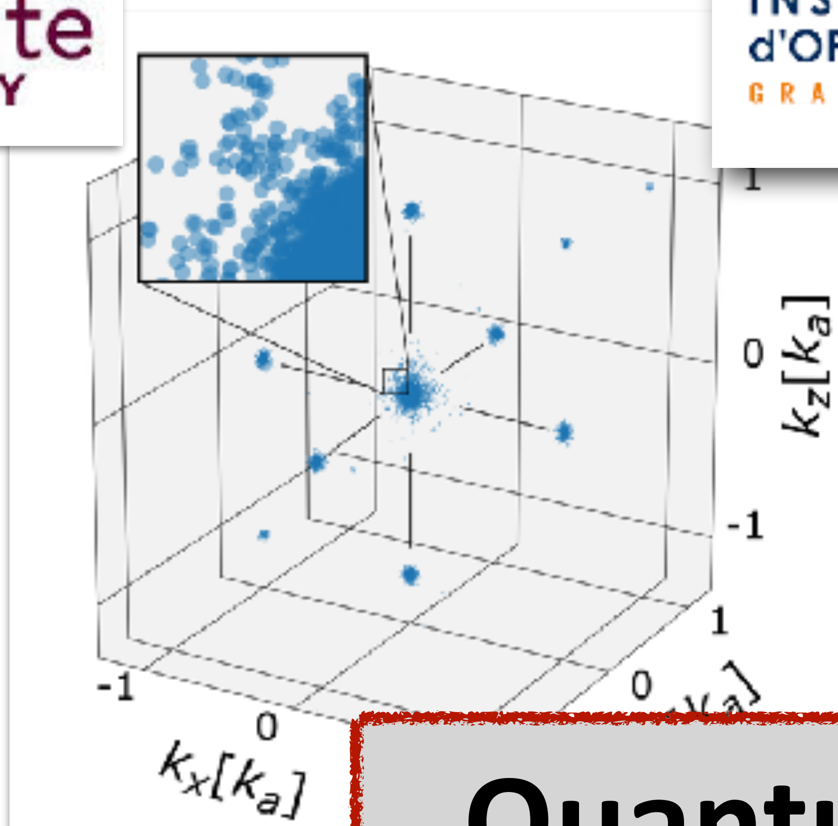
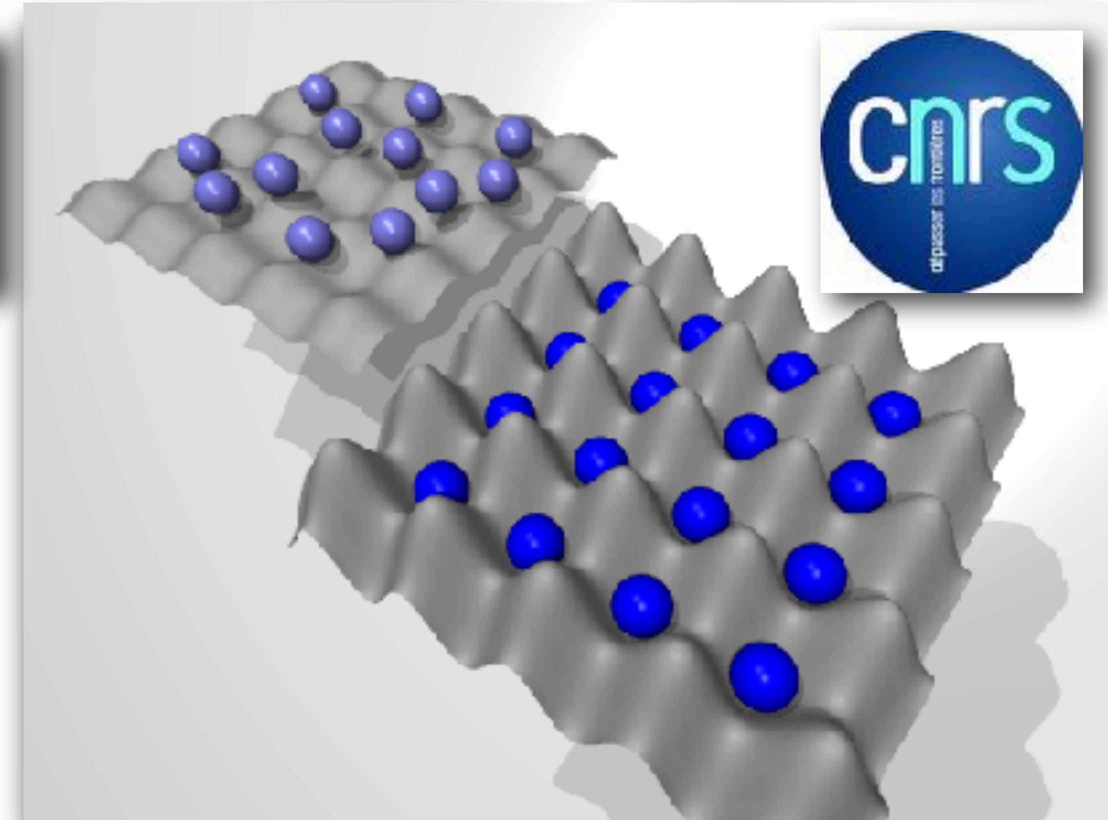
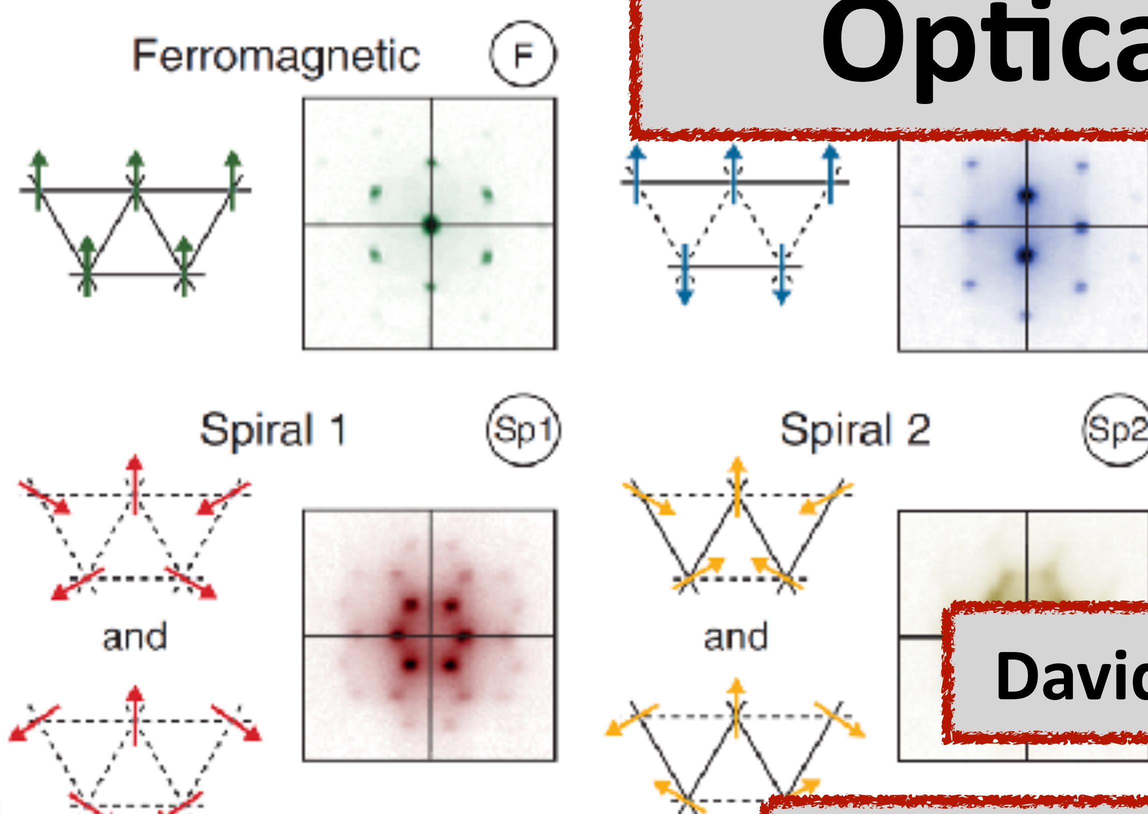
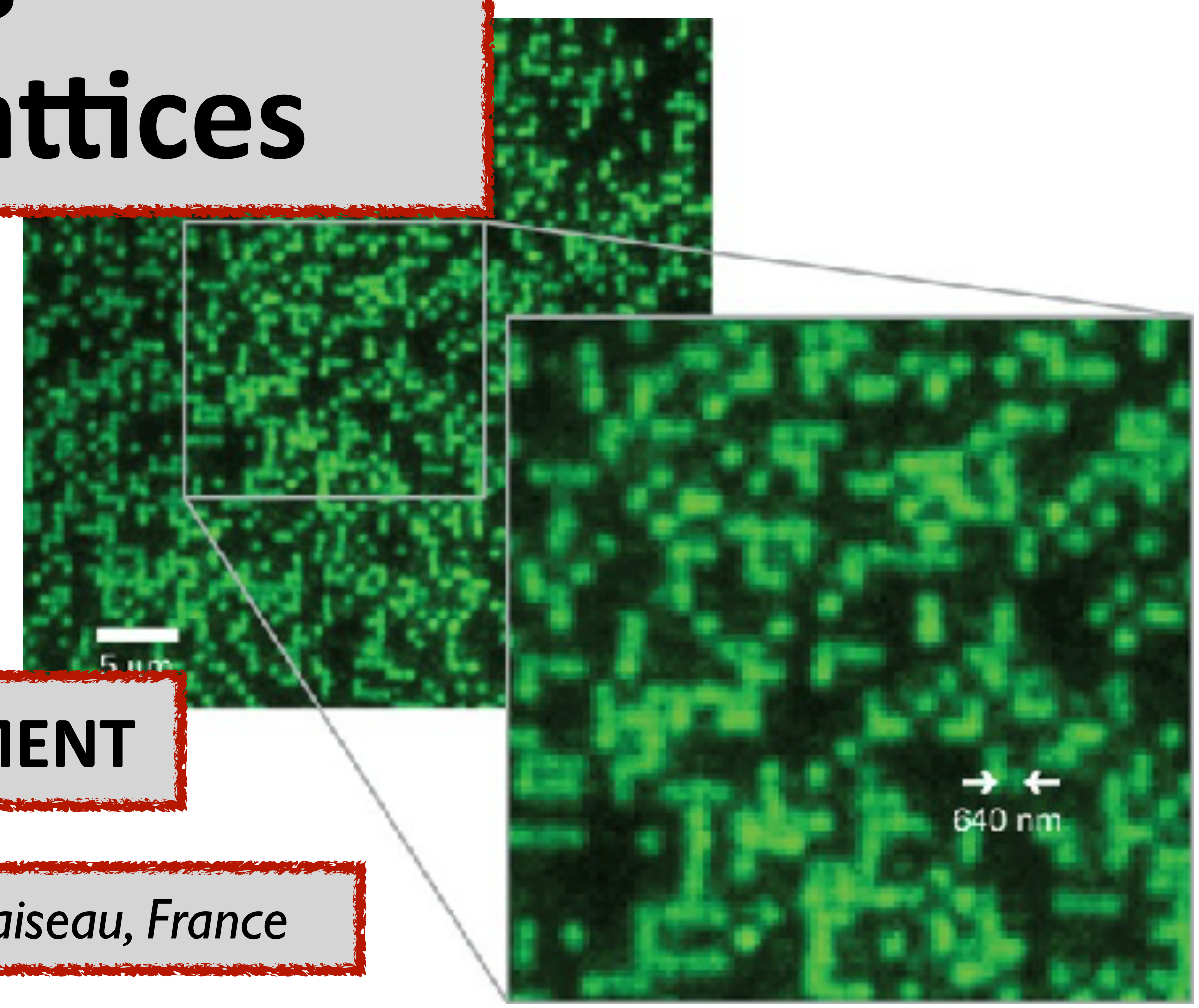




Quantum gases in Optical Lattices





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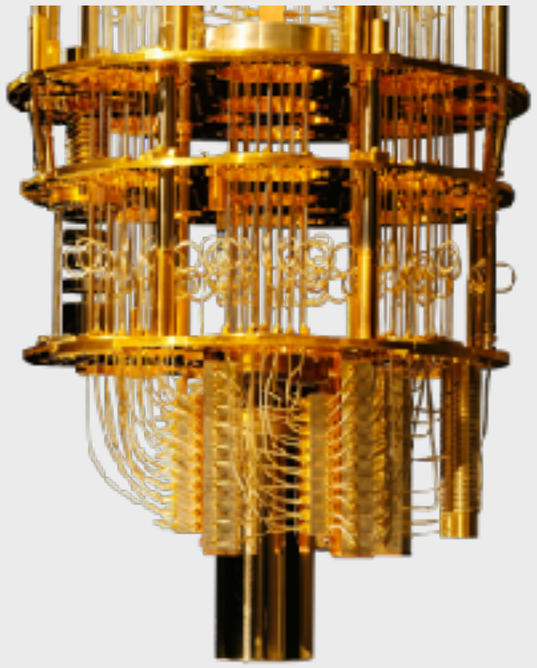
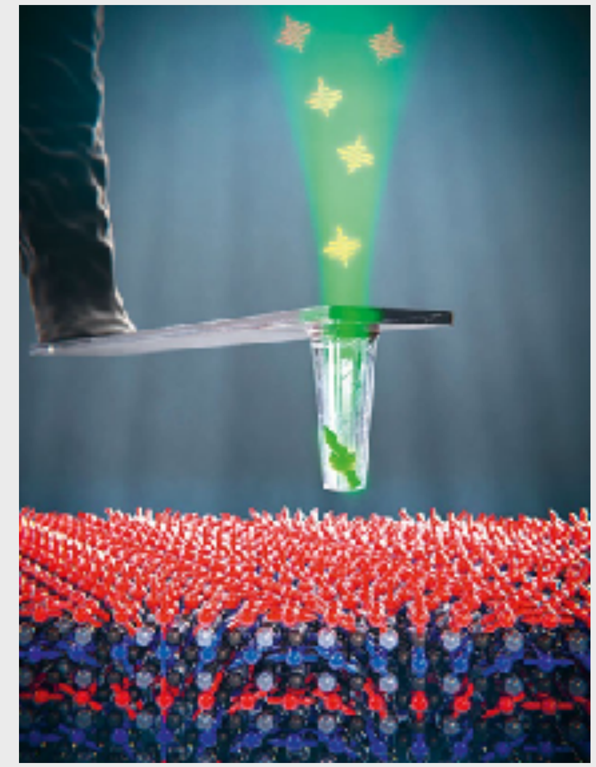
Quantum technologies - 4 pilars

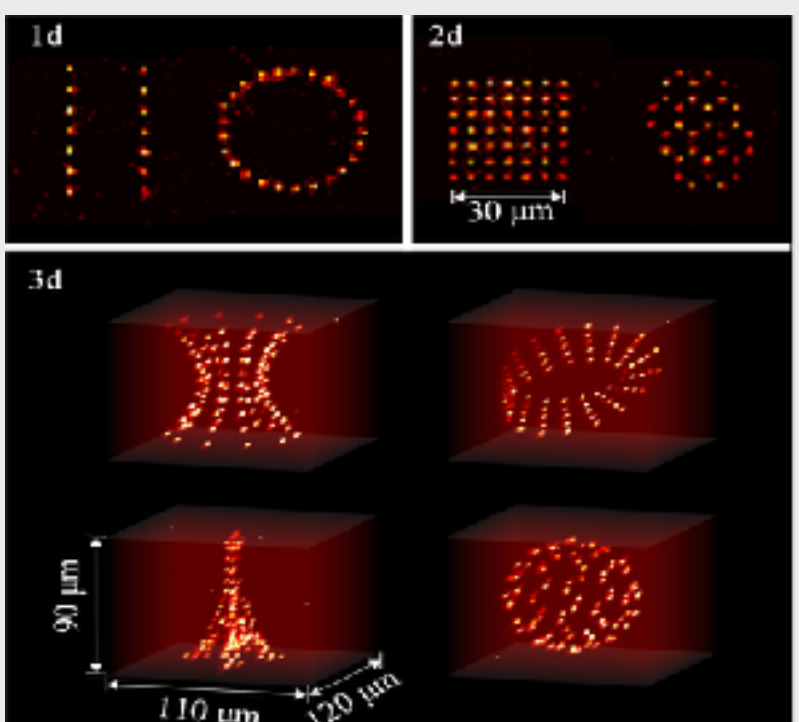
Quantum computation



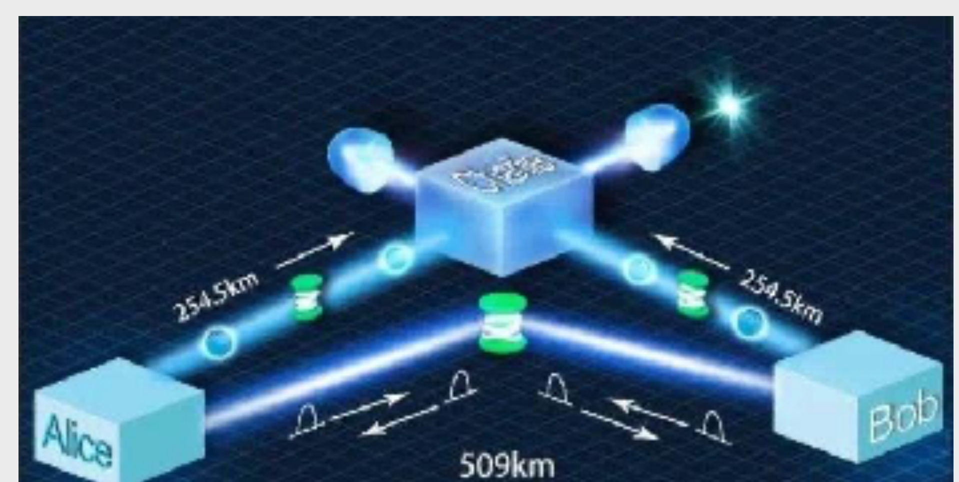
Quantum sensing



Quantum simulation

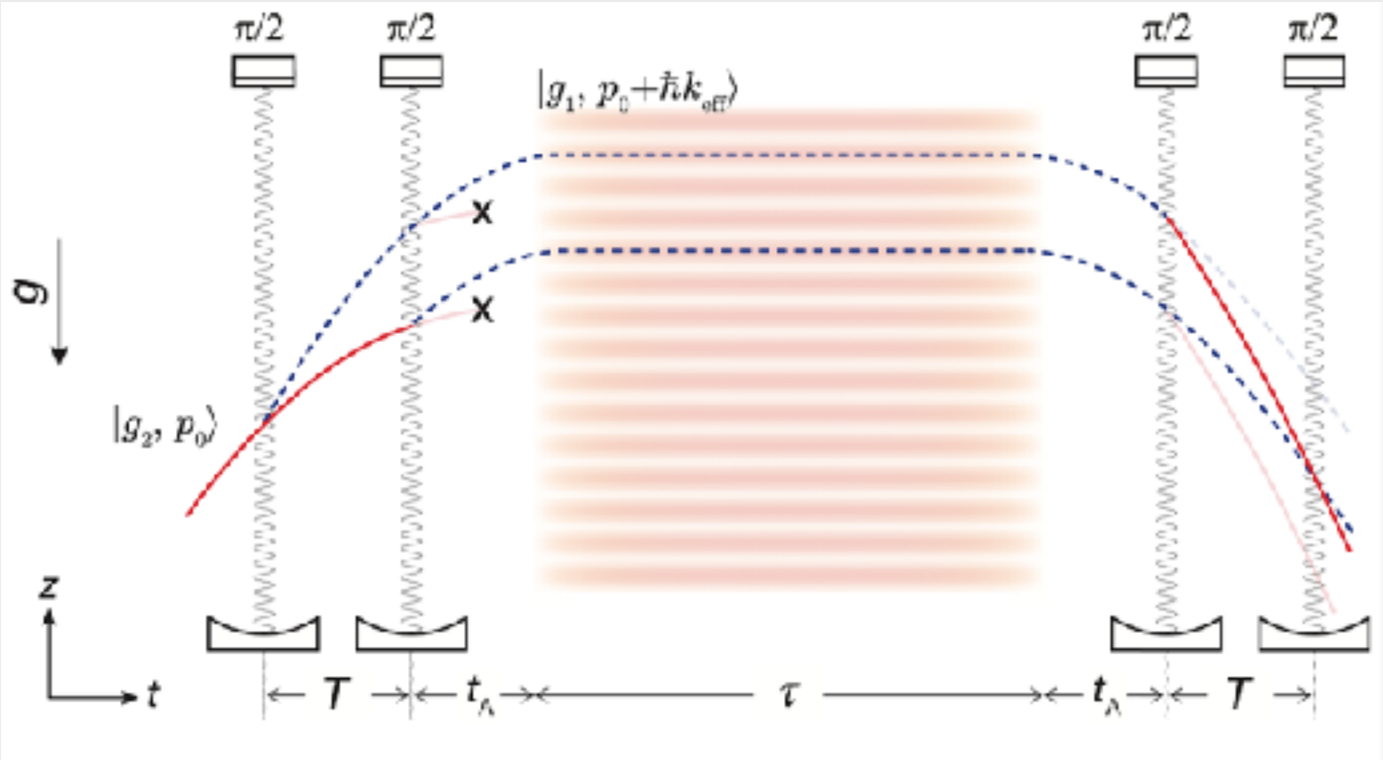


Quantum communication



Quantum sensing - metrology

Atom interferometers



Probing gravity by holding atoms for 20s

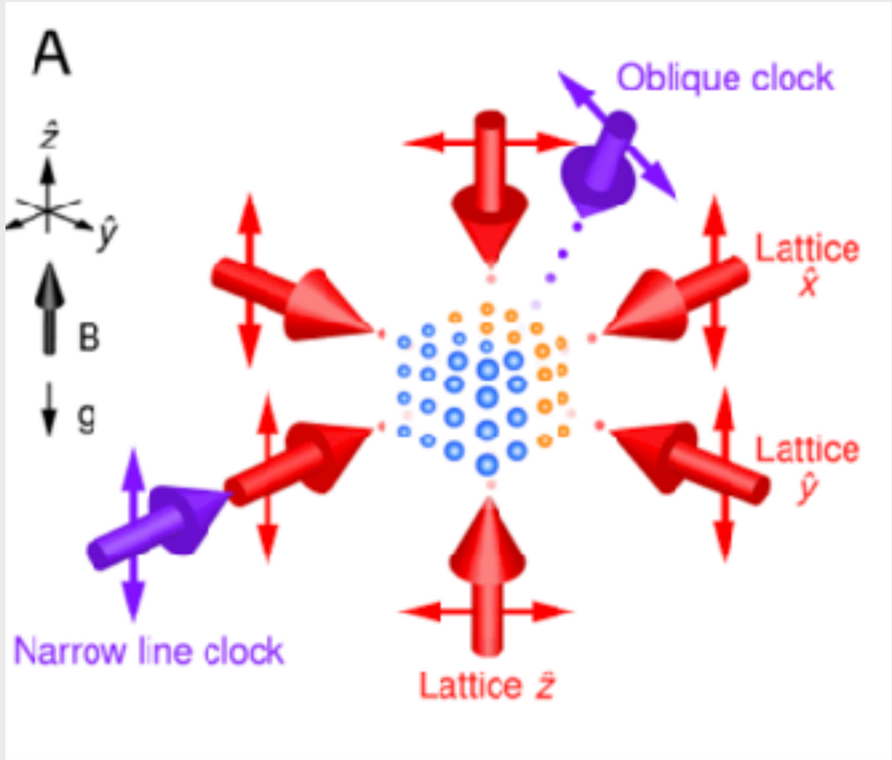
*Science **366**, 745 (2019)*

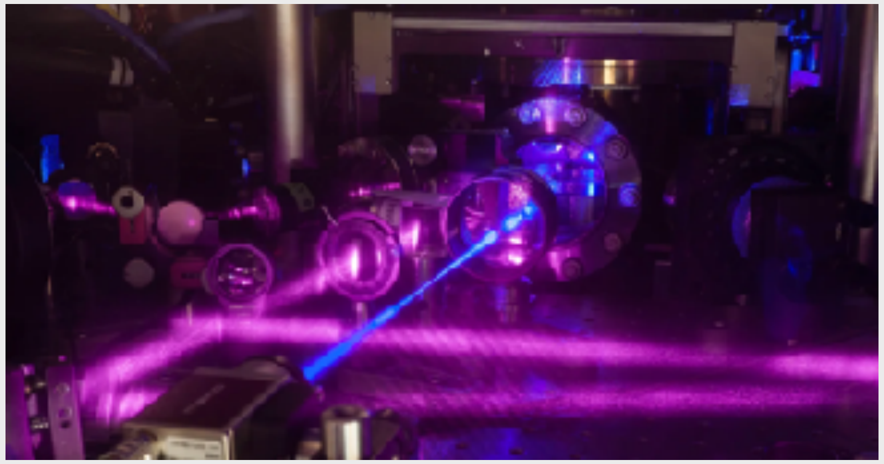
Optical lattices to manipulate momentum states:
beamsplitters and mirrors

(lecture #1)

...also Bloch oscillations to measure forces

Optical clocks in lattices





Precision $<10^{-18}$ over 1 hour

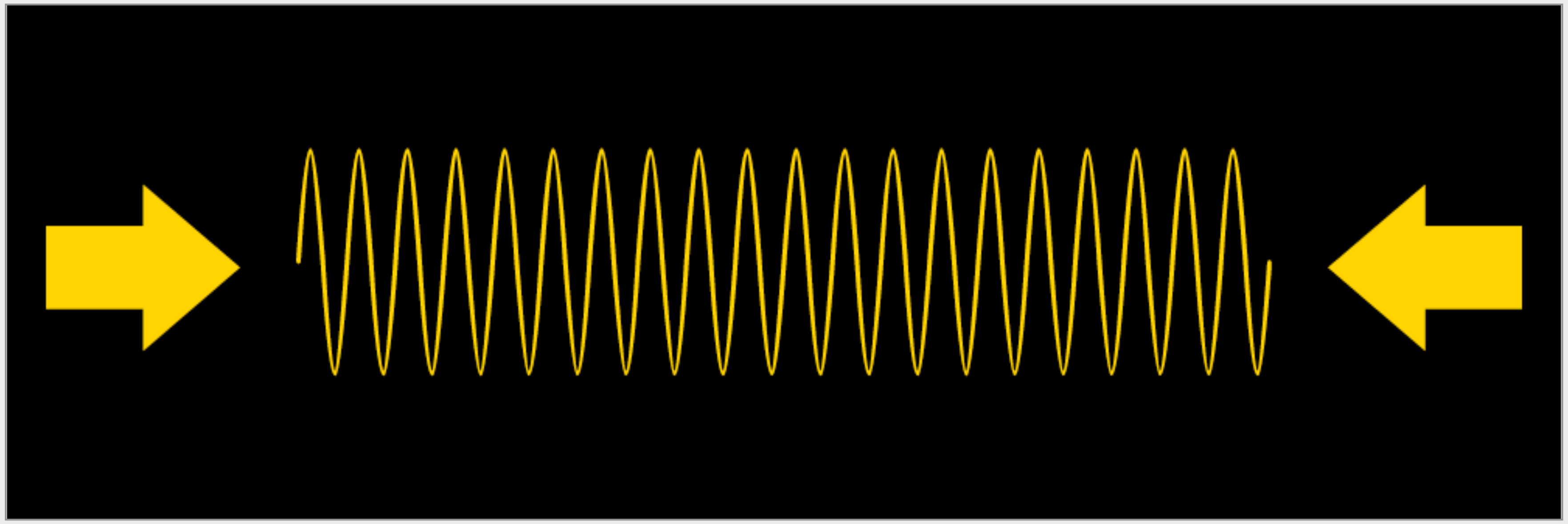
*Campbell et al. Science **358**, 90 (2017)*

Atoms in deep optical lattices

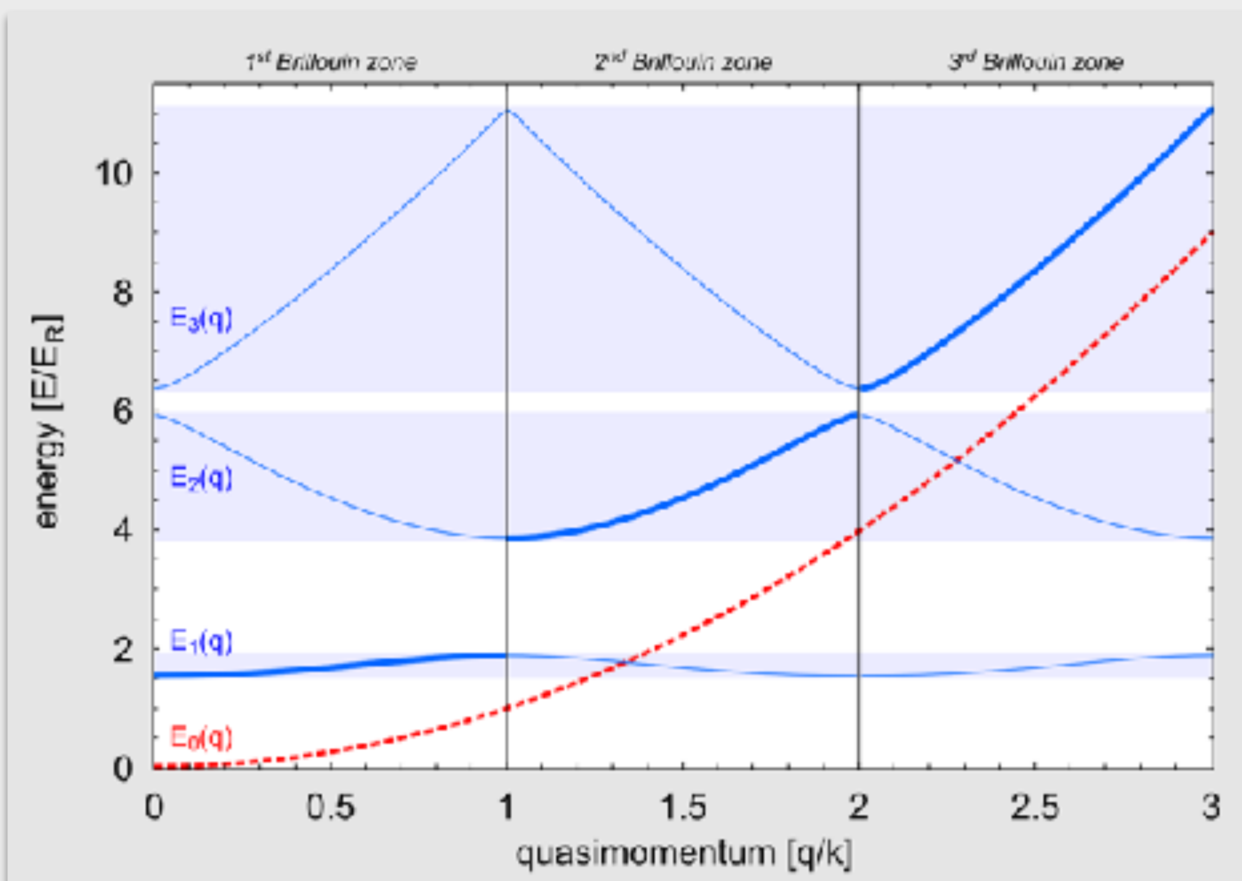
(lecture #3)

Quantum simulation

Realisation cristalline structures to simulate correlated matter



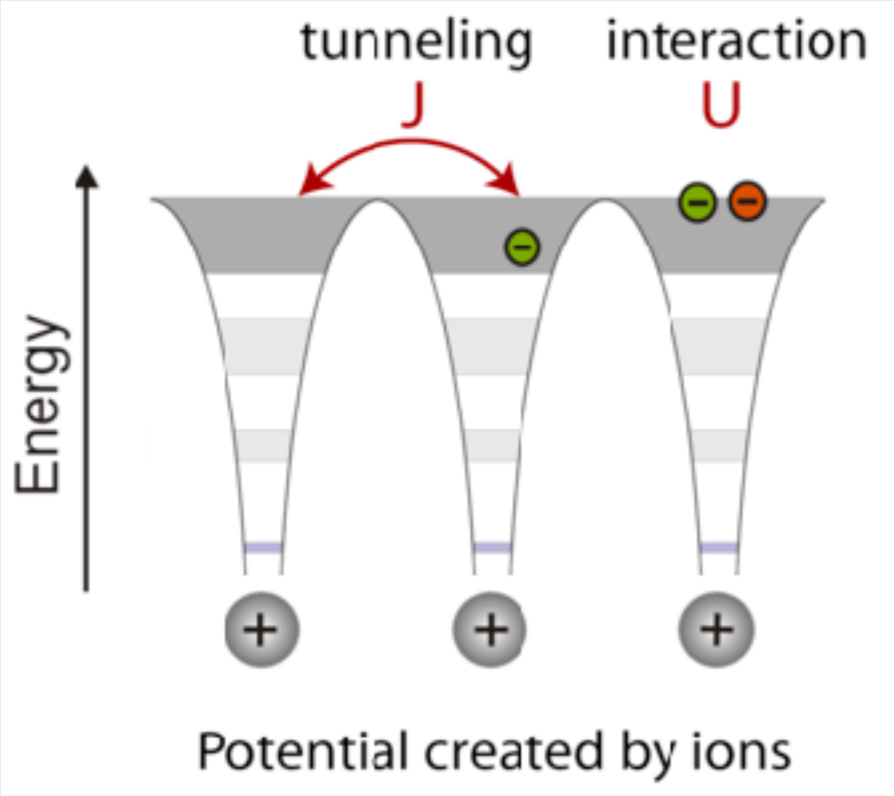
Optical lattices to create band structures as in solids *(lecture #2)*

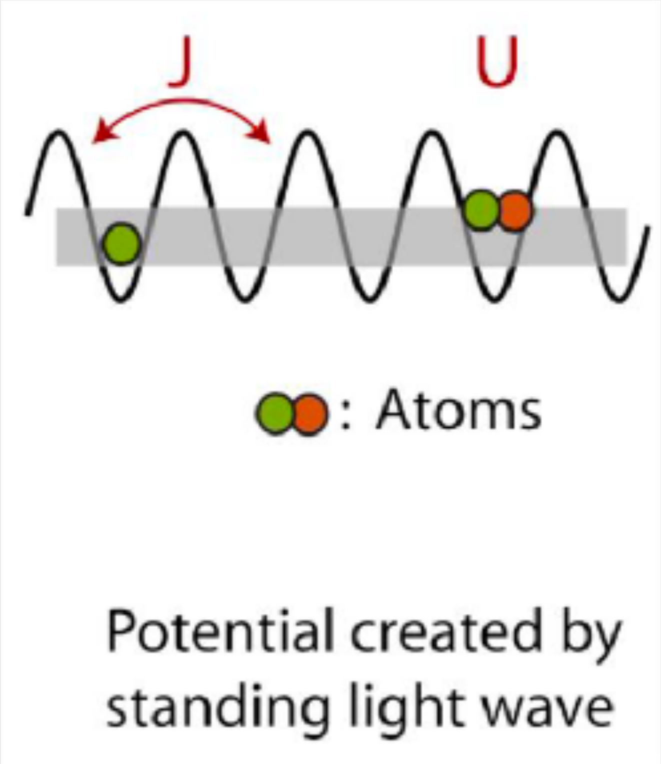


Quantum simulation

Realisation cristalline structures to simulate correlated matter

Implementation of Hubbard hamiltonians *(lectures #3 et #4)*





Understand and design strongly-correlated quantum matter

- interplay quantum fluctuations/interactions
- quantum phase transitions
- quantum magnetism
- ...

Lectures on optical lattice: *(tentative)* program

Lecture #1 - introduction to optical lattices

- short reminder on light shifts
- description of optical lattices
- pulsed lattices: coherent coupling of momentum states

Lecture #2 - band structure for non-interacting gases

- Bloch theorem and wave-functions
- band structure
- non-interacting lattice bosons and fermions

Lecture #3 - interacting bosons

- tight-binding regime
- Bose-Hubbard hamiltonian
- superfluid-to-Mott transition

Lecture #4 - interacting fermions

- Fermi-Hubbard hamiltonian
- Mott transition
- super-exchange and magnetism

Quantum gases in Optical Lattices
Lecture #1

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Short reminder on light atom interactions

ELSEVIER
Advances In Atomic, Molecular, and Optical Physics
Volume 42, 2000, Pages 95-170

Optical Dipole Traps for Neutral Atoms

Rudolf Grimm, Matthias Weidemüller, Yurii B. Ovchinnikov

$$U_{\mathrm{dip}}(\mathbf{r}) = -\frac{3\pi c^2}{2\omega_0^3}\left(\frac{\Gamma}{\omega_0-\omega}+\frac{\Gamma}{\omega_0+\omega}\right) I(\mathbf{r}),$$

$$\Gamma_{\mathrm{sc}}(\mathbf{r}) = \frac{3\pi c^2}{2\hbar\omega_0^3}\left(\frac{\omega}{\omega_0}\right)^3\left(\frac{\Gamma}{\omega_0-\omega}+\frac{\Gamma}{\omega_0+\omega}\right)^2 I(\mathbf{r})$$

For most practical purposes $|\Delta| \ll \omega_0$

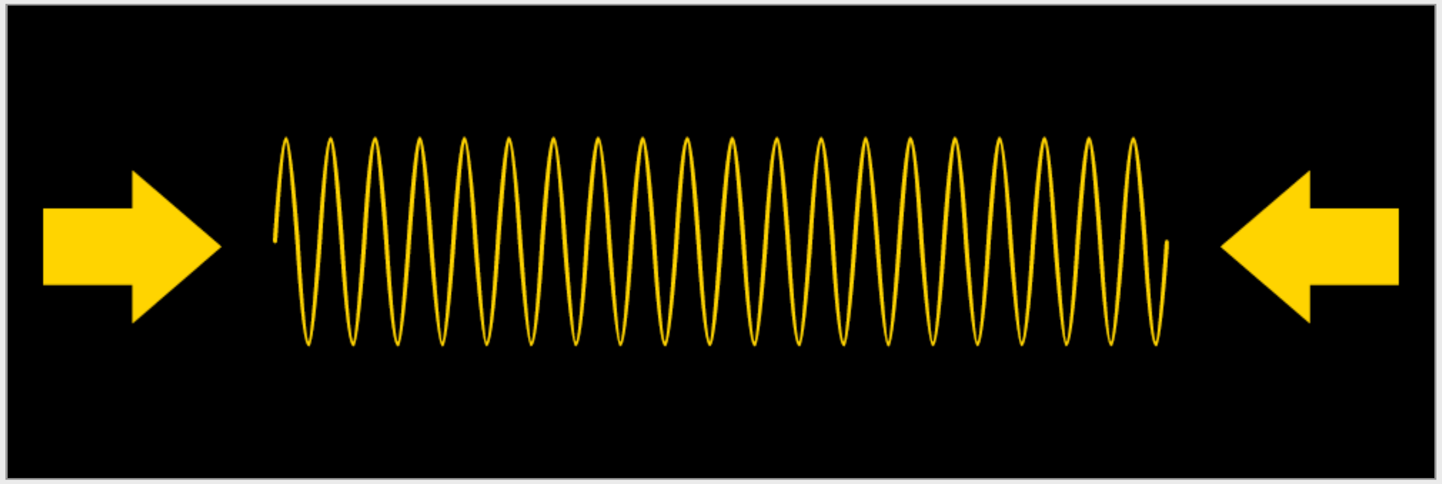
$$\hbar\Gamma_{\mathrm{sc}} = \frac{\Gamma}{\Delta} U_{\mathrm{dip}}$$

neglected spontaneous emission at large detuning!

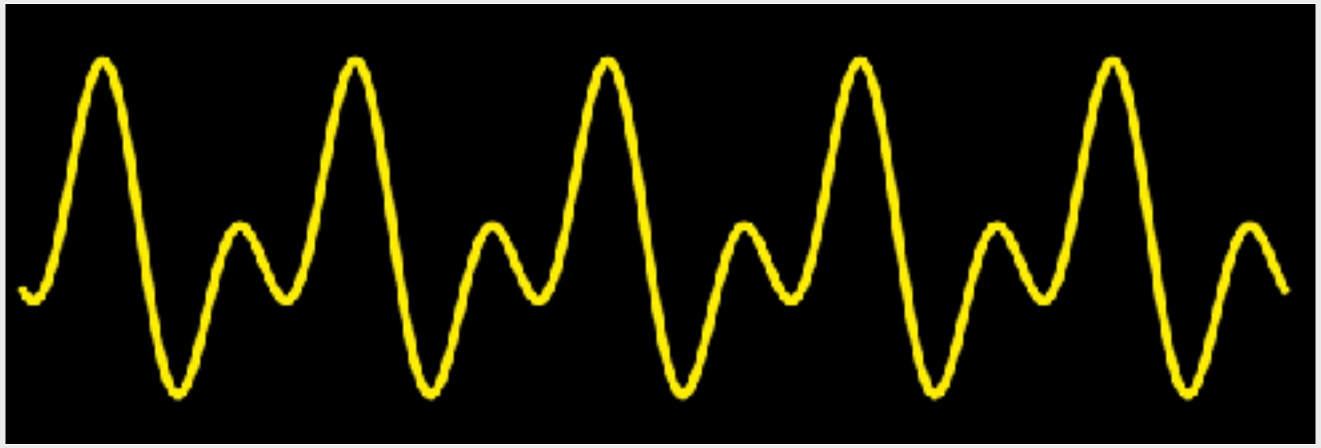
Optical lattice

Simple counter-propagating 1D lattice
(no defects, no phonons)

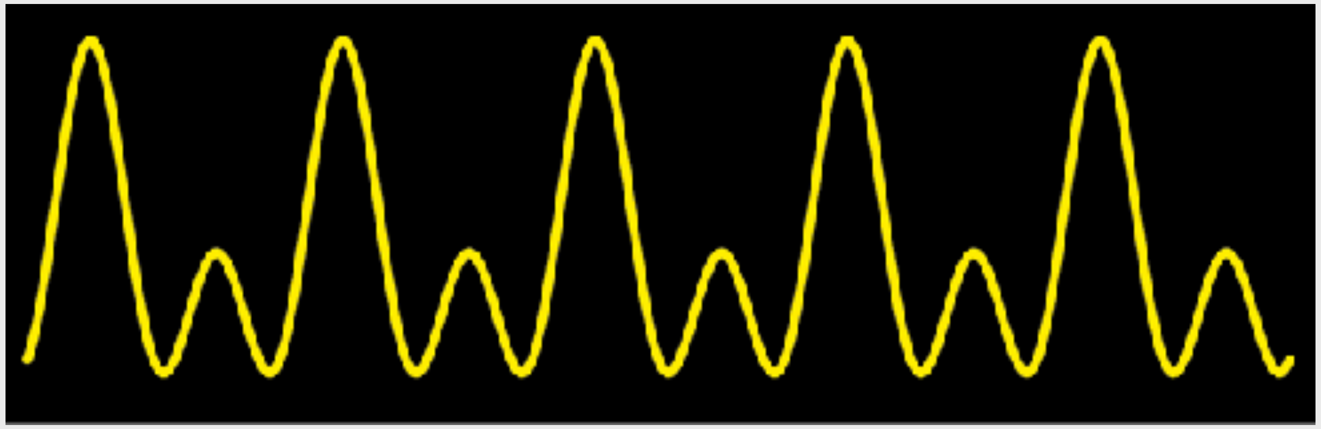
$$V(x) = V_0 \sin(kx)^2$$



Superlattices with two periods $\lambda, \quad 2\lambda$

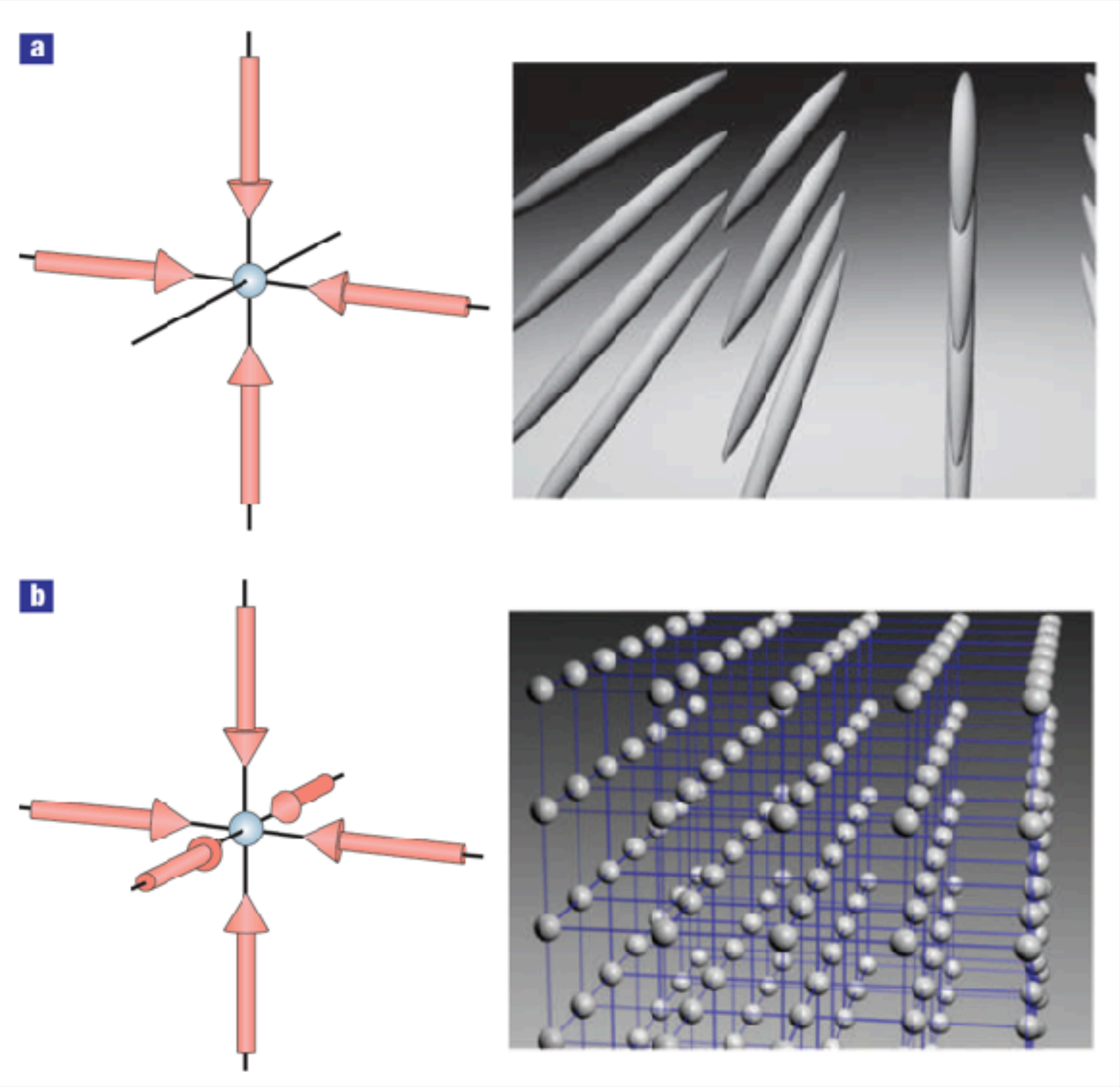


tilted double-wells



balanced double-wells

Optical lattice in higher-dimensions



I. Bloch - Review Optical lattices - Nature Physics (2005)

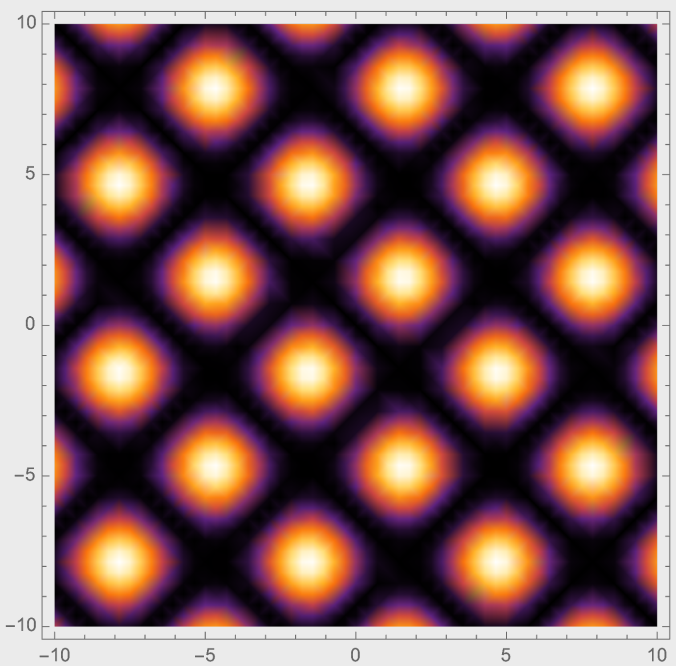
Detuning of beams in the different directions to average interference effects between different axis to zero

$$\omega_x - \omega_y \sim 10 - 100 \text{ MHz}$$

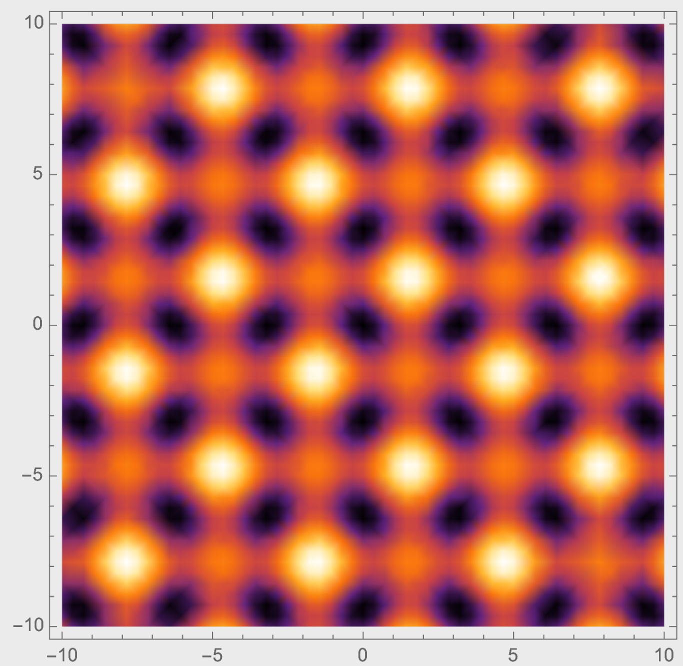
More exotic optical lattices

lattices with varying spacing, orientation and symmetry

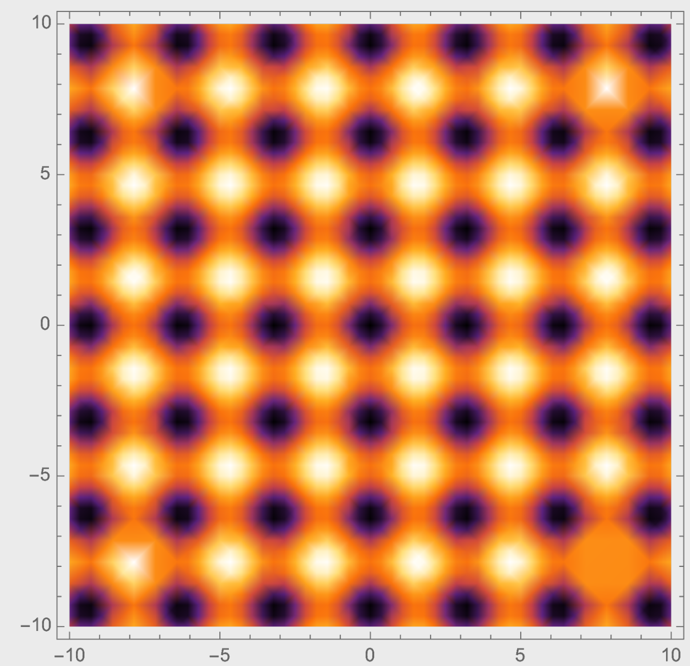
$$I(x,y) \propto [\sin(kx) + \sin(ky)\mathrm{e}^{\mathrm{i}\phi}]^2$$



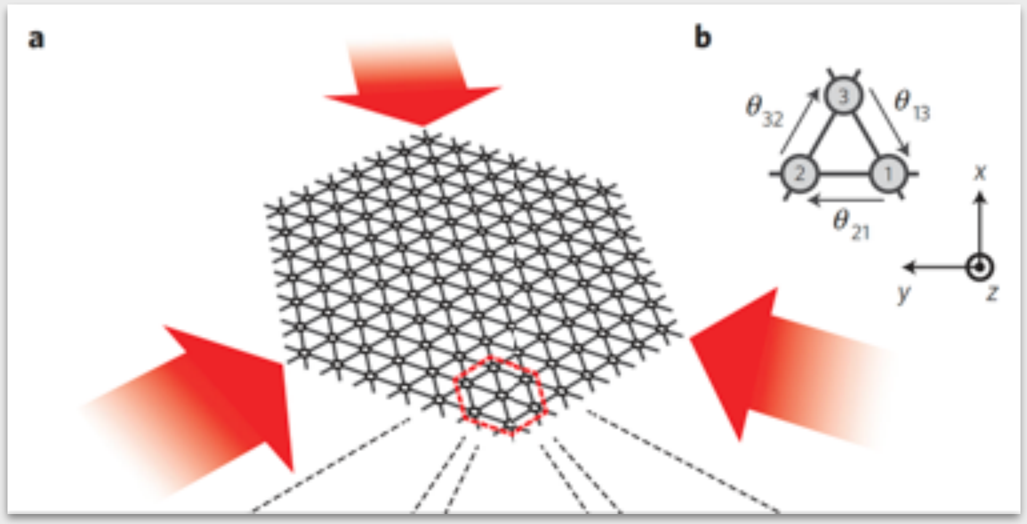
$\phi = 0$



$\phi = 2\pi/5$



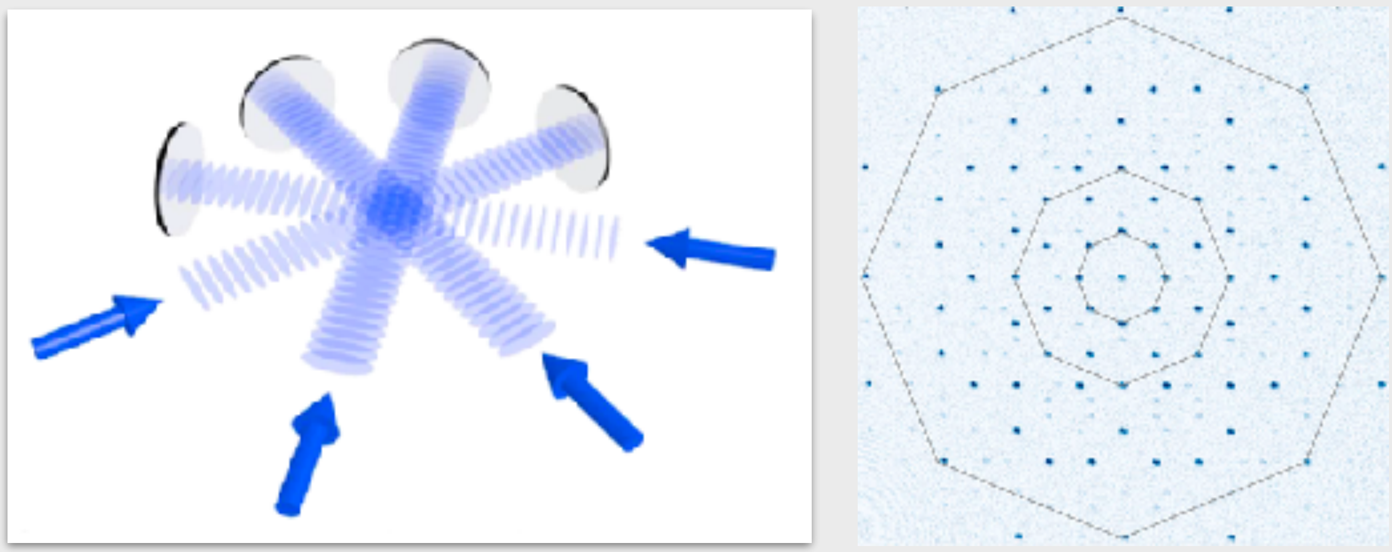
$\phi = \pi/2$



honeycomb and triangular

Struck et al., Nat. Phys. (2013)

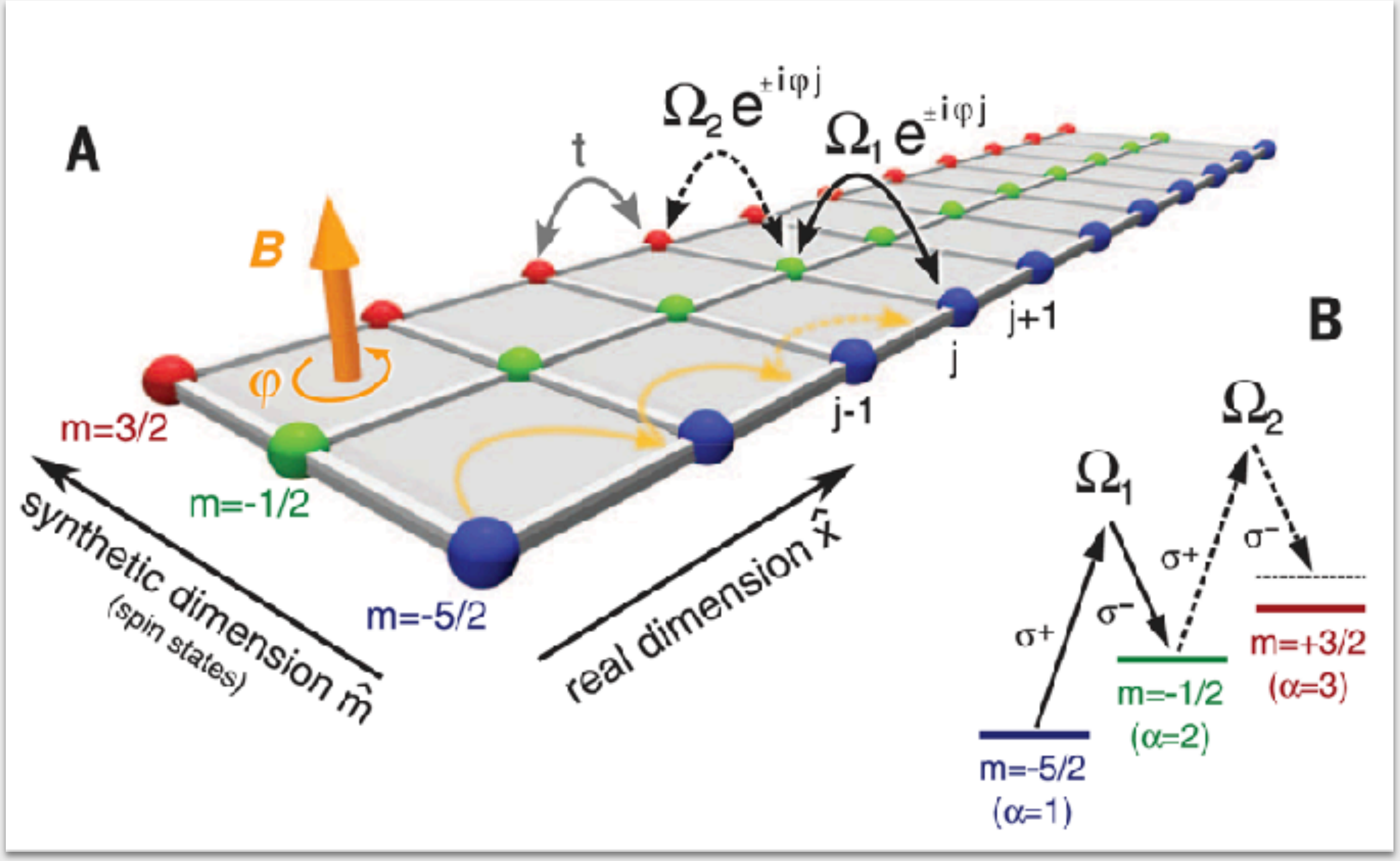
quasi-cristal (self similarity in *k*-space)



Viebahn et al., PRL ***122****, 110404 (2019)*

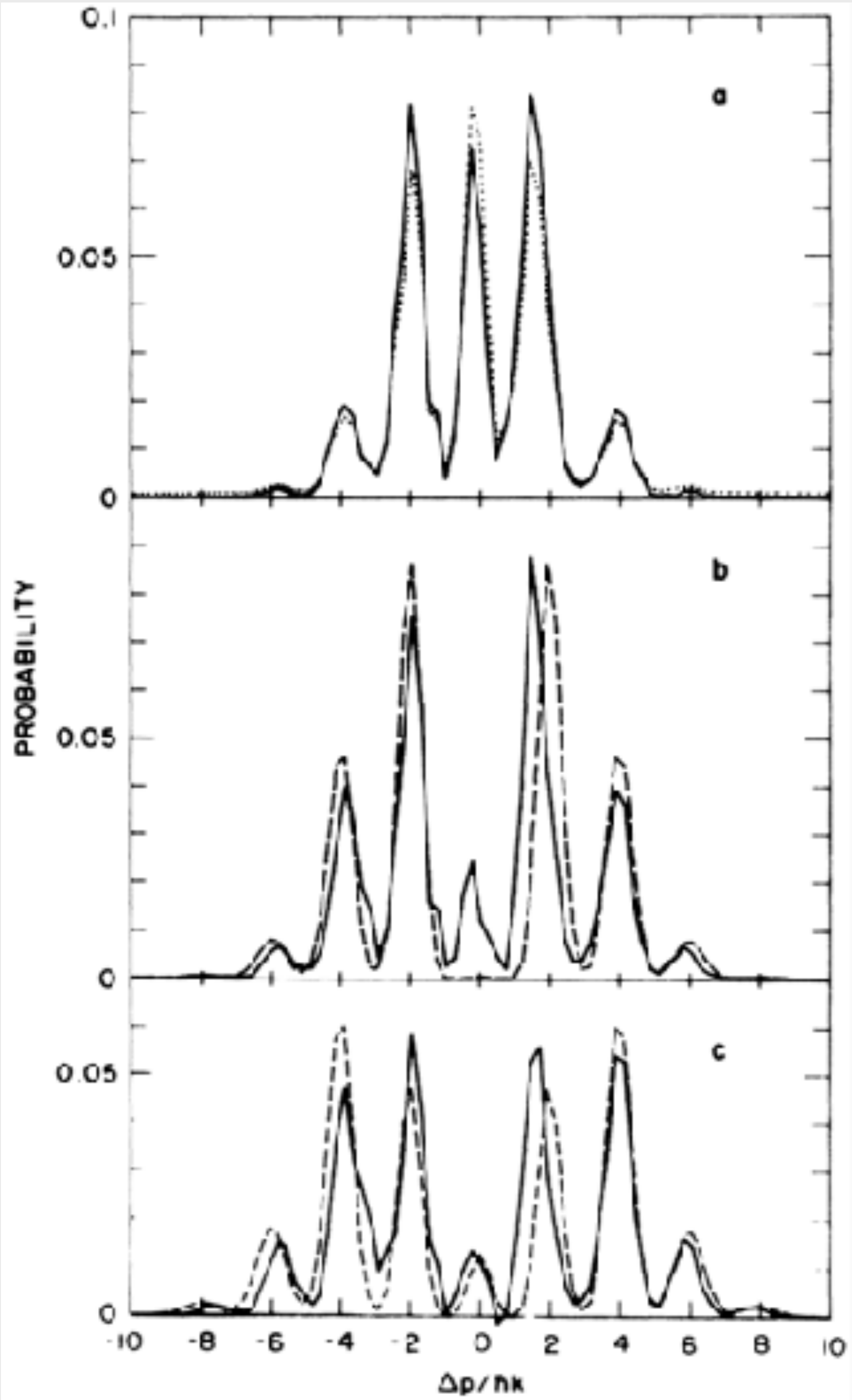
(even) more exotic optical lattices

Lattices with synthetic dimensions: internal degrees of freedom of the atoms



Mancini et al., Science (2015)

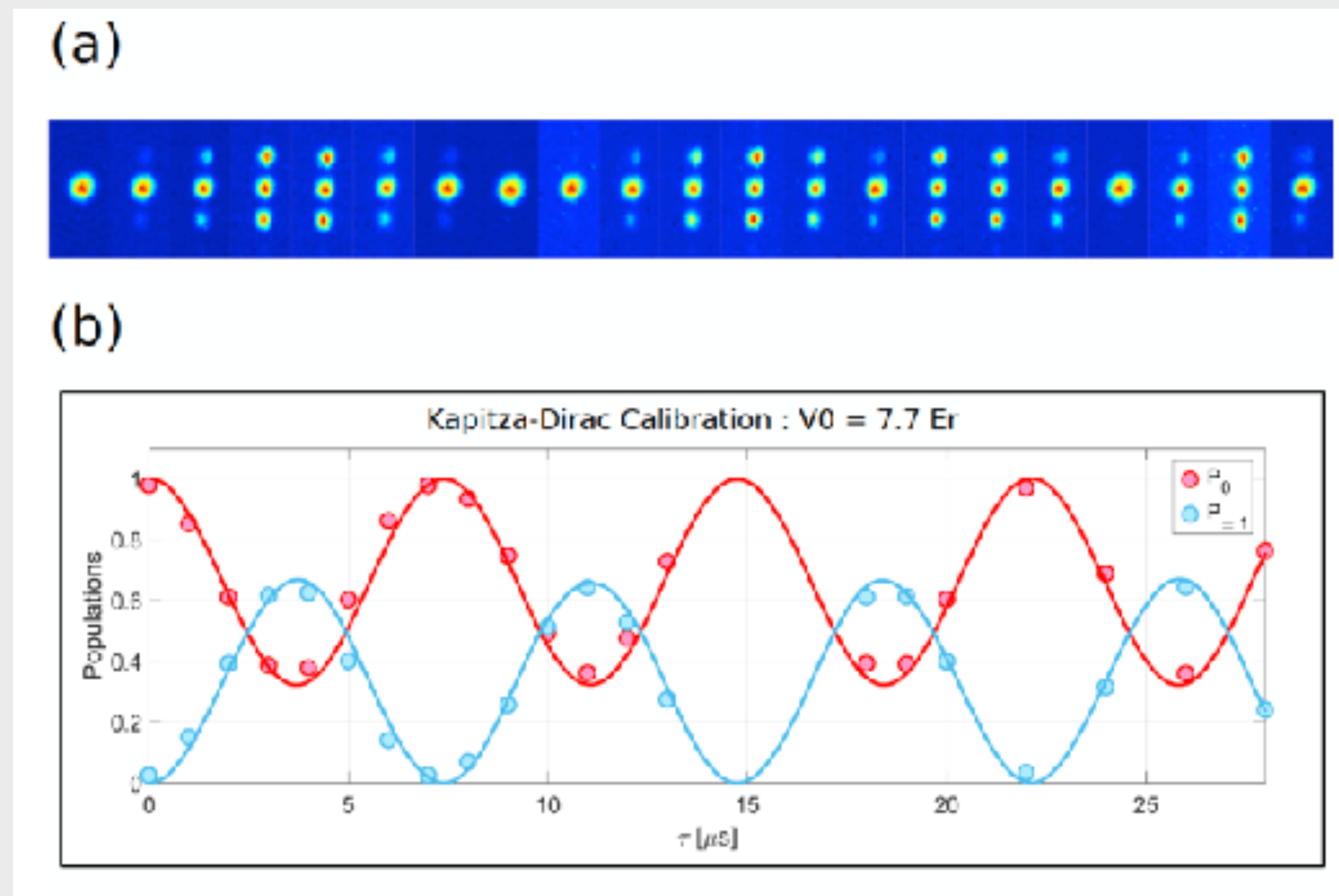
Pulsed 1D lattice



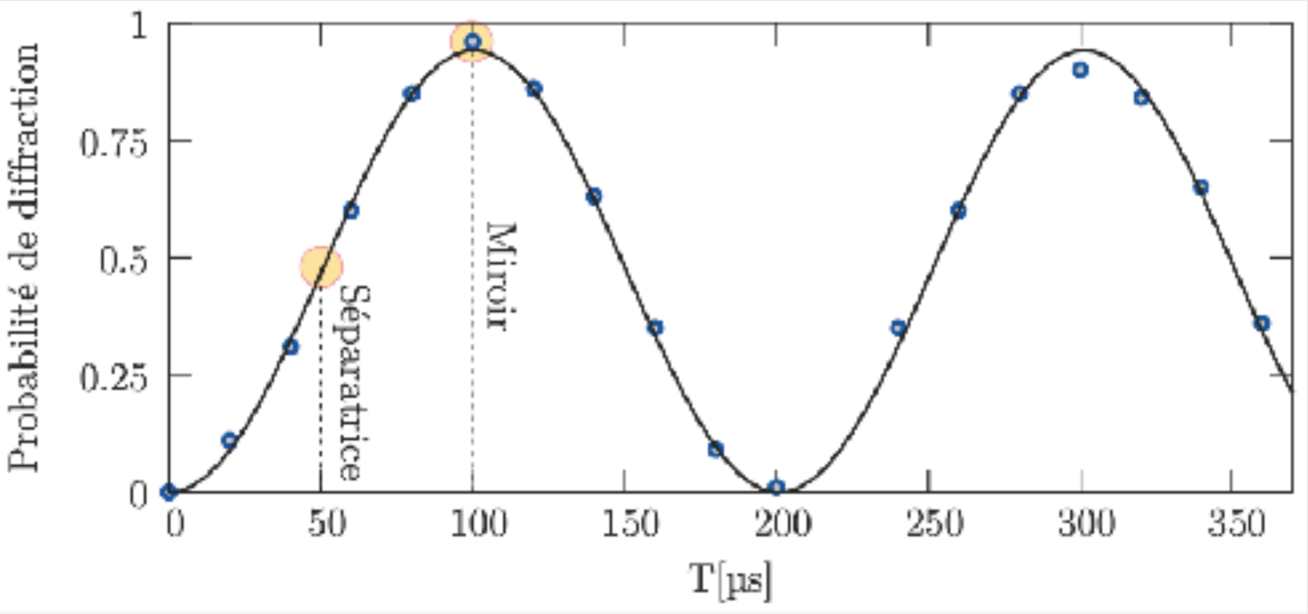
*Gould et al. PRL **56**, 827 (1986)*

Calibrate lattice amplitudes

Institut d'Optique (2021)

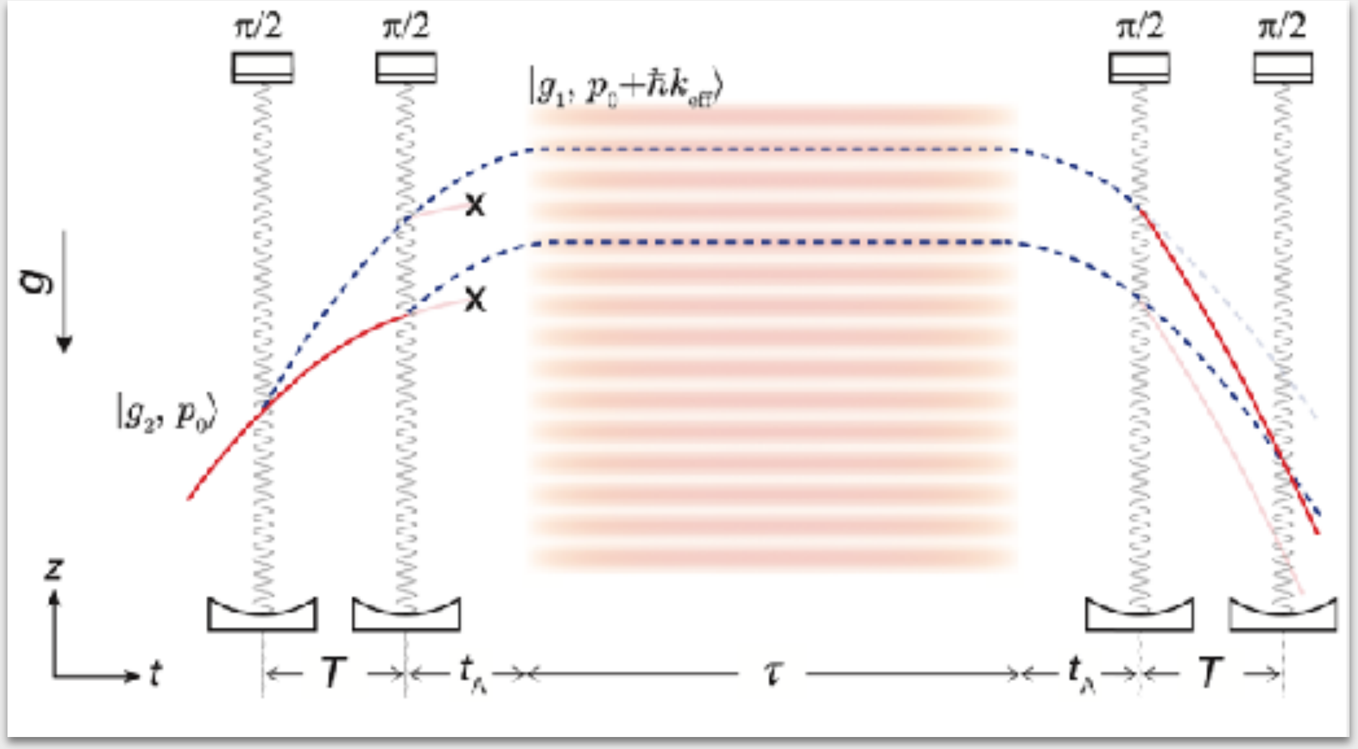


Beamsplitters and mirrors

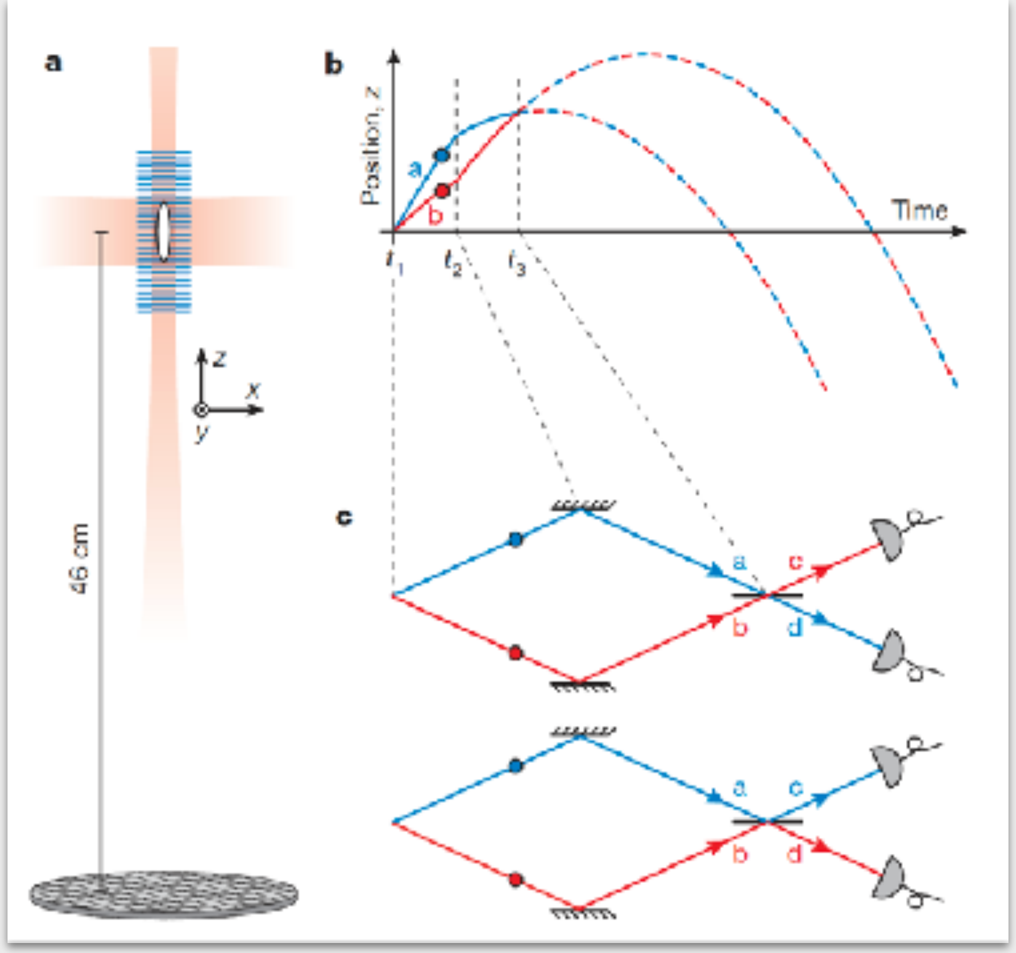


Atom optics: Hong-Ou-Mandel exp.

Atom interferometry

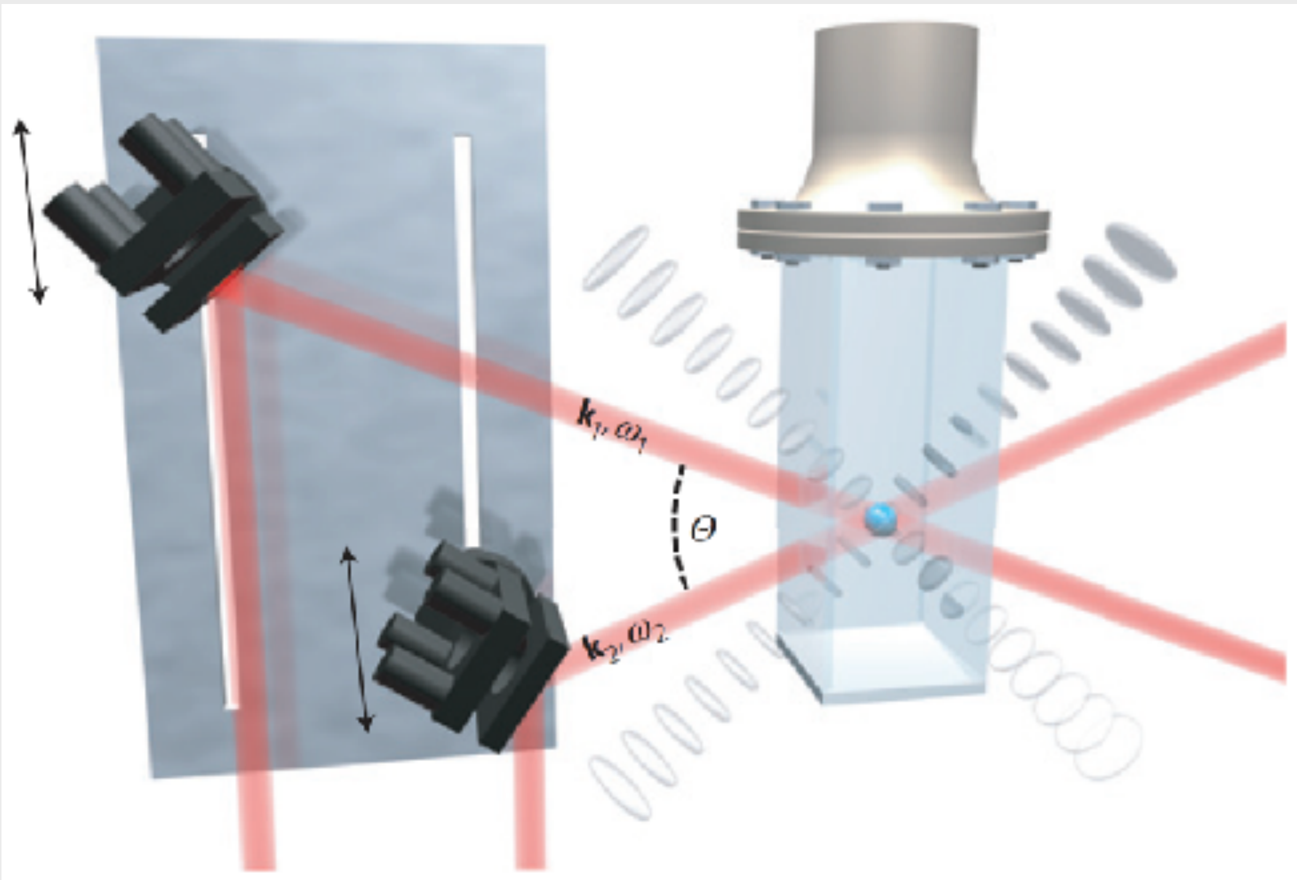


*Science **366**, 745 (2019)*



Lopes et al. Nature (2015)

Bragg diffraction: dynamical structure factor



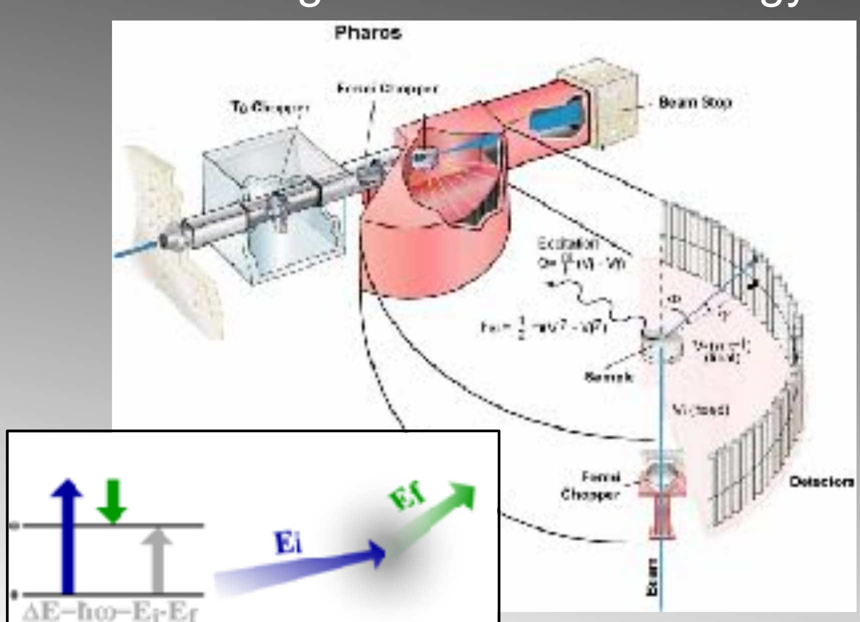
Ernst et al. Nat Phys. (2010)

Momentum transfer: $\mathbf{q} = \mathbf{k}_1 - \mathbf{k}_2$

Energy transfer: $\hbar\omega = \hbar(\omega_1 - \omega_2)$

If the perturbation is small (linear response), measure of the **dynamical structure factor** $S(\mathbf{q}, \omega)$

Neutron scattering in Superfluid Helium: exchange momentum & energy



$$S(\mathbf{q}, \omega) = \frac{1}{Z} \sum_{i,f} e^{-\beta E_i} |\langle \phi_f | \psi^\dagger(\mathbf{q} - \mathbf{k}) \psi(\mathbf{k}) | \phi_i \rangle|^2 \, \delta(\hbar\omega + E_f - E_i)$$

For a given momentum transfer, only one (or a few) energy transfer would resonantly excite the system

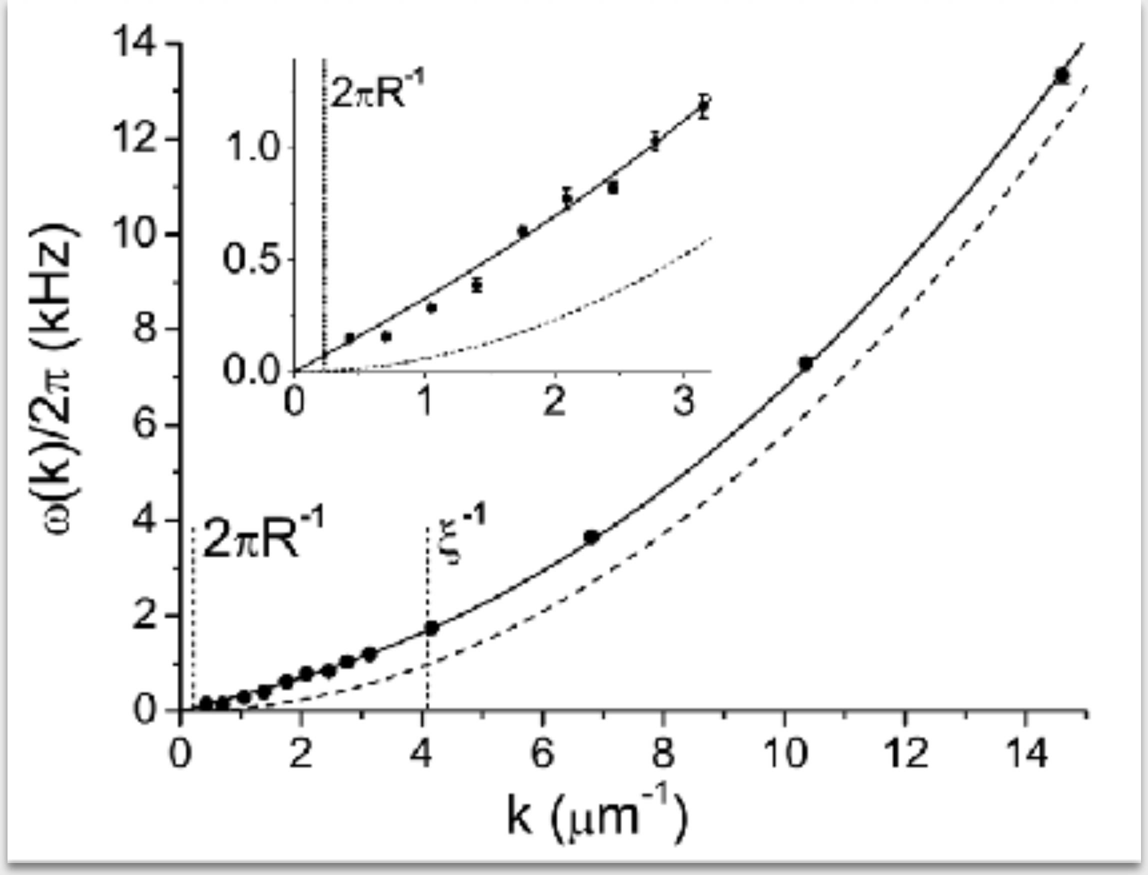
Dispersion relation of interacting BECs

$$S(\mathbf{q},\omega)=\frac{1}{Z}\sum_{i,f}e^{-\beta E_i}|\langle\phi_f|\psi^\dagger(\mathbf{q}-\mathbf{k})\psi(\mathbf{k})|\phi_i\rangle|^2\,\delta(\hbar\omega+E_f-E_i)$$

Start from a BEC with $q=0$

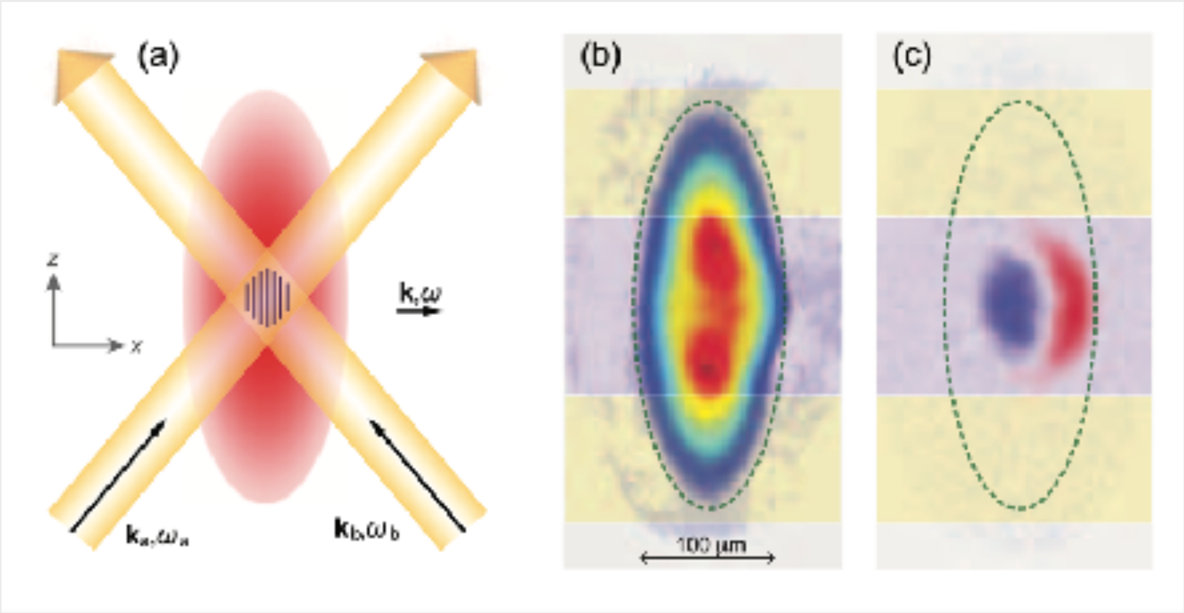
$$\delta(\hbar\omega+\epsilon(\mathbf{q})-\epsilon(\mathbf{0}))$$

Observation of **Bogoliubov spectrum of excitations**, with phonons at low momenta

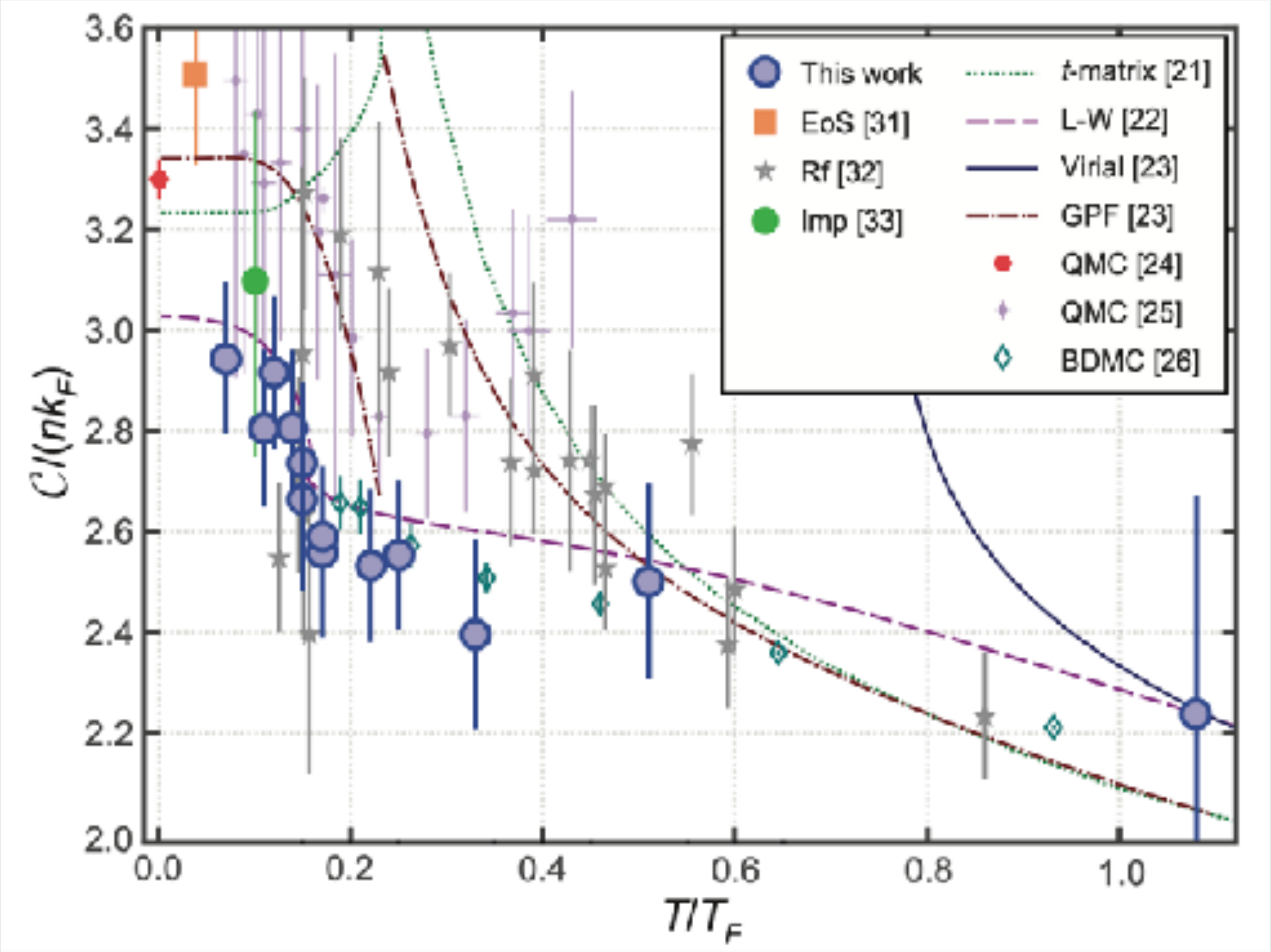


PRL ***88****, 120407 (2002)*

Probing strongly-correlated fermions

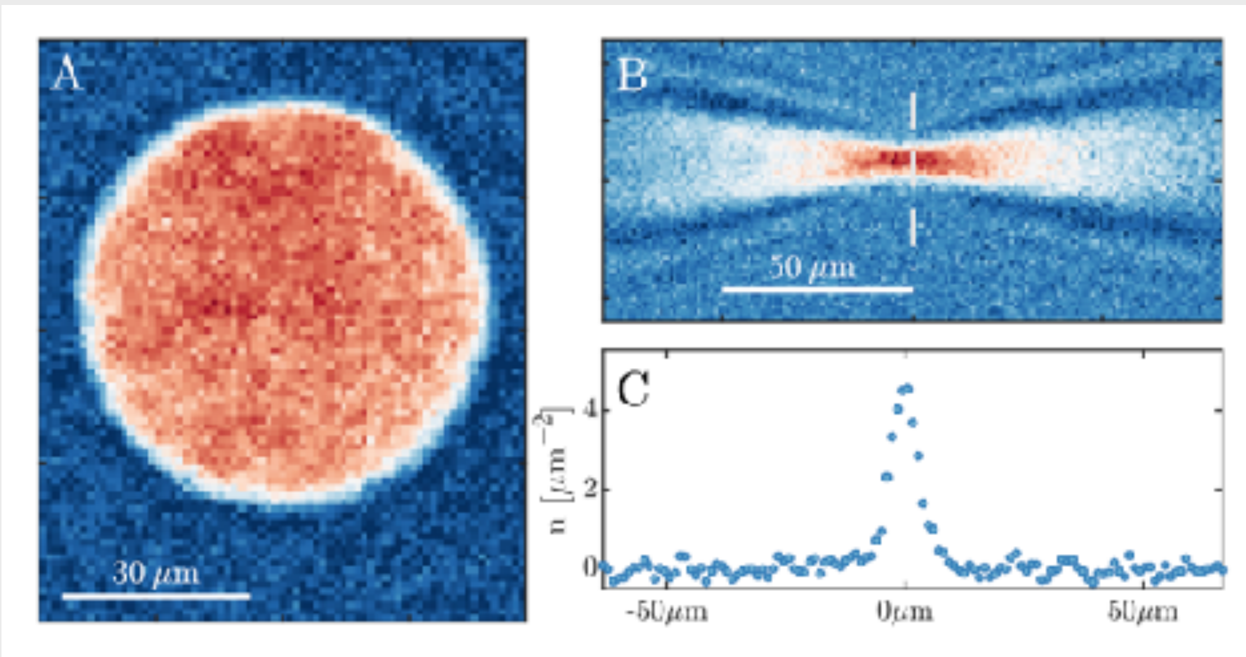


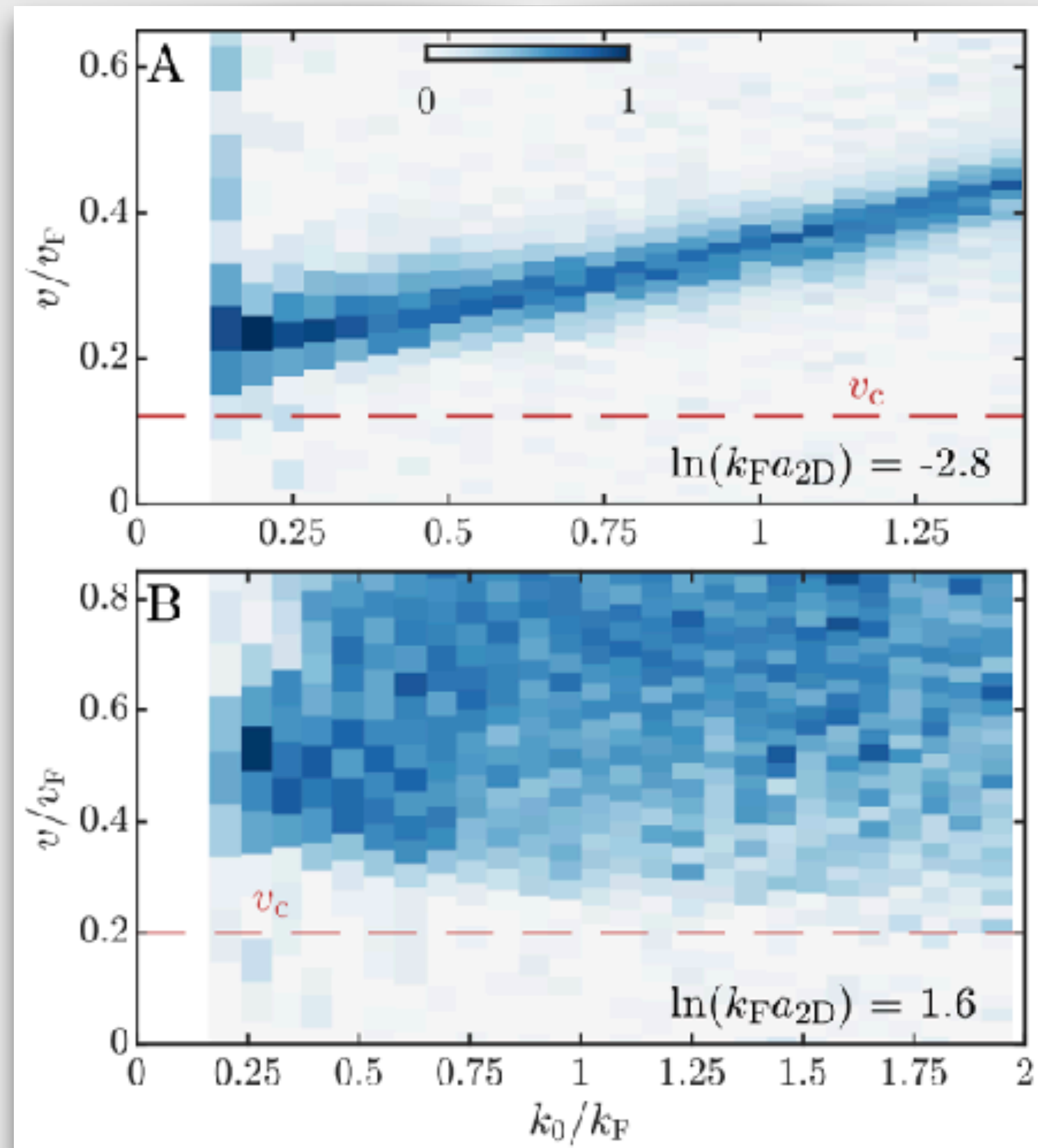
At large momentum transfer, dynamical structure factor contains information about short-distance two-body wave-function: **measure of Tan's contact**



*Carcy et al. PRL **122**, 203401 (2019)*

Superfluidity in 2D correlated fermions





Superfluidity observed in correlated 2D Fermi gas: no excitations (either phonons or pairs) below critical velocity

*Sobirey et al. Science **372**, 844 (2021)*