The QCD Phase Diagram

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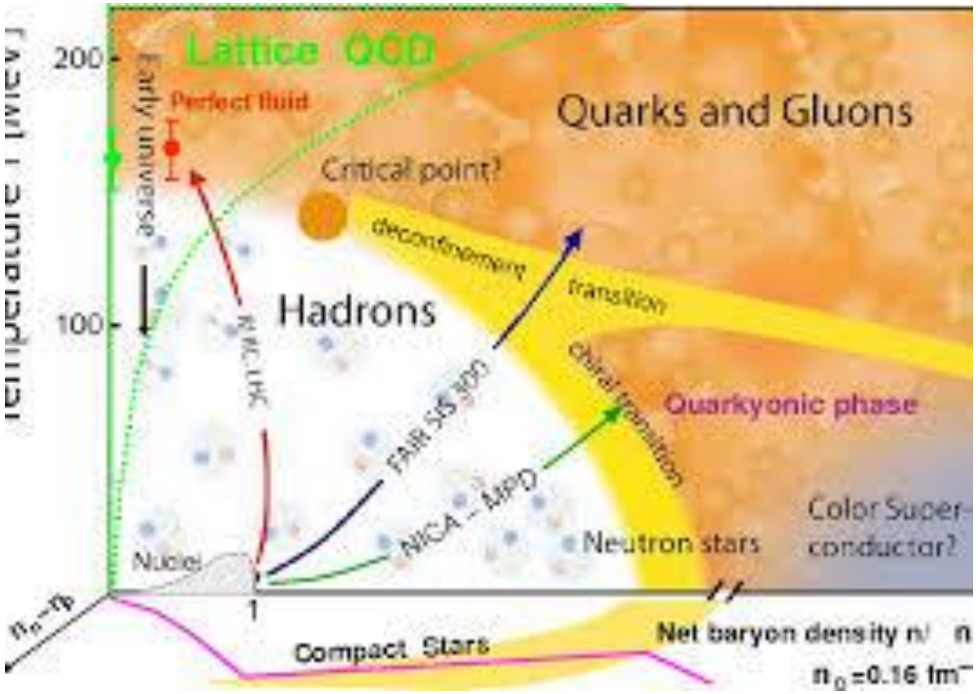
Outlook

- General features of the QCD Phase Diagram
- Different approaches
  - Lattice QCD
  - Functional Methods
  - Effective Models
  - Sum Rules, etc
- Physics interests of MPD Collaboration
- Theory Meets Experiment
- Final Remarks

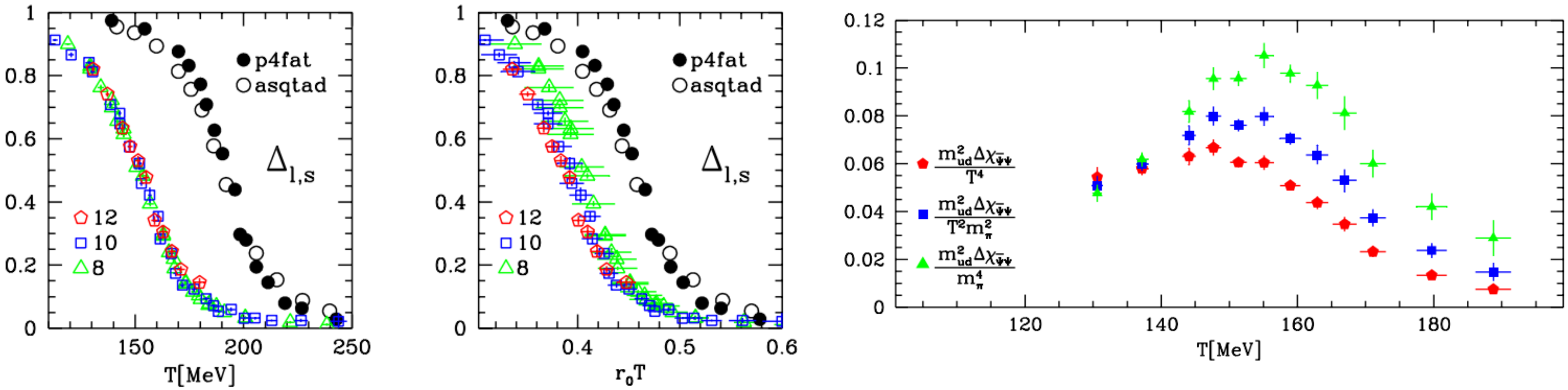
The QCD Phase Diagram



Adapted from J. Pawlowski's "Thermodynamics, Order Parameters & Dynamics "Lecture Notes

Different approaches

› Lattice Simulations
  – Chiral Condensate
  – Chiral Susceptibilities



Adapted from J. High Energy Phys. 2009

Different Approaches

› Functional Methods:

› Schwinger-Dyson equations

› Functional Renormalization Group

$$\langle \bar{\psi}\psi \rangle_f = -3 Z_2^f Z_m^f \sum_{\ell_k} \int \frac{d^3 \boldsymbol{k}}{(2\pi)^3} \mathrm{Tr}\left[S_f(k)\right]$$

Different Approaches

- Effecctive Models
- NJL Model (Angelo's talk)
- Sigma Model (Marcelo's talk)
- Many, many others (Rest of the talks)

Different Approaches

› Sum Rules

– Finite Energy Sum Rules

$$\frac{1}{\pi}\int_0^{s_0} ds\, K(s)\, \mathrm{Im}\,\Pi(s)|_{\mathrm{Had}} = \frac{-1}{2\pi i}\oint_{s_0} ds\, K(s)\, \Pi(s)|_{\mathrm{QCD}},$$

$$\Pi(q) = \not{q}\,\Pi_1(q^2) + \Pi_2(q^2).$$

$$\Pi_1(s) = -\frac{1}{64\pi^4}\, s^2 \ln(-s/\nu^2) - \frac{1}{32\pi^3}\langle\alpha_s G^2\rangle \ln(-s/\nu^2) - \frac{2}{3}\frac{\langle\bar{q}q\bar{q}q\rangle}{s} + C_8\frac{\langle\mathcal{O}_8\rangle}{s^2} + C_{10}\frac{\langle\mathcal{O}_{10}\rangle}{s^3} + \ldots, \quad (6)$$

$$\Pi_2(s) = \frac{1}{4\pi^2}\langle\bar{q}q\rangle s \ln(-s/\nu^2) - \frac{1}{12\pi}\frac{\langle\alpha_s G^2\,\bar{q}q\rangle}{s} + C_9'\frac{\langle\mathcal{O}_9\rangle}{s^2} + C_{11}'\frac{\langle\mathcal{O}_{11}\rangle}{s^3} + \ldots, \quad (7)$$

C. A. Dominguez, Quantum Chromodynamics Sum Rules, Springer Briefs in Physics (Springer International Publishing, Cham, 2018).

NICA

PROGRAM:

- Hadronic interactions and multiparticle production mechanisms at high barionic density abundances produced in Heavy Ion collisions
- Even by evento basis
- Global variables: Multiplicity and transverse energy
- Quark confinement
- Hadrons to partons
- Critical End Point

MPD Physics

› Hadron abundances produced in Heavy Ion collisions

  – Different regions of the pase diagram correspond to different collision energies

  – Below (and above) a threshold, hadronic multiplicity will be different

  – Sizable change in the hadronic freez-out pattern

MPD Physics

› Anisotropic Flow measurements

  – Strongly-coupled QGP

  – EoS, Sound velocity, viscosities

  – Fourier coefficients

MPD Physics

› Equation of State

  – First order transition characterized by a softening in the EoS

  – Dramatic dop of pressure

  – Strongly connected with anisotropic flow

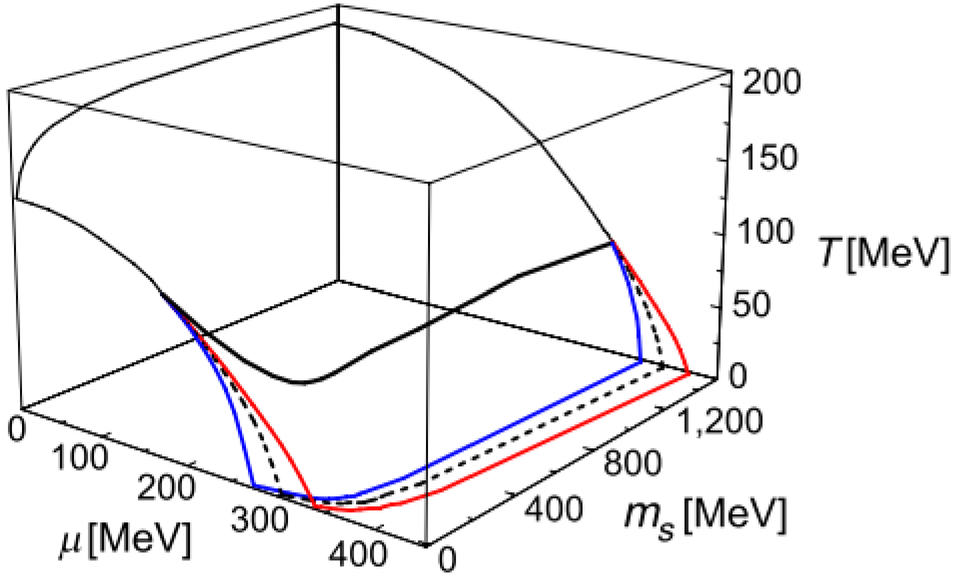
MPD Physics

› Femptoscopy: Pion interferometry

- Spatio-temporal dynamics of the evolution
- Two-pion measurements
- Pion interferometry varying with the collision energy

MPD Physics

› Strangeness
  – Deconfinement: Strangeness yield higher than that of hadron gas
  – Novel effect on the pase diagram: Second critical point



PRD88, 016008

Theory Meets Experiment (EoS)

Thermodynamics

$$\Omega(T,\mu) = -\frac{T}{V}\log \mathcal{Z}(T,\mu)$$

$$p(T,\mu) = -\big(\Omega(T,\mu) - \Omega(0,0)\big)\,,$$

$$s(T,\mu) = -\frac{\partial \Omega(T,\mu)}{\partial T}$$

$$n(T,\mu) = -\frac{\partial \Omega(T,\mu)}{\partial \mu}$$

$$\varepsilon(T,\mu) = Ts(T,\mu) + \mu n(T,\mu) - p(T,\mu)$$

$$I(T,\mu) = \varepsilon(T,\mu) - 3p(T,\mu)$$

Theory Meets Experiment (EoS)

$$\langle\bar{\psi}\psi\rangle(T,\mu;m) = \frac{\partial\Omega(T,\mu;m)}{\partial m}$$

$$\Omega(T,\mu;m_2) - \Omega(T,\mu;m_1) = \int_{m_1}^{m_2} \mathrm{d}m' \, \langle\bar{\psi}\psi\rangle(T,\mu;m') \, .$$

Not useful

$$s(T,\mu;m_2) - s(T,\mu;m_1) = -\int_{m_1}^{m_2} \mathrm{d}m' \, \frac{\partial\langle\bar{\psi}\psi\rangle}{\partial T}(T,\mu;m')$$

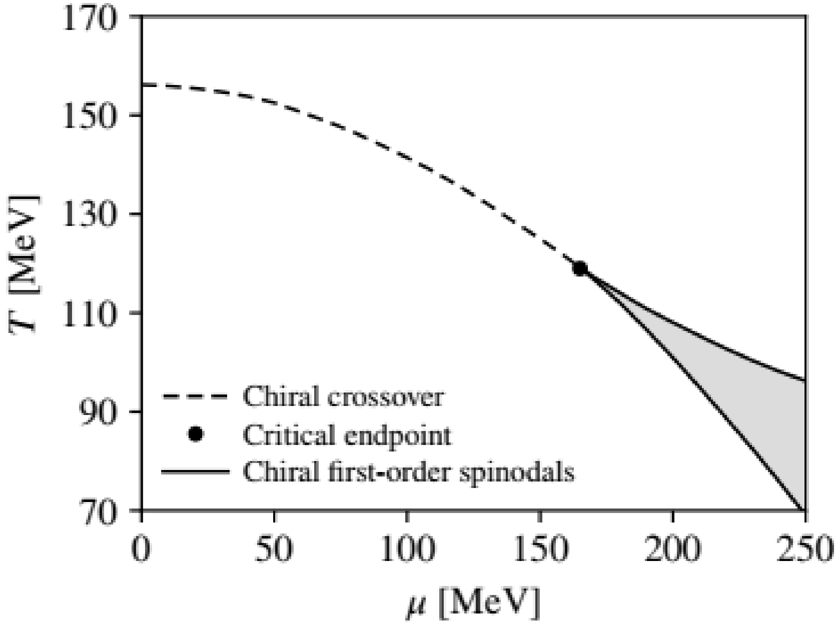
Divergence free

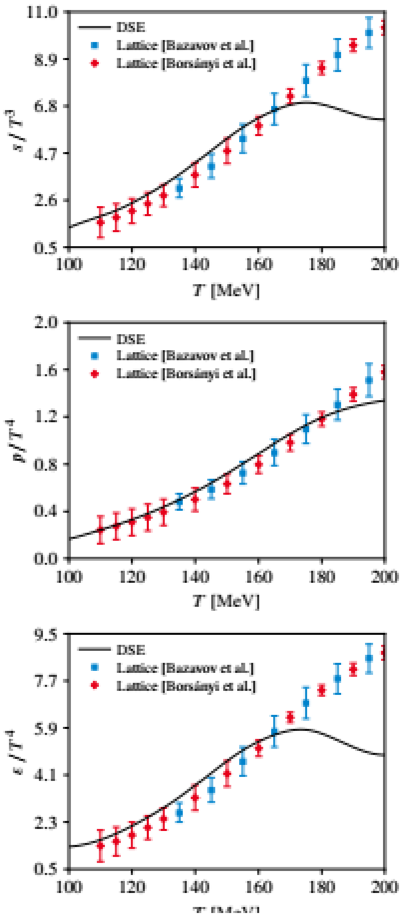
$$s(T,\mu;m) = s_{\mathrm{YM}}(T) + \int_{m}^{\infty} \mathrm{d}m' \, \frac{\partial\langle\bar{\psi}\psi\rangle}{\partial T}(T,\mu;m')$$

C. Fischer et al.arXiv:2012.04991

Theory Meets Experiment (EoS)

$$p(T,\mu) = p(T_0,0) + \int_{T_0}^{T} \mathrm{d}T'\, s(T',0) + \int_0^{\mu} \mathrm{d}\mu'\, n(T,\mu')\,.$$





C. Fischer et al.arXiv:2012.04991

Final Remarks

- It is possible to obtain thermodynamics information from theoretical quantities obtained in different frameworks
- This information is constrained by the observed EoS
- Physics com MPD would help to refine these approaches