

What cold atomic Fermi gases can tell us about the hot QGP

Marcus Bluhm

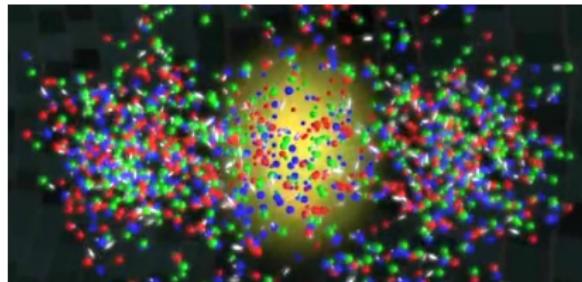
University of Wrocław



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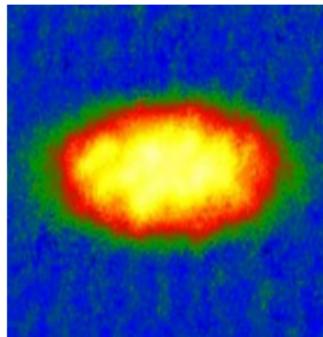
Zimányi Winter School 2017 – Budapest, Hungary – December 8, 2017

Two (very?) different strongly coupled quantum fluids



Quark Gluon Plasma

$T \sim 10^{12}$ K

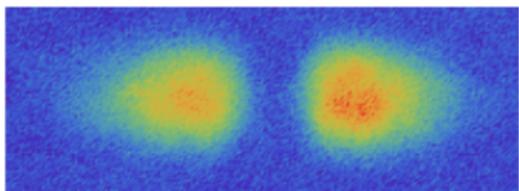


Ultracold Fermi Gases

$T \sim \mu\text{K}$

- ▶ despite apparent differences QGP and UFG exhibit similar fluid dynamical behavior
- ▶ UFG provide unique experimental playground to study fermionic many-body problem: variable densities, compositions, temperatures and interaction strengths

Prelude – Ultracold Fermi Gas cloud collisions



evolution within first 12 ms

- ▶ repulsive optical potential divides trapped gas into two clouds
 - ▶ collide once repulsive potential switched off
- ⇒ formation of propagating shock fronts

J. Joseph et al., PRL 106 (2011) 150401

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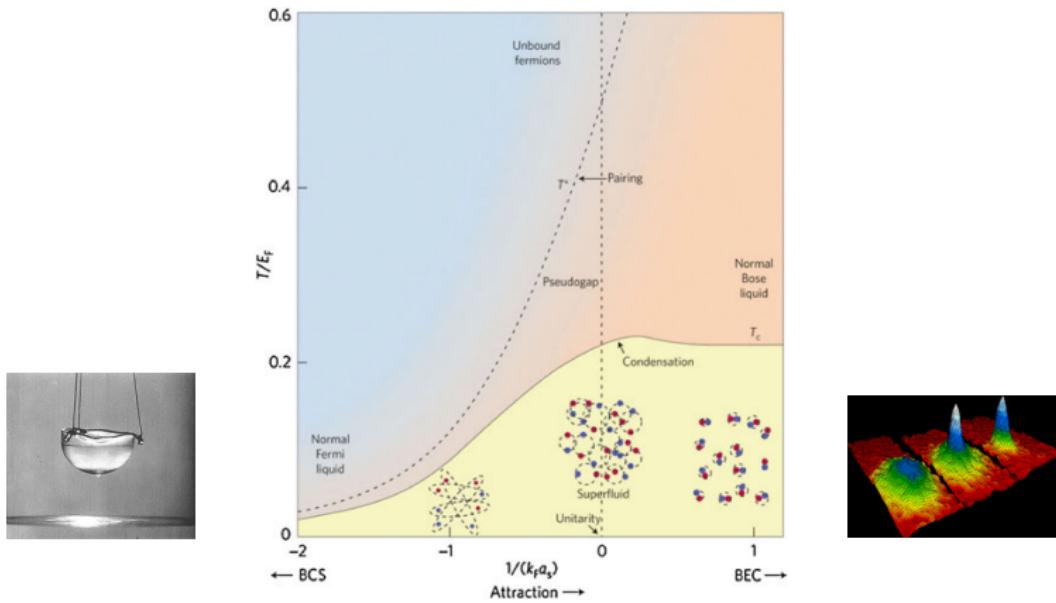
superfluid

normal fluid

J. Joseph et al., PRL **106** (2011) 150401

Phase diagram – BCS - BEC crossover

- competition between different scales: interparticle distance, thermal wave-length, interaction strength $k_F a$

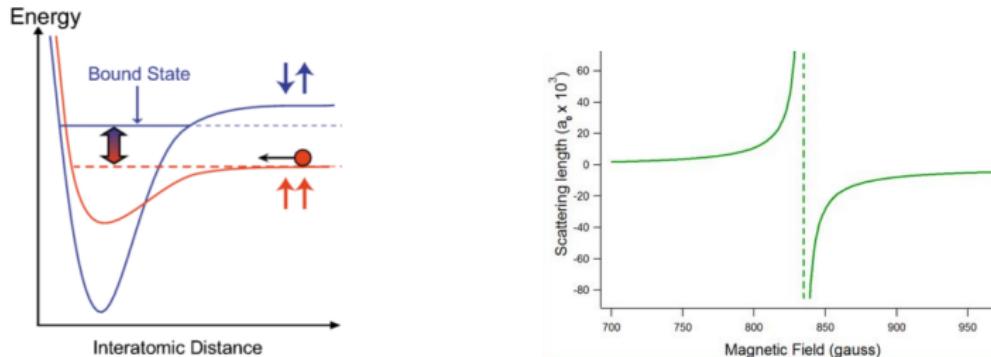


(equal mixture of two different "spin" states)

Manipulating the interaction strength

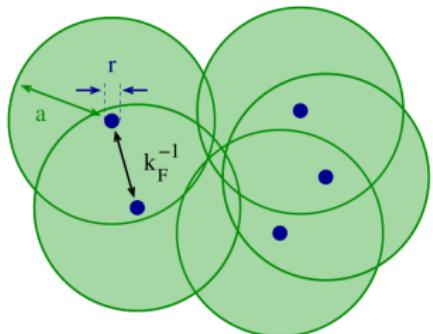
- ▶ Feshbach resonance mechanism ← tune B -field

consider mixture of two hyperfine "spin" states $|m_f = \pm \frac{1}{2}\rangle$



- ▶ scattering between atoms in Open Channel (predominantly **triplet state**)
- ▶ Closed Channel (**singlet state**) with a different magnetic moment
- ▶ B -field allows to bring **bound state** of CC into resonance with OC scattering continuum
- ▶ dramatic increase of cross-section (temporary capture in quasi-bound states)

Unitary Fermi gas



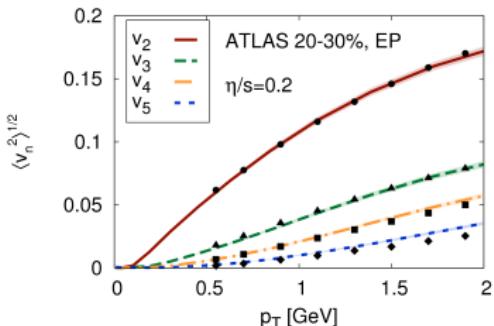
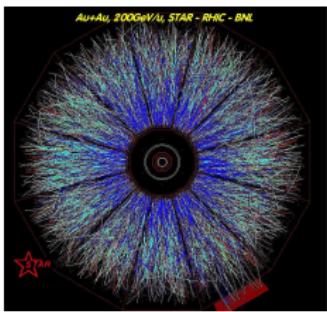
- very special situation:
even for a very dilute gas
 $(n^{1/3} \ll 1/r)$ strong coupling
regime reached when a exceeds
interparticle distance
 $(|a|n^{1/3} \gg 1)$

unitarity limit ($|a| \rightarrow \infty$):

- ▶ scale invariance, conformal invariance \rightarrow bulk viscosity vanishes
- ▶ universal scattering cross-section: $\sigma_{\text{coll}} = 4\pi/q^2$
- ▶ properties of the gas are universal functions of T and n

Shear viscosity η in the QGP

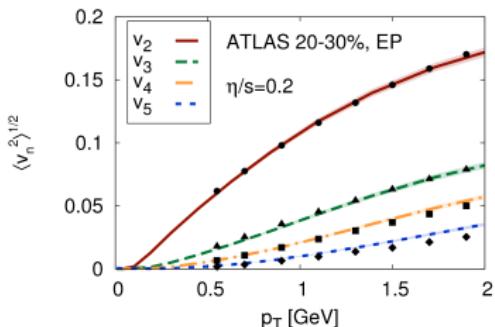
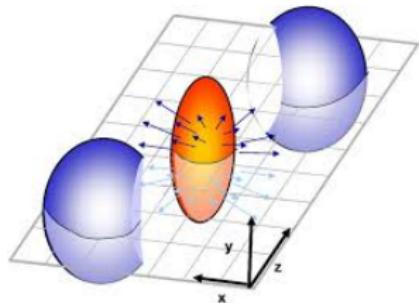
information about viscosities come from observables associated with fluid dynamical flow in HIC



- ▶ in non-central HIC find anisotropies in azimuthal particle distribution
- ▶ analysis of flow harmonics:
 $\eta/s \simeq 0.12 \dots 0.24$
⇒ nearly perfect fluidity

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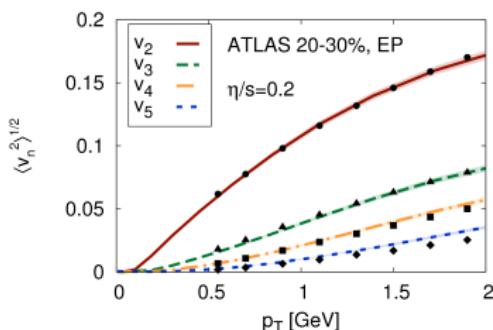
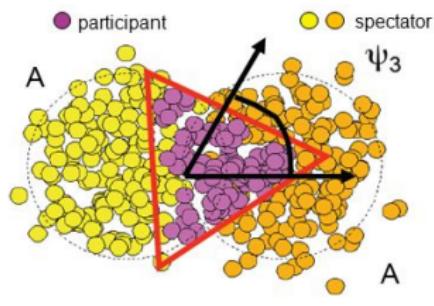
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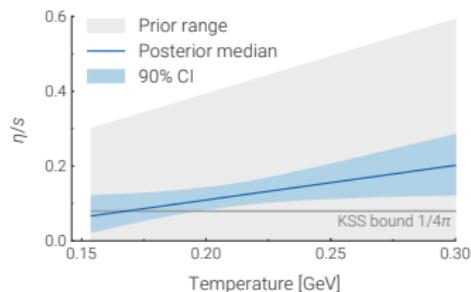
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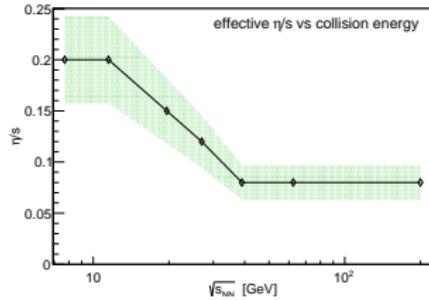
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Local determination of η in the QGP

recent efforts aim at determining dependence of η/s on T and n



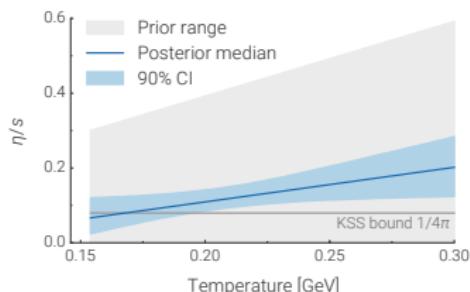
Bayesian analysis (LHC)



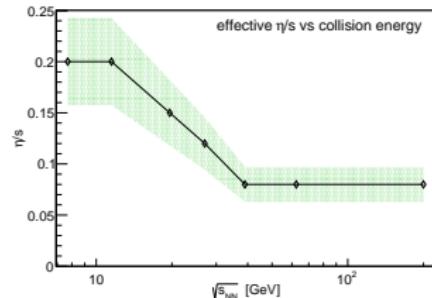
tuning in QCD phase diagram

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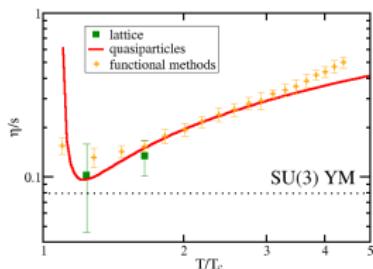
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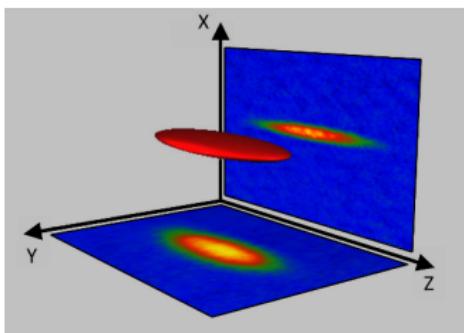
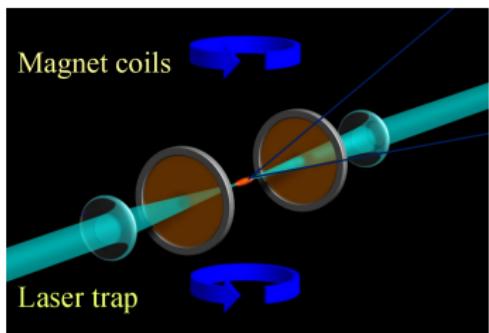
MB et al., PRC 84 (2011) 025201

FRG methods and simple quasiparticle models give similar results

Shear viscosity in unitary Fermi gases

- **elliptic flow measurement:**

analysis of the *expansion dynamics* of the gas after release from a deformed optical trap

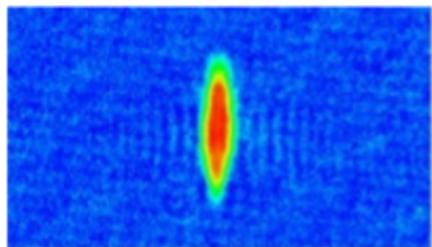


K.M. O'Hara et al., Science **298** (2002) 2179; C. Cao et al., Science **331** (2011) 58; J. Kinast et al., PRA **70** (2004) 051401 (R);
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100 μ s ... 2 ms

- ▶ time-evolution of gas cloud geometry
- ▶ shows fluid dynamical behavior

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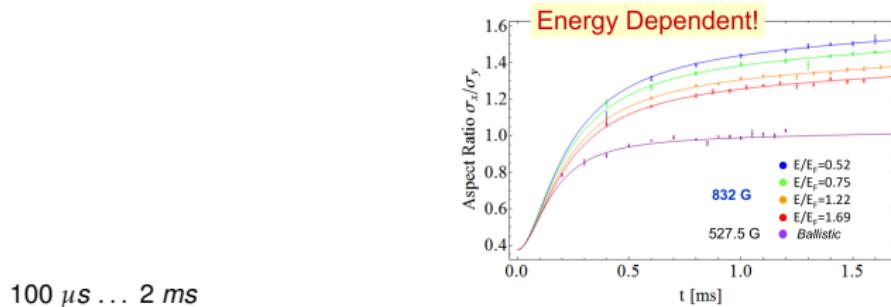
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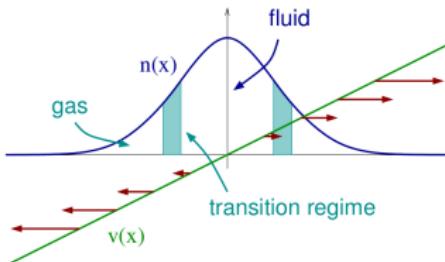
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075007; E. Elliott et al., PRL **112** (2014) 040405

Toward a local determination of η

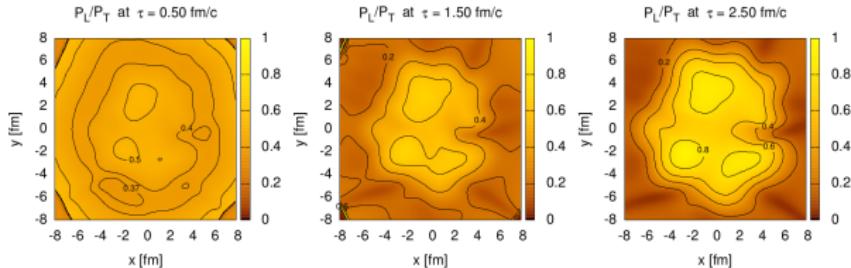
Navier-Stokes theory breaks down in the dilute corona \rightarrow must either assume $\eta \sim n$ or introduce cut-off radius



- reliable treatment of low density regime:
solve Boltzmann equation numerically; Lattice Boltzmann simulation; Quantum Monte Carlo simulation; combine fluid dynamics with kinetic transport approach; **or ...**

Recent development in fluid dynamics for HICs

⇒ (viscous) anisotropic hydrodynamics for relativistic fluids

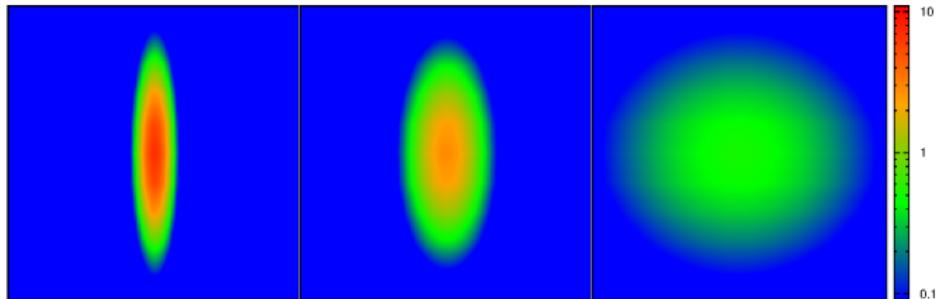


at early times large momentum-space anisotropies within fireball from pre-equilibrium evolution exist

- ▶ viscous hydrodynamics and AdS/CFT estimate $P_L/P_T \lesssim 0.3$:
→ anisotropy stronger for larger η/s and lower T

M.P. Heller et al., PRL **108** (2012) 201602; W. van der Schee et al., PRL **111** (2013) 222302; M. Martinez, M. Strickland, NPA **848** (2010) 183; W. Florkowski, R. Ryblewski, PRC **83** (2011) 034907; M. Martinez et al., PRC **85** (2012) 064913; W. Florkowski et al., NPA **916** (2013) 249; *ibid.* PRC **88** (2013) 024903; D. Bazow et al., PRC **90** (2014) 054910; L. Tinti, W. Florkowski, PRC **89** (2014) 034907; W. Florkowski et al., PRC **89** (2014) 054908; *ibid.* PRC **89** (2014) 054909; G.S. Denicol et al., PRL **113** (2014) 202301; *ibid.* PRD **90** (2014) 125026; M. Nopoush et al., PRD **91** (2015) 045007; W. Florkowski et al., PRC **92** (2015) 054912; M. Alqahtani et al., PRC **92** (2015) 054910; *ibid.* 1605.02101; E. Molnár et al., 1602.00573

Non-relativistic anisotropic fluid dynamics



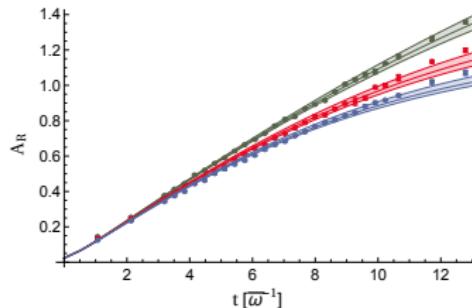
MB, T. Schäfer, PRA **92** (2015) 043602

- ▶ small η : fast relaxation to Navier-Stokes theory
 - ▶ large η : additional conservation laws for non-hydrodynamic d.o.f.
→ ballistic expansion
- ⇒ provides graceful exit for fluid dynamics in dilute regime

Application of anisotropic fluid dynamics

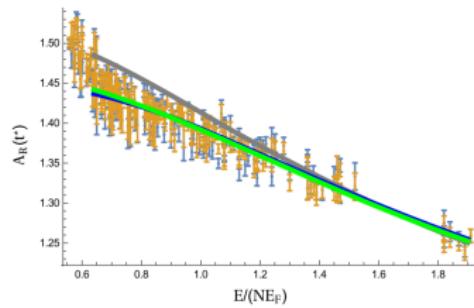
⇒ expansion data analysis:

high T



MB, T. Schäfer, PRL 116 (2016) 115301

high and low T above T_c



MB et al., PRL 119 (2017) 065302

- ▶ fit result matches kinetic theory expectation $\eta = 0.269(mT)^{3/2}$ to 1% accuracy

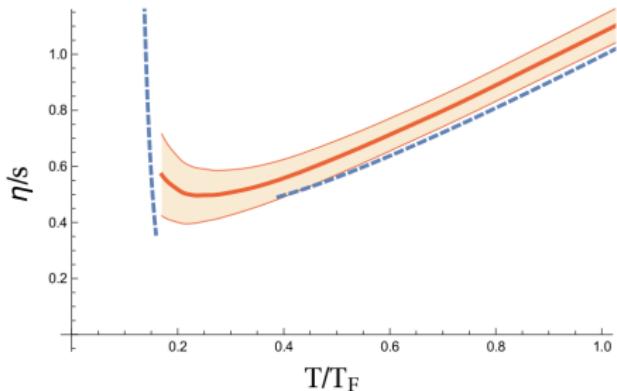
- ▶ virial expansion

$$\eta = \alpha_T (mT)^{3/2} + \alpha_{n1} n + \alpha_{n2} n^2 (mT)^{-3/2}$$

gives $\alpha_T = 0.265$ and modest density corrections near T_c

Shear viscosity in the normal phase

based on expansion data analysis

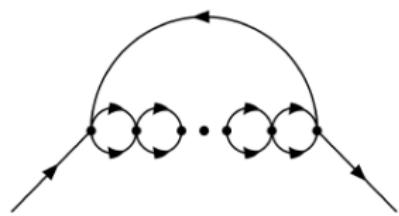


- ▶ $\eta/s \gtrsim 0.5$ with minimum above superfluid phase transition
- ▶ matches kinetic theory expectations in low- and high- T limits
- ▶ agrees with T-matrix calculations near T_c

Bulk viscosity ζ and conformal symmetry breaking

- ▶ away from unitarity \rightarrow conformal symmetry broken
- ▶ impact on ζ \rightarrow in high- T limit: $\zeta \sim \left(z \frac{\lambda}{a}\right)^2$
 \Rightarrow symmetric deviation from $\zeta_\infty = 0$

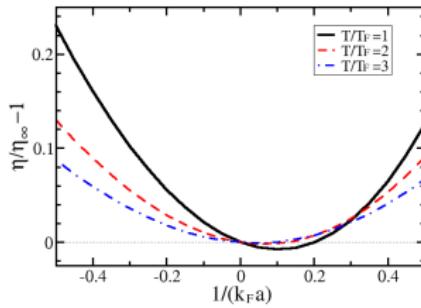
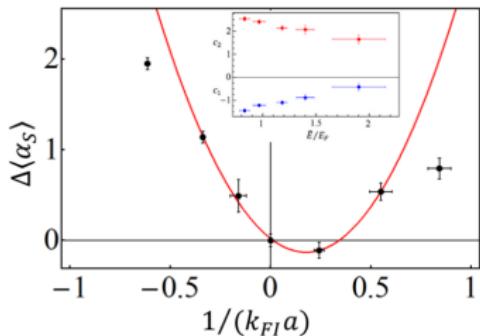
\rightarrow physical origin:



\rightarrow well-defined fermionic quasiparticles with
scale-invariance breaking self-energy

$$Re \Sigma(p) \sim \left(z \frac{\lambda}{a}\right) \sqrt{\frac{T^3}{E_p}}$$

Shear viscosity and conformal symmetry breaking



MB, T. Schäfer, PRA **90** (2014) 063615

experiment: $\eta/n = \alpha_S$

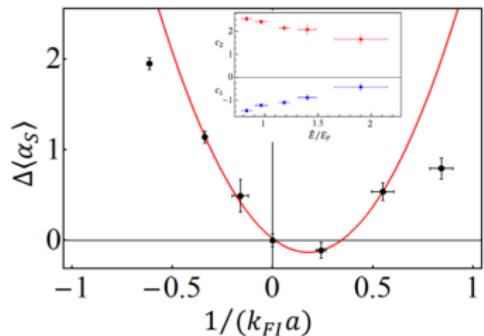
→ minimum on BEC-side

in high- T limit:

$$\eta = \eta_\infty \left(1 + \hat{c}_2 \left(\frac{\lambda}{a} \right)^2 + \hat{c}_1 \left(\frac{z\lambda}{a} \right) + \dots \right); \hat{c}_1 < 0$$

$\mathcal{O}(z\lambda/a)$ originates from in-medium effects in scattering amplitude and quasiparticle properties ⇒ asymmetric deviation from η_∞

Shear viscosity and conformal symmetry breaking



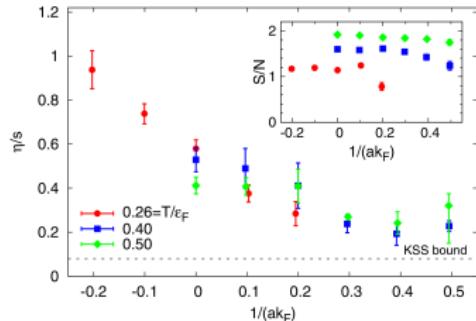
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QMC also in qualitative agreement

→ $(\eta/s)_{\min} \simeq 0.2$ for $1/(k_F a) \simeq 0.4$

Summary

- ▶ ultracold atomic Fermi gases are unique systems and help to understand other strongly coupled many-body systems
- ▶ analysis of expansion data in the normal phase reveals nearly perfect fluid nature of ultracold Fermi gases at unitary similar to super-hot QGP

- ▶ study of superfluid phase → connections with QCD?
- ▶ study of spin diffusion → connection with shear viscosity, connection with heavy-quark diffusion?
- ▶ study influence of fluctuations on the fluid dynamical behavior and the diffusion processes (fluctuation \leftrightarrow dissipation)
- ▶ study of small systems → connections with high-multiplicity p-p collisions (flow)?