EDM searches on atoms with deformed nuclei: Radium-225

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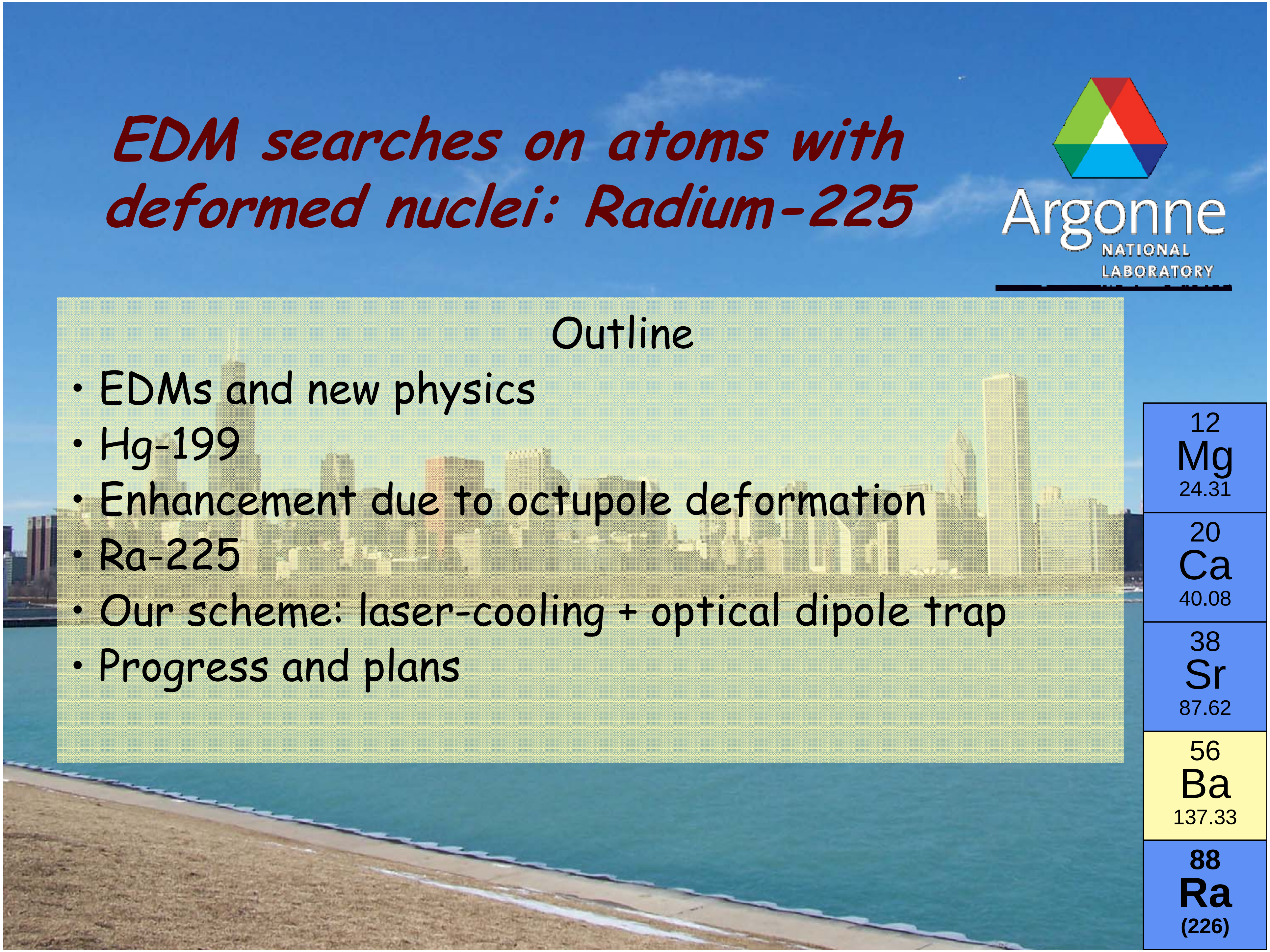
J. R. Guest, N. D. Scielzo, I. Ahmad, K. Bailey,
J. P. Greene, R. J. Holt, Z.-T. Lu, T. P. O'Connor,
D. H. Potterveld, D. W. Wang

October 9th, 2006
Flavour in the Era of the LHC, 4th meeting
EDM and g-2 miniworkshop

Department of Energy, Office of Science, Nuclear physics



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Outline

- EDMs and new physics
- Hg-199
- Enhancement due to octupole deformation
- Ra-225
- Our scheme: laser-cooling + optical dipole trap
- Progress and plans

12 Mg 24.31

20 Ca 40.08

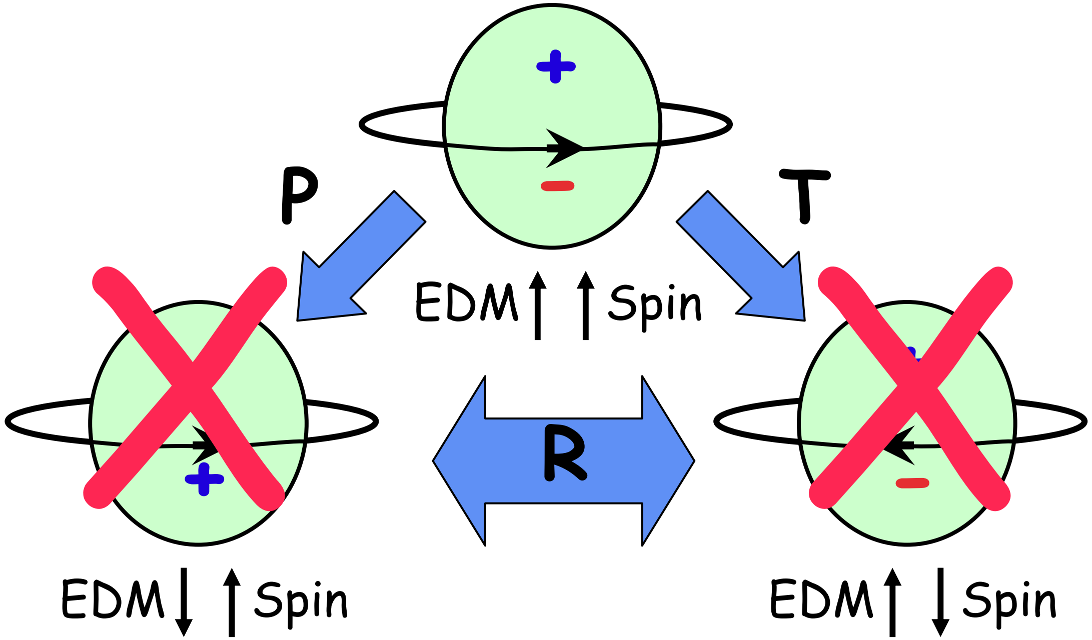
38 Sr 87.62

56 Ba 137.33

88 Ra (226)

What is an EDM?

A permanent electric dipole moment (EDM) is aligned along the spin axis and violates both time-reversal symmetry and parity



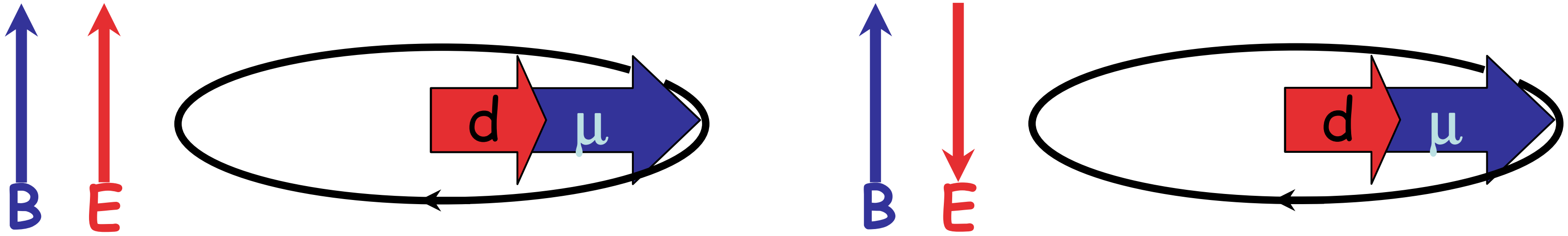
Standard Model predicts EDMs many orders of magnitude below current levels of experimental sensitivity … **BUT**

Theories beyond SM predict EDMs within range of current experiments

Where has all the antimatter gone? Need stronger CP violation

EDM Measurement

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



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

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

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

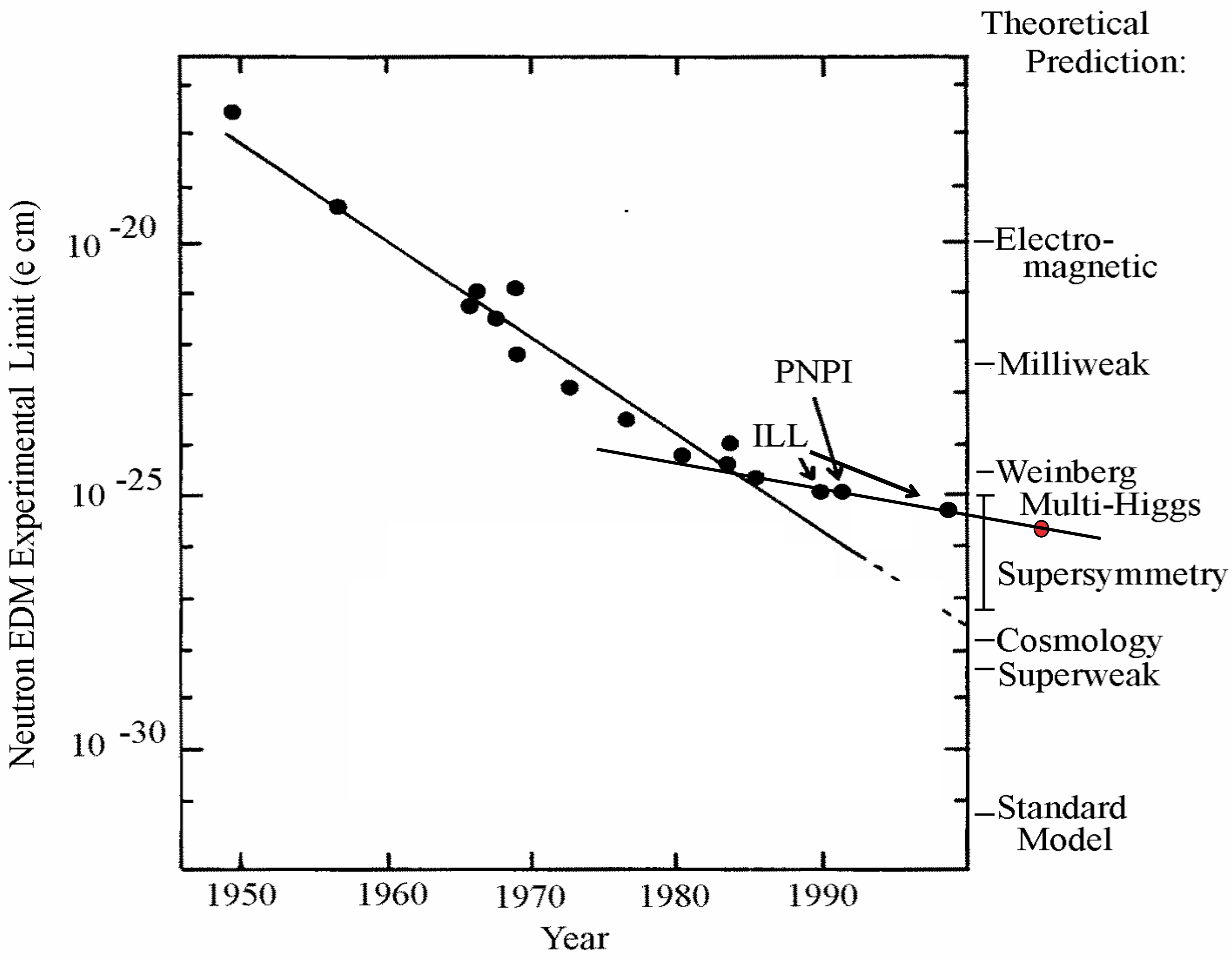
Single atom measured over single coherence time τ:

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

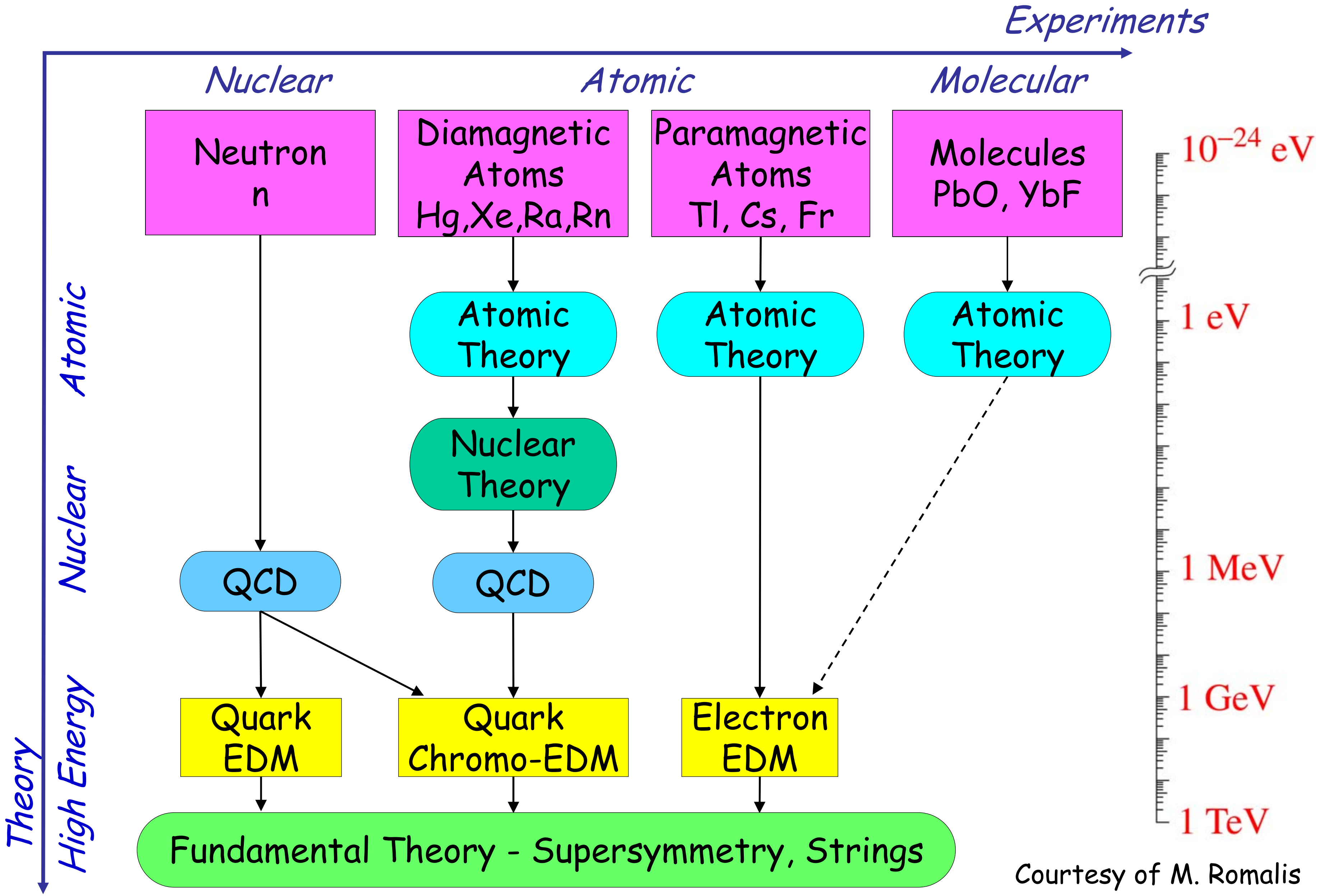
N atoms measured over time T with efficiency ε:

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

Neutron EDM limits: the first 50+ years

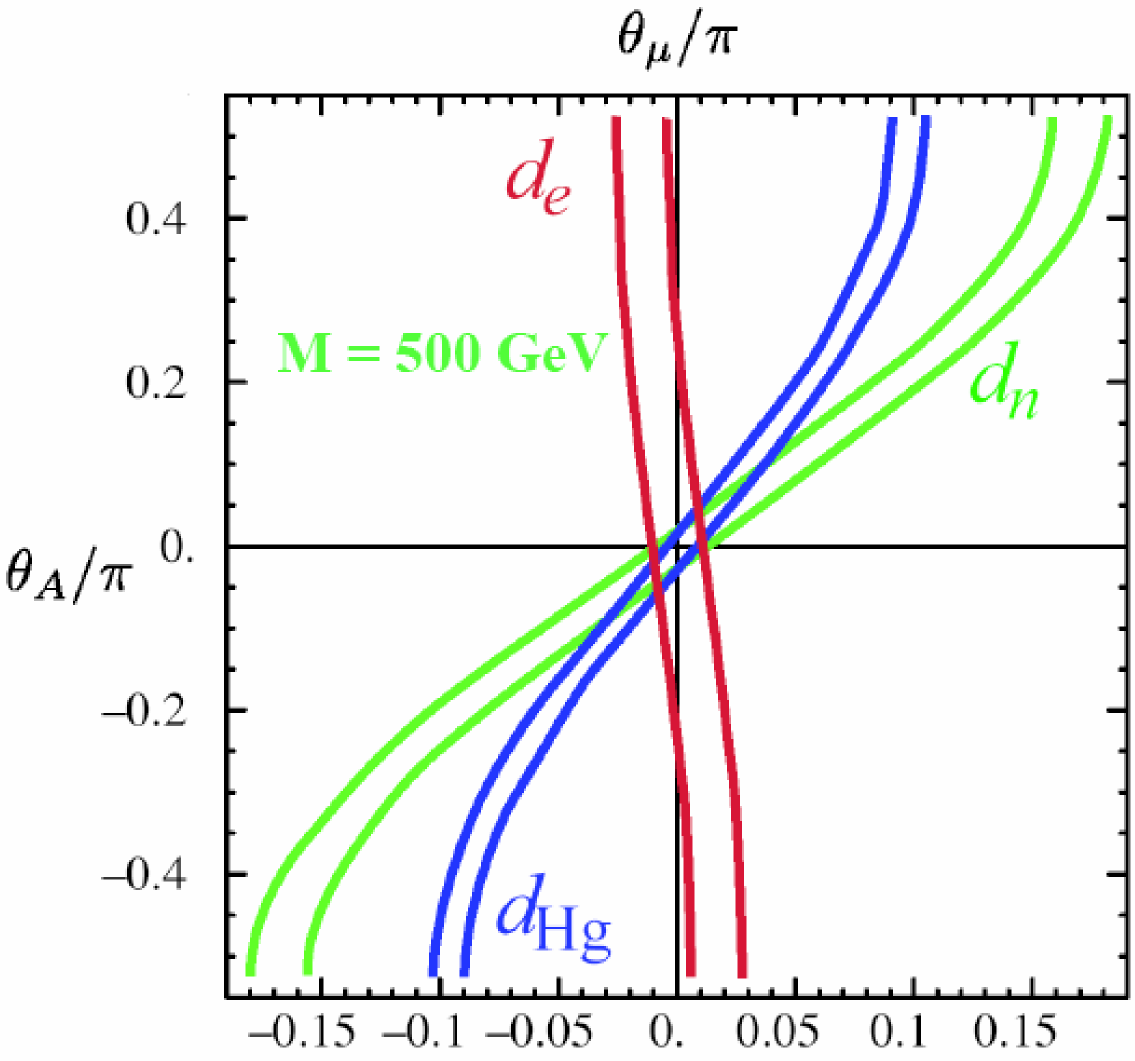


EDM Searches



Courtesy of M. Romalis

Limits on CP-violating SUSY phases

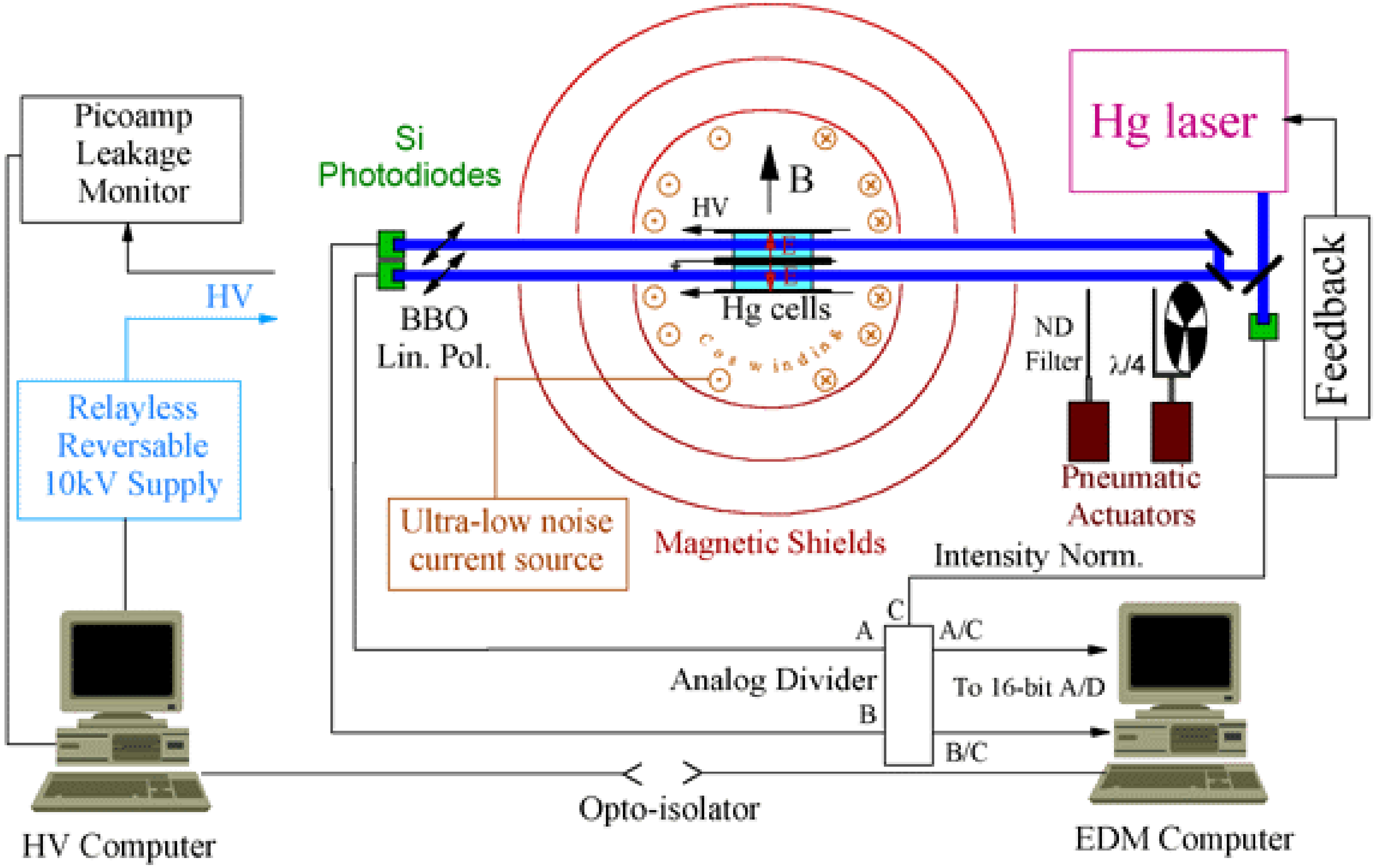


T. Falk, K. Olive, M. Pospelov, R. Roiban, Nucl. Phys. B560 3 (1999). Update M. Pospelov.

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)
- dν = 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

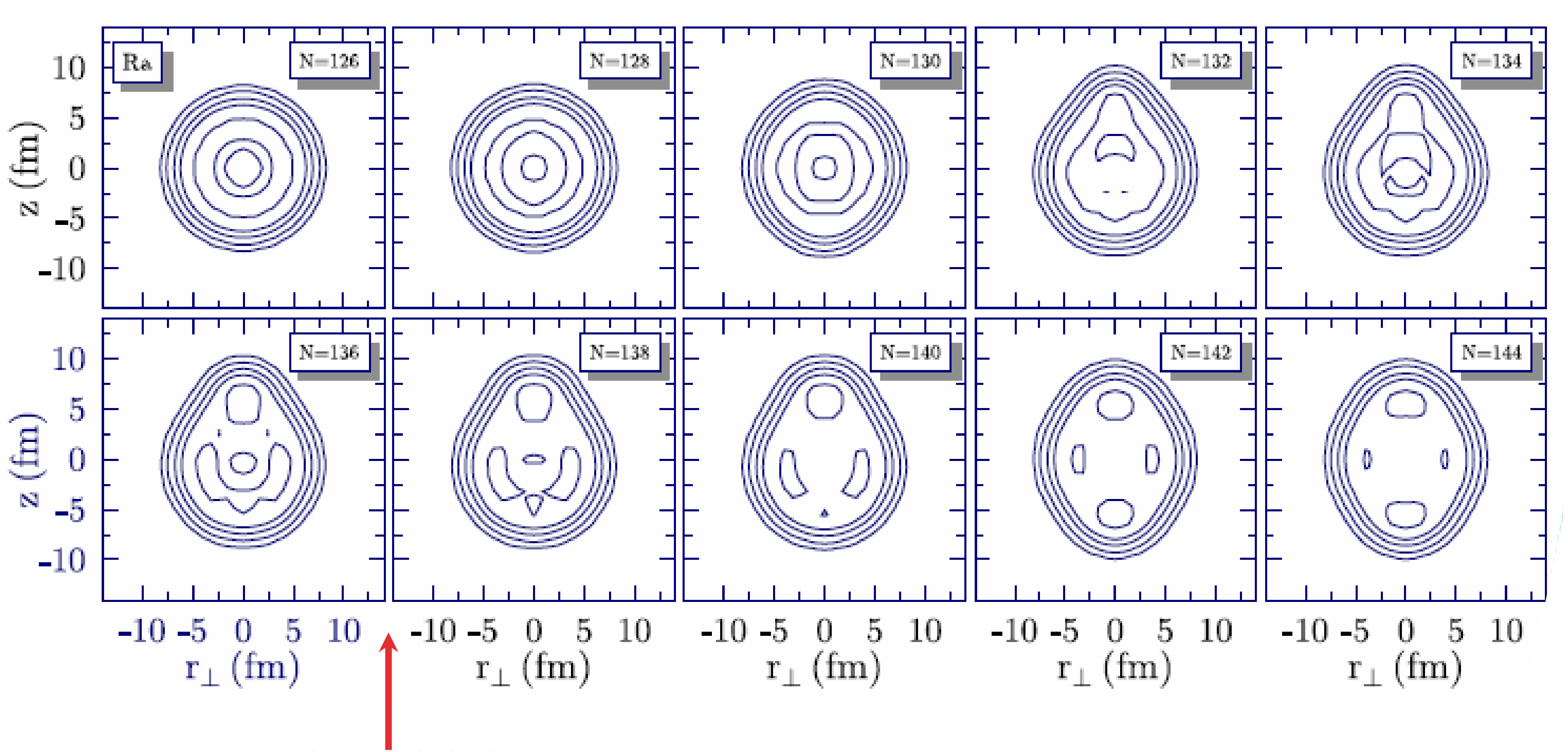
V.A. Dzuba *et al.*,
PRA **66**, 012111 (2002)

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

a 'radially-weighted dipole moment'

Density distributions of the radium isotopes

Contours of constant density for series of even-N radium isotopes



Ra-225

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

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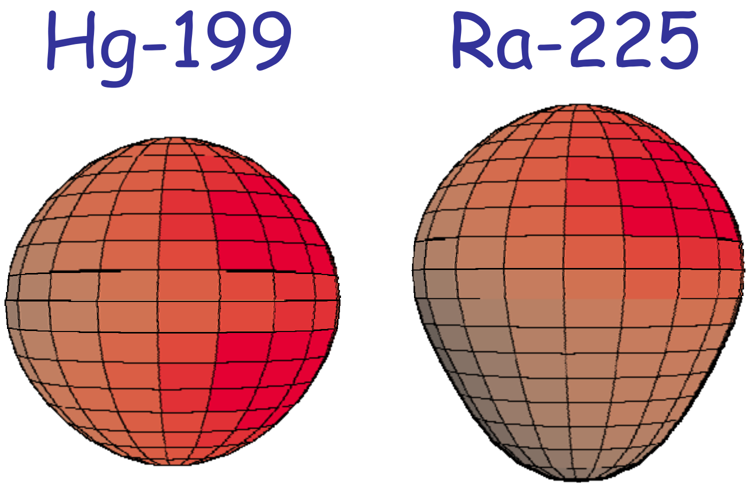


$$\mathbf{S}_{\mathbf{int}} \ll \mathbf{S}_{\mathbf{int}}$$

Enhancement due to octupole deformation

With no correlation between spin and intrinsic deformation:

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

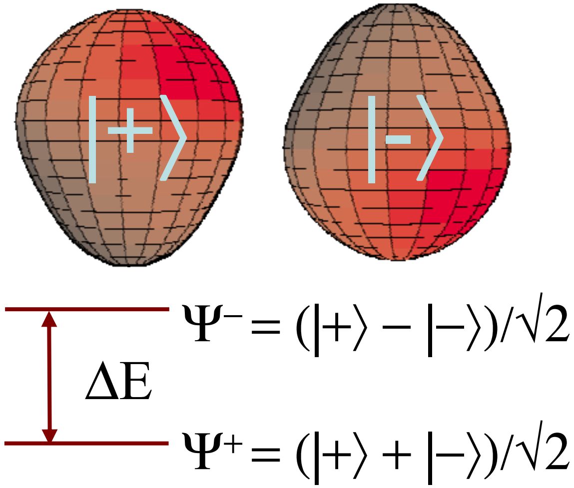
But, with a T-, P-odd interaction V_{PT}:

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

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

So, in the lab frame we see:

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



$\Psi^- = (|+\rangle - |-\rangle)/\sqrt{2}$

$\Psi^+ = (|+\rangle + |-\rangle)/\sqrt{2}$

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

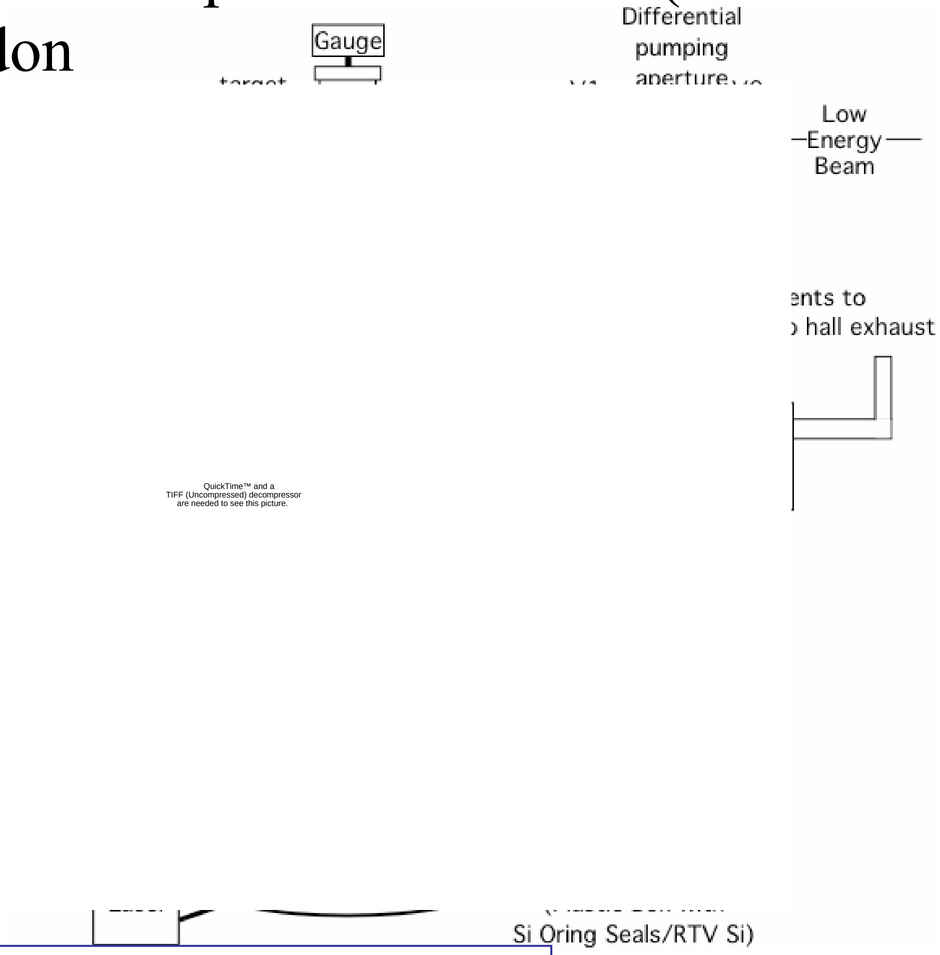
Haxton and Henley; Auerbach, Flambaum & Spevak; Dobaczewski, de Jesus & Engel

EDM Searches in heavy diamagnetic atoms

Isotope	Current Limit (e cm)	Institution	Factor of Improvement Meas d(A)	T-odd Sensitivity	Technique
Xe-129	(0.7 ± 3.3)E-27 Michigan	Princeton	$10^3 - 10^9$	0.47	Liquid cell
Hg-199	-(1.1 ± 0.6)E-28 Washington	Washington	2-4	4	4 cells
Rn-223	N/A	Michigan & TRIUMF	~ Hg	2000	Cell
Ra-225	N/A	Argonne, KVI	~ Hg	2500	Trap

E929: TRIUMF Radon EDM Experiment

- Measure 223Rn levels and octupole deformation (8-π detector)
- Collect and polarize radon
- Measure ^{223}



QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

E-929 Collaboration (Guelph, Michigan, SFU, TRIUMF)

TRIUMF

Canada's National Laboratory for Particle and Nuclear Physics

Tim Chupp
U of Michigan

Radon EDM Progress

Noble gas (Xe) collected and transferred to cell on-line
- High efficiency: 43% is 3/4 of ε_{max} (@TRIUMF)

^{209}Rn polarized once again (@ Stony Brook)
Systematic studies feasible

^{223}Rn EDM projections (t_2=100 s)

Gamma Anisotropy (A=0.2)

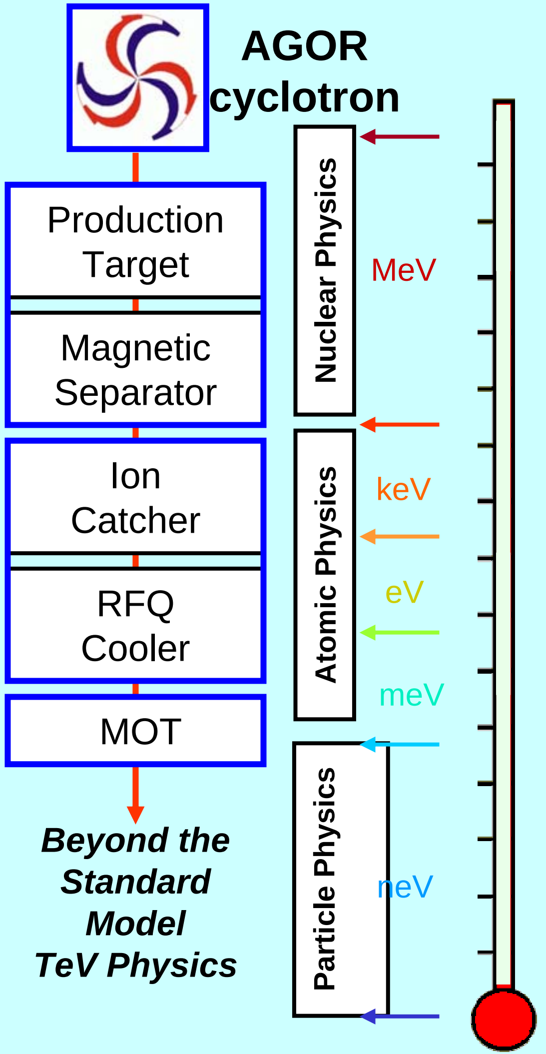
$N_\gamma = 2\text{x}10^{12}$ (Tigress count rate limit - 3 months)
$\sigma_d = 2\text{x}10^{-27}$ e-cm (10x better than ^{199}Hg)

Beta Asymmetry

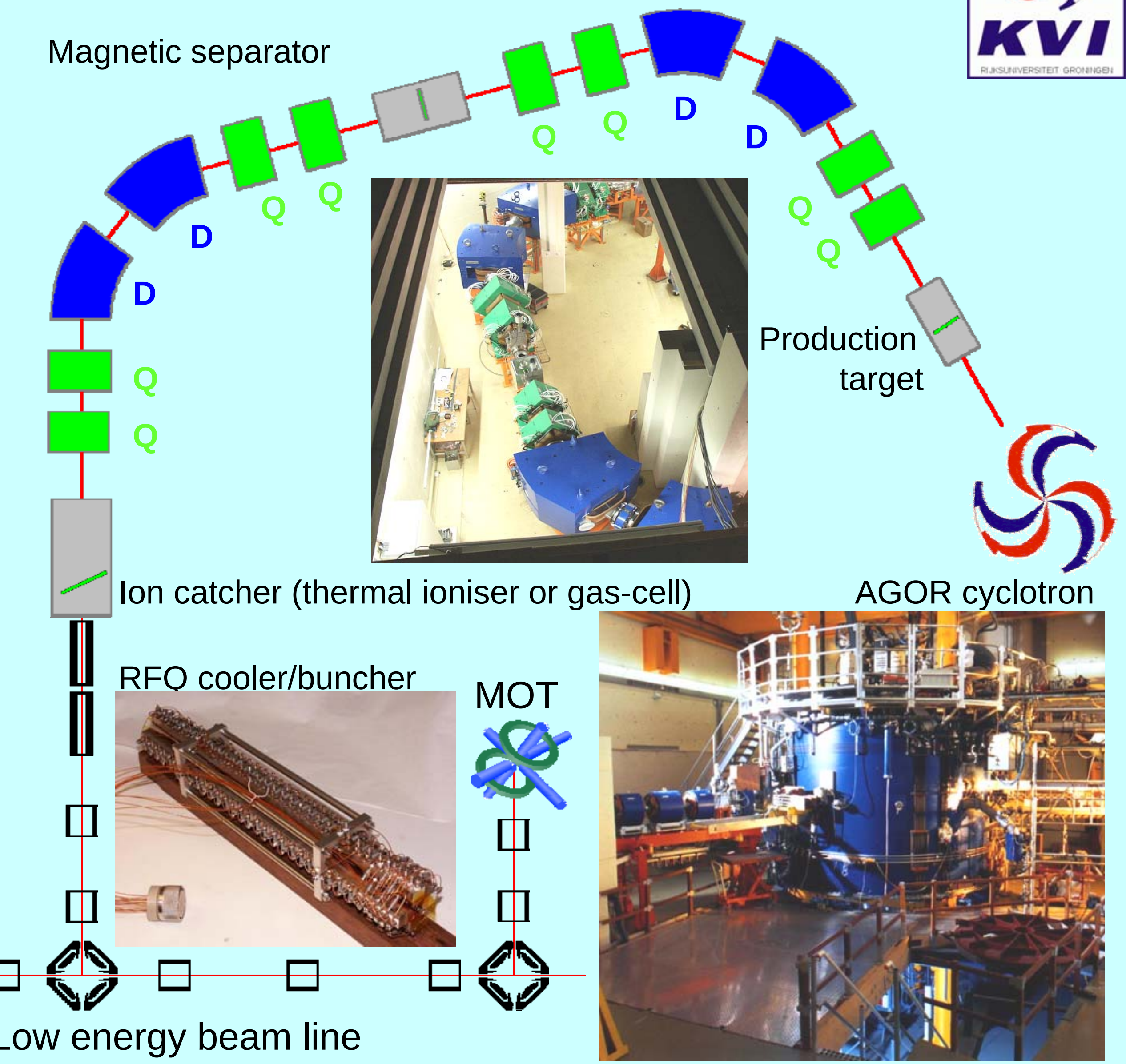
Rate	σ_d (100 days)	
2x10^7	6x10^{-28}e-cm	TRIUMF
10^9	1x10^{-28}e-cm	RIA

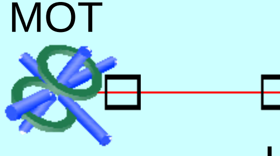
Tim Chupp
U of Michigan

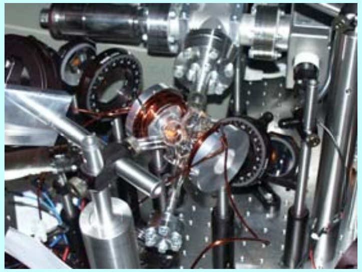
TRIμP Facility



Beyond the Standard Model TeV Physics







Towards Ra EDM …

(Klaus Jungmann)

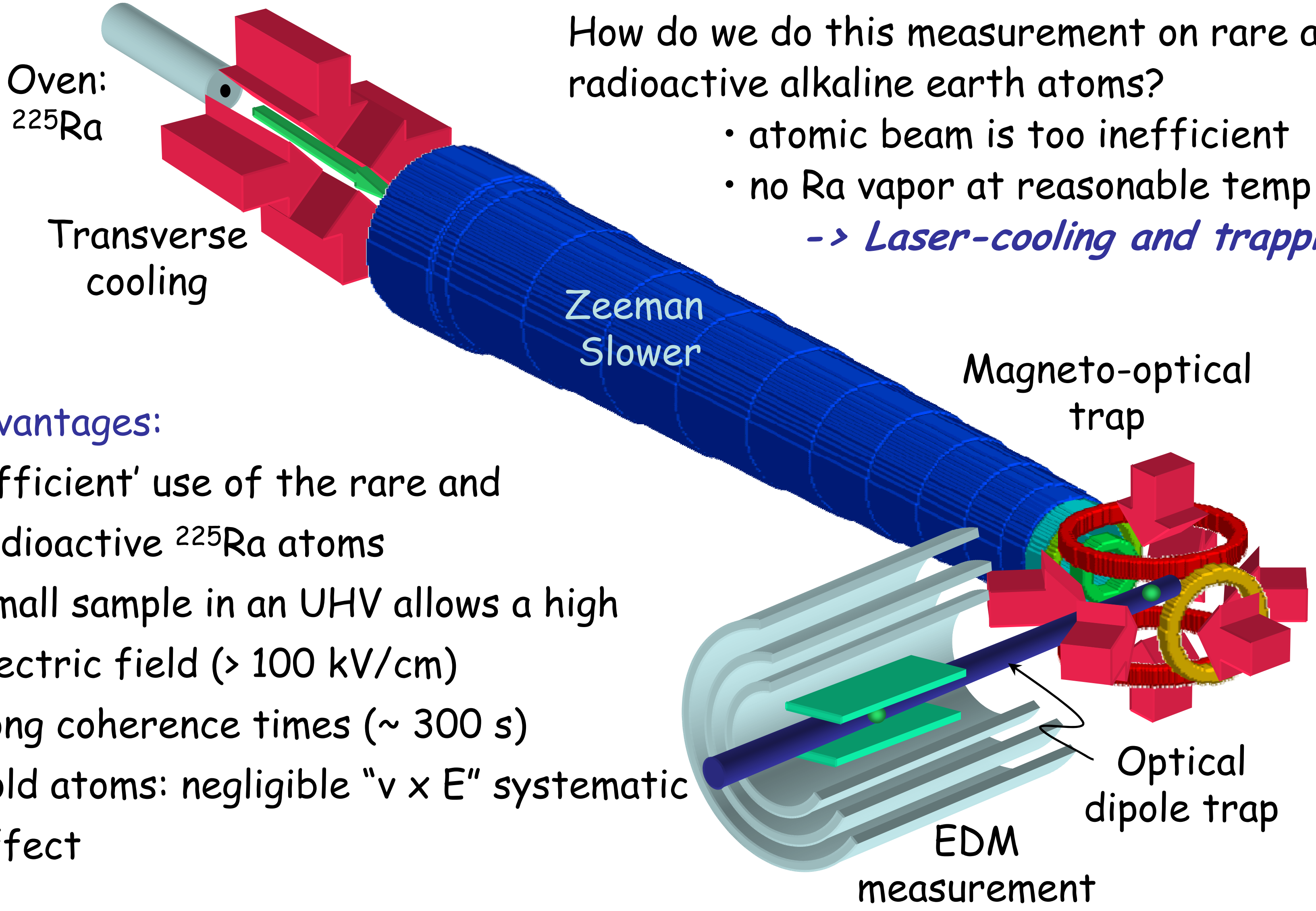
Argonne National Laboratory

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

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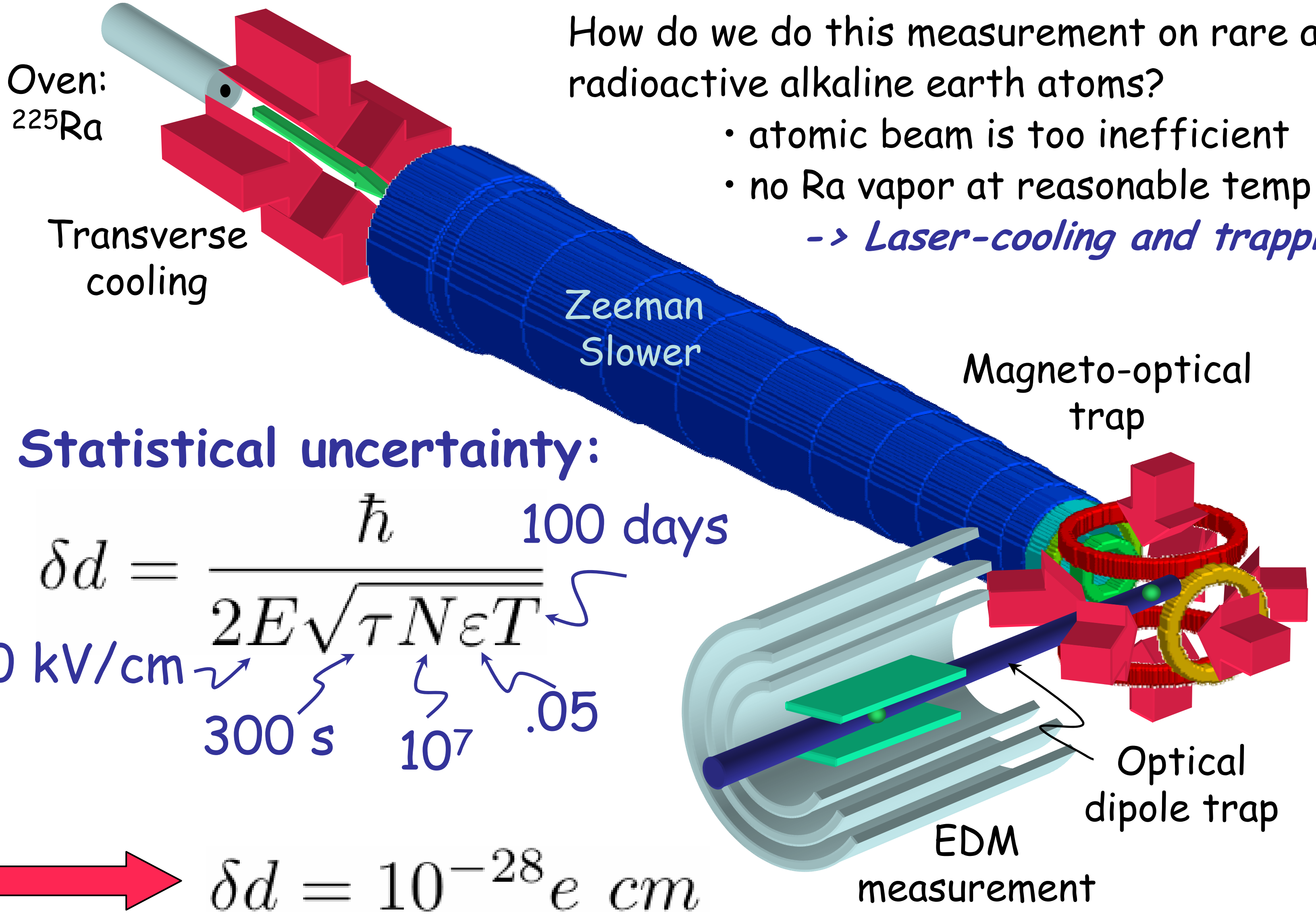


Statistical uncertainty:

$$\delta d = \frac{\hbar}{2\underset{100\text{ kV/cm}}{E}\sqrt{\underset{300\text{ s}}{\tau}\,\underset{10^{7}}{N}\,\underset{.05}{\varepsilon}\,\overset{100\text{ days}}{T}}}$$

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

Where do we get Ra-225?

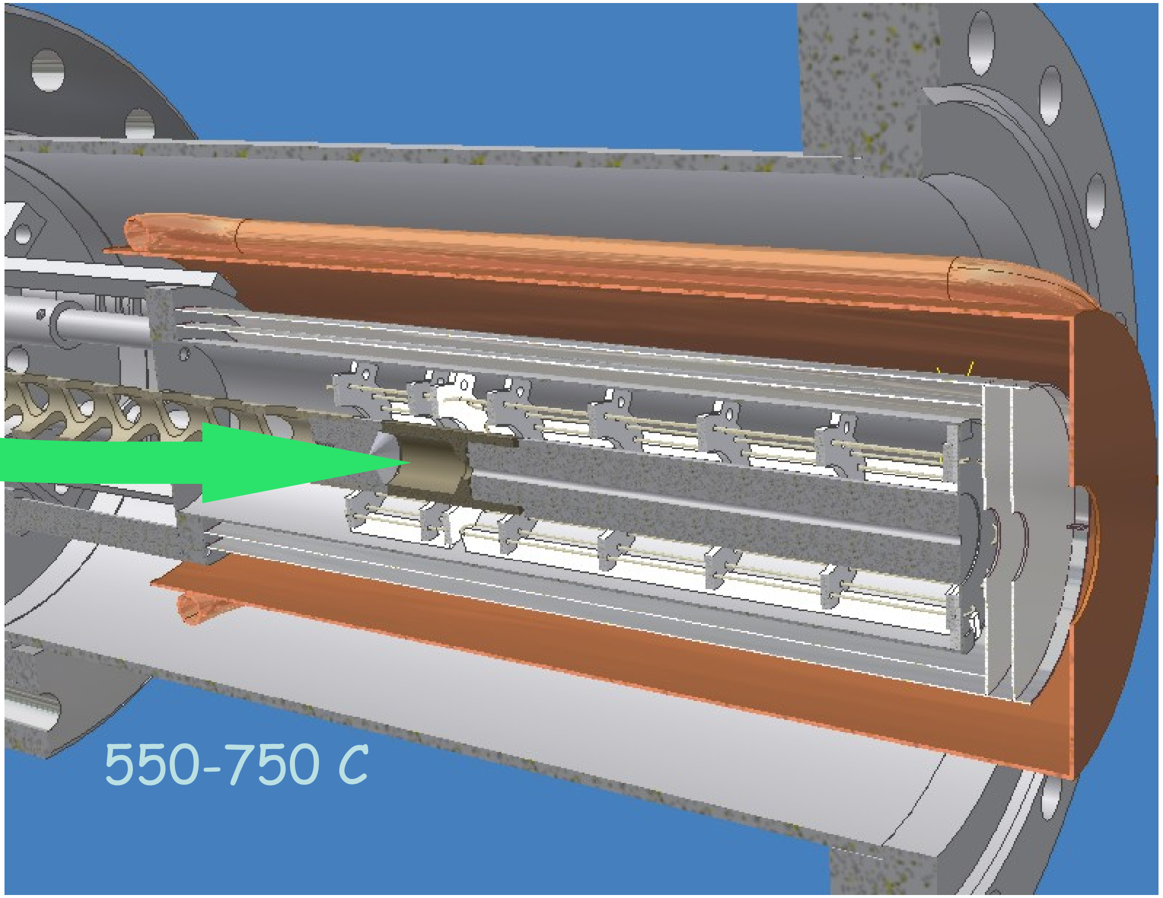
229Th 7300 yr $\xrightarrow{\alpha}$ **225Ra 15 days** $\xrightarrow{\beta}$ 225Ac 10 days $\xrightarrow{\alpha}$ Fr, At, Bi… ~ 4 hours $\xrightarrow{\alpha,\beta}$ 209Bi stable

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

+ Al foil
+ 50 mg Ba

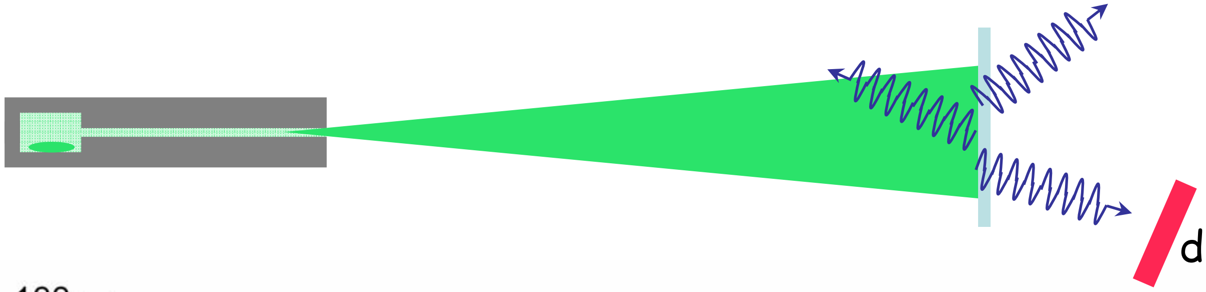
Reduces RaO
Passivates surfaces
Optical tracer

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

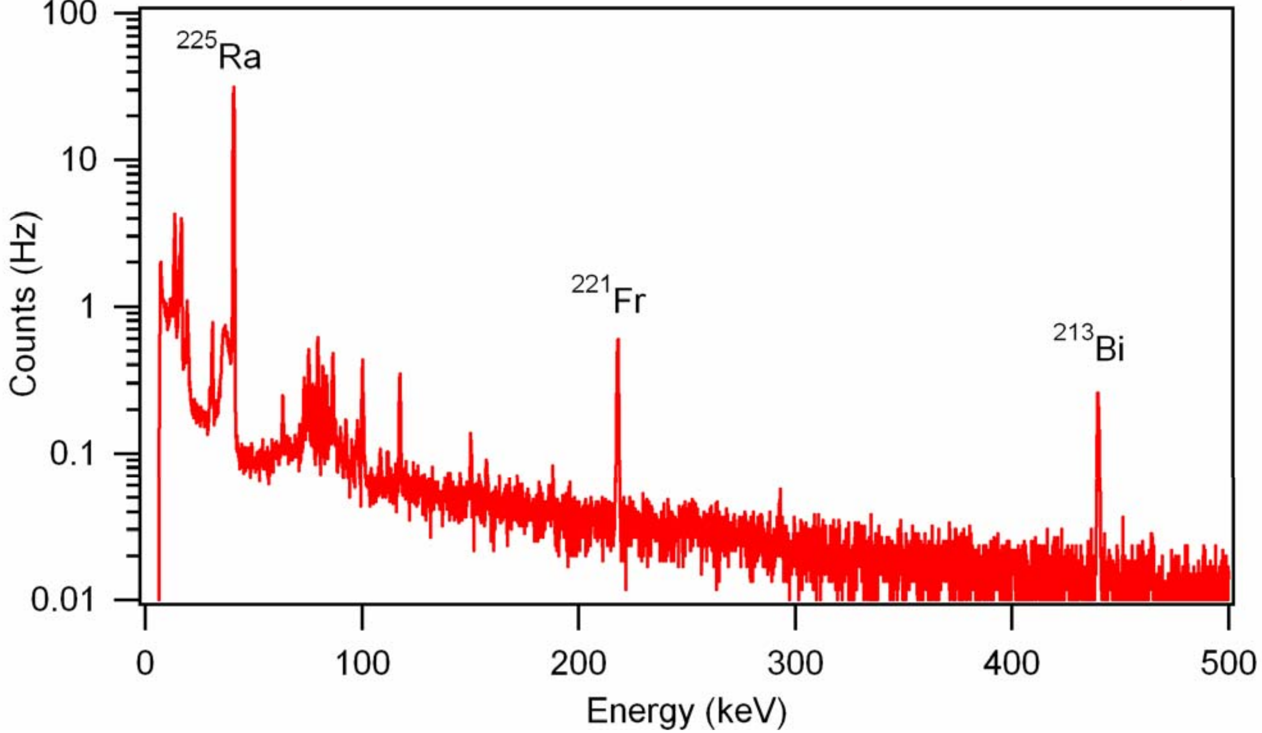


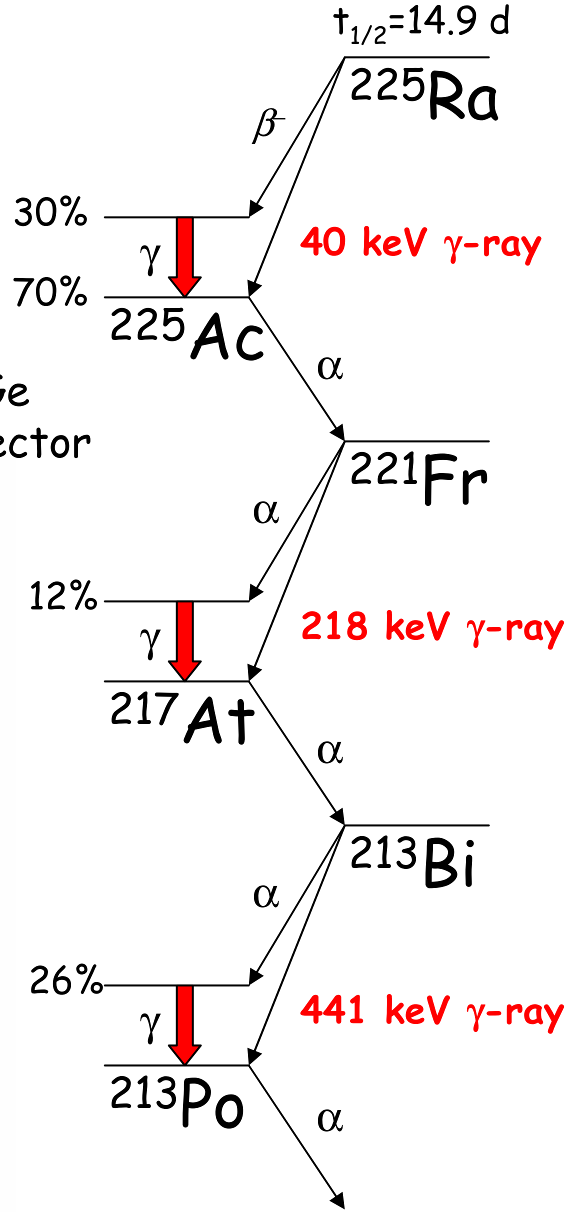
Gamma-ray detection of Ra-225

^{225}Ra can be monitored by watching for its characteristic γ-ray line



Ge detector





$t_{1/2}$=14.9 d

^{225}Ra

β-

30%

γ

70%

40 keV γ-ray

^{225}Ac

α

^{221}Fr

α

12%

γ

218 keV γ-ray

^{217}At

α

^{213}Bi

α

26%

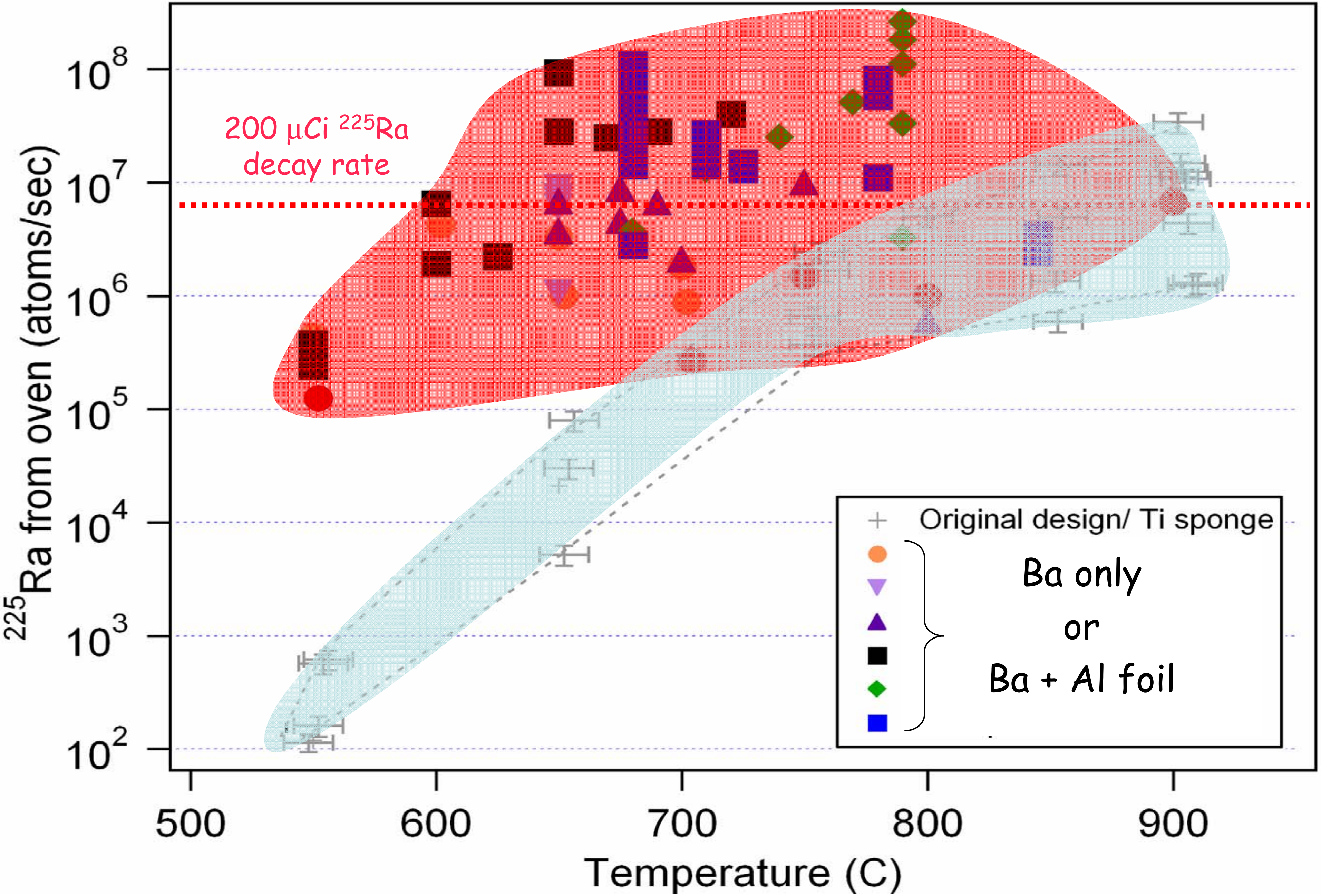
γ

441 keV γ-ray

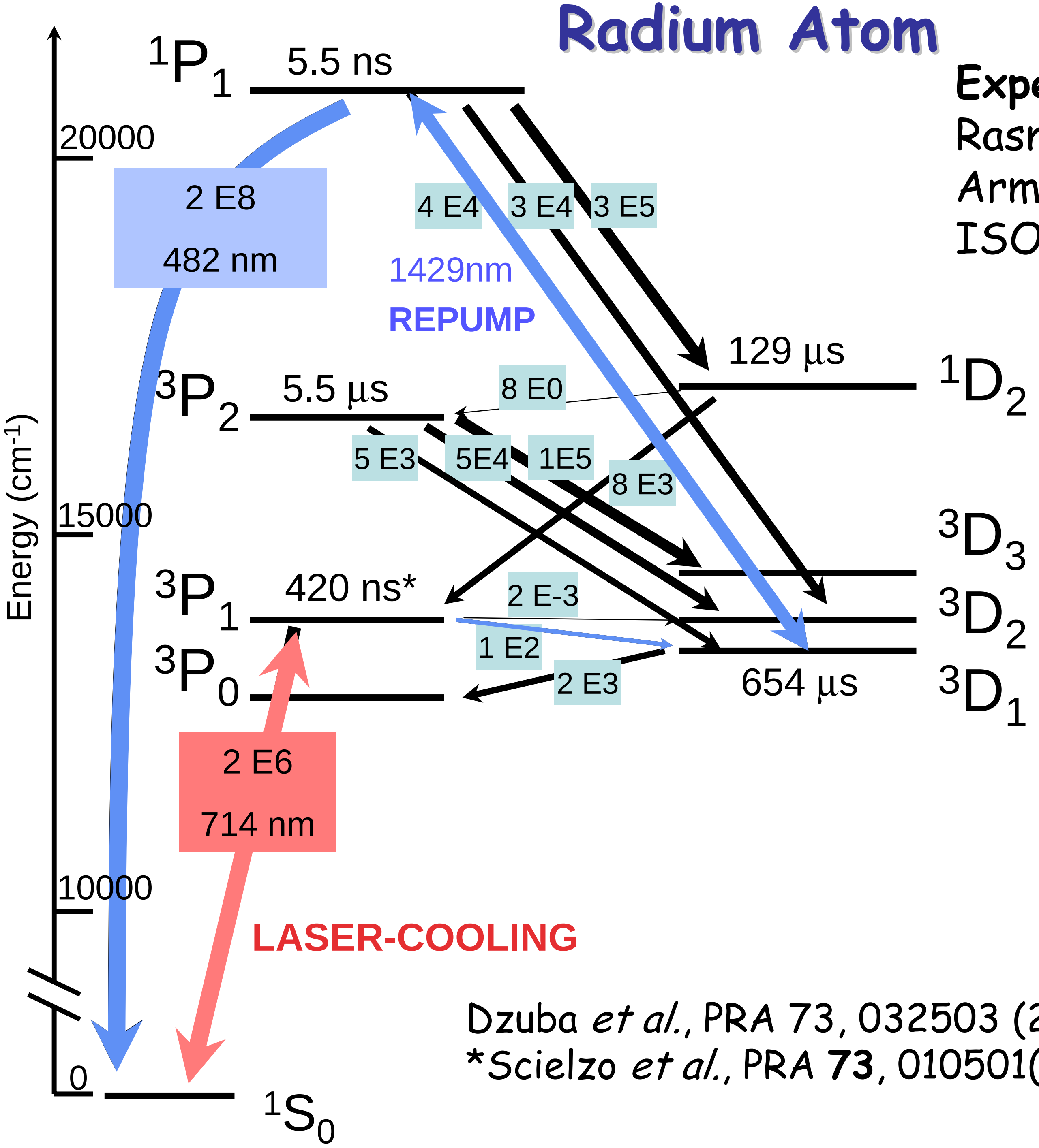
^{213}Po

α

^{225}Ra atomic beam (~200 μCi source)



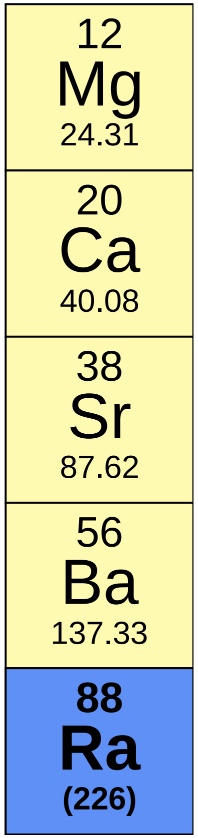
Radium Atom



Experimental work:
Rasmussen, Russell (1934)
Armstrong (1979)
ISOLDE (1983-1988)

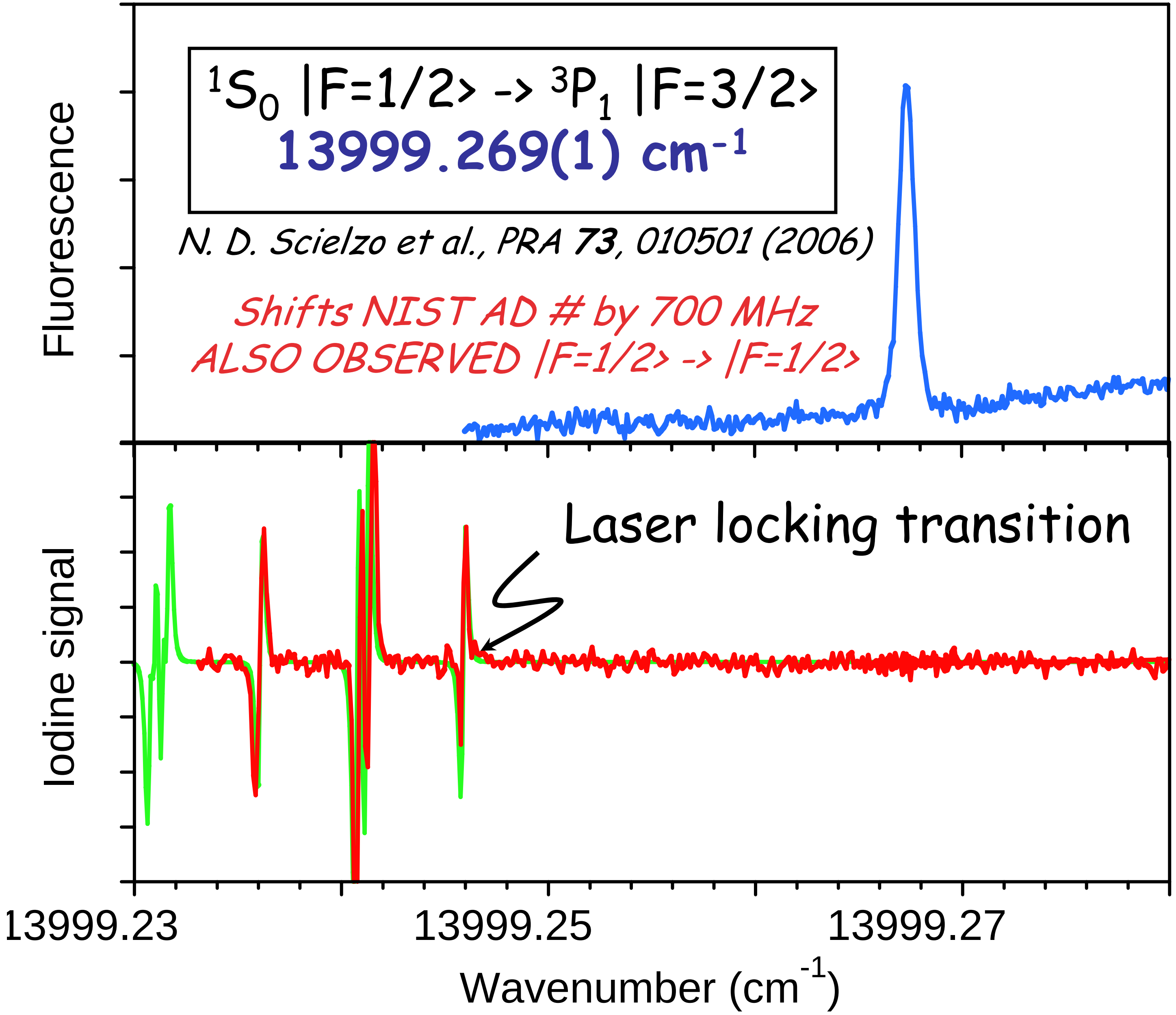
w/o REPUMP:
2.4x10^4 cycles
(20 ms)

w/ 1428 nm
REPUMP:
x6800 cycles
(140 s in trap)



Dzuba *et al.*, PRA 73, 032503 (2006)
*Scielzo *et al.*, PRA **73**, 010501(R) (2006)

Ra-225 atomic beam



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

13999.269(1) cm^{-1}

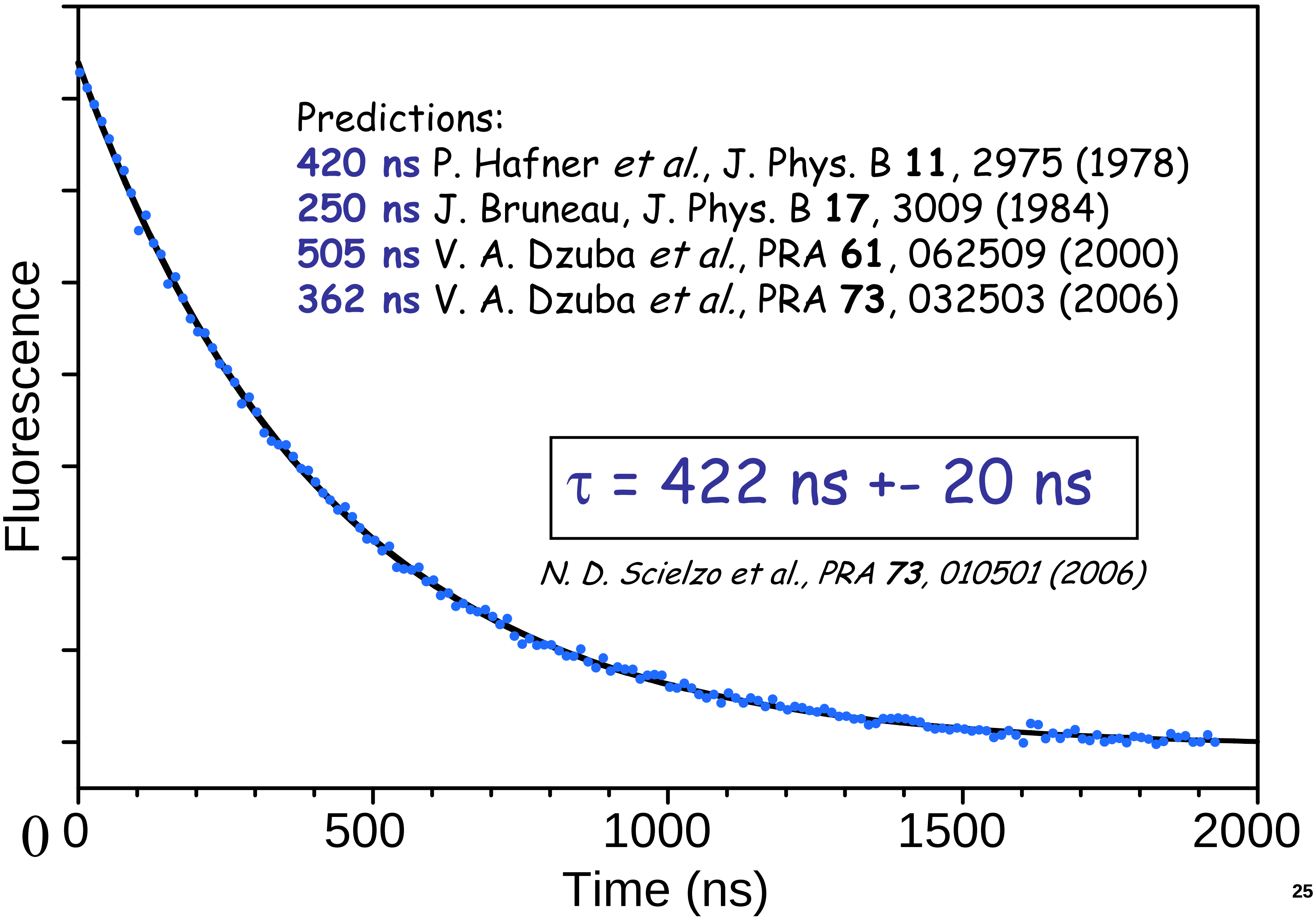
*N. D. Scielzo et al., PRA **73**, 010501 (2006)*

Shifts NIST AD # by 700 MHz

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

Laser locking transition

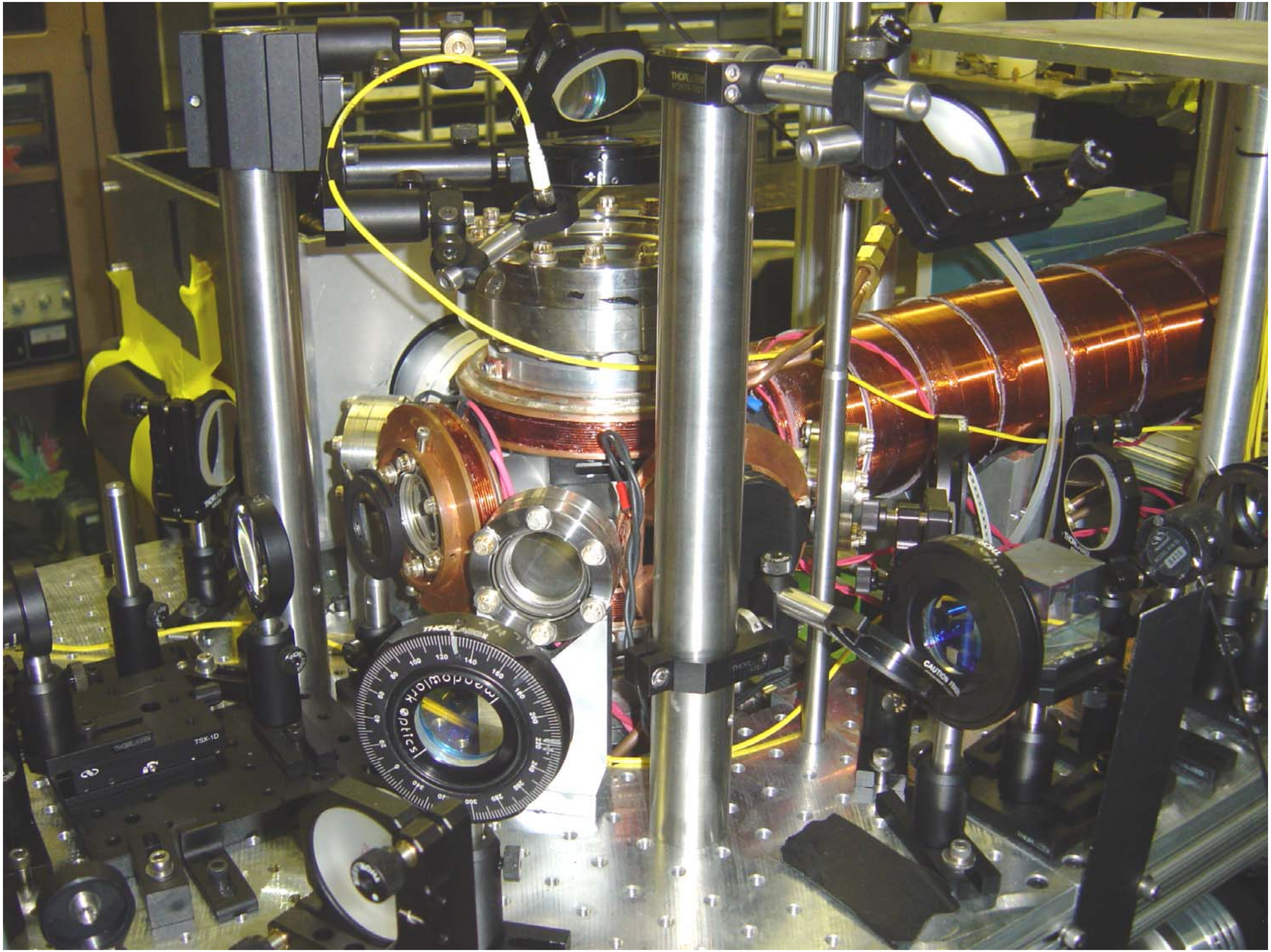
Ra 7s7p $^3P_1$ lifetime measurement



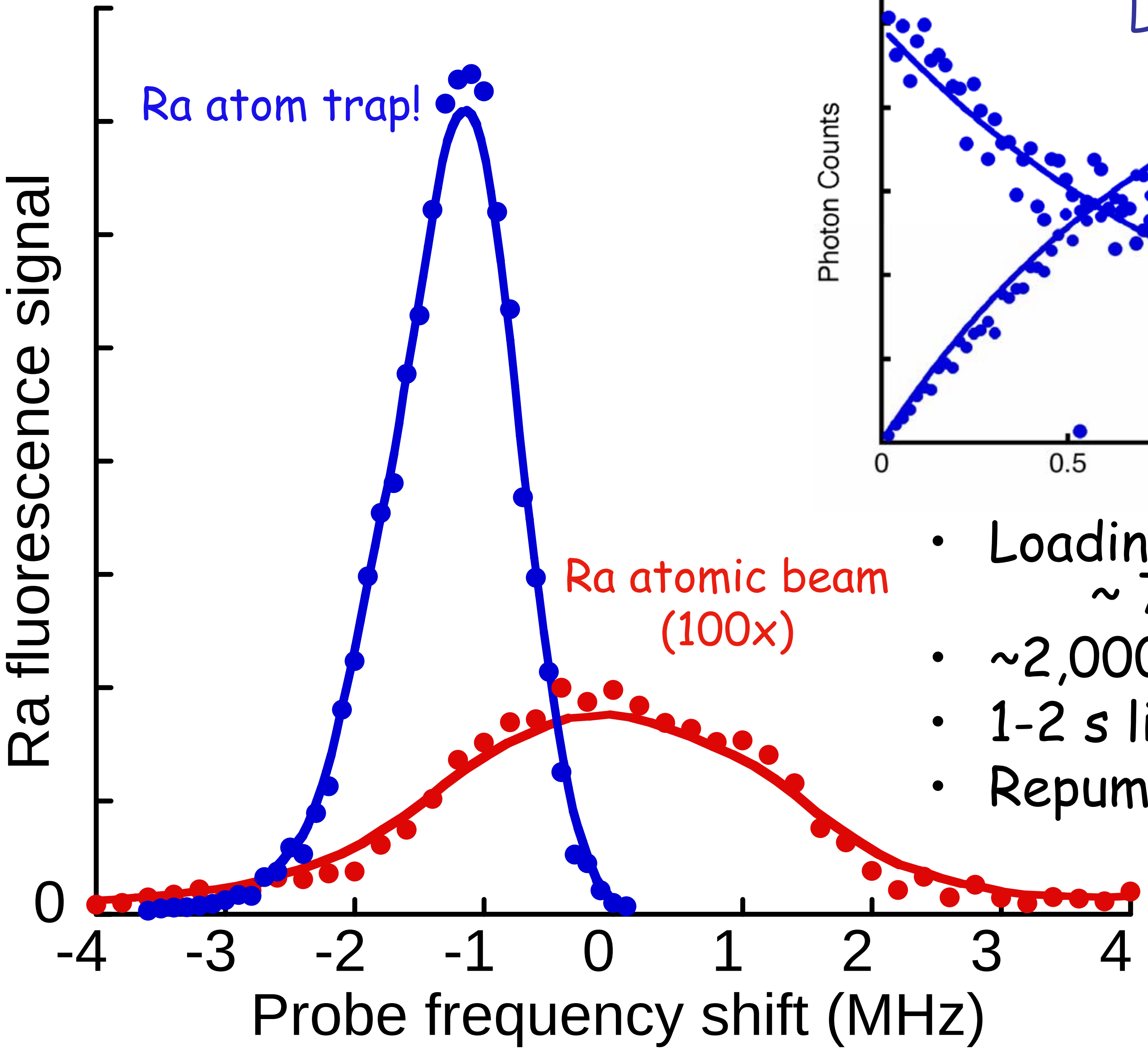
Predictions:
420 ns P. Hafner *et al.*, J. Phys. B **11**, 2975 (1978)
250 ns J. Bruneau, J. Phys. B **17**, 3009 (1984)
505 ns V. A. Dzuba *et al.*, PRA **61**, 062509 (2000)
362 ns V. A. Dzuba *et al.*, PRA **73**, 032503 (2006)

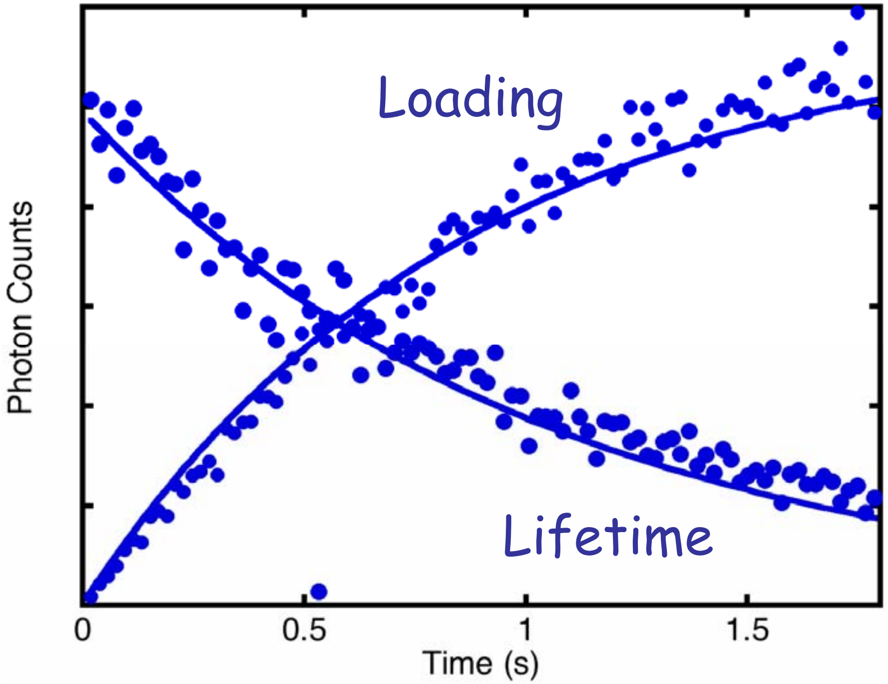
τ = 422 ns +- 20 ns

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


THORLABS
TSX-1D
meadowlark optics

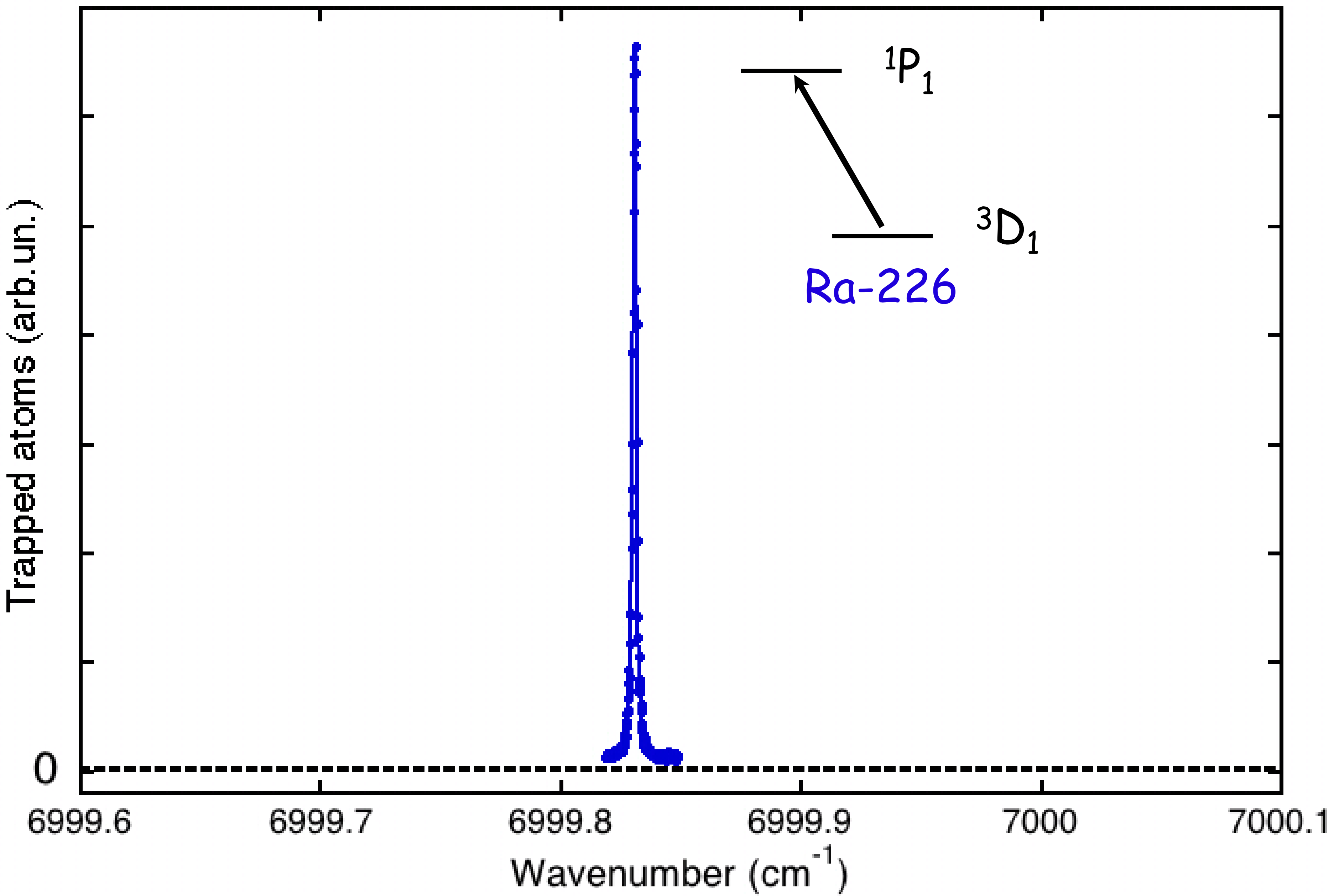
Ra-226 atom trap



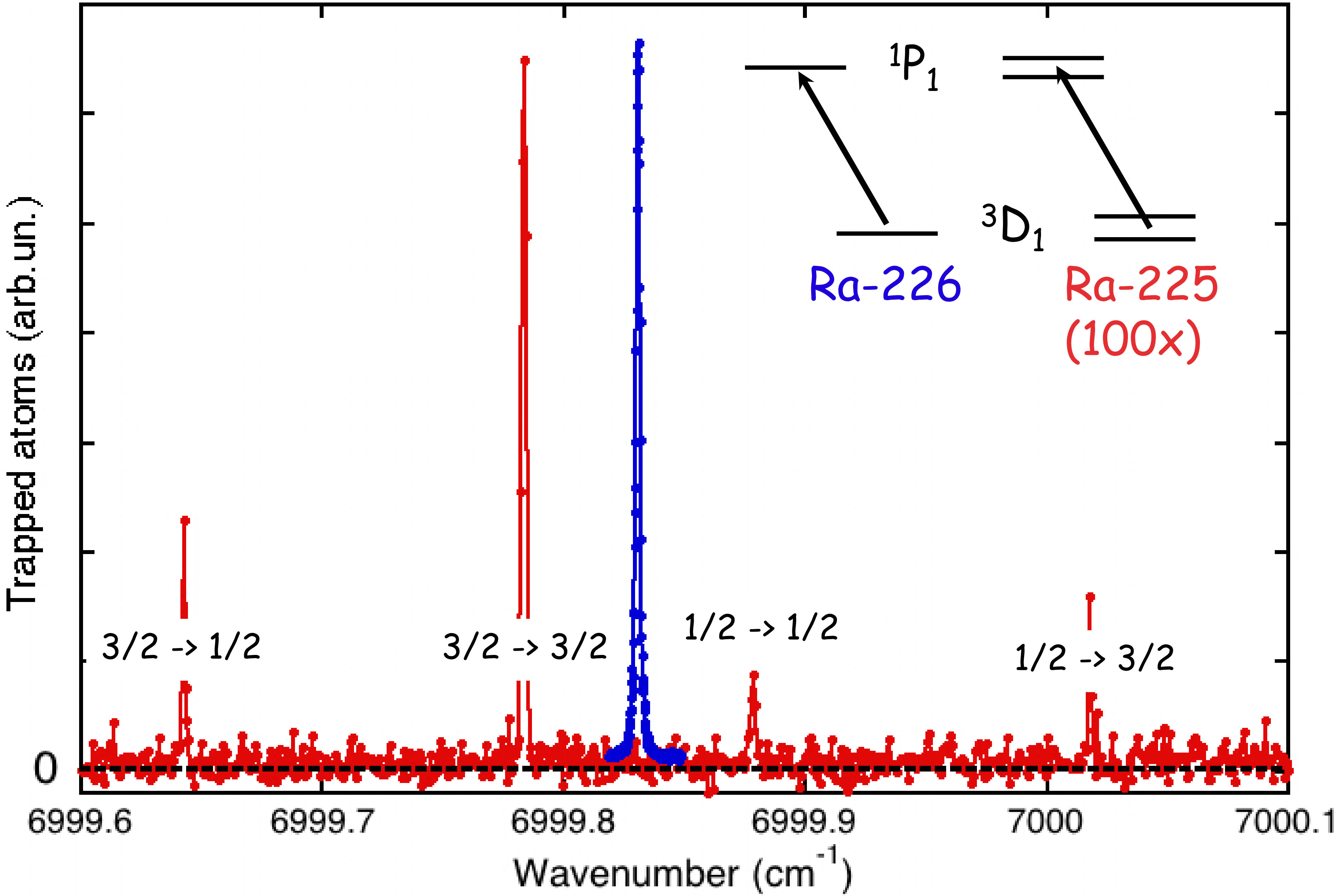


- Loading efficiency
  ~ $7x10^{-7}$
- ~2,000 trapped atoms
- 1-2 s lifetime
- Repump critical

Repump spectrum

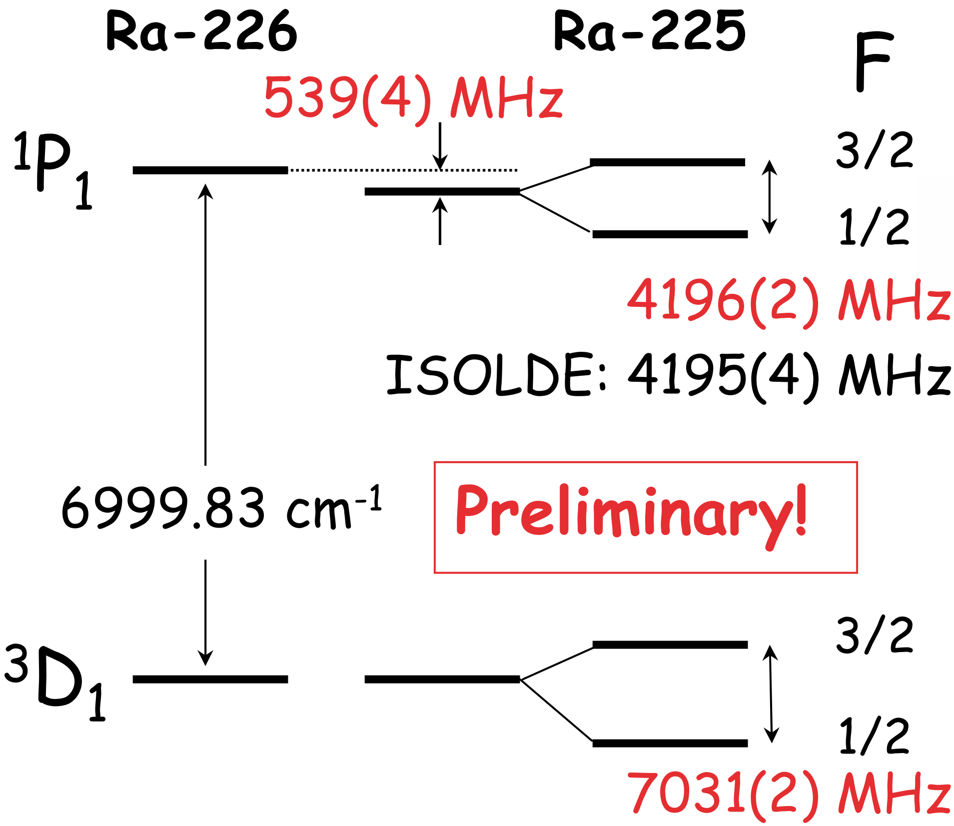


Repump spectrum



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

539(4) MHz

$^1P_1$

3/2

1/2

4196(2) MHz

ISOLDE: 4195(4) MHz*

6999.83 cm^{-1}

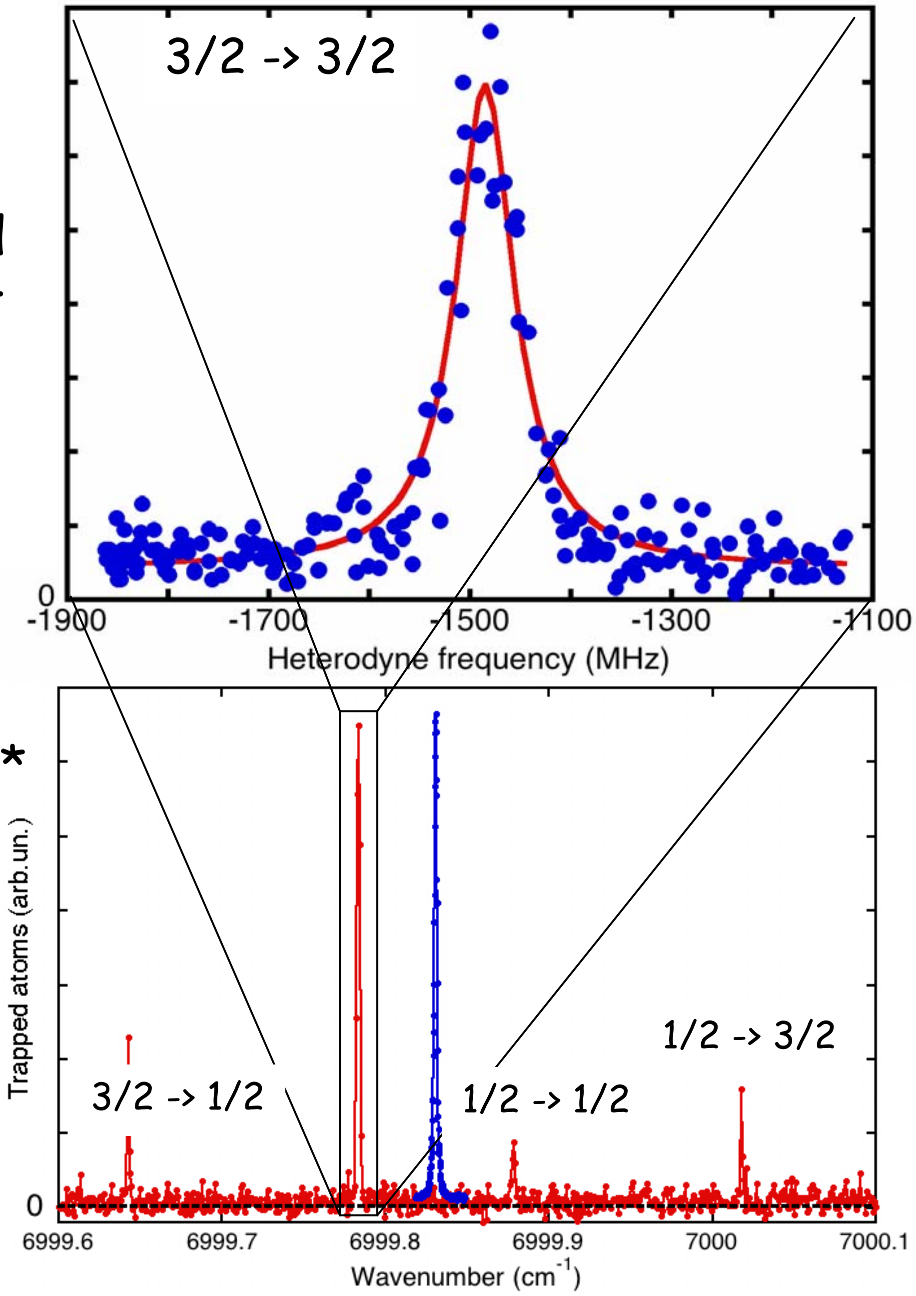
Preliminary!

$^3D_1$

3/2

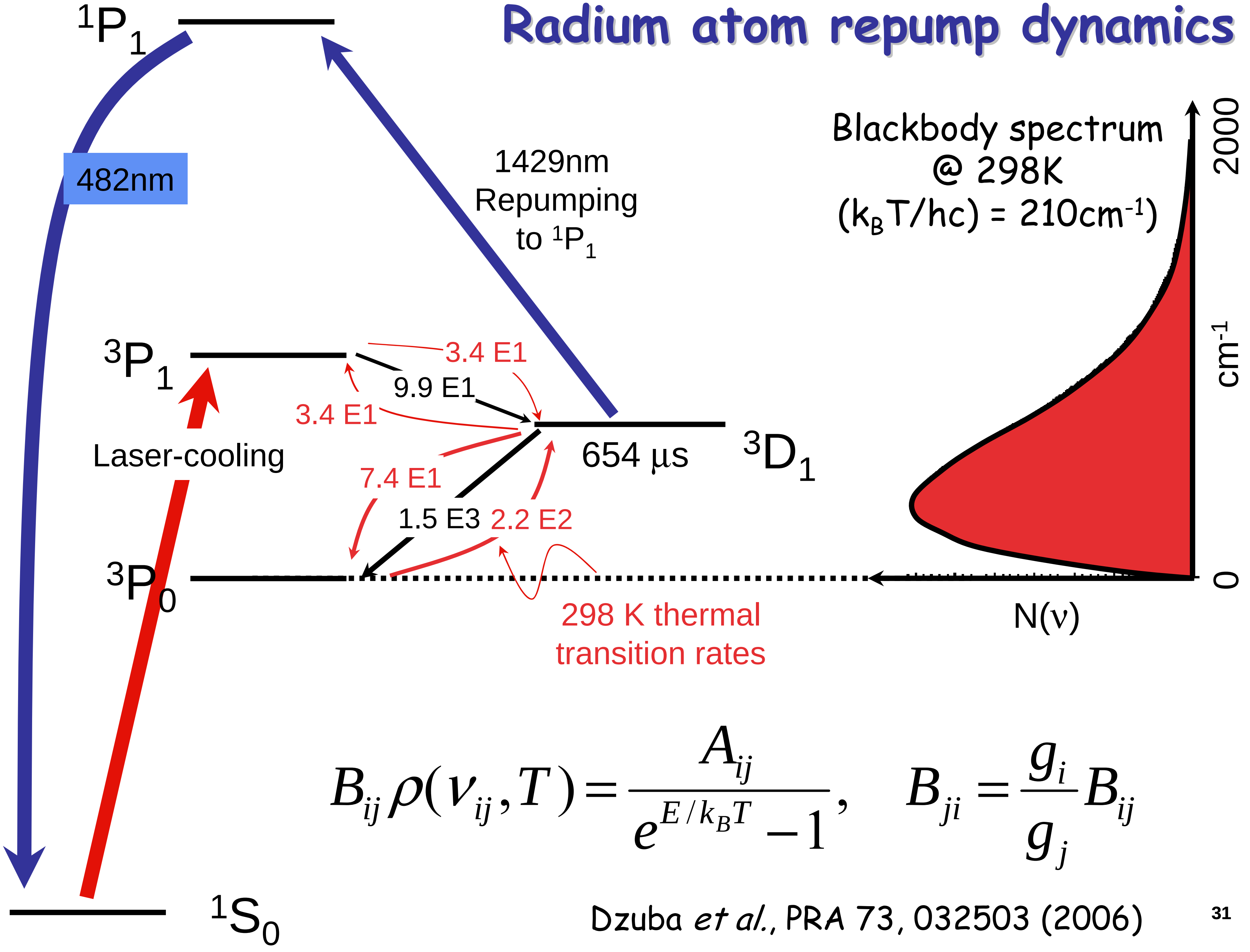
1/2

7031(2) MHz



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

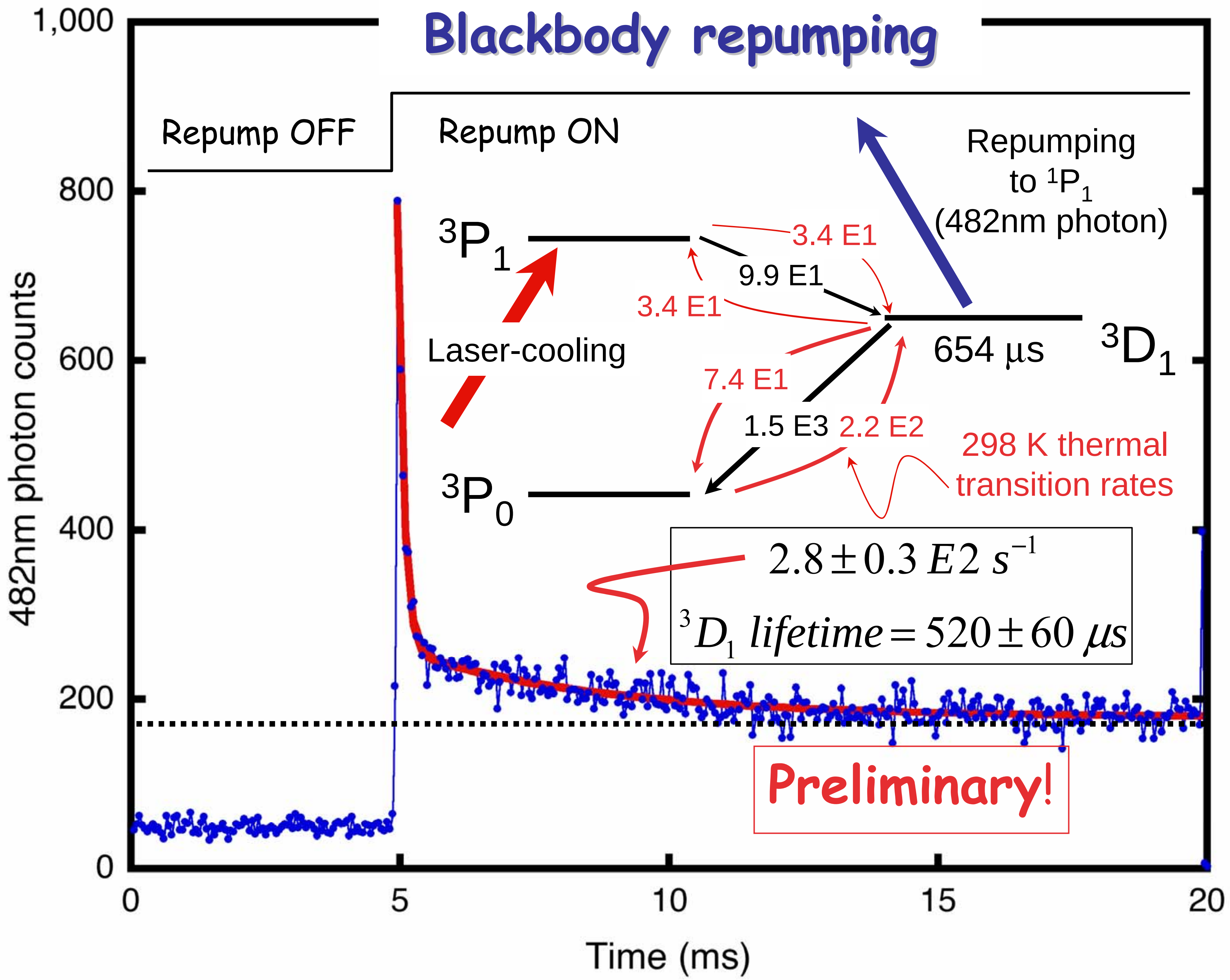
Radium atom repump dynamics



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

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

Blackbody repumping



Repumping to $^1P_1$ (482nm photon)

298 K thermal transition rates

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

$$^3D_1\ lifetime = 520 \pm 60\ \mu s$$

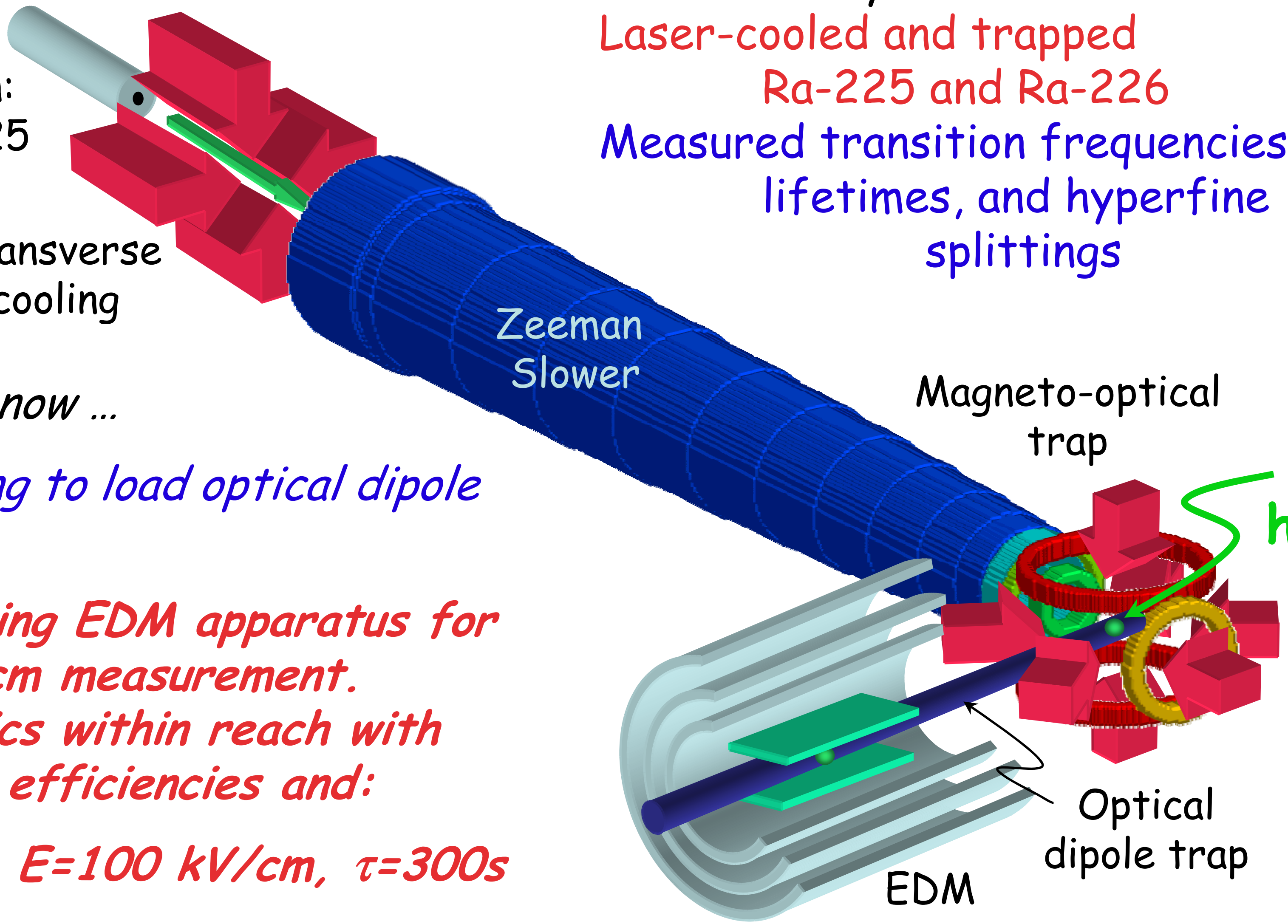
Preliminary!

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



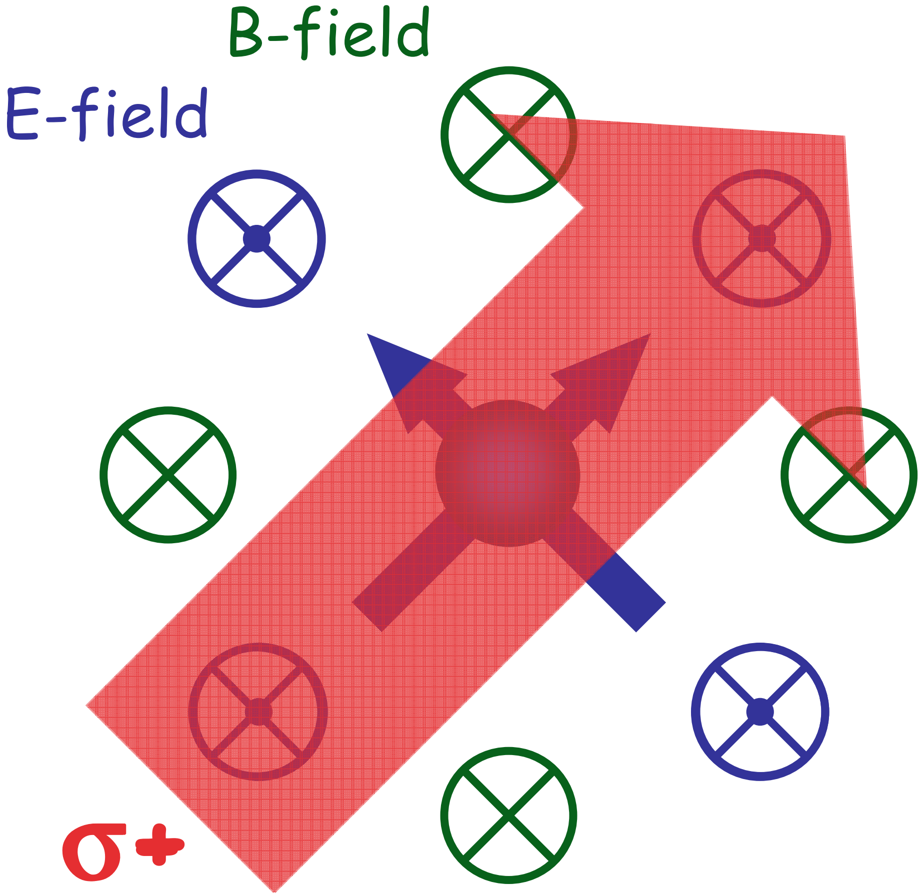
We are now …

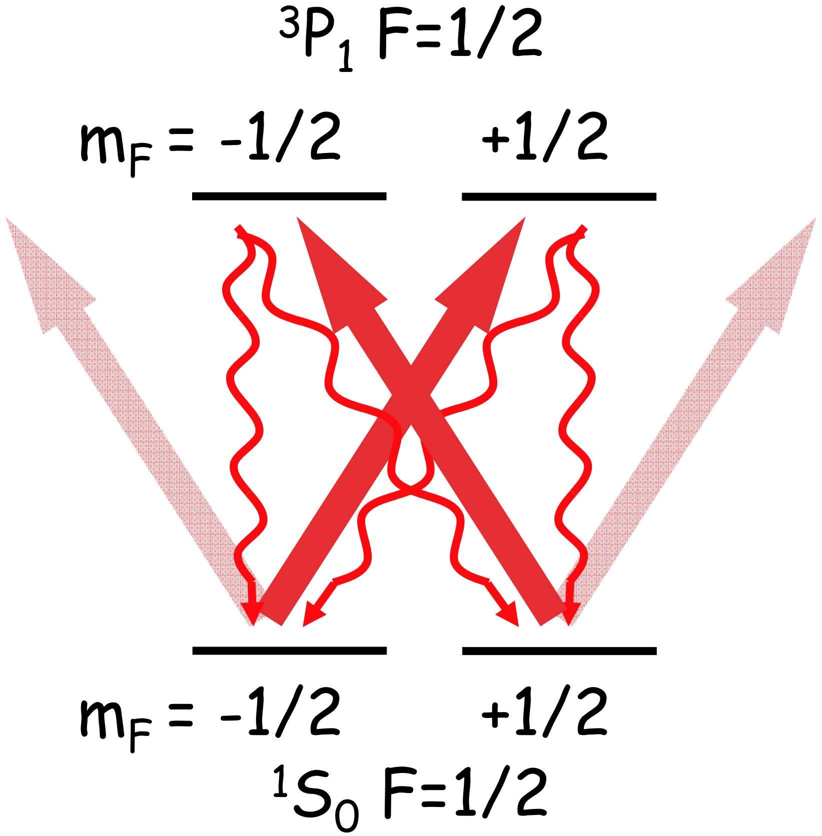
Preparing to load optical dipole trap

Developing EDM apparatus for 10^{-26} ecm measurement. Statistics within reach with current efficiencies and:

10 mCi, E=100 kV/cm, τ=300s

EDM measurement





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

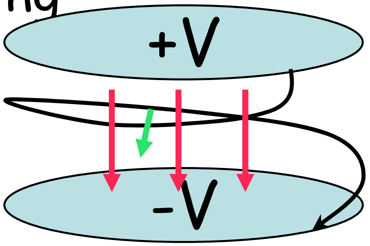
Optical pumping

B = 10 mG: ν = 10 Hz

E = 100 kV/cm: d = 10^{-26} ecm? dν = 1 μHz

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 $\mathbf{B}_{leak}$ which changed direction with **E**

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

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

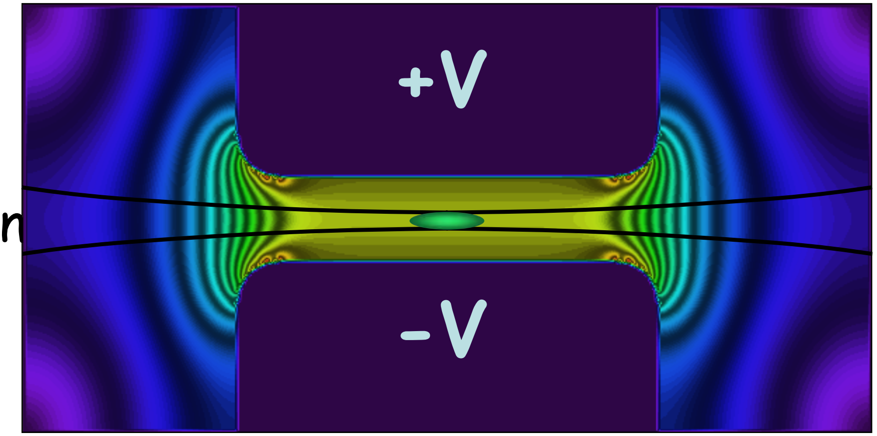
Collisions? Cold spin-polarized fermions

Magnetic field noise? Homogeneity?

Stable current supply -> 40 ppb over 40 s

Magnetic shielding (We have trap fields!)

Possible dipole trap systematics and noise



Systematics:

COM Potentials? $|E_{plat}|^2 \sim 100x|E_{dip}|^2$

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

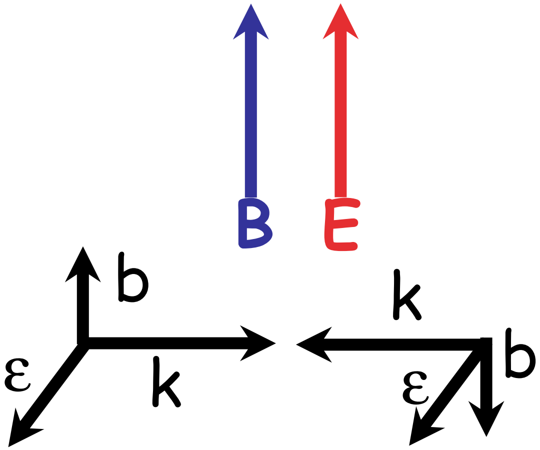
Noise, coherence limiting mechanisms:

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)

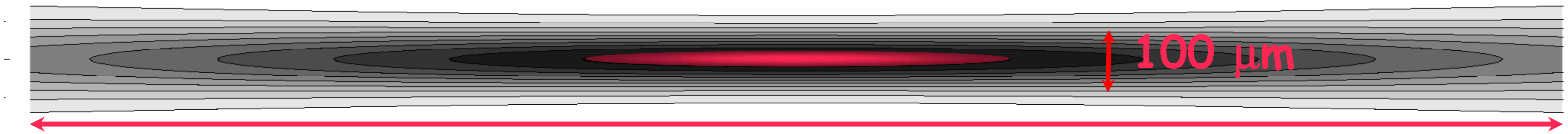
C. Chin *et al.*, PRA **63**, 033401 (2001)



Kr, He, and Ra :) atom trappers

Optical dipole trap

With conservative potential due to AC Stark shift and scalar polarizability, we can trap atoms in the focus of a red-detuned laser:



10 mm

With intensity I(r), laser frequency Ω, atomic scattering rate Γ_i and frequency ω_i for state i:

Trap potential:

$$U_{dip}(\mathbf{r}) \propto -I(\mathbf{r}) \sum_i \frac{\Gamma_i}{\omega_i^2 \left(\omega_i^2 - \Omega^2\right)}$$

Sum over atomic transitions

Scattering rate:

$$\Gamma_{dip}(\mathbf{r}) \propto I(\mathbf{r})\, \Omega^3 \sum_i \left(\frac{\Gamma_i}{\omega_i^2 \left(\omega_i^2 - \Omega^2\right)} \right)^2$$