

# An Electron EDM Search in $HfF^+$ :

Probing P & T-violation Beyond the Standard Model



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Experiment: Laura Sinclair, Russell Stutz & Eric Cornell

Theory: Ed Meyer & John Bohn

JILA, NIST, and University of Colorado



March 21, 2007

# $e^-$ EDM Search @ JILA



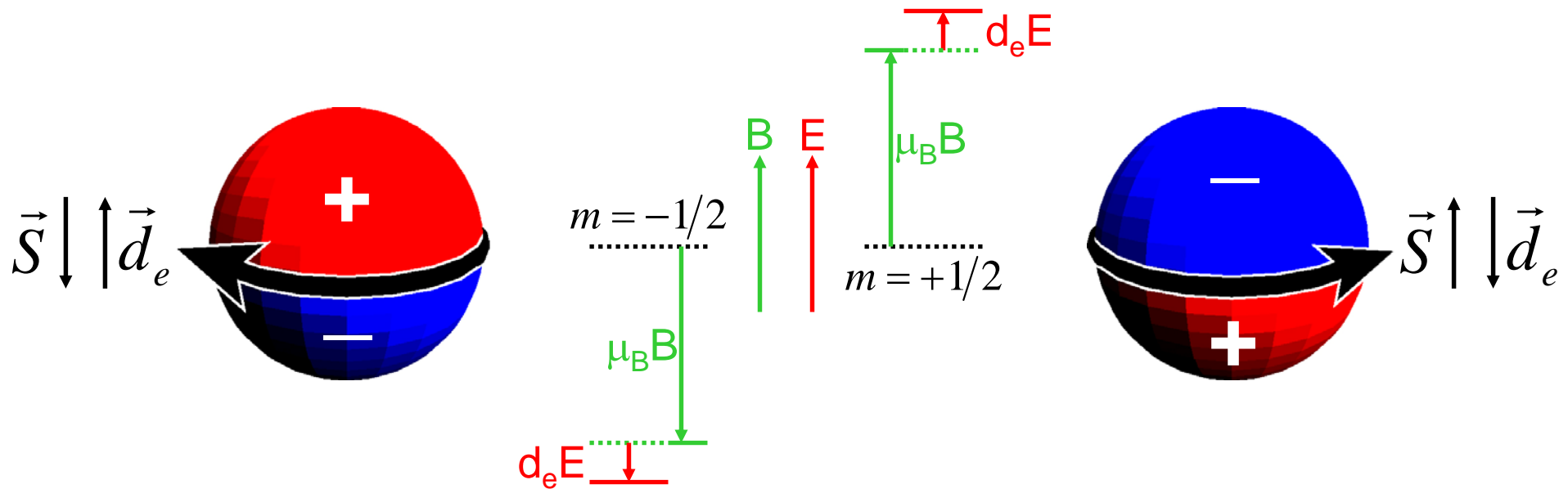
# $e^-$ Energy Levels

$$H_B \propto \vec{S} \cdot \vec{B}$$

P-even, T-even

$$H_E \propto \vec{S} \cdot \vec{E}$$

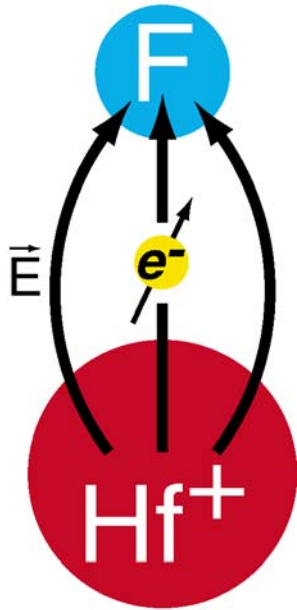
P-odd, T-odd



Frequency Shift:  $\Delta\omega = \frac{2d_e E}{\hbar}$

Frequency Resolution:  $\Delta\omega = \frac{1}{\tau\sqrt{N}}$

# Advantages of Molecules



1. **Large** internal electric fields.
  - Effective E-field seen by  $e^-$ ,  $E_{\text{eff}} \sim 10^{10}$  V/cm.
  - Compared to **maximum**  $E_{\text{lab}} \sim 10^5$  V/cm.
2. **Accessible** internal electric fields.
  - Easy to polarize, need only  $E_{\text{lab}} \sim 1$  V/cm.
3. Rejection of systematic errors.
  - Magnetic field **insensitive** transitions.
  - $E_{\text{eff}}$  **independent** of  $E_{\text{lab}}$ .

# Advantages of Ions

1. **Easy** to trap.
2. **Long** spin coherence times.

# Molecular Ion of Choice: $\text{HfF}^+$

$\text{HfF}^+$  Theory { Meyer *et. al.*, PRA 73, 062108 (2006).  
 Petrov *et. al.*, arXiv:physics/0611254 (2006).

**PERIODIC TABLE**  
**Atomic Properties of the Elements**

**NIST**  
 National Institute of Standards and Technology  
 Technology Administration, U.S. Department of Commerce

**Frequently used fundamental physical constants**  
 For the most accurate values of these and other constants, visit [physics.nist.gov/constants](http://physics.nist.gov/constants)  
 1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of  $^{133}\text{Cs}$

speed of light in vacuum $c$	299 792 458 $\text{m s}^{-1}$ (exact)
Planck constant $h$	$6.6261 \times 10^{-34} \text{ J s}$ ( $h = h/2\pi$ )
elementary charge $e$	$1.6022 \times 10^{-19} \text{ C}$
electron mass $m_e$	$9.1094 \times 10^{-31} \text{ kg}$
$m_e c^2$	0.5110 MeV
proton mass $m_p$	$1.6726 \times 10^{-27} \text{ kg}$
fine-structure constant $\alpha$	1/137.036
Rydberg constant $R_\infty$	$10 973 732 \text{ m}^{-1}$
$R_\infty c$	$3.289 842 \times 10^{15} \text{ Hz}$
$R_\infty hc$	$13.6057 \text{ eV}$
Boltzmann constant $k$	$1.3807 \times 10^{-23} \text{ J K}^{-1}$

Solids  
 Liquids  
 Gases  
 Artificially Prepared

1 1A <b>H</b> Hydrogen 1.00794 $1s$ 13 5084	2 IIA <b>Li</b> Lithium 6.941 $2s^2 2s$ 5.3917	3 IIIB <b>Na</b> Sodium 22.989770 $[Ne]3s$ 5.1391	4 IIA <b>Be</b> Beryllium 9.012182 $1s^2 2s^2$ 9.3227	5 IIIB <b>Mg</b> Magnesium 24.3050 $[Ne]3s^2$ 7.6462	6 VIB <b>Ca</b> Calcium 40.078 $[Ar]4s$ 4.3407	7 VIIB <b>Sc</b> Scandium 44.955910 $[Ar]3d^1 4s^2$	8 VIIB <b>Ti</b> Titanium 47.867 $[Ar]3d^2 4s^2$	9 VIIB <b>V</b> Vanadium 50.9415 $[Ar]3d^3 4s^2$	10 VIIB <b>Cr</b> Chromium 51.9961 $[Ar]3d^5 4s^1$	11 VIIB <b>Mn</b> Manganese 54.938049 $[Ar]3d^5 4s^2$	12 VIIB <b>Fe</b> Iron 55.845 $[Ar]3d^6 4s^2$	13 VIII <b>Co</b> Cobalt 58.933200 $[Ar]3d^7 4s^2$	14 VIII <b>Ni</b> Nickel 58.9334 $[Ar]3d^8 4s^2$	15 VIII <b>Cu</b> Copper 63.546 $[Ar]3d^{10} 4s^1$	16 VIII <b>Zn</b> Zinc 65.409 $[Ar]3d^{10} 4s^2$	17 VIII <b>Ga</b> Gallium 69.723 $[Ar]3d^{10} 4s^2 4p^1$	18 VIII <b>Ge</b> Germanium 72.64 $[Ar]3d^{10} 4s^2 4p^2$	19 VIII <b>As</b> Arsenic 74.92160 $[Ar]3d^{10} 4s^2 4p^3$	20 VIII <b>Se</b> Selenium 78.96 $[Ar]3d^{10} 4s^2 4p^4$	21 VIII <b>Br</b> Bromine 79.904 $[Ar]3d^{10} 4s^2 4p^5$	22 VIII <b>Kr</b> Krypton 83.798 $[Ar]3d^{10} 4s^2 4p^6$	23 VIII <b>Rb</b> Rubidium 85.4678 $[Kr]5s$ 4.1771	24 IIA <b>Sr</b> Strontium 88.90585 $[Kr]5s$	25 IIIB <b>Y</b> Yttrium 88.90585 $[Kr]4d^1 5s^2$	26 IIIB <b>Zr</b> Zirconium 91.224 $[Kr]4d^2 5s^2$	27 IIIB <b>Nb</b> Niobium 92.90638 $[Kr]4d^4 5s^1$	28 IIIB <b>Mo</b> Molybdenum 95.94 $[Kr]4d^5 5s^1$	29 IIIB <b>Tc</b> Technetium 98 $[Kr]4d^5 5s^2$	30 IIIB <b>Ru</b> Ruthenium 101.07 $[Kr]4d^7 5s^1$	31 IIIB <b>Rh</b> Rhodium 102.90550 $[Kr]4d^8 5s^1$	32 IIIB <b>Pd</b> Palladium 106.42 $[Kr]4d^10$	33 IIIB <b>Ag</b> Silver 107.8682 $[Kr]4d^10 5s^1$	34 IIIB <b>Cd</b> Cadmium 112.411 $[Kr]4d^10 5s^2$	35 IIIB <b>In</b> Indium 114.818 $[Kr]4d^10 5s^2 5p^1$	36 IIIB <b>Sn</b> Tin 118.710 $[Kr]4d^10 5s^2 5p^2$	37 IIIB <b>Sb</b> Antimony 121.760 $[Kr]4d^10 5s^2 5p^3$	38 IIIB <b>Te</b> Tellurium 127.60 $[Kr]4d^10 5s^2 5p^4$	39 IIIB <b>I</b> Iodine 126.90447 $[Kr]4d^10 5s^2 5p^5$	40 IIIB <b>Xe</b> Xenon 131.29 $[Kr]4d^10 5s^2 5p^6$	41 IIIB <b>Cs</b> Cesium 132.90545 $[Xe]6s$ 3.8939	42 IIA <b>Ba</b> Barium 137.327 $[Xe]6s$	43 IIIB <b>Hf</b> Hafnium 178.49 $[Xe]4f^{14} 5d^2 6s^2$	44 IIIB <b>Ta</b> Tantalum 180.9479 $[Xe]4f^{14} 5d^3 6s^2$	45 IIIB <b>W</b> Tungsten 183.84 $[Xe]4f^{14} 5d^4 6s^2$	46 IIIB <b>Re</b> Rhenium 186.207 $[Xe]4f^{14} 5d^5 6s^2$	47 IIIB <b>Os</b> Osmium 190.23 $[Xe]4f^{14} 5d^6 6s^2$	48 IIIB <b>Ir</b> Iridium 192.217 $[Xe]4f^{14} 5d^7 6s^2$	49 IIIB <b>Pt</b> Platinum 195.078 $[Xe]4f^{14} 5d^9 6s^1$	50 IIIB <b>Au</b> Gold 196.96655 $[Xe]4f^{14} 5d^{10} 6s^1$	51 IIIB <b>Hg</b> Mercury 200.59 $[Xe]4f^{14} 5d^{10} 6s^2$	52 IIIB <b>Tl</b> Thallium 204.3833 $[Xe]6s^2$	53 IIIB <b>Pb</b> Lead 207.2 $[Xe]6s^2$	54 IIIB <b>Bi</b> Bismuth 208.98038 $[Xe]6s^2$	55 IIIB <b>Po</b> Polonium (209) $[Xe]6s^2$	56 IIIB <b>At</b> Astatine (210) $[Xe]6s^2$	57 IIIB <b>Rn</b> Radon (222) $[Xe]6s^2$	58 IIIB <b>La</b> Lanthanum 138.9055 $[Xe]5d^1 6s^2$	59 IIIB <b>Ce</b> Cerium 140.116 $[Xe]4f^1 5d^1 6s^2$	60 IIIB <b>Pr</b> Praseodymium 140.90765 $[Xe]4f^3 6s^2$	61 IIIB <b>Nd</b> Neodymium 144.24 $[Xe]4f^4 6s^2$	62 IIIB <b>Pm</b> Promethium (145) $[Xe]4f^5 6s^2$	63 IIIB <b>Sm</b> Samarium 150.36 $[Xe]4f^6 6s^2$	64 IIIB <b>Eu</b> Europium 151.964 $[Xe]4f^7 6s^2$	65 IIIB <b>Gd</b> Gadolinium 157.25 $[Xe]4f^7 5d^1 6s^2$	66 IIIB <b>Tb</b> Terbium 158.92534 $[Xe]4f^9 6s^2$	67 IIIB <b>Dy</b> Dysprosium 162.500 $[Xe]4f^{10} 6s^2$	68 IIIB <b>Ho</b> Holmium 164.93032 $[Xe]4f^{11} 6s^2$	69 IIIB <b>Er</b> Erbium 167.259 $[Xe]4f^{12} 6s^2$	70 IIIB <b>Tm</b> Thulium 168.93421 $[Xe]4f^{13} 6s^2$	71 IIIB <b>Yb</b> Ytterbium 173.04 $[Xe]4f^{14} 6s^2$	72 IIIB <b>Lu</b> Lutetium 174.967 $[Xe]4f^{14} 5d^1 6s^2$	73 IIIB <b>Ac</b> Actinium 227 $[Rn]5f^7 6s^2$	74 IIIB <b>Th</b> Thorium 232.0381 $[Rn]6d^2 7s^2$	75 IIIB <b>Pa</b> Protactinium 231.03689 $[Rn]5f^2 6d^1 7s^2$	76 IIIB <b>U</b> Uranium 238.02891 $[Rn]5f^3 6d^1 7s^2$	77 IIIB <b>Np</b> Neptunium 237 $[Rn]5f^4 6s^2$	78 IIIB <b>Pu</b> Plutonium 244 $[Rn]5f^6 6s^2$	79 IIIB <b>Am</b> Americium 243 $[Rn]5f^7 6s^2$	80 IIIB <b>Cm</b> Curium 247 $[Rn]5f^7 6s^2$	81 IIIB <b>Bk</b> Berkelium 247 $[Rn]5f^7 6s^2$	82 IIIB <b>Cf</b> Californium 251 $[Rn]5f^10 6s^2$	83 IIIB <b>Es</b> Einsteinium 252 $[Rn]5f^{11} 6s^2$	84 IIIB <b>Fm</b> Fermium 257 $[Rn]5f^{12} 6s^2$	85 IIIB <b>Md</b> Mendelevium 258 $[Rn]5f^{13} 6s^2$	86 IIIB <b>No</b> Nobelium 259 $[Rn]5f^{14} 6s^2$	87 IIIB <b>Lr</b> Lawrencium 262 $[Rn]5f^{14} 7s^2 7p^1$
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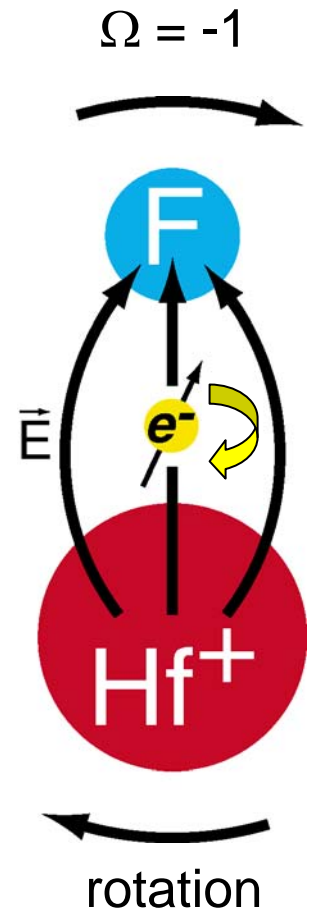
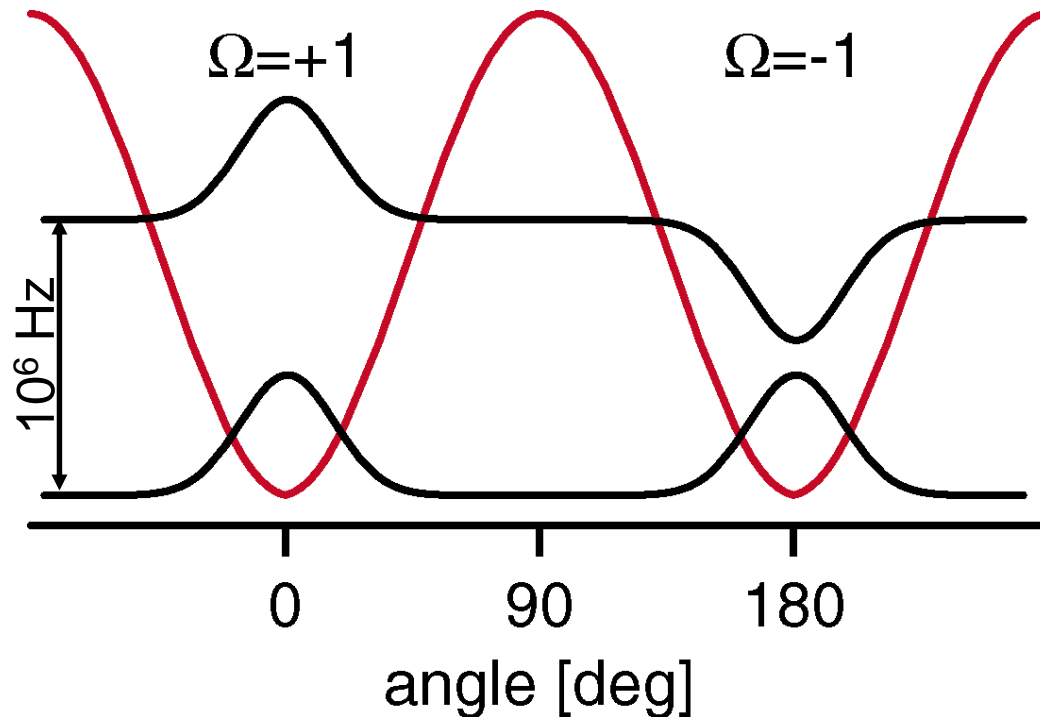
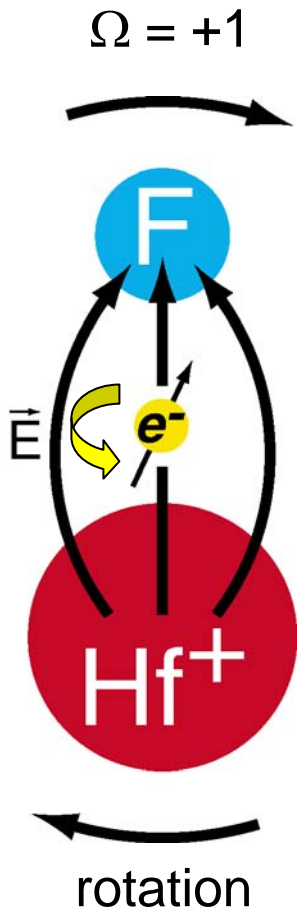
Atomic Number    Ground-state Level  
 Symbol    **58**  $1G_4$   
 Name    Cerium  
 Atomic Weight    140.116  
                           $[Xe]4f^6 5d^1 6s^2$   
 Ground-state Configuration    Ionization Energy (eV)    5.5387

1Based upon  $^{12}\text{C}$ . ( ) indicates the mass number of the most stable isotope.  
 For a description of the data, visit [physics.nist.gov/data](http://physics.nist.gov/data)  
 NIST SP 966 (September 2003)

# Polar Molecules

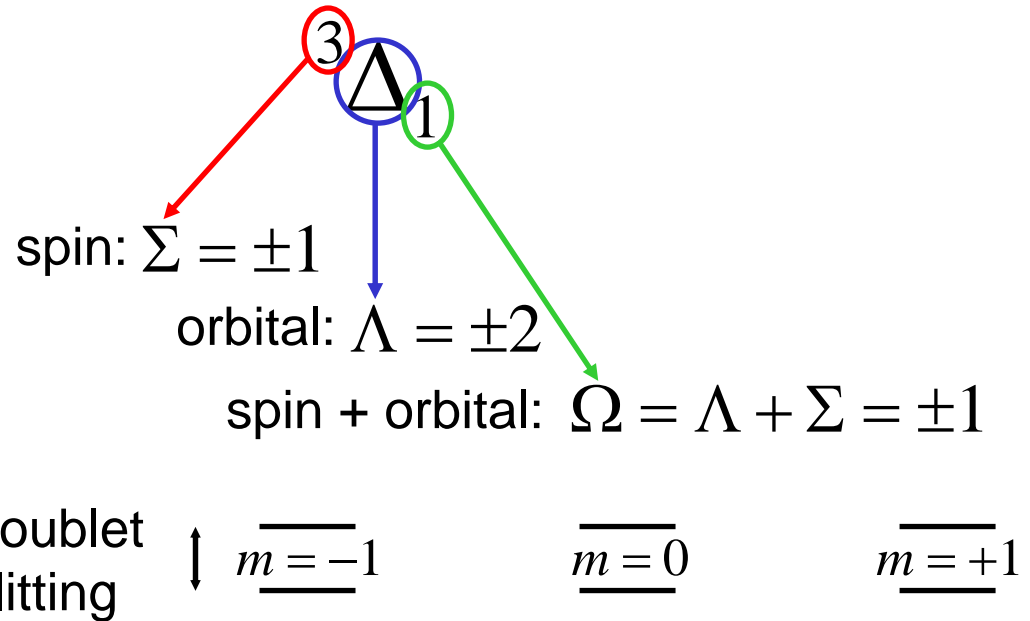
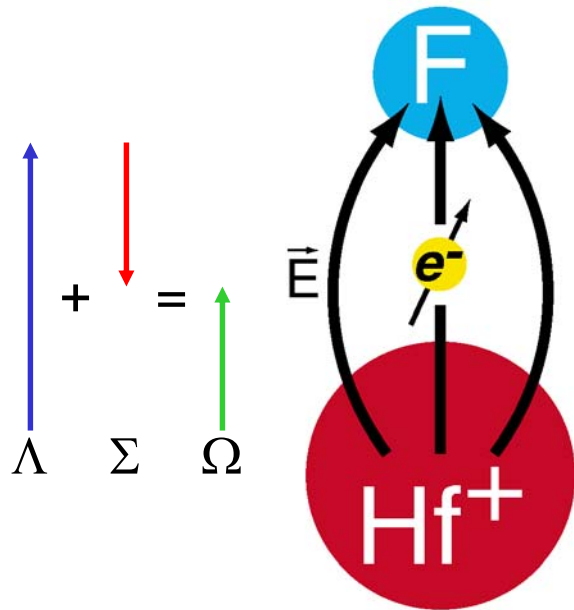
- Molecules do **not** have permanent electric dipole moments.
- Molecules do have closely spaced levels of opposite parity.
  - $\Omega$ -doubling  $\sim 10^6$  Hz vs. s/p splitting  $\sim 10^{14}$  Hz in atoms.

$\Omega$  = projection of  $e^-$  angular momentum along molecular axis.



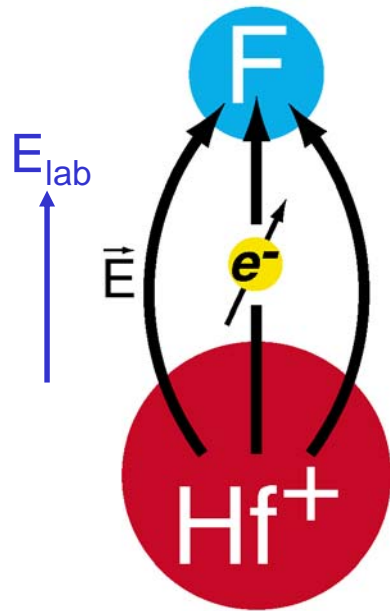
# HfF<sup>+</sup> in the <sup>3</sup>Δ<sub>1</sub> State

- Net e<sup>-</sup> spin: |Σ|=1
- Small magnetic moment: μ<sub>m</sub> ≪ μ<sub>B</sub>
- Hf nucleus: I=0 & I=1/2 isotopes



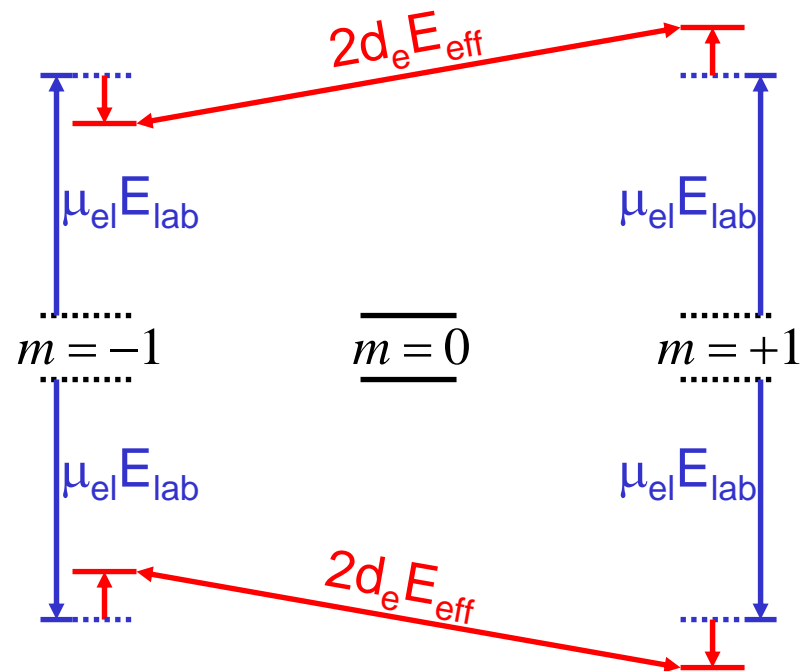
# Intramolecular Electric Fields

- $E_{\text{lab}}$  mixes states of opposite parity inducing a net molecular dipole moment in the lab frame.
- Sign of  $E_{\text{eff}}$  is set by sign of induced molecular dipole moment.



$$\langle E_{\text{eff}} \rangle > 0$$

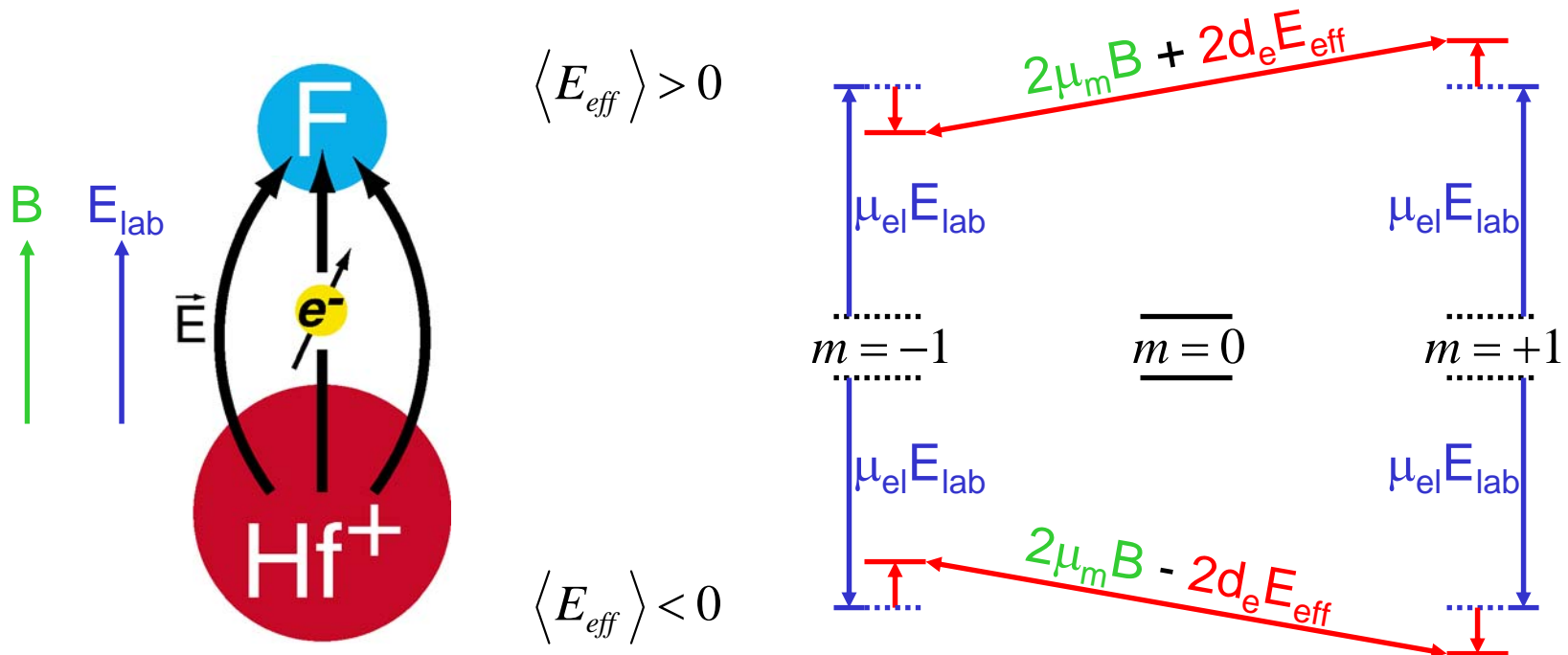
$$\langle E_{\text{eff}} \rangle < 0$$





# Systematic Checks

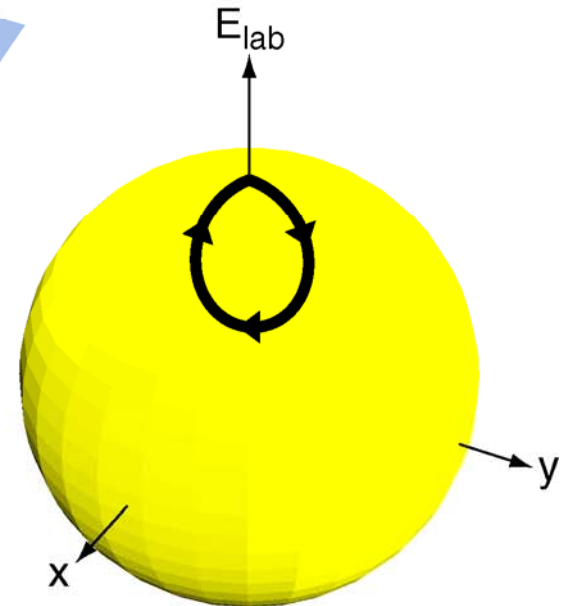
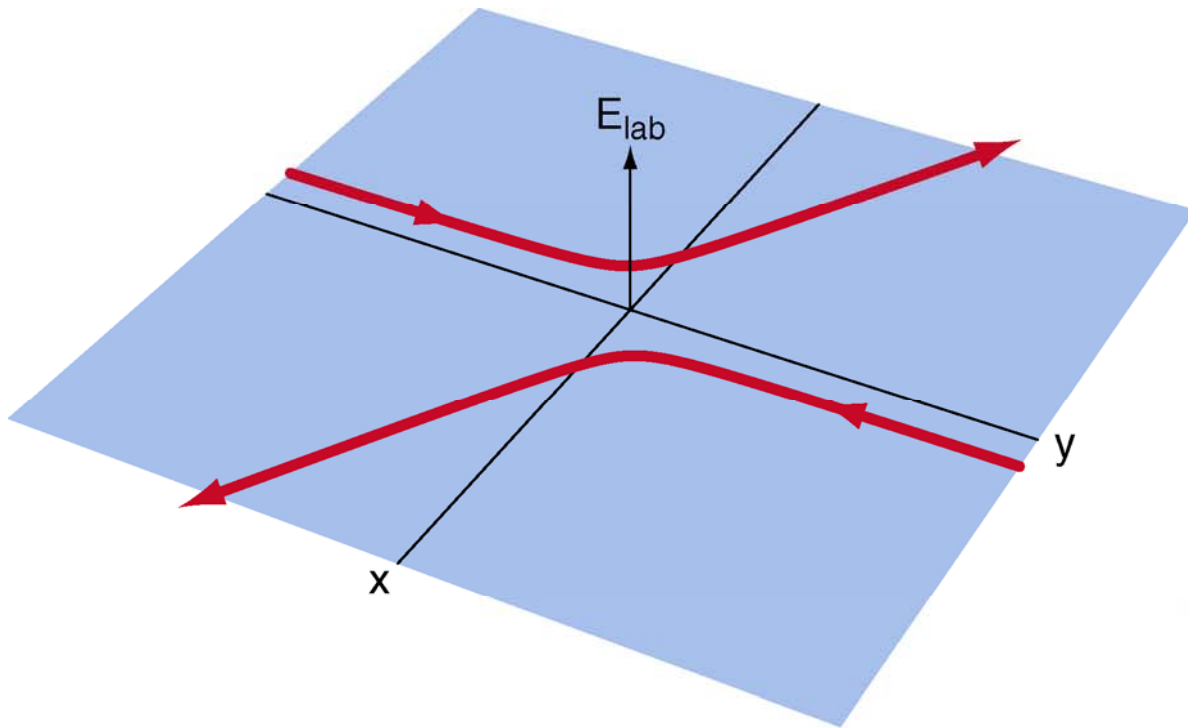
- Measure frequency splitting in both  $\Omega$ -doublet levels.
  - Zeeman shift is **common mode**.
- Vary magnitude of  $E_{\text{lab}}$ .
  - Linear Stark shift implies fully mixed states of opposite parity and  $E_{\text{eff}}$  nominally **independent** of  $E_{\text{lab}}$ .



# Ion-Ion Collisions & Decoherence

- Electric field between two ions during a collision tips the quantization axis and generates a geometric phase shift.
- Sets limits on ion number,  $N \sim 100$ , and interrogation time,  $\tau \sim 1$  s.

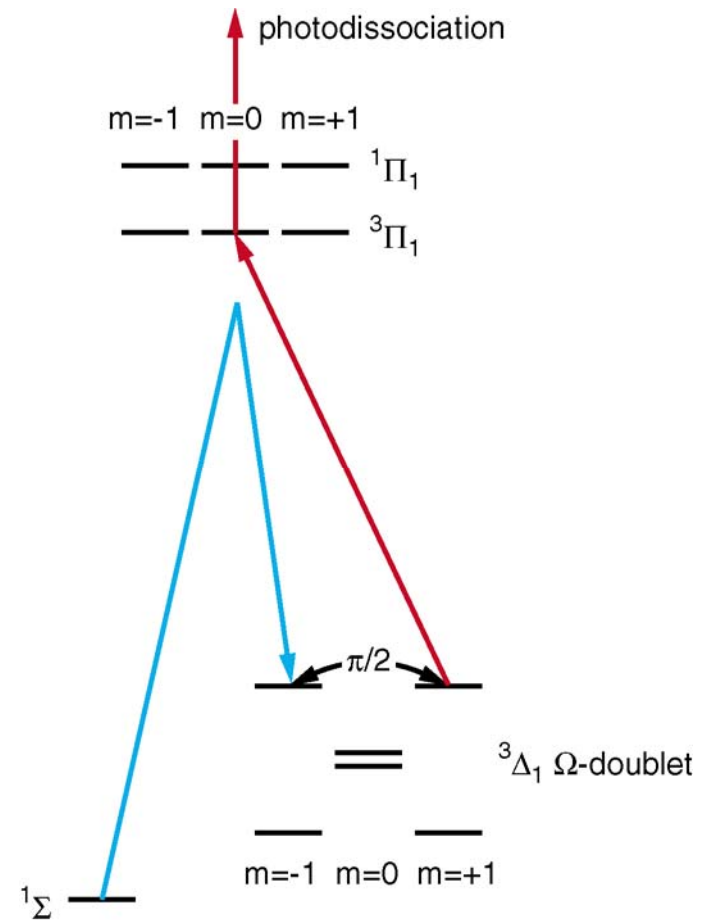
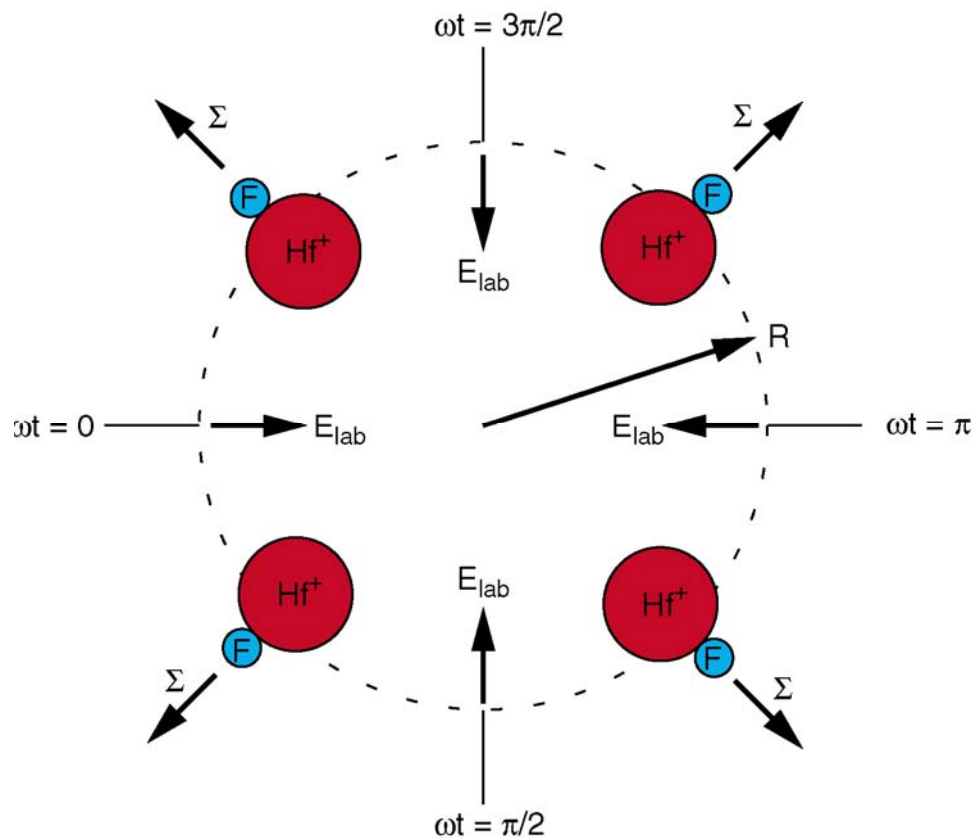
$$\Delta\varphi \propto \Omega \propto T^4$$



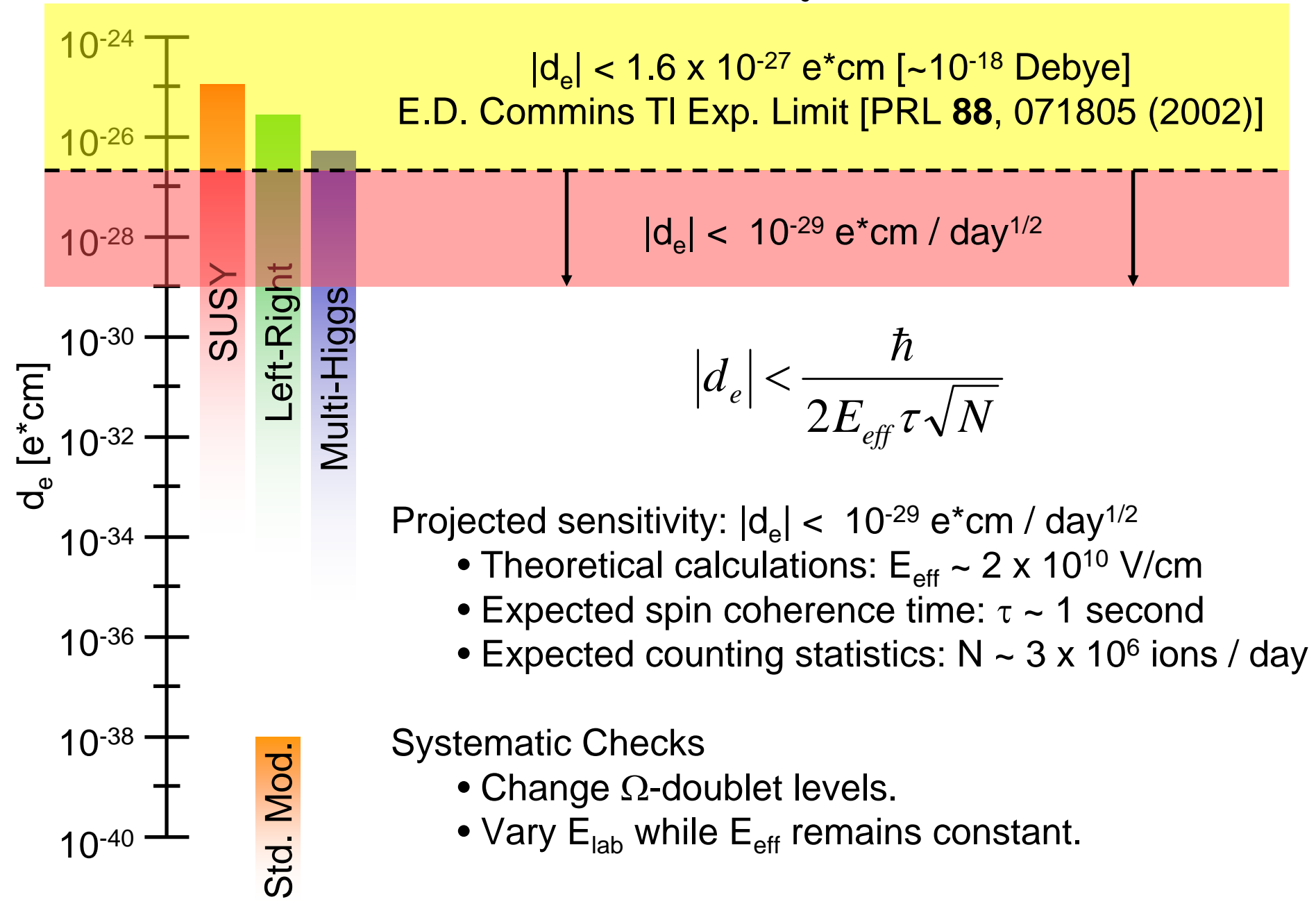
# Envisioned Experimental Sequence

1. Apply rotating  $E_{lab}$ .
2. Raman  $\pi$  pulse.
3. Ramsey  $\pi/2$  pulse.
4. Coherent evolution.
5. Ramsey  $\pi/2$  pulse.
6. Raman  $\pi$  pulse.
7. Photodissociation:  $HfF^+ \rightarrow Hf^+ + F$ .
8. Separately detect  $Hf^+$  and  $HfF^+$ .

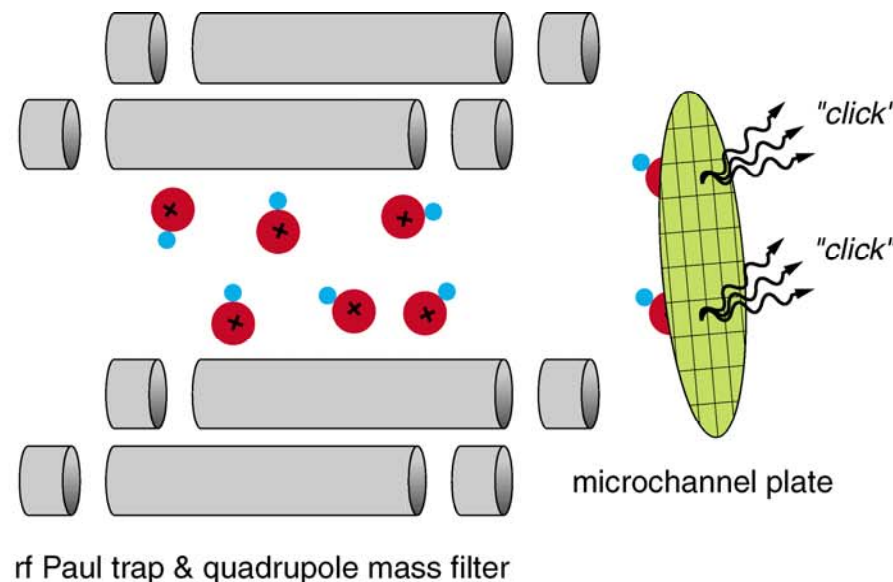
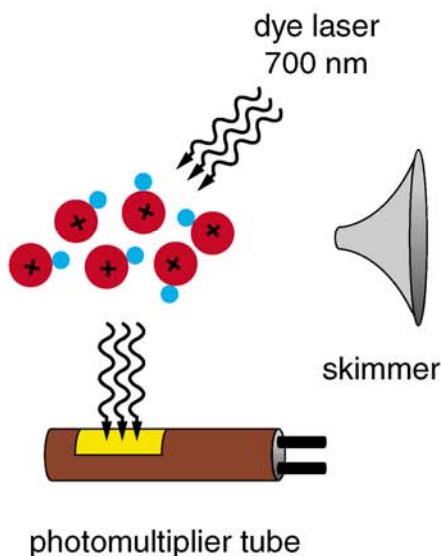
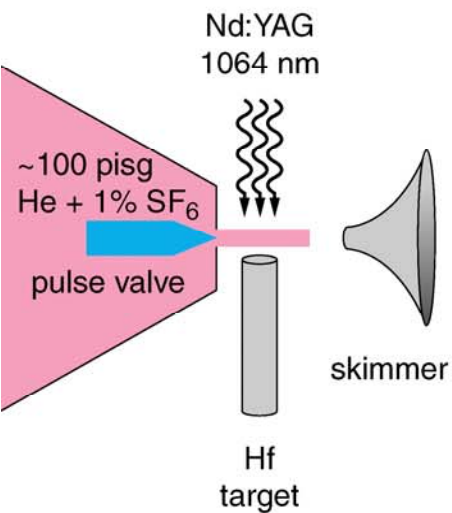
$$\vec{E}_{lab}(t) \propto E_{lab} [\cos(\omega t) \hat{x} + \sin(\omega t) \hat{y}]$$



# $e^-$ EDM Sensitivity Estimate



# Experimental Setup



## Laser Ablation in a Supersonic Jet

- Create HfF<sup>+</sup>.
- Cool rotational, vibrational, and translational motion.

## Fluorescence Spectroscopy

- Measure rotational temperature of neutral HfF molecular beam.

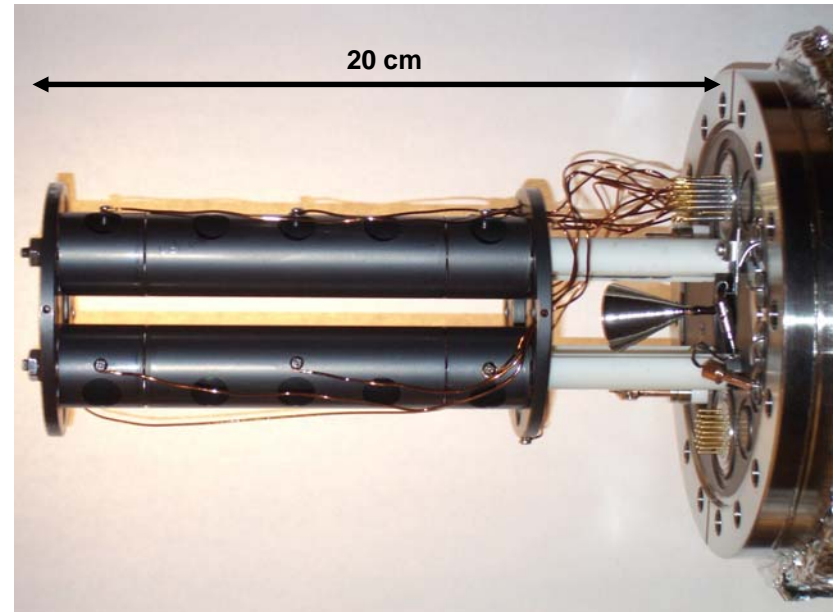
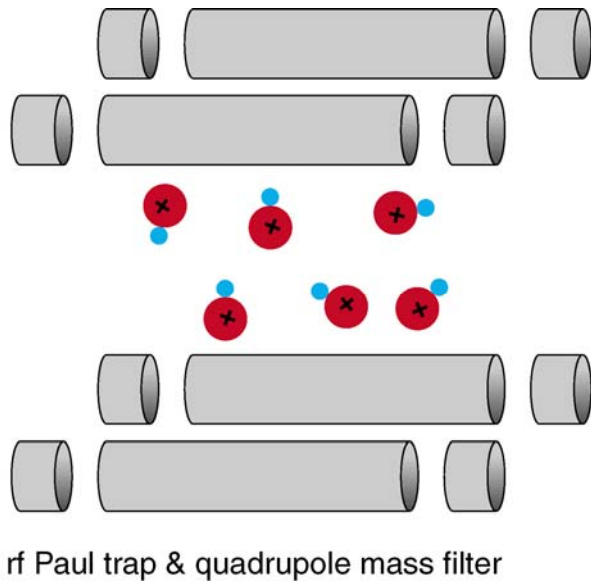
## Mass Spectrometry

- Trap Hf<sup>+</sup>, HfF<sup>+</sup>, HfF<sub>2</sub><sup>+</sup>, and HfF<sub>3</sub><sup>+</sup>.

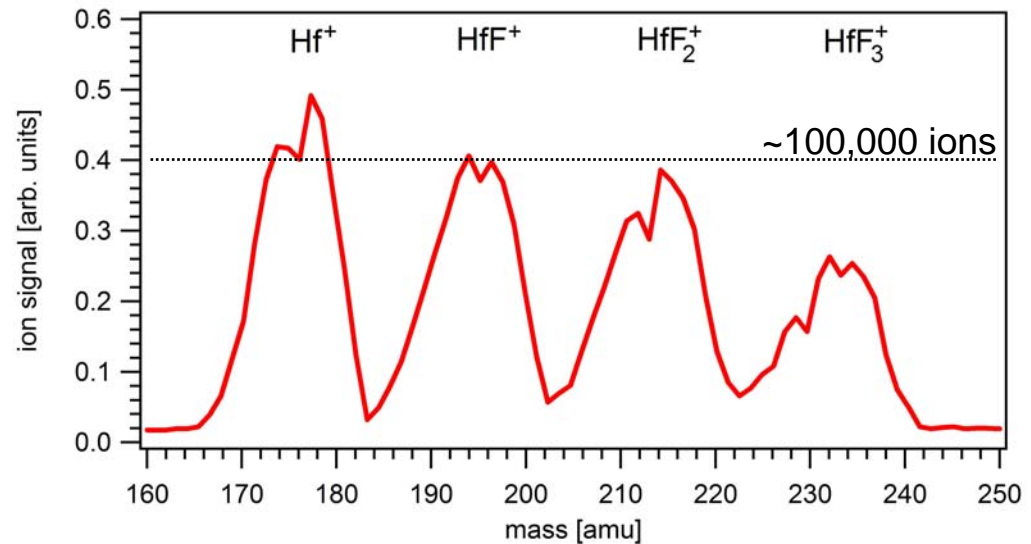
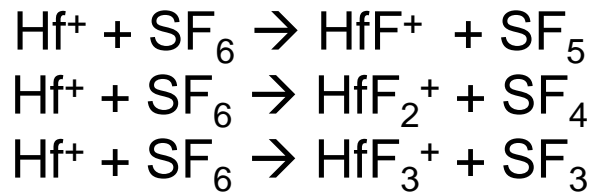
## Ion Beam Imaging

- Measure translational temperature of ion beam.

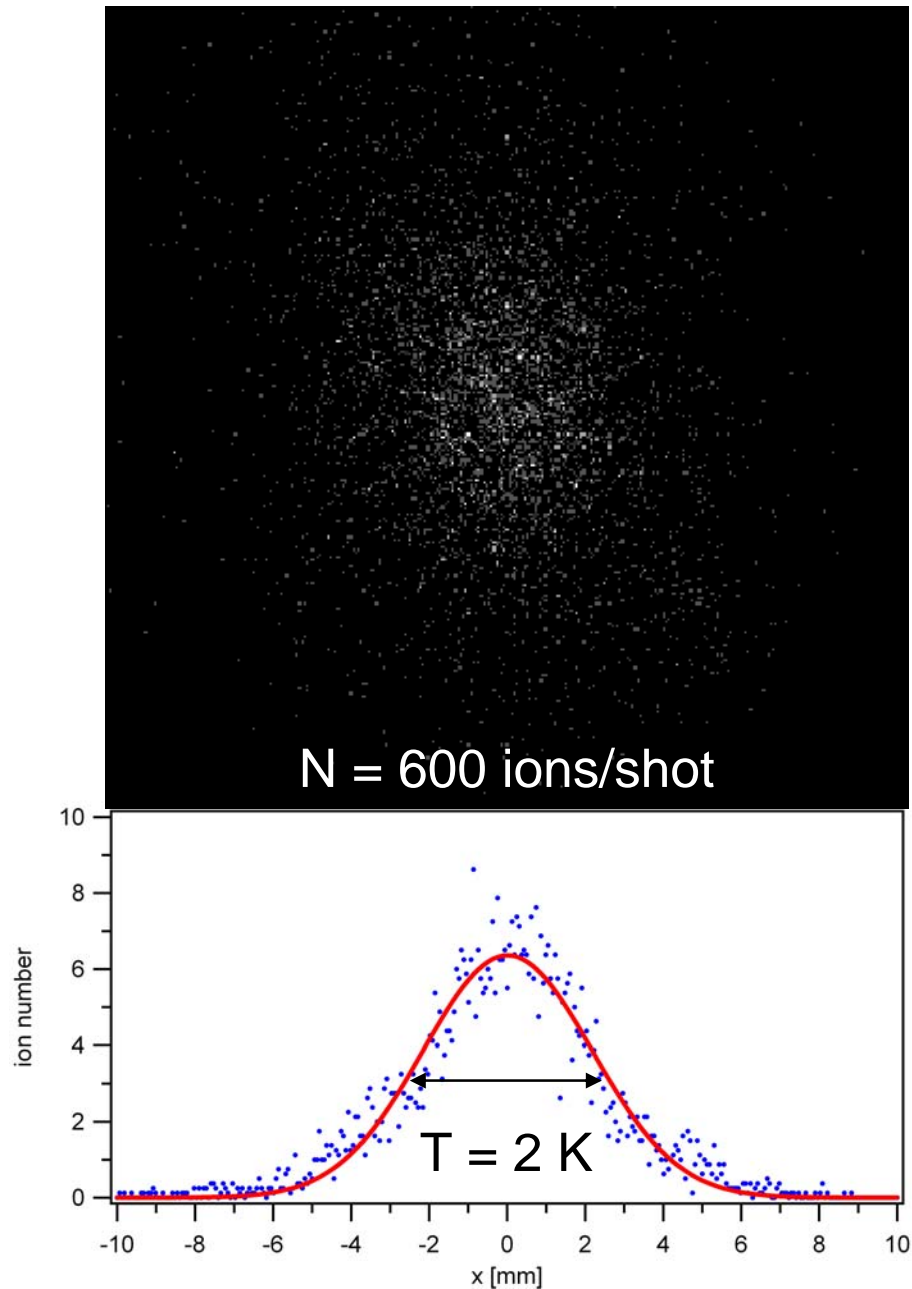
# Mass Spectrometry



## Exothermic Chemical Reactions

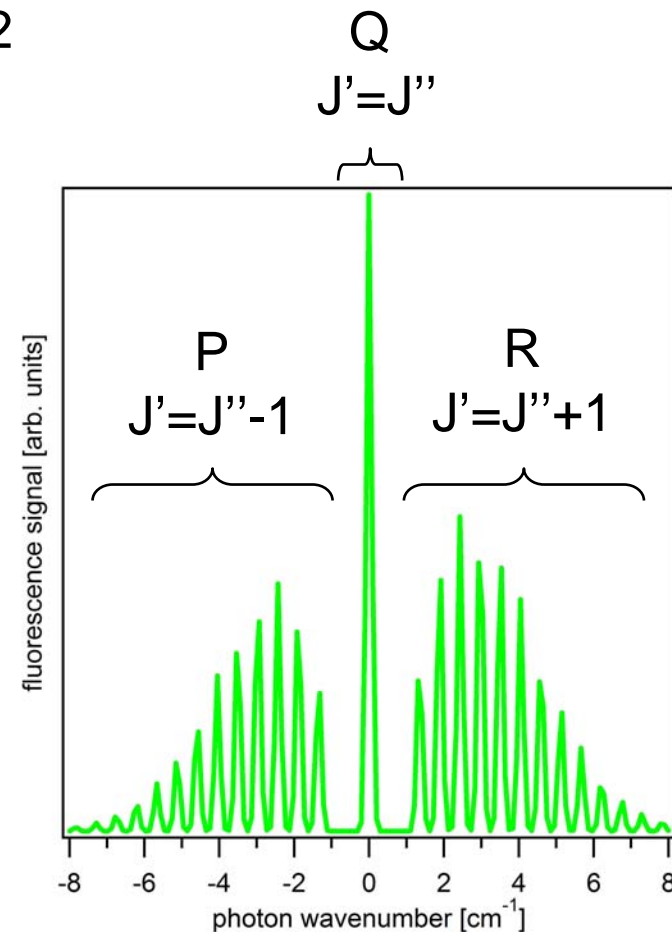
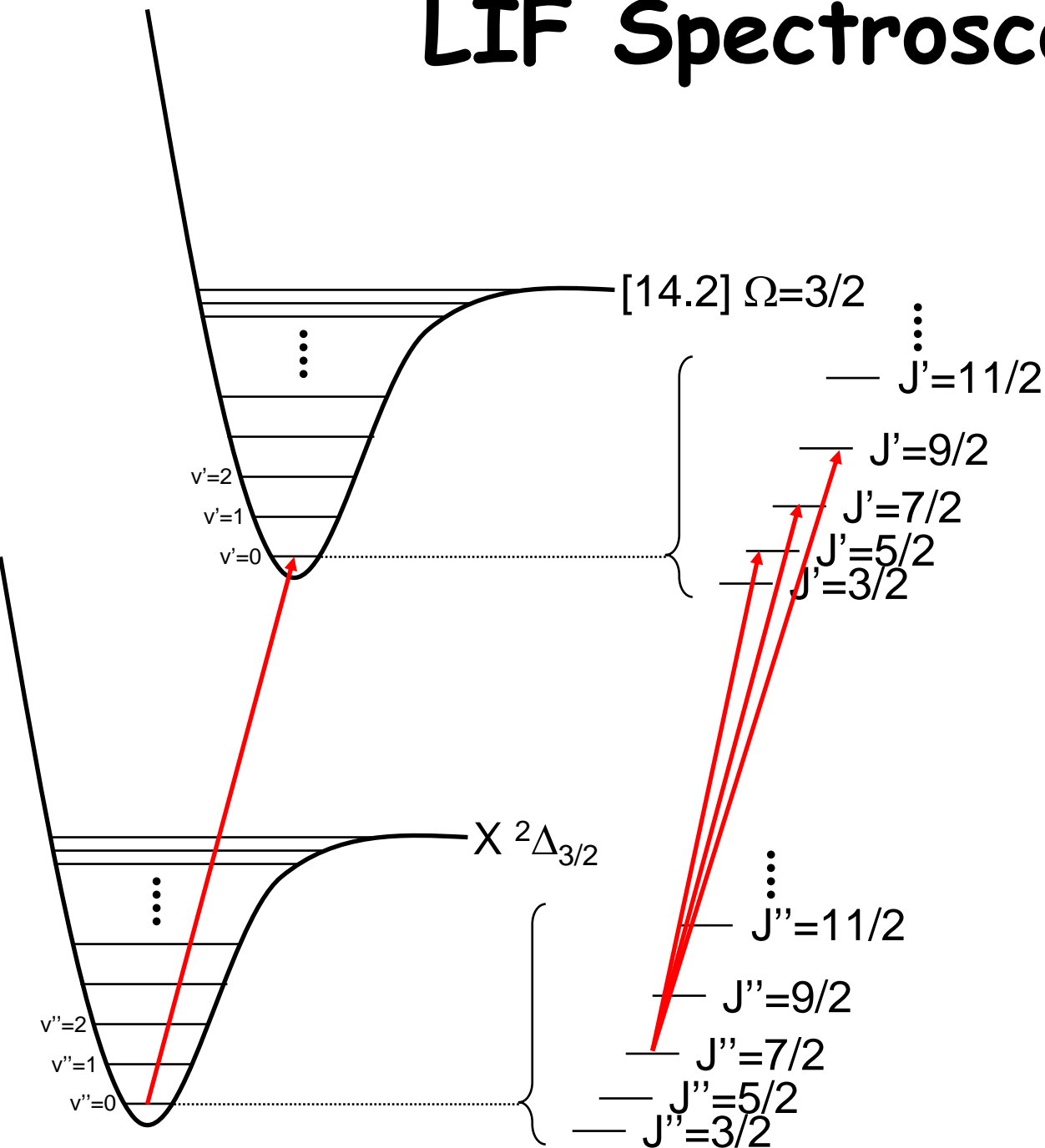


# Ion Beam Imaging



# LIF Spectroscopy

- 3 transitions per J level.
- Count lines to measure rotational temperature.

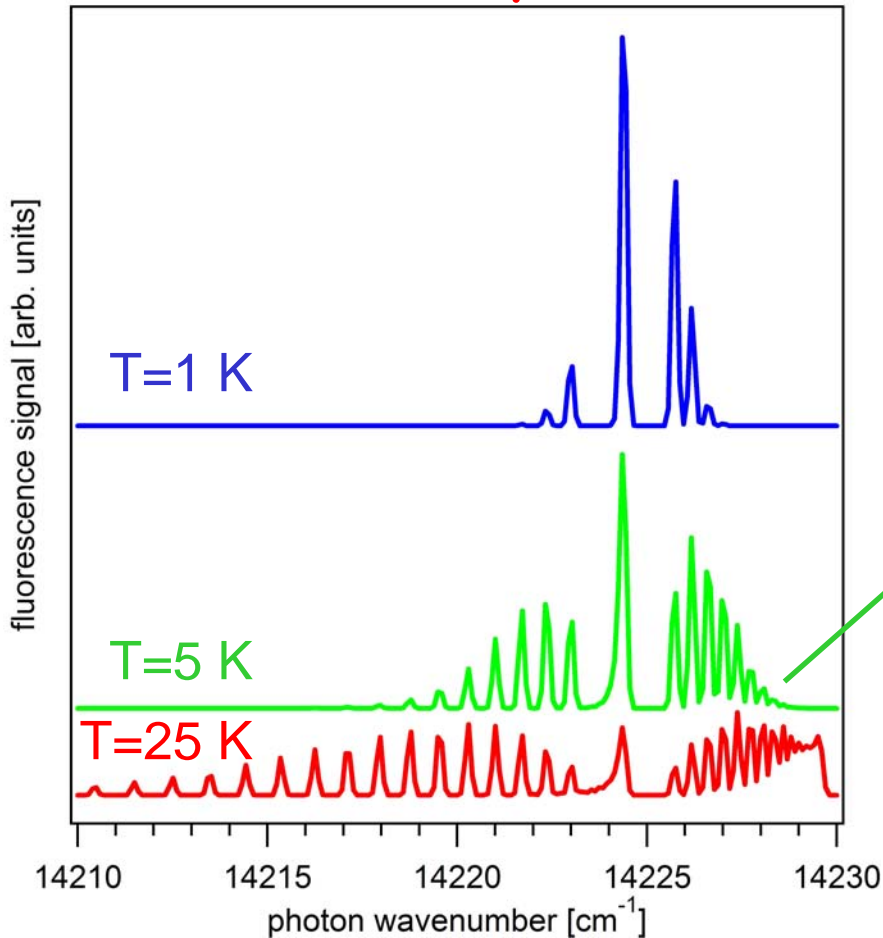




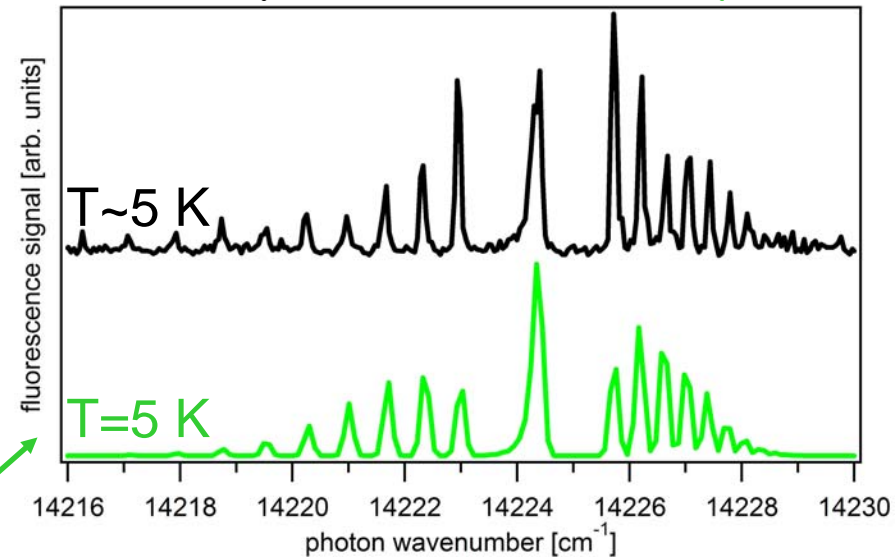
# New Neutral HfF Spectroscopy

$$[14.2] \Omega=3/2 \leftarrow X \ ^2\Delta_{3/2} (0 \leftarrow 0)$$

Theory



Experiment & Theory



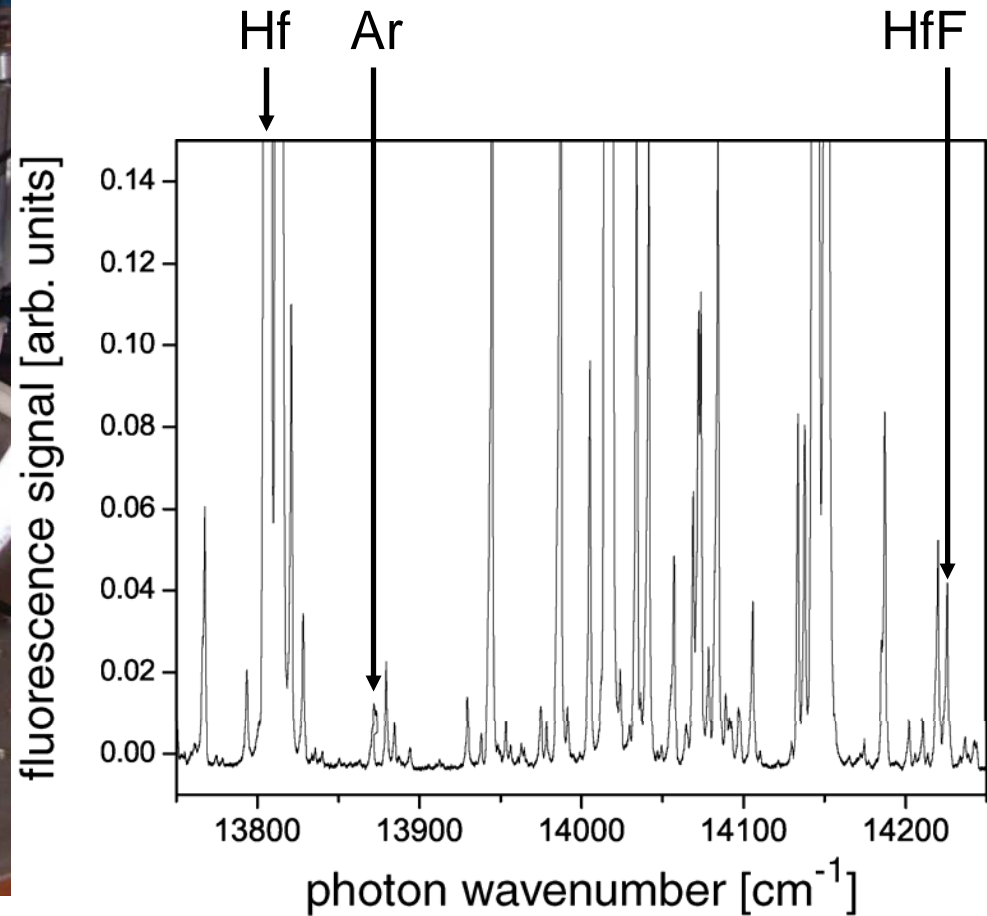
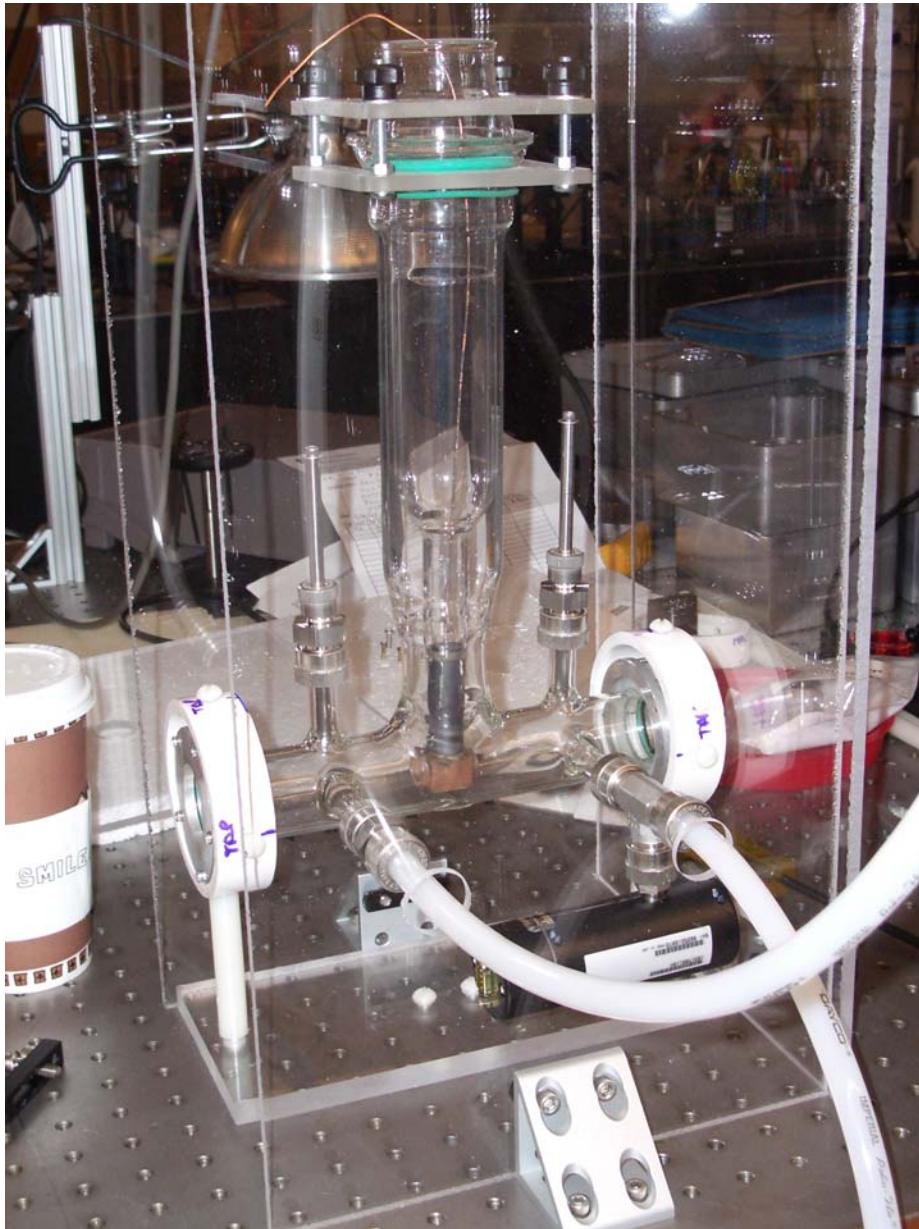
Difference in rotation constants gives chirp in line spacing.

- $B'' = 0.2805 \text{ cm}^{-1}$
- $B' = 0.2660 \text{ cm}^{-1}$

See also: J. Mol. Spect. **225**, 1 (2004).

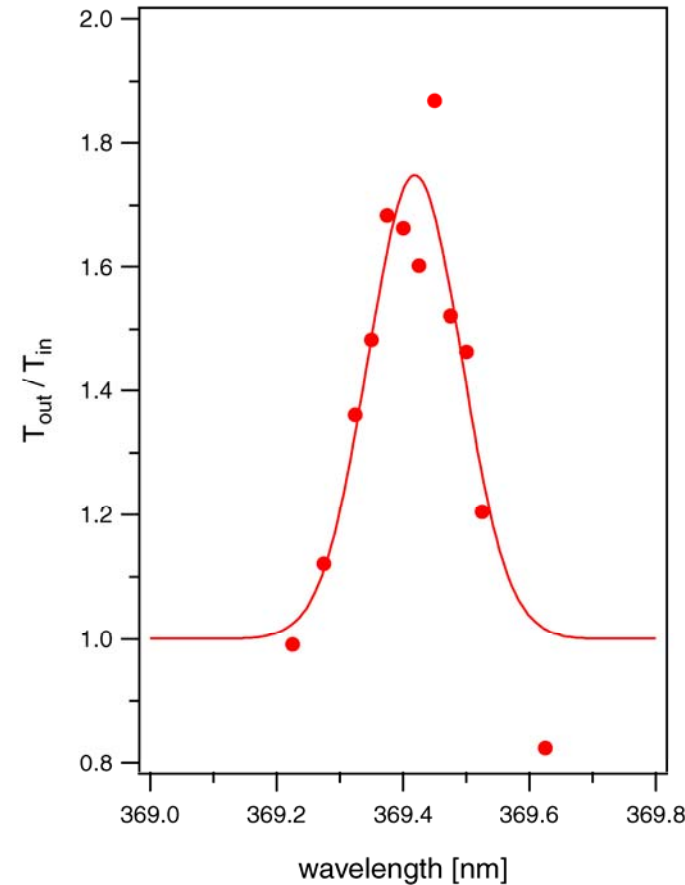
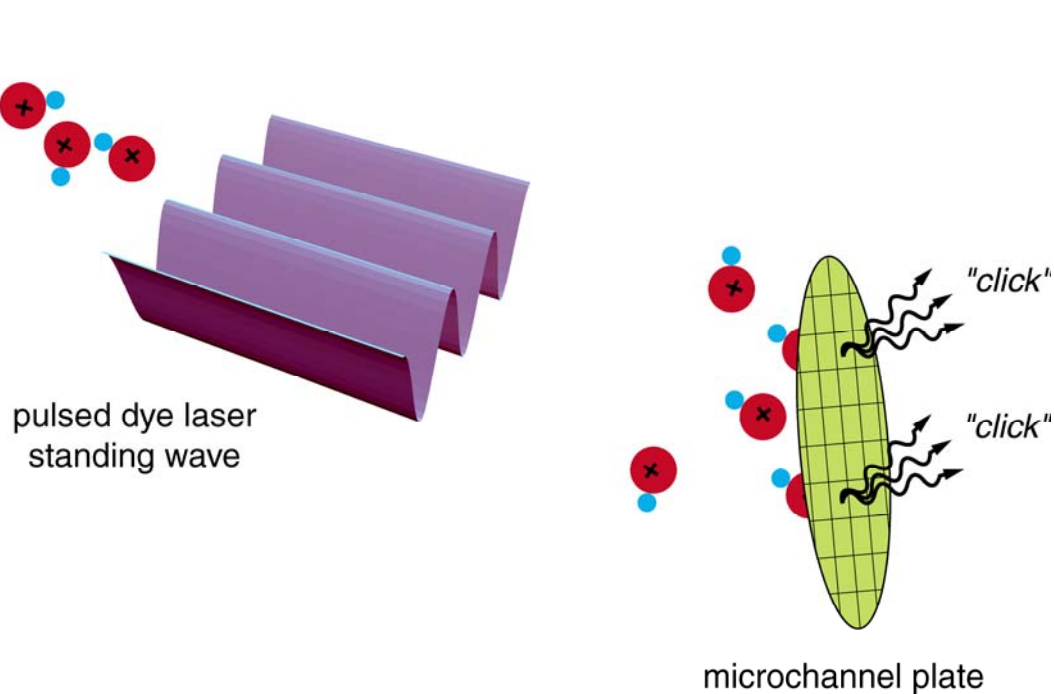
# Traditional Discharge Spectroscopy

- Neutral and ionic atomic lines.
- Neutral molecular lines.
- Unassigned lines well above noise.

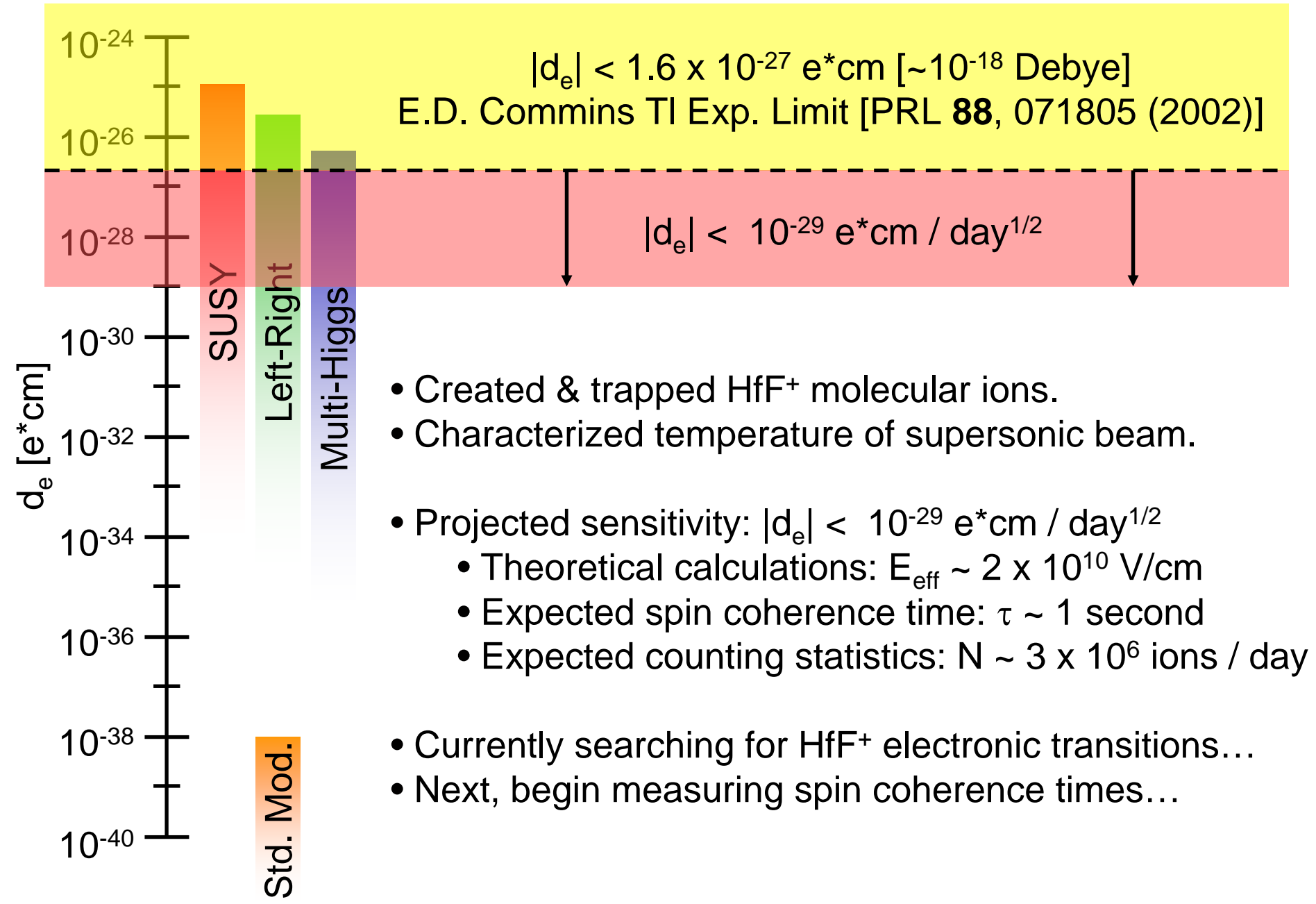


# Novel Ion-Sensitive Spectroscopy

- **Near resonance**, optical potential from pulsed standing wave has:
  - ~10 K depth.
  - ~300 GHz power broadened linewidth.
- Microchannel plate only detects ions.
- Test idea on known Yb<sup>+</sup> transition at 370 nm.



# $e^-$ EDM Search Outlook



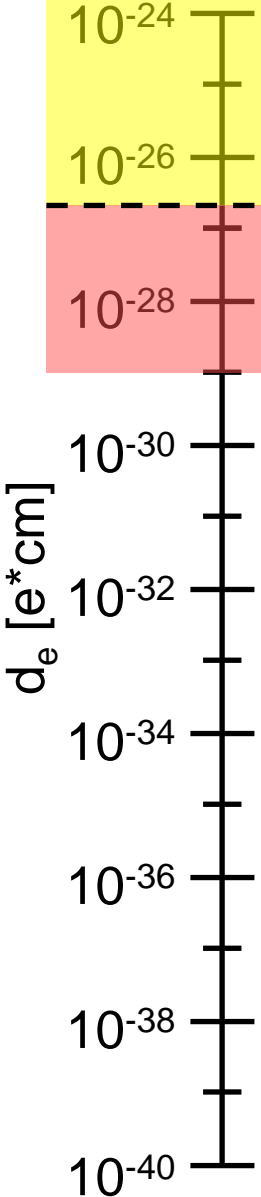
- Created & trapped  $\text{HfF}^+$  molecular ions.
- Characterized temperature of supersonic beam.
- Projected sensitivity:  $|d_e| < 10^{-29} \text{ e}^*\text{cm} / \text{day}^{1/2}$ 
  - Theoretical calculations:  $E_{\text{eff}} \sim 2 \times 10^{10} \text{ V/cm}$
  - Expected spin coherence time:  $\tau \sim 1 \text{ second}$
  - Expected counting statistics:  $N \sim 3 \times 10^6 \text{ ions} / \text{day}$
- Currently searching for  $\text{HfF}^+$  electronic transitions...
- Next, begin measuring spin coherence times...

# $e^-$ EDM Search @ JILA

$$|d_e| < 1.6 \times 10^{-27} \text{ e}^* \text{cm} [\sim 10^{-18} \text{ Debye}]$$

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

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



SUSY

Left-Right

Multi-Higgs

Std. Mod.



Aaron Leanhardt   Russell Stutz

Laura Sinclair   Eric Cornell