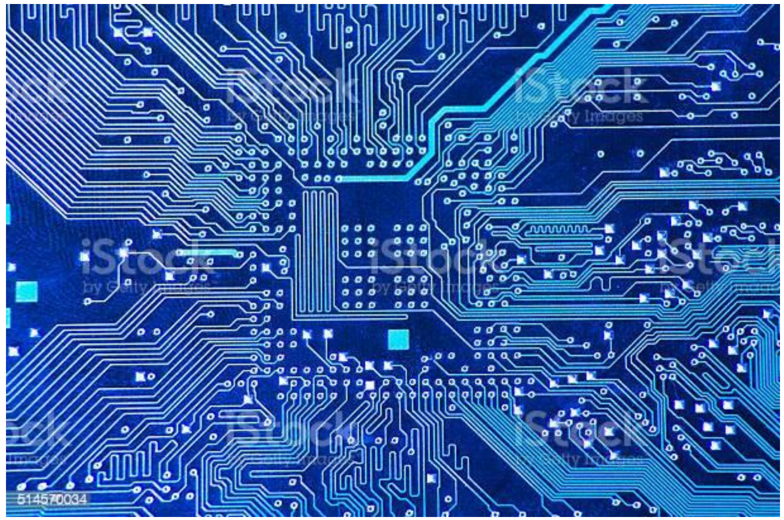
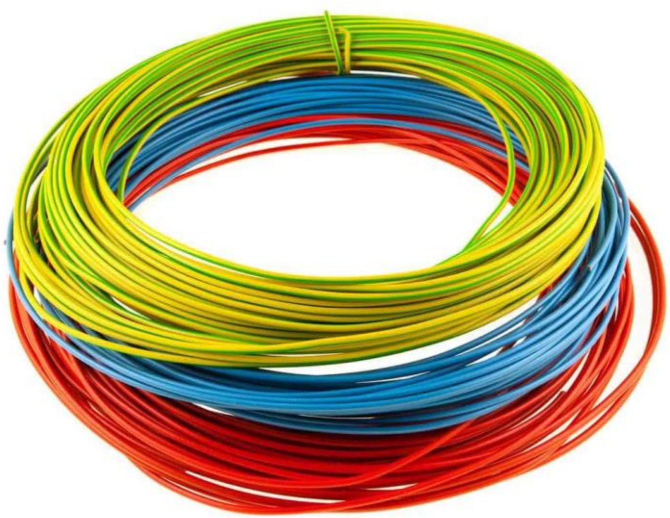
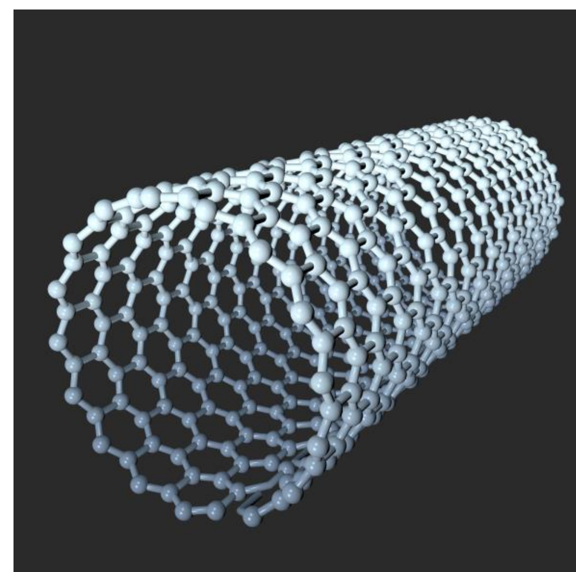
Ultracold fermions in quantum wires

Frédéric Chevy

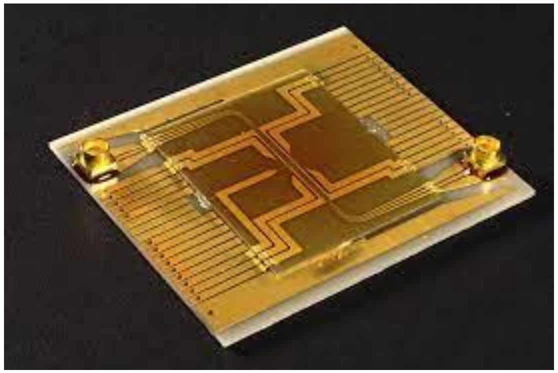
Quantum wave-guides in atomtronics

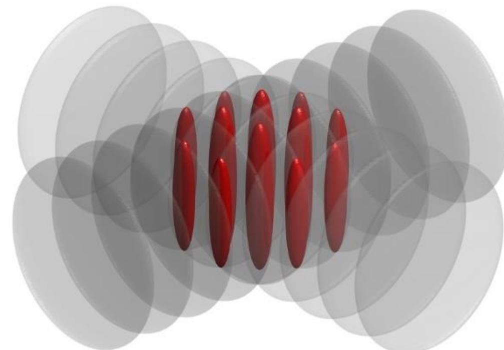






Cold atoms in 1D





- Bosons

  J. Schmiedmayer (Vienna), I. Bouchoule (IOGS), D. Weiss (PennState), H.C. Nagerl (Innsbruck)…

- Fermions

  T. Esslinger (ETH), R. Hulet (Rice)…
  I. Bloch (Munich), M. Greiner (Harvard) – lattice.

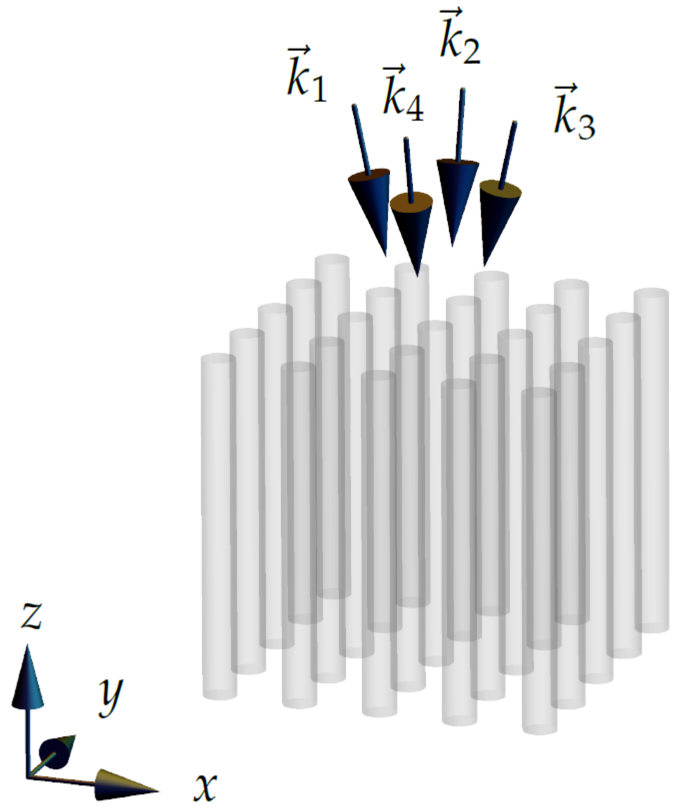
THERMOMETRY OF A 1D FERMI GAS

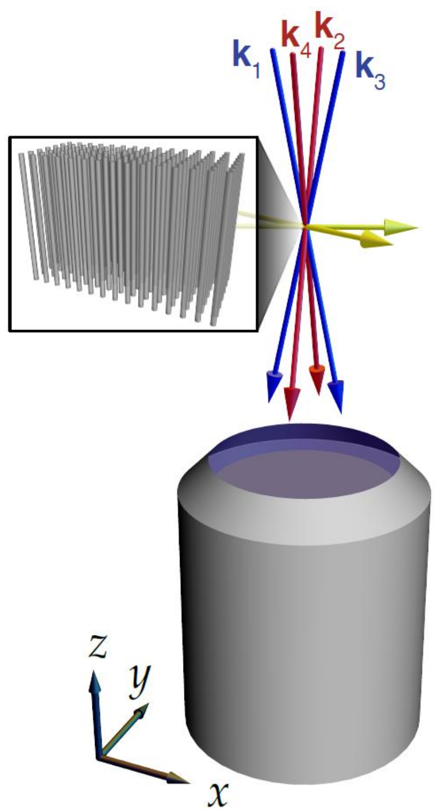
C. De Daniloff, M. Tharrault, C. Enesa, T. Reimann, J. Struck, C. Salomon

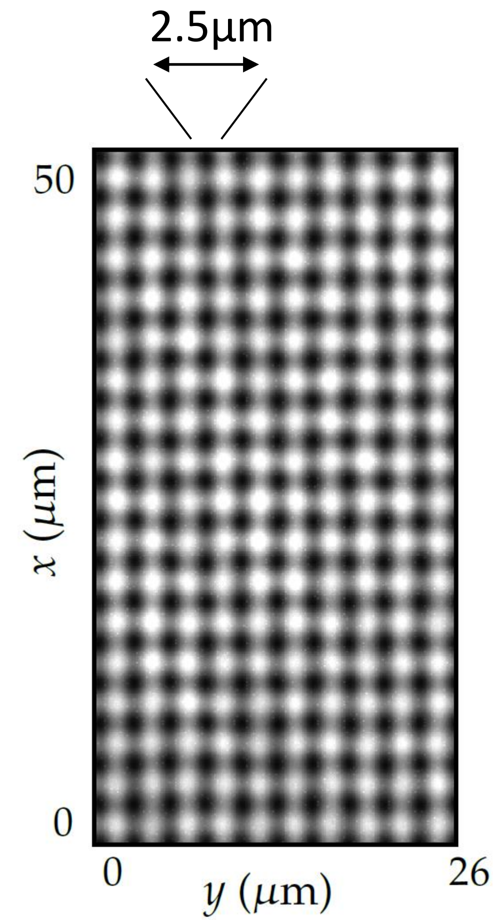
De Daniloff et al., PRL **127**, 113602 (2021)

FERMI GASES IN OPTICAL LATTICES

1D Fermi gas@ENS

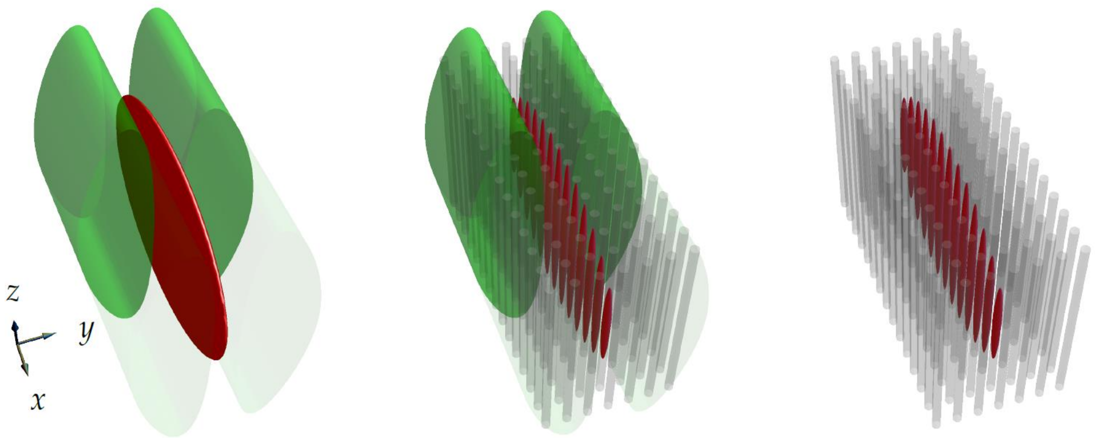


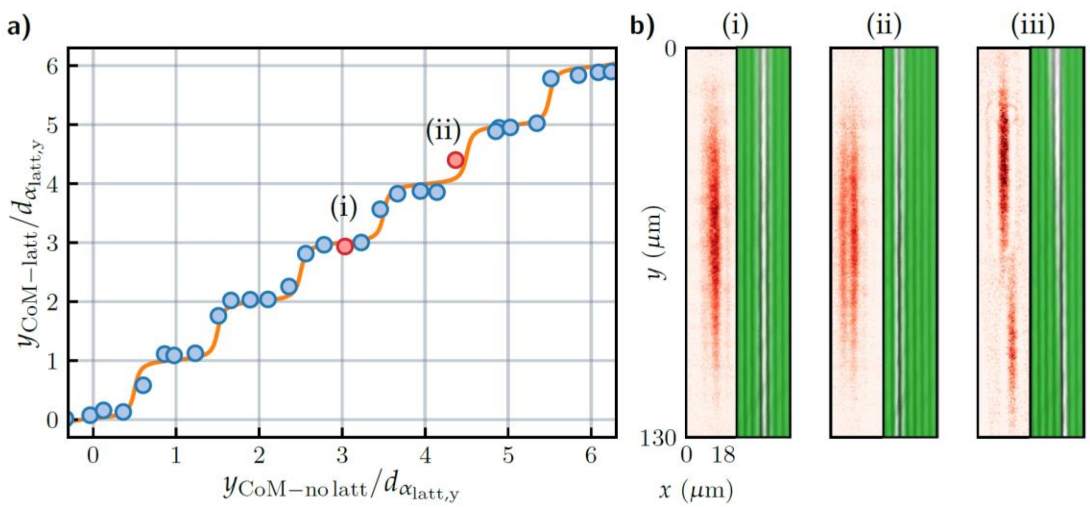




Loading a single layer

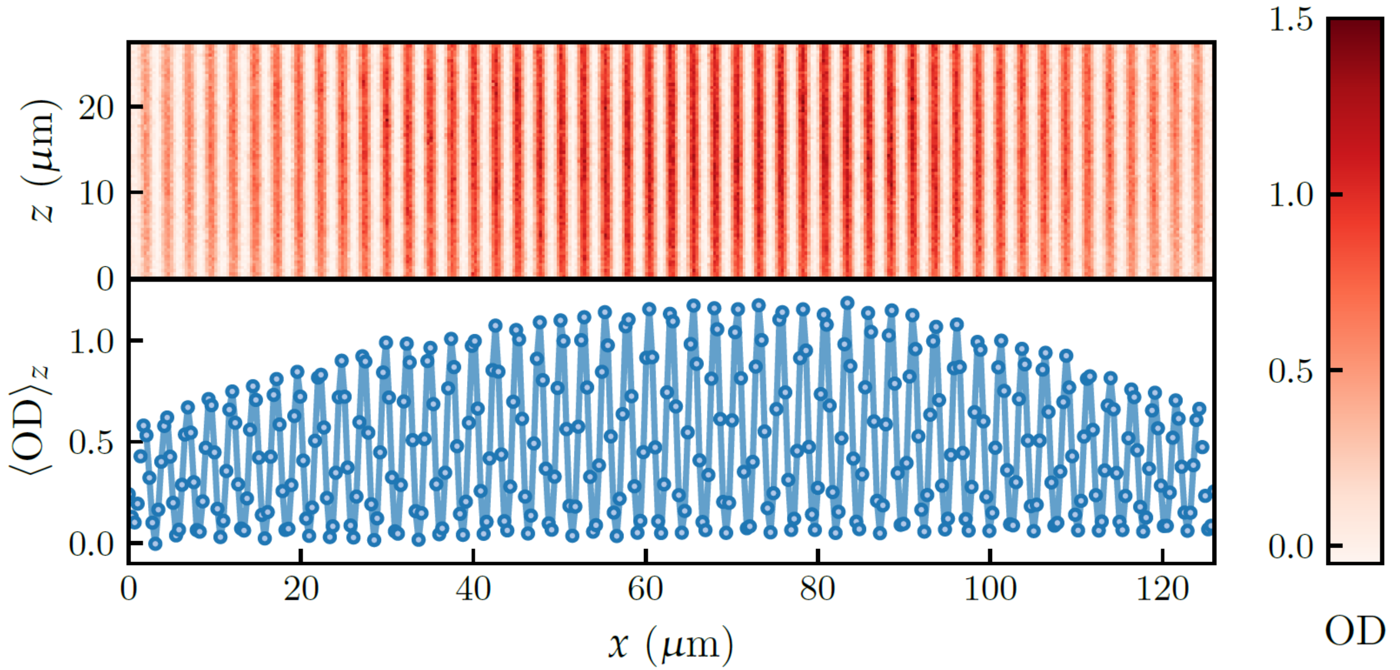
Goal: load a single layer of tube in order to get rid of line of signt integration.
Compression using a TEM(0,1) green laser beam.





Imaging an array of one dimensional ^{40}K atoms

Initial condition before loading: $N \approx 2 \times 10^4$, $T/T_F \approx 0.15$



Optical resolution ≈1μm

Approximately harmonic confinement in all three directions $\omega_z = 2\pi \times 100$ Hz

$\omega_\perp = 2\pi \times 20$ kHz

THE IDEAL FERMI GAS

Global thermodynamics

In a box, thermodynamic quantity:
(T, N, V)

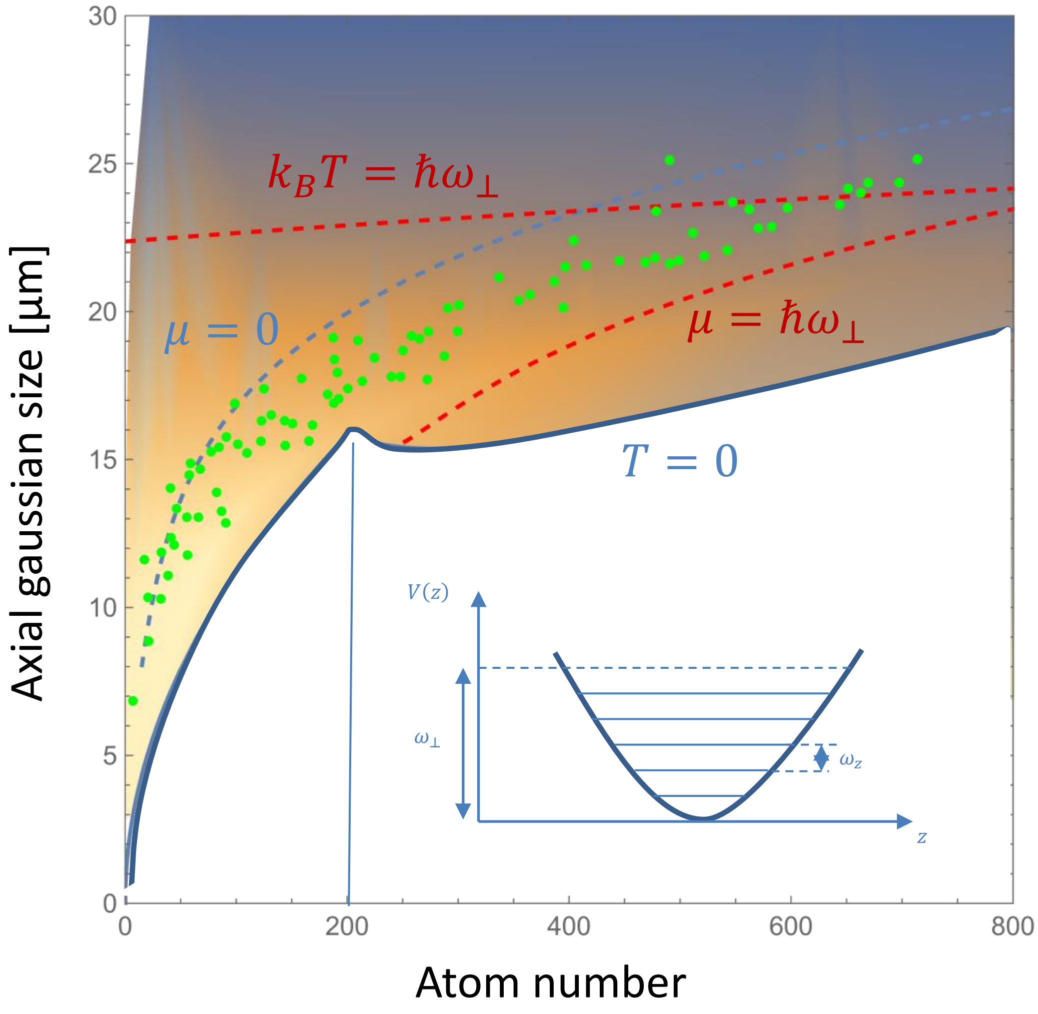
In a harmonic potential: $(T, N, \langle z^2 \rangle)$

$$\Omega = \frac{(k_\beta T)^2}{\hbar\omega_z} \sum_{n=0}^{\infty} (n+1) Li_2\left(-\zeta e^{-\beta\hbar\omega_\perp n}\right)$$

$$N = -\frac{\partial\Omega}{\partial\mu}$$

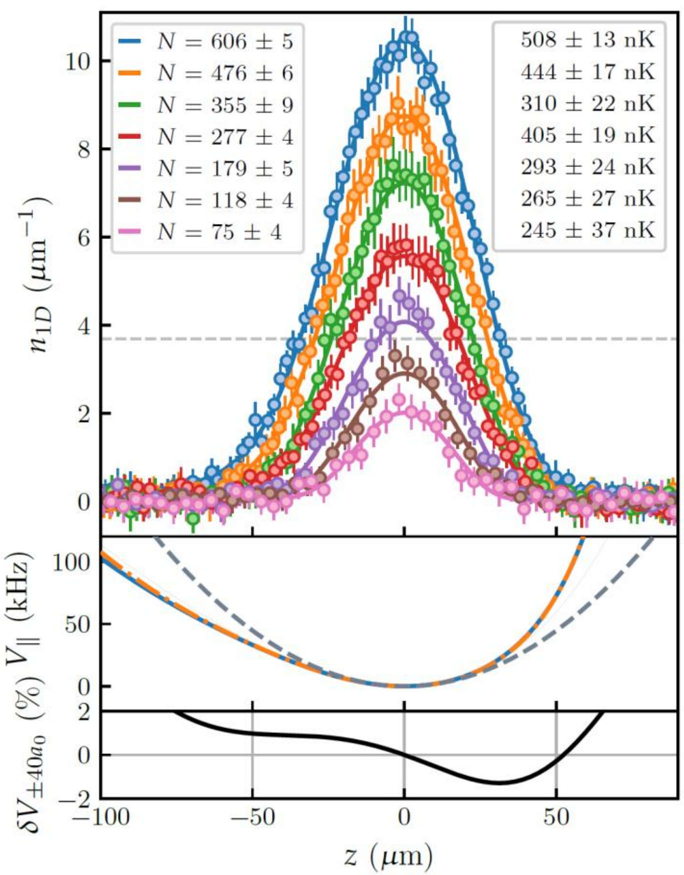
$$\langle z^2 \rangle = \frac{2}{mN} \frac{\partial\Omega}{\partial\omega_z^2}$$

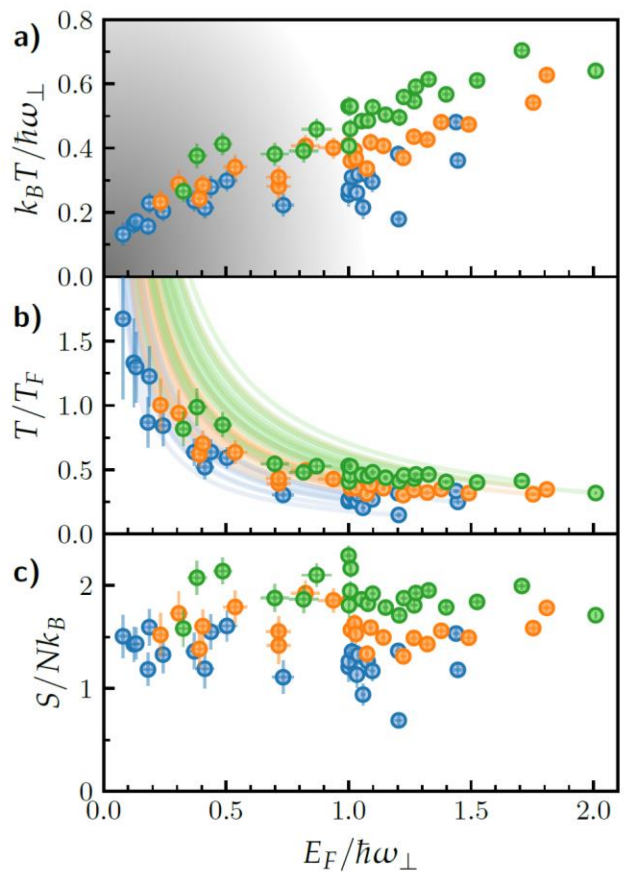
(Trapping spring constant = pressure)

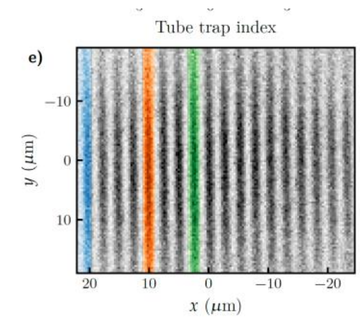


Local density approximation

For an arbitrary potential $V(z)$: $n_{1D}(z) = -\frac{1}{\lambda_{th}} \sum_{n=0}^{\infty} Li_{1/2}\left(-\zeta e^{-\beta V(z)}\right)$



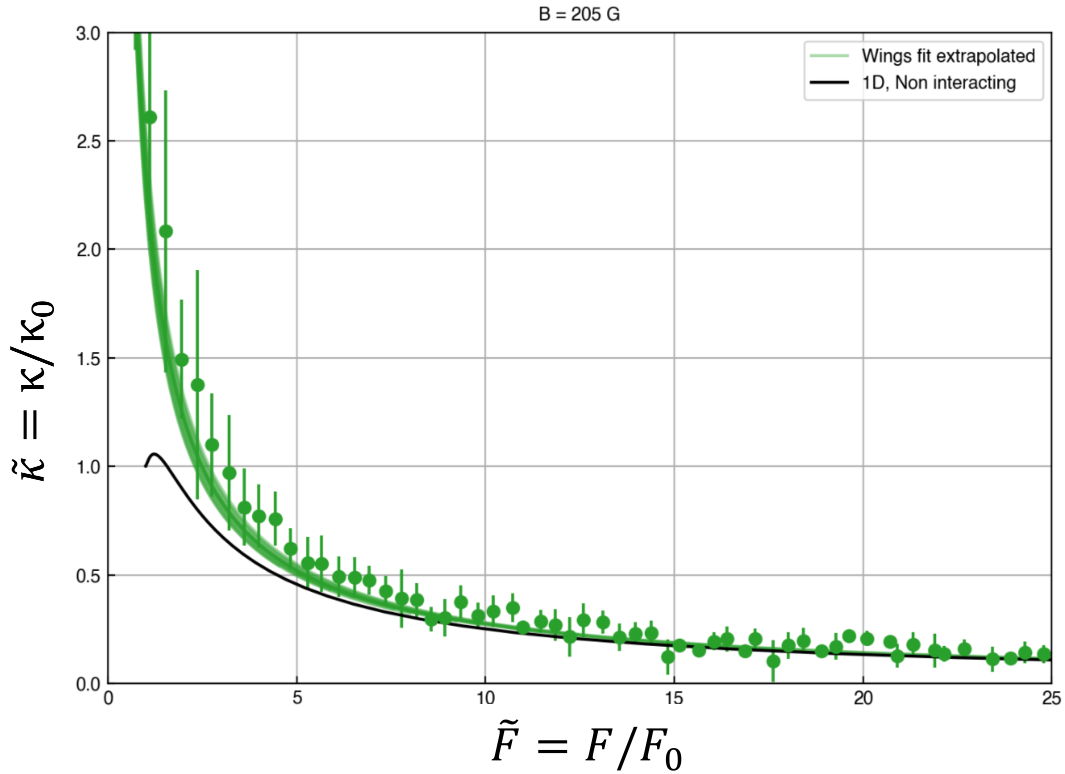




Ramping up interaction

Reconstructing the equation of state of a strongly correlated system using LDA (J. Ho 2004, ENS 2010, MIT 2012, Swinburen 2015…)

$B = 205G;\ a_{3D} \approx -270a_0$



Experimental data: $n(z), V(z)$

LDA: $\mu(z) = \mu_0 - V(z)$

Compressibility: $\kappa = \frac{1}{n^2}\frac{dn}{d\mu} = -\frac{1}{n^2}\frac{dn}{dV}$

Gibbs-Duhem: $dF = n\,d\mu = -ndV$

Equation of state: $\frac{T}{T_F} = \left(\frac{T}{T_F}\right)_0 \exp\left[\frac{2}{3}\int \frac{d\tilde{F}}{\tilde{F}-\tilde{\kappa}}\right]$

$\frac{k_B T}{\hbar\omega_\perp} = 0.4$

WHEN IS 1D REALLY 1D ?

G. Orso, L. Barasic. Work in progress

1D, quasi-1D and universality

$$H = \sum_i \frac{\boldsymbol{p}_i^2}{2m} + \frac{m\omega_\perp^2}{2}\rho^2 + \sum_{i,j} V(\boldsymbol{r}_i - \boldsymbol{r}_j)$$

Characterized by a two dimensionless numbers $1/k_F\, a_{3D}$, $E_F/\hbar\,\omega_\perp$

Yang-Gaudin's Hamiltonian $H_{YG} = \sum_i \frac{p_i^2}{2m} + g_{1D} \sum_{i,j} \delta(z_i - z_j)$

Characterized by a single dimensionless parameter $\gamma = \frac{m}{\hbar^2}\frac{g_{1D}}{n}$

Is it sufficient to have $k_B T \ll \hbar\omega_\perp$ and $E_F \ll \hbar\omega_\perp$ to be able to describe the system using Yang-Gaudin's Hamiltonian?

The 2-body problem in a quantum wire

In 1D (2-body Yang-Gaudin): g_{1D}=- $\hbar^2/ma_{1D}$

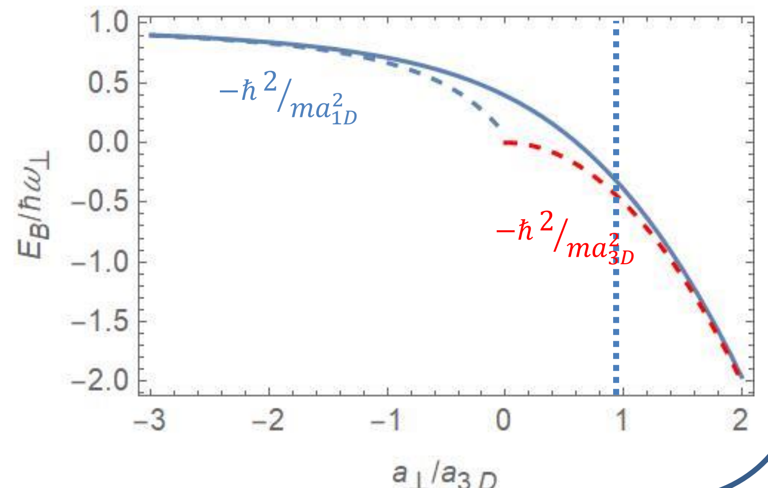
- Scattering amplitude: $f = 1/(1 + ika_{1D})$,.
- There is a bound state of energy $-\hbar^2/ma_{1D}^2$ when a_{1D} is positive (g_{1D}<0).

In a quantum wire (Olshanii, PRL 1998):

- Low energy scattering $f = \frac{1}{1+ika_{1D}}$, $a_{1D} = -\frac{a_\perp^2}{2a_{3D}}\left(1 - A\frac{a_{3D}}{a_\perp}\right)$ (confinement induced resonance).

- There is *always* a bound state:

Breakdown of 2-body universality relating the energy of the bound state and the low-energy scattering amplitude in the strongly attractive regime.



Transverse radius

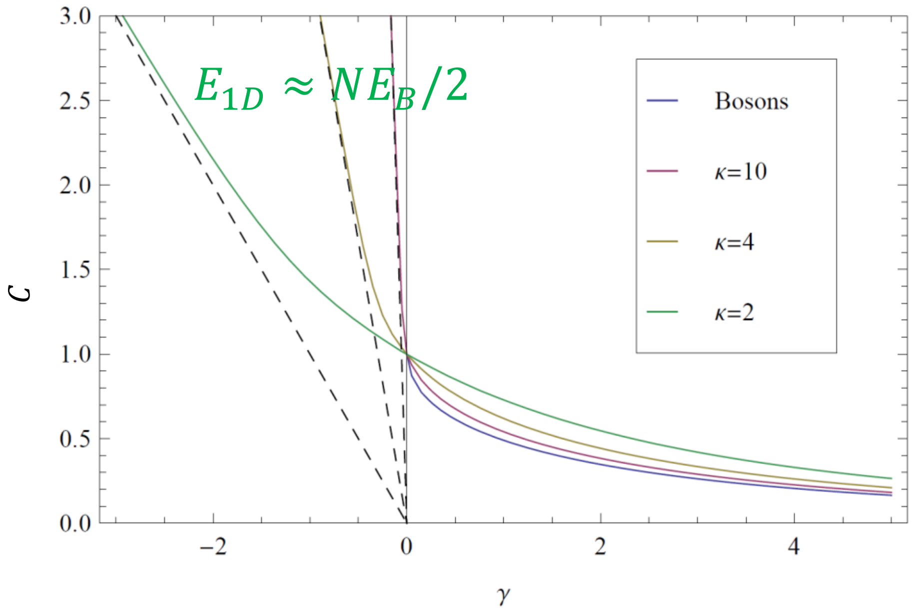
A many-body system is 1D if its transverse degrees of freedom are frozen and the transverse wavefunction is that on the ground state of the confining potential $\Rightarrow E = N\hbar\omega_\perp + E_{1D}$

$$\langle R_\perp^2 \rangle = \frac{2}{N}\frac{\partial E}{\partial m\omega_\perp^2} = a_\perp^2\left(1 + \frac{\pi}{2\gamma}\frac{C}{2}\frac{da_{1D}^{-3}}{da_\perp^{-3}}\right) \qquad \gamma = -\frac{1}{na_{1D}}$$

$C = \frac{m}{N\hbar^2 k_F}\frac{dE_{1D}}{d1/a_{1D}}$=dimensionless Tan's contact for the 1D system.

Repulsive system: C bounded, 1D can be achieved at low density.

Attractive system: C is not bounded. At **unitarity** the correction is **density independent**. It's impossible to freeze the transverse motion even at low T and low E_F



Guan et al. RMP 2013

Beyond Yang-Gaudin?

Perturbative expansion for a weakly interacting 1D gas:

$$E_{1D} = \frac{NE_F}{3}\left[1 + \frac{6\gamma}{\pi^2} - \frac{\gamma^2}{\pi^2} + \cdots\right]$$

In a quantum wire:

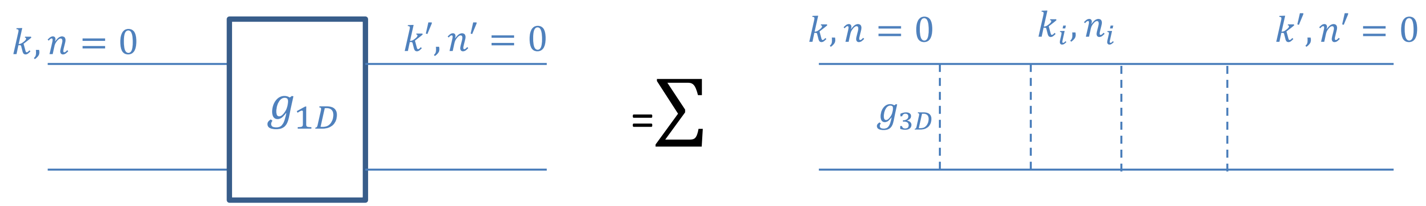
$$E = E_{1D}\left(1 - 4\frac{\gamma^2}{\pi^3}\zeta(\frac{3}{2})\left(\frac{E_F}{\hbar\omega_\perp}\right)^{\frac{3}{2}} - 4Li_2\left(\frac{1}{4}\right)\frac{\gamma^2}{\pi^2}\left(\frac{E_F}{\hbar\omega_\perp}\right)^2 + \cdots\right)$$

Finite range correction

Three-body effective interaction
(Mazets et al. 2008, Pricoupenko 2019)

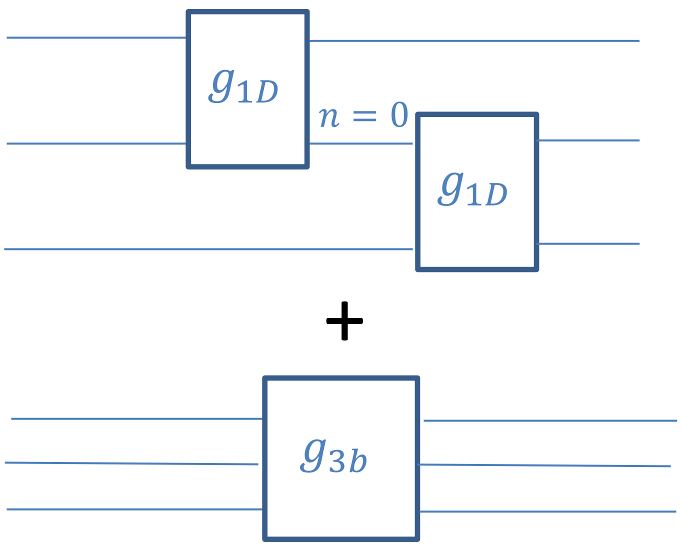
Origin of the three-body interactions

Olshanii revisited



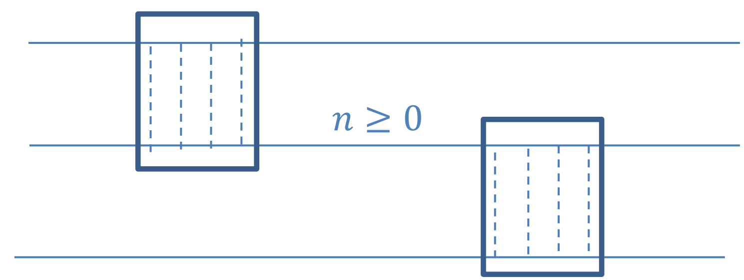
Three body scattering

True 1D

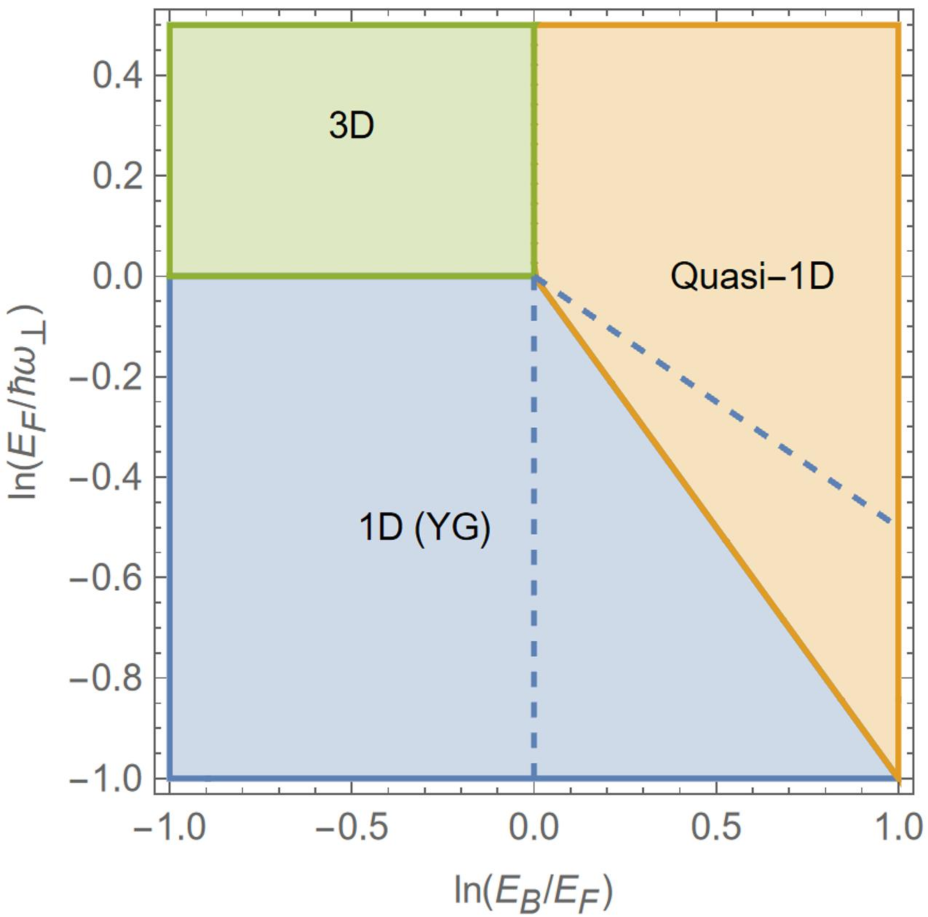


=

Quantum wire



Conclusion and outlook



Open question:

- Is there an effective 1D hamiltonian describing a quasi-1D system for arbitrary interaction?
- How do additional terms in the Hamiltonian affect the dynamical properties of the system (integrability, dissipation…)

Thanks for your attention!