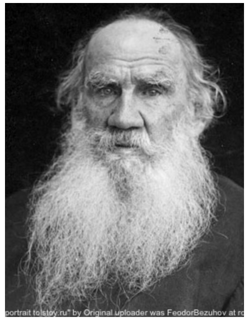
Nonequilibrium phenomena in (homogeneous) quantum gases

All equilibrium systems are alike;
each nonequilibrium one is out of equilibrium in its own way
(Anna Karenina principle in many-body physics)



Leo Tolstoy, 1877

Zoran Hadzibabic
University of Cambridge

EPSRC Engineering and Physical Sciences Research Council

DesOEQ

THE ROYAL SOCIETY

Les Houches, Sep 2021

MARIE CURIE ACTIONS

QUANTERA ERA-NET Cofund in Quantum Technologies

NAQUAS

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Outline

Part 1: Intro

1.1 Some general concepts

1.2 Experimental system(s) and tools

Part 2: Two examples of nonequilibrium stuff

2.1 first one

2.2 second one

Part 3: Three different examples of nonequilibrium stuff

3.1 first one

3.2 second one

3.3 third one

Universality(?)

Physics has always been about explaining a lot with a little. (Eric Cornell)

(something same for…)

Different system parameters (or initial conditions)

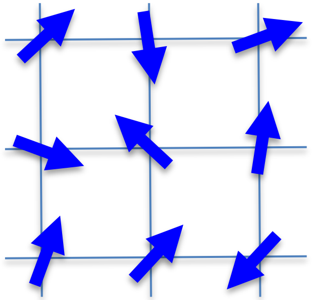
Seemingly different physical processes

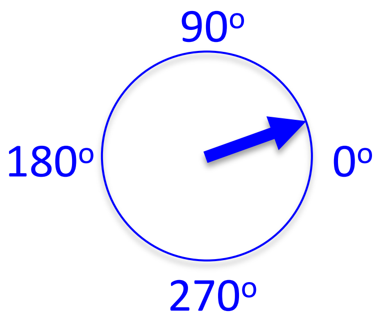
Seemingly disparate physical systems

Equilibrium:

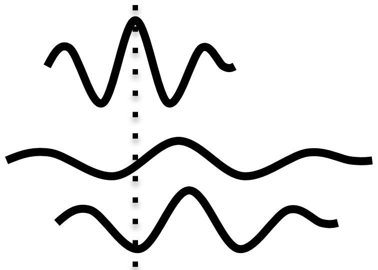
Nonequilibrium:

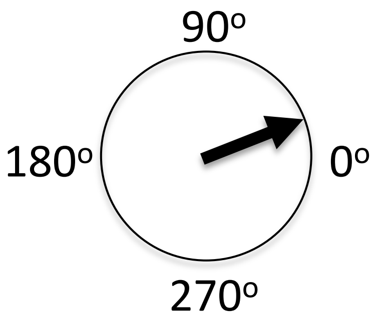
XY (ferro)magnetism





BEC in a gas





Same universality class

Some attempts at classification (for these lectures)

Origins	Contexts	Advanced concepts ("explanations")
Quenched	Critical (phase transition) dynamics	Turbulence
Driven	Turbulence	Nonthermal steady states
"Intrinsic" (dissipation, disorder, integrability…)	Closed systems	Prethermalization
	…	Nonthermal fixed points
		Dynamic scaling
		Universality far from equilibrium
		…
		…

Not in these lectures: lattices, light-cone dynamics, many-body localization, quantum scars, time crystals…

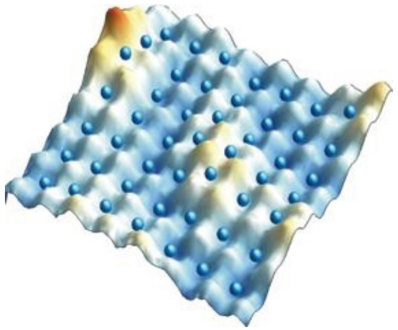
Part 1.2: Quantum gases in general…

Dynamically tuneable – easily induce nonequilibrium dynamics

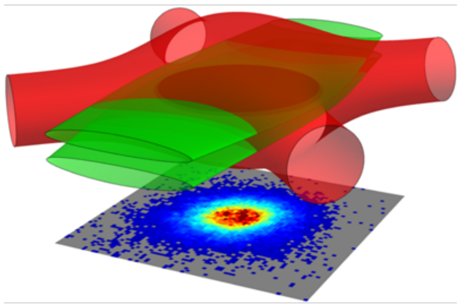
Resolvable timescales – microseconds to seconds

Tuneable speed of the dynamics (interactions)

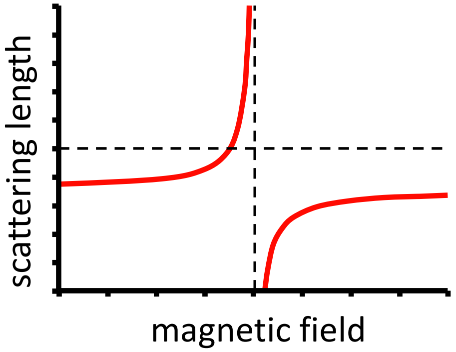
Trapping potentials



Dimensionality



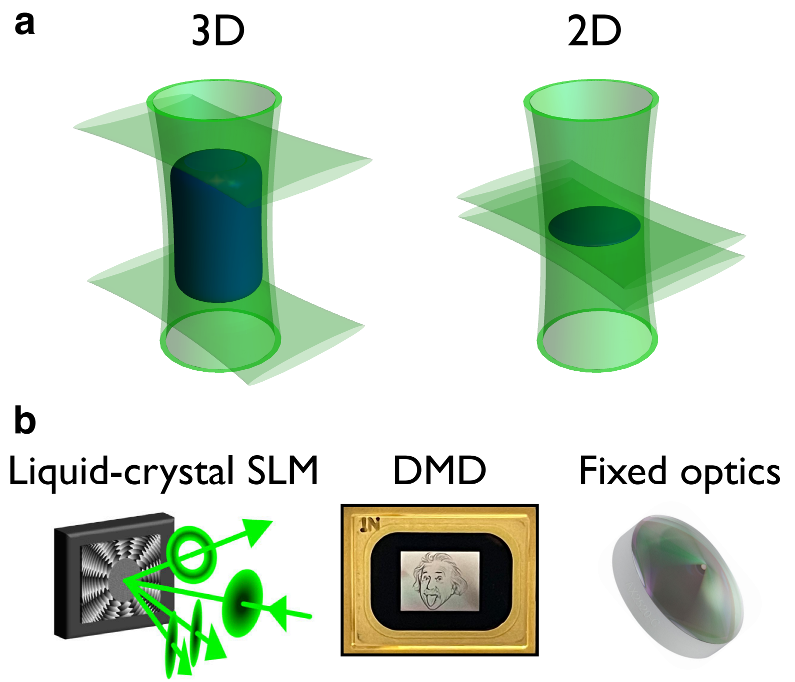
Interactions



Homogeneous quantum gases (in optical boxes)

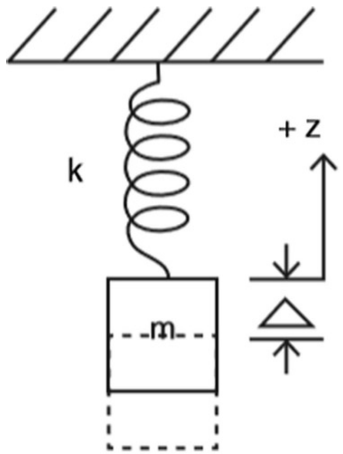
… as opposed to harmonic traps, where we rely on the local density approximation (LDA)

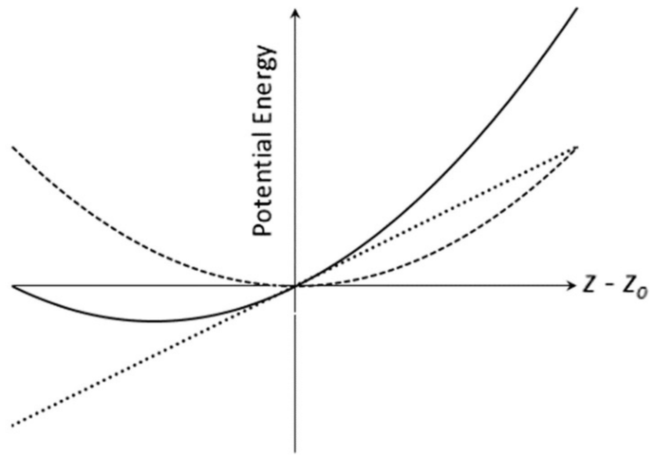
Review: Nir Navon, Rob P. Smith, ZH, arXiv:2106.09716



Blue-detuned laser beams are repulsive

Do you know this?





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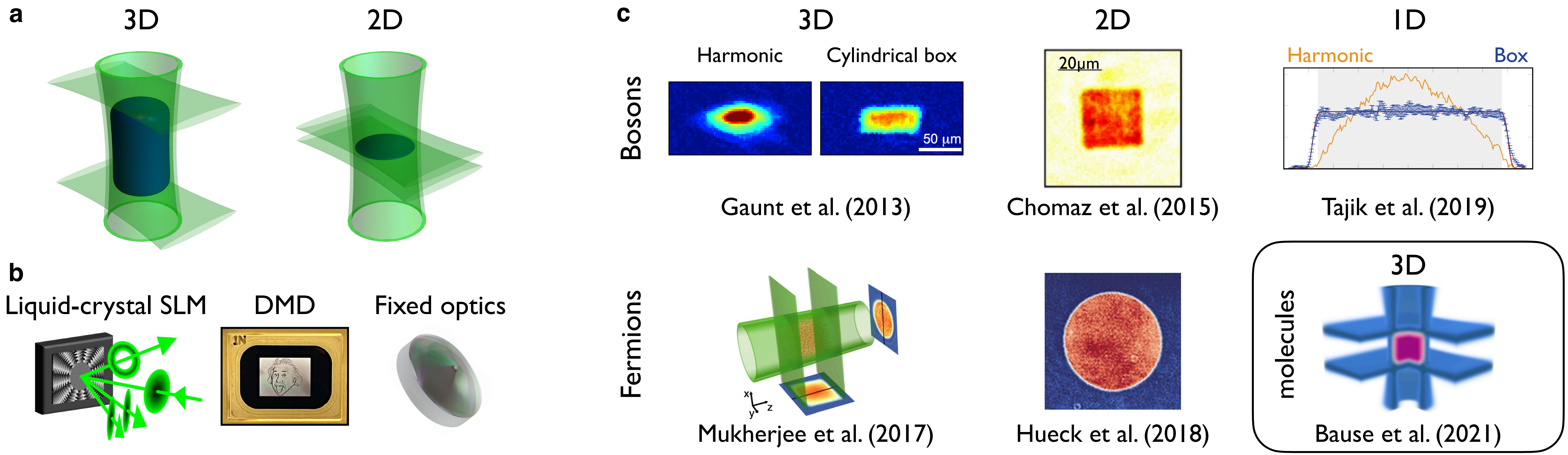
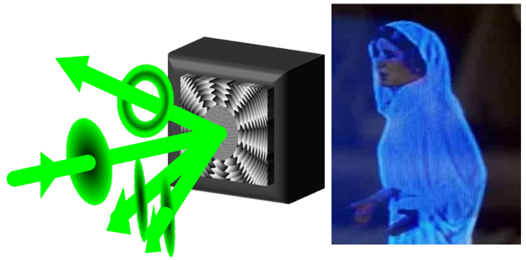
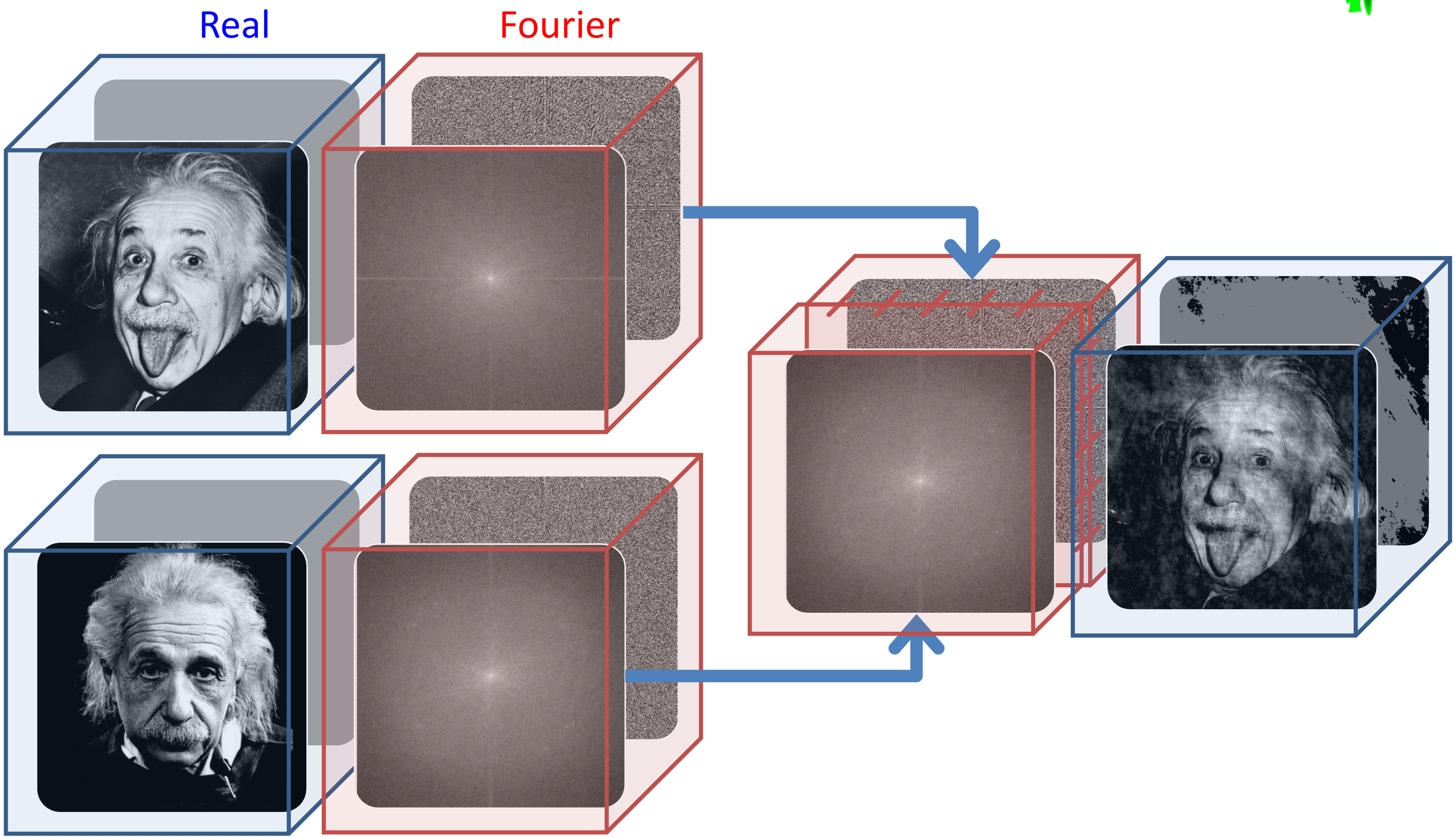


- Diverging correlations
- Some things naturally in momentum space
- Fast local density-dependent processes

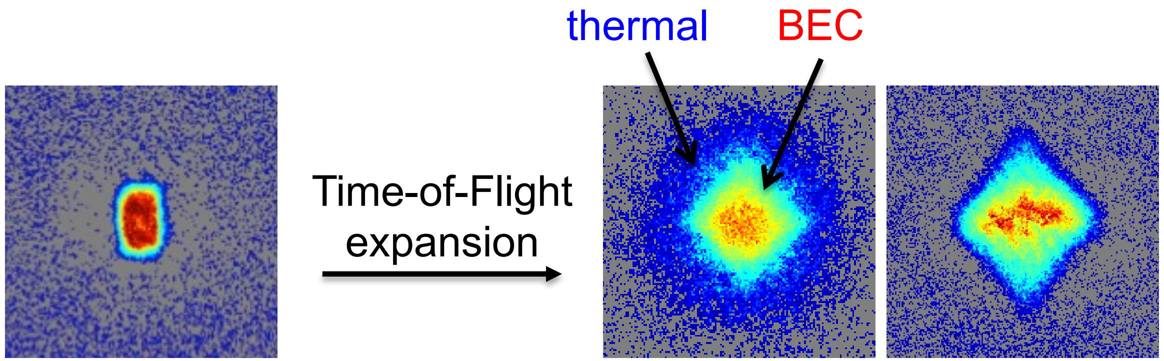
Phase dominance in digital holography



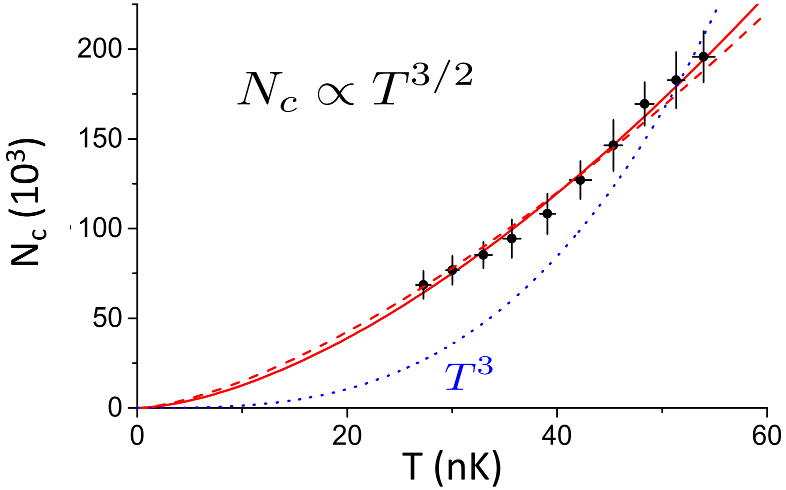


BEC in a box

Simplest quantitative diagnostic:



Critical point (weak interactions):



$$N_{ex} = \int \frac{g(\varepsilon)\, d\varepsilon}{e^{\beta(\varepsilon-\mu)} - 1}$$

$g(\varepsilon)$ – density of states

$\mu \to 0$ $$N_c(T) = \int \frac{g(\varepsilon)\, d\varepsilon}{e^{\varepsilon/kT} - 1}$$

3D harmonic $g(\varepsilon) \propto \varepsilon^2 \Rightarrow N_c \propto T^3$

3D box $g(\varepsilon) \propto \sqrt{\varepsilon} \Rightarrow N_c \propto T^{3/2}$

Question for the audience

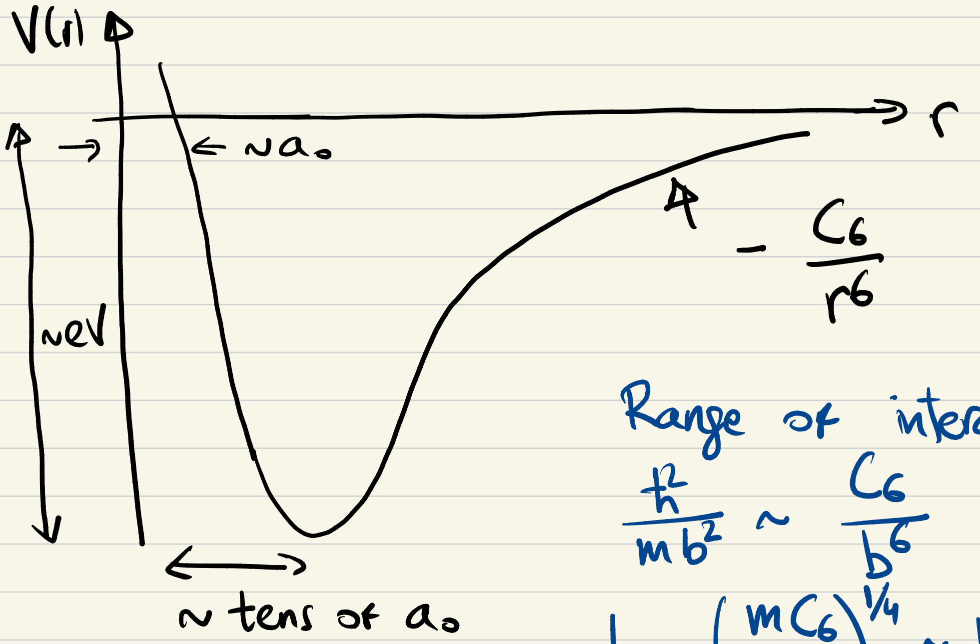
In some trap, the BEC critical temperature for a million (non-interacting spinless bosonic) atoms is 400 nK.

If there are 2 million atoms in the same trap at 400 nK, what is the condensed fraction?

Crash course in tuneable s-wave interactions (very sloppy)

Professional stuff: Jean Dalibard, Collisional dynamics, Varenna 1998
http://www.phys.ens.fr/~dalibard/publications/varenna98.pdf
Cheng Chin et al., Feshbach resonances, RMP 2010

Neutral atoms, van der Waals



Range of interaction, b:

$$\frac{\hbar^2}{m b^2} \sim \frac{C_6}{b^6}$$

$$b \sim \left(\frac{m C_6}{\hbar^2}\right)^{1/4} \sim 100\, a_0$$

c.f. @ T_c: $\lambda = \frac{h}{\sqrt{2\pi m k T}} \sim d = n^{-1/3} \sim 10^4 a_0$

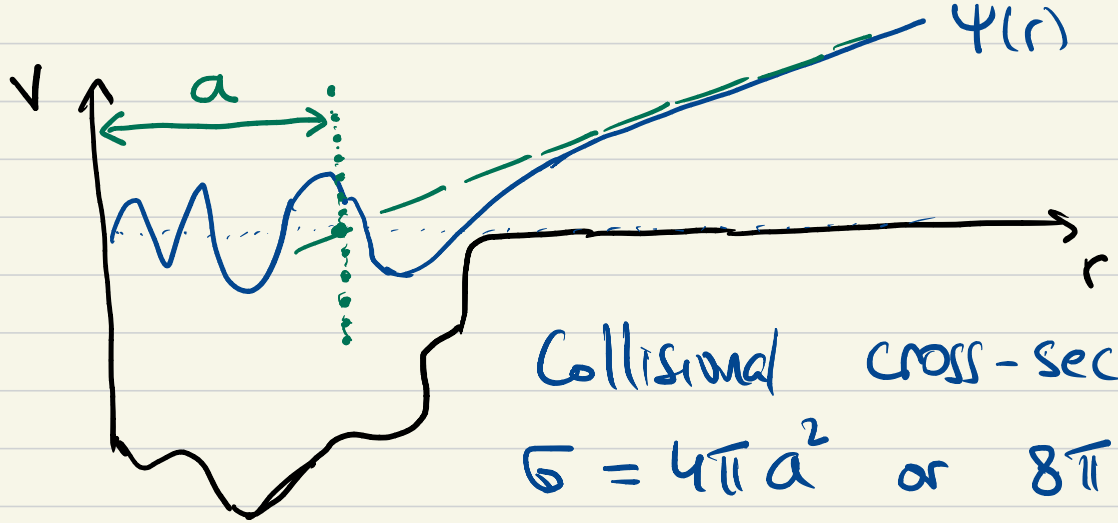
$b \ll \lambda, d \Rightarrow$ dilute gas, only s-wave

$$U(\mathbf{r}) = U_0\, \delta(\mathbf{r})$$

So, e.g., mean-field potential in a BEC $U_0\, n$

Crash course in tuneable s-wave interactions (very sloppy)

S-wave scattering length, a



Collisional cross-section

$$\sigma = 4\pi a^2 \quad \text{or} \quad 8\pi a^2$$

$$U_0 = \frac{4\pi\hbar^2}{m} a \quad \text{or} \quad \frac{8\pi\hbar^2}{m} a$$

$a > 0$ repulsive

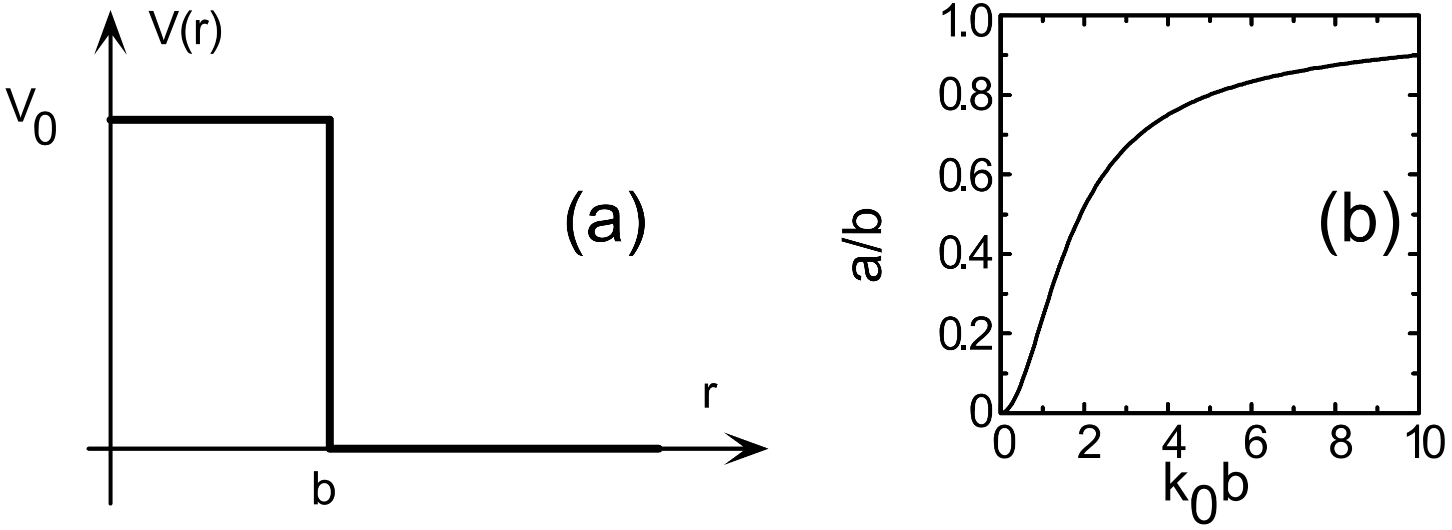
$a < 0$ attractive

a vs. b ?

$a = b$?

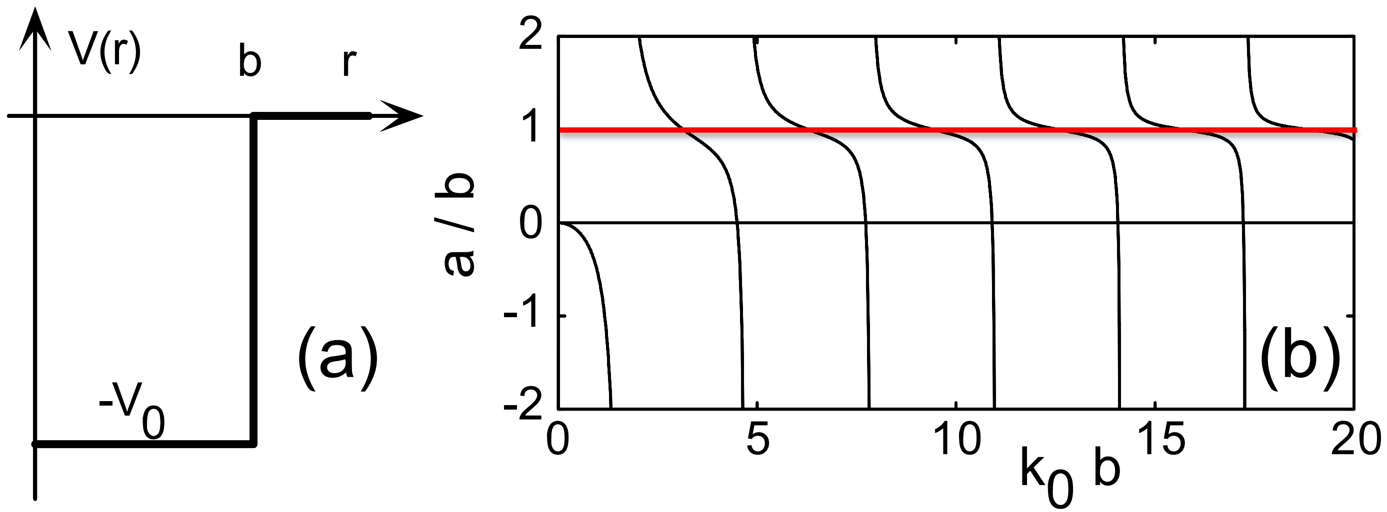
Crash course in tuneable s-wave interactions (very sloppy)

Repulsive potential:



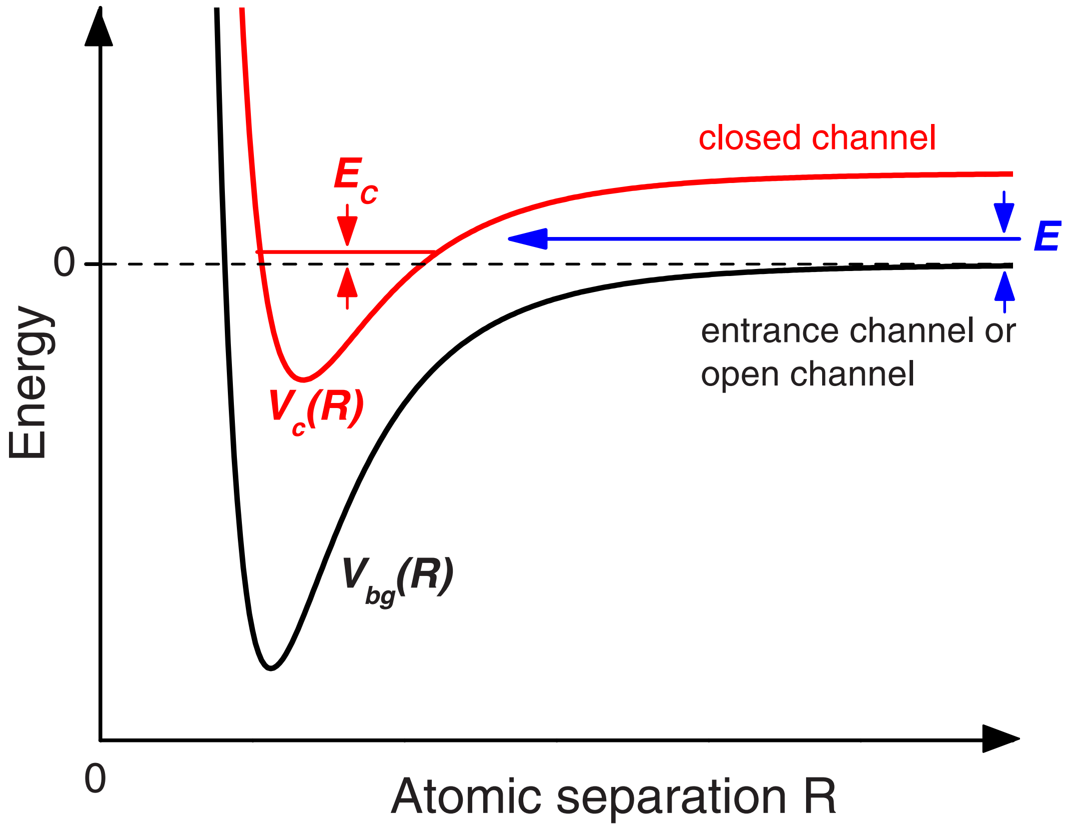
$$k_0 = \sqrt{mV_0}/\hbar$$

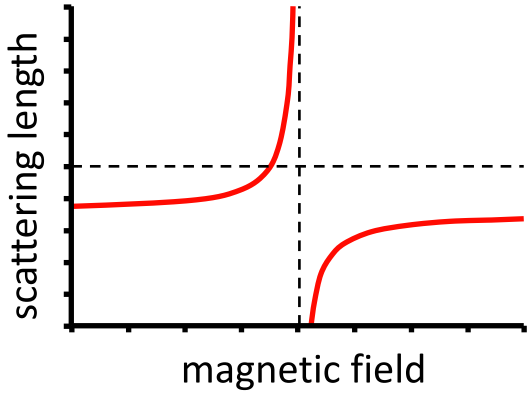
Attractive potential:



Crash course in tuneable s-wave interactions (very sloppy)

Feshbach resonance(s)… the 2-channel model





$$a(B) = a_{\mathrm{bg}}\left(1 - \frac{\Delta}{B - B_0}\right)$$

WARNING:

3-body loss rate (simplest theory, bosons)

$$\dot{N}/N \propto -N^2 a^4$$

Outline

Part 1: Intro

1.1 Motivation, universality vs. stamp collecting

1.2 Experimental system(s) and tools

Part 2: Two unintentionally-nonequilibrium stories

2.1 Weak interactions + losses

2.2 Strong interactions + quench + losses (example of prethermalization)

Part 3: Three related intentionally-nonequilibrium stories

3.1 Critical dynamics

3.2 Turbulence

3.3 Universality far from equilibrium