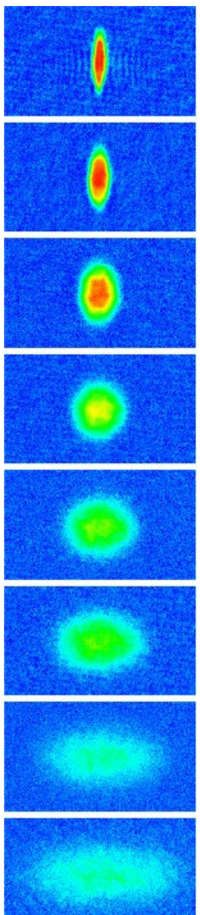
What can heavy ion physics learn from physics of ultra-cold atoms?

T. Csörgő [1,2]

csorgo@physics.harvard.edu

[1] **MTA KFKI RMKI**, Budapest, Hungary

[2] **Department of Physics, Harvard University,** Cambridge, USA.



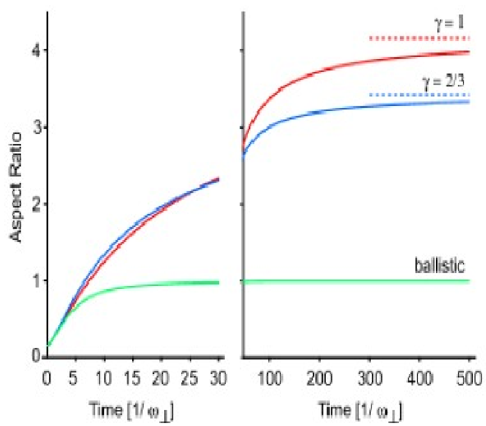
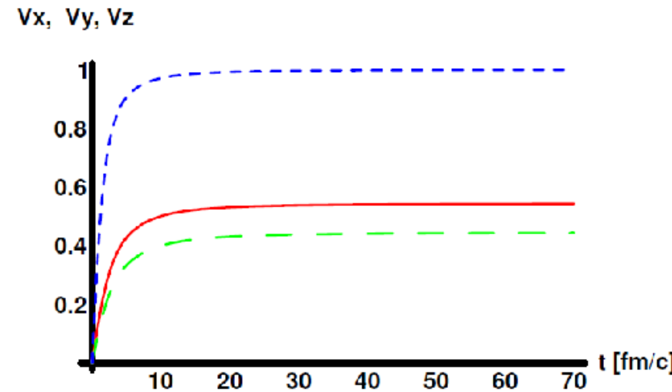
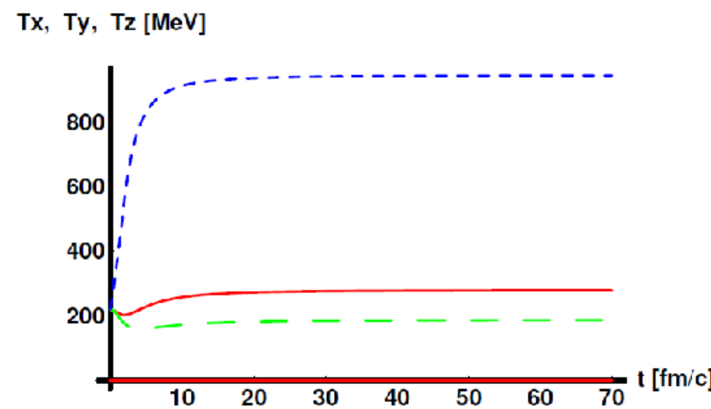


Fig. 16. – Aspect ratio $\epsilon(t) = R_x(t)/R_z(t)$ as a function of time for the MIT trap ($\epsilon = 1/6$) in ballistic, collisional or superfluid hydrodynamic expansion ($\gamma = 2/3$) and superfluid hydrodynamic expansion of a molecular BEC ($\gamma = 1$).





NEARLY PERFECT analogies between NEARLY PERFECT FLUIDs:
Same equations in heavy ion physics and the physics of ultra-cold atoms !

Heavy Ion Collisions

dynamical equations

$$\begin{aligned} \partial_t n + \nabla(\mathbf{v}n) &= 0\,, \\ \partial_t \mathbf{v} + (\mathbf{v}\nabla)\mathbf{v} &= -(\nabla(p+p_G))/(mn)\,, \\ \partial_t \epsilon + \nabla(\epsilon\mathbf{v}) + p\nabla\mathbf{v} &= j_G\,, \end{aligned}$$

Ultra-Cold Fermi-gases

$$\frac{\partial n}{\partial t} + \nabla\cdot(n\mathbf{v}) = 0$$

$$m\frac{\partial \mathbf{v}}{\partial t} + m(\mathbf{v}\cdot\nabla)\mathbf{v} = -\nabla\left(V + \mu(n)\right)$$

Euler+ energy equation may have source terms: (gluon wind at RHIC, or potential of the optical trap)

Equations of state:

$$p = \lambda_p n T - B$$ $$\epsilon = \lambda_e n T + B$$ $$\kappa = \lambda_e/\lambda_p$$

$$\mu(n) \propto n^{\gamma},$$

Self-similar, ellipsoidal solutions. Scaling parameters:

$$\begin{aligned} n(t,\mathbf{r}') &= n_0 \frac{V_0}{V} \exp\left(-\frac{r_x'^2}{2X^2} - \frac{r_y'^2}{2Y^2} - \frac{r_z'^2}{2Z^2}\right), \\ \mathbf{v}'(t,\mathbf{r}') &= \left(\frac{\dot X}{X} r_x',\ \frac{\dot Y}{Y} r_y',\ \frac{\dot Z}{Z} r_z'\right), \\ T(t) &= T_i(t)\left(\frac{V_0}{V}\right)^{1/\kappa}, \end{aligned}$$

$$V = XYZ$$

$$x_i(t) = b_i(t)\, x_{0i}$$

$$v_i(t) = \frac{\dot b_i}{b_i} x_i(t)$$

unit volume scales as $\mathcal{V}(t) = b_x\, b_y\, b_z$

$$\ddot X X = \ddot Y Y = \ddot Z Z = \frac{T_i(t)}{m}\left(\frac{V_0}{V}\right)^{1/\kappa}$$

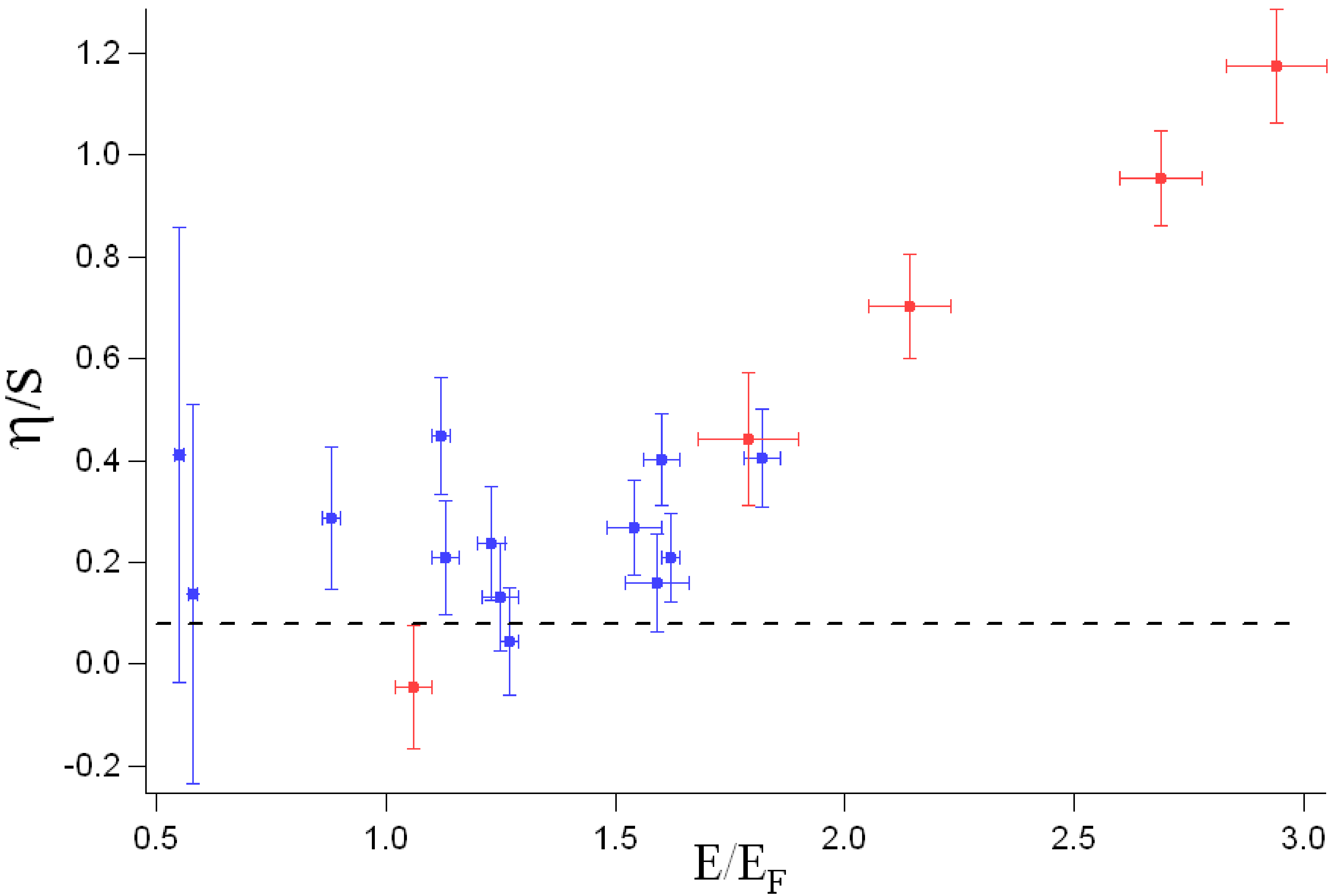
dynamical equations for the scales are similar, too:

$$\ddot b_i = -\omega_i^2(t)\, b_i + \frac{\omega_i^2(0)}{b_i \mathcal{V}^{\gamma}}$$

T. Cs, J. Zimányi, nucl-th/0206051
hep-ph/0012127, hep-ph/0108067

W. Ketterle and M. Zwierlein,
arXiv.org:0801.2500 [cond-mat.other]

Summary of UCA data



Summary

(NEARLY) PERFECT FLUID hydrodynamics:
(nearly) perfect formal analogies between

T.Cs. J. Zimányi, nucl-th/0206051 and
W. Ketterle and M. Zwierlein, arXiv.org:0801.2500 [cond-math.other]

Similar families of exact hydrodynamical solutions
Universality of (directional) Hubble flow

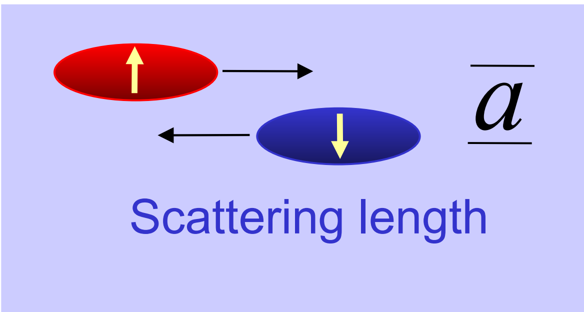
Conjectures:

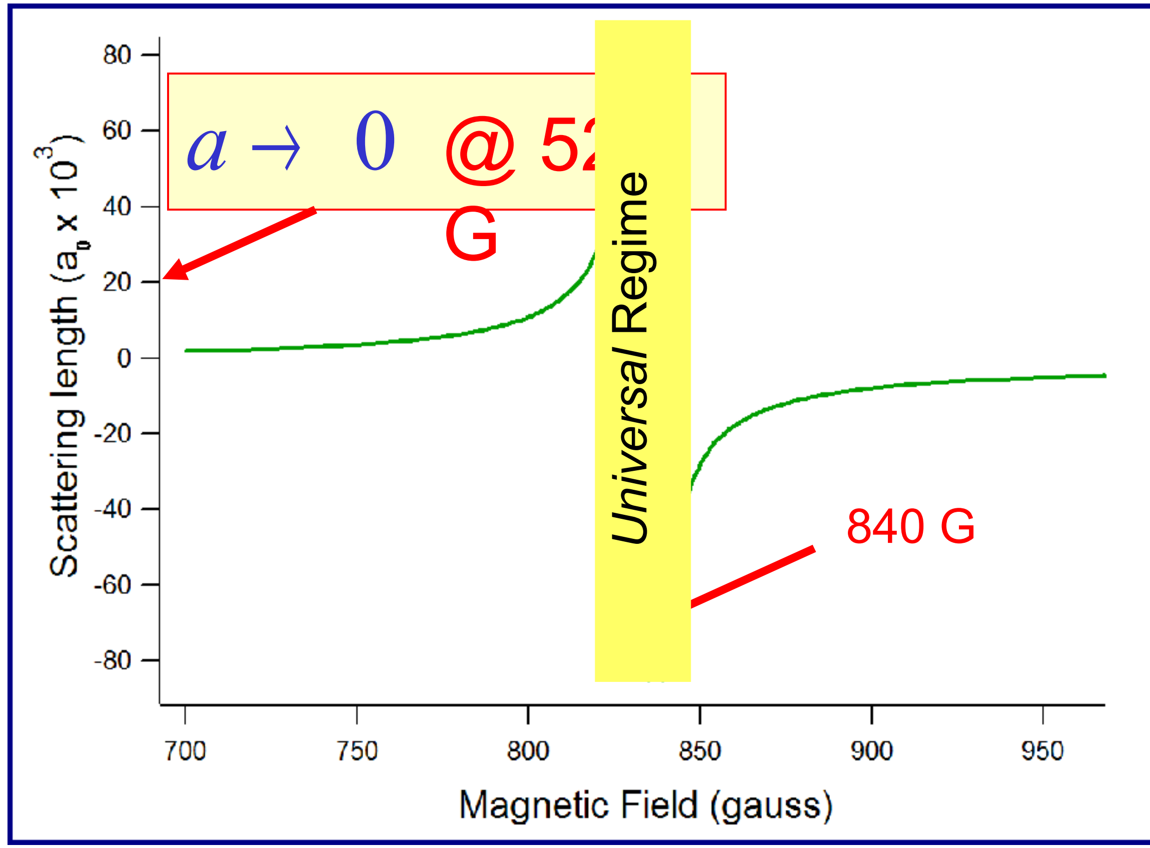
Fluid of quarks at RHIC = ultra-cold, relativistic Fermi gas?
(Cold, as far as quarks are concerned!)

Aspect ratio of slope parameters in plane/out of plane:
sensitivite to EoS, and simpler than v_2

Backup slides
from J. Thomas, QM09

Tunable Interactions: Feshbach Resonance





Interparticle Spacing :

$L \approx 2000\, a_0$

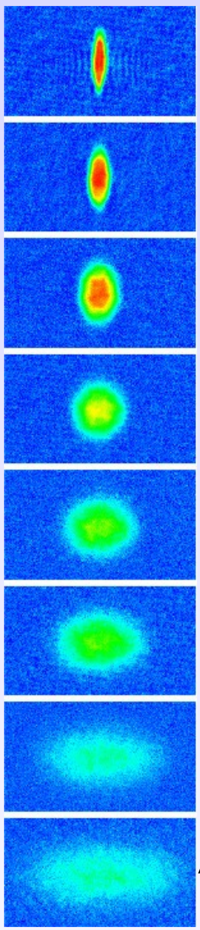
*Generated using formula published in Bartenstein, et al, *PRL* **94** 103201 (2005)

Strongly Interacting Systems in Nature

Duke Physics

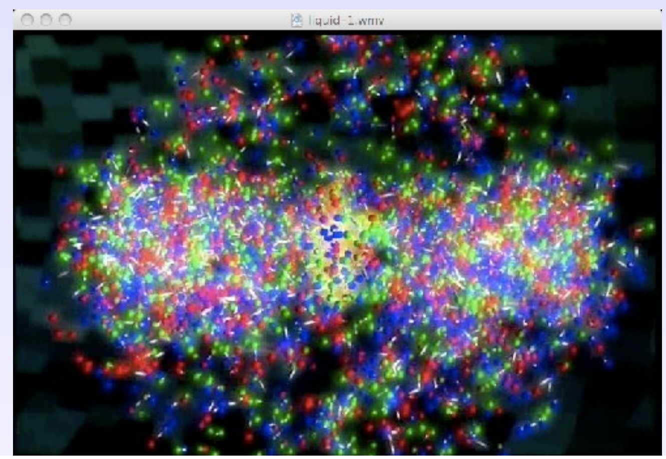
Atom Cooling and Trapping

- Ultracold Atomic ^{6}Li Gas
- Quark-Gluon Plasma
- High T_c Superconductors
- Neutron Matter
- Black Holes in String Theory



Strongly Interacting ^{6}Li gas T = 10^{-7} K

Duke, Science (2002)

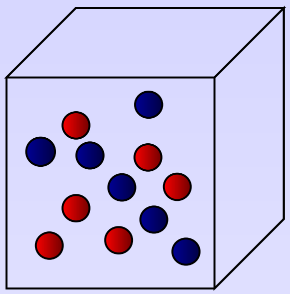


APS99 **Similar "Elliptic" Flow**

Quark-gluon plasma T = 10^{12} K

The *Universal* Regime

Ideal Fermi Gas



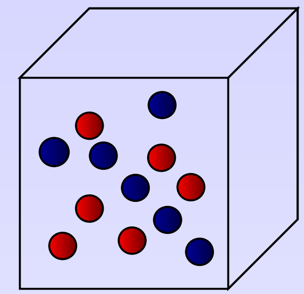
$$E_{\mathrm{ideal}} \approx \frac{\hbar^2}{2mL^2}$$

Fermi Energy

<u>T= 0</u>

Interparticle spacing L is the *only* length scale.

Strongly Interacting Fermi Gas



$$\frac{L}{a} \to 0$$

$$\mathrm{E}_{\mathrm{gnd}} = (1+\beta)\,E_{\mathrm{ideal}}$$

Bertsch 1998, Baker 1999, Heiselberg, 2001

Theory: Carlson (2008) $\beta = -0.60(1)$

Experiment: Duke (2008) $\beta = -0.61(2)$

Viscosity/entropy density (units of $\hbar / k_B$)