The physics of cold atoms
from fundamental problems
to time measurement and quantum technologies

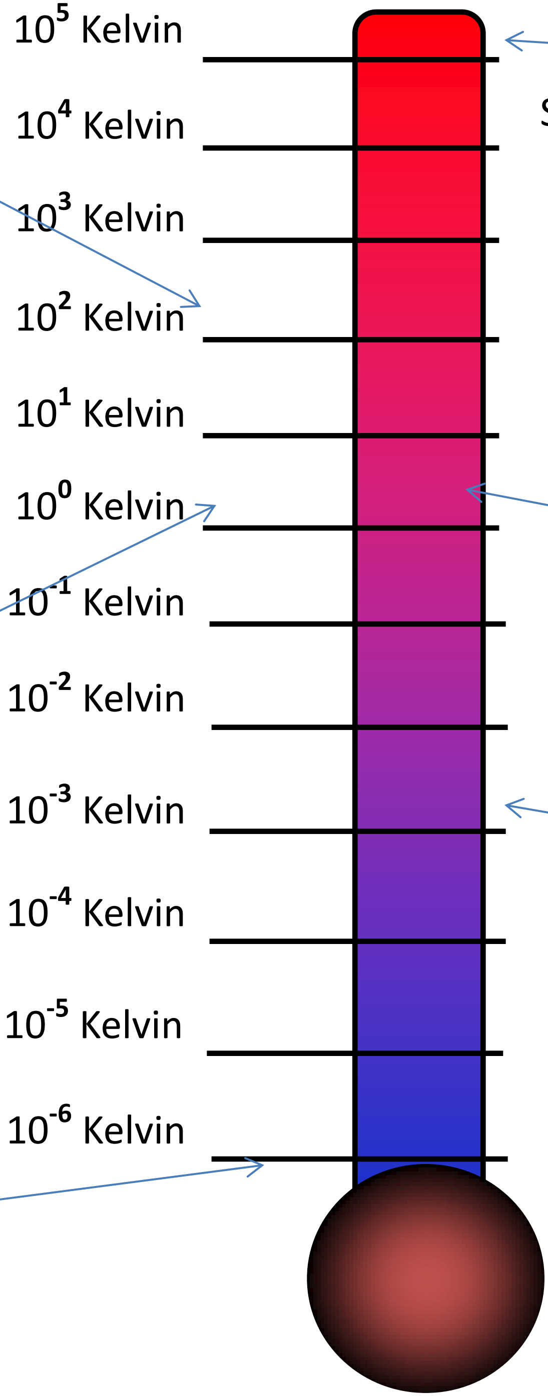
Michèle Leduc

Laboratoire Kastler Brossel
Physique quantique et applications

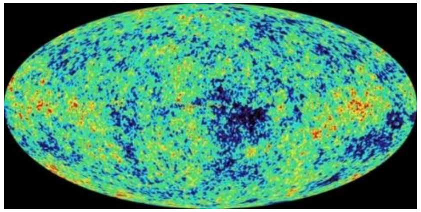
cnrs Ens UPMC SORBONNE UNIVERSITÉS

Institut Francilien de Recherche sur les Atomes Froids
IFRAF

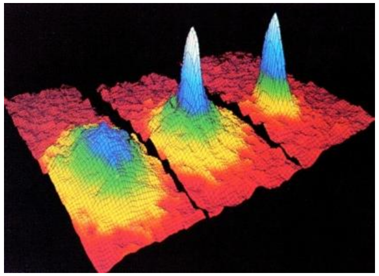
Lima, 20 October 2016



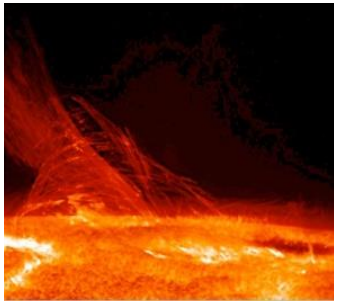
earth



Cosmic background radiation

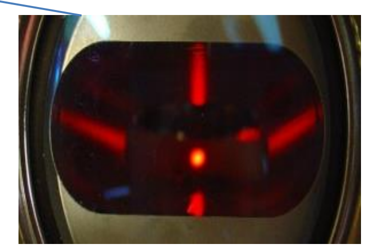


Bose-Einstein-Condensate



Surface of the sun

Liquid helium



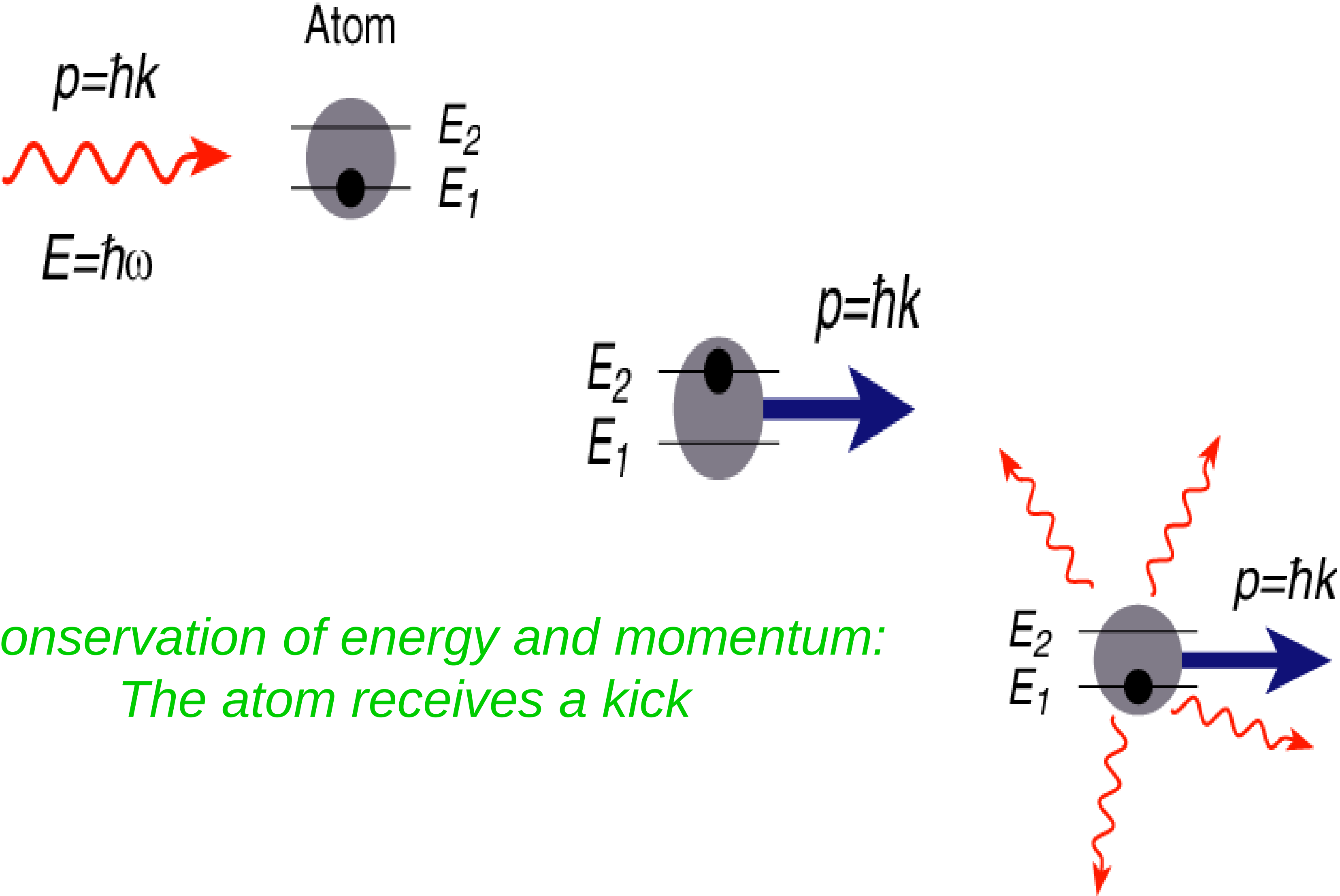
Cloud of ultracold atoms

Outlook

- Principles of laser cooling and trapping
- Bose-Einstein condensation
- Quantum simulations with cold atoms
- Cold atom instruments (clocks, gravimeters…)
- Quantum communication

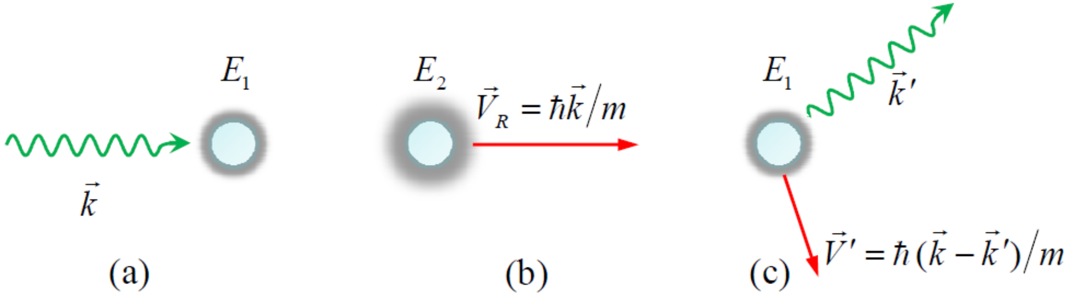
Principles

Cooling an atom with radiation pressure

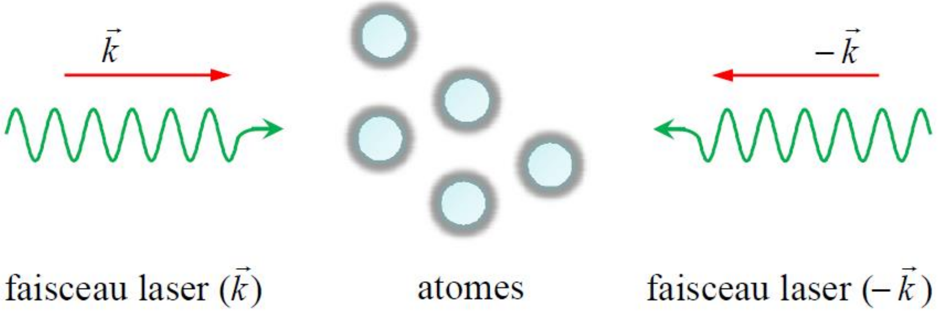


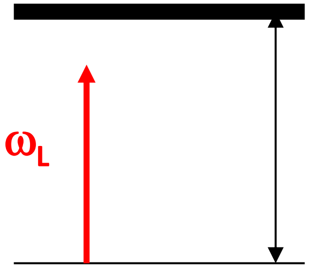
Conservation of energy and momentum:
The atom receives a kick

Slowing an atom with radiation pressure

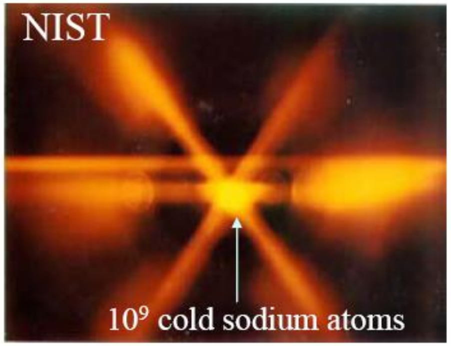


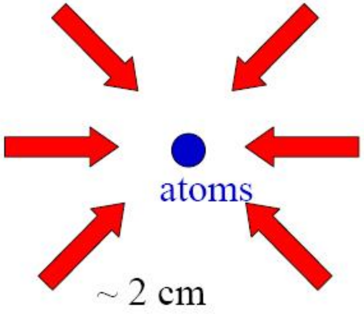
Doppler cooling : friction force





3D trapping
Doppler friction forces

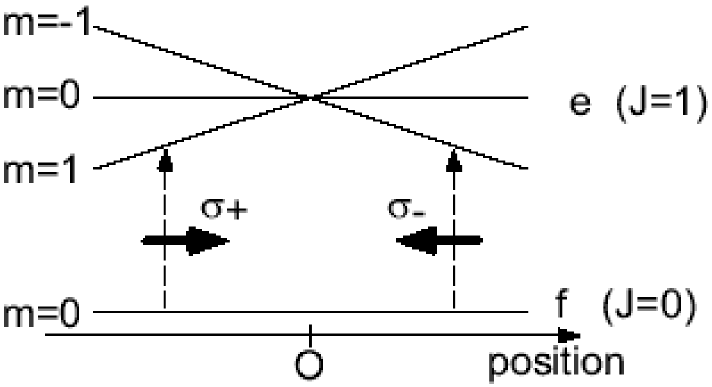




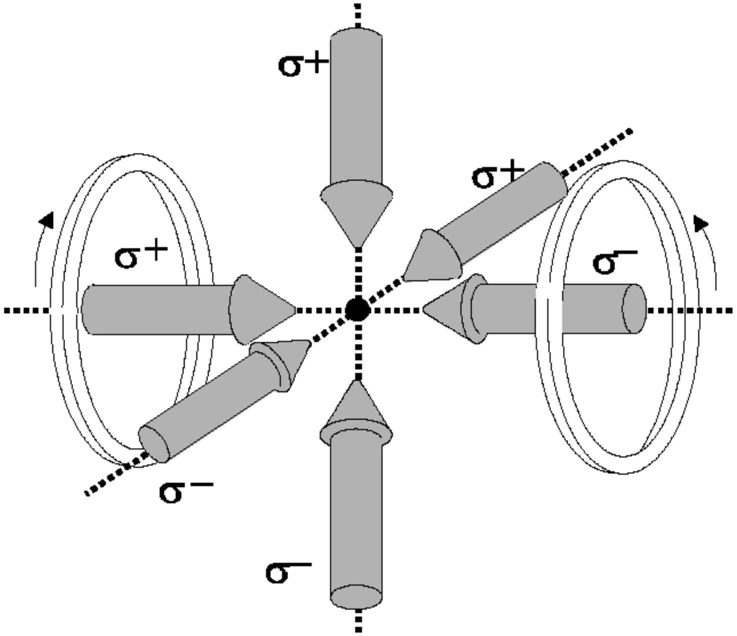
1st optical molasses: Bell Labs (S. Chu et al), 1985

Optical molasses
Temperature : 1 à 10 micro K, velocity 7mm/s

The magneto-optical trap



Restauring force

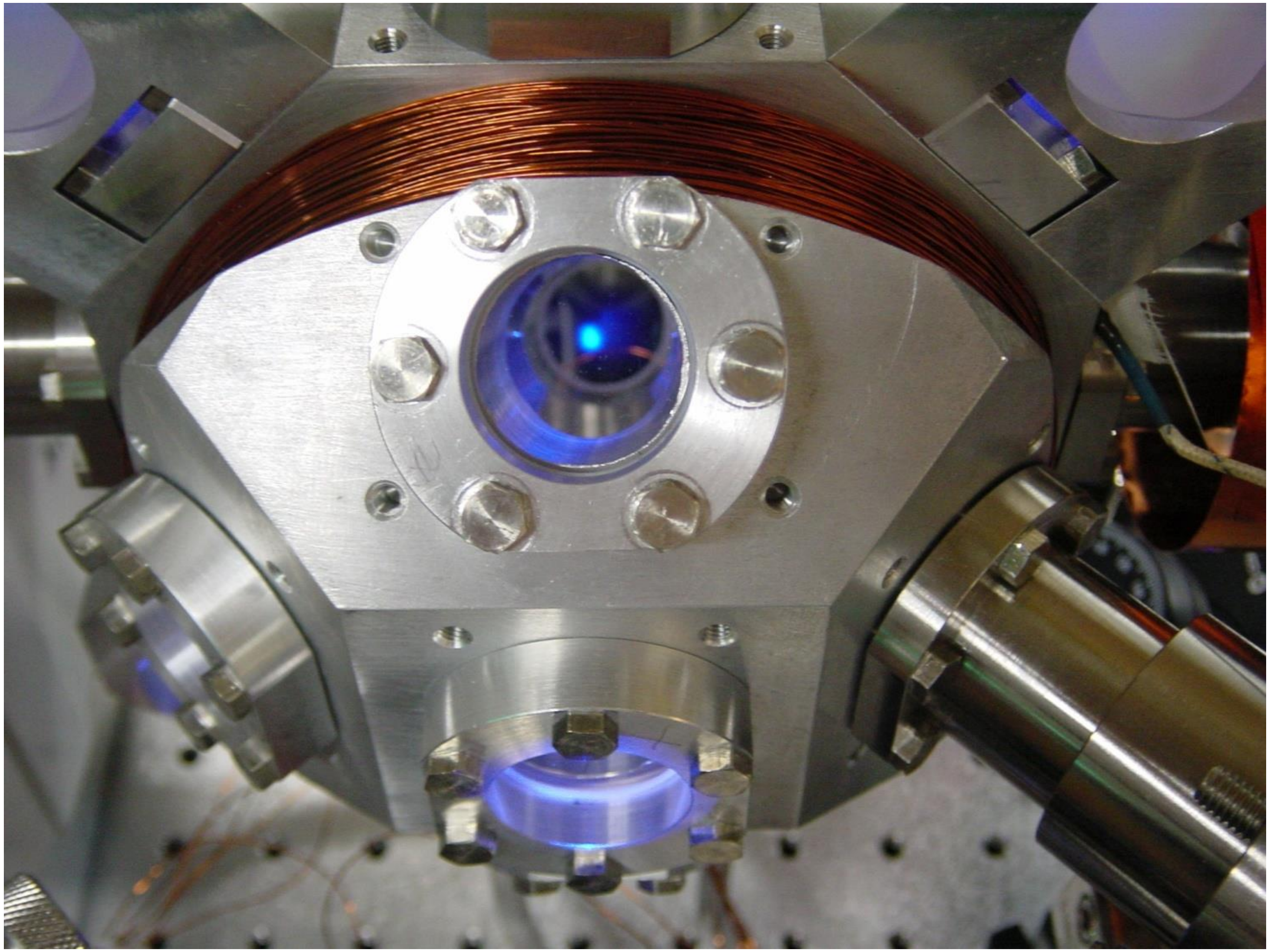


Coils anti-Helmholtz
Polarised light

1 billion atoms at 1 mK

Universal tool in atomic physics

Strontium atoms in a MOT



Cooling and trapping of atoms

1997 Physics Nobel prize

W. Phillips, S. Chu and C. Cohen-Tannoudji

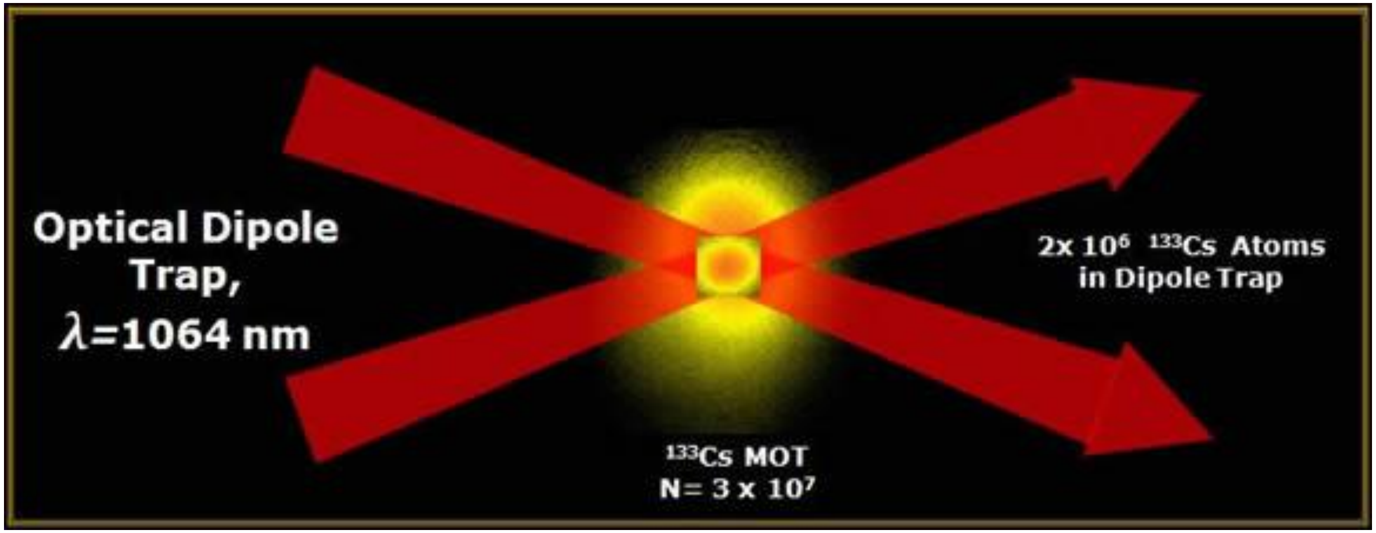
Zeeman Slower
Molasses

First realization of
the magneto-optical
trap

Sub-Doppler
cooling mechanism

"for development of methods to cool and trap atoms with laser light"

The dipolar optical trap



Laser beams focussed and detuned from resonance

Atoms attracted to the high intensity regions

Bose-Einstein Condensation

A pure quantum phenomenon

De Broglie hypothesis:
With every particle of matter with mass ***m*** and velocity ***v*** a real wave must be associated related to the momentum by the equation:

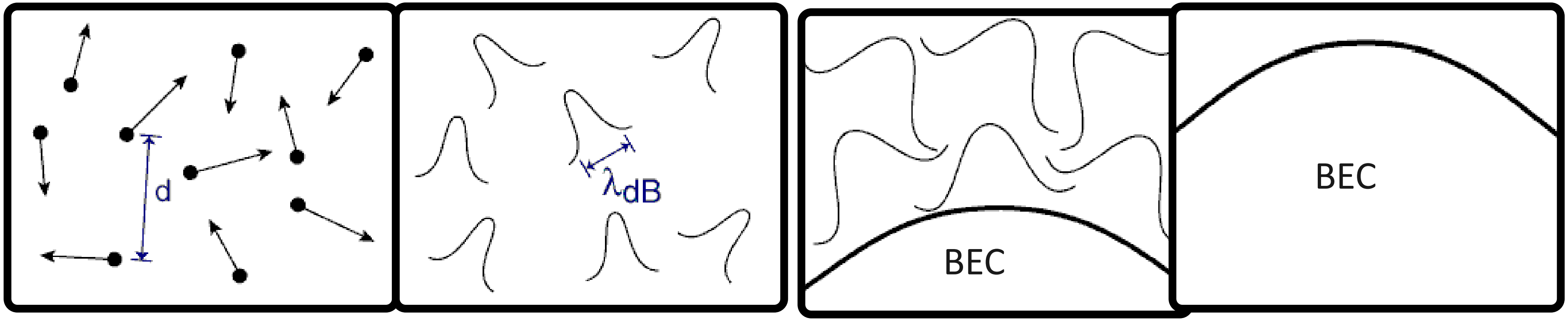
$$\lambda_{dB} = \frac{h}{mv}$$

High temperature:
$\lambda_{dB} << d$
Particles like

Low temperature:
$\lambda_{dB} > 10^{-10}$ m
Wave behaviour

$T=T_c$: $\lambda_{dB} > d$
Overlap of the wave functions

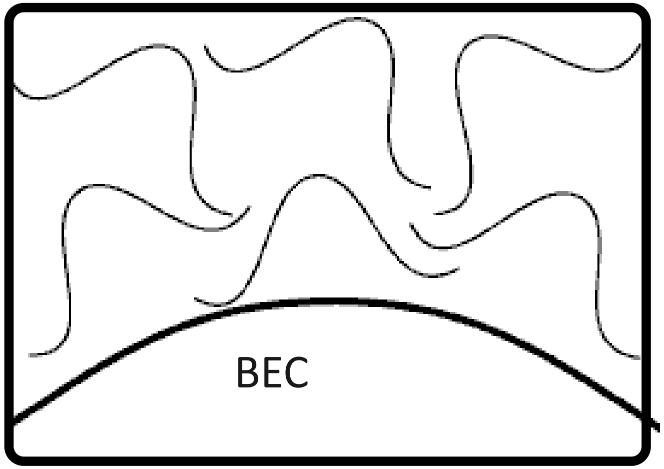
T=0 K :
All particles are in the ground state



Density in phase space

$T=T_c$: $\lambda_{dB} > d$

Overlap of the wave functions



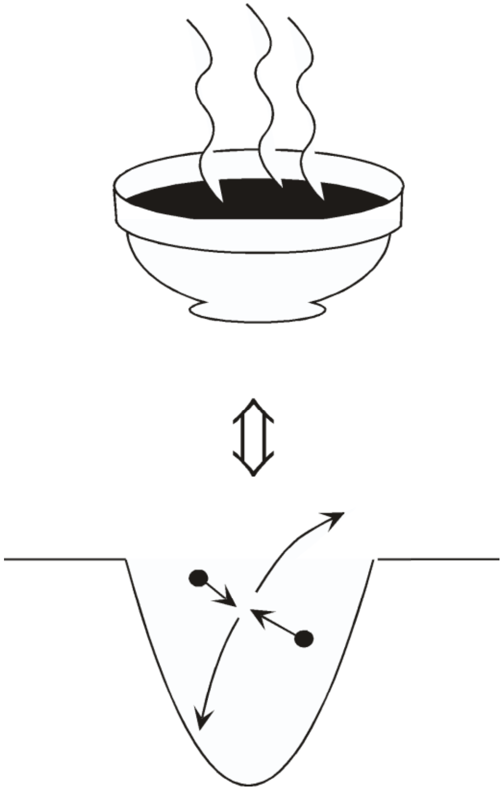
A phase transition occurs when

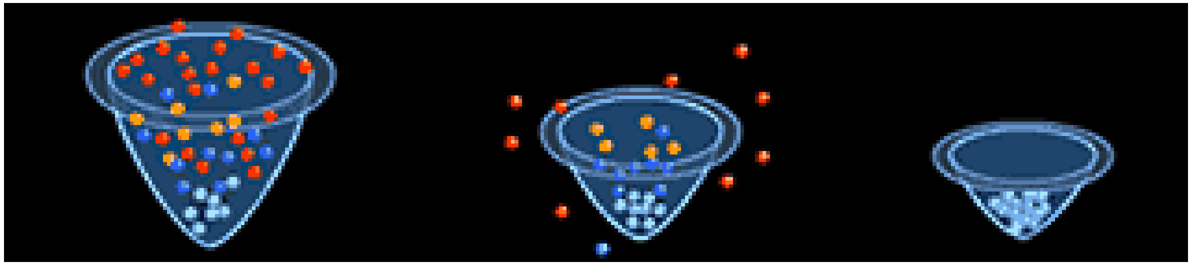
$$n\lambda_{dB}^3 \sim 1$$

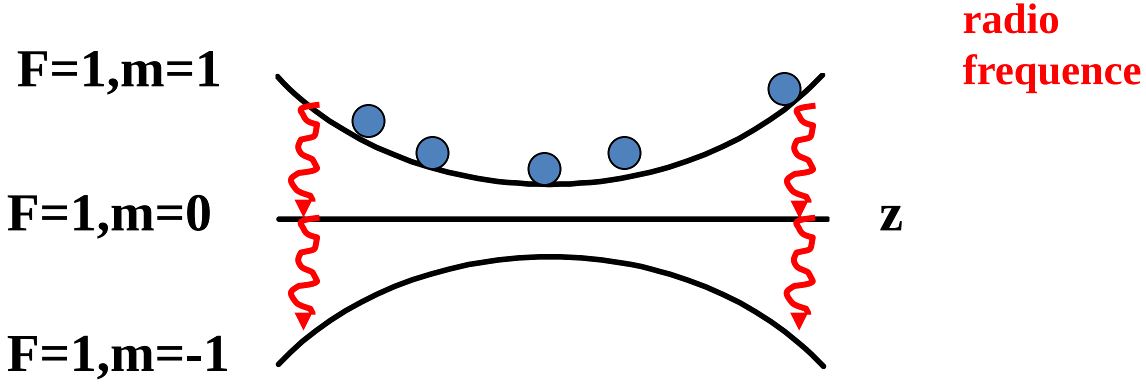
In a magneto-optical trap

$n\lambda^3 = 10^{-7}$

Evaporative cooling

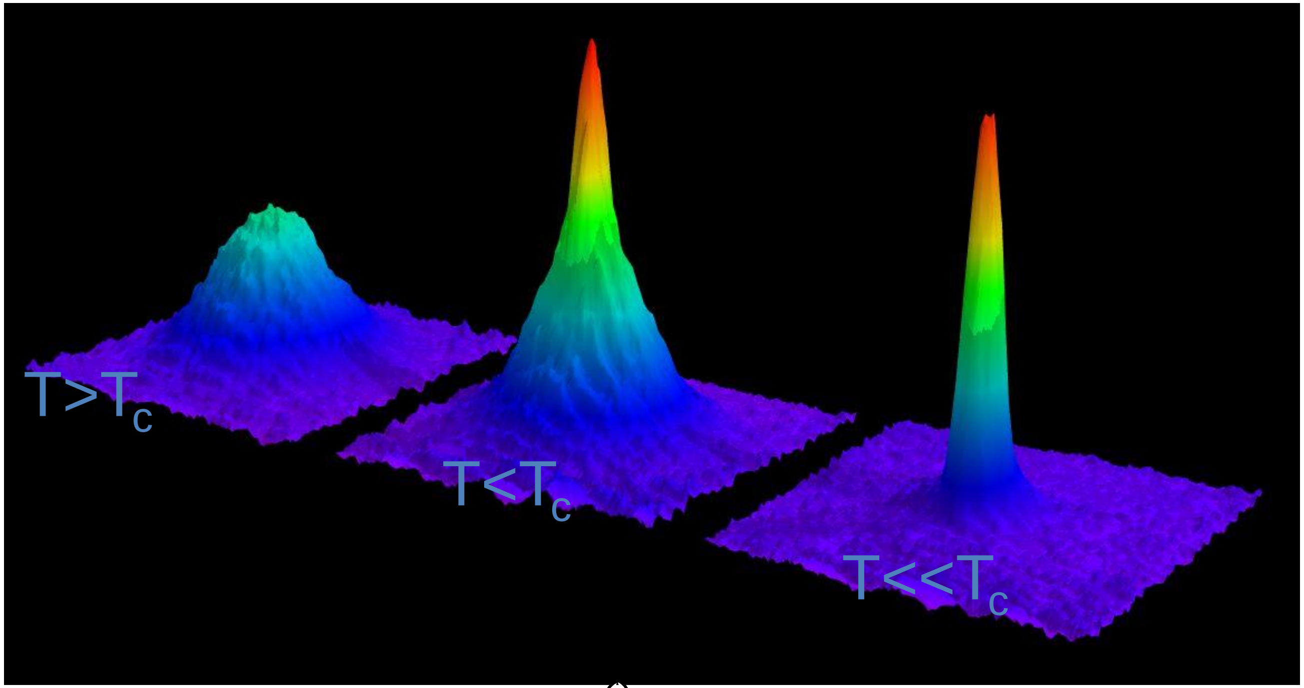


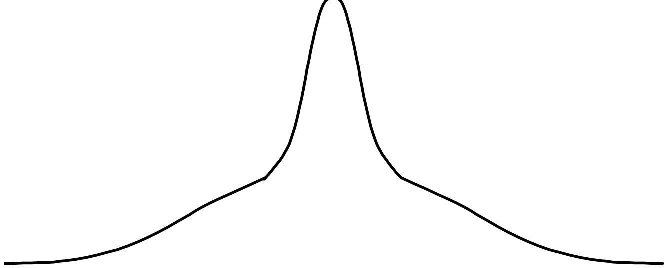




Based on energy redistribution by elastic collisions

Observation of Bose-Einstein Condensation 1995





First condensates of dilute gases in 1995

E. Cornell

Rb

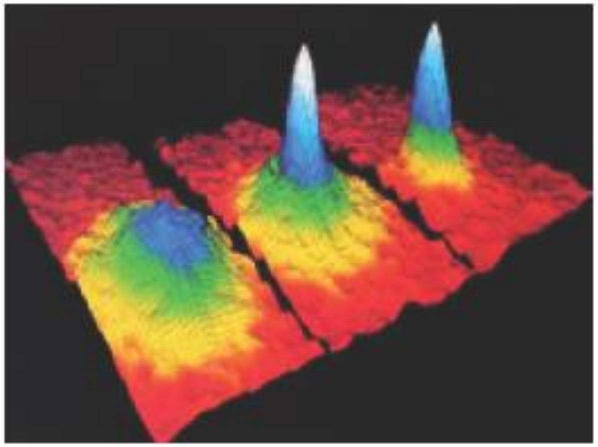
C. Wieman

Na

W. Ketterle

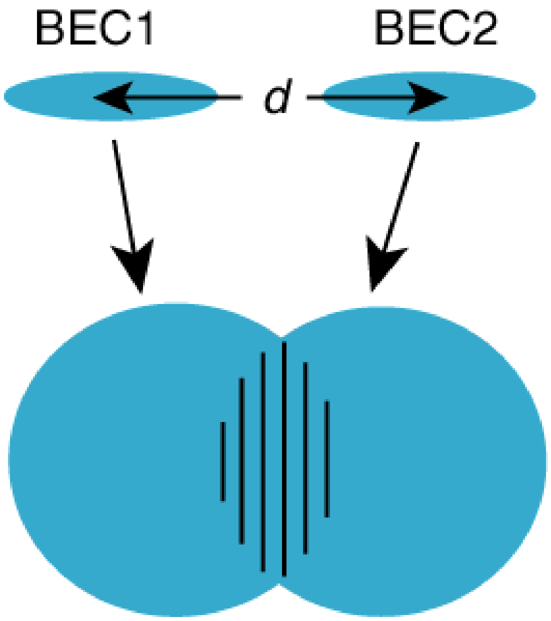
prix Nobel de
physique 2001

$T > T_C$

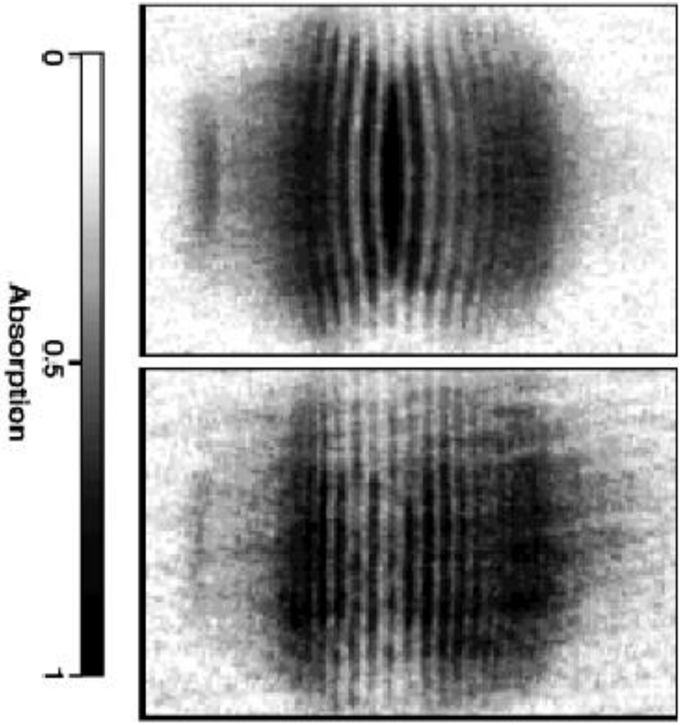


$T < T_C$

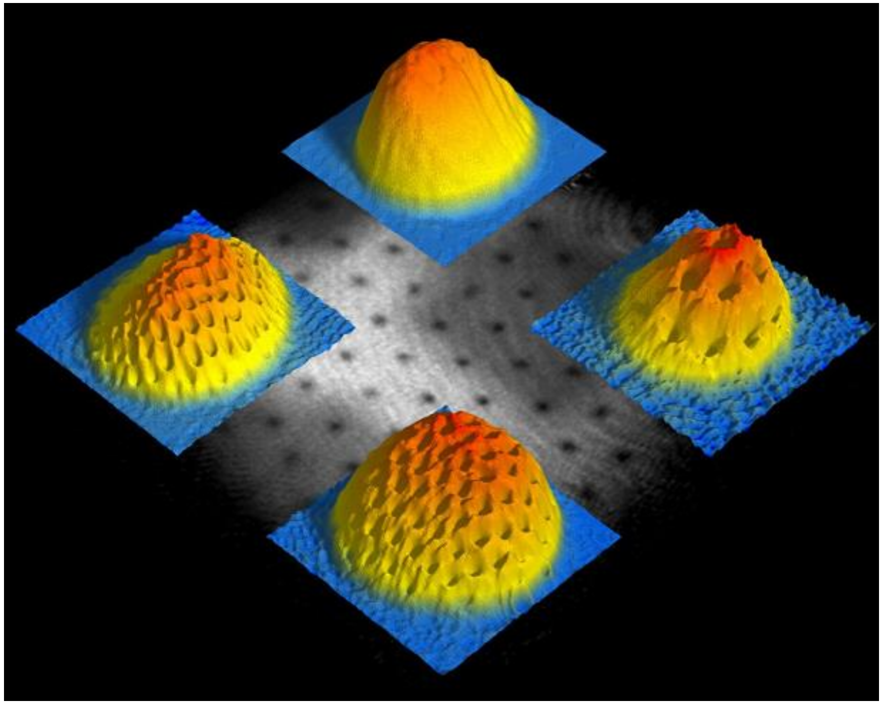
Interference between
2 Bose-Einstein Condensates

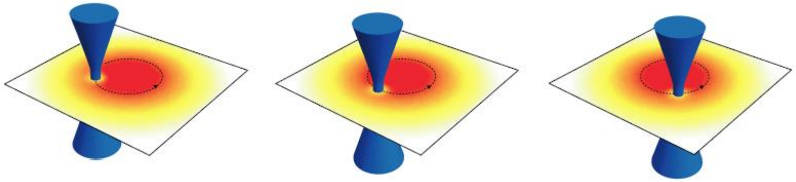


M. R. Andrews *et. al.*
Science 275, ff. 637, 1997

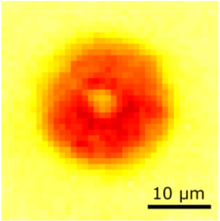


Vortices generation in a condensate





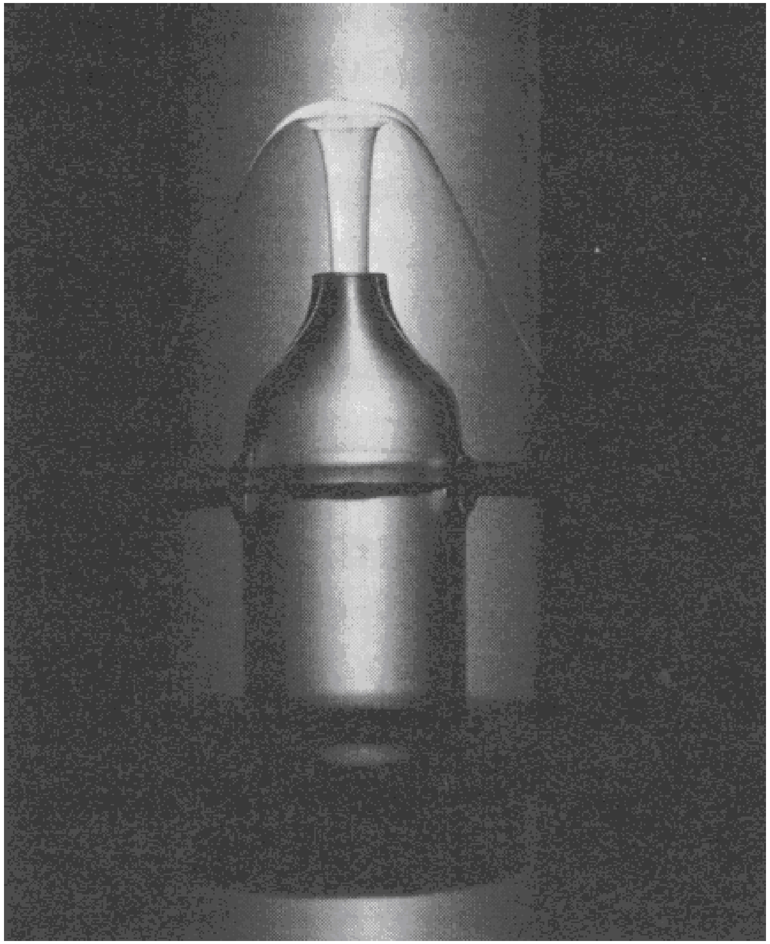
Stirring a laser spoon
with increasing velocity



Lattice of vortices in a BEC
Similar to Abricosov lattices in super conductors in magnetic fields

Bose-Einstein Condensates are superfluid

Manifestations Bose-Einstein statistics



- Prediction of gas condensation by Bose and Einstein (1924)

- Discovery of superfluidity of liquid helium (Kapitza, Allen, Misener, 1938)

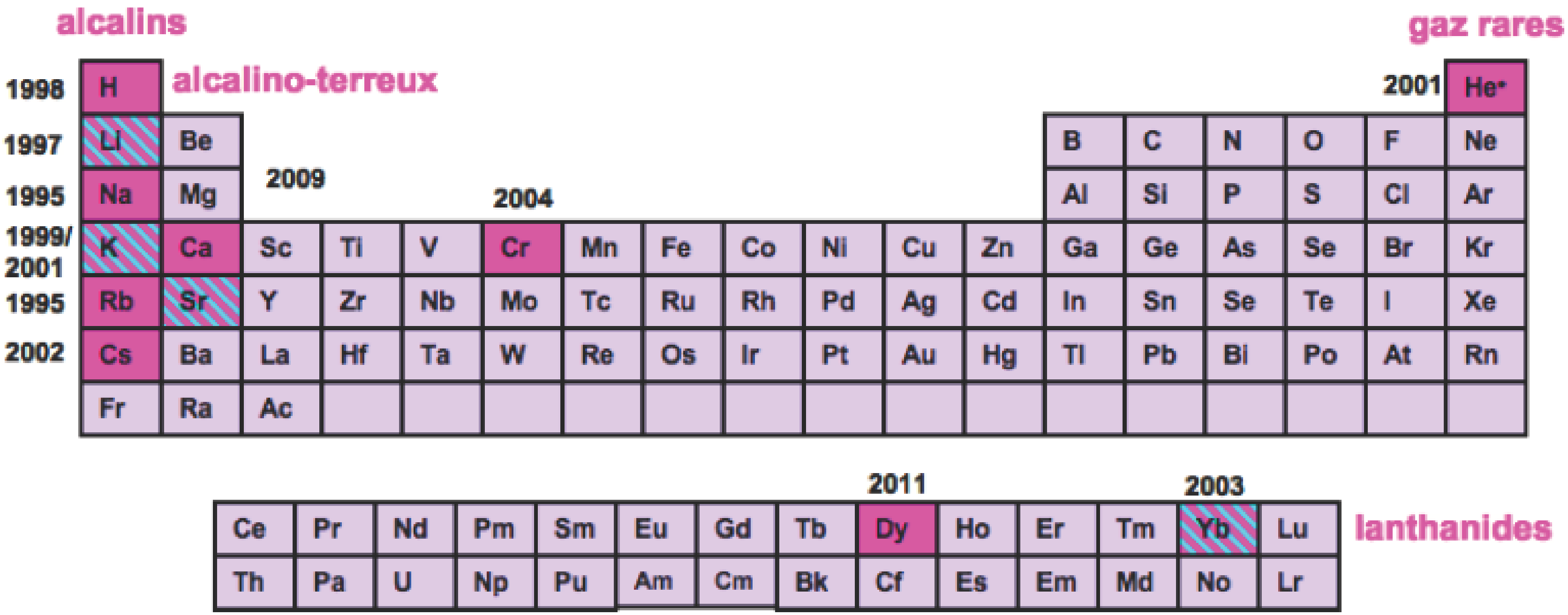
- London makes a connection between superfluidity and BEC of gases

- Discovery of superconductivity of metals (1911 et 1954)

- Discovery of BEC quantum gases (1995)

- Evidence for the superfluidity of BEC gases (1998)

Atomic Bose-Einstein Condensates



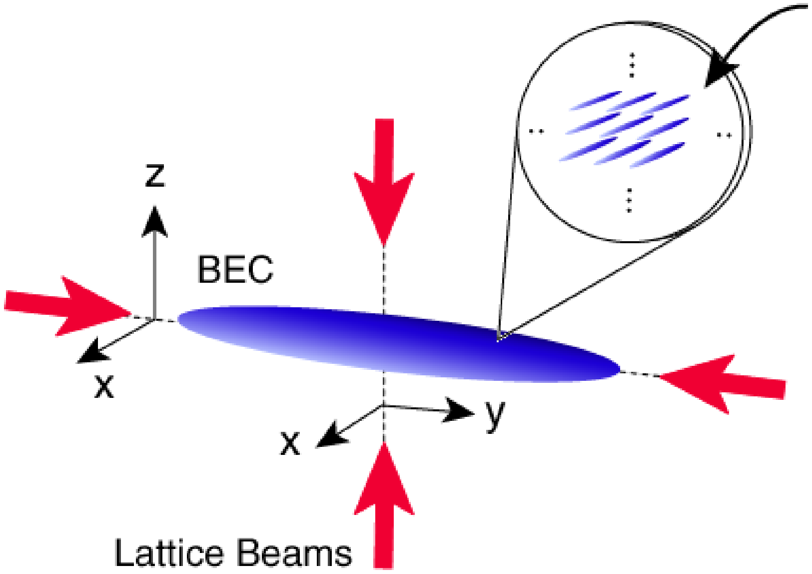
1998	H																	He*
1997	Li	Be												B	C	N	O	F	Ne
1995	Na	Mg												Al	Si	P	S	Cl	Ar
1999/ 2001	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
1995	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Se	Te	I	Xe
2002	Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
	Fr	Ra	Ac															

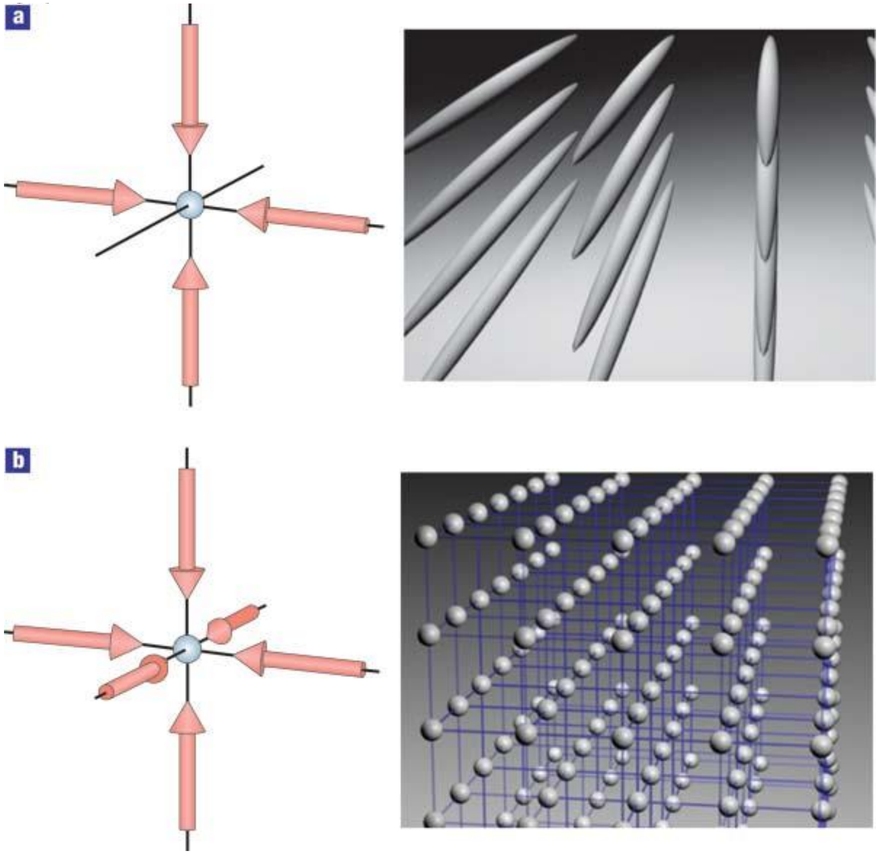
Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Em	Md	No	Lr

Quantum simulations with cold atoms

Creating a lattice potential

spacing between
lattice sites





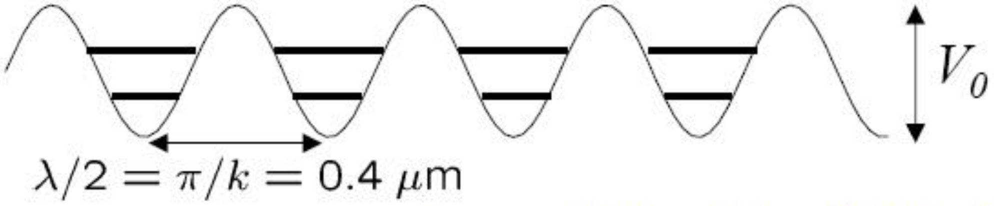
2D

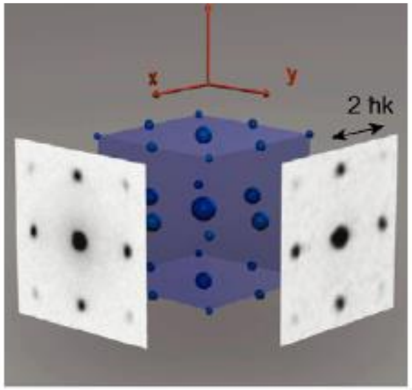
3D

1D, 2D, 3D optical lattices

Transition BEC / Mott insulator

3D periodic potential created by a laser standing wave

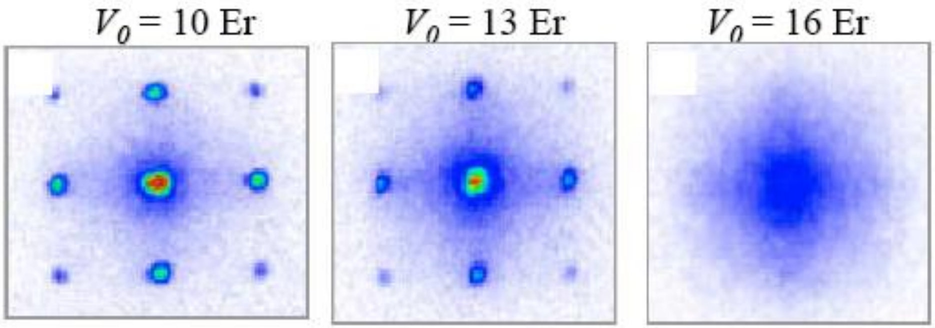




~ one atom per lattice site and 10^5 sites

For small V_0, tunnelling dominates and maintains full coherence over the lattice:

→ time of flight with Bragg peaks



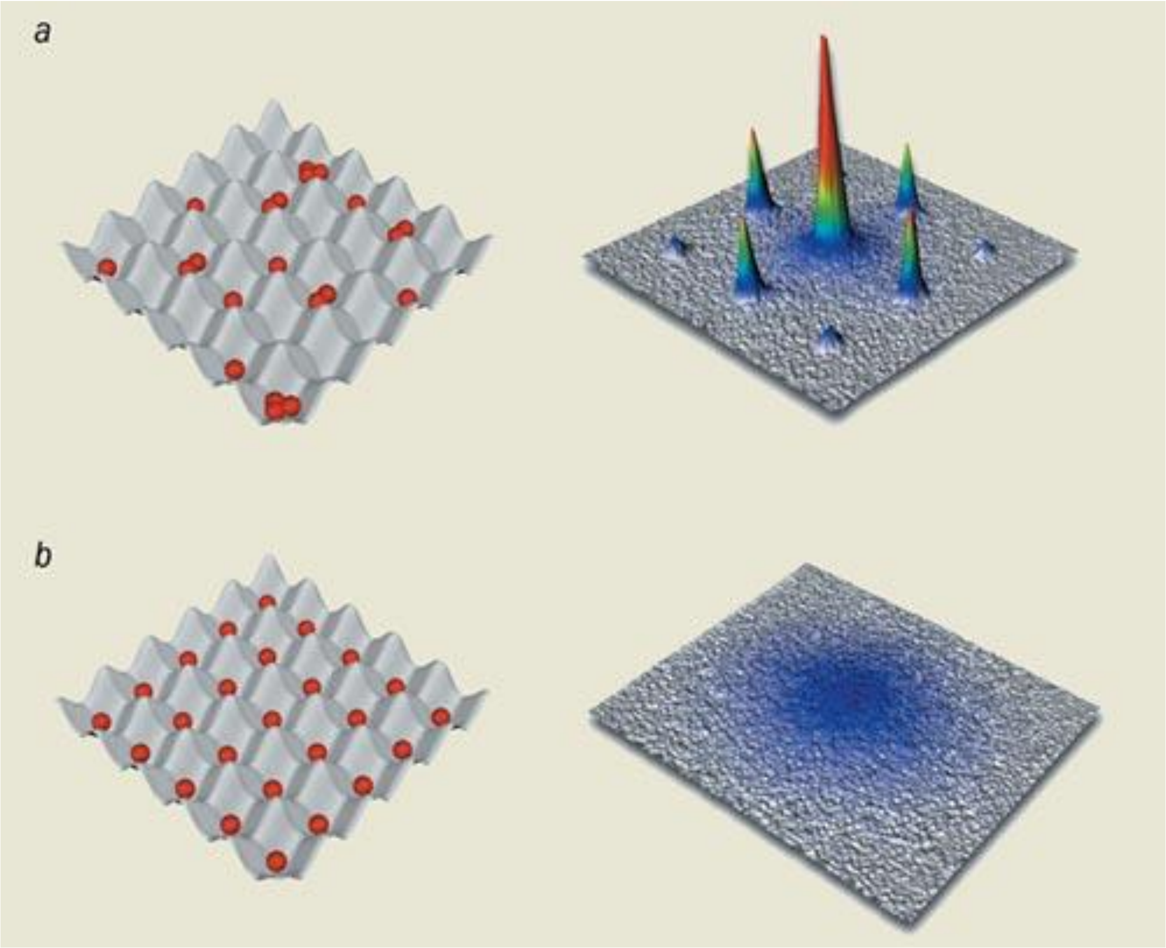
For larger V_0, repulsive interactions dominate over tunnelling:
the system evolves to a state with « exactly » one atom/site

$E_r = \hbar^2 k^2 / 2m$

Munich 2002

coherence is lost!

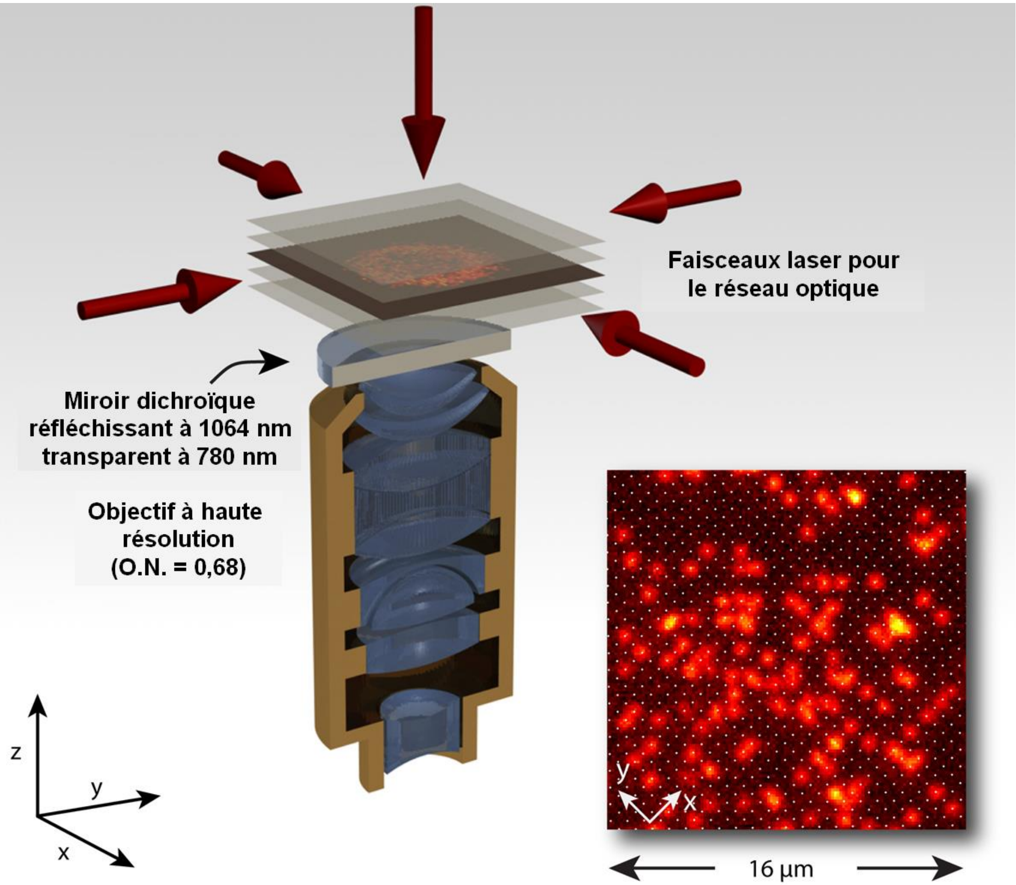
From superfluid to Mott insulator



superfluide

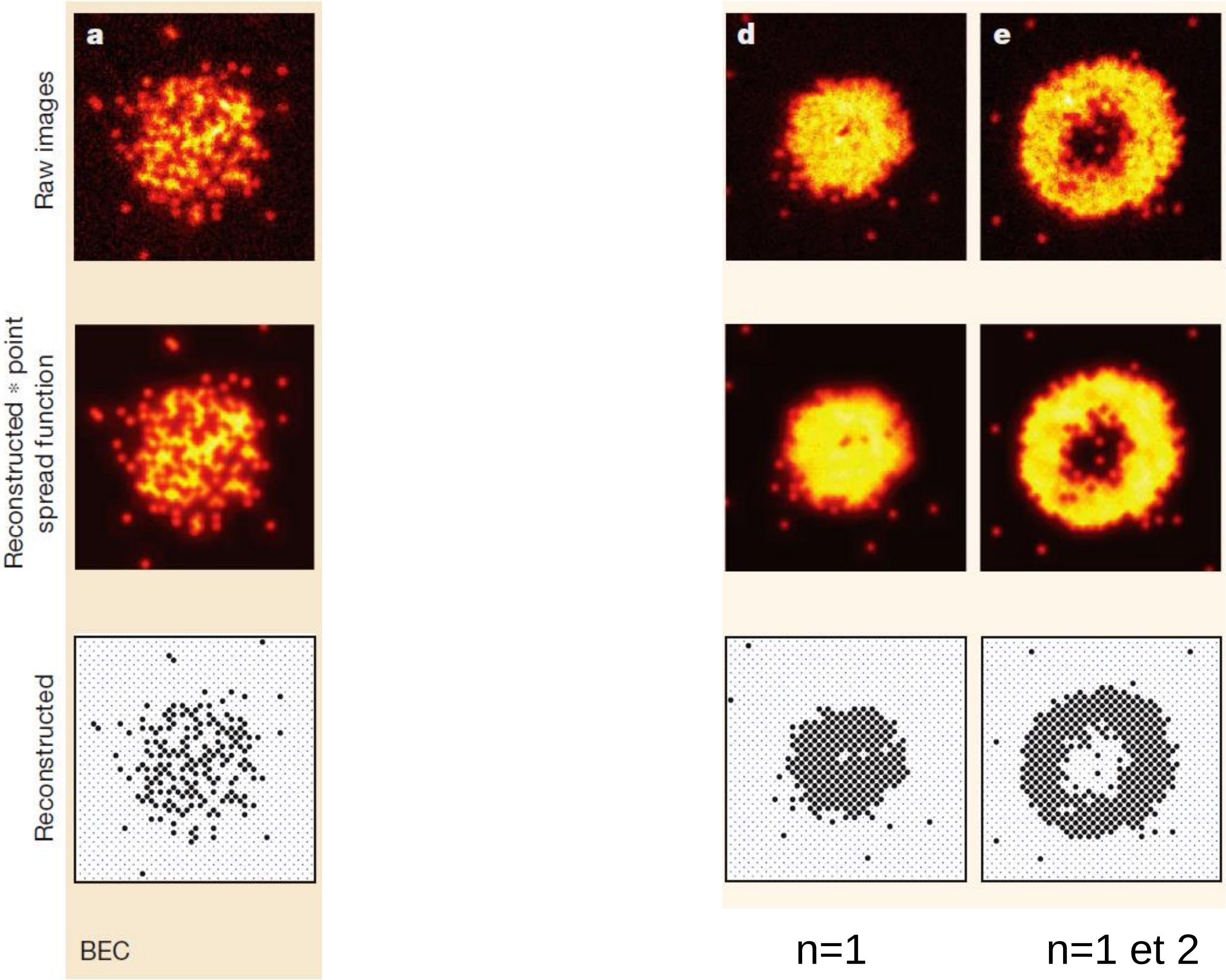
Isolant de Mott

Images of individual atoms in an optical lattice



MPQ Munich 2010

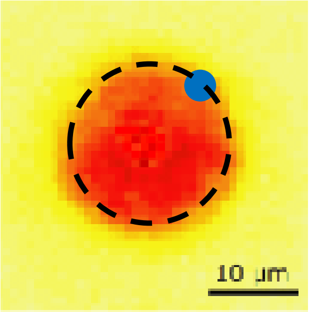
J. Sherson, C. Weitenberg, M. Endres, M. Cheneau, I. Bloch and S. Kuhr, Nature,467, 2010

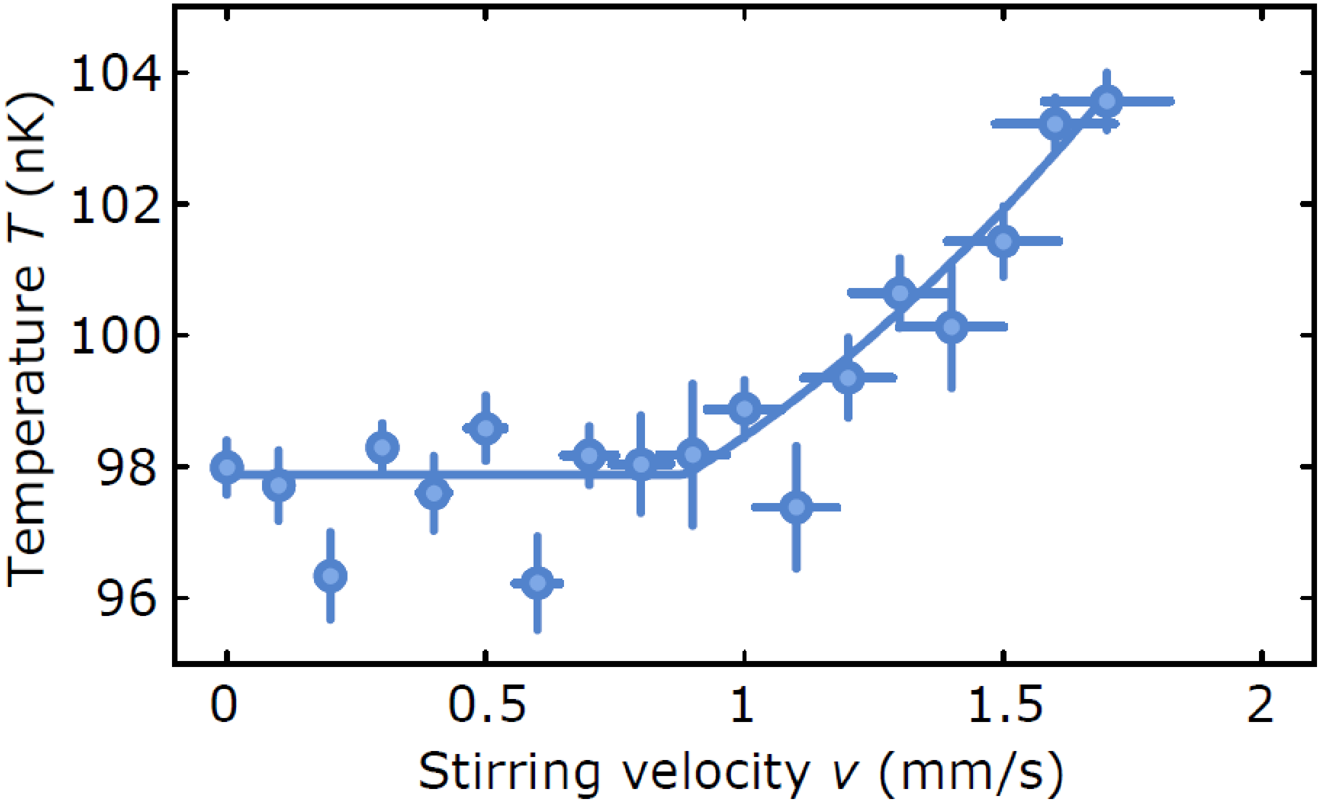


n=1

n=1 et 2

Stirring a 2D Bose-Einstein gas



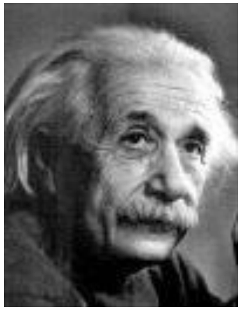


Clear evidence for a critical velocity for vortices generation

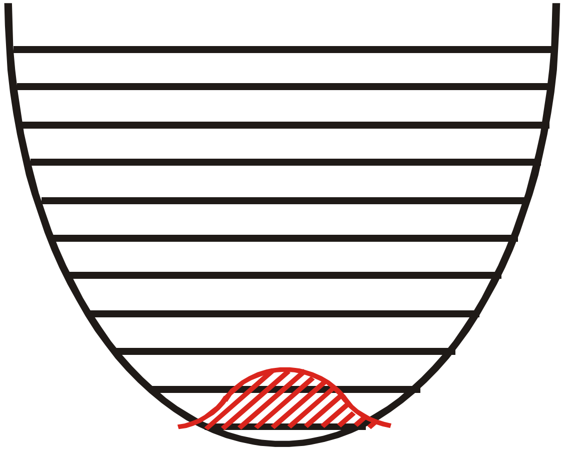
Kosterlitz-Thouless phase transition

Quantum statistics

Bose-Einstein statistics (1924)

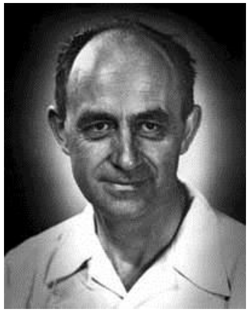


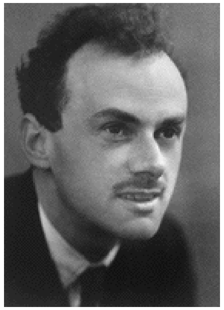
Bose-Einstein condensate



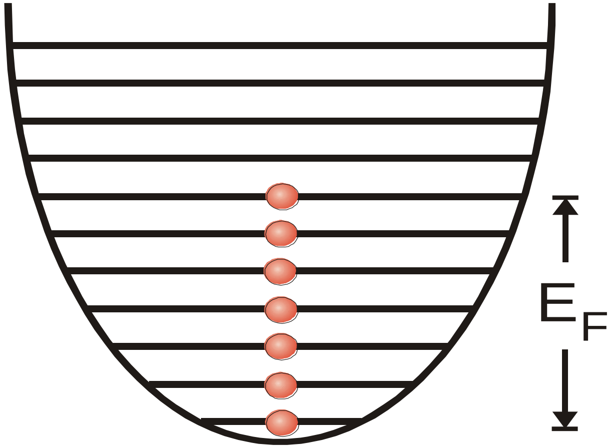
Bose enhancement

Fermi-Dirac statistics (1926)





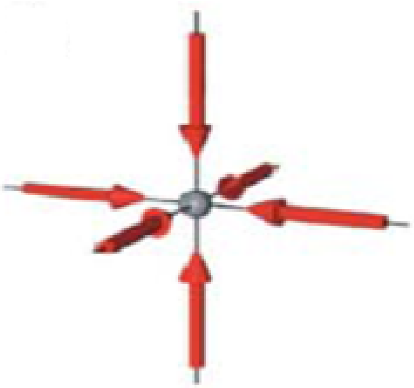
Fermi sea

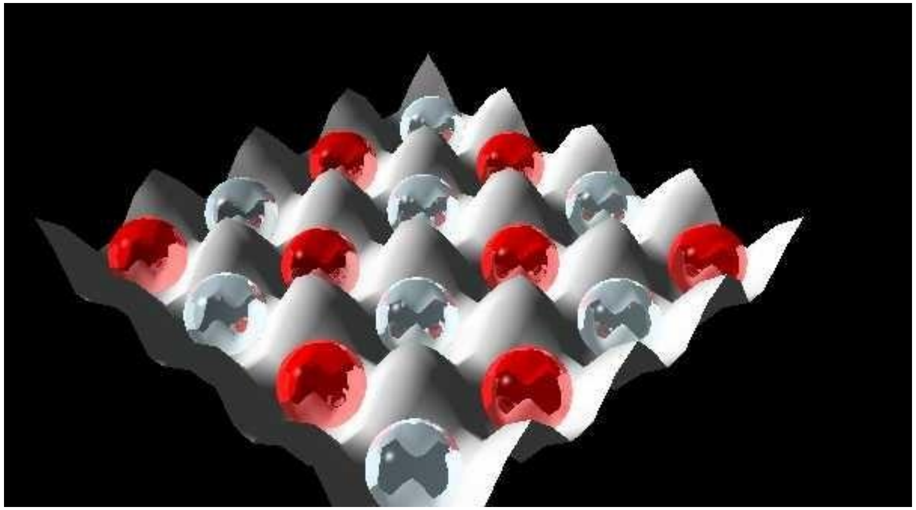


Pauli Exclusion

Quantum simulation of n-particles physics problems with ultracold fermions

- Artificial crystals using optical lattices
- Electrons, holes and impurities = fermions





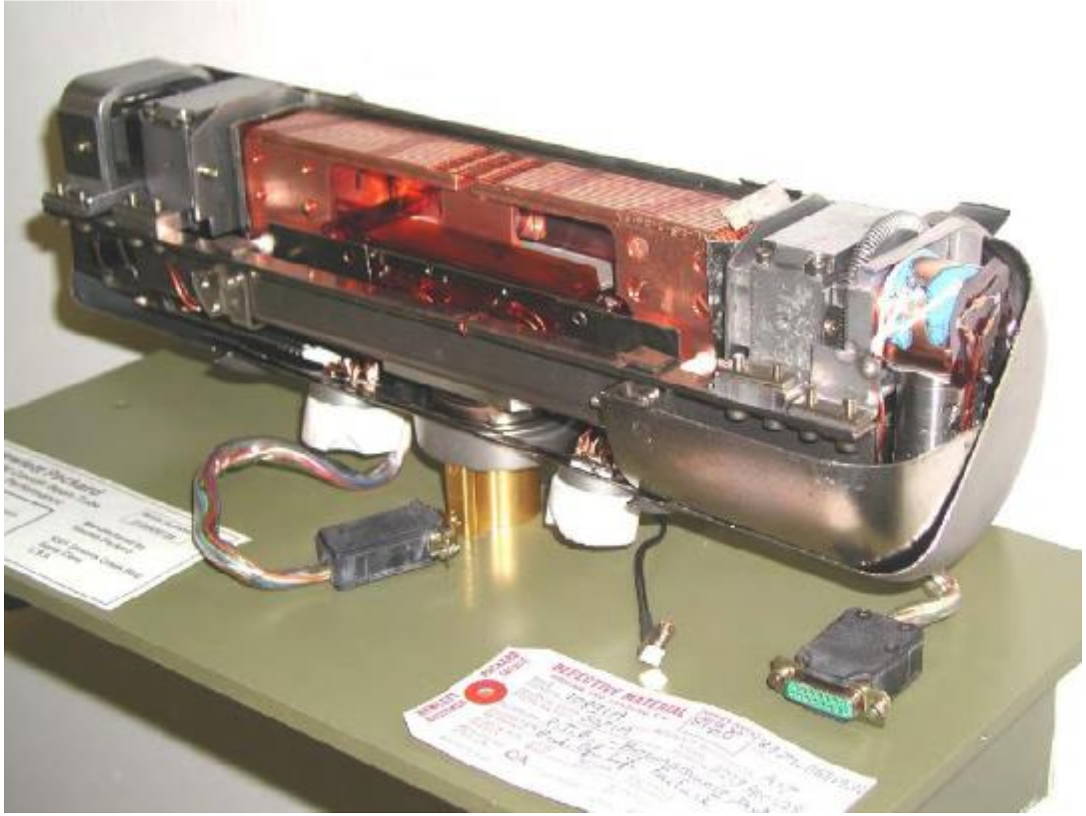
Questions:

- High Tc Superconductivity (2D)
- Anderson localization (^{40}K = impurities)
- Néel phase: antiferromagnetism
- Quantum Hall effect in 2D Fermi gas

$T_{\text{Néel}} \sim 30$ nK

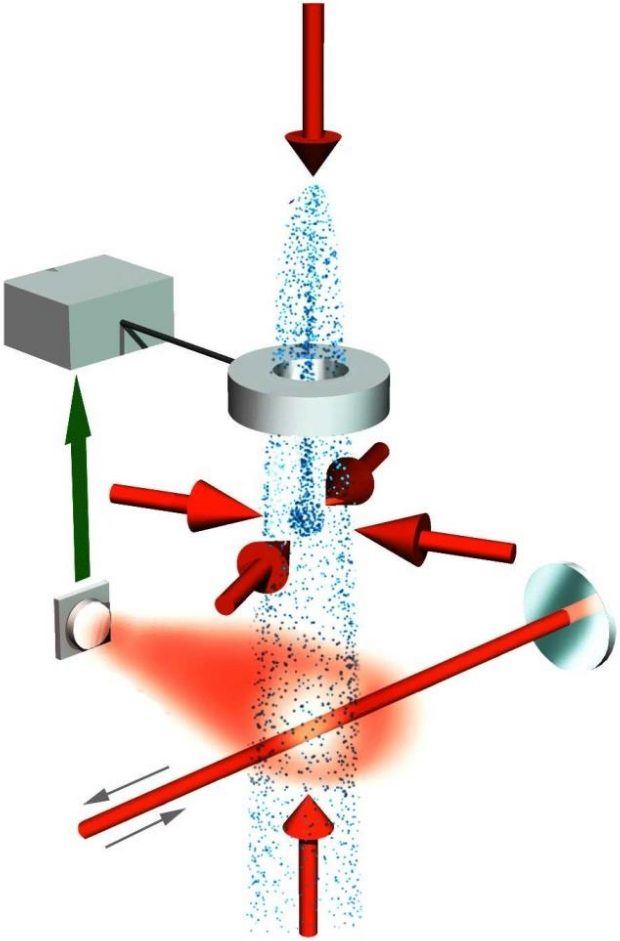
Cold atom instruments
Clocks, gravimeters…

The Hewlett Packard atomic clock



Measurement of the frequency of the hyperfine splitting of the ground state of Cs133 at 9.9 GHz

The fountain clock



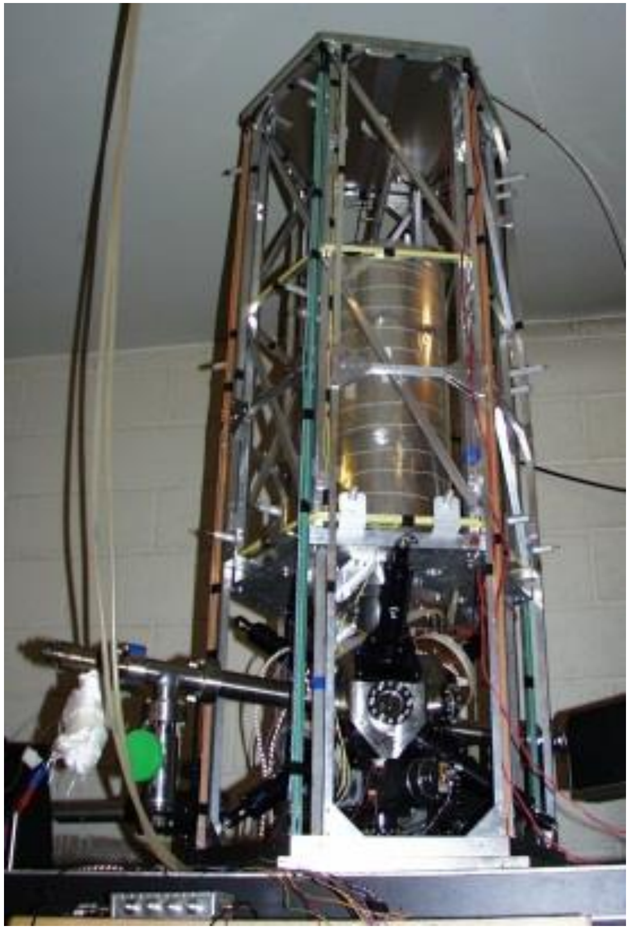
laser cooling : 4 microKelvin

rms velocity : 7 mm/s

Interrogation time : seconds

Precision increased by a factor 100…

The first atomic fountain clock



Paris Observatory

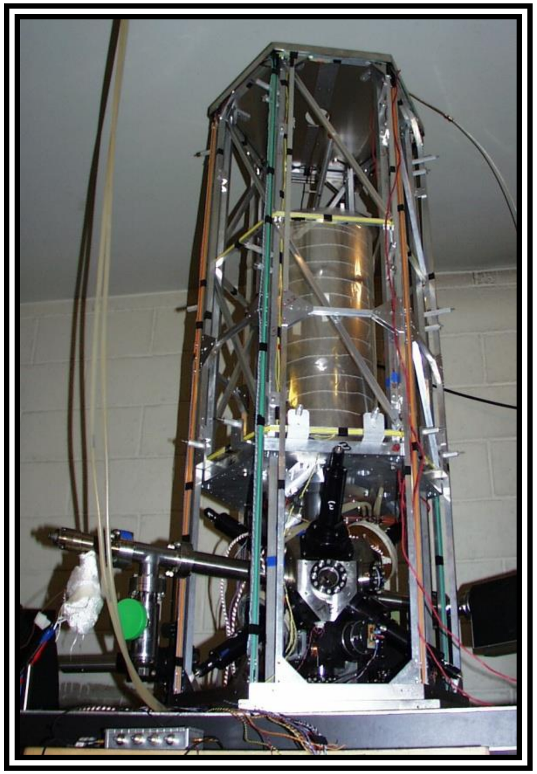
Relative accuracy

10^{-15}

Drift less than
1 second in 1 million years

Atomic fountain clocks in the world in many countries

Build-up of the TAI (international atomic time)



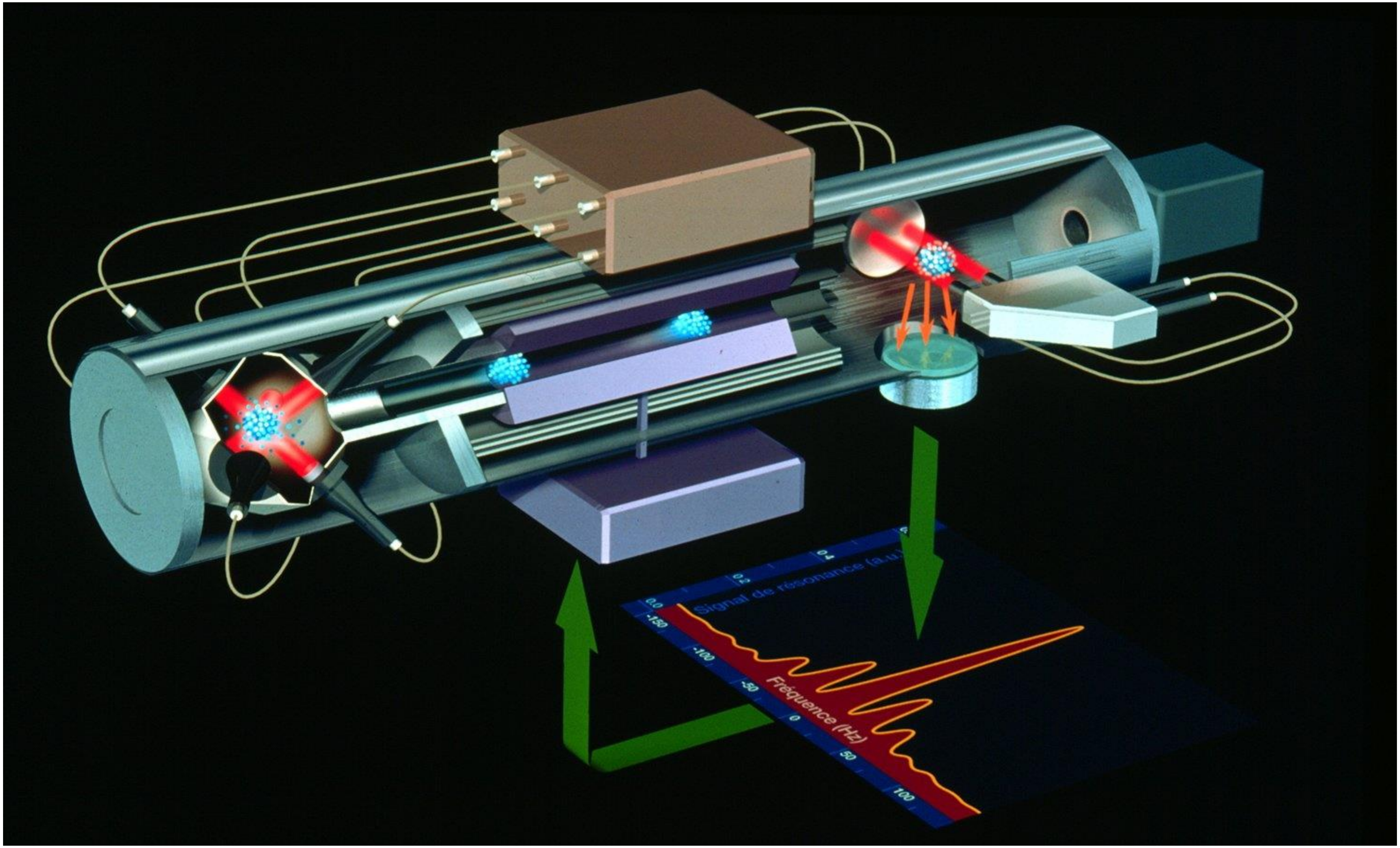
BNM-SYRTE, FR

PTB, D

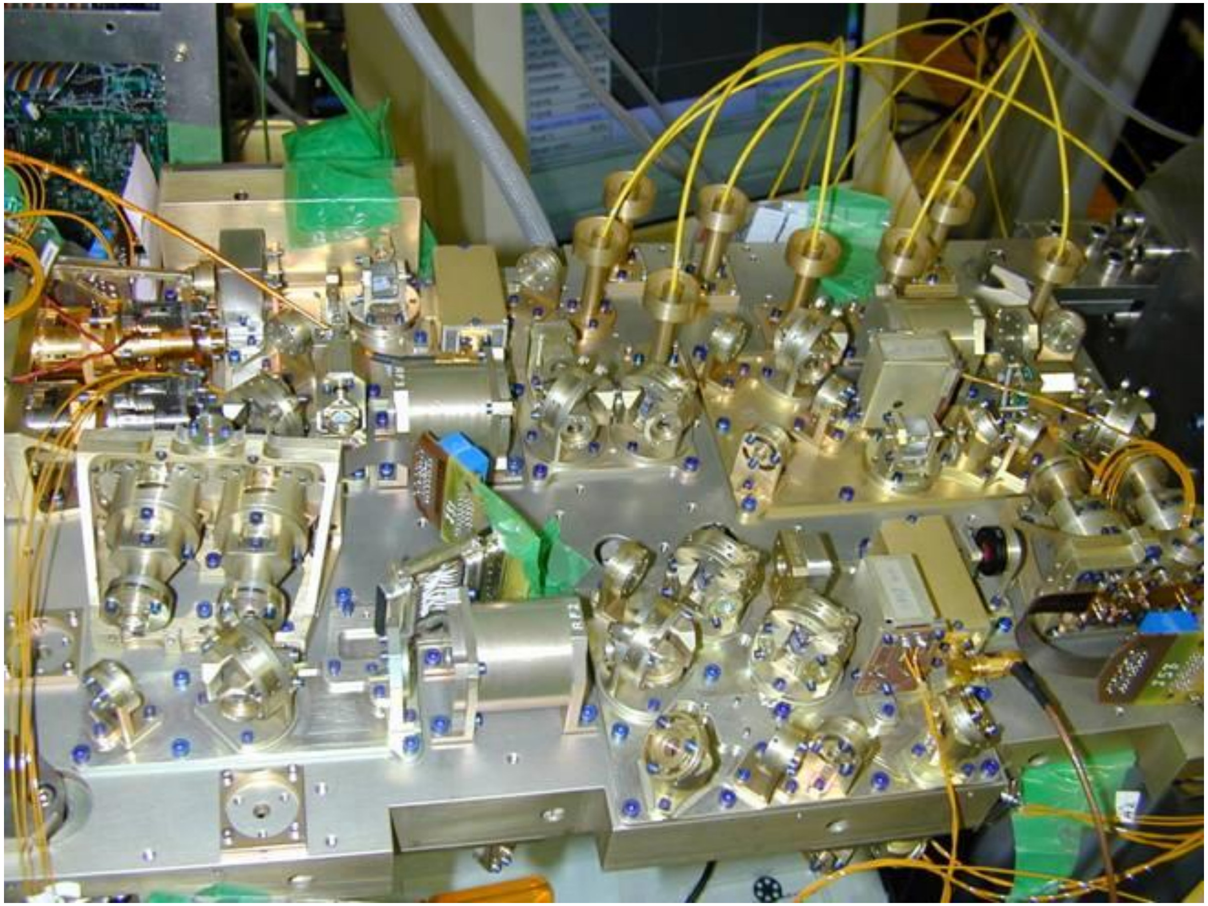
NIST, USA

The cold atom clock PHARAO

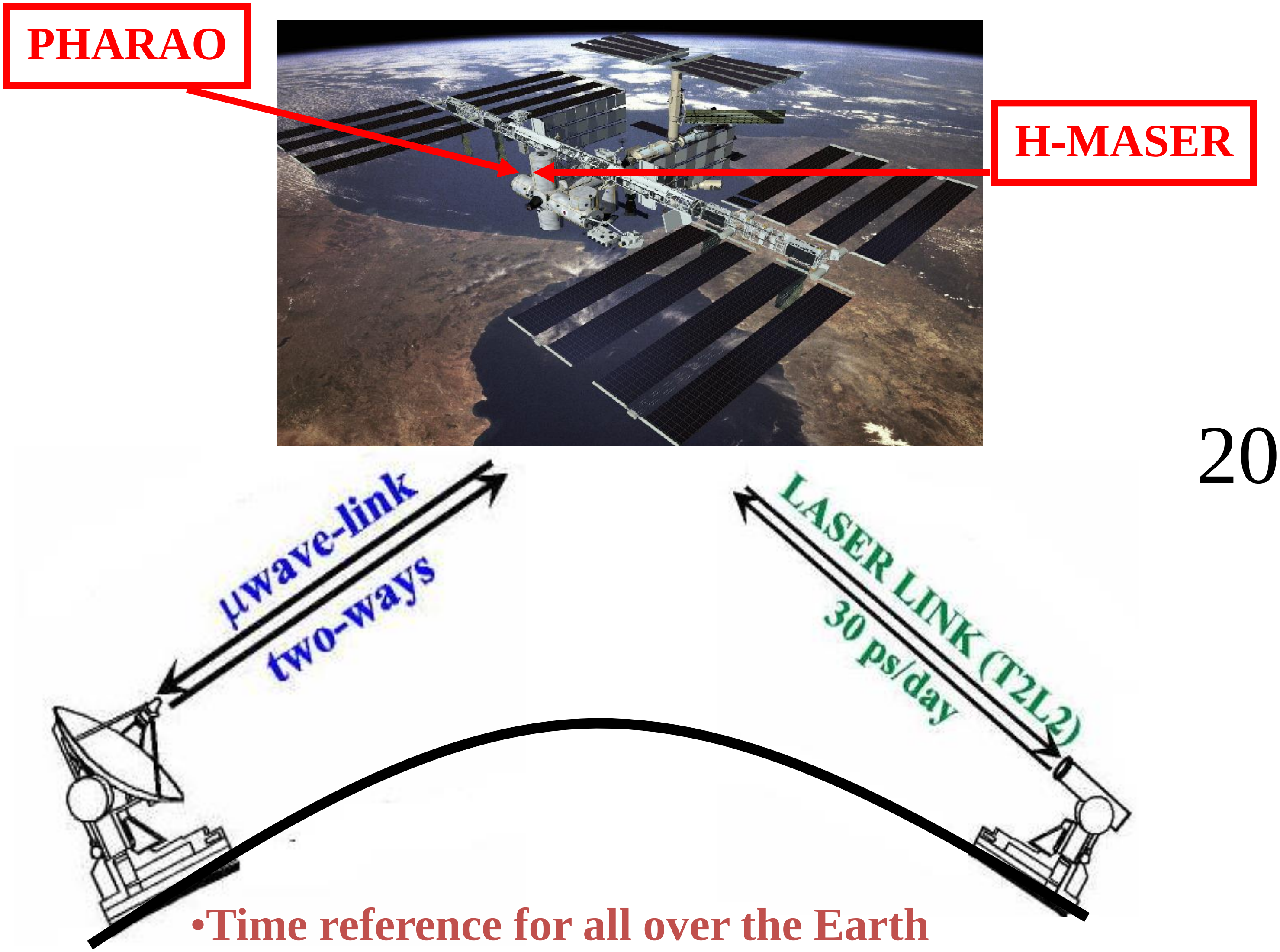
CENTRE NATIONAL D'ETUDES SPATIALES



A technological challenge



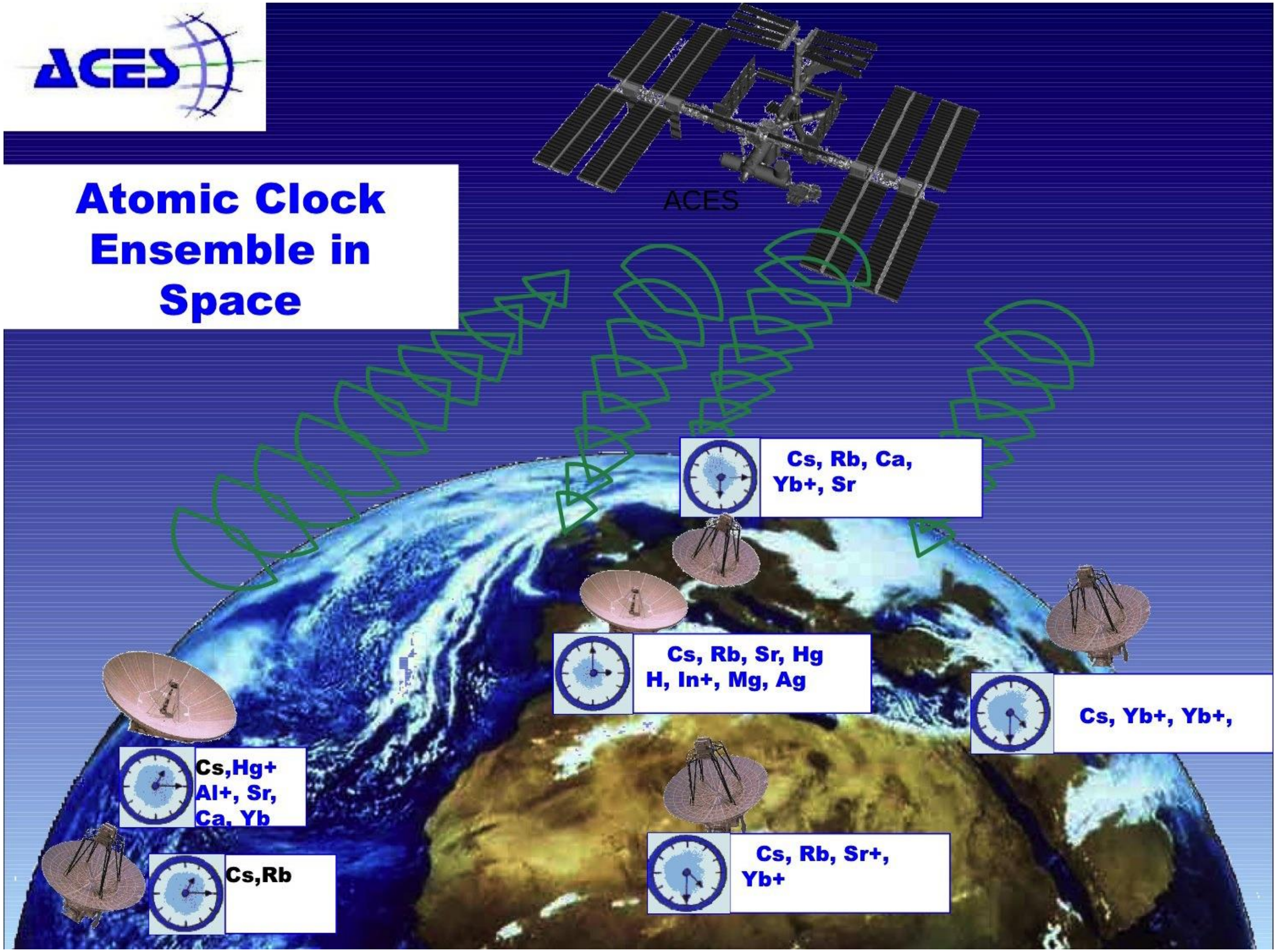
An atomic clock on the International Space Station



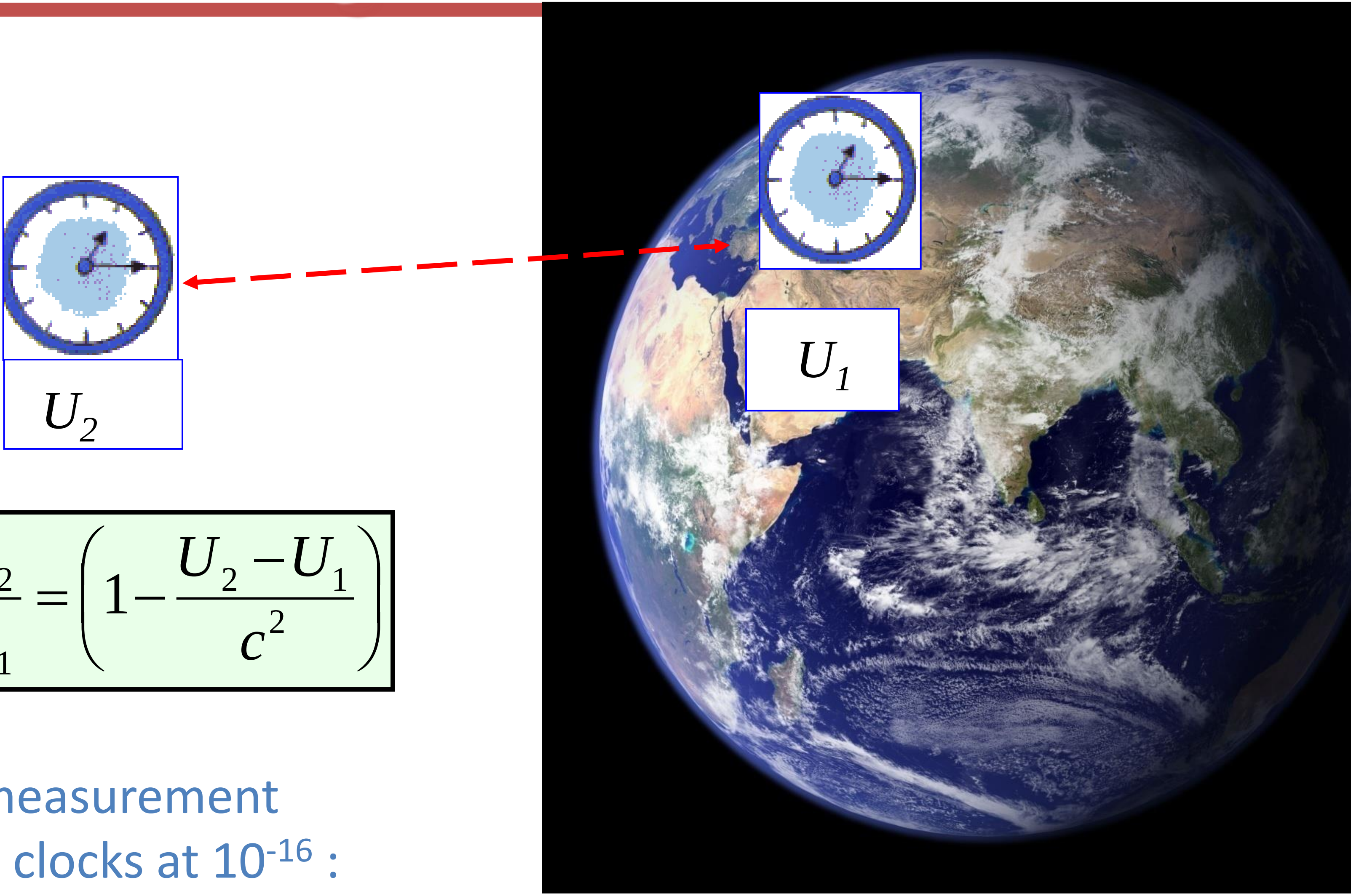
2017

- **Time reference for all over the Earth**
- **Validation of space clocks**
- **Tests of fundamental physics**

Atomic Clock Ensemble in Space



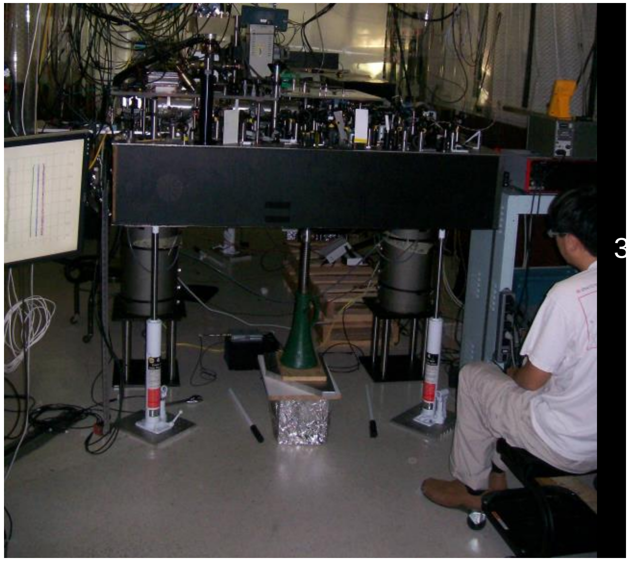
Prediction of general relativity
Einstein gravitationnal redshift



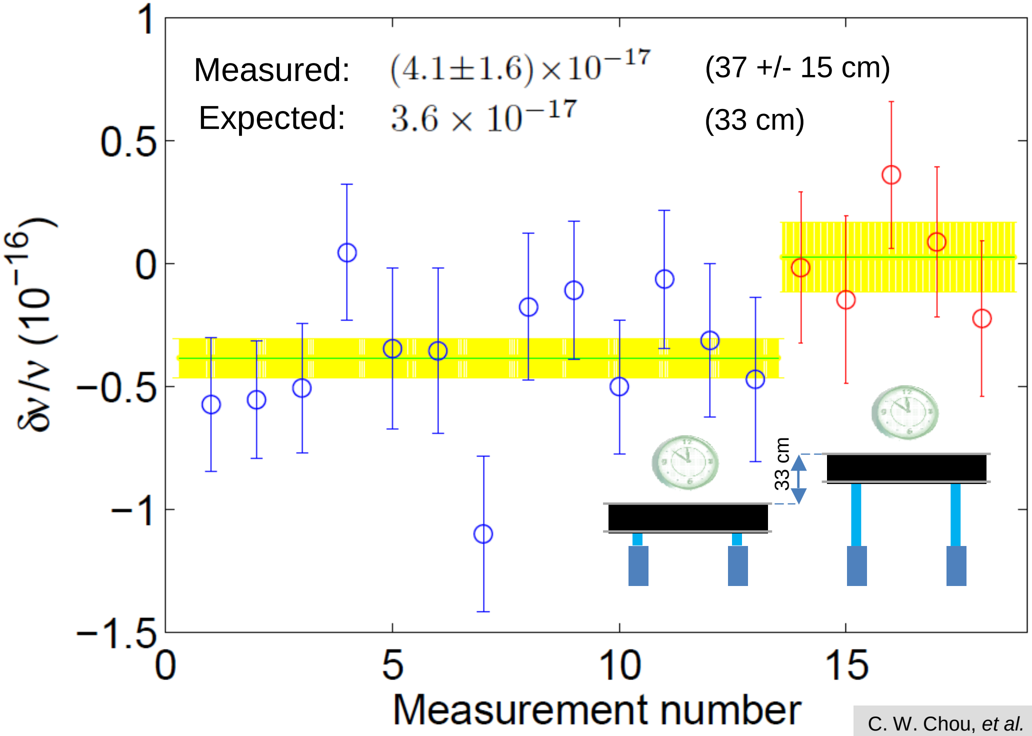
$$\frac{\nu_2}{\nu_1} = \left(1 - \frac{U_2 - U_1}{c^2}\right)$$

Redshift measurement
with ACES clocks at 10^{-16} :
an improvement of 35 over GPA, 1978

The ion clock of Dave Wineland at Boulder

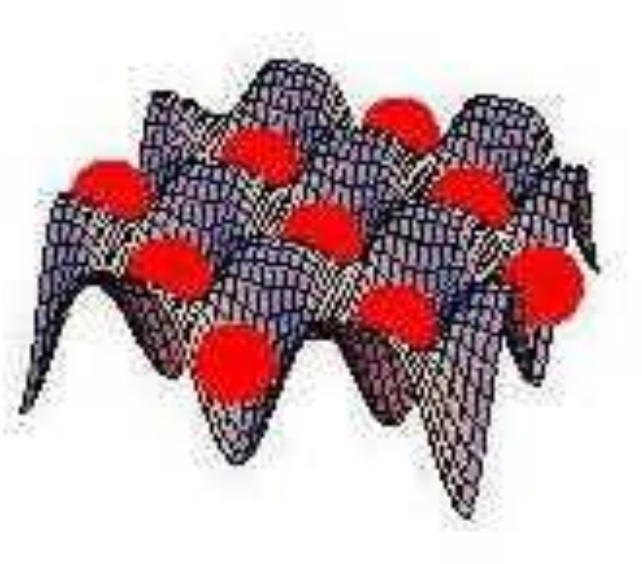


General relativity test: clocks 33 cm apart in gravitational fields tick at different rates!



C. W. Chou, *et al.*
Science **329**, 1630 (2010)

Optical cold atom clocks



Measurement of a frequence
in the **optical** domain rather than Rf:
Large gain in precision

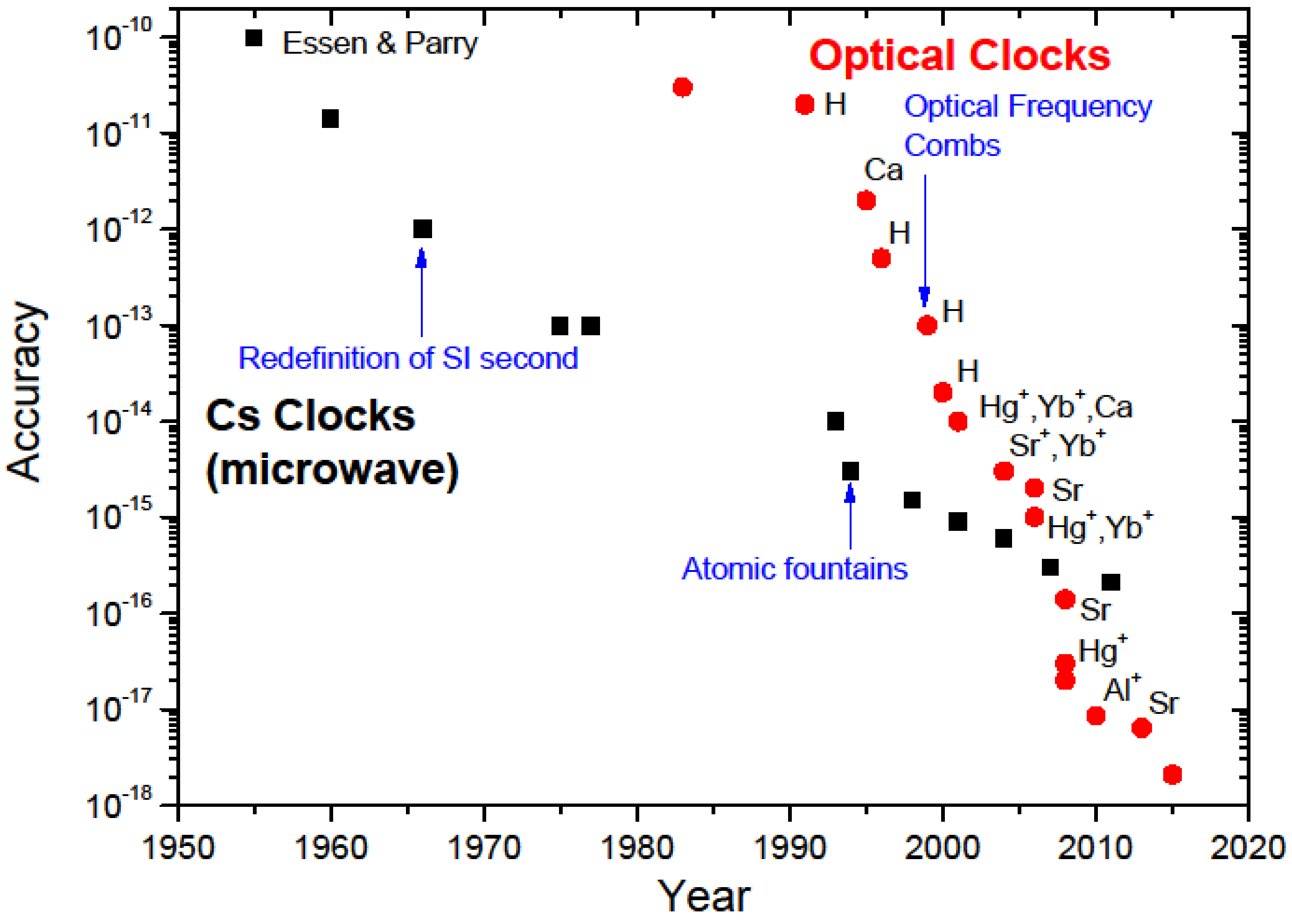
Atoms interrogated in an optical lattice

Long interaction time
Large number of atoms

Atoms at rest
Small frequency shifts

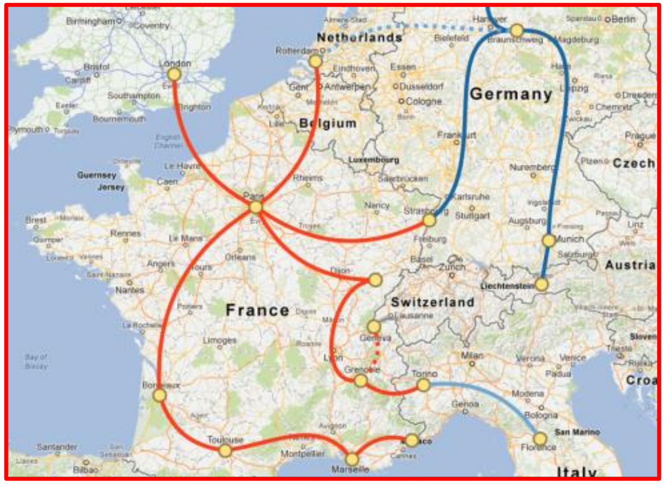
Excellent frequency stability

Accuracy of atomic clocks



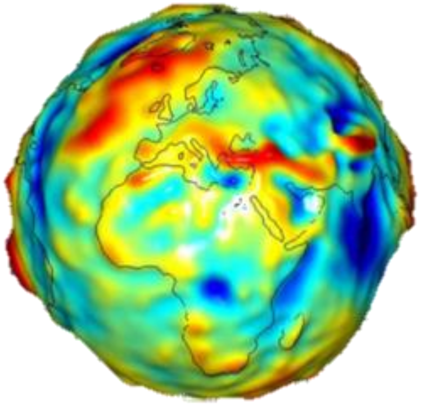
Clocks for earth science

- Remote clock comparisons to determine gravity potential differences
- Sensitivity: 10^{-18} ⇔ 1 cm in height

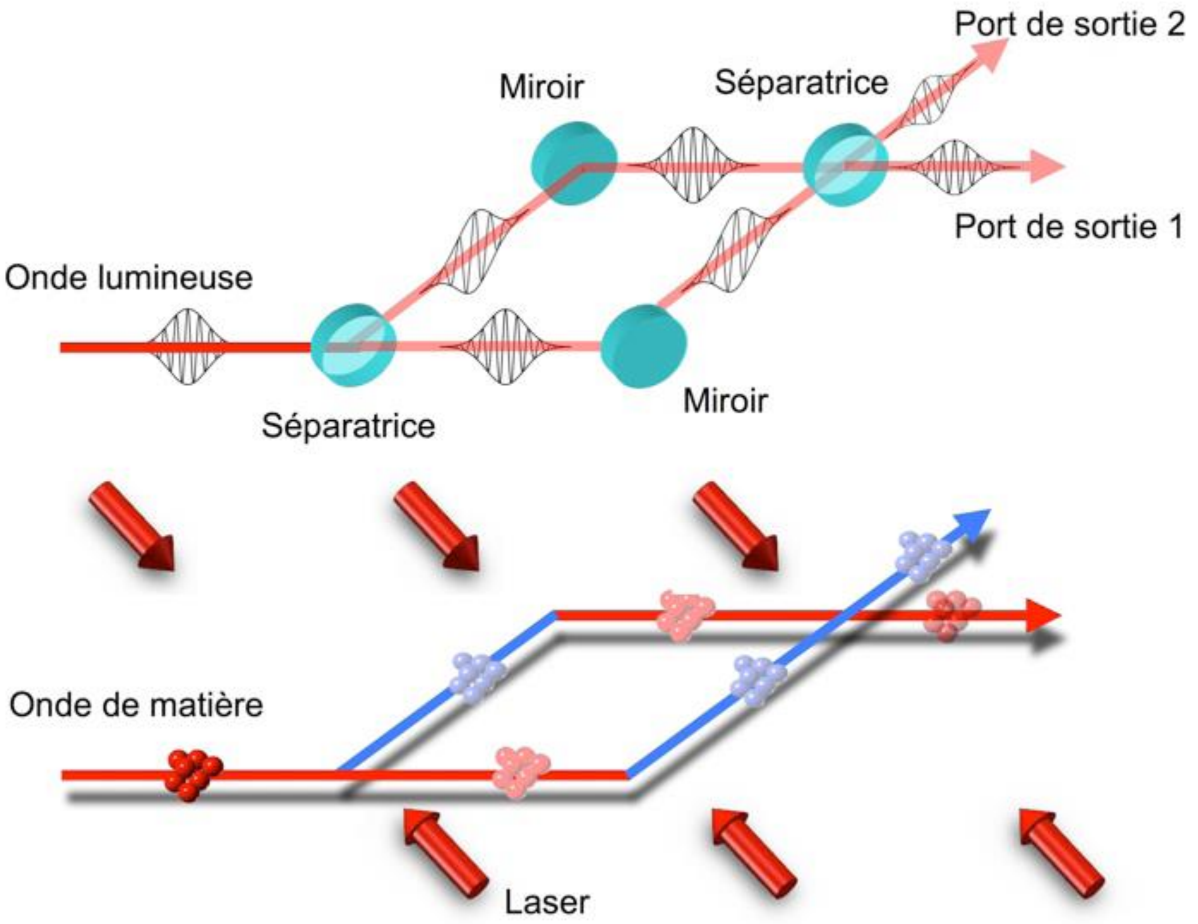


New Coherent Optical Fiber Link Network

- Sense geophysical phenomena (sisimic…)
- Improve references: global/local geoid models, height of tide gauges, etc.



Interferometers with matter waves

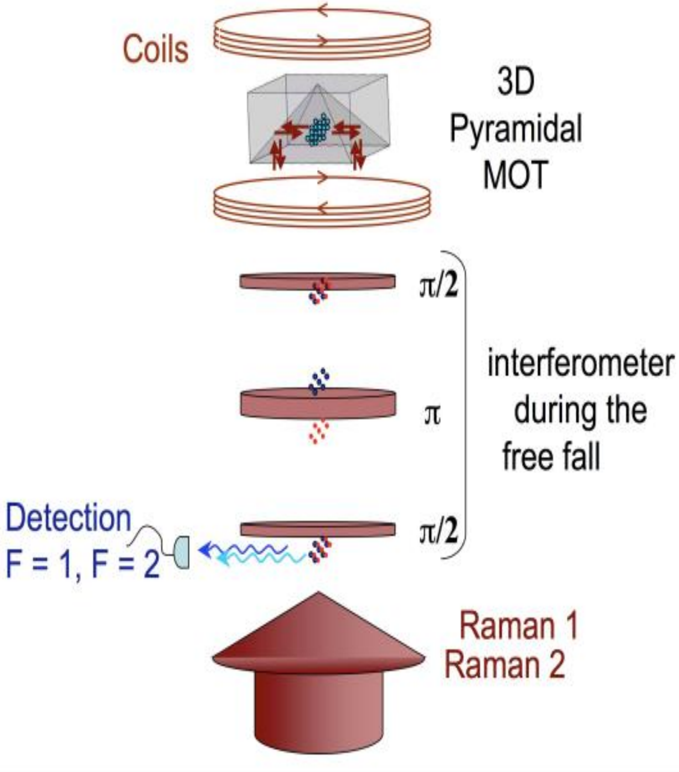


For the same area between the arms

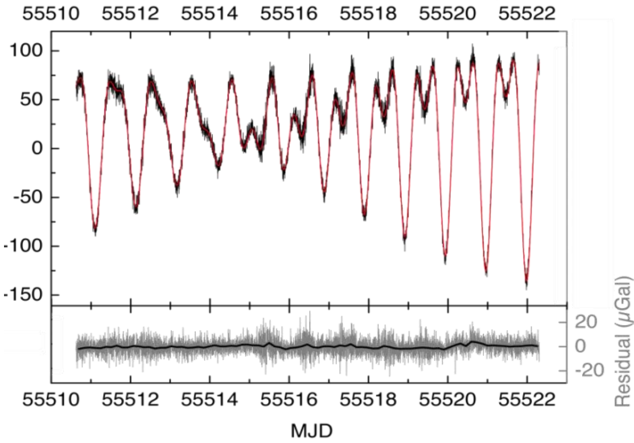
$$\frac{\Delta\phi_{atomic}}{\Delta\phi_{optic}} = \frac{mc^2}{h\nu} \approx 10^{11}$$

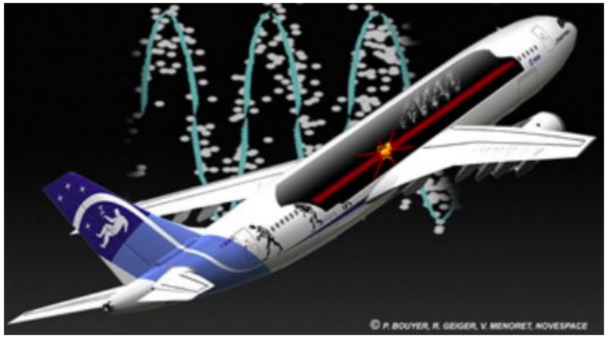
Cold atom gravimeter

Sensitivity :2 10^{-8}g @ 1s
Accuracy : 5 10^{-9}g



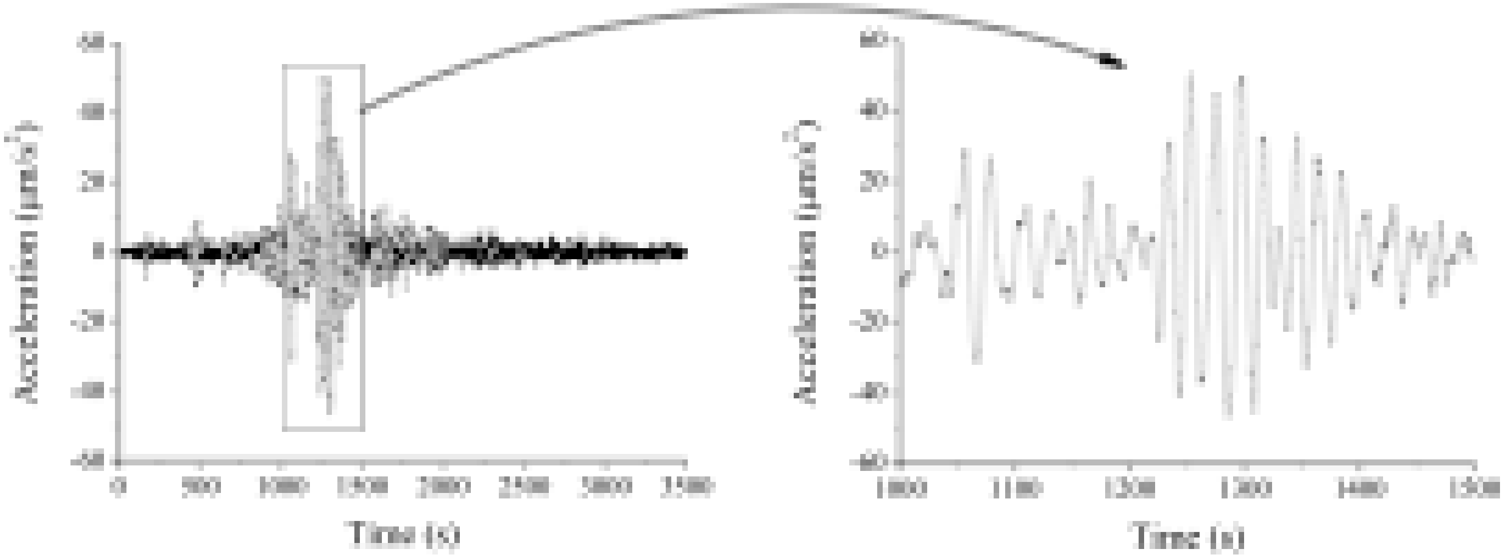
12 days of continuous operatio





Test of the equivalende prnciple In 0-g

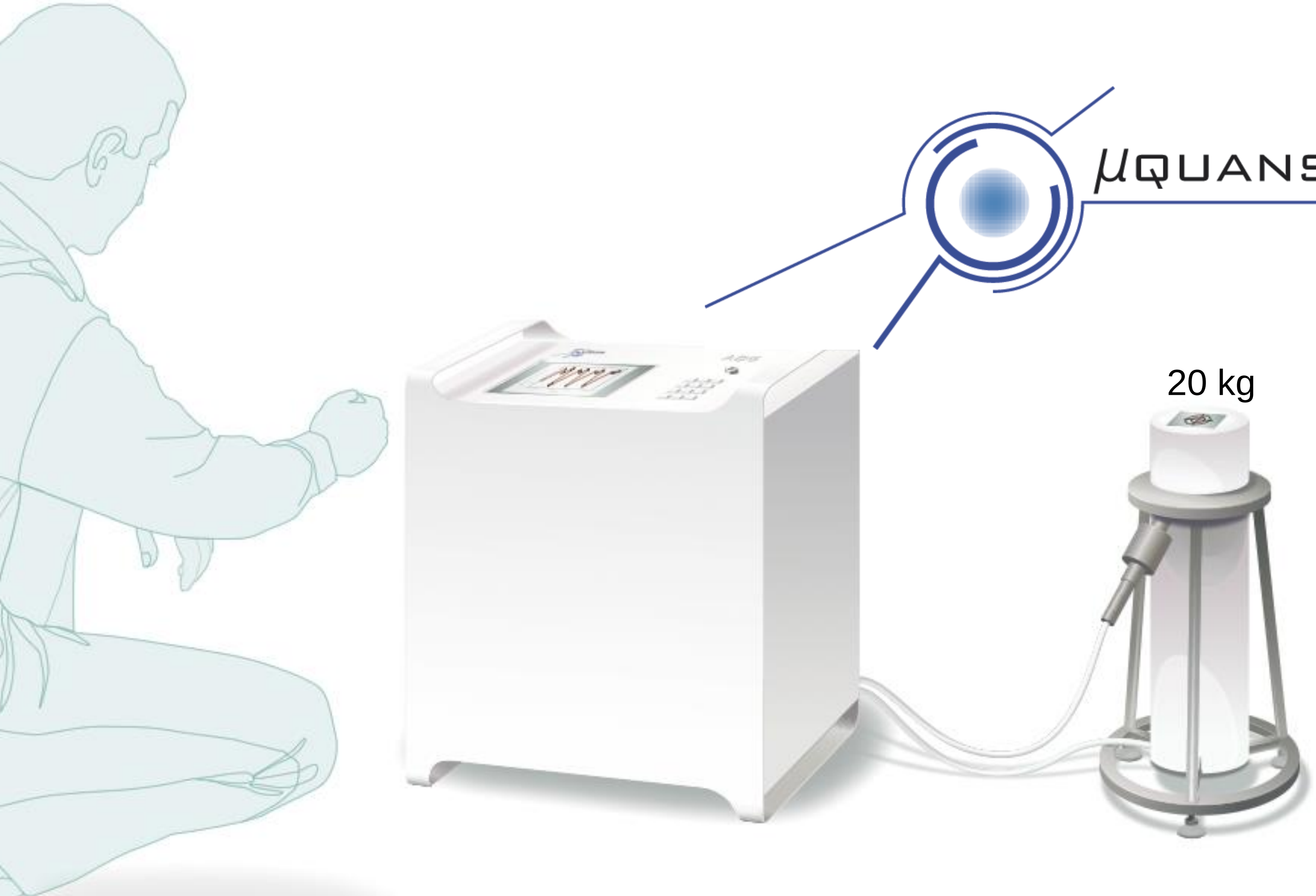
The atomic gravimeter at Observatoire de Paris



Tremblement de terre en Chine le 20 mars 2008 (magnitude 7,7)

Earthquake in China in 2008

μQUANS



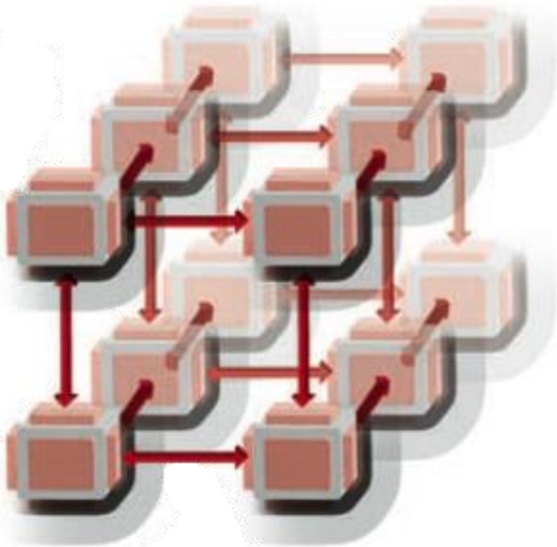
Mater wave gravimeter now avaible

Quantum communications

« Quantum Networks »

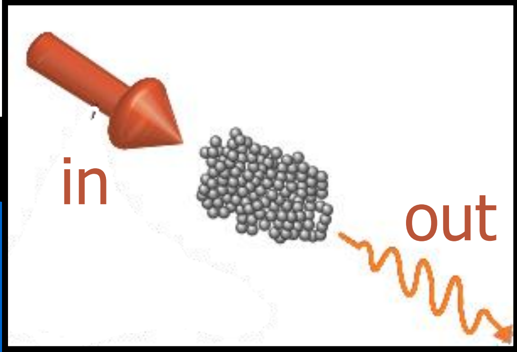
Fundamental scientific questions and diverse experimental challenges

Quantum node
generate, process, store
quantum information locally



Quantum channel
transport / distribute
quantum information
over the entire network

Distributed Q. computing
Scalable Q. Communication
Quantum resource sharing
Quantum simulation



Experimental implementation ?

- Physical processes for
reliable generation, processing, & transport of quantum states

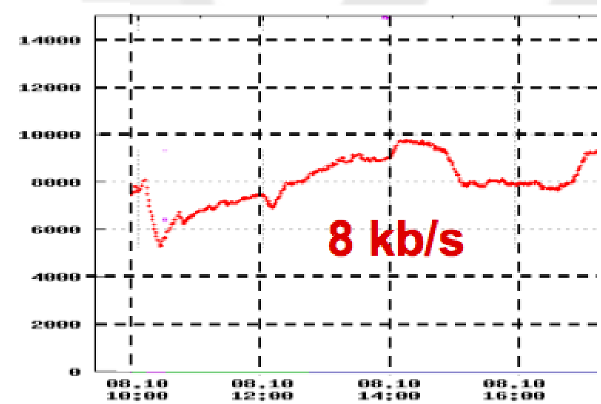
- A quantum interface between matter and light
'Quantum Memory'

Quantum Cryptography at Work

Real size demonstration of a secure quantum cryptography network

Project SECOQC, Vienna, October 2008

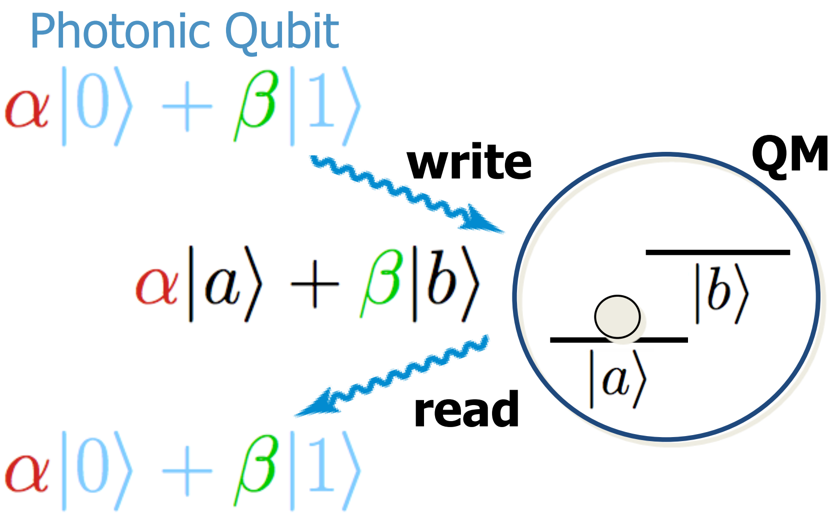
SECOQC



IO/Thales
CV link – 9km

Light-Matter Interfaces

Mapping light quantum superposition into quantum superposition of elements of the storing medium

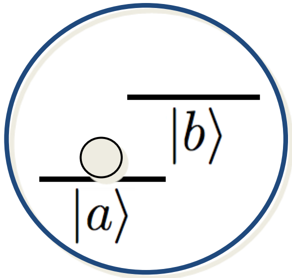


$$\alpha|0\rangle + \beta|1\rangle$$

$$\alpha|a\rangle + \beta|b\rangle$$

$$\alpha|0\rangle + \beta|1\rangle$$

Single Atom

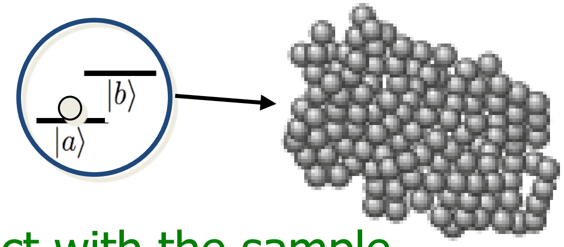


Requires a high-finesse cavity (CQED)

Example for storage of a single photon

$$|a\rangle \rightarrow |b\rangle$$

Atomic ensembles



Light easily interact with the sample
Collective state (enhancement)

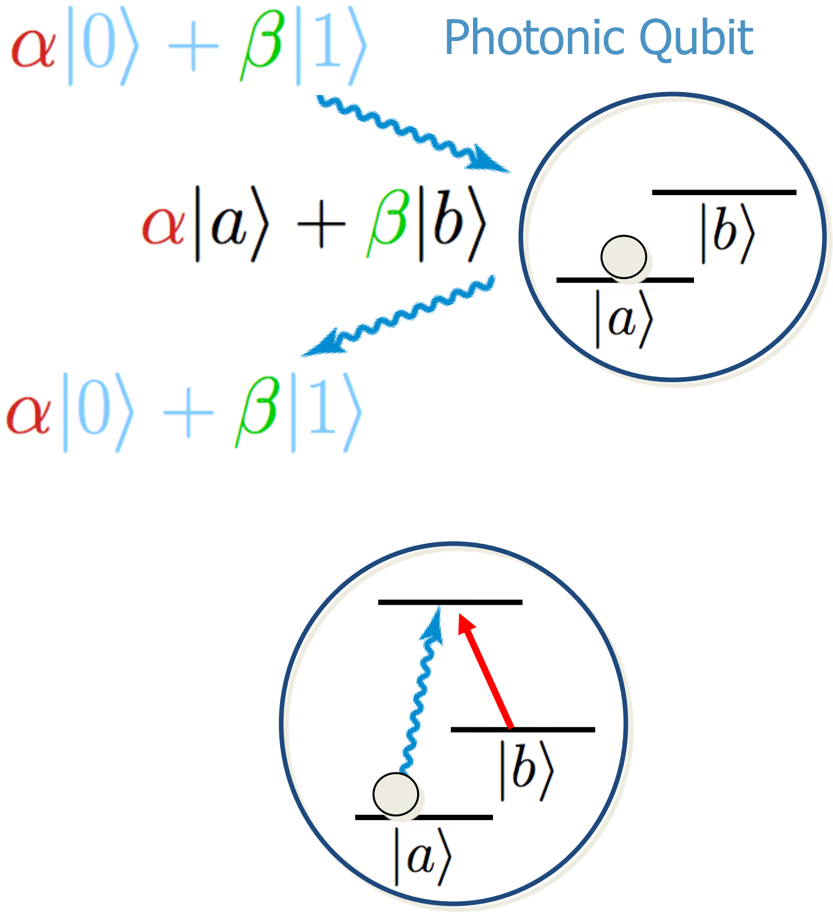
Example for storage of a single photon

$$|a_1 \ldots a_i \ldots a_N\rangle \rightarrow \frac{1}{\sqrt{N}} \sum_i |a_1 \ldots b_i \ldots a_N\rangle$$

Quantum Memories

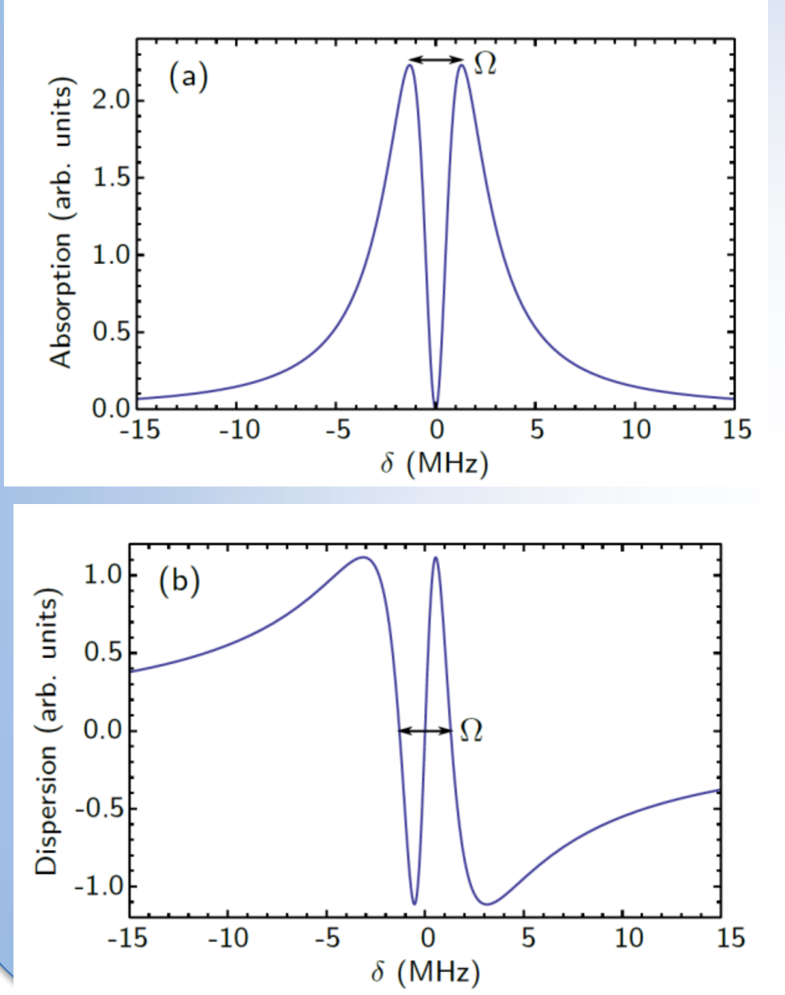
But |a> and |b> usually have to be ground states to avoid fast decoherence

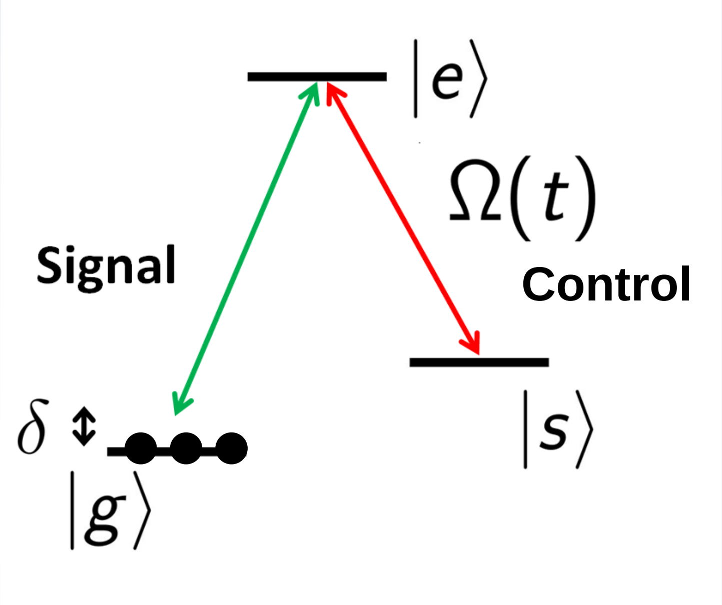
General recipe: Two ground states connected via an excited state by a **control field**



Other desiderata : λ, bandwidth, memory time, multimode…

The resource : Electromagnetically induced transparency (EIT)°

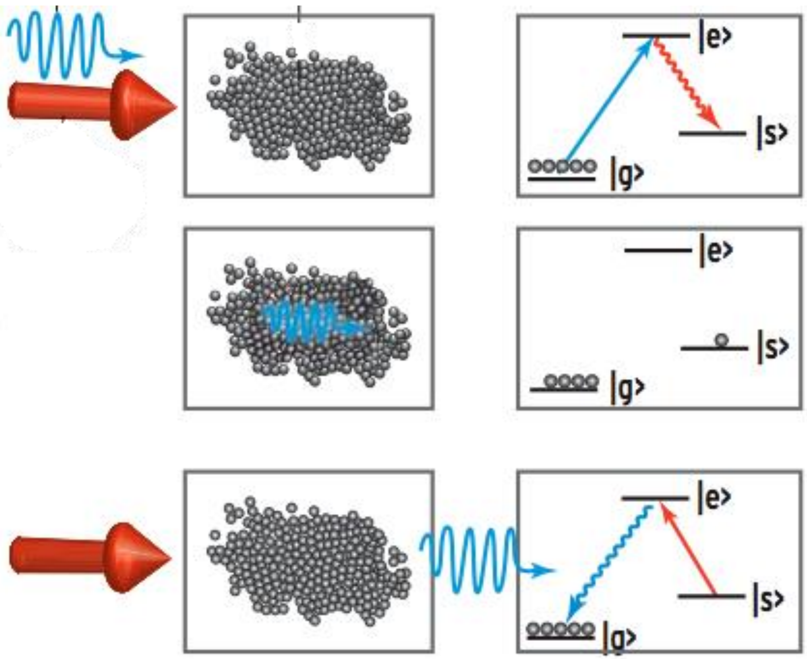




Reduced group velocity

$$v_g = \frac{c}{1+\frac{g^2N}{\Omega^2}}$$

Mapping a signal In and Out

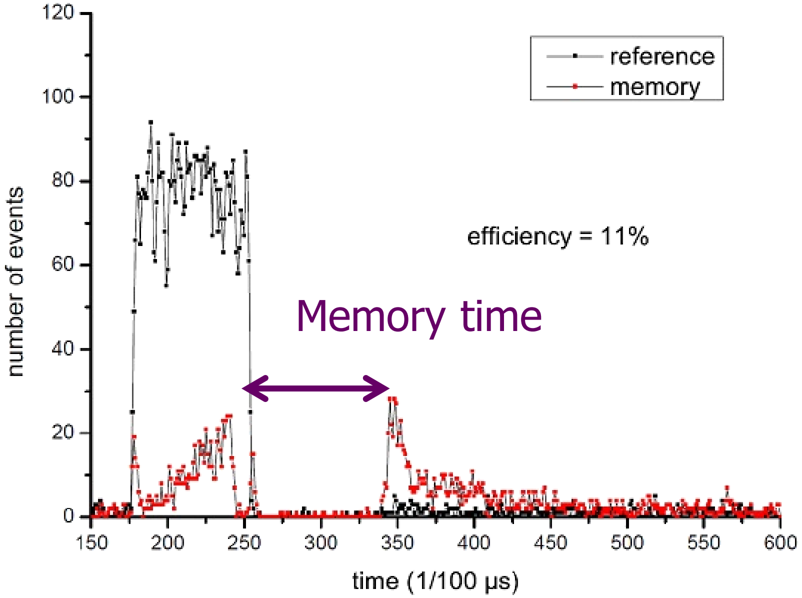


When the pulse has been spatially compressed into the medium, the control field is adiabatically switched off.

The quantum state of light is in this way transferred to the atomic coherence between the two ground states.

on demand, by switching on again the control field, the coherence is mapped back to light field.

Example with cold atoms at LKB



Conclusion

The field of cold atoms is 30 years old,
but still in full expansion for :

- Quantum simulations of condensed matter phenomena
- Precision instruments (clocks, gyroscopes, interferometers)
- Secure inter-cities quantum communications