SEARCHES FOR ATOMIC ELECTRIC DIPOLE MOMENTS

MATTHEW R. DIETRICH
Assistant Physicist
Argonne National Laboratory

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SAKHAROV'S CONDITIONS

- Baryon number violation
  – Protons, neutrons
- C- and CP-symmetry violation
  – CP implies T
- Interactions out of thermal equilibrium, or CPT violated

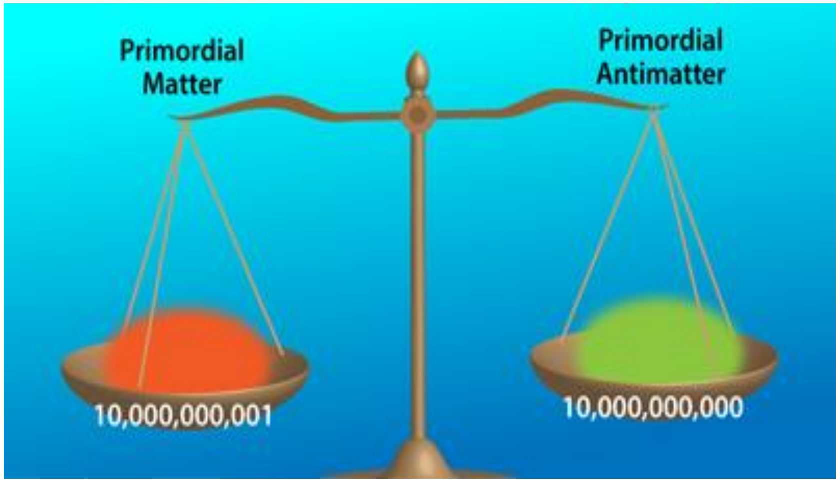

Image credit: APS/Alan Stonebraker

Andrei Sakharov

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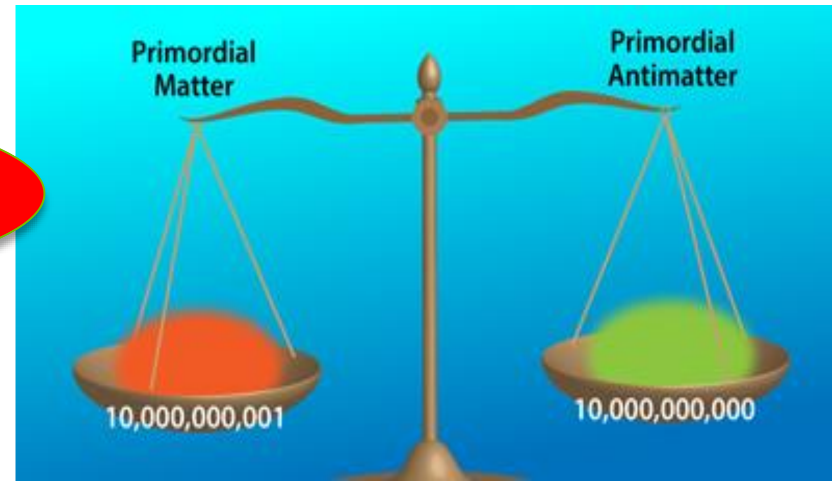


Image credit: APS/Alan Stonebraker

Although CP Violation exists in the Standard Model, and has been observed, it is insufficient to explain the observed matter/anti-matter asymmetry of the universe

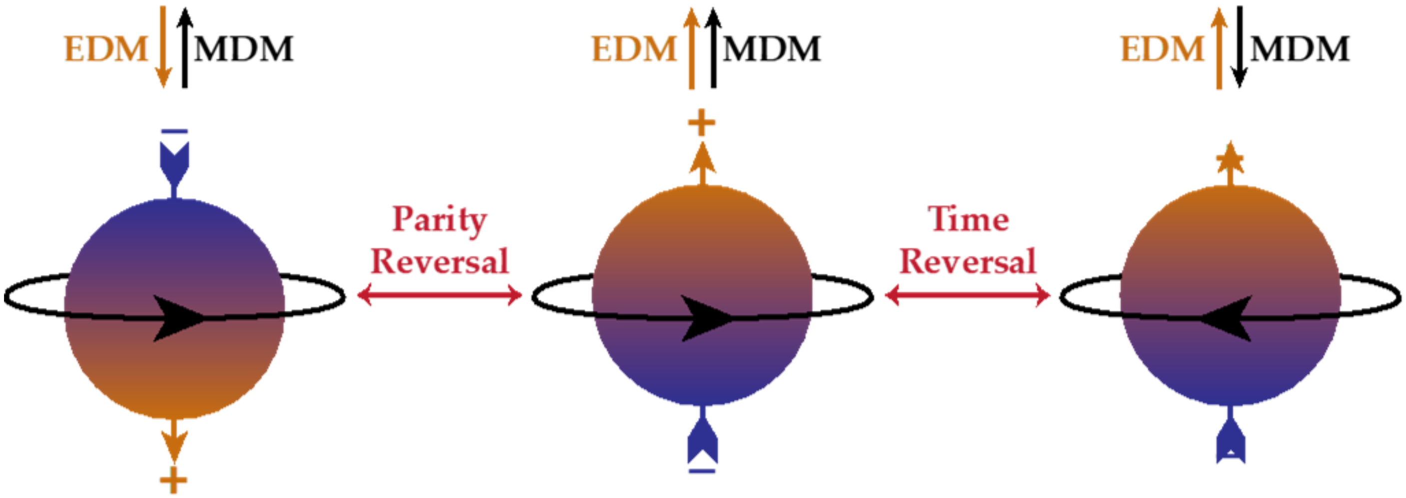
WHERE'S THE CP?

- There was once CP-violation, but no longer
  - Axions, "The Thinking Persons' Dark Matter" – M. Turner
  - Oscillating EDMs – see Yevgeny Stadnik's talk
- Neutrino's Made us All
  - leptogenesis, Majorana neutrinos
- New Symmetries and Degrees of Freedom
  - SUSY, GUT, ???

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

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EDM SECTORS

$\underbrace{d_e \qquad C_S}$ $\qquad$ $\underbrace{C_T \qquad g_\pi^{(0)} \qquad g_\pi^{(1)} \qquad \bar{d}_n}$

$\underbrace{\text{Paramagnetic}}$ $\qquad$ $\underbrace{\text{Diamagnetic}}$ $\quad$ Neutrons

ThO, YbF, Cs, Tl, Fr… $\qquad$ Hg, Ra, Xe, TlF

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 SECTORS

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Sector	Exp Limit (e-cm)	Location	Method	Standard Model
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Neutron	3×10^{-26}	Talks by Kirch, Franke, Fierlinger		10^{-31}
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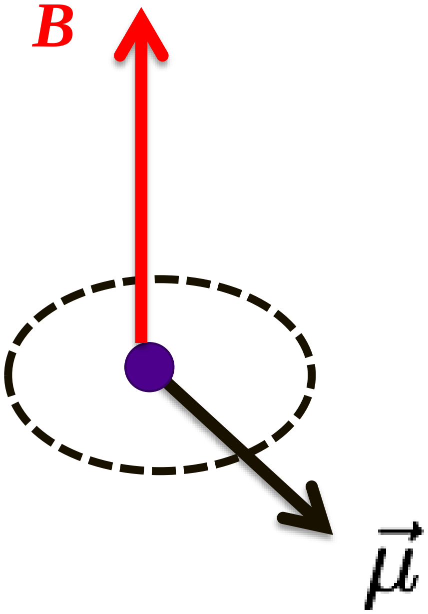
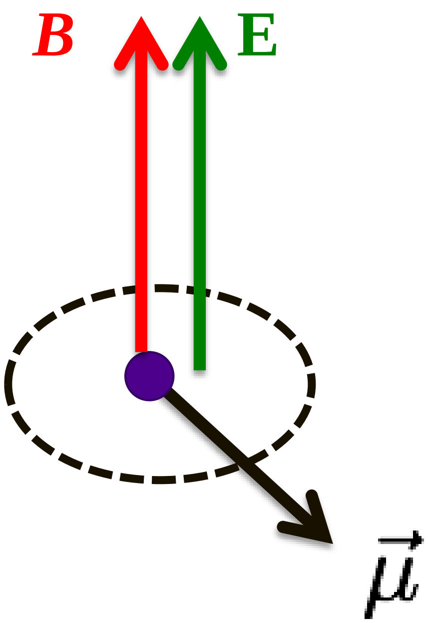
EDM MEASUREMENTS



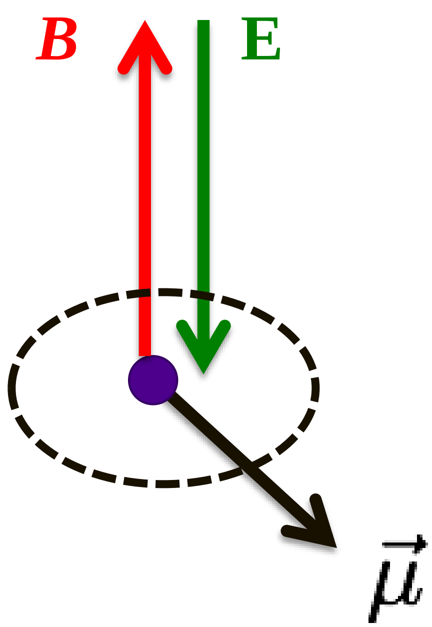
$$h\nu = \frac{\mu B}{S}$$

EDM MEASUREMENTS



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

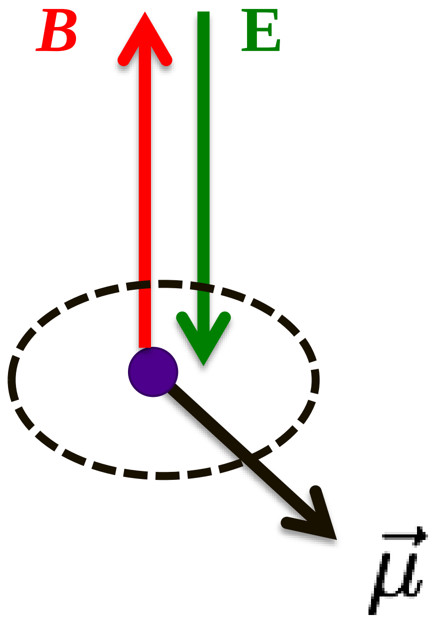
EDM MEASUREMENTS



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

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

EDM MEASUREMENTS

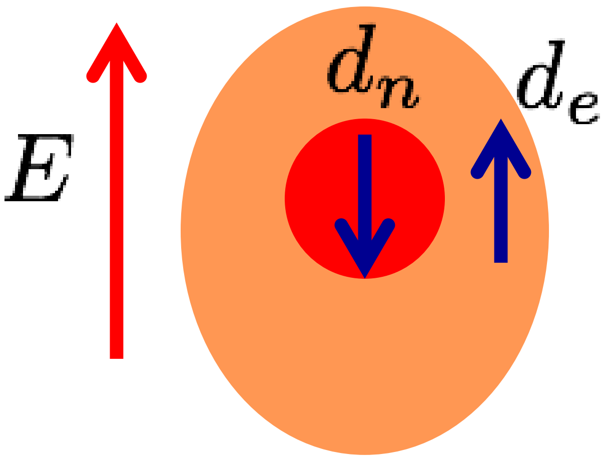


$$h\nu_+ = \frac{\mu B + dE}{S}$$

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

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

SCHIFF MOMENTS AND EDMS



Schiff Moment

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

Leonard Schiff's Theorem (1963):

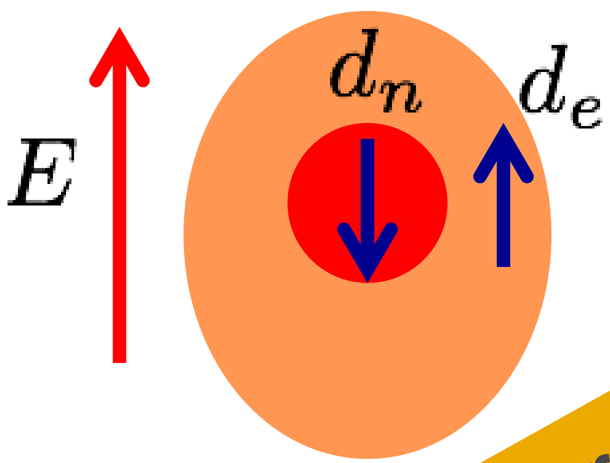
- Any permanent dipole moment of the nucleus is perfectly shielded by its electron cloud
- True for point-like nuclei, non-relativistic electrons

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!

SCHIFF MOMENTS AND EDMS



Leonard Schiff's Theorem (19…

- Any permanent dipole m… nucleus is perfectl… cloud
- True for … elec…

… moment" is not … is effect

- … point-like, spherical nuclei
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Sc…

$$\ldots \rangle \langle e\vec{r} \rangle \over 6$$

Look for heavy nuclei with large quadrupole and octupole deformations!

Exception: Storage Ring EDMs. Stay Tuned! (Rathmann, Nass, Kononov)

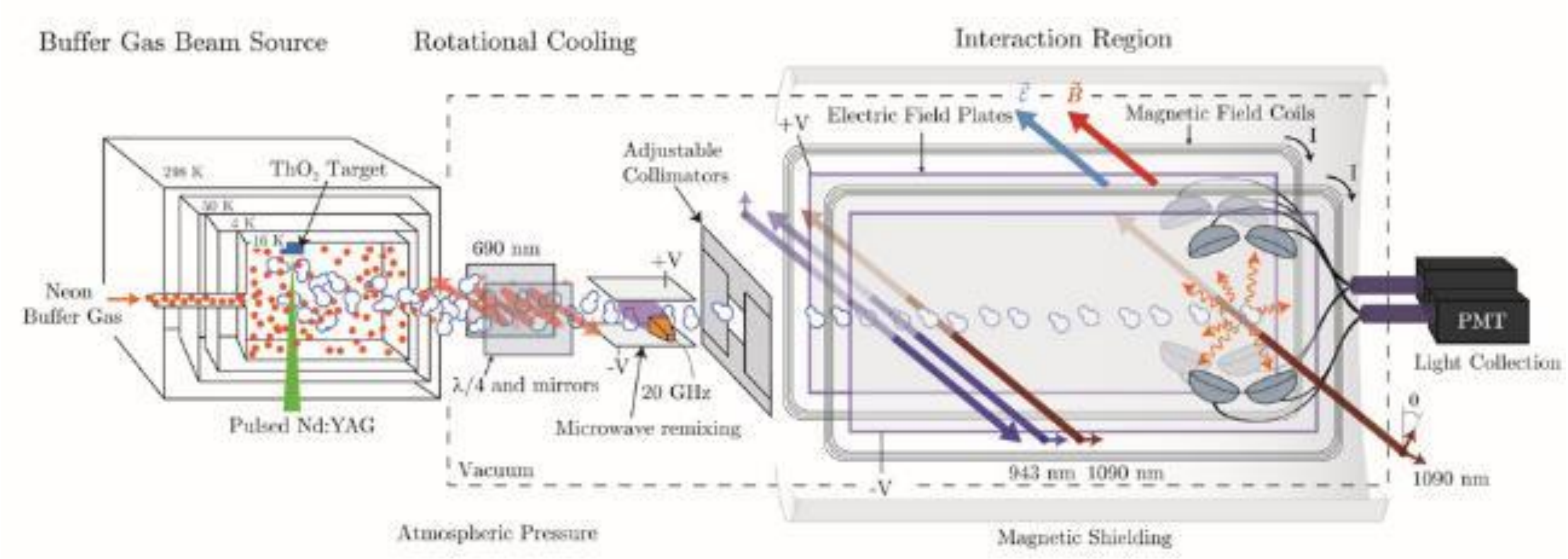
TECHNIQUES

Standard disclaimer: Roughly speaking, and incomplete lists…

Technique	Pros	Cons	Examples
Atomic Beam	Large N Almost any species	Short lifetime Large systematics “Small” applied E field	**Tl, ThO, YbF, TlF**
Vapor cell	Huge N Large lifetime	Limited species Small applied E field	**Hg, Xe**, Rn
Cold Atom	Long lifetime Large applied E field	Small N Limited species	**Ra**, Cs, Fr, Yb
Trapped Ions	Intermediate length lifetime(?) and N	Limited species? Systematics???	**HfF+**

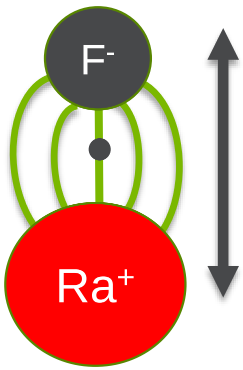
How to prepare and detect state of sample?
How to create uniform and constant electric and magnetic fields?

BEAM EXPERIMENTS



- A cold, collimated beam of molecules is produced by buffer gas cooling
- The beam is then optically prepared and detected (usually)
- Because of Exv and the large gap size, maximum E field is generally limited
- Lifetimes measured in milliseconds

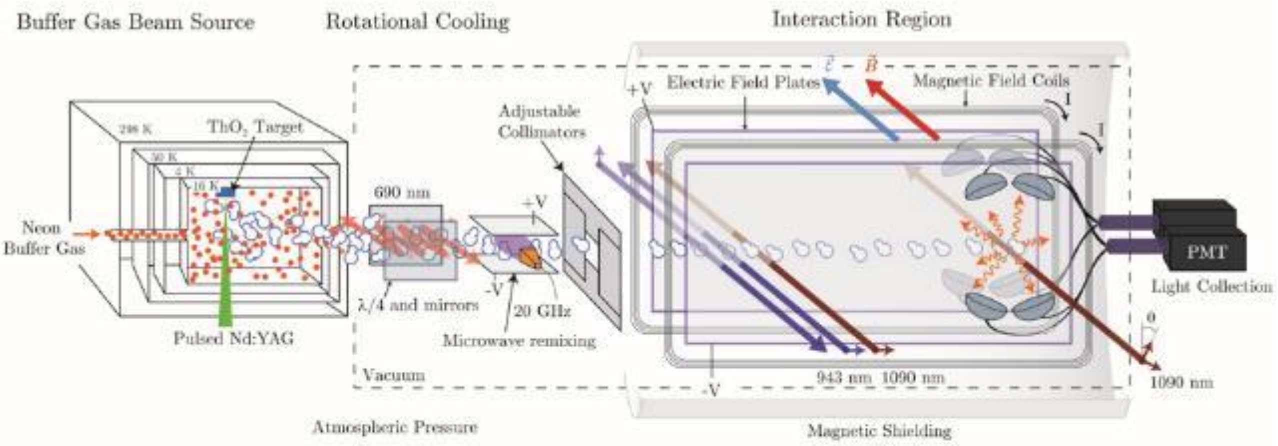
MOLECULES AND EDMS



$$E \approx k_e \frac{e}{r^2} \approx 290 \text{ MV/cm}$$

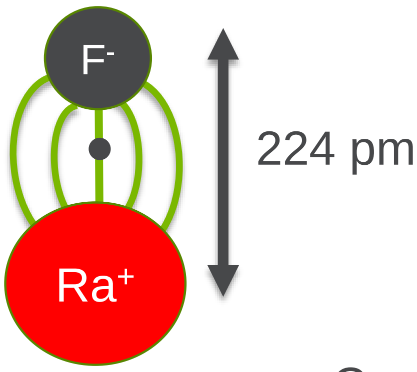
Nuclei experience fields of 100's MV/cm, while the electron experiences 100's GV/cm

Compare with 250 kV/cm in the new generation of electrodes



This effect allows beam experiments to use low applied fields, yet still achieve good limits on the EDM (Courtesy ACME)

MOLECULES AND EDMS



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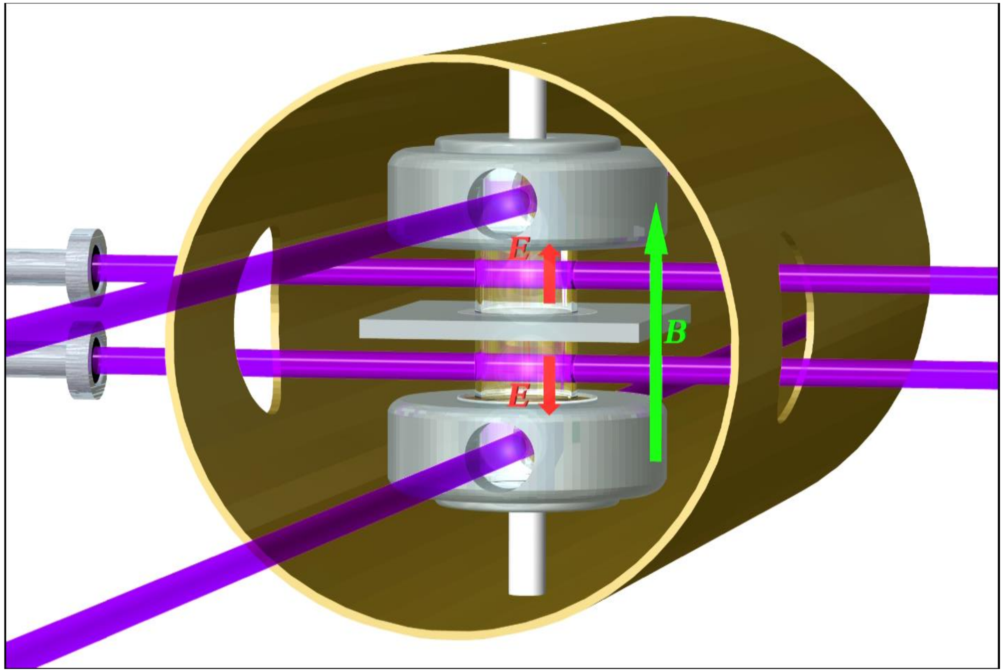
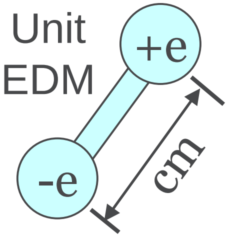
ThO	Harvard-Yale	Electron
YbF	Imperial College	Electron
YbOH	Harvard, CalTech	MQM
RaF	ANL	Schiff
TlF	Yale, Columbia	Schiff
HfF+	Boulder	Electron

THE SEATTLE MERCURY EDM EXPERIMENT



Properties of Hg-199 and experiment

- Stable
- Spin I=½ nucleus (no quadrupole moment)
- Nuclear T2 ~ 100-200 seconds
- **High Vapor Pressure at room temperature**, 4*10^13 cm^{-3}
- High Z=80
- Nearly spherical nucleus
- Glass cell limits E field to 10 kV/cm
- Leakage current through cell is leading systematic



EDM(Hg-199) < 7 x 10^{-30} e cm

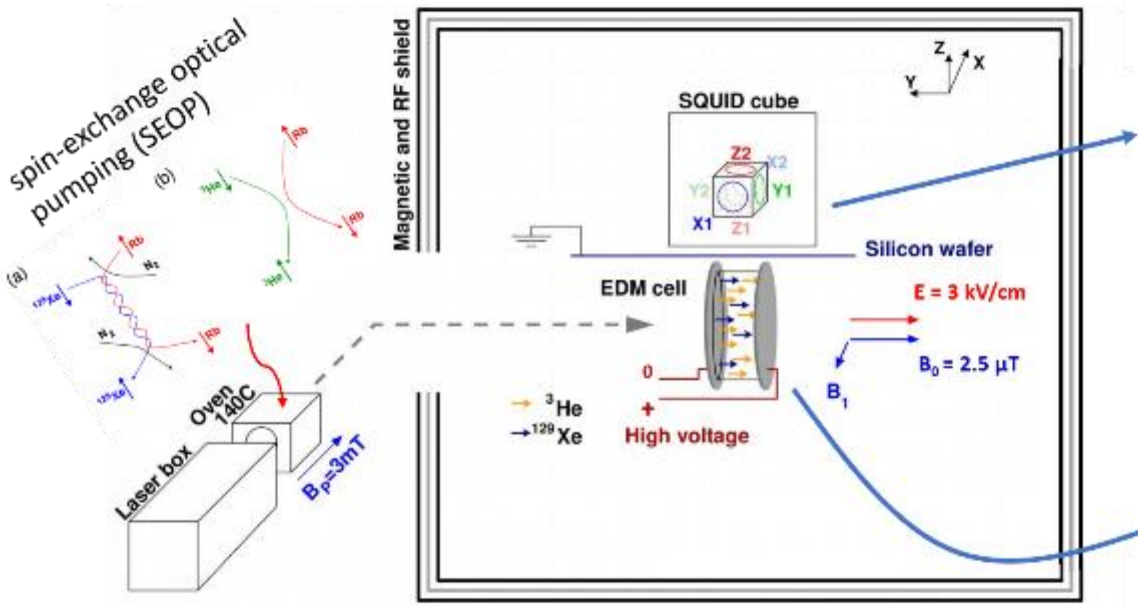
If Hg nucleus is size of earth, then this is two charges separated by 50 pm

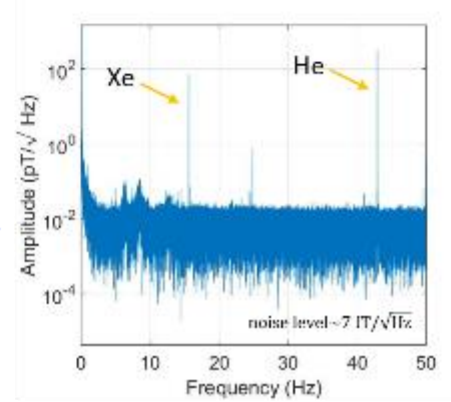
Griffith *et al*., Phys Rev Lett (2009)
Graner *et al*., Phys Rev Lett (2016)

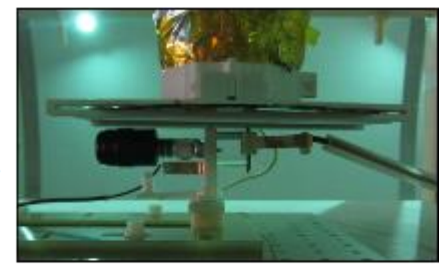
HEXE EDM EXPERIMENT AT BMSR-2 (BERLIN)

^{129}Xe EDM measurement using ^{3}He comagnetometer

Goal: 100x improvement on previous value, $d(^{129}\mathrm{Xe})=0.7 \pm 3 \times 10^{-27}\ e \cdot \mathrm{cm}^{\dagger}$







F. Kuchler, *Electric dipole moment searches using the isotope 129-xenon* (2014), Doctoral dissertation.

Current status:

- Results from an initial 2017 measurement expected Fall 2018
  - Limited by statistics, not systematics
  - Blinded
  - 2017 EDM sensitivity comparable to Rosenberry and Chupp (2001) result
- Completed 2018 data collection, potentially 10x improvement in sensitivity

Future:

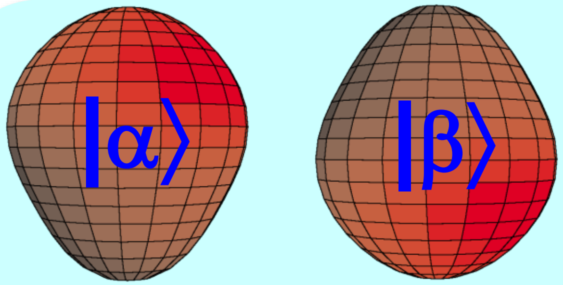
- Improved SNR (better gas purity, increased polarization, lower SQUID noise with upgraded dewar)
- Improved systematic control (cell shape optimization, better leakage current monitoring, cell motion measurement)
- Increased electric field (higher gas pressure, bipolar HV)
- 10-100x improvement in EDM sensitivity

† M. A. Rosenberry and T. E. Chupp, Phys. Rev. Lett. 86, 22 (2001)

(Also see Talks by Heil, Zimmer)

Slide courtesy Natasha Sachdeva

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)

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

	C_T	g(0)	g(1)
Ra/Hg	2	430	833
Ra/Xe	38	4200	23000
Ra/n	∞	.1	20

J. Engel et al., Progress in Particle and Nuclear Phys. (2013)

RADIUM SETUP

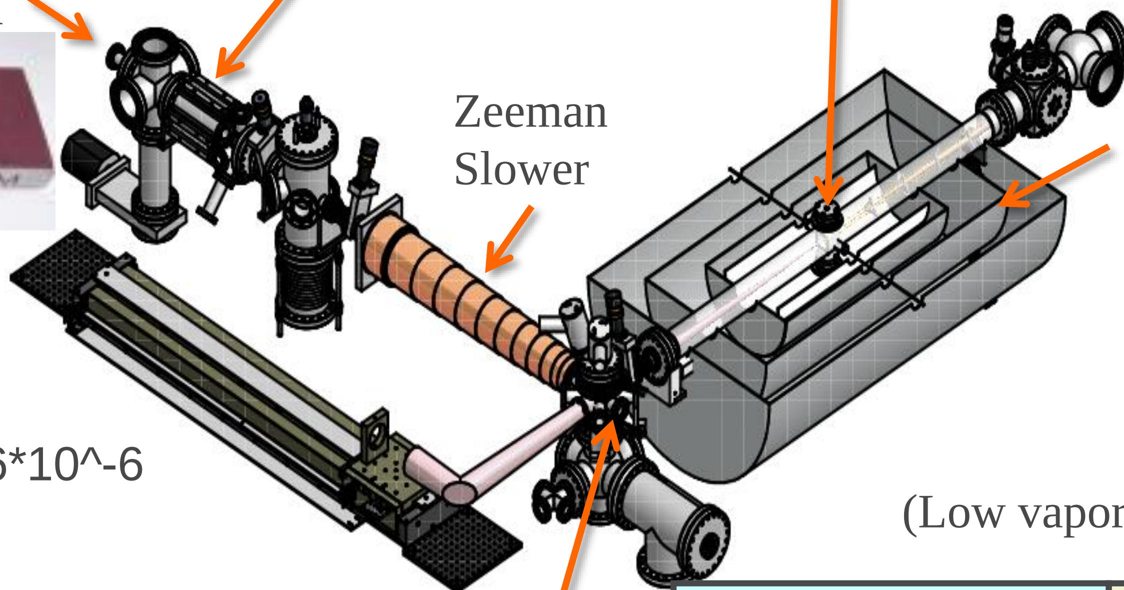
$Ra(NO_3)_2$+Ba Oven

Transverse Cooling

HV Electrodes

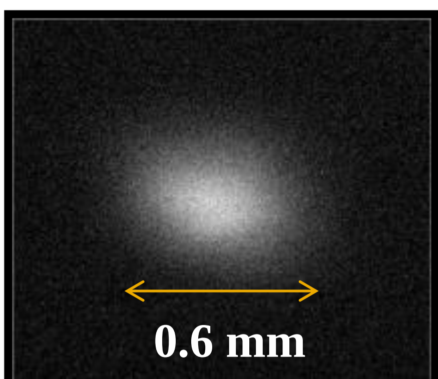
Zeeman Slower

Magnetic Shielding & Magnet Coils



η ~ 1.6*10^-6

(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

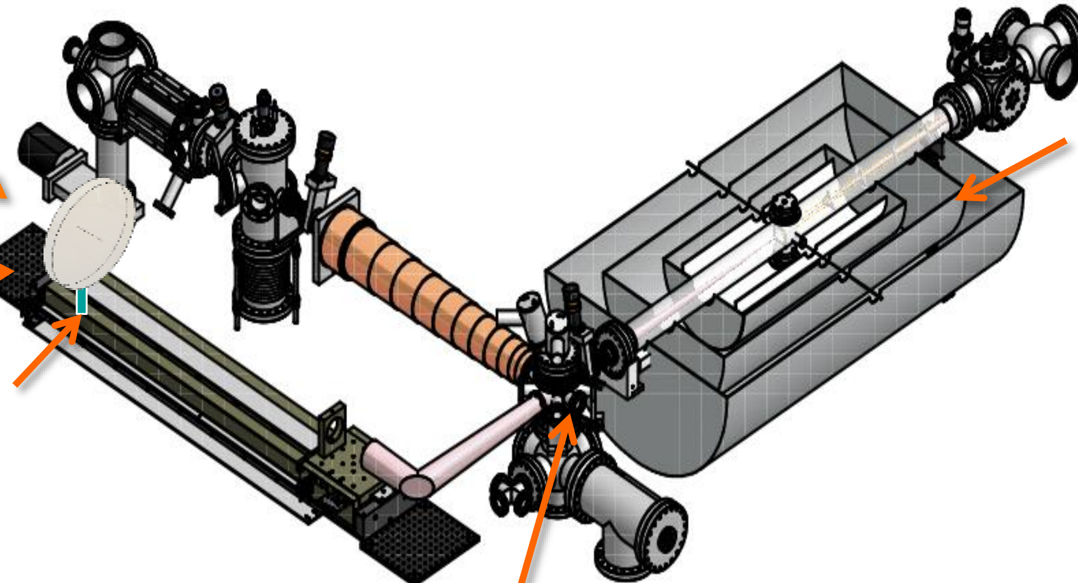
J. R. Guest et al., PRL 98 093001 (2007)

TRANSFER ATOMS FROM MOT TO "BUS" ODT

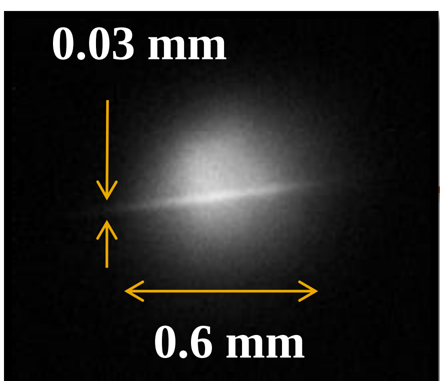
"Bus" ODT
50 W 1550 nm

Translation Stage

Lens



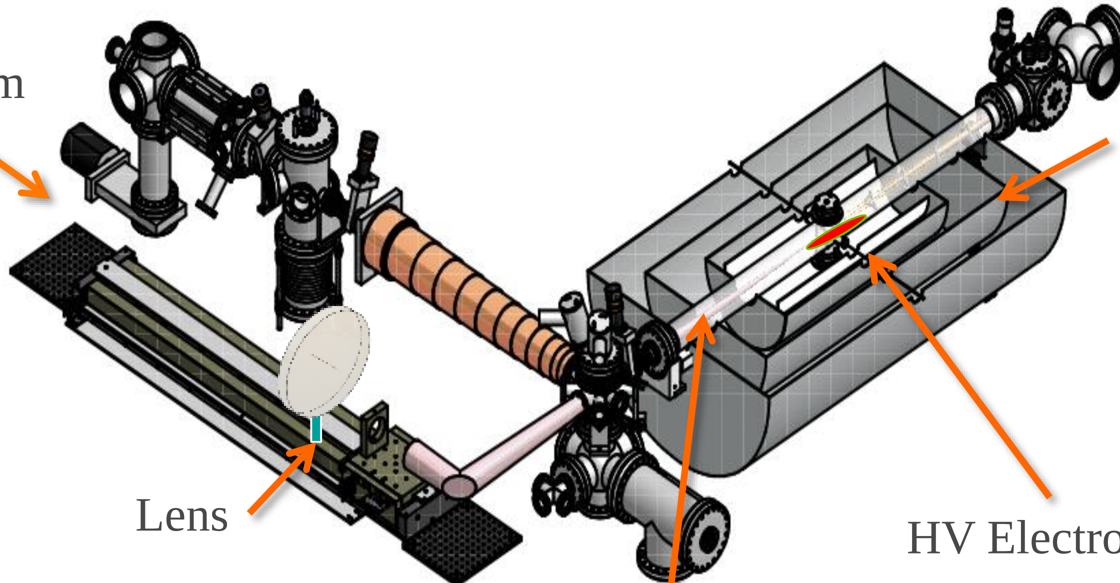
Magnetic Shielding & Magnet Coils



MOT + ODT
80% Efficiency

TRANSFER ATOMS FROM “BUS” TO “HOLDING” ODT

“Bus” ODT
50 W 1550 nm

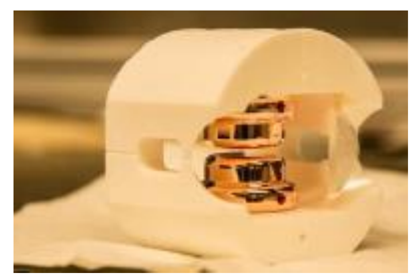


Lens

Magnetic Shielding
& Magnet Coils

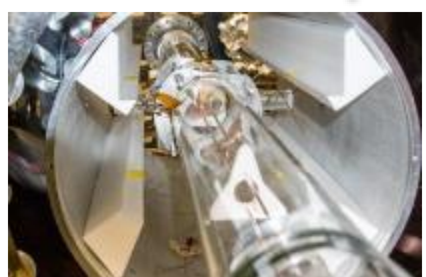
30 mG

HV Electrodes

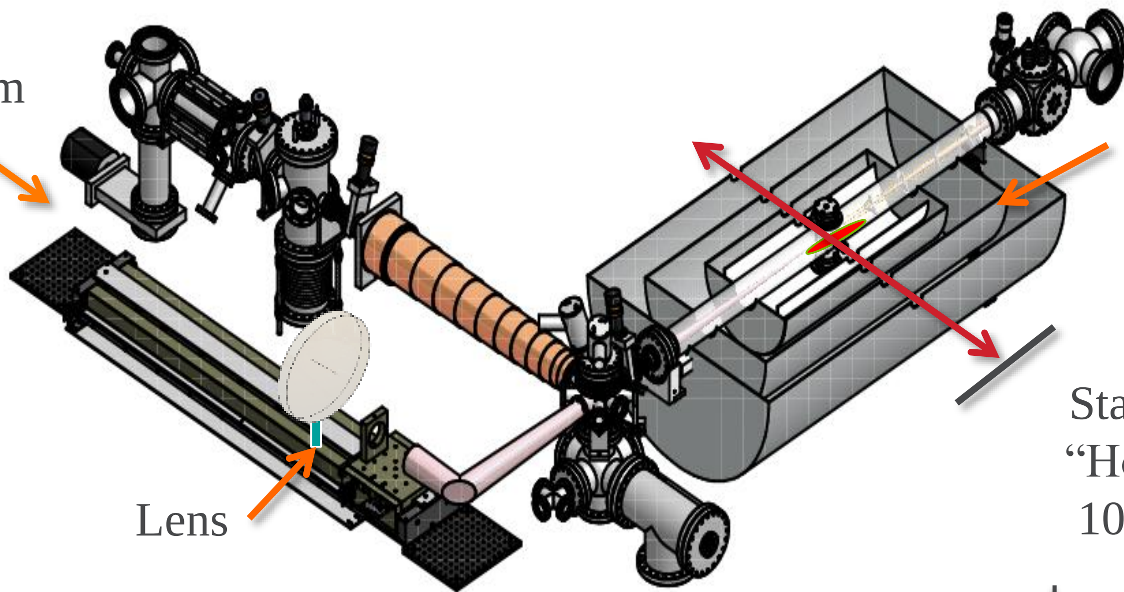


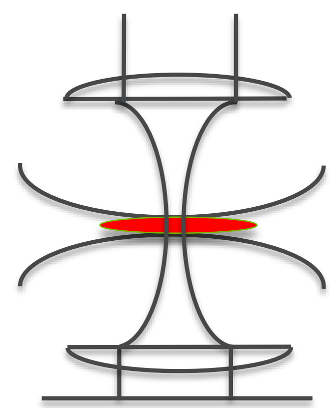
70 kV/cm

Glass Tube
Vacuum chamber
10^{-11} Torr



TRANSFER ATOMS FROM “BUS” TO “HOLDING” ODT





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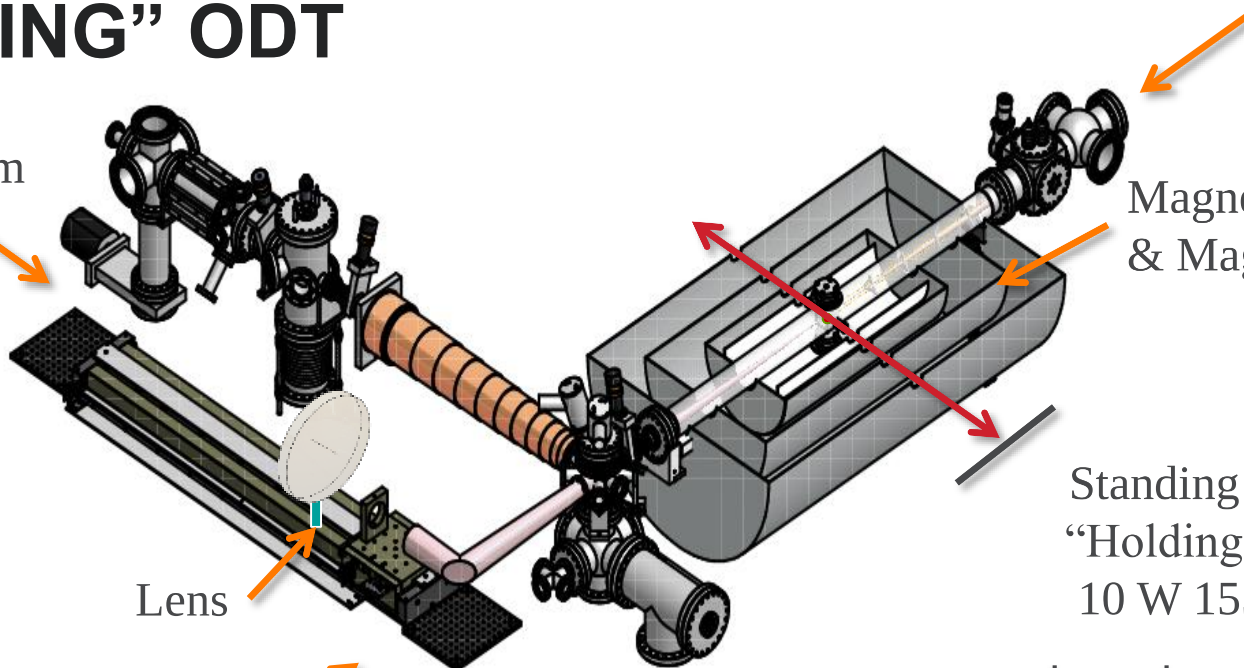

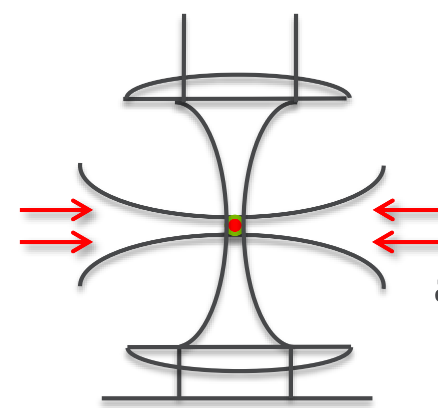

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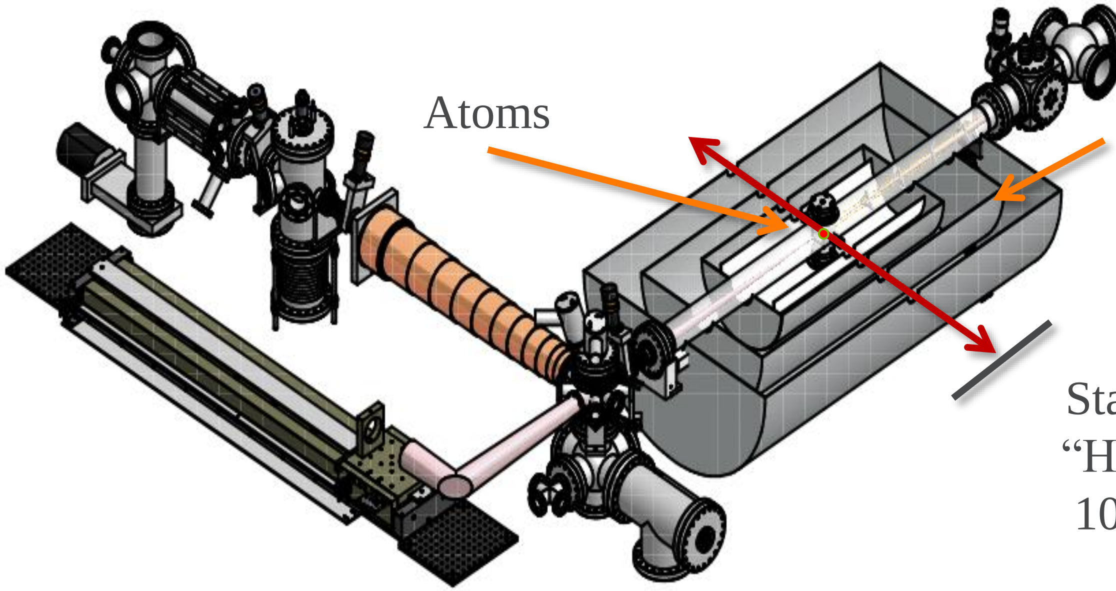
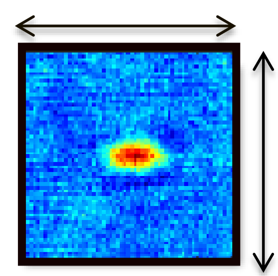
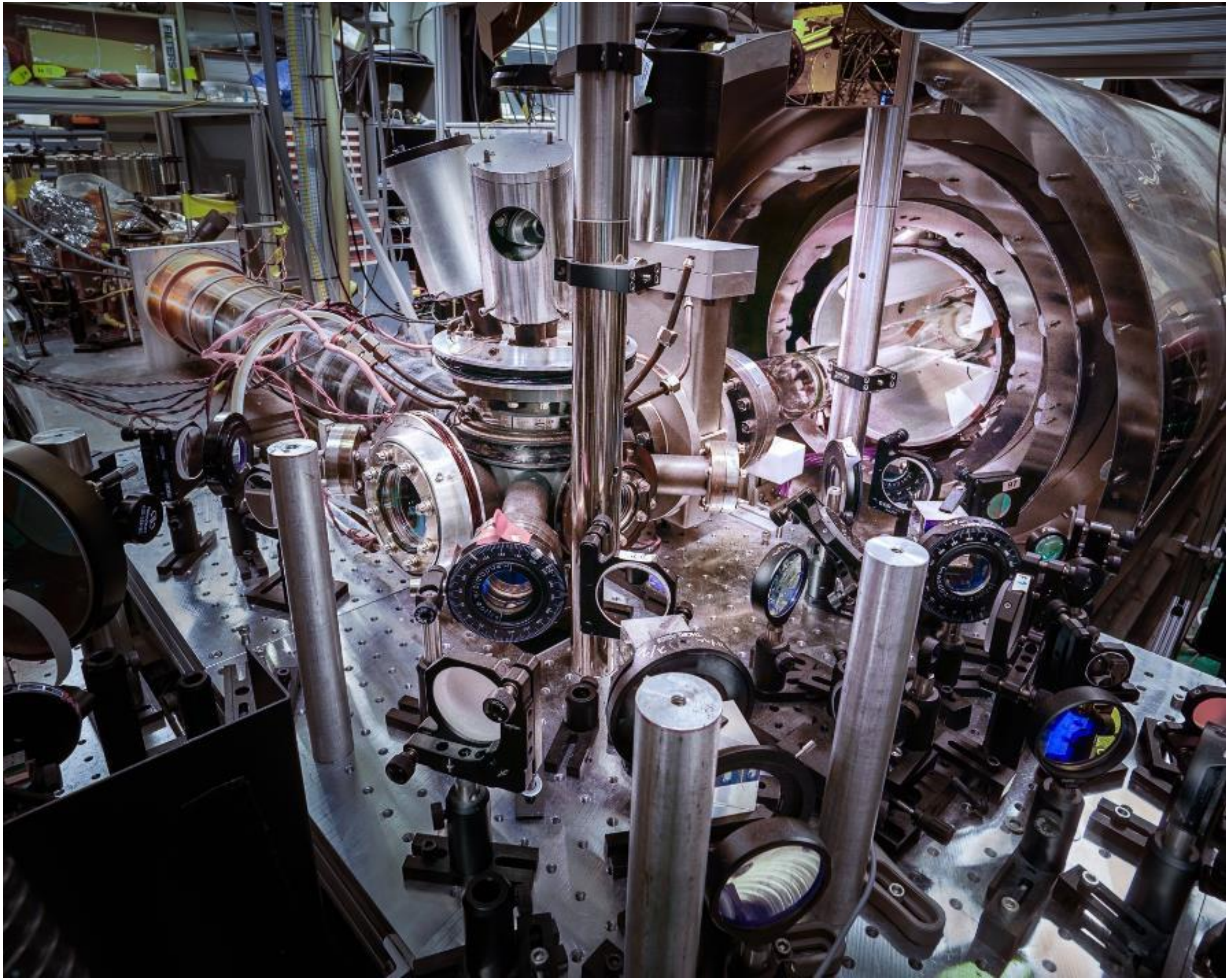


ODT→ODT Transfer: 70% Efficiency

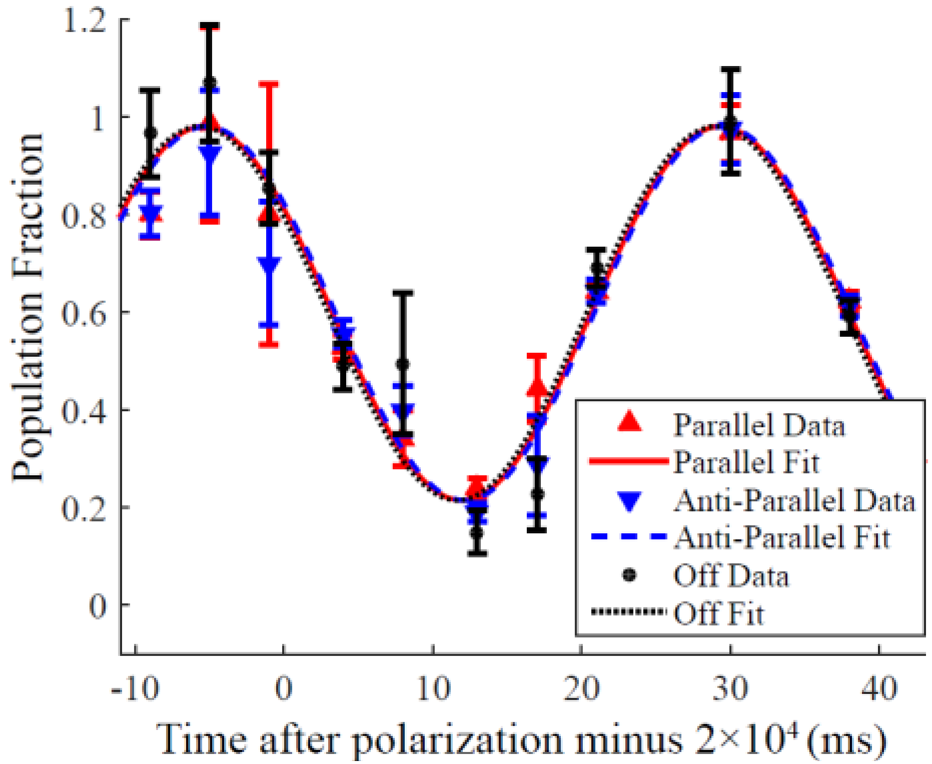
R. H. Parker *et al.*, PRC **86**, 065503 (2012)



Absorption Imaging


FILTERS

EDM RESULT



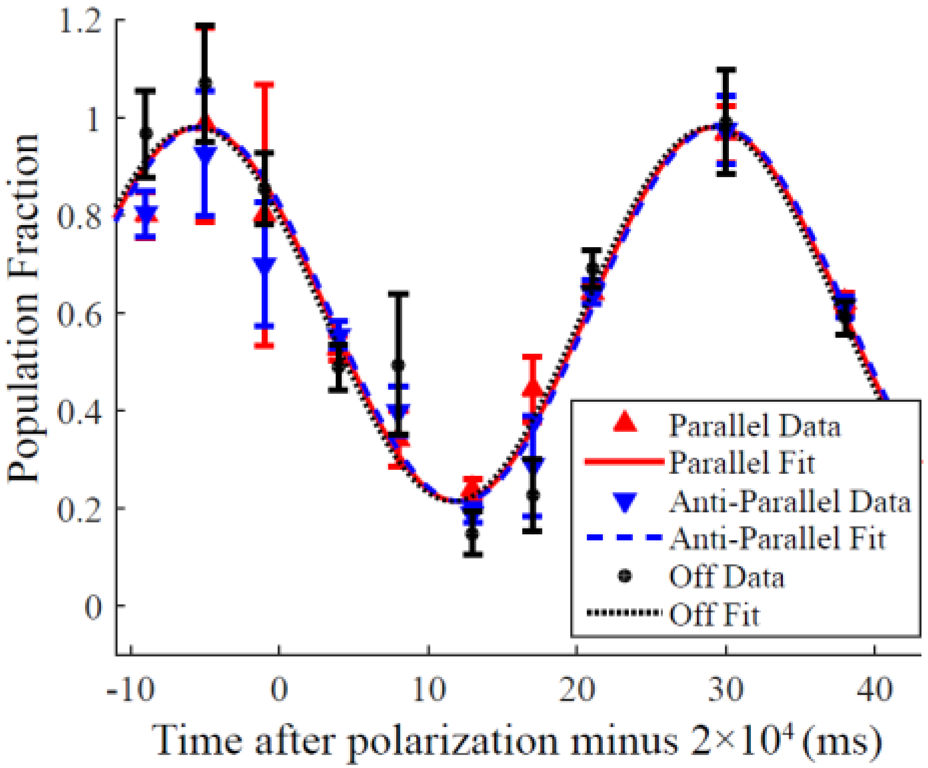
$\chi^2/25 = 1.4$

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

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

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

EDM RESULT



$\chi^2/25 = 1.4$

$$d_{Ra\text{-}225} = (4 \pm 6_{stat} \pm 0.2_{syst}) \times 10^{-24}\ \text{e-cm}$$
$$d_{Ra\text{-}225} < 1.4 \times 10^{-23}\ \text{e-cm 95\% C.L.}$$

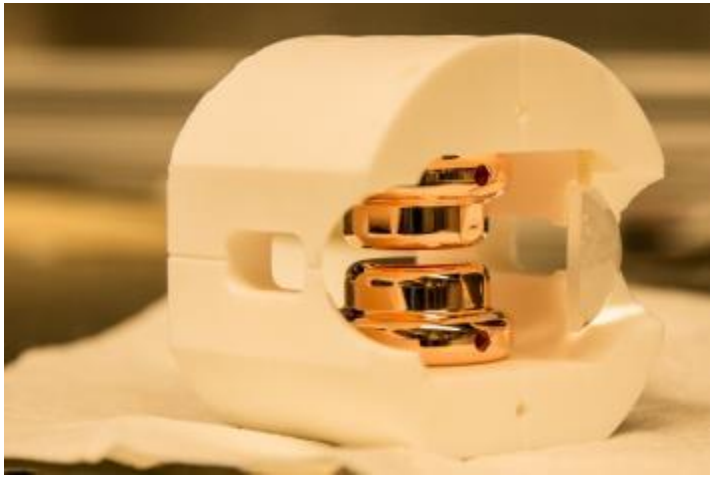
M. Bishof *et al.* PRC 94, 025501 (2016)

SYSTEMATICS

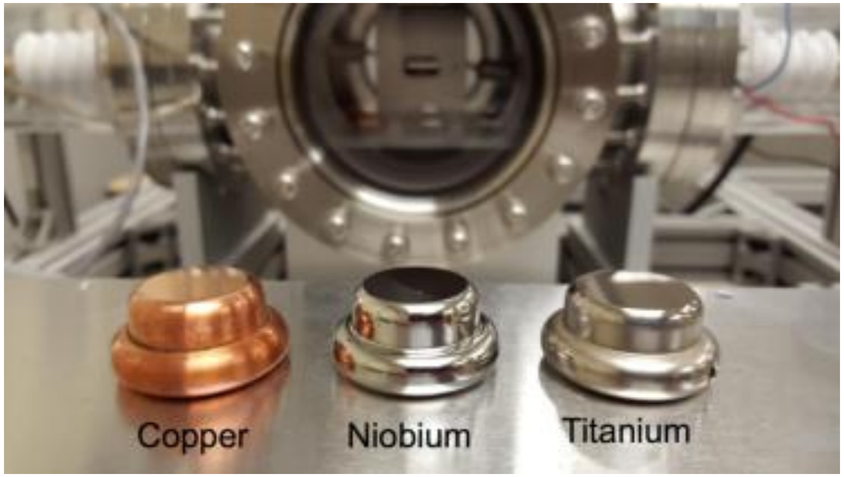
Effect (e-cm)	2016 Measurement	Improved Statstics	Co-magnetometer
E-squared Effects	1×10^{-25}	7×10^{-29}	7×10^{-31}
B-field Correlations	1×10^{-25}	5×10^{-27}	3×10^{-29}
ODT Power Corr.	6×10^{-26}	9×10^{-30}	9×10^{-32}
Stark Interference	6×10^{-26}	2×10^{-27}	3×10^{-29}
Blue Power Corr.	7×10^{-28}	1×10^{-31}	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)

IMPROVEMENT 1: INCREASED FIELD



Previously: Copper Electrodes, E = 70 kV/cm



Niobium electrodes newly installed:
>200 kV/cm demonstrated
(J. Singh/MSU, M. Kelly, T. Reid/ANL, M. Poelker/Jlab)

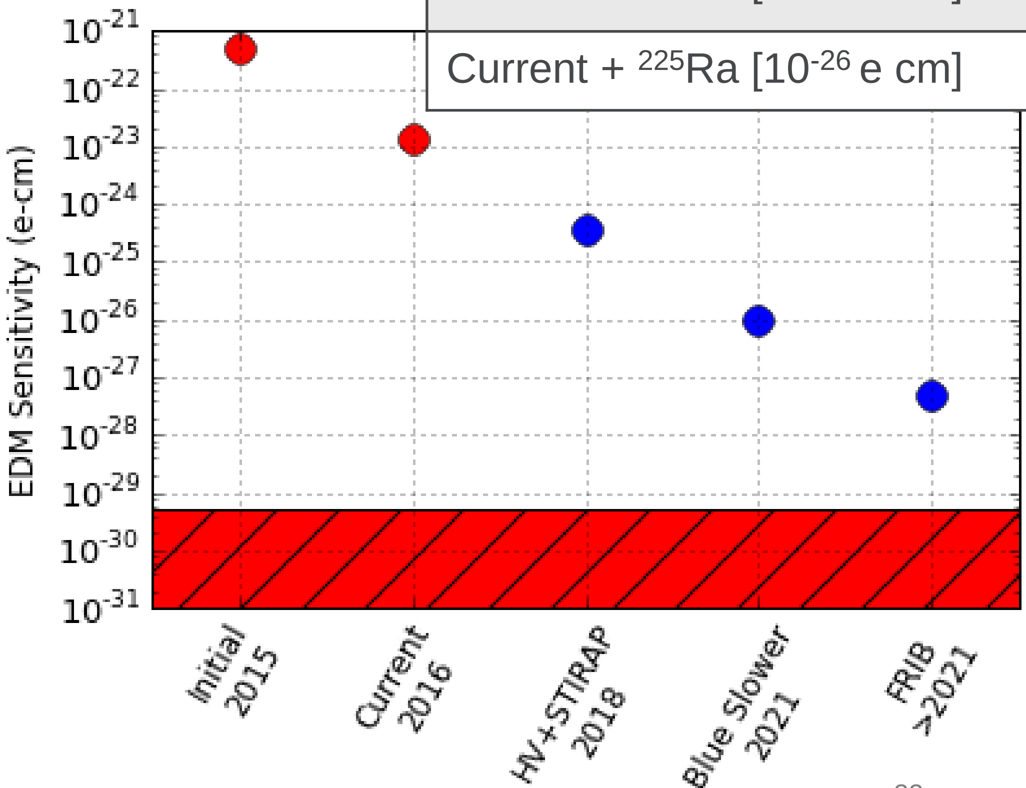
Phys. Rev. Spec. Top. – Acc. and Beams, **15**, 083502 (2012)

Factor of ~4 increase in EDM Sensitivity
Combined with improvement in detection efficiency (STIRAP) and increased source, we expect about 100 fold improvement in next measurement

EFFECT ON STANDARD MODEL EXTENSIONS

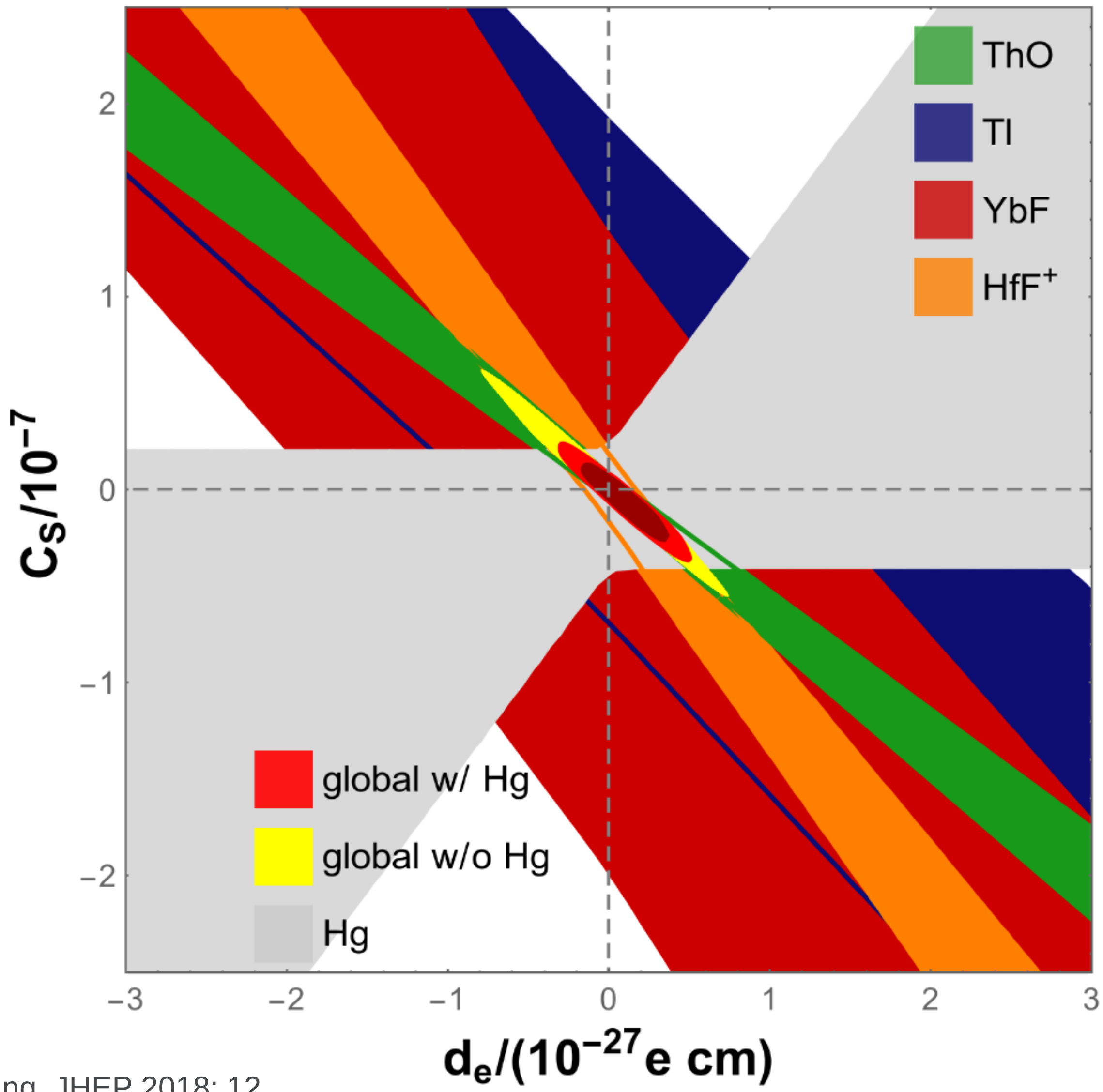
BSM parameter	**C_T**	**$g_p^{(0)}$**	**$g_p^{(1)}$**	**$đ_n$ (e cm)**
Current limits (95% CL)	2×10^{-6}	8×10^{-9}	1.2×10^{-9}	1.2×10^{-22}
Improvement Factor (over current limit)				
Current + ^{225}Ra [10^{-25} e cm]	40	2	1.2	20
Current + ^{225}Ra [10^{-26} e cm]	200	8	4	60

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



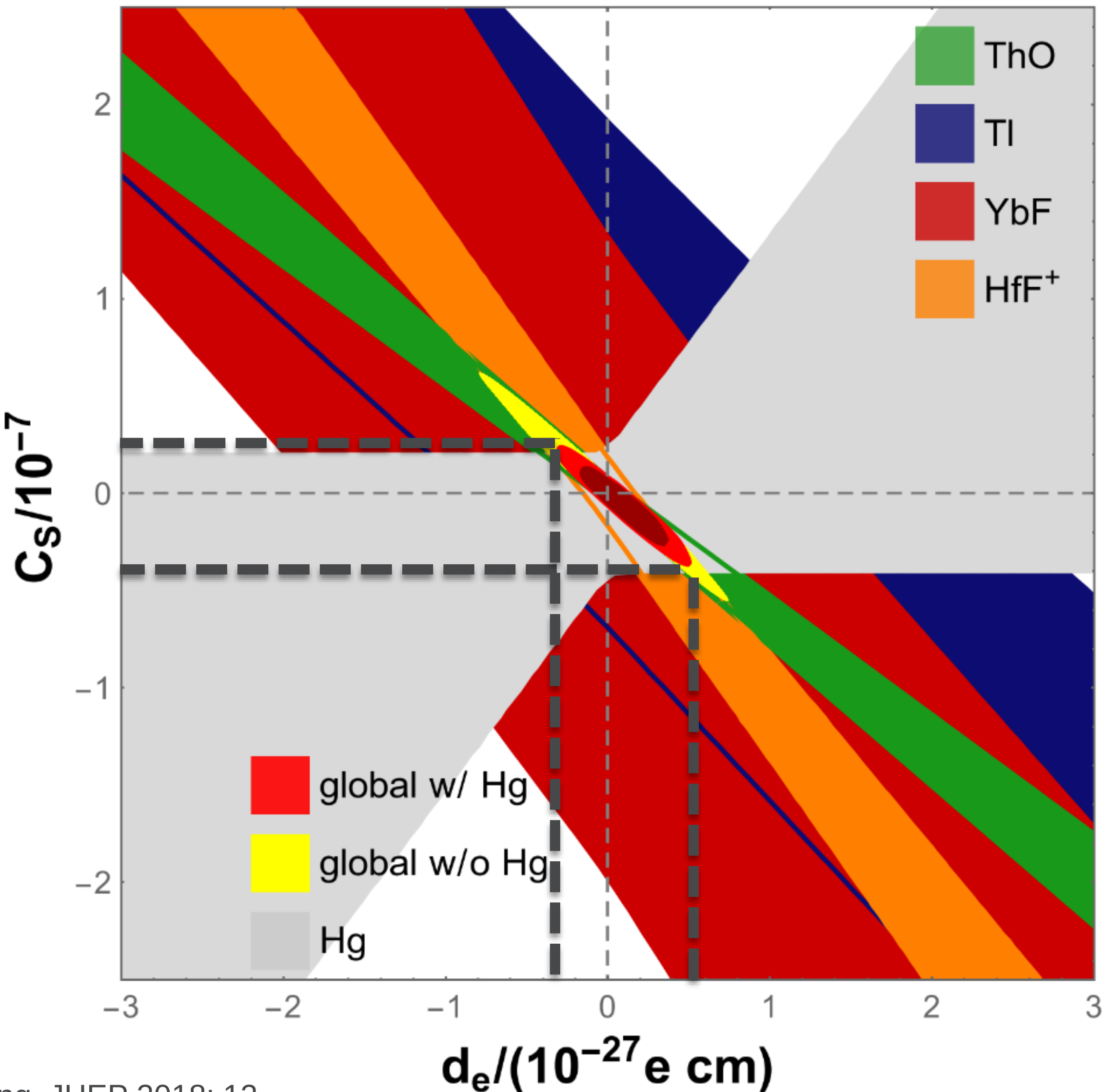
At the level available with those upgrades, radium will improve significantly on the global sensitivity for all parameters

PHASE SPACE IN ELECTRON EDM



T. Fleig, M. Jung, JHEP 2018: 12

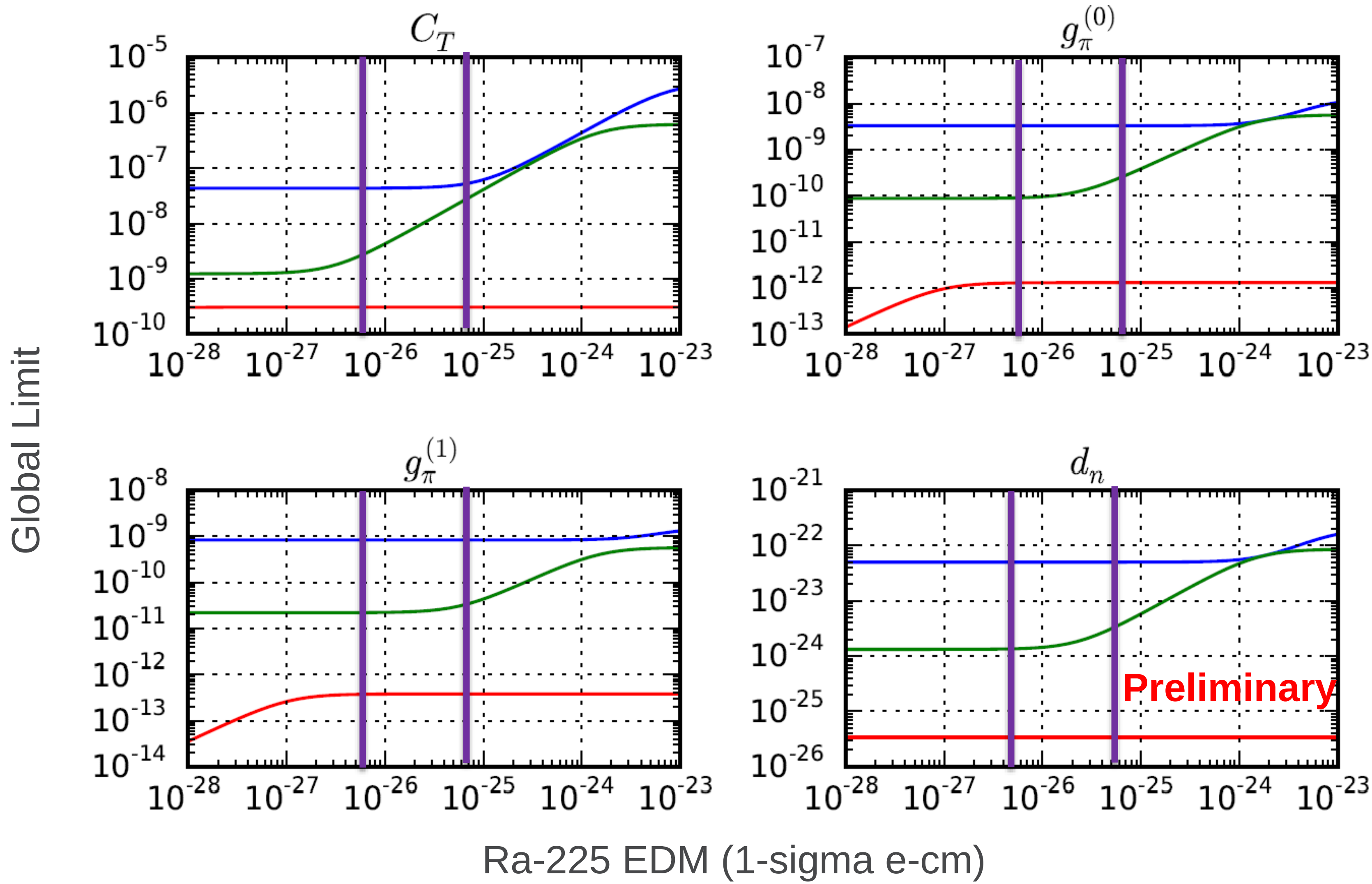
PHASE SPACE IN ELECTRON EDM



T. Fleig, M. Jung, JHEP 2018: 12

SENSITIVITIES

Blue without new Xenon result
Green with 3e-29 e cm



Improved Xe result strengthens new Ra result, and vice versa

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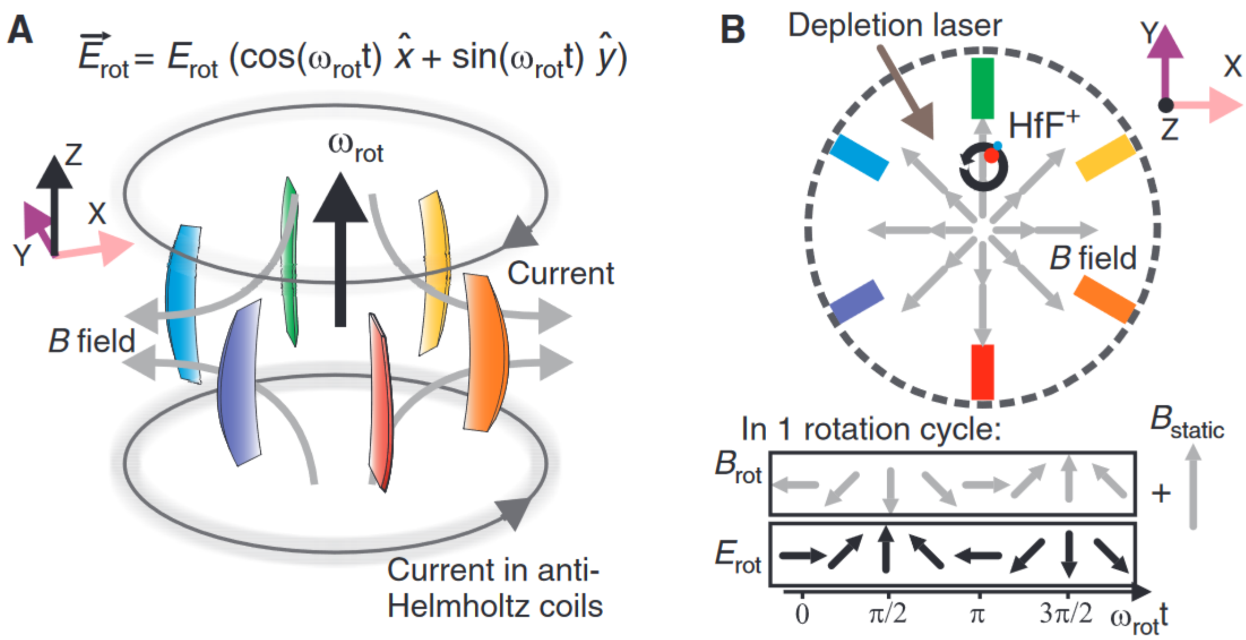
ION TRAP EDM

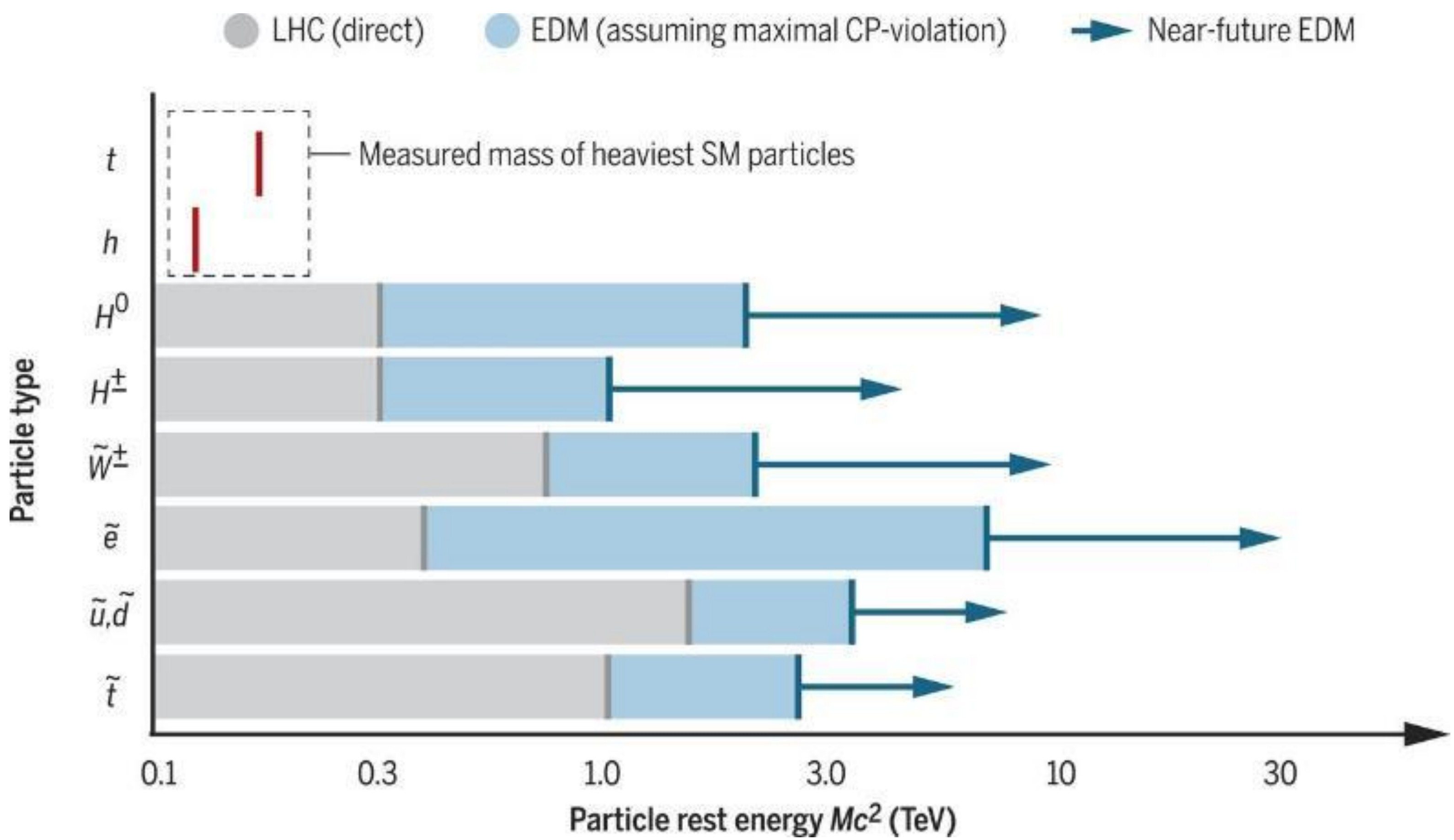


H. Loh et al., Science 342, 1220 (2013)

- An ion trap is formed with a hexapole, rotating electric field, and a DC magnetic quadrupole field, outwardly facing
- The ion and its polarization rotates around in a circle, always phase-locked to the direction of the magnetic field
- This requires that the molecule is very easily polarized (about 10 V/cm), placing somewhat demanding constraints on the electronic structure

ENERGY REACH

Sensitivity of EDMs generally, not specifically radium



D. DeMille, J. Doyle, A. Sushkov, Science 357, 990 (2017)

ATOM TRAPPERS @ ARGONNE

mdietrich@anl.gov

U.S. DEPARTMENT OF ENERGY

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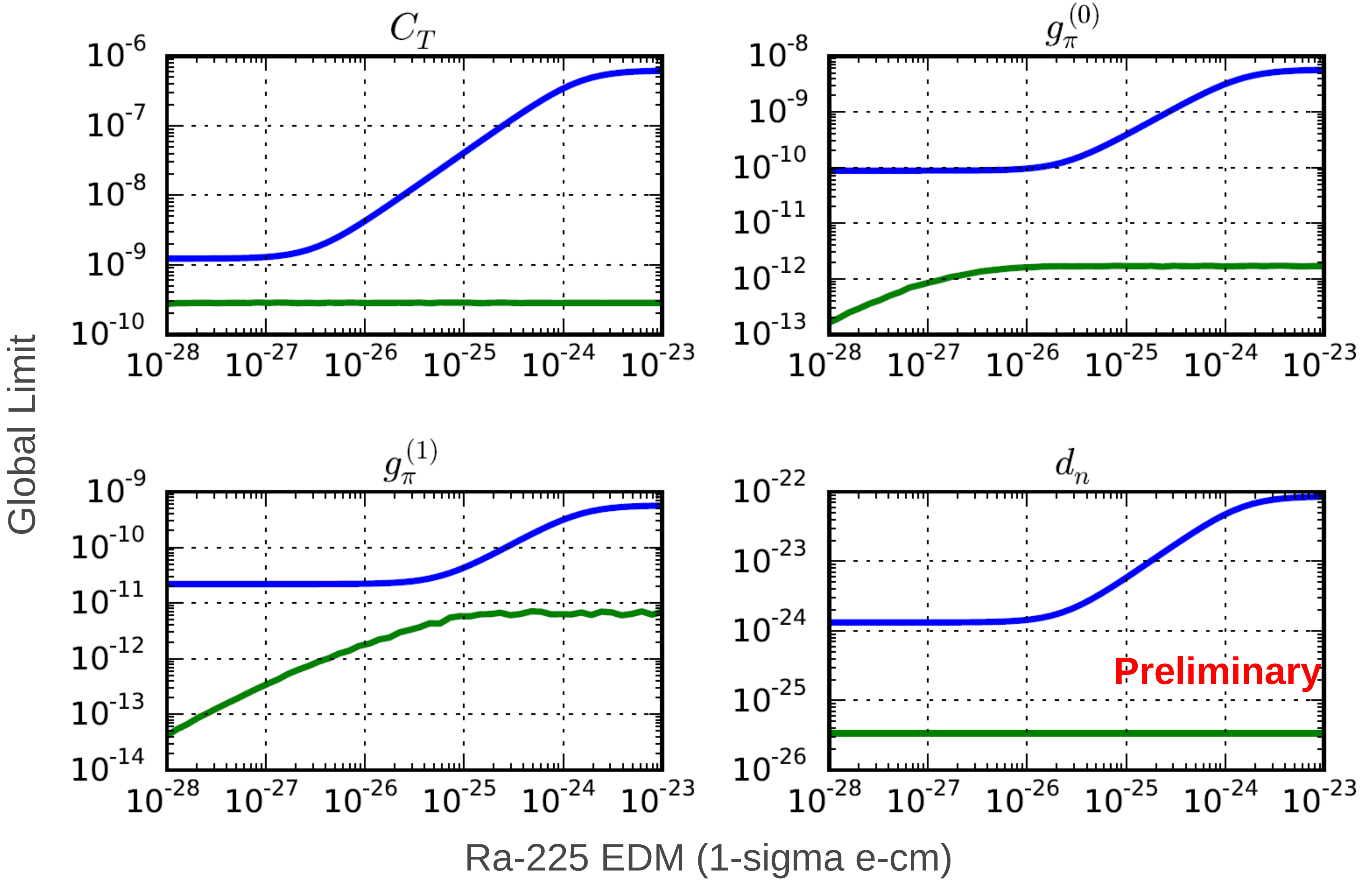
SENSITIVITIES

Assuming new Xe result



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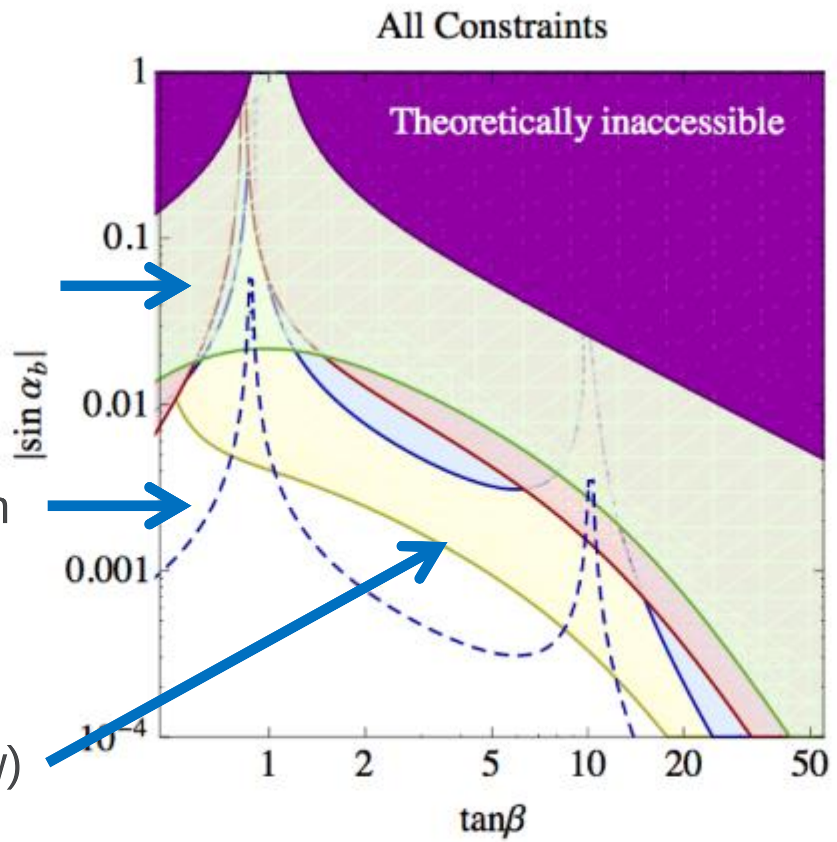
TWO-HIGGS DOUBLET

LANL neutron EDM (Green)

Future electron EDM (blue)

Radium Blue Slower (yellow) 10^-27 e-cm

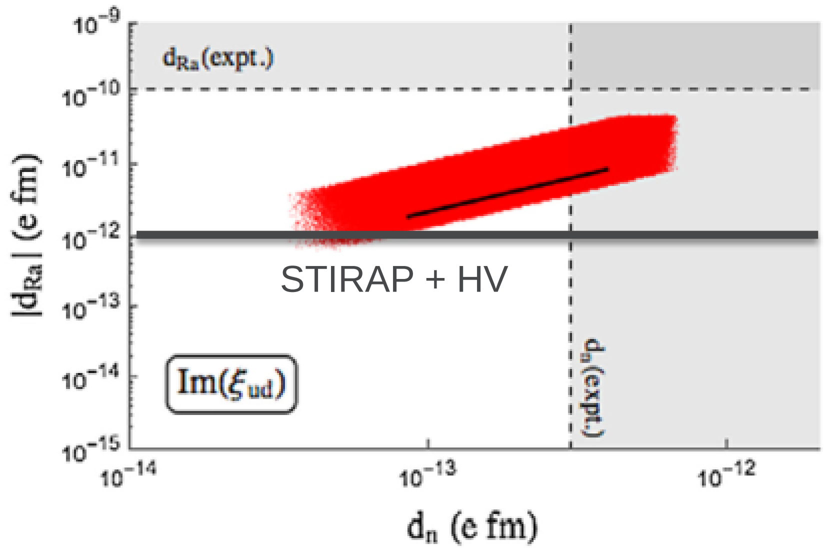


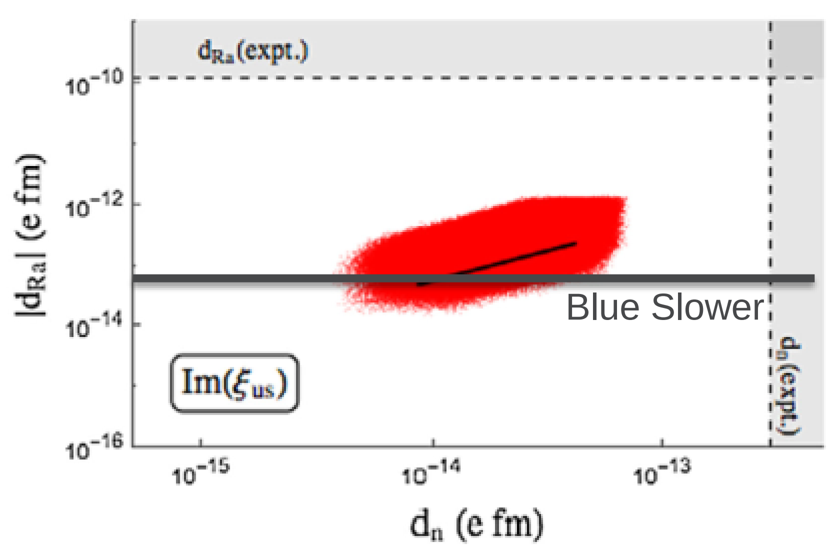
S. Inoue, M. J. Ramsey-Musolf, Y. Zhang Phys. Rev. D 89, 115023 (2014)
C.-Y Chen, H.-L Li, M. J. Ramsey-Musolf, Phys. Rev. D 97, 015020 (2018)

- 2HDM is a simple extension to the SM allowing for CP-violation and natural mechanisms for baryogenesis
- Radium has strong sensitivity to 2HDM, in spite of electroweak nature of theory
- Complementary to electron EDM, which exhibits interference

RIGHT-HANDED CHARGED CURRENTS

- Apparent tension in CP-violating parameters from Kaon decays could be explained by a right-handed charged weak current, which would be detectible with Hadronic EDM experiments
- Due to large theoretical uncertainties in Hg, present constraints on such a model are very weak
- The upcoming radium measurement will be sensitive to this possibility





V. Cirigliano, W. Dekens, J. de Vries, and E. Mereghetti, Phys. Lett. B 767, 1 (2017) arXiv:1708.00797v2