Experimental evidence for non-hydrodynamic modes

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In collaboration with J. Brewer

Based on arXiv: 1508.xxxxx

Experimental ~~evidence for~~ non-hydrodynamic modes

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Experimental hints of non-hydrodynamic modes

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Universality in Strongly Interacting Quantum Fluids (SIQFs)

- Strongly coupled N=4 SYM: $\eta/s \approx 0.08$
- QCD @ T~200 MeV: $\eta/s \approx 0.1$-0.3
- Cold ^6Li close to unitarity: $\eta/s \approx 0.3$
- $Bi_2Sr_2CaCu_2O_{8+\delta}$ @ T~100K: $\eta/s \approx 0.1$-0.2

Very different systems, very similar hydrodynamic transport properties

Universality beyond hydro

Hydrodynamic Transport in SIQFs is similar

What if this similarity extends beyond Hydrodynamics?

Let's look for similarities at non-zero frequency/ transient timescales

Non-hydrodynamic Transport

What it is:

- Transient phenomena
- Transport at non-zero frequency, w(k->0)=const
- Damping non-vanishing in large coupling limit

What it is not:

- Hydrodynamic dispersions, e.g. w(k->0)=c k
- Damping vanishing in large coupling limit

Example: QNMs

- Sound mode excitations in N=4 SYM: Linear response function (correlator) has poles:

$$\omega_h = \pm c_0|\mathbf{k}| - i\frac{\eta\mathbf{k}^2}{4P_0}\frac{2}{3}, \quad \omega_{nh,1} \simeq 2\pi T(\pm 1.73 - 1.34i),$$

- These are QN modes of black hole in AdS_5
- Real time energy density response:

$$\delta\rho_{BH}(t,\mathbf{x}) \propto e^{\pm ic_0|\mathbf{k}|+i\mathbf{k}\cdot\mathbf{x}-\Gamma_h t\mathbf{k}^2} + \sum_{n=1}^{\infty} a_{nh,n} e^{\pm i\mathrm{Re}\omega_n t-\Gamma_{nh,n}t},$$

So what?

- QNMs tell us about far-from-equililibrium thermalization
- First non-vanishing QNM gives convergence radius of hydrodynamic (gradient) expansion
- Strong coupling: QNMs; weak coupling: branch cuts; finding QNMs (maybe) tells us about presence of quasiparticles?

Universality beyond hydro

- If similarity between SIQFs extends beyond hydro, there should be something like QNMs in all SIQFs
- Generically, I call these ‘non-hydro modes’
- If universality argument holds, knowing non-hydro modes in one SIQFs could teach you about transport in another…
- …maybe high-Tc-superconductors ☺

Wouldn’t it be nice to have experimental data on non-hydro modes?

Hunt for “experimental” non-hydro mode signatures in SIQFs

- Heavy-ions: hopeless (no real-time info)
- Lattice QCD: very hard (sign problem)
- High-Tc-superconductors: ???
- Ultracold Quantum Gases: ☺
- Others????

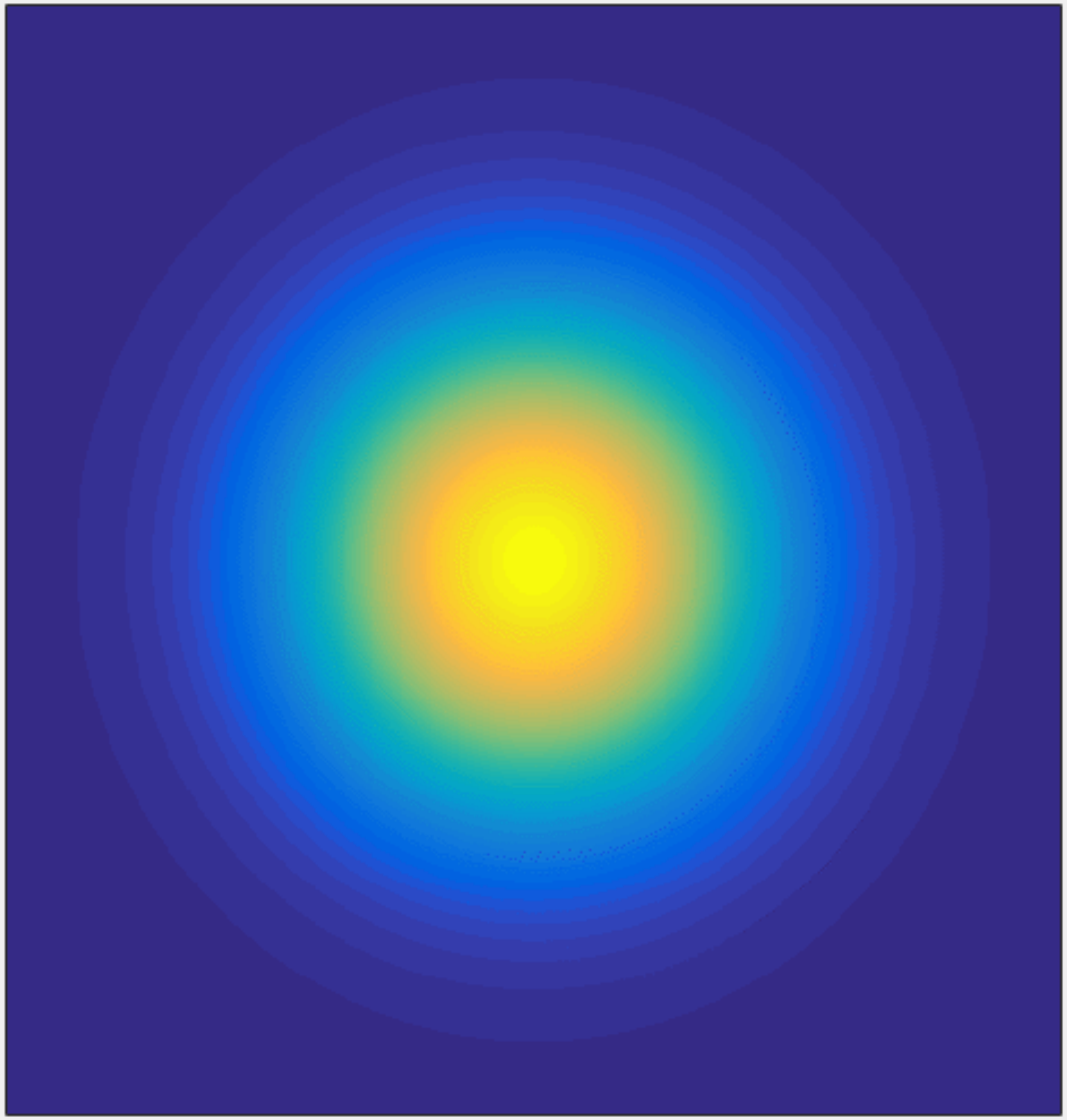
Ultracold Fermi gases

- Cloud of cold atoms in a trapping potential
- Interactions tunable via magnetic field
- Experimentally realized in D=2,3
- For strong interactions, “unitary Fermi gas”

Collective modes in trapped Fermi gases

- Trapping potential (e.g. $\omega^2_T\ \ x^2$) determines hydrostatic density profile of atoms
- By suddenly changing the potential (e.g. from asymmetric to symmetric) one can excite oscillations in the whole atom cloud
- Several "modes" possible: sloshing, breathing and quadrupole mode
- All versions of forced sound mode excitations at zero k, but finite $\omega \sim \omega_T$

Breathing mode



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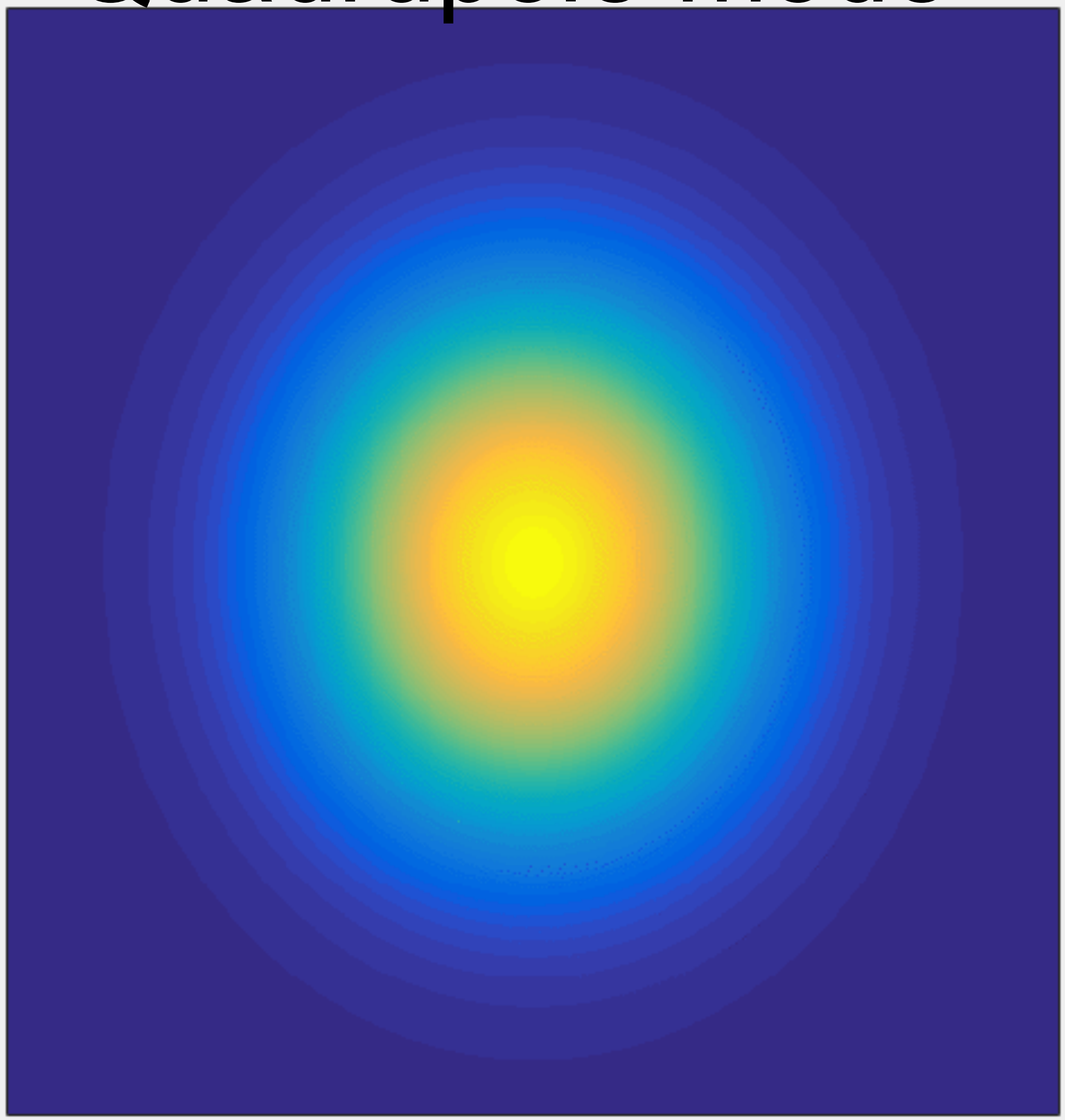
Quadrupole mode



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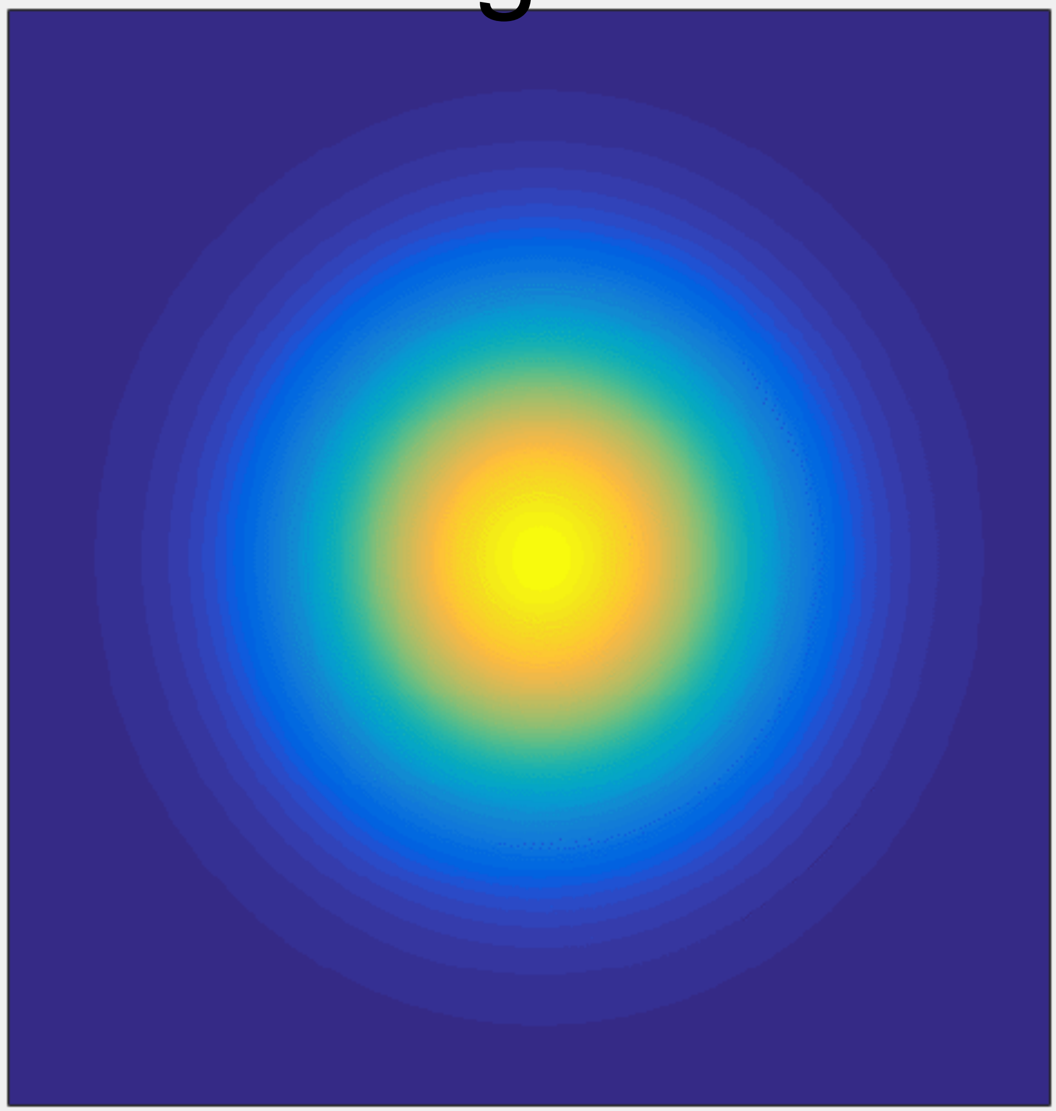
Sloshing mode



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Fermi Gas Collective Modes: Navier Stokes

$$\frac{\omega_{S,h}}{\omega_\perp} = \pm 1$$

$$\frac{\omega_{B,h}}{\omega_\perp} = \pm\sqrt{2 + \frac{4}{D}} - \frac{i\eta\omega_\perp}{P_0}\left(1 - \frac{2}{D}\right),$$

$$\frac{\omega_{Q,h}}{\omega_\perp} = \pm\sqrt{2} - \frac{i\eta\omega_\perp}{P_0}.$$

Fermi Gas Collective Modes: 2nd order hydro

Navier-Stokes hydro modes, plus:

$$\frac{\omega_{B,nh}}{\omega_\perp} = -\frac{i}{\tau_\pi \omega_\perp}, \quad \frac{\omega_{Q,nh}}{\omega_\perp} = -\frac{i}{\tau_\pi \omega_\perp}.$$

Non-hydro modes from hydro!

(Unreliable!)

Fermi Gas Collective Modes: Boltzmann in RTA

- Reliable in weak coupling

$$i\omega_Q(w_Q^2 - 4\omega_\perp^2)\tau_R + (2\omega_\perp^2 - \omega^2) = 0\,, \quad D = 2,3$$

$$i\omega_B(w_B^2 - 4\omega_\perp^2)\tau_R + \left(\frac{10}{3}\omega_\perp^2 - \omega_B^2\right) = 0\,, \quad D = 3\,, \quad (9)$$

- Navier-Stokes hydro modes
- Non-hydro modes, reliable in weak coupling: $\omega_T\tau_R \ll 1$

$$\frac{\omega_{B,nh}}{\omega_\perp} = -\frac{5i}{6\tau_R\omega_\perp}\,(D=2)\,, \quad \frac{\omega_{Q,nh}}{\omega_\perp} = -\frac{i}{2\tau_R\omega_\perp}\,,$$

Fermi Gas Collective Modes --Experimental Signatures

- Track cloud profile
- Monitor time evolution of cloud size in x, y
- $B(t)=size_x(t)+size_y(t)$…breathing m.
- $Q(t)=size_x(t)-size_y(t)$…quadrupole m
- (sloshing mode used to calibrate time-scale)

Fermi Gas Collective Modes

- Fit time-evolution
- Hydro-inspired fitting function

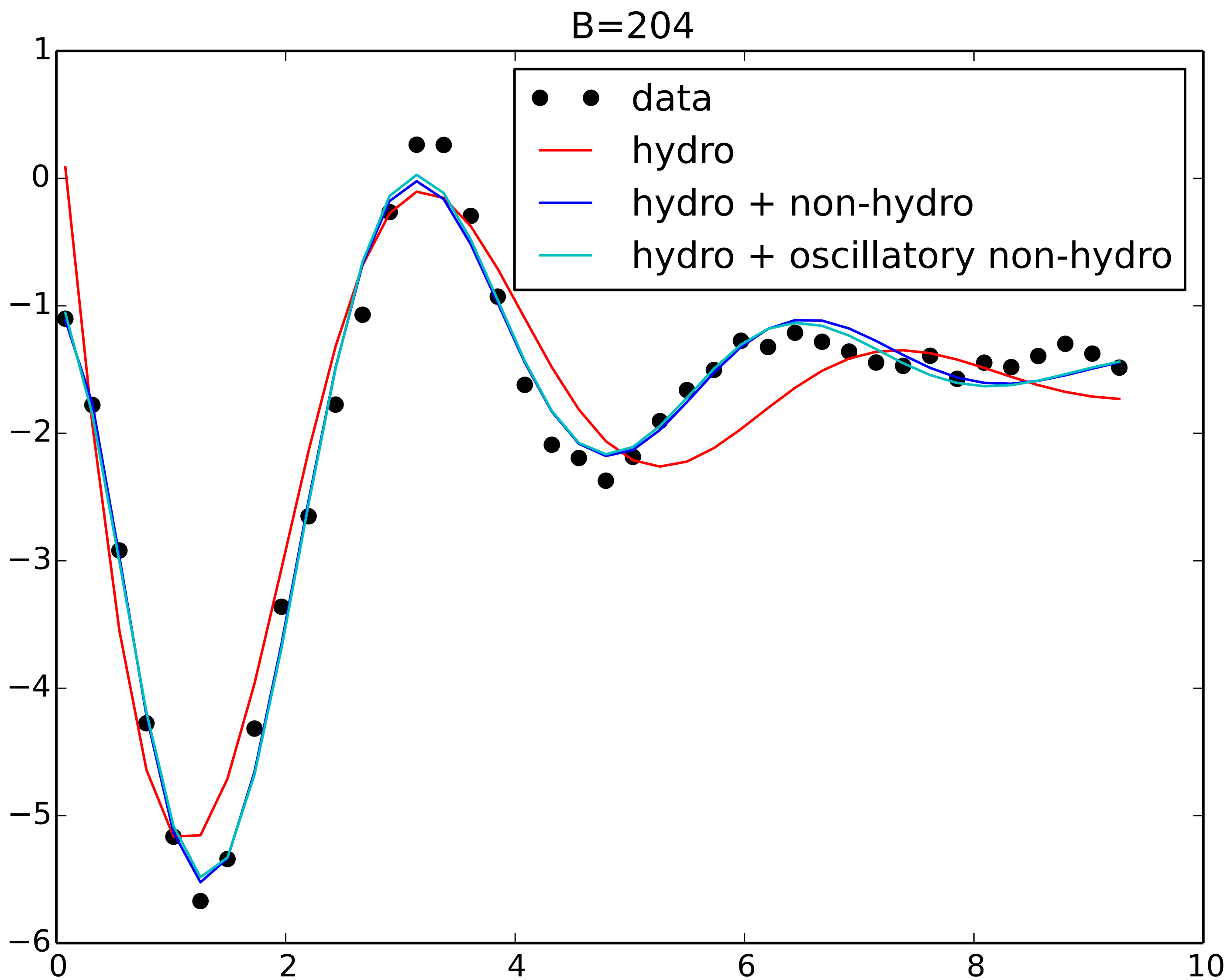
$$F(t) = a_h \cos(w_h t) e^{-\Gamma_h t}$$

- Hydro+non-hydro inspired fitting function

$$F(t) = a_h \cos(w_h t) e^{-\Gamma_h t} + a_{nh} \cos(w_{nh} t) e^{-\Gamma_{nh} t}$$

Trapped Fermi Gas in D=2
Data by Vogt et al. (2011)

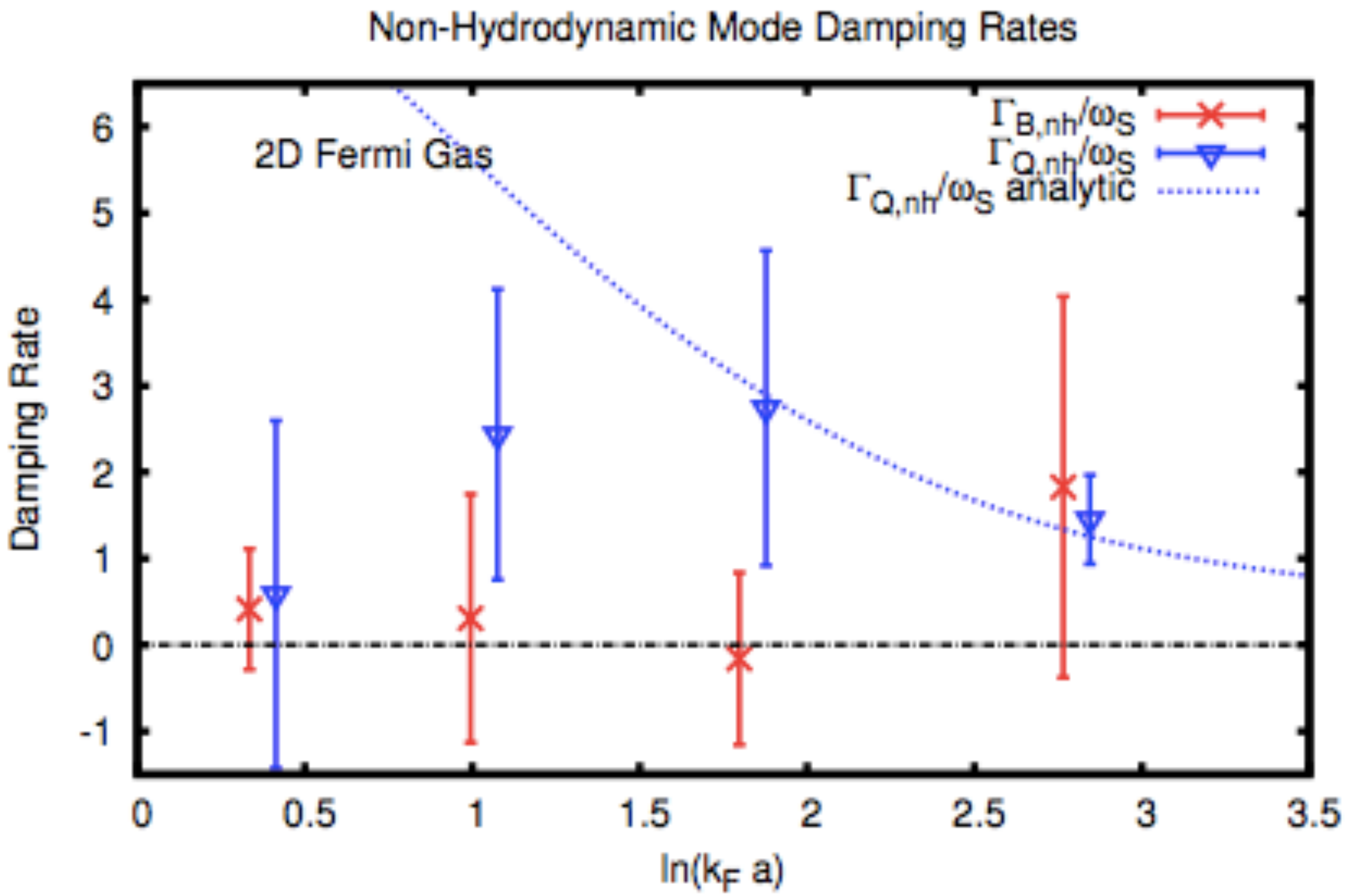
D=2, quadrupole mode



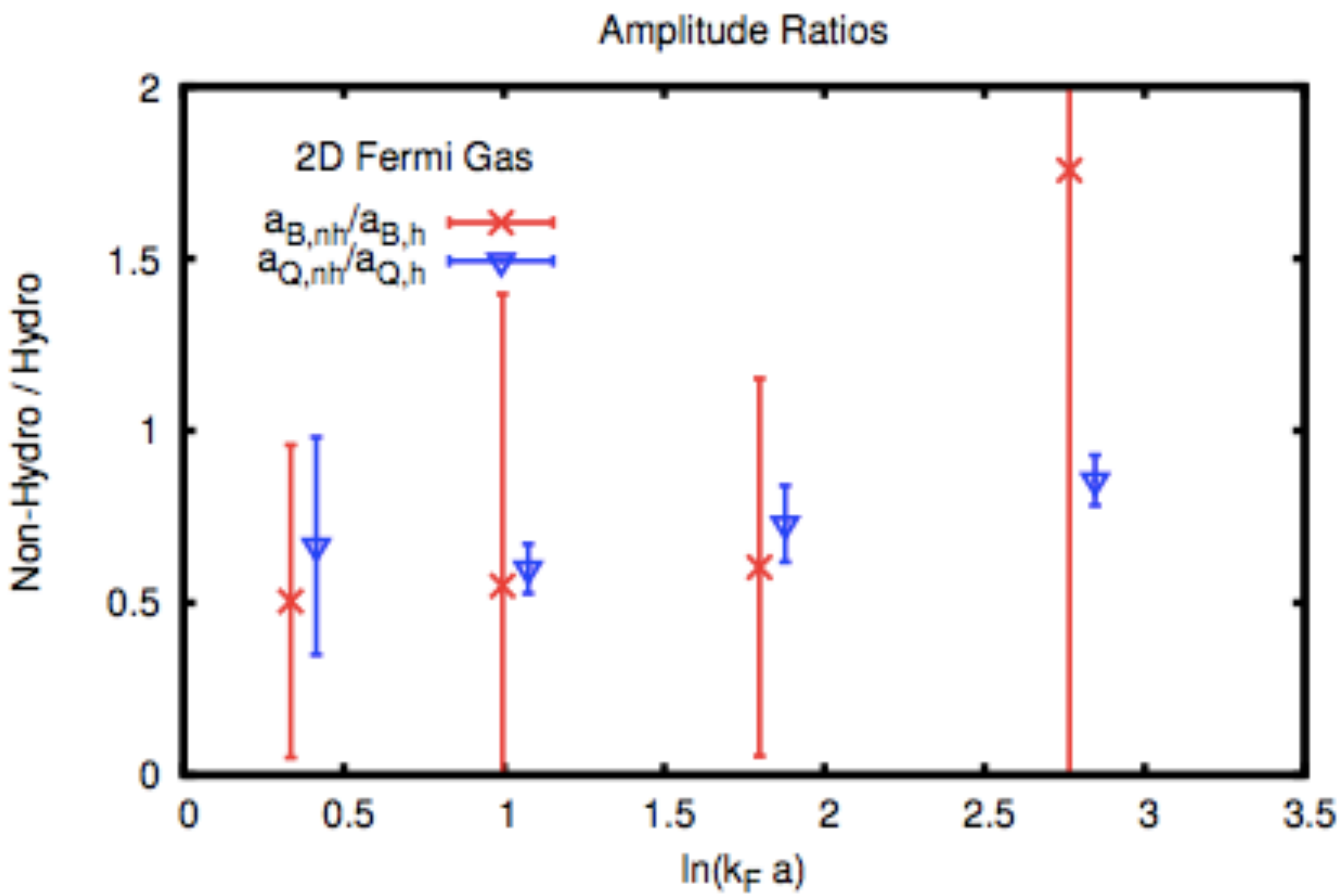
Fitting available experimental data

- Hydro information very well accessible; we confirm published results on ω_h,Γ_h
- Non-hydro frequency information not accessible
- Non-hydro damping rate information *maybe* accessible
  - Look only for non-hydro modes with $\omega_{nh}=0$ (Strong restriction!!!)

Hints for non-hydro modes D=2



Hints for non-hydro modes D=2



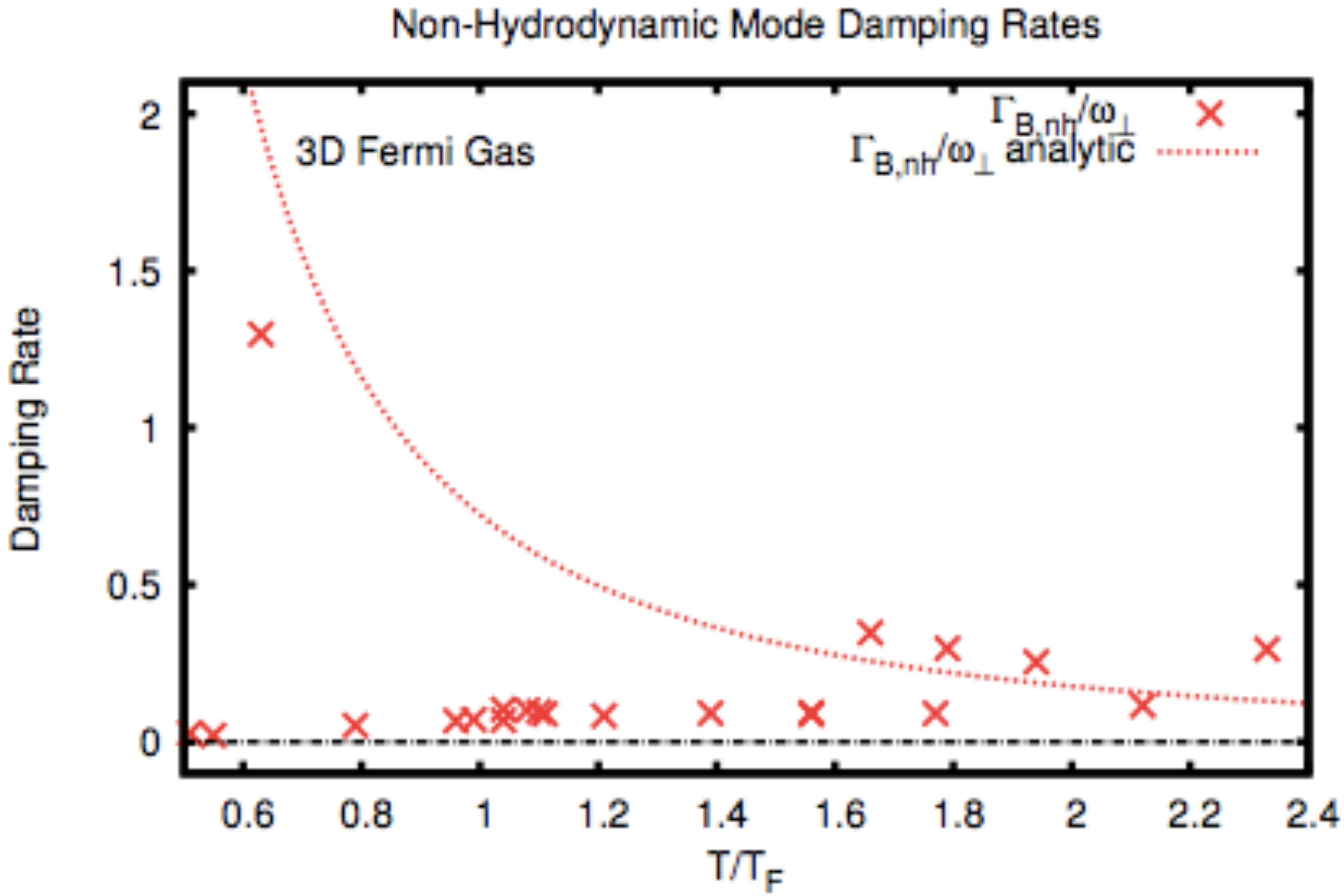
Hints for non-hydro in D=2

- No hint for a non-hydro mode in D=2 breathing mode
- Some hints for a non-hydro mode in D=2 quadrupole mode
- Damping rate for non-hydro quadrupole mode consistent with kinetic theory analytic estimate; uses $\omega_\perp \tau_R = 0.12\left(1 + \frac{4}{\pi^2}\ln^2(k_F a)\right)$

[1507.05975]

Trapped Fermi Gas in D=3
Data by Kinast et al. (2005)

Hints for non-hydro modes D=3



Hints for non-hydro in D=3

- Some hints for a non-hydro mode in D=3 breathing mode
- (Some) extracted damping rates for non-hydro breathing mode consistent with kinetic theory analytic estimate; uses

$$\omega_\perp \tau_R = \frac{45\pi}{4} \frac{\omega_\perp}{T_F} \frac{T^2}{T_F^2}$$

[0809.1814]

Conclusions

- Transport universality in SIQFs could extend beyond hydrodynamics
- N=4 SYM SIQF has QNMs => non-hydro modes
- Other SIQFs could also have non-hydro modes
- There are hints for non-hydro modes in experimental data for cold trapped Fermi gases close to unitarity in D=2,3; more data/studies needed to corroborate this finding
- Studying non-hydro modes is new & interesting!