

Far from equilibrium hydrodynamics of nonthermal fixed points

Michał P. Heller



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



17–21 Aug 2026
Helsinki, Finland

Strong and Electro-Weak Matter 2026

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

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Scientific Program

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Book of Abstracts

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[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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The banner features a stylized illustration of the Helsinki skyline, including the main dome of St. Nicholas' Cathedral, set against a background of wavy lines representing water or energy. The text '17-21 Aug 2026 Helsinki, Finland' is positioned to the right of the illustration.

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Participant List	+ cold atoms
Venue	
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The main motivating question

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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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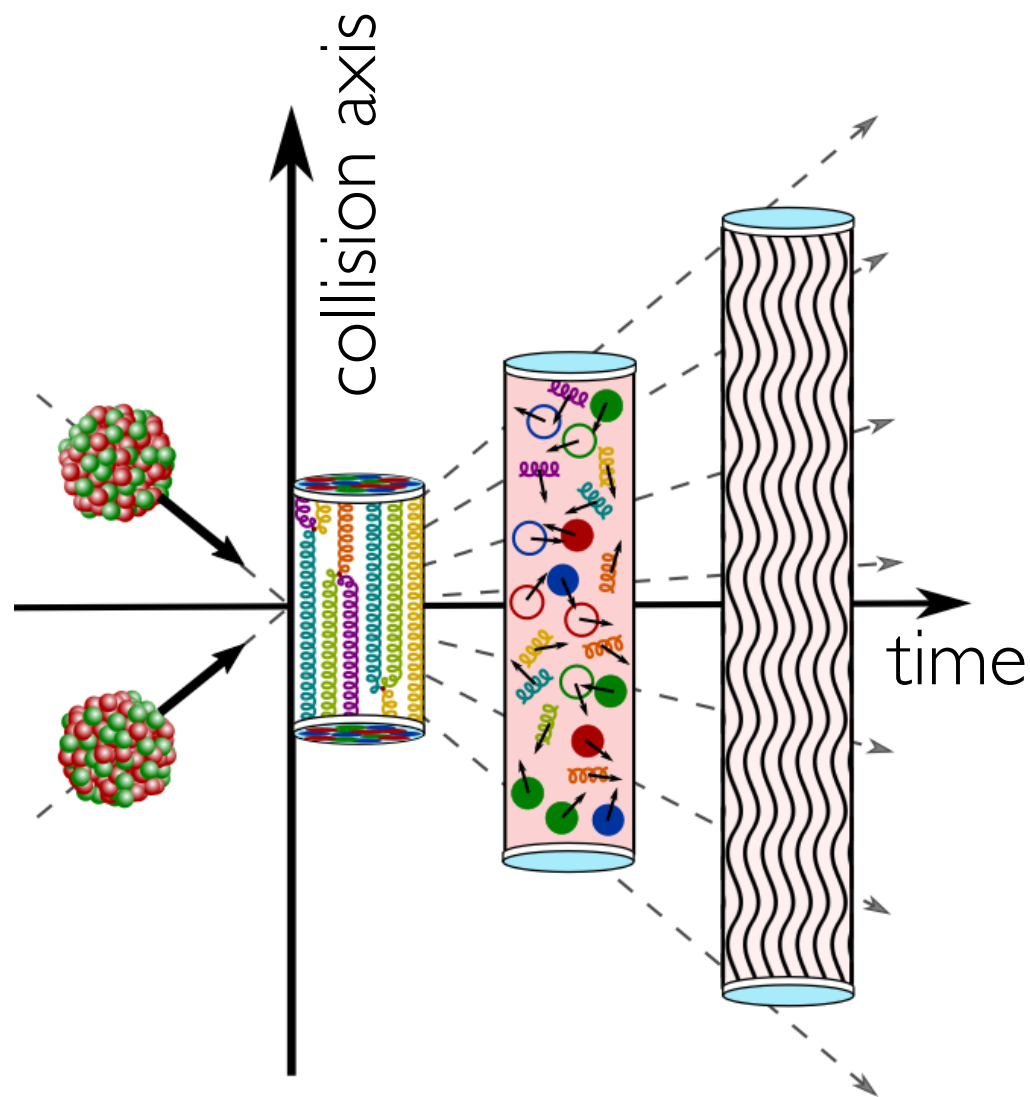
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Why this question?

Relativistic hydro and ab initio simulations

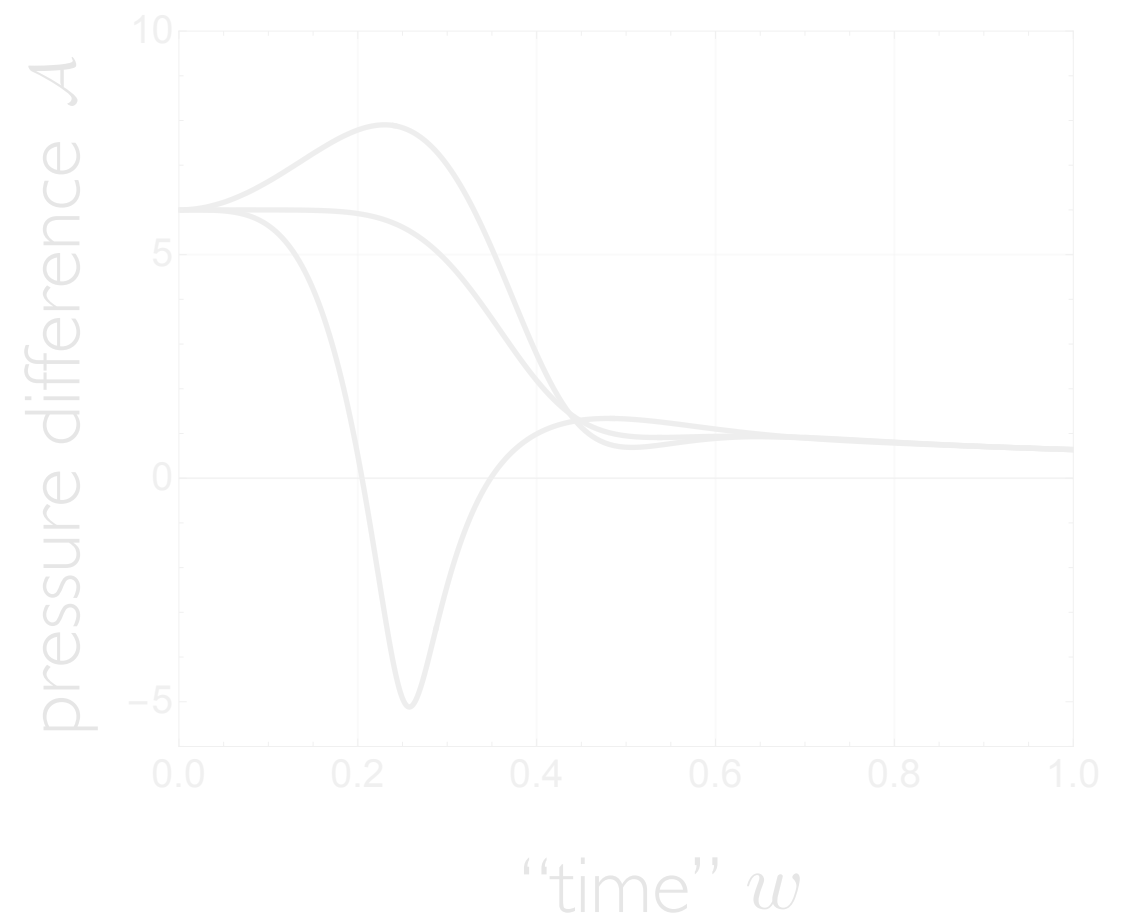
heavy-ion collisions
at RHIC and LHC



2005.12299

with Berges, Mazeliauskas & Venugopalan

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

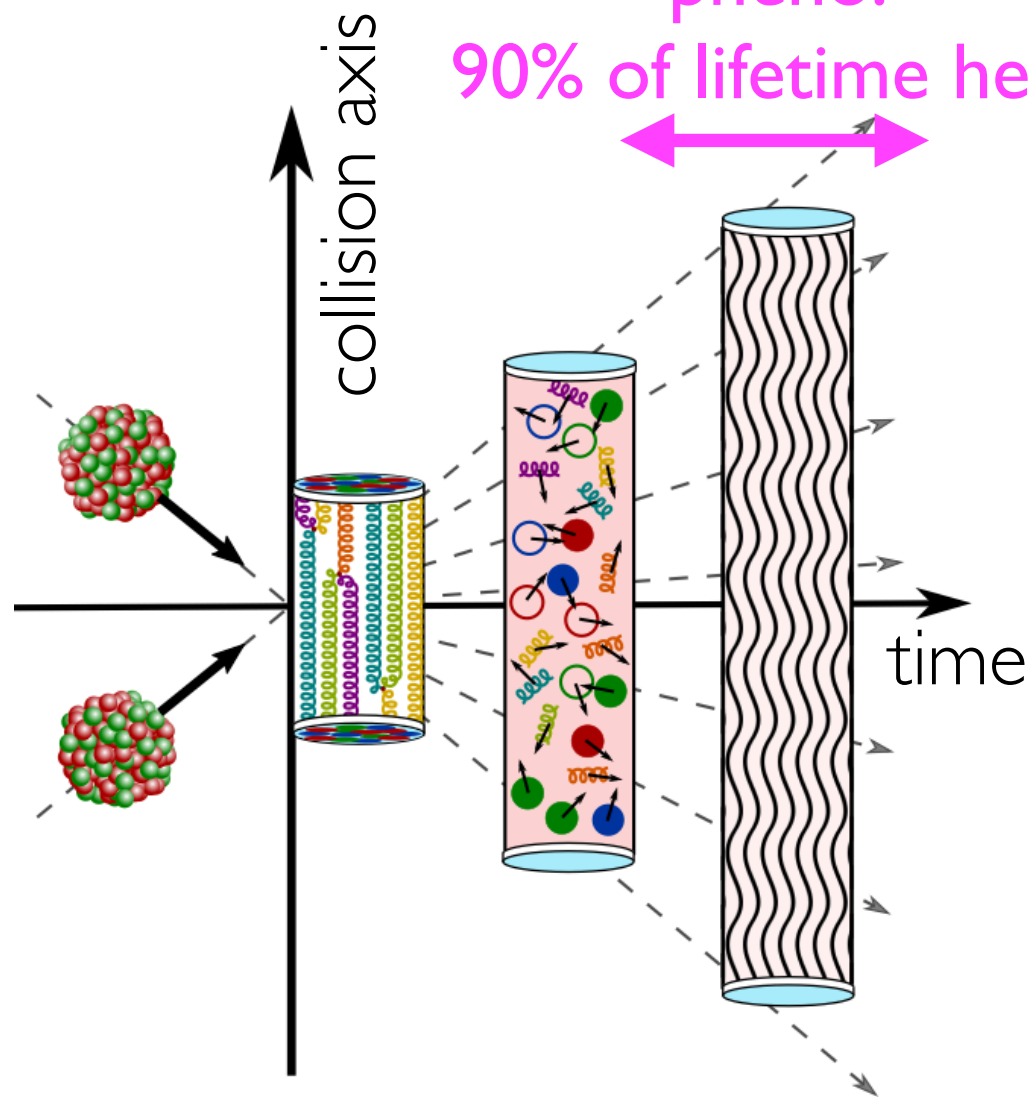


1103.3452 with Janik & Witaszczyk

Relativistic hydro and ab initio simulations

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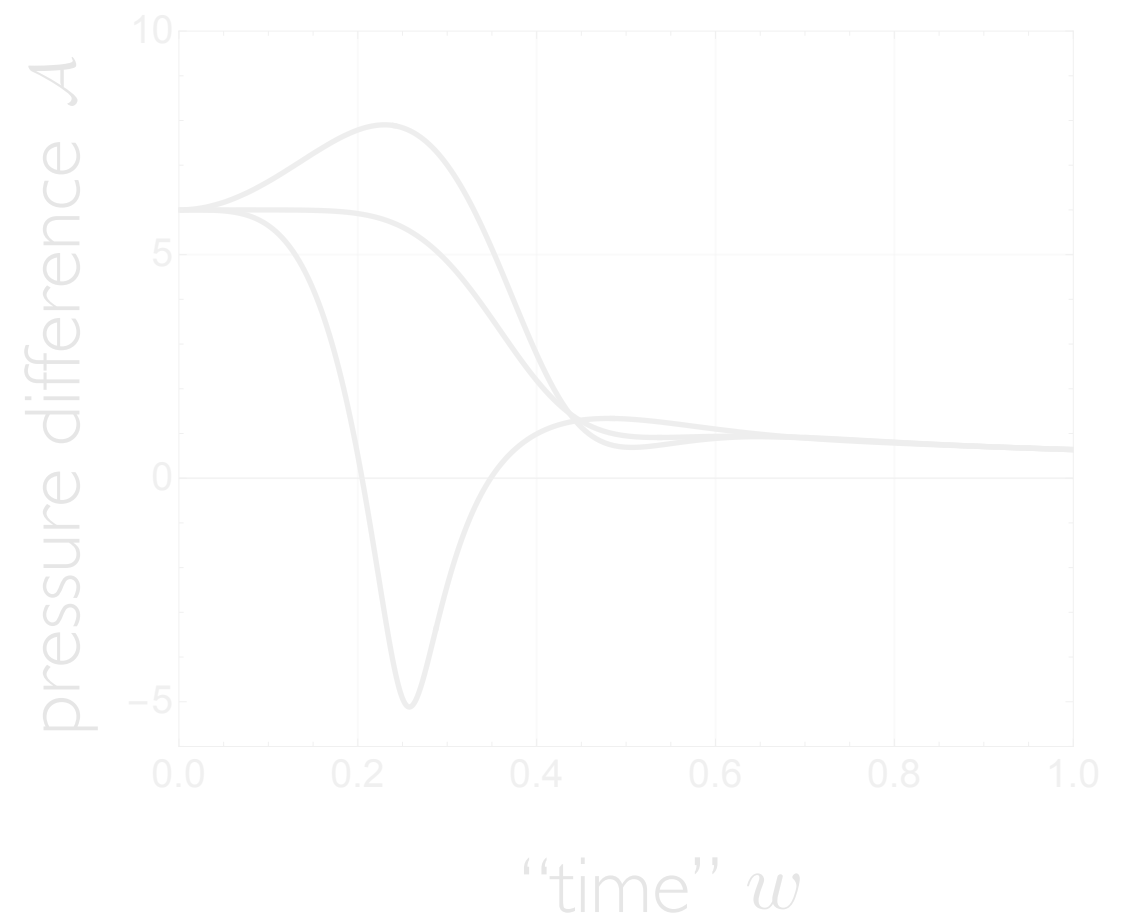
pheno:
90% of lifetime here



2005.12299

with Berges, Mazeliauskas & Venugopalan

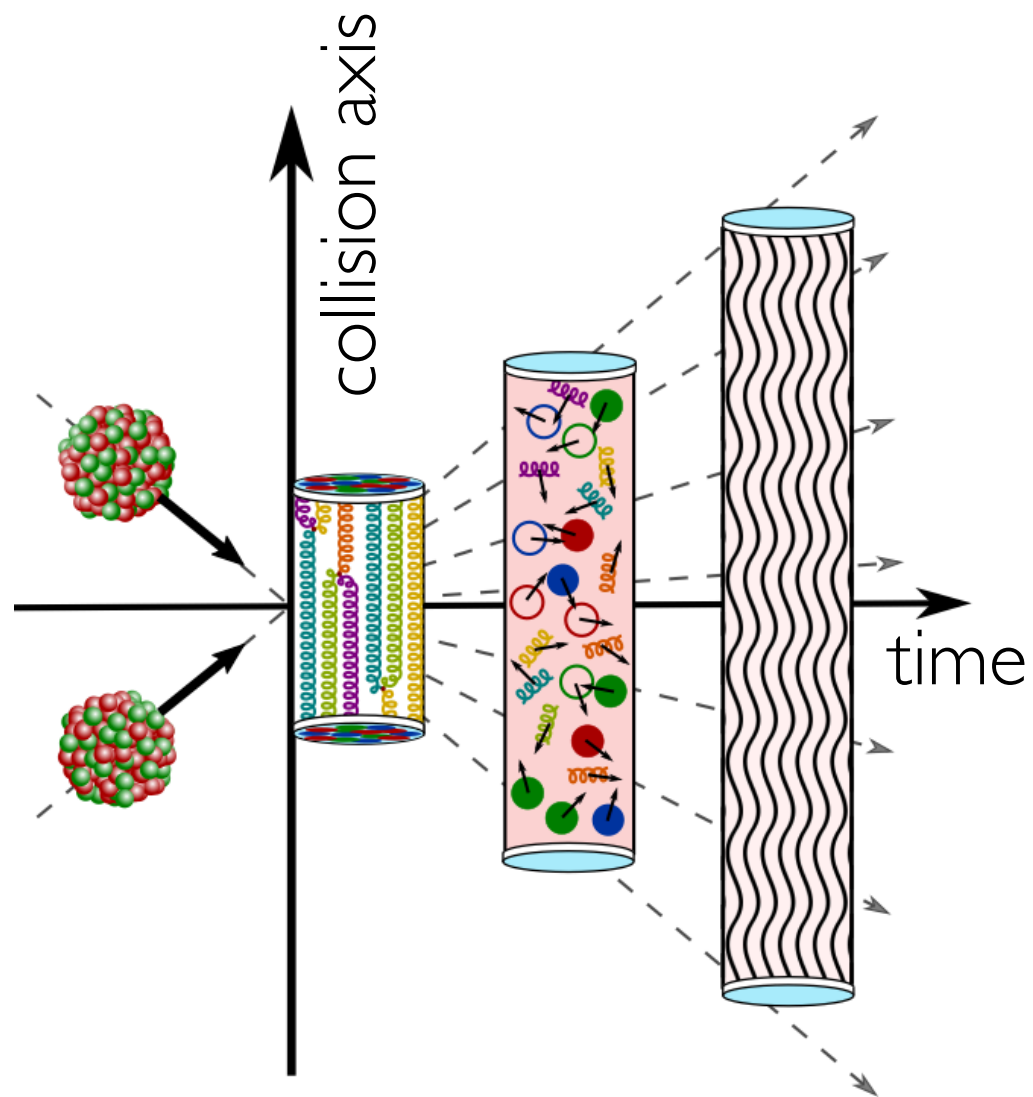
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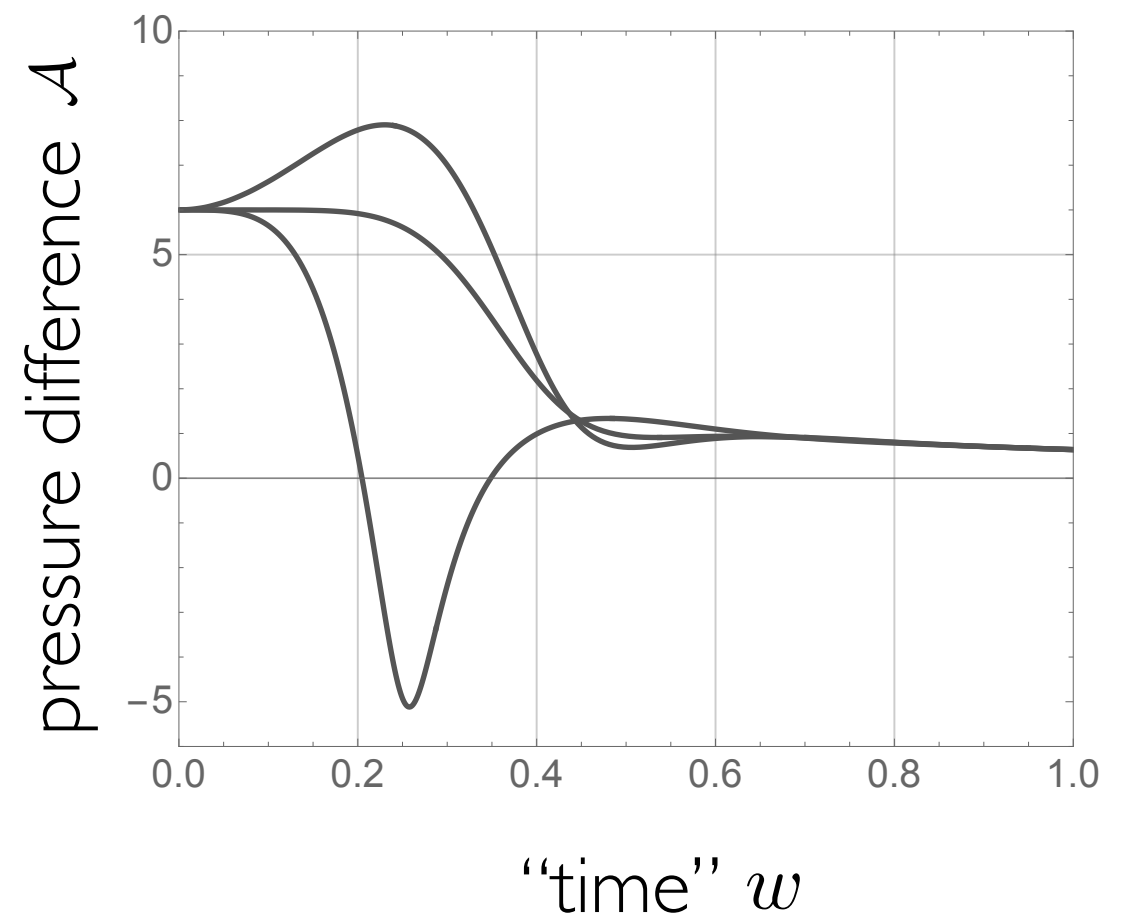
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Hydro works $\equiv$ its constitutive relations hold

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

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

@ 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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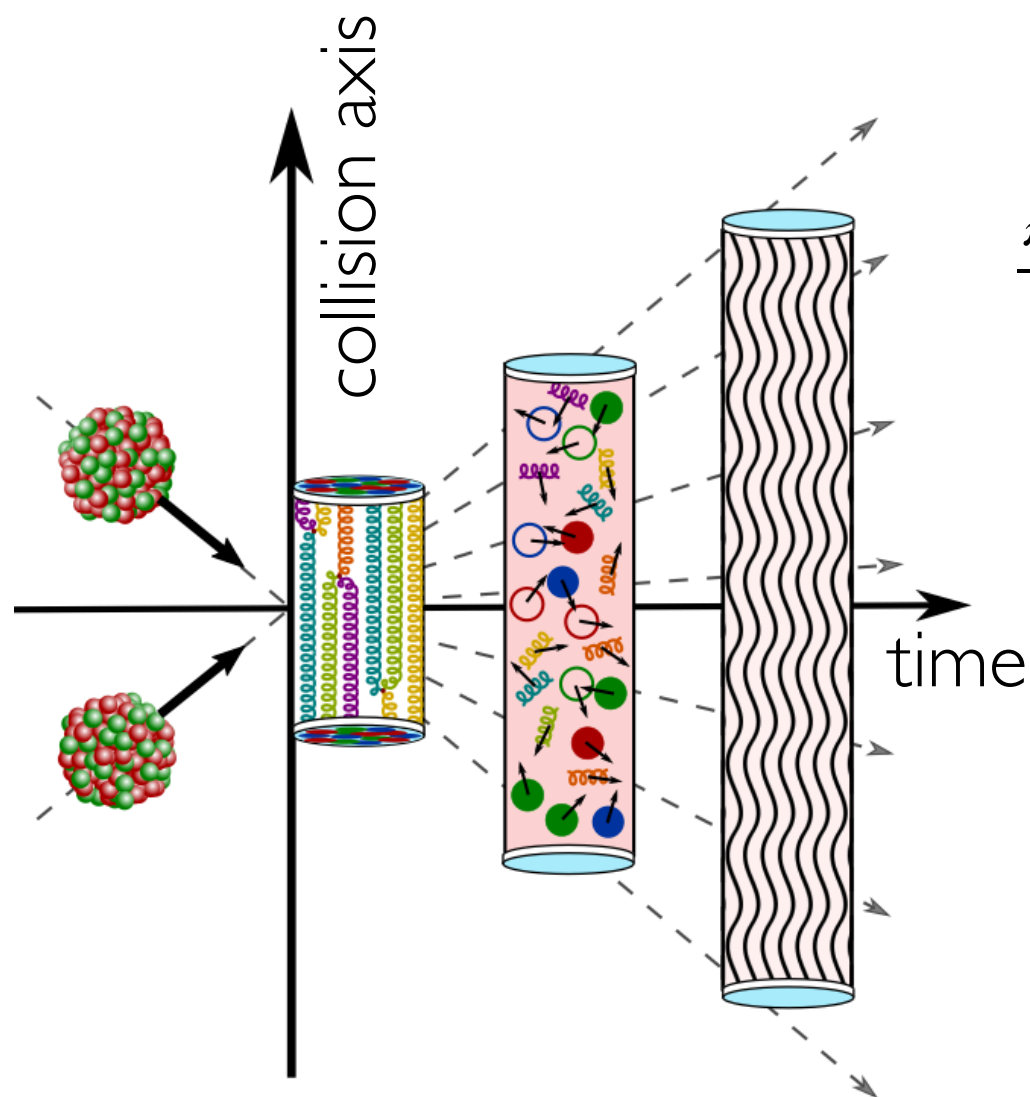
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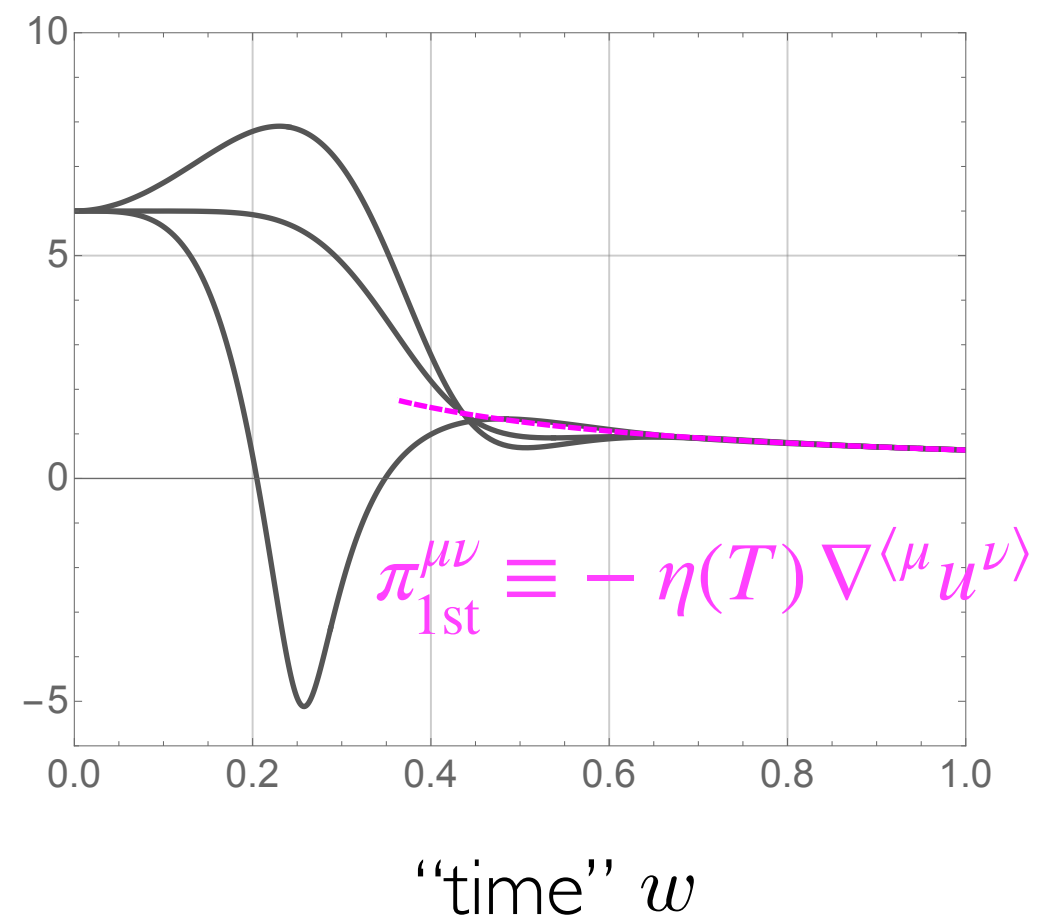
heavy-ion collisions
at RHIC and LHC

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



$$\frac{\pi_T^T - \pi_L^L}{\mathcal{P}(T)} = \mathcal{A}$$

pressure difference $\mathcal{A}$



2005.12299

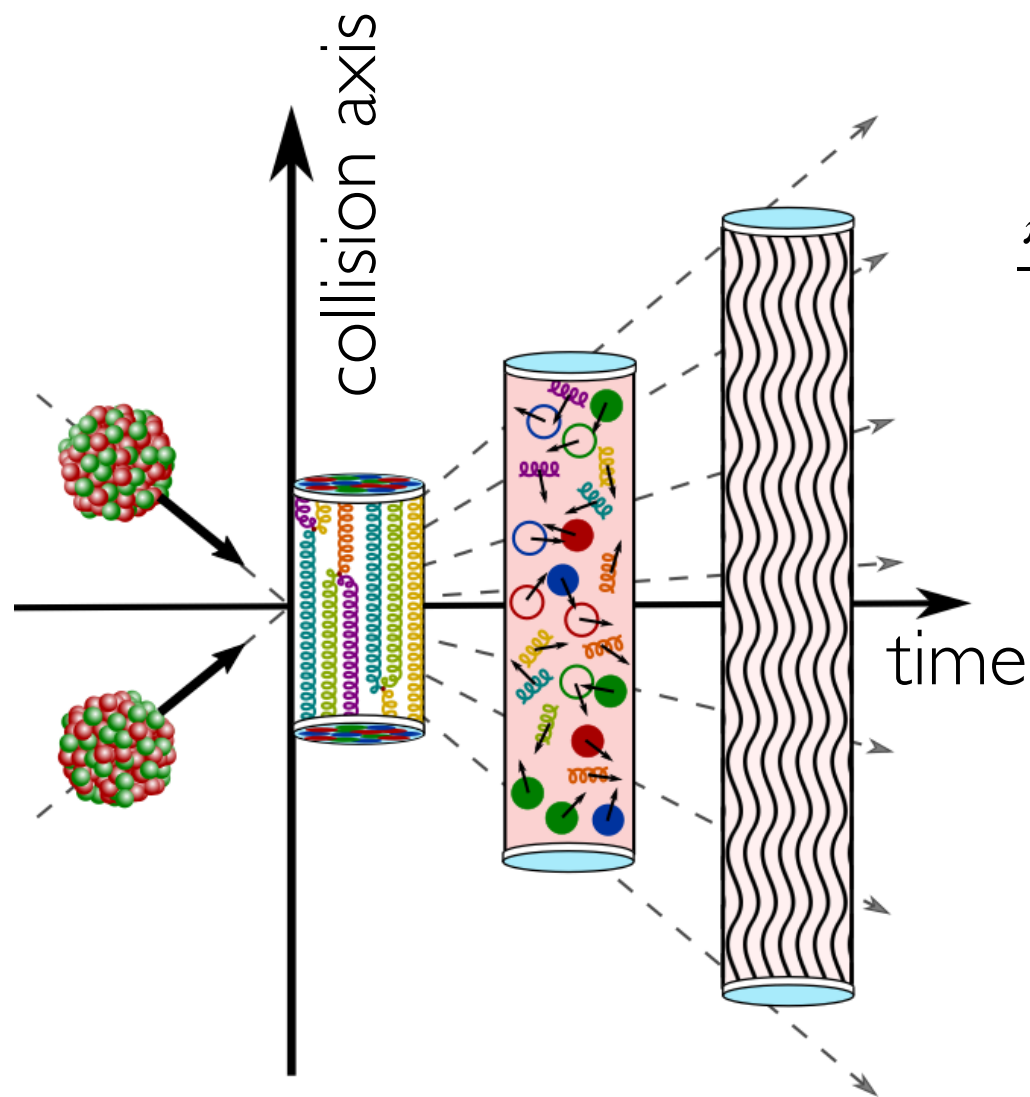
with Berges, Mazeliauskas & Venugopalan

1103.3452 with Janik & Witaszczyk

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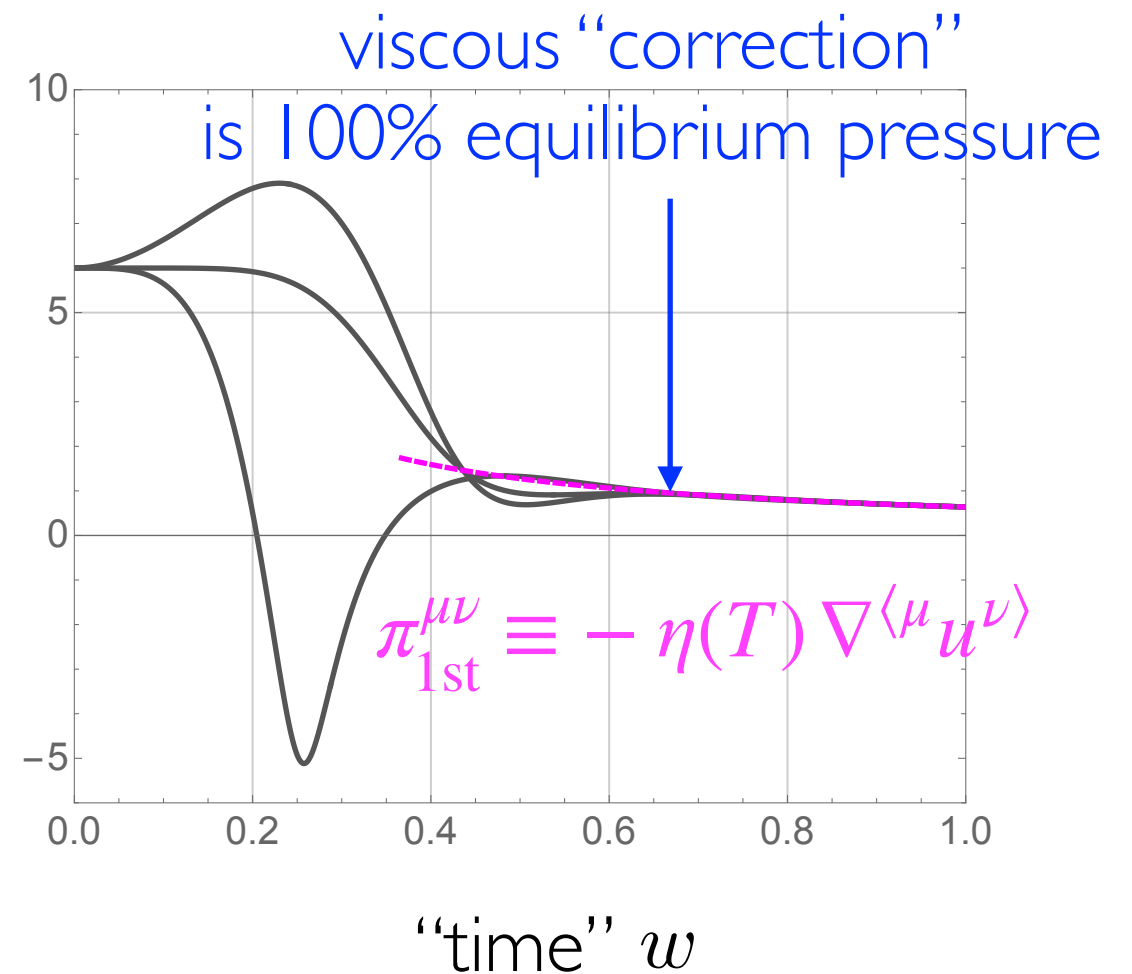
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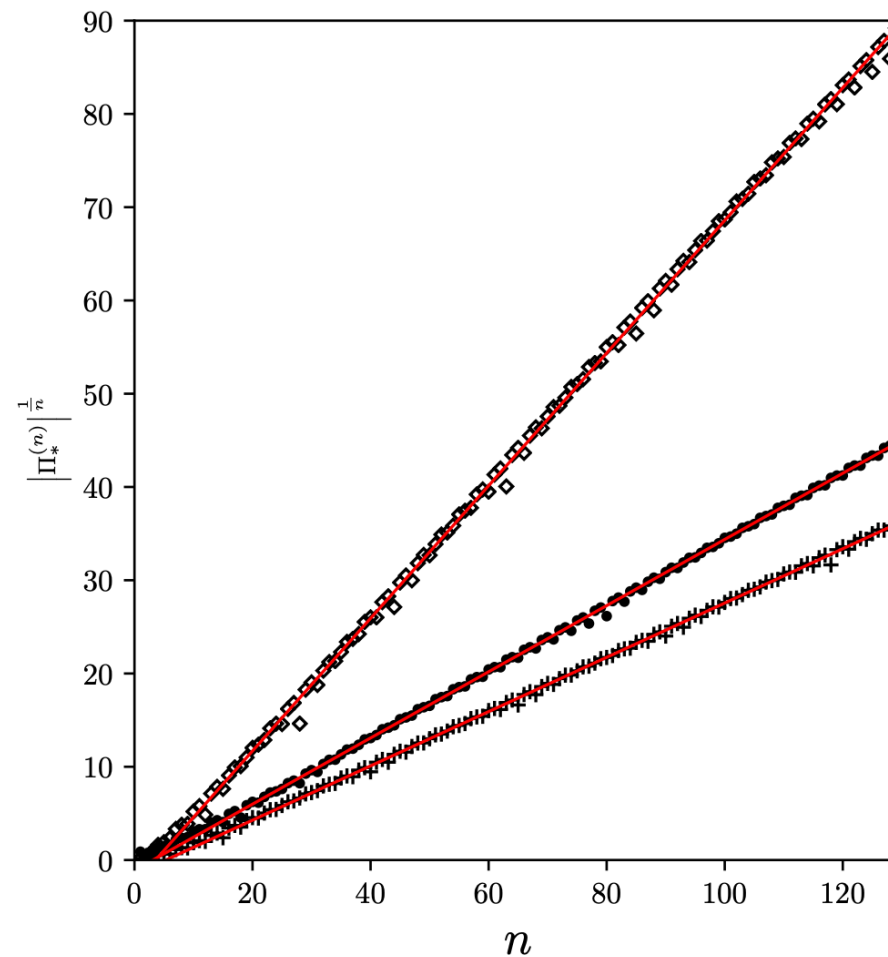
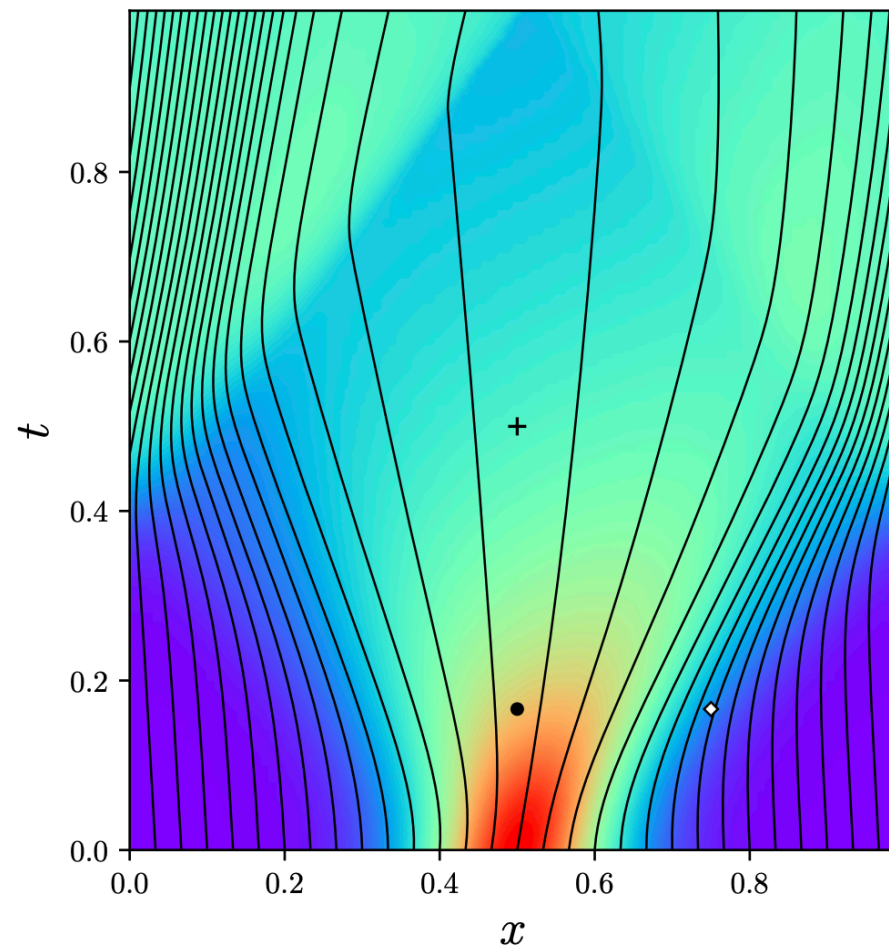


2005.12299

with Berges, Mazeliauskas & Venugopalan

1103.3452 with Janik & Witaszczyk

2011 → 2025



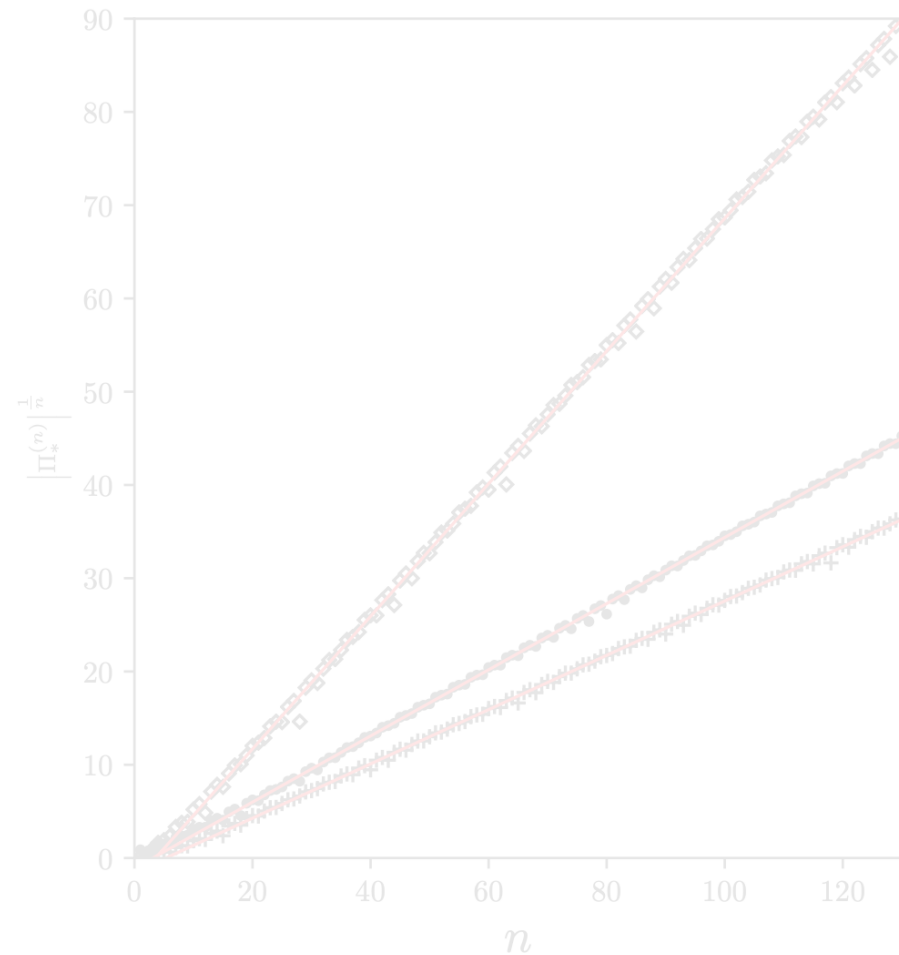
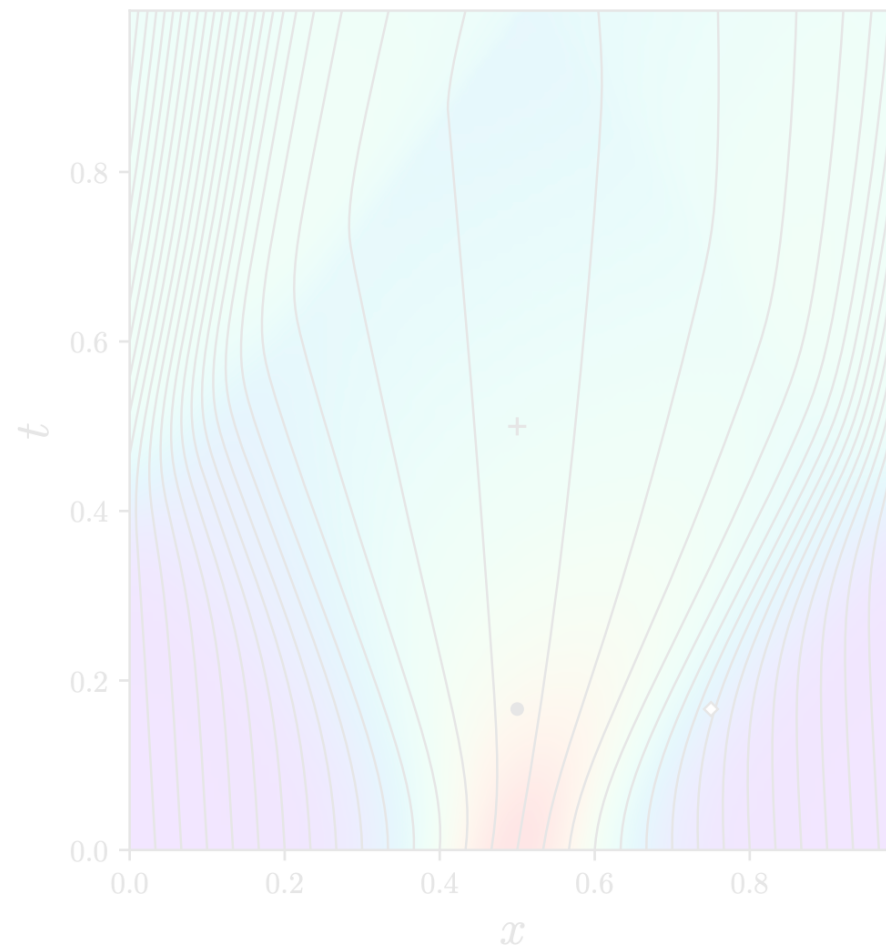
Hydro constitutive relations generally diverge factorially on-shell

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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1302.0697 with Janik, Witaszczyk; 1503.07514 with Spaliński;
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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

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

Isotropic nonthermal fixed points

e.g. **1810.08143** by Schmied, Mikheev and Gasenzer
or **2005.12299** with Berges, Mazeliauskas, Venugopalan
2307.07545 with Mazeliauskas and Preis

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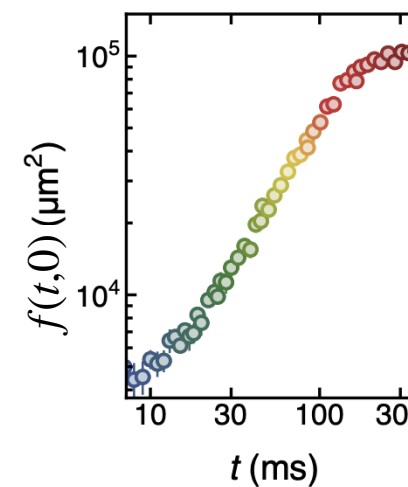
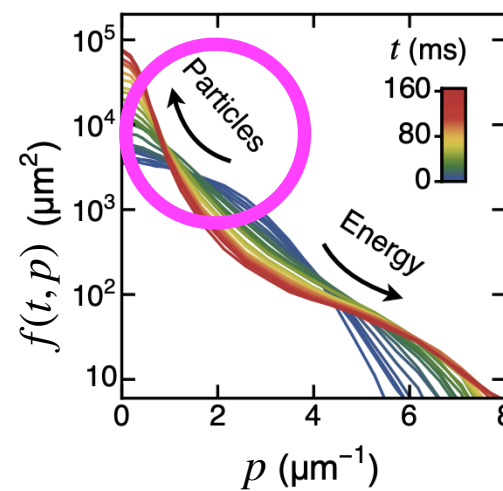
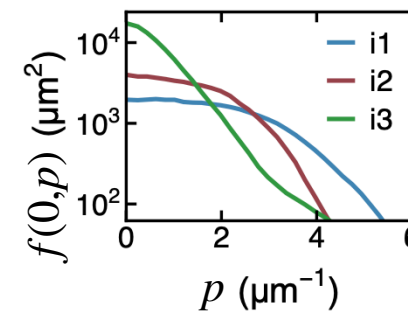
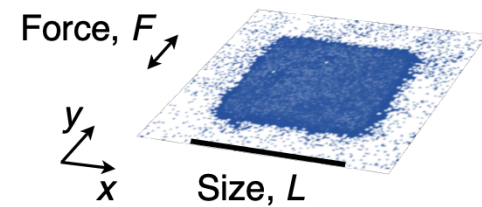
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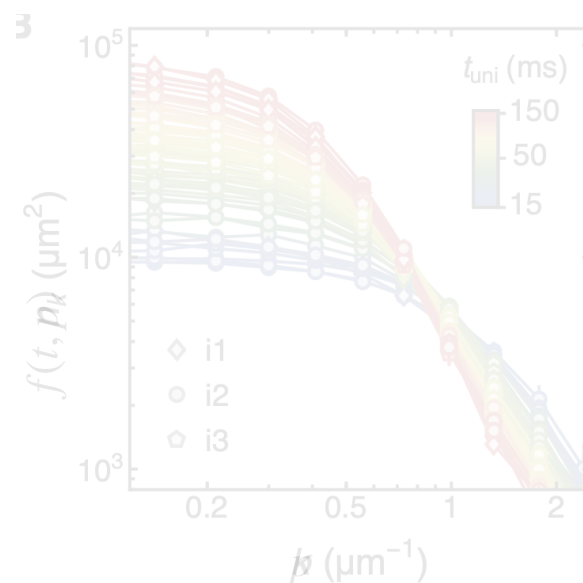
$$f(t, p) \approx A(t) \times f_s \left(B(t) \frac{p}{Q} \right) \text{ with } A(t) = ((t - t_*) Q)^\alpha \text{ and } B(t) = ((t - t_*) Q)^\beta$$

The flagship cold atom experiment

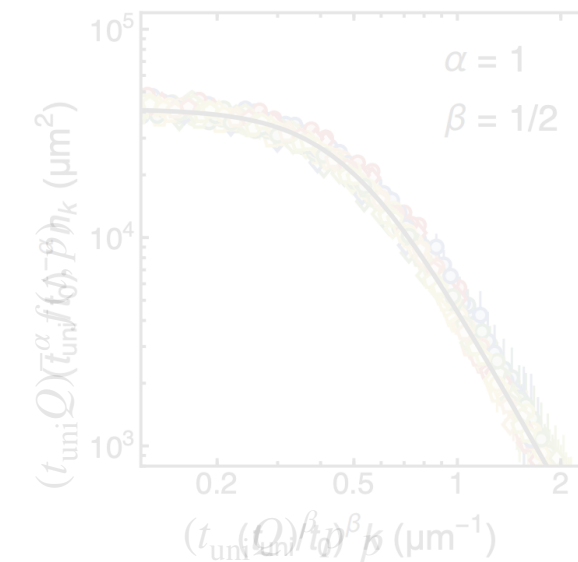
2312.09248 by Gazo, Karailiev, Satoor, Eigen, Galka and Hadzibabic



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 $L = 50 \mu\text{m}$ [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 ($a \rightarrow 0$) 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 ($a \rightarrow 30 a_0$, where a_0 is the Bohr radius), and let the gas relax. The states i1–i3 do not have a defined temperature, but $E = \int \varepsilon(k) dk$, where $\varepsilon = 2\pi\hbar^2 k^3 n_k / (2m)$ and m is the atom mass, gives the total energy. We get $E/k_B = 4.1(3)$ 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].

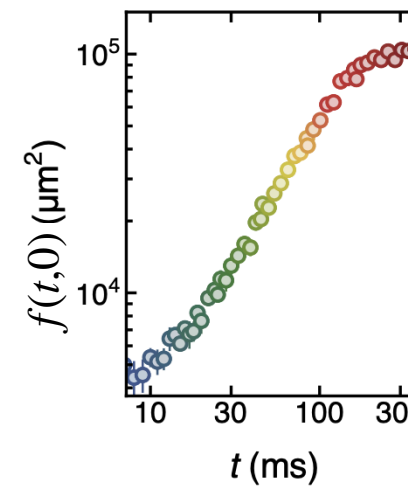
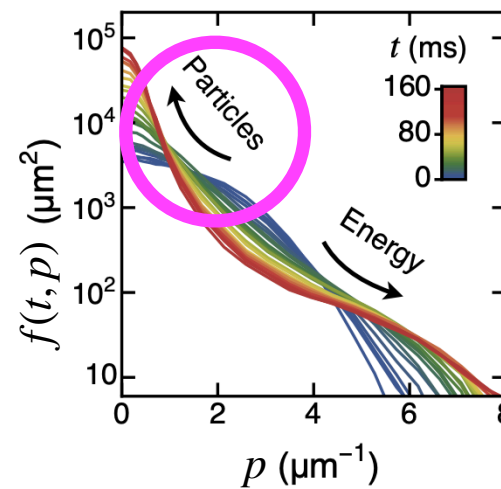
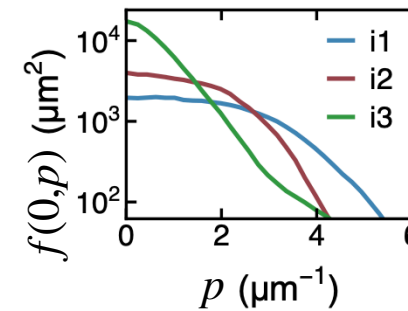
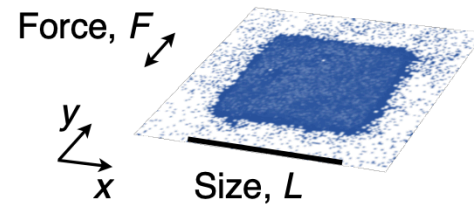


$$t_{\text{uni}} \equiv t - t_*$$

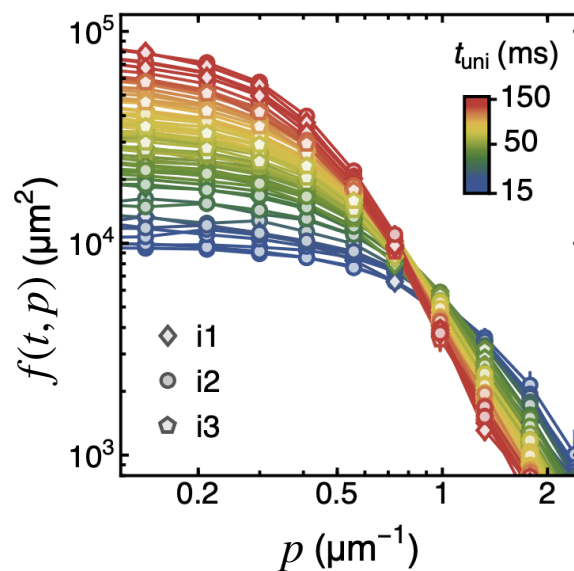


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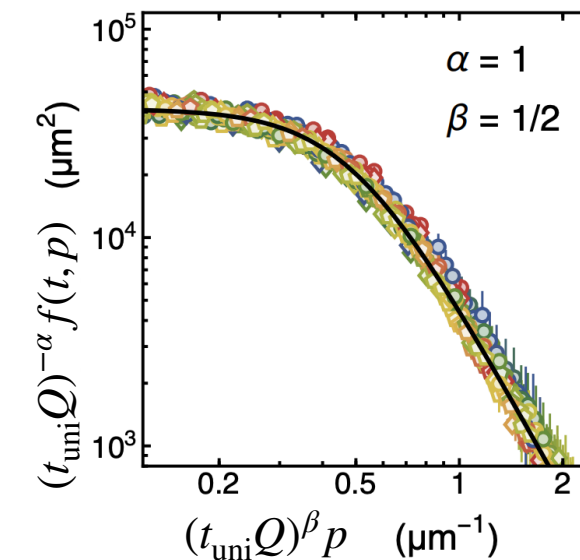
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Comments on nonthermal fixed points

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*
(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

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

Input:

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

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

$$: \quad \tau_\pi(t) D\pi^{\mu\nu} = -\pi^{\mu\nu} + \bar{\eta}(t) \sigma^{\mu\nu} + \dots \quad \text{with}$$

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

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

$$c_{\bar{\eta}} \approx 1.05 \quad \text{Fokker-Planck (fit)}$$

$$c_{\tau_\pi} \approx 3.97 \quad \text{see Matisse' poster}$$

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

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

Input:

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

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

$$: \quad \tau_\pi(t) D\pi^{\mu\nu} = -\pi^{\mu\nu} + \bar{\eta}(t) \sigma^{\mu\nu} + \dots \quad \text{with}$$

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

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

$c_{\bar{\eta}} \approx 1.05$ Fokker-Planck
(fit)
 $c_{\tau_\pi} \approx 3.97$
see Matisse' poster

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Hydrodynamic constitutive relation

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

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

Power-law relaxation

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

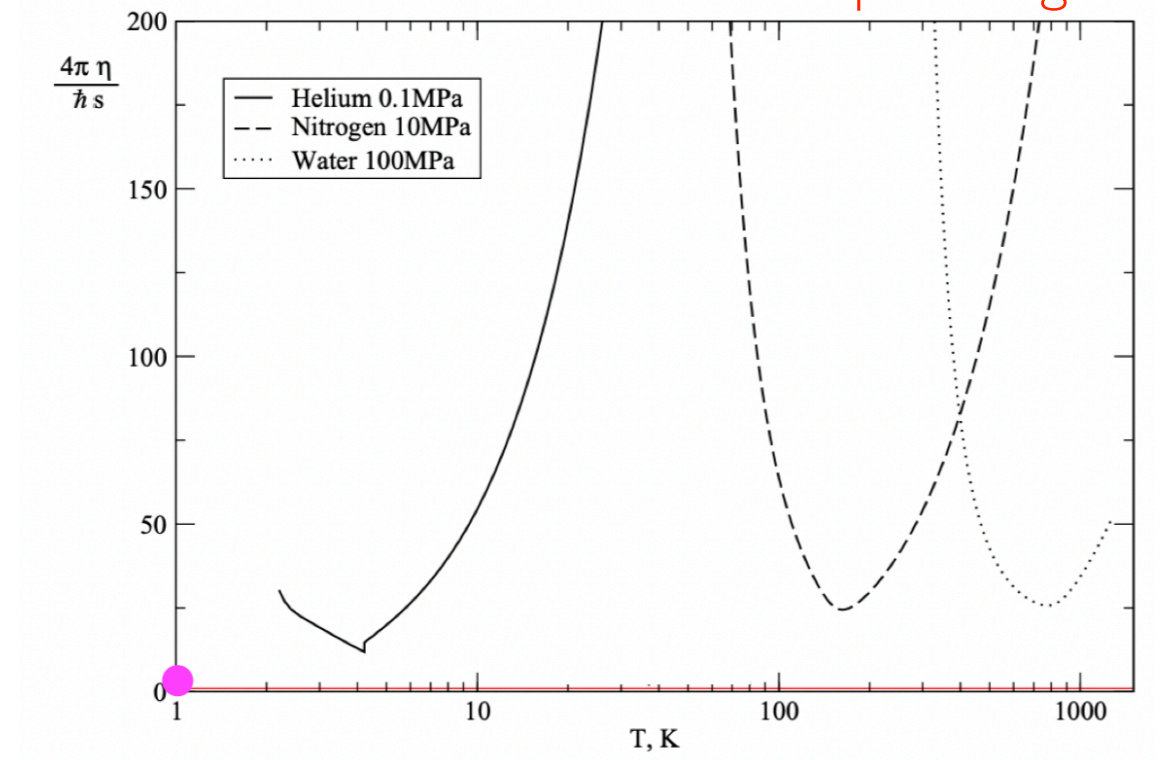


The relaxation of the anisotropy is governed by a power-law*

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



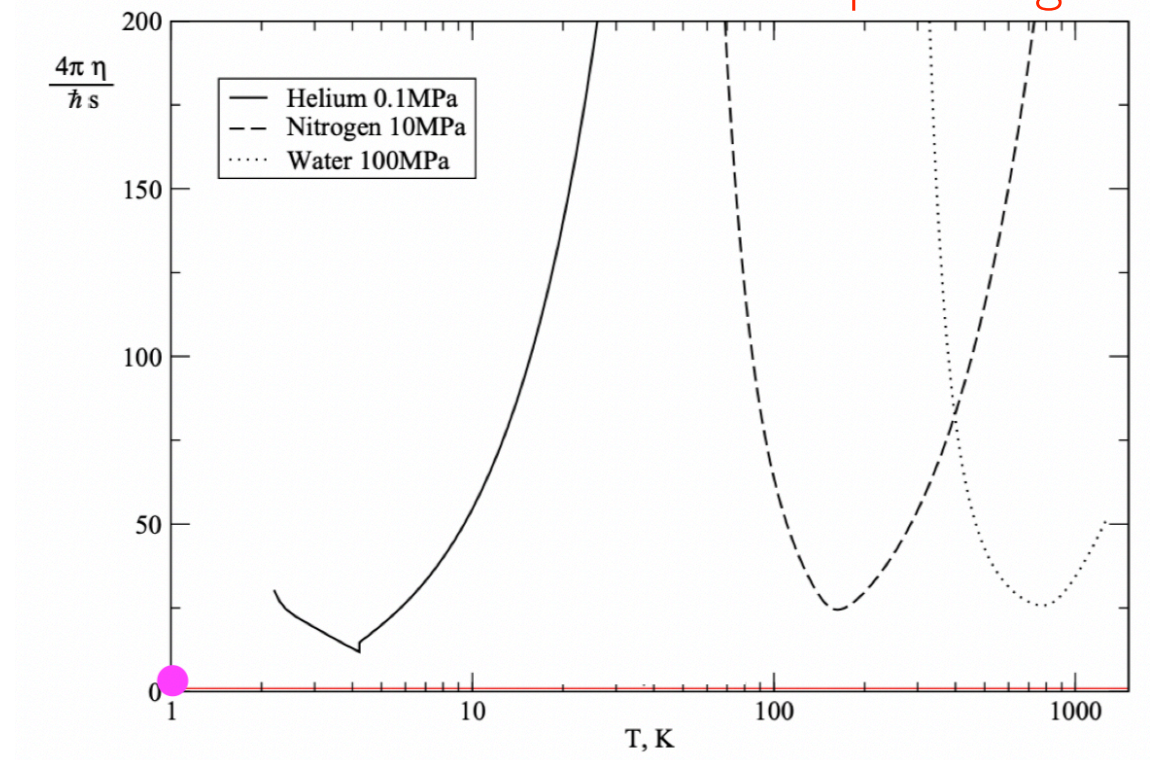
One idea: consider $\frac{\eta}{2\tau_\pi \times (\text{energy density}) \times (c_s/c)^2}$

- ≈ 1 in holography
- ≈ 0.4 water in room temperature
- ≈ 0.4 kinetic theory*: near eq.
- ≈ 0.08 kinetic theory*: far from eq.

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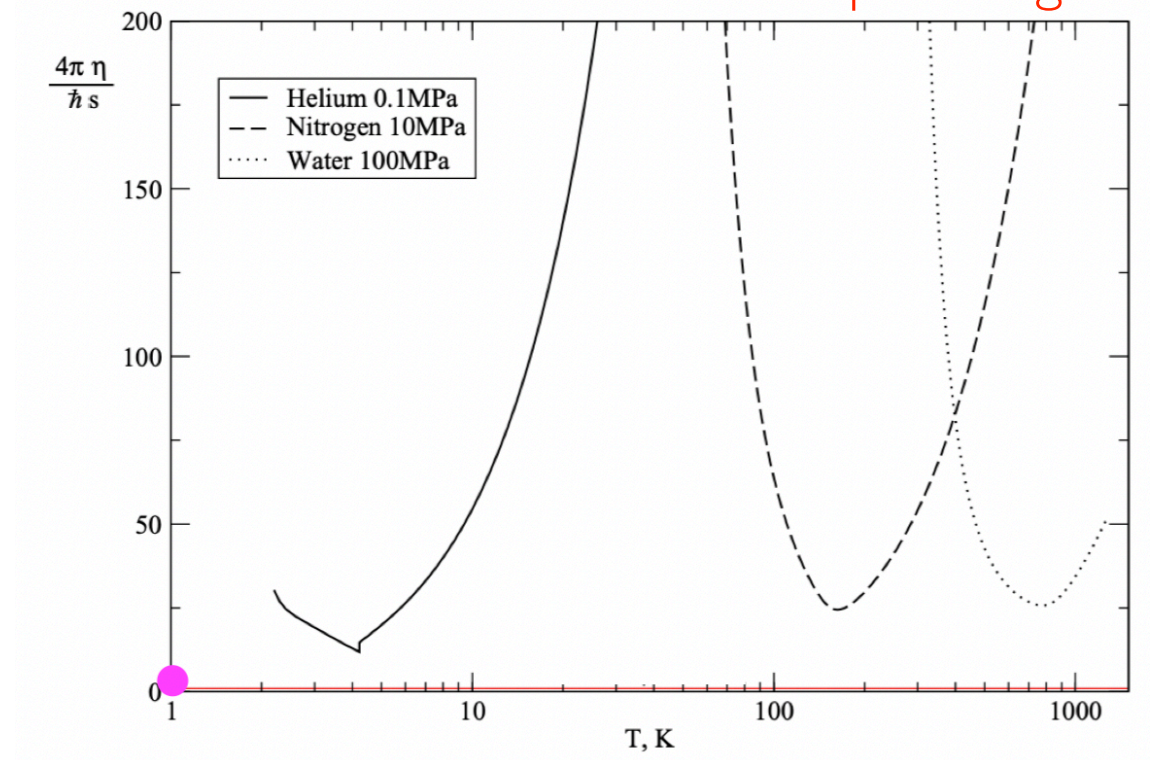
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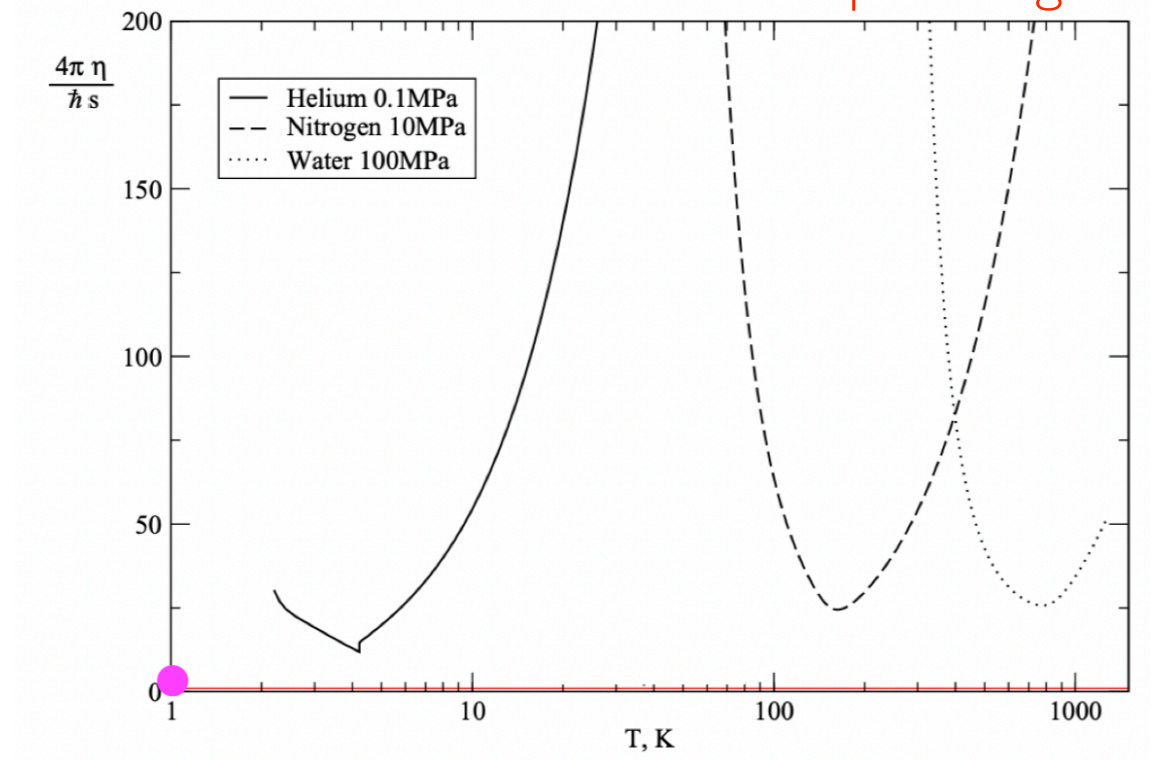
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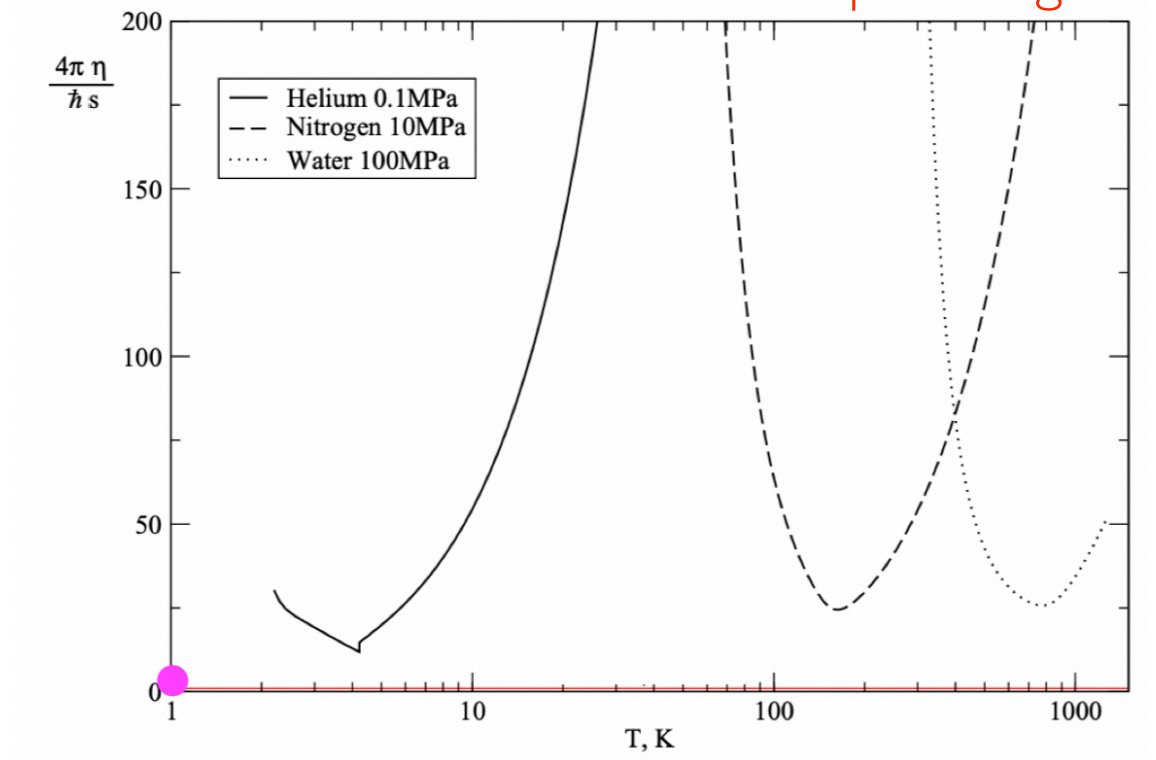
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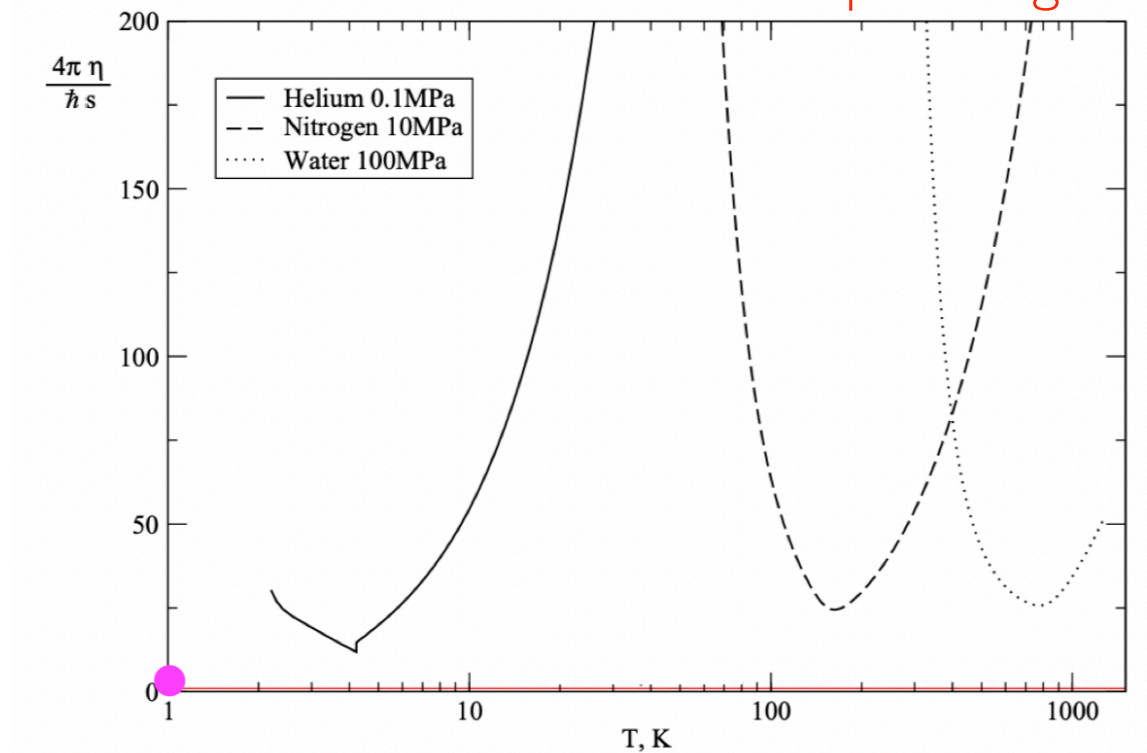
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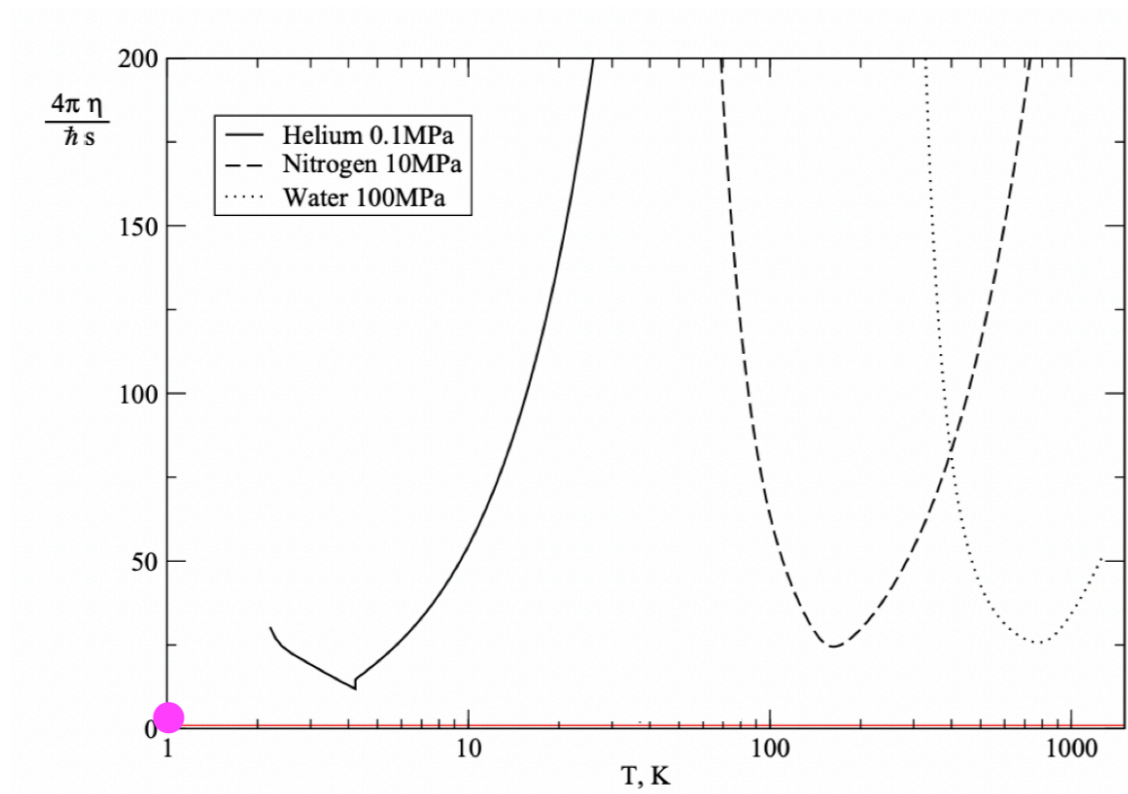
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Summary so far

Nonthermal fixed points indicate novel, exotic realizations of hydrodynamics



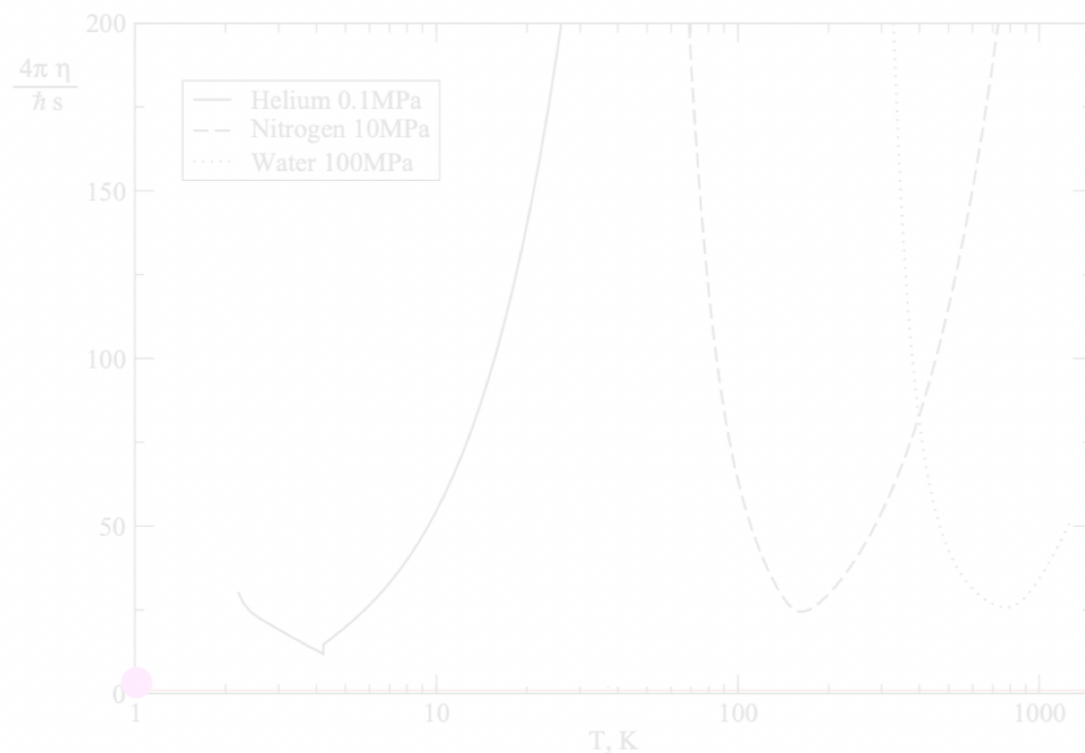
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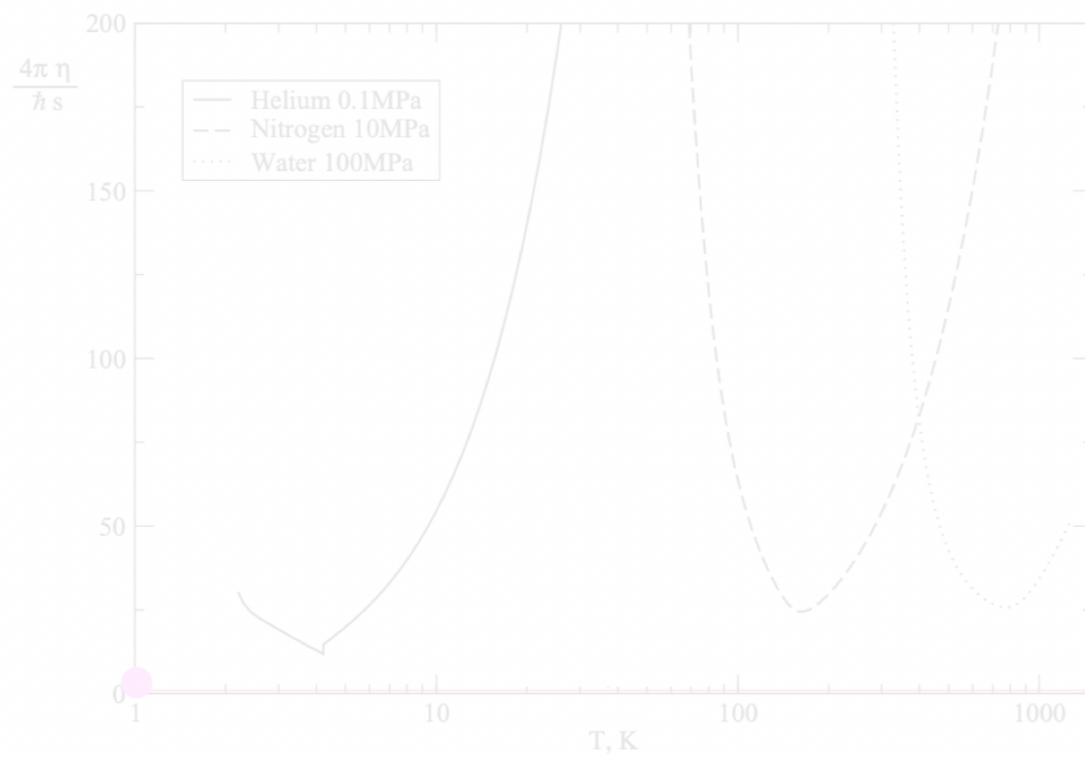
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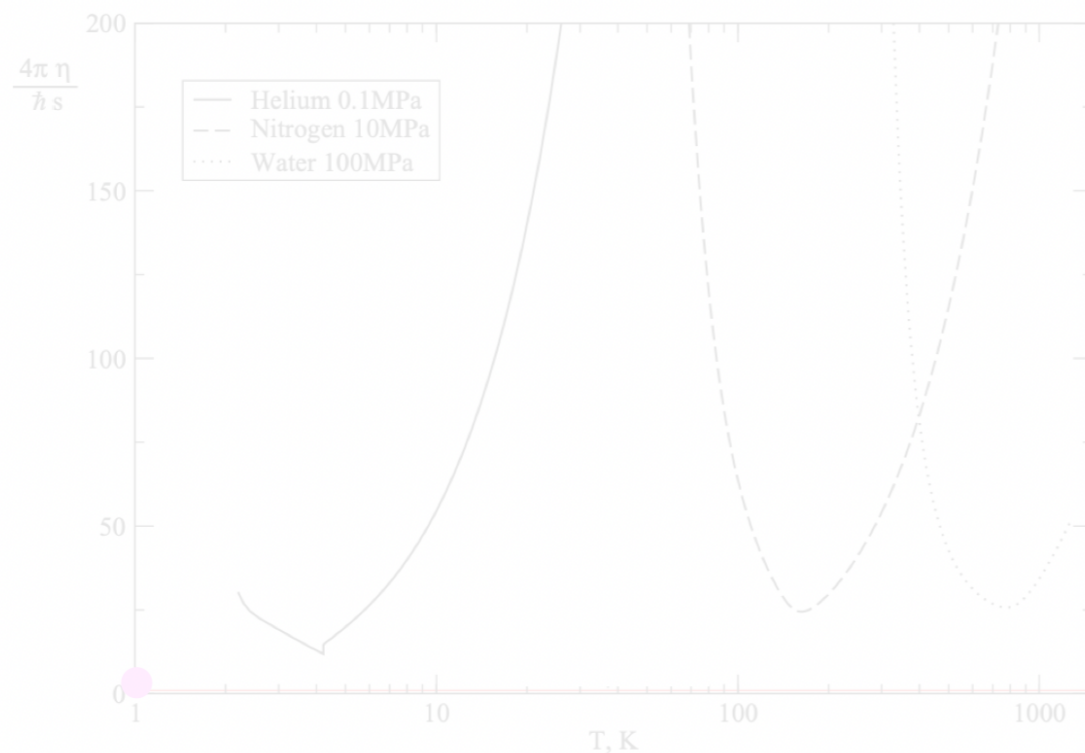
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New idea:

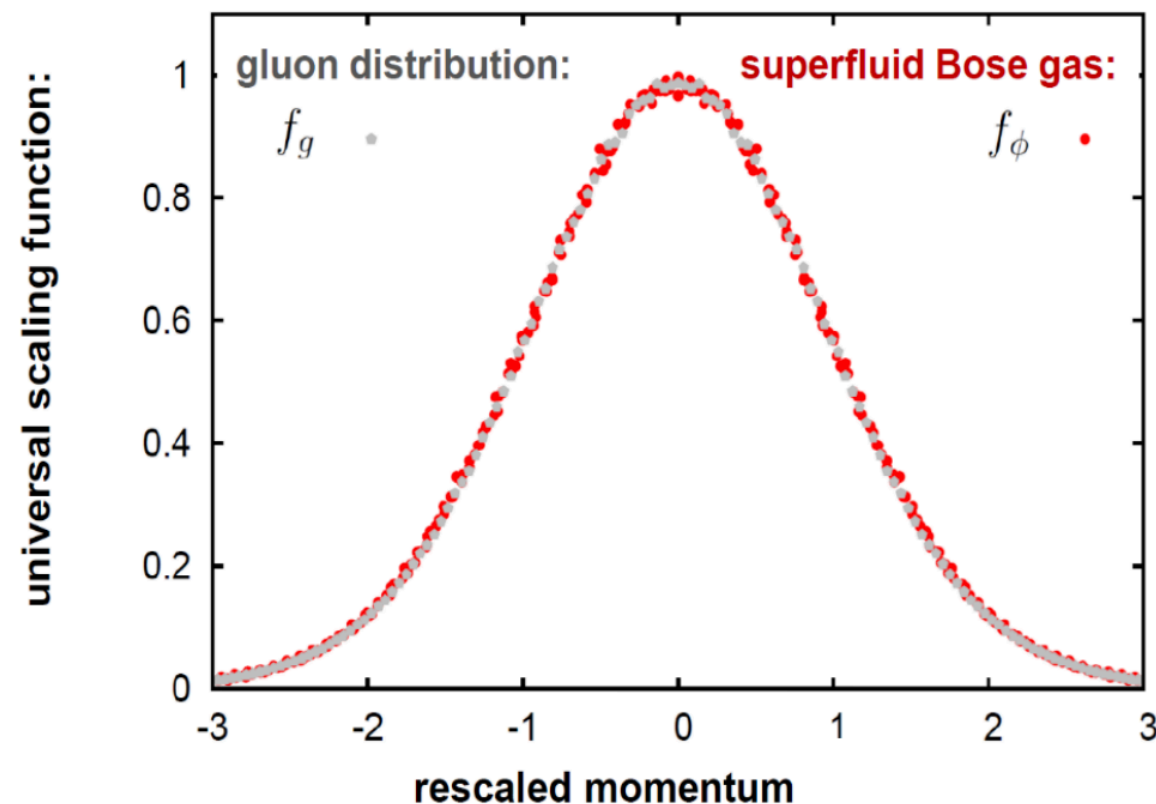
Berges-Boguslavski-Schlichting-Venugopalan nonthermal fixed points from hydrodynamics

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

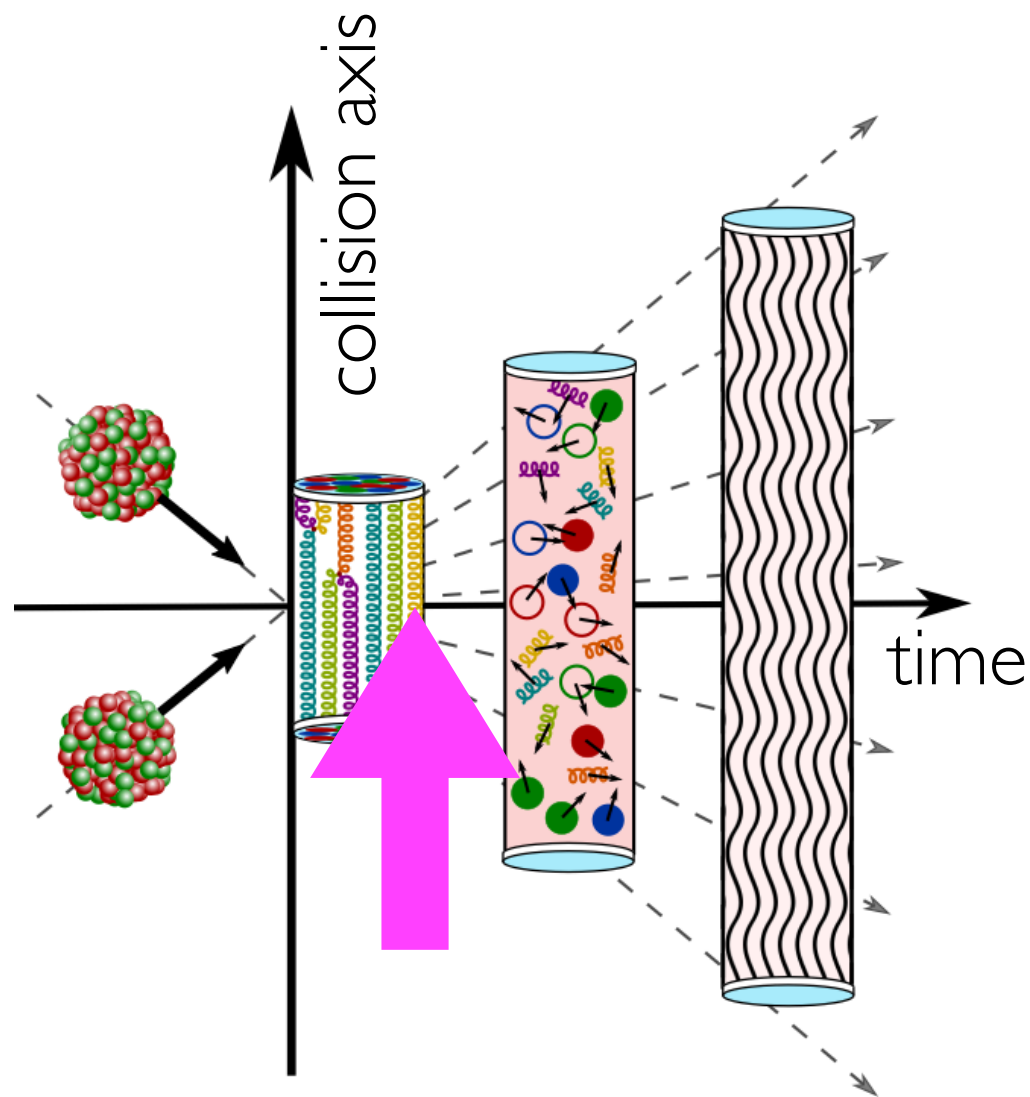
$$\left((t - t_*) Q\right)^\alpha \times f_s \left(\left((t - t_*) Q\right)^\beta p \right) \neq f_{eq} + \delta f$$

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

Truly ideal testing ground for pushing hydrodynamics further

Relativistic hydro and ab initio simulations

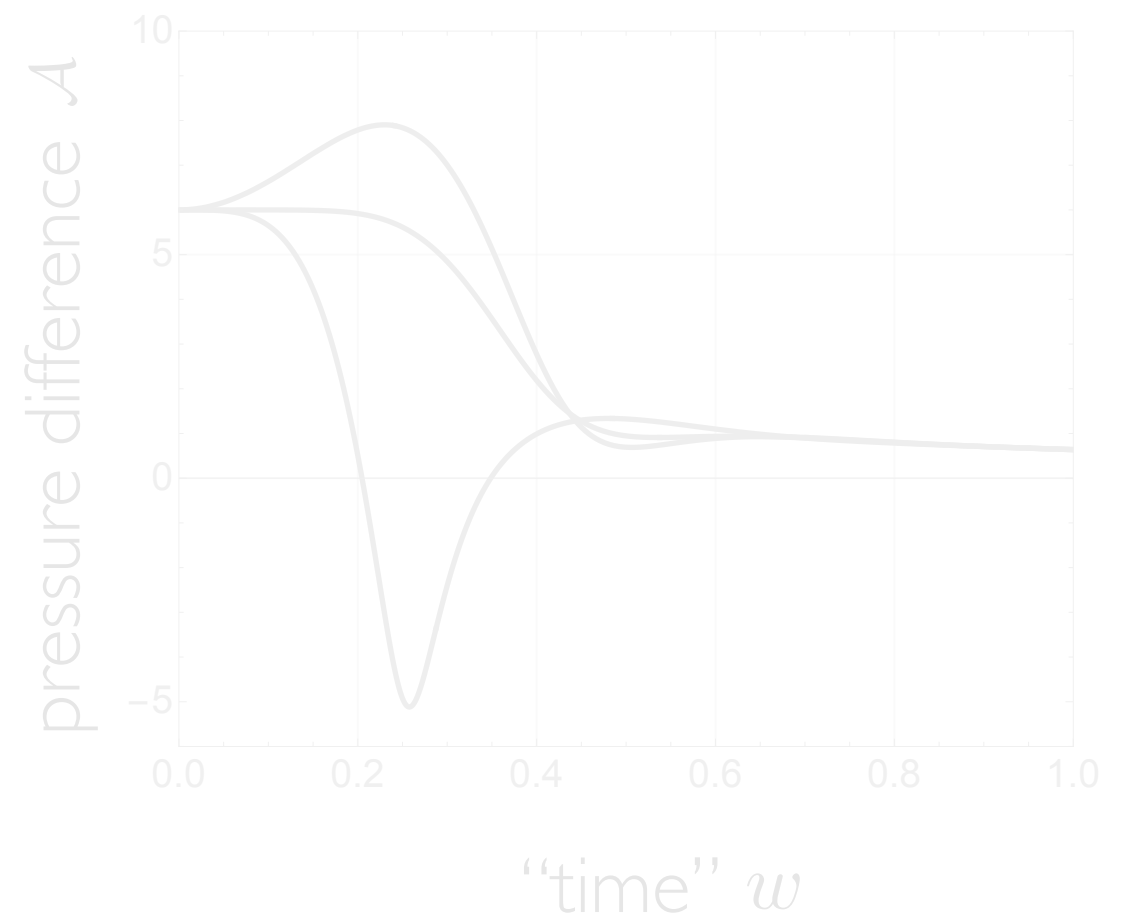
heavy-ion collisions
at RHIC and LHC



2005.12299

with Berges, Mazeliauskas & Venugopalan

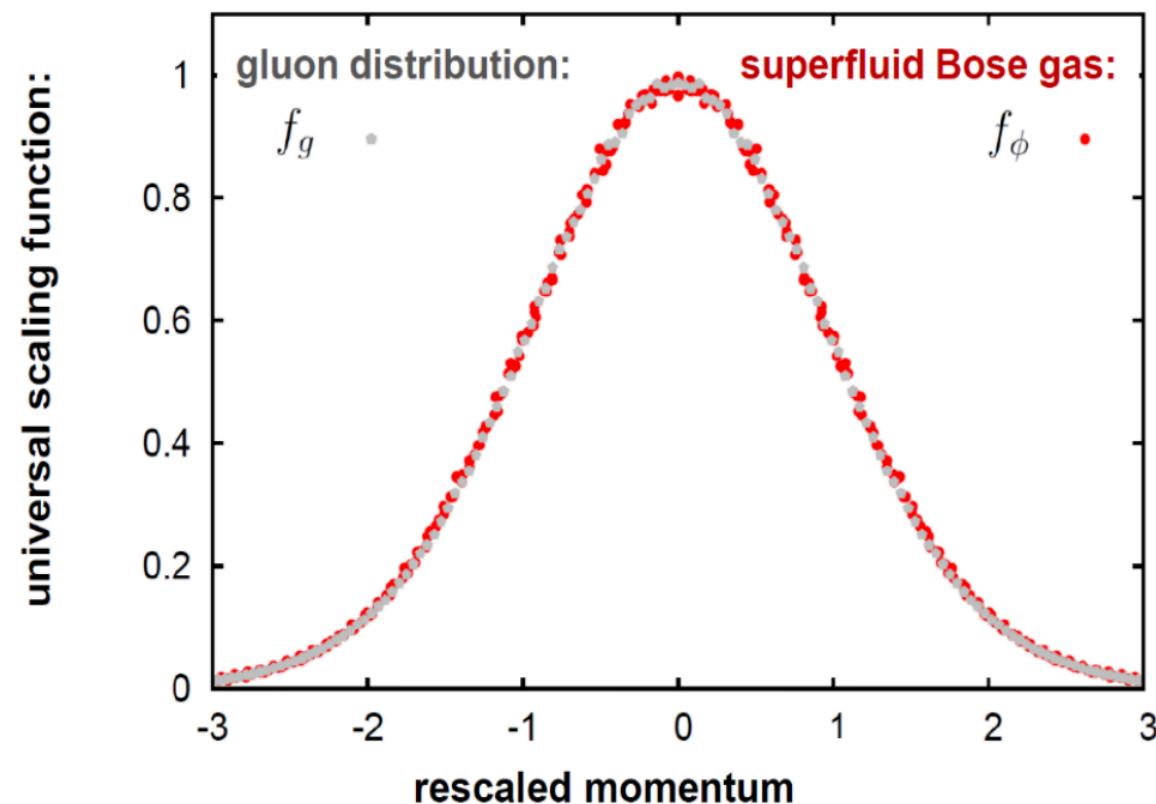
behaviour in
of theoretical models
(here: holographic boost-invariant dynamics)



1103.3452 with Janik & Witaszczyk

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

Bjorken hydrodynamics

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Our result

260x.xxxx with De Lescluze and García Fariña

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

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

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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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Motivation

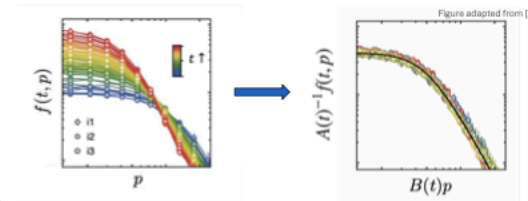
- Thermalization of many-body systems
- Loss of microscopic details at late times
- Local equilibrium: $T(x)$, $P(x)$, $u(x)$, ...
- Dynamics described by hydrodynamics

Is local equilibrium necessary to observe hydrodynamic behavior?

Self-similar evolution of NTFP

Near an isotropic NTFP distribution function is given by:

$$f(t, p) = A(t)f_s(B(t)p) \quad A(t) = B(t)^\sigma \quad \text{and} \quad B(t) = \left(\frac{t - t_*}{t_{ref}} \right)^\beta$$



Test in Bjorken flow

- Longitudinal expansion with velocity $v_z = z/t$ + boost invariance
→ only $\tau = \sqrt{t^2 - z^2}$ dependence
- $\partial_\tau \epsilon + \frac{\epsilon + P_L}{\tau} = 0$: $\epsilon(\tau) \propto \tau^{-4/3}$ → $Q(\tau) \propto \tau^{-1/3}$

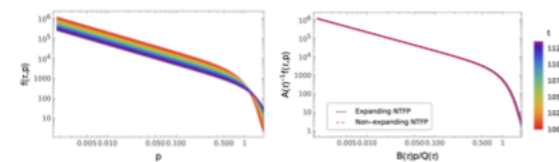
Non-expanding:

$$B(t) = (tQ + c)^{-1/7}$$

Expanding:

$$B(t) = (3/2 \tau^{2/3} \Lambda + c)^{-1/7} = (3/2 \tau Q(\tau) + c)^{-1/7}$$

- Simulation of $\partial_t f - \frac{p_z}{\tau} \partial_{p_z} f = C[f]$ for small-angle elastic gluon scatterings initialized on static NTFP solution f_s

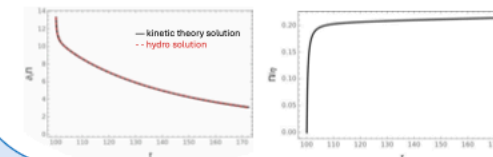


Beyond ideal hydro

$$T_v^\mu = \text{diag}(-\epsilon(\tau), P(\tau) + \frac{2\Pi(\tau)}{3\tau}, P(\tau) + \frac{2\Pi(\tau)}{3\tau}, P(\tau) - \frac{4\Pi(\tau)}{3\tau})$$

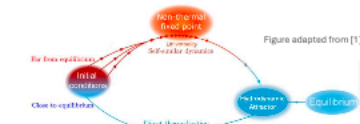
MIS-like: $\tau_{\pi}(\tau) \partial_{\tau} \Pi + \Pi = \eta(\tau) + \frac{\tau_{\pi}(\tau) \Pi}{\tau}$

with $\eta/Q^3, \tau_\pi Q \propto (\tau Q + c)$ time-dependent transport coefficients^[3]



Nonthermal fixed points

- Heavy-ion collisions, cold atom gases, early universe cosmology
 - Far from equilibrium attractors
 - Loss of microscopic memory
 - Collective dynamics in terms of scaling variables
 - Strongly constrained by conservation laws
- Hydrodynamics



Conservation laws

$$\partial_t \epsilon = 0 \text{ for } f(t, p) = A(t)f_s(B(t)p/Q)$$

$$\epsilon = \int d^3p p f(t, p) = A(t)B(t)^{-4}Q^4 \int d^3\bar{p} \bar{p} \bar{f}_s(\bar{p})$$

To be constant:

$$A(t) = B(t)^4$$

Momentum scale Q defined by energy density ϵ :

$$Q \propto \epsilon^{1/4}$$

Global to local

If gradients are present, system first reaches local equilibrium

$$f_{eq}(p/T) \rightarrow f_{eq}(p/T(x))$$

Generalization for NTFP

$$A(t)f_s(B(t)p/Q) \rightarrow A(x)f_s(B(x)p/Q(x))$$

$$Q(x) \propto \epsilon(x)^{1/4}$$

Anisotropic NTFP

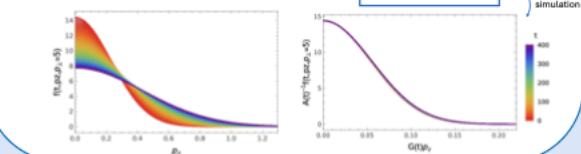
First stage of BMMS bottom-up thermalization scenario^[4]

$$f(\tau, p_{\perp}, p_z) = A(\tau) f_S(B(\tau) p_{\perp} / Q_{\perp}(\tau), G(\tau) p_z / Q_z(\tau))$$

$$G = \left(\frac{r^2 Q_1^2}{2\Lambda} + c \right)^{-1/3} = \left(\frac{r Q_1^2}{2 Q_2(r)} + c \right)^{-1/3} \quad A = G, \quad B = \text{const}$$

$Q_z(\tau) = \Lambda / \tau$ and $Q_\perp = \text{const}$ follow from $\partial_\tau(\tau n) = 0$ and $\partial_\tau(\tau \epsilon) = 0$ ^[5]

Implies non-expanding anisotropic NTFP with $G = \left(\frac{\tau Q_z^2}{Q_x} + c \right)^{-1/3}$



[1] Mikheev, A.N., Sovitz, I. & Gasenzer, T. Universal dynamics and non-thermal fixed points in quantum fluids far from equilibrium. *Eur. Phys. J. Spec. Top.* **232**, 3393–3415 (2023)

[2] M. Geco, A. Karateev, T. Cogen, M. Galke and Z. Hadzibabic, Universal Coarsening in a Homogeneous Two-Dimensional Bose Gas, *arXiv:2312.02424*

[3] J. Berges, G. S. Denicol, M. Hecht, and T. Preis, Far from equilibrium hydrodynamics of nonthermal fixed points, *arXiv:2504.18754*

[4] R. Baier, A. H. Mueller, D. Schiffrin, and D. T. Son, "Bottom up" thermalization in heavy ion collisions, *Phys. Lett. B* **502**(2001) 51–58

[5] D. de Leuzio, M. P. Heller, A. Mazeliauskas, B. Scheuing-Hirschfeld, and C. Werthmann, Adiabatic hydrodynamization and quasimodal modes of nonthermal attractors, *arXiv:2510.15016*

see Matisse' poster tomorrow
for a complementary discussion

Outlook

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

260x.xxxx with De Lescluze and García Fariña

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- 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
- cold atoms realization?

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Backup

Quasinormal modes of nonthermal fixed points

2502.01622 with De Lescluze

On a nonthermal fixed point:

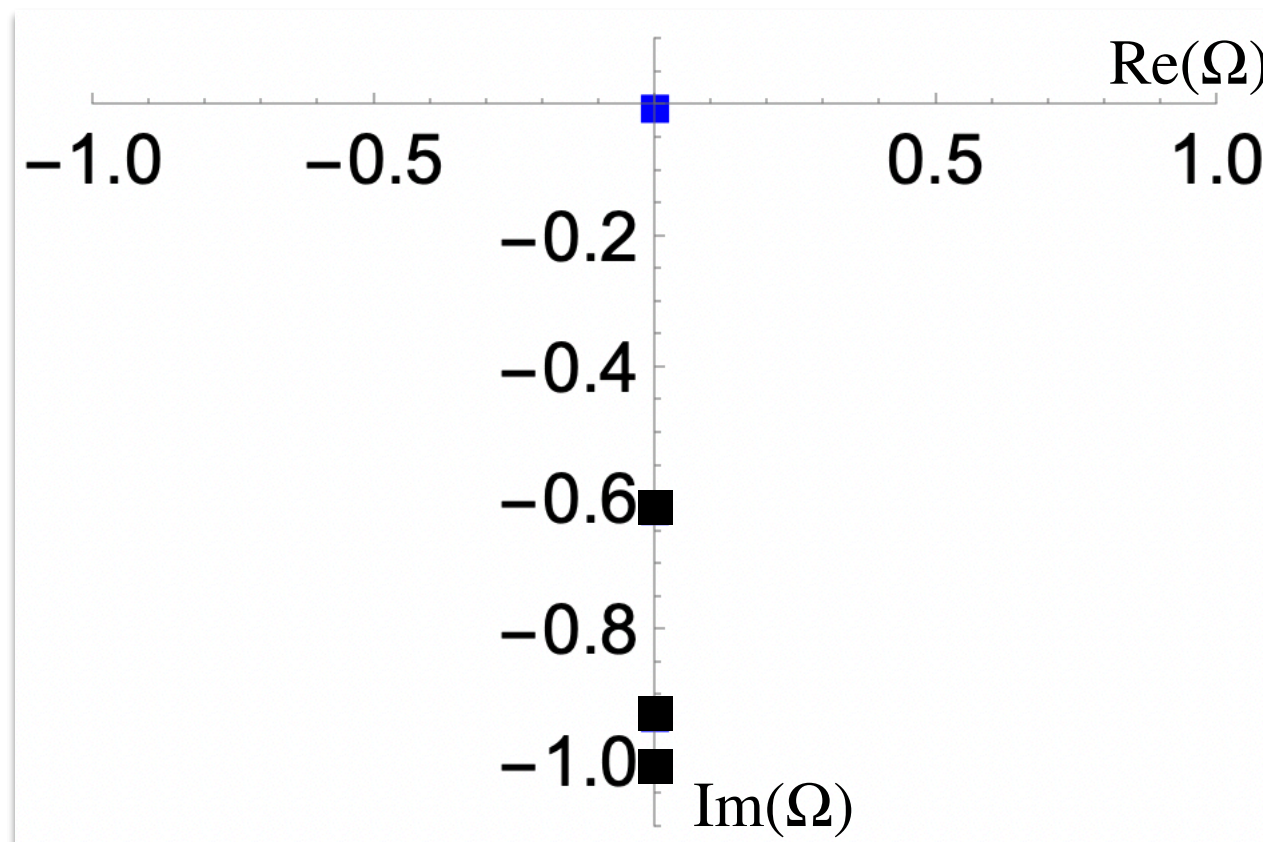
$$f(t, p) \approx (t_{\text{uni}} Q)^\alpha f_{\text{scaling}} \left[(t_{\text{uni}} Q)^\beta p/Q \right]$$

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

directly before that:

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

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



backup