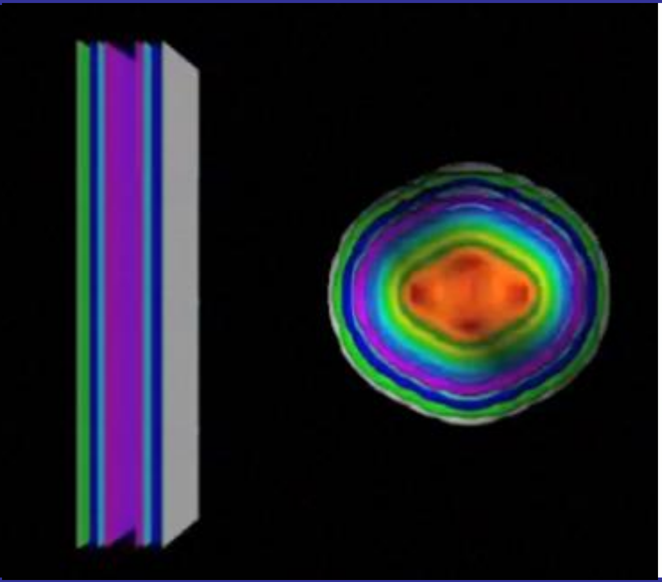
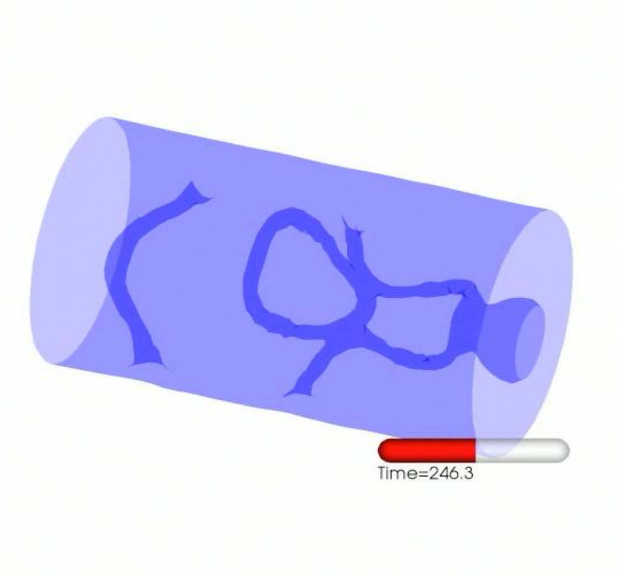
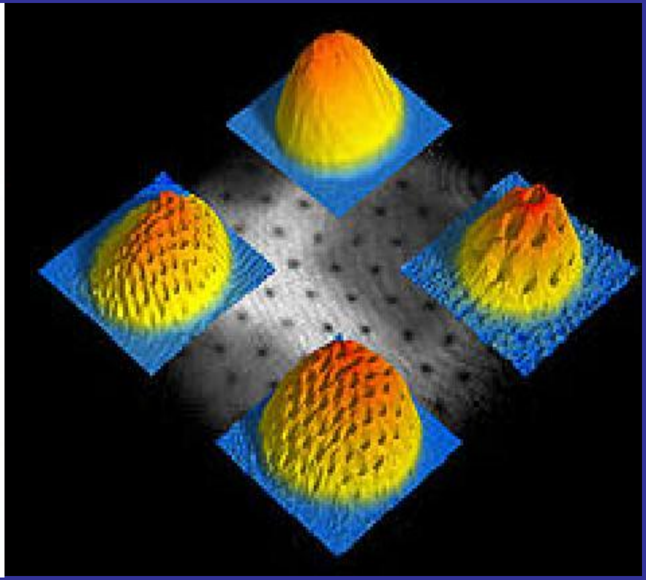
Od kwantowej turbulencji do rozszczepienia jądra atomowego.

(Wyzwania fizyki układów kwantowych daleko od stanu równowagi.)





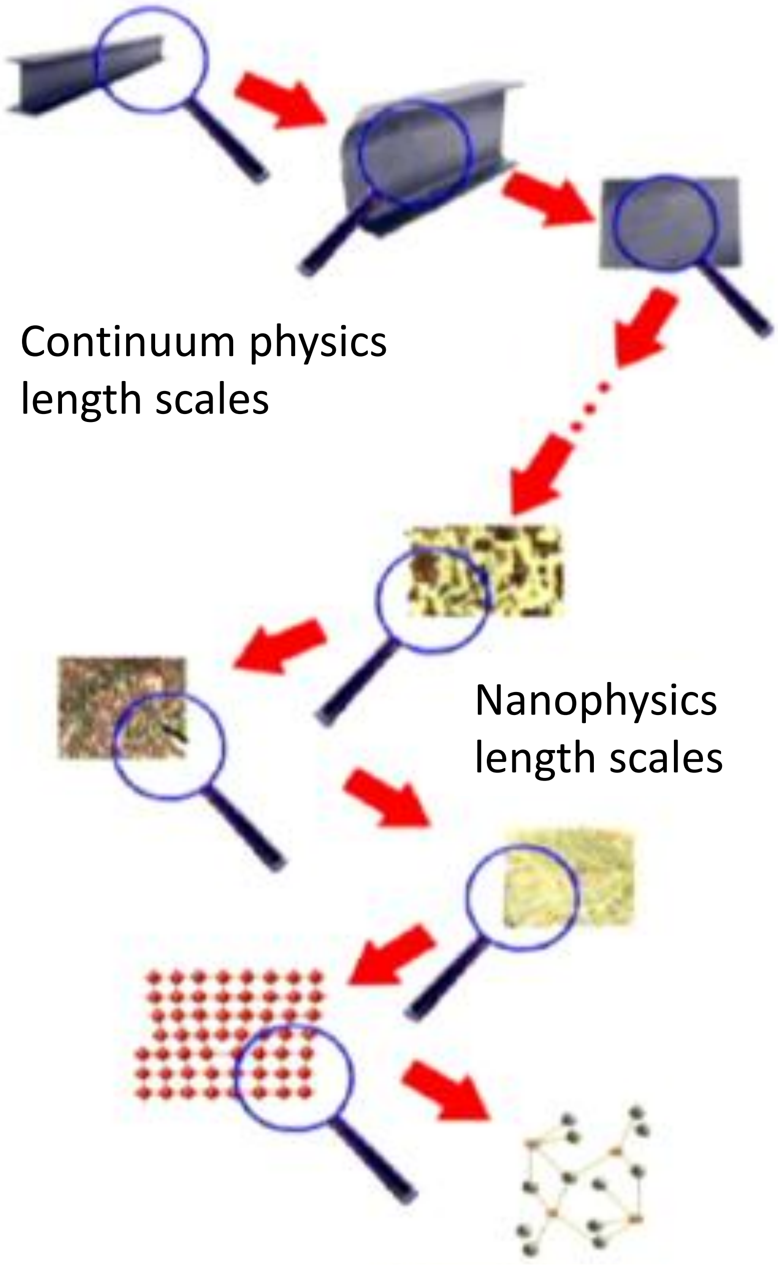


Provocative statement:

In comparison to many body quantum systems, few body quantum systems are pretty dull objects.

Friction, entropy, phase transitions, superfluidity, superconductivity, quantum Hall effect, spontaneous symmetry breaking, temperature, pressure, quantum chaos are all examples of things that happen in complex systems.

To be more precise: all these phenomena are best seen in the thermodynamic limit, i.e. when number of constituents tends to infinity.



Continuum physics
length scales

Nanophysics
length scales

Atomic physics lengths scales

Reductionist paradigm:

A system can be completely understood by studying its parts.

However:

More Is different…

P.W. Anderson
Science, 177 (1972) 393

i.e. qualitatively new emergent phenomena appear on larger scales

Radical view

Robert B. Laughlin, Nobel Lecture, December 8, 1998:

One of my favorite times in the academic year occurs [..] when I give my class of extremely bright graduate students [..] a take home exam in which they are asked TO DEDUCE SUPERFLUIDITY FROM FIRST PRINCIPLES.
There is no doubt a special place in hell being reserved for me at this very moment for this mean trick, for the task is IMPOSSIBLE. Superfluidity [..] is an EMERGENT phenomenon – a low energy collective effect of huge number of particles that CANNOT be deduced from the microscopic equations of motion in a RIGOROUS WAY and that DISAPPEARS completely when the system is taken apart.

[..]students who stay in physics long enough [..] eventually come to understand that the REDUCTIONIST IDEA IS WRONG a great deal of the time and perhaps ALWAYS.

Less radical view:

On a larger scale some phenomena are very predictable and allow us to formulate LAWS. These LAWS do not depend on microscopic details and therefore, and this is a bad news, we cannot deduce them from these LAWS. The procedure of „loosing details" is called: RENORMALIZATION.

An example of such generic phenomenon is superfluidity:

100 years of superconductivity and superfluidity in Fermi systems

Discovery: H. Kamerlingh Onnes in 1911 cooled a metallic sample of mercury at T<4.2K

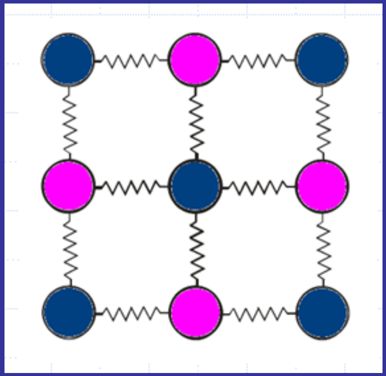
20 orders of magnitude over a century of (low temperature) physics

- ✓ Dilute atomic Fermi gases $T_c \approx 10^{-12} - 10^{-9}$ eV
- ✓ Liquid ^{3}He $T_c \approx 10^{-7}$ eV
- ✓ Metals, composite materials $T_c \approx 10^{-3} - 10^{-2}$ eV
- ✓ Nuclei, neutron stars $T_c \approx 10^{5} - 10^{6}$ eV
- QCD color superconductivity $T_c \approx 10^{7} - 10^{8}$ eV

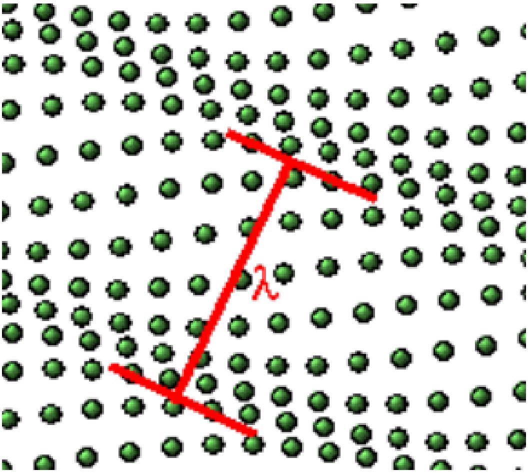
units (1 eV $\approx 10^4$ K)

We prefer a complex system with strong interaction between constituents. In such a case most likely a qualitatively new phenomena occurs.

Consider e.g. atoms in a crystal:

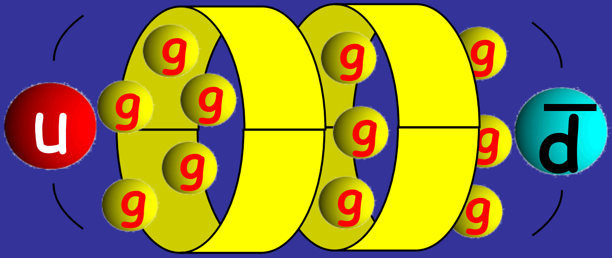


The true low energy excitation modes of such systems are collective oscillations (phonons) which have all attributes of particles: they carry energy, momentum, can scatter, etc.

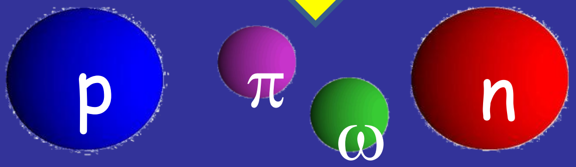


Other „particles" in solids: holes, plasmons, polarons, magnons, excitons,…

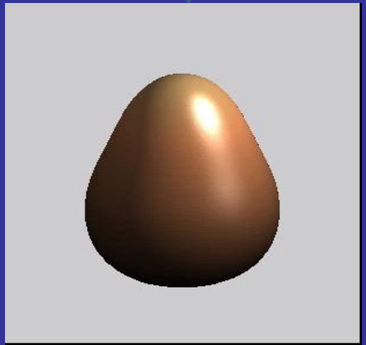
Analogous situation occurs in high energy physics



Strongly interacting
quarks and gluons
Energy scale: > 1000 MeV



Baryons and mesons
Energy scale: 100MeV



Collective degrees of freedom of atomic nuclei, eg. shape vibration
Energy scale: 0.1-1 MeV

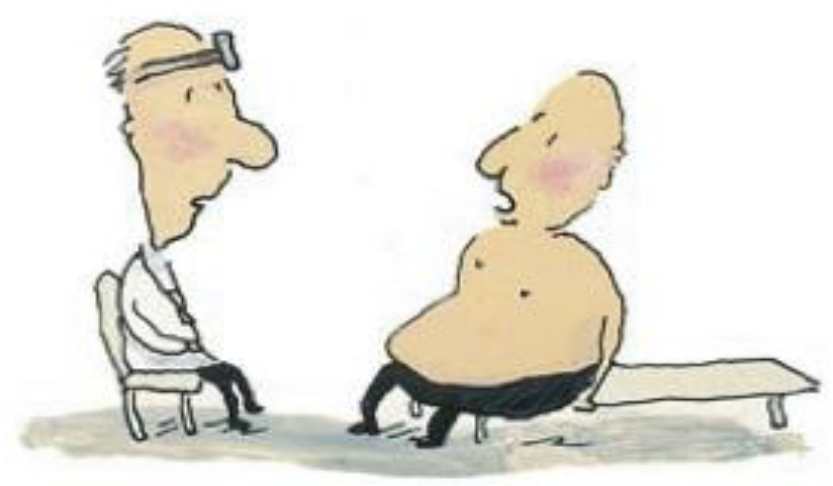
Weinberg's Laws of Progress in Theoretical Physics

From: "Asymptotic Realms of Physics" (ed. by Guth, Huang, Jaffe, MIT Press, 1983)

First Law: "The conservation of Information" (*You will get nowhere by churning equations*)

Second Law: "Do not trust arguments based on the lowest order of perturbation theory"

Third Law: "You may use any degrees of freedom you like to describe a physical system, but if you use the wrong ones, you'll be sorry!"



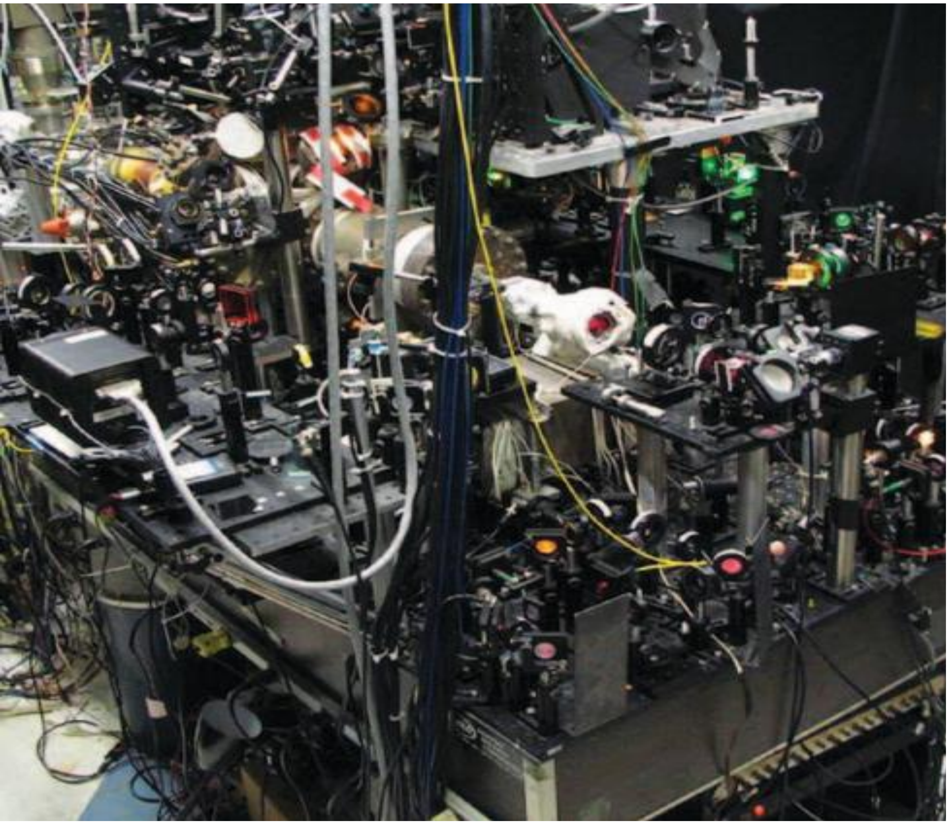
Patient: Doctor, doctor, it hurts when I do this!
Doctor: Then don't do that.

D. Furnstahl, INT Fall'05

Gases of ultracold atoms and quark gluon plasma teach us how matter behaves under the strongest interactions that nature allows

Little Fermi Collider (MIT)

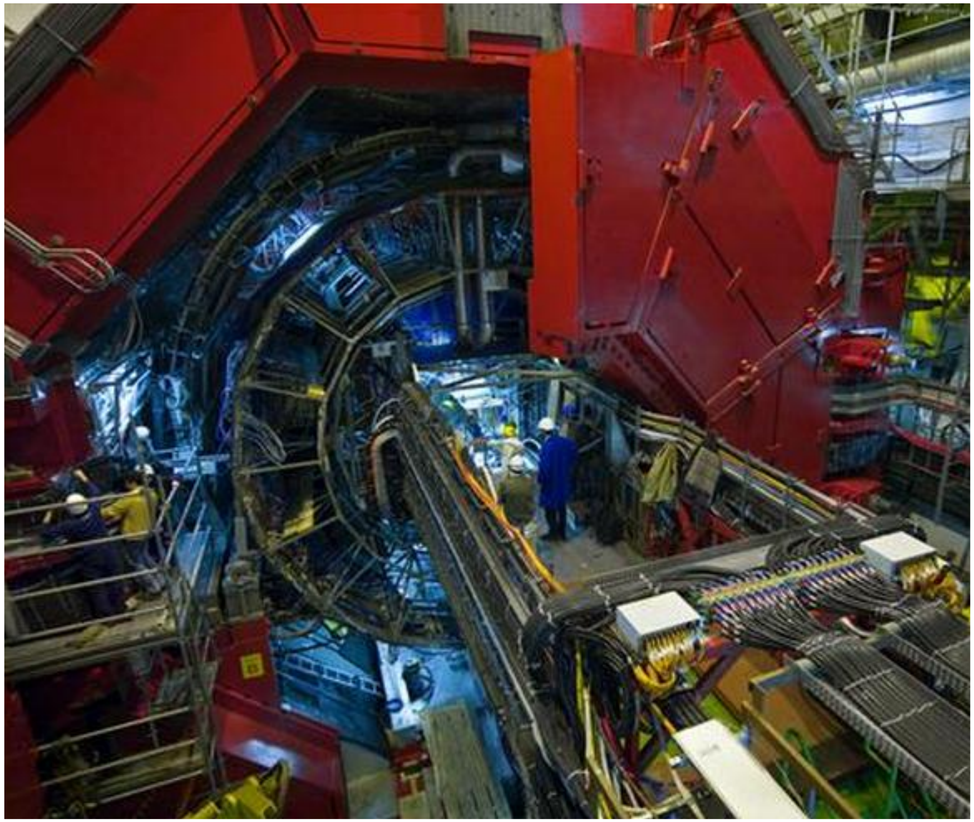
Cooling and trapping of 0.1-1 million of atoms



Vacuum chamber, countless mirrors, magnetic coils, water cooling, CCD cameras and lasers for laser cooling of atomic gases (human size)

Large Hadron Collider (CERN)

Collision of heavy nuclei in order to create quark gluon plasma



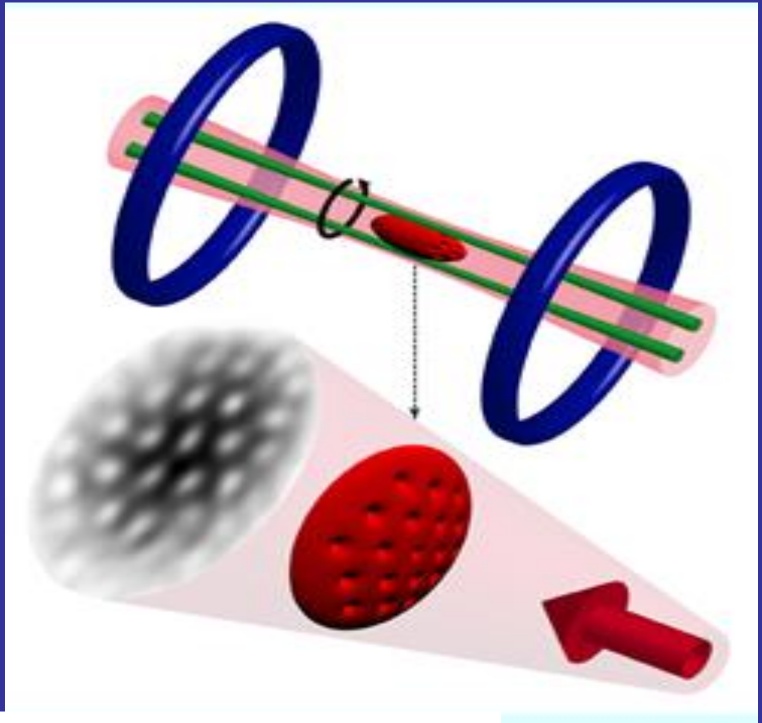
ALICE experiment: search for quark gluon plasma view of the ALICE detector: 26m x 16m x 16 m + particle collider in a tunnel of 27 km circumference

Short (selective) history:

- ✓In 1999 DeMarco and Jin created a degenerate atomic Fermi gas.
- ✓In 2005 Zwierlein/Ketterle group observed quantum vortices which survived when passing from BEC to unitarity – evidence for superfluidity!

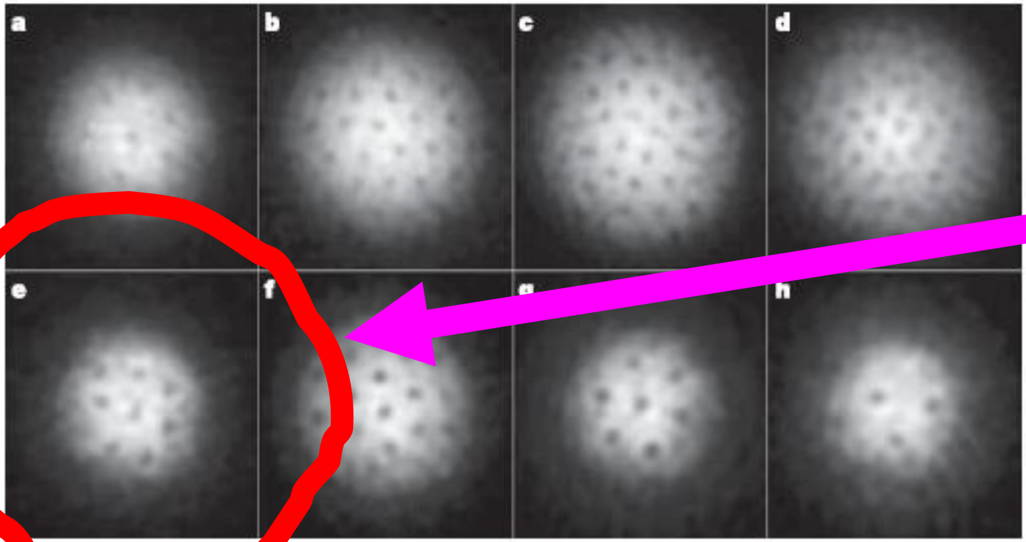
system of fermionic ^{6}Li atoms

Feshbach resonance: B=834G



BEC side: a>0

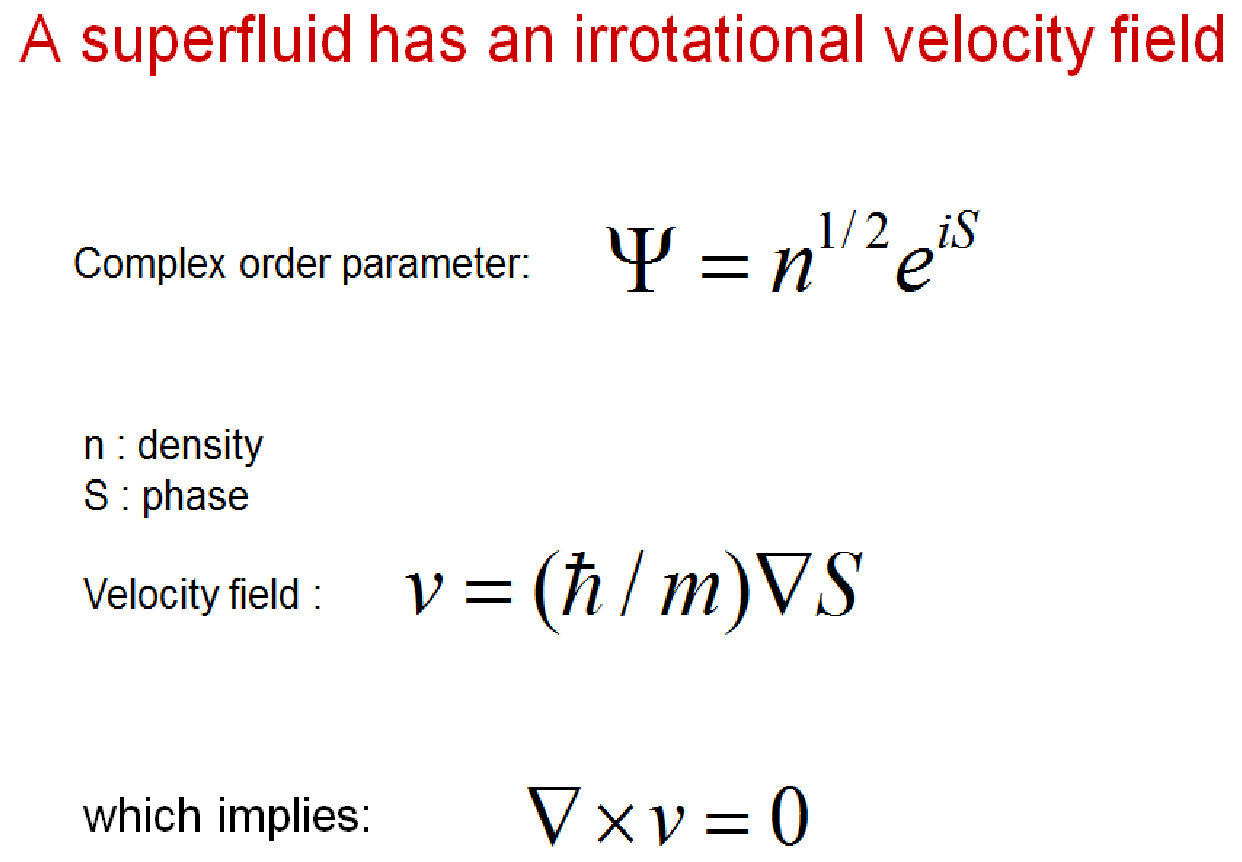
BCS side: a<0



UNITARY REGIME

Figure 2 | Vortices in a strongly interacting [illegible] fermionic atoms on the BEC- and the BCS-side of the Feshbach resonance. At the given field, the cloud of lithium atoms was stirred for 300 ms (**a**) or 500 ms (**b**–**h**) followed by an equilibration time of 500 ms. After 2 ms of ballistic expansion, the magnetic field was ramped to 735 G for imaging (s magnetic fields were 740 G (**a**), 766 G (**b**), 792 G (**c** 843 G (**f**), 853 G (**g**) and 863 G (**h**). The field of vie 880 μm × 880 μm.

M.W. Zwierlein *et al.*, Nature, 435, 1047 (2005)



A superfluid has an irrotational velocity field

Complex order parameter: $$\Psi = n^{1/2} e^{iS}$$

n : density
S : phase

Velocity field : $$v = (\hbar / m) \nabla S$$

which implies: $$\nabla \times v = 0$$

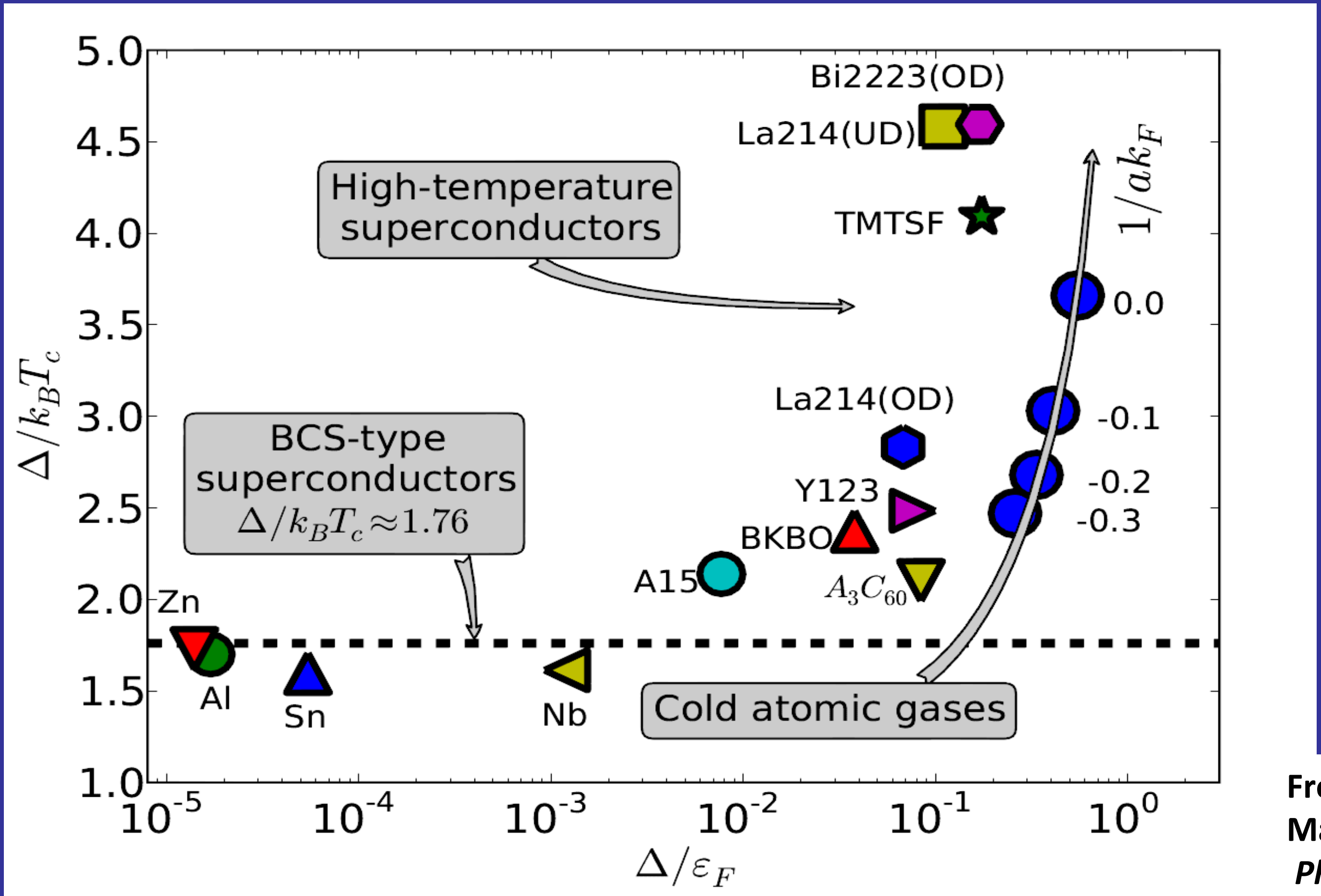
Consequences: **- no circulation in a simply connected region.**

- quantized circulation in a toroidal geometry

- appearance of quantized vortices with vanishing order parameter inside

Feynman suggestion (1950s): superfluids rotate through the presence of quantized vortex lines carrying angular momentum

Cold atomic gases and high Tc superconductors



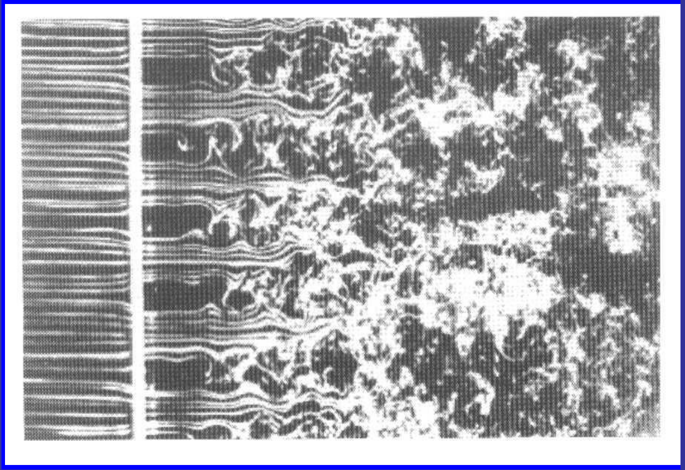
From:
Magierski, Wlazłowski, Bulgac,
*Phys. Rev. Lett.*107,145304(2011)

Δ/ε_F – Ratio of the strength of two interparticle correlations to the kinetic energy of the fastest particle in the system.

Standard theory of superconductivity (BCS theory) fails!
Qualitatively new phenomena occur like e.g. pseudogap characteristic for high-Tc superconductors

Magierski, Wlazłowski, Bulgac, Drut, *Phys. Rev. Lett.*103,210403(2009)

Road to quantum turbulence



Classical turbulence: energy is transfered from large scales to small scales where it eventually dissipates.

Kolmogorov spectrum: $E(k)=C\ \varepsilon^{2/3}\ k^{-5/3}$

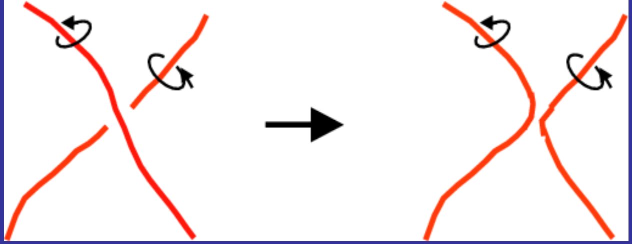
E – kinetic energy per unit mass associated with the scale 1/k
ε - energy rate (per unit mass) transfered to the system at large scales.
k - wave number (from Fourier transformation of the velocity field).
C – dimensionless constant.

Superfluid turbulence (quantum turbulence): disordered set of quantized vortices. The friction between the superfluid and normal part of the fluid serves as a source of energy dissipation.

Problem: how the energy is dissipated in the superfluid system at small scales at T=0? - „pure" quantum turbulence

Possibility: vortex reconnections → Kelvin waves → phonon radiation

Vortex reconnections



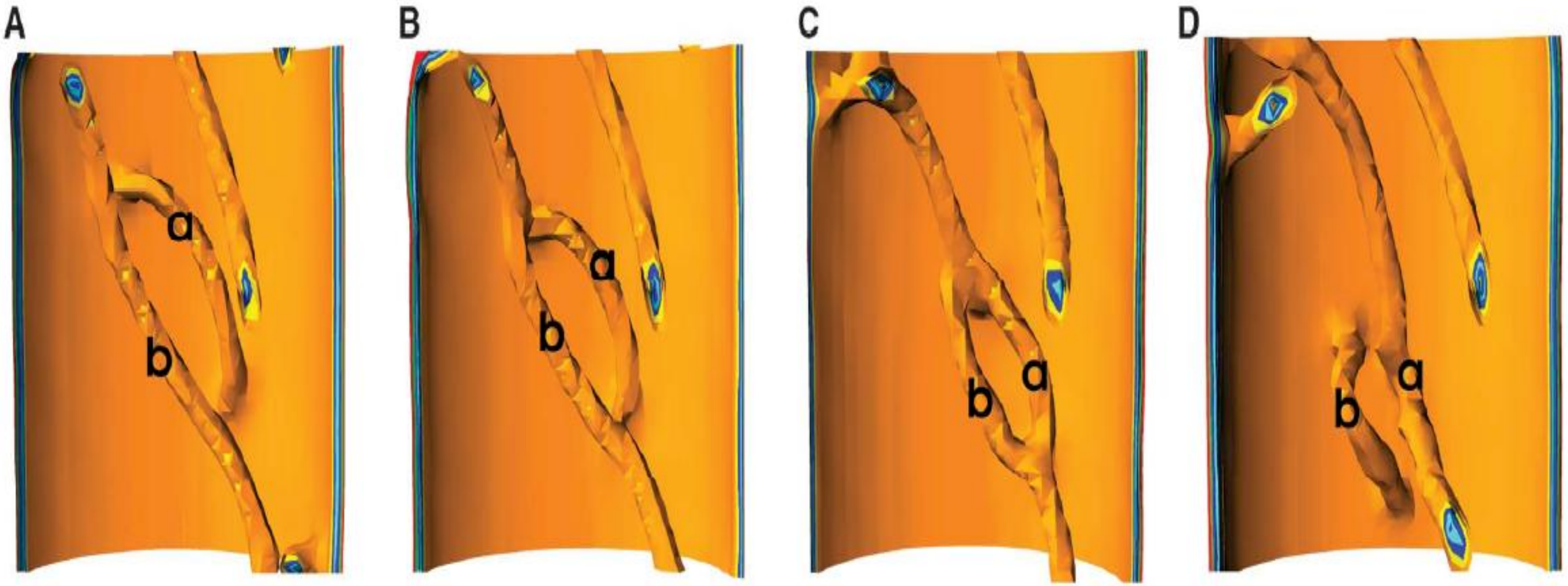
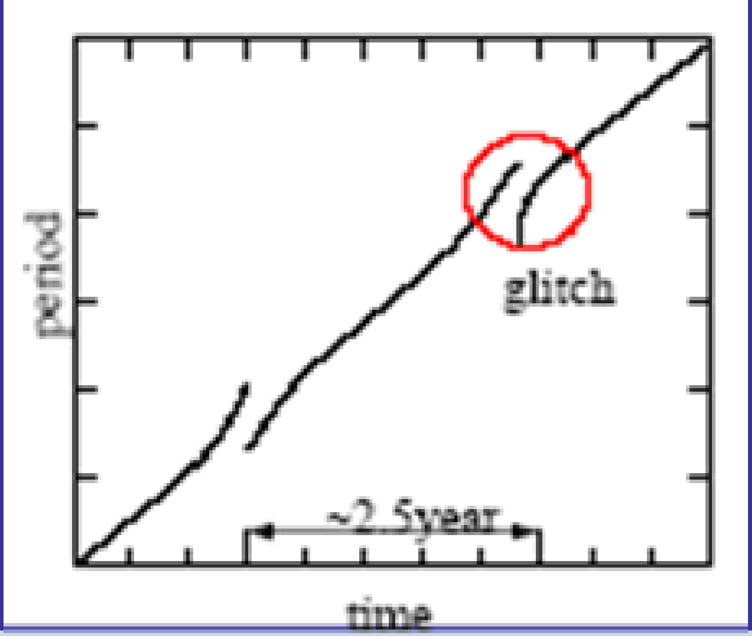


Fig. 3. (**A** to **D**) Two vortex lines approach each other, connect at two points, form a ring and exchange between them a portion of the vortex line, and subsequently separate. Segment (a), which initially belonged to the vortex line attached to the wall, is transferred to the long vortex line (b) after reconnection and vice versa.

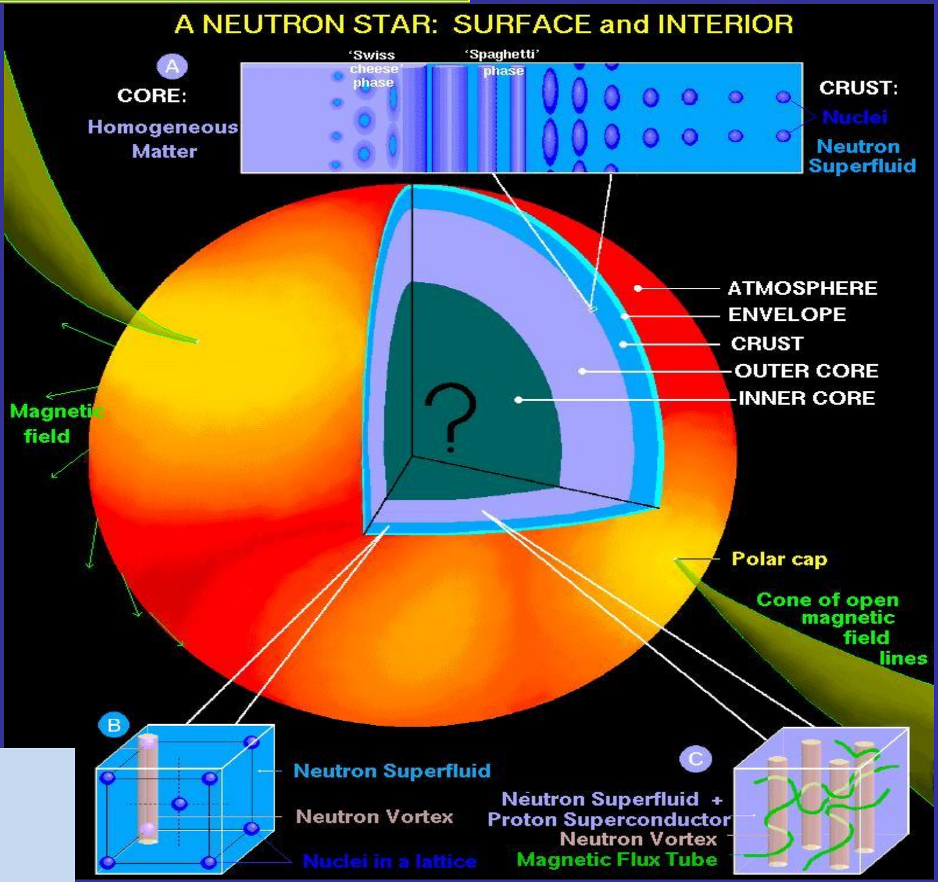
Bulgac, Luo, Magierski, Roche, Yu, *Science* 332, 1288 (2011)

Neutron stars and quantum turbulence

Neutron star is a huge superfluid



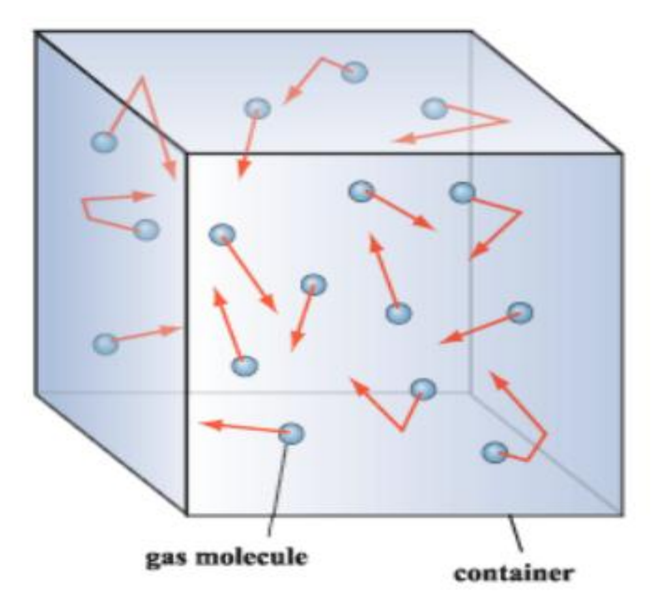
glitch phenomenon=a sudden speed up of rotation.
To date more than 300 glitches have been detected in more than 100 pulsars



Glitch phenomenon is commonly believed to be related to rearrangement of vortices in the interior of neutron stars. It would require however a correlated behavior of huge number of quantum vortices and the mechanism of such collective rearrangement is still a mystery.

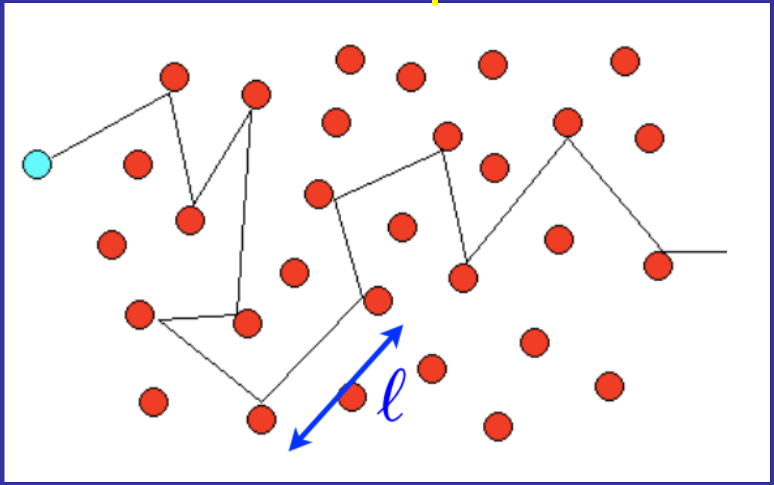
Viscosity in strongly correlated quantum systems:

Water and honey flow with different rates: different viscosity



In the light of the kinetic theory of gases molecules are moving mostly along straight lines and occasionally bump onto each other.

Mean free path



This leads to the Maxwell’s formula for viscosity (1860):

$$\eta \sim \rho v \ell = \text{mass density} \times \text{velocity} \times \text{mean free path}$$

Consequences:

- Non interacting gas is a pathological example of the system with an <u>infinite viscosity</u>
- Strongly interacting system can have low viscosity since the mean free path is short **but…**

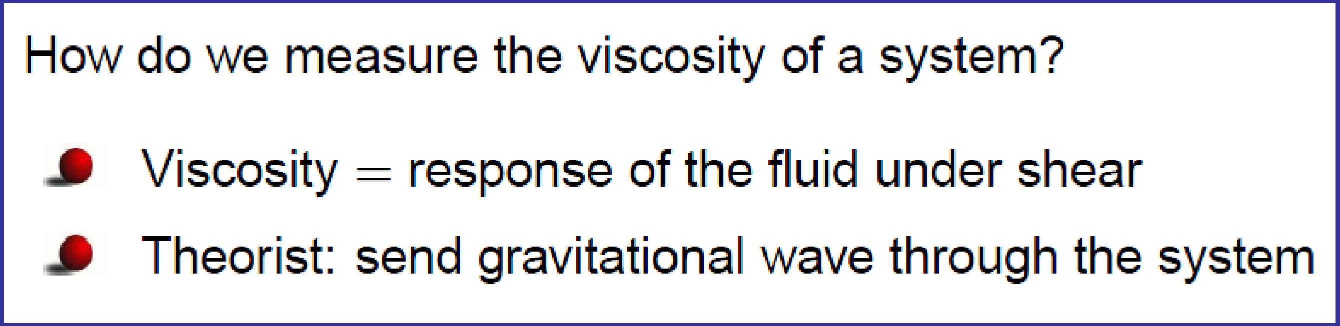
…but when the system is strongly correlated then the kinetic theory fails!

However:
If we blindly use this formula we may notice that the Heisenberg uncertainty principle would give the following relation:

$$\frac{\eta}{\rho} \sim \bar{p} l \geq \hbar$$

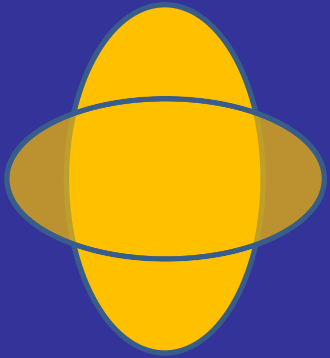
$\bar{p}$ - average momentum

Can we make the above statement more precise?



How do we measure the viscosity of a system?

- Viscosity = response of the fluid under shear
- Theorist: send gravitational wave through the system

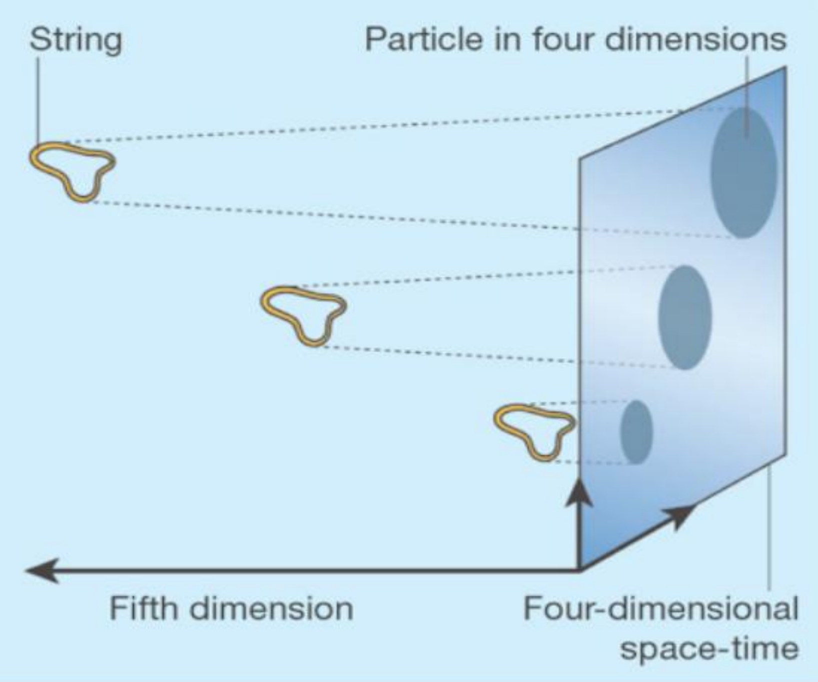


Maldacena's breakthrough (1997):

1997: gauge/gravity duality

particles in 4 dimensions = strings in 5 dimensions

Sometimes, the string picture is clearer than the particle picture!



(from Nature)

Consequence of Maldacena's hypothesis (string theory turned out to be useful in a very unexpected way)

$$\frac{\eta}{S} = \frac{\hbar}{4\pi}$$

Kovtun,Son,Starinets, (2005) from AdS/CFT correspondence

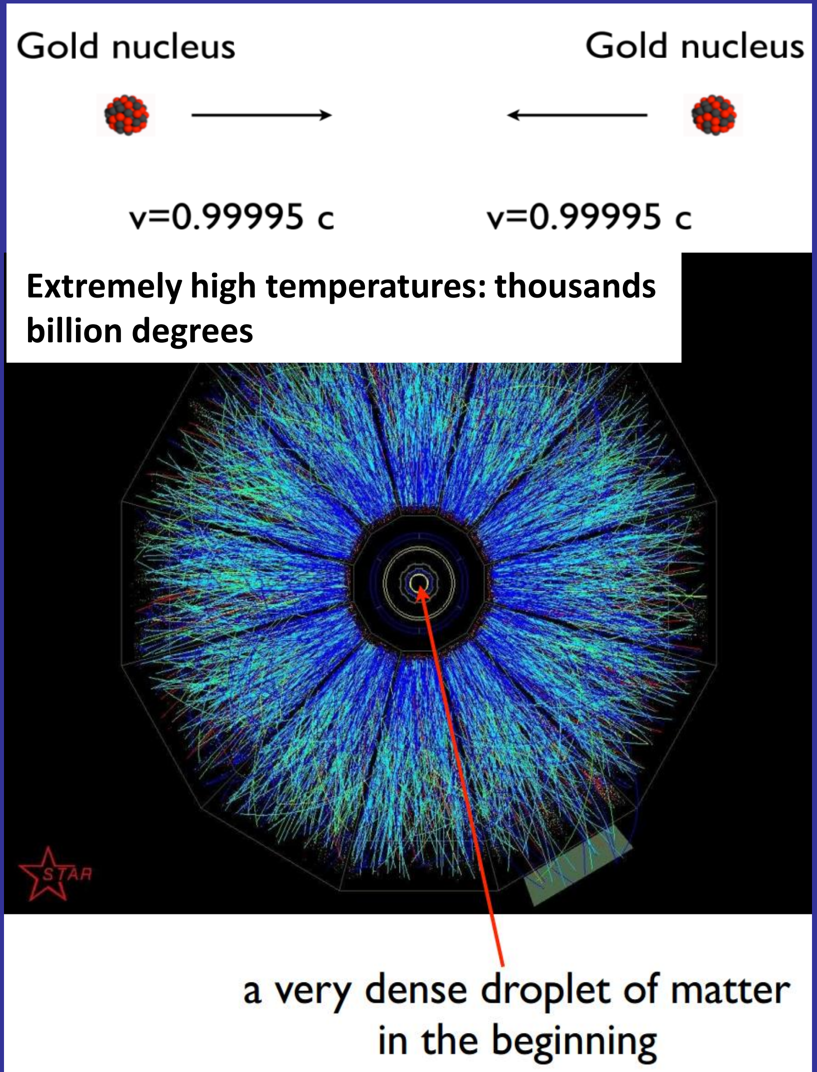
S – entropy density

KSS conjecture: all known fluids satisfy:

$$\frac{\eta}{S} \geq \frac{\hbar}{4\pi}$$

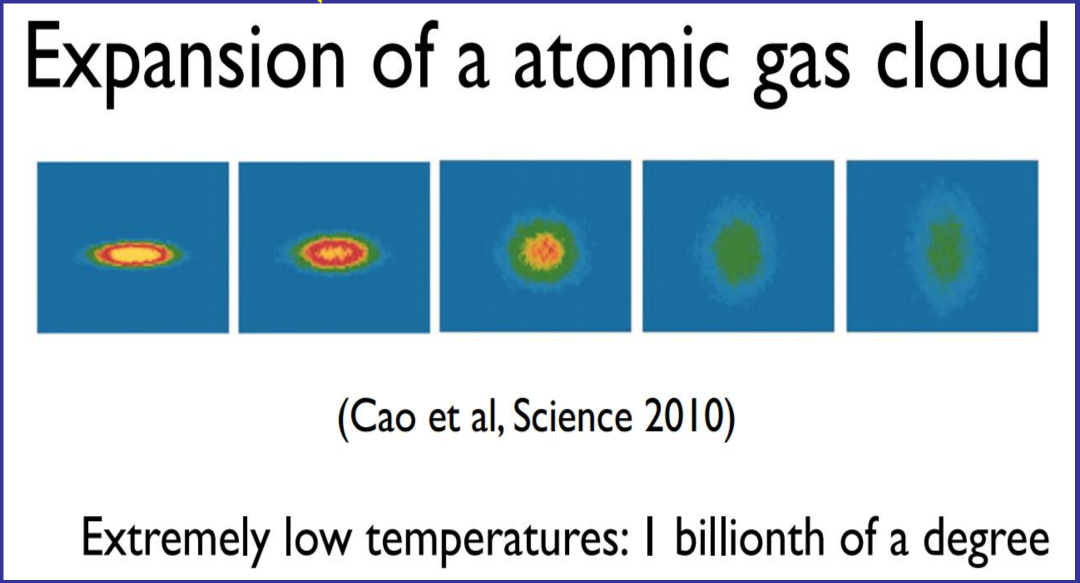
Perfect fluid $\frac{\eta}{S} = \frac{\hbar}{4\pi k_B}$ - strongly interacting quantum system = No well defined quasiparticles

Candidates: quark gluon plasma, atomic gas



Extremely high temperatures: thousands billion degrees

a very dense droplet of matter in the beginning



Expansion of a atomic gas cloud

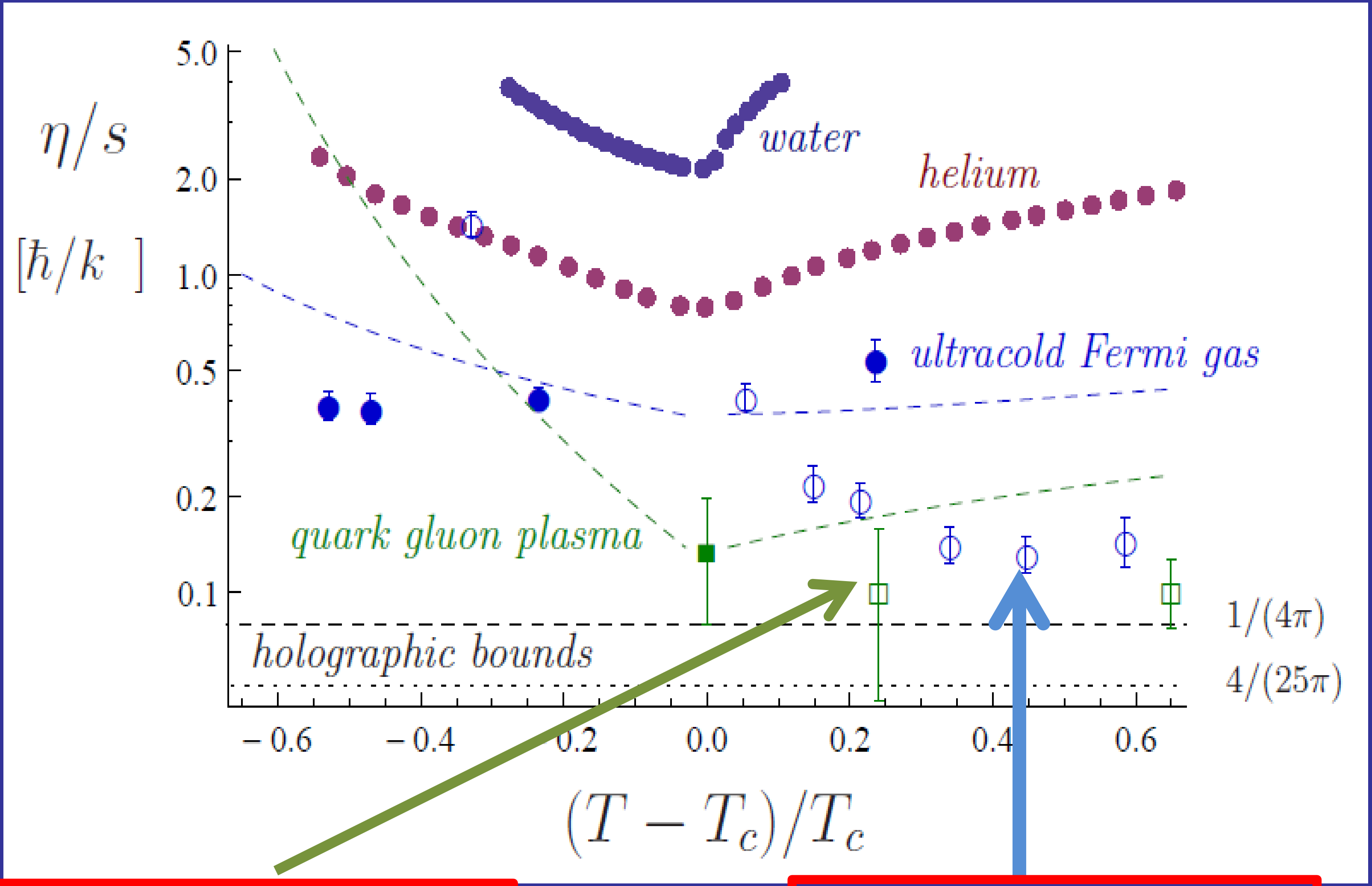
(Cao et al, Science 2010)

Extremely low temperatures: 1 billionth of a degree

Despite of energy scales differing by many orders of magnitude, expansion of both system is pretty much similar and in particular exhibts the so-called <u>elliptic flow</u>.

Shear viscosity to entropy ratio – experiment vs. theory

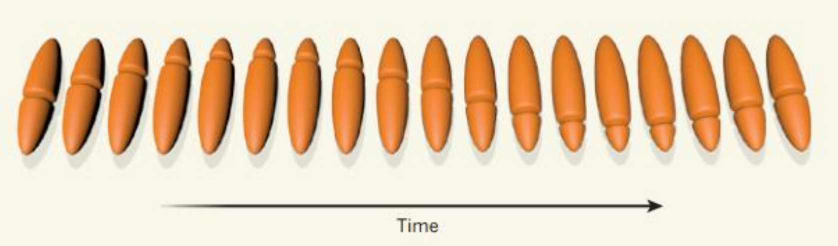
(from A. Adams et al. New Journal of Physics, "Focus on Strongly Correlated Quantum Fluids: from Ultracold Quantum Gases to QCD Plasmas,, arXive:***1205.5180)***



Lattice QCD (SU(3) gluodynamics):
H.B. Meyer, Phys. Rev. D 76, 101701 (2007)

QMC calculations for UFG:
G. Wlazłowski, P. Magierski, J.E. Drut,
Phys. Rev. Lett. 109, 020406 (2012)

Soliton dynamics vs ring vortex – a controversy



MIT Experiment:
Nature 499 (2013) 426

Theory prefers ring vortices:
A. Bulgac, M. M. Forbes, M.M. Kelley, K. J.Roche, G. Wlazłowski, Phys. Rev. Lett. (in press)

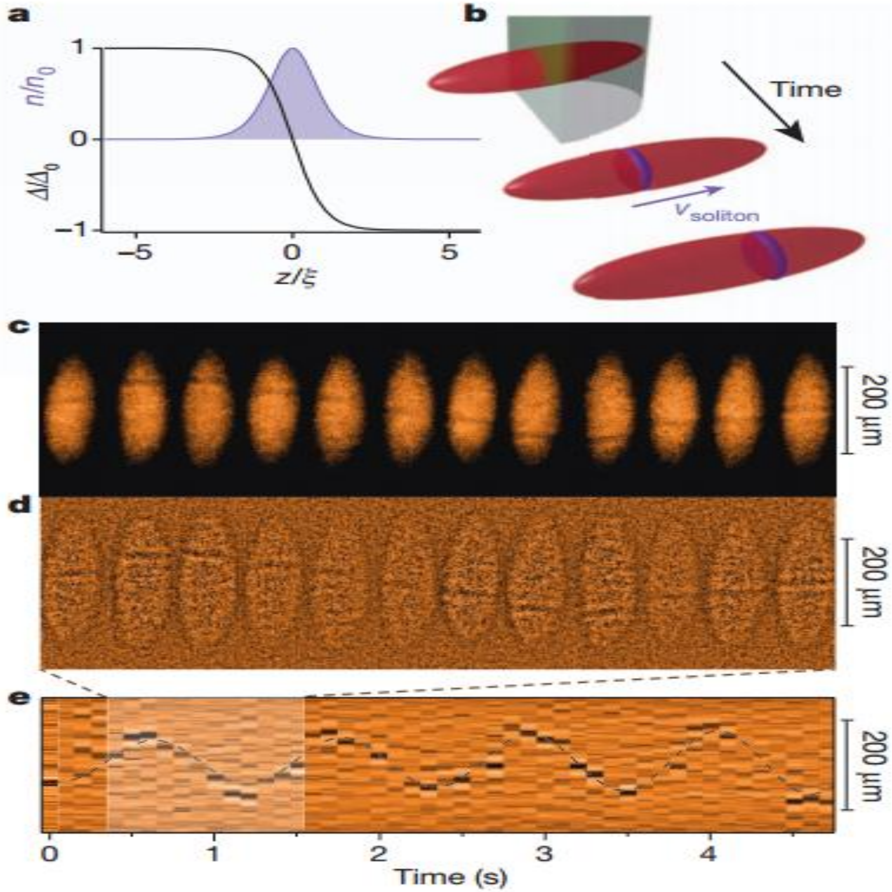
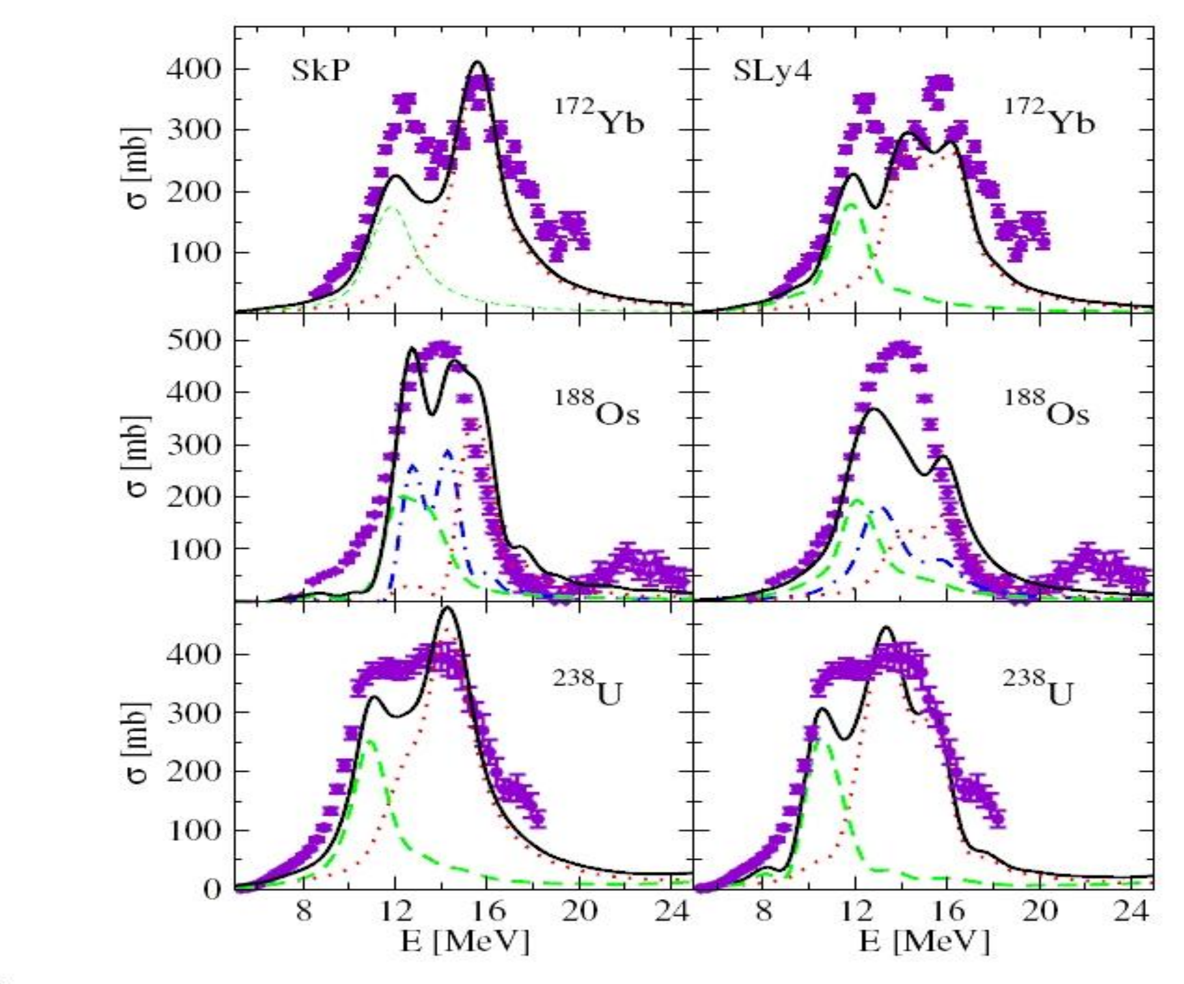


Figure 1 | Creation and observation of solitons in a fermionic superfluid. **a**, Superfluid pairing gap $\Delta(z)$ for a stationary soliton, normalized by the bulk pairing gap Δ_0, and density $n(z)$ of the localized bosonic (fermionic) state versus position z, in the BEC (BCS) regime of the crossover, in units of the BEC healing length (BCS coherence length) ξ. **b**, Diagram of the experiment. A phase-imprinting laser beam twists the phase of one-half of the trapped superfluid by approximately π. The soliton generally moves at non-zero velocity v_{soliton}. **c**, Optical density and **d**, residuals (optical density minus a smoothed copy of the same image) of atom clouds at 815 G, imaged via the rapid ramp method[34], showing solitons at various hold times after creation. One period of soliton oscillation is shown. The in-trap aspect ratio was $\lambda = 6.5(1)$. **e**, Radially integrated residuals as a function of time revealing long-lived soliton oscillations. The soliton period is $T_s = 12(2)T_z$, much longer than the trapping period of $T_z = 93.76(5)$ ms, revealing an extreme enhancement of the soliton's relative effective mass, M^*/M.

Application to nuclear physics - strongly correlated system.

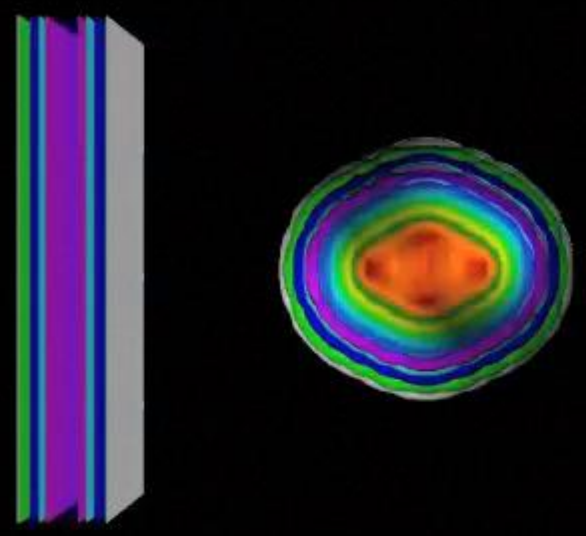
Photoabsorption cross section for heavy, deformed nuclei.

(gamma,n) reaction through the excitation of GDR



I.Stetcu, A.Bulgac, P. Magierski, K.J. Roche, Phys. Rev. C84 051309 (2011)

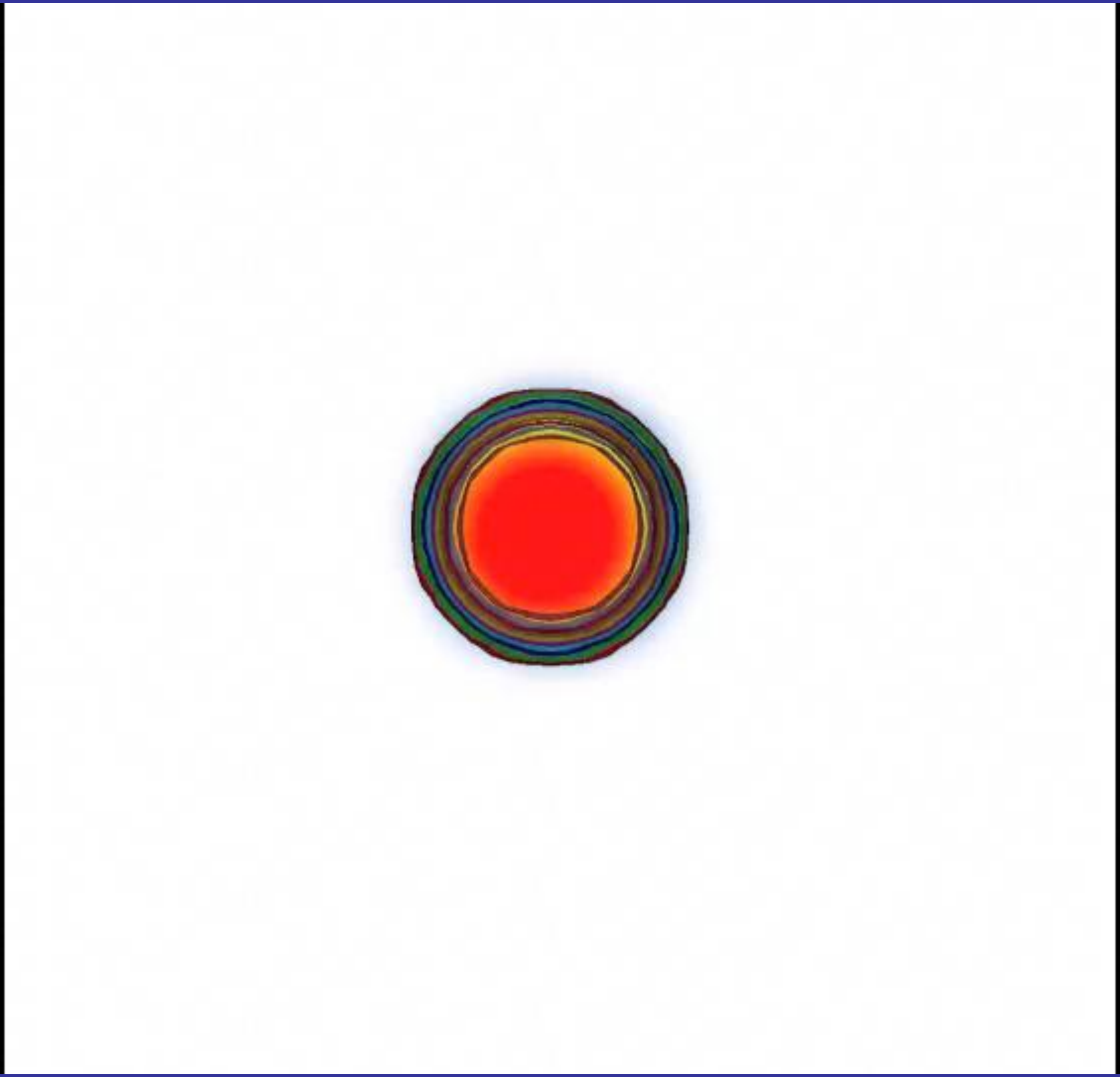
Holy Grail of nuclear physics:
Describe microscopically the induced fission process.



Neutron scattering of ^{238}U computed in TDSLDA with absorbing boundary conditions

Movie

I. Stetcu *et al.*



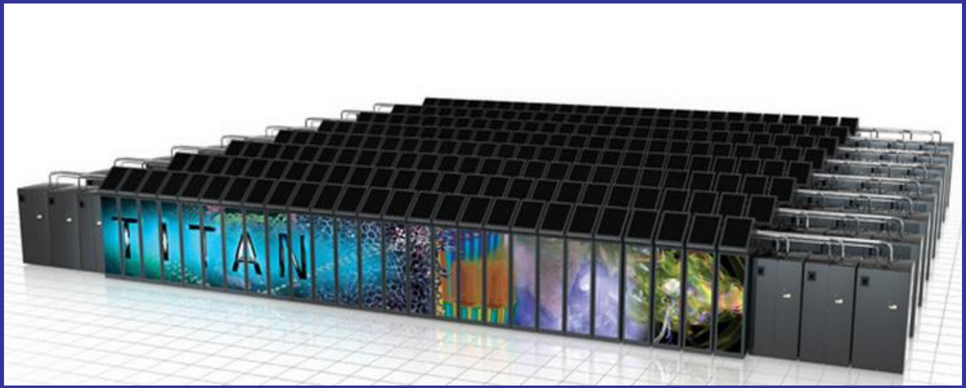
Real-time induced fission of ^{280}Cf computed in TDSLDA

I. Stetcu *et al.*

Movie

Computational resources

Titan, Oak Ridge USA,
Hybrid architecture (CPU+GPU),
Ranking: no. 1



Various CPU machines at NERSC (USA) :
mainly Edison and Hopper. Ranking: no. around 20

K Computer, Kobe, Japan
CPU architecture , Ranking: no. 4

icm
interdyscyplinarne centrum
modelowania matematycznego
i komputerowego

In practice we solve about 100 thousands of nonlinear partial differential equations which allow to simulate the time evolution of about 10 thousands strongly interacting atoms or nucleons.

Collaborators:

Aurel Bulgac
(U. Washington)

Joaquin E. Drut
(U. North Carolina)

Michael M. Forbes
(INT)

Kenneth J. Roche
(PNNL)

Ionel Stetcu
(LANL)

Gabriel Wlazłowski
(PW/ U. Washington)

Now I am going to present computer simulations which basically come from solving this fundamental equation of nonrelativistic quantum mechanics:

$$i\hbar \frac{\partial}{\partial t}\psi = \hat{H}\psi$$

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In practice we solve about 100 thousands of nonlinear partial differential equations which allow to simulate the time evolution of about 10 thousands strongly interacting atoms.

SLDA for unitary Fermi gas

SLDA – Superfluid Local Density Approximation

SLDA energy density functional at unitarity

$$\varepsilon(\vec{r}) = \left[\alpha \frac{\tau_c(\vec{r})}{2} - \Delta(\vec{r})\nu_c(\vec{r})\right] + \beta \frac{3(3\pi^2)^{2/3} n^{5/3}(\vec{r})}{5}$$

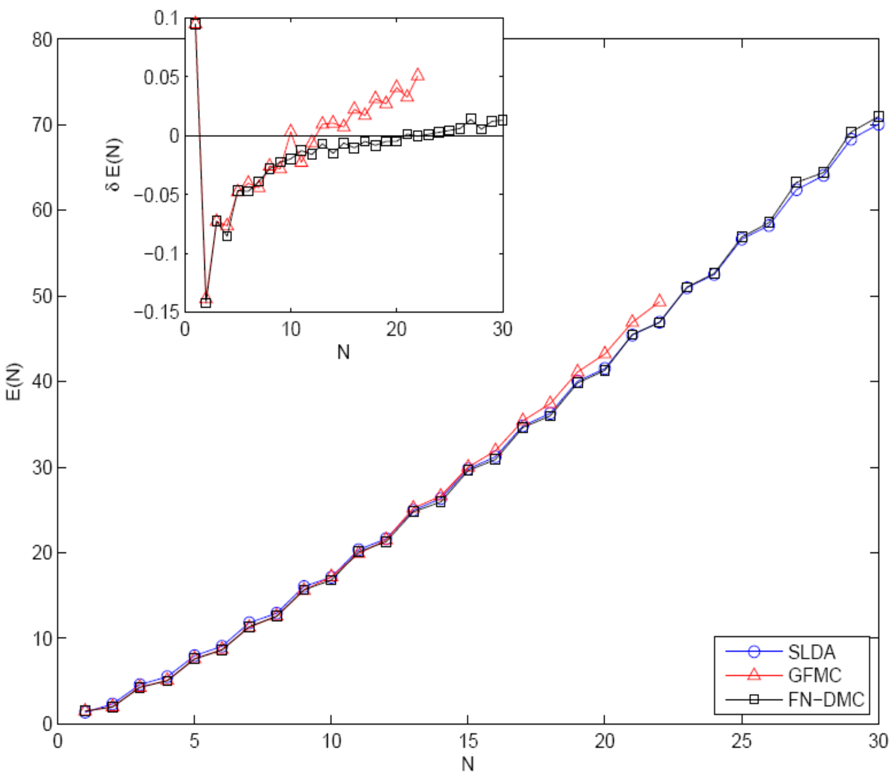
$$n(\vec{r}) = 2 \sum_{0<E_k<E_c} \left|\mathrm{v}_k(\vec{r})\right|^2, \quad \tau_c(\vec{r}) = 2 \sum_{0<E_k<E_c} \left|\vec{\nabla}\mathrm{v}_k(\vec{r})\right|^2,$$

$$\nu_c(\vec{r}) = \sum_{0<E<E_c} \mathrm{u}_k(\vec{r})\mathrm{v}_k^*(\vec{r})$$

$$U(\vec{r}) = \beta \frac{(3\pi^2)^{2/3} n^{2/3}(\vec{r})}{2} - \frac{\left|\Delta(\vec{r})\right|^2}{3\gamma n^{2/3}(\vec{r})} + V_{ext}(\vec{r})$$

$$\Delta(\vec{r}) = -g_{eff}(\vec{r})\nu_c(\vec{r})$$

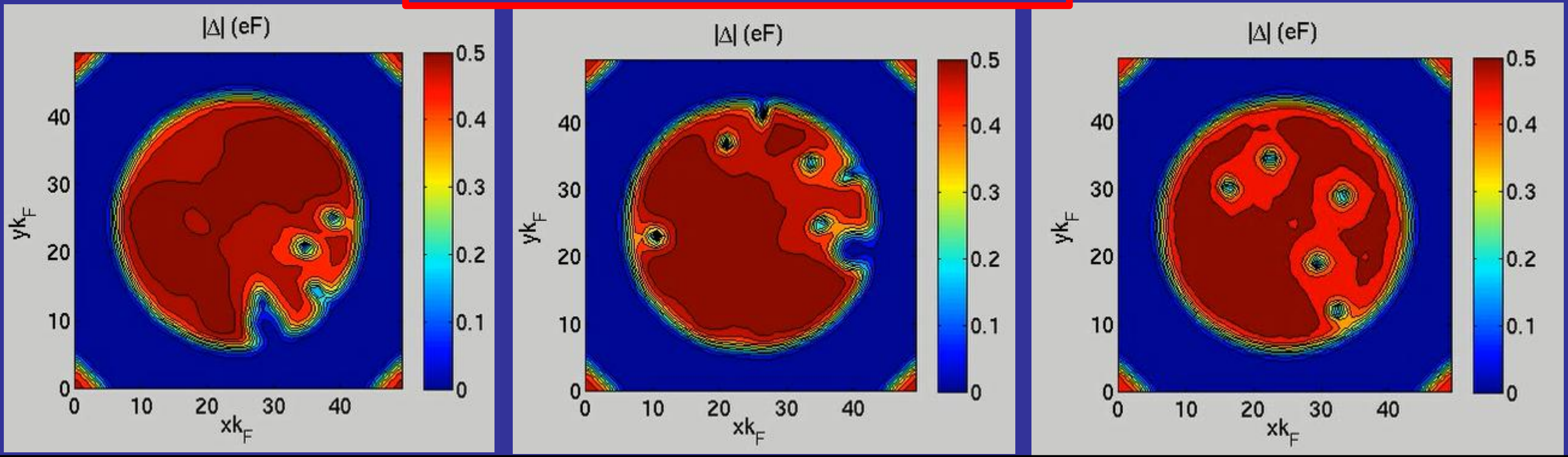
Fermions at unitarity in a harmonic trap
Total energies E(N)



GFMC - Chang and Bertsch, Phys. Rev. A 76, 021603(R) (2007)
FN-DMC - von Stecher, Greene and Blume, PRL 99, 233201 (2007)
PRA 76, 053613 (2007)

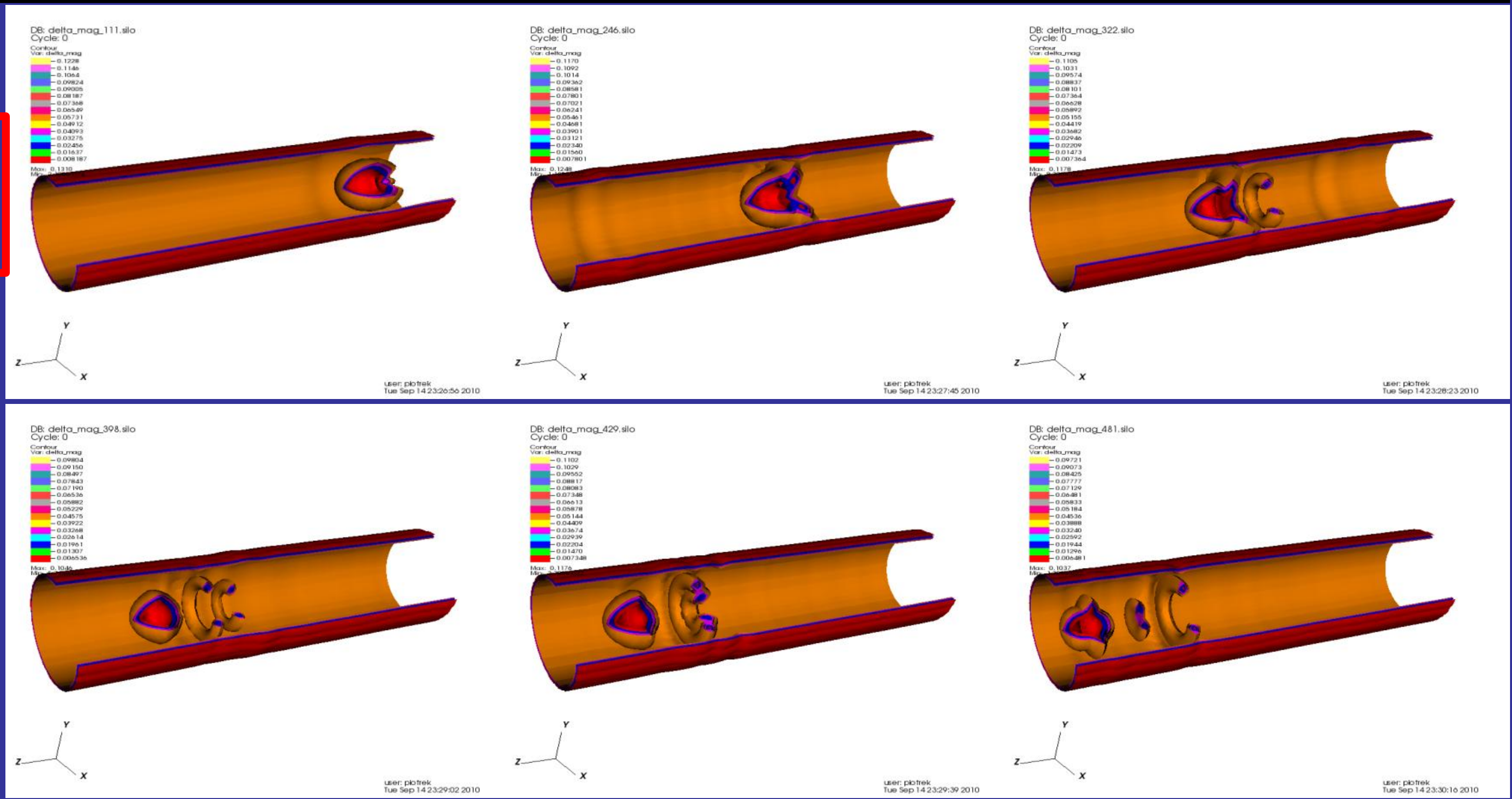
Bulgac, PRA 76, 040502(R) (2007)

Excitation of vortices through stirring



dynamics of vortex rings

Heavy spherical object moving through the superfluid unitary Fermi gas



A new method to construct the ground state which eschews big matrix diagonalization:

adiabatic switching with quantum friction

$$i\hbar\dot{\Psi}(x,t)=\left[H(x,t)+U(x,t)\right]\Psi(x,t)$$

$$E=\langle\Psi|H|\Psi\rangle$$

$$\dot{E}=\langle\Psi|\dot{H}|\Psi\rangle+\frac{2}{\hbar}\mathrm{Im}\langle\Psi|HU|\Psi\rangle$$

$$\text{if }\ U\propto-\hbar\vec{\nabla}\cdot\vec{j}=\hbar\dot{\rho}\ \ \Rightarrow\ \ \dot{E}\le\langle\Psi|\dot{H}|\Psi\rangle$$

$$\text{We choose }\ U=-\beta\frac{\hbar\vec{\nabla}\cdot\vec{j}}{\rho}$$

$$\vec{j}(\vec{r})=\frac{\hbar}{m}\mathrm{Im}\sum_{n}\psi_{n}^{*}(\vec{r},t)\vec{\nabla}\psi_{n}(\vec{r},t)$$

Main advantage:
Replace iterative procedure which requires $O(N^3)$ operations for diagonalization with time evolution which requires only $O(N^2\ln(N))$ operations per time step.

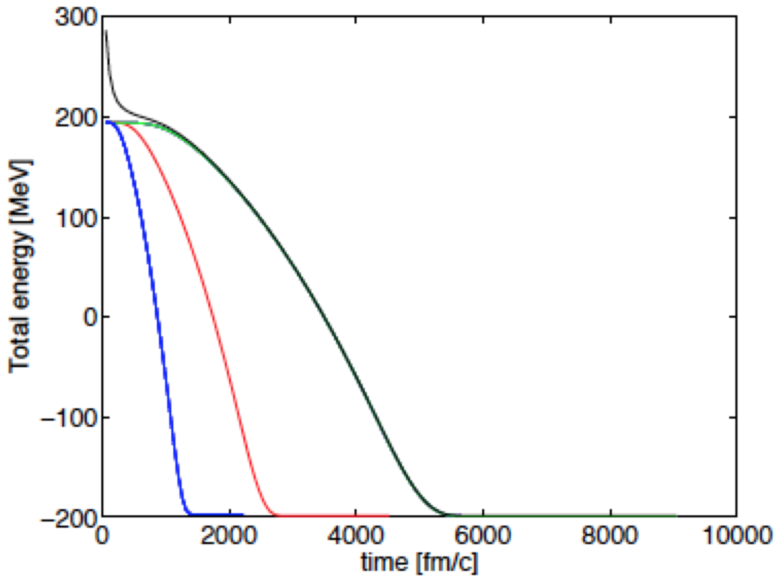


FIG. 2. (Color online) The total instantaneous energy of a system of twenty non-interacting neutrons evolving from an initial 3D harmonic oscillator potential to a final symmetrized Woods-Saxon potential. The curves correspond to quasi-adiabatic evolution with friction $(1-s_t)H_0+s_tH_1+U_t$ for various switching periods T (two-thirds of the simulation time) and just friction H_1+U_t for the remaining third of the simulation. That the energy is constant during this time demonstrates that the ground state has been reached. Note: there are three curves for the longest T corresponding to different simulations with $\{24^3, 32^3, 40^3\}$ lattices of 1 fm spacing: this demonstrates the infrared (IR) convergence.

TDSLDA applications:

1) Nuclear physics:

- Electromagnetic response
- Pairing vibrations
- Heavy ion collisions
- Induced fission
- Neutron scattering/capture

2) Neutron stars:

- Dynamics of vortices
- Vortex pinning mechanism in the neutron star crust (glitches)

3) Various applications in cold atom physics.

Papers we published so far on SLDA and TDSLDA
(stars indicate papers with significant nuclear physics content):

arXiv:1306.4266
* arXiv:1305.6891
* Phys. Rev. Lett. 110, 241102 (2013)
* Phys. Rev. C 87 051301(R) (2013)
* Ann. Rev. Nucl. Part. Phys. 63, 97 (2013)
* Phys. Rev. C 84, 051309(R) (2011)
Phys. Rev. Lett. 108, 150401 (2012)
Science, 332, 1288 (2011)
J. Phys. G: Nucl. Phys. 37, 064006 (2010)
Phys. Rev. Lett. 102, 085302 (2009)
Phys. Rev. Lett. 101, 215301 (2008)
* J.Phys. Conf. Ser. 125, 012064 (2008)
arXiv:1008.3933 chapter 9 in Lect. Notes Phys. vol. 836
Phys. Rev. A 76, 040502(R) (2007)
* Int. J. Mod. Phys. E 13, 147 (2004)
Phys. Rev. Lett. 91, 190404 (2003)
* Phys. Rev. Lett. 90, 222501 (2003)
* Phys. Rev. Lett. 90, 161101 (2003)
* Phys. Rev. C 65,051305(R) (2002)
* Phys. Rev. Lett. 88, 042504 (2002)
Plus a few other chapters in various books.