MAGNETO-OPTICAL TRAPPING OF CADMIUM ATOMS

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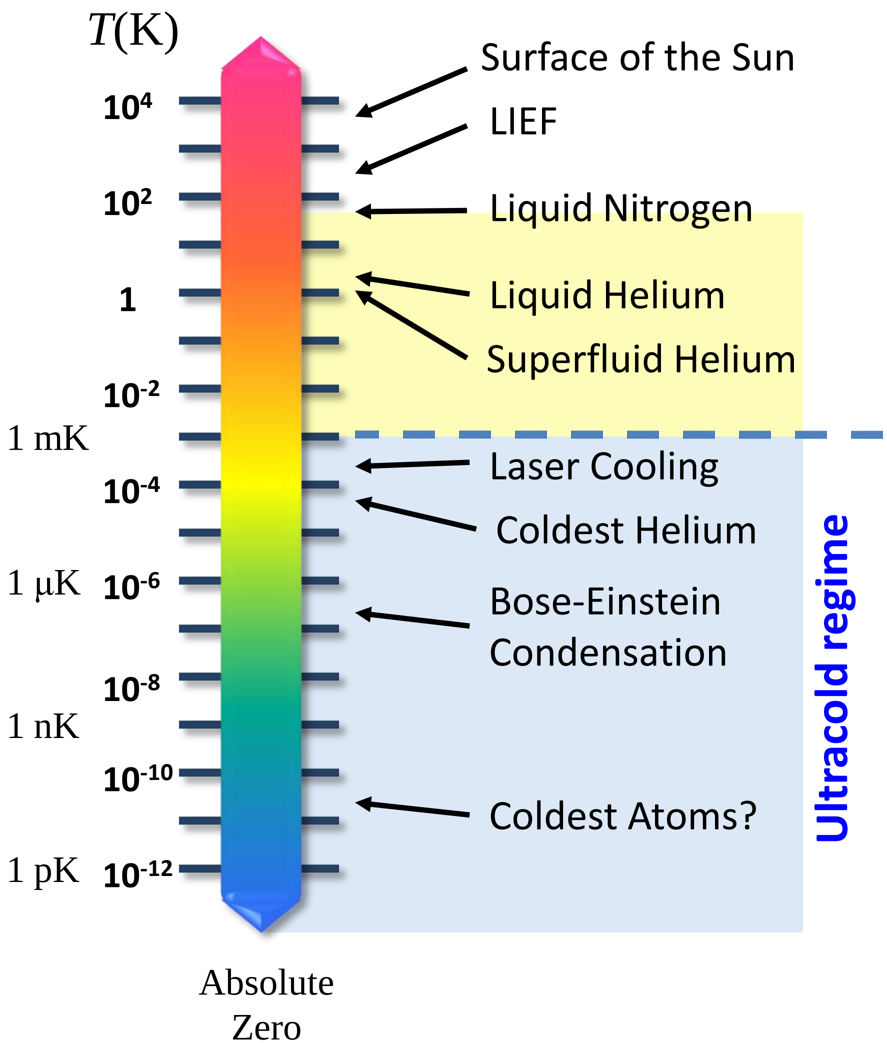
IAMS

NSF PFC

Outline

- Introduction to ultracold atomic physics
- How does laser cooling work
- Cadmium MOT
- Outlook

Define the "Ultracold"



- Laboratory energy scales
  - 1 peV < energy < 1 TeV

BEC

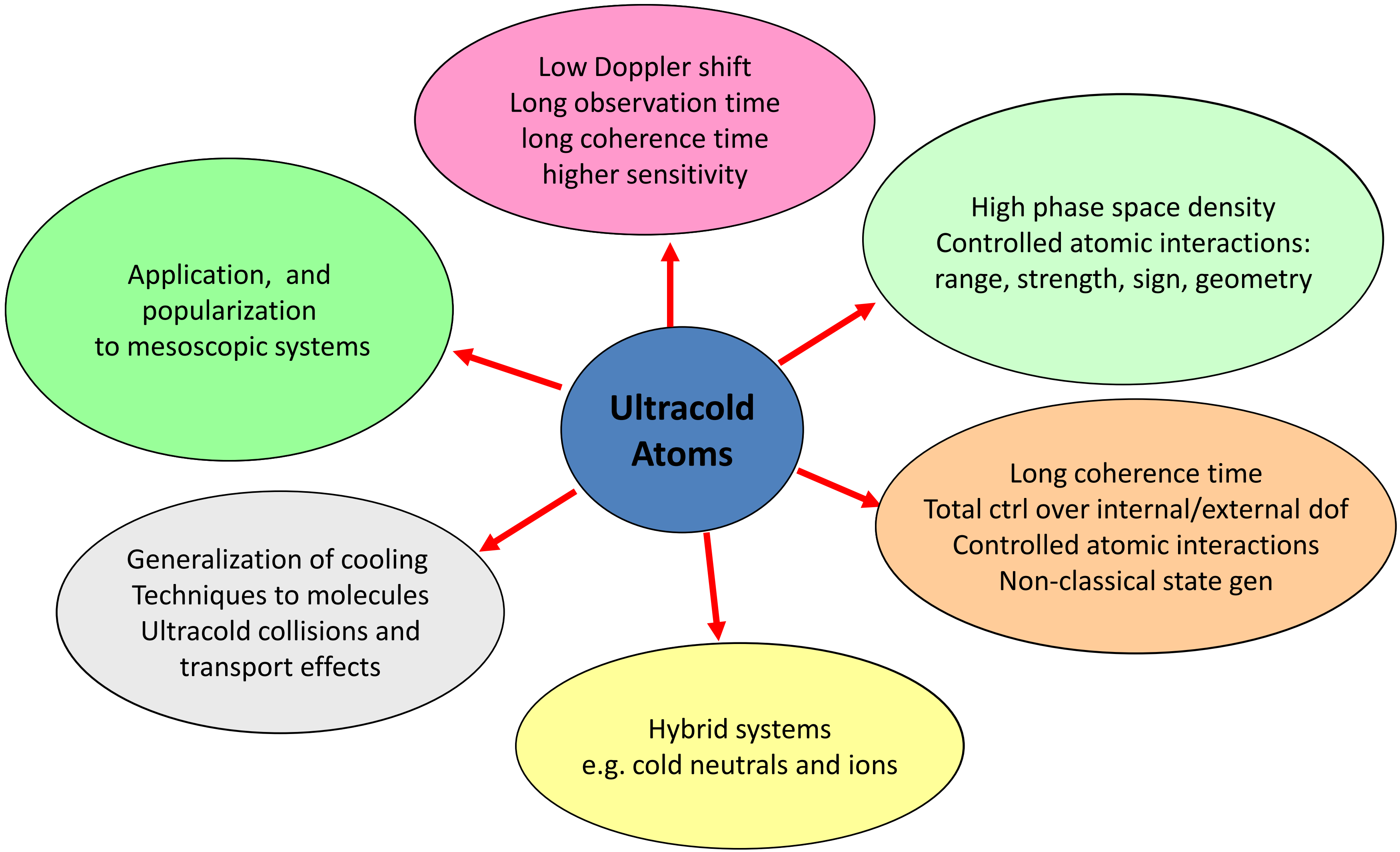
Tevatron, Fermilab

Atomic velocities

room temperature gas:	**300 meters/sec**
ultracold gas:	**6 meters/hour**

$$\tfrac{1}{2}mv^2 = k_B T$$

Cold atoms:
much more than just cool atomic physics



Cold atoms:
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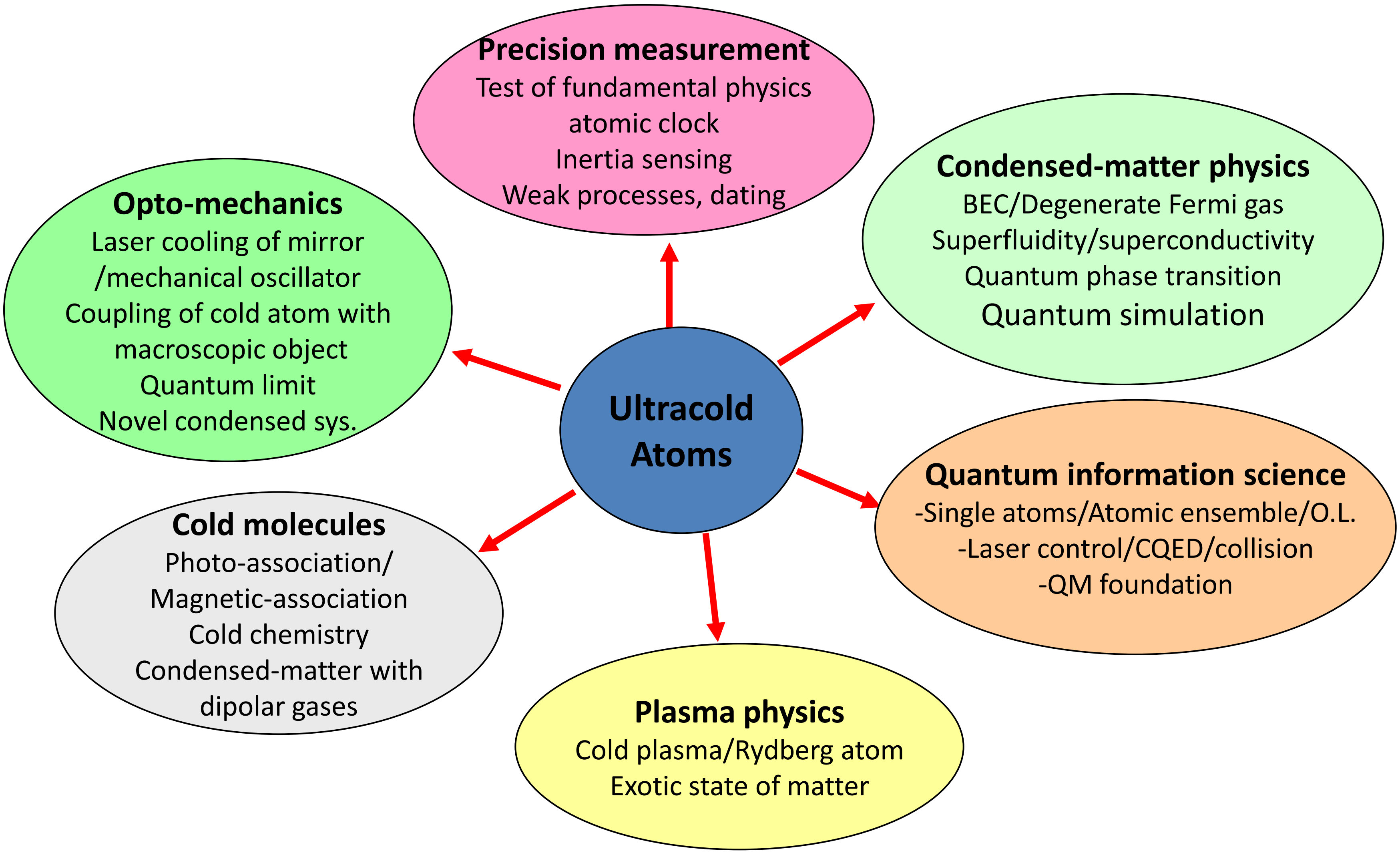
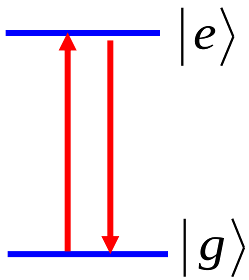
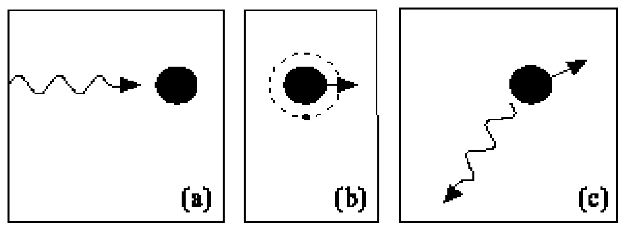


How does lasers cooling work?

Manipulating atoms with light - I

Photons carry momentum: can be used to accelerate/decelerate an object

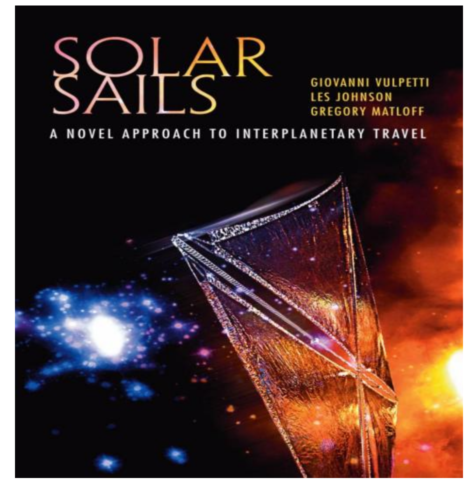




$$E = \hbar\omega_i \qquad E' = \hbar\omega_s$$

$$\vec{p} = \hbar\vec{k}_i \qquad \vec{p}' = \hbar\vec{k}_s$$

$$\langle \vec{k}_i \rangle = \vec{k} \qquad \langle \vec{k}_s \rangle = 0$$



Photon energy $E = \hbar\omega \sim \text{ eV}$

Photon recoil energy $E_r = (\hbar\vec{k})^2 / 2m \sim 10^{-7}\,\text{eV}$

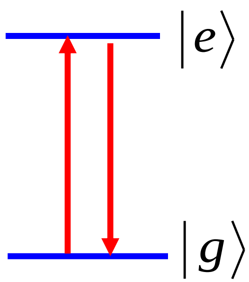
Thermal energy (@ 293K) $E_{R.T.} \sim 25\times10^{-3}\text{ eV}$

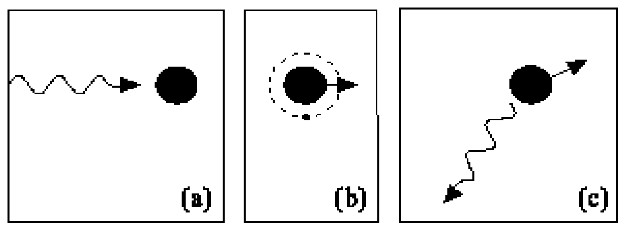
Laboratory applications:

1. Laser cooling
2. Raman cooling
3. Coherent control of Motional D.O.F.

Manipulating atoms with light - I

Photons carry momentum: can be used to accelerate/decelerate an object





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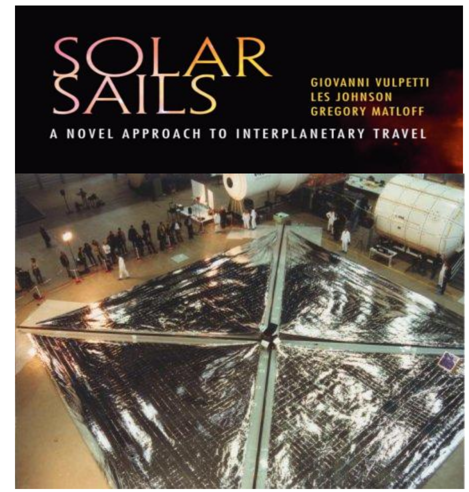
$$\vec{p} = \hbar\vec{k}_i \qquad \vec{p}\,' = \hbar\vec{k}_s$$

$$\langle \vec{k}_i \rangle = \vec{k} \qquad \langle \vec{k}_s \rangle = 0$$



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Laboratory applications:

1. Laser cooling
2. Raman cooling
3. Coherent control of Motional D.O.F.

Manipulating atoms with light - II

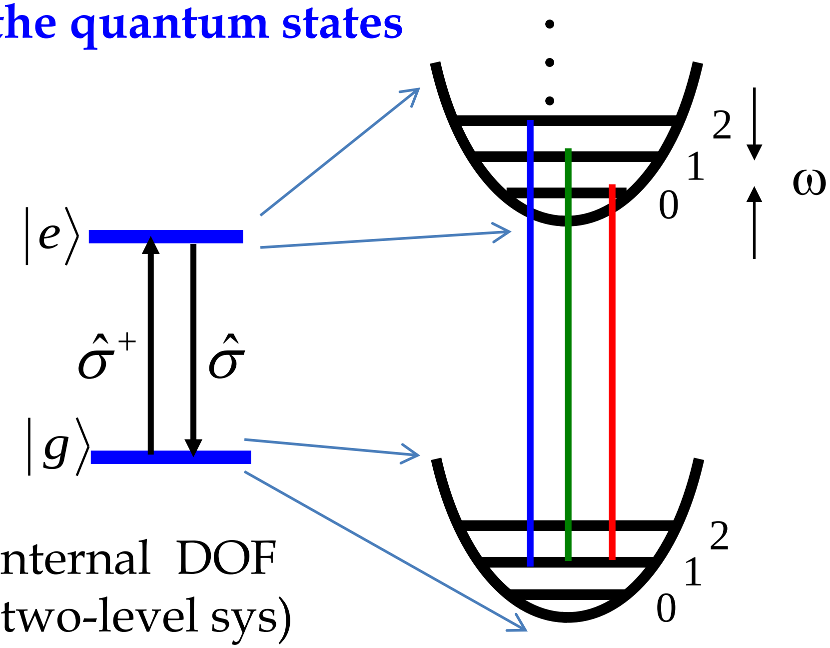
When external motional-states are spectroscopically resolved and quantized, light can be used to control the quantum states of the external degrees of freedom (DOF).

Let's assume no spontaneous decay from $|e\rangle$

$$\hat{H}_I = \hbar\Omega\hat{\sigma}^+ e^{-i\delta t} e^{ik\hat{x}} + h.c.$$

When $kx_0 << 1$, (Lamb-Dicke regime)

$$e^{ik\hat{x}} \sim 1 + ik\hat{x}$$
$$= 1 + ikx_0(\hat{a} + \hat{a}^+).$$



$$\hat{H}_I \sim \hbar\Omega e^{-i\delta t}\hat{\sigma}^+(1 + ik(\hat{a} + \hat{a}^+)) + h.c.$$

detuning

carrier

Motional sidebands { red sideband / blue sideband

Valid when
Lamb-Dicke Parameter

$$\eta = kx_0 \propto \frac{x_0}{\lambda} << 1$$

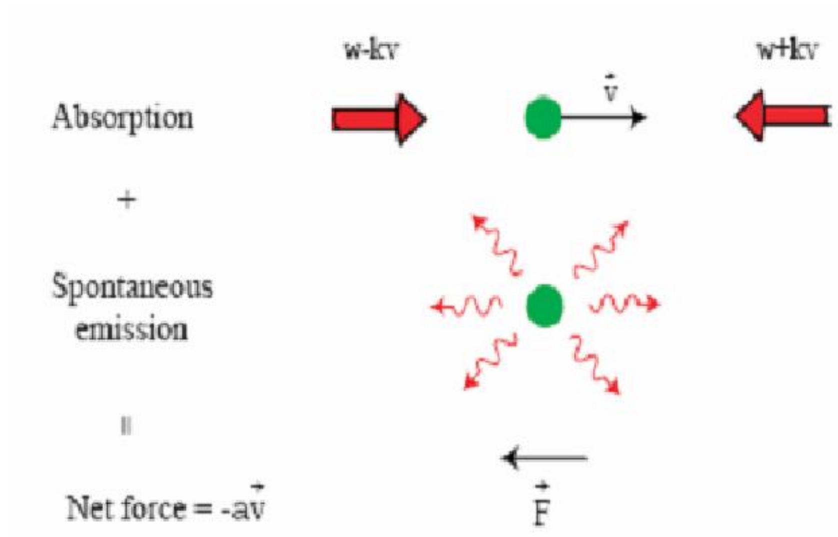
Doppler cooling

Doppler shift $\omega_D = 2\pi \frac{v}{c} f = \frac{2\pi v}{\lambda} = kv$

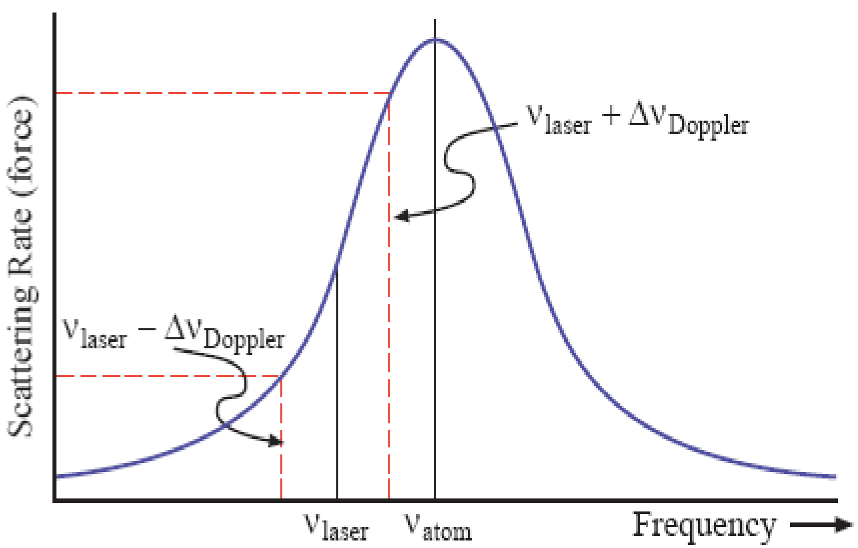
$$\vec{F} = \vec{F}_+ + \vec{F}_-$$

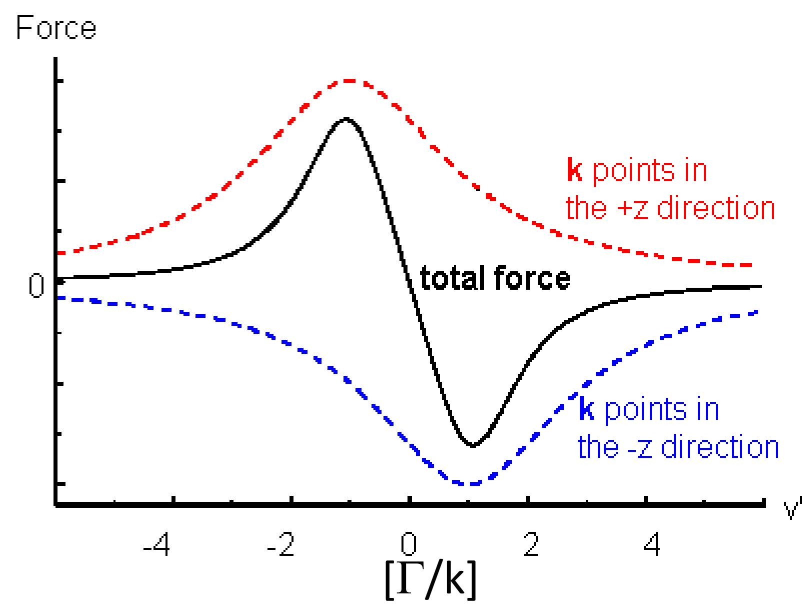
$$\vec{F}_\pm = \pm \frac{\hbar \vec{k} \Gamma}{2} \frac{s_0}{1 + s_0 + [2(\delta \mp kv)/\Gamma]^2}$$

$$F \approx \frac{8\hbar k^2 \delta s_0 \vec{v}}{\Gamma(1 + s_0 + (2\delta/\Gamma)^2)^2} \equiv -\beta\vec{v}, if \left(\frac{kv}{\Gamma}\right)^2 << 1$$



For a red-detuned (δ<0) laser,
the force damps the velocity.



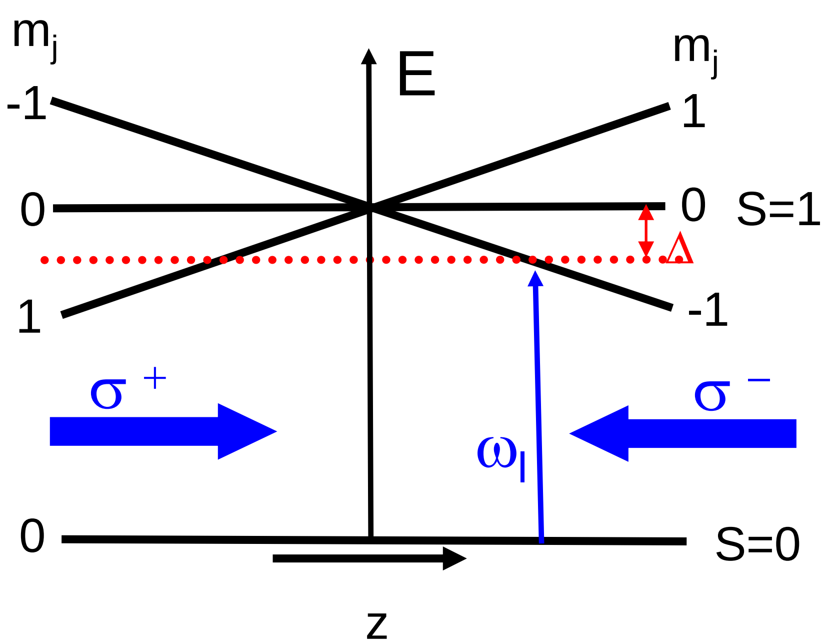


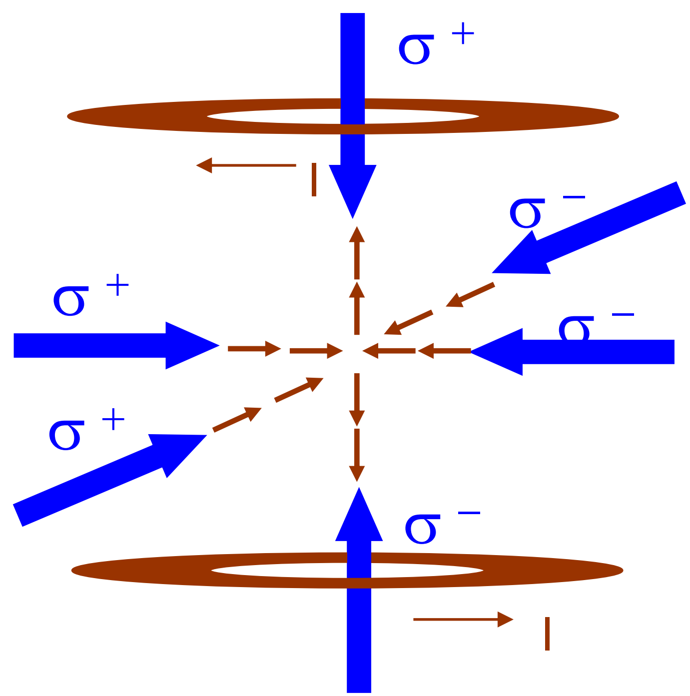
How to make a MOT?

VOLUME 59, NUMBER 23 PHYSICAL REVIEW LETTERS 7 DECEMBER 1987

Trapping of Neutral Sodium Atoms with Radiation Pressure

E. L. Raab,[a] M. Prentiss, Alex Cable, Steven Chu,[b] and D. E. Pritchard[a]
AT&T Bell Laboratories, Holmdel, New Jersey 07733
(Received 16 July 1987)



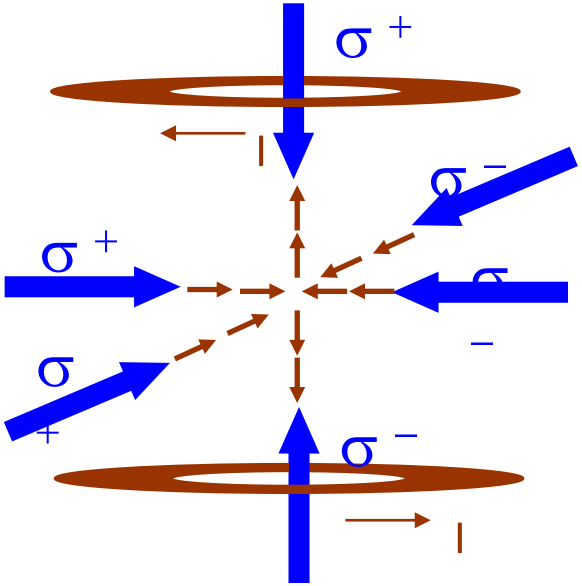


3D Monte-Carlo simulation of a MOT

Initial position: uniform distribution, initial velocity: Boltzmann distribution

Acceleration:

$$a_x(\vec{r}, v_x) = \frac{\hbar k \gamma}{2m} s_x(\vec{r}) \Bigg[\sum_q \frac{p_{+,q}(\vec{r})}{1 + s_{\rm tot}(\vec{r}) + (2\delta_{+,q}(\vec{r}, v_x))^2} - \sum_q \frac{p_{-,q}(\vec{r})}{1 + s_{\rm tot}(\vec{r}) + (2\delta_{-,q}(\vec{r}, v_x))^2} \Bigg]$$



Saturation parameter:

$$s_x(\vec{r}) = \frac{I_x}{I_{\rm sat}} e^{\frac{-2(y^2+z^2)}{w_0^2}},$$

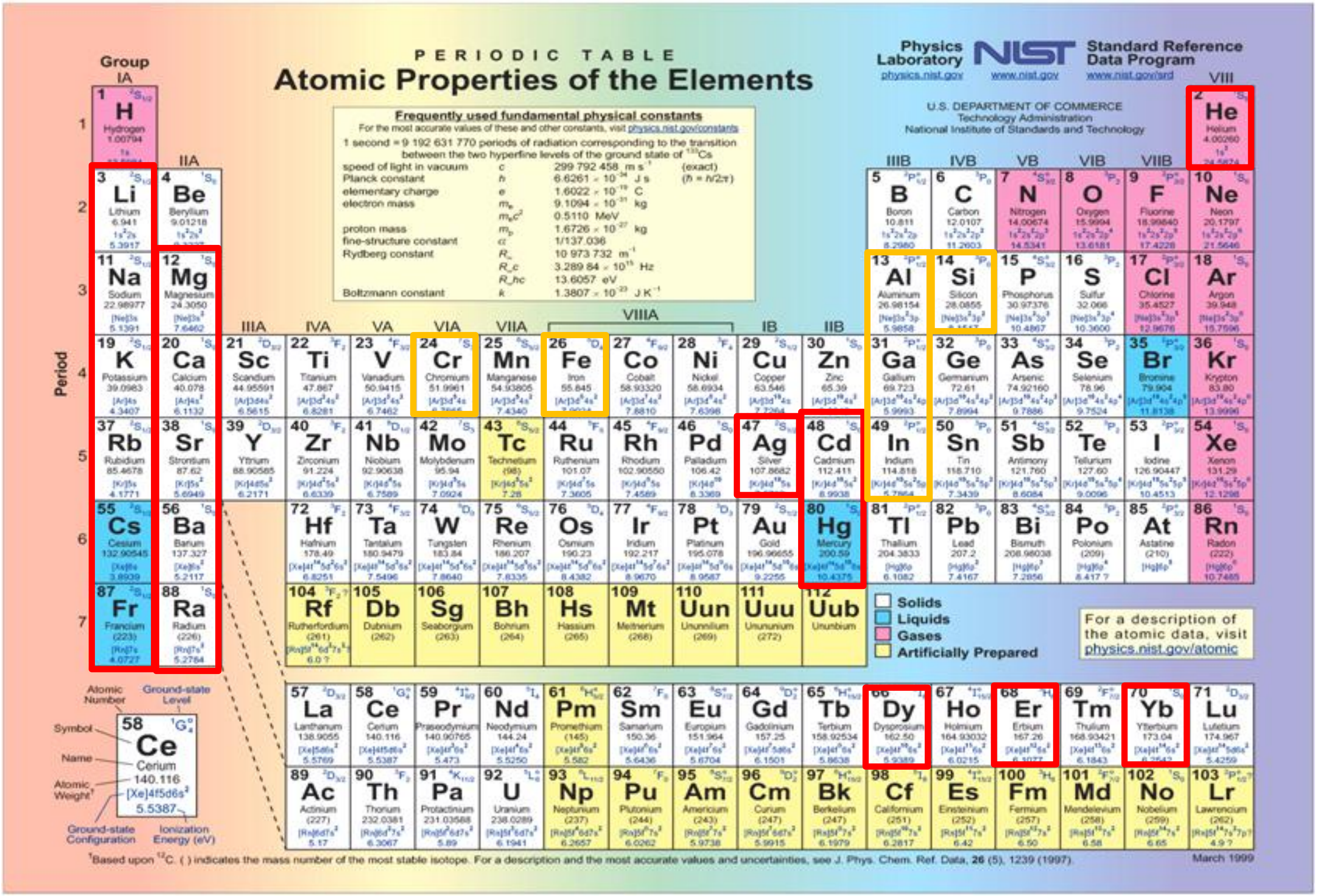
$$s_{\rm tot}(\vec{r}) = 2s_x(\vec{r}) + 2s_y(\vec{r}) + 2s_z(\vec{r}),$$

Polarization:

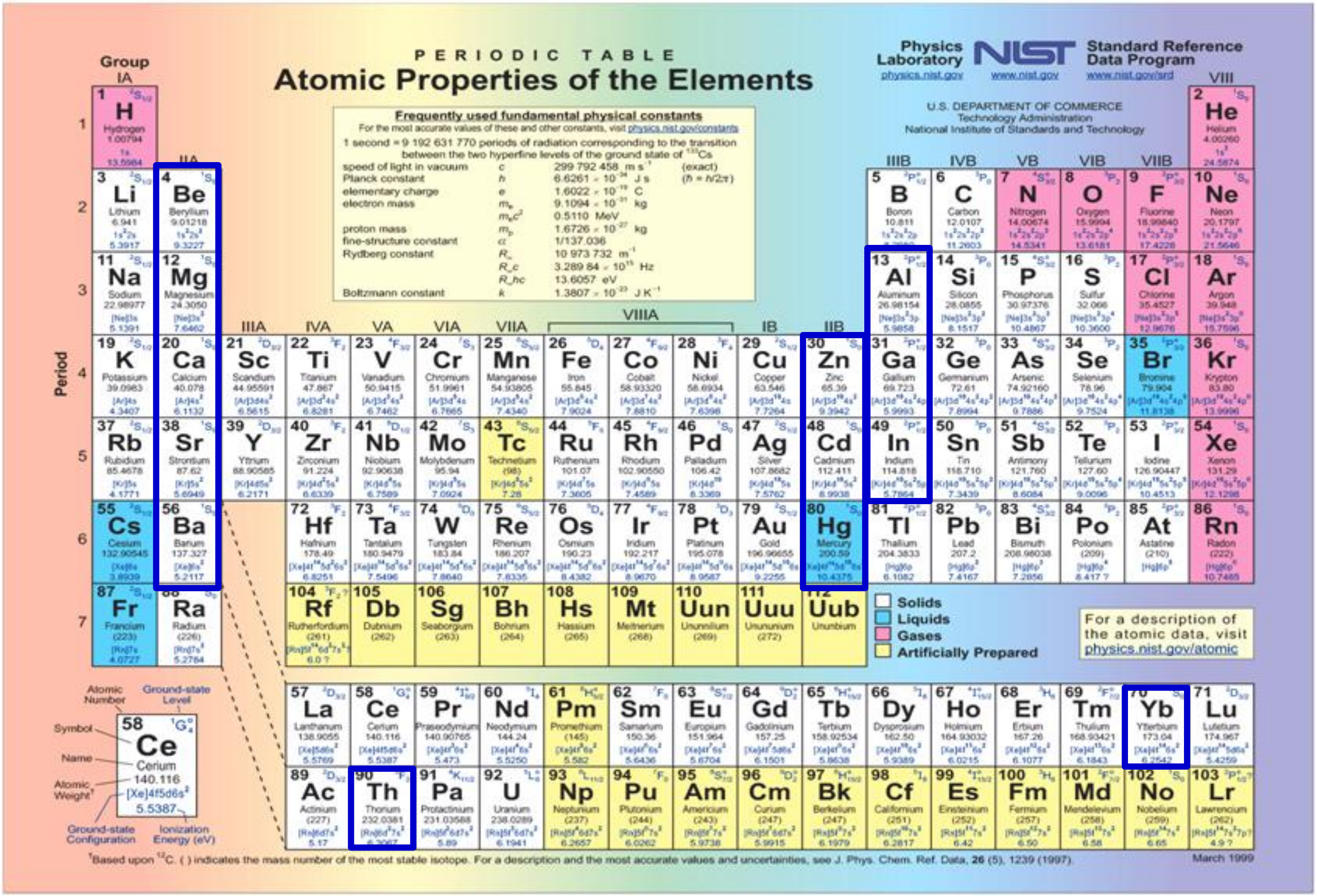
$$p_{\pm,q}(\vec{r}) = \begin{cases} (\frac{1}{2}[1 \mp \frac{1}{2}\frac{xB'}{B(\vec{r})}])^2, & q = -1 \quad (\sigma^-) \\ (\frac{1}{2}[1 \pm \frac{1}{2}\frac{xB'}{B(\vec{r})}])^2, & q = +1 \quad (\sigma^+) \\ 1 - (p_{\pm,-1} + p_{\pm,+1}), & q = 0 \quad (\pi) \end{cases}$$

Effective detuning: $\delta_{\pm,q}(\vec{r}, v_x) = (\Delta \mp k v_x)/\gamma + q\frac{\mu_B g_F B(\vec{r})}{\gamma \hbar}$

Demonstrated laser cooling of neutral atoms

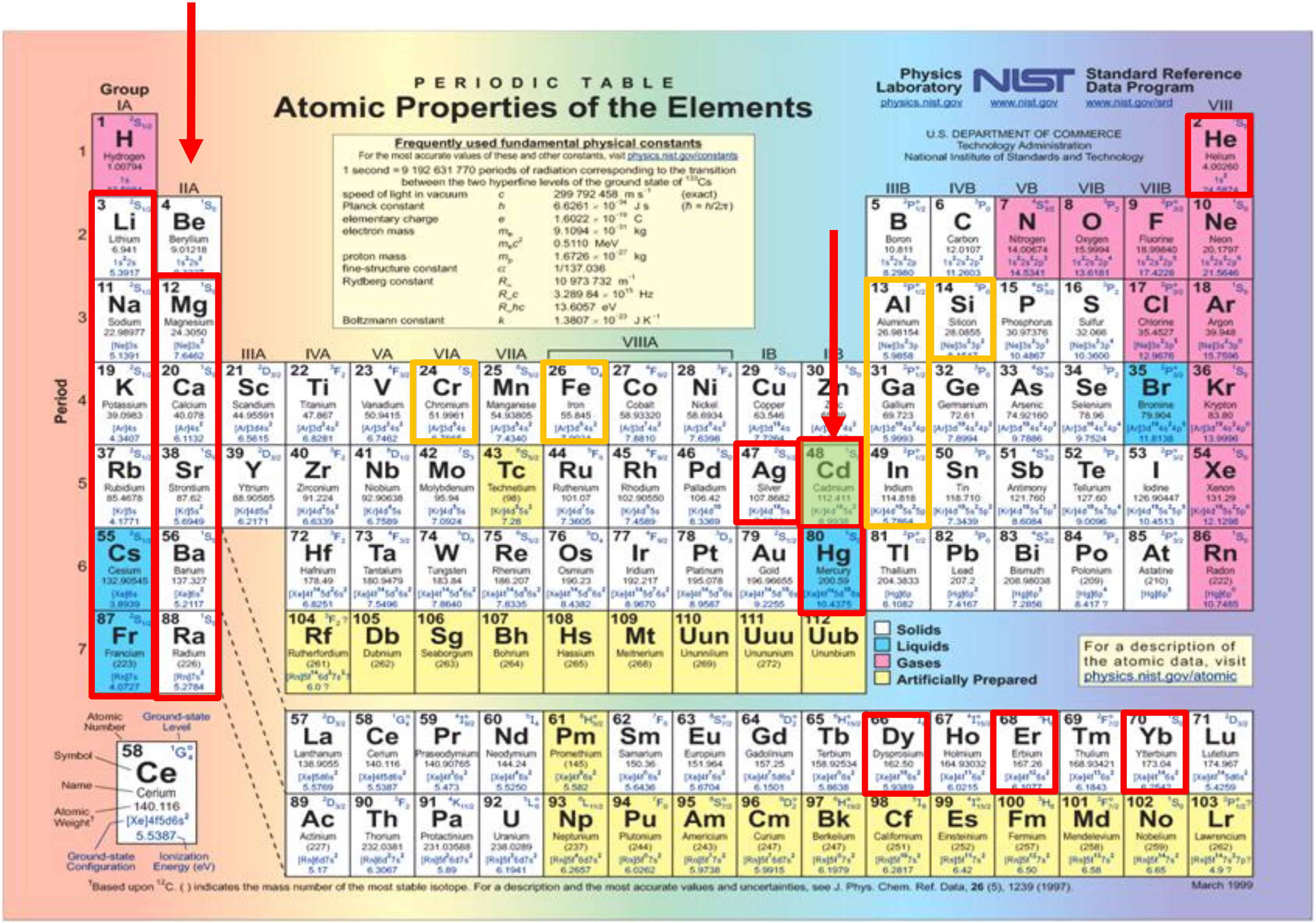


Demonstrated laser cooling of ionic atoms



Magneto-Optical Trapping of Cadmium

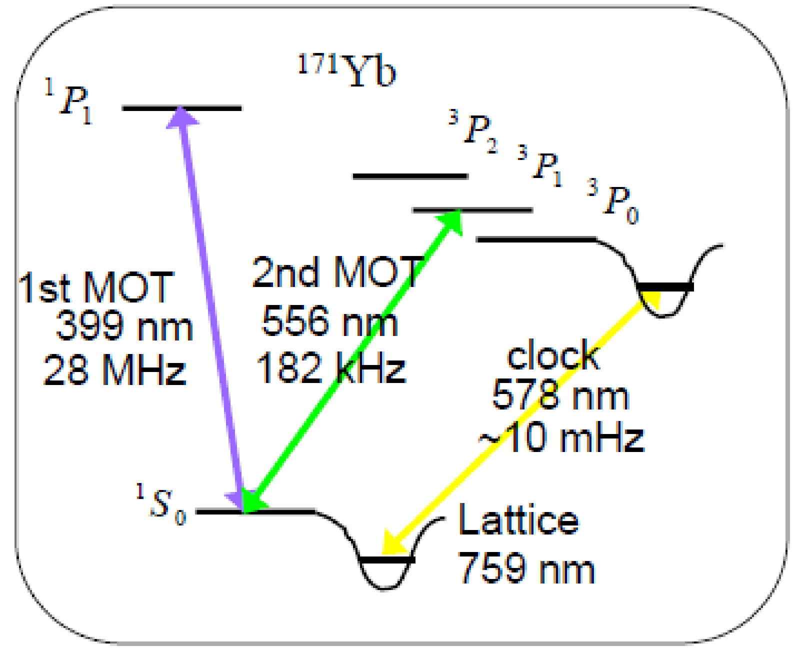
Demonstrated laser cooling of neutral atoms



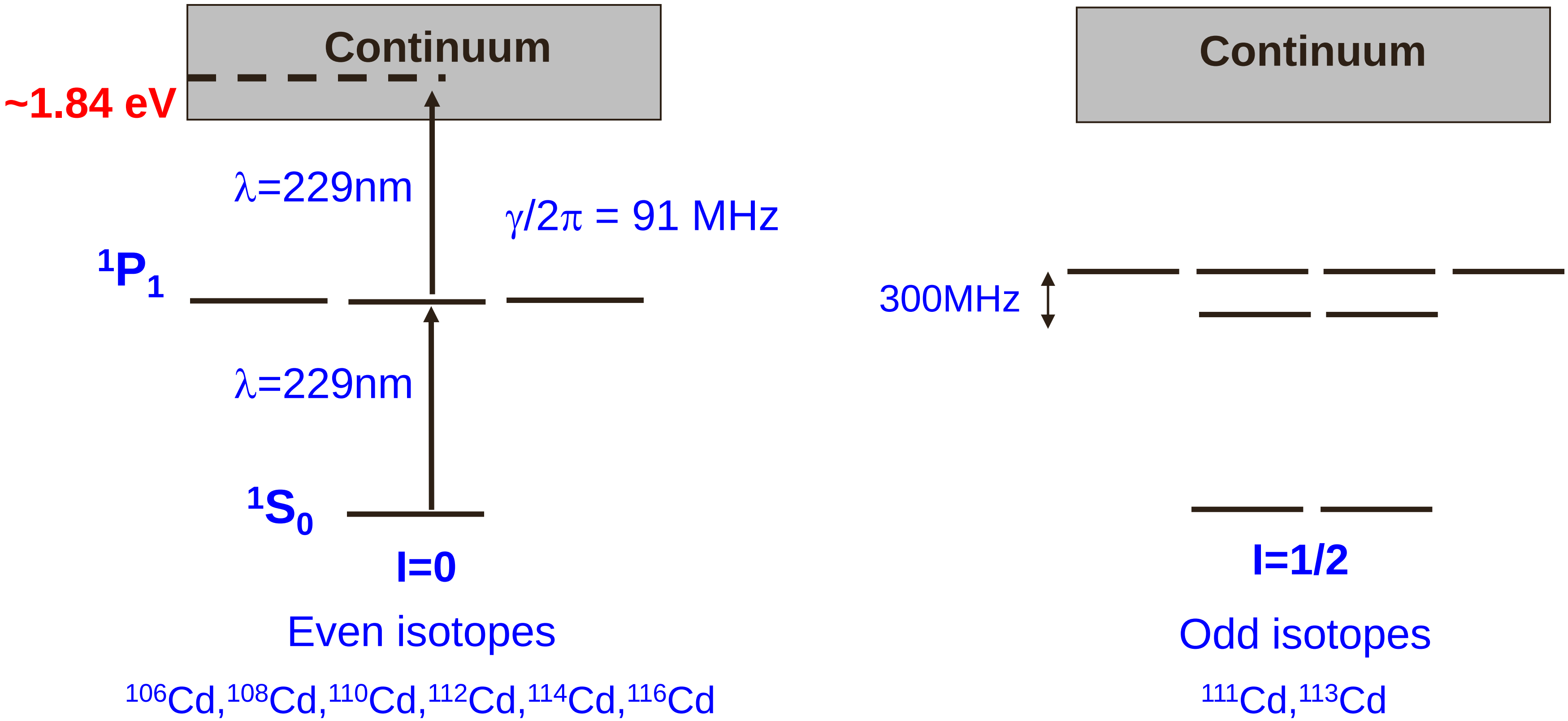
Why two-electron atoms?

- Textbook two-level atom
- Possess intercombination transition lines
  - Lower Doppler limit temperature
  - atomic clock: Sr, Mg, Hg, Yb
- EDM, T/CP violation: ^{225}Ra, ^{199}Hg
- Trappable neutrals and ions
  - Build a hybrid system

Intercombination lines:
$^{1}S_{0}$ - $^{3}P0_{0,1,2}$



Cadmium overview

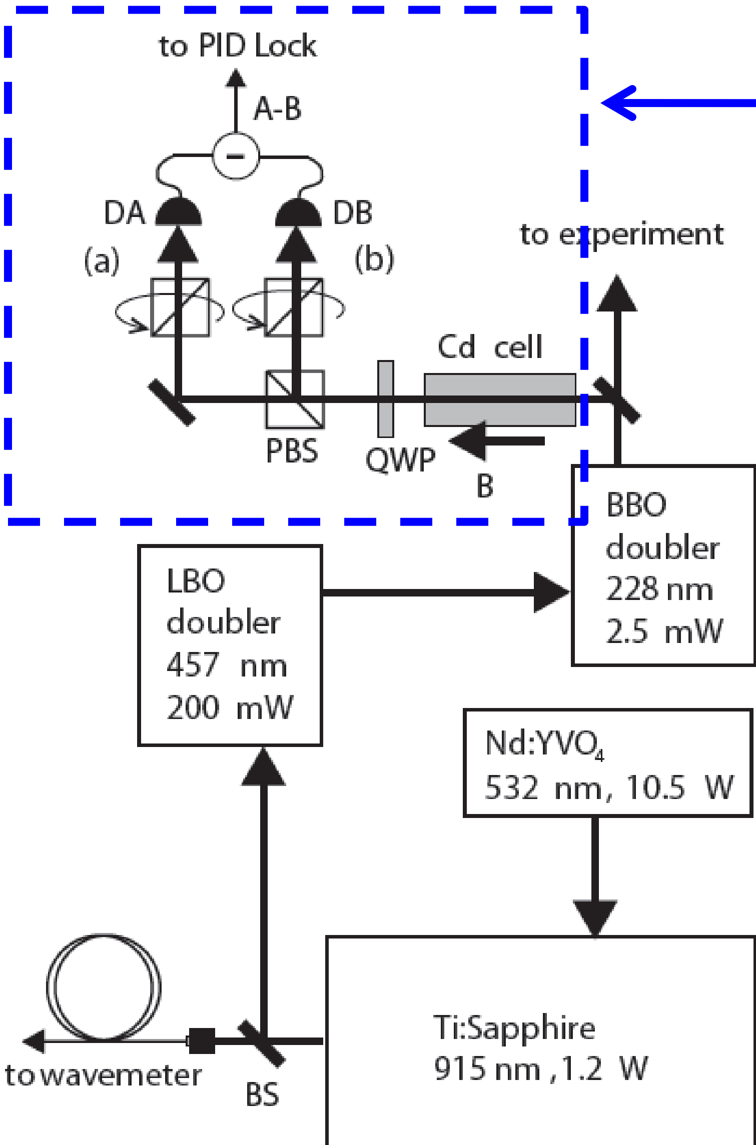


Large $k=2\pi/\lambda$
- **Large linewidth**
- **Photo-ionization**

⇒

- **Large I_{sat} (1.0 W/cm^2)**
- **Large photon recoil acceleration (~50x Rb)**
- **Large B-field gradients**

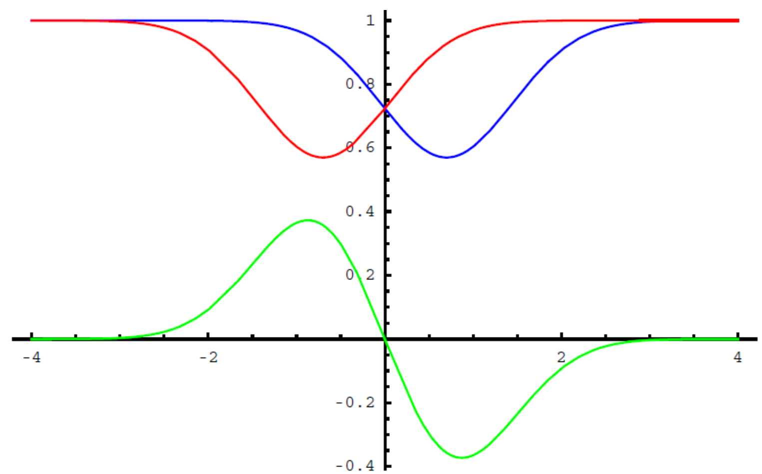
Laser System and freq stabilization



DAVLL lock:
$\Delta\nu$ ~ 30 MHz ~ $\gamma/3$
1.5 GHz capture range

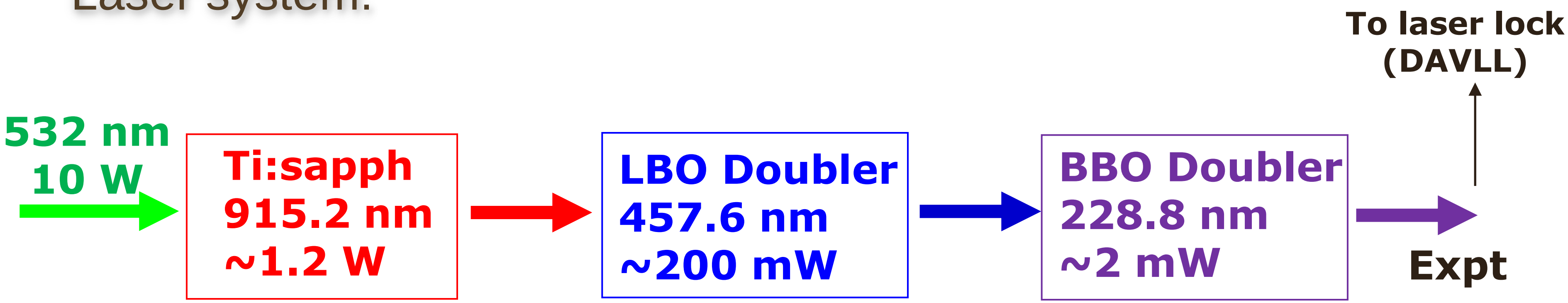
DA
(sig. from Detector A)

DB
(sig. from Detector B)

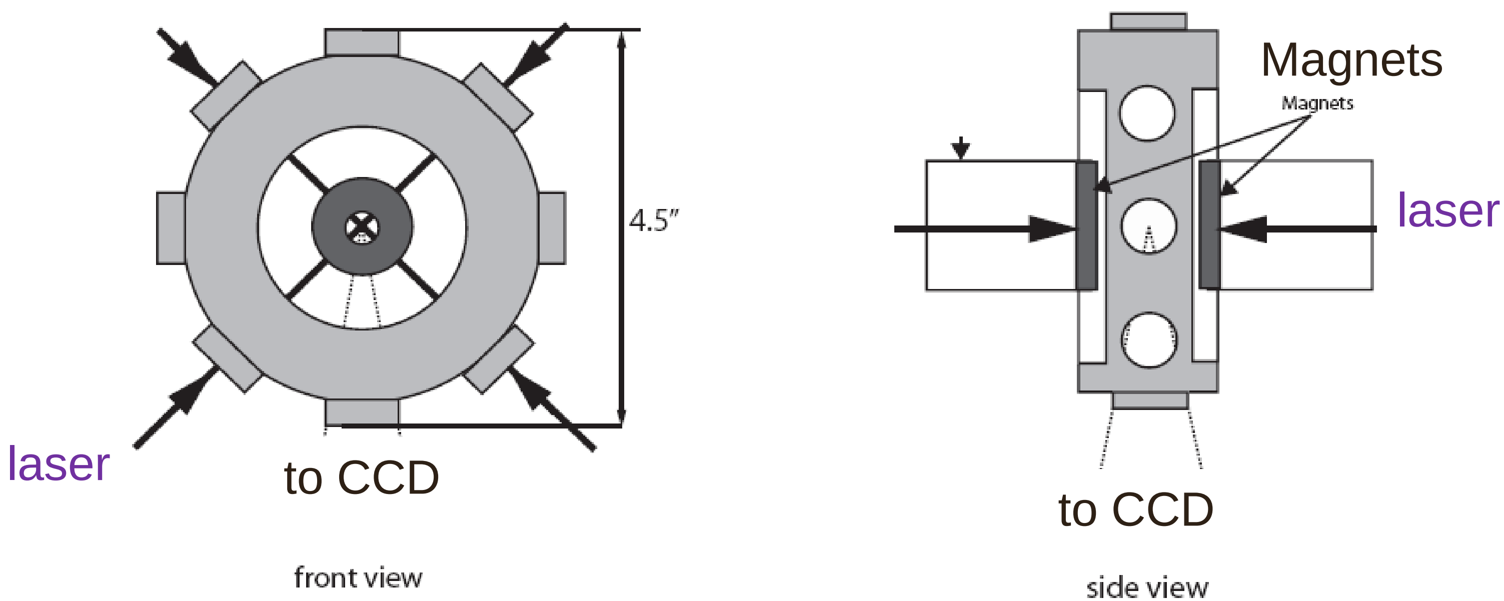


DB - DA

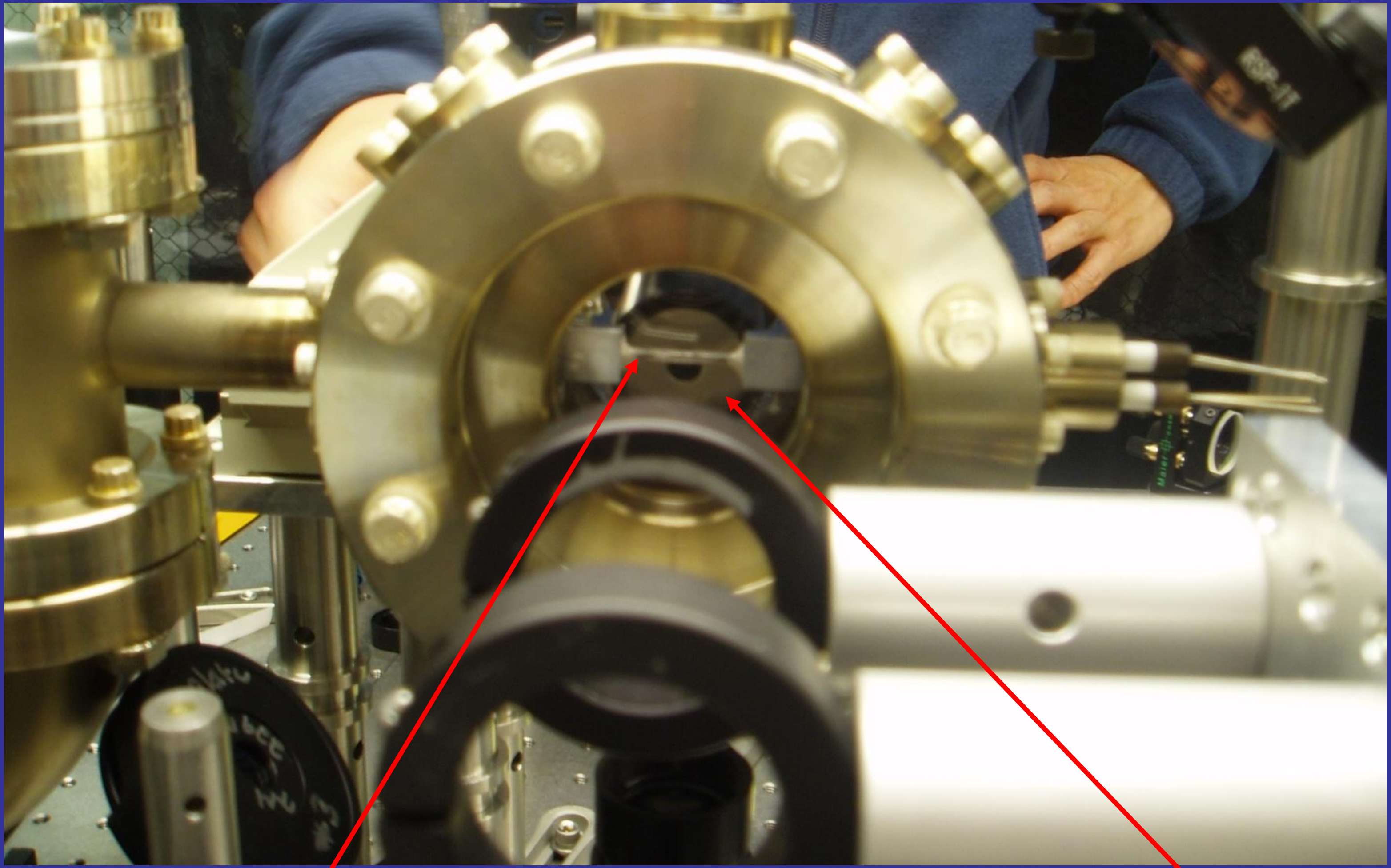
Laser system:



Vacuum chamber:



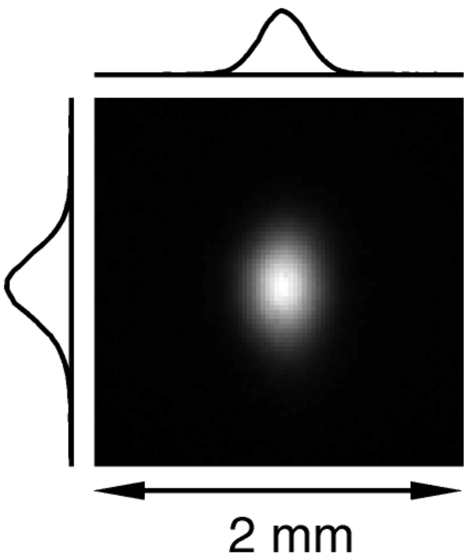
Cd vapor pressure P~10^{-11} Torr at 300K



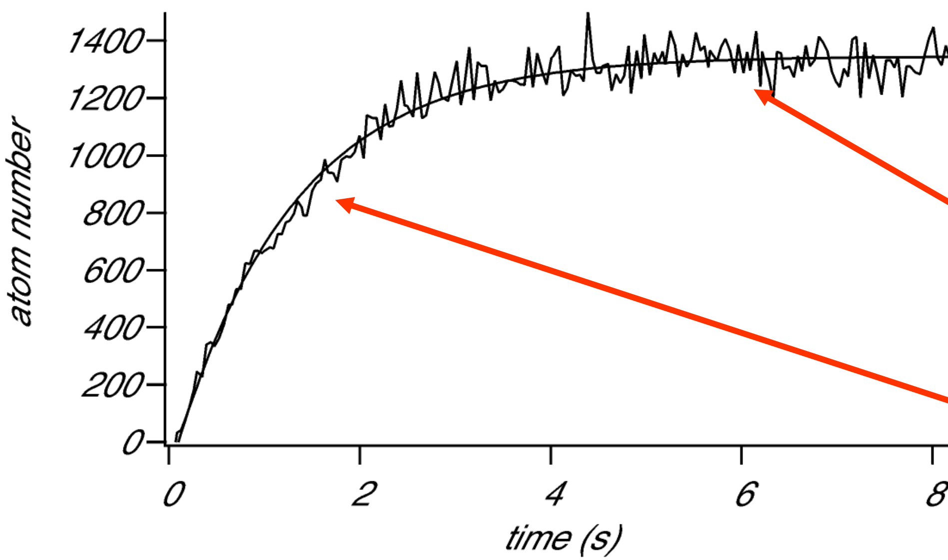
Ion trap: Four-rod linear Paul trap

Permanent magnets give
large magnetic field gradients:
B’ ~ 300-1500 G/cm

Cadmium MOT parameters



- MOT Atom Number (N): ~10 – 10000
- MOT Density: ~10^8 - 10^9 cm^{-3}
- Beam waist (w_0): 0.5 – 1.5 mm
- Beam power: 0.7 – 2.5 mW
- Saturation parameter (s): 0.02 – 0.77
- Magnetic field gradient (B'): 300 – 1200 G/cm
- Gaussian cloud shape: temperature limited
- Thus not density limited: two-body collision loss ignored



In a vapor cell:

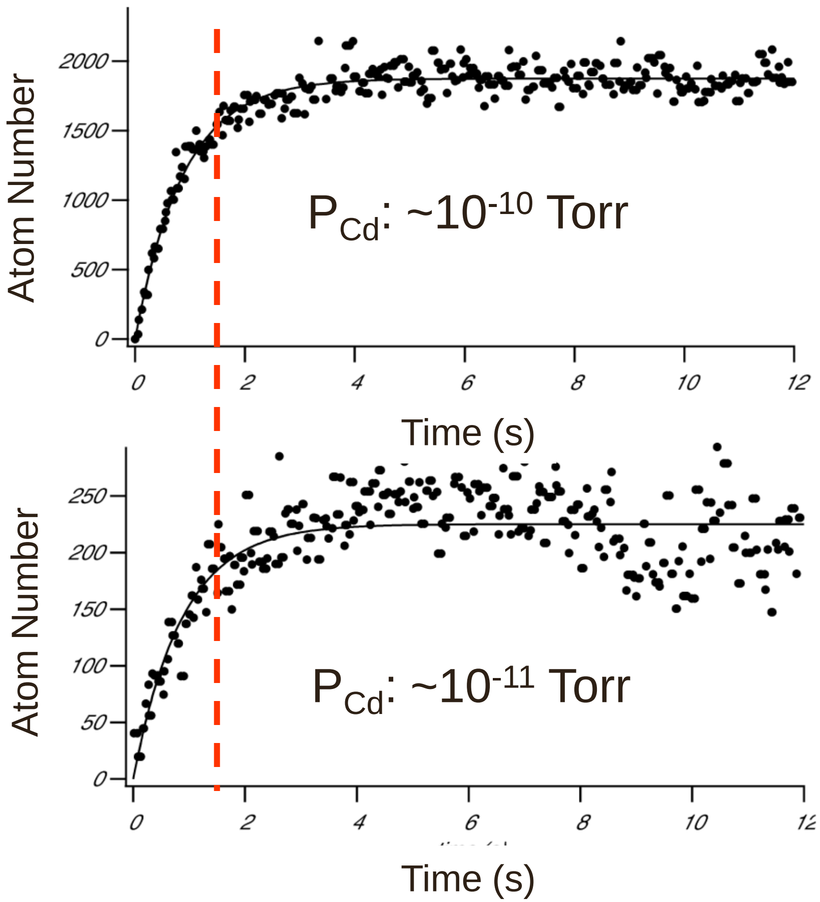
$$\frac{dN}{dt} = L - \Gamma_{eff} N - \beta \frac{N^2}{V}$$

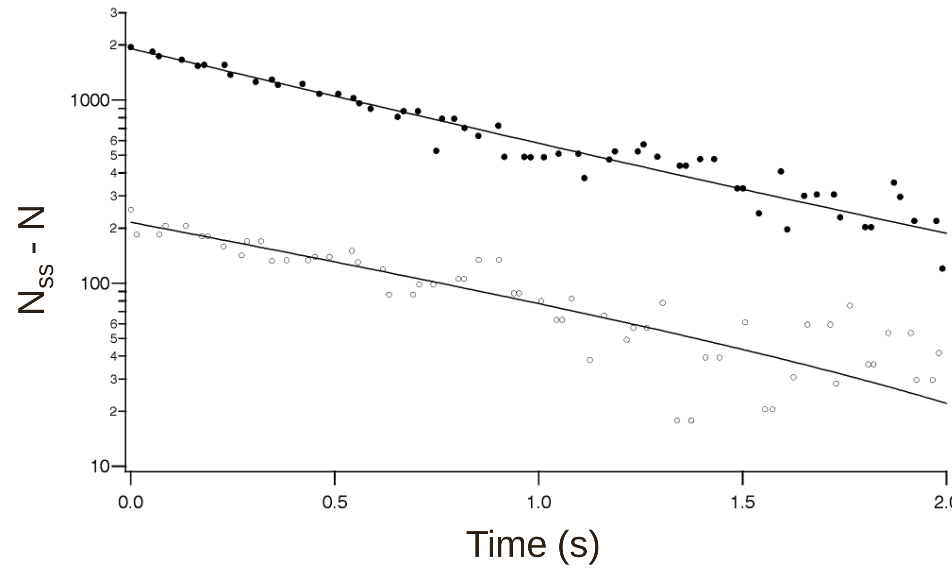
$$N_{ss} = \frac{L}{\Gamma_{eff}} \Rightarrow L = \Gamma_{eff} N_{ss}$$

$$\Gamma_{eff} = \Gamma_0 + \Gamma_{PI}$$

C. Monroe, et. al, PRL **65**, 1571 (1990)

Dominant loss: photoionization





MOT growth rate independent of the vapor pressure: one-body collision loss is small and ignored.

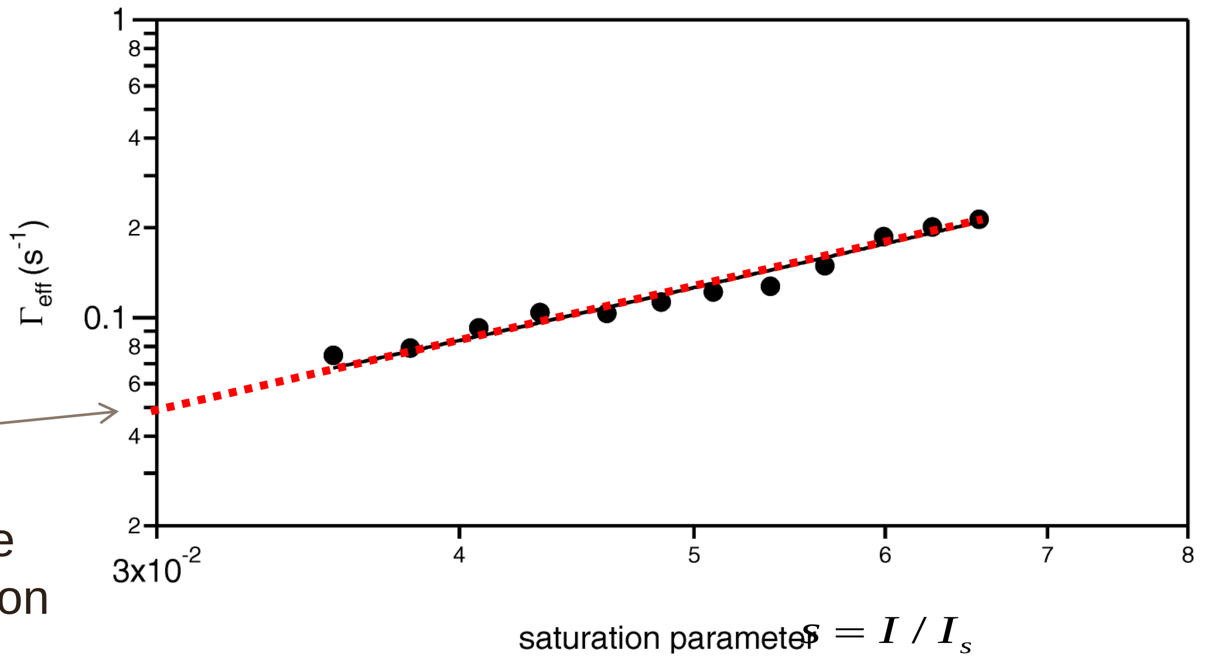
$$\Gamma_{eff} = \cancel{\Gamma_0} + \Gamma_{PI}$$

$$\Gamma_{PI} = \frac{\sigma_{PI} I \Pr(I,\delta)}{\hbar\omega} \qquad \Pr(s,\delta) = \frac{s/2}{1+s+4(\frac{\delta}{\gamma})^2}$$

σ_{PI}: Photoionization cross-section from P state

D.N. Madsen, et. al, J. Phys. B **35**, 2173 (2002)

Photoionization cross-section



$\Gamma_0 << \Gamma_{PI}$

Consistent with the previous assumption

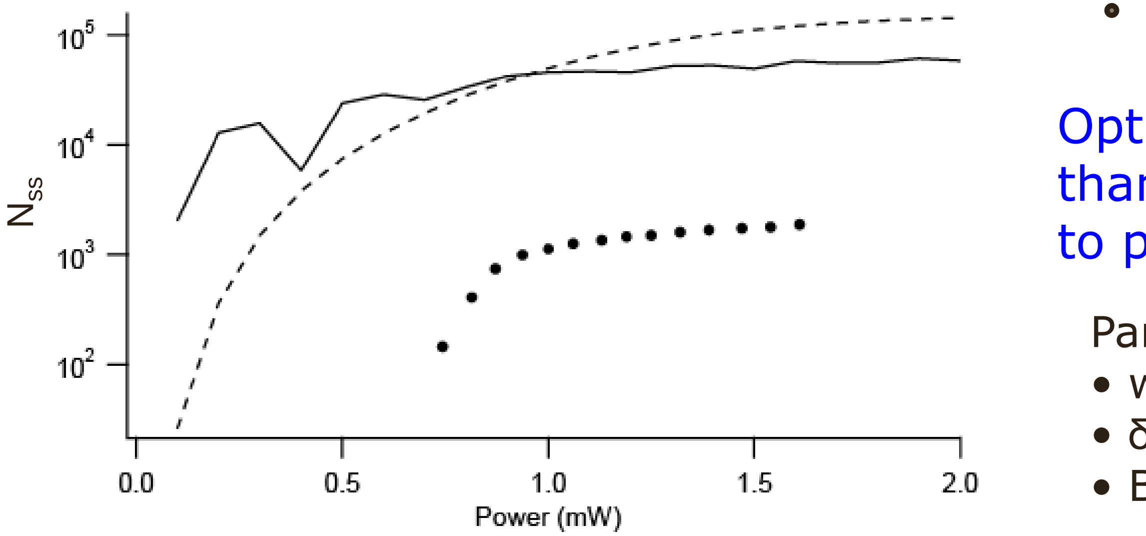
$$\Gamma_{PI} = \frac{\sigma_{PI} I \Pr(s,\delta)}{\hbar\omega} \qquad \Pr(s,\delta) = \frac{s/2}{1+s+4(\frac{\delta}{\gamma})^2}$$

$$\sigma_{PI} = 2\,(1)\times 10^{-16}\ \text{cm}^2$$

σ_{PI}: Photoionization cross-section from P state

Limited by intensity and detuning uncertainty

Power / intensity:



Optimum intensity is lower than that of typical MOTs due to photoionization

Parameters:

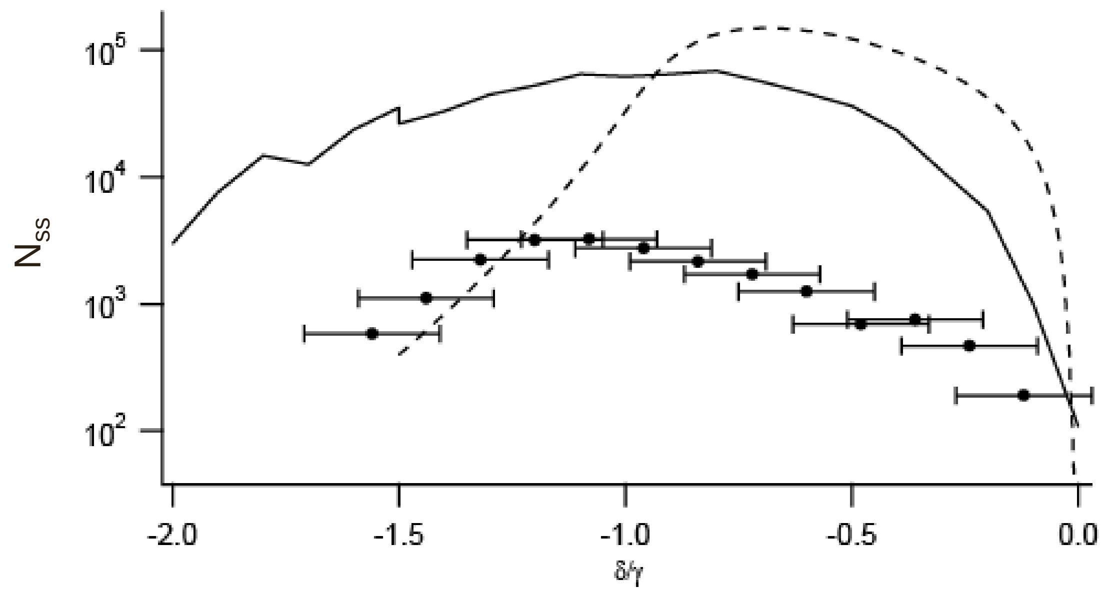
- w_0=1.25 mm
- δ=-0.6γ
- B'=500 G/cm

Detuning:

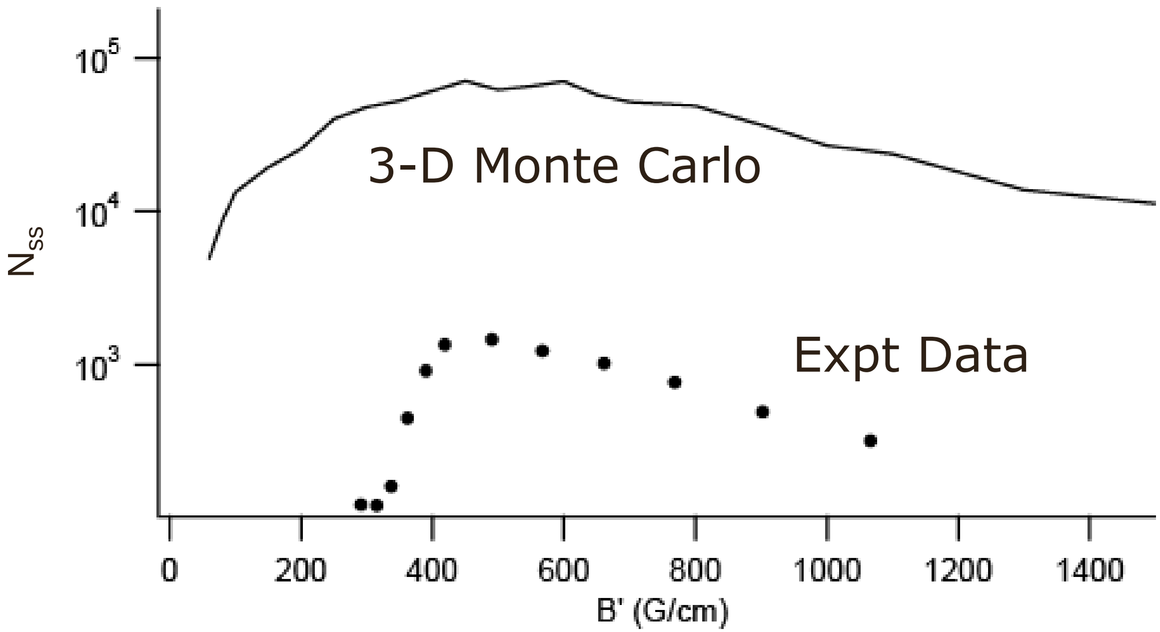
Large DAVLL capture range leads to uncertainty in detuning

Parameters:

- P=1.8 mW
- w_0=1.25 mm
- B' = 500 G/cm



Magnetic field gradient

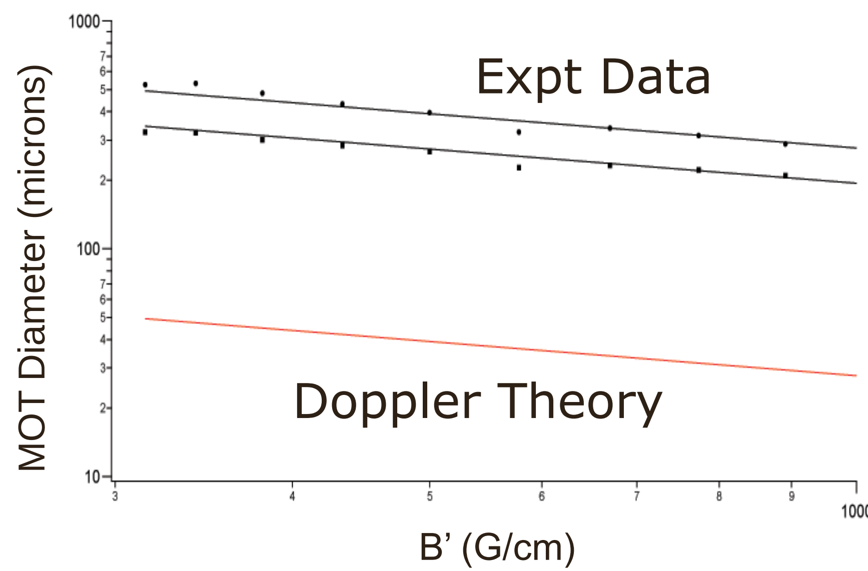


Optimal B-field gradient when Zeeman shift at beam waist = linewidth

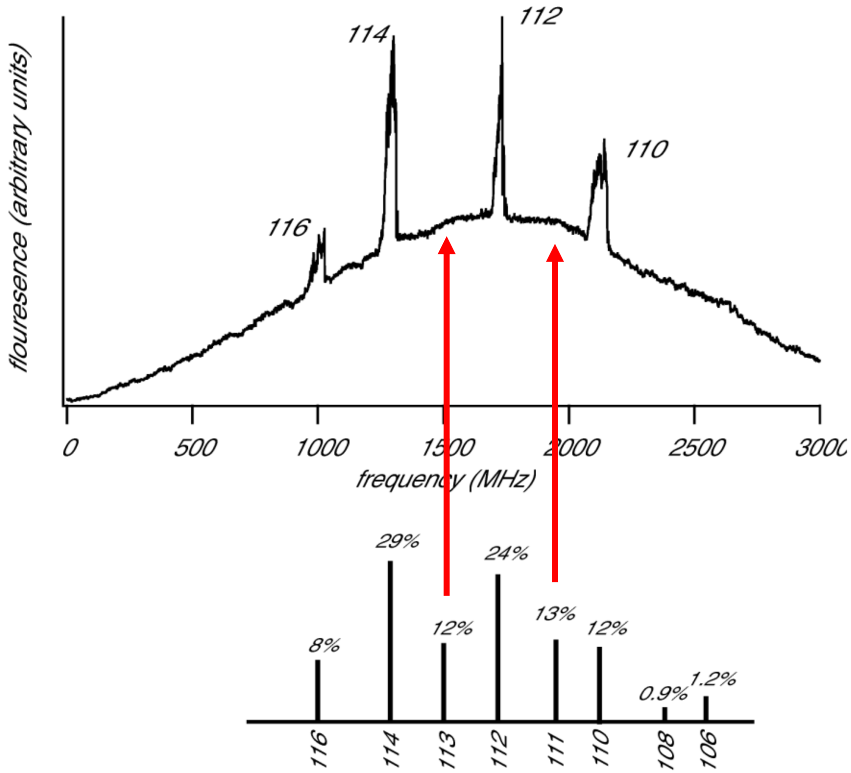
Parameters:
- P=1.8 mW
- w_0=1.25 mm
- δ=-0.6γ

MOT size scales as $1/\sqrt{B'}$ (temperature-limited regime), but absolute size is ~10x Doppler-expected size

Similar results observed in Sr:
X. Xu, et. al, PRA **66**, 011401 (2002)



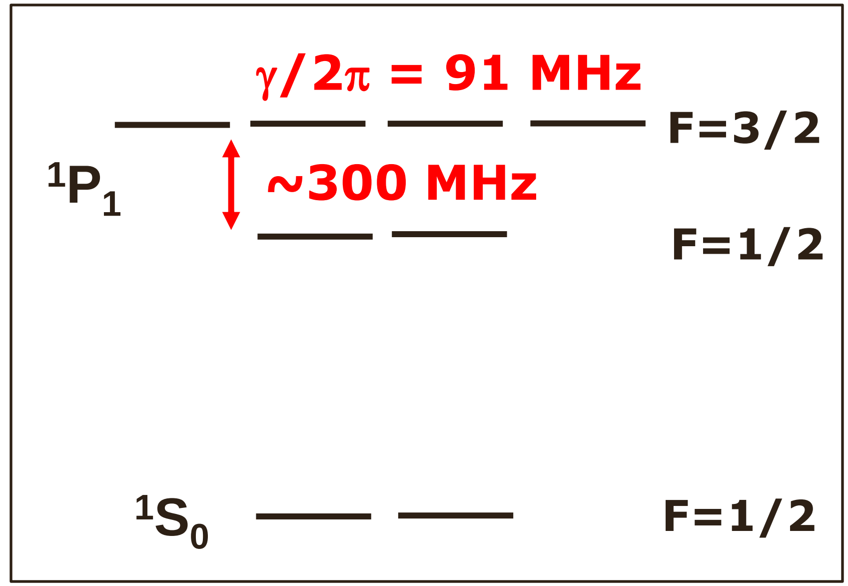
Odd vs. even isotopes



MOT for odd isotopes were not observed.

Similar results observed in Yb:
H. Katori, et. al, PRL **82**, 1116 (1999)

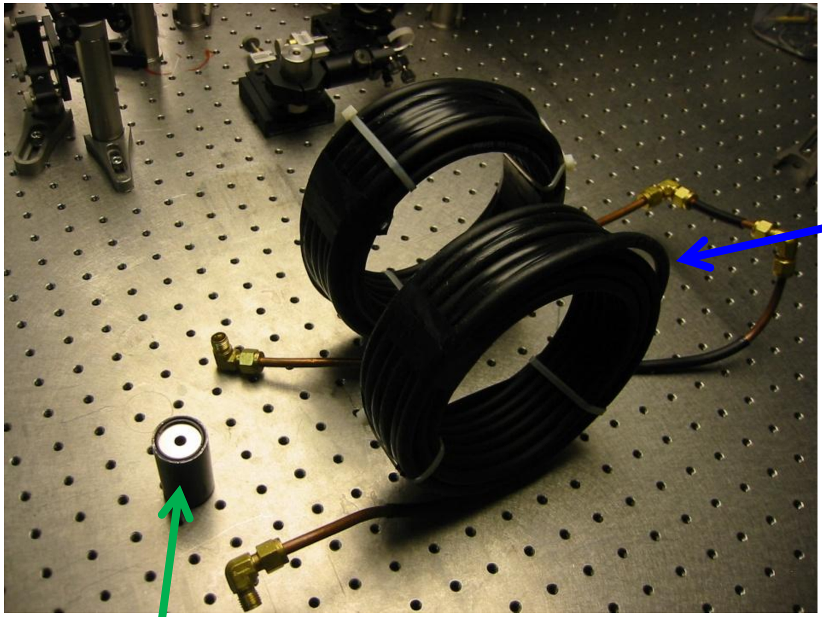
Odd isotopes of Cd (I=1/2):



Linewidth ~ the $^1P_1$ state hyperfine splitting: bad for laser cooling.

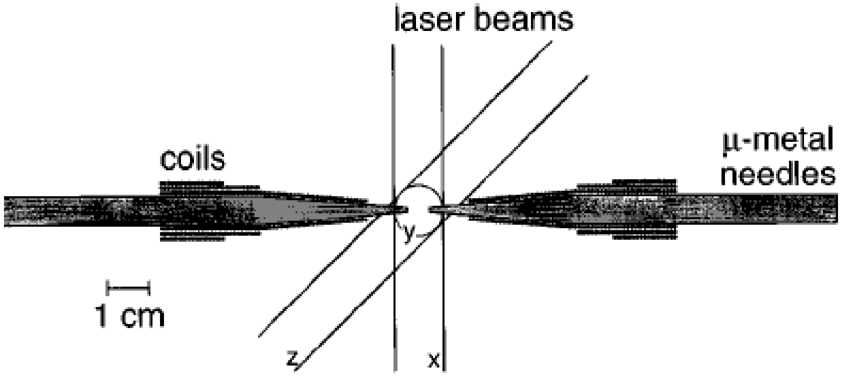
Possible solutions:
- Dichroic MOT
- Operates in a very high B gradient (Paschen-Bach regime)
- Large laser power with large red detuning

Improve Cd MOT: generate even higher B field gradient



AH coil w/ up to 400 Amp
But …
bulky
needs water cooling
B' up to <200 G/cm only

A pair of NdFeB magnets
compact
B' up to 1500 G/cm !
But …
not switchable

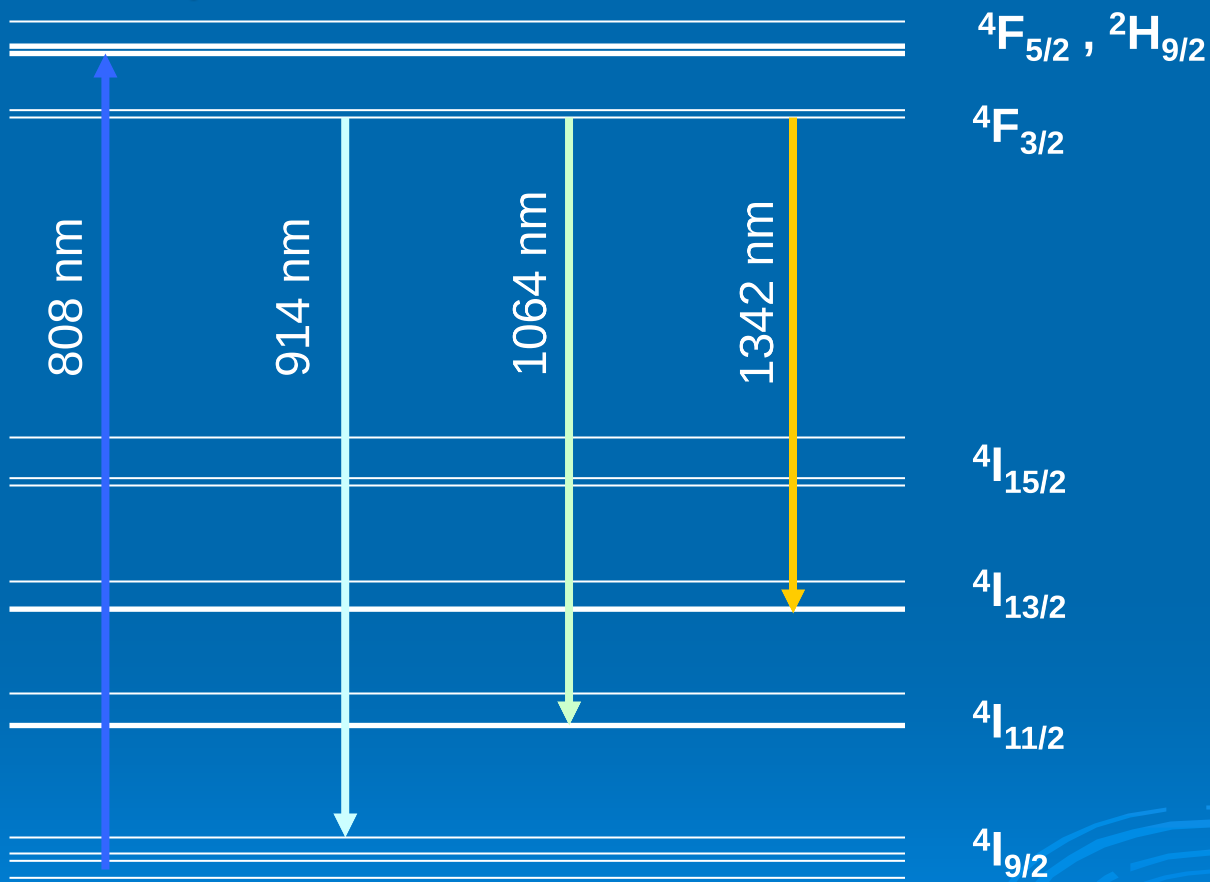


B' up to 10^4 G/cm
compact
switchable

V. Vuletic et al., Europhys. Lett., **36**, 349 (1996)

Improve Cd MOT: generate higher laser power at 229 nm - I

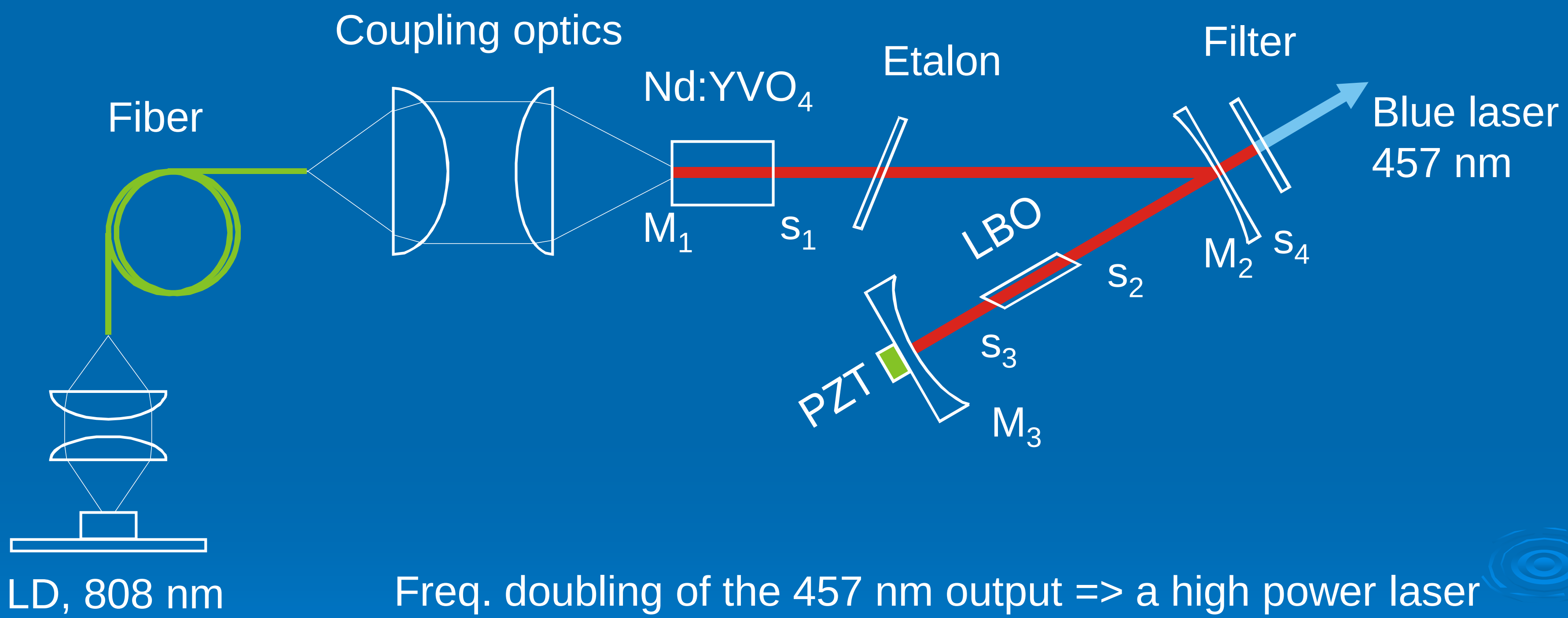
Nd:YVO_4 Crystal Based RGB lasers



(1342, 1064, 914) nm → x 2 → (671, 532, 457) nm

Improve Cd MOT: generate higher laser power at 229 nm - II

Single Mode 457 nm high power DPSS Laser for Ultracold Atomic Physics

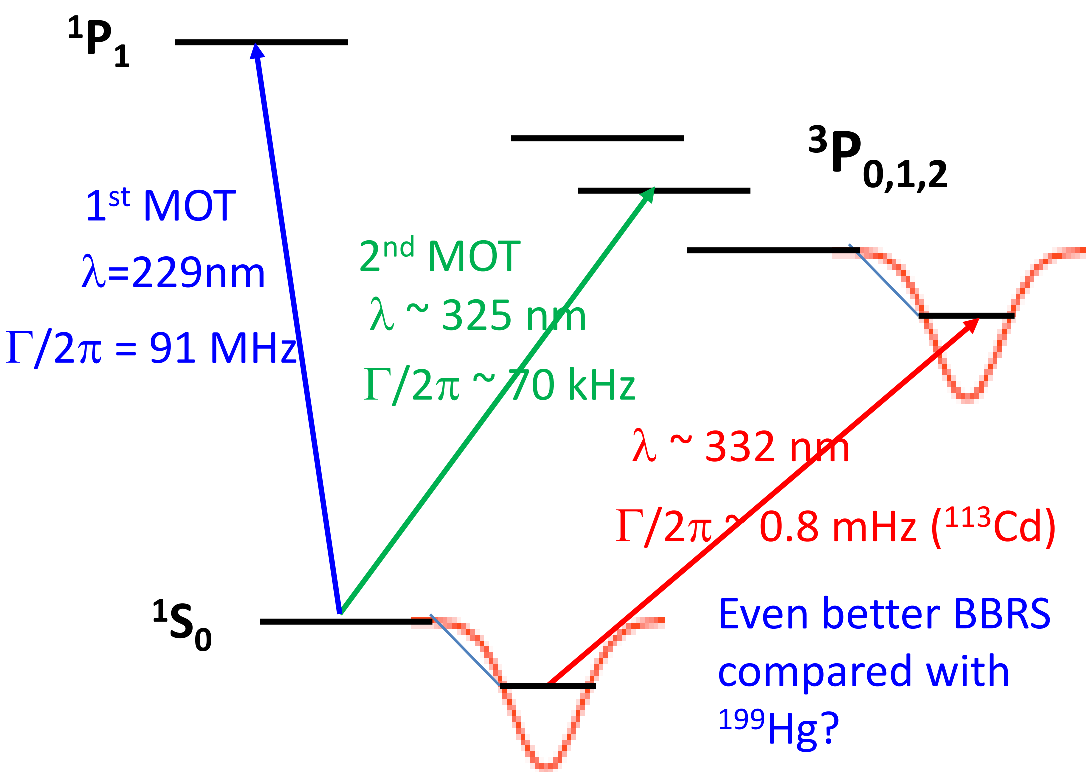


Freq. doubling of the 457 nm output => a high power laser at 229 nm.

Q. H. Xue *et al.*, Opt. Lett. **v. 31**, 1070 (2006)

What can we do with a Cadmium MOT?

Cadmium for an optical lattice clock?



^{199}Hg

$^1S_0$ - $^3P_1$ (2nd MOT)

λ ~ 253.7 nm

Γ/2π ~ 1.3 MHz

$^1S_0$ - $^3P_0$ (clock trans.)

λ ~ 265.6 nm

Γ/2π ~ 111 mHz

Blackbody radiation shift

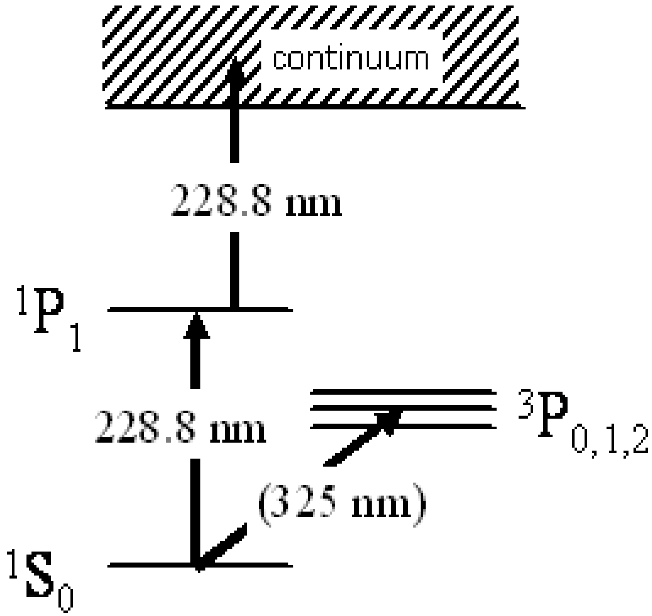
$\Delta\nu/\nu$ (T=300 K) ~ $-1.6\cdot10^{-16}$

BBRS better than Yb, Sr.

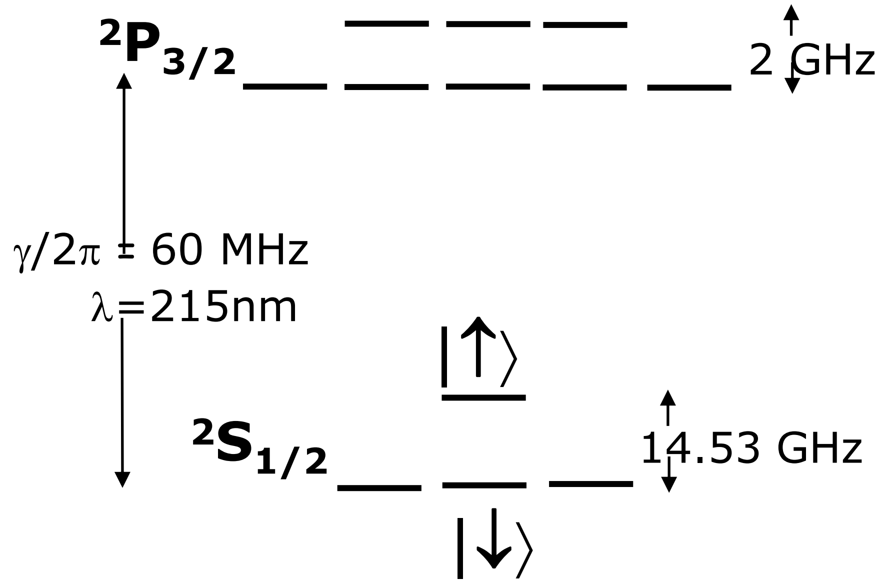
Currently lowest BBRS: $^{27}Al^+$ ion.
$\Delta\nu/\nu$ (T=300 K) ~ $8(3)\cdot10^{-18}$
T. Rosenband *et al., arXiv:physics/0611125*

Hg MOT & Opt Lattice Clock
H. Hacish et al., PRL, **100**, 053001 (2008)

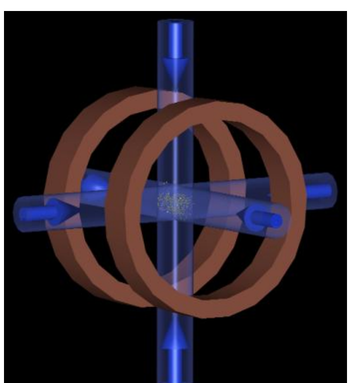
Combining Cd neutrals and ions



Laser cooling work s at both 228.8 nm and 325 nm

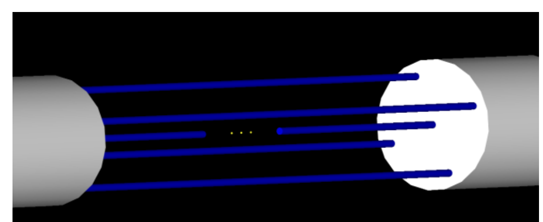


Laser cooling work s at 215 nm



MOT

+

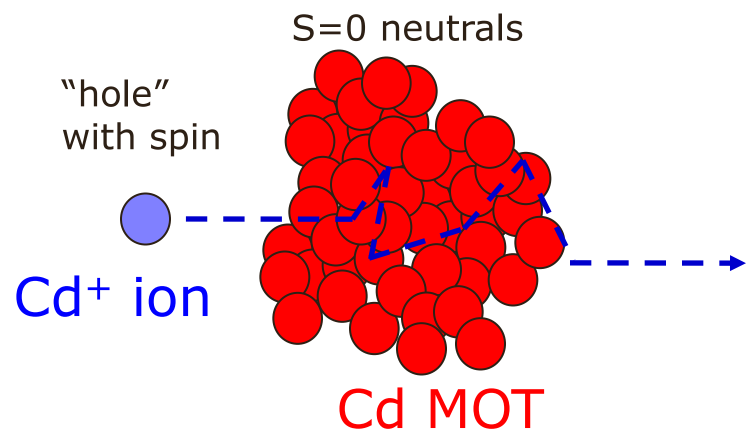


Linear Paul Trap

Combining neutrals and ions

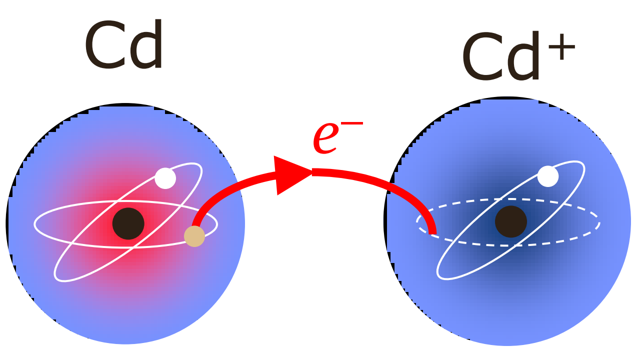
- Transport effects
  - Ultracold charge-exchange collisions
  - “Hole” transport through disordered media
  - Ultracold Quantum chemistry
- Coherence-preserving charge exchange

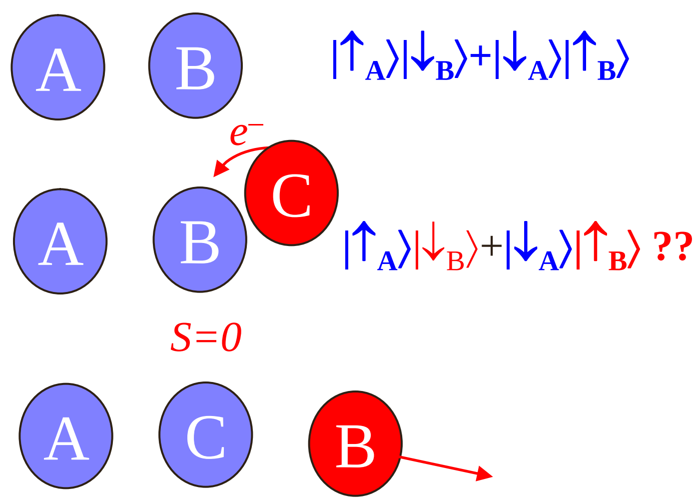
Single ion and a MOT

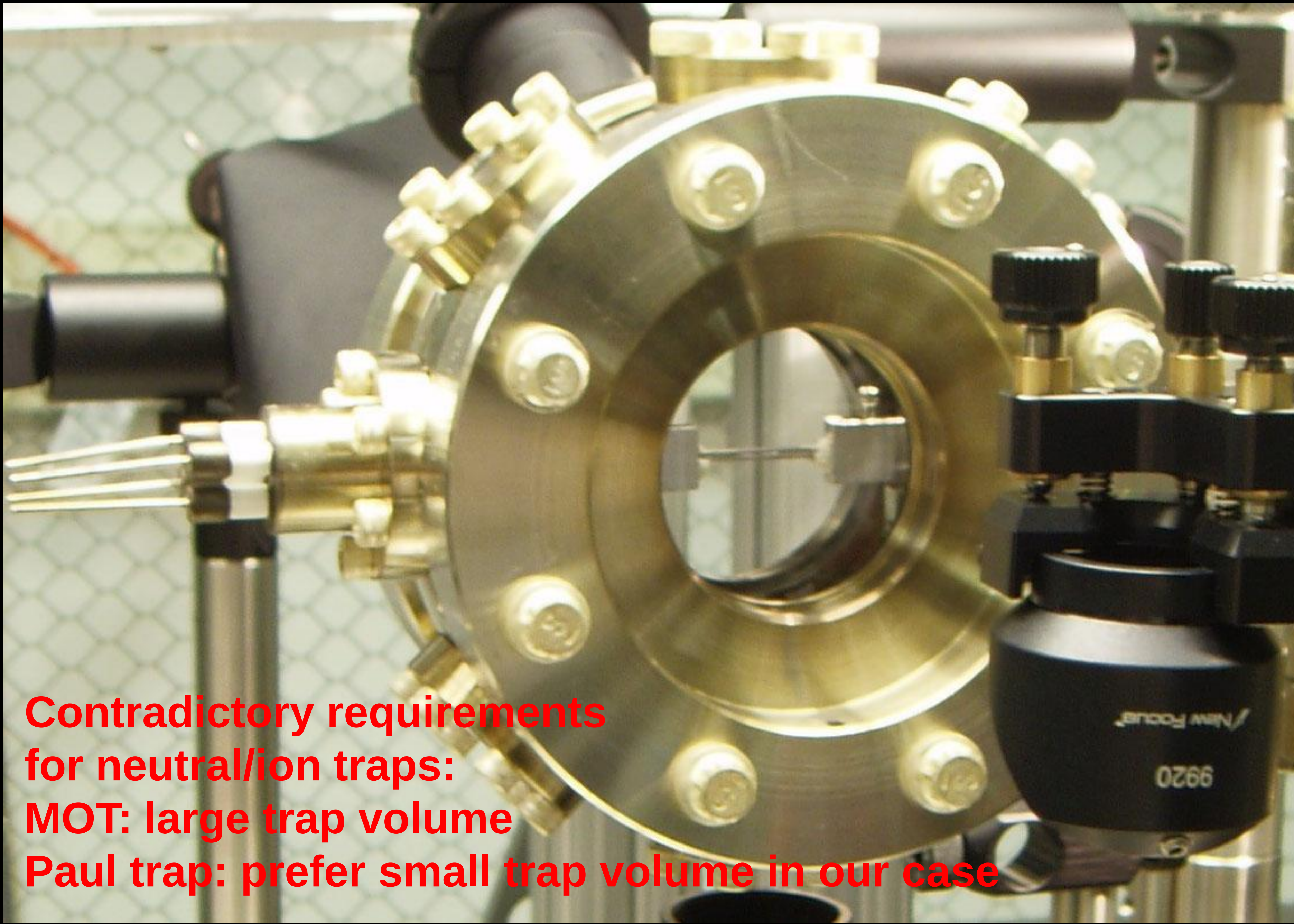


Ensemble of Yb neutrals and ions:
A. Grier, et al. PRL **102**, 223201 (2009)

Single ion and a single neutral atom

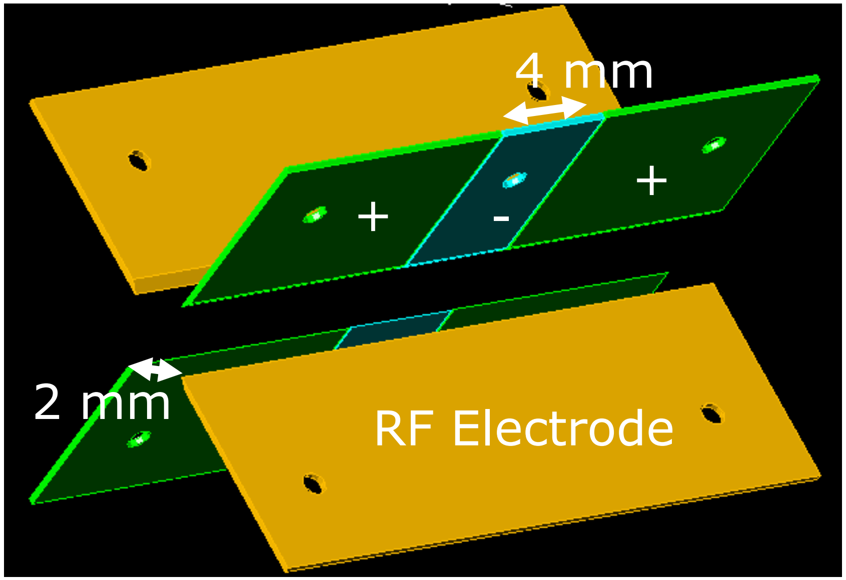


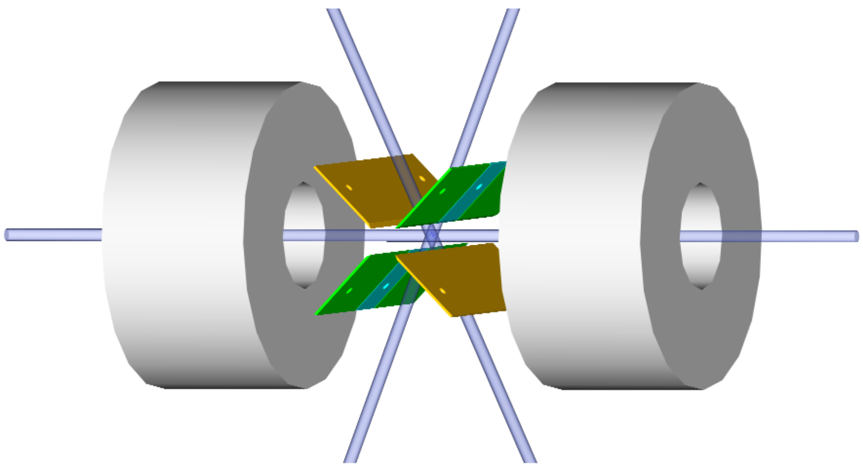


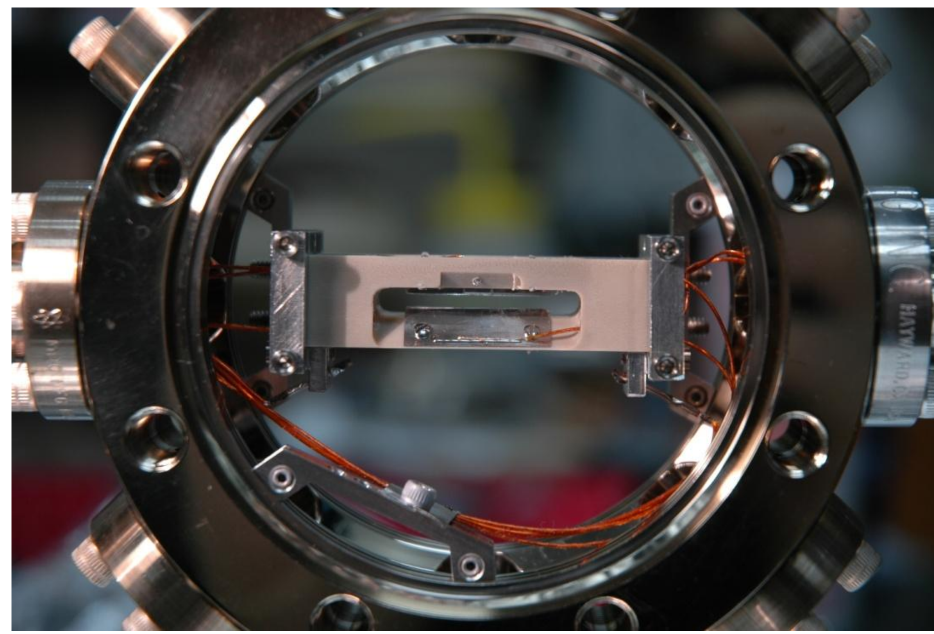


Contradictory requirements for neutral/ion traps:
MOT: large trap volume
Paul trap: prefer small trap volume in our case

Neutral-Ion hybrid-trap design







Yb MOT / ion surface trap: M. Cetina, et al. PRA **76**, 041401(R) (2007)

Summary

- Realized a magneto-optical trap for Cadmium
  - MOT with extreme trapping parameters:
    large linewidth, short wavelength, low laser power, PI loss
  - Determined photo-ionization cross-section
  - Characterized the data with 1D and 3D models

- Outlook
  - Possible research avenues in the future
  - Key enabling techniques for Cd MOT and proposed experiments

University of Michigan
Trapped Ion Quantum Computing

http://iontrap.physics.lsa.umich.edu/

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