QM 2019 highlights:

QCD matter at finite density

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Based on contributions:

- **QCD equation of state at finite densities for nuclear collisions**, *A. Monnai*
- **Universality driven analytic structure of QCD crossover: radius of convergence and QCD critical point**, *V. Skokov*
- **Towards a reliable lower limit on the location of critical endpoint**, *A. Pasztor*

Nuclear and Quark Matter Seminar **December 2, 2019**

QCD EoS at finite densities for nuclear collisions, A. Monnai

Monnai, Schenke, Shen, 1902.05095

Lattice QCD provides detailed
EoS in terms of Taylor series up to 4th order:

$$\frac{P}{T^4} = \frac{P_0}{T^4} + \sum_{l,m,n}^{B,Q,S} \frac{\chi_{l,m,n}^{B,Q,S}}{l!m!n!} \left(\frac{\mu_B}{T}\right)^l \left(\frac{\mu_Q}{T}\right)^m \left(\frac{\mu_S}{T}\right)^n$$

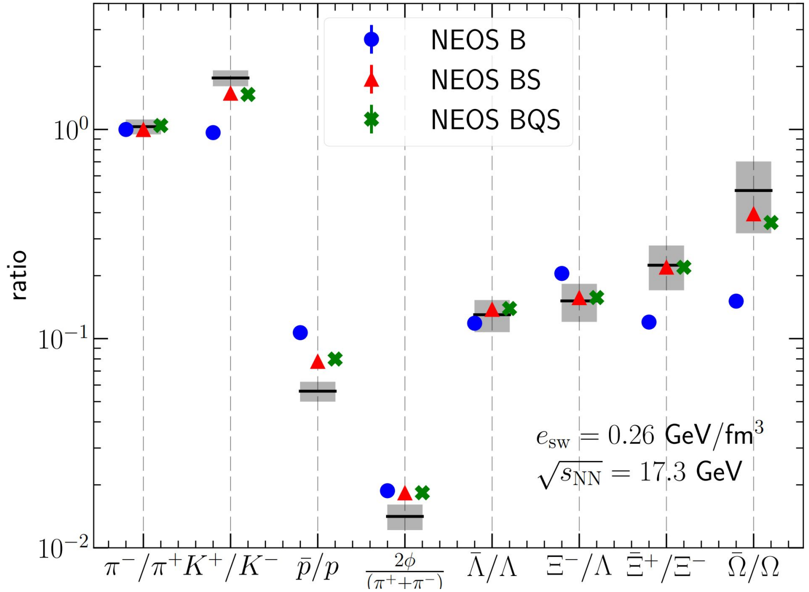
At lower T should be matched to HRG:

$$\frac{P}{T^4} = \frac{1}{2}[1 - f(T,\mu_J)]\frac{P_{\text{had}}(T,\mu_J)}{T^4} + \frac{1}{2}[1 + f(T,\mu_J)]\frac{P_{\text{lat}}(T,\mu_J)}{T^4}$$

Matching is incorporated by shmooth switching function:

$$f(T,\mu_J) = \tanh[(T - T_{pc}(\mu_B))/\Delta T_{pc}]$$

The tabulated EoS is available at:
https://sites.google.com/view/qcdneos/home



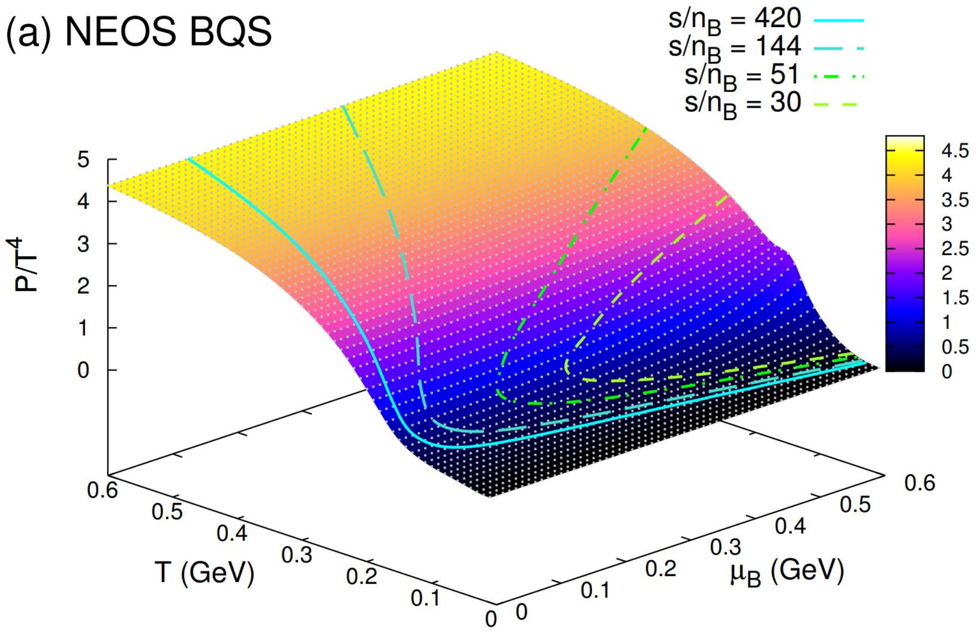
3+1D viscous hydro + UrQMD
for Pb-Pb 17.3 GeV in SPS

QCD EoS at finite densities for nuclear collisions, A. Monnai

Now we have almost **first-principle calculated EoS** that can be used for hydro simulations. The EoS was successfully used for heavy ion collisions at moderate energies, 17.3 GeV.

To which extent this EoS is reliable? The Taylor expansion has a **finite radius of convergence**…

Note also other models, e.g. based on Fourier expansion
Vovchenko et al., 1711.01261



EoS for strange-neutral matter with $n_Q = 0.4 n_B$

Analytic structure of QCD crossover: convergence radius, V. Skokov

Skokov, Mukherjee, 1909.04639

Radius of convergence — distance to the closest singularity of ***P/T⁴*** in the **complex μ_B/T plane**, could be QCD critical point.

Second order transition in **chiral limit** at μ_B=0, T_c=**132** MeV (*Ding et al., 1903.04801*).

Assume mass scaling of Thermodynamics in the vicinity of transition:

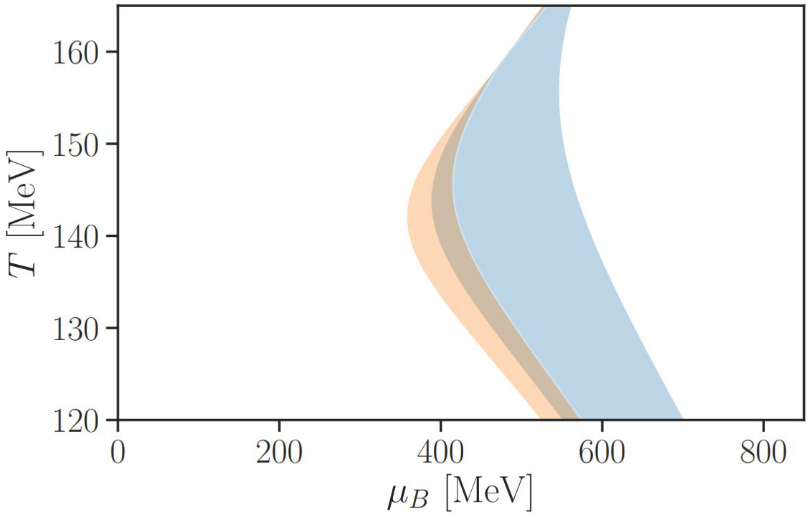
$$P = -\left(\frac{m_{u,d}}{m_s}\right)^{(2-\alpha)/\beta\delta} f_{\text{sing}}(z) - f_{\text{reg}}(T, \mu_B)$$

Scaling variable z is defined by critical line:

$$z = z_0 \left[\frac{T - T_c}{T_c} + \kappa_2^B \left(\frac{\mu_B}{T}\right)^2\right] \left(\frac{m_{u,d}}{m_s}\right)^{-1/\beta\delta}$$

For large $N\to\infty$ limit (close to O(4) universality)

$$z_c = \frac{5}{2^{8/5}} e^{i\frac{\pi}{5}}$$



Radius of convergence in μ_B for physical quark masses. The orange band is for z_0 = 2 and incorporates a 15% uncertainty on N → ∞ limit value of $|z_c|$. The blue band depicts variation of z_0 = 1 – 2.

Lower bound on the location of the critical endpoint, A. Pasztor

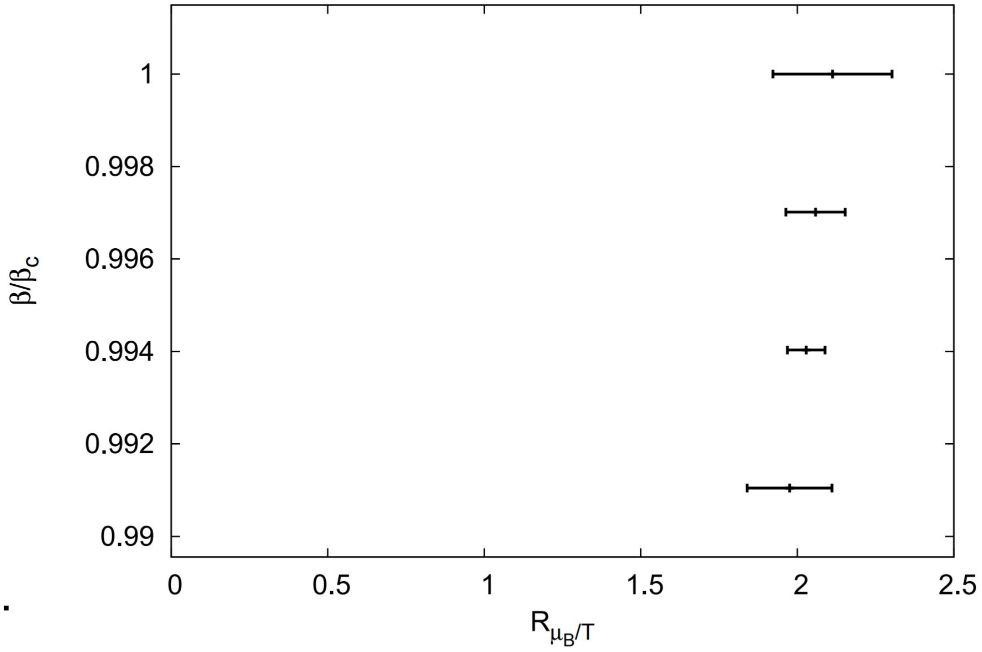
Giordano, Kapas, Katz, Nogradi, Pasztor , 1911.00043

Direct determination of the radius of convergence without relying on a finite order Taylor expansion.

Brute-force Lee-Yang polynomial was calculated as well as its roots.

Numerical results on N_t=4 lattices suggest a radius of convergence of $\mu_B/T \approx 2$ at and slightly below T_{pc}.

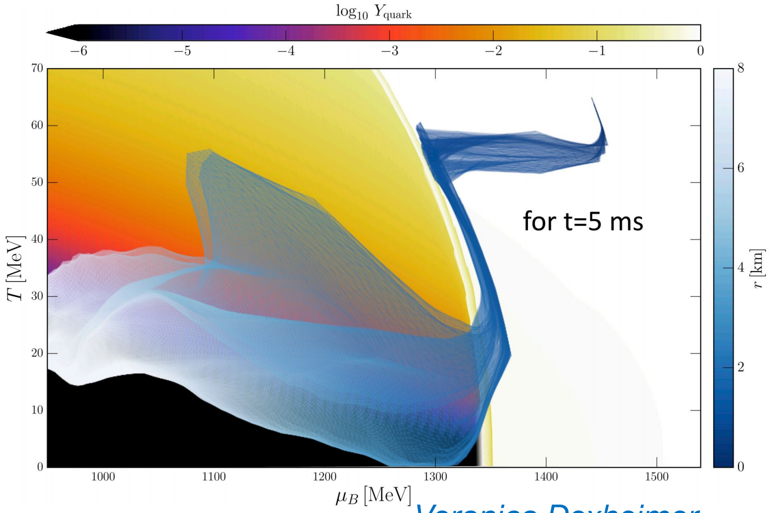
Hope to get soon data on a finer lattice...



Vertical — inverse temperature, **horizontal** — radius in μ_B/T

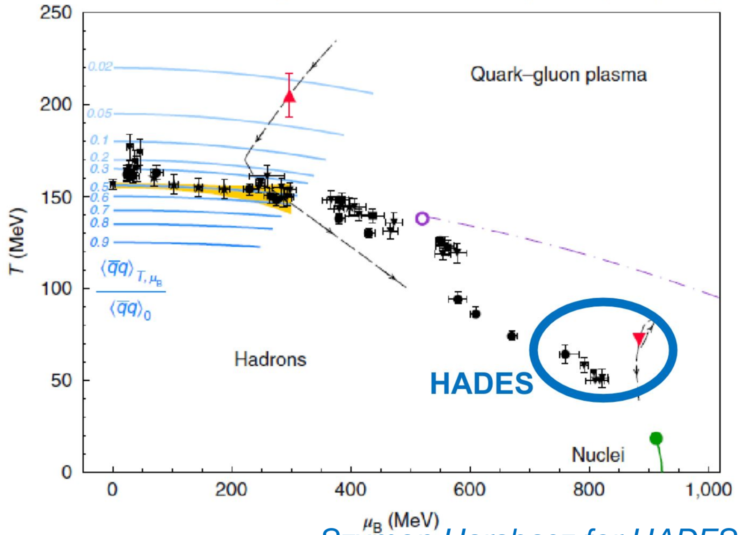
Summary

- Lattice QCD provides QCD thermodynamics close to μ_B=0 and up to $\mu_B/T \approx$ 2-3.
  lQCD EoS is useful for high energy HIC, other physics may be relevant at low energies.
- Estimations of radius of convergence suggest validity of the EoS up to $\mu_B/T \approx$ 2-3.
- At $\mu_B/T \approx$ 2-3 Taylor series breaks. **Critical point** or **singularities in complex plane**?..
- Other theoretical approaches for high baryon density matter are needed:
  Can be tested at HADES, FAIR, and in neutron stars.



Veronica Dexheimer

[HADES Collab., Nature Physics 15 (2019) 1040]



Szymon Harabasz for HADES