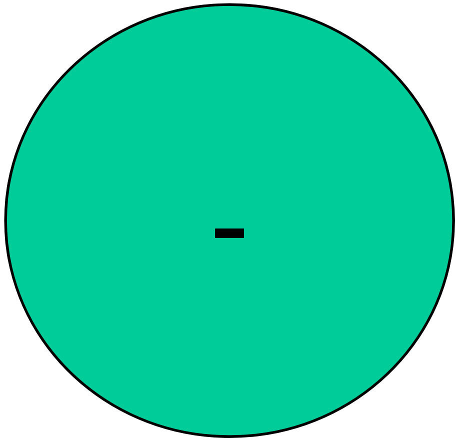
How symmetric is the electron? Looking for out-of-roundness of 10^{-14} femtometers

Eric Cornell
JILA -- NIST/CU Boulder, CO

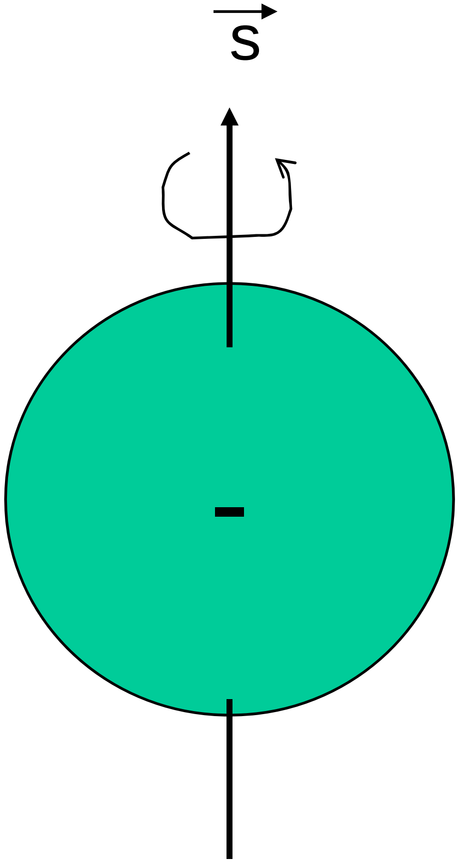
Meet Mr. Electron.

charge = $-q$
mass = m_e



Meet Mr. Electron.

charge = -q
mass = m_e
spin = hbar/2



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magnetic moment
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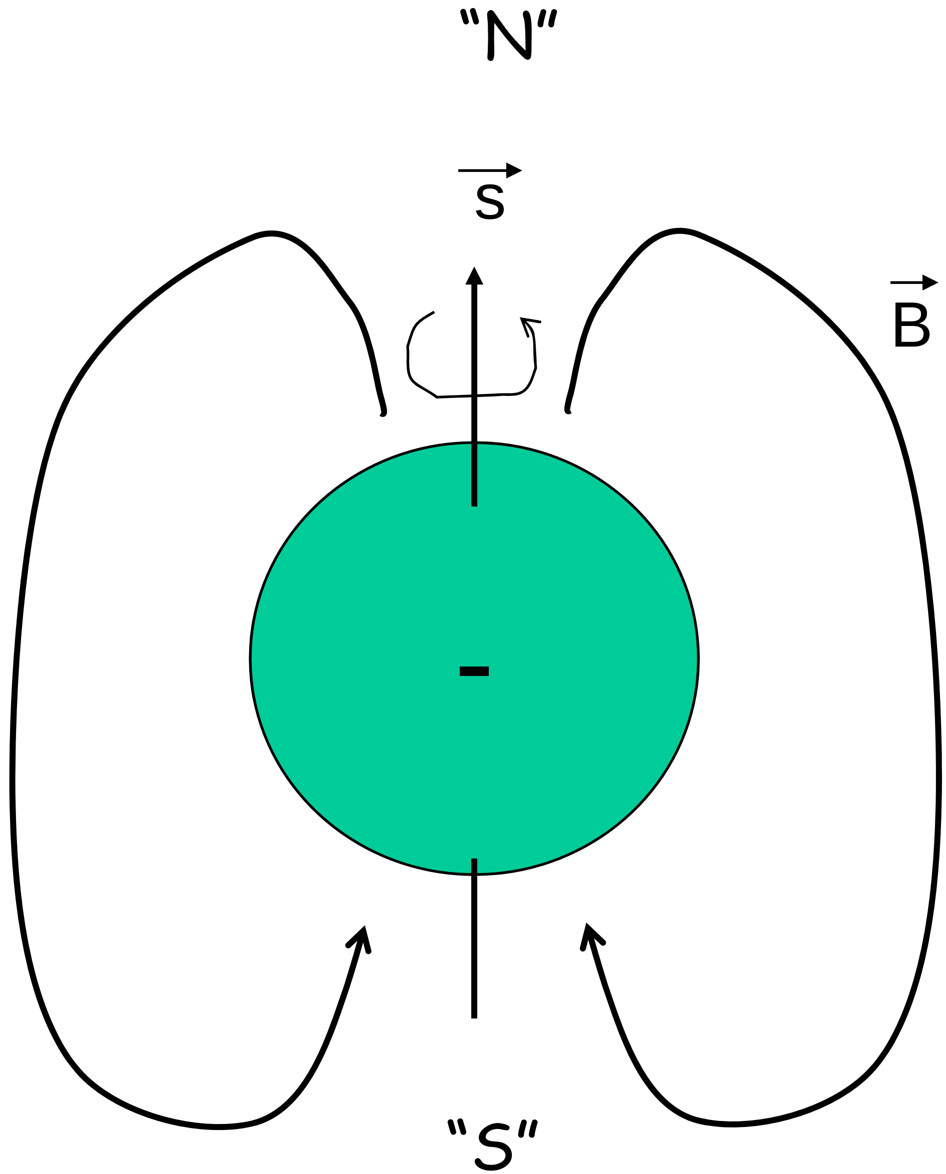

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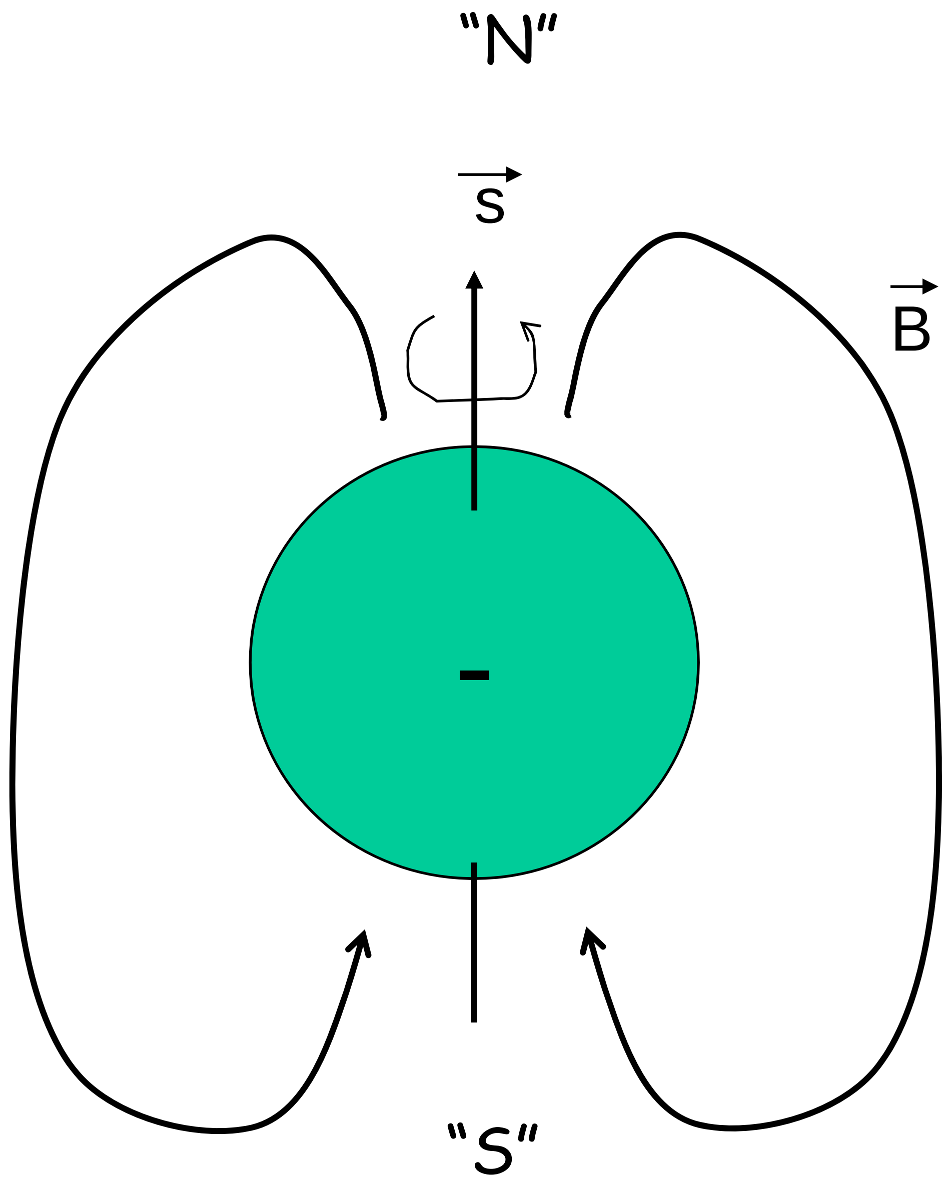
mass = m_e
spin = hbar/2
magnetic moment
= μ_B

and that's pretty much it.

Or is it?



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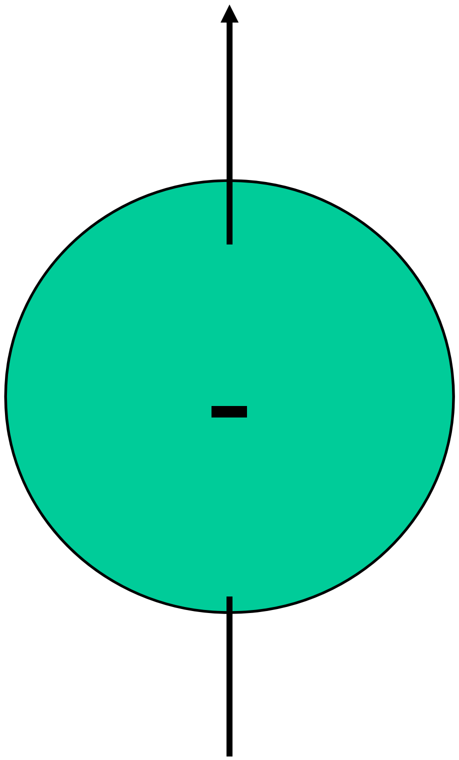

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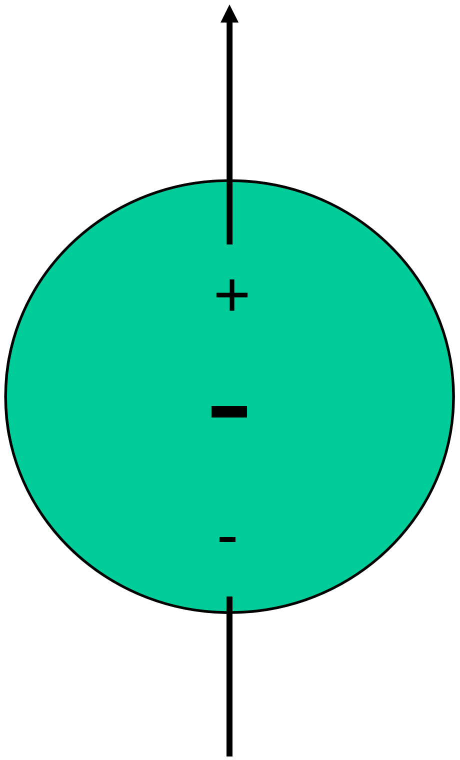

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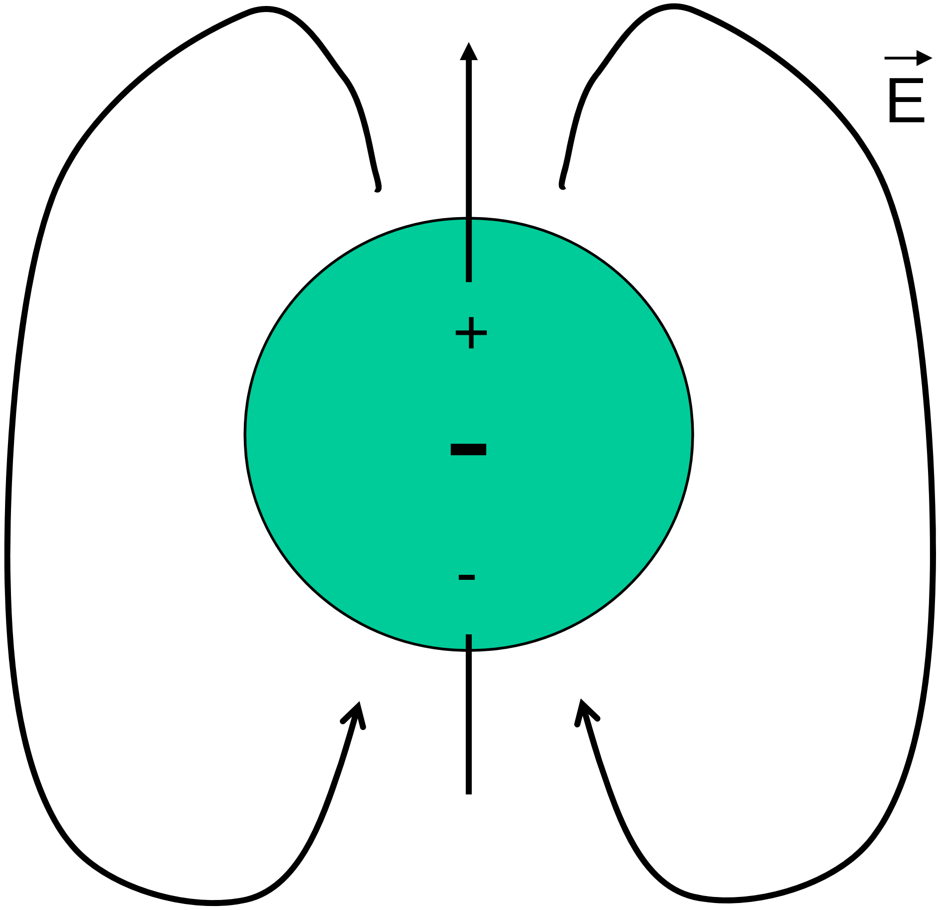

electron
Electric
Dipole
Moment
(eEDM)?

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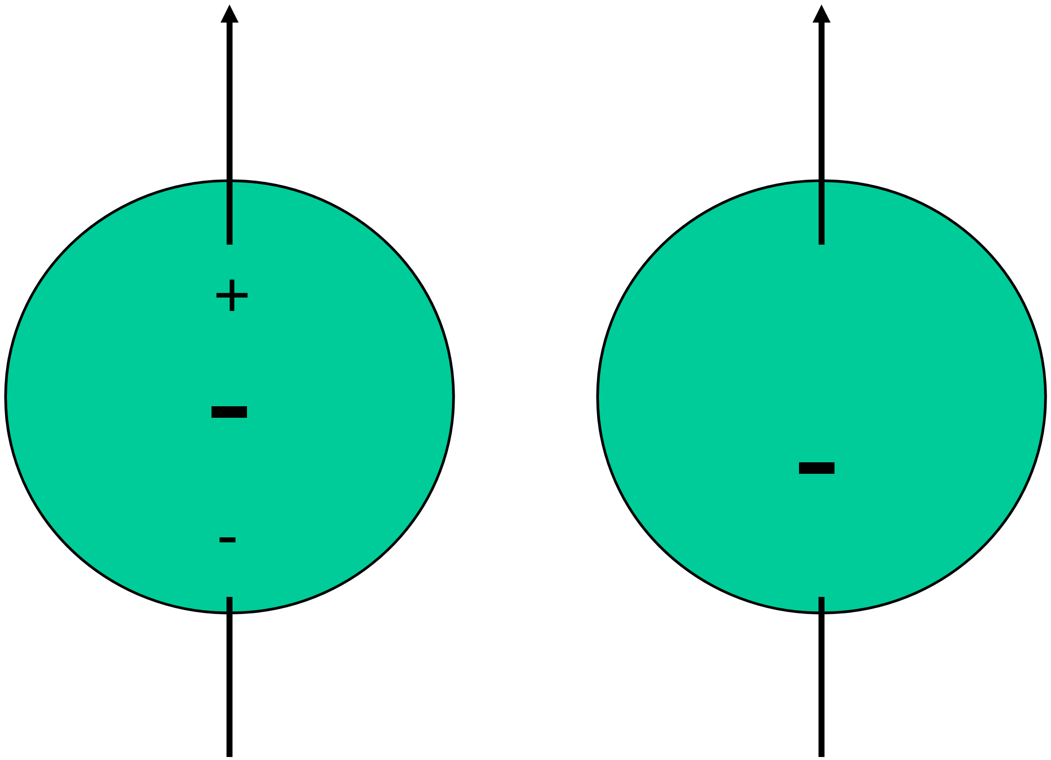
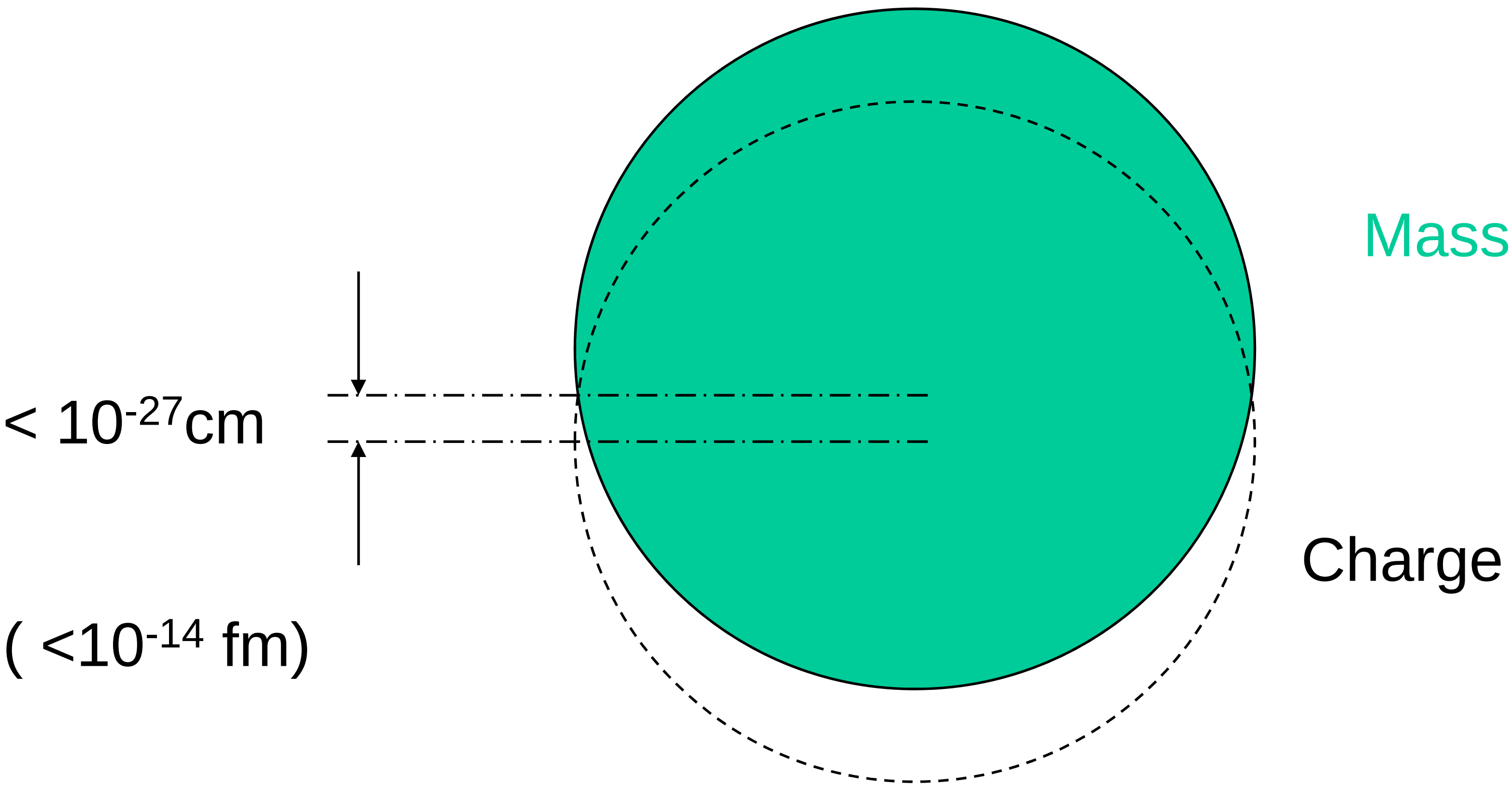


eEDM looks like offset between center of mass and center of charge!

Experimental Limit: eEDM $< 10^{-27}$ e-cm



If the electron were the size of the earth, its asymmetry (scaled up) has been measured to be less than the diameter of a virus.

Asymmetry less than 10^{-27} cm. Commins, 2002. Pretty good!

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Q: Why?

New particle physics from precision dipole moments ---- long tradition

Electron's magnetic moment: $\mu_e = g\mu_b$

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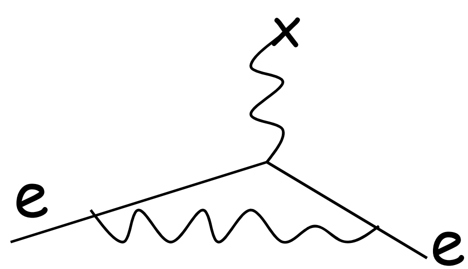

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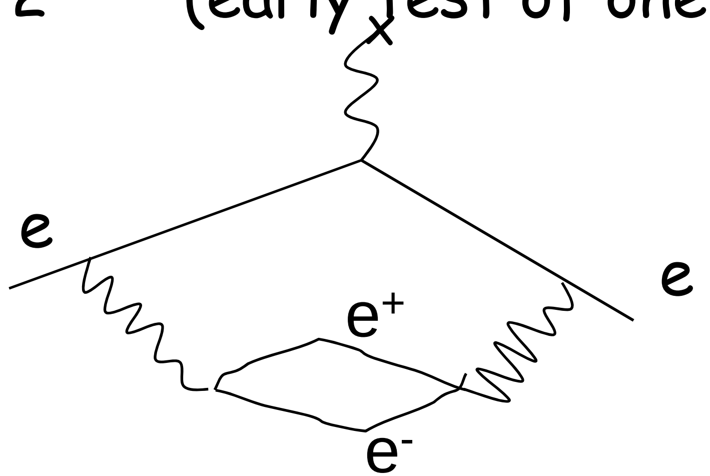
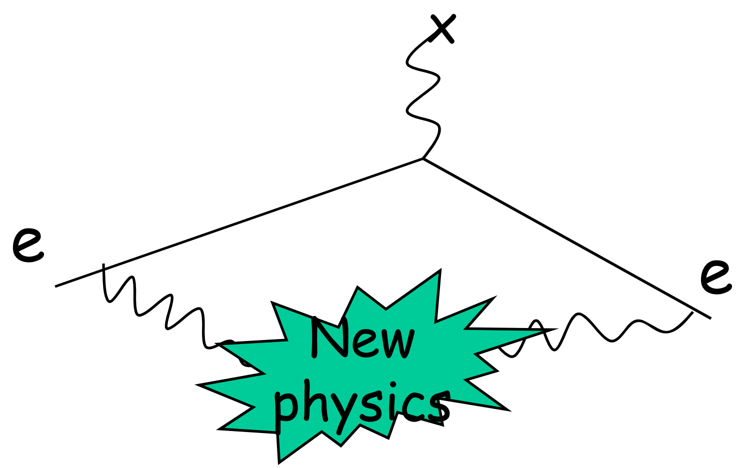


3. $g = 2 + a_1\alpha + a_2\alpha^2 + a_3\alpha^3 + a_4\alpha^4 + \ldots$

(best test of many-loop field theory)

Q: Can we get still more particle physics, beyond SM, from electron μ_{mag}?



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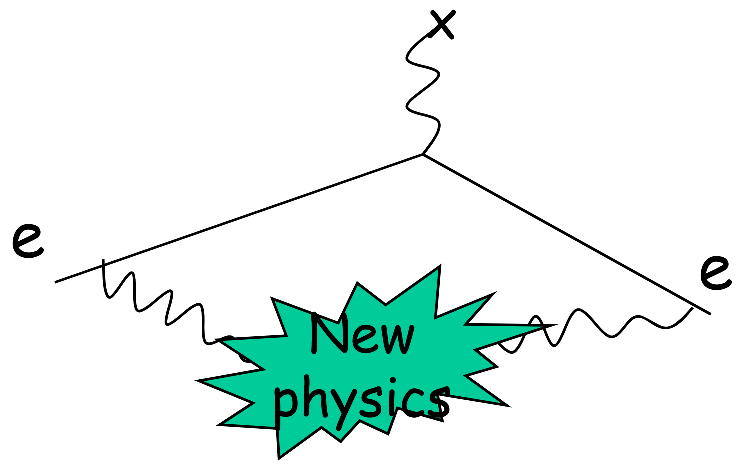
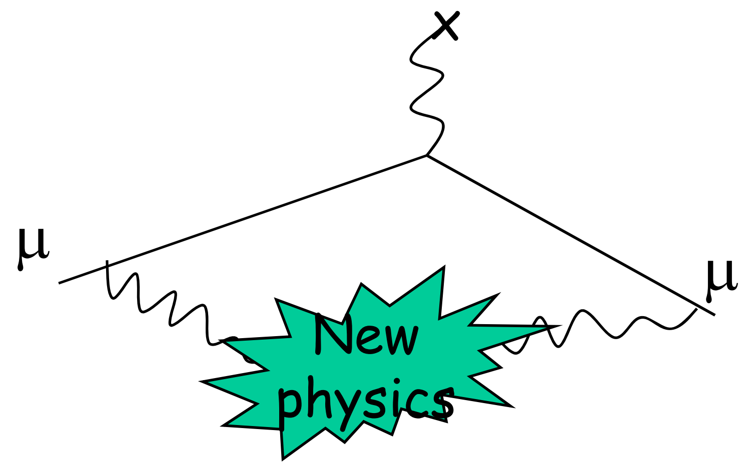


A: Probably not. m_e is too small.

Q: How about new particle physics from muon μ_{mag}?



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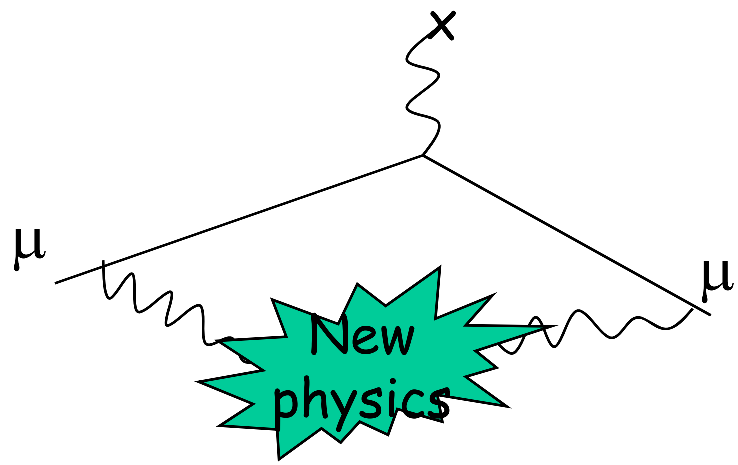
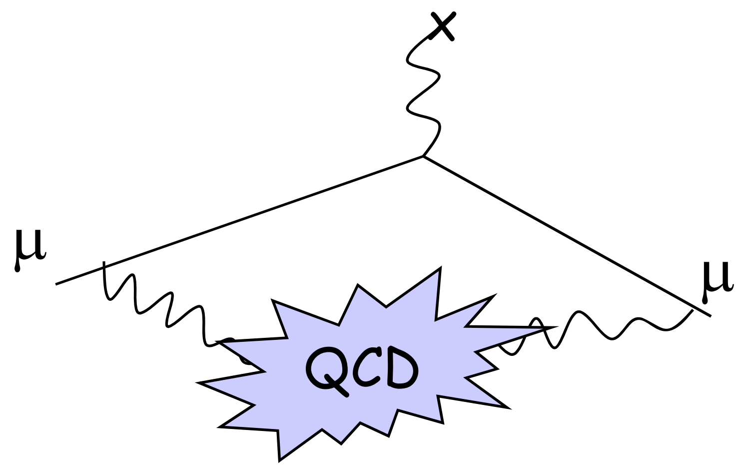


A: Probably not (although there has been a big effort) due to uncertainties in QCD "theory background".

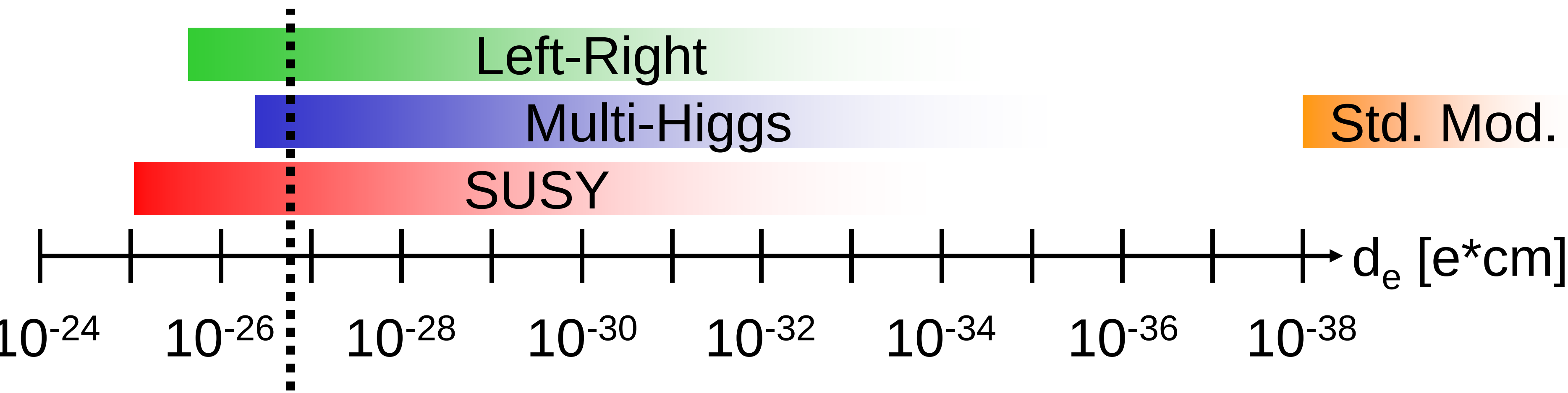


New particle physics from precision dipole moments

Advantage of *electric* dipole moments, with respect to *magnetic* dipole moments:

d_e, d_n, d_μ, d_{Hg}...

have very small SM theory background



$|d_e| < 1.6 \times 10^{-27}$ e*cm

E.D. Commins Tl Exp. Limit [PRL **88**, 071805 (2002)]

New physics against zero background – and (maybe) not too far away?

Sociology comment.

nEDM,   nuclear Schiff moments, μEDM

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Q: How?

Cornell, Eric A.
Arrest date: 6/2/08
Arrest complaint:
Symmetry violation
in a public space

Charge:Symmetry violation in a public space

CONVICTED

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Q: How?

A: With a lot of help.

JILA eEDM project

Cornell [Aaron Leanhardt] Russell Stutz
Laura Sinclair, Huanqian Loh, Herbert Looser
John Bohn Ed Meyer

Q: “Who are your influences?”
--- The Commitments (1991)

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Carl Lineberger
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remote help: Peter Bernath and St. Pete's bunch:
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Carl Wieman. Commins/Budker/Demille

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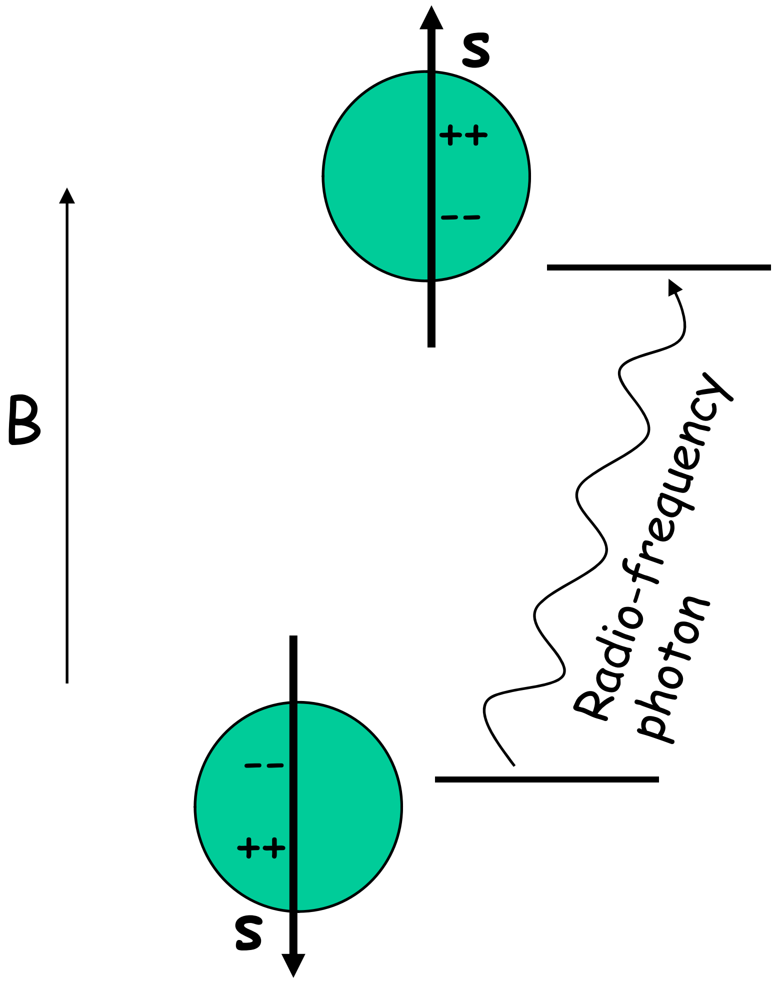
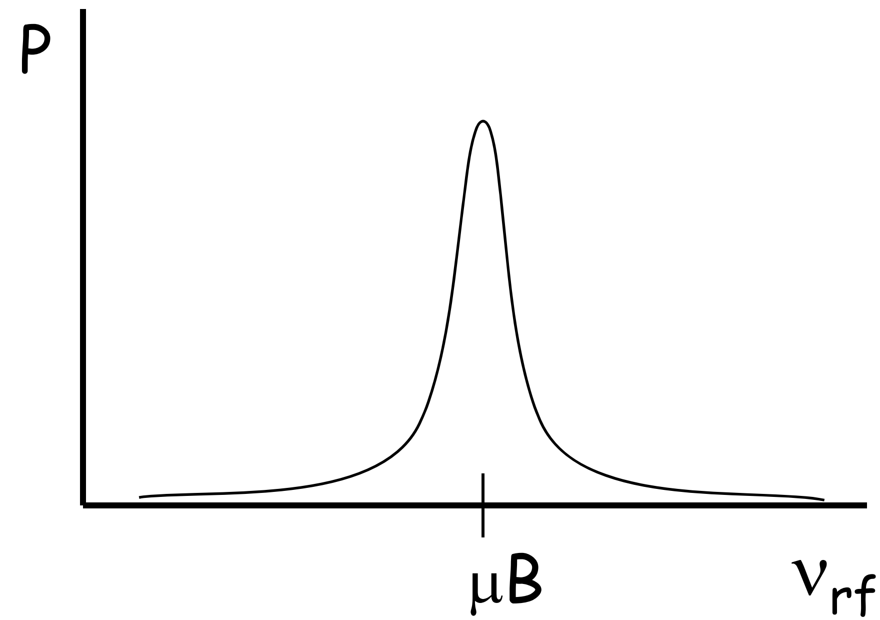
Q: How?

How to measure eEDM? First, how do we measure eMDM?





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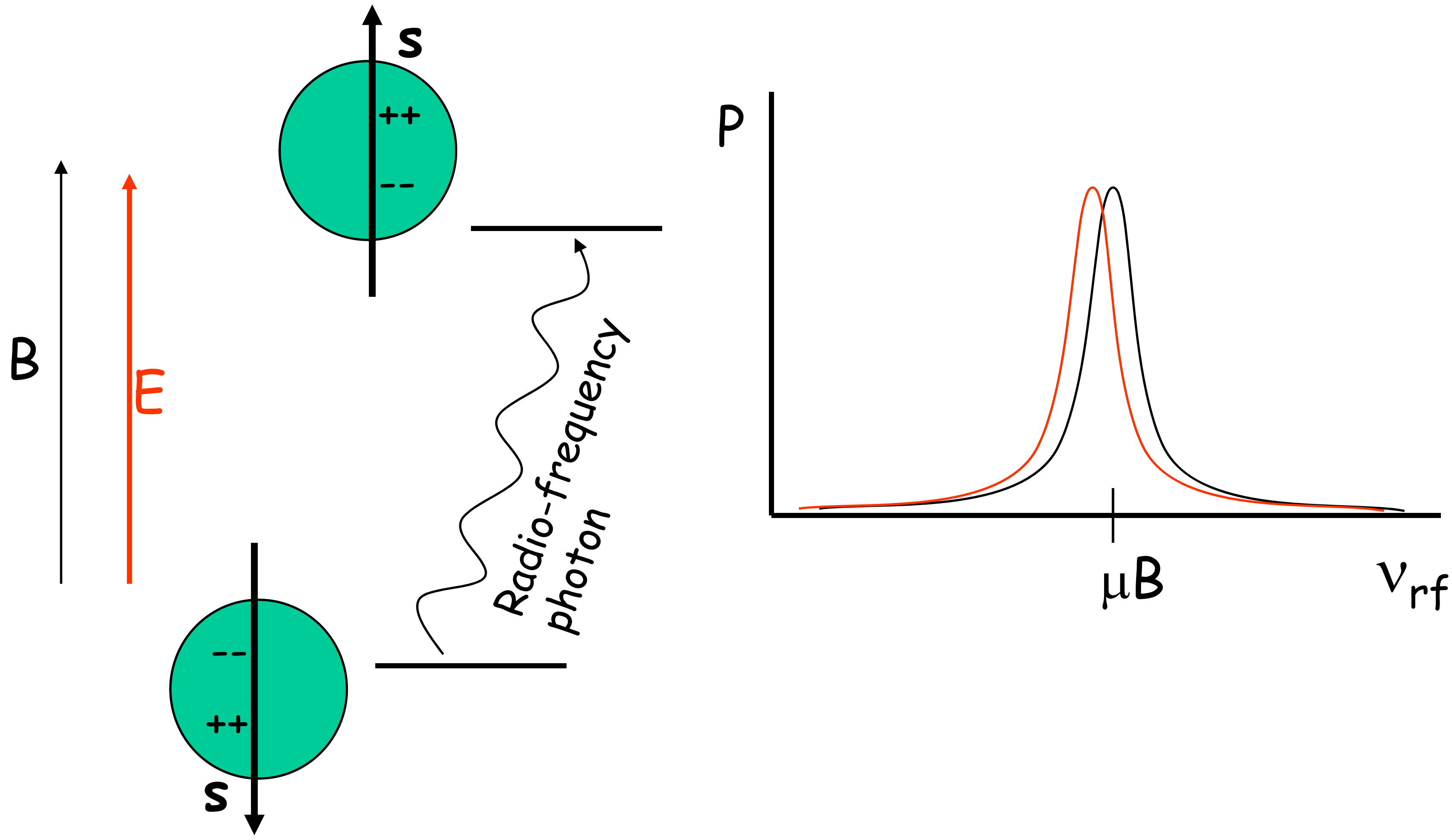

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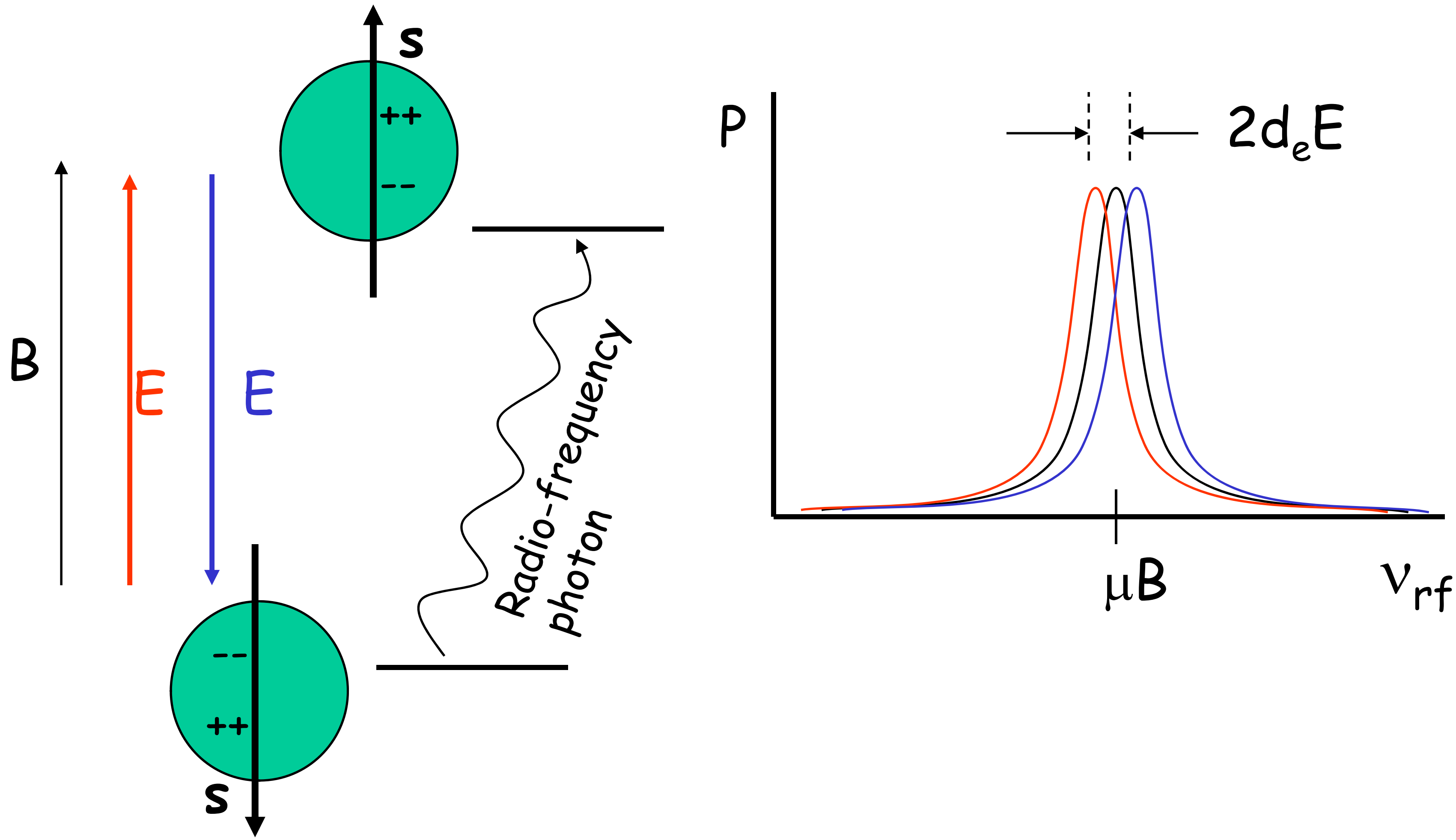
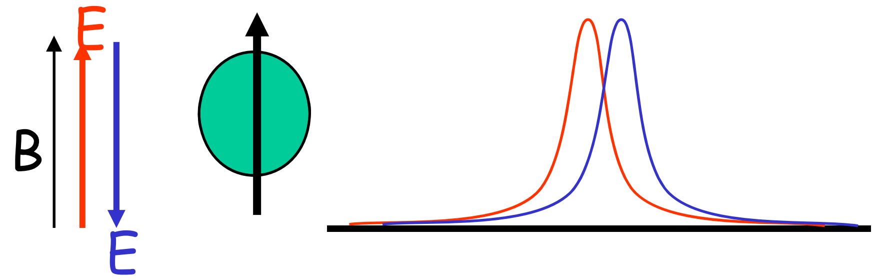
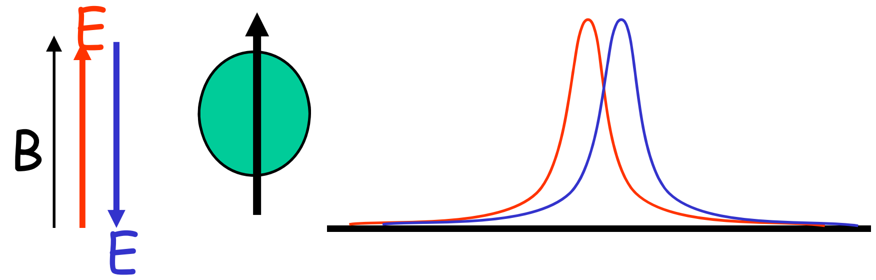




E
B
E

Figure-of-merit:
What makes a good EDM experiment?



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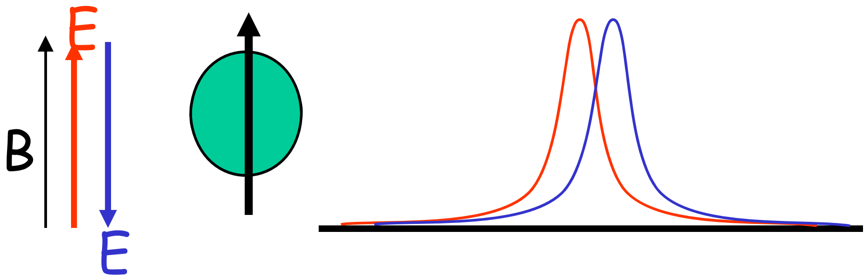

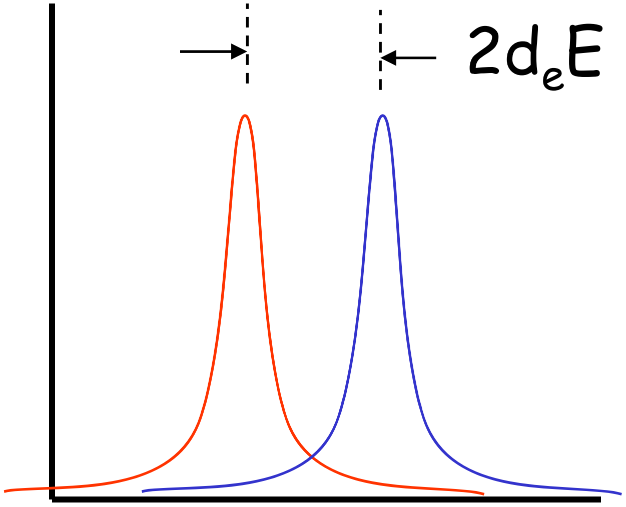

Big Electric Field!

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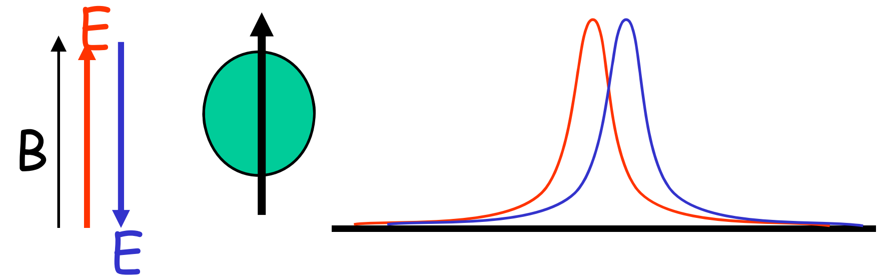

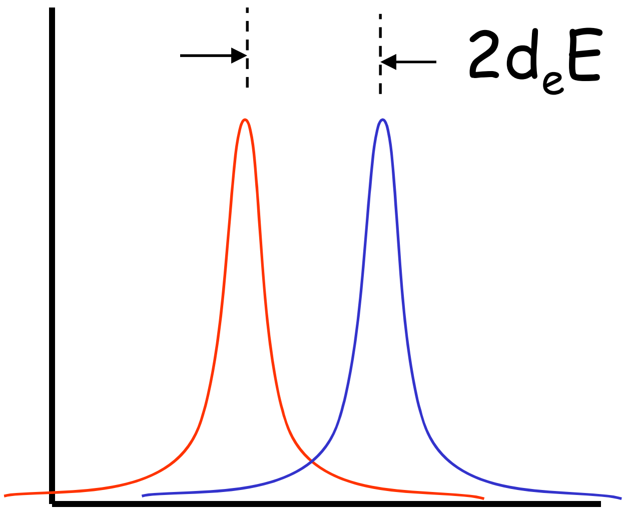

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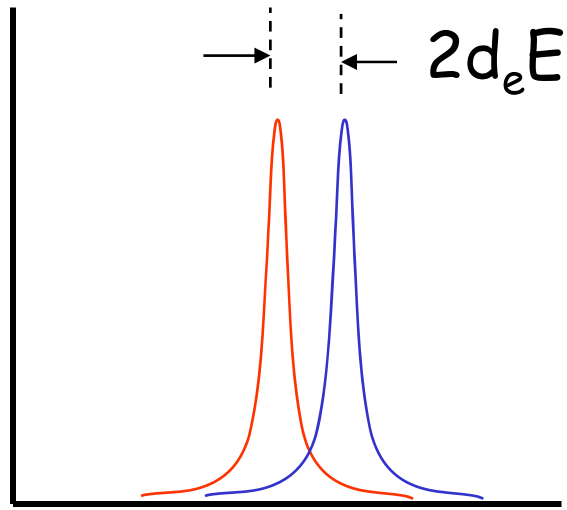

Big Coherence Time (narrow resonances)!

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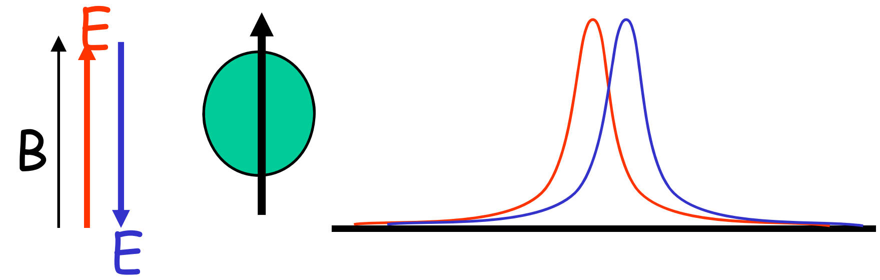

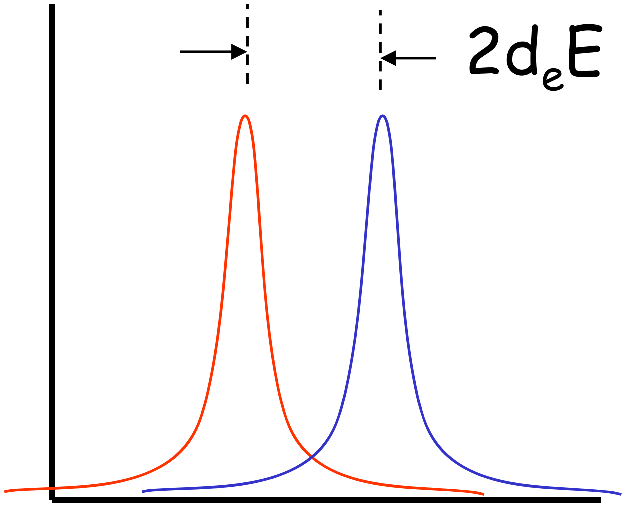

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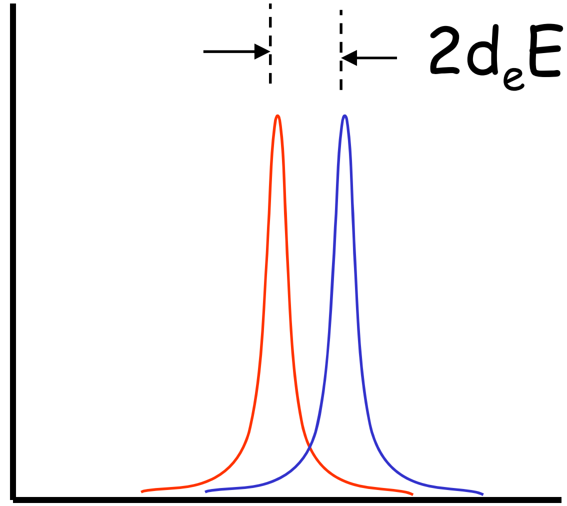

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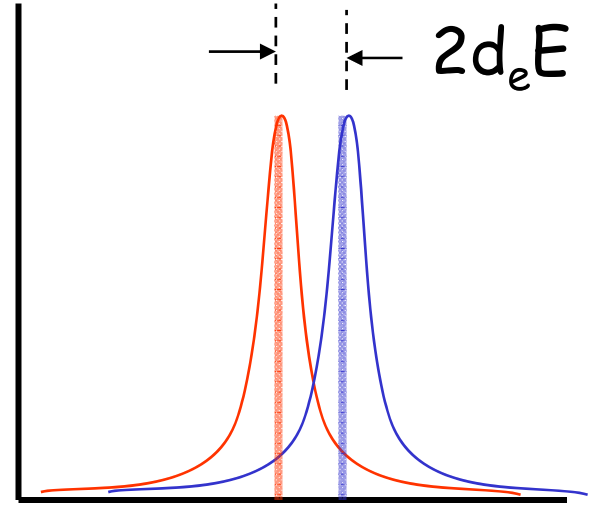
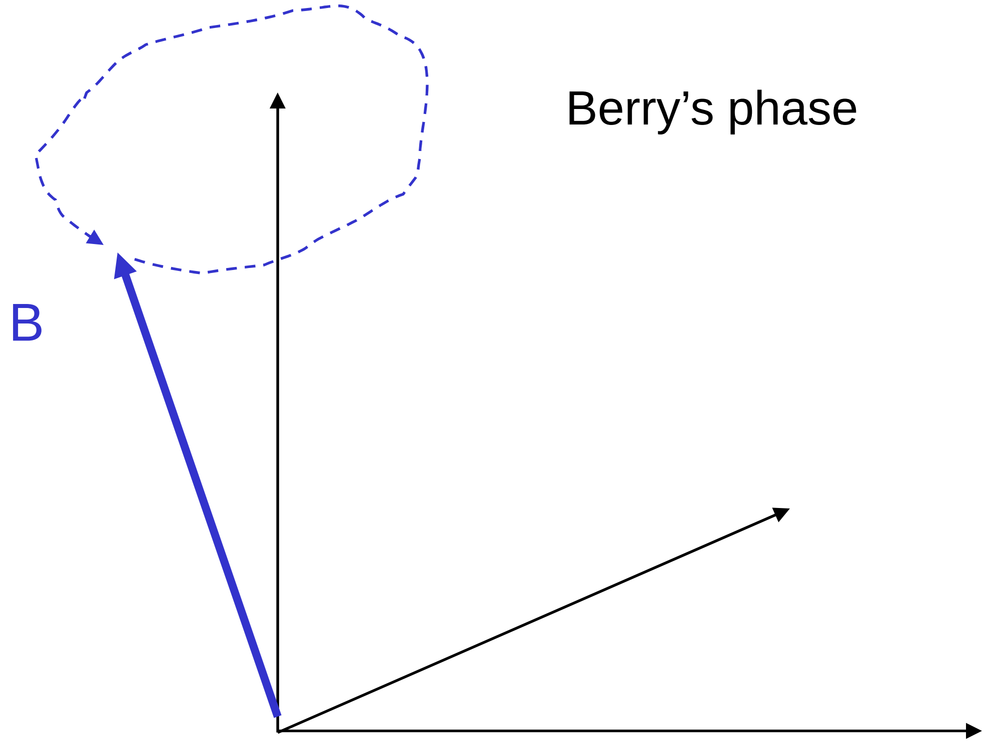


Large count rate (split resonance by $\sqrt{N_{eff}}$)

Combined
Figure-of-merit: $E_{eff}\,\tau\,\sqrt{N_{eff}}$

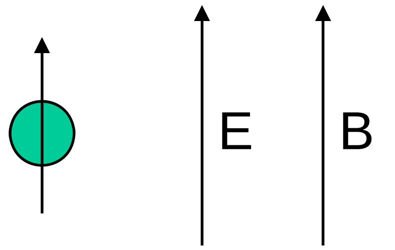
Berry’s phase



When quantization axis B traces out a closed loop that encloses solid angle Ω, then a quantum spin* with angular momentum projection m on the quantization axis picks up a phase $m\Omega$ with each cycle (in the limit of really slow change.)

*Note, true for composite objects, like molecules, too. What matters is total m.

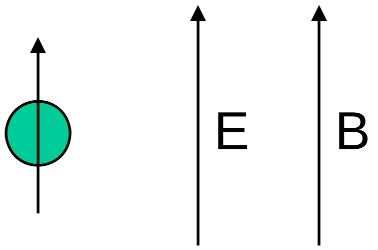
Who's Our Daddy? Neutron EDM experiment



Ez	Bz	E(m=1/2)-E(m=-1/2)	Chop
$E_0+\delta E$	$B_0+\delta B$	$d(E_0+\delta E)\ +\mu(B_0+\delta B)$	+1
$E_0+\delta E$	$-B_0+\delta B$	$d(E_0+\delta E)\ +\mu(-B_0+\delta B)$	+1

Total: $4d(E_0+\delta E) + 2\mu\delta B$

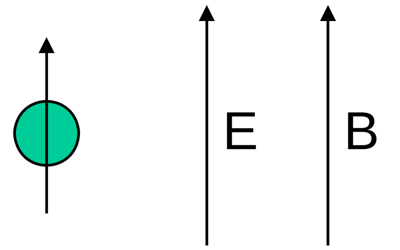
Who's Our Granddaddy? Neutron EDM experiment



Ez	Bz	E(m=1/2)-E(m=-1/2)	Chop
$E_0+\delta E$	$B_0+\delta B$	$d(E_0+\delta E) + \mu(B_0+\delta B)$	+1
$E_0+\delta E$	$-B_0+\delta B$	$d(E_0+\delta E) + \mu(-B_0+\delta B)$	+1

Total: $4d(E_0+\delta E) + 2\mu\delta B$

Who's Our
Great Granddaddy?
Neutron EDM experiment



Ez	Bz	E(m=1/2)-E(m=-1/2)	Chop
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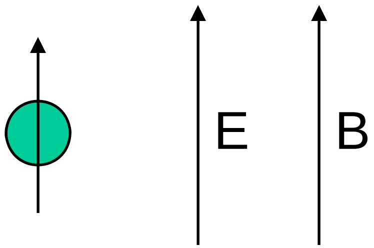

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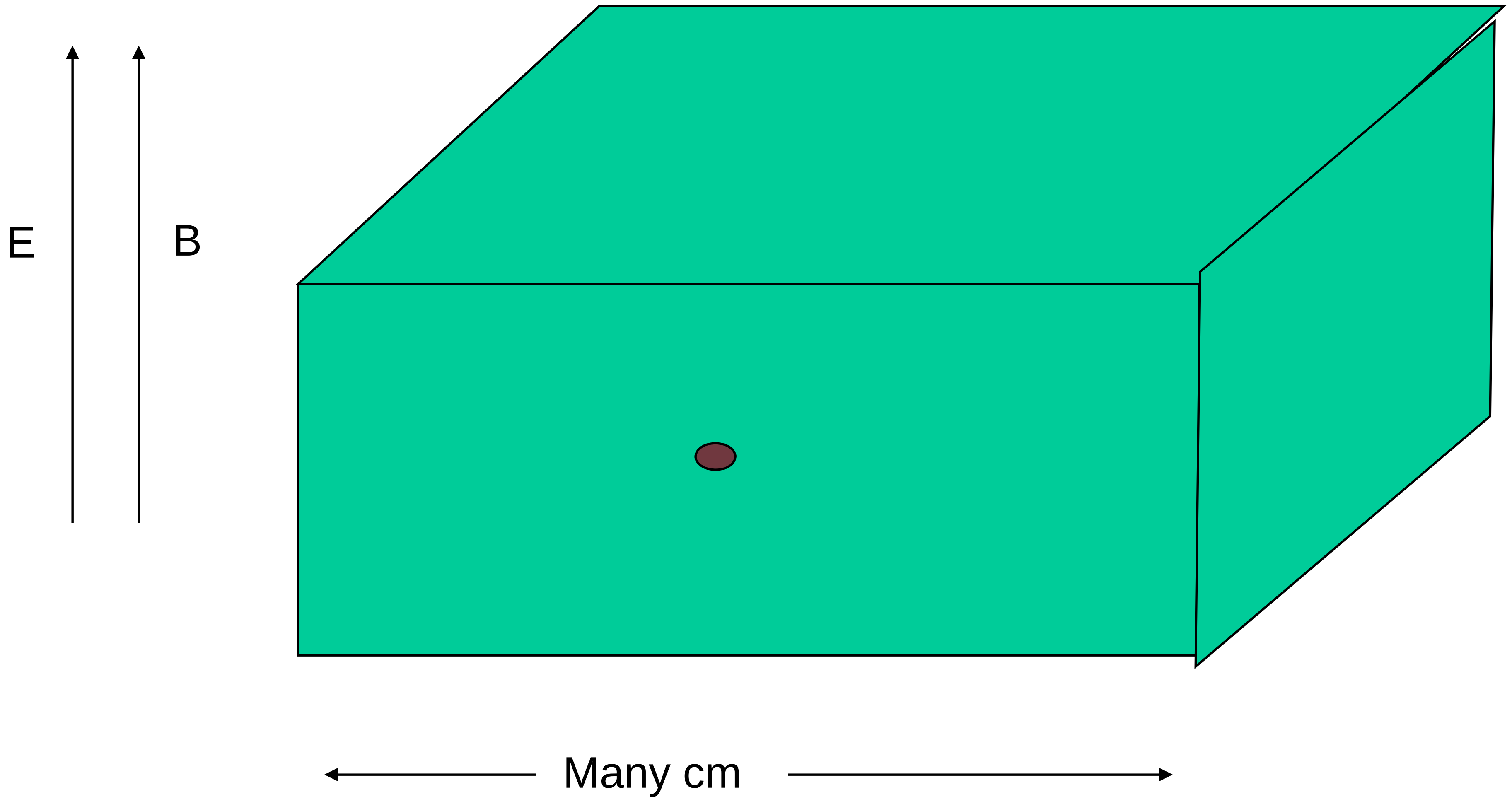
$E_0+\delta E$	$-B_0+\delta B$	$d(E_0+\delta E) + \mu(-B_0+\delta B)$	+1
$-E_0+\delta E$	$B_0+\delta B$	$d(-E_0+\delta E) + \mu(B_0+\delta B)$	-1
$-E_0+\delta E$	$-B_0+\delta B$	$d(-E_0+\delta E) + \mu(-B_0+\delta B)$	-1

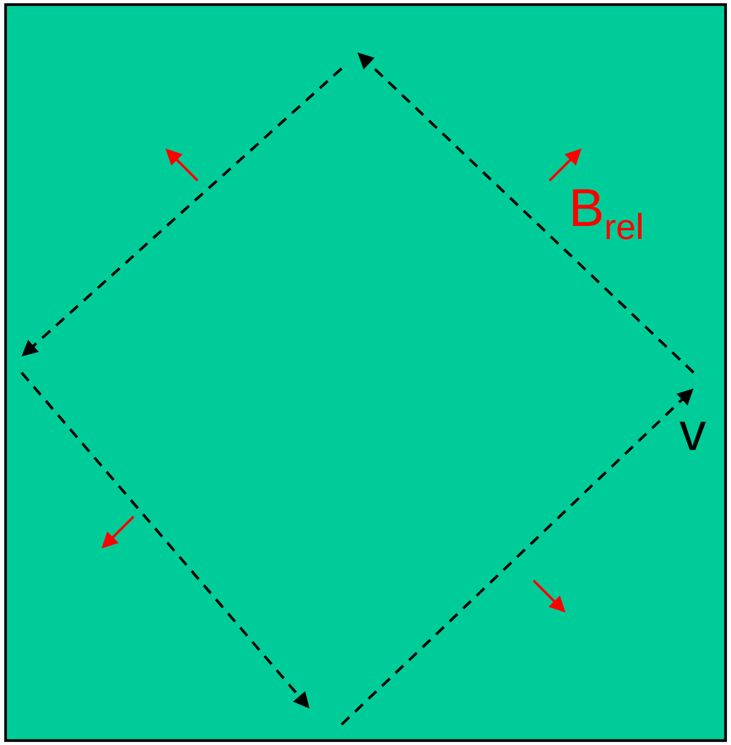
Total: $4E_0$

Neutron-in-a-box (literally)



B_0, E_0, point up out of the screen

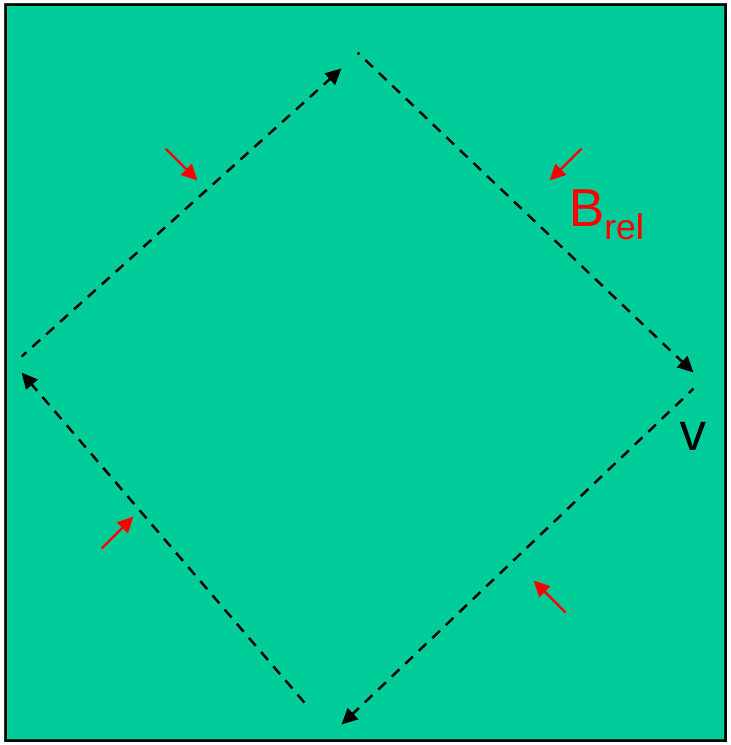
Neutron motion partially transforms strong electric field into B-field.



Enclosed area of neutron trajectory means enclosed area of B-vector in time. A shift in phase between m=1/2 and m=-1/2 levels!

B_0, E_0, point up out of the screen

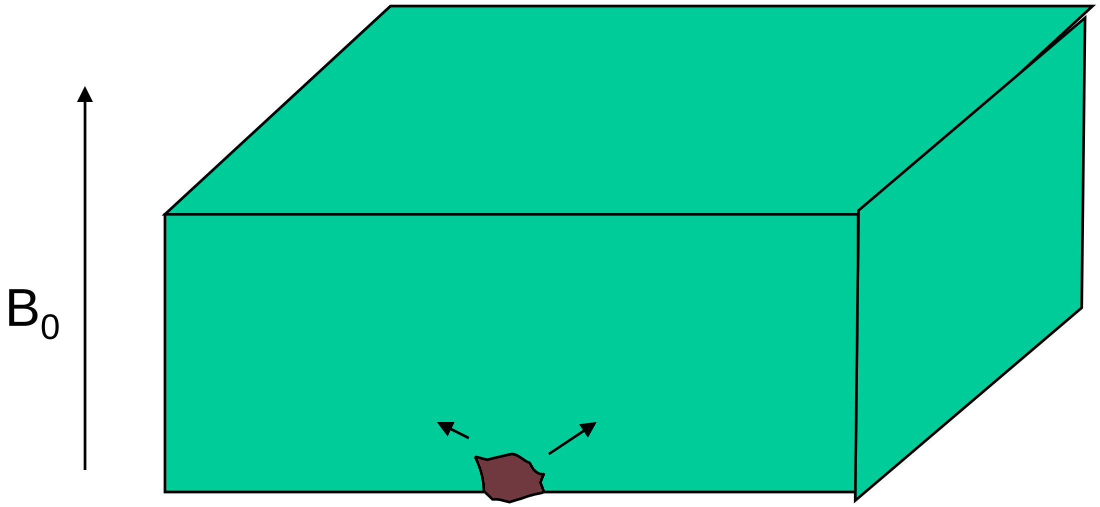
Neutron motion partially strong electric field into B-field.



Thermal distribution of trajectories means this effect as no net sign.

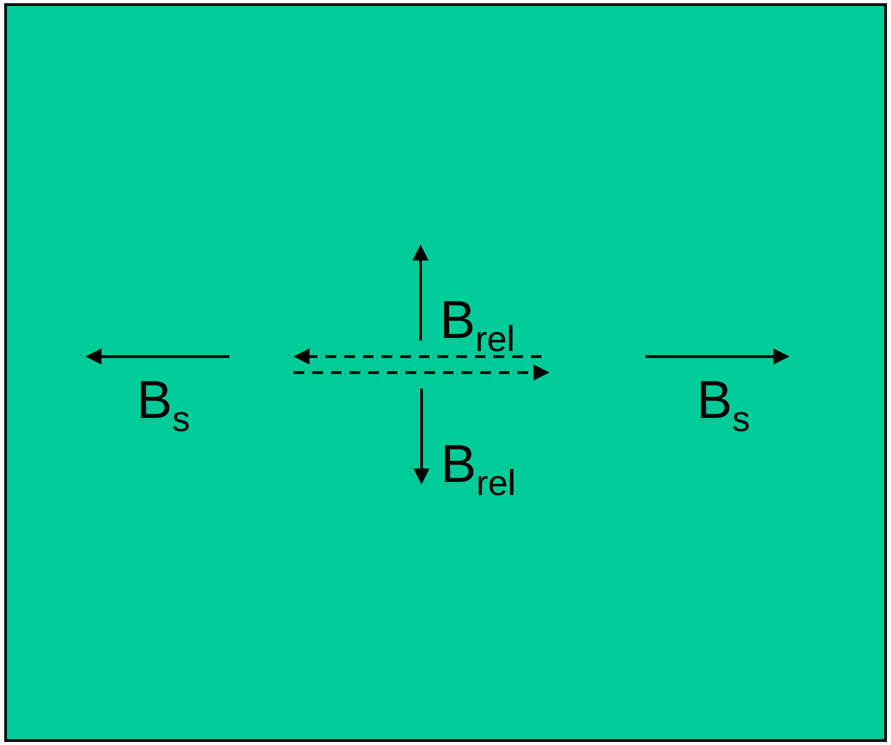
Enclosed area of neutron trajectory means
enclosed area of B-vector in time. A shift in phase between
m=1/2 and m=-1/2 levels!

Not an important source of dephasing (decoherence) in the nEDM experiments. But, with the addition of an stray gradient, can cause systematic error.



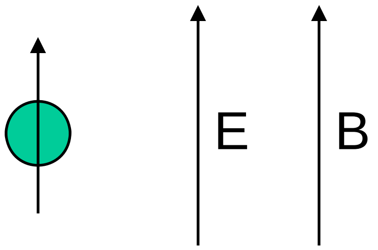
Stray gradient due to permanently magnetized piece of schmutz

Top view, B_0 out of the page.



You can now get enclosed B-field trajectory over time even when neutron's coordinate-space trajectory enclose no area.

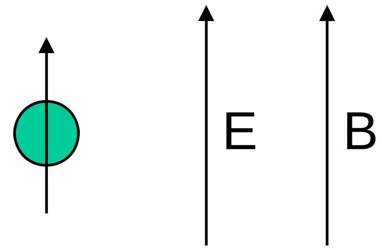
Neutron EDM experiment



Ez	Bz	E(m=1/2)-E(m=-1/2)	Chop
$E_0+\delta E$	$B_0+\delta B$	$d(E_0+\delta E) \ +\mu(B_0+\delta B)$	+1
$E_0+\delta E$	$-B_0+\delta B$	$d(E_0+\delta E) \ +\mu(-B_0+\delta B)$	+1
$-E_0+\delta E$	$B_0+\delta B$	$d(-E_0+\delta E) \ +\mu(B_0+\delta B)$	-1
$-E_0+\delta E$	$-B_0+\delta B$	$d(-E_0+\delta E) \ +\mu(-B_0+\delta B)$	-1

Total: $4E_0$

Neutron EDM experiment



Ez	Bz	E(m=1/2)-E(m=-1/2)	Rel.Berry	Chop
$E_0+\delta E$	$B_0+\delta B$	$d(E_0+\delta E) \ +\mu(B_0+\delta B)$	cw	+1
$E_0+\delta E$	$-B_0+\delta B$	$d(E_0+\delta E) \ +\mu(-B_0+\delta B)$	cw	+1
$-E_0+\delta E$	$B_0+\delta B$	$d(-E_0+\delta E) \ +\mu(B_0+\delta B)$	ccw	-1
$-E_0+\delta E$	$-B_0+\delta B$	$d(-E_0+\delta E) \ +\mu(-B_0+\delta B)$	ccw	-1

Total: $4dE_0$ + 4 cw phase units. Ouch.

Gets worse for big E_0 and long free paths. Leakage currents.

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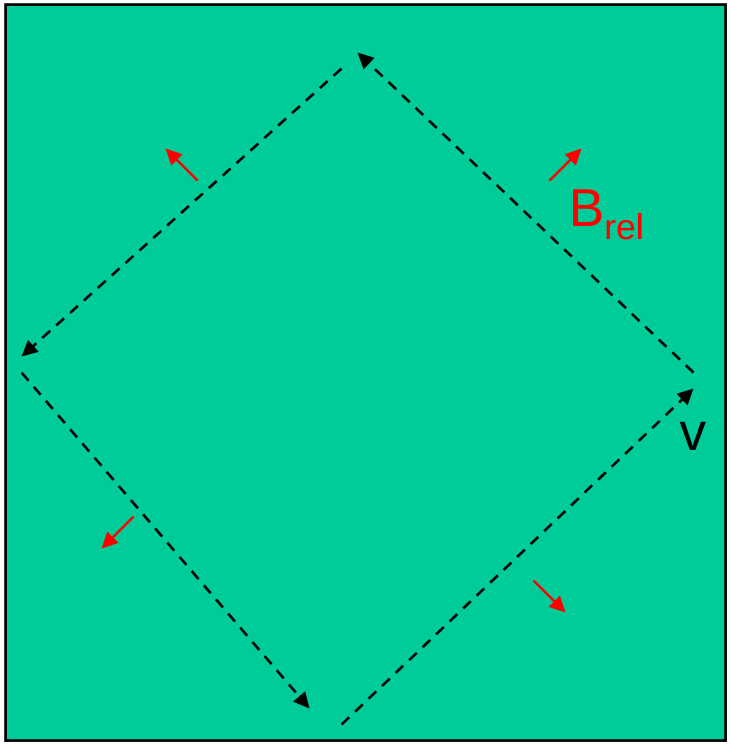
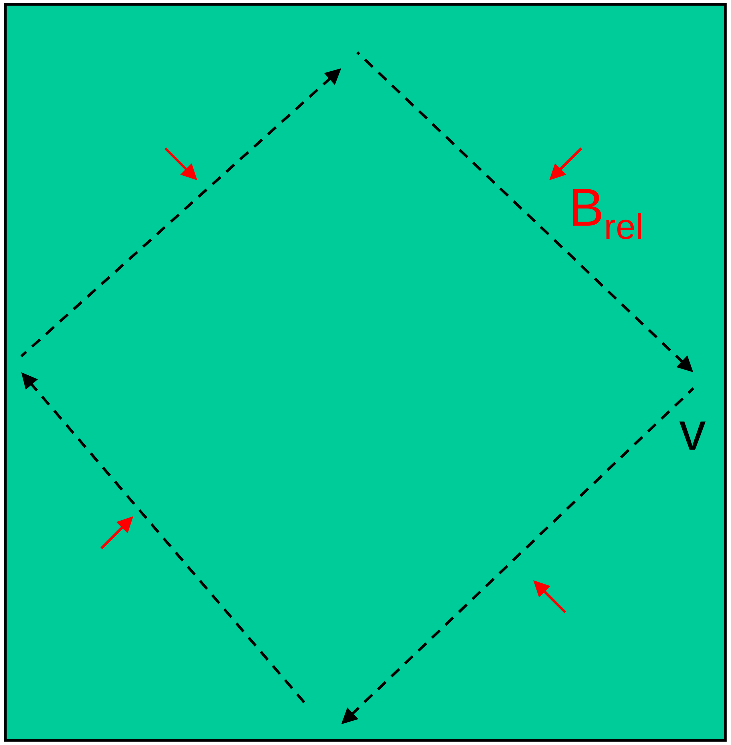


Go back to this case: No dirt (no spatial gradient in B) means no systematic. But, what about dephasing?

Enclosed area of neutron trajectory means enclosed area of B-vector in time. A shift in phase between m=1/2 and m=-1/2 levels!

B_0, E_0, point up out of the screen

Neutron motion partially strong electric field into B-field.



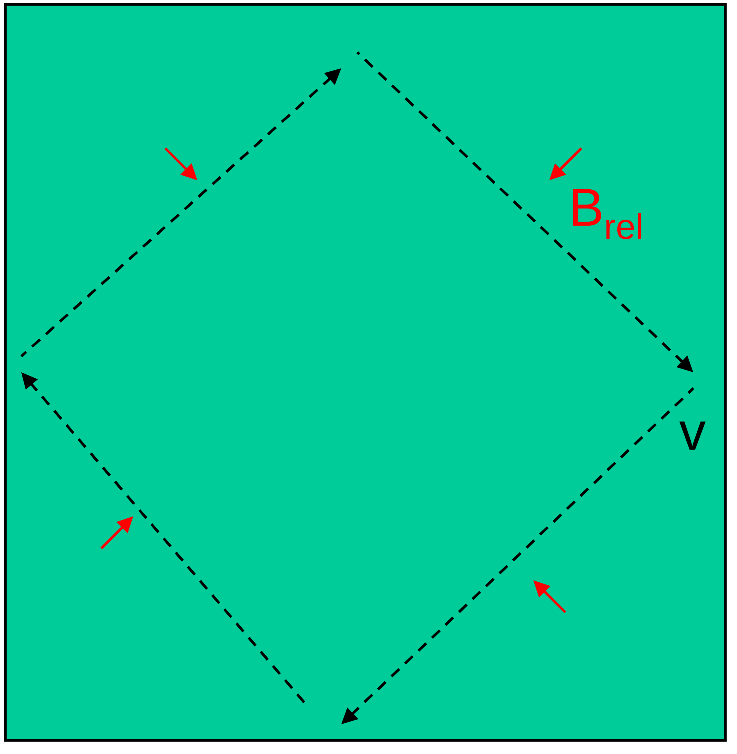
Go back to this case:
No dirt (no spatial gradient in B) means no systematic. But, what about dephasing?

Thermal distribution of trajectories means this effect as no net   sign.

Enclosed area of neutron trajectory means enclosed area of B-vector in time. A shift in phase between m=1/2 and m=-1/2 levels!

B_0, E_0, point up out of the screen

Neutron motion partially strong electric field into B-field.



Thermal distribution of trajectories means this effect as no net   sign.

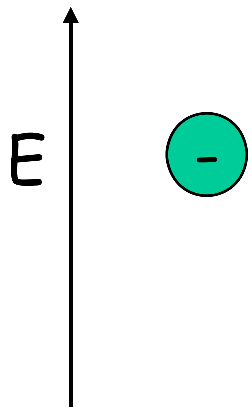
Enclosed area of neutron trajectory means
enclosed area of B-vector in time. A shift in phase between
m=1/2 and m=-1/2 levels!

OK for a box. What about trapped particles!?

Aside: the granddaddy

Problem:

Big E, long τ. Electron accelerates quickly, and is gone????



Problem:

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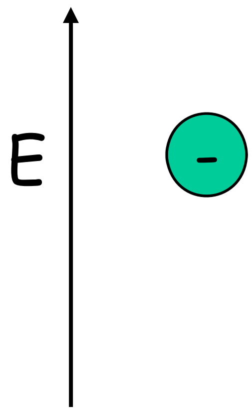
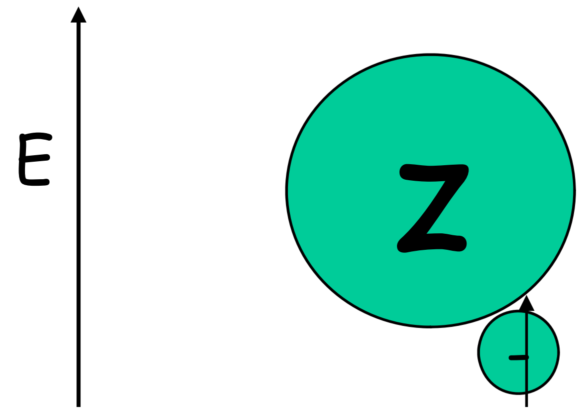
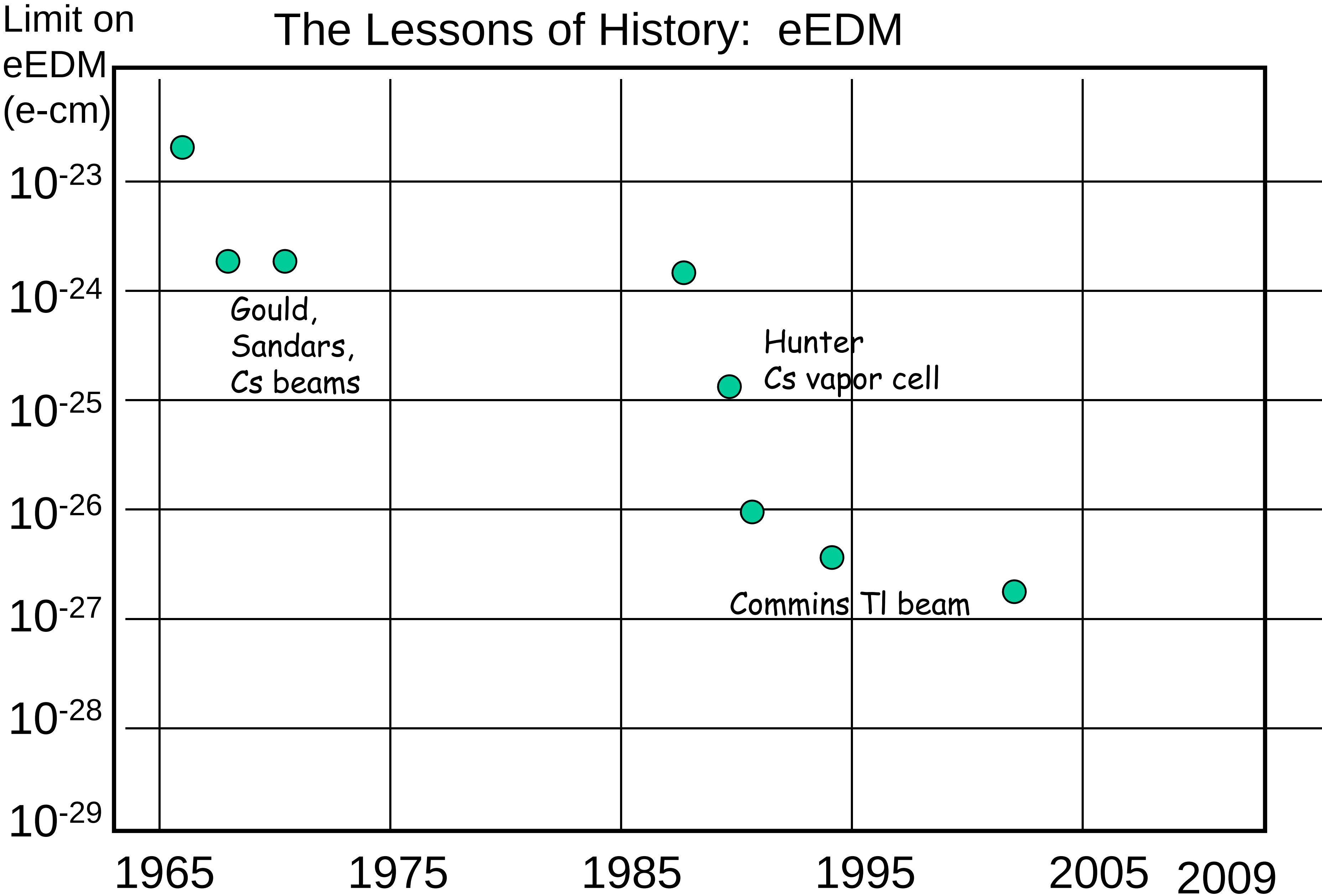


Solution: Attach electron spin to a big atomic nucleus!

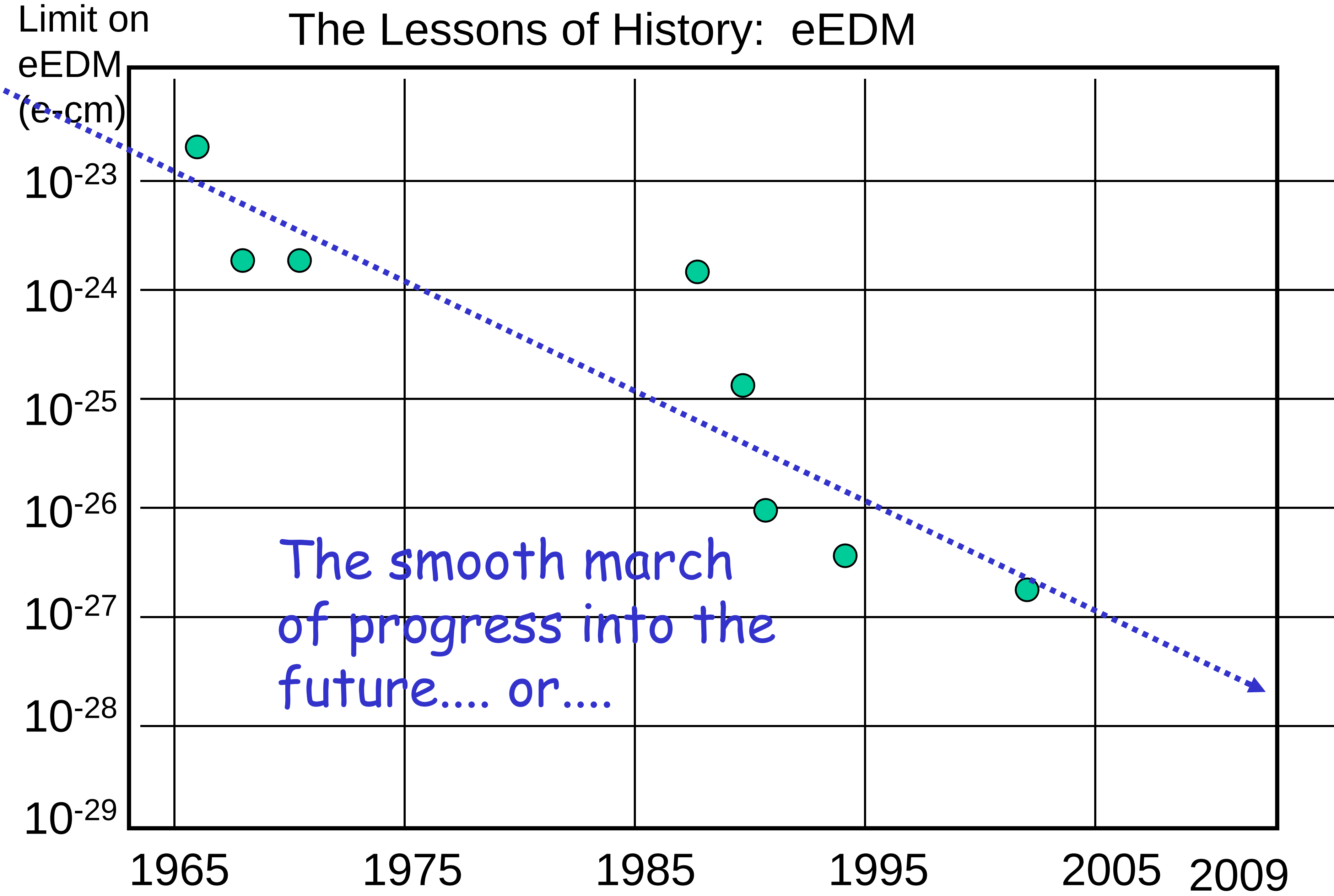


$$E_{eff} = a\, E_{lab}\, Z^3$$

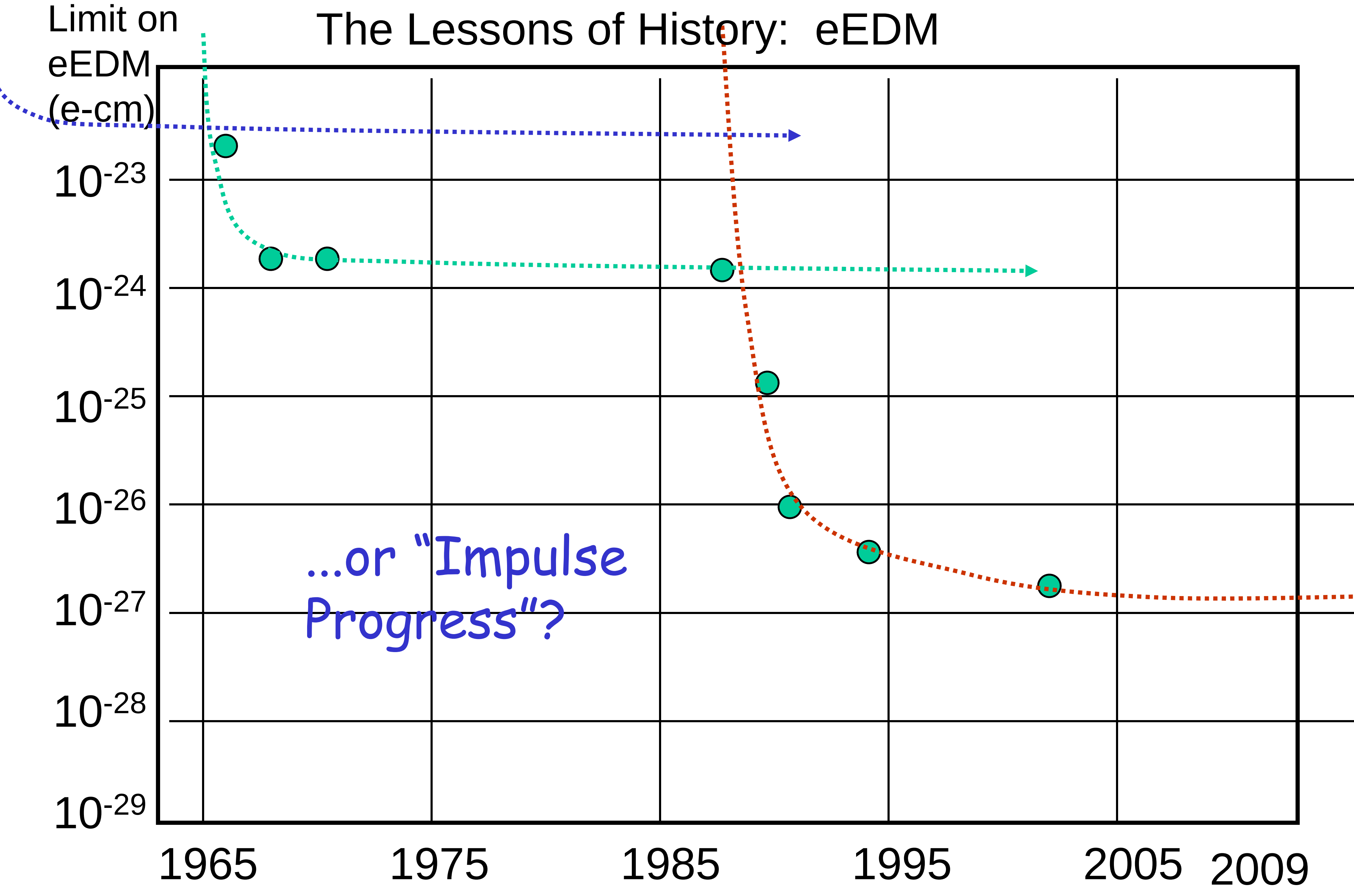
The Lessons of History: eEDM



The Lessons of History: eEDM



The Lessons of History: eEDM



Current limit, beam of atomic Thallium:

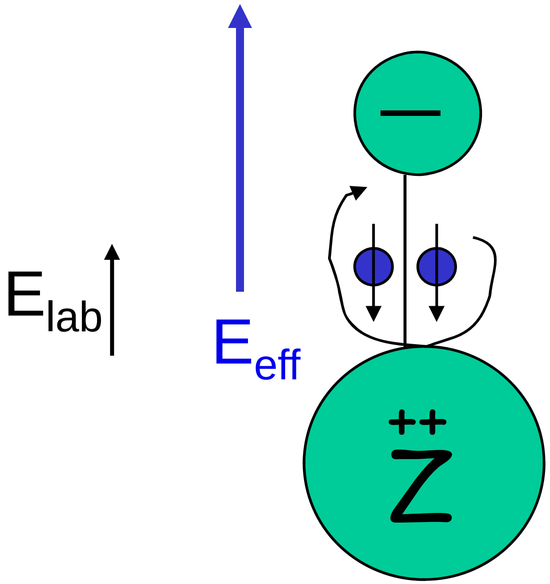
B. Regan, E. Commins, C. Schmidt, D. DeMille, Phys. Rev. Lett. **88**, 071805 (2002)

$|d_e| < 1.6 \times 10^{-27}$ e*cm (90% c.l.)

	E_{eff}	τ	$\sqrt{N_{eff}}$
Commins Tl beam	6×10^{7} V/cm	2 msec	10^{9} s^{-1}

Our approach. 1. Use molecule for big E_{eff}

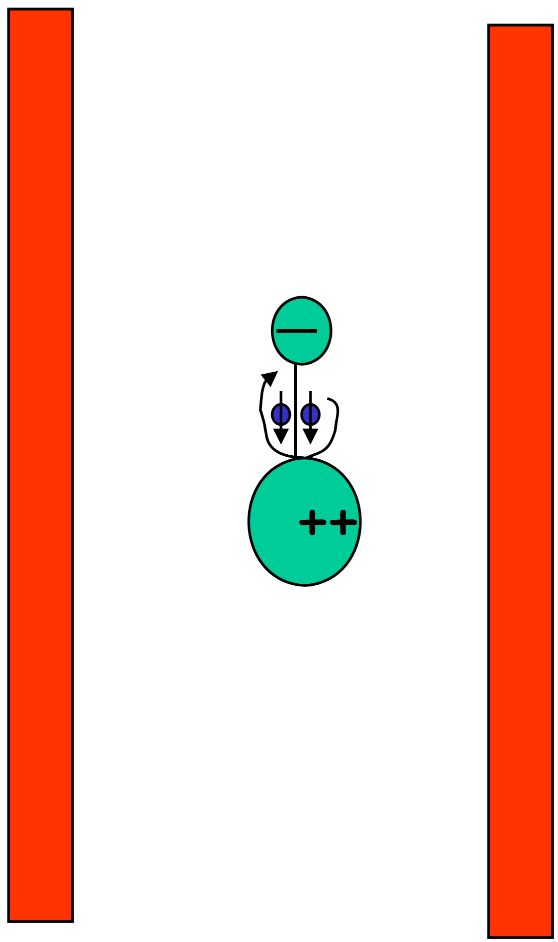
(we follow Hinds and Demille in this)



$E_{lab} = 10$ V/cm $E_{eff} > 10^{10}$ V/cm

Our approach. 2. Use trapped ion for long τ

(atomic spectroscopy in ion traps sees many seconds)



We will work in
a linear Paul trap.

Current limit, beam of atomic Thallium:

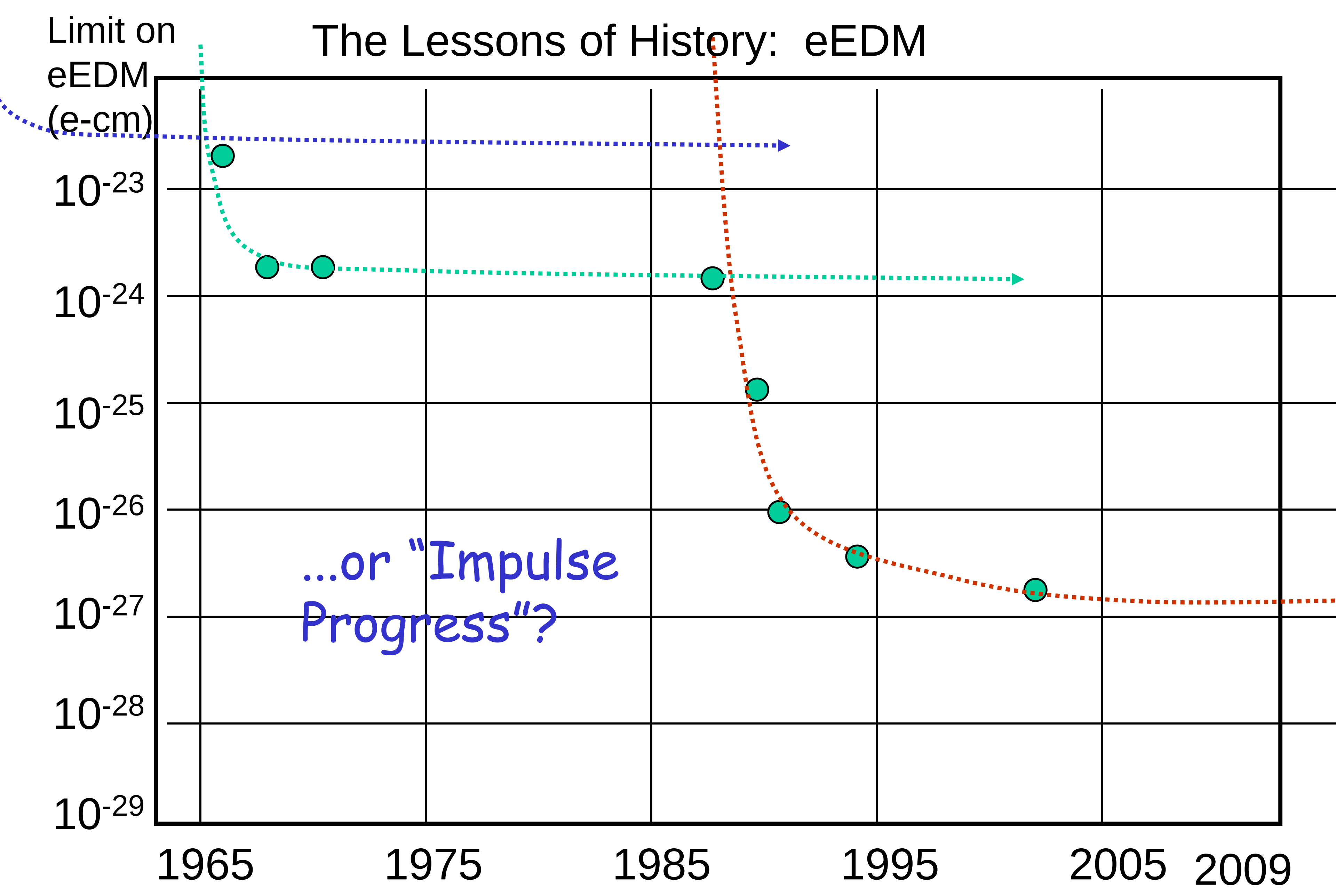
B. Regan, E. Commins, C. Schmidt, D. DeMille, Phys. Rev. Lett. **88**, 071805 (2002)

$|d_e| < 1.6 \times 10^{-27}$ e*cm (90% c.l.)

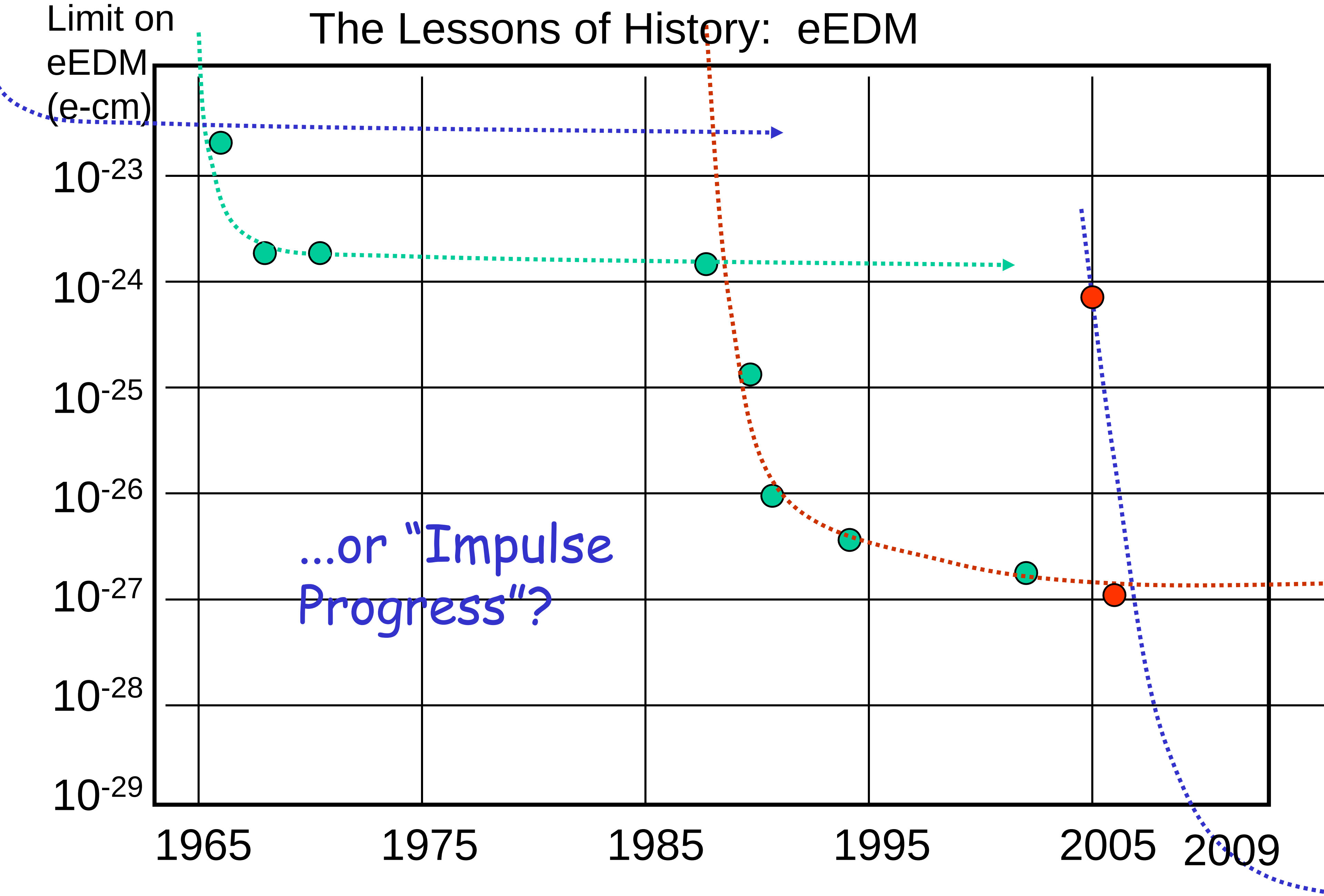
	E_{eff}	τ	$\sqrt{N_{eff}}$
Commins Tl beam	6×10^{7} V/cm	2 msec	10^{9} s^{-1}
Hinds YbF beam	>		<
DeMille PbO vapor cell	>	<	
Weiss trapped Cs	<	>	<
Heinzen trapped Cs	<	>	<
Gould Cs fountain	<	>	<
Shafer-Ray PbF beam	>		<
Cornell trapped HfF+ or ThF+	>	>	<<

Solid State

The Lessons of History: eEDM



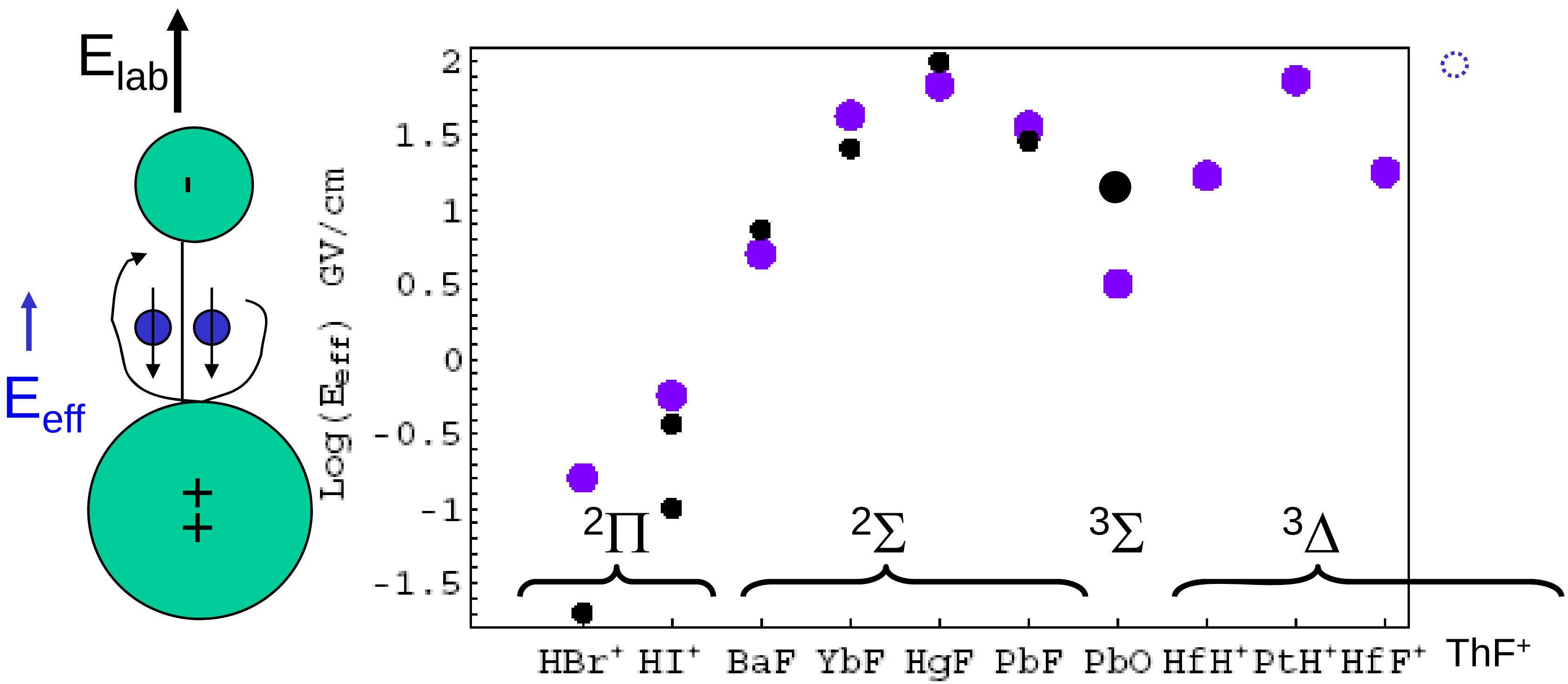
The Lessons of History: eEDM



Candidate Molecular Ions

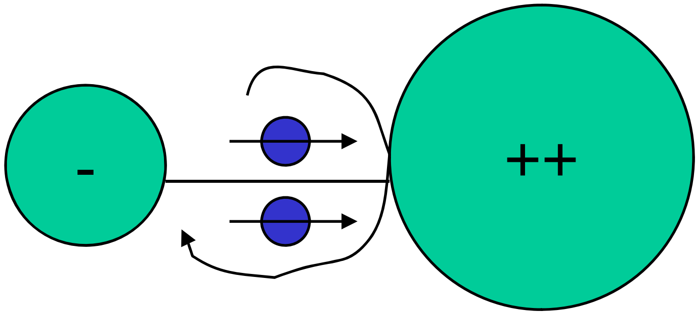
HfF$^+$ and ThF$^+$

- $^3\Delta$ ground states → 1 V/cm to fully polarize
- strong atomic 6s character → large E_{eff}



Meyer and Bohn "jiffycalc" points in blue. PRA 73, 062108 (2006)
Full-on "one-calculation-equals-one-publication", various authors, in black, arXiv:physics/0506038 and refs. therein

Why Use $^3\Delta_1$ state of molecule?



$$\vec{L}\bullet\hat{z} = 2, \quad \hat{s}\bullet\hat{z} = -1$$

$$g \approx 0 \quad (= 0.03\mu_B)$$

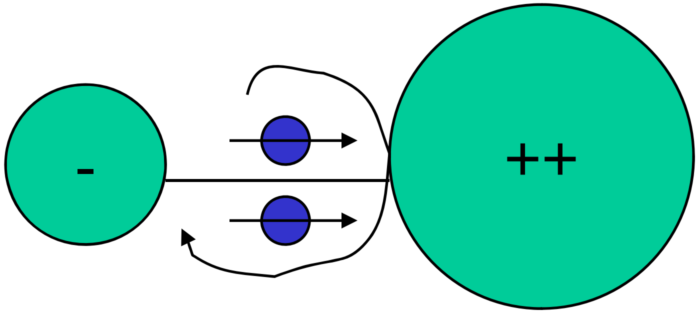
Thallium: $E_{lab} = 10^5$ V/cm $E_{eff} = 6\times10^7$ V/cm $\mu_{mag} = 1.0\ \mu_B$

HfF^+ or ThF^+: $E_{lab} = 10^1$ $E_{eff} = 1.5\times10^{10}$ $\mu_{mag} = 0.03$

E-field-systematic Figure-of-merit: $E_{eff}/(E_{lab}\ \mu_{mag})$

Our experiment is >10^7 to the good. Probably will not even need mu-metal shielding.

Why Use $^3\Delta_1$ state of molecule?



$$\vec{L} \bullet \hat{z} = 2, \quad \hat{s} \bullet \hat{z} = -1$$

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HfF^+ or ThF^+: $E_{lab} = 10^1$ $E_{eff} = 1.5\times10^{10}$ $\mu_{mag} = 0.03$

Figure-of-merit: $E_{eff}/(E_{lab}\ \mu_{mag})$

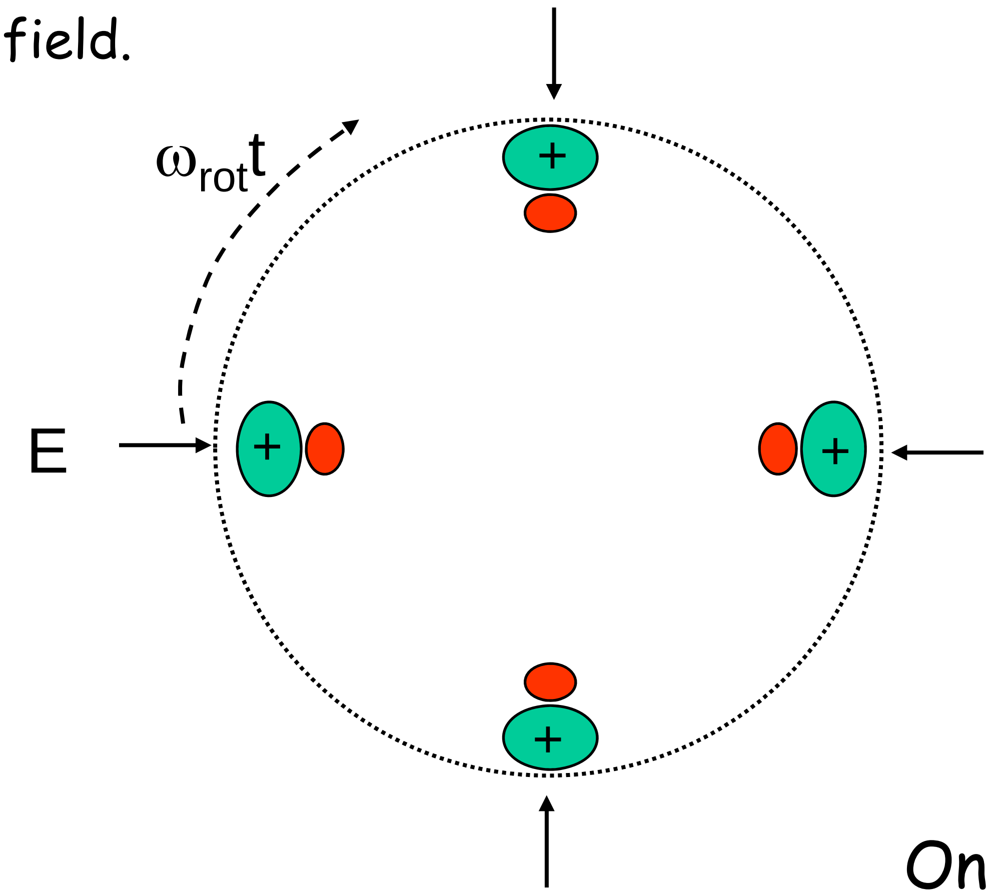
Our experiment is $>10^7$ to the good

?????But even 10 V/cm is enough to make an ion accelerate out of trap????

!!!!!Use rotating E-field bias!!!!!

-E-field defines quantization axis

-Excellent rejection of lab-frame residual B-field.



ω_{rot} is:

BIG enough that radius of "micromotion" circle is small compared to trap size.

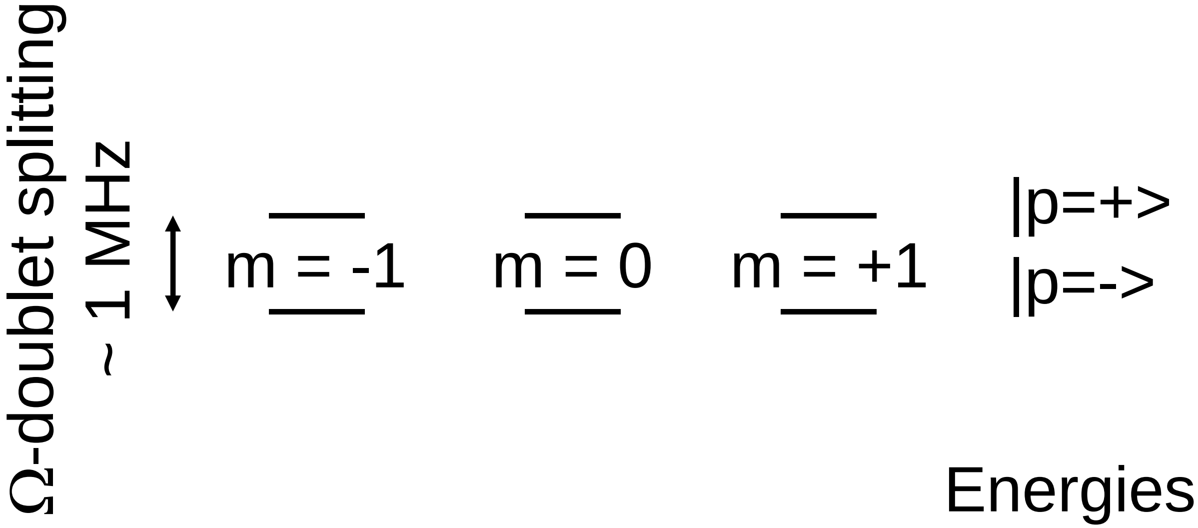
SMALL enough so that d_{mol} E >> ω_{rot} and the molecule axis stays aligned with E.

One does Zeeman-level spectroscopy then in the rotating frame.

Experimental Procedure

HfF^+ $^3\Delta_1$ J=1 ground state

- Ω-doublet splitting ~ 1 MHz



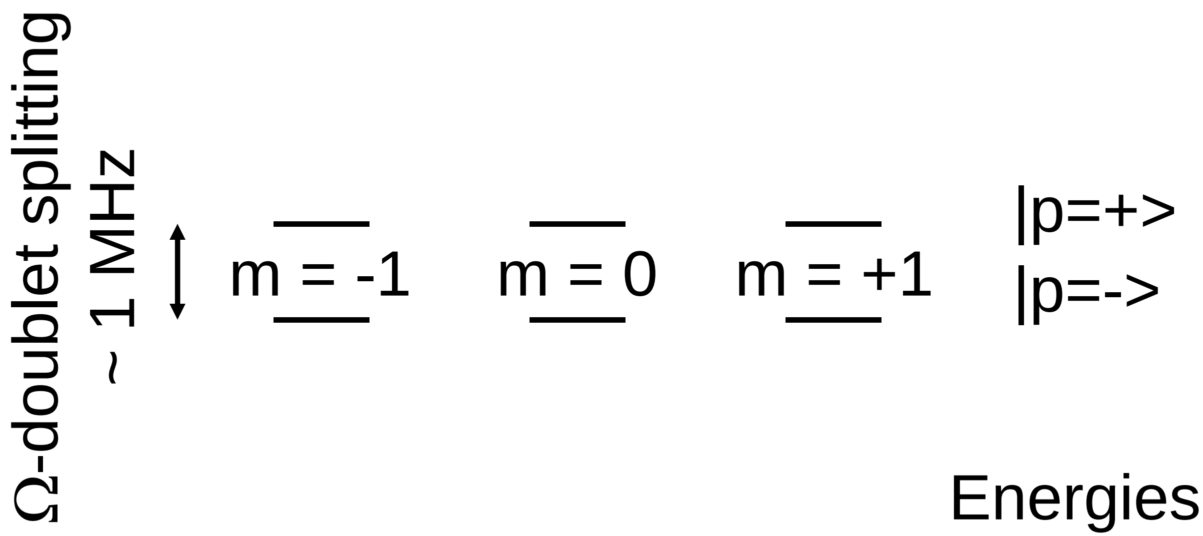
Energies not to scale.
Nuclear spin of ½
excluded for clarity.

An aside about lambda, or omega doubling.

Experimental Procedure

HfF^+ $^3\Delta_1$ J=1 ground state

- Ω-doublet splitting ~ 1 MHz

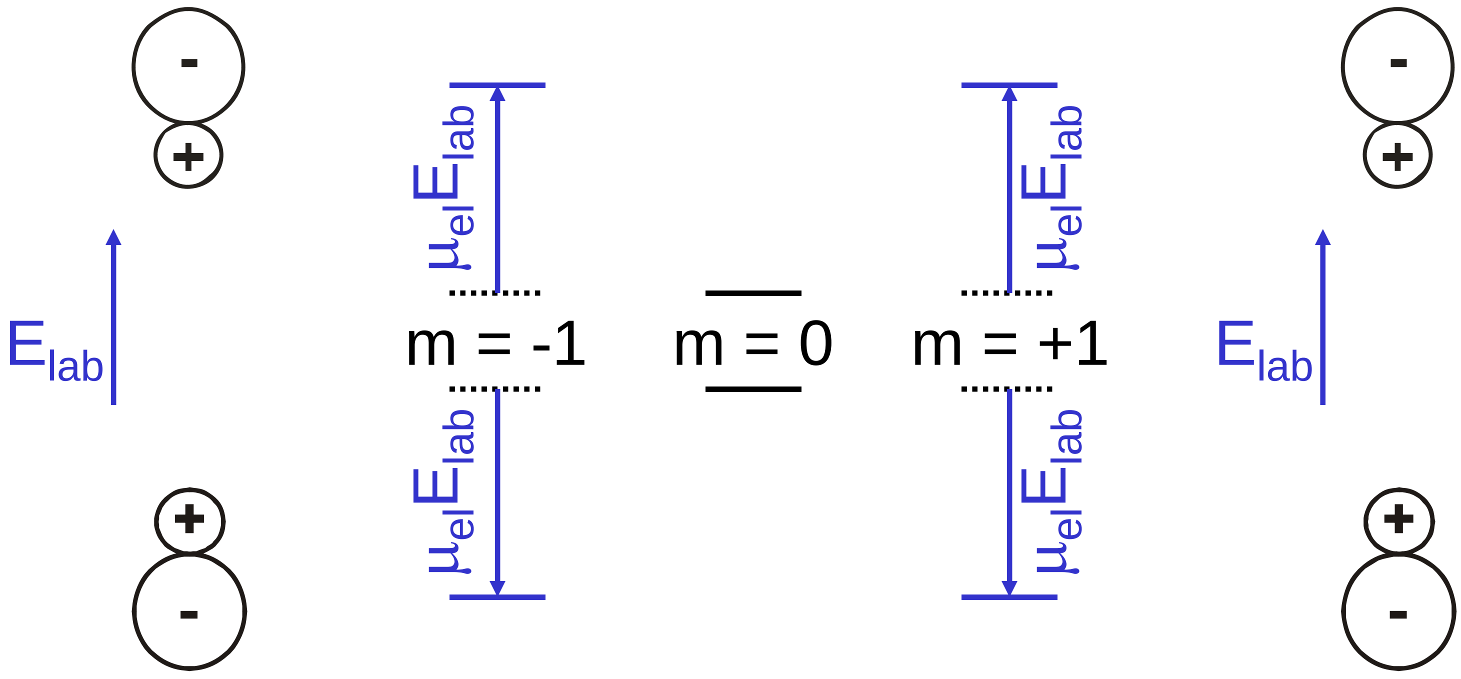


Energies not to scale.
Nuclear spin of ½
excluded for clarity.

Experimental Procedure

HfF^+ $^3\Delta_1$ J=1 ground state

- Electric field 1 V/cm mixes states of opposite parity.

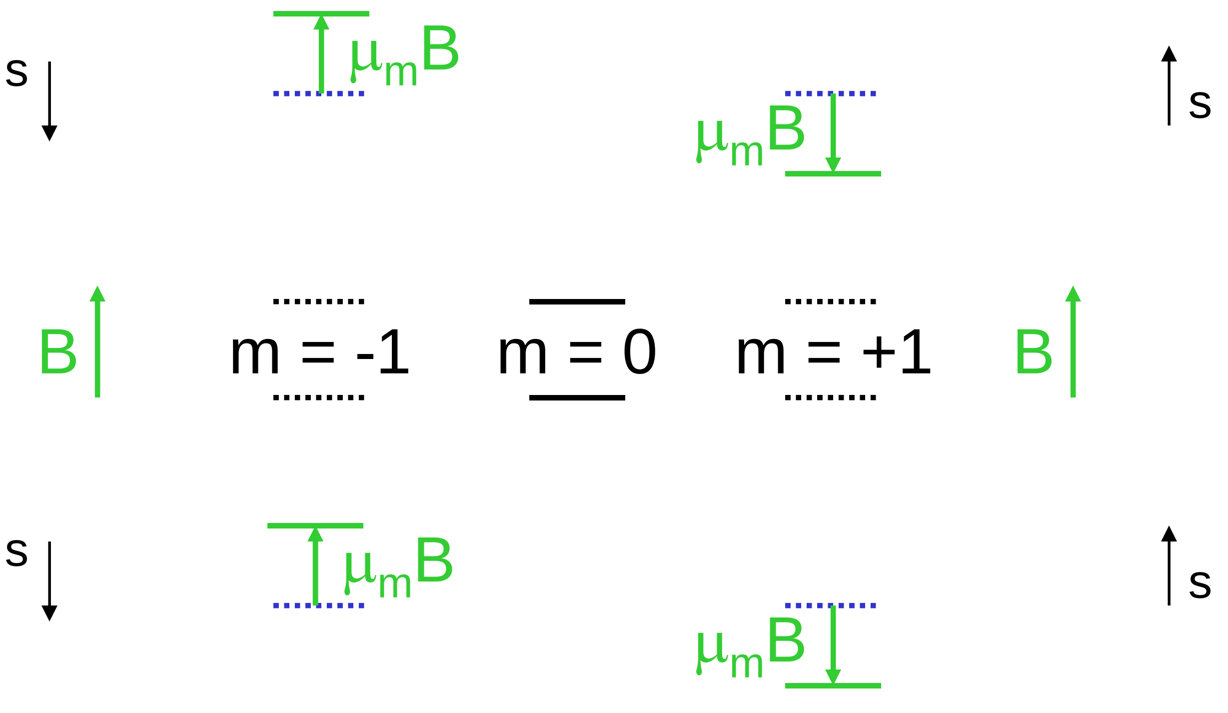


Energies not to scale.

Experimental Procedure

HfF^{+} $^{3}\Delta_1$ J=1 ground state

- Magnetic field lifts degeneracy between |m|=1 levels.

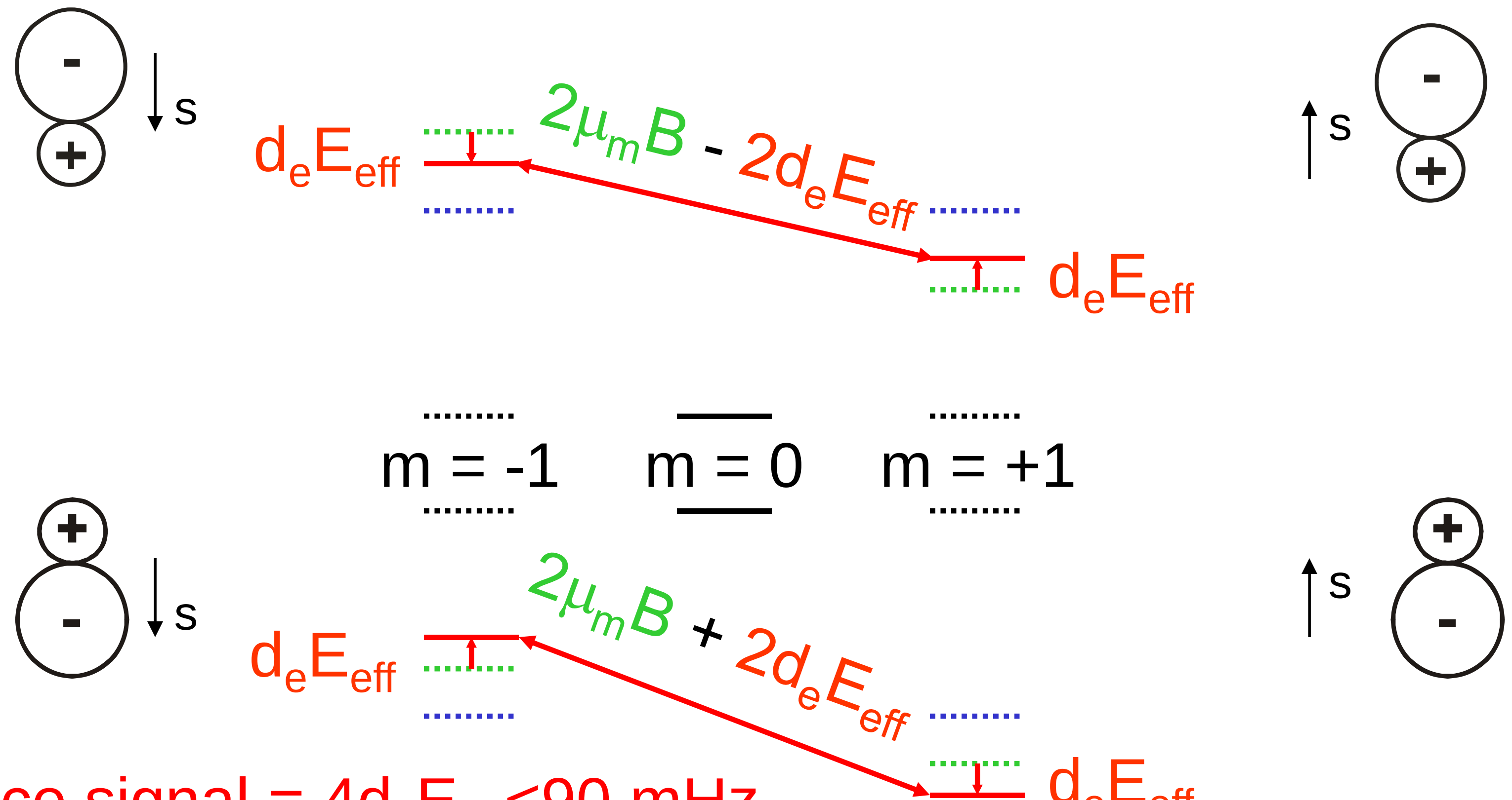


Energies not to scale.

Experimental Procedure

ThF^+ $^3\Delta_1$ J=1 ground state

- Electron EDM shifts the |m|=1 levels in opposite directions in the two Ω-doublet levels.



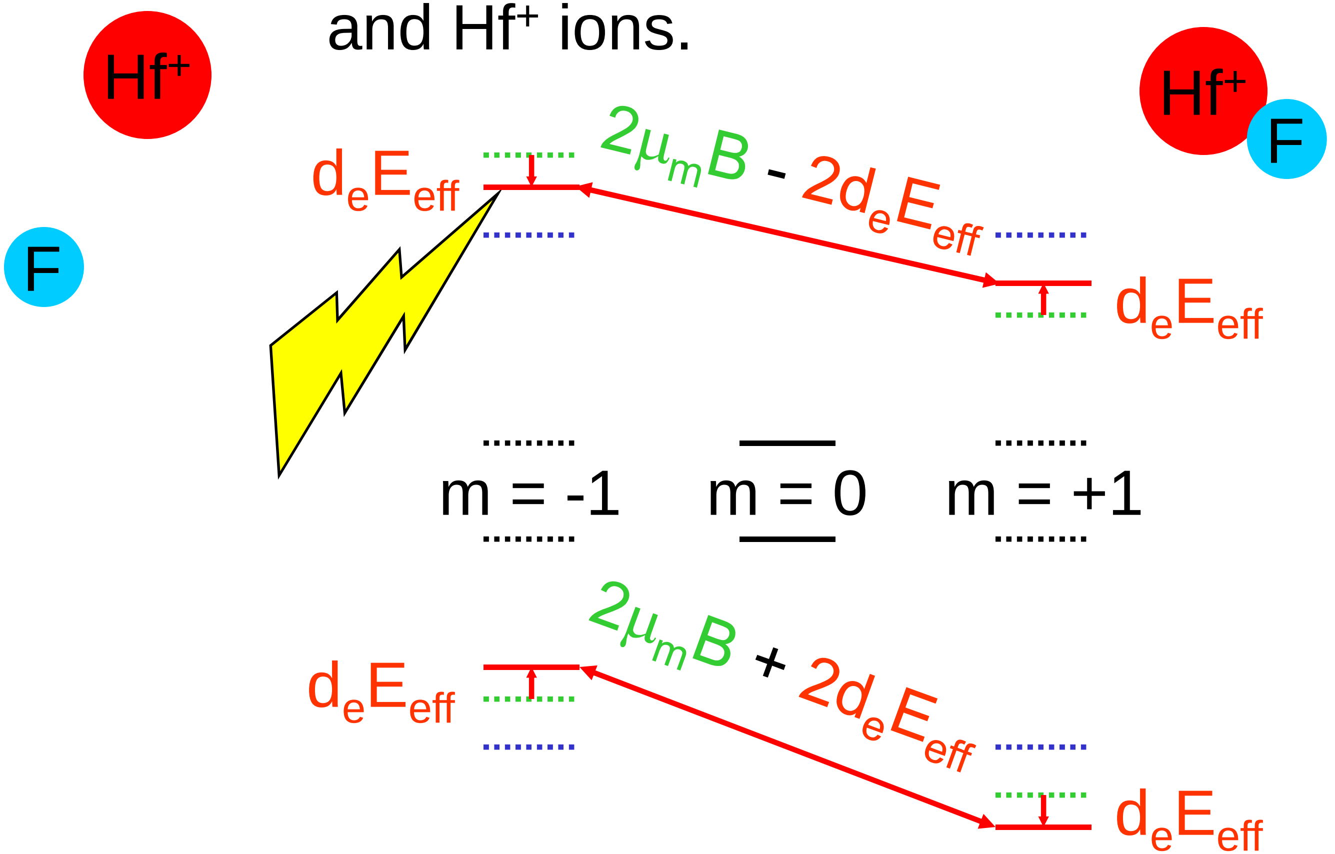
Science signal = $4d_eE_{eff}$<90 mHz, out of "Berry's offset" of 250 kHz

Energies not to scale.

Experimental Procedure

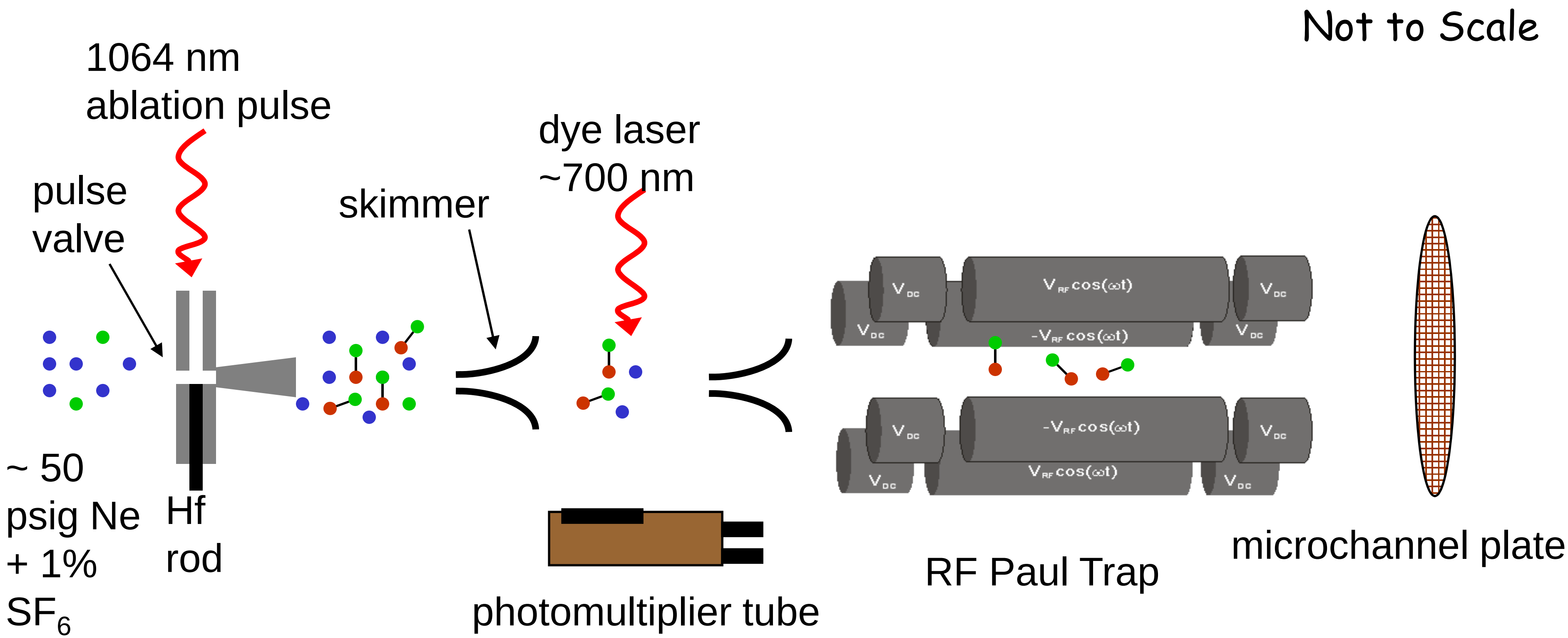
HfH^+ $^3\Delta_1$ J=1 ground state

- Perform electron spin resonance (ESR) frequency measurement via the Ramsey Method.
- Photodissociate one spin state and count HfH^+ and Hf^+ ions.



Energies not to scale.

Current Experimental Progress



Laser Ablation in a Supersonic Jet

- Creation of HfF+,ThF+
- Cooling of rotational, vibrational and translational motion

Fluorescence Spectroscopy

- Measure rotational temperature of neutral HfF molecular beam

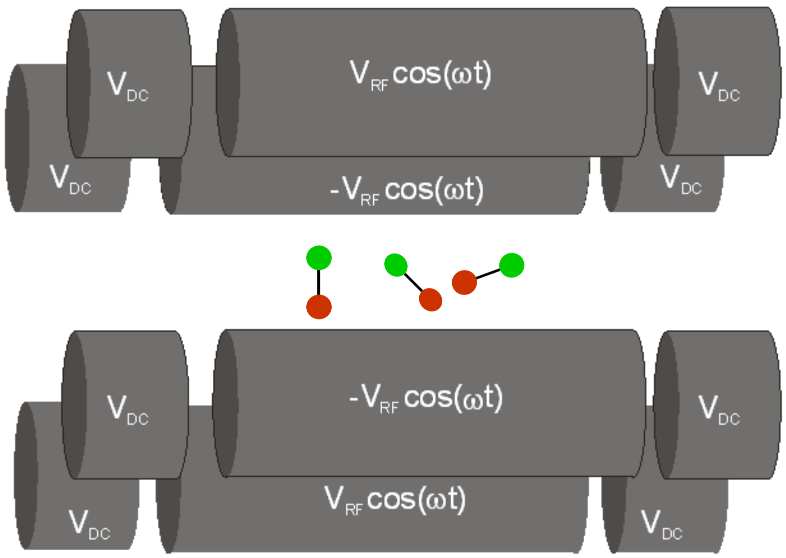
Mass Spectrometry

- Trap Hf+, HfF+, HfF_2+, HfF_3+, Th+, ThF+, ThF_2+,ThF_3+

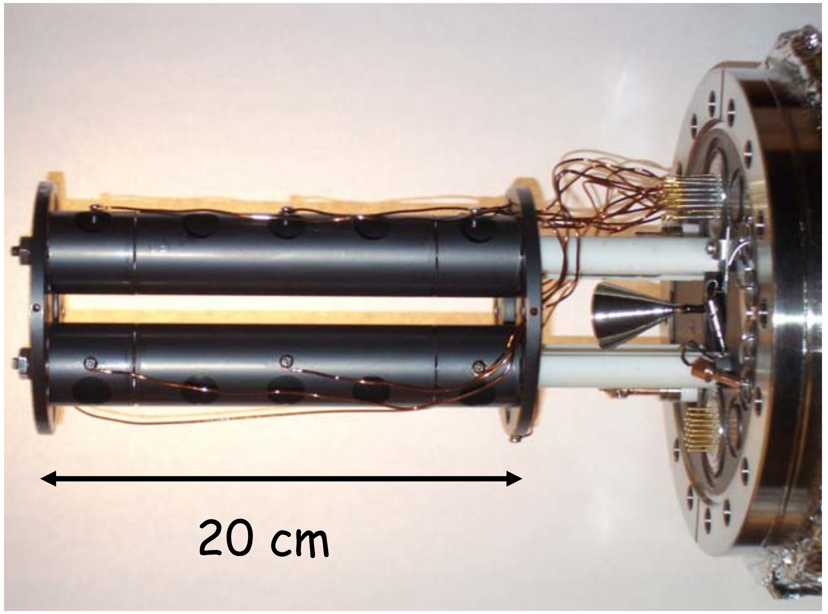
Ion Beam Imaging

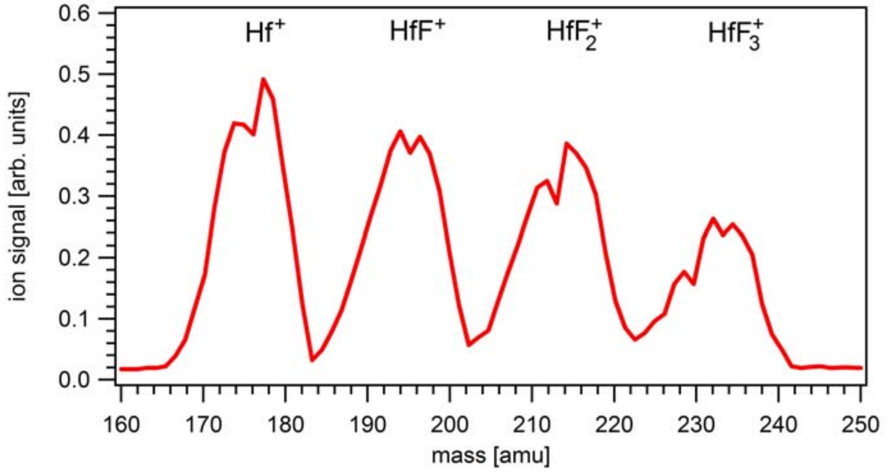
- Measure translational temperature of ion beam

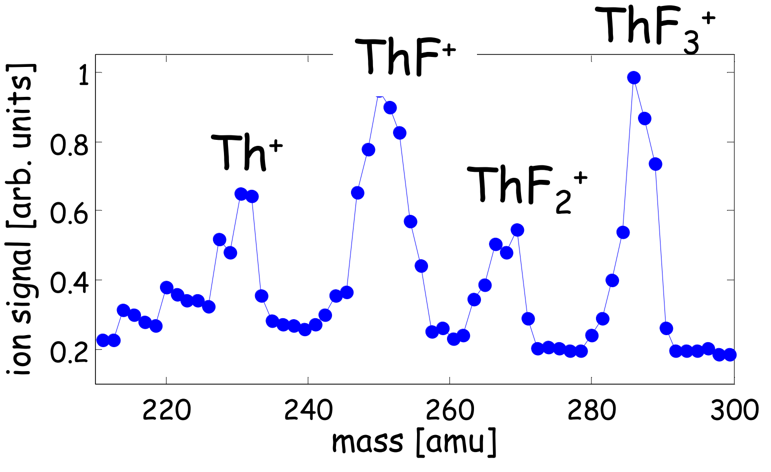
Molecular Ion Production and Trapping



RF Paul Trap and Quadrupole Mass Filter

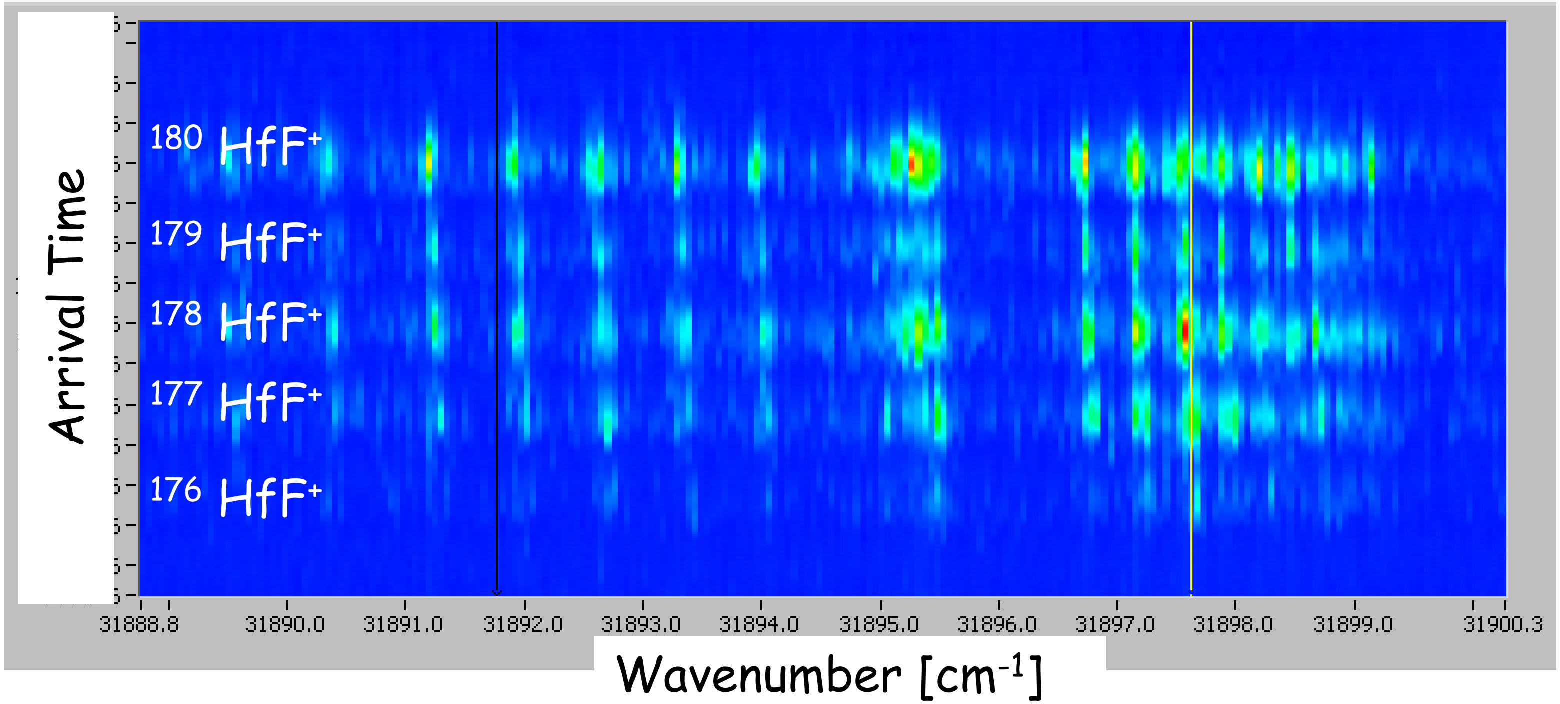






1 amu Mass Resolution for Time of Flight Mass Spectrometry

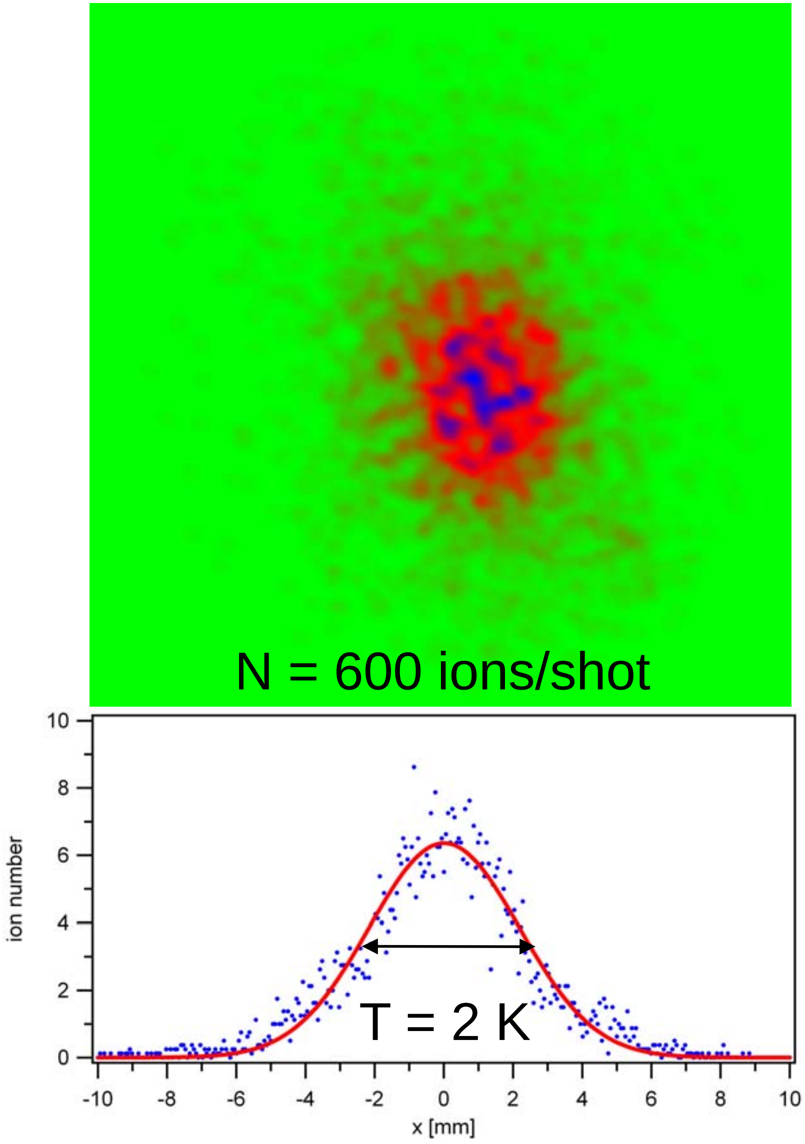
Data from 2-photon REMPI from HfF $X^2\Delta_{3/2}$



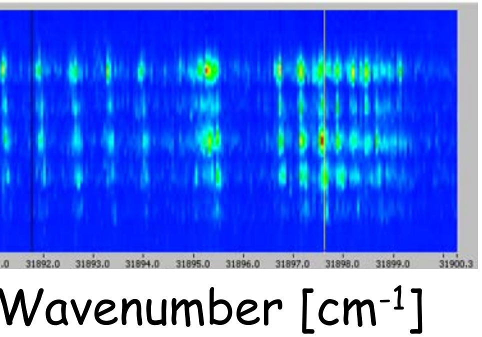
Characterizing Temperatures

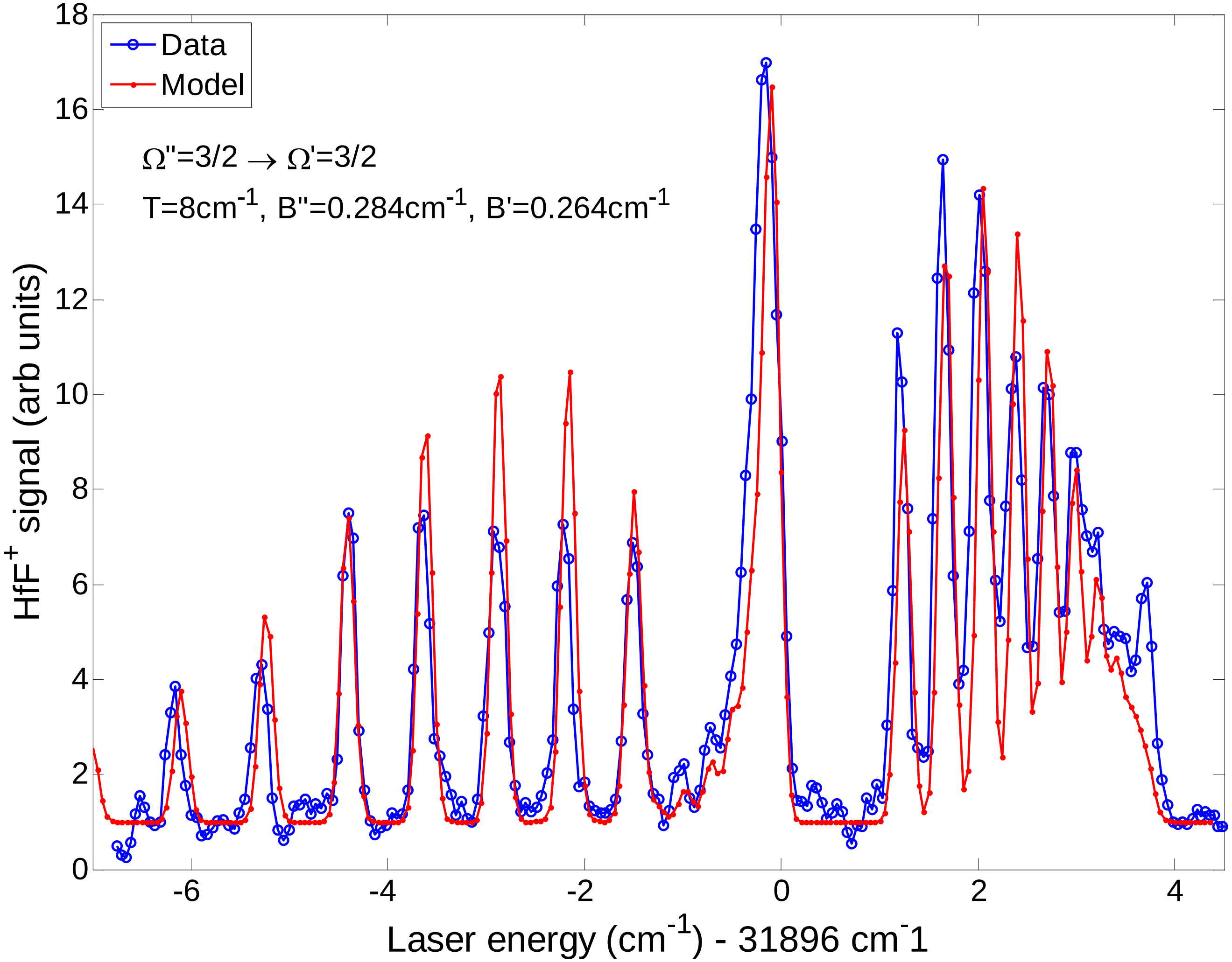
- Only get to use molecules in **one** electronic, vibrational and rotational state for measurement
- Ions not in the right state can still collide leading to decoherence
- Decoherence depends on temperature
    - Too hot → Ions see inhomogeneous fields
    - As temperature decreases Ion-Ion collision rate increases

Supersonic Expansion and Translational Cooling



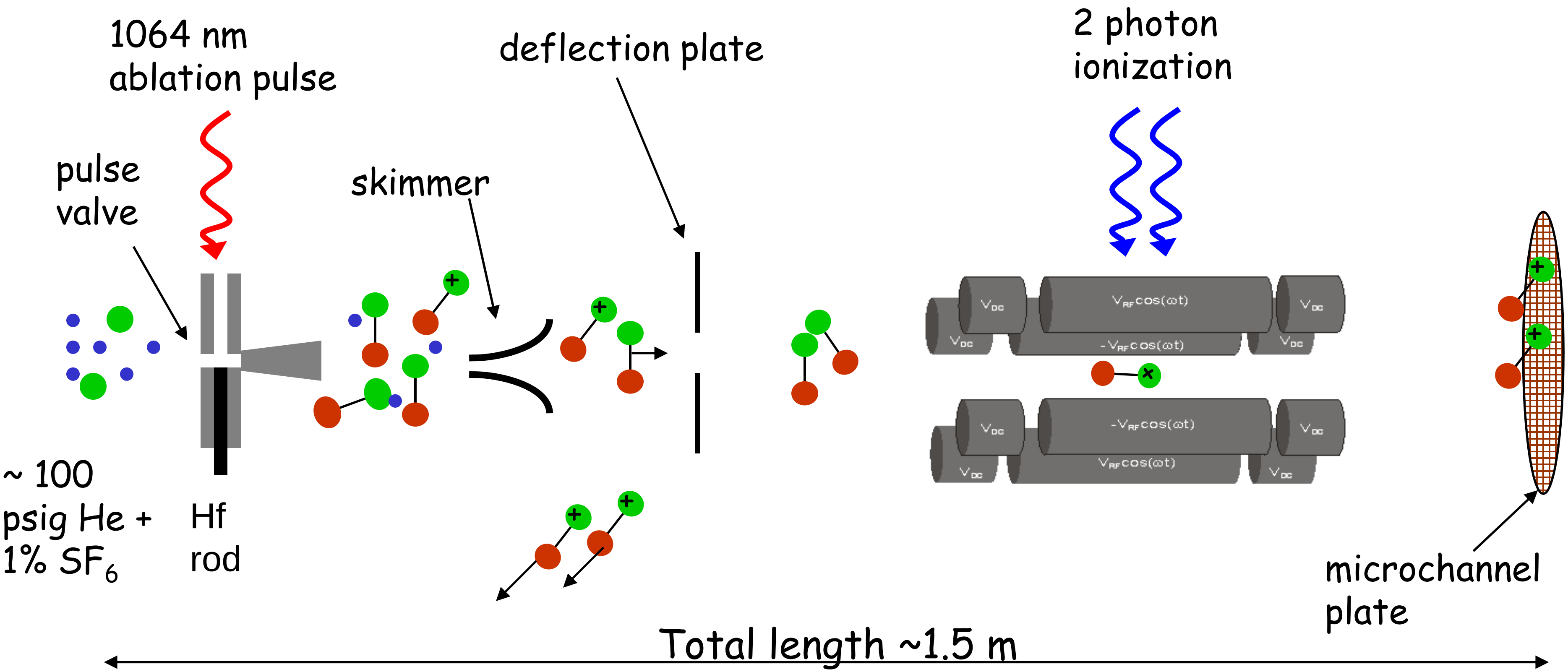
Neutral HfF states observed via 2 photon ionization show low rotational temperatures





Rethinking Ion Trap Loading

Create pre-polarized sample of ions via 2 photon process



Not to Scale

Current Experiment Status

✓ Created and Trapped HfF+ and ThF+

✓ Mass resolution to distinguish 1 amu differences

✓ Characterized supersonic expansion and beam

✓ Internal and External temperatures in the right range for final experiment

✓ Theoretical considerations of Berry's phase and decoherence effects

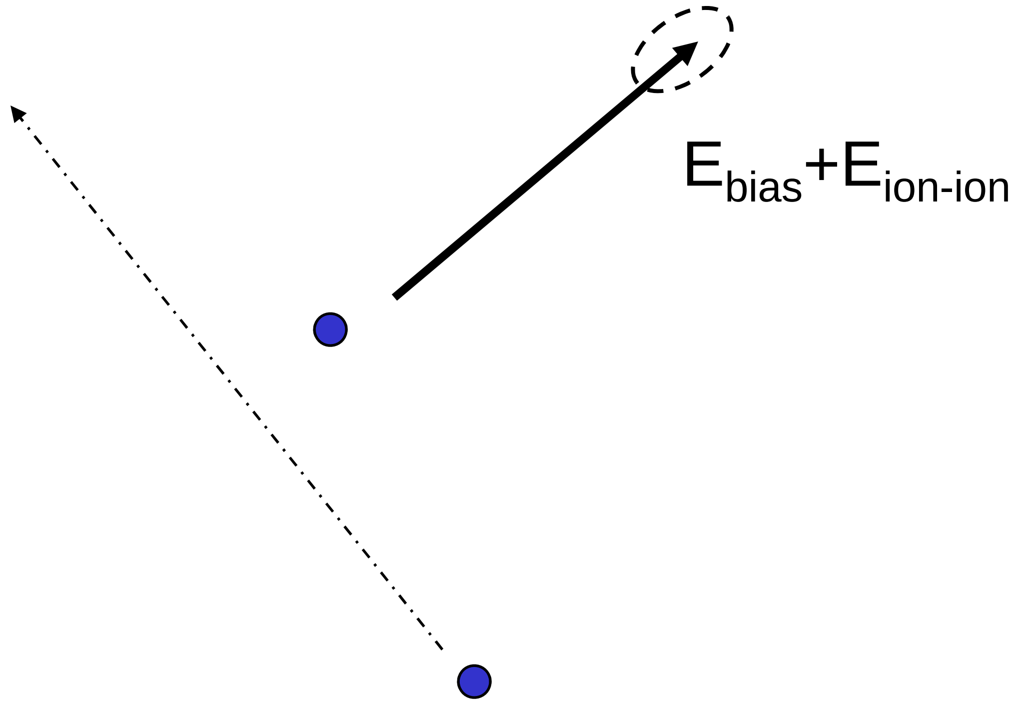
o Ongoing survey spectroscopy of HfF+ and ThF+

o Ongoing development of methods for loading trap with ions pre-polarized

o Spin level readout and characterization of coherence times

o On to measurement of the electron EDM…

The decohering effects of ion-ion collisions:



Ion picks up a little random Berry's phase with each near miss. $\tau_{cohere} \propto n_{ion}{}^{-1}$

Sensitivity to EDM fairly flat with N_{ion}, but N_{usable}/N_{ion} is critical. (And rather uncertain).

Sensitivity Estimate

$$|d_e| < \frac{h}{2E_{eff}\tau\sqrt{N}}$$

- N = 10 ions/shot (10^7 ions/day)
- E_{eff} = 9×10^{10} V/cm
- τ = 0.1 second

proj. sensitivity: $|d_e| <$ few x 10^{-29} e*cm with 1 day of data

Systematic Error Rejection. Key Chops.

Chop:	B	E	E/E_{eff}	v	Other
Tl beam	Y	Y	N	Y	
YbF beam	Y	Y	N	N*	
PbO vapor cell	Y	Y	Y	N*	
trapped Cs	Y	Y	N	Trap	
Cs fountain	Y	Y	N	N	
PbF beam	Y	Y	N	N*	
Trapped MF+	Y	N	Y	→	Rotation sense

Systematic Error Rejection. Key Chops.

We've got the chops, and:

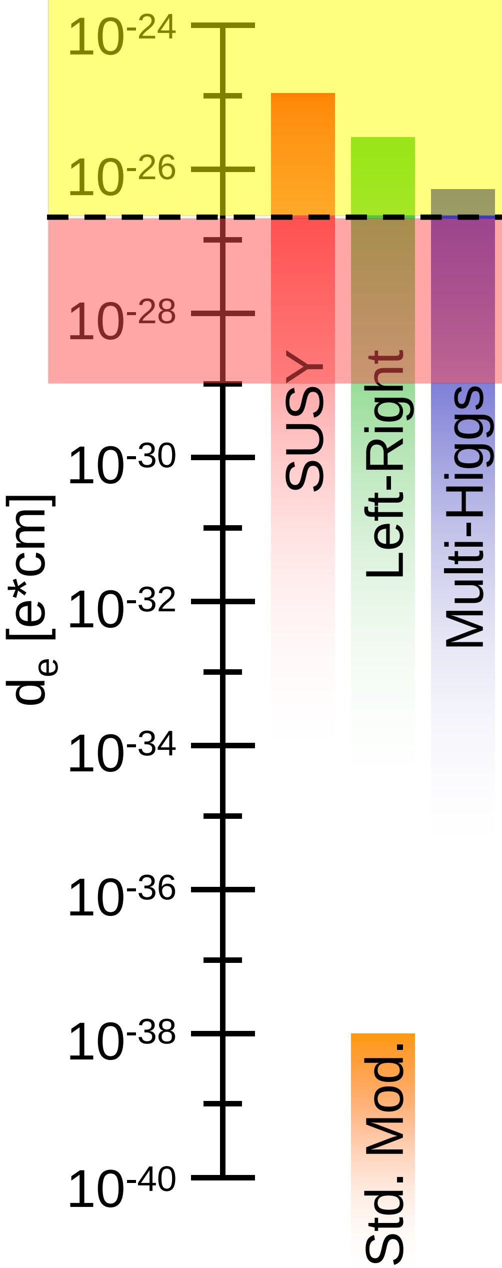
Key fact: $\nu_{science}$ is independent of magnitude of E, B, and ω_{rot}. Also should be independent of strength of ion trap confinement, T, and n_{ion}.

Trapped MF+	Y	N	Y	Y*	Rotation sense

Systematics bottom line:
We haven't thought of a killer systematic at the 10^{-28} level yet.   We will have a number of powerful techniques for smoking out unforeseen ones.

In the end, we've got to try it.

Test of Physics Beyond the Standard Model



$|d_e| < 1.6 \times 10^{-27}$ e*cm [~10^{-18} Debye]
E.D. Commins Tl Exp. Limit [PRL **88**, 071805 (2002)]

$|d_e| < 10^{-29}$ e*cm / day$^{1/2}$

Projected sensitivity: |de| < few x 10^{-29} e*cm / day$^{1/2}$

- Theoretical calculations: Eeff ~ 9 x 10^{10} V/cm
- Expected spin coherence time: τ ~ 100 ms
- Expected counting statistics: N ~ 9 x 10^6 ions / day