The Reasonable and Unreasonable Effectiveness of Hydrodynamics in Exotic Quantum Matter

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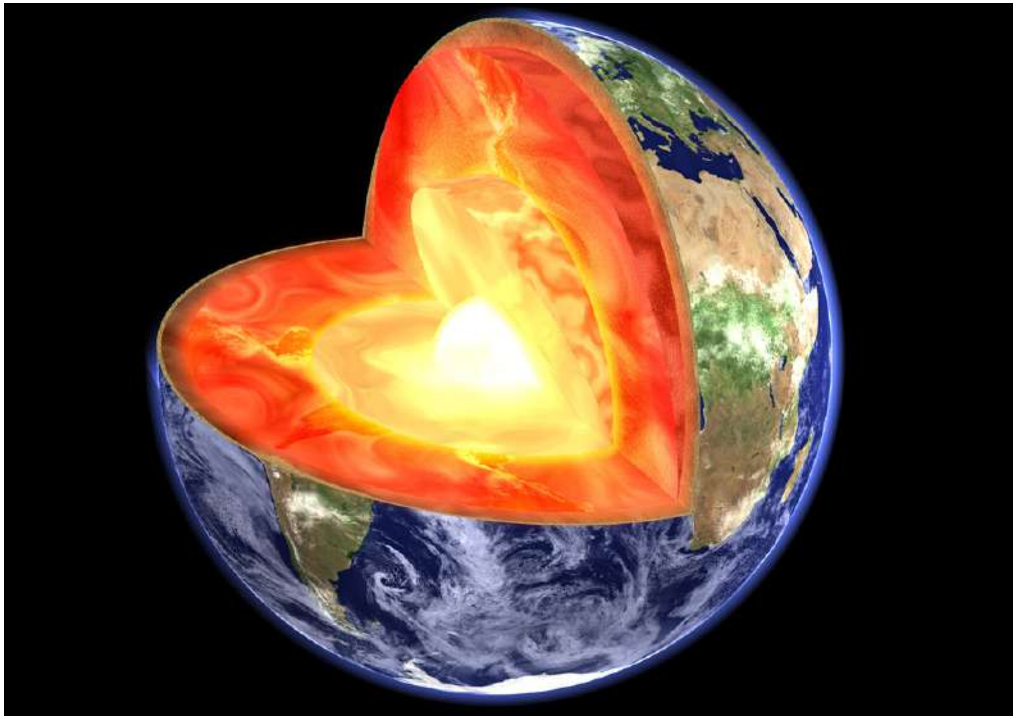
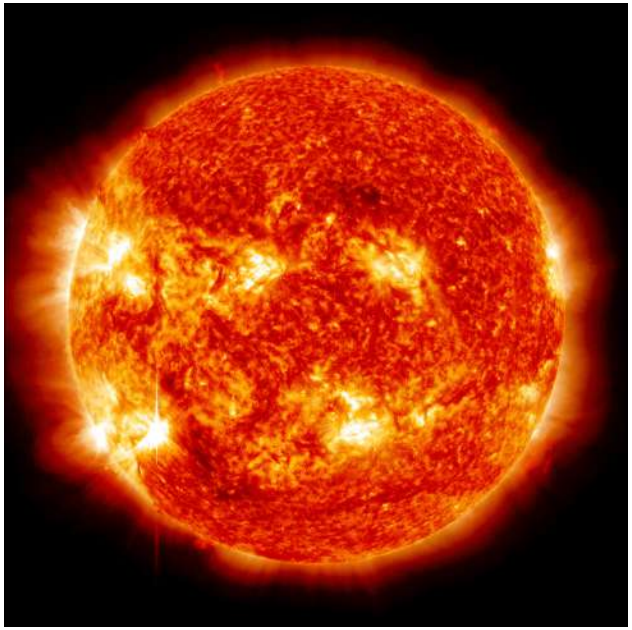
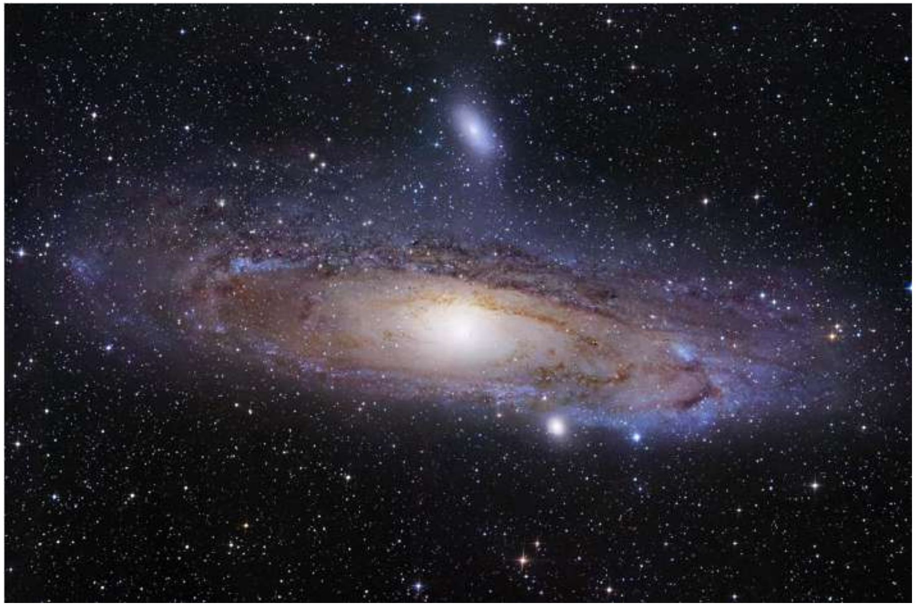
1861

Theoretical Physics colloquium, Nov. 3rd 2020, Arizona State Univerity

Fluid phenomena are ubiquitous in our life:







Hydrodynamics

Long history, dating back to Archimedes (~200 BC), Da Vinci, Newton, Euler, Bernoulli, Navier, Stokes,……

Fluid approximation:

a continuum of fluid elements each of which is considered to be a macroscopic object in local equilibrium:

$\rho(t,\vec{x}), T(t,\vec{x})$, $v^i(t,\vec{x})$

(Eulerian)

Express energy, momentum in terms of these variables

Equations: Energy + momentum conservation, continuity equation

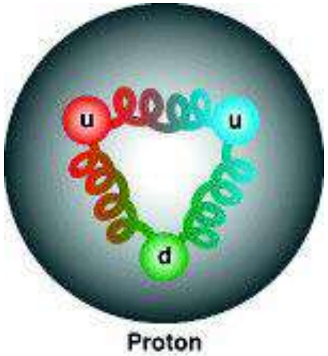
Hydrodynamics has also made unexpected entries in 21st century physics.

I will quickly describe three examples.

Quark-Gluon Plasma

At room temperature, quarks and gluons are always confined inside colorless objects (hadrons):

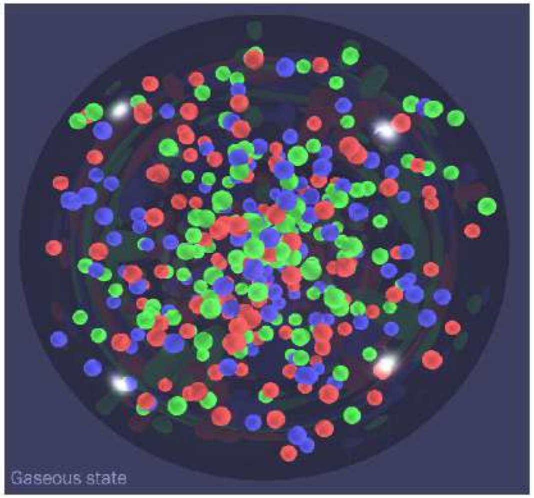
protons, neutrons, pions, …..



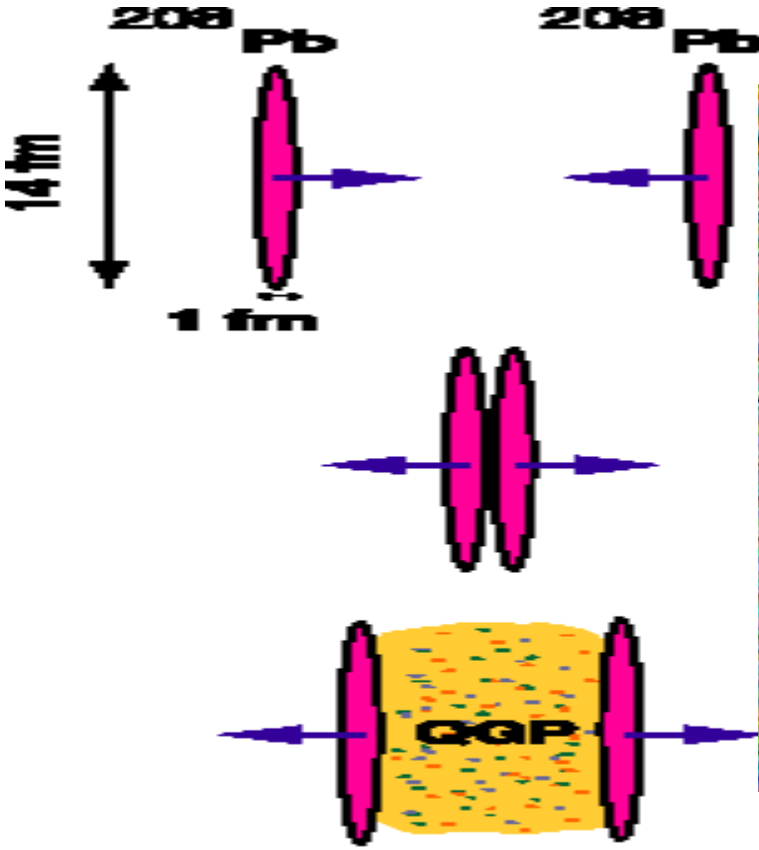
Hadrons melt at sufficient high temperatures

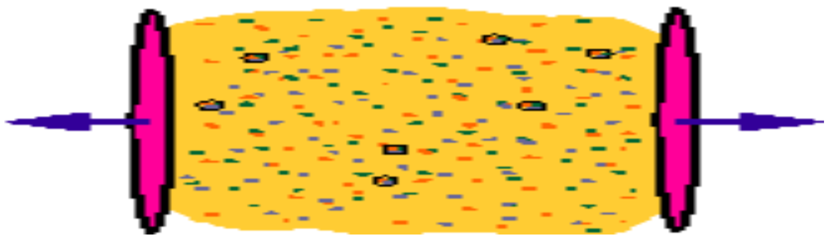
→ quarks and gluons deconfined

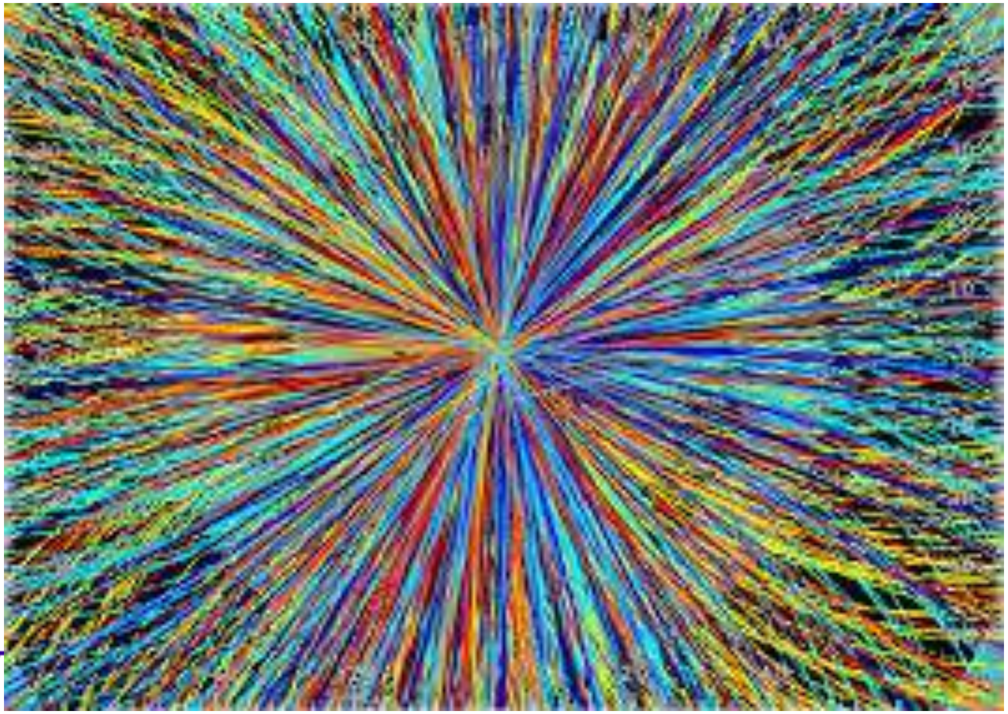
→ Quark-gluon plasma (QGP)



Relativistic Heavy ion collisions







Size: 10^{-14} m

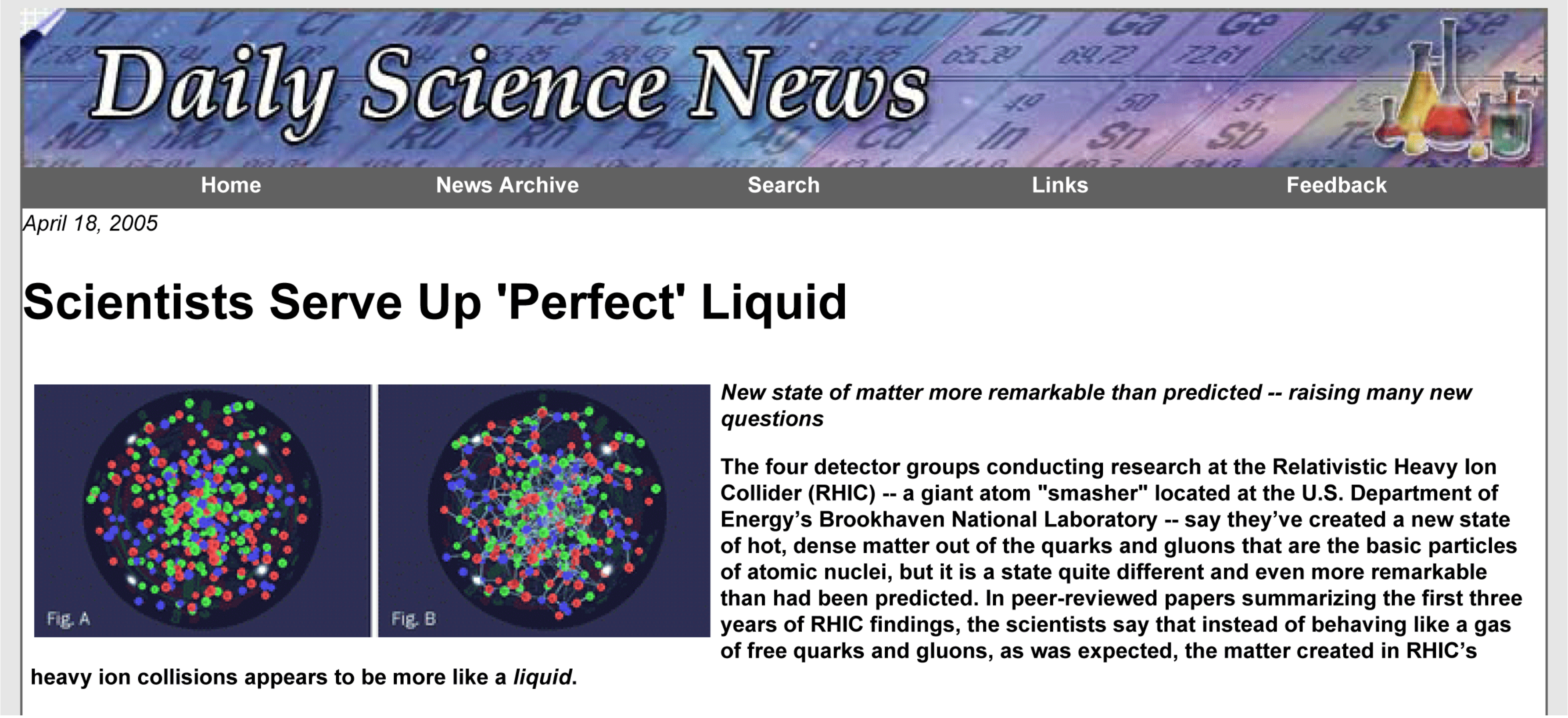
Lifetime: 10^{-23} sec

Temperature: ~ 10^{12} K

To explain correlations of detected particles:

evolution of QGP after its creation should follow hydrodynamics

The QGP behaves like a fluid



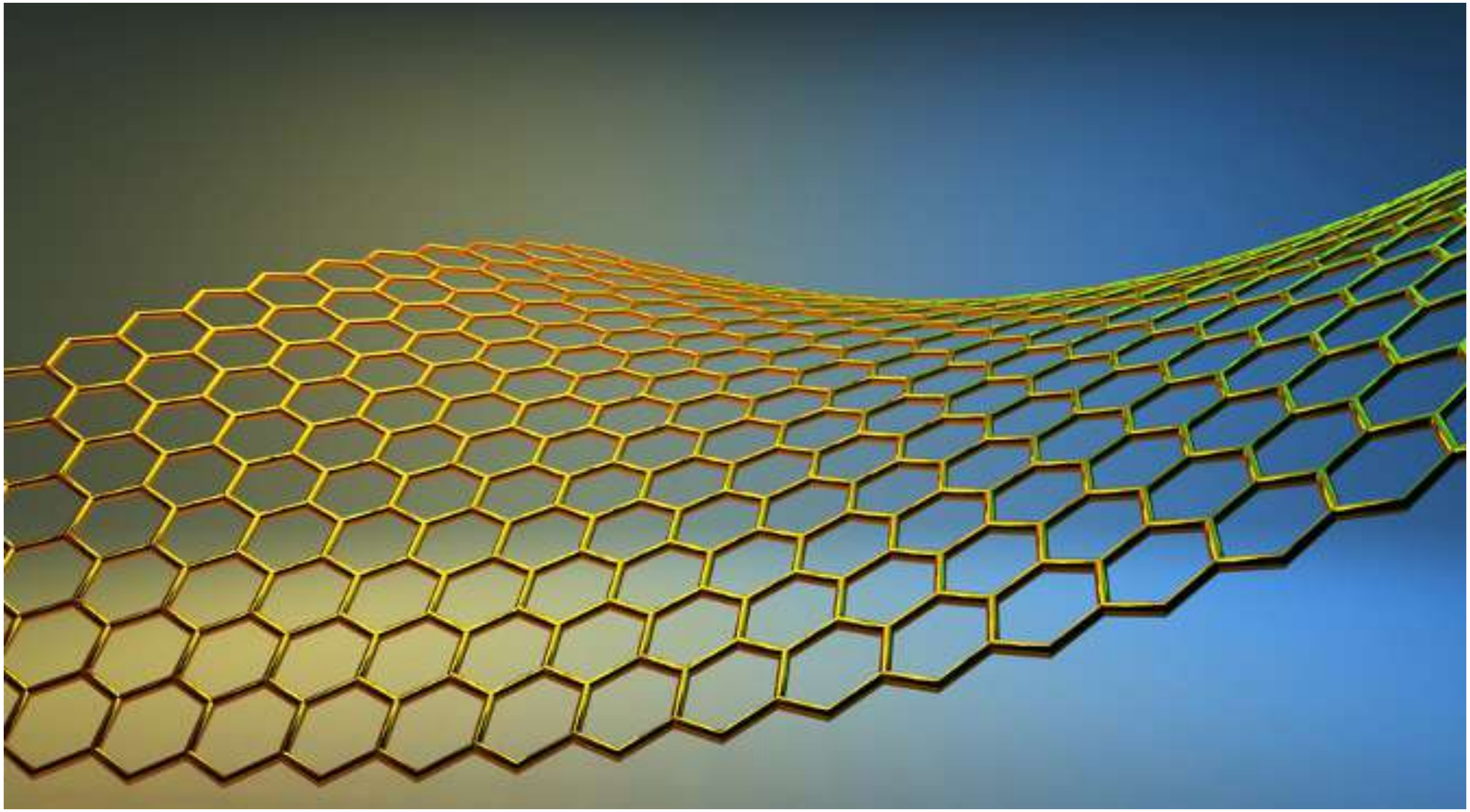
April 18, 2005

Scientists Serve Up 'Perfect' Liquid

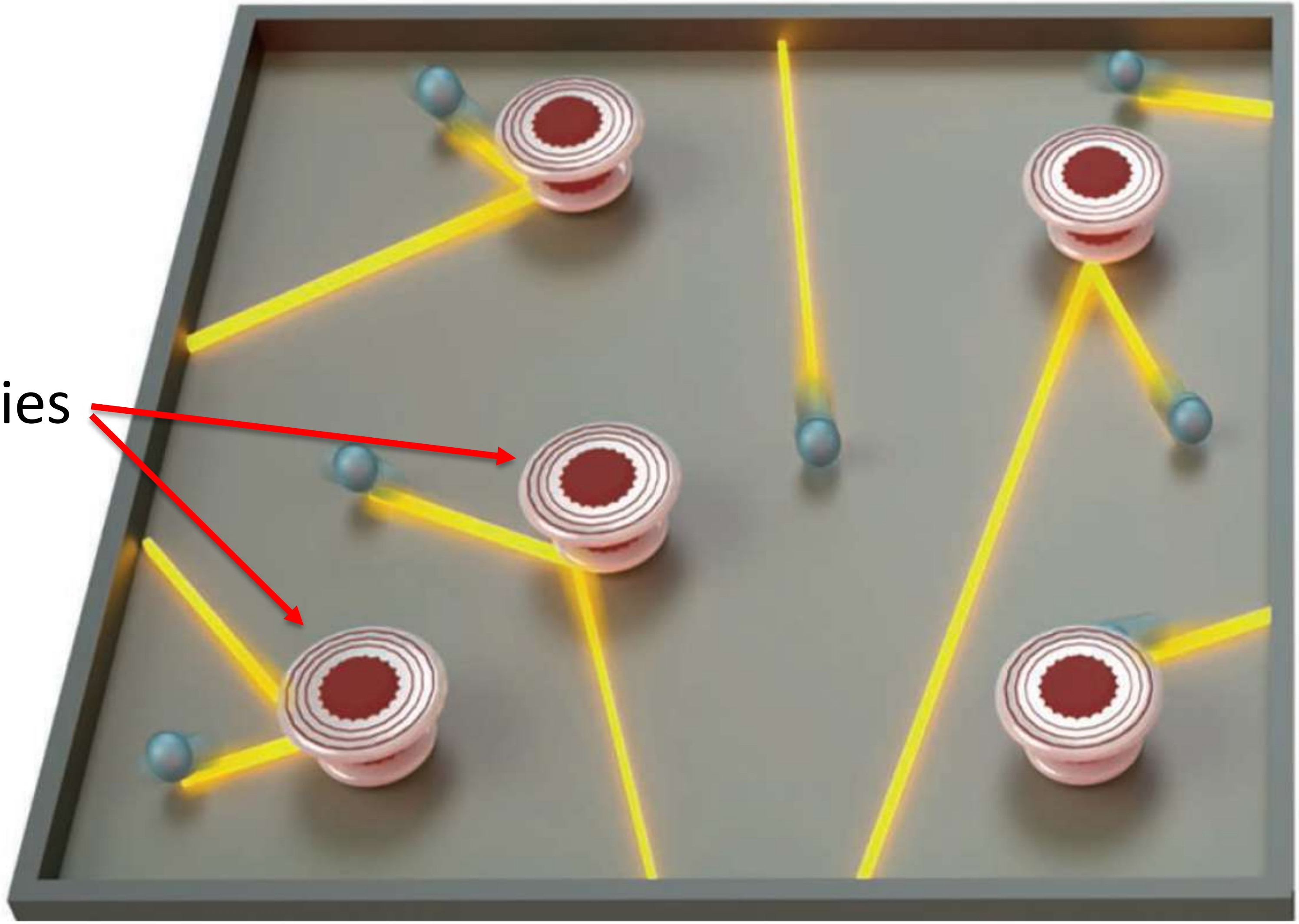
New state of matter more remarkable than predicted -- raising many new questions

The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

Graphene



Electrons in a metal

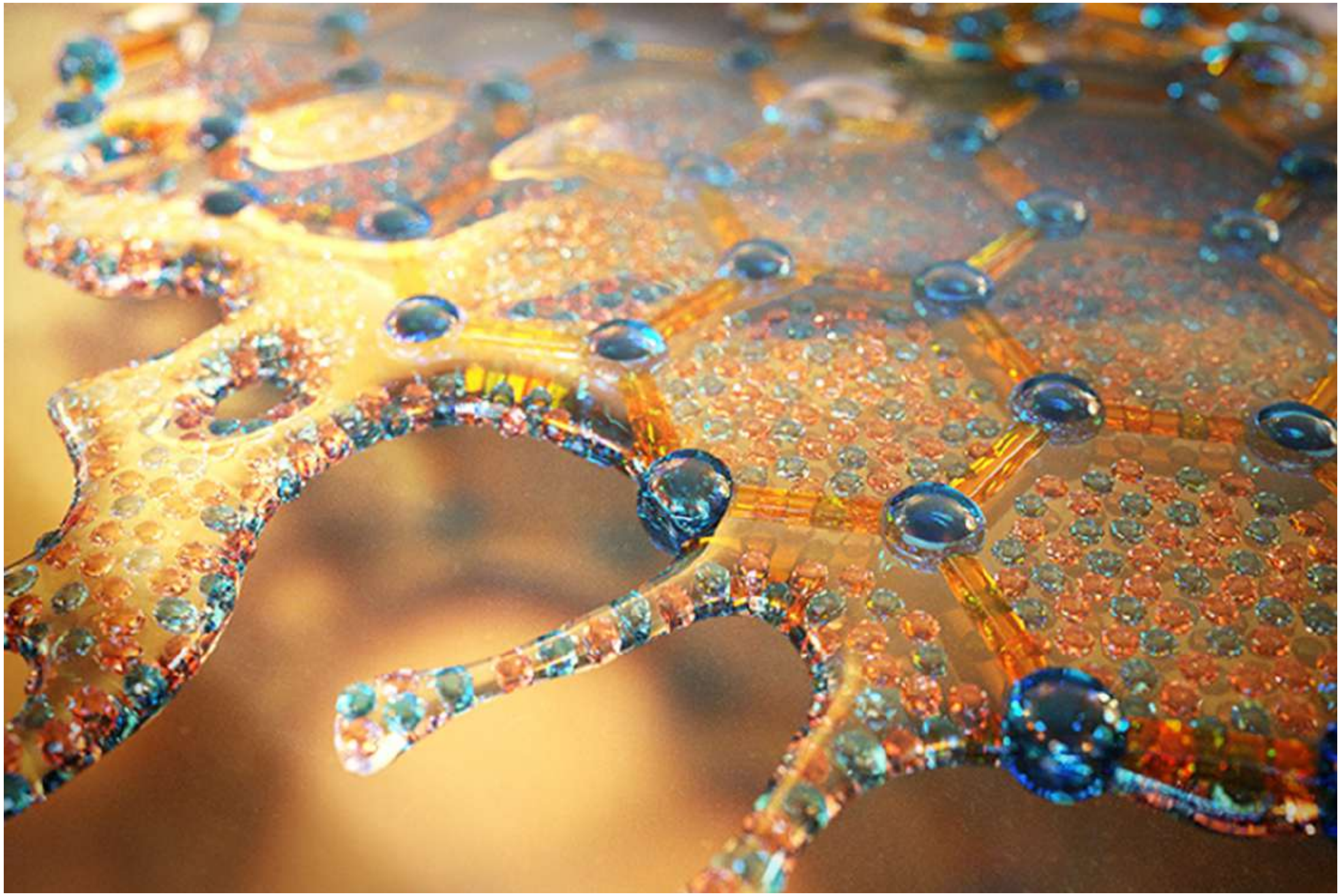


Impurities

Taken from: J. Zaanen Science 351 (2016)

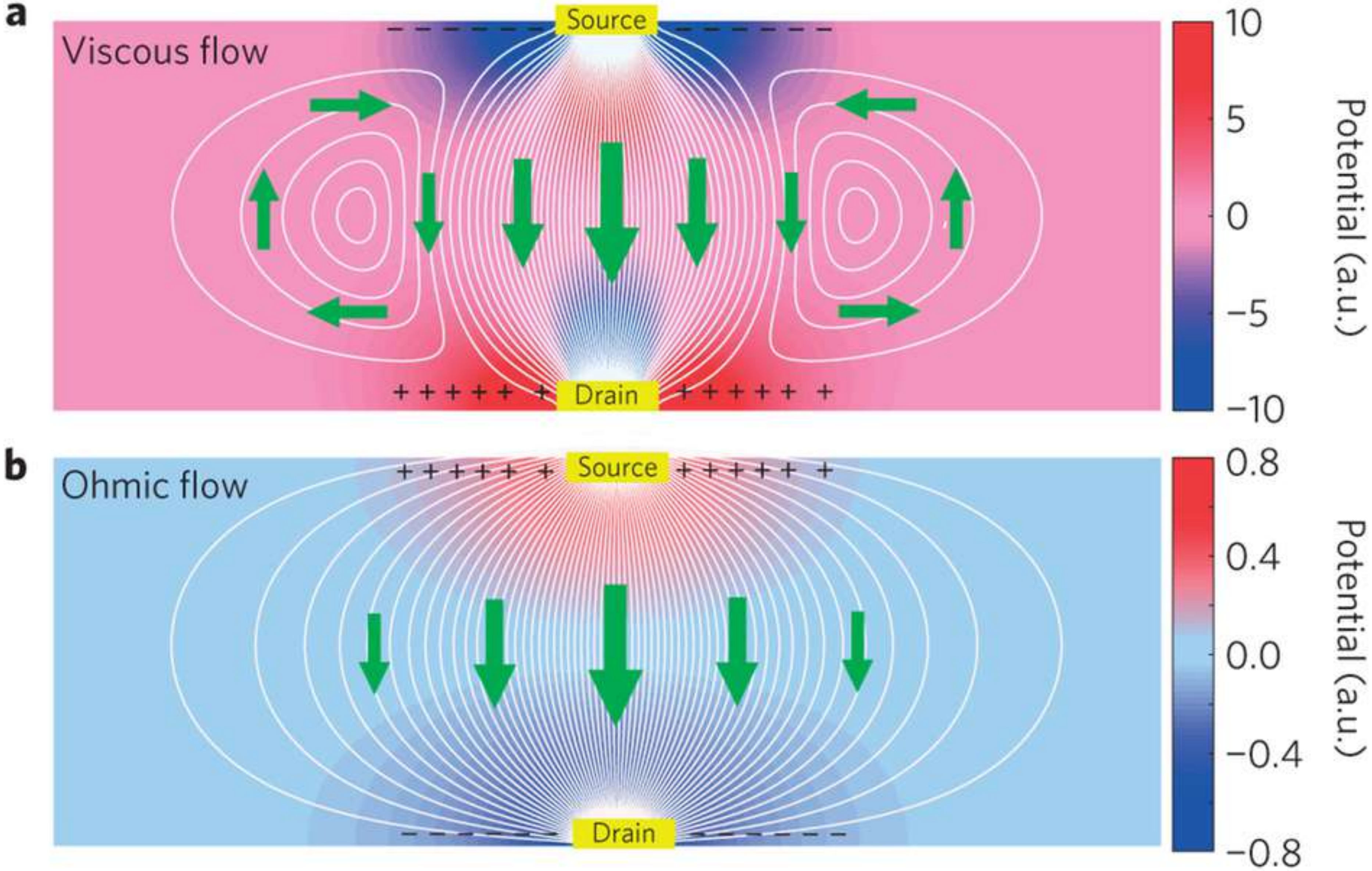
Electrons in Graphene

Graphene can made very pure and one can assume impurities do not exists.

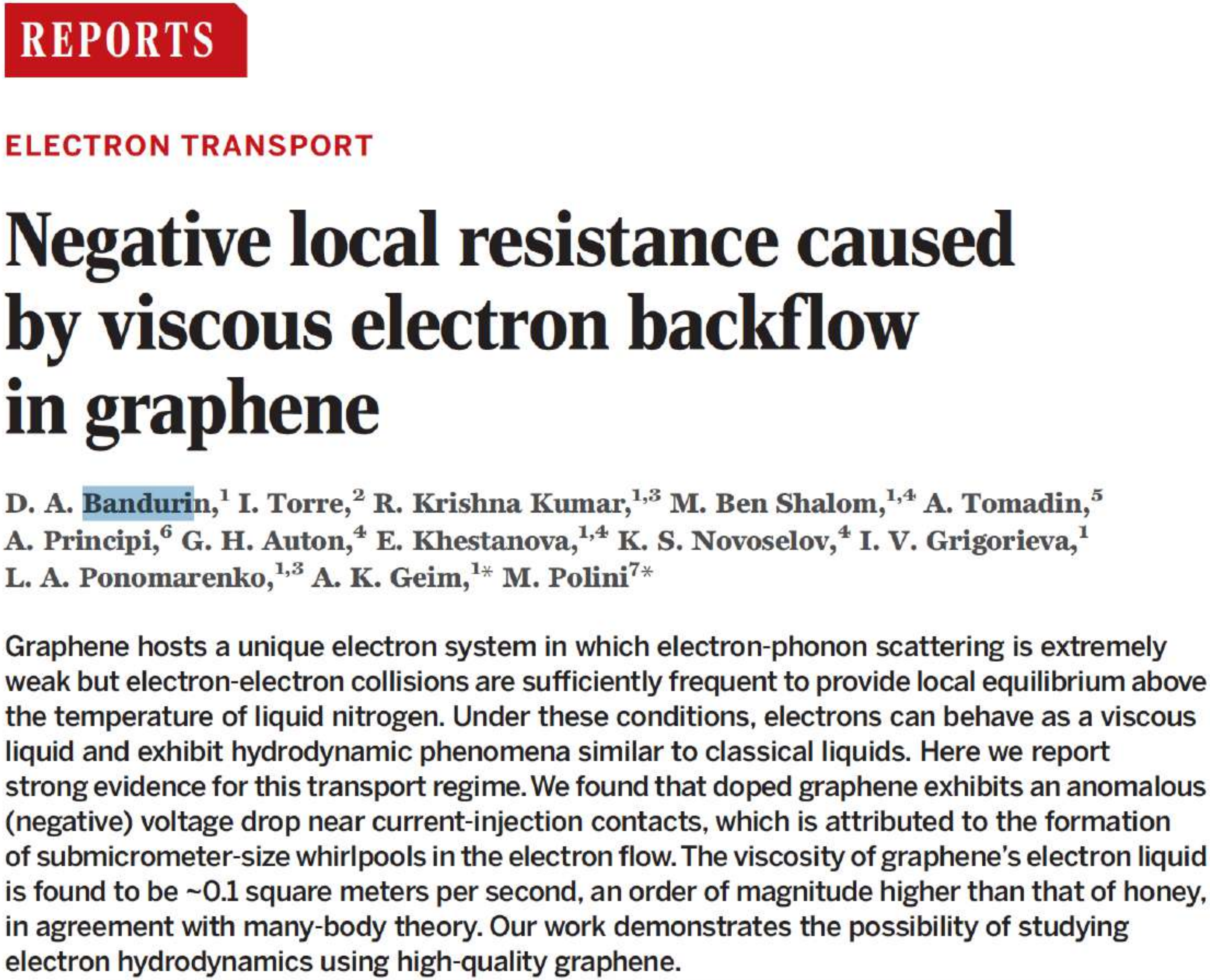


J. Trinastic,
GotScience
Magazine,
2016

From Levitov and Falkovich, Nature Physics, Feb. 2016



Science **315** March 2016



REPORTS

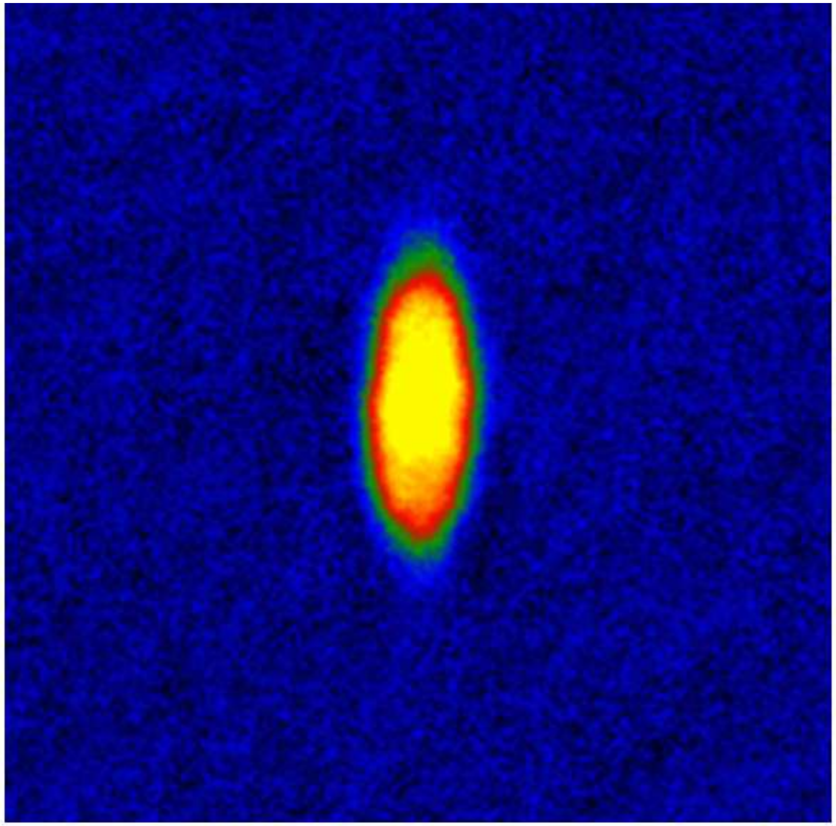
ELECTRON TRANSPORT

Negative local resistance caused by viscous electron backflow in graphene

D. A. Bandurin,[1] I. Torre,[2] R. Krishna Kumar,[1,3] M. Ben Shalom,[1,4] A. Tomadin,[5]
A. Principi,[6] G. H. Auton,[4] E. Khestanova,[1,4] K. S. Novoselov,[4] I. V. Grigorieva,[1]
L. A. Ponomarenko,[1,3] A. K. Geim,[1*] M. Polini[7*]

Graphene hosts a unique electron system in which electron-phonon scattering is extremely weak but electron-electron collisions are sufficiently frequent to provide local equilibrium above the temperature of liquid nitrogen. Under these conditions, electrons can behave as a viscous liquid and exhibit hydrodynamic phenomena similar to classical liquids. Here we report strong evidence for this transport regime. We found that doped graphene exhibits an anomalous (negative) voltage drop near current-injection contacts, which is attributed to the formation of submicrometer-size whirlpools in the electron flow. The viscosity of graphene's electron liquid is found to be ~0.1 square meters per second, an order of magnitude higher than that of honey, in agreement with many-body theory. Our work demonstrates the possibility of studying electron hydrodynamics using high-quality graphene.

Ultracold Fermi gases



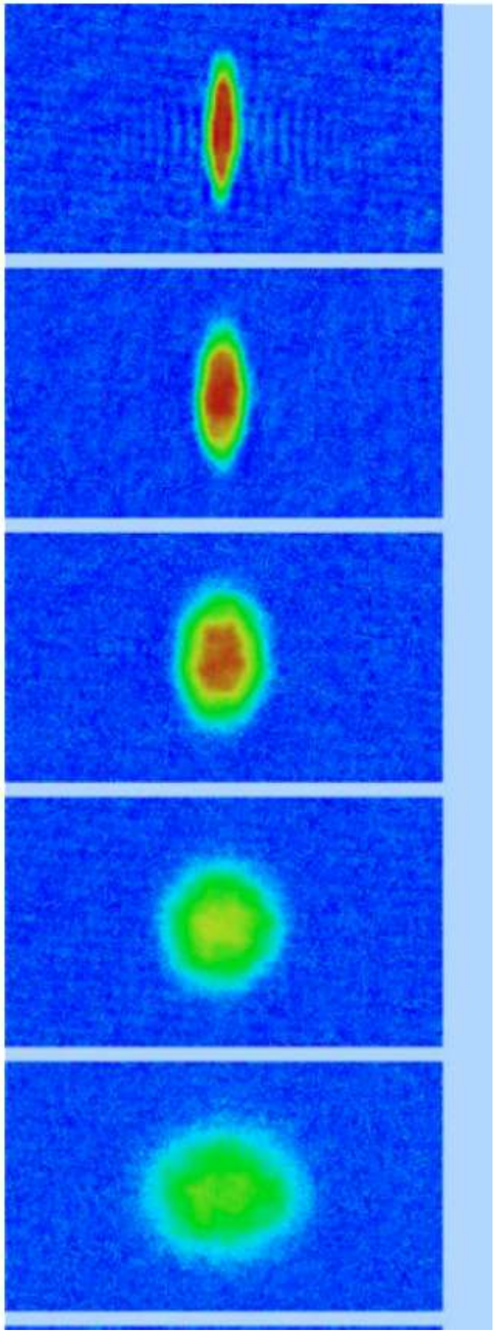
Courtesy of John Thomas's group

T: 10^{-9} K

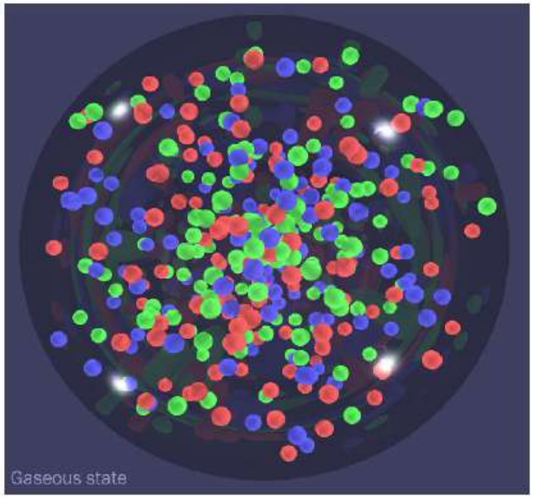
A confined cigar-shaped cloud of fermionic ^{6}Li atoms, strongly interacting

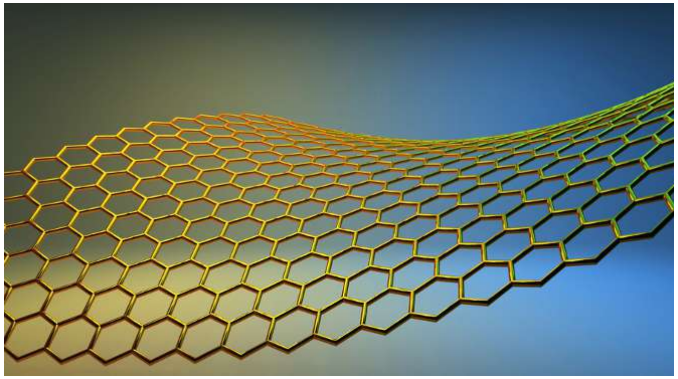
O’Hara et al
Science, **298**, (2002)

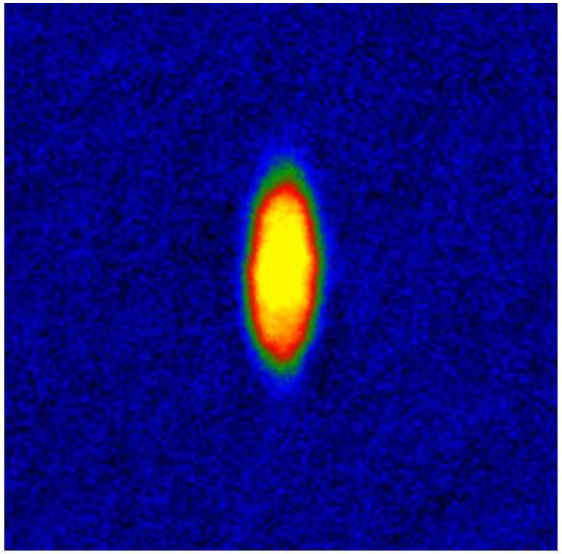
Exhibit collective flows governed by hydrodynamics, indicating a viscous fluid.



Why is hydrodynamics so effective in describing these exotic quantum matter?







Strong interactions

$\sim 10^{12} K$

Coulomb interactions

$\sim 300 K$

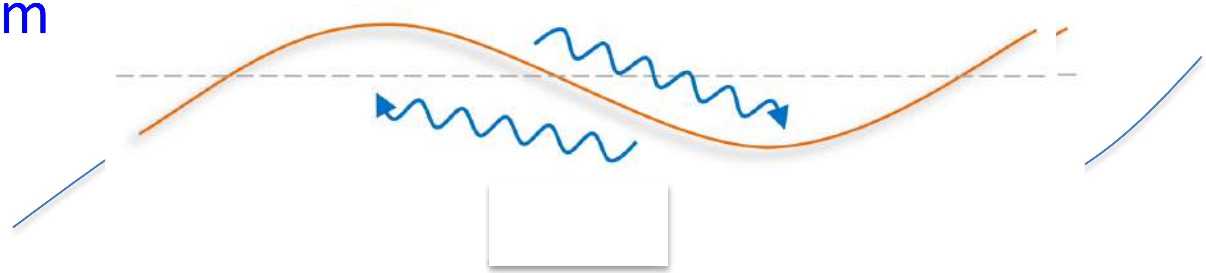
Atomic interactions at unitarity limit

$\sim 10^{-9} K$

There is in fact a simple reason behind it.

Universality of hydrodynamics

Consider a long wavelength disturbance of a system in thermal equilibrium



non-conserved quantities: relax locally, $\tau_{\text{relax}} \sim \tau_{\text{mfp}}$

conserved quantities: cannot relax locally, only via transports

$$\lambda \to \infty, \quad \Rightarrow \quad \tau_{\text{relax}} \to \infty$$

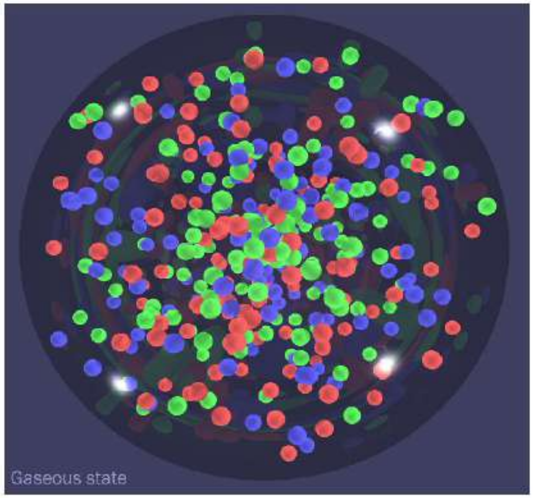
If we are interested in physics at scales: $L \gg \ell_{\text{mfp}}, \quad t \gg \tau_{\text{mfp}}$

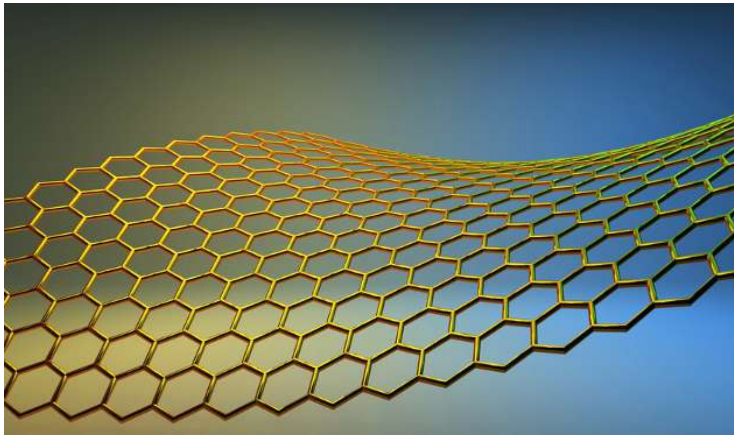
Only dynamics of conserved quantities are relevant, all other details are washed out by interactions !

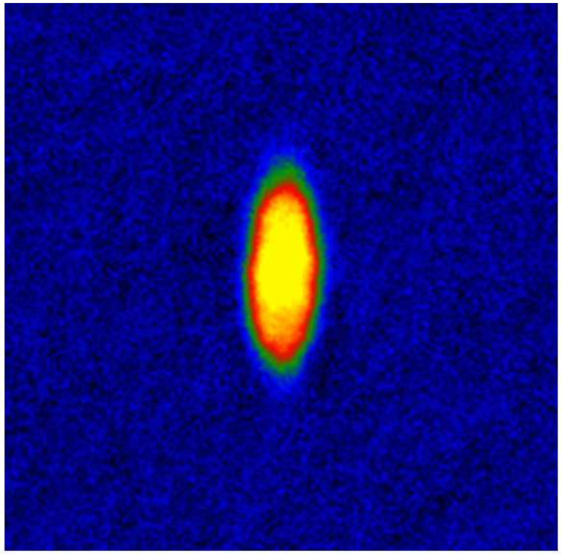
Hydrodynamics is a theory of conserved quantities.

Thus a universal theory for non-equilibrium dynamics of generic many-body systems at sufficiently long distances and times!

Key: $L \gg \ell_{\mathrm{mfp}}, \quad t \gg \tau_{\mathrm{mfp}}$







Their mean free paths have to be sufficiently short, i.e. strongly interacting

Strongly interacting quantum liquids !

Despite the long and glorious history of hydrodynamics

There is an important defect:

formulated as equations of motion, cannot capture fluctuations

(There exist phenomenological fixes, but not applicable to far-from-equilibrium situations.)

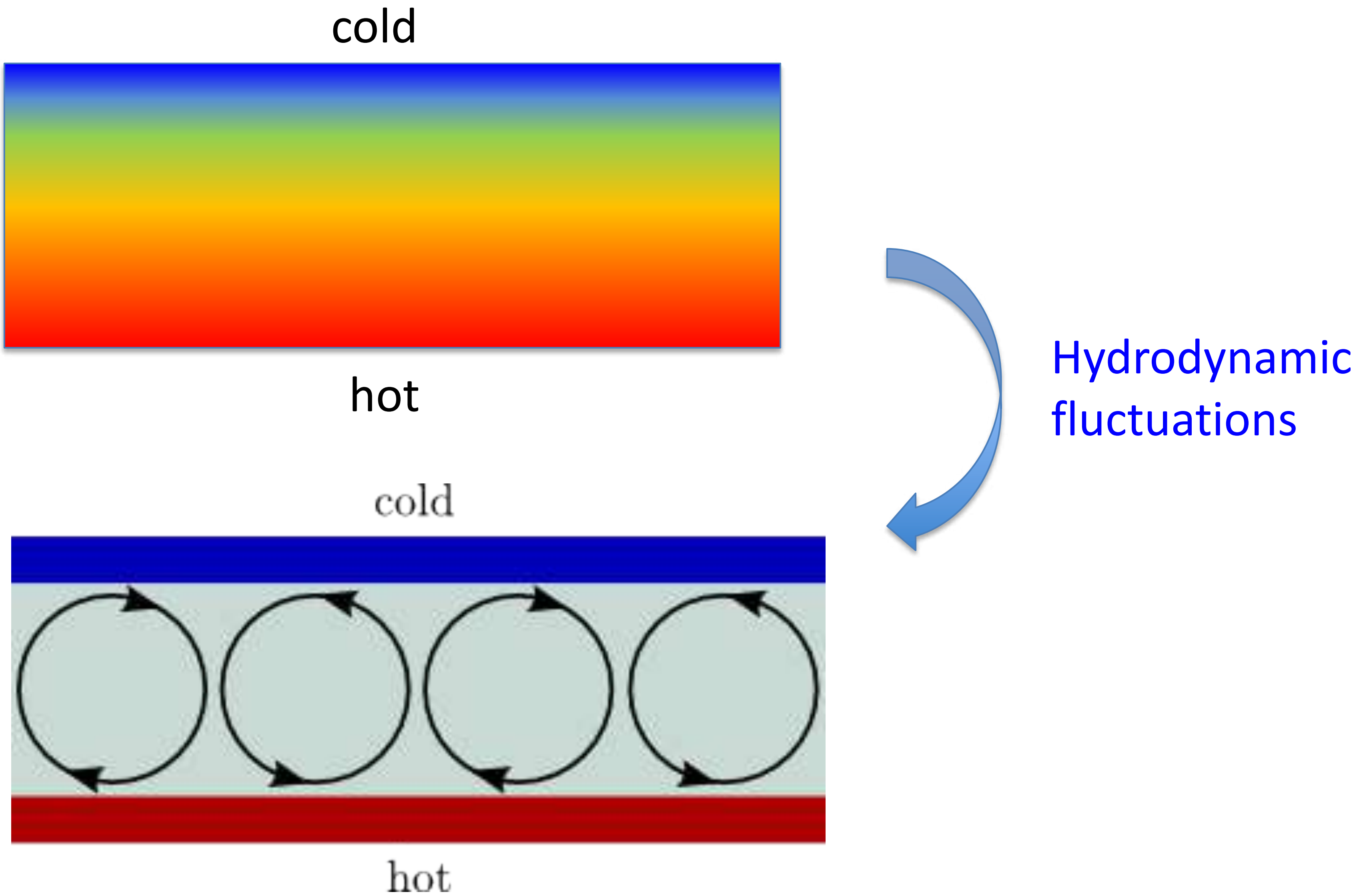
There are always statistical fluctuations …..

Thermal noises are everywhere ……

Important in many physical contexts.

At low temperatures, quantum fluctuations can also be important.

Non-equilibrium phase transitions: Rayleigh-Benard problem



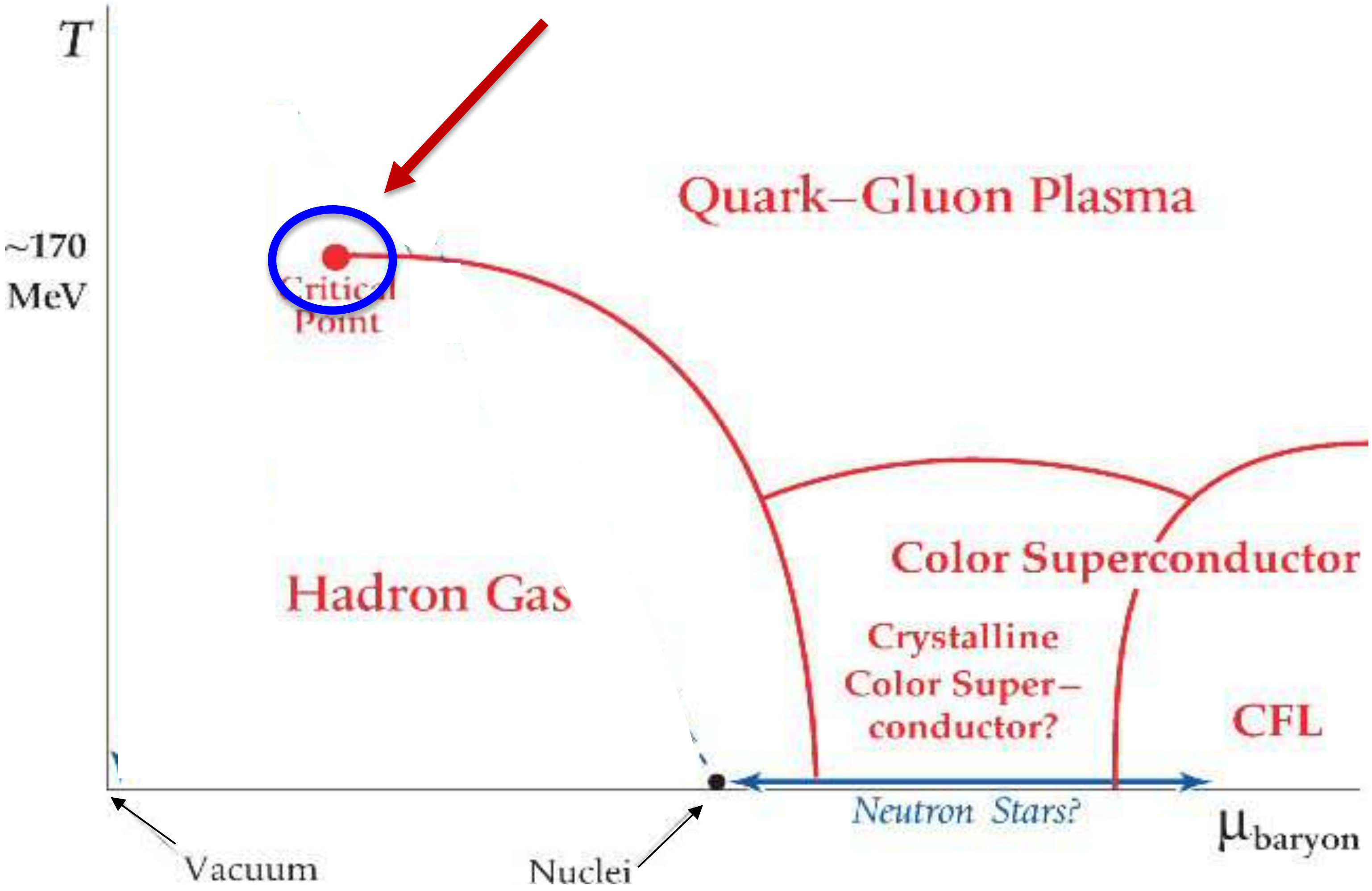
cold

hot

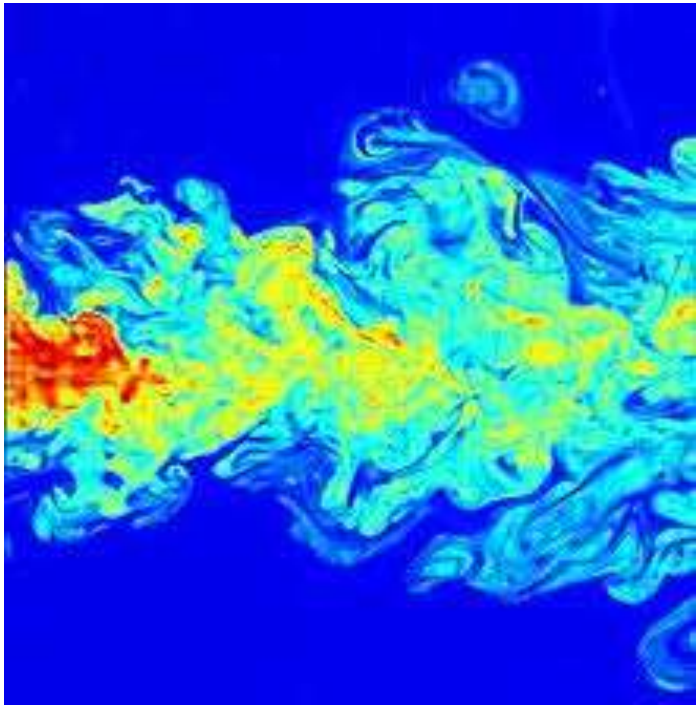
Hydrodynamic fluctuations

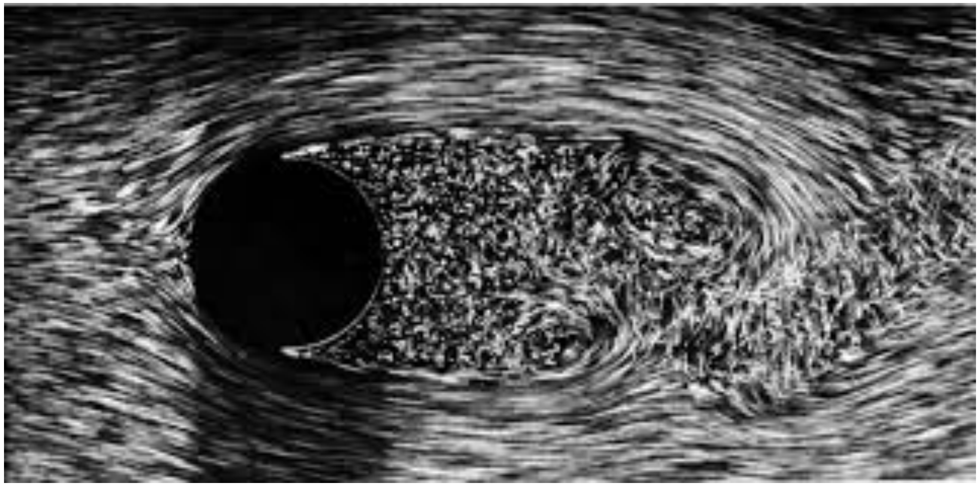
Searching for QCD critical point

Large fluctuations



Thermal fluctuations in turbulence





Need a formulation of fluctuating hydrodynamics in far-from-equilibrium situations

Need a formulation based on action principles.

Searching for an action principle for dissipative hydrodynamics has been a long standing problem, dating back at least to the ideal fluid action of G. Herglotz in 1911.

The last decade has seen a renewed interest:

Dubovsky, Gregoire, Nicolis and Rattazzi hep-th/0512260

Dubovsky, Hui, Nicolis and Son, arXiv:1107.0731

Grozdanov and Polonyi, arXiv:1305.3670

Kovtun, Moore and Romatschke, arXiv:1405.3967

Harder, Kovtun, and Ritz, arXiv:1502.03076

Haehl, Loganayagam and Rangamani, arXiv:1502.00636, 1511.07809

…….

Paolo Glorioso

Michael Crossley

Recently we were able to have a complete formulation of fluctuating hydrodynamics from first principles (i.e. based on symmetries and action principle).

arXiv: 1511.03646, 1612.07705, 1701.07817, 1701.07445

A review: 1805.09331 Paolo Glorioso, HL

Used techniques and insights from quantum field theories, gravity, and string theories.

Framework: Effective field theory

Full path integral of a quantum many-body system

Identify ϕ : Low energy degrees of freedom

Integrate out the rest

$$\int D\phi \; e^{iS_{eff}[\phi]}$$

$S_{eff}[\phi]$: low energy effective action

Direct computation: rarely possible

Identify symmetries and constraints of $S_{eff}[\phi]$

Write down the most general theory consistent with the symmetries

Should be able to formulate hydrodynamics this way

Challenges

1. Dissipation

Standard lore: Dissipative systems don't have an action formulation

$$m\ddot{x} + \nu\dot{x} = 0$$

2. Dynamical variables

Standard variables: $\rho(t,\vec{x}), T(t,\vec{x}) \quad v^i(t,\vec{x})$ Unsuitable!

Need analogue of potentials for Electromagnetism

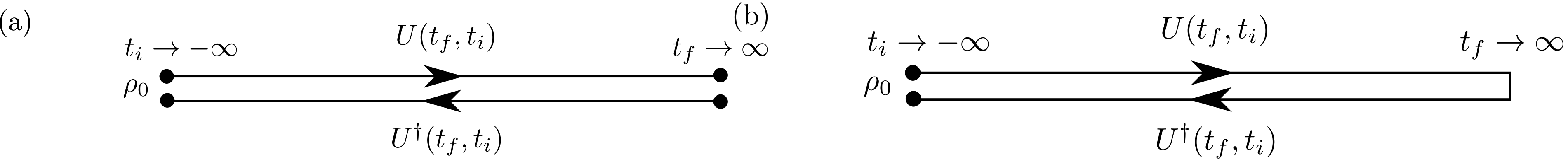
3. Symmetries

What symmetries define a fluid?

Dissipations

This issue is naturally resolved by quantum mechanics.

interested in dynamics of a non-equilibrium state.



$$\rho(t_f) = U(t_f, t_i)\rho_0 U^\dagger(t_f, t_i)$$

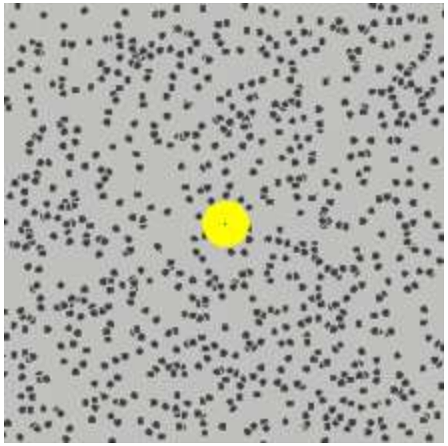
$$\mathrm{Tr}\left(\rho_0 \cdots\right)$$

Closed time path (CTP) or Schwinger-Keldysh contour

Key: develop effective field theories for systems on a closed time path (double d.o.f.)

Example: Brownian motion

Quantum → Classical (action principle for Langevin equation)



Dynamical variables

Key: identify universal variables associated with energy-momentum conservation.

Trick: put the system in a curved spacetime: because of energy-momentum conservation, the system should be diffeomorphism invariant

That is, invariant under any coordinate transformations

Promote spacetime coordinates into dynamical variables

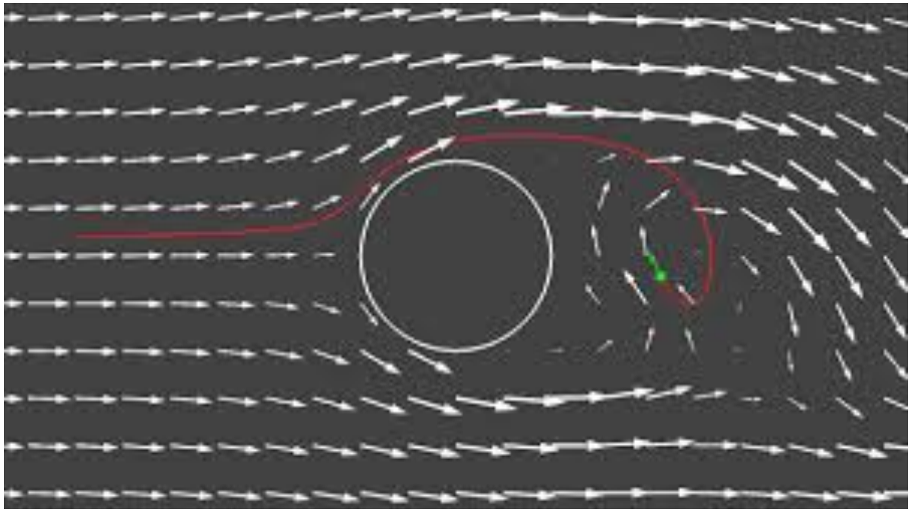
$$x^\mu \to X^\mu(\sigma^a)$$

⇨ Equations of X^μ equivalent to energy-momentum conservation.

Need a new auxiliary spacetime with coordinates σ^a

Dynamical variables: $X_1^\mu(\sigma^i, \sigma^0), \quad X_2^\mu(\sigma^i, \sigma^0)$

This is just a generalization of the Lagrange description!

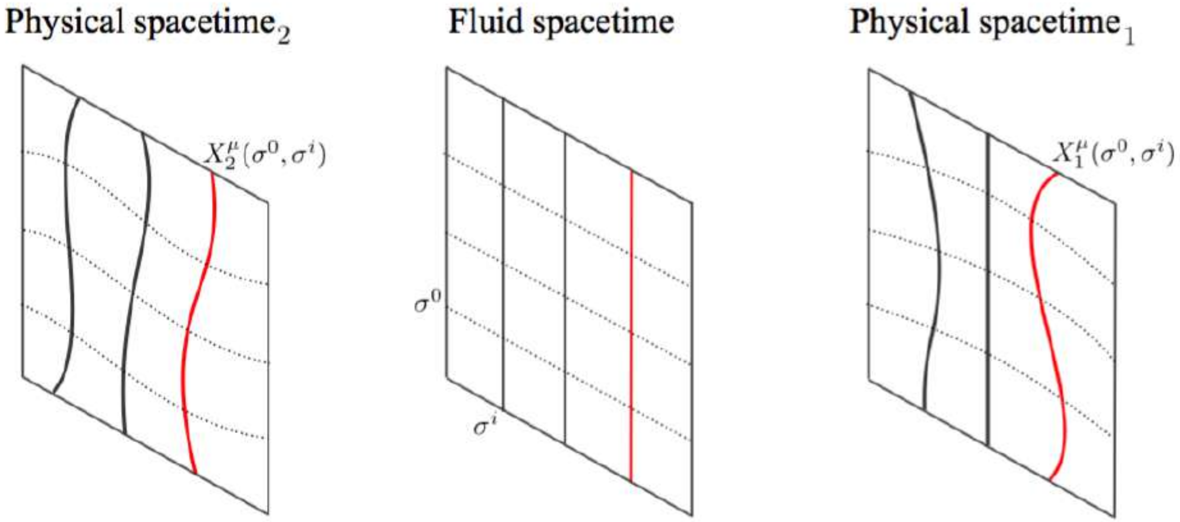


σ^i: label fluid elements

$x^i(t, \sigma^i),$

Dynamical variables: $X_1^\mu(\sigma^i,\sigma^0), \quad X_2^\mu(\sigma^i,\sigma^0)$

σ^i label individual fluid elements, σ^0 internal time



Symmetries

1. Symmetries defining a fluid:

$$\sigma^i \to \sigma'^i(\sigma^i), \quad \sigma^0 \to \sigma^0$$

$$\sigma^0 \to \sigma'^0 = f(\sigma^0, \sigma^i), \quad \sigma^i \to \sigma^i$$

2. Constraints from quantum unitarity (survive in the classical limit)

3. A Z_2 symmetry: dynamical KMS symmetry, which imposes micro-time-reversibility and local equilibrium

➡ A “statistical” field theory which fully recovers the standard hydrodynamic as equations of motion, but also treats statistical and quantum hydrodynamic fluctuations systematically.

Emergent entropy as a Noether charge

Combination of unitarity constraints and dynamical KMS symmetry leads to a remarkable consequence:

One can construct a local current s^μ, the “charge” of which never decreases.

$$\Delta S \equiv \int_{t=t_f} d^{d-1}x\, s^0 - \int_{t=t_i} d^{d-1}x\, s^0 = \mathcal{R} \geq 0$$

$\mathcal{R}$ can be found explicitly using the action

Universal expression for entropy production.

Emergent supersymmetry

The action is such that it can always be supersymmetrized: an emergent supersymmetry.

Consequence of unitarity and dynamical KMS, independent of details of any specific system.

This framework is very general and can be generalized to other continuous media such as solids, liquid crystals, quasicrystals, systems undergoing chemical reactions, MHD, ...

M. Landry: arXiv: 1912.12301, arXiv: 2006.13220,

Baggioli and Landry: arXiv: 2008.05339,

A. Jain: arXiv: 2008.03004,

....

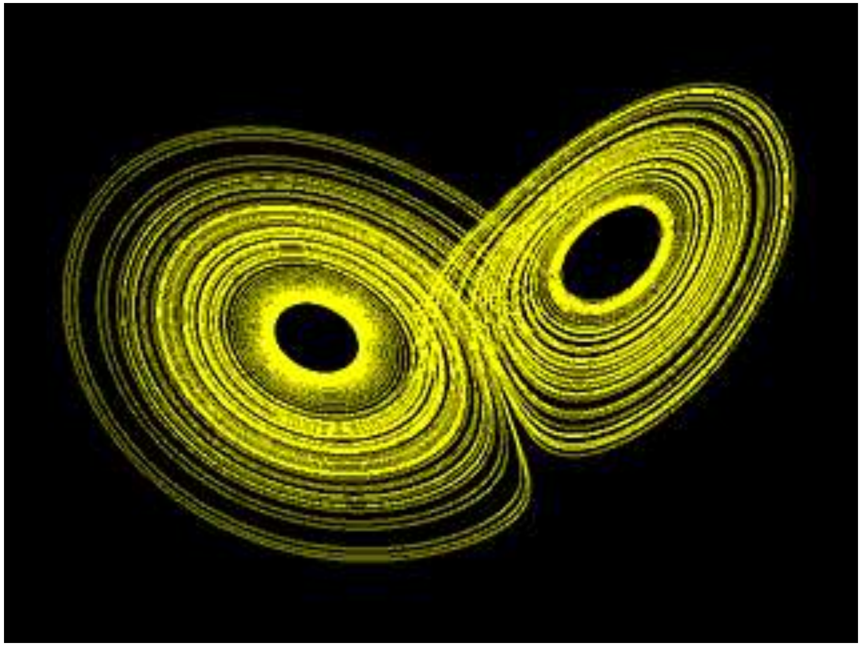
Application to quantum scrambling and quantum chaos

Mike Blake

Hyunseok Lee

arXiv: 1801.00010

Chaotic phenomena are ubiquitous in nature.



(strange attractor of the Lorenz model)

Much has been learned about chaos in classical systems

But much to be understood in quantum many-body systems.

There have been intense recent studies of out-of-time-ordered correlation functions.

Our proposals (for maximally chaotic systems) :

1. Chaotic behavior can be described by the propagation an effective chaos mode

2. Chaos mode can be identified with the hydrodynamic mode associated with Energy conservation.

Effective field theory of chaos = Quantum hydro theory

Implications and predictions:

1. Explain connection between energy diffusion constant and quantum chaos observed in the literature.

2. Predict a new manifestation of quantum chaos: pole-skipping phenomenon, which has been checked in a large number of systems.

   (See also Grozdanov, Schalm, and Scopelliti, arXiv:1710.00921)

3. The surprising connection between quantum chaos and hydrodynamics remains mysterious (very different regime from turbulence).

Summary

- Hydrodynamics plays important role in characterizing various exotic quantum matter.

a universal definition of strongly coupled quantum liquids

- We now have a first principle formulation of hydrodynamics which incorporates statistical and quantum fluctuations.

- Unreasonable effectiveness: maximal quantum chaos.

Thank you!