Vortical QGP fluid near critical point

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Talk based on EPJC (2023) 83:585

Florence Theory Group Day

March 25, 2024

Structure of Matter

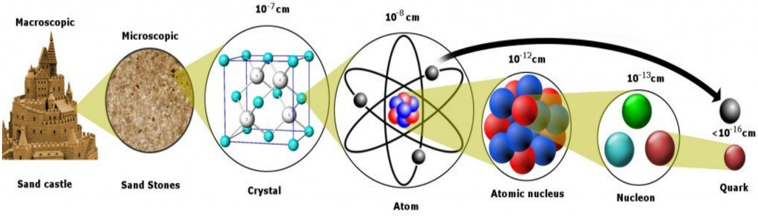
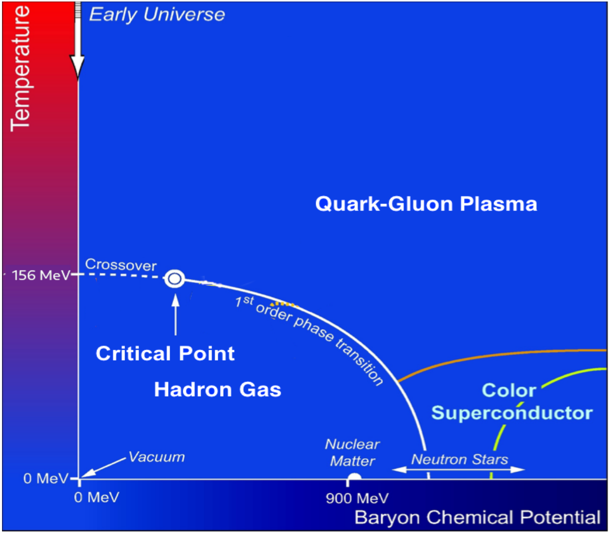


Image Source : www.educatingphysics.com

Quantum chromodynamics (QCD)

- Quantum chromodynamics is the theory of interactions between quarks mediated by gluons, somewhat similar to how electrons interact through photons.
- Gluons possess the "color" charge and interact among themselves making QCD rich and complex.
- For energy scales $\gg 1$ GeV, perturbative methods can be used.
- For scales ~ 1 GeV, the theory becomes non-perturbative. Lattice QCD is currently the only known way of solving QCD for such scales.
- Lattice QCD computations are limited to baryon chemical potential (μ_B) close to 0 due to numerical sign problem.
- Mapping the QCD phase diagram is theoretically challenging.

Conjectured phase diagram of QCD

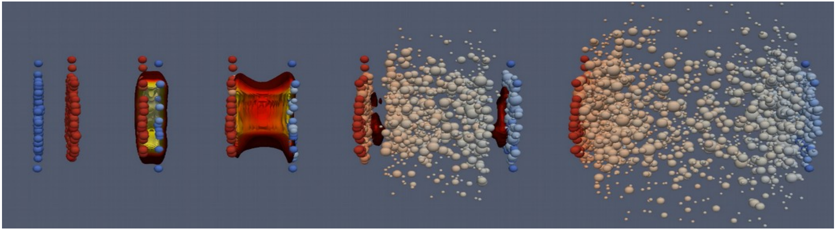


QGP in laboratory

- To create QGP in laboratory : heat up the matter to temperatures $\sim 10^{12}$ K or compress it to densities $\sim 10^{15}$ g/cm^3.
- Possible by smashing together heavy-ions like Gold (Au), Lead (Pb) at ultra relativistic energies.
- Two largest experimental facilities are Large Hadron Collider (LHC) with a circumference of about 27 km and Relativistic Heavy Ion Collider (RHIC) with a circumference of about 3.8 km.
- The maximum center-of-mass collision energy ($\sqrt{s_{NN}}$) at RHIC is 200 GeV per nucleon pair. Remember mass of proton is about 1 GeV.

QGP in laboratory

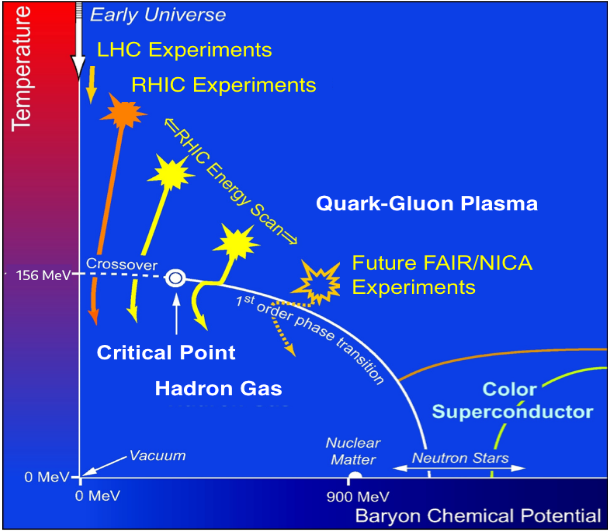
Locally equilibrated droplet of QGP expands and breaks down into a multitude of hadrons. The detectors collect information on number, energy and momentum distributions of final state hadrons.



$\sim 10^{-23}$ s

Image Source : MADAI collaboration, Hannah Petersen and Jonah Bernhard

Mapping the phase diagram through HICs



Observables for Locating the QCD Critical Point

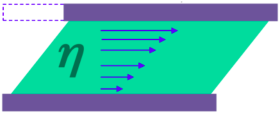
- A critical point is characterized by diverging correlation length ($\xi \to \infty$) indicating that fluctuations in the system occur on all length scales.

- Fluctuations of conserved quantities, such as baryon, electric charge and strangeness number must grow near critical point. Hence, measure fluctuations in net-proton ($N_p - N_p$), net-charge ($N_q - N_{\bar{q}}$), and net-kaons ($N_K - N_{\bar{K}}$).

- Two strategies:
  a) Energy scan, expect non-monotonic behavior : vary collision energy ($\sqrt{s_{NN}}$).
  b) Rapidity scan, expect qualitative change : vary rapidity for the same $\sqrt{s_{NN}}$. Rapidity is defined as $y = \frac{1}{2}\log\left(\frac{E+p_z}{E-p_z}\right)$.

Dynamic critical phenomena

- What is the behavior of non-equilibrium systems near a critical point ?
- A few examples of dynamic universality classes are
  a) Model A: non-conserved order parameter
  b) Model B: conserved order parameter
  c) Model C: non-conserved order parameter coupled to conserved slow variable with no mode coupling
  d) Model H: non-conserved order parameter coupled to conserved slow variable with mode coupling
- The dynamical universality class of the QCD critical point is Model H. (PRD 70 (2004) 056001)
- In model H: $\zeta \sim \xi^{z-\alpha/\nu}$, $\eta \sim \xi^{x_\eta}$, $\tau \sim \xi^{z}$. ($z \approx 3$, $x_\eta \approx 0.05$ for QCD)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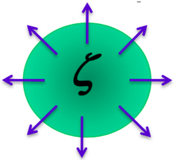
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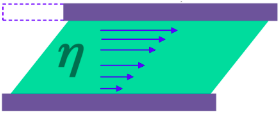
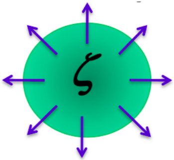
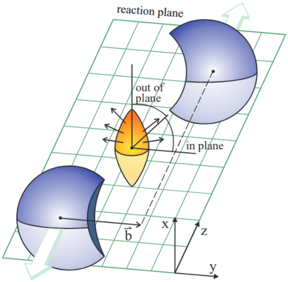




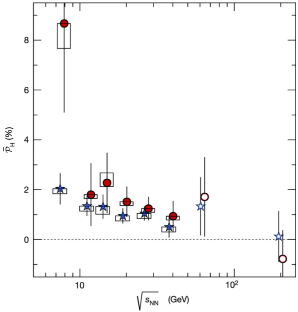
A new indicator for the critical point ?

Rapidity profile of the slope of spin polarization

Spinning into Focus



arXiv:0910.4114



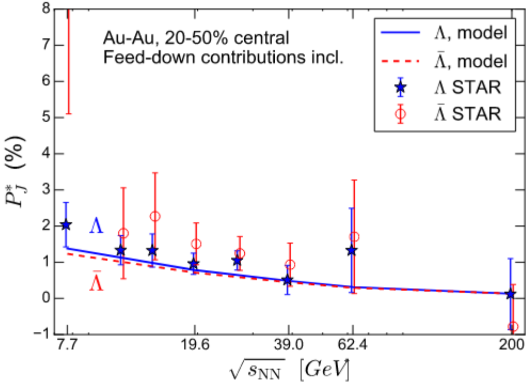
Nature 548, 62-65 (2017)

The spin polarization vector in the rest frame of a hyperon is

$$\vec{S}^*(x,p) \propto \frac{\gamma}{T^2}\vec{v} \times \nabla T + \frac{1}{T}\left(\vec{\omega} - (\vec{\omega}\cdot\vec{v})\vec{v}\right) + \frac{1}{T}\gamma\vec{A} \times \vec{v}$$

F. Becattini and M. A. Lisa, Ann. Rev. Nucl. Part. Sci. 70 (2020) 395

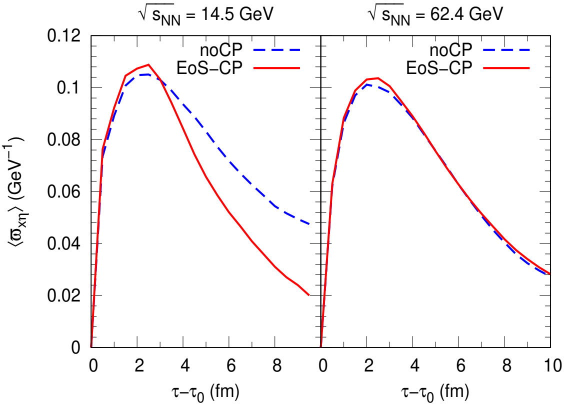
Hydrodynamic description of global spin polarization



I. Karpenko and F. Becattini, Nuc. Phys. A 967 (2017) 764-767

Effect of critical point on thermal vorticity

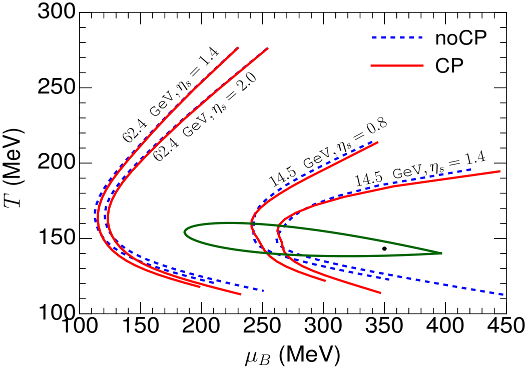
- Thermal vorticity, $\varpi_{\mu\nu} = \frac{1}{2}[\partial_\nu(\beta u_\mu) - \partial_\mu(\beta u_\nu)]$, gets suppressed at late times when we are closer to the critical point.



SKS and J. Alam, EPJC (2023) 83:585

Hydrodynamic trajectories in phase diagram

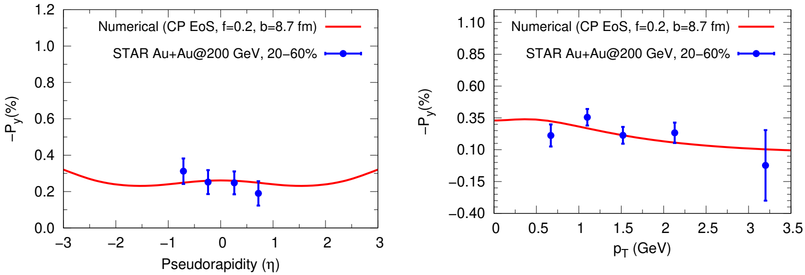
Trajectories of fluid cells at $x = y = 0$ and different space-time rapidities, η_s, for collision energies, $\sqrt{s_{NN}} = 14.5$ and 62.4 GeV.



$$\eta_s = \frac{1}{2}\log\left(\frac{t+z}{t-z}\right)$$

SKS and J. Alam, PRD 107, 074042 (2023)

Comparison with experimental data at $\sqrt{s_{NN}} = 200$ GeV



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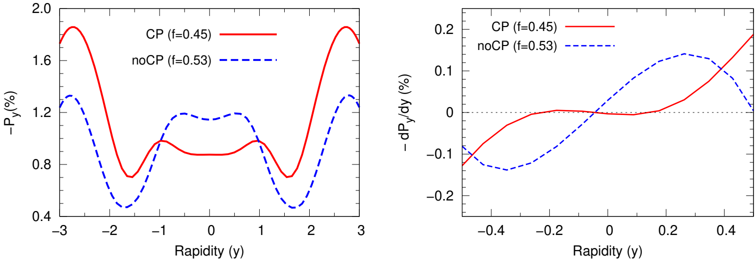
Prediction near critical point

- A qualitative change in the behavior of rapidity profile observed near CP.



SKS and J. Alam, EPJC (2023) 83:585

- Other bulk observables like momentum spectra etc. are not much affected due to the CP.

Summary

- We study the effect of QCD critical point on vorticity.
- We observe a suppression in thermal vorticity and hence, spin polarization of Λ-hyperons, as the CP is approached.
- We propose the qualitative change in the rapidity distribution of spin polarization as an indicator for the critical point.
- Questions needed to be investigated:
  a) Effect of critical fluctuations on hydrodynamics.
  b) Dependence on the location of critical point and on the size of critical region.
  c) Sensitivity towards initial condition.
  d) Effect of resonance decays.

Thank You !!!