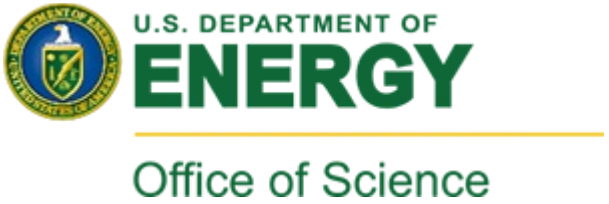
The Search for Time-Reversal Violation in Radium Nuclei

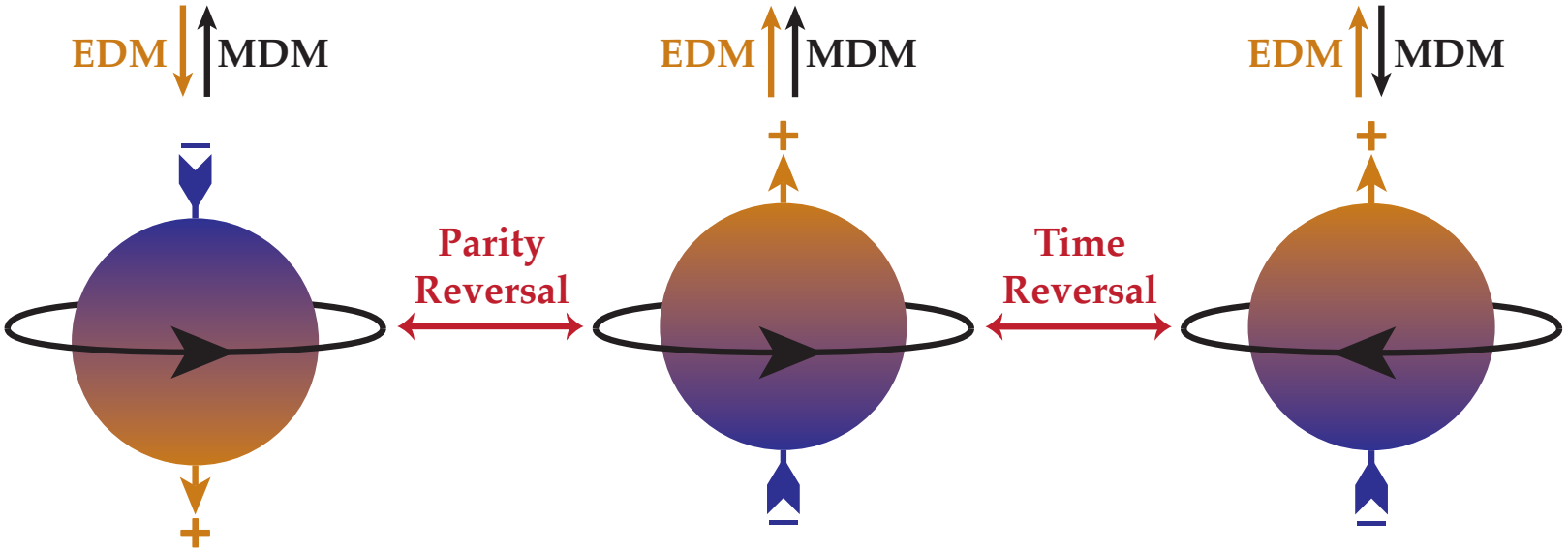
M. R. Dietrich



Electric Dipole Moments and Discrete Symmetries

Electric dipole moment (EDM):

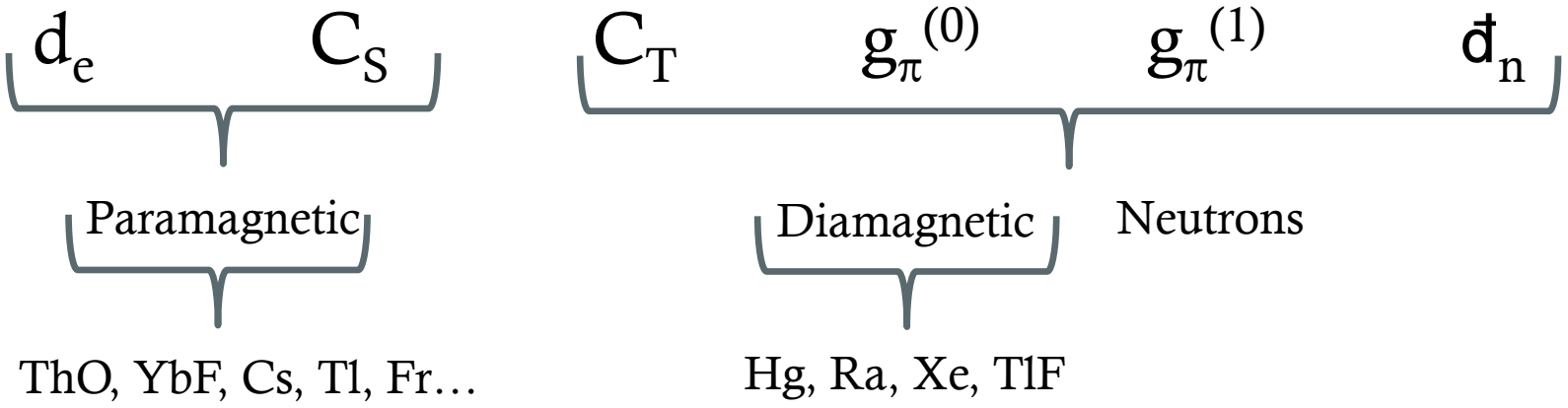
* displacement vector from a particle's center of mass to its center of charge.
* violates both *P*-parity (spatial inversion) and *T*-time reversal symmetries:



Assuming the combination of *C*-charge conjugation (particle <-> antiparticle), *P*, and *T* is conserved:

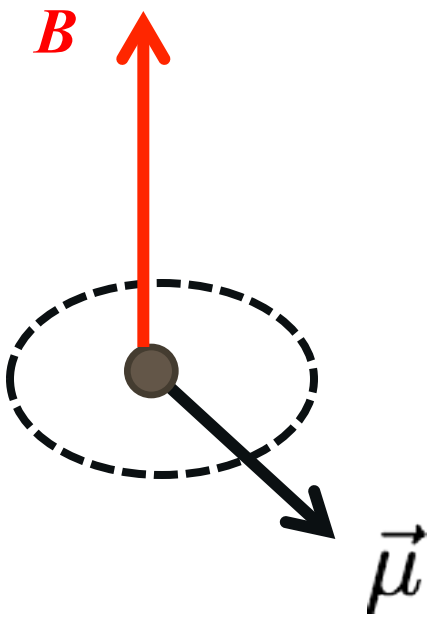
* *T*-violation implies *CP*-violation
* EDMs are a very sensitive probe of *CP*-violation

EDM Sectors



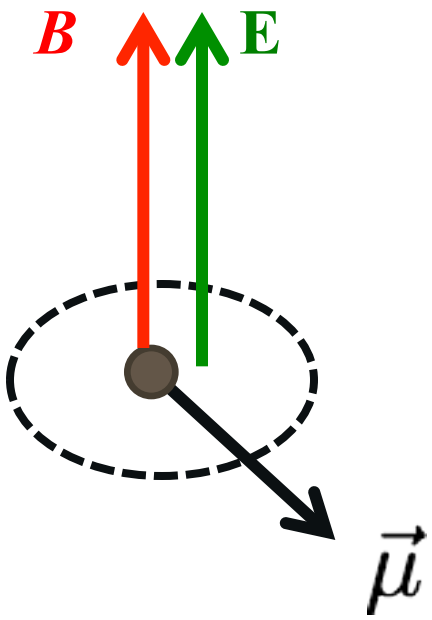
Sector	Exp Limit (e-cm)	Location	Method	Standard Model
Electron	9×10^{-29}	Harvard-Yale	ThO molecules in a beam	10^{-38}
Neutron	3×10^{-26}	ILL	UCN in a bottle	10^{-31}
Nuclear	7×10^{-30}	U. Washington	^{199}Hg atoms in a cell	10^{-33}

EDM Measurements



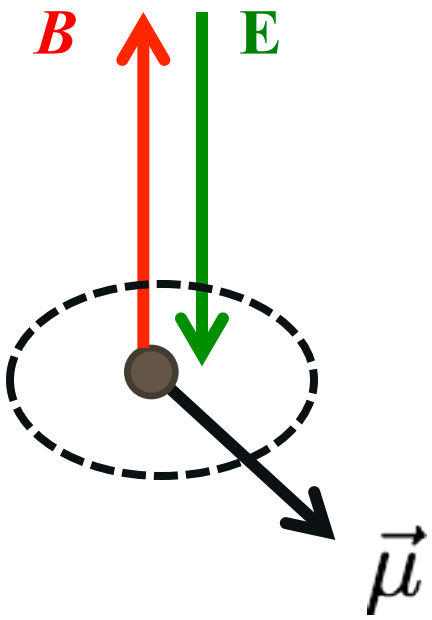
$$h\nu = \frac{\mu B}{S}$$

EDM Measurements



$$h\nu_+ = \frac{\mu B + dE}{S}$$

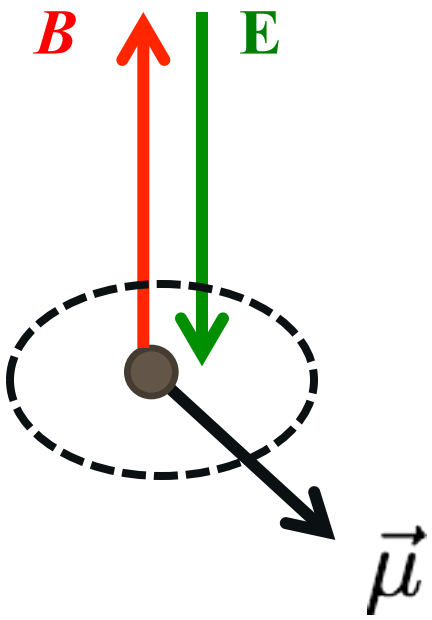
EDM Measurements



$$h\nu_+ = \frac{\mu B + dE}{S}$$

$$h\nu_- = \frac{\mu B - dE}{S}$$

EDM Measurements

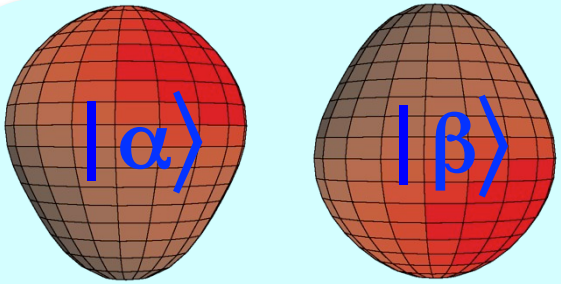


$$h\nu_+ = \frac{\mu B + dE}{S}$$

$$h\nu_- = \frac{\mu B - dE}{S}$$

$$\nu_+ - \nu_- = \frac{2dE}{hS}$$

Radium EDM



A large quadrupole and octupole deformation results In an enhanced Schiff moment
– Auerbach, Flambaum & Spevak (1996)

Relativistic atomic structure weakens the Schiff theorem, resulting in a strong enhancement with increasing Z
(^{225}Ra/^{199}Hg ~ 3)

– Dzuba, Flambaum, Ginges, Kozlov (2002)

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

55 keV

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

A closely spaced parity doublet enhances the appearance of parity violating terms in the underlying Hamiltonian
– Haxton & Henley (1983)

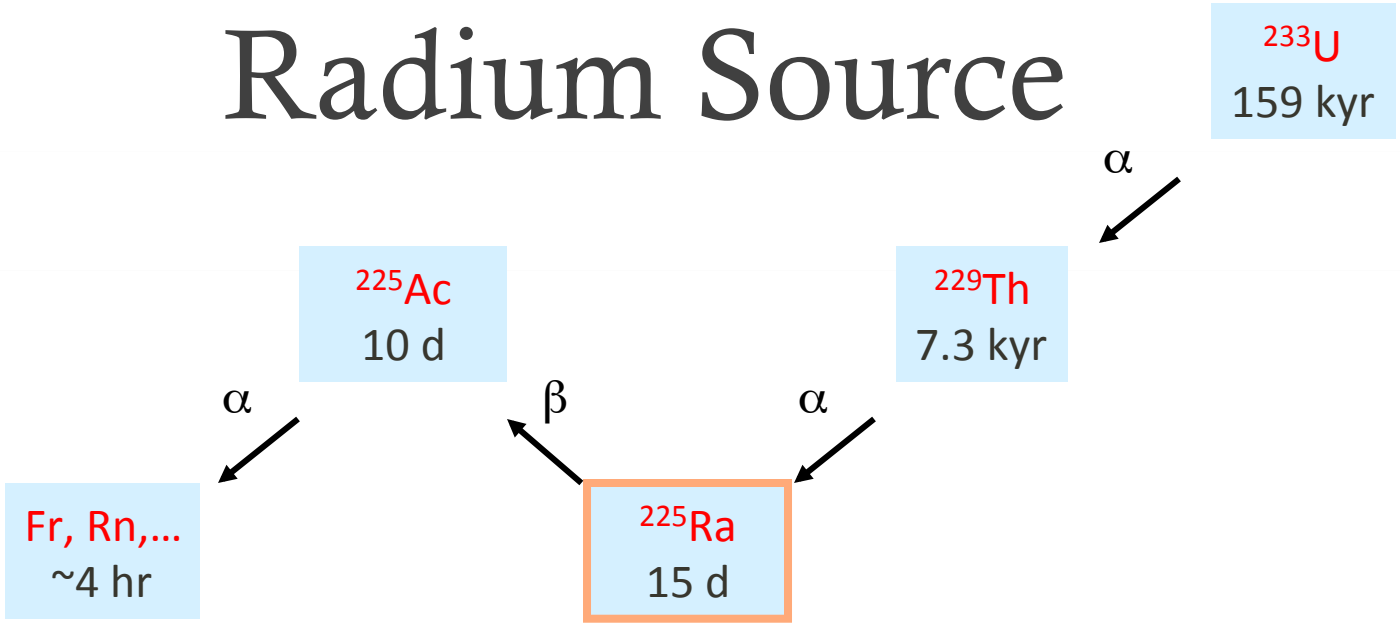
$$S \propto \sum_{i \neq 0} \frac{\left\langle \psi_0 \left| \hat{S}_z \right| \psi_i \right\rangle \left\langle \psi_i \left| \hat{H}_{PT} \right| \psi_0 \right\rangle}{E_i - E_0} + c.c.$$

Enhancement Factor: EDM (^{225}Ra) / EDM (^{199}Hg)

Skyrme Model	Isoscalar	Isovector	Isotensor
SIII	300	4000	700
SkM*	300	2000	500
SLy4	700	8000	1000

Schiff moment of ^{225}Ra, Dobaczewski, Engel (2005)
Schiff moment of ^{199}Hg, Ban, Dobaczewski, Engel, Shukla (2010)

Radium Source



- Up to 10 mCi (250 ng, 7*10^14 atoms) ^{225}Ra sources from:

  National Isotope Development Center (Oak Ridge, TN)

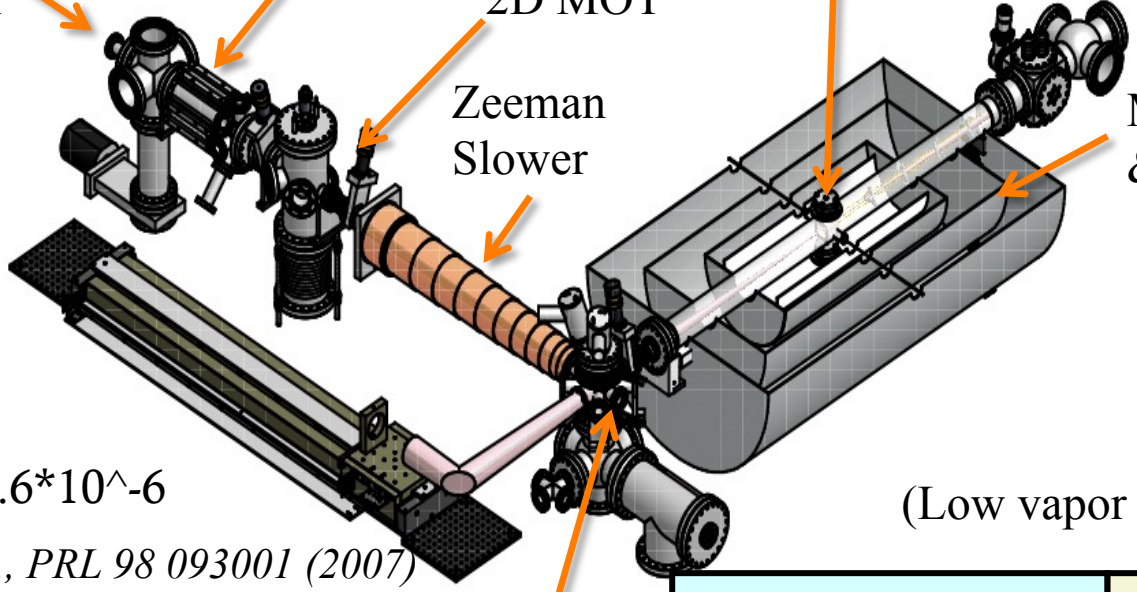
- Test source: 5 μCi (5 μg, 1.3*10^16 atoms) ^{226}Ra

- Integrated Atomic Beam Flux ~ 10^9/s ^{226}Ra, 10^7 – 10^8/s ^{225}Ra

- Special Thanks: John Greene, HP Staff

- Vapor pressure 10^13 cm^{-3}… at 450C

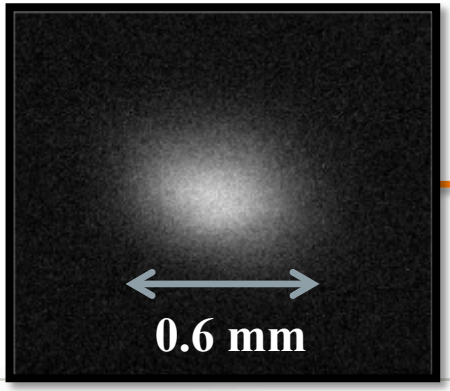
Radium Setup



$\eta \sim 1.6*10^{-6}$

J. R. Guest et al., PRL 98 093001 (2007)

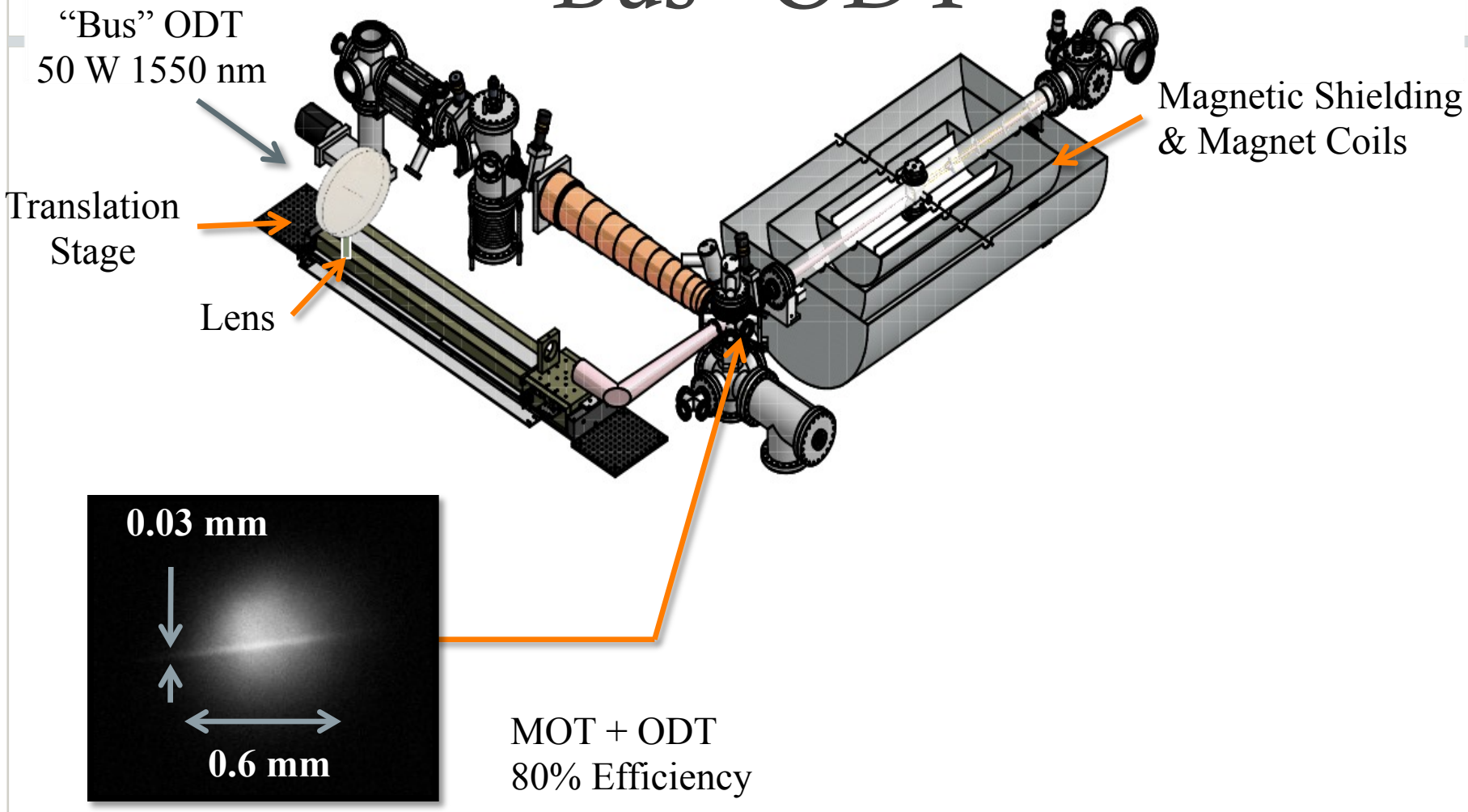
(Low vapor pressure)



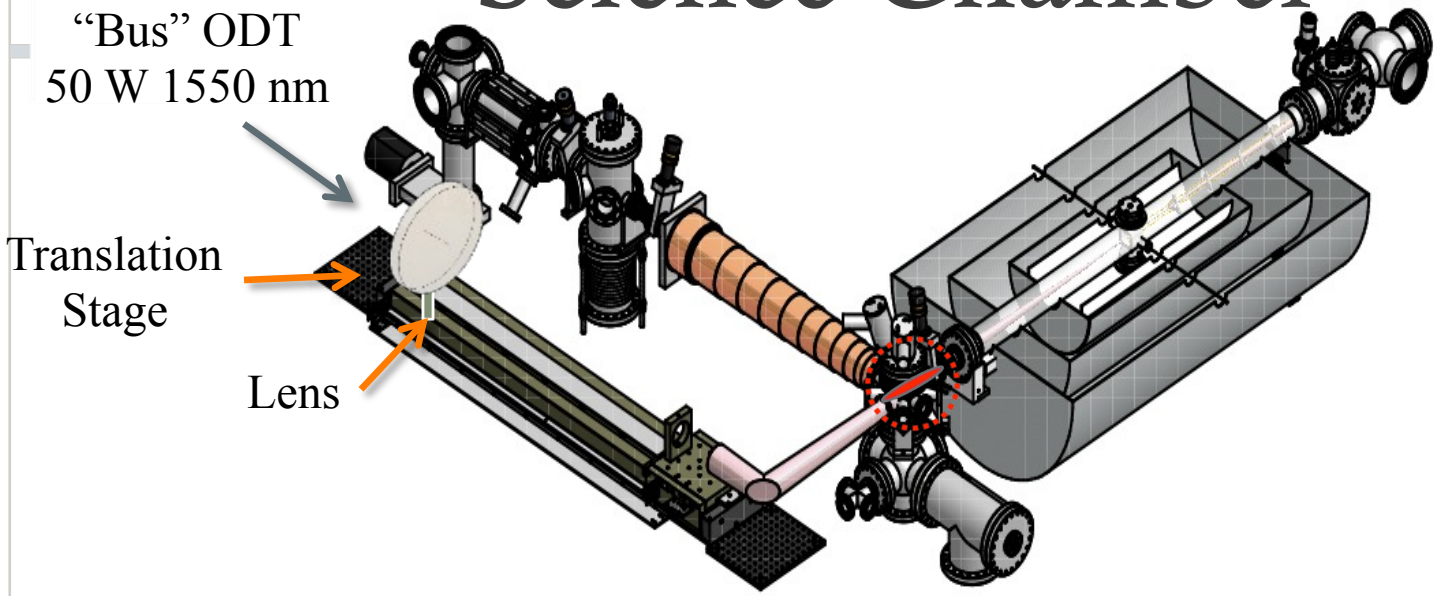
^{226}Ra MOT
200,000 atoms
40 μK

For EDM:	For Testing:
Ra-225	Ra-226
I = 1/2, J = 0	I = 0, J = 0
$t_{1/2}$ = 15 days	$t_{1/2}$ = 1600 yrs

Transfer Atoms from MOT to "Bus" ODT



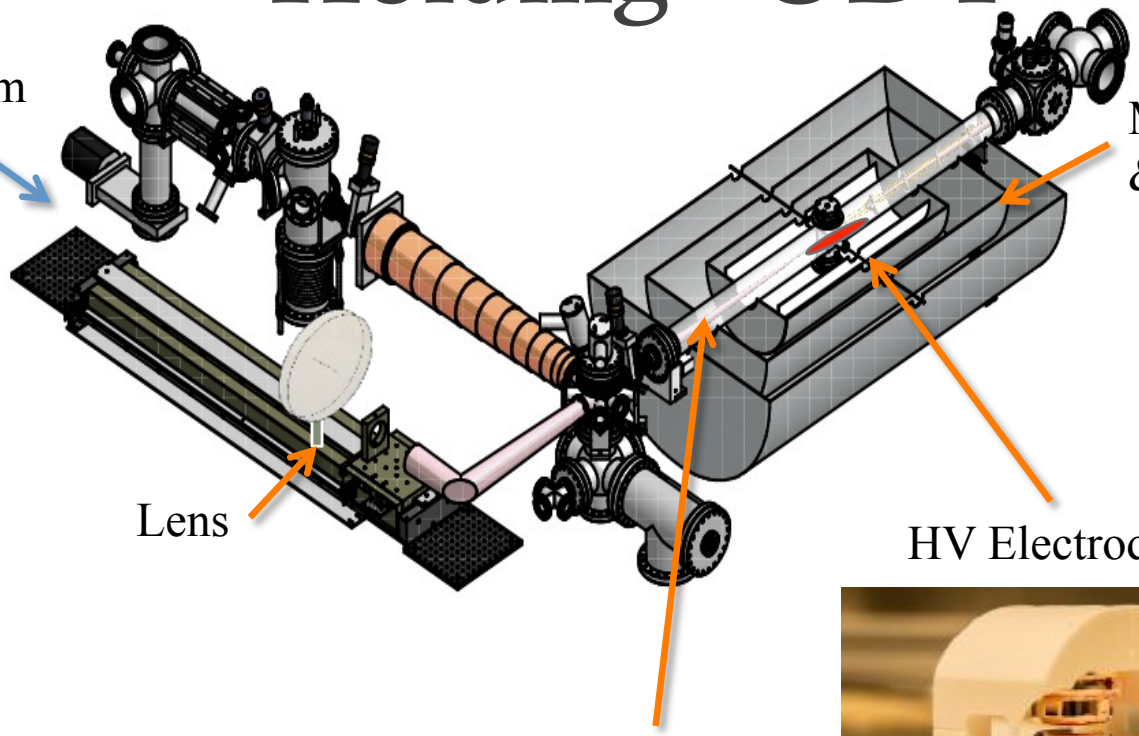
“Bus” ODT Atom Transport to Science Chamber



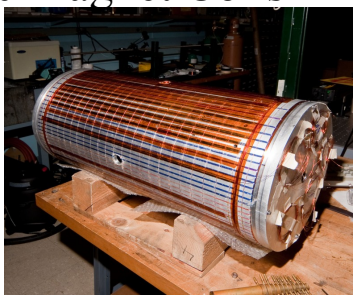
Traveling Wave
“Bus” ODT
Loading Efficiency: 50-70%

Transfer Atoms from "Bus" to "Holding" ODT

"Bus" ODT
50 W 1550 nm



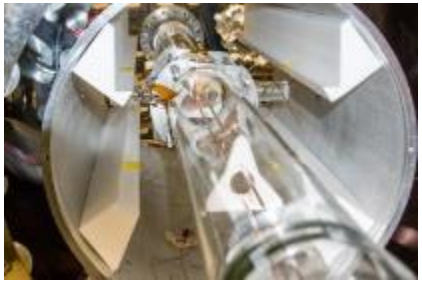
Magnetic Shielding & Magnet Coils



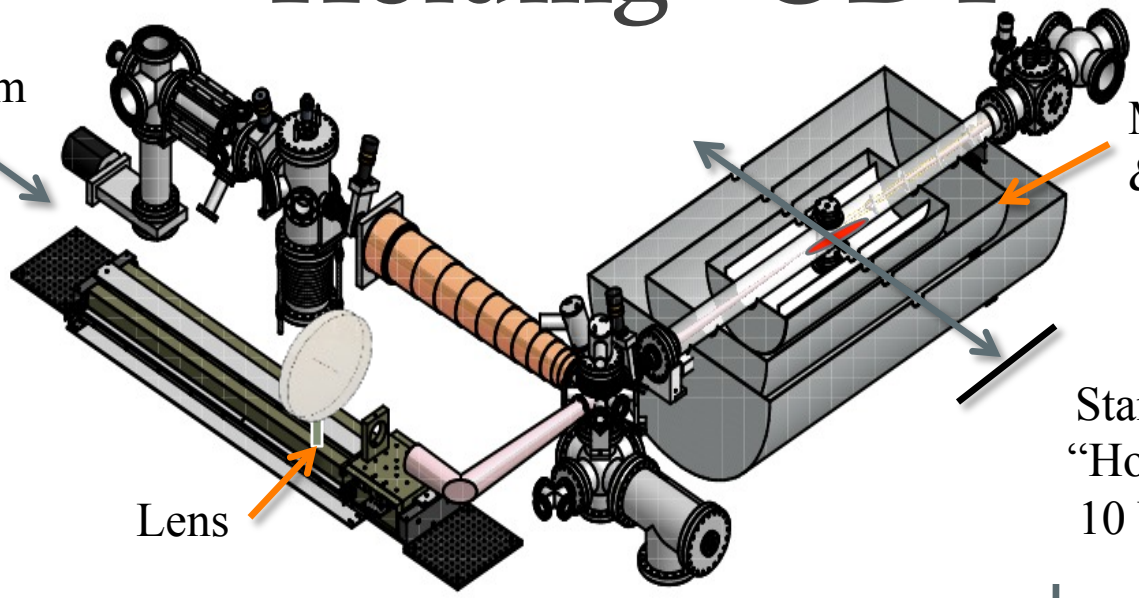
Lens

HV Electrodes

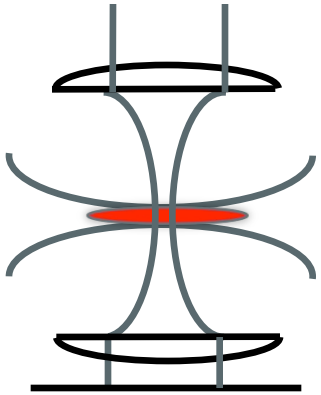
Non-magnetic Glass Tube



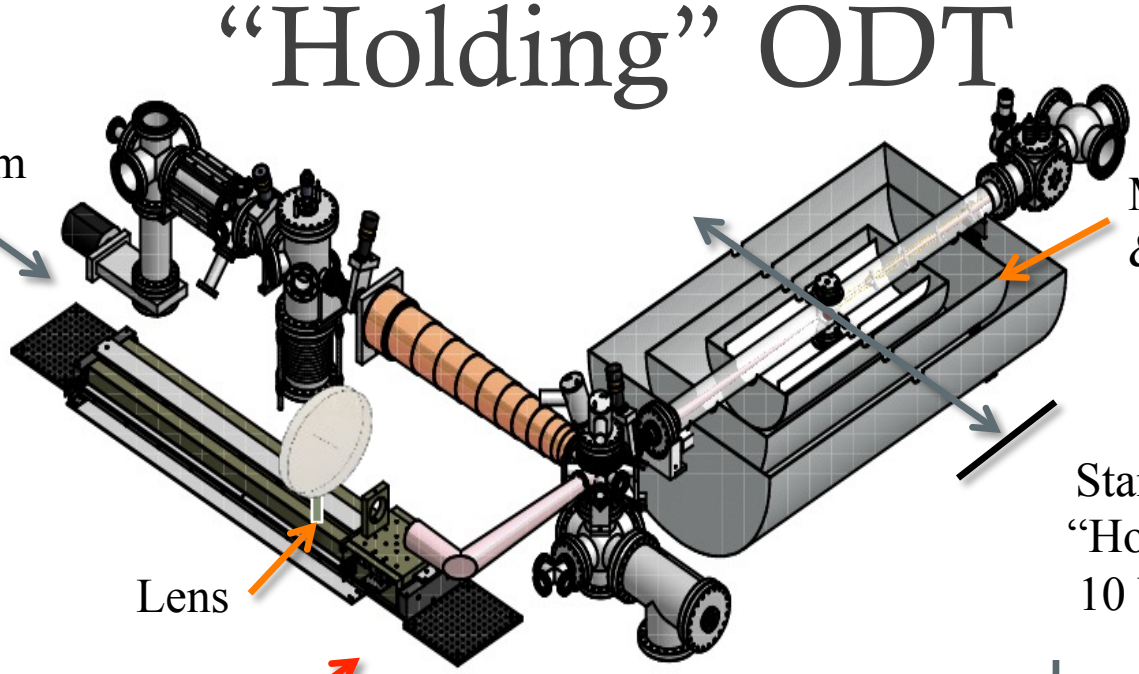
Transfer Atoms from "Bus" to "Holding" ODT



Traveling Wave
"Bus" ODT



Transfer Atoms from "Bus" to "Holding" ODT



"Bus" ODT
50 W 1550 nm

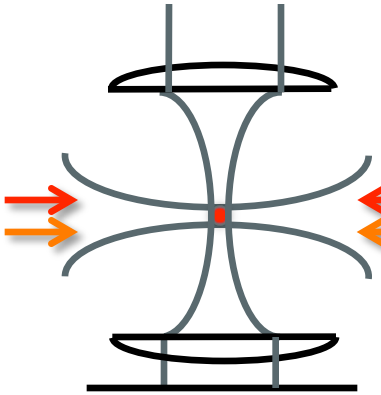
Magnetic Shielding
& Magnet Coils

Standing Wave
"Holding" ODT
10 W 1550 nm

Lens

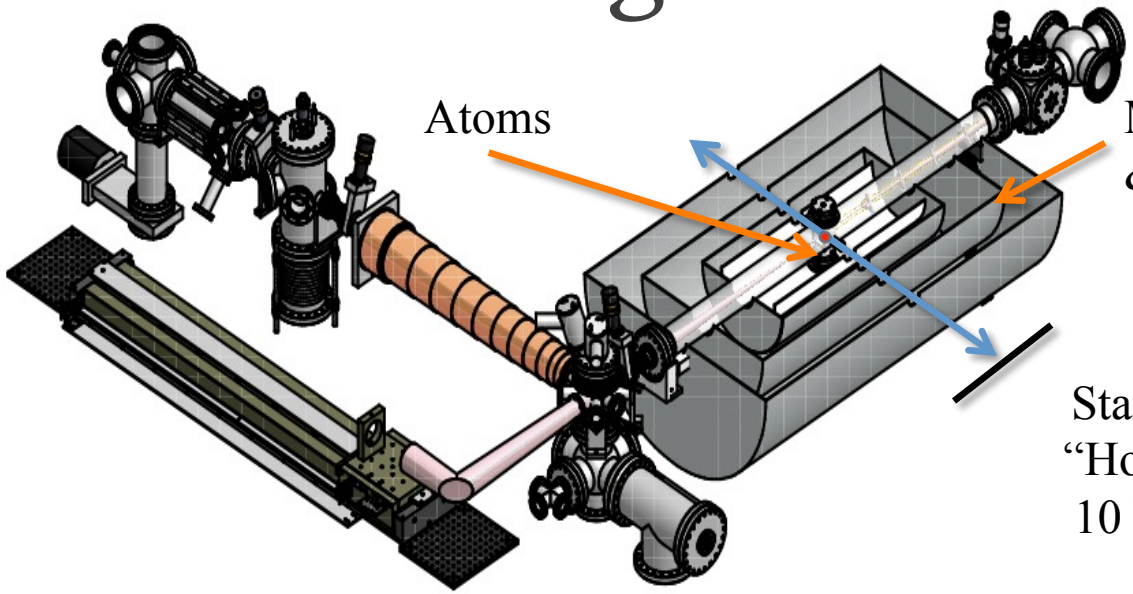
Laser Cooling
100 μW 714 nm

Traveling Wave
"Bus" ODT



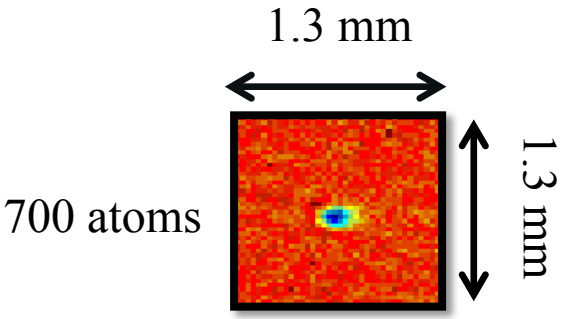
Laser
Cooling
and B Field

Transfer Atoms from "Bus" to "Holding" ODT

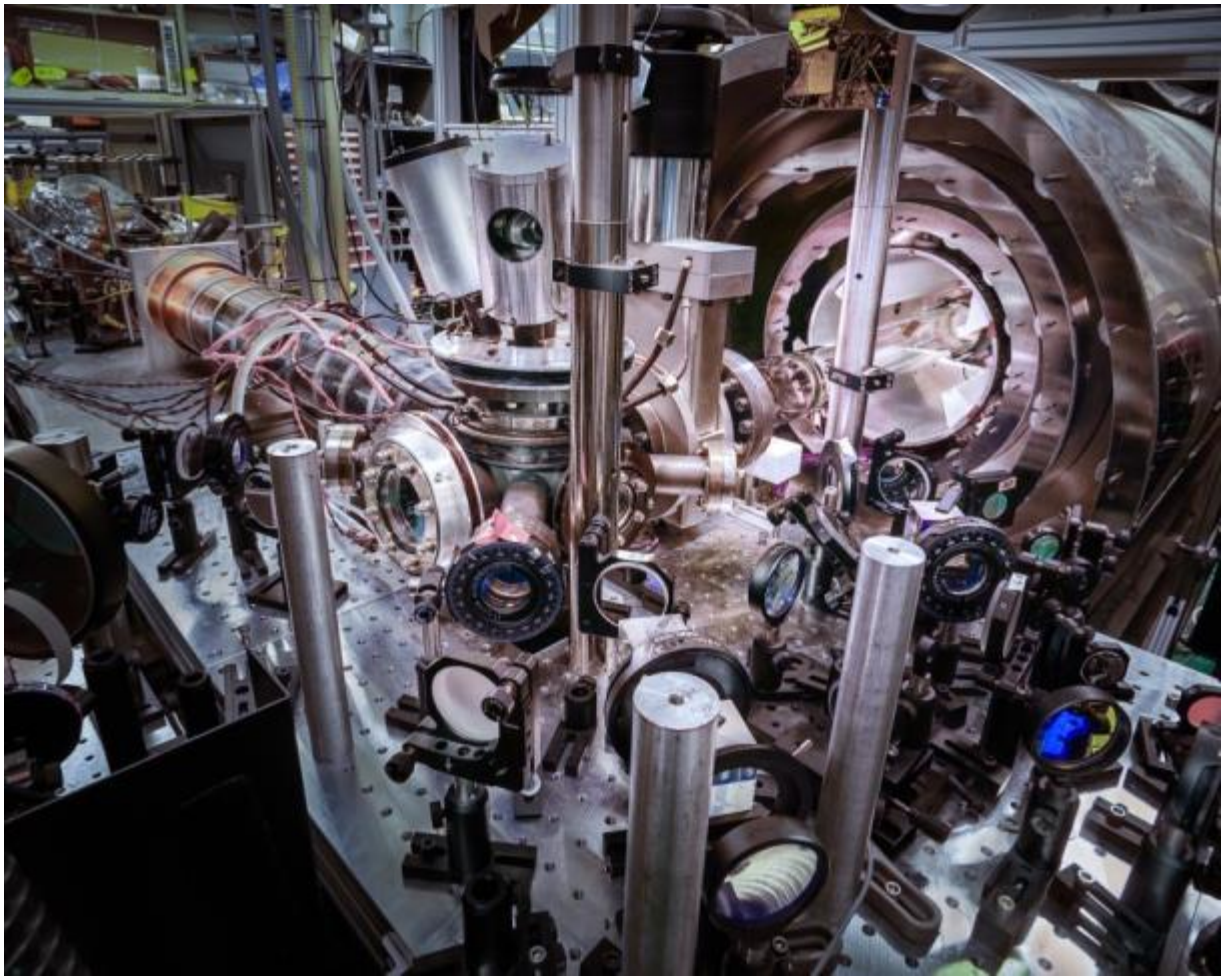


ODT→ODT Transfer: 70% Efficiency

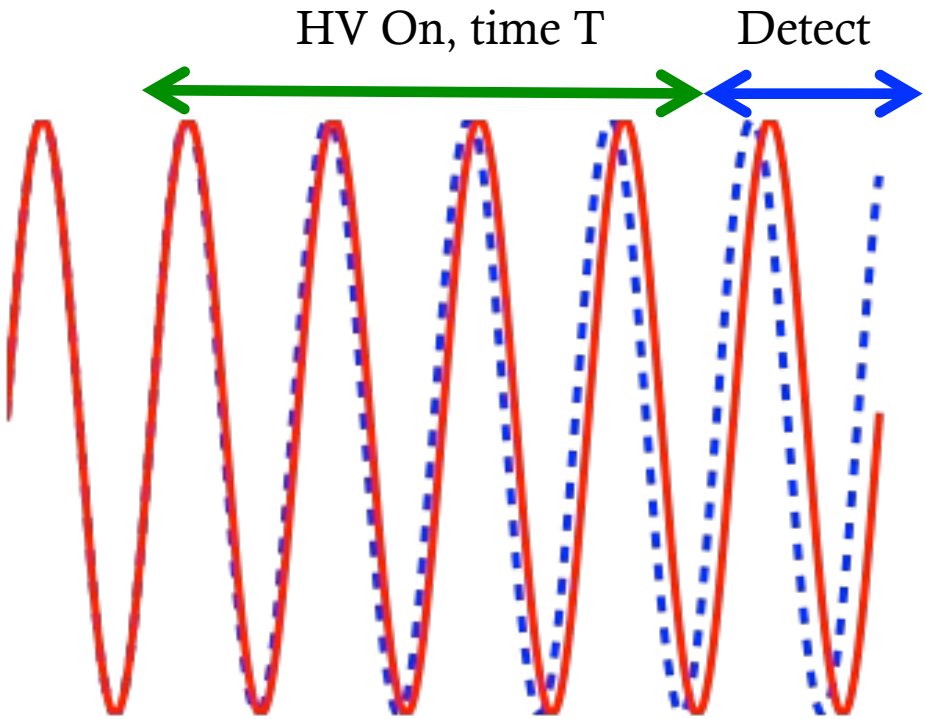
R. H. Parker *et al.*, PRC **86**, 065503 (2012)



Apparatus

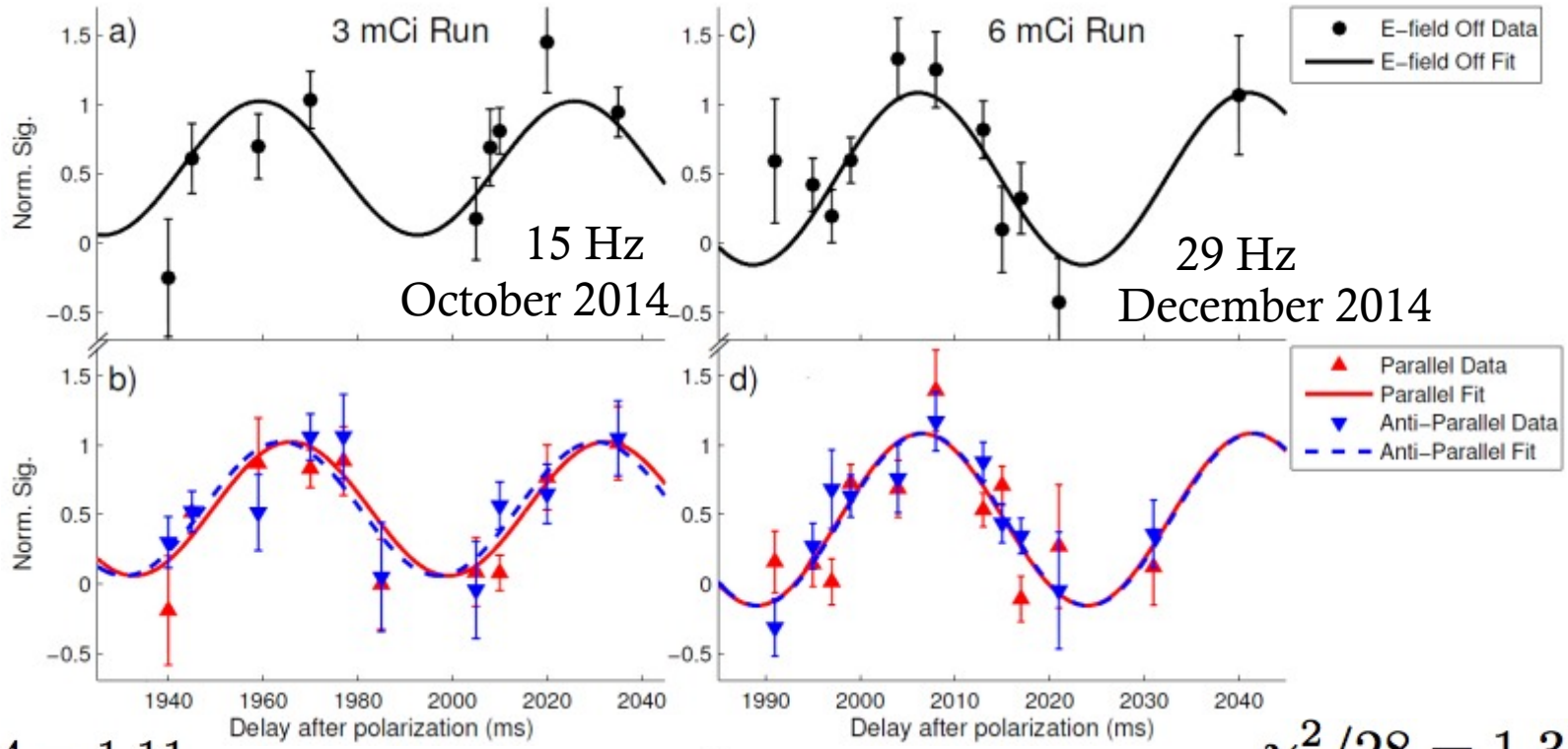


Experimental Cycle



$$\Delta\nu = \frac{\Delta\phi}{2\pi T} = \frac{2dE}{hS} \qquad d = \frac{\hbar S \Delta\phi}{2ET}$$

Signal



$\chi^2/24 = 1.11$

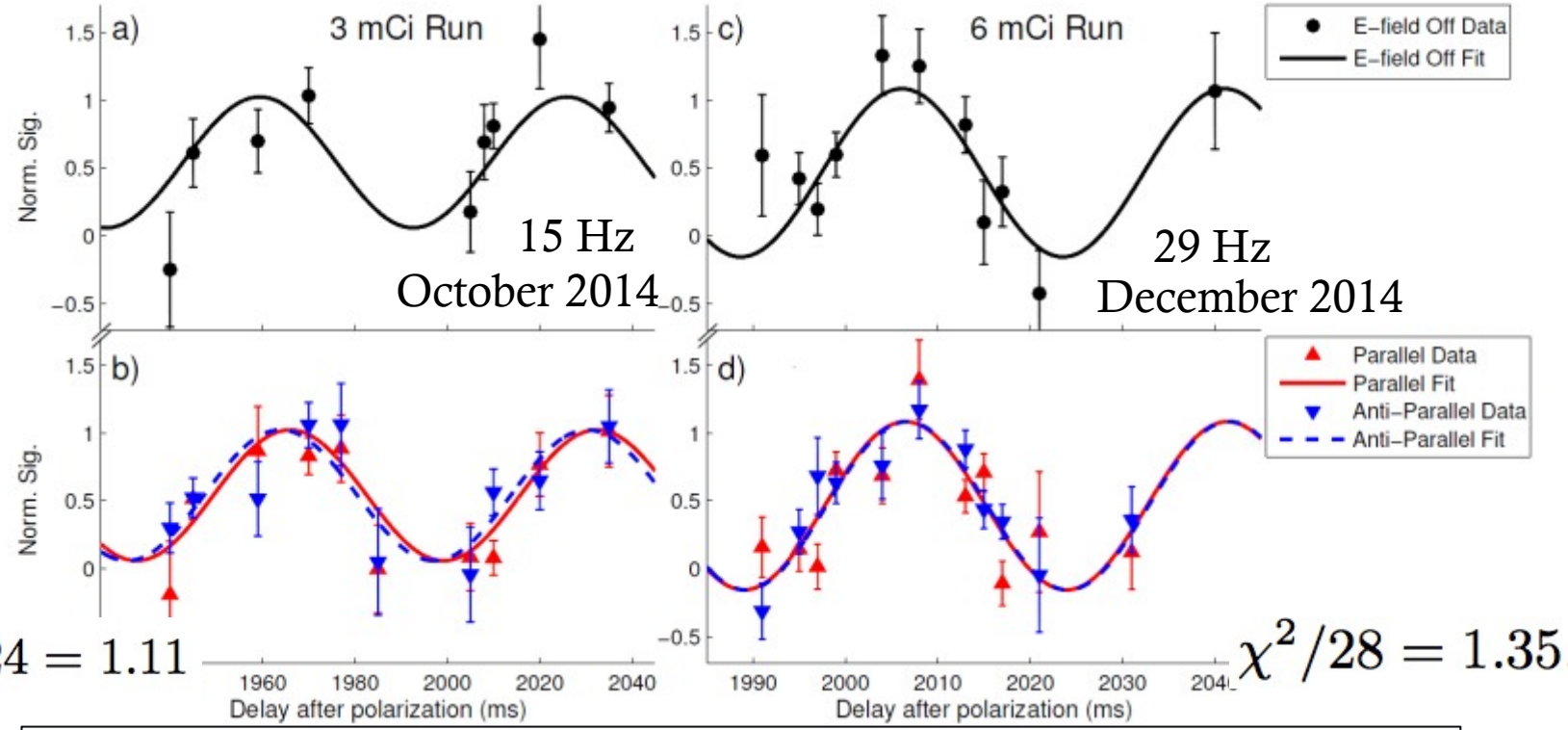
$\chi^2/28 = 1.35$

$$y_{\text{E-field Off}} = \frac{A}{1+P}\left[1 - P\cos(\omega t)\right]$$

$$y_{\text{Parallel, Anti-Parallel}} = \frac{A}{1+P}\left[1 - P\cos(\omega t + \theta \pm \Delta\phi/2)\right]$$

R. H. Parker *et al.* PRL **114**, 233003 (2015).

Signal

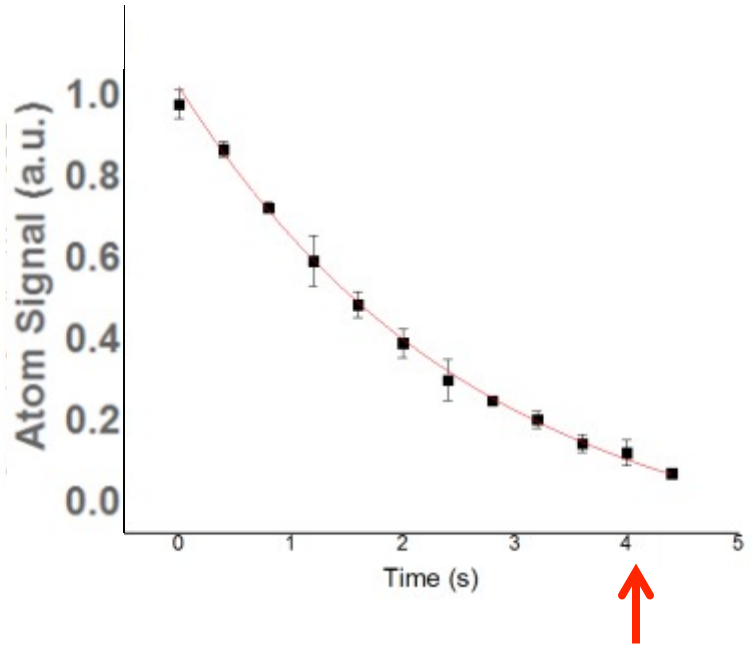


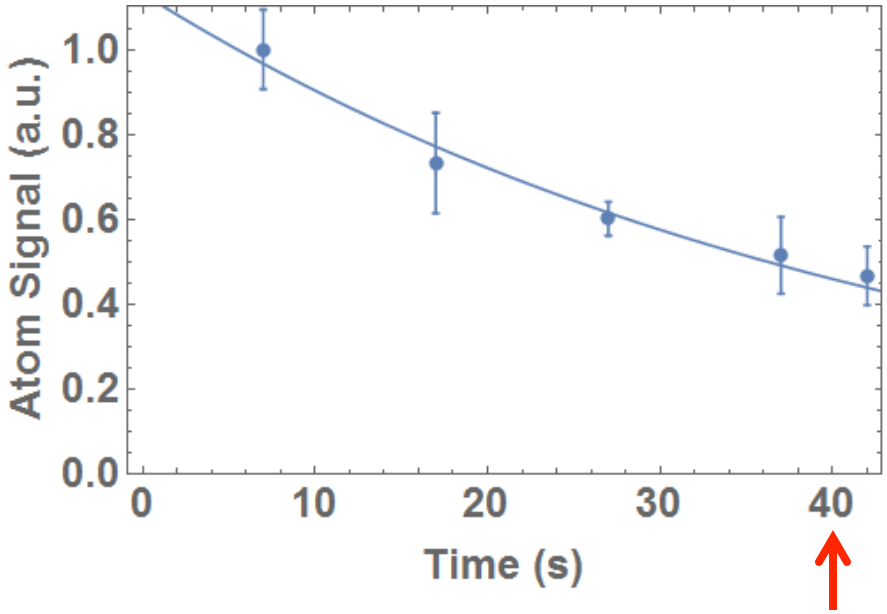
$d_{Ra\text{-}225} = (-0.5 \pm 2.5_{stat} \pm 0.2_{syst}) \times 10^{-22}$ e-cm
5.0×10^{-22} e-cm 95% confidence upper limit

R. H. Parker *et al.* PRL **114**, 233003 (2015).

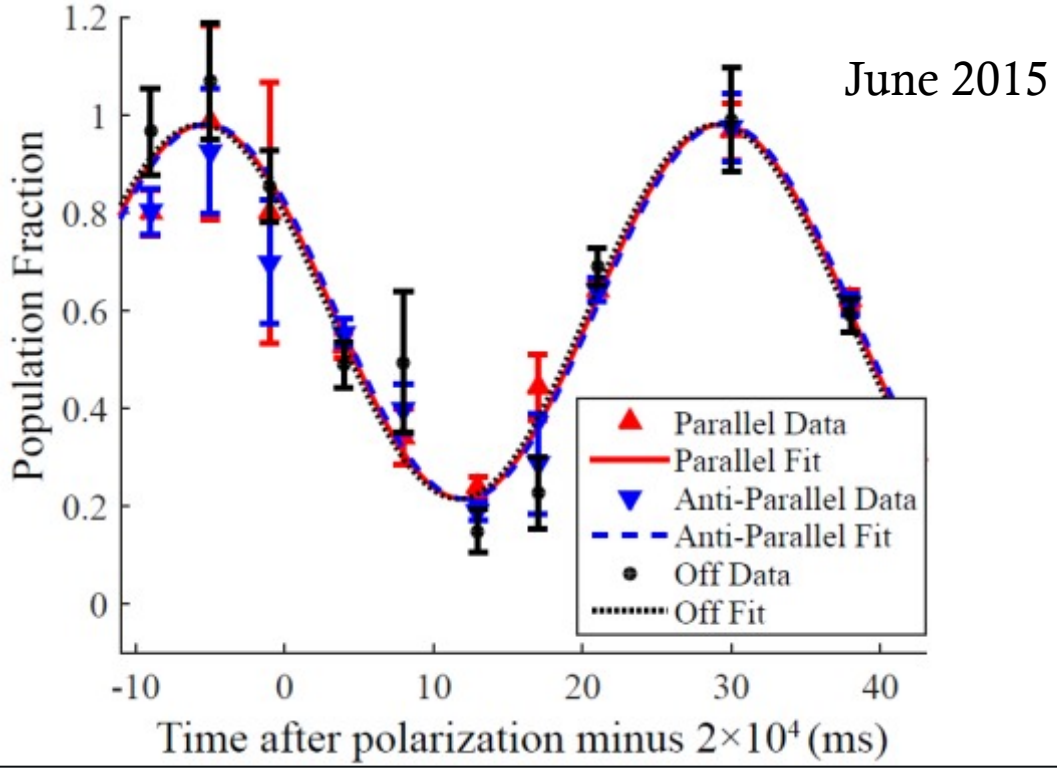
Improved Lifetime

- **6 mCi → 9 mCi**
- τ: **2 s → 20 s** after vacuum upgrade, traveling wave





New Result!



$d_{Ra\text{-}225} < 1.4 \times 10^{-23}$ e-cm 95% C.L.

36-fold improvement in 6 months

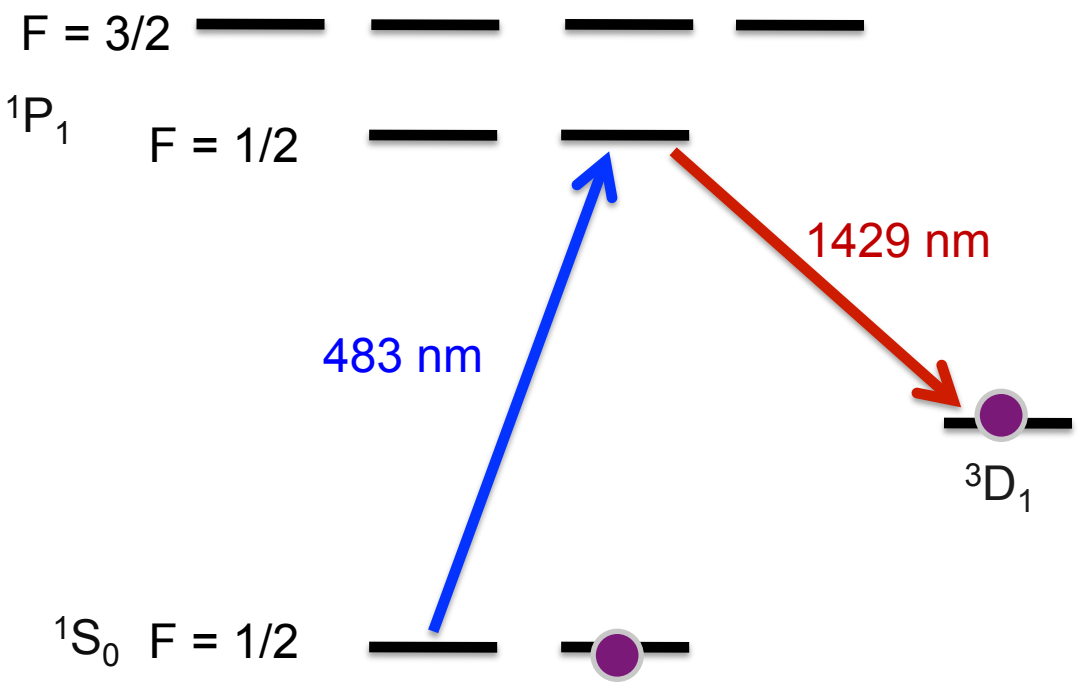
M. Bishof *et al.* PRC 94, 025501 (2016)

Systematics

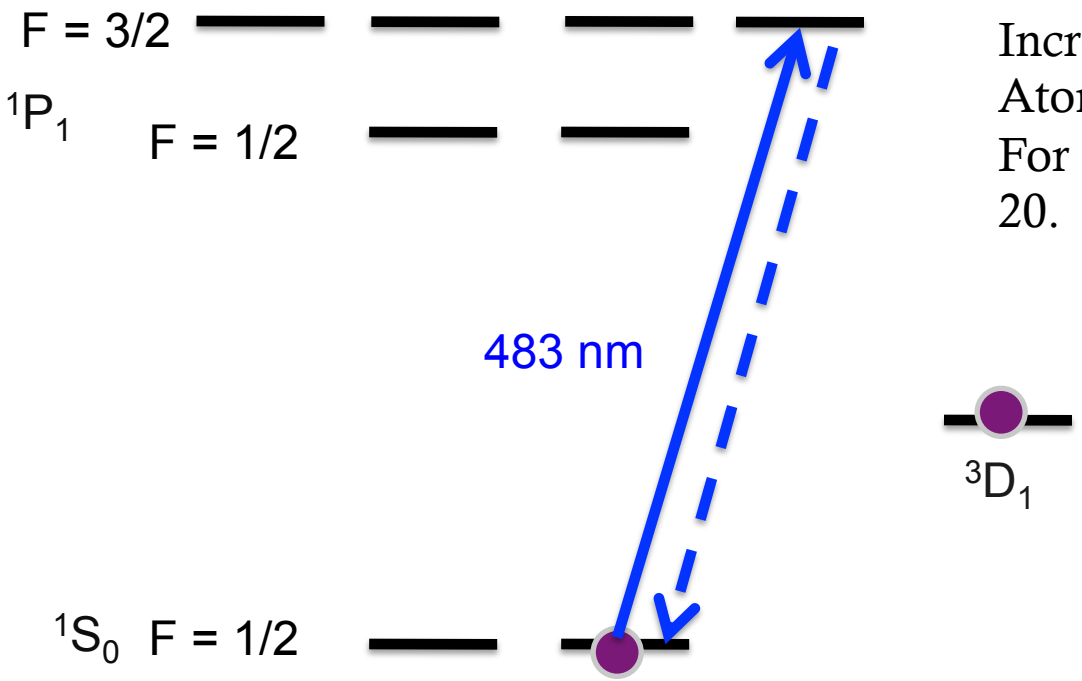
Effect (e-cm)	2016 Measurement	Improved Statstics	Co-magnetometer
E-squared Effects	1×10^{-25}	7×10^{-29}	7×10^{-31}
B-field Correlations	1×10^{-25}	5×10^{-27}	3×10^{-29}
ODT Power Corr.	6×10^{-26}	9×10^{-30}	9×10^{-32}
Stark Interference	6×10^{-26}	2×10^{-27}	3×10^{-29}
Blue Power Corr.	7×10^{-28}	1×10^{-31}	1×10^{-31}
Blue Freq. Corr.	4×10^{-28}	8×10^{-30}	8×10^{-30}
E x v Effects	4×10^{-28}	7×10^{-30}	-
Leakage Current	3×10^{-28}	9×10^{-29}	-
E-field Ramping	9×10^{-28}	2×10^{-29}	-
Geometric Phase	3×10^{-31}	7×10^{-30}	5×10^{-33}
Total	$\mathbf{2\times10^{-25}}$	$\mathbf{5\times10^{-27}}$	$\mathbf{4\times10^{-29}}$

M. Bishof *et al.* PRC 94, 025501 (2016)

Improved Detection

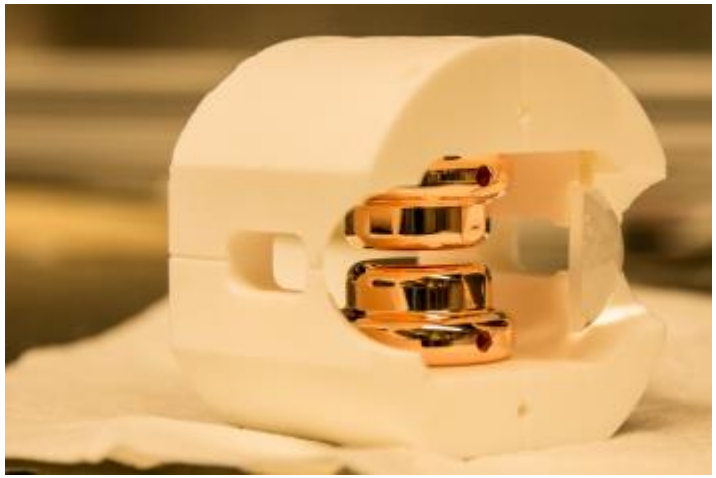


Improved Detection



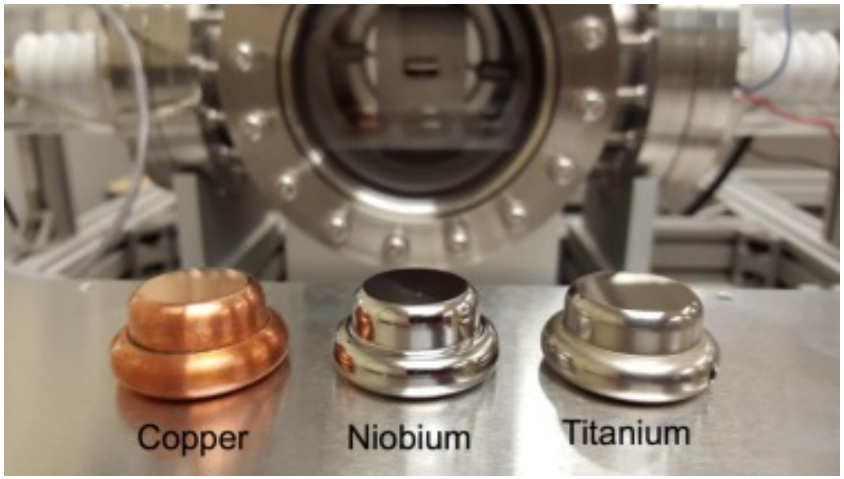
Increase from 2.5 photons per Atom to 1000 photons per atom, For a nominal SNR improvement of 20.

Increased Field



Present: Copper Electrodes, E = 70 kV/cm

In Development: Niobium and Titanium: 300-500 kV/cm



Phys. Rev. Spec. Top. – Acc. and Beams, **15**, 083502 (2012)

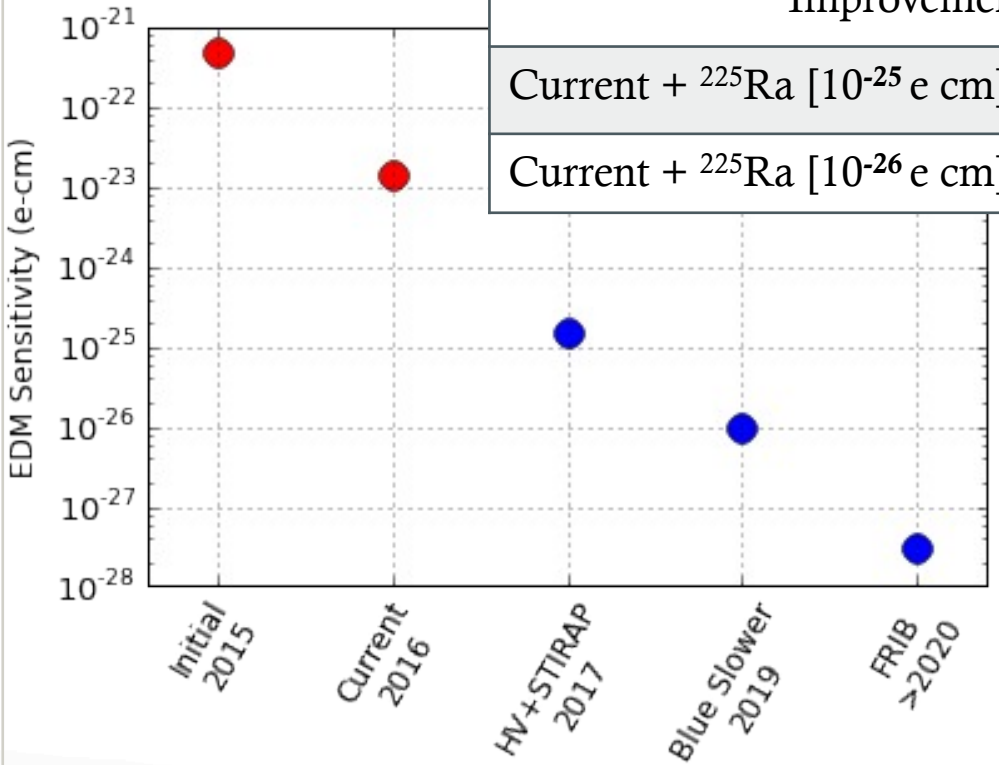
Factor of 5-7 increase in EDM Sensitivity

Together, a factor of 100 increase, bringing us to high 10^{-26} or low 10^{-25} e-cm level

Effect on Standard Model Extensions

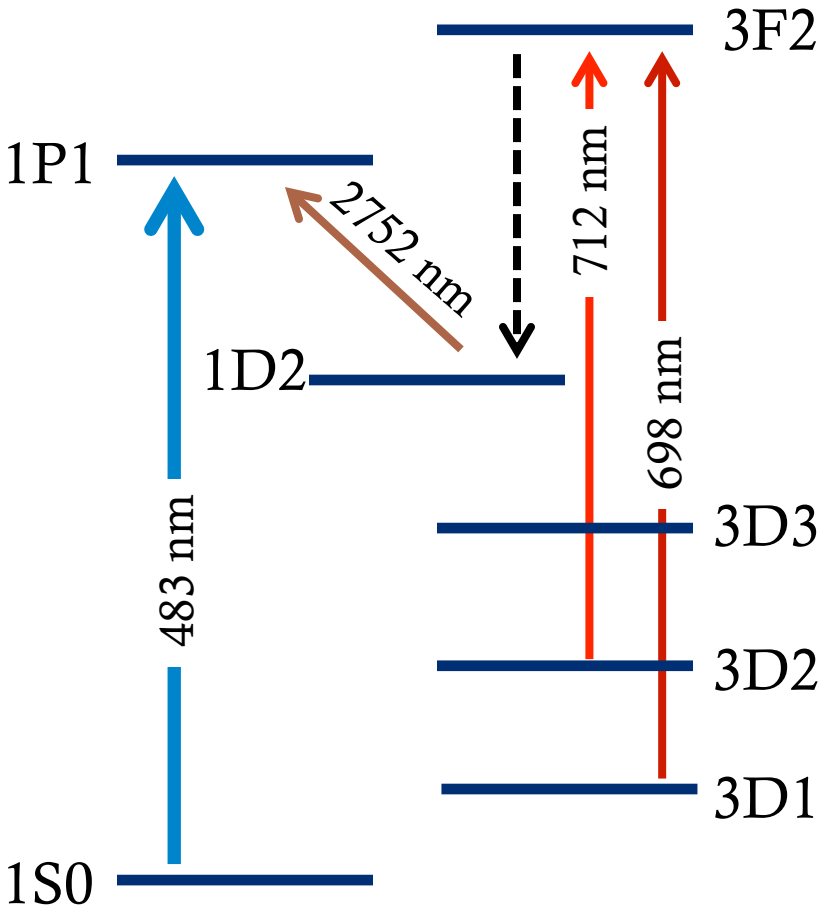
BSM parameter	C_T	$g_\pi^{(0)}$	$g_\pi^{(1)}$	$\tilde{d}_n$ (e cm)
Current limits (95% CL)	2×10^{-6}	8×10^{-9}	1.2×10^{-9}	1.2×10^{-22}
Improvement Factor (over current limit)				
Current + ^{225}Ra [10^{-25} e cm]	40	2	1.2	20
Current + ^{225}Ra [10^{-26} e cm]	200	8	4	60

T. Chupp and M. Ramsey-Musolf, PRC 91, 035502 (2015)



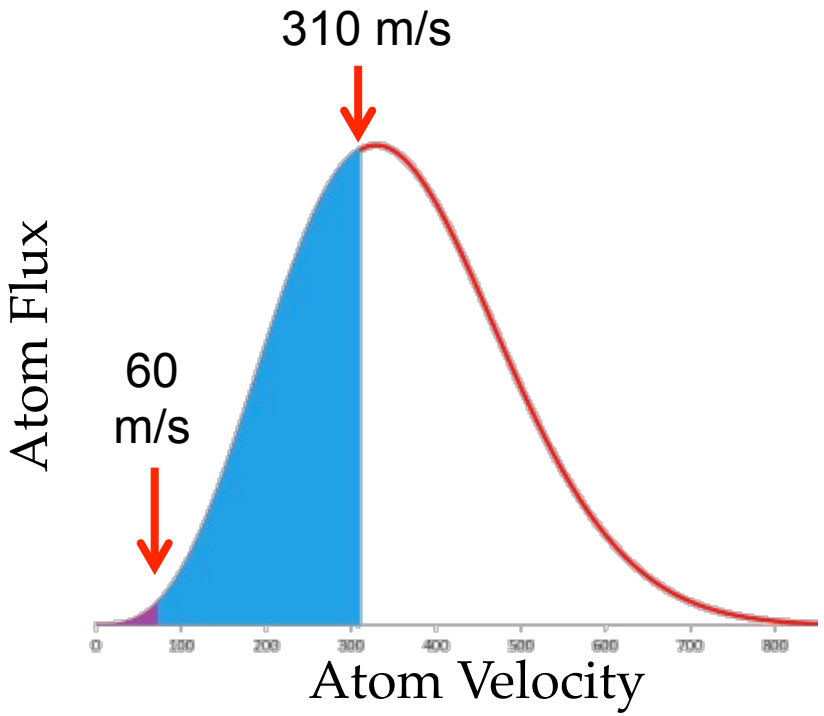
At the level available with those upgrades, radium will improve significantly on the global sensitivity for all parameters

Better Living Through Statistics – Blue Slower



$\eta \sim 1.6*10^{-6}$

30x - 100x increase in N



Better Living Through Statistics – Long Term

Presently available

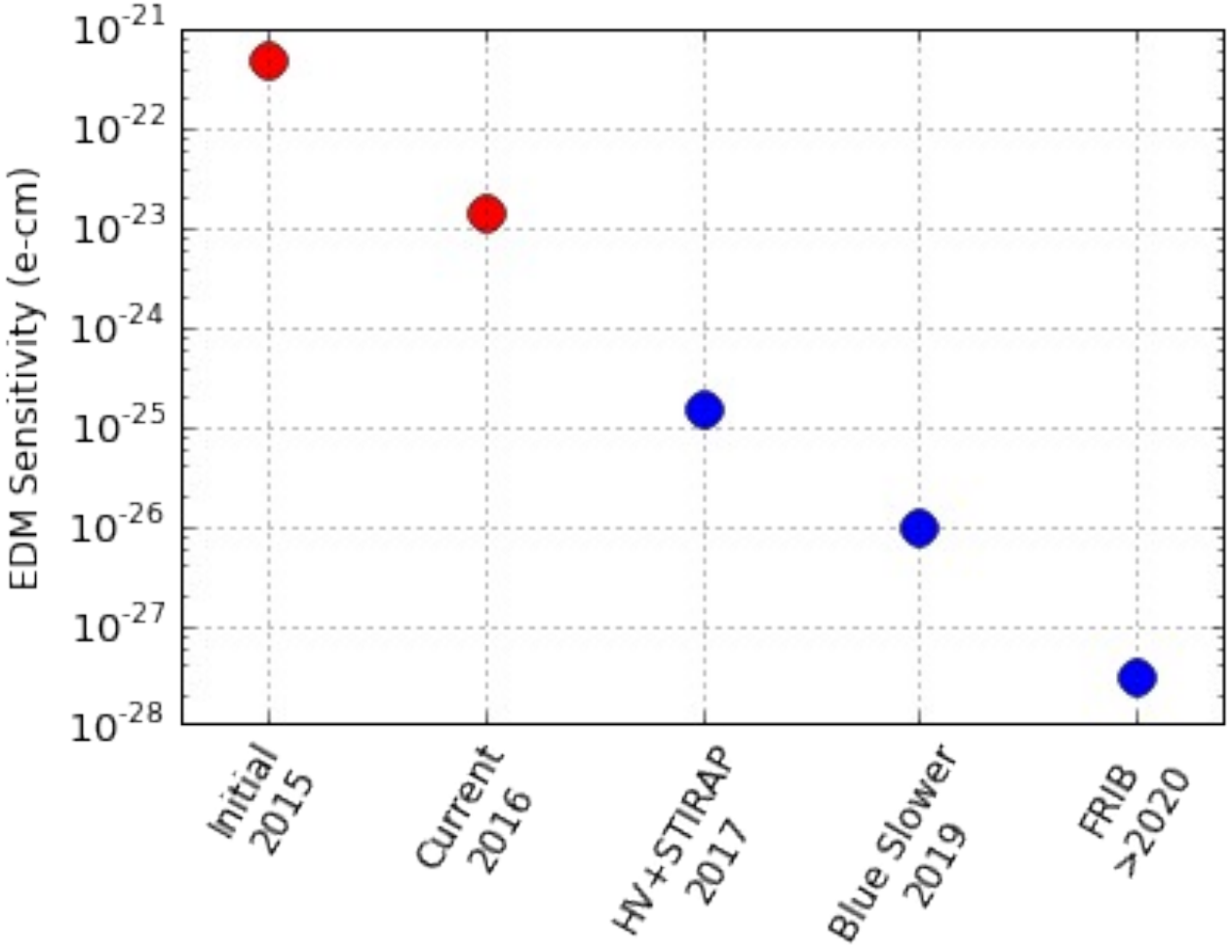
- Decay daughters of ^{229}Th, National Isotope Development Center, ORNL
  - ^{225}Ra: 10^{8} /s

Projected rates at FRIB (B. Sherrill, MSU)

- Beam dump recovery with a ^{238}U beam
  - Parasitic operation, available ~ 150 days per year
  - ^{225}Ra: 6 x 10^{9} /s ; ^{223}Rn: 8 x 10^{7} /s; $^{208\text{-}220}$Fr: 10^{9} -10^{10} /s.
- Dedicated running with a ^{232}Th beam
  - ^{225}Ra: 5 x 10^{10} /s ; ^{223}Rn: 1 x 10^{9} /s; $^{208\text{-}220}$Fr: 10^{10} /s;

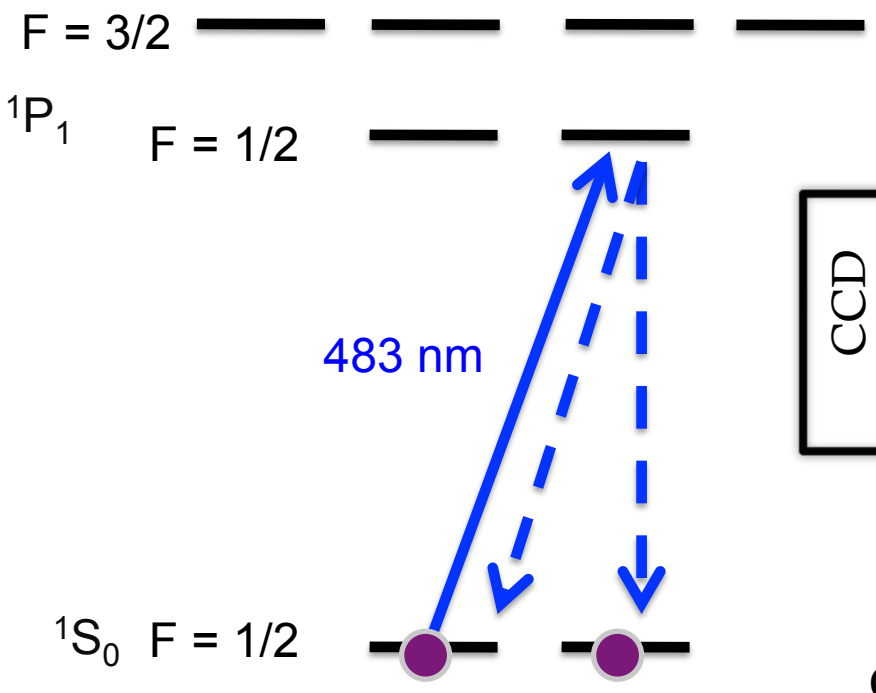
FRIB will produce isotopes with enhanced sensitivity to fundamental symmetries, and provide opportunities for discovering physics beyond the Standard Model.

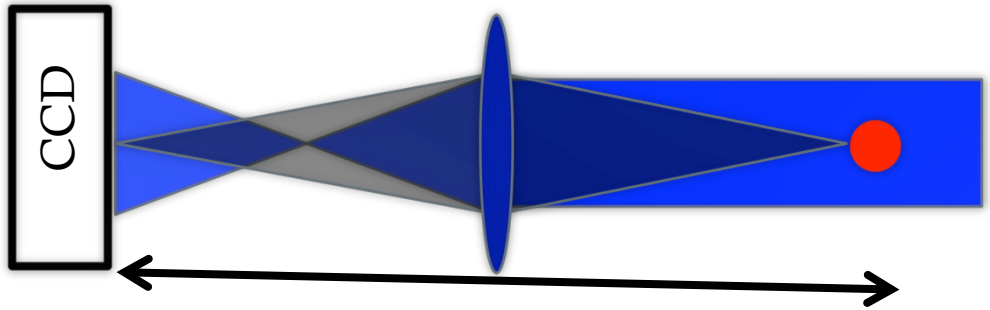
Effect on Standard Model Extensions



Atom Trappers @ Argonne

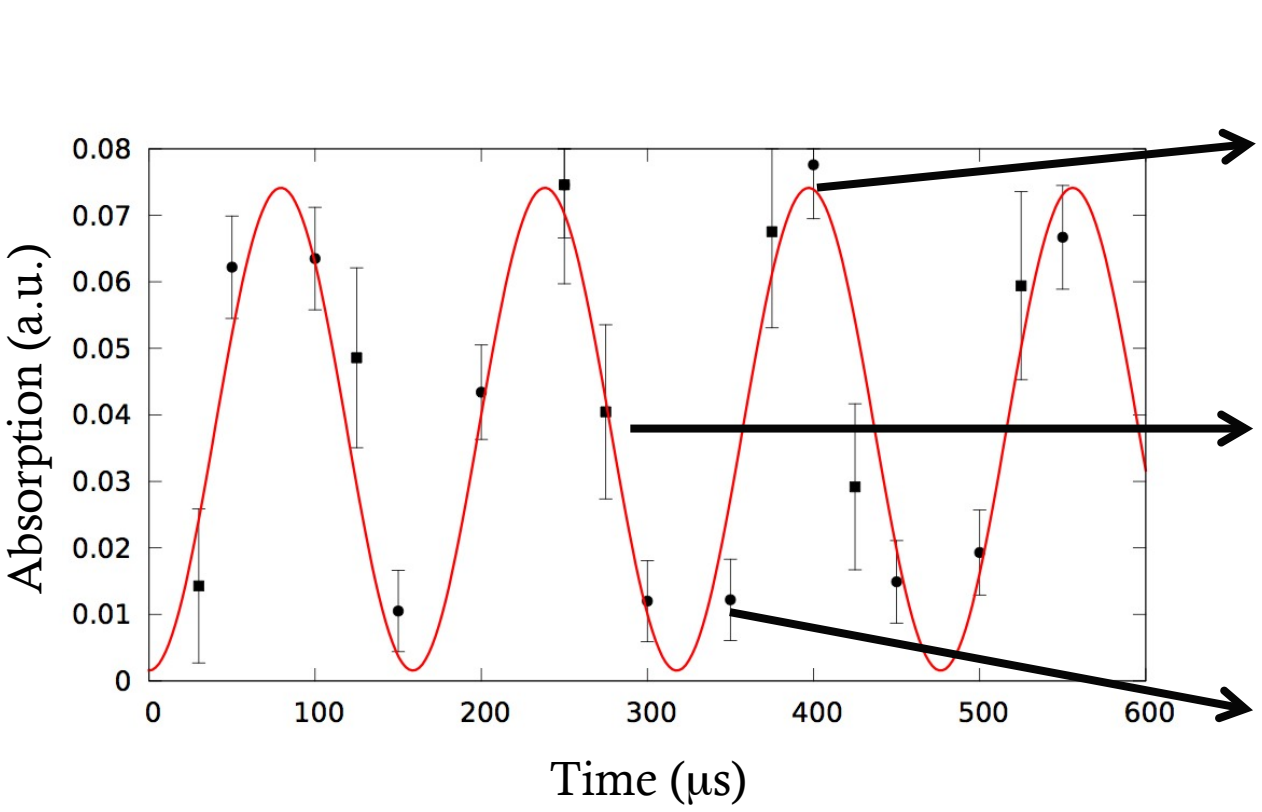
Optical Pumping and Detection

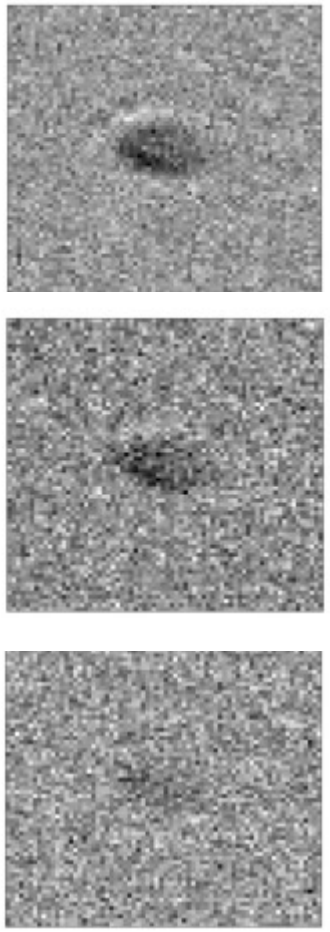




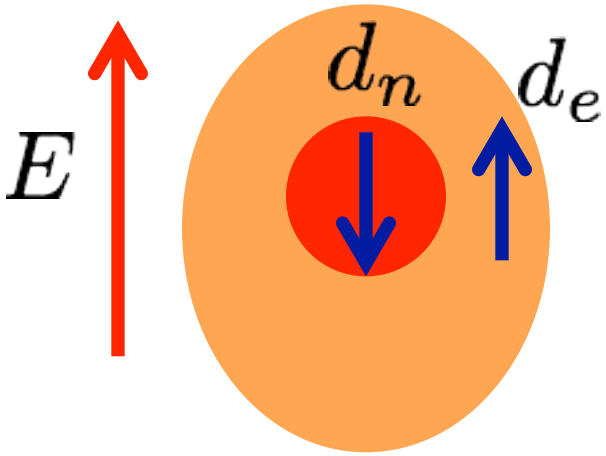
Optimal SNR after 2.1 photons/atom

Detection


0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
Absorption (a.u.)
0
100
200
300
400
500
600
Time (μs)



Schiff Moments and EDMs



Schiff Moment

$$\vec{S} = \frac{\langle er^2\vec{r}\rangle}{10} - \frac{\langle r^2\rangle\langle e\vec{r}\rangle}{6}$$

Leonard Schiff's Theorem (1963):

- Any permanent dipole moment of the nucleus is perfectly shielded by its electron cloud
- True for point-like nuclei, non-relativistic electrons

However, the "Schiff moment" is not shielded by this effect

- Zero for point-like, spherical nuclei
- Arises from deformations in the nucleus or its constituent nucleons
- Very large in nuclei with both a quadrupole and octupole deformation

Look for heavy nuclei with large quadrupole and octupole deformations!

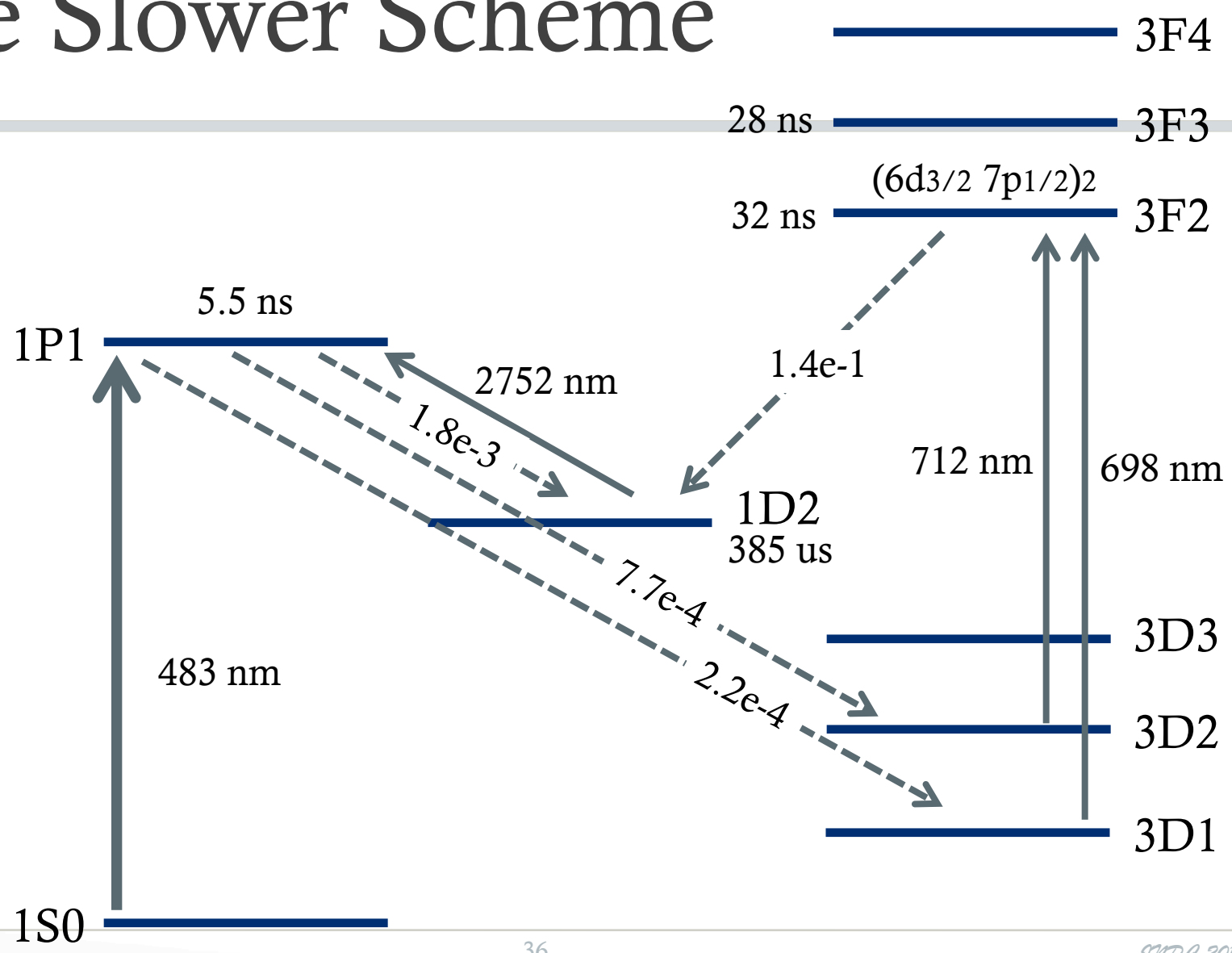
Effect on Standard Model Parameters

BSM parameter	C_T	$g_\pi^{(0)}$	$g_\pi^{(1)}$	d_n (e cm)
Current limits (95% CL):	2×10^{-6}	8×10^{-9}	1.2×10^{-9}	1.2×10^{-22}
Improvement Factor (over current limit)				
Current + next-gen neutron [10^{-28}] and ^{129}Xe [3×10^{-29}]	20	8	3	6
Current + ^{225}Ra [10^{-25} e cm]	40	2	1.2	20
[10^{-26} e cm]	200	8	4	60

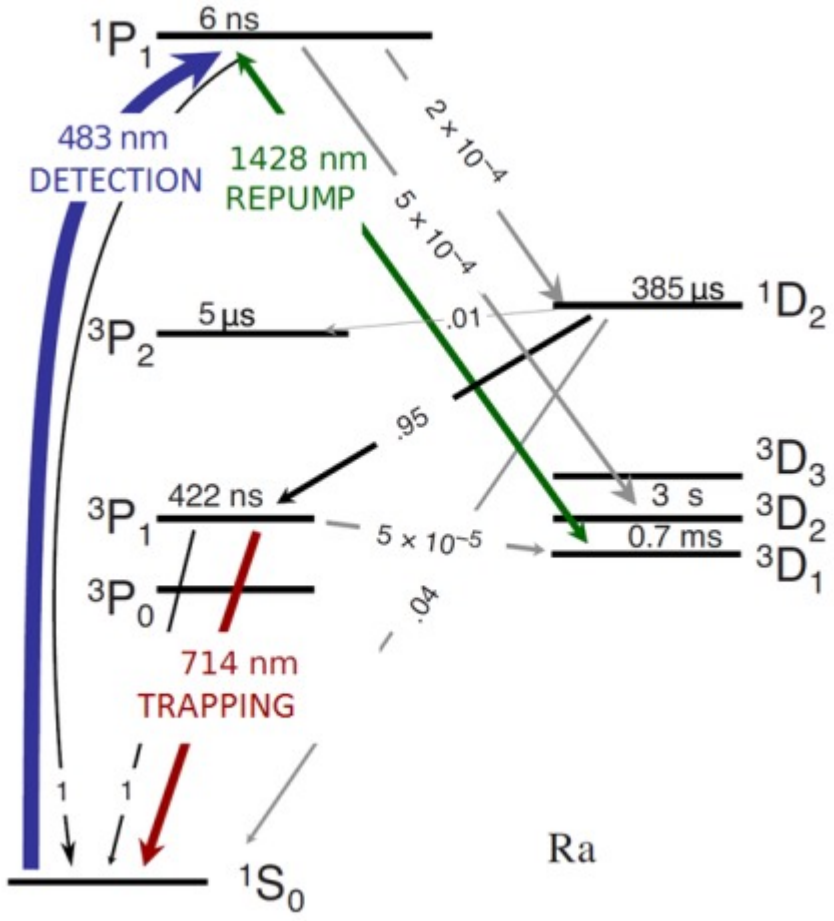
Adapted from T. Chupp and M. Ramsey-Musolf, PRC 91, 035502 (2015)

At that level, radium will improve significantly on the global sensitivity for all parameters

Blue Slower Scheme



Radium Atomic Structure



- Doppler Temperature: 7 uK
- I=1/2
- Blackbody Repump