William Cairncross
Cornell & Ye groups
JILA

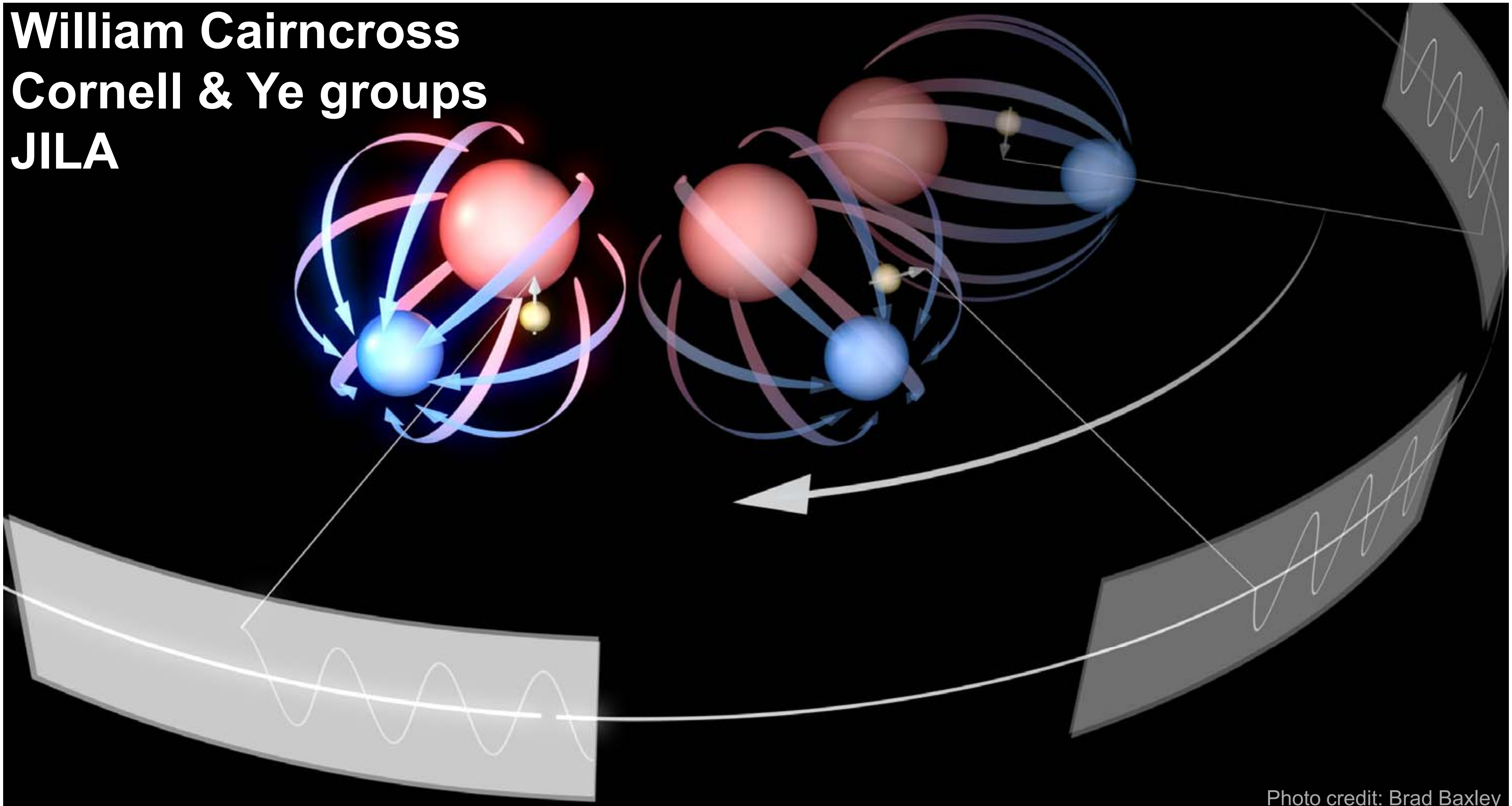
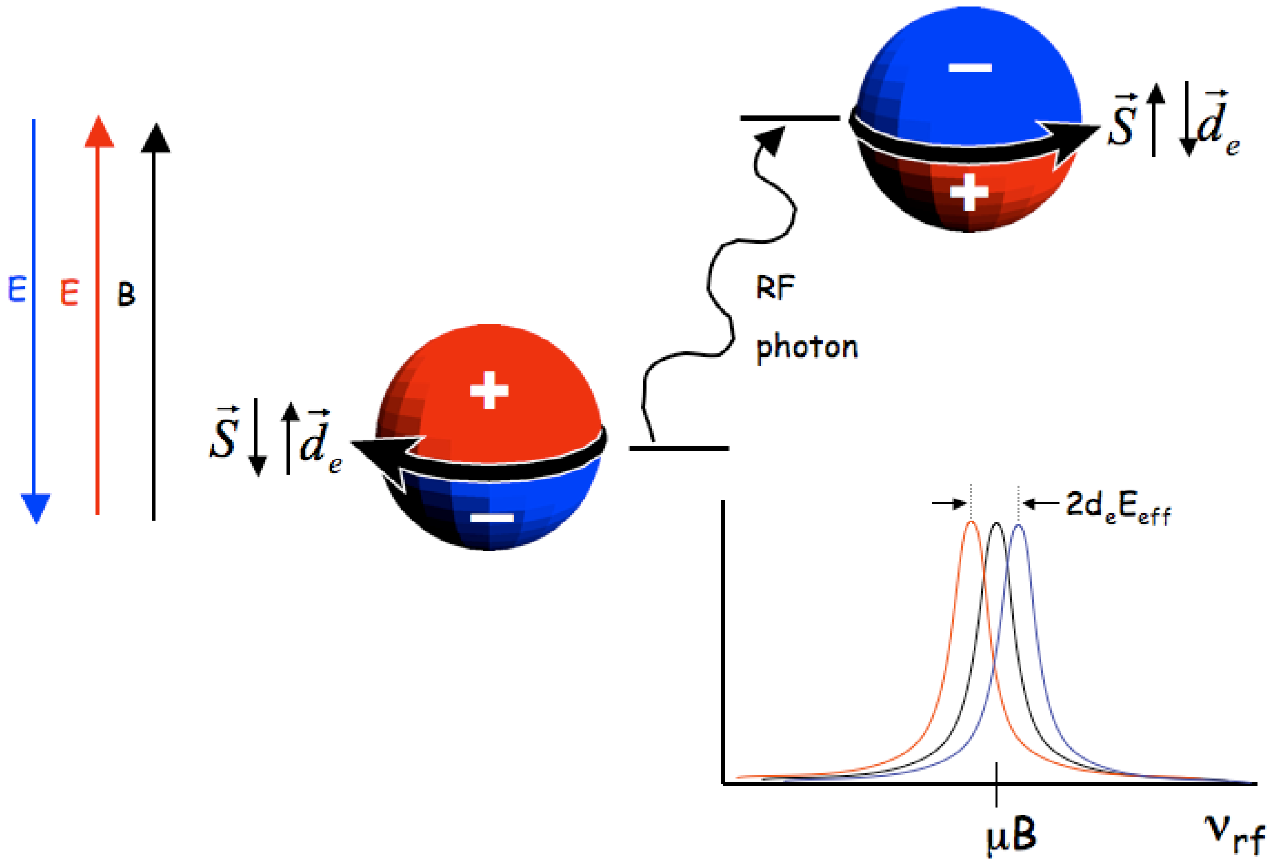


Photo credit: Brad Baxley

EDMs from Molecular Ions

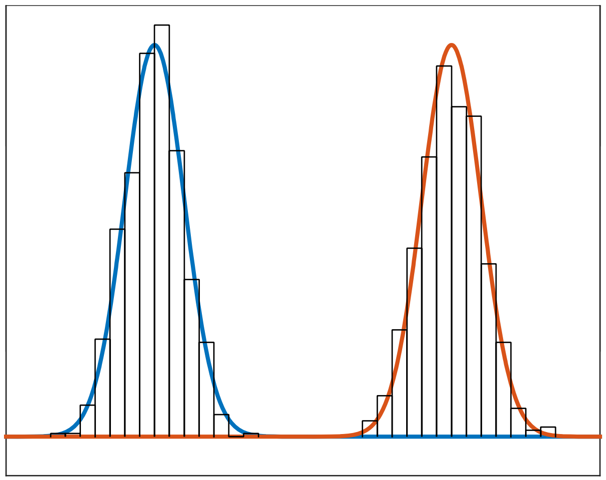
CU
JILA pfc an NSF physics frontier center
JILA CU-Boulder and NIST

Measuring an eEDM

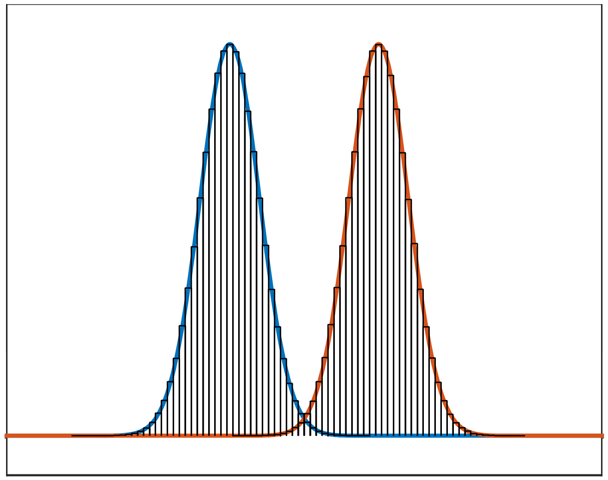


Measurement precision: $$\delta d_e \sim \frac{1}{|\mathcal{E}_{\mathrm{eff}}|\tau\sqrt{N}}$$

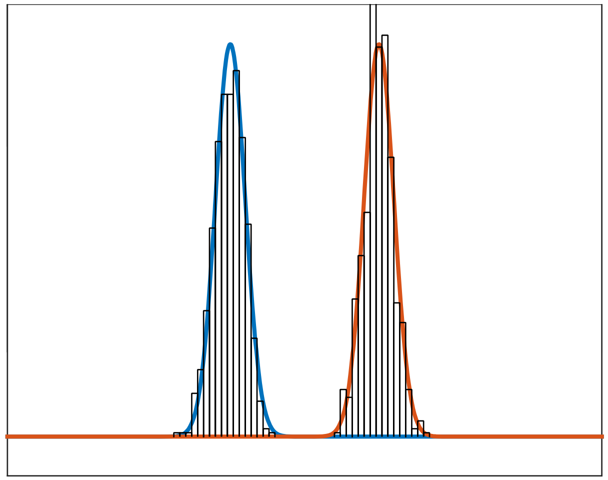
Sensitivity



Large Electric Field



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



Long coherence time
(narrow resonance)

$$\delta d_e \sim \frac{1}{|\mathcal{E}_{\text{eff}}|\tau\sqrt{N}}$$

Molecular Ions

$$\delta d_e \sim \frac{1}{|\mathcal{E}_{\text{eff}}|\sqrt{\tau N}}$$

Molecules provide large effective electric fields

E_{lab} = 10 V/cm

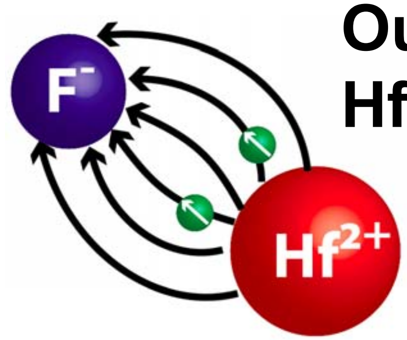
$|E_{eff}| > 10^{10}$ V/cm

Trap molecular ions to probe for long time

- Trap lifetime of many seconds
- Science state lifetime 2.1(1)s
- May trap many ions in thermal cloud 1~10 K

Ω-doublet

- Switch E-field with AOM frequency



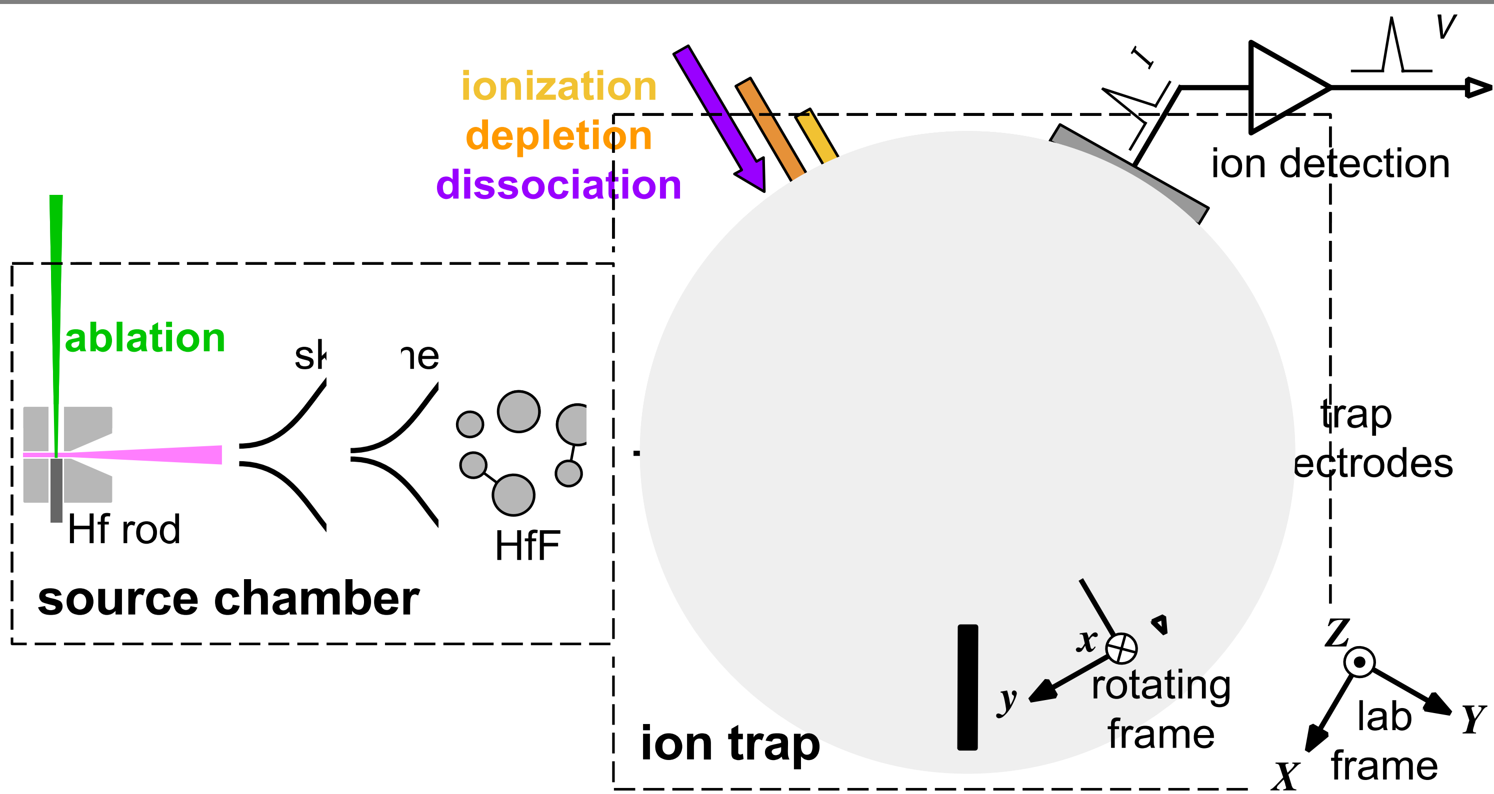
Our choice: HfF^+

P. G. H. Sandars, Physics Letters **14**, 194 (1965).
E. A. Hinds, Physica Scripta **T70**, 34 (1997).
D. DeMille, *et al.*, Physical Review A **61**, 1 (2000).

Talk Overview

- Introduction
- Experimental Details
- Ramsey Spectroscopy
- Systematic Errors
- Current eEDM Measurement

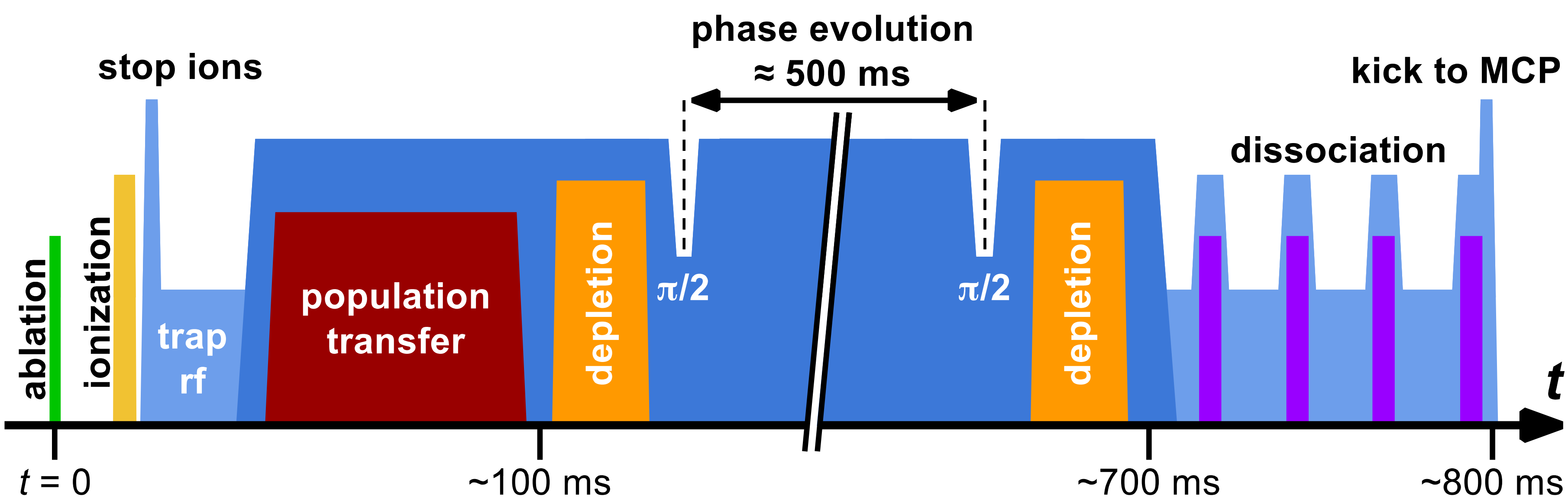
Apparatus



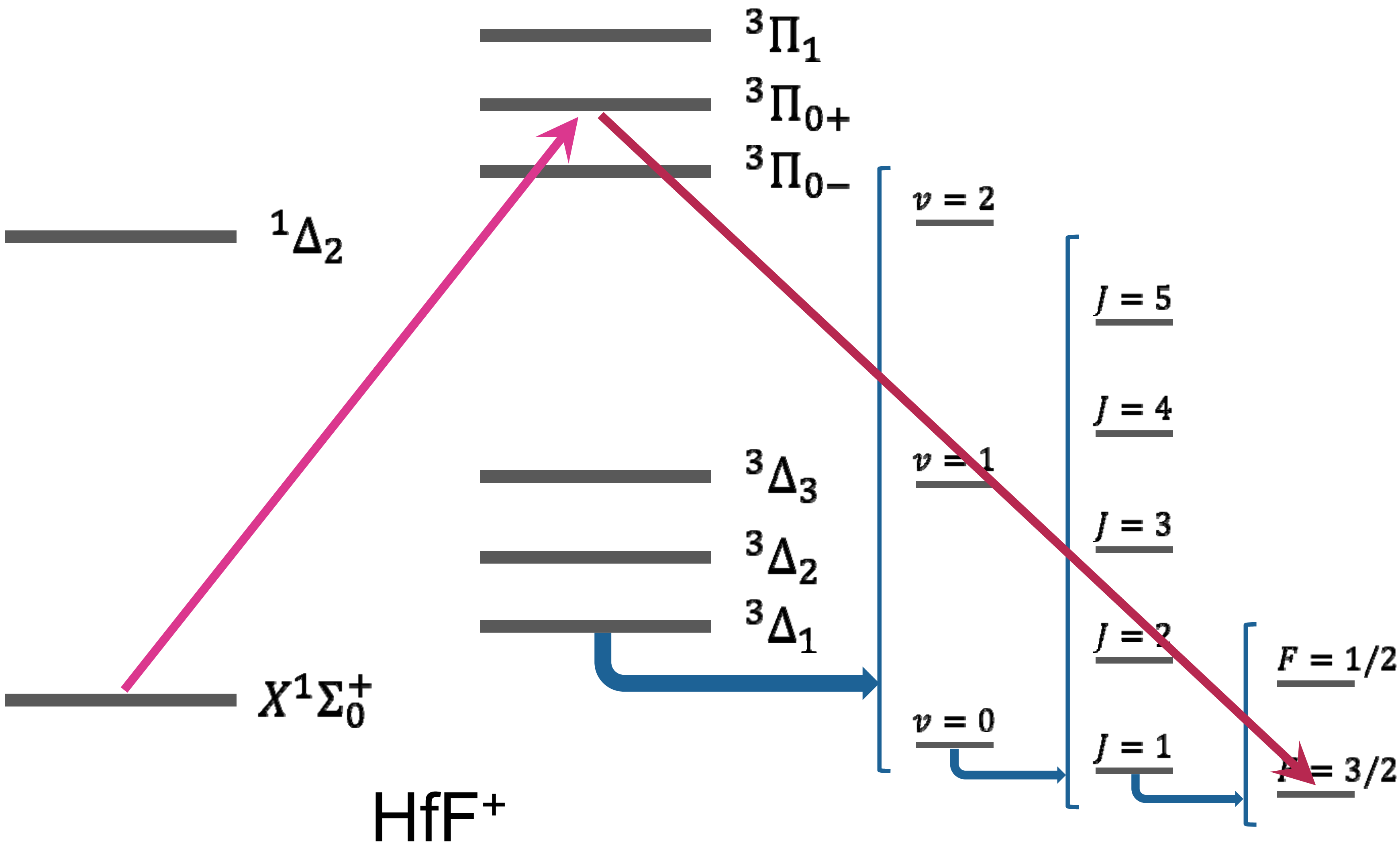
Secular trap motion at $\omega_{sec} \sim 2\pi(4\ kHz)$
"RF" micromotion at $\omega_{rf} = 2\pi(50\ kHz)$
Rotational micromotion at $\omega_{rot} = 2\pi(250\ kHz)$

Rotating magnetic field: <u>not sensitive to DC fields</u>

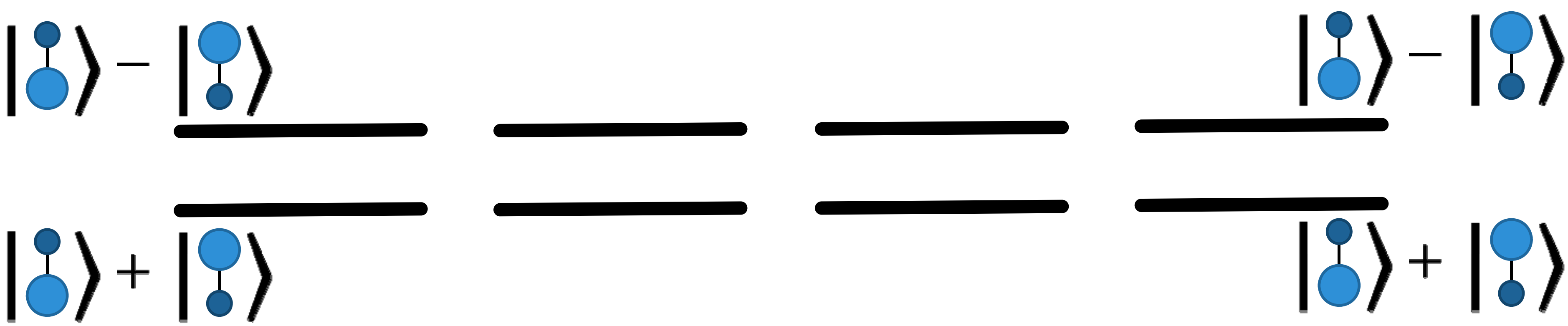
Experiment Sequence



State Transfer

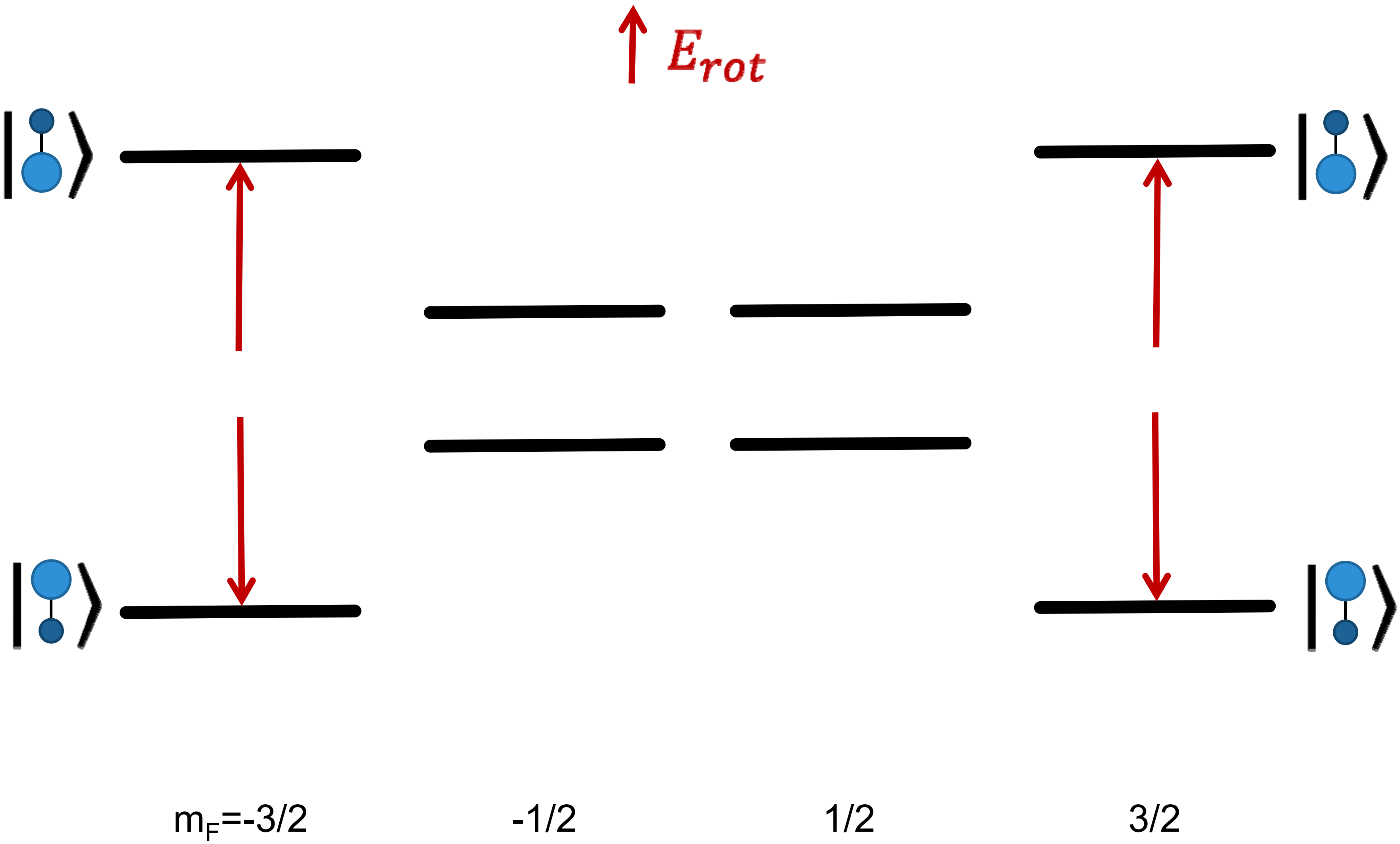


$^3\Delta_1$, J=1, F=3/2

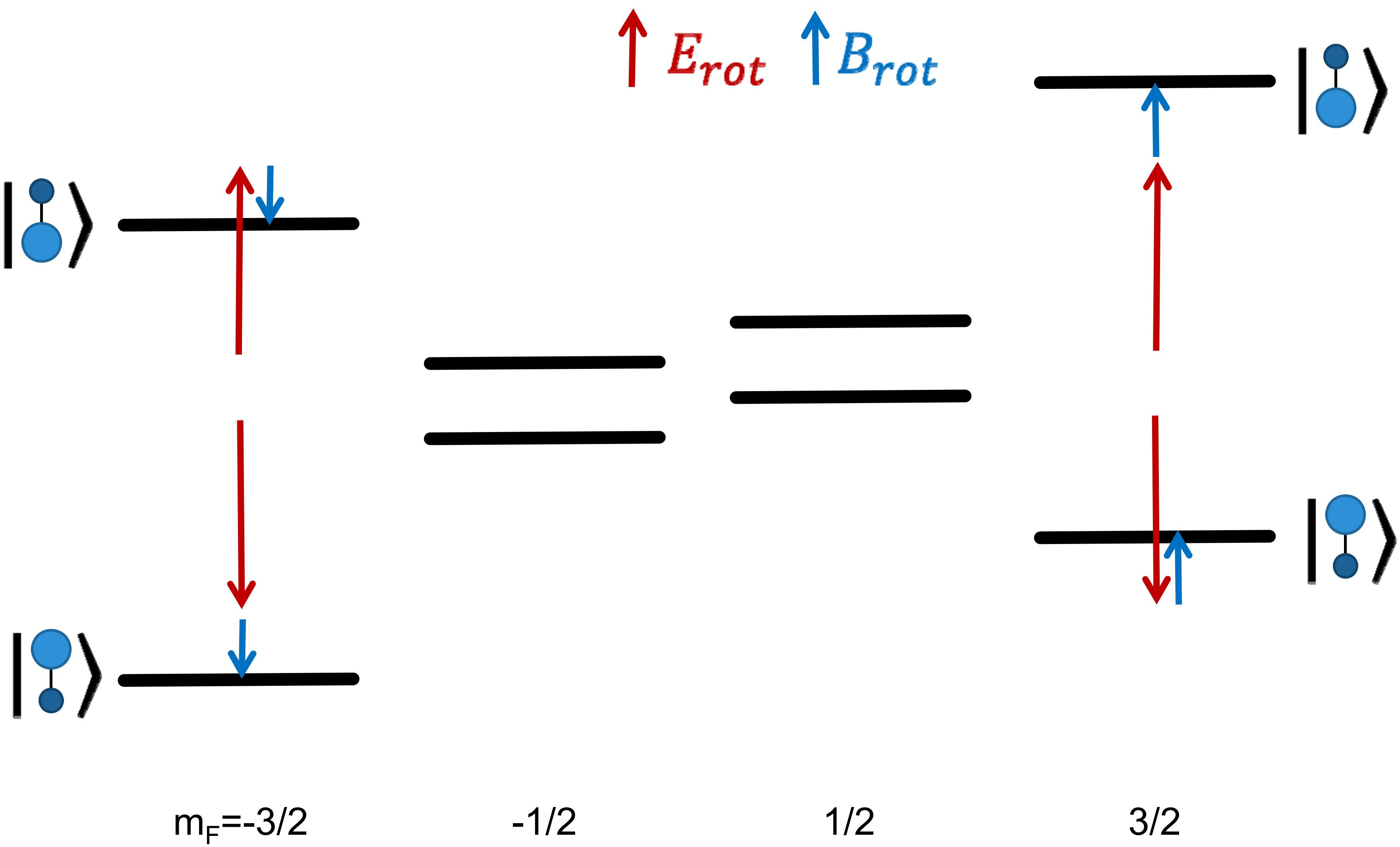


m_F=-3/2 -1/2 1/2 3/2

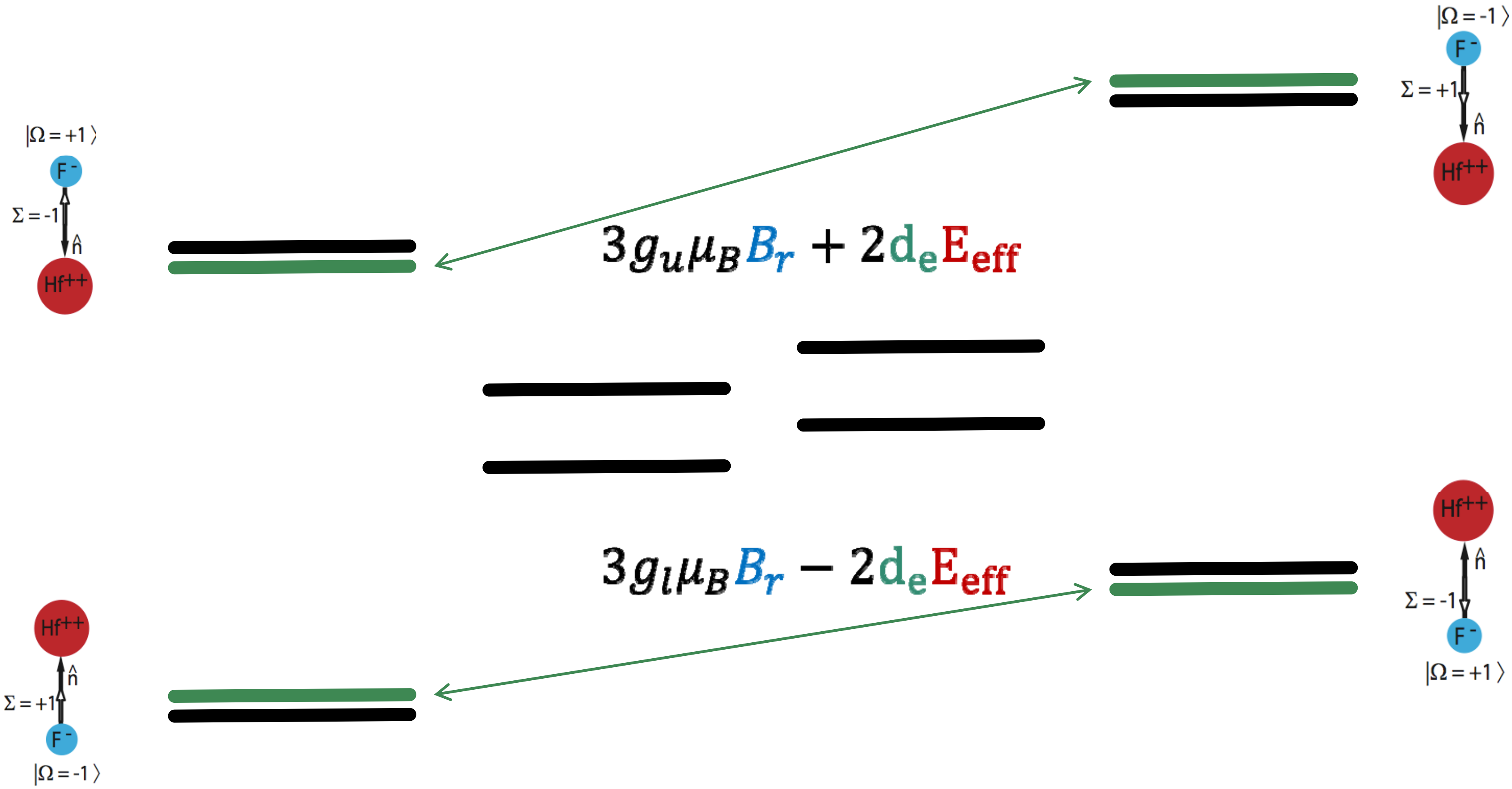
$^3\Delta_1$, J=1, F=3/2



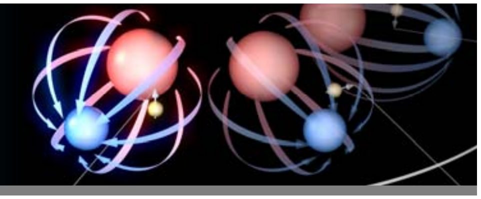
$^3\Delta_1$, J=1, F=3/2



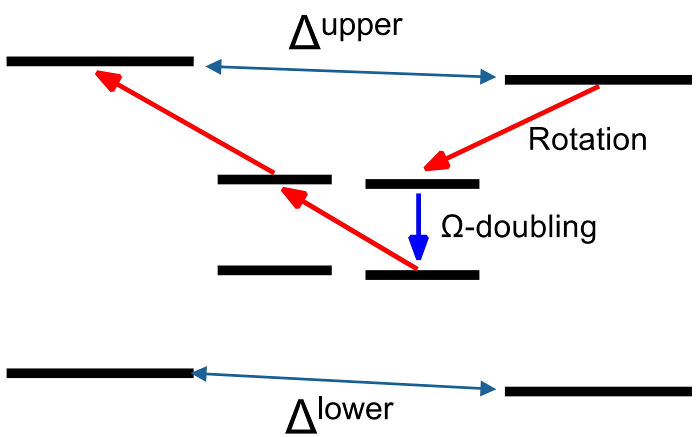
$^3\Delta_1$, J=1, F=3/2



Effect of Rotation



$$H_{\text{rot}} = -\vec{\omega} \cdot \vec{J}$$

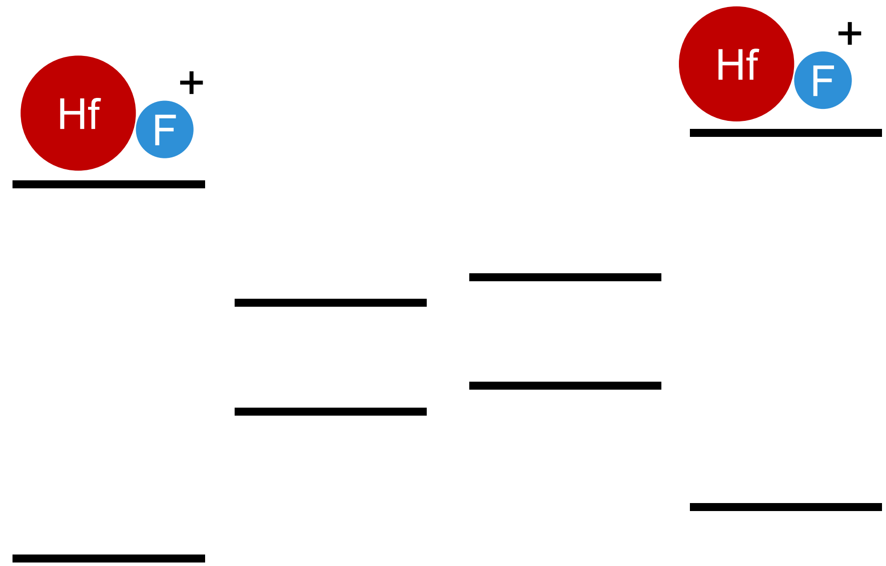


- Rotation and Ω-doubling couple states of opposite m_F and Ω
- Presence of F=1/2 hyperfine level creates doublet dependence δΔ
- Disadvantages
  - Potential source of systematics?
  - Added complexity
- Advantage: Method for pi/2 pulses!

$$H_{\text{eff}}^{u/l} = \frac{1}{2}\begin{pmatrix} 3(g_F \pm \delta g_F)\mu_B \mathcal{B}_{\text{rot}} \pm 2d_e\mathcal{E}_{\text{eff}} & \bar{\Delta} \pm \delta\Delta \\ \bar{\Delta} \pm \delta\Delta & 3(g_F \pm \delta g_F)\mu_B \mathcal{B}_{\text{rot}} \pm 2d_e\mathcal{E}_{\text{eff}} \end{pmatrix}$$

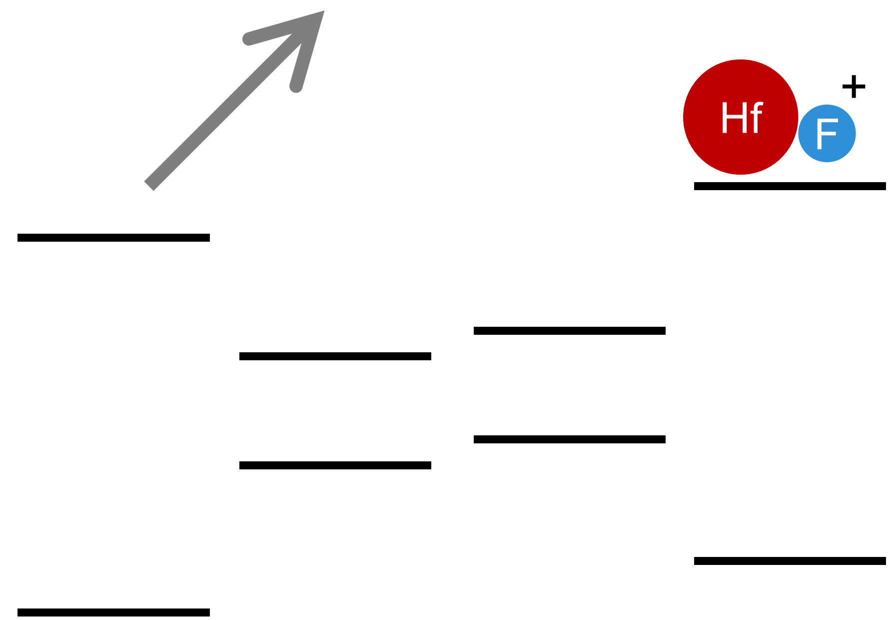
Ramsey Sequence

Transfer lasers prepare population in a single pair of Stark states



Ramsey Sequence

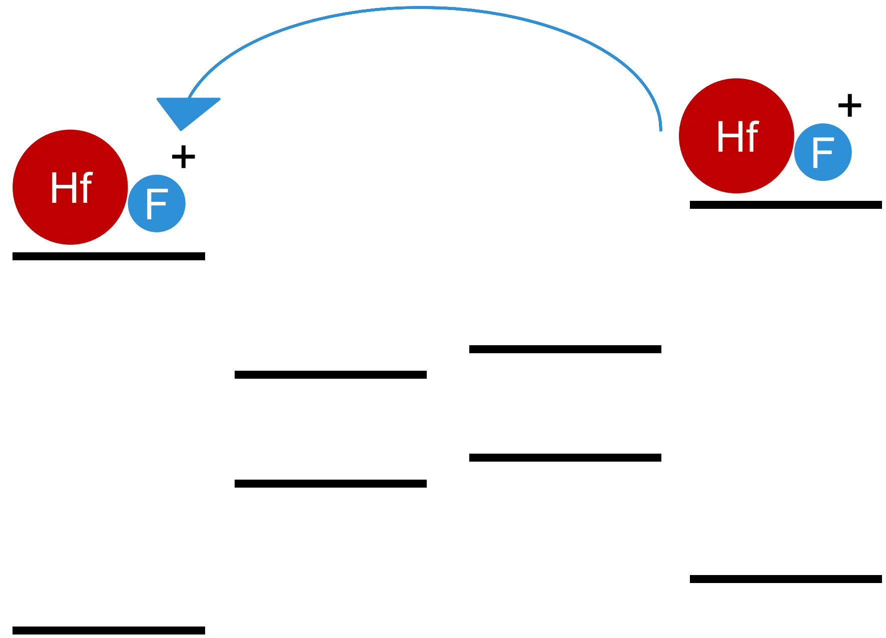
Optically deplete the population of one m_F level using strobed circularly polarized light



Ramsey Sequence

$\pi/2$ pulse puts system into the superposition

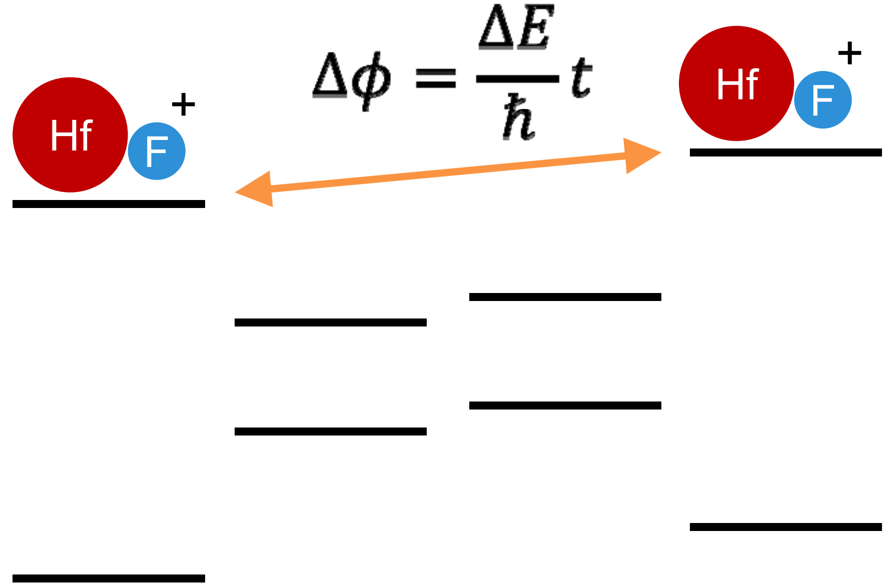
$\left|m_F = -\frac{3}{2}\right\rangle + \left|m_F = +\frac{3}{2}\right\rangle$



Ramsey Sequence

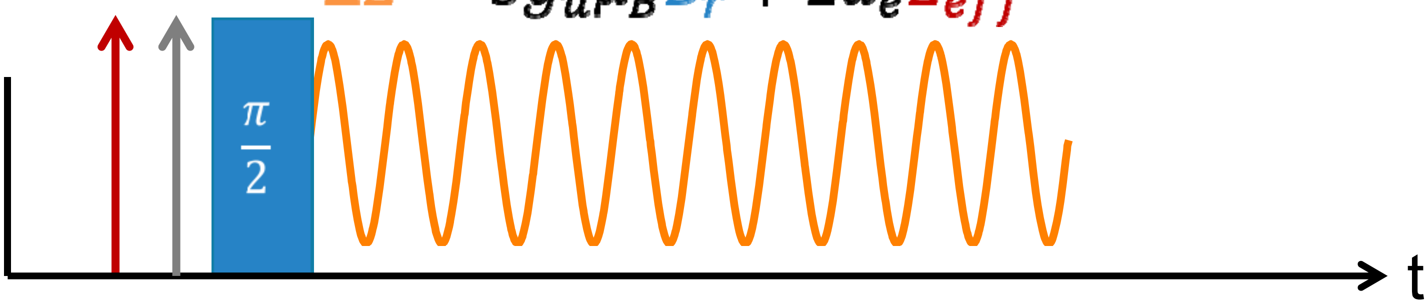
Free evolution

$$\Delta\phi = \frac{\Delta E}{\hbar} t$$



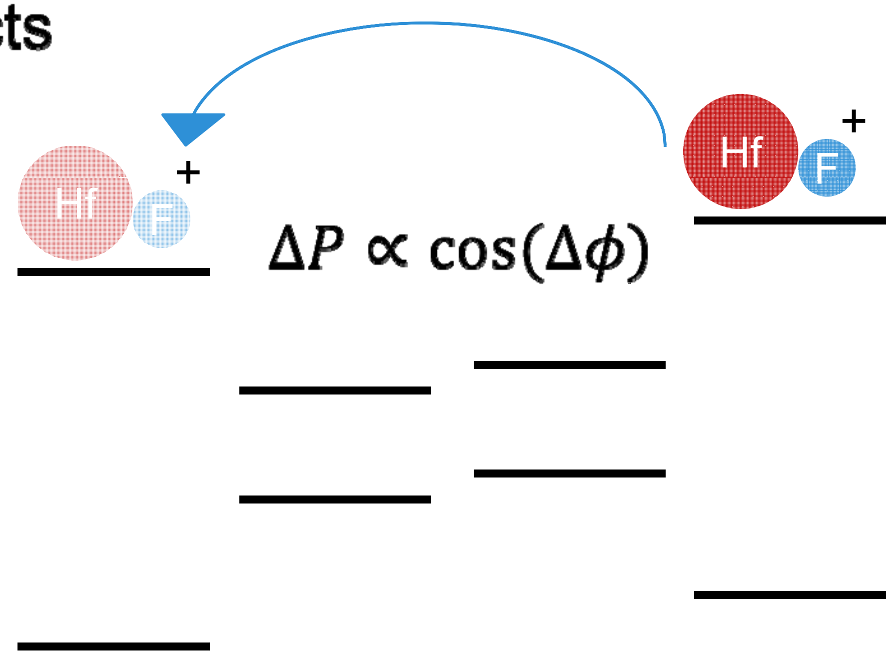
Transfer

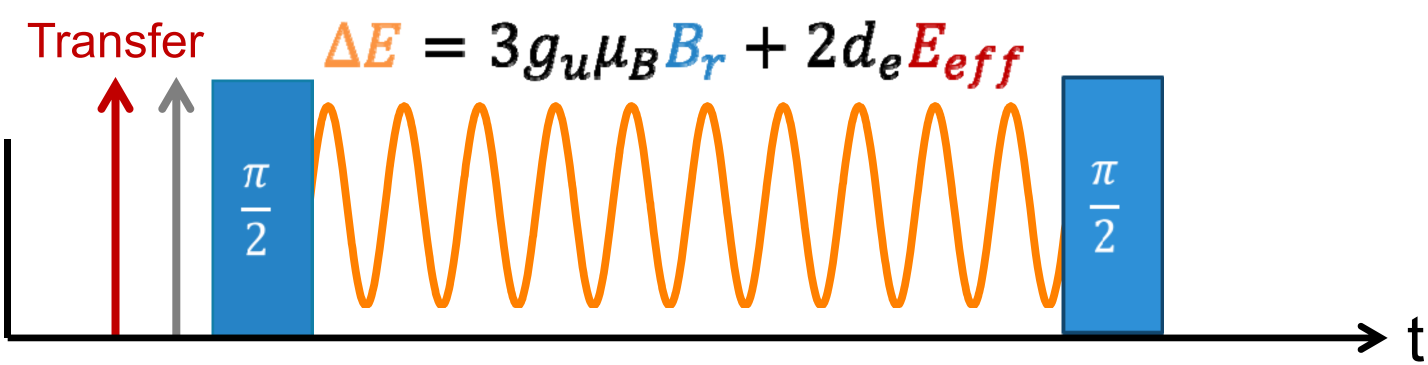
$$\Delta E = 3 g_u \mu_B B_r + 2 d_e E_{eff}$$



Ramsey Sequence

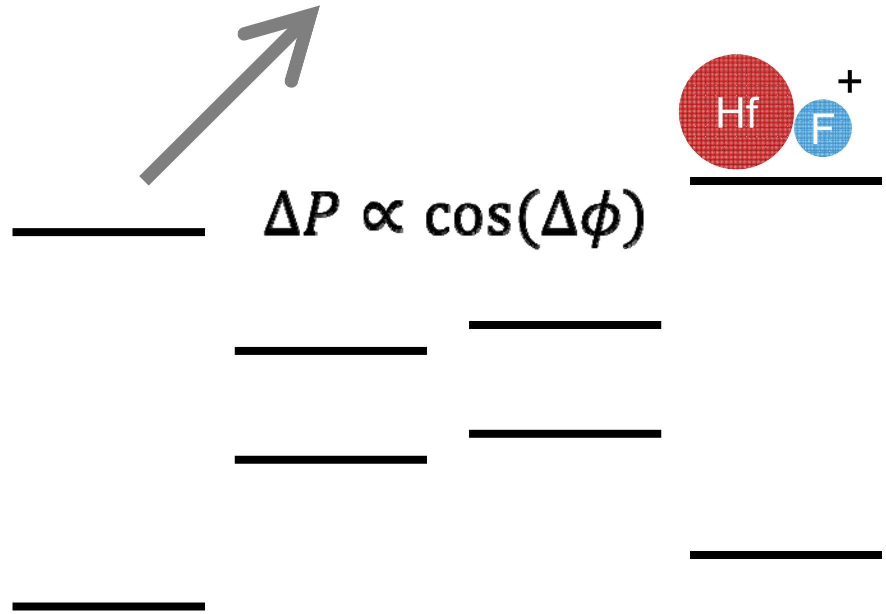
A second $\pi/2$ pulse projects the phase onto population



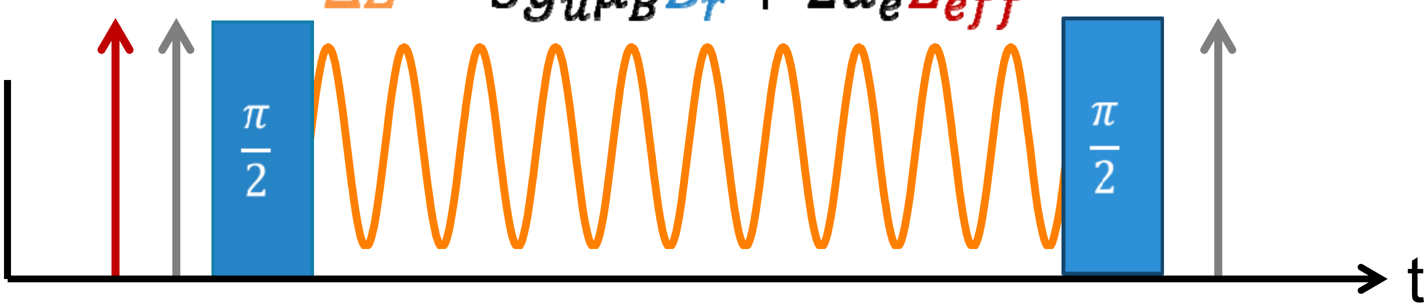


Ramsey Sequence

Optically deplete population out of one of the m_F levels

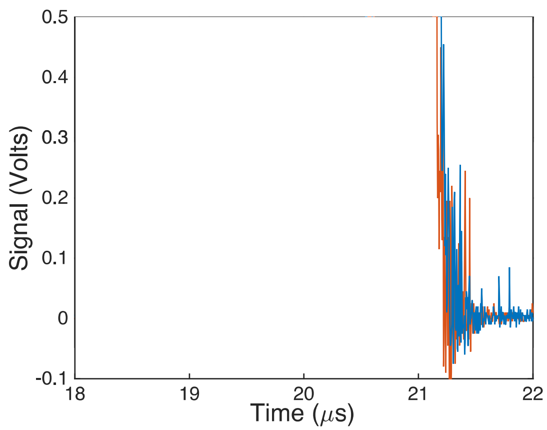


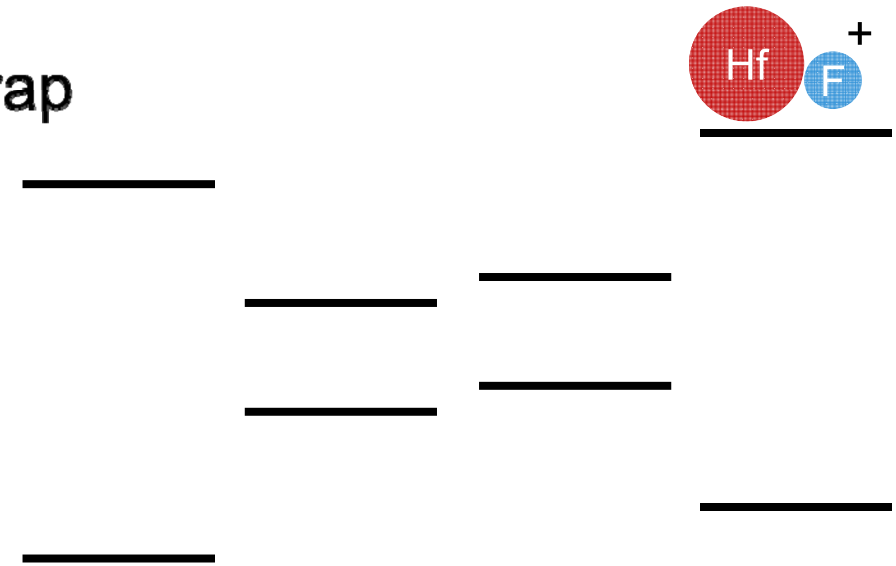
$$\Delta E = 3 g_u \mu_B B_r + 2 d_e E_{eff}$$



Ramsey Sequence

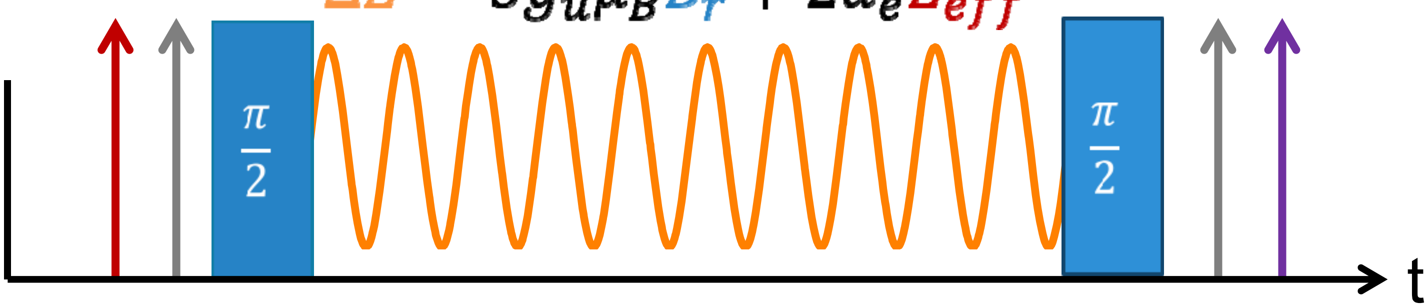
Dissociate all of the ions in the $J = 1$ level, and count Hf^+ ions in the trap



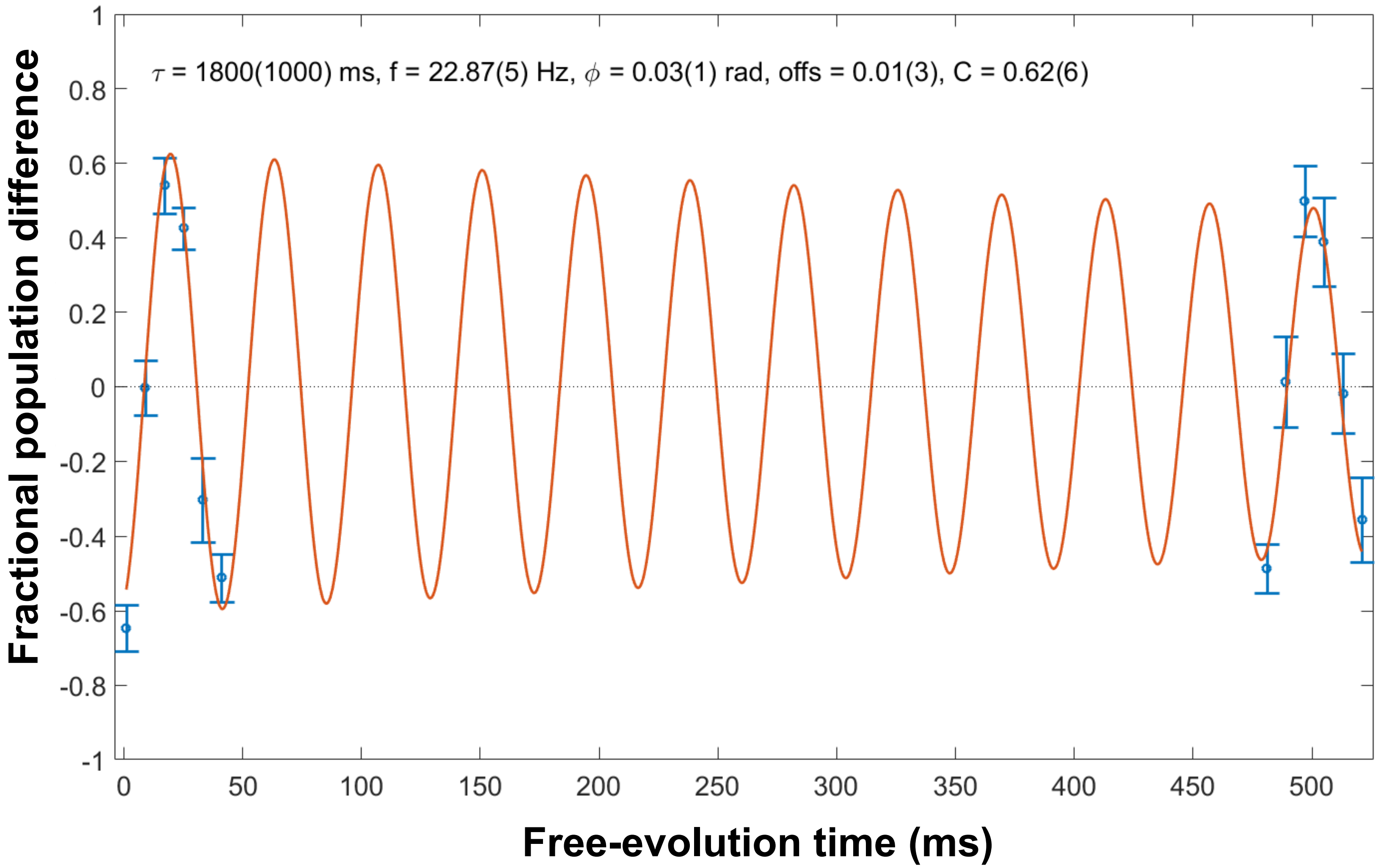


Transfer

$$\Delta E = 3 g_u \mu_B B_r + 2 d_e E_{eff}$$

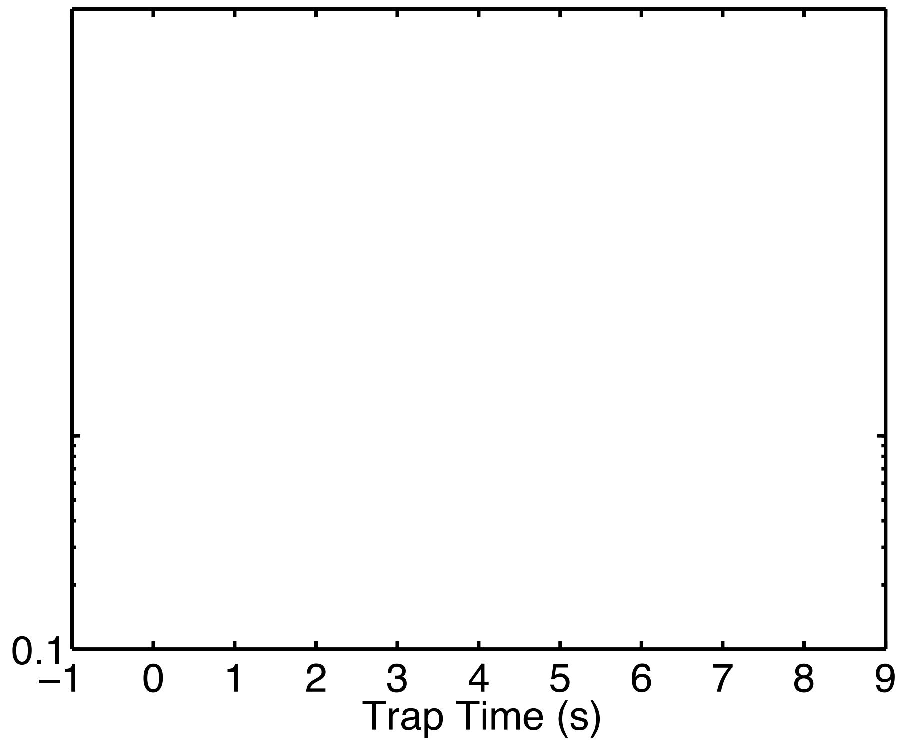


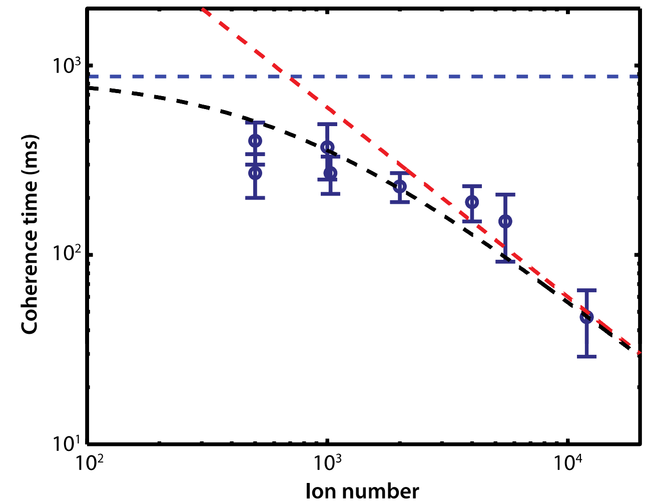
Ramsey Fringe

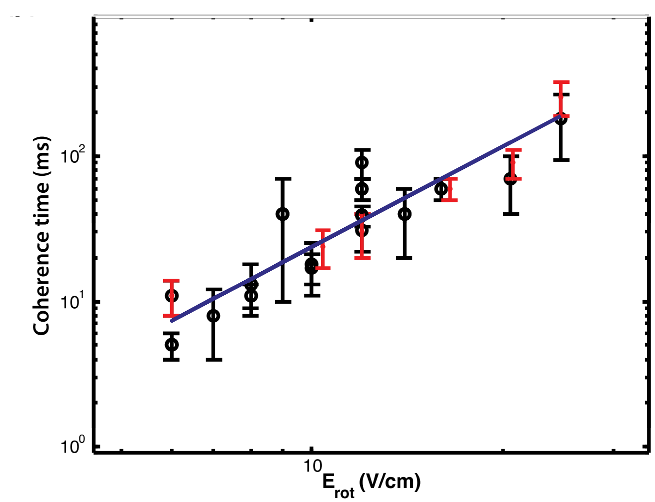


Limits to Coherence

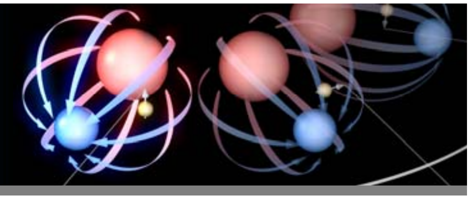
- Ultimate limit: $^3\Delta_1$ state lifetime
- Collisions and inhomogeneity



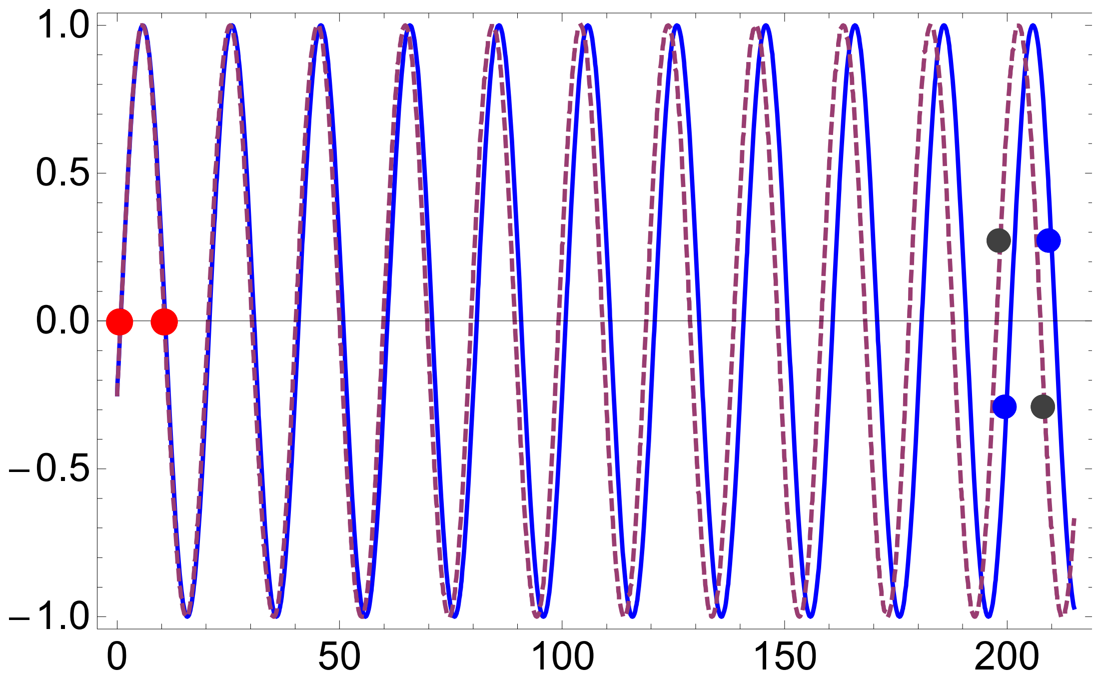


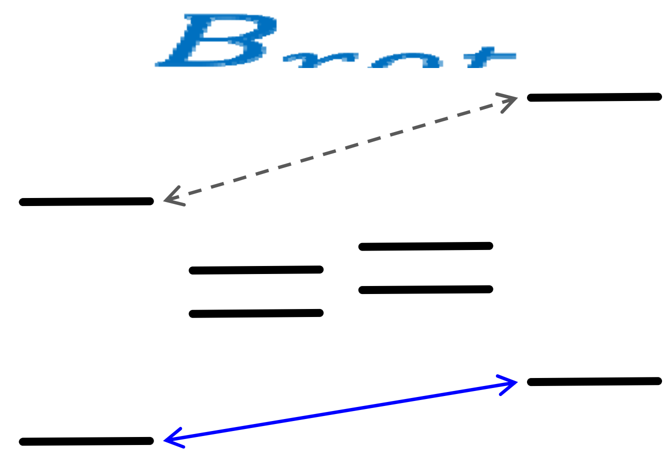


eEDM measurement



1. Measure initial phase and phase at long time
2. Compare upper and lower transitions
3. Switch B field sign





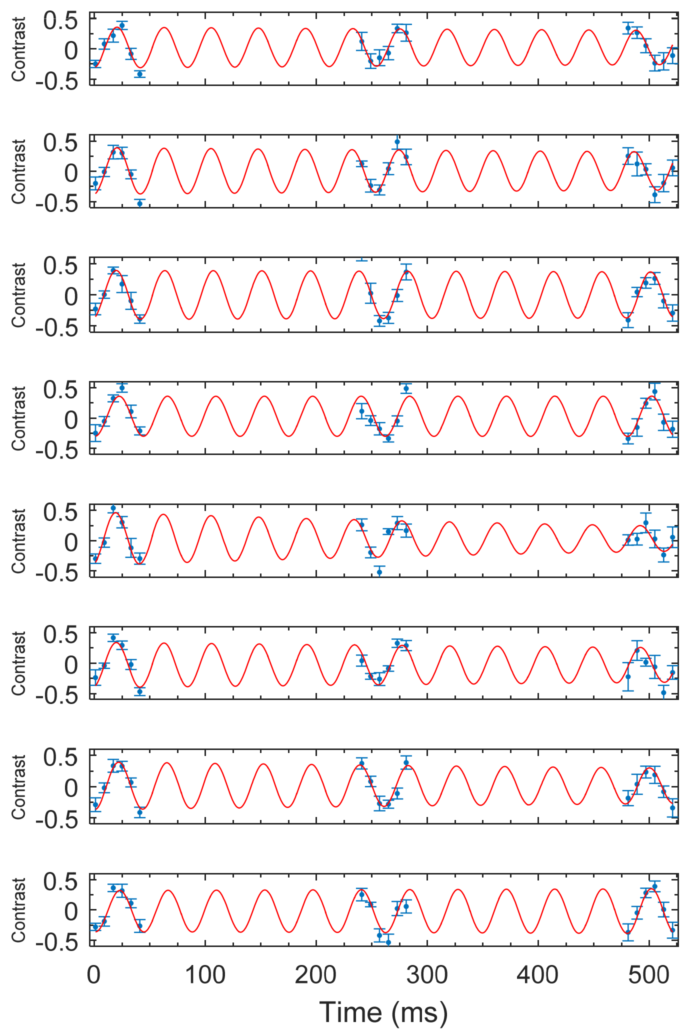
$$\Delta E = \mu_B B - d_e E$$

need to isolate eEDM from signals with different parity

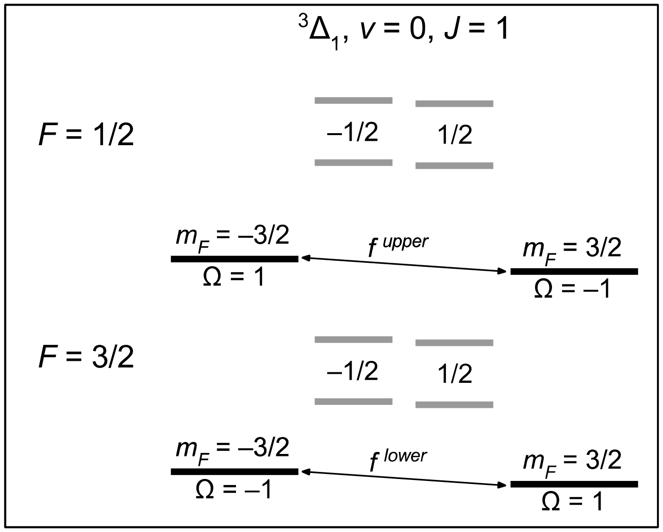
Frequency "Channels"

$\vec{B}$	$\vec{E}_{eff}$	$\vec{R}$	f^0	f^B	f^D	f^R	f^{BD}	f^{BR}	f^{DR}	f^{BDR}
↓	↓	↺	+	−	−	−	+	+	+	−
↓	↓	↻	+	−	−	+	+	−	−	+
↓	↑	↺	+	−	+	−	−	+	−	+
↓	↑	↻	+	−	+	+	−	−	+	−
↑	↓	↺	+	+	−	−	−	−	+	+
↑	↓	↻	+	+	−	+	−	+	−	−
↑	↑	↺	+	+	+	−	+	−	−	−
↑	↑	↻	+	+	+	+	+	+	+	+

"switches"



Modeling Frequency "Channels"



- Analytic calculations
  - Perturbation theory for effective Hamiltonian between $m_F = \pm 3/2$
- Numerical modeling
  - Classical motion of ions in numerically modeled time-dependent fields
  - Propagate 12-state or 32-state effective Hamiltonian

$$f_{\text{meas}} \approx \sqrt{\left(3g_F\mu_B\mathcal{B}_{\text{rot}} \pm 3\delta g_F\mu_B\mathcal{B}_{\text{rot}} \pm 2d_e\mathcal{E}_{\text{eff}} + 3\alpha\omega_{\text{rot}}\right)^2 + \left(\bar{\Delta} \pm \delta\Delta\right)^2}$$

$$\bar{f} = 3g_F\mu_B\mathcal{B}_{\text{rot}} + \ldots$$

$$f^B = 3g_F\mu_B\mathcal{B}_{\text{nr}} + \ldots$$

$$f^D = 3\delta g_F\mu_B\mathcal{B}_{\text{rot}} + \ldots$$

$$f^{BR} = 3\alpha\omega_{\text{rot}} + \ldots$$

$$f^{BD} = 2d_e\mathcal{E}_{\text{eff}} + 3\delta g_F\mu_B\mathcal{B}_{\text{nr}} + \ldots$$

Systematics

- Tune parameter, model change in frequency channels
  - Ion position in trap
  - External magnetic fields
  - Electric field magnitude
  - Rotation frequency
  - Ion density
  - $\pi/2$ pulse duration
  - ....

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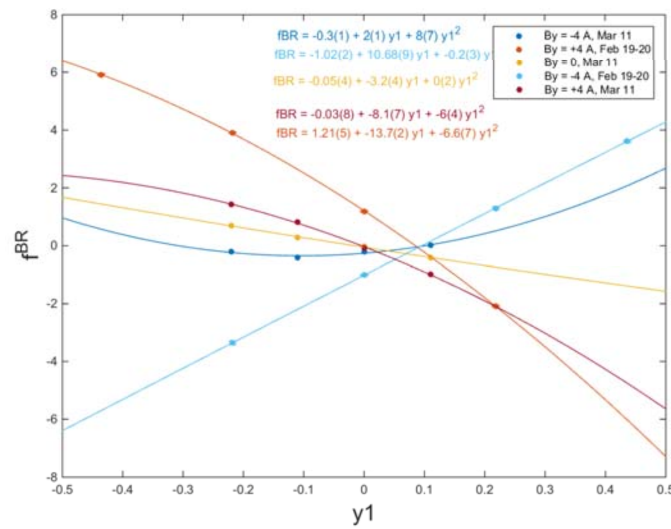

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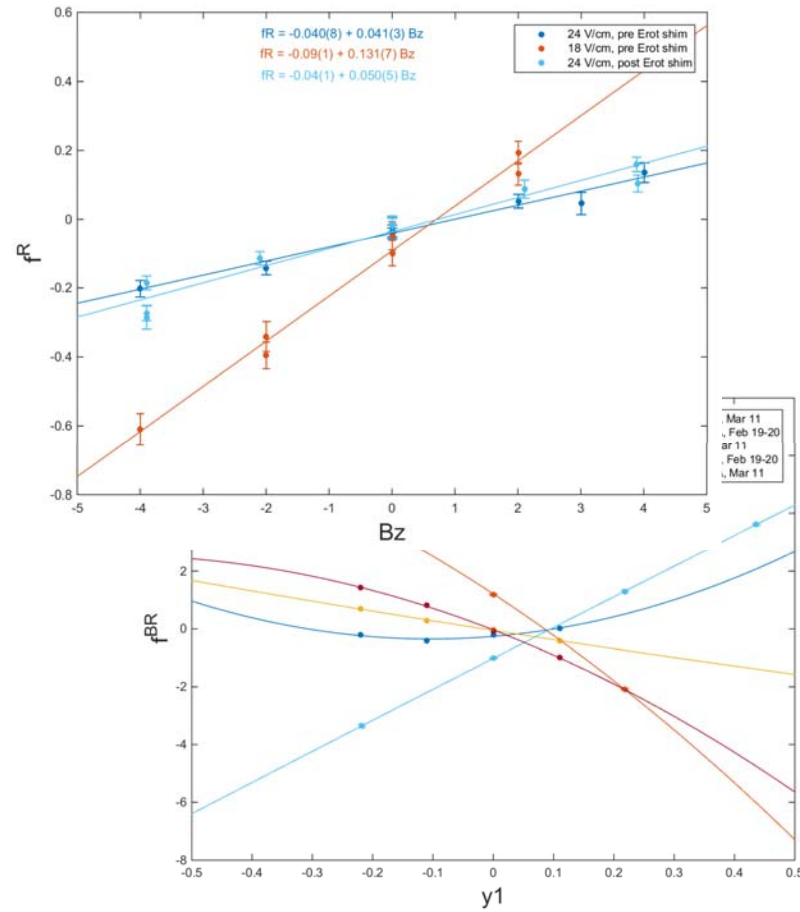

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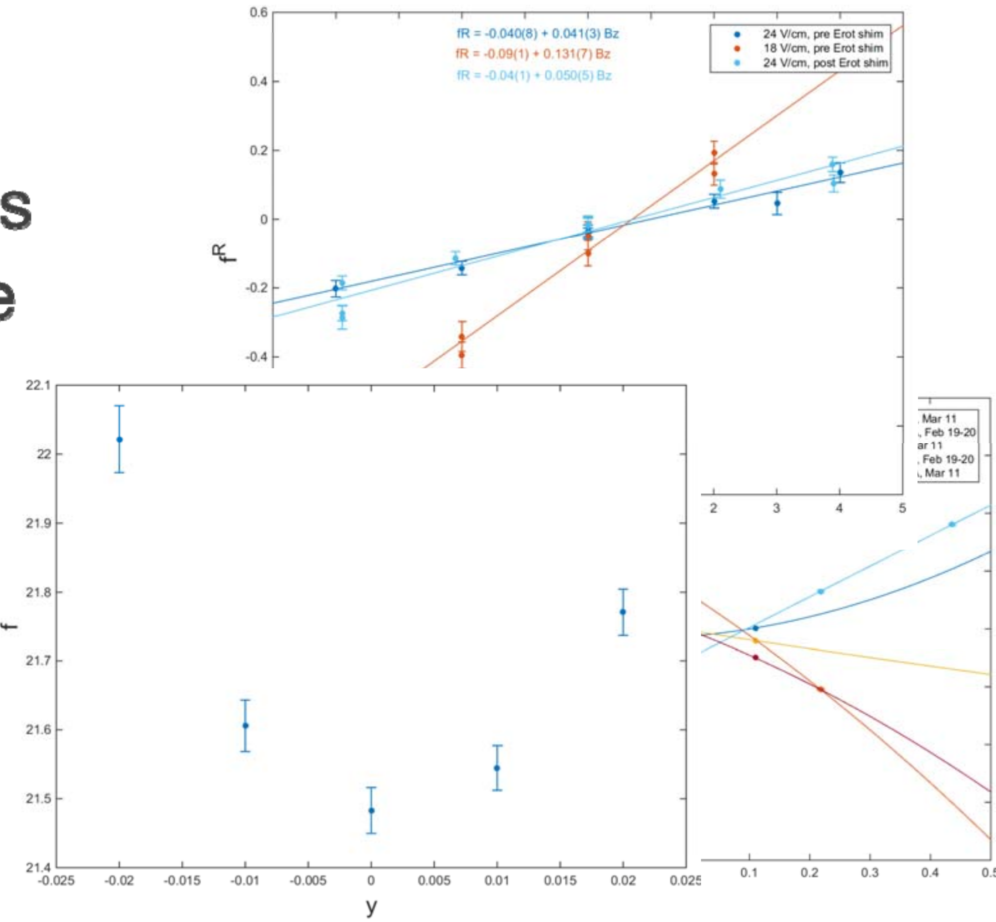

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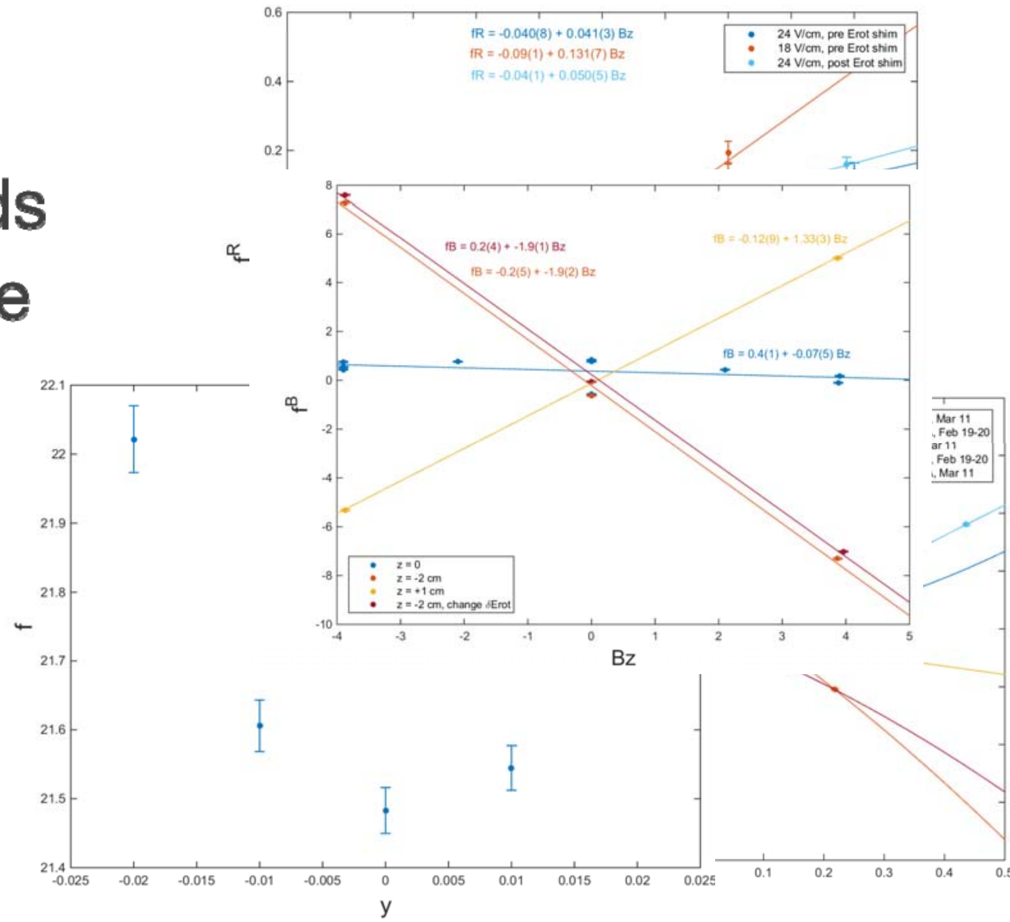

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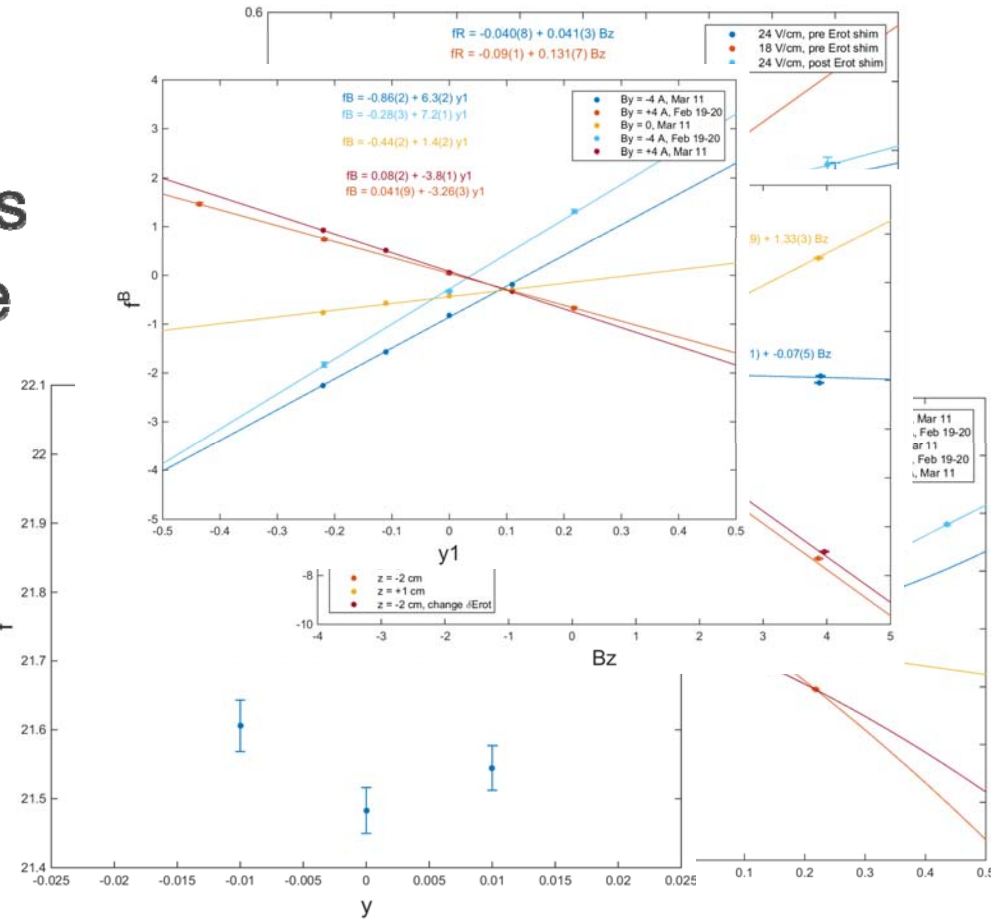

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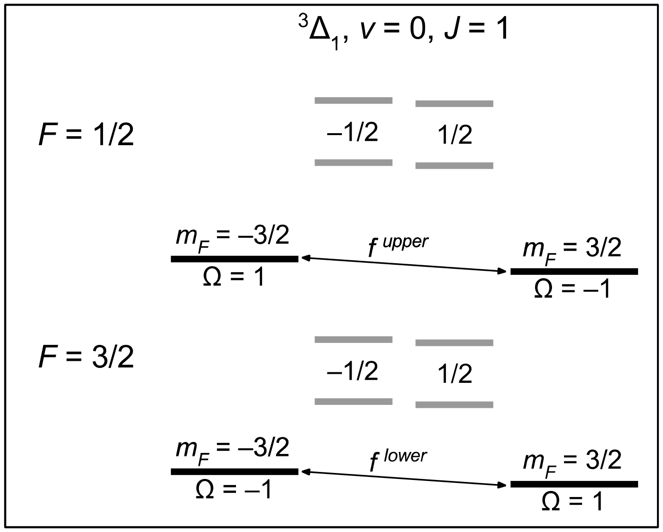

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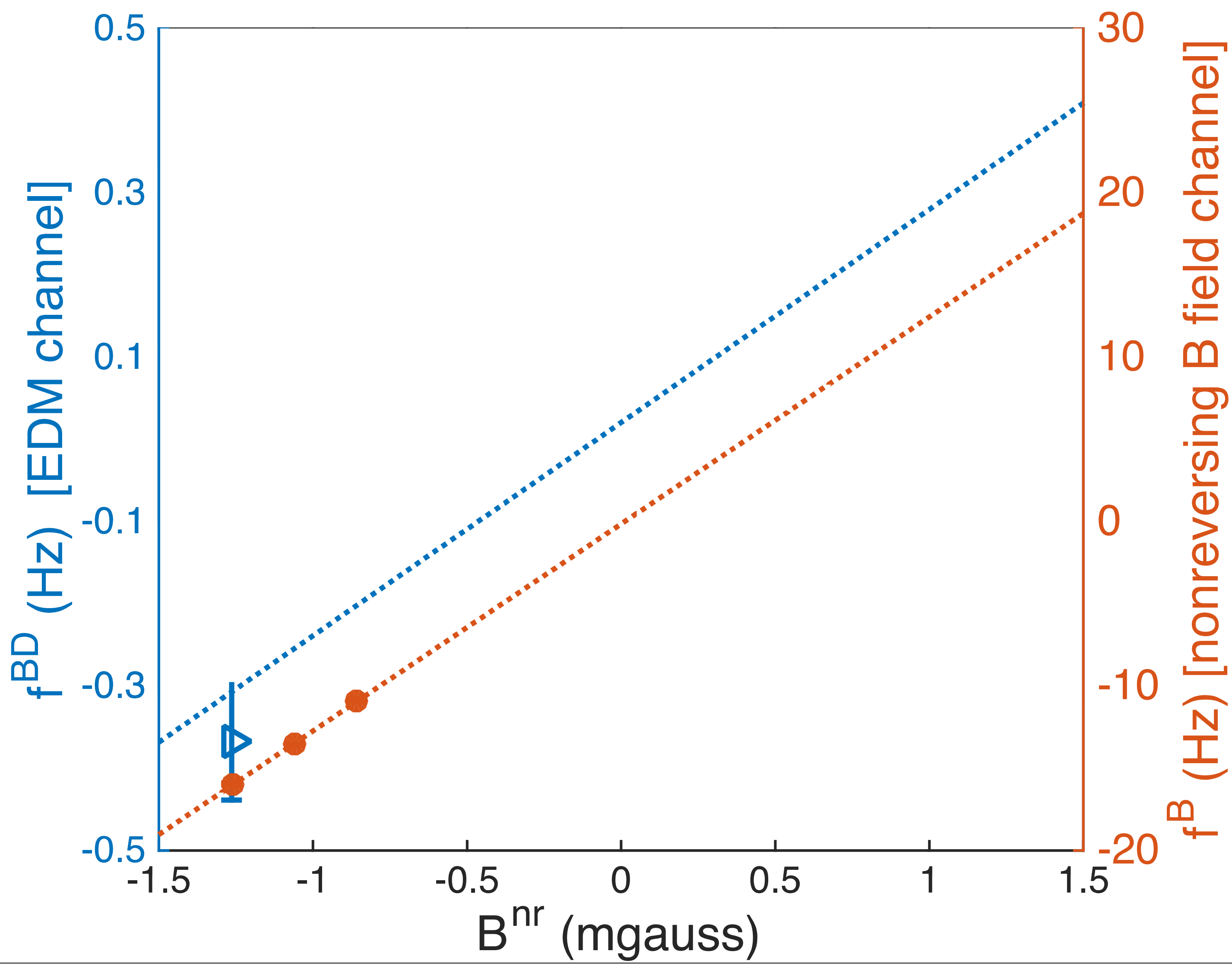
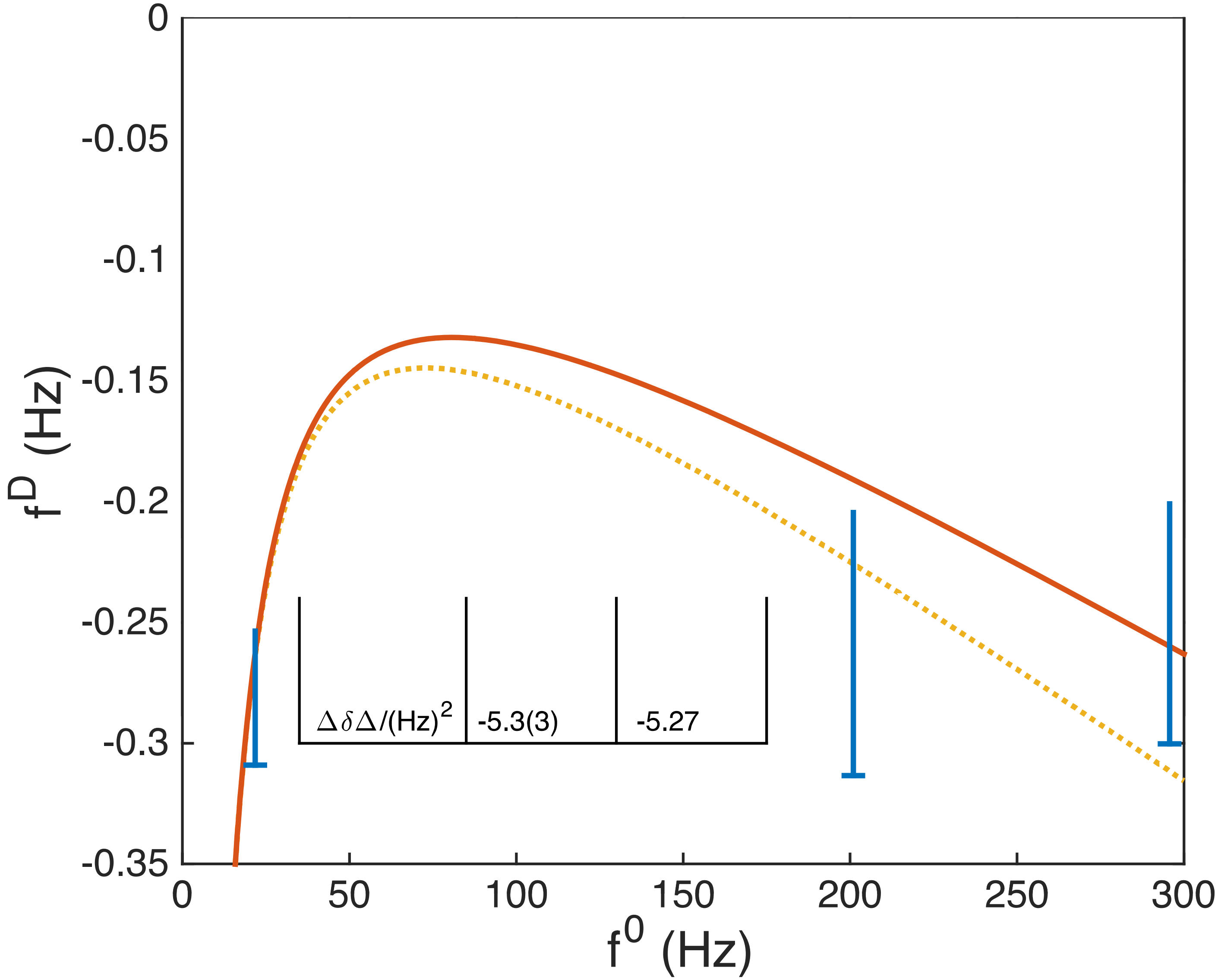
Non-reversing magnetic field



Effective differential g-factor



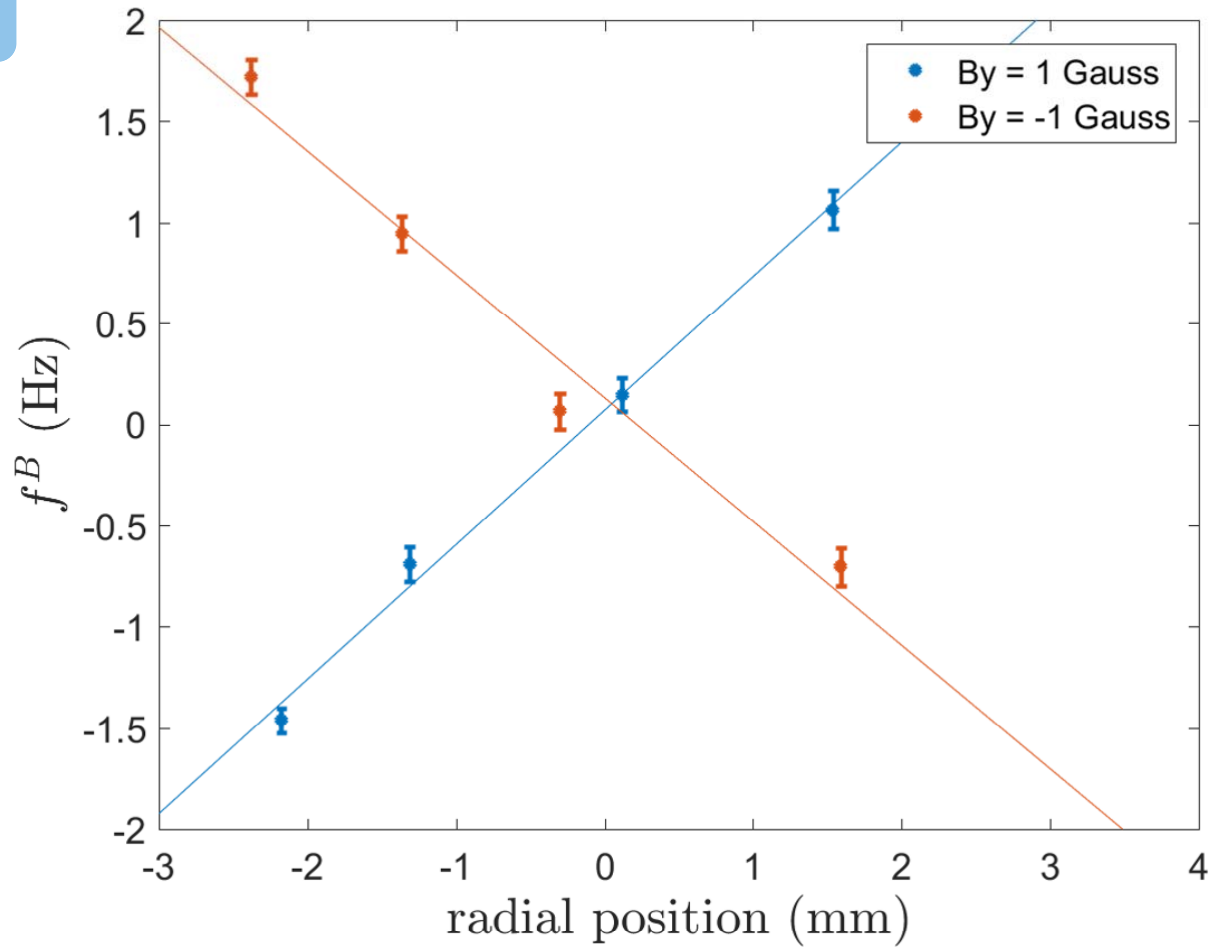
Electric field inhomogeneity

y (mm)

Uniform B-field systematic

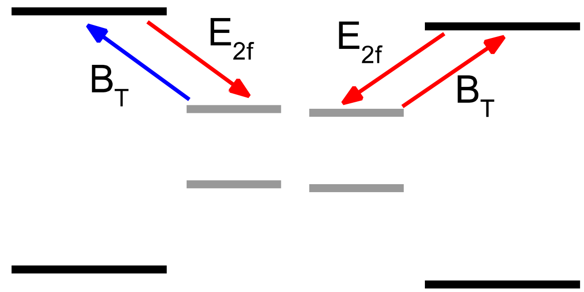
$$f^B = 3 g_F \mu_B \mathcal{B}_{\rm nr} + \ldots$$

- Large frequency shift in f^B and f^{BR} channels with applied uniform B-field
- Scales with position of ions in trap and magnitude of B-field

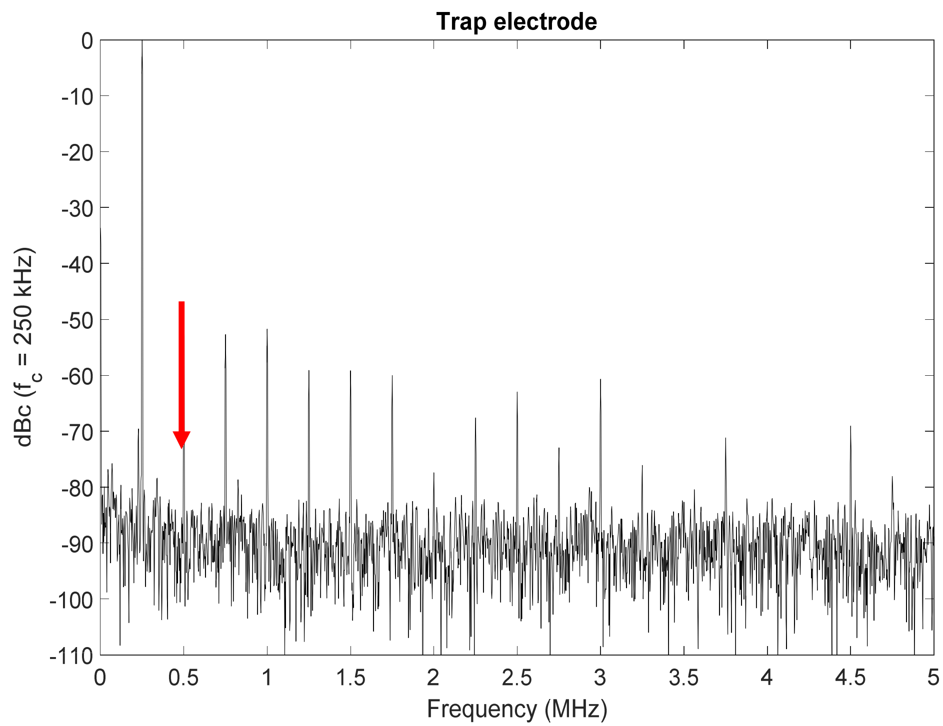


Uniform B-field systematic

$$f^B = 3g_F\mu_B\mathcal{B}_{\rm nr} + \ldots$$



- Caused by **2nd harmonic of E_{rot}** on trap electrodes
- Suppressed by feeding forward at $2f_{rot}$
- Systematic error uncertainty < 10^{-30} e cm



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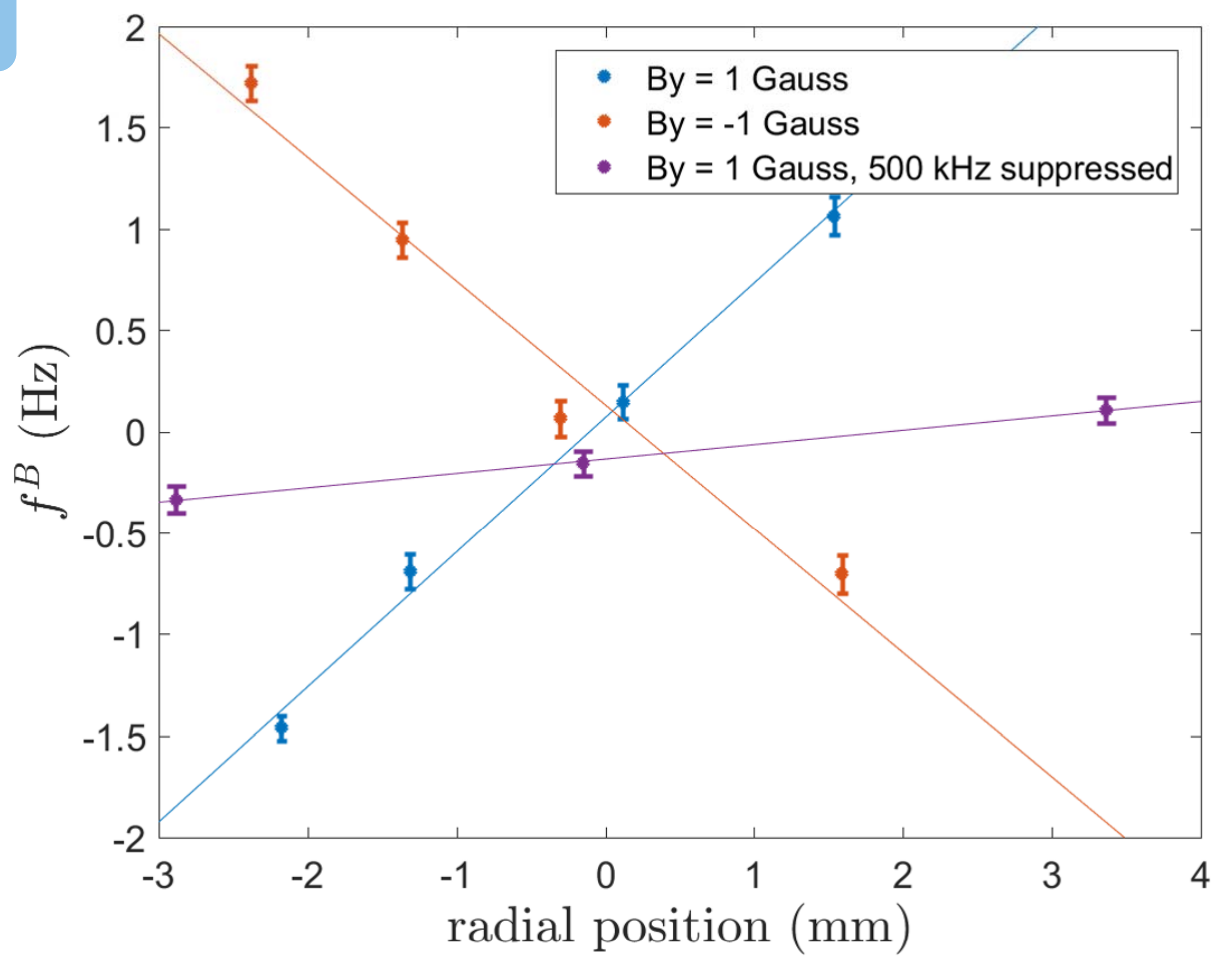
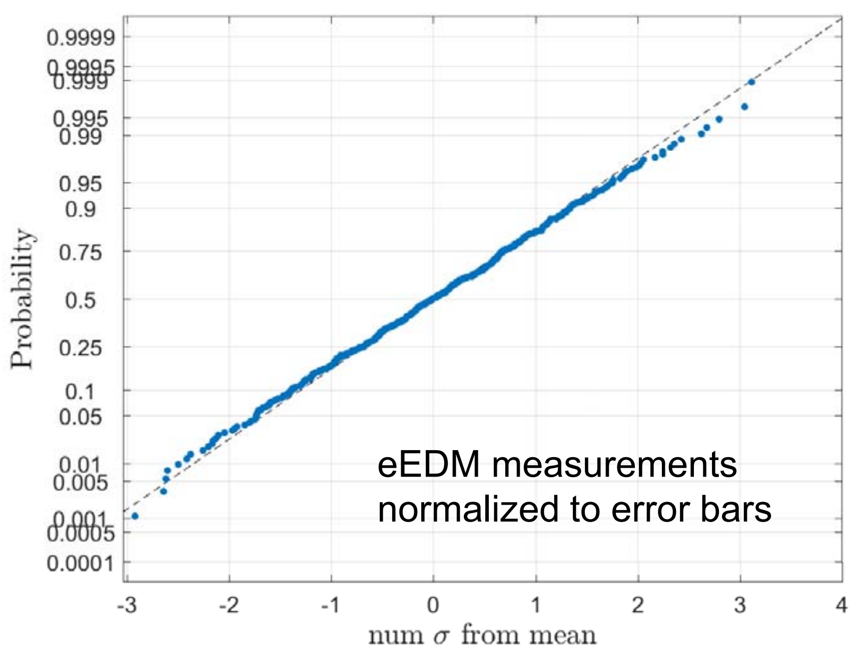
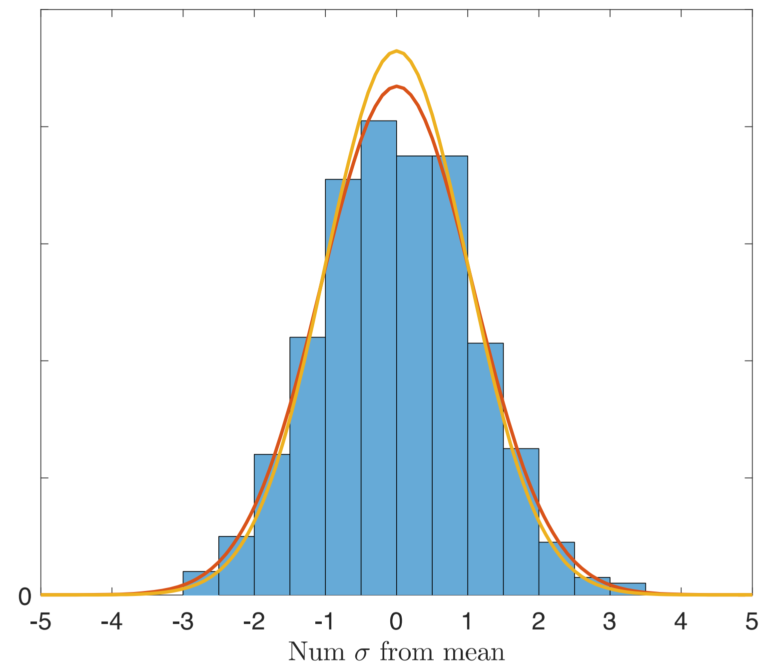


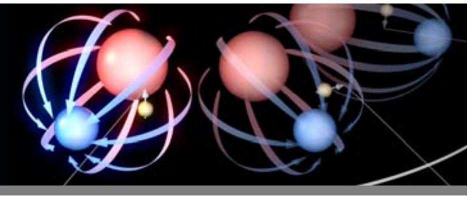
Current Measurement

- 5 hours of blinded data
- ıts
  - Short coherence time
  - Low contrast
  - No cuts based on f^{BD}
- ≈ 1.5 x 10^{-28} *e* cm
- on on arXiv



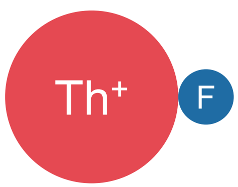


Where to go next?



- Short term improvements planned over the next ~year should increase sensitivity by 10x
- Longer term – switch to ThF^+

	Improvement	Sensitivity improvement	Est. date
Ion number (new trap)	5	2.2	6 months
Coherence time (new trap)	2	1.7	6 months
Ion counting noise	1.5	1.5	6 months
Ion counting number/MCP	1.5	1.2	6 months
STIRAP	1.5	1.2	3 months
Contrast	1.25	1.25	
Dead time reduction	1.1	1.05	1-3 months
Total		**10**	



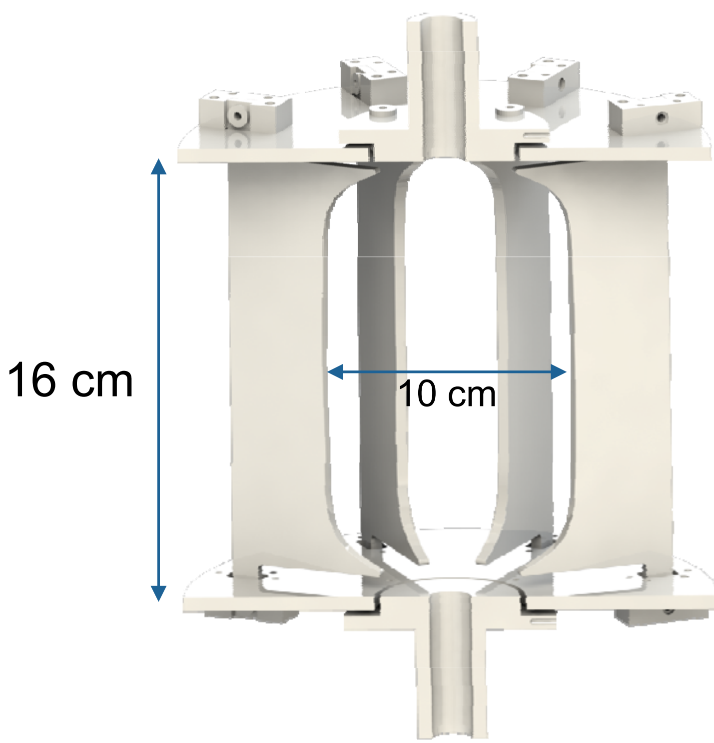
Larger E_{eff}: 35 GV/cm
Ground state $^3\Delta_1$

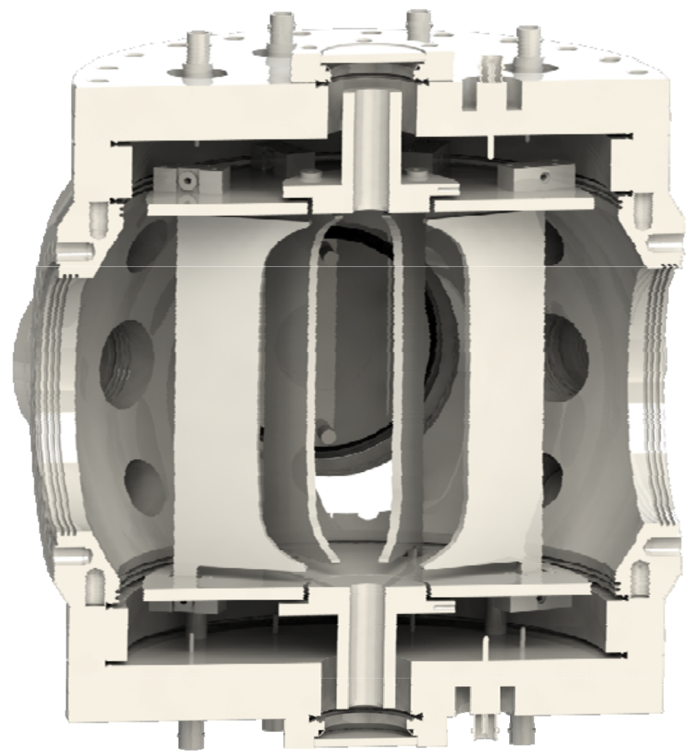
https://www.skotcher.com/thor_hammer_mjolnir_marvel_minimal_element_thorium-wallpaper-14220.html

2^{nd} Generation Ion Trap

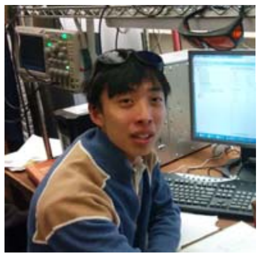
- **More uniform E_{rot}**
  - Larger trapping volume – conservatively 10x more ions
  - Reduce ion density: realize full 2.1(1) s state lifetime

- **Larger E_{rot} and f_{rot}, less magnetic material, improved trap symmetry**



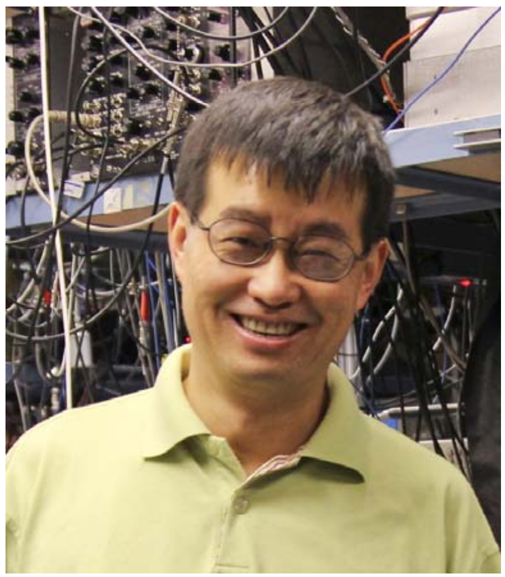


Acknowledgements



HfF^+ Ion Trap
Dan Gresh
Tanya Roussy

ThF and ThF^+ LIF Spectroscopy
Dr. Yan Zhou
Kia Boon Ng



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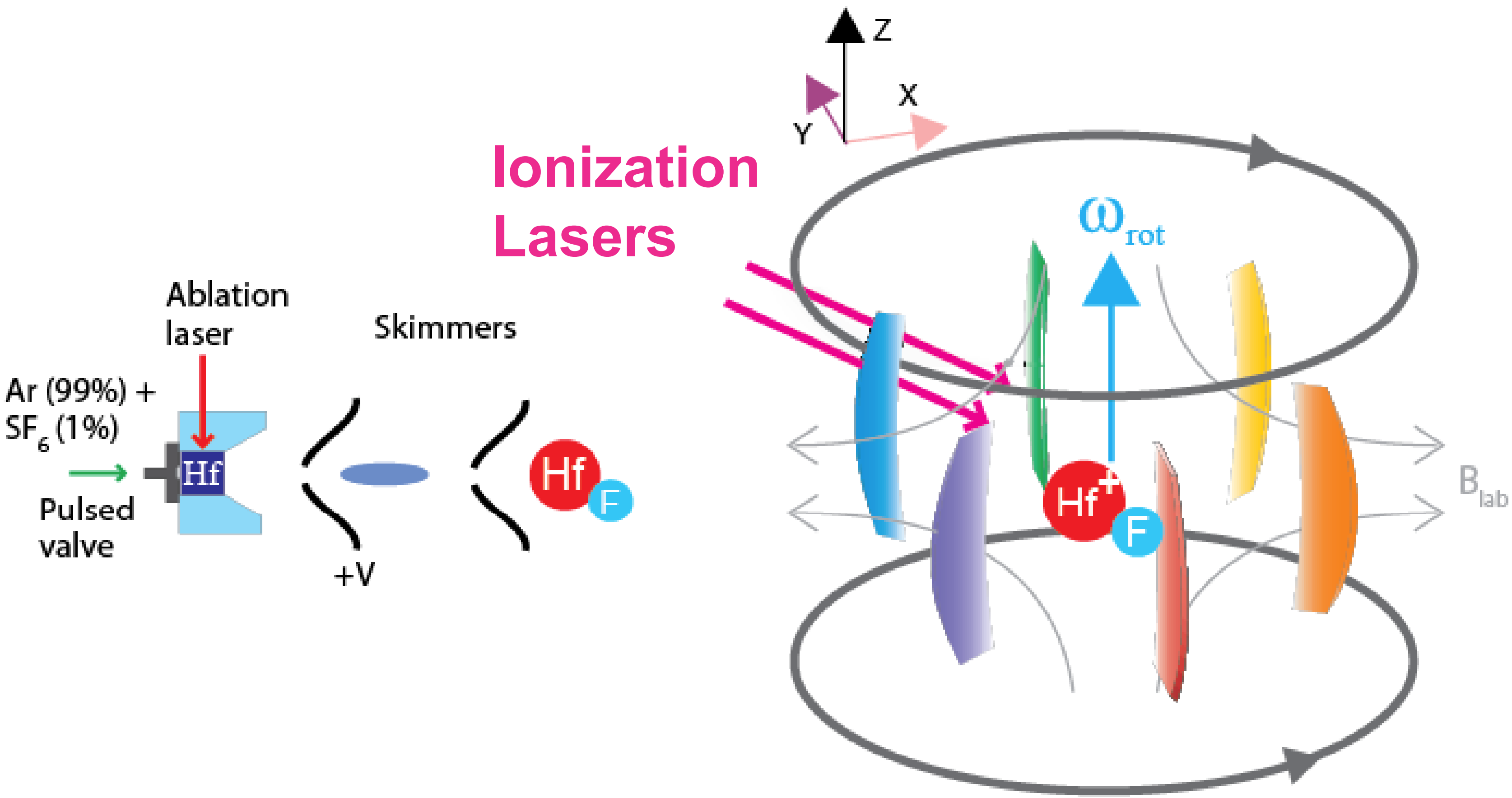
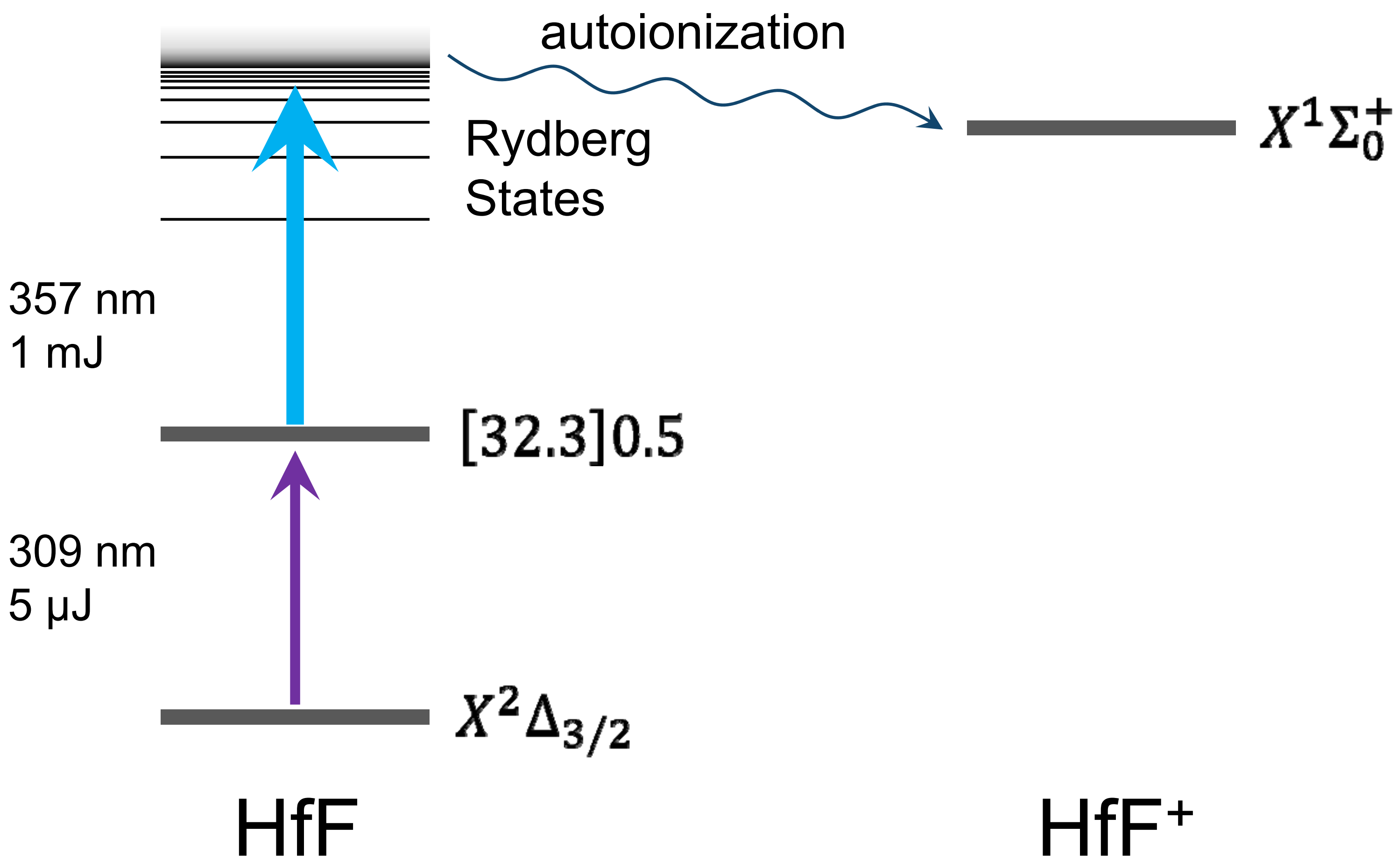
Jun Ye
Eric Cornell

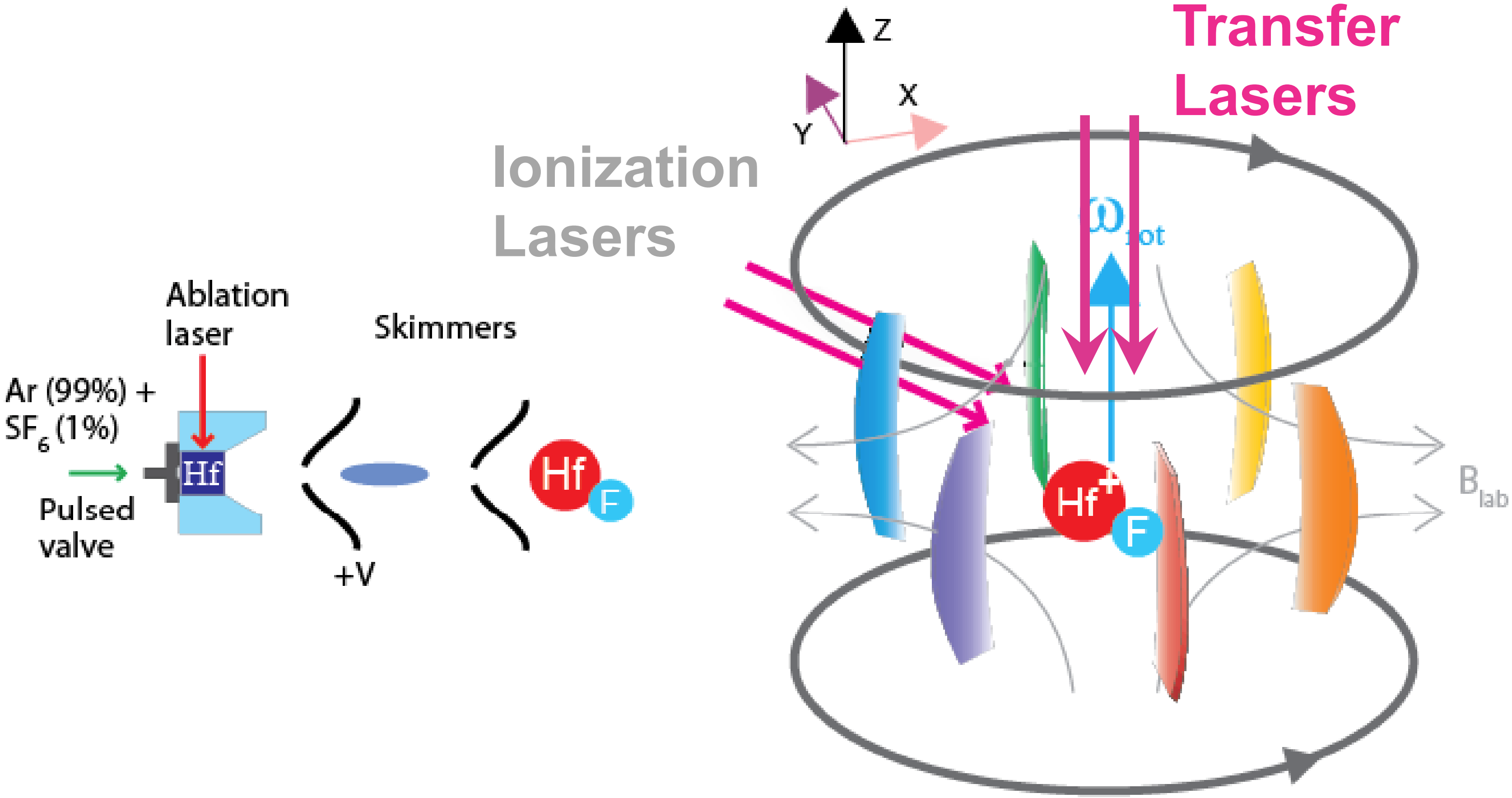
Photo-ionization



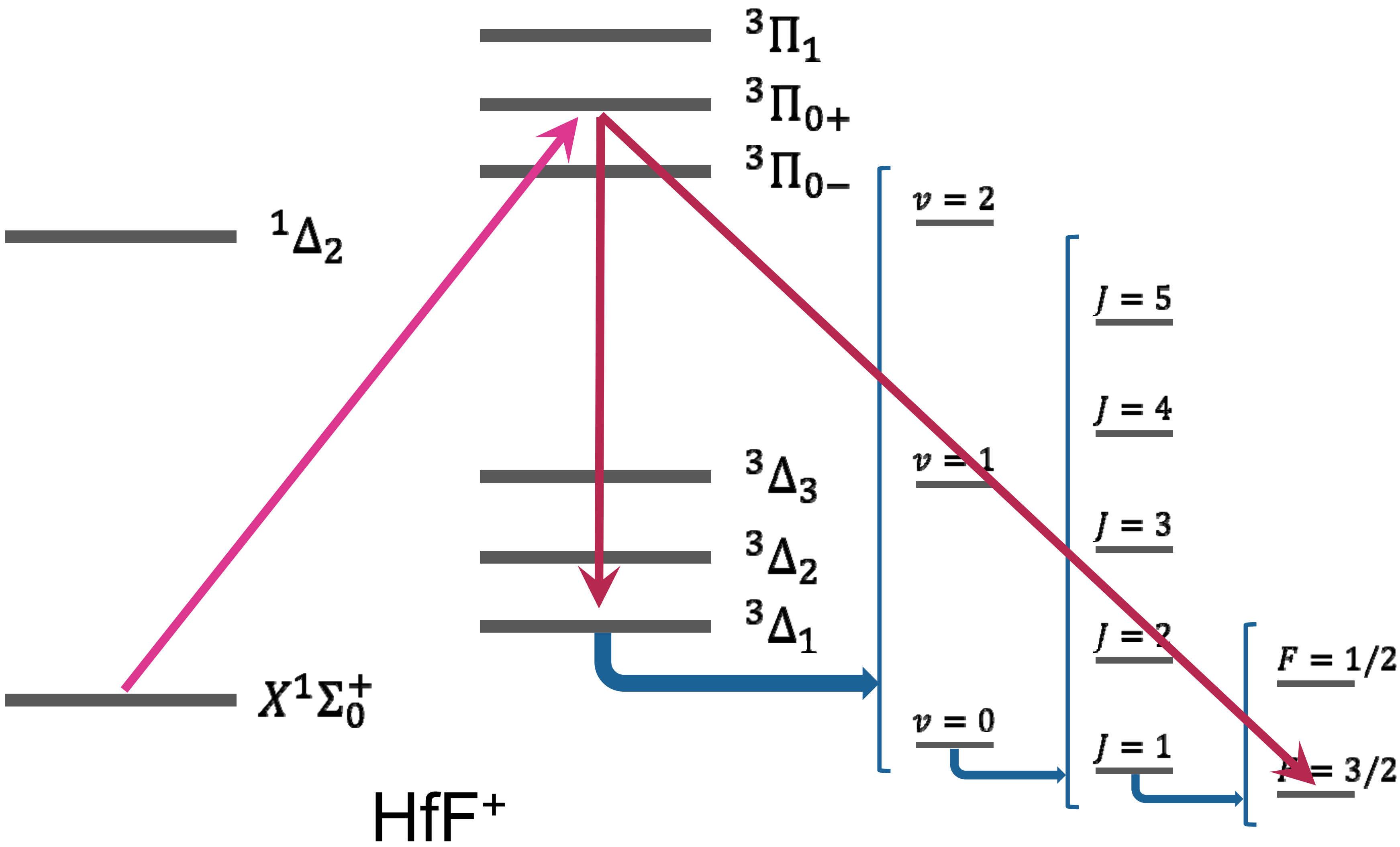
Photoionization



State Transfer



State Transfer



State Detection

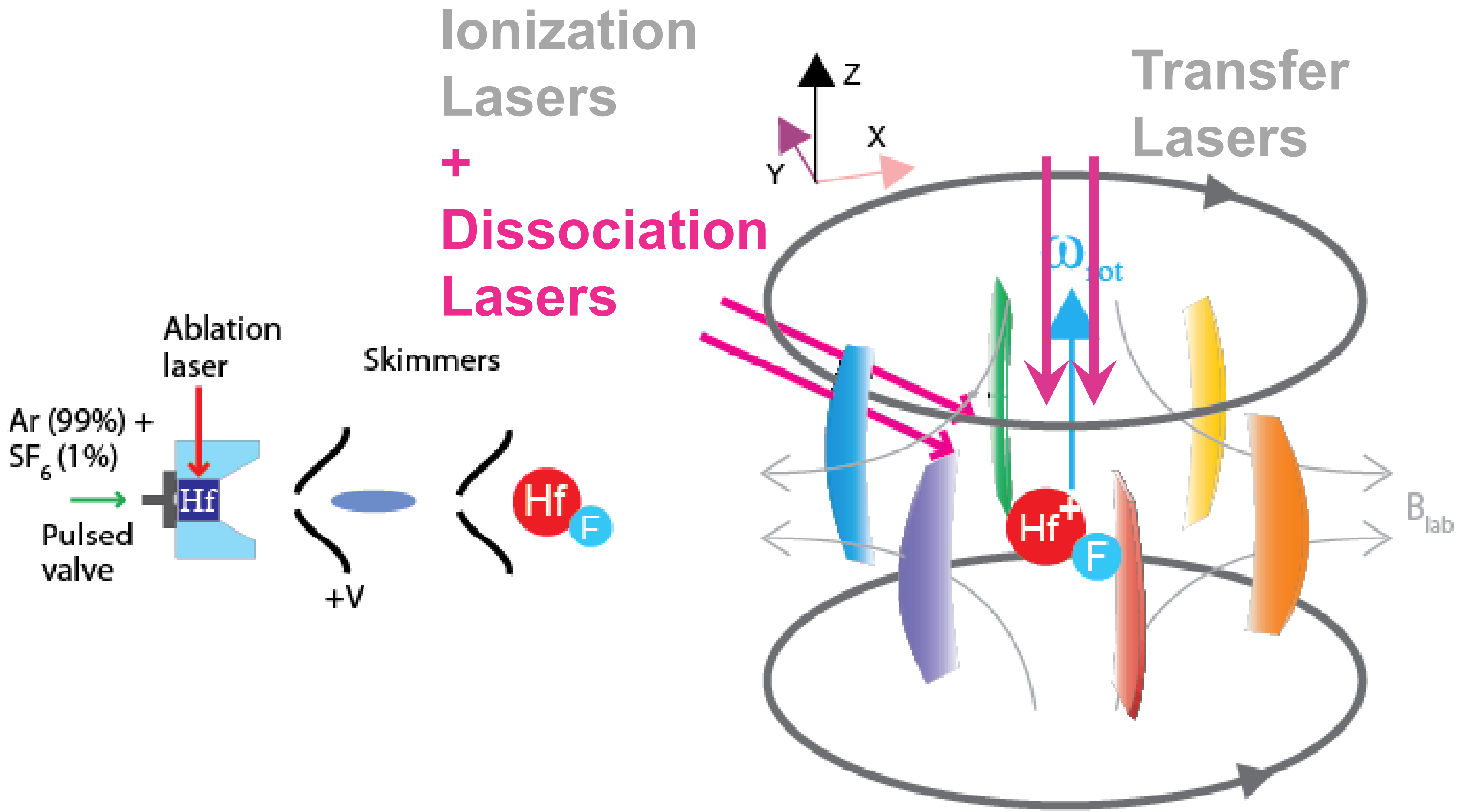
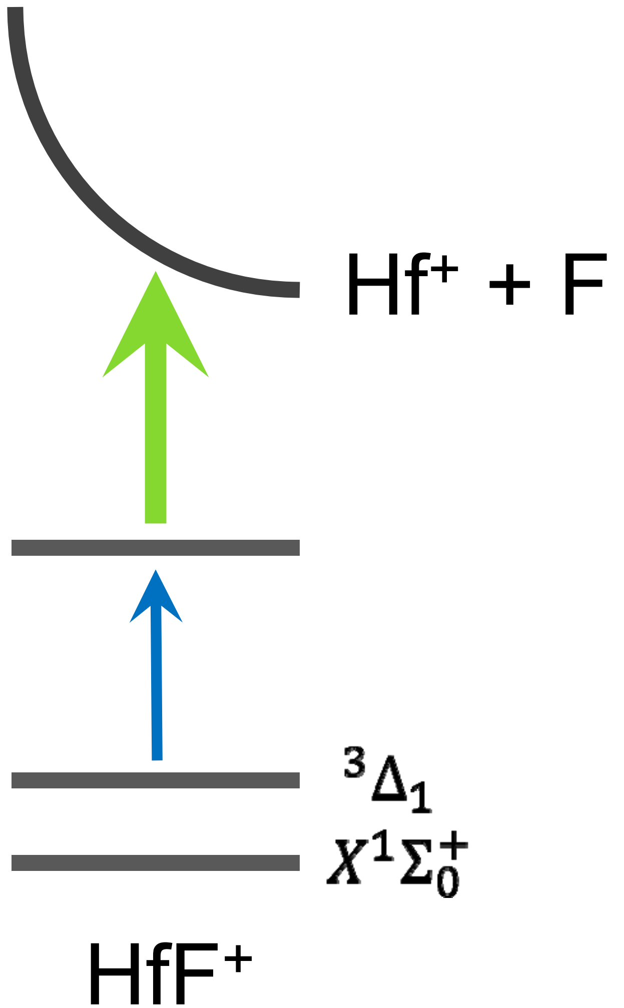
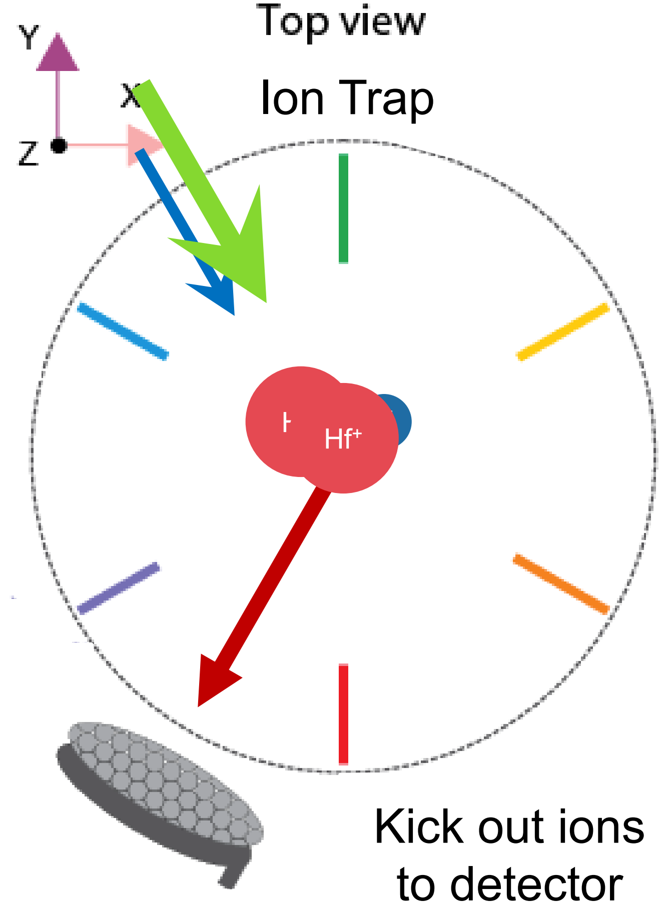


Photo-dissociation





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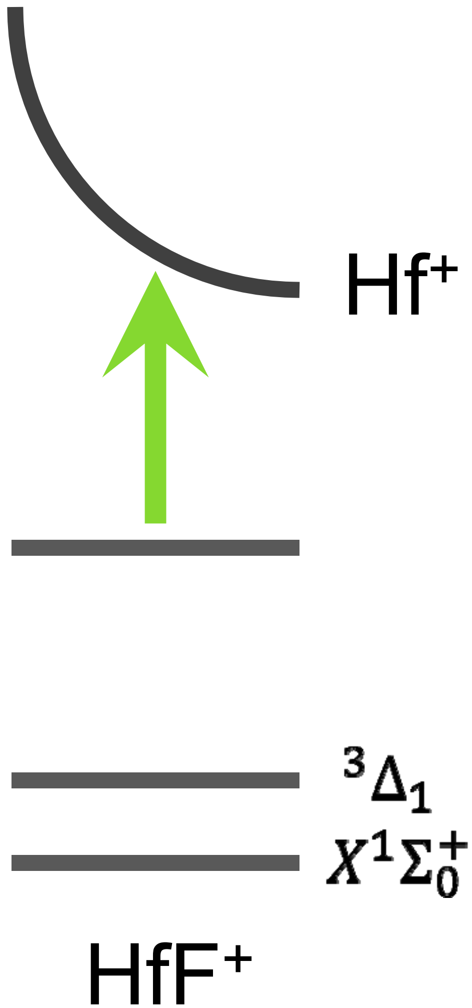

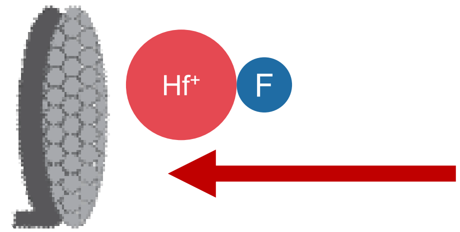

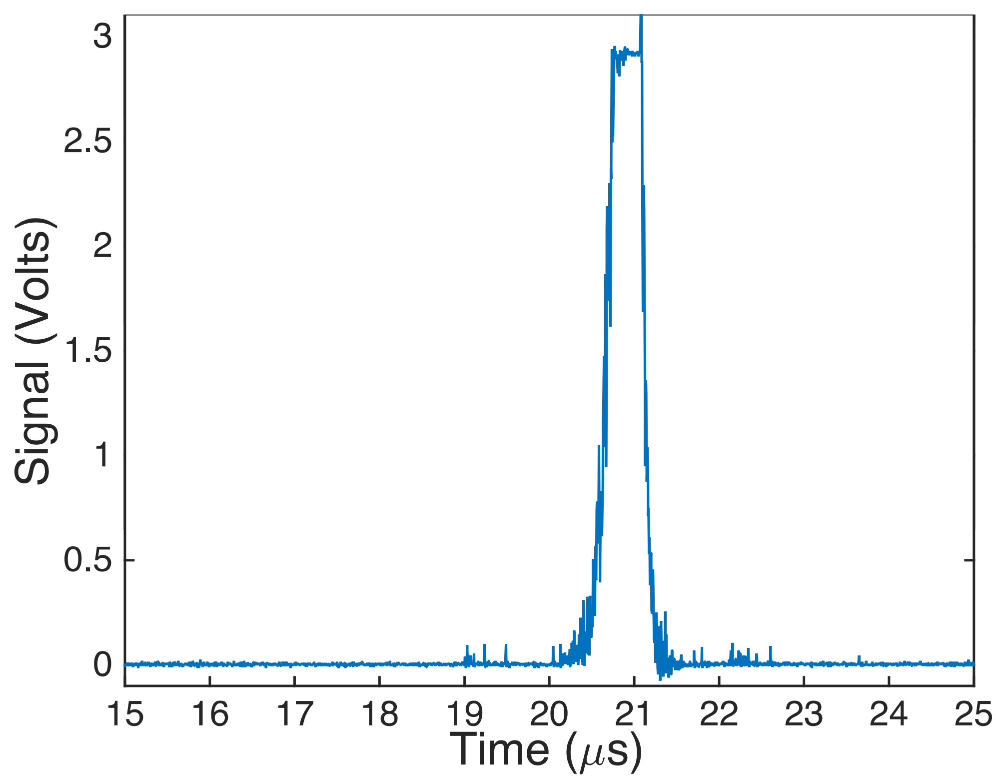

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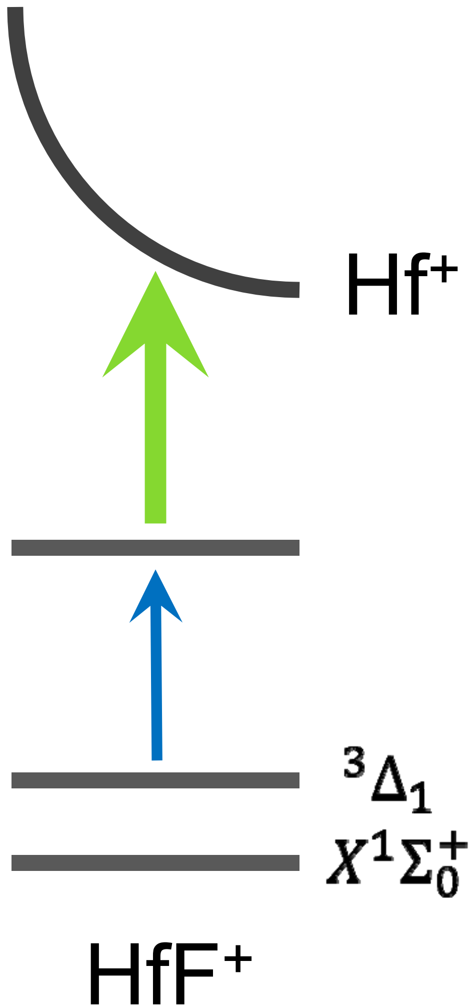
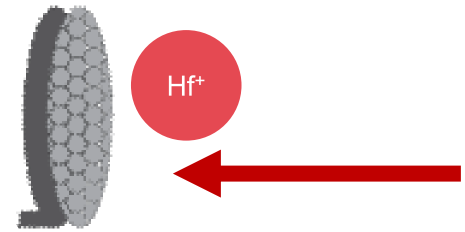




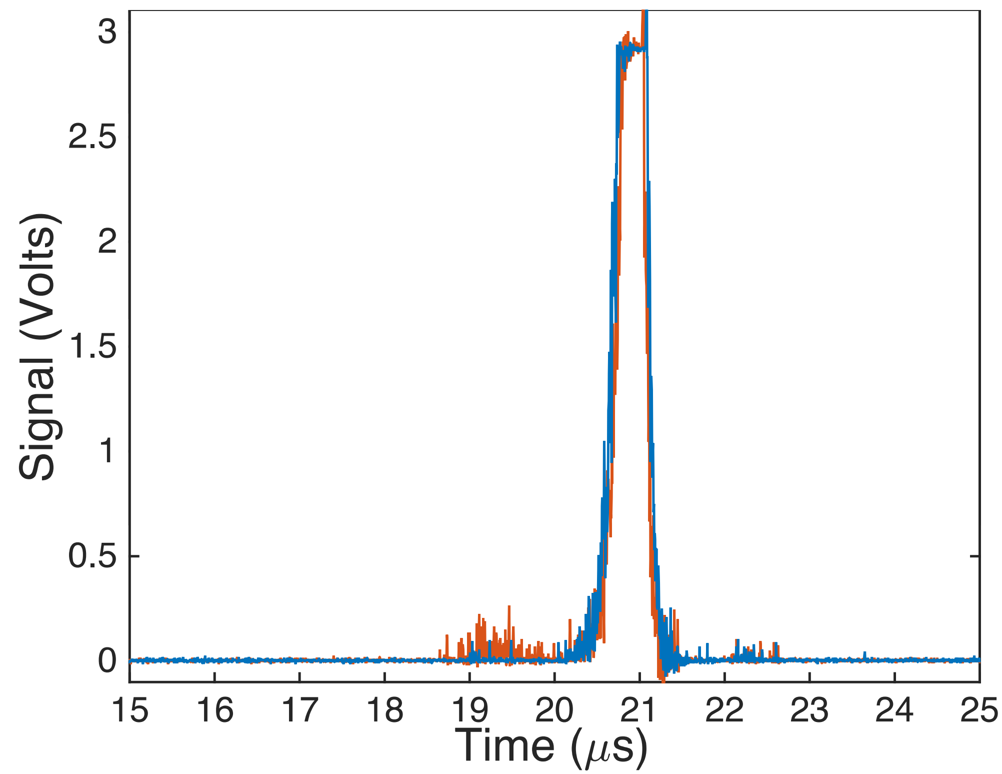
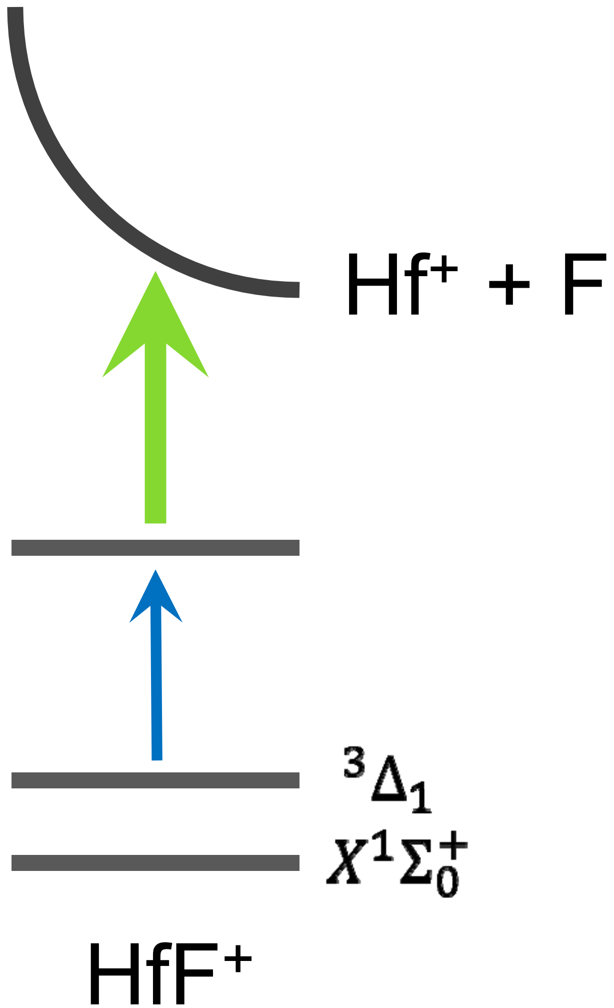
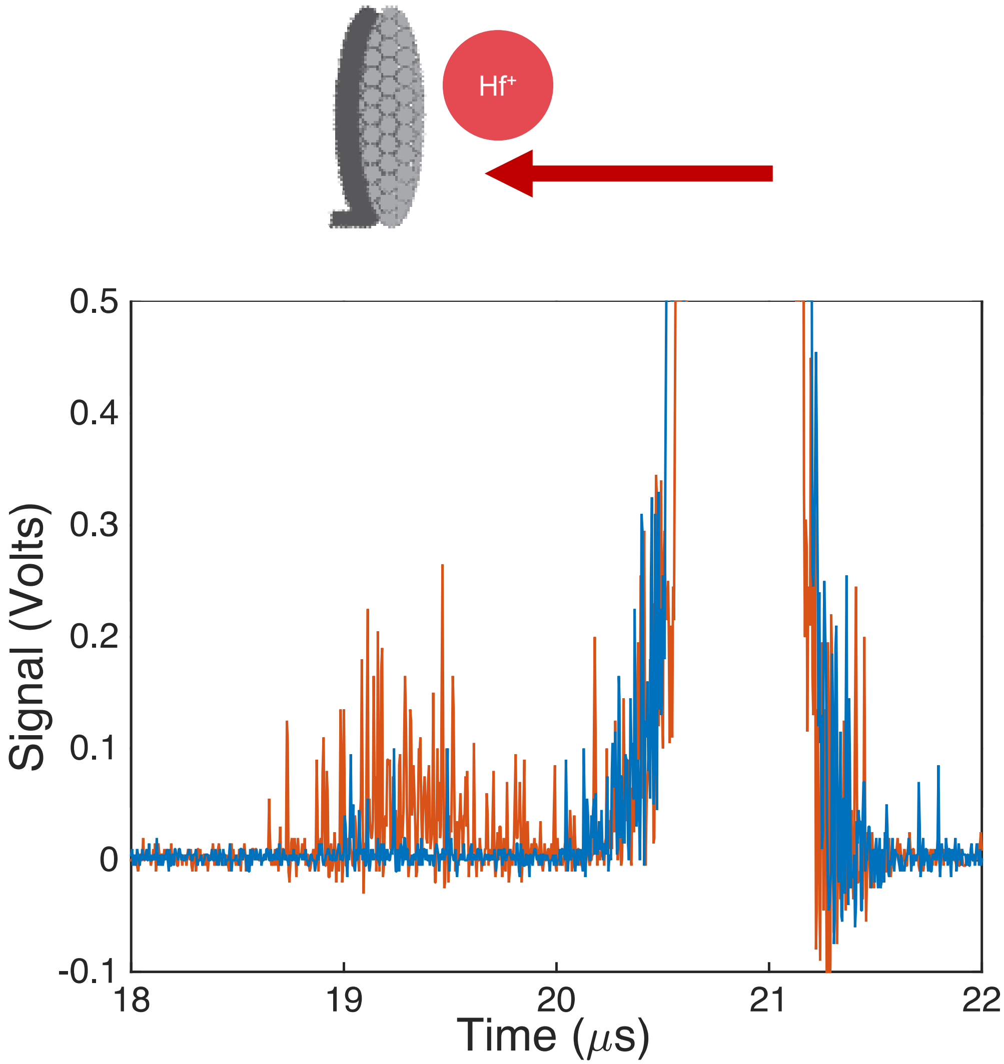
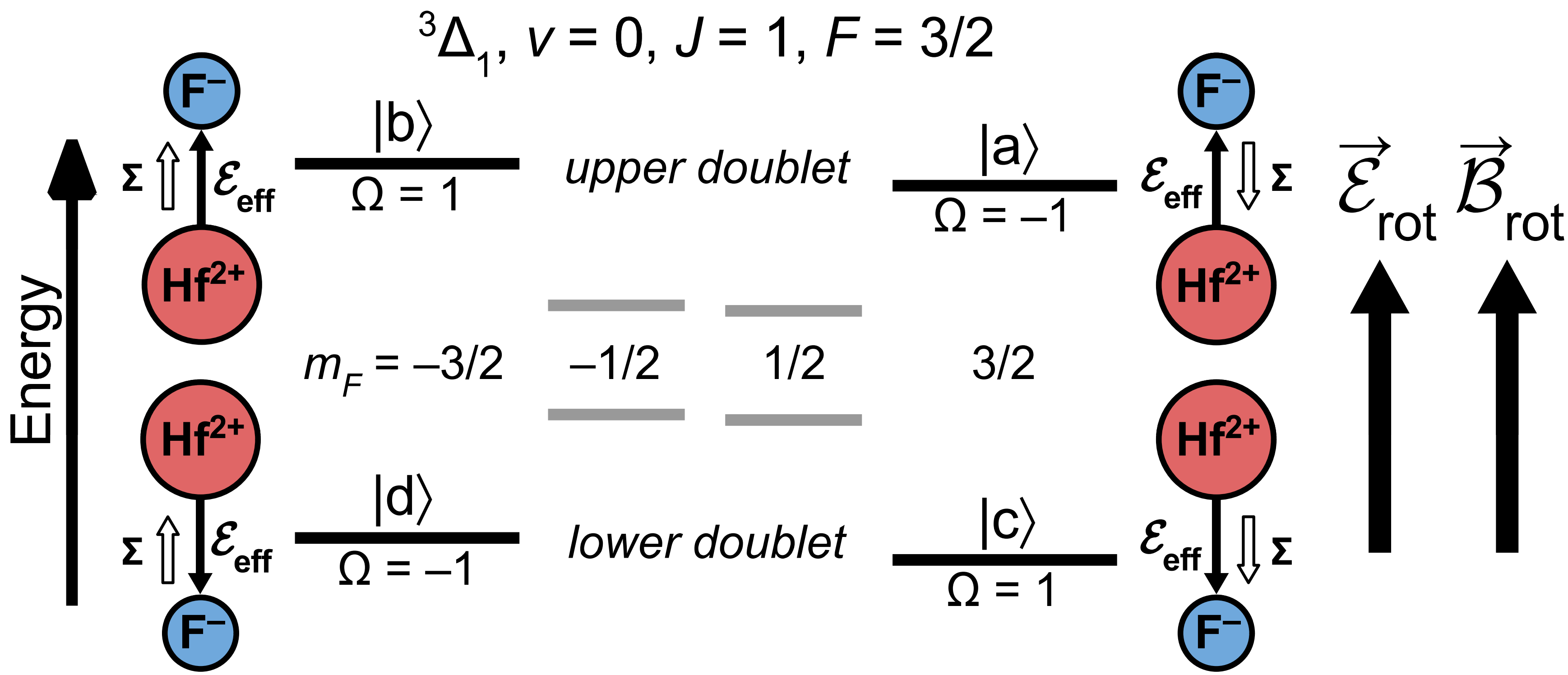


Photo-dissociation



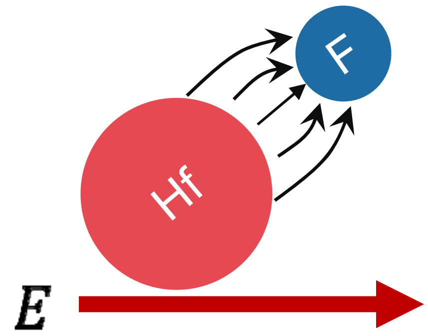


$^3\Delta_1$, J=1, F=3/2

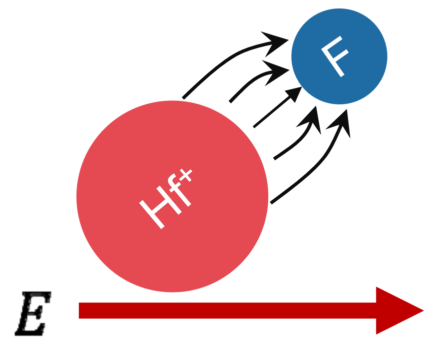


Electric Field

- To take advantage of large E_{eff} we must polarize the molecule with an electric field

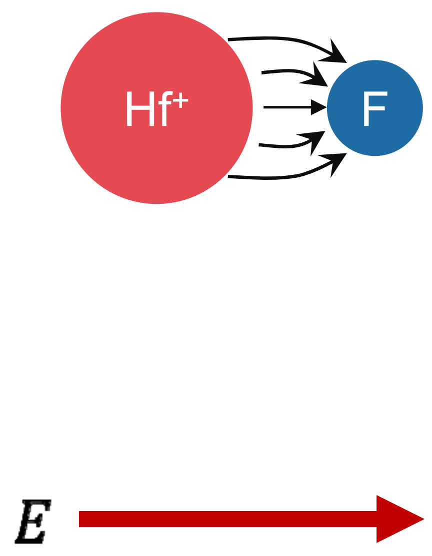


- But because the molecule is also an ion, this won't work

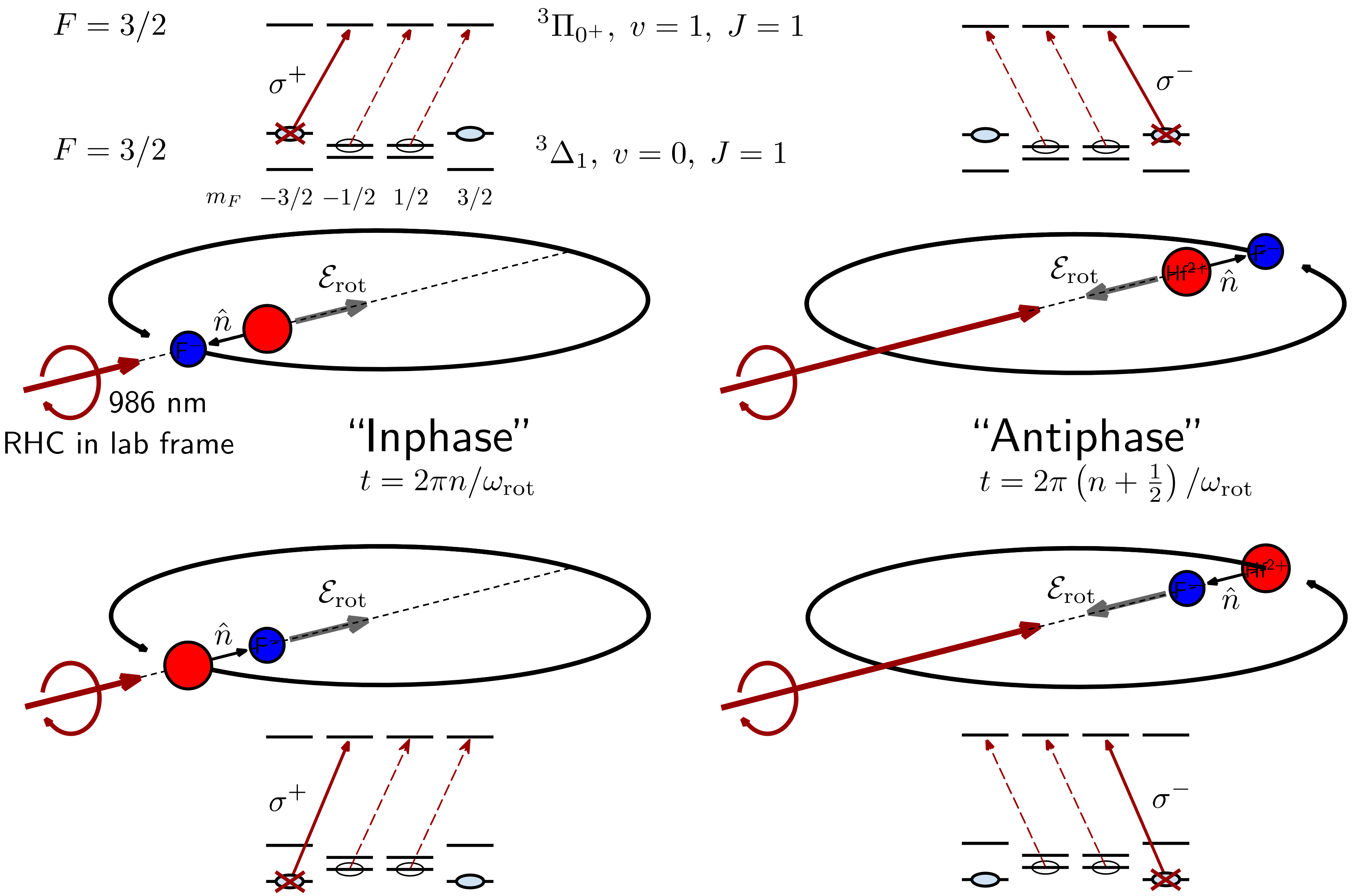


Rotating Electric Field

- Solution! Rotate the electric field



Depletion


$F = 3/2$
$^3\Pi_{0^+},\ v = 1,\ J = 1$
σ^+
σ^-
$F = 3/2$
$^3\Delta_1,\ v = 0,\ J = 1$
m_F $-3/2$ $-1/2$ $1/2$ $3/2$
$\mathcal{E}_{\rm rot}$
$\hat{n}$
F⁻
Hf²⁺
986 nm
RHC in lab frame
"Inphase"
$t = 2\pi n/\omega_{\rm rot}$
"Antiphase"
$t = 2\pi\left(n + \frac{1}{2}\right)/\omega_{\rm rot}$