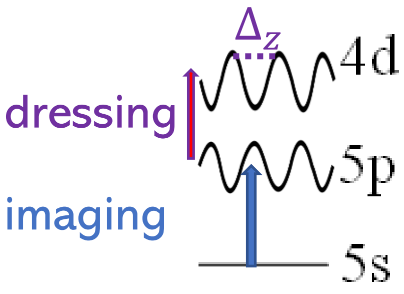
Vincent Mançois
COOLME 2020

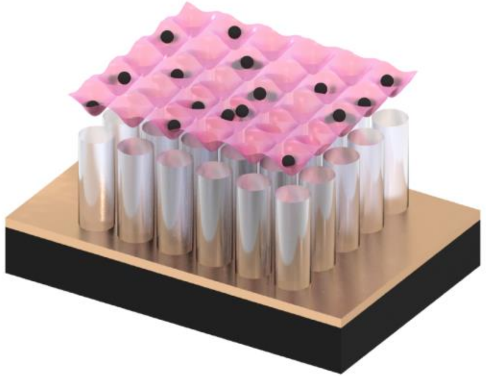
Absorption spectroscopy and atom number measurement of subwavelength volumes of cold atoms

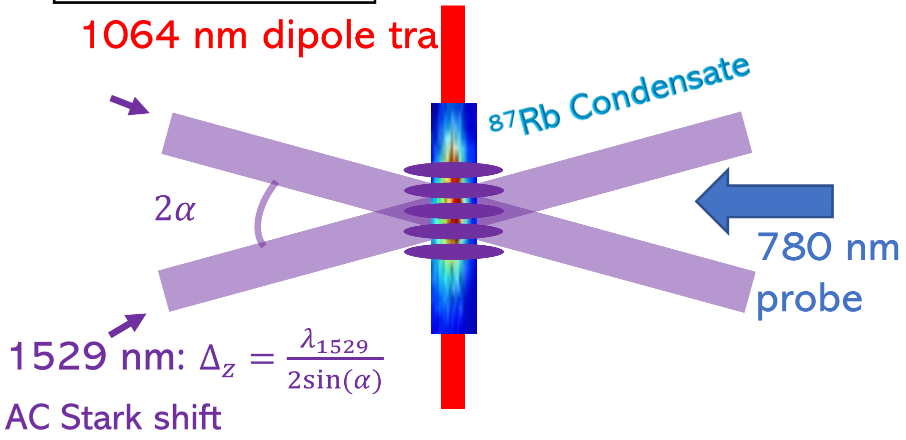
AUFRONS group in Bordeaux (LP2N)

Atomes UltraFroids dans des Réseaux Optiques NanoStructurés
(ultracold atoms in nanostructured optical lattices)

While implementing a nanostructured atomic chip, we develop in parallel a subwavelength imaging system. Using excited state dressing, we selectively image volumes of atoms smaller than the Point Spread Function of our imaging system.







The thin layers of atoms we obtain can be adjusted to various sizes and densities. From a dilute and thermal to degenerate. We can test models of linear optics and calibrate absorption and number of atoms for nanometric systems.

Aim of this project / Long term

2D Physics with large coupling (driven by the surface)

- *Role of multiple levels (magnetism, spin textures)*
- *Role of thermal & quantum fluctuations (QPT)*
- *Role of topology (B field, periodical drive…)*
- *Inverse problem: substrate characterization*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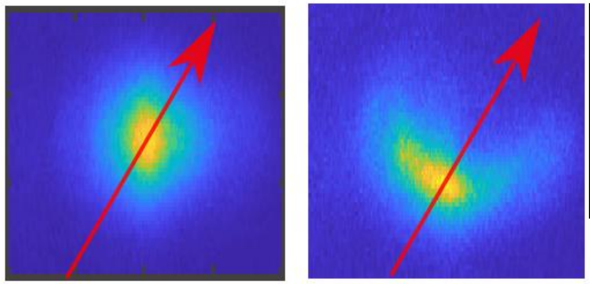
Bellouvet et al. PRA **98**, 0,23429, 2017

(How to) Observe small details with atoms

Single shot fluorescence

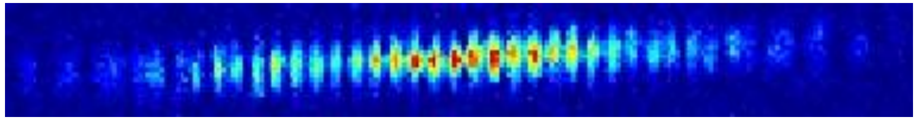
$s_0 >> 1$ $s_0 << 1$



Imaging the whole atomic cloud at once means losing details smaller than the point spread function (PSF)…

Example 1: MOT fluorescence

Tomography (our method)

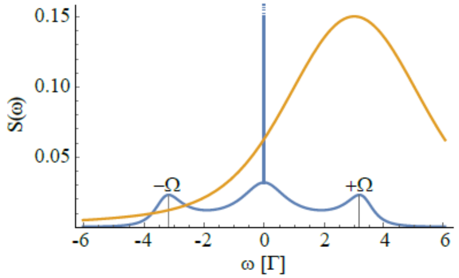


Example 2: BEC tomography

Partial repumping of subwavelength layers of atoms allows us to reconstruct the whole suystem with a precision better than the PSF.

However both require large saturation of the laser probe

Inelastic scattering



The fluorescence spectrum (blue curve) of a red detuned laser is centered at the laser frequency and displays inelastic lobes.

Non-linear absorption

$$\frac{\mathrm{d}I}{\mathrm{d}x} = -b(I)I$$

The usual Beer Lambert formula has to be modified in the saturated regime.

Also, due to density…

Sub/Superradiance
Index effect

Dipole-Dipole interaction

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Simulating transmission imaging

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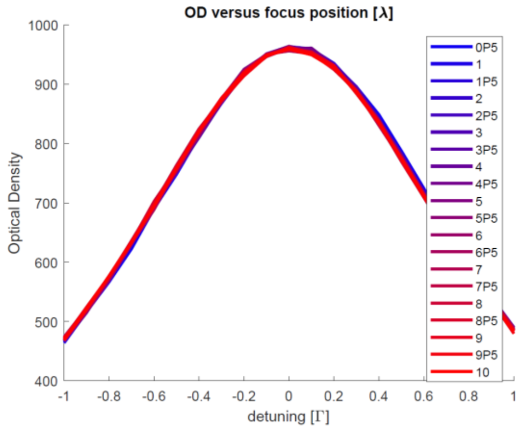
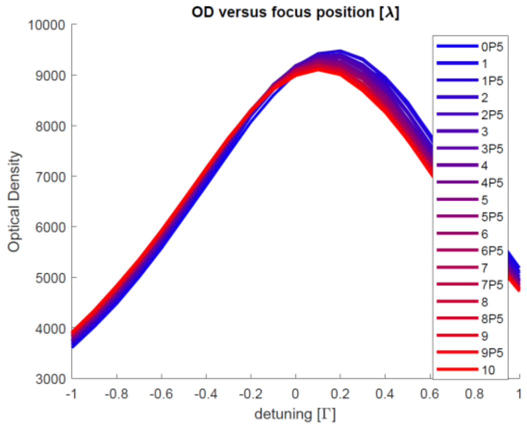
Transmission imaging simulations

- *Compute coupled dipoles (steady state, linear regime)*
- *(choice 1) Fresnel integral for far field component of transmitted field*

$\rho k^{-3} = 0.001$



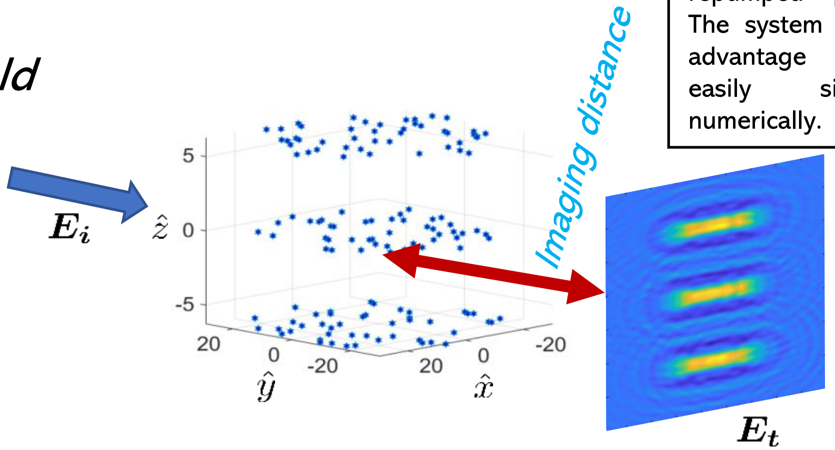
$\rho k^{-3} = 0.01$



Optical thickness

$$b = -\ln(|\boldsymbol{E_t}/\boldsymbol{E_i}|^2)$$

We revover Beer Lambert at low enough density. Otherwise the absorption spectra is shifted and broadened. Also usual transmission imaging of dense medium are realized at large saturation, which need to be accounted for.



Our atomic cloud is repumped partially. The system has tha advantage to be easily simulated numerically.

Coupled dipoles equations

$$\begin{cases} \dot{\beta}_n = \left(\mathrm{i}\Delta - \dfrac{\Gamma}{2}\right)\beta_n - \mathrm{i}W_n \\ W_n = \dfrac{\Omega_n}{2} - \mathrm{i}\sum_{m\neq n} G^s_{nm}\beta_m \end{cases}$$

n-th dipole; Laser drive; nm dipole couplin

Those equations are very well defined in the linear regime (when atoms spend most of the time in the ground state) and behave as classical scatterers.

Too simple and ambiguous for numerous reasons

Does not account for a numerical apperture
Sensitive to the imaging plane (which one to take?)
Effect of saturation neglected

We thus modify Beer Lambert law in its simplest extension (the lambert W function). We also account for an imaging system (a f-2f-f telescope)

Journal of Modern Optics **9**, 1215564, 2016
Phys. Rev. A **101**, 013617, 2020

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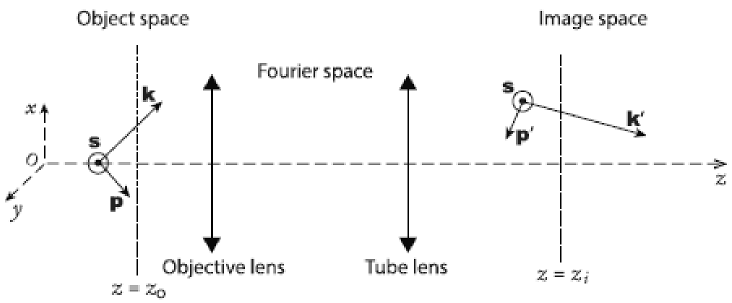
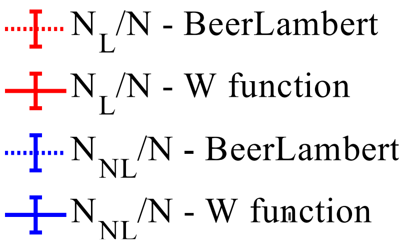
Simulating (improved) transmission imaging

Transmission imaging simulations 2.0

- *Compute coupled dipoles with saturation*
- *(choice 2) Simulate imaging apparatus*

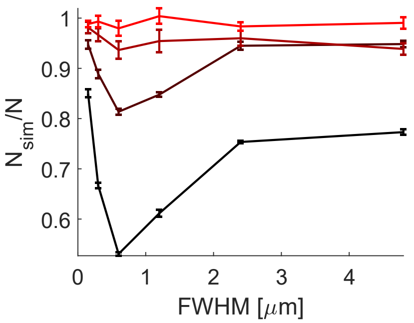


Archetype of an imaging system. It accounts for a numerical apperture. Which is fundamental in our case since the layer of atoms are subwavelength and diffract.



Comparison with Beer Lambert prediction

The question we ask here is whether the optical thickness can be used to deduce an accurate number of atoms or not. Beer Lambert law and its extenstion to saturated regime assumes a homogeneous medium. What happens when the system is sub-PSF sized?



Densities from 0,001 k^3 (red) to 0,01 k^3 (black).

For a PSF diameter of 2,6 microns, we vary the size of a single Gaussian layer at constant peak density. The number of atoms deduced from Beer Lambert is accurate for a fringe large enough (than PSF) and dilute. But we lack realism, because denser media mean in reality larger saturation parameters…

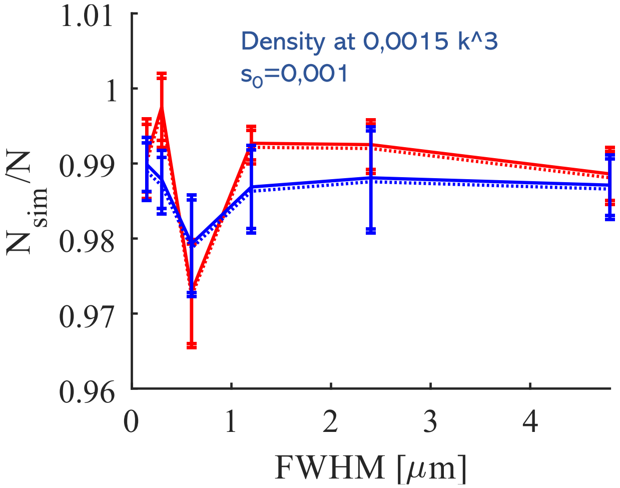
Can we do better? Adding **saturation** in Beer Lambert and **inelastically scattered light** as an incoherent population pumping.

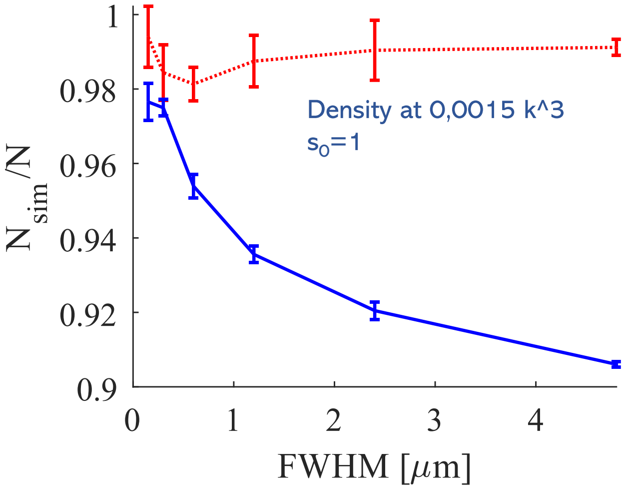
Beer Lambert

$$n\sigma L = -\ln(T)$$

W Function

$$n\sigma L = -\ln(T) + s_0(1-T)$$





Beer Lambert is accurate when the medium is dilute and homogeneous, however deviates at increasing densities (more than few 0,001 k^3) and for subwavelength atomic volumes (1,22λ/2NA). Including saturation and incoherent pumping solves only partially the problem. ***Ongoing with experiments!***

Credits for the drawing: Khadir et al. Vol. 36, No. 4 / April 2019 / JOSAA