Exploring baryon-rich QCD matter and search for the QCD critical point : a theoretical perspective

1. Motivation: exploring the uncharted regions in QCD phase diagram with discovery potential of *locating the critical point*.

2. Off-equilibrium effect is prominent near the critical point:

   ★ Its characteristic features have been understood and a quantitative framework is under rapid development.

3. BESII: new observables.

4. Summary and outlook.

BEST COLLABORATION

Yi Yin

QM18

MIT

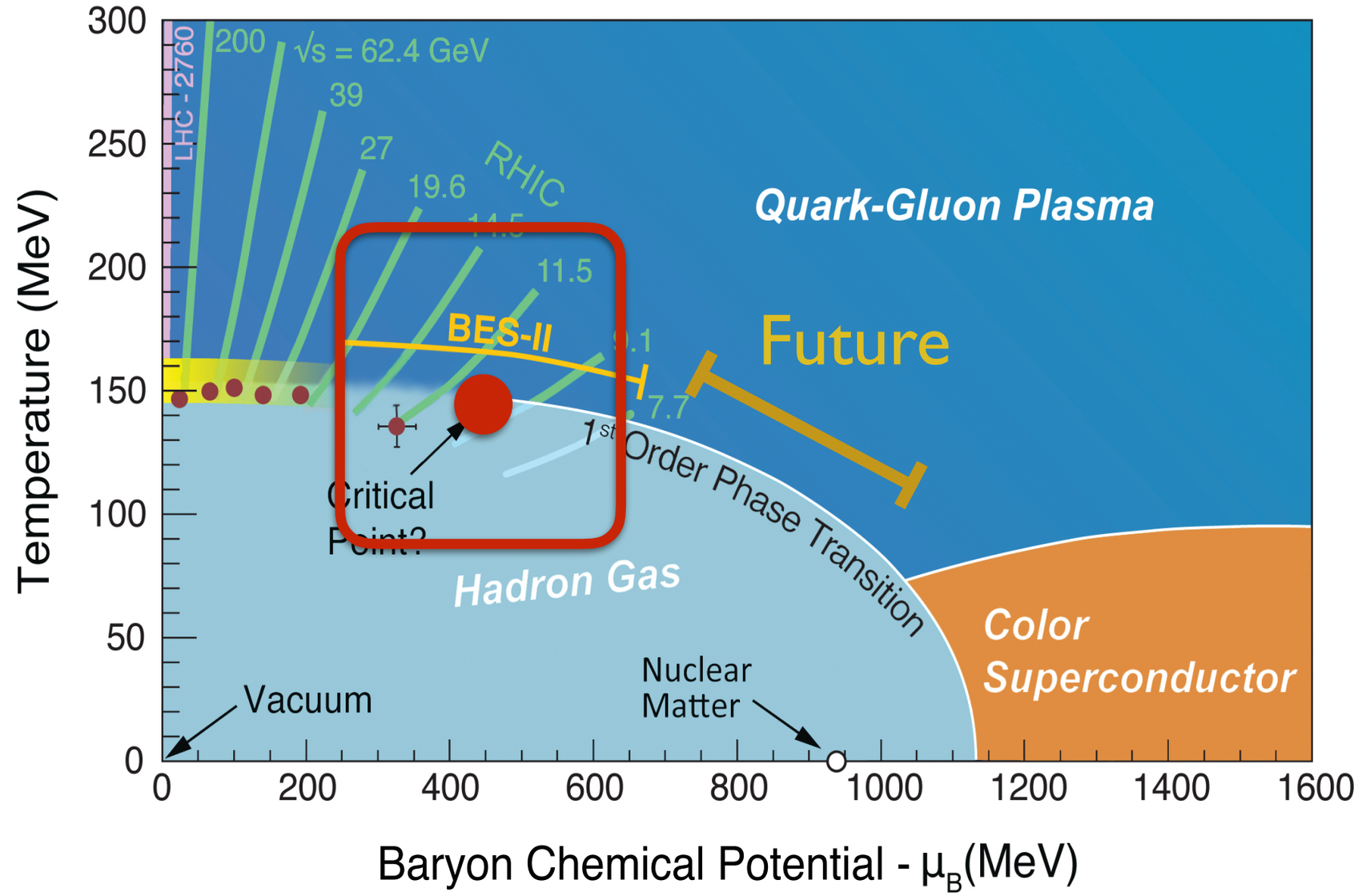
$T_c \approx 154 \pm 9$MeV

$\eta/s \cong (1\sim3)/4\pi$

$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC,} \\ 3.7 \pm 1.4 & \text{at LHC,} \end{cases}$$

…

See also D'Elia's talk



The baryon-rich regions in QCD phase diagram: uncharted. But this situation might change in the near future.

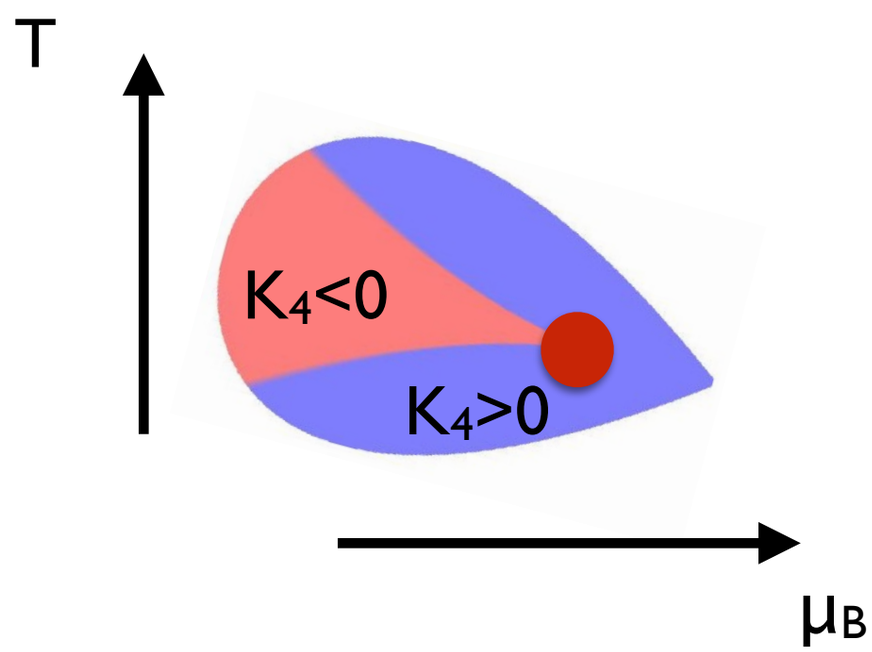
Discovery potential: the QCD critical point.

The signature of critical point: enhanced thermodynamic fluctuations.

Search for the QCD critical point: measure hadron (in particular proton) number fluctuations.

See Reed's talk

$$K_2 \sim \xi^2 \qquad K_3 \sim \xi^{4.5} \qquad K_4 \sim \xi^7$$



While the current trends in data is encouraging, its interpretation is quite intriguing as off-equilibrium effects would become important.

Equilibration rate of diffusive modes (such as baryon density):

$$\Gamma_D(k) = \frac{\lambda}{\chi} k^2$$

Larger fluctuation, smaller equilibration rate.

Near the critical point ⇒ critical slowing down.

$$\Gamma_\xi = \Gamma_D(k = \xi^{-1}) \sim \frac{\xi}{\xi^2} (\xi^{-1})^2 \sim \xi^{-3}$$

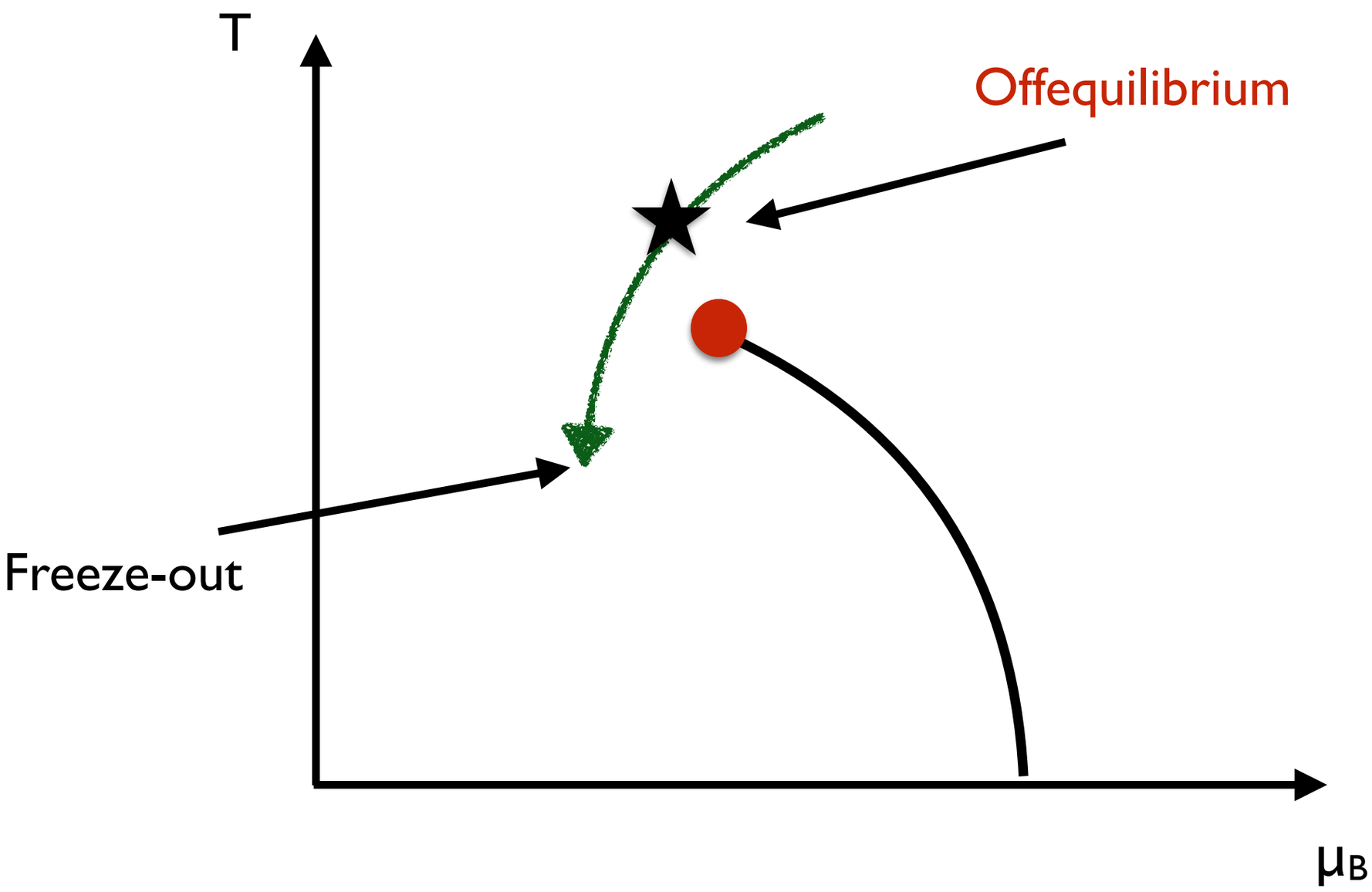
Landau-Khalatnikov, '1954

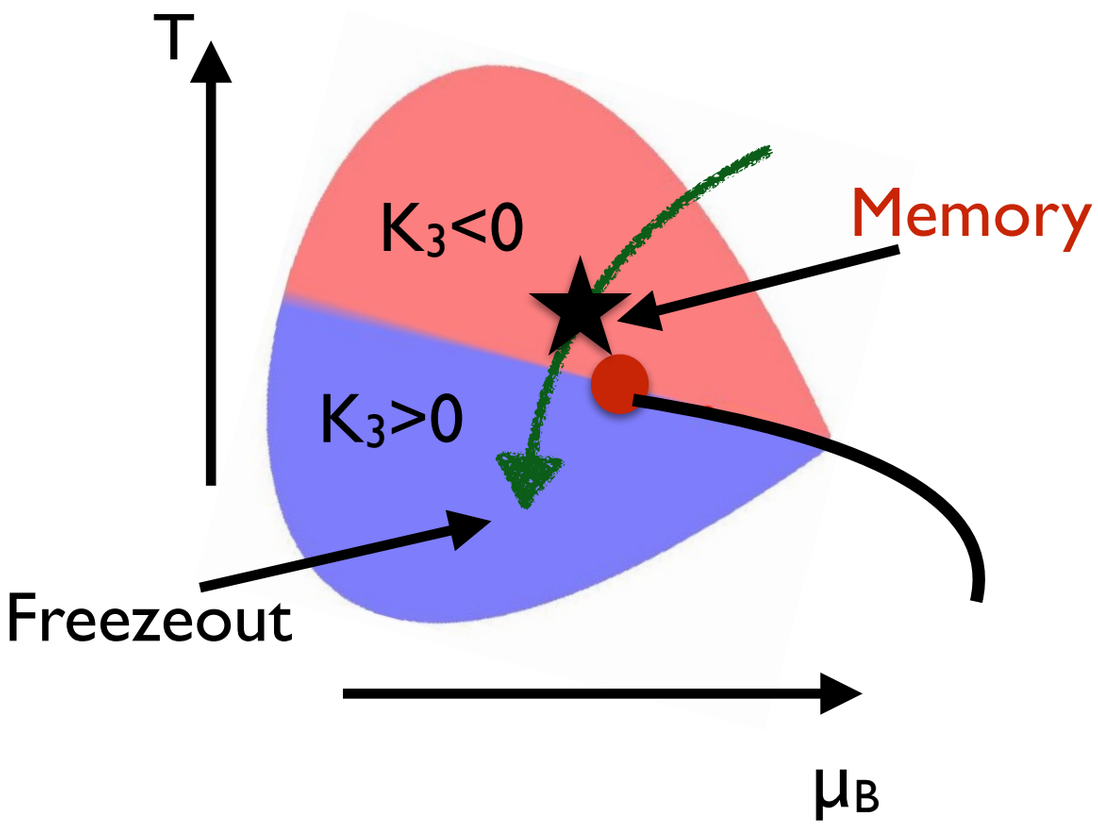
For QCD C.P.

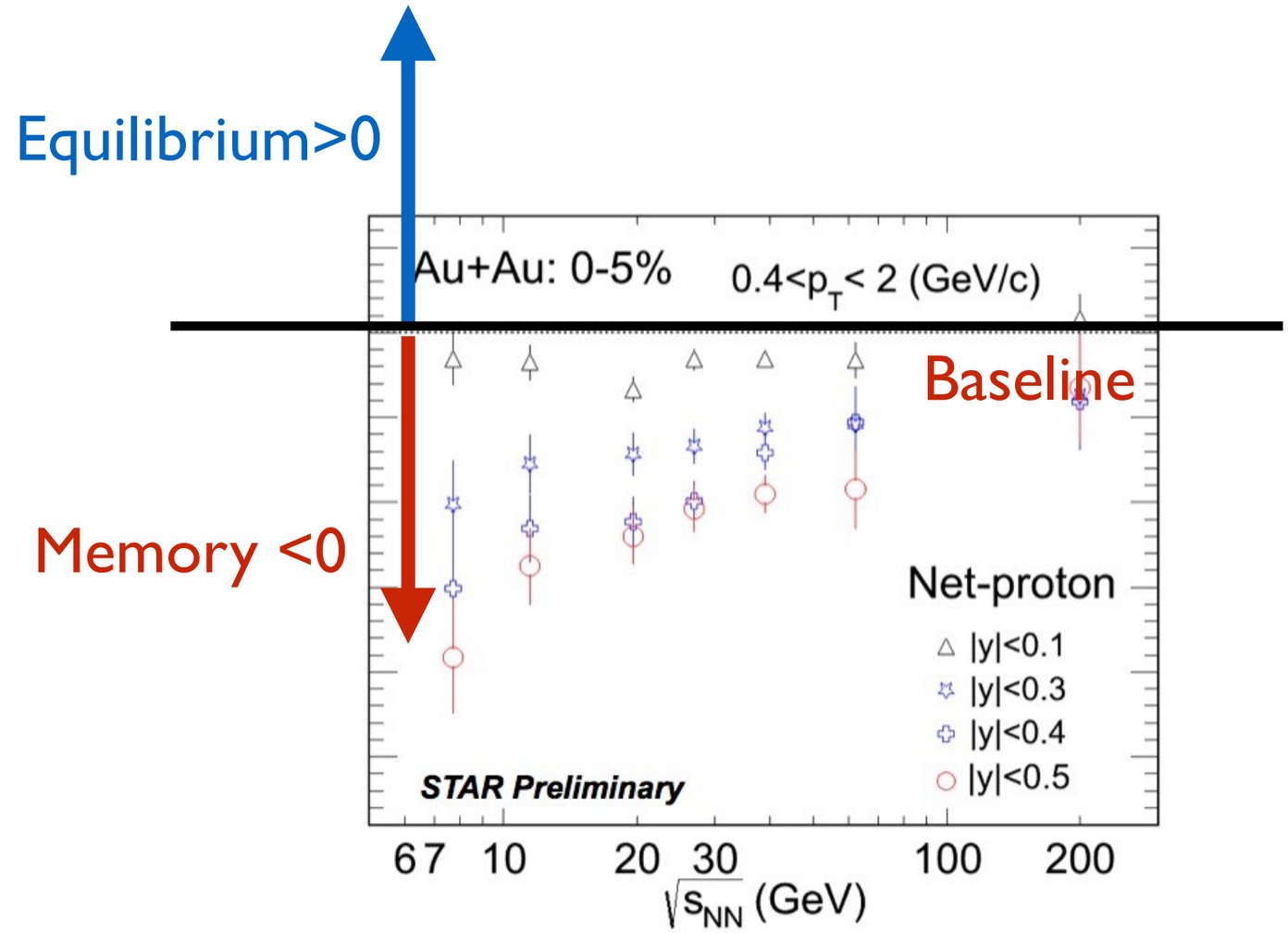
Son-Stephanov, PRD 04'

It is unlikely to see a large fluctuation without seeing off-equilibrium effect for a expanding system.

The evolution of critical fluctuation is offequilibrium near the critical point.







The sign of critical K_3 (third cumulant) is opposite to the equilibrium expectation.

Jiang-Song-Li, PRC' 16; Bzdak-Koch-Strodthoff, PRC' 17

Off-equilibrium cumulants can be qualitatively different due to the "jet lag" of critical fluctuations.

Mukherjee-Venugopalan-YY, PRC' 15

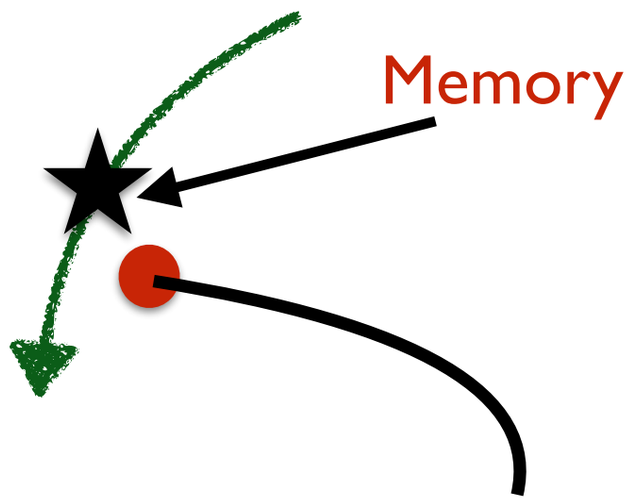
Many studies on off-equilibrium effects of critical fluctuations

Berdnikov-Rajagopal PRD '99 ;
Nahrgang-Leupold-Mishustin-Herold-Bleicher, 1105.1962 ;
Mukherjee-Venugopalan-YY, PRC' 15
Herold-Nahrgang-Yan-Kobdaj, PRC '16;
Sakaida-Asakawa-Fujii-Kitazawa, PRC '17 ;
…

Results depend on many non-universal inputs.

Can we characterize the qualitative feature of "jet-lag" of critical fluctuations?

Observation: the main feature of the offequilibrium evolution is the existence of the turning point ★



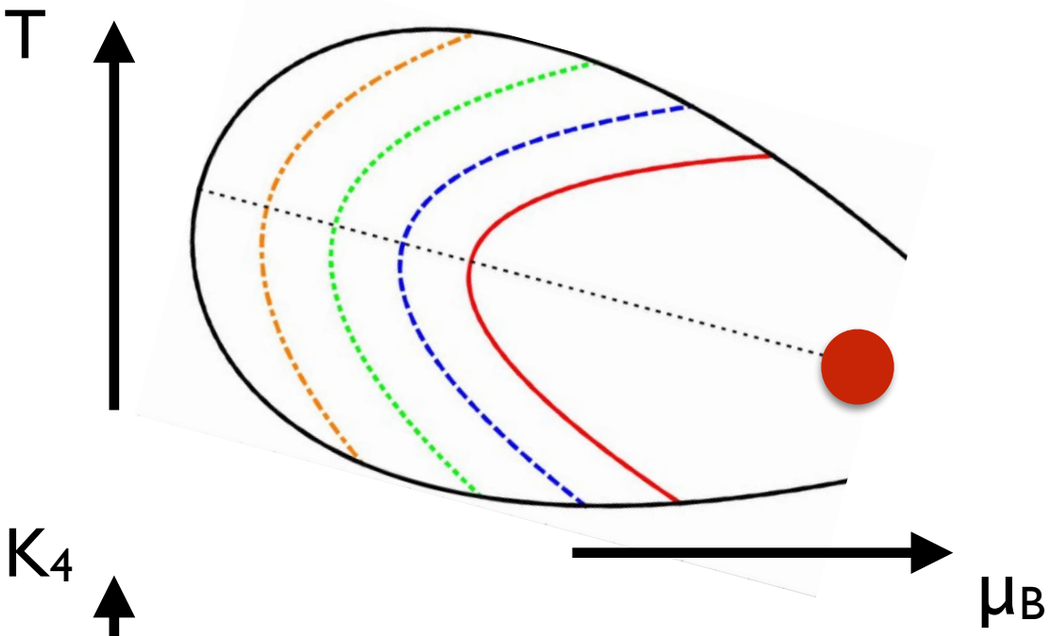
Emergent scales:

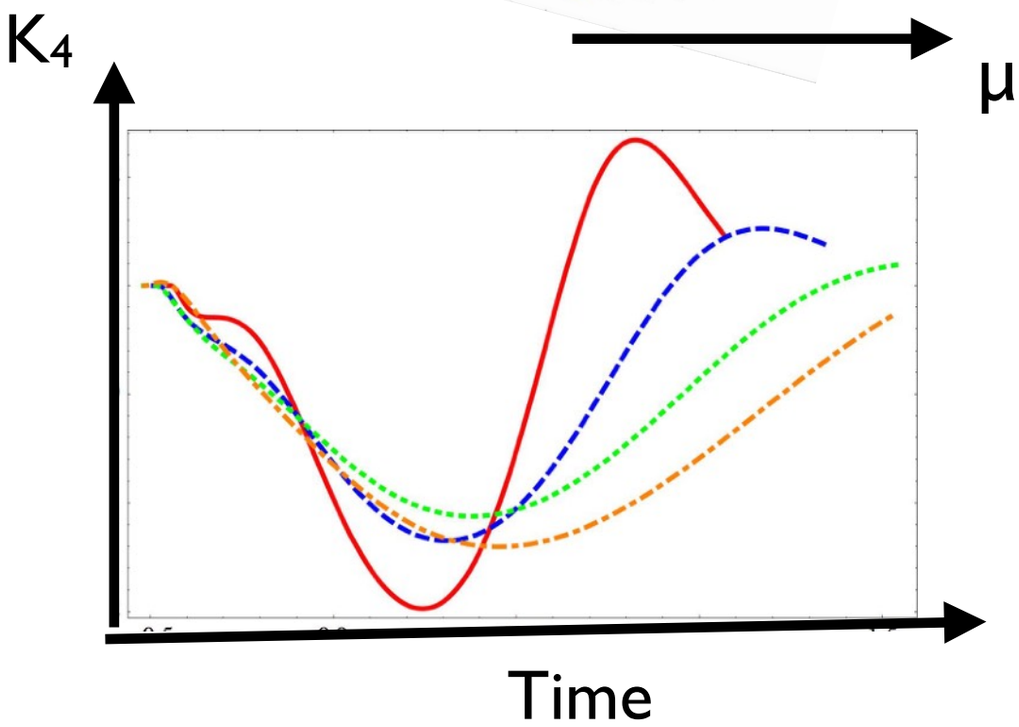
τ_{KZ}: proper time at ★ .

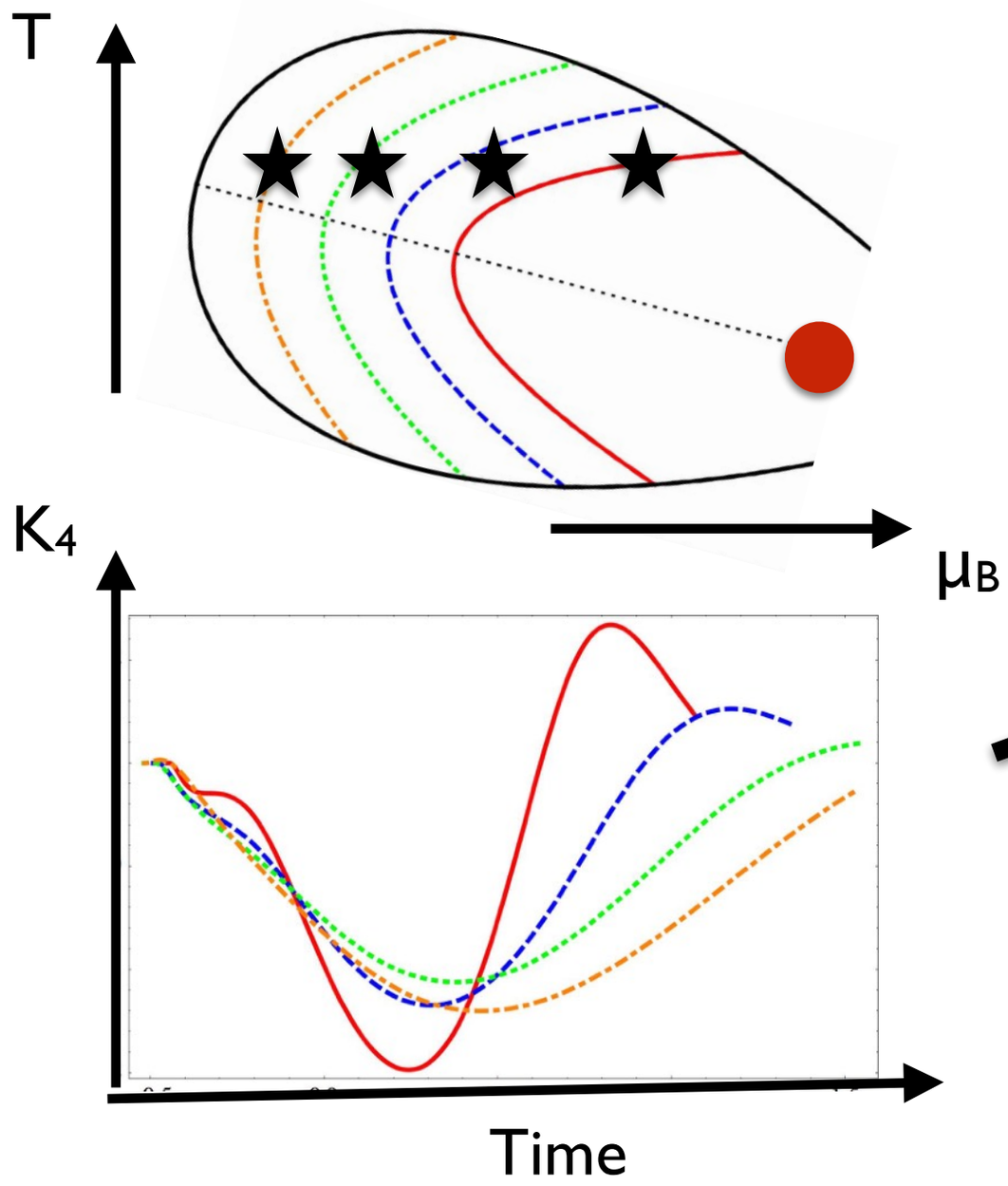
l_{KZ}: correlation length at ★ .

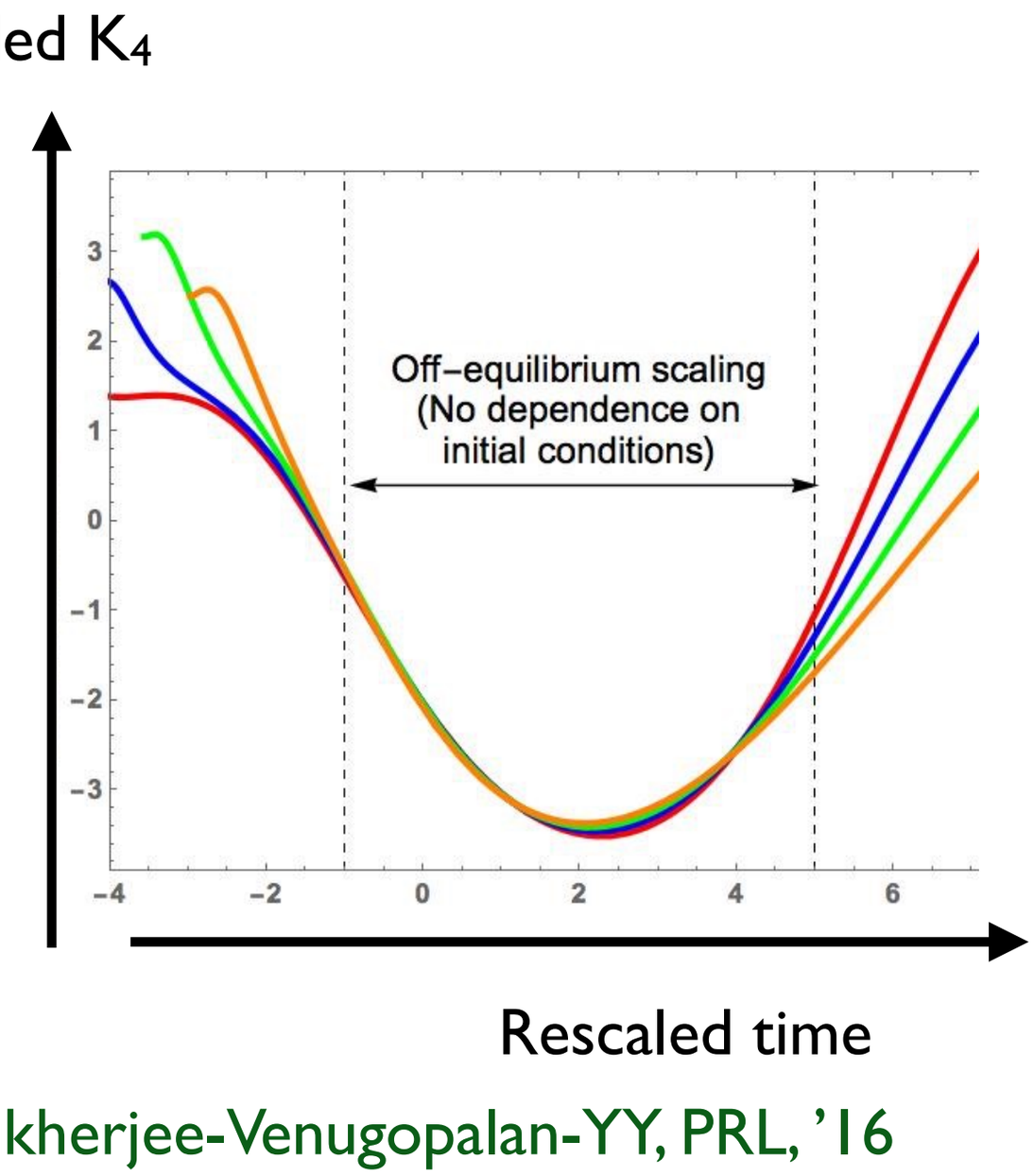
NB: Idea was originated by Kibble (Physics Reports, '80) and Zurek (Nature, '85); Recently, KZ scaling was observed in condensed matter experiments (Hexagonal Manganites, Griffin et al, Phys.Rev.X ' 12; Clark et al, optical lattice, Science' 16)

Can τ_{KZ} and l_{KZ} characterize the evolution of critical fluctuation near the QCD critical point?


T
μB


K4
Time





Mukherjee-Venugopalan-YY, PRL, '16

(New): l_{KZ} also characterizes of the structure of the correlation

Akamatsu-Teaney-Yan-YY, in preparation; Fanglida Yan's talk, Wed.

So far, qualitative feature.

Mapping out the location of the critical point requires quantitative study !

Quantitative framework

Input parameters (the location of C.P., etc)

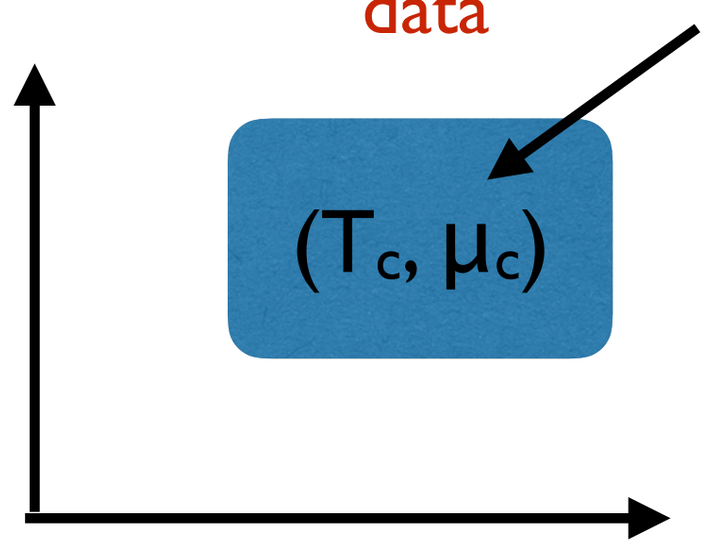
Output

V.S.

BES Data

(RHIC, NA61, ..)

Location favored by data



This is the goal of the BEST collaboration (in US) and achieving this goal requires the efforts from the whole community.

A lot of progress has been made!

Initial state

Chun-Schenke PRC 17'; Okai-Kawaguchi-Tachibana-Hirano PRC 17'; Critelli-Rougemont-Noronha, 1805.00882 .

E.o.S

Fu-Pawlowski-Rennecke-Schaefer PRD '16; Critelli-Noronha-Noronha-Hostler-Portillo-Ratti-Rougemont, PRD '17; Li-Chen-Li-Huang, CPC '18; Parotto et al, 1805.05249, Parotto's poster;

D'Elia talk

Bulk evolution

Denicol-Gale-Jeon-Monnai-Schenke-Shen, 1804.10557 ;

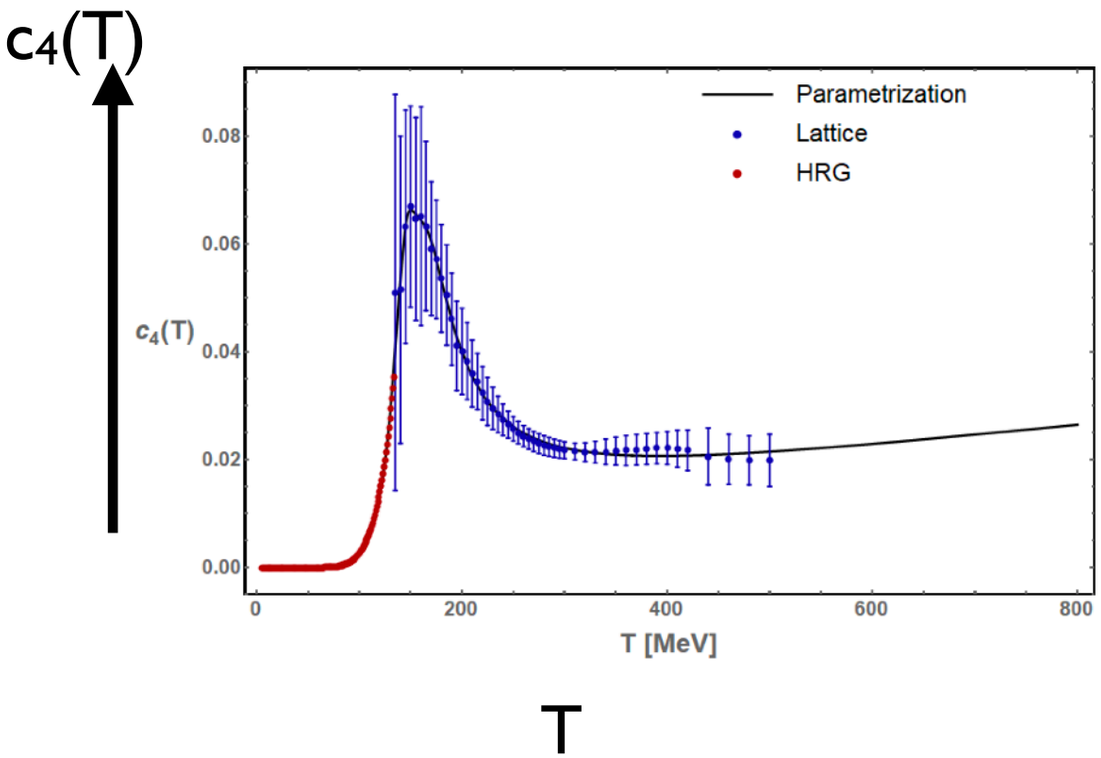
Noronha's talk

Final state

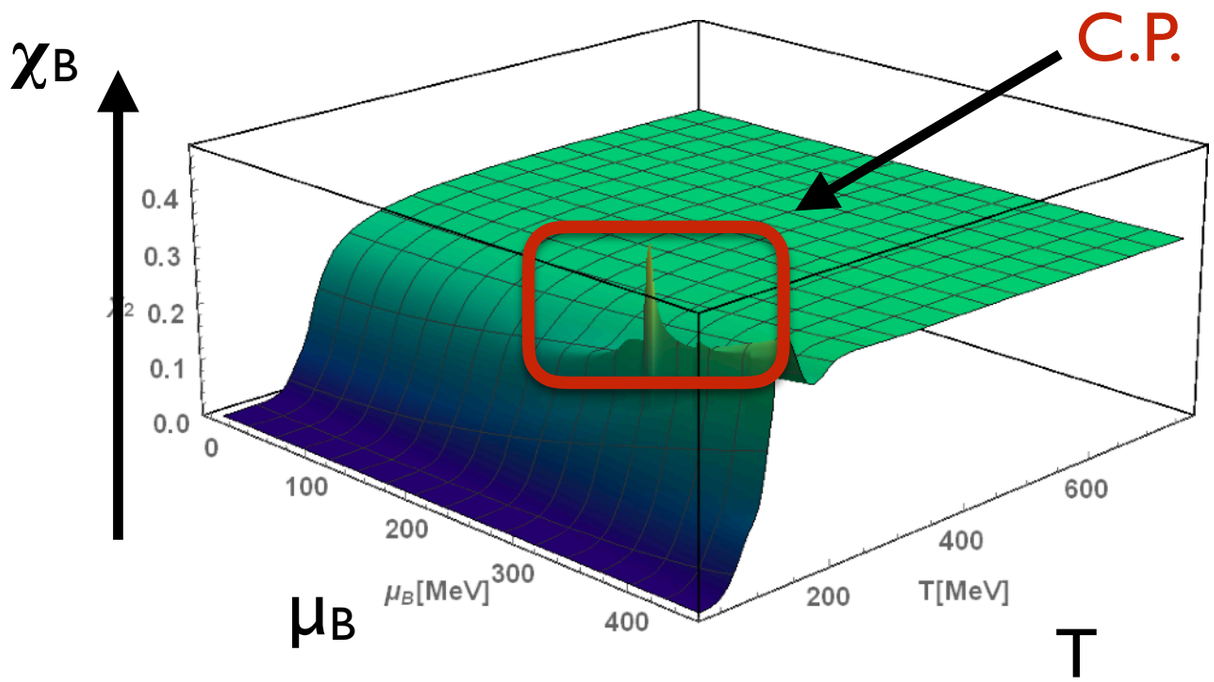
Shuryak-Rincon, 1805.04444, Shryak's talk ;

A family of E.o.S with an Ising-like C.P.

Parotto-Bluhm-Mroczek-Nahrgang-Noronha-Hostler-Rajagopal-Ratti-Schaefer-Stephanov, 1805.05249; Parotto's poster.



Matching lattice results at μ_B



Adding a (Ising-like) C.P. in T-μ_B plane

A first step towards exploring parameter space as favored by the data.

Comment: a similar exercise yet to be done for the transport coefficients.

e.g. Rougemont-Noronha-Noronha, PRL' 15
Mukherjee-Monnai-YY, PRC'17.

However, an important ingredient is missing so far:

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The description of the interplay among hydro. flow and critical fluctuations.

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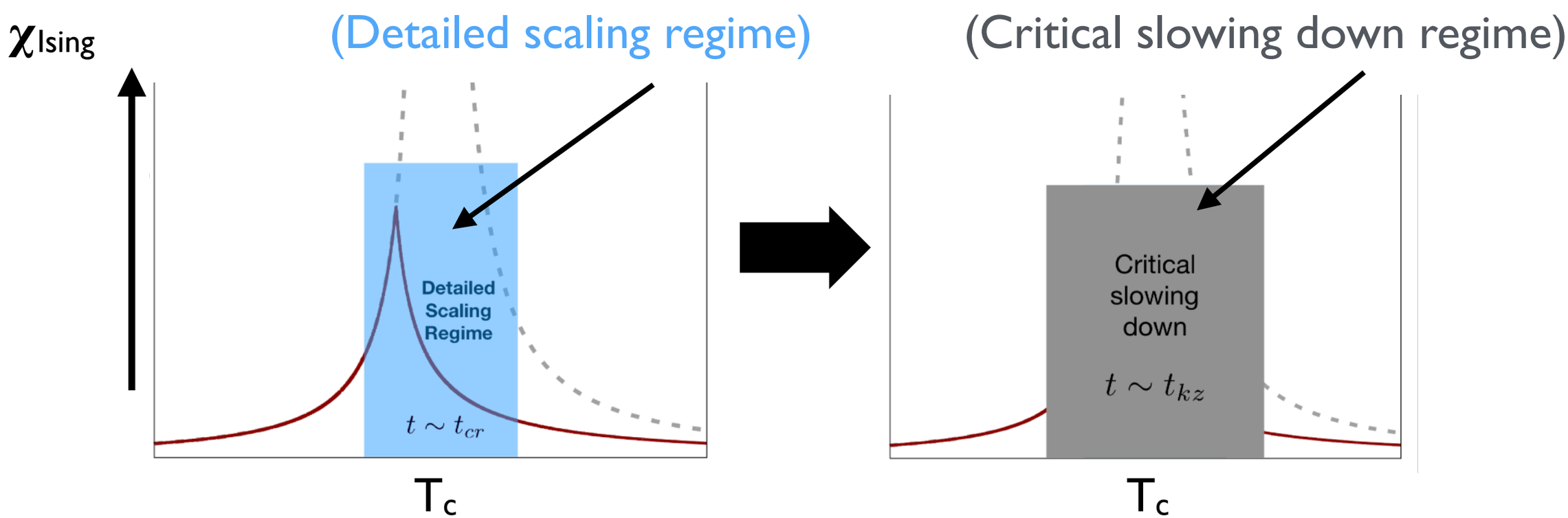
The description of the interplay among hydro. flow and critical fluctuations.

Why? Due to the non-linearity of hydro. (c.f.: turbulence.).

A demonstration: the scaling behavior of equilibrium E.o.S distorted by the off-equilibrium behavior.



Quantitative theory?

From Fanglida Yan's talk, Wed

Three approaches for studying hydro. with thermal fluctuations in general.

I. Stochastic hydro. approach: (adding noise to hydro. equations).

Landau-Lifshitz, Statistical Mechanics; Kapusta-Mueller-Stephanov, PRC '11;…
Nahrgang-Bluhm-Schaefer-Bass, 1804.05728 (with a critical E.o.S);Sakai's talk

(New!) "MUSIC with noise": Mingh, Tues., encouraging and intriguing! .

II. "Effective field theory" (EFT) approach: formulating hydro on the Schwinger-Keldysh contour.

Kovtun-Moore-Romatschke, JHEP 14'; Glorioso-Crossley-Liu, JHEP 17';
Haehl-Loganayagam-Rangamani, 1803.11155, …

Growing interests in a new approach

III: Treating off-equilibrium fluctuations as slow modes in additional to "hydro" modes.

⇒ Coupled deterministic equation.

Kawasaki, Ann. Phys. '70; Andreev, JTEP, '1971; …
"hydro-kinetic", Akamatsu-Mazeliauskas-Teaney, PRC 16, PRC '18 (*Bjorken-flow*);
"hydro+", Stephanov-YY, 1712.10305 (*near a critical point*)

Comment:

For a fluid in a static box, all three approaches agree in linearized regime.

A preliminary analysis based on approach II suggests that "approach III" re-organizes (re-sums) off-equilibrium effects induced by expansion. Lau-Liu-YY, in progress; Lau, Wed.

Application of "approach III" near the critical point: "hydro+".

Stephanov-YY, 1712.10305; Stephanov, Wed

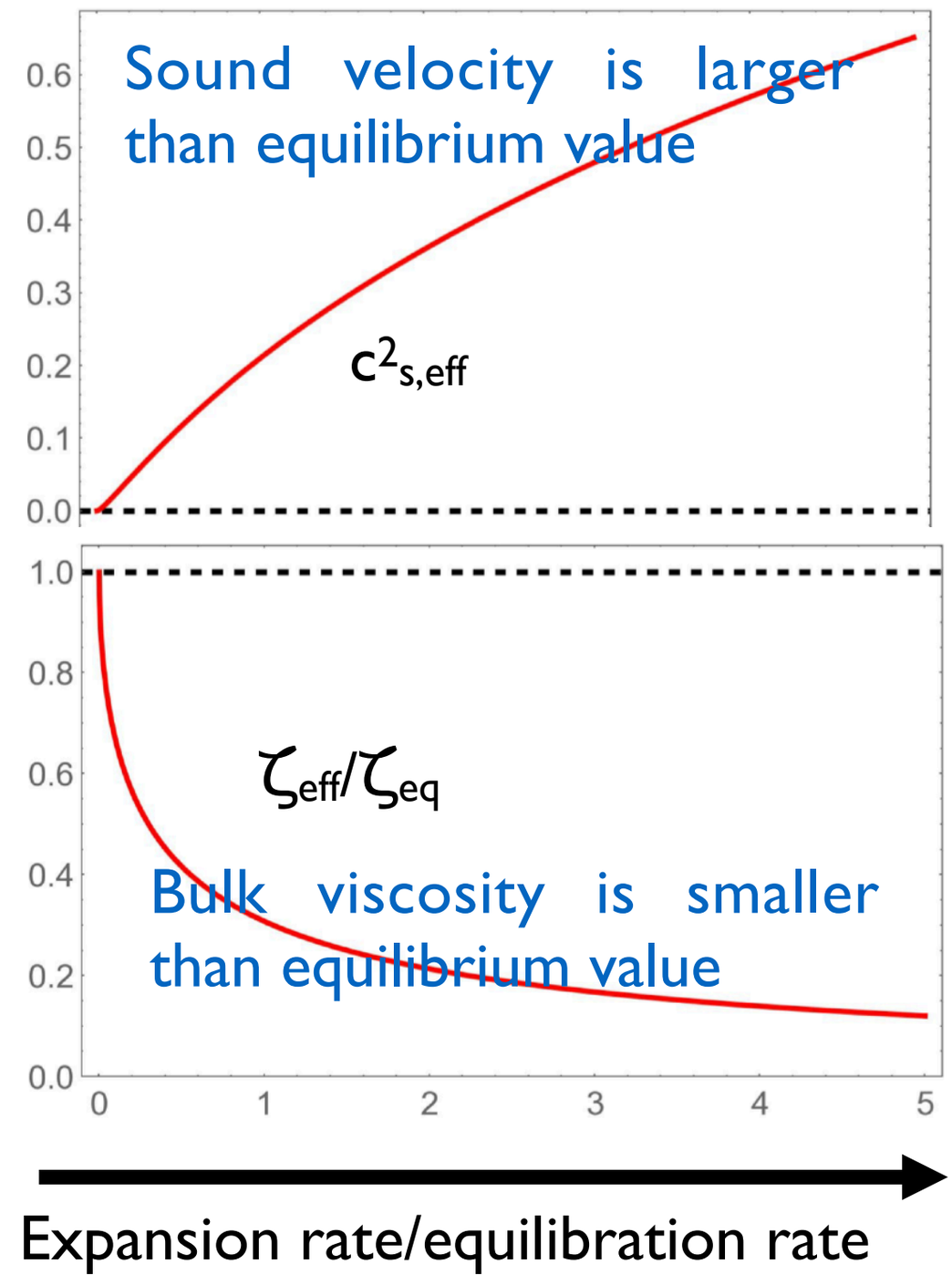
"+": Gaussian fluctuation density per entropy.

$$\phi \sim \langle \delta(\frac{n}{s})\delta(\frac{n}{s})\rangle$$

Hydro: replacing pressure with generalized pressure (which can be derived)

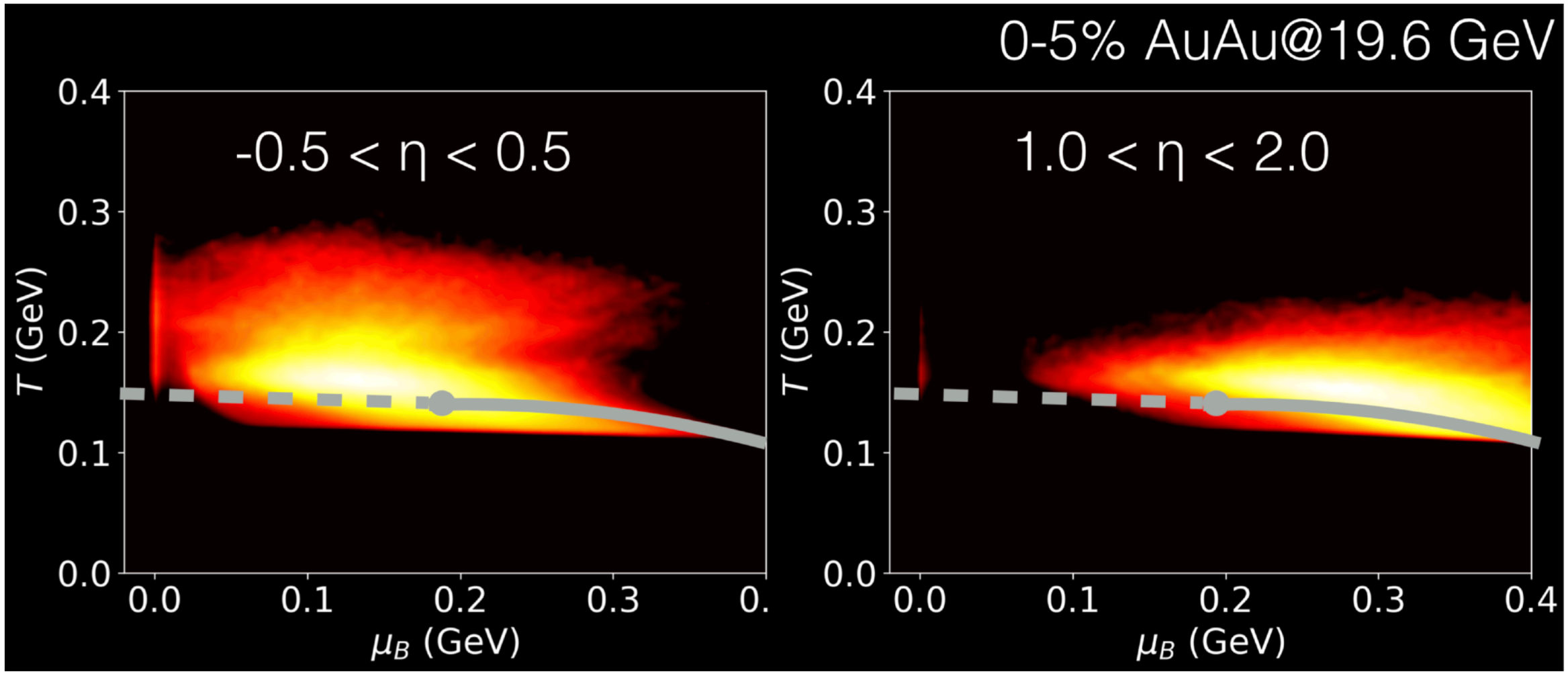
$$p(\epsilon, n) \to p_+(\epsilon, n, \phi)$$

(similar for transport coefficients)



Numerical implementation is under way (Rajagopal-Ridgway-Weller-YY; Huichao Song's group at Peking U.)

BESII: new observables



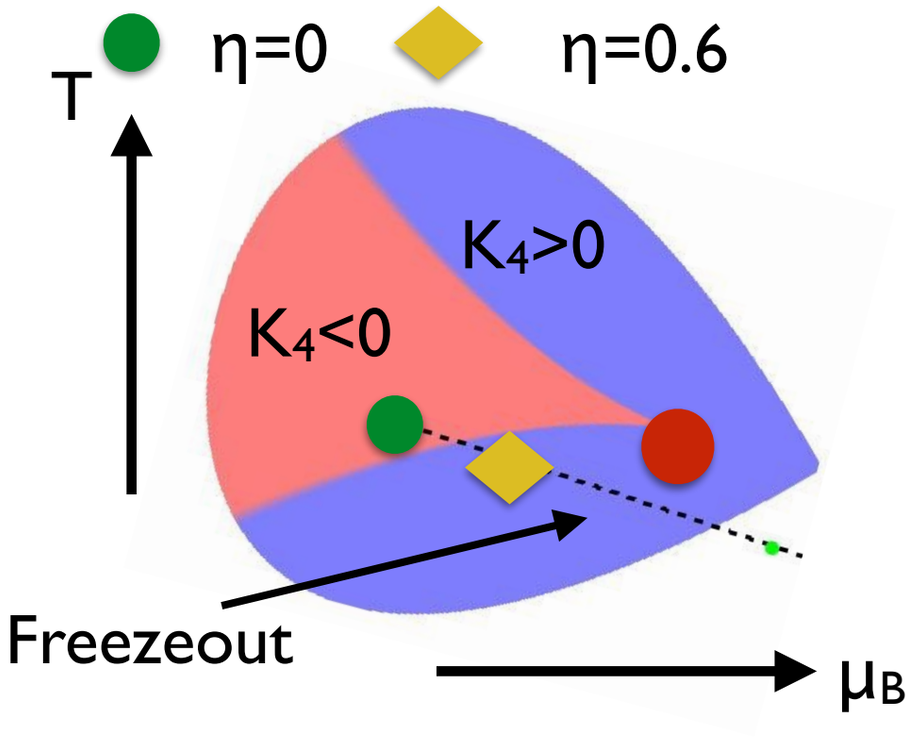
Shen's talk, Wed

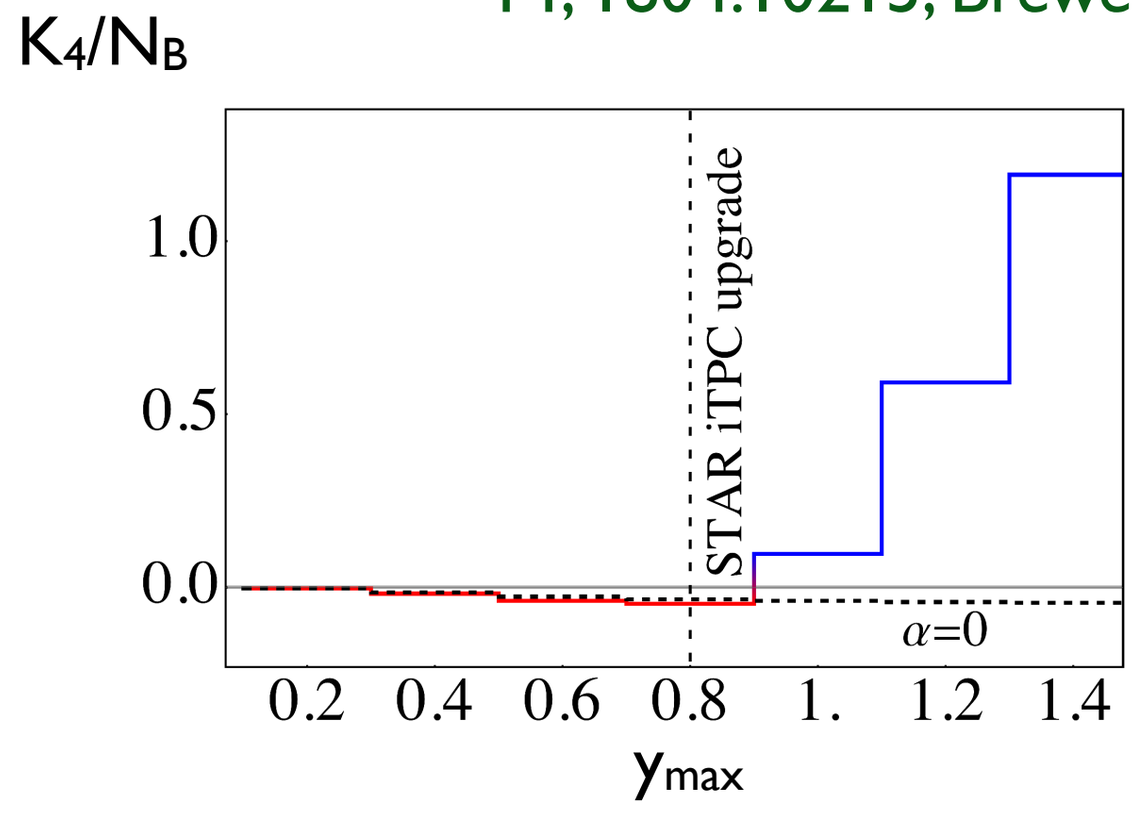
At low $\sqrt{s}$, n_B depends non-trivially on (fluid) rapidity.

Scan the phase diagram through the rapidity dependence?

See Kapusta, Tues for discussion on top RHIC energy

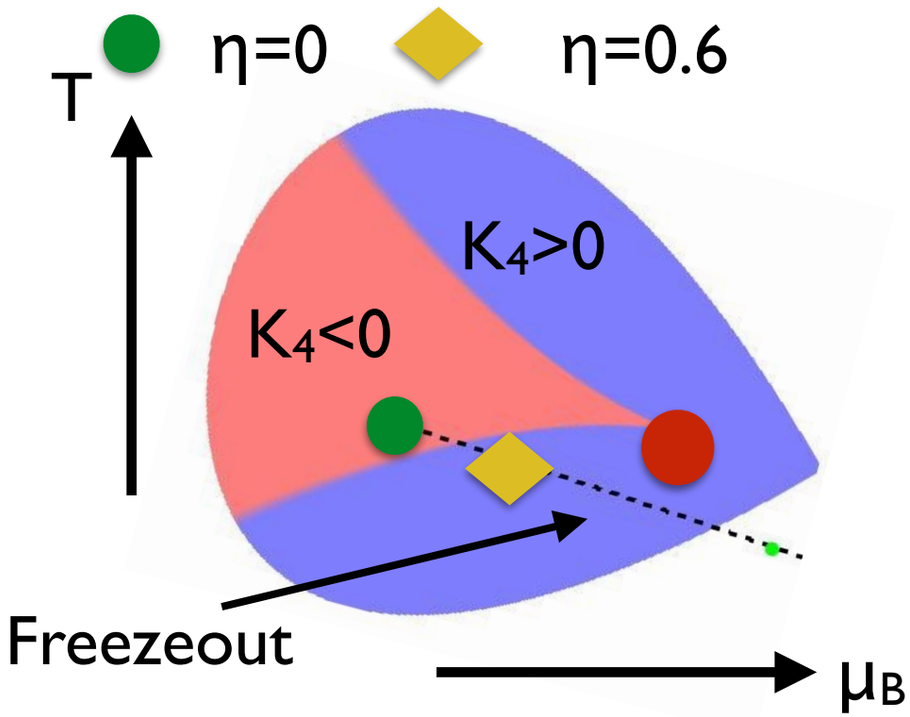
Brewer-Mukherjee-Rajagopal-YY, 1804.10215; Brewer, Wed

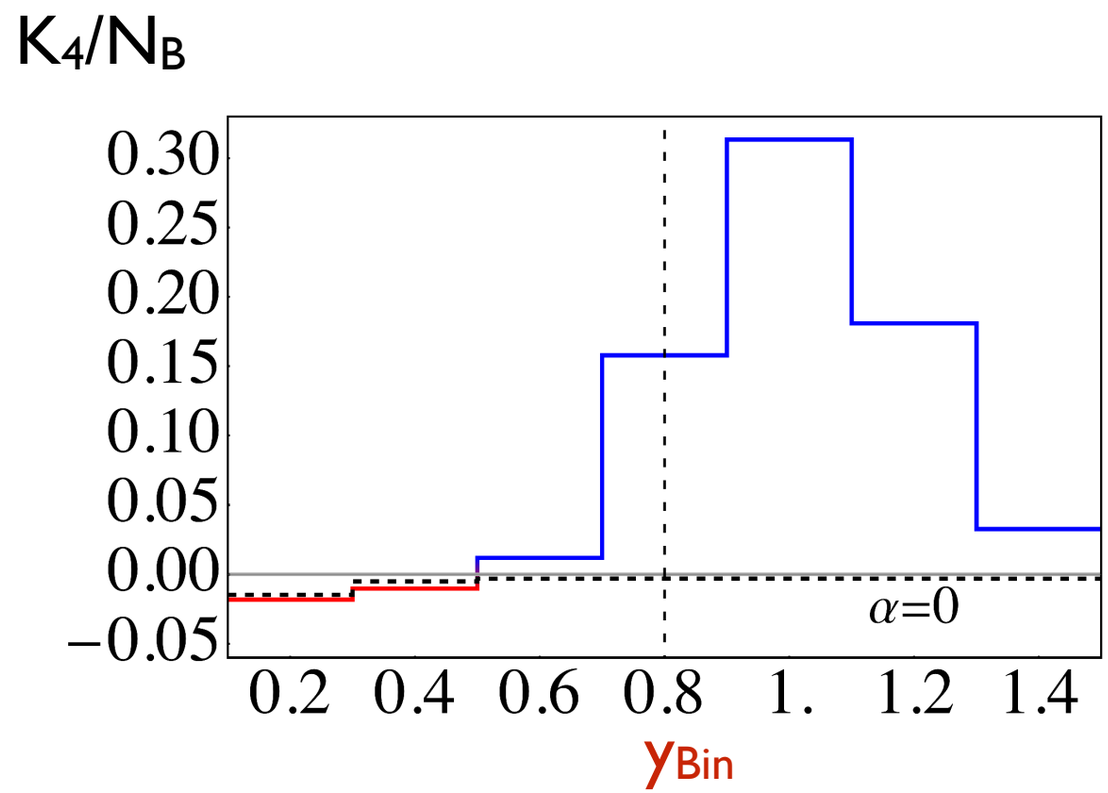




K_4 might depend nontrivially on the rapidity acceptance y_{max} !

However, the integration over full acceptance might average over interesting feature of critical cumulants.





Binning in rapidity gives a more sensitive probe of the structure of critical region!

Brewer-Mukherjee-Rajagopal-YY, 1804.10215; Brewer, Wed

A general lesson: looking into the differential data (New opportunity offered by BESII!).

From qualitative feature to quantitative study: the dynamical modeling is indispensable !

Open questions

Freeze-out,

First order

….

New development

LongGang Pang's talk; Hengfeng Huang's talk (*deep learning*)

Other possibilities

Deng-Schlichting-Venugopalan-Wang, PRD '18;
Pisarski-Skokov-Tsvelik, 1801.08156 ;

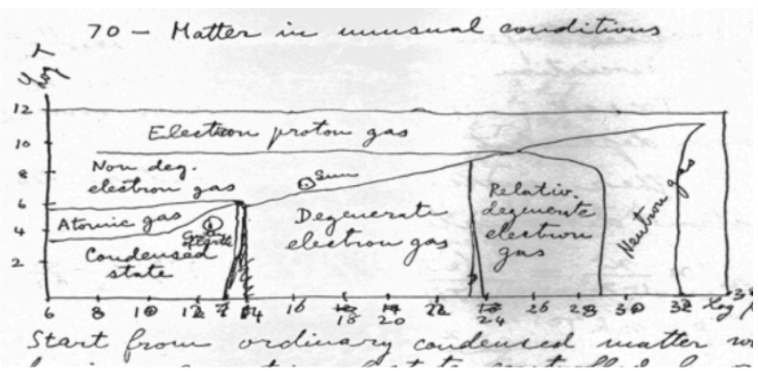
Conclusion and outlook

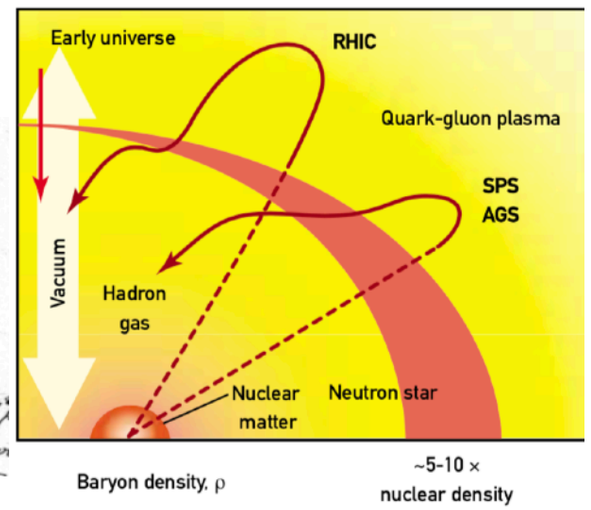
Conclusion

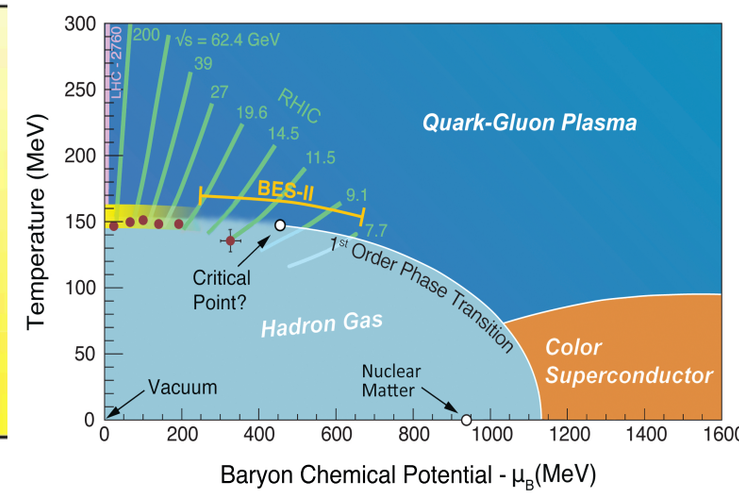
The qualitative feature of the off-equilibrium effects near a critical point can be characterized by the specific emergent length and time scale.

The intriguing interplay between critical fluctuation and hydro, flow can be studied quantitatively.

Studying differential data (together with dynamical modeling) offers new opportunities to explore the Baryon-rich QCD matter.





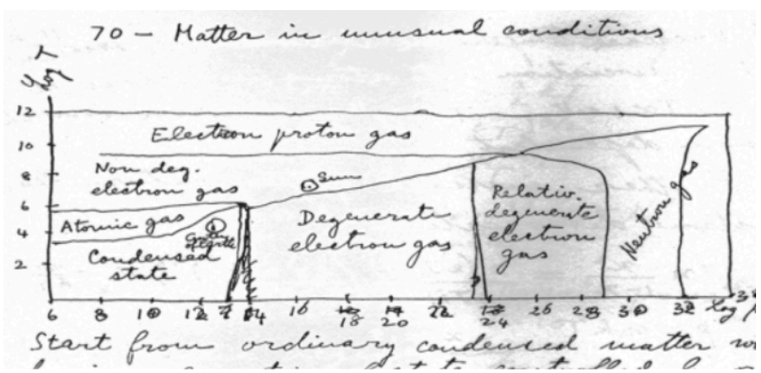


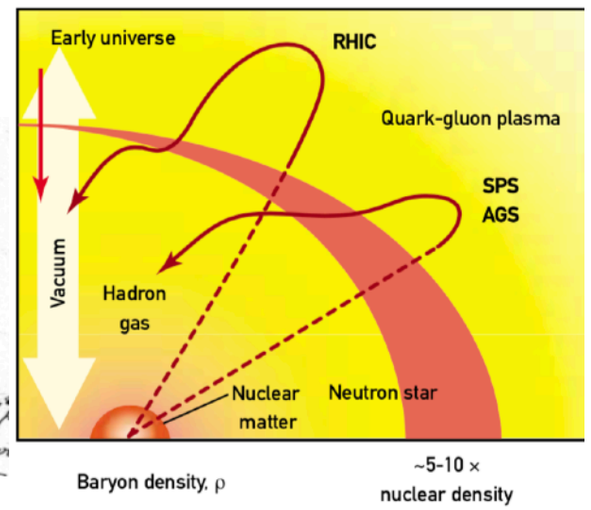
Fermi (1952) 2002 2015 2020+

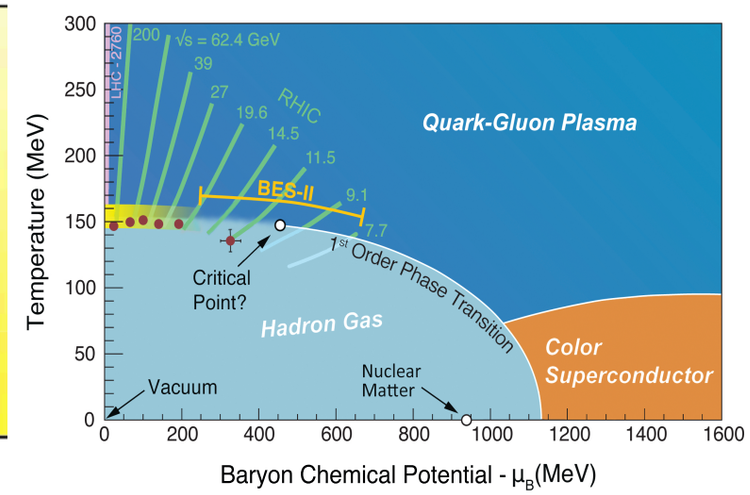
RHIC starts running

BESII

Perspective: it is the right time for theoretical efforts on maximizing the discovery potential of BESII as well other experiments and exploring baryon-rich QCD matter.







Fermi (1952) 2002 2015 2020+

RHIC starts running

BESII

Looking forward to QM19 (welcome to Wuhan btw) and future QMs.

Looking forward to the updated version of the QCD phase diagram in the near future.

Back-up

A general comment

The competition between expansion and equilibration is one of the central themes in heavy-ion physics! (e.g. anisotropy hydro. , small colliding system, …)

Li Yan; Aleksi Kurkela
Strickland, Thur.
Noronha, Thur.

Broad interests:

Carrasco-Hertzberg-Senator, JHEP, '12; Floerchinger-Garny-Tetradis-Wiedemann, JCAP, '16 (Cosmology); Aminov-Kafri-Kardar, PRL '15 (condensed matter physics)

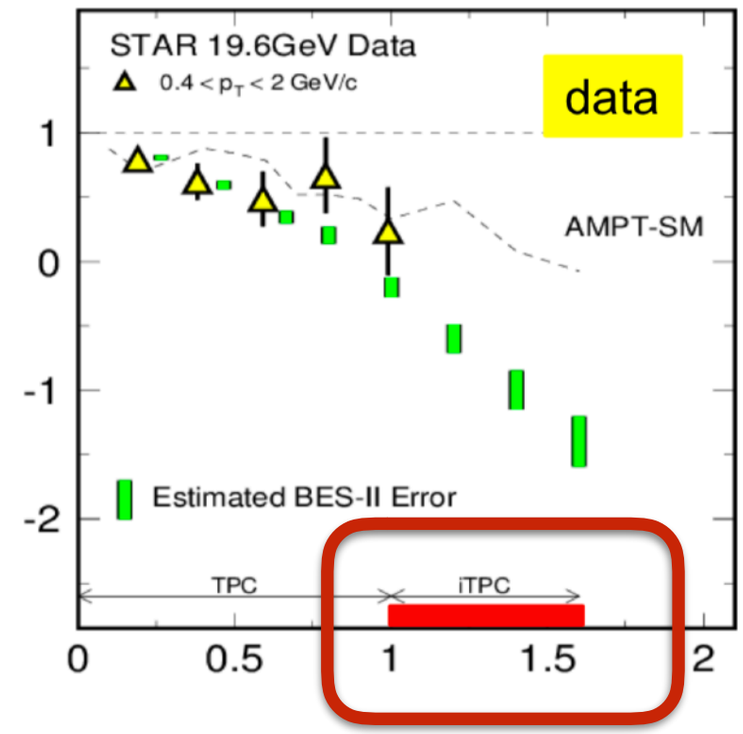
Looking forward to fruitful cross-fertilization among different subfields!

News alert!

Next year (2019), beam energy scan phase II (BESII) will kick off to search for the QCD critical point. (Exactly 150 years after Andrews coined the term "the critical point".)

Unprecedented high statistics.

Upgraded detector with extended rapidity acceptance. ("high resolution camera")



Qian Yang's talk, Wed
Reed's talk

The creative use of this "high resolution camera"?

I apologize for my omissions.

I thank

…

General comments

Off-equilibrium effect is important near the crossover and affects balance function.

Ling-Stephanov-Springer, PRC '13
Pratt-Kim-Plumberg, 1712.09298

"effective η" is smaller when fluct. is offequilibrium (related to hydrodynamic tail).

The competition between expansion and equilibration is one of the central themes in heavy-ion physics! (e.g. anisotropy hydro. , small colliding system, …)

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Fruitful cross-fertilization among different subfields!

Key equation

Einstein, 1905, (Brownian motion,)

$$\text{Relaxation rate} \propto \frac{\text{transport coefficient}}{\text{magnitude of fluctuation}}$$

Equilibration rate of diffusive modes (such as baryon density):

$$\Gamma_D(k) = \frac{\lambda}{\chi} k^2$$

Larger fluctuation, smaller equilibration rate.

Near the critical point ⇒ critical slowing down.

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$$\Gamma_\xi = \Gamma_D(k = \xi^{-1}) \sim \frac{\xi}{\xi^2} (\xi^{-1})^2 \sim \xi^{-3}$$

For QCD C.P.

Son-Stephanov, PRD 04'

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