Francium studies at LNL

E.Mariotti

mariotti@unisi.it, https://sites.google.com/a/unisi.it/emilio-mariotti

CNISM

Dipartimento di Scienze Fisiche, della Terra e dell'Ambiente

Sezione di Fisica

Fundamental Physics using Atoms, RIKEN 2015/12/1

The "traprad"/"francium"/"wade" collaboration

Ferrara University and INFN:
R.Calabrese, (H.Arikawa), (S.N.Atutov), (T.Ishikawa), (G.Mazzocca), (Z.Peshev), (G.Stancari), L.Tomassetti

Legnaro National Laboratories INFN:
L.Corradi, A.Dainelli

Pisa University:
(P.Minguzzi), (S.Sanguinetti), M.L.Chiofalo

Siena University:
E.Mariotti, S.Agustsson, (Y.Aoki), G.Bianchi, (V.Coppolaro), (C.de Mauro) (K.Kato), A.Khanbekyan, C.Marinelli, (L.Marmugi), (L.Moi), (N. Papi), A.Vanella, (S.Veronesi)

University College London:
Ferruccio Renzoni

Trento University:
Leonardo Ricci

The "traprad"/"francium"/"wade" location (?)

The "traprad"/"francium" (real) location

Outline

- **Introduction/Motivation**

- The LNL apparatus

- Precision frequency measurements
  Detection of lines by change in trapped atom number
  Application of Light Induced Atom Desorption

- Perspectives

(Bad) facts about francium

	Mass no. (A)	Half-life
Fr	202	0.34 s
	203	0.55 s
	205	3.85 s
	206	15.9 s
	207	14.8 s
	209	50 s
	211	3.1 min
	213	34.6 s
	220	27.4 s
	223	21.8 min
	224	3.3 min
Fr	225	4.0 min
	226	48 s
	227	2.47 min
	228	39 s
	230	19.1 s
	232	5 s

Fr has no stable isotopes

The longest lifetime is 22min

There is at most a tea spoon of francium in the whole Earth at any given time

$\Rightarrow$ **continuos production and trapping for further studies is necessary**

^{210}Fr $\rightarrow$ 3.2 min

Facts about francium

-First spectroscopy measurements at CERN (ISOLDE):

S. Liberman *et al.*, C. R. Acad. Sci. Ser. B **286**, 253 (1978).
Francium is produced by spallation reactions in Th or U Carbide targets bombarded with protons: 10^9 **Fr/s**.

A = 208-213, 220-228

-Francium Magneto-Optical Trap (MOT):

J.E. Simsarian *et al.*, PRL **76**, 003522 (1996). (STONY-BROOK) A = 210
S.N. Atutov *et al.*, JOSA B **20**, 953 (2003). (LEGNARO) A = 209-211
Nuclear fusion-evaporation reactions in a Au target: 10^6 **Fr/s**.

Z.-T. Lu *et al.*, PRL **79**, 994 (1997). (Boulder/Berkeley)
Radioactive source: Francium produced in the decay chain $^{229}\mathrm{Th} \rightarrow {}^{225}\mathrm{Ra} \rightarrow {}^{225}\mathrm{Ac} \rightarrow {}^{221}\mathrm{Fr} \Rightarrow 10^4$ **Fr/s**.

Commissioning of the Francium Trapping Facility at TRIUMF

M. Tandecki et al (Submitted on 12 Dec 2013)

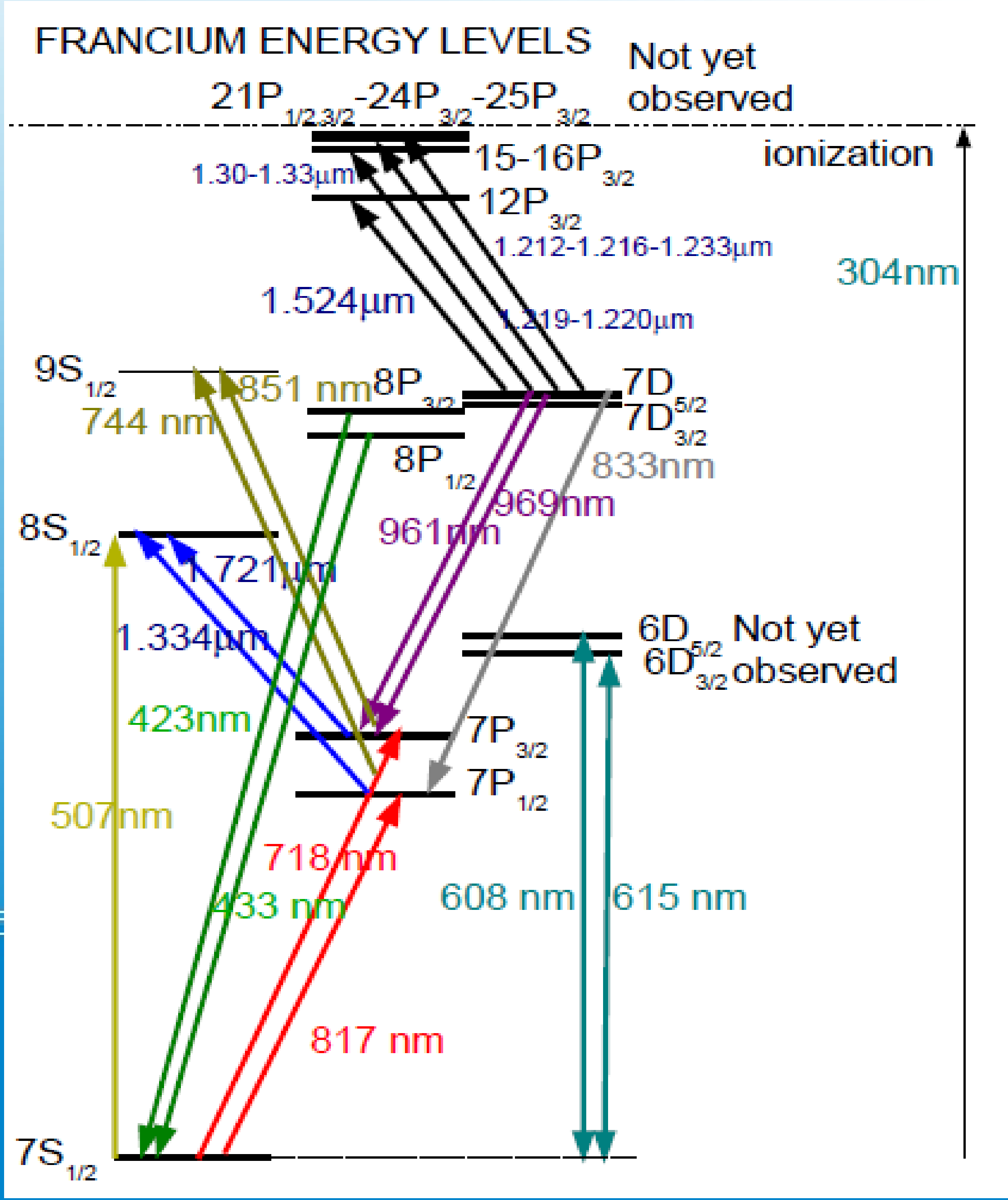
A = 207, 209, 221

Decay-Assisted Laser Spectroscopy of Neutron-Deficient Francium

Phys. Rev. X 4, 011055 – Published 28 March 2014

K. M. Lynch etal. A = 202-207, 218-221, 229, 231

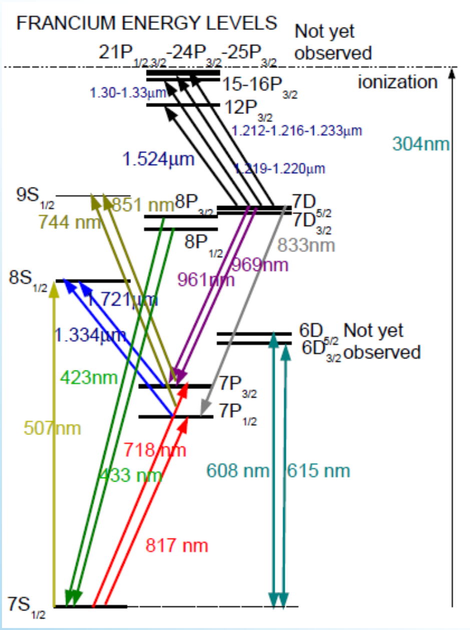
Facts about francium



(Interesting) facts about francium

spectroscopically poorly known
"simple" electronic structure
several isotopes suitable for trapping
enhanced P and T violations (Z=87)

$\Downarrow$



Parity Violation for the 7S – 8S transition:
test of neutral weak interactions

Parity Violation for the ground state hyperfine atomic transition: measurement of Nuclear Anapole Moment (TRIUMF/ISAC, production rate 10^{10} Fr/s, trap number 10^7 Fr)

Search for permanent Electric Dipole Moment:
test of Time reversal violation and SUSY
(RNCP @Sendai, trap number 10^8 Fr)

Outline

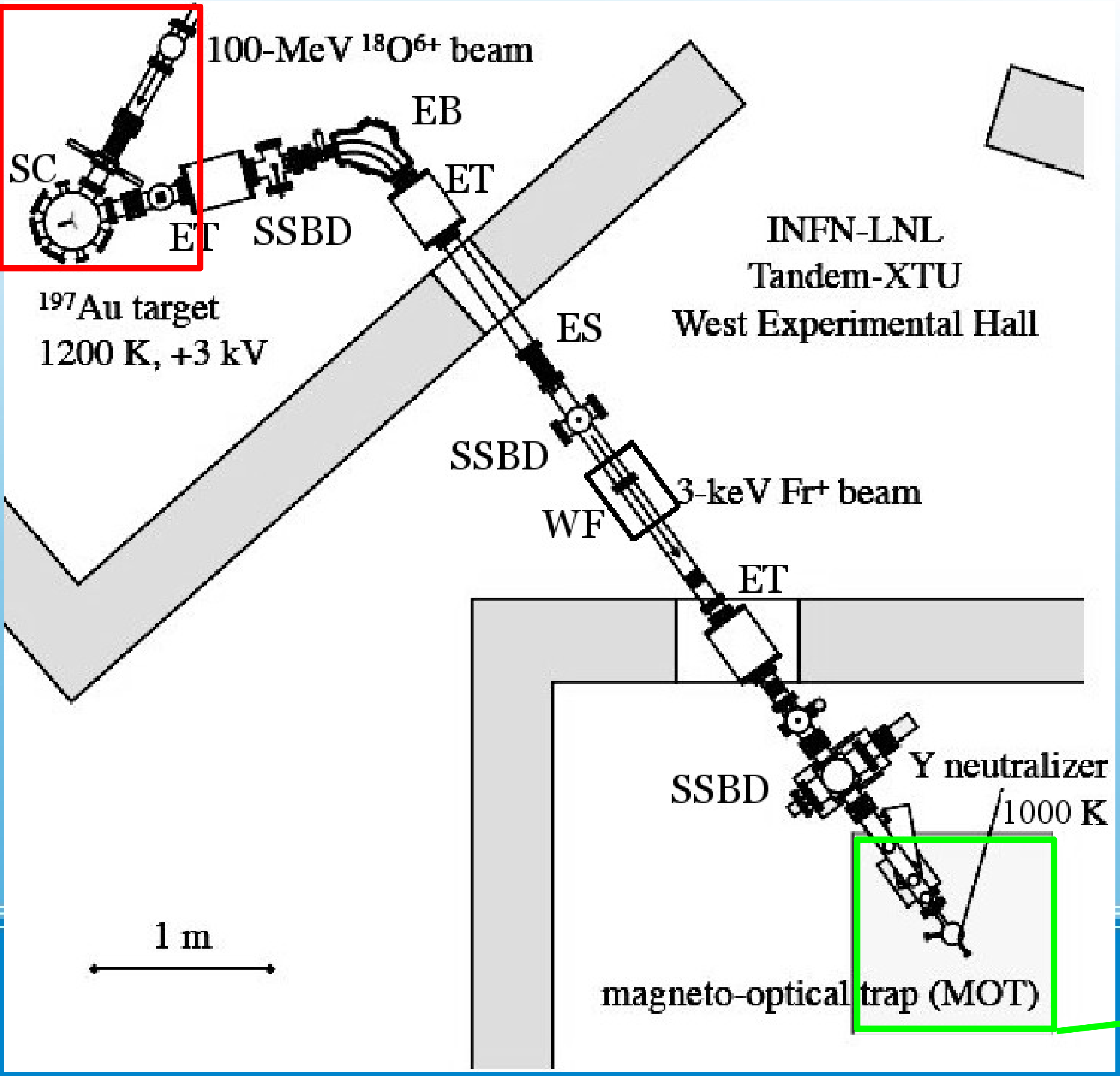
- Introduction/Motivation

- The LNL apparatus

- Precision frequency measurements
  Detection of lines by change in trapped atom number
  Application of Light Induced Atom Desorption

- Perspectives

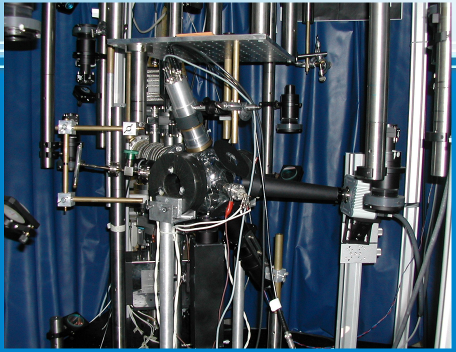
The “traprad”/“francium”/“wade” experiment



Fr production

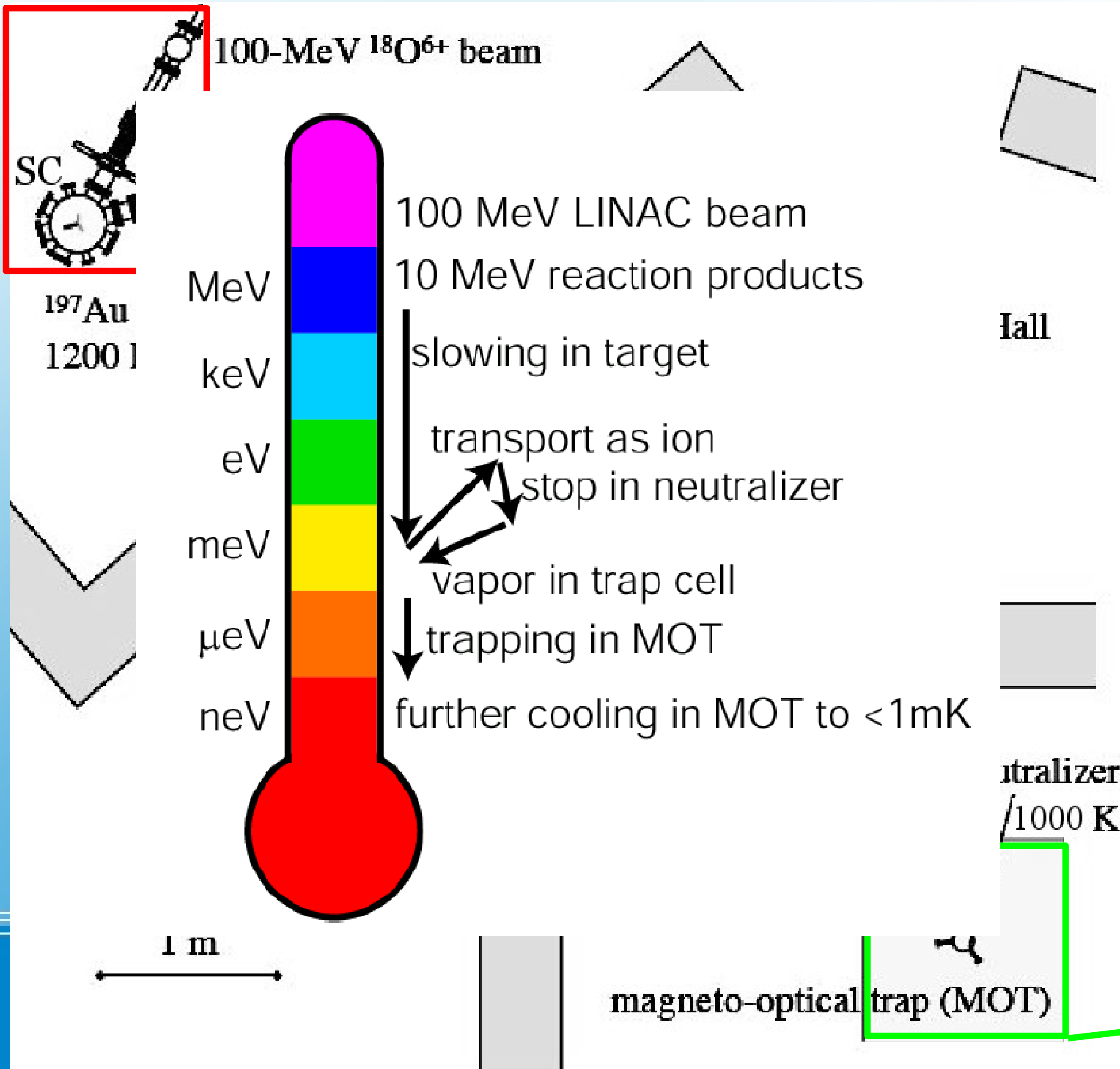
$^{197}Au + ^{18}O \rightarrow xn + ^{215-x}Fr$

Fr^+ (and Rb^+) ions transport at 3 keV



Eur Phys J ST 150 389 (2007)

The "traprad"/"francium"/"wade" experiment



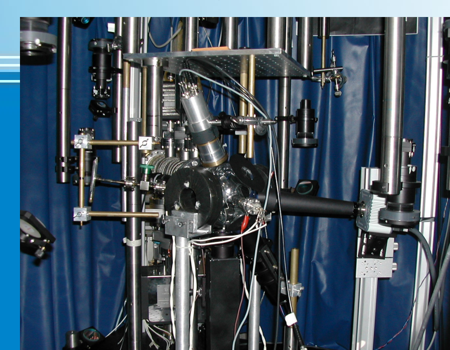
UNIVERSITÀ DI SIENA 1240

L.N.L.

Fr production

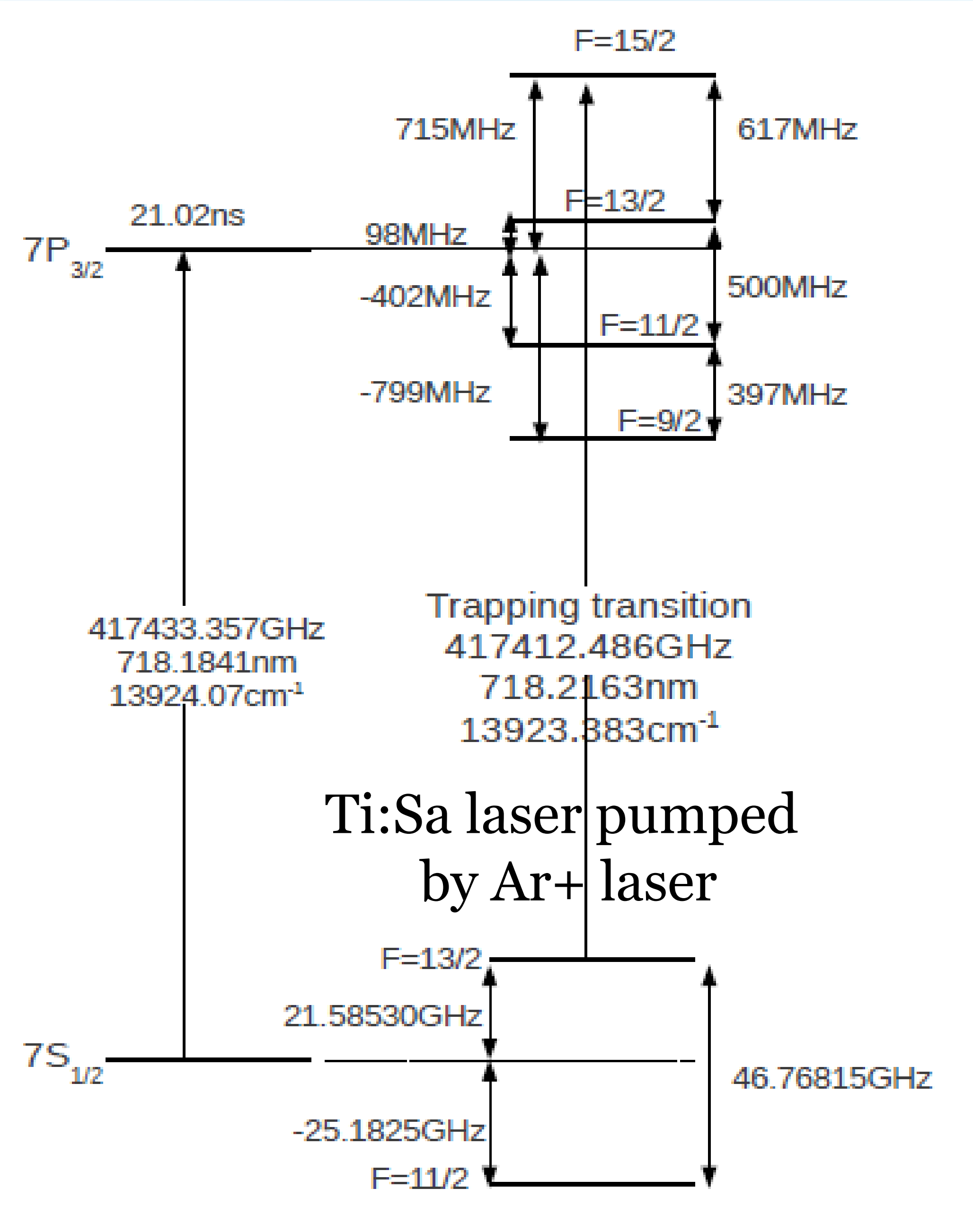
$^{197}Au + ^{18}O \rightarrow xn + ^{215-x}Fr$

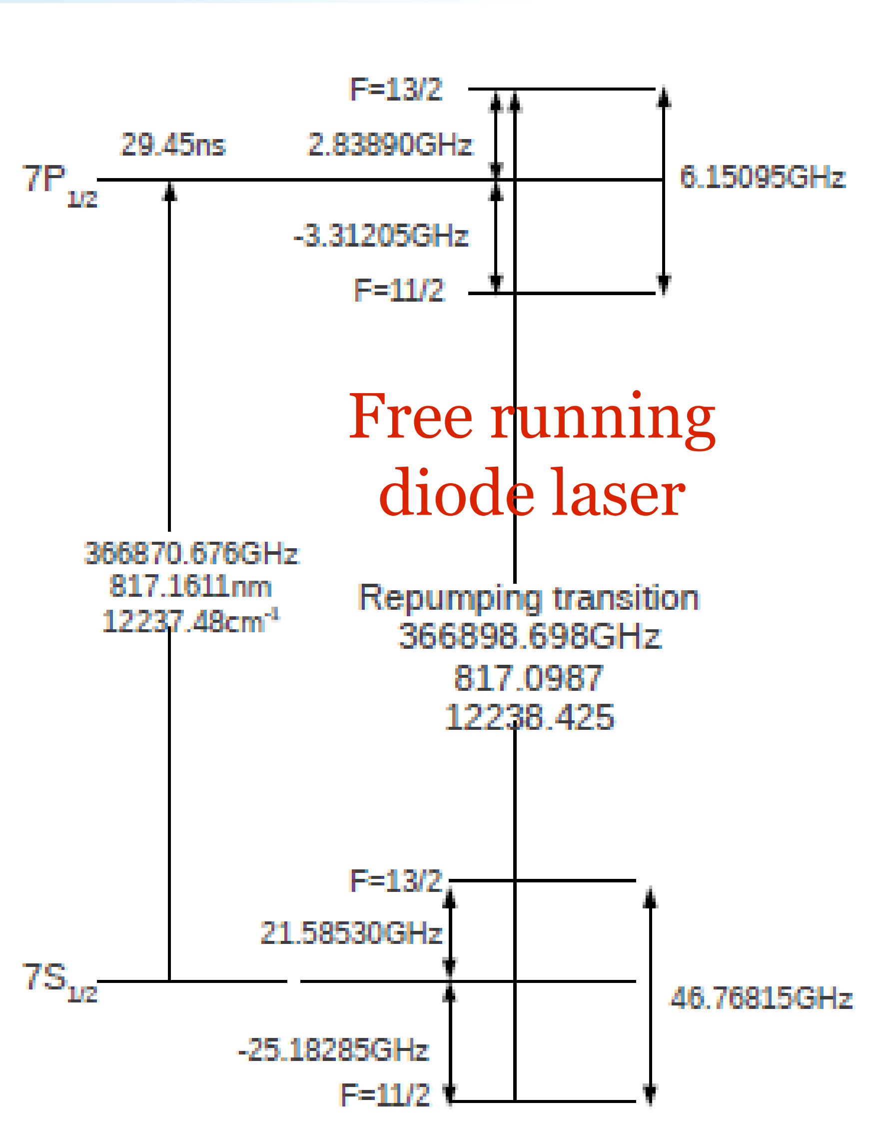
Fr^{+} (and Rb^{+}) ions transport at 3 keV



Eur Phys J ST 150 389 (2007)

The trapping and repumping transitions





The MOT cell

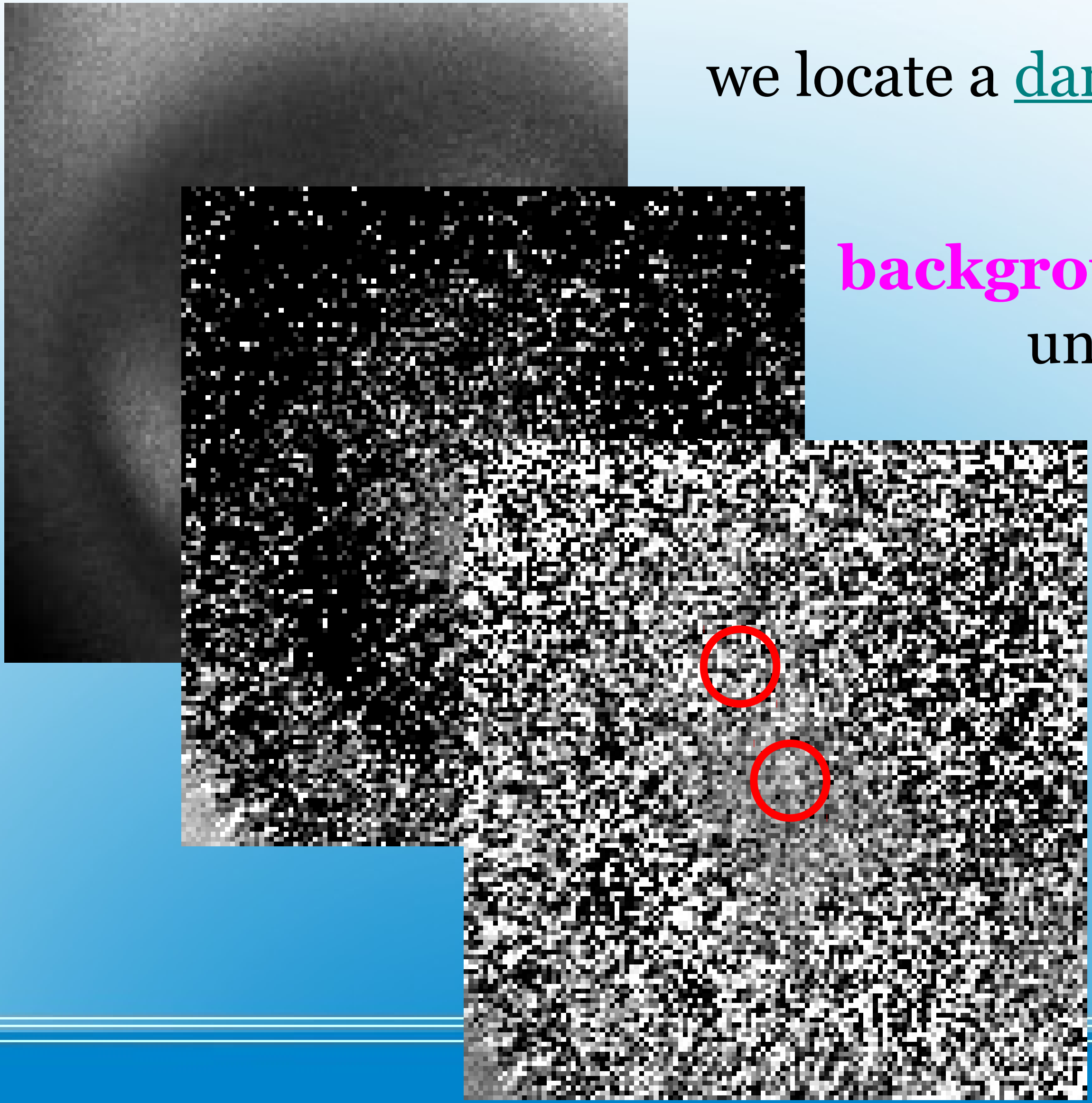
$\phi_{Au} = 5.1$ eV

$\phi_{Y} = 3.1$ eV

$I = 4.1$ eV

$$\frac{n_+}{n_a} = \frac{g_+}{g_a} \exp\left(\frac{\phi - I}{k_B T}\right)$$

CCD Detection of the MOT

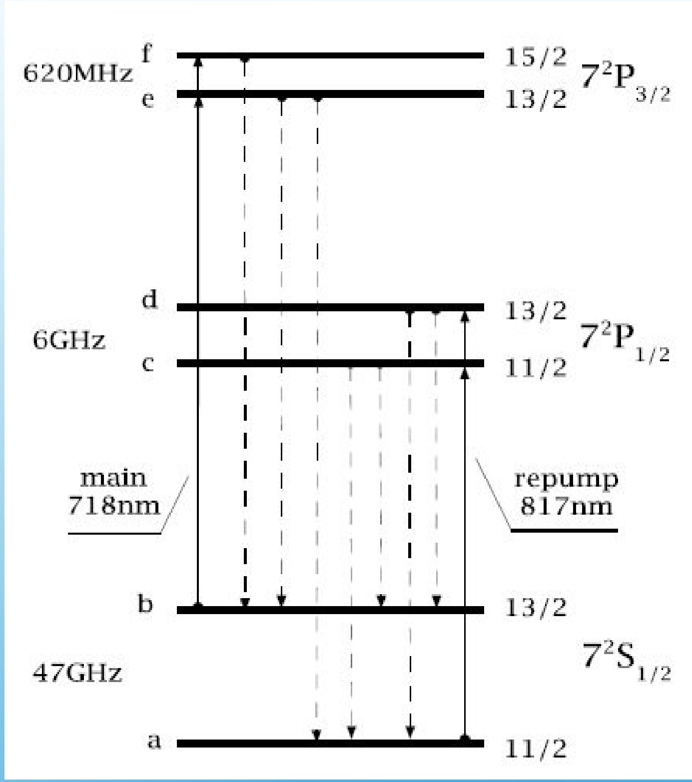


we locate a dark region behind the MOT

background subtraction:
uniform image

weighted background subtraction: compensation for laser intensity fluctuations

Calibration power-number of atoms



$$H = \hbar \begin{pmatrix} 0 & 0 & A & A & 0 & 0 \\ 0 & \omega_b & 0 & 0 & C & C \\ A^* & 0 & \omega_c & 0 & 0 & 0 \\ A^* & 0 & 0 & \omega_d & 0 & 0 \\ 0 & C^* & 0 & 0 & \omega_e & 0 \\ 0 & C^* & 0 & 0 & 0 & \omega_f \end{pmatrix}$$

hyp: trap laser detuning $-5\gamma_f$

$$\Gamma = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \gamma_c & 0 & 0 & 0 \\ 0 & 0 & 0 & \gamma_c & 0 & 0 \\ 0 & 0 & 0 & 0 & \gamma_f & 0 \\ 0 & 0 & 0 & 0 & 0 & \gamma_f \end{pmatrix}$$

Rb: 1pW 1400 atoms

Fr: 1pW 1900 atoms

noise level less than 30 atoms

Electronic noise: 3 atoms, shot noise: 8 atoms

Francium trapping

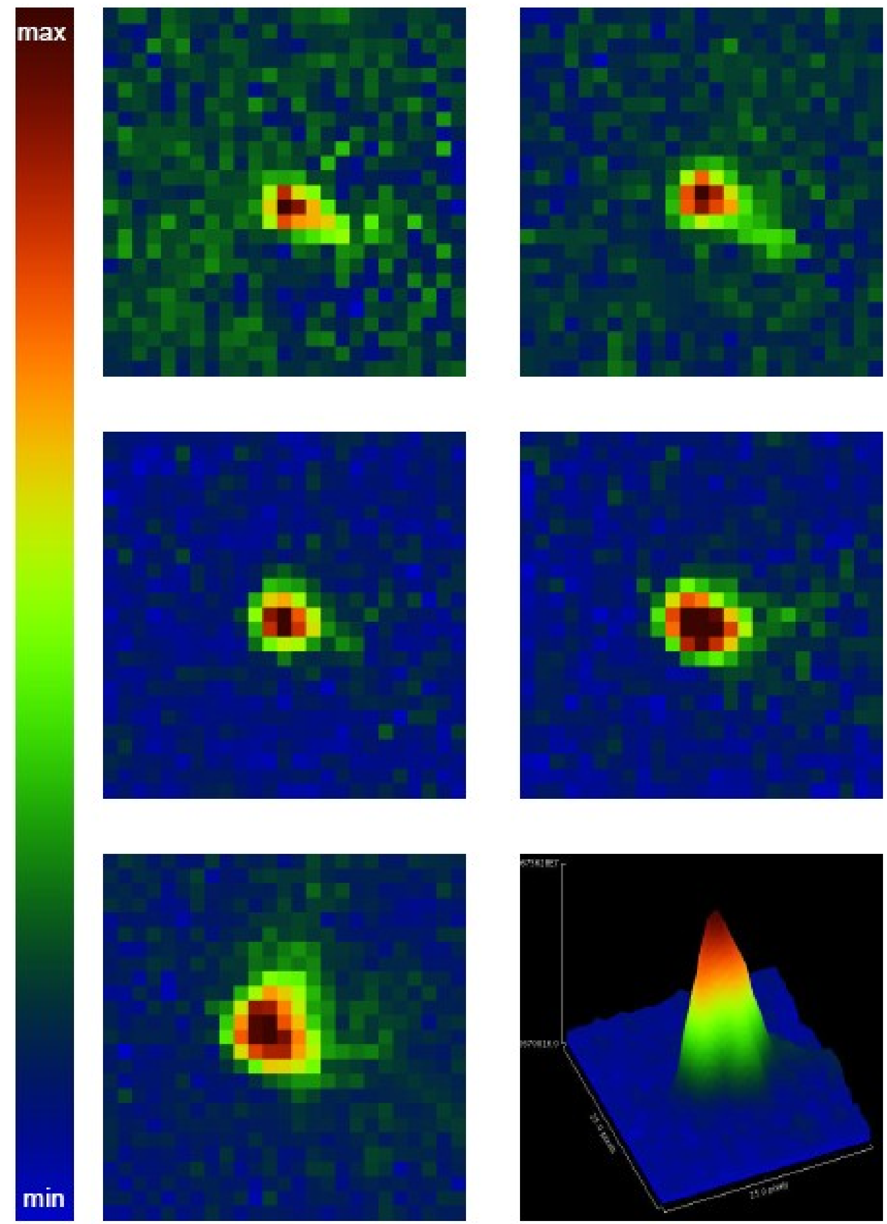
220 atoms

450 atoms

560 atoms

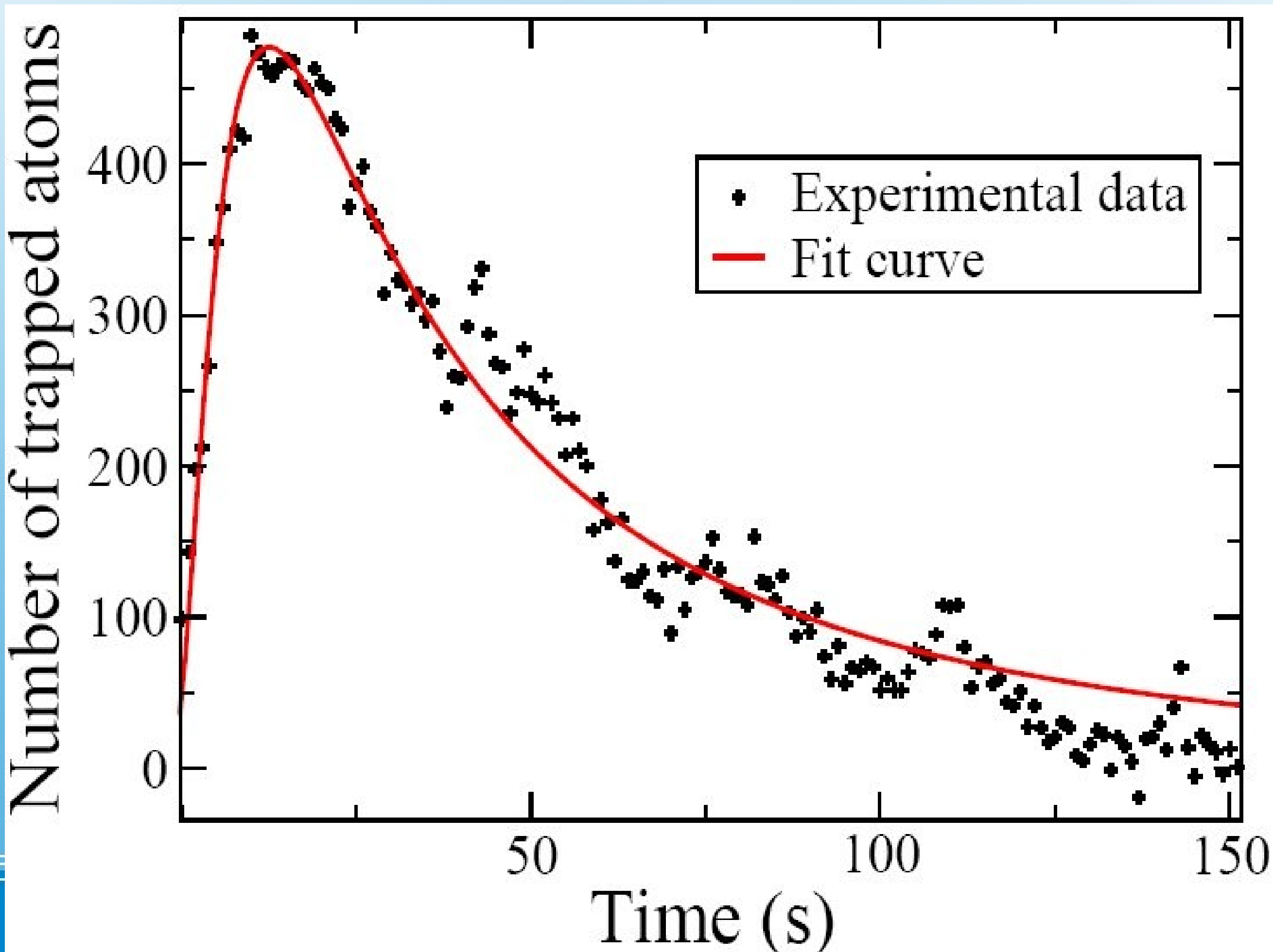
930 atoms

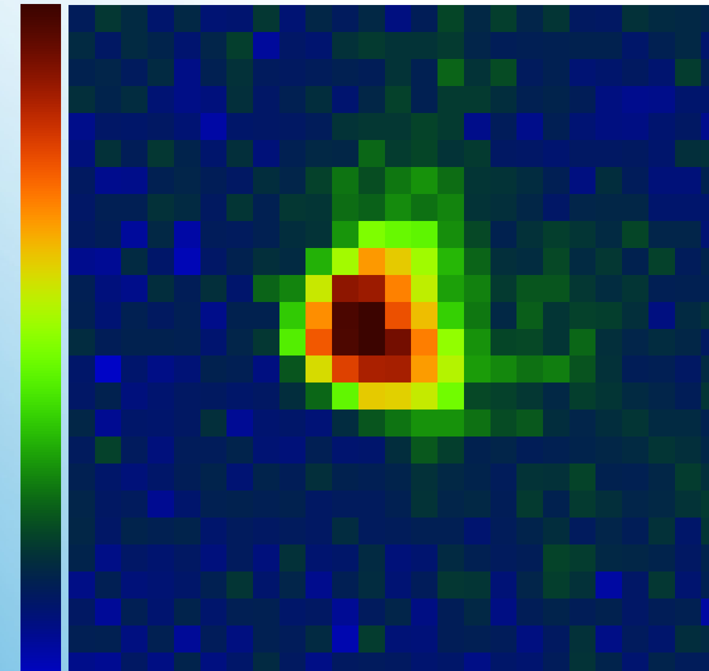
1100 atoms

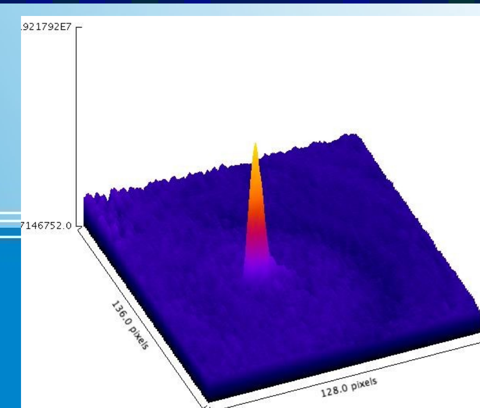


Francium trapping

accumulation in the cold yttrium and fast release
by suddenly switching on the heating of neutraliser

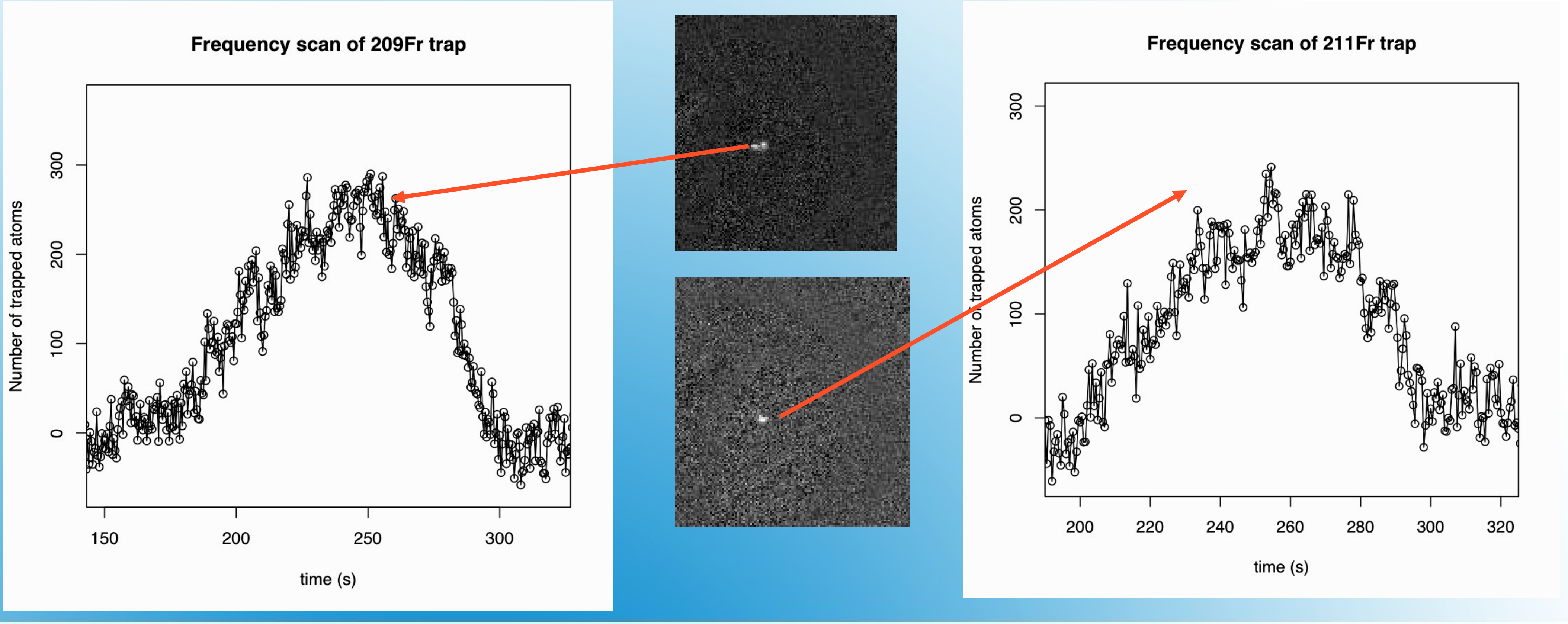






up to 10000 atoms !!

Other Fr isotopes (209, 211)



Melting the target.....

....means to start since the beginning!
(and fight with radioprotectors)

....breaking the cell
or the neutralizer,
preparing a wrong coating,
cumulating too much Rb,
exhausting the argon tube,

....

...again means to start since the beginning!

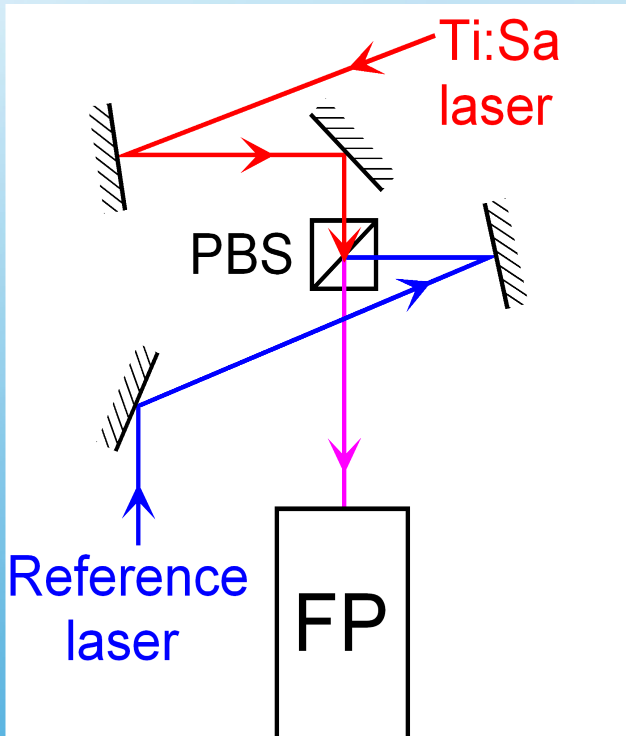
A few days of beam time per year

Outline

- Introduction/Motivation
- The LNL apparatus
- Precision frequency measurements
  - Detection of lines by change in trapped atom number
  - Application of Light Induced Atom Desorption
- Perspectives

Precision measurements

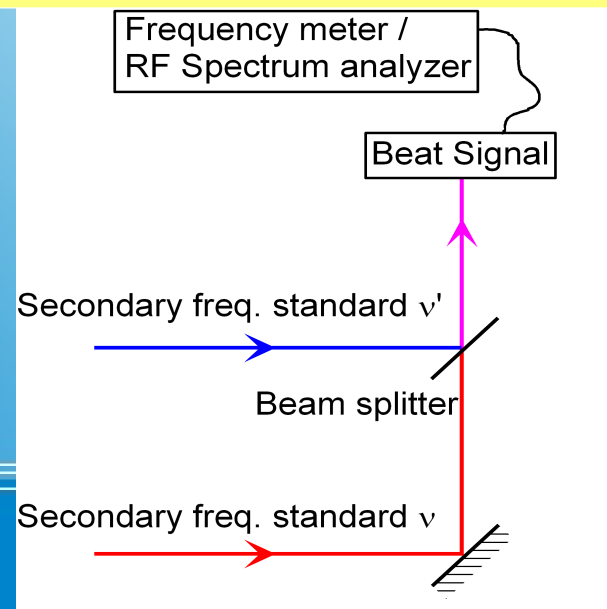
We compare the frequency of 2 lasers transmitted by a confocal FP cavity (finesse 200, FSR 2 GHz) .....



$$\nu_i \cdot n(\nu_i) = \frac{c}{4d}\left(N_i - \frac{2\psi(\nu_i)}{\pi}\right), \quad i = 1,2$$

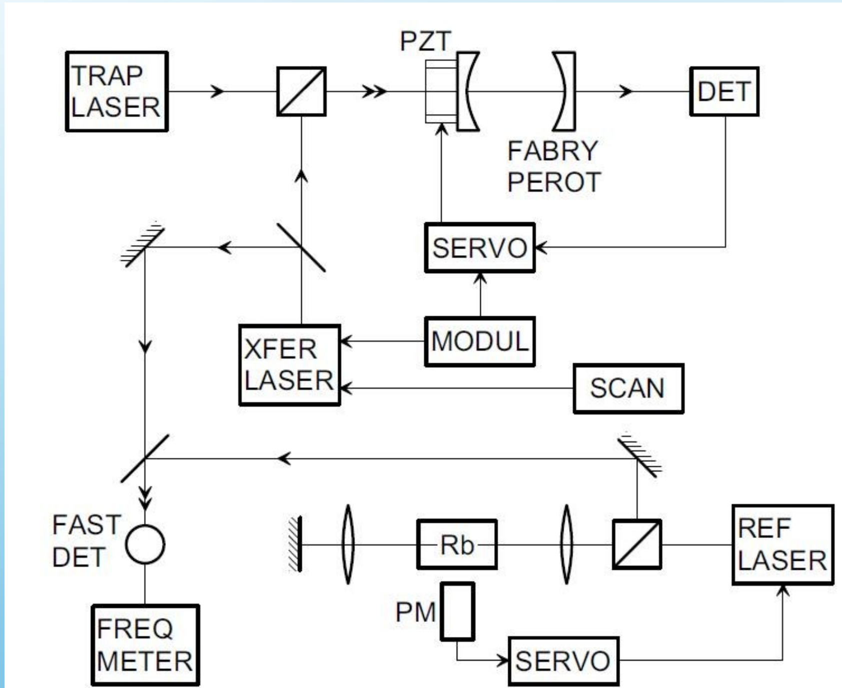
$$\Rightarrow \nu_2 \; n(\nu_2) - \nu_1 \; n(\nu_1) = \frac{c}{4d}\,(N_2 - N_1)$$

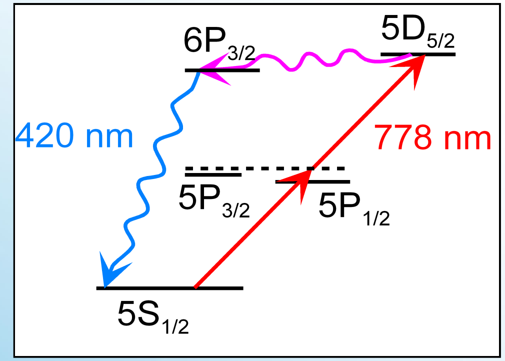
$$\nu_2 \,\frac{n(\nu_2)}{n(\nu_1)} = \nu_1 + \frac{c}{4d\; n(\nu_1)} \cdot (N_2 - N_1)$$



....Measuring the beat signal with a frequency meter (accuracy better than 300 kHz)

Precision measurements





Secondary frequency standard:
Rb 5S–5D$_{5/2}$ 2 photon transition @ 778 nm
measured with 8 kHz accuracy

Isotope	209	210	211
Trapping freq. (GHz)	417415.0914(90)	417412.4493(90)	417412.6303(90)
Repumping freq. (GHz)	366897.43(5)	366898.70(5)	366895.57(5)

Accuracy:

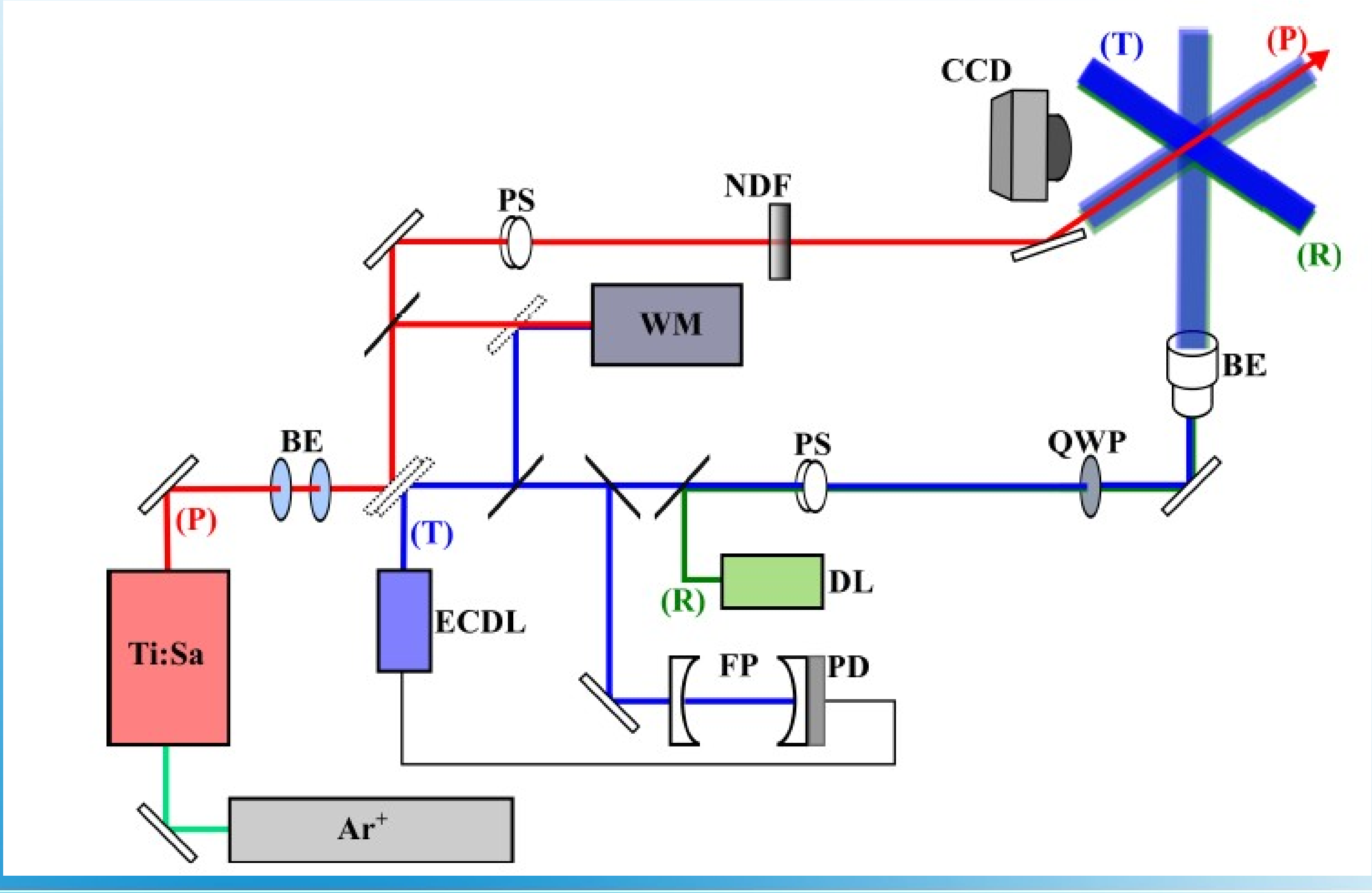
Calibration	5 MHz
Fabry-Perot maxima	2 MHz
Refractive index of air	2 MHz
TOTAL	9 MHz

Published in Opt. Lett. 34, 893,2009

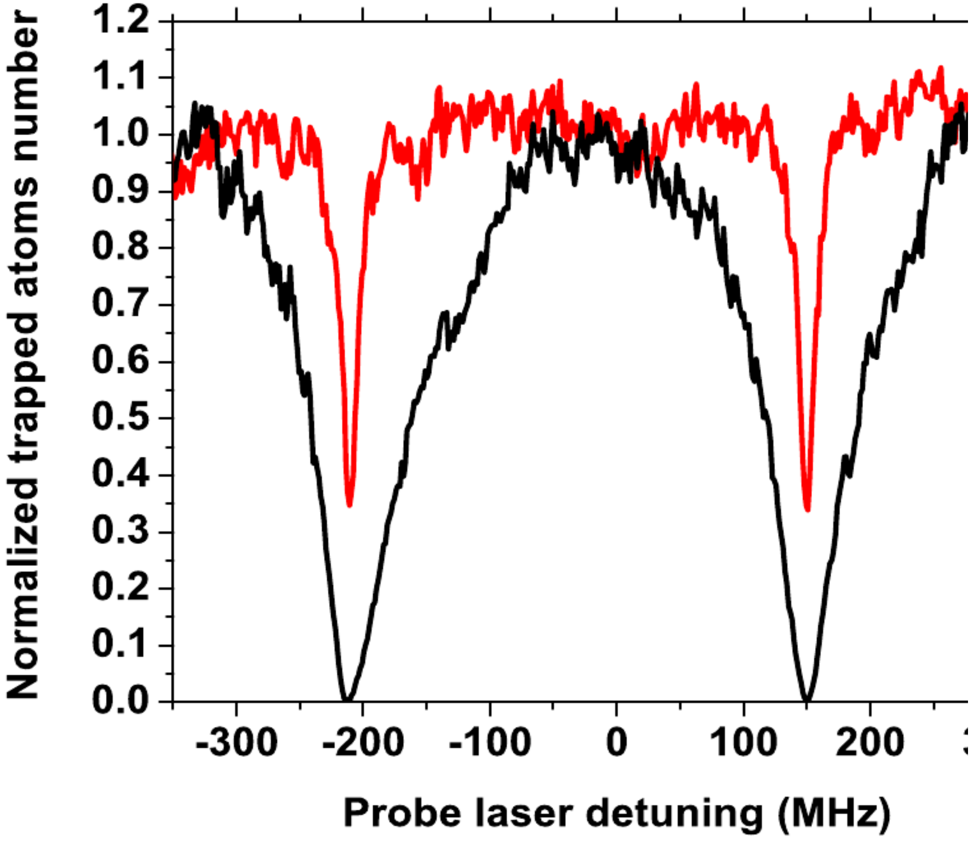
Outline

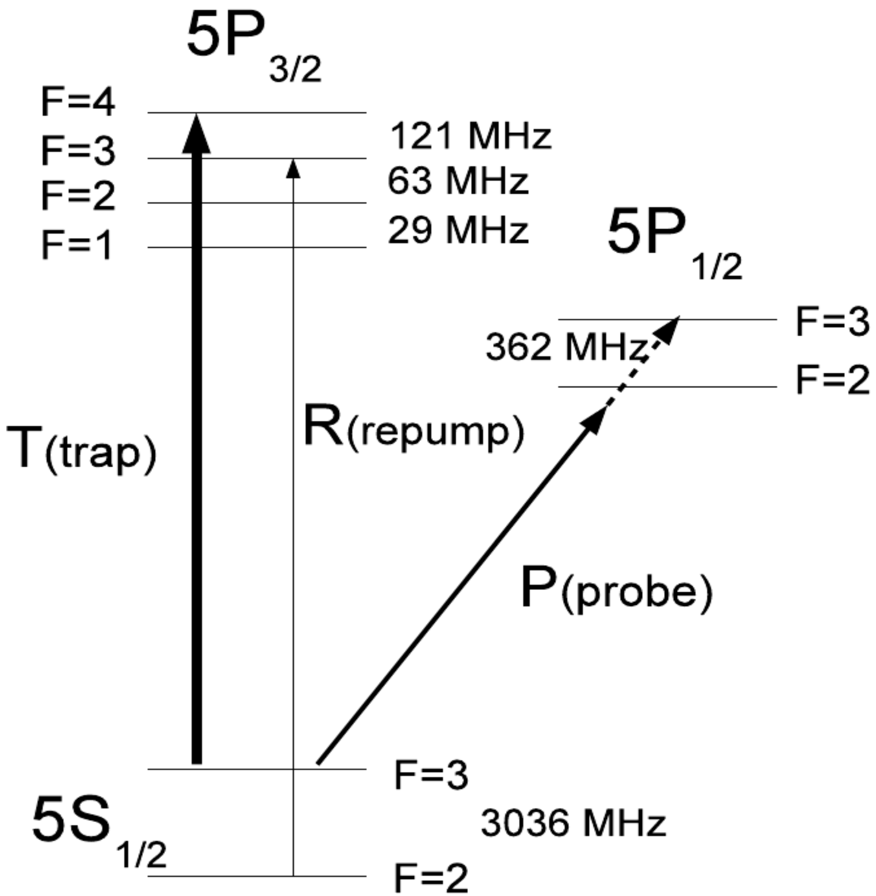
- Introduction/Motivation
- The LNL apparatus
- Precision frequency measurements
  Detection of lines by change in trapped atom number
  Application of Light Induced Atom Desorption
- Perspectives

Detection setup (Rb or Fr)

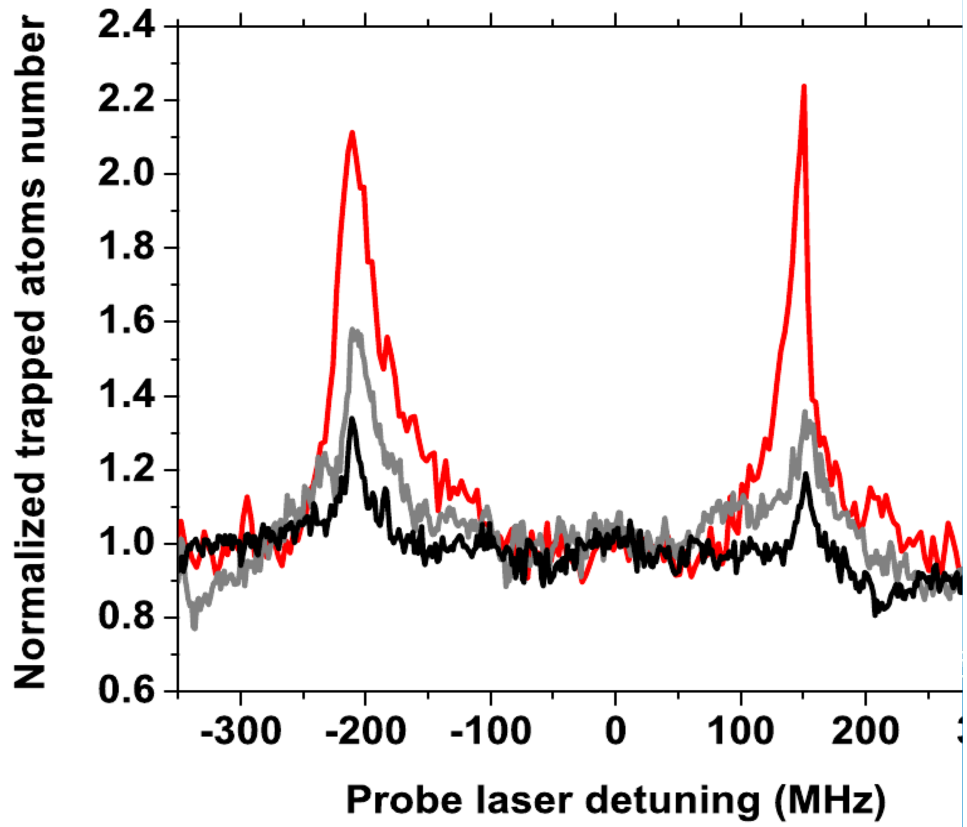


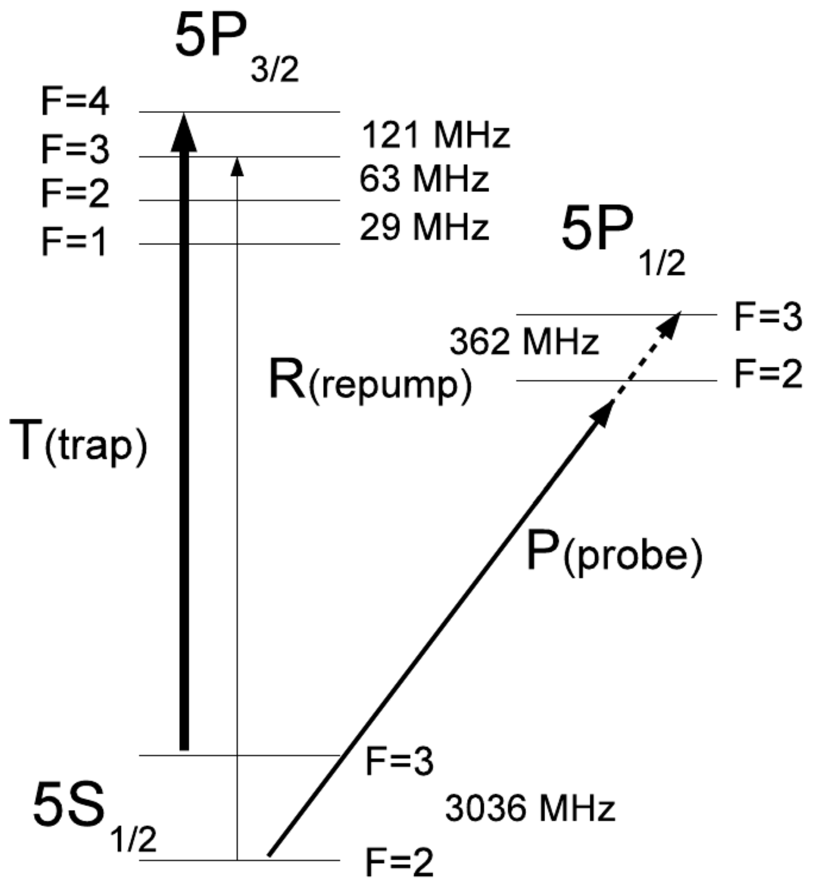
Detection results (Rb)



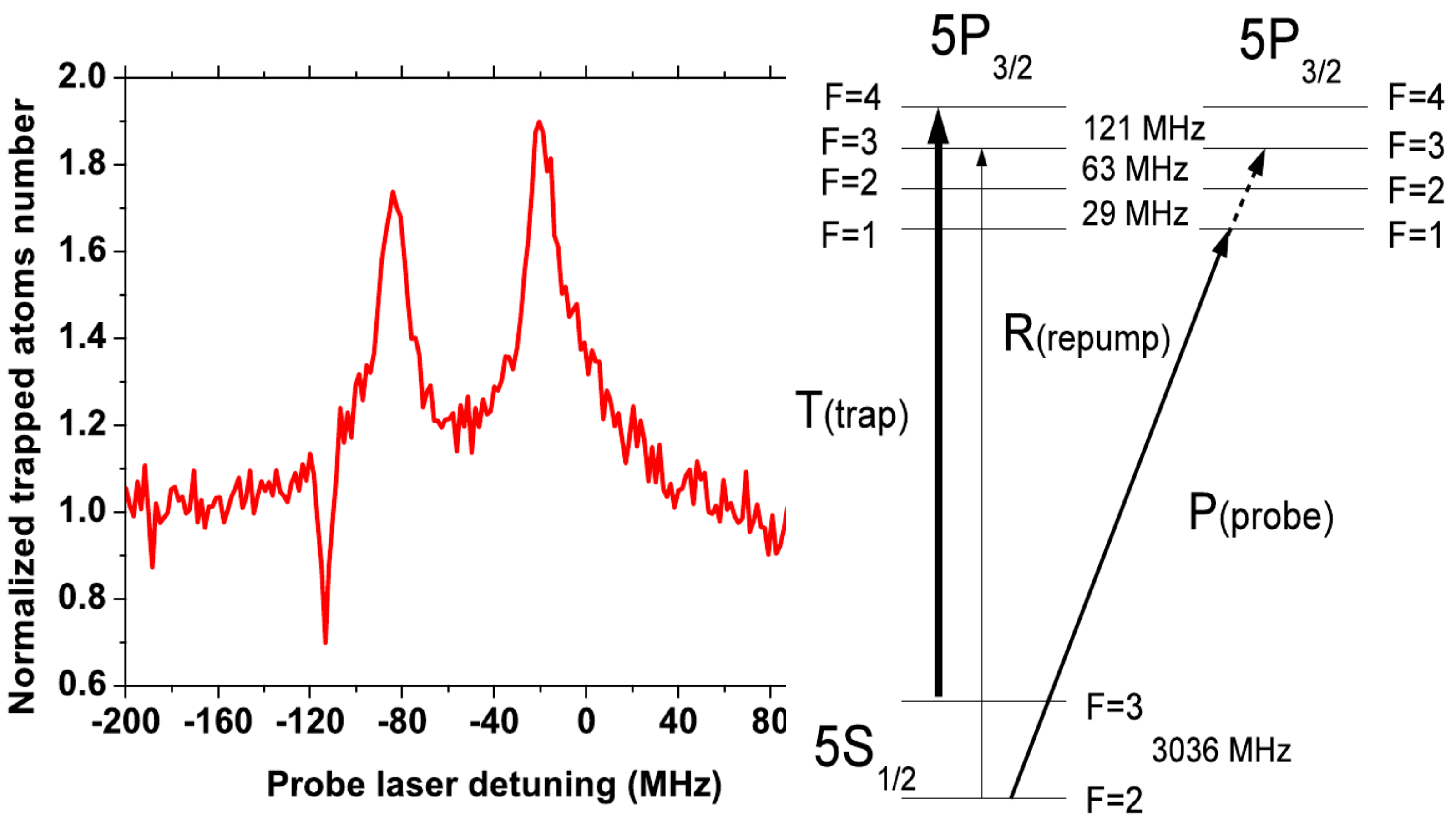


Detection results (Rb)

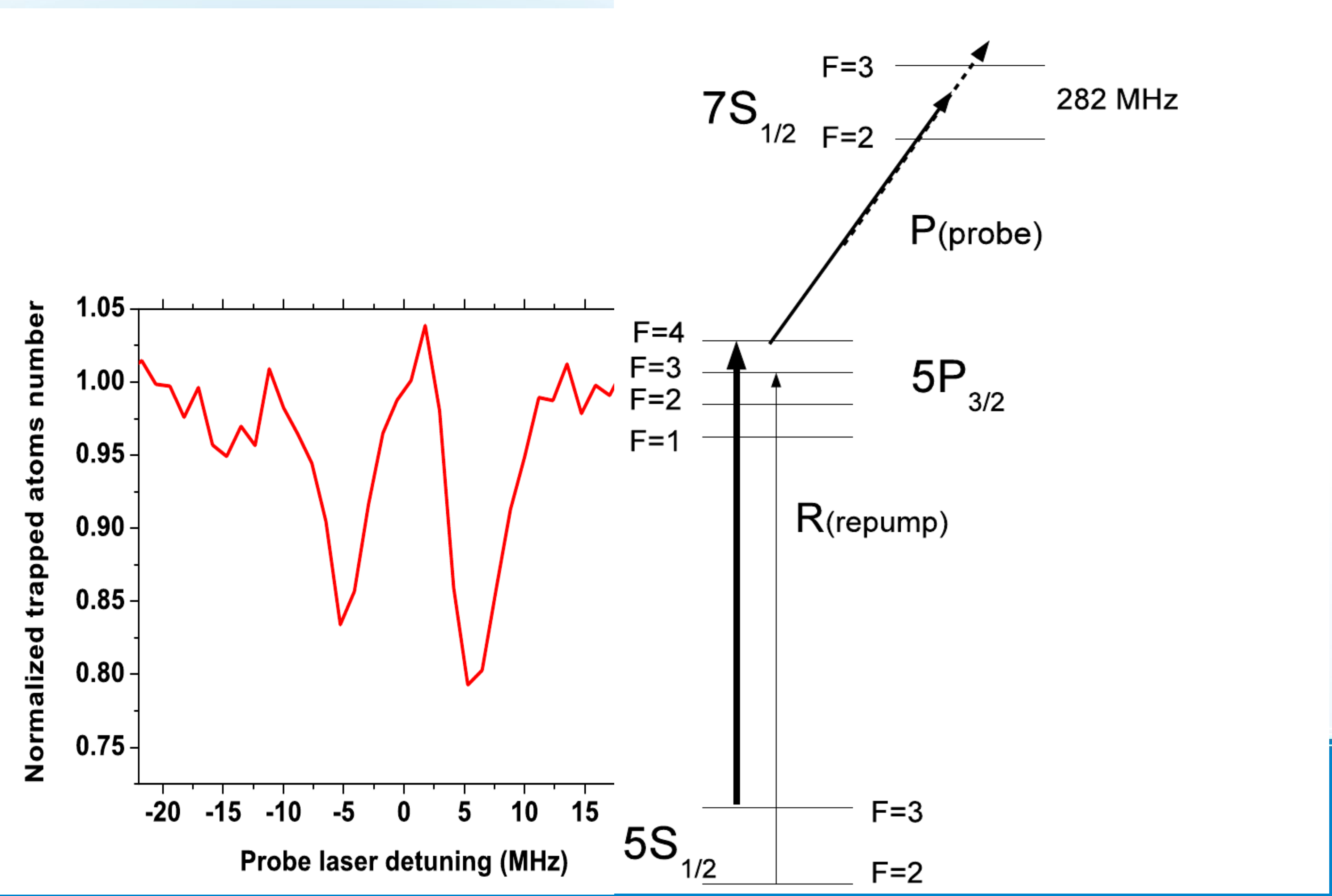




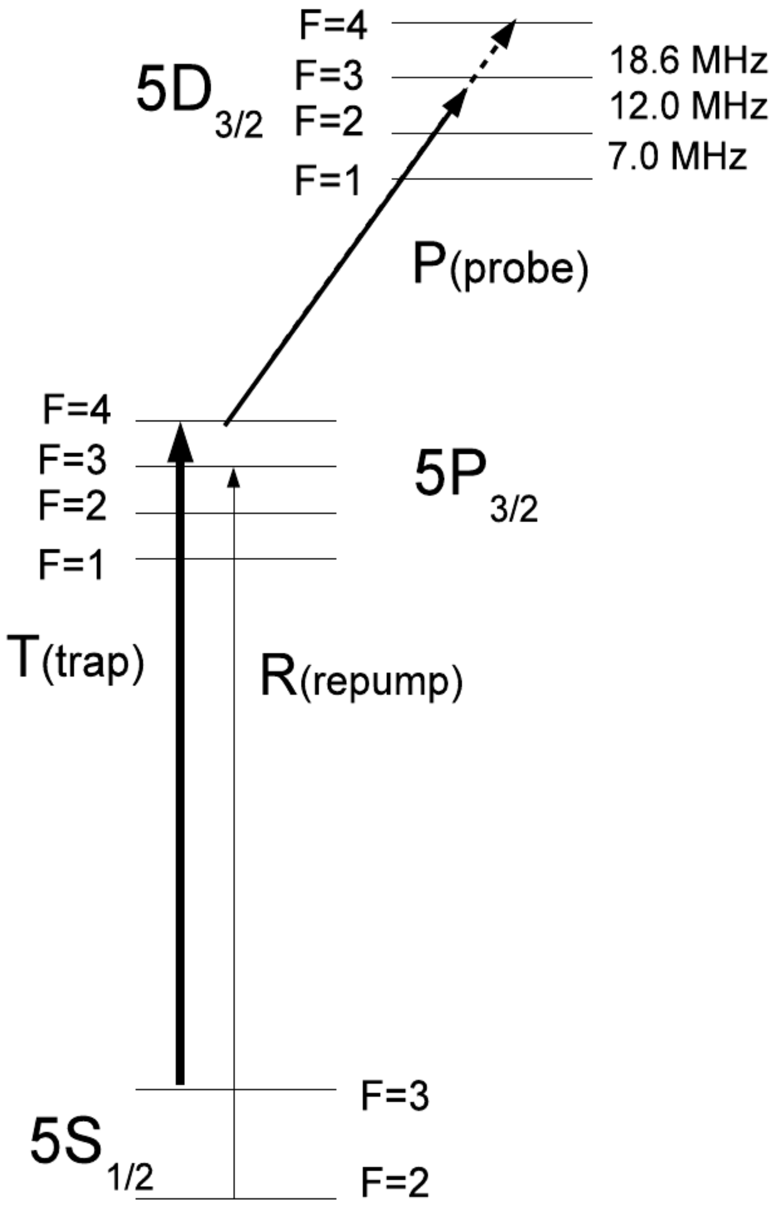
Detection results (Rb)

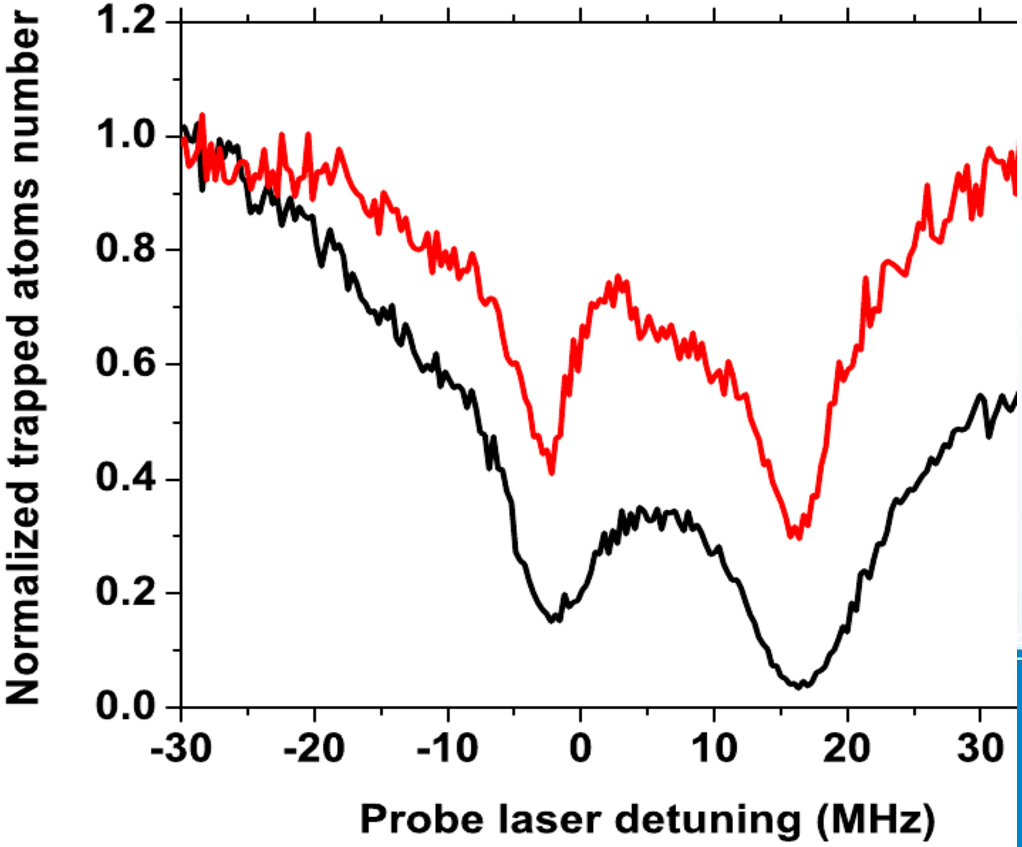


Detection results (Rb)

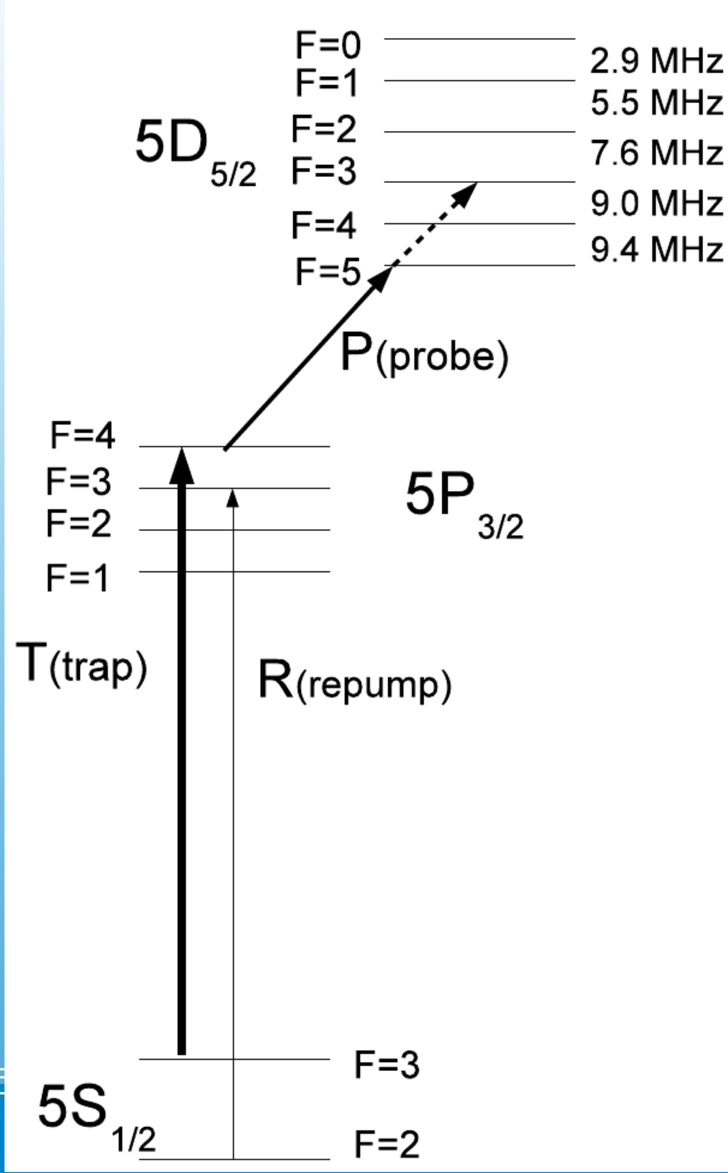


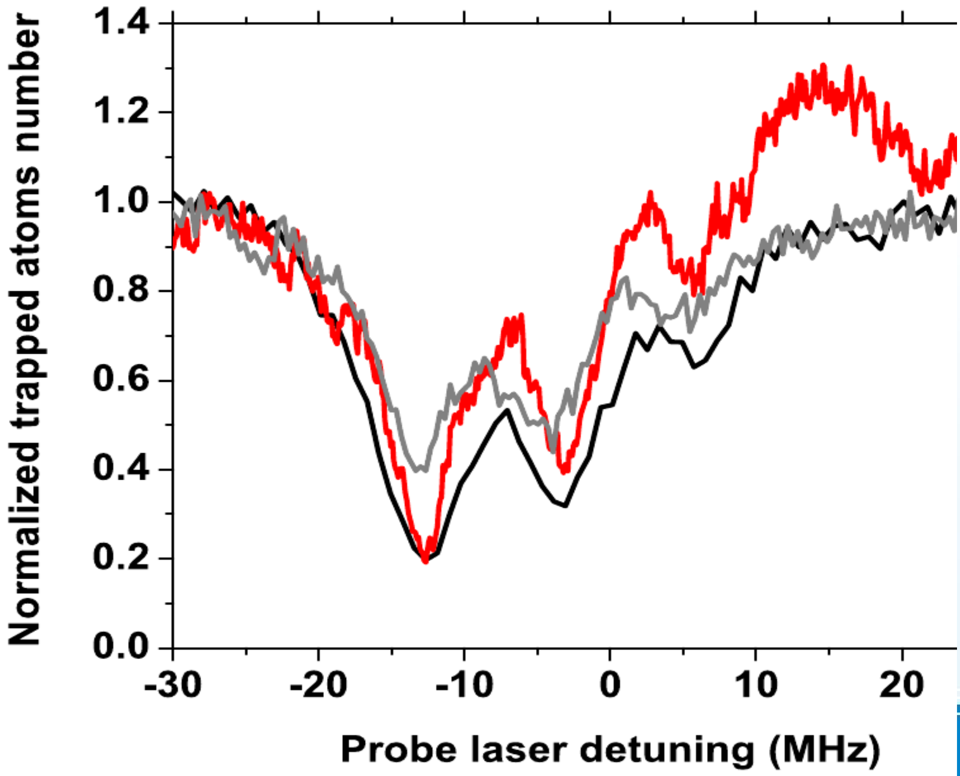
Detection results (Rb)





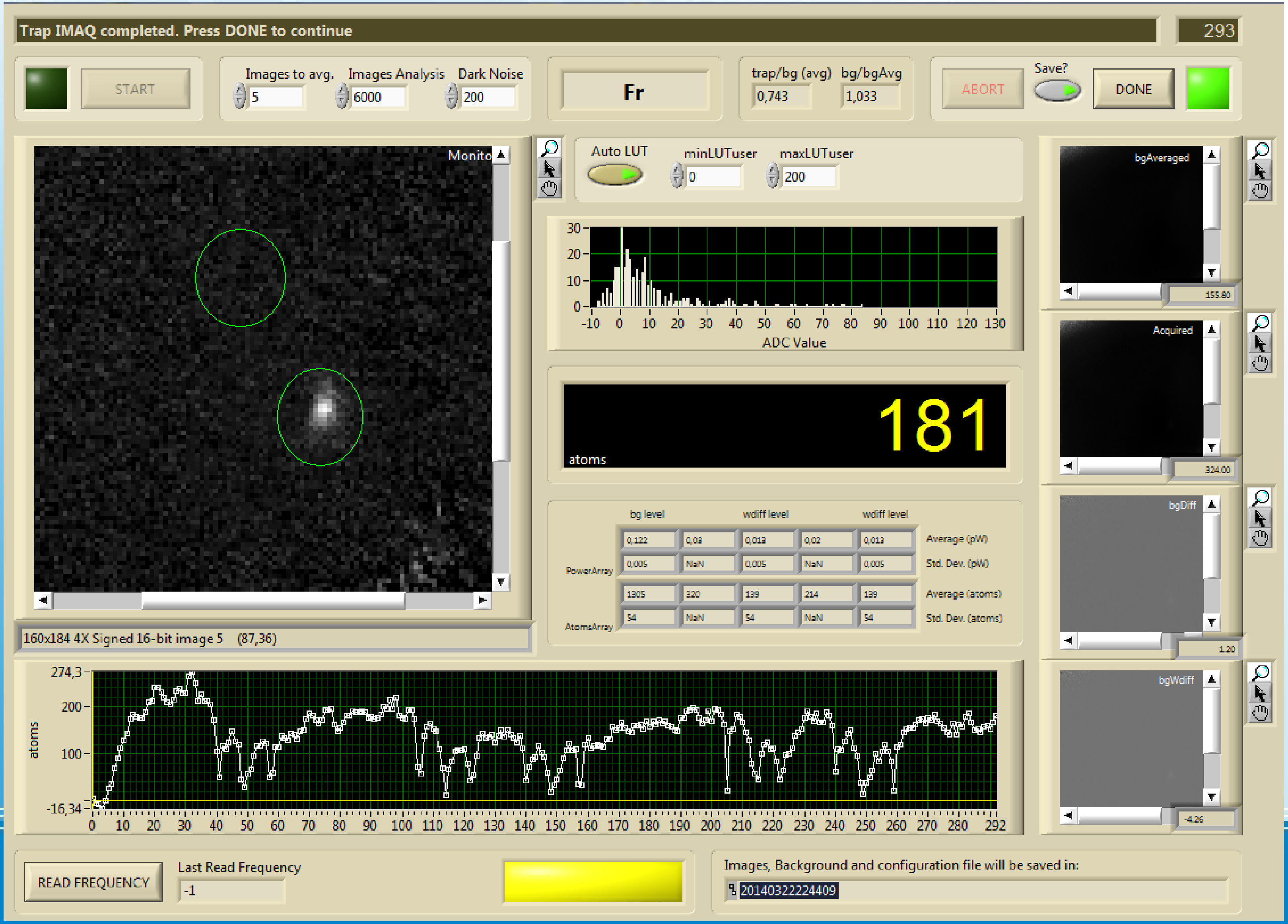
Detection results (Rb)





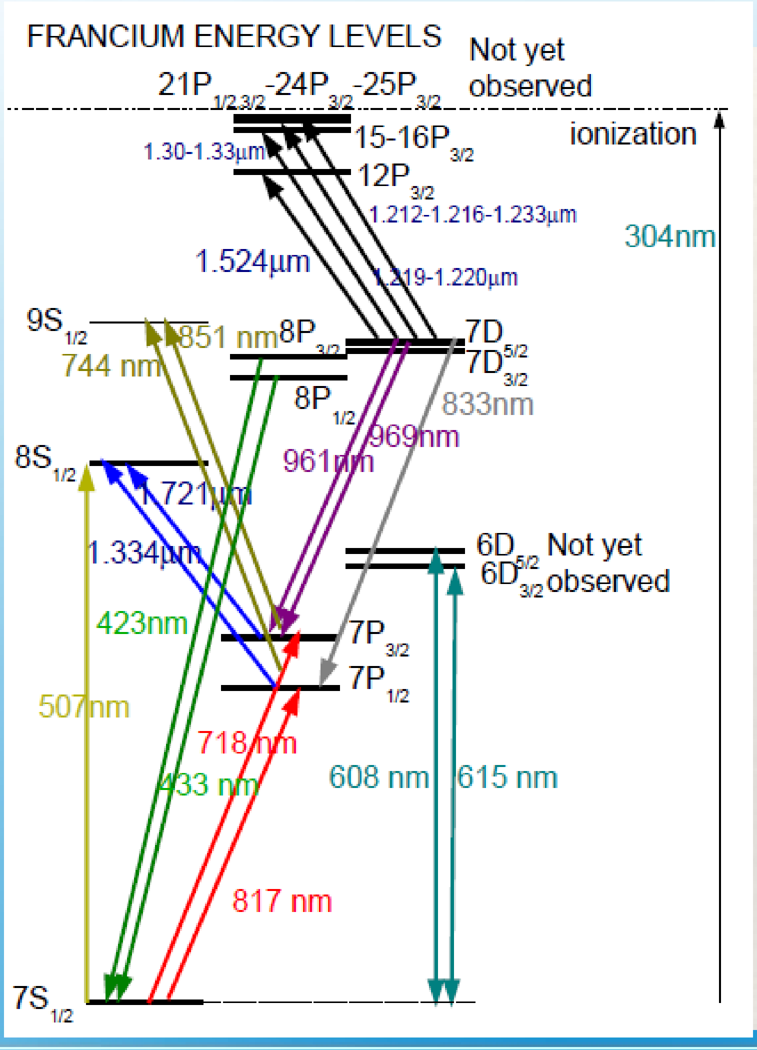
Published in Meas. Sci. Technol. **24**, 015201 2013
Measurement Science and Technology's Outstanding Paper awards for 2013
http://iopscience.iop.org/0957-0233/25/7/070201

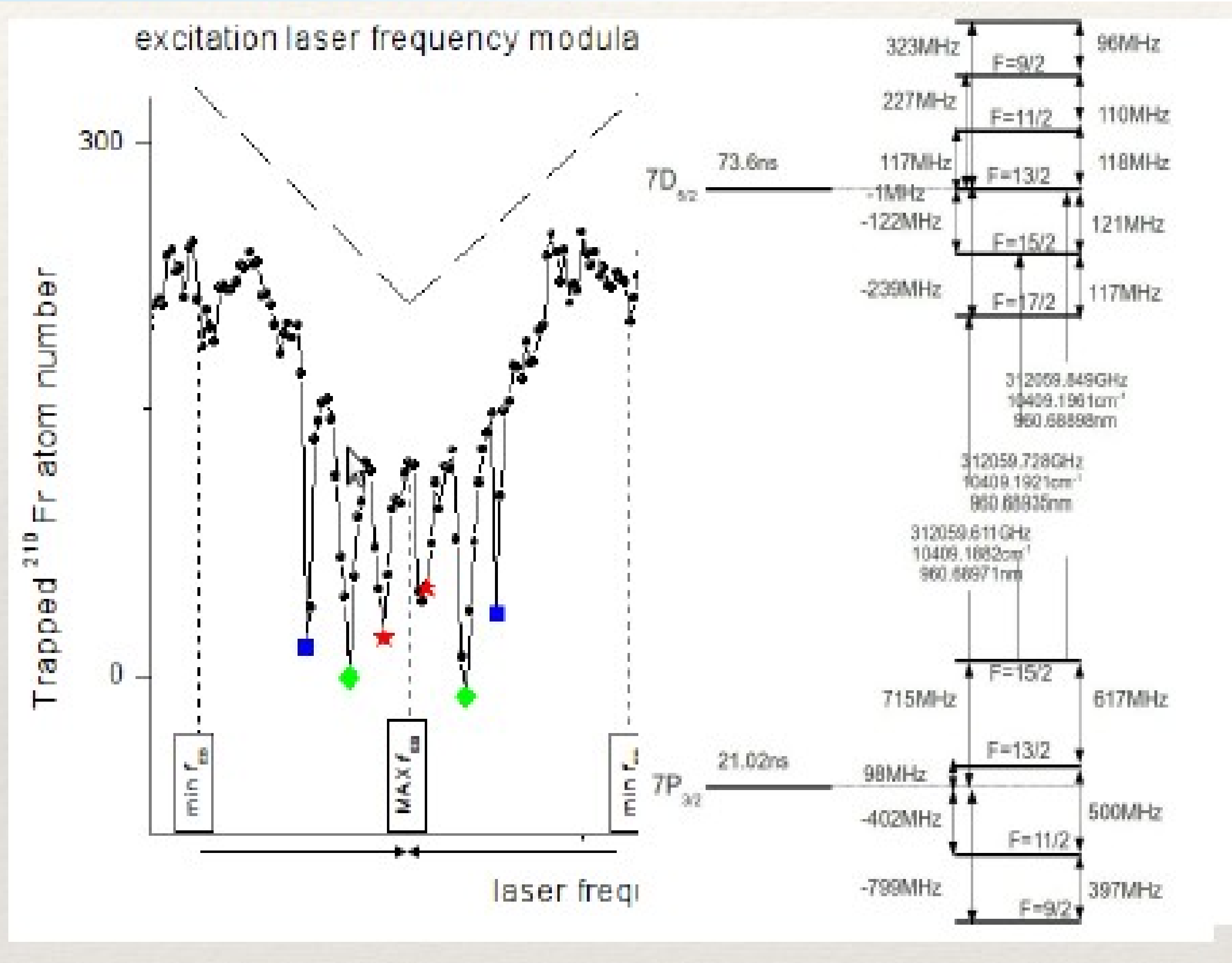
Detection results (Fr – isotope 210)



BEAM TIME OF 22-23 OF JULY 2014

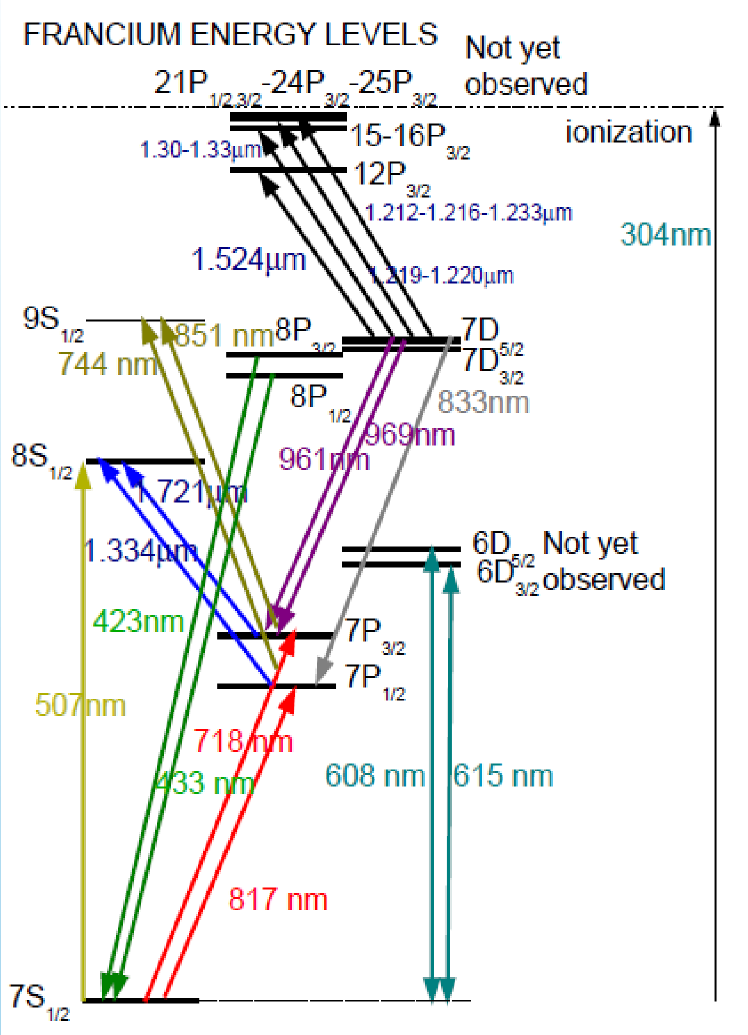
Detection results (Fr – isotope 210)

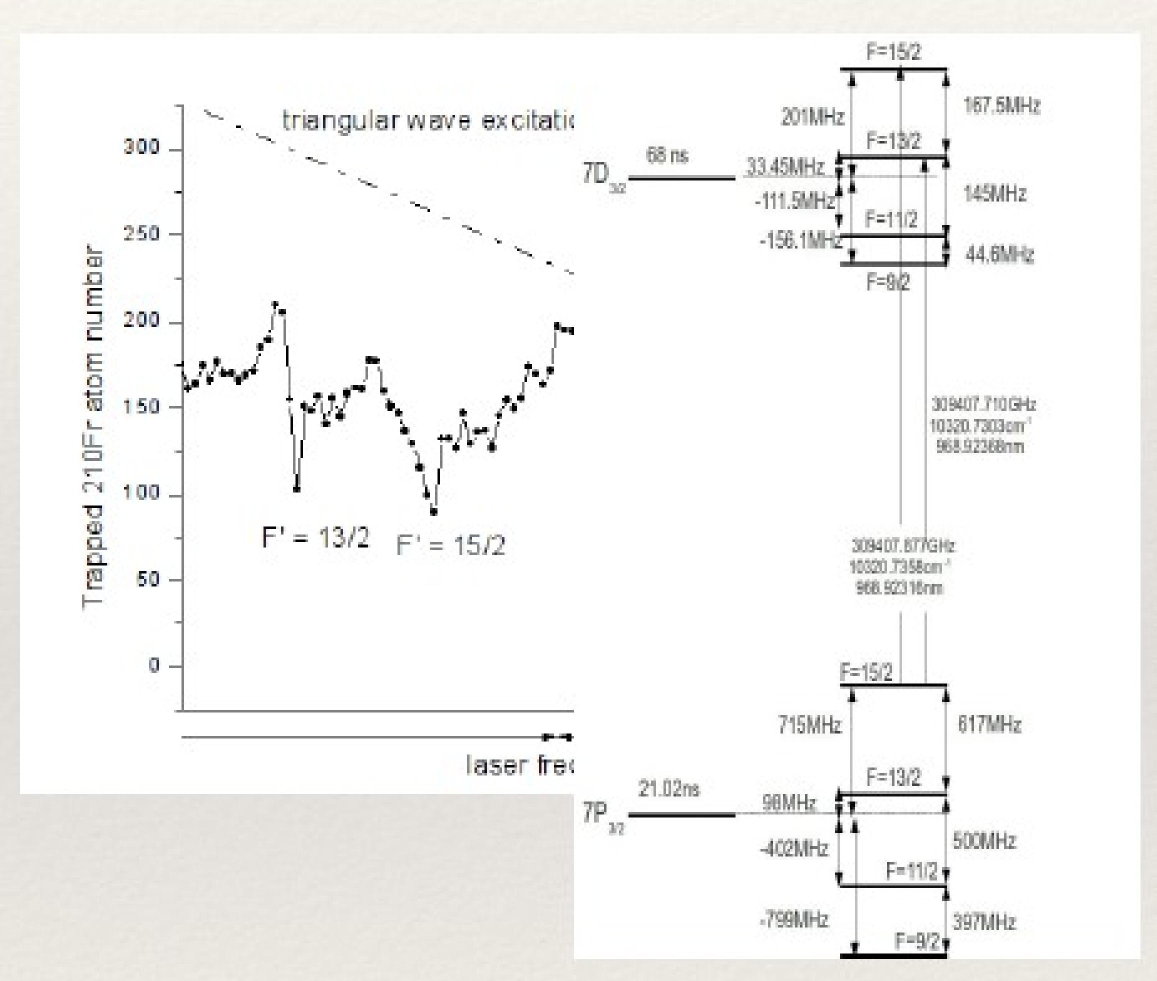




BEAM TIME OF 22-23 OF JULY

Detection results (Fr – isotope 210)

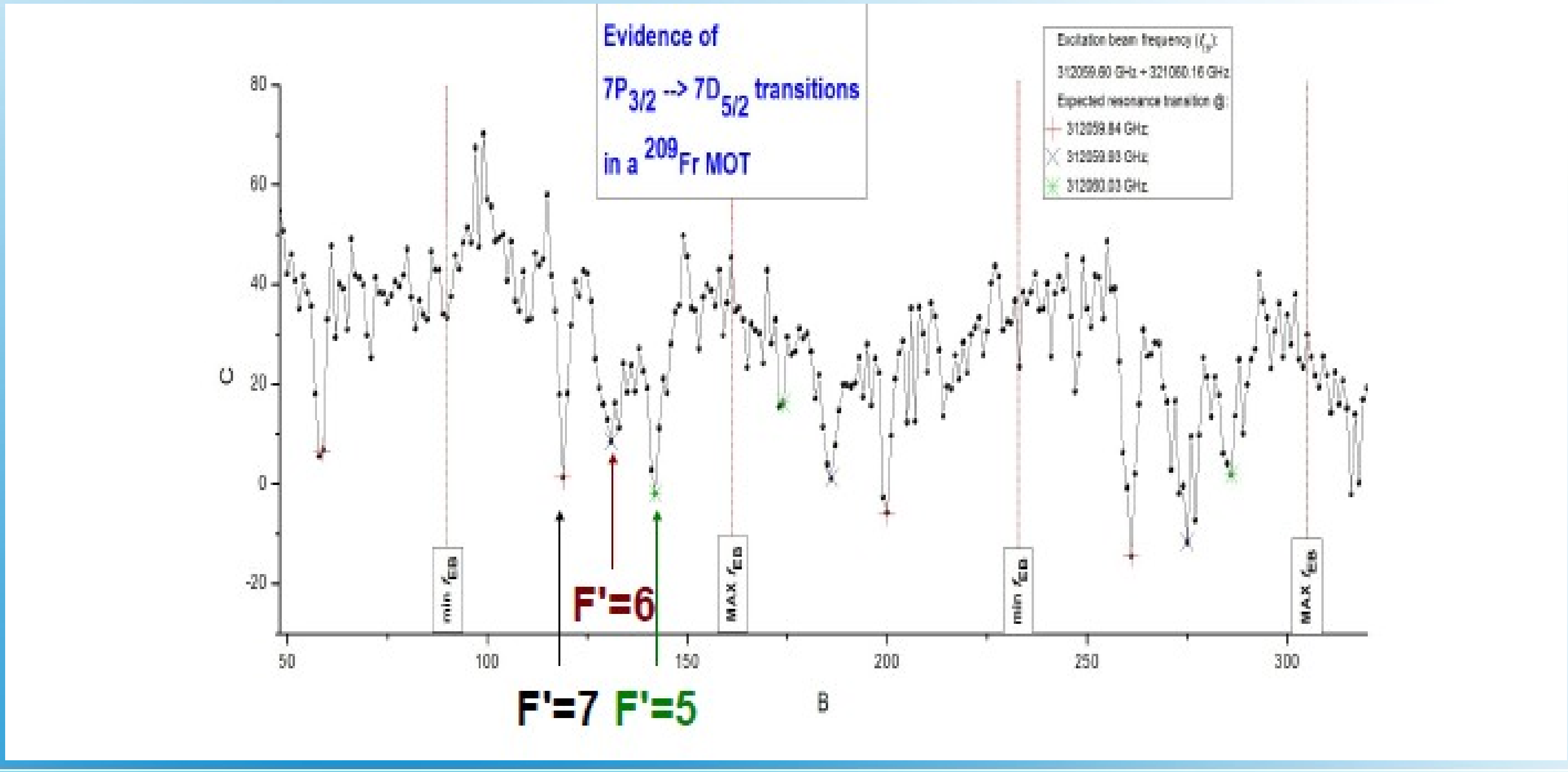




BEAM TIME OF 22-23 OF JULY

Detection results (Fr – isotope 209)

$$H_{\mathrm{hfs}} = A_{\mathrm{hfs}}\mathbf{I}\cdot\mathbf{J} + B_{\mathrm{hfs}}\frac{3(\mathbf{I}\cdot\mathbf{J})^2 + \frac{3}{2}(\mathbf{I}\cdot\mathbf{J}) - I(I+1)J(J+1)}{2I(2I-1)J(2J-1)}$$
$$+ C_{\mathrm{hfs}}\frac{10(\mathbf{I}\cdot\mathbf{J})^3 + 20(\mathbf{I}\cdot\mathbf{J})^2 + 2(\mathbf{I}\cdot\mathbf{J})[I(I+1) + J(J+1) + 3] - 3I(I+1)J(J+1) - 5I(I+1)J(J+1)}{I(I-1)(2I-1)J(J-1)(2J-1)},$$

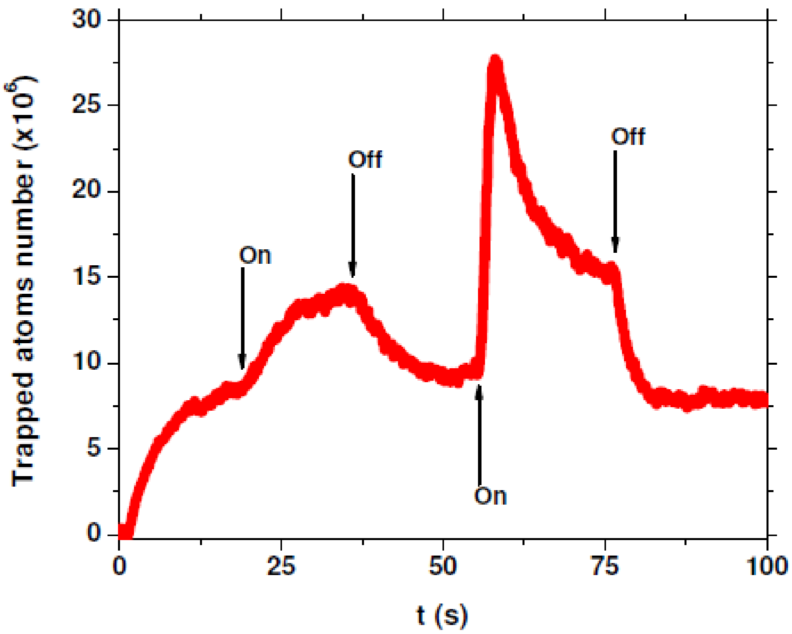


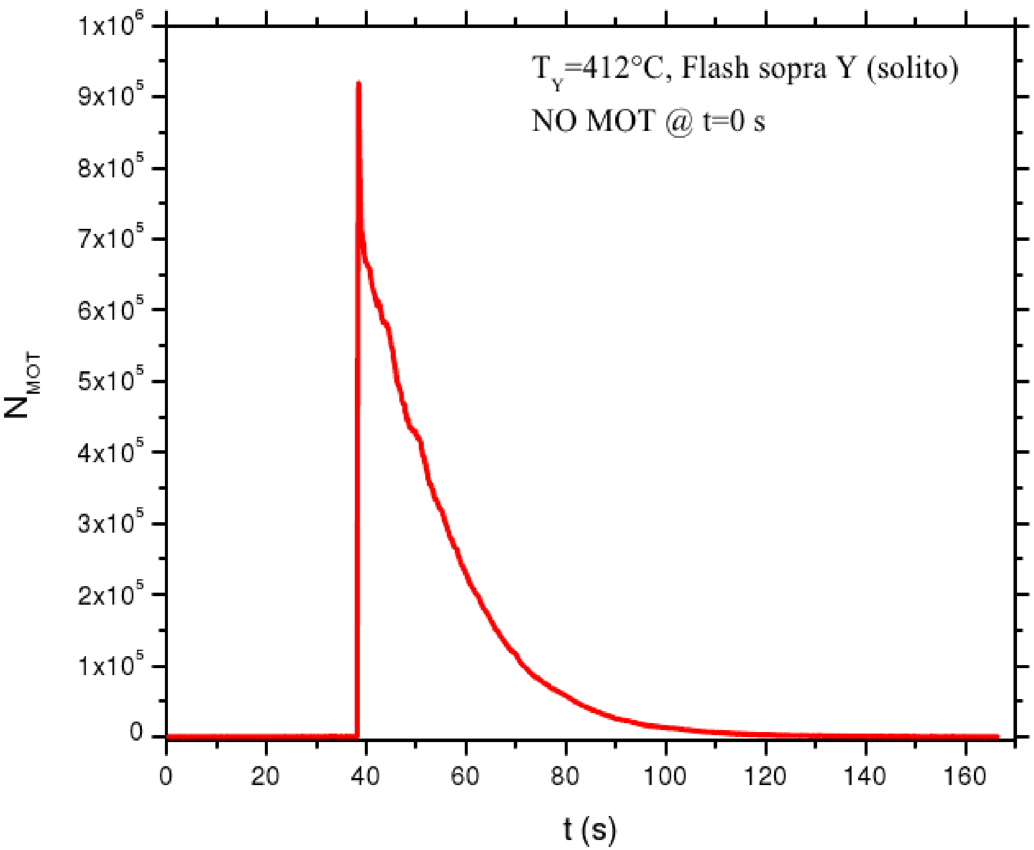
BEAM TIME OF 22-23 OF JULY

Outline

- Introduction/Motivation
- The LNL apparatus
- Precision frequency measurements
  Detection of lines by change in trapped atom number
  Application of Light Induced Atom Desorption
- Perspectives

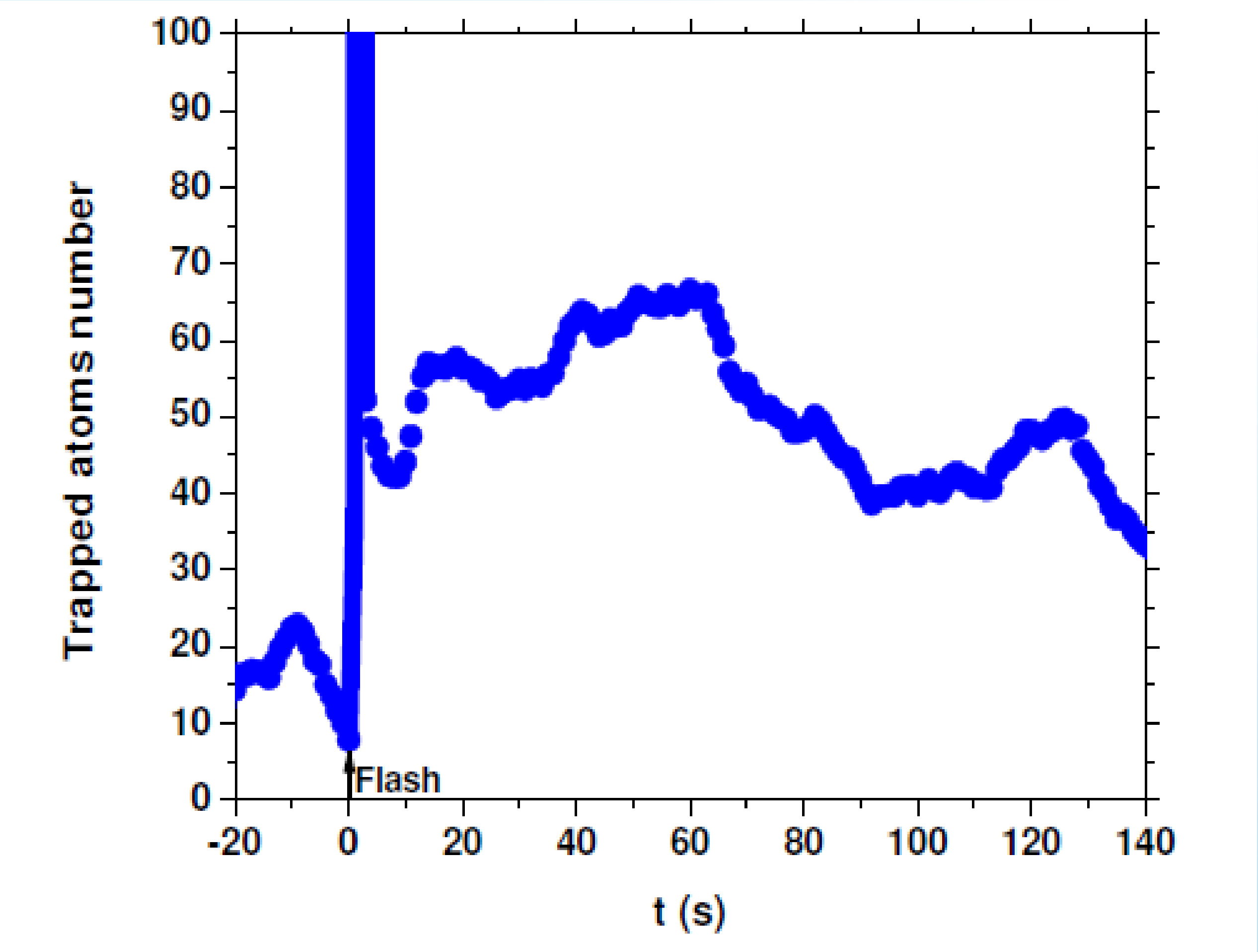
Rb MOT loading from Yttrium!





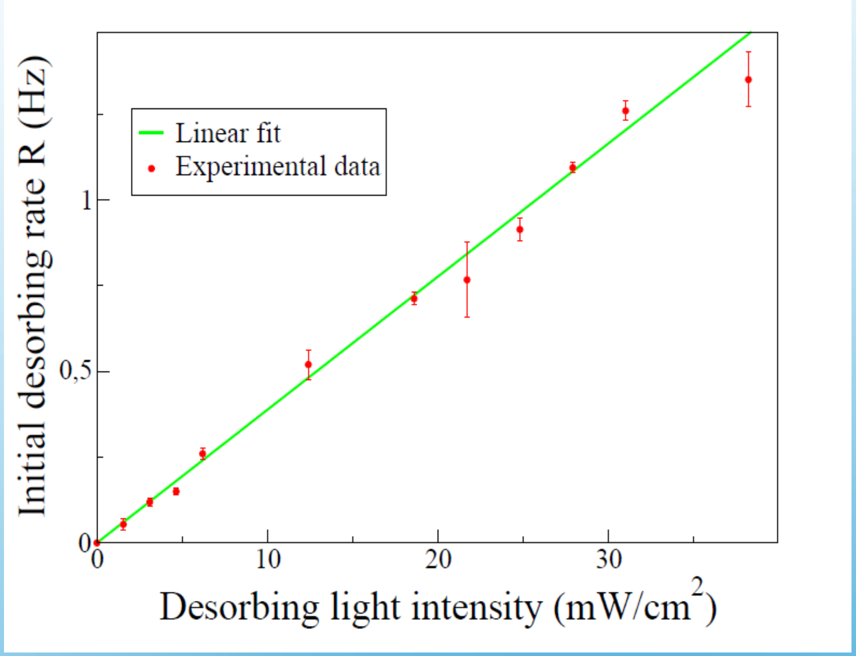
No MOT at the beginning
Very long restoring time – signature of a good coating

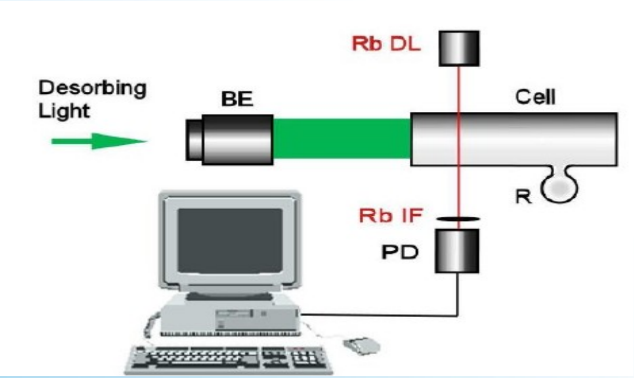
Fr LIAD MOT loading from Yttrium



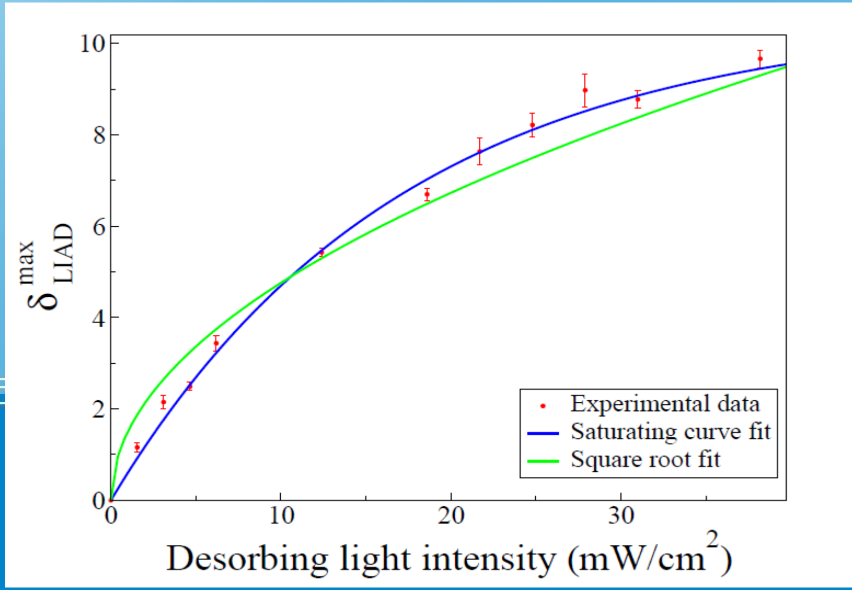
THE JOURNAL OF CHEMICAL PHYSICS, 141, 134201 (2014)

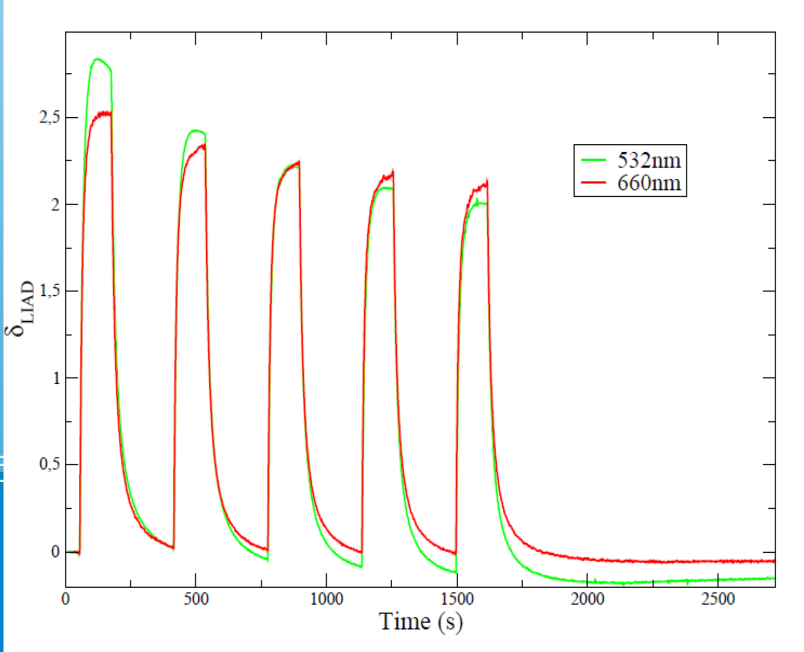
Rb desorption from OTS coated pyrex





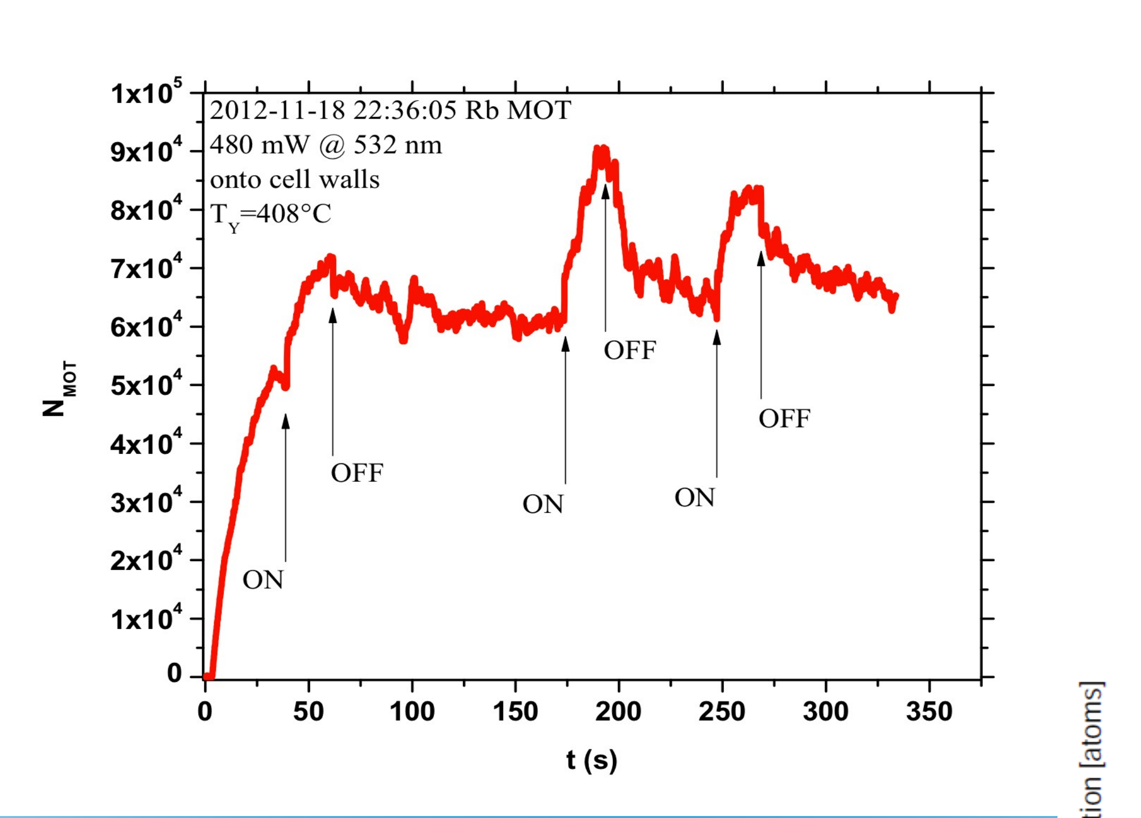
$$\eta \sim 5,3 \times 10^{11} \frac{\text{atoms}}{\text{J}} \qquad \gamma \sim 2,1 \times 10^{-7} \frac{\text{atoms}}{\text{photon}}$$

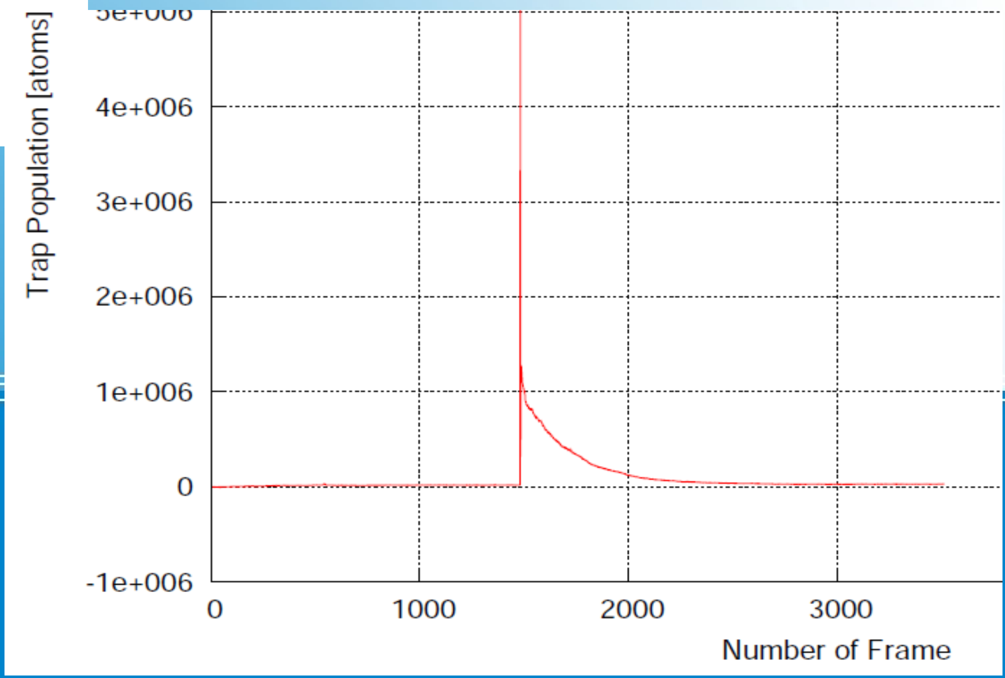




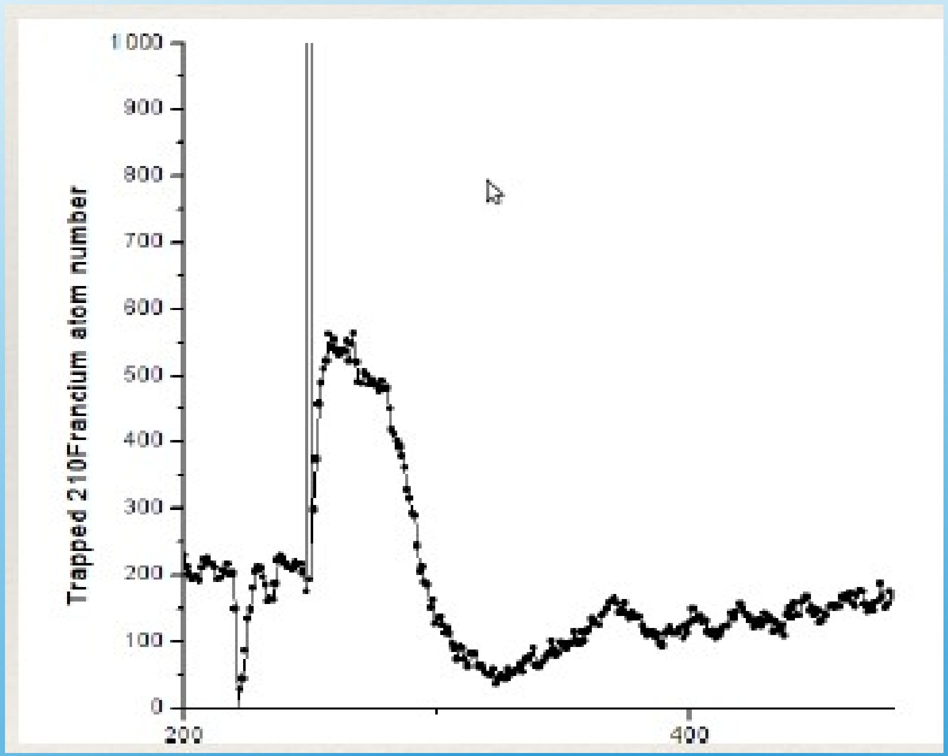
THE JOURNAL OF CHEMICAL PHYSICS **127**, 1 2007

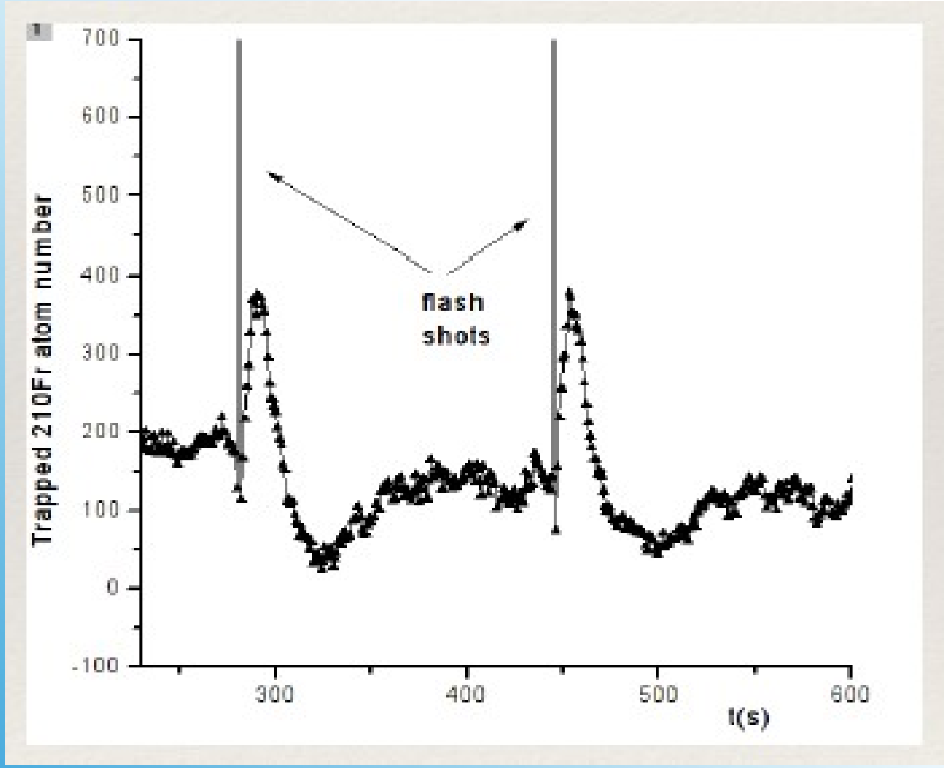
Rb MOT loading from OTS





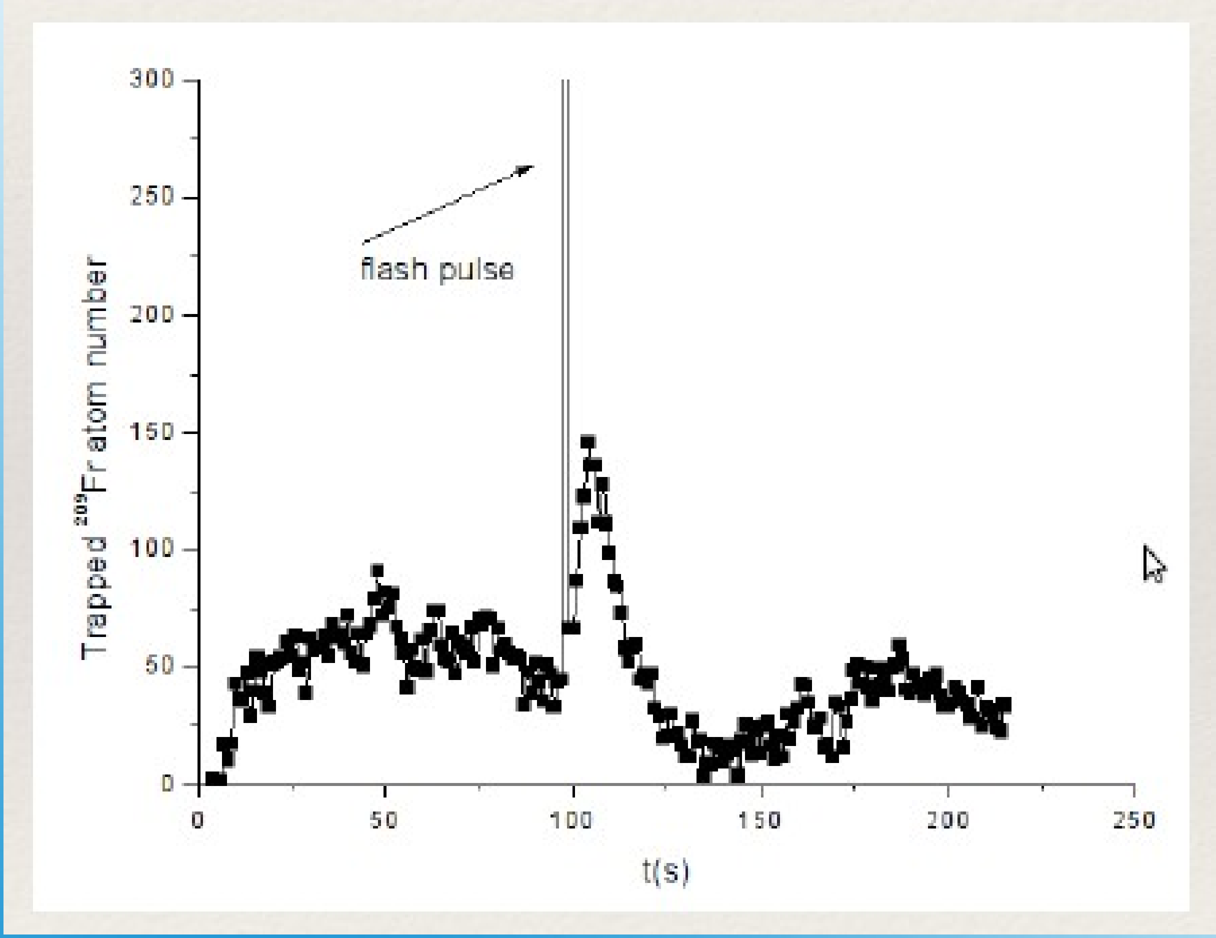
^{210}Fr MOT loading from OTS





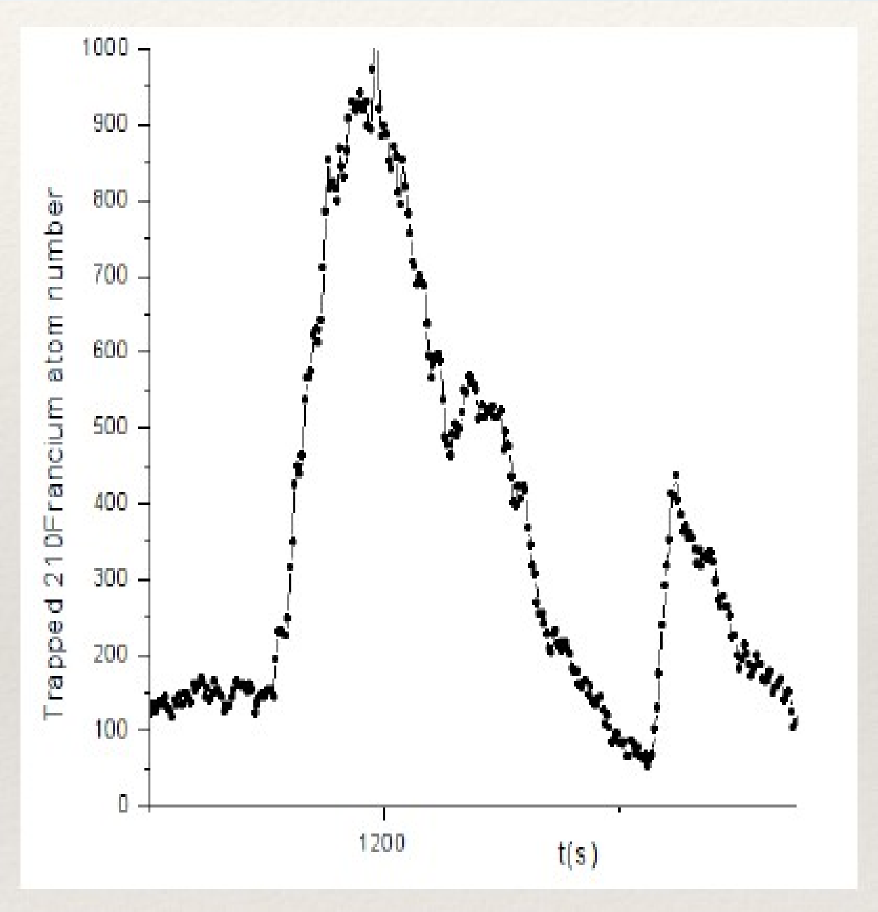
beam time of March 2014

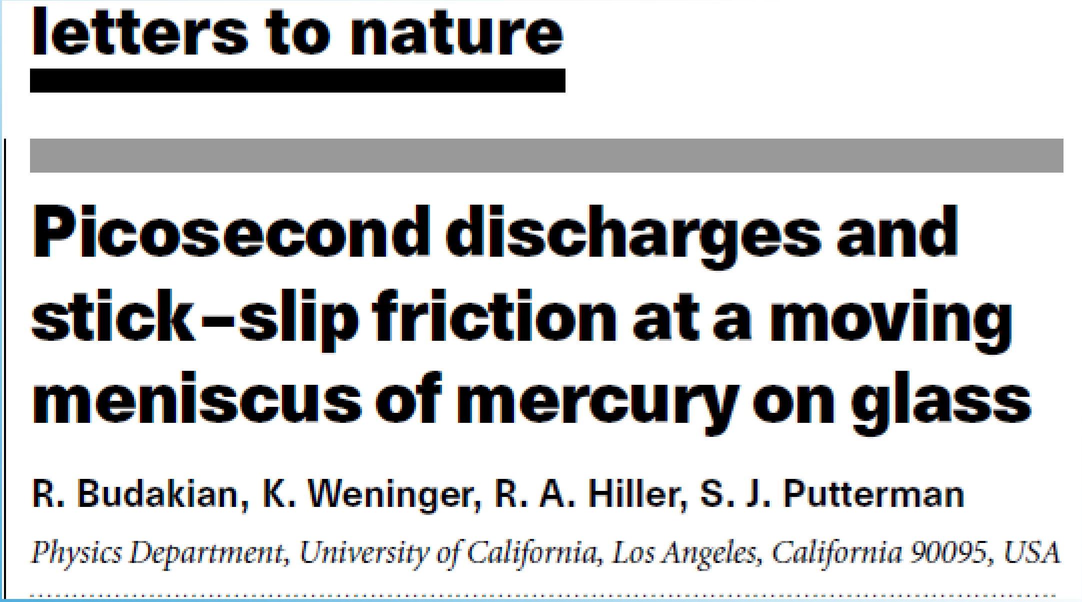
^{209}Fr MOT loading from OTS



beam time of March 2014

SURPRISING……




letters to nature

Picosecond discharges and stick–slip friction at a moving meniscus of mercury on glass

R. Budakian, K. Weninger, R. A. Hiller, S. J. Putterman

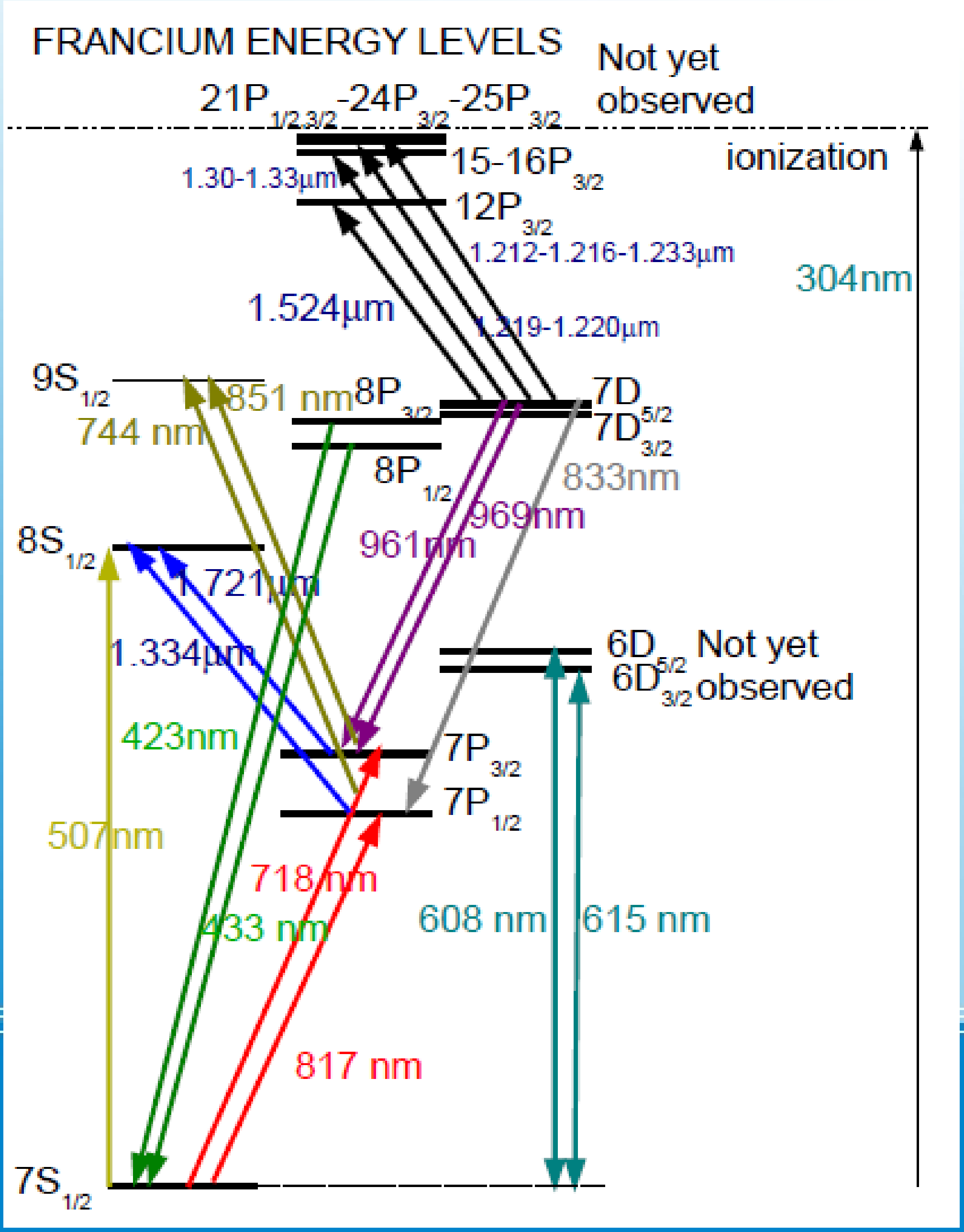
Physics Department, University of California, Los Angeles, California 90095, USA

beam time of JULY 2014

Outline

- Introduction/Motivation
- The LNL apparatus
- Precision frequency measurements
  Detection of lines by change in trapped atom number
  Application of Light Induced Atom Desorption
- Perspectives

New spectroscopic measurements



New spectroscopic measurements

- ENERGY LEVEL DETERMINATION
- LIFETIMES MEASUREMENTS
- COLLISIONAL STUDIES
- DIMER FORMATION (??)

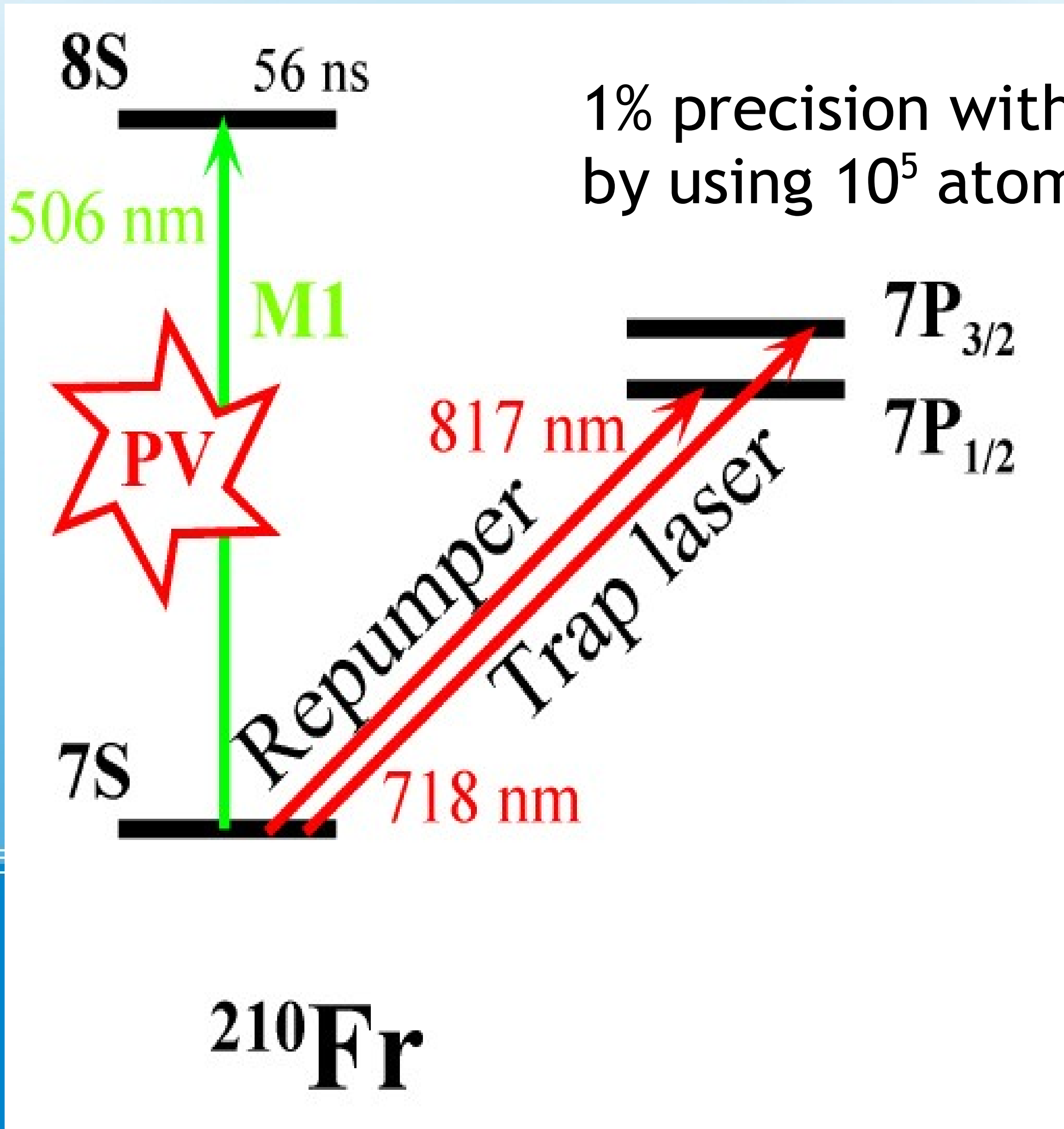
Atomic parity violation

A possible experimental approach:

1. Capture Fr atoms in a MOT
2. Accumulate and cool in the MOT
3. Transfer to a second trap (purely optical)
4. Establish a "coordinate system" by dc electric field, dc magnetic field, k vector of the exciting laser
5. Excite 7S to 8S using a build up cavity and detect using the 7S to 7P transition.
6. Reverse the coordinate axis.
7. Change isotope.

"Towards" APV measurement

$$\vec{d}^{\,\mathrm{eff}}_{F,F'} = -\alpha\vec{E} - i\beta\vec{\sigma}\wedge\vec{E} + M_1'\vec{\sigma}\wedge\vec{k} - iIm(E_1^{PV})\vec{\sigma}$$



1% precision with 3 weeks measurements by using 10^5 atoms

preliminary measure of the ratios α/β, β/M_1, M_1/M_1^{hf}: in the MOT cloud to "calibrate" APV

Expected signal to noise ratio

- Fr production rate in Legnaro: up to 10^6 ions/s.
- Trapping efficiency $\sim 10^{-2} \Rightarrow N = 10000$ atoms in 1 mm^3 (0.01 mm^3) (optical dipole trap).
- **Laser intensity: 100 mW/mm^2**, enhanced by a factor $\zeta = 1000$ with a Fabry-Perot cavity (cf. Boulder) $\Rightarrow P/S = 10$ kW/cm^2.
- Fluorescence detection efficiency: $\eta \sim 10\%$.

$$\Rightarrow S/N = \Im m E_1^{pv} \sqrt{\frac{4\pi}{3\hbar c}\frac{1}{\hbar\Gamma}\frac{P}{S}}\,\eta N\sqrt{t} = 0.009\sqrt{t(s)} \quad (1 \text{ for } t = 3 \text{ hours})$$

How can we improve S/N ?

- Higher laser power, BUT: – heating due to photon scattering
  – photoionization from $8S$ and $7P$.
- Higher Fr^+ Rate: $\geq 4 \cdot 10^9$ ions/s at the ISOLDE facility.
  $\Rightarrow S/N = \mathbf{0.55\sqrt{t(s)}}$

$\Rightarrow$ **In 9 hours we can get $S/N = 100$**

Conclusion

あなたの注意をありがとう