Pion condensation in the early Universe at nonvanishing lepton flavor asymmetry

Volodymyr Vovchenko (LBNL)

(Virtual) Nuclear Theory Seminar at LBNL

October 29, 2020

with B. Brandt, G. Endrödi (Bielefeld U.), F. Cuteri, F. Hajkarim, J. Schaffner-Bielich (Frankfurt U.)

based on 2009.02309

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

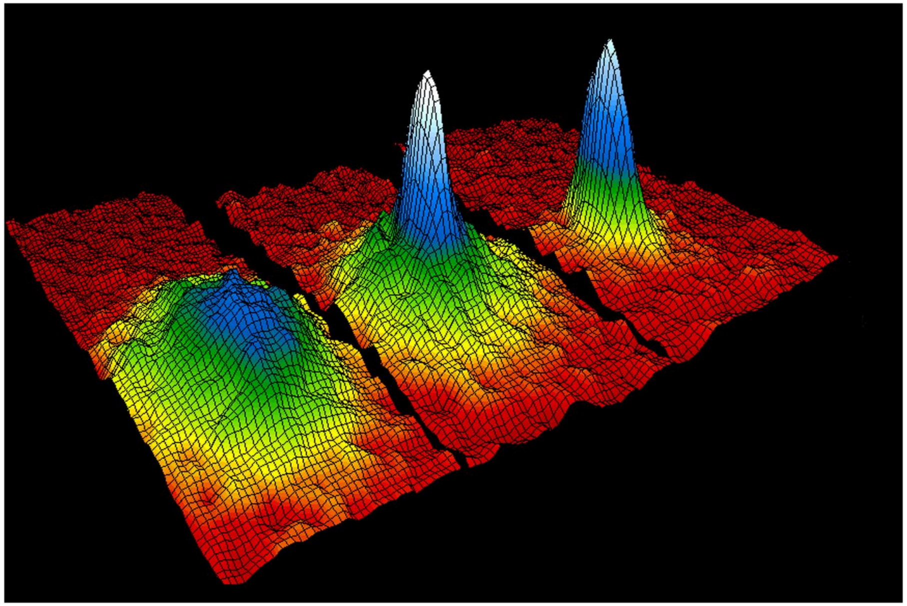


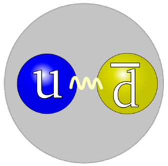
Image courtesy of NIST/JILA/CU-Boulder

Pion condensation

The relevant QCD degrees of freedom at low energies are pions

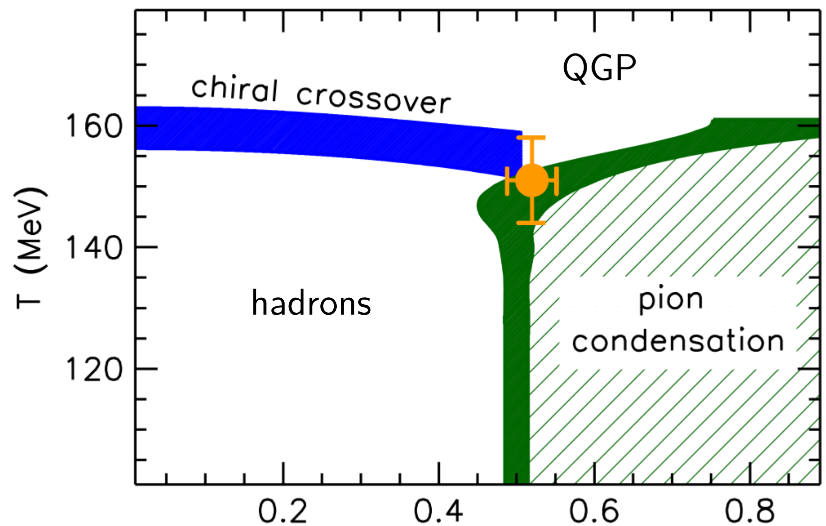
$$\mu_{\pi^\pm} = \pm\mu_I, \qquad n_I = (n_u - n_d)/2$$

isospin



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

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

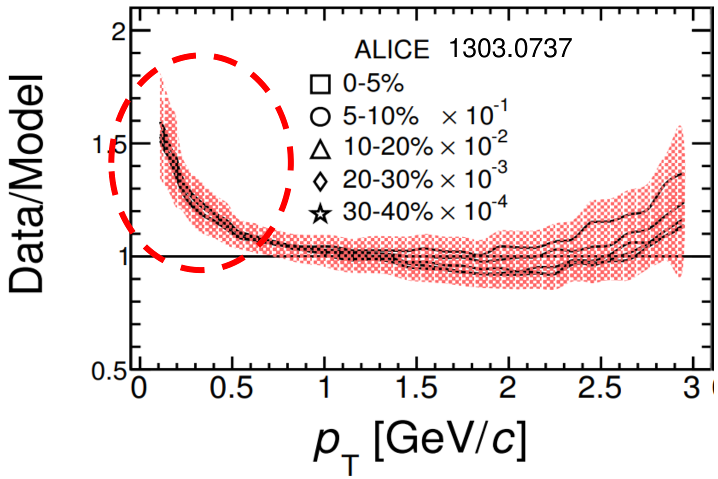


[Brandt, Endrodi, Schmalzbauer, PRD '18]

Pion condensation and heavy-ion collisions

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

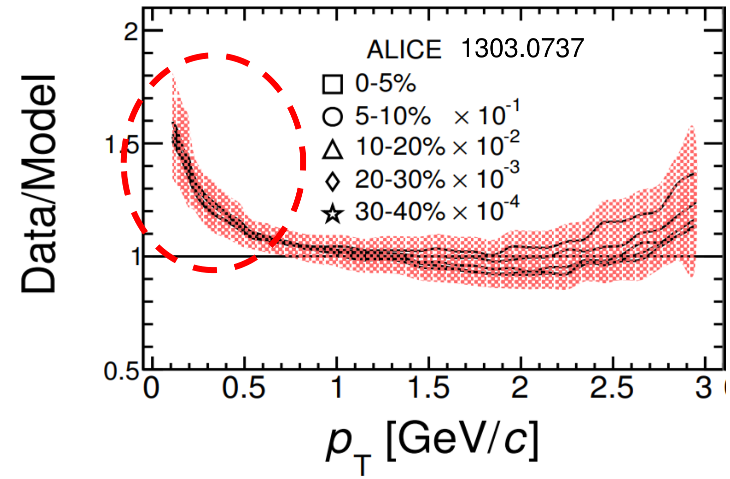
Figure from Devetak et al., JHEP '20



Pion condensation and heavy-ion collisions

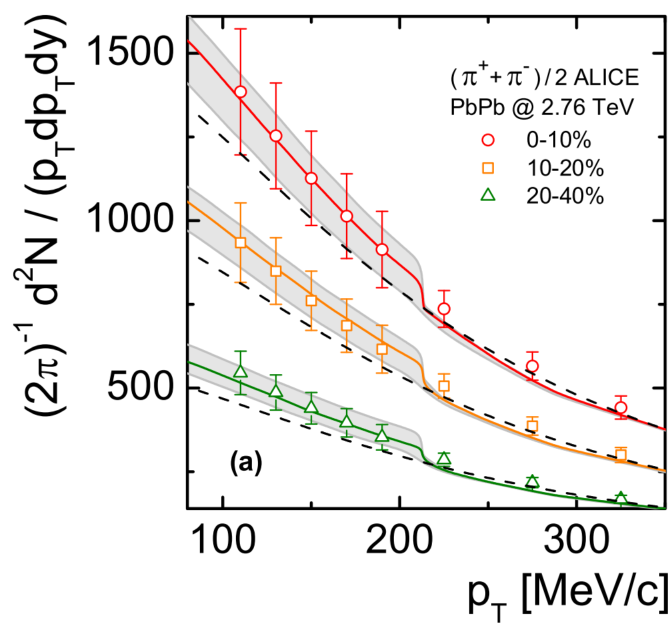
- Low-p_T enhancement of pions produced in Pb-Pb collisions at LHC energies relative to hydro predictions

Figure from Devetak et al., JHEP '20



- Formation of a pion condensate may explain the data?

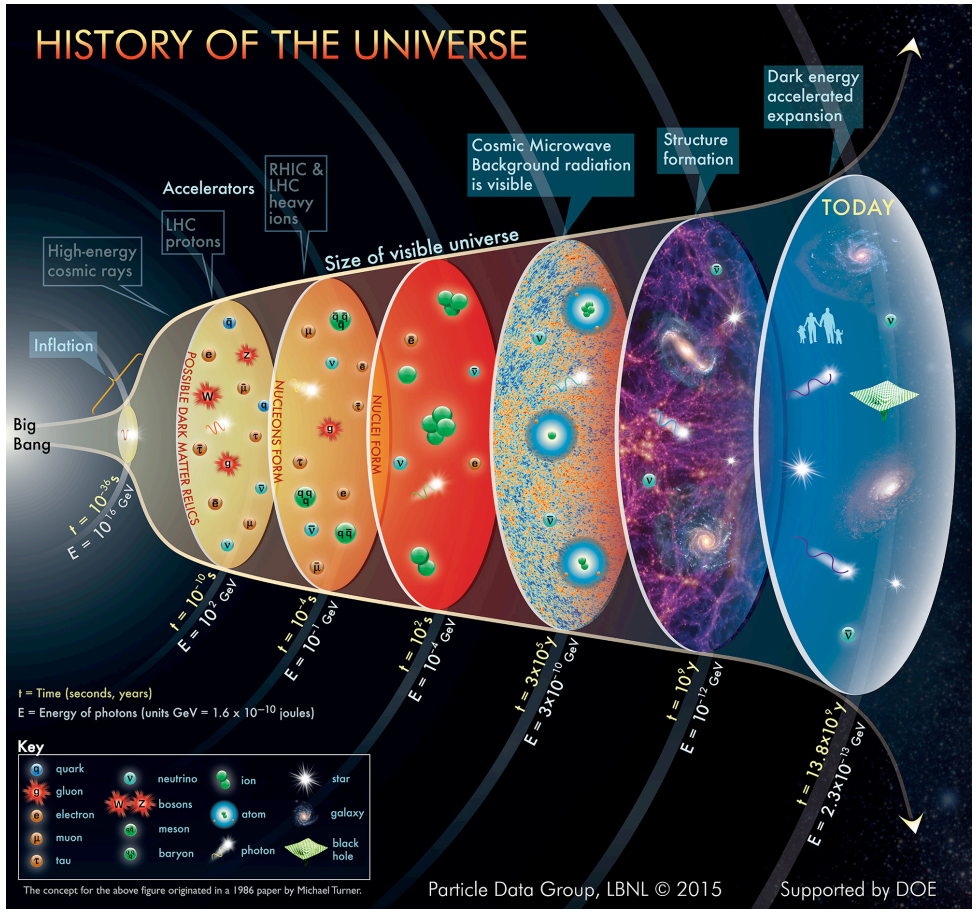
[Begun, Florkowski, Rybczynski, PRC '14, '15]



- But requires strong non-equilibrium effects, e.g. an off-equilibrium hadronization of quark-gluon plasma

[Rafelski, Letessier, et al., EPJA '08, PRC '13]

Early Universe



QCD epoch: ~10 MeV < T < ~100 GeV

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)

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

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

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

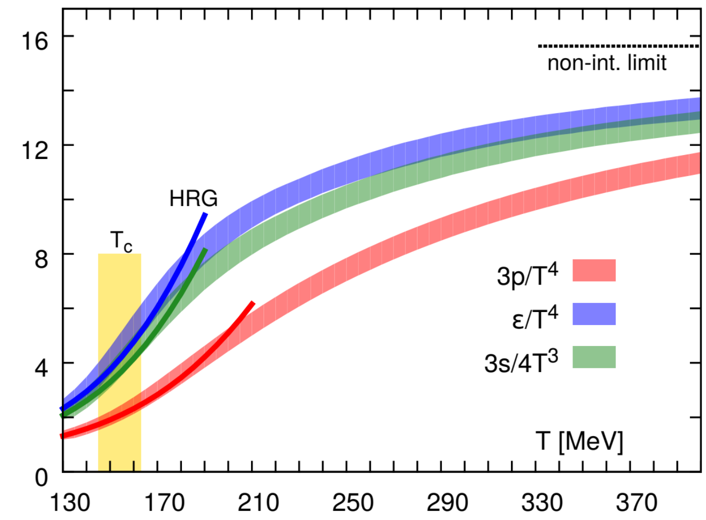
$$p_{\text{leptons}}(T, \mu_Q, \mu_{L_\alpha}) = \sum_{\alpha \in \{e,\mu,\tau\}} \left[p_\alpha^{\text{id}}(T, \mu_Q, \mu_{L_\alpha}) + p_{\nu_\alpha}^{\text{id}}(T, \mu_{L_\alpha}) \right] \; + \; \text{antiparticles}$$

- photons

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

- QCD?

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



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: $p'_f(m^*) = n_\sigma^{\mathrm{id}}(T,\mu_\pi;m^*)$

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:

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

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

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

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 $\mu_\pi > m_\pi$

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

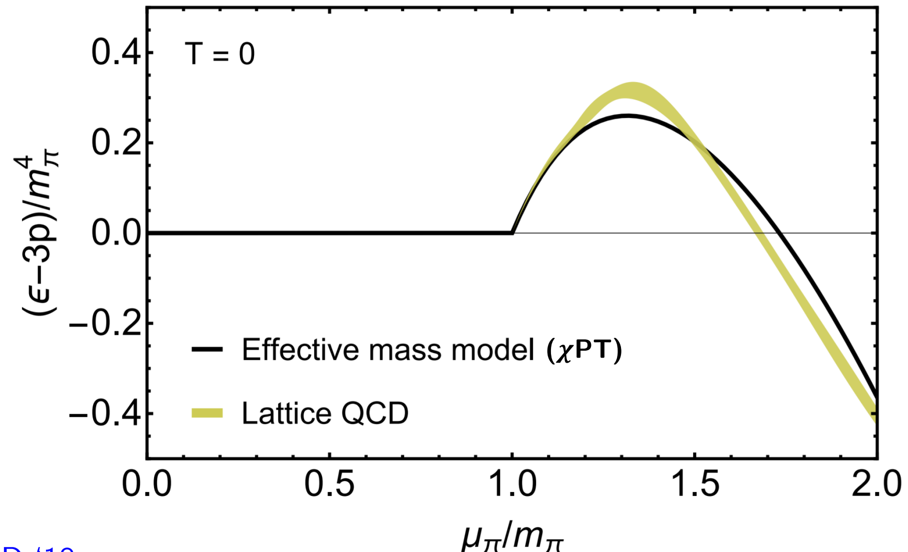
χPT:
$$n_{\chi\mathrm{PT}}(T=0,\mu_\pi) = \frac{\mu_\pi f_\pi^2}{2}\left[1 - \frac{m_\pi^4}{\mu_\pi^4}\right]\theta(\mu_\pi - m_\pi)$$

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

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

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

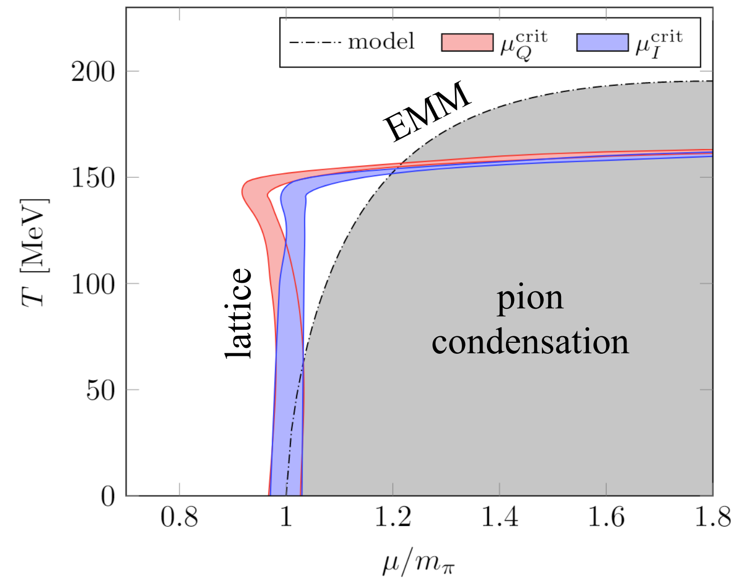
$$f_\pi = 133\ \mathrm{MeV}$$



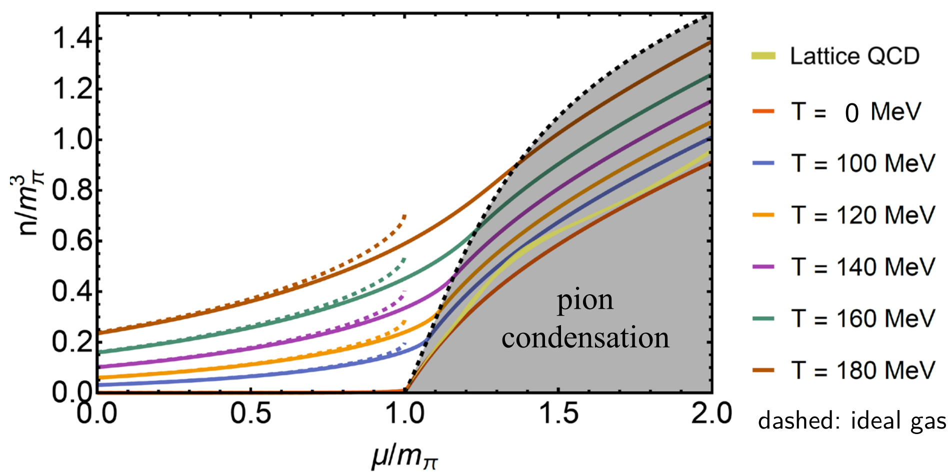
Lattice data from Brandt, Endrodi, et al., 1802.06685, PRD '18

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 → 2^{nd} order phase transition
  - Does not turn 1^{st} order at finite T
  - Consistent with lattice QCD observations



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

HRG model with pion interactions

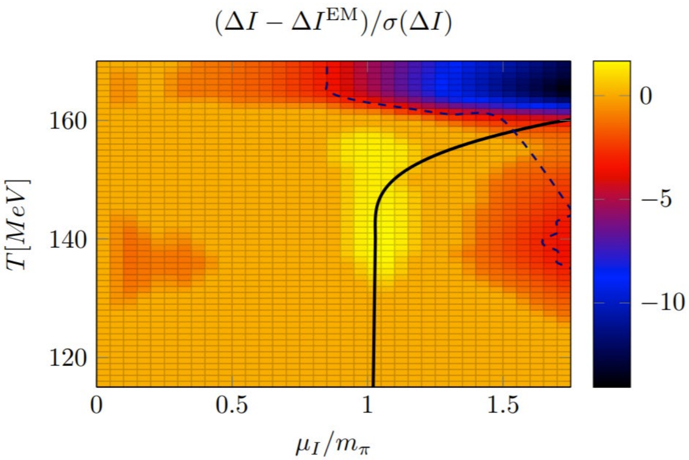
$$p_{\mathrm{QCD}}(T,\mu_B,\mu_Q) \approx \underbrace{\sum_{i\in\pi^\pm,\pi^0} p_i^{\mathrm{EM}}(T,\mu_i)}_{\textit{interacting pions}} + \underbrace{\sum_j p_j^{\mathrm{id}}(T,\mu_j)}_{\textit{free hadrons and resonances}}.$$

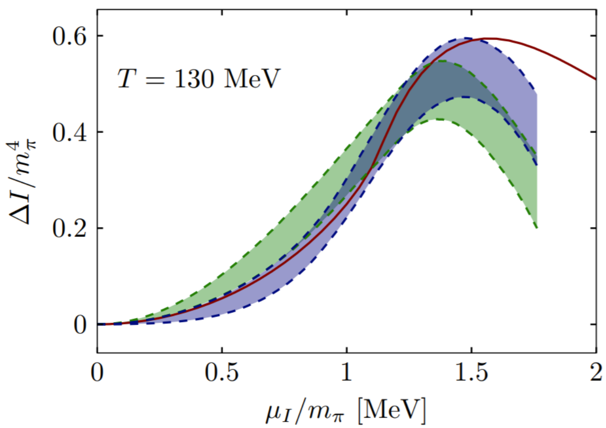
HRG model with pion interactions

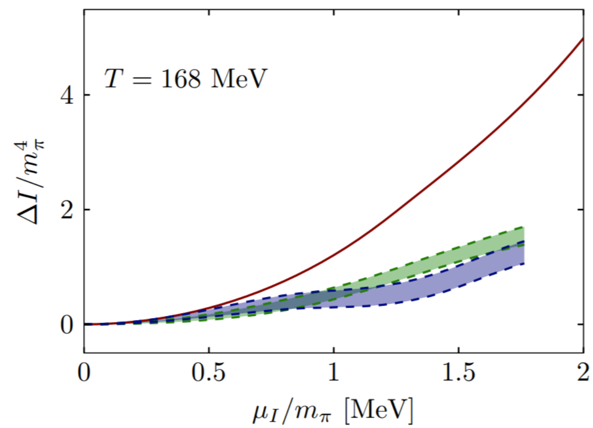
$$p_{\rm QCD}(T,\mu_B,\mu_Q) \approx \underbrace{\sum_{i\in\pi^\pm,\pi^0} p_i^{\rm EM}(T,\mu_i)}_{\text{interacting pions}} + \underbrace{\sum_j p_j^{\rm id}(T,\mu_j)}_{\text{free hadrons and resonances}}.$$

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

$$T \lesssim 160 \text{ MeV}, \quad \mu_I \lesssim 1.5\, m_\pi$$



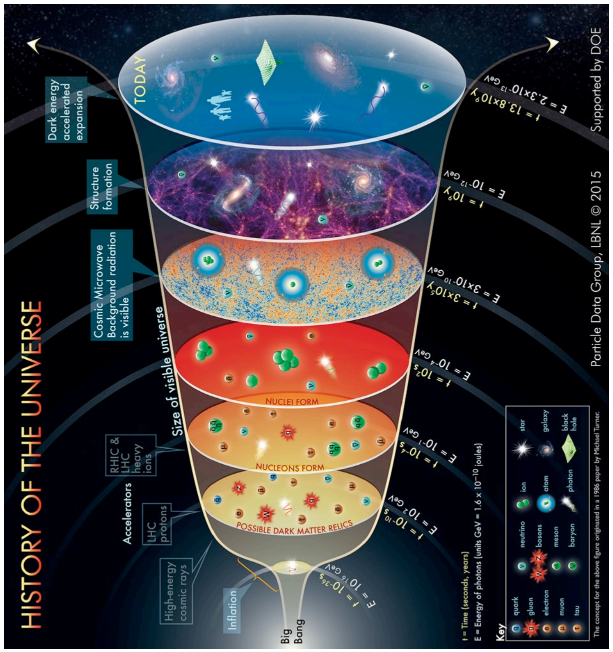




The lattice data and comparison details: VV, Brandt, Cuteri, Endrodi, Hajkarim, Schaffner-Bielich, 2009.02309

Calculating the cosmic trajectories

Early universe



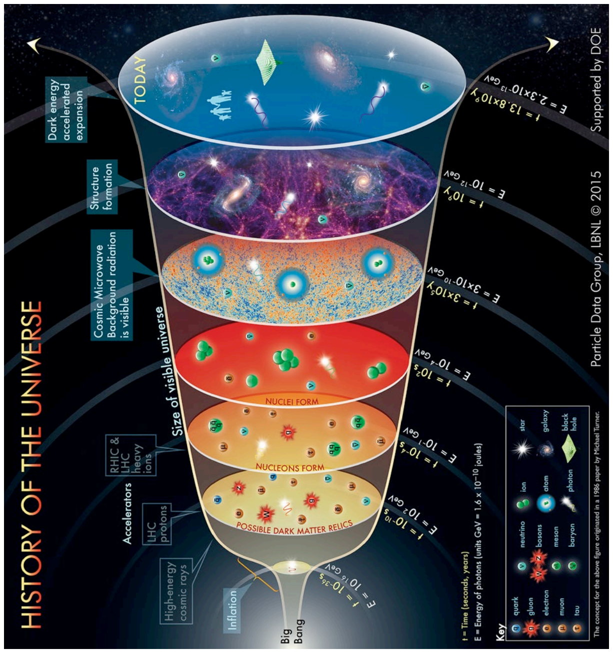
(c) PDG

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

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

Calculating the cosmic trajectories

Early universe

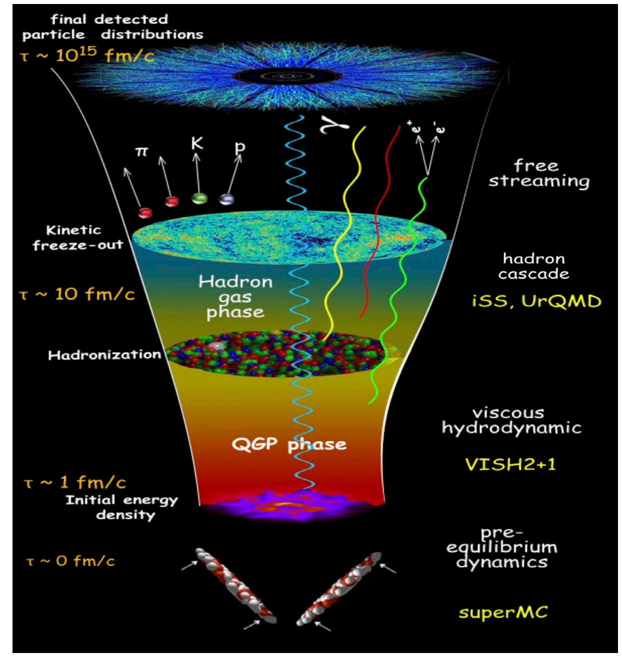


(c) PDG

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

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

Heavy-ion collision



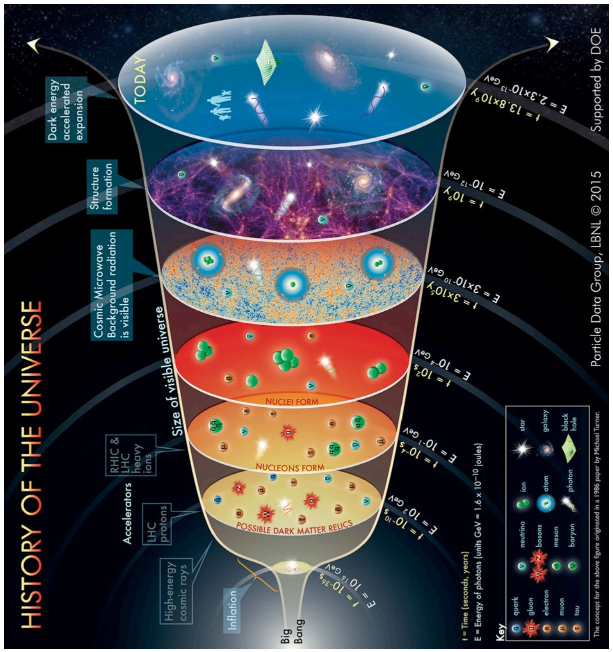
(c) (C. Shen, Ohio State U.)

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

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

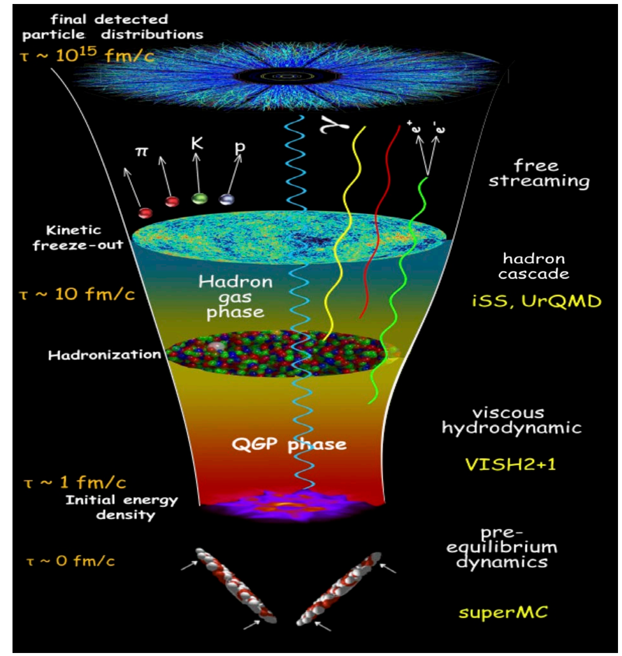
Calculating the cosmic trajectories

Early universe



(c) PDG

Heavy-ion collision



(c) (C. Shen, Ohio State U.)

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

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

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

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

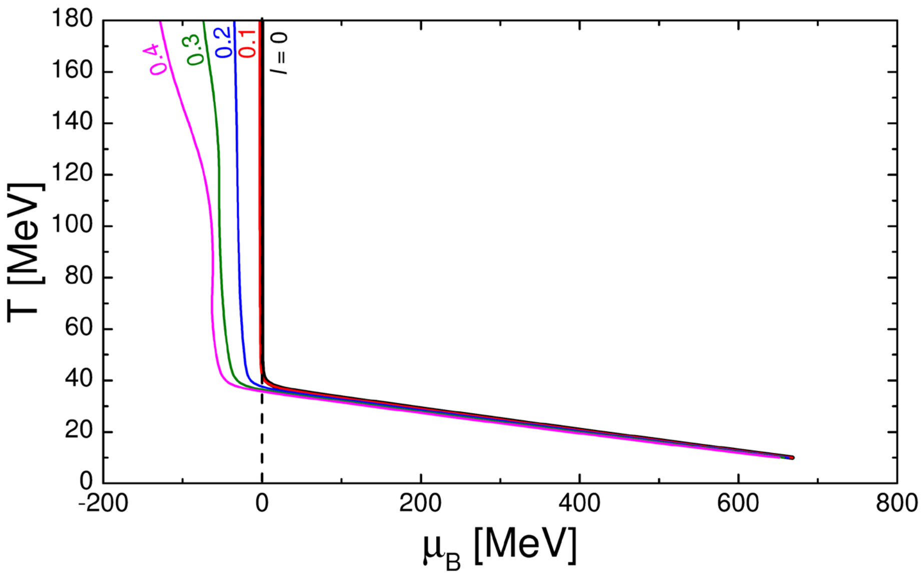
Cosmic trajectories implemented within (extended) **Thermal-FIST** package 

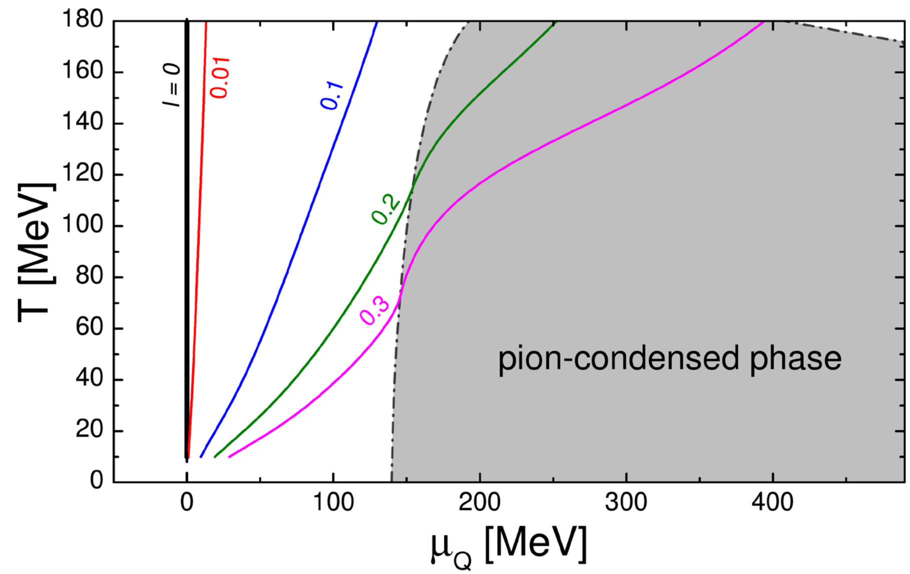
[**V.V.**, H. Stoecker, *Computer Physics Communications **244**, 295 (2019)*]

https://github.com/vlvovch/Thermal-FIST

Lepton-flavor symmetric case

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

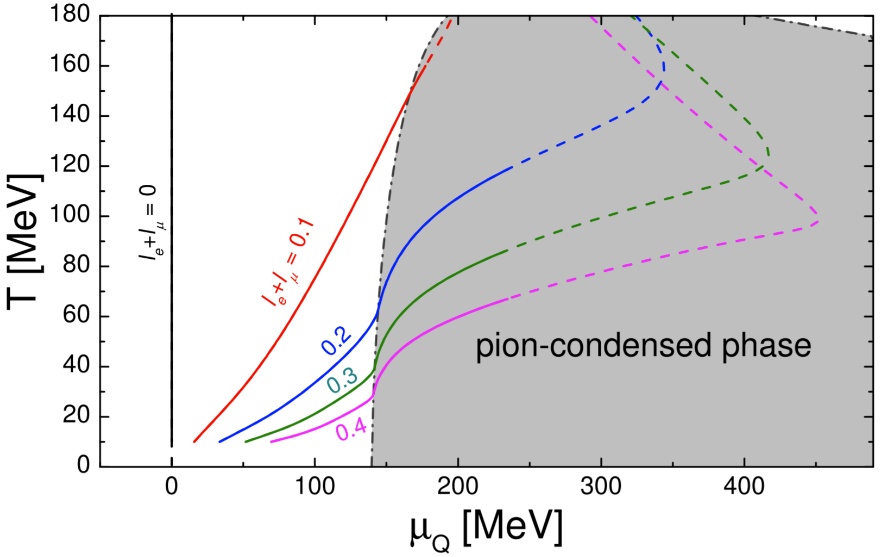


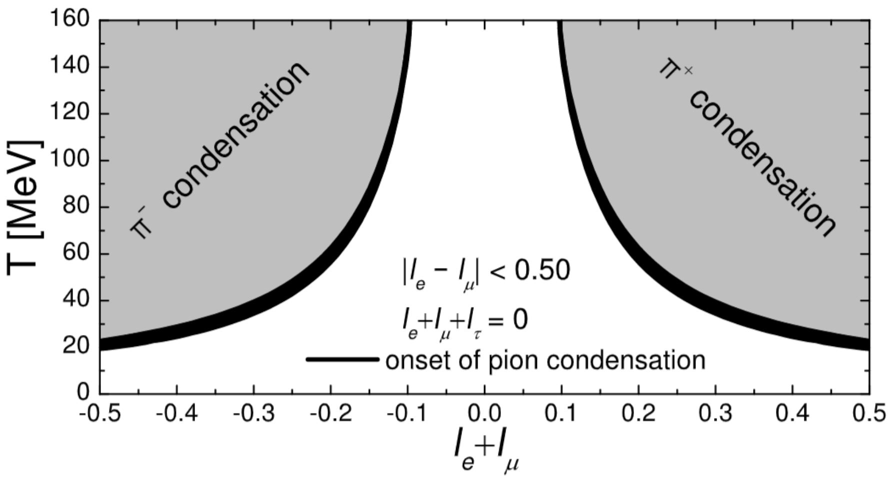


- Pion condensation in the symmetric scenario occurs if $|l| > \sim 0.15$
- However, this violates the empirical constraint $|l| < 0.012$

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

Lepton-flavor asymmetric case





- Individual lepton flavor asymmetries are much less constrained

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

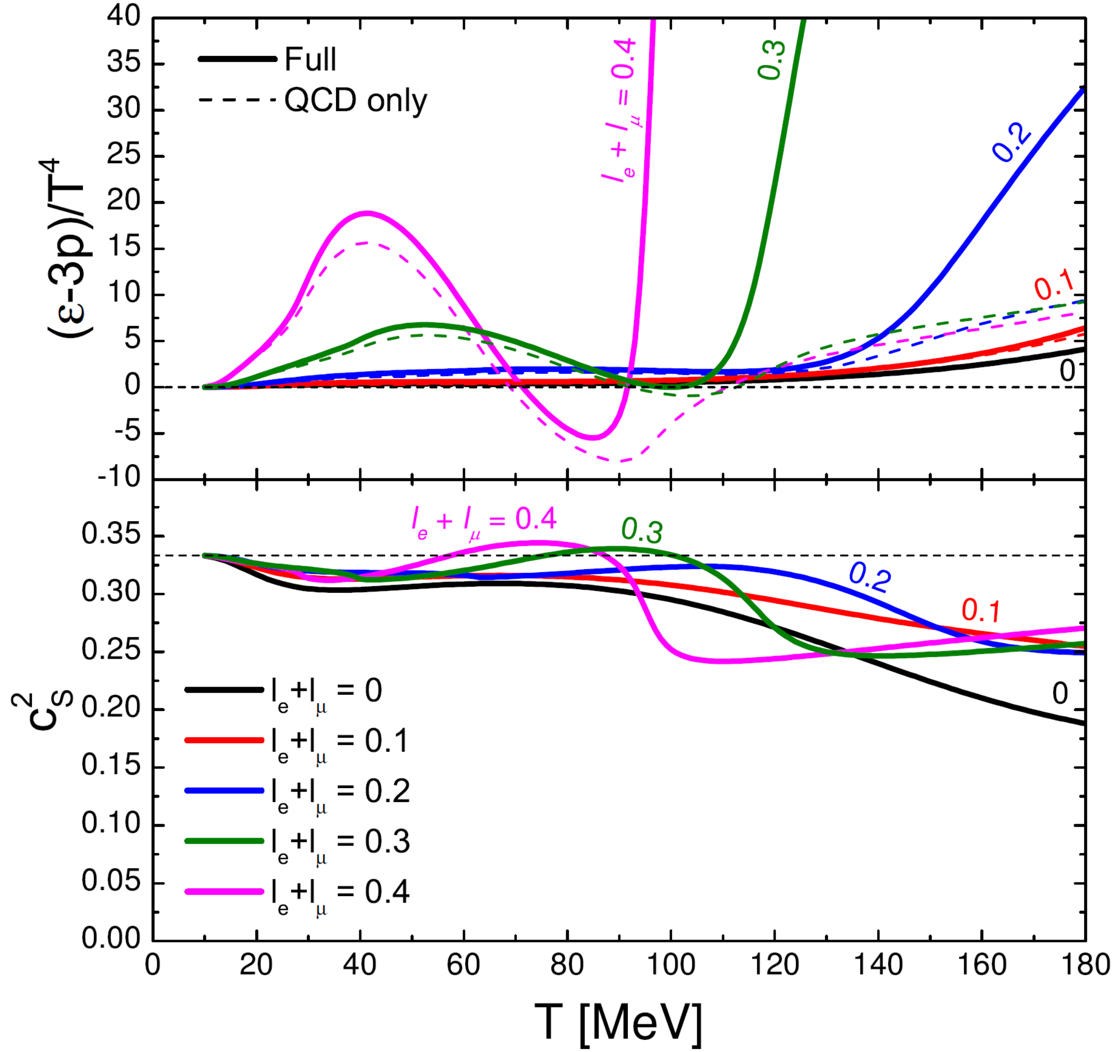
  $l_e + l_\mu + l_\tau = 0$ but $l_e \neq l_\mu \neq l_\tau$

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

Pion condensation occurs if

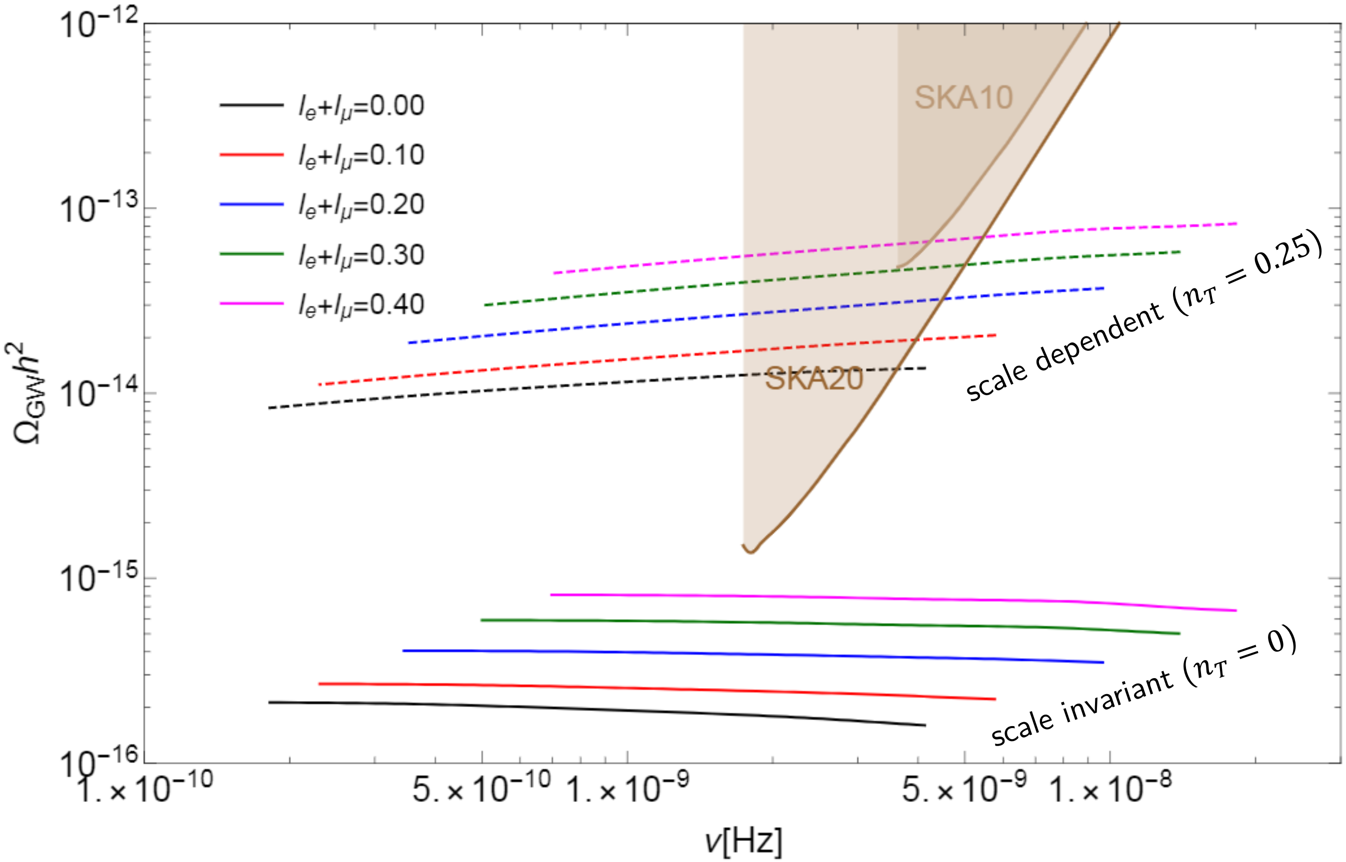
$$|l_e + l_\mu| \gtrsim 0.1$$

Lepton-flavor asymmetric case: Cosmic EoS



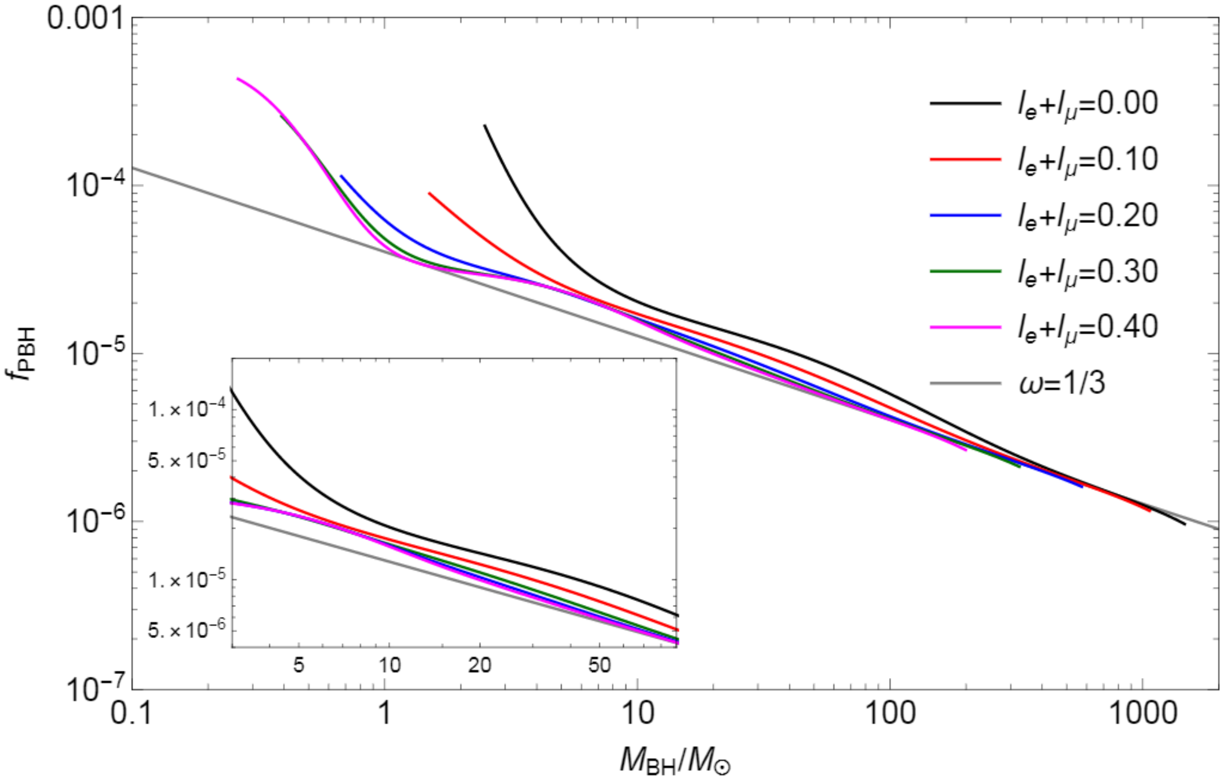
- Cosmic equation of state affected strongly by large lepton asymmetry
- Pion condensation leads to (nearly) negative interaction measure and $c_s^2 > 1/3$
- At higher temperatures large I/T^4 driven by heavy tau leptons

Primordial gravitational waves (PGW)



- Enhanced relic density of primordial gravitational waves (relative to amplitude at $l_e + l_\mu = 0$)
- Possibly reachable by SKA over 10-20 years of operation

Primordial black holes (PBHs)



- Changed fraction of primordial black holes heavier than solar mass
- Pion condensation epoch is a source of PBHs?
- Speculation: BHs merger event LIGO GW190521

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

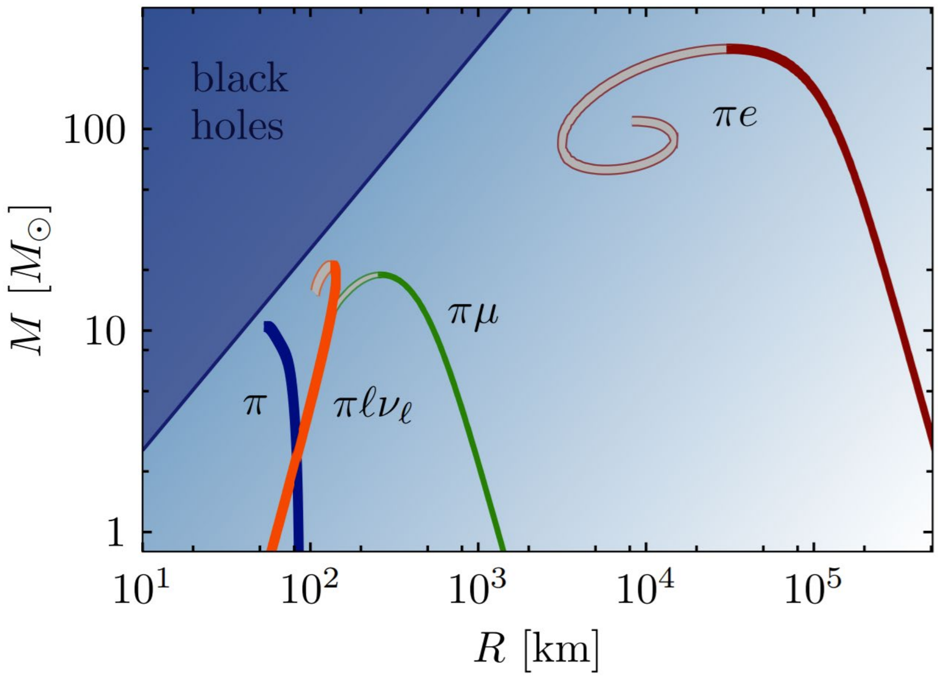


Figure from Brandt et al., 1802.06685

- If pion stars decay around the time of BBN, the produced high energy leptons would 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:**
  - 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

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:**
  - 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

Thank you!