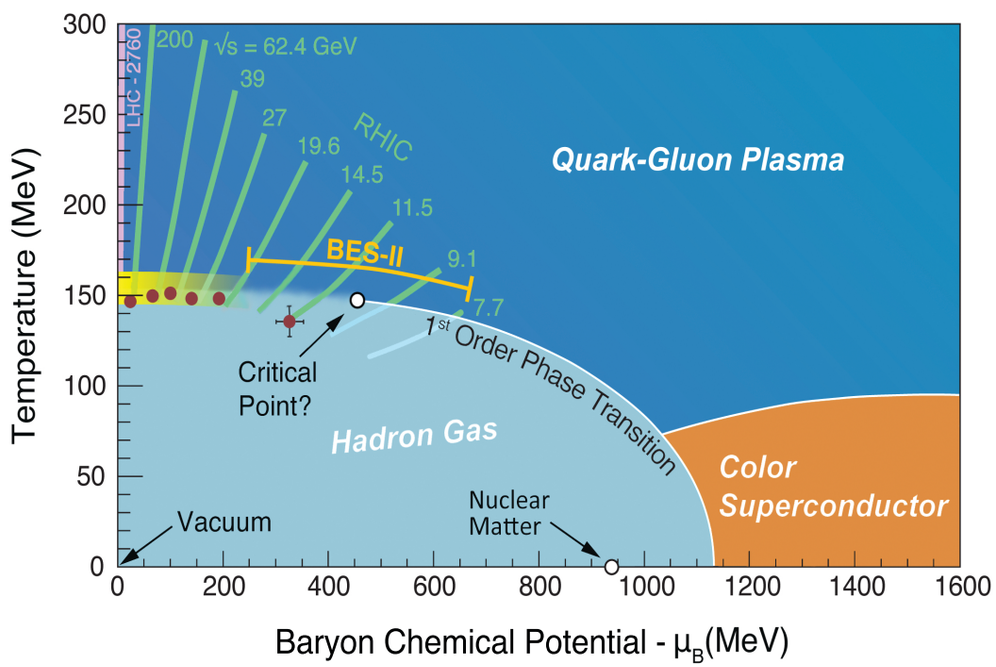
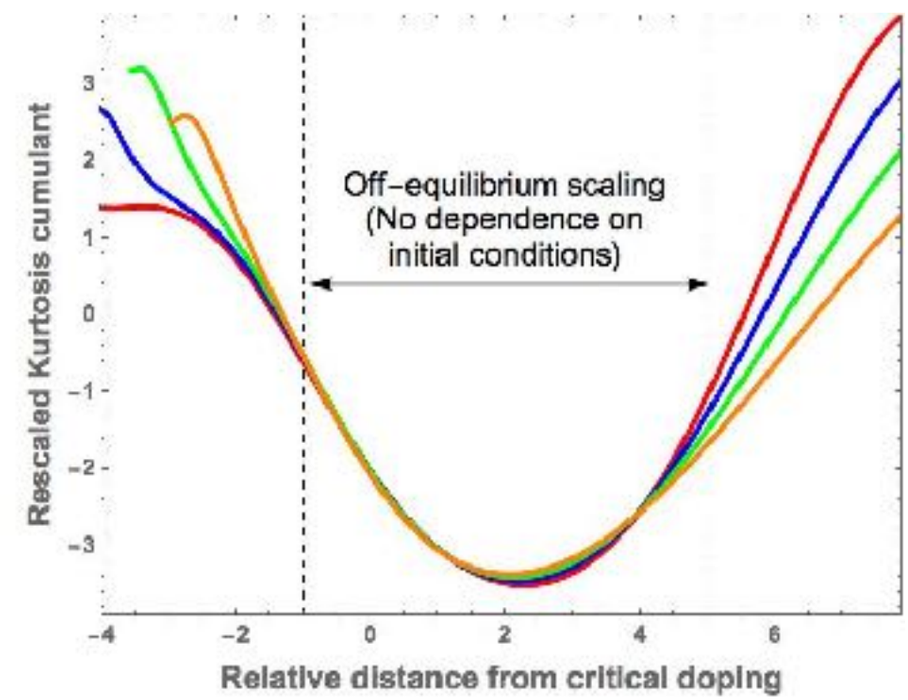
Off-equilibrium scaling and search for QCD critical point



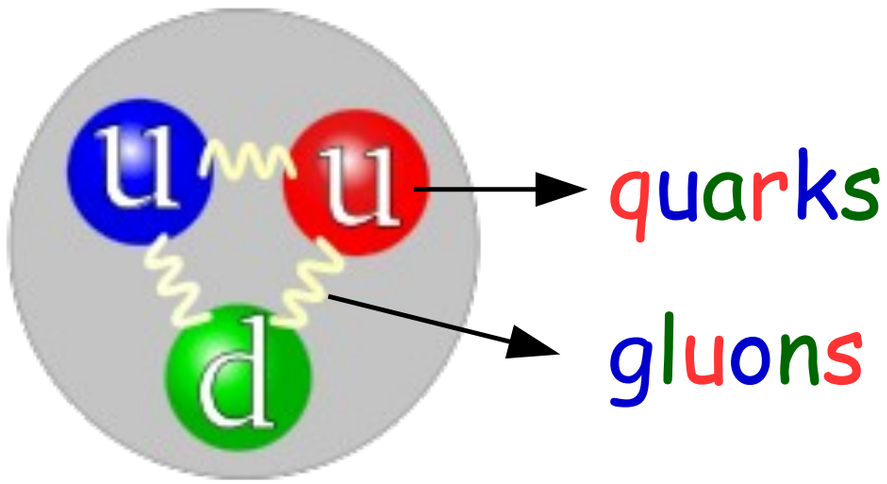


(Based on S. Mukherjee, R. Venugopalan, YY, PRL, Editors' suggestion, 16'; featured in DOE science highlights, "*The Roadmap to Quark Soup*", Apr. 17)

BEST COLLABORATION

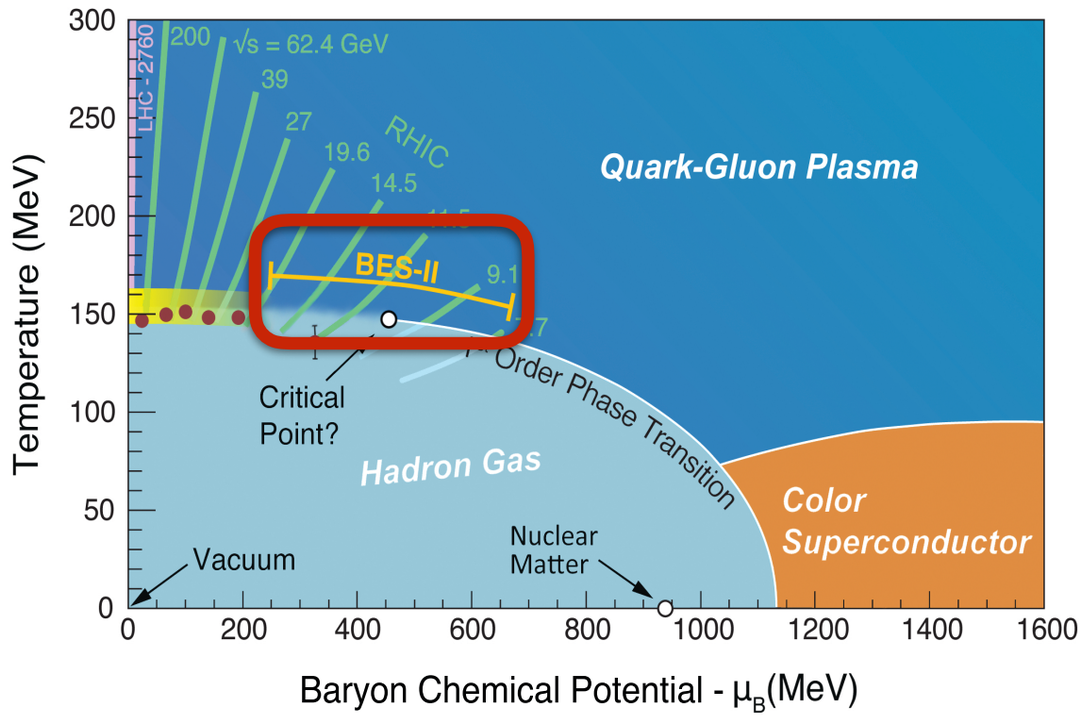
Yi Yin

MIT



- QCD at short distance: well understood.
- QCD at Λ_{QCD} : strongly interacting and changeling.
- Phases of QCD matter: studying QCD at extreme conditions. (T, $\mu_B \sim \Lambda_{QCD}$).

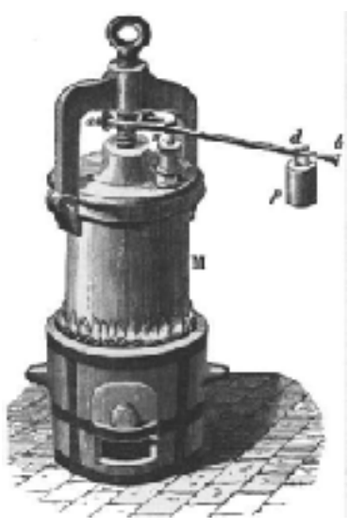
The critical point of QCD matter?



- (Conjectured) QCD critical point: a landmark point where the difference between hadron gas and quark-gluon plasma disappears.
- Locating the Critical point form Lattice QCD: challenging !
- Another approach: search for QCD critical point experimentally.

Search for the critical point (liquid-gas like) in 19th century

- In 1822, Cagniard de la Tour discovered the critical point
  - by heating and compressing liquid (varying temperature and pressure) in a digester ,
  - and by listening to discontinuities in the splashing sound (critical signature).

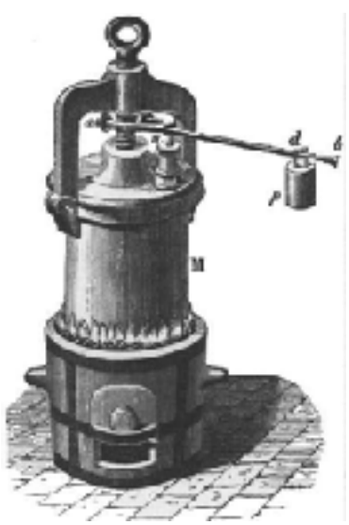


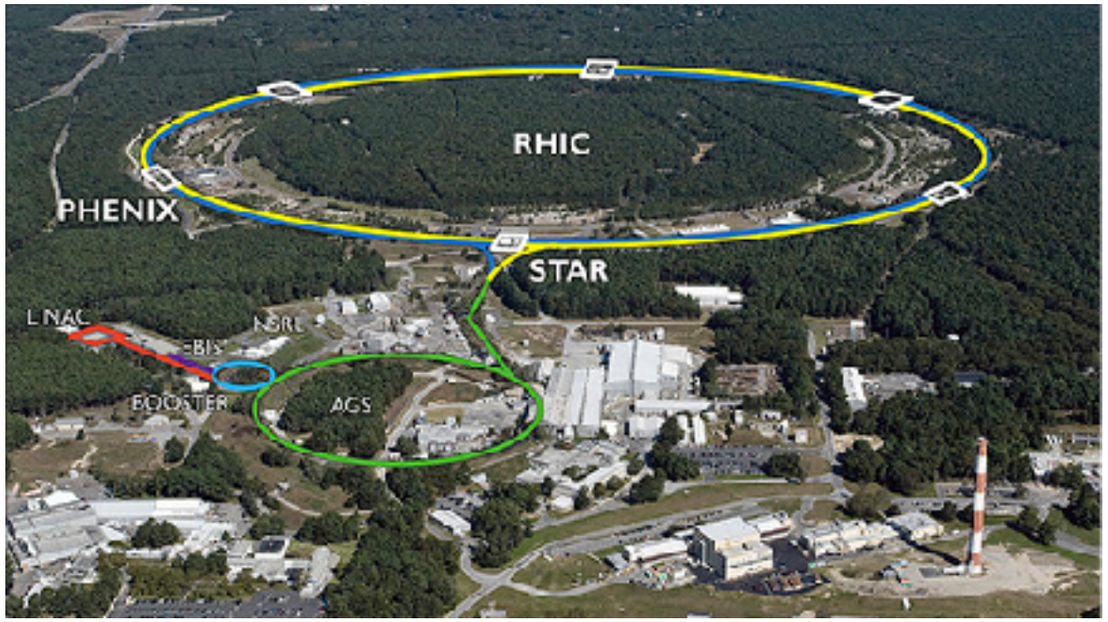
(Digester)

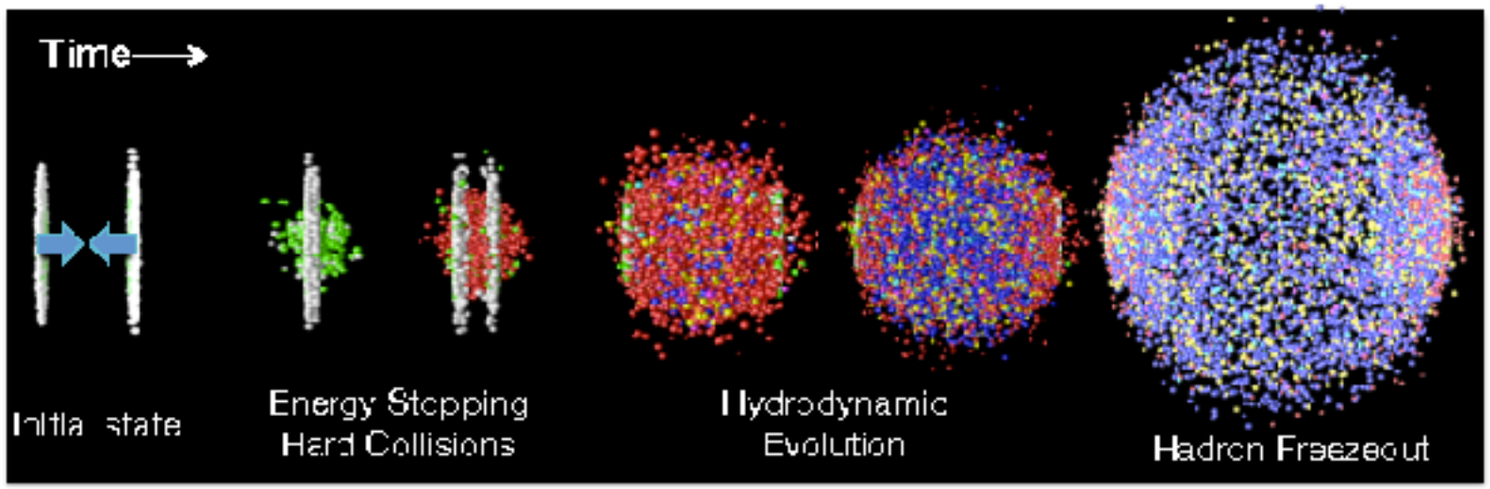
High Energy Frontier of 19th century (Cagniard de la Tour made the Digester from a cannon barrel.)

Experimental Search for the QCD critical point in 21st century

- Two crucial ingredient:
  - Creating QCD matter with different temperature T and baryon density μB .
  - Identifying observables sensitive to criticality.





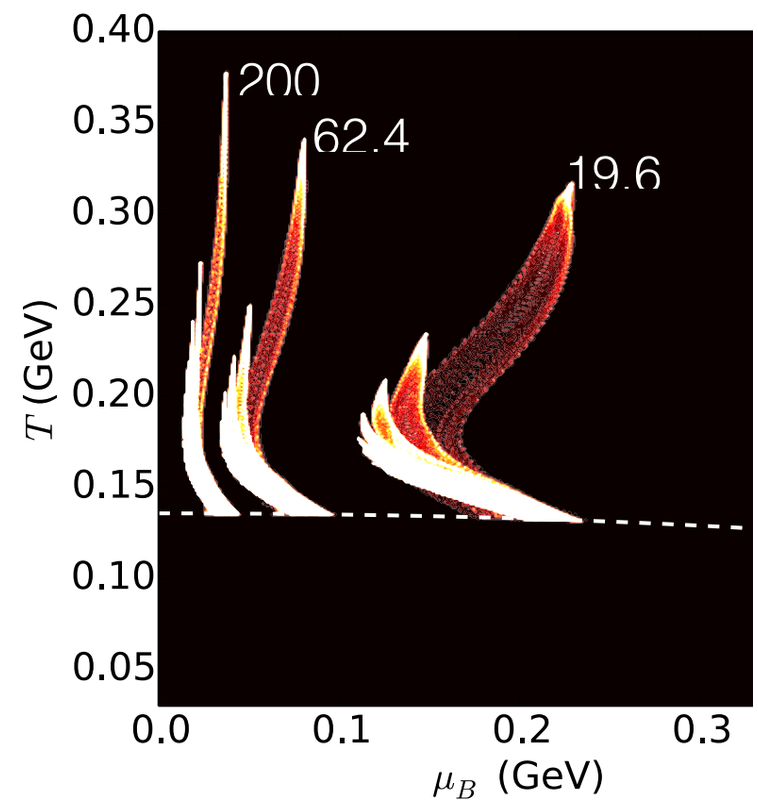


- Heavy-ion collisions: creating hot QCD matter which cools during expanding.

- Beam energy scan program: "quench" across QCD phase diagram.

$$(\sqrt{s}, b) \longrightarrow (\mu_B(\tau), T(\tau))$$

- Looking for signatures if critical regime is probed.



(hydro. simulation by McGill group)

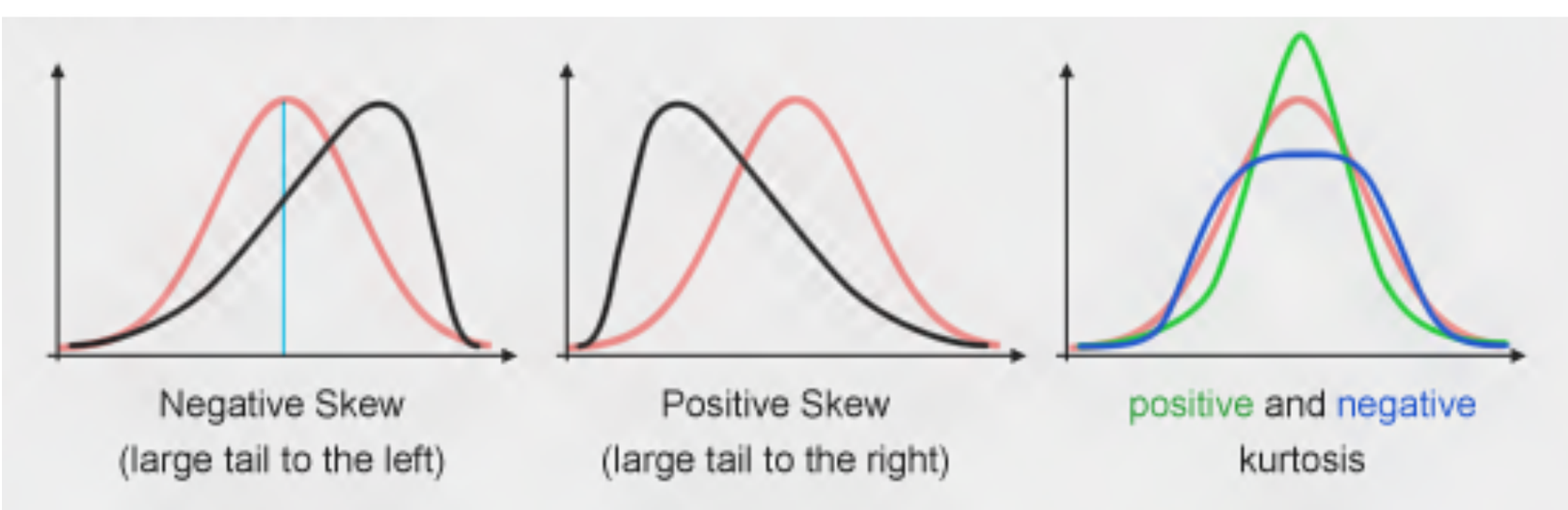
Critical signature (equilibrium)

- The growth of baryon number fluctuations (the order parameter M of QCD critical point is mixed with baryon density).

$$<(\delta N_B)^n> \sim \kappa_n = <(\delta M)^n>$$

- Non-Gaussian fluctuations: more sensitive to the growth of correlation length ξ.

$$\kappa_2^{eq} \sim \xi_{eq}^2 \qquad \kappa_3^{eq} \sim \xi_{eq}^{9/2} \qquad \kappa_4^{eq} \sim \xi_{eq}^7$$



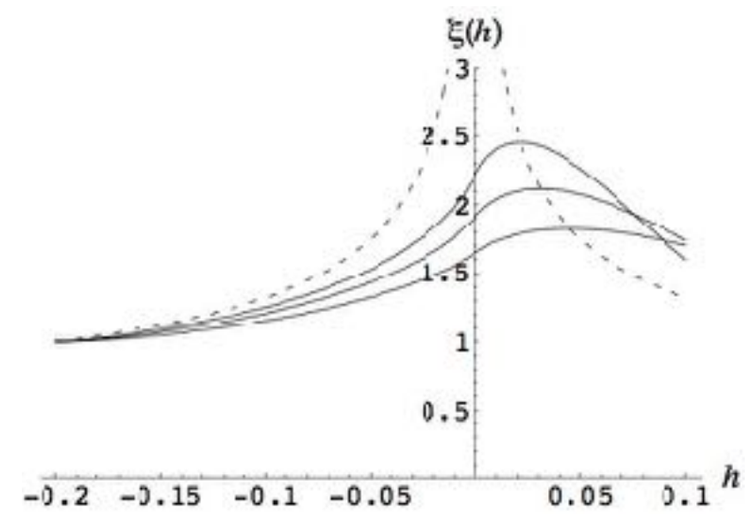
(from wikipedia)

Critical fluctuations are off-equilibrium

- Unlike liquid in a digester, QCD matter is expanding and changing over time.

- The QCD matter might expand too fast for the equilibration of critical fluctuations. Critical slowing down: relaxation time also grows.

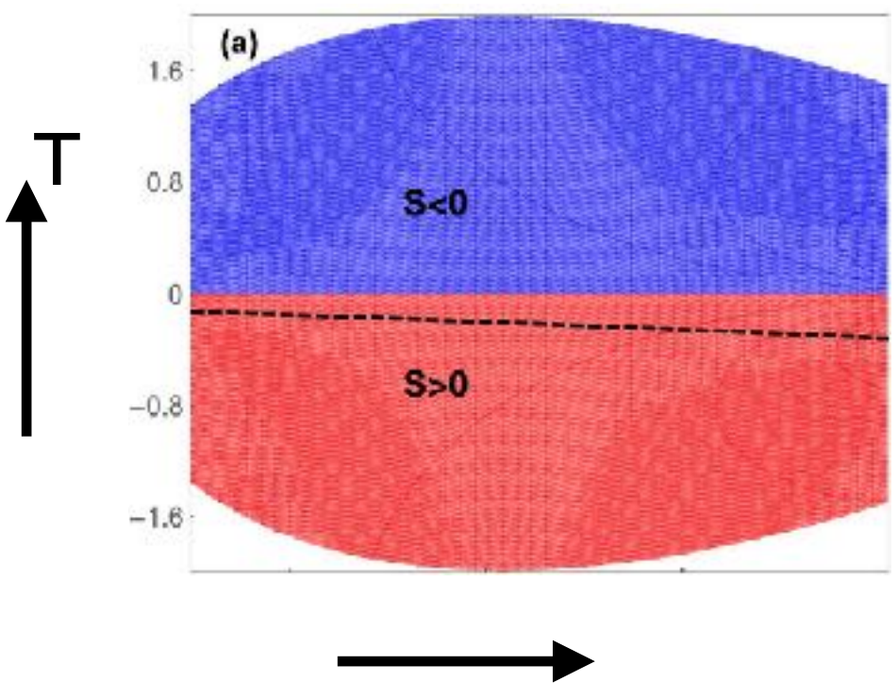
- Off-equilibrium effect limits the growth of correlation length.

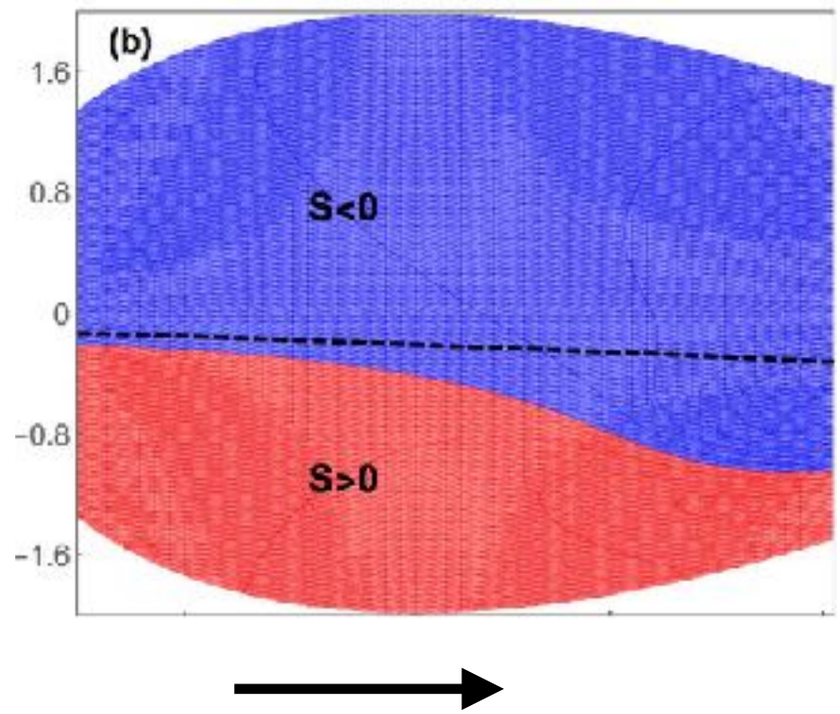


(Berdinkov-Rajagopal, 99')

Equilibrium Skewness
(third moment)

non-equilibrium





- Off-equilibrium non-Gaussian cumulants can be different from the equilibrium expectation qualitatively

(S. Mukherjee, R. Venugopalan and YY, PRC, 2015)

What we learned so far:

- Critical fluctuations are off-equilibrium !

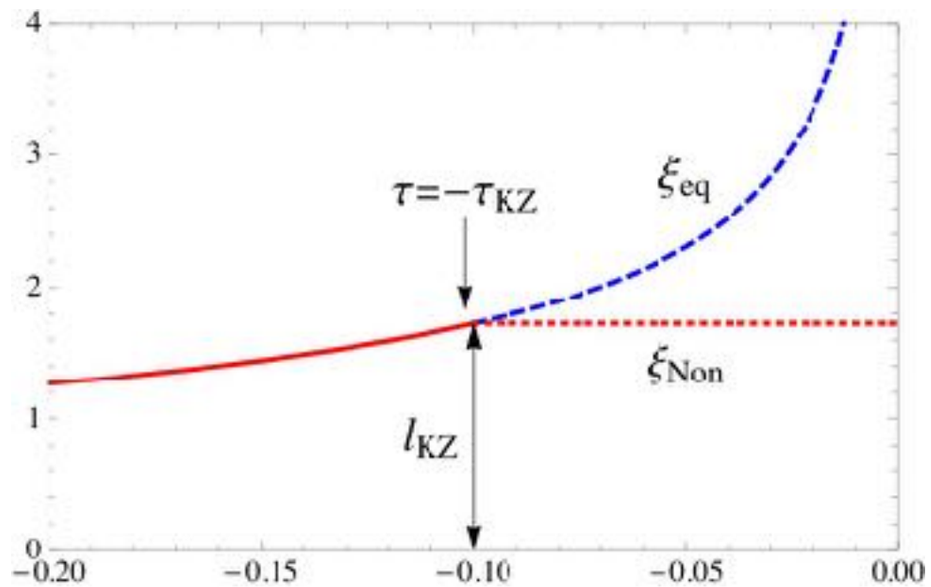
Questions:

- Off-equilibrium evolution depends on many non-universal inputs and real time evolution looks complicated. (complexity)

- Is there a simple way to characterize off-equilibrium evolution? Is critical universality lost in complexity?

Next:

- Universality is regained by the Kibble-Zurek (KZ) mechanics (Originally discussed in the context of cosmological and superfluid) .



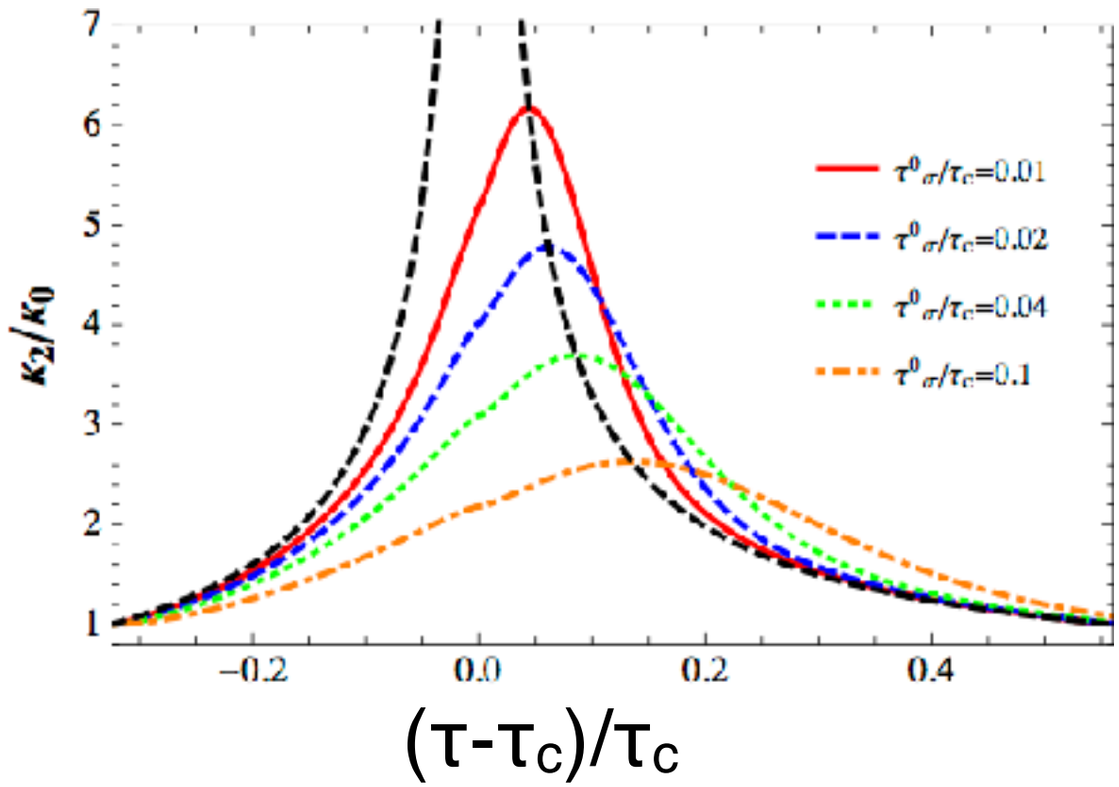
- The correlation length is frozen when:

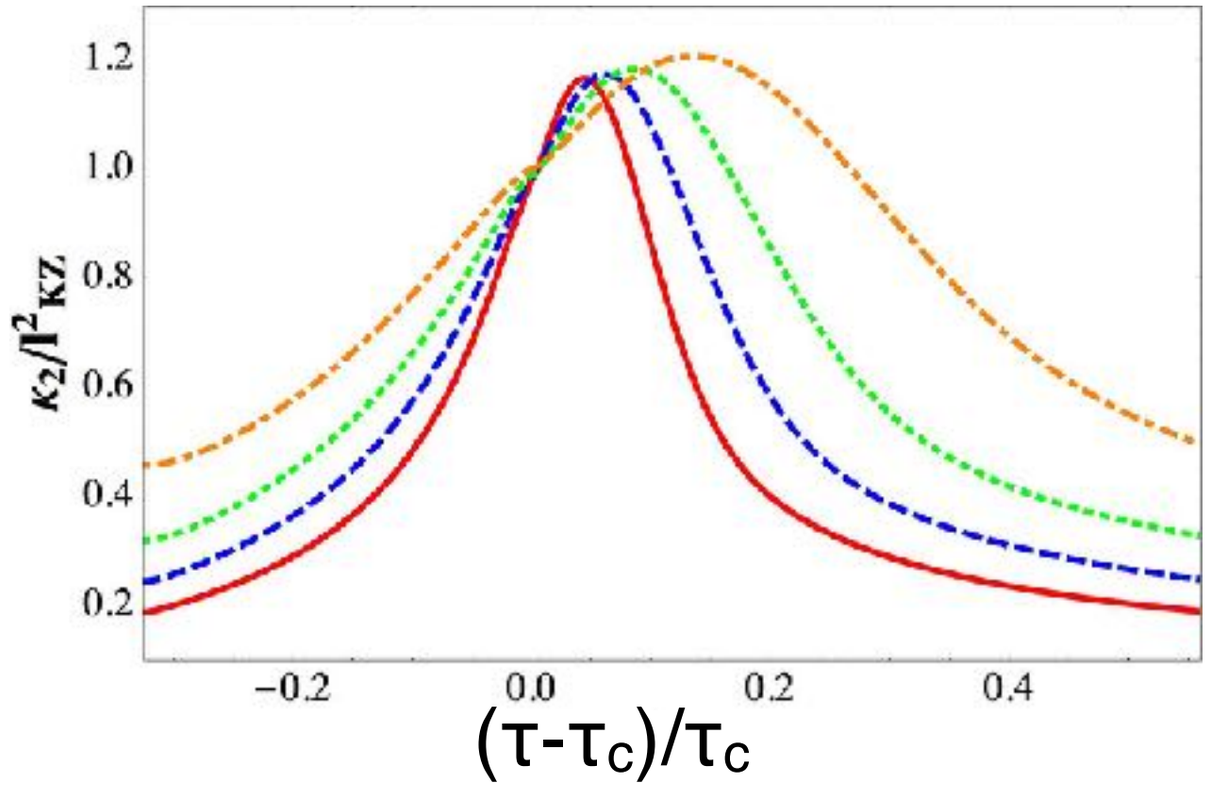
Quench (expansion) time = Relaxation time

- Kibble-Zurek dynamics:

$$l_{KZ} = \xi_{eq}(\tau_{KZ})$$ Magnitude (1980s).

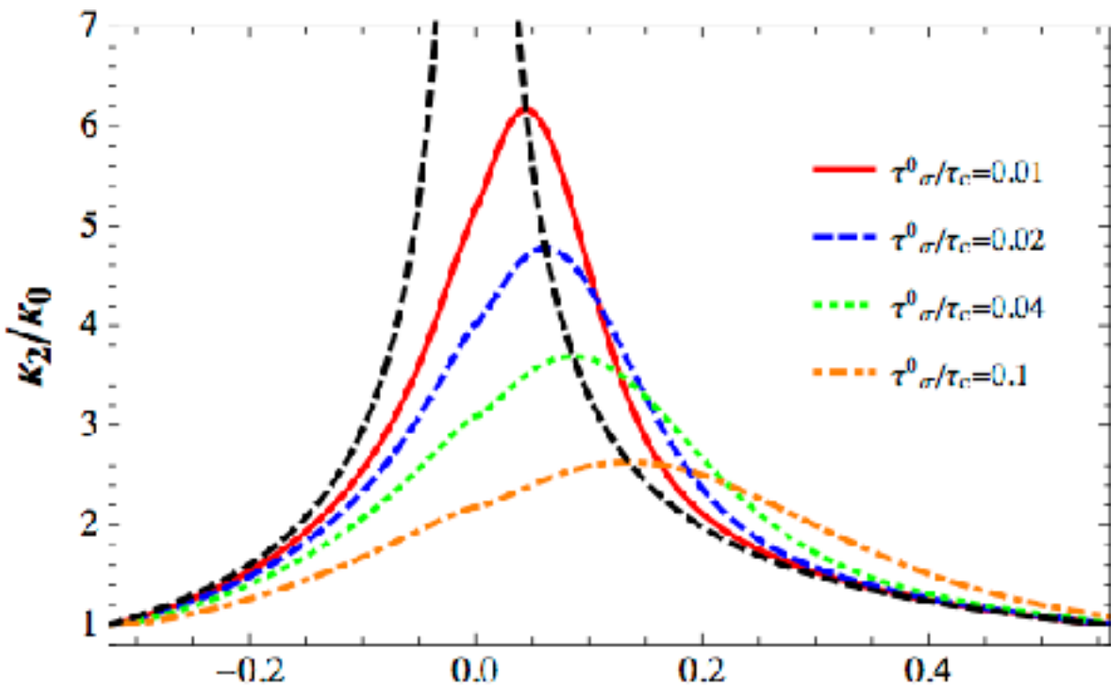
τ_{KZ} Time evolution (2010s).

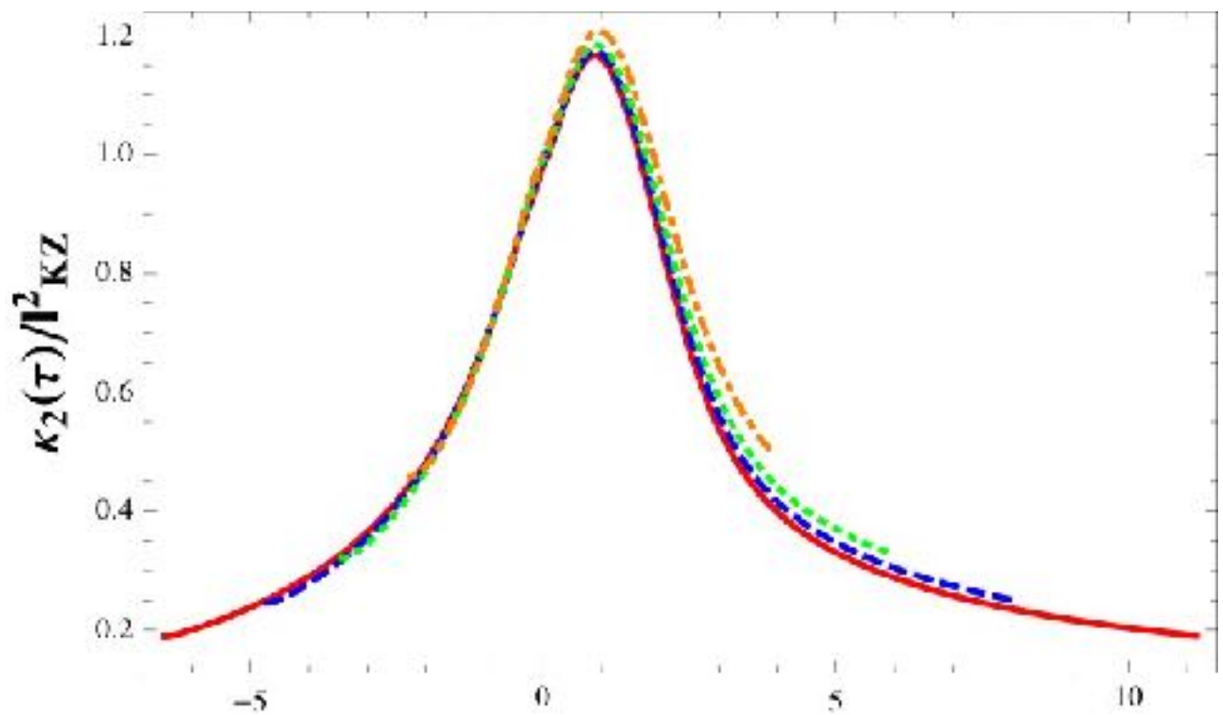




An illustrative example: non-equilibrium evolution of Gaussian fluctuations.

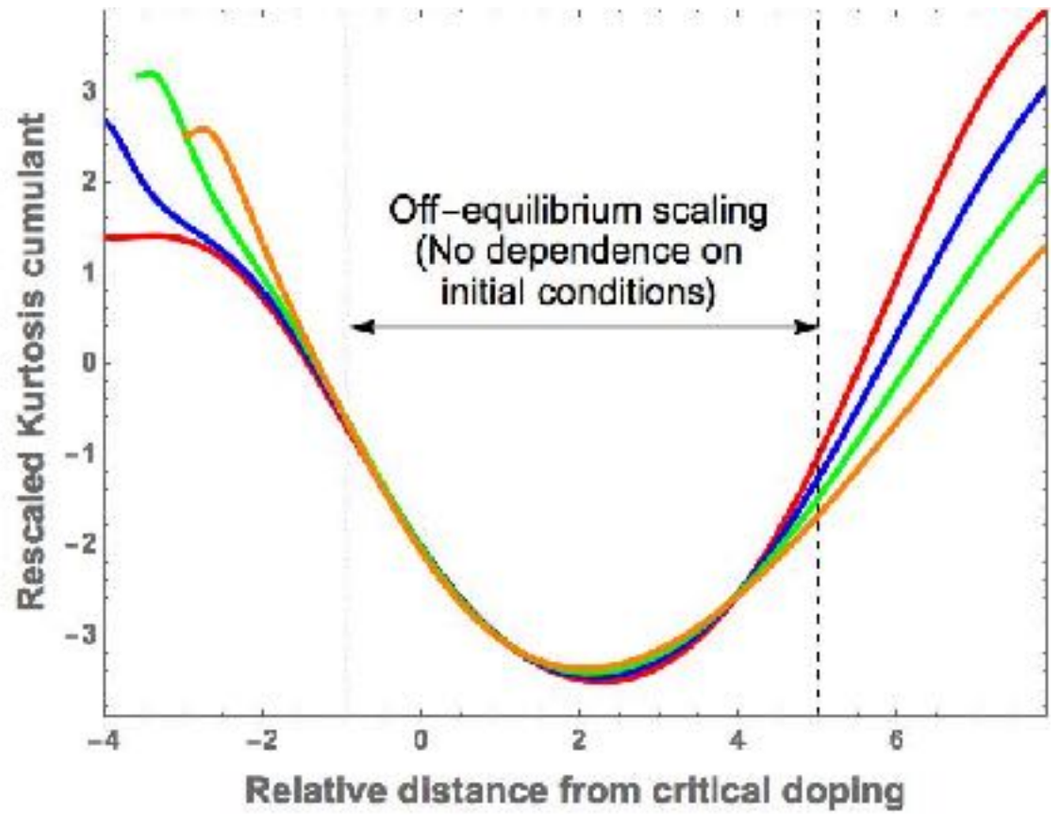
- Step I: Rescale Gaussian cumulants by $(l_{kz})^2$ (Scaling with length is not enough!).
- Step II: A step forward: rescale time by τ_{kz} !

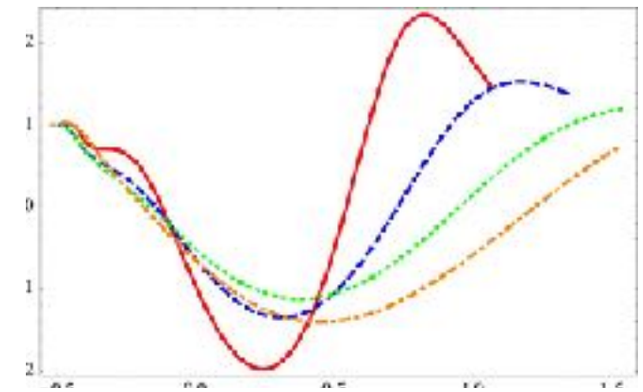




"you can hide but you can not run."

Extending off-equilibrium scaling to non-gaussian cumulants





(Before scaling)

- Our prediction: data will exhibit the off-equilibrium critical scaling behavior near the critical point.

(S. Mukherjee, R. Venugopalan and YY, PRL, Editors' suggestion, 16'. featured in DOE science highlights, "The Roadmap to Quark Soup", Apr. 17')

Summary and outlook

- Understanding off-equilibrium effects is crucial for search for the QCD critical point.

- Off-equilibrium critical scaling: the signature of the criticality !

- High luminosity data from Beam energy scan Phase II (2019-2020) provides unique discovery opportunity — a lot of work to be done in theory as well (the goal of Beam Energy Scan Theory Collaboration)!