Laser-trapped Ra-225 for an electric dipole moment search

Argonne
NATIONAL
LABORATORY

J. R. Guest, N. D. Scielzo, I. Ahmad, K. Bailey,
J. P. Greene, R. J. Holt, Z.-T. Lu, T. P. O'Connor,
D. H. Potterveld, J. W. Wang

March 20th, 2007
INT EDM and CP violation workshop, U. of Washington

Department of Energy, Office of Science, Nuclear physics

Laser-trapped Ra-225 for an electric dipole moment search

Argonne
NATIONAL
LABORATORY

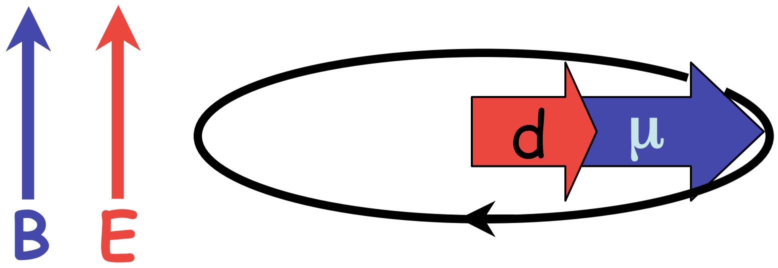
Outline

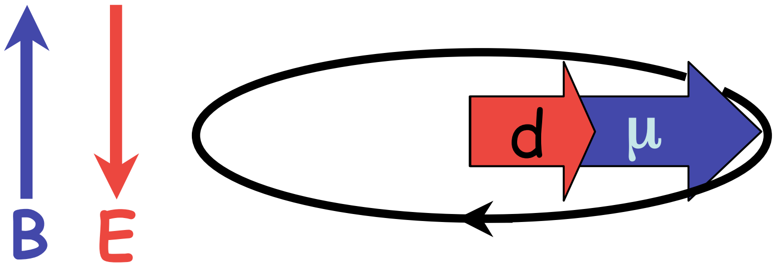
- Hg-199
- Enhancement due to octupole deformation
- Ra-225 and our scheme
- Radium atomic structure
- *Laser-trapped radium!*
- Blackbody-assisted repumping?
- Expected systematics and noise
- Plans

12	Mg	24.31
20	Ca	40.08
38	Sr	87.62
56	Ba	137.33
88	**Ra**	**(226)**

EDM Measurement

$$H = -(\mu\mathbf{B} + d\mathbf{E})\cdot\mathbf{I}/I$$





$$\nu_1 = \frac{2\mu B + 2dE}{h}$$

$$\nu_2 = \frac{2\mu B - 2dE}{h}$$

$$\boxed{d \approx \frac{h\left(\nu_1 - \nu_2\right)}{4E} = \frac{h\,\Delta\nu}{4E}}$$

Single atom measured over single coherence time τ:

$$\delta d \approx \frac{\sqrt{2}h}{8\pi E\tau}$$

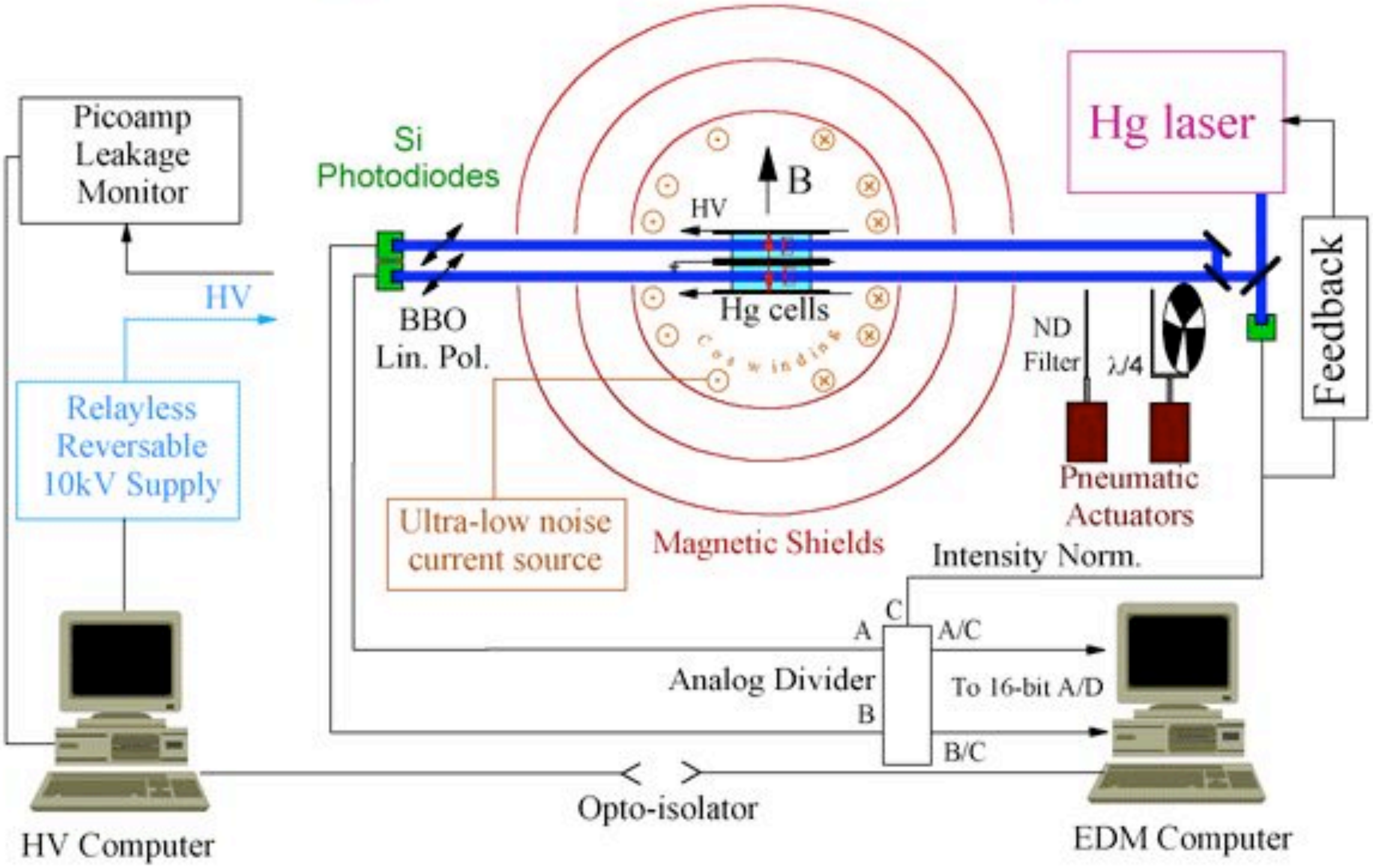
N atoms measured over time T with efficiency ε:

$$\delta d \approx \frac{h}{4\pi E\sqrt{\tau N T \varepsilon}}$$

The Seattle ^{199}Hg EDM Experiment

M. V. Romalis, W. C. Griffith, J. P. Jacobs and E. N. Fortson
Phys. Rev. Lett. 86, 2505 (2001)

$$\boxed{d(^{199}\mathrm{Hg}) = -\,(1.06 \pm 0.49 \pm 0.40)\ 10^{-28}\ e\ \mathrm{cm}}$$



- E = 10 kV/cm
- B = 15 mG
- dB<25 ppb (100s)
- $d\nu$ = 0.4 nHz
- Double cell

T-violating interaction -> atomic EDM

Nuclear charge is screened from applied electric fields by electrons.

But, if dipole moment distribution is different than charge distribution, and there is a gradient in the electronic wavefunction, then the atomic EDM is proportional to the nuclear ***Schiff moment:***

$$d_z(V_{PT}) = k\, S_z(V_{PT})$$

k ← Atomic

Nuclear

	$[10^{-17}$ cm/fm$^3]$
Xe-129	0.38
Hg-199	-2.8
Rn-223	2.0
Ra-225	-8.5

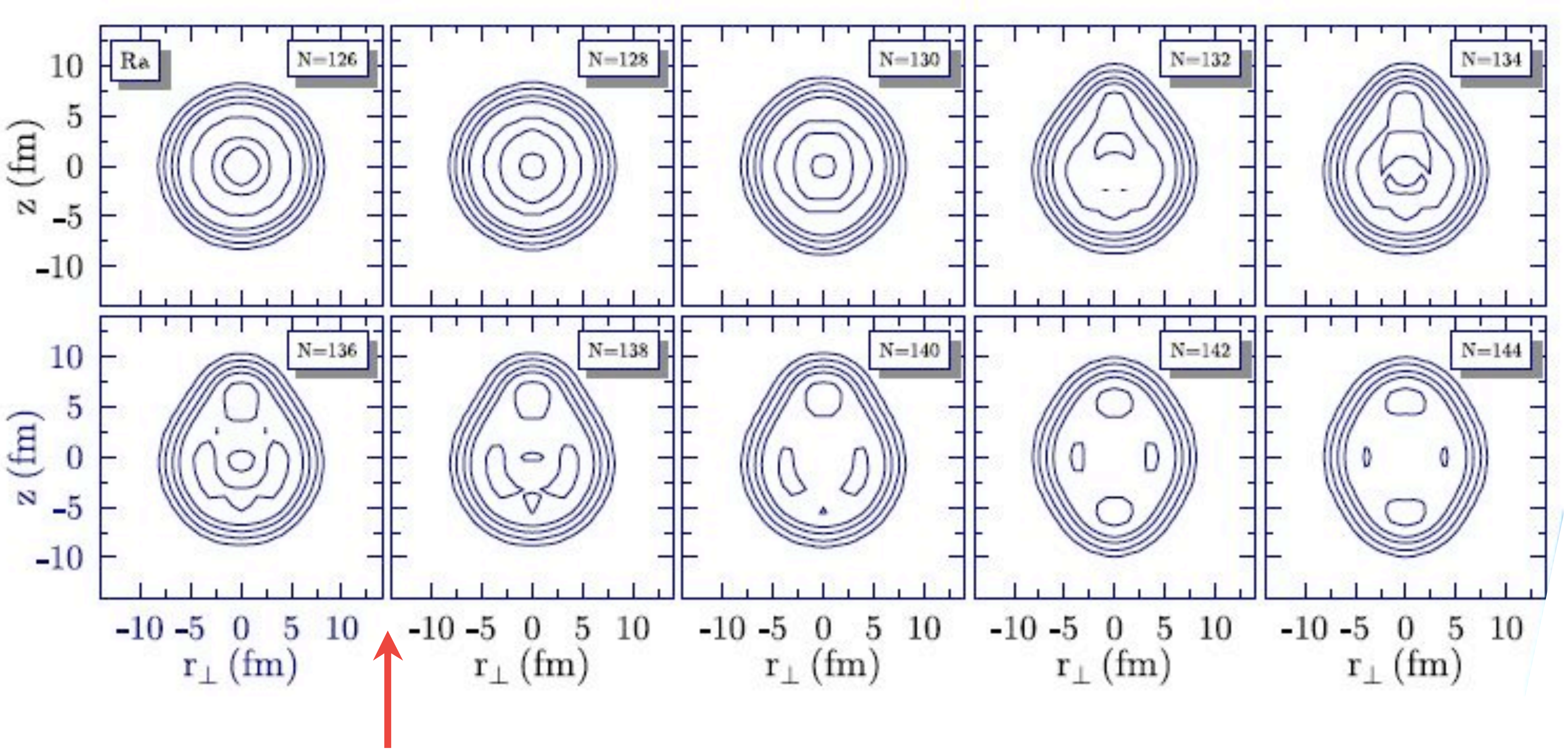
V.A. Dzuba *et al.*,
PRA **66**, 012111 (2002)

$$\langle \vec{S} \rangle = \left\langle \frac{e}{10} \sum_p \left(r_p^2 - \tfrac{5}{3} \overline{r_{ch}^2} \right) \vec{r}_p \right\rangle$$

a 'radially-weighted dipole moment' (PCP)

Density distributions of the radium isotopes

Contours of constant density for series of even-N radium (Z-88) isotopes



Ra-225

J. Engel et al., PRC 68, 025501 (2003)

T-violating interaction -> atomic EDM

Nuclear charge is screened from applied electric fields by electrons.

But, if dipole moment distribution is different than charge distribution, and there is a gradient in the electronic wavefunction, then the atomic EDM is proportional to the nuclear ***Schiff moment:***

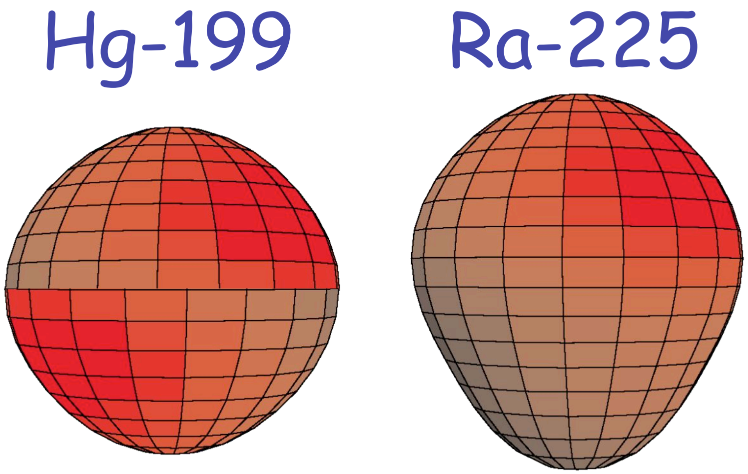
$$d_z(V_{PT}) = k\, S_z(V_{PT})$$

k ← Atomic

Nuclear

	$[10^{-17}$ cm/fm$^3]$
Xe-129	0.38
Hg-199	-2.8
Rn-223	2.0
Ra-225	-8.5

V.A. Dzuba *et al.*,
PRA **66**, 012111 (2002)



$$\mathbf{S}_{\mathbf{int}} \ll \mathbf{S}_{\mathbf{int}}$$

Enhancement due to octupole deformation

With no correlation between spin and intrinsic deformation:

$$\left\langle \Psi^+ \middle| \mathbf{S}_{\mathbf{int}} \middle| \Psi^+ \right\rangle = 0$$

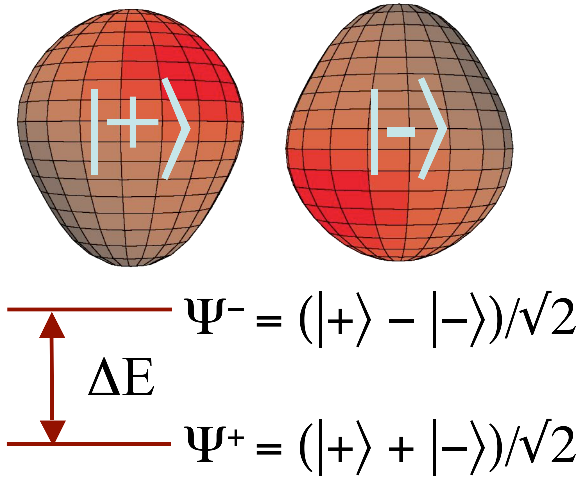
But, with a T-, P-odd interaction V_{PT}:

$$\Psi = \Psi^+ + \alpha \Psi^-$$

$$\alpha = \frac{\left\langle \Psi^+ \middle| V_{PT} \middle| \Psi^- \right\rangle}{\Delta E}$$

So, in the lab frame we see:

$$\left\langle S_z \right\rangle = 2\alpha\, S_{\text{int}} \frac{I}{I+1}$$



$\Psi^- = (|+\rangle - |-\rangle)/\surd 2$

$\Psi^+ = (|+\rangle + |-\rangle)/\surd 2$

Enhancement: EDM(225Ra) / EDM(199Hg)

Model	Isoscalar	Isovector	Isotensor
SkM*	1500	900	1500
SkO′	**450**	**240**	**600**

*PRL **94** 232502 (2005), PRC **72** 045503 (2005)*

Ra-225:
Spin I = 1/2 (like Hg-199)
$t_{1/2}$ = 15 days

Haxton and Henley; Auerbach, Flambaum & Spevak; Dobaczewski, de Jesus & Engel

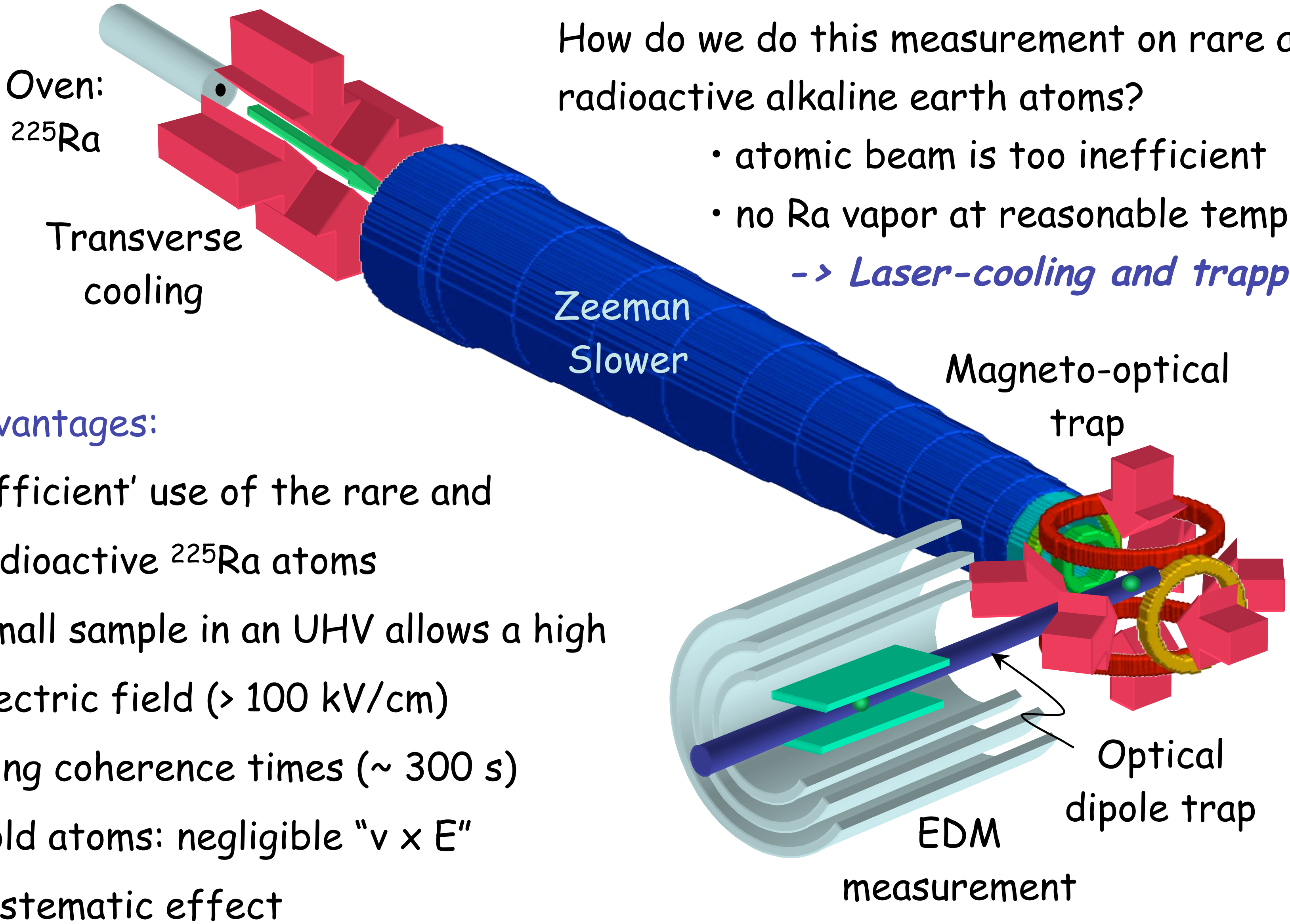
Argonne National Laboratory

EDM measurement on Ra-225

How do we do this measurement on rare and radioactive alkaline earth atoms?

- atomic beam is too inefficient
- no Ra vapor at reasonable temp

-> Laser-cooling and trapping



Advantages:

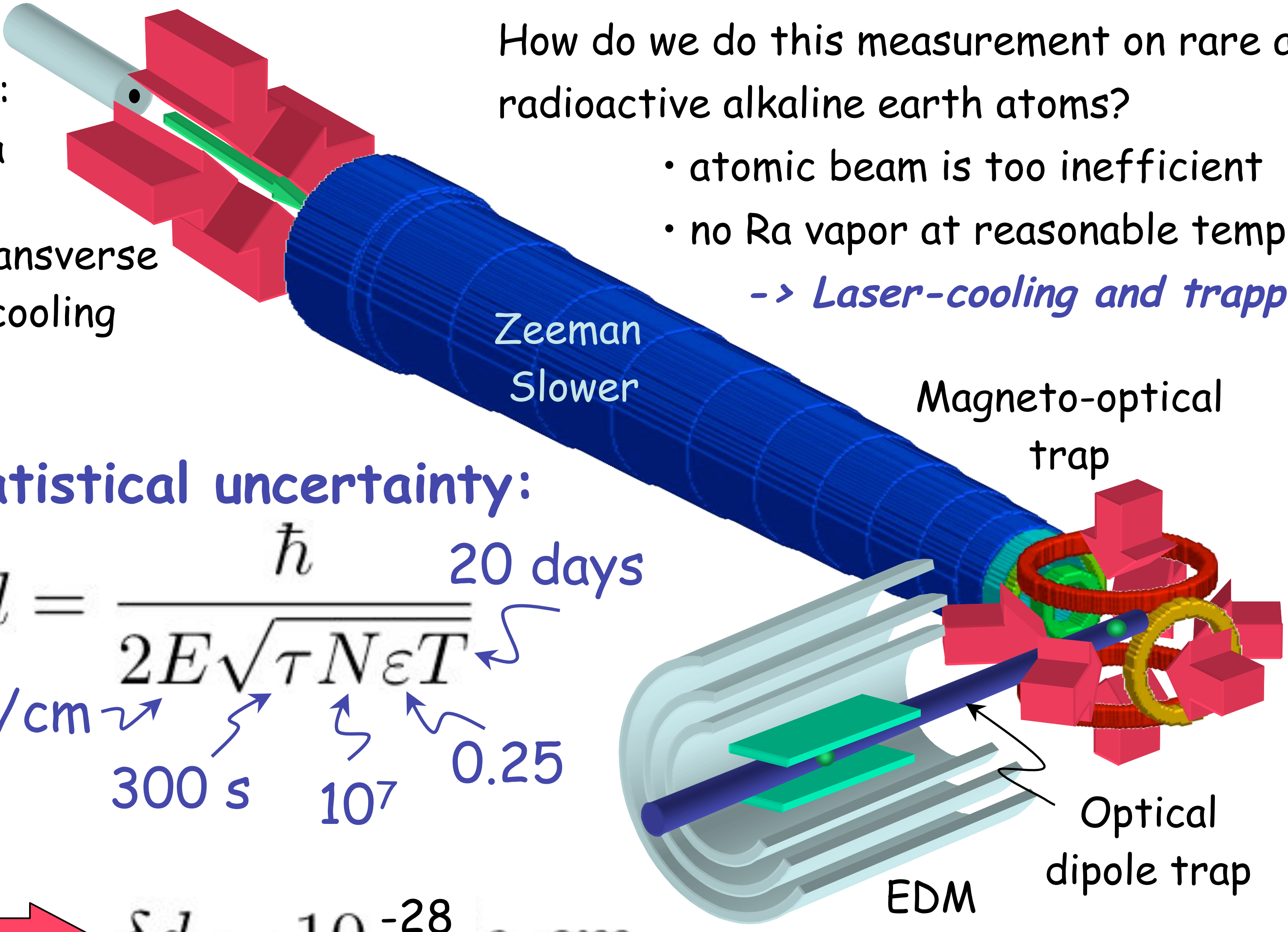
- 'Efficient' use of the rare and radioactive ^{225}Ra atoms
- Small sample in an UHV allows a high electric field (> 100 kV/cm)
- Long coherence times (~ 300 s)
- Cold atoms: negligible "v x E" systematic effect

EDM measurement on Ra-225

How do we do this measurement on rare and radioactive alkaline earth atoms?

- atomic beam is too inefficient
- no Ra vapor at reasonable temp

-> Laser-cooling and trapping



Statistical uncertainty:

$$\delta d = \frac{\hbar}{2E\sqrt{\tau N \varepsilon T}}$$

20 days

100 kV/cm

300 s

10^7

0.25

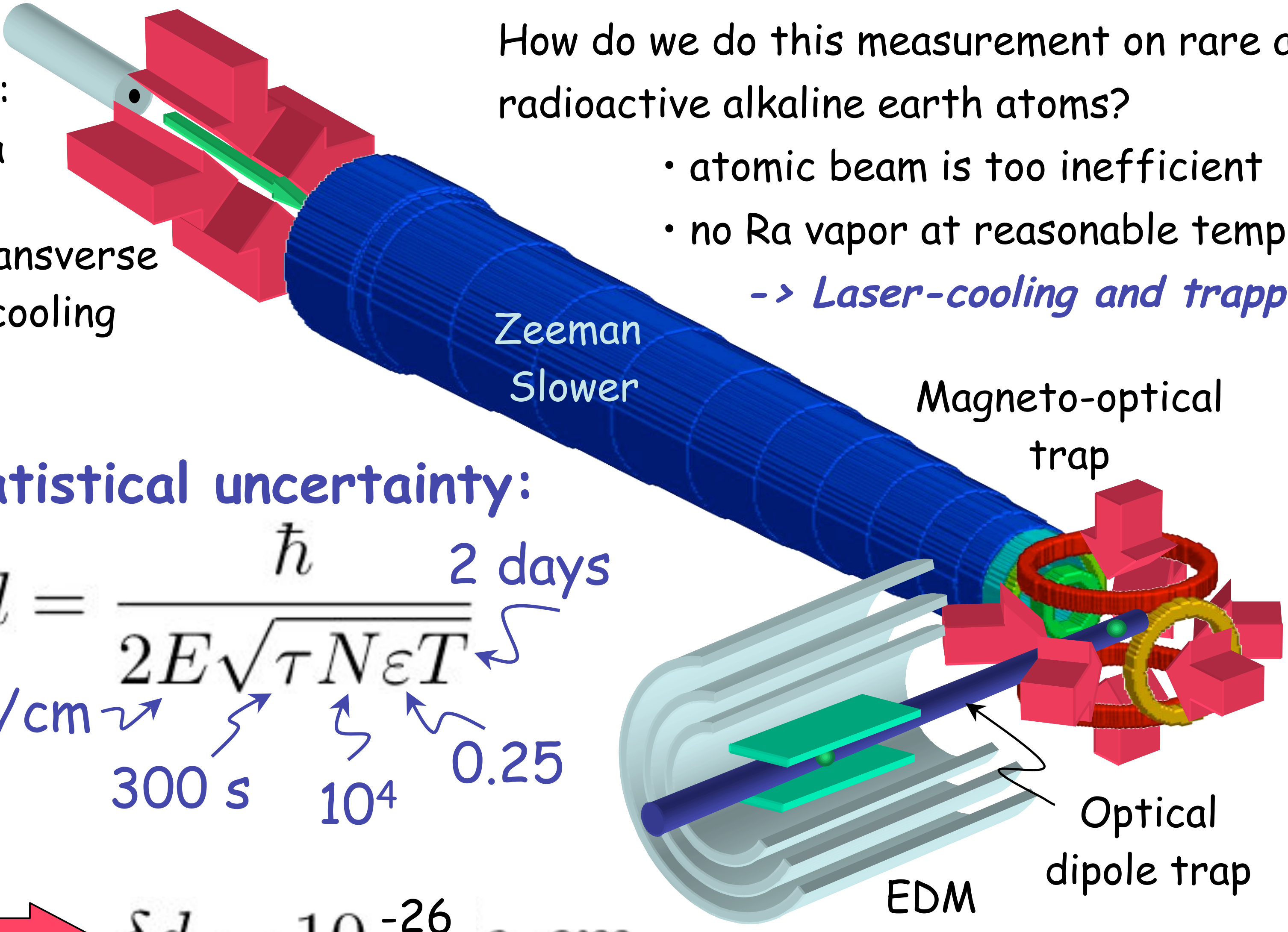
$$\delta d = 10^{-28}\ e\ cm$$

EDM measurement on Ra-225

How do we do this measurement on rare and radioactive alkaline earth atoms?

- atomic beam is too inefficient
- no Ra vapor at reasonable temp

-> Laser-cooling and trapping



Statistical uncertainty:

$$\delta d = \frac{\hbar}{2E\sqrt{\tau N \varepsilon T}}$$

2 days

100 kV/cm

300 s

10^4

0.25

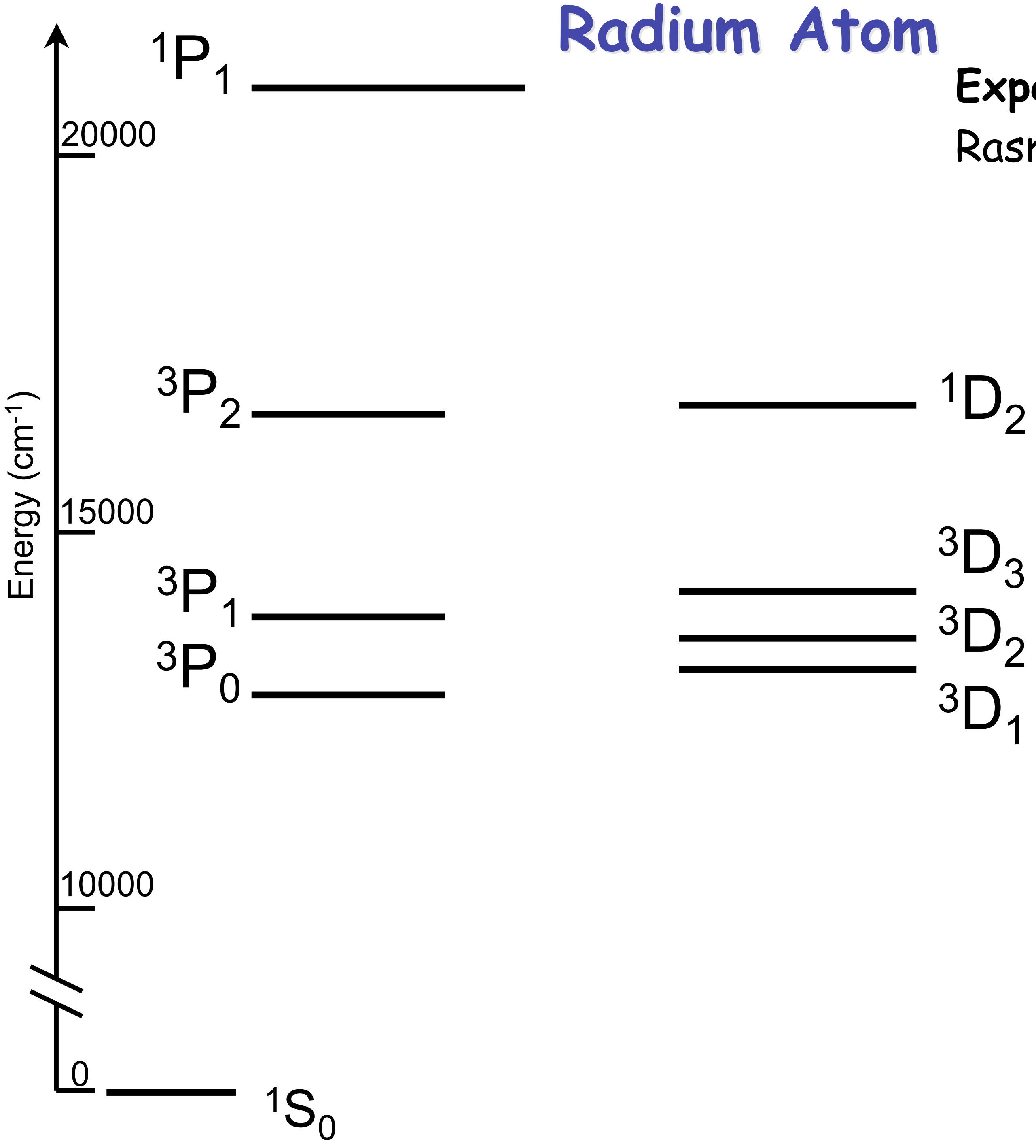
$$\delta d = 10^{-26}\ e\ cm$$

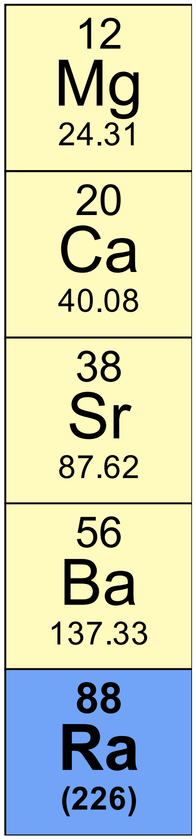
With enhancement competitive with Hg-199

Radium Atom

Experimental work:

Rasmussen (1934)



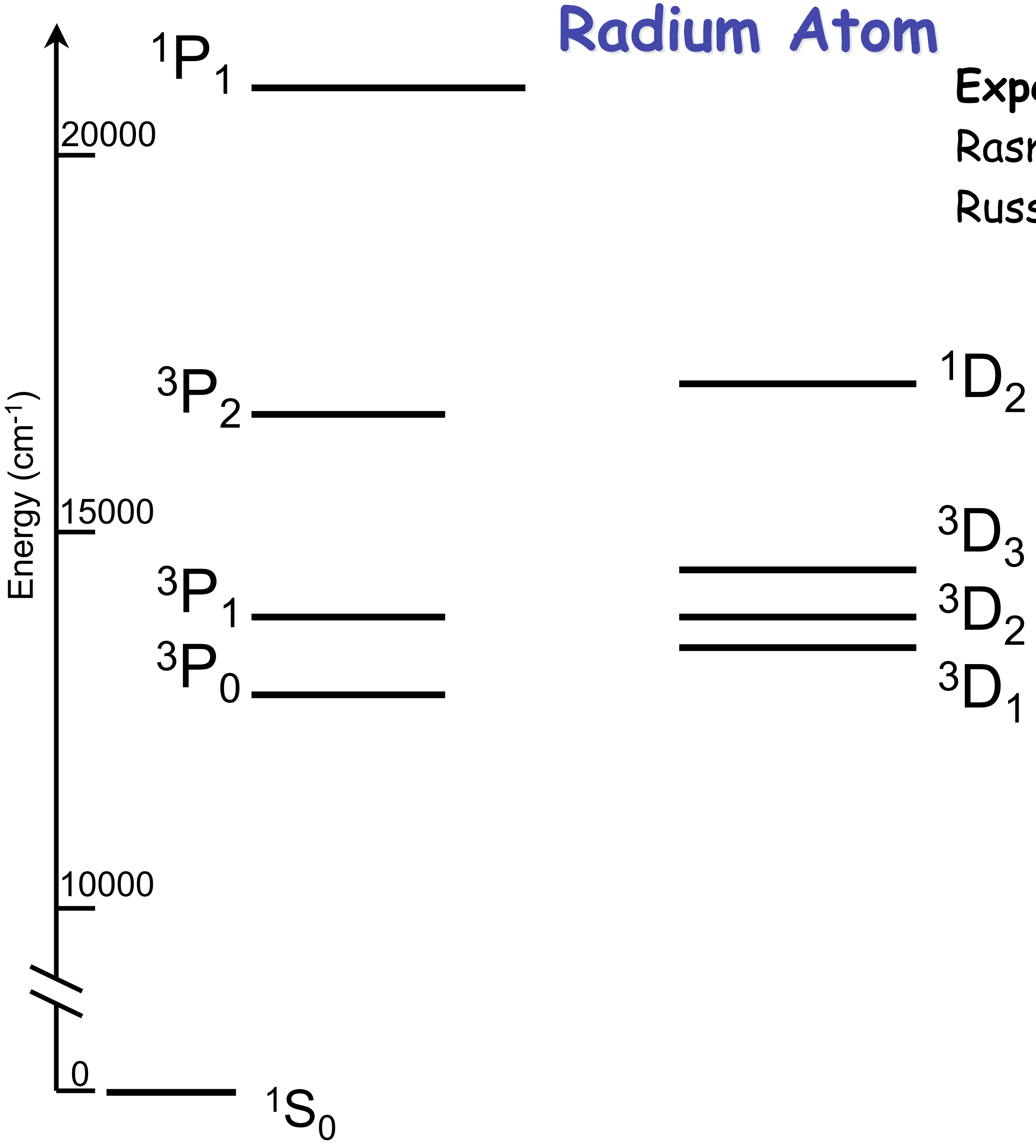


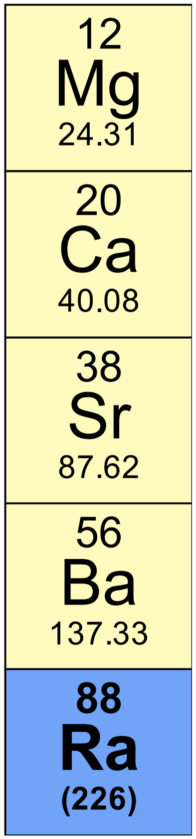
Radium Atom

Experimental work:

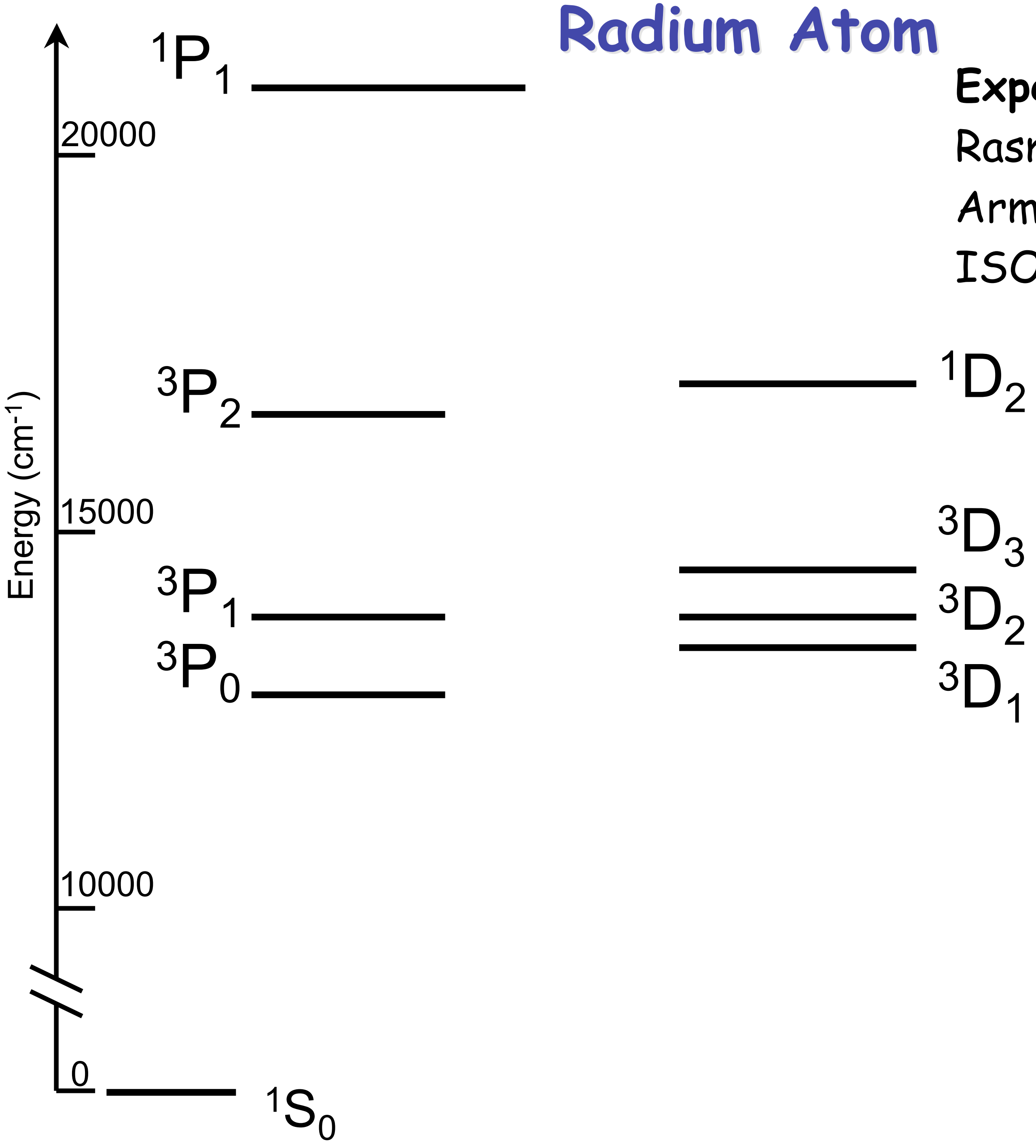
Rasmussen (1934)

Russell adjustment (1934)





Radium Atom

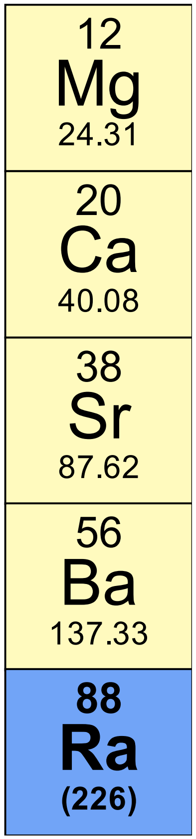


Experimental work:

Rasmussen, Russell (1934)

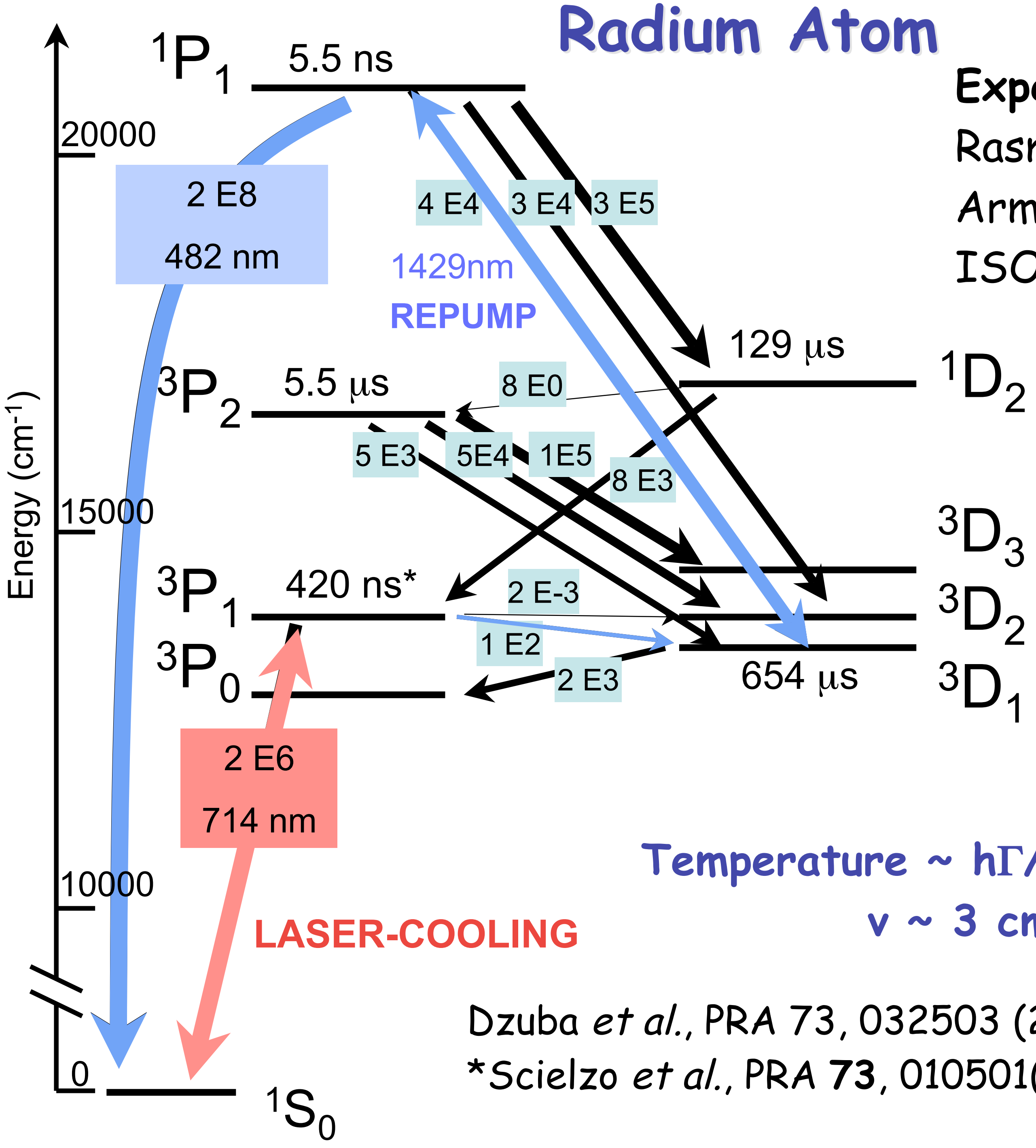
Armstrong (1979)

ISOLDE (1983-1988)



12	Mg	24.31
20	Ca	40.08
38	Sr	87.62
56	Ba	137.33
88	**Ra**	**(226)**

Radium Atom



Experimental work:

Rasmussen, Russell (1934)

Armstrong (1979)

ISOLDE (1983-1988)

w/o REPUMP:
2.4×10^4 cycles
(20 ms)

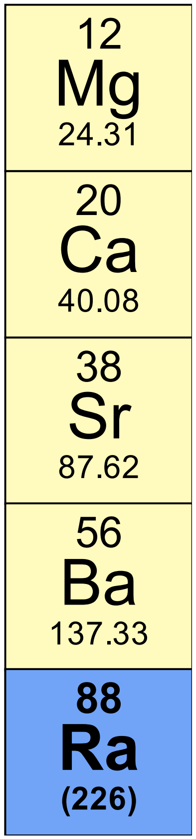
w/ 1429 nm
REPUMP:
x6800 cycles
(140 s in trap)

Temperature ~ $h\Gamma/4\pi k_B$ ~ 10 μK

v ~ 3 cm/s

Dzuba *et al.*, PRA 73, 032503 (2006)

*Scielzo *et al.*, PRA **73**, 010501(R) (2006)



12	Mg	24.31
20	Ca	40.08
38	Sr	87.62
56	Ba	137.33
88	**Ra**	**(226)**

Where do we get Ra-225?

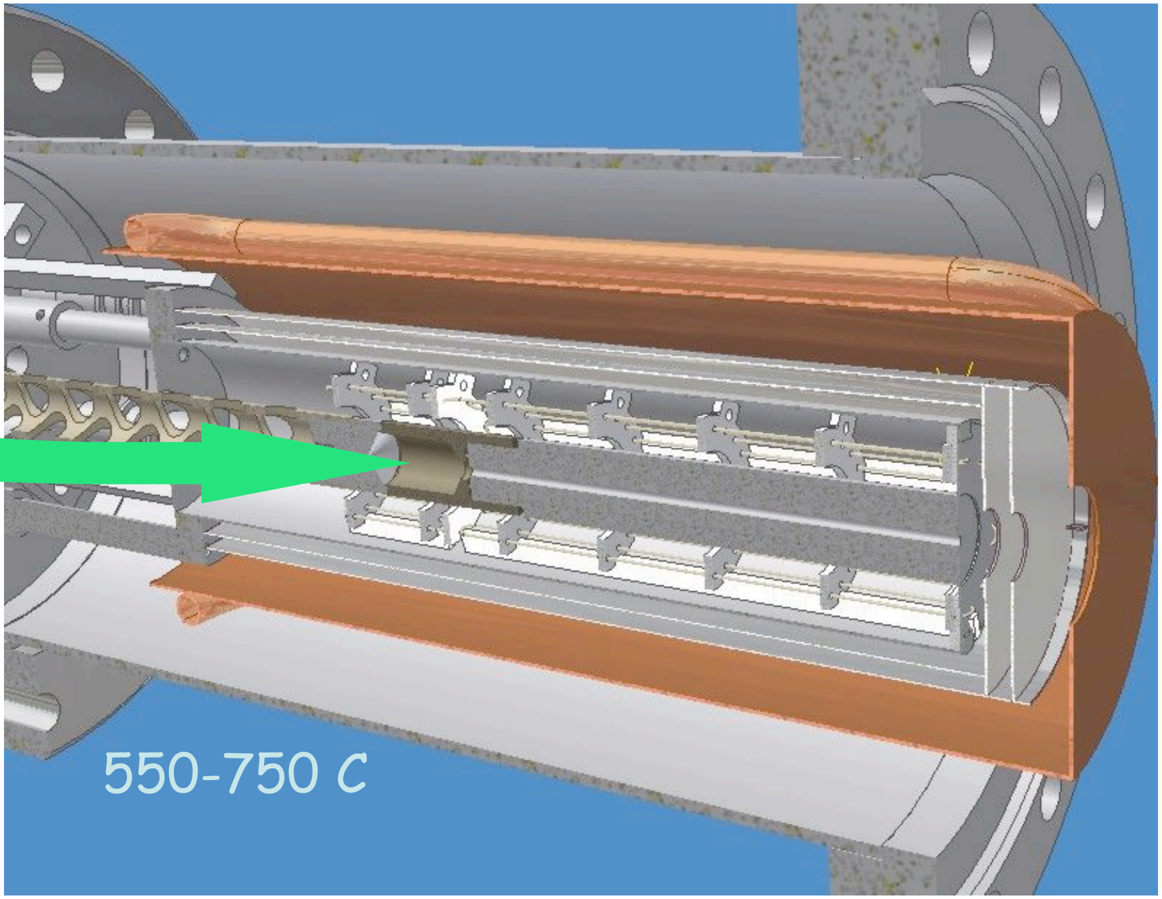
229Th 7300 yr $\xrightarrow{\alpha}$ **225Ra 15 days** $\xrightarrow{\beta}$ 225Ac 10 days $\xrightarrow{\alpha}$ Fr, At, Bi… ~ 4 hours $\xrightarrow{\alpha,\beta}$ 209Bi stable

1 mCi ^{225}Ra
(20 nano-g)

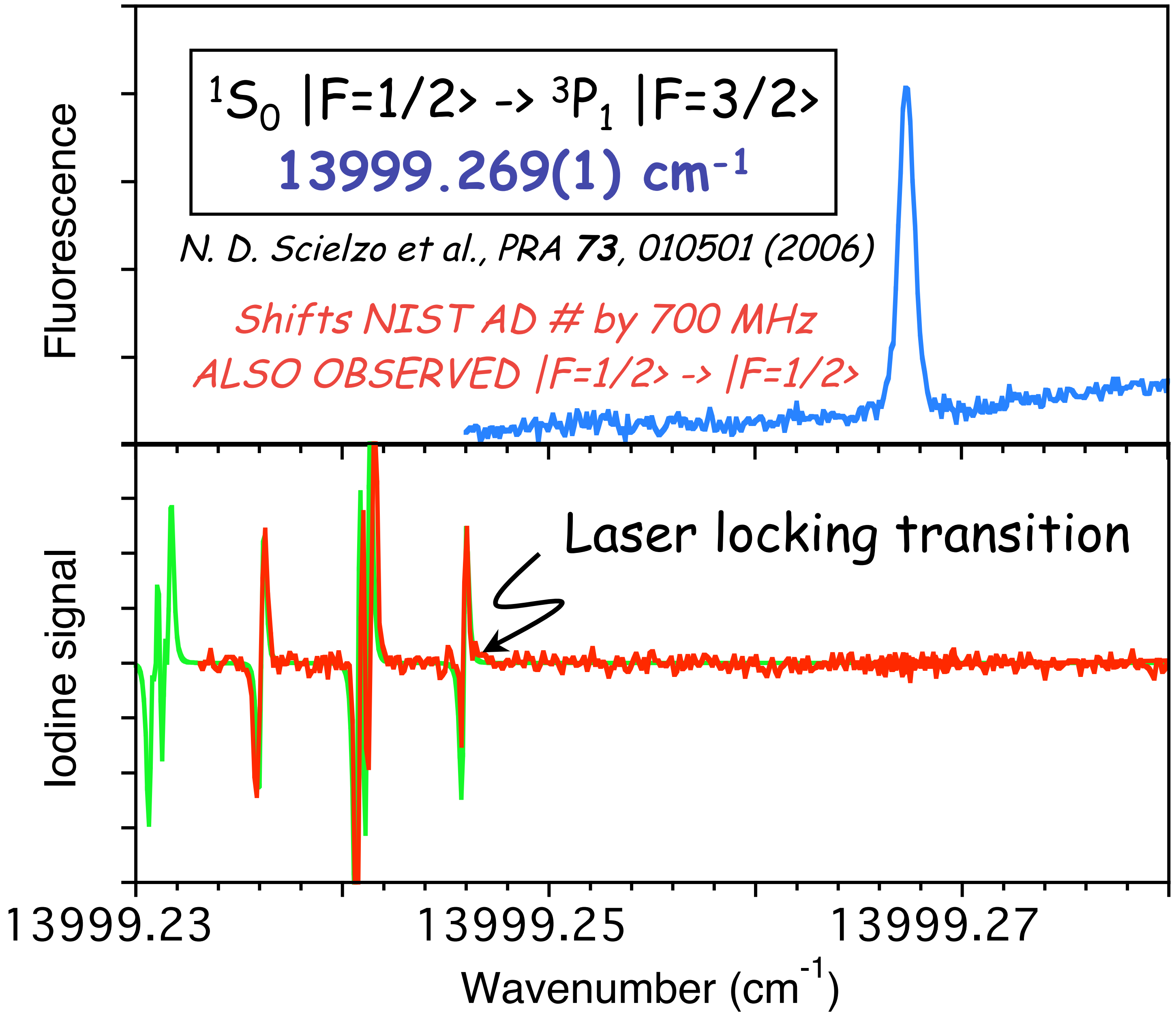
+ Al foil
+ 50 mg Ba

Reduces RaO
Passivates surfaces
Optical tracer

For trap development, using
226Ra ($t_{1/2}$=1600 yr)
~1 μCi (~1 μg)



Ra-225 atomic beam



$^1S_0$ |F=1/2> -> $^3P_1$ |F=3/2>

13999.269(1) cm^{-1}

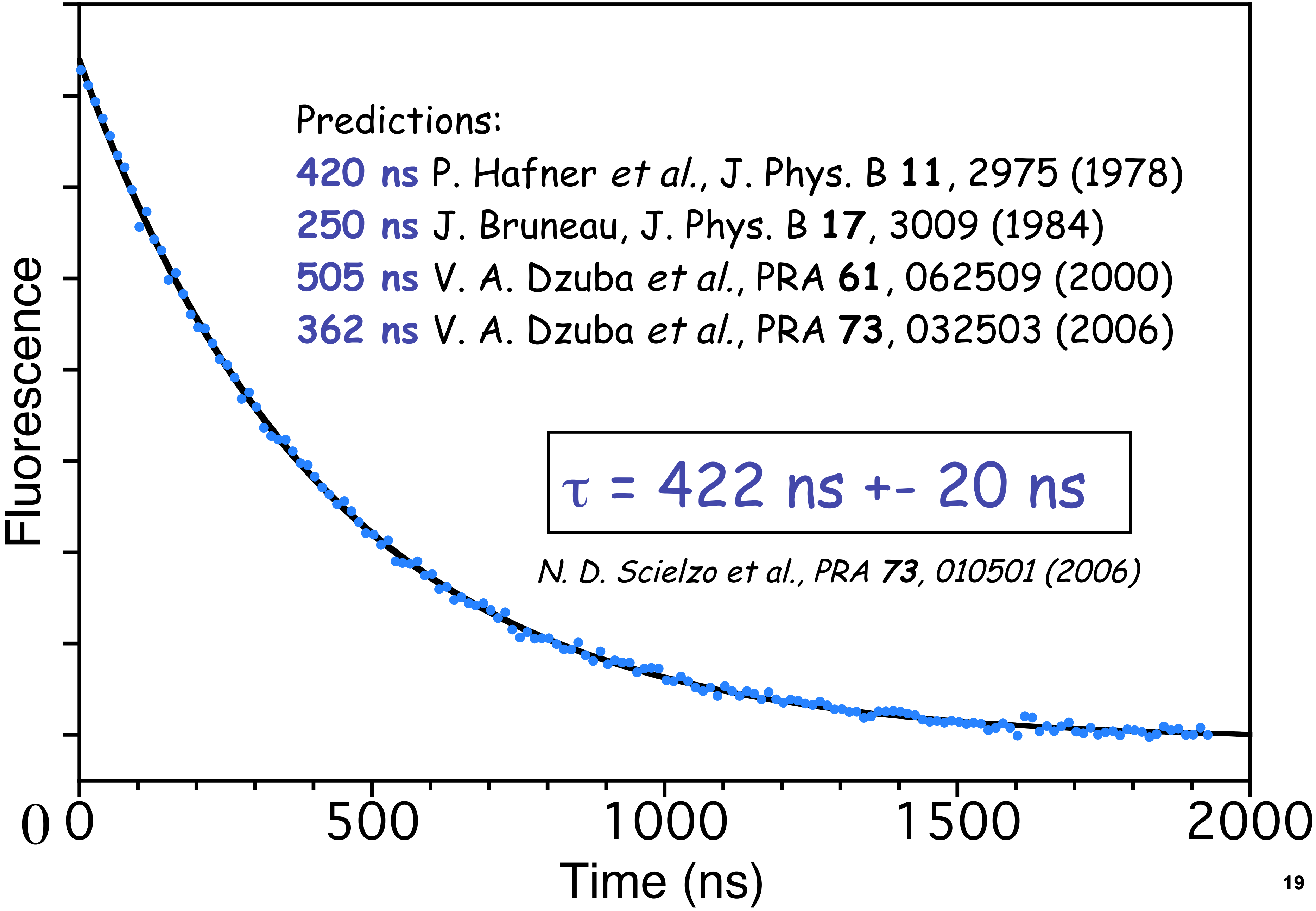
*N. D. Scielzo et al., PRA **73**, 010501 (2006)*

Shifts NIST AD # by 700 MHz

ALSO OBSERVED |F=1/2> -> |F=1/2>

Laser locking transition

Ra 7s7p $^3P_1$ lifetime measurement

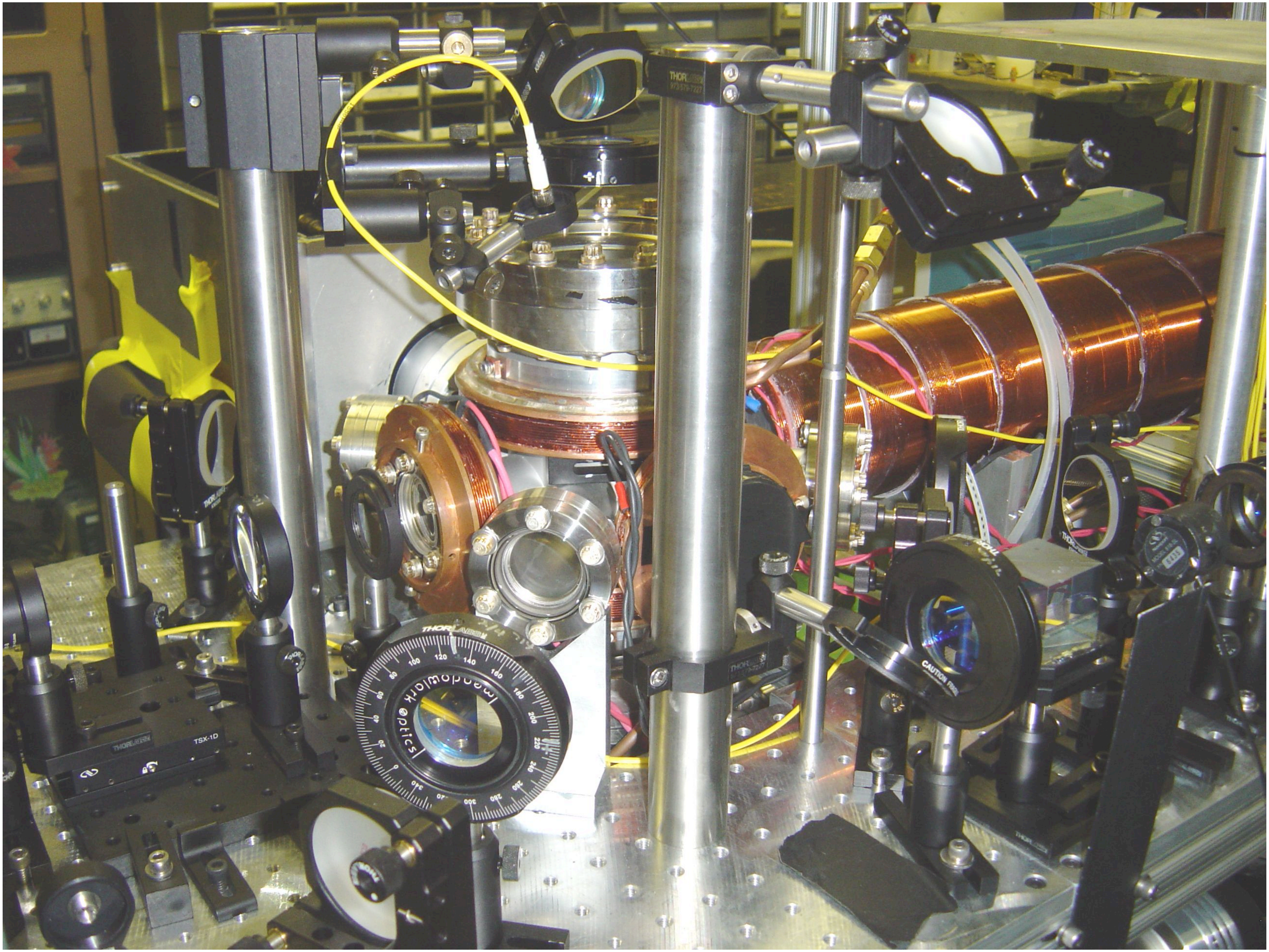


Predictions:

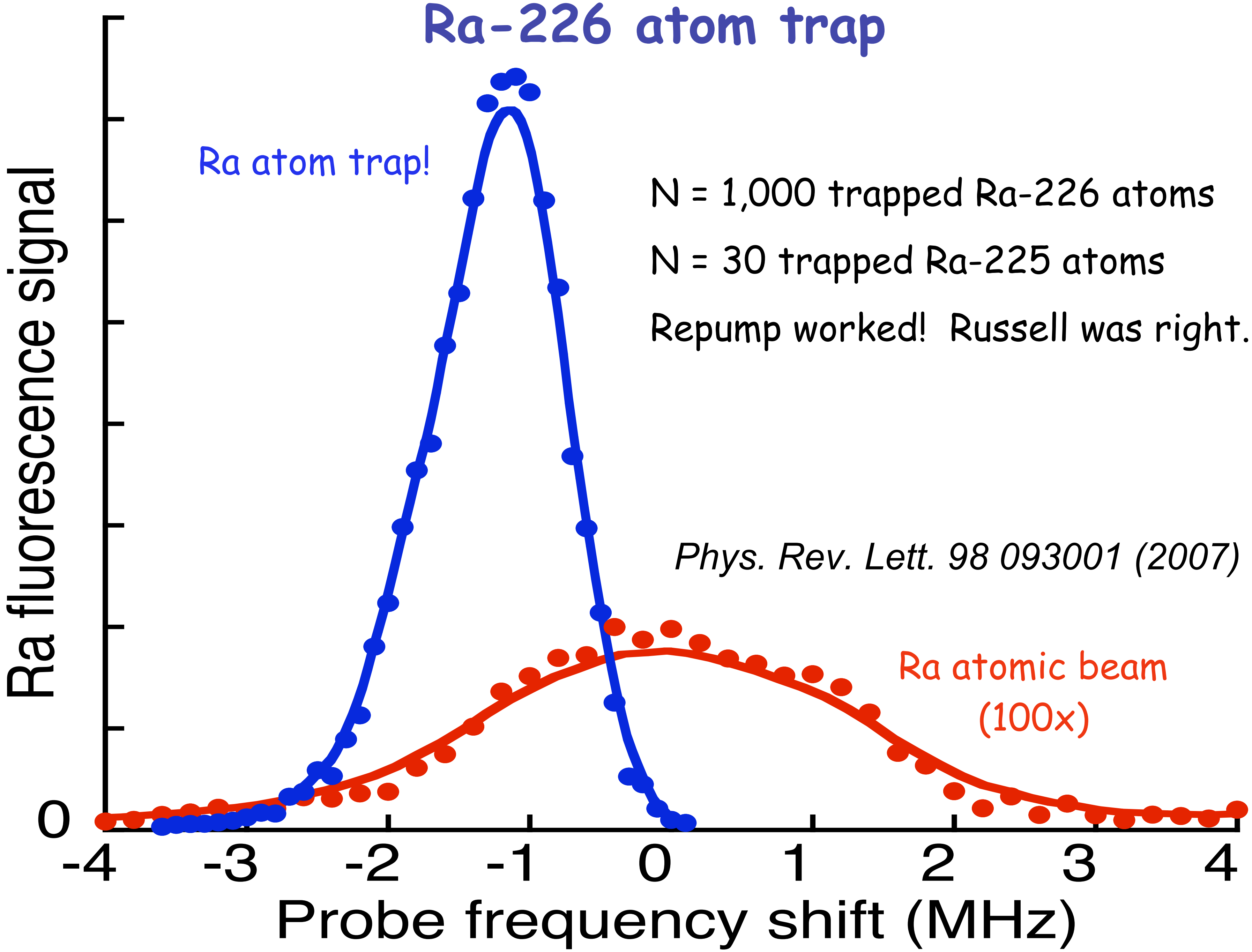
420 ns P. Hafner *et al.*, J. Phys. B **11**, 2975 (1978)
250 ns J. Bruneau, J. Phys. B **17**, 3009 (1984)
505 ns V. A. Dzuba *et al.*, PRA **61**, 062509 (2000)
362 ns V. A. Dzuba *et al.*, PRA **73**, 032503 (2006)

τ = 422 ns +- 20 ns

N. D. Scielzo et al., PRA ***73****, 010501 (2006)*


THORLABS
TSX-1D
meadowlark optics
CAUTION

Ra-226 atom trap



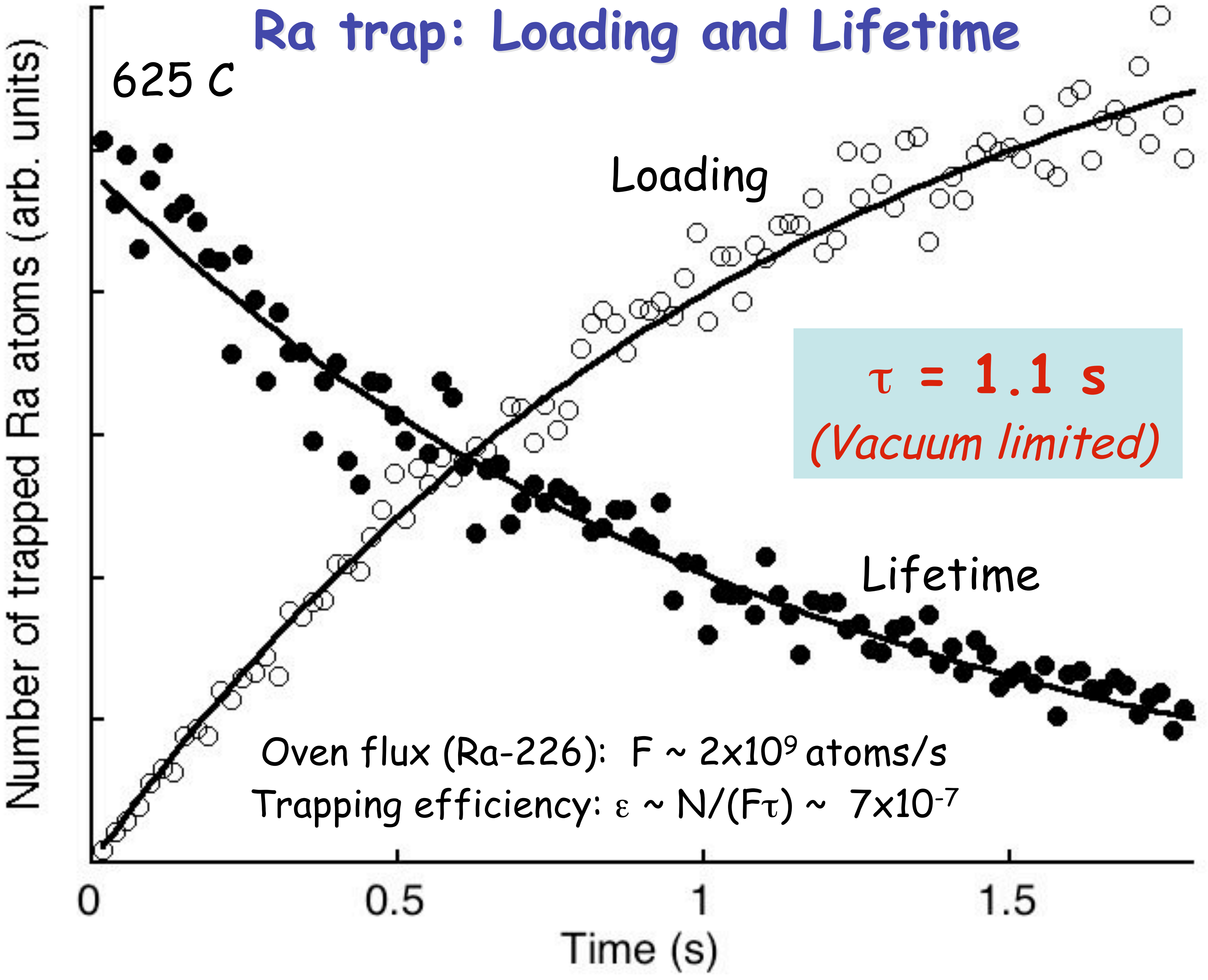
N = 1,000 trapped Ra-226 atoms

N = 30 trapped Ra-225 atoms

Repump worked! Russell was right.

Phys. Rev. Lett. 98 093001 (2007)

Ra trap: Loading and Lifetime



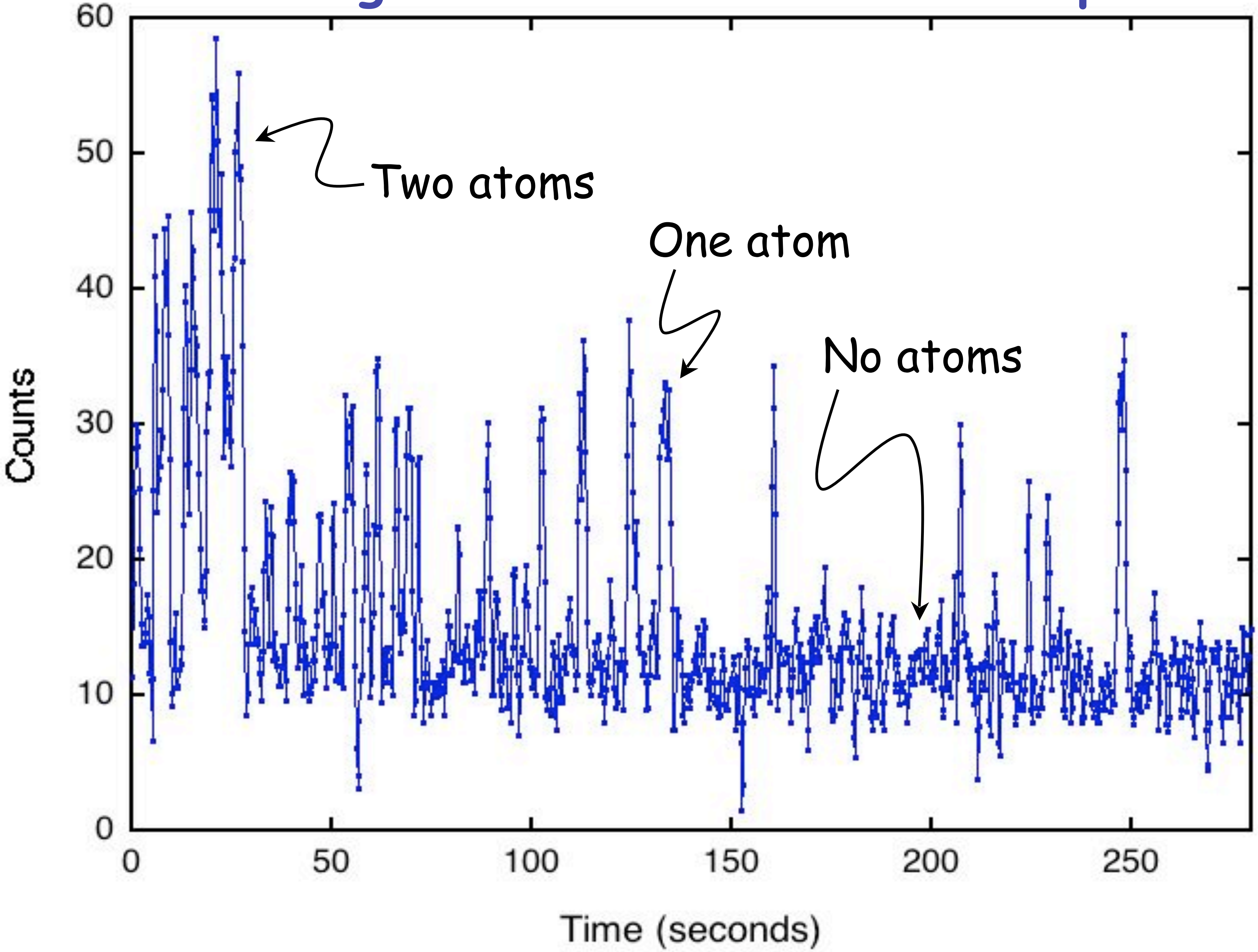
τ = 1.1 s

(Vacuum limited)

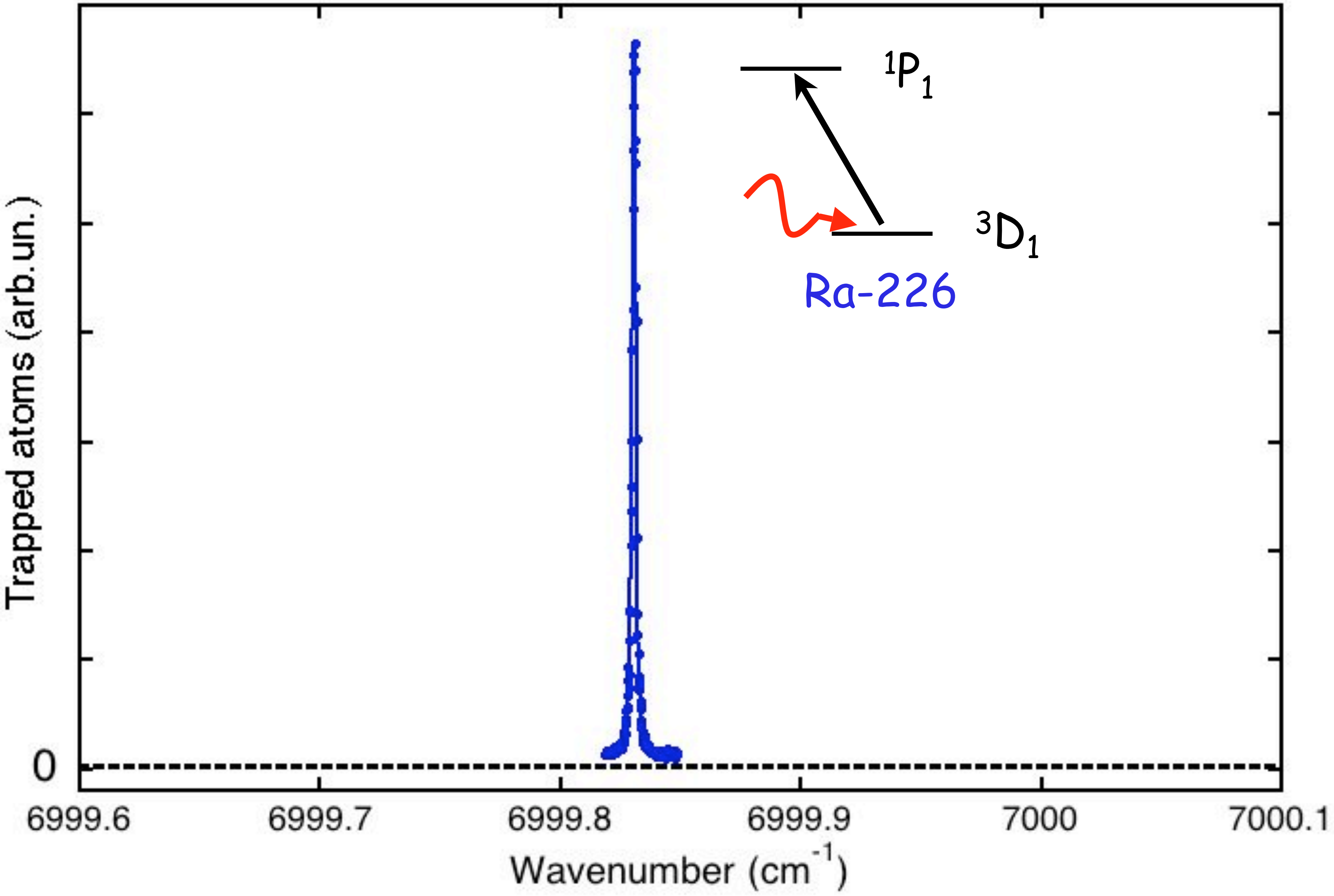
Oven flux (Ra-226): $F \sim 2 \times 10^9$ atoms/s

Trapping efficiency: $\varepsilon \sim N/(F\tau) \sim 7 \times 10^{-7}$

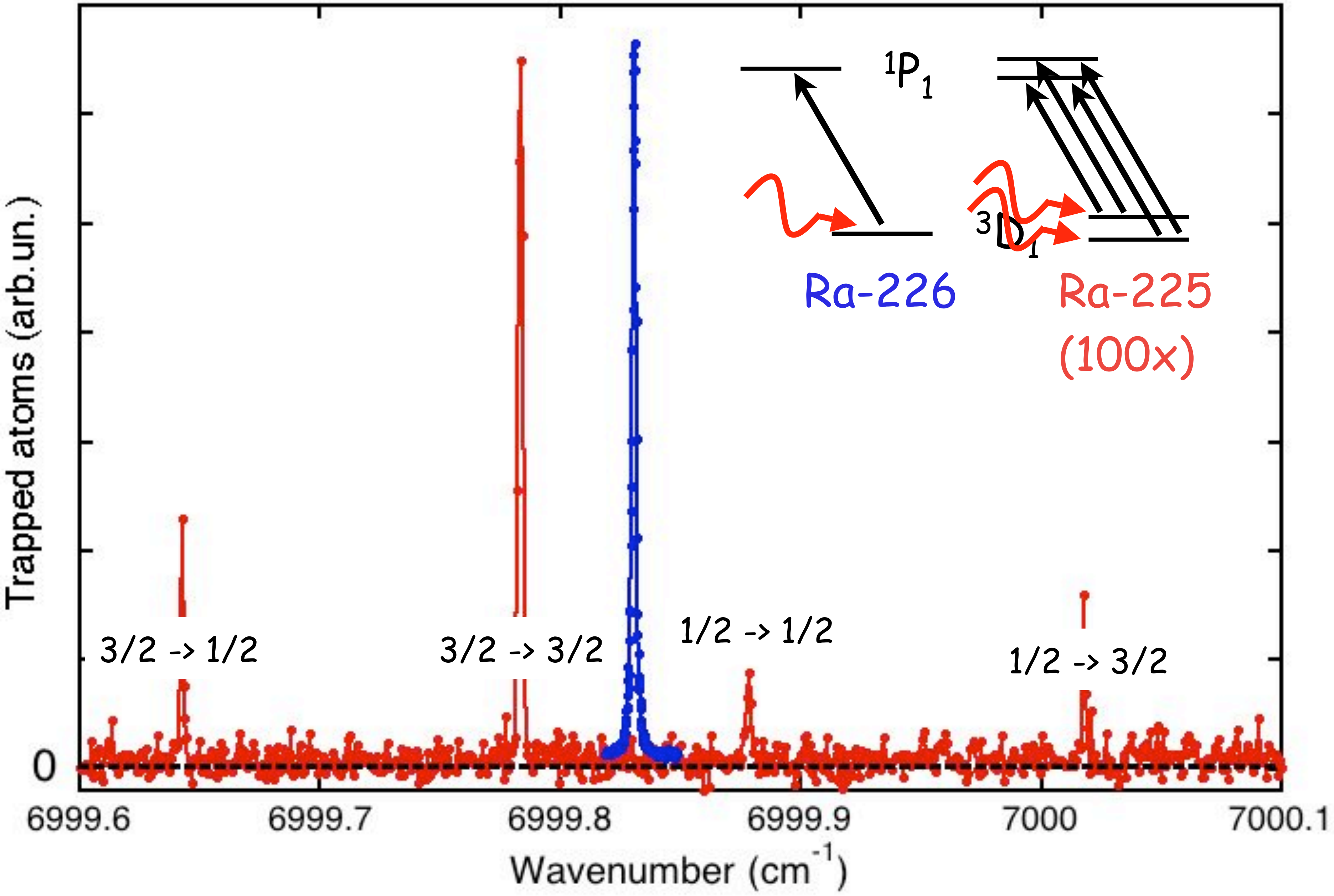
Single radium atoms in the trap



Repump spectrum

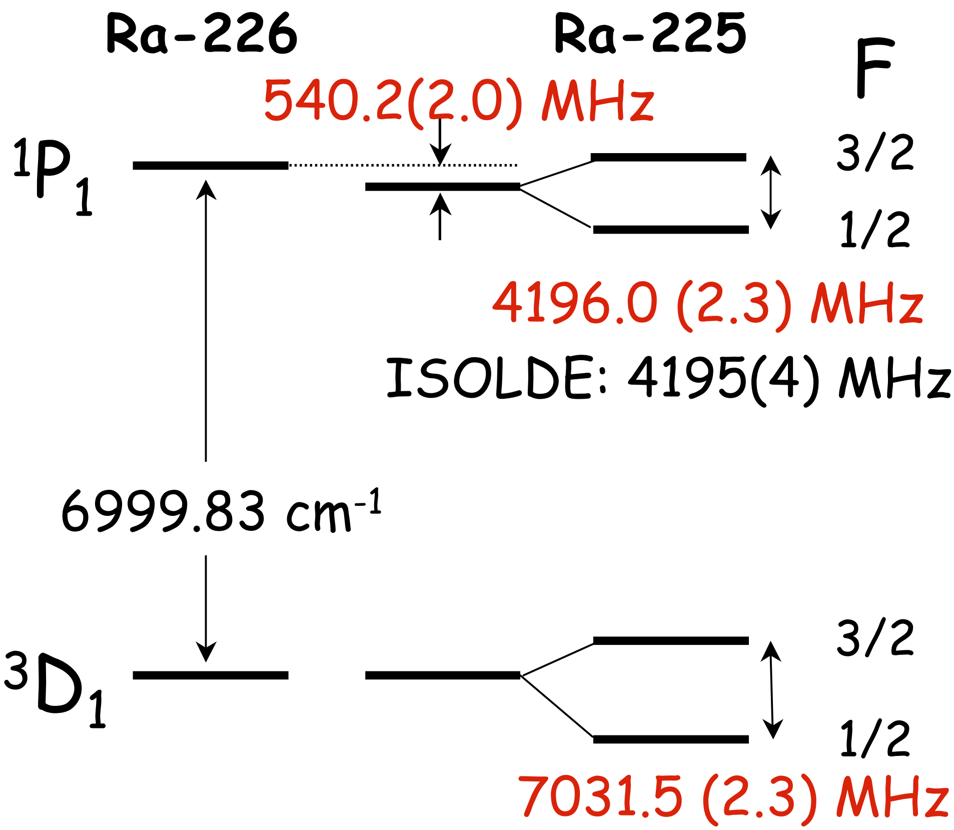


Repump spectrum



Hyperfine constants and isotope shift on $^3D_1$ - $^1P_1$

Repump laser is heterodyned with 2nd laser locked to stabilized Fabry-Perot



Ra-226 **Ra-225** F

540.2(2.0) MHz

$^1P_1$ 3/2 1/2

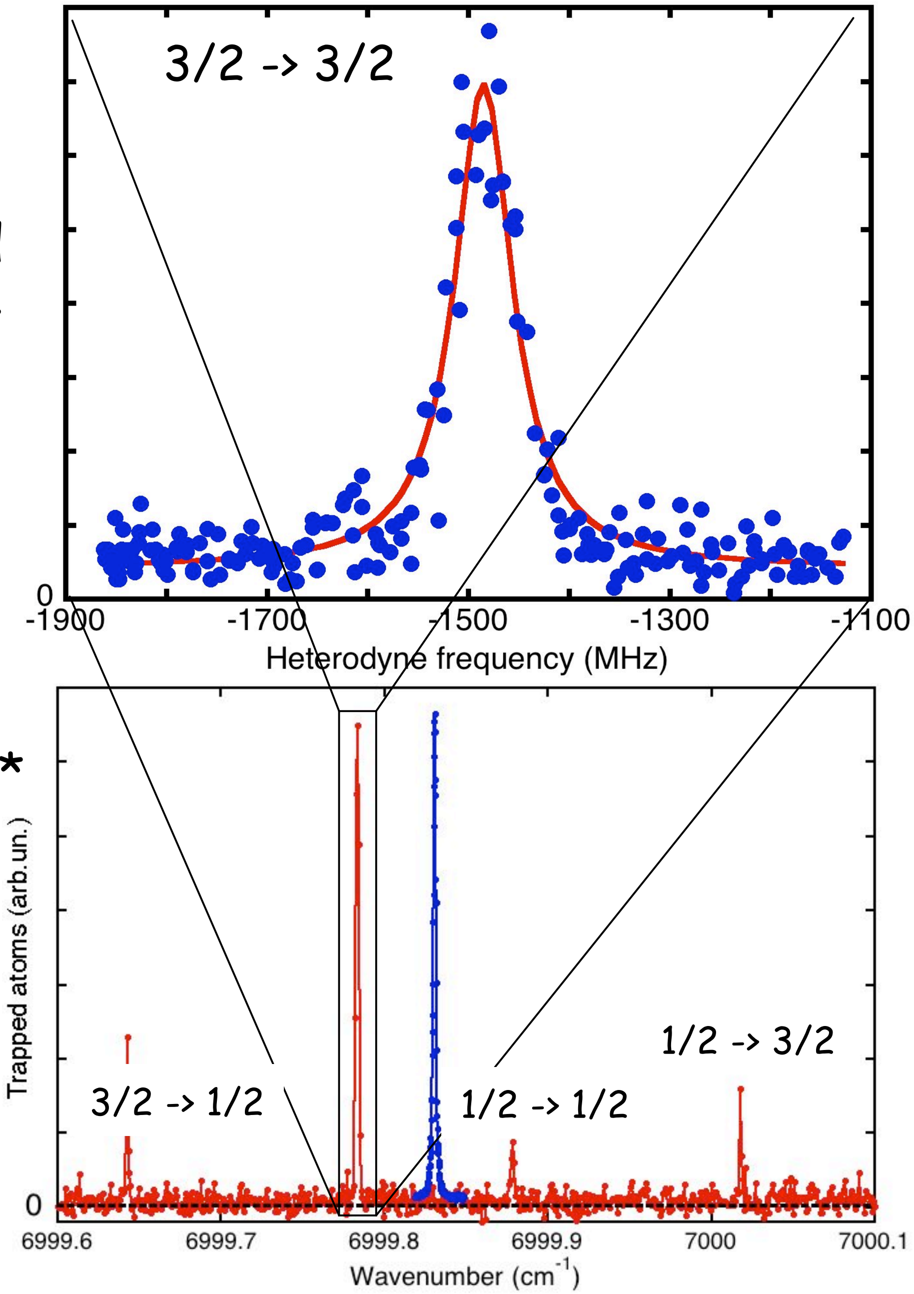
4196.0 (2.3) MHz

ISOLDE: 4195(4) MHz*

6999.83 cm^{-1}

$^3D_1$ 3/2 1/2

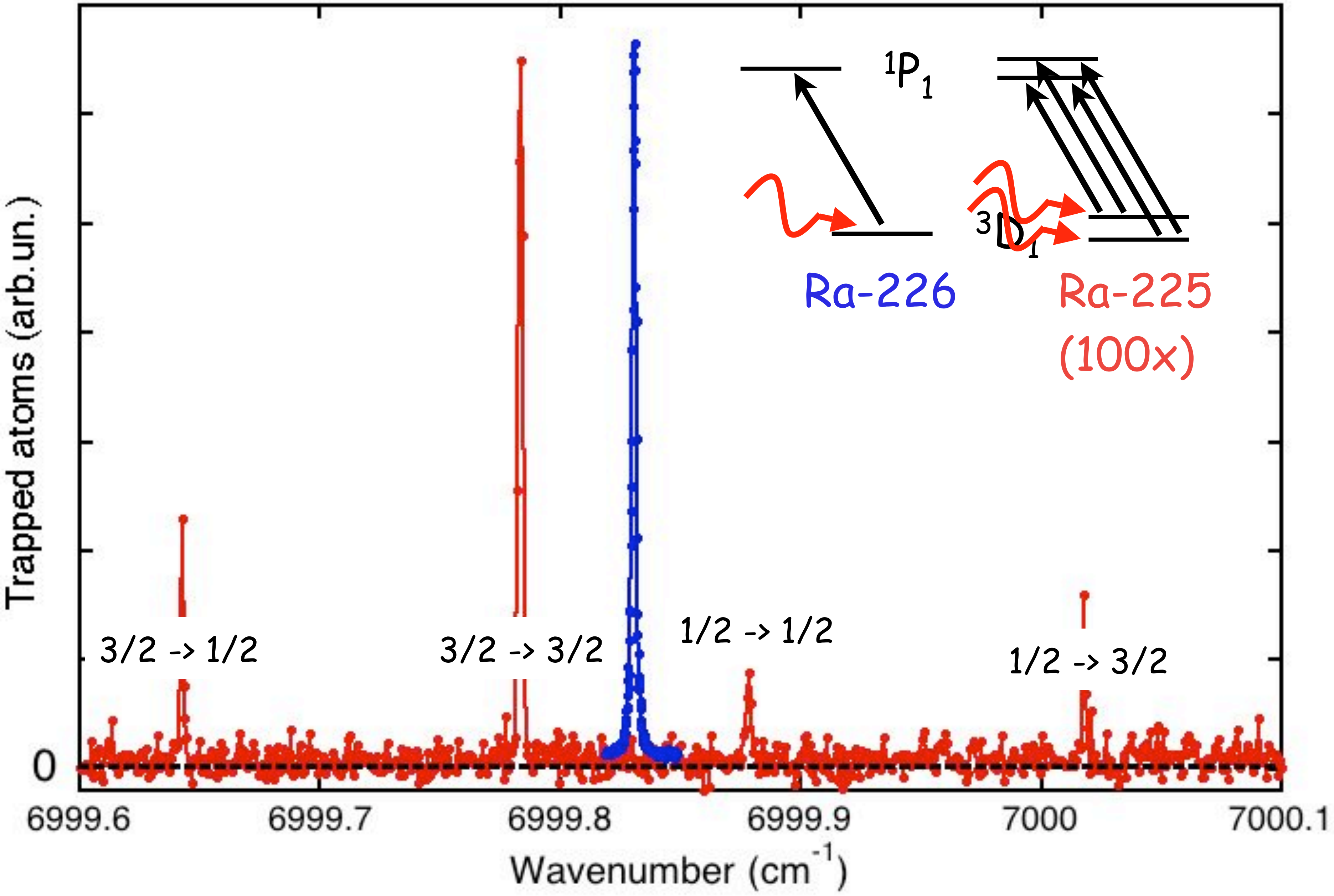
7031.5 (2.3) MHz



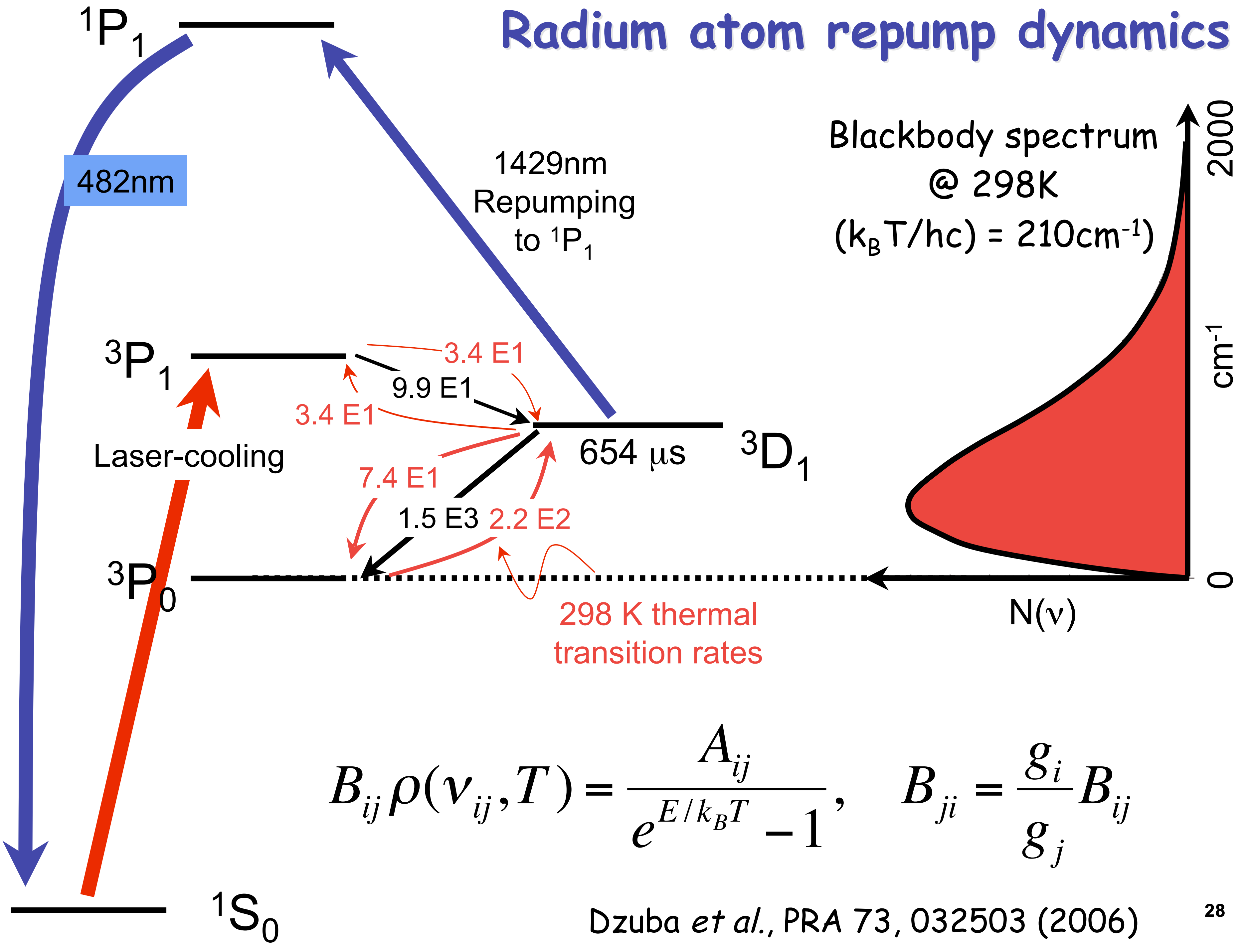
*Ahmad *et al., Phys. Lett.* ***133B****, 47 (1983)*

Phys. Rev. Lett. 98 093001 (2007)

Repump spectrum



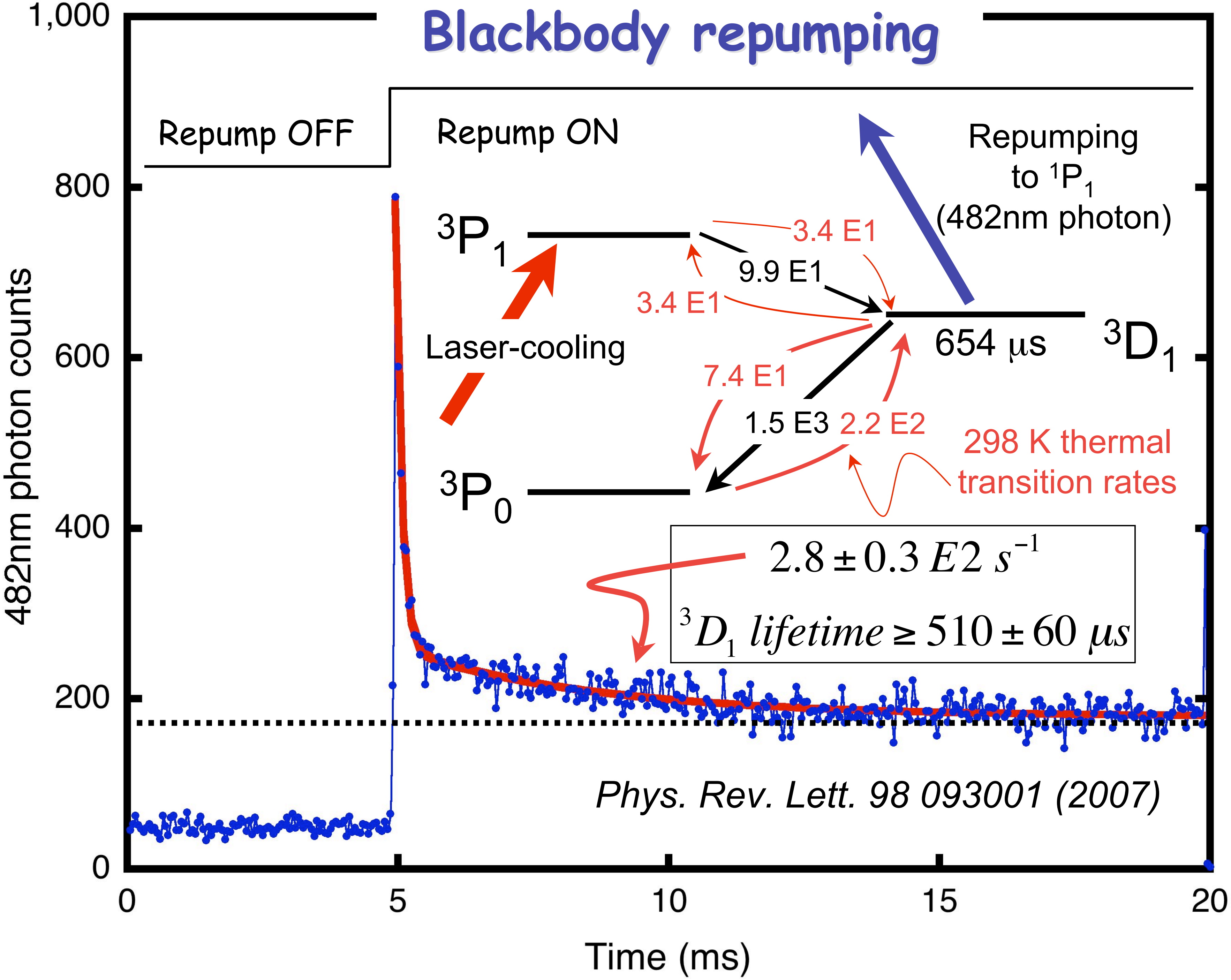
Radium atom repump dynamics



$$B_{ij}\rho(\nu_{ij},T) = \frac{A_{ij}}{e^{E/k_BT}-1}, \quad B_{ji} = \frac{g_i}{g_j}B_{ij}$$

Dzuba *et al.*, PRA 73, 032503 (2006)

Blackbody repumping



$2.8 \pm 0.3\, E2\, s^{-1}$

$^3D_1$ *lifetime* $\geq 510 \pm 60\, \mu s$

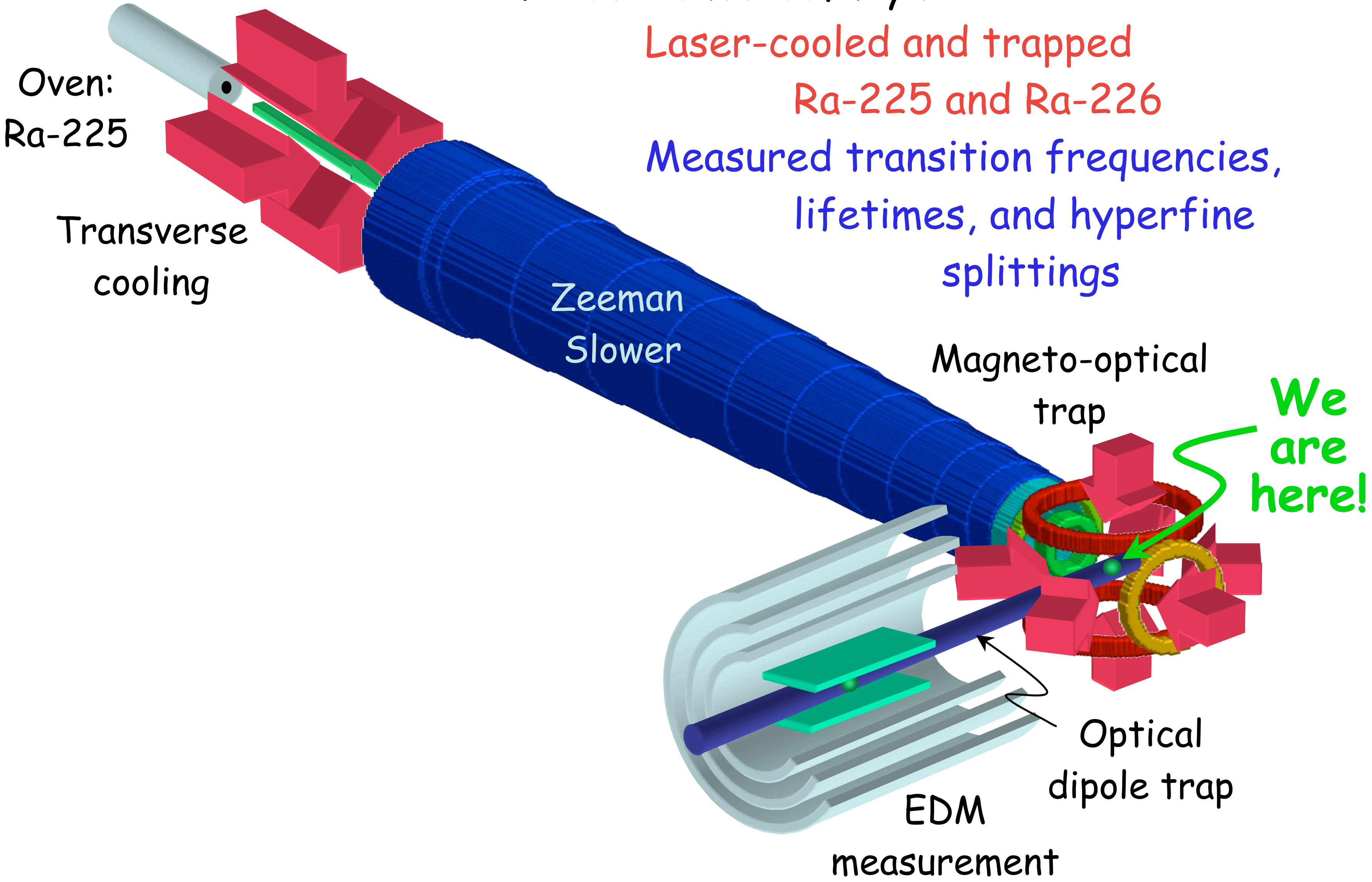
Phys. Rev. Lett. 98 093001 (2007)

Where we are and where we're going …

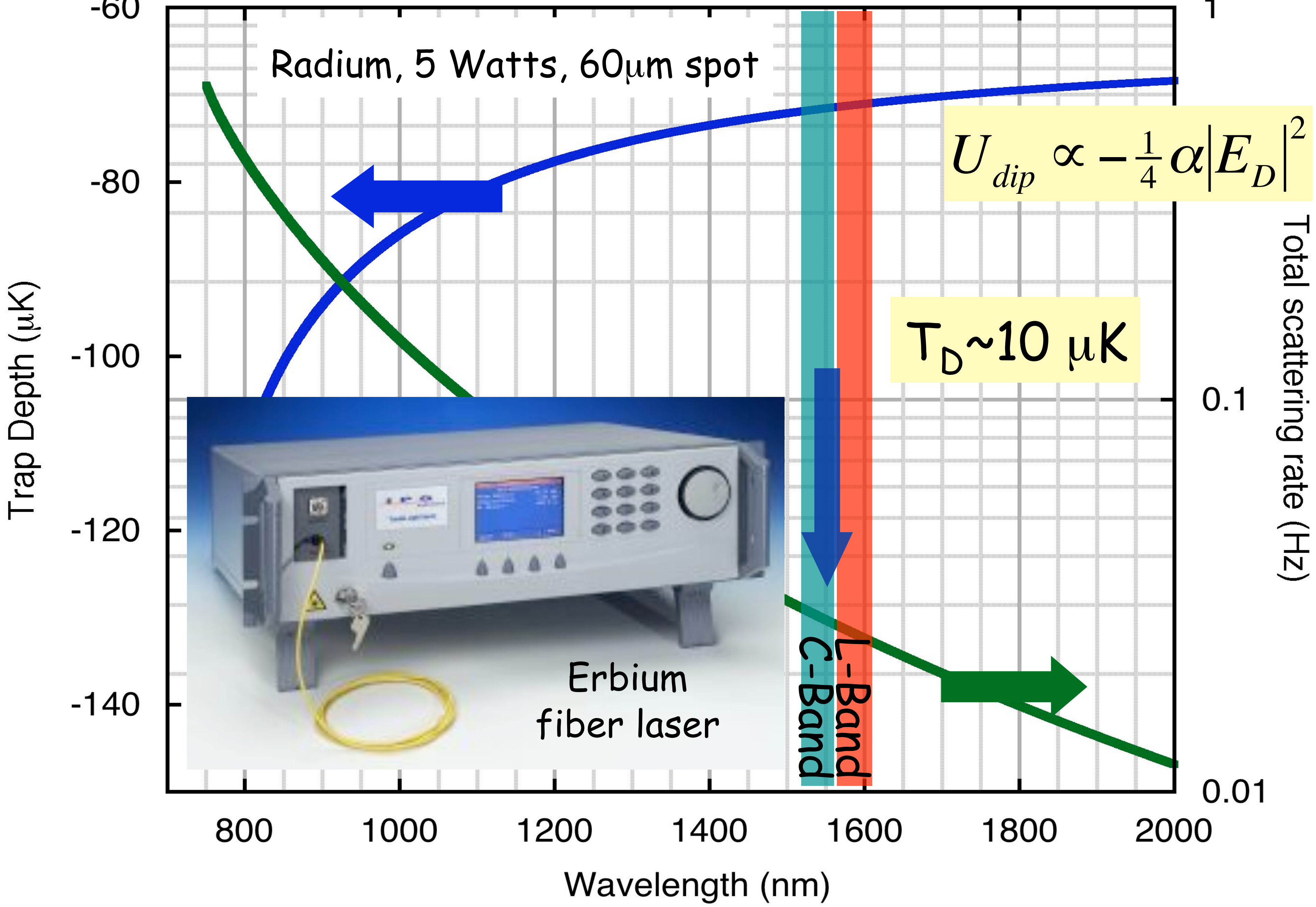
We have successfully …

Laser-cooled and trapped Ra-225 and Ra-226

Measured transition frequencies, lifetimes, and hyperfine splittings



Optical dipole trap laser



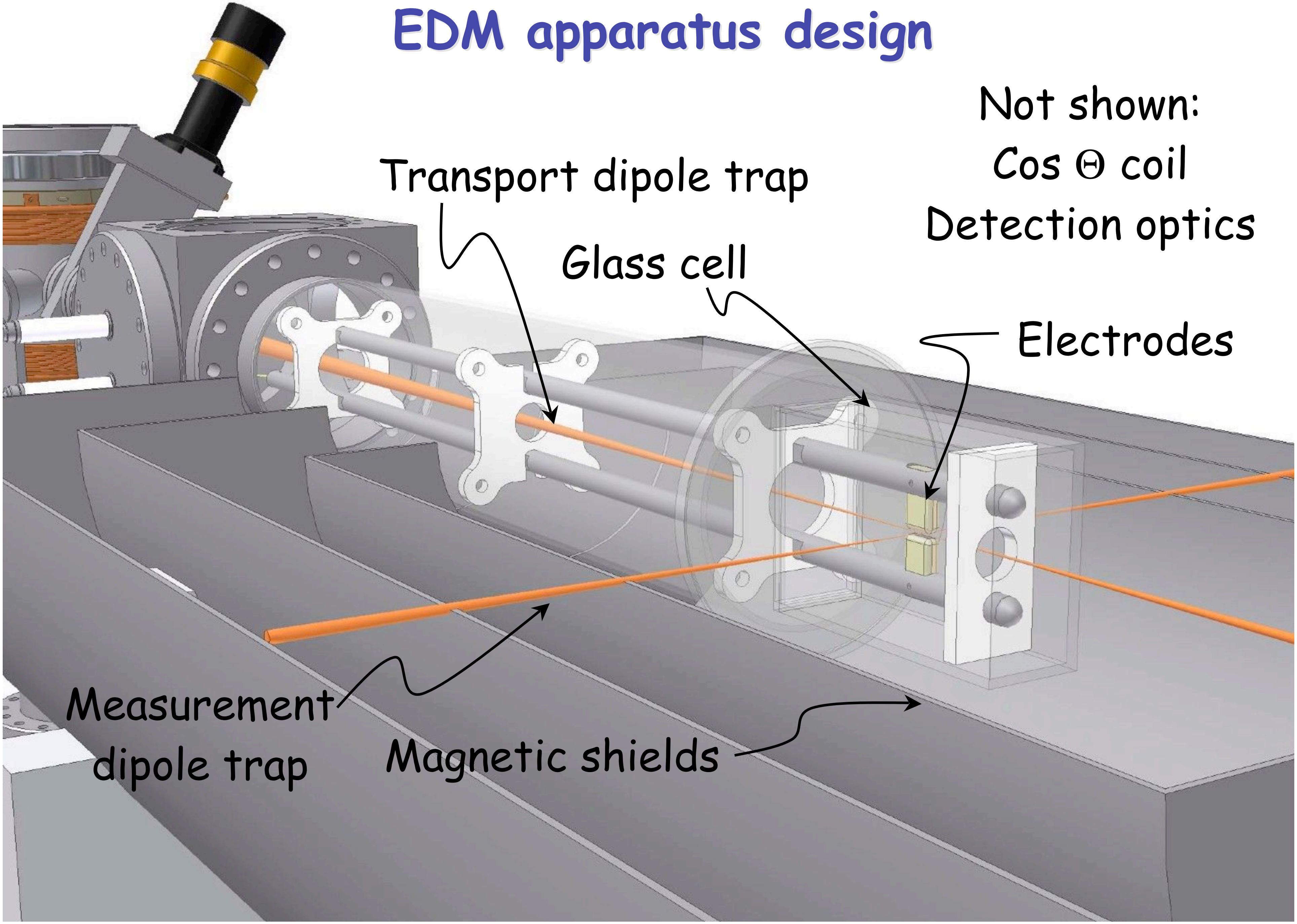
Radium, 5 Watts, 60μm spot

$$U_{dip} \propto -\tfrac{1}{4}\alpha\left|E_D\right|^2$$

T_D~10 μK

Erbium fiber laser

EDM apparatus design



Not shown:
Cos Θ coil
Detection optics

Transport dipole trap

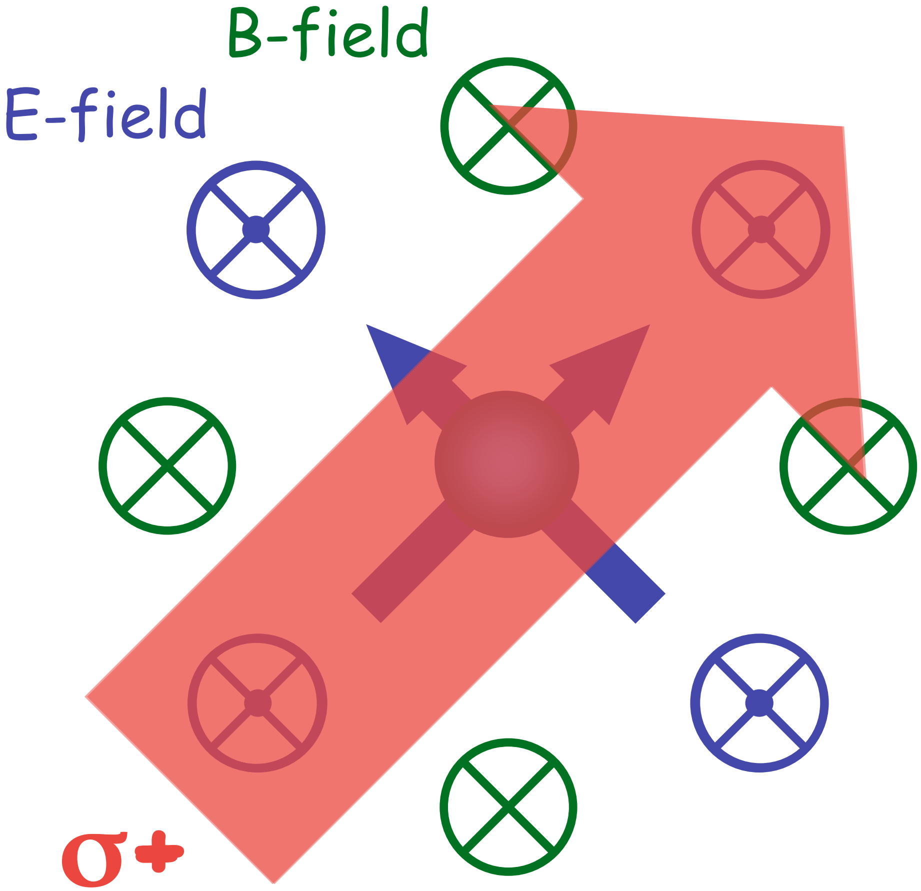
Glass cell

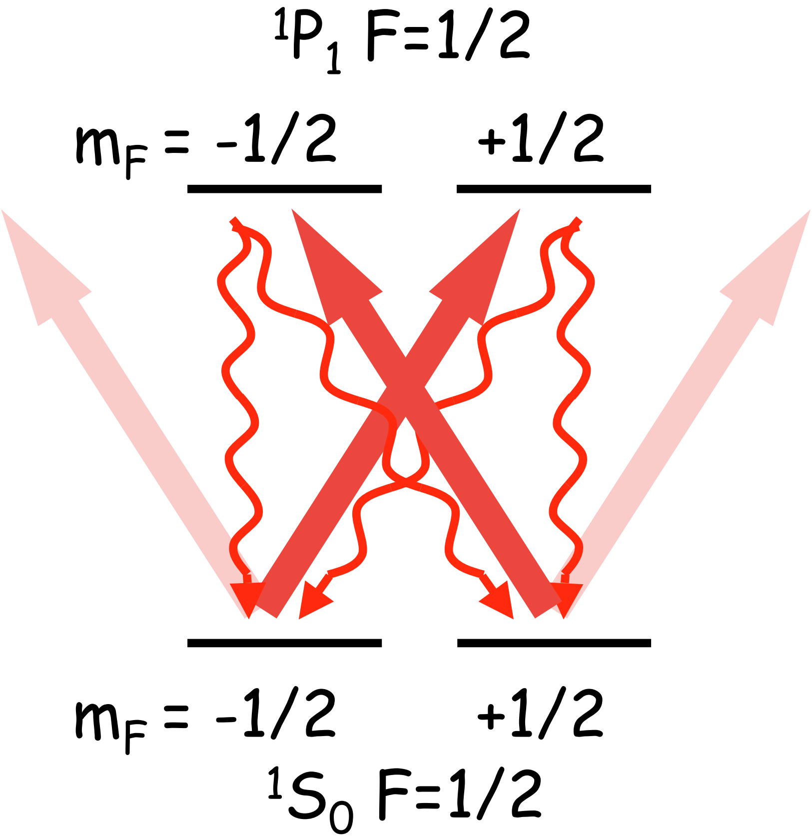
Electrodes

Measurement dipole trap

Magnetic shields

EDM measurement





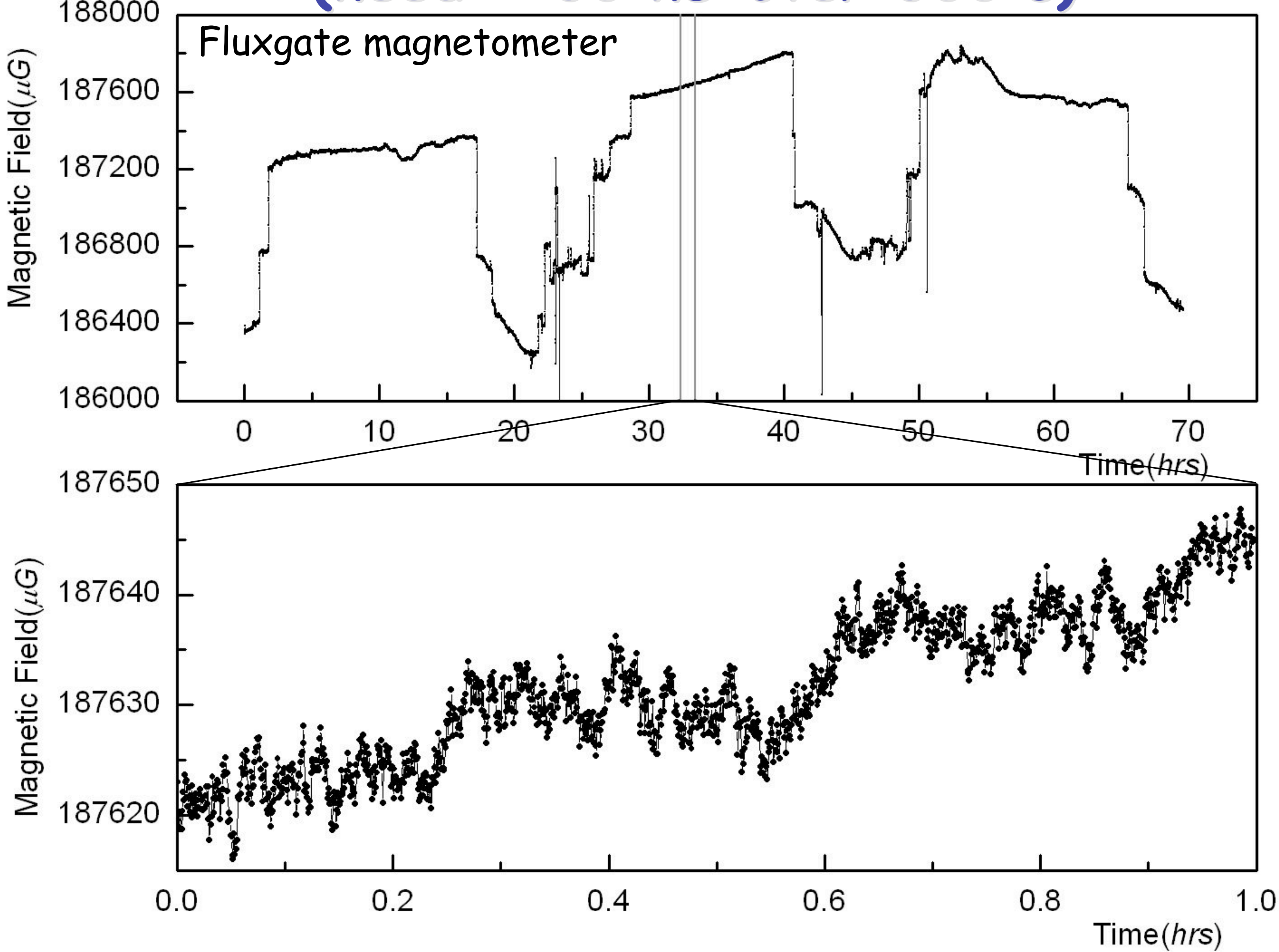
Optical pumping

$$\nu t \approx \frac{1}{2\pi}\frac{N^+ - N^-}{N^+ + N^-} + m$$

B = 10 mG: ν = 10 Hz …. E = 100 kV/cm: d = 10^{-26} ecm?

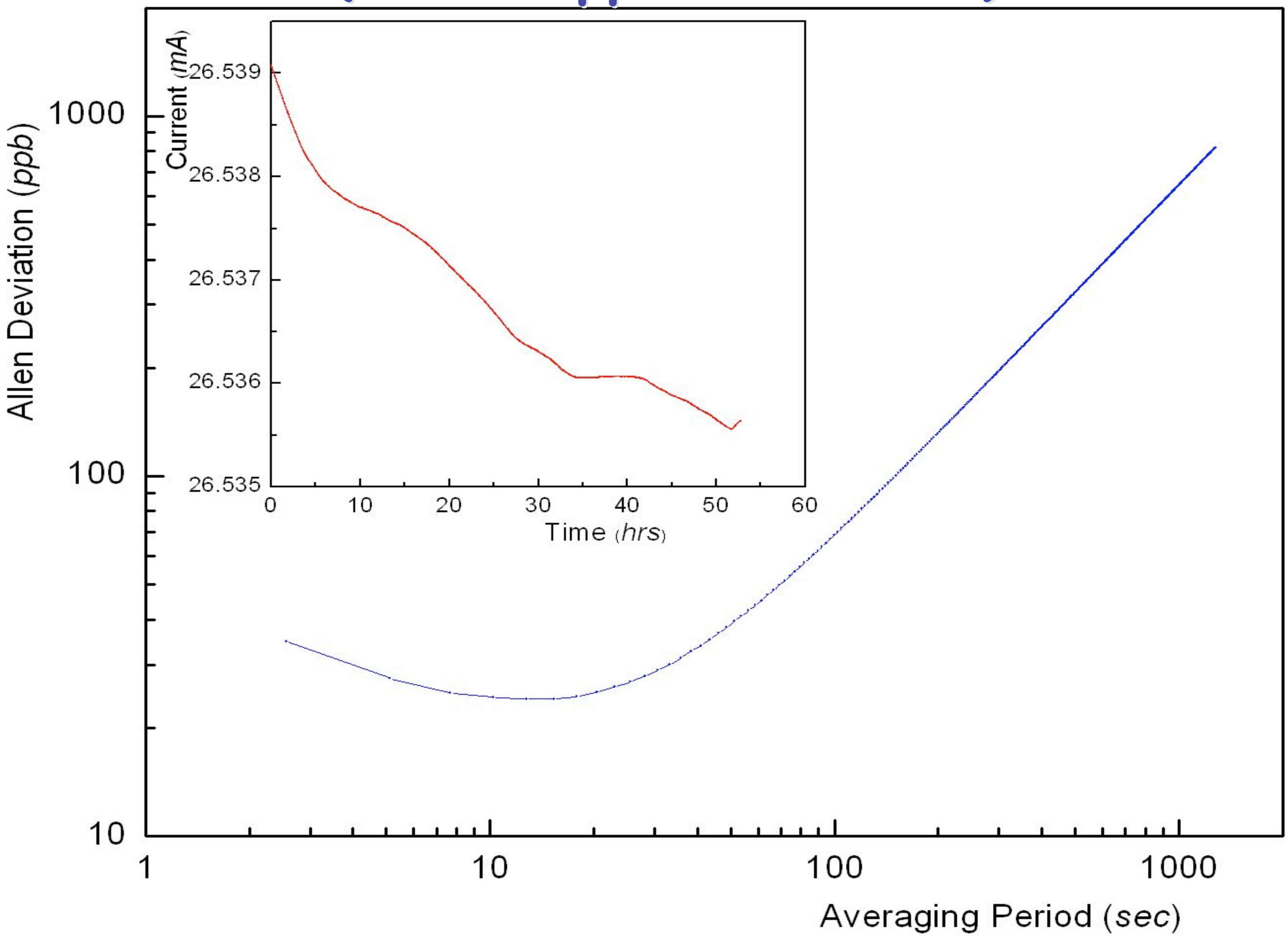
dν = 1 μHz = 30 μHz / $(1000)^{1/2}$

Environmental magnetic fields (need < 30 nG over 300 s)



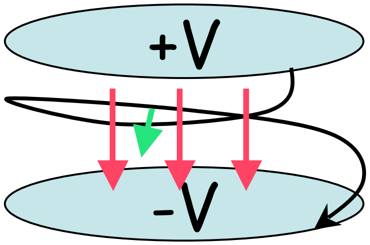
Magnetic shielding: >10^4 suppression

Stable current supply for applied B field (need <3ppm over 300s)



Systematics and noise

Largest systematics arise from magnetic fields which change with direction of applied electric field



Leakage current between plates could run in loop causing a magnetic field $\mathbf{B}_{\text{leak}}$ which changed direction with **E**

Motional magnetic field $\mathbf{B}_{\text{mot}} = 1/c^2\, \mathbf{v} \times \mathbf{E}$ changes direction with **E**

Electric quadrupole terms $H \sim |E|^2$ may lead to systematic with incomplete field reversal (0 for spin-1/2)

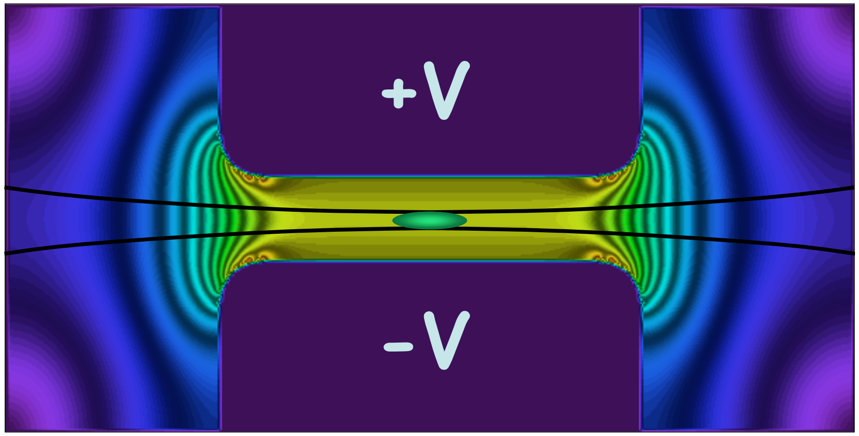
Geometric phase small due to small trap size, velocity

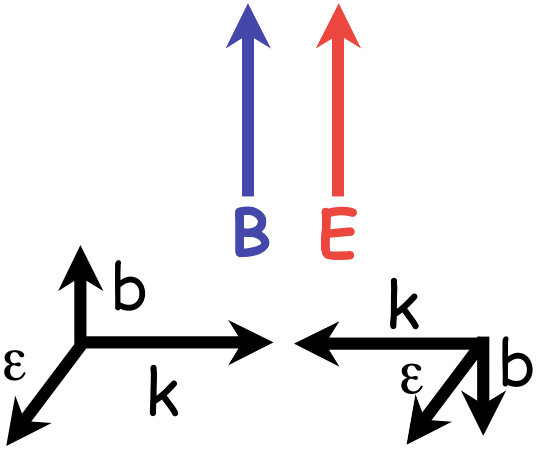
Collisions? Low density, Cold spin-polarized fermions

Possible dipole trap systematics and noise

Systematics:

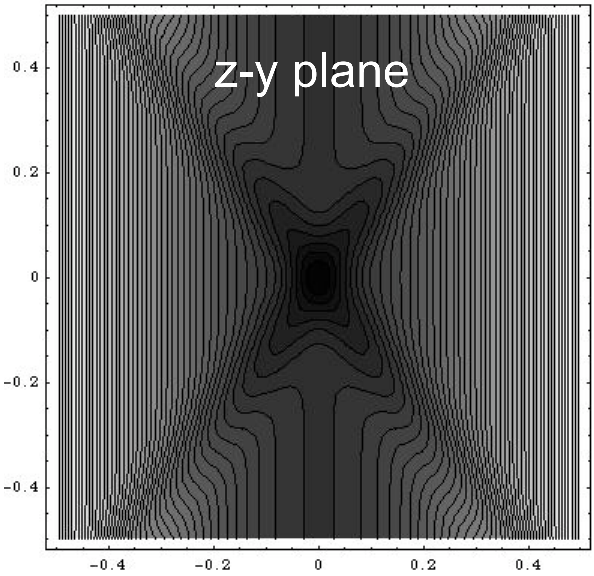
COM Potentials? $|E_{HV}|^2 \sim 100x|E_D|^2$

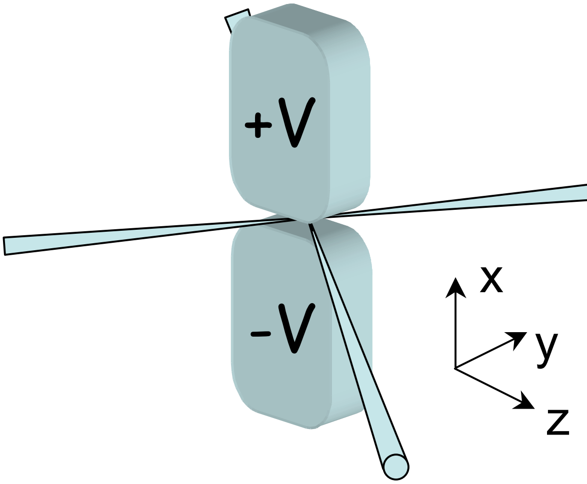


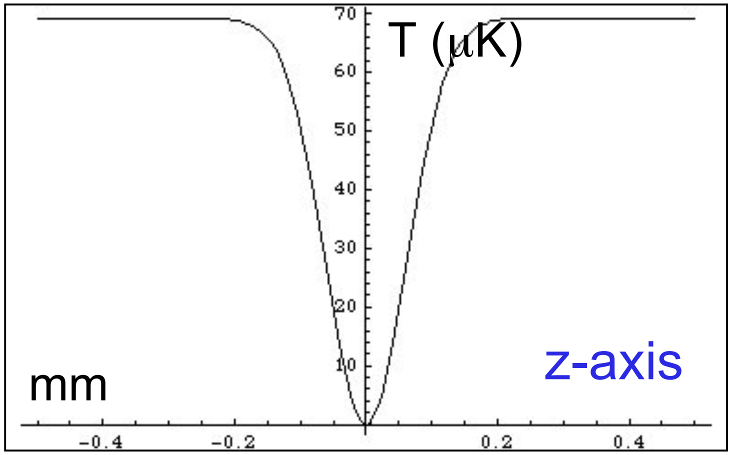


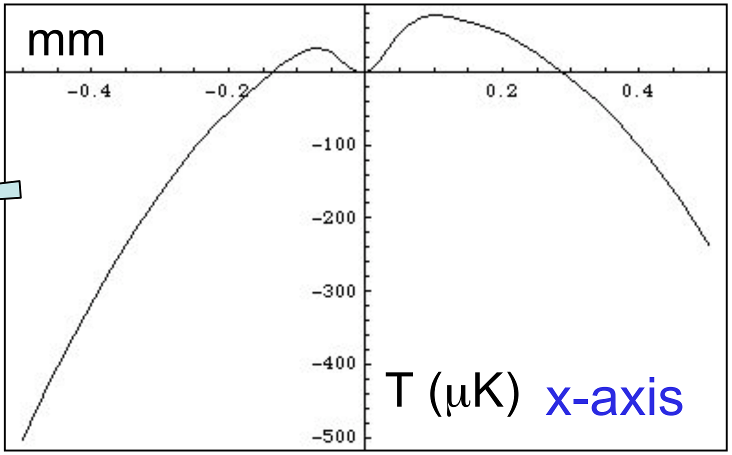
Dipole + HV potential + gravity

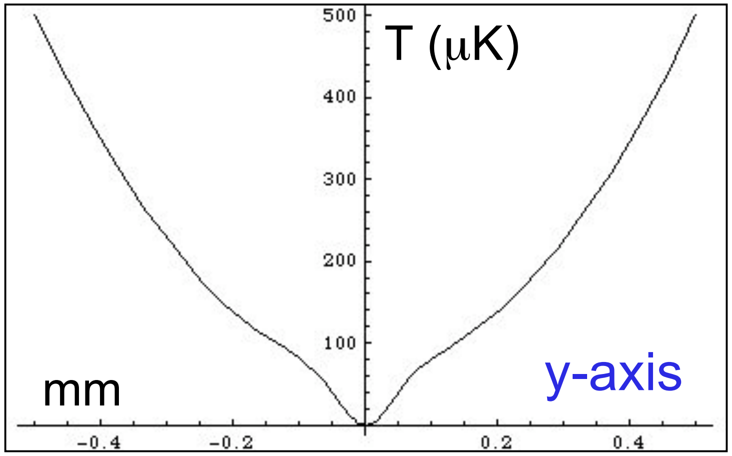
$$U(\mathbf{r}) =$$
$$-\alpha/2\,(|E_{HV}(\mathbf{r})|^2 + 1/2|E_D(\mathbf{r})|^2) + Mgx$$











Trap stability?

- Need plates parallel to 10 mrad

Systematics? 10 μm shift with reversal?

- Need < 100 nG/mm at center

Possible dipole trap systematics and noise

Systematics:

COM Potentials? $|E_{HV}|^2 \sim 100x|E_D|^2$

E-field mixes opposite parity states, can cause magnetic dipole shifts

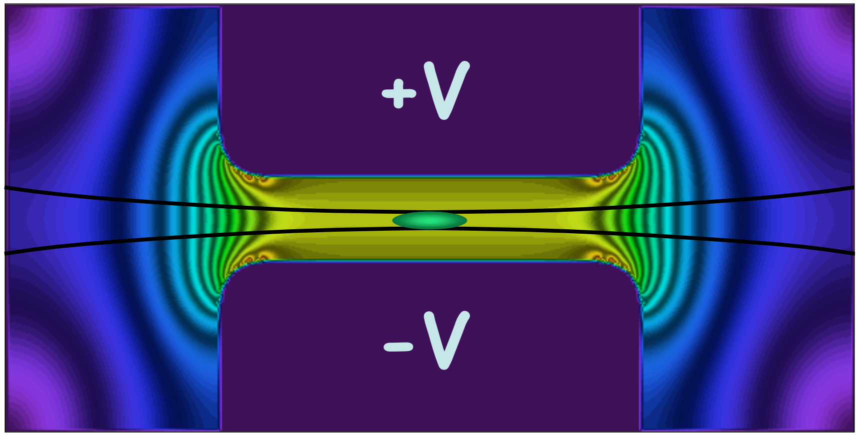
Noise, coherence limiting mechanisms:

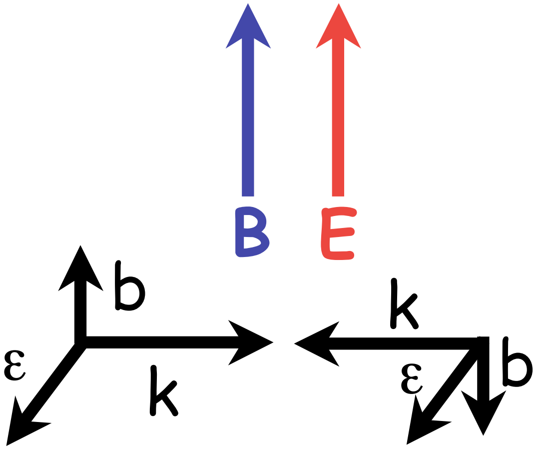
Residual circular polarization of dipole laser provide a vector light shift, linear in m (no tensor shift I=1/2)

Use trans lin pol, lattice

M. V. Romalis and E. N. Fortson,
PRA **59**, 4547 (1999)

C. Chin *et al.*, PRA **63**, 033401 (2001)



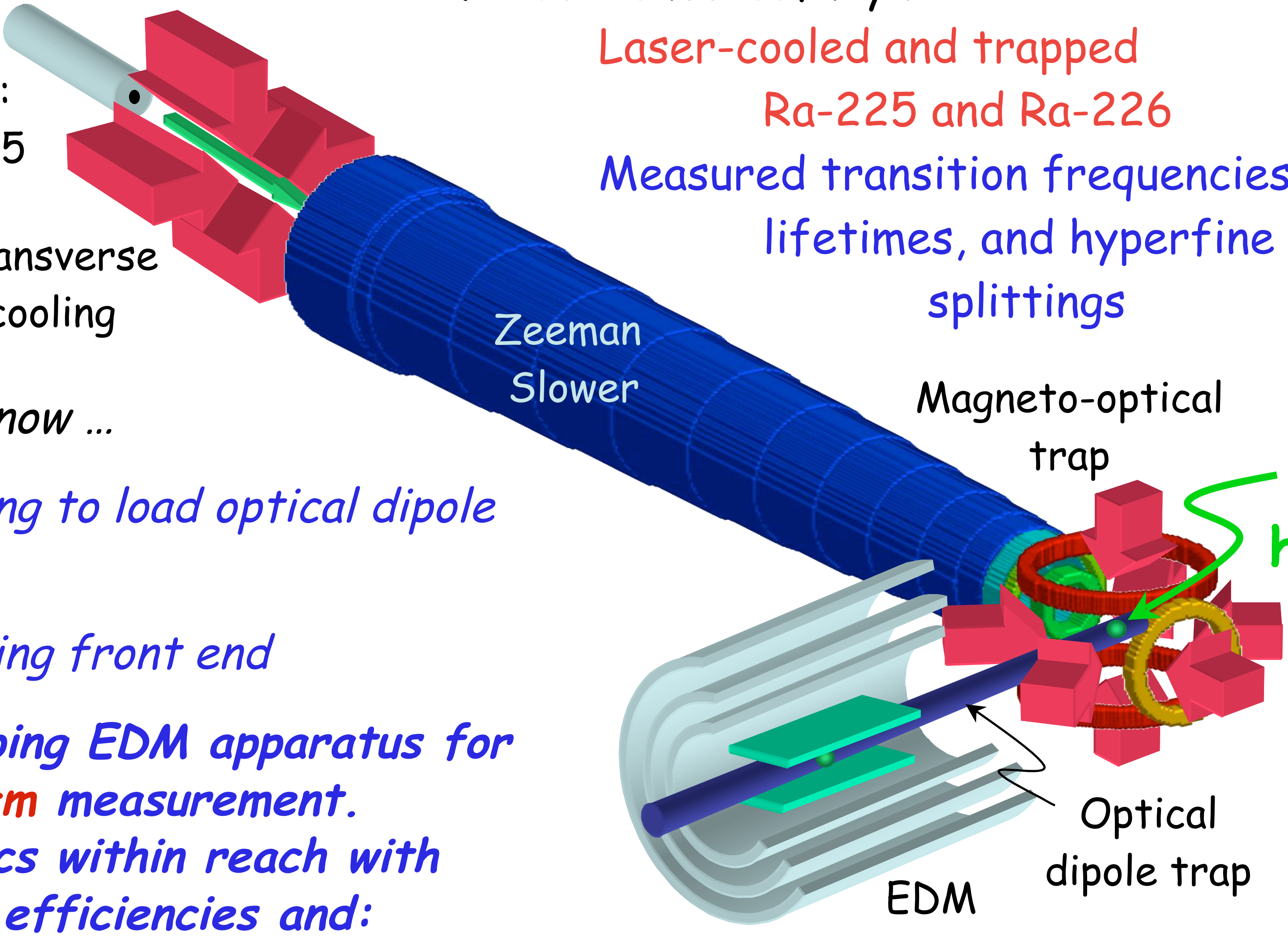


Where we are and where we're going …

We have successfully …

Laser-cooled and trapped
Ra-225 and Ra-226

Measured transition frequencies,
lifetimes, and hyperfine
splittings



We are now …

- *Preparing to load optical dipole trap*
- *Improving front end*
- ***Developing EDM apparatus for 10^{-26} ecm measurement. Statistics within reach with current efficiencies and:***

10 mCi, E=100 kV/cm, τ=300s

Kr, He, and Ra :) atom trappers