Hydrodynamic Properties of the Unitary Fermi Gas

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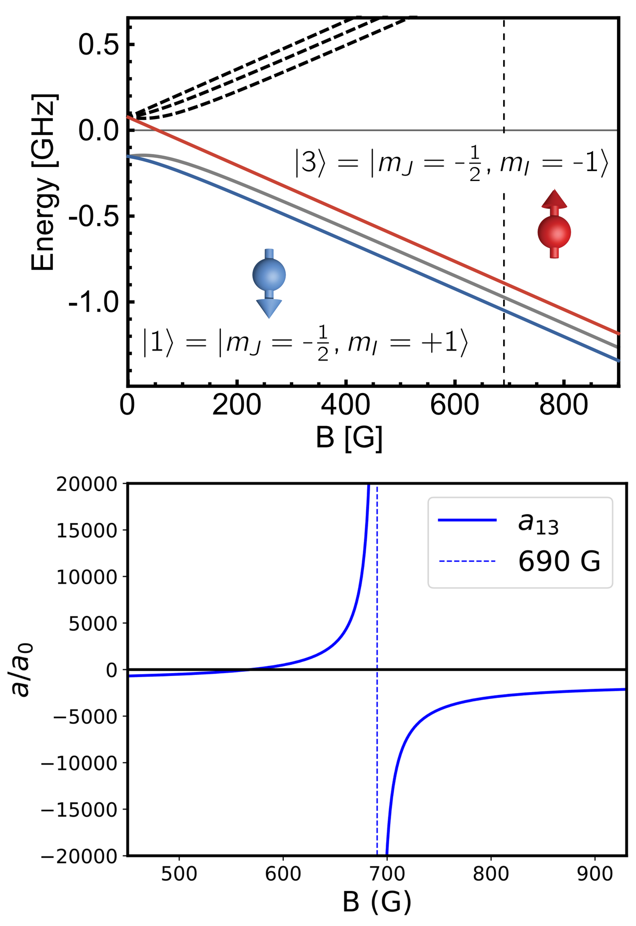
Unitary Fermi Gas in a Box Potential

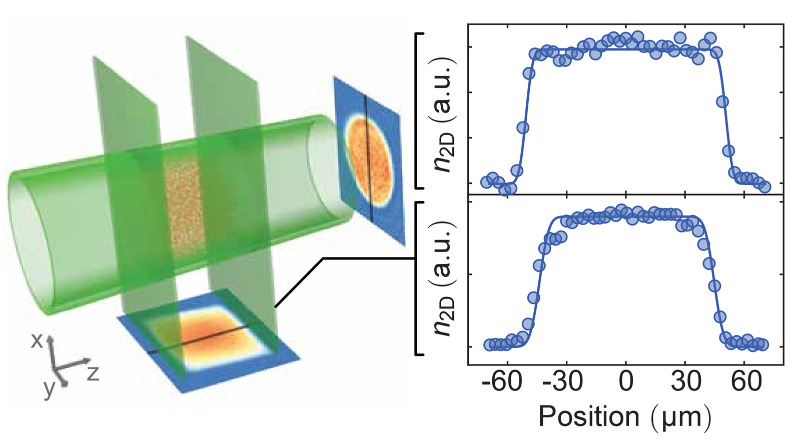
Unitary Fermi Gas

- Strongly-interacting fermion systems - difficult to analyze a priori
- Relevant to systems ranging from neutron stars to high-T_c superconductors
- Unitary Fermi gas is scale-invariant
- Realize unitarity with $|1\rangle - |3\rangle$ Feshbach resonance in ^{6}Li
- Evaporatively cool spin mixture to below T_F



Box Potential [1]

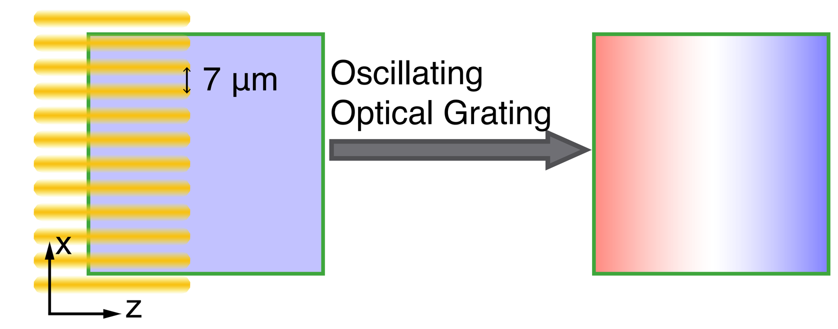
- Hollow blue-detuned beams realize (quasi) flat potential
- Reduces influence of trap averaging & targets smaller range of densities
- Residual harmonic trap in axial dimension allows momentum-space imaging

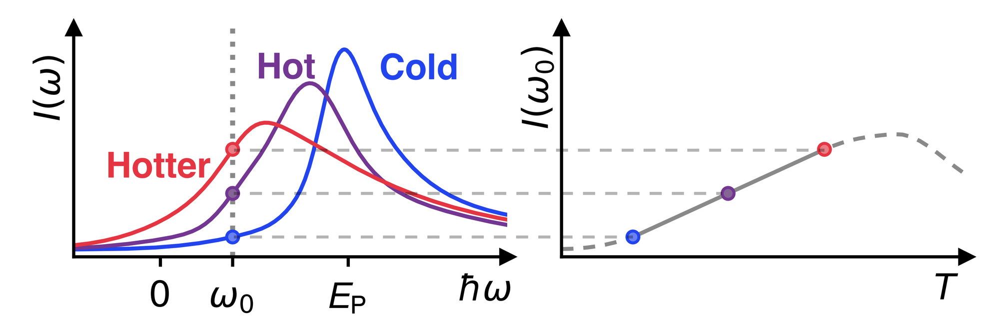


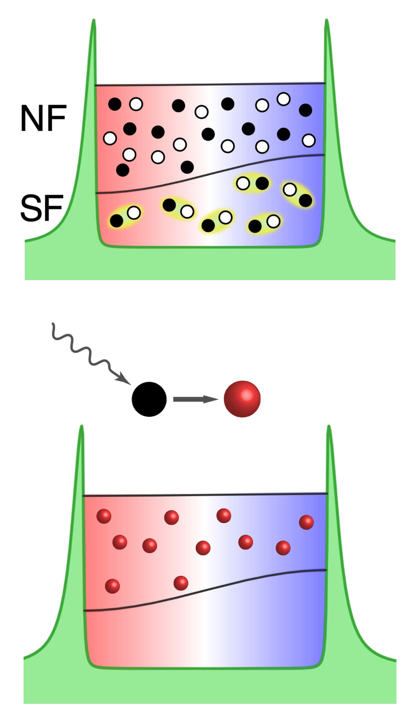
Temperature Response – Second Sound [3]

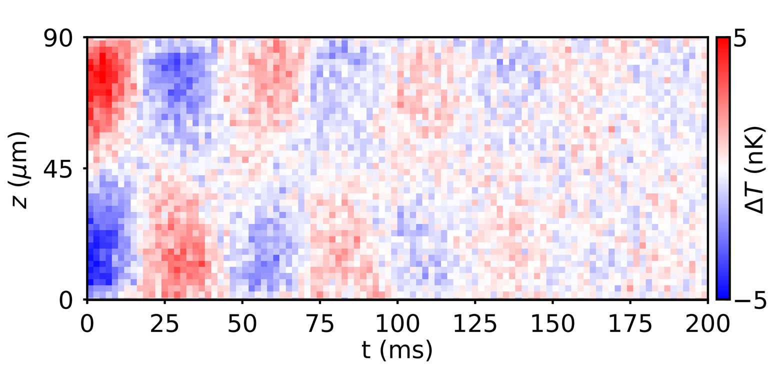
Second Sound

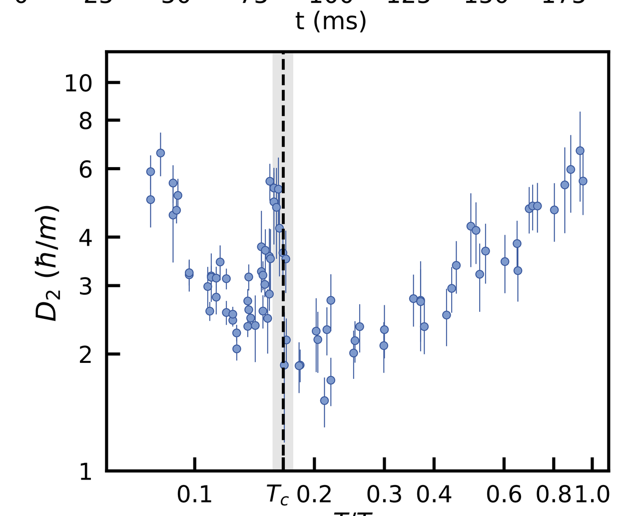
- Temperature oscillations: out-of-phase oscillations of normal and superfluid phase
- Excite oscillations by driving high-frequency sound waves to locally heat the gas
- Measure temperature locally using RF spectroscopy
- Second sound is only present below the superfluid transition temperature
- Damping rate of second sound gives thermal conductivity

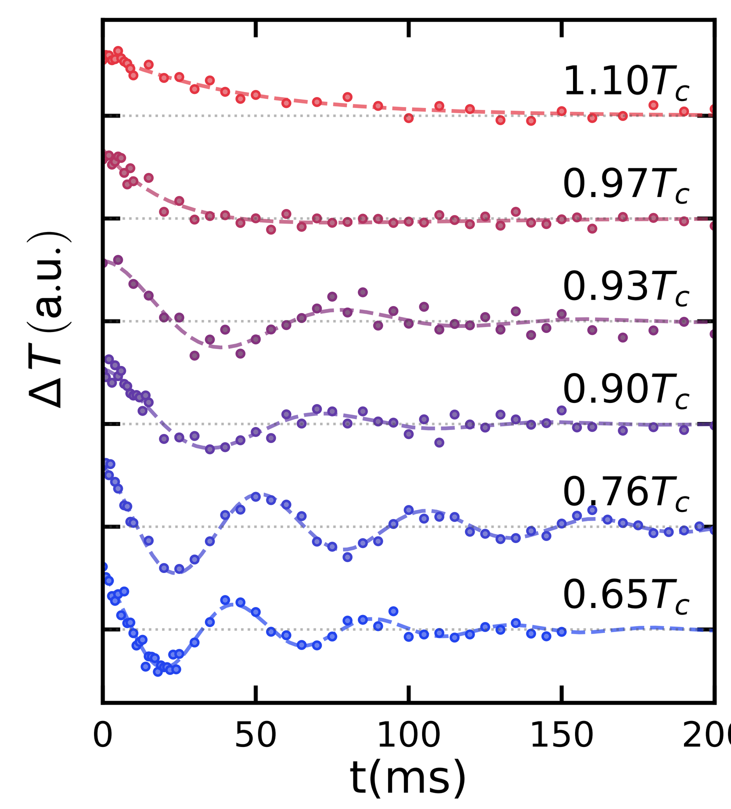








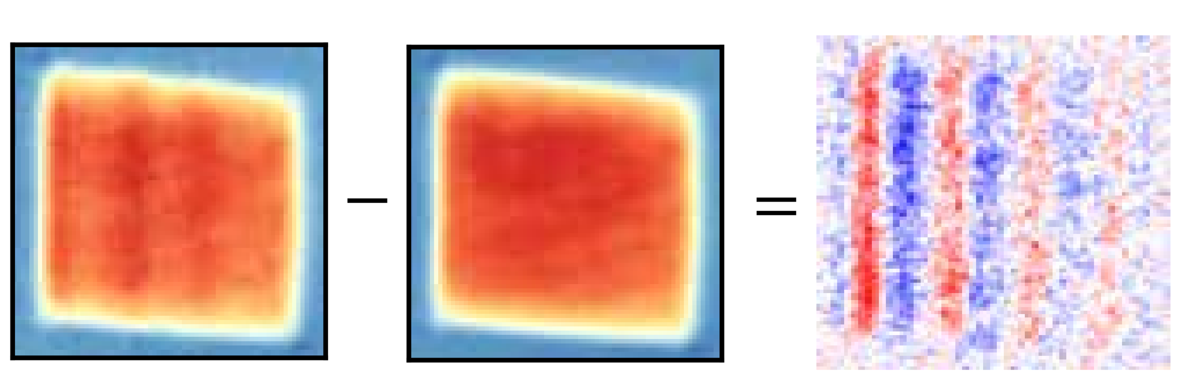


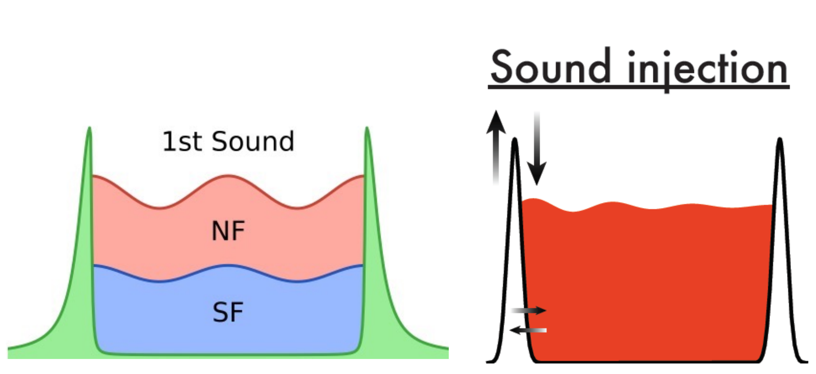


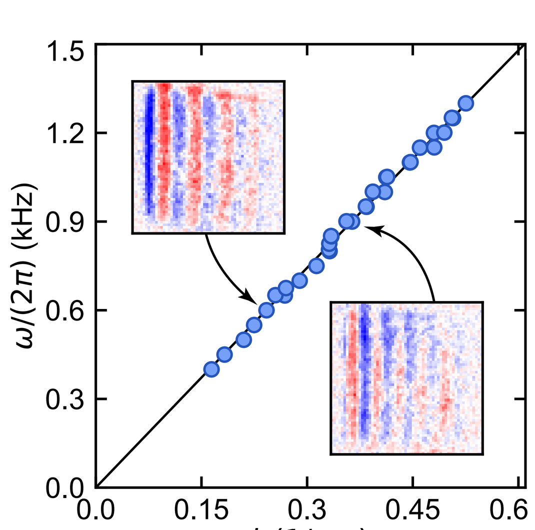
Density Response – First Sound [2]

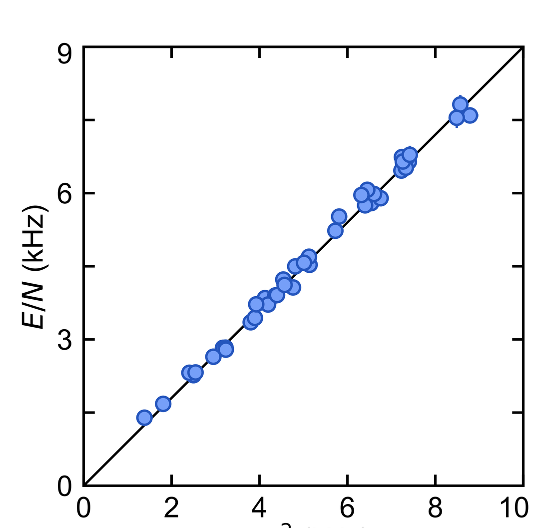
First Sound

- Density oscillations: in-phase oscillation of normal and superfluid phase
- Excite by shaking box walls
- Image density waves in situ – extract wavevector k for a given ω to get c
- Speed of sound in scale-invariant system given by system energy: $mc^2 = \frac{10}{9}\frac{E}{N}$
- Agrees with experimental results



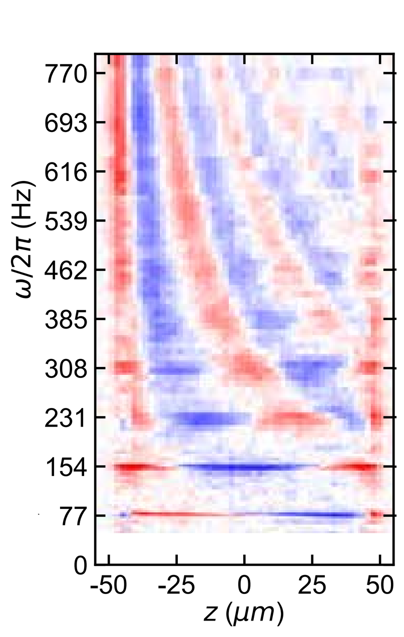


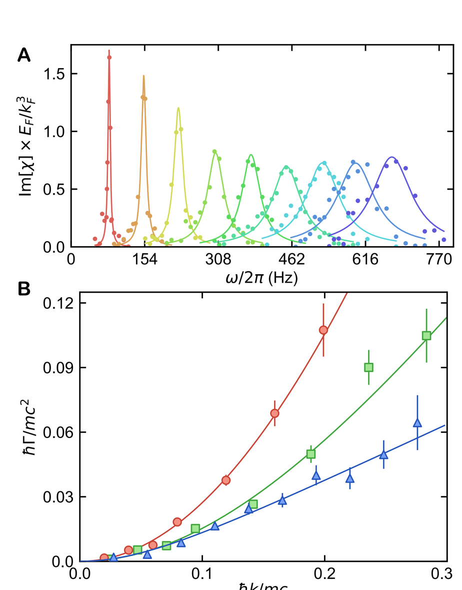


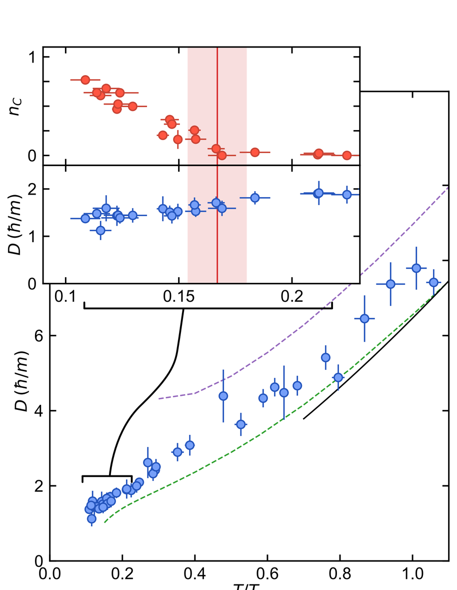


Resonant Modes and Dissipation

- Sound speed constrained by scale invariance, but dissipation is not
- Hydrodynamics predicts damping rate $\Gamma \propto k^2$, with proportionality constant D_s, the sound diffusivity
- D_s depends on shear viscosity and thermal conductivity
- Measure damping vs. k using width of resonant box modes – extract D_s



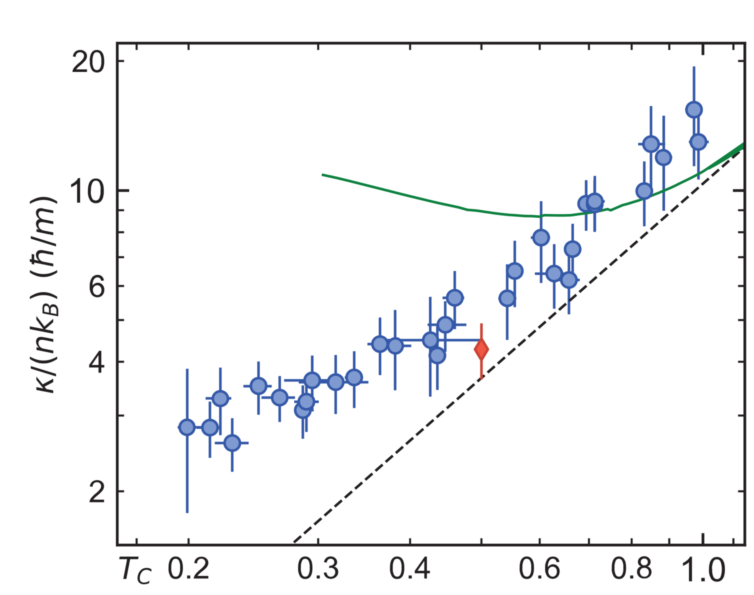


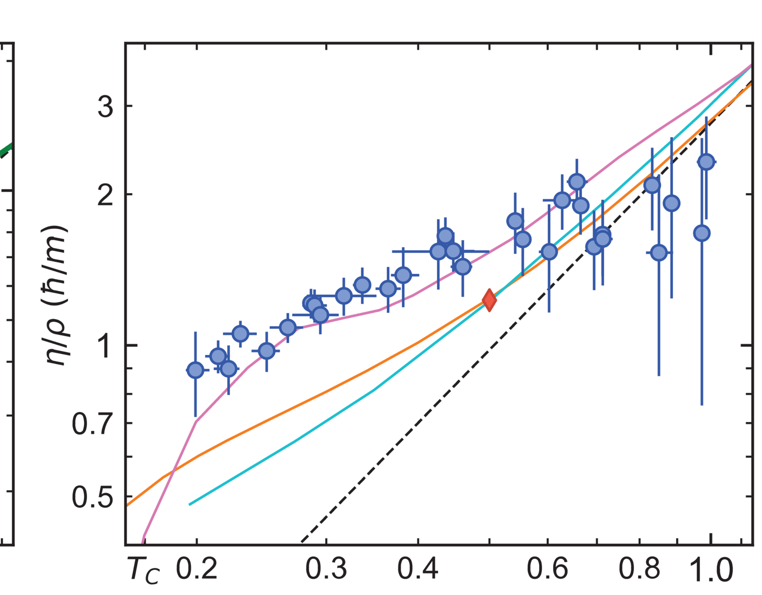


Hydrodynamics – Transport Properties

Hydrodynamic Quantities

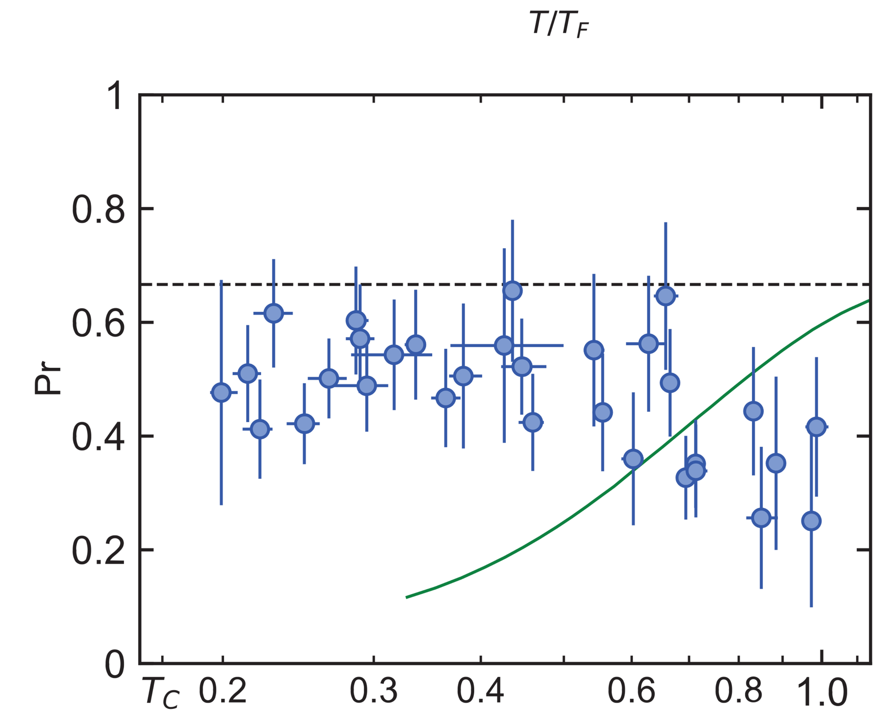
- Hydrodynamic quantities above T_c: shear viscosity η and thermal conductivity κ
- Bulk viscosity vanishes for scale invariant system; below T_c, superfluid density is conserved
- First sound dissipation given by κ and η; second sound dissipation by κ and c_P
- Together with equation of state [4], first and second sound give η and ρ above T_c





Results

- Viscosity in reasonable agreement with prior results and theory
- Thermal conductivity differs strongly from theory predictions near T_c
- Prandtl number $\frac{c_P\eta}{\kappa}$, ratio of momentum to thermal diffusivity, remains close to typical 2/3 value for gases



Red diamond [5], green line [6], pink line [7], cyan line [8], orange line [9]

References

[1] B. Mukherjee et al., *PRL* 2017
[2] P.B. Patel et al., *Science* 2020
[3] Z. Yan et al., in preparation
[4] M.J.H. Ku et al., *Science* 2012
[5] L. Baird et al., *PRL* 2019
[6] B. Frank et al., *Phys Rev Research 2020*
[7] J. A. Joseph et al., *PRL* 2015
[8] M. Bluhm et al., *PRL* 2017
[9] T. Enss et al., *Annals of Physics* 2011

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