# Non-monotonic specific entropy on the transition line near the QCD critical point

arXiv: 2402.09519; PRC (to appear)

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# Introduction

- How does the fireball approach the first-order chiral phase transition in heavy-ion collisions?
- Ideal hydrodynamics:

  Entropy and baryon number conservation $\longrightarrow$ $\hat{s} = \frac{s}{n} = \text{const}\,.$
- The universality of critical phenomena

  $\longrightarrow$ QCD thermodynamics ≃ 3D Ising model

  $\longrightarrow$ Universal properties of the isentropic trajectory (constant $\hat{s}$)

# Non-monotonic specific entropy

M. Pradeep, NS, M. Stephanov, and H. Yee, (2024)
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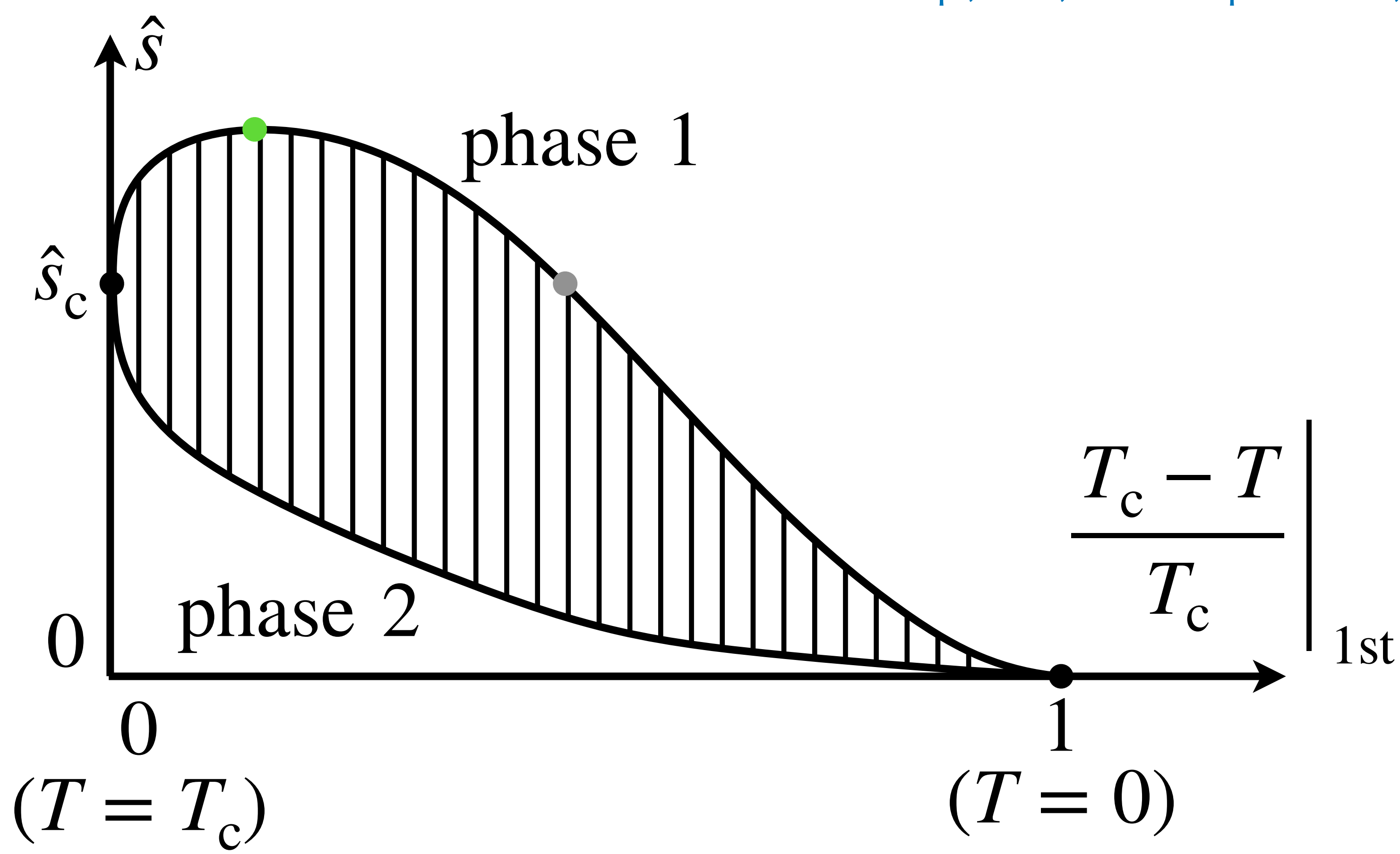
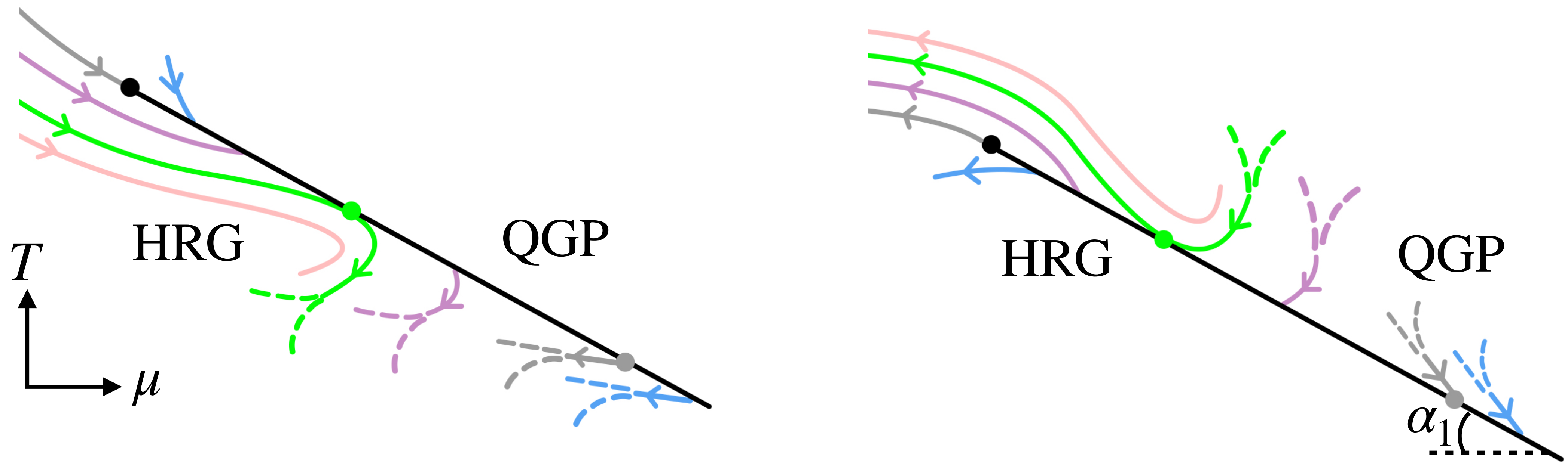



- Near $T_c$ : $\hat{s} \sim$ (order parameter) $\sim \pm (T - T_c)^\beta$ $(\beta = 0.326)$
- The third law of thermodynamics: $\hat{s}(T=0) = 0$

# Isentropes near the critical point

M. Pradeep, NS, M. Stephanov, and H. Yee (2024)




$\hat{s}_c - \cot\alpha_1 > 0$ $\hat{s}_c - \cot\alpha_1 < 0$

Criticality on the isentropes + Freeze-out curve
(e.g., lensing effect, etc.)

⟶ Non-fluctuation signature of the critical point

Preliminary

# Outline

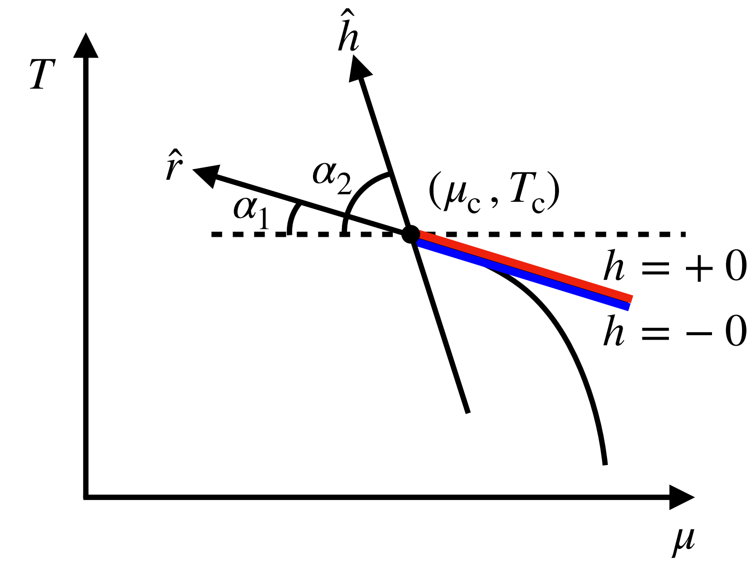
1. Critical equation of state (EOS)
2. $\hat{s}$ along the coexistence line
3. Isentropes on $(\mu, T)$ plane
4. Freeze-out points

# Critical EOS

C. Nonaka and M. Asakawa (2005), Parotto et al. (2020)

- Pressure: $P \sim G(h, r)$ with external field/reduced temperature
- Linear map: $(\mu, T) \leftrightarrow (h, r)$ with parameters $\alpha_1, \alpha_2$, etc.
- Entropy and baryon number density:

$$s \equiv \left(\frac{\partial P}{\partial T}\right)_\mu + s_c\,, \quad n \equiv \left(\frac{\partial P}{\partial \mu}\right)_T + n_c$$




- Specific entropy:

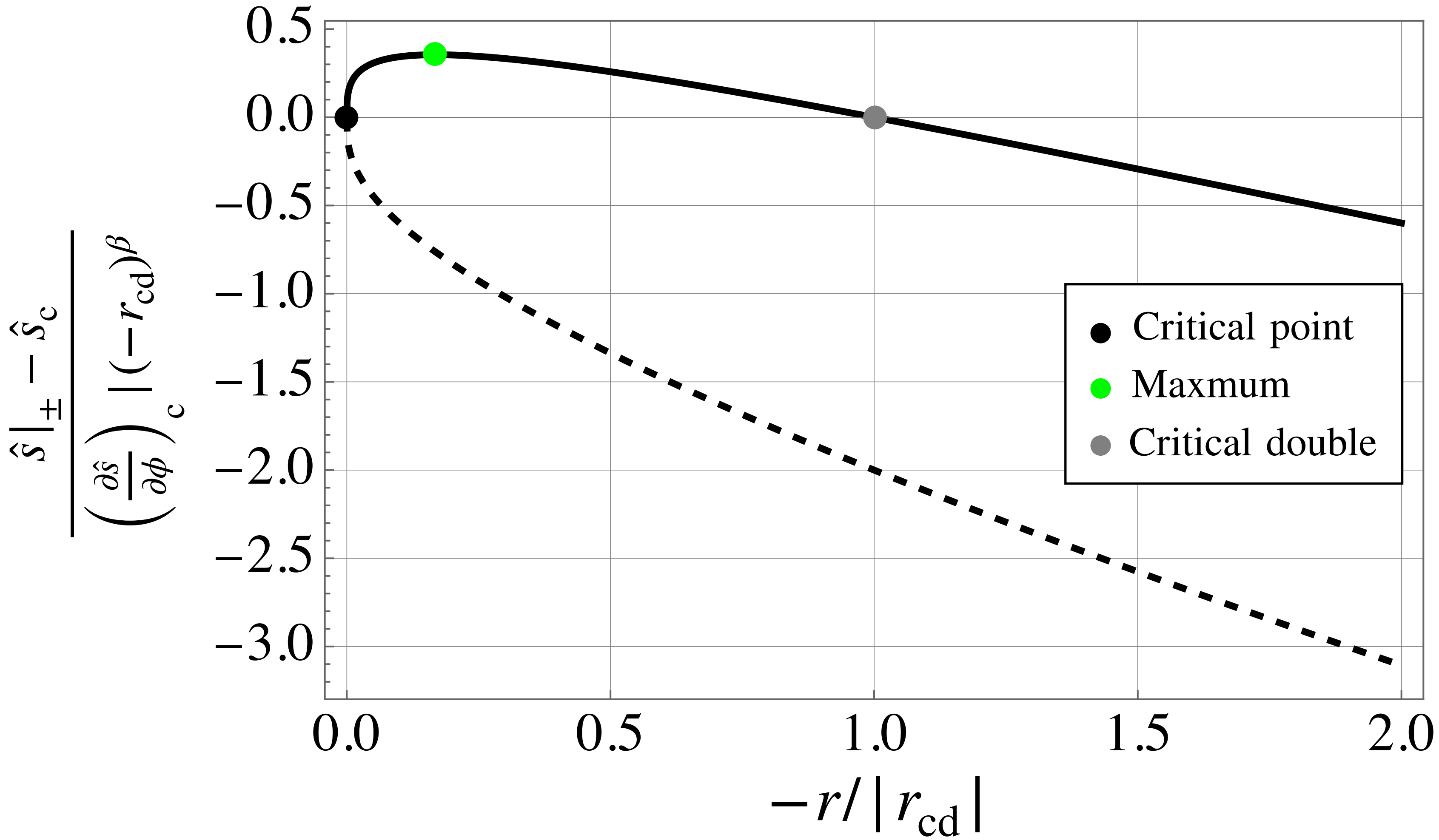
$$\hat{s} = \left(\frac{\partial \hat{s}}{\partial \phi}\right)_c \phi + \left(\frac{\partial \hat{s}}{\partial \varepsilon}\right)_c \varepsilon + \cdots$$

Order parameter: $\phi = \left(\dfrac{\partial G}{\partial h}\right)_r$ Energy density: $\varepsilon = \left(\dfrac{\partial G}{\partial r}\right)_h$

# Non-monotonic Specific entropy

M. Pradeep, NS, M. Stephanov, and H. Yee (2024)

$$\hat{s}\,|_{h=\pm 0}(r) - \hat{s}_\mathrm{c} = \pm \left(\frac{\partial \hat{s}}{\partial \phi}\right)_\mathrm{c} (-r)^\beta + C \left(\frac{\partial \hat{s}}{\partial \varepsilon}\right)_\mathrm{c} (-r)^{1-\alpha} + \cdots$$



# Parameters

M. Pradeep, NS, M. Stephanov, and H. Yee (2024)

- BEST-collaboration parameters Parotto et al. (2020)
- Vary $\alpha_2 \quad \because |\alpha_2 - \alpha_1| \sim \mathcal{O}(m_{\mathrm{q}}^{2/5})$ M. Pradeep and M. Stephanov (2019)

| Set | $\mu_{\mathrm{c}}$ (MeV) | $T_{\mathrm{c}}$ (MeV) | $w$ | $\rho$ | $\alpha_1$ (°) | $\alpha_2$ (°) | |
|---|---|---|---|---|---|---|---|
| 1 | 350 | 143.2 | 1 | 2 | 3.85 | -86.75 | Default |
| 2 | “ | “ | “ | “ | “ | -5 | Realistic |

# Isentropes

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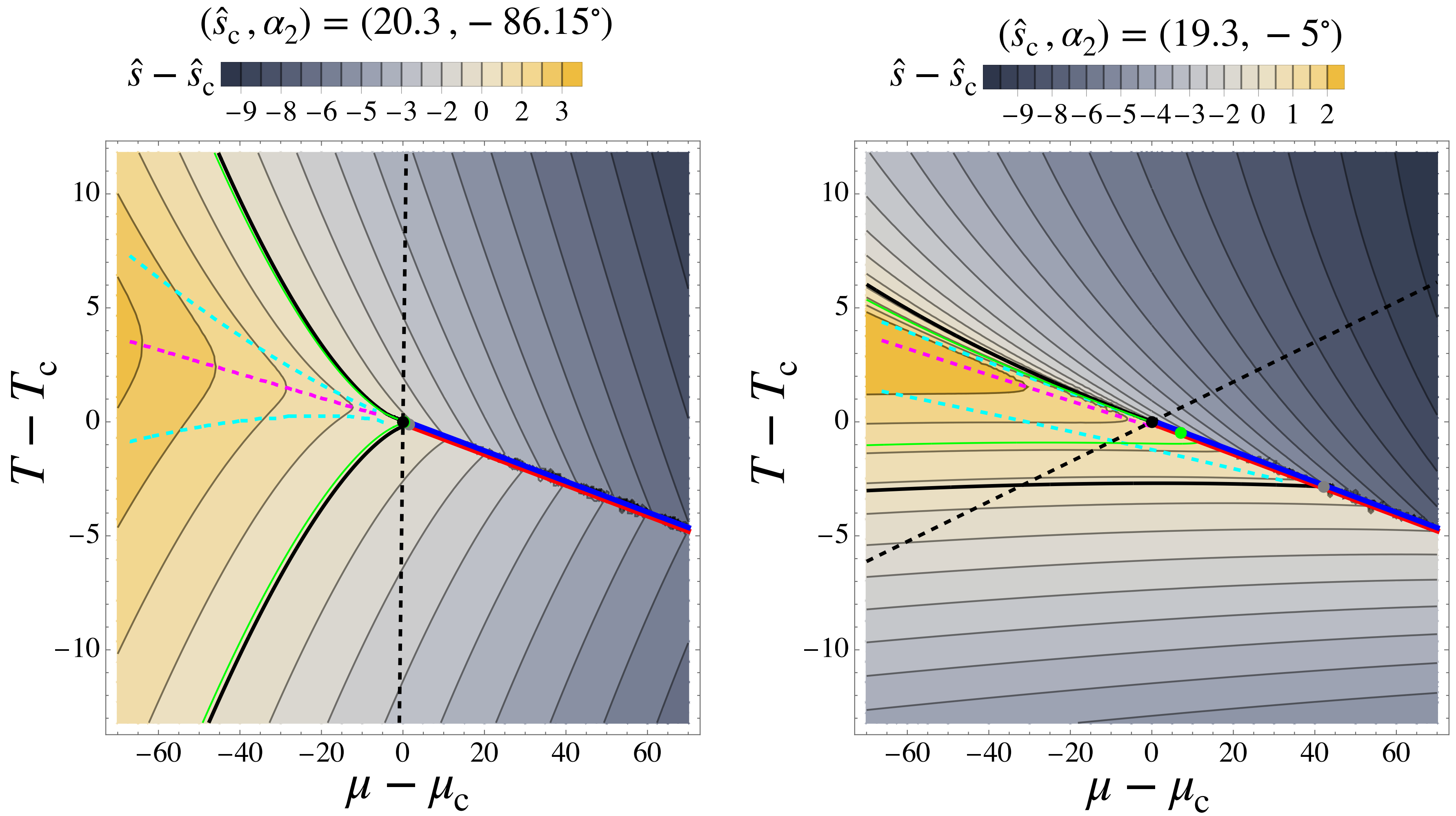
- $\hat{s}_c > \cot \alpha_1$ (HRG side) within BEST-collaboration



# Isentropes

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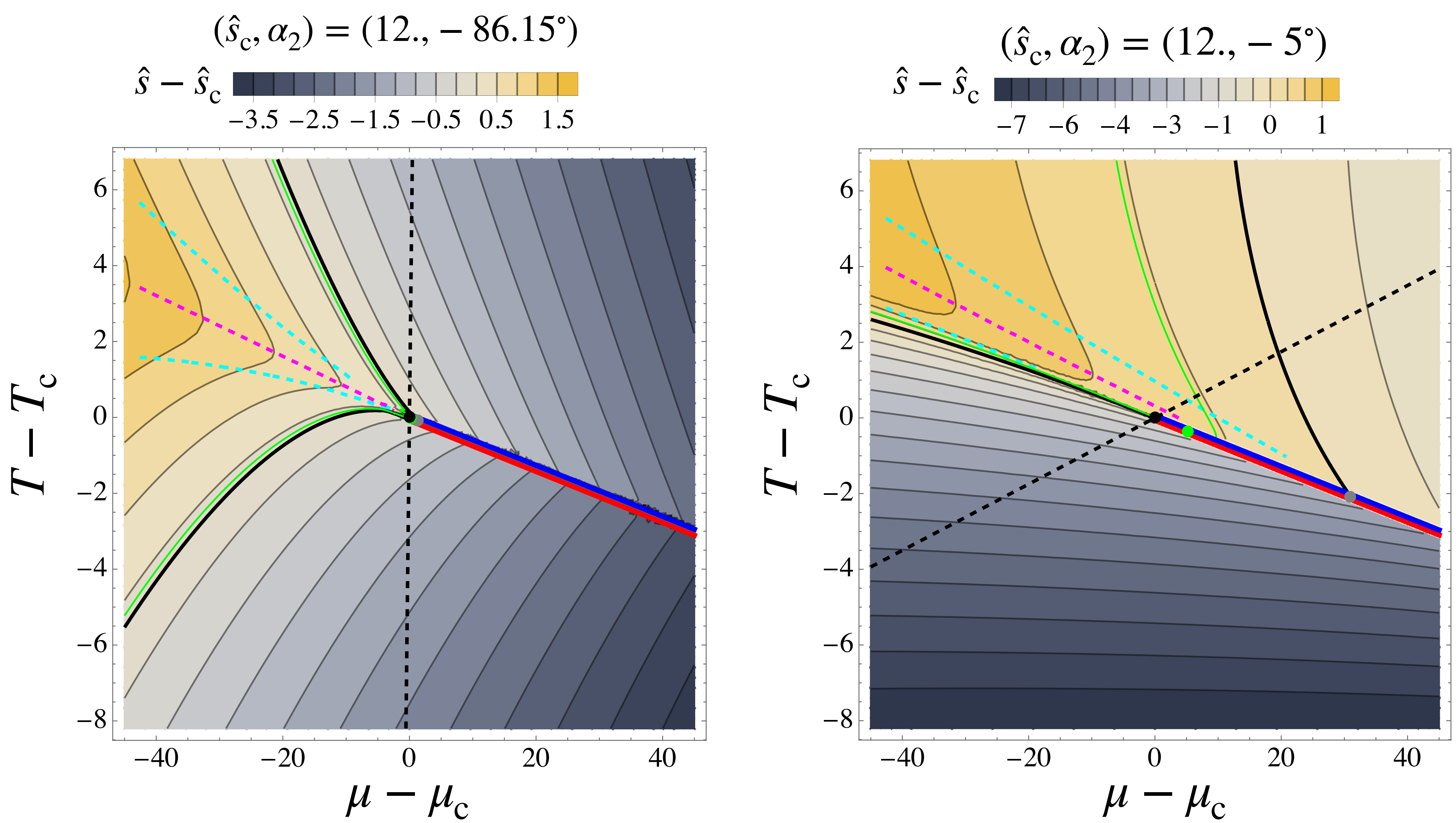
- Set $\hat{s}_c < \cot \alpha_1$ by hand ($\alpha_1 = 3.85^\circ$ fixed)

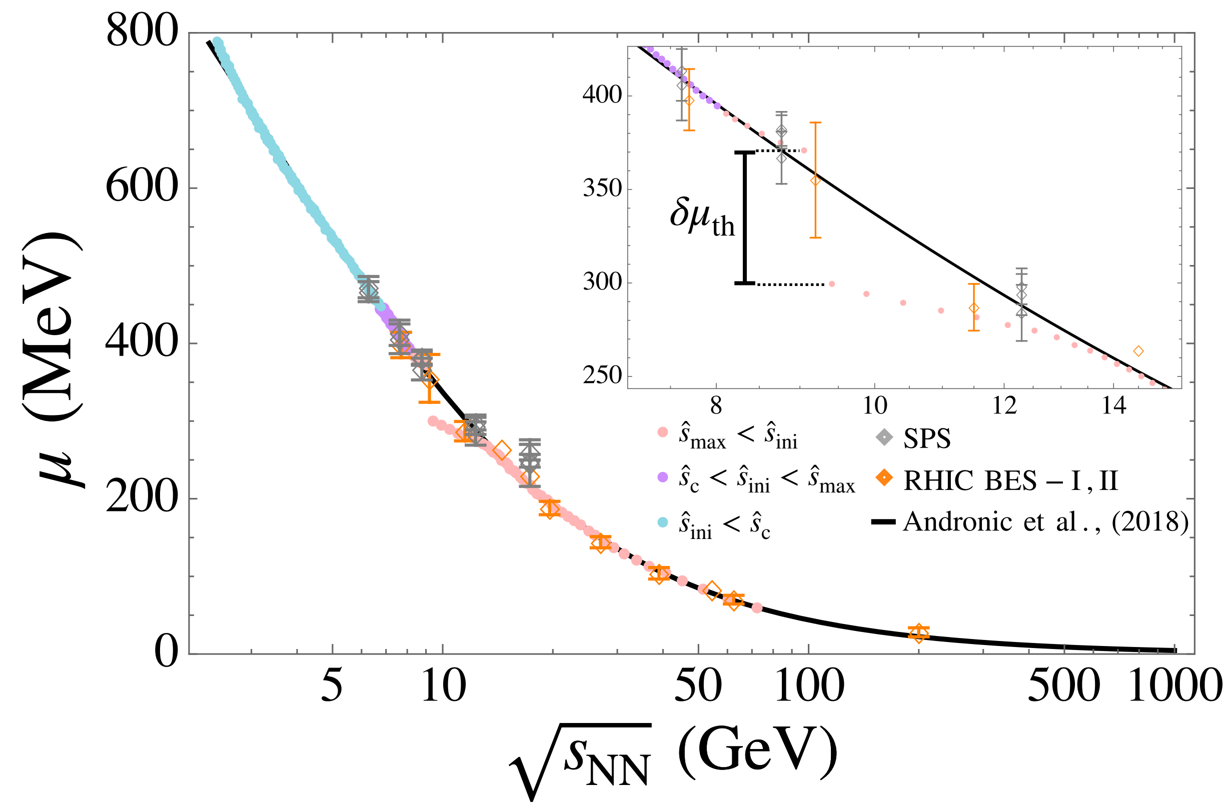


# Freeze-out point jump

Preliminary

RHIC BES-I,II data

| $\sqrt{s_{NN}}$ (GeV) | $\mu$ (MeV) | $\delta\mu$ (MeV) |
|---|---|---|
| 7.7 | 398 | |
| 9.2 | 355 | 43 |
| 11.5 | 287 | 68 |
| 14.5 | 264 | 23 |
| 17.3 | 230 | 34 |
| 19.6 | 188 | 42 |
| 27 | 144 | 44 |
| 39 | 104 | 40 |
| 54.4 | 83 | 21 |
| 62.4 | 70 | 13 |
| 200 | 28 | 42 |




Freeze-out curve
+ Criticality $\longrightarrow$ $\delta\mu_{th} \sim \delta\mu$

Fit by $(\mu_c, T_c) = (370, 144.5)$ MeV, $(\alpha_1, \alpha_2) = (4.7^\circ, -5^\circ)$

More data points between, e.g., 9.2 and 11.5 GeV may capture a critical point signature.

High event statistics are **not** needed for non-fluctuation signatures

# Summary

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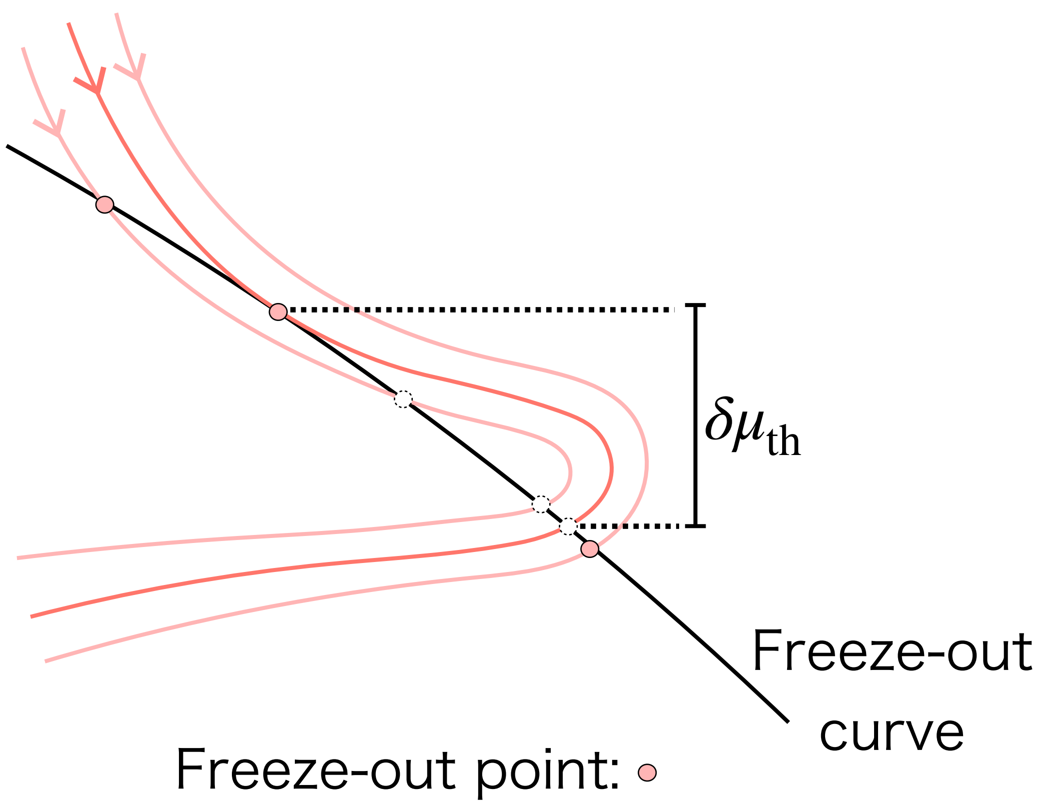
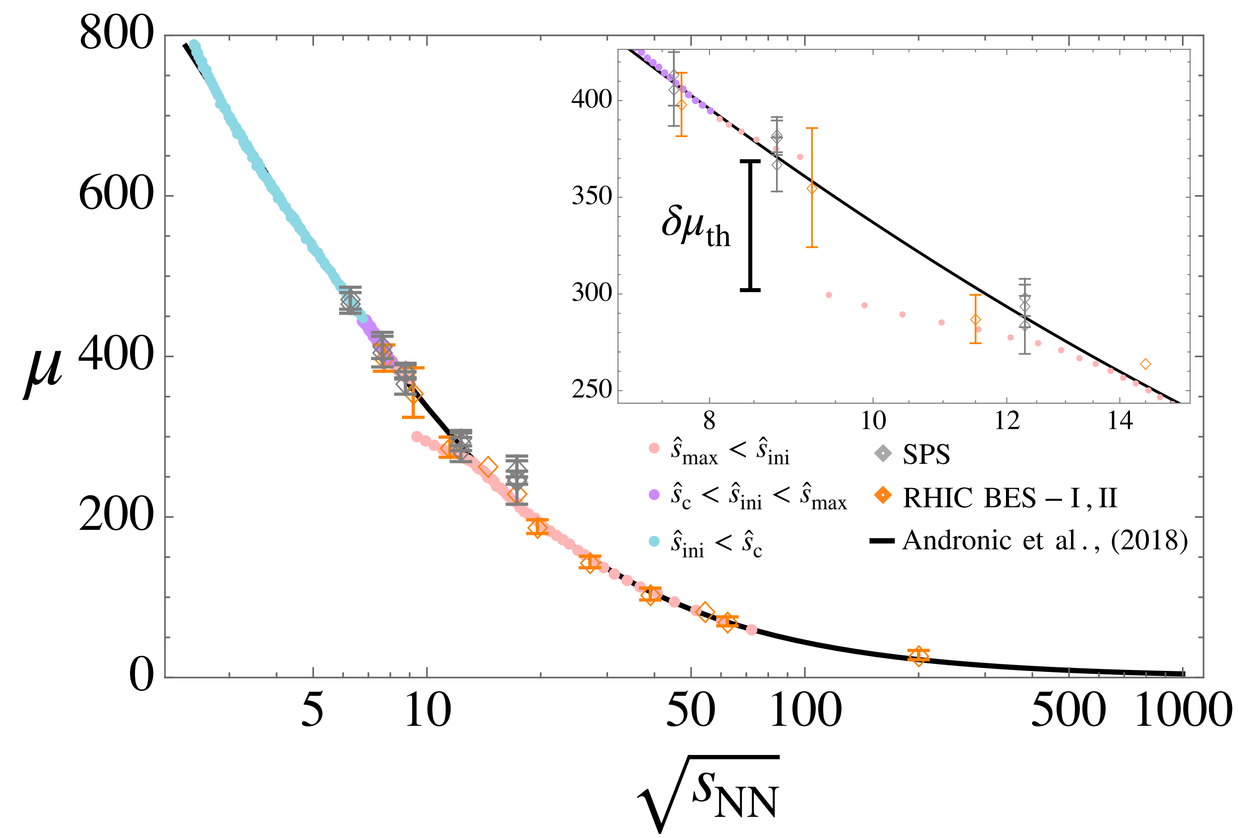
- Universal properties of isentropes near the QCD critical point
- Non-monotonic specific entropy determines which side of the fireball approaches the chiral phase transition line
- Non-fluctuation signature of the critical point along the freeze-out curve: chemical potential jump Preliminary

# Backup

# Mechanism of the jump




$$\delta\mu_{\rm th} \propto \Delta\mu_{\rm cd} = \mu_{\rm cd} - \mu_{\rm c} \sim T_{\rm c} \cos\alpha_1(-r_{\rm cd})$$