Far from equilibrium hydrodynamics of nonthermal fixed points

Michal P. Heller

GHENT UNIVERSITY

UNIWERSYTET JAGIELLOŃSKI W KRAKOWIE

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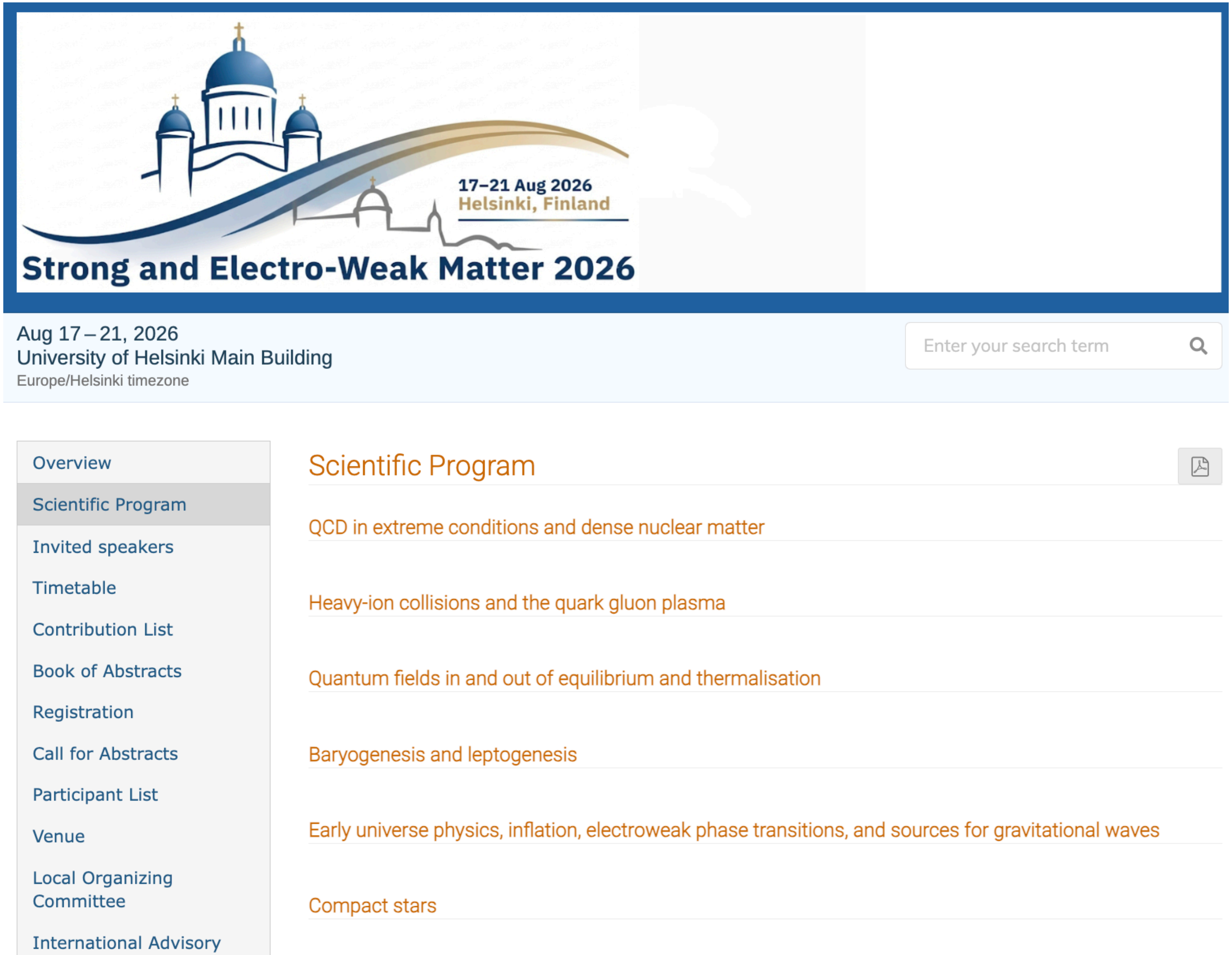
Established by the European Commission

2504.18754 with Berges, Denicol, Preis + De Lescluze and García Fariña in the upcoming v2

260x.xxxx with De Lescluze and García Fariña

Introduction

Positioning



Positioning

Aug 17 – 21, 2026
University of Helsinki Main Building
Europe/Helsinki timezone

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Scientific Program

QCD in extreme conditions and dense nuclear matter

Heavy-ion collisions and the quark gluon plasma

Quantum fields in and out of equilibrium and thermalisation

Baryogenesis and leptogenesis

Early universe physics, inflation, electroweak phase transitions, and sources for gravitational waves

Compact stars

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+ cold atoms

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what are the limits of applicability of hydrodynamics?

In other words,
how much far from equilibrium hydrodynamics applies?

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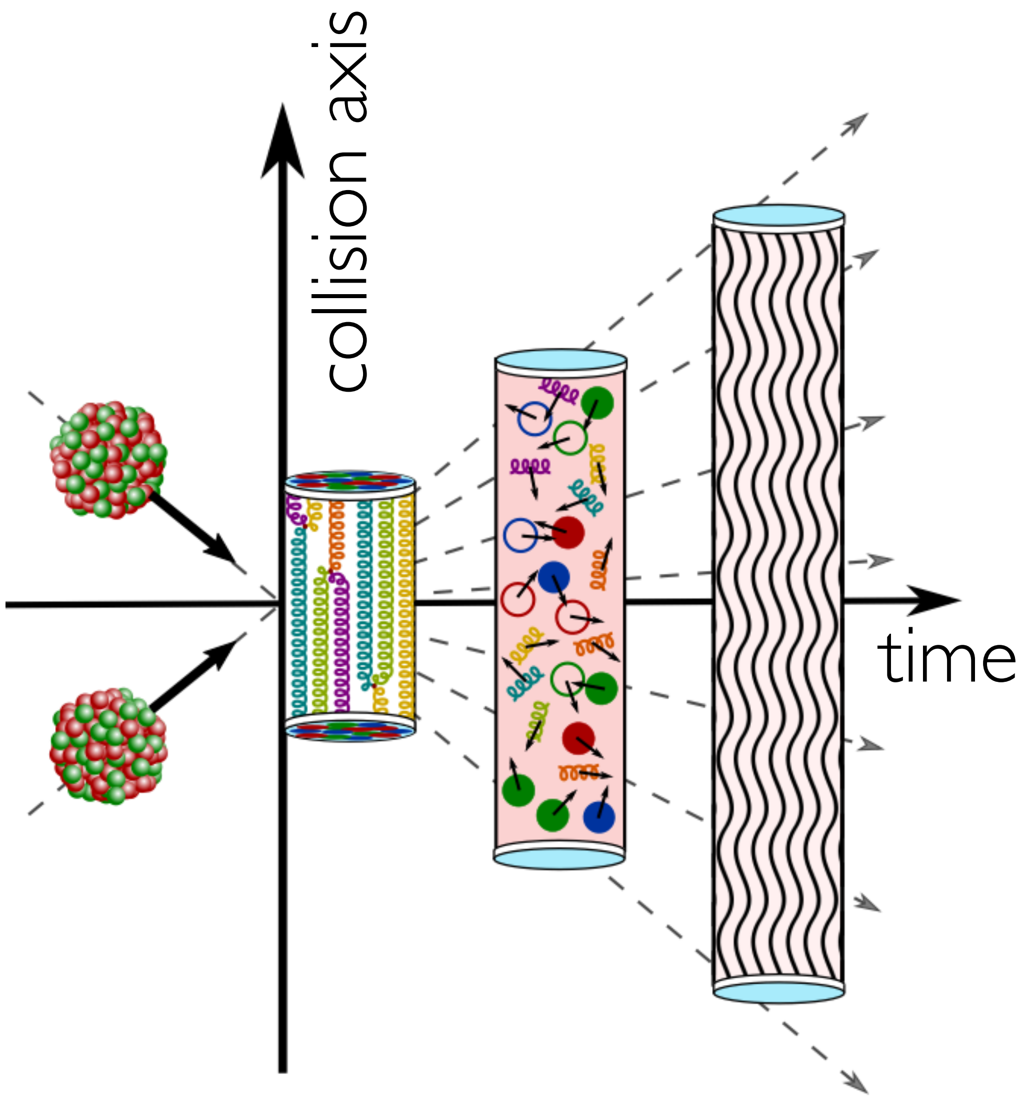
Why this question?

Relativistic hydro and ab initio simulations

heavy-ion collisions
at RHIC and LHC



2005.12299
with Berges, Mazeliauskas & Venugopalan

behaviour in
of theoretical models
(here: holographic boost-invariant dynamics)

1103.3452 with Janik & Witaszczyk

Relativistic hydro and ab initio simulations

heavy-ion collisions
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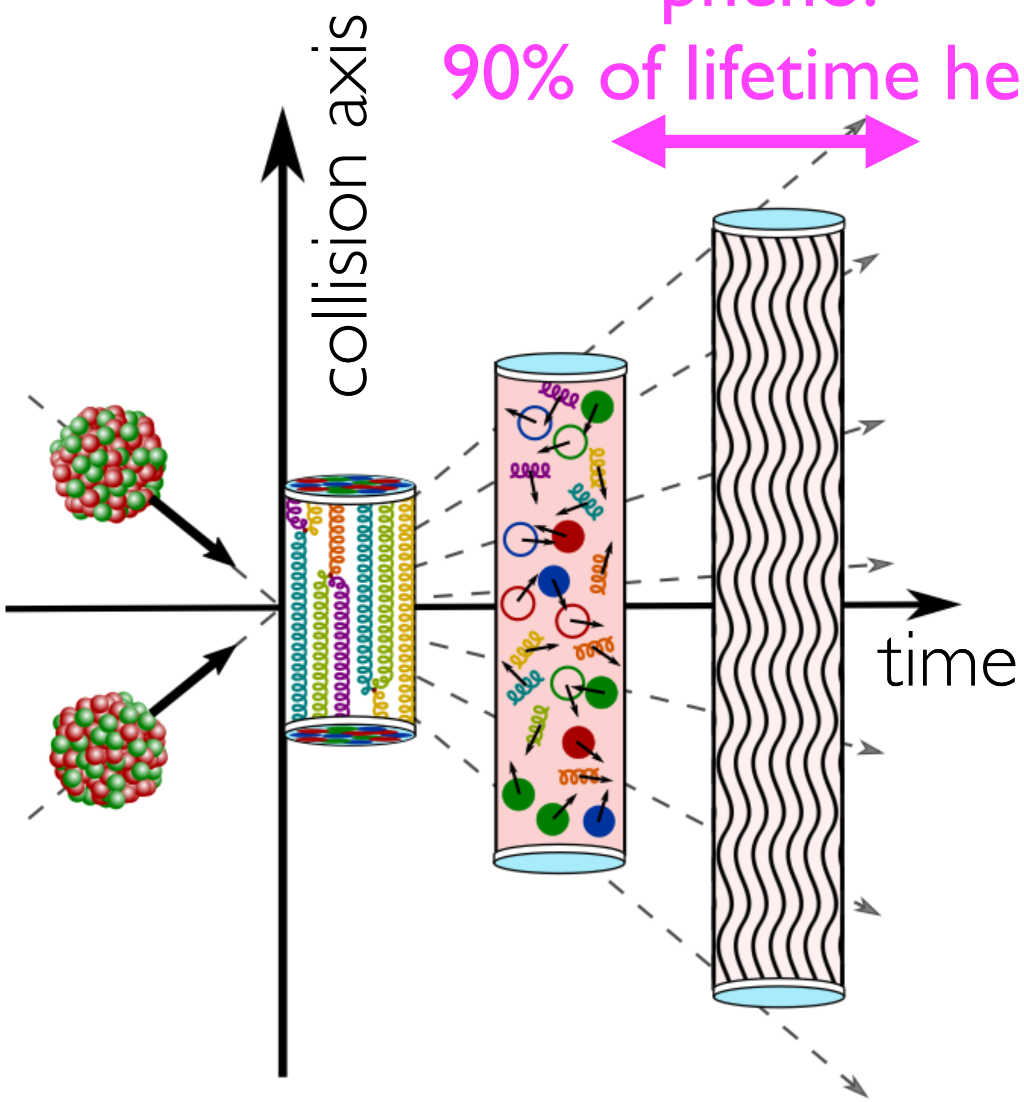
pheno:
90% of lifetime here



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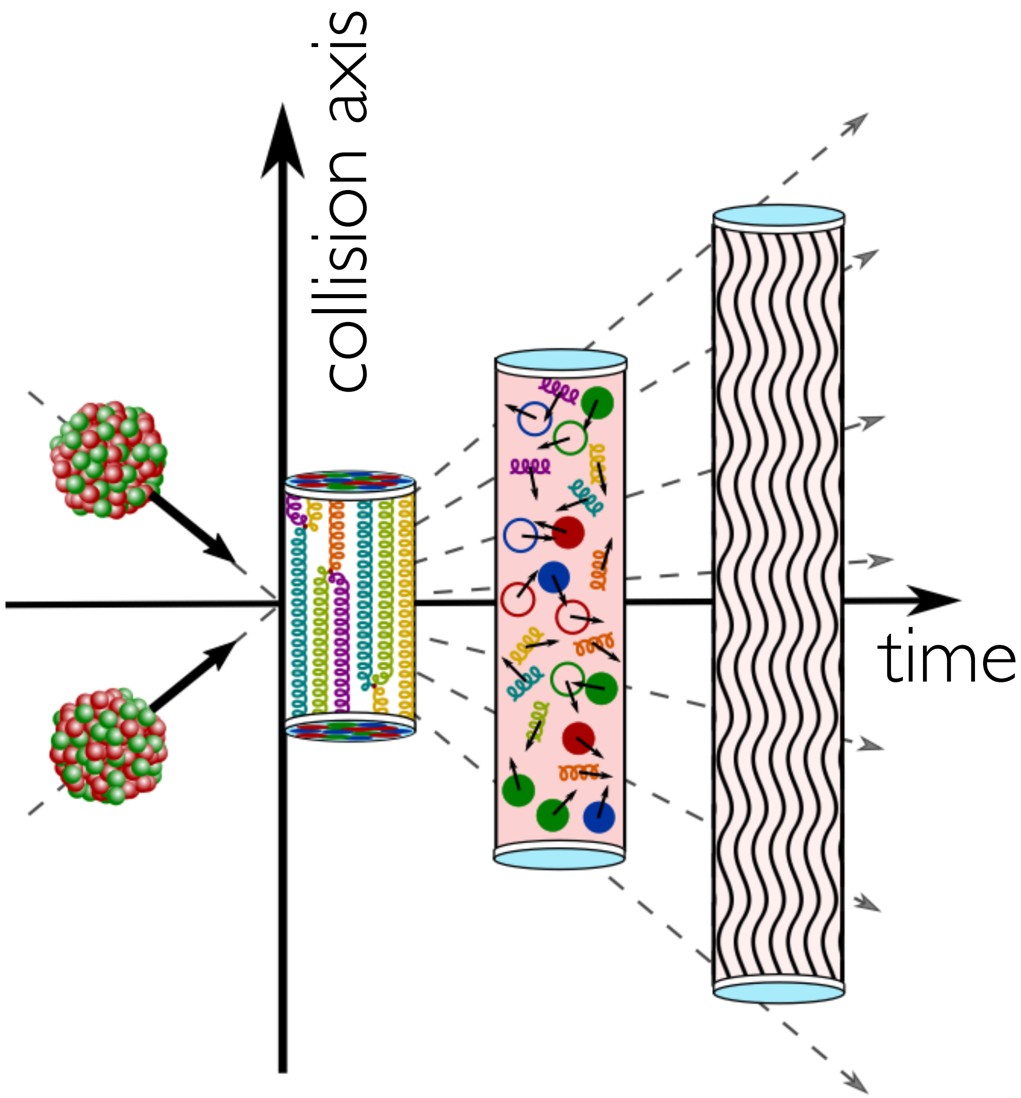

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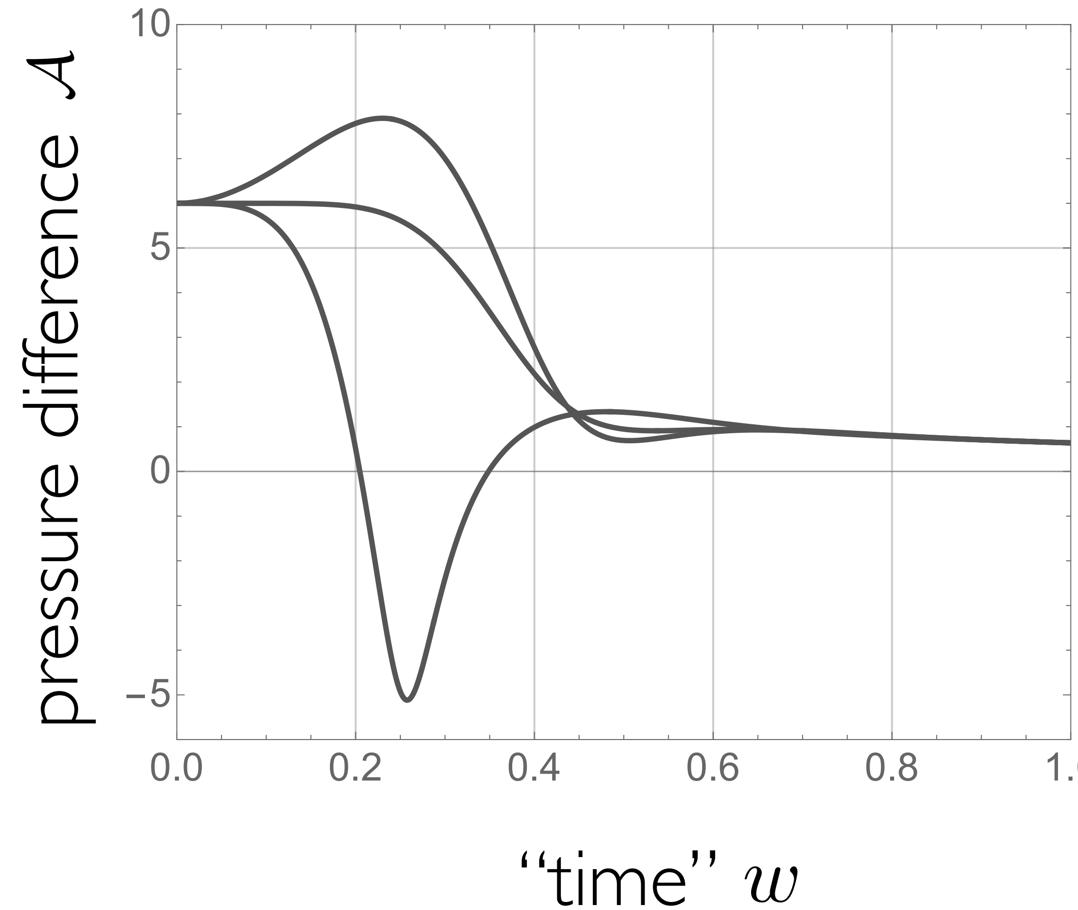

1103.3452 with Janik & Witaszczyk

Hydro works ≡ its constitutive relations hold

see also Lorenzo's talk

General $T^{\mu\nu}$ has 10 functions of 4 variables freedom subject to $\nabla_\mu T^{\mu\nu} = 0$

Relativistic hydro: $T^{\mu\nu}$ is systematically approx. in terms of 4 functions only

$$T^{\mu\nu} = \mathcal{E}(T)u^\mu u^\nu + \mathcal{P}(T)\left(g^{\mu\nu} + u^\mu u^\nu\right) + \pi^{\mu\nu}$$

@ conformality = 0

$$\pi^{\mu\nu} = -\eta(T)\,\nabla^{\langle\mu}u^{\nu\rangle} - \zeta(T)(g^{\mu\nu} + u^\mu u^\nu)\nabla_\alpha u^\alpha + \mathcal{O}(\nabla^2)$$

shear term

bulk term

@ conformality:
2 order: 5 terms
0712.2451 by Baier et al.
3 order: ~20 terms
1507.02461 by Grozdanov & Kaplis

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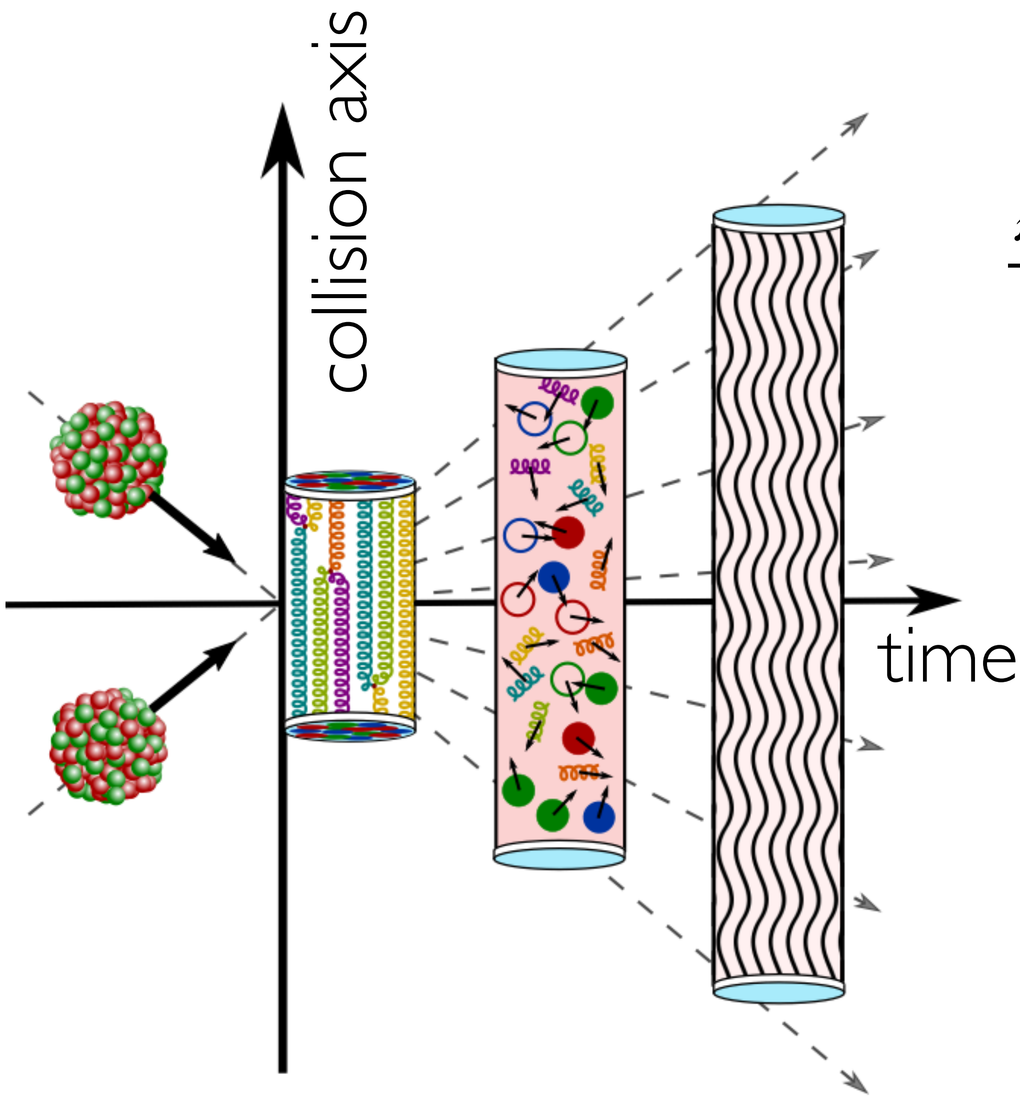

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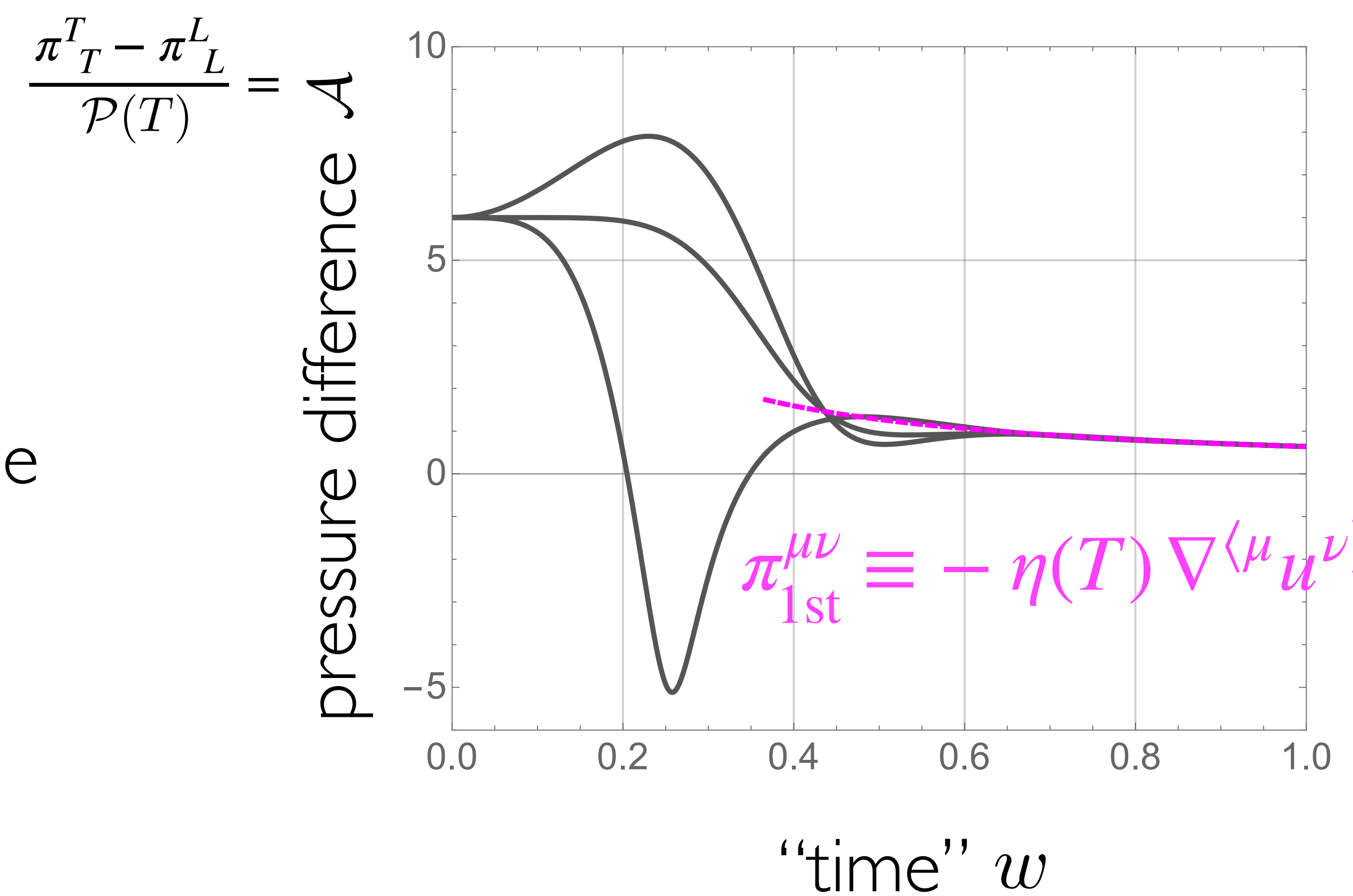

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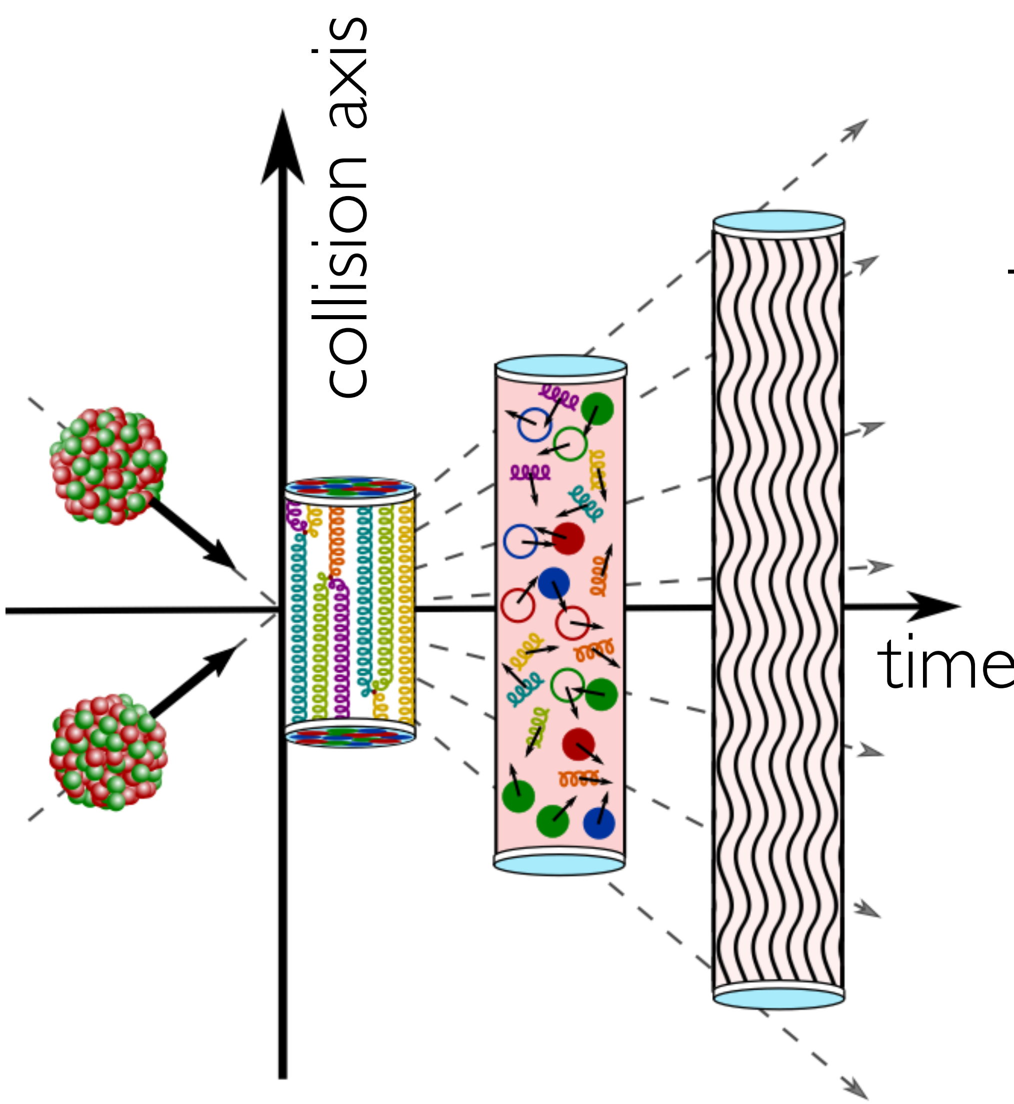

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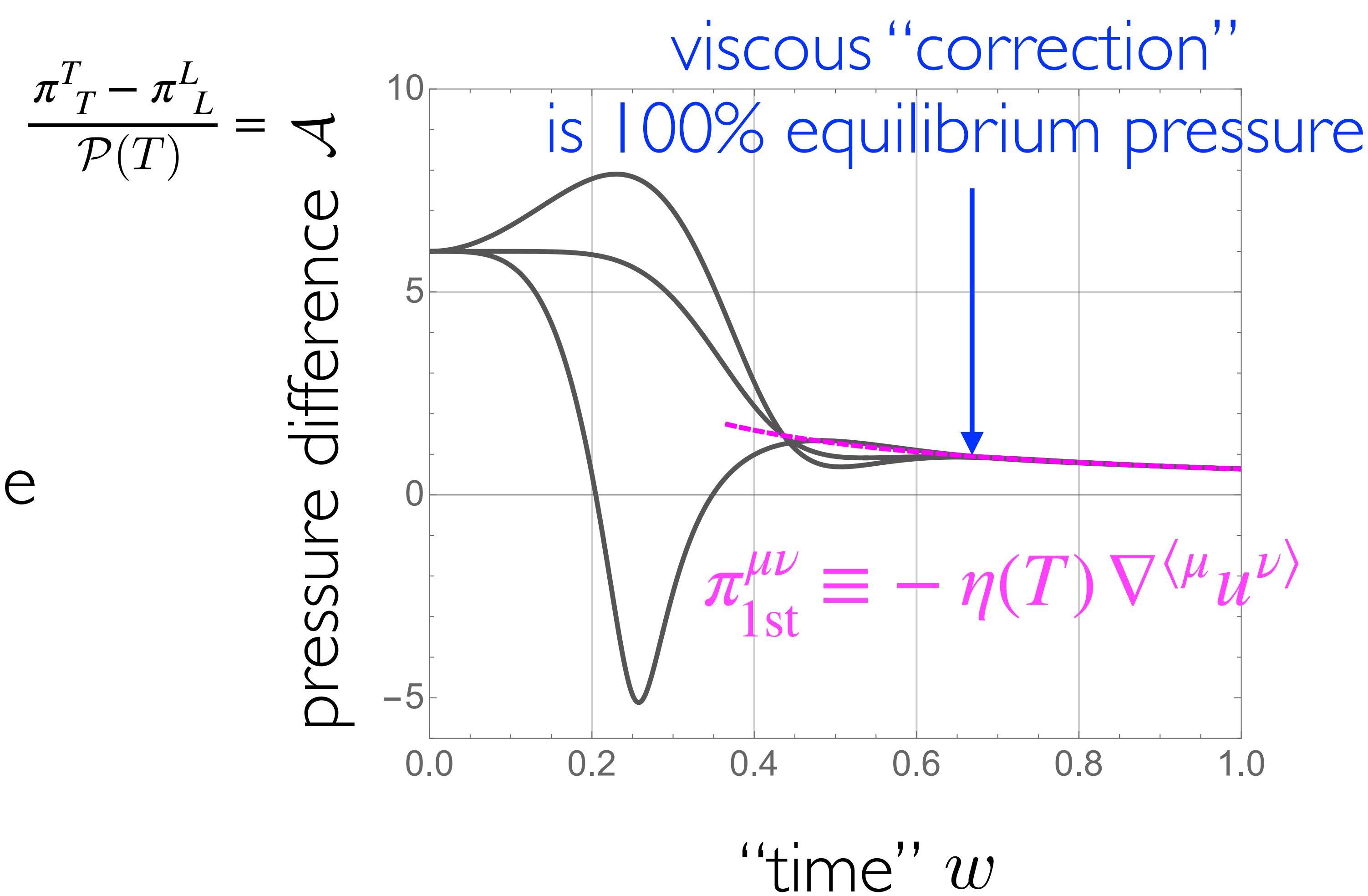
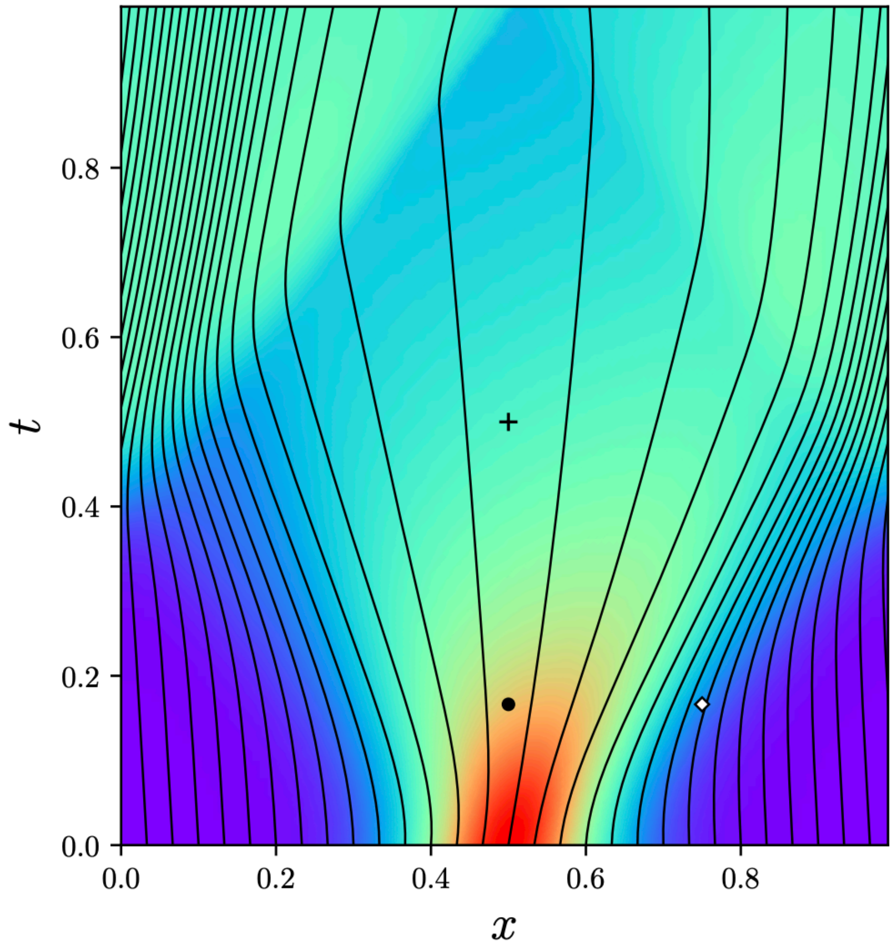
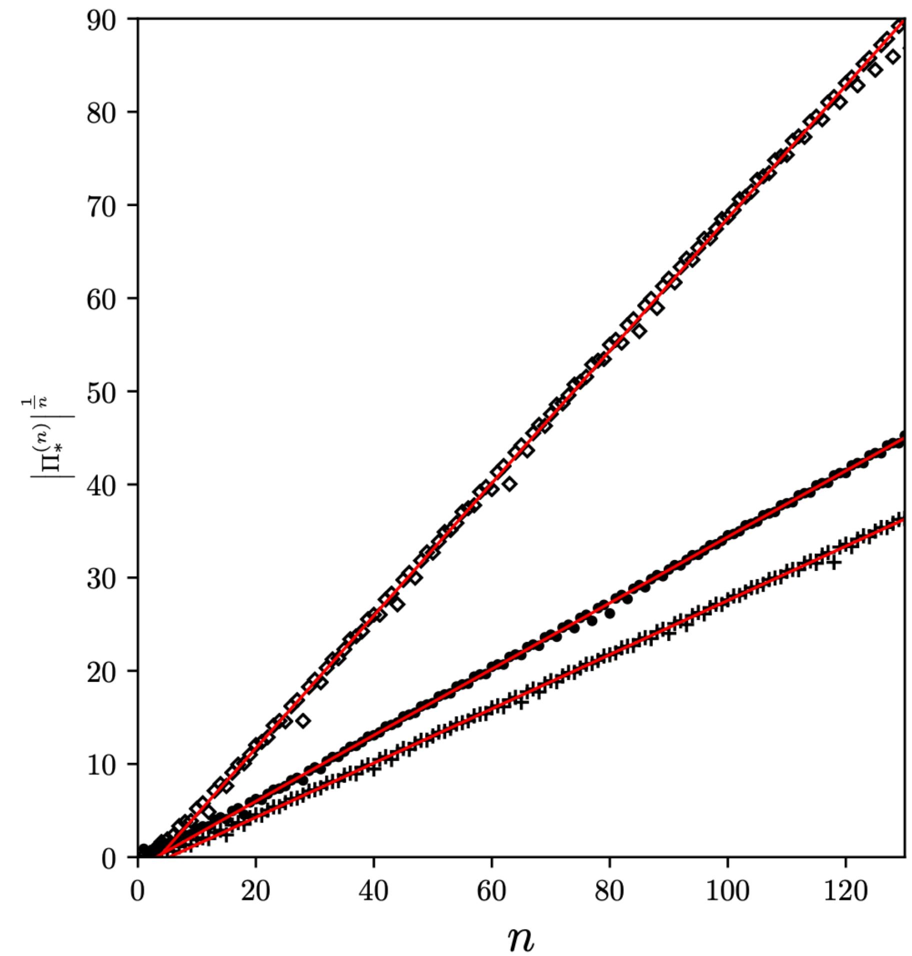


1103.3452 with Janik & Witaszczyk

2011 ⟶ 2025





Hydro constitutive relations generally diverge factorially on-shell

1302.0697 with Janik, Witaszczyk; **1503.07514** with Spaliński;
2110.07621 with Serantes, Spaliński, Svensson, Withers

Optimal or near-optimal truncation can happen to have large derivative terms

2011 ⟶ 2025

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2025-

What I described so far, even though it can certainly be far from equilibrium, still takes the equilibrium as the starting point

In the rest of the talk I will start far from equilibrium and nevertheless be able to show the emergence of a structure that is hydrodynamic

see also Rachel's talk

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Structured far from equilibrium states: nonthermal fixed points

Isotropic nonthermal fixed points

e.g. **1810.08143** by Schmied, Mikheev and Gasenzer
or **2005.12299** with Berges, Mazeliauskas, Venugopalan

Conditions:

weak coupling + overoccupied initial states $f(t=0,p) \gg f_{eq}(p)\Big|_{\text{same energy density}}$

Outcome:

simulations + cold atom experiments show prolonged self-similar time evolution

$$f(t,p) \approx A(t) \times f_s\left(B(t)p\right) \quad \text{with} \quad A(t) = \left(\frac{t-t_*}{t_0}\right)^{\alpha} \quad \text{and} \quad B(t) = \left(\frac{t-t_*}{t_0}\right)^{\beta}$$

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2307.07545 with Mazeliauskas and Preis

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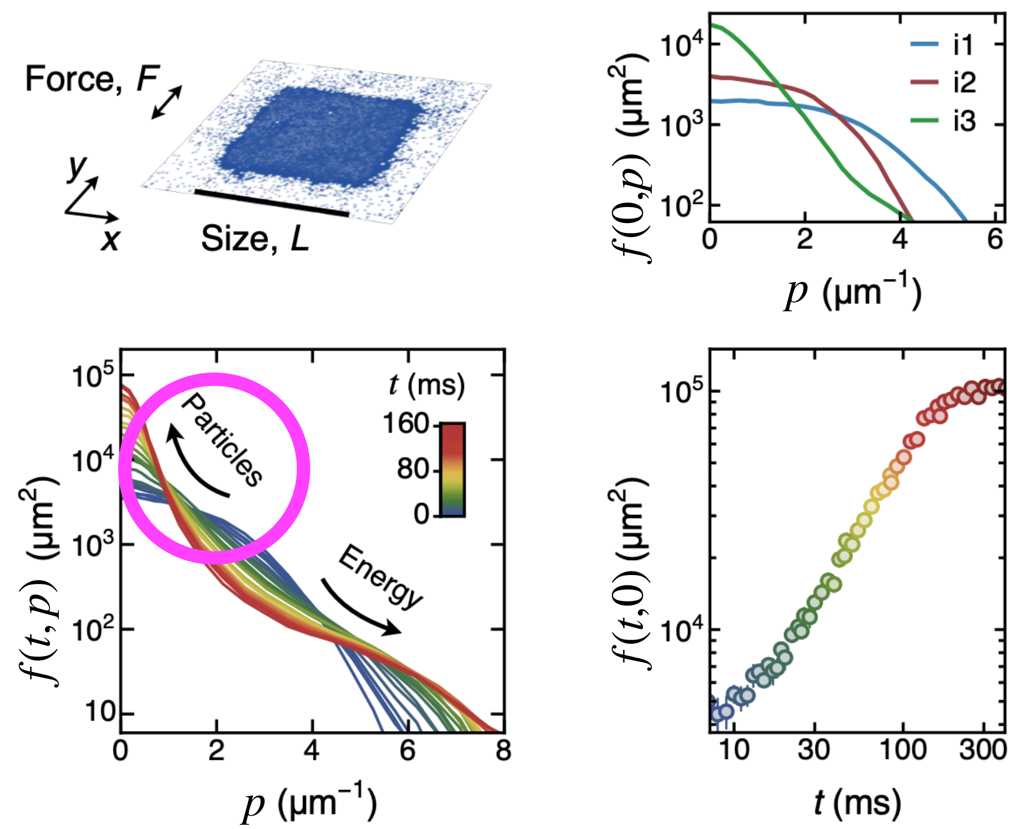
$$f(t,p) \approx A(t) \times f_s\left(B(t)\frac{p}{Q}\right) \text{ with } A(t) = \big((t-t_*)\,Q\big)^{\alpha} \text{ and } B(t) = \big((t-t_*)\,Q\big)^{\beta}$$

The flagship cold atom experiment

2312.09248 by Gazo, Karailiev, Satoor, Eigen, Gałka and Hadzibabic



We start with a quasi-pure interacting 2D condensate of 7×10^4 atoms of ^{39}K in the lowest hyperfine state, confined in a square box trap of size $L = 50\,\mu$m [40]. The interactions in the gas, characterized by the scattering length a, are tuneable via the magnetic Feshbach resonance at 402.7 G [41]. To prepare our far-from-equilibrium initial states, we temporarily turn off the interactions ($a \to 0$) and shake the gas with a spatially uniform oscillating force F (see Fig. 1A). This destroys the condensate and, as previously studied in 3D [42, 43], results in an isotropic highly nonthermal f distribution. After preparing one of the three different initial states i1–i3 shown in Fig. 1A, we stop the shaking, reinstate the interactions ($a \to 30\,a_0$, where a_0 is the Bohr radius), and let the gas relax. The states i1–i3 do not have a defined temperature, but $E = \int \varepsilon(k)\,\mathrm{d}k$, where $\varepsilon = 2\pi\hbar^2 k^3 n_k/(2m)$ and m is the atom mass, gives the total energy. We get $E/k_\mathrm{B} = 4.1(3)$ mK, 2.2(3) mK, and 1.0(3) mK, for i1–i3 respectively; in all cases E is sufficiently low for a condensate to emerge during relaxation [44].

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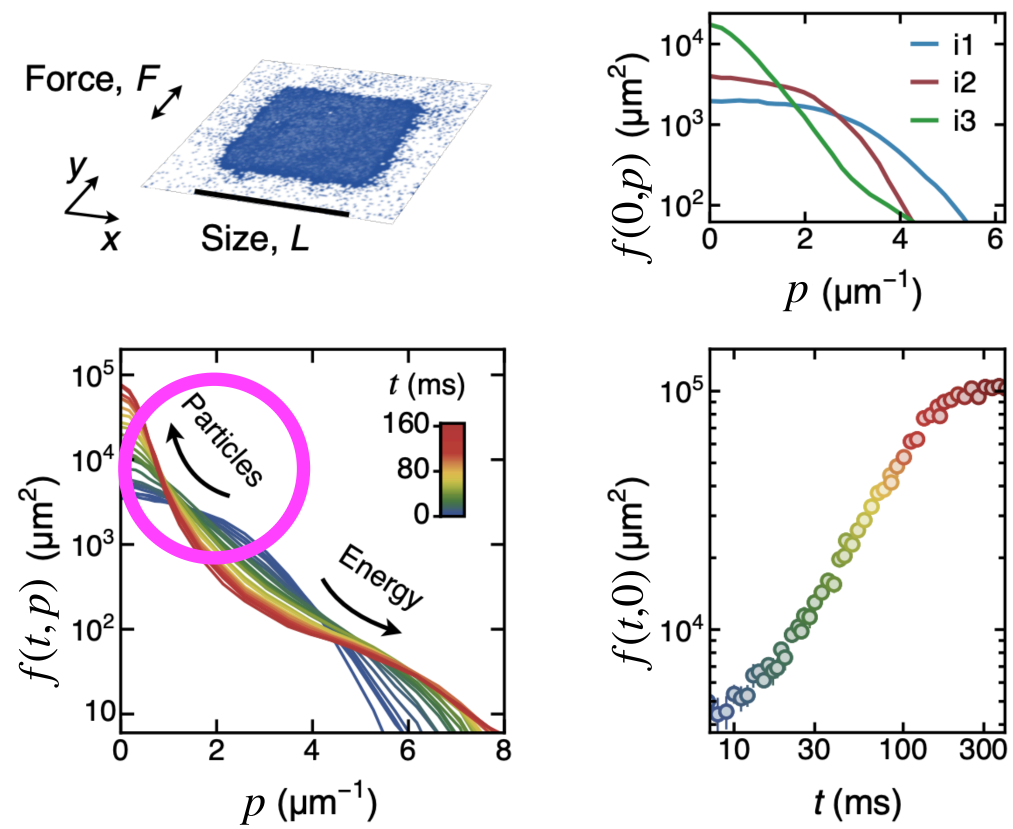

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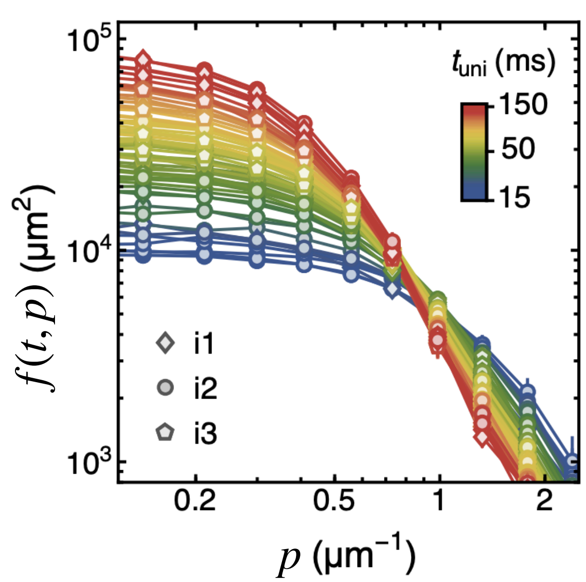
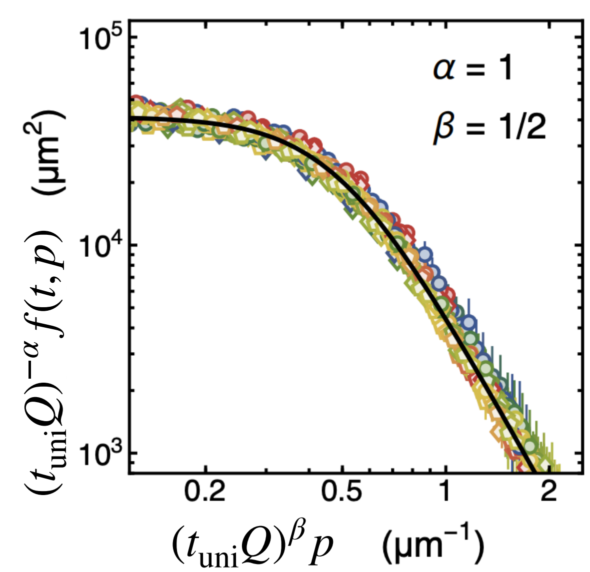


$$t_{\text{uni}} \equiv t - t_* \longrightarrow$$



Comments on nonthermal fixed points

Nonthermal fixed points are intrinsically far from equilibrium

$$\Big((t-t_*)\,Q\Big)^{\alpha} \times f_s\left(\Big((t-t_*)\,Q\Big)^{\beta}\,p\right) \neq f_{eq} + \delta f$$

They are of broad th relevance: + cosmology + ultrarelativistic nuclear collisions*
(many seemingly different nonthermal fixed points)

Truly ideal testing ground for pushing hydrodynamics further

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Hydrodynamics of nonthermal fixed points

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2504.18754 with Berges, Denicol, Preis + De Lescluze and García Fariña in the upcoming v2

Input:

$$f(t,p) = \left(t_{\text{uni}}/t_0\right)^{\alpha} f_{\text{scaling}}\left[\left(t_{\text{uni}}/t_0\right)^{\beta} p\right] + \delta f(x^\mu, p)$$

with $\delta f(t,p) \sim p_\mu p_\nu \pi^{\mu\nu}(x^\alpha)$

Method: take truncated low moments expansion of the Boltzmann equation that was used before to derive DNMR-type equations

~ Israel-Stewart, see Lorenzo's talk

Outcome for 2-2 scattering of gluons : $\tau_\pi(t) D\pi^{\mu\nu} = -\pi^{\mu\nu} + \bar{\eta}(t)\sigma^{\mu\nu} + \ldots$ with

$$\bar{\eta}(t) = c_{\bar{\eta}}(t - t_*)Q^4$$

$$\tau_\pi(t) = c_{\tau_\pi}(t - t_*)$$

$c_{\bar{\eta}} \approx 1.05$

$c_{\tau_\pi} \approx 3.97$

Fokker-Planck (fit)

see Matisse' poster

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Hydrodynamic constitutive relation

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$$\downarrow$$

$$\pi^{\mu\nu} = \frac{1}{1 + \tau_\pi(t)D}(-\bar{\eta}(t)\sigma^{\mu\nu}) + \ldots = -\frac{4c_{\tau_\pi}}{15(1 + c_{\tau_\pi})}(t - t_*)Q^4\sigma^{\mu\nu} + \ldots$$

This is the shear viscosity of a nonthermal fixed point for 2-2 scattering of gluons within a DNMR approximation

Power-law relaxation

2504.18754 with Berges, Denicol, Preis + De Lescluze and García Fariña in the upcoming v2

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$$\tau_\pi(t) = c_{\tau_\pi}(t - t_*)$$

$$\downarrow$$

$$\pi^{\mu\nu} = \ldots + \# \times (t - t_*)^{1/c_{\tau_\pi}} + \ldots$$

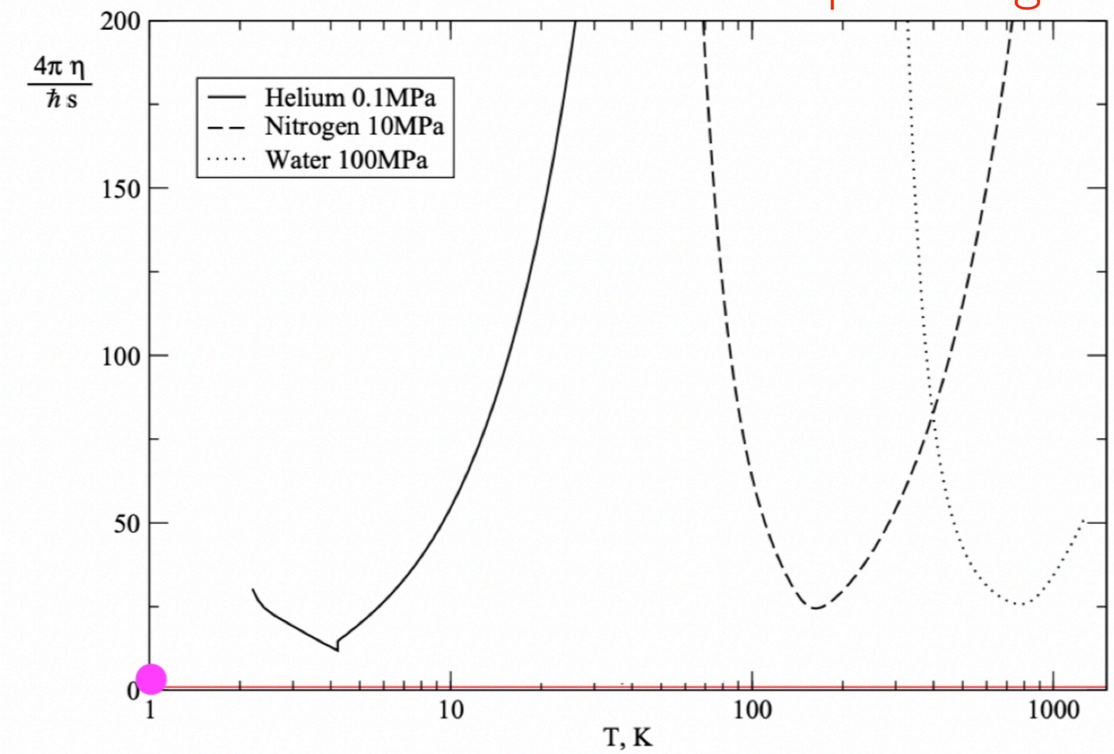
$$\downarrow$$

The relaxation of the anisotropy is governed by a power-law*

Beyond η/s

2504.18754 with Berges, Denicol, Preis + De Lescluze and García Fariña in the upcoming v2

Comparing the nonthermal fixed point liquid with near-equilibrium liquids requires going beyond the η/s paradigm, as this ratio is now time dependent



One idea: consider $\dfrac{\eta}{2\tau_\pi \times (\text{energy density}) \times (c_s/c)^2}$

≈ 1 in holography

≈ 0.4 water in room temperature

≈ 0.4 kinetic theory*: near eq.

≈ 0.08 kinetic theory*: far from eq.

Beyond η/s

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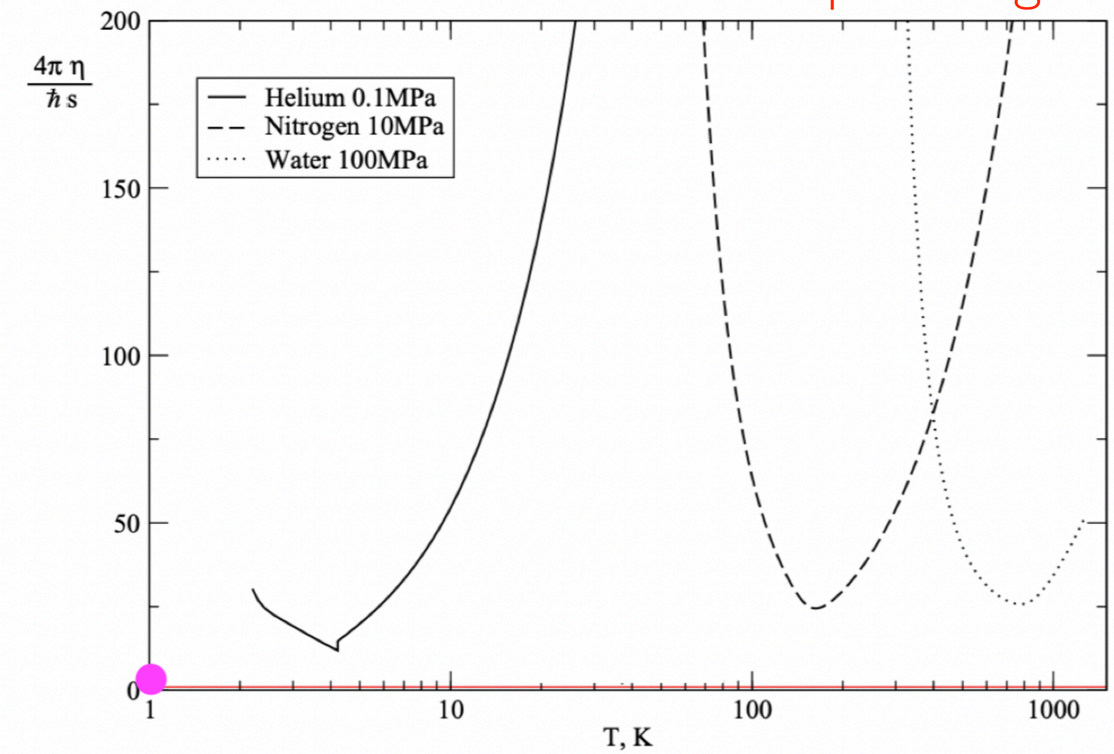

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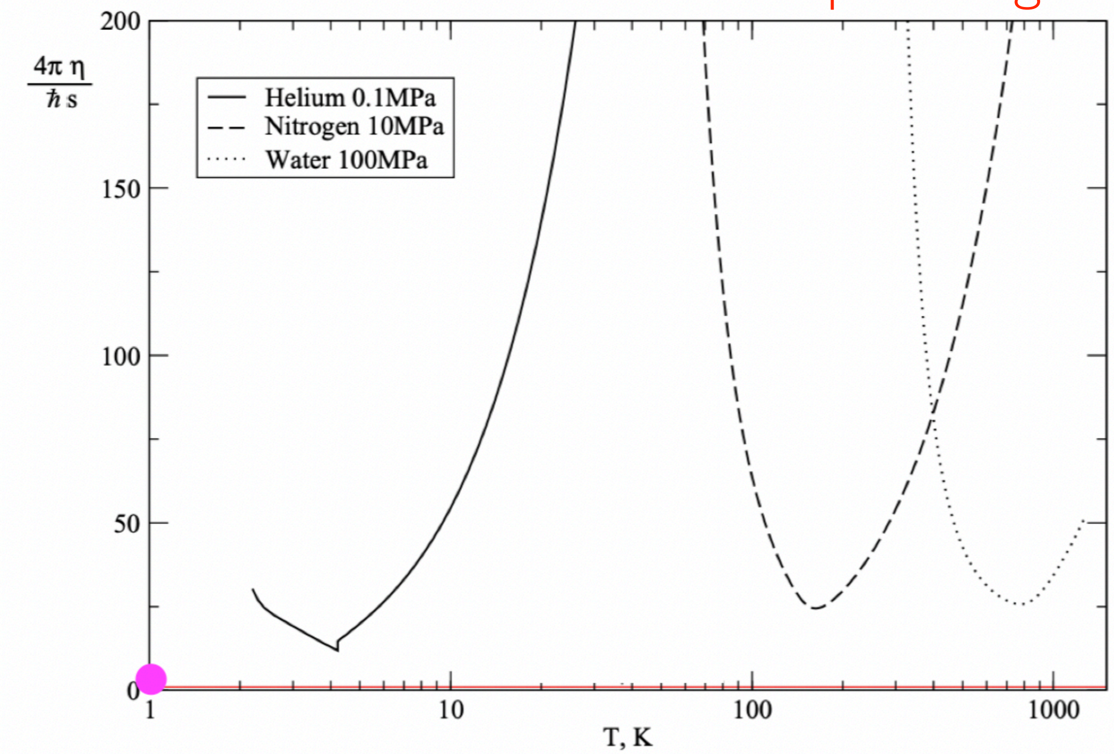

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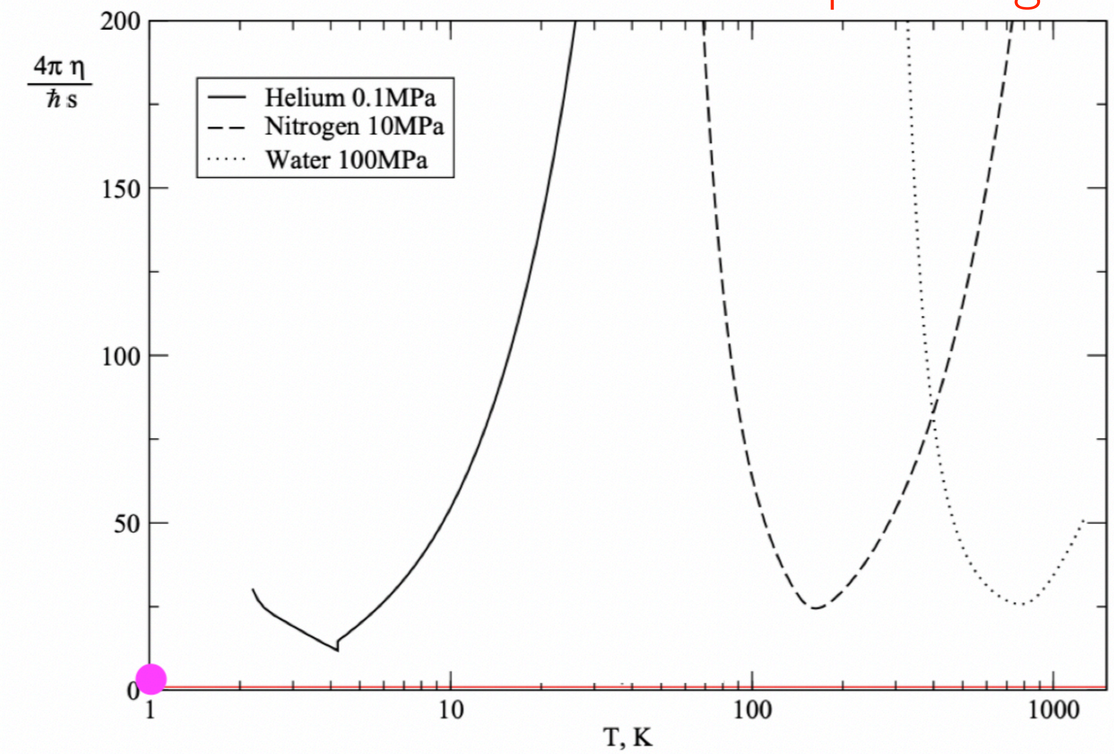

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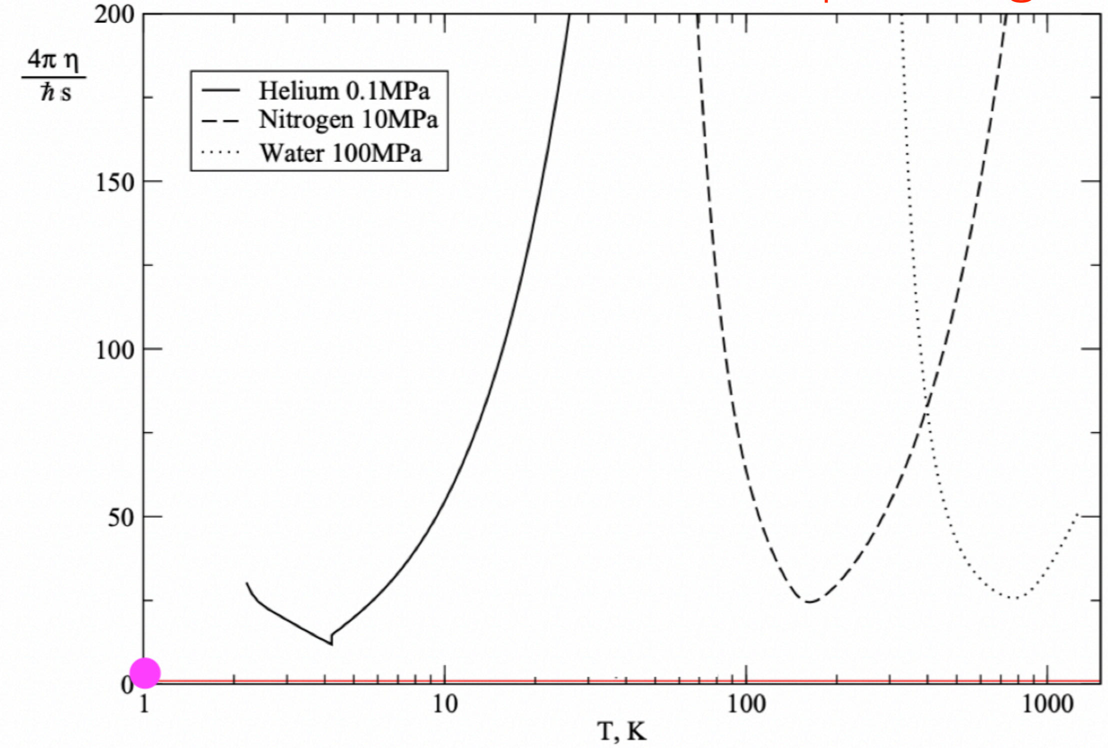

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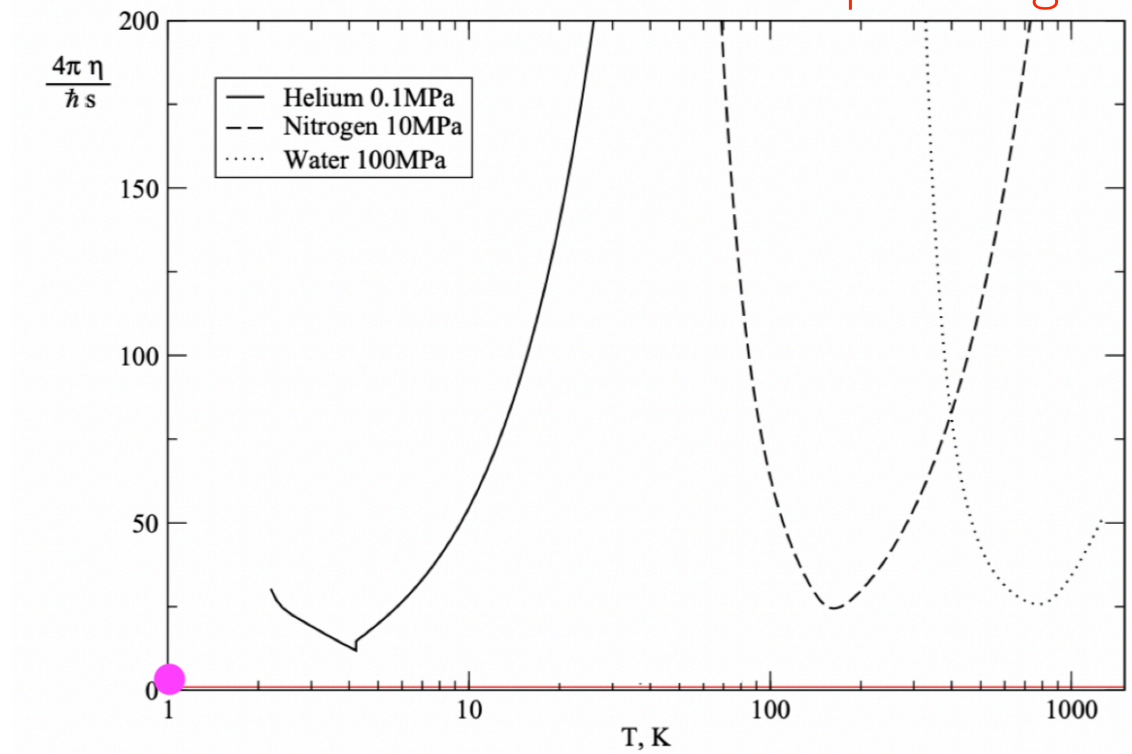

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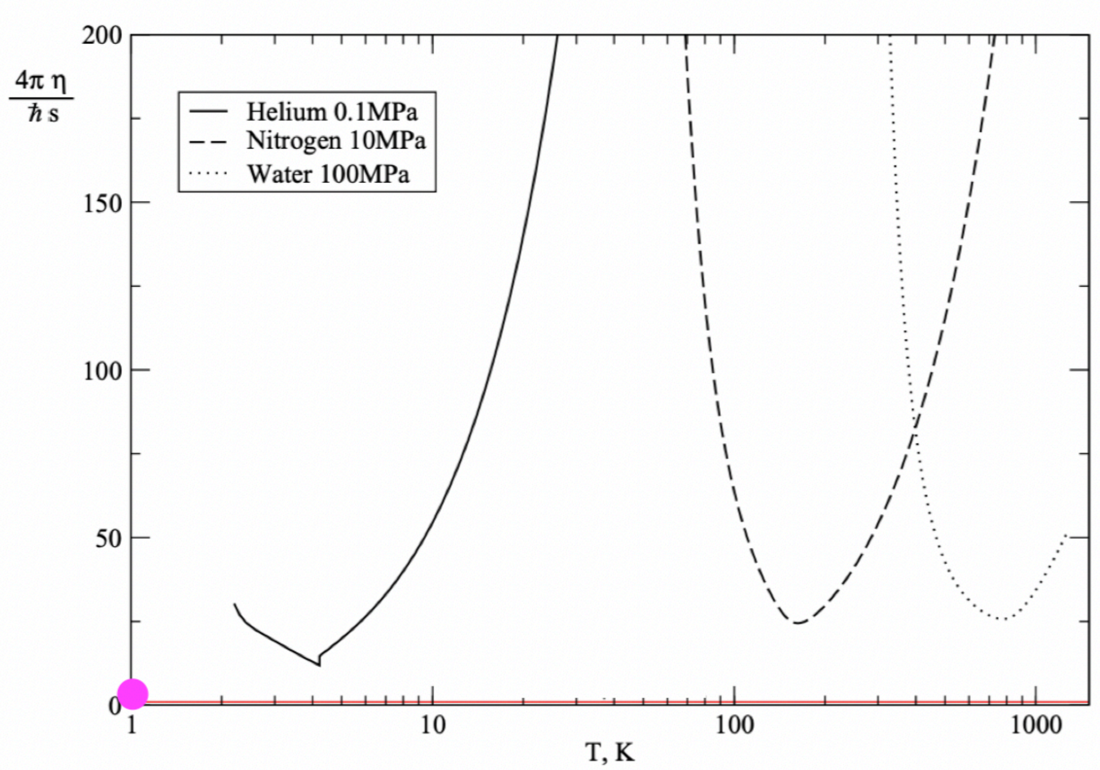
Summary so far

Nonthermal fixed points indicate novel, exotic realizations of hydrodynamics



$$\frac{\eta}{2\tau_\pi \times (\text{energy density}) \times (c_s/c)^2}$$

12.5x smaller than in holography

5x smaller than in near-eq. kinetic theory*

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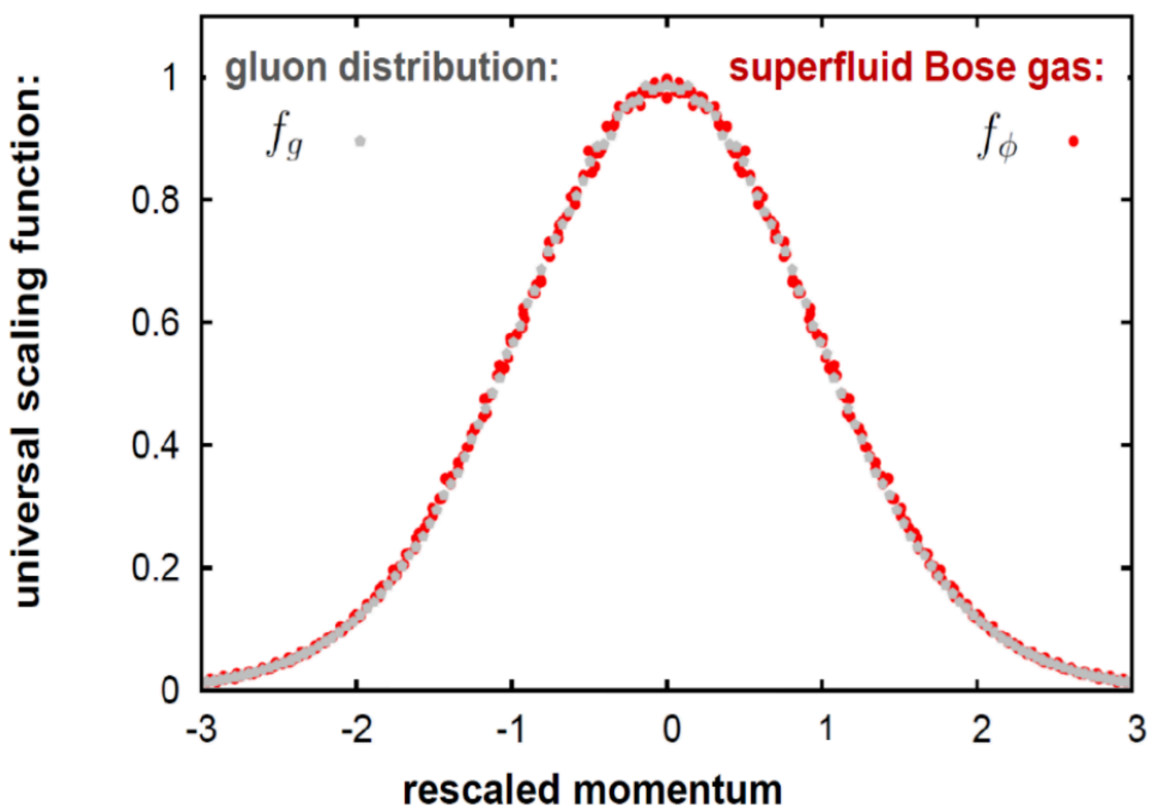
New idea:
Berges-Boguslavski-Schlichting-Venugopalan nonthermal fixed points from hydrodynamics

260x.xxxx with De Lescluze and García Fariña

see also Rachel's talk

The Glasma and overoccupied ultracold quantum gases

Simulations of self-interacting scalar fields with identical initial conditions demonstrates remarkable *universality of longitudinally expanding world's hottest and coolest fluids*



In a wide inertial range, scalar & gauge fields have identical scaling exponents & functions

$$f(p_T, p_z, \tau) = \tau^\alpha f_S(\tau^\beta p_T, \tau^\gamma p_z)$$

$$\tau = \sqrt{t^2 - z^2}$$

$$\alpha = -\frac{2}{3}, \beta = 0, \gamma = 1/3$$

Berges, Boguslavski, Schlichting, RV, PRL (2015)

taken a talk by Raju Venugopalan at CERN in May 2026

Comments on nonthermal fixed points

Nonthermal fixed points are intrinsically far from equilibrium

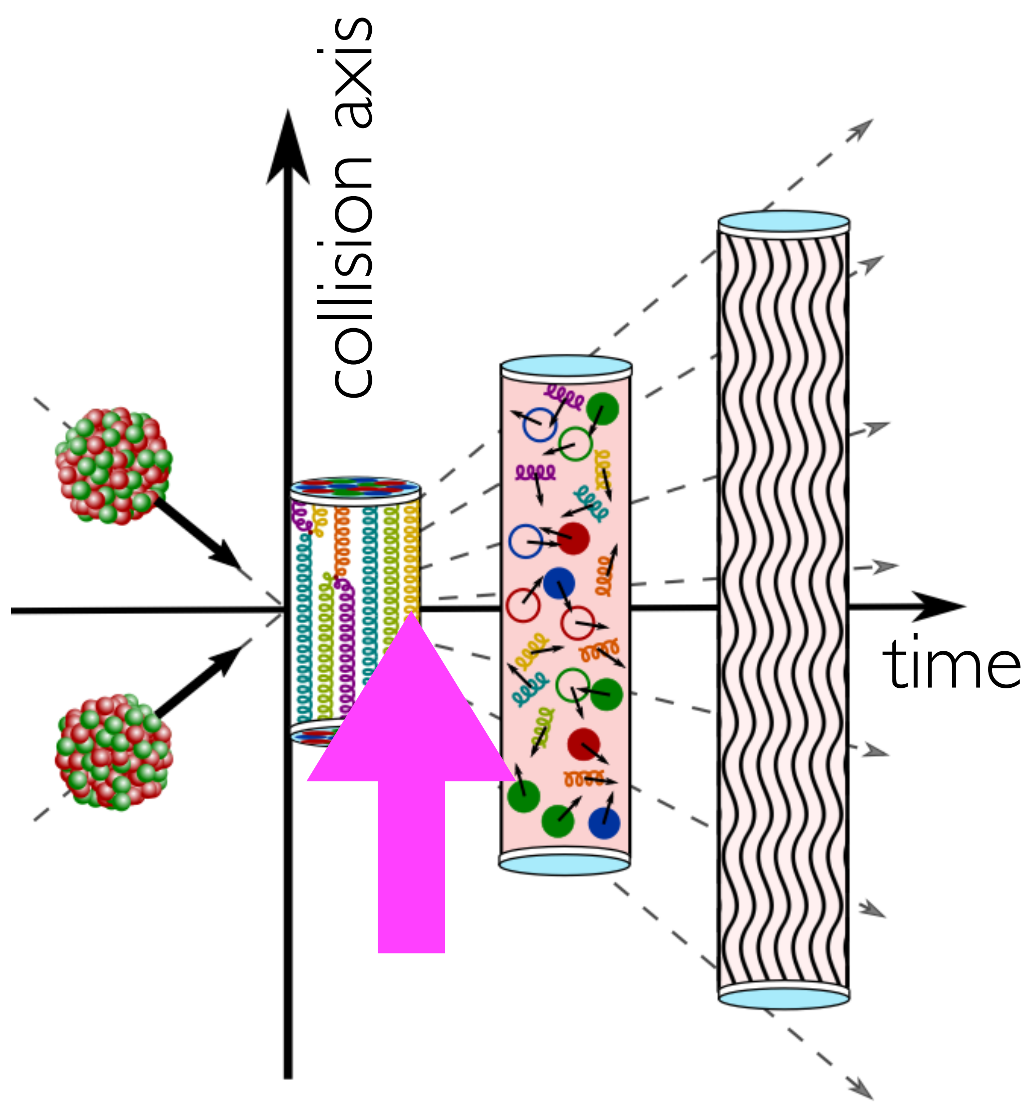
$$\left((t-t_*)\,Q\right)^{\alpha} \times f_s\left(\left((t-t_*)\,Q\right)^{\beta} p\right) \neq f_{eq} + \delta f$$

They are of broad th relevance: + cosmology + ultrarelativistic nuclear collisions*

Truly ideal testing ground for pushing hydrodynamics further

Relativistic hydro and ab initio simulations

heavy-ion collisions
at RHIC and LHC



2005.12299
with Berges, Mazeliauskas & Venugopalan

behaviour in
of theoretical models
(here: holographic boost-invariant dynamics)

1103.3452 with Janik & Witaszczyk

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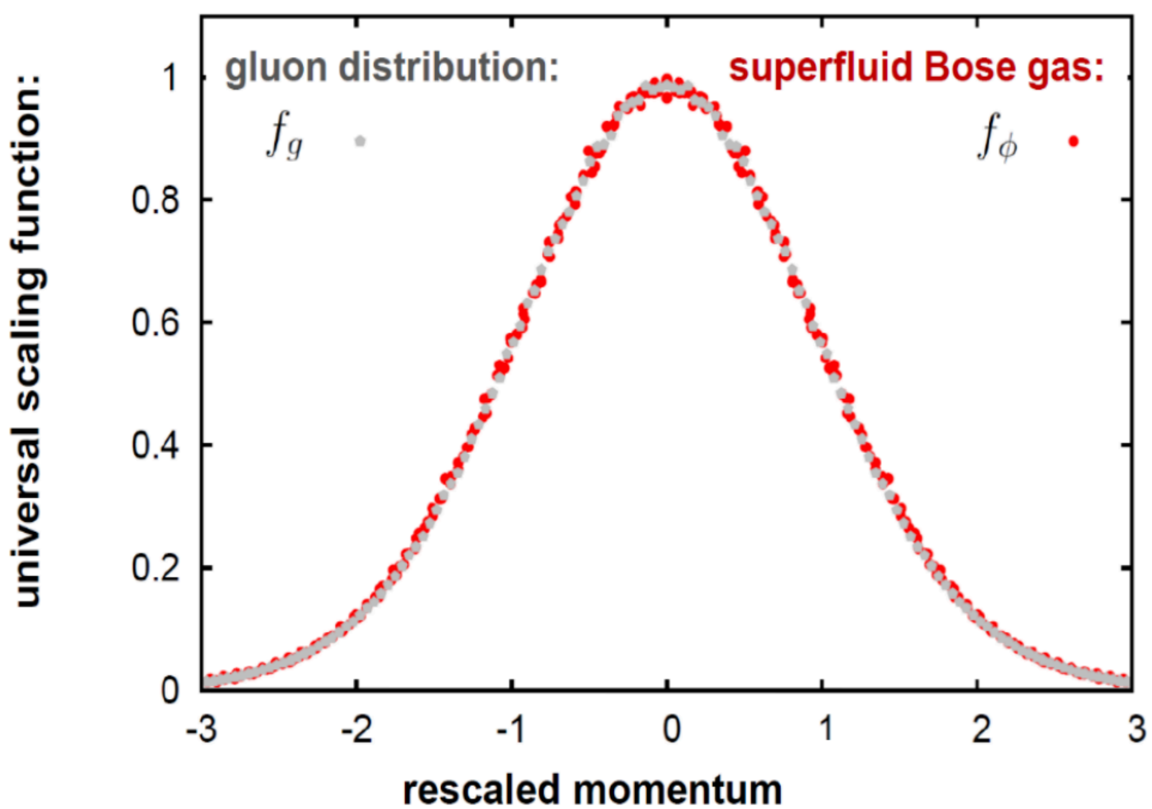

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Two key observations

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$$f(t,p) \approx (t_{\mathrm{uni}}Q)^\alpha f_{\mathrm{scaling}}\left[(t_{\mathrm{uni}}Q)^\beta p/Q\right]$$

with $t_{\mathrm{uni}} \equiv t - t_*$

Is then the strong longitudinal expansion crucial for the Berges-Boguslavski-Schlichting-Venugopalan nonthermal fixed point?

Bjorken hydrodynamics

$$f_{\mathrm{hydro}}(p) = f_{\mathrm{eq}}((-u_\mu(x)p^\mu)/T(x))$$

with $u^\mu(x)\partial_\mu = \partial_\tau$ and $T \sim \tau^{-1/3}$

(and more generally solves ideal fluid eoms)

equilibrium

$$f(p) = f_{\mathrm{eq}}(p/T)$$

T is constant

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Our result 260x.xxxx with De Lescluze and García Fariña

$\exists$ **nonexpanding** anisotropic nonthermal fixed point

$$f(t, p_z, p_\perp) = A(t) \times f_{\text{scaling}} \left(G(t) p_z / Q_z, p_\perp / Q_\perp \right)$$

with $A(t) = G(t)$ and $\partial_t G(t) = -\frac{Q_\perp^2}{Q_z} G(t)^4 \longrightarrow G(t) = \left((t - t_*) \frac{3 Q_\perp}{Q_z} \right)^{-1/3}$

Berges-Boguslavski-Schlichting-Venugopalan nonthermal fixed point:

nonexpanding anisotropic nonthermal fixed point $\Big|_{Q_z \sim \tau^{-1}}$ and being careful about the eq. for G

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Implications 260x.xxxx with De Lescluze and García Fariña

Significant simplification of classification of nonthermal fixed points

Expansion not great for cold atoms, but nonexpanding seed carries most of the essential physics and may be realizable in cold atom experiments

Hydrodynamics throughout the whole or most post-collision evolution?

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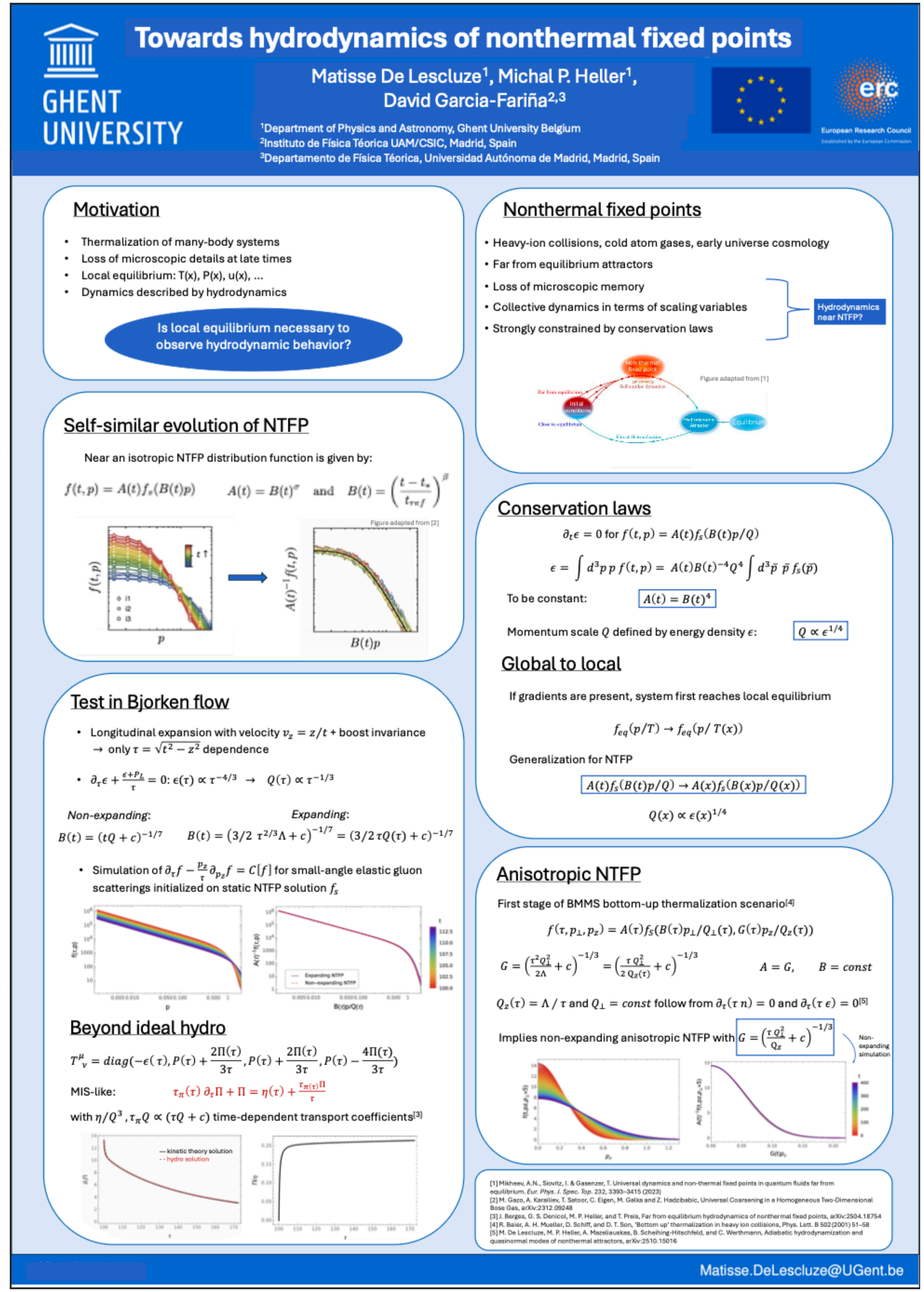
see Matisse' poster tomorrow
for a complementary discussion



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Scientific Program

QCD in extreme conditions and dense nuclear matter

Heavy-ion collisions and the quark gluon plasma new view on early time dynamics

Quantum fields in and out of equilibrium and thermalisation new instance of hydrodynamics

Baryogenesis and leptogenesis

Early universe physics, inflation, electroweak phase transitions, and sources for gravitational waves implications?

Compact stars

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Backup

Quasinormal modes of nonthermal fixed points

2502.01622 with De Lescluze

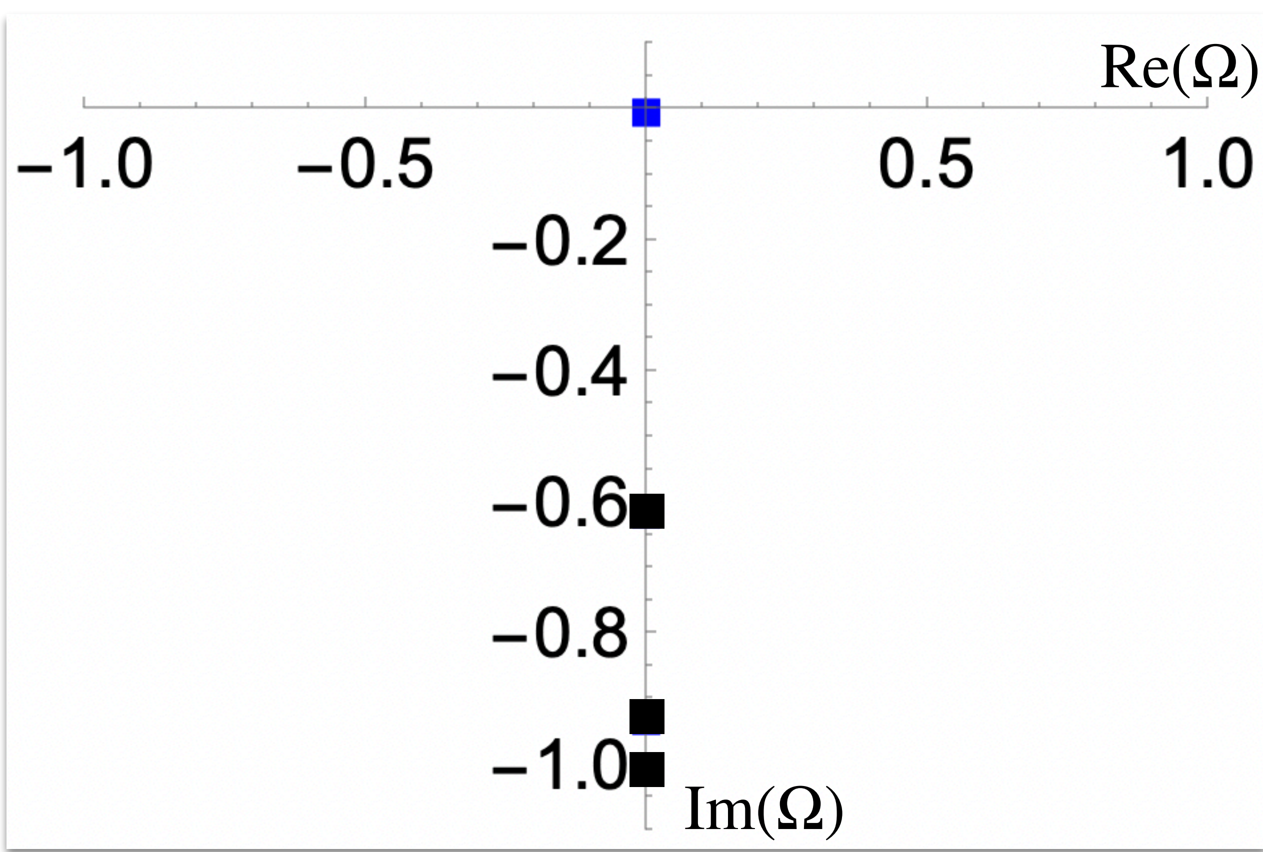
On a nonthermal fixed point:

$$f(t,p) \approx (t_{\text{uni}}Q)^{\alpha} f_{\text{scaling}}\left[(t_{\text{uni}}Q)^{\beta} p/Q\right]$$

with $t_{\text{uni}} \equiv t - t_*$

directly before that:

$$(t_{\text{uni}}Q)^{-\alpha} f(t,p) \approx f_{\text{scaling}}\left[(t_{\text{uni}}Q)^{\beta} p/Q\right] + \sum_{\Omega} (t_{\text{uni}}Q)^{-i\Omega} \delta f_{\Omega}\left[(t_{\text{uni}}Q)^{\beta} p/Q\right]$$



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