Dynamics of shock waves in strongly interacting systems

Shock waves in ultracold atomic Fermi gases with Boltzmann equation

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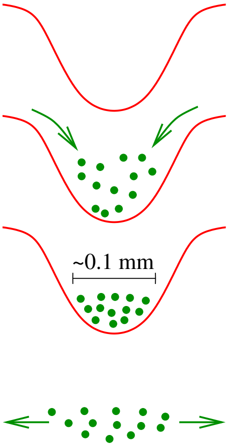
Outline

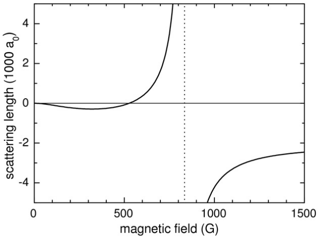
- Introduction
  - Cold atomic gases
  - Physical applications in nuclear and particle physics
- Shock waves
  - Qualitative description
  - Boltzmann equation simulations (preliminary)
- Conclusion

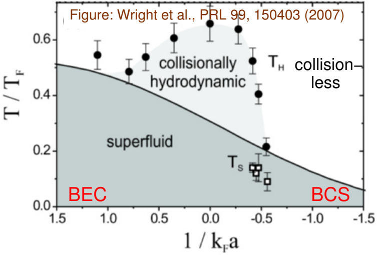
Cold atomic gases

- Create trap potential
  (combining lasers and/or magnetic fields)
- Load the atoms into the trap: $N \sim 10^5 - 10^6$
- Cool them down : $\simeq$ 10-100 nK
- Trap size : 10-100 μm
- Dilute : typical density $< 10^{15}$ cm$^{-3$}
  (air $\simeq 10^{19}$ cm^{-3})
- Measure density profile
  (switch off the trap)

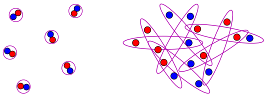


Cold atoms





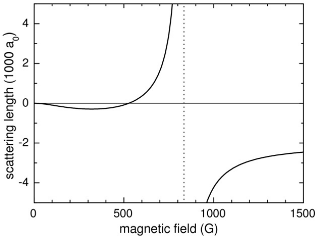
Novelty : interaction strength and sign can be tuned!

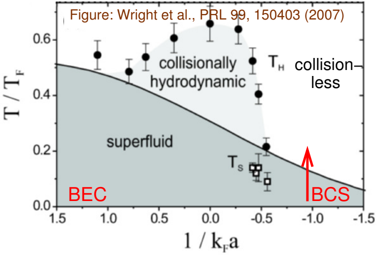


Cross-over BEC-BCS

Dynamical regimes : superfluid/hydrodynamics/collisionless

Cold atoms





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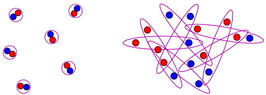

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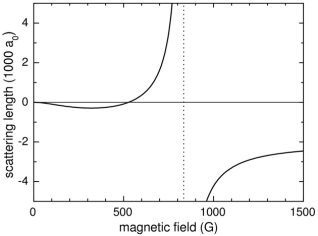

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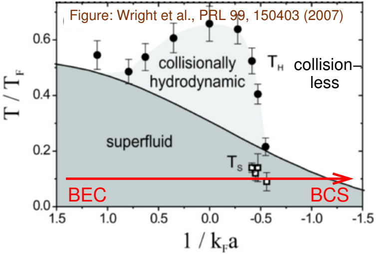
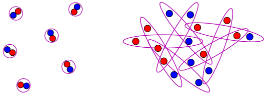




Cross-over BEC-BCS

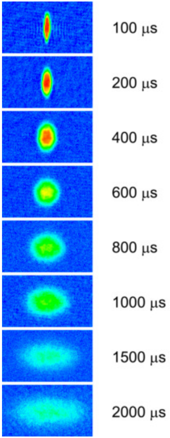
Dynamical regimes : superfluid/hydrodynamics/collisionless

Possible applications

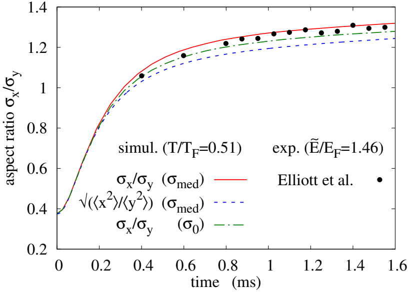
- Pairing among fermions : nuclear physics (some differences : isospin, finite size effects, small number of pairs)
- BEC-BCS cross-over in nuclear matter : deuterons $\rightarrow$ Cooper pairs
- Cold atoms at unitarity $\equiv$ neutron matter at low density ($k_F R < 1 < k_F a_{nn}$)
- Color superconductivity of quark matter :
  pairing of quarks of different masses $\rightarrow$ pairing between different atoms in a trap
- Superfluid hydrodynamics : hadronic phase

Non equilibrium phenomena

Anisotropic expansion



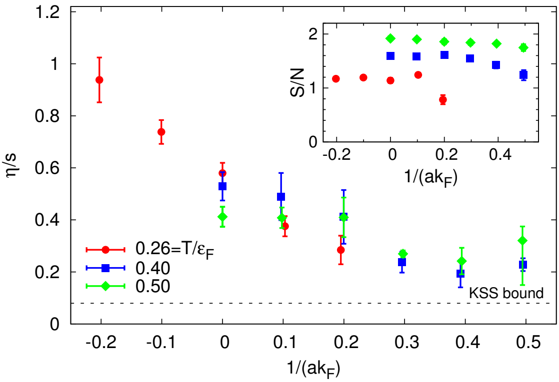
O'Hara et al. Science 298 (2002)



Pantel et al. PRA 91 (2015)

Viscosity/entropy ratio

G. Wlazlowski et al. Phys. Rev. A 92 (2015)

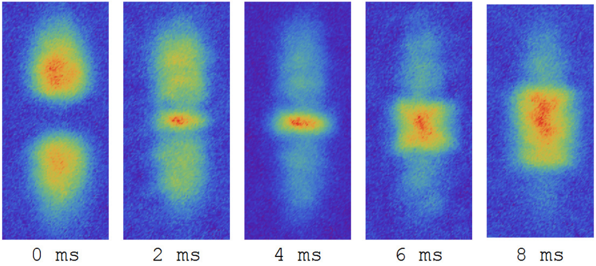


$$\frac{\eta}{s}\Big|_{atoms} \approx 0.2\,\frac{\hbar}{k_B} \approx \frac{\eta}{s}\Big|_{QGP}$$

Shock waves

- General problem : how density perturbations propagate through matter?
  - Small perturbations : sound waves
  - Abrupt change of density : shock waves
- Used in AdS/CFT correspondance
- Experiments in BEC and Fermi gases

J. A. Joseph et al. PRL 106 (2011)



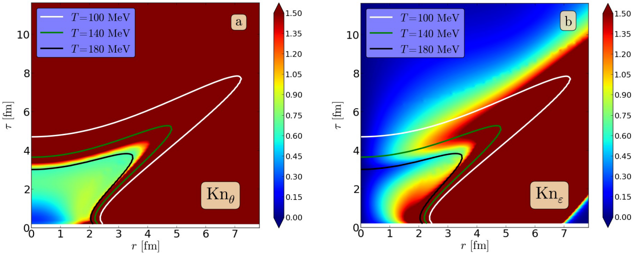
Hydrodynamic/Boltzmann equation

$$\mathrm{Ma}\,\partial_t \tilde{f} + \vec{v}.\vec{\nabla}_x \tilde{f} = \frac{1}{\mathrm{Kn}} C[\tilde{f}]$$

Boltzmann equation $\rightarrow$ hydrodynamic when Kn $\ll 1$

K. Dusling et al. Int. J. Mod. Phys. E25 (2016)

H. Niemi and G. S. Denicol arXiv:1404.7327

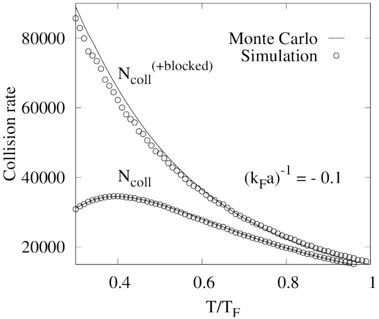


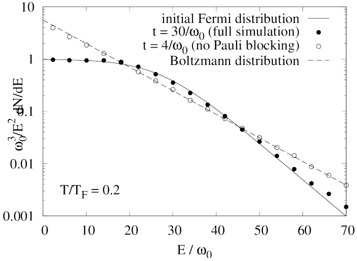
Boltzmann equation

General framework :

test particles method

and Pauli blocking



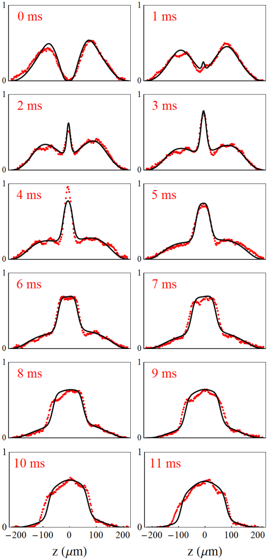


To be checked :

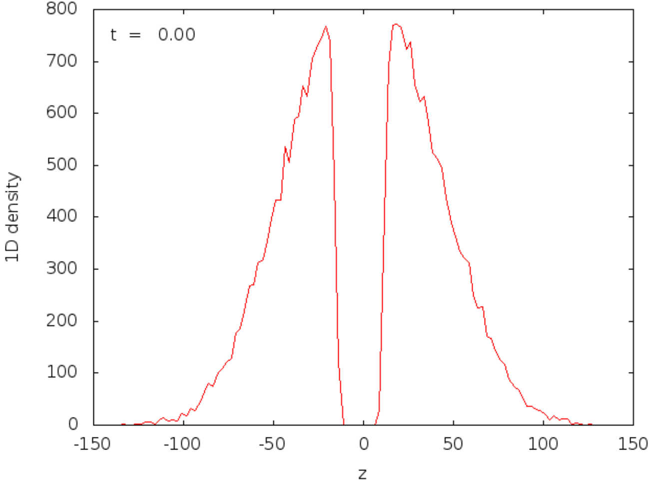
- Energy conservation
- Time step
- Collision rate
- Equilibrium distribution
- ...

Shock wave experimental observation

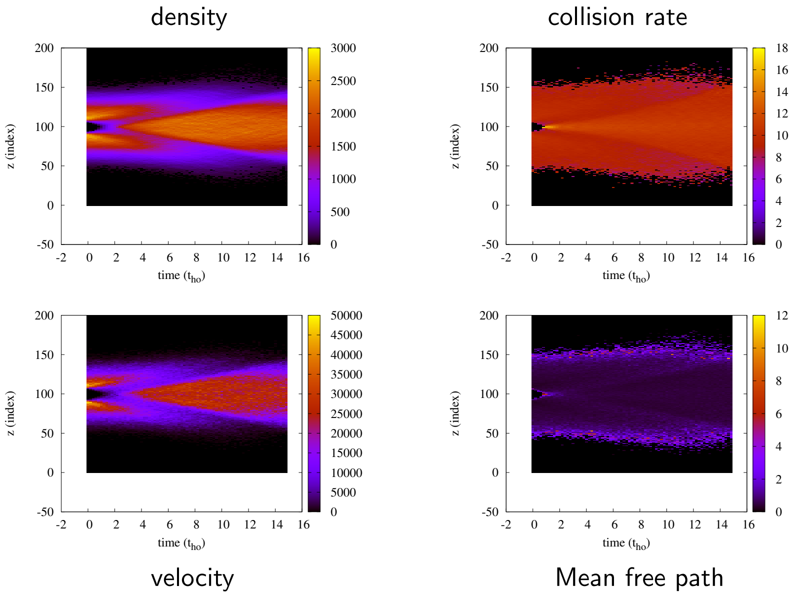
J. A. Joseph et al. PRL 106 (2011)



Shock waves :preliminary results



Shock wave simulation



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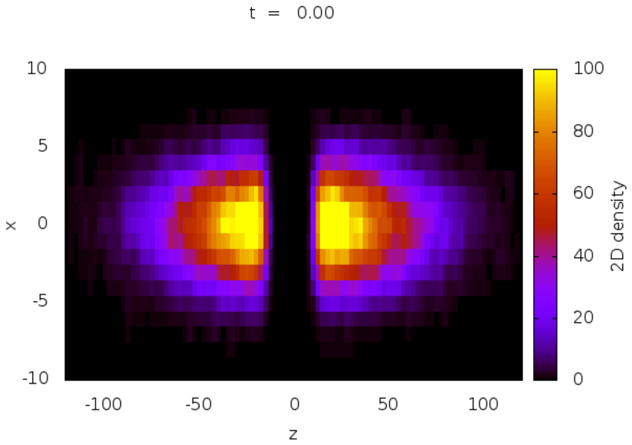


Conclusion

Trapped atomic gases :

a laboratory for non-equilibrium processes

for strongly correlated particles and with a lot of available data!

THANK YOU!

Pion hydrodynamics

Modification of hydrodynamic theory itself :

$$\partial_\mu(n_0 u^\mu - V^2 \partial^\mu \phi) = 0$$
$$\partial_\mu T^{\mu\nu} = 0$$
$$u^\mu \partial_\mu \phi = -\mu_0$$

with :

$$T^{\mu\nu} = (\epsilon + p) u^\mu u^\nu - p g^{\mu\nu} + V^2 \partial^\mu \phi \partial^\nu \phi$$

For pions : $SU(2)$-matrix $\Sigma \equiv e^{i\vec{\tau}.\vec{\pi}/f_\pi}$
and :

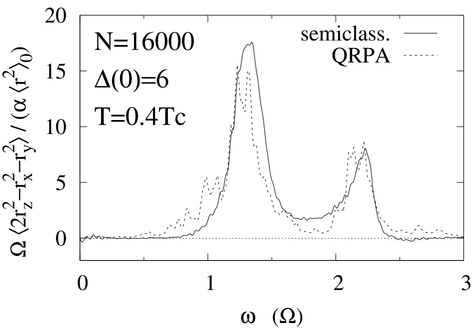
$$T^{\mu\nu} = (\epsilon + p) u^\mu u^\nu - p g^{\mu\nu} + V^2 \mathrm{tr}(\partial^\mu \Sigma \partial^\nu \Sigma^\dagger + \partial^\nu \Sigma \partial^\mu \Sigma^\dagger)$$

Y. Lallouet, D. D., C. Pujol Phys.Rev. C67(2003) 0149010 ; Phys.Rev. C67 (2003) 057901

Boltzmann equation and superfluidity : quasiparticle method

- Semi-classical approach for $T < T_c$
- Hydrodynamical equation for phase $\phi(\vec{r}, t)$ of the order parameter coupled to a Vlasov-type equation for the quasiparticles distribution function $\nu(\vec{r}, \vec{p}, t)$

- Numerical solution using the test-particle method
- Example: quadrupole mode
- Transport theory vs. QRPA: reasonable agreement
- Two peaks corresponding to the superfluid and normal parts, respectively



M. Urban, Phys. Rev. A 75 (2007)