QCD dynamics: some theory developments

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C²QA

Non-perturbative and Topological Aspects of QCD Workshop, CERN

Plan

Frontiers of hydro

1) "Critical" hydro and soft pions

PRD 2022 , PRD 2024 with E. Grossi, D.Teaney, A. Soloviev

+ wip A. Mazeliauksas

2) Chiral magnetic effect and progress on chiral MHD

arXiv:2309.14438 with A. Das, N. Iqbal, N. Poovutikul

Emergence of hydro

3) Entanglement generation and equilibration in $1+1$D

PRL 2023, arXiv:2404.00087 with D. Frenklakh, K. Ikeda, D. Kharzeev, V. Korepin, S. Shi, K. Yu

My memories of hydro

Euler,

Navier-Stokes, . . .

$$\partial_t(\rho v_i) + \partial_j(\cdots ?) = 0$$

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Poiseuille

Fig. 20. Chien curarisé par ingestion. — La branche horizontale d'un manomètre est engagée dans l'artère carotide [1].

www.cardio-online.fr

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Hydro from symmetries

Symmetries $\longleftrightarrow$ Conservation laws

Equilibrium (static) state $\hat{\rho}$

Hydro: Systematic expansion of cons. laws around $\hat{\rho}$

[Kovtun, 12], [Gloriosio, Liu, 18] for reviews

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Charge cons.: $\partial_t n = \vec{\nabla} \cdot \vec{j}$

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Hydro variables: energy density ϵ
pressure density p
charge density n

What if...

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Critical slowing down

2^{nd} order phase transition

↓

In space: diverging correlation length

||

Fluctuations correlated all over

In time: critical slowing down

||

Order parameter is frozen

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2^{nd} order phase transition

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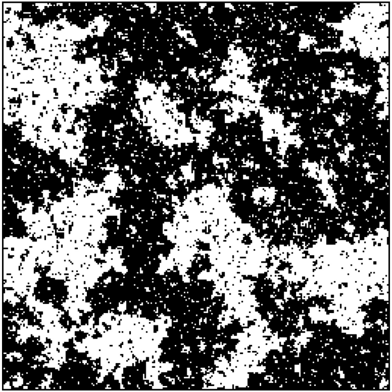
Order parameter is frozen

Example: 2D Ising at T_c



mattbierbaum.github.io

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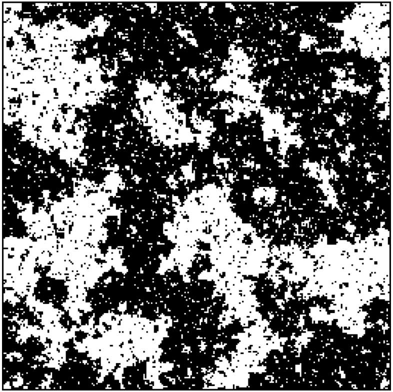

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Critical hydro

Frozen order parameter

↓

Extra slow variable

↓

Changes hydro near criticality!

Relevant to QCD:

- Close to putative (T, μ) crtical point

"Model H":

[Chattopadhyay, Ott, Schaefer, Skokov, 24]

- Close to $(T, \mu = 0)$ crossover

"Model G": [Schlichting, Smith, von Smekal, 19]

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"Model G" story

Fact from lattice: $m_{up} = m_{down} = 0$

deconfinement phase trans. 2^{nd} order

Fact from life: m_{up}, m_{down} are small

Remnant of critical behavior?

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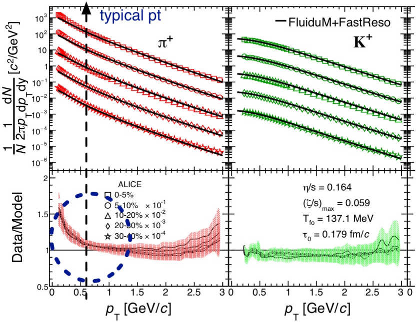
Fact from ALICE

A recent ordinary hydro fit from Devetak et al 1909.10485



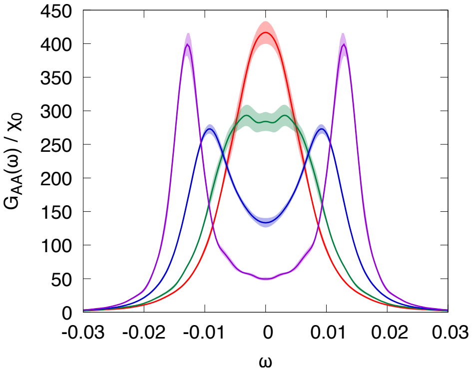
A glimpse at results

Detailed numerical simulations of Model G: ✓

PRD 2022 , PRD 2024

Pheno. prediction of excess pion yield: work in progress

Trailer: emergence of pions below T_c



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Chiral Magnetic Effect

Chiral Magnetic Effect (CME):

Constant $\vec{B}$ background

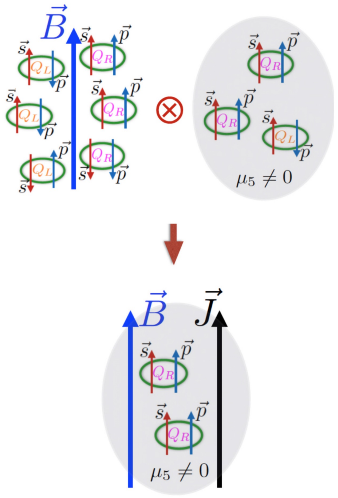
$+$

Chiral imbalance μ_5

$=$

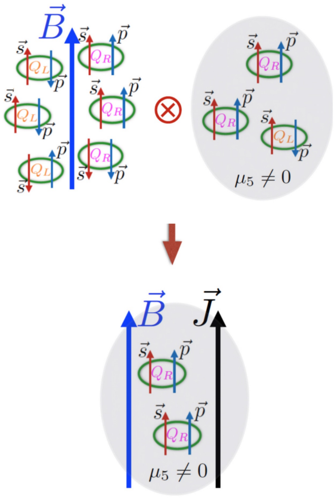
Magnetic current

$$\vec{j} = \sigma \vec{E} + \frac{1}{4\pi^2}\mu_5 \vec{B}$$



Credit: Kharzeev, Liao, Voloshin, Wang, arXiv: 1511.04050

But wait...



Credit: Kharzeev, Liao, Voloshin, Wang, arXiv: 1511.04050

$\mu_5 \longleftrightarrow$ axial charge $\sim n_5 = n_L - n_R$

$\downarrow$

Not conserved: $\frac{\partial n_5}{\partial t} \propto \vec{E} \cdot \vec{B}$

?!

Recent developments

- Derivation as an hydro theory

[Landry, Liu, 22] [Das, Iqbal, Poovutikul, 22]

- Relevant transport coeff. Γ_5 is now properly understood

resistivity (r) $\neq$ 1/conductivity (σ) in general

[Grozdanov, Hofman, Iqbal, 16]

- Extreme example $\sigma = 0$, $r \sim 1$ in scalar ED at strong coupling

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- Affects microscopic computation of chiral transport

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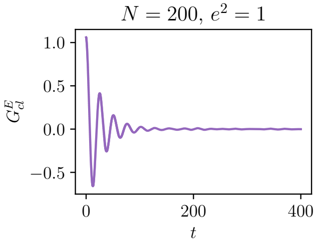
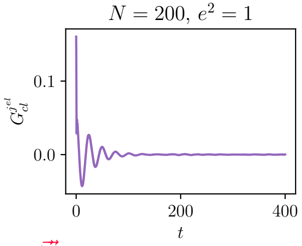


$$r \sim \langle \vec{E}\vec{E} \rangle = 1.059 \pm 0.032$$



$$\sigma \sim \langle \vec{j}\vec{j} \rangle = -0.0001 \pm 0.00014\ ?!$$

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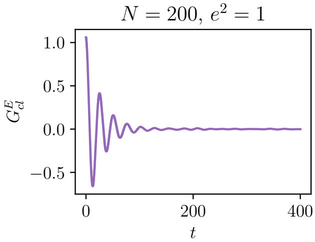

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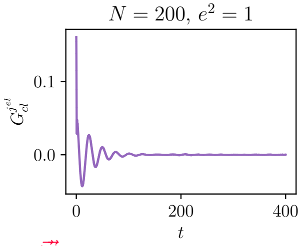

$\sigma \sim \langle \vec{j}\vec{j} \rangle = -0.0001 \pm 0.00014$?!

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3) Entanglement generation and equilibration in $1+1$D

Emergence of hydro in real-time

Thermalization from unitary evolution?

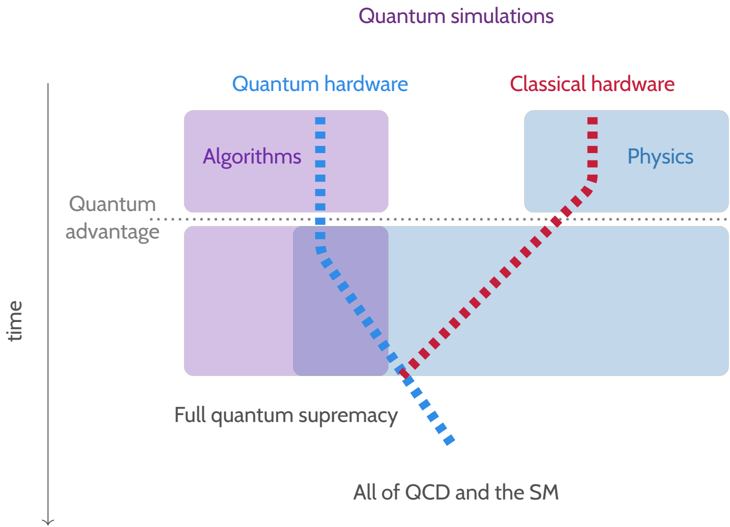
Chaos ⟷ Decoherence

Eigenstate thermalization hypothesis

...

TODO: see hydro emerge from micro
for an interacting relativistic system

Opportunity: quantum simulations



A toy-model

Schwinger model: QED in $1+1D$

- Confines
- Chiral condensate and anomaly
- Interacting
- Simple enough to solve the *quantum* dynamics: $|\psi(t)\rangle = e^{-iHt}|\psi_0\rangle$

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Setup: fly hard particles ($\bar{q}q$) on the light cone, in opposite direction

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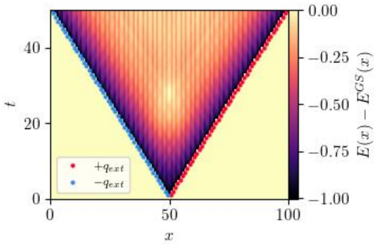

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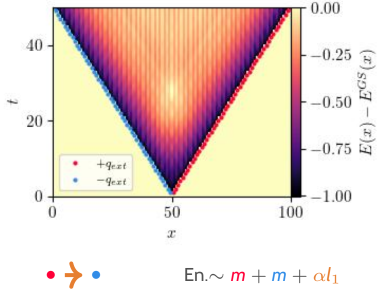

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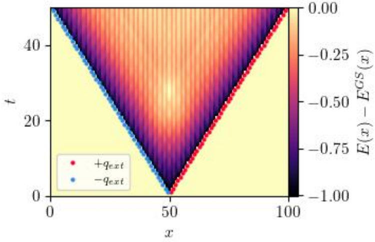

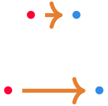

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En.$\sim m + m + \alpha l_2$

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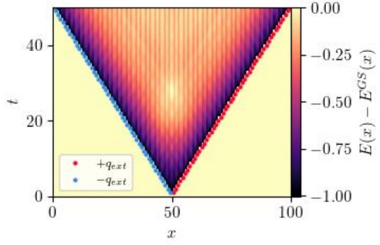

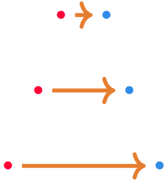

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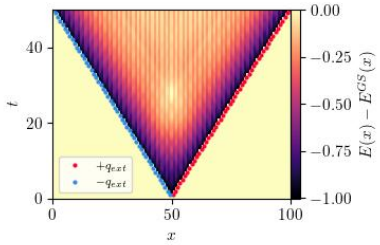

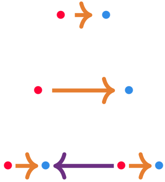

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$\downarrow$

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when $\alpha l_3 > 2m$

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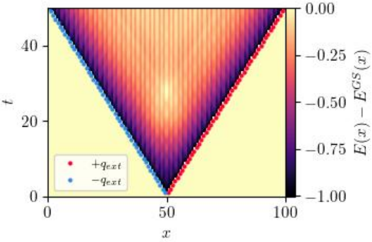

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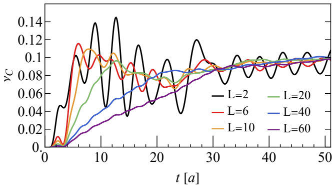
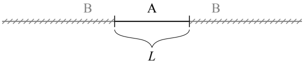
Relaxation

Condensate in the center





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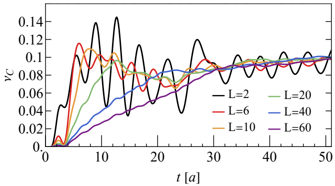

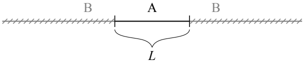

And more!

More:
- Inspiration for new observables
- Entanglement generation

Next:
- Thermal?
- Hydro?

Take home

- Theory is progressing on QCD dynamics

- Hydro is modified by criticality

- Hydro is modified by anomalous transport

- First principle quantum simulations start to tackle the emergence of hydro

Frontiers of hydro

↕

Emergence of hydro

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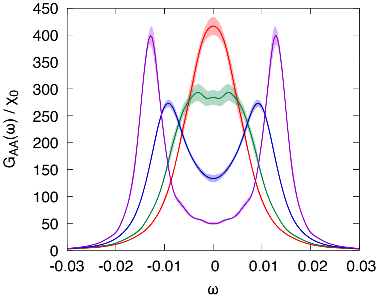
Trailer: emergence of pions below T_c



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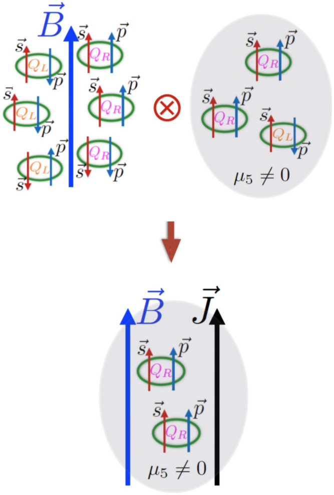

Credit: Kharzeev, Liao, Voloshin, Wang, arXiv: 1511.04050

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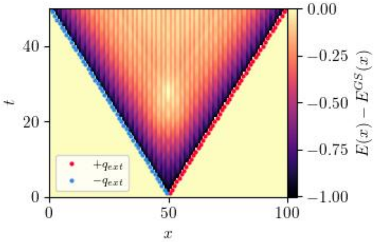
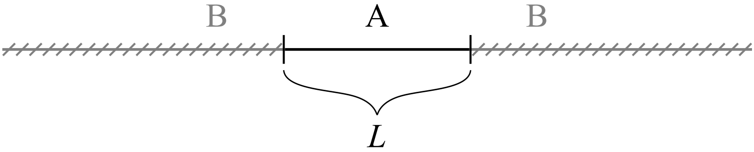


“QCD Dynamics” by DALL·E 3

Area versus volume law



Gapped ground states: area law

Thermal states: volume law

Ent. entropy: $S = -\mathrm{Tr}\left(\rho_A \ln \rho_A\right)$ ✓

Renyi entropy: $S = -\ln\left(\mathrm{Tr}\left(\rho_A^2\right)\right)$ ✓

Area versus volume law