Holographic approach to criticality

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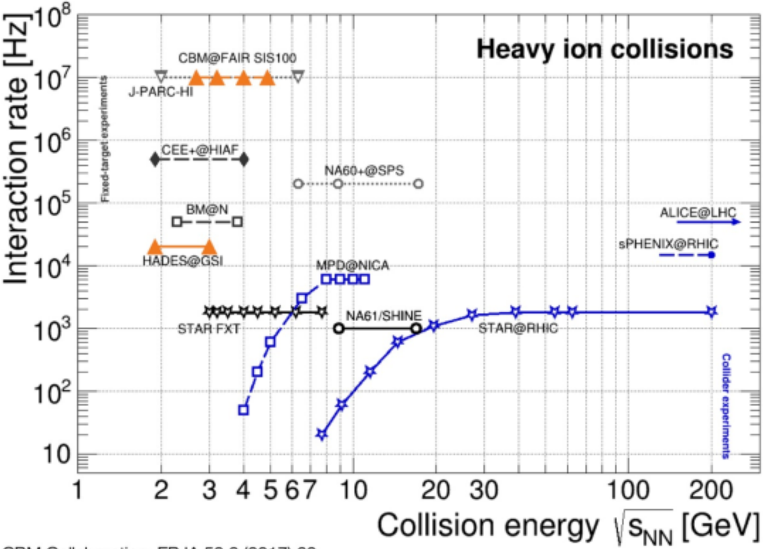
ECT* workshop on Gauge Topology, Flux Tubes and Holographic Models: the intricate dynamics of QCD in vacuum and extreme environments

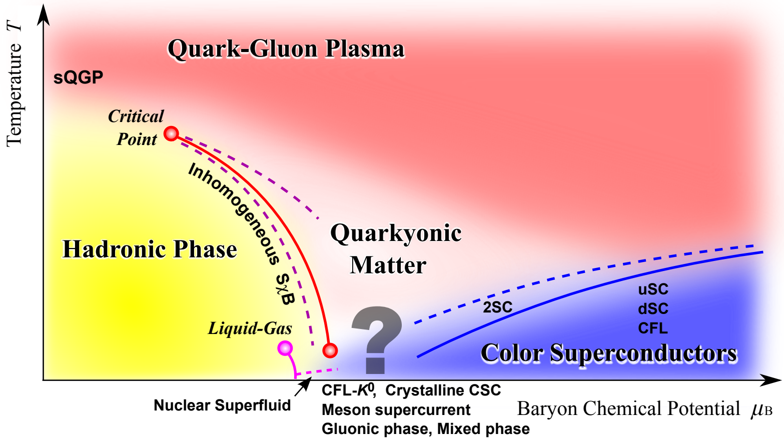
Motivation - world wide HI ex



CBM Collaboration, EPJA 53 3 (2017) 60
T. Galatyuk, NPA982 (2019), update (2021)

Motivation - many unknows in the QCD phase diagram

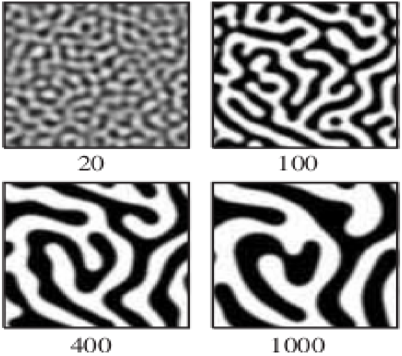
The critical point (CP) is the endpoint of the 1st order phase transition between the Quark-Gluon Plasma and the hadrons:



Assumed QCD phase diagram [Fukushima, Hatsudo 2010]

Holographic setup

spinodal instability:



spinodal decomposition in a two phase system

[Onuki 1987]

Gregory-Laflamme instability:

thin black ring pinching off

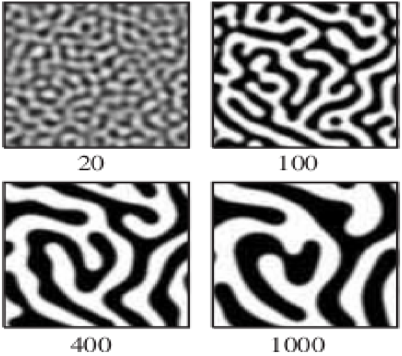
[Figueras, Kunesch, Tunyasuvunakool 2015]

gauge/gravity correspondence:

bridge between physical phenomena in gauge theories and gravity.

Holographic setup

spinodal instability:



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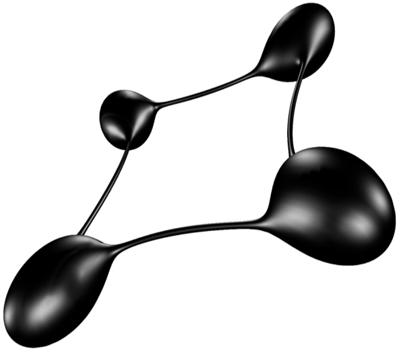

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[Figueras, Kunesch, Tunyasuvunakool 2015]

gauge/gravity correspondence:

bridge between physical phenomena in gauge theories and gravity.

Dual field theory: "mimics" a deformation of N=4 SYM with a dimension 3 operator O and source Λ as " mass"

$$S_{\mathrm{GaugeTheory}} = S_{\mathrm{conformal}} + \int d^4x \Lambda O$$

Einstein-Hilbert action coupled to a scalar with non-trivial potential in five-dimensional bottom-up model:

$$S = \frac{2}{\kappa_5^2} \int d^5x \sqrt{-g} \left[\frac{1}{4}\mathcal{R} - \frac{1}{2} (\nabla\phi)^2 - V(\phi) \right]$$

We derive the potential from the superpotential [Bianchi, Freedman, Skenderis 2002]: $V(\phi) = -\frac{4}{3} W(\phi)^2 + \frac{1}{2} W'(\phi)^2$

$$\ell^2 W(\phi) = -\frac{3}{2} - \frac{\phi^2}{2} - \frac{\phi^4}{4\phi_M^2}$$

with a single dimensionless parameter ϕ_M

$$\ell^2 V(\phi) = -3 - \frac{3\phi^2}{2} - \frac{\phi^4}{3} - \frac{\phi^6}{3\phi_M^2} + \frac{\phi^6}{2\phi_M^4} - \frac{\phi^8}{12\phi_M^4}$$

$\phi_M = 2.521$ is critical value (above crossover, subcritical 1st-order)

Growth rate of the dynamical instability

Dual field theory: 'mimics'a deformation of N=4 SYM with a dimension 3 operator O and source Λ as 'mass'

$$S_{\mathrm{GaugeTheory}} = S_{\mathrm{conformal}} + \int d^4x \Lambda O$$

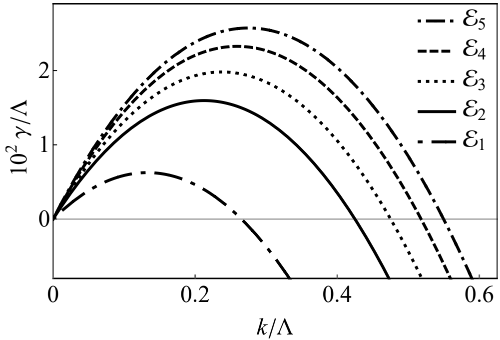
Growth rate for small momenta

$$\gamma(k) = |c_s|\, k - \Gamma k^2$$

sound attenuation constant

$$\Gamma = \frac{1}{2T}\left(\frac{4}{3}\frac{\eta}{s} + \frac{\zeta}{s}\right)$$

raise dynamical instability



Spinodal instability - stages

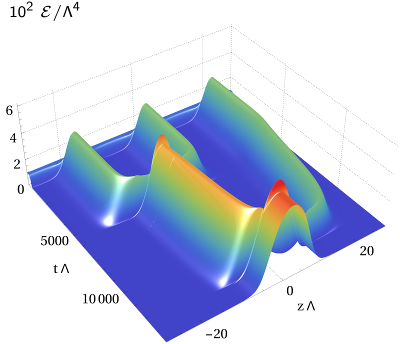
four generic stages:

1. linear stage
2. reshaping
3. merger
4. final:
   static + phase-separated

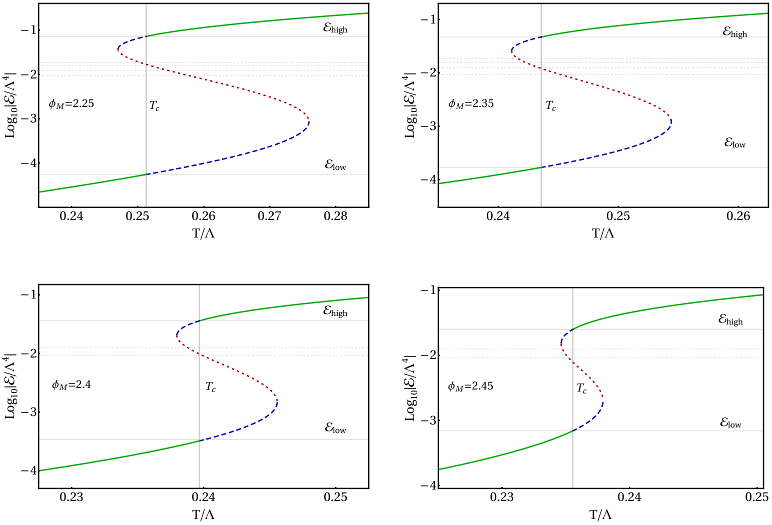
Homogeneous initial state in periodic unstable region, initial instability triggered by $n = 3$

endstate:
phase-separated configuration

conjecture:
all static, non-phase separated configurations are dynamically unstable

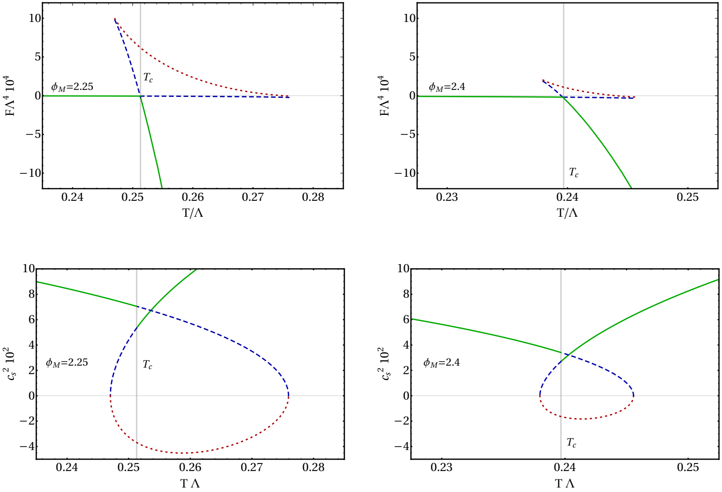


Bottom-up model: tuning criticality



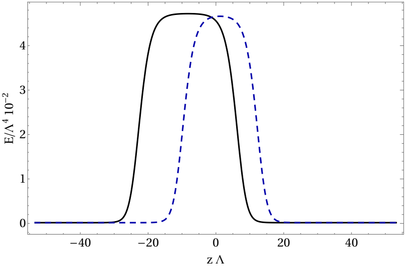
Energy density over T for theories with first order phase transition (blue) metastable (red) spinodal region (green) stable phases

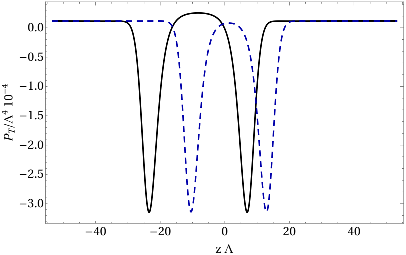
Bottom-up model: tuning criticality II



Thermodynamical properties of hard/soft transition:
(top row) Free energy over temperature
(bottom row) Speed of sound squared over temperature

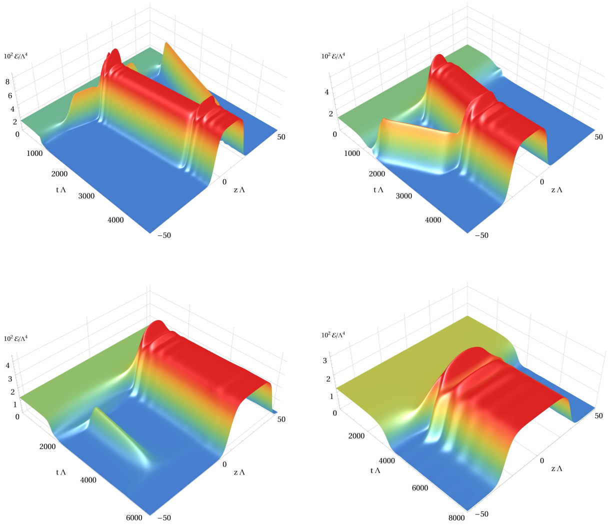
New criterium plateau (full black) where $P_T \geq 0.8 P_c$ versus peak (dashed blue) where $P_T < 0.8 P_c$





Longitudinal profiles of (left) local energy density (right) transverse pressure PT

Spinodal instability evolution



Phase separated final solution seen in the evolution of the local energy density of harder/softer phase transitions

Spinodal instability - formation time

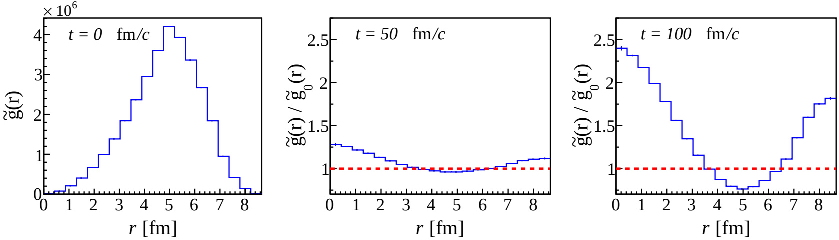
The formation time is defined as the time from the start of the evolution to when the system first reaches one of the two stable phases. It starts from an only slightly perturbed homogenous unstable solution.

Formation time of the spinodal instability with varying criticality:

ϕ_{M}	2.25	2.35	2.4	2.45
$t_{\mathrm{formation}}\Lambda$	880	1380	1725	2660

The formation time correlates with the strength of the first order phase transition: the strongest phase transition with the largest spinodal region shows the fastest formation time.

Time evolution of the baryon number distribution of a spinodal region in the hadronic transport model SMASH:



Demonstrating the spontaneous separation inside the spinodal region shows that hadronic transport can be used to study critical behavior in dense nuclear matter [A. Sorensen, V. Koch 2020]

Summary: spinodal instability approaching a critical point

Demonstration of the full dynamics of strongly coupled spinodal instability first order phase transitions.

Near a critical point the interface between cold and hot stable phases, given by its width and surface tension, features

- a **wider phase separation**,
- a **smaller surface tension** and
- a **longer formation time**.

Hence the spinodal instability is easier to detect far from a critical point along the first order phase transition.

New discovery of an atypical setup with dissipation of a peak into a plateau.

Push for new holographic theoretical developments:

New formula for domain wall velocities (M. Jarvinen talk)

Gravitational-wave production mechanism in cosmological, first-order, thermal phase transitions. (D. Mateos talk)

The Alps

Hope for all present you enjoy ECT*.


Thank you for your attention.