Search for the QCD critical point: challenges, progress and perspectives

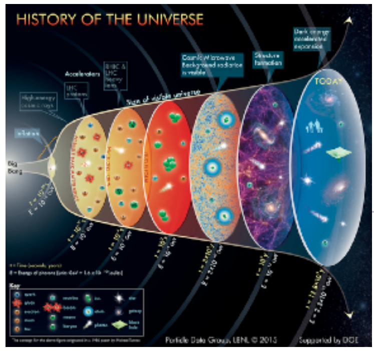
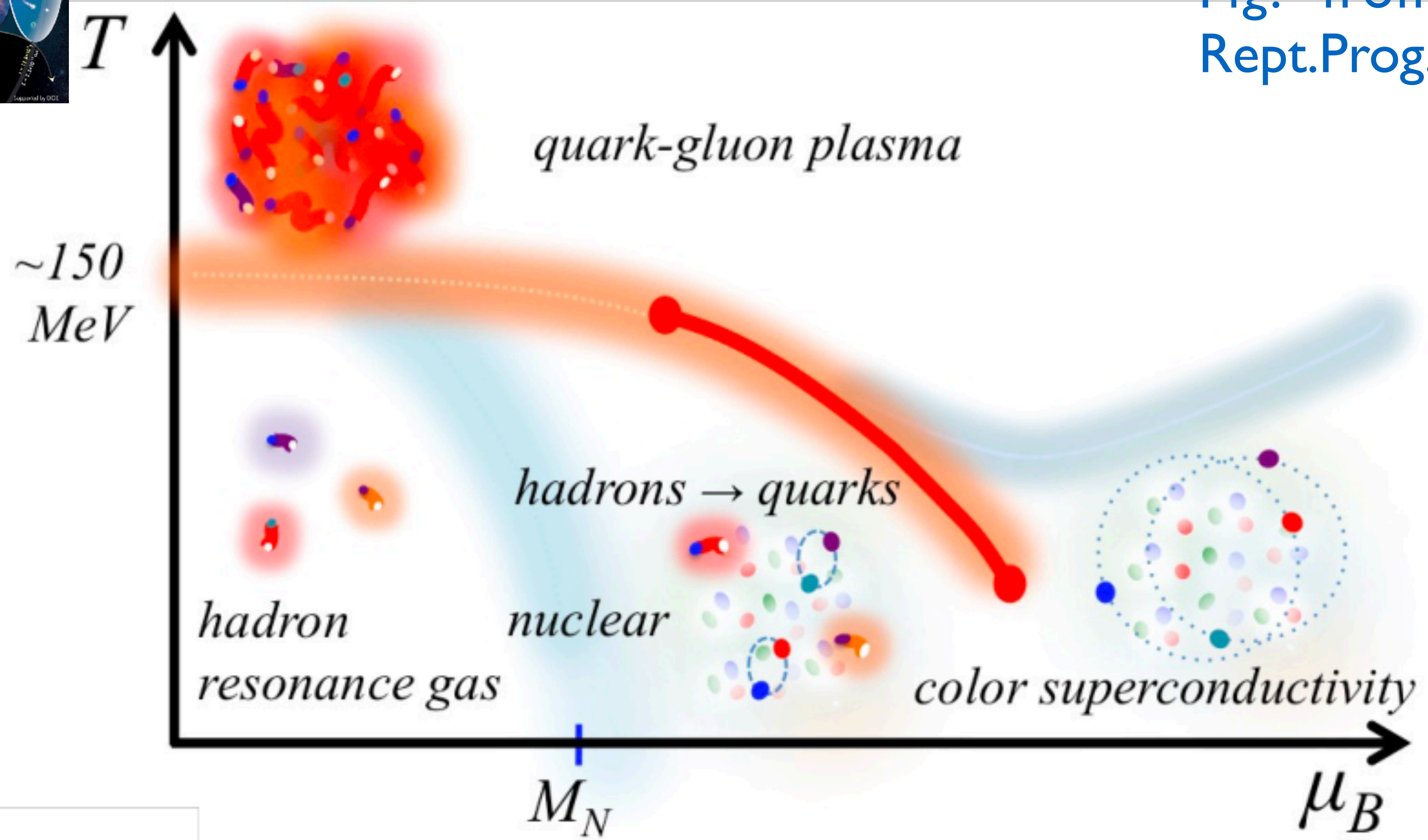
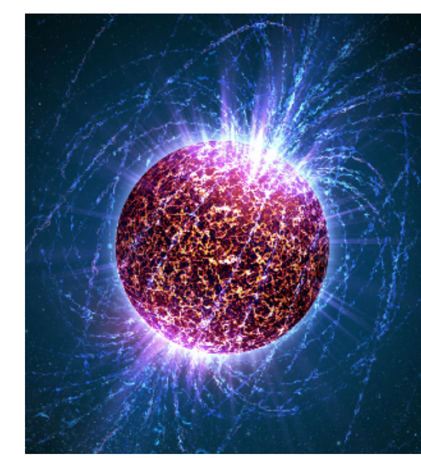


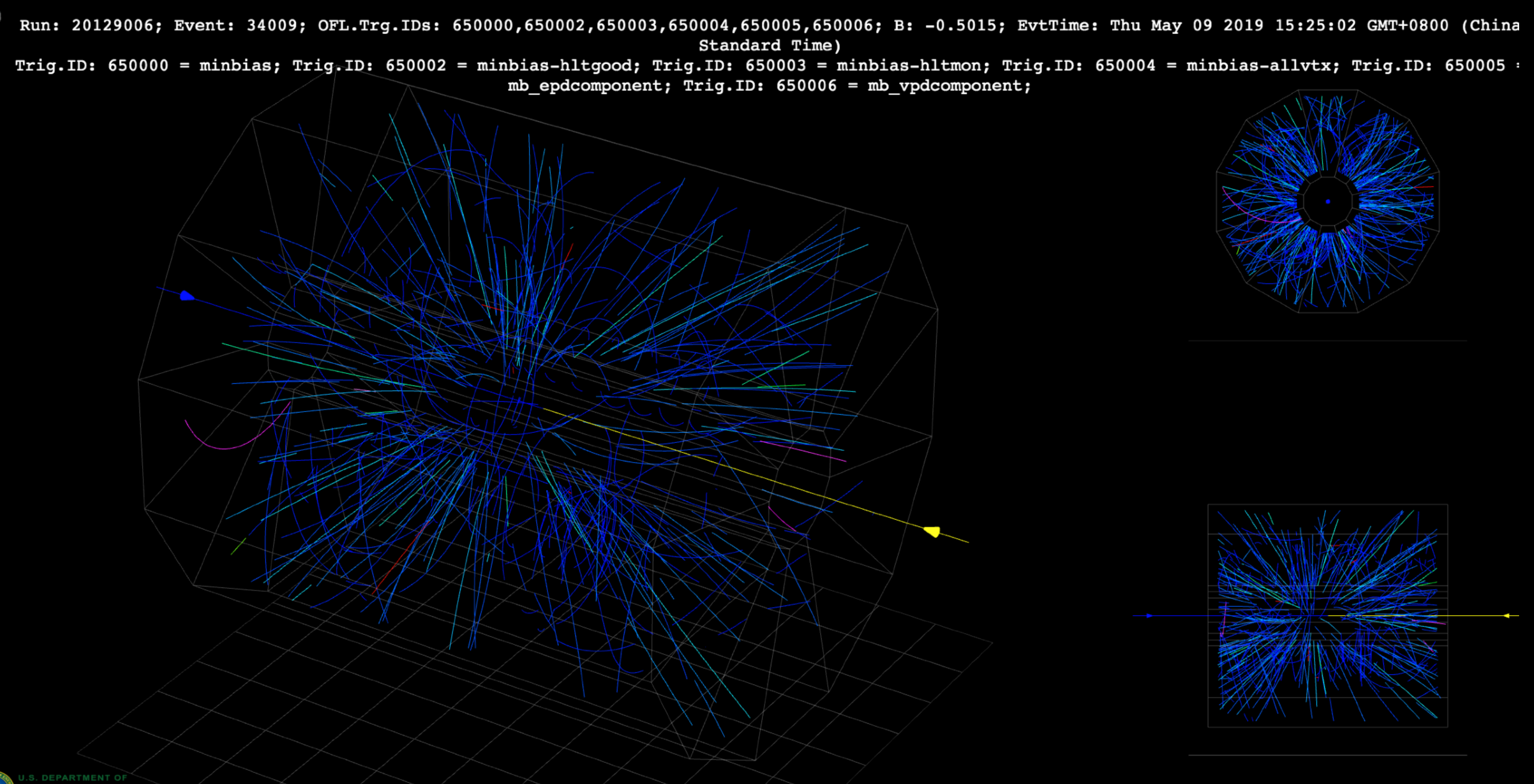
Fig. from Baym et al, Rept.Prog.Phys. 81,2018



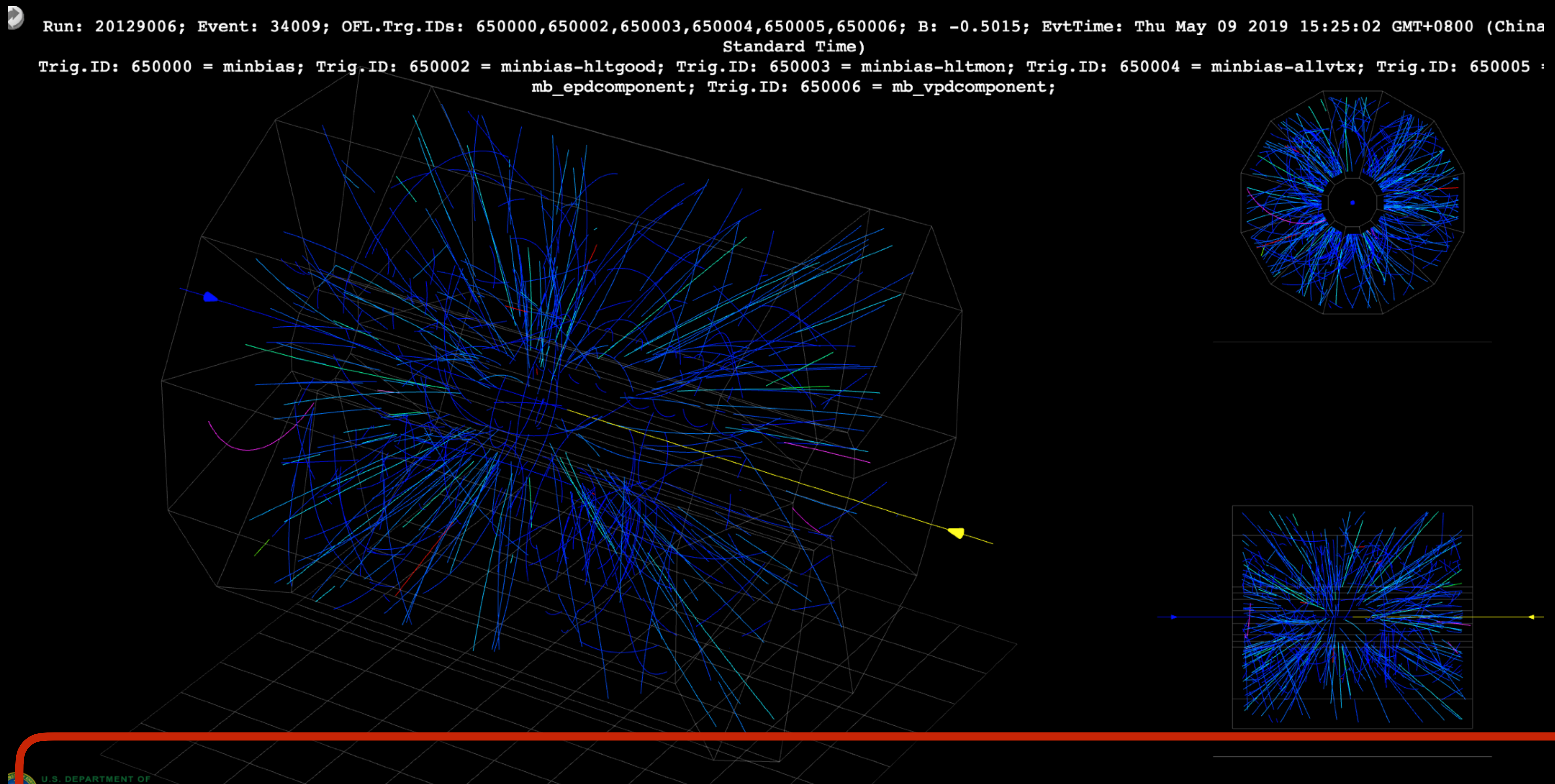


Yi Yin

中国核物理大会, CCNU, Wuhan, China, Oct.10, 2019



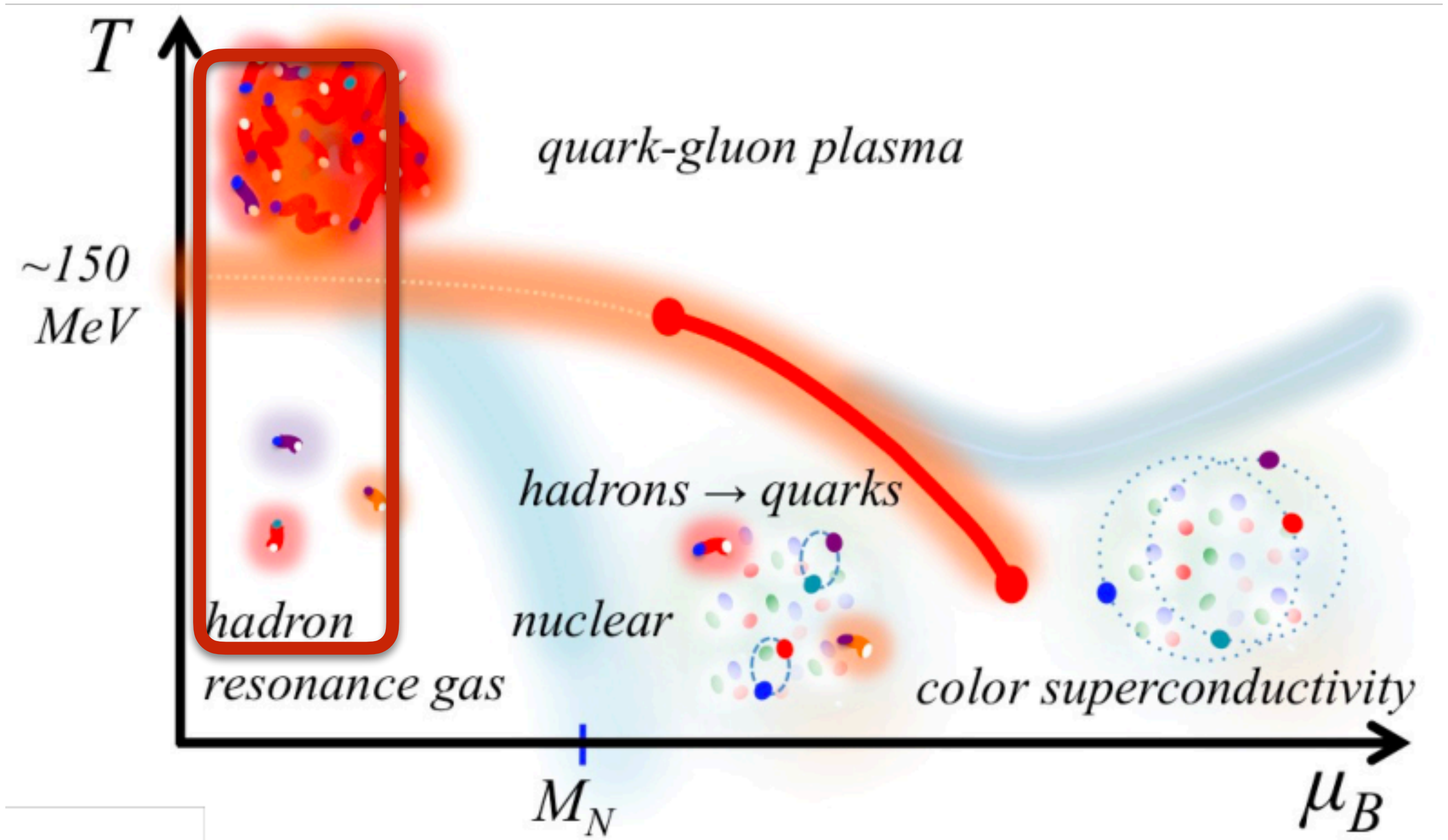
The display of an actual heavy-ion collision event on May. 9th, 2019 at RHIC at Brookhaven national lab. Millions of such events will be created for exploring the uncharted region of QCD phase diagram and for the search for the QCD critical point.



Motivation.

The needed theoretical tools to extract the info. about the QCD critical point from experimental data.

Future perspectives.



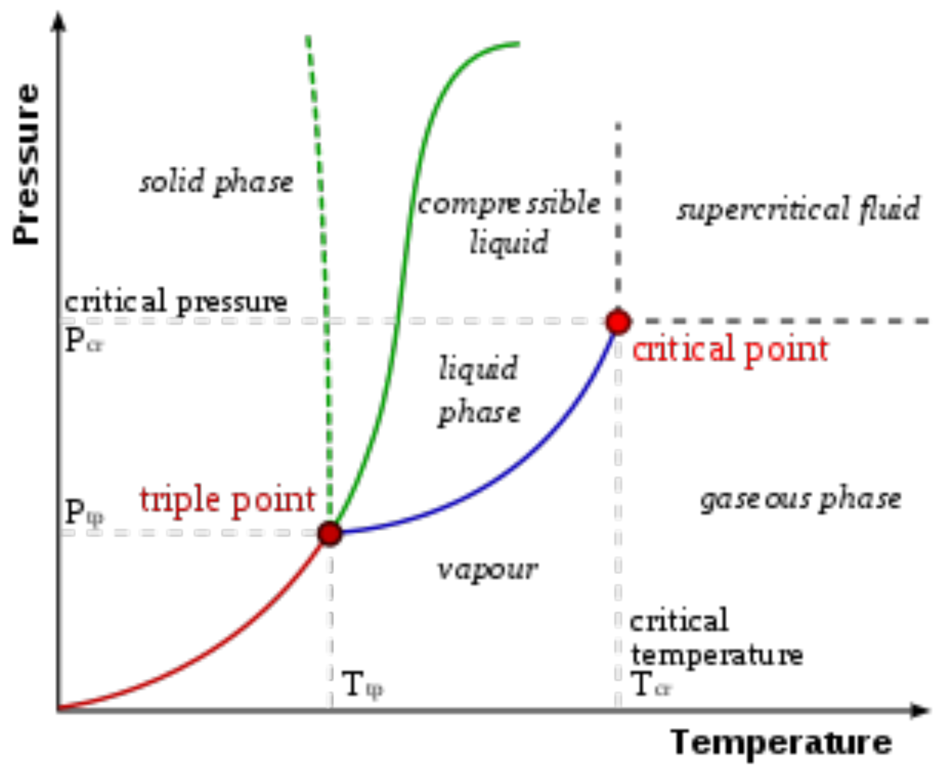
$$\frac{\eta}{s} = (1 \sim 3)\frac{1}{4\pi}$$

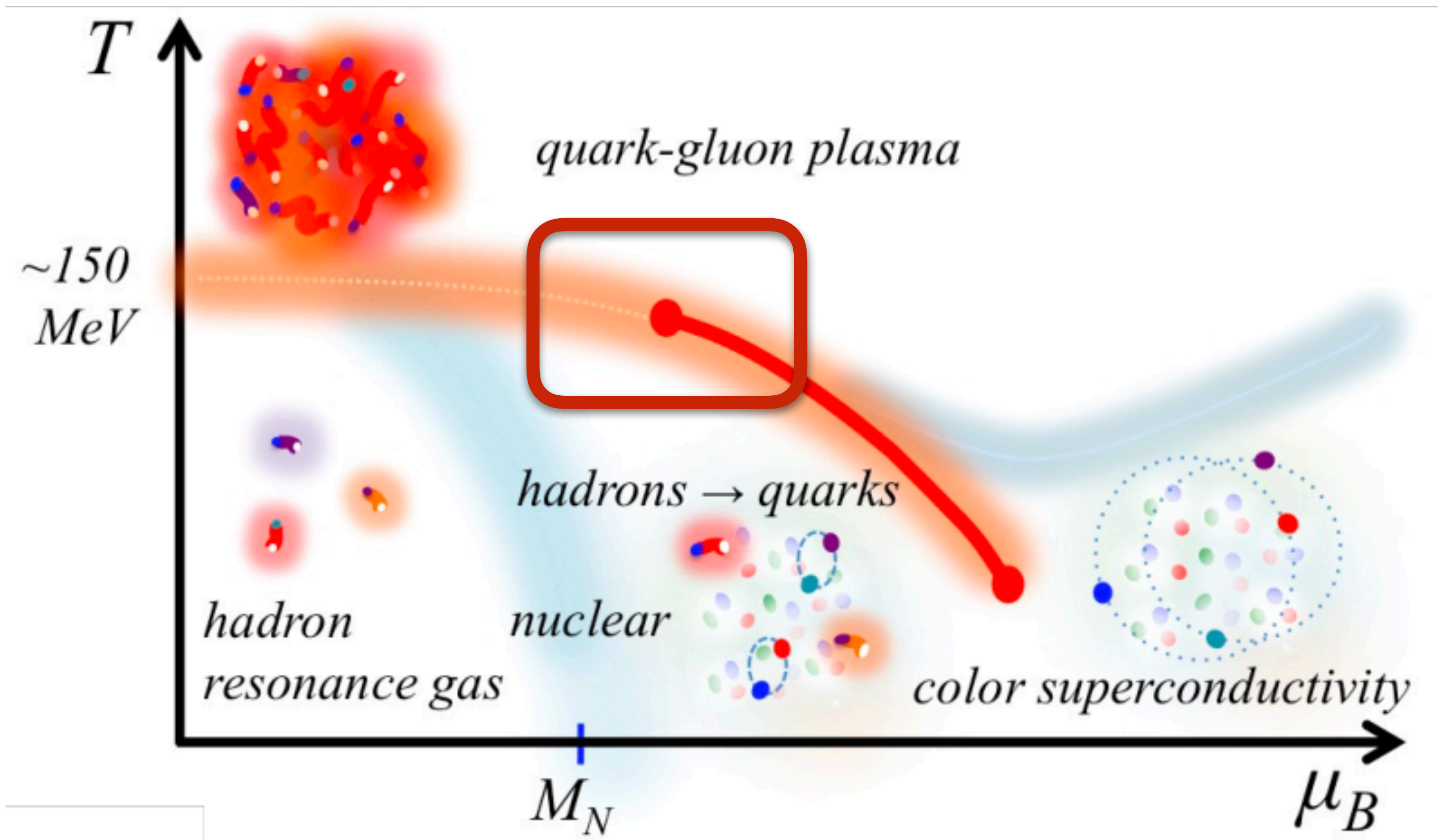
$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC,} \\ 3.7 \pm 1.4 & \text{at LHC,} \end{cases}$$

The past decade has seen significant advances on the characterization of the properties of QCD matter at small μ_B (< 200MeV).

The QCD phase diagram at hot and finite baryon density regime is still uncharted.

Will the properties of nuclear matter change dramatically with the variation of the baryon density? If so, why?



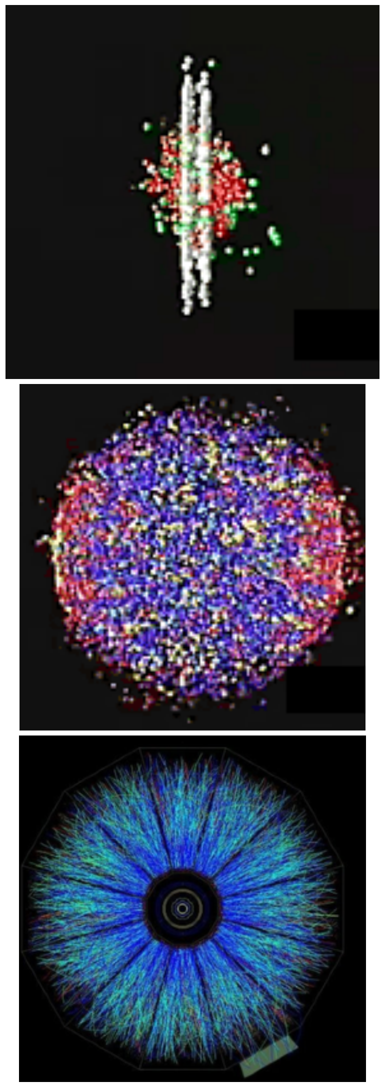


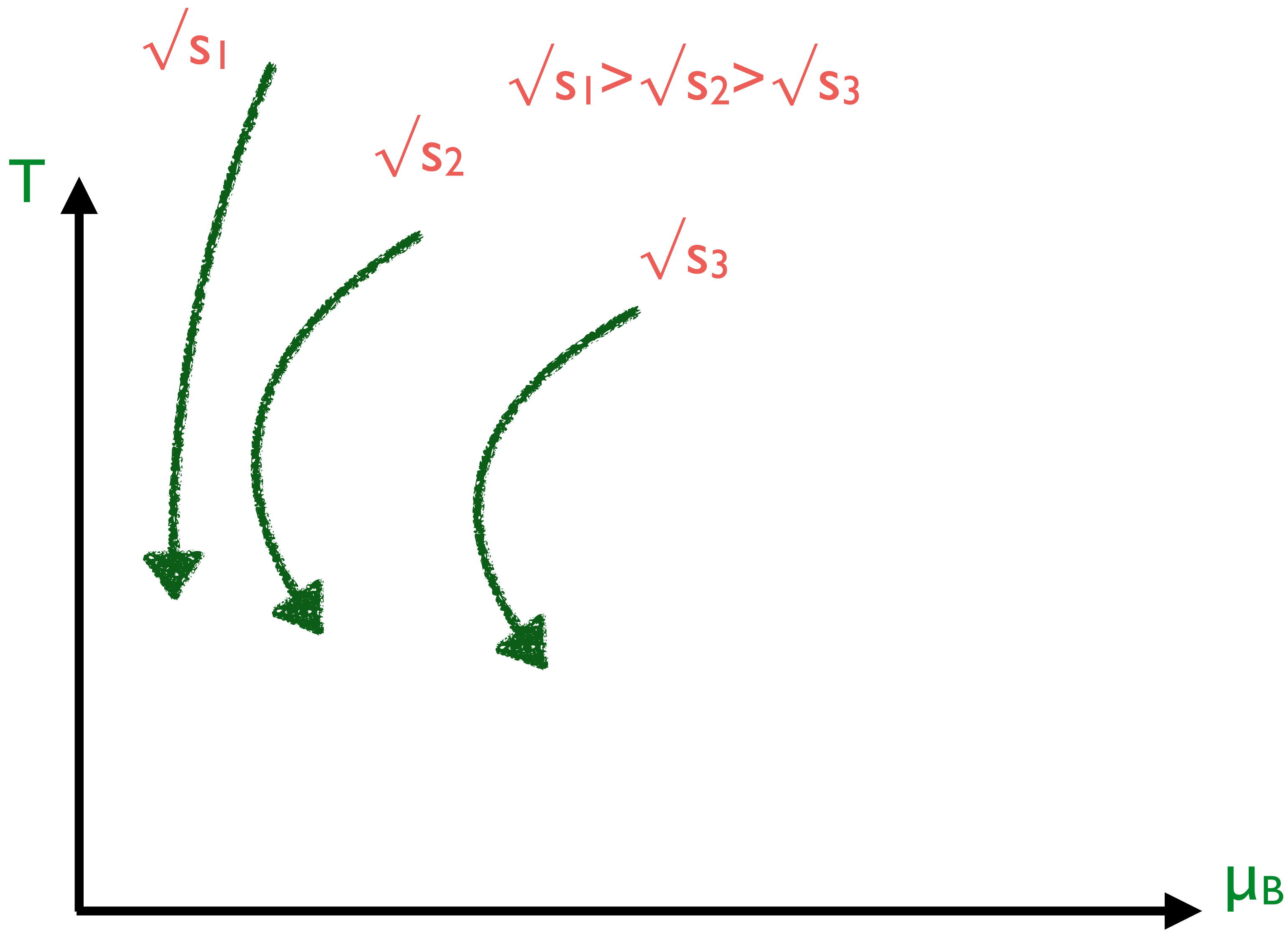
Phase digram of water (from wiki)

The critical point is a ubiquitous phenomenon. (150 years ago, Andrews coined term "the critical point" in his Bakerian lecture.)

The QCD critical point: the landmark point on the phase diagram.

The discovery of the QCD critical point will tell us that the properties of nuclear matter will change dramatically with the variation of the baryon density.





The first principle lattice simulation is prohibitively challenging at finite chemical potential to date.

The QCD phase diagram can be scanned by changing beam energy $\sqrt{s}$ (lower beam energy, larger baryon density), "beam energy scan" (BES).

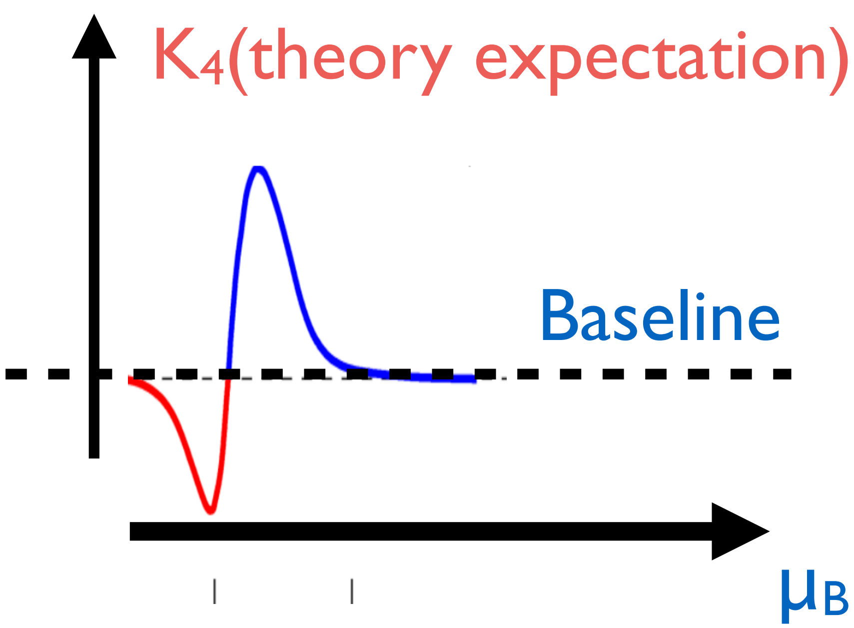
Experimental search for C.P.: fluctuation is the key

Xiaofeng Luo, Nu Xu 1701.02105 for a review.

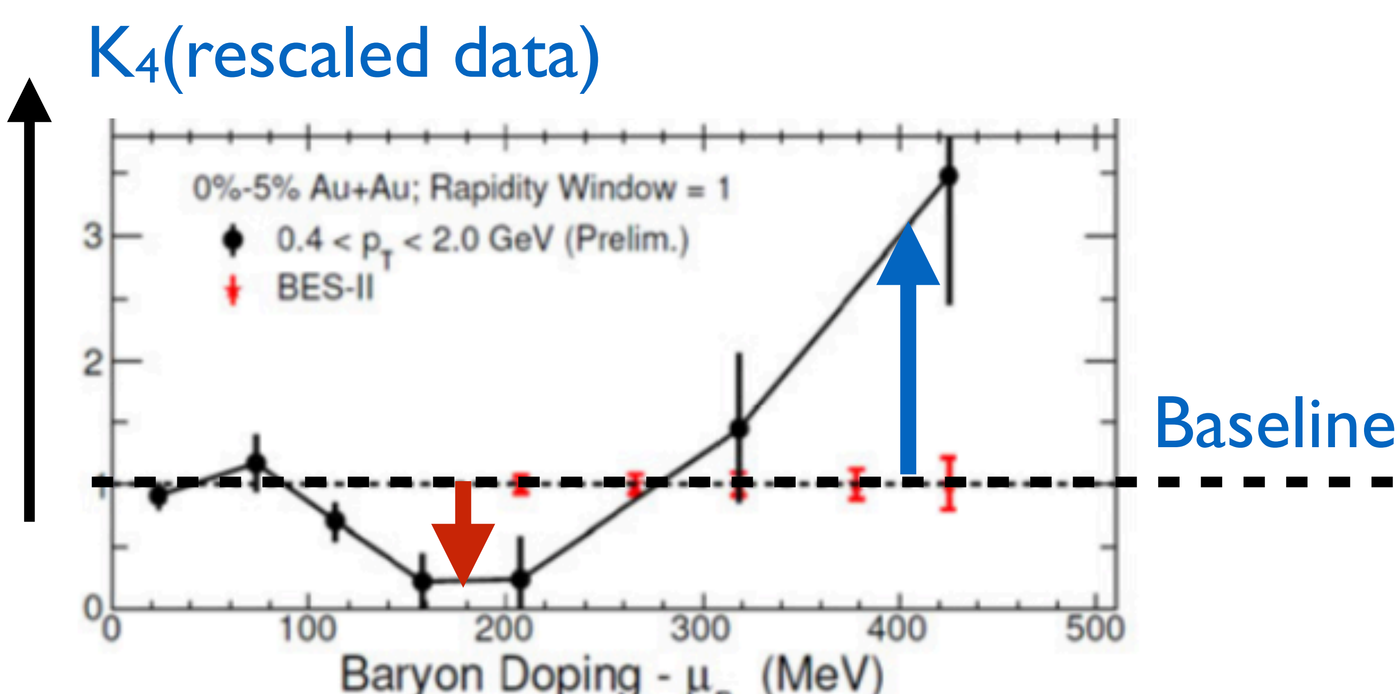
Hadrons (e.g. protons) multiplicity fluctuations are expected to be enhanced near C.P. .

$$K_2 \sim \sum_{\text{event}} \left(N_{\text{proton}} - \bar{N}_{\text{proton}}\right)^2, \; K_4 \sim \sum_{\text{event}} \left(N_{\text{proton}} - \bar{N}_{\text{proton}}\right)^4 - 3K_2^2 .$$

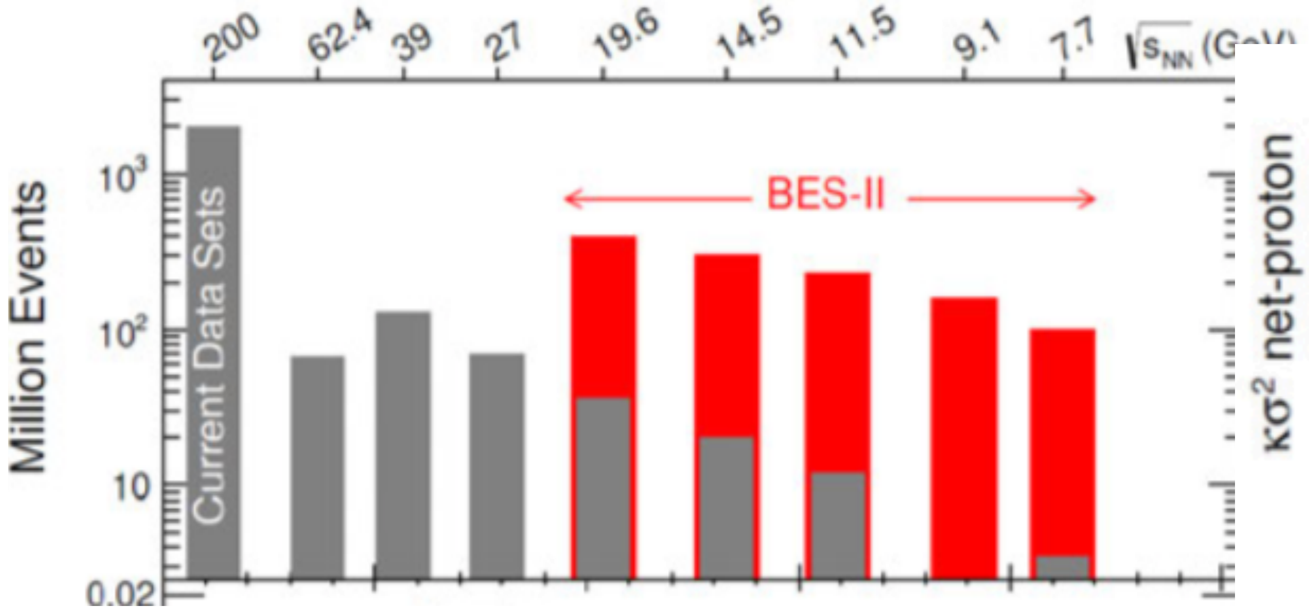
Hints: non-monotonicity and sign change of fourth cumulant (i.e. K_4) as a function of beam energy within line of theory expectation.

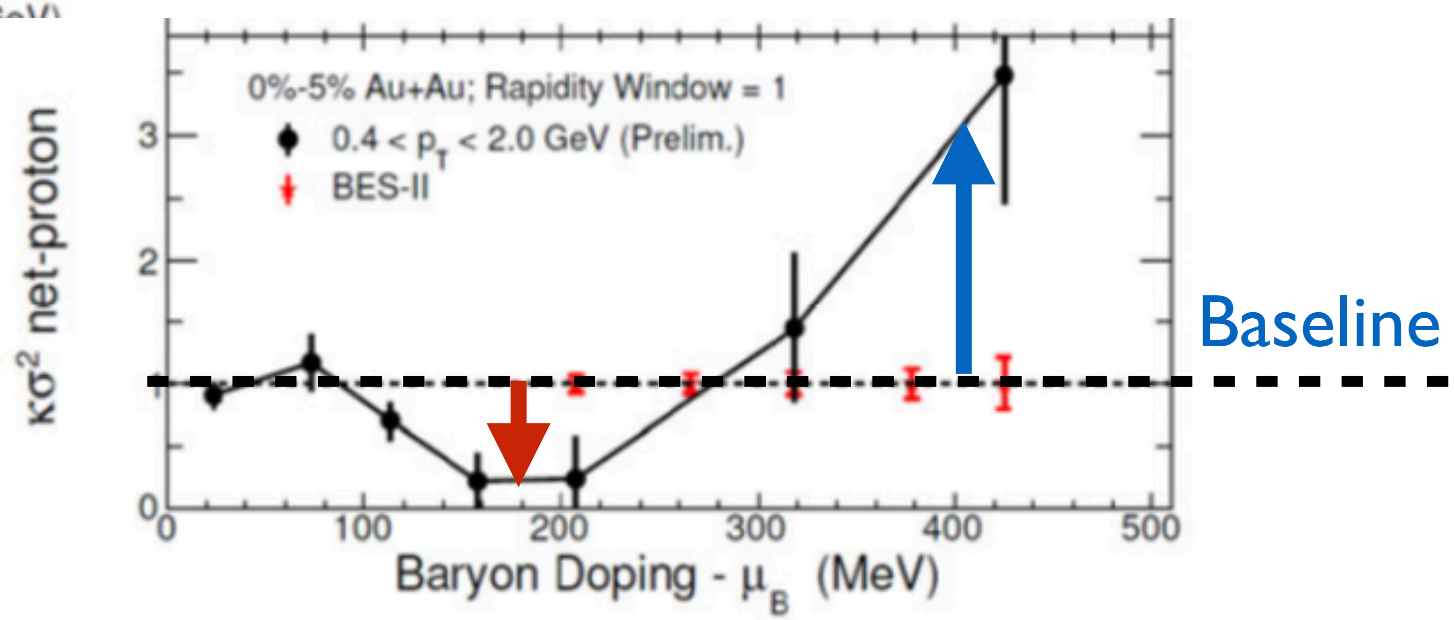


Stephanov, PRL 11



STAR preliminary data from BESI (Xiaofeng Luo, 1503.02558)



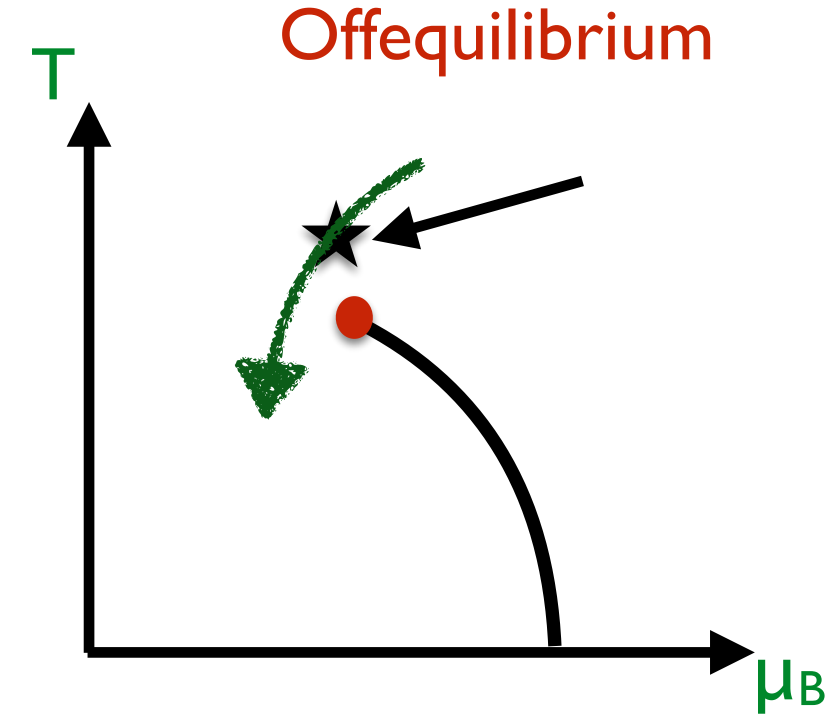


BESII (2019-22) will bring data with unprecedented precision. This is exciting time.

This in turn presents both outstanding challenging and opportunity for theory: a comprehensive quantitative framework is needed.

In what follows, I will discuss the core ingredient of this framework: hydro with critical fluctuations.

The critical fluctuation is inescapably offequilibrium near the critical point. ("Critical slowing down": critical fluctuation relaxes very slowly!)



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

Characteristic feature of off-equilibrium effects on critical fluctuations have been well understood.

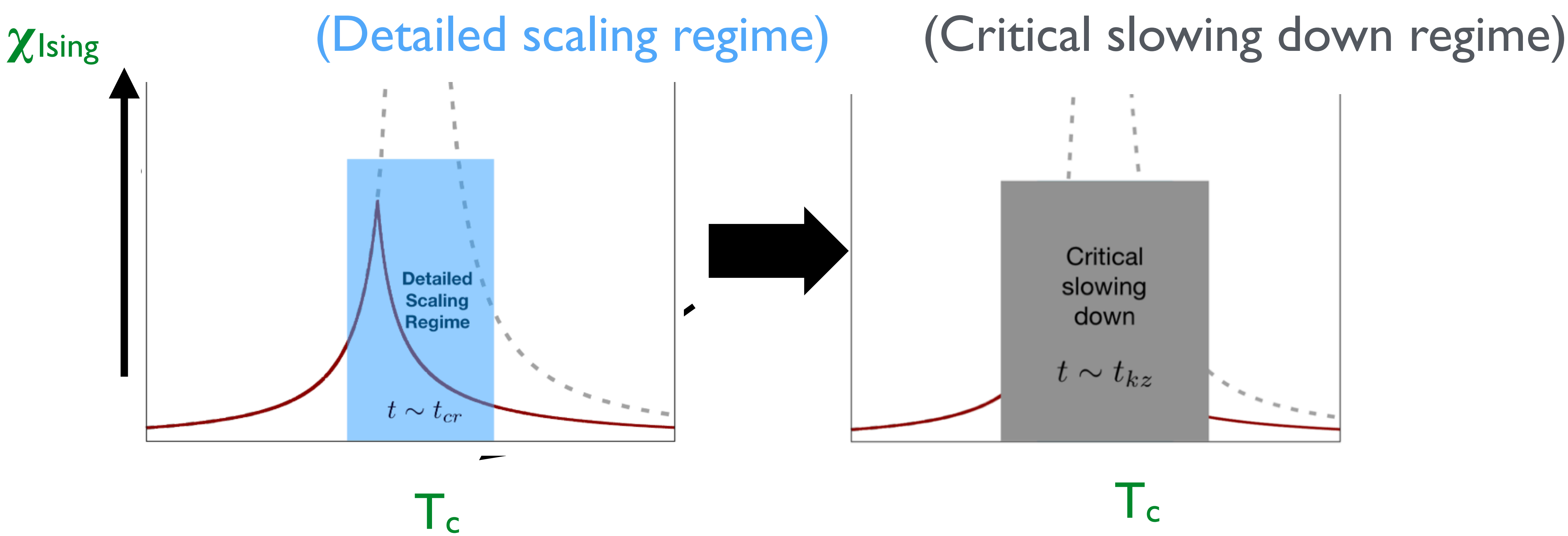
see YY, 1811.06519 for a mini-review

For example, critical fluctuation can be different from the equilibrium expectation both quantitatively and qualitatively !

e.g. S. Mukherjee, R. Venugopalan and YY, PRC15'

Further, the evolution of fluctuation will feedback the hydro evolution. (Hydro is non-linear theory. c.f. turbulence)

E.g., the equilibrated fluctuations lead to the scaling behavior of equilibrium E.o.S. When fluctuations are offequilibrium, equilibrium scaling near C.P. is distorted. *Akamatsu-Teaney-Yan-YY, 1811.05081, PRC 19'*



gradient of (?)+dissipation (?) ≃ acceleration of flow

Hydro. itself can not provide a quantitative description near C.P.

A new dynamical framework: hydro+

Stephanov-YY, 1712.10305, PRD '18;

Conventional approach: adding noise into hydro. (stochastic hydro). Difficult to implement for expanding system.

Instead, we develop a framework of "Hydro+". It is a hydro-like theory which couples hydro. d.o.f with long wavelength critical fluctuations using deterministic equations.

Equations for the evolution of long wavelength fluctuations.

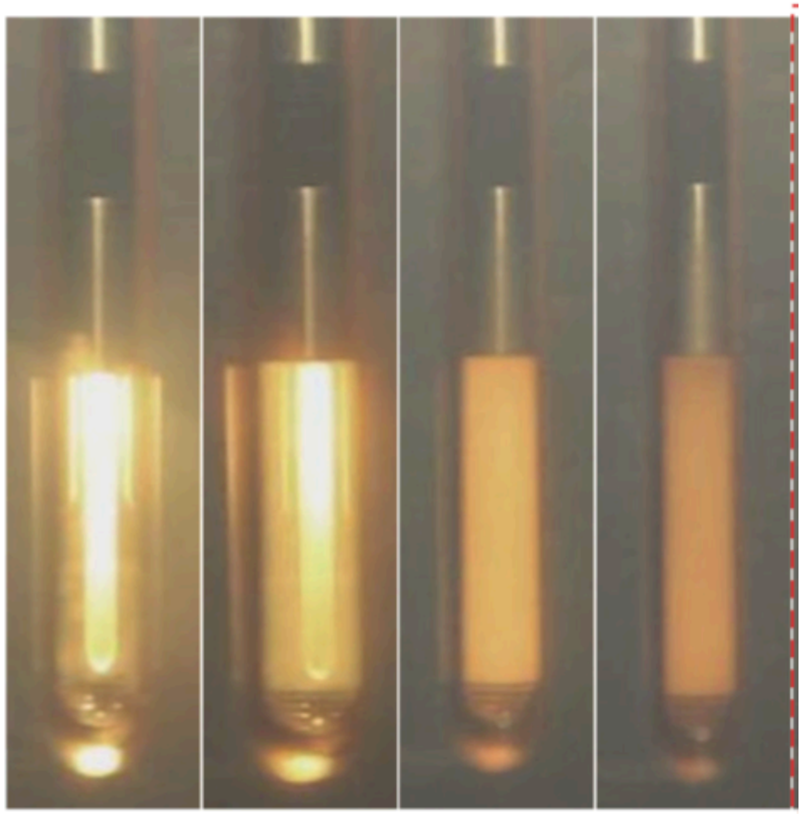
+

Gradient of $p_{(+)}$+dissipation ≃ acceleration of flow

Generalizing pressure, $p_{(+)}$: depends on offequilibrium fluct.

Similar for transport coefficients:

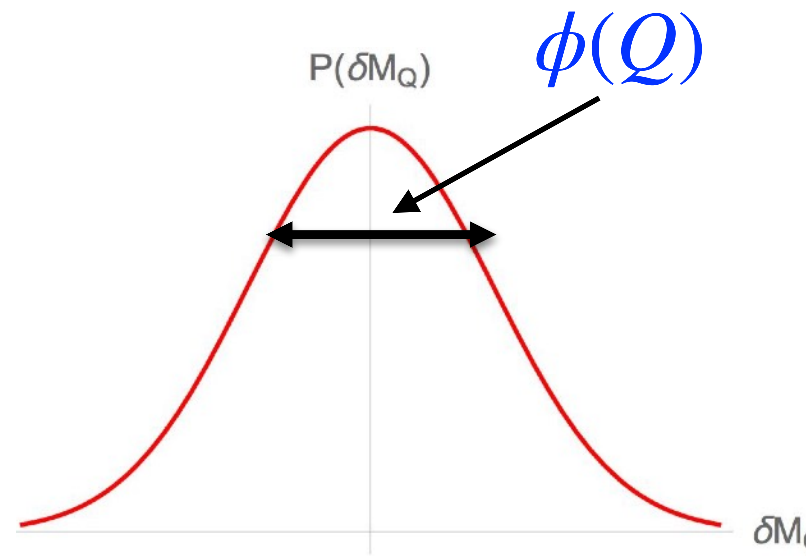
The long range critical fluctuations and critical opalescence



Hou et al, Journal of Chemistry 16'.

"As the density fluctuations become of a size comparable to the wavelength of light, the light is scattered and causes the normally transparent liquid to appear cloudy." — wikipedia

The construction of hydro+



The "+" of "hydro+" is (Winger transform of) the two point function of the fluctuating order parameter field δM (For QCD critical point and for description of the dynamics of ϕ, we will consider M ~ s/n):

$$\phi(t,x;Q) = \int d\Delta x\, e^{-i\Delta x Q} \langle\, \delta M(t, x+\Delta x/2)\, \delta M(t, x-\Delta x/2)\,\rangle$$

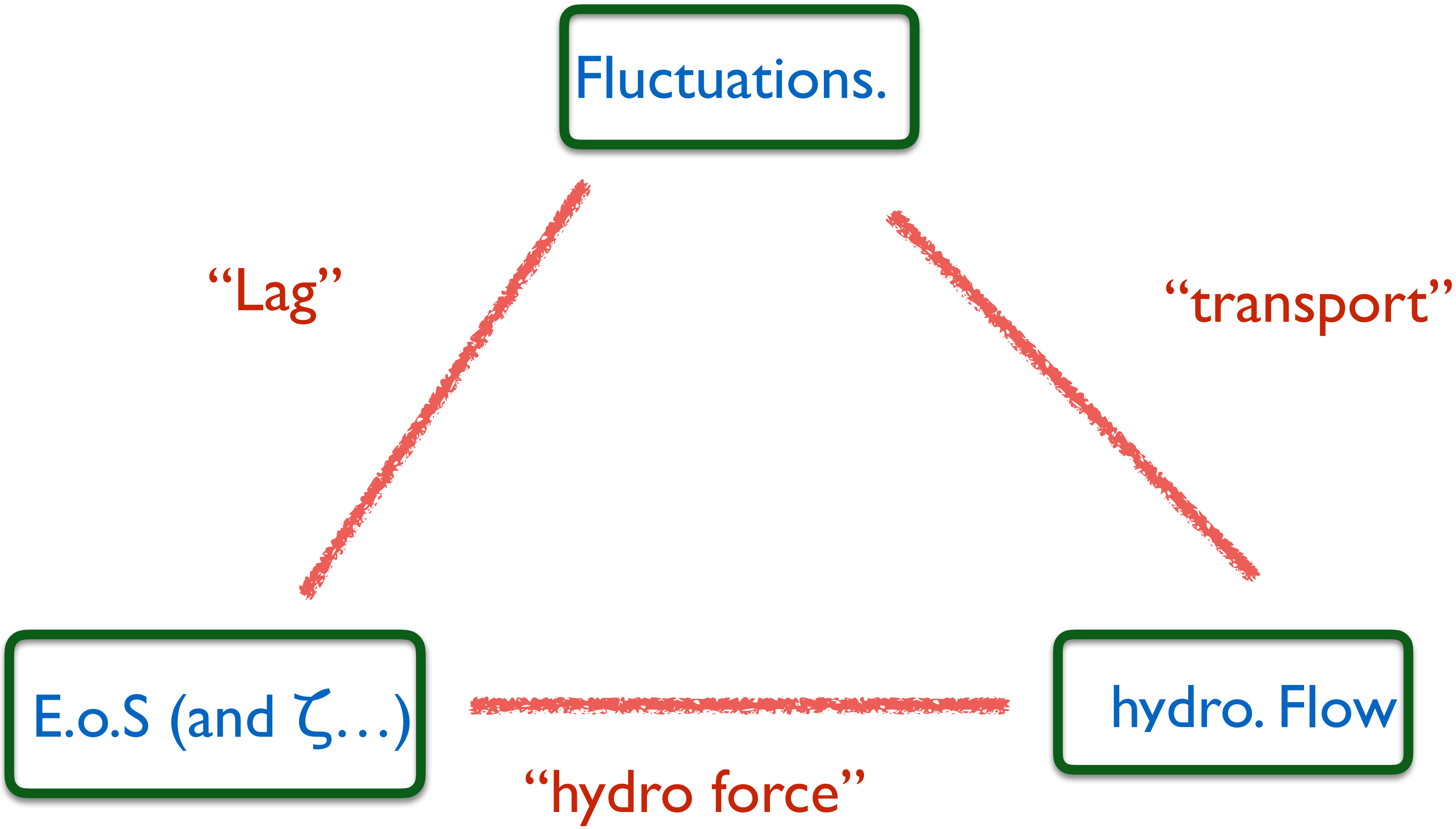
The fluctuations depend non-trivially on momentum Q (resolution scale or inverse of the size of the fluctuation) near C.P. E.g, for a homogeneous and equilibrated system.

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

$$\begin{cases} \phi_{eq}(Q \gg \xi^{-1}) \sim Q^{-2} \\ \phi_{eq}(Q \sim \xi^{-1}) \sim \xi^{2} \end{cases}$$

Those enhanced long wavelength flucts. is responsible for the phenomena of the critical opalescent.

Physics of "hydro+" is much richer than hydro!



I will show the first simulation of "hydro+" in a setting in which all the physics that is unique to Hydro+ is manifest, and in an environment that is analogous to the experimentally relevant setting modulo all the simplifications.

First simulation results.

Rajagopal-Ridgway-Weller-YY, 1908.08539

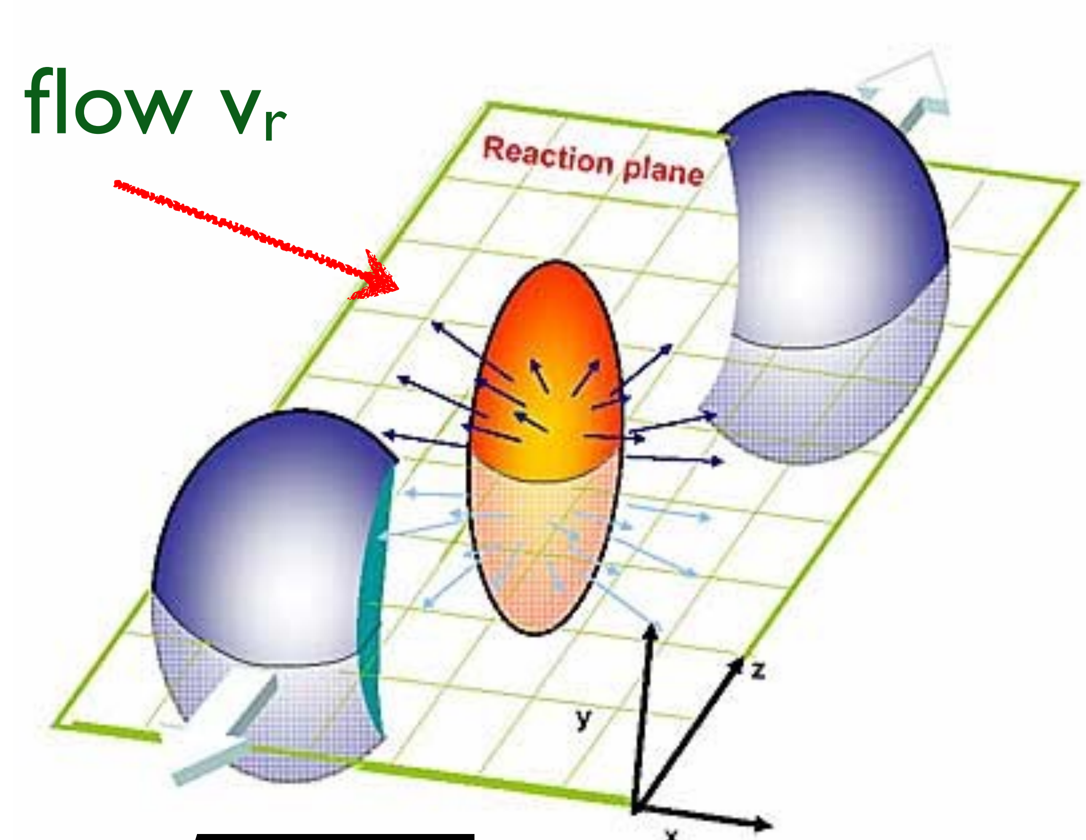
We consider a Bjorken and radial expanding ($v_r \neq 0$) and inhomogeneous fluid.

By assuming certain geometrical symmetry, we solve full hydro+ equation for energy density $e(\tau,r)$, radial flow $v_r(\tau,r)$ and wavelength-dependent fluctuations $\phi(\tau,r,Q)$, and showcase the intertwined dynamics among them.

radial flow v_r

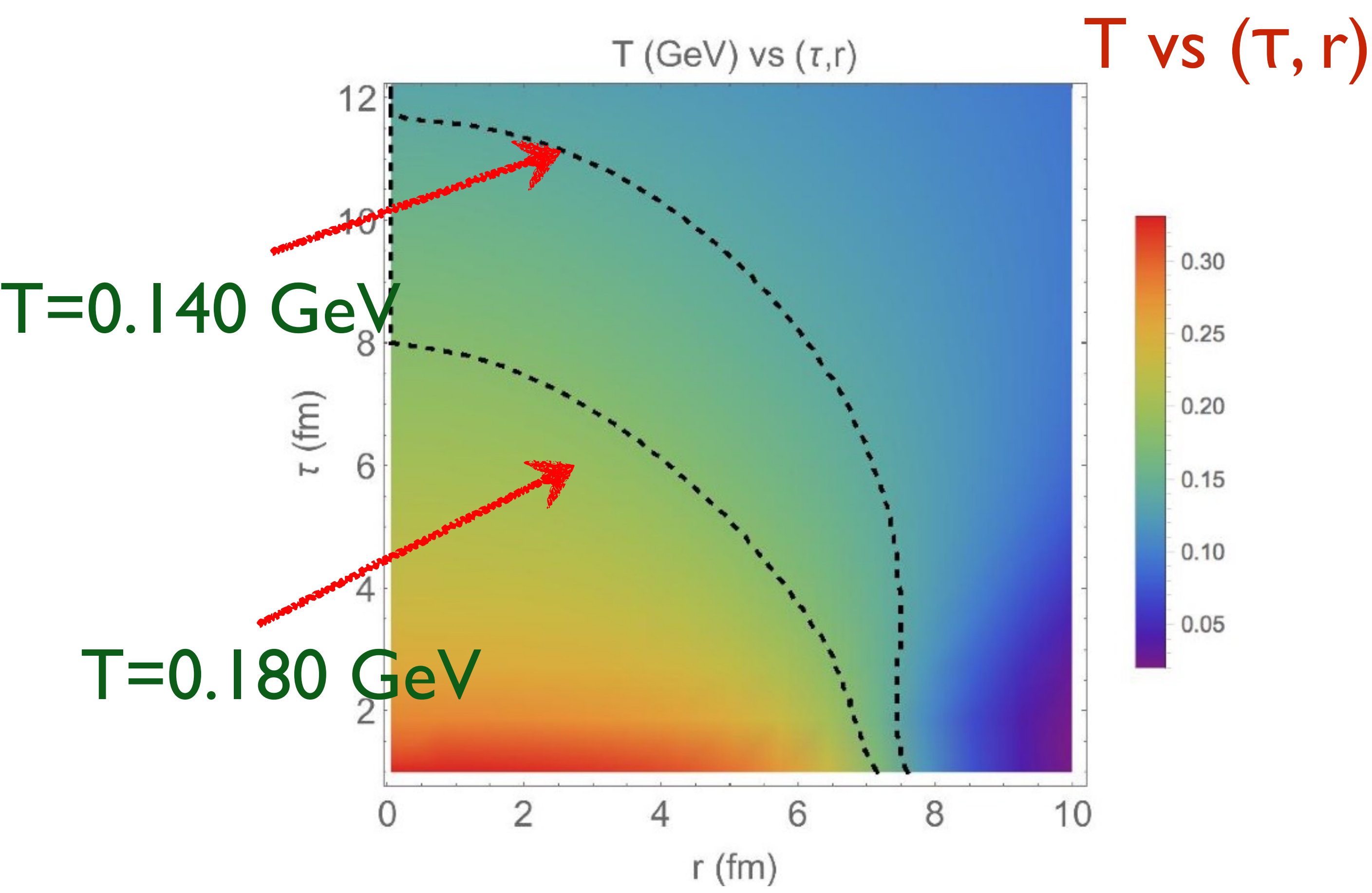
Greg Ridgway
grad of MIT

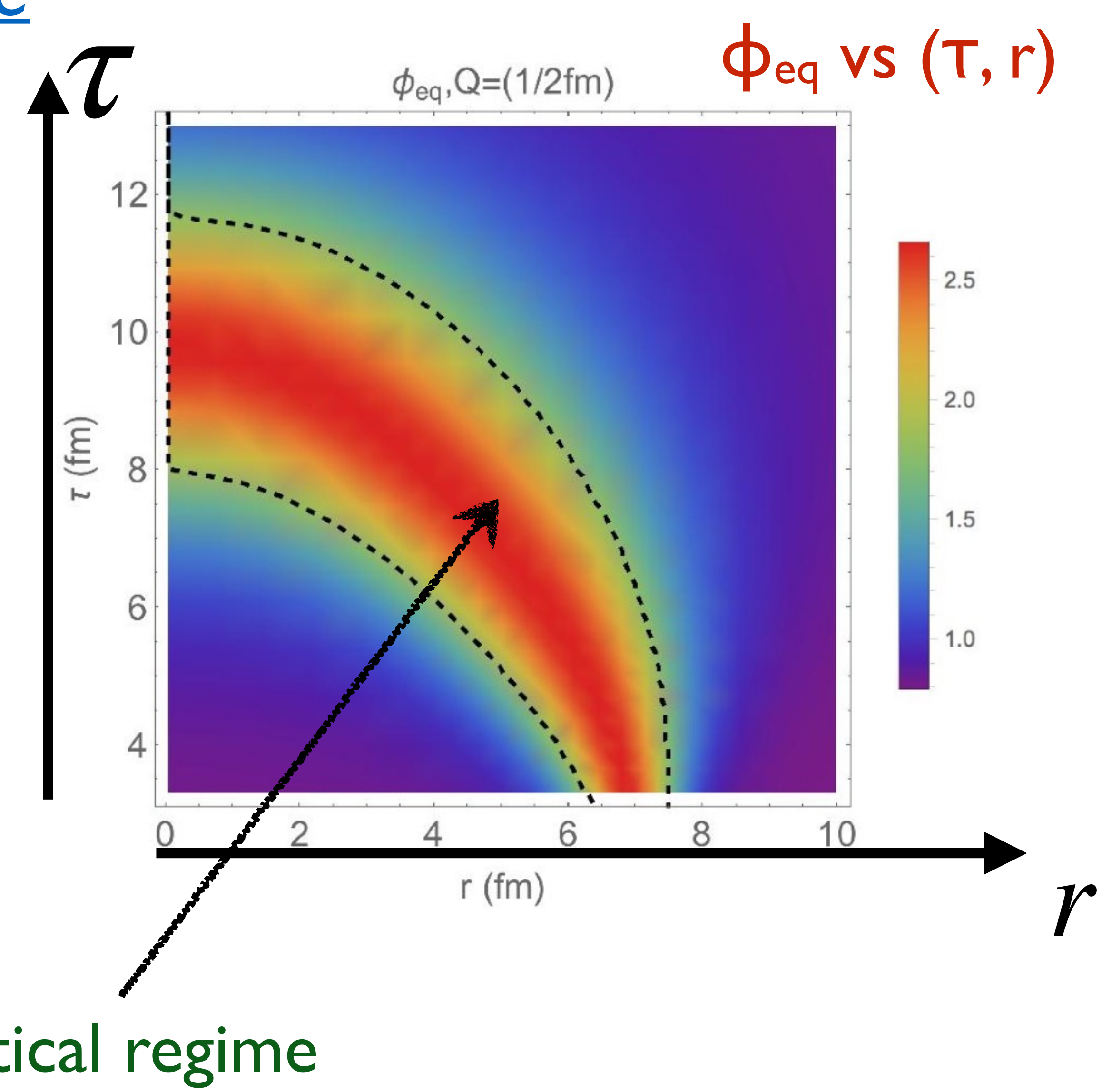
Ryan Weller
grad of MIT



$$r = \sqrt{x^2 + y^2} \qquad , \tau = \sqrt{t^2 - z^2}$$

Setting up the stage: temperature profile

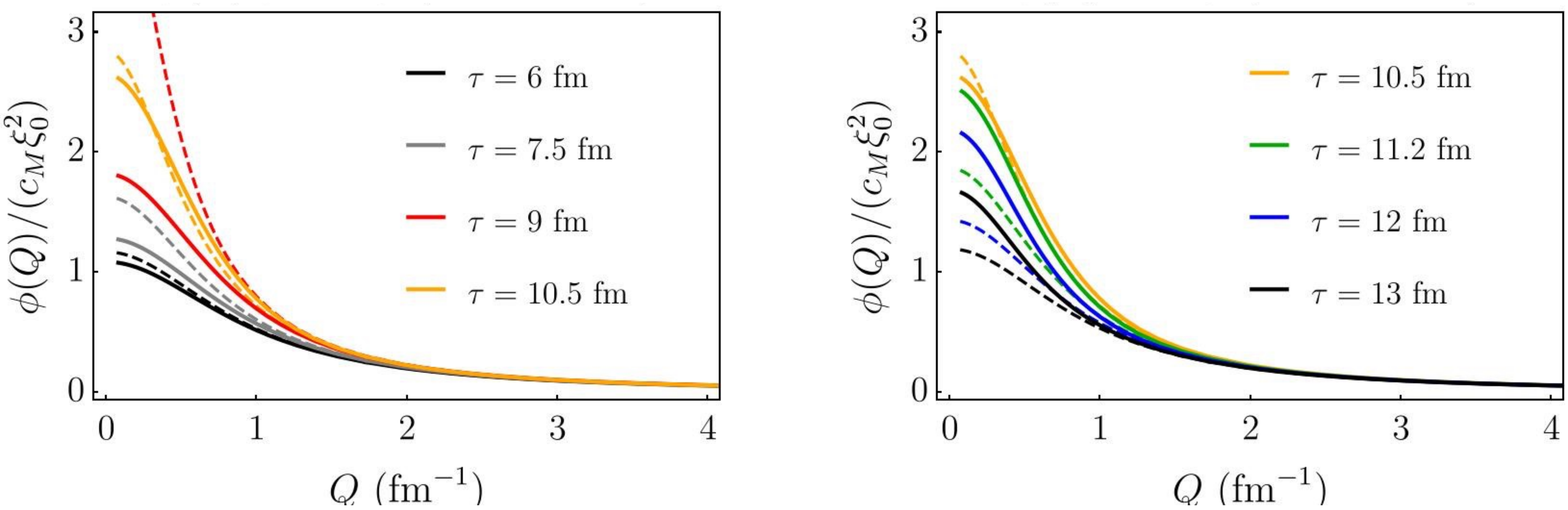




We place a hypothetical C.P. near μ=0 (no eq for baryon density.)
The critical fluctuation reaches its maximum around Tc=0.160 GeV.

The off-equilibrium evolution of long wavelength fluctuations at r=1 fm.

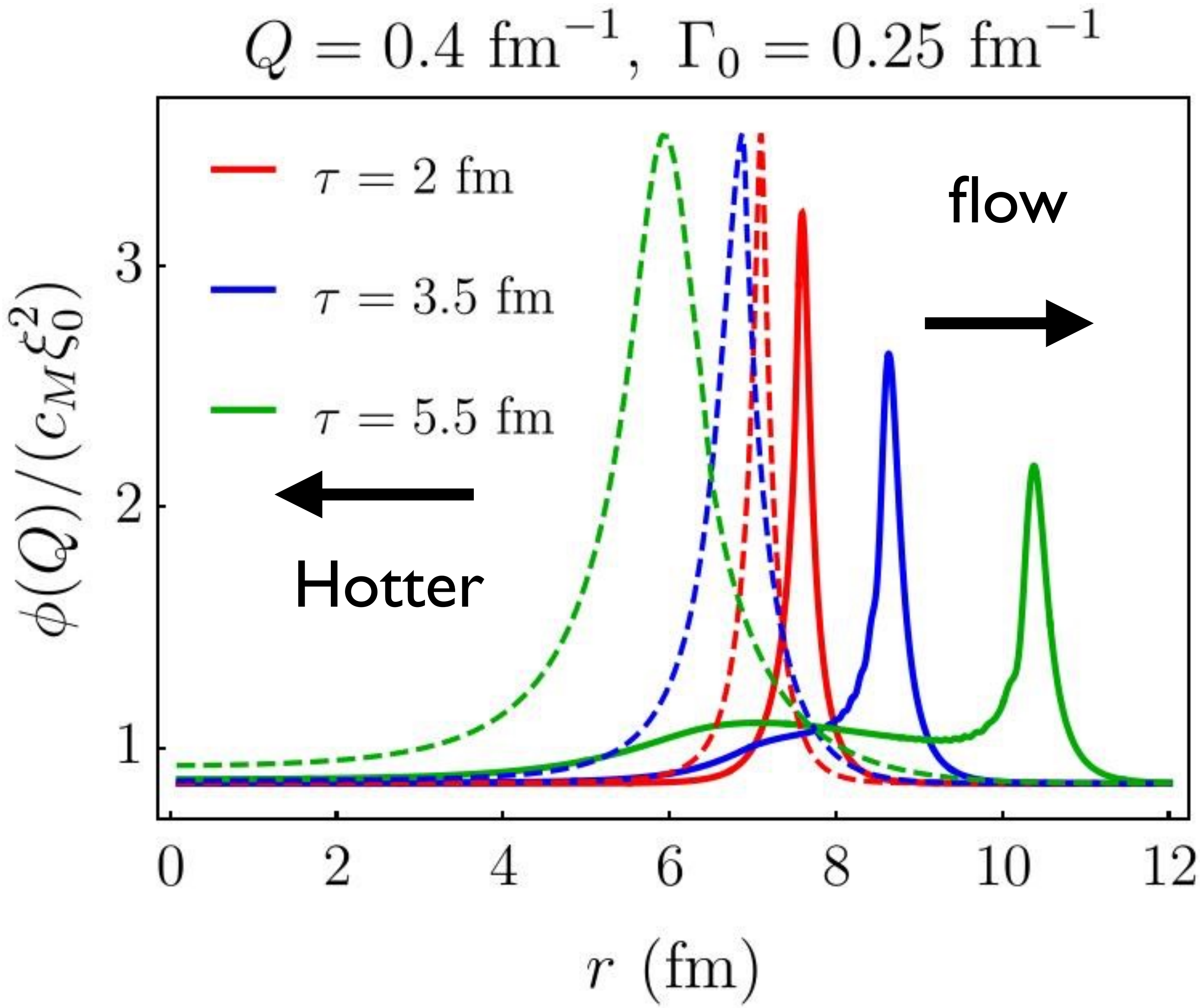
Off-quilibrium ϕ: solid. Equilibrium ϕeq: dashed.



Resolution-scale dependence: large Q (shortwave length) modes are in equilibrium while small Q (long wavelength) modes are not.

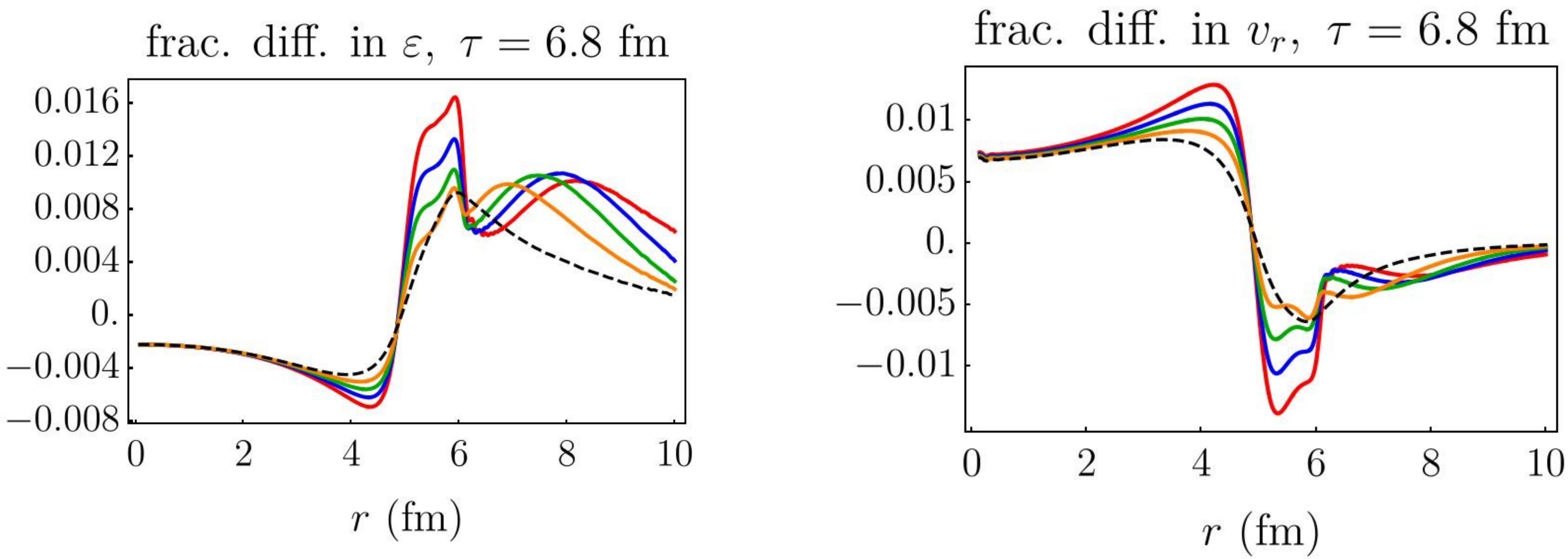
Equilibrium long wavelength fluct. : first rises and then falls

Off-equilibrium evolution of long wavelength mode: first lags behind, and then remembers info about the criticality.



The spatial dependence of the evolution of ϕ is driven by critical slowing down effect and advection by the flow.

The snapshot of energy density and radial flow vs r



From: red, blue, green and orange, results including back-reaction with decreasing relaxation rate. Dashed, no back-reaction.

More those long wavelength fluctuations are away from the equilibrium, the stronger their influence on the energy density and flow.

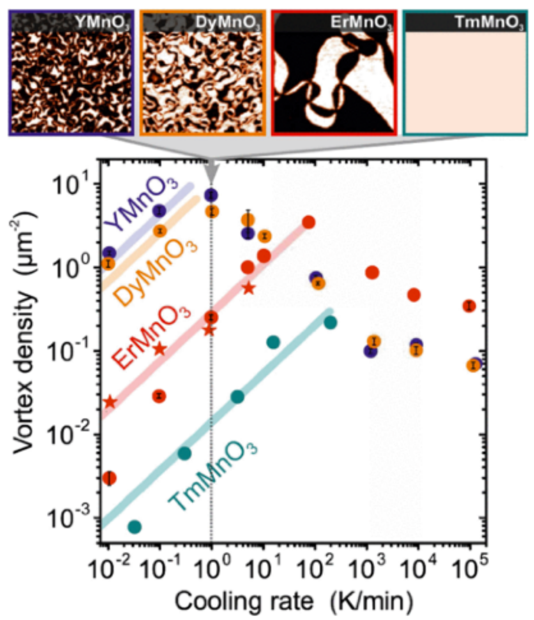
We have developed a new dynamical framework, hydro+ to couple bulk evolution and offequilibrium fluctuations in a self-consistent fashion.

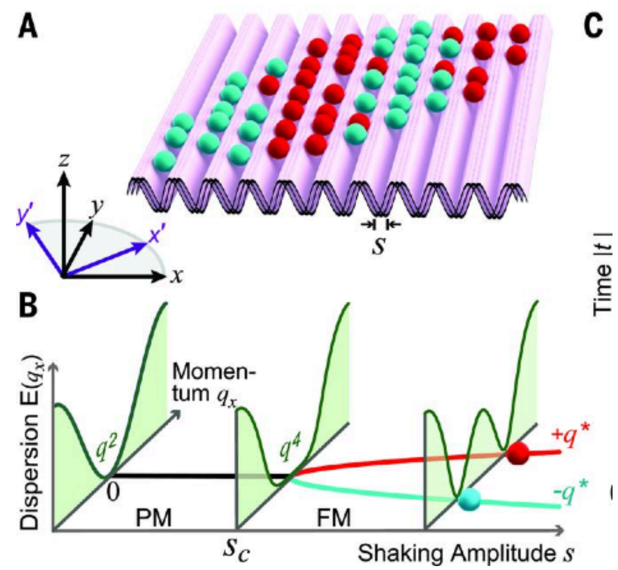
This new theory has been successfully exercised in a concrete, albeit simplified settings. We have seen that interplay among flow and fluctuations manifest explicitly.

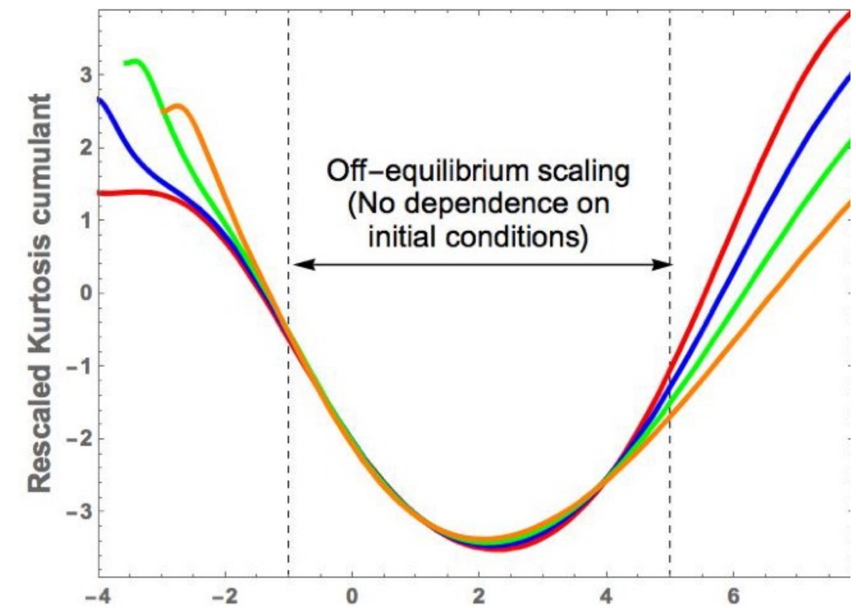
Encouraging progress has been reported from the two different groups (Ohio state U., Wayne state U.) on full numerically simulation of hydro+ .

The era of quantitative studies of critical dynamics has just begun!

The physics of critical dynamics search is very rich, and is of broad interest.







(Bosons in a shaken optical lattice, W. Clark et al, Science' 16)

Hexagonal Manganites, M. Griffin et al, Phys.Rev.X ' 12

(Conjecture for critical quark matter, S. Mukherjee, R. Venugopalan and YY, PRL, Editors' suggestion, '16.)

For example, the offequlibrium critical scaling (Kibble-Zurek scaling) behavior in HIC is expected to be observed. If so, this would be a nice demonstration of the unity of physics.

Main questions of the field

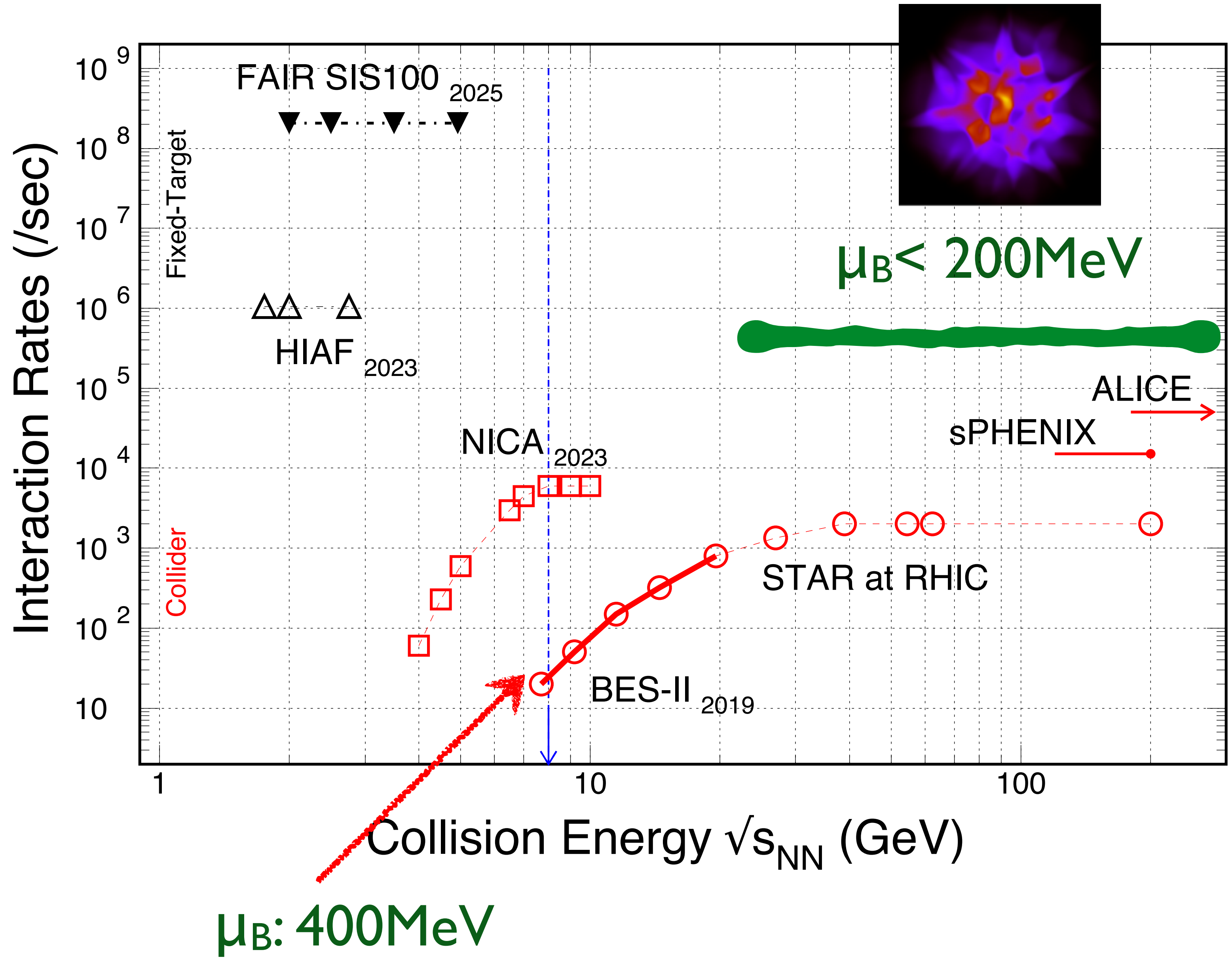
How does strongly coupled fluid emerge from the asymptotic free QCD as resolution scale decreases?

How does the fluid-like behavior emerges from highly an-isotropic and non-equilibrium quark-gluon matter at early time?

How does the properties of QGP liquid change as baryon density increases? (this talk).

Summary and outlook

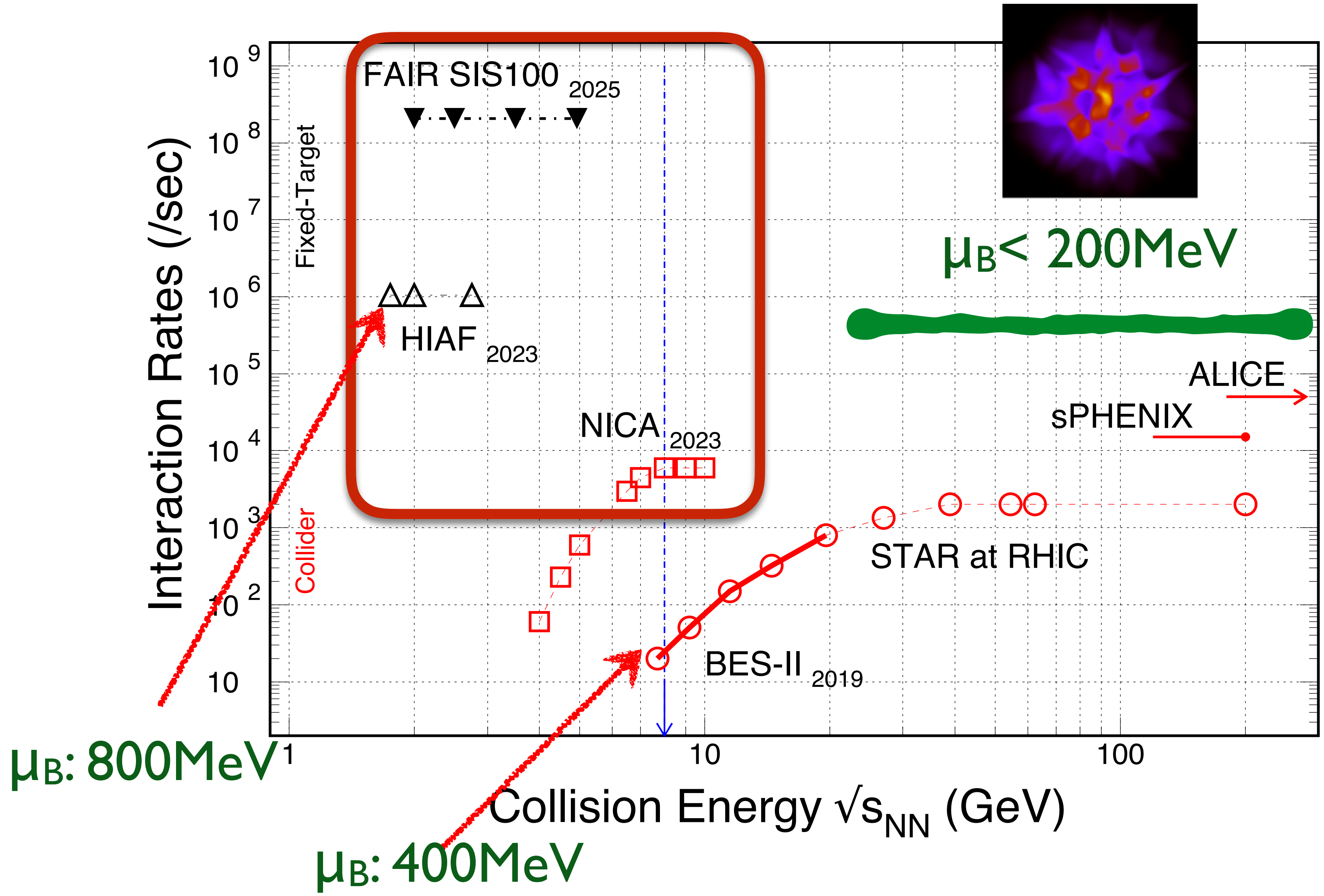
The voyage of discovery on the QCD phase diagram: from past to now



Earlier "voyages" (μ_B<200 MeV): discovery of QGP liquid.

"Voyage" now: BESII will scan the phase diagram up to μ_B~400MeV, and search for the critical point. — we are working to build the needed theoretical tools

The voyage of discovery on the QCD phase diagram: from now to future

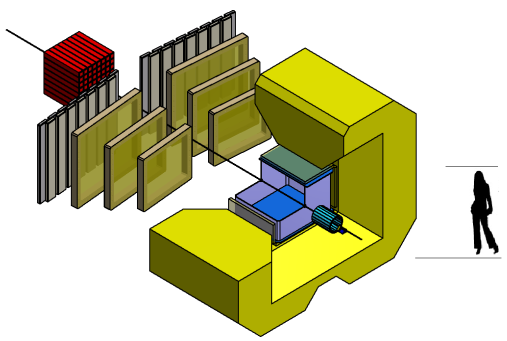


Future: facilities worldwide (LHC,FAIR/CBM, NICA,HIAF, …) will open new observational frontier in the next decade (μ_B up to 800MeV~M_N). Opportunities around !

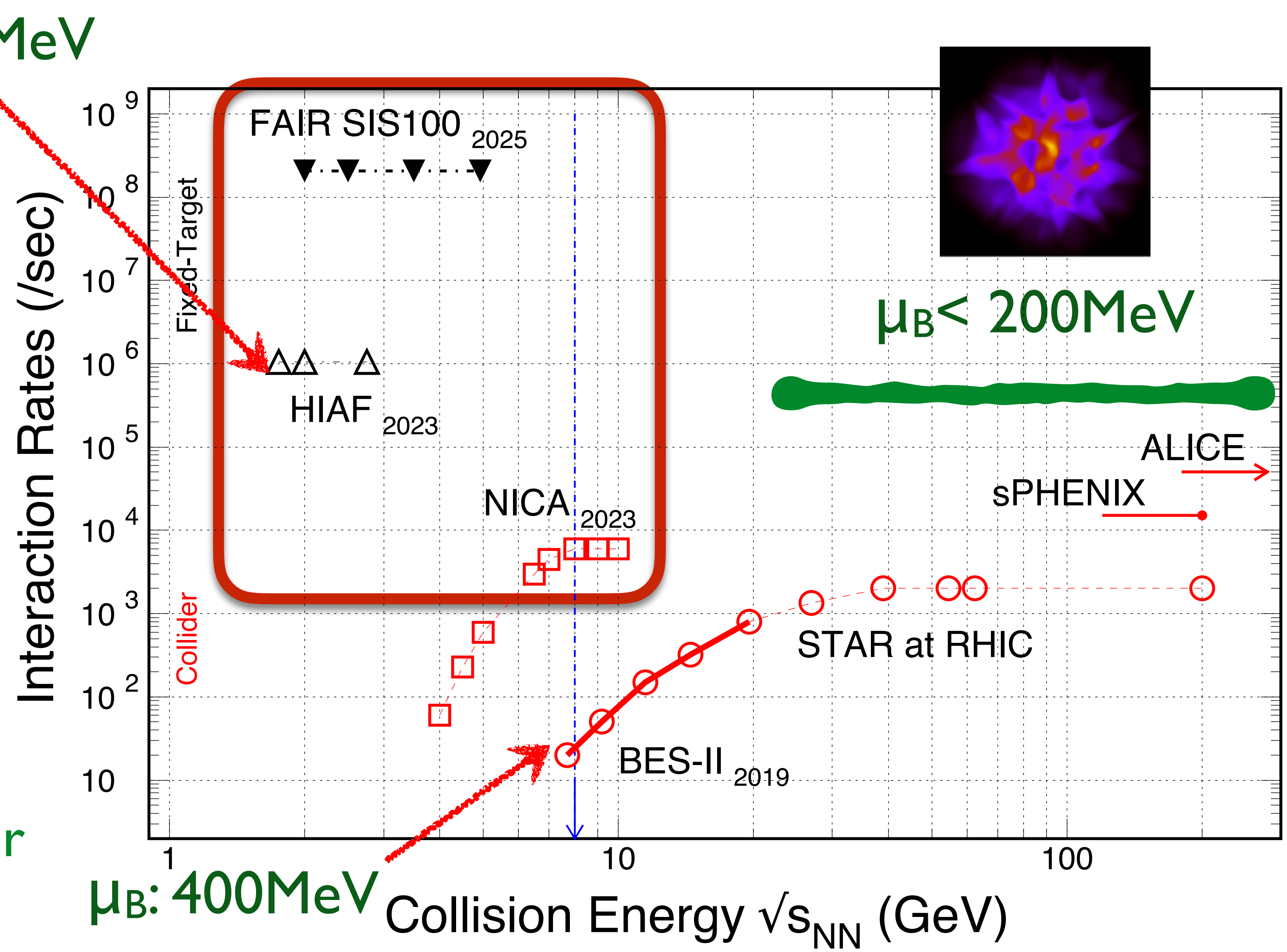
Russian	NICA	2023
Germany	FAIR	2025
China	HIAF	2025

Pushing towards the boundary

HIAF at Huizhou (construction began on 2018)

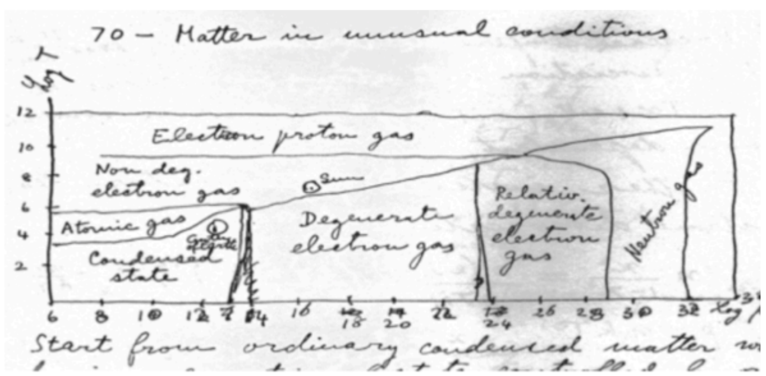


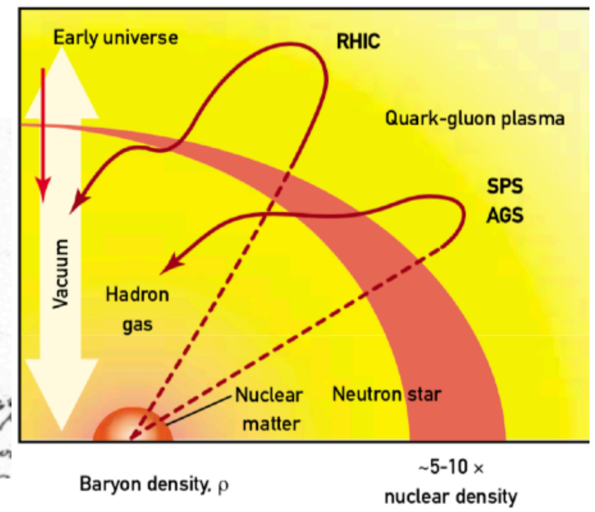
Design of CEE (detector) for fixed target collision at HIAF

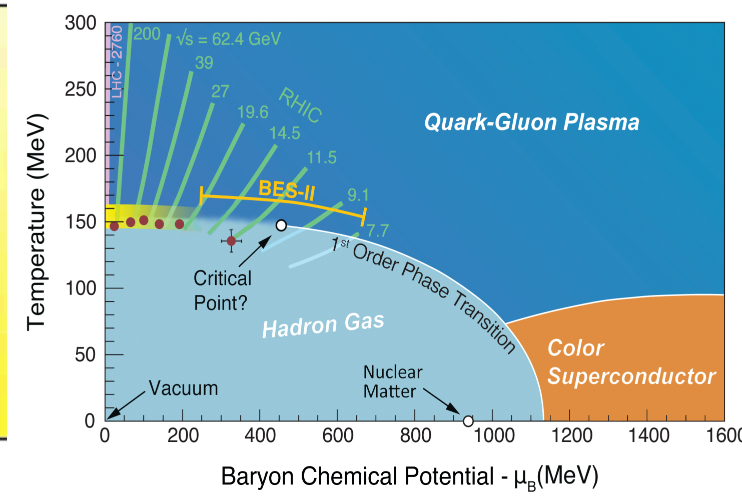


Future heavy-ion collision experiment in China and Germany will explore the high density regime with high precision!

Outlook







?

Fermi (1952)

2002

2015

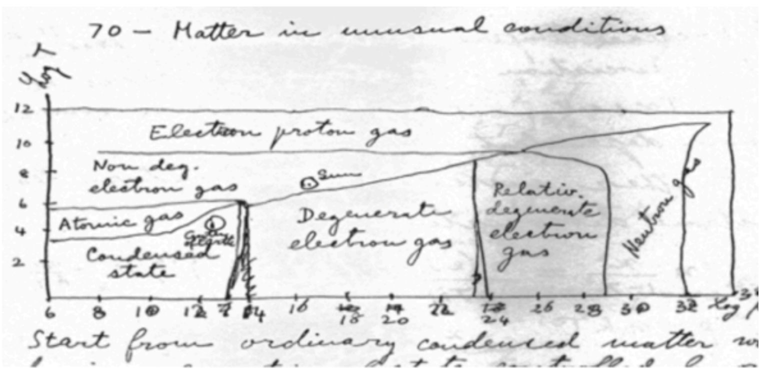
2020+

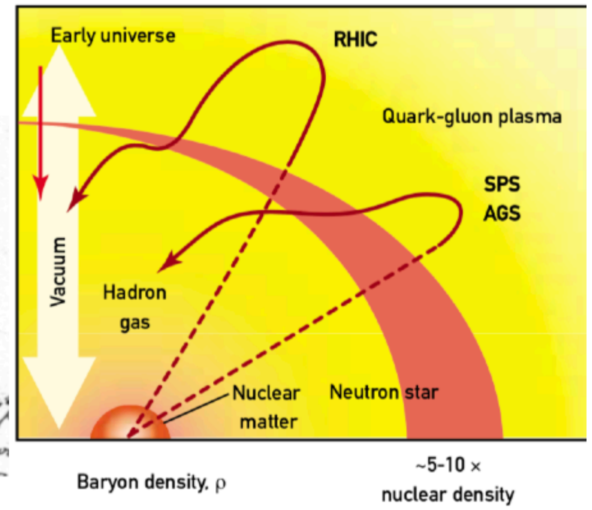
RHIC starts running

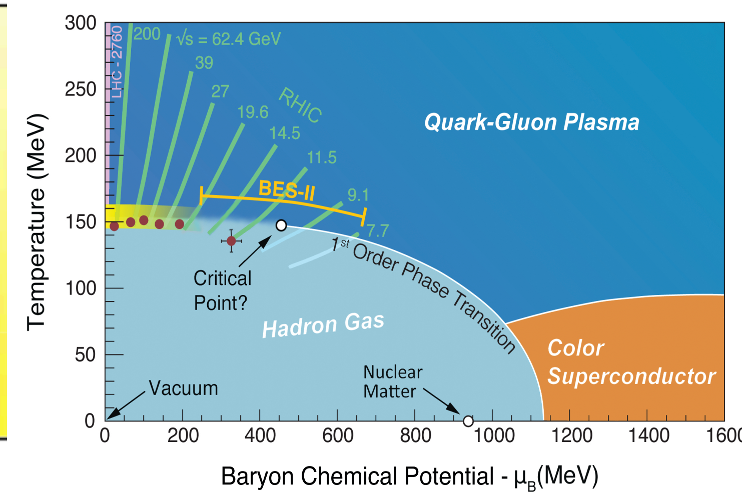
Future experiment

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

Outlook







?

Fermi (1952)

2002

2015

2020+

RHIC starts running

Future experiment

Welcome come to join this scientific journey!

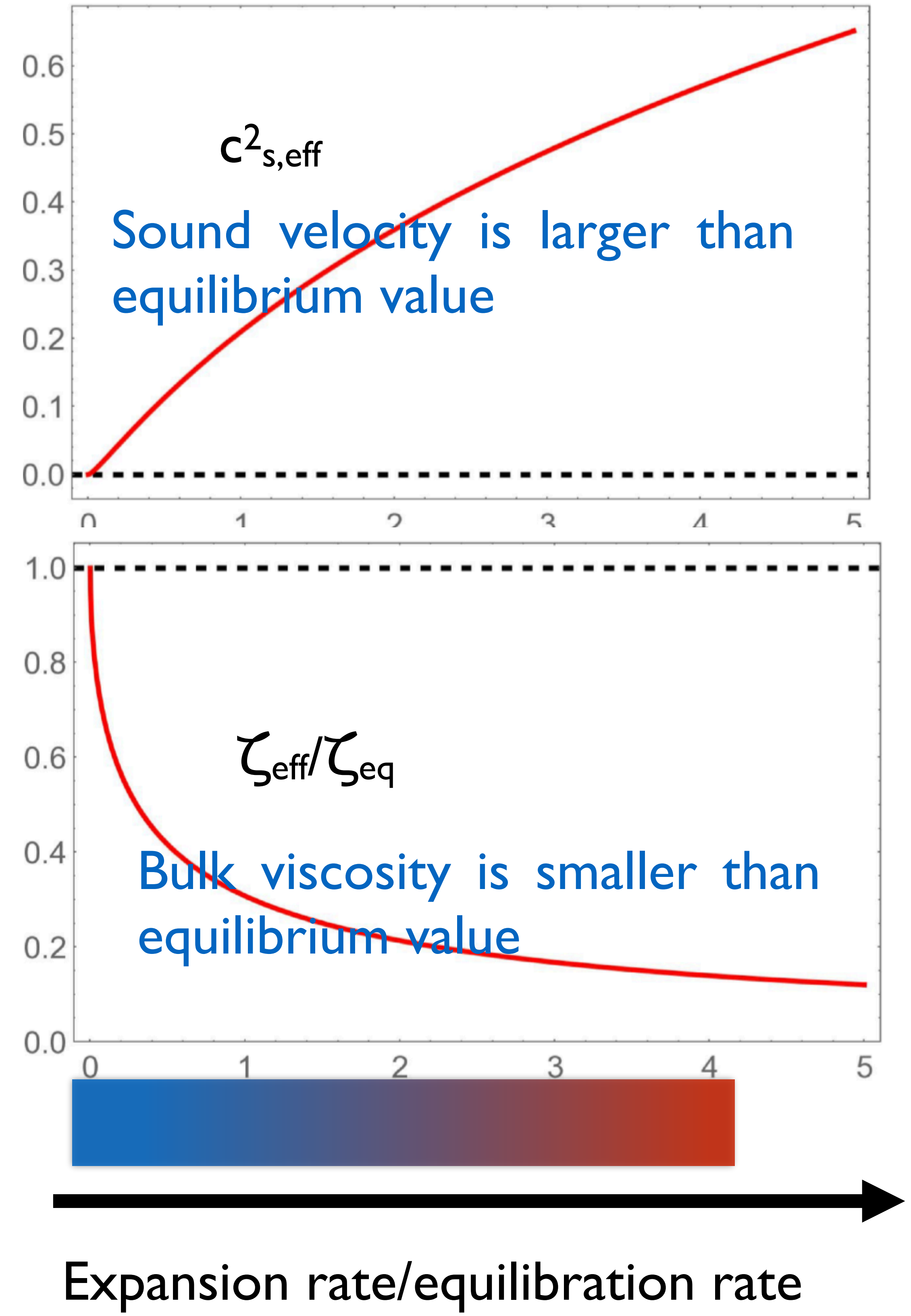
Back-up

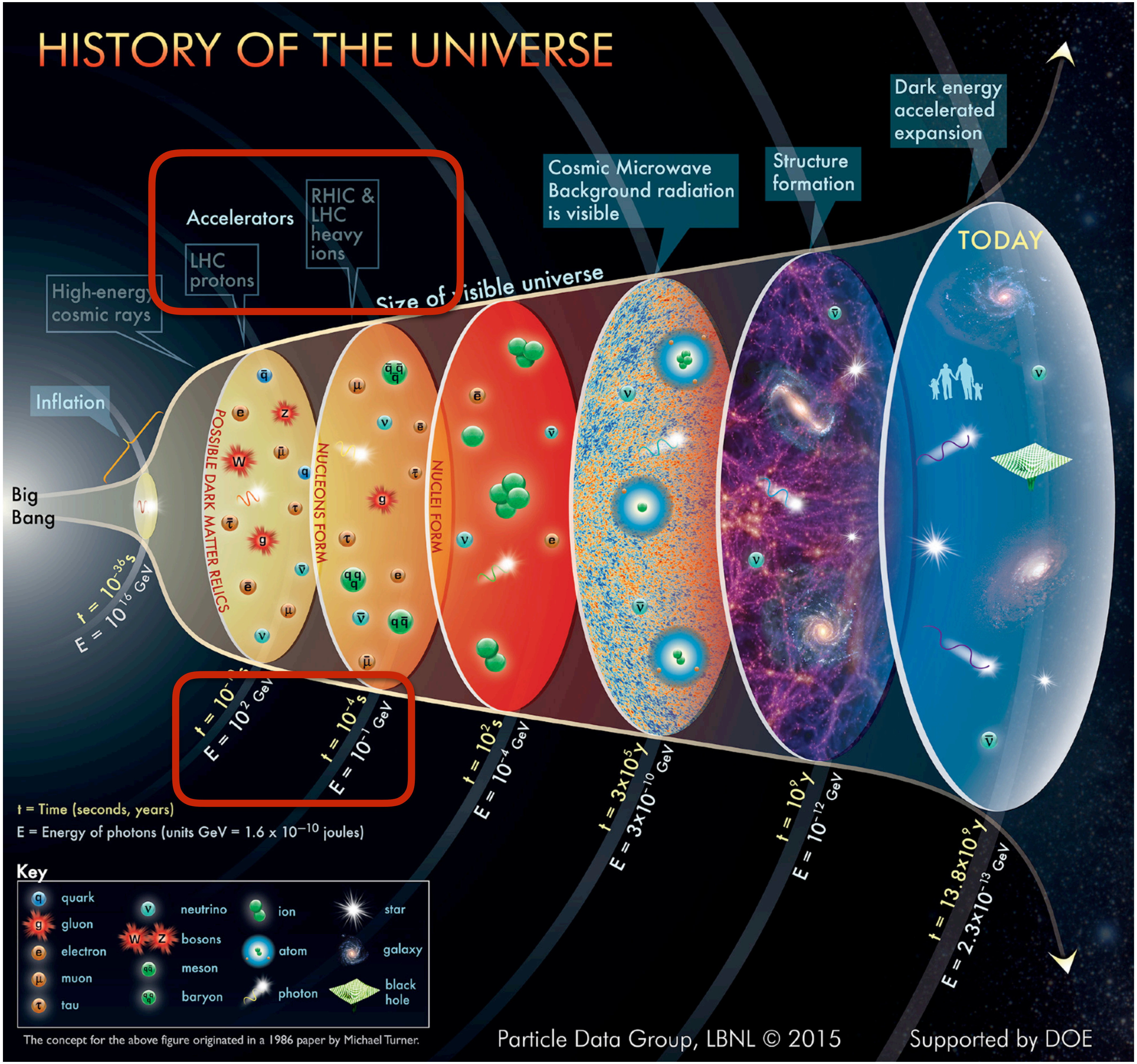
Effective sound velocity and bulk viscosity from "hydro+"

By solving linearized "hydro+", we could determine frequency-dependent "effective sound velocity" and "effective bulk viscosity".

"Hydro+" captures the off-equilibrium effects on effective E.o.S and effective transport coefficients.

(At linearized level, "hydro+"="one loop" calculation of hydro. fluctuations, e.g. by Onuki, PRA,1997. However, "hydro+" is intrinsically nonlinear.)





HISTORY OF THE UNIVERSE
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Inflation
Big Bang
Size of visible universe
Cosmic Microwave Background radiation is visible
Structure formation
Dark energy accelerated expansion
TODAY
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10⁻³⁶ s E = 10¹⁶ GeV
t = 10⁻¹⁰ s E = 10² GeV
t = 10⁻⁴ s E = 10⁻¹ GeV
t = 10² s E = 10⁻⁴ GeV
t = 3x10⁵ y E = 3x10⁻¹⁰ GeV
t = 10⁹ y E = 10⁻¹² GeV
t = 13.8x10⁹ y E = 2.3x10⁻¹³ GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10⁻¹⁰ joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE

MENU

nature COMMUNICATIONS

Article | OPEN

An equation-of-state-meter of quantum chromodynamics transition from deep learning

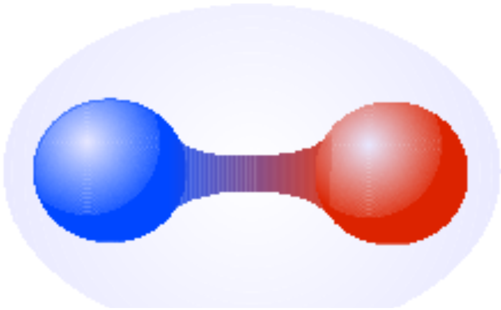
Long-Gang Pang, Kai Zhou, Nan Su, Hannah Petersen, Horst Stöcker & Xin-Nian Wang

Nature Communications **9**, Article number: 210 (2018)
doi:10.1038/s41467-017-02726-3

Received: 20 March 2017
Accepted: 20 December 2017
Published online: 15 January 2018

Two outstanding questions on QCD vacuum

Unseen quark.



Broken symmetry.

Both questions are related to the fascinating properties of QCD vacuum.

To understand QCD vacuum:

- Sending energetic messengers.
- Breaking the vacuum by heating it up or compressing it.