Non-Equilibrium Physics with Quantum Gases

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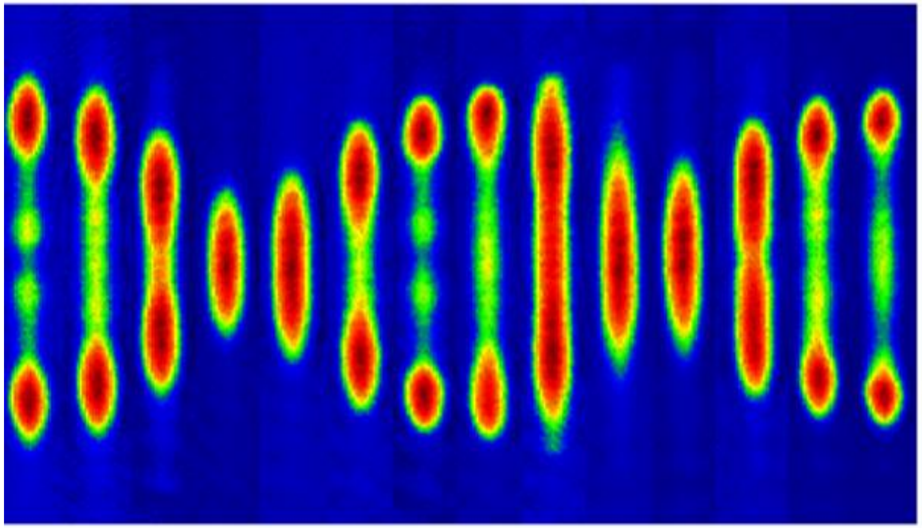


NSF, ARO, DARPA,

Outline

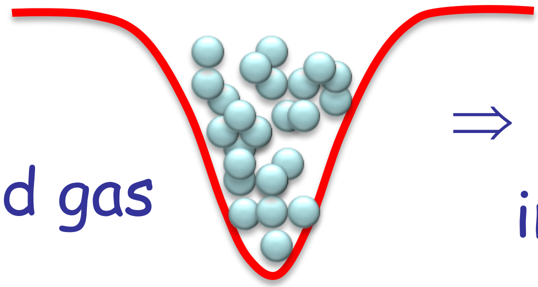
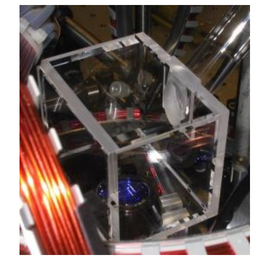
Intro: cold atoms as isolated quantum systems
Mean field experiments at various T
Gases with correlations
1D gases with δ-interactions: thermalization

Lightly sampled

Time scales, Integrability,
Correlations, Thermalization

Cold gas experiments

Cold gases are metastable

trapped gas  ⇒  inelastic 3-body collisions ⇒  (typically) metal coating the vacuum chamber

This is usually unimportant

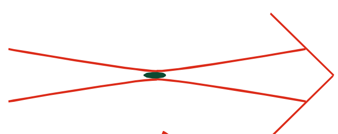
Any study of dynamics has to be concerned with timescales

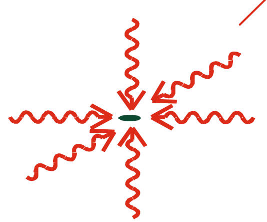
Cold gases are *very well* isolated quantum systems

light trapping

$\mathbf{p} \propto \mathbf{E}$, $U = -\mathbf{p}\cdot\mathbf{E}$

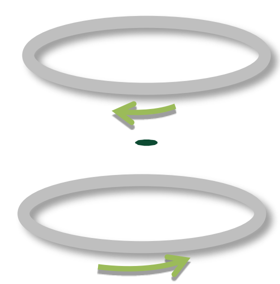
$U_{AC} \propto$ Intensity





magnetic trapping

$U = -\mu\cdot\mathbf{B}$



small complications: intensity, current, position fluctuations; background gas collisions; spontaneous emission

The Mean Field

S-wave interactions can be accounted for with the Huang pseudo-potential

$$V(r) = \frac{4\pi\hbar^2}{m} a\delta^3(\vec{r})$$

- Long range behavior correct $R \propto 1 - a/r$
- Enforces boundary condition $\Psi(r=a) = 0$

This leads to the Gross-Pitaevskii equation (non-linear S.E.)

$$\left[-\frac{\hbar^2}{2m}\nabla^2 + V(\vec{r}) + \frac{4\pi\hbar^2}{m} a|\Psi|^2\right]\Psi = E\Psi = \mu\Psi \qquad \psi = \frac{1}{\sqrt{N}}\phi_0$$

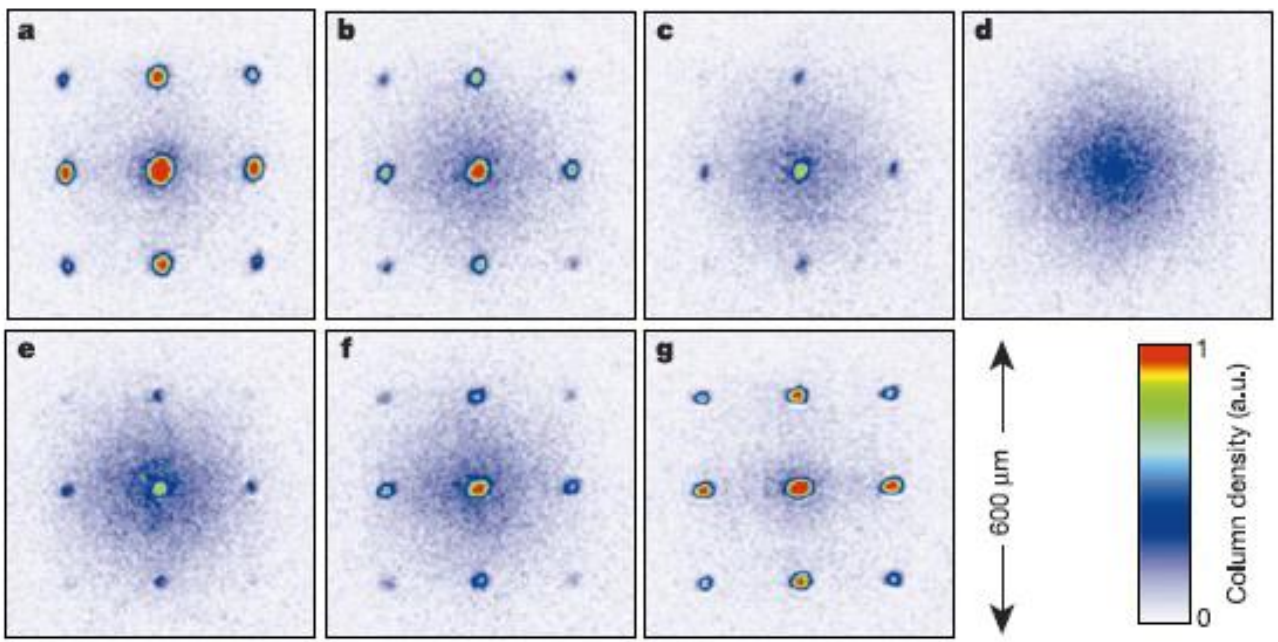
The effects of collisions are in the mean field term.
There is nothing irreversible about it!

The evolution is **integrable**, with excitations of Ψ the only degrees of freedom

Collapse and Revival

Prepare atoms in a superposition of number states at each lattice site

$$|\alpha\rangle(t) = e^{-|\alpha|^2/2}\sum_n \frac{\alpha^n}{\sqrt{n!}} e^{-i\frac{1}{2}Un(n-1)t/\hbar}|n\rangle$$



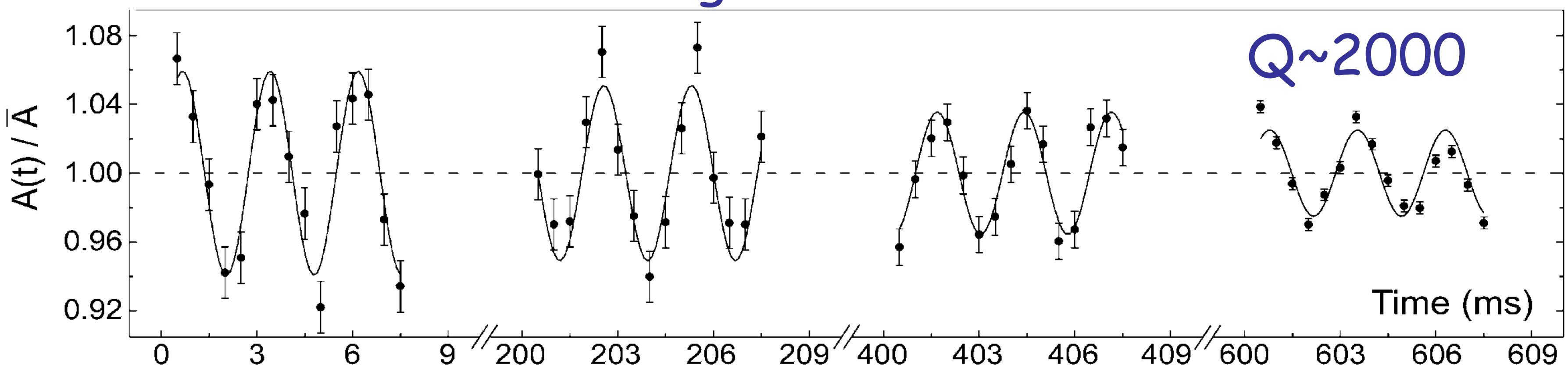
Hansch/Bloch

These collisions are coherent

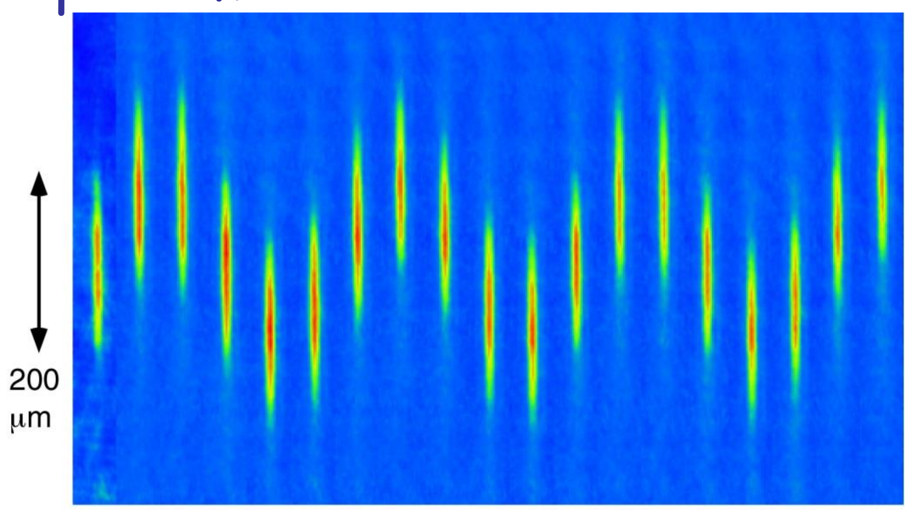
3D BEC Integrable Evolution

Dalibard

breathing mode



dipole mode



10 milliseconds per frame

Ketterle

mean-field frequency scale

$$\frac{4\pi\hbar a}{m} n_{BEC}$$

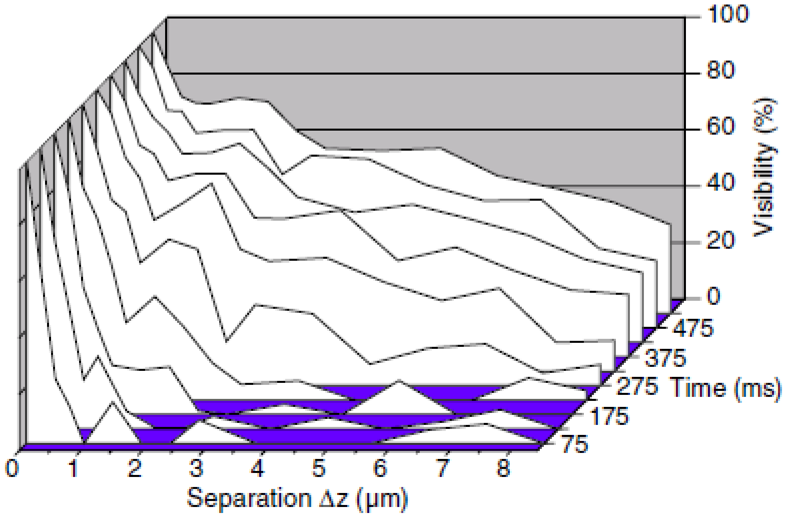
thermal collision rate

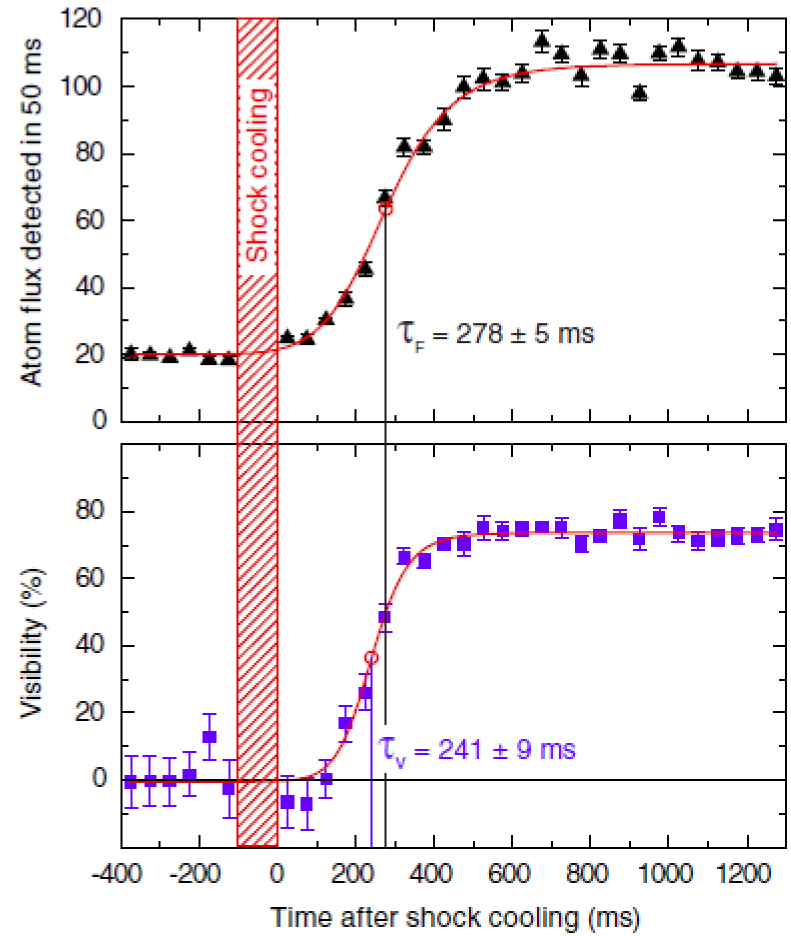
$$n_{th}\pi a^2 v$$

It's GP-simple when

$\lambda_{dB} \gg a\dfrac{n_{th}}{n_{BEC}}$, for short enough time scales

BEC Formation



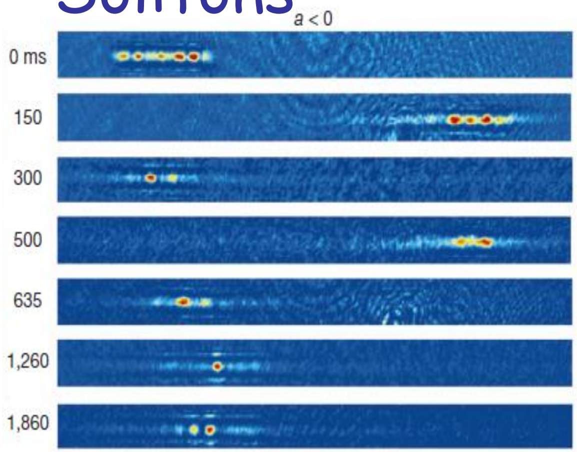


Esslinger

The coherence grows faster than the N_{BEC}

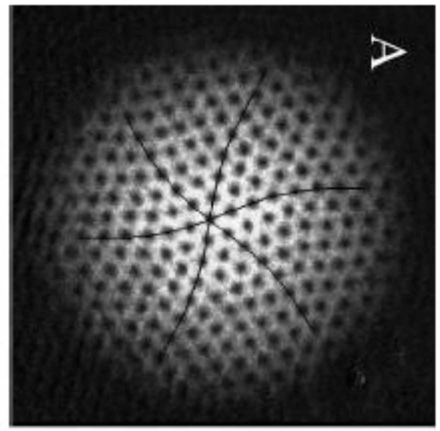
Some Mean Field Non-Eq. Expts.

Solitons



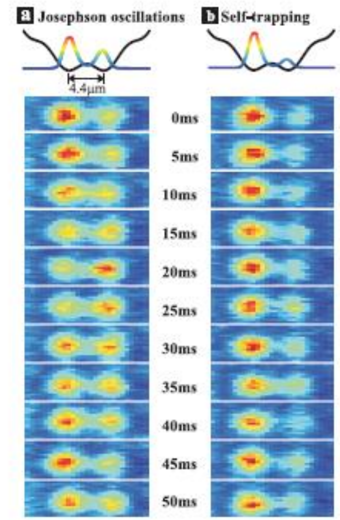
Hulet

Tkachenko oscillations



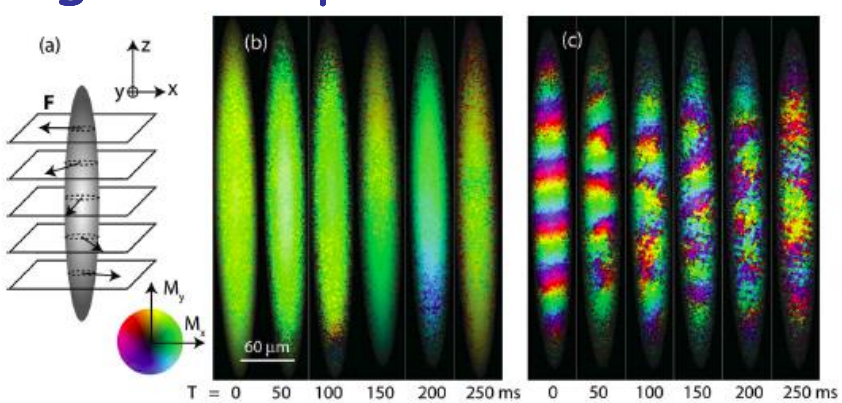
Cornell

Josephson Oscillations



Oberthaler

Magnetic dipole+ mean field



Stamper-Kurn

Also:
Cold neutral plasmas
Rydberg blockaded gases
Cold molecules…

Coupling strength

In a Bose gas, the ratio of two energies, γ, governs the extent of correlations in a quantum gas:

$$E_{int} = \frac{4\pi\hbar^2 a}{m} n_{3D}$$

Mean field energy

$$E_K = \frac{\hbar^2 k_F^2}{2m}$$

Kinetic energy

$$\gamma = \frac{E_{int}}{E_K}$$

$$k_F = \frac{2\pi}{\text{interparticle spacing}}$$

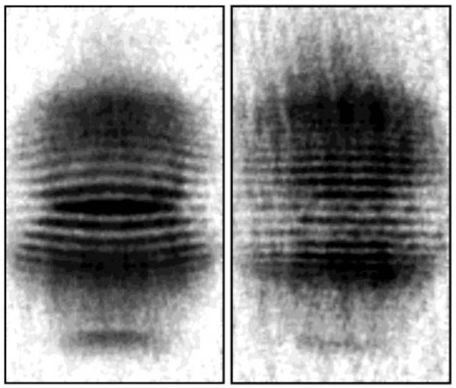
For low γ, it is less energetically costly for single particle wavefunctions to overlap than be separated ➔ Mean field theory & the G-P equation apply: **weak coupling**

For high γ, it is less energetically costly for wavefunctions to avoid each other ➔ **strong coupling**

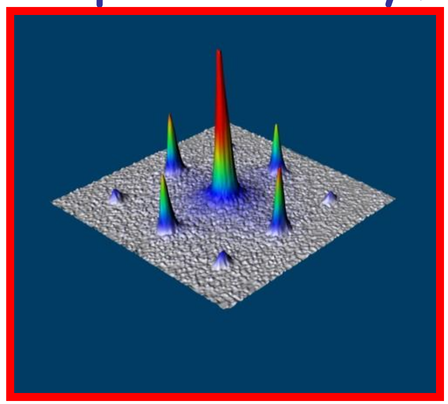
As γ increases, dynamics becomes a quantum many-body problem

Significance of correlations

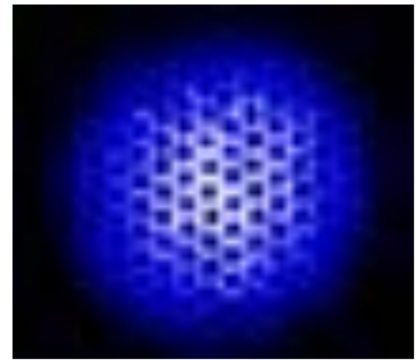
Weak correlations allow long range phase coherence, and macroscopic wavefunction phenomena ➔ Eg.,
interference, superfluidity, vortices



Ketterle



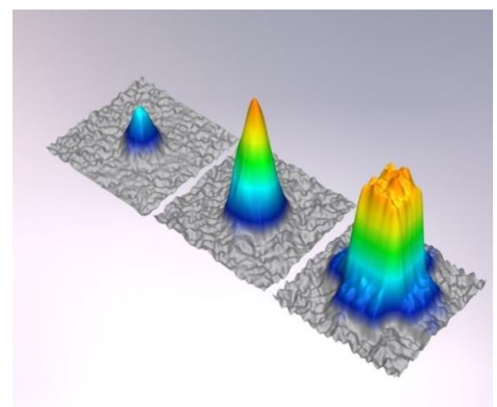
Bloch



Cornell

Semi-classical

Strongly correlated systems are much harder to calculate, especially out of equilibrium

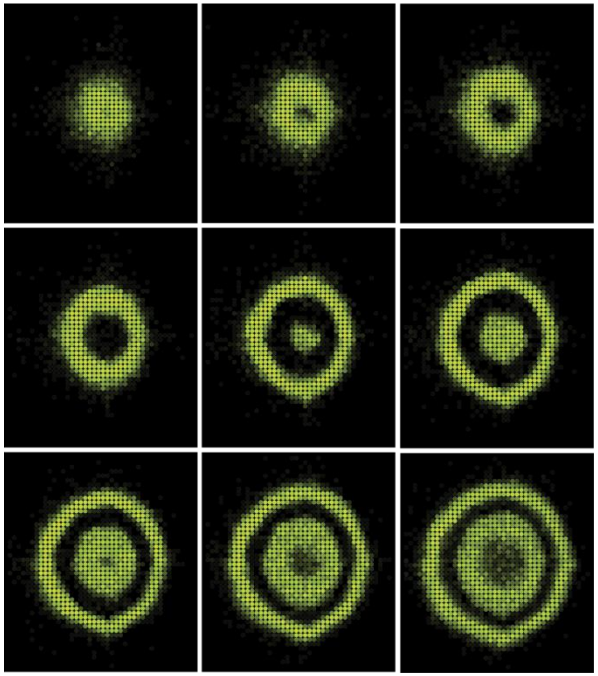


Esslinger

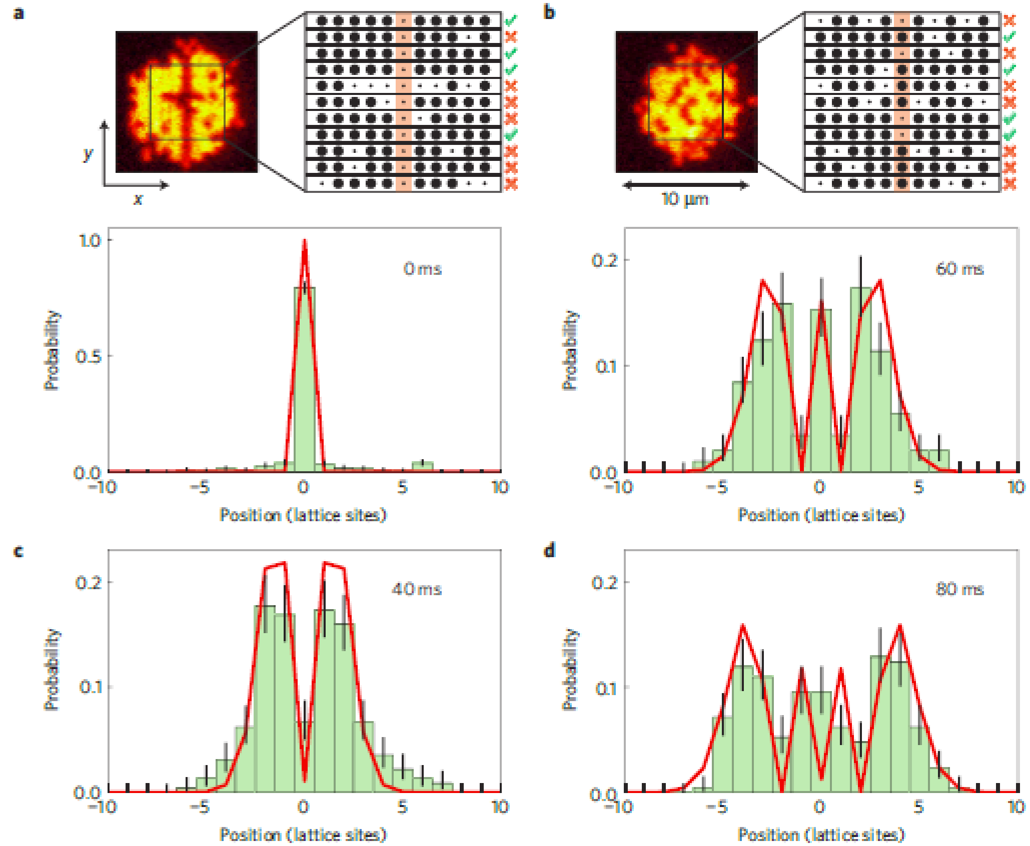
Quantum

$\gamma\uparrow$ for bosons at high density in 3D, in optical lattices, or in reduced dimensions

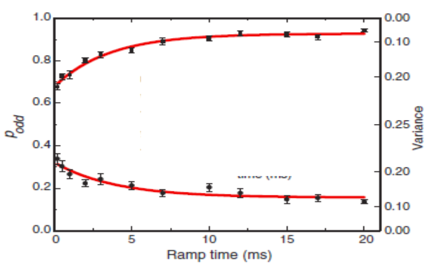
Single atom dynamics



Mobile spin impurities



MI→SF



coherence grows fast

Greiner

Bloch

1D Bose gases with variable point-like interactions

Elliot Lieb and Werner Liniger, 1963: Exact solutions for 1D Bose gases with arbitrary $\delta(z)$ interactions

$$H_{1D} = \sum_{j=1}^{N} -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial z_j^2} + \sum_{i<j} g_{1D}\,\delta(z_i - z_j)$$

A Bethe ansatz approach yields solutions parameterized by

$$\gamma = \frac{m}{\hbar^2}\frac{g_{1D}}{n_{1D}}$$

Lieb & Liniger, Phys Rev **130** 1605 (1963)

Wavefunctions and all other (local and non-local) properties are exactly calculable.

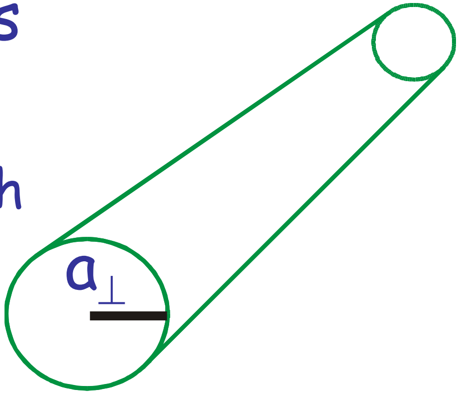
Maxim Olshanii, 1998: Adaptation to real atoms

$$\gamma = \frac{4a_{3D}}{a_\perp^2 n_{1D}}\left(1 - \frac{Ca_{3D}}{a_\perp}\right)^{-1}$$

a_{3D} = 3D scattering length

$a_\perp$ = transverse oscillator length

$C \approx 1.46$



The Lieb-Liniger limits

$\gamma \gg 1$
Tonks-Girardeau gas

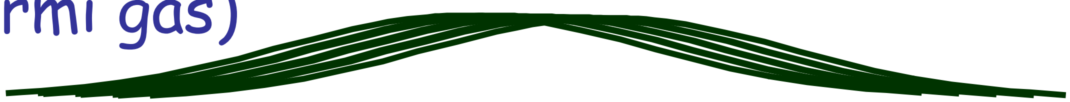
kinetic energy dominates

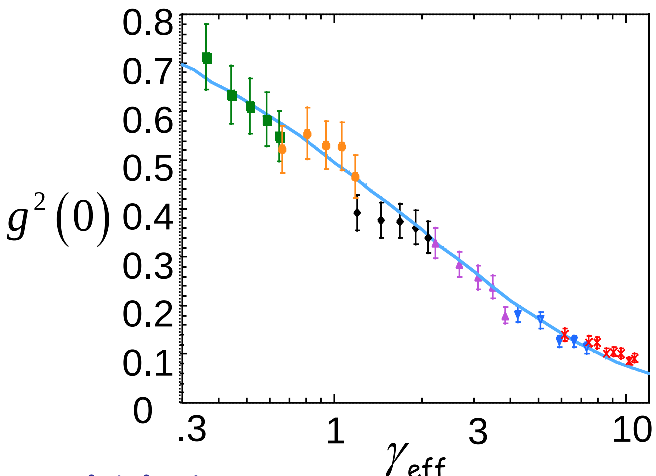
large g_{1D}
low density

$\gamma \ll 1$
mean field theory (Thomas-Fermi gas)

mean field energy dominates

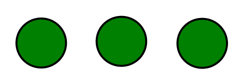
small g_{1D}
high density





Weiss

Integrable systems have N constants of motion
$\Rightarrow$ they cannot thermalize

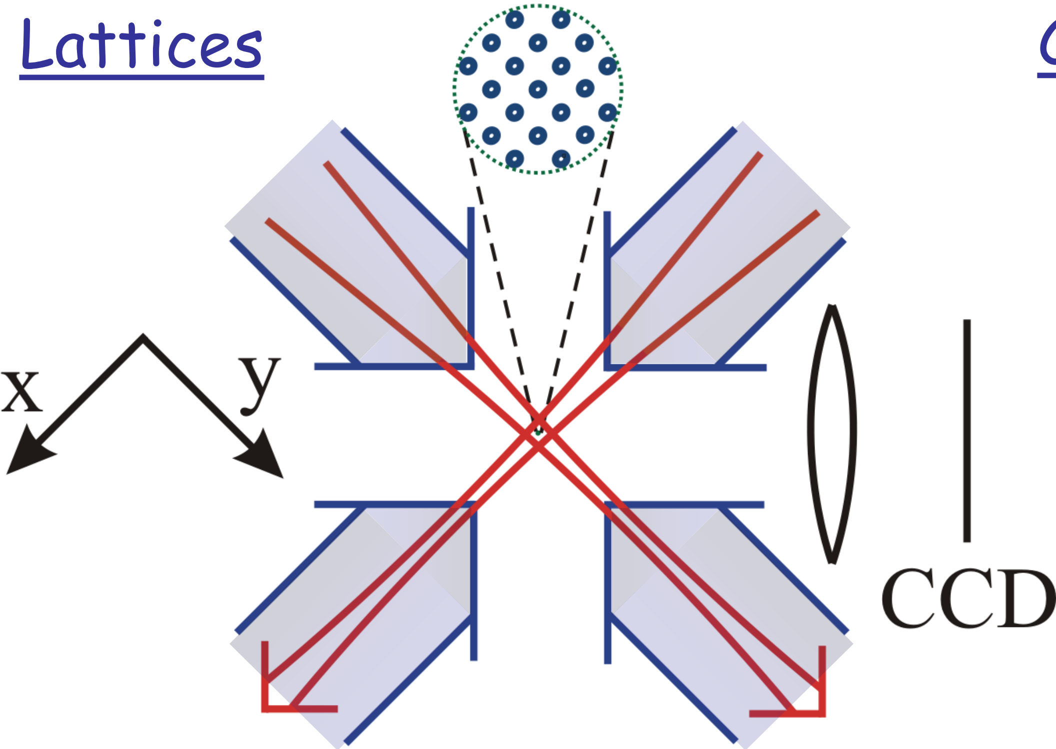


p_a, p_b, p_c  p_a, p_b, p_c

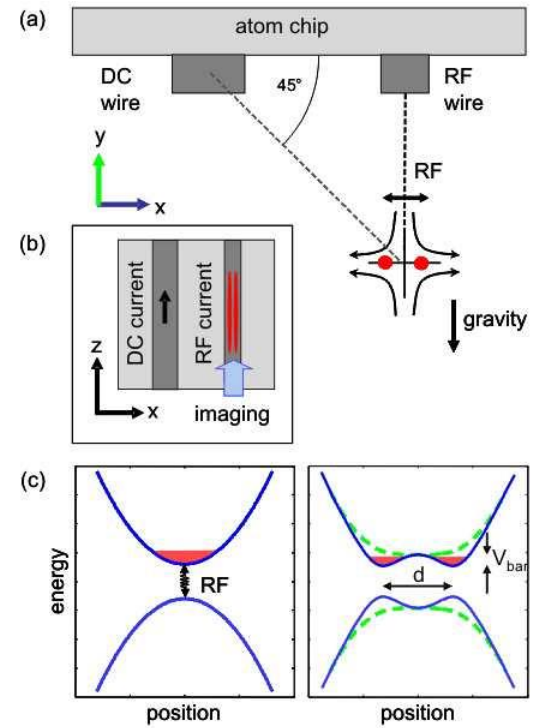
(no "diffractive" collisions)

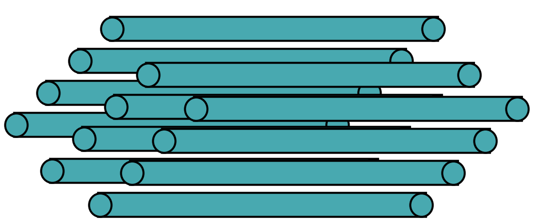
Experimental 1D gases

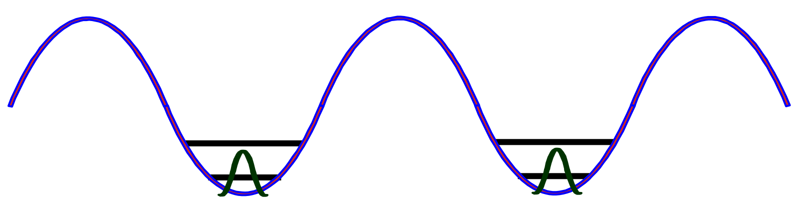
Lattices



Chips



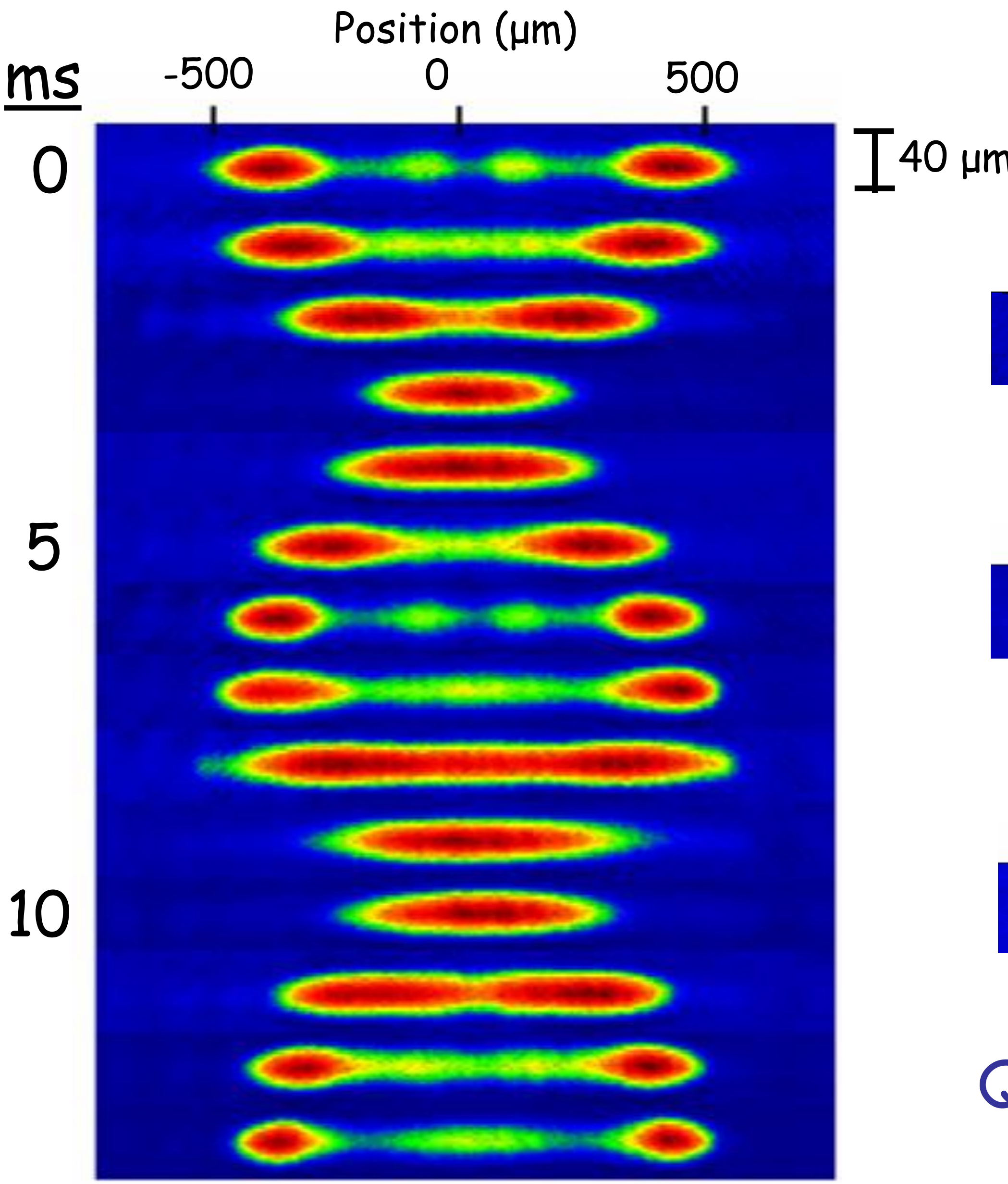


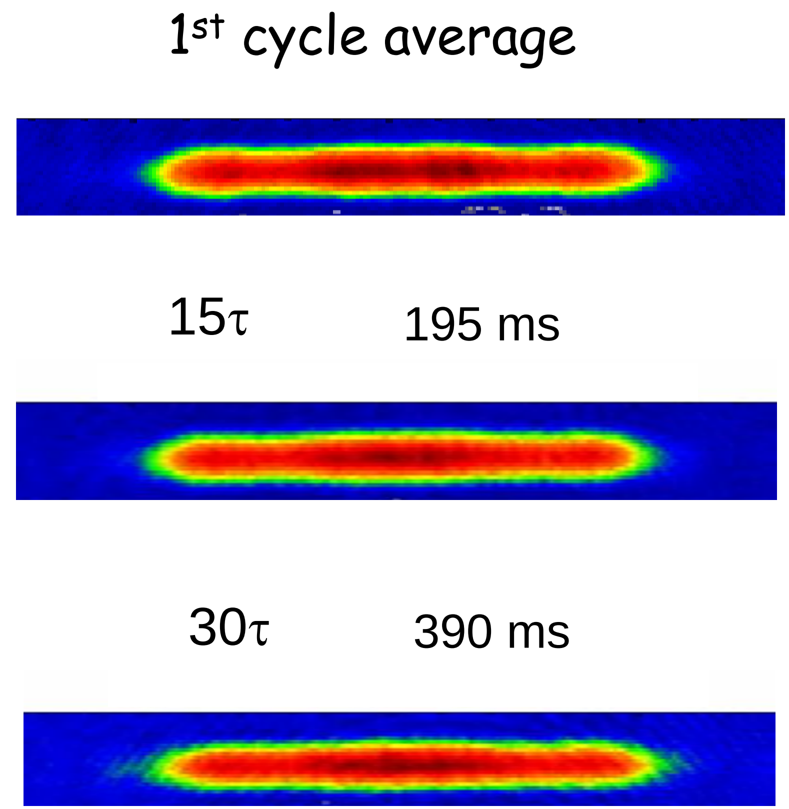


For 1D:all energies < $\hbar\omega_\perp$;
negligible tunneling

1D Evolution in a Harmonic Trap

Weiss



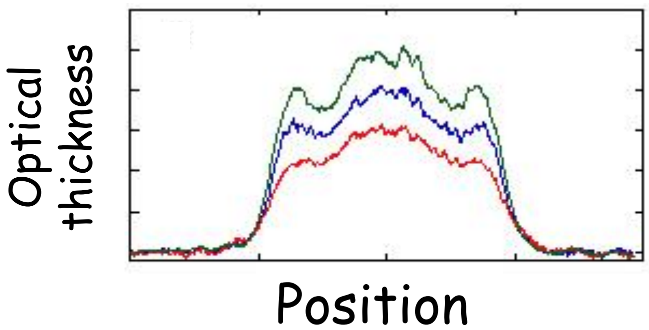


Quantum Newton's Cradles

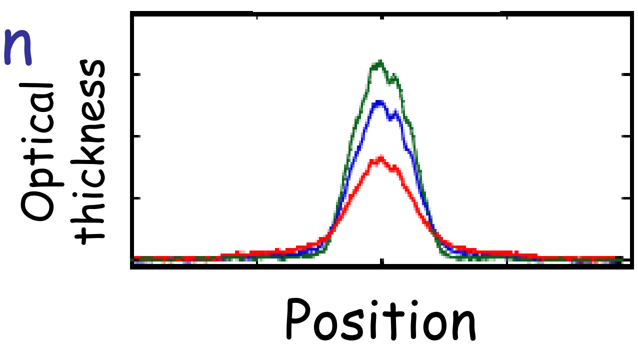
Steady-state Momentum Distributions

1st cycle average
15 τ distribution
40 τ distribution

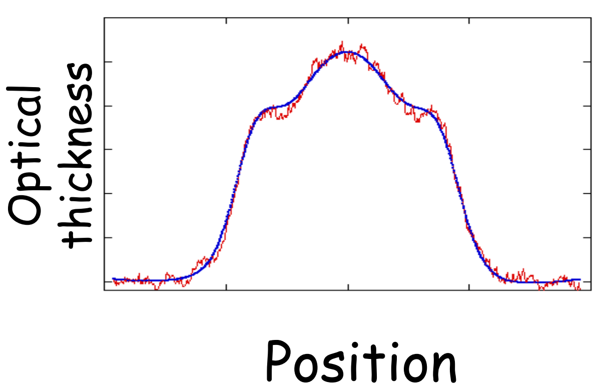
Lattice depth: 63 E_r



Evolution without grating pulses



Project the evolution



After dephasing (**prethermalization**), the 1D gases reach a steady state that is not thermal equilibrium

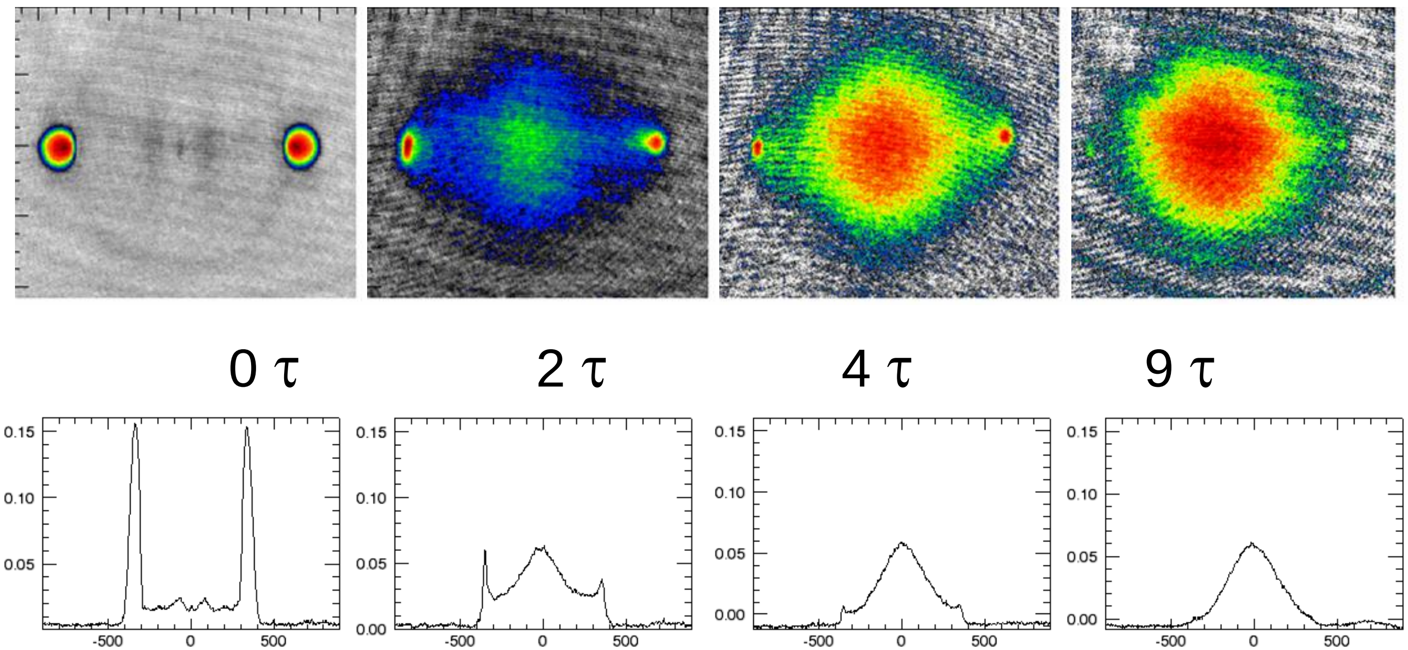
Generalized Gibbs Ensemble- Rigol/Olshanii

Each atom continues to oscillate with its original amplitude

Lower limit: thousands of 2-body collisions without thermalization

What happens in 3D?

Thermalization is known to occur in ~3 collisions.



How does thermalization begin in a slightly non-integrable systems? Will it always eventually thermalize?

Summary

A lot of non-equilibrium physics can be studied with cold atoms.

stronger correlations →

Classical ⟺ Semi-Classical ⟺ Quantum

mechanics

⇩⇧

statistical mechanics

Mean field
integrability is fragile

When integrability is built into the interaction Hamiltonian, the system is robust against thermalization. But how robust?

From many diverse phenomena, perhaps universal behavior can be identified