Improved Limit on the ^{225}Ra Electric Dipole Moment

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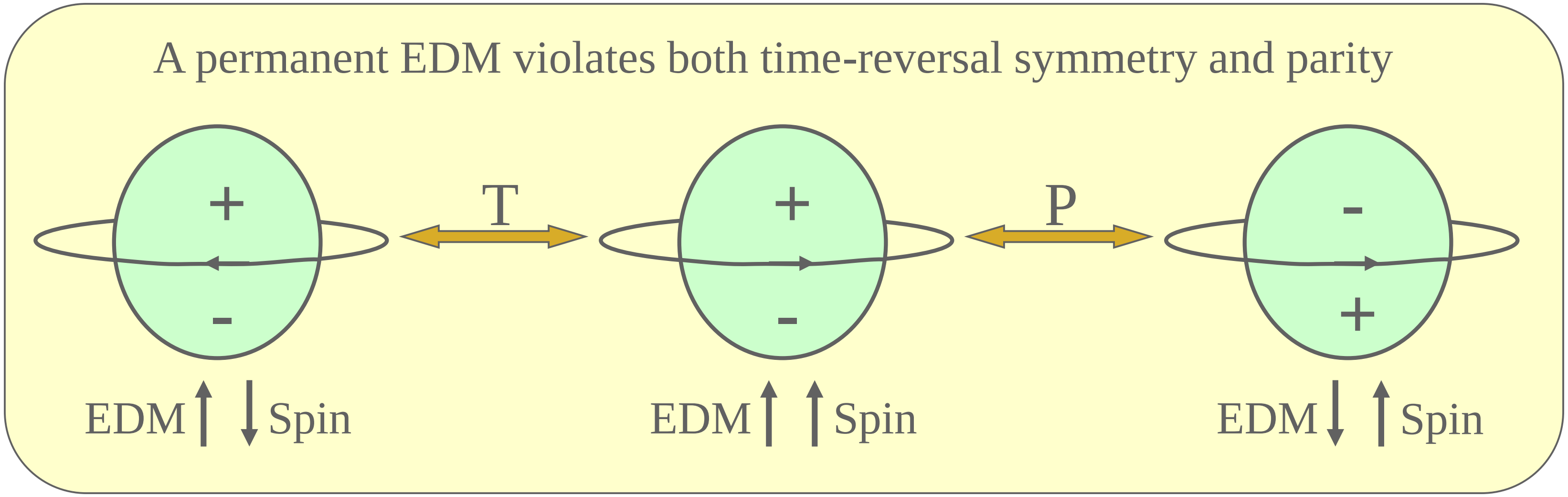
Electric Dipole Moment (EDM) Violates Both P and T



Sector	Exp Limit (e-cm)	Location	Method	Standard Model
Electron	9×10^{-29}	Harvard (ACME)	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}

More CP-Violation Mechanisms?

Matter-antimatter asymmetry

Require additional CP-violation mechanism(s)

Supersymmetry

More particles → More CP-violating phases

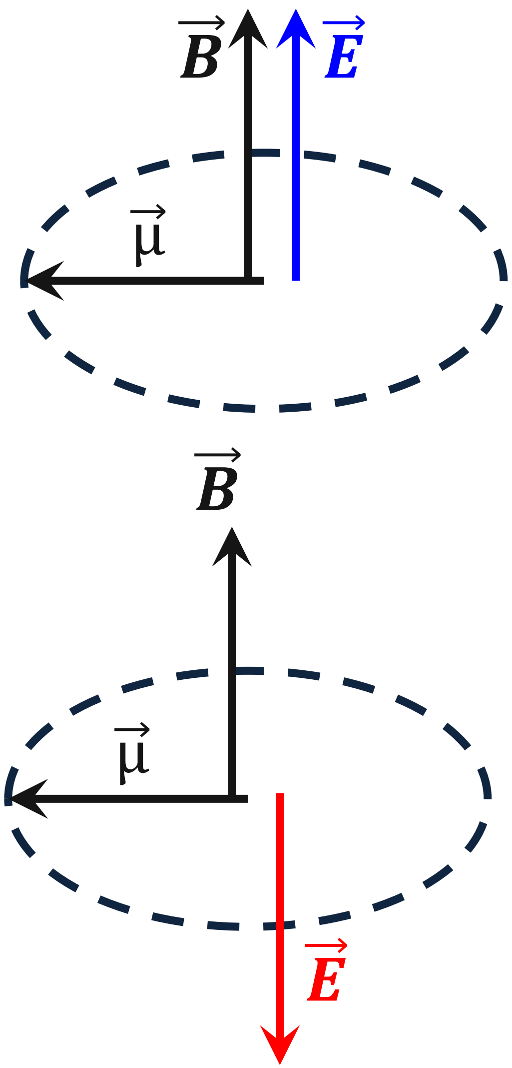
Strong CP problem

CP-violating phase in Quantum Chromodynamics

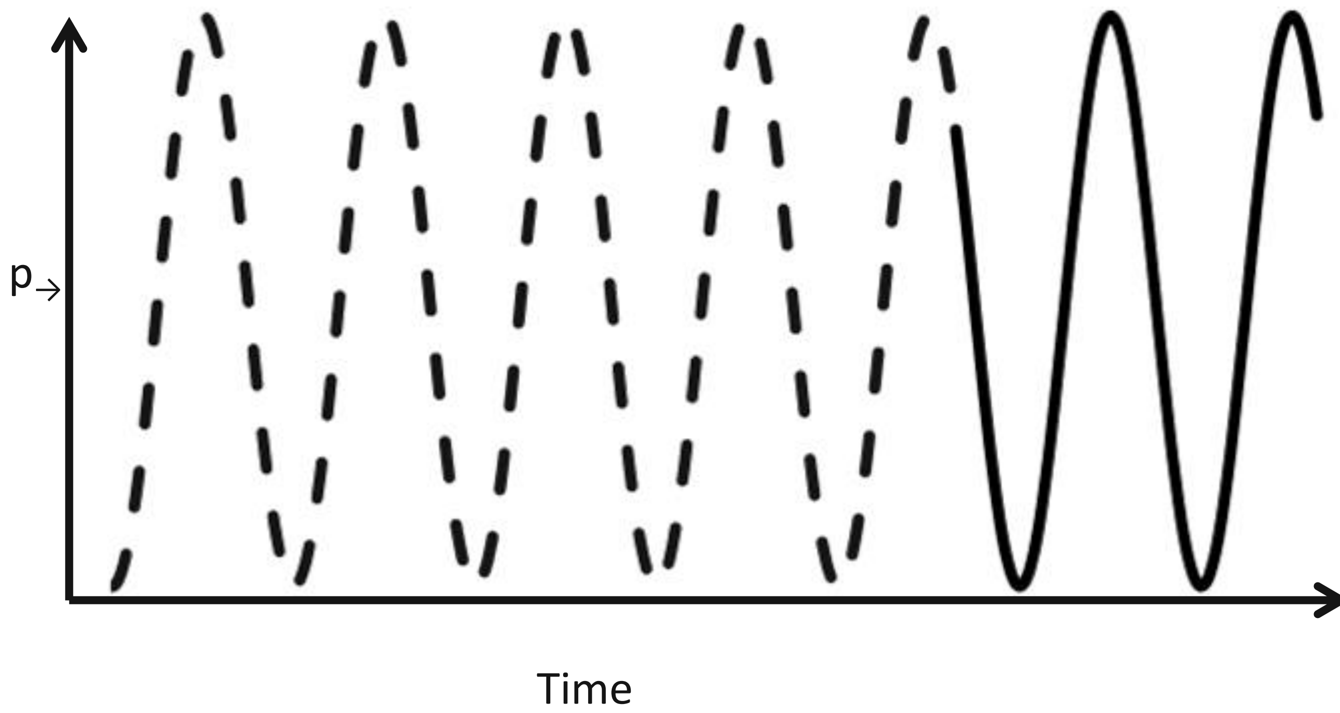
$$\mathcal{L}_{\mathrm{mass}} \rightarrow -m(\bar{\psi}_{\mathrm{L}}\psi_{\mathrm{R}} + \bar{\psi}_{\mathrm{R}}\psi_{\mathrm{L}}) + \frac{\theta g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

Fortson, Sandars, Barr, Physics Today (June 2003)

EDM measurement principle

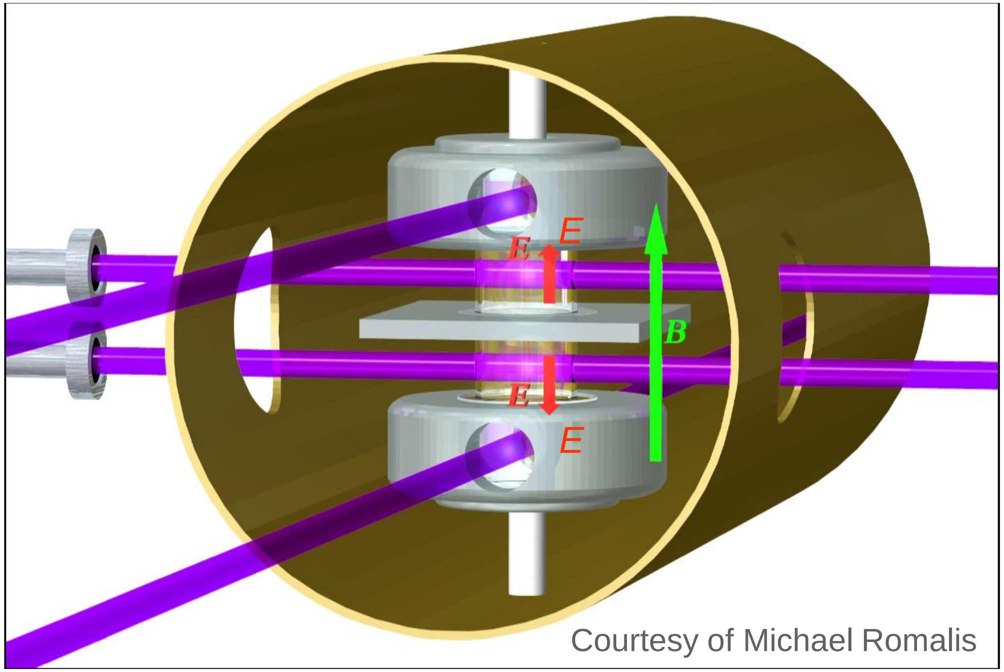


$$h\nu = 2\mu B$$



The Seattle EDM Measurement

^{199}Hg stable, high Z, J = 0, I = ½, high vapor pressure



$$f_+ = \frac{2\mu B + 2dE}{h} \approx 15 \text{ Hz}$$

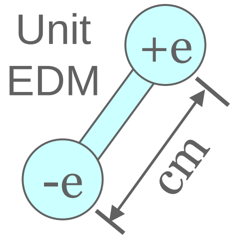
$$f_- = \frac{2\mu B - 2dE}{h} \approx 15 \text{ Hz}$$

$$|f_+ - f_-| < 0.2 \text{ nHz}$$

The best limit on atomic EDM

EDM (^{199}Hg) < 7.4 x 10^{-30} e-cm

Graner *et al*., Phys Rev Lett (2016)

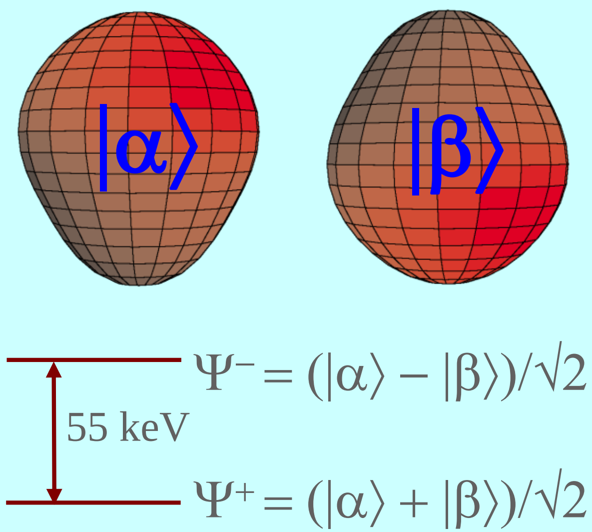


EDM of ^{225}Ra enhanced

^{225}Ra:
I = ½
$t_{1/2}$ = 15 d

- Closely spaced parity doublet – *Haxton & Henley (1983)*
- Large intrinsic Schiff moment due to octupole deformation
  – Auerbach, Flambaum & Spevak (1996)
- Relativistic atomic structure (^{225}Ra / ^{199}Hg ~ 3)
  – Dzuba, Flambaum, Ginges, Kozlov (2002)

Parity doublet



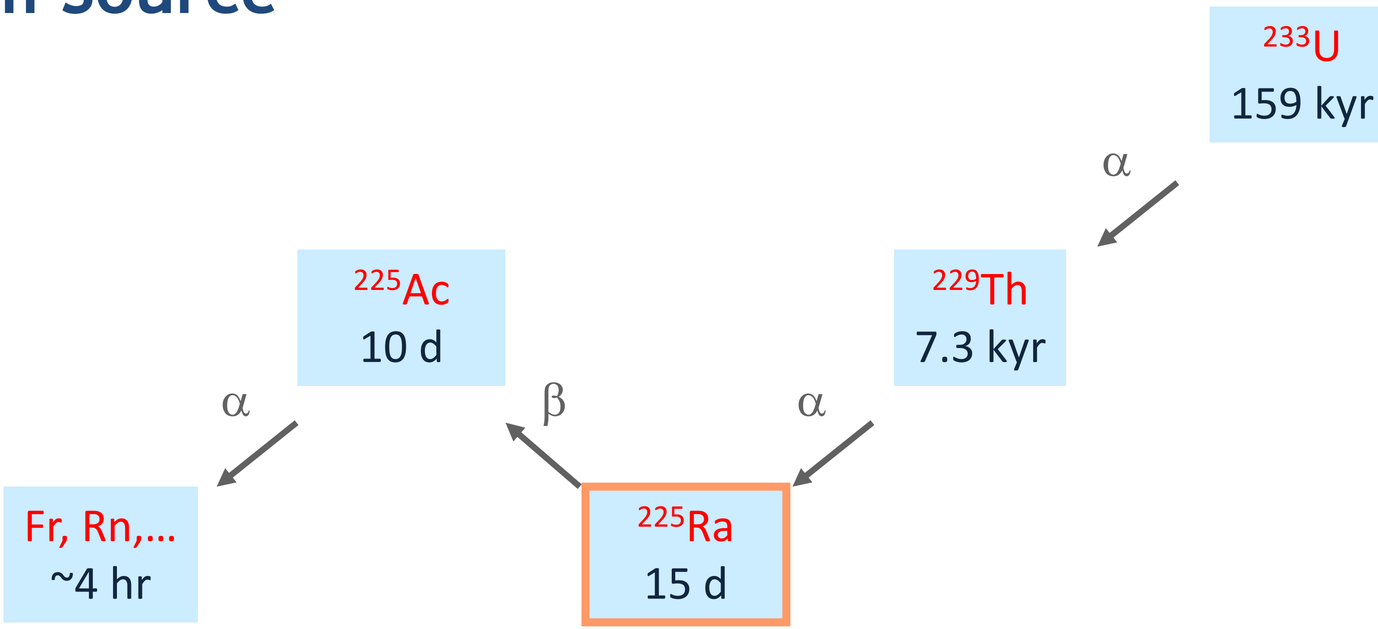
$$S \equiv \langle \psi_0 | \hat{S}_z | \psi_0 \rangle = \sum_{i \neq 0} \frac{\langle \psi_0 | \hat{S}_z | \psi_i \rangle \langle \psi_i | \hat{H}_{PT} | \psi_0 \rangle}{E_0 - E_i} + c.c.$$

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

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

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

Radium Source

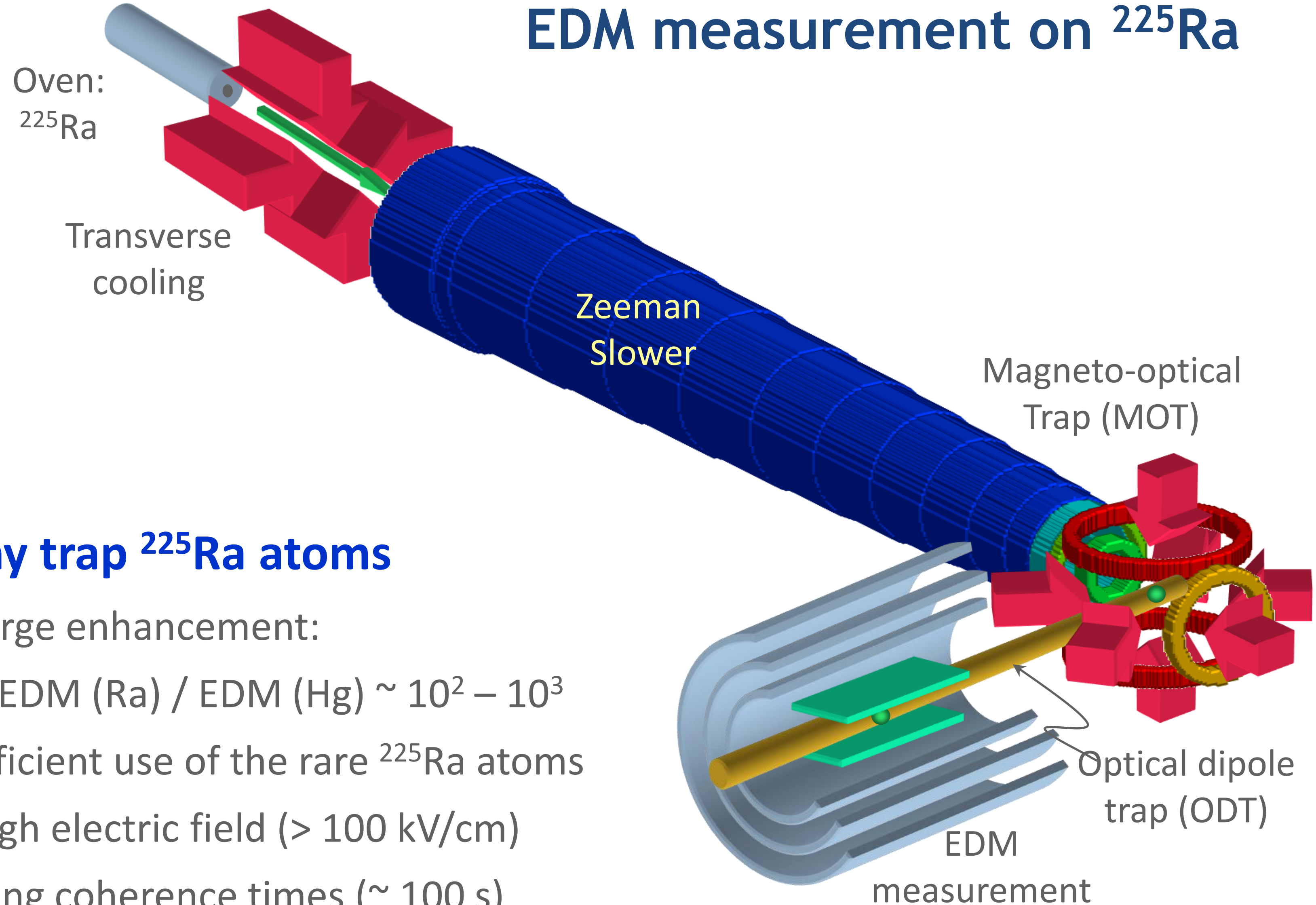


- Up to 10 mCi (750 ng, 2*10^15 atoms) ^{225}Ra sources from:

  National Isotope Development Center (Oak Ridge, TN)

- Test source: 5 μCi (5 μg, 1.3*10^16 atoms) ^{226}Ra
- Atomic Beam Flux ~ 10^9/s ^{226}Ra, 10^7 – 10^8/s ^{225}Ra

EDM measurement on ^{225}Ra



Why trap ^{225}Ra atoms

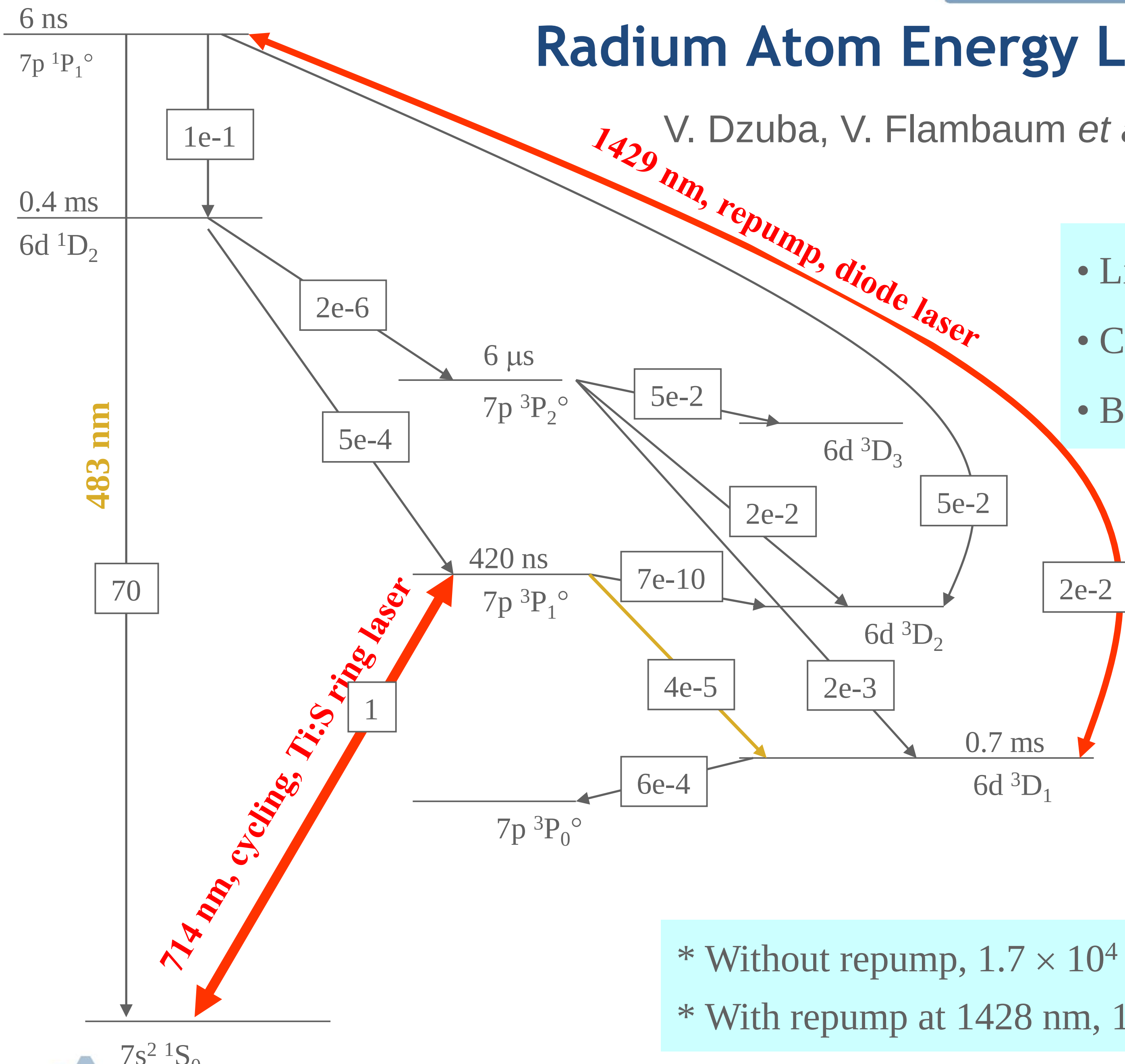
- Large enhancement:

  EDM (Ra) / EDM (Hg) ~ $10^2 – 10^3$

- Efficient use of the rare ^{225}Ra atoms
- High electric field (> 100 kV/cm)
- Long coherence times (~ 100 s)
- Negligible "v x E" systematic effect

Radium Atom Energy Level Diagram

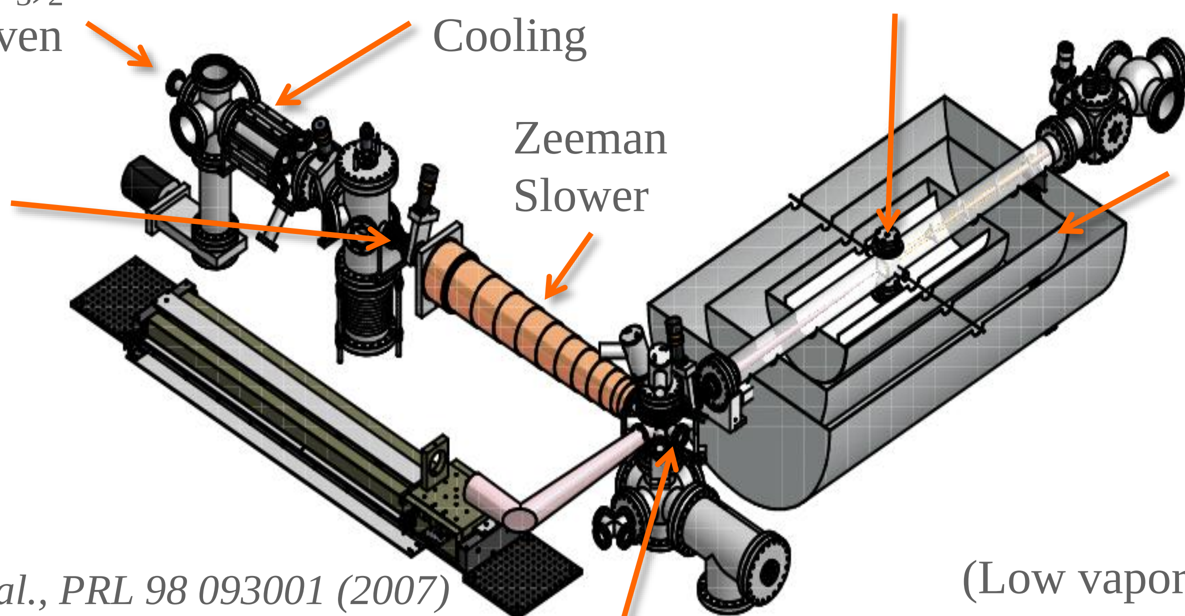
V. Dzuba, V. Flambaum *et al.*, PRA 61 (2000)



- Linewidth ~ 400 kHz
- Cooling 7 μK, 14 mm/s
- B gradient ~ 1 G / cm

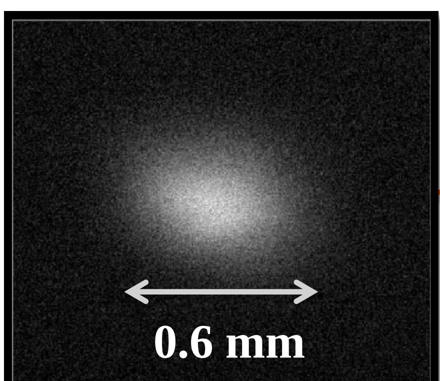
* Without repump, 1.7×10^4 cycles.
* With repump at 1428 nm, 1.7×10^7 cycles.

Collect Atoms in MOT



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

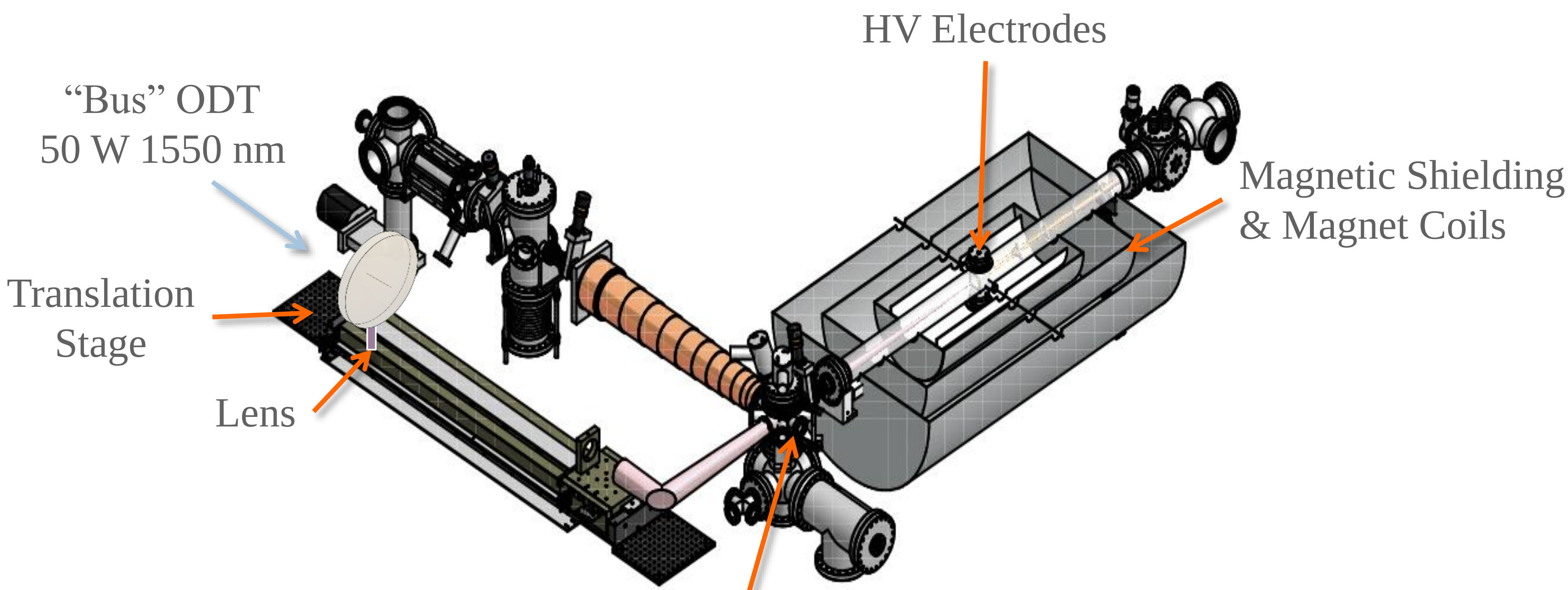
(Low vapor pressure)

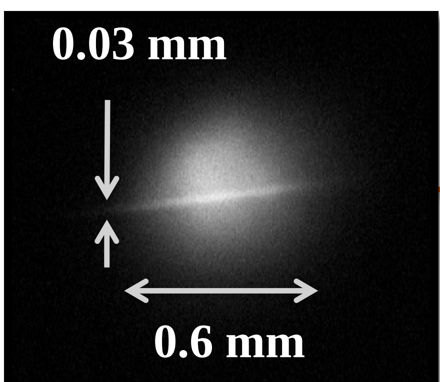


^{226}Ra MOT

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
Activity = 3mCi	Activity = 2uCi
MOT = 2500 atoms	MOT = 70000 atoms

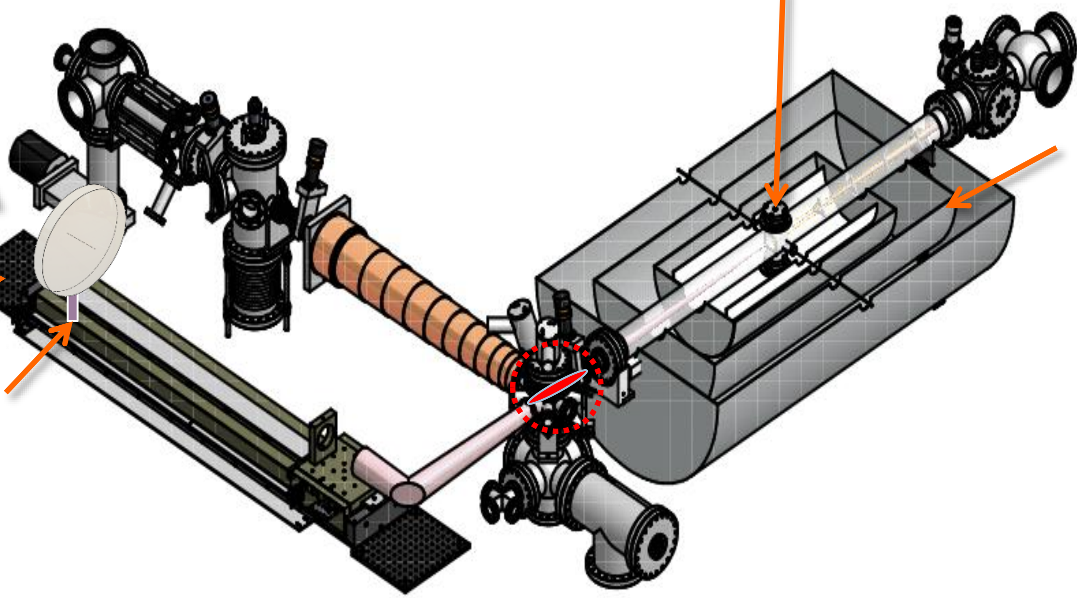
Transfer Atoms from MOT to “Bus” ODT

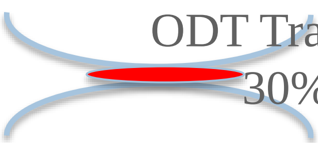


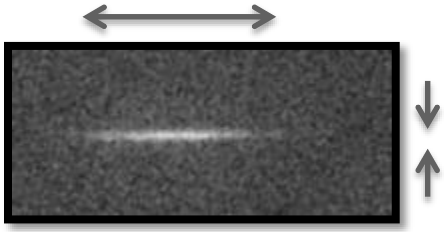


MOT + ODT
80% Efficiency

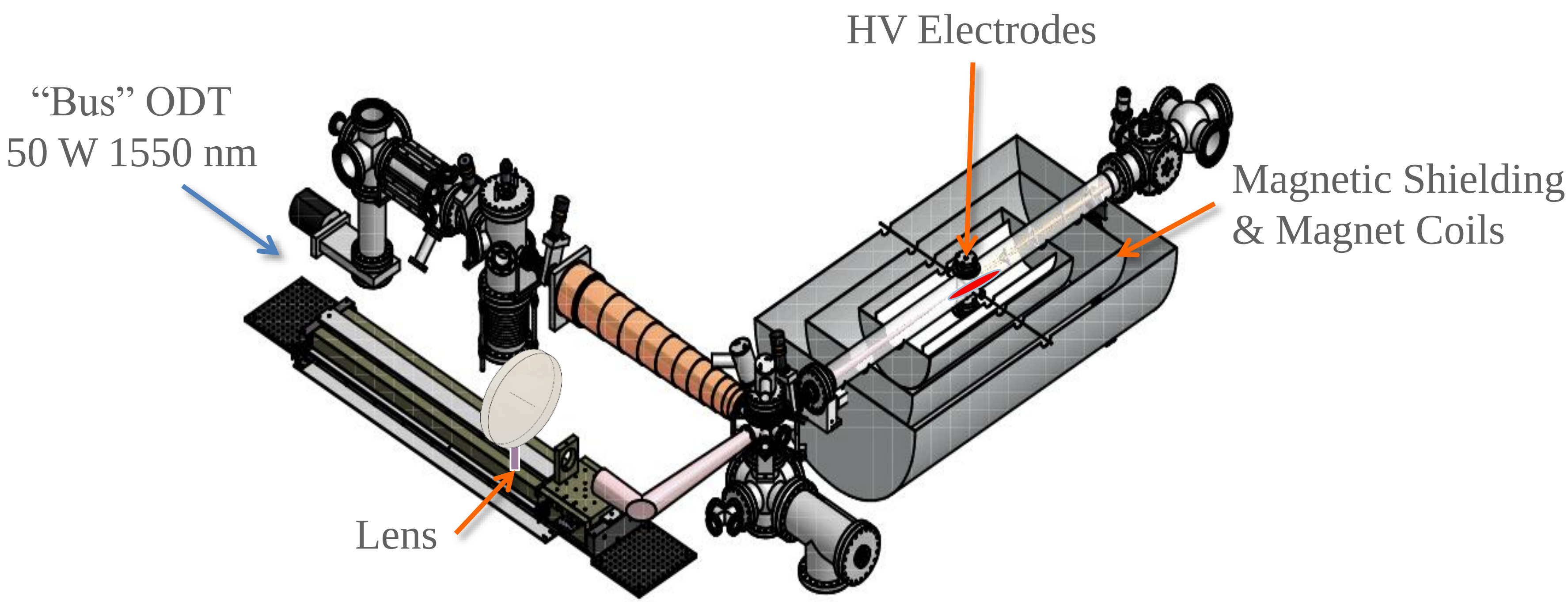
"Bus" ODT Atom Transport to Science Chamber



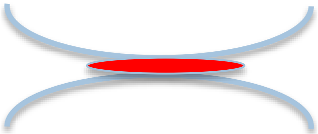




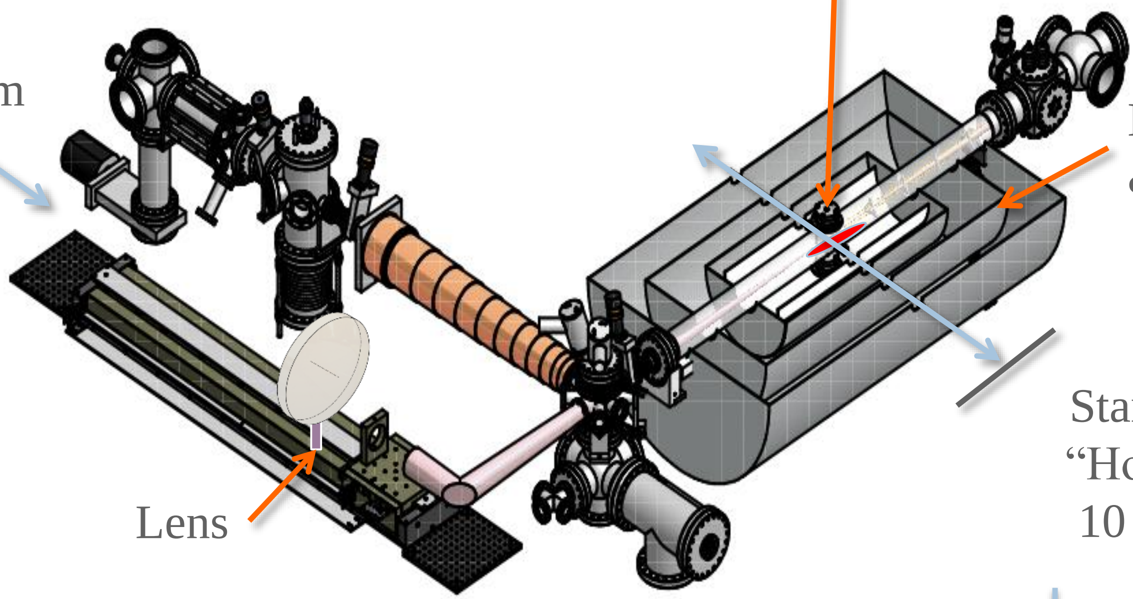
Transfer Atoms from “Bus” to “Holding” ODT

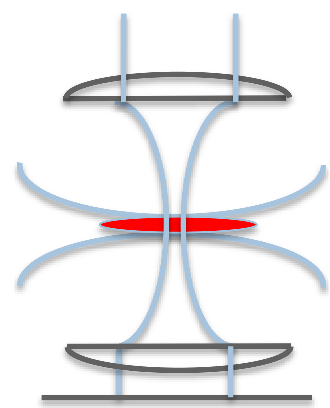


Traveling Wave
“Bus” ODT

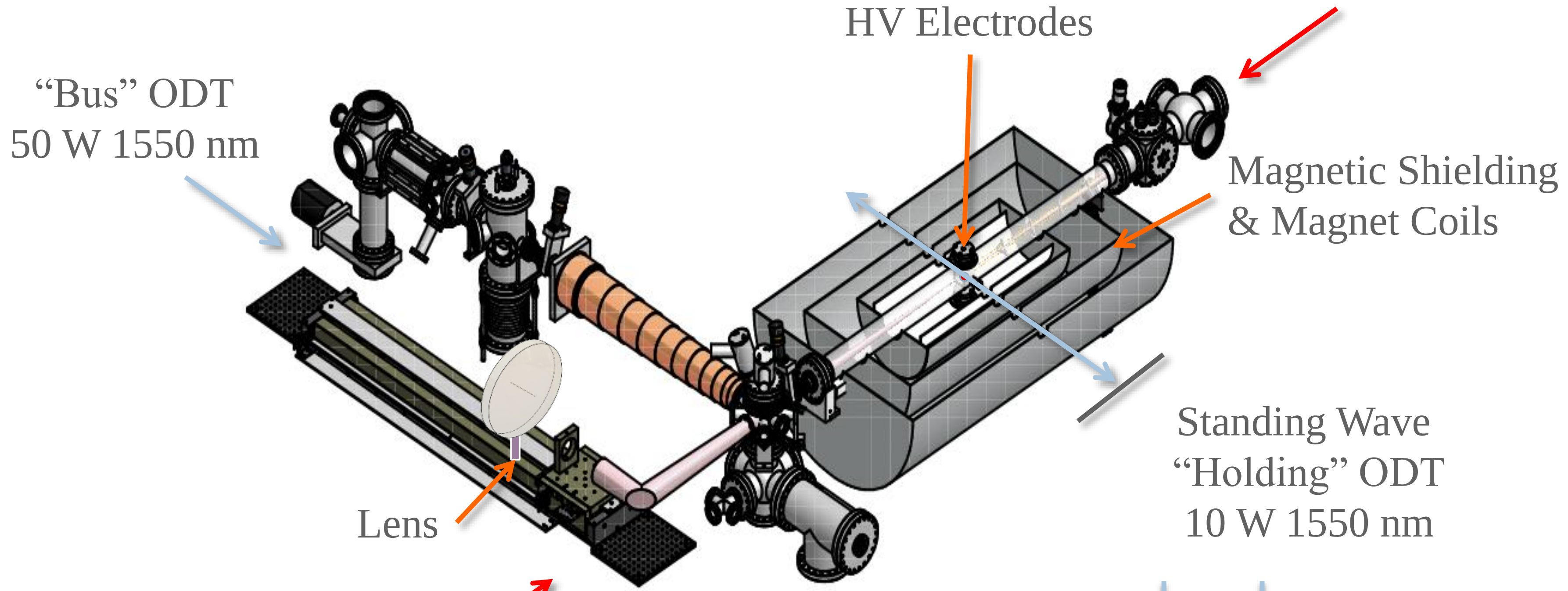


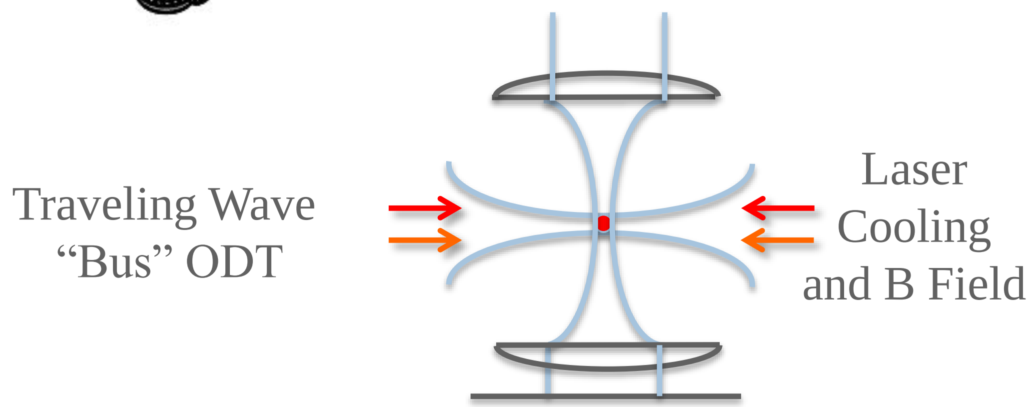
Transfer Atoms from “Bus” to “Holding” ODT



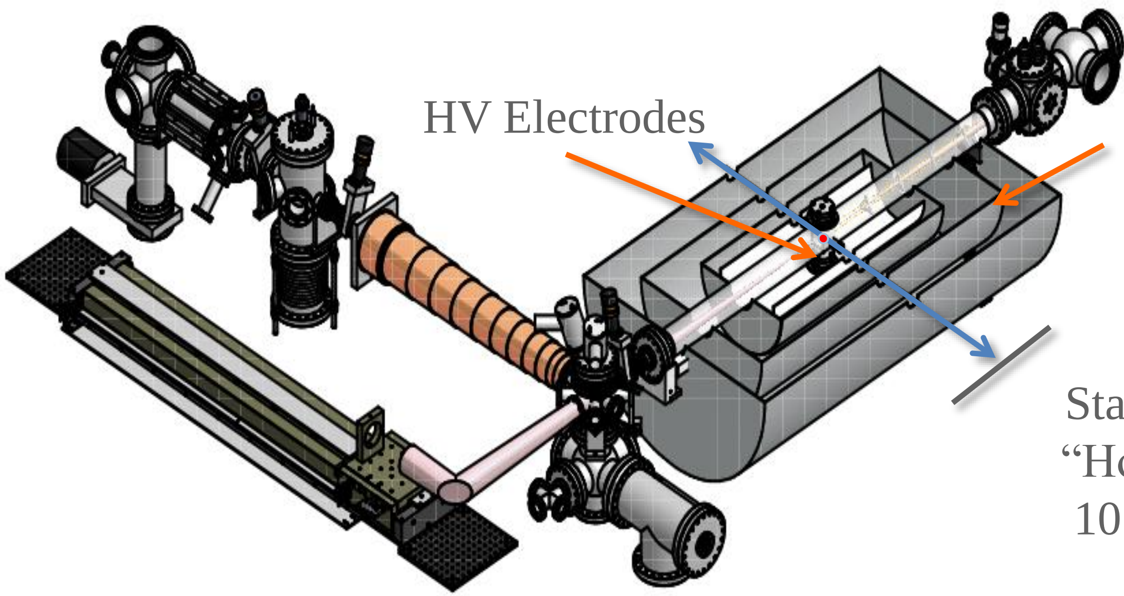


Transfer Atoms from “Bus” to “Holding” ODT



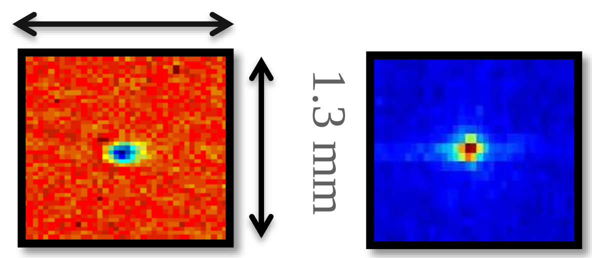


Transfer Atoms from “Bus” to “Holding” ODT

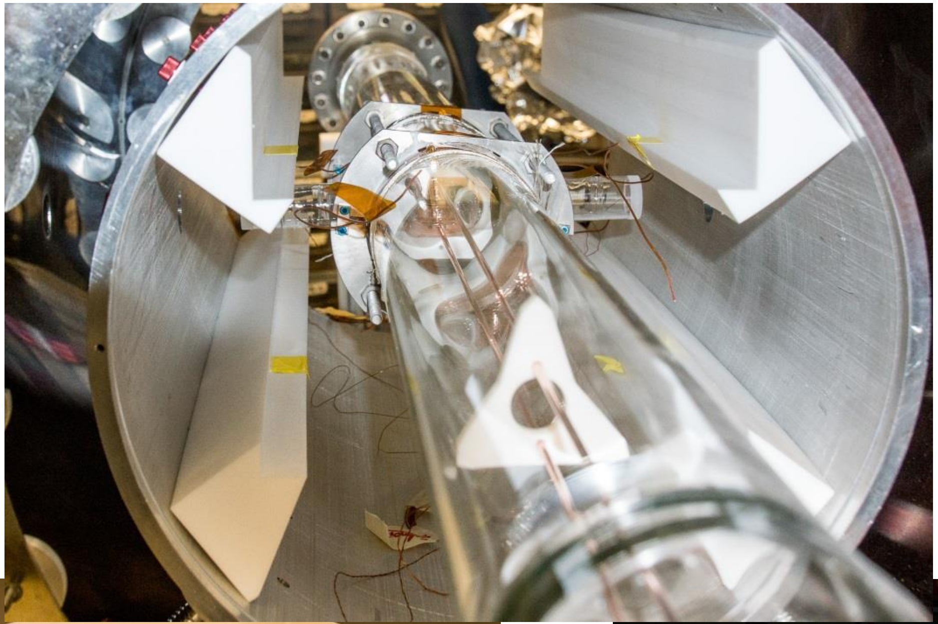


ODT→ODT Transfer: 70% Efficiency

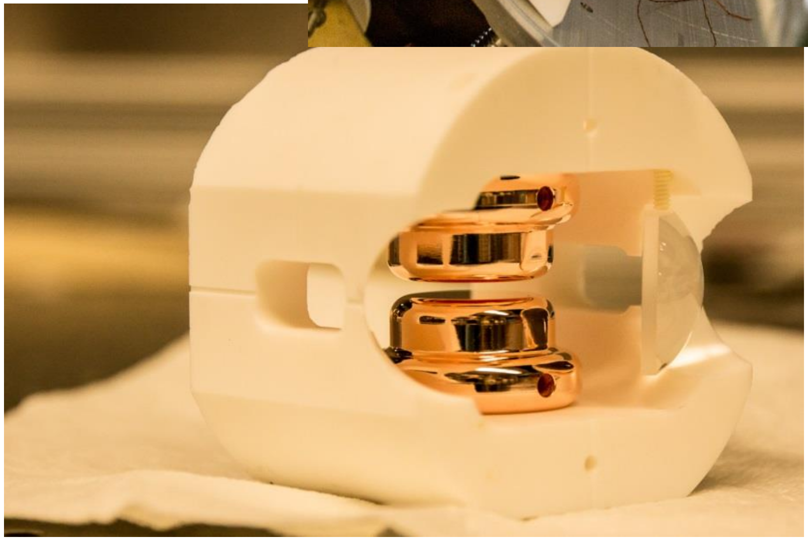
R. H. Parker *et al.*, PRC **86**, 065503 (2012)



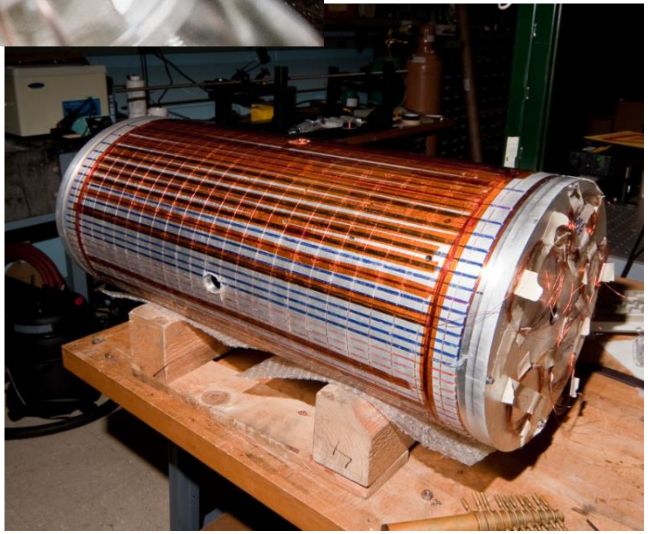
Application of Fields



~ 1 x 10^{-11} Torr

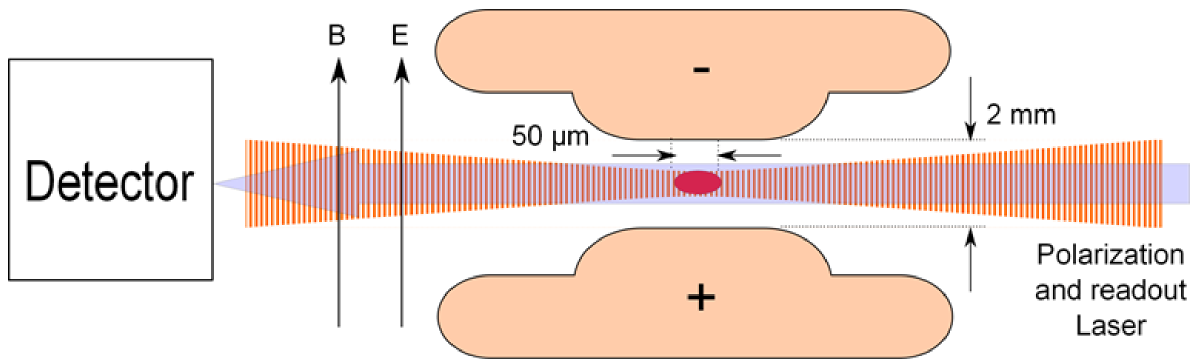


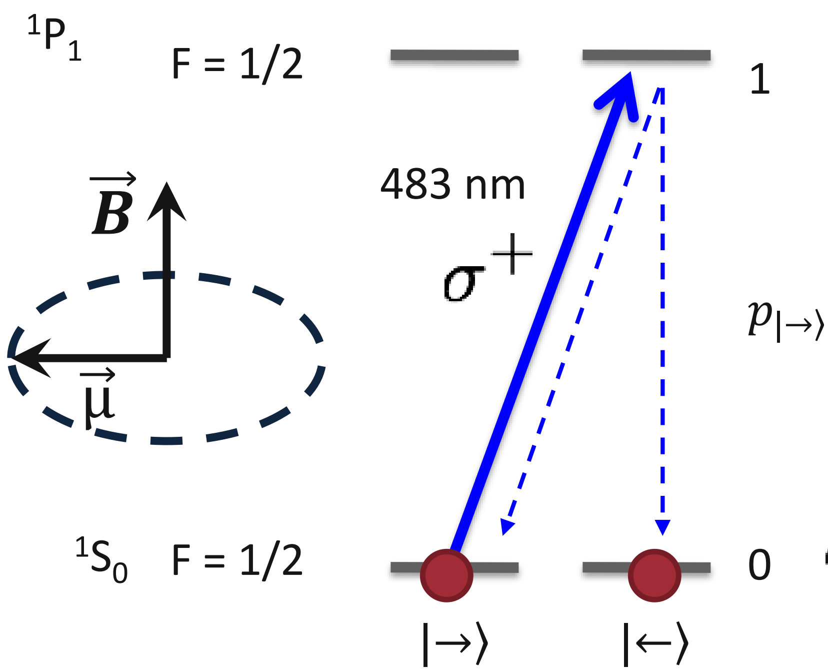
Max = 75 kV/cm



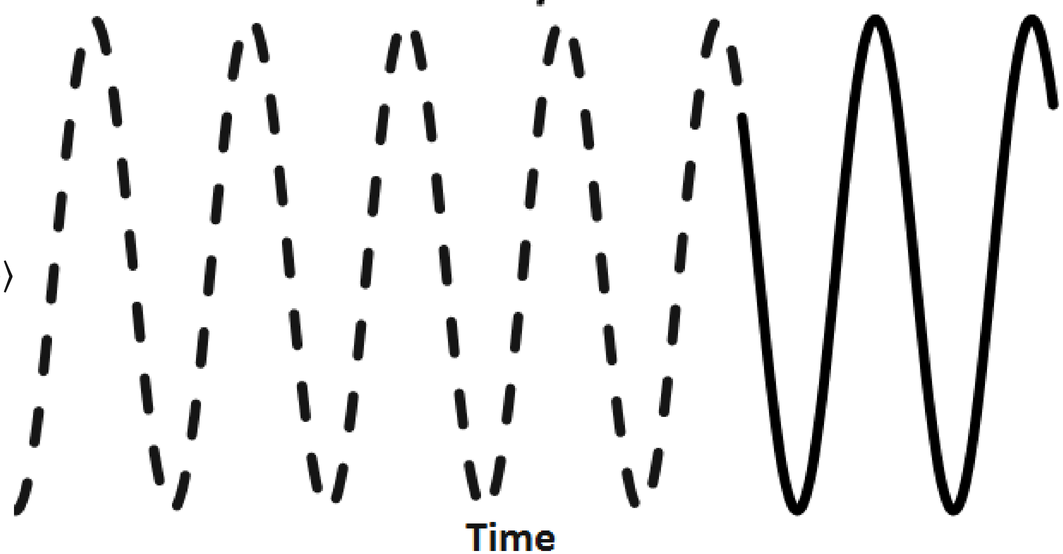
B gradient < 10 μG/cm

EDM Measurement Principle

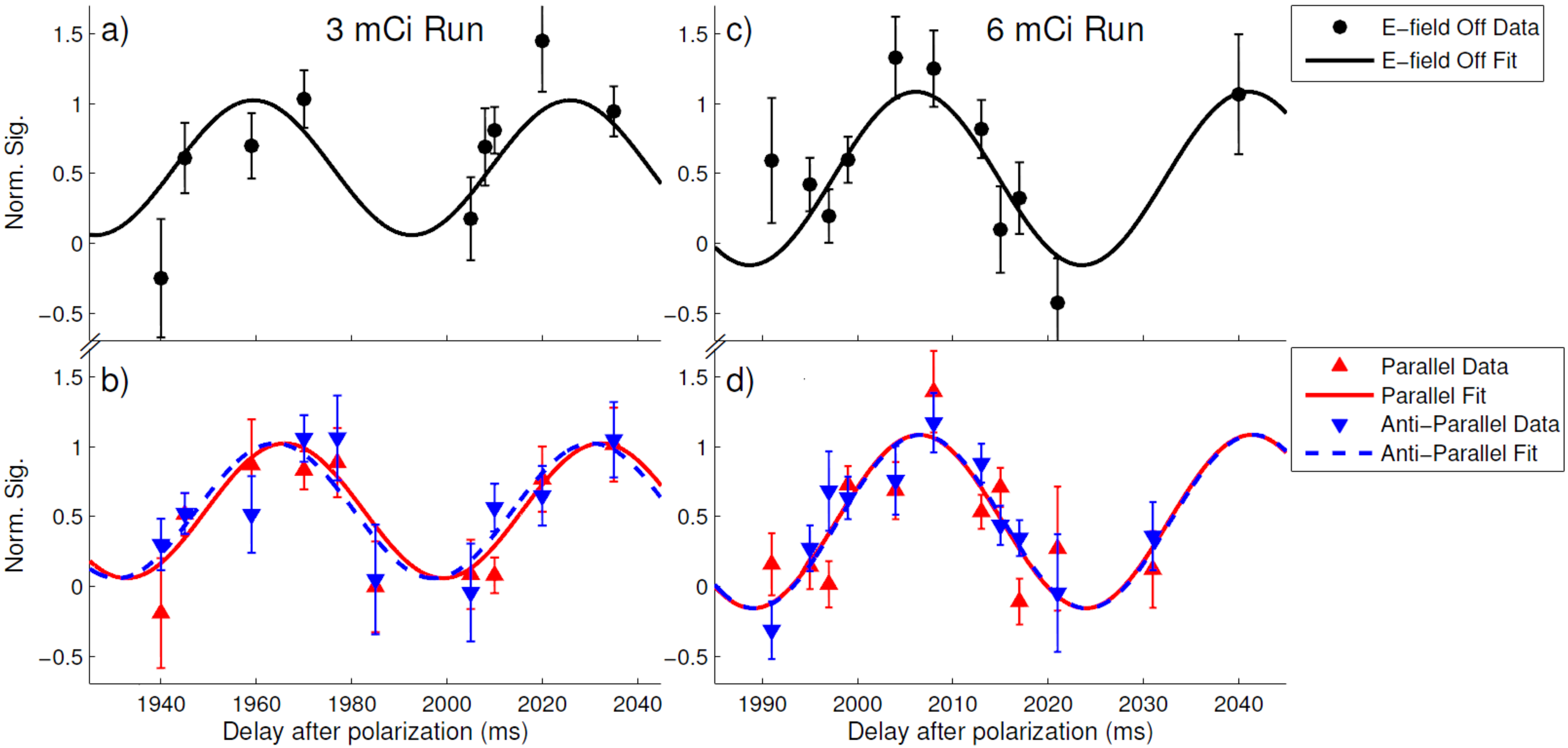




$$h\nu_{\pm} = 2\mu B \pm 2dE$$



First Ra-225 EDM limit



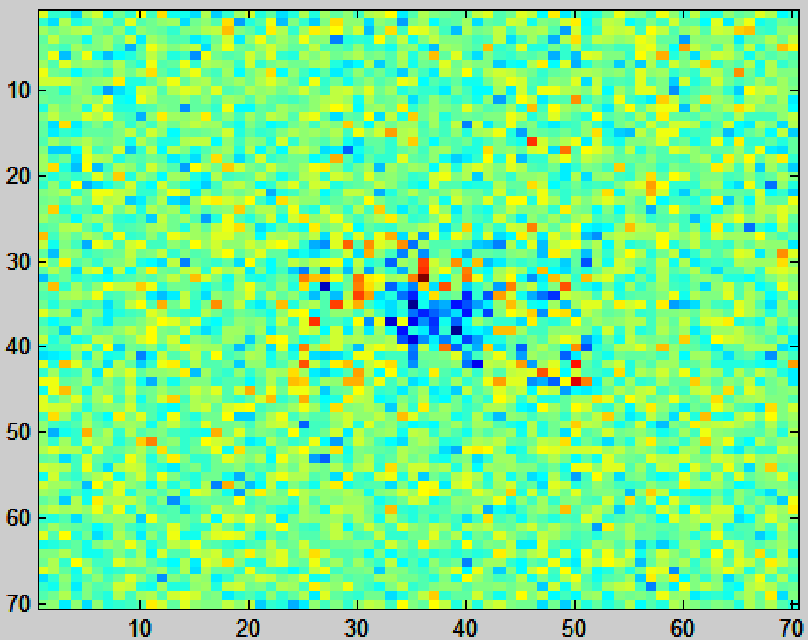
$$d_{Ra\text{-}225} = (-0.5 \pm 2.5_{stat} \pm 0.2_{syst}) \times 10^{-22}\ e\text{-cm}$$

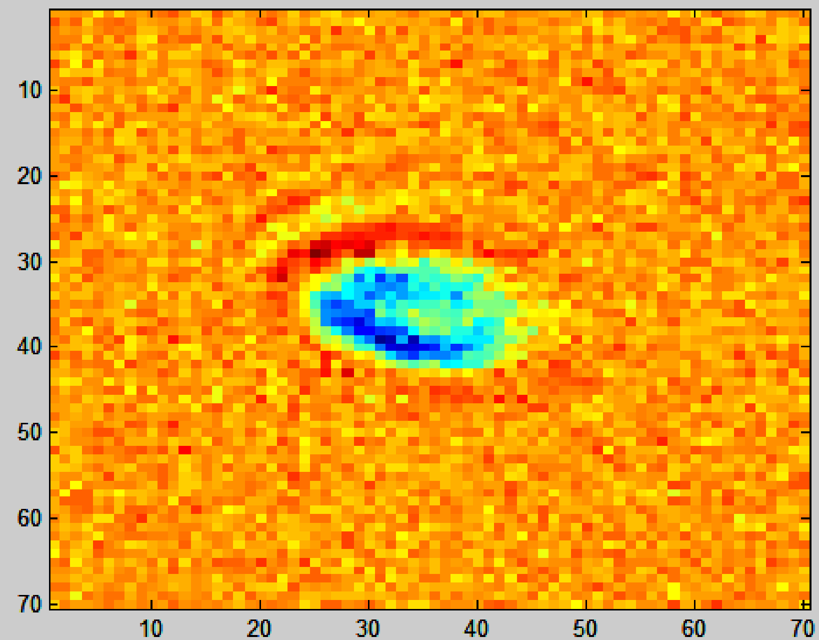
5.0×10^{-22} e-cm 95% confidence upper limit

R. Parker *et al., PRL* ***114**, 233002 (2015)*

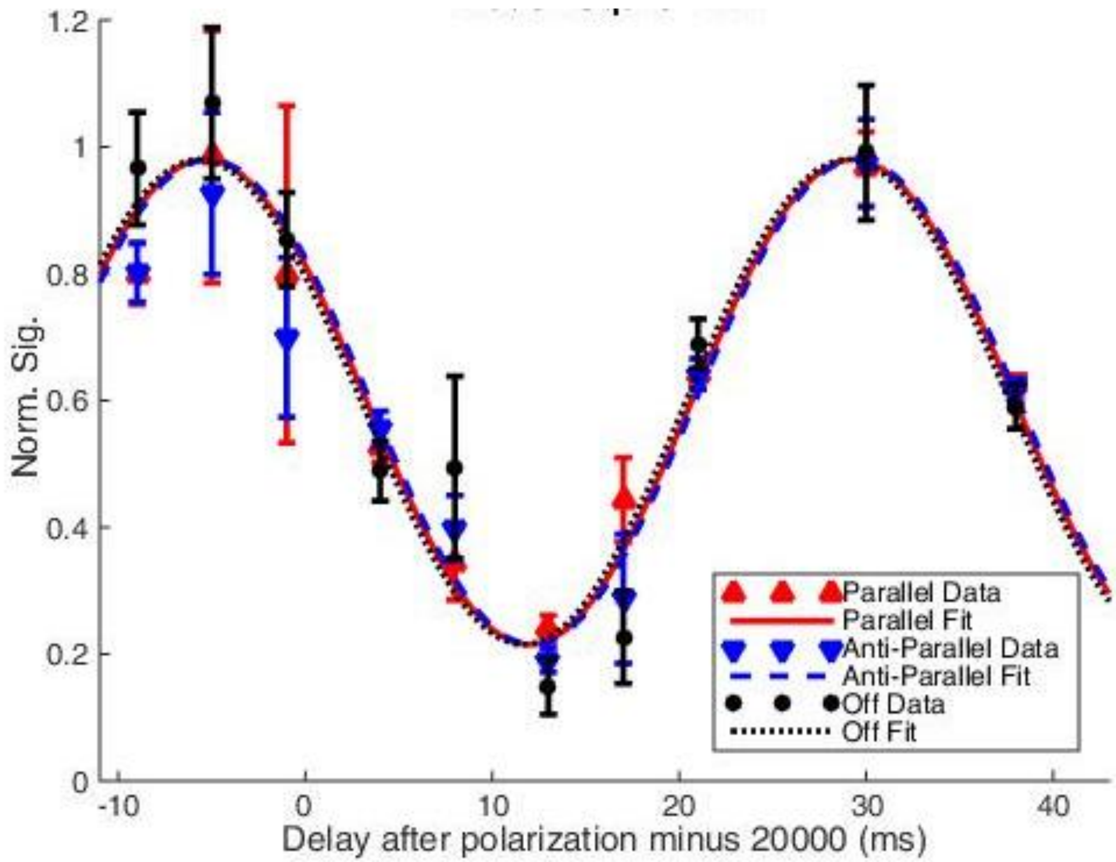
“Casimir” Run - Improvements

October + December 2014		June 2015
~150 Atoms	→	~600 Atoms
2 s precession time	→	20 s precession time
E-field on for 1.2 s	→	E-field on for 19.2 s





Improved Ra-225 EDM limit



1.4×10^{-23} e-cm 95% confidence upper limit

EDM limit improved by factor of 36

M. Bishof *et al.* (Phys. Rev. C **94**, 025501)

Systematic Effects & Projections

Effect	Current Uncert.	α Scen. Uncert.	β Scen. Uncert.
E-squared effects	1×10^{-25}	7×10^{-29}	7×10^{-31} [a]
B-field correlations	1×10^{-25}	5×10^{-27}	3×10^{-29} [a]
Holding ODT power Correlations	6×10^{-26}	9×10^{-30}	9×10^{-32} [a]
Stark Interference	6×10^{-26}	2×10^{-27}	3×10^{-29} [a]
Blue laser power correlations	7×10^{-28}	1×10^{-31}	1×10^{-31}
Blue laser freq. correlations	4×10^{-28}	8×10^{-30}	8×10^{-30}
E x v effects	4×10^{-28}	7×10^{-30}	N/A
Leakage current	3×10^{-28}	9×10^{-29}	N/A
E-field Ramping	9×10^{-28}	2×10^{-29}	N/A
Geometric phase	3×10^{-31}	7×10^{-30}	5×10^{-33}
Total	2×10^{-25}	5×10^{-27}	4×10^{-29} [a]

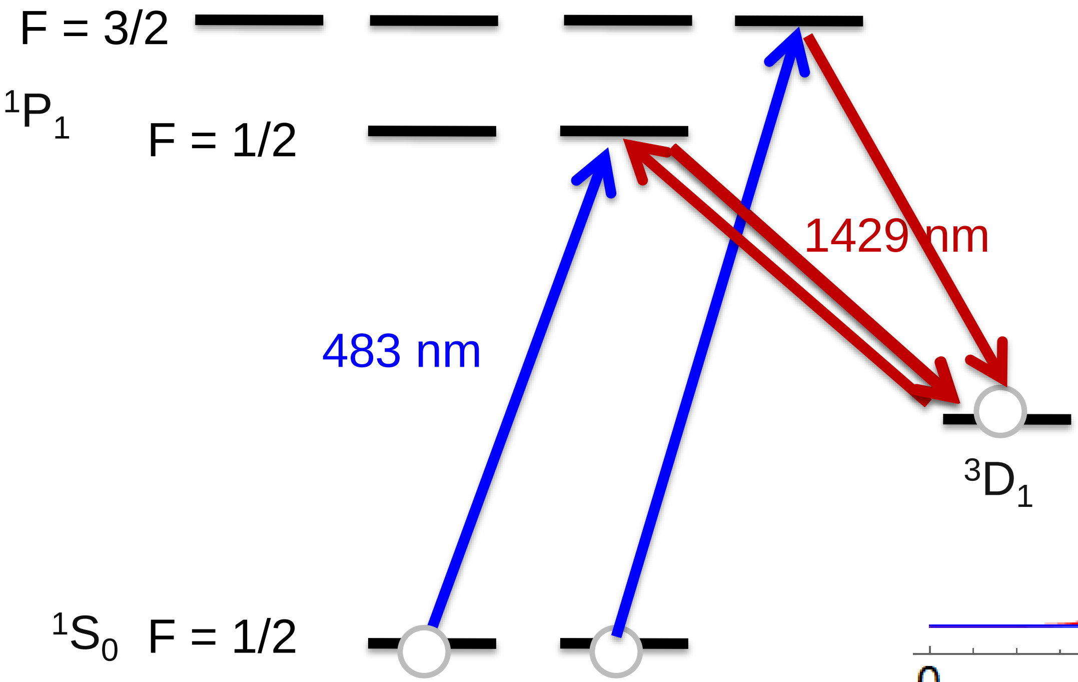
[a] This uncertainty will improve with the statistical sensitivity of the experiment

see M. Bishof *et al.*, PRC **94**, 025501
and Romalis and Fortson, PRA 59(6) 4547 (1999)

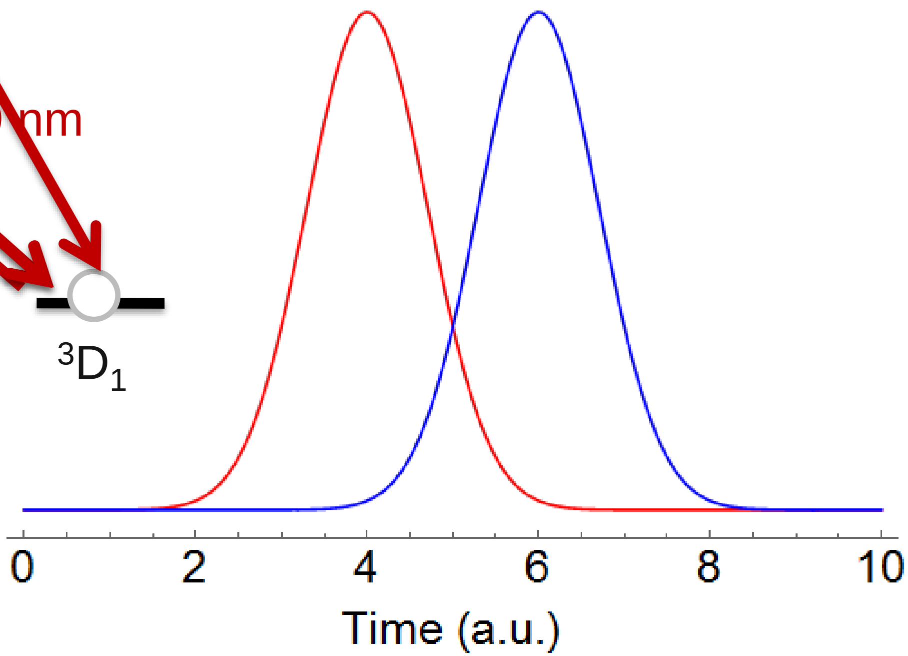
Short term: **< 5×10^{-27} e cm**

Long term: **< 4×10^{-29} e cm**

Room for Improvement: Detection with Electron Shelving



γ_{atom} increases from 2.5 to 1000

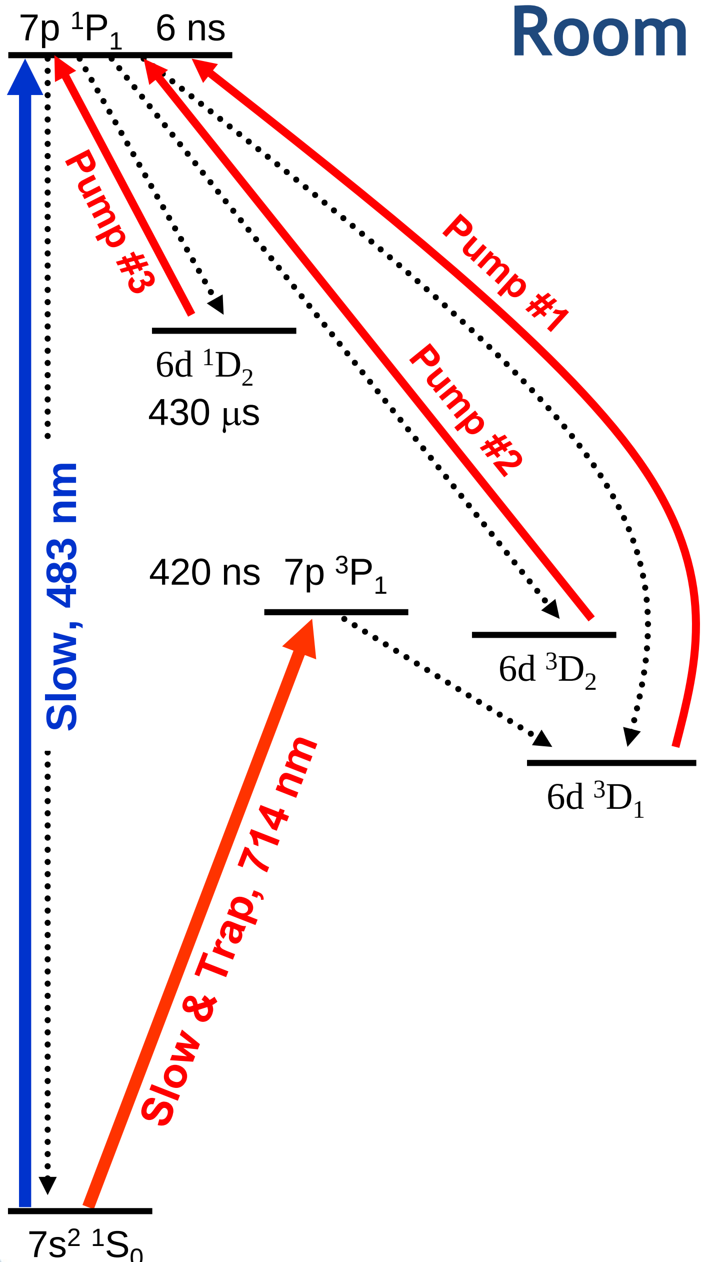


Stat. Sensitivity Near Term Goal

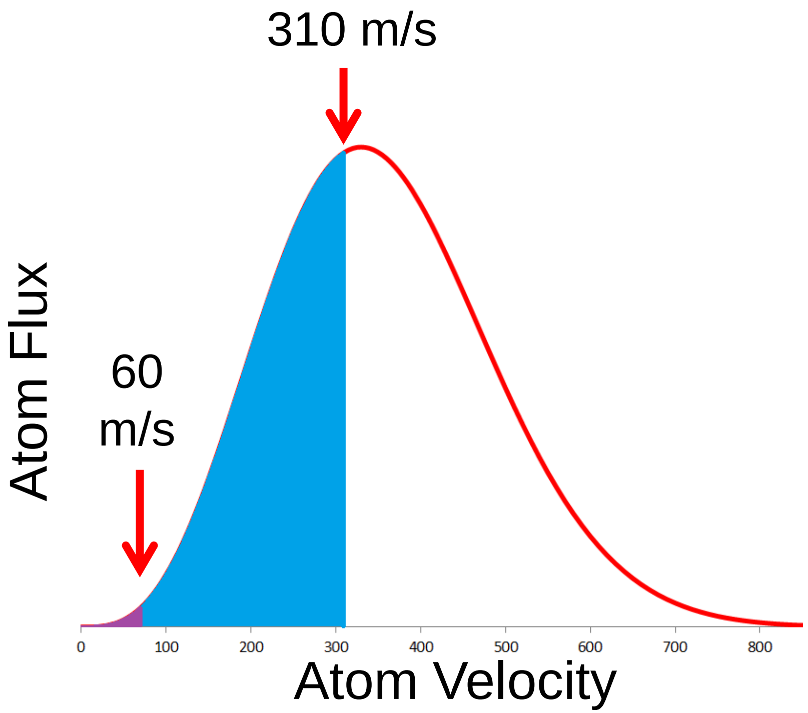
$$\Delta d = \frac{\hbar\sqrt{2}}{2E\tau} \times \sqrt{\frac{5\gamma_{laser}}{4\gamma_{atom}^2 N^2} + \frac{1}{4N}} \times \sqrt{\frac{2*(\tau+T_d)}{T}}$$

	Currently	Near Term Goal
N: # atoms detected	600	600
E: Effective E-field (kV/cm)	75	75
τ: Precession Time (s)	20	20
T_d: Dead time (s)	48	48
T: Total time (s)	**2** × 86,400	**5** × 86,400
γ_{atom}: Photons per atom	**2.5**	**1,000**
γ_{laser}: Photons per laser pulse	**10^6**	**4×10^8**
EDM sens. (e-cm)	**1×10^{-23}**	**2×10^{-25}**

Room for Improvement: Blue Upgrade

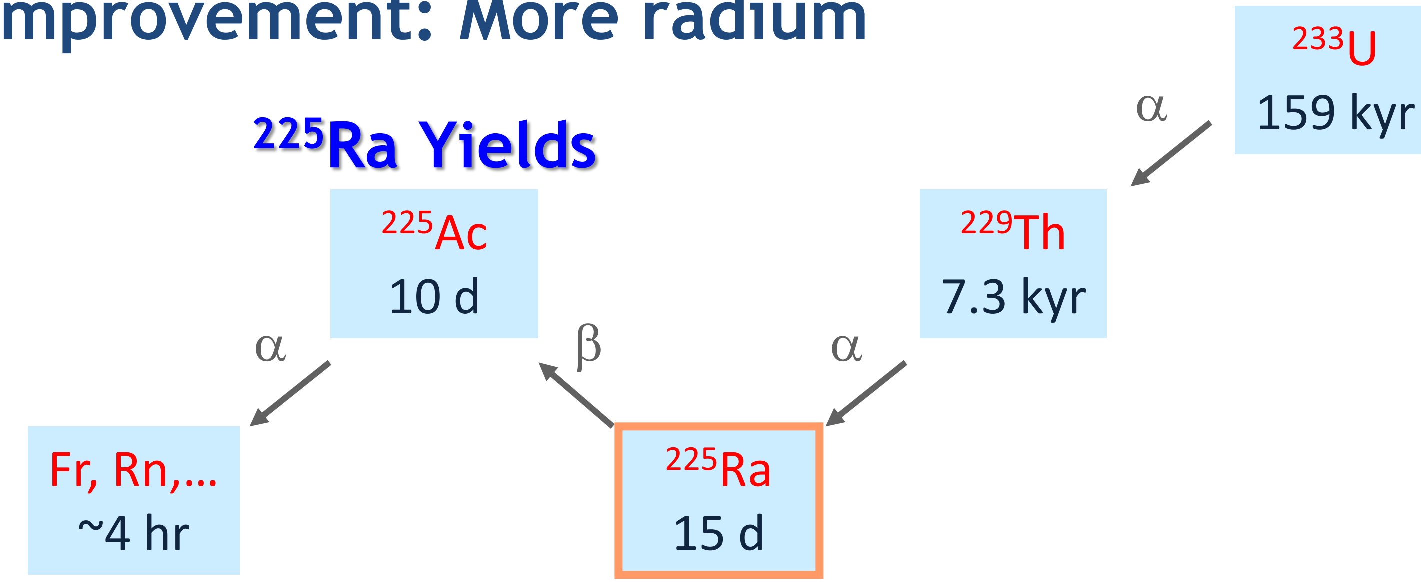


100x increase in N



Room for Improvement: More radium

^{225}Ra Yields



Presently available

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

Projected

- FRIB (B. Sherrill, MSU)
  - Beam dump recovery with a ^{238}U beam -------------------- 6×10^9 /s
  - Dedicated running with a ^{232}Th beam ---------------------- 5×10^{10} /s

- ISOL@FRIB (I.C. Gomes and J. Nolen, Argonne)
  - Deuterons on thorium target, 1 mA x 400 MeV = 400 kW 10^{13} /s

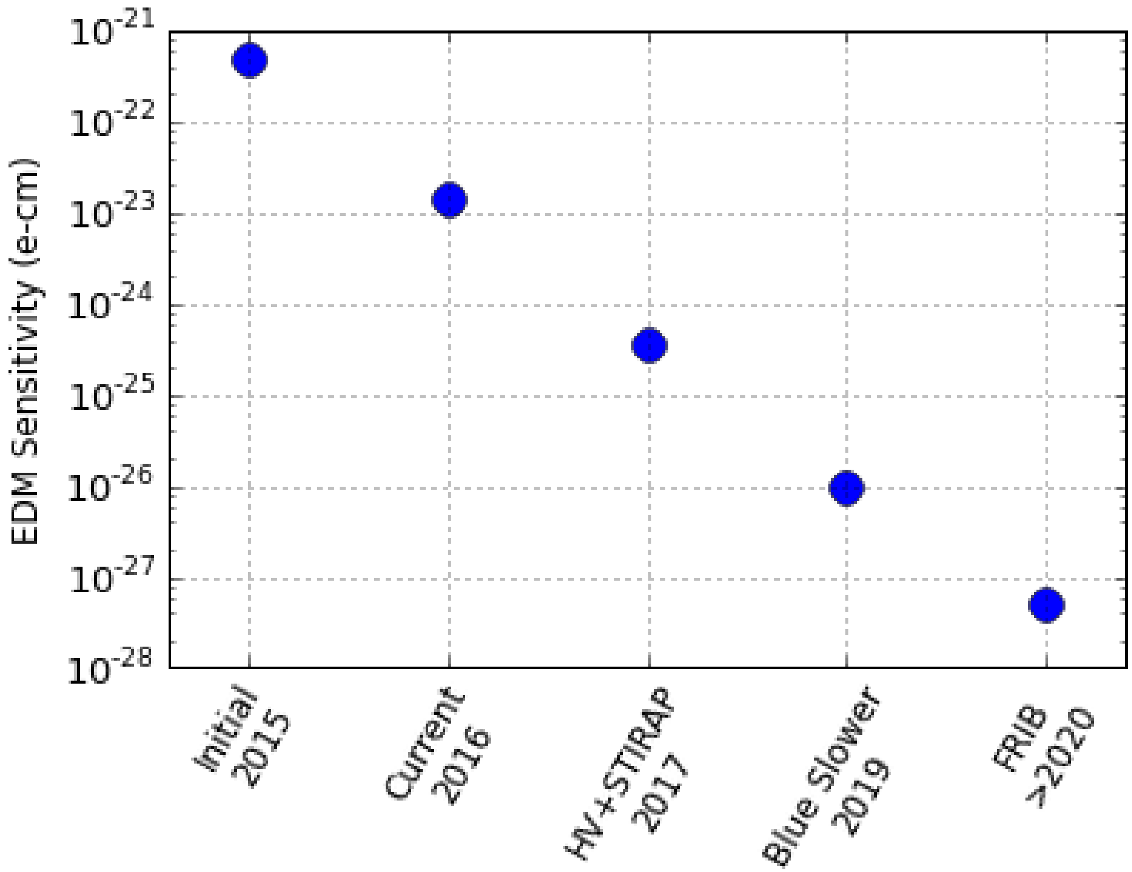
- MSU K1200 (R. Ronningen and J. Nolen, Argonne)
  - Deuterons on thorium target, 10 uA x 400 MeV = 4 kW 10^{11} /s

Stat. Sensitivity Longer Term

$$\Delta d = \frac{\hbar\sqrt{2}}{2E\tau} \times \sqrt{\frac{5\gamma_{laser}}{4\gamma_{atom}^{2}N^{2}} + \frac{1}{4N}} \times \sqrt{\frac{2*(\tau+T_d)}{T}}$$

	Currently	LongTerm Goal
N: # atoms detected	150	**5×10^{6}**
E: Effective E-field (kV/cm)	75	**150**
τ: Precession Time (s)	20	40
T_d: Dead time (s)	48	10
T: Total time (s)	$2 \times 86{,}400$	**60** $\times$ 86,400
γ_{atom}: Photons per atom	2.5	1,000
γ_{laser}: Photons per laser pulse	10^{6}	4×10^{8}
EDM sens. (e-cm)	**1×10^{-23}**	**1×10^{-28}**

Ra-225 EDM Sensitivity



The Radium Collaboration

Argonne: Kevin Bailey, Michael Bishof, Matt Dietrich, John Greene, Roy Holt, Peter Mueller, Richard Parker, Tom O'Connor
University of Kentucky: Mukut Kalita, Wolfgang Korsch
Michigan State University: Jaideep Singh, Steve Fromm, Tenzin Rabga, Roy Ready
USTC: Zheng-Tian Lu