Thermalization in small and large systems ~~in heavy ion collisions~~

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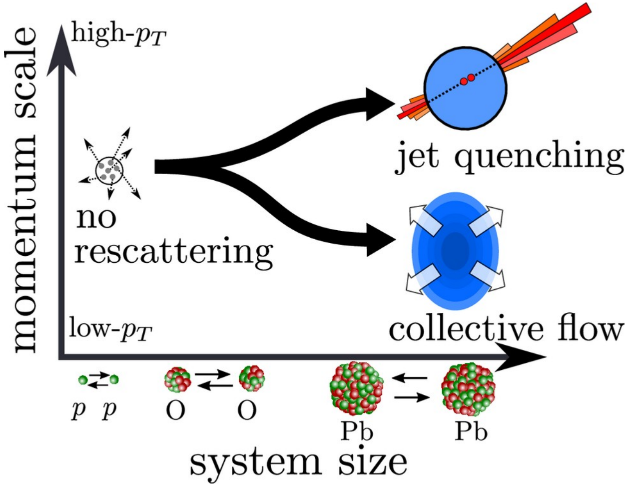
Institute for Theoretical Physics, Heidelberg University

June 19, 2024   Present and future perspectives in Hadron Physics



aleksas.eu

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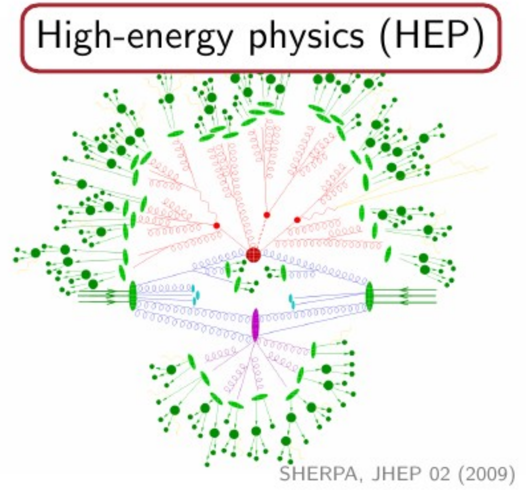
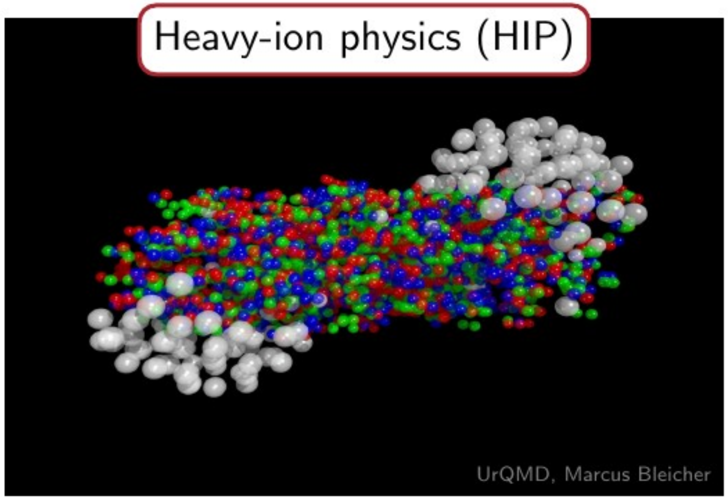
Emergent phenomena in complex systems

- HEP: concentrate higher energy in smaller and smaller volume.
- HIP: distribute high energy or high nucleon density over a relatively large volume. – T.D. Lee, 1974, Bear Mountain workshop



more scatterings



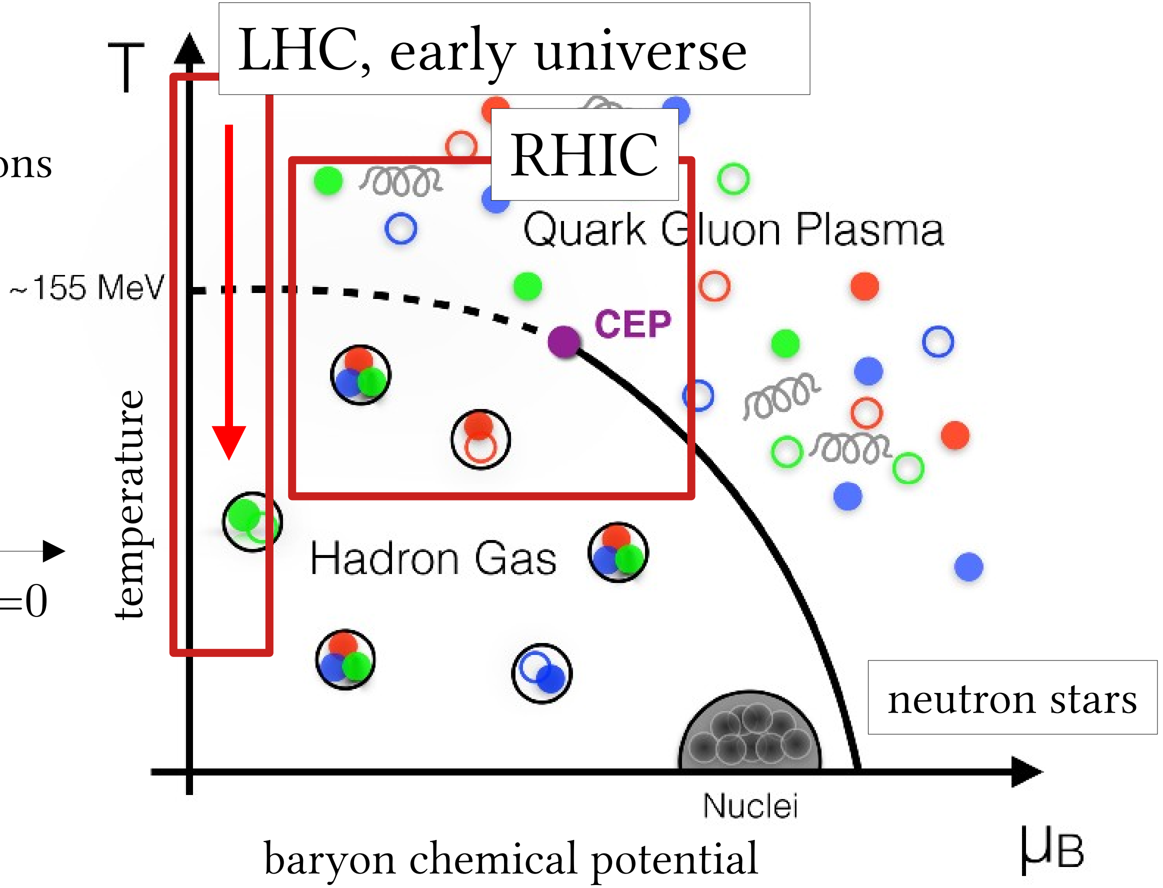
"More is different" – P.W. Anderson (1972)

QCD phase diagram

Ding et al., QGP 5

transition from hadrons
to quarks and gluons

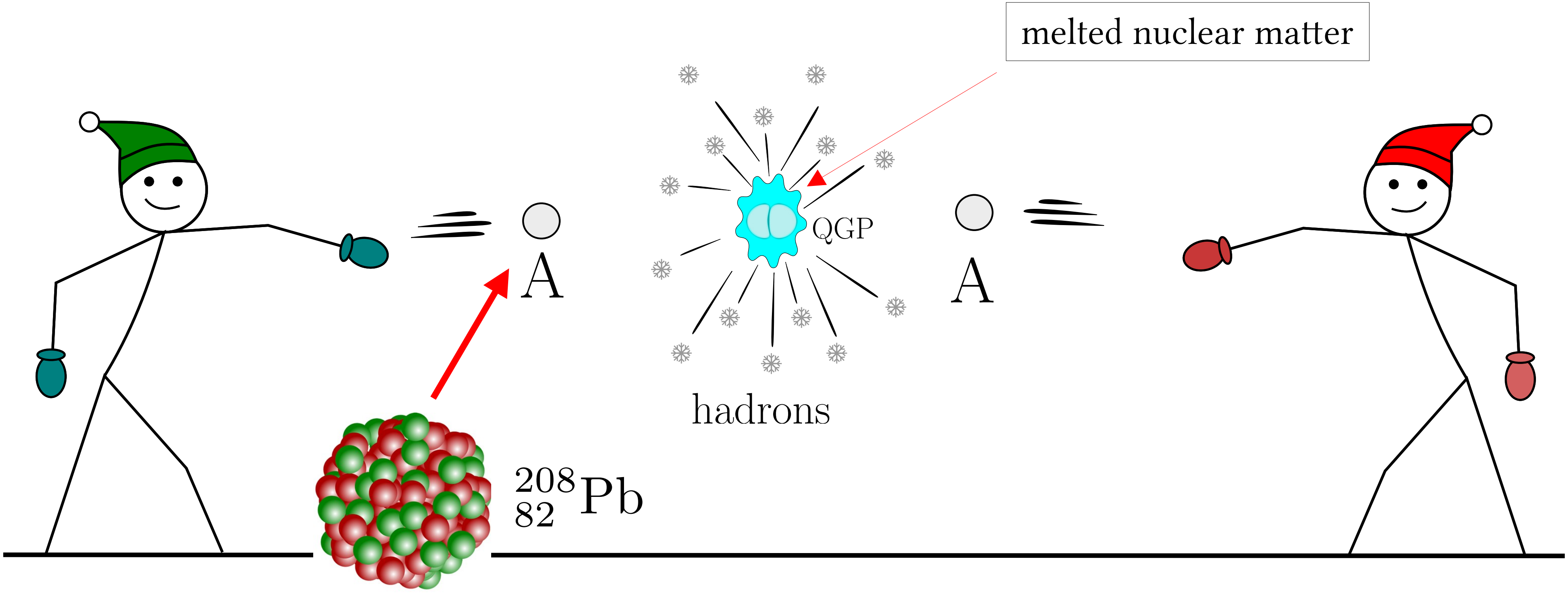
lattice QCD gives
thermodynamics at μ_B=0



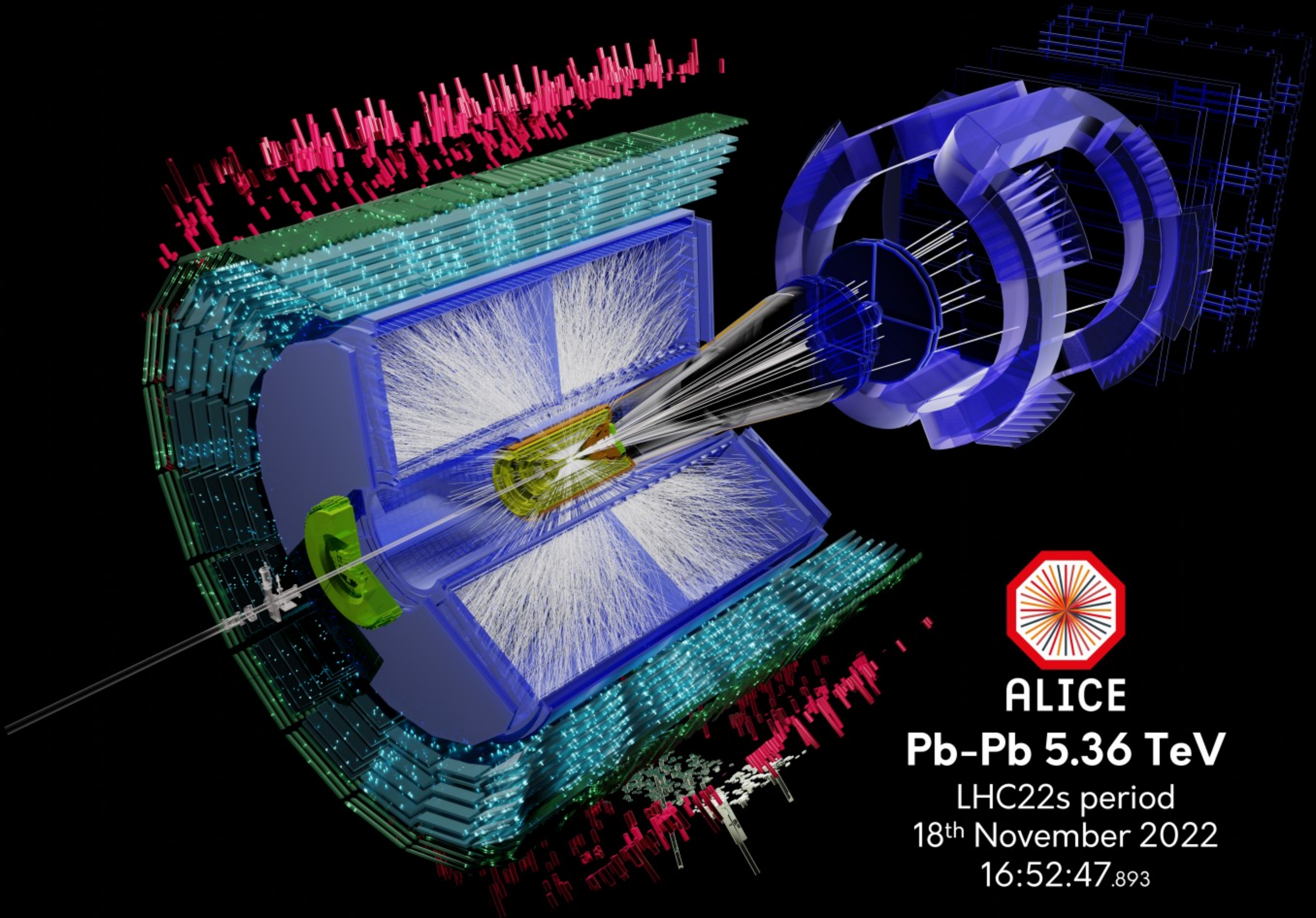
Dynamics of QCD thermalization is an active research field!

QCD thermalization in “large” systems

How to create Quark-Gluon Plasma

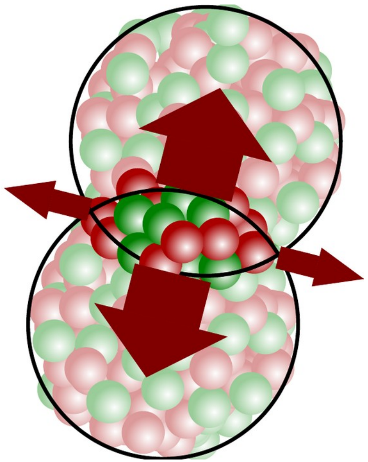


See also talk by Jan Fiete Grosse-Oetringhau on Tuesday

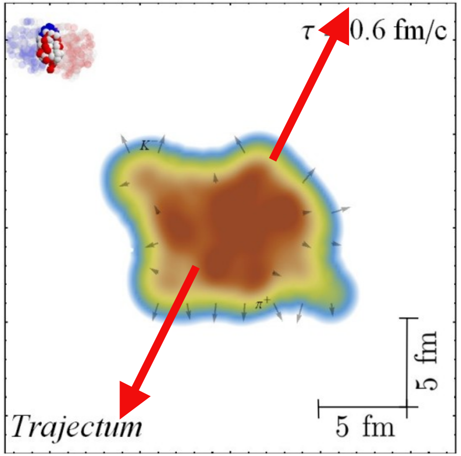

ALICE
Pb-Pb 5.36 TeV
LHC22s period
18th November 2022
16:52:47.893

What do we see: gradient driven expansion

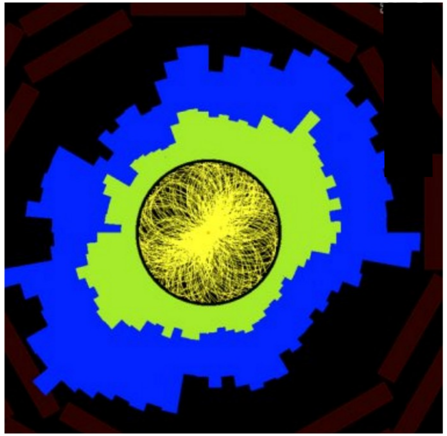
spatial anisotropy

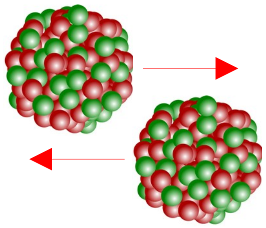


pressure gradients



momentum anisotropy
"elliptic flow"





relativistic hydro simulation

initial conditions + equation of state + viscosities

lattice QCD

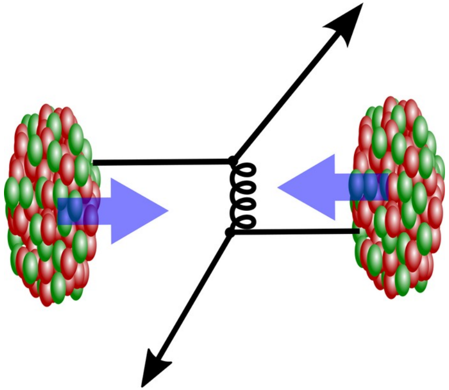
fitted

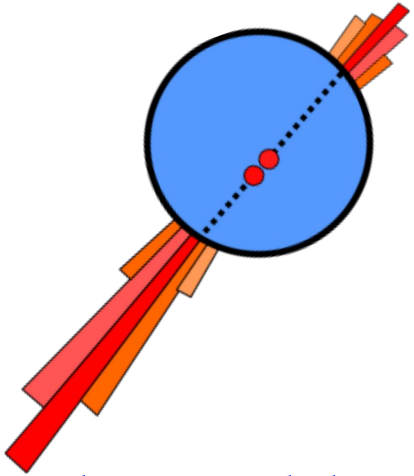
What do we see: medium induced quenching

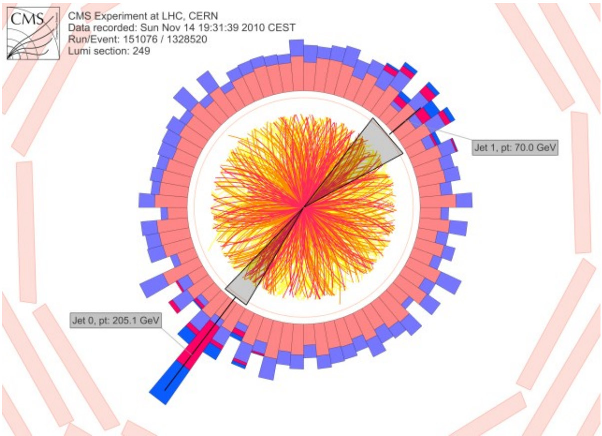
high-momentum parton scattering

interaction with QGP

jet quenching







energy loss models

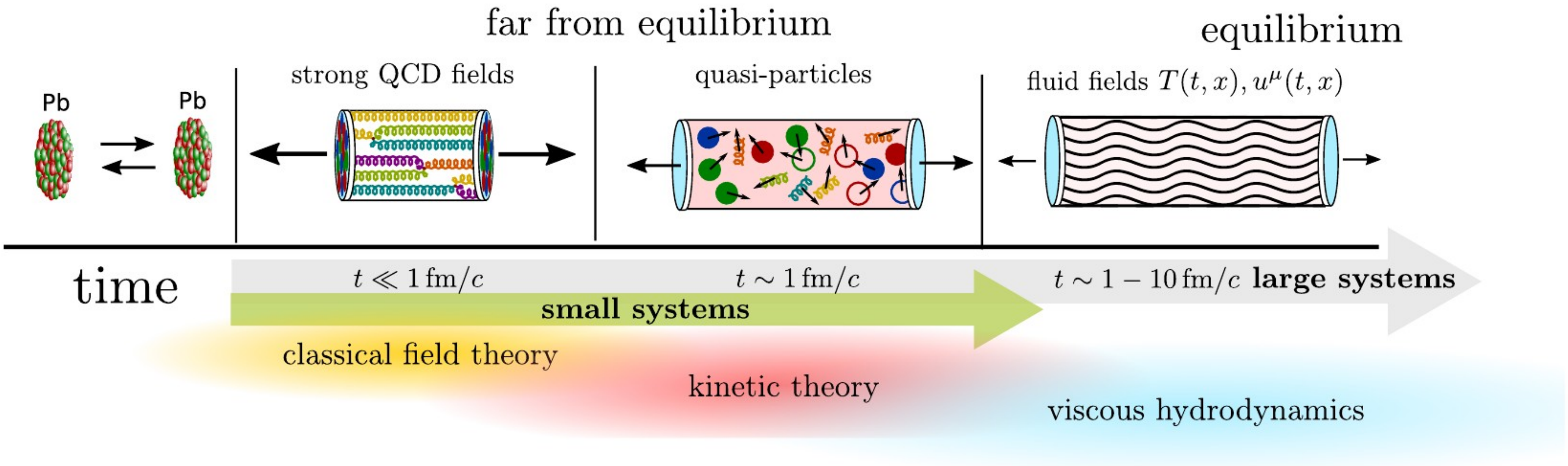
initial conditions + medium evolution + interactions

See also talk by Carlota Andres on Wednesday

QCD thermalization in heavy-ion collisions

High-energy ($\alpha_s \ll 1$), infinite size limit

Berges, Heller, AM, Venugopalan RMP (2021)
Schlichting, Teaney, Ann.Rev.Nucl.Part.Sci. (2019)



- Initial conditions: highly occupied gluons fields
- Intermediate times: quark and gluon quasi-particles
- Later times: fluid fields

QCD effective kinetic theory

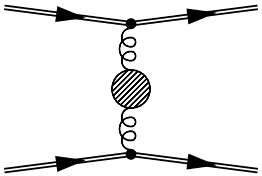
Arnold, Moore, Yaffe JHEP (2003)

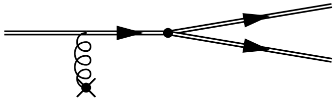
Underlying quantum field theory

2-point correlations $\mathcal{L}_{\text{QCD}} = \bar{q}\left(i\gamma^{\mu} D_{\mu} - m\right) q - \frac{1}{4} F^{a}_{\mu\nu} F^{\mu\nu}_{a}$

Boltzmann equation for quark and gluon distributions

phase-space distribution $\partial_t f(t, \mathbf{x}, \mathbf{p}) + \frac{\mathbf{p}}{|p|} \cdot \nabla_{\mathbf{x}} f(t, \mathbf{x}, \mathbf{p}) = -\mathcal{C}_{2\leftrightarrow 2}[f] - \mathcal{C}_{1\leftrightarrow 2}[f]$





Leading order scattering processes:

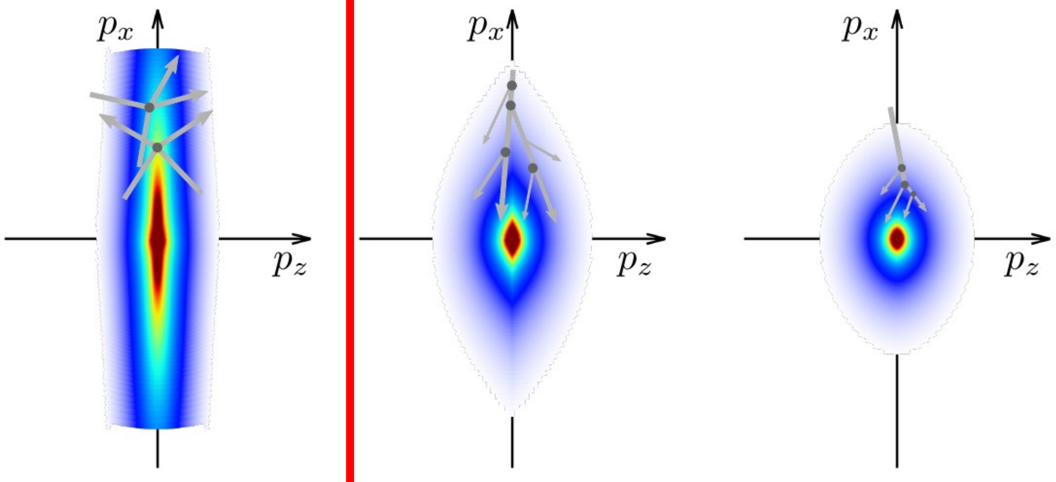
- Elastic scattering
- Medium-induced collinear radiation

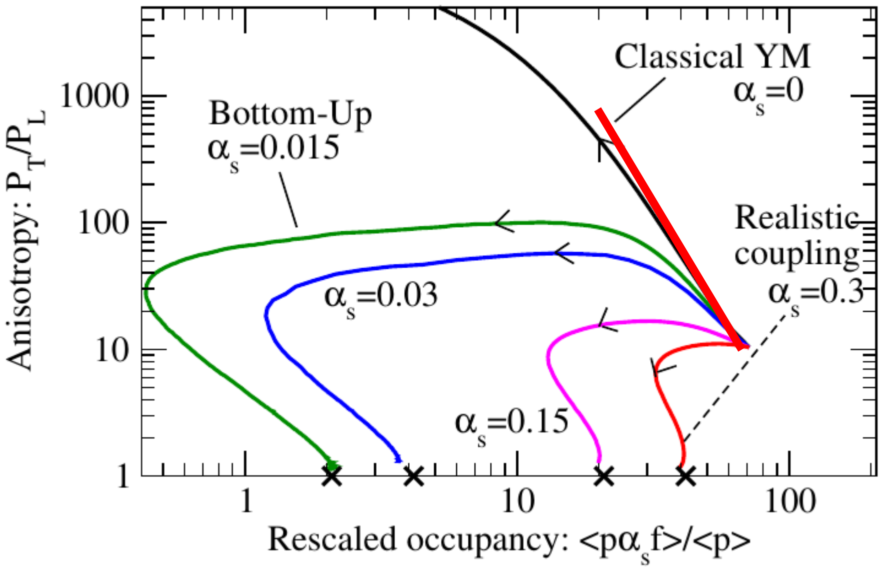
Low-momentum thermalization $\Longleftrightarrow$ high-momentum energy loss

“Bottom-up” thermalization scenario

Baier, Mueller, Schiff, and Son (2001)

Boltzmann eq.: $\partial_\tau f - \underbrace{\frac{p_z}{\tau}\partial_{p_z} f}_{\text{longitudinal expansion}} = - \underbrace{\mathcal{C}_{2\leftrightarrow 2}[f] - \mathcal{C}_{1\leftrightarrow 2}[f]}_{\text{in-medium QCD collisions}}$





Kurkela and Zhu (2015), Keegan, Kurkela, AM and Teaney (2016), Kurkela, AM, Paquet, Schlichting and Teaney (2018)

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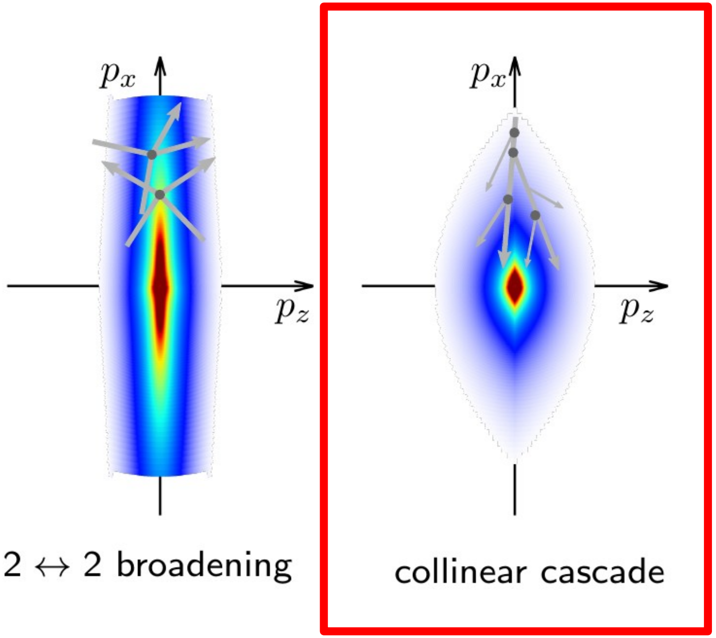

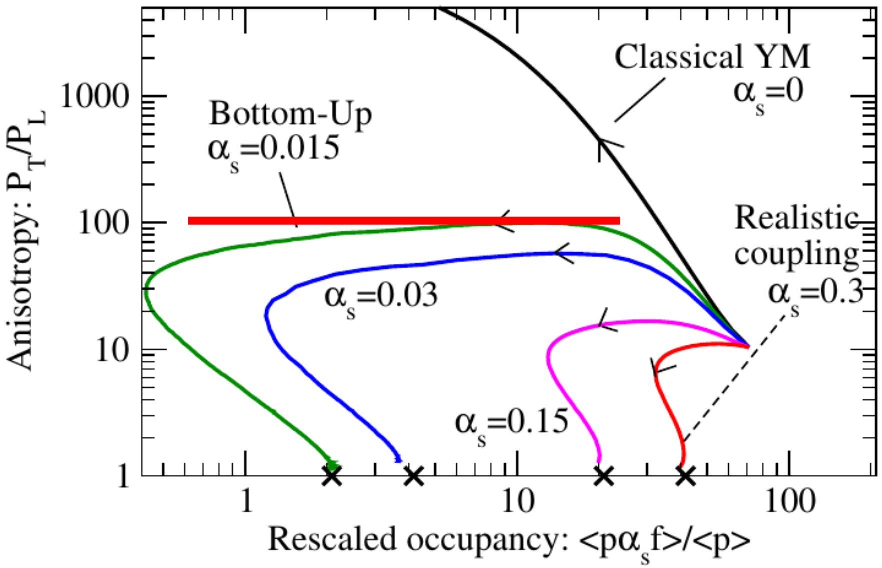

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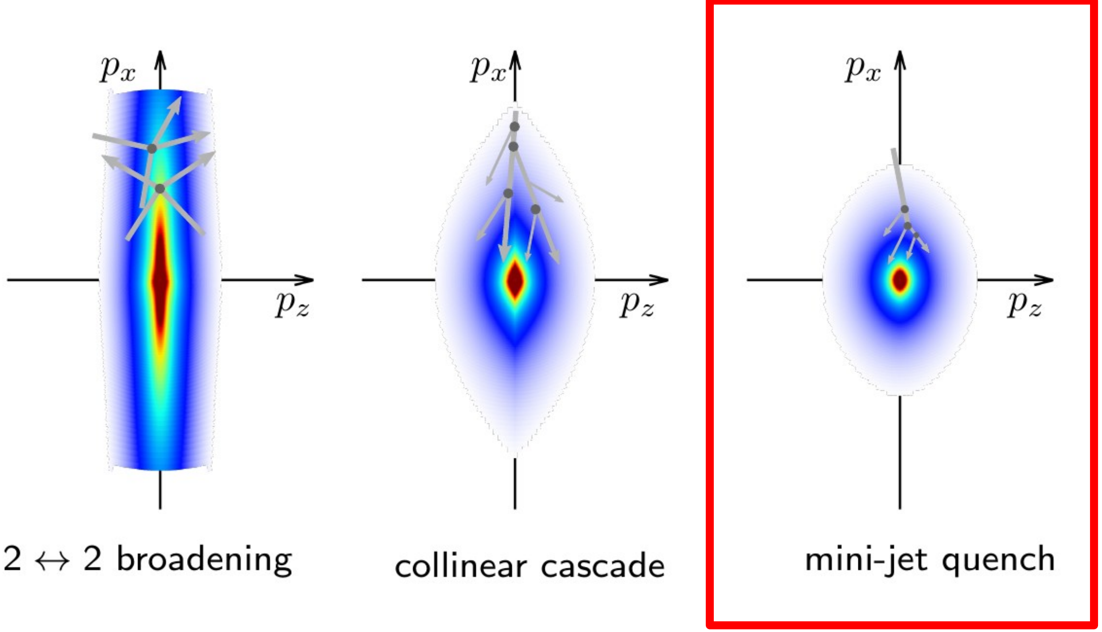
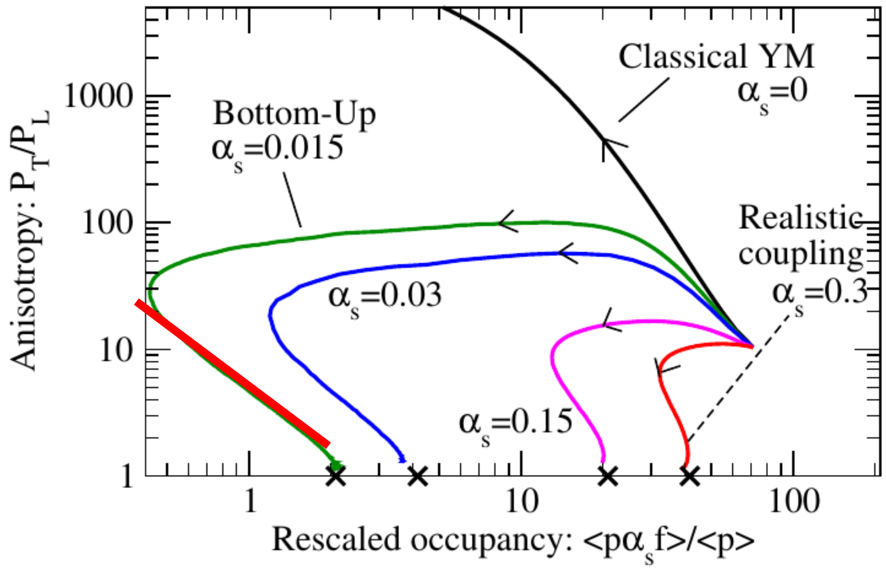
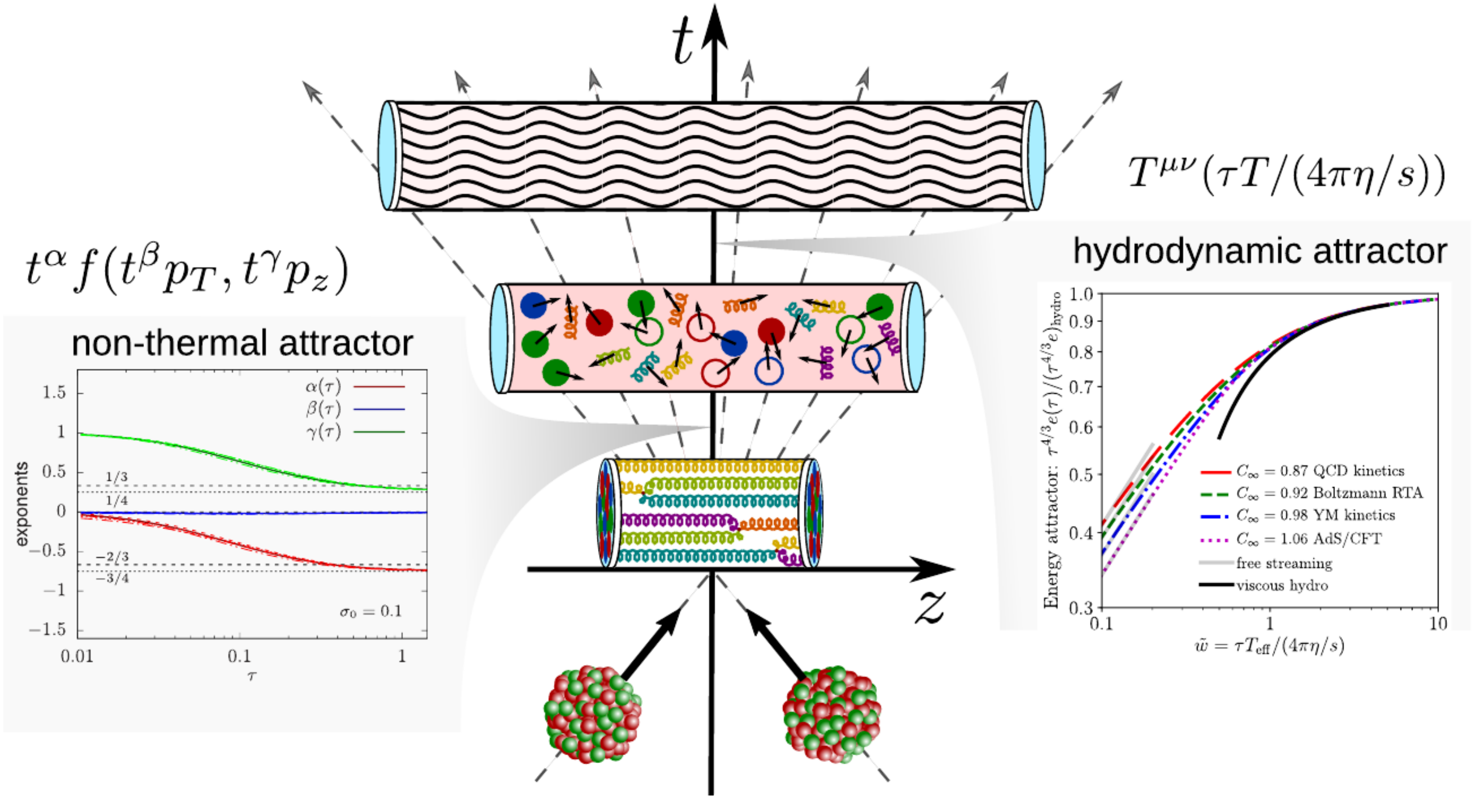




Kurkela and Zhu (2015), Keegan, Kurkela, AM and Teaney (2016), Kurkela, AM, Paquet, Schlichting and Teaney (2018)

Attractors in QCD thermalisation

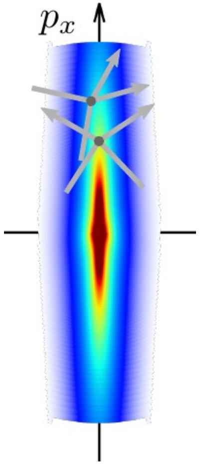
Universality and simplification of non-equilibrium evolution

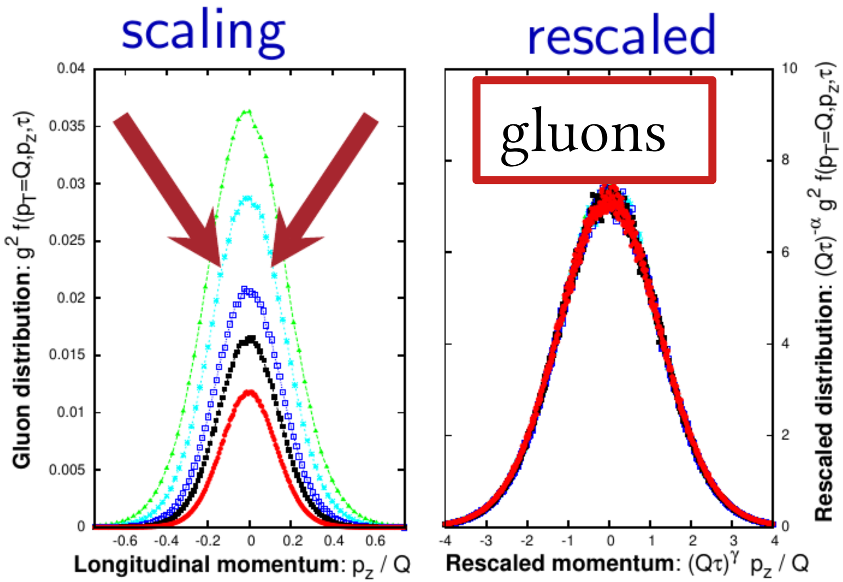


See reviews by Berges, Heller, AM, Venugopalan (2020), Florkowski, Heller and Spalinksi (2017), Romatschke and Romatschke (2017)

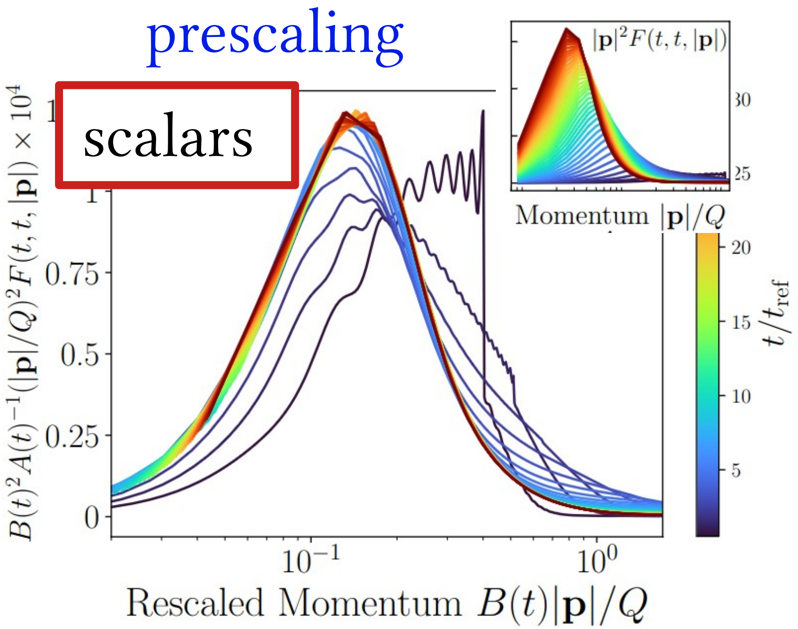
Stage I: non-thermal attractors

Self-similar evolution: $f(\tau, p_T, p_Z) = \tau^\alpha f_S(\tau^\beta p_T, \tau^\gamma p_z)$





Berges, Schenke, Schlichting, Venugopalan (2014)



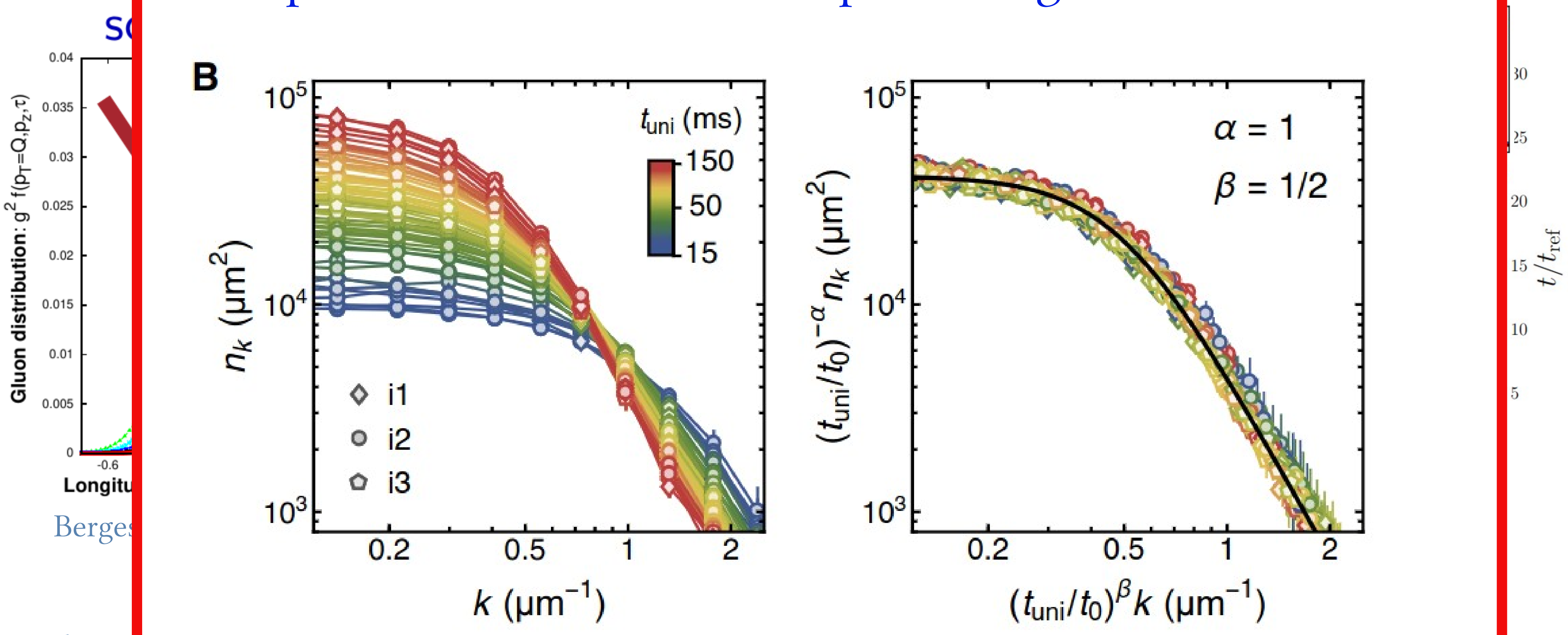
Heller, AM, Preis, PRL (2024)

See also: Brewer, Scheihing-Hitschfeld, Yin, 2203.02427, Mikheev, AM, Berges, 2203.0229,
Preis, Heller and Berges 2209.14883, Rajagopal, Bruno Scheihing-Hitschfeld, Steinhorst, 2405.17545

Stage I: non-thermal attractors

Self-simila

Experimental realization of prescaling with cold atoms

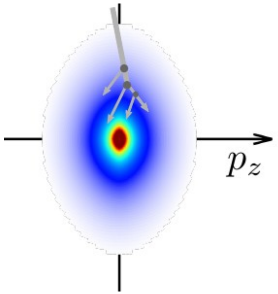


Hadzibabic group, 2312.09248

Berges

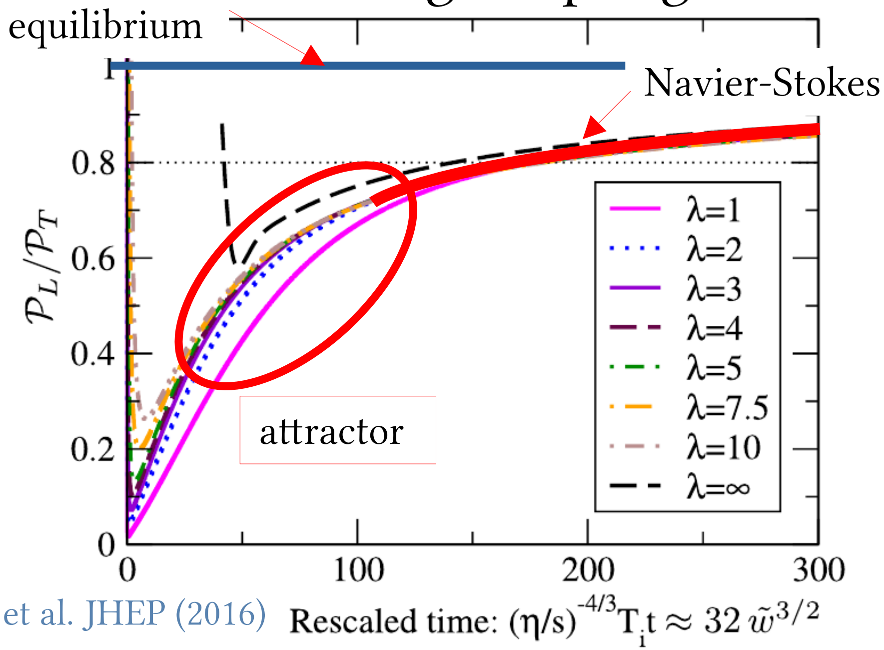
See also: B
Preis, Hell

Stage III: hydrodynamic attractors



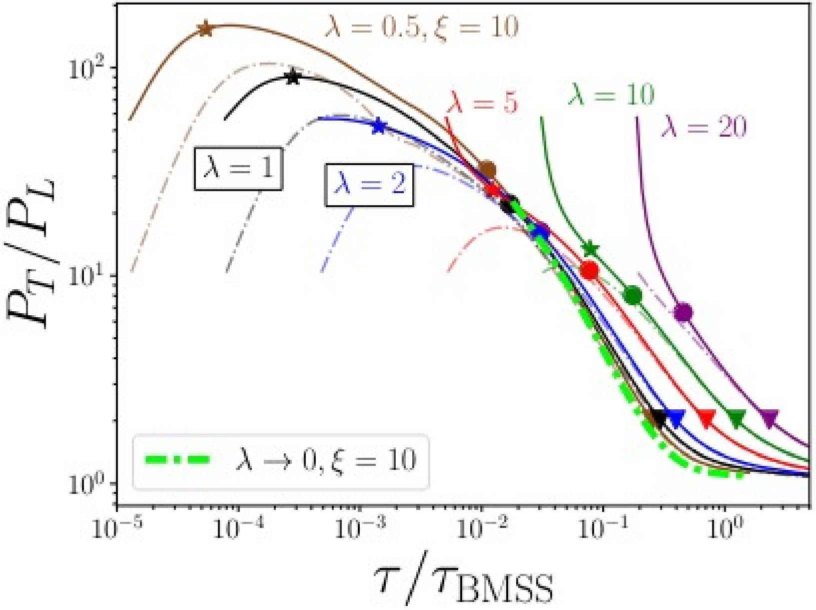
Pressure collapse to a hydrodynamic attractor

strong coupling



Keegan et al. JHEP (2016)

weak coupling



Boguslavski et al., PLB (2024)

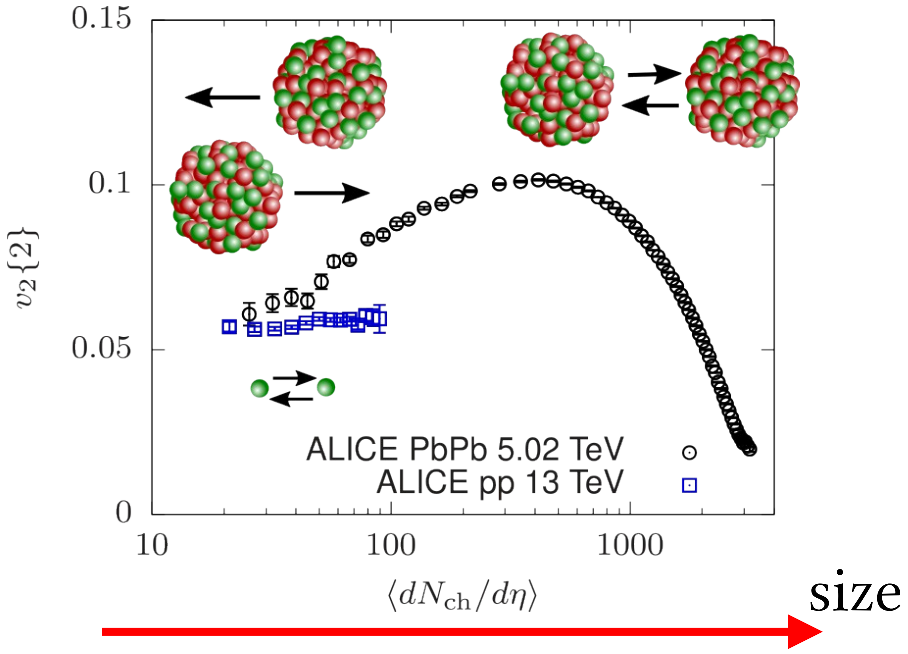
Hydrodynamization: $\tau_{\rm hydro} \approx 1{\rm fm}/c$

Kurkela, AM, Paquet, Schlichting and Teaney, PRL, (2018)

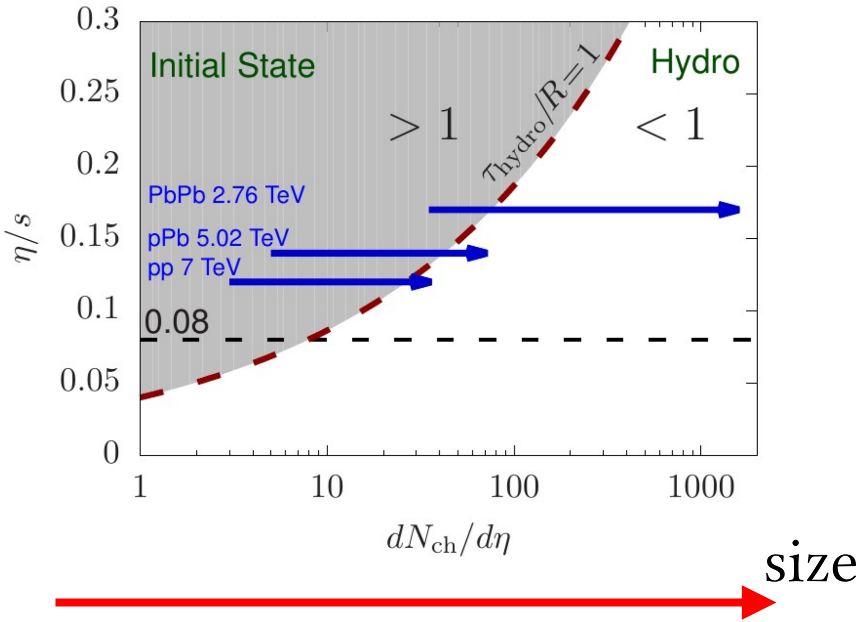
See also Giacalone, AM, Schlichting, PRL (2019), proposal for cold atoms: Fuji, Enss, 2404.12921

Collectivity in small collision systems

Elliptic flow vs system size



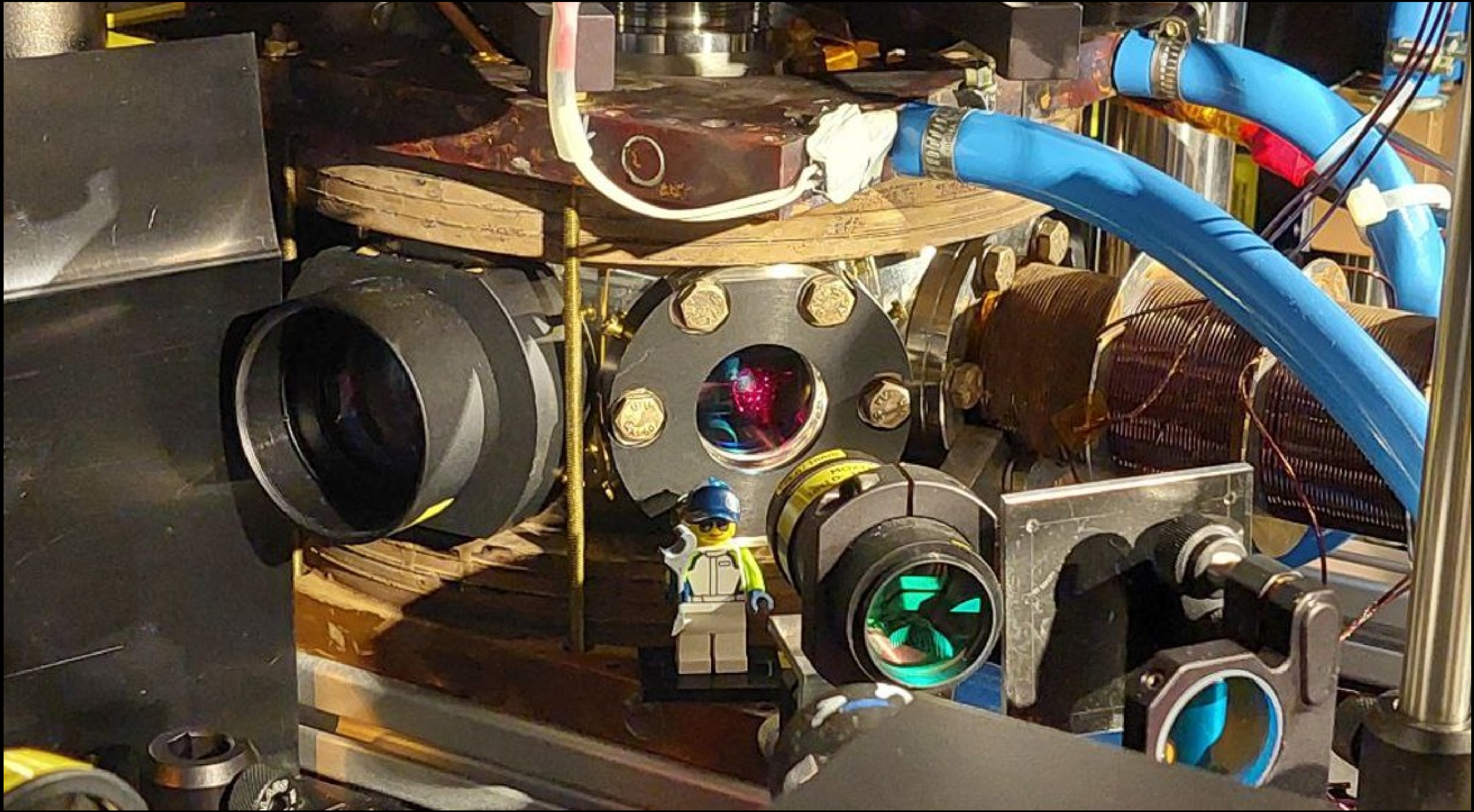
Hydrodynamization time



Kurkela, AM, Paquet, Schlichting and Teaney PRL (2018)
See also Ambrus,Schlichting, Werthmann PRL (2023)

What is the origin of collectivity in small systems?

Collective phenomena with few ultracold atoms

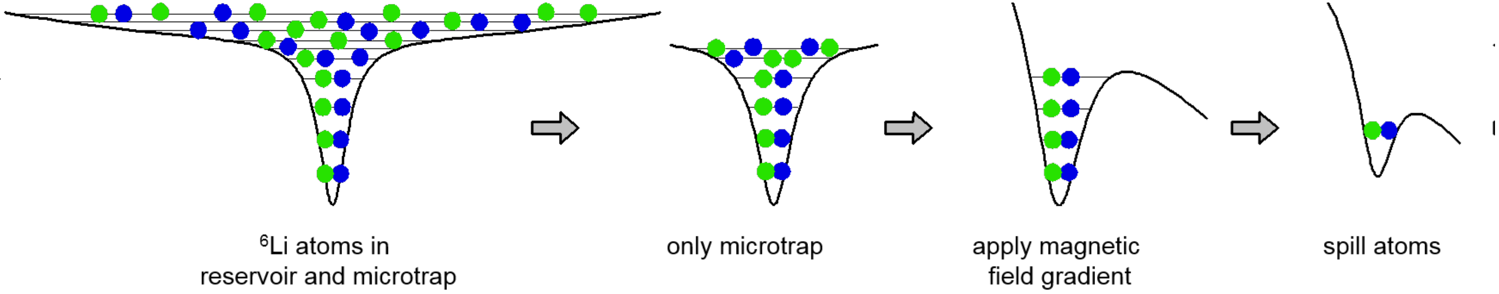


Brandstetter @ Jochim's lab, Heidelberg University

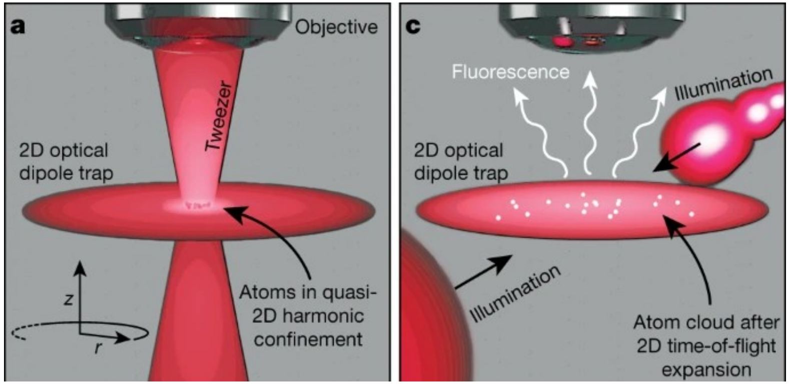
Lithium atoms in 2D harmonic trap

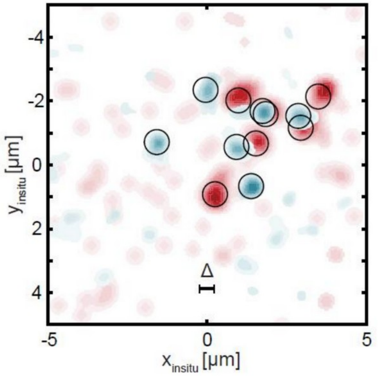
Serwane et al., Science **332** (2011) 6027

Preparation of few atoms in a trap



- time-resolved imaging
- spatial or momentum
- individual atoms
- controllable interactions

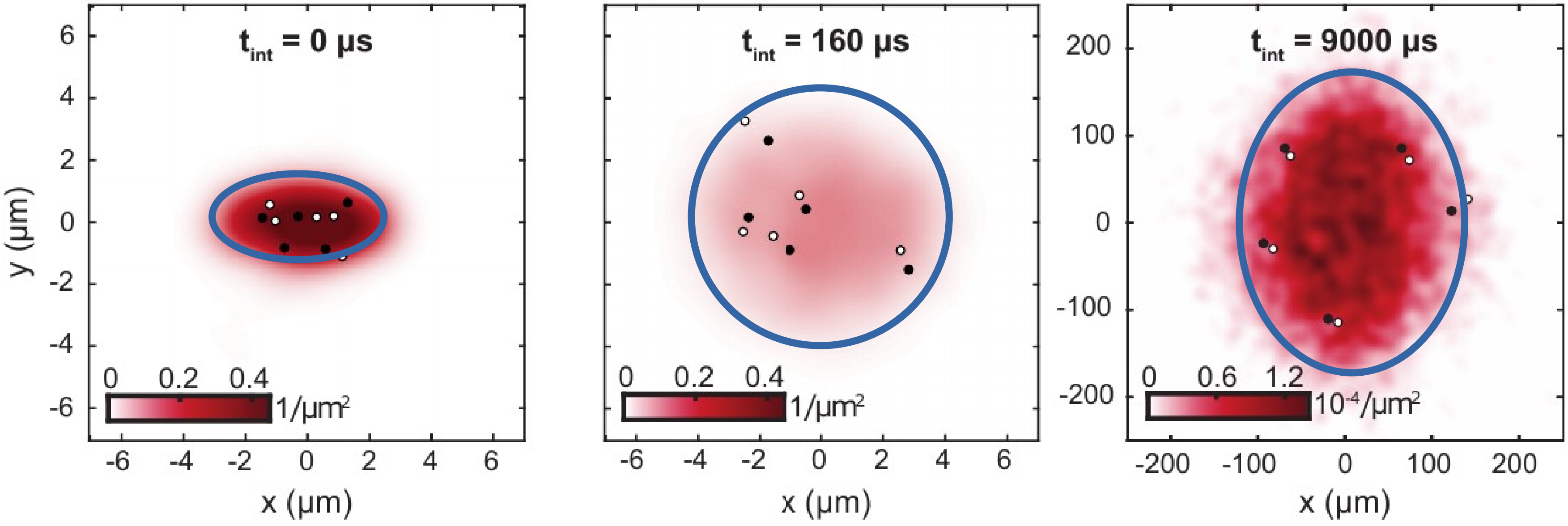




Holten *et al.*, Nature **606**, 287-291 (2022)

Geometry inversion of 10 atoms

Theory proposal: Flörchinger, Giacalone, Heyen, Tharwat, PRC 105 (2022) 4, 044908
Experimenta: Brandstetter, Lunt, Heintze, Giacalone, Heyen, Gałka, Subramanian, Holten, Preiss, Floerchinger, Jochim arXiv:2308.09699

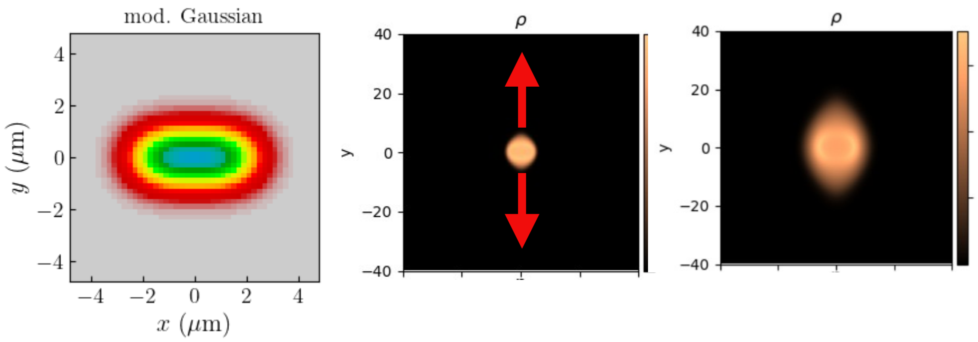


Elliptic flow of 10 Lithium atoms

Fluid dynamic description

Brandstetter, Lunt, et al. arXiv:2308.09699

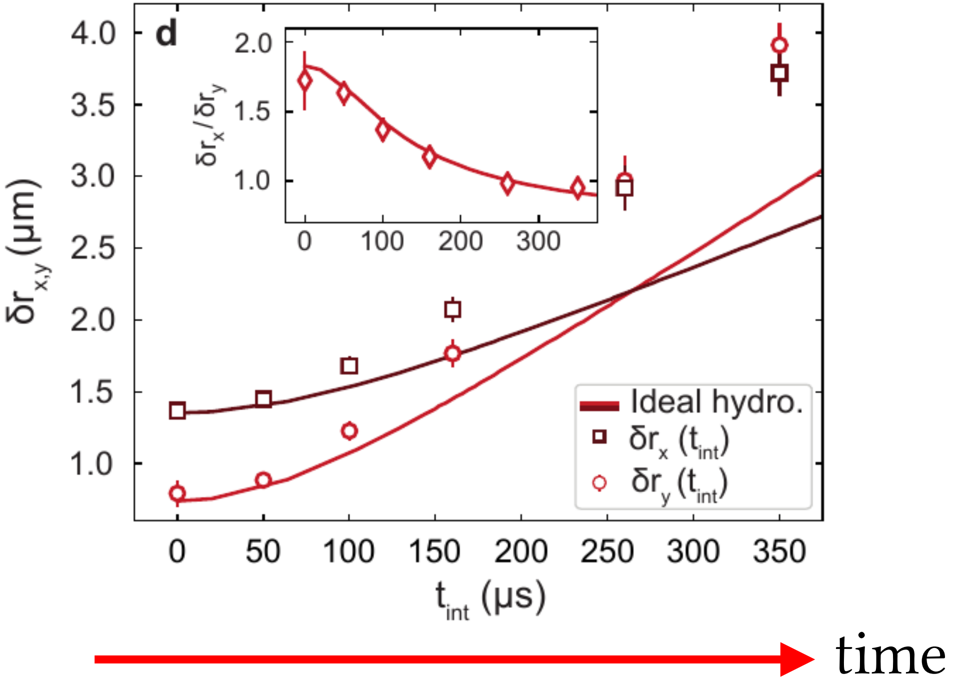
average geometry → expansion → inversion



ideal hydro simulation

initial conditions + equation of state

shape vs time



Good hydrodynamic description of 10 atoms!

Summary

High-energy proton and nuclear collisions:

- Unique access to rich real-time dynamics of QCD.
- Multi-faceted problems with interdisciplinary connections.
- Detailed understanding of QCD thermalization in large systems.

Outstanding challenges:

- Origins of collective behavior in all hadronic collisions
  $\longrightarrow$ opportunities with light ion collisions
- Macroscopic behavior in few-body cold atom systems
  $\longrightarrow$ rich area for interdisciplinary collaboration

isoQuant SFB1225

PhD (inspirehep.net/jobs/2786994) and postdoc (soon) openings:
contact a.mazeliauskas@thphys.uni-heidelberg.de

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