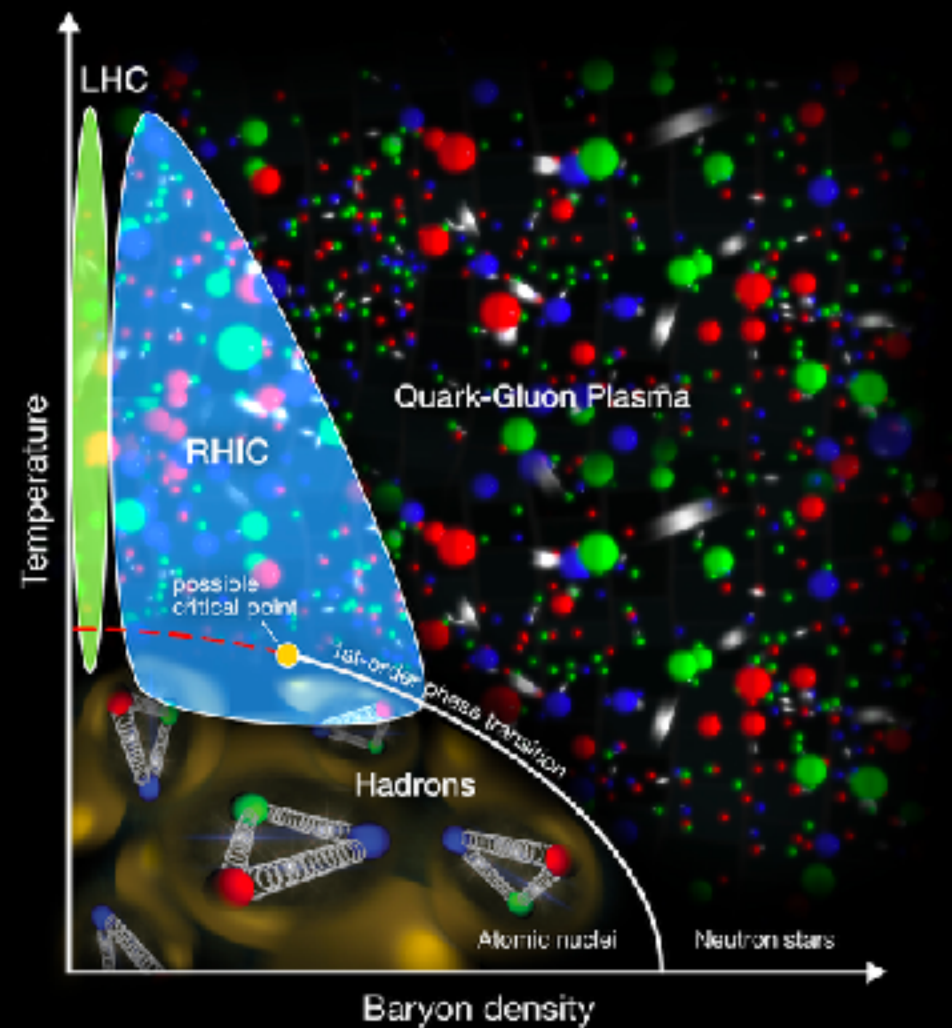
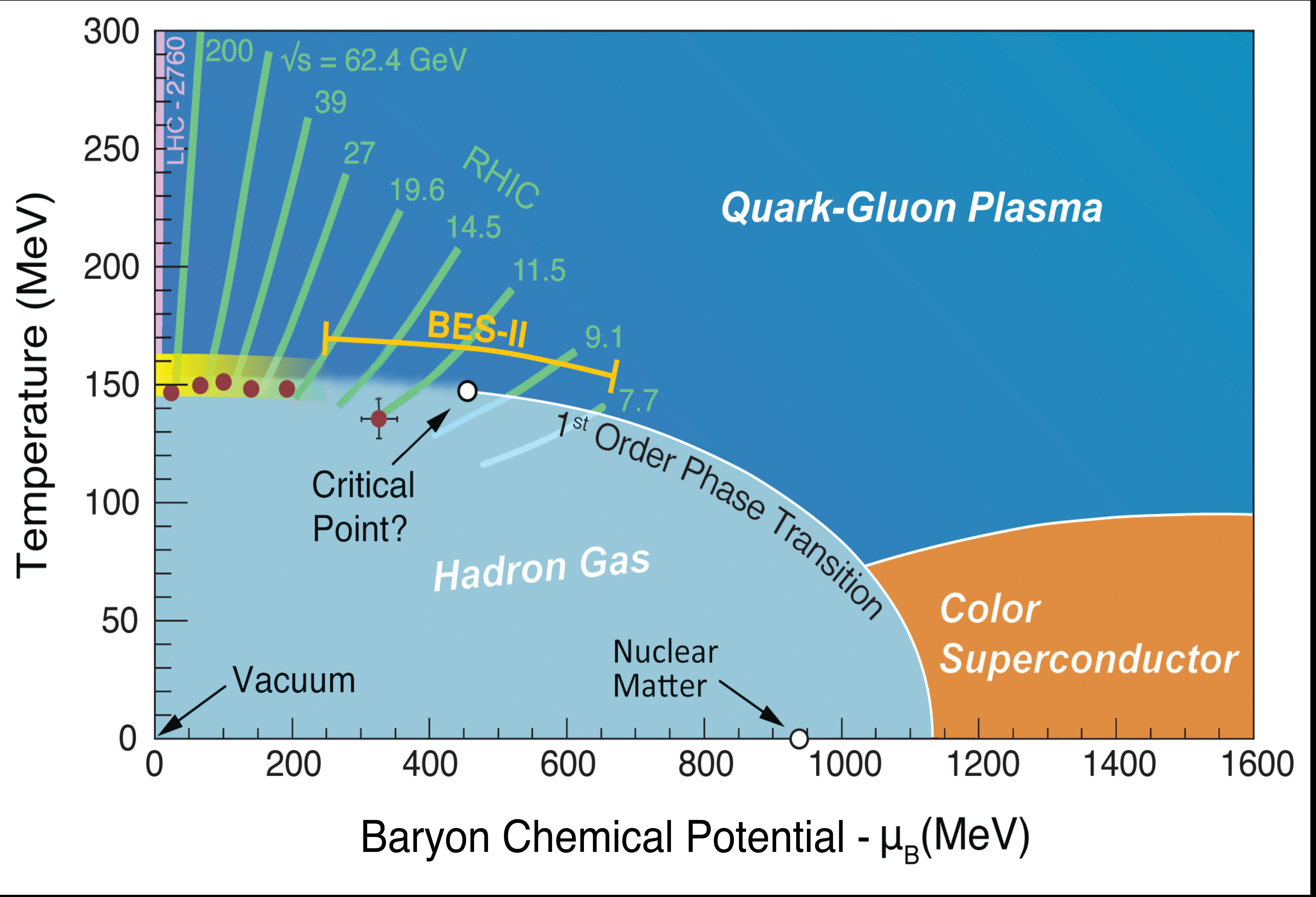
Search for the QCD critical point: new angles and new theoretical developments



BEST COLLABORATION

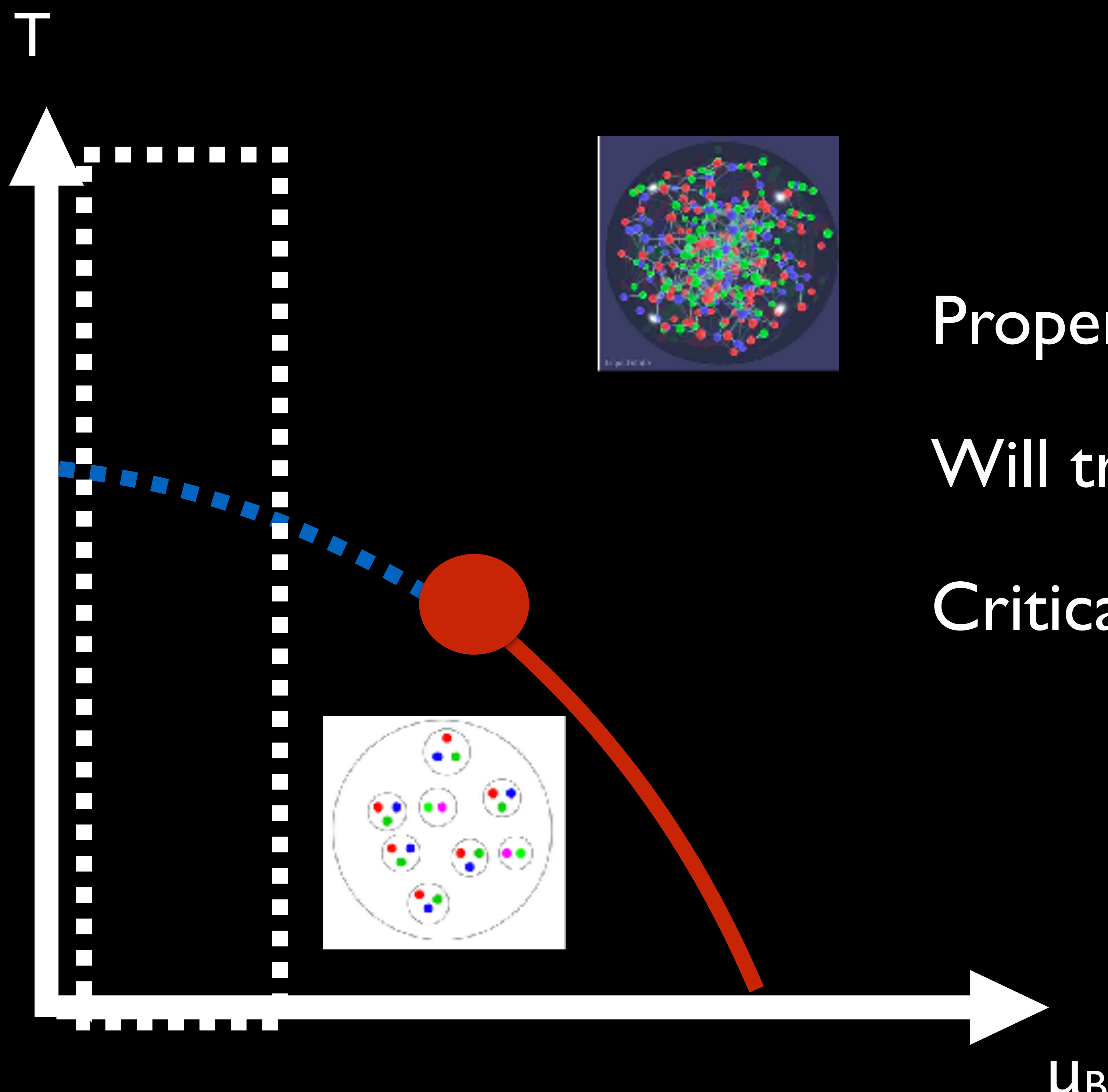
Yi Yin

iHIC workshop, Tsinghua, Apr.9, 2018



Temperature (MeV)
Baryon Chemical Potential - μB(MeV)
LHC - 2760
200
√s = 62.4 GeV
39
27
19.6
14.5
11.5
9.1
7.7
RHIC
BES-II
Quark-Gluon Plasma
Critical Point?
1st Order Phase Transition
Hadron Gas
Color Superconductor
Vacuum
Nuclear Matter
0
50
100
150
200
250
300
0
200
400
600
800
1000
1200
1400
1600

Sailing form the safe landscape

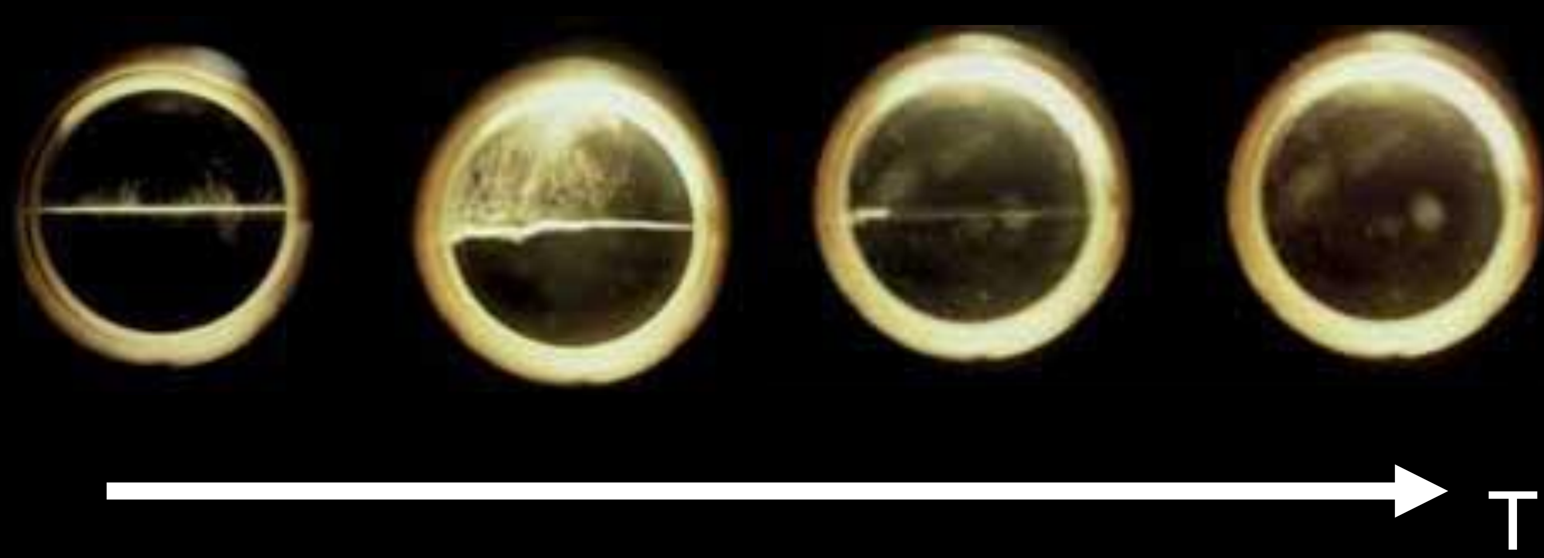


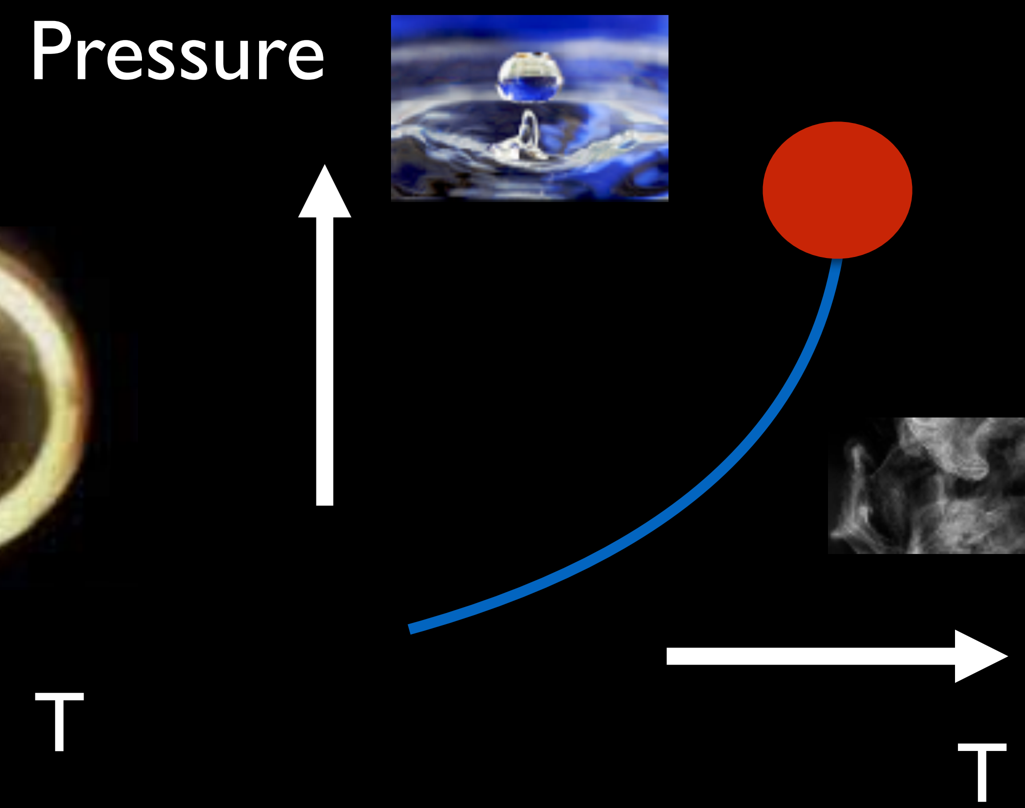
Properties of Baryon rich QGP?

Will transition become stronger?

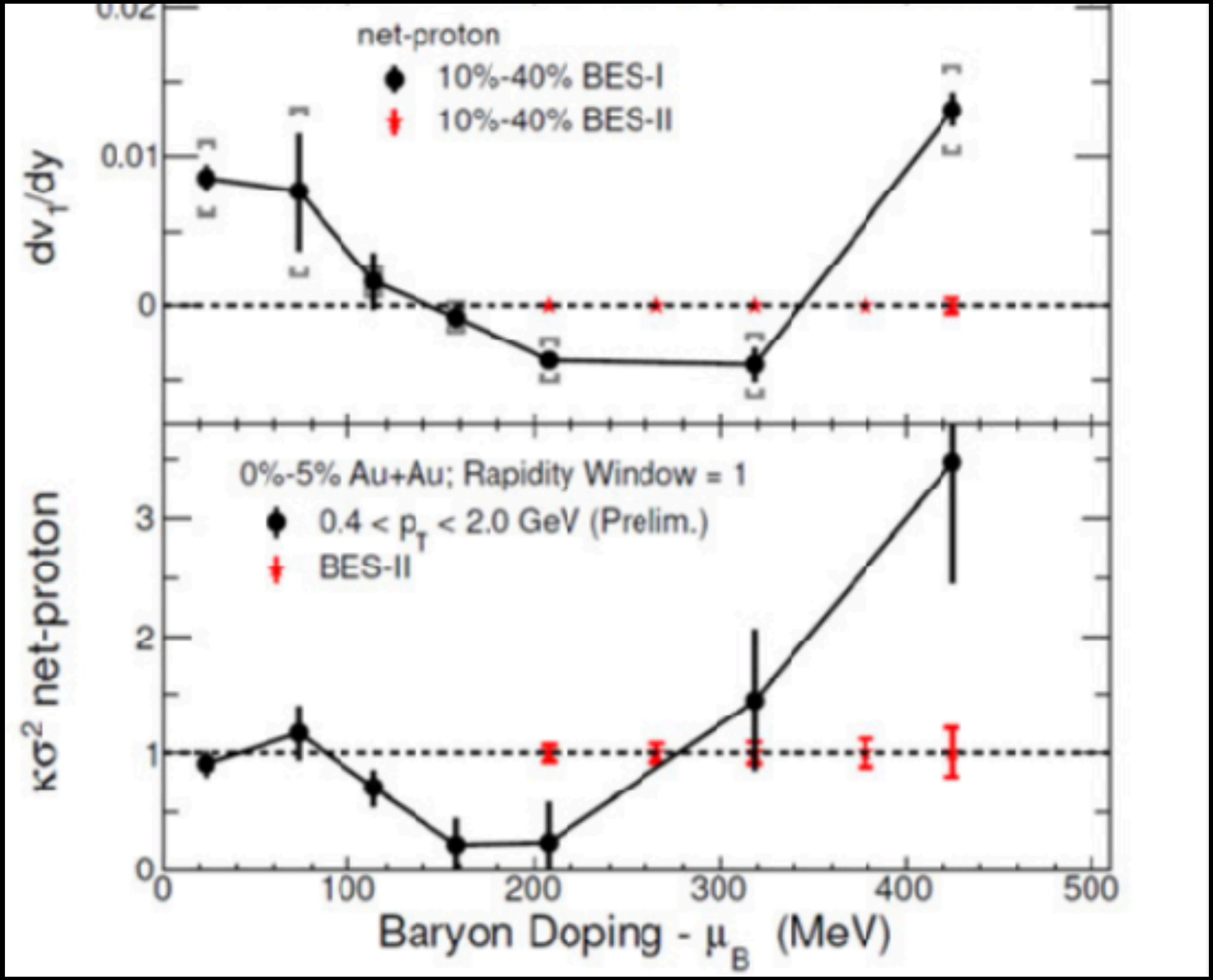
Critical point?

In 1869, Andrews coined term “the critical point” in his Bakerian lecture.





In the 150th anniversary (2019) of Andrew’s lecture, BESII will kick off to search for the QCD critical point.



Results from BESI: interesting, encouraging (but error bar is large).

BESII: unprecedented precision.

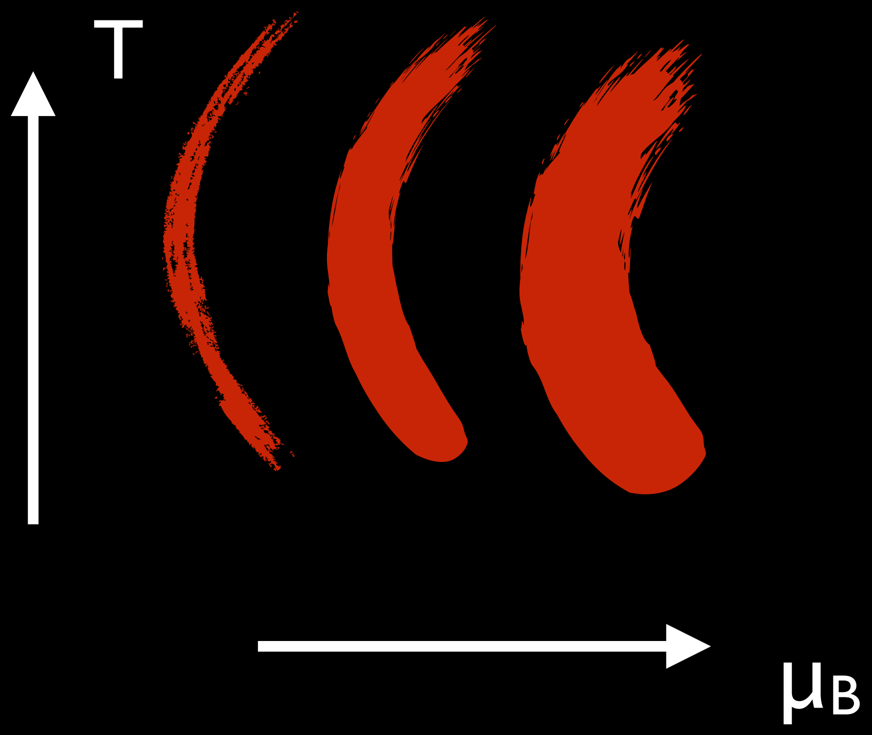
Part I

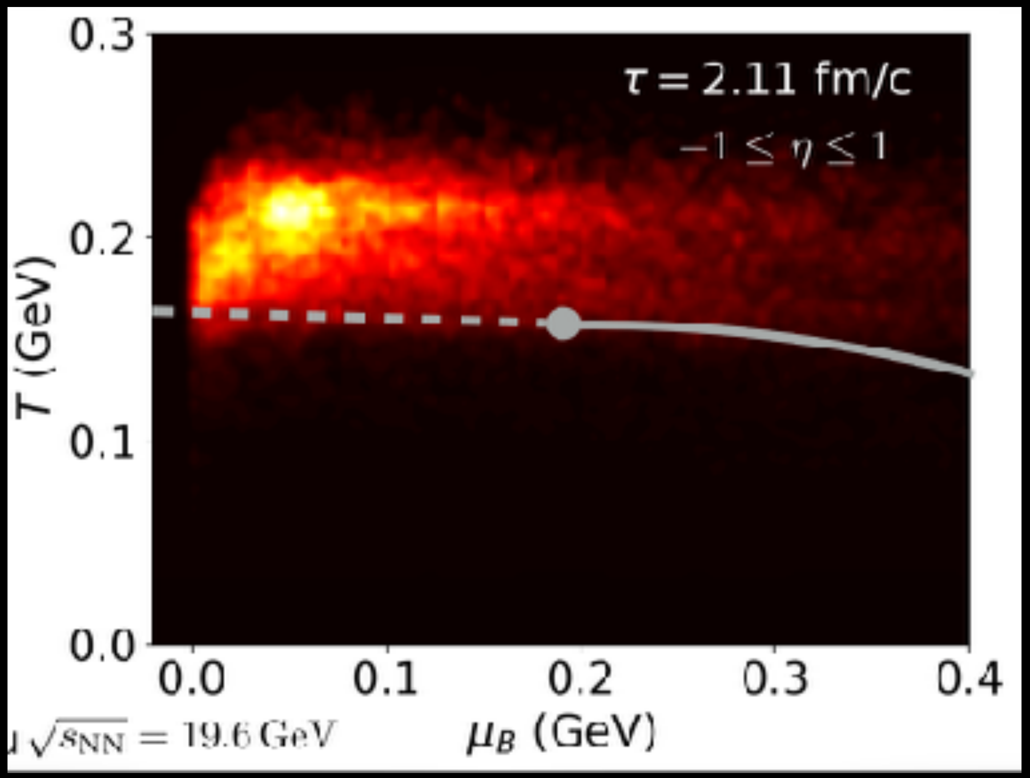
Can we facilitate new angles to search for the QCD critical point and can we take the advantage of BESII?

(J. Brewer, S. Mukherjee, K. Rajagopal and YY, in preparation)

J. Brewer, Grad. of MIT

Basic idea





Hydro. Simulation: Chun Shen and B. Schenke

The fireball at a given $\sqrt{s}$ evolves as a "worldsheet" (in contrast to a "worldline") swiping the phase diagram.

When freeze-out happens, the fireball at different spatial rapidity η_s will have different μ_B .

η_s is related to hadron momentum rapidity y. We therefore could explore the phase diagram through y-dependence.

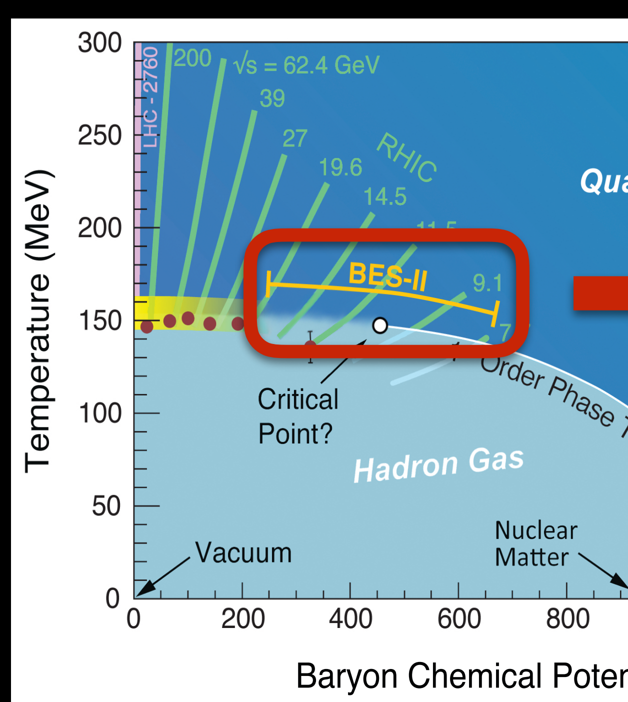
Counting baryon (e.g. proton) number fluctuations.

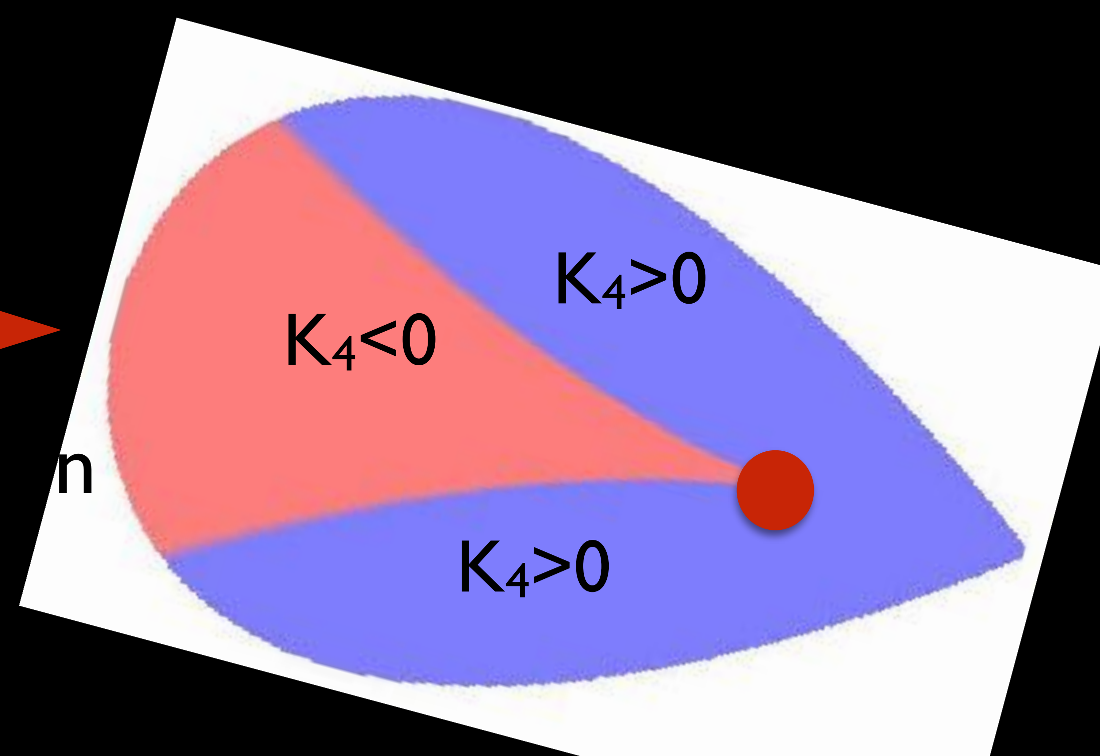
$$K_2 \sim \sum_{\text{event}} (N_B - \bar{N}_B)^2 \qquad\qquad K_4 \sim \sum_{\text{event}} (N_B - \bar{N}_B)^4$$

Higher (non-Gaussian) cumulants, K4 are more sensitive to the growth of the correlation length ξ.

$$K_2 \sim \xi^2 \qquad\qquad K_4 \sim \xi^7$$

The sign of K_4 changes in a specific way as we move around the critical point.





Our model (for illustrative purpose)

A freezeout formula

Stephanov, PRL 09'

$$K_{4,p} \sim K_{4,M} \times (\#\text{ of proton coupleds to M})^4$$

Introducing α to parametrize η_s-dependence of μ_B on f-curve.

$$\mu_B(\eta_s) = \mu_B^0 + \alpha\,\eta_s^2\,, \qquad \eta_s \le \eta_{\max}$$

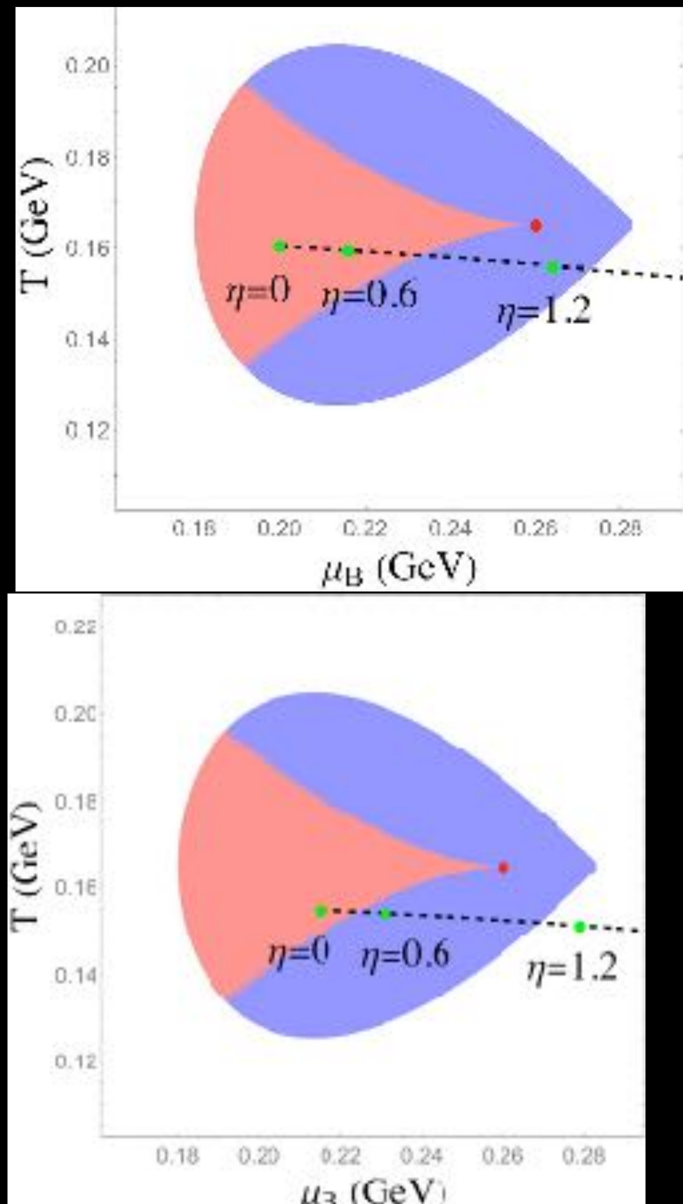
e.g. F. Becattini et al, CPOD proceedings 07'

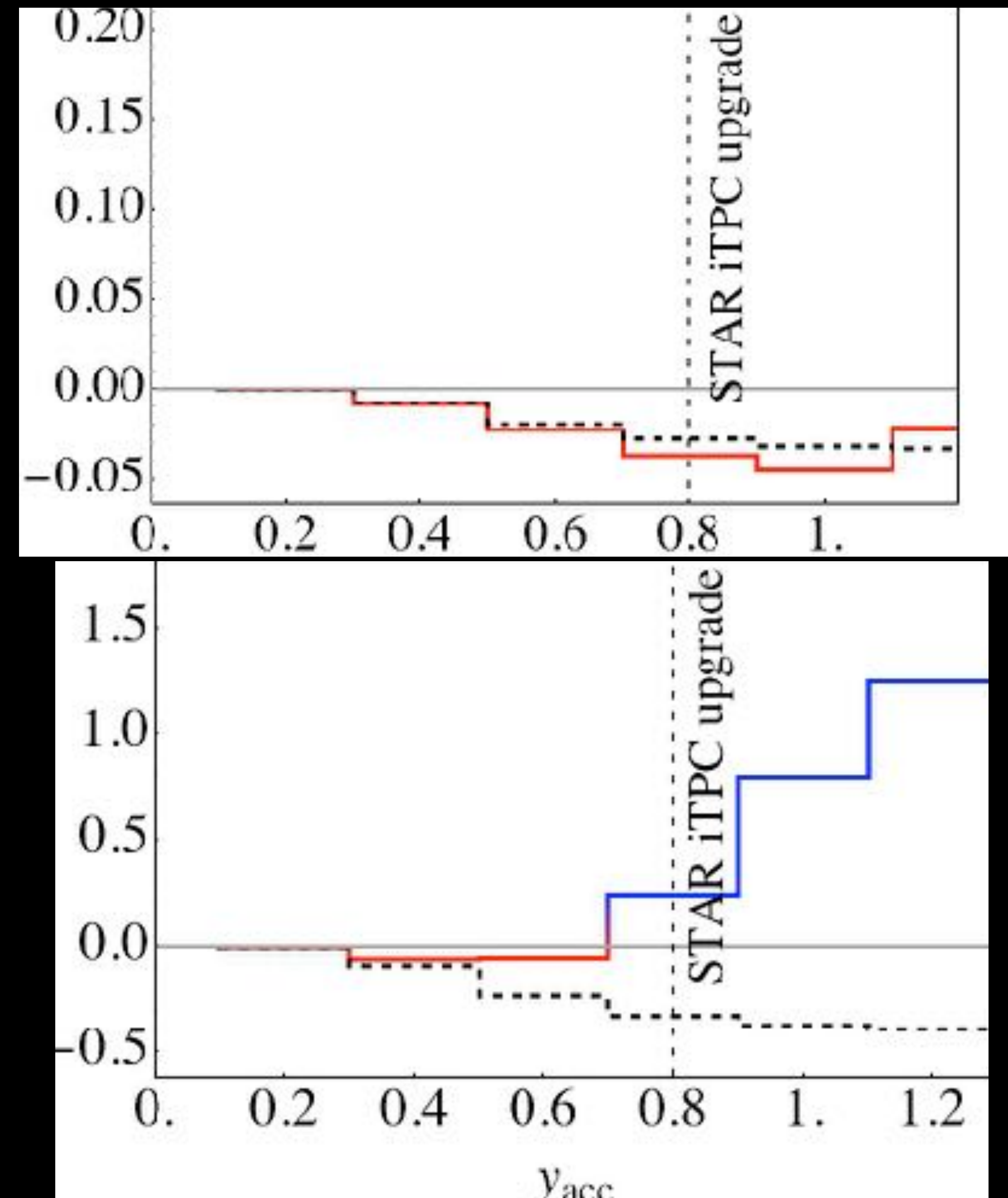
For example, for $\sqrt{s}$=19.6 GeV, we estimate $\alpha \approx 44$ MeV.

Focus on ω_4 (=1 for Poisson distribution):

$$\omega_4 = \frac{K_{4,p}}{N_p}$$

Dependence on y_{acc} (how many protons included)

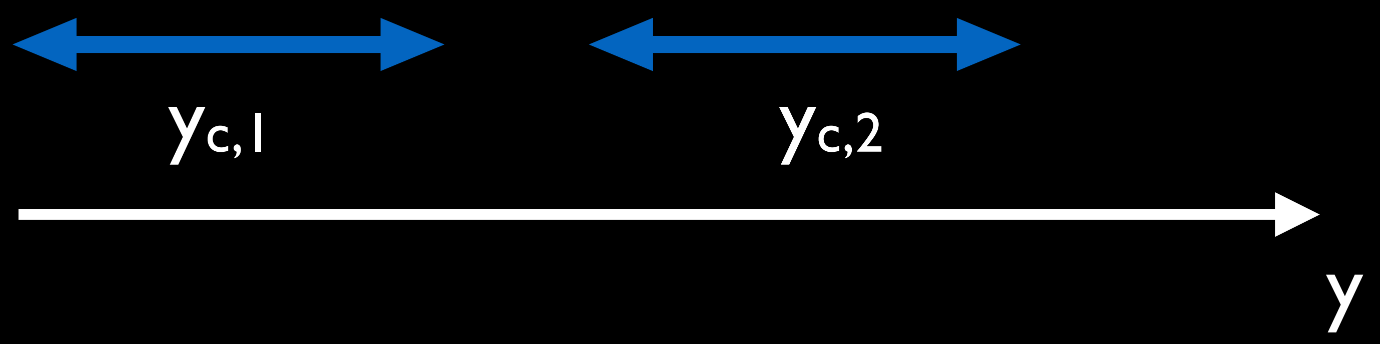




Non-trivial dependence.

Some information is blurred due to integration over y

Measure proton fluctuations from each rapidity bin.

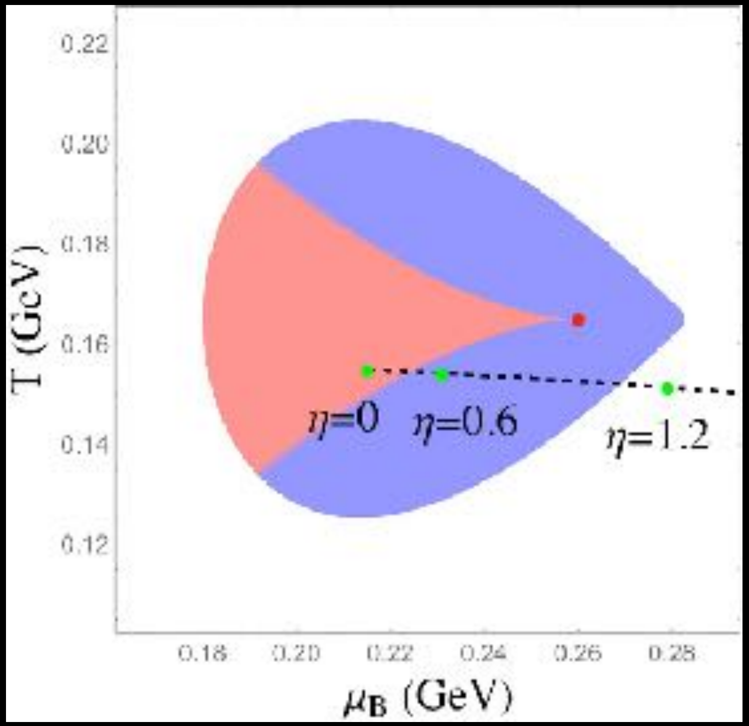


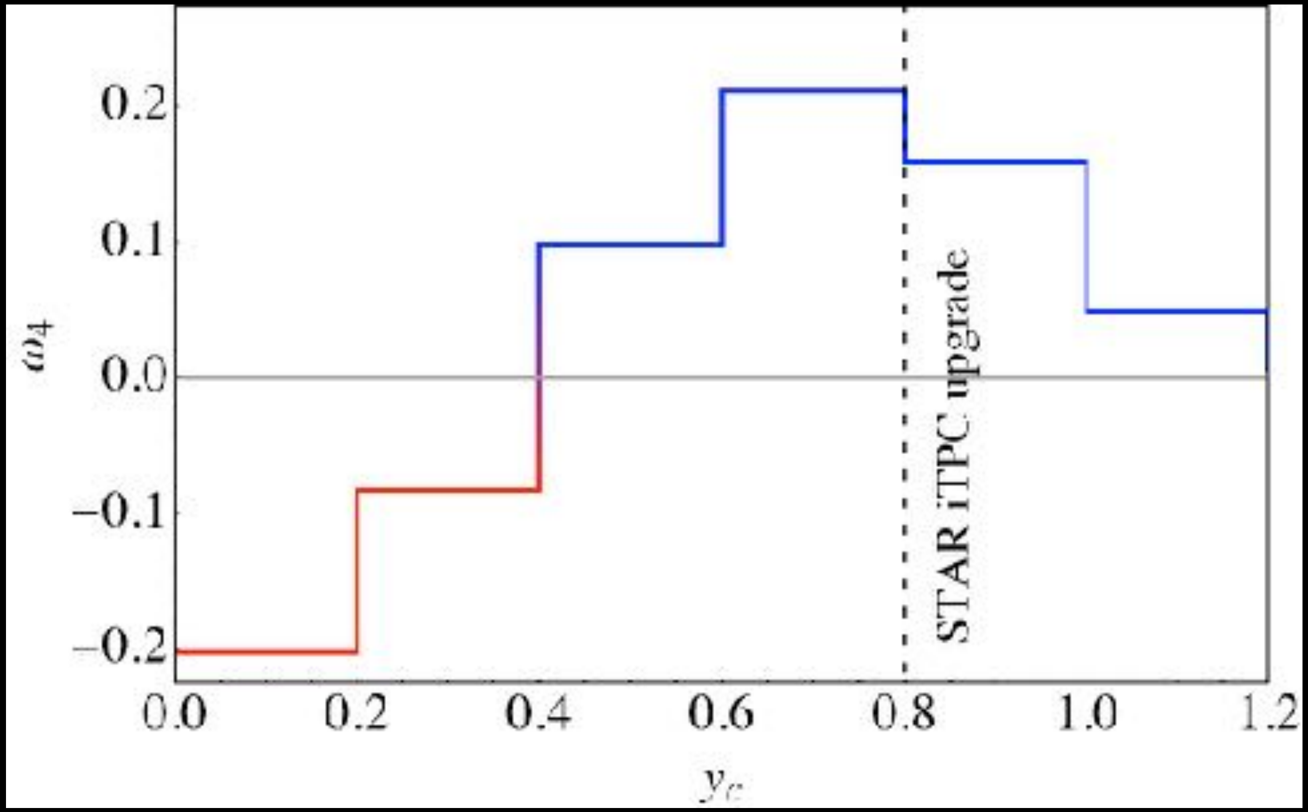
Changing y_c : probing different locations in the critical regime.

Δy: more protons coupled to critical fluctuations

An example

(Δy=0.4)





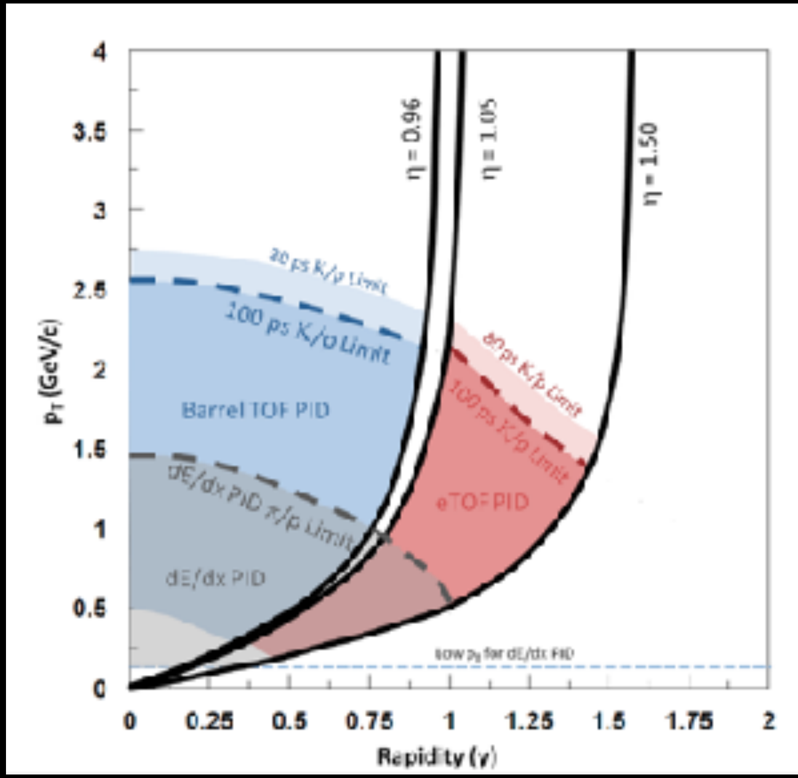
y_c

Looking for non-trivial dependence of ω_n on y_{bin} .

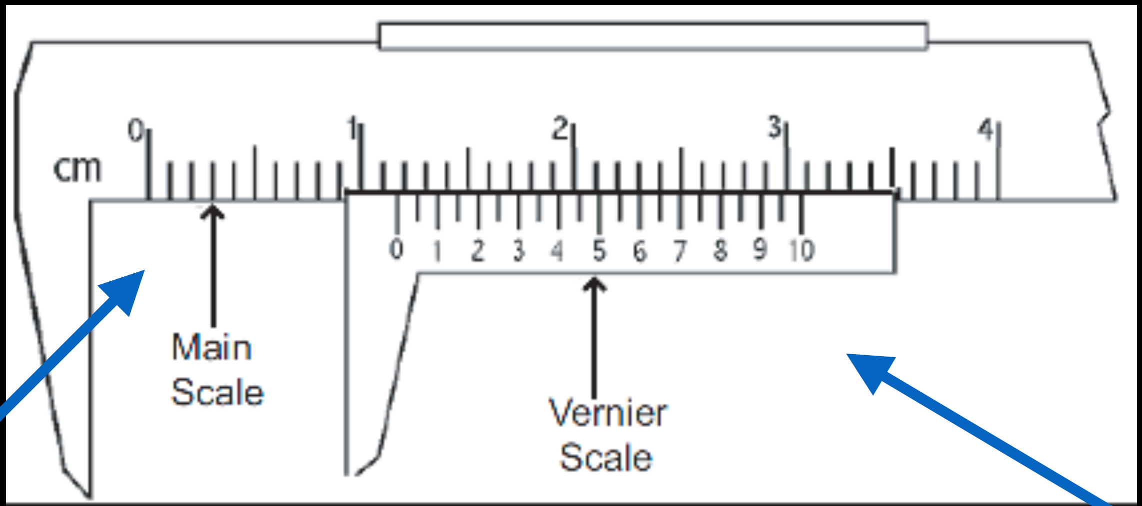
Different rapidity bins probe different "points" in the phase diagram.

This requires detector to have the sufficient acceptance.

We wait with a great interest for the running of BESII (2019).



Upgraded detector for BESII



Main scale: varying $\sqrt{s}$

Vernier scale: varying y

Part II

A number of new theoretical developments in different context are deeply related and might lead to a new unified framework essential for the exploration of the baryon-rich QCD matter.

YY, Quark Matter 18 proceedings, in progress .

"Nature uses only the longest threads to weave her patterns, so that each small piece of her fabric reveals the organization of the entire tapestry." -- Feynman

Fluctuations of energy (charge) density (specific heat, susceptibility) contain rich information about QCD matter.

Intermedia HIC offers unique opportunities to study them.

Recent theoretical developments :

- Off-equilibrium effects are important to understand.
- Emergent scale associated with off-equilibrium dynamics
- Interplay between fluctuations and bulk evolution.

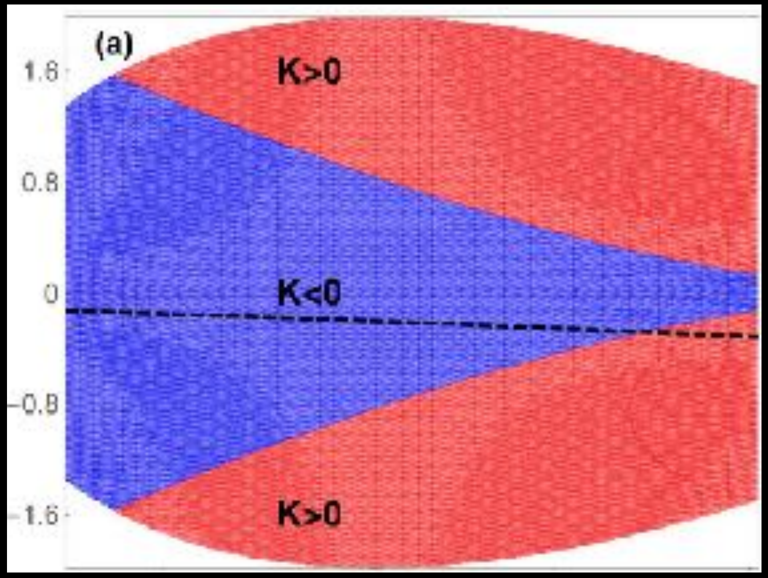
Relaxation time $\propto$ transport coeff. /fluct.

E.g. $$\text{Diffusive constant} = \frac{\text{conductivity}}{\text{susceptibility}}$$

The off-equilibrium effects are important when fluctuations are large.

E.g.1, near the critical point.

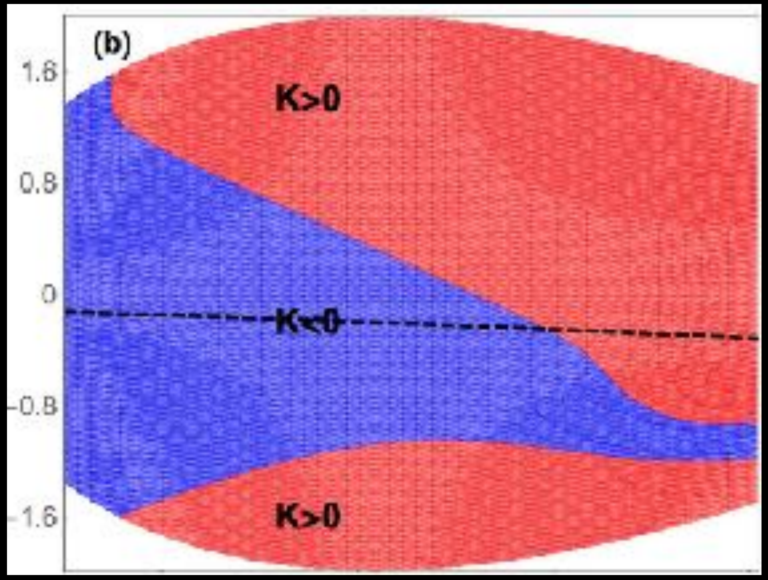
S. Mukherjee, R. Venugopalan and YY, PRC 15' .



equilibrium

E.g.2: charge fluctuations near the crossover

S. Pratt, J. Kim and C. Plumberg, 1712.09298

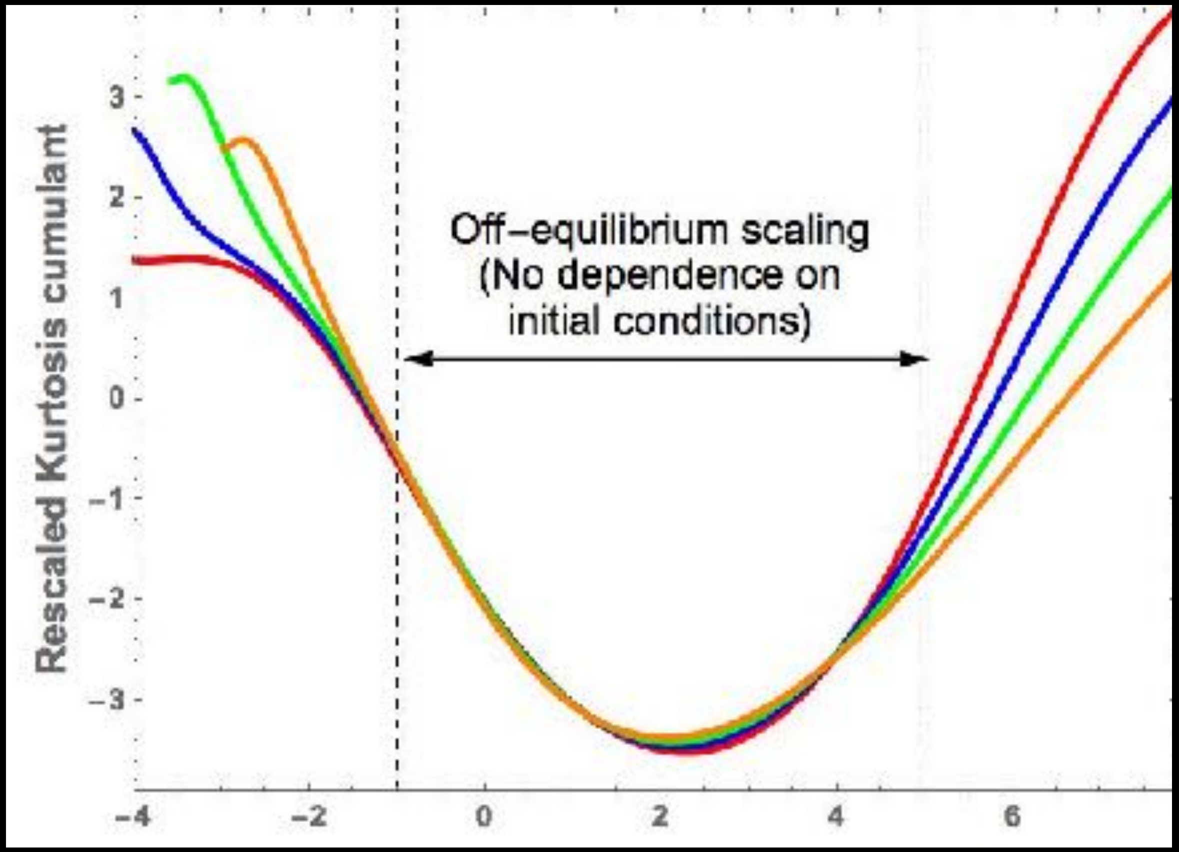


Off-equilibrium

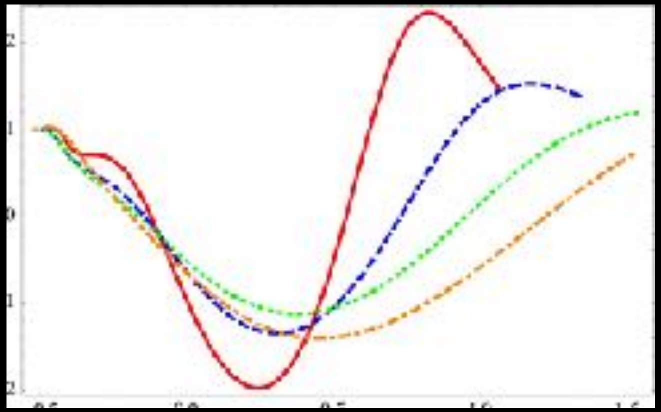
Emergent scales: Expansion time = Relaxation time

E.g. 1: Kibble-Zurek scaling near the QCD critical point.

Rescaled K_4



Rescaled time

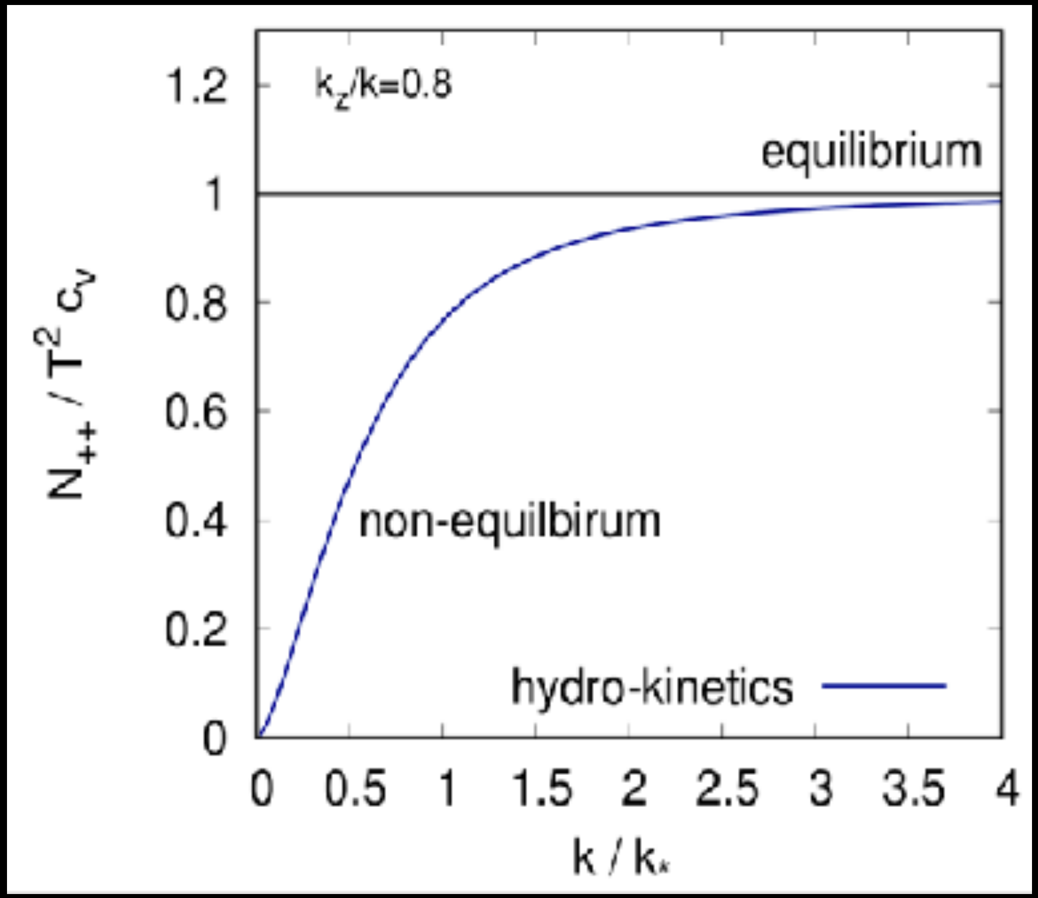


K_4 before scaling

S. Mukherjee, R. Venugopalan and YY, PRL, Editors' suggestion, '16.

E.g. 2: "k*" characterizes fluctuation around Bjorken expansion.

Akamatsu, Mazeliauskas, Teaney, PRC 16.



Off-equilibrium effect corrects transport coefficient.

$$\eta_{eff} = \eta - \#(k^*)^3$$

Connection to Kibble-Zurek dynamics? Yes.

Y. Akamatsu, D. Teaney, Fanglida Yan and YY, in preparation

Fanglida Yan, Grad. of SBU.

“Effective” equation of state and “effective” transport coefficients are modified values due to off-equilibrium effects.

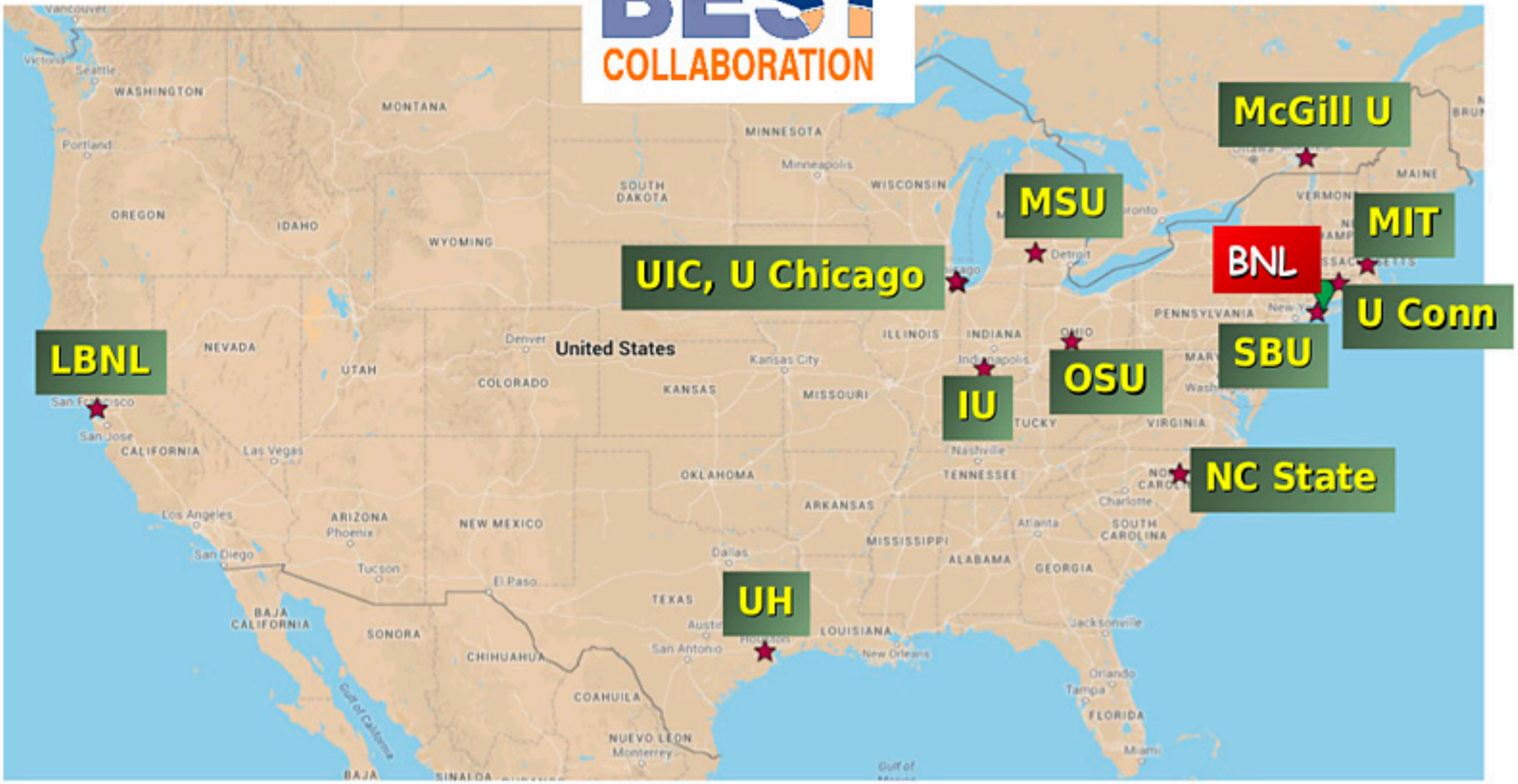
We need to couple bulk evolution with fluctuations.

Near the critical point : “hydro+”.

M. Stephanov and YY, 1712.10305

Formal aspect: that emergent scale seems to be needed to derive “hydro+” as an effective field theory.

BEST COLLABORATION



The NA61/SHINE Collaboration:

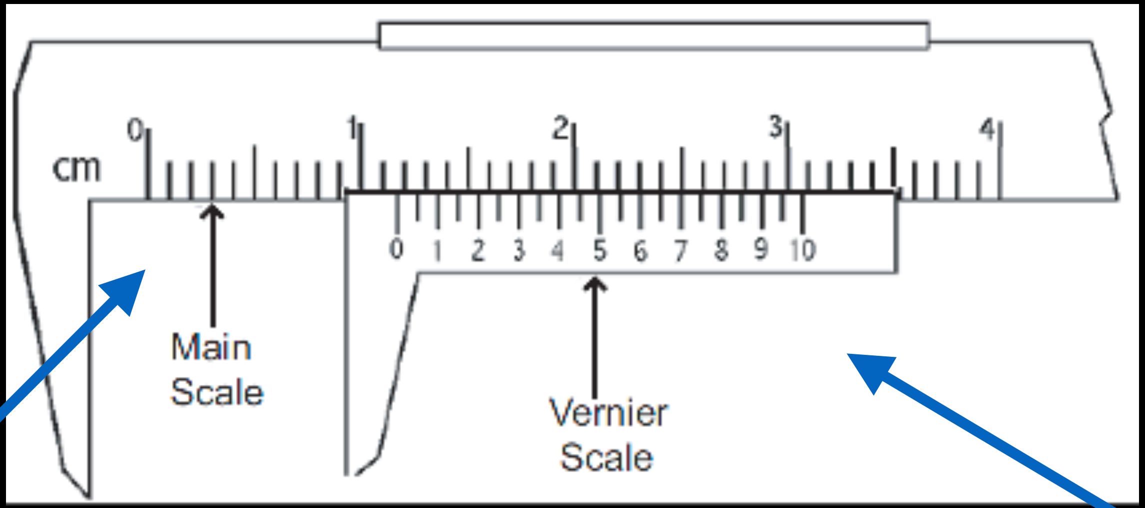
114 physicists from 24 institutes and 14 countries:

University of Athens, Athens, Greece
University of Bergen, Bergen, Norway
University of Bern, Bern, Switzerland
KFKI IPNP, Budapest, Hungary
Cape Town University, Cape Town, South Africa
Jagellionian University, Cracow, Poland
Joint Institute for Nuclear Research, Dubna, Russia
Fachhochschule Frankfurt, Frankfurt, Germany
University of Frankfurt, Frankfurt, Germany
University of Geneva, Geneva, Switzerland
Forschungszentrum Karlsruhe, Karlsruhe, Germany
Swietokrzyska Academy, Kielce, Poland
Institute for Nuclear Research, Moscow, Russia
LPNHE, Universites de Paris VI et VII, Paris, France
Pusan National University, Pusan, Republic of Korea
Faculty of Physics, University of Sofia, Sofia, Bulgaria
St. Petersburg State University, St. Petersburg, Russia
State University of New York, Stony Brook, USA
KEK, Tsukuba, Japan
Soltan Institute for Nuclear Studies, Warsaw, Poland
Warsaw University of Technology, Warsaw, Poland
University of Warsaw, Warsaw, Poland
Rudjer Boskovic Institute, Zagreb, Croatia
ETH Zurich, Zurich, Switzerland

Summary and perspectives

Conclusion

New angle:



Main scale: varying $\sqrt{s}$

Vernier scale: varying y

New theoretical framework: “hydro” coupled with fluctuations.

Perspective:

Anaximander (600 BC)

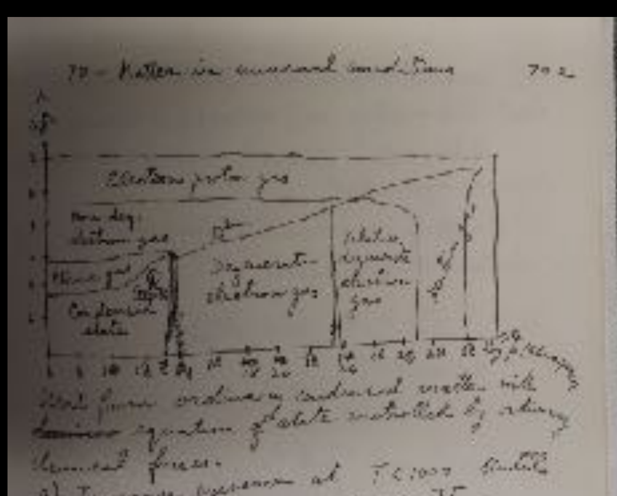
1490

Maggiolo (1531)

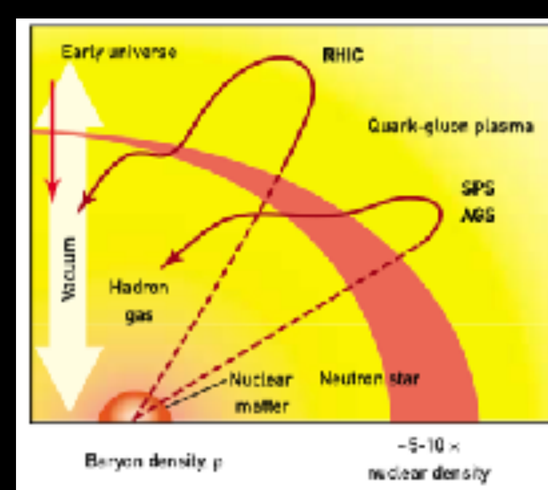
Visscher (1652)

Columbus' voyages

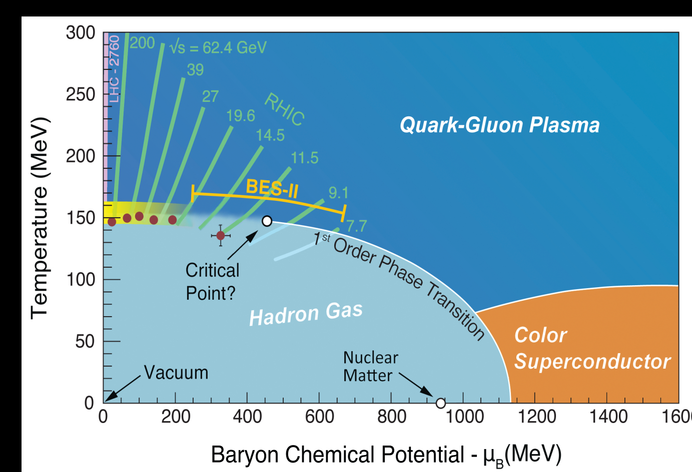
ages of discovery



Fermi (1952)



2002

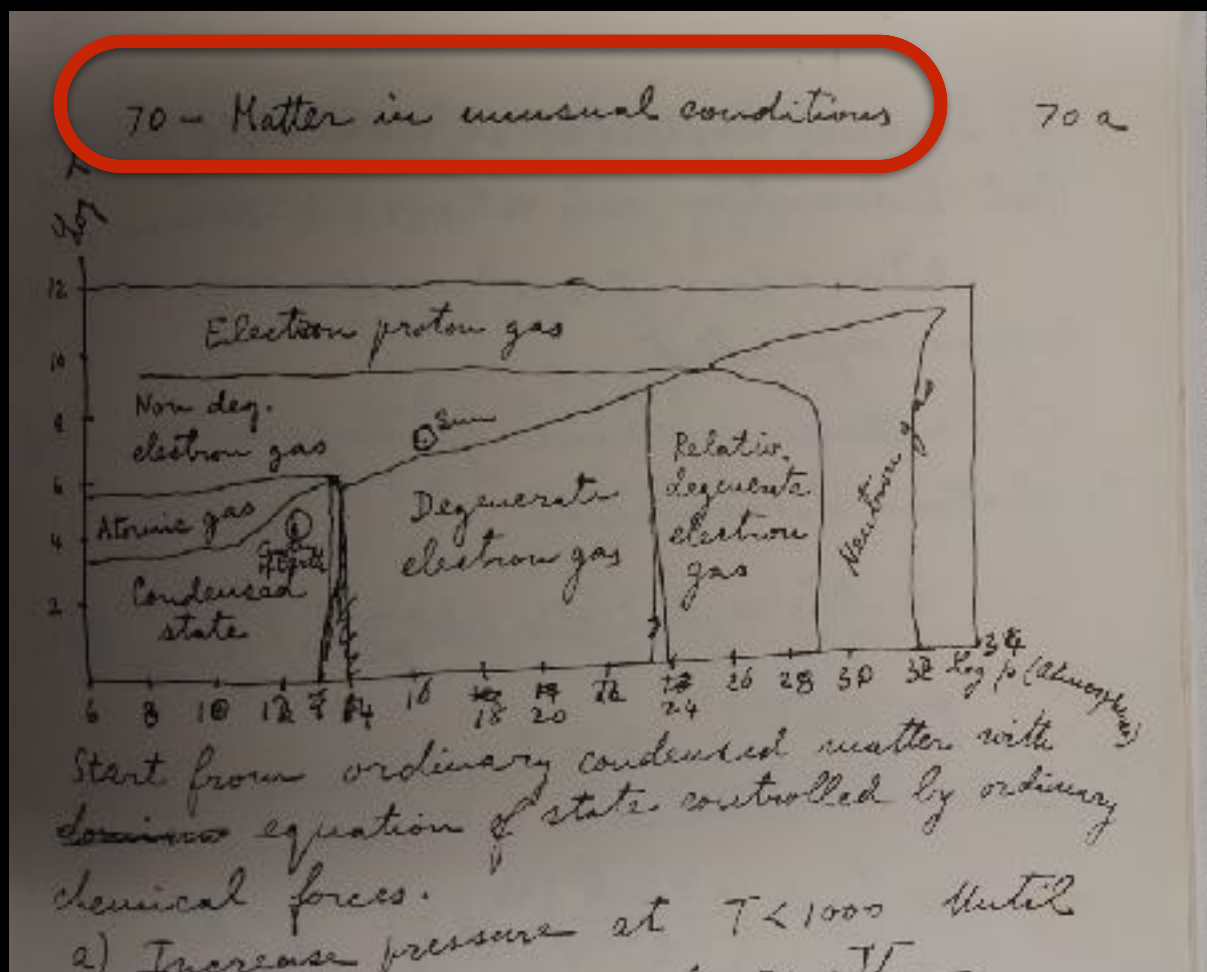


2015

RHIC starts running

BESII

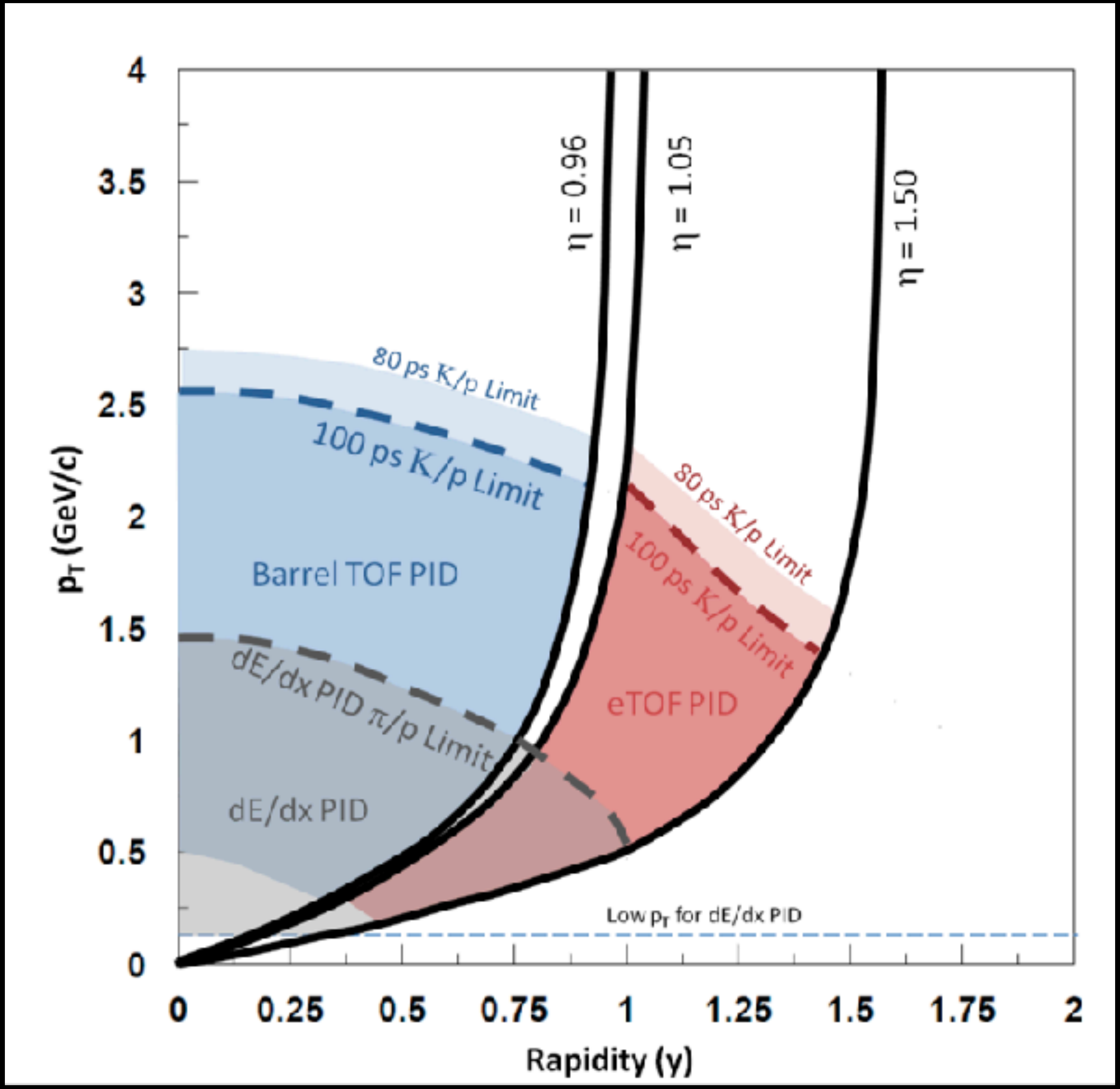
A fundamental question: phases of matter under extreme conditions?



Fermi's notes: "Matter in unusual conditions", 1952

Answer to this question will be summarized in the knowledge of the QCD phase diagram.

iTPC upgrades



Coupling "+" to hydro

The conservation law remains the same:

$$\partial_\mu T^{\mu\nu} = 0 \qquad\qquad \partial_\mu J^\mu = 0$$

E.o.S and transport coefficients are different:

$$T^{\mu\nu} = \epsilon\, u^\mu u^\nu + p_{(+)}(\epsilon, n, \phi(Q))\ (g^{\mu\nu} + u^\mu u^\nu) + \Delta T^{\mu\nu}_{\rm viscous}$$

$$\Delta T^{ij}_{\rm viscous} = -\zeta_{(+)}\,\delta^{ij}\,\theta - \text{shear term}$$

$\zeta_{\rm hydro} \sim \zeta_{(+)}$ + dissipation due to equilibration of ϕ .

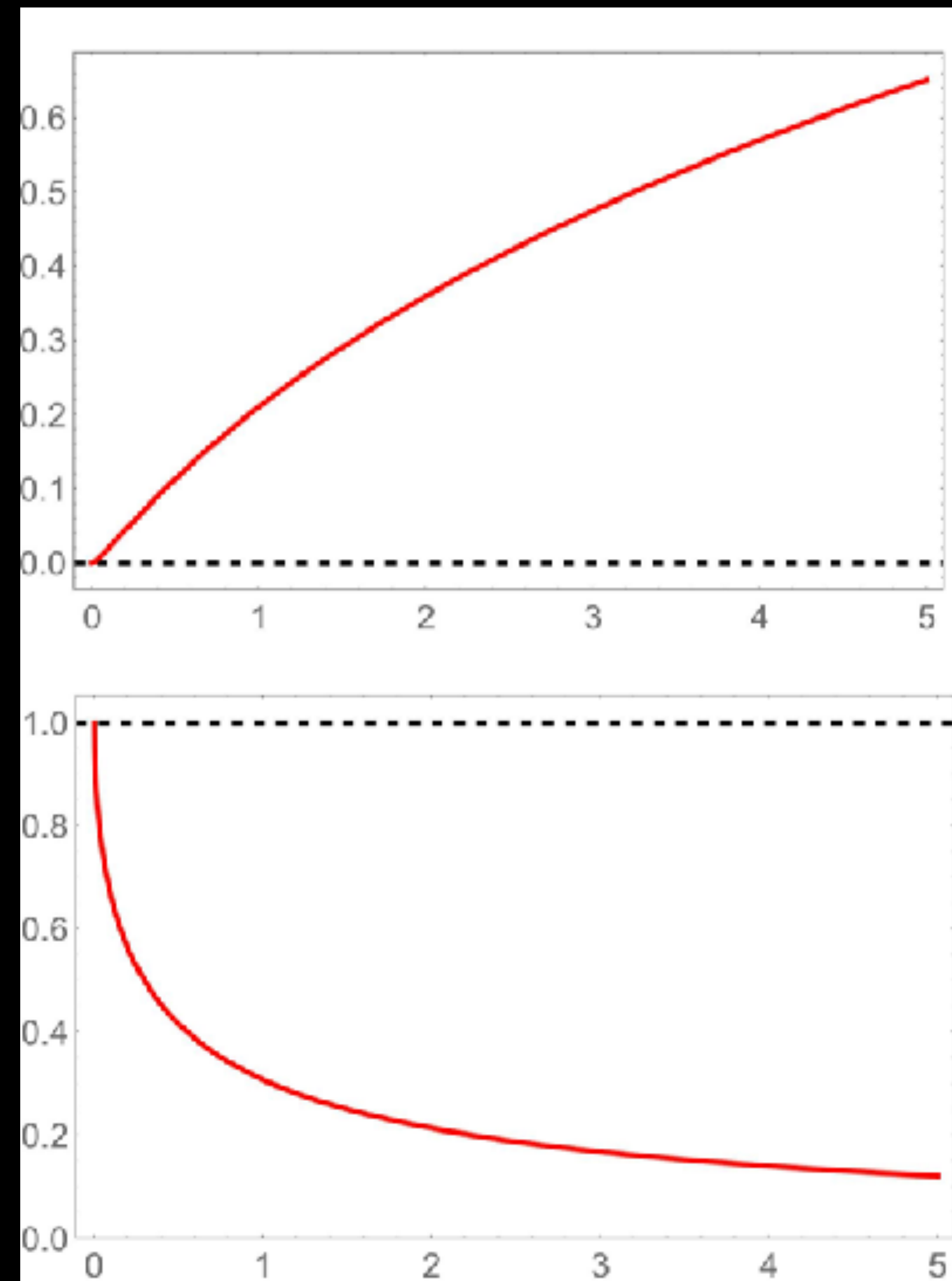
Similar expression for J^μ

Frequency dependent c_s, ζ from linearized “hydro+”

Frequency dependence of e.o.s. and transport coefficients are “absorbed” in the evolution of $\phi(Q)$

$(c_s(\omega))^2$

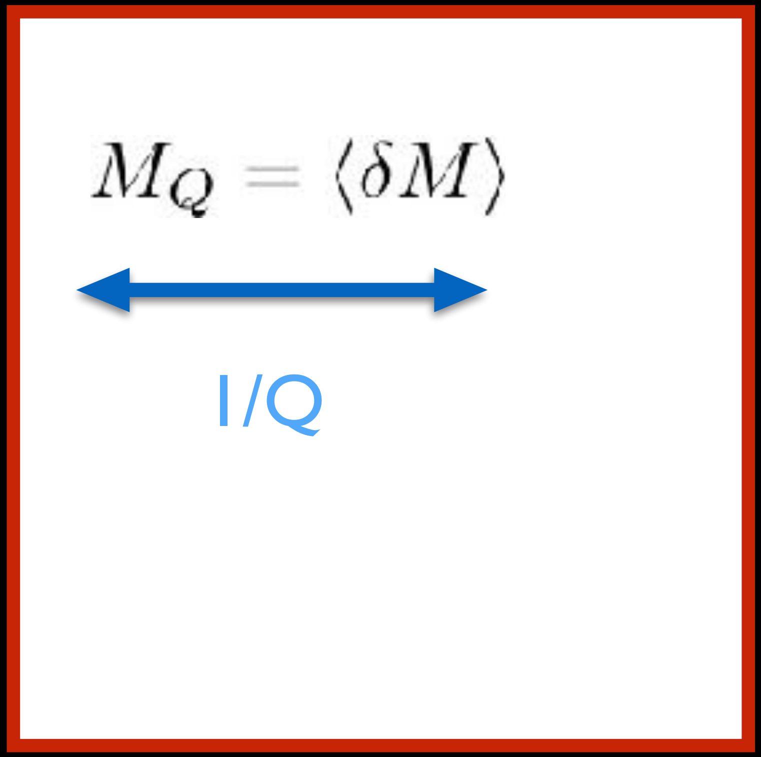
$\zeta(\omega)$

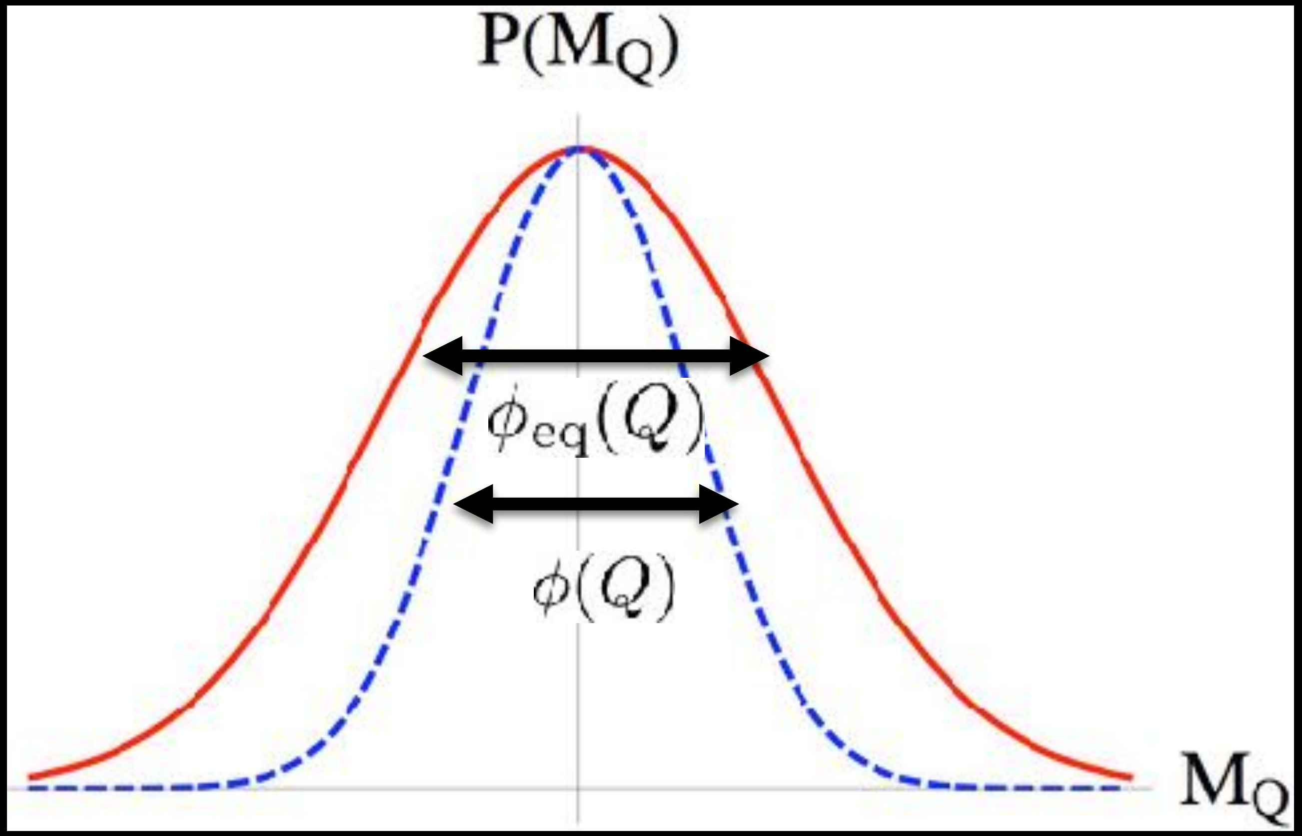


$\omega\ t_\xi$

References

M. Stephanov and YY, 1712.10305
C. Lau, Hong Liu, YY in progress





ϕ(Q): "occupation number" of critical fluctuations.

In equilibrium:

$$\phi_{\rm eq}(Q) \approx \frac{1}{\xi^{-2} + Q^2}$$

Definition

$$\phi(t, x; Q) \equiv \int_{\Delta x} \langle \delta M(t, x + \Delta x)\, \delta M(t, x - \Delta x) \rangle\, e^{-iQ\Delta x}$$