2012 International workshop on ultracold atoms/molecules, *Sun-moon lake, 5/19/2012*

Observation of Sakharov Oscillations in a Quenched Superfluid

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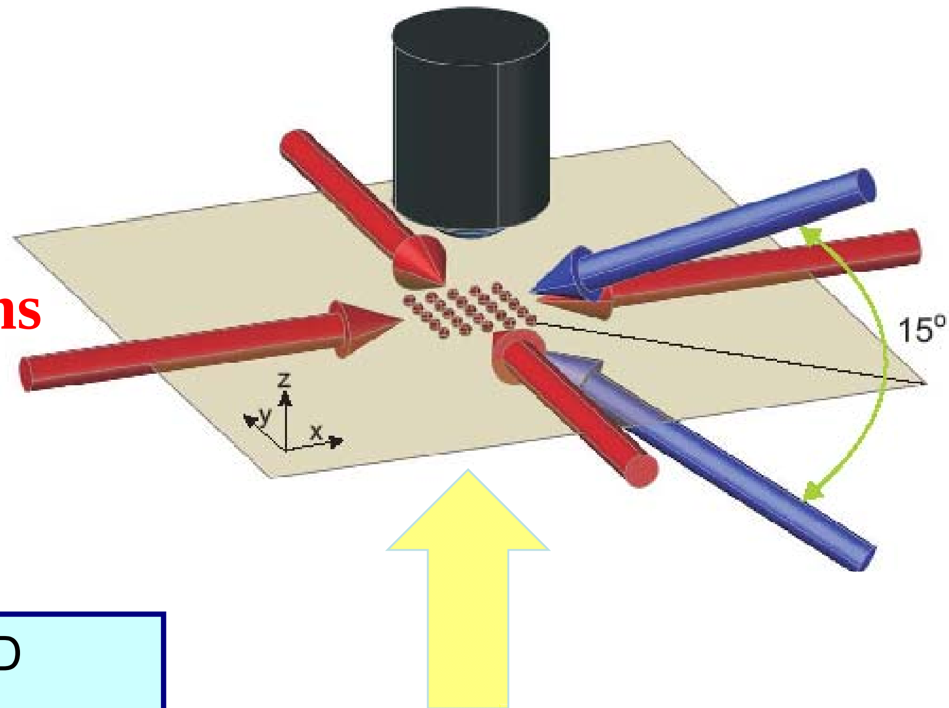
Funding:

In situ Imaging a single layer of 2D gas

Microscope objective

4 lattice beams



2 Vertical compress. beams

Imaging beam

Cesium atoms in 2D

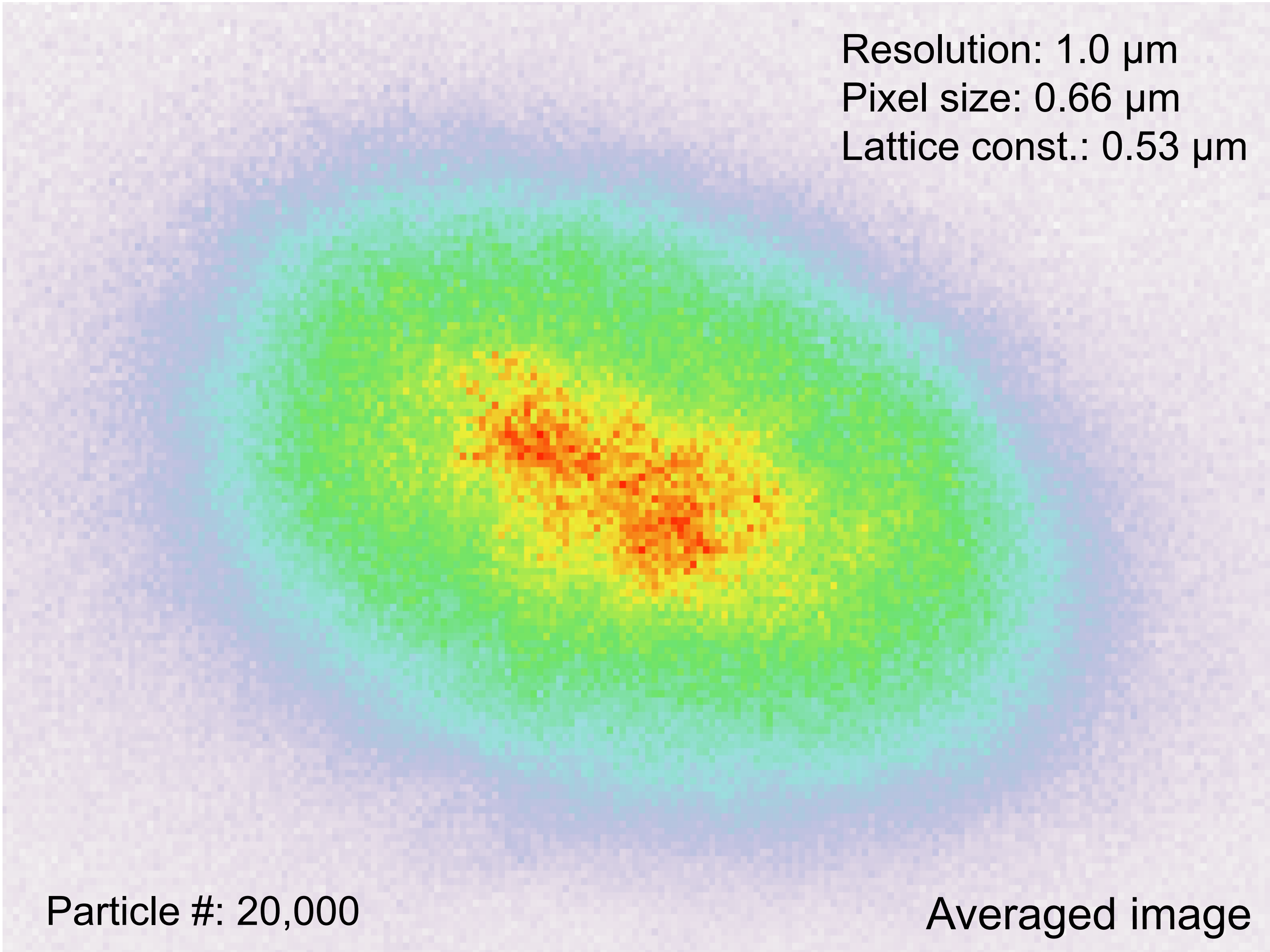
$$15\,\hbar\omega_r \sim k_B T \text{ and } \mu \sim \frac{\hbar\omega_z}{10}$$

Gemelke et al., Nature 460 (2009)

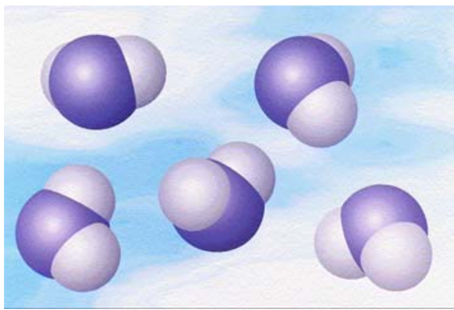
See also: (Harvard) Bakr et al., Nature 462 (2009)

(MPQ) Sherson et al., Nature 467 (2010)

A closer look



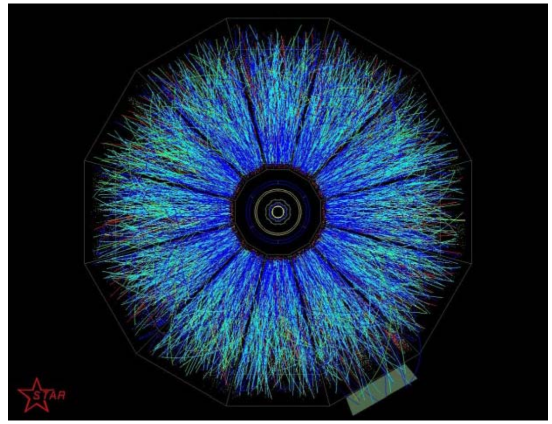
Quantum Simulation



Atoms and molecules

Examples:
Condensed matter,
nuclear physics,
HEP, QIP,
cosmology…

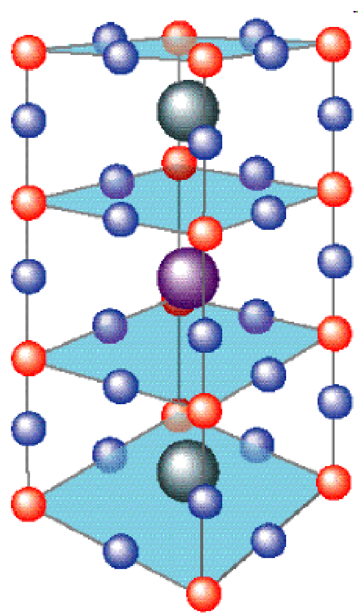
Nuclear physics



Quantum clusters

Efimov state
Efimov (1970)

Condensed matter

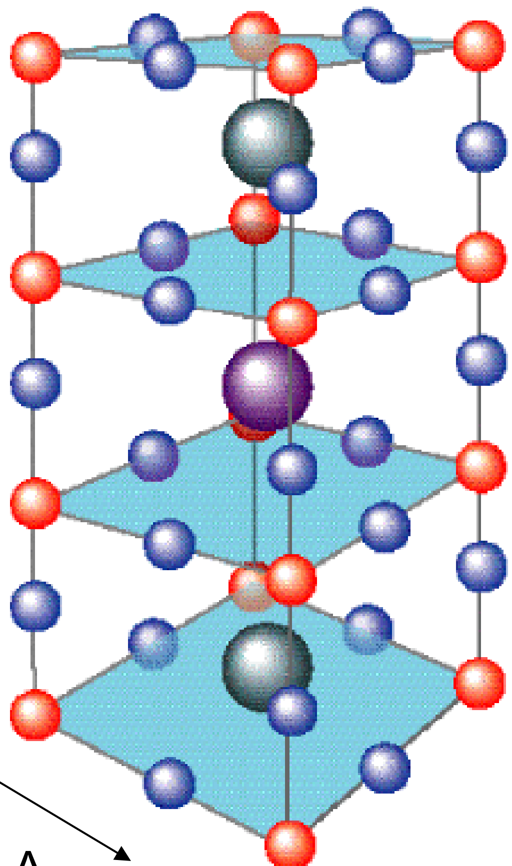


Superconductivity

BCS-BEC crossover
Eagles (1969) Leggett (70)

Quantum simulation and universality

Time scale
1ps



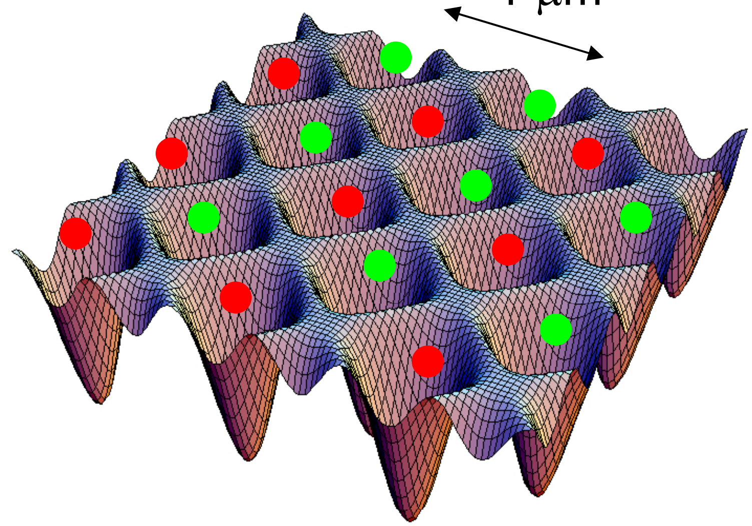
T=100 K

1 A

T=100 nK

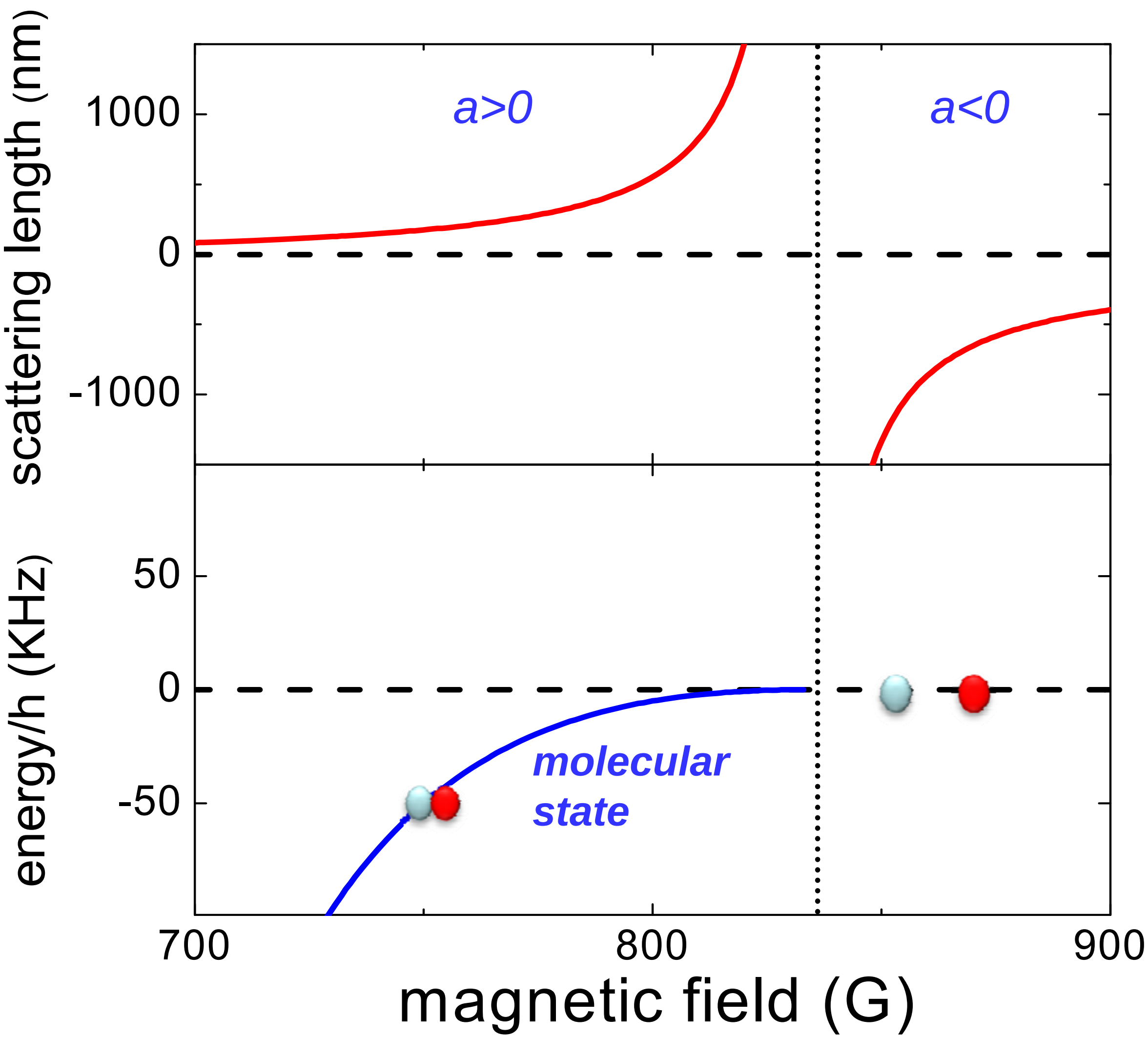
Time scale
1ms

1 μm



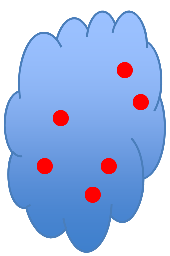
Ultracold atoms in optical lattices

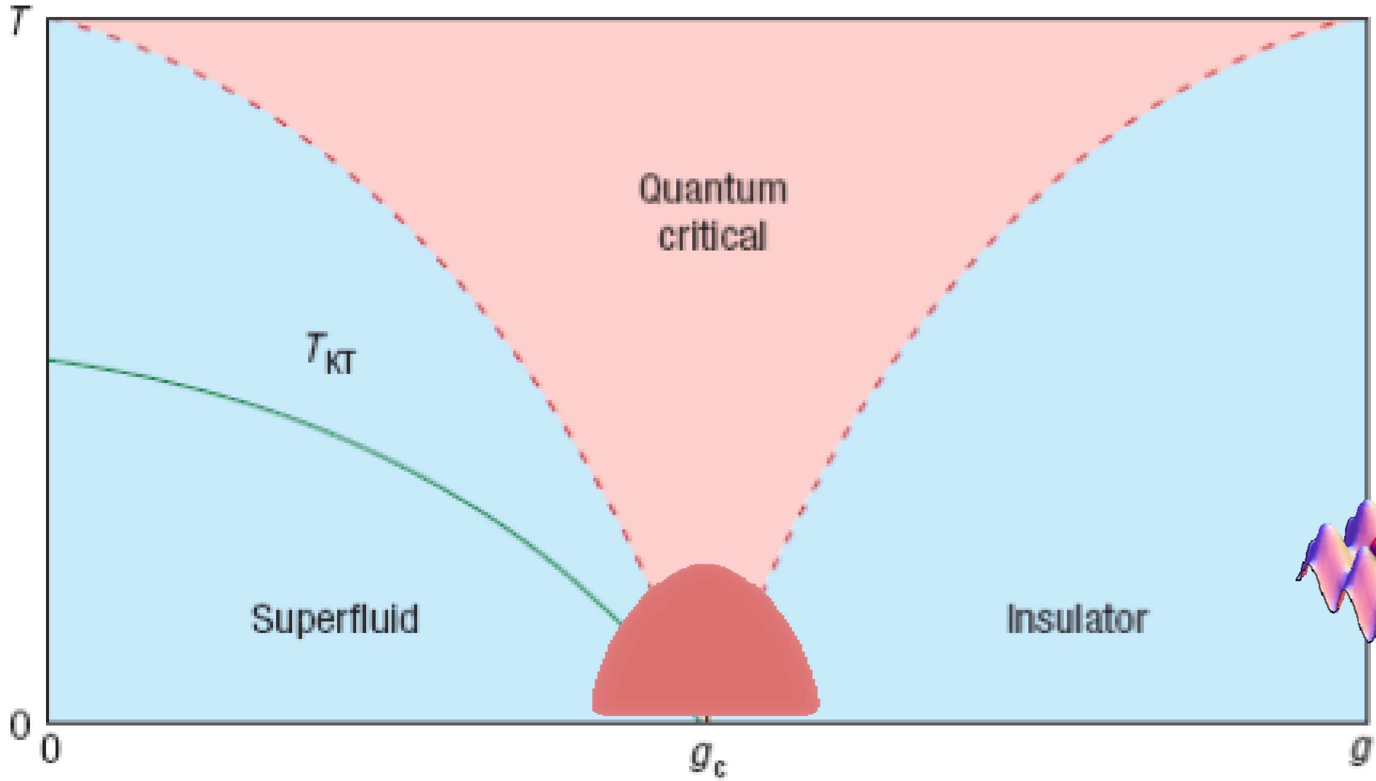
Feshbach resonance in ultracold gases

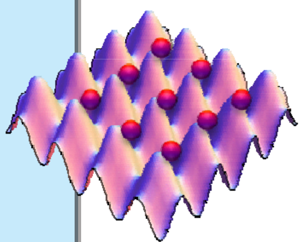


Chin, Grimm, Julienne and Tiesinga, Rev. Mod. Phys. (2010)

Quantum phase transition of bosons in 2D lattices







Ads-CFT duality: Sachdev, Nature physics (2007)

$$\frac{n - n_c}{T^{d/z+1-1/\nu z}} = h(\frac{\mu - \mu_c}{T^{1/\nu z}})$$

Critical thermodynamics: Zhou and Ho, PRL (2010)

Hazzard and Mueller , PRA (2011)

AdS-CFT (gauge-gravity) duality

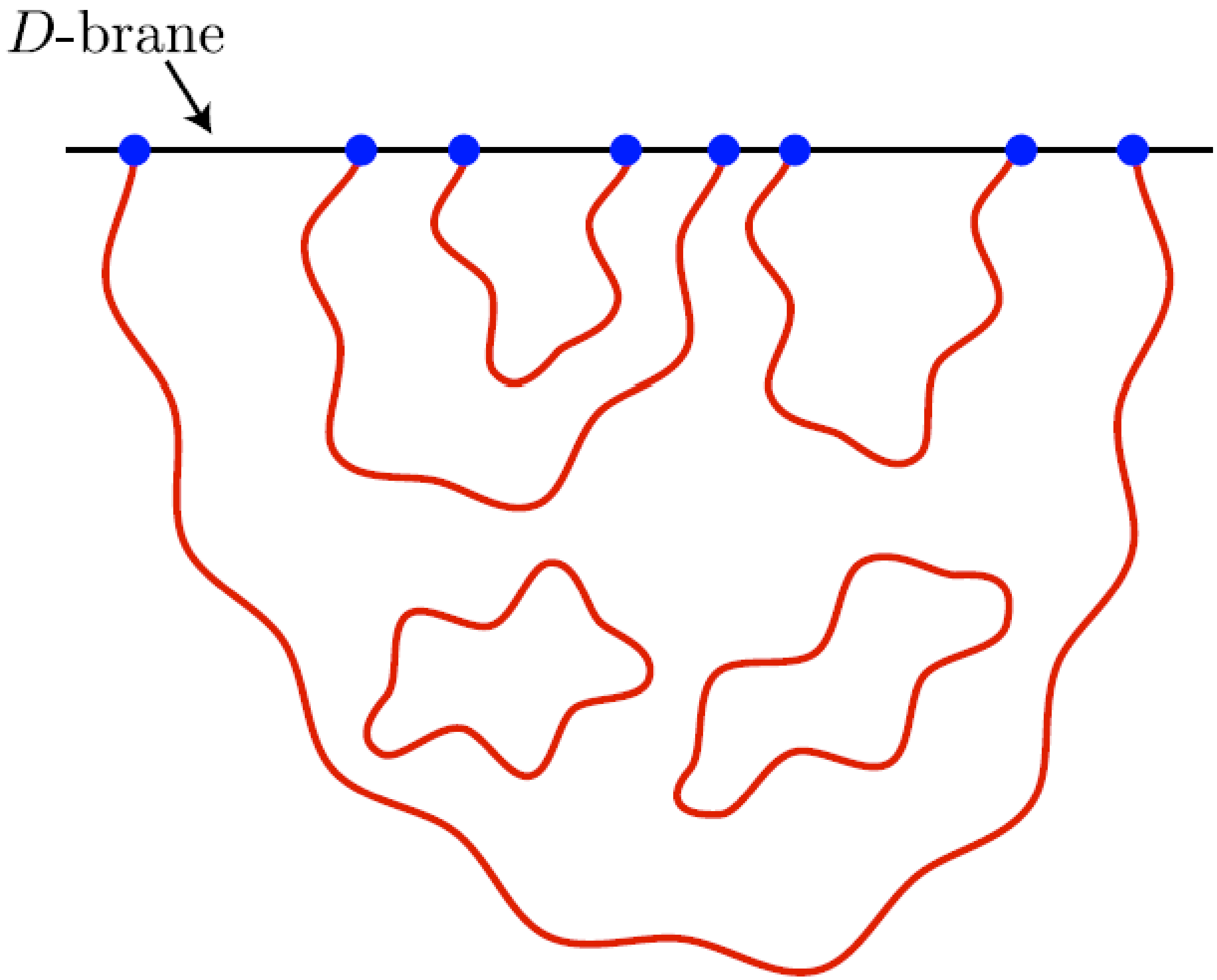
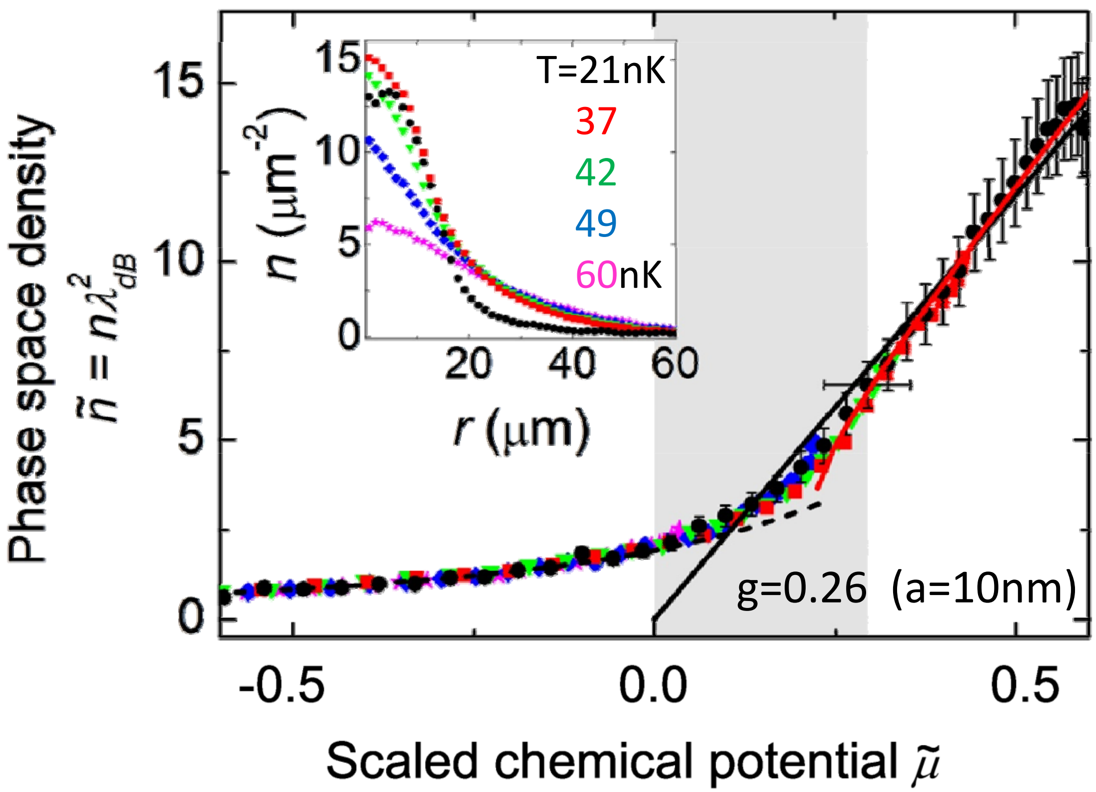


Figure: Subir Sachdev (2011)

Theory: Juan Maldacena (1997)

Scale Invariance of Eq. of State $\tilde{n} = n\lambda_{dB}^2 = F(\frac{\mu}{kT})$

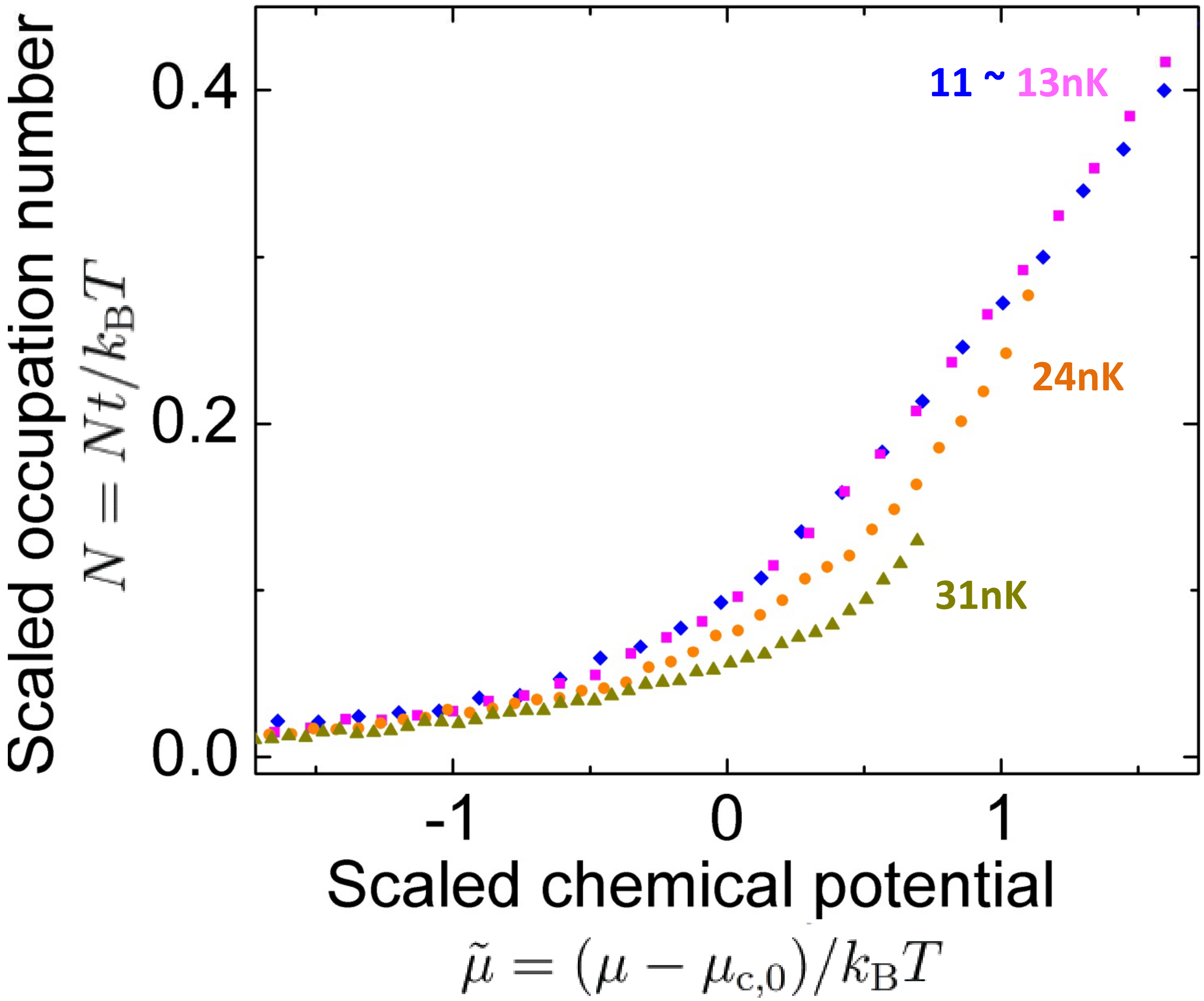


$$n(\mu, T) = -\lambda_{dB}^{-2} \ln[1 - \exp(\mu/k_B T - g n \lambda_{dB}^2/\pi)]$$

$$\tilde{n} = 2\pi\tilde{\mu}/g + \ln(\frac{2\tilde{n}g}{\pi} - 2\tilde{\mu})$$

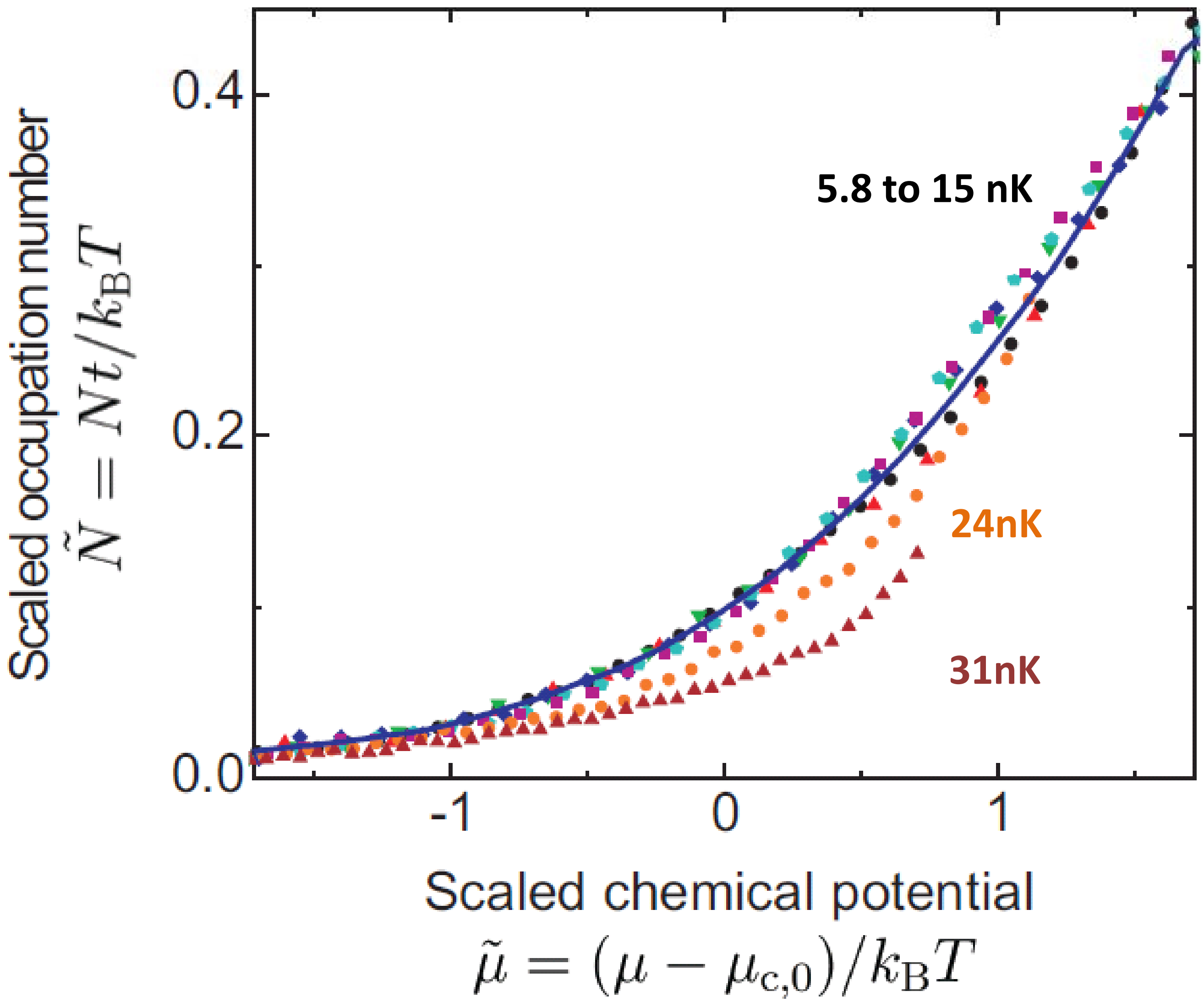
Prokof'ev and Svistunov, PRA 66, 043608 (2002)

Universal scaling at low temperatures



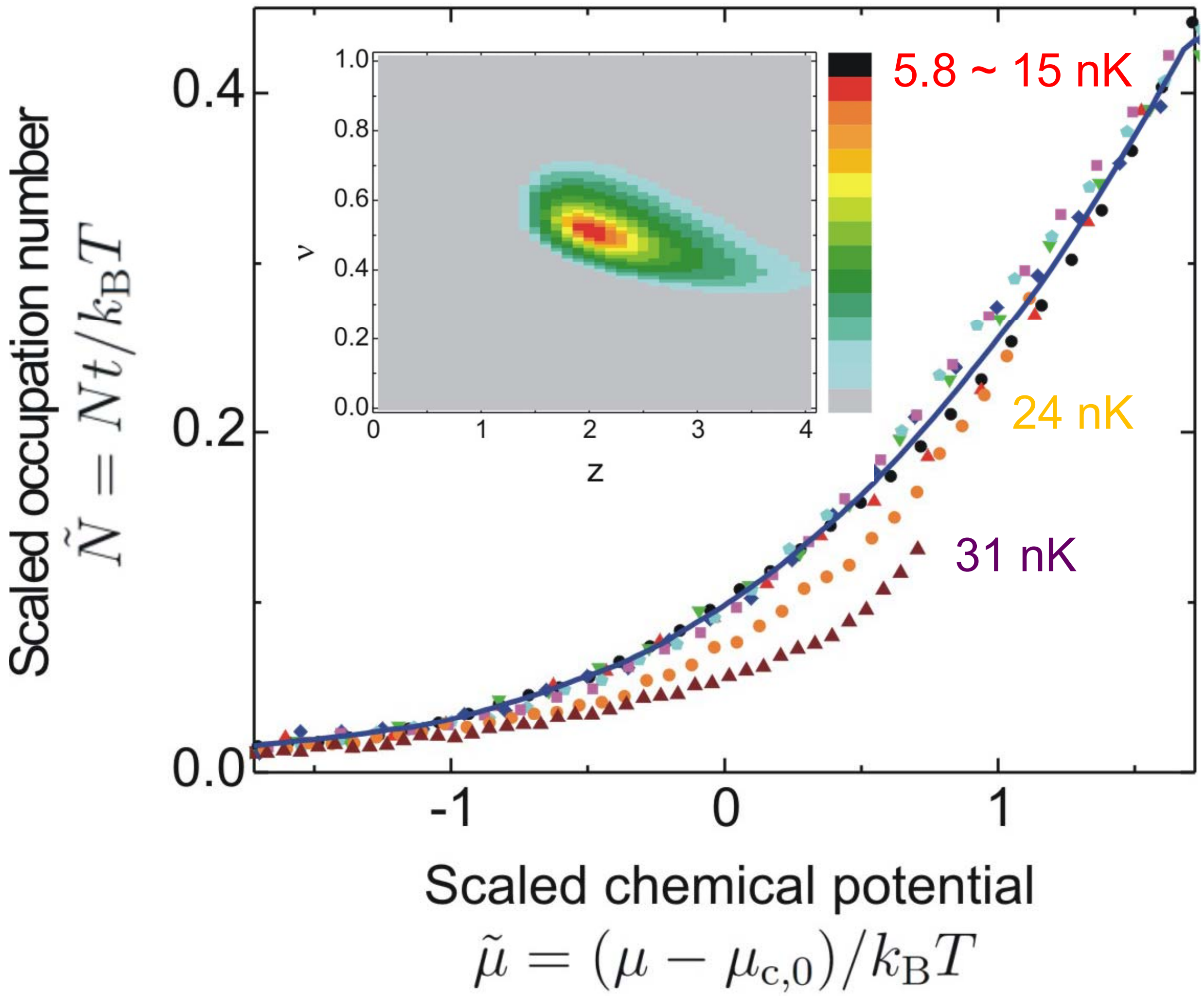
Tunneling=3nk

Universal scaling at low temperatures



Tunneling=3nk

Critical exponents *z* and *v*: $$\frac{n - n_c}{T^{d/z+1-1/\nu z}} = h(\frac{\mu - \mu_c}{T^{1/\nu z}})$$

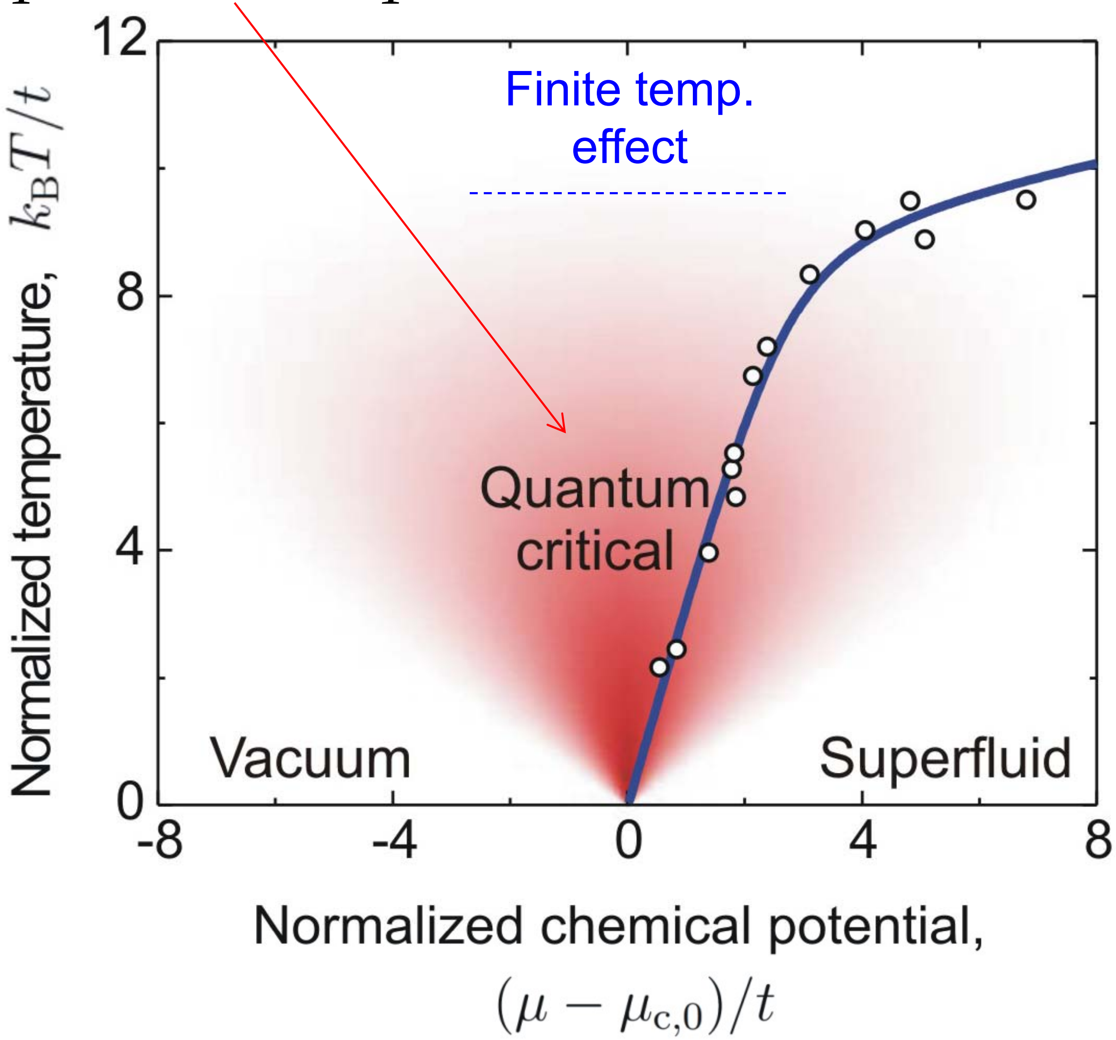


Theory:
z=2
v=1/2

Experiment:
z=2.0 (3)
v=0.53 (5)

Quantum phase transition in 2D lattice

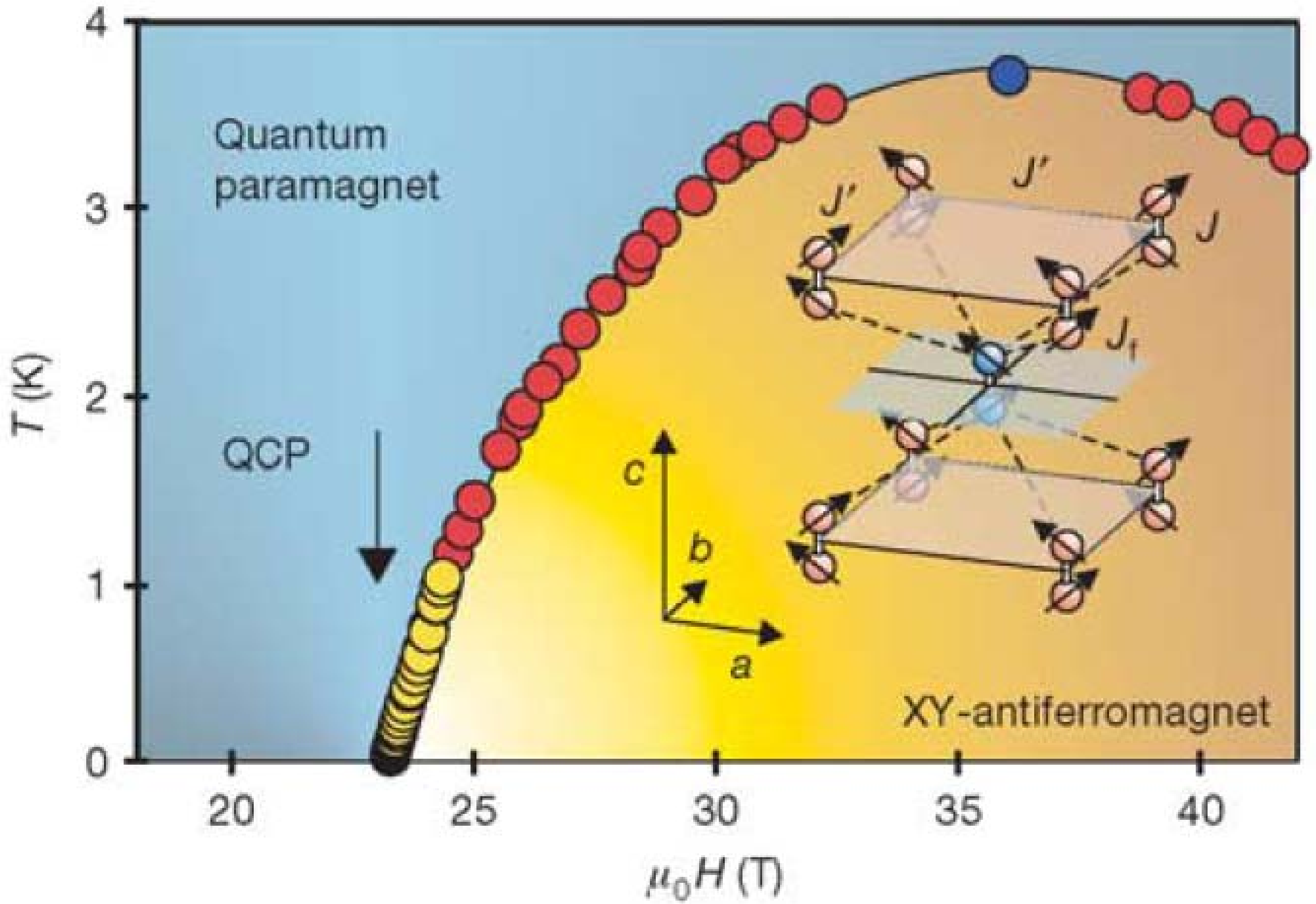
critical scaling law $$\frac{n}{T^{d/z+1-1/\nu z}} = G\left(\frac{\mu-\mu_{c,0}}{T^{1/\nu z}}\right)$$



$$\frac{n-n_c}{T} = F\left(\frac{\mu-\mu_c}{T}\right)$$

Our paper: X. Zhang, C. Hung, S. Tung and CC, Science (2012)

Quantum Criticality near a 2D BEC of spin-triplets



I.R. Fisher group: S.E. Sebastian et al., Nature 441 617 (2006)

Synopsis

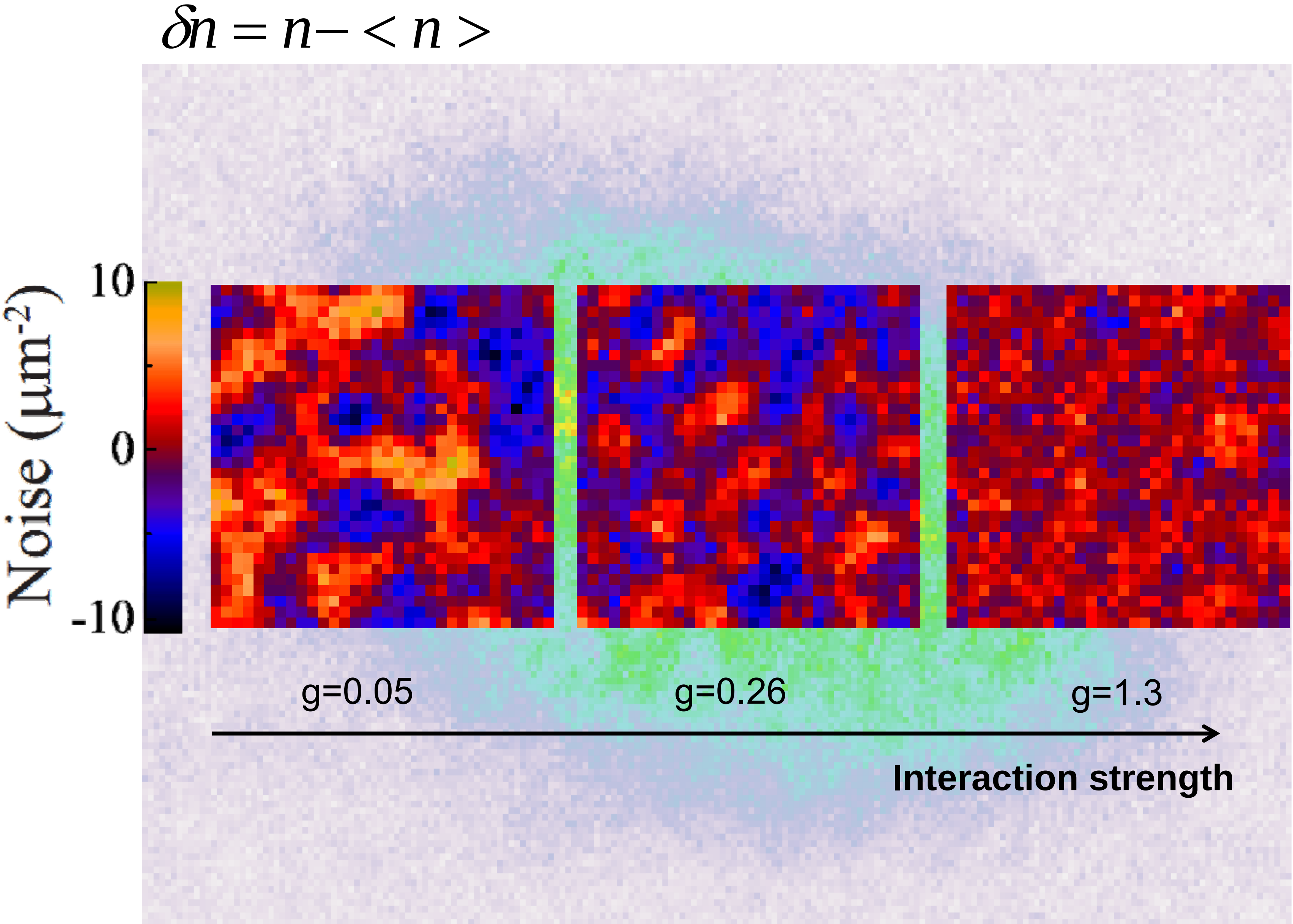
Experimental tools and observables

Earlier projects

In situ imaging of Mott domains	(Lattice)
Scale invariance and universality	(2D gas)
Quantum criticality	(Lattice)

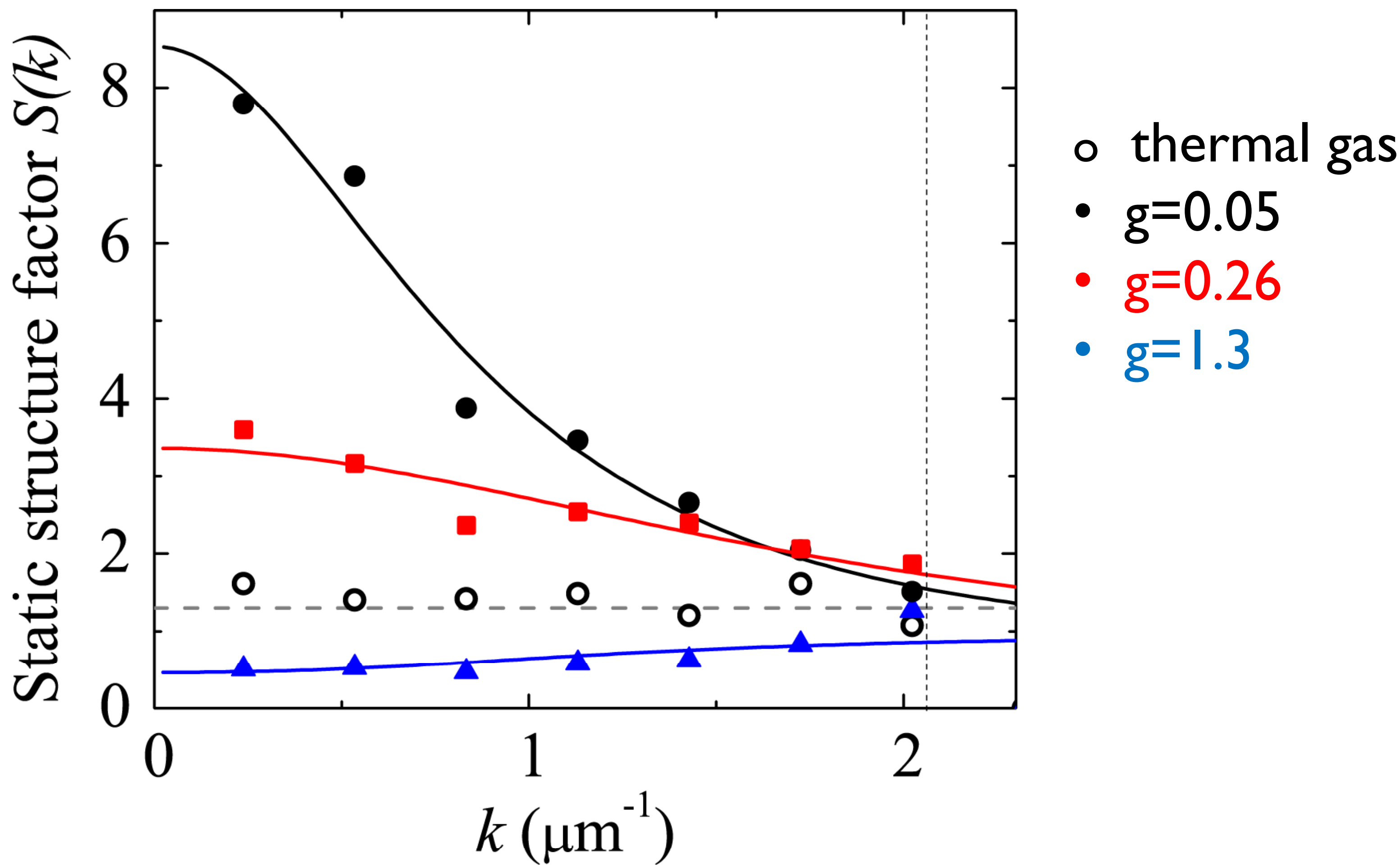
New projects

Quantum quench	(2D gas)
Strongly interacting 2D gas	(both)
Critical transport	(both)


$\delta n = n - \langle n \rangle$
Noise (μm^{-2})
10
0
-10
g=0.05
g=0.26
g=1.3
Interaction strength

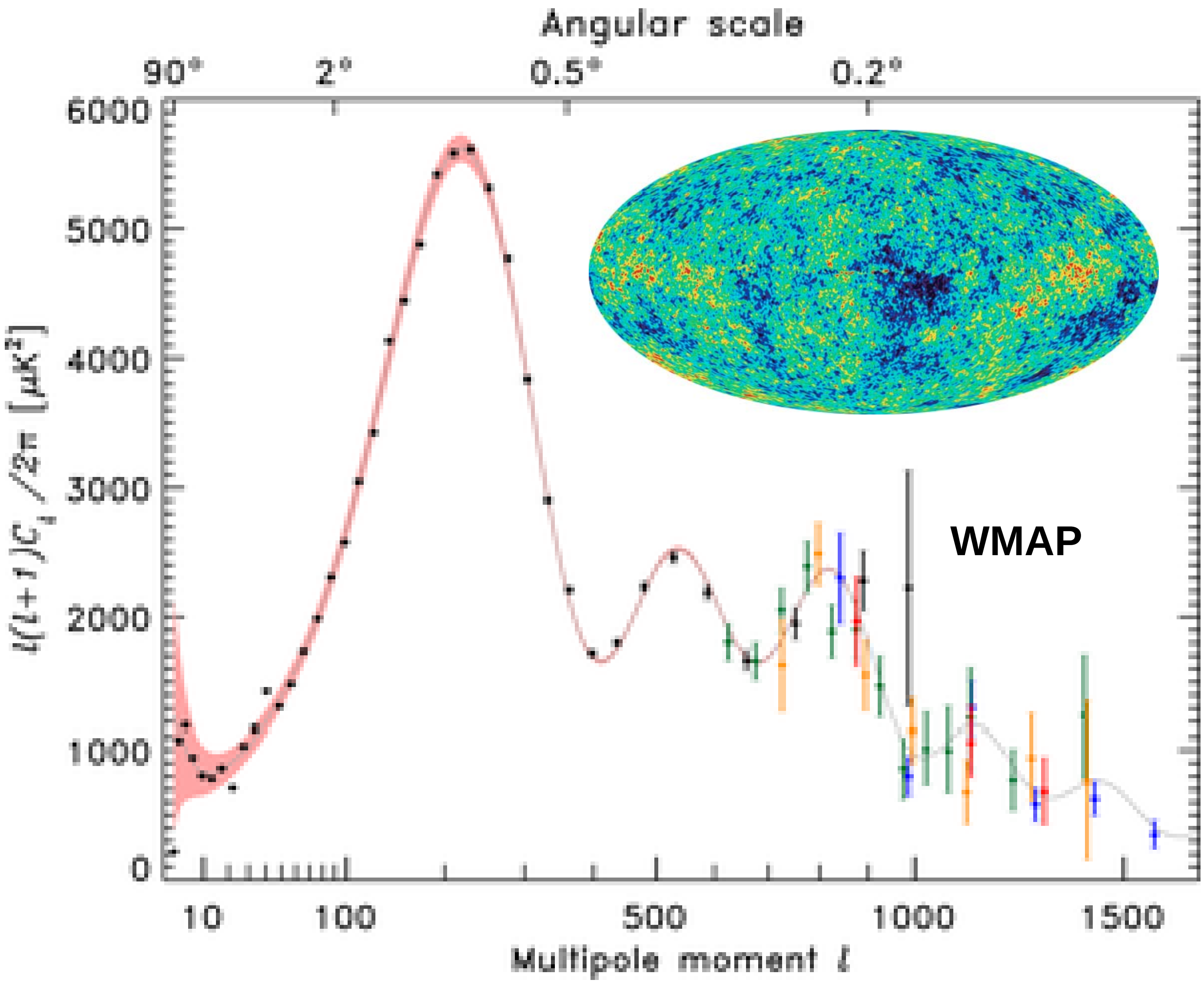
Static structure factor $S(k)=n^{-1}\langle\delta n(-k)\delta n(k)\rangle$

- power spectrum of the density fluctuations



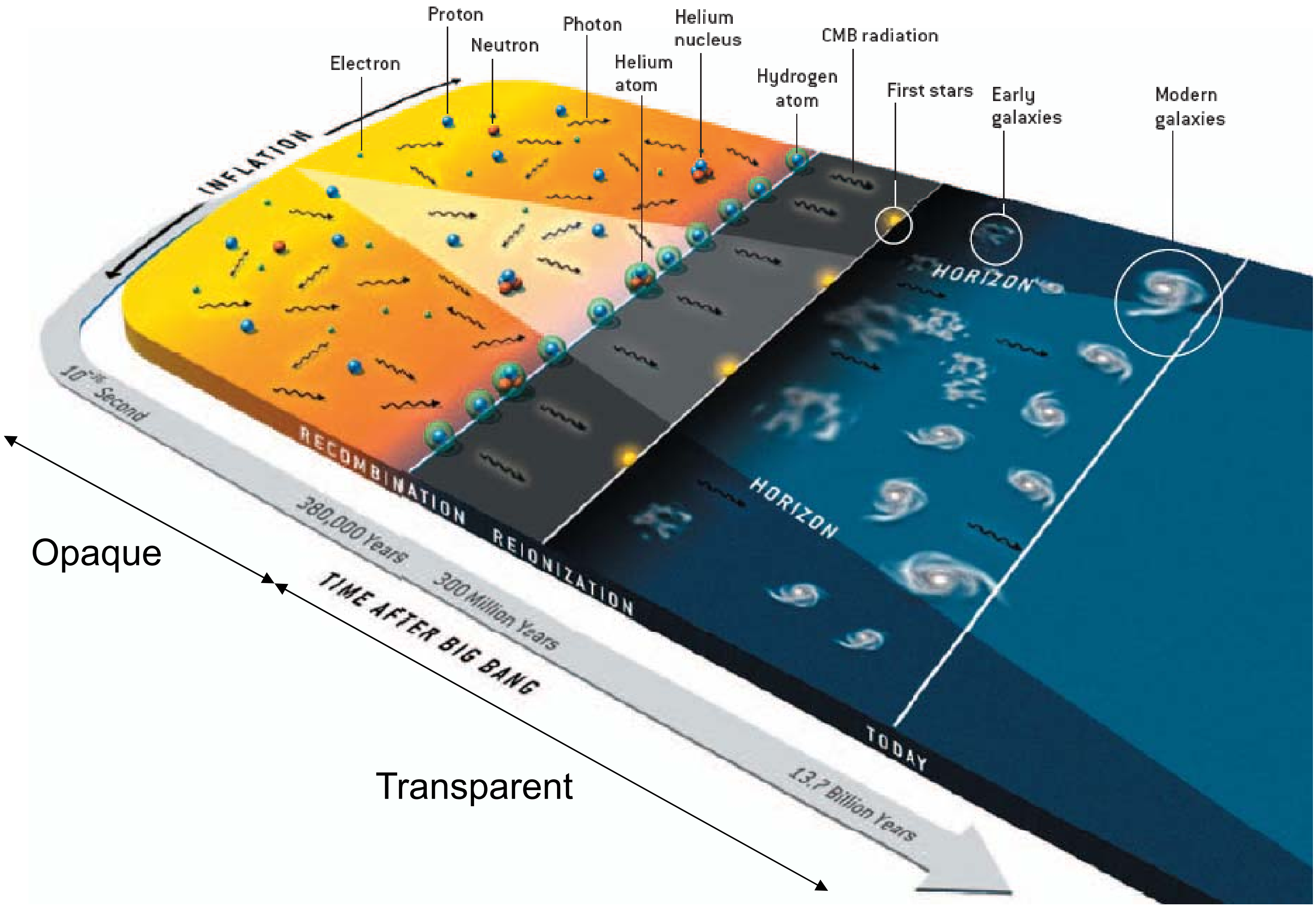
Hung, Zhang, Gemelke, Tung and CC, New Journal of Physics (2011)

Sakharov Oscillations in CMB



A.D. Sakharov, Soviet Physics JETP (1966)

Evolution of the universe

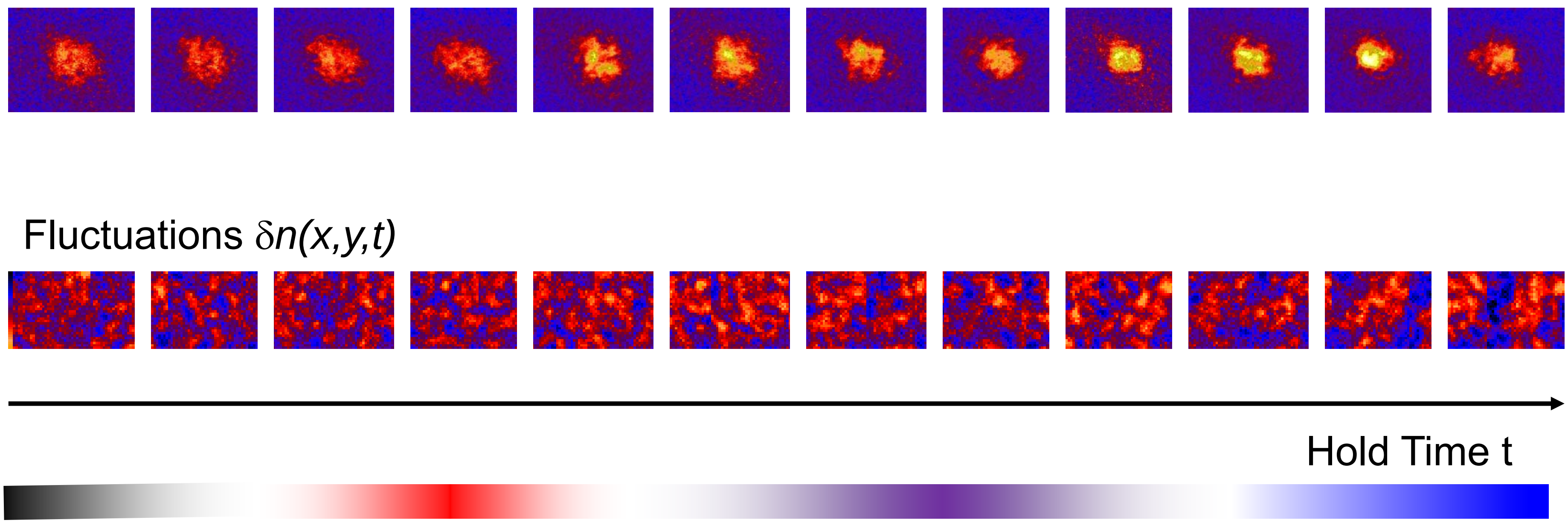


Hu & White, Sci. Am., 290 44 (2004)

Quantum Quench (2D gas g= 0.26 → 0.05)

Density $n(x,y,t)$

Fluctuations $\delta n(x,y,t)$



Initial state

Coherent excitation

Transport

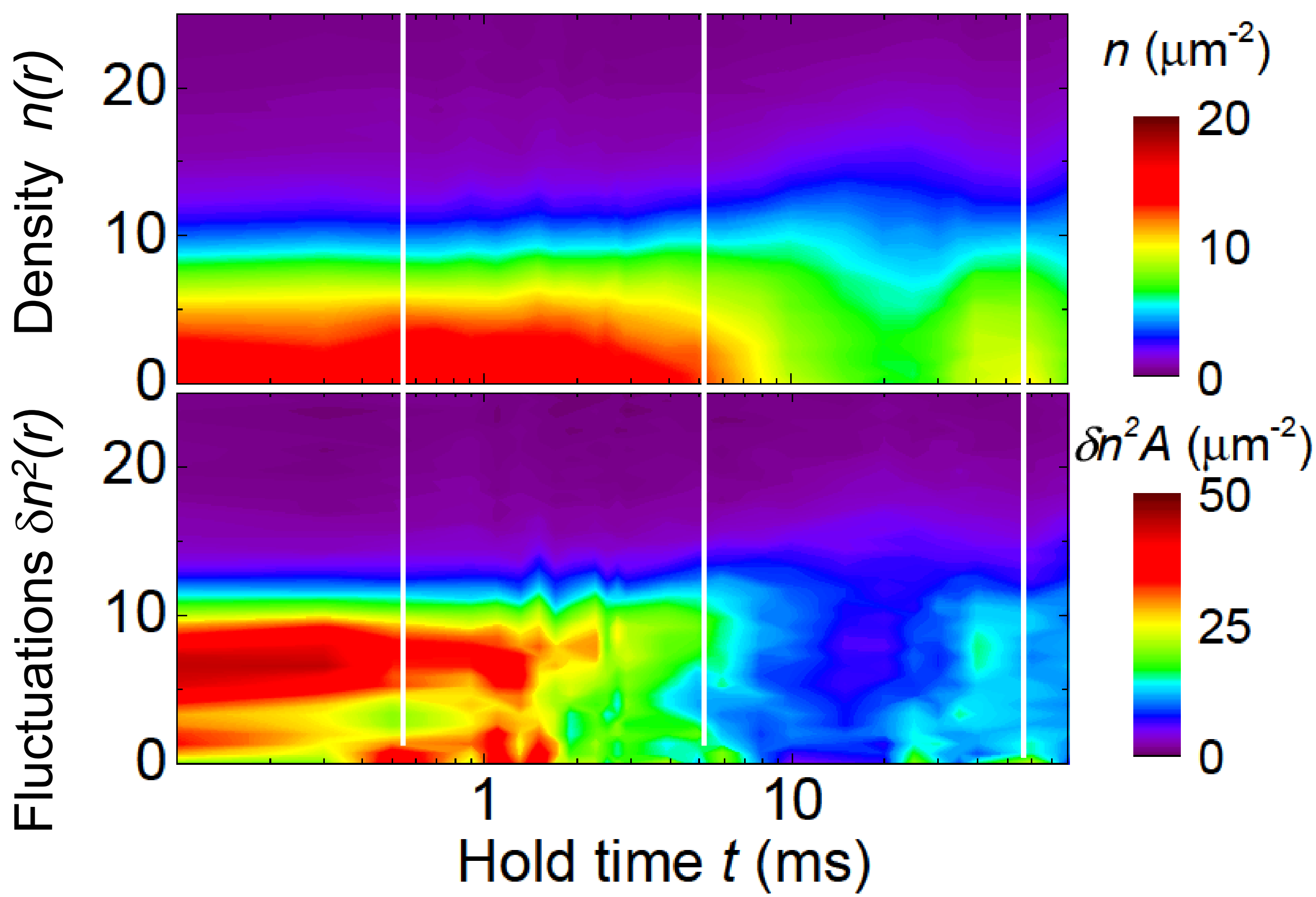
New equilibrium

Interaction
~ 0.1 ms

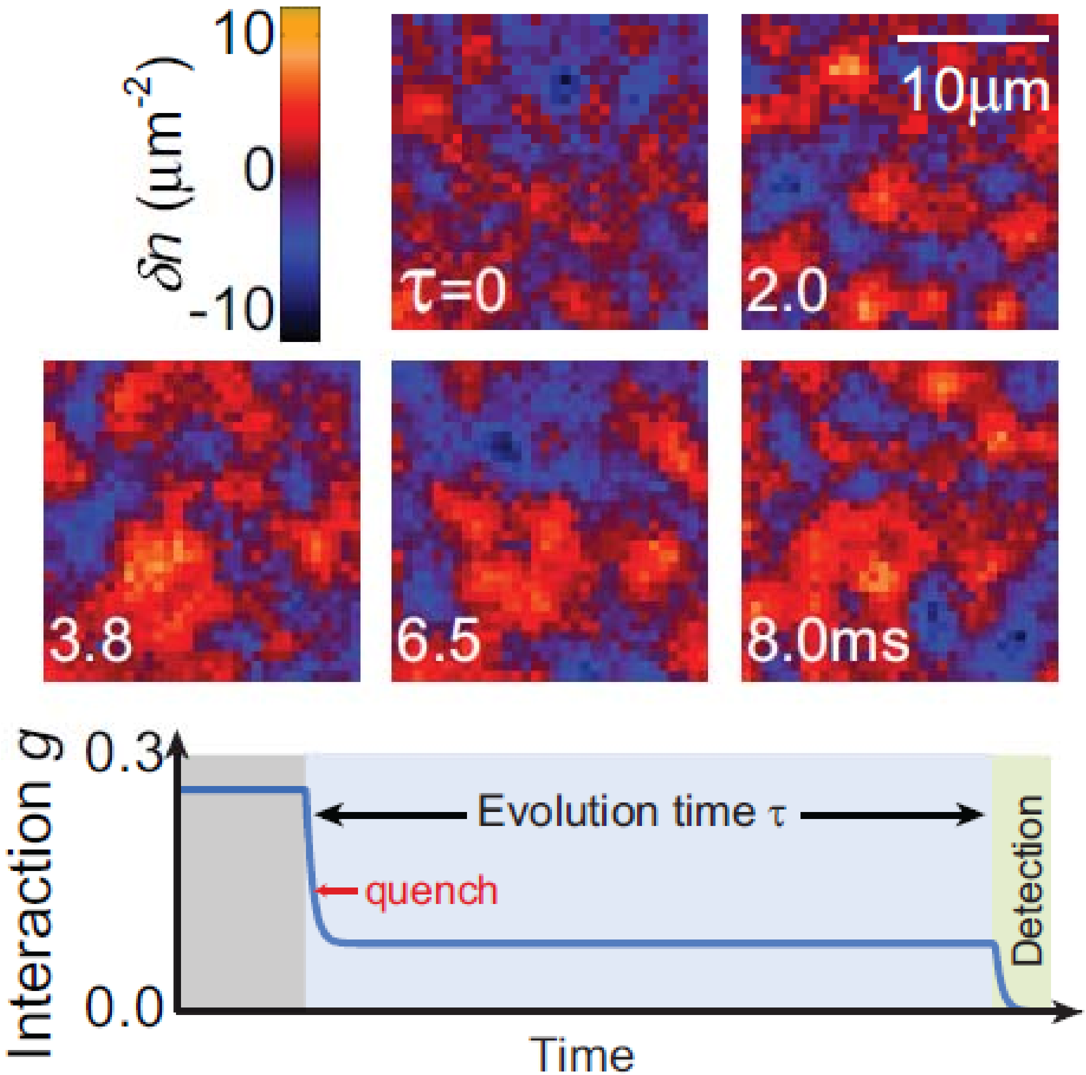
Dephasing
~ 10ms

Equilibration
> 300 ms

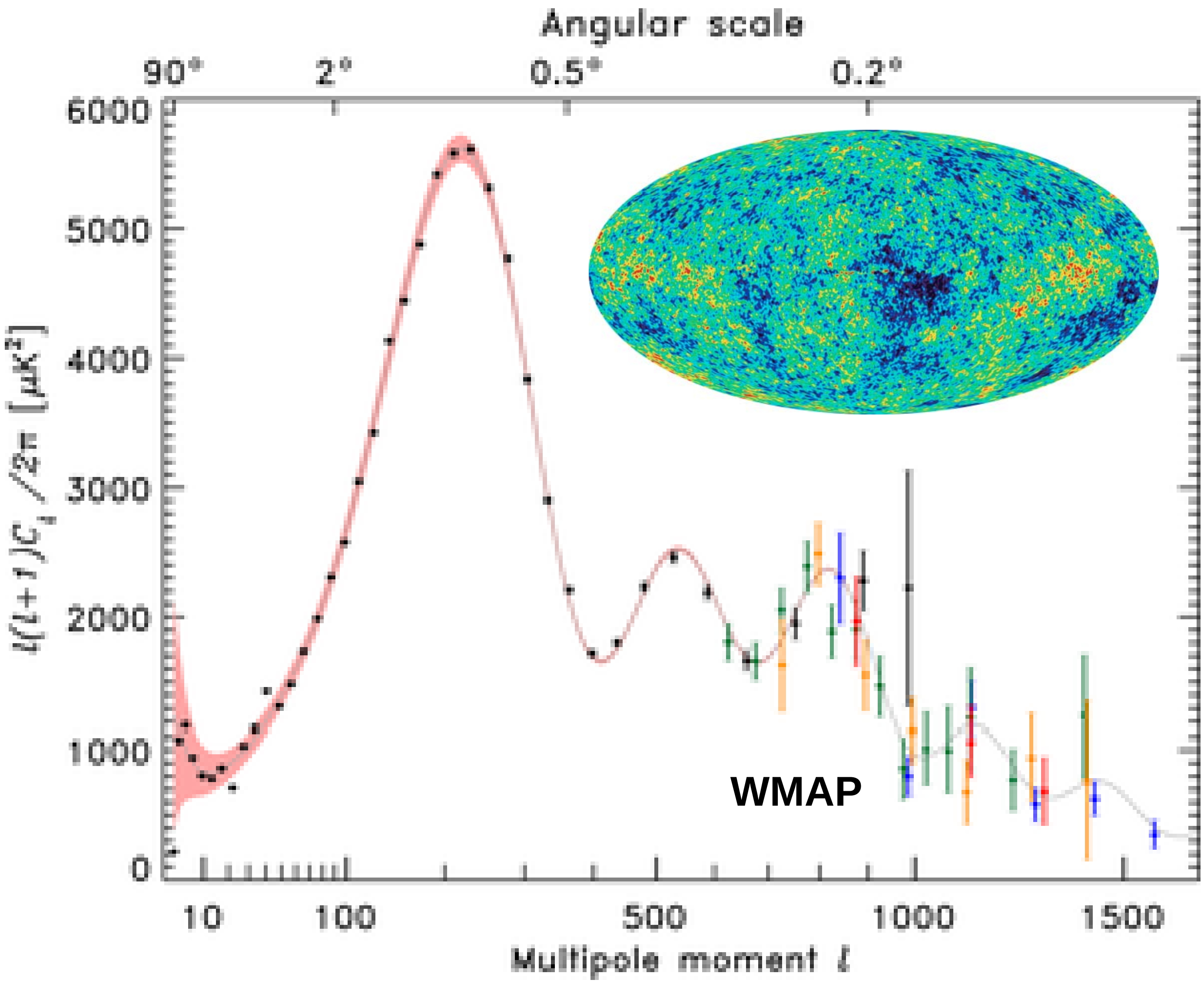
Quantum Quench (from g=0.05 to 0.26 in 0.1 ms)



Quantum Quench (from g=0.05 to 0.26 in 0.1 ms)

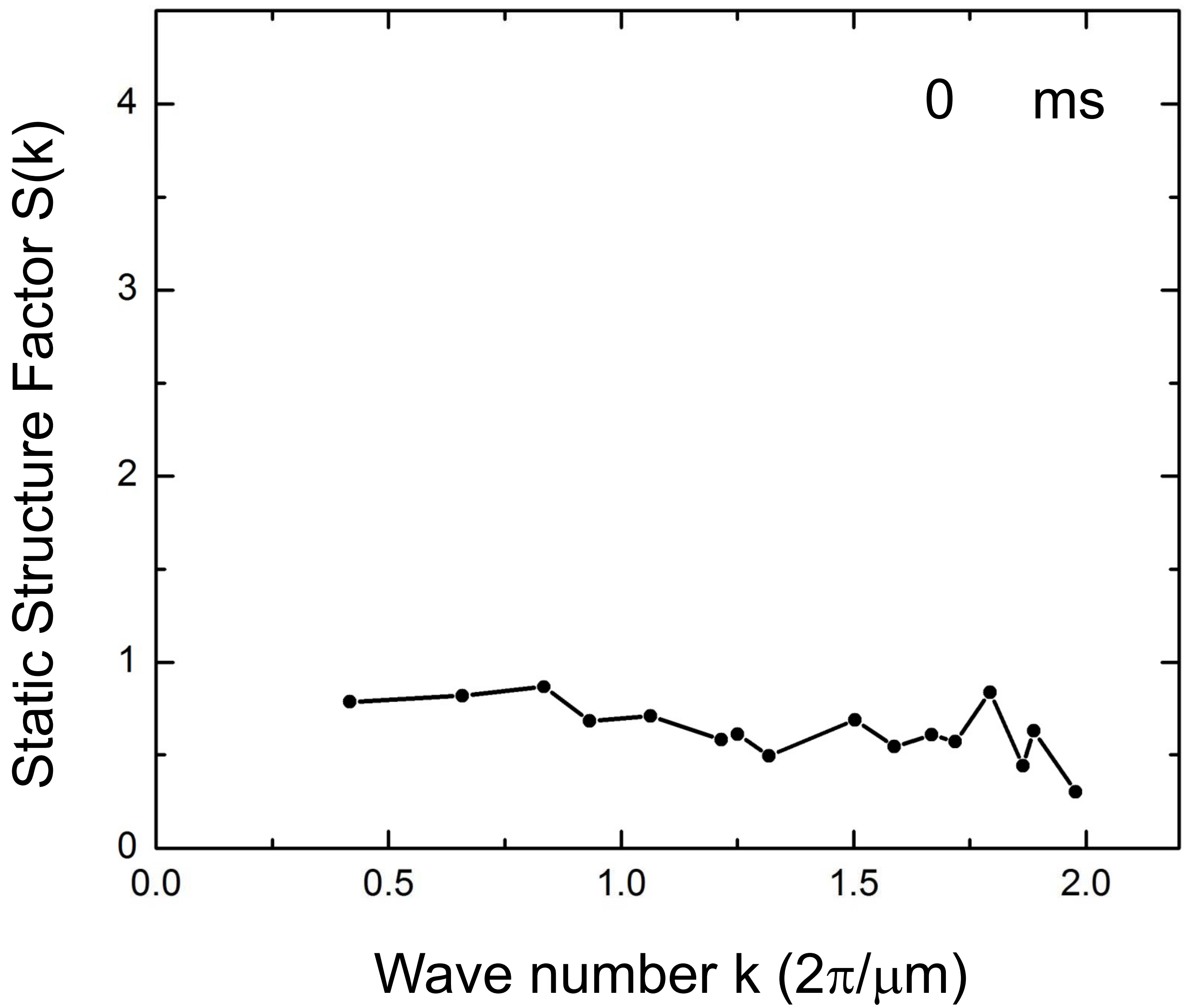


Sakharov Oscillations in CMB

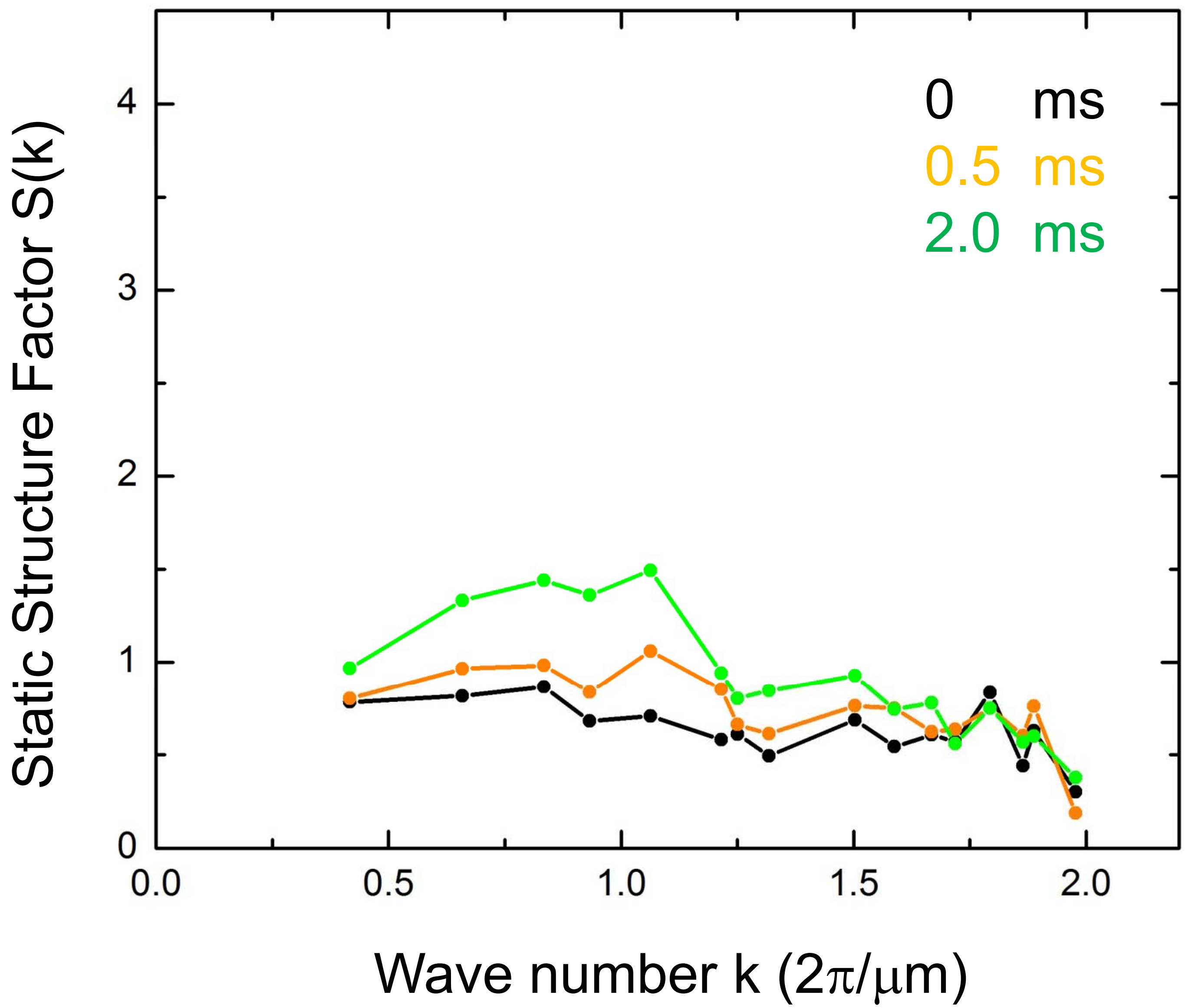


A.D. Sakharov, Soviet Physics JETP (1966)

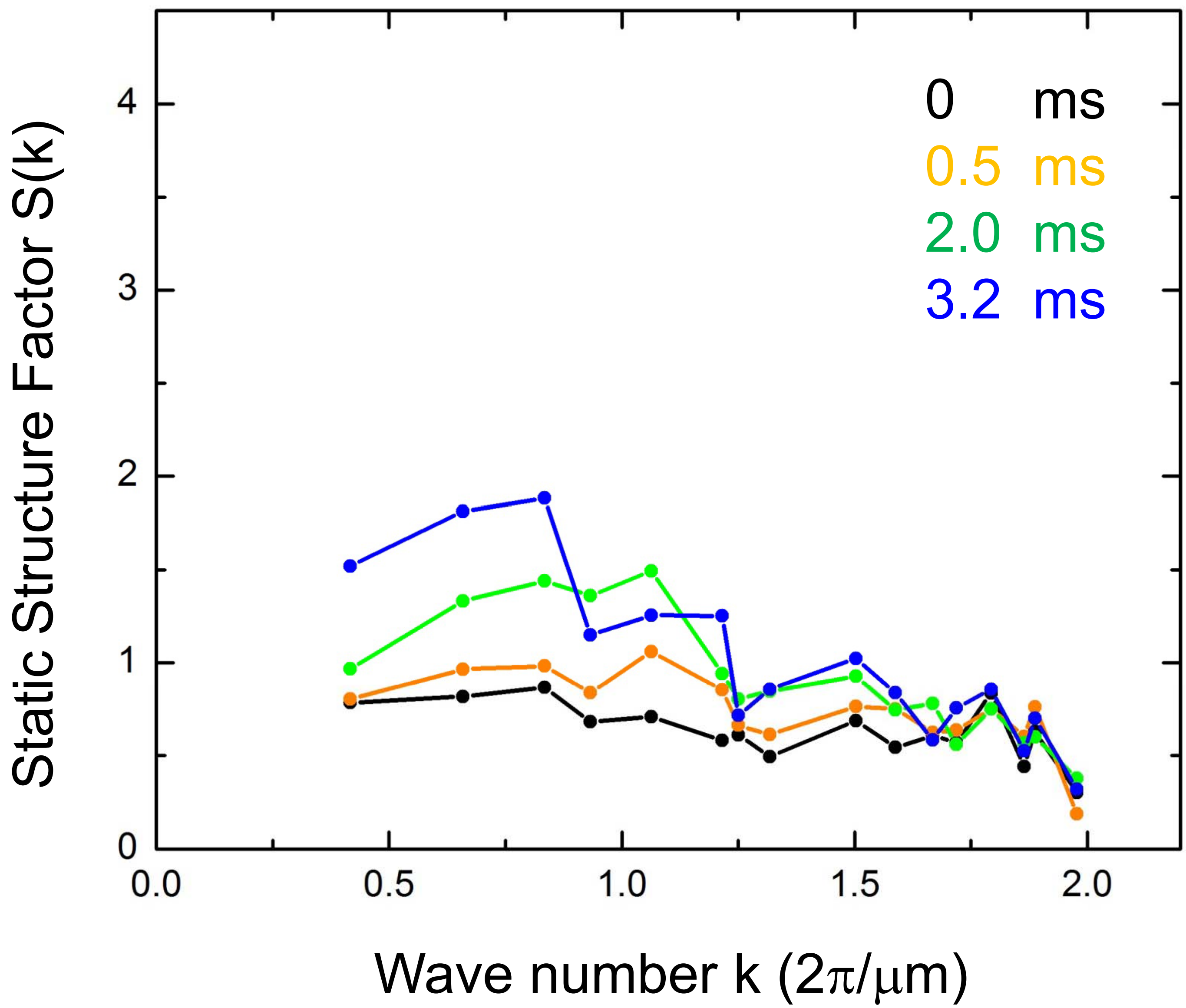
Evolution of density-density correlations



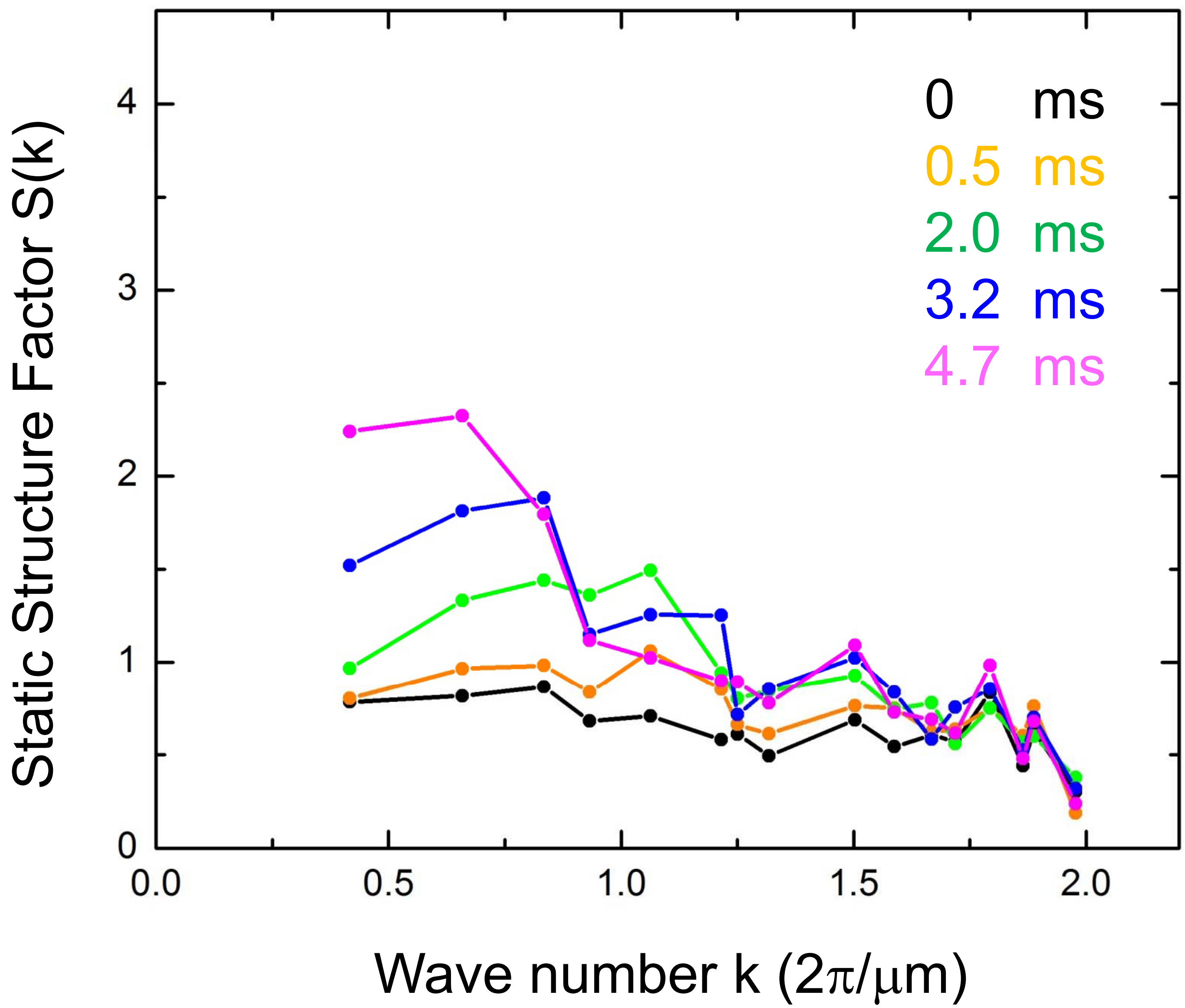
Evolution of density-density correlations



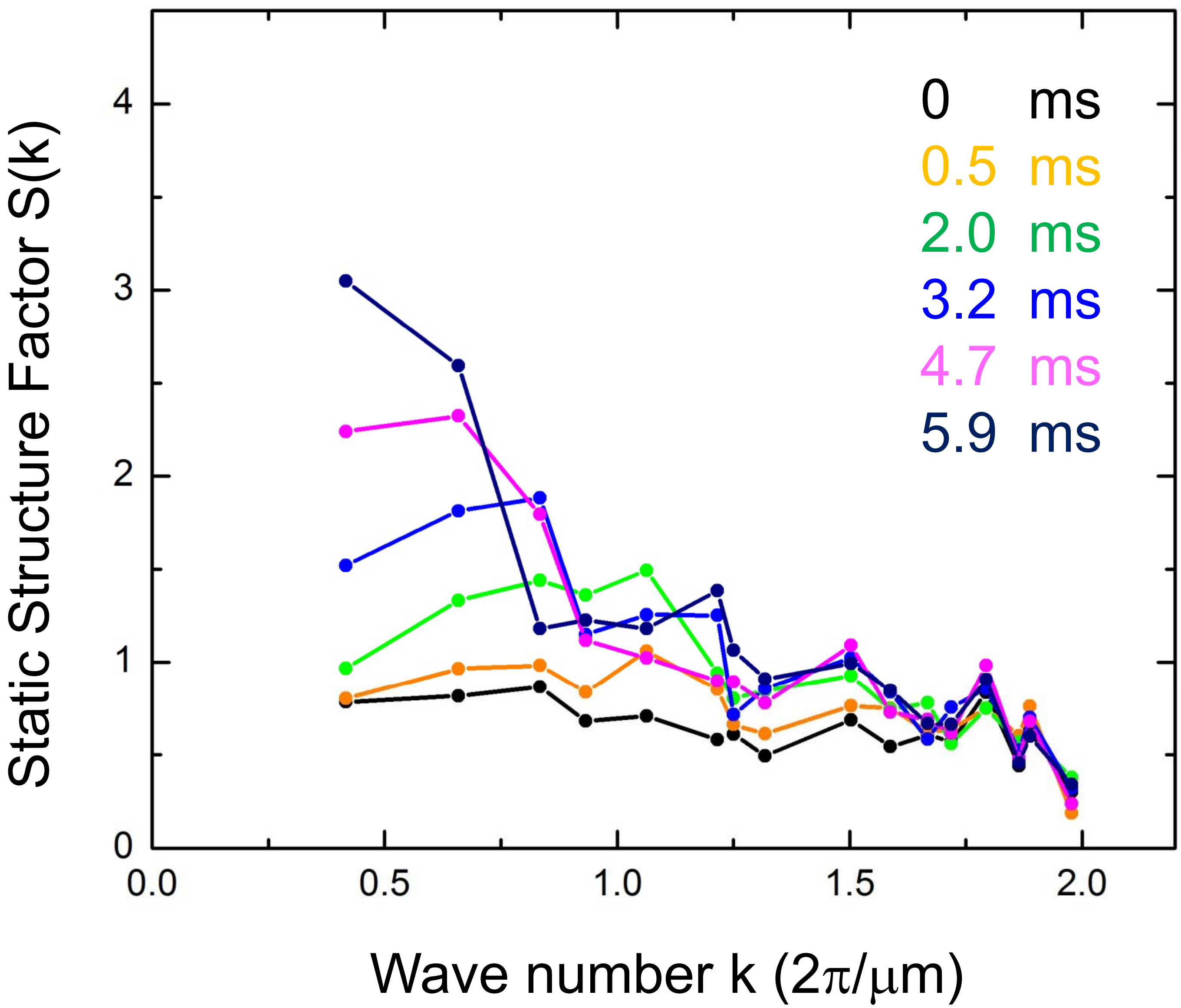
Evolution of density-density correlations



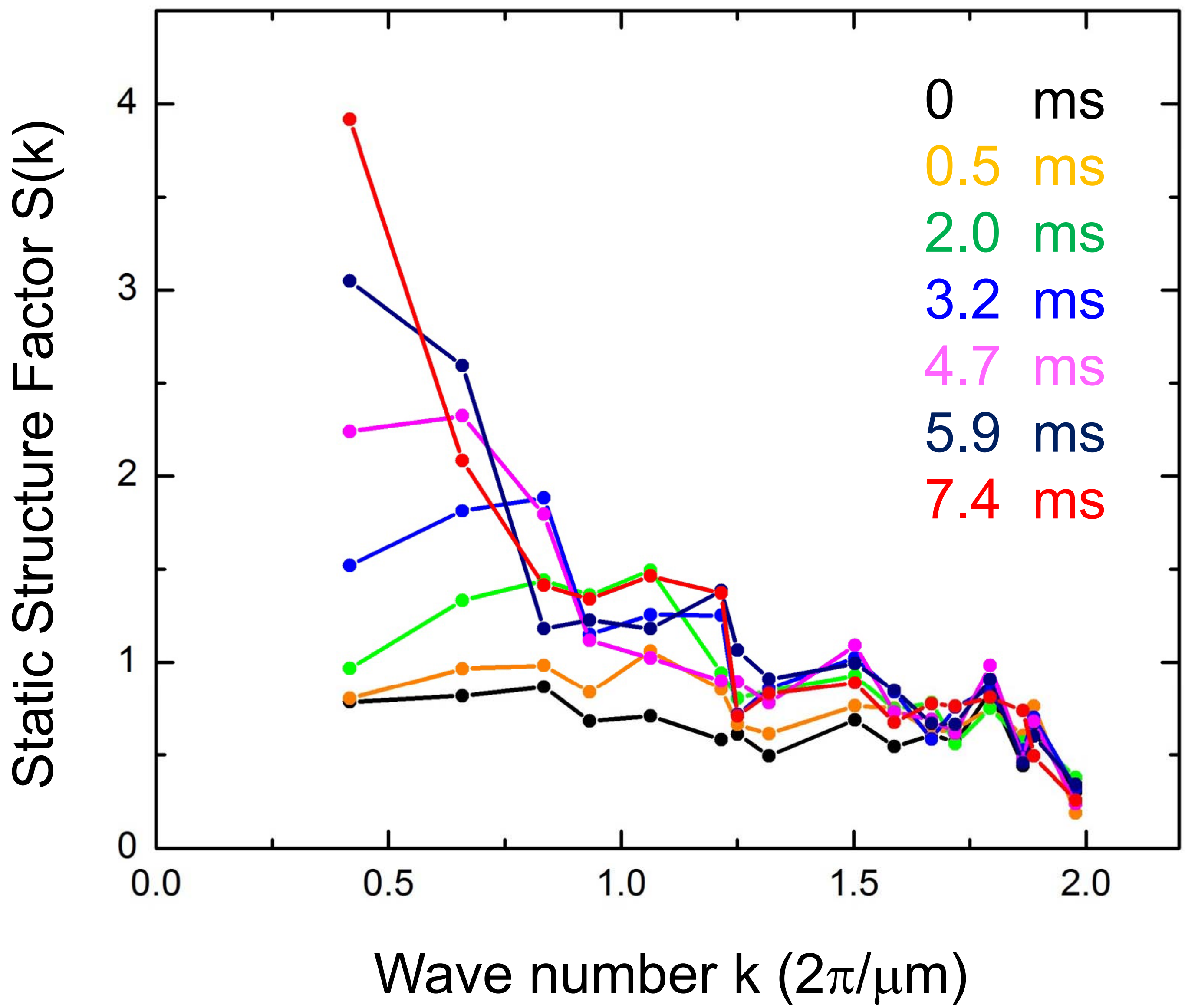
Evolution of density-density correlations



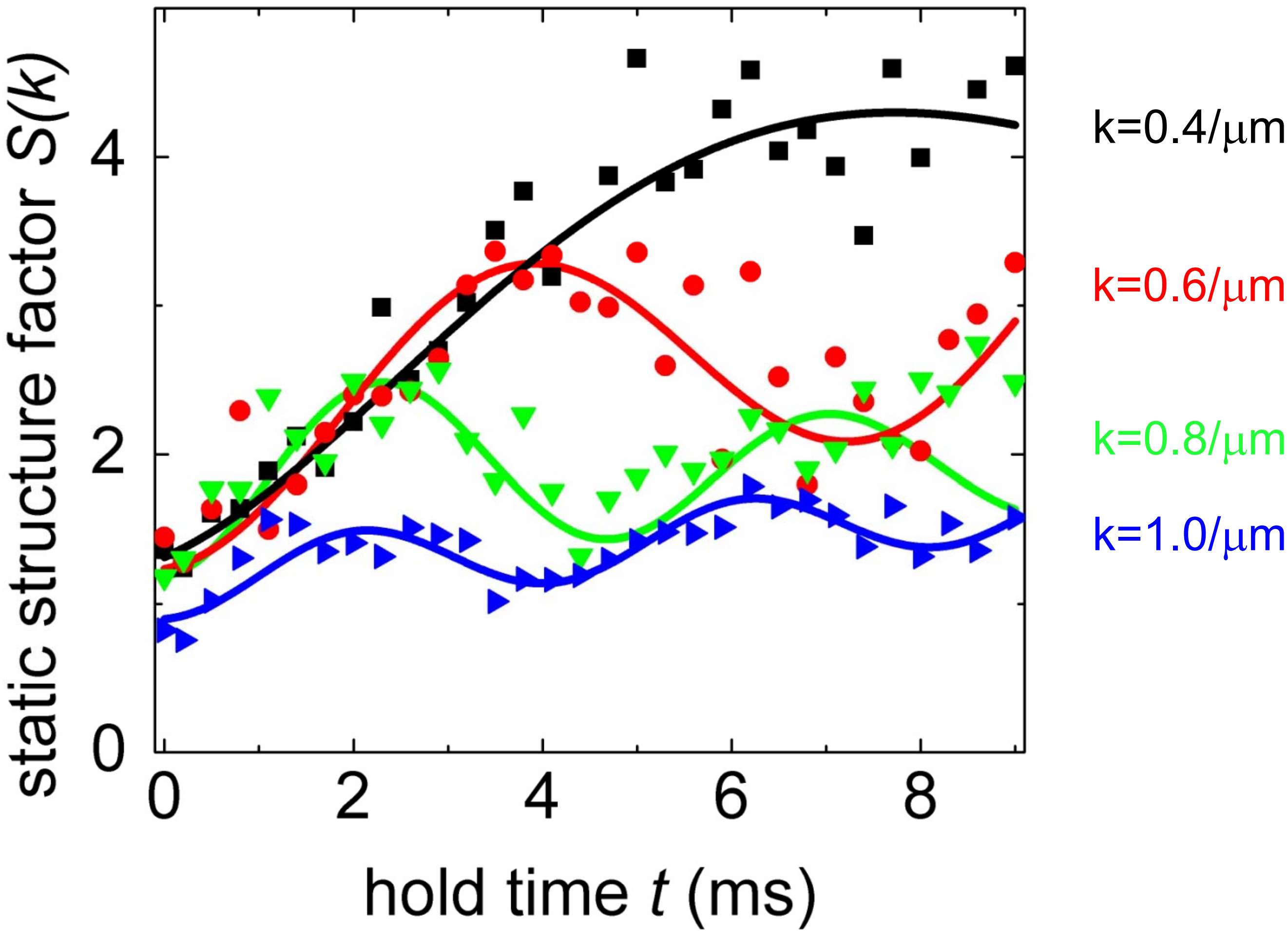
Evolution of density-density correlations



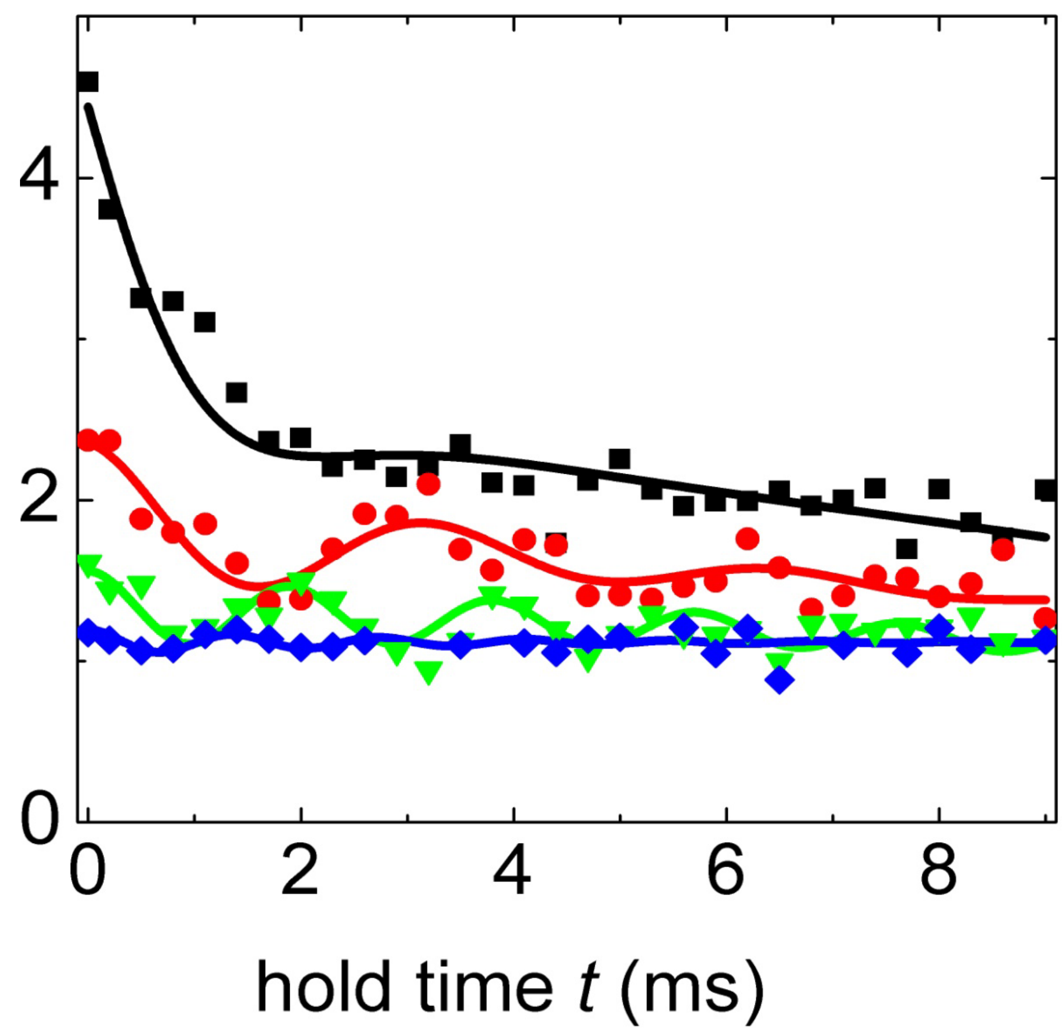
Evolution of density-density correlations



Quantum Quench (from g=0.26 to 0.05)



Quantum Quench (Big Crunch, g=0.05 to 0.26)

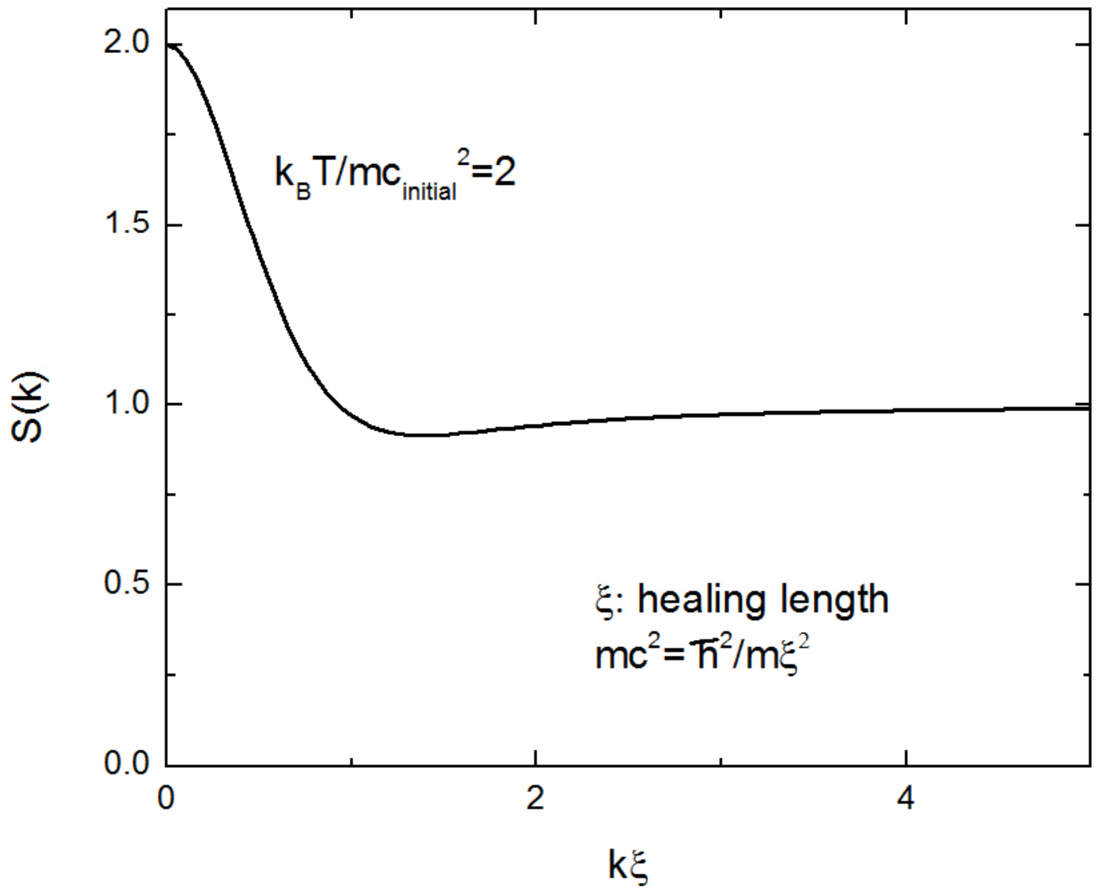


Theoretical model (a=0.05 → 0.26)

$$S(k) = \frac{\hbar^2 k^2}{2m\epsilon_0(k)} \coth \frac{\epsilon_0(k)}{2kT}$$

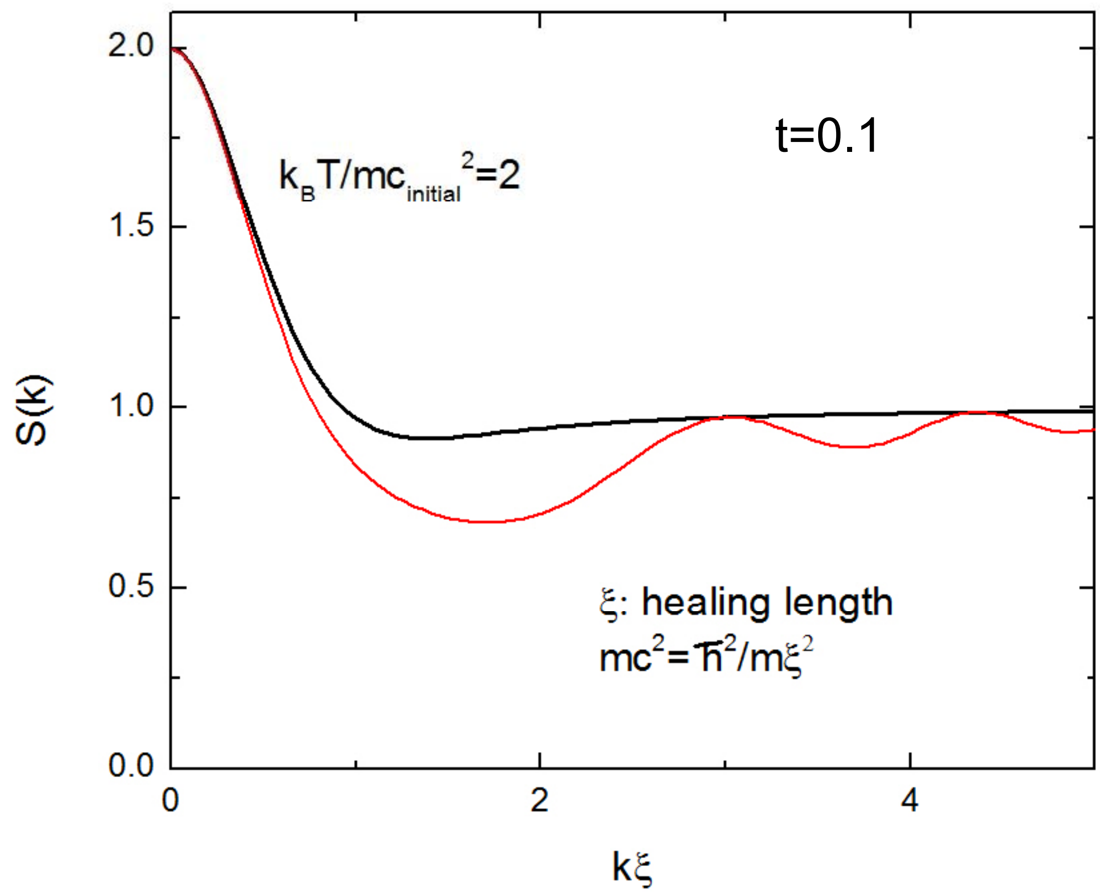
$\epsilon_0(k)$: initial dispersion

Landau and Lifshitz, Vol. 9 p.386

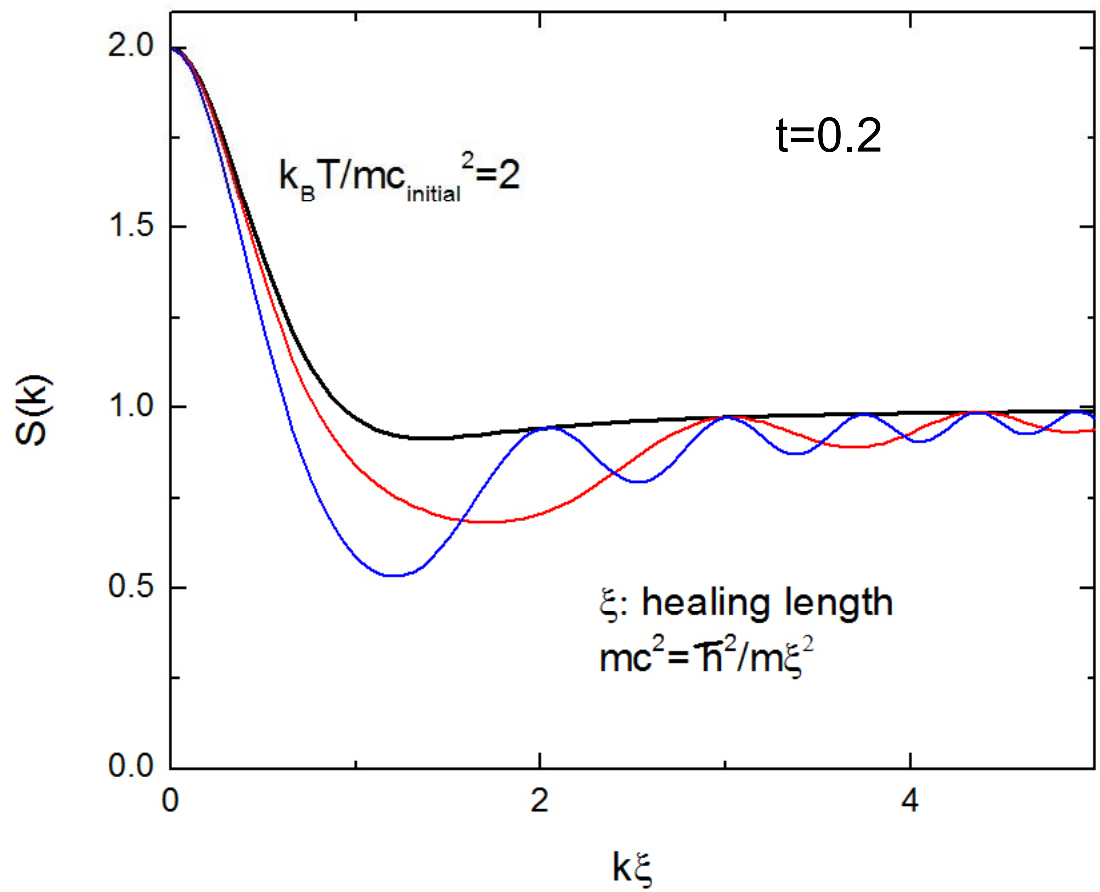


Theoretical model (Bogoliubov approximation)

$$S(k) = \frac{\hbar^2 k^2}{2m\epsilon_0(k)} \coth\frac{\epsilon_0(k)}{2kT}\left[1 - \frac{\epsilon(k)^2 - \epsilon_0(k)^2}{\epsilon(k)^2}\sin^2\epsilon(k)t\right]$$



$$S(k) = \frac{\hbar^2 k^2}{2m\epsilon_0(k)} \coth \frac{\epsilon_0(k)}{2kT} \left[1 - \frac{\epsilon(k)^2 - \epsilon_0(k)^2}{\epsilon(k)^2} \sin^2 \epsilon(k) t\right]$$

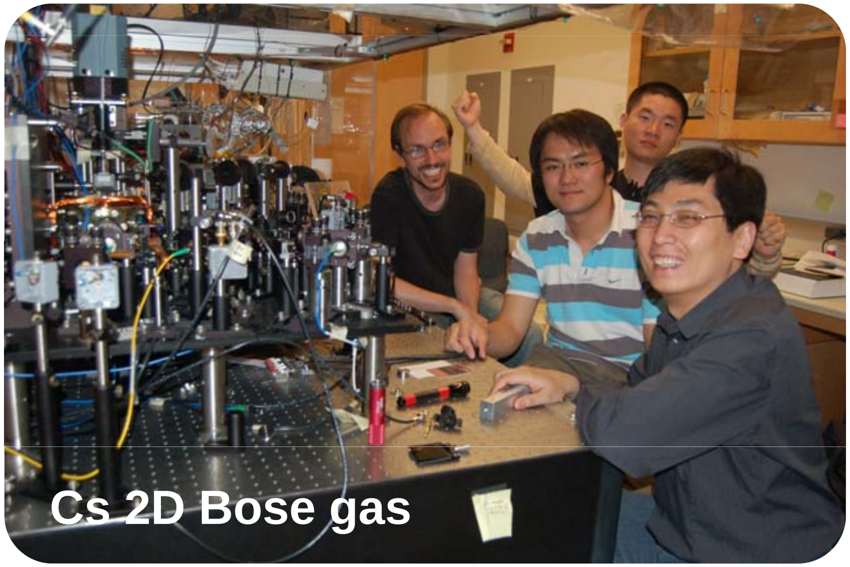


Conclusion and future projects

1. Quantum criticality
   - Conformal symmetry of 2D critical gas
   - Quantum critical transport and test of gauge-gravity duality
   - Quantum critical quench?

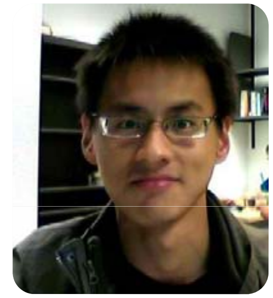
2. Extension beyond bosons
   - In situ imaging of Fermi gas
   - Heavy Boson (Cs) and light fermion (Li) mixture
   - Scalable quantum information processing based on 2-color lattices

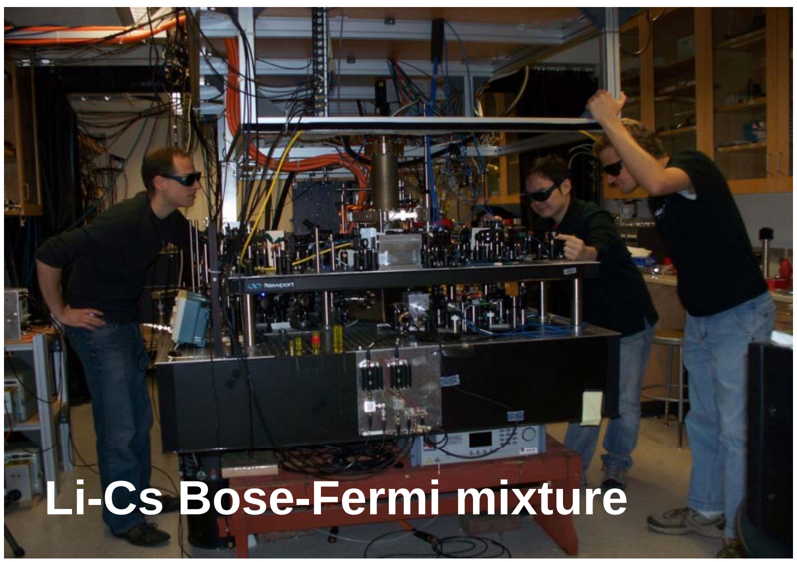
Group members



Left to right:
Prof. Nathan Gemelke (Penn state)
Dr. Chen-Lung Hung(Caltech)
Dr. Xibo Zhang (JILA) and CC


Dr. Shih-Kuang Tung


Harry L.C. Ha




Dr. Colin V. Parker


Jacob Johansen