



Consiglio Nazionale delle Ricerche



INO - CNR

Istituto Nazionale di Ottica
S.S. «A. Gozzini»
Via Moruzzi 1
56124 Pisa



**Dai nanoKelvin alla
fusione nucleare:
esperimenti al CNR-
INO di Pisa**

Andrea Fioretti

9 Maggio2017
Dipartimento di Fisica, Pisa

Via Moruzzi 1, 56124 Pisa

Tel. +39 050 3152528 - Fax +39 050 3152522

Outline

- **CNR e INO: chi siamo?**
- **Esperimenti all'INO-Pisa:**
dai nanokelvin alla fusione nucleare
- **Raffreddamento e intrappolamento di atomi
tramite laser**
- **Conclusioni**

Disclaimer: part of the following slides have been provided by the following authors: (S. Gozzini, L.A. Gizzi, F. Dinelli, A. Lucchesini, E. Lucioni) or come from material available freely on the web. To the best of my knowledge, no copyrighted material is present. I apologize in advance for any exception.

Outline

- **CNR e INO: chi siamo?**
- **Esperimenti all'INO-Pisa:**
dalla fusione nucleare ai nanokelvin
- **Raffreddamento e intrappolamento di atomi
tramite laser**
- **Conclusioni**

Disclaimer: part of the following slides have been provided by the following authors: (S. Gozzini, L.A. Gizzi, F. Dinelli, A. Lucchesini, E. Lucioni) or come from material available freely on the web. To the best of my knowledge, no copyrighted material is present. I apologize in advance for any exception.

CNR: chi siamo?

18 novembre del 1923 *Istituito con Regio Decreto di Vittorio Emanuele III*

Presidenti

- 1923-1927 Vito Volterra
- 1927-1937 Guglielmo Marconi

- **2015-... Massimo Inguscio**



La missione del Cnr è quella di svolgere, diffondere e promuovere attività di ricerca nei principali settori della conoscenza, e studiare la loro applicazione per lo sviluppo scientifico, tecnologico ed economico del Paese.

Strutture scientifiche e numeri

- Dipartimenti
 - •Scienze del sistema terra e tecnologie per l'ambiente
 - •Scienze bio-agroalimentari
 - •Scienze chimiche e tecnologie dei materiali
 - •Scienze fisiche e tecnologie della materia
 - •Scienze biomediche
 - •Ingegneria, ICT e tecnologie per l'energia e i trasporti
 - •Scienze umane e sociali, patrimonio culturale
- 103 Istituti articolati in una Sede e Sedi Secondarie diffuse nel territorio
- 18 Aree di Ricerca
- Risorse umane CNR: oltre 8.000 dipendenti (**+ precari**): il 61% di questi sono ricercatori e tecnologi, il 28% tecnici e l'11% personale amministrativo-gestionale.
- Il CNR gestisce circa 1G€/anno

Area CNR di Pisa



- Inaugurata il 6 dic. 2000;
- Personale >1.500 (~1.000 CNR);
- Superficie 123.300 m²
- **Istituti:** Fisiologia Clinica, Geoscienze e Georisorse, Istituto di Informatica e Telematica, Linguistica Computazionale, Neuroscienze, Scienza e Tecnologie dell'Informazione
- **Sedi Secondarie:** Biofisica, Biologia e Biotecnologia Agraria, Chimica dei Composti Organo Metallici, Tecnologie Biomediche, **Istituto Nazionale di Ottica**, Processi Chimico-Fisici , Studio degli Ecosistemi
- **Altri:** FTGM, Scuola S. Anna, Normale...



Istituto Nazionale di Ottica

1927: nasce il Regio Istituto Nazionale di Ottica RINDO

→ 1946 INDO → 2000 INOA

→ L'attuale INO è nato il 1 FEBBRAIO 2010

- 151 Dipendenti (28 Pisa)**
- 2016 43 progetti con un bilancio complessivo finanziato all'istituto di 13,565,331.57 €.**



Istituto Nazionale di Ottica



INO-Pisa: Laboratorio ILIL



Intense Laser Irradiation Lab

<http://ilil.ino.it>

PEOPLE

- Leonida A. GIZZI (CNR)* (Resp.)
 - Giancarlo BUSSOLINO (CNR)
 - Gabriele CRISTOFORETTI (CNR)
 - Luca LABATE (CNR)*
 - Fernando BRANDI (CNR), Ric. TD.
 - Petra KOESTER (CNR), Ric. Contr.
 - Federica BAFFIGI (CNR), A.R.
 - Lorenzo FULGENTINI (CNR), A.R.
 - Antonio GIULIETTI(CNR), Assoc
 - Danilo GIULIETTI (Univ. Pisa), Ass.*
 - Daniele PALLA, PhD student *
 - Antonella ROSSI (CNR) – Tech.
- * Also at INFN

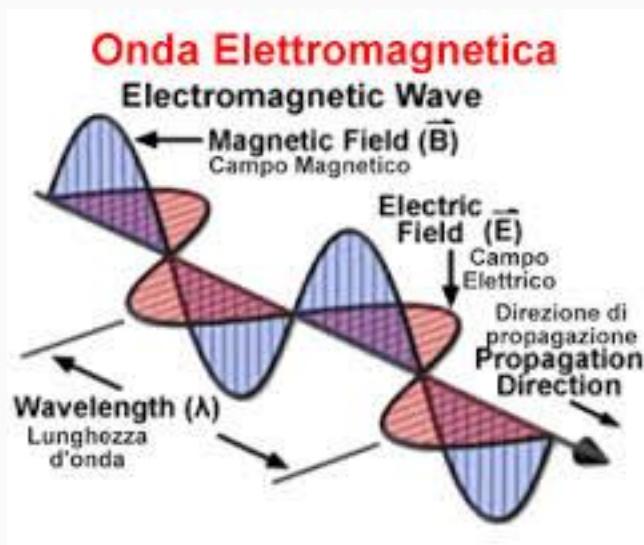


Main Topics @ ILIL

- **Laser-driven plasma acceleration of particles**
 - Electron acceleration in laser-gas interaction
 - Ion acceleration with target
 - Ultra-intense laser development and metrology
- **Laser-plasma interaction relevant for inertial fusion ignition**
 - Fast electron generation and transport
 - Intense shock wave generation
 - Laser-driven instabilities
- **Bright X-ray radiation sources and spectroscopy**
 - Plasma sources
 - Secondary radiation sources (from accelerated electrons)

La materia ad alti campi elettrici

Laser di alta potenza – Alto campo elettrico



Forza = Carica · Campo Elettrico

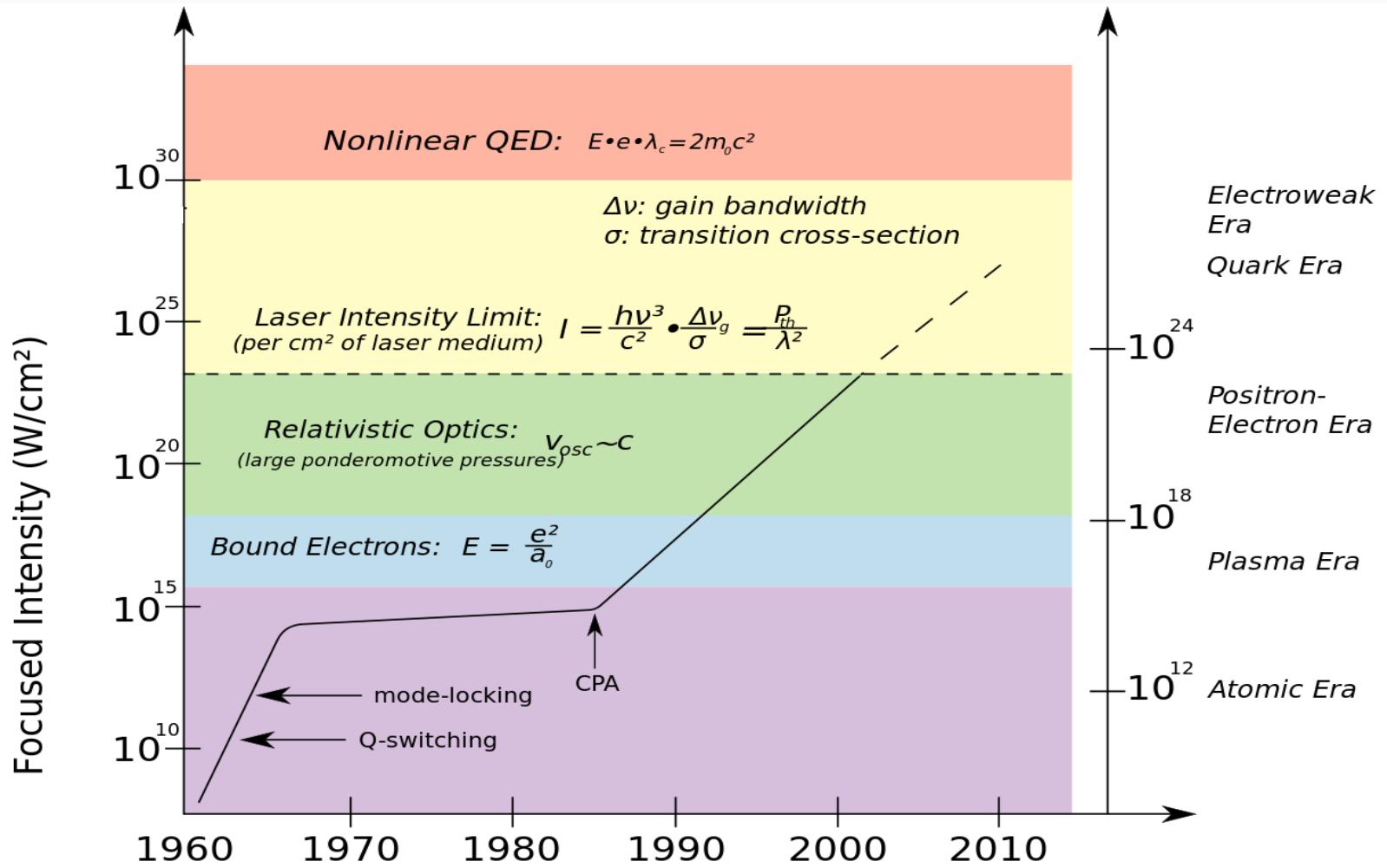
$$\text{Campo Elettrico} \propto \sqrt{\frac{\text{Potenza}}{\text{Superficie}}}$$

$$\text{Potenza} = \frac{\text{Energia}}{\text{Tempo}}$$

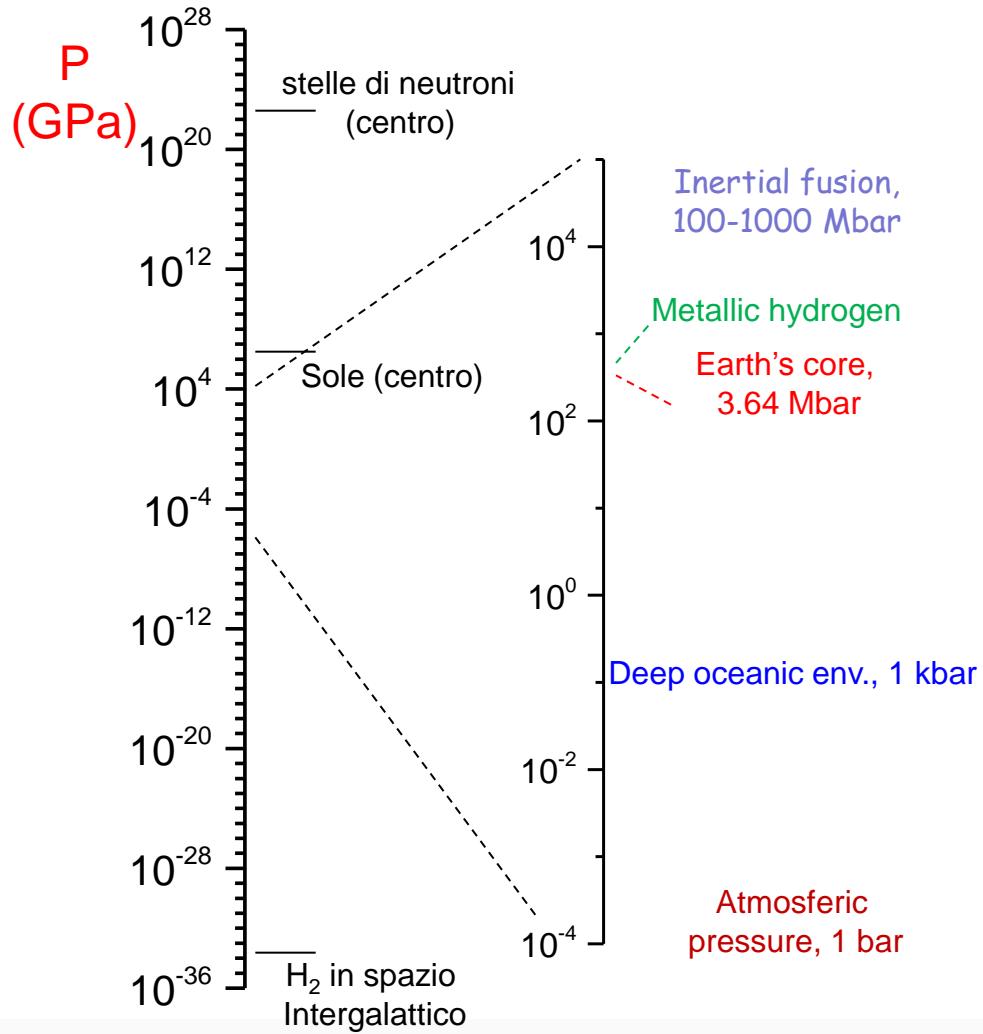
Nuovi processi fisici si attivano
ad altissimi campi elettrici

Evoluzione dei laser impulsati

Densità di potenza focalizzata, dai laser “Q-switch” ai laser “CPA”



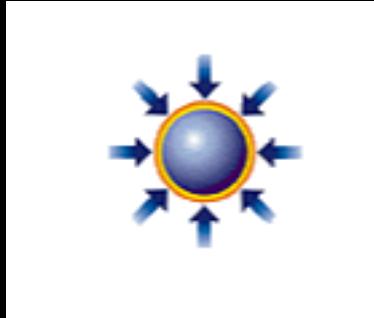
Laser per scaldare la materia



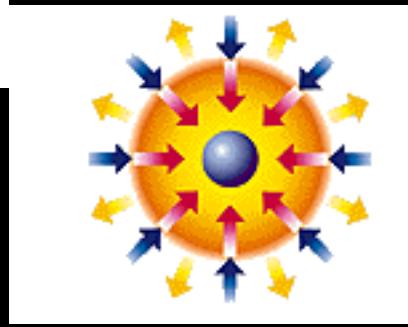
Riprodurre in laboratorio lo stato della materia nel nucleo della Terra e degli altri pianeti o delle stelle



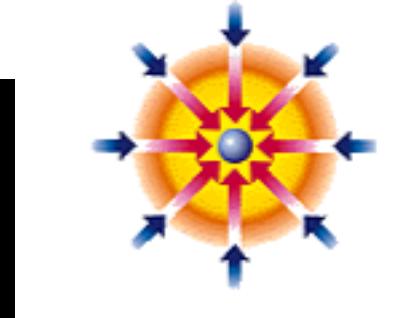
La fusione “Inerziale”



Fase 1: irraggiamento tramite laser



Fase 2: Compressione

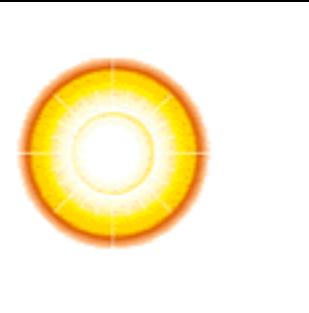


Fase 3: Ignizione

Con l'ignizione, il processo di fusione si autosostiene con il calore generato dagli stessi eventi di fusione

La fusione completa del combustibile avviene per il breve tempo durante il quale la pallina resta compressa (inerzia)

Fase 4: Fusione



Laser per accelerare cariche

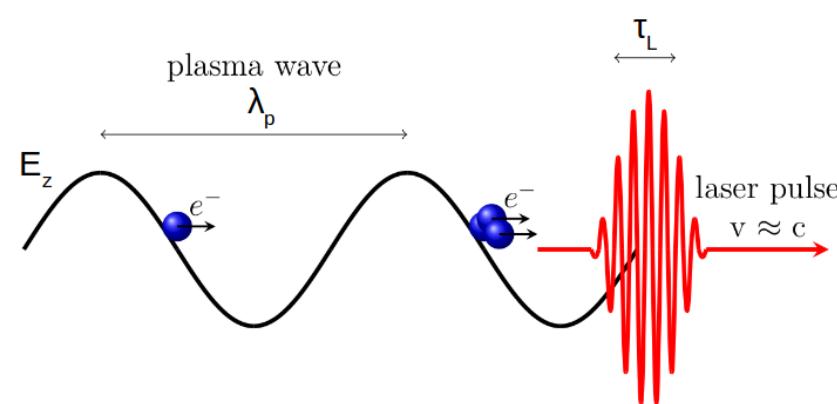


Wakefields....

... to accelerate
particles

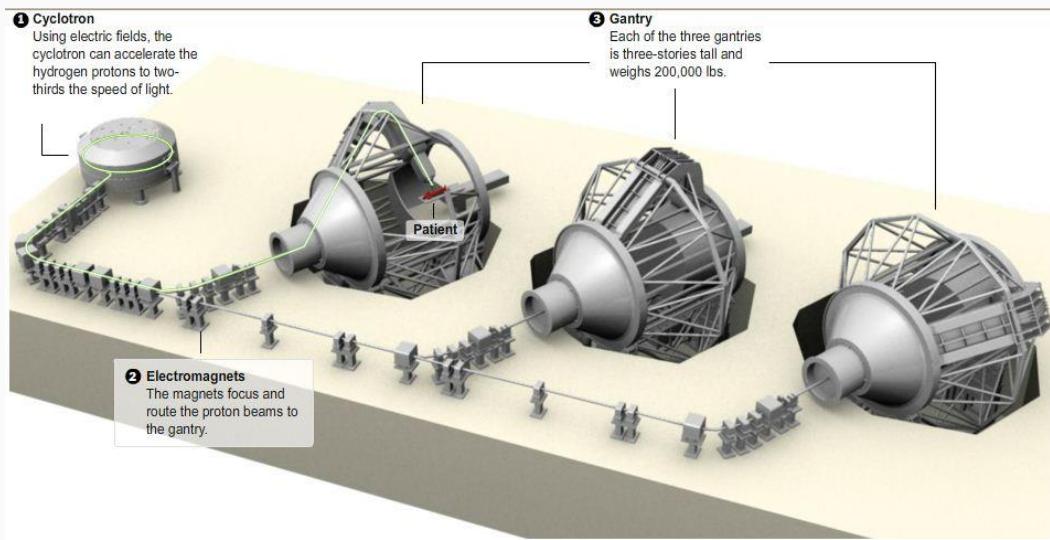
Boat/ laser pulse

Wave/ plasma wave



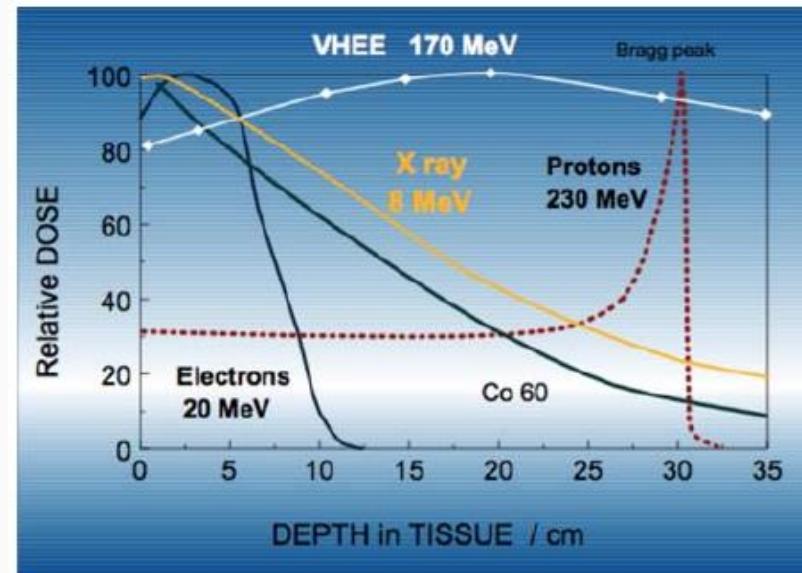
Cariche accelerate in medicina

- **Applicazioni mediche degli ioni di alta energia**
 - Needs MeV, high average power, affordable accelerators;
 - IORT, e-, <12 MeV;
 - 3DCRT, IMRT, IGRT, e-, <20 MeV
 - Hadron therapy, protons, carbon, up to 250 MeV/nucleon



Sources: University of Florida Proton Therapy Institute

Vu Nguyen / The New York Times



Acceleratori laser in medicina

Case Study: IntraOperative RadioTherapy (IORT)



Terapia

Case Study: Very-High Energy Electron Radiotherapy (VHEE)

IOP PUBLISHING

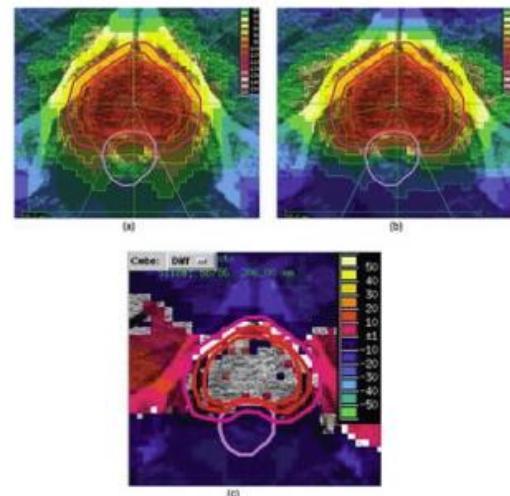
Phys. Med. Biol. 54 (2009) 3315–3328

PHYSICS IN MEDICINE AND BIOLOGY

doi:10.1088/0031-9155/54/11/003

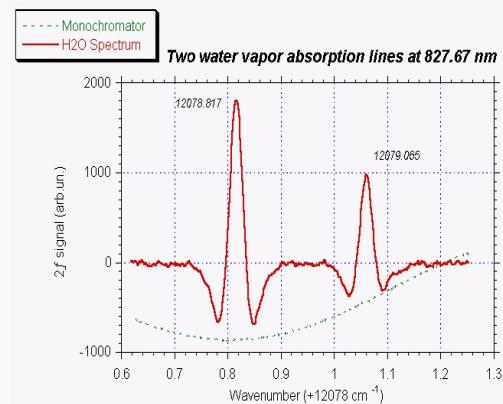
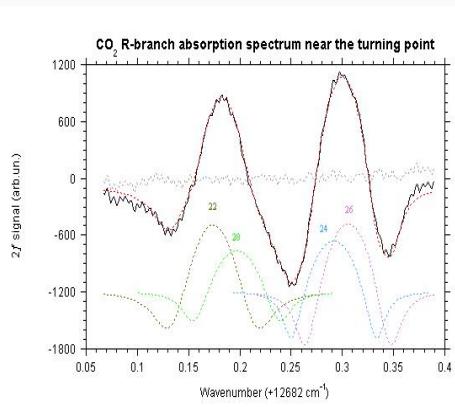
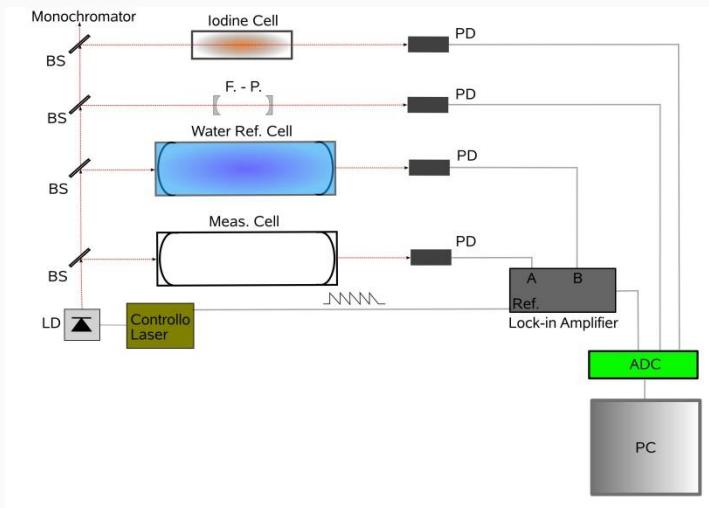
Treatment planning for laser-accelerated very-high energy electrons

T Fuchs¹, H Szymanowski¹, U Oelfke¹, Y Glinec², C Rechatin², J Faure² and V Malka²



Laser per applicazioni ambientali

Diode Laser Spectroscopy @ INO - CNR



Laser per applicazioni ambientali

Diode laser spectroscopy of trace species: CH_4 , C_2H_2 , C_2H_4 , CH_3Cl , CH_3F , CH_3I , CO_2 , H_2O , NH_3 , O_2 by Wavelength Modulation and 2nd harmonic detection technique;

Detection sensitivity: C_2H_2 , H_2O , NH_3 and $\text{O}_2 \approx 10\text{-}100 \text{ ppm} \cdot \text{meter}$; CH_4 , C_2H_2 and $\text{CO}_2 \approx 0.01\text{-}0.1\% \cdot \text{meter path-length}$;

Fast time responses: $\approx 10\text{-}100 \text{ ms}$;

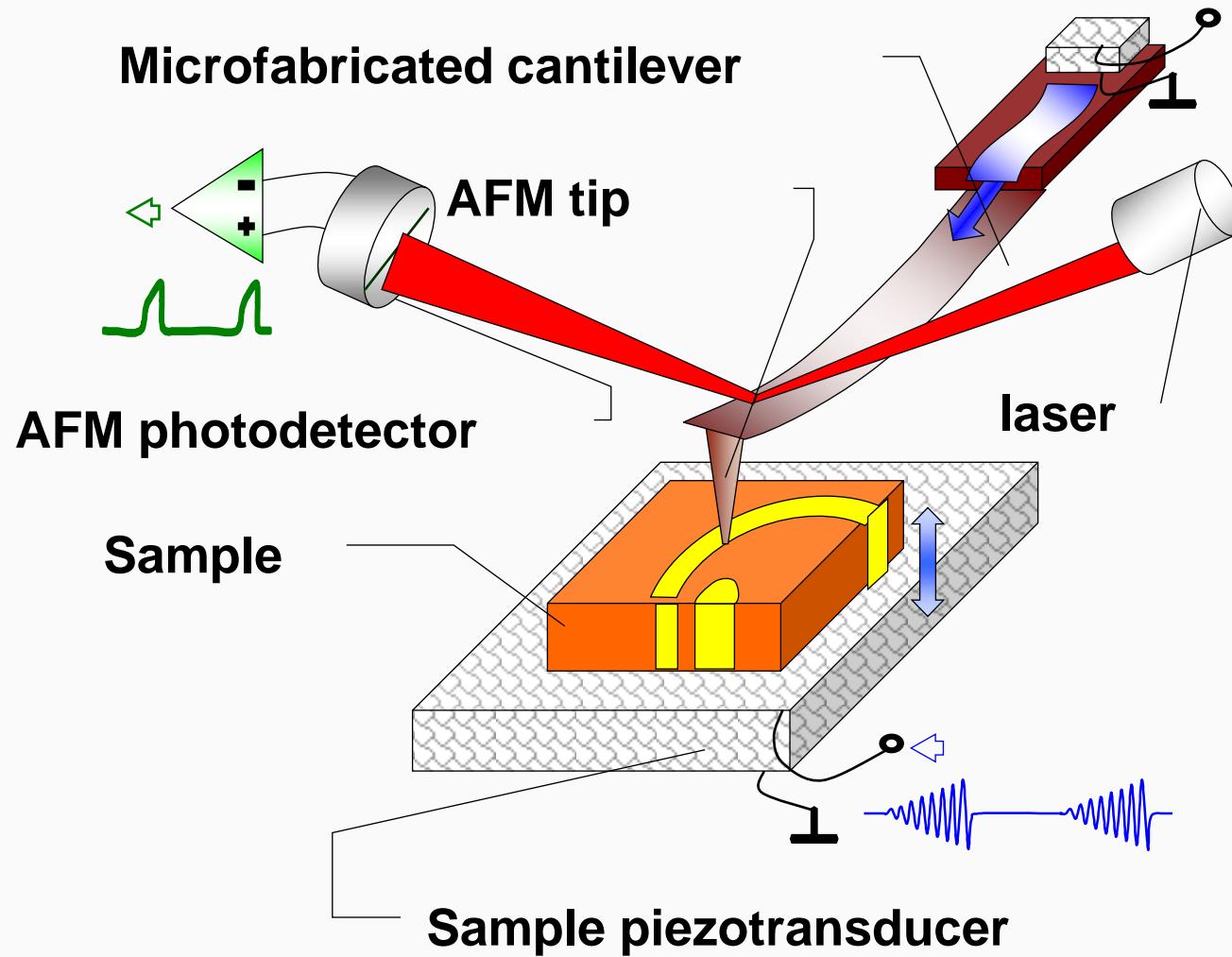
High selectivity, bound to single or multiple absorption resonances: Resolution $\leq 0.1 \text{ cm}^{-1}$;

Non invasive “optical” diagnostic application to different and hostile environments.

Possibilità di collaborazione e inserimento in aziende!

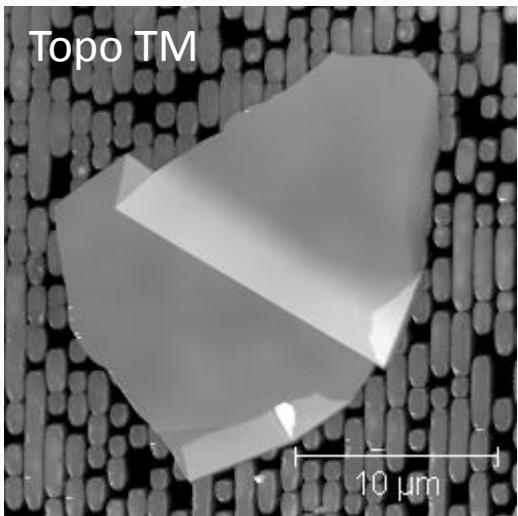
Microscopie a sonda..

Ultrasonic Force Microscope

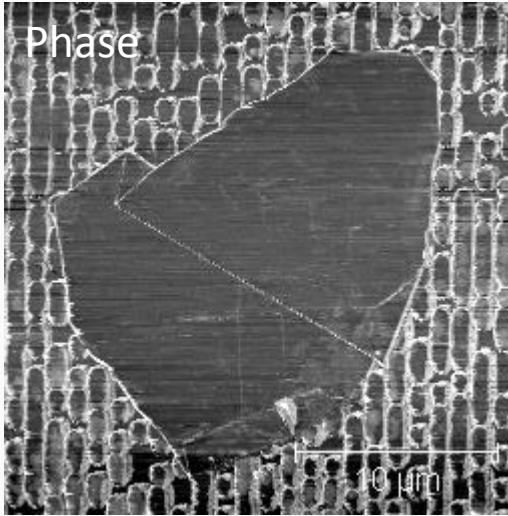


Subsurface detection

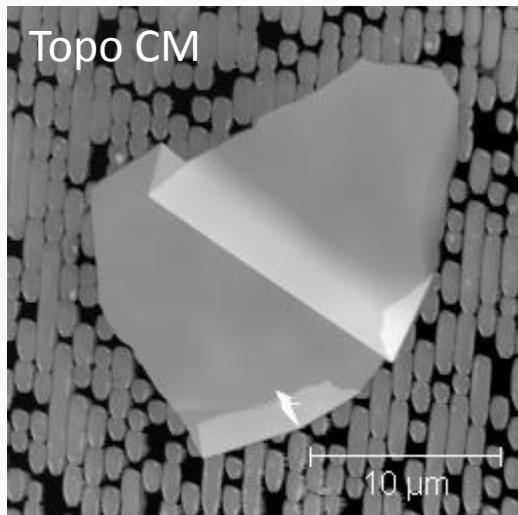
Topo TM



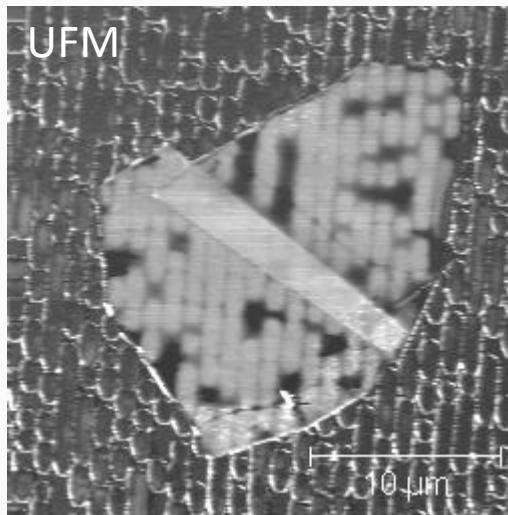
Phase



Topo CM

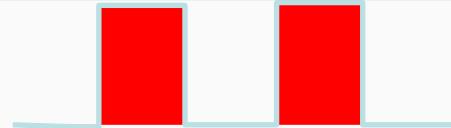


UFM



Graphene slab placed
on a structured
polymer film.

Graphite (50-100nm)

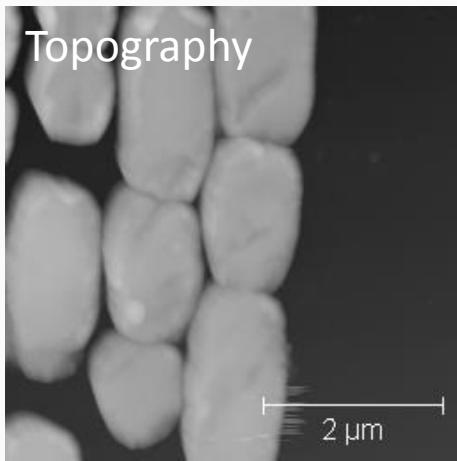




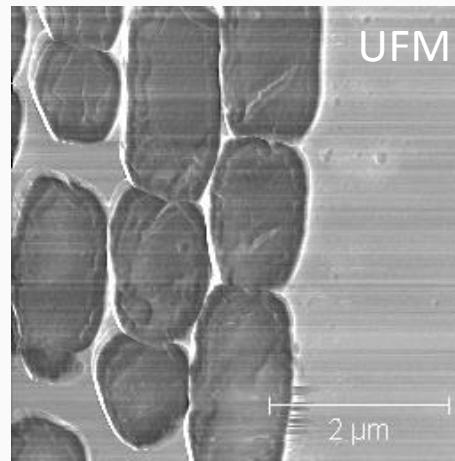
Subsurface detection

Graphene slab placed on a structured polymer film.

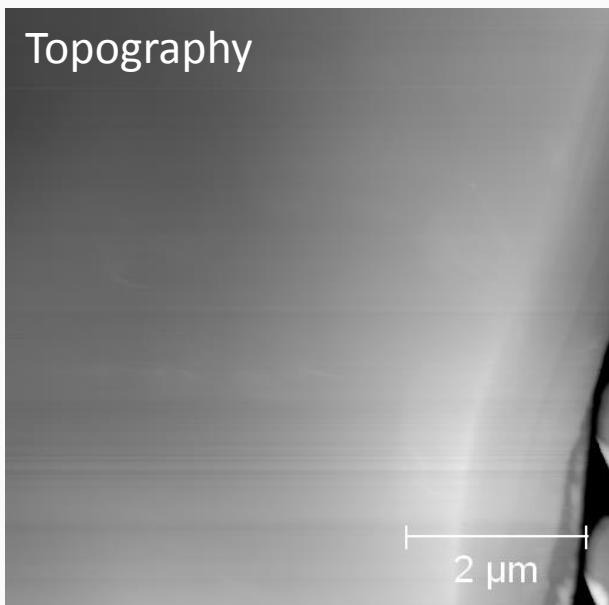
Topography



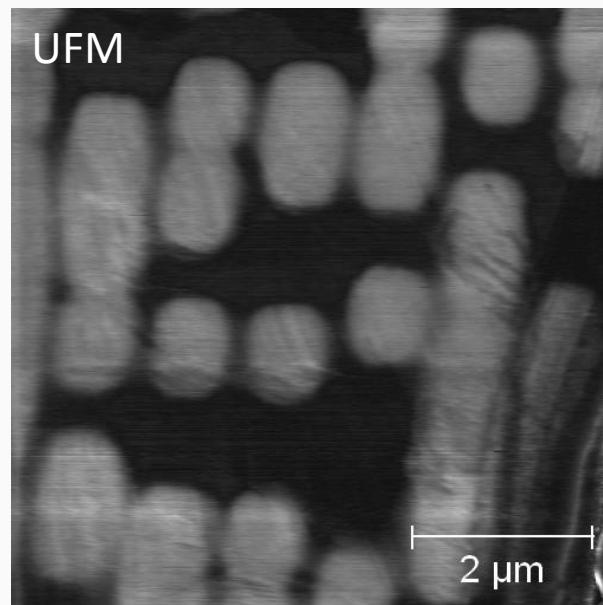
UFM



Topography



UFM



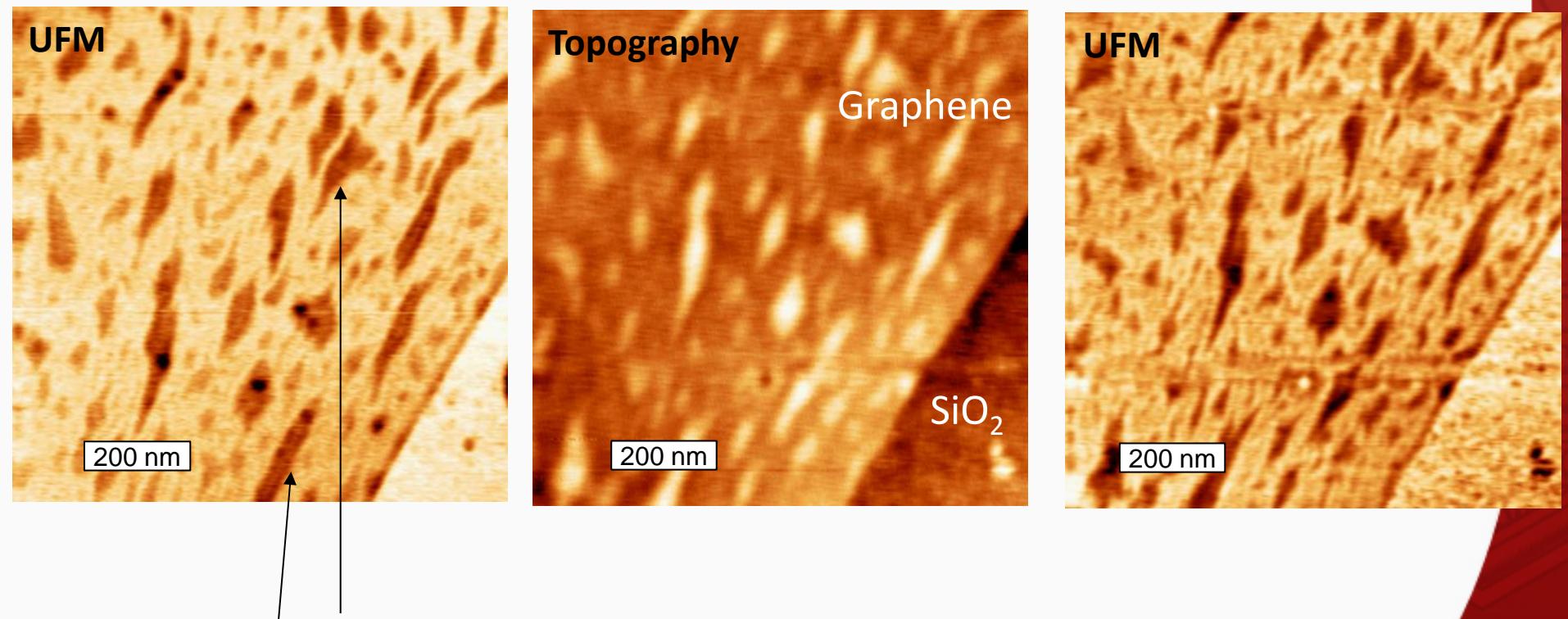
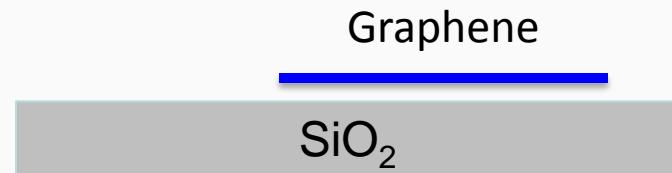
Polymer Steps



Graphite (50-100nm)



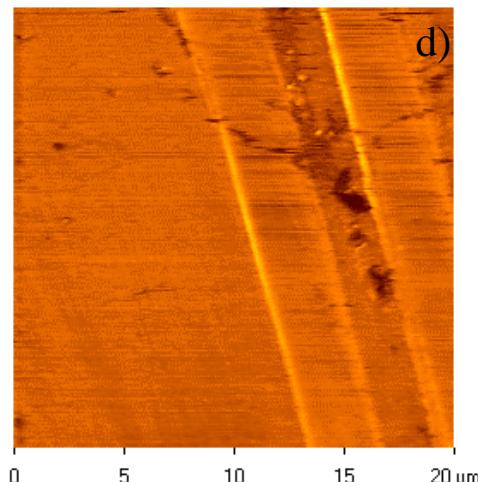
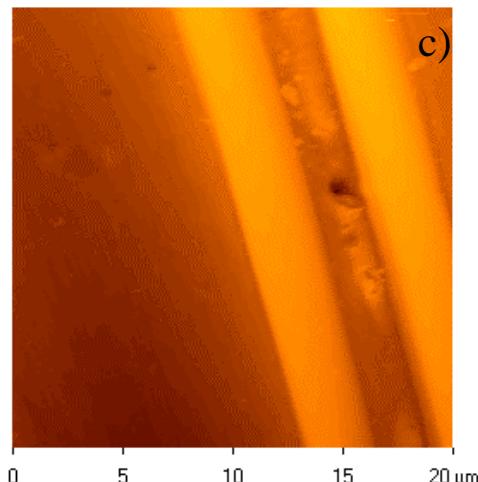
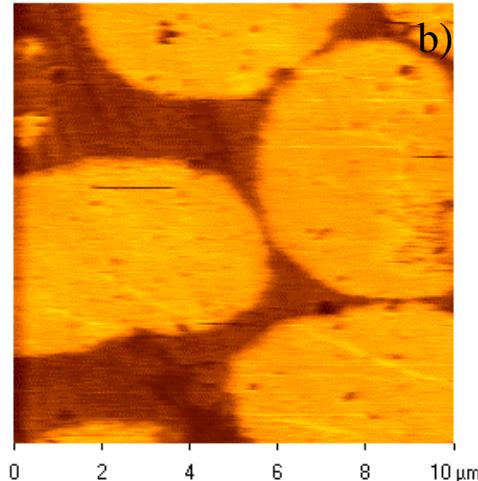
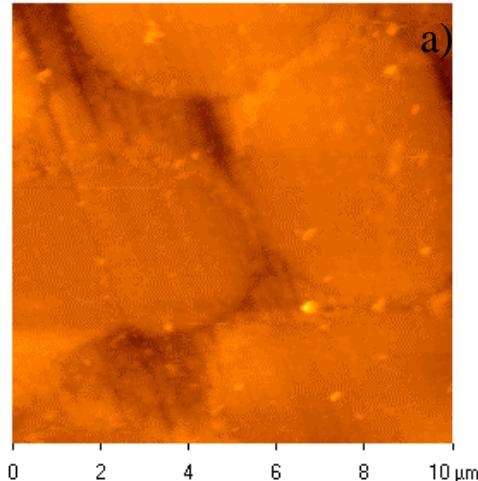
Graphene Transfer on SiO_2



Delaminations

Elastic contrast

Carbon Fibers in Epoxy Matrix

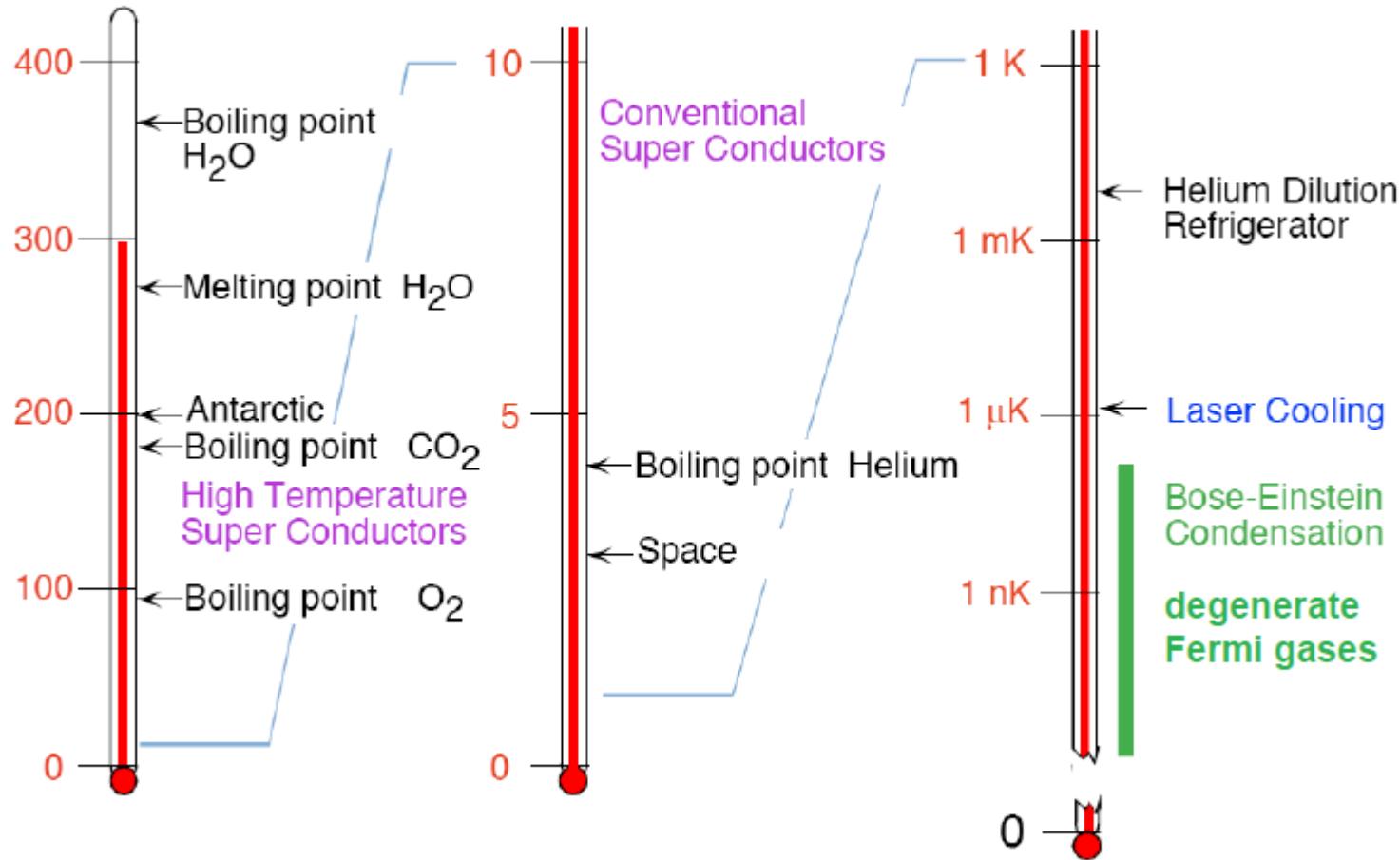


294 GPa

1-10 GPa



Laser per *raffreddare* la materia

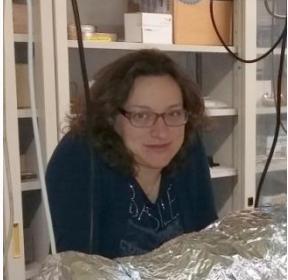




Laser cooling experiments

- **Quantum simulations with a Dysprosium BEC
(collaboration with LENS in Florence)**
- **Magnetic Induction Tomography with ultracold
atoms (collaboration with UCL in London)**

The team



Alessandro Fregosi (Diploma Th. student)

Eleonora Lucioni (INO - LENS)

Andrea Fioretti (INO Pisa)

Carlo Gabbanini

Silvia Gozzini



Giovanni Modugno (Unifi - INO - LENS)

Jacopo Catani

Massimo Inguscio



Luca Marmugi (University College, London)

Ferruccio Renzoni



Guido Masella (former graduate student)

Matteo Archimi (former graduate student)

Leonardo Del Bino (former diploma th. Student)



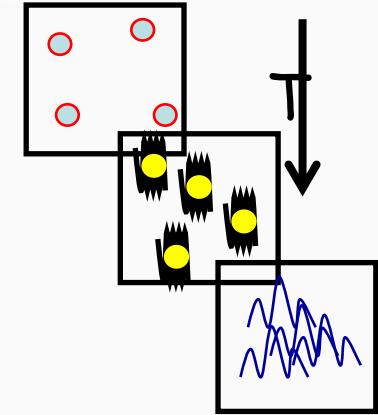
Ultracold atoms



Quantum gases:
atoms cooled down to quantum
degeneracy:

Matter wave with interactions:
superfluidity

Atomic gases are million times thinner
than air and more than million times
colder than space: cold atoms are diluted
quantum systems...





Quantum gas experiments

- Statistics (Bosons or fermions)
- Dimensionality (1D, 2D, 3D)
- Control and tune of the interactions (attractive/repulsive, short/long range)
- Shaping of the potential (optical potentials)



Extremely versatile tool characterized by good control
and large tunability of the system parameters

Quantum simulators

(with ultracold atoms)



Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

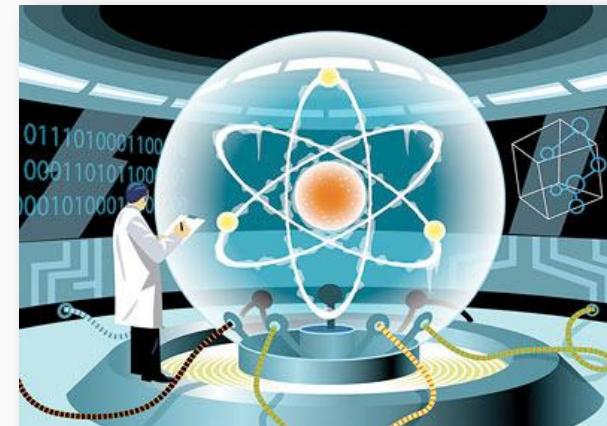
Received May 7, 1981

International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

The first question is, What kind of computer are we going to use to simulate physics? Computer theory has been developed to a point where it realizes that it doesn't make any difference; when you get to a *universal computer*, it doesn't matter how it's manufactured, how it's actually made. Therefore my question is, Can physics be simulated by a universal computer? I would like to have the elements of this computer *locally intercon-*

$$H\psi = E\psi$$

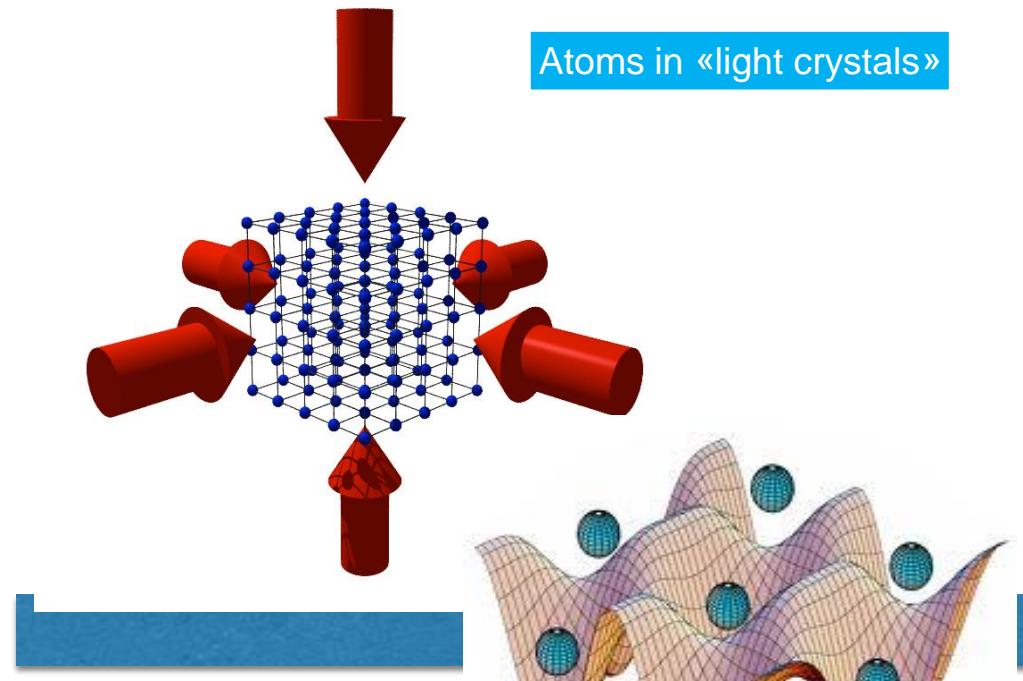
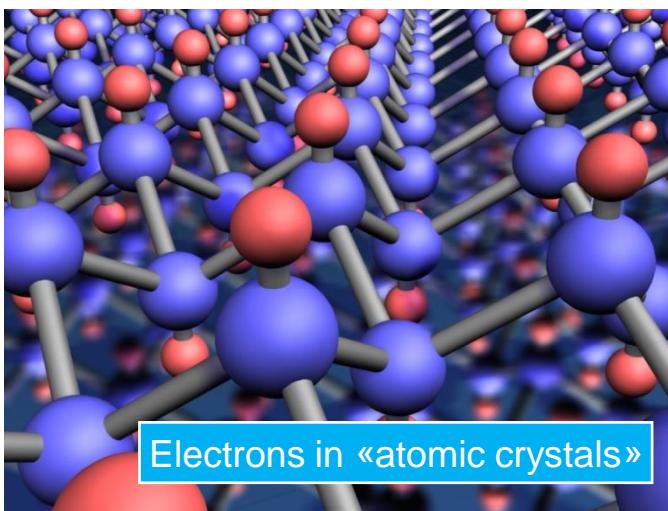
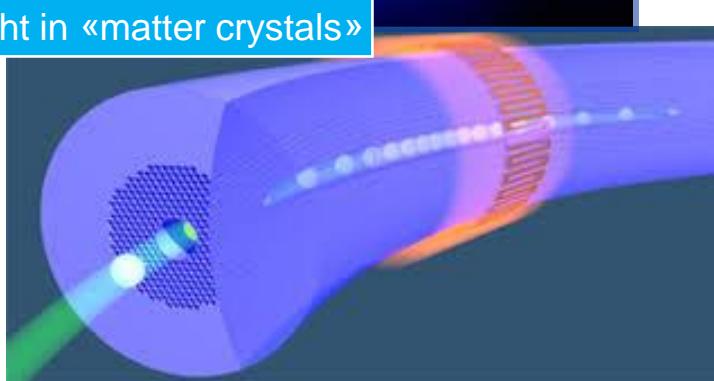
or



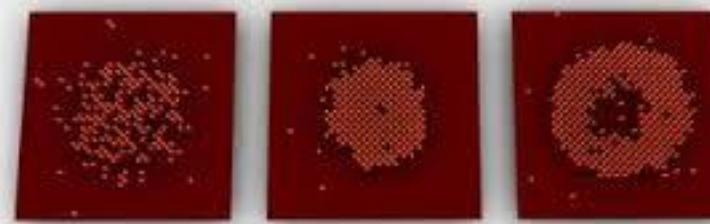
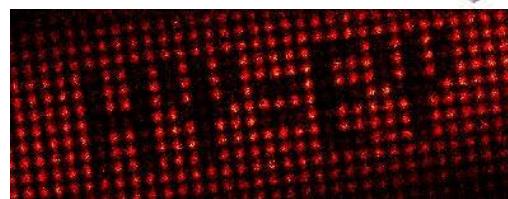
Light crystals



Light in «matter crystals»



Atoms in «light crystals»



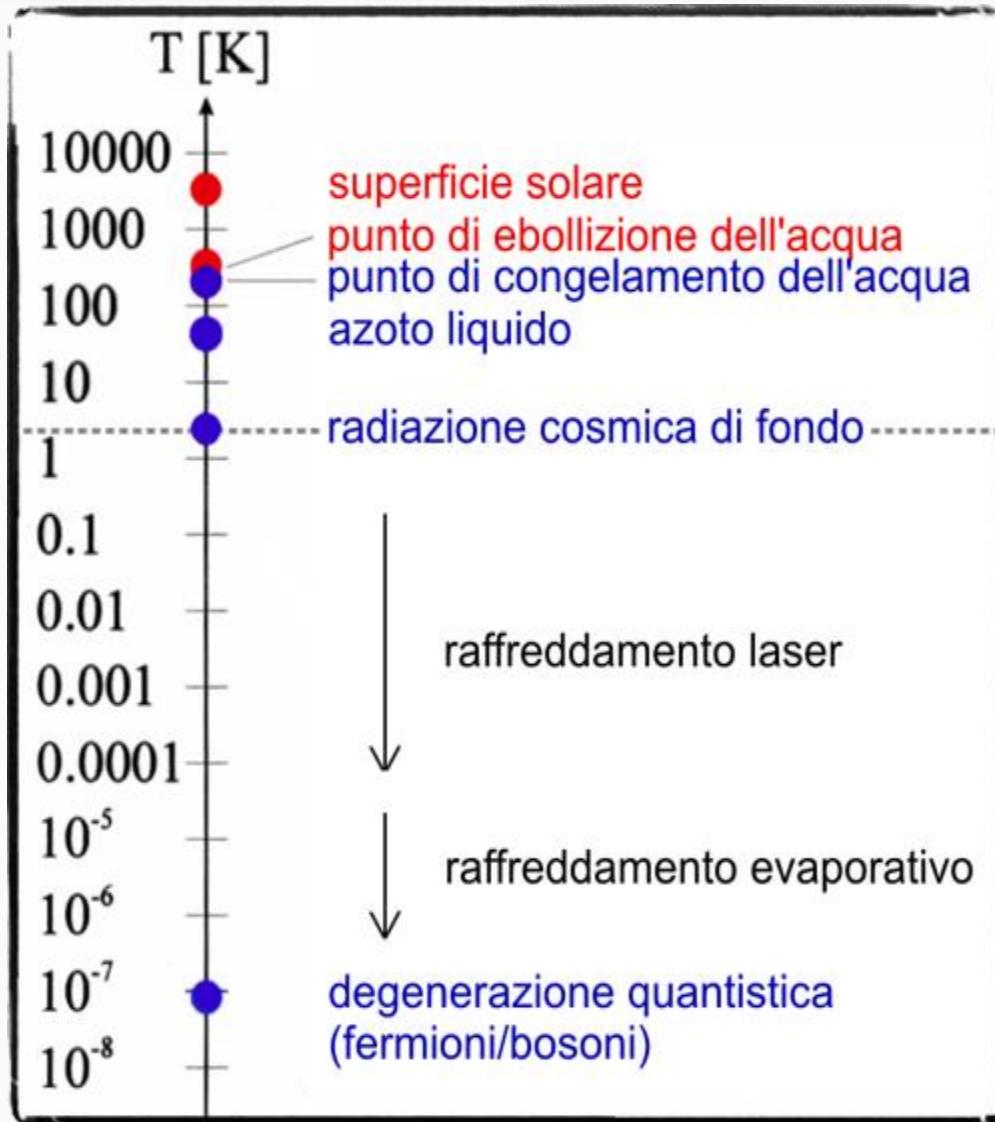
A powerful toolbox

Atomic gases and optical potentials: a powerful tool box for condensed matter physics that allow total control of all the system parameters:

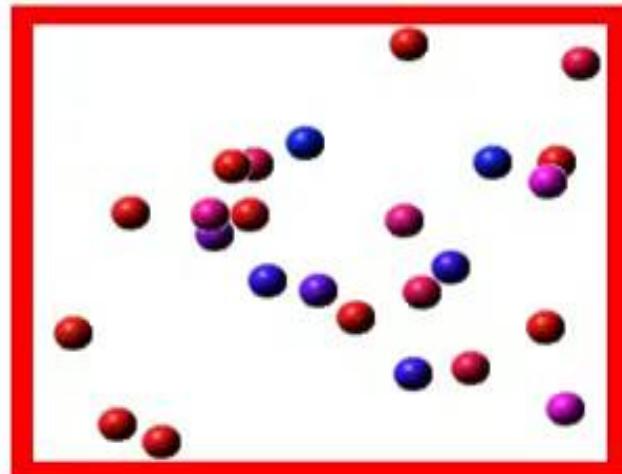
- Optical lattices are perfect lattices: no impurities, no phonons
- Optical lattices: depths, spacing can be changed @ will
- Optical lattices and dimensionality: low dimensional physics (1d,2d) is possible!
- Disordered potentials: control main lattice and disorder @ will
- Correlated systems: MOTT insulator - superfluid, BKT transitions, Tonk gases...

- Atom density and temperature (N,T)
- Atoms interactions: tuning scattering length via Feshbach resonances
- Weakly interacting regimes: ideal systems
- Fermi and Bose statistics
- Fermi-Fermi, Bose-Bose, Bose-Fermi systems can be investigated
-

Way to quantum degeneracy

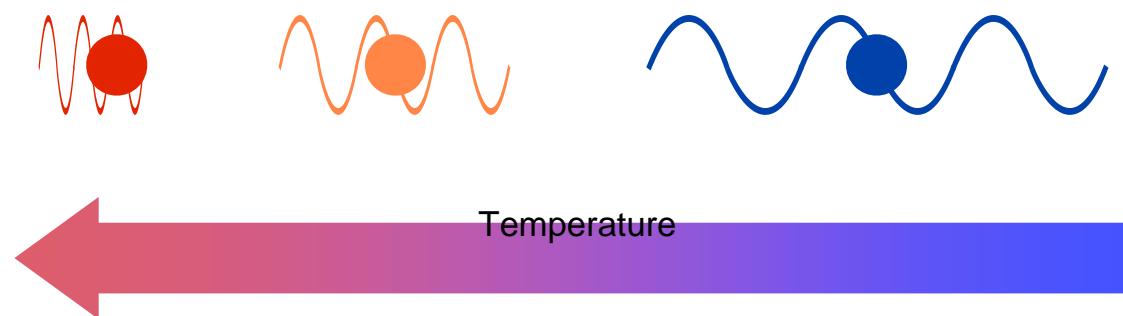


Why so cold?



Condensation
de Bose
Einstein

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

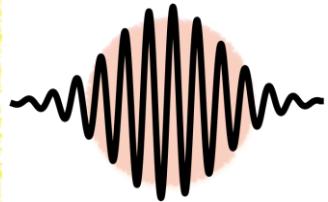


Why so diluted?

In most cases quantum degeneracy is pre-empted by a more familiar transition to liquid or solid.

In order to prevent this classical condensation, one has to deal with very low densities so that three-body collisions (that allow the formation of molecules or clusters) are very rare.



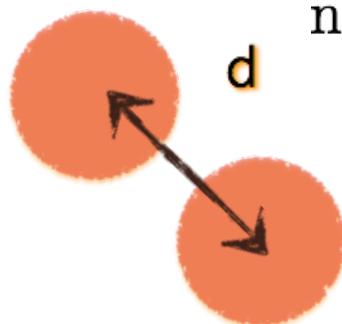


$$\lambda_{dB} = \frac{h}{mv}$$

(Rb atom)

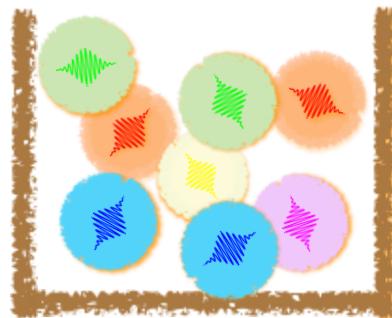
@ T=300K, $\lambda_{dB} = 10^{-11} m !!$

@ T=100 nK, $\lambda_{dB} = 10^{-6} m !!$

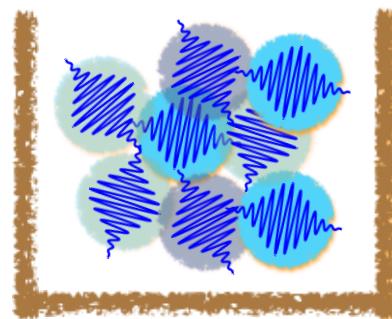


$$n \propto d^{-3}$$

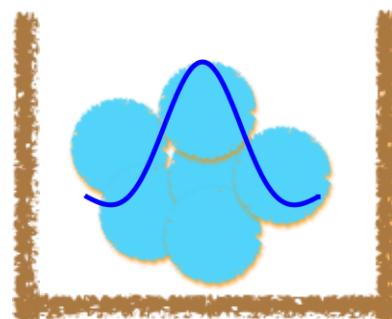
$$n\lambda^3 \ll 1$$



$$n\lambda^3 \sim 1$$

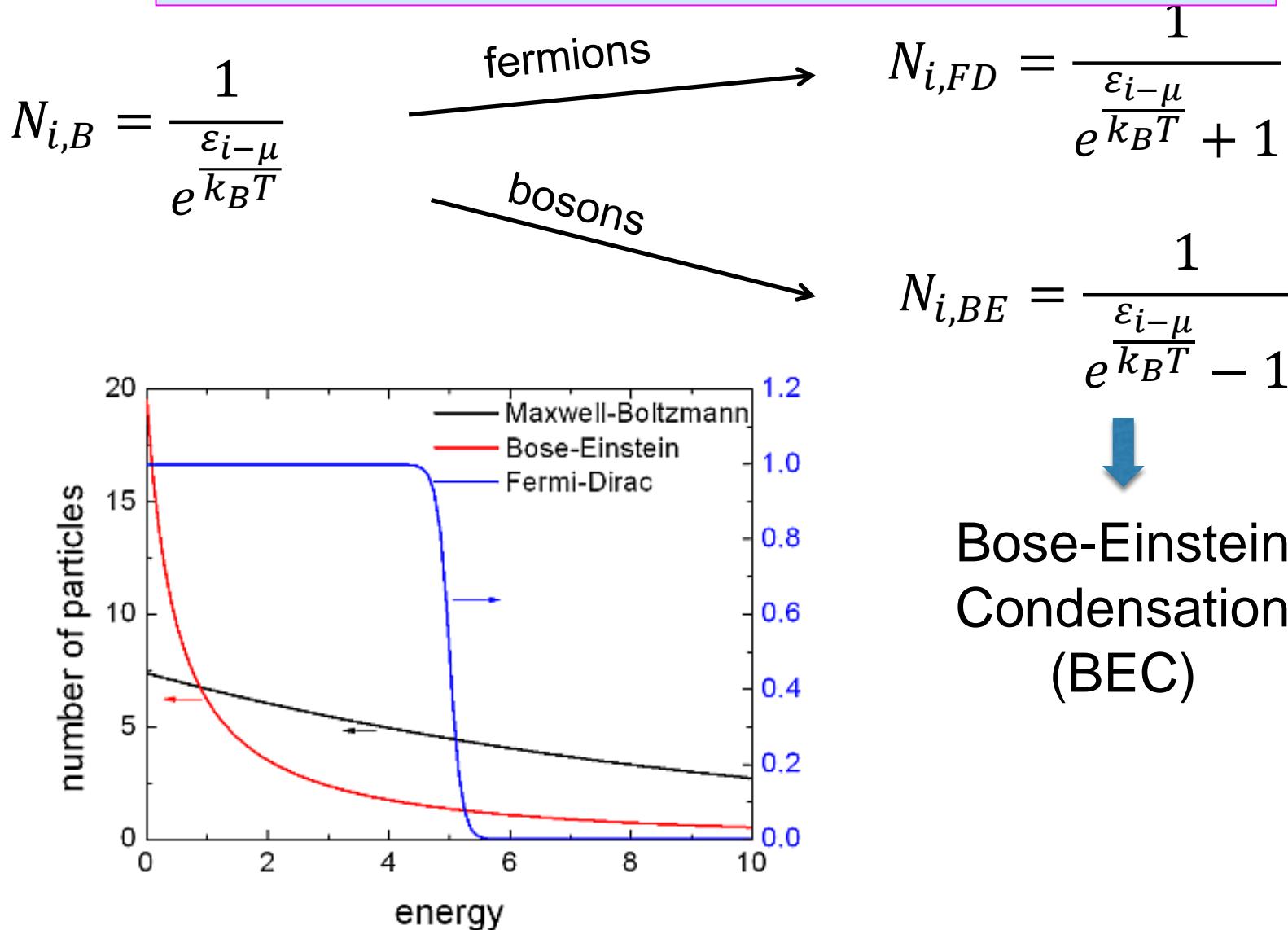


$$n\lambda^3 > 1$$

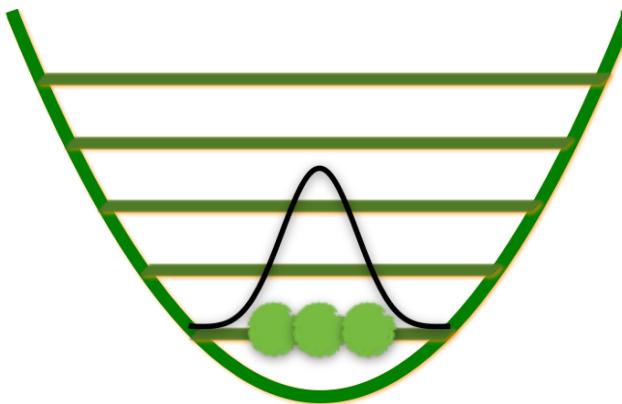


Typical densities for quantum gases: $10^{14}\text{-}10^{15}$ atoms/cm³

Classical vs quantum particles



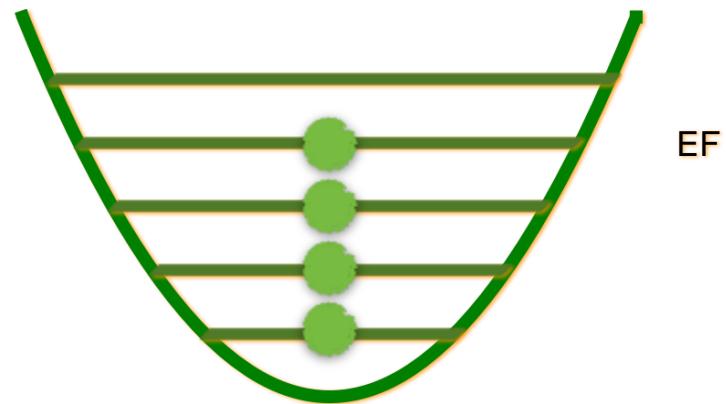
Bose-Einstein condensate



- Statistical “attraction” between the particles

- Atomic gases
- Photons
- Phonons in crystal
- ^4He

Fermi gas

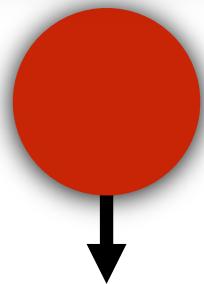


- Statistical “repulsion” between the particles

- Atomic gases
- Electrons and nuclei
- Neutron stars
- ^3He

Fermionic pressure: fermions can be constrained in a too narrow space. This prevents collapse of neutron stars

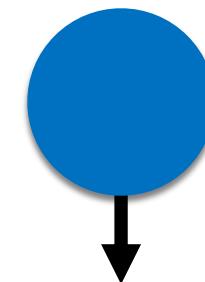
Room temperature



$$v_{av}=300 \text{ m/s}$$

$$t \sim 1/10 \text{ s}$$

«Ultracold» temperature



$$v_{av}=2 \text{ mm/s}$$

$$t \sim \text{a few hours}$$



Experimental techniques

$T \approx 300 \text{ K}$
Room T



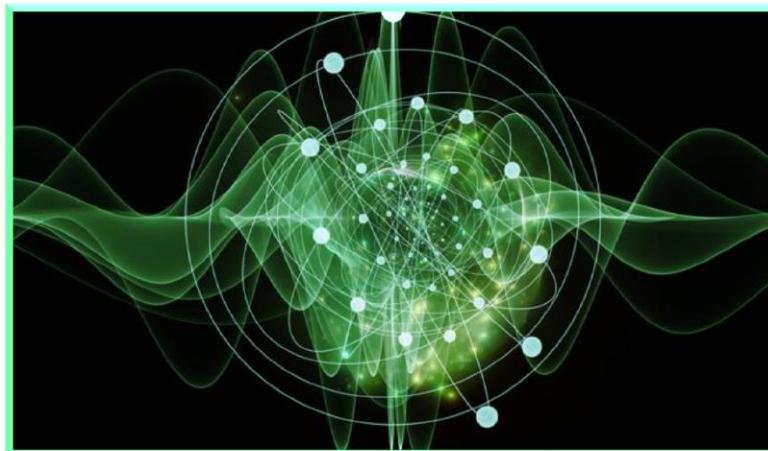
Laser
cooling

$T \approx 10 \mu\text{K}$



Evaporative
cooling

$T \approx 100 \text{ nK}$



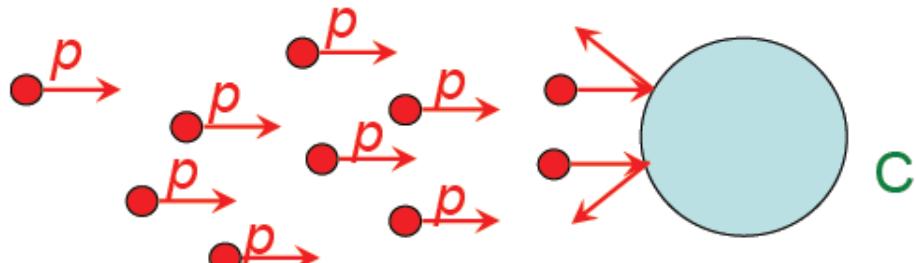
ENTERING
QUANTUM WORLD

Laser cooling

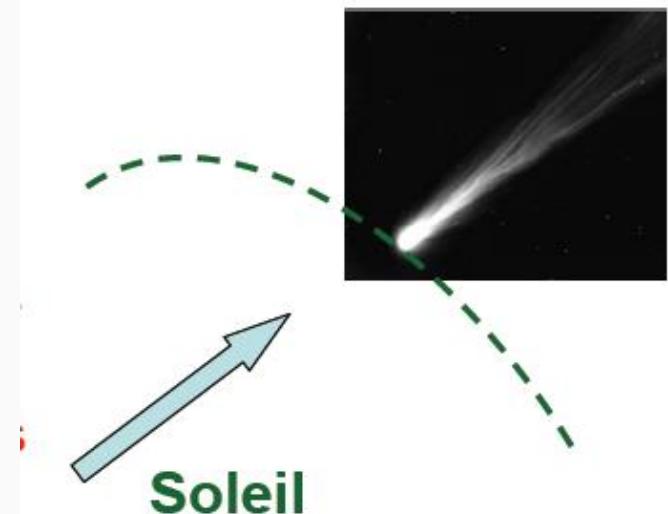


Light forces on atoms 1/3

- Momentum transfer between photons and atoms



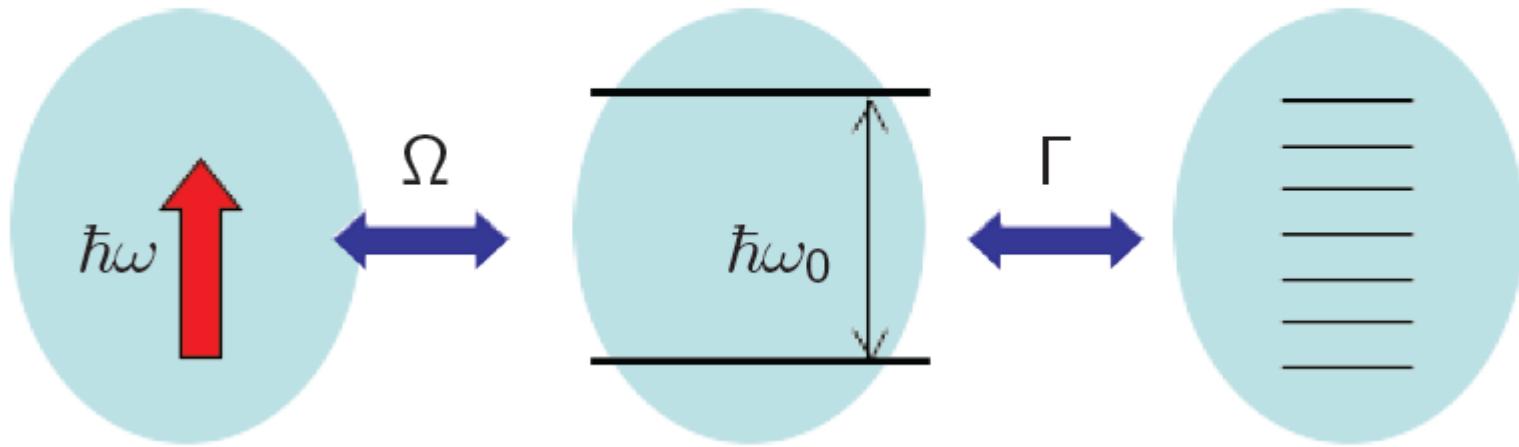
- Kepler already imagined the existence of a radiation pressure to explain the tails of comets



- In 1933 Otto Frisch observed the deflection of a sodium beam by an intense light beam

Light forces on atoms 2/3

3 systems in interaction : laser – atom – vacuum



atomic electric dipole moment $\mathbf{d} = \langle e | \hat{\mathbf{D}} | g \rangle$

$$\hbar\Omega(\mathbf{r}) = - (\mathbf{d} \cdot \boldsymbol{\epsilon}(\mathbf{r})) \mathcal{E}(\mathbf{r}) \quad \text{Rabi frequency}$$

Spontaneous emission rate Γ

$$I_s = \frac{\Gamma \hbar \omega_0^3}{12\pi c^2}.$$

N.B. link with saturation intensity I_s : $\Omega^2/\Gamma^2 = I/2I_s$

Typical value of I_s : a few mW/cm²

Light forces on atoms 3/3

- The **radiation pressure** force arises from a phase gradient.
ex: plane wave $\phi(\mathbf{r}) = -\mathbf{k} \cdot \mathbf{r}$

$$\mathbf{F}_{\text{pr}} = \hbar \mathbf{k} \frac{\Gamma}{2} \frac{s}{1 + s}$$

$$s = \frac{\Omega^2/2}{\delta^2 + \Gamma^2/4} = \frac{I/I_s}{1 + 4\delta^2/\Gamma^2}$$

s is the *saturation parameter*. $\delta = \omega - \omega_0$ is the *detuning*.

- The **dipole force** is due to an intensity gradient.

$$\mathbf{F}_{\text{dip}} = -\frac{\hbar \delta}{2} \frac{\nabla s(\mathbf{r})}{1 + s(\mathbf{r})}$$

It derives from the **dipole potential** $U_{\text{dip}} = \frac{\hbar \delta}{2} \ln(1 + s(\mathbf{r}))$.

Light forces on atoms 3/3

- The **radiation pressure** force arises from a phase gradient.
ex: plane wave $\phi(\mathbf{r}) = -\mathbf{k} \cdot \mathbf{r}$

$$\mathbf{F}_{\text{pr}} = \hbar \mathbf{k} \frac{\Gamma}{2} \frac{s}{1 + s}$$

$$s = \frac{\Omega^2/2}{\delta^2 + \Gamma^2/4} = \frac{I/I_s}{1 + 4\delta^2/\Gamma^2}$$

s is the *saturation parameter*. $\delta = \omega - \omega_0$ is the *detuning*.

- The **dipole force** is due to an intensity gradient.

For two-level atoms it becomes:

Trapping potential: $U_{\text{dip}}(\mathbf{r}) = \frac{3\pi c^2}{2\omega_0^3} \frac{\Gamma}{\Delta} I(\mathbf{r})$

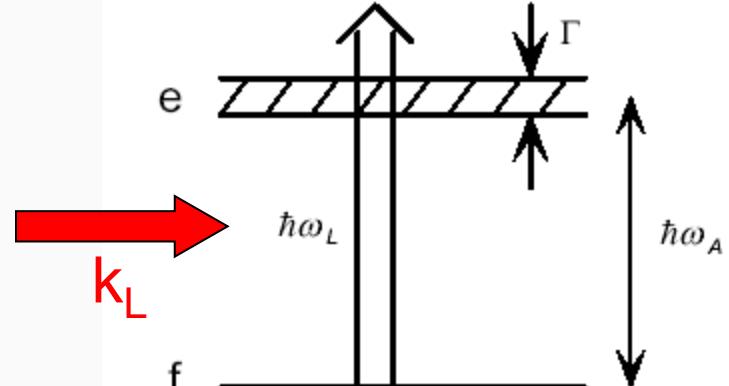
Scattering rate: $\Gamma_{\text{sc}}(\mathbf{r}) = \frac{3\pi c^2}{2\hbar\omega_0^3} \left(\frac{\Gamma}{\Delta} \right)^2 I(\mathbf{r})$

Radiation Pressure

Two-level atom

Γ^{-1} lifetime : 32 ns for Cesium

$$\delta = \omega_L - \omega_A \quad \text{detuning}$$



Recoil Velocity: change of velocity due to the absorption of a photon:

$$v_{\text{rec}} = \frac{\hbar k_A}{m} = \frac{\hbar}{m\lambda_A} \quad \begin{matrix} 3,5 \text{ mm s}^{-1} \\ \text{cesium atoms} \end{matrix} \quad <<\text{ thermal velocity}$$

For alkali, $3 \leq v_{\text{rec}} \leq 30 \text{ mm.s}^{-1}$, $\Gamma^{-1} \sim 10 \text{ to } 100 \text{ ns}$. Corresponding acceleration: $a_{\text{pr}} \simeq \Gamma v_{\text{rec}} \sim 10^4 \text{ to } 10^5 g$

Atomic beam slowing 1/2

$$V^2(z) = V_0^2 - 2a_{\max}z \quad \text{stopping distance} \quad z_0 = V_0^2 / (2a_{\max})$$

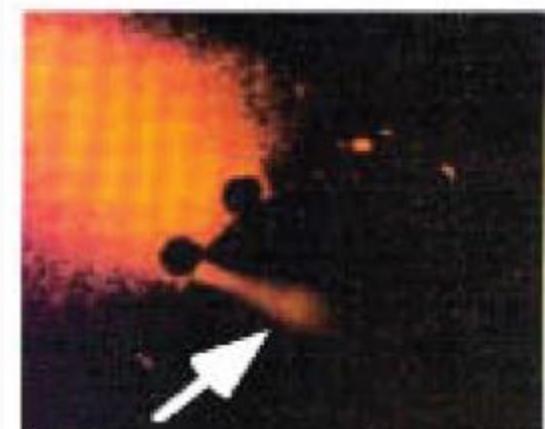
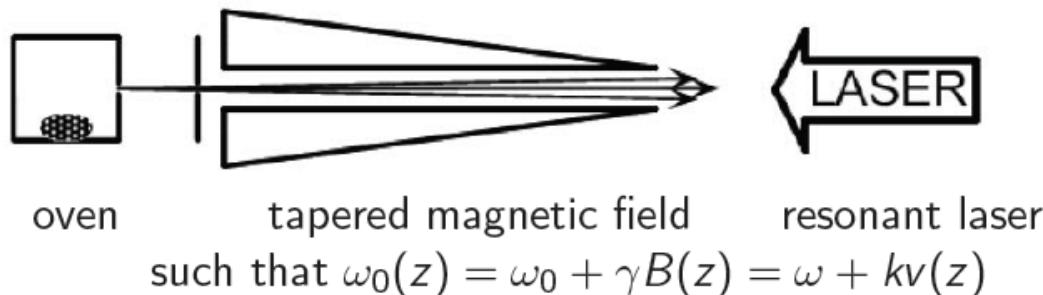
$$\text{maximal value: } F_{\text{pr}} = \hbar k \frac{\Gamma}{2} \quad \text{resonance condition} \quad \omega_L - k_L V(z) = \omega_A(z)$$

1) inhomogeneous magnetic field -> cw method

$$F(z, v) = \frac{\hbar k \Gamma}{2} \frac{s_0}{1 + s_0 + 4[\delta + kv - \mu' B(z)/\hbar]^2/\Gamma^2}.$$

$$B(z) = B_b + B_p \sqrt{1 - z/z_s}.$$

Zeeman slower (B. Phillips et al., J. Hall et al., 1985)

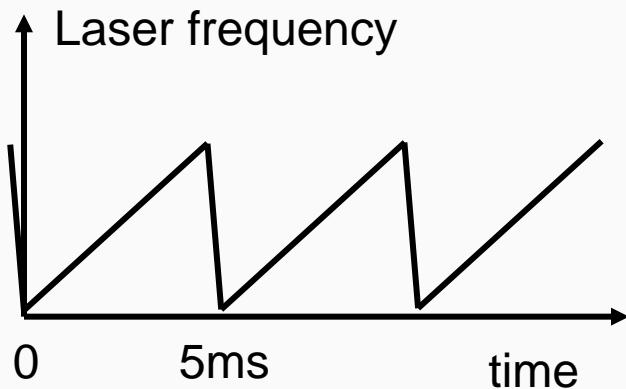


stopped atomic beam

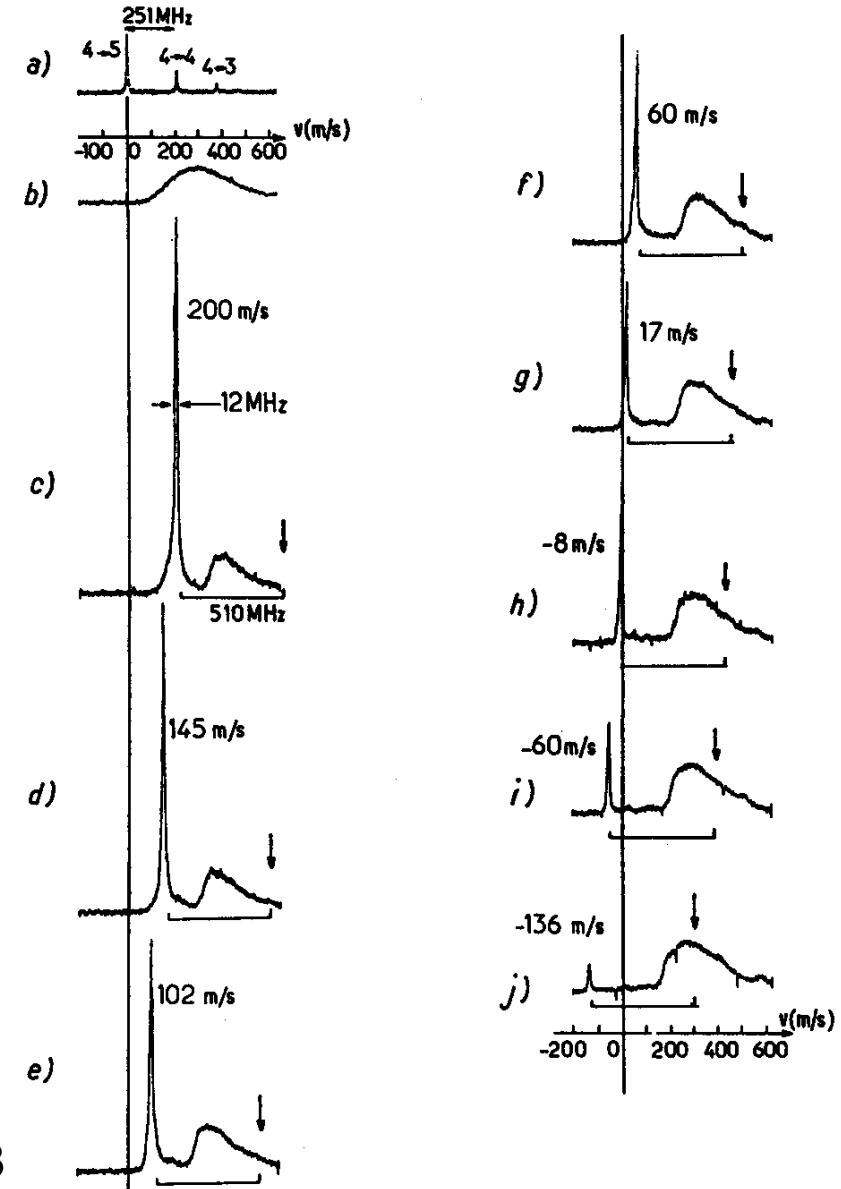
Atomic beam slowing 2/2

2) chirped cooling
(pulsed method)

$$\omega_L(t) - k_L V(t) = \omega_A$$

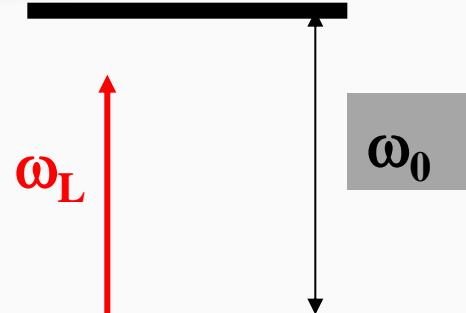


Extremely simple
with diode lasers !

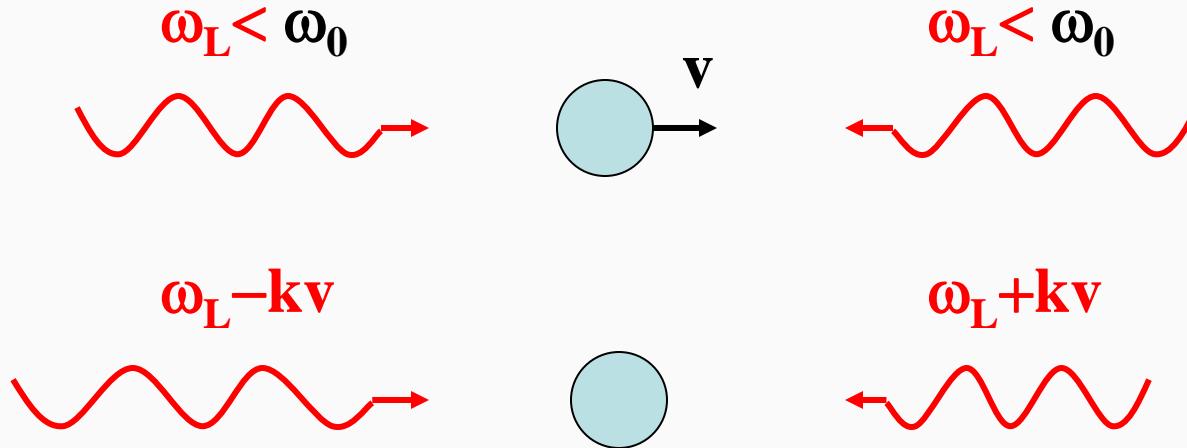


Doppler Cooling 1/2

Theory by Hänsch, Schawlow (neutrals)
and Wineland, Dehmelt (ions) 1975



Doppler effect



Laboratory frame

Atom frame

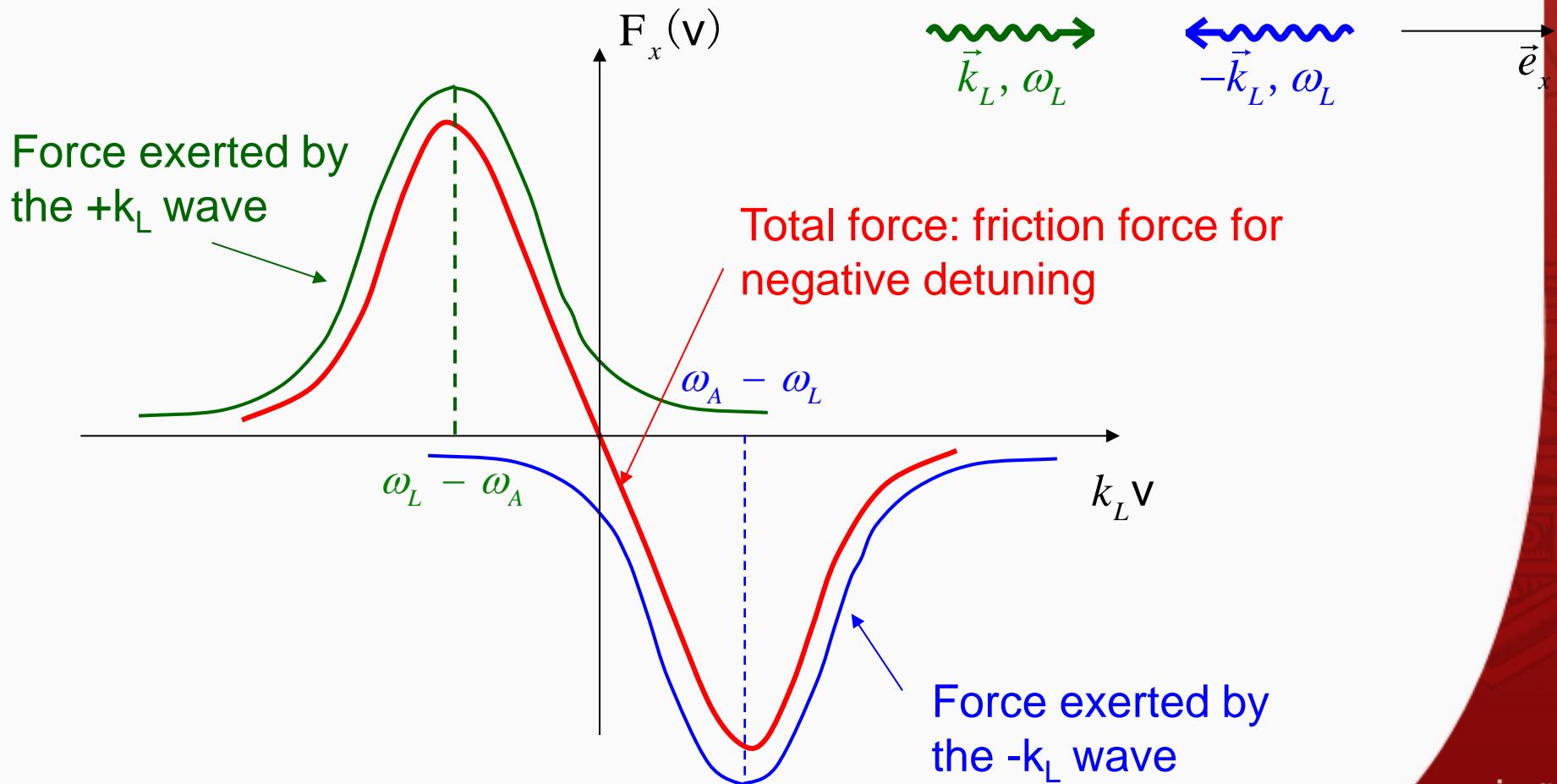
Absorption of the photon $\omega_L + kv$, followed by a spontaneous emission equiprobable in all directions of the space.

Act as: $F = -\alpha v$ (friction force) = mdv/dt

Doppler Cooling 2/2

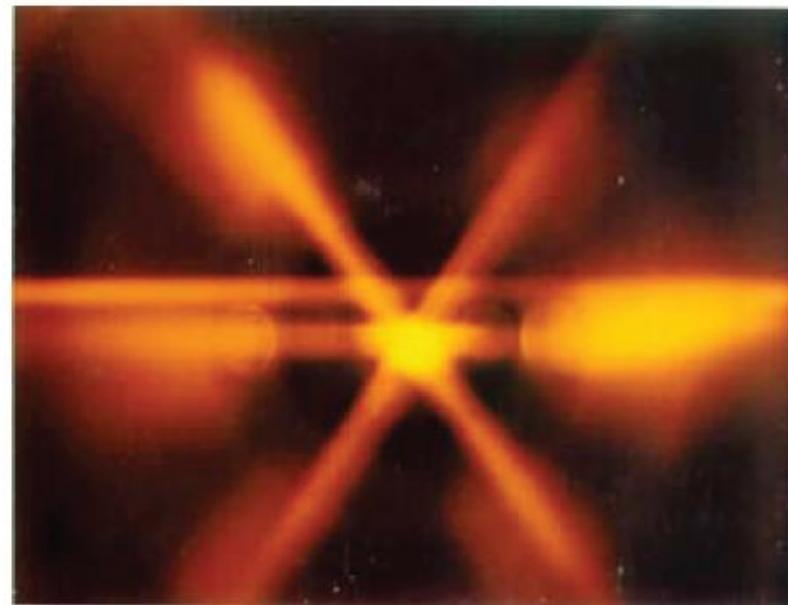
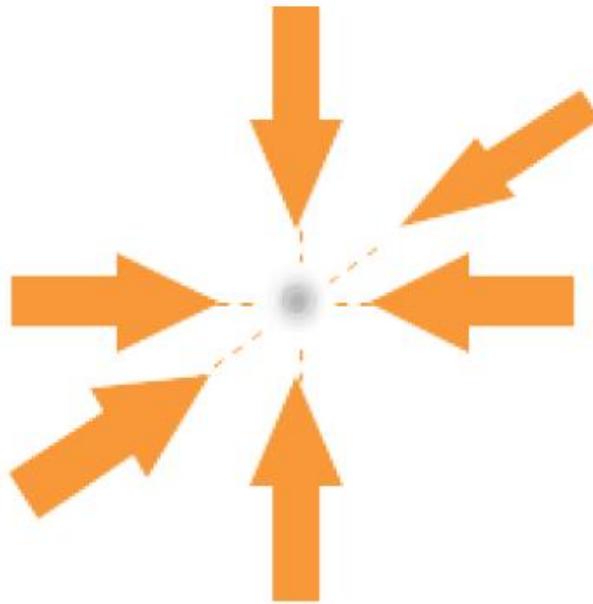
(for a red detuning : $\delta = \omega_L - \omega_A < 0$)

One supposes that one can independently add the radiation pressure forces of the 2 waves.



Optical molasses

Generalization to 3D:



first Na molasses at NIST

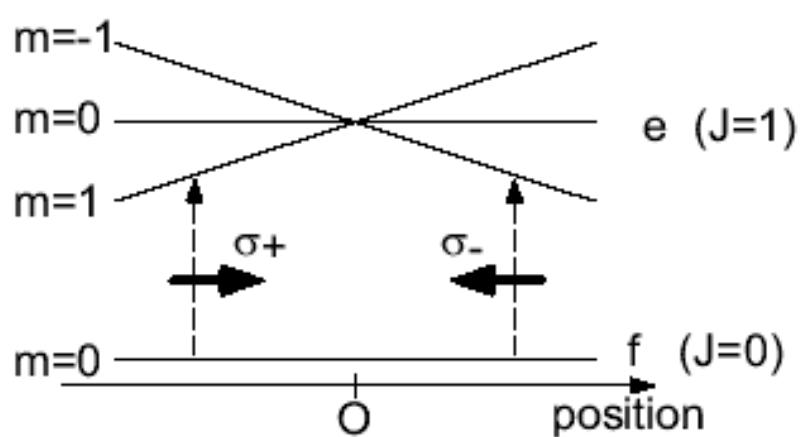
⇒ Competition cooling vs random walk in momentum space

diffusion coefficient $D_p = \hbar^2 k^2 \Gamma s_0$

limit temperature : $k_B T_D = \frac{D_p}{\alpha} > \frac{D_p}{\alpha_{\max}} = \frac{\hbar \Gamma}{2}$ for $\delta = -\Gamma/2$

The magneto-optical trap 1/3

Seminal idea: J. Dalibard, 1987,

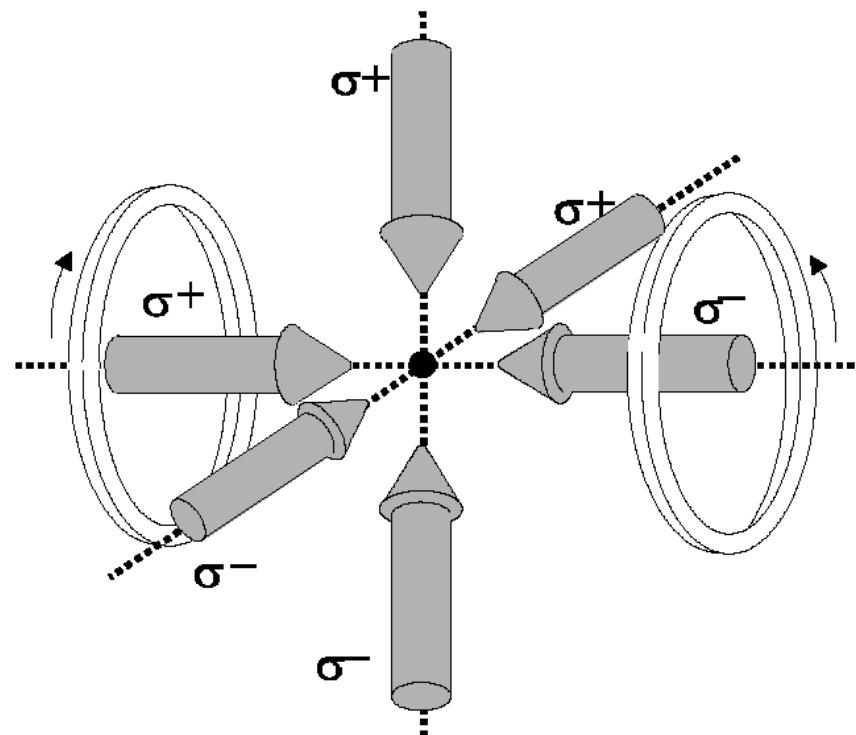


$$\mathbf{F} = -\alpha \mathbf{v} - k \mathbf{r}$$

3D Molasses
Doppler effect

Trapping
Zeeman effect
Produces imbalance
in rad pressure forces

1st realization: S. Chu, 1987



$b' = 10 \text{ Gauss / cm}$
 $I = \text{a few mW per beam}$

The magneto-optical trap 2/3

$$F_{-z} = + \frac{\hbar k}{2} \Gamma \frac{\Omega^2/2}{\left(\Delta - kv_z - \frac{\mu_B}{\hbar} \frac{dB}{dz} z \right)^2 + (\Gamma/2)^2 + \Omega^2/2}$$

$$F_{\text{MOT}} = F_{+z} + F_{-z} = -\alpha \dot{z} - K z$$

Damping
Doppler effect

Trapping
Zeeman effect

The magneto-optical trap 2/3

$$F_{-z} = + \frac{\hbar k}{2} \Gamma \frac{\Omega^2/2}{\left(\Delta - kv_z - \frac{\mu_B}{\hbar} \frac{dB}{dz} z \right)^2 + (\Gamma/2)^2 + \Omega^2/2}$$

$$F_{\text{MOT}} = F_{+z} + F_{-z} = -\alpha \dot{z} - K z$$

Damping
Doppler effect

Trapping
Zeeman effect

The magneto-optical trap 2/3

$$F_{-z} = + \frac{\hbar k}{2} \Gamma \frac{\Omega^2/2}{\left(\Delta - kv_z - \frac{\mu_B}{\hbar} \frac{dB}{dz} z \right)^2 + (\Gamma/2)^2 + \Omega^2/2}$$

$$F_{\text{MOT}} = F_{+z} + F_{-z} = -\alpha \dot{z} - K z$$

Damping
Doppler effect

Trapping
Zeeman effect



Laser cooling of atomic species

Group IA	
1	H
	Hydrogen 1.00794 $1s^1$ 13.9984
2	Li
	Lithium 6.941 $1s^2 2s^1$ 7.3917
3	Na
	Sodium 22.98977 $1s^2 2s^2 2p^6$ 11.999
4	Mg
	Magnesium 24.3052 $1s^2 2s^2 2p^6 3s^2$ 12.999
5	K
	Potassium 39.0963 $1s^2 2s^2 2p^6 3s^2 3p^6$ 18.999
6	Ca
	Calcium 40.079 $1s^2 2s^2 2p^6 3s^2 3p^6 4s^1$ 19.992
7	Rb
	Rubidium 85.4678 $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 4p^1$ 37.999
8	Cs
	Cesium 126.9054 $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 4p^6 5s^1$ 55.999
9	Fr
	Francium (223) $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 4p^6 5s^2 5p^1$ 40.727

PERIODIC TABLE Atomic Properties of the Elements

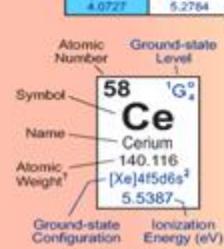
Frequently used fundamental physical constants									
For the most accurate values of these and other constants, visit physics.nist.gov/constants									
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs									
speed of light in vacuum									
c									
299 792 458 m s ⁻¹ (exact)									
Planck constant									
h									
6.6261 × 10 ⁻³⁴ J s ($\hbar = h/2\pi$)									
elementary charge									
e									
1.6022 × 10 ⁻¹⁹ C									
electron mass									
m_e									
0.5110 MeV									
proton mass									
m_p									
1.6726 × 10 ⁻²⁷ kg									
fine-structure constant									
α									
1/137.036									
Rydberg constant									
R_{∞}									
10 973 732 m ⁻¹									
$R_{\infty c}$									
3.289 84 × 10 ¹⁵ Hz									
$R_{\infty hc}$									
13.6057 eV									
Boltzmann constant									
k									
1.3807 × 10 ⁻²³ J K ⁻¹									

Physics Laboratory NIST Standard Reference Data Program
physics.nist.gov www.nist.gov www.nist.gov/ard

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology

IIIB	IVB	VB	VIB	VIIB	VIII
5 ${}^3\text{P}_{1/2}$ B	6 ${}^1\text{P}_0$ C	7 ${}^3\text{S}_{1/2}$ N	8 ${}^3\text{P}_{1/2}$ O	9 ${}^3\text{P}_{2/3}$ F	2 ${}^1\text{S}_{1/2}$ He
Boron 10.811 $1s^2 2s^2$	Carbon 12.0107 $1s^2 2s^2 2p^2$	Nitrogen 14.00674 $1s^2 2s^2 2p^3$	Oxygen 16.9994 $1s^2 2s^2 2p^4$	Fluorine 18.99840 $1s^2 2s^2 2p^5$	Neon 20.17197 $1s^2 2s^2 2p^6$
Aluminum 26.99154 $1s^2 2s^2 2p^6 3s^1$	Silicon 28.0855 $1s^2 2s^2 2p^6 3s^2$	Copper 30.93260 $1s^2 2s^2 2p^6 3s^2 3p^1$	Zinc 32.6596 $1s^2 2s^2 2p^6 3s^2 3p^2$	Gallium 36.97216 $1s^2 2s^2 2p^6 3s^2 3p^3$	Argon 39.948 $1s^2 2s^2 2p^6 3s^2 3p^6$
Titanium 47.867 $[Ar]3d^2 4s^2$	Vanadium 50.9415 $[Ar]3d^3 4s^2$	Chromium 54.9365 $[Ar]3d^4 4s^2$	Iron 55.845 $[Ar]3d^5 4s^2$	Ruthenium 101.07 102.05500 $[Kr]4d^5 5s^1$	Krypton 39.994 $[Ar]3d^10 4s^2 4p^6$
Scandium 44.95591 $[Ar]3d^1 4s^2$	Scandium 44.95591 $[Ar]3d^1 4s^2$	Manganese 54.9365 $[Ar]3d^5 4s^2$	Cobalt 58.93320 $[Ar]3d^7 4s^2$	Palladium 105.42 102.90550 $[Kr]4d^9 5s^1$	Xenon 53.98 $[Ar]3d^10 4s^2 4p^6 5s^2$
Tantalum 180.9479 $[Xe]4f^15 5d^1 6s^2$	Tungsten 183.84 $[Xe]4f^15 5d^2 6s^2$	Rhenium 186.207 $[Xe]4f^15 5d^5 6s^2$	Osmium 190.217 $[Xe]4f^15 5d^7 6s^2$	Rhodium 106.42 102.90550 $[Kr]4d^9 5s^1$	Radon (222) $[Xe]4f^15 5d^10 6s^2$
Hafnium 178.49 $[Xe]4f^15 5d^1 6s^2$	Dysprosium 162.97 $[Xe]4f^15 5d^6 6s^2$	Iridium 192.217 $[Xe]4f^15 5d^9 6s^2$	Platinum 195.078 $[Xe]4f^15 5d^8 6s^2$	Promethium 144.24 $[Xe]4f^5 5d^2 6s^2$	Francium (223) $[Xe]4f^14 5d^1 6s^2$
Ruthenium (261)	Praseodymium (140)	Ruthenium (261)	Platinum (209)	Neodymium (141)	
Dubnium (262)	Curium (158)	Dubnium (262)	Plutonium (244)	Europium (159)	
Seaborgium (263)	Berkelium (140)	Protactinium (231)	Americium (243)	Gadolinium (157)	
Bohrium (264)	Thorium (232)	Thorium (232)	Curium (144)	Terbium (158)	
Hassium (265)	Actinium (227)	Actinium (227)	Curium (144)	Europium (159)	
Meltanium (266)					
Ununium (269)					
Ununium (272)					
Ununium (273)					
Ununium (274)					
Uub					

For a description of the atomic data, visit physics.nist.gov/atomic

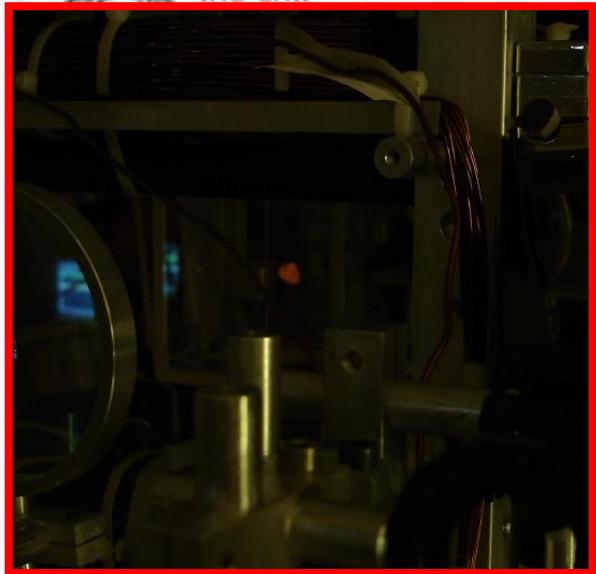


^aBased upon ^{12}C . () indicates the mass number of the most stable isotope. For a description and the most accurate values and uncertainties, see J. Phys. Chem. Ref. Data, 26 (5), 1239 (1997).

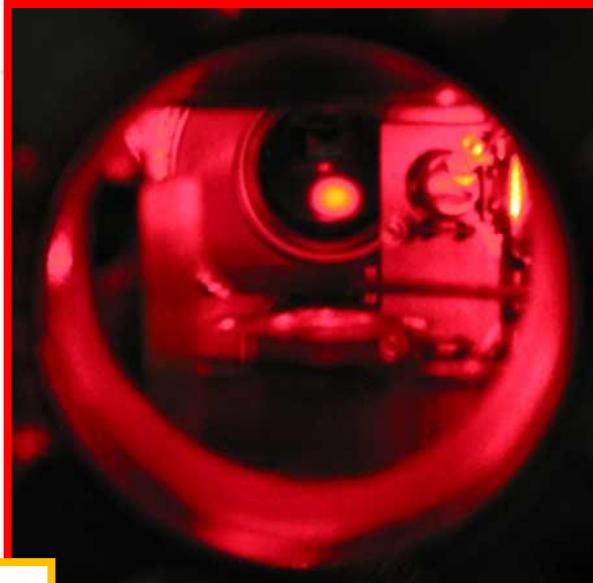
March 1999

Rb MOT - 780nm

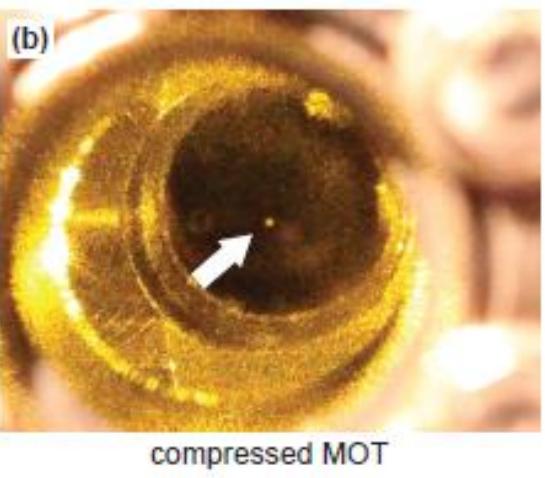
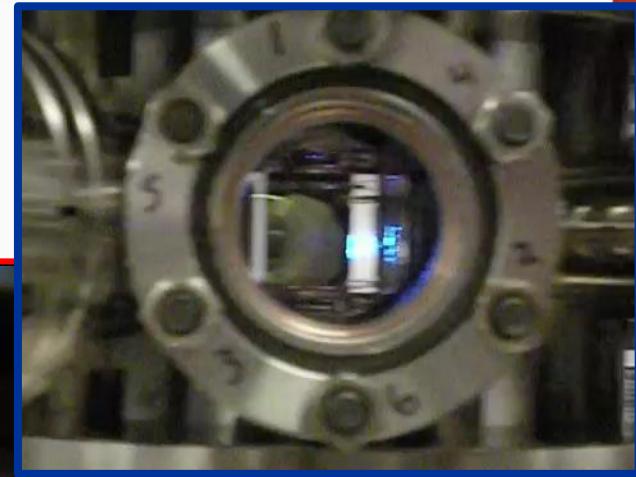
INO-CNR



Li MOT - 671nm



Sr MOT - 461nm



Er MOT – 583nm



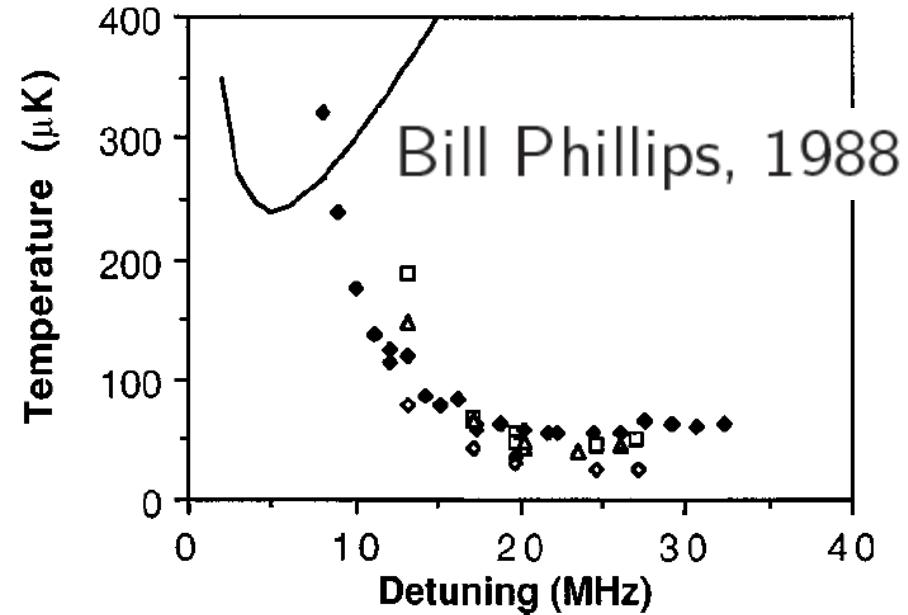
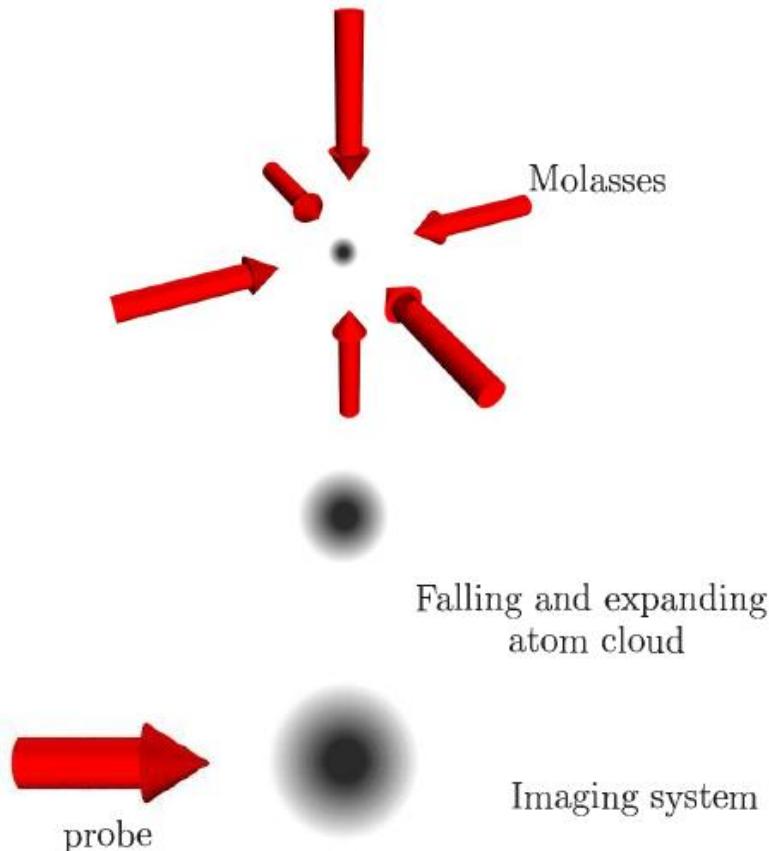
Dy MOT – 626nm



Temperature measurement

T_D is the Doppler temperature

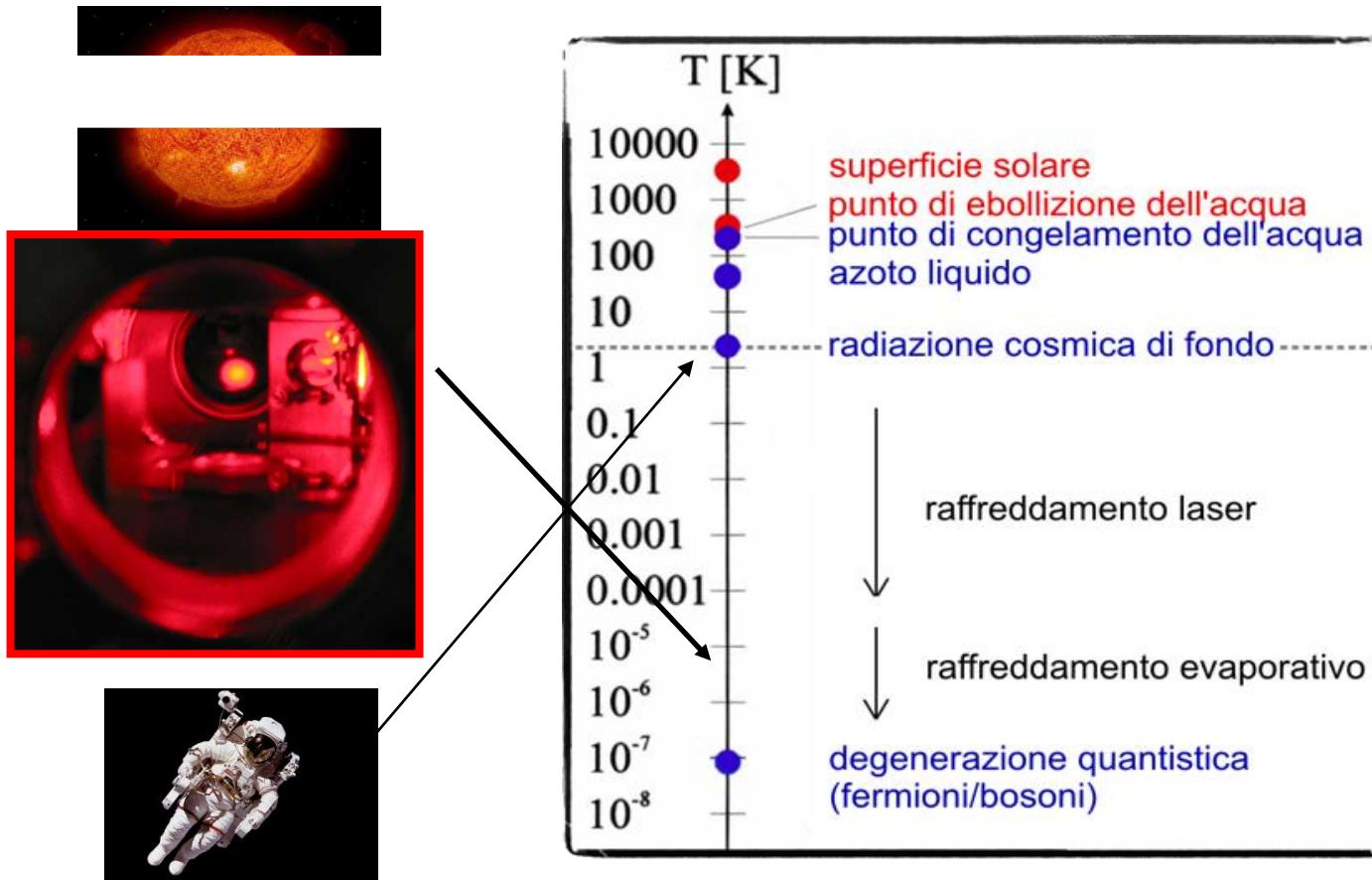
ex: $T_D = 240 \mu\text{K}$ for sodium, $T_D = 125 \mu\text{K}$ for cesium



The measured temperature is lower than expected!
The scaling with laser detuning is also different.

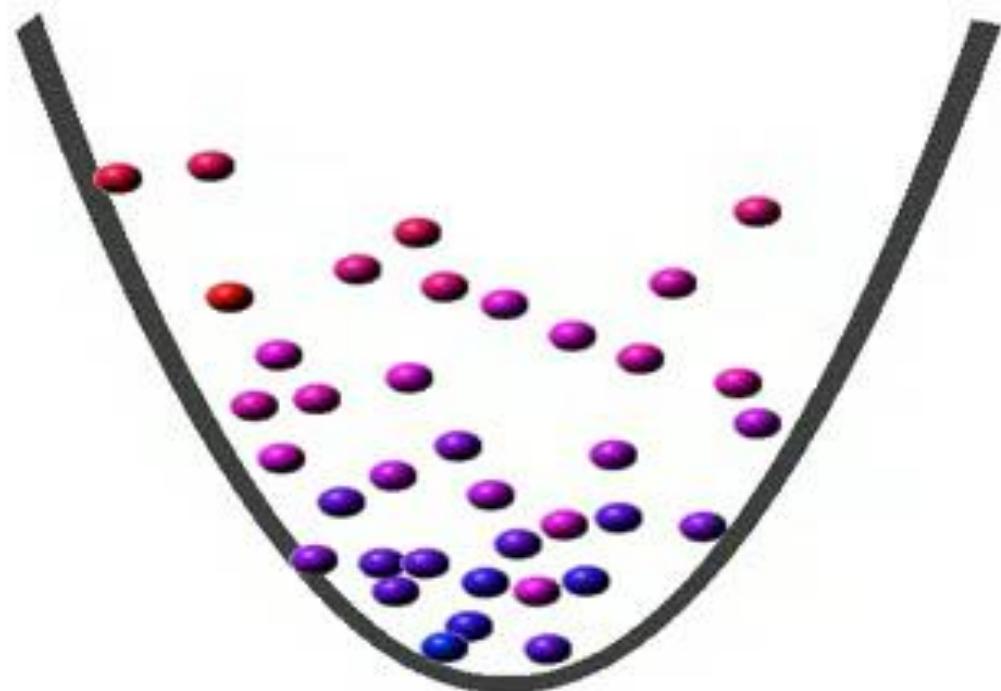
Which is the minimum achievable MOT temperature?

- Recoil temperature $T_{rec} = \hbar^2 k^2 / 2mk_B$ hundreds nK
- Doppler temperature $T_{Doppler} = h\Gamma / 2k_B$ few-hundreds μK

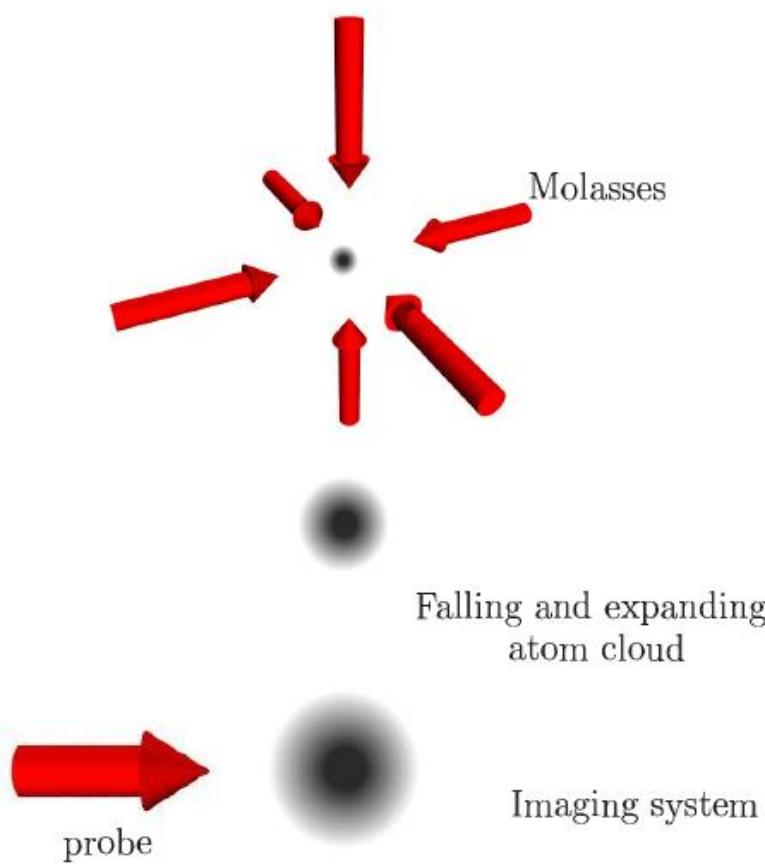


Evaporative cooling





Temperature measurement



T_D is the Doppler temperature

ex: $T_D = 240 \mu\text{K}$ for sodium, $T_D = 125 \mu\text{K}$ for cesium



The dipole force

Induced dipole $\vec{D} = \alpha(\omega) \vec{E}$

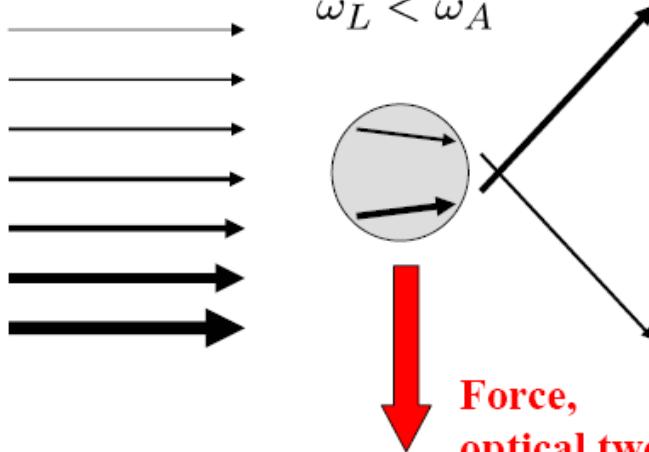
→ Interaction energy: $V(\vec{r}) = -\frac{1}{2}\alpha(\omega) E^2(\vec{r})$

n = refraction index

$$\alpha > 0$$

$$n > 1$$

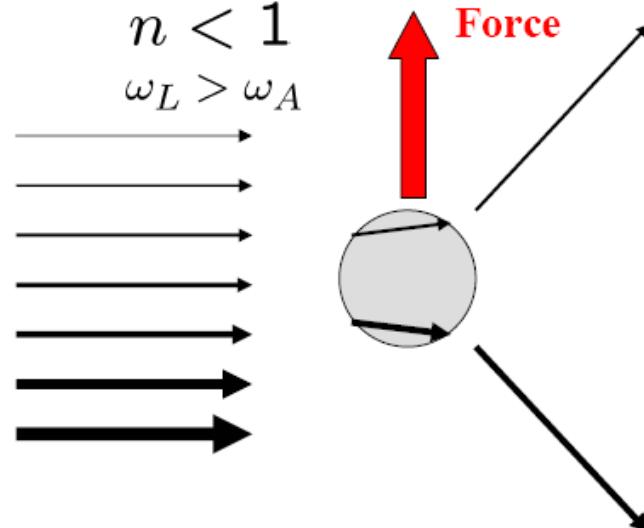
$$\omega_L < \omega_A$$



$$\alpha < 0$$

$$n < 1$$

$$\omega_L > \omega_A$$

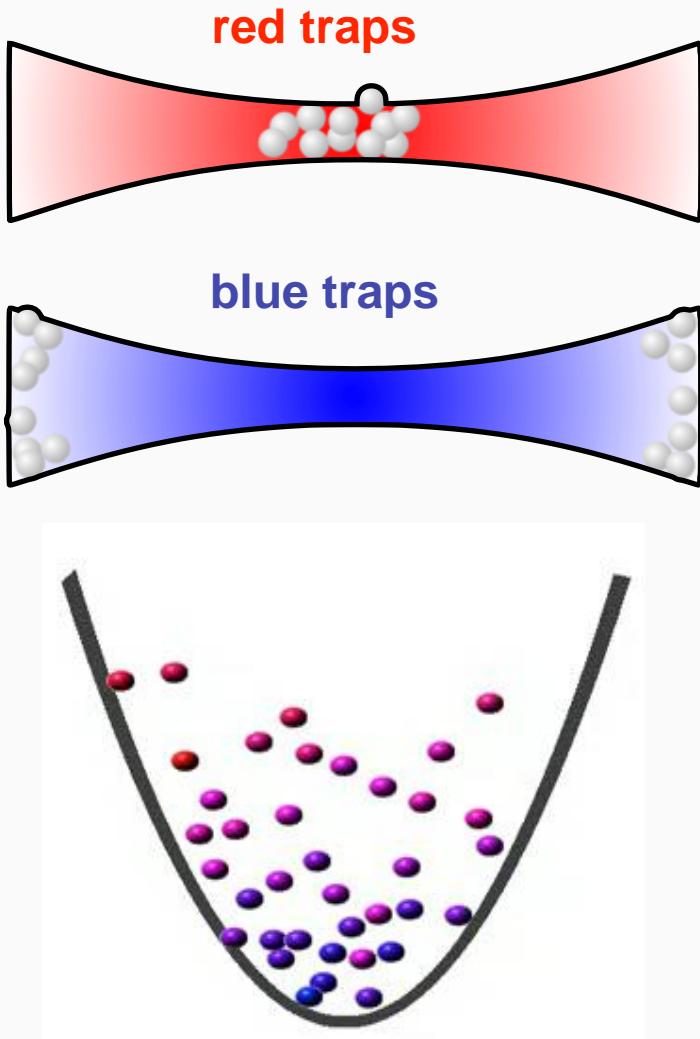


This is a conservative force!

Trapping of micrometer sized particles (Arthur Ashkin, 1970)

Trapping of atoms / molecules had to wait for laser cooling (S. Chu, 1986)

Optical traps



red traps

blue traps

Far-detuned gaussian beam

$$U(r) \propto \frac{I(r)}{\Delta} \quad \text{Trapping depth}$$

$$\Gamma \propto \frac{I(r)}{\Delta^2} \quad \text{Heating rate}$$

Many advantages vs magnetic traps:

- High degree of freedom: 1D, 2D and 3D systems
- All the spin states trappable
- High density

With far-detuned laser one can shape conservative potentials at will

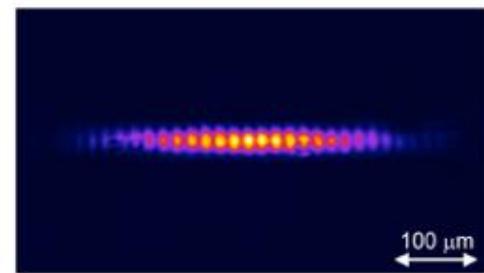
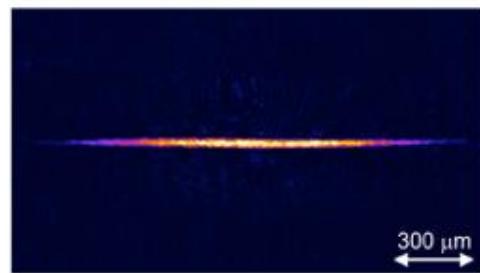
a) trappola a singolo fascio



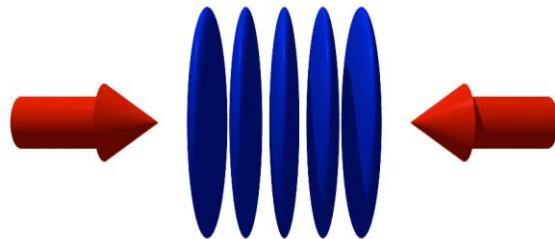
b) trappola a fasci incrociati



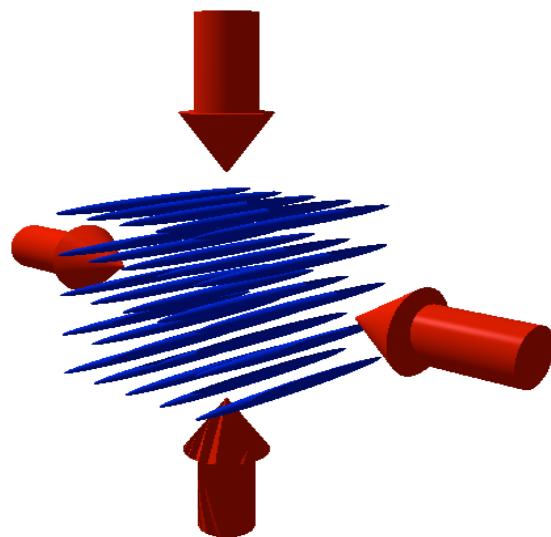
c) reticolo ottico



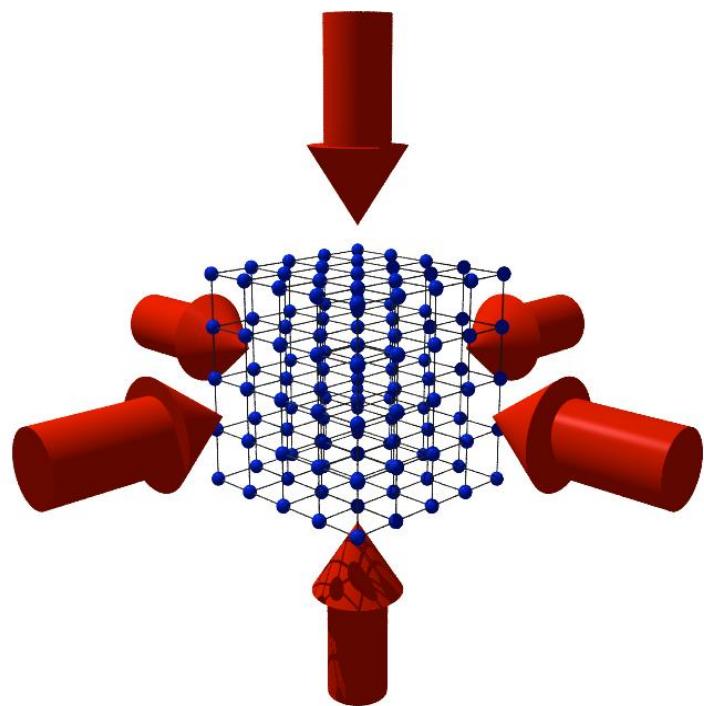
1D optical lattice (2D systems)



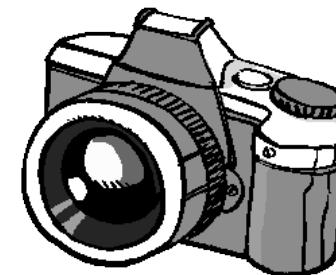
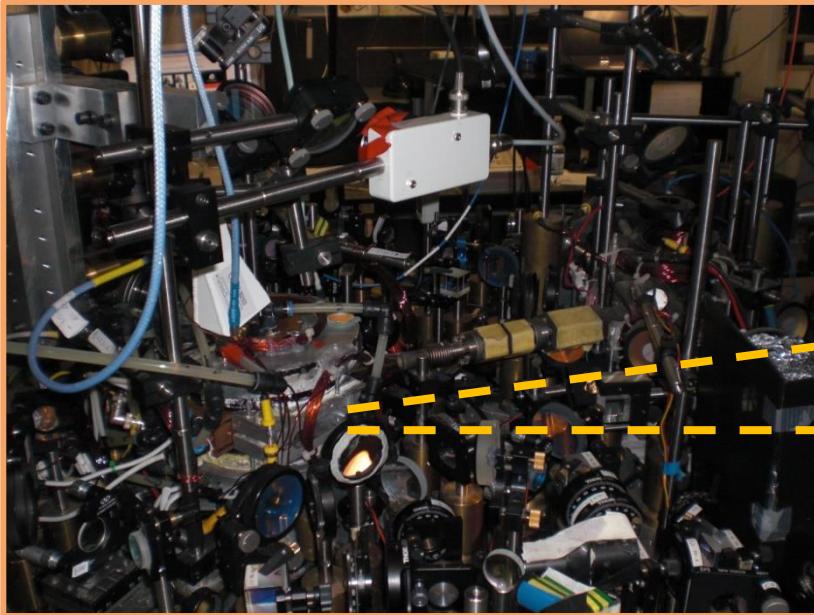
2D optical lattice (1D systems)



3D optical lattice (crystal-like systems)



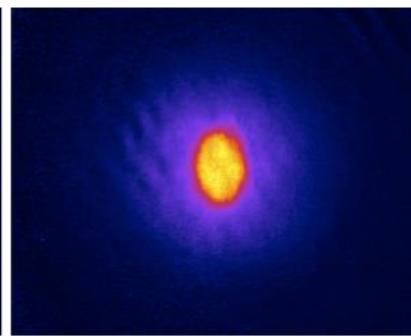
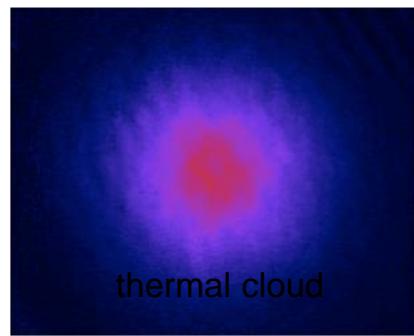
Principal diagnostic method: in resonance imaging



$T > T_C$

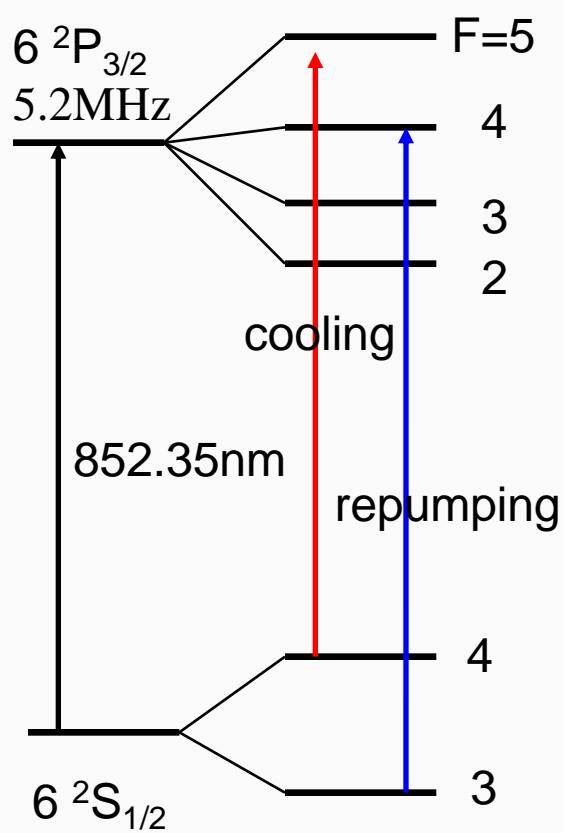
$T \sim T_C$

$T < T_C$

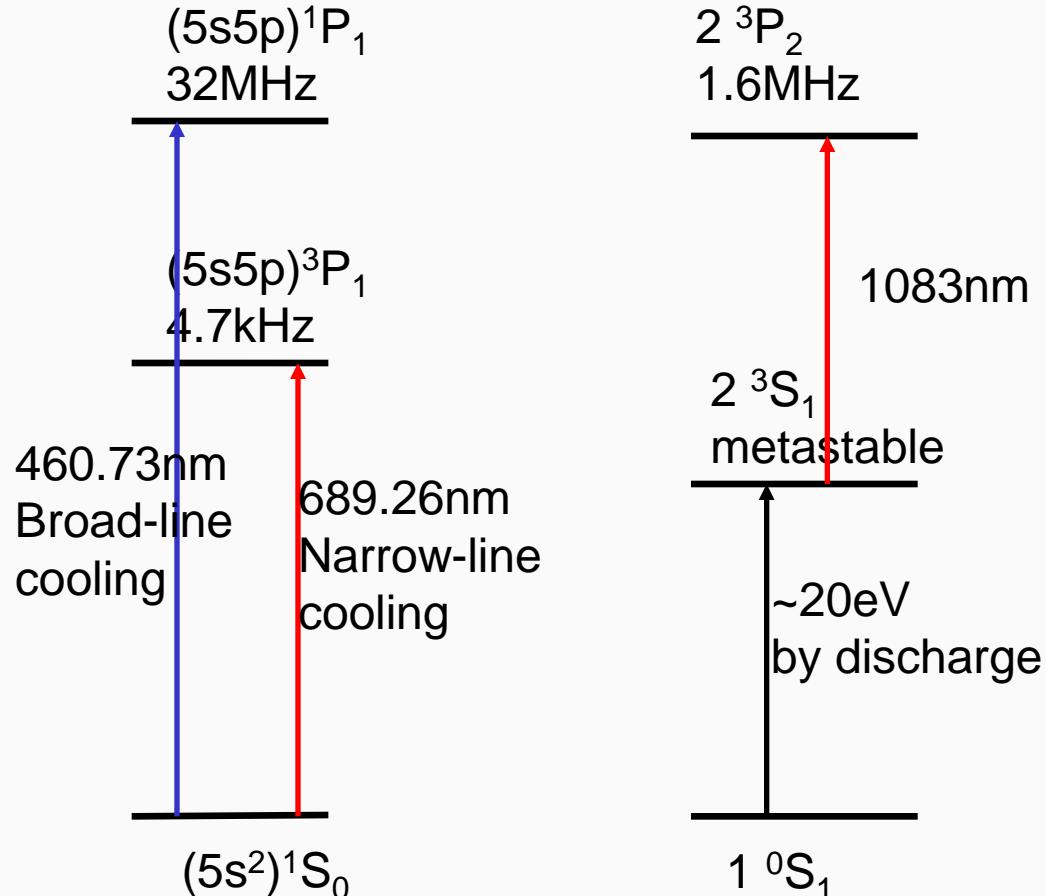


Laser requirements

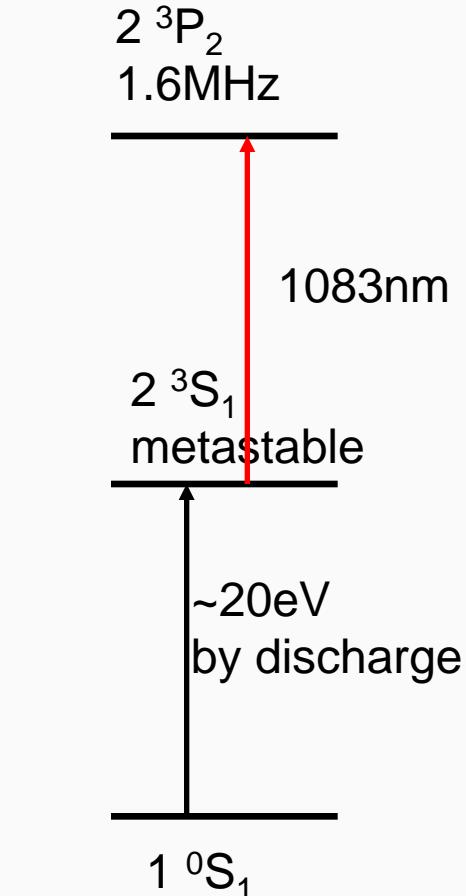
Each different atomic species has its unique feature!



^{133}Cs , alkali metal, $I=7/2$



^{88}Sr , alkaline earth, $I=0$



^4He , nobel gas, $I=0$

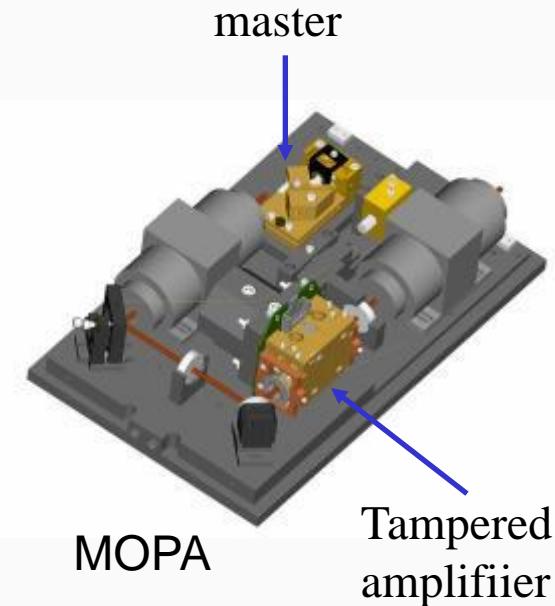


Example: diode lasers

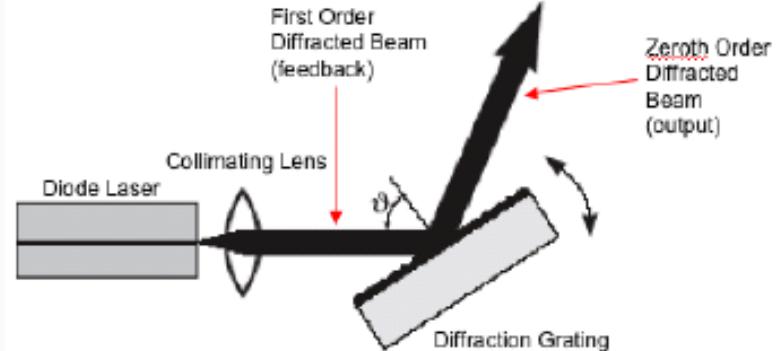
- Diode lasers are extensively used in laser cooling community due to inexpensive cost and frequency tunability.
- Diode lasers in external cavity configuration are used to reduce the laser linewidth.
- Master oscillator power amplifier (MOPA) configuration is used to increase the available laser power.



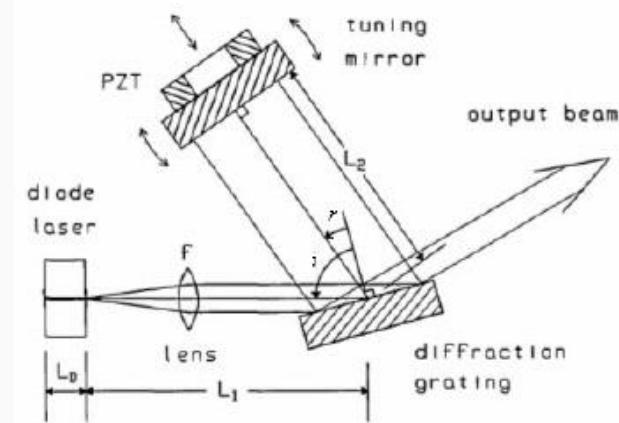
Diode laser



MOPA



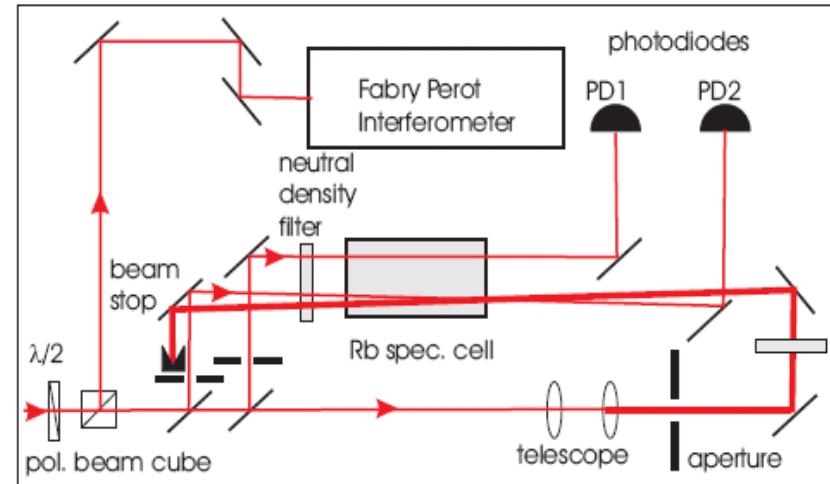
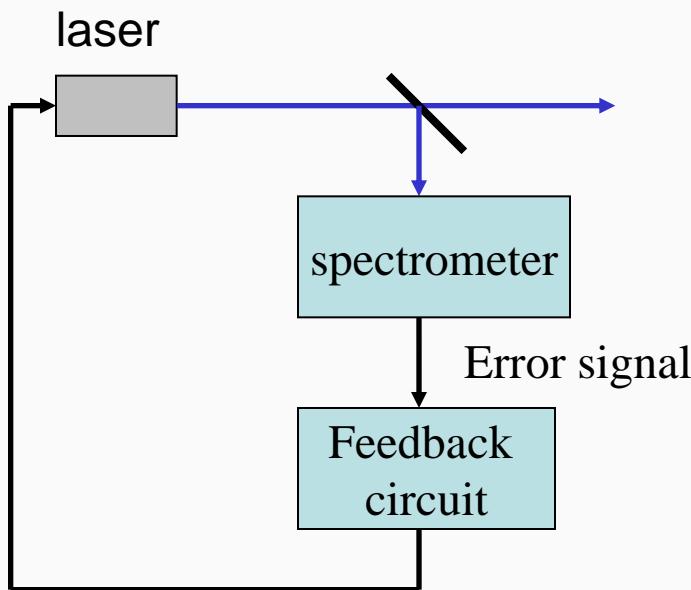
ECDL in Littrow configuration



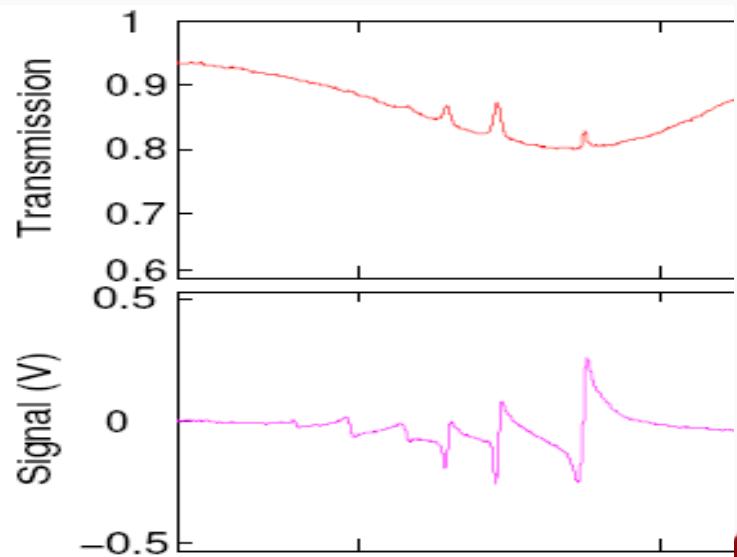
ECDL in Littman-Metcalf configuration

Laser frequency stabilization

- Frequency-modulated saturation spectroscopy is the standard setup to generate the error signal for frequency stabilization.
- Feedback circuits are usually built to lock the laser frequency.

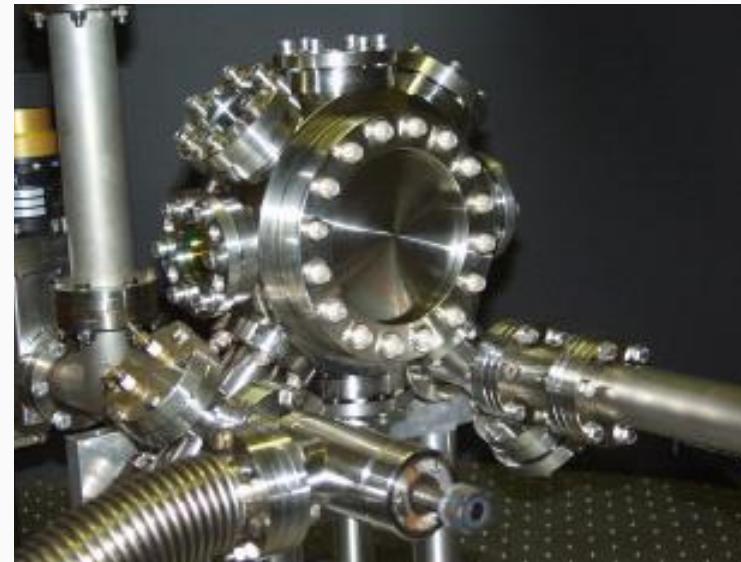
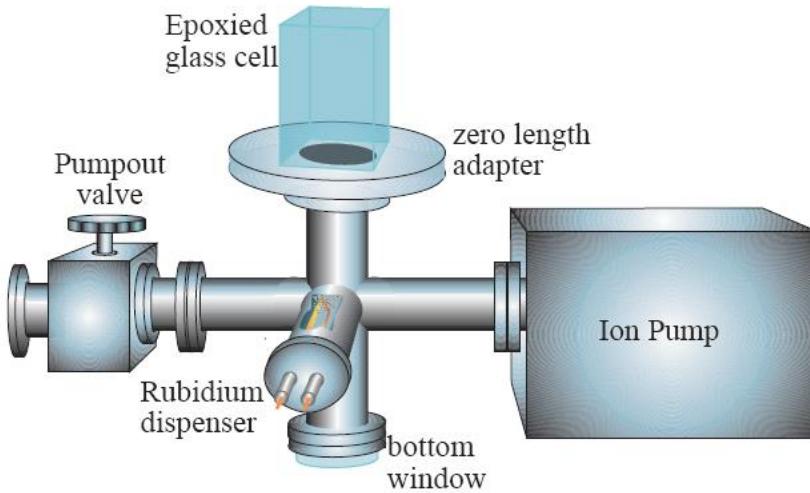


Background subtracted saturation spectrometer



Vacuum apparatus

- Two different kinds of vacuum setup are mainly used, one is glass vapor cell, the other is stainless chamber.
- Ion pump and titanium sublimation pump are standard setup to achieve ultrahigh vacuum.

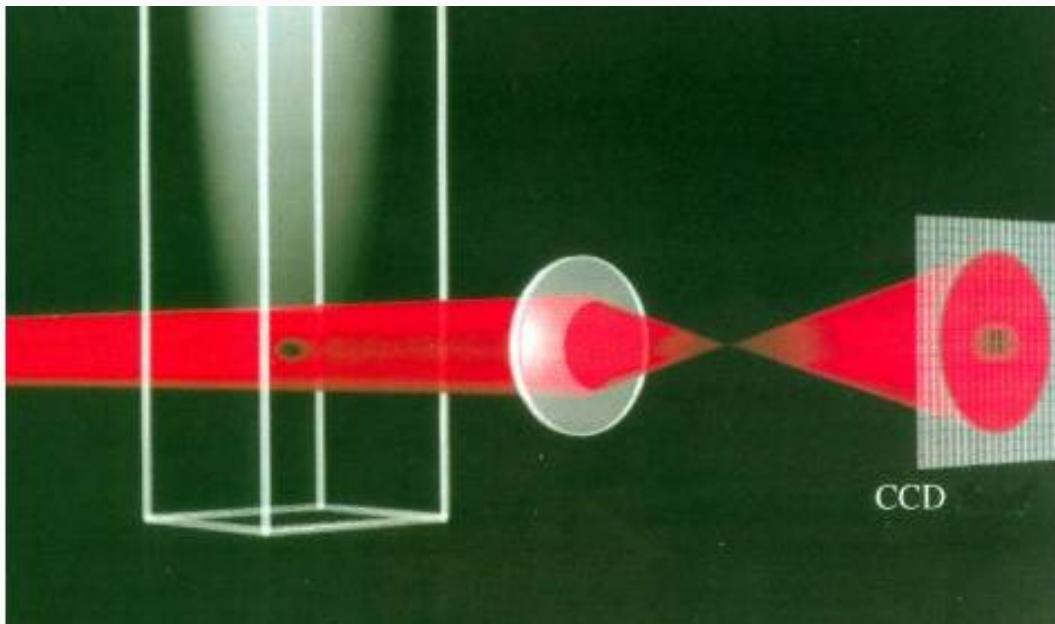


Background pressure $< 10^{-8}$ mbar

Detection

Quantities of interest: number of atoms N , density $n(x, y, z)$, momentum distribution

- 1) Fluorescence -> number N (large errors)
- 2) Absorption imaging -> integrated density $n(x, y)$, number N , velocity
- 3) Ionization -> state or mass selective



Imaging:
In situ -> density
After TOF -> velocity

1	1.008
H Hydrogen	[He]1s ¹

2	IIA 2A
---	-----------

3	6.941
Li Lithium	[He]2s ¹

4	9.012
Be Beryllium	[He]2s ²

11	22.990
Na Sodium	[Ne]3s ¹

12	24.305
Mg Magnesium	[Ne]3s ²

19	39.098
K Potassium	[Ar]4s ¹

20	40.078
Ca Calcium	[Ar]4s ²

21	44.956
Sc Scandium	[Ar]3d ¹ 4s ²

22	47.88
Ti Titanium	[Ar]3d ² 4s ²

23	50.944
V Vanadium	[Ar]3d ³ 4s ²

24	51.996
Cr Chromium	[Ar]3d ⁵ 4s ¹

25	54.938
Mn Manganese	[Ar]3d ⁵ 4s ²

26	55.933
Fe Iron	[Ar]3d ⁶ 4s ²

27	58.833
Co Cobalt	[Ar]3d ⁷ 4s ²

28	58.693
Ni Nickel	[Ar]3d ⁸ 4s ²

29	63.546
Cu Copper	[Ar]3d ¹⁰ 4s ¹

30	65.39
Zn Zinc	[Ar]3d ¹⁰ 4s ²

31	69.732
Ga Gallium	[Ar]3d ¹⁰ 4s ² 4p ¹

32	72.61
Ge Germanium	[Ar]3d ¹⁰ 4s ² 4p ²

33	74.922
As Arsenic	[Ar]3d ¹⁰ 4s ² 4p ³

34	78.672
Se Selenium	[Ar]3d ¹⁰ 4s ² 4p ⁴

35	79.904
Br Bromine	[Ar]3d ¹⁰ 4s ² 4p ⁵

36	84.80
Kr Krypton	[Ar]3d ¹⁰ 4s ² 4p ⁶

37	84.468
Rb Rubidium	[Kr]5s ¹

38	87.62
Sr Strontium	[Kr]5s ²

39	88.908
Y Yttrium	[Kr]4d ¹ 5s ²

40	91.224
Zr Zirconium	[Kr]4d ² 5s ²

41	92.906
Nb Niobium	[Kr]4d ³ 5s ¹

42	95.95
Mo Molybdenum	[Kr]4d ⁵ 5s ¹

43	98.907
Tc Technetium	[Kr]4d ⁵ 5s ¹

44	101.07
Ru Ruthenium	[Kr]4d ⁷ 5s ¹

45	102.908
Rh Rhodium	[Kr]4d ⁹ 5s ¹

46	106.42
Pd Palladium	[Kr]4d ¹⁰ 5s ₁

47	107.868
Ag Silver	[Kr]4d ¹⁰ 5s ₁

48	112.411
Cd Cadmium	[Kr]4d ¹⁰ 5s ₂

49	114.818
In Indium	[Kr]4d ¹⁰ 5s ₂ 5p ¹

50	118.71
Sn Tin	[Kr]4d ¹⁰ 5s ₂ 5p ³

51	121.760
Te Tellurium	[Kr]4d ¹⁰ 5s ₂ 5p ⁵

52	127.8
Sb Antimony	[Kr]4d ¹⁰ 5s ₂ 5p ⁵

53	128.904
I Iodine	[Kr]4d ¹⁰ 5s ₂ 5p ⁶

54	131.29
Xe Xenon	[Kr]4d ¹⁰ 5s ₂ 5p ⁶

55	132.905
Cs Cesium	[Xe]6s ¹

56	137.327
Ba Barium	[Xe]6s ²

57	138.908
La Lanthanum	[Xe]6s ² 5f ₁

58	140.115
Ce Cerium	[Xe]6s ² 5f ₂

59	140.908
Pr Praseodymium	[Xe]6s ² 5f ₃

60	144.24
Nd Neodymium	[Xe]6s ² 5f ₄

61	144.913
Pm Promethium	[Xe]6s ² 5f ₅

62	150.36
Sm Samarium	[Xe]6s ² 5f ₆

63	151.966
Eu Europium	[Xe]6s ² 5f ₇

64	157.25
Gd Gadolinium	[Xe]6s ² 5f ₈

65	158.5
Tb Thulium	[Xe]6s ² 5f ₉

66	162.50
Dy Dysprosium	[Xe]6s ² 5f ₁₀

67	164.50
Ho Holmium	[Xe]6s ² 5f ₁₁

68	167.28
Er Erbium	[Xe]6s ² 5f ₁₂

69	168.0
Tm Thulium	[Xe]6s ² 5f ₁₃

70	173.04
Lu Lutetium	[Xe]6s ² 5f ₁₄

71	174.957
Yb Ytterbium	[Xe]6s ² 5f ₁₅

Dipolar atomic quantum gases

Periodic Table of the Elements

Atomic Number	Symbol
Atomic Mass	Name
Electron Configuration	

$$\mu = 6\mu_B$$

Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Kr

Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Kr

Y, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu

Ac, Th, Pa, U, Np, Pu, Am, Cm, Curium, Californium, Einsteinium, Nobelium, Lawrencium

Rb, Sr, Yttrium, Zirconium, Hafnium, Tantalum, Tungsten, Rhenium, Osmium, Iridium, Platinum, Ruthenium, Rhodium, Palladium, Gold, Thallium, Lead, Bismuth, Polonium, Livermorium, Ununseptium, Ununoctium, Radon

Francium, Radium, Rutherfordium, Dubnium, Seaborgium, Bohrium, Hassium, Meitnerium, Darmstadtium, Copernicium, Ununpentium, Einsteinium, Nobelium, Lawrencium

Hydrogen, Helium, Lithium, Sodium, Magnesium, Potassium, Calcium, Rubidium, Strontium, Barium, Lanthanum, Cerium, Praseodymium, Neodymium, Promethium, Samarium, Europium, Gadolinium, Thulium, Ytterbium, Lutetium

Hydrogen, Helium, Lithium, Sodium, Magnesium, Potassium, Calcium, Rubidium, Strontium, Barium, Lanthanum, Cerium, Praseodymium, Neodymium, Promethium, Samarium, Europium, Gadolinium, Thulium, Ytterbium, Lutetium

Hydrogen, Helium, Lithium, Sodium, Magnesium, Potassium, Calcium, Rubidium, Strontium, Barium, Lanthanum, Cerium, Praseodymium, Neodymium, Promethium, Samarium, Europium, Gadolinium, Thulium, Ytterbium, Lutetium

Hydrogen, Helium, Lithium, Sodium, Magnesium, Potassium, Calcium, Rubidium, Strontium, Barium, Lanthanum, Cerium, Praseodymium, Neodymium, Promethium, Samarium, Europium, Gadolinium, Thulium, Ytterbium, Lutetium

Hydrogen, Helium, Lithium, Sodium, Magnesium, Potassium, Calcium, Rubidium, Strontium, Barium, Lanthanum, Cerium, Praseodymium, Neodymium, Promethium, Samarium, Europium, Gadolinium, Thulium, Ytterbium, Lutetium

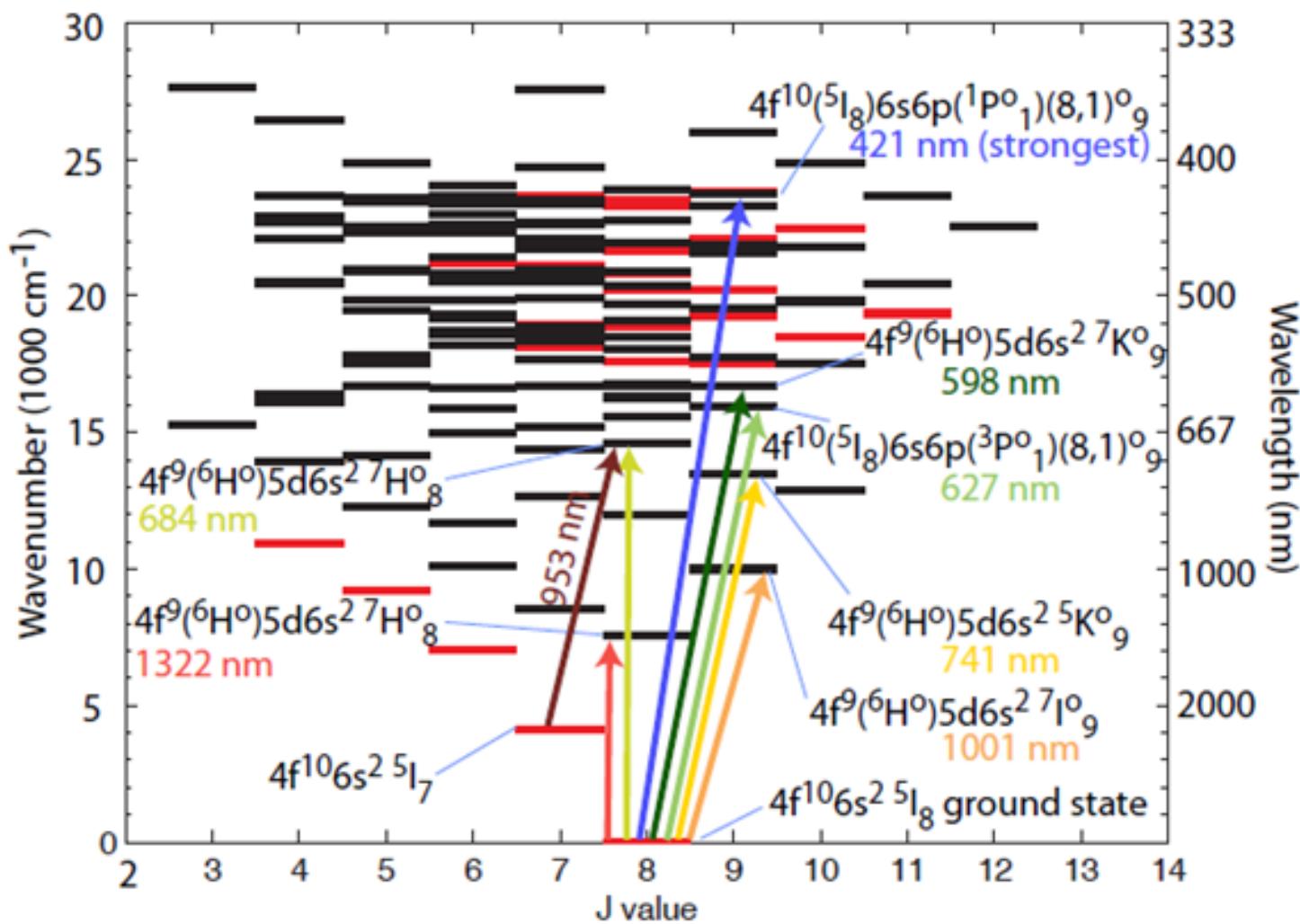
Hydrogen, Helium, Lithium, Sodium, Magnesium, Potassium, Calcium, Rubidium, Strontium, Barium, Lanthanum, Cerium, Praseodymium, Neodymium, Promethium, Samarium, Europium, Gadolinium, Thulium, Ytterbium, Lutetium

Hydrogen, Helium, Lithium, Sodium, Magnesium, Potassium, Calcium, Rubidium, Strontium, Barium, Lanthanum, Cerium, Praseodymium, Neodymium, Promethium, Samarium, Europium, Gadolinium, Thulium, Ytterbium, Lutetium

Hydrogen, Helium, Lithium, Sodium, Magnesium, Potassium, Calcium, Rubidium, Strontium, Barium, Lanthanum, Cerium, Praseodymium, Neodymium, Promethium, Samarium, Europium, Gadolinium, Thulium, Ytterbium, Lutetium

Hydrogen, Helium, Lithium, Sodium, Magnesium, Potassium, Calcium, Rubidium, Strontium, Barium, Lanthanum, Cerium, Praseodymium, Neodymium, Promethium, Samarium, Europium, Gadolinium, Thulium, Ytterbium, Lutetium

Dysprosium energy levels

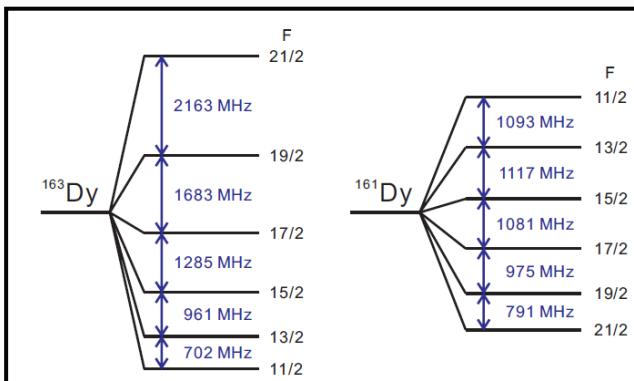




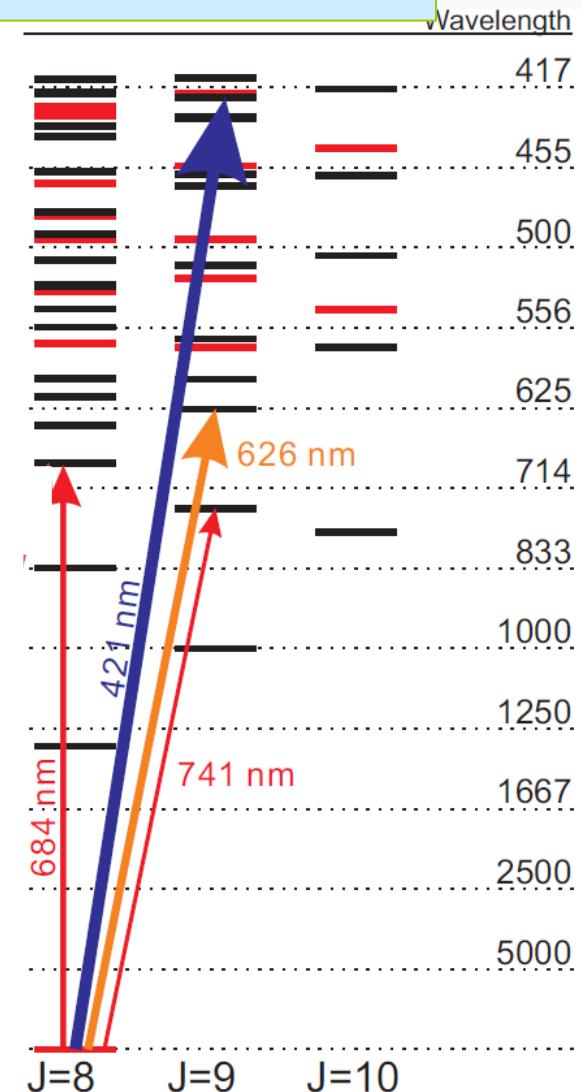
Dysprosium properties

isotope	mass [au]	abundance [%]	nuclear spin	statistics
^{160}Dy	160	2.34	0	boson
^{161}Dy	161	18.9	$5/2$	fermion
^{162}Dy	162	25.5	0	boson
^{163}Dy	163	24.9	$5/2$	fermion
^{164}Dy	164	28.2	0	boson

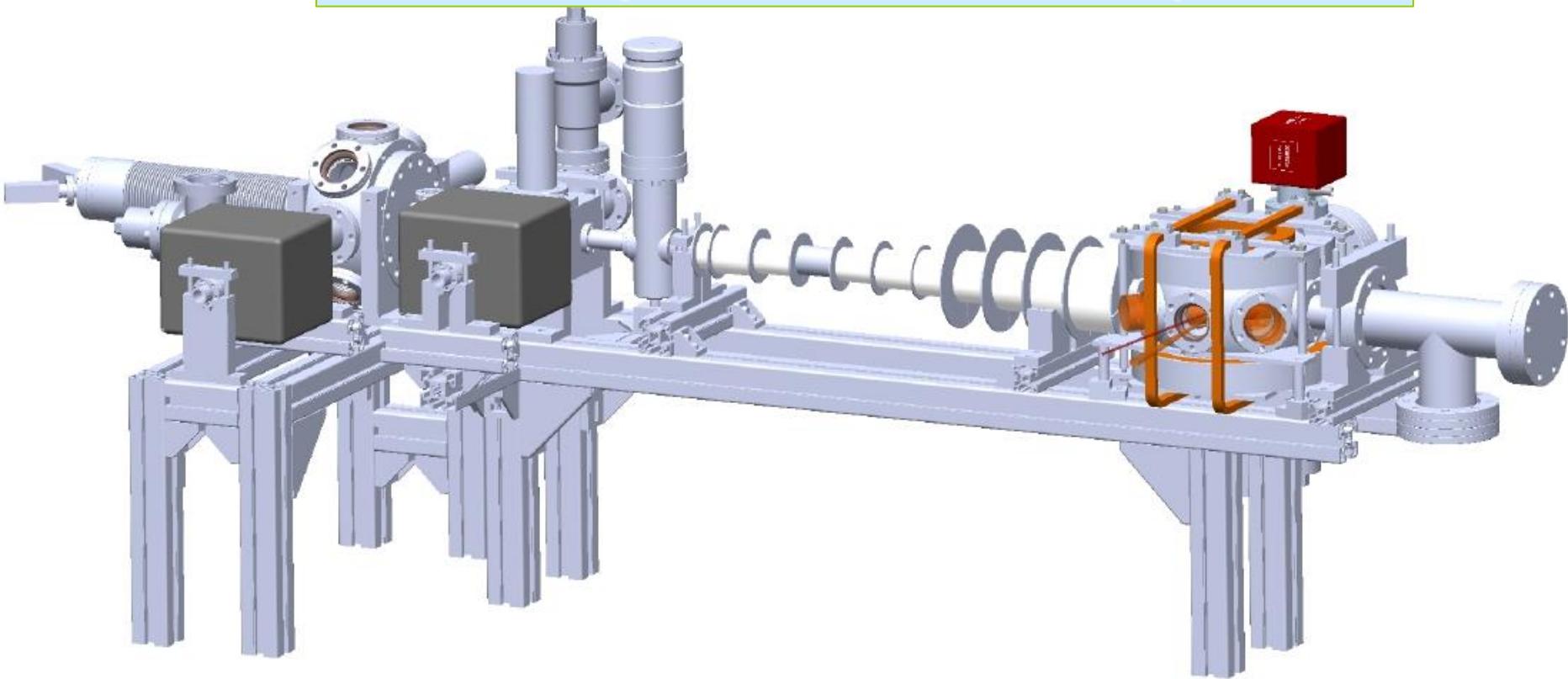
Hyperfine
structure
of fermionic
isotopes



λ	$\Delta\nu$	I_{sat}	T_{Doppler}
421 nm	32 MHz	56 mW/cm ²	770 μK
626 nm	135 kHz	72 $\mu\text{W}/\text{cm}^2$	3.2 μK
741 nm	1.78 kHz	0.57 $\mu\text{W}/\text{cm}^2$	43 nK

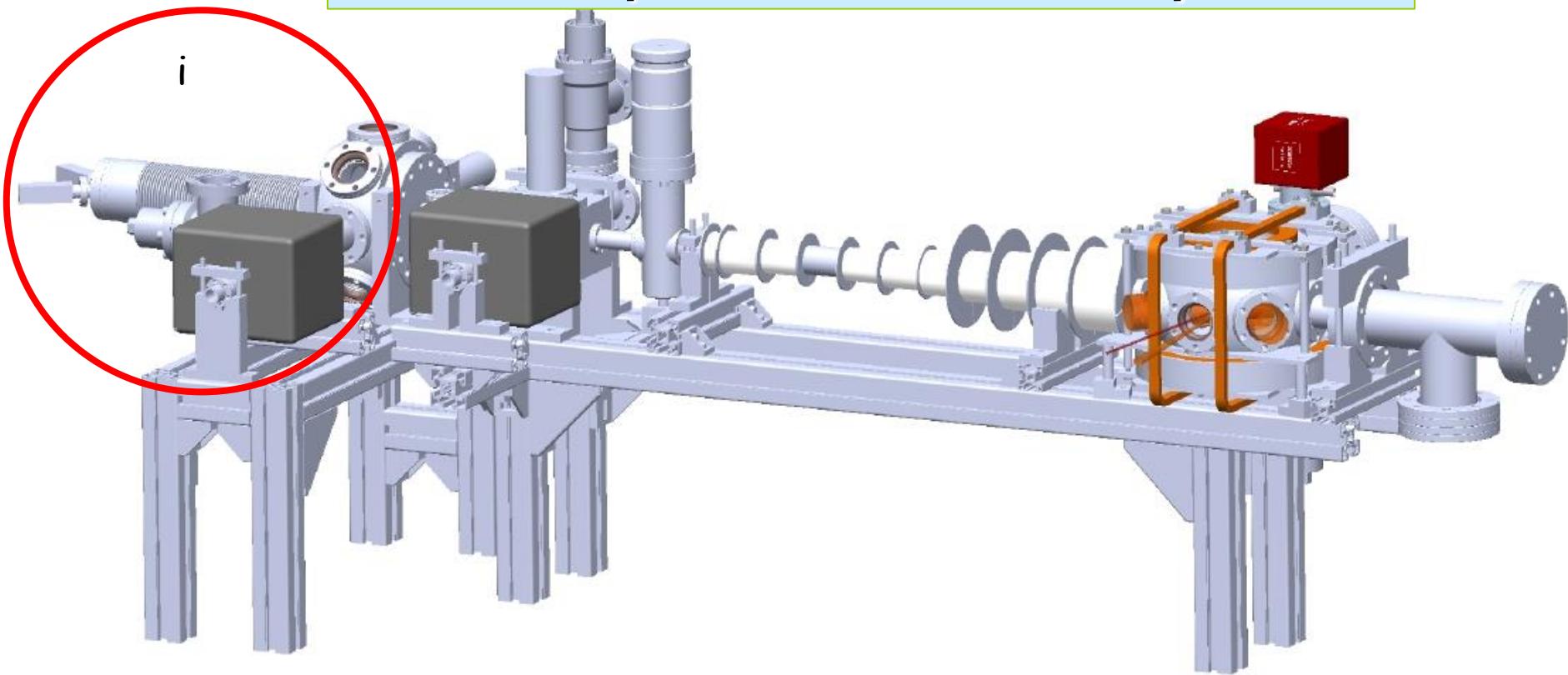


Experimental setup



Melting temperature: 1420°C
Operating temperature: 1175°C
Avg velocity of the atomic beam: **400**
m/s

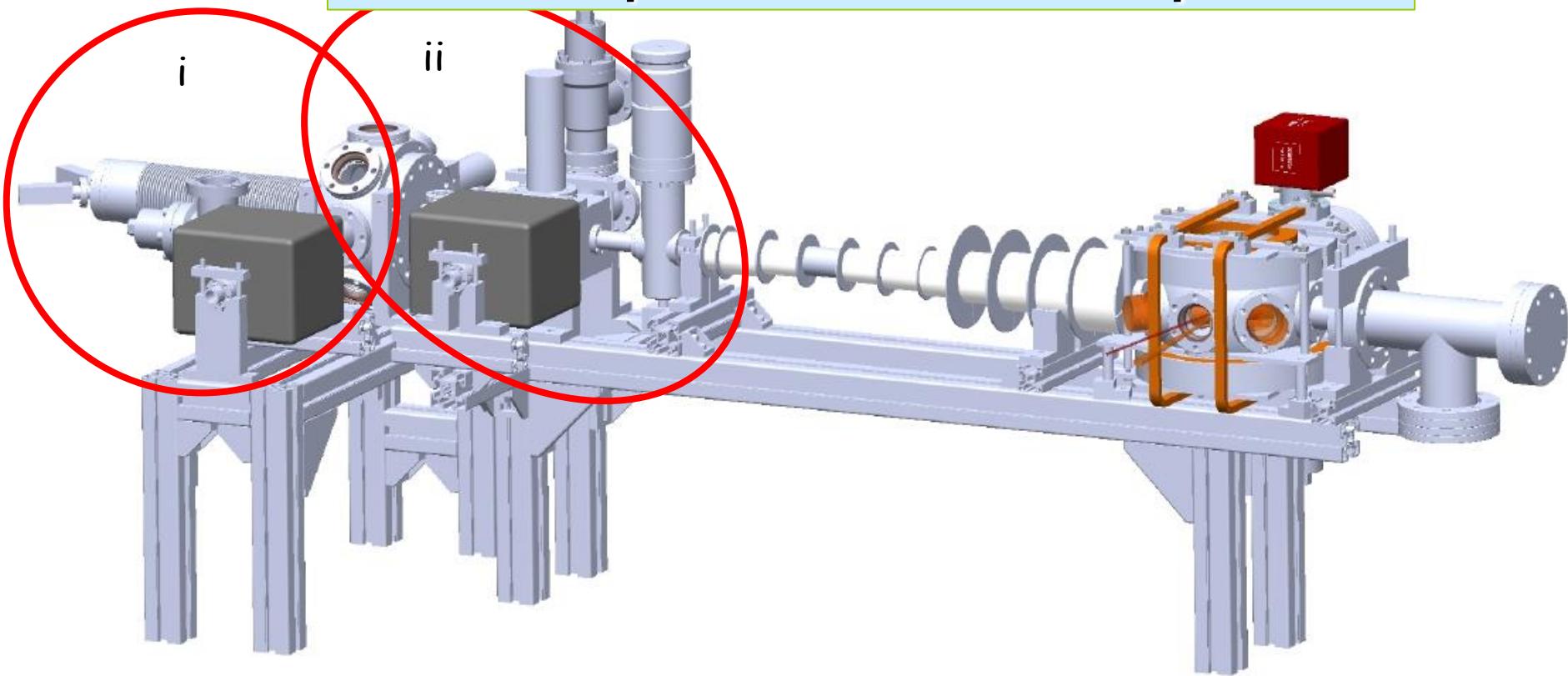
Experimental setup



Melting temperature: 1420°C
Operating temperature: 1175°C
Avg velocity of the atomic beam: **400**
m/s

i) Oven, Transverse Cooling

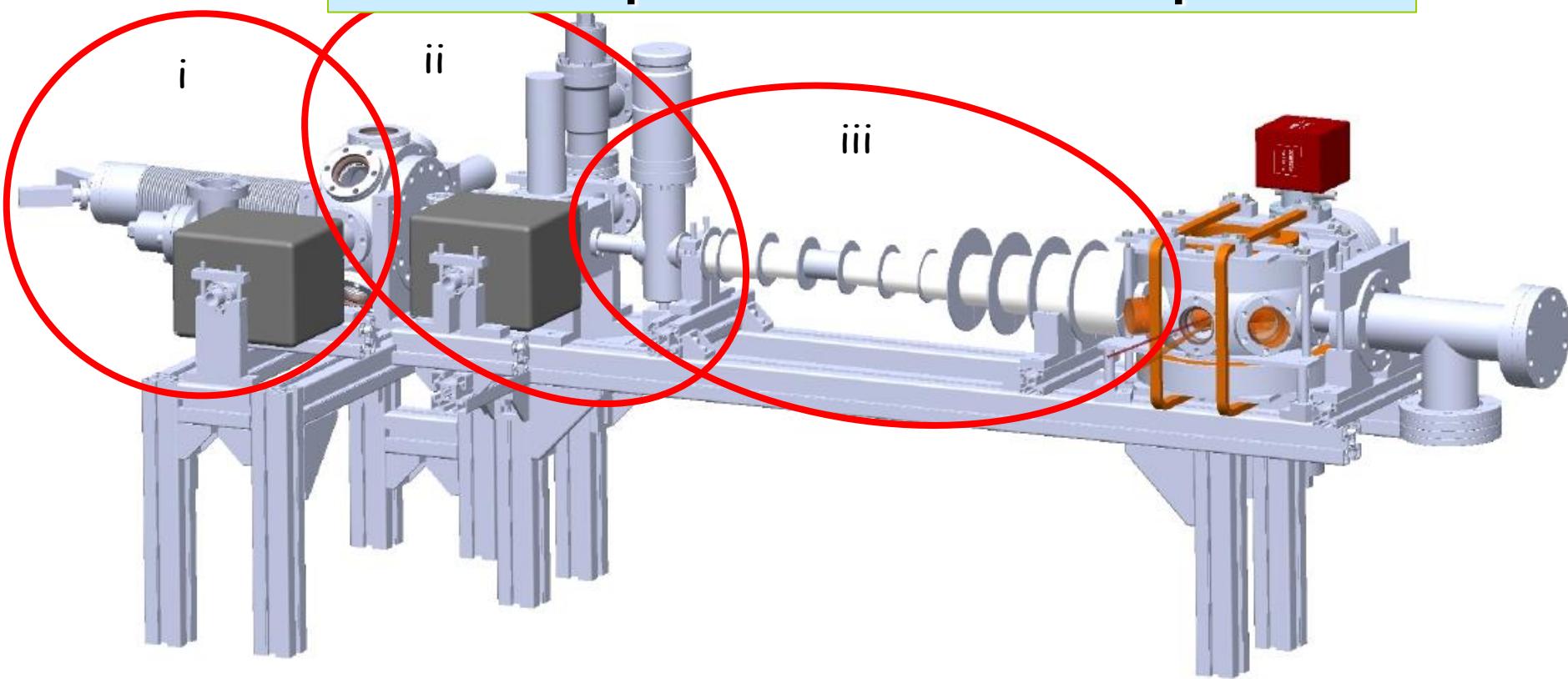
Experimental setup



Melting temperature: 1420°C
Operating temperature: 1175°C
Avg velocity of the atomic beam: 400 m/s

- i) Oven, Transverse Cooling
- ii) Differential Pumping

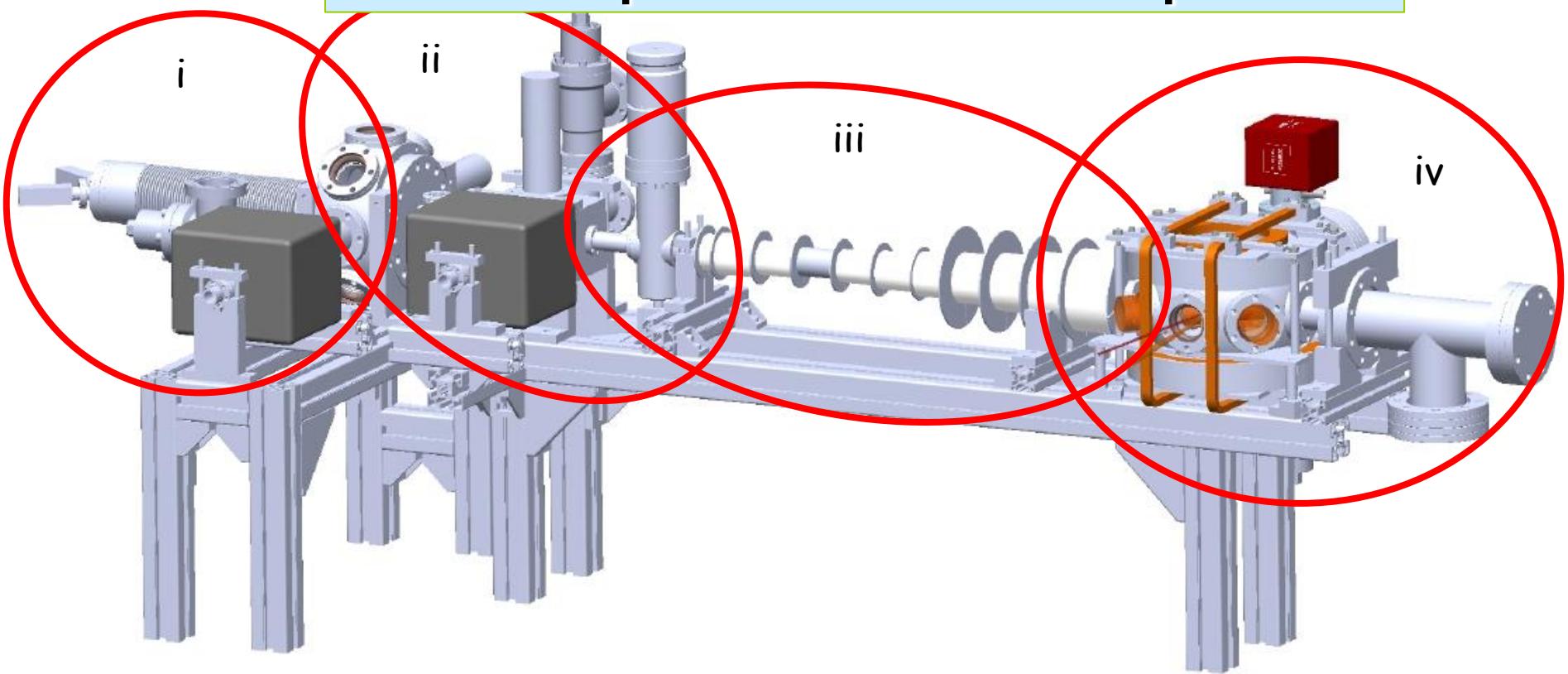
Experimental setup



Melting temperature: 1420°C
Operating temperature: 1175°C
Avg velocity of the atomic beam: **400**
m/s

- i) Oven, Transverse Cooling
- ii) Differential Pumping
- iii) Zeeman Slower

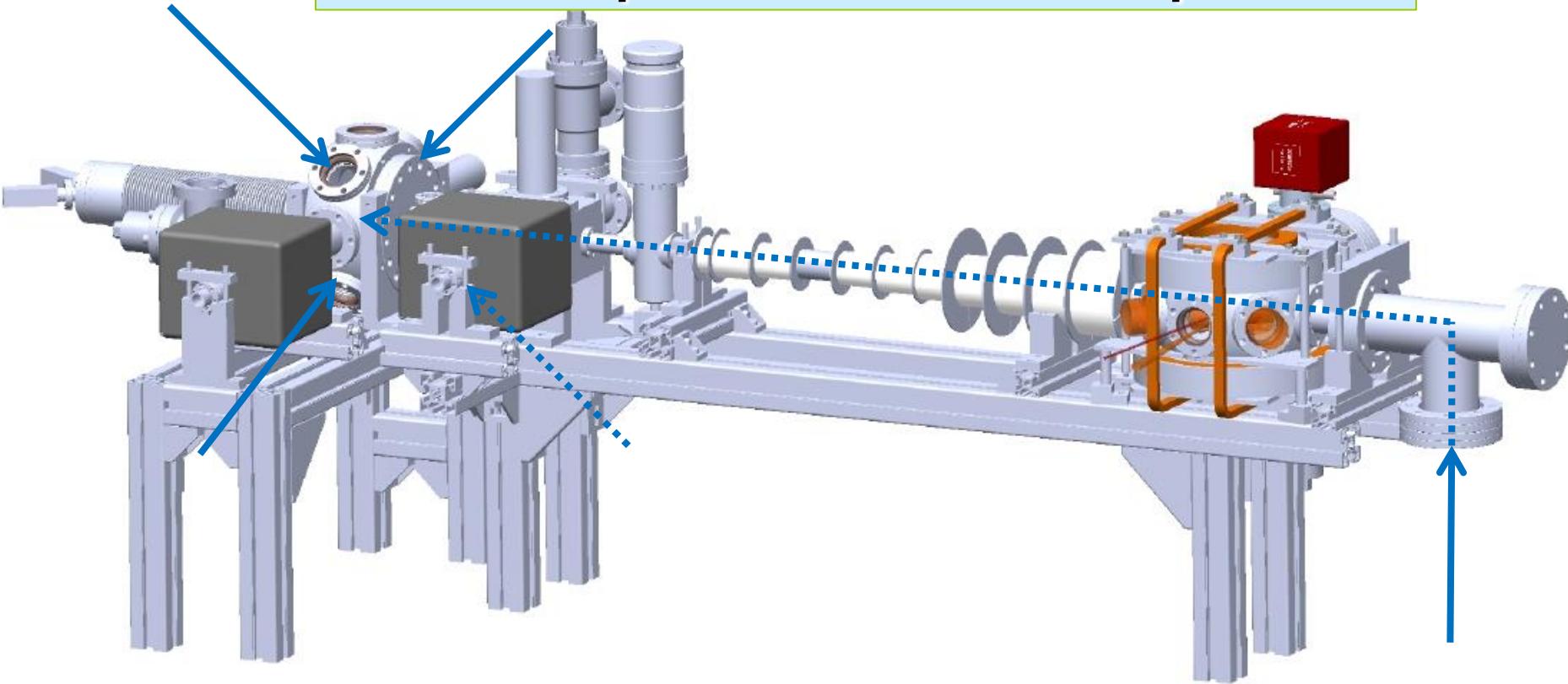
Experimental setup



Melting temperature: 1420°C
Operating temperature: 1175°C
Avg velocity of the atomic beam: **400**
m/s

- i) Oven, Transverse Cooling
- ii) Differential Pumping
- iii) Zeeman Slower
- iv) Science chamber (MOT, ODT, Manipulation, detection³⁵)

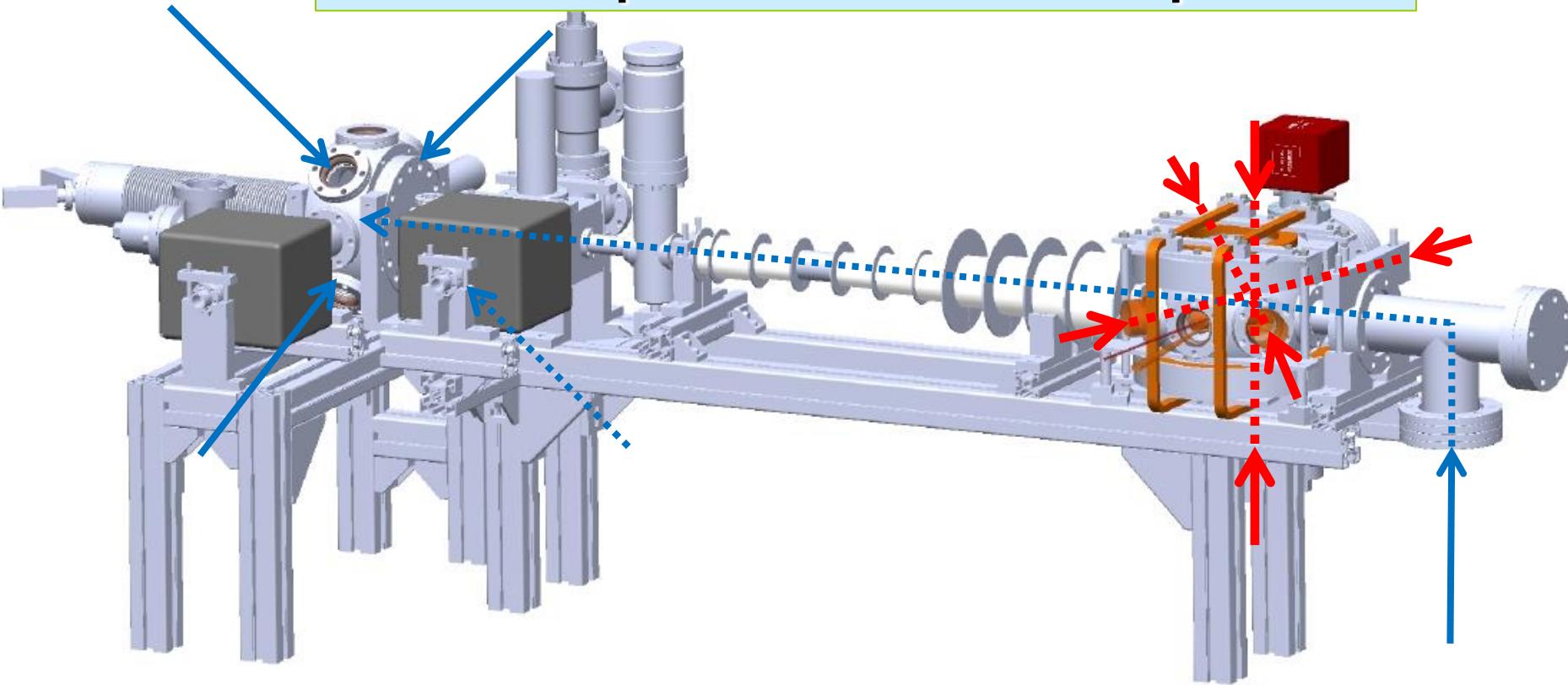
Experimental setup



Melting temperature: 1420°C
Operating temperature: 1175°C
Avg velocity of the atomic beam: **400**
m/s

- i) Oven, Transverse Cooling
- ii) Differential Pumping
- iii) Zeeman Slower
- iv) Science chamber (MOT, ODT, Manipulation, detection³⁵)

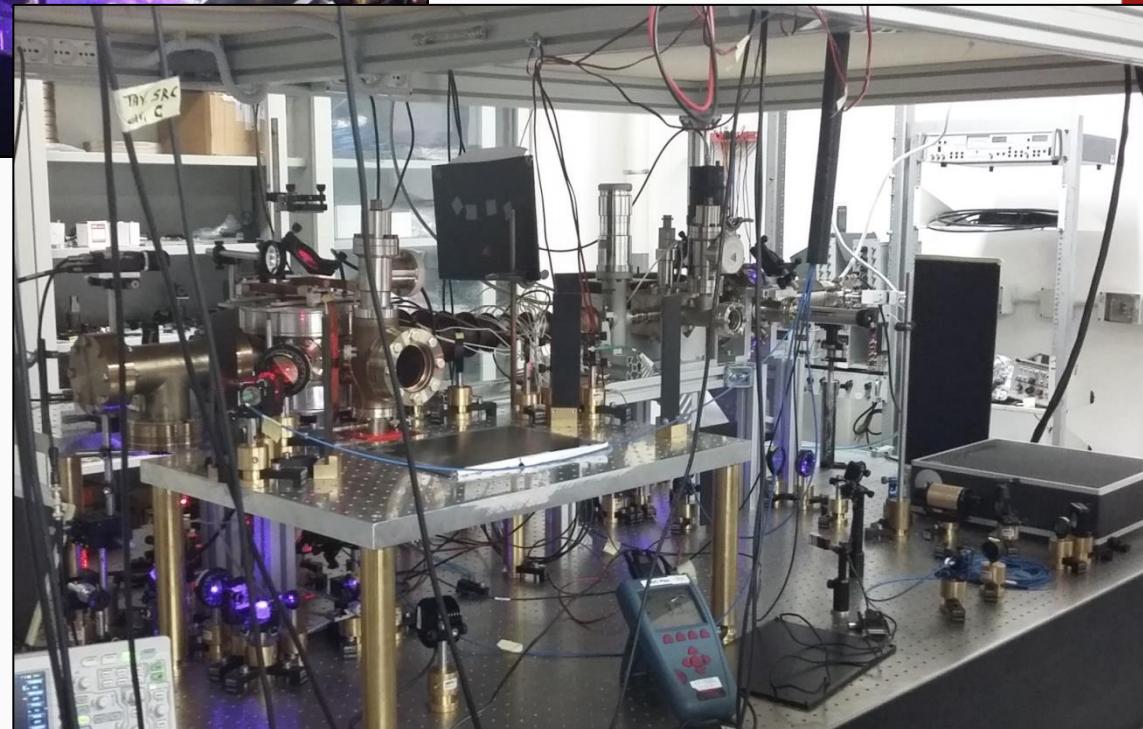
Experimental setup



Melting temperature: 1420°C
Operating temperature: 1175°C
Avg velocity of the atomic beam: 400 m/s

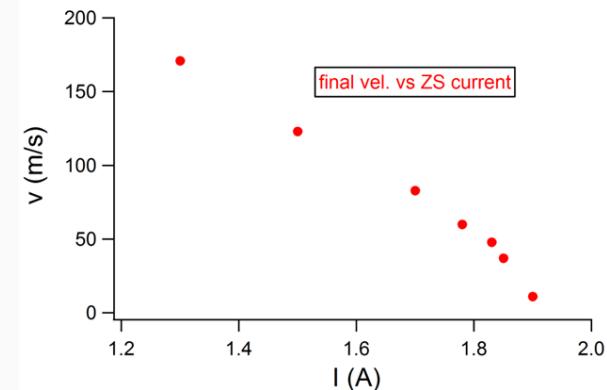
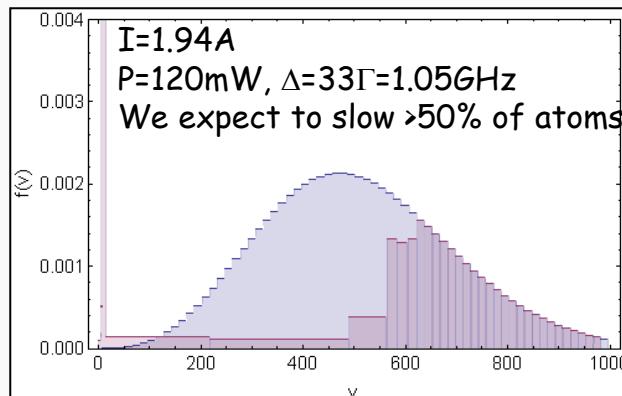
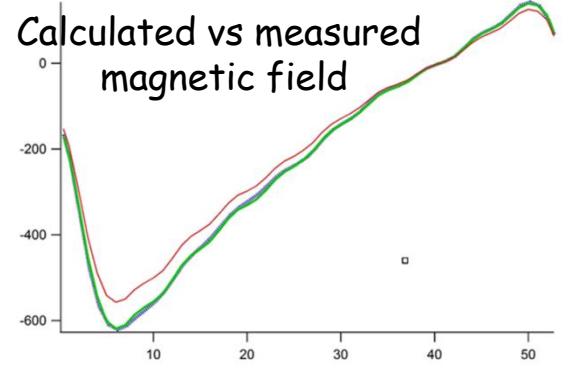
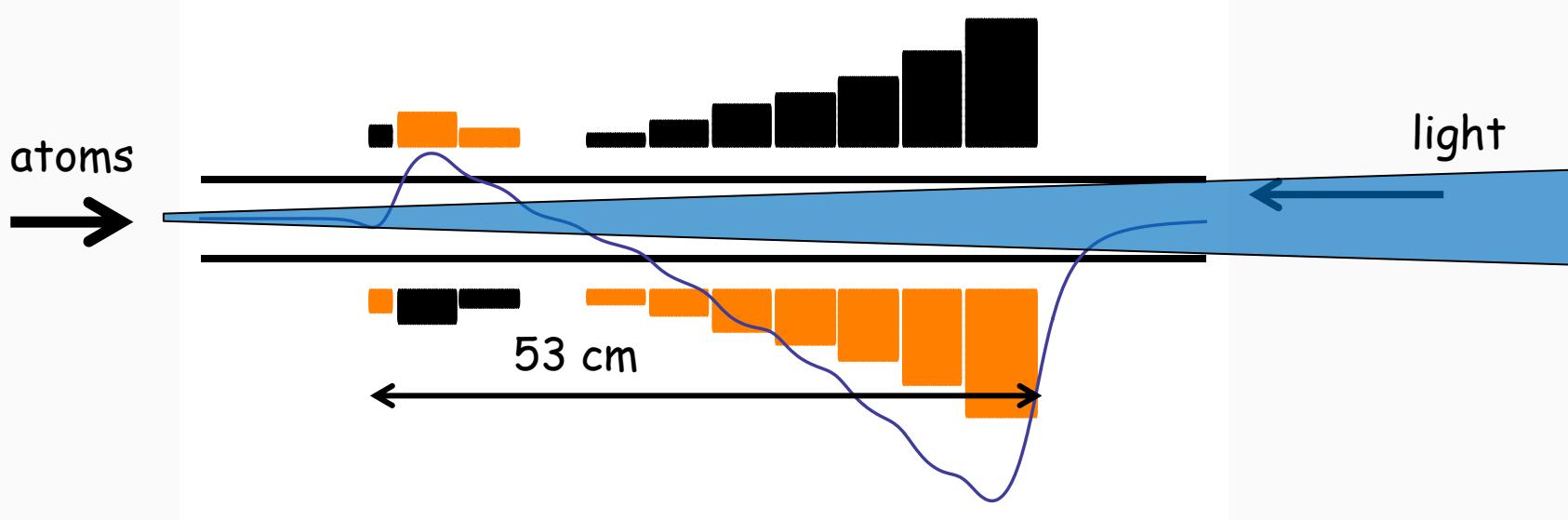
- i) Oven, Transverse Cooling
- ii) Differential Pumping
- iii) Zeeman Slower
- iv) Science chamber (MOT, ODT, Manipulation, detection³⁵)

Experimental setup

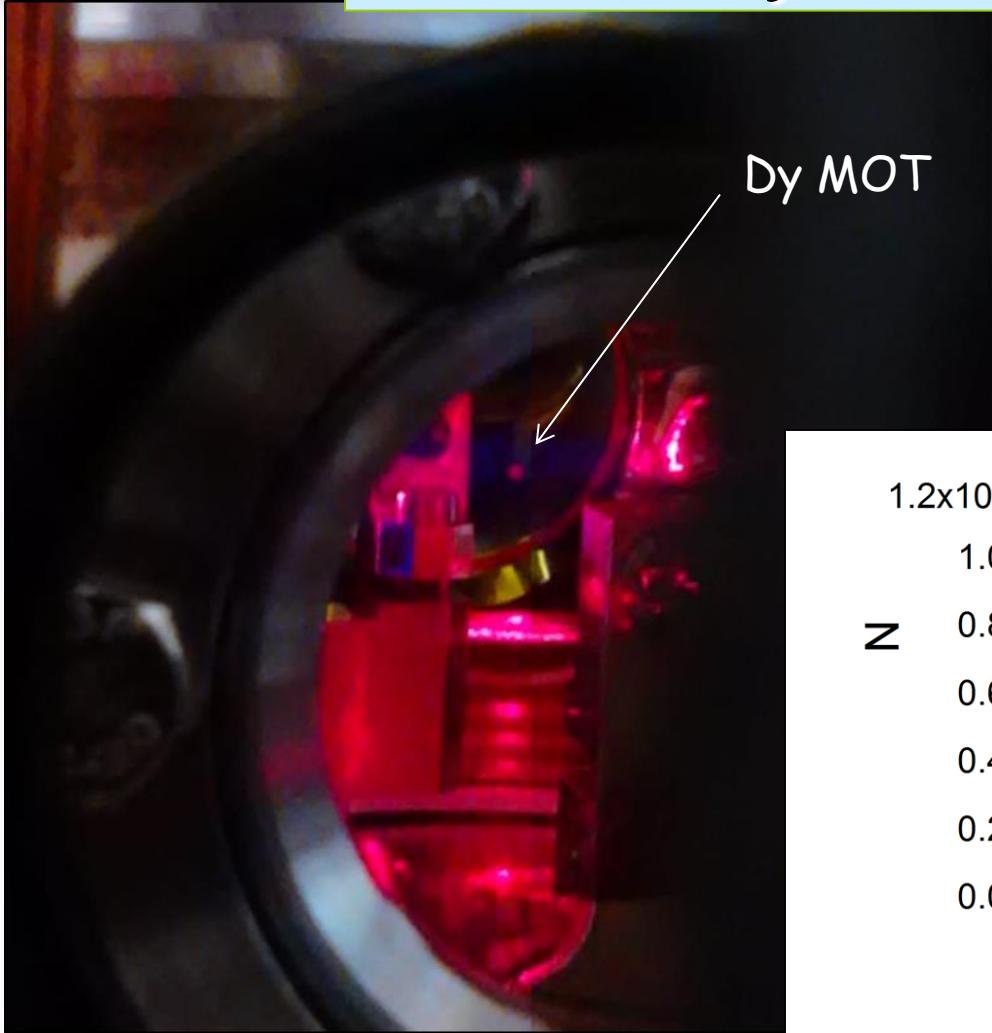


The Zeeman slower

Spin flip configuration: the B field changes sign

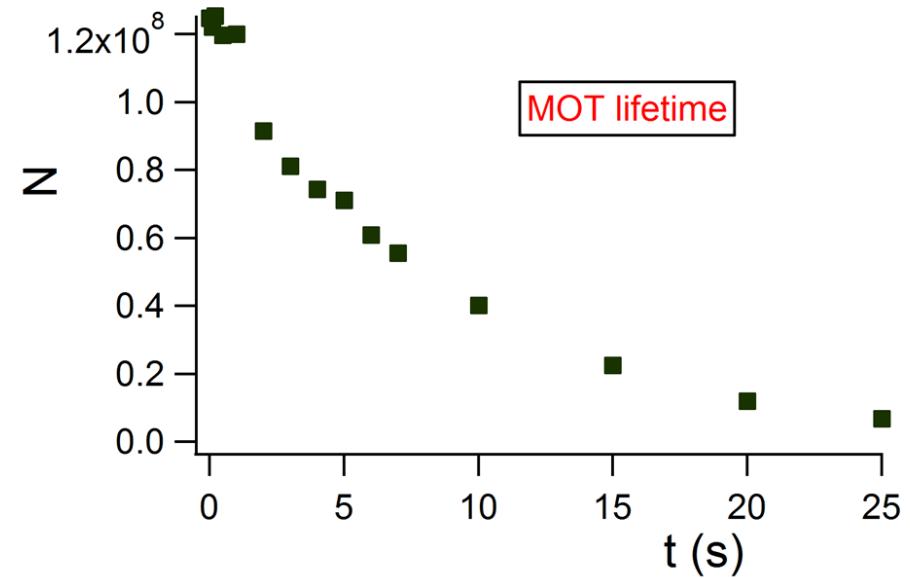


The Dy MOT @ 626nm

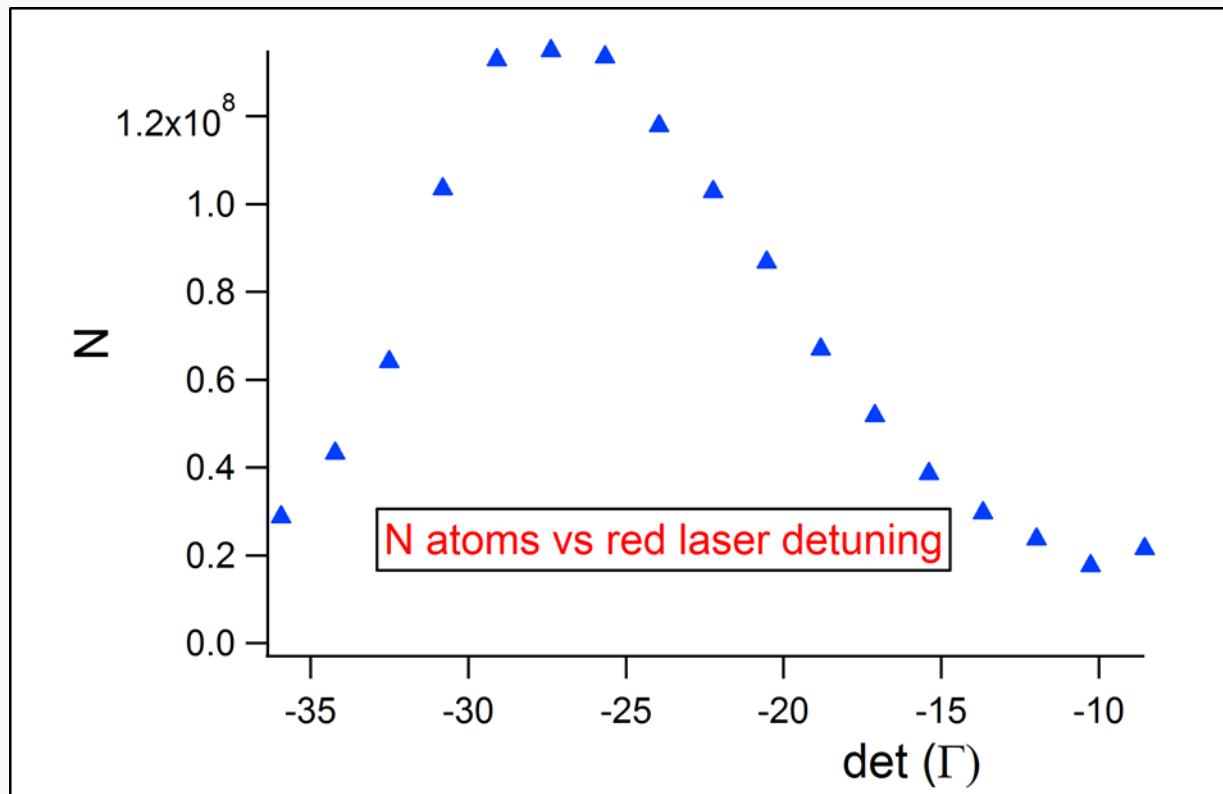


Preliminary results with
 $I = 200 I_s$

Measured final temperature
 $T = 20 \mu\text{K}$



The Dy MOT @ 626nm



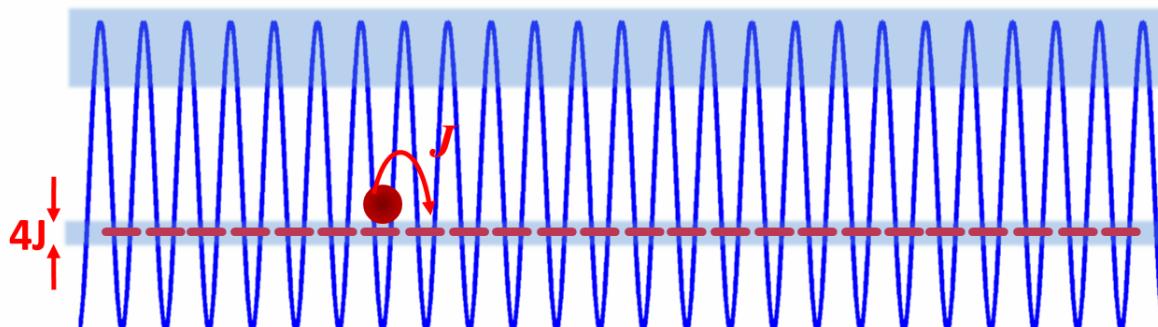
Next steps: ODT -> BEC

Next planned steps are:

- Atom transfer from MOT to Optical Dipole Trap in a in-vacuum cavity
- Atom transfer from the “cavity” trap to a crossed ODT
- Evaporation
- Dy BEC (or Fermi quantum degenerate gas)
- Loading BEC into a Optical Lattice
- Experiments in reduced dimensionality

$$d = \lambda/2$$

↔



UCL, September 28th, 2016

GRAZIE !

Disponibilità di **tesi magistrale (o triennali)** su:

- Dy BEC
- Magnetometria con atomi ultrafreddi di Rb

andrea.fioretti@ino.it

lucioni@lens.unifi.it

carlo.gabbanini@ino.it