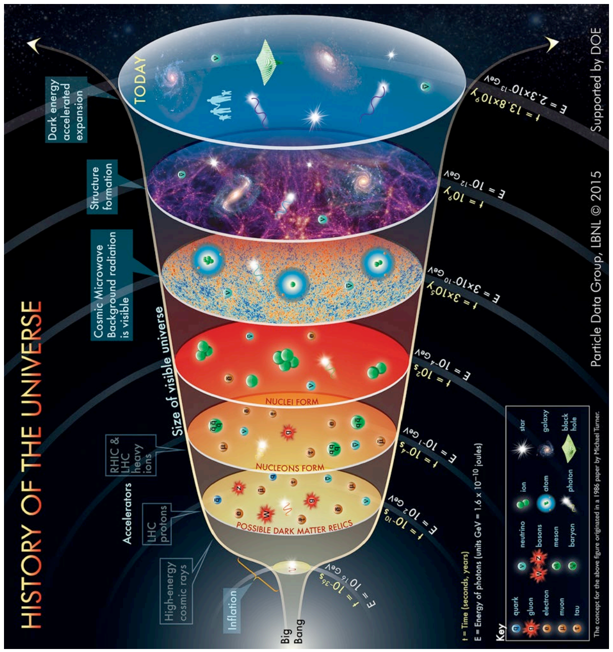

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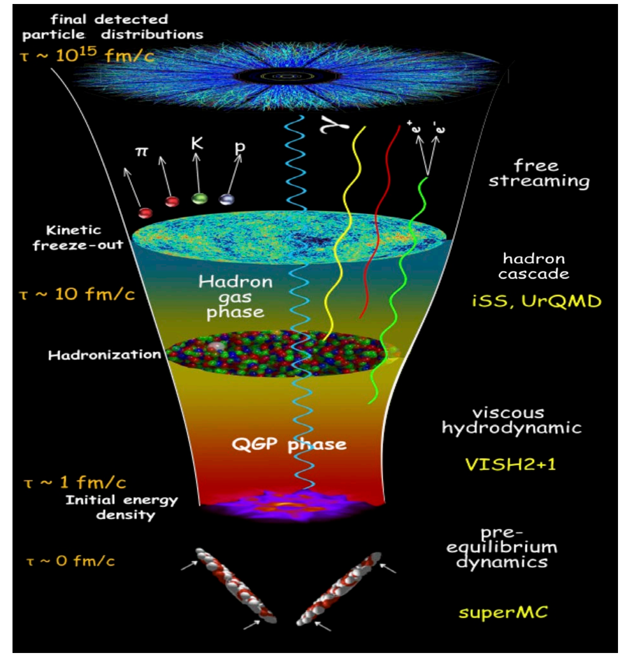
Heavy-ion collision



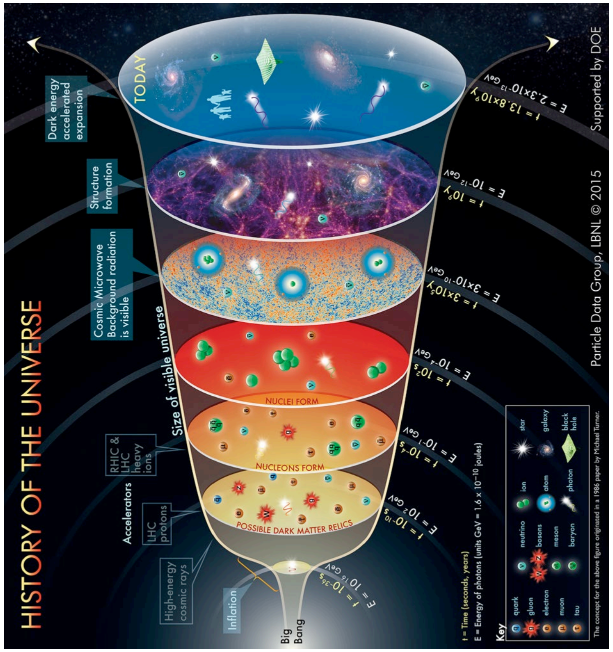
C. Shen, Ohio State U.

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

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

Calculating the cosmic trajectories

Early universe

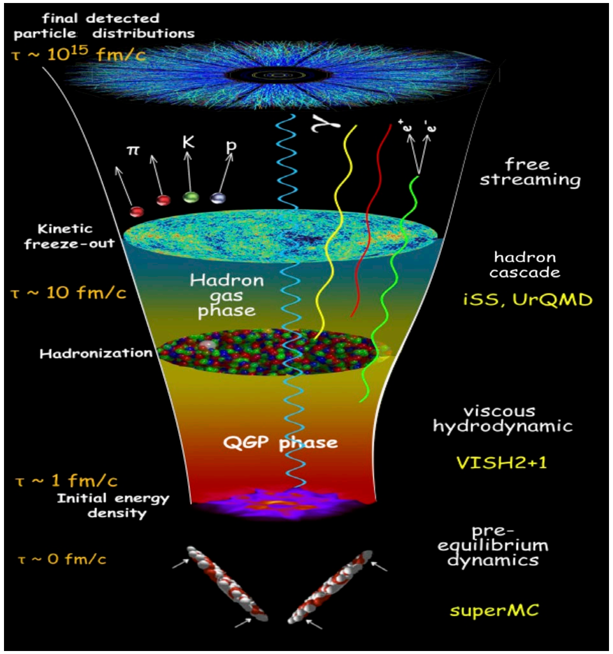


PDG

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

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

Heavy-ion collision



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

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

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

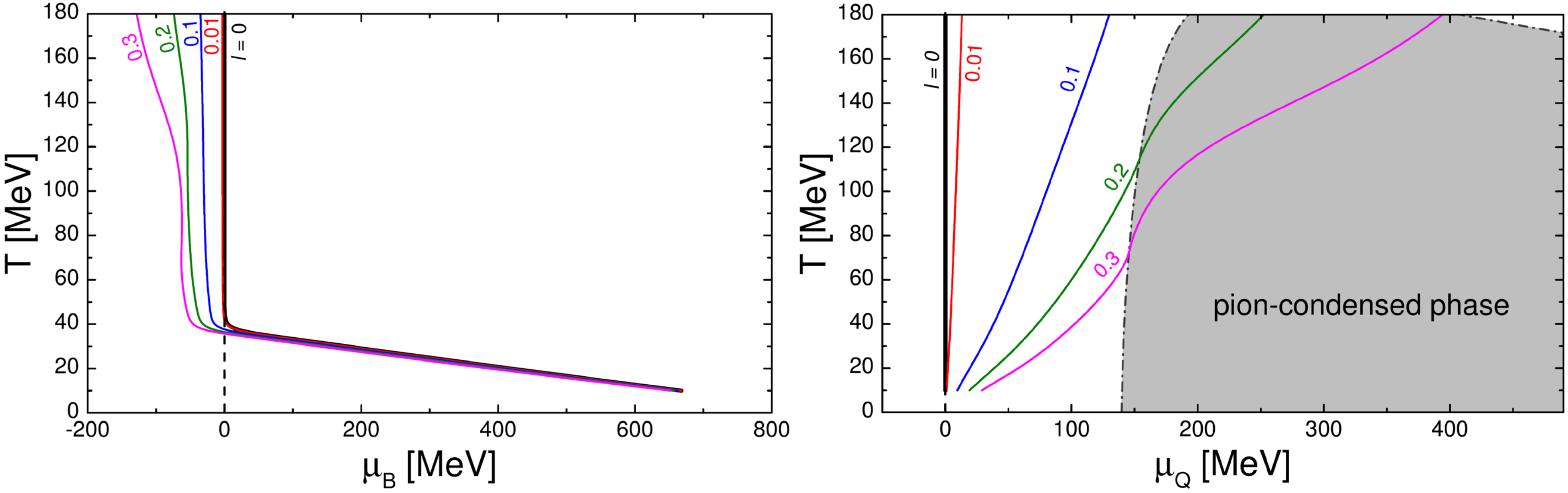
[**V.V.**, H. Stoecker, *Computer Physics Communications* ***244,*** *295 (2019);* github link]

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

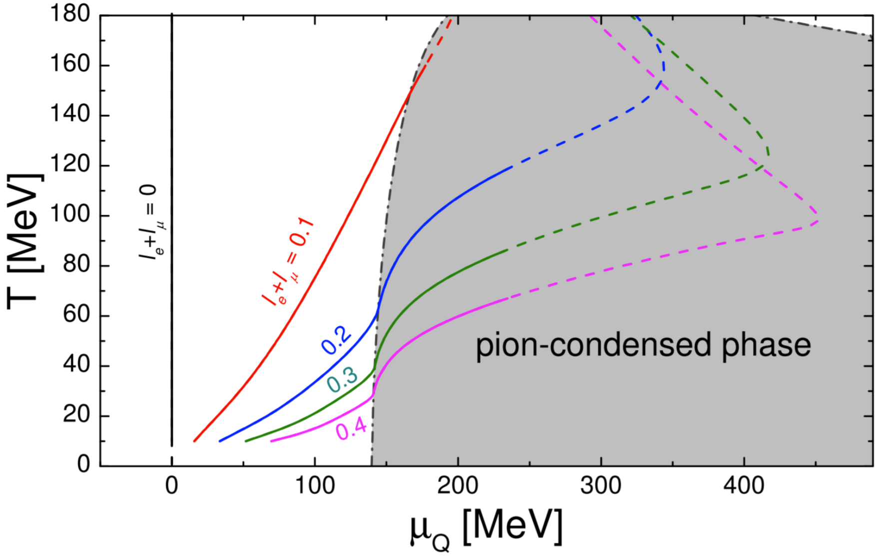
First consider $l_e = l_\mu = l_\tau = l/3$

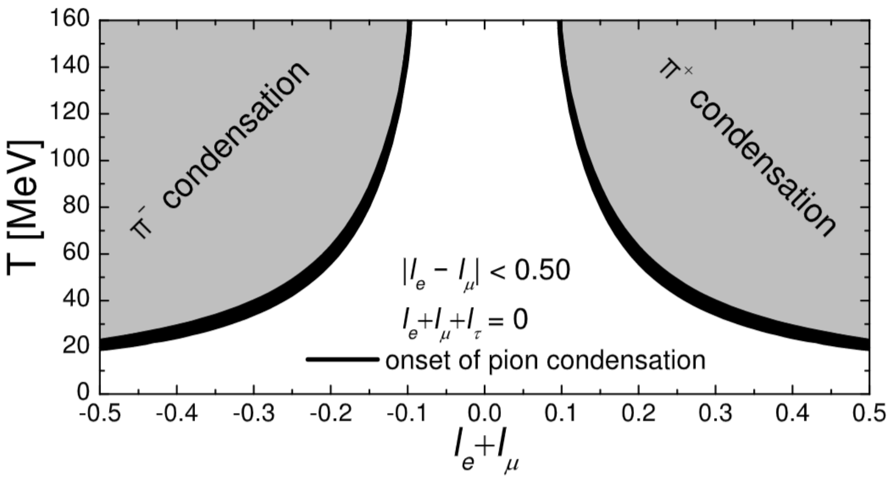


- Pion condensation in the symmetric scenario occurs if $|l| > \sim 0.15$
- However, this violates the empirical constraint $|l| < 0.012$

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

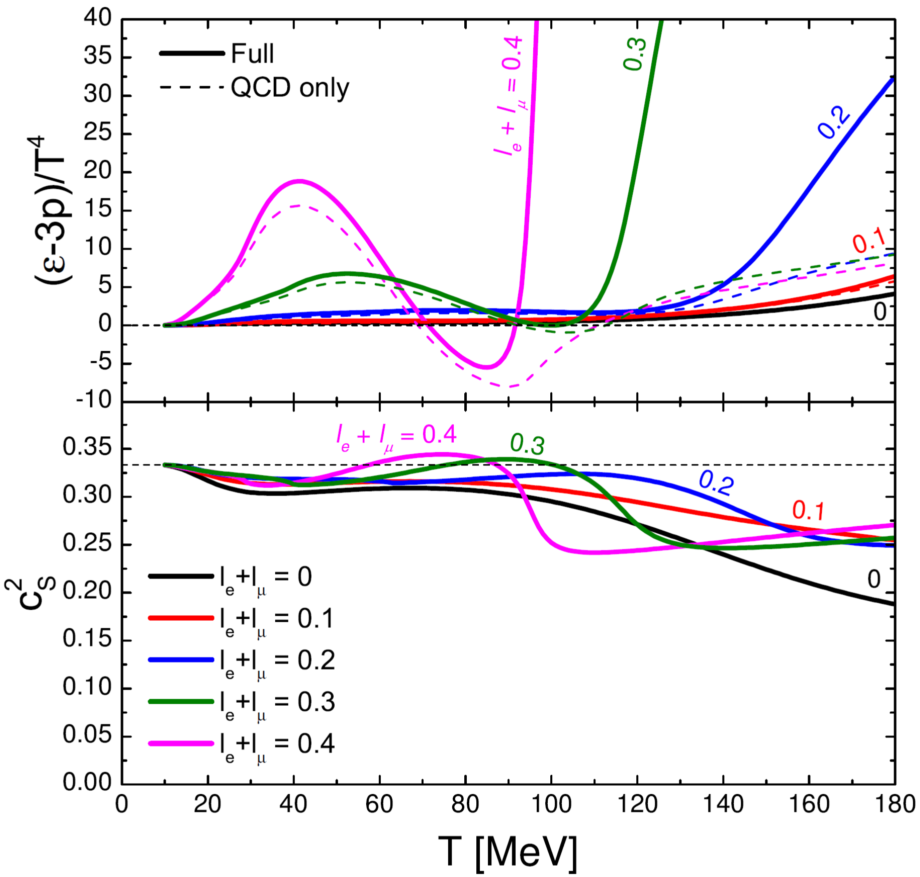
  $l_e + l_\mu + l_\tau = 0$ but $l_e \neq l_\mu \neq l_\tau$

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

Pion condensation occurs if

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

Lepton-flavor asymmetric case: Cosmic EoS



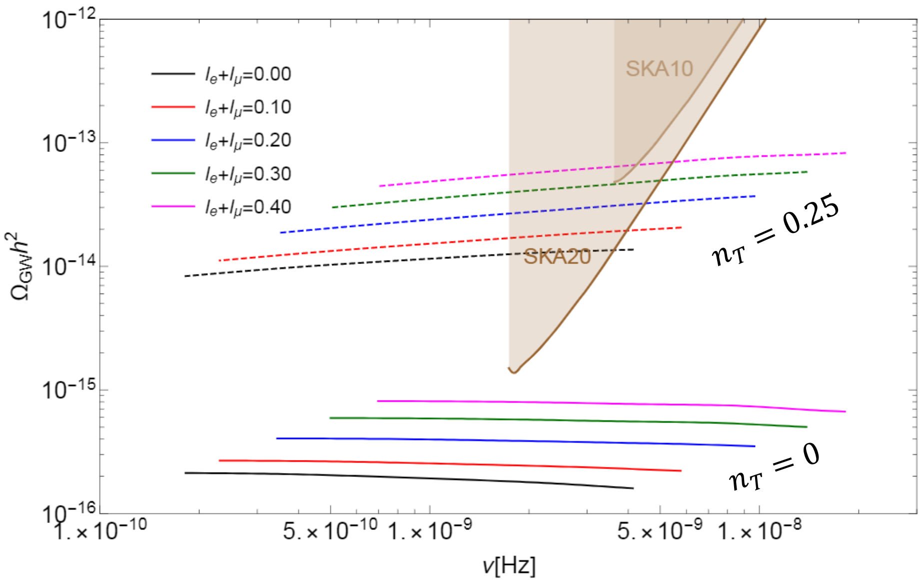
- Cosmic equation of state affected strongly by large lepton asymmetry
- Pion condensation leads to (nearly) negative interaction measure and $c_s^2 > 1/3$
- At higher temperatures large I/T^4 driven by large lepton chemical potentials

The changed EoS has cosmological implications

$$\underbrace{s(T)[a(T)]^3 = \text{const}}_{\textit{scale factor}} \qquad \underbrace{H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\varepsilon}_{\textit{Hubble rate}} \qquad \frac{a''}{a} = \frac{4\pi G}{3}(\varepsilon - 3p)$$

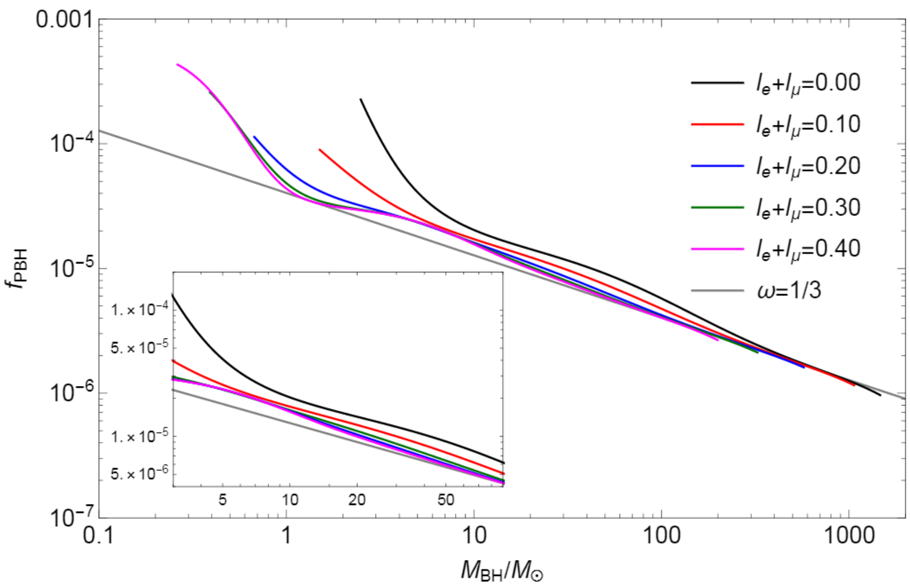
Primordial gravitational waves and black holes

Primordial gravitational waves from inflationary scenario



- Enhanced relic density of primordial gravitational waves (relative to amplitude at $l_e + l_\mu = 0$)
- Possibly reachable by pulsar-timing arrays, e.g. Square Kilometer Array (SKA) over 10-20 years of operation

Fraction of primordial black holes relative to cold dark matter



- Changed fraction of primordial black holes heavier than solar mass
- Pion condensation epoch is a source of PBHs?
- Speculation: BHs merger events, e.g. LIGO GW190521, …

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]

- Pion condensation serves as a primordial production mechanism

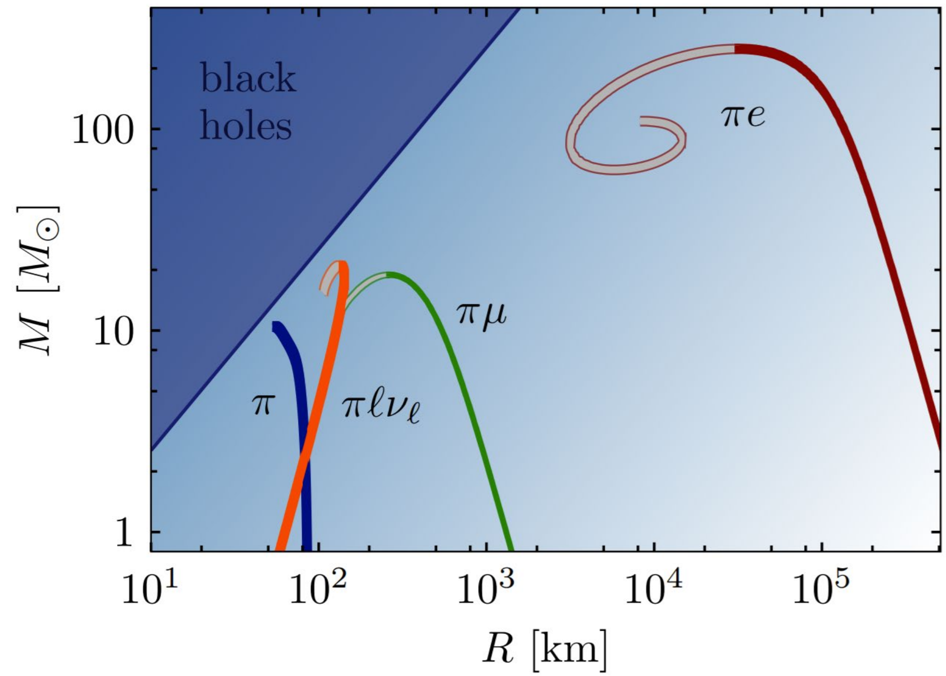


Figure from Brandt et al., 1802.06685

- 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 $l_e + l_\mu = 0$)
  - Changed fraction of primordial black holes with mass larger than $M_\odot$
  - Possible formation and decay of pion stars, effect on big bang nucleosynthesis

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Thank you!

Backup slides

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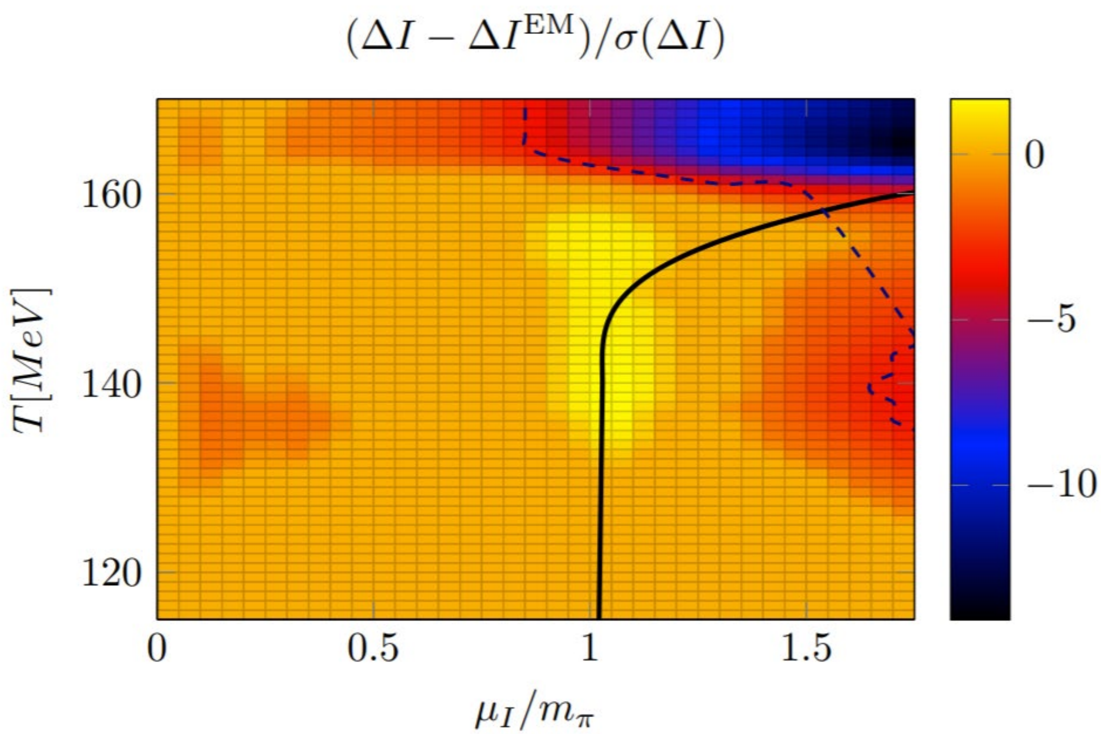

The lattice data and comparison details: VV, Brandt, Cuteri, Endrodi, Hajkarim, Schaffner-Bielich, 2009.02309

Lepton chemical potentials