Phenomenological signals of QCD critical point in heavy-ion collisions

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Introduction

- Beam energy scans: exploration of QCD phase diagram

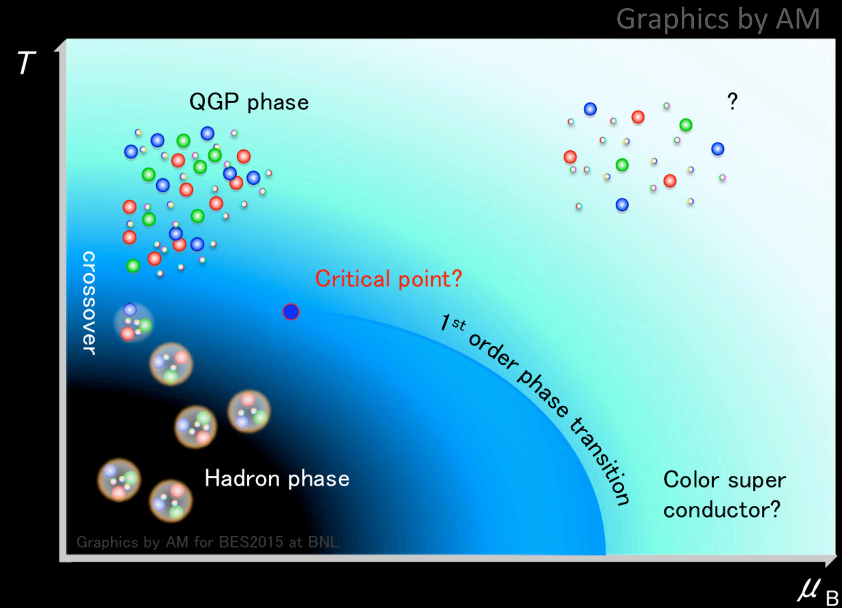
- RHIC (BNL)

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

  Phase II (2017-20?): 3.0 GeV?

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

  + LHC (CERN): 5.5 TeV



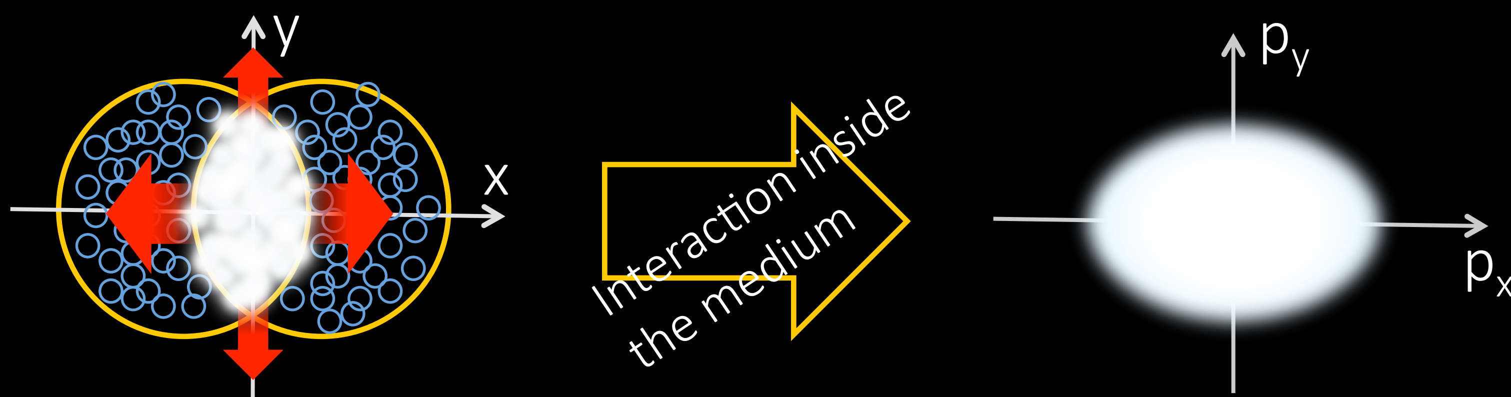
We use hydrodynamics to:

- Look for signals of a QCD critical point
- Determine the QGP properties at finite T, μ_B
- Understand the origin of "fluidity"

Introduction

- Observable: Elliptic flow (v_2)

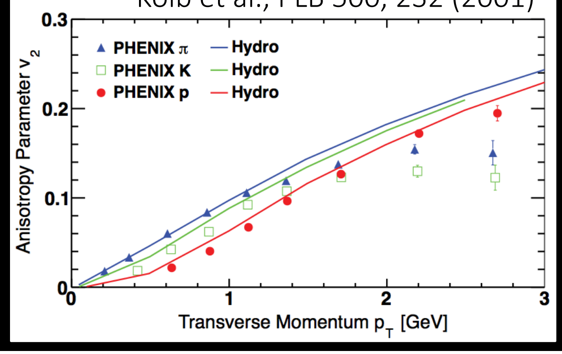
$$\frac{dN}{d\phi} = \frac{N}{2\pi}[1 + 2v_1 \cos(\phi - \Psi_1) + 2v_2 \cos(2\phi - 2\Psi_2) + 2v_3 \cos(3\phi - 3\Psi_3) + ...]$$



Spatial anisotropy

Momentum anisotropy

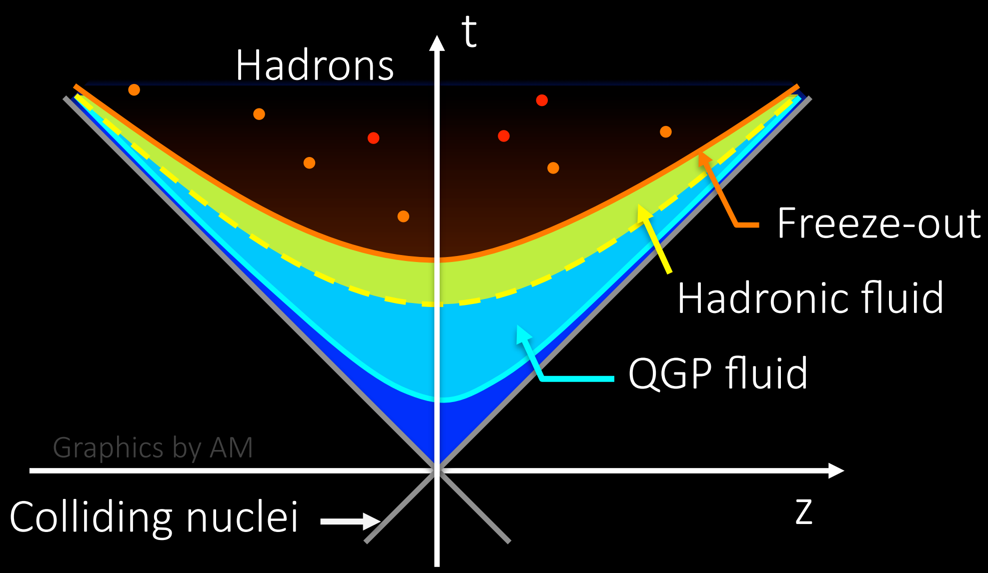
- Hadron v_2 is found to be large
  - It follows hydrodynamic description
  - An "evidence" for strongly-coupled QGP early equilibration of bulk medium ($\tau < 1$ fm/c)?



Kolb et al., PLB 500, 232 (2001)

Overview of a collision

- Hadronic point of view



Hadronic transport (> 10 fm/c)

⇧ Freeze-out

Hydrodynamic stage (~1-10 fm/c)

⇧ Equilibration

Glasma (~0-1 fm/c)

⇧ Little bang

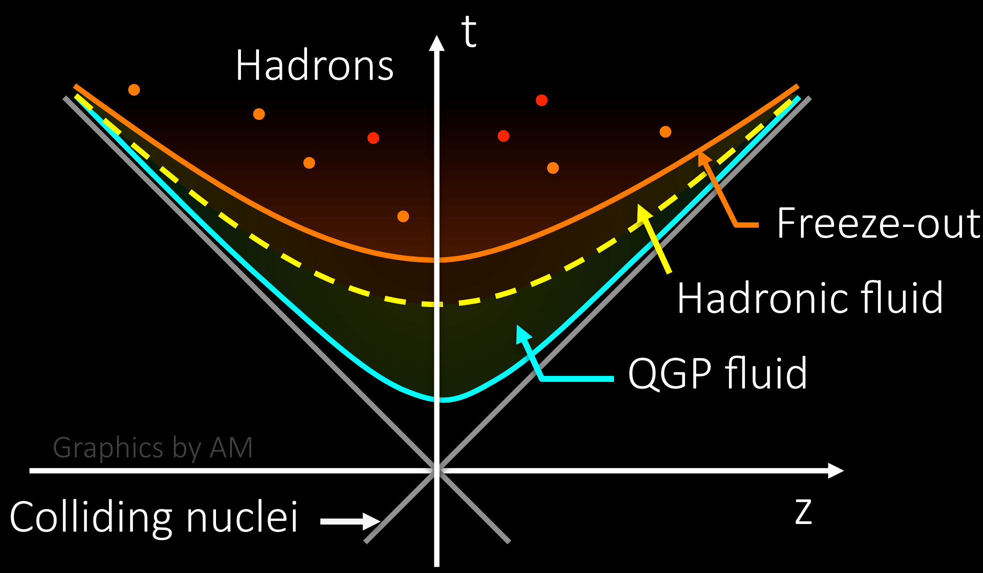
Color glass condensate (< 0 fm/c)

▶ Color opaque

Hadrons are easy to observe; some info before freeze-out can be lost

Overview of a collision

■ Photonic point of view



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Color glass condensate (< 0 fm/c)

▶ **Color opaque**

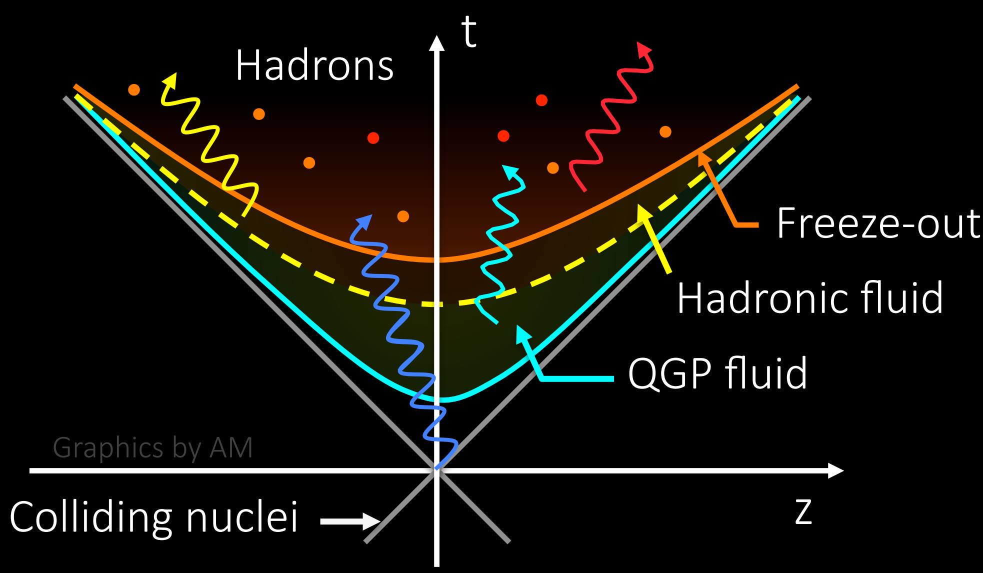
Hadrons are easy to observe; some info before freeze-out can be lost

▶ **Electroweak transparent**

Photons retain information during time-evolution

Observables

- Photonic point of view



Decay photons
- from hadronic decay

Thermal photons (hadronic)
Thermal photons (QGP)
- from black-body radiation

Prompt photons
- from hard processes

Direct photons

Color opaque

Hadrons are easy to observe; some info before freeze-out can be lost

Electroweak transparent

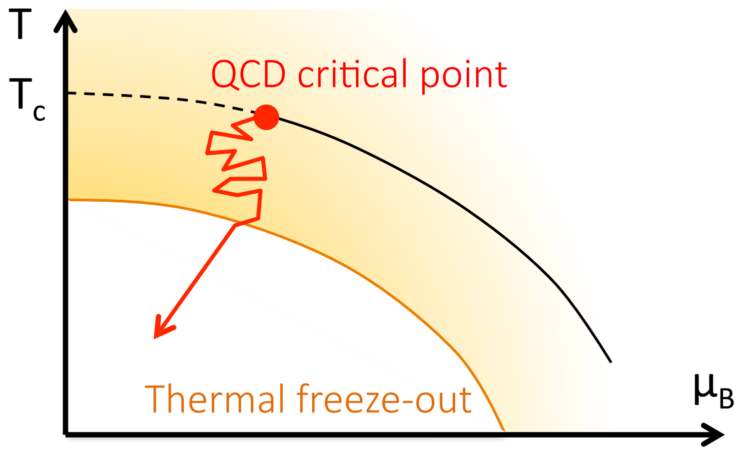
Photons retain information during time-evolution

Observable?

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

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

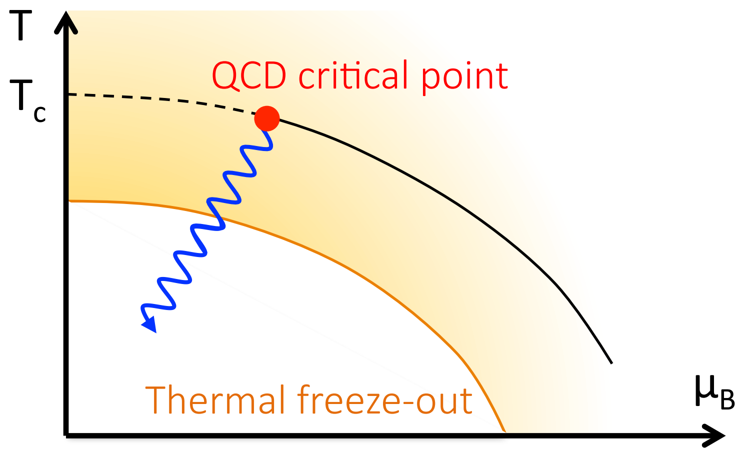
PART 1



- QCD medium is thermalized; colored objects (hadrons) are scattered

  Signals can be washed away unless

  1. QCP is near enough to freeze-out
  2. Its effect on evolution is large enough



- Thermal photons penetrate through the medium

  Can the QCP signals be more direct?

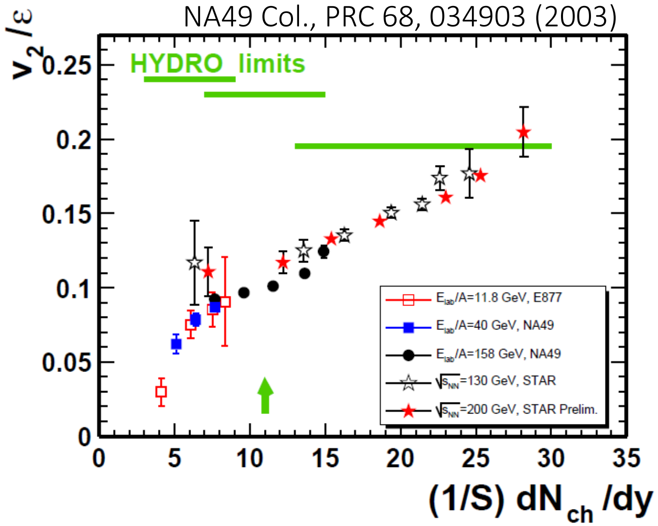
PART 2

AM, Y. Yin and S. Mukherjee,
In preparation

Hydrodynamic model for BES

- A path we have been through

NA49 Col., PRC 68, 034903 (2003)



▶ Integrated v_2 becomes small at lower E

"HYDRO limits" estimated with

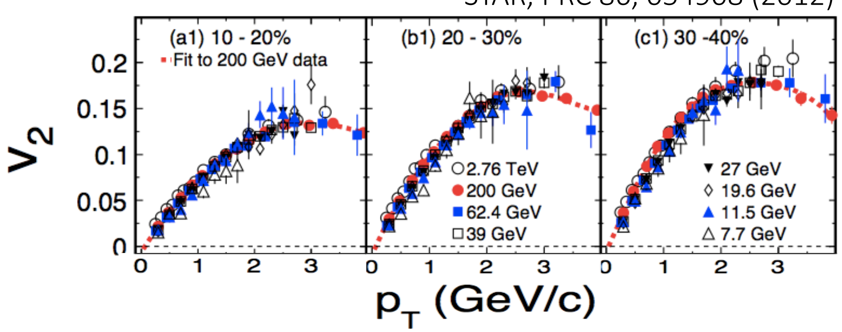
+ Analytical Glauber model
+ EoS with 1st order PT
+ Ideal hydro

Kolb et al., PRC62, 054909 (2000)

▶ Once thought hydro is only for AA at top energies (which may still be true)

- Applicability tests

STAR, PRC 86, 054908 (2012)



▶ Differential v_2 stays large

⇨ We should see if the state-of-art hydrodynamic interpretations work

Equations to solve

- Relativistic formalism

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

Baryon conservation $\partial_\mu N^\mu_B = 0$

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

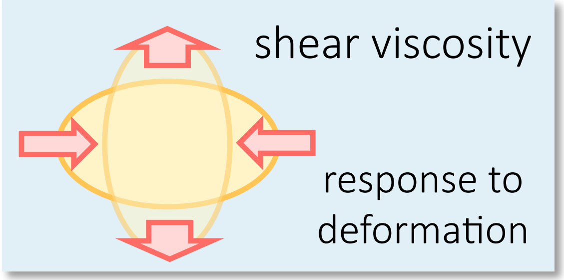
→ Ideal hydrodynamics

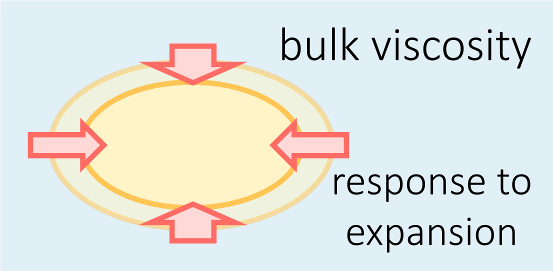
Shear viscosity $\pi^{\mu\nu} = 2\eta\nabla^{\langle\mu}u^{\nu\rangle} - \tau_\pi D\pi^{\langle\mu\nu\rangle} + \dots$

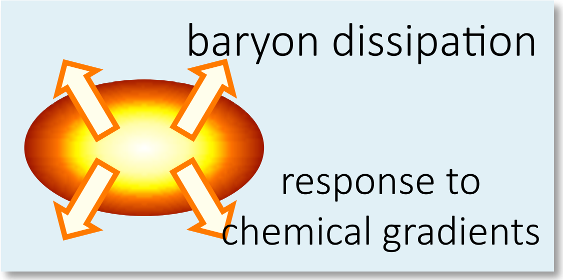
Bulk viscosity $\Pi = -\zeta\nabla_\mu u^\mu - \tau_\Pi D\Pi + \dots$

Baryon diffusion $V^\mu_B = \kappa_{V_B}\nabla^\mu \frac{\mu_B}{T} - \tau_{V_B}\Delta^{\mu\nu}DV_\nu + \dots$

→ Dissipative hydrodynamics







Near the QCD critical point

■ Bulk viscosity becomes dominant

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

- Shear viscosity: $\eta = \xi^{(4-d)/19}$
  Bulk viscosity: $\zeta = \xi^3$
  Baryon diffusion: $D_B = \xi^{-1}$

We consider bulk viscosity

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

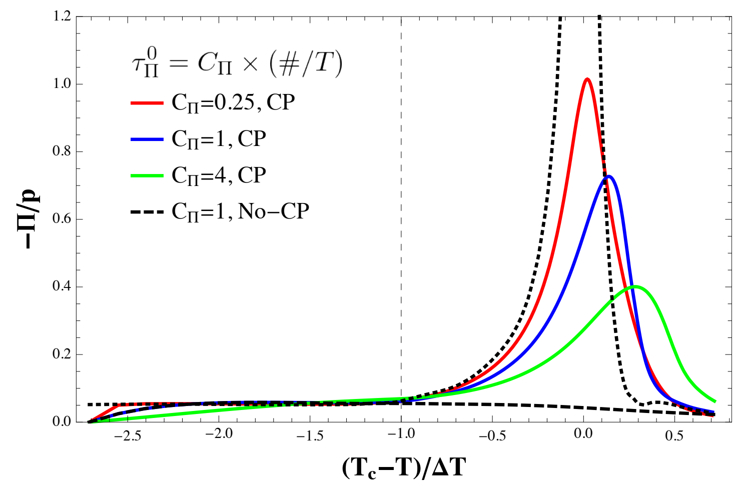
but 1st order theory is unstable

- Relaxation time

$$\tau_\Pi = \tau_{\Pi,0} \left(\frac{\xi_{eq}}{\xi_0}\right)^3$$ as causality suggests

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

- 2nd order theory can applicable because
Π is "frozen" for large τ_Π



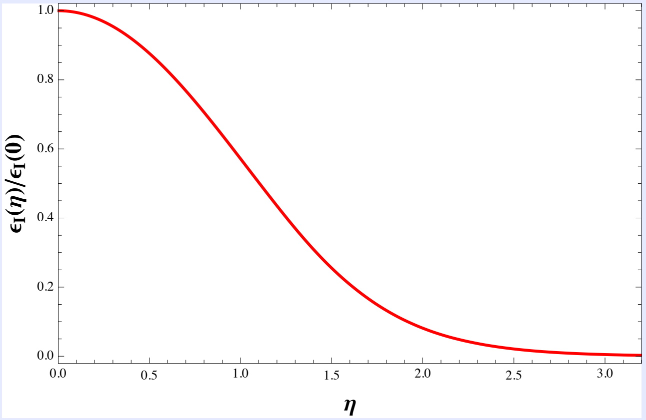
- We use $\zeta_0 = 2\left(\frac{1}{3} - c_s^2\right)\frac{e+P}{4\pi T}$, $\tau_{\Pi,0} = C_\Pi \frac{18 - (9\ln 3 - \sqrt{3}\pi)}{24\pi T}$ based on AdS/CFT

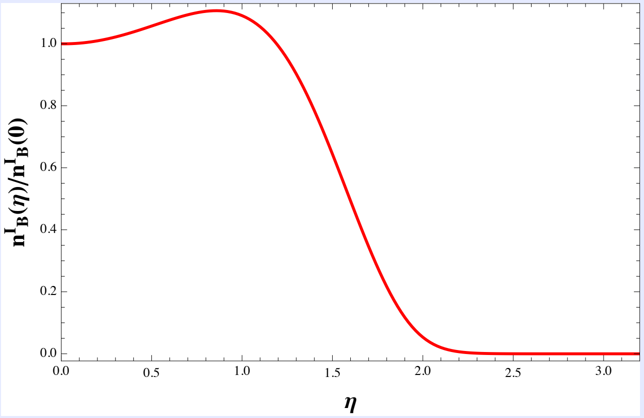
Initial conditions

- 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

- Color glass models extrapolated to lower energies for the shapes of energy and net baryon distribution





Energy density peaks at η=0, while net baryon density at finite η

⇨ Chemical potential is larger at forward rapidity η

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* $\eta_s = \frac{1}{2}\ln\frac{t+z}{t-z}$ is the "angle" of hyperbolic coordinate

Equation of state

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

Lattice QCD has a sign problem at finite density

- Taylor expansion up to the 4th order is used for QGP phase

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

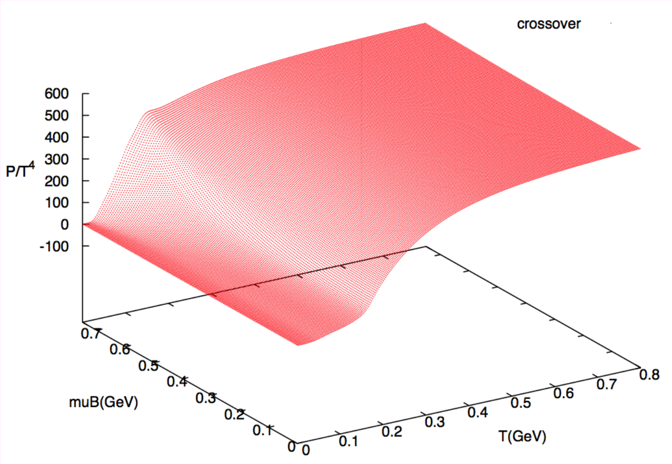
HotQCD, PRD 90, 094503 (2014), PRD 86, 034509 (2012), PRD 92, 074043 (2015)

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

where

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

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

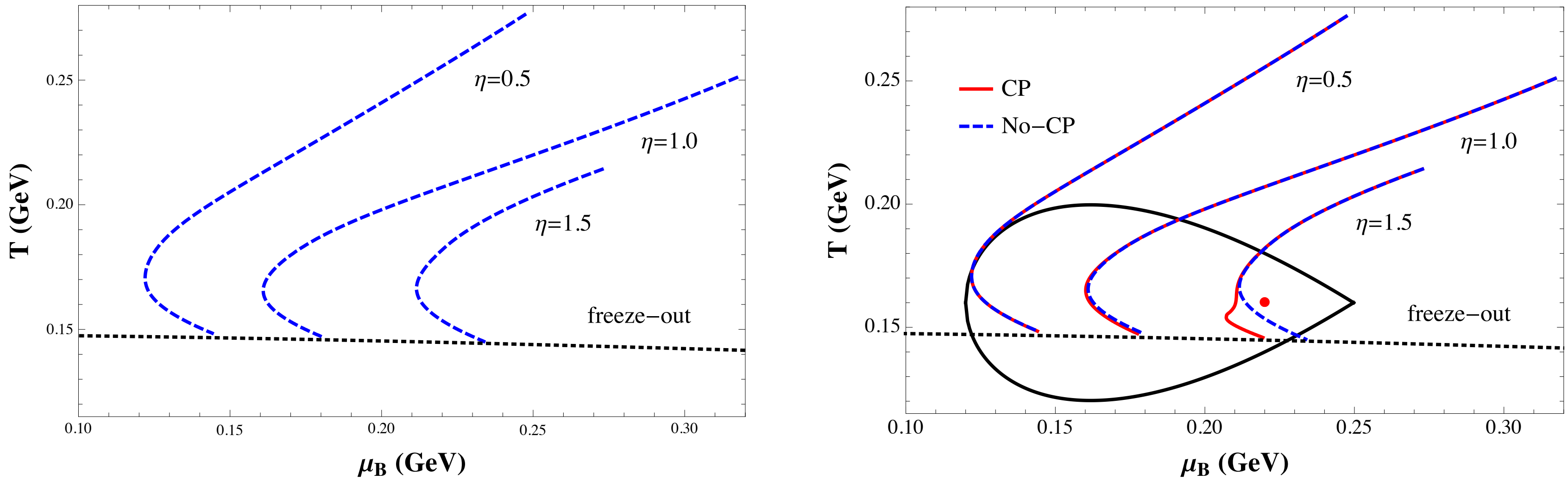


*Currently no QCP; effects of 1st order phase transition may not be dramatic

Trajectories on μ_B-T plane

- 1+1 dimensional hydrodynamic demonstration

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

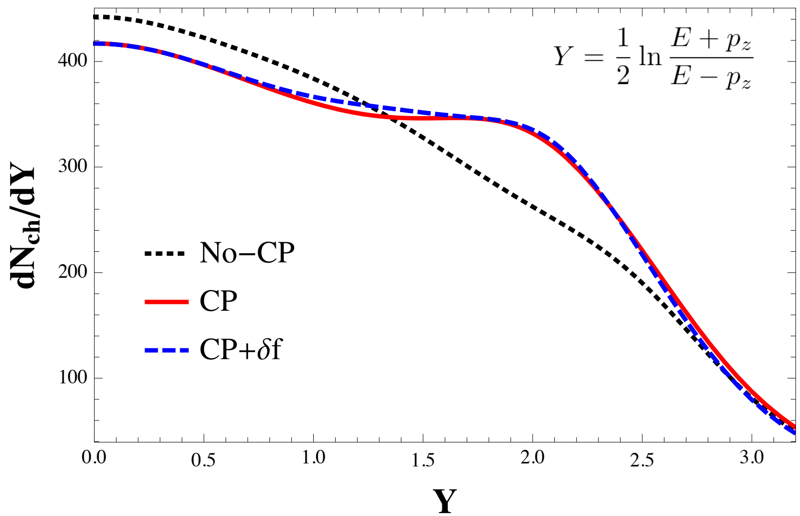


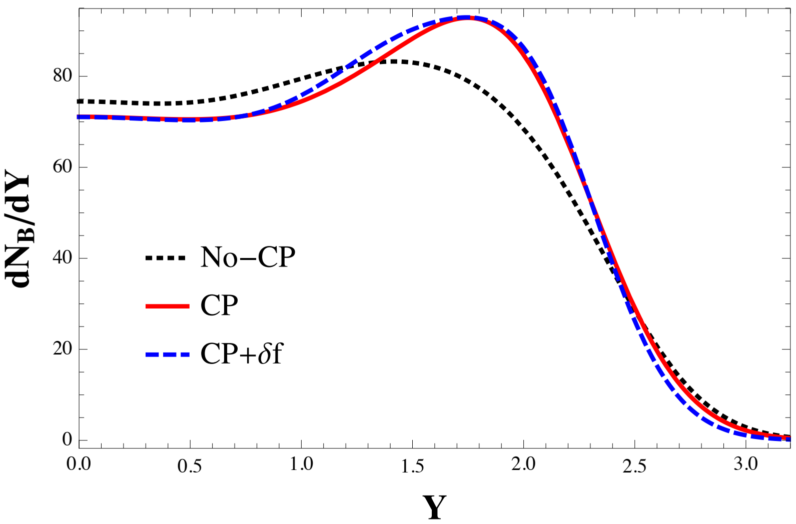
- Critical point is placed by hand at (μ_B, T) = (0.22 GeV, 0.16 GeV) by mapping the critical region of Ising model onto the μ_B-T plane
- If the QCP exists, the trajectory is pushed away from it on the lower μ_B side because of bulk viscous entropy production

Rapidity distributions

- 1+1 dimensional hydrodynamic demonstration

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



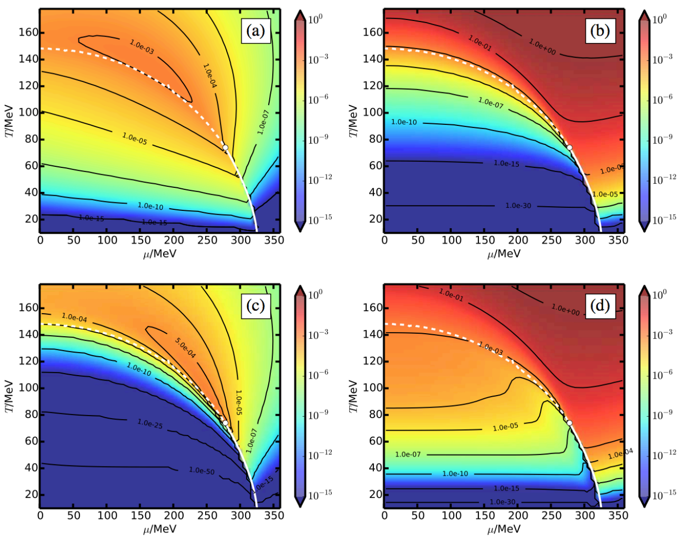


- Charged particle and net baryon distributions are deformed if the critical point is contacted
- dN_{ch}/dy deformation is caused by entropy production and enhanced flow convection due to the reduction in effective pressure P - Π
- dN_B/dy deformation is by convection only

Thermal photons

- Does emission rate contains a signal of QCP?

Few studies on the emission rate at finite density in the vicinity



Linear sigma model suggests no dramatic enhancement at QCP

F. Wunderlich and B. Kämper., PoS CPOD 2014, 027 (2015)

Bulk viscosity can change the emission rate via the distortion of the phase-space distribution

$$E\frac{dR_i}{d^3p} = \int \frac{d^3p_1}{2E_1(2\pi)^3}\frac{d^3p_2}{2E_2(2\pi)^3}\frac{d^3p_3}{2E_3(2\pi)^3}(2\pi)^4\delta(p_1^\mu + p_2^\mu - p_3^\mu - p^\mu)|\mathcal{M}_i|^2 f_1(E_1)f_2(E_2)[1 \pm f_3(E_3)]$$

Bulk viscous corrections

- How to determine δf_{bulk}

▶ Step 1: Expand the exponent y^i in $f^i = \frac{1}{\exp(y^i) \mp 1}$ around equilibrium in terms of Π

The tensor structure allowed in Israel-Stewart theory is

$$\delta y^i = [b_i D_\Pi u_\mu p_i^\mu + B_\Pi g_{\mu\nu} p_i^\mu p_i^\nu + (\tilde{B}_\Pi - B_\Pi) p_i^\mu p_i^\nu] \Pi$$

▶ Step 2: Have it satisfy the self-consistency conditions

$$\delta T^{\mu\nu} = \sum_i \int \frac{g_i d^3 p}{(2\pi)^3 E_i} p_i^\mu p_i^\nu \delta f^i \qquad \delta N_J^\mu = \sum_i \int \frac{q_i^J g_i d^3 p}{(2\pi)^3 E_i} p_i^\mu \delta f^i$$

▶ We have the coefficients

$$D_\Pi = 3(J_{40} J_{31}^B - J_{41} J_{30}^B) \mathcal{J}_3^{-1} \qquad \mathcal{J}_3 = 5 J_{42} J_{30}^B J_{30}^B + 3 J_{31}^B J_{40} J_{31}^B + 3 J_{41} J_{41} J_{20}^{BB}$$

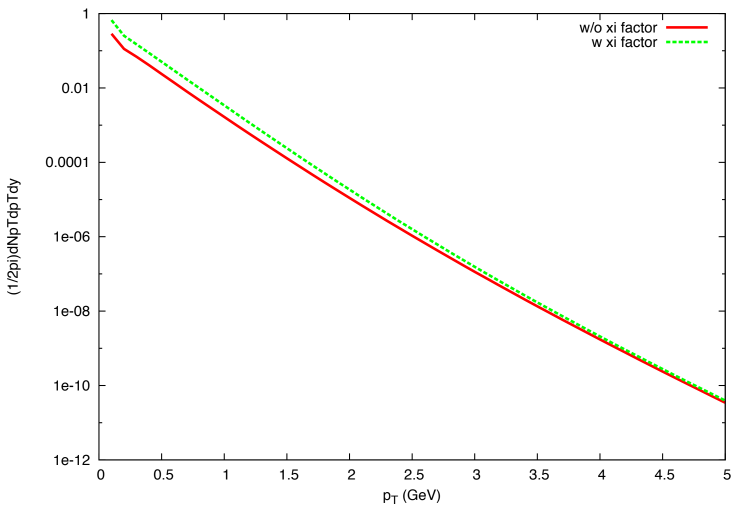
$$B_\Pi = (J_{30}^B J_{30}^B - J_{40} J_{20}^{BB}) \mathcal{J}_3^{-1} \qquad - 3 J_{31}^B J_{41} J_{30}^B - 3 J_{41} J_{30}^B J_{31}^B - 5 J_{42} J_{40} J_{20}^{BB}$$

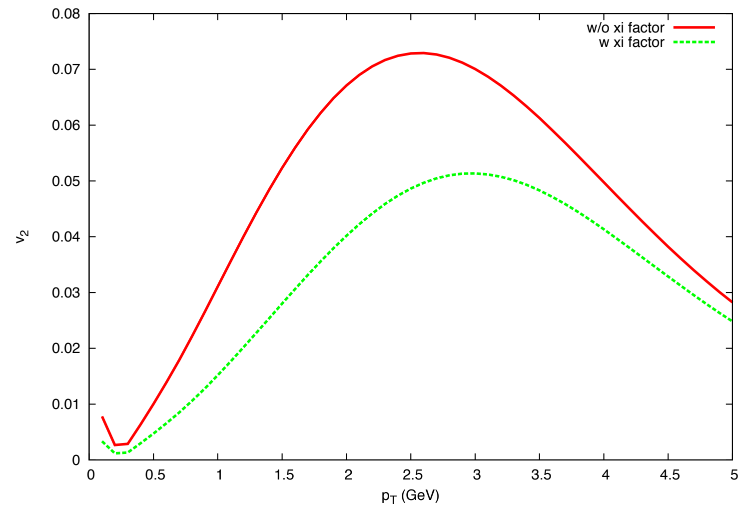
$$\tilde{B}_\Pi = 3(J_{41} J_{20}^{BB} - J_{30}^B J_{31}^B) \mathcal{J}_3^{-1}$$

J_{mn} : momentum integrals of f_0^i

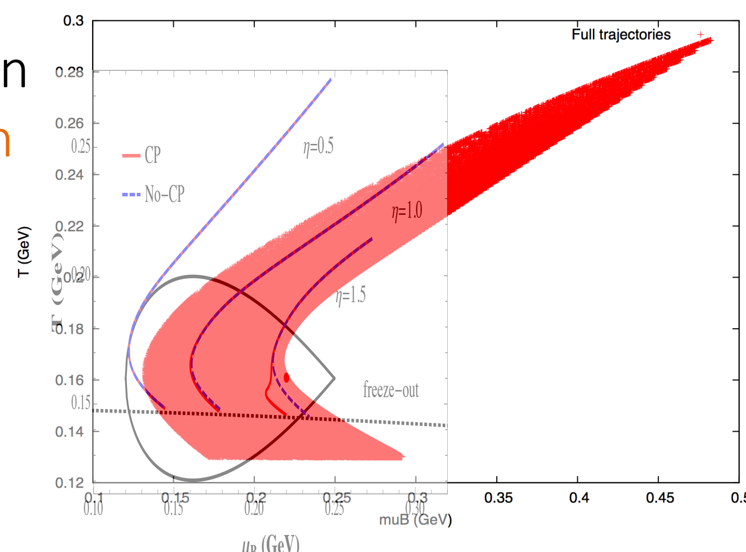
Critical enhancement

- (2+1)-D hydrodynamic tests with $E\frac{dR}{d^3p} = [1 + 0.1(\xi/\xi_0)^3] \times E\frac{dR_0}{d^3p}$





- The magnitude and sign of correction is sensitive to the shape and location of the critical region
- Early emission leads to small momentum anisotropy v_2
- *Work in progress – stay tuned*



Summary and outlook

- QCD critical point is a hot topic in heavy-ion collisions
  - Bulk viscosity can become dominant near QCP
  - Medium evolution itself can be affected if the system came across QCP

    - Trajectories and rapidity distributions are warped by entropy production and enhanced convection
  - Thermal photons can be a good signal of QCP

    - Bulk viscous enhancement is a key

  - Full estimation of off-equilibrium and finite-density photon emission rate is important (work in progress)
  - Will be interesting to have the photon data from BES-RHIC, SPS, FAIR, NICA etc.

The end

Thank you!