Consiglio Nazionale delle Ricerche

INO - CNR
Istituto Nazionale di Ottica
S.S. «A. Gozzini»
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56124 Pisa

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

Andrea Fioretti

…………….

9 Maggio2017
Dipartimento di Fisica, Pisa

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Outline

- CNR e INO: chi siamo?
- Esperimenti all'INO-Pisa:

  dai nanokelvin alla fusione nucleare
- Raffreddamento e intrappolamento di atomi tramite laser
- Conclusioni

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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

INO-CNR Istituto Nazionale di Ottica

Area CNR di Pisa

- Inaugurata il 6 dic. 2000;
- Personale >1.500 (~1.000 CNR);
- Superficie 123.300 m^2
- 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

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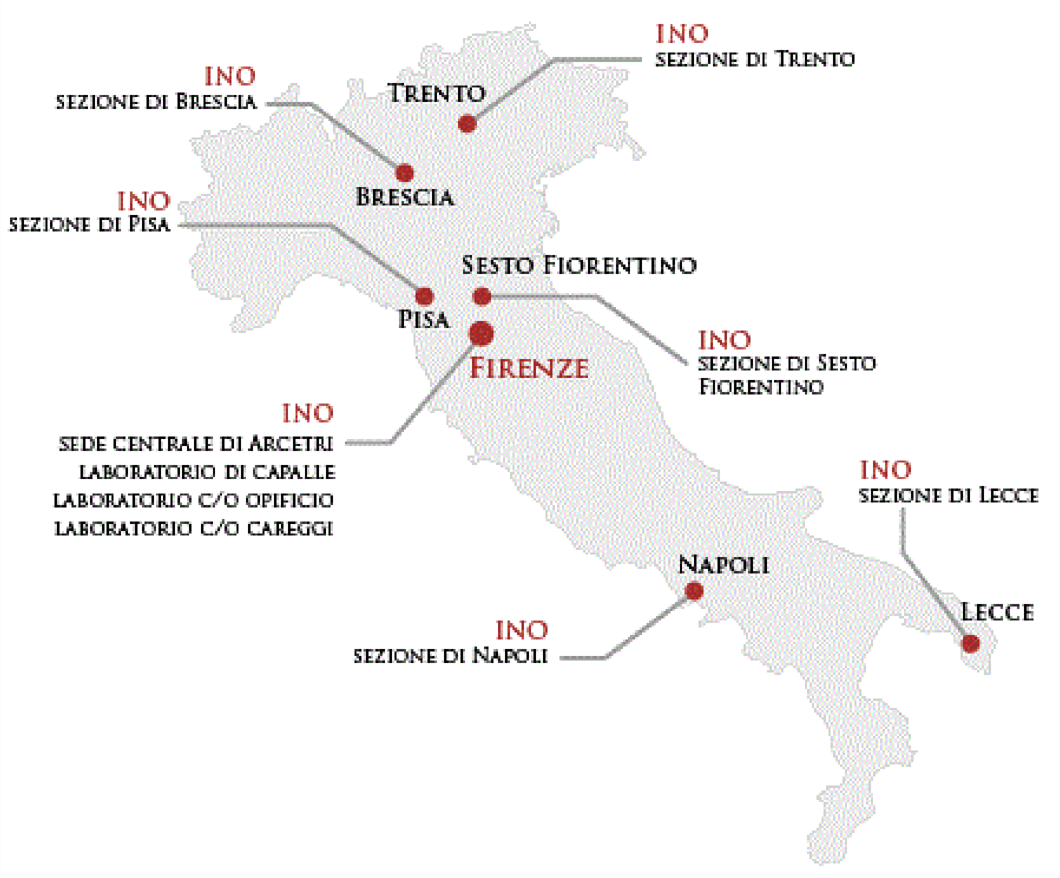
Istituto Nazionale di Ottica

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 €**.



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Sede Secondaria "Adriano Gozzini«, Pisa

Sede Secondaria of Sesto F. LENS

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INO-Pisa: Laboratorio ILIL

INO-CNR Istituto Nazionale di Ottica

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

MINISTERO DELL'ISTRUZIONE, DELL'UNIVERSITÀ E DELLA RICERCA

Ministero della Salute

INFN Istituto Nazionale di Fisica Nucleare

ELI-ITALY INO-CNR (Pisa)

EuPRAXIA

HiPER

Laserlab Europe

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)

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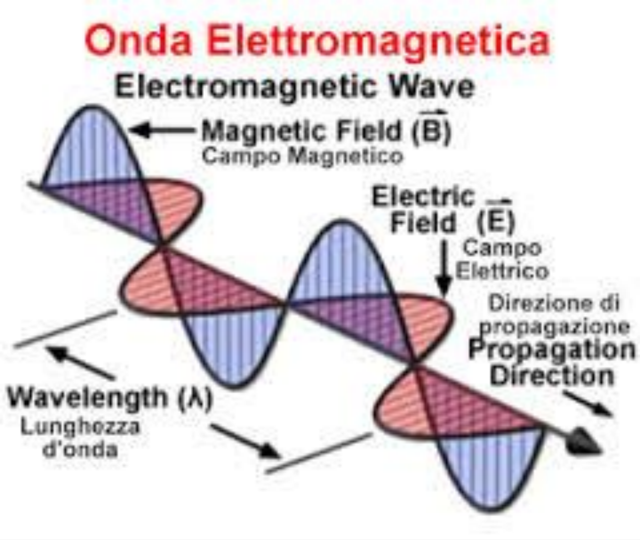
La materia ad alti campi elettrici

Laser di alta potenza – Alto campo elettrico



$$Forza = Carica´\ CampoElettrico$$

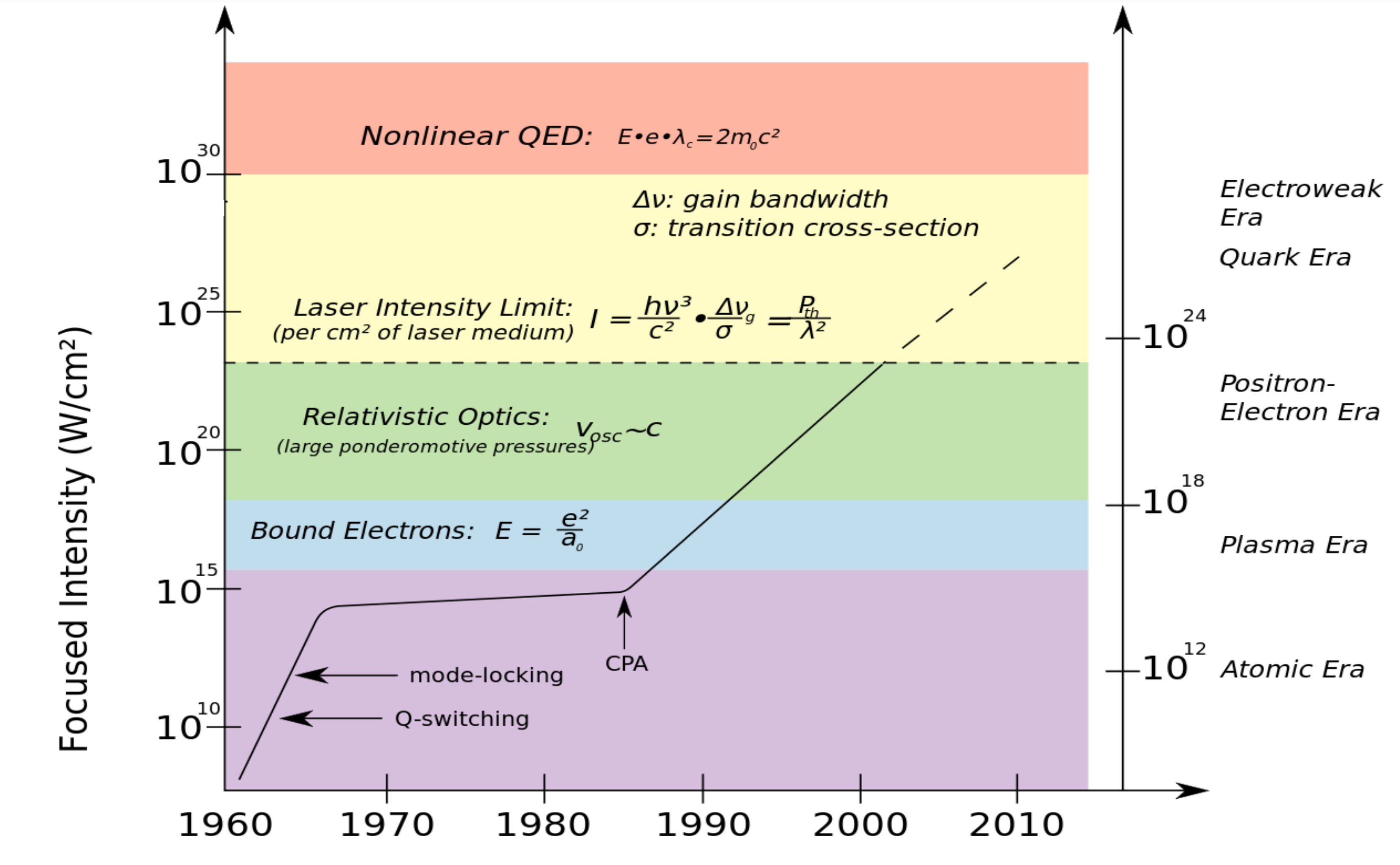
$$CampoElettrico\ \mu \sqrt{\frac{Potenza}{Superficie}}$$

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

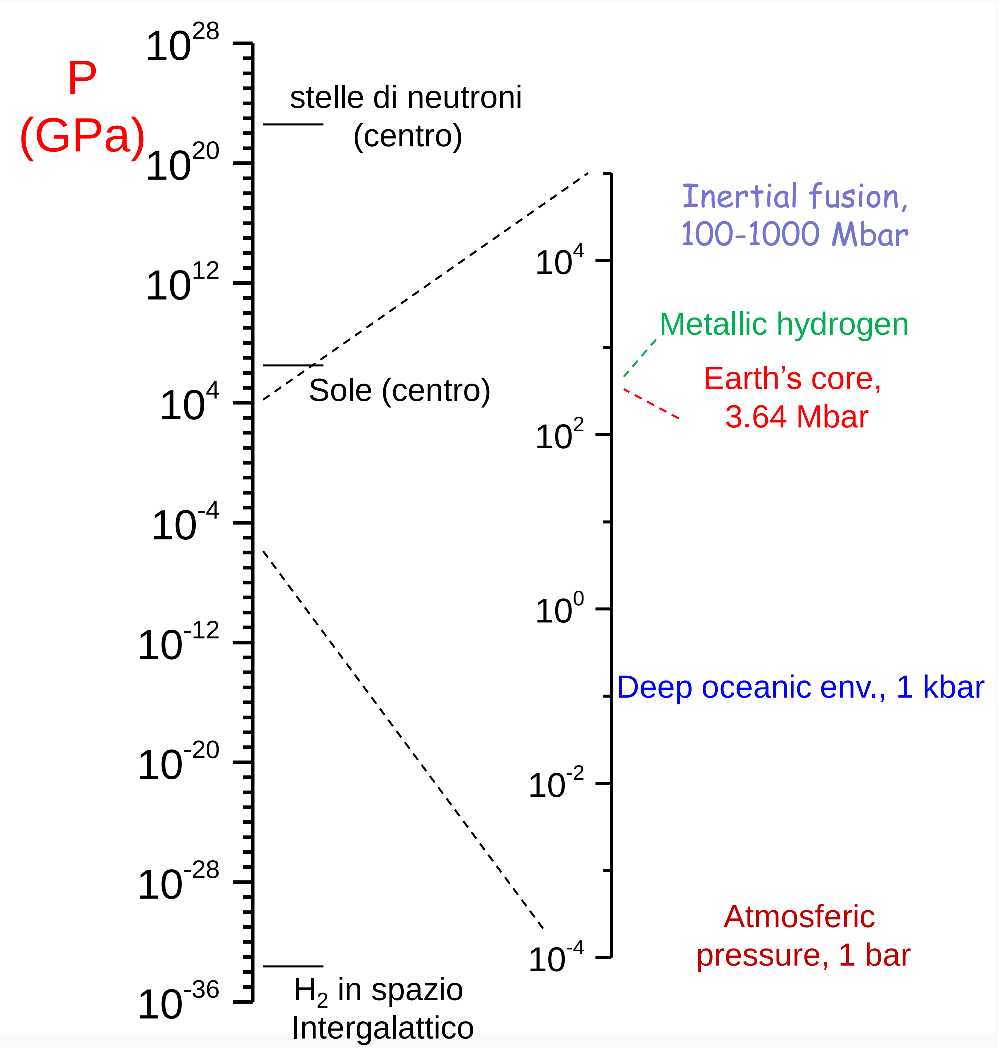
Nuovi processi fisici si attivano ad altissimi campi elettrici

Evoluzione dei laser impulsati

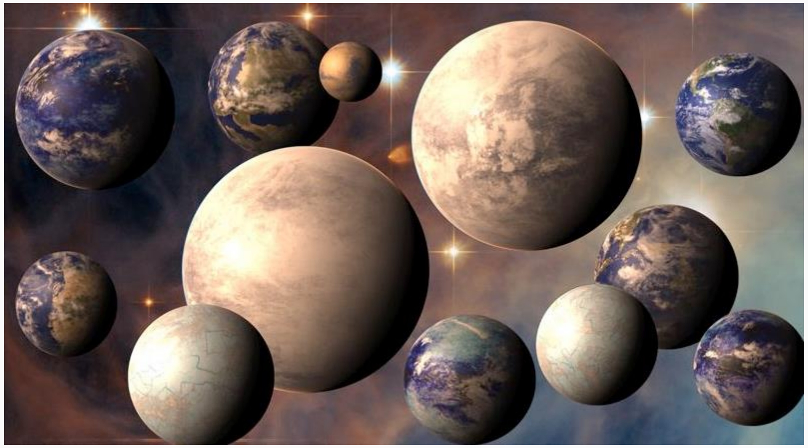
Densità di potenza focalizzata, dai laser “Q-switch” ai laser “CPA”



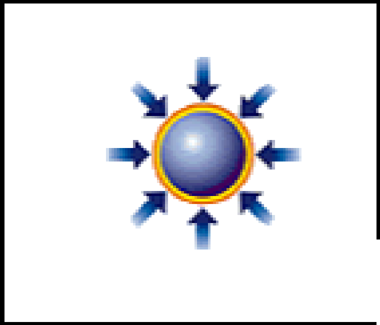
Laser per scaldare la materia



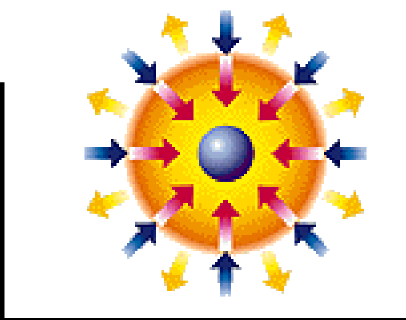
Riprodurre in laboratorio lo stato della materia nel nucleo della Terra e degli altri pianeti o delle stelle



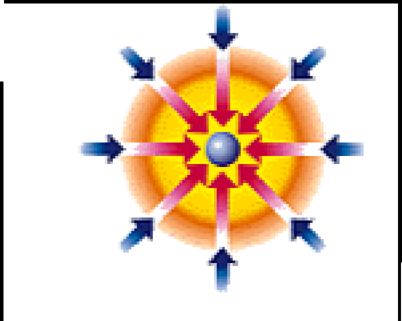
La fusione "Inerziale"



Fase 1: irraggiamento tramite laser

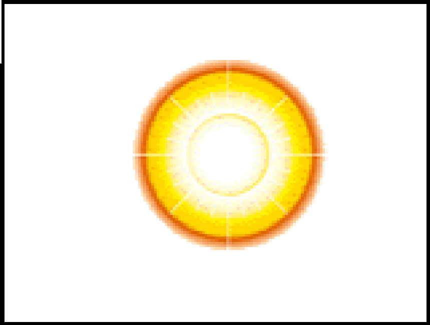


Fase 2: Compressione



Fase 3: Ignizione

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

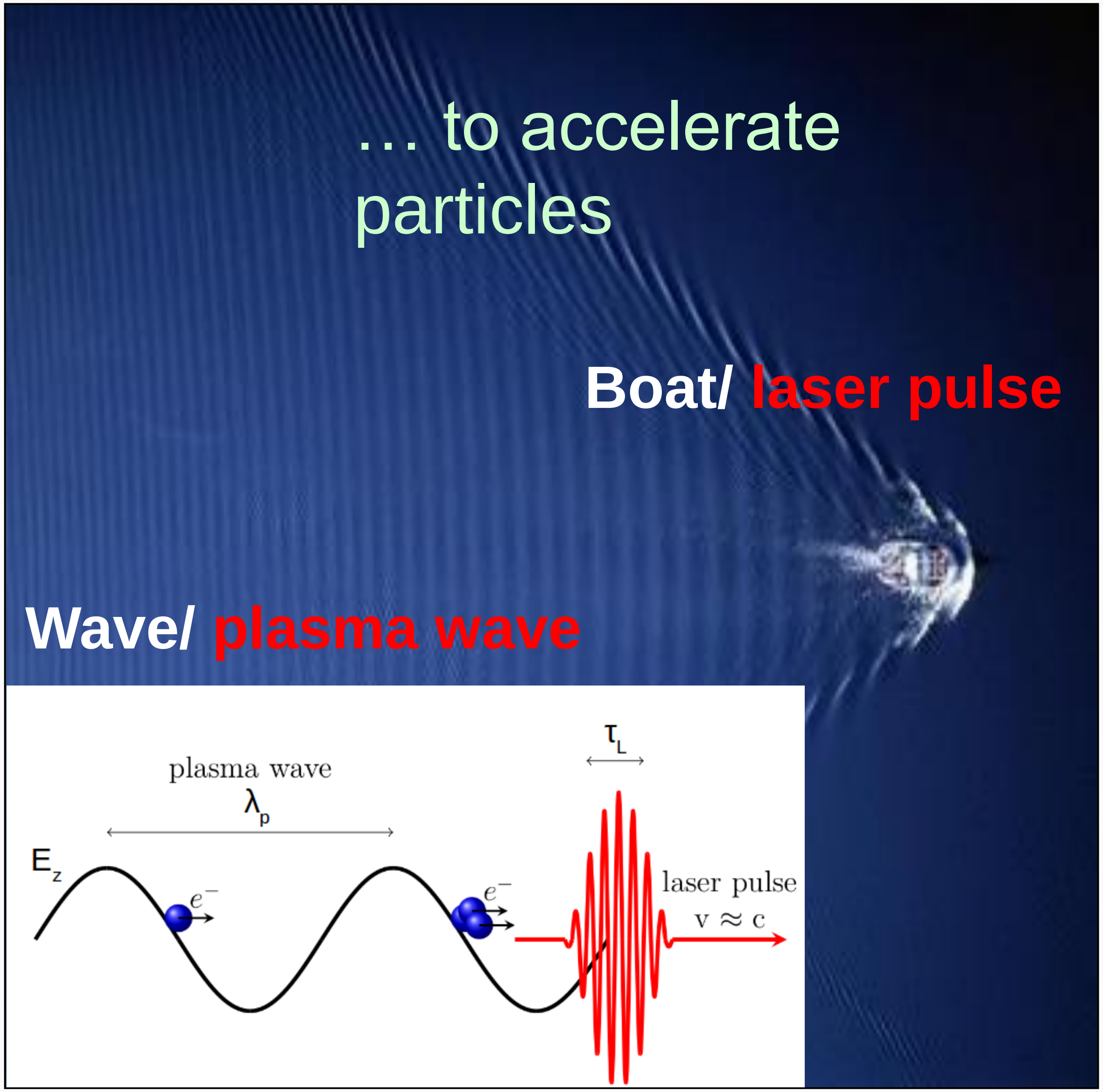


Fase 4: Fusione

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

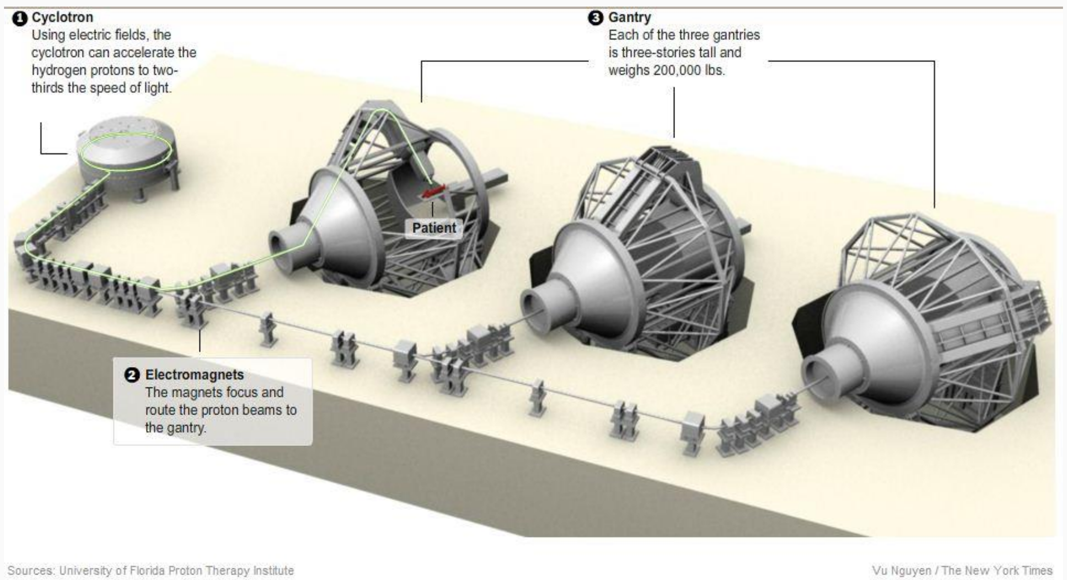
Laser per accelerare cariche

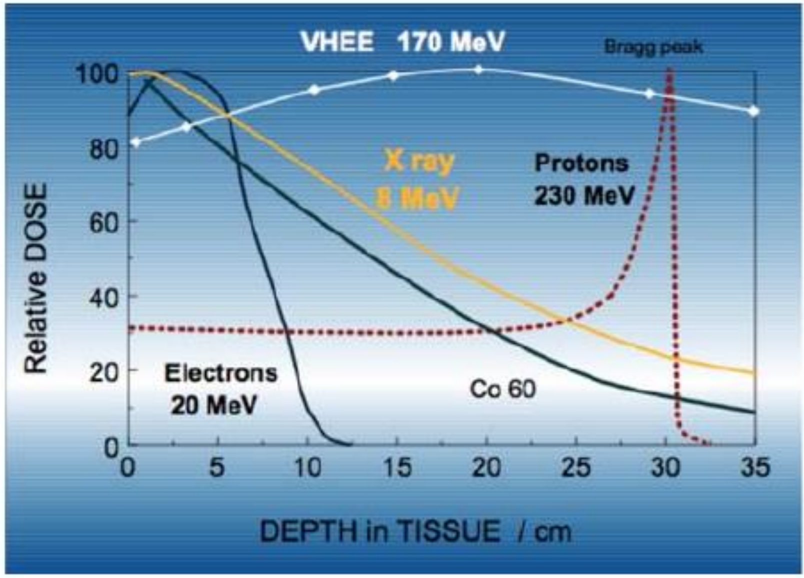
Wakefields….


… to accelerate particles
Boat/ laser pulse
Wave/ plasma wave
plasma wave
λp
τL
Ez
e−
e−
laser pulse
v ≈ c

Cariche accelerate in medicina

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





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Acceleratori laser in medicina

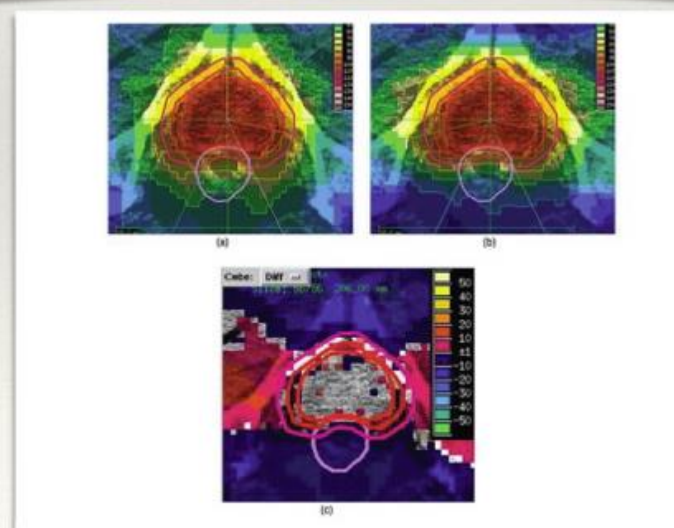
Case Study: IntraOperative RadioTherapy (IORT)

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

IOP Publishing — Physics in Medicine and Biology
Phys. Med. Biol. 54 (2009) 3315–3328 doi:10.1088/0031-9155/54/11/003

Treatment planning for laser-accelerated very-high energy electrons

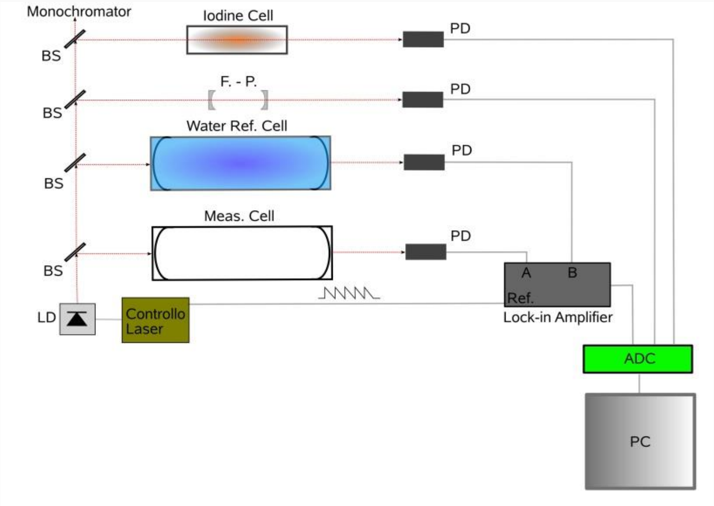
T Fuchs[1], H Szymanowski[1], U Oelfke[1], Y Glinec[2], C Rechatin[2], J Faure[2] and V Malka[2]

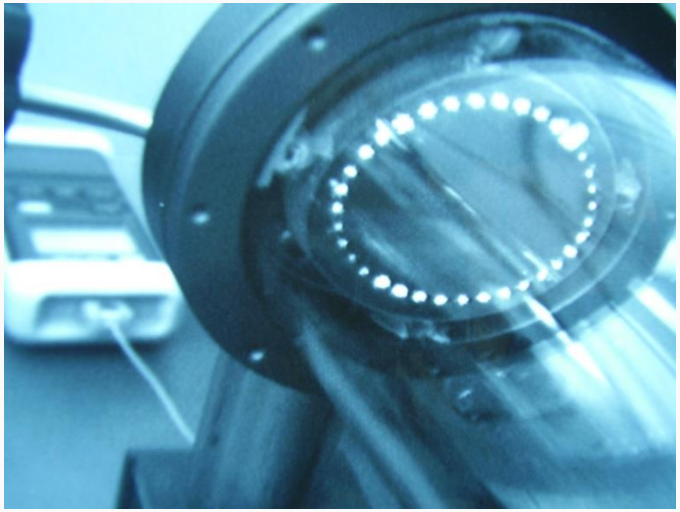


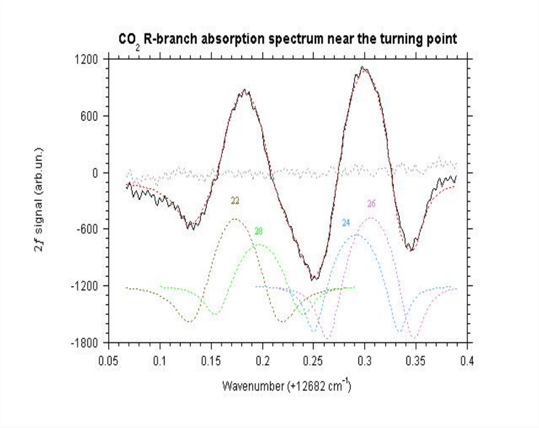
Terapia

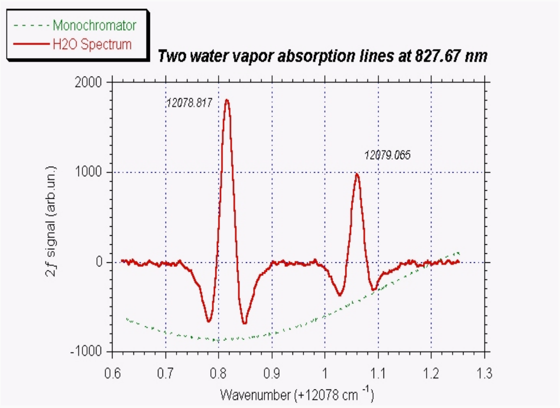
Laser per applicazioni ambientali

Diode Laser Spectroscopy @ INO - CNR









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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 O_2 ≈ 10-100 ppm · meter; CH_4, C_2H_2 and CO_2 ≈ 0.01 - 0.1% · meter path-length;

Fast time responses: ≈ 10-100 ms;

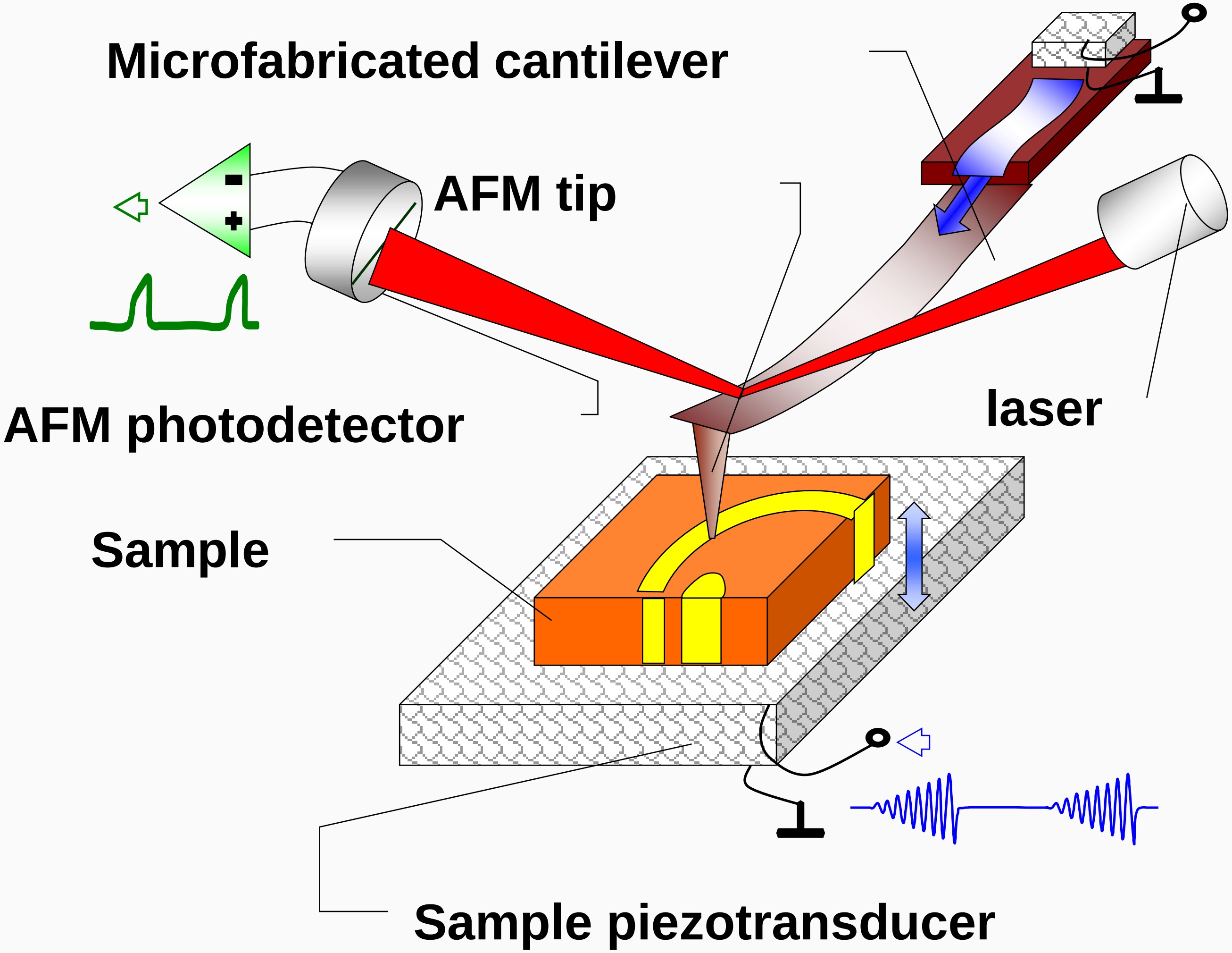
High selectivity, bound to single or multiple absorption resonances: Resolution ≤ 0.1 cm^{-1};

Non invasive "optical" diagnostic application to different and hostile environments.

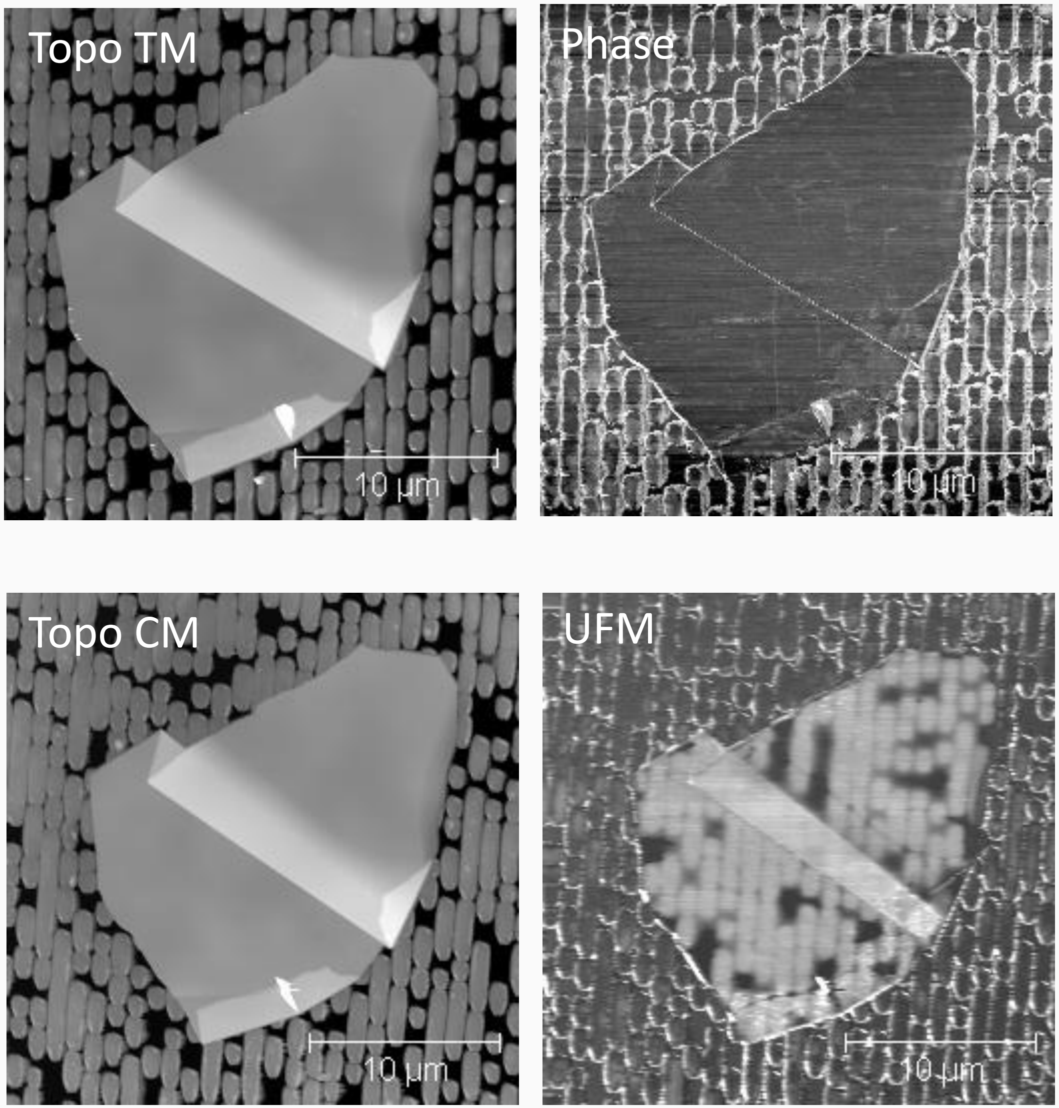
Possibilità di collaborazione e inserimento in aziende!

Microscopie a sonda..

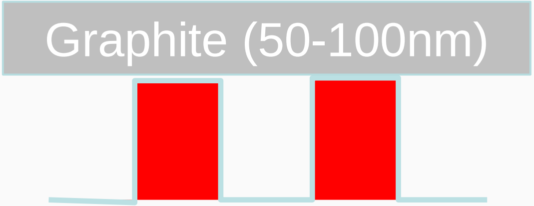
Ultrasonic Force Microscope



Subsurface detection



Graphene slab placed on a structured polymer film.



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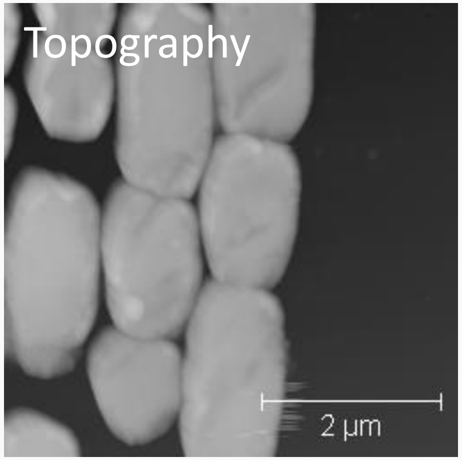
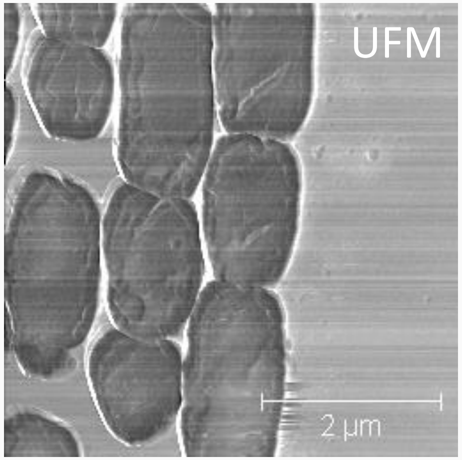
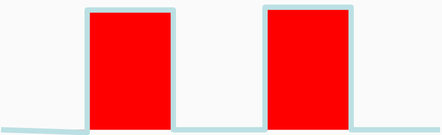
Subsurface detection

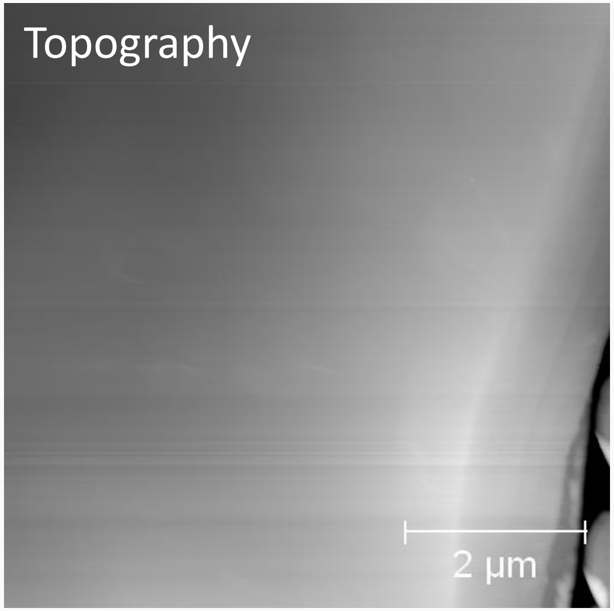
Graphene slab placed on a structured polymer film.

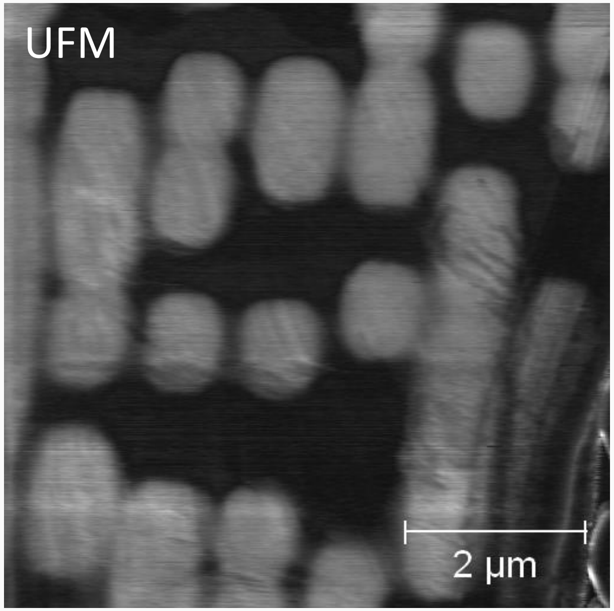


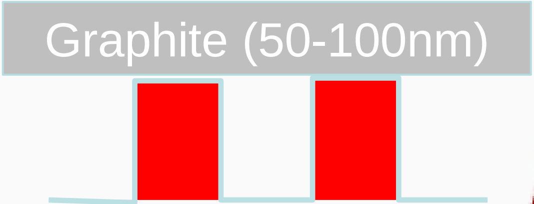


Polymer Steps

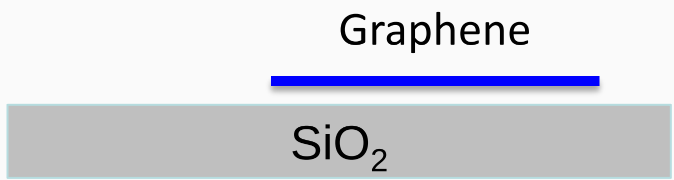


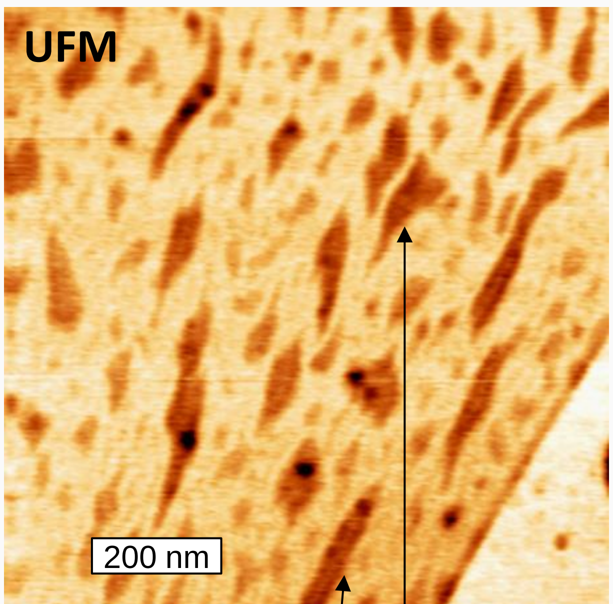


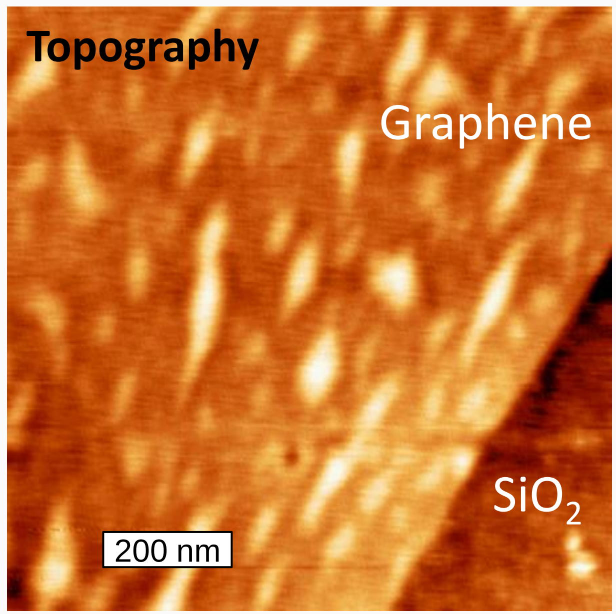


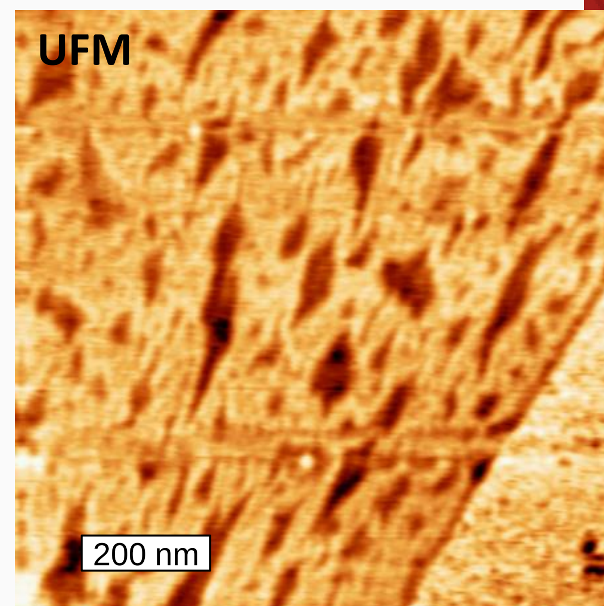


Graphene Tranfer on SiO_2





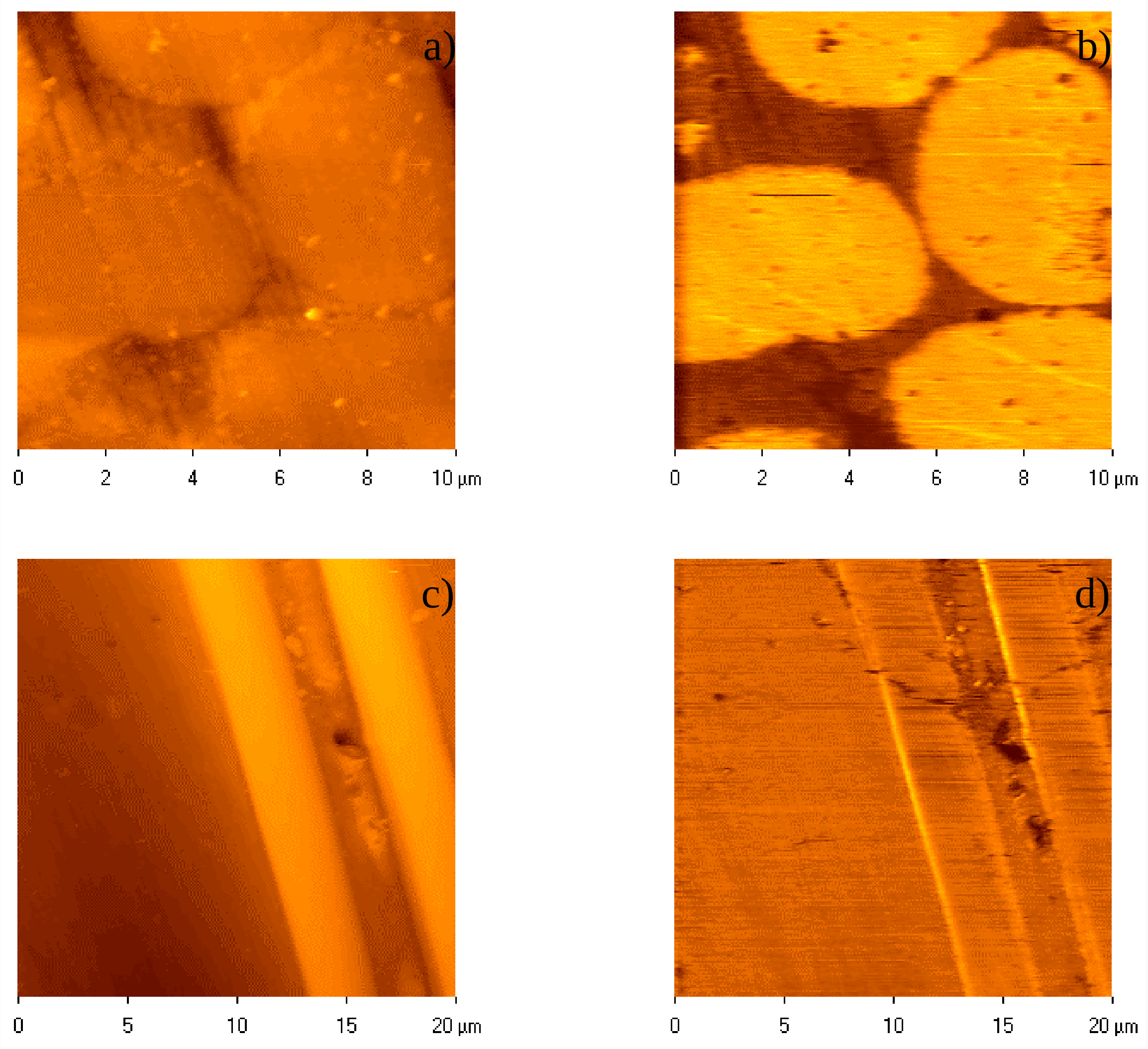




Delaminations

Elastic contrast

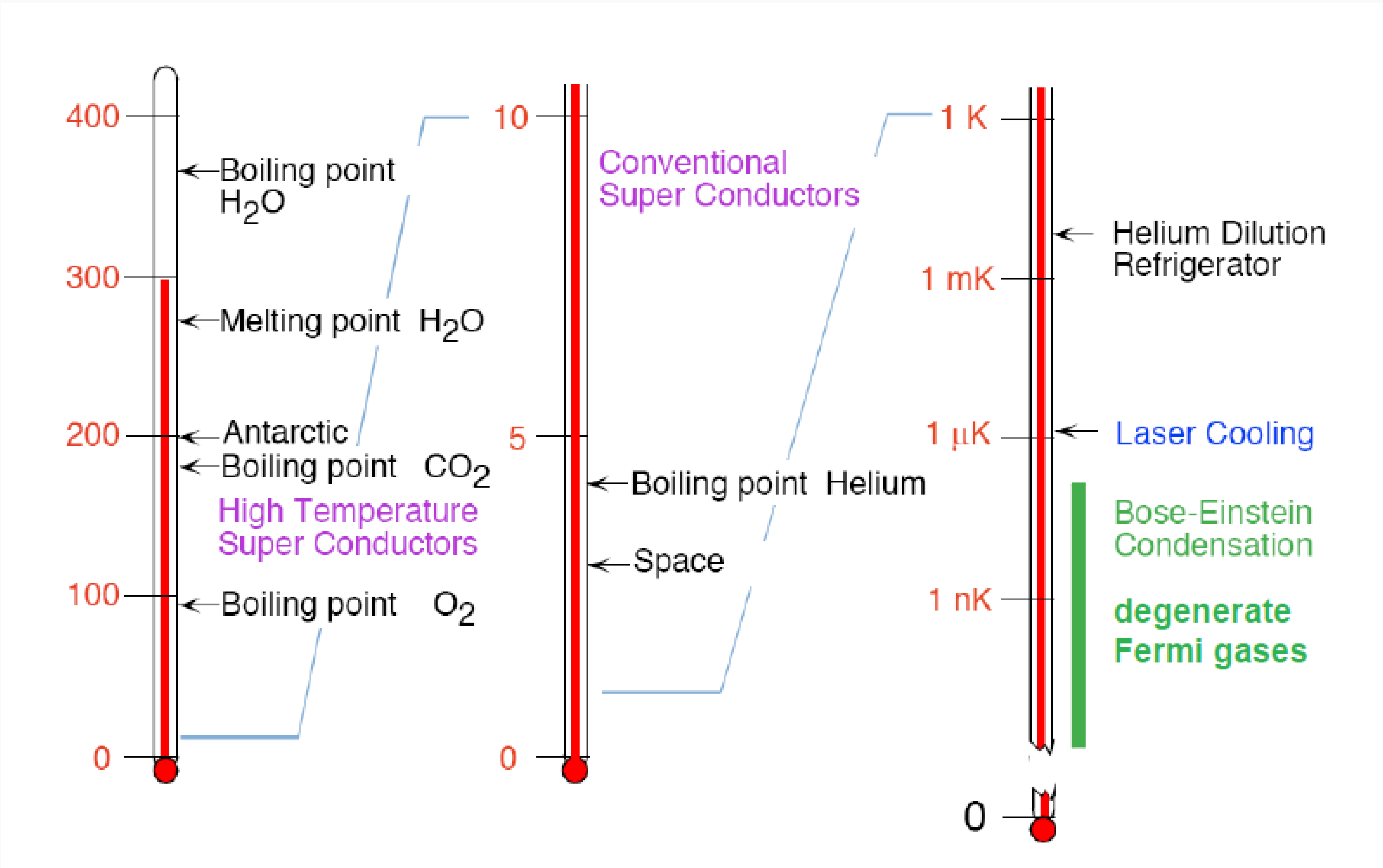
Carbon Fibers in Epoxy Matrix



294 GPa

1-10 GPa

Laser per *raffreddare* la materia



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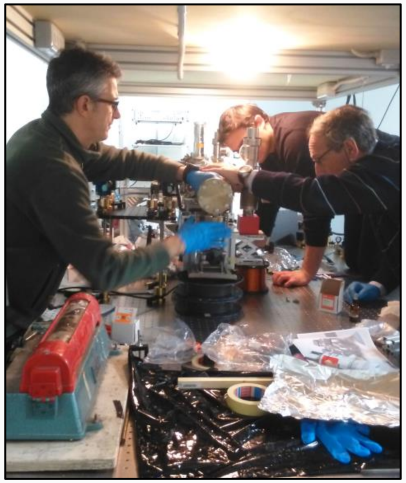
Laser cooling experiments

- 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



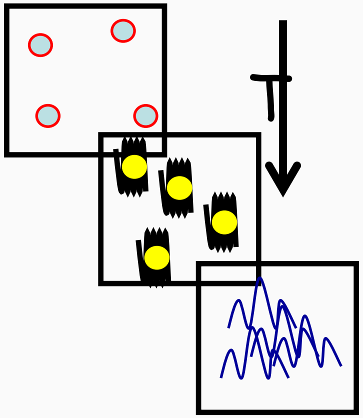
Giovanni Modugno (Unifi – INO - LENS)
Jacopo Catani
Massimo Inguscio

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

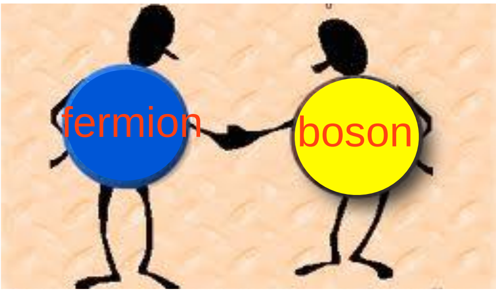
Quantum gases:
atoms cooled down to quantum degeneracy:



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

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Quantum simulators

(with ultracold atoms)

Simulating Physics with Computers

Richard P. Feynman

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

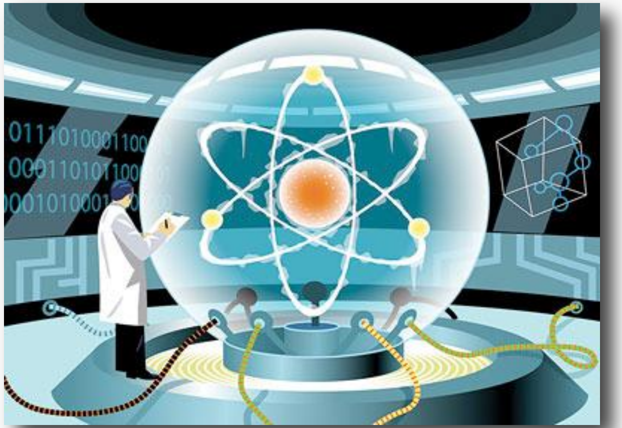
Received May 7, 1981

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-*

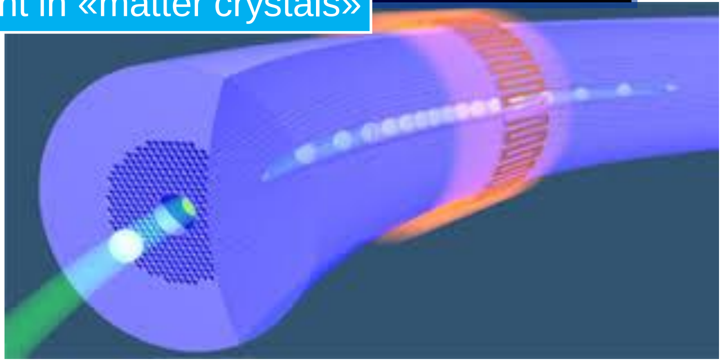
$$H\psi = E\psi$$

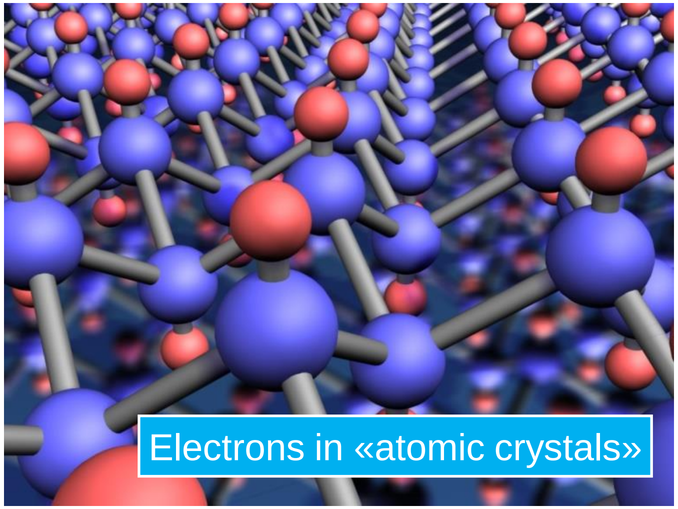
or



Light crystals

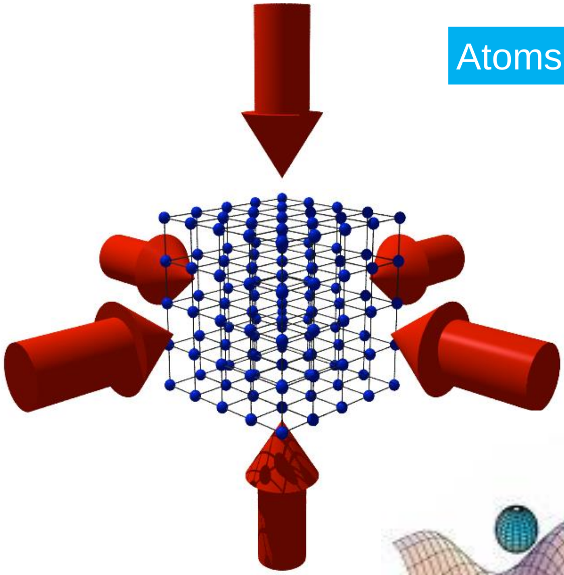
Light in «matter crystals»

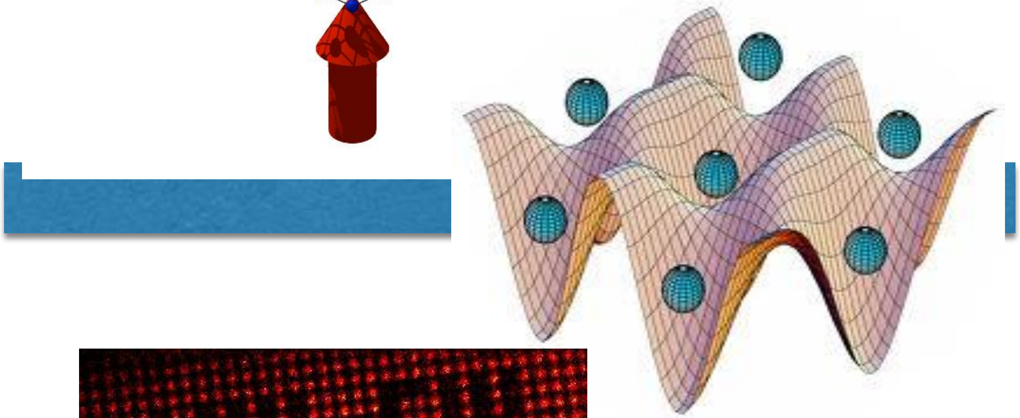


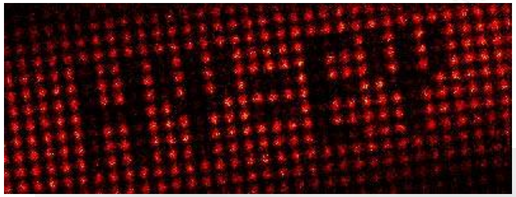


Electrons in «atomic crystals»

Atoms in «light crystals»







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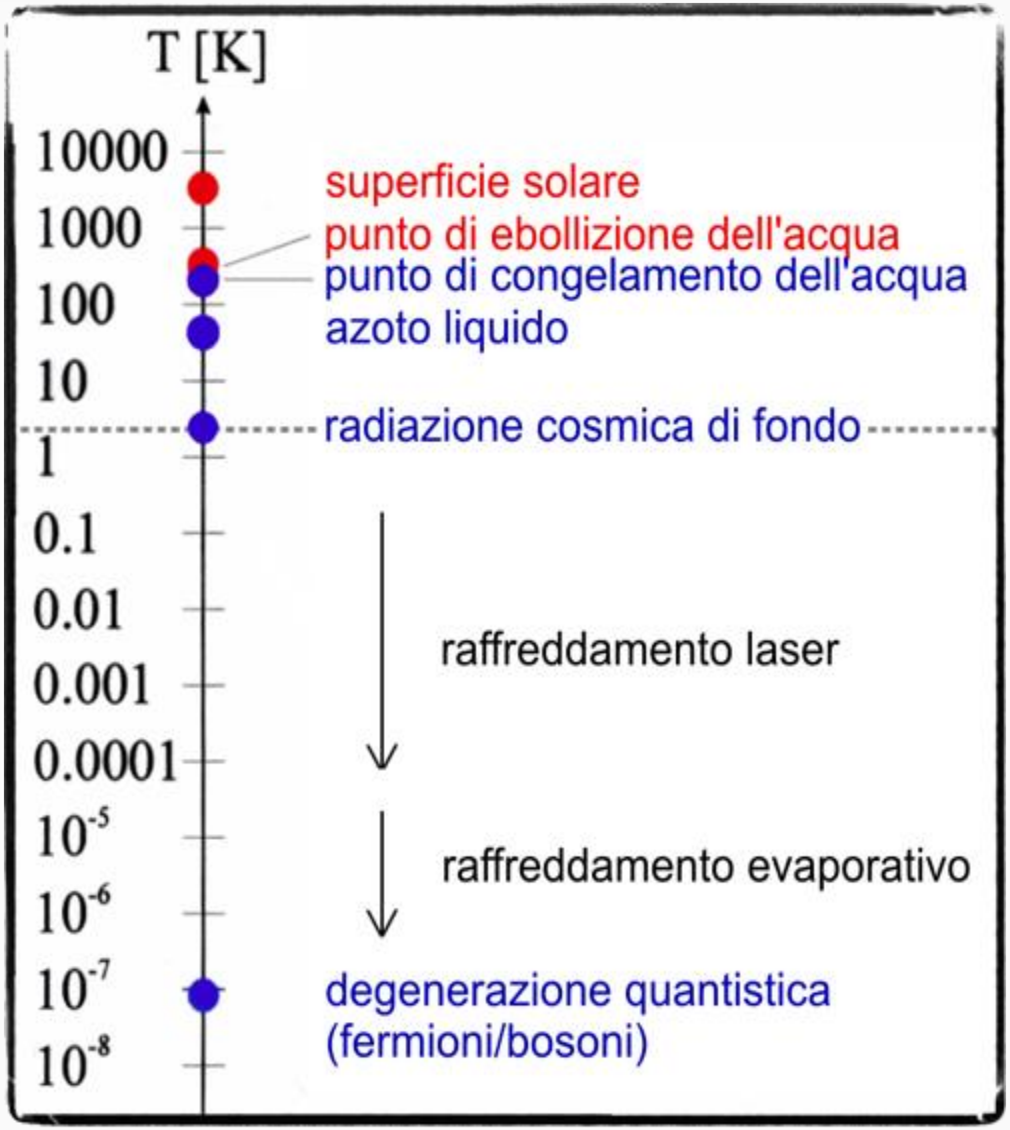
A powerful toolbox

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

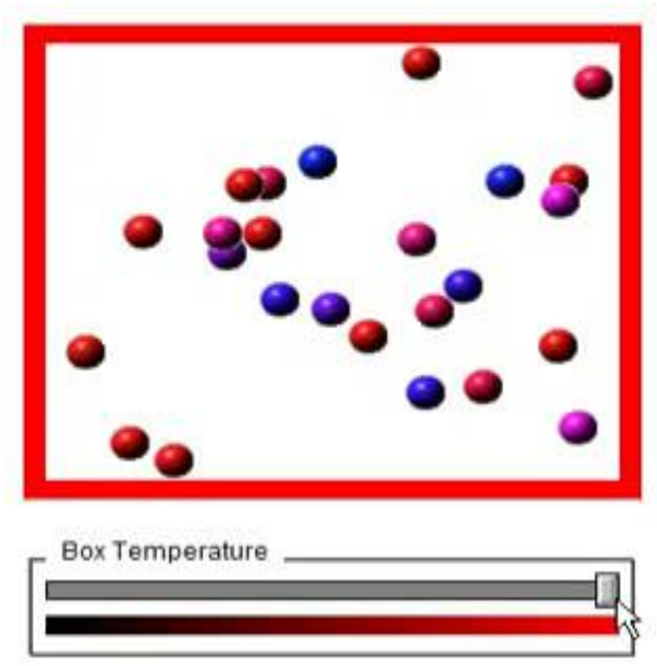
- ☑ Optical lattices are perfect lattices: no impurities, no phonons
- ☑ Optical lattices: depths, spacing can be changed @ will
- ☑ Optical lattices and dimensionality: low dimensional physics (1d,2d) is possible!
- ☑ Disordered potentials: control main lattice and disorder @ will
- ☑ Correlated systems: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

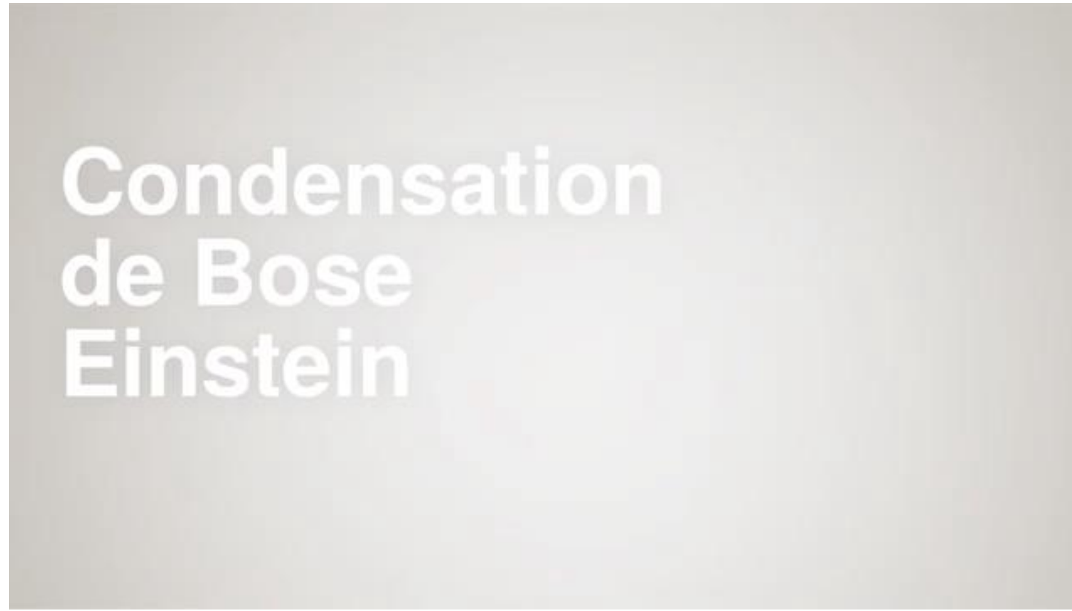
- ☑ Atom density and temperature (N,T)
- ☑ Atoms interactions: tuning scattering length via Feshbach resonances
- ☑ Weakly interacting regimes: ideal systems
- ☑ Fermi and Bose statistics
- ☑ Fermi-Fermi, Bose-Bose, Bose-Fermi systems can be investigated
- ☑ .....

Way to quantum degeneracy

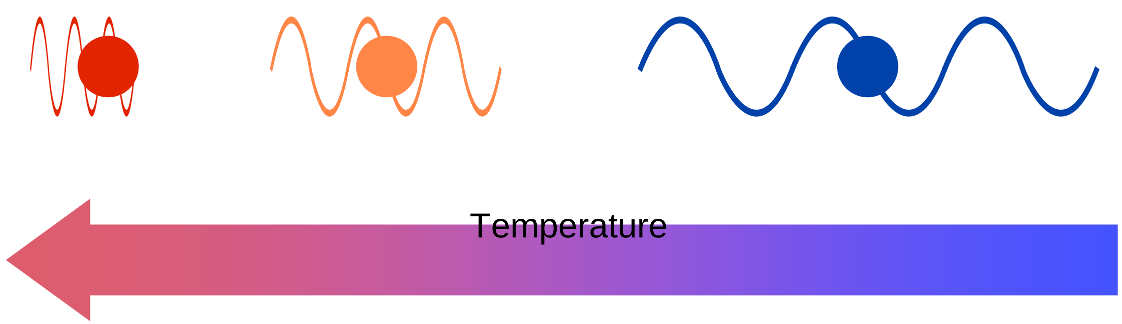


Why so cold?



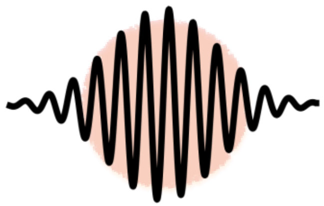


$$\lambda_{dB} = \frac{h}{mv}$$



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.



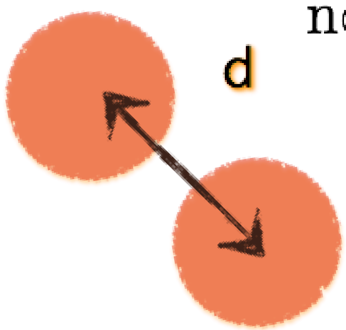
$$\lambda_{dB} = \frac{h}{mv}$$

(Rb atom)

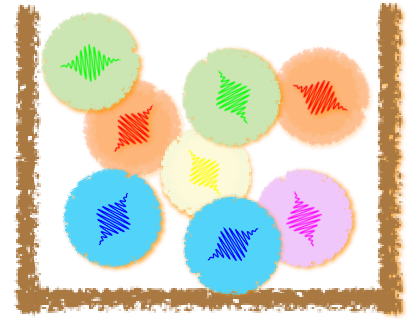
@ T=300K, $\lambda_{dB} = 10^{-11}\, m$!!

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

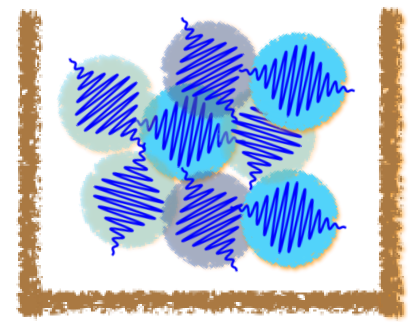
$n \propto d^{-3}$



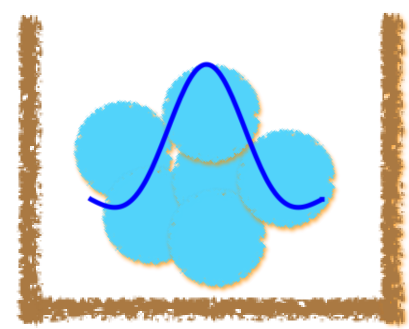
$n\lambda^3 \ll 1$



$n\lambda^3 \sim 1$



$n\lambda^3 > 1$



Typical densities for quantum gases: 10^{14}-10^{15} atoms/cm^3

Classical vs quantum particles

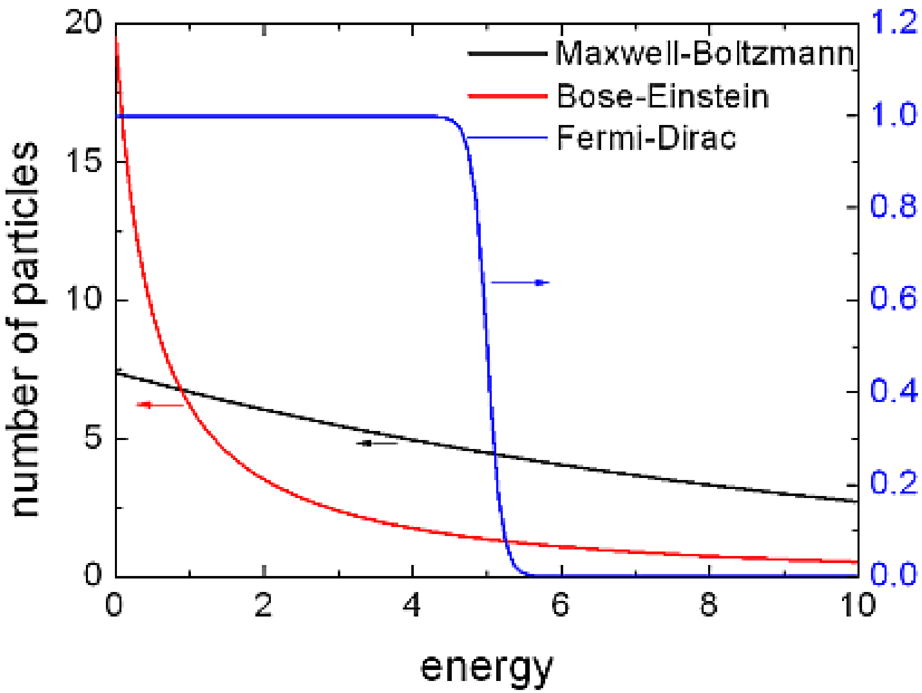
$$N_{i,B} = \frac{1}{e^{\frac{\varepsilon_{i-\mu}}{k_B T}}}$$

fermions

$$N_{i,FD} = \frac{1}{e^{\frac{\varepsilon_{i-\mu}}{k_B T}} + 1}$$

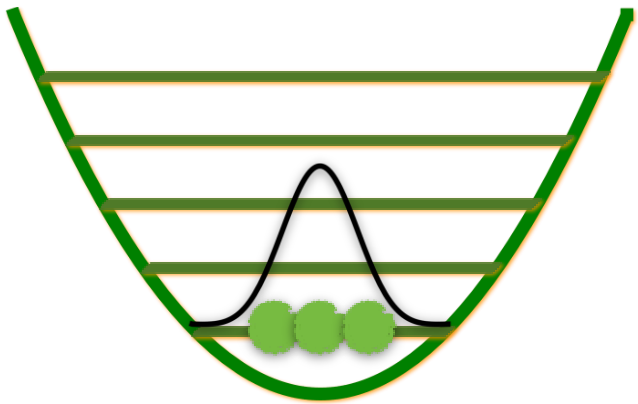
bosons

$$N_{i,BE} = \frac{1}{e^{\frac{\varepsilon_{i-\mu}}{k_B T}} - 1}$$

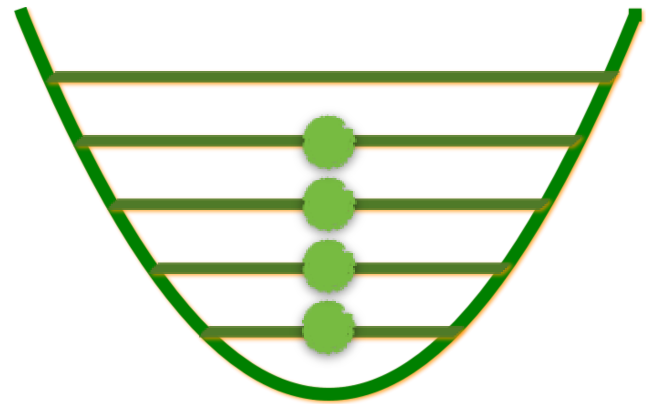


Bose-Einstein Condensation (BEC)

Bose-Einstein condensate



Fermi gas



• Statistical "attraction" between the particles

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

• Statistical "repulsion" between the particles

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

Fermionic pressure: fermions can be constrained in a too n arrow space. This prevents co llapse of neutron stars

Room temperature

«Ultracold» temperature

l=20 m

v_{av}=300 m/s

t~ 1/10 s

v_{av}=2 mm/s

t~ a few hours

Experimental techniques

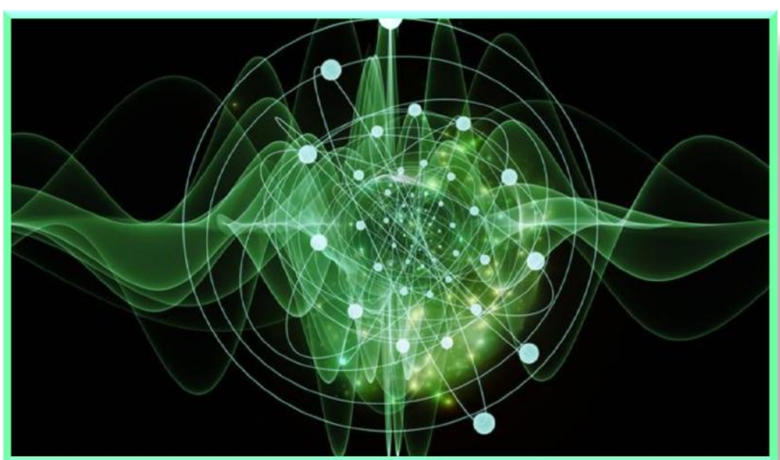
T ≈ 300 K
Room T

Laser cooling

T ≈ 10 μK

Evaporative cooling

T≈ 100 nK

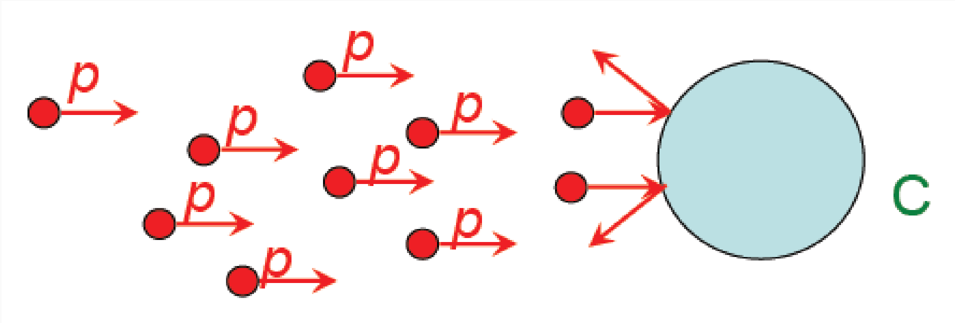


ENTERING
QUANTUM WORLD

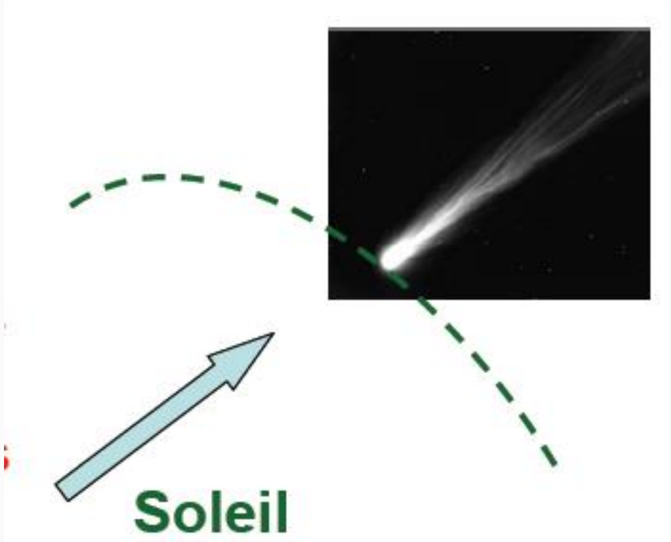
Laser cooling

Light forces on atoms 1/3

- Momentum transfer between photons and atoms



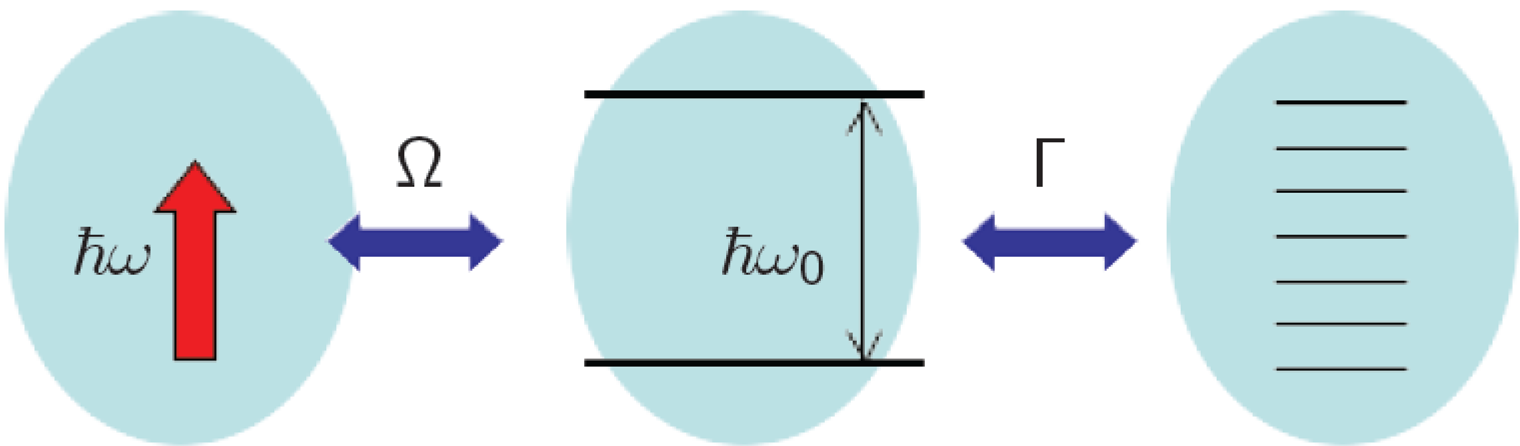
- Kepler already imagined the existence of a radiation pressure to explain the tails of comets



- 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 $\mathbf{d} = \langle e|\hat{\mathbf{D}}|g\rangle$

$\hbar\Omega(\mathbf{r}) = -(\mathbf{d}.\epsilon(\mathbf{r}))\,\mathcal{E}(\mathbf{r})$ Rabi frequency

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

Spontaneous emission rate Γ

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

Typical value of I_s: a few mW/cm^2

Light forces on atoms 3/3

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

$$\boxed{\mathbf{F}_{\mathrm{pr}} = \hbar\mathbf{k}\frac{\Gamma}{2}\frac{s}{1+s}} \qquad s = \frac{\Omega^2/2}{\delta^2 + \Gamma^2/4} = \frac{I/I_s}{1 + 4\delta^2/\Gamma^2}$$

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

- The dipole force is due to an intensity gradient.

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

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

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Light forces on atoms 3/3

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

$$\boxed{\mathbf{F}_{\mathrm{pr}} = \hbar \mathbf{k} \frac{\Gamma}{2} \frac{s}{1+s}} \qquad s = \frac{\Omega^2/2}{\delta^2 + \Gamma^2/4} = \frac{I/I_s}{1 + 4\delta^2/\Gamma^2}$$

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

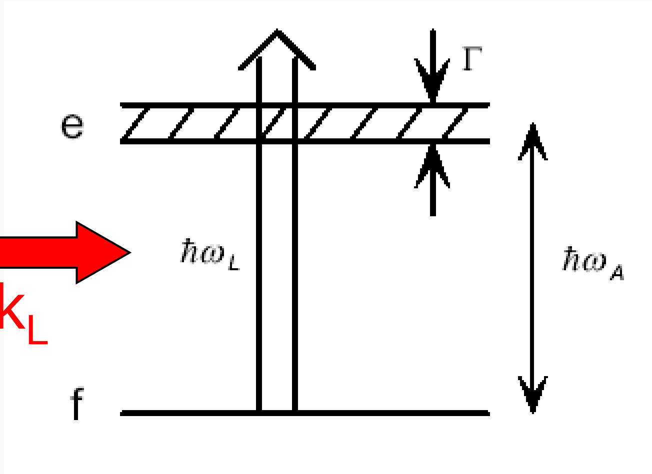
Scattering rate: $$\Gamma_{\mathrm{sc}}(\mathbf{r}) = \frac{3\pi c^2}{2\hbar\omega_0^3} \left(\frac{\Gamma}{\Delta}\right)^2 I(\mathbf{r})$$

Radiation Pressure

Two-level atom

Γ^{-1} lifetime : 32 ns for Cesium

k_L



$\delta = \omega_L - \omega_A$ detuning

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

$$v_{\text{rec}} = \frac{\hbar k_A}{m} = \frac{h}{m\lambda_A}$$

$3{,}5\ \text{mm s}^{-1}$ cesium atoms

<<< thermal velocity

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

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Atomic beam slowing 1/2

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

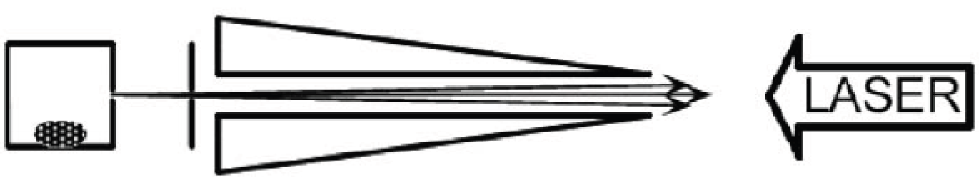
maximal value: $\mathbf{F}_{\mathrm{pr}} = \hbar \mathbf{k} \frac{\Gamma}{2}$ resonance condition $\omega_L - k_L V(z) = \omega_A(z)$

1) **inhomogeneous magnetic field** -> cw method

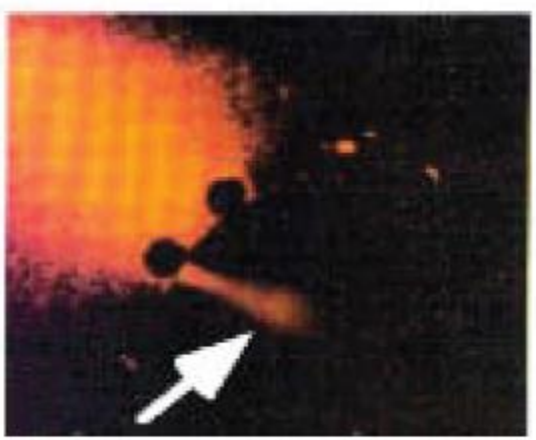
$$F(z,v) = \frac{\hbar k \Gamma}{2} \frac{s_0}{1 + s_0 + 4[\delta + kv - \mu' B(z)/\hbar]^2/\Gamma^2}.$$

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

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



such that $\omega_0(z) = \omega_0 + \gamma B(z) = \omega + kv(z)$

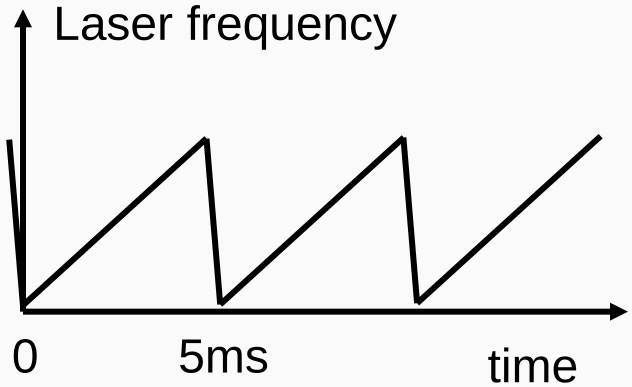


stopped atomic beam

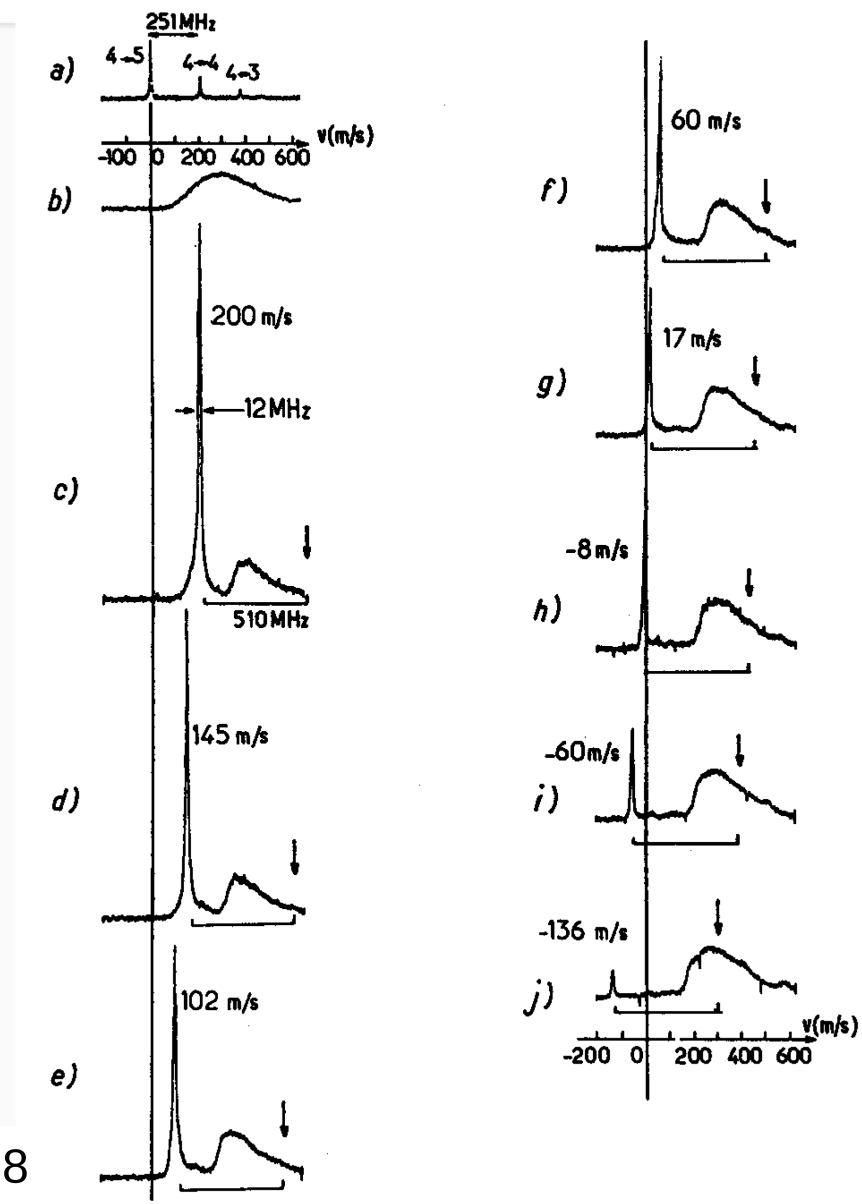
Atomic beam slowing 2/2

2) chirped cooling
(pulsed method)

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



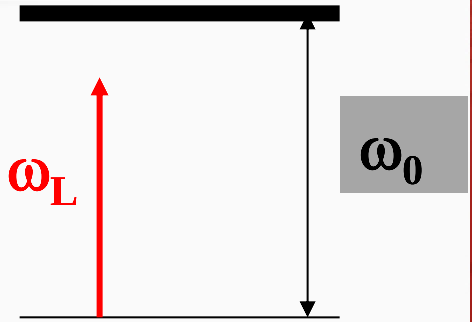
Extremely simple
with diode lasers !



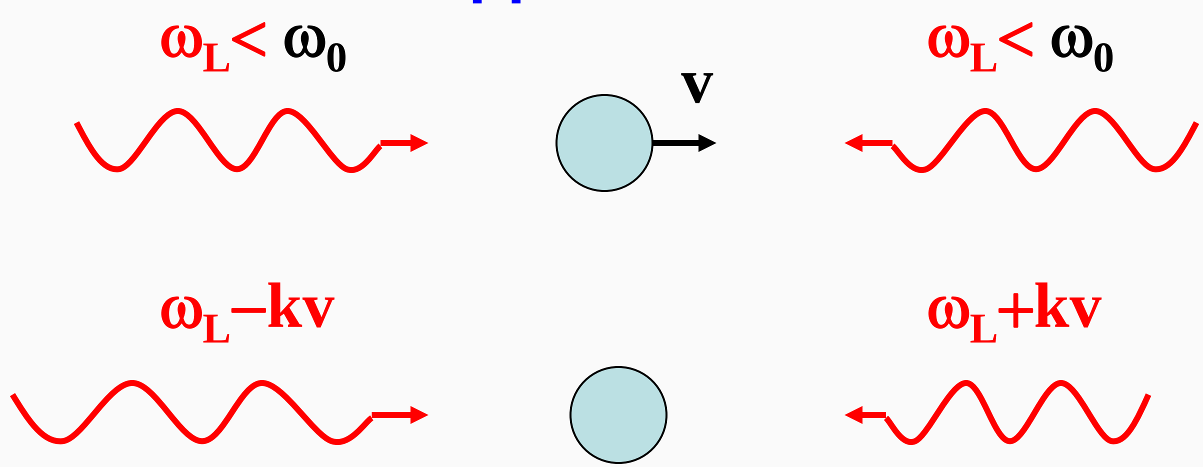
C. Salomon and J. Dalibard, 1988

Doppler Cooling 1/2

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



Doppler effect



Laboratory frame

Atom frame

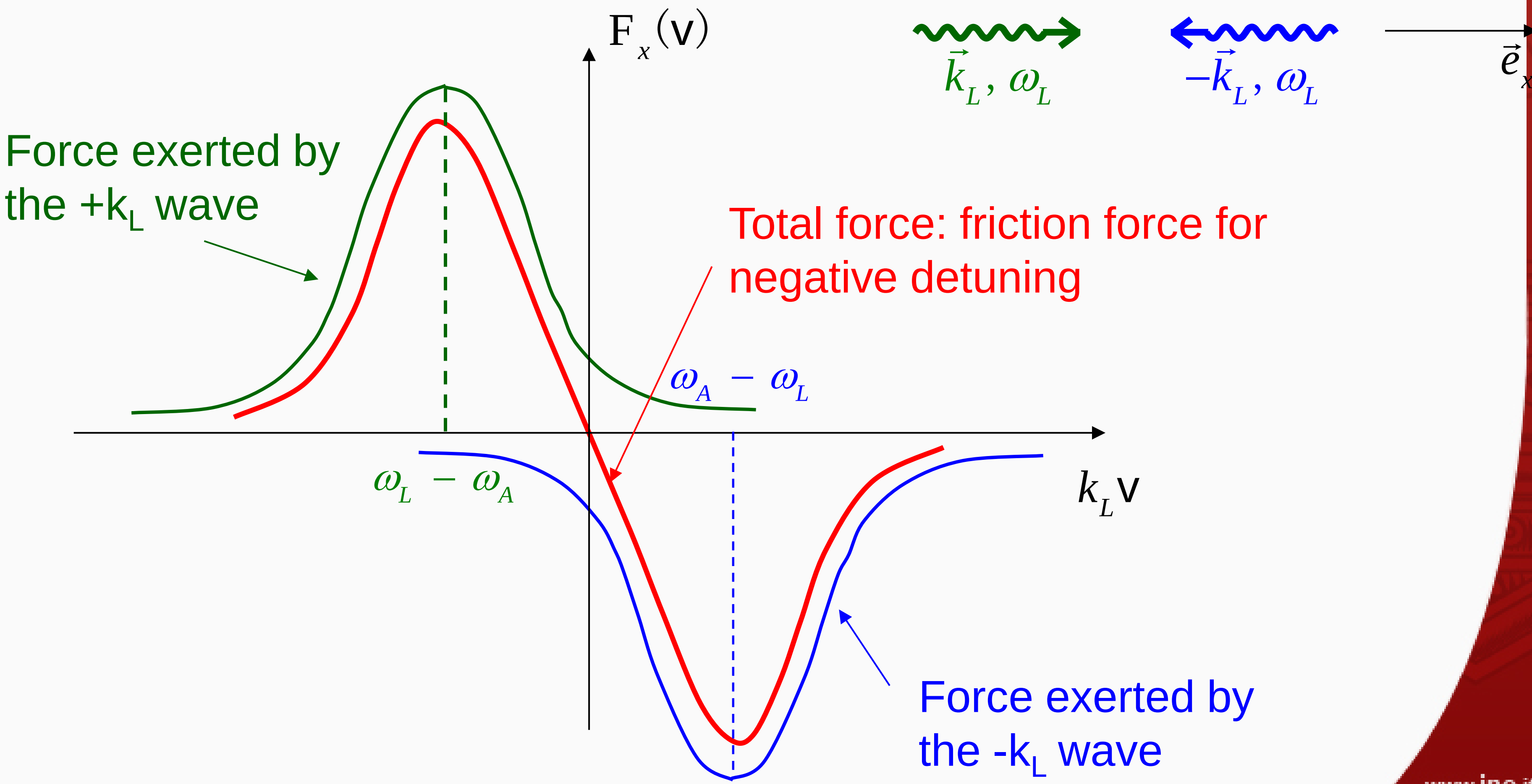
Absorption of the photon $\omega_L + kv$, followed by a spontaneous emission equiprobable in all directions of the space.

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

Doppler Cooling 2/2

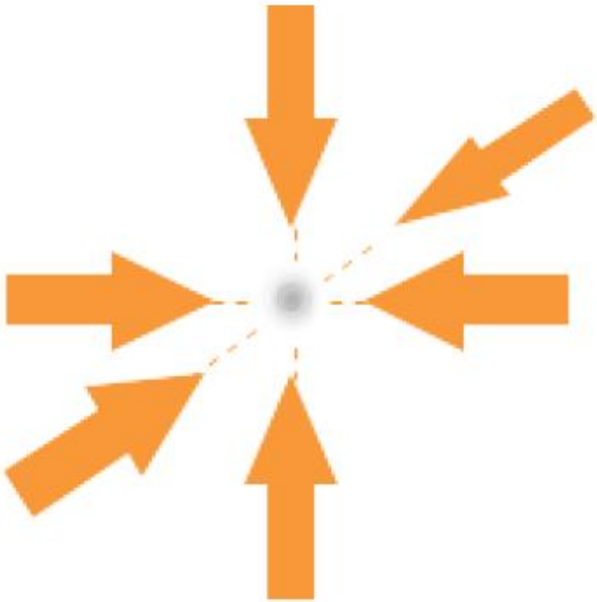
(for a red detuning : $\delta = \omega_L - \omega_A < 0$)

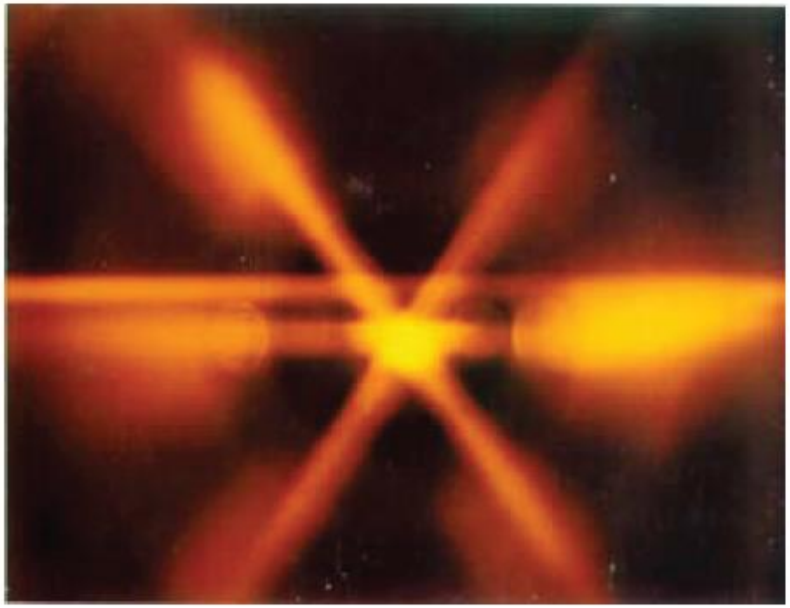
One supposes that one can independently add the radiation pressure forces of the 2 waves.



Optical molasses

Generalization to 3D:





first Na molasses at NIST

$\Rightarrow$ Competition cooling vs random walk in momentum space

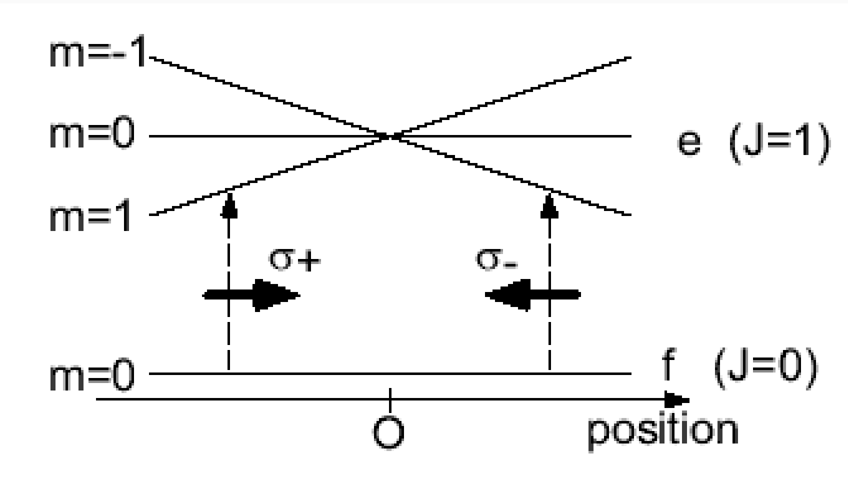
diffusion coefficient $D_p = \hbar^2 k^2 \Gamma s_0$

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

The magneto-optical trap 1/3

Seminal idea: J. Dalibard, 1987,

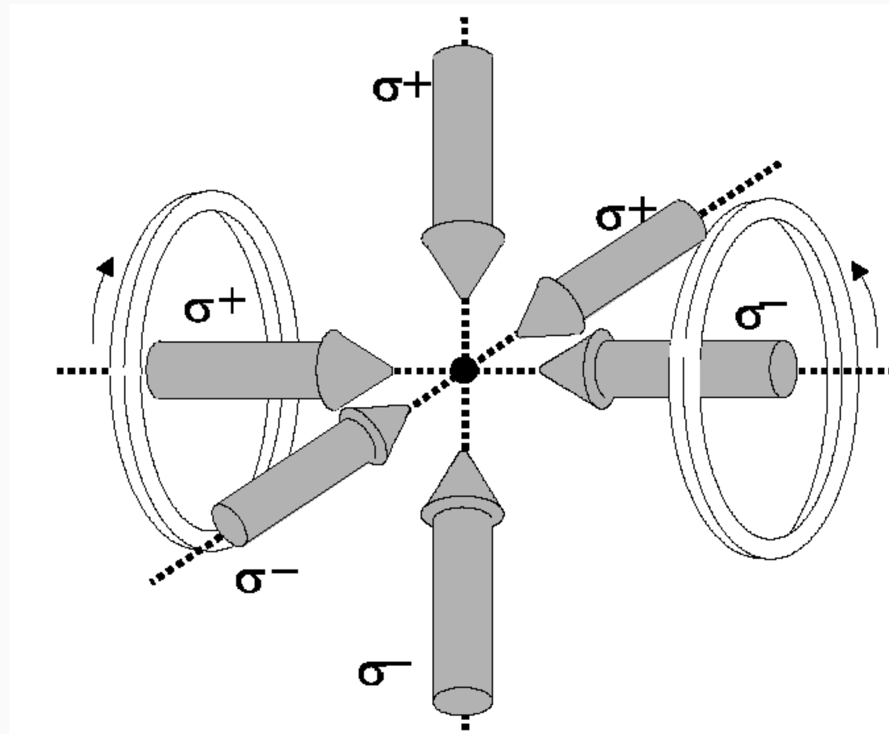
1st realization: S. Chu, 1987



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

3D Molasses
Doppler effect

Trapping
Zeeman effect
Produces imbalance
in rad pressure forces



b' = 10 Gauss / cm
I = a few mW per beam

The magneto-optical trap 2/3

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

$$F_{\mathrm{MOT}} = F_{+z} + F_{-z} = -\alpha\dot{z} - Kz$$

Damping
Doppler effect

Trapping
Zeeman effect

The magneto-optical trap 2/3

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

$$F_{\mathrm{MOT}}=F_{+z}+F_{-z}=-\alpha\dot{z}-Kz$$

Damping
Doppler effect

Trapping
Zeeman effect

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The magneto-optical trap 2/3

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

$$F_{\mathrm{MOT}} = F_{+z} + F_{-z} = -\alpha\dot{z} - Kz$$

Damping
Doppler effect

Trapping
Zeeman effect

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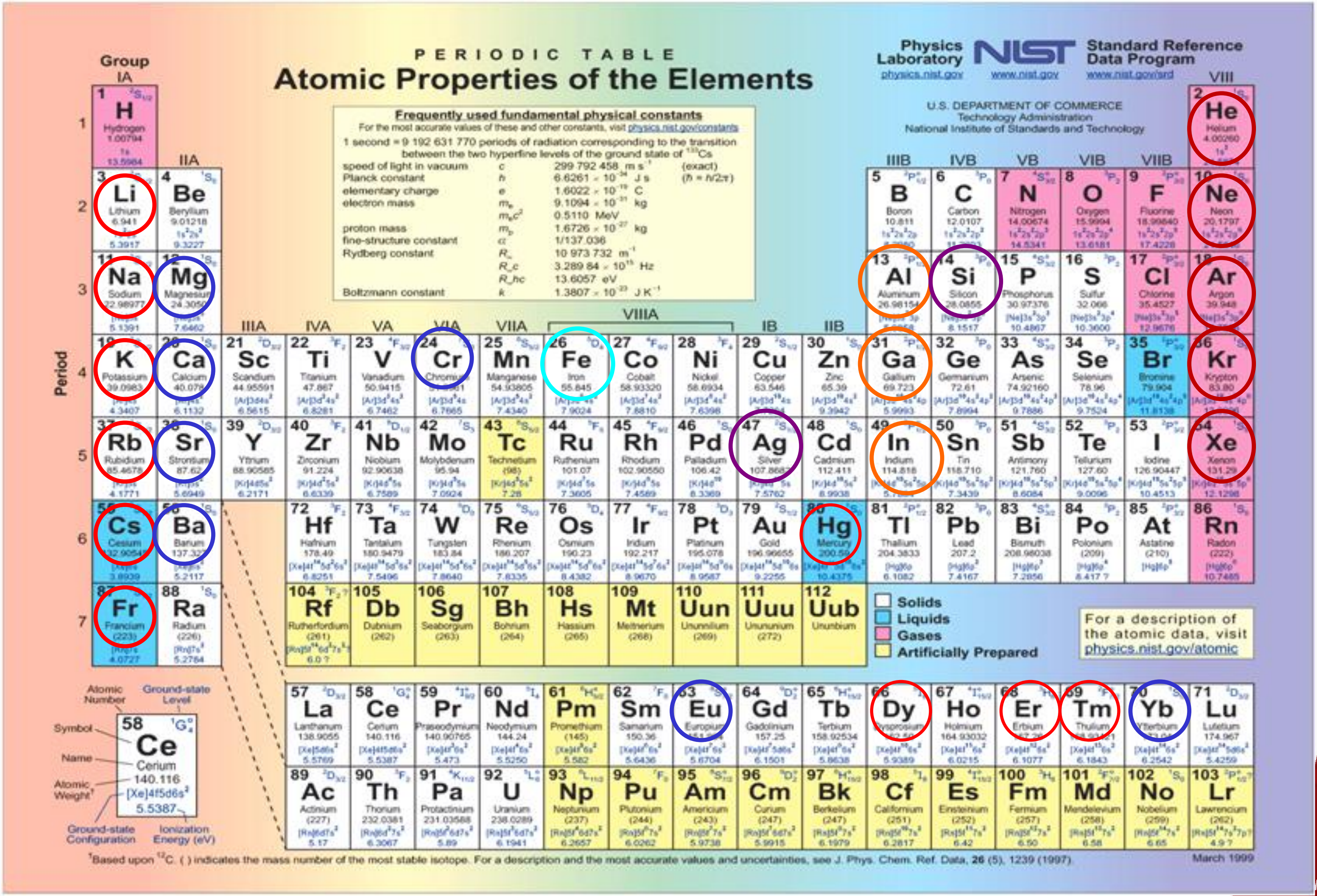
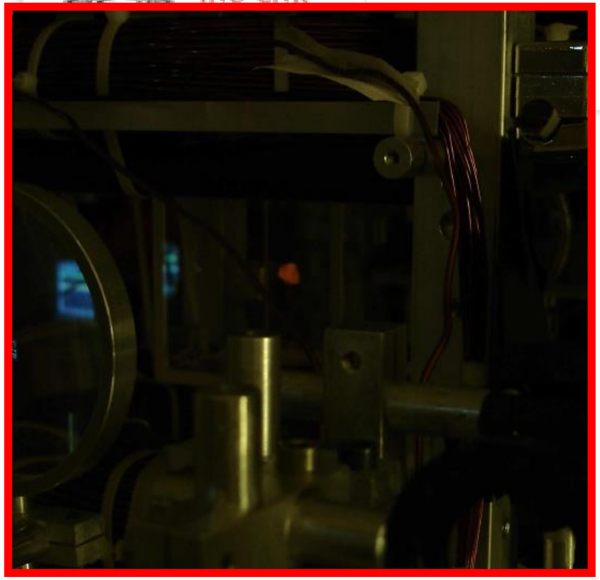
Laser cooling of atomic species

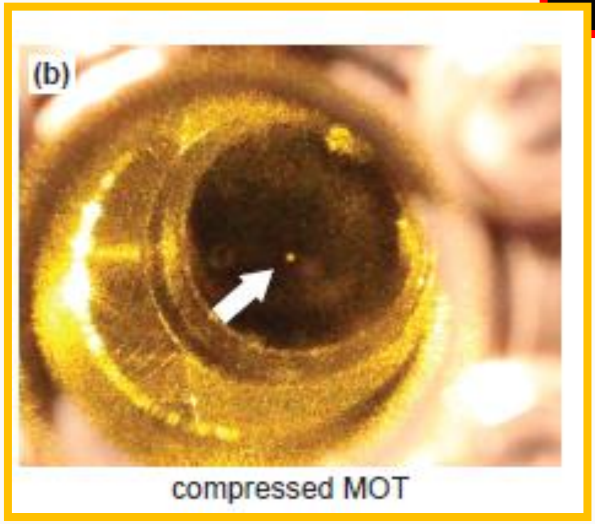


Rb MOT - 780nm

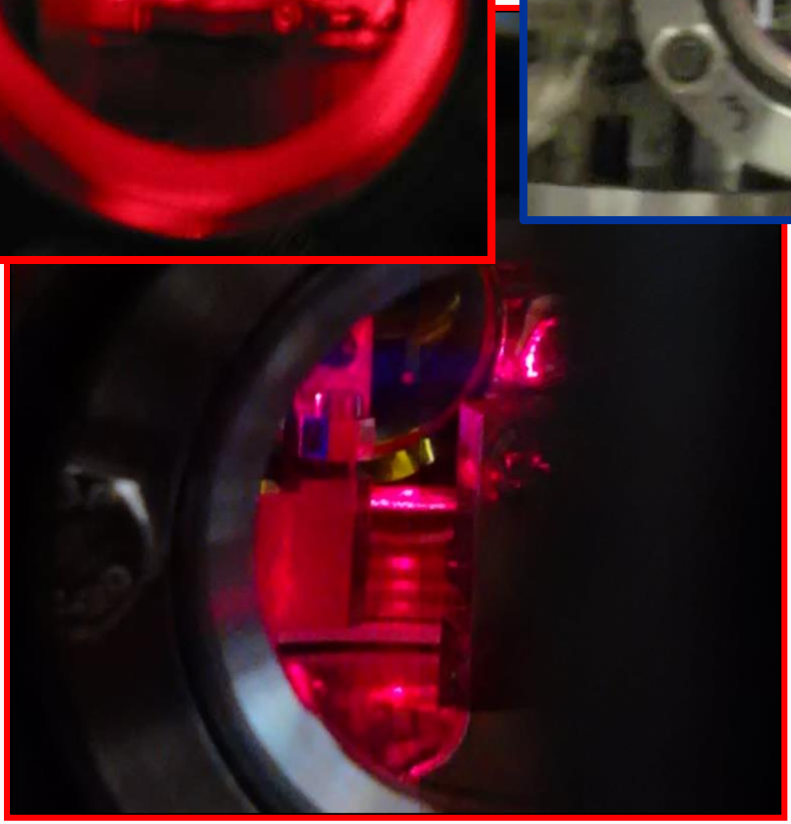


Li MOT - 671nm

Sr MOT - 461nm



Er MOT – 583nm

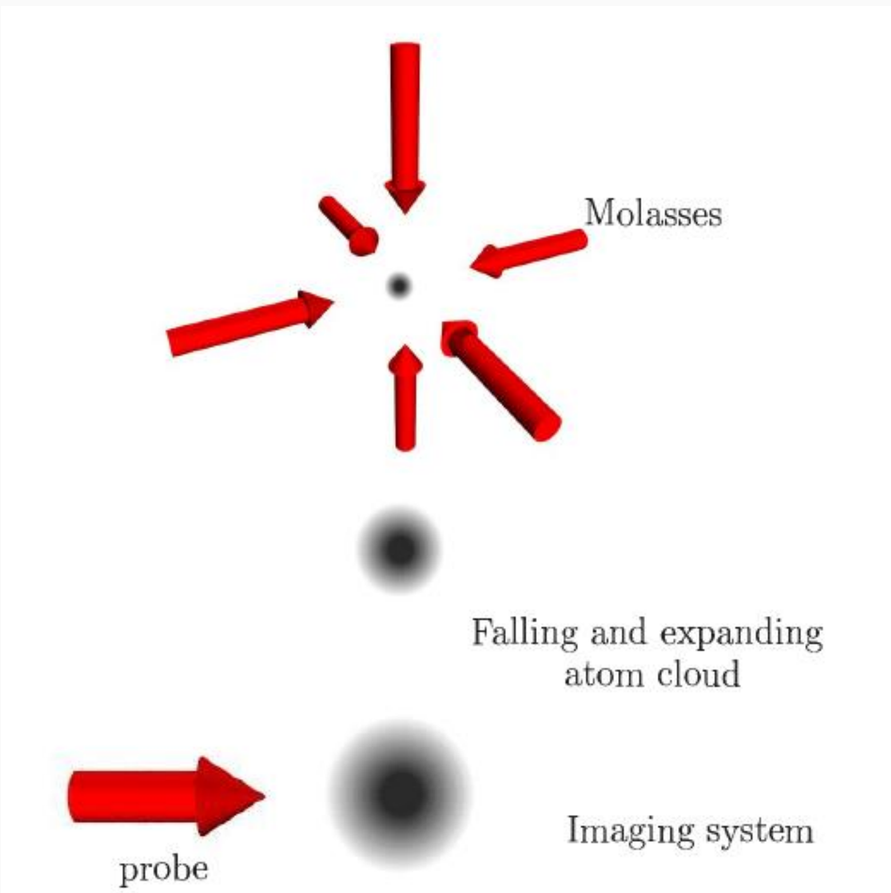


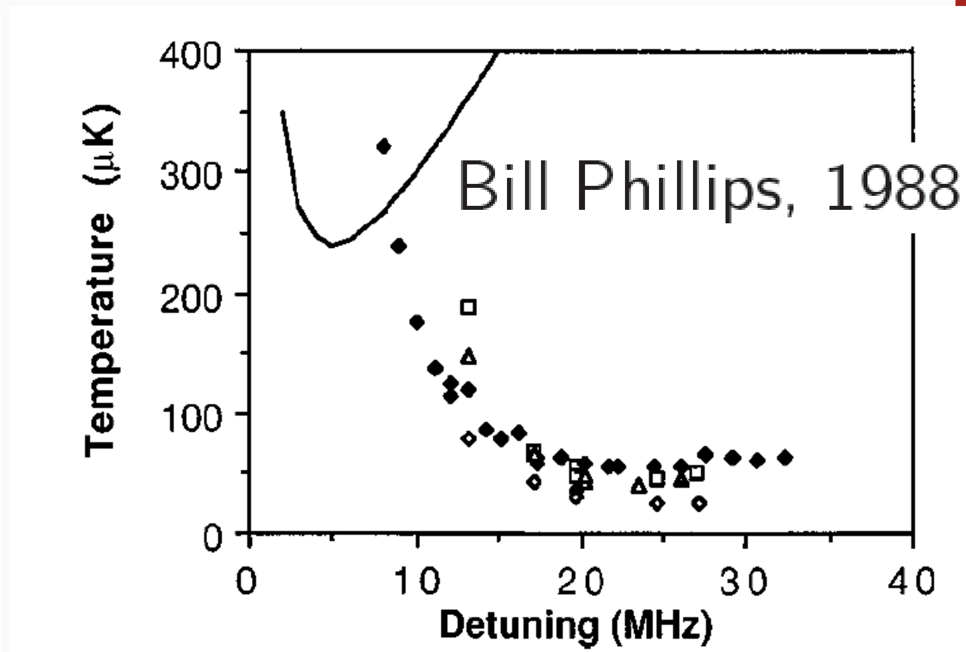
Dy MOT – 626nm

Temperature measurement

T_D is the Doppler temperature

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

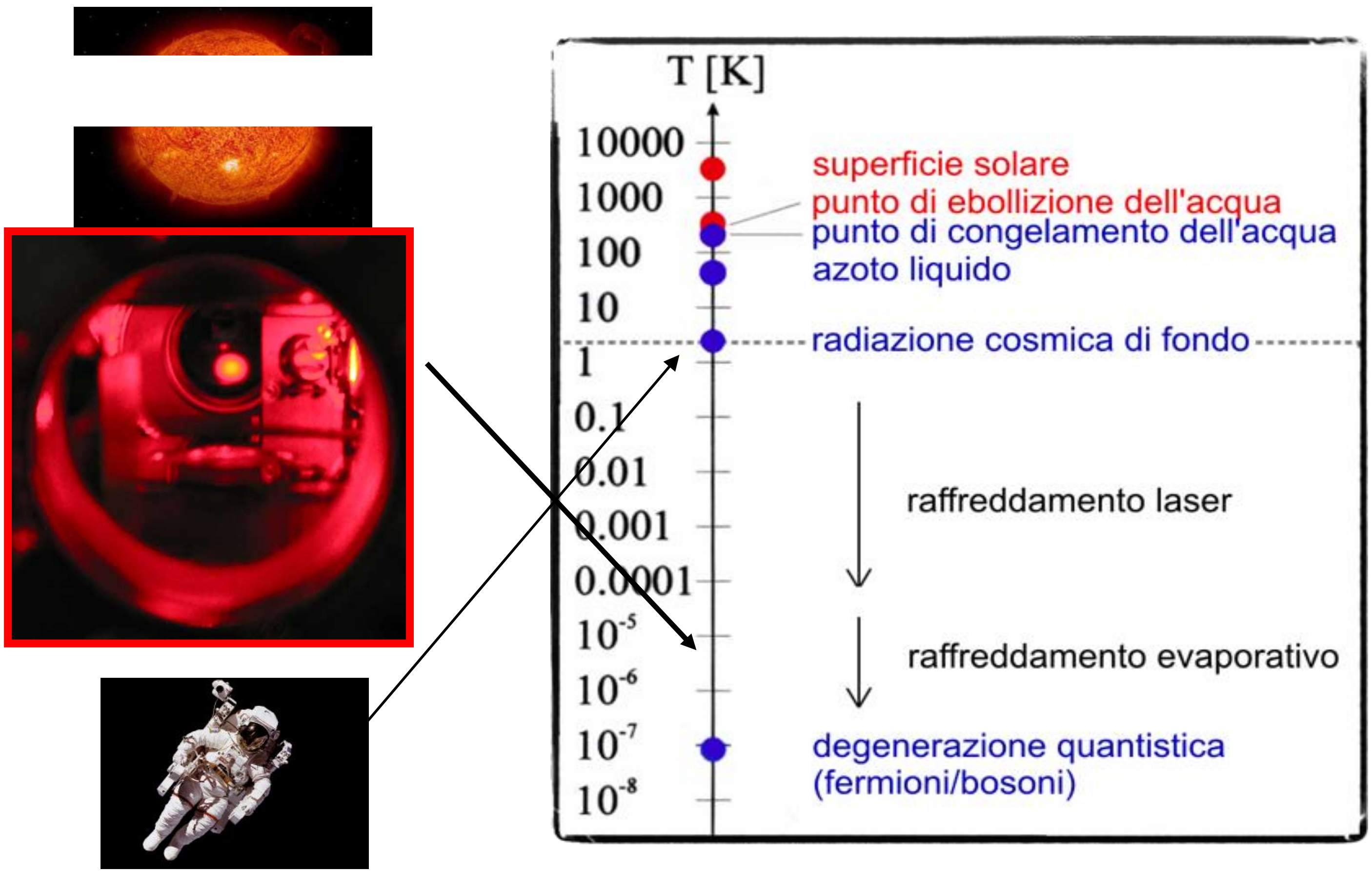




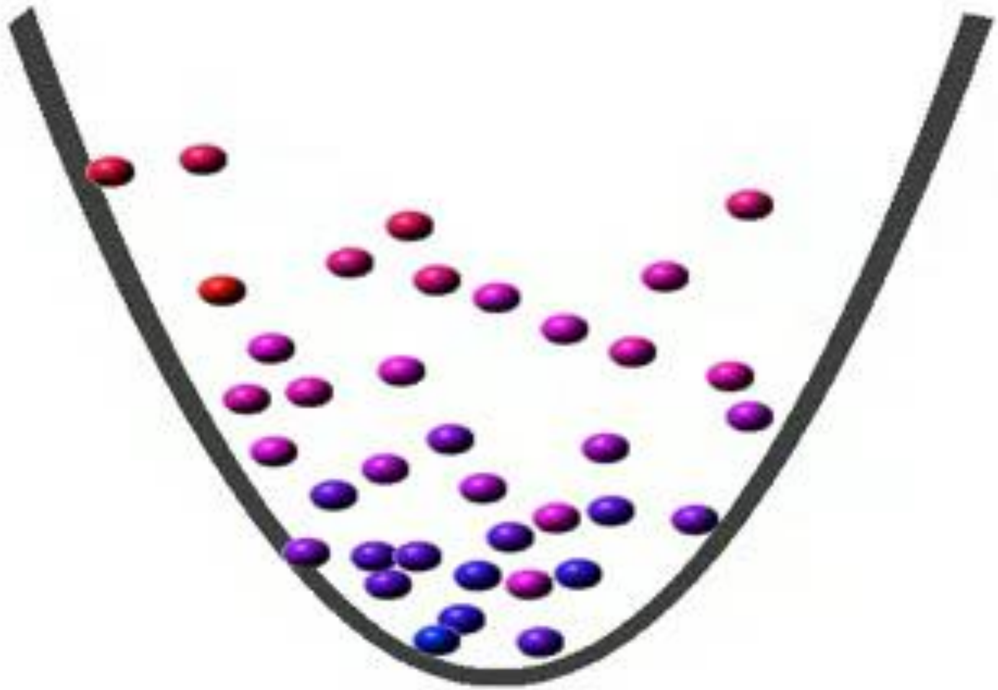
The measured temperature is lower than expected!
The scaling with laser detuning is also different.

Which is the minimum achivable MOT temperature?

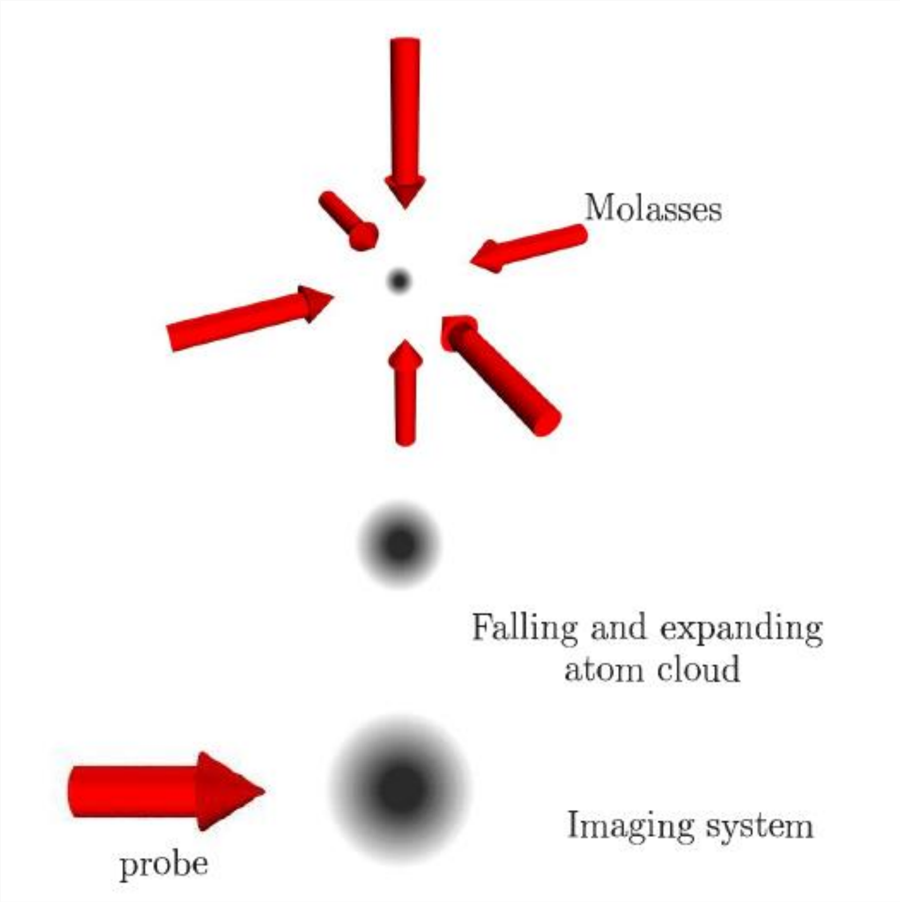
- Recoil temperature $T_{rec} = \hbar^2 k^2 / 2 m k_B$ hundreds nK
- Doppler temperature $T_{Doppler} = \hbar\Gamma / 2 k_B$ few-hundreds μK



Evaporative cooling



Temperature measurement



T_D is the Doppler temperature

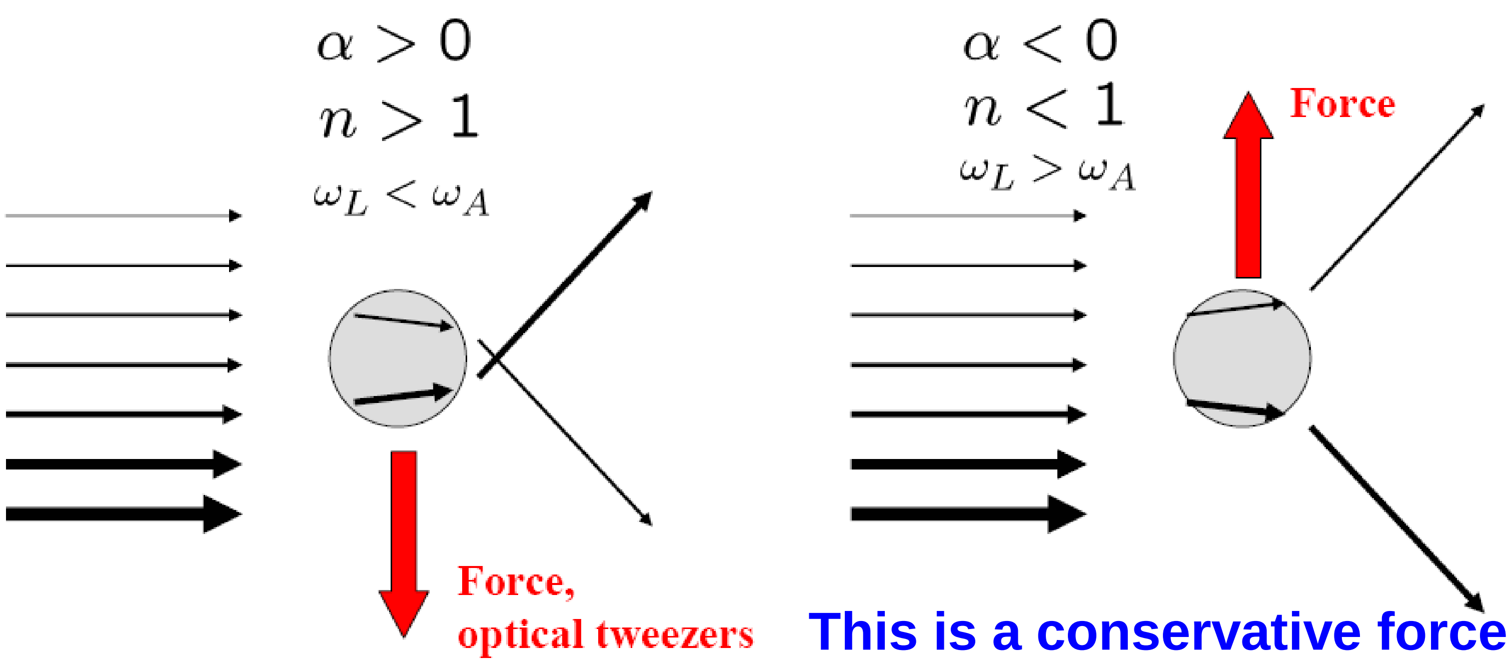
ex: $T_D = 240\,\mu$K for sodium, $T_D = 125\,\mu$K for cesium

The dipole force

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

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

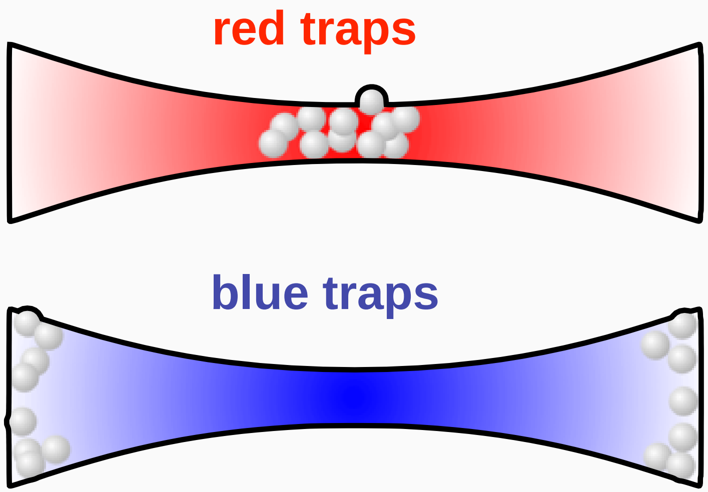
n= refraction index

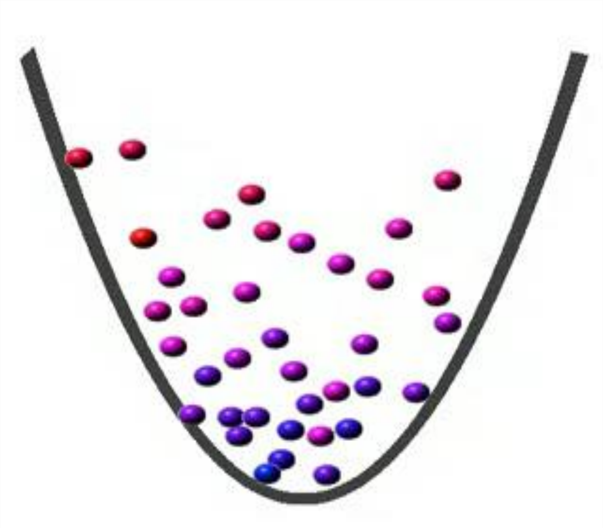


This is a conservative force!

Trapping of micrometer sized particles (Arthur Ashkin, 1970)
Trapping of atoms / molecules had to wait for laser cooling (S. Chu, 1986)

Optical traps





Far-detuned gaussian beam

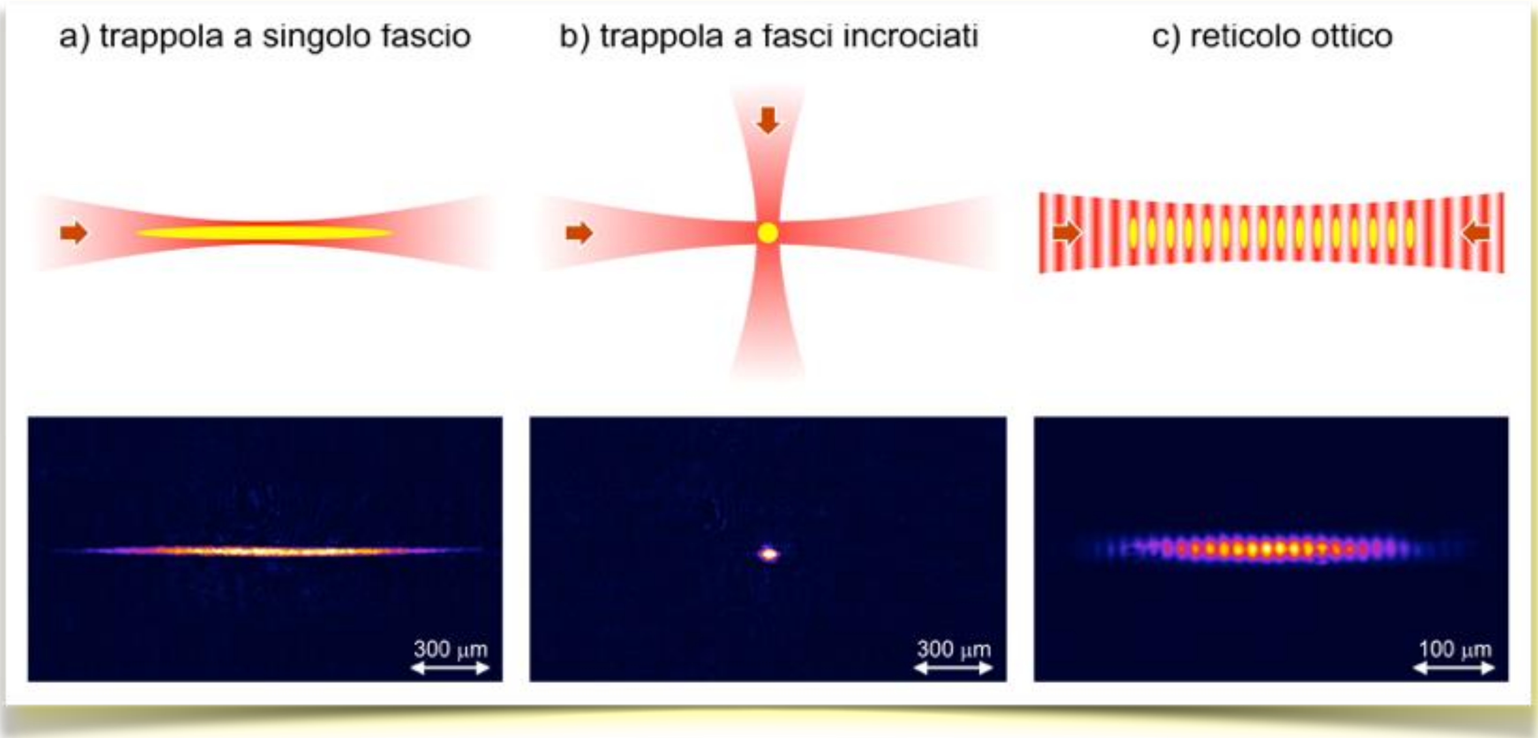
$$U(r) \propto \frac{I(r)}{\Delta}$$ Trapping depth

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

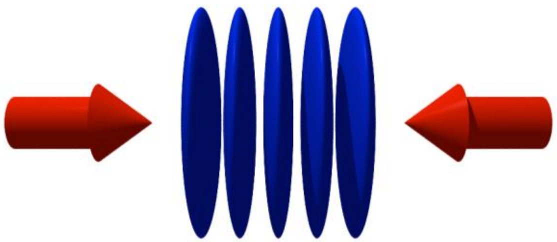
Many advantages vs magnetic traps:

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

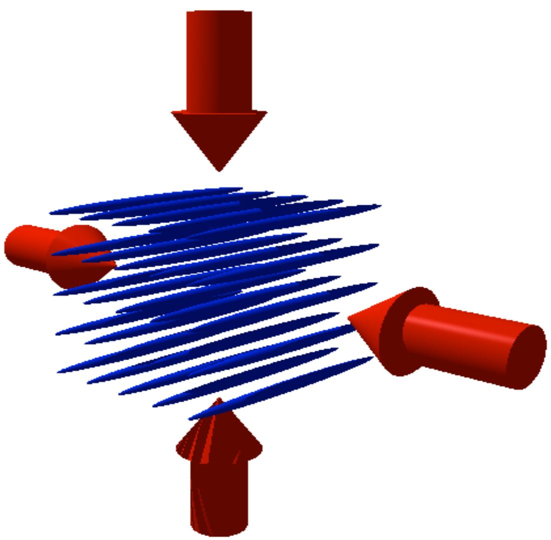
With far-detuned laser one can shape conservative potentials at will



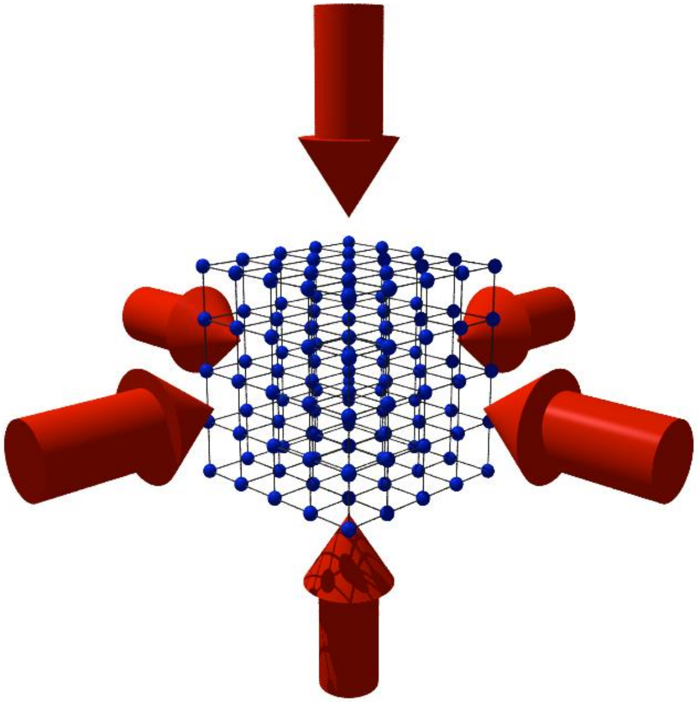
1D optical lattice (2D systems)



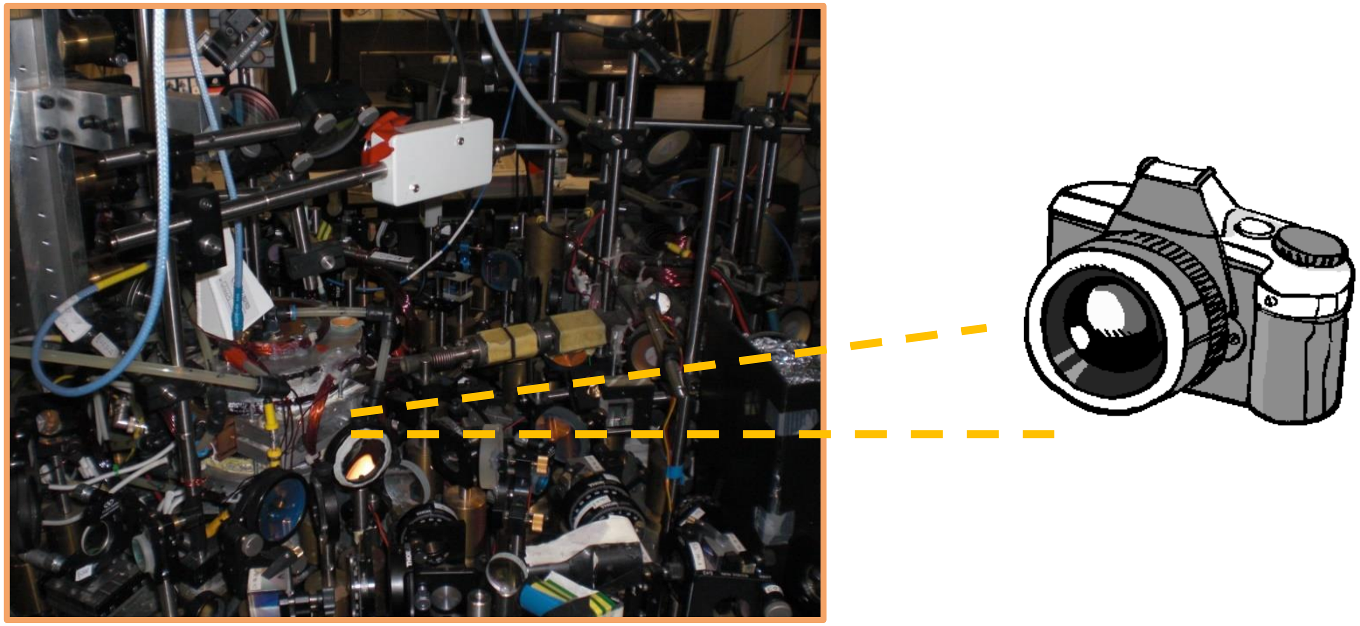
2D optical lattice (1D systems)



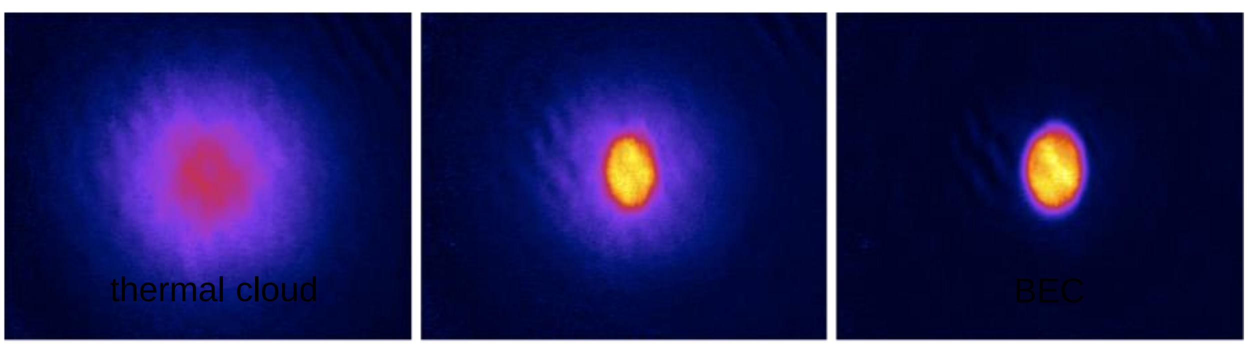
3D optical lattice (crystal-like systems)

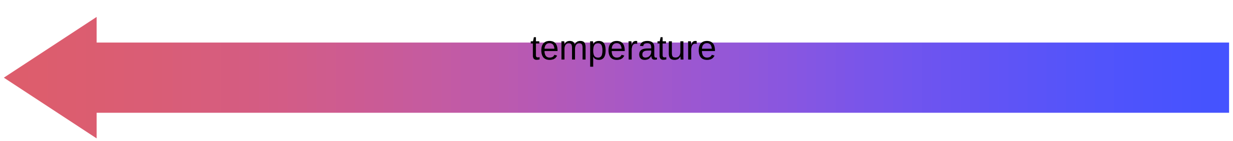


Principal diagnostic method: in resonance imaging



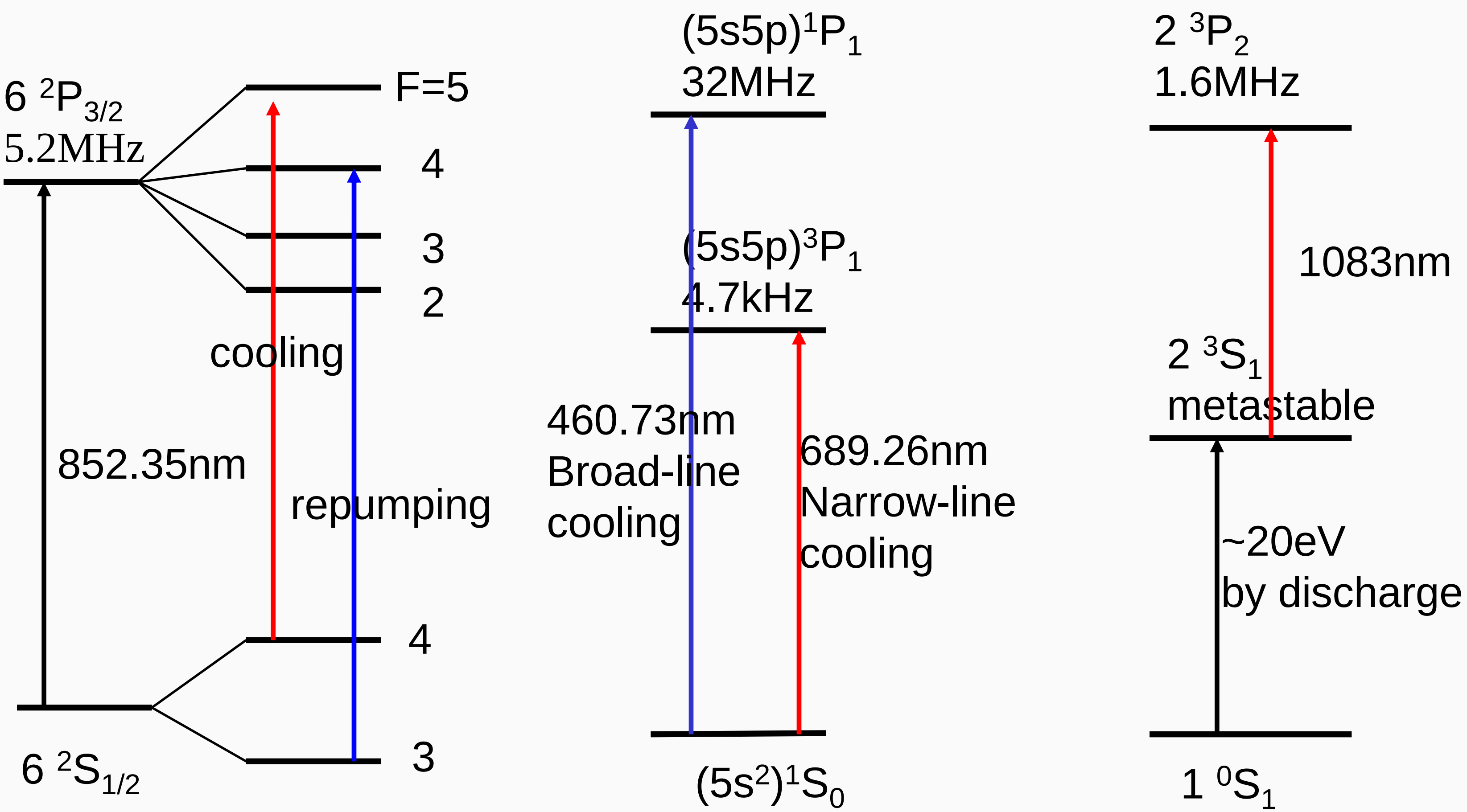
T > TC   T ~ TC   T < TC





Laser requirements

Each different atomic species has its unique feature!



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

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

^{4}He, nobel gas, I=0

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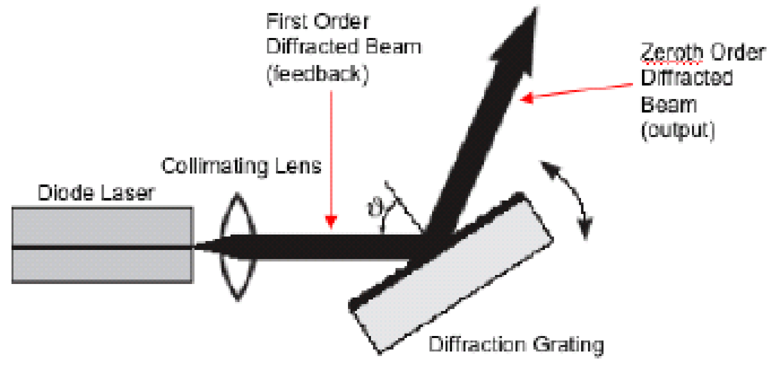
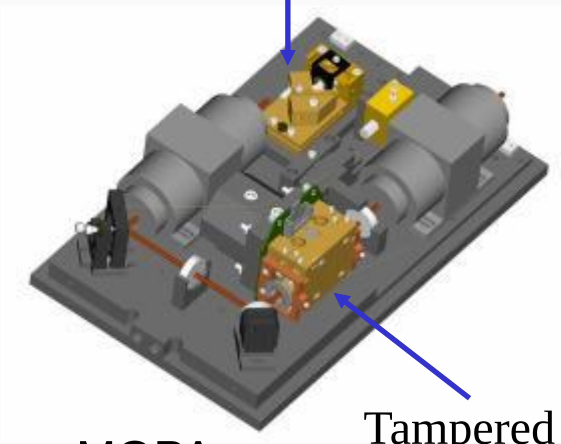
Example: diode lasers

- 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.



ECDL in Littrow configuration

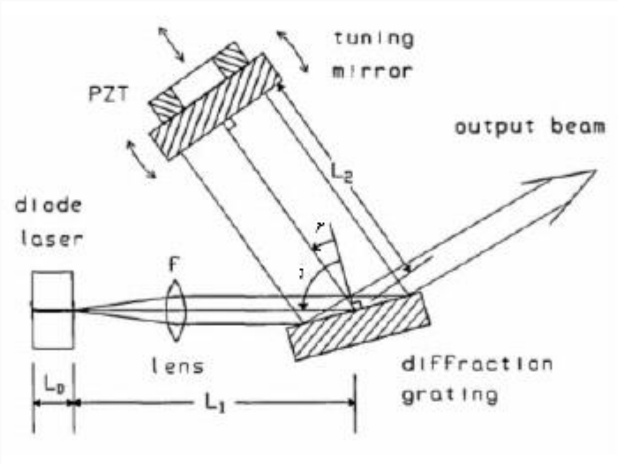
master



MOPA

Tampered amplifiier

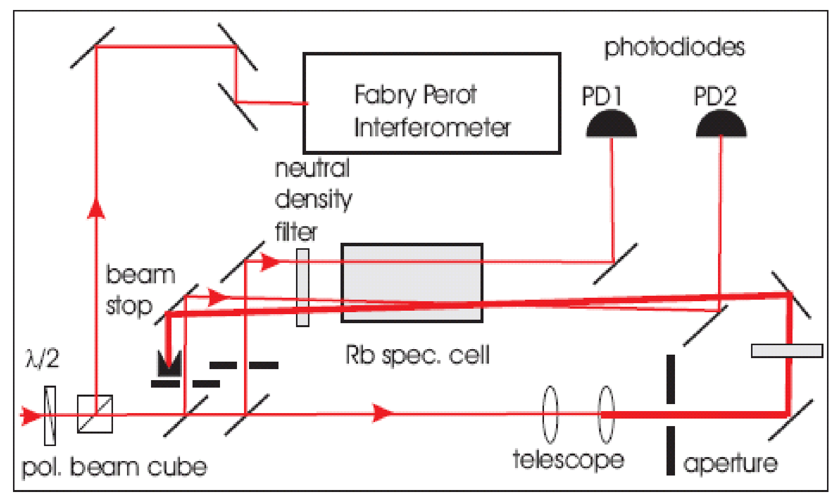
Diode laser



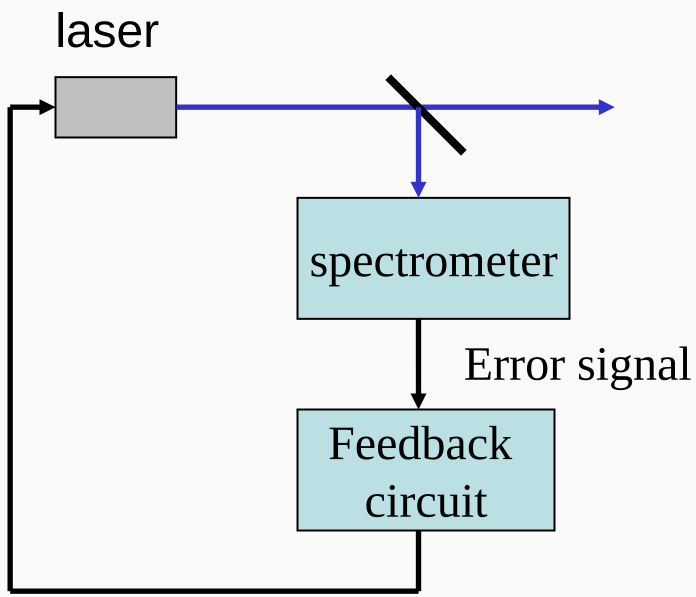
ECDL in Littman-Metcalf configuration

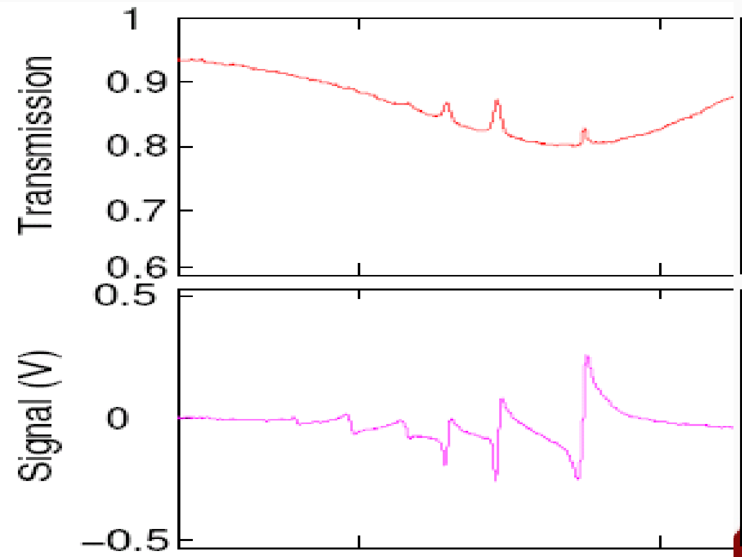
Laser frequency stabilization

- 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.



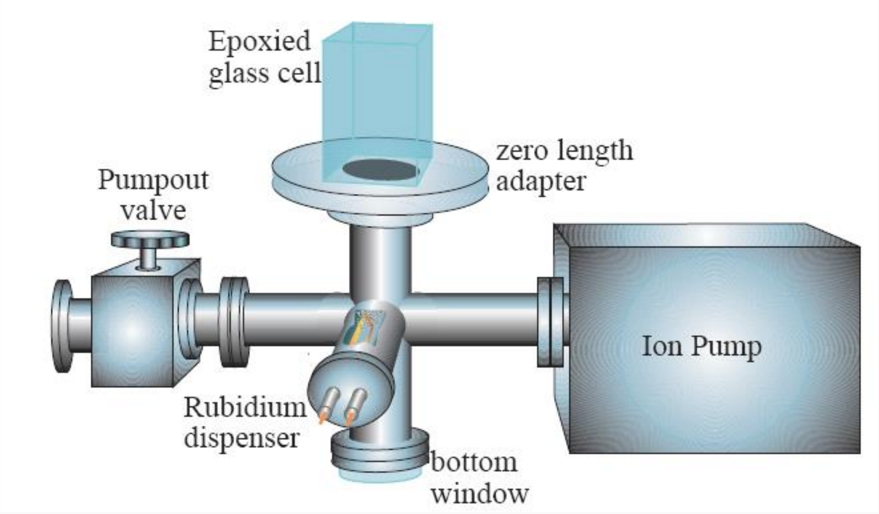
Background subtracted saturation spectrometer

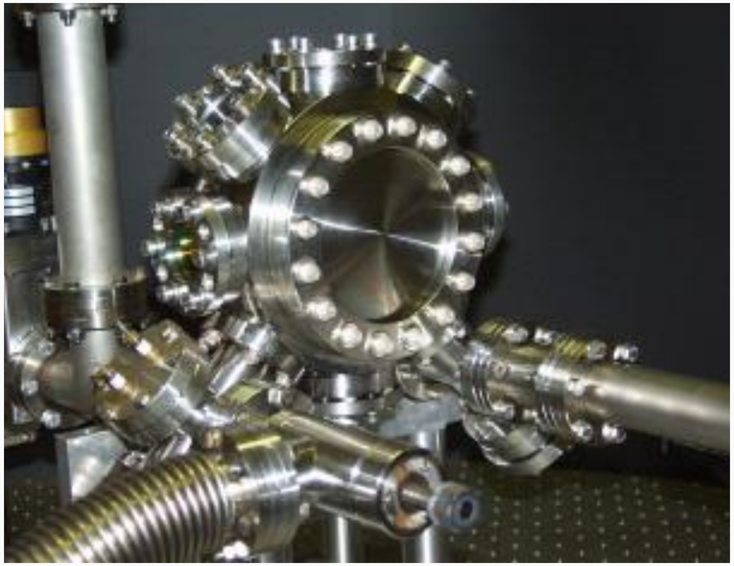




Vacuum apparatus

- 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.



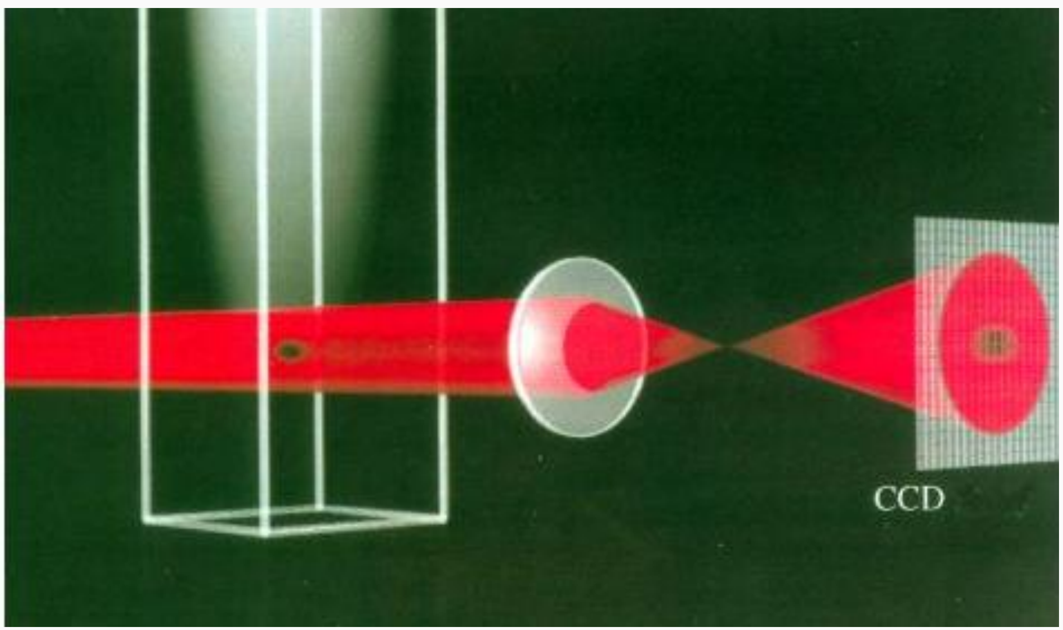


Background pressure < 10^{-8} mbar

Detection

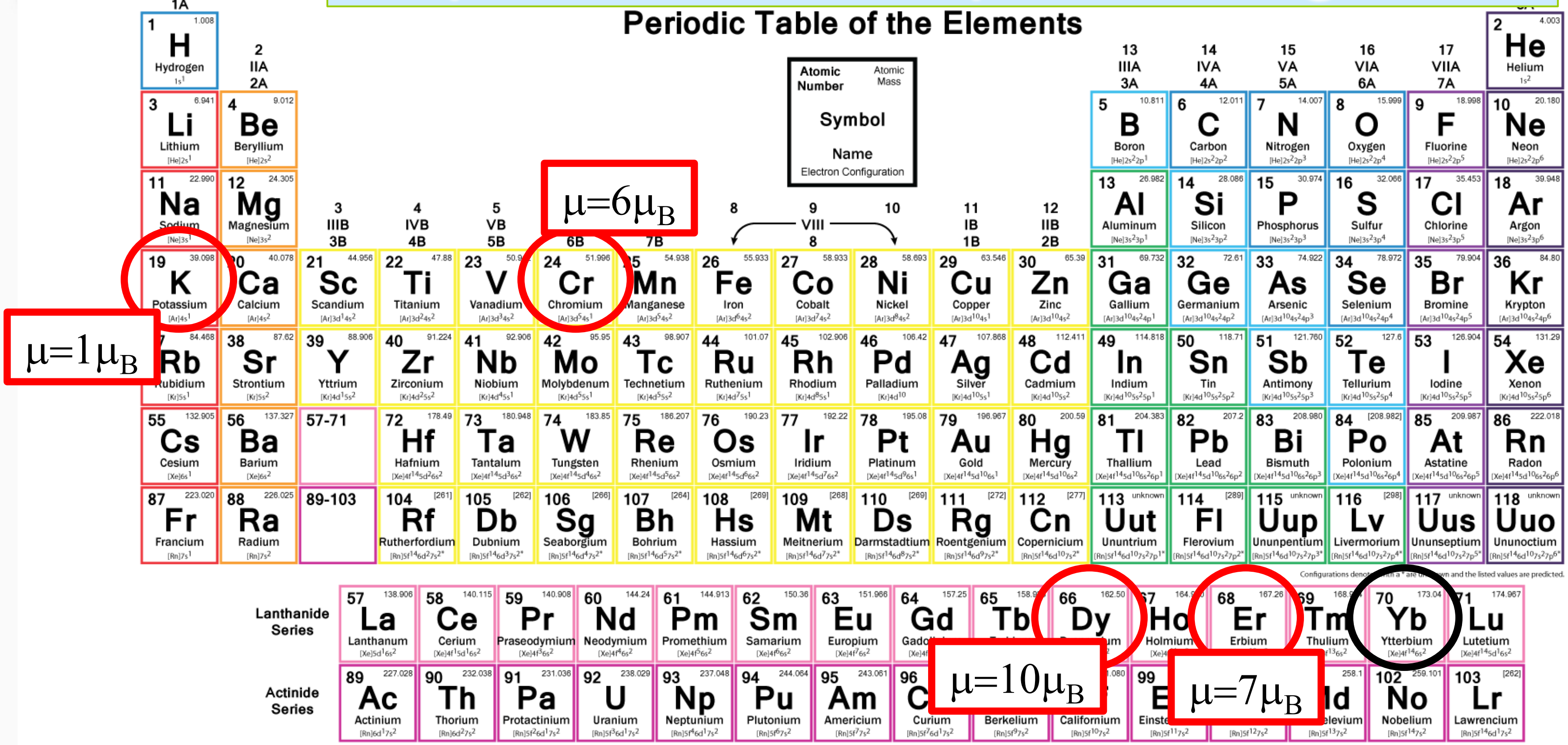
Quantities of interest: number of atoms *N*, density *n(x, y, z)*, *momentum distribution*

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

Dipolar atomic quantum gases



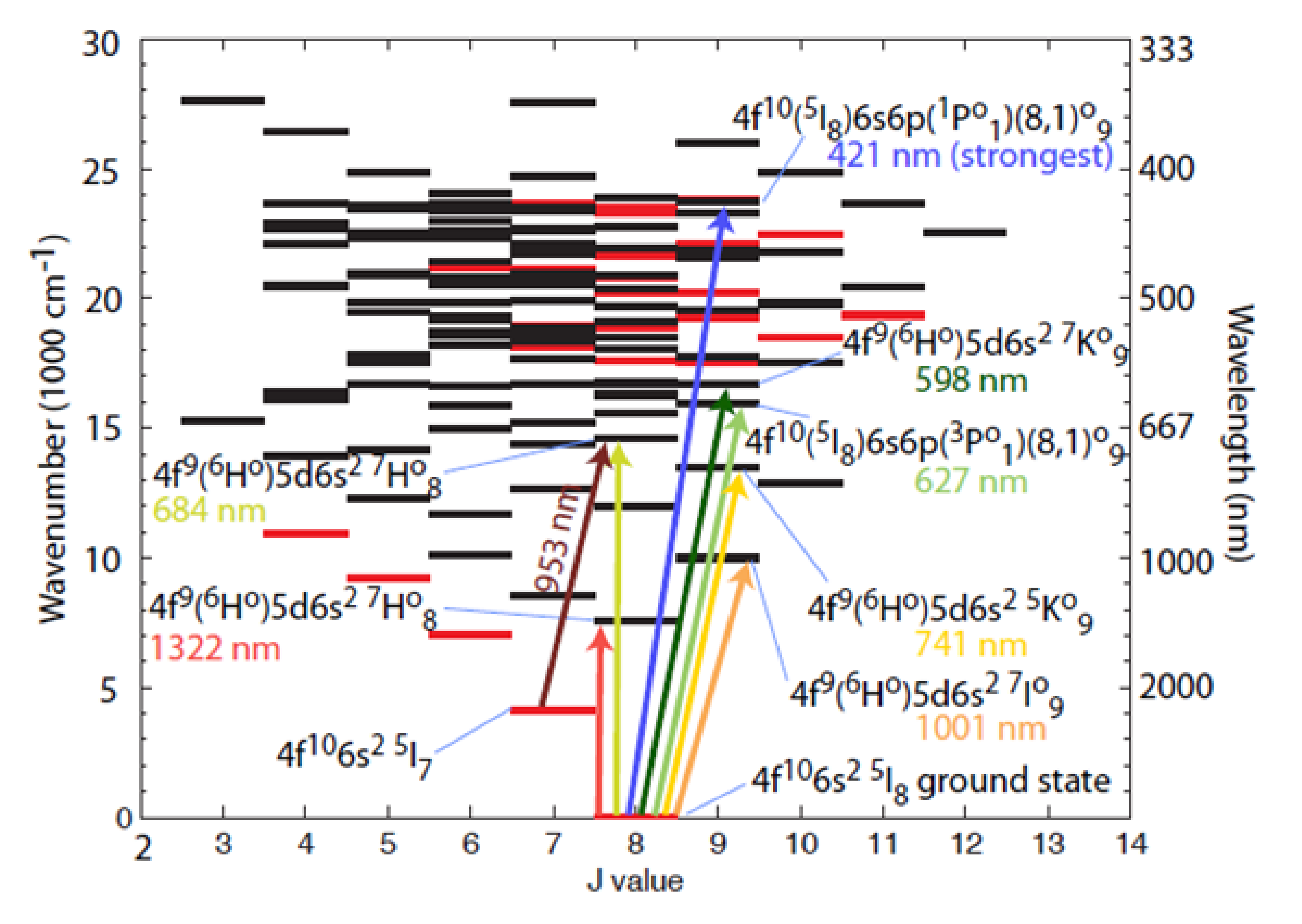
Xe: $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^{10} 5s^2 5p^6$

Dy: $[Xe]4f^{10}6s^2$ $\quad {}^5I_8$ $(L=6, S=2, J=8)$ $\quad \mu=10\mu_B$

Er: $[Xe]4f^{12}6s^2$ $\quad {}^3H_6$ $(L=5, S=1, J=6)$ $\quad \mu=7\mu_B$

Yb: $[Xe]4f^{14}6s^2$ ${}^1S_0$ $(L=0, S=0, J=0)$ $\quad \mu=0$

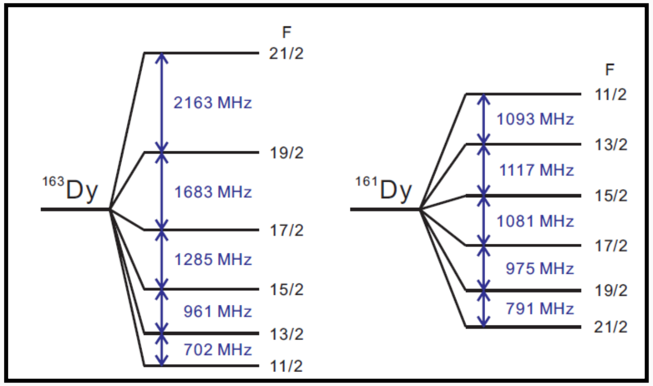
Dysprosium energy levels



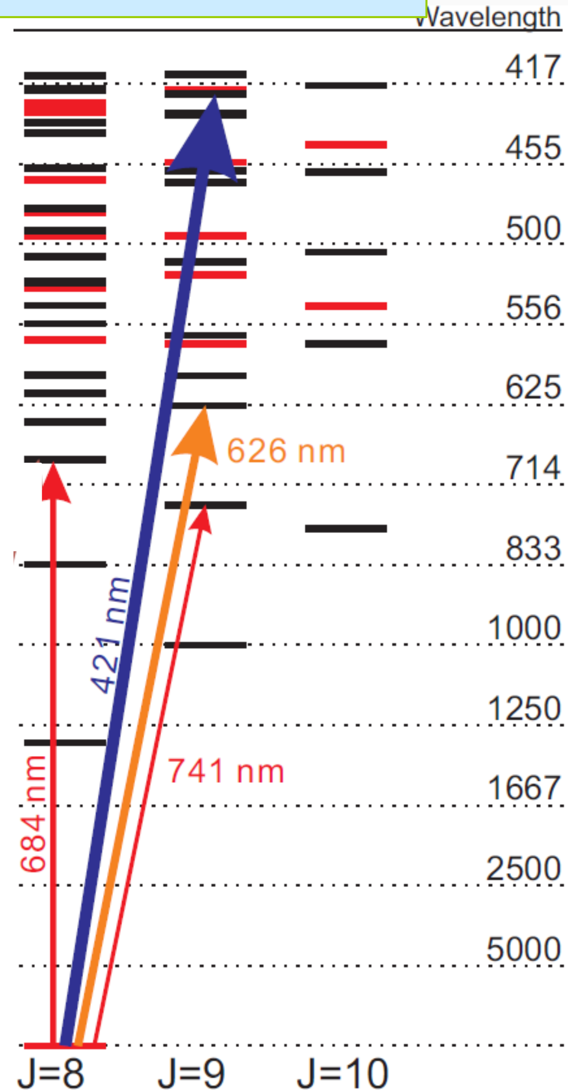
Dysprosium properties

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

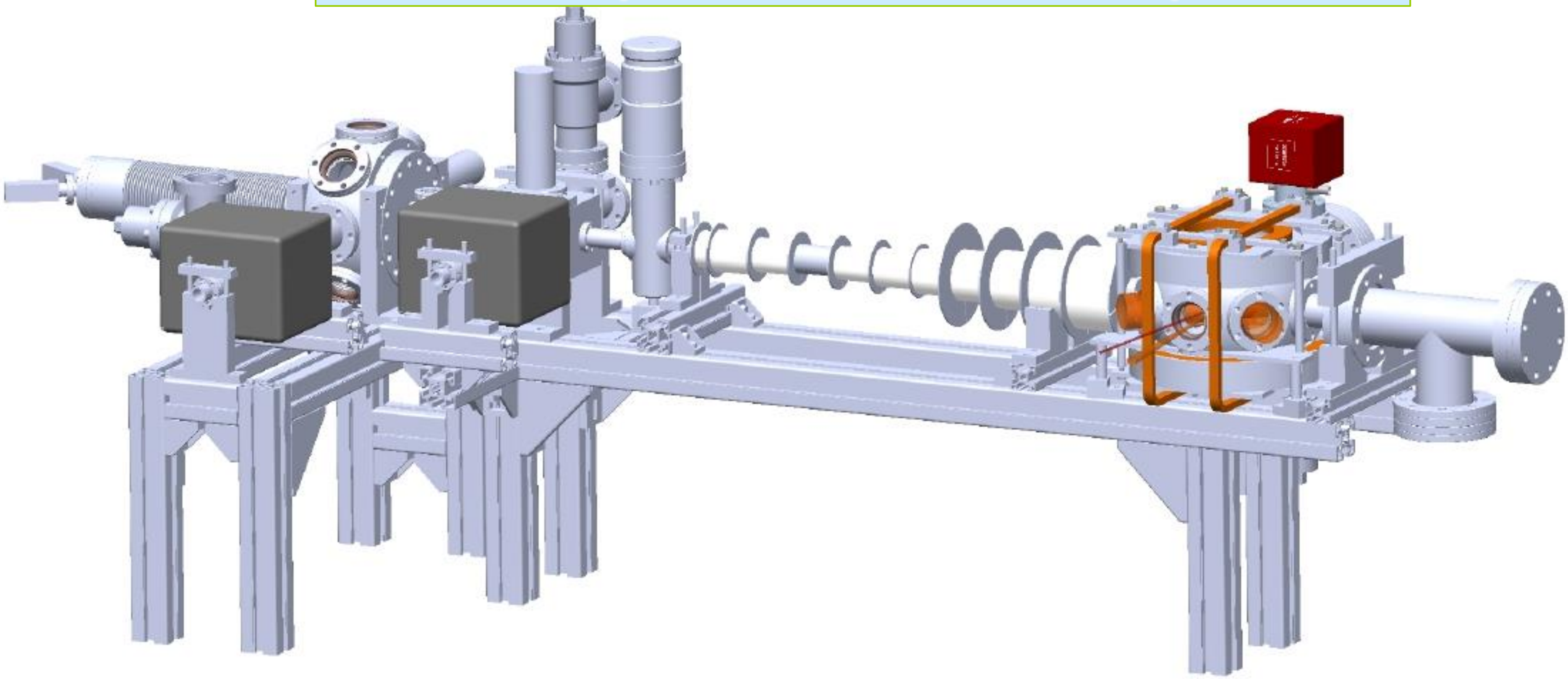
Hyperfine structure of fermionic isotopes



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

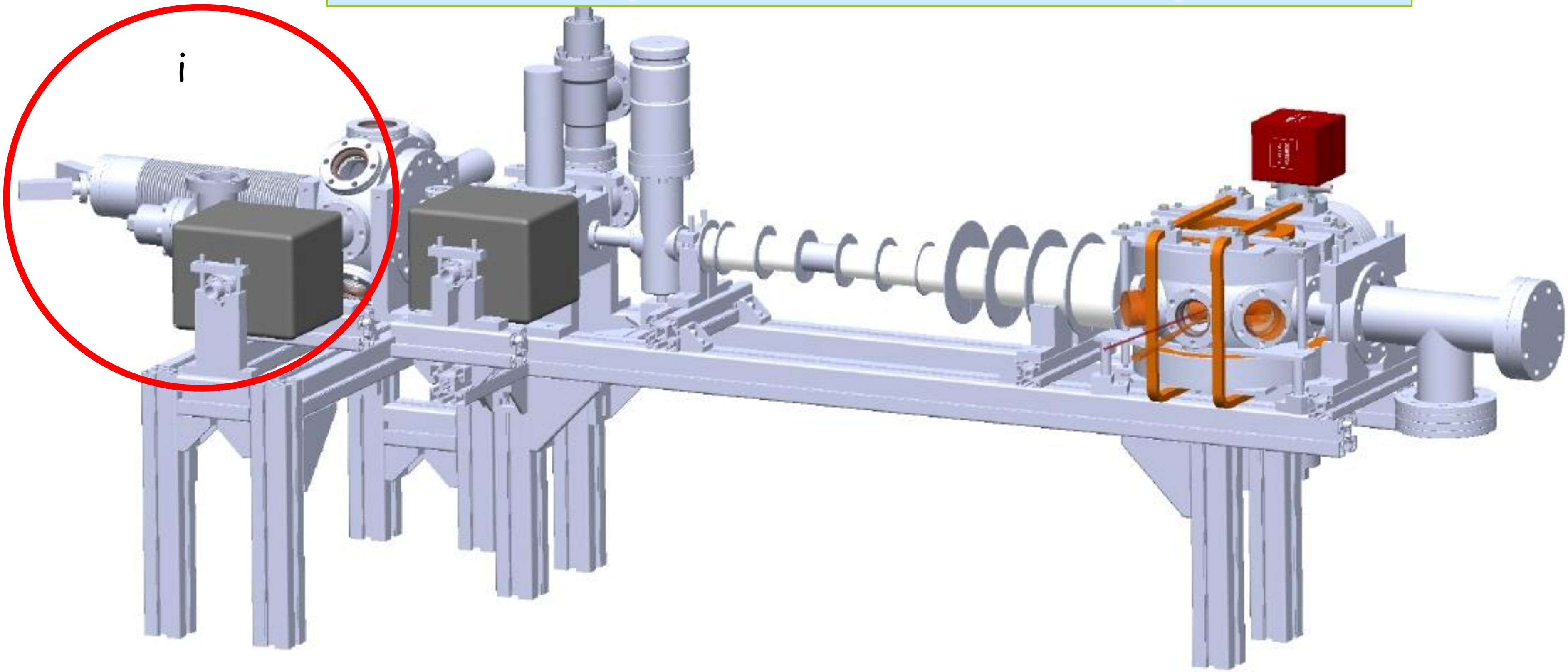


Experimental setup



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

Experimental setup



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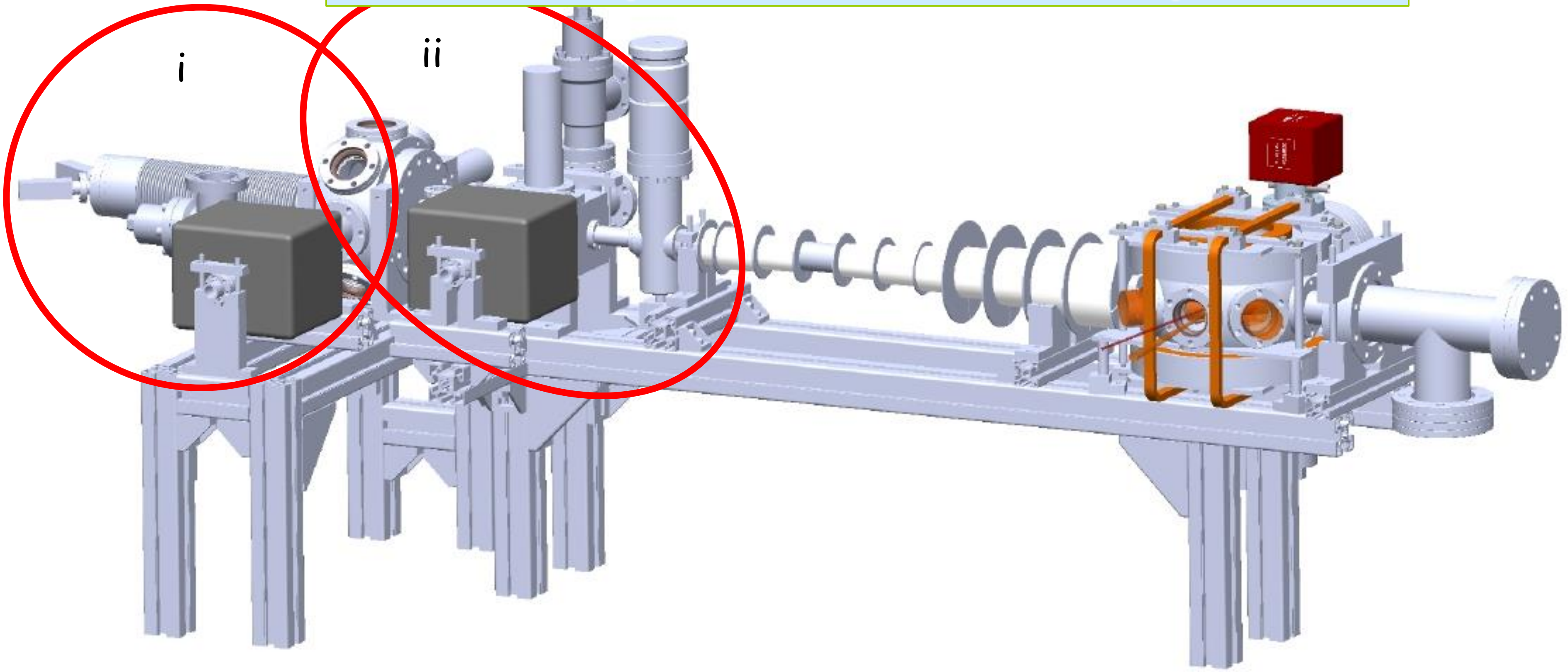
Avg velocity of the atomic beam: **400 m/s**

i) Oven, Transverse Cooling

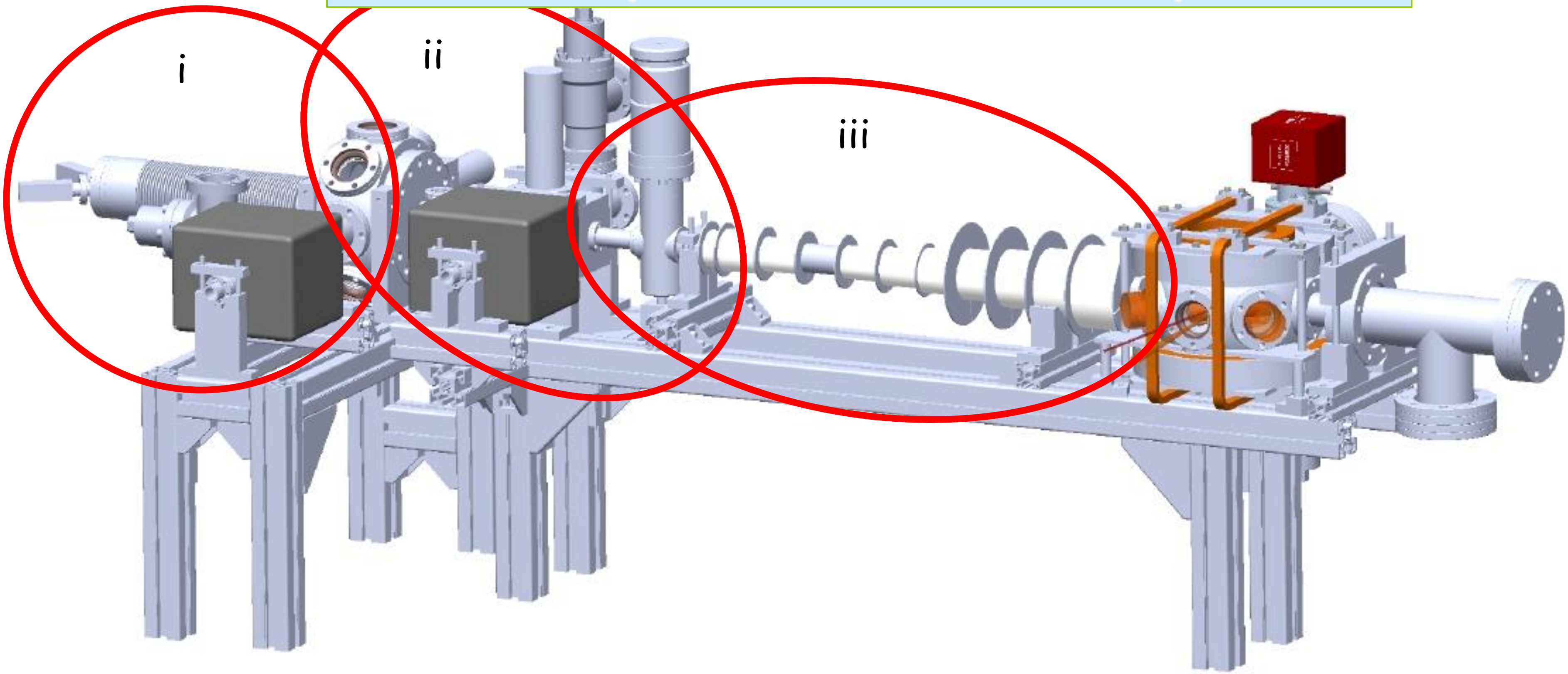
Experimental setup



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

i) Oven, Transverse Cooling
ii) Differential Pumping

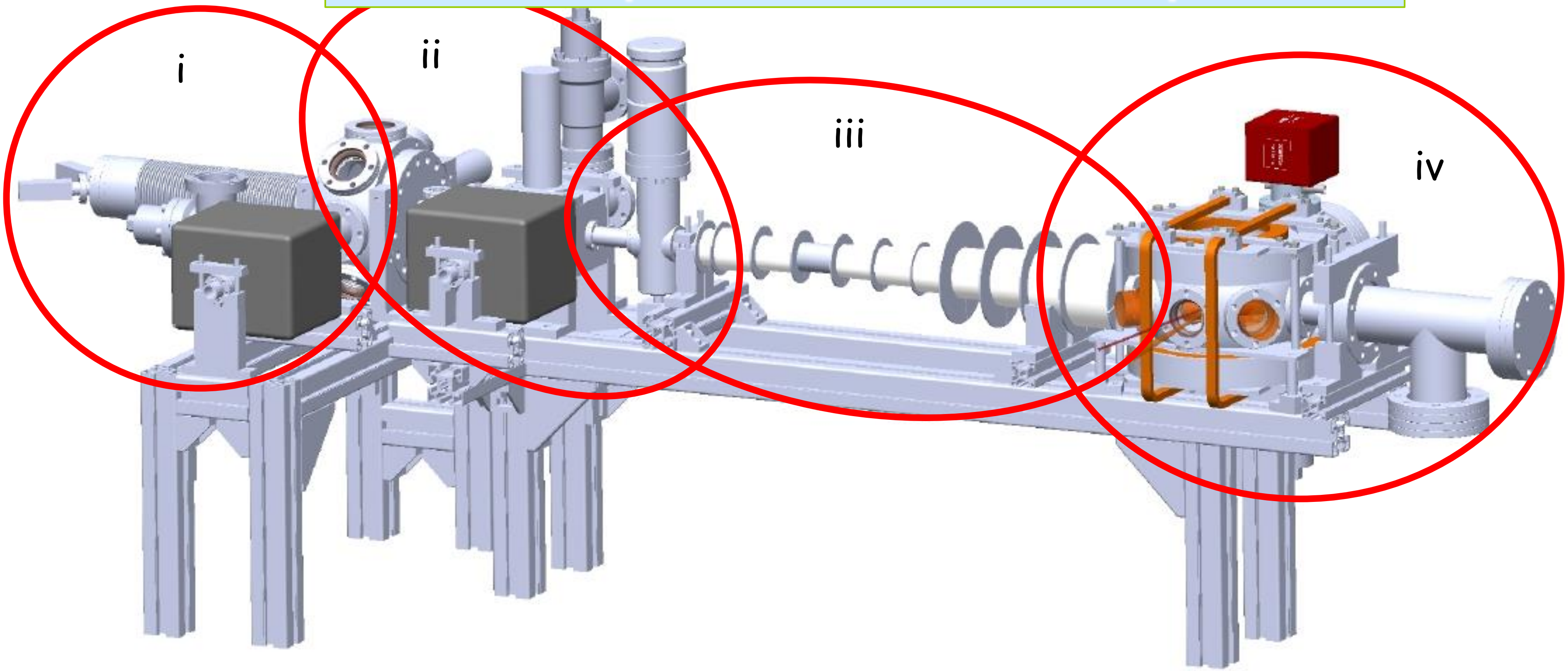
Experimental setup



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
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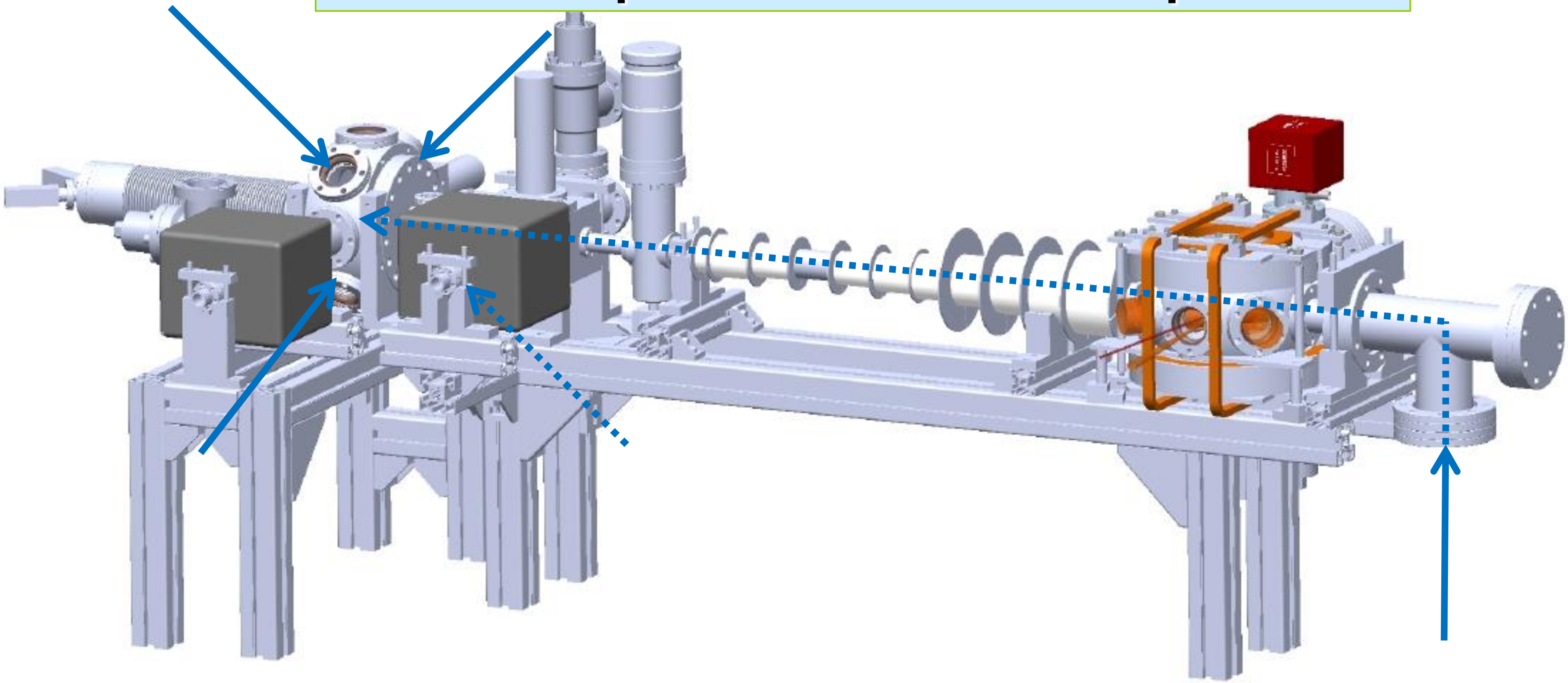
iii) Zeeman Slower
iv) Science chamber (MOT, ODT, Manipulation, detection)

Experimental setup



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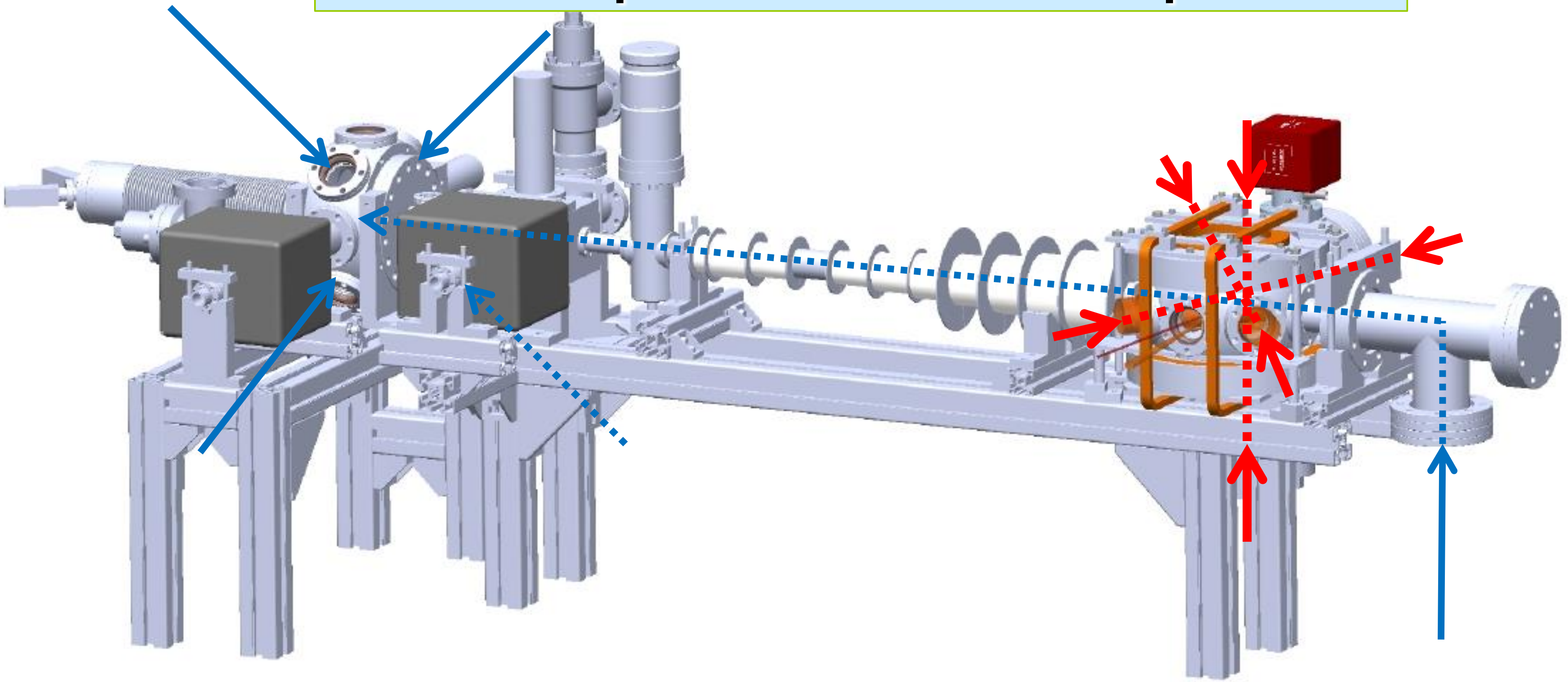

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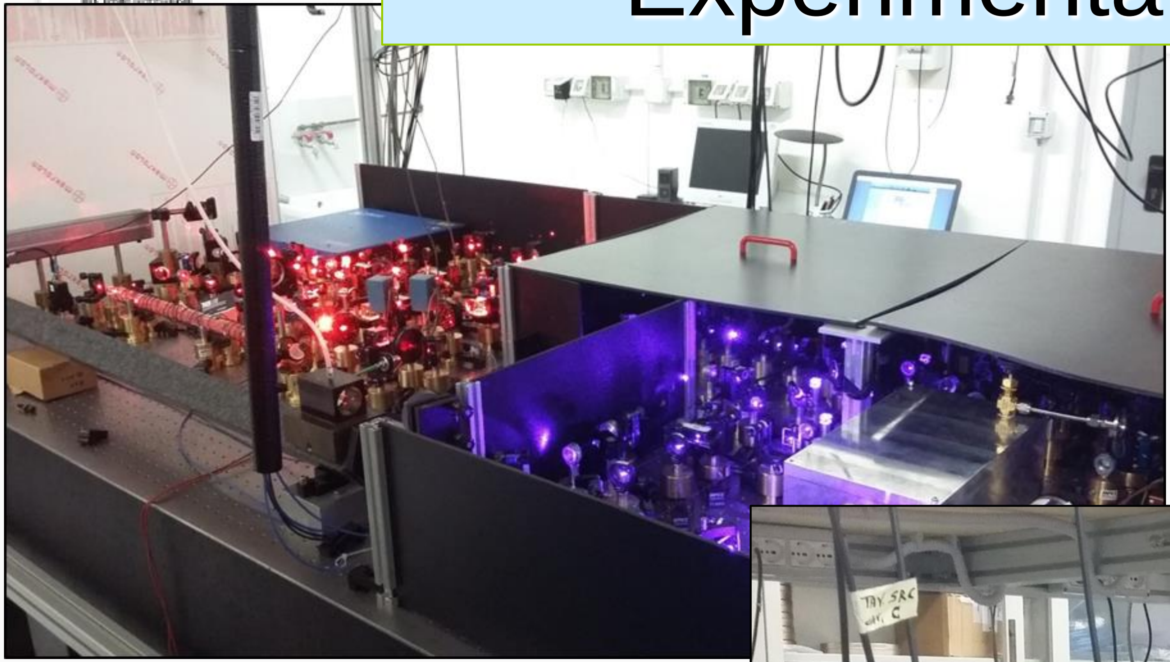
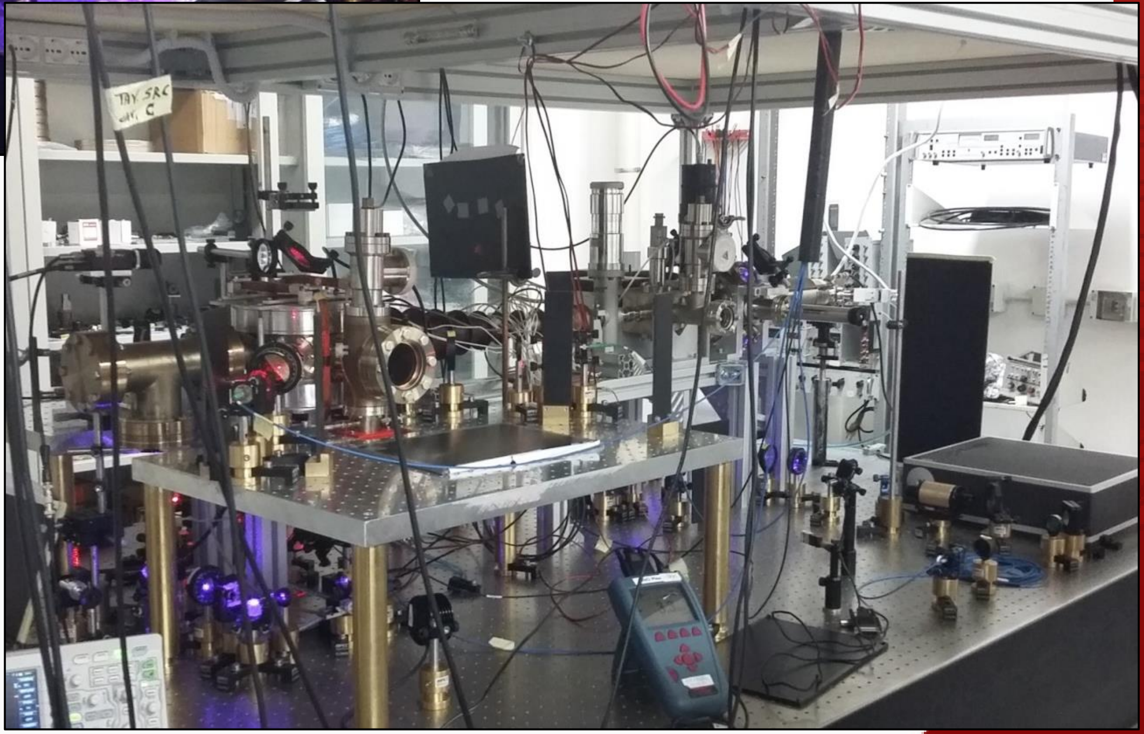
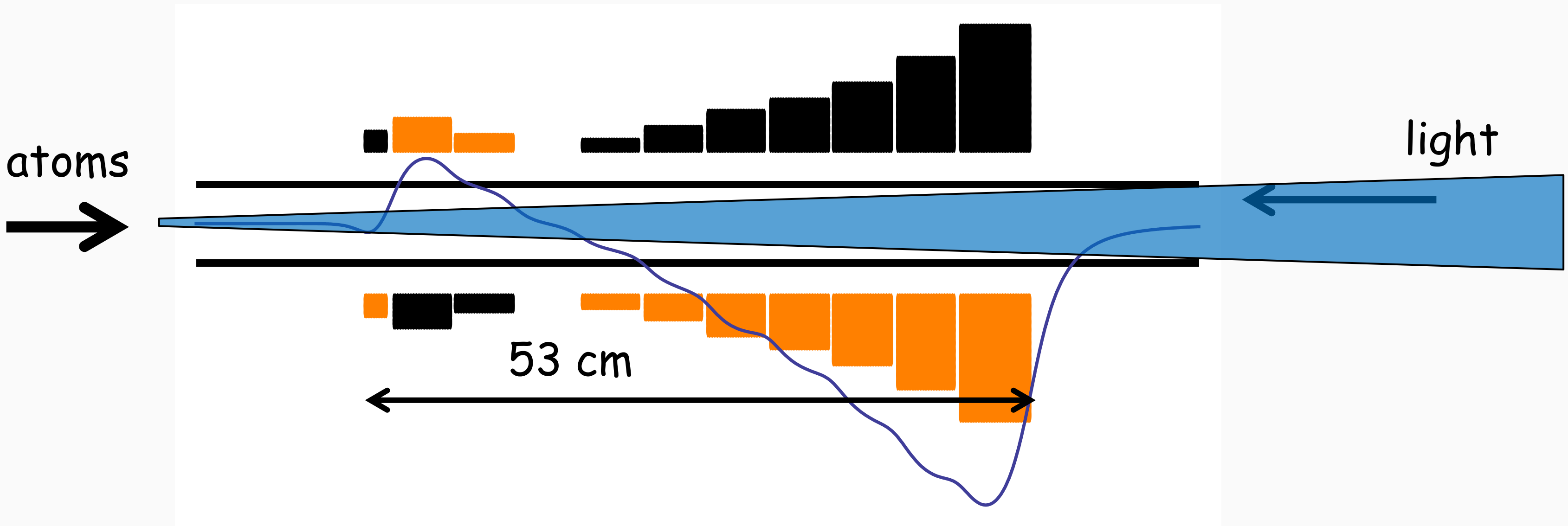
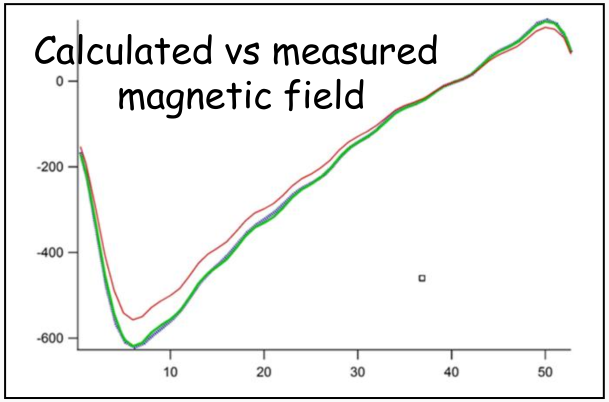


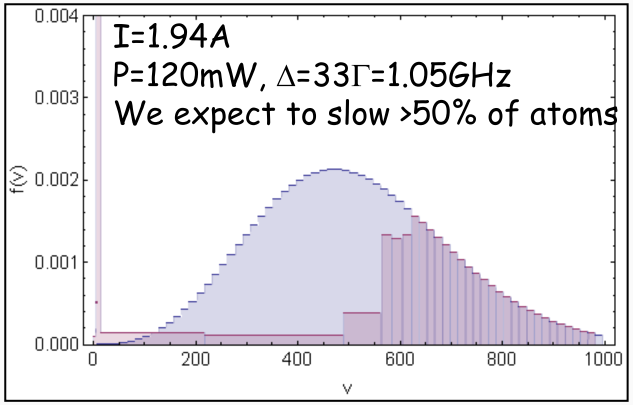


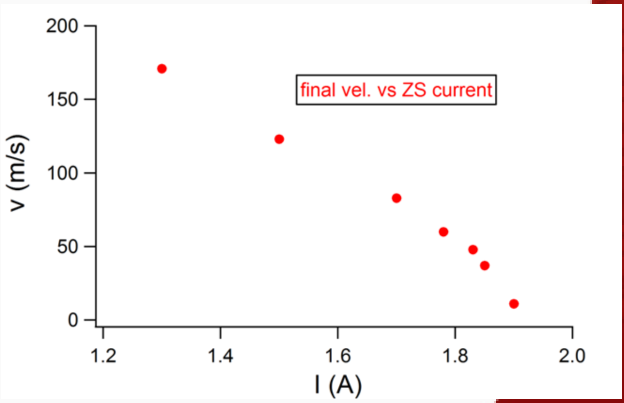
The Zeeman slower

Spin flip configuration: the B field changes sign

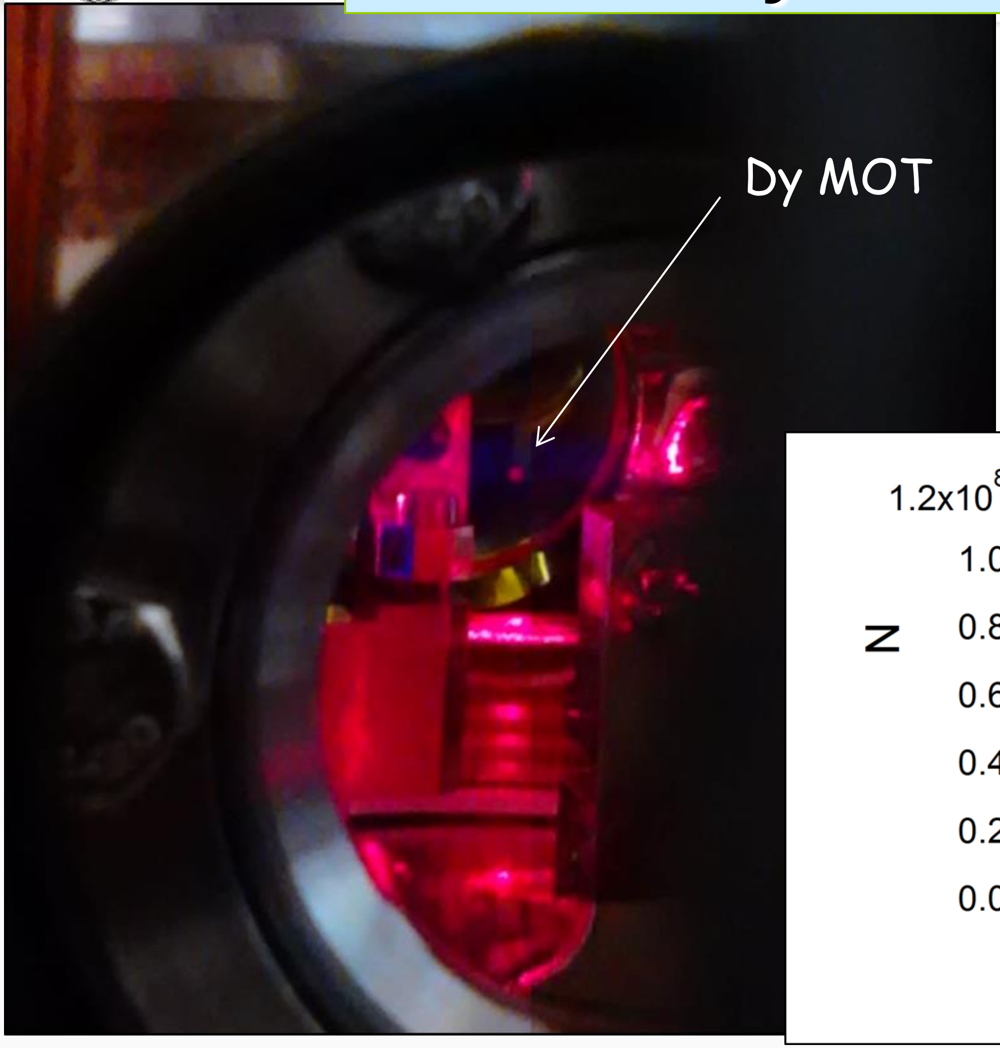






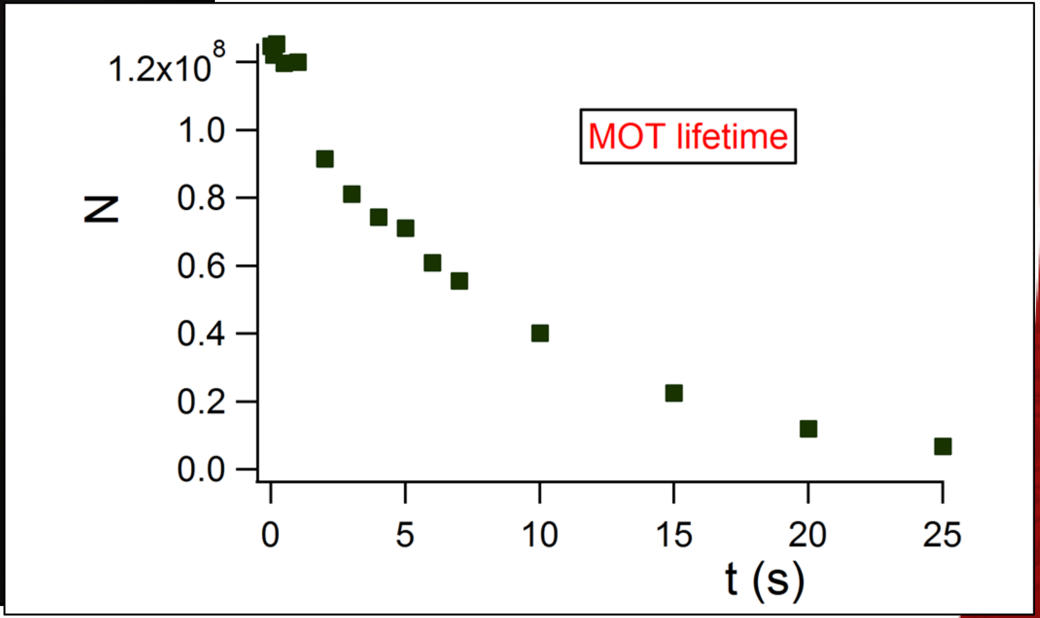


The Dy MOT @ 626nm

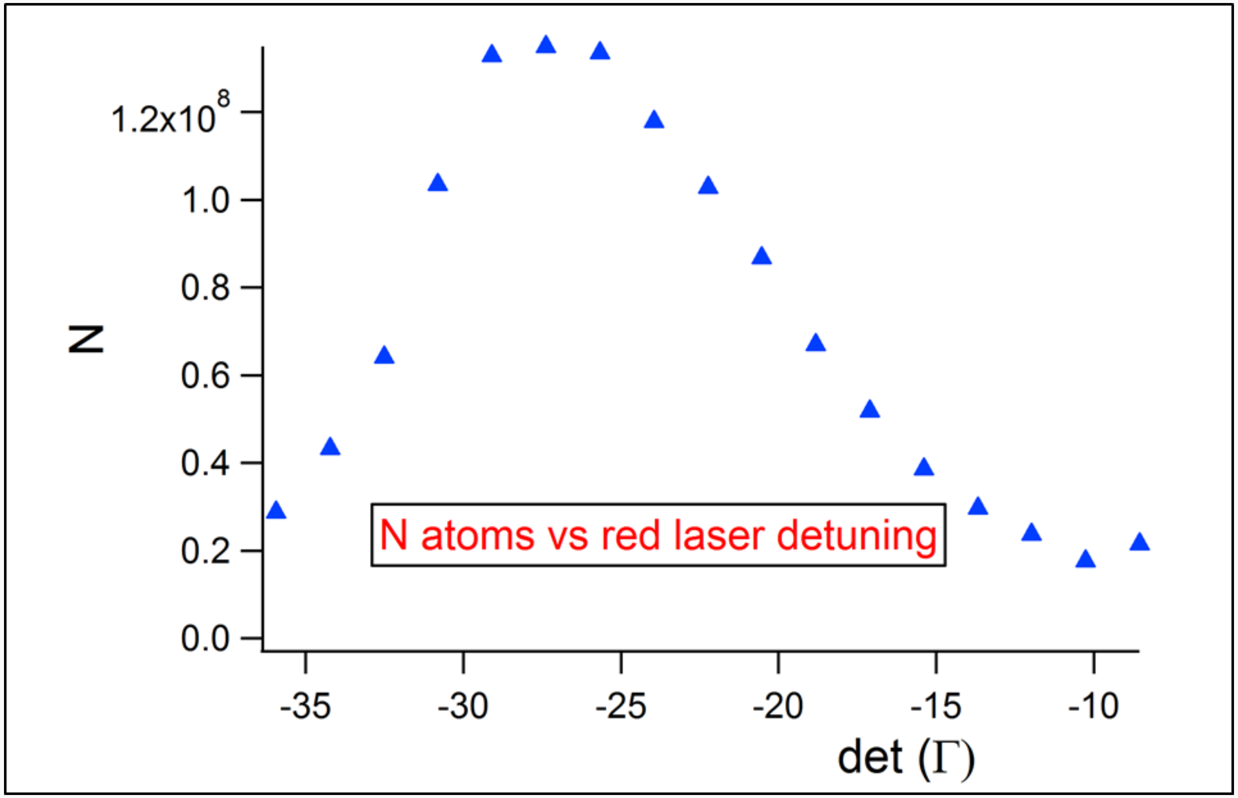


Preliminary results with
$I = 200\ I_S$

Measured final temperature
$T = 20\ \mu K$



The Dy MOT @ 626nm



Next steps: ODT -> BEC

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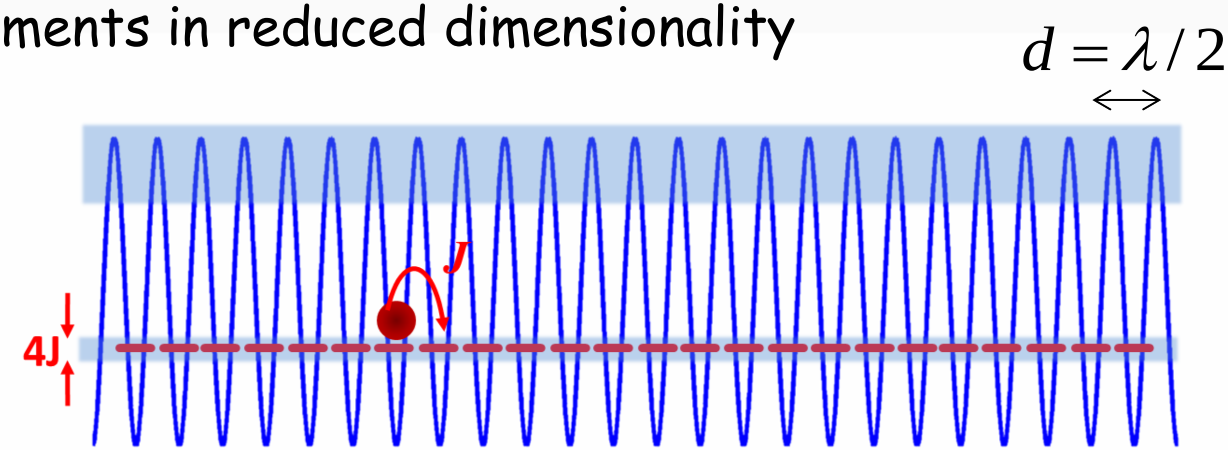
Next planned steps are:

- 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



GRAZIE !

Disponibilità di **tesi magistrale (o triennali)** su:
- Dy BEC
- Magnetometria con atomi ultrafreddi di Rb

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