Effects of enhanced bulk viscosity near the QCD critical point

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In collaboration with: Swagato Mukherjee (BNL) and Yi Yin (MIT)

AM, S. Mukherjee and Y. Yin, arXiv:1606.00771

Quark Matter 2017

8th February 2017, Chicago, USA

Introduction

- Beam energy scan program: exploration of QCD phase diagram

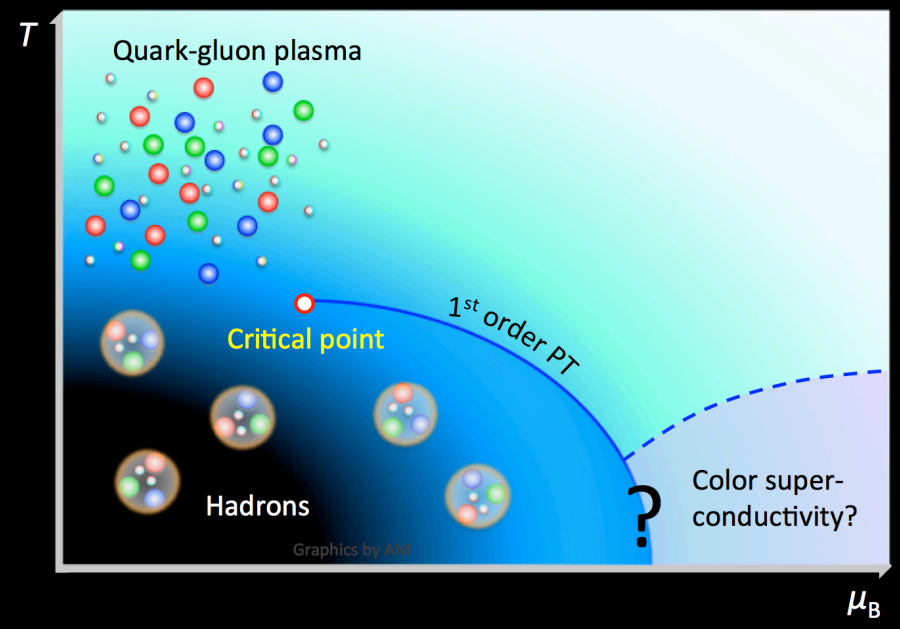
- Performed and planned at

  ✓ RHIC (BNL)

  Phase I (2009-11): 7.7-62.4 GeV

  Phase II (2018-19?): 3.0- GeV?

  ✓ HADES, FAIR (GSI), SPS (CERN), NICA (JINR), J-PARC etc.

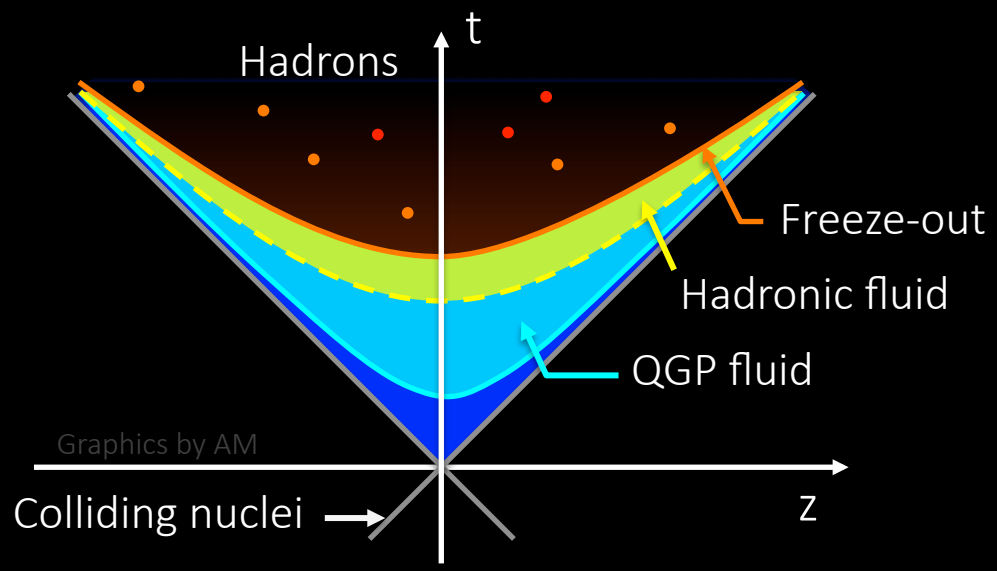


- Big goals are to

  - Verify the existence of a QCD critical point (QCP)
  - Determine the QGP properties at finite T, μ_B

Introduction

- A standard model of heavy-ion collisions



Hadronic transport (> 10 fm/c)

Freeze-out

Hydrodynamic stage (~1-10 fm/c)

Equilibration

Glasma (~0-1 fm/c)

Little bang

Color glass condensate (< 0 fm/c)

Introduction

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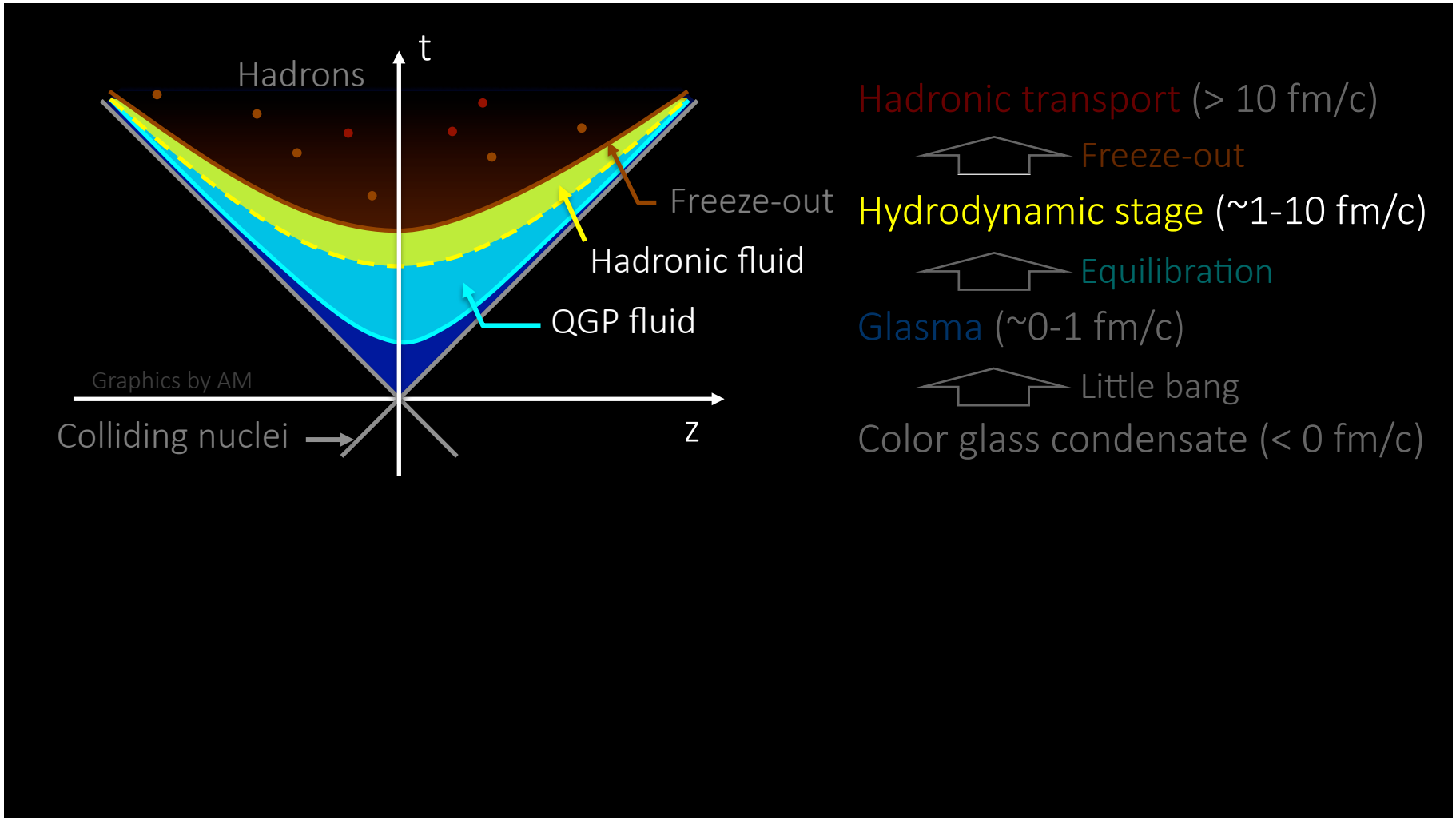

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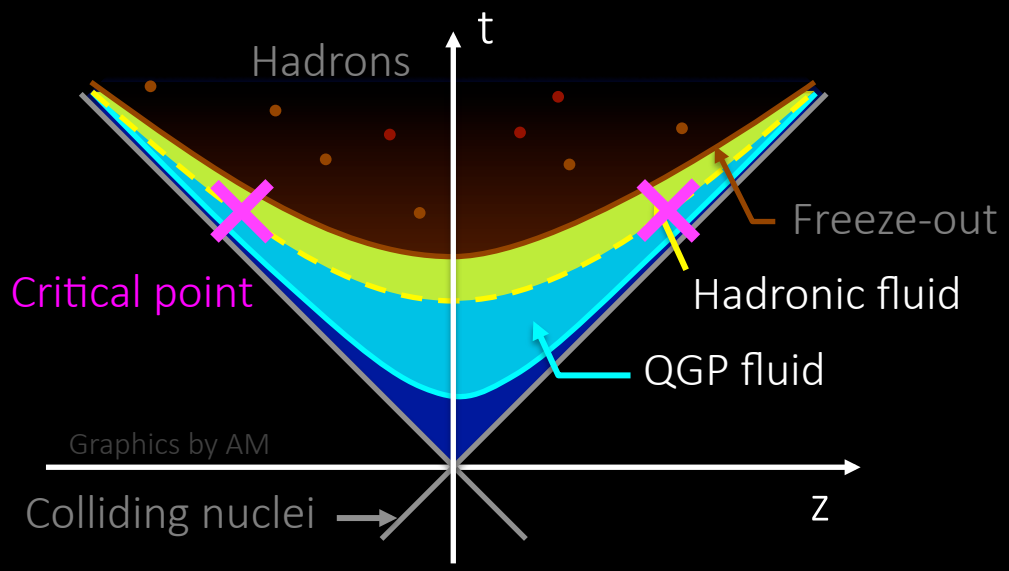

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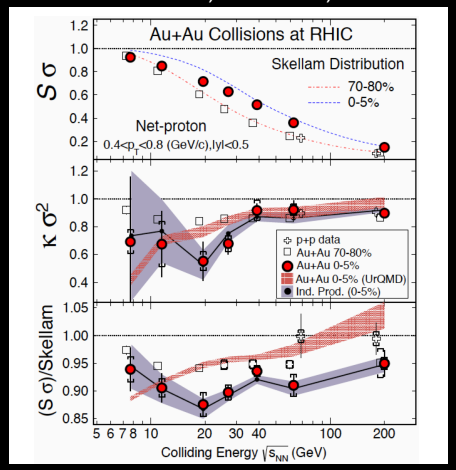
Motivation of this talk

- IF there is a critical point, what kind of signals would we have?

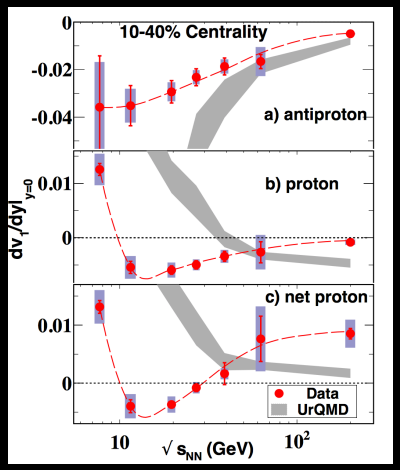
Introduction

- What observables are sensitive to a QCP?

STAR, PRL 112, 032302



STAR, PRL 108, 202301



- Proposed so far:

  - Event-by-event fluctuation of multiplicities

  - Rapidity slope of directed flow v_1

  etc.

- We consider the effects of a QCP on bulk evolution by looking at:

✓ Rapidity distributions of charged particles and net baryon number

(and spectra of electromagnetic probes)

Bulk evolution

- Relativistic hydrodynamic equations

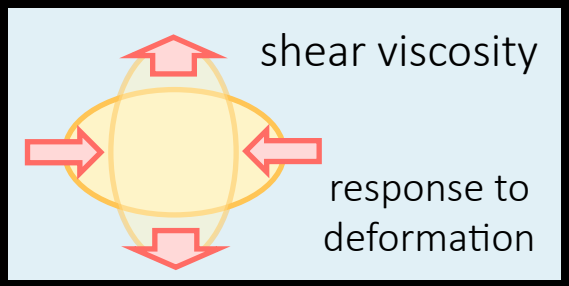
Energy-momentum conservation	$\partial_\mu T^{\mu\nu} = 0$
Baryon conservation	$\partial_\mu N_B^\mu = 0$

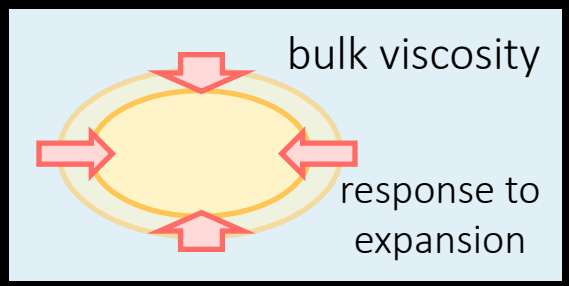
\+

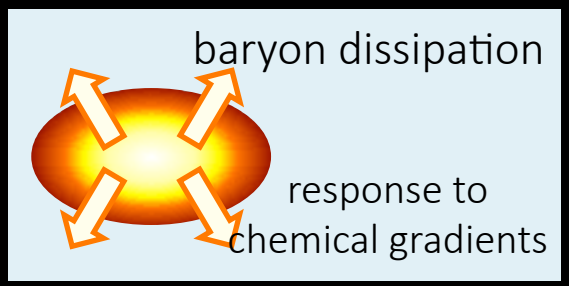
Equation of state	$P = P(e, n_B)$

Shear viscosity	$D\pi^{\langle\mu\nu\rangle} = -\frac{1}{\tau_\pi}[\pi^{\mu\nu} - 2\eta\nabla^{\langle\mu}u^{\nu\rangle}]$
Bulk viscosity	$D\Pi = -\frac{1}{\tau_\Pi}[\Pi + \zeta\nabla_\mu u^\mu]$
Baryon diffusion	$\Delta^\mu{}_\nu DV_B^\nu = -\frac{1}{\tau_{V_B}}[V_B^\mu - \kappa_{V_B}\nabla^\mu\frac{\mu_B}{T}]$

Constitutive equations







Near the critical point

- Bulk viscosity becomes dominant

- Shear viscosity: $\eta = \xi^{(4-d)/19}$ ξ : correlation length

  Bulk viscosity: $\zeta = \xi^3$

  Baryon diffusion: $D_B = \xi^{-1}$

⇨ We focus on bulk viscosity in this study

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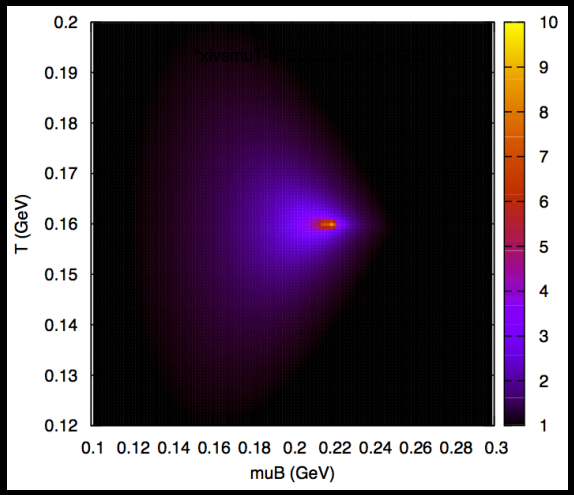
- Parameterization for bulk viscosity

$$\zeta = \zeta_0 \left(\frac{\xi}{\xi_0} \right)^3$$

where $\zeta_0 = 2\left(\frac{1}{3} - c_s^2\right)\frac{e+P}{4\pi T}$

A. Buchel, PLB 663, 286 (2008)

ξ is parameterized based on Ising model



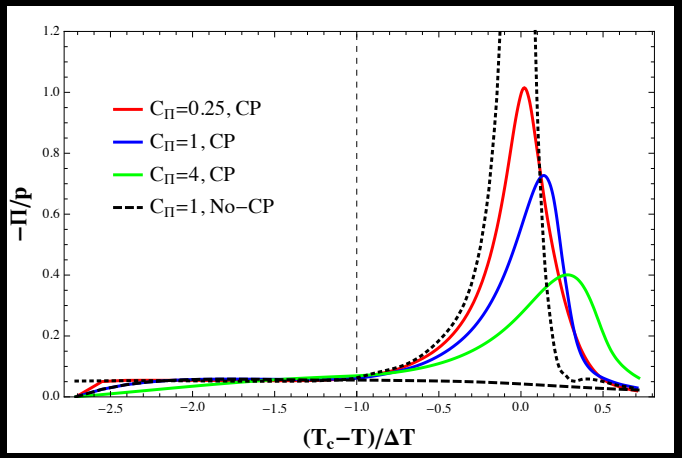
Near the critical point

- Bulk viscosity becomes dominant

- Relaxation time

$$\tau_\Pi = \tau_{\Pi,0}\left(\frac{\xi}{\xi_0}\right)^3$$ as causality demands

$$\lim_{k\to\infty}\frac{d\omega}{dk} = \sqrt{c_s^2 + \frac{\zeta}{\tau_\Pi(e+P)}} < 1$$



- Causal hydro is applicable when Π is "frozen" at large τ_Π

- The relaxation time from a holographic approach

$$\tau_{\Pi,0} = C_\Pi \frac{18 - (9\ln 3 - \sqrt{3}\pi)}{24\pi T} \quad (C_\Pi = 1)$$

M. Natsuume and T. Okamura, PRD 77, 066014

is free of cavitation ($P + \Pi > 0$)

Equation of state

- Hadron resonance gas + lattice QCD AM and B. Schenke, Phys. Lett. B **752**, 317 (2016)

- Lattice: Taylor expansion up to the 4th order

HotQCD, PRD 86, 034509 (2012), PRD 90, 094503 (2014), PRD 92, 074043 (2015)

$$\frac{P_{\rm lat}}{T^4} = \frac{P_0}{T^4} + \frac{1}{2}\chi_B^{(2)}\left(\frac{\mu_B}{T}\right)^2 + \frac{1}{4!}\chi_B^{(4)}\left(\frac{\mu_B}{T}\right)^4 + \mathcal{O}\left(\frac{\mu_B}{T}\right)^6$$

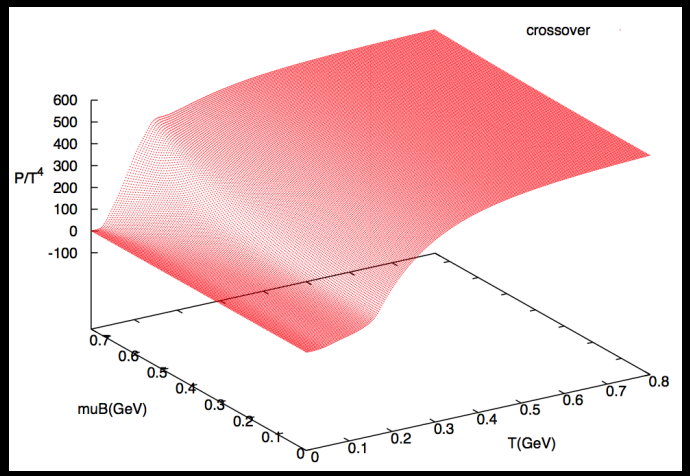
- Connect to HRG at low T:

$$\frac{P}{T^4} = \frac{1}{2}\left[1 - \tanh\frac{T - T_c(\mu_B)}{\Delta T_c}\right]\frac{P_{\rm HRS}(T)}{T^4} + \frac{1}{2}\left[1 + \tanh\frac{T - T_c(\mu_B)}{\Delta T_c}\right]\frac{P_{\rm lat}(T_s)}{T_s^4}$$

where

$$T_c = 0.166 - 0.4 \times (0.139\mu_B^2 + 0.053\mu_B^4)$$

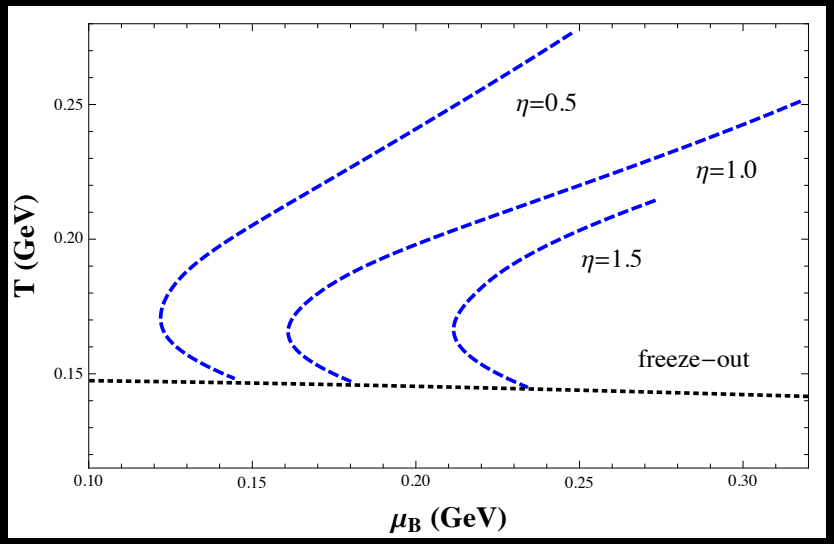
$$T_s = T + 0.4 \times [T_c(0) - T_c(\mu_B)]$$

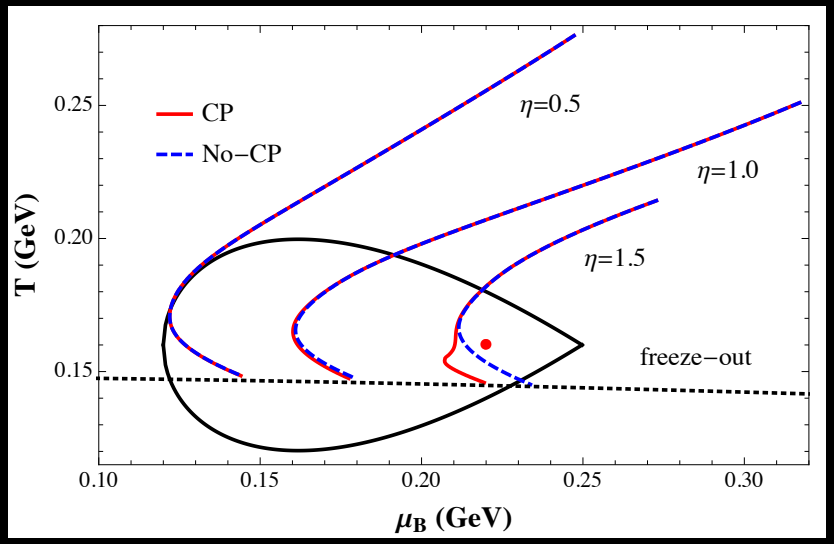


*Currently no QCP; effects of 1st order phase transition may not be dramatic

Trajectories on μ_B-T plane

- Hydrodynamic model estimation: non-boost invariant 1+1 D

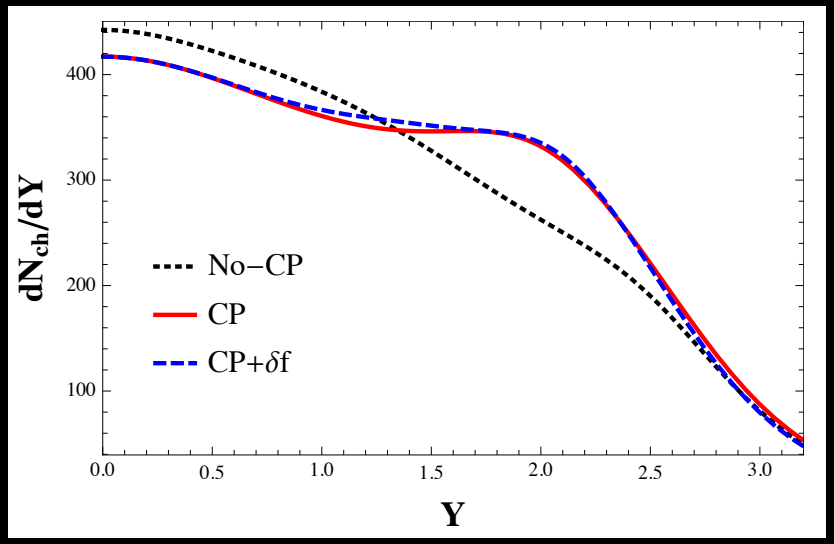


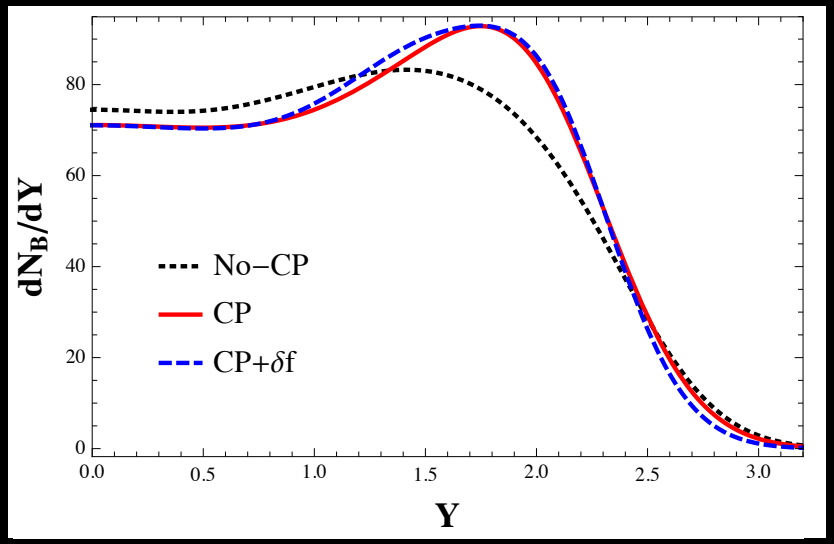


- A critical point is placed by hand at (μ_B, T) = (0.22 GeV, 0.16 GeV) by mapping the critical region of Ising model onto the μ_B-T plane
- The trajectory is pushed away from it on the lower μ_B side near the critical point

Rapidity distributions

- Hydrodynamic model estimation: non-boost invariant 1+1 D



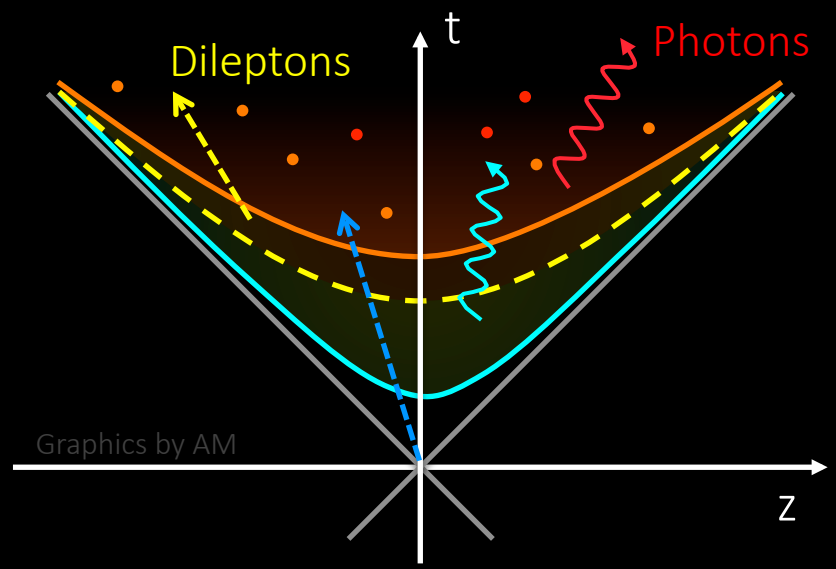


- Initial conditions are extrapolated CGC adjusted to Pb-Pb at 17 GeV
- dN_{ch}/dy is affected by entropy production and enhanced convection by the reduction in effective pressure $P + \Pi$
- dN_B/dy is by flow convection only

Electromagnetic probes

- Can they be sensitive to the QCP?

AM, S. Mukherjee, Y. Yin, in preparation



- The QGP is EM transparent

Photons and dileptons know the history of the time evolution

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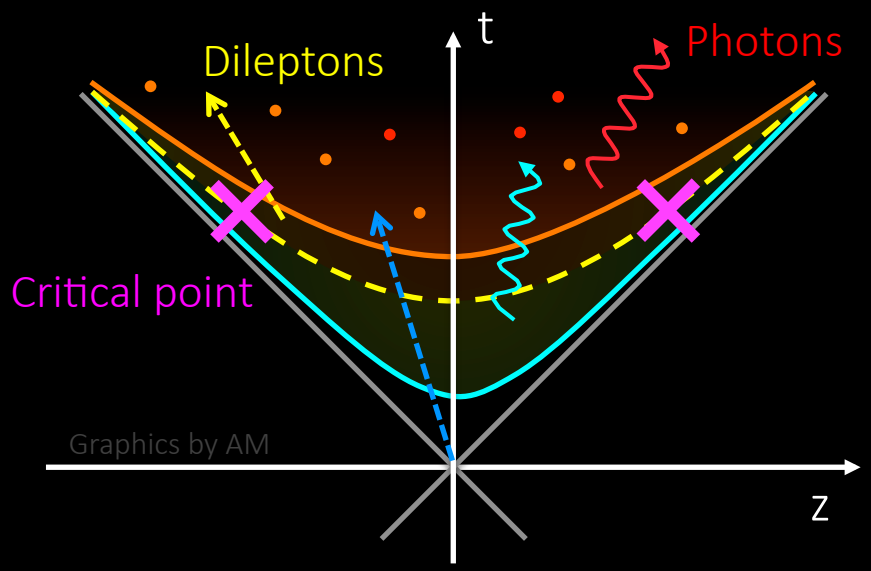

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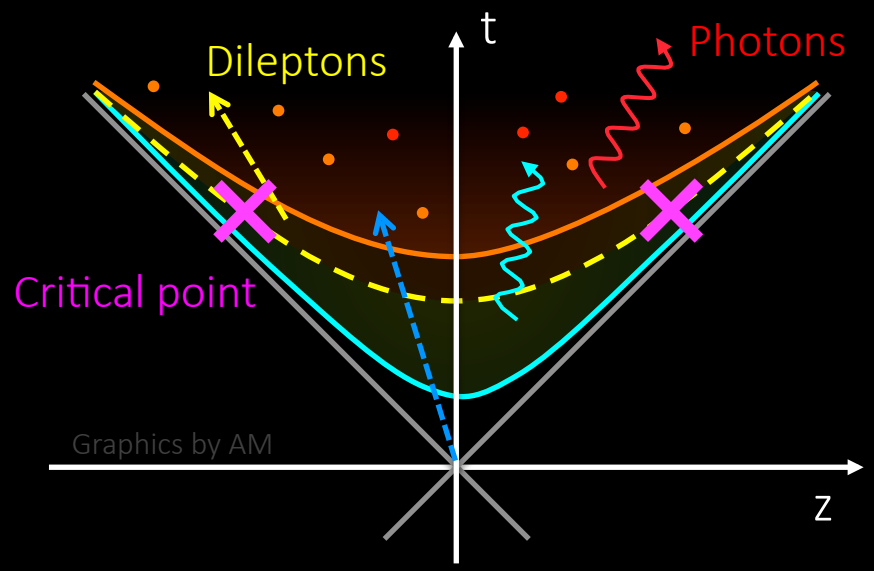

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  Photons and dileptons know the history of the time evolution

- The QCP can leave imprint via bulk viscosity in two ways:
  1. Bulk evolution (as already discussed)
  2. δf correction in the emission rate

Dileptons

- How is the emission rate affected?

AM, S. Mukherjee, Y. Yin, in preparation

- δf correction in the emission rate

$$\frac{dN}{d^4x} = \int \frac{d^3p_1}{(2\pi)^3}\frac{d^3p_2}{(2\pi)^3} f_1(E_1) f_2(E_2)\sigma(M) v_{\rm rel}$$

$$= \underbrace{\frac{dN_0}{d^4x}}_{(1)} + \underbrace{\int \frac{d^3p_1}{(2\pi)^3}\frac{d^3p_2}{(2\pi)^3}[f_1^0(E_1)\delta f_2(E_2) + (1 \leftrightarrow 2)]\sigma(M) v_{\rm rel}}_{(2)}$$

$$\left(\begin{array}{ll} \text{QGP} & q^+q^- \to l^+l^- \\ \text{Hadron} & \pi^+\pi^- \to l^+l^- \end{array}\right)$$

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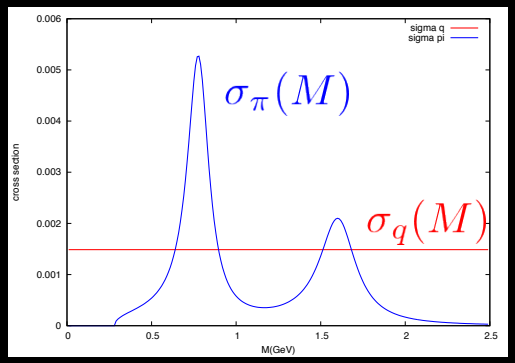
(1) Equilibrium emission rate

K. Kajantie, J. Kapusta, L. McLerran, A. Mekjian, PRD 34, 2746

$$\boxed{\frac{dN_0}{d^4x dM^2 d^2p_T dy} = \frac{\sigma(M)}{2(2\pi)^5}\frac{M^2}{2} e^{-E/T}\left(1 - \frac{4m_a^2}{M^2}\right)}$$



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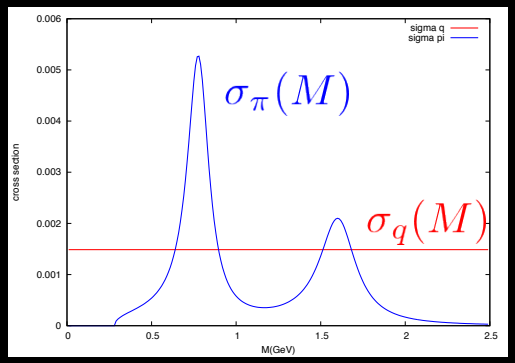
(2) Off-eq. emission rate needs δf_i



Dileptons

- Bulk viscous corrections

- Grad moment method (Israel-Stewart) in Boltzmann approx.

$$\delta f^i = -f_0^i[b_i D_\Pi E_i + B_\Pi(m_a^2 - E_i^2) + \tilde{B}_\Pi E_i^2]\Pi$$

⇨ The off-equilibrium rate is

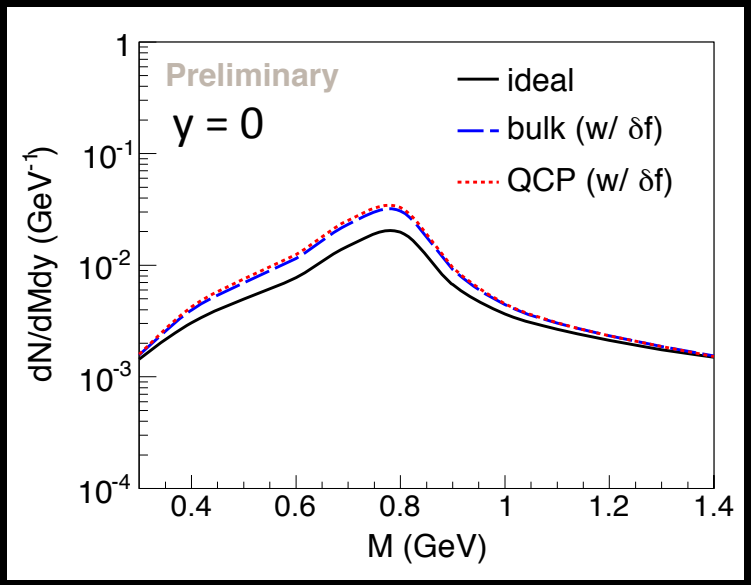
$$\frac{d\delta N}{d^4x dM^2 d^2p_T dy} = -\frac{\sigma(M)}{2(2\pi)^5} M e^{-E/T}\left(1 - \frac{4m_a^2}{M^2}\right) \times 2\Pi\left[B_\Pi m_a^2 \frac{M}{2} + (\tilde{B}_\Pi - B_\Pi)\frac{M^3}{8}\right]$$

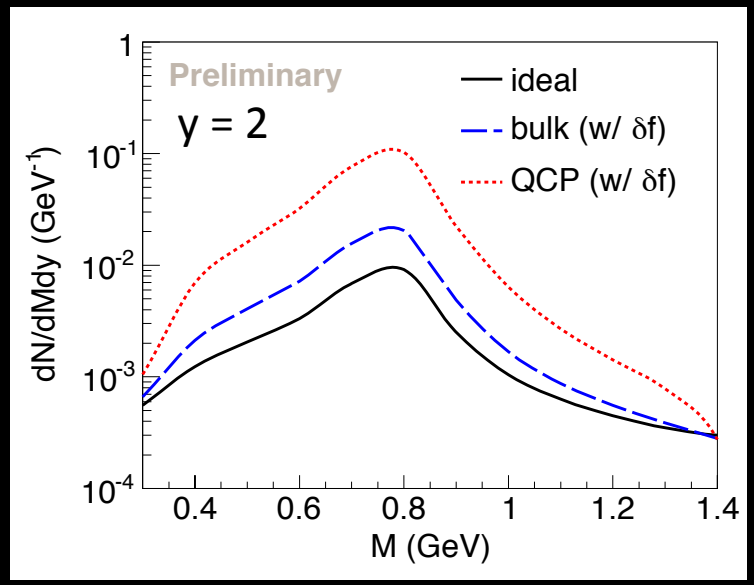
(B_Π and $\tilde{B}_\Pi$ can be calculated in kinetic theory as functions of T and μ_B)

For a different approach, see Vujanovic (Tue, 9:50)

Dileptons

- Invariant mass spectra: w/ 1+1 D non-boost invariant hydro





- Bulk viscosity enhances low M spectra; the QCP effect can be visible

QGP: parton gas w/ m_{th}
Hadron: pion gas

*The results are sensitive to the form of δf, m_{th}, hadronic components, etc.

Summary and outlook

- Search for the QCD critical point

- Bulk viscosity becomes dominant near a critical point
- Medium evolution is affected if the system comes across the QCP

  - Rapidity distributions are warped by entropy production and enhanced convection

- Electromagnetic probes can be used to quantify the QCP

- Estimation of full viscous rate at finite density is needed
- Comparison of different forms of bulk viscous δf is underway
- Will be interesting to have the EM probe data at BES-RHIC, SPS, FAIR, NICA, J-PARC etc.

The end

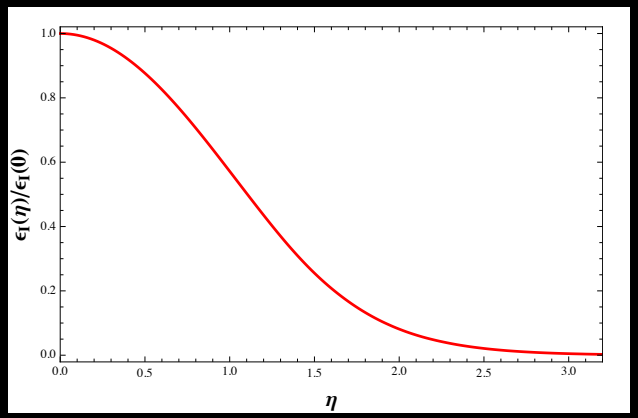
Thank you!

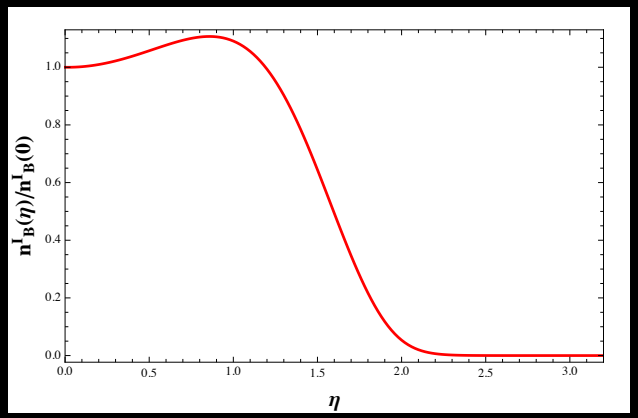
Initial conditions

- Longitudinal distribution

H. J. Drescher and Y. Nara, PRC 75, 034905; 76, 041903
Y. Mehtar-Tani and G. Wolschin, PRL 102, 182301; PRC 80, 054905

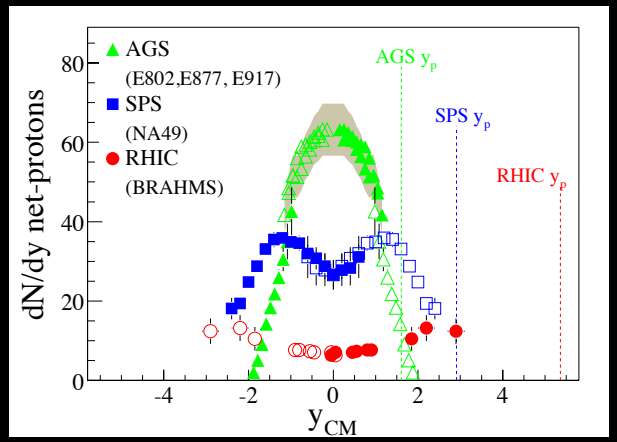
- CGC is used for the shapes of energy and net baryon distribution





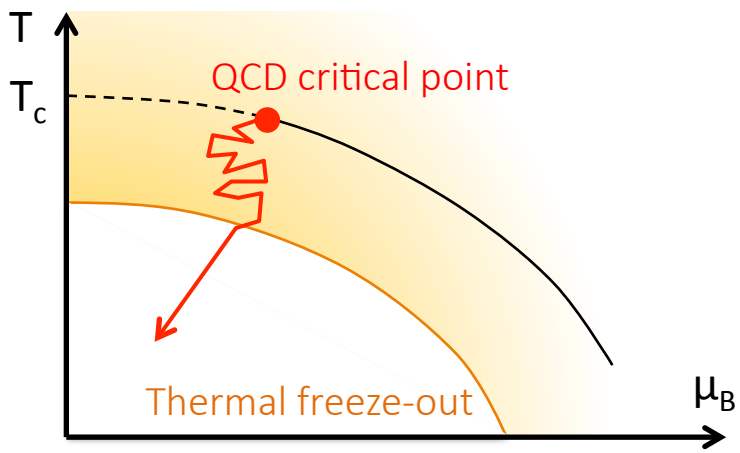
- The peak of net baryon is still at "forward" rapidity at 17 GeV

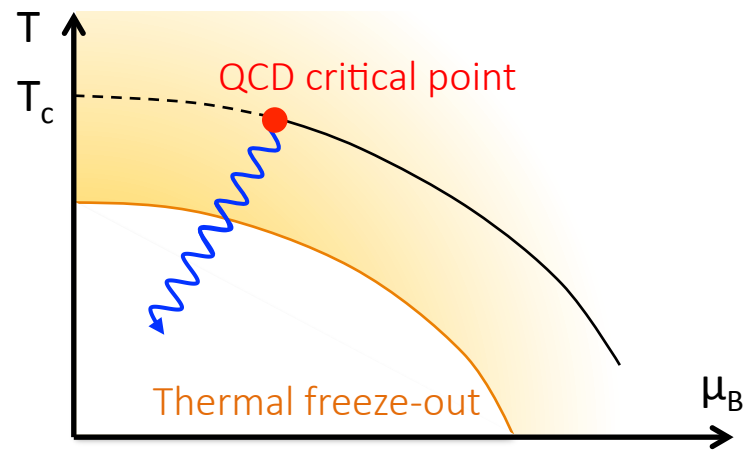
(Data: AGS 5 GeV, SPS 17 GeV, RHIC 200 GeV)



Electromagnetic signals

- QCD critical point (QCP) vs. Thermal freeze-out





- QCD medium is thermalized; colored objects (hadrons) are scattered
- Thermal photons penetrate through the medium

Can QCP signals be more direct?