Pre-equilibrium dynamics in small and large systems

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1. Motivation

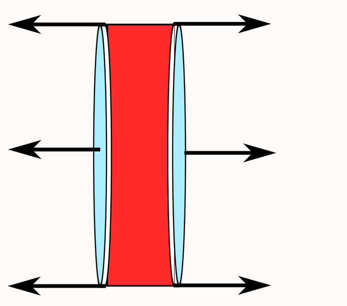
- Plasma of quarks and gluons (QGP) is produced in relativistic nucleus-nucleus collisions.
- Observed *flow anisotropy*, *jet quenching*, *strangeness enhancement* are signals of QGP equilibration.
- Smooth transition of observables from large to small collision systems $\Longrightarrow$ pre-equilibrium phase is important for understanding origins of collectivity.

2. Hydrodynamic attractors

Equilibration at early-times: boost-invariant 1D expansion.

$$\partial_\tau e = -\frac{e+P_L}{\tau}$$

$$\underbrace{e_0 \propto \tau_0^{-1}}_{\text{free streaming}} \Longrightarrow \underbrace{e_{\text{hydro}} \propto \tau_{\text{hydro}}^{-4/3}}_{\text{Bjorken scaling}}$$



Hydrodynamic attractor — universal approach to equilibrium via a single scaling variable $\tilde{w}$

$$\frac{e(\tau)\tau^{4/3}}{e_{\text{hydro}}\tau_{\text{hydro}}^{4/3}} = \mathcal{E}\left(\tilde{w} = \frac{T_{\text{eff}}(\tau)\tau}{4\pi\eta/s}\right).$$

$$\mathcal{E}(\tilde{w} \ll 1) = C_\infty^{-1}\tilde{w}^{4/9} \quad \text{(free streaming)},$$

$$\mathcal{E}(\tilde{w} \gg 1) = 1 - \frac{2}{3\pi\tilde{w}} \quad \text{(viscous hydro)}.$$

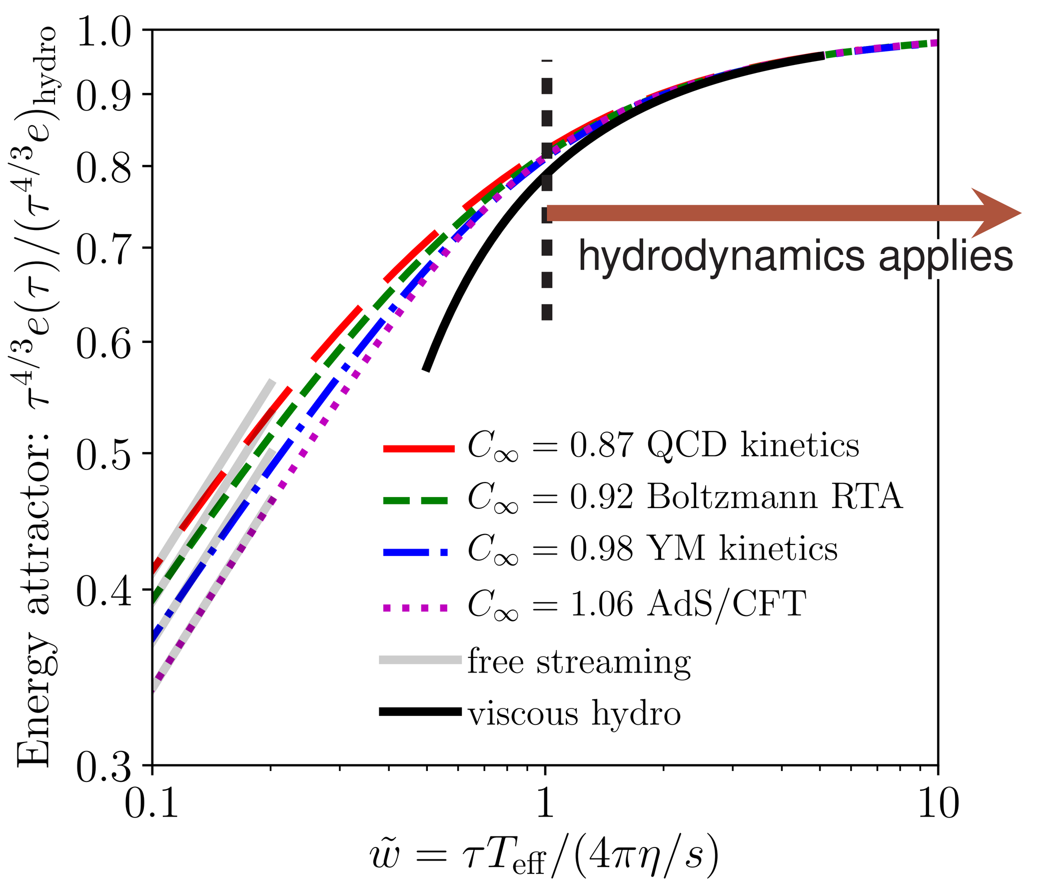


Figure 1: Hydrodynamic attractors in different theories [4].

Conclusions & Outlook

- Hydrodynamic attractors observed in many theories $\Rightarrow$ equilibration is only a function of scaling time $\tau T/(\eta/s)$.
- Entropy production in pre-equilibrium important for multiplicity predictions $\Rightarrow$ universal centrality dependence of $dN_{\text{ch}}/d\eta$ reproduced by initial-state model.
- Initial-state energy estimates including work done $\Rightarrow$ new constraints on non-equilibrium properties of QGP.
- For small systems highest multiplicities are at the boundary of reaching hydrodynamic equilibrium.
- Full QCD kinetic theory simulations predict chemical equilibration of systems with $dN_{\text{ch}}/d\eta \gtrsim 110 \Longrightarrow$ strangeness saturation in small systems at Run 3?
- 2D+1 pre-equilibrium dynamics can be studied with KøMPøST package: github.com/KMPST/KoMPoST.
- Future plans:
  - Equilibration with early transverse expansion.
  - Observables of in-complete QGP equilibration.
  - Jet quenching in pre-equilibrium.

References

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[3] P. Hanus, A. Mazeliauskas and K. Reygers, [arXiv:1908.02792].

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3. Entropy production

Hydrodynamic attractor (Figure 1) relates the final-state entropy and the initial-state energy [4]:

$$(s\tau)_{\text{hydro}} = \frac{4}{3}C_\infty^{3/4}\left(4\pi\frac{\eta}{s}\right)^{1/3}\left(\frac{\pi^2}{30}\nu_{\text{eff}}\right)^{1/3}(e\tau)_0^{2/3}.$$

$\Longrightarrow$ can predict produced charged particle multiplicity:

$$\underbrace{\frac{dN_{\text{ch}}}{d\eta} \propto \int d\mathbf{x}_\perp (n\tau)_0}_{\text{no equilibration}}, \quad \text{vs} \quad \underbrace{\frac{dN_{\text{ch}}}{d\eta} \propto \int d\mathbf{x}_\perp (s\tau)_{\text{hydro}}}_{\text{with equilibration}}.$$

First principle calculations give initial gluon number and energy density is terms of nuclear thickness:

$$(n\tau)_0(\mathbf{x}_\perp) \propto T^<(\mathbf{x}_\perp),$$
$$(e\tau)_0(\mathbf{x}_\perp) \propto T^<(\mathbf{x}_\perp)\sqrt{T^>(\mathbf{x}_\perp)}.$$

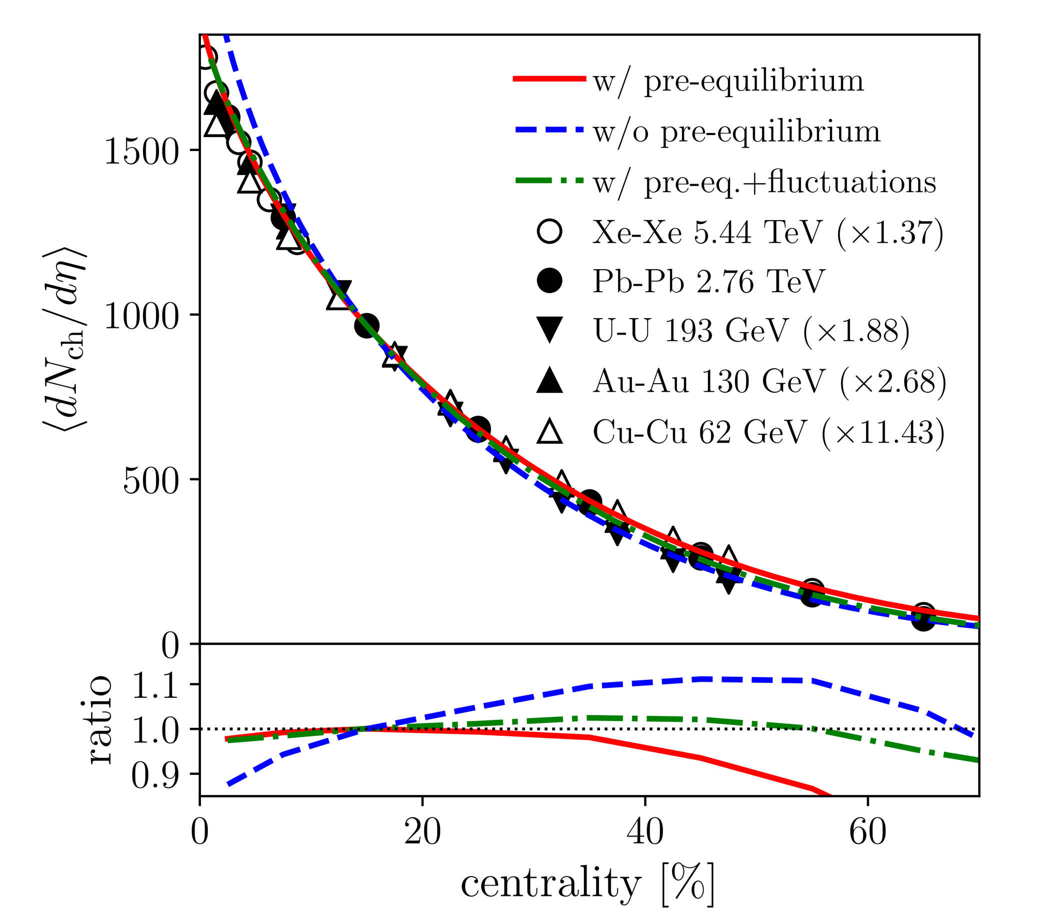


Figure 2: Universal centrality dependence of multiplicity in nucleus-nucleus collisions [4].

4. Initial-state energy

Measured particle multiplicity $\Longrightarrow$ initial state energy.
For central Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV:

$$e_0 \approx \frac{270\,\text{GeV/fm}^3}{\tau_0/(0.1\,\text{fm/c})}\left(\frac{C_\infty}{0.87}\right)^{-\frac{9}{8}}\left(\frac{\eta/s}{2/4\pi}\right)^{-\frac{1}{2}}\left(\frac{dN_{\text{ch}}/d\eta}{1600}\right)^{\frac{3}{2}}$$

NB: This includes work done during the equilibration.

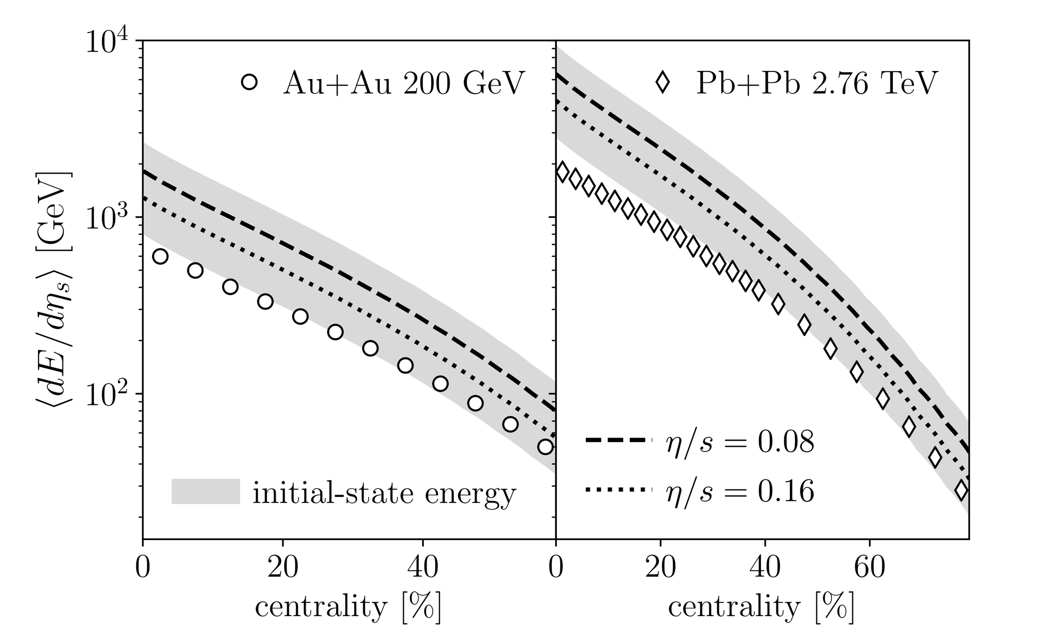


Figure 3: Initial state energy versus centrality for different $\eta/s = 0.08$–0.24 and $C_\infty = 0.80$–1.15. Symbols represent measured final-state energy. [4]

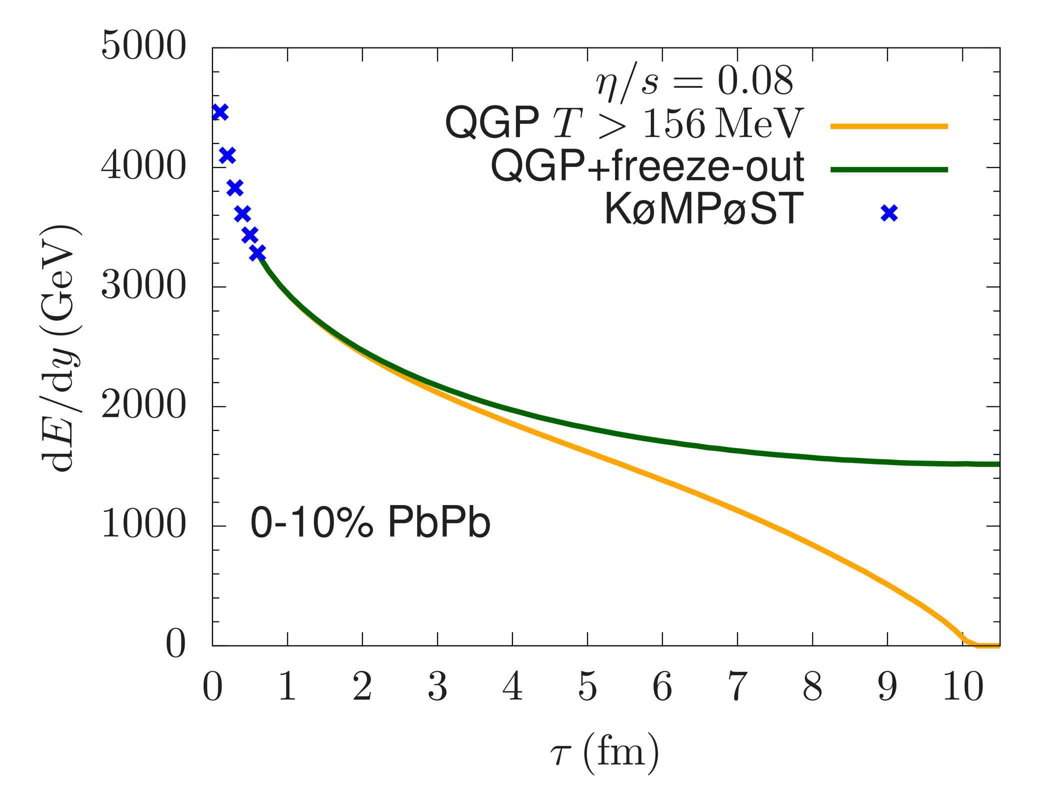
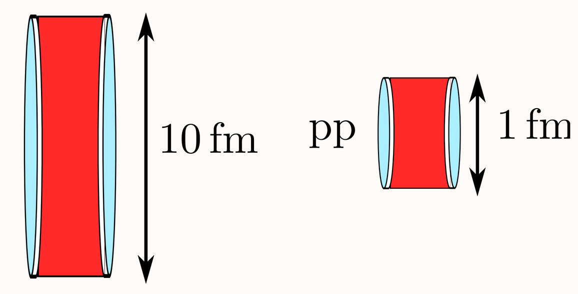


Figure 4: Integrated energy per rapidity evolution in QGP with 2D+1 kinetic pre-equilibrium (KøMPøST) and viscous hydrodynamics (FluiduM) [3]

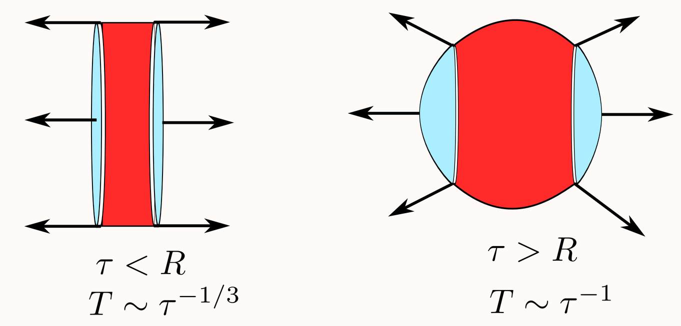
5. System size vs lifetime

- Smaller systems are hotter (at fixed $dN_{\text{ch}}/d\eta$)

$$T_0^3 \propto \frac{dN_{\text{ch}}/d\eta}{\tau_0\pi R^2}$$



- Smaller systems live shorter ($\tau \sim R$)



Are small systems reaching equilibrium, i.e. $\tau_{\text{hydro}} < R$? [1]

$$\underbrace{\frac{\tau_{\text{hydro}}T}{4\pi\eta/s} \approx 1}_{\text{hydrodynamics applies}} \Longrightarrow \underbrace{\frac{\tau_{\text{hydro}}}{R} = \left(\frac{4\pi(\eta/s)}{2}\right)^{\frac{3}{2}}\left(\frac{dN_{\text{ch}}/d\eta}{63}\right)^{-\frac{1}{2}}}_{\text{hydrodynamization time over system size}}$$

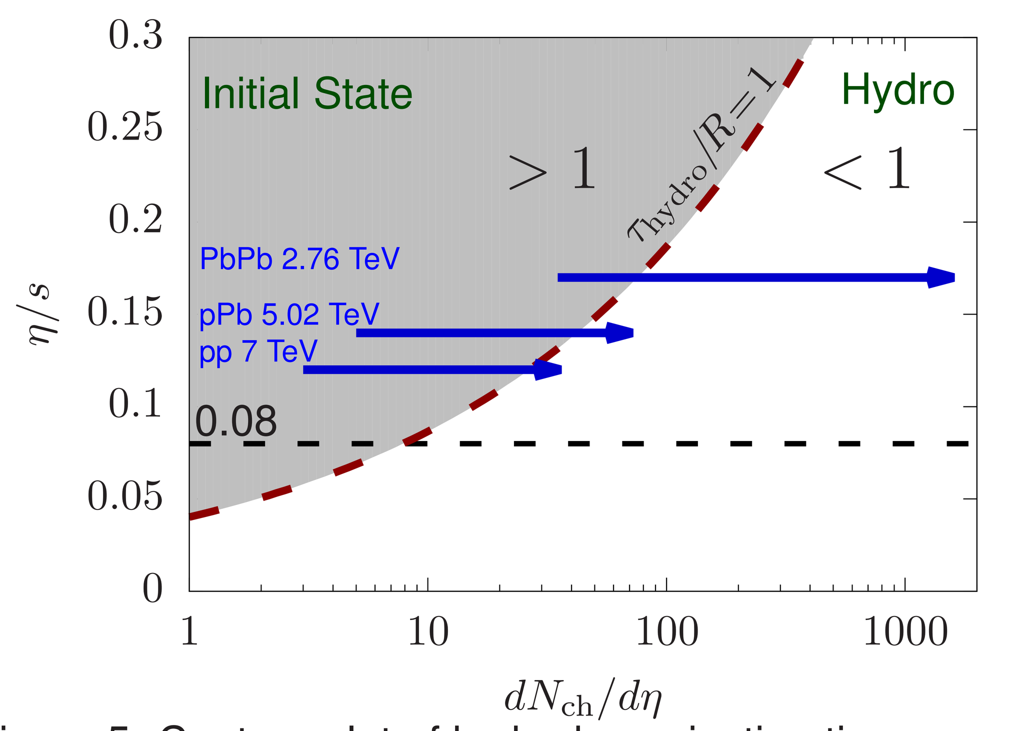


Figure 5: Contour plot of hydrodynamization time τ_{hydro} over system size R as a function of η/s and $dN_{\text{ch}}/d\eta$.

6. Chemical equilibration of QGP

- At high collision energies the mid-rapidity region is populated by small Bjorken-x gluons.
- Quark production can be modelled with QCD kinetic theory; processes at leading order in coupling $\lambda = 4\pi\alpha_s N_c$:
  - Gluon fusion: $gg \leftrightarrow q\bar{q}$

$$|\mathcal{M}_{q\bar{q}}^{gg}|^2 = \lambda^2\, 16\frac{d_F C_F}{C_A^2}\left[C_F\left(\frac{u}{t}+\frac{t}{u}\right) - C_A\left(\frac{t^2+u^2}{s^2}\right)\right]$$

  - Medium induced gluon splitting: $g \leftrightarrow q\bar{q}$

$$|\mathcal{M}_{q\bar{q}}^{g}|^2 = \frac{k'^2+p'^2}{k'^2p'^2p^3}\underbrace{\mathcal{F}_q(k';-p',p)}_{\text{splitting rate}}$$

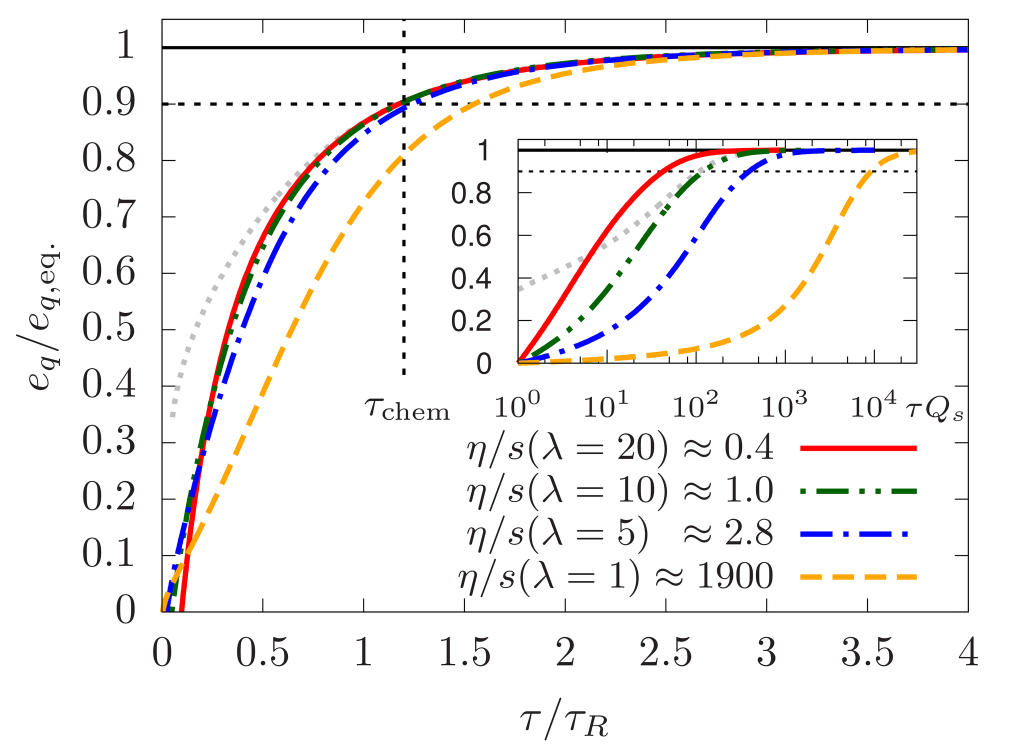


Figure 6: Fermion energy relaxation to chemical equilibrium for different coupling strengths [2].

Minimum multiplicity for reaching chemical equilibrium [2]:

$$\frac{dN_{\text{ch}}}{d\eta} \gtrsim 110\left(\frac{\eta/s}{0.16}\right)^3\left(\frac{\tau_{\text{chem}}}{1.2\tau_R}\right)^3\left(\frac{\tau_{\text{chem}}}{R}\right)^{-2}$$

Acknowledgements

This work was supported in part by the German Research Foundation (DFG) Collaborative Research Centre (SFB) 1225 (ISOQUANT).

IsoQuant SFB1225