Heavy Ion Physics and Non-Perturbative Renormalization Group Equations

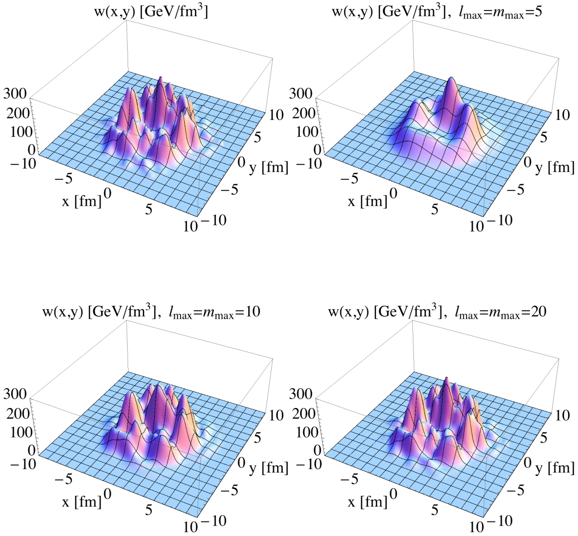
Stefan Flörchinger

CERN Theory Retreat 2013, Les Houches, 07/11/2012

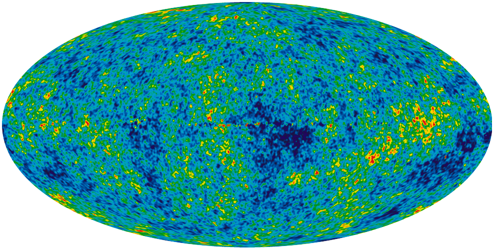
What fluctuations are interesting and why?

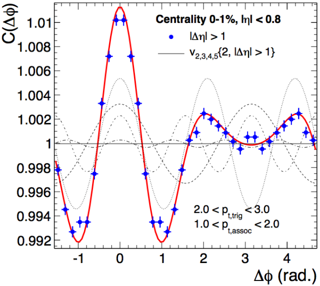
- **Initial hydro fluctuations**: Event-by-event perturbations around the average of hydrodynamical fields at time τ_0:
  - energy density ϵ
  - fluid velocity u^μ
  - shear stress $\pi^{\mu\nu}$
  - more general also: baryon number density n_B, electric charge density, electromagnetic fields, ...
- measure for deviations from equilibrium
- contain interesting information from early times
- governed by universal evolution equations
- can be used to constrain thermodynamic and transport properties

Transverse density from Glauber model



Similarities to cosmic microwave background





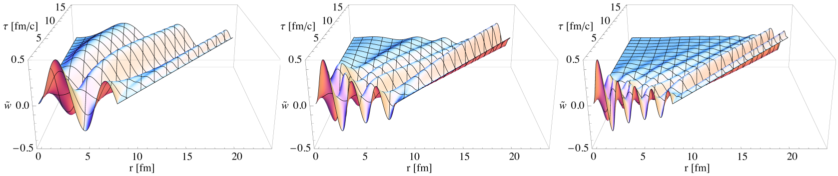
- fluctuation spectrum contains info from early times
- many numbers can be measured and compared to theory
- can lead to detailed understanding of evolution and properties
- could trigger precision era in heavy ion physics

Perturbations in hydrodynamics

- Hydrodynamic description

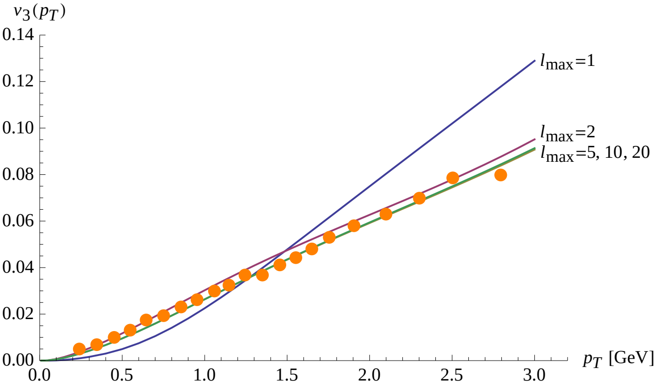
$$D\epsilon + (\epsilon + p)\partial_\mu u^\mu - u_\nu \partial_\mu \pi^{\mu\nu} = 0$$
$$(\epsilon + p) D u^\alpha + \Delta^{\alpha\beta}\partial_\beta \, p + \Delta^\alpha{}_\nu \partial_\mu \pi^{\mu\nu} = 0$$

- Develop perturbation theory in small fluctuations around smooth average fields: $\epsilon = \bar{\epsilon} + \delta\epsilon$ etc.
- In spirit similar to treatment of fluctuations in cosmology.



Harmonic flow coefficients for central collisions

Triangular flow for charged particles



Points: 2% most central collisions, ALICE [PRL 107, 032301 (2011)]
Curves: Different maximal resolution l_{max}

Non-perturbative Renormalization Group Equations 1

Exact flow equation [S.F. and C. Wetterich, PLB 680, 371 (2011)]

$$\partial_k \Gamma_k[\phi] = \frac{1}{2}\mathsf{STr}\,\left(\Gamma_k^{(2)}[\phi] + R_k\right)^{-1}\left(\partial_k R_k - R_k(\partial_k Q_k^{-1})R_k\right) - \frac{1}{2}\Gamma_k^{(1)}[\phi]\,\left(\partial_k Q_k^{-1}\right)\,\Gamma_k^{(1)}[\phi]$$

for a variant of the 1-PI or quantum effective action with

$$\lim_{k\to\Lambda} \Gamma_k[\phi] = S[\phi]$$
$$\lim_{k\to 0} \Gamma_k[\phi] = \Gamma[\phi]$$

- R_k is an infrared cutoff that is removed when $k \to 0$
- Fluctuations are included step by step
- Differential formulation of functional integral
- Q_k Implements k-dependent Hubbard-Stratonovich transformation

Non-perturbative Renormalization Group Equations 2

Conceptual topics I work on

- Analytic continuation of flow equations from Euclidean to Minkowski space
- Determination of real-time properties such as decay width and transport coefficients
- Skale-dependent changes in the relevant degrees of freedom
- Composite fields / bound states

Applications of the formalism I work on

- Scalar $O(N)$-models
- Yukawa type theories
- Composite fermions