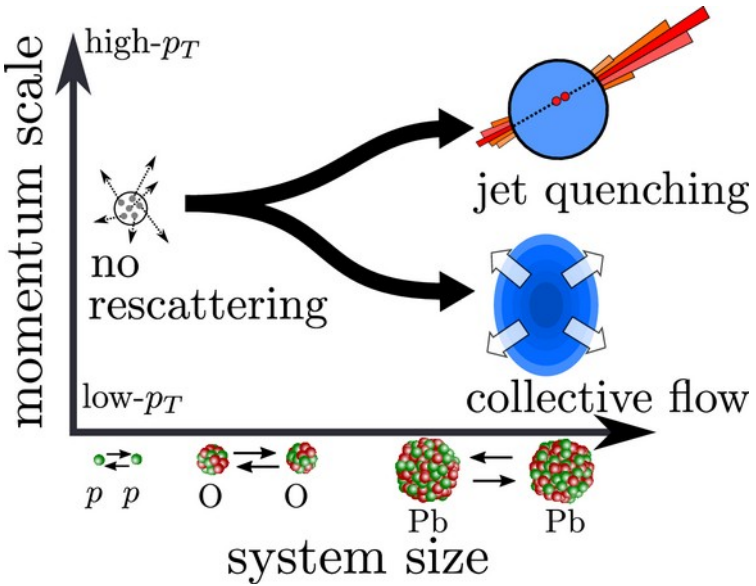
# Many-body phenomena in quantum systems

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December 06, 2024 KHuK Jahrestagung

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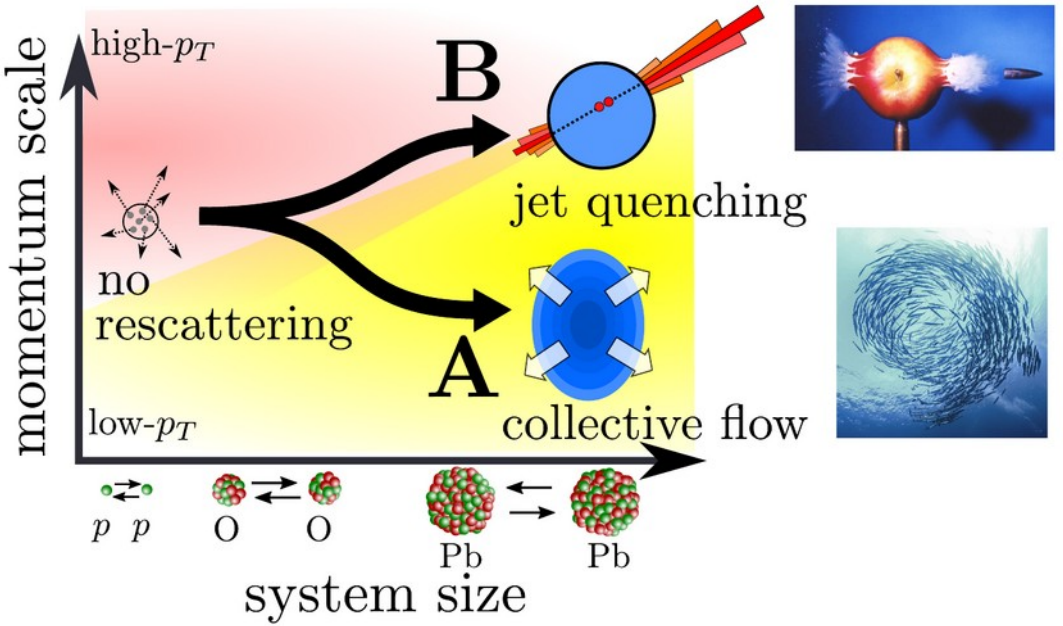
# Many-body QCD phenomena

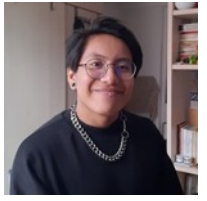







Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

2022-2028



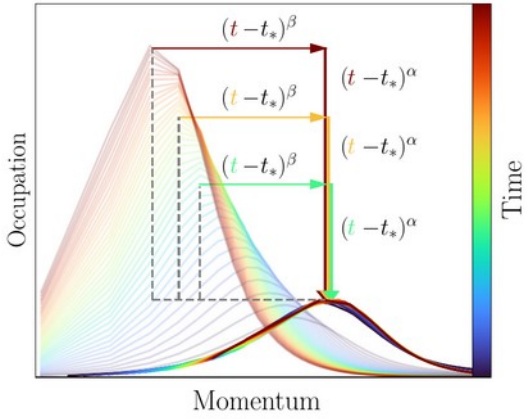
Main research directions:

- A Uncovering origins of collectivity in small systems.
- B Discovering energy loss effects in small systems.

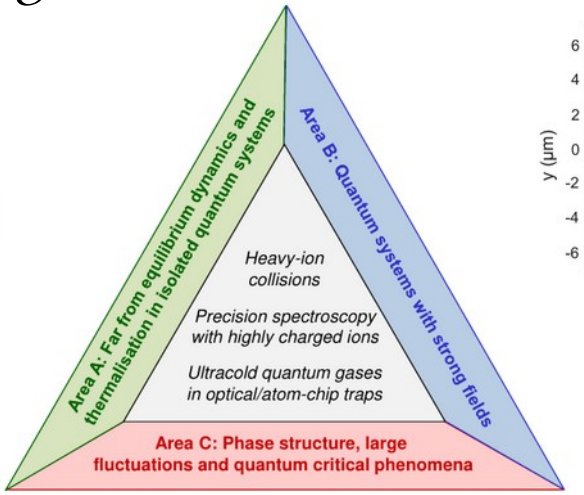
Postdoc opening: https://inspirehep.net/jobs/2846988

# Isolated quantum systems in extreme conditions

## Self-similar scaling of gluons

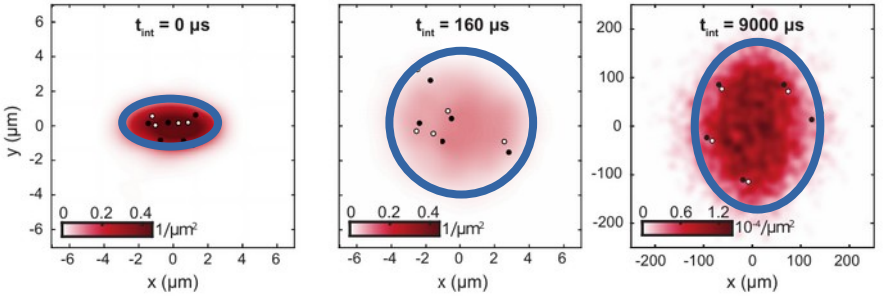



Heller, AM, Preis, PRL (2024)




Jochim lab, 2308.09699

## Expansion of 10 Lithium atoms




2024-2028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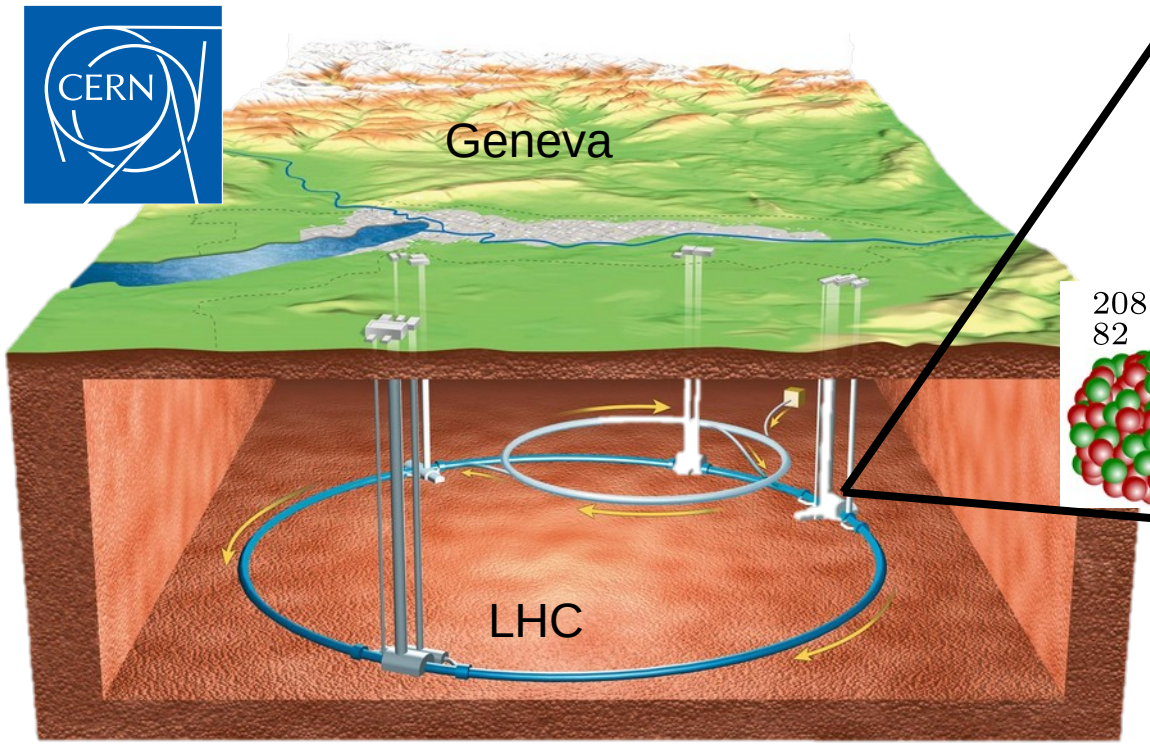
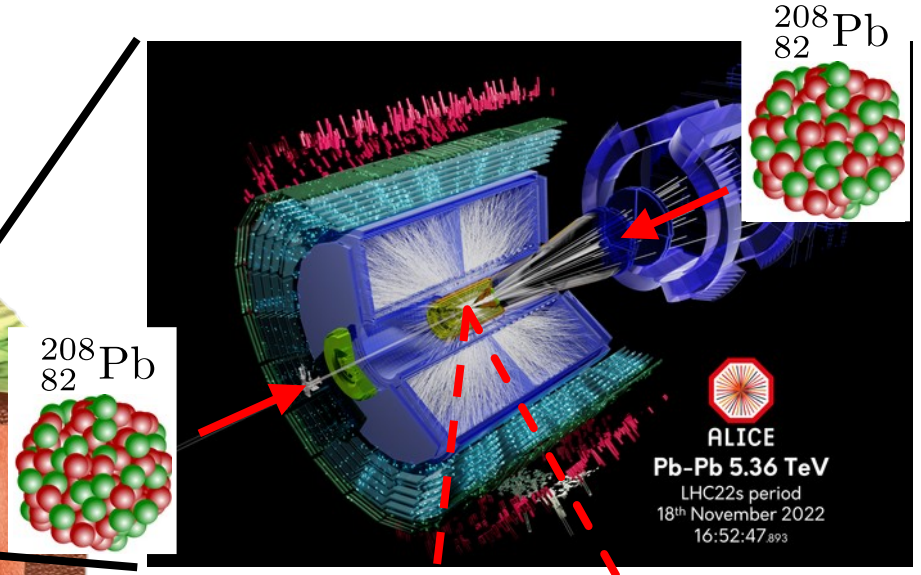
## Projects:

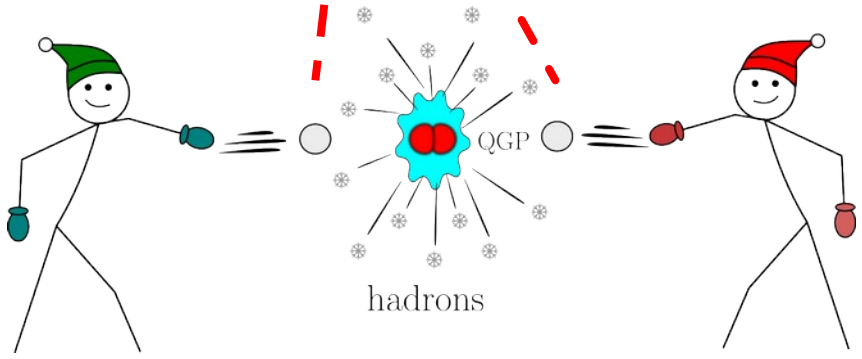
- A01 Scaling and attractor phenomena
- ABC Collectivity with few ultracold fermionic atoms

# QCD thermalisation

# Ion collisions at the Large Hadron Collider



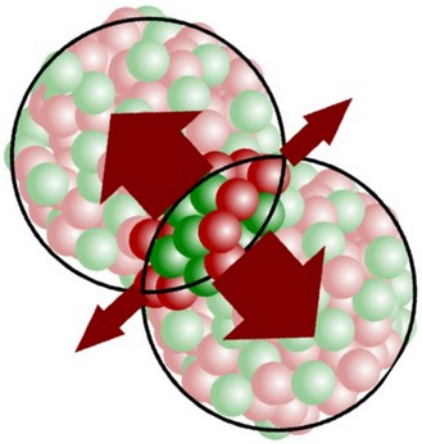



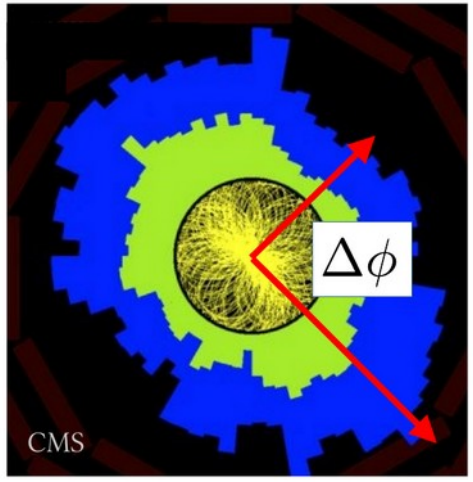




New: short oxygen ion run next year!

# Collective phenomena in nuclear collisions

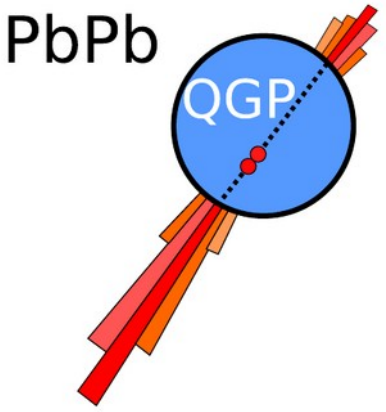
## Elliptic flow

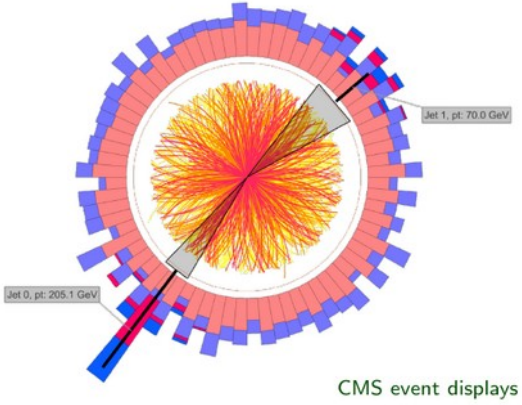





hydro expansion

## Jet quenching



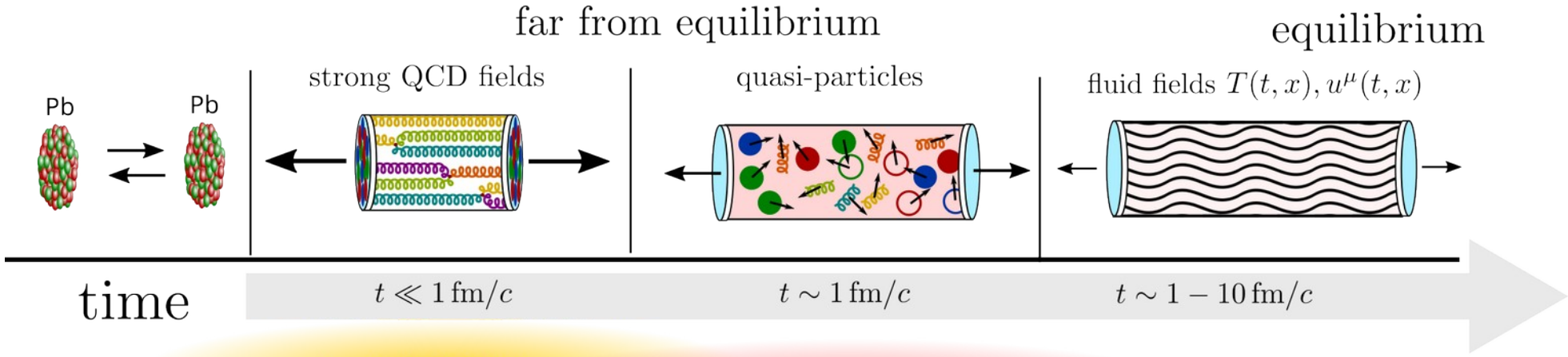

path length

Strong experimental evidence for QCD medium created in heavy ion collisions

# QCD thermalisation

Berges, Heller, AM, Venugopalan RMP (2021)

## High-energy limit $\alpha_s \ll 1$ of QCD




QCD effective kinetic theory — bridge between initial state and equilibrium.

# QCD effective kinetic theory

Arnold, Moore, Yaffe JHEP (2003)

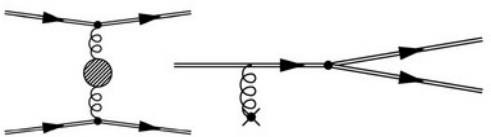
$$\mathcal{L}_{\mathrm{QCD}} = \bar{q}\left(i\gamma^{\mu}D_{\mu} - m\right)q - \frac{1}{4}F^{a}_{\mu\nu}F^{\mu\nu}_{a}$$

2-point correlations $\longrightarrow$ phase-space distribution of quarks and gluons

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

Leading order processes:

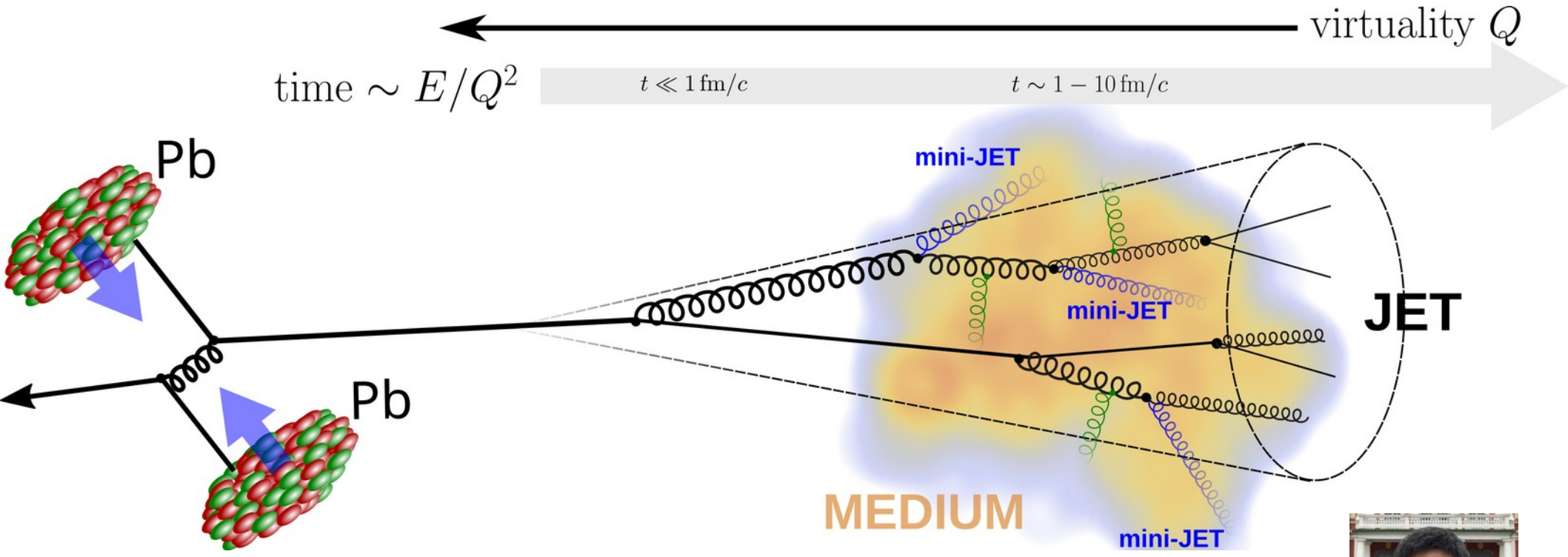
- Elastic scattering
- Medium induced radiation



Low-momentum thermalisation $\Longleftrightarrow$ high-momentum energy loss in quark-gluon plasma (QGP)

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

# Minijet quenching in QGP



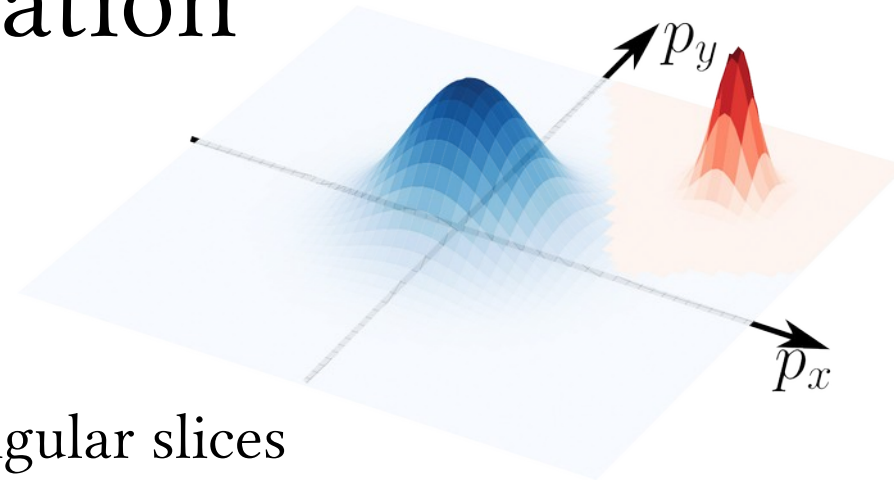

Goal: how energetic partons (minijets) thermalise in QGP

Zhou, Brewer, AM JHEP (2024)

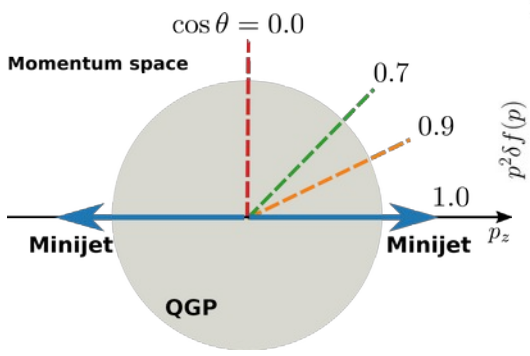
# Angle resolved thermalisation

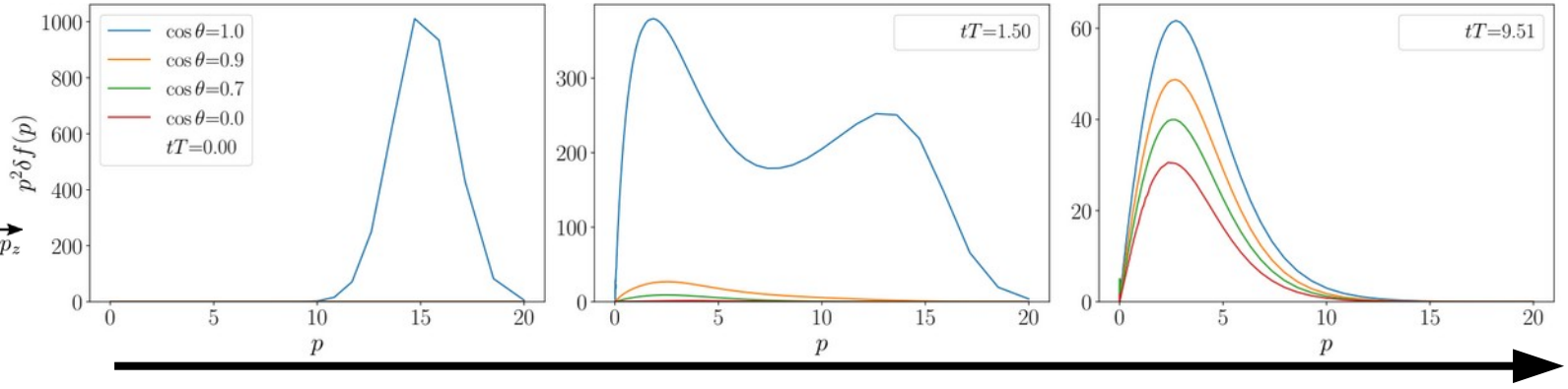
$$f(\tau, \mathbf{p}) = \bar{f}(\tau, \mathbf{p}) + \delta f(\tau, \mathbf{p})$$

background perturbation




Angular slices




Time

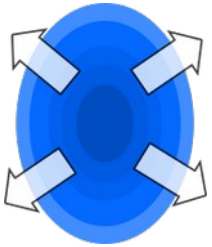
Each angular slice thermalises first, before isotropising!

Zhou, Brewer, AM JHEP (2024)

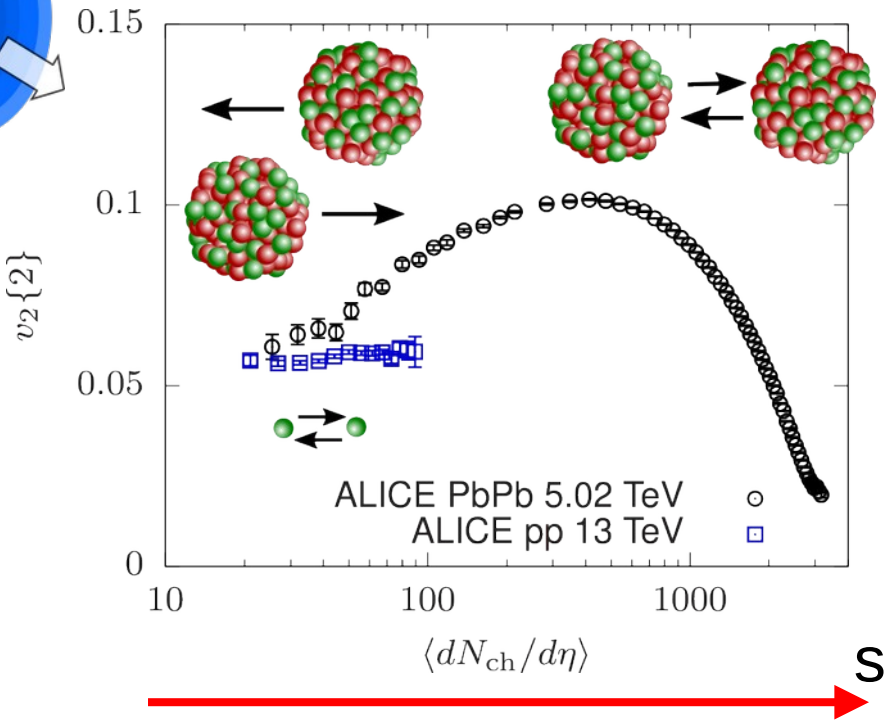
# Small system puzzle

# Collectivity in small collision systems

Huss et al. PRL (2021)

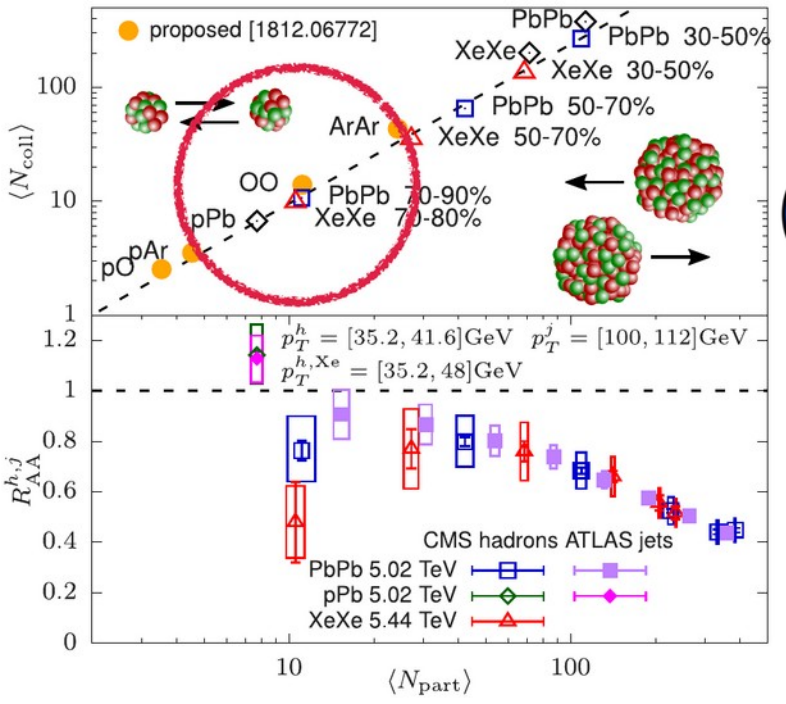


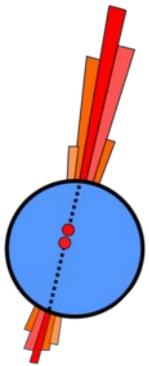
elliptic flow




size

energy loss

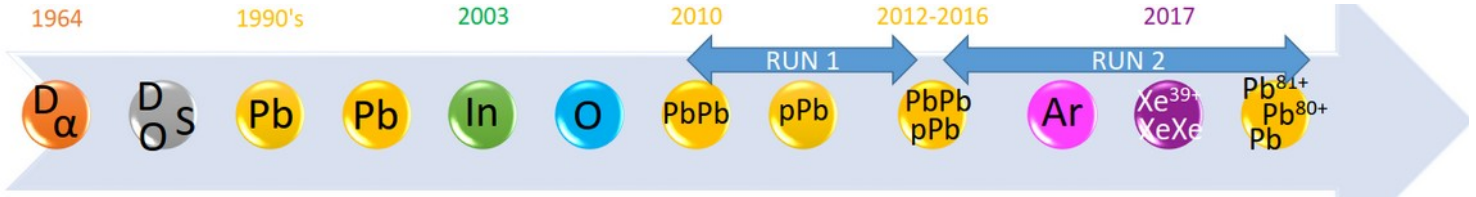


size

Small system puzzle: elliptic flow, but no jet quenching signal

# Light ion collisions at LHC

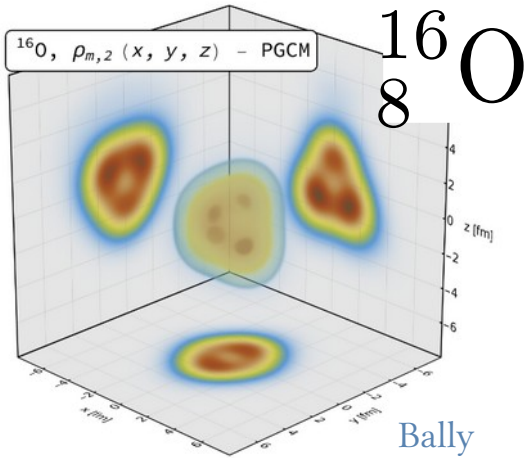




cern.ch/OppOatLHC


cern.ch/lightions → summary report

Fernandez




Bally

$^{16}_{8}O$

6-8 day OO and pO run
week 27-28, 2025

- Precision studies of collectivity in small systems.
- Synergy with nuclear structure physics.

Even short light ion runs contribute significantly to the richness of LHC program!

# Discovering energy loss in small systems

Compare measurements to no-medium baseline ⟶ perturbative QCD

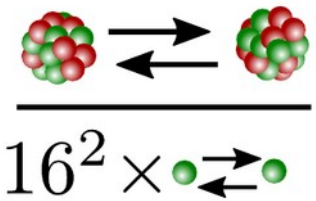
$$\sigma_{ab\to X} = f_a(x_a)\, f_b(x_b) \cdot \hat{\sigma}_{ab\to x} \cdot \mathcal{S}_{x\to X}$$

**parton distribution functions** **partonic scattering** **final state evolution**

- systematically improvable baseline computation (LO, NLO, ...)
- quantifiable uncertainties (scale, nPDF,...)

Precise computation of jet and hadron spectra
in OO and pp collisions

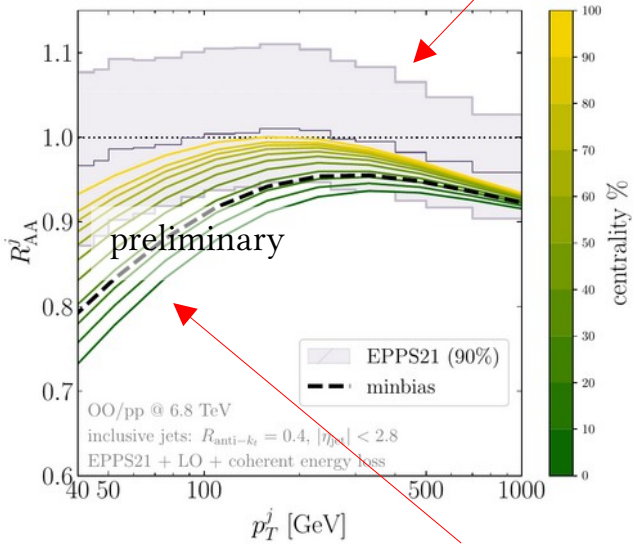
# Predictions for jet and hadron modification

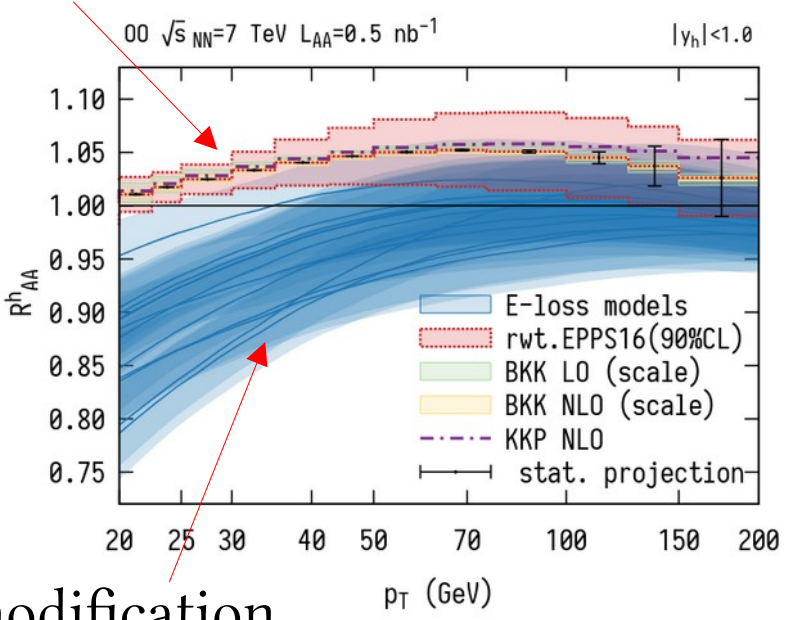


jets

nPDF uncertainty

hadrons




medium modification

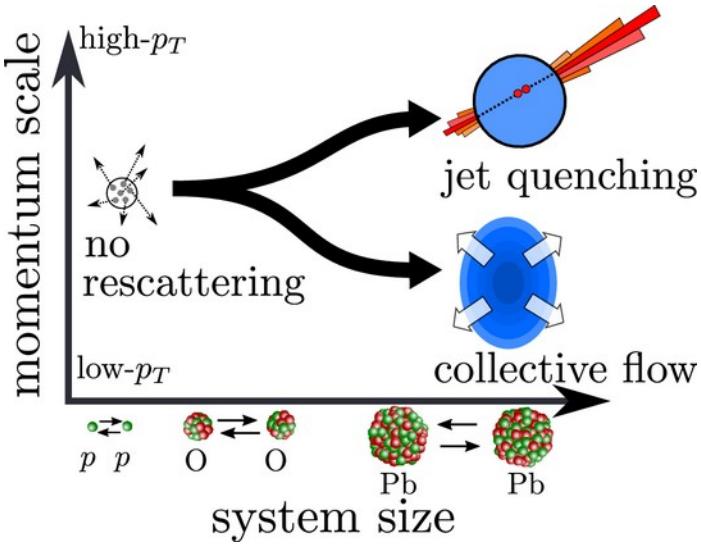
Gebhard, AM, Takacs, arXiv:2410.22405

Huss et al., PRL (2021), PRC (2021)

Measurable energy loss signal in oxygen-oxygen collisions!

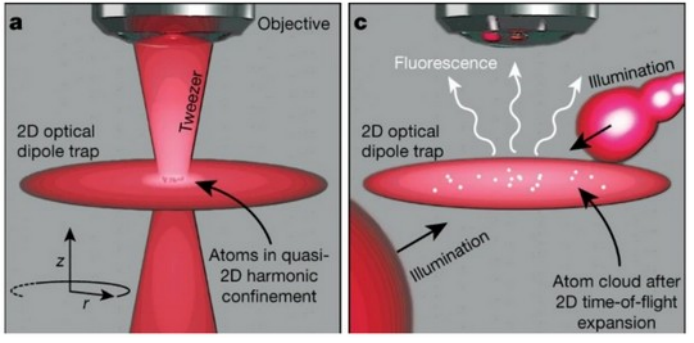
# Conclusions

- Detailed understanding of QCD thermalisation in large systems.
- Persistent signals of collectivity in smaller systems.




Outlook:

- Light ions collisions – a new tool to study emergent QCD phenomena.
- Interdisciplinary connections to nuclear structure and cold atom experiments.




Holten et al., Nature (2022)

Postdoc opening: https://inspirehep.net/jobs/2846988