The voyage of discovery in the phase diagram of nuclear matter via heavy-ion collisions

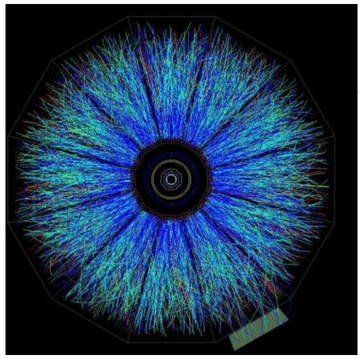
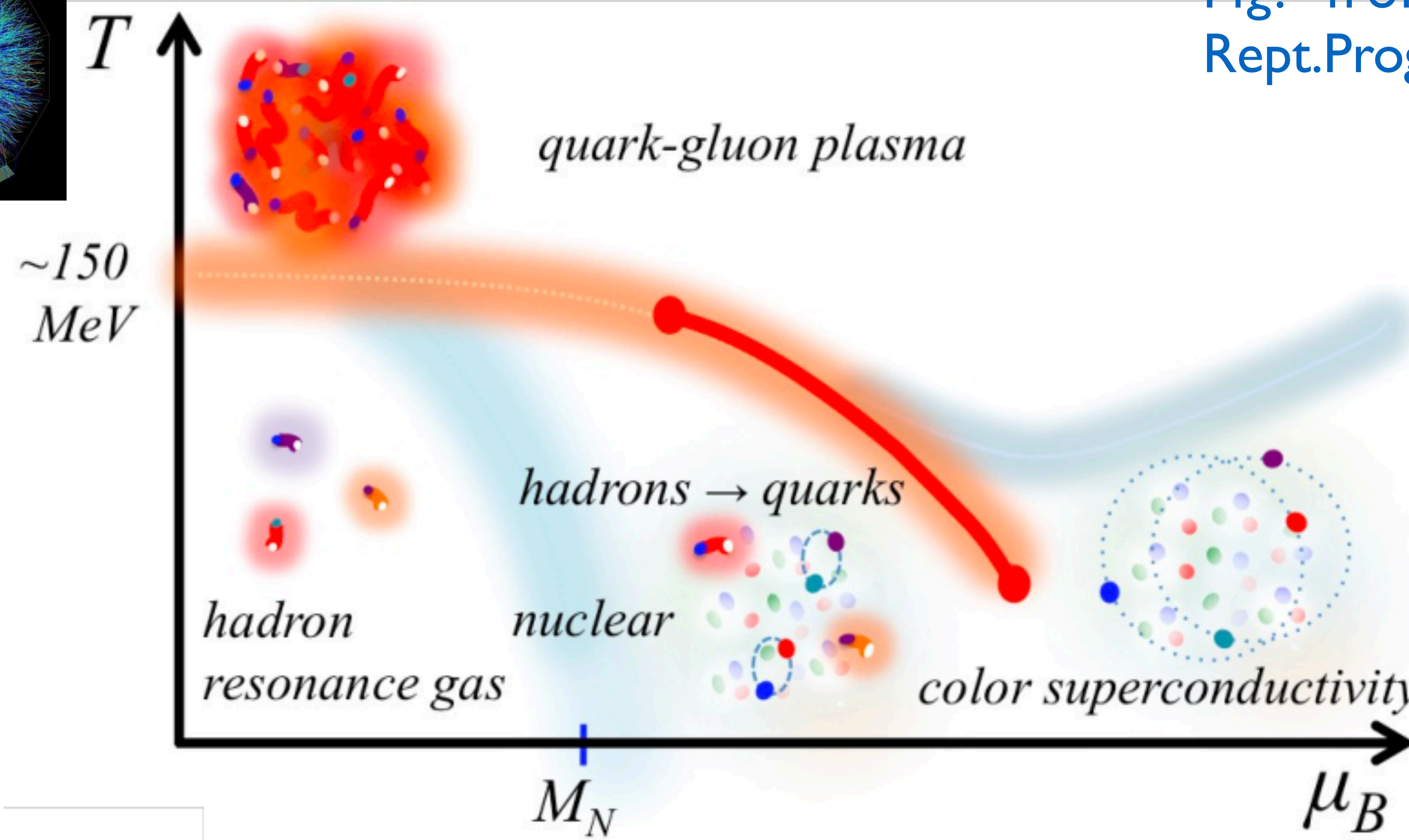
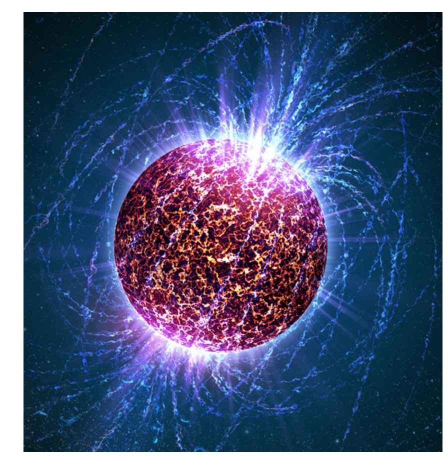


Fig. from Baym et al, Rept.Prog.Phys. 81,2018

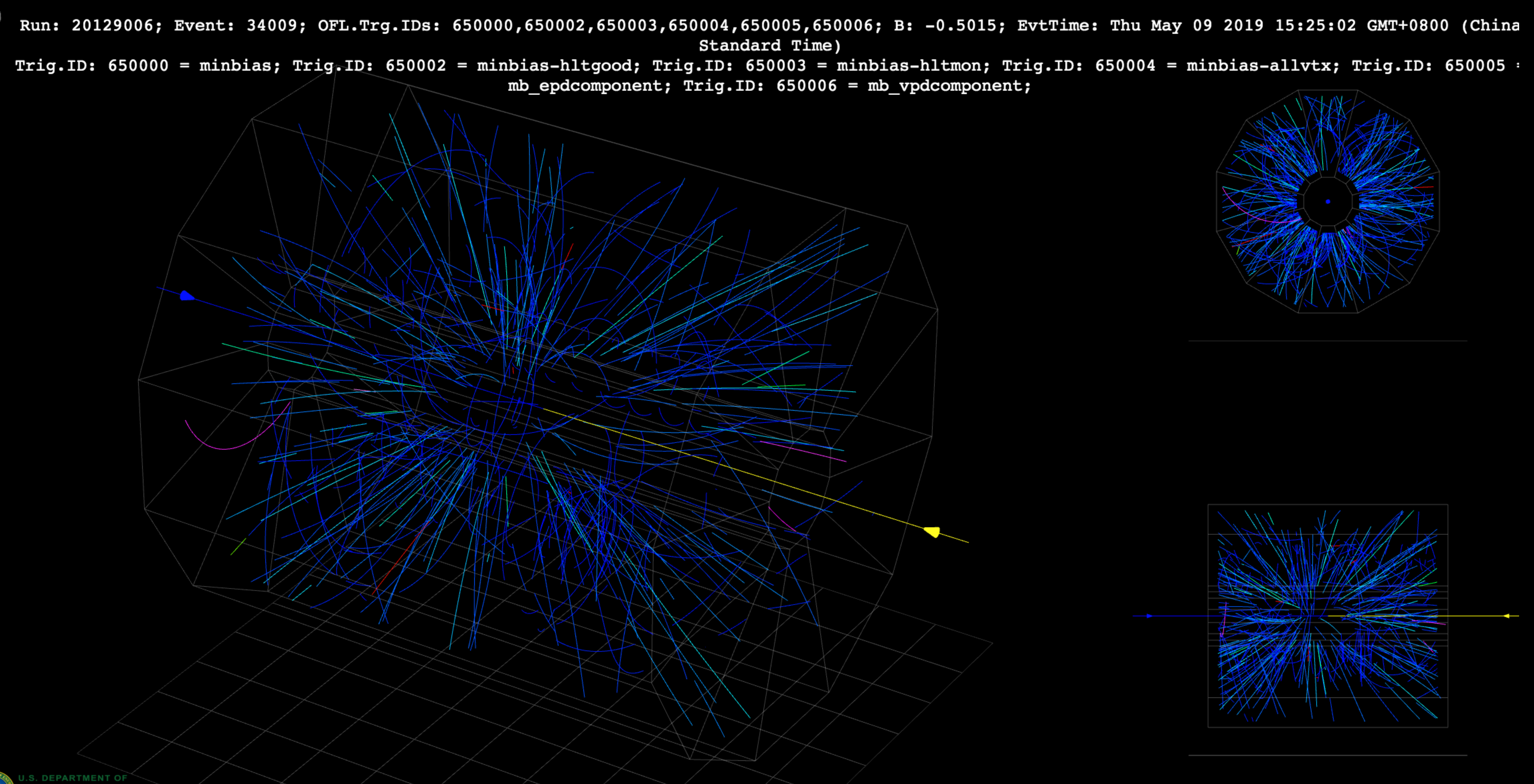




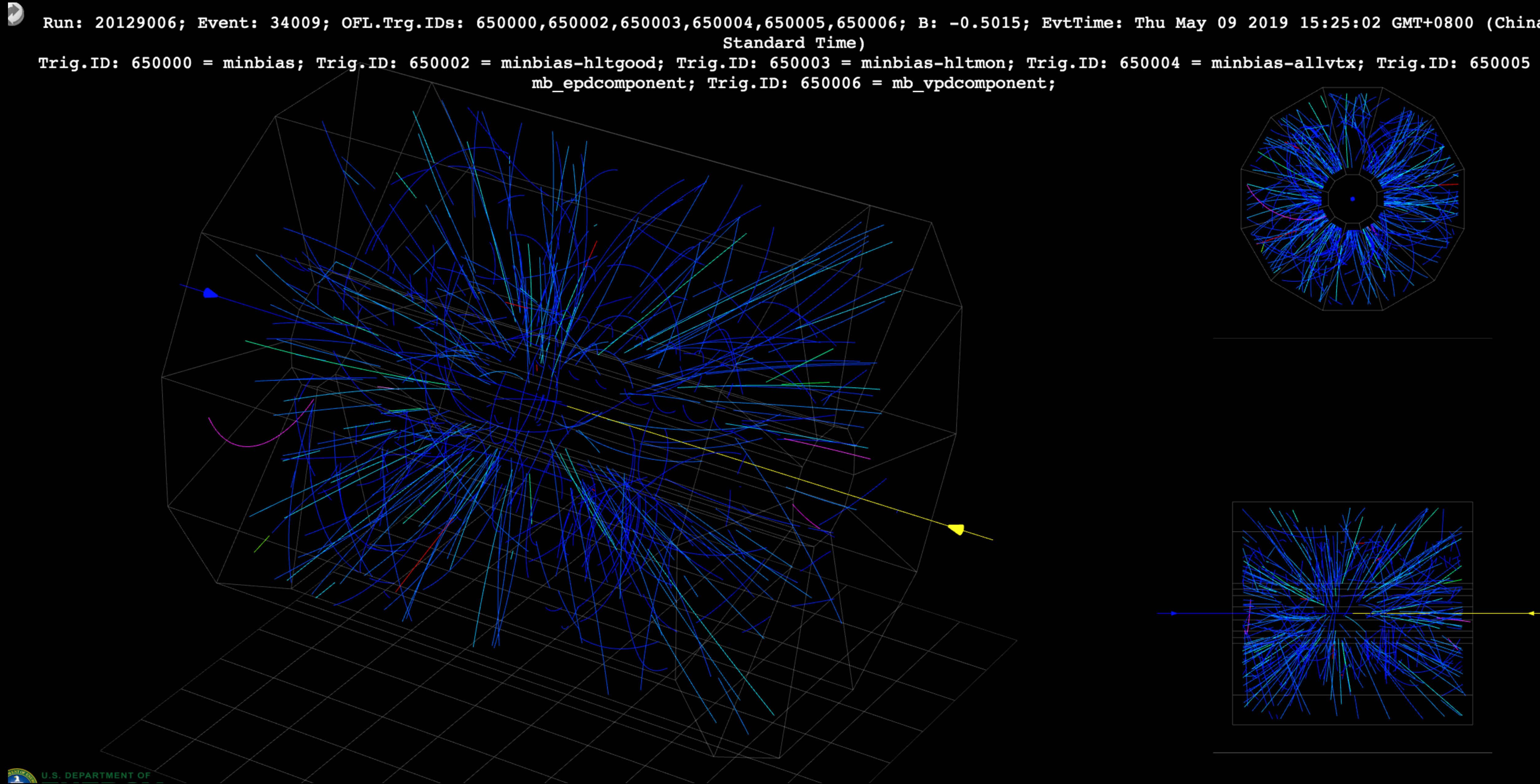
Yi Yin

BEST COLLABORATION

8th Huada School, May.9, 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.

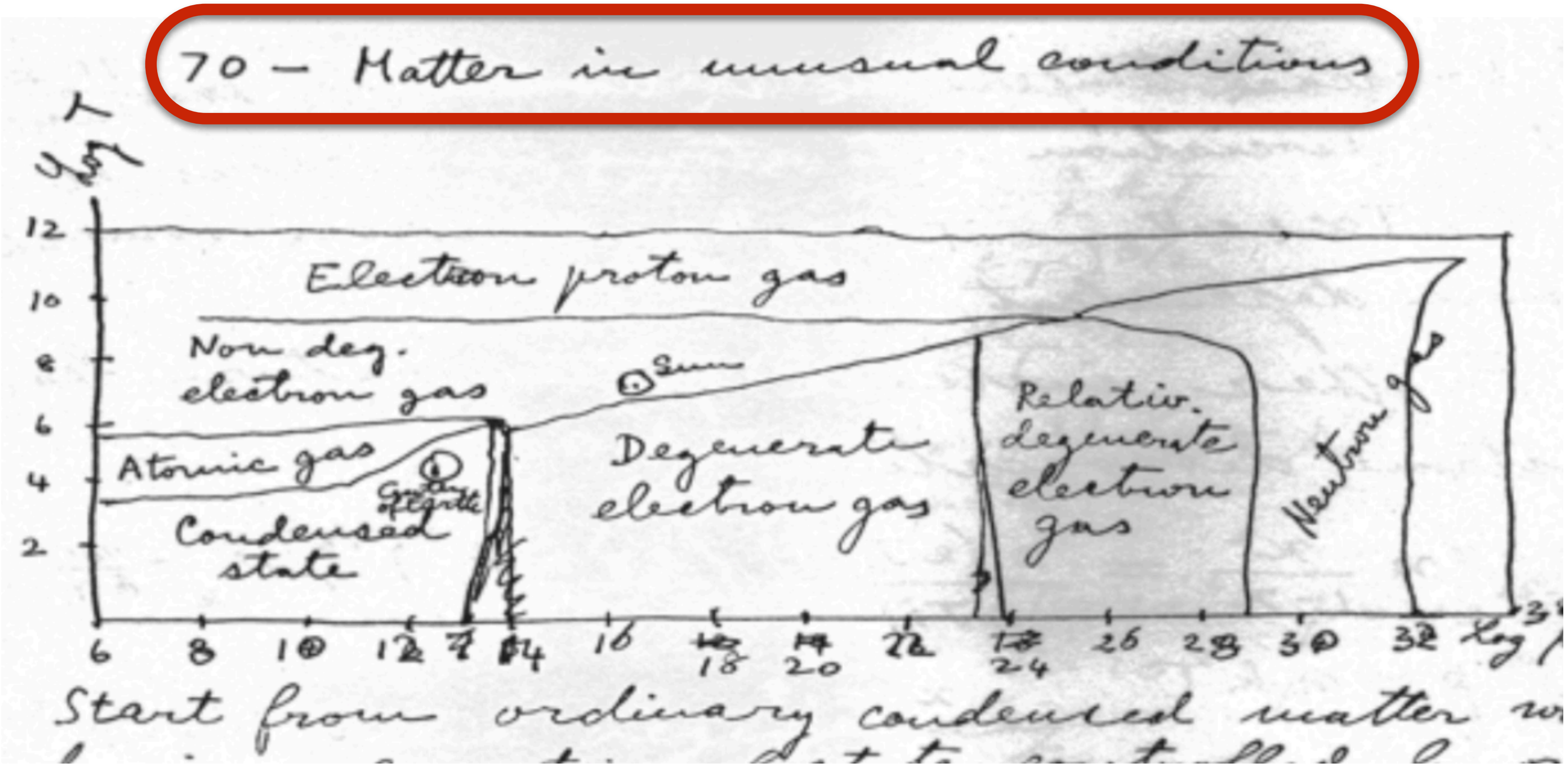


What have we learned about the properties of quark-gluon matter via heavy-ion collisions?

How to search for the QCD critical point experimentally?

Future prospect?

Fundamental question: phases of matter under extreme conditions



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

Under extreme hot/dense condition, quark-gluon matter (matter with quarks and gluons as degree of freedom) can be created.

Quark-gluon matter exhibits interesting properties and rich phase structure.

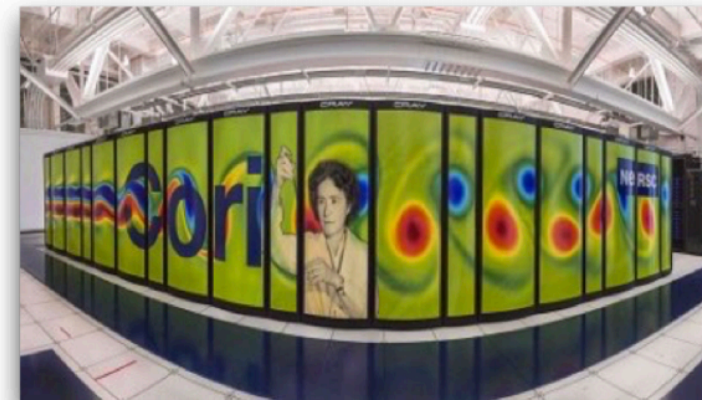
c.f. Baym and Reddy's lecture

Thermodynamics of QCD at small baryon density can be studied via first principle lattice simulation

Summit (TOP500: 1)

Titan (TOP500: 9)

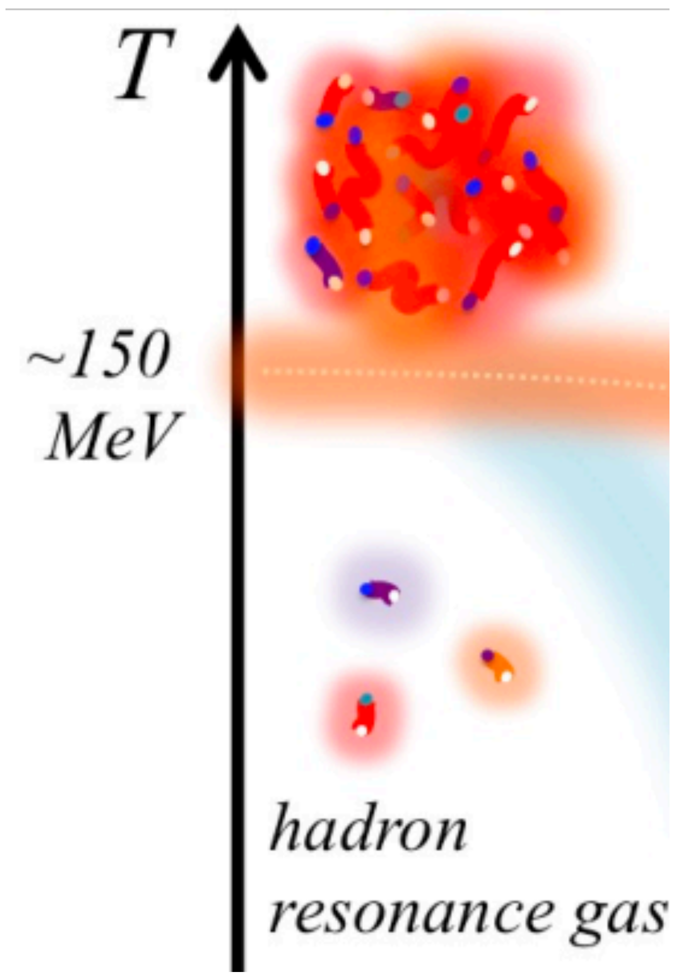
Cori (TOP500:12)



Piz Daint (TOP500: 5)

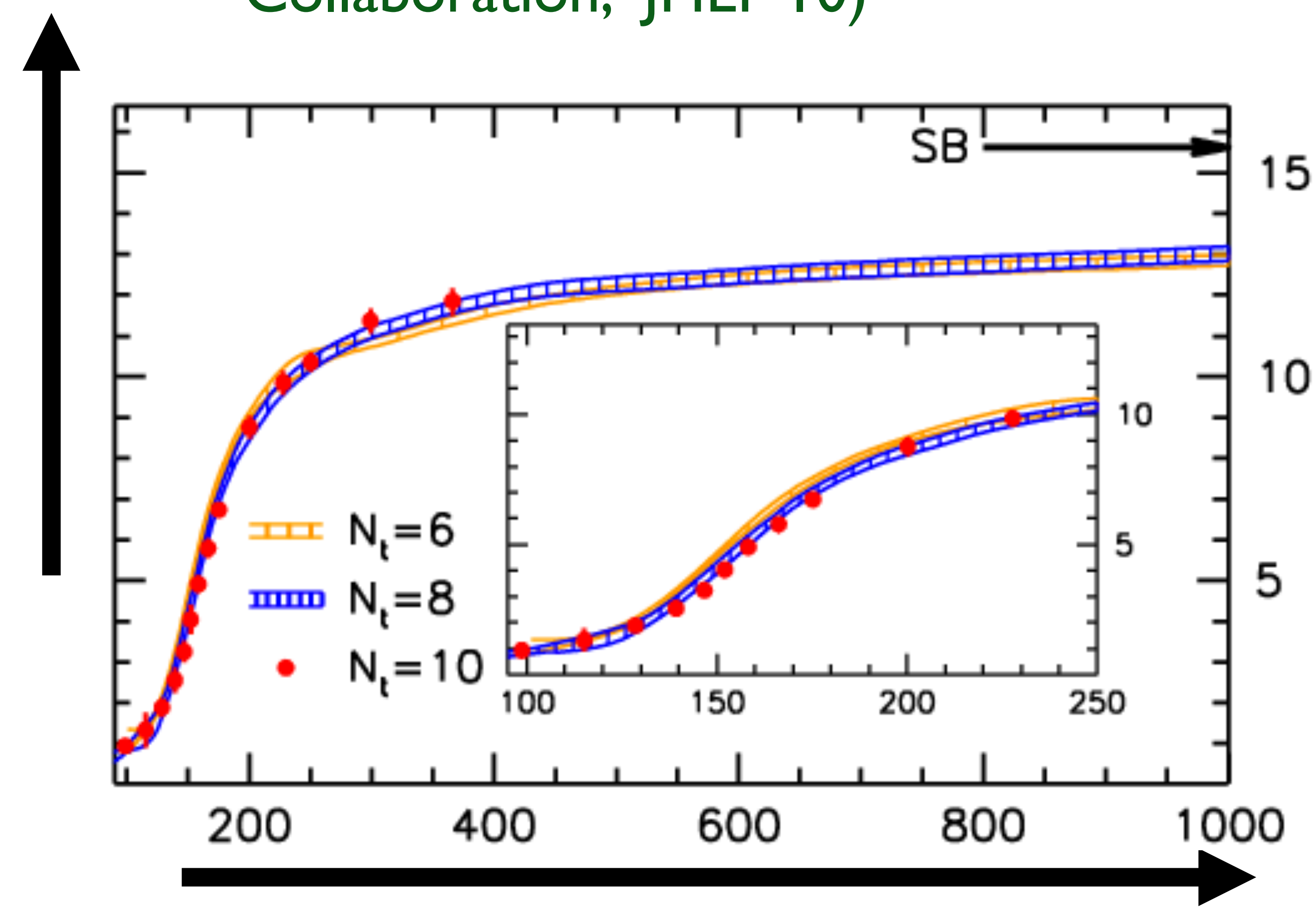
NSC^3 (CCNU, Wuhan, China)

NSC3 Nuclear Science Computing Center at CCNU



e/T^4~# of d.o.f

(Budapest-Marseille-Wuppertal Collaboration, JHEP'10)



T (MeV)

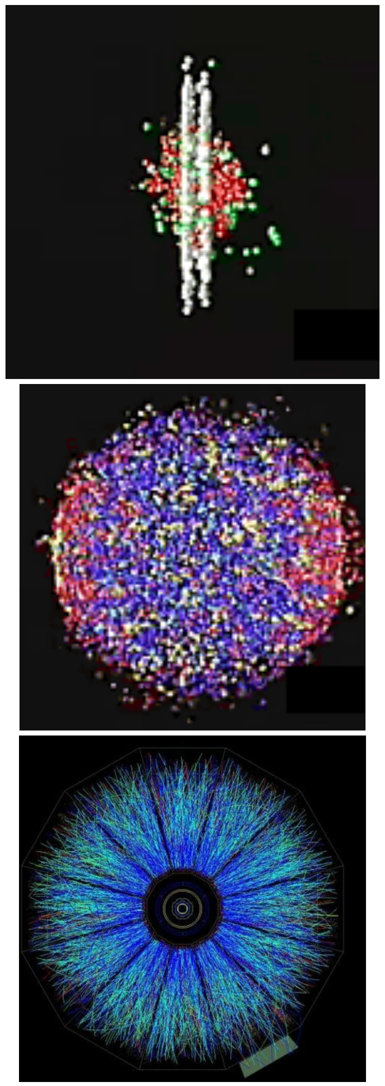
The lattice calculation demonstrates the transition from hadron gas to quark-gluon plasma (QGP). This transition is a rapid but smooth crossover at small μ_B .

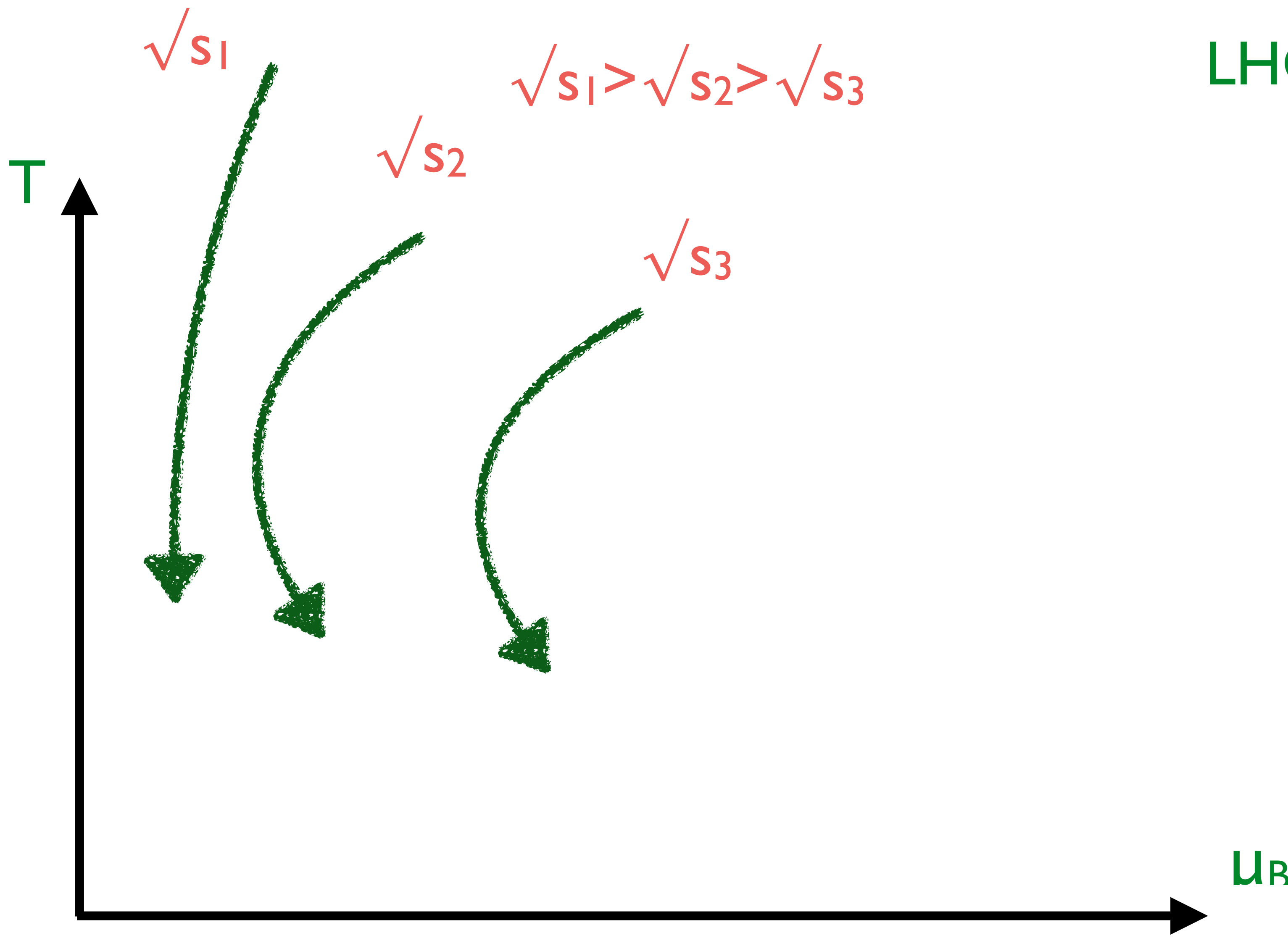
But is quark-gluon plasma QGP like a gas or fluid?

Heavy-ion collision: (re)creating Quark-gluon plasma !

RHIC (USA), 2000

LHC (Europe), 2010



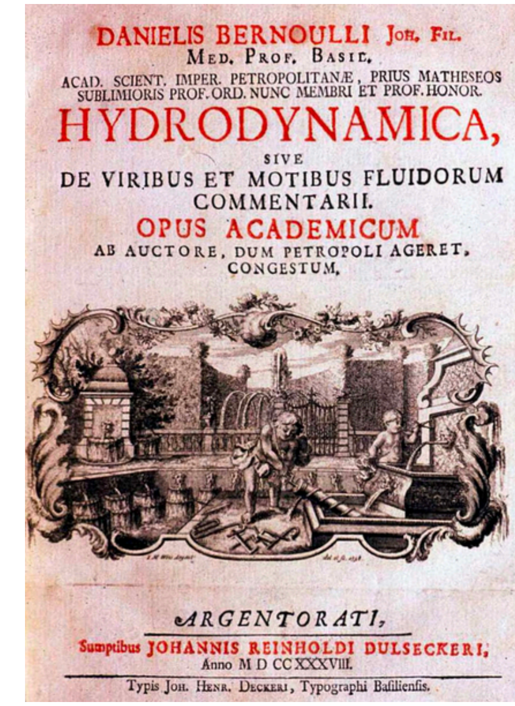


The QCD phase diagram can be scanned by changing beam energy $\sqrt{s}$ (lower beam energy, larger baryon density), “beam energy scan”.

Dynamical simulation shows that QGP (at small μ_B) expands hydrodynamically!

Hydrodynamics

Hydro. describes slow evolution of conserved densities, e.g, energy density e and momentum density (related to flow velocity u^μ) through energy-momentum conservation equations.



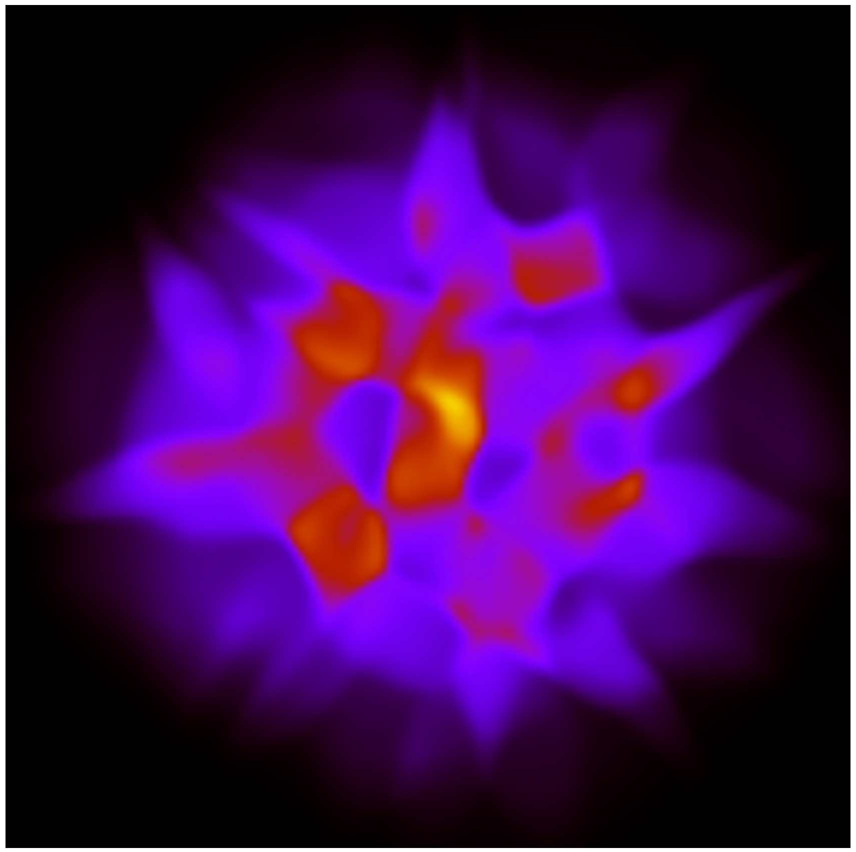
Bernoulli, "Hydrodynamica", 1738

E.g. : momentum conservation part of hydro. equation

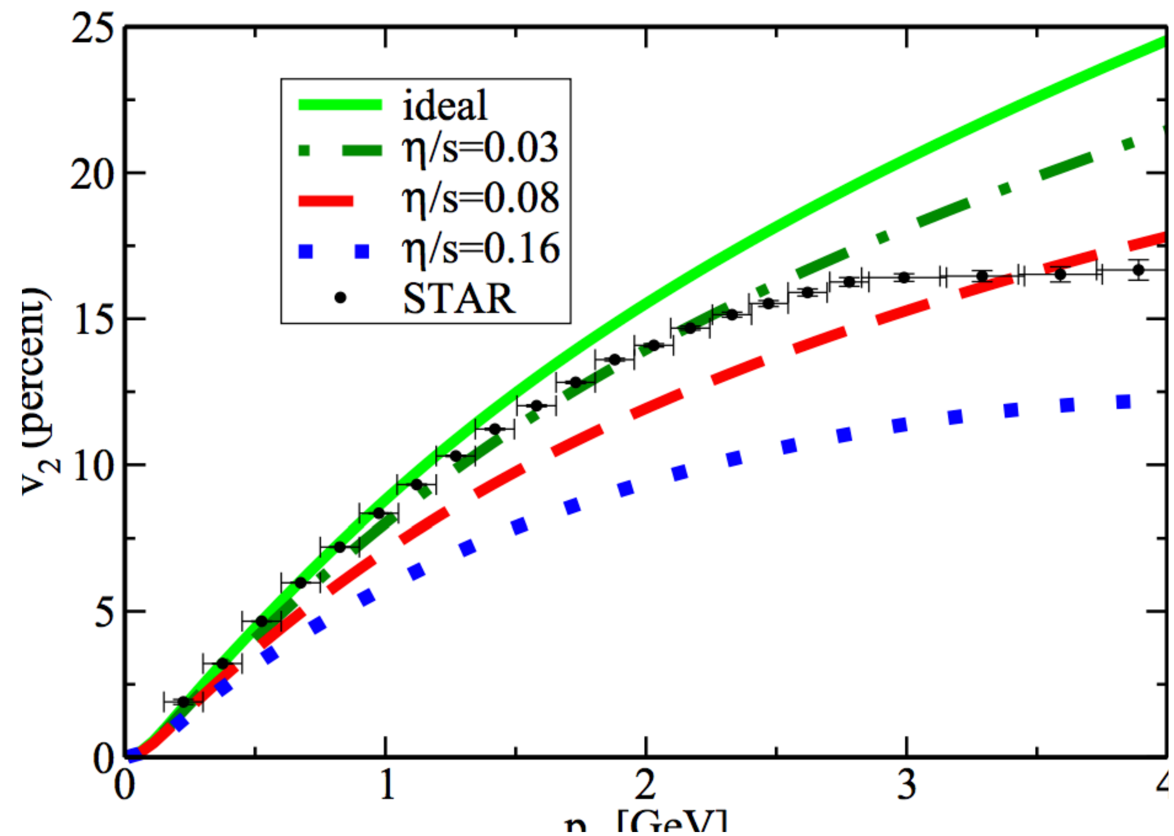
$\boxed{\text{gradient of pressure+dissipation} \simeq \text{acceleration of flow}}$

NB: Dissipation (friction of flow) is characterized by transport coefficient, including shear viscosity η and bulk viscosity ζ.

The discovery of near perfect QGP liquid



Hydro. simulation for heavy-ion collisions (by Schenke)

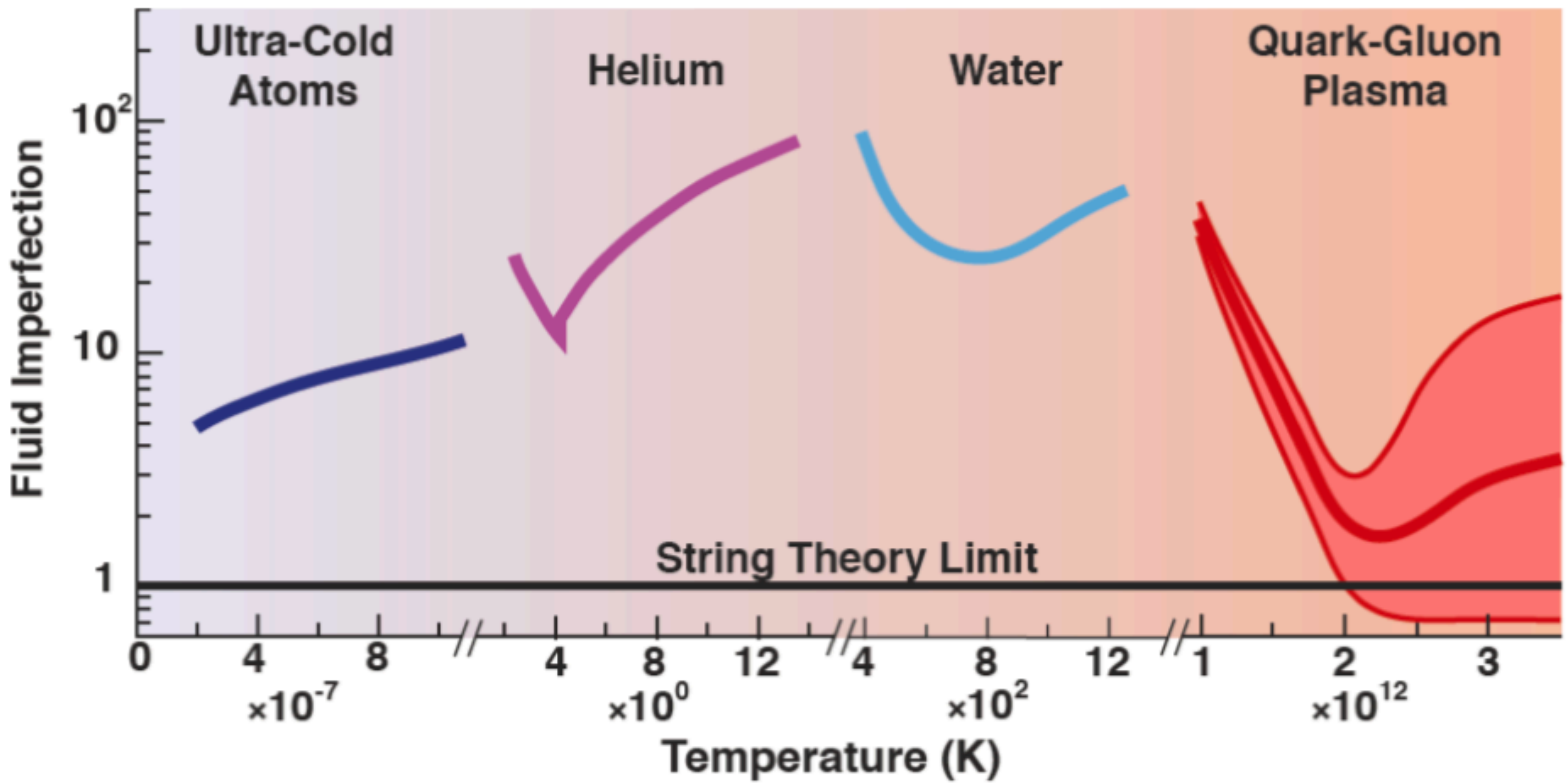


Romatschke-Romatschke PRL 2007

The success of hydro. modeling shows that QGP is like a liquid.

Such modeling also extracts shear viscosity η (over entropy) of QGP.

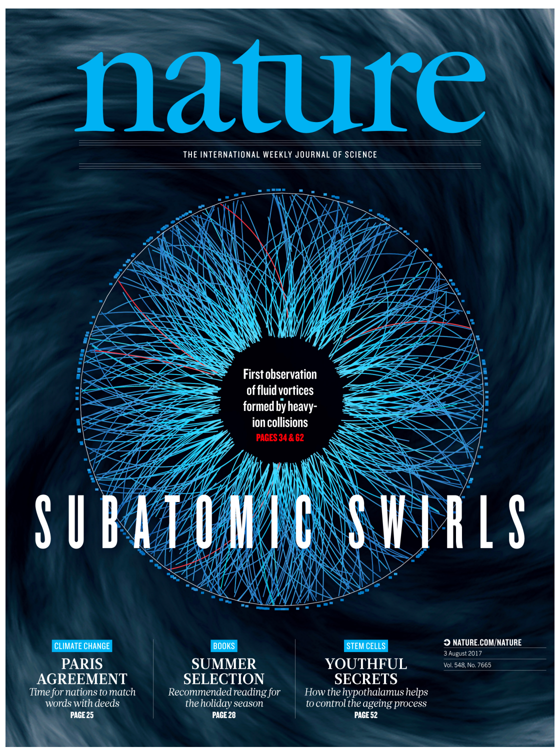
Viscosity in strongly interacting quantum field theories from black hole physics P. Kovtun, D. Son, A. Starinets, Phys. Rev. Lett. 94 (2005) 111601



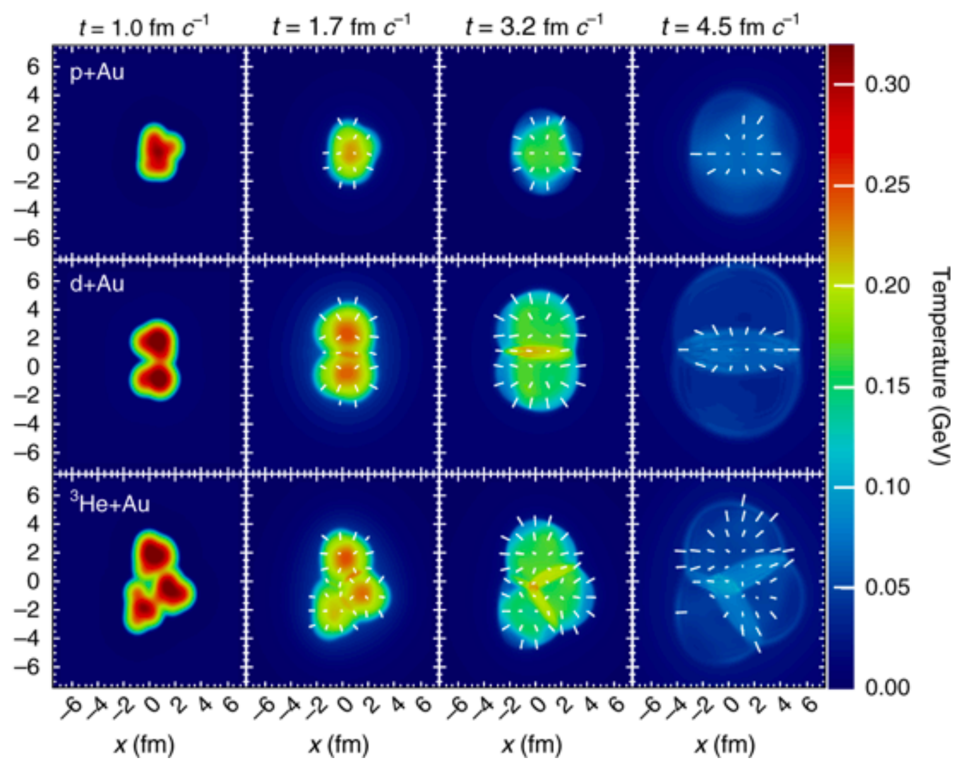
A discovery: QGP is the most "fluid" liquid. $\frac{\eta}{s} = (1 \sim 3)\frac{1}{4\pi}$

There are many other interesting physics of QGP. (not in this talk)

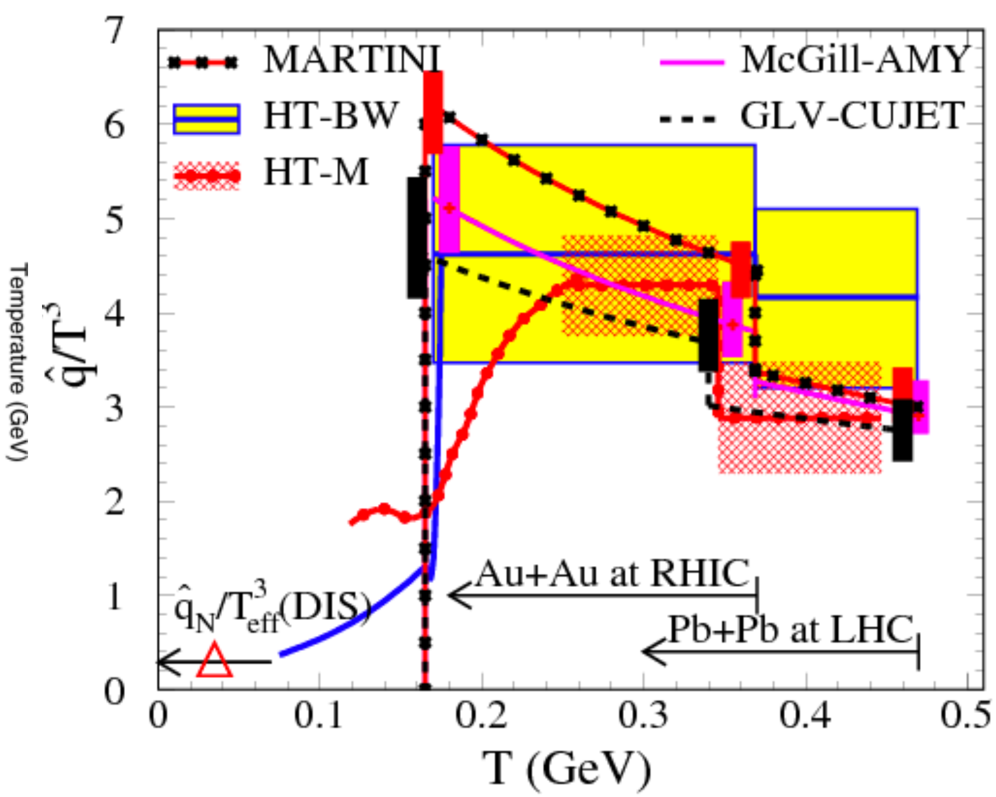
(Talk to other participants working on this field, read posters in this floor.)



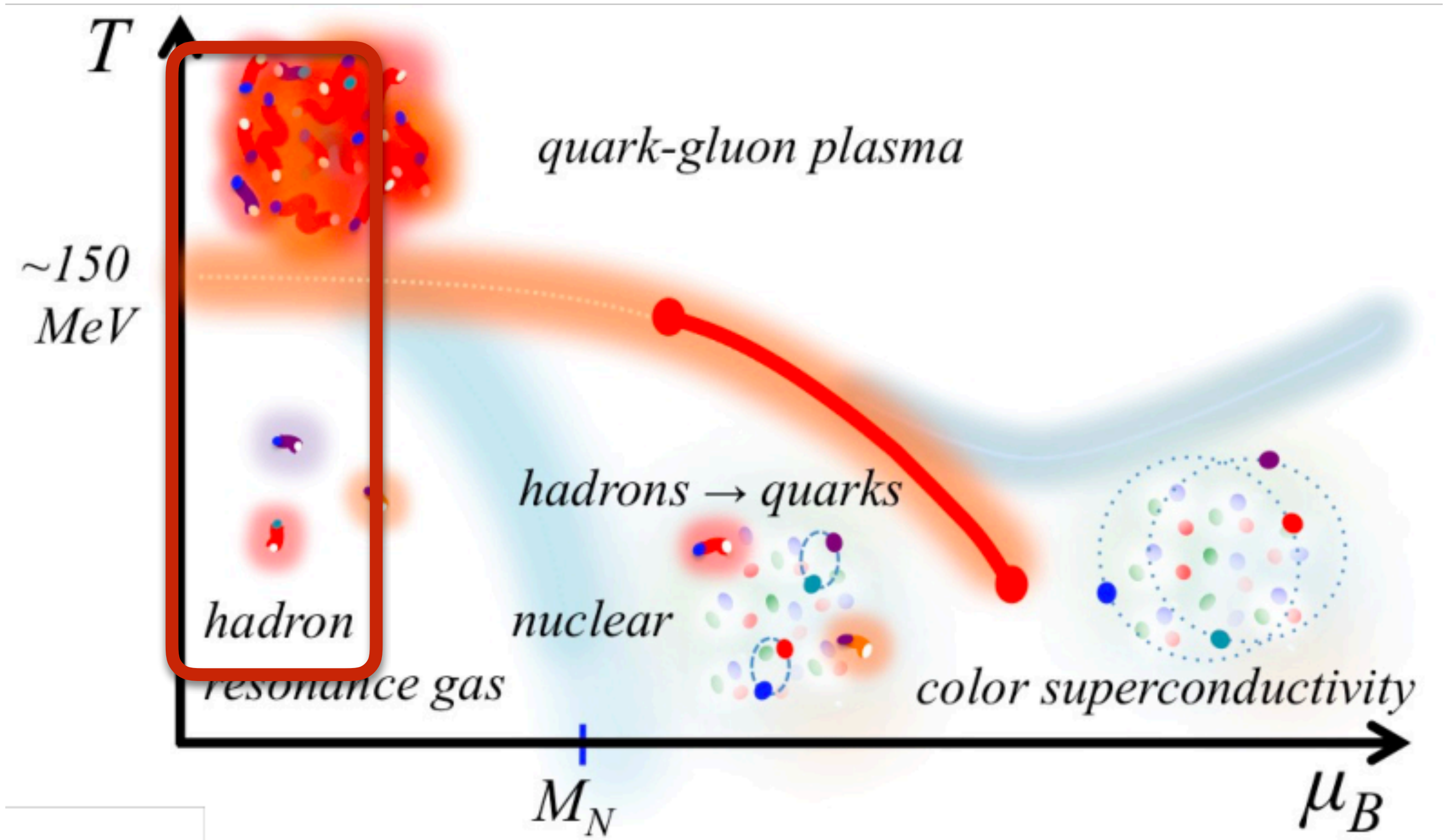
Nature 17', STAR collaboration



Nature 18' , PHENIX collaboration



JET (theory) collaboration



$$T_c \simeq 156.5 \pm 1.5$$

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

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

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

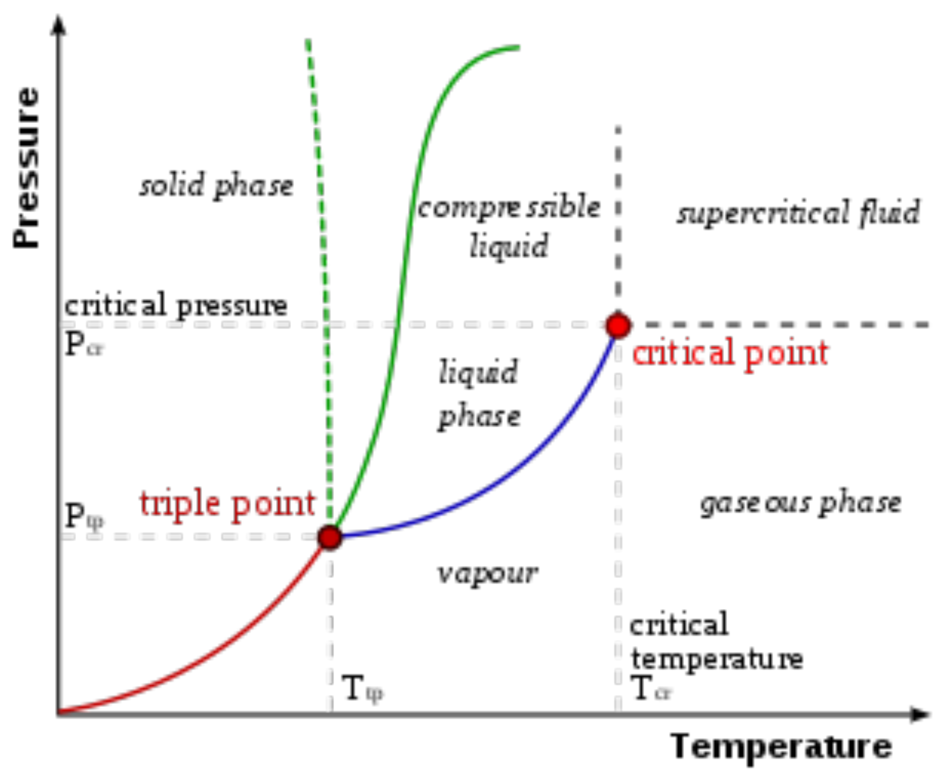
The QCD phase diagram at finite baryon density is still uncharted.

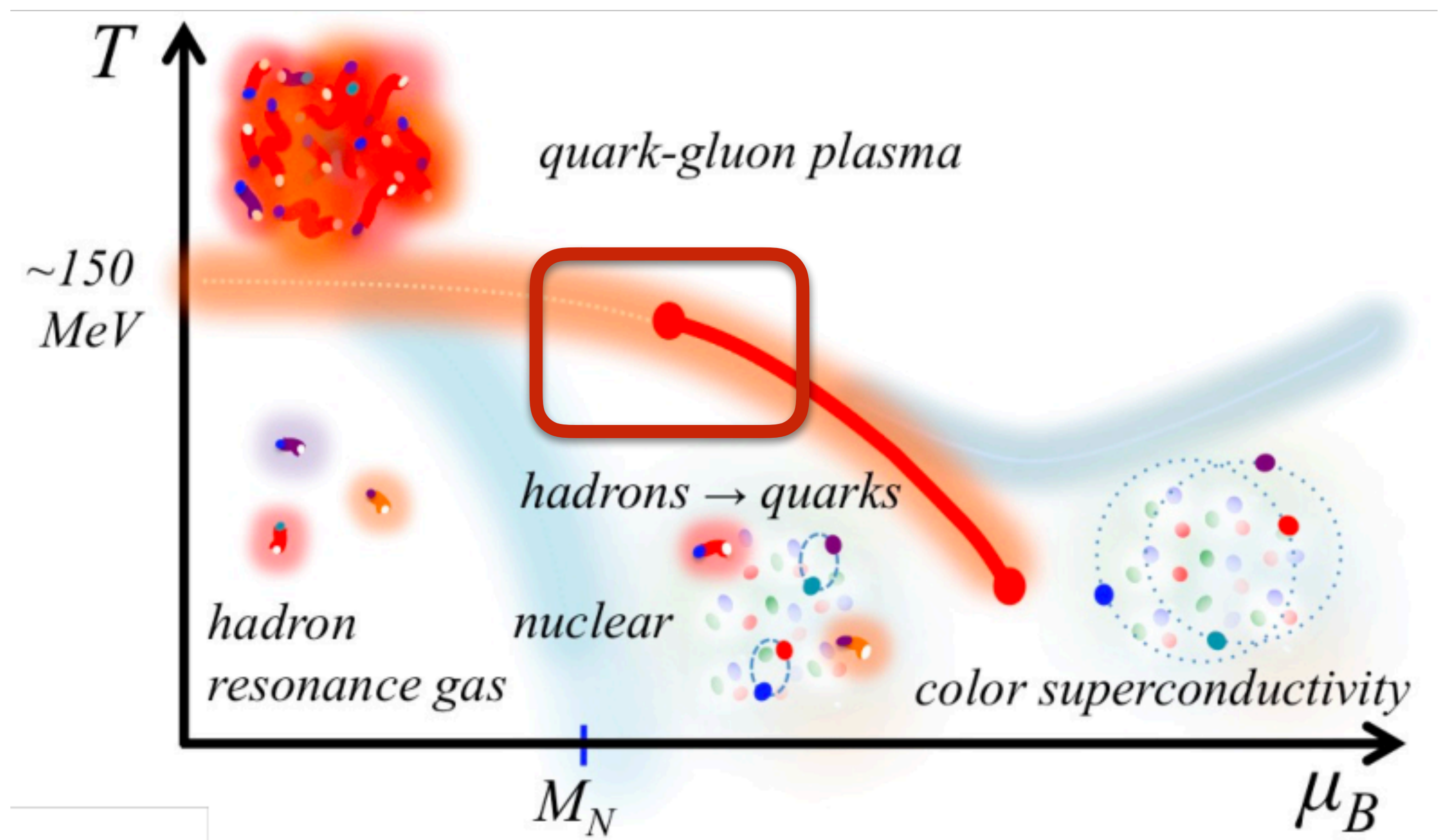
Is QGP more like liquid or gas with increasing baryon density?

New phases?

Discovery of the QCD critical point?

The search for the QCD critical point





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.

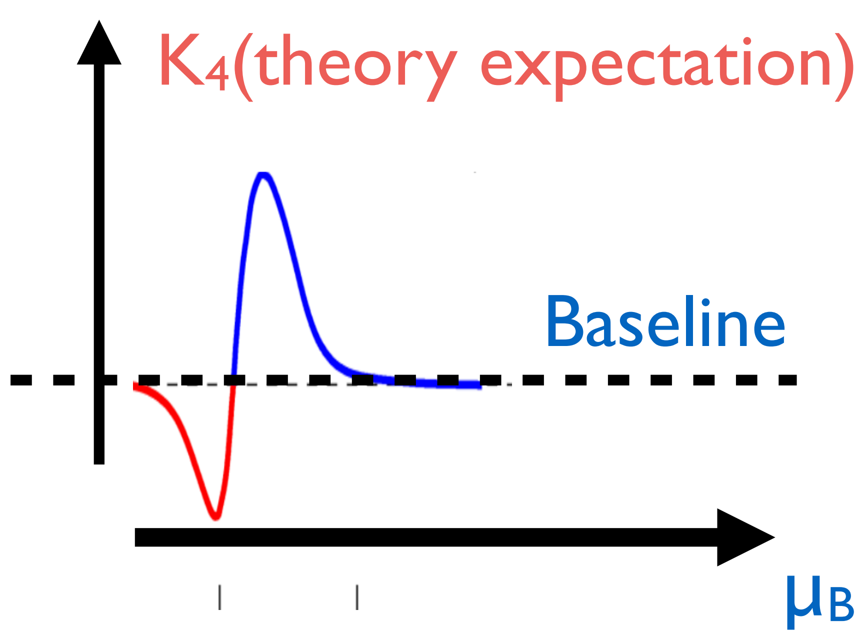
Experimental search for C.P.: fluctuation is the key

Xiaofeng Luo, Nu Xu 1701.02105 for a review.

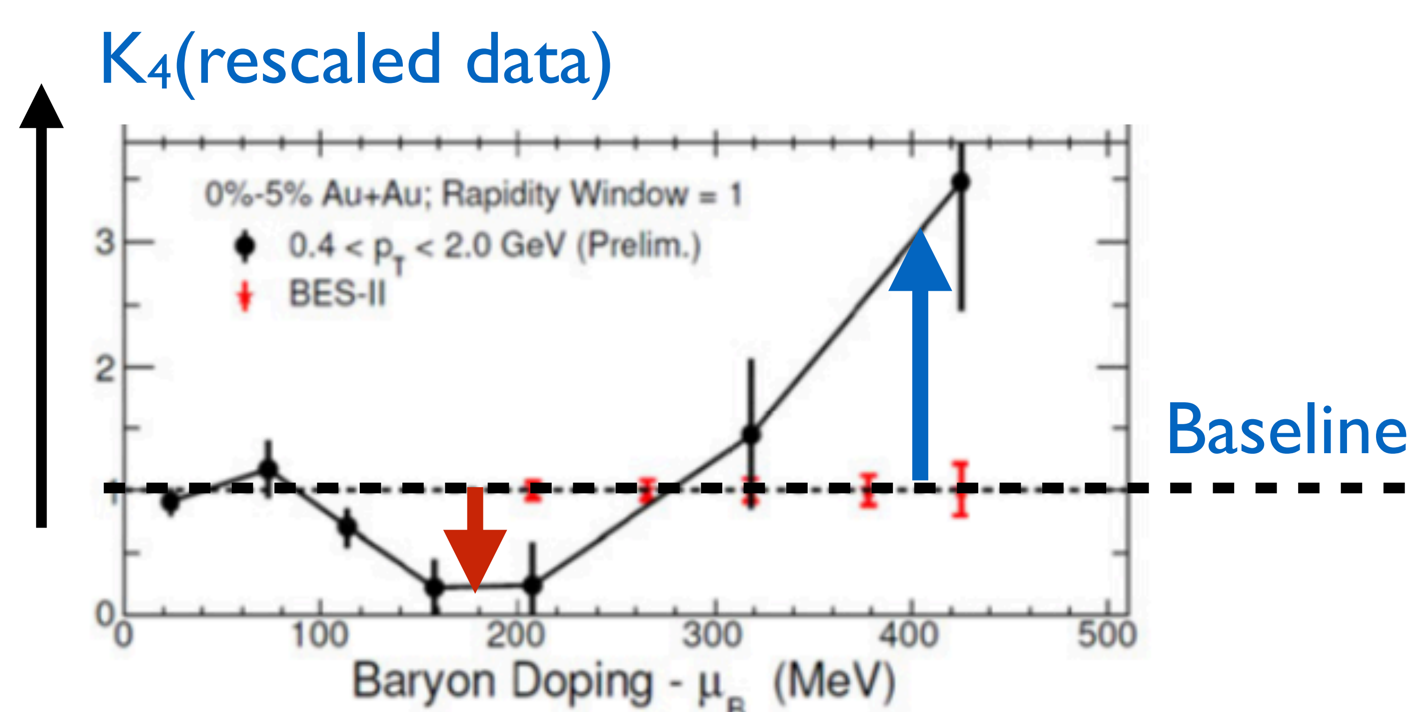
Hadrons (e.g. protons) multiplicity fluctuations are expected to be enhanced near C.P. .

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

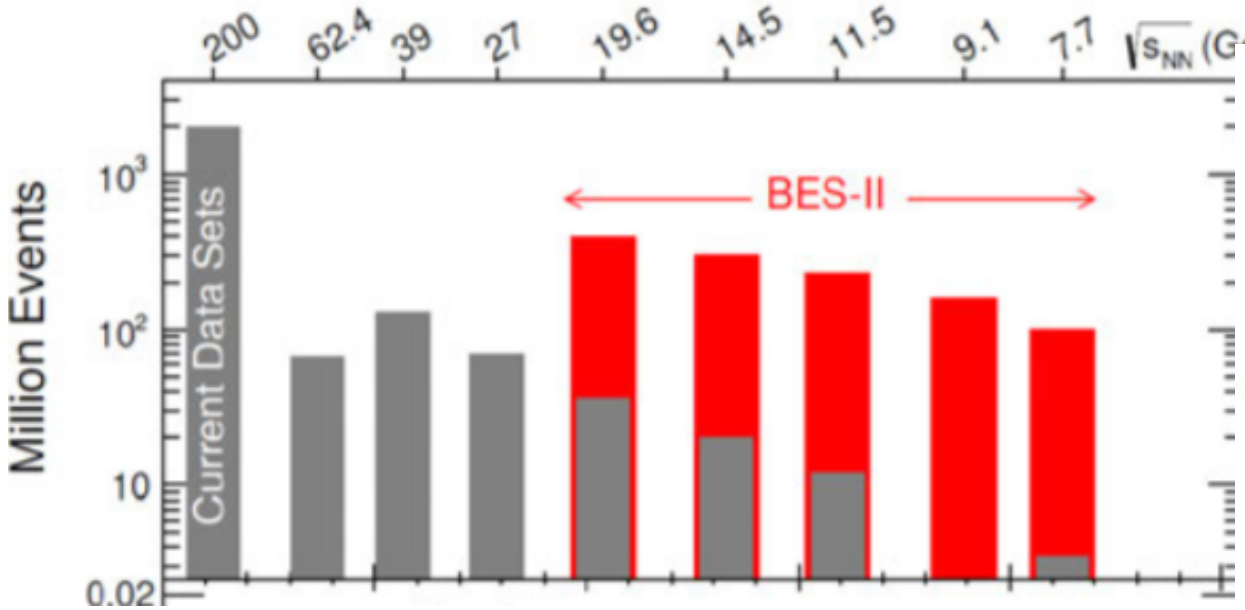
Hints: non-monotonicity and sign change of fourth cumulant (i.e. K_4) as a function of beam energy within line of theory expectation

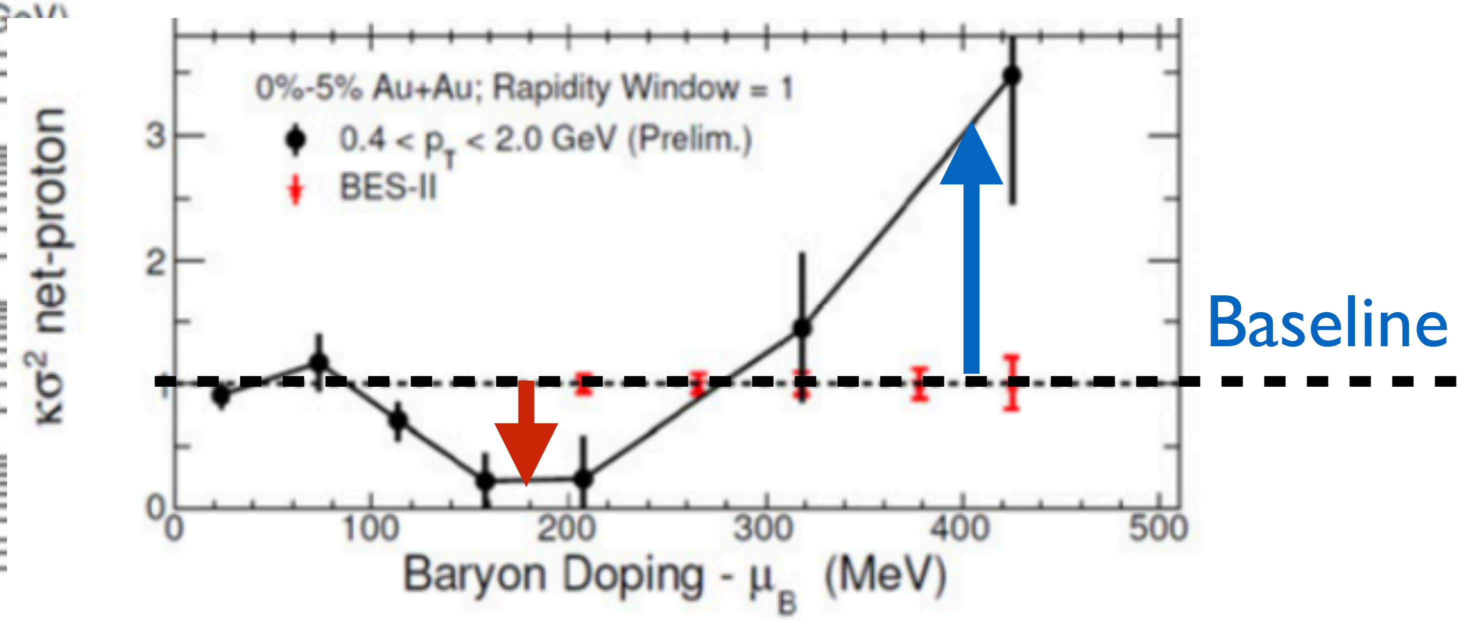


Stephanov, PRL 11



STAR preliminary data from BESI (Xiaofeng Luo, 1503.02558)



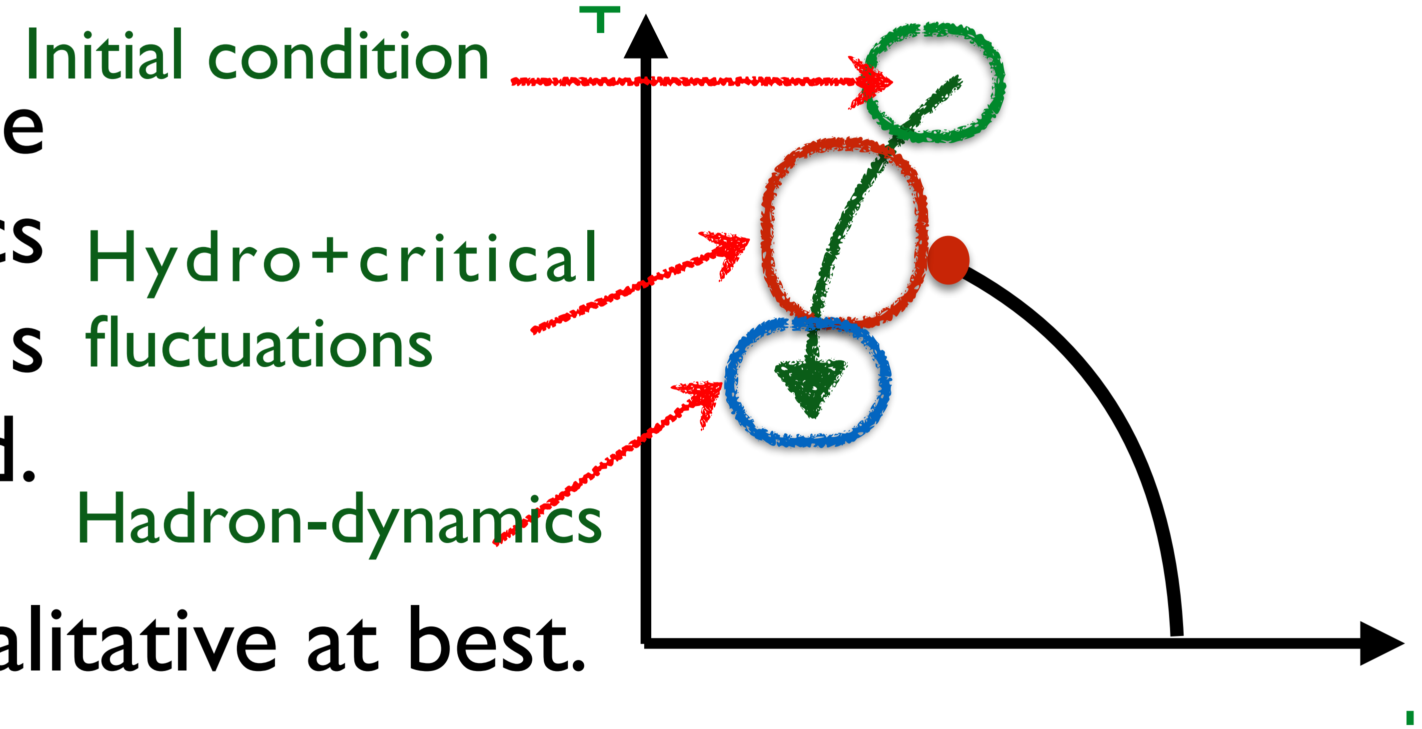


BESII at RHIC kicked off earlier this year (2019). This three-year program will bring data with unprecedented precision. This is exciting time.

This in turn presents both outstanding challenging and opportunity for theory.

Quantification of critical signature is essential for the discovery of C.P.

The needed quantitative framework describing dynamics for critical point search is comprehensive and complicated.



Previous studies are mostly qualitative at best.

There are growing interests in the building up of this comprehensive quantitative framework in the community.

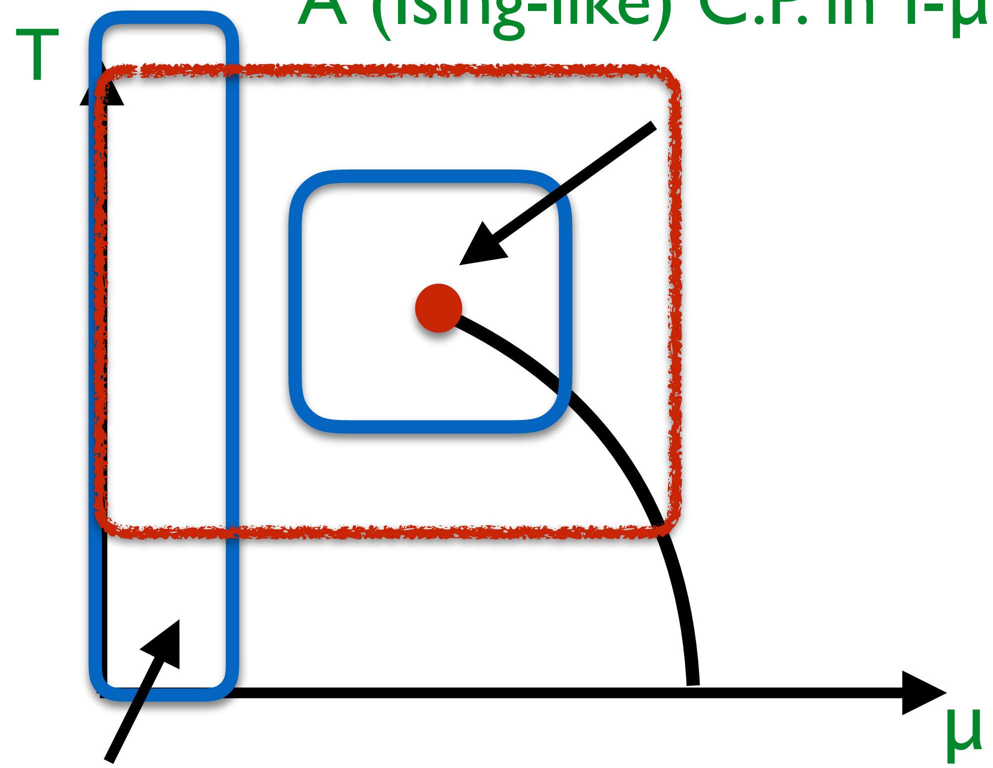
e.g.: Beam Energy Scan Theory Collaboration in US includes 12 universities/national lab.

BEST COLLABORATION

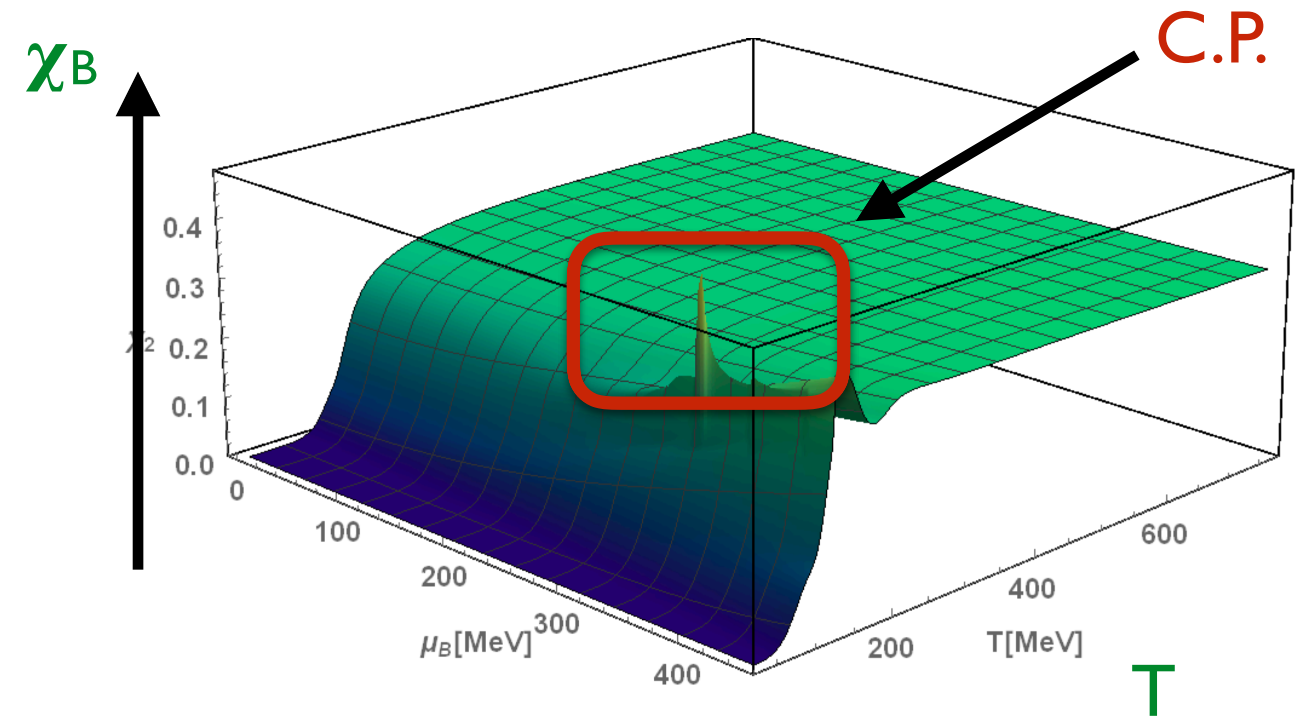
In what follows, I will walk you through two core ingredients of this framework: construction of E.o.S with a critical point and hydro with critical fluctuations.

E.o.S. with an Ising-like C.P.

A (Ising-like) C.P. in T-μ_B plane



Matching lattice results at small μ_B



A minimum model by Parotto et al, 1805.05249.

E.o.S with a C.P. (i.e. p(e,n)) is needed in the experimental accessible region in the phase diagram.

E.o.S. determines thermal fluct. (e.g. taking derivatives of pressure) along a trajectory at given beam energy.

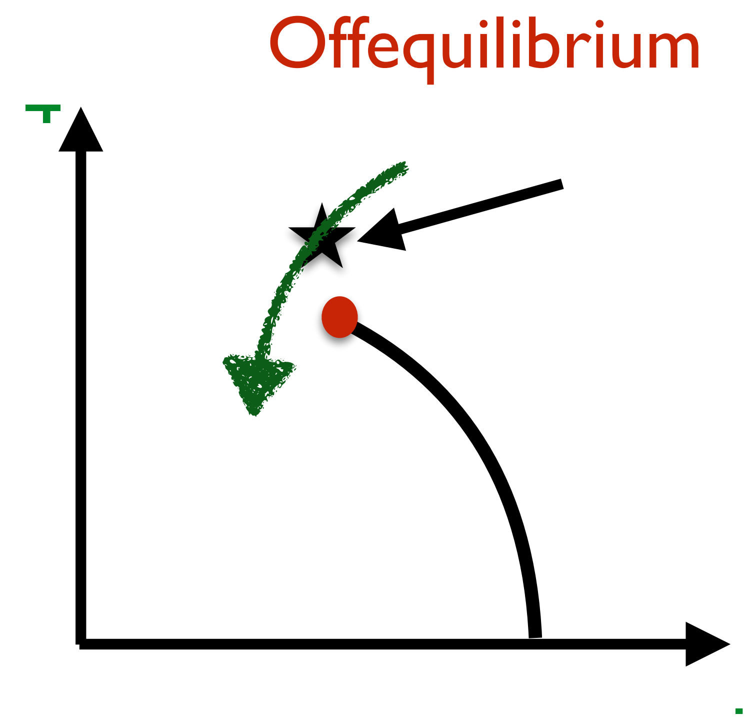
E.o.S is crucial input for solving hydro. equations.

The strategy for this construction is similar to that for neutron star study.

So far, assuming fluctuation is in equilibrium

However, the dynamics of fluctuations are important!

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.

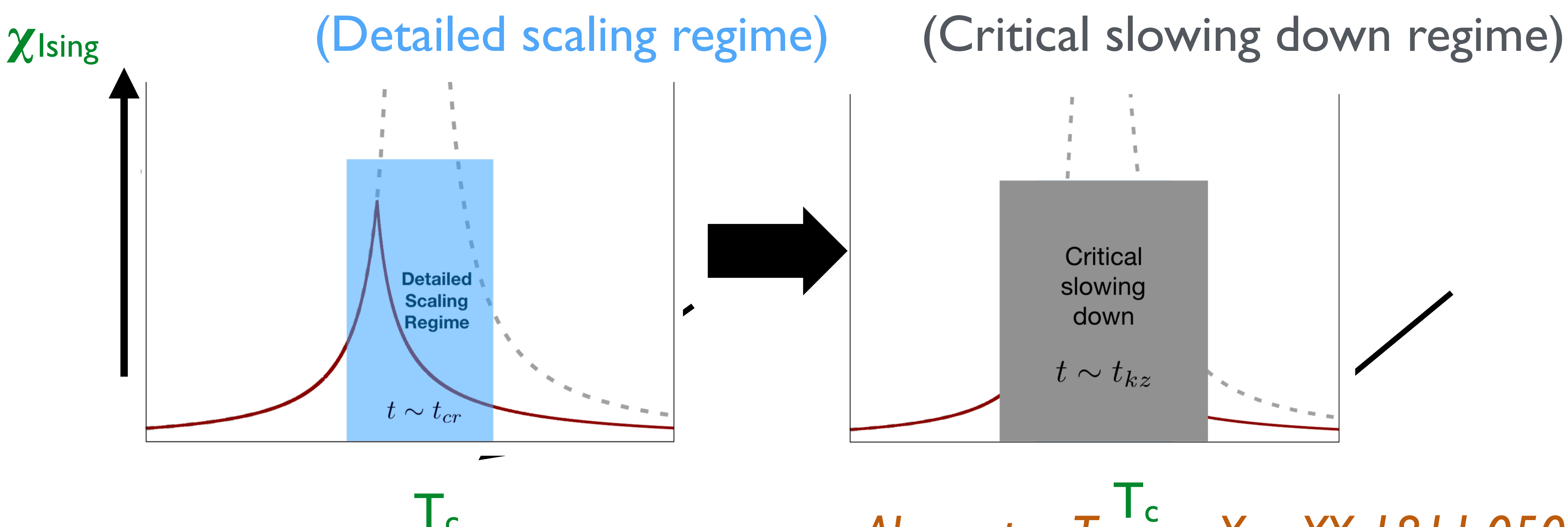
see YY, 1811.06519 for a mini-review

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)

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.

$\boxed{\text{gradient of (?)+dissipation (?)} \simeq \text{acceleration of flow}}$?

Hydro. will no longer 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 describing intertwined dynamics of hydro. d.o.f and critical fluctuations using deterministic equations.

$\boxed{\text{Equations for the evolution of fluctuations.}}$

$$+$$

$\boxed{\text{Gradient of } p_{(+)} + \text{dissipation} \simeq \text{acceleration of flow}}$

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

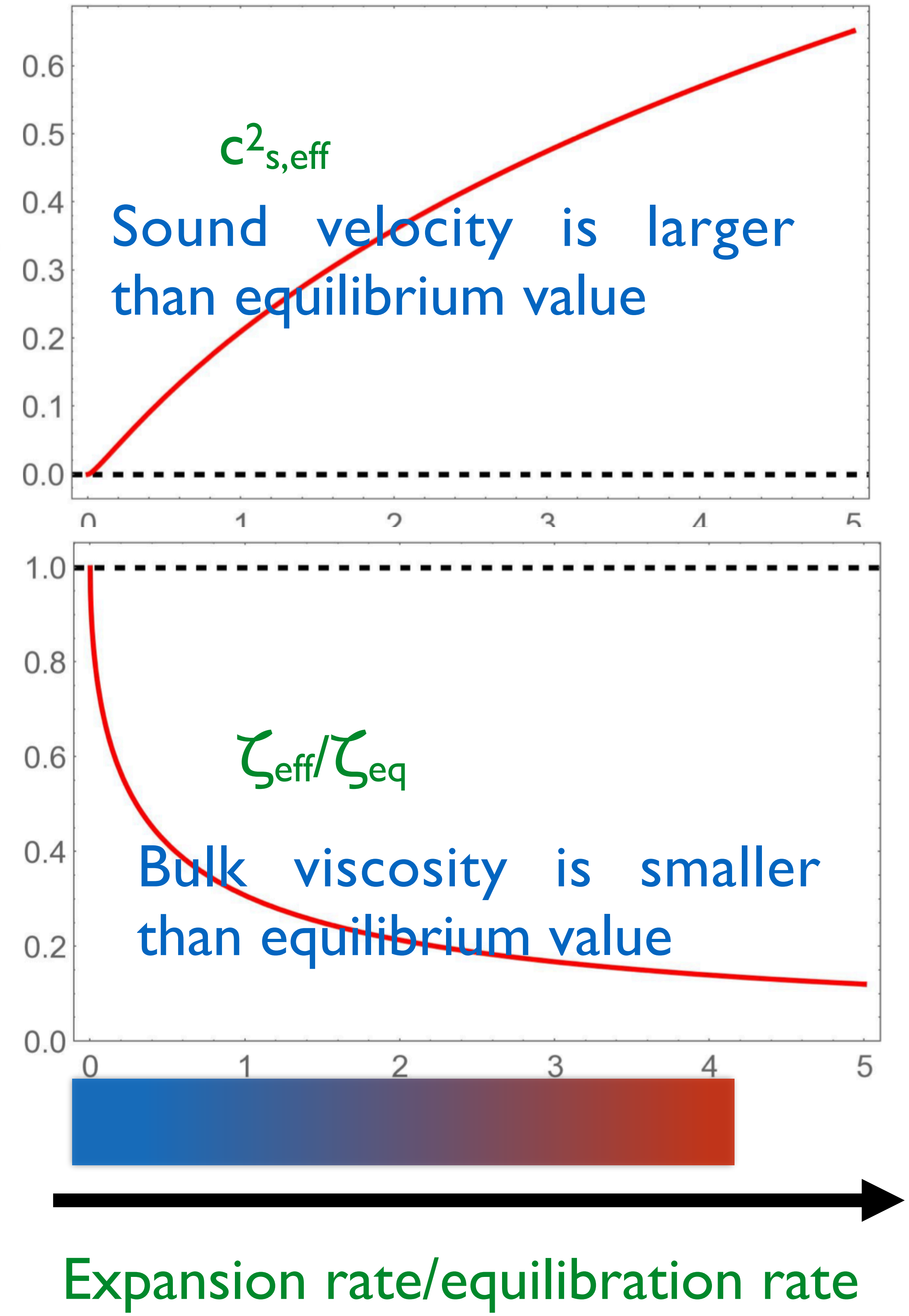
Similar for transport coefficients:

Effective sound velocity and bulk viscosity from (linearized)“hydro+”

Stephanov-YY, 1712.10305, PRD ’18;

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.

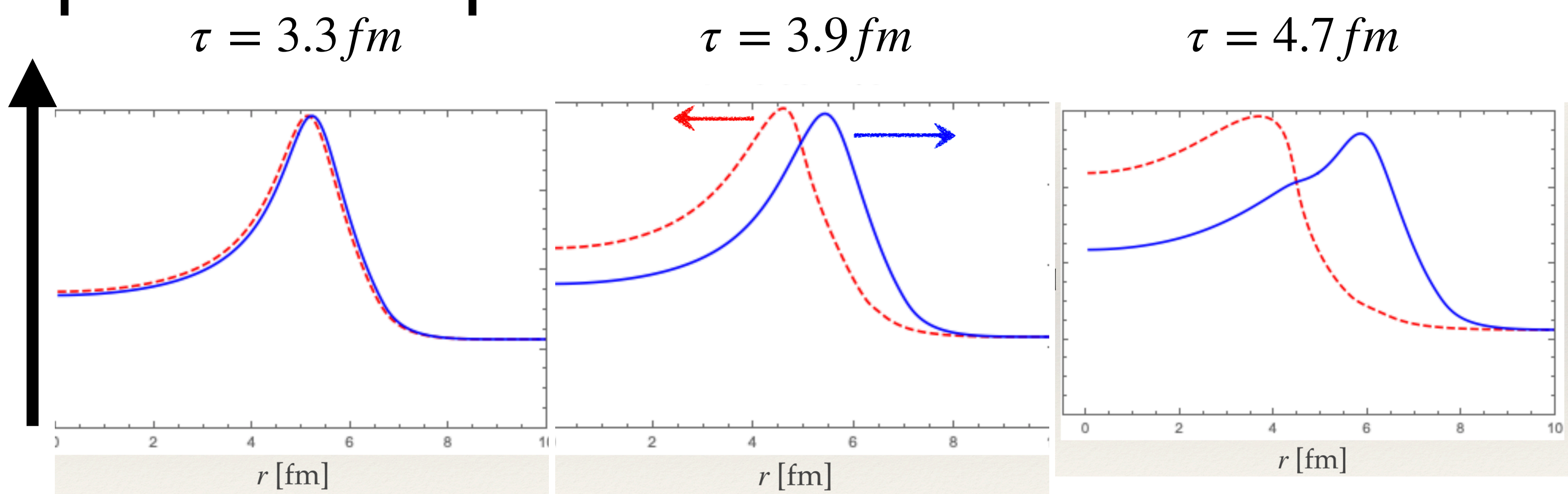


Simulating "hydro+": First results

Rajagopal-Ridgway-Weller-YY in preparation

Ridgway (Graduate of MIT)

We have simulated full non-linear "hydro+" in a simplified set-up.



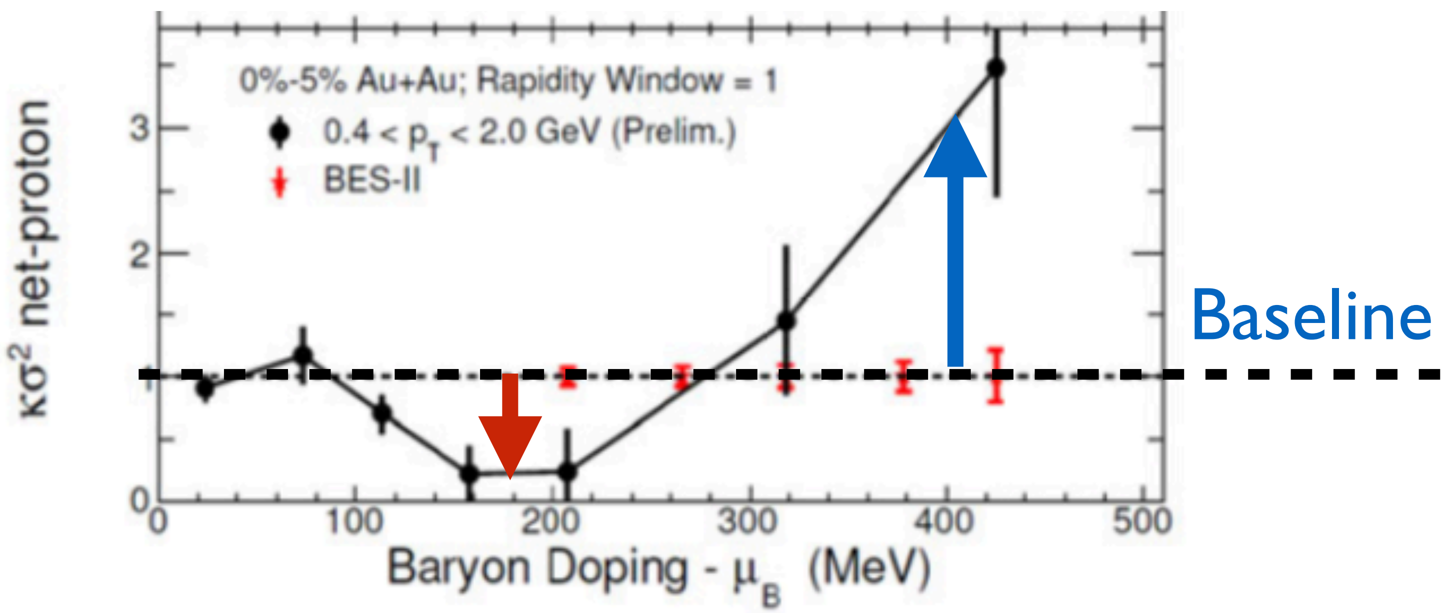
Equilibrium Fluct. in red. Offequilibrium Fluct. in blue.

The implementation of "hydro+" by upgrading the state of art 3d hydro codes are in progress.

Lipei Du, U. Heinz at OSU; Chun at Wayne state U

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

Summary on search for the critical point.

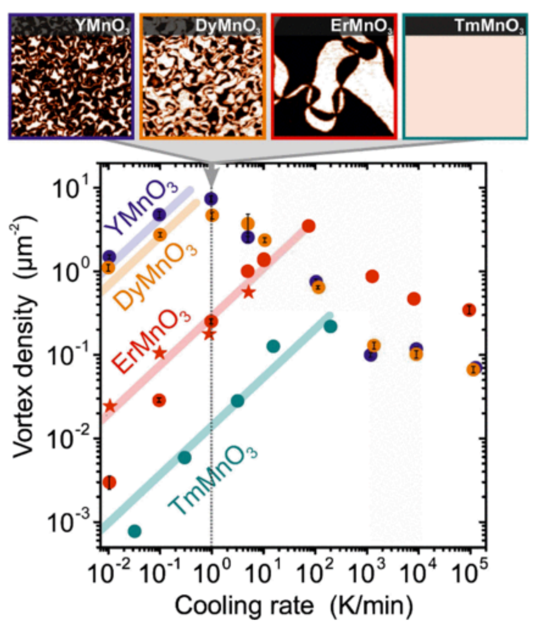


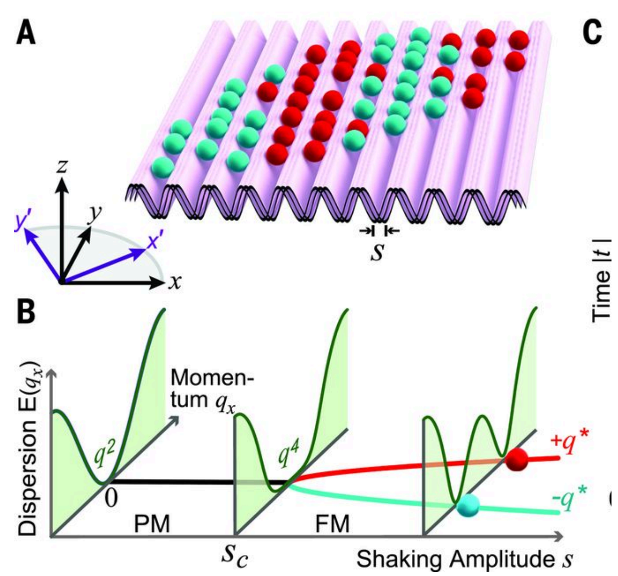
BESII will explore region with hints about criticality with unprecedented precision.

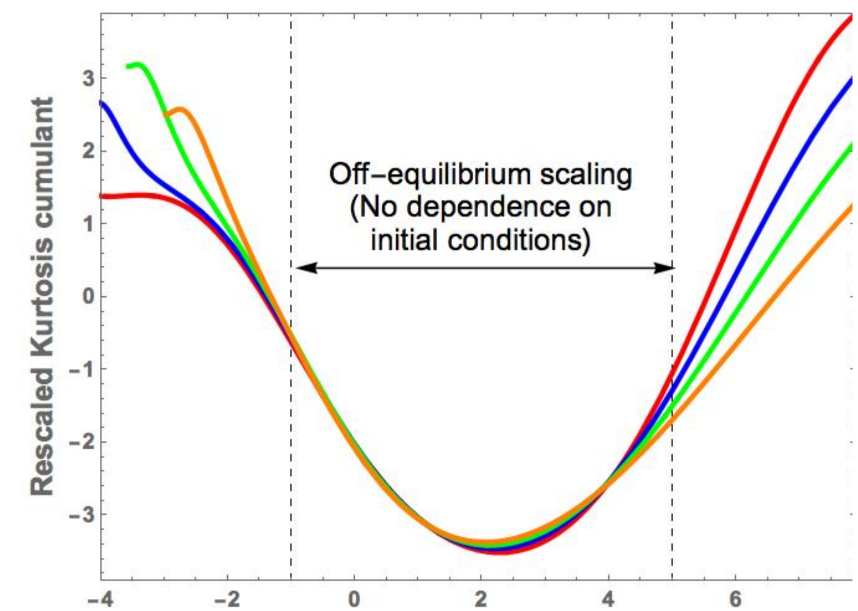
Understanding critical dynamics are crucial to maximize the discovery potential of ongoing HIC experiments — we are working to build the needed theoretical tools.

Stay tuned for new results from both experiments and quantitative theoretical studies.

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)

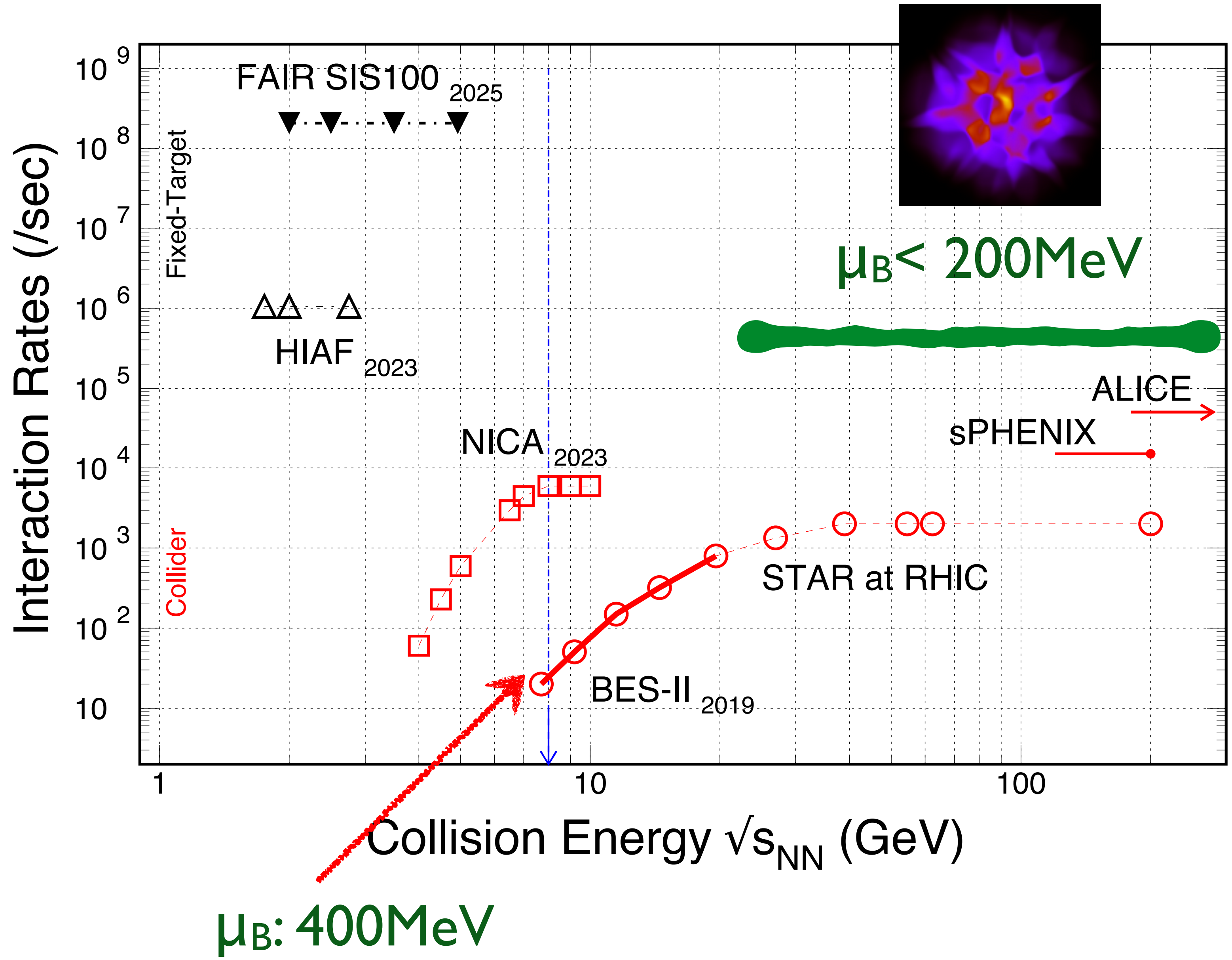
Hexagonal Manganites, M. Griffin et al, Phys.Rev.X ' 12

(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.

Summary and outlook

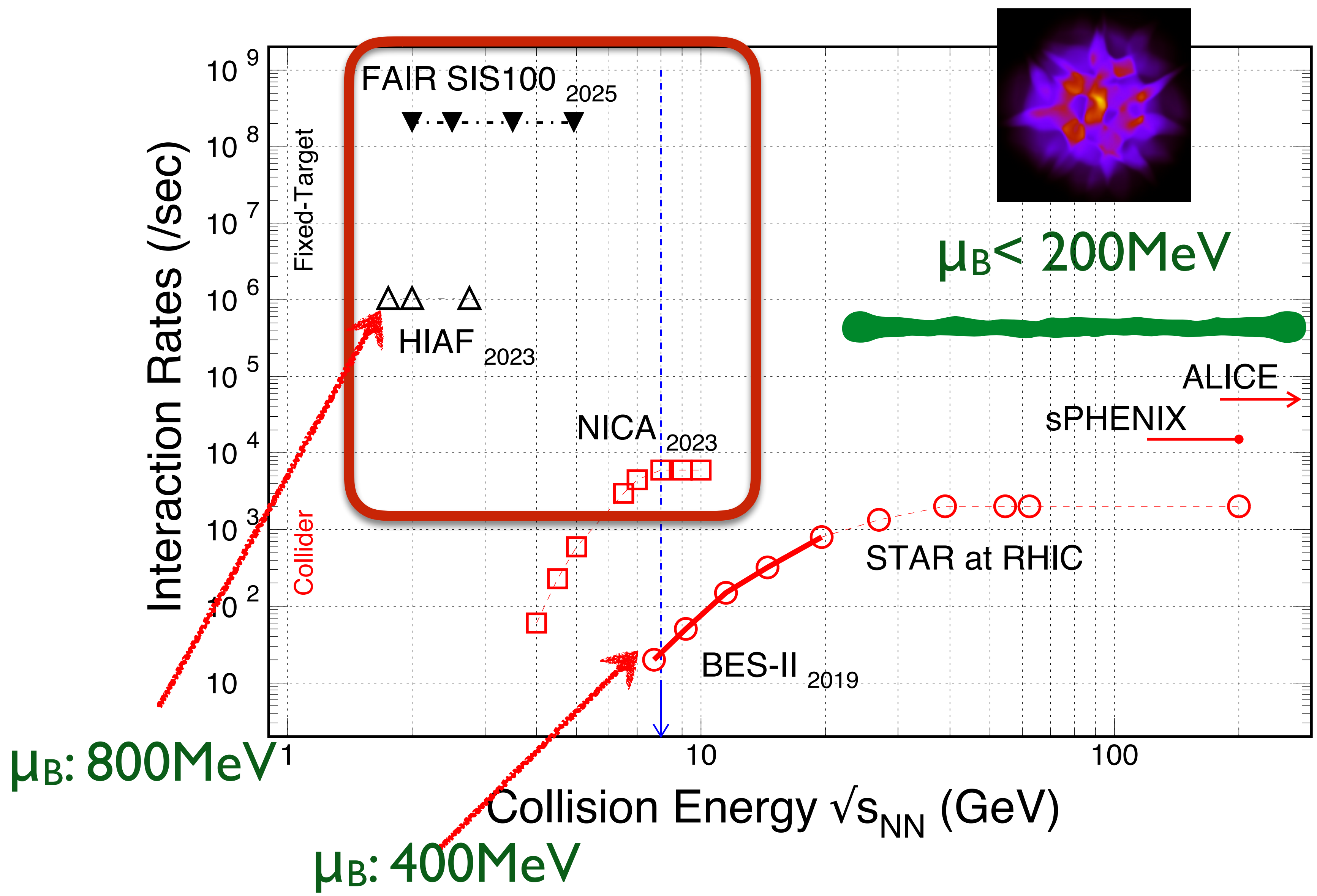
The voyage of discovery on the QCD phase diagram: from past to future I



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.

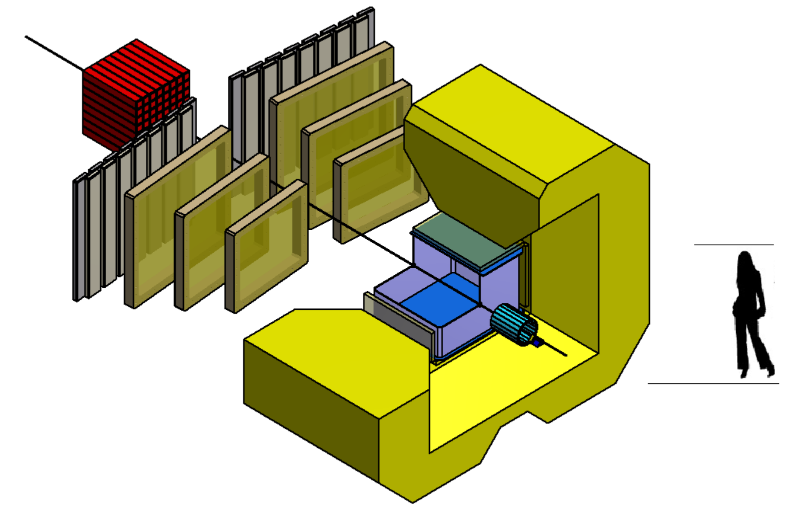
The voyage of discovery on the QCD phase diagram: from past to future II



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

Russian	NICA	2023
Germany	FAIR	2025
China	HIAF	2025

HIAF at Huizhou (construction began on 2018)



Design of CEE

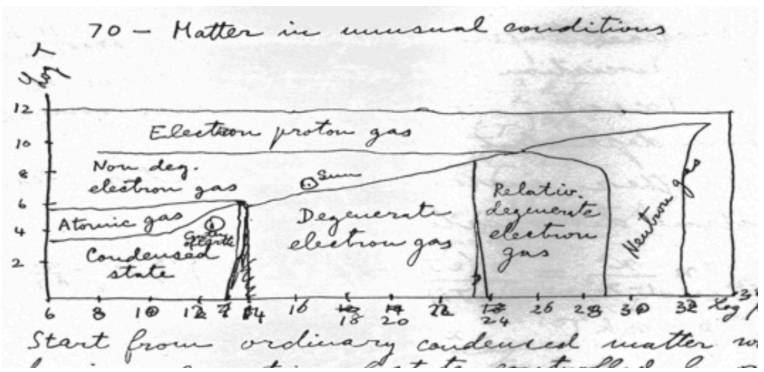
CSR external experiment (CEE) at HIAF will study baryon-rich matter up to μ_B~800MeV.

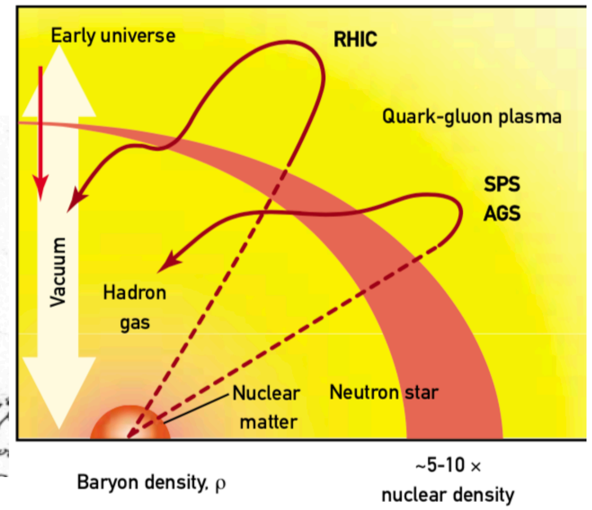
Also, Electron-ion collider experiment at HIAF is proposed, aiming at revealing the secret life of quarks and gluons inside proton.

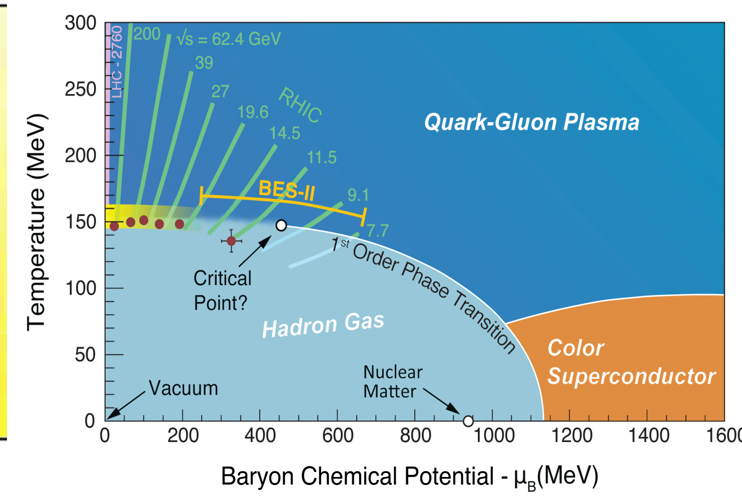
CEE detector: an innovative "digital camera" for tracking the particles created in heavy-ion collisions.

New research center for advanced nuclear science in Huizhou: Quark Matter Research Center.

Outlook







?

Fermi (1952)

2002

2015

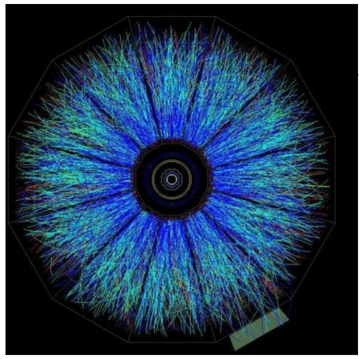
2020+

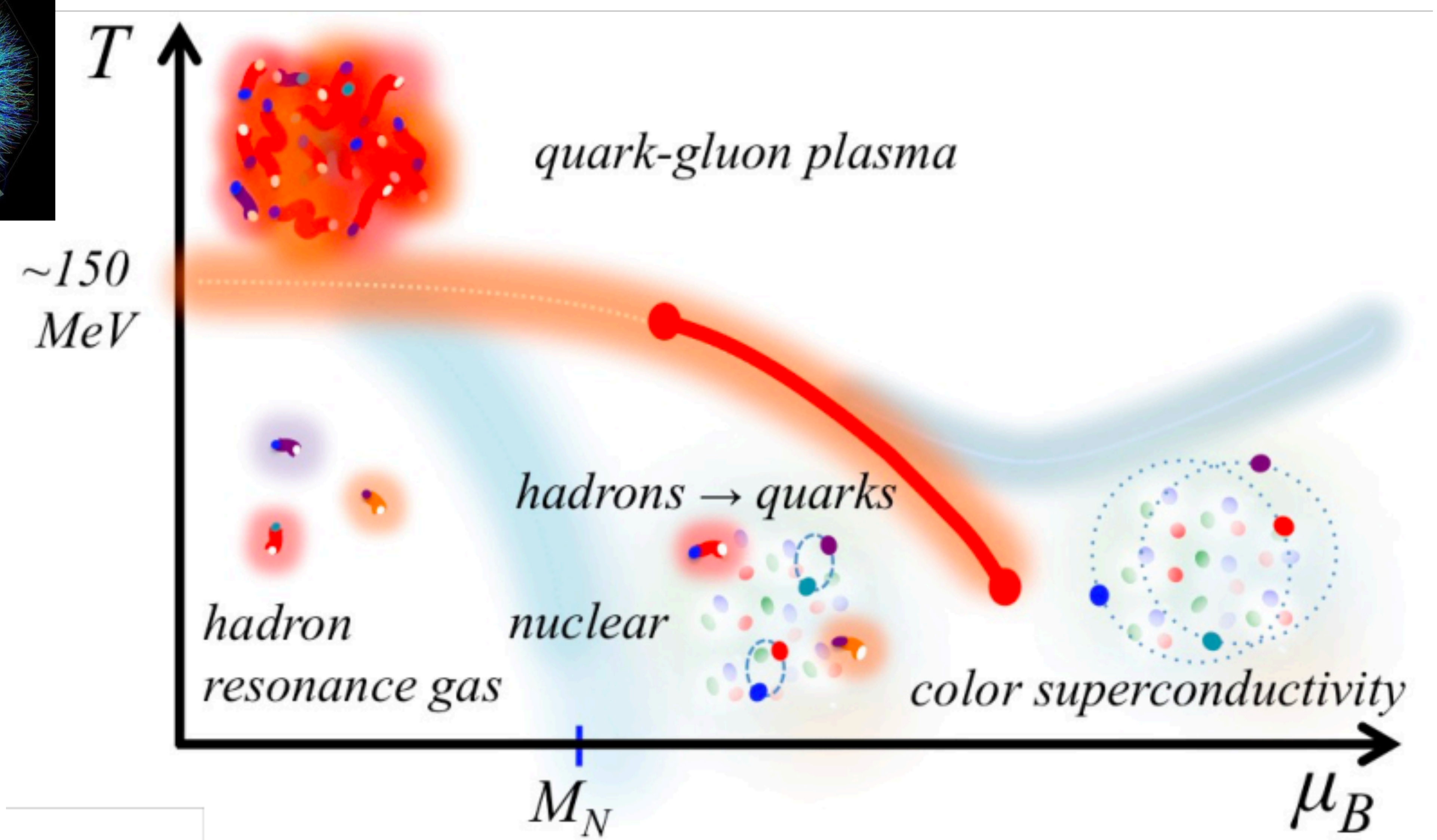
RHIC starts running

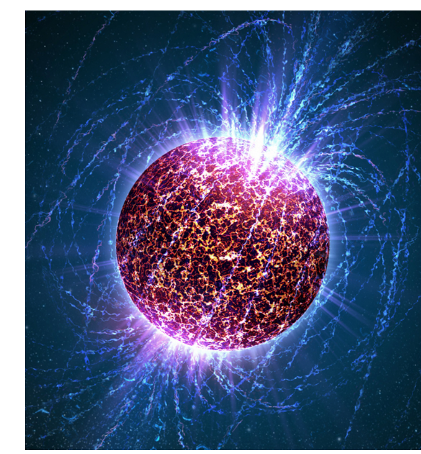
Future experiment

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

My question:



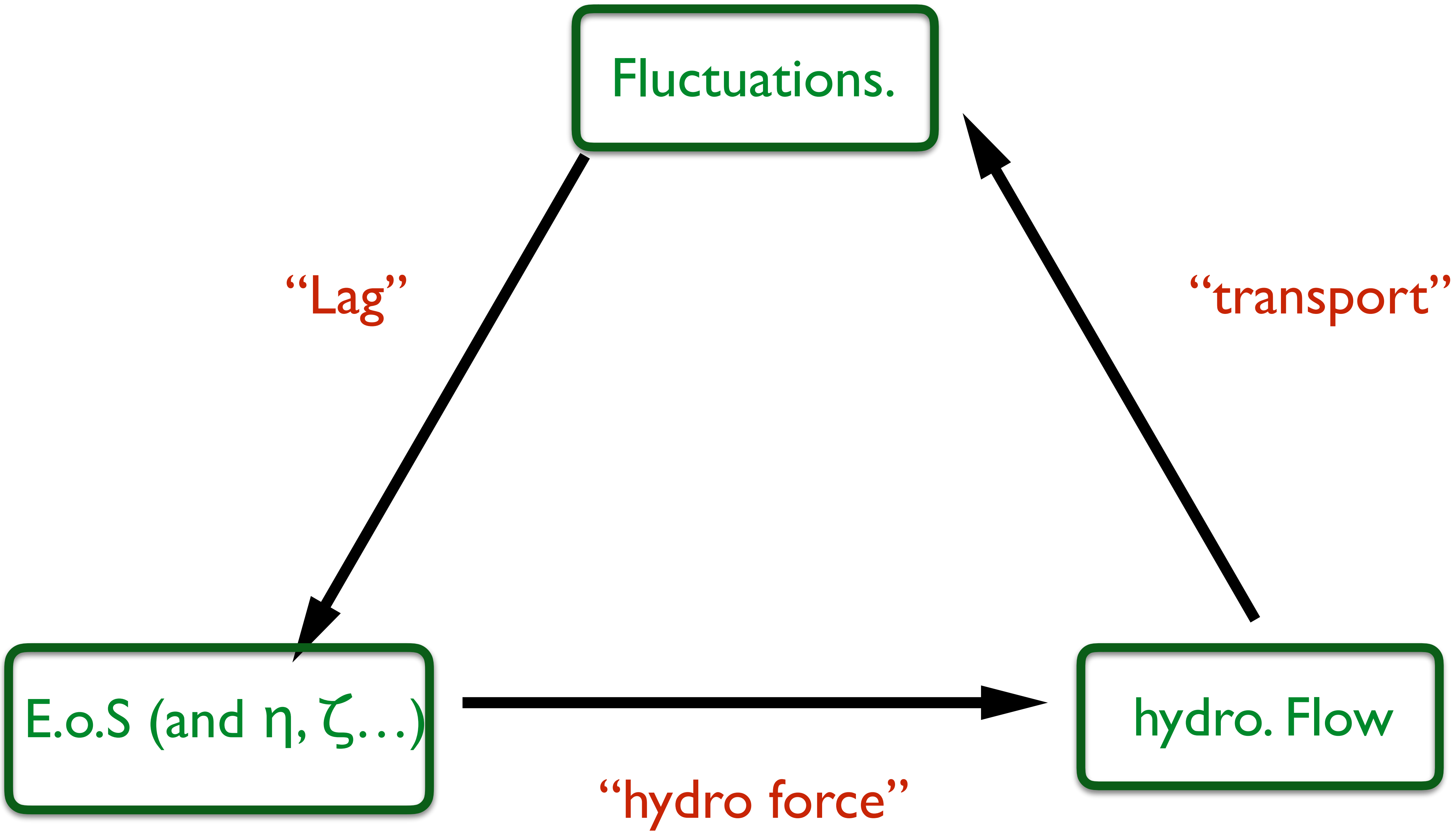




A question: cross-fertilization between heavy-ion collisions and neutron star community?

Back-up

A pictorial summary of "hydro+"



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

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