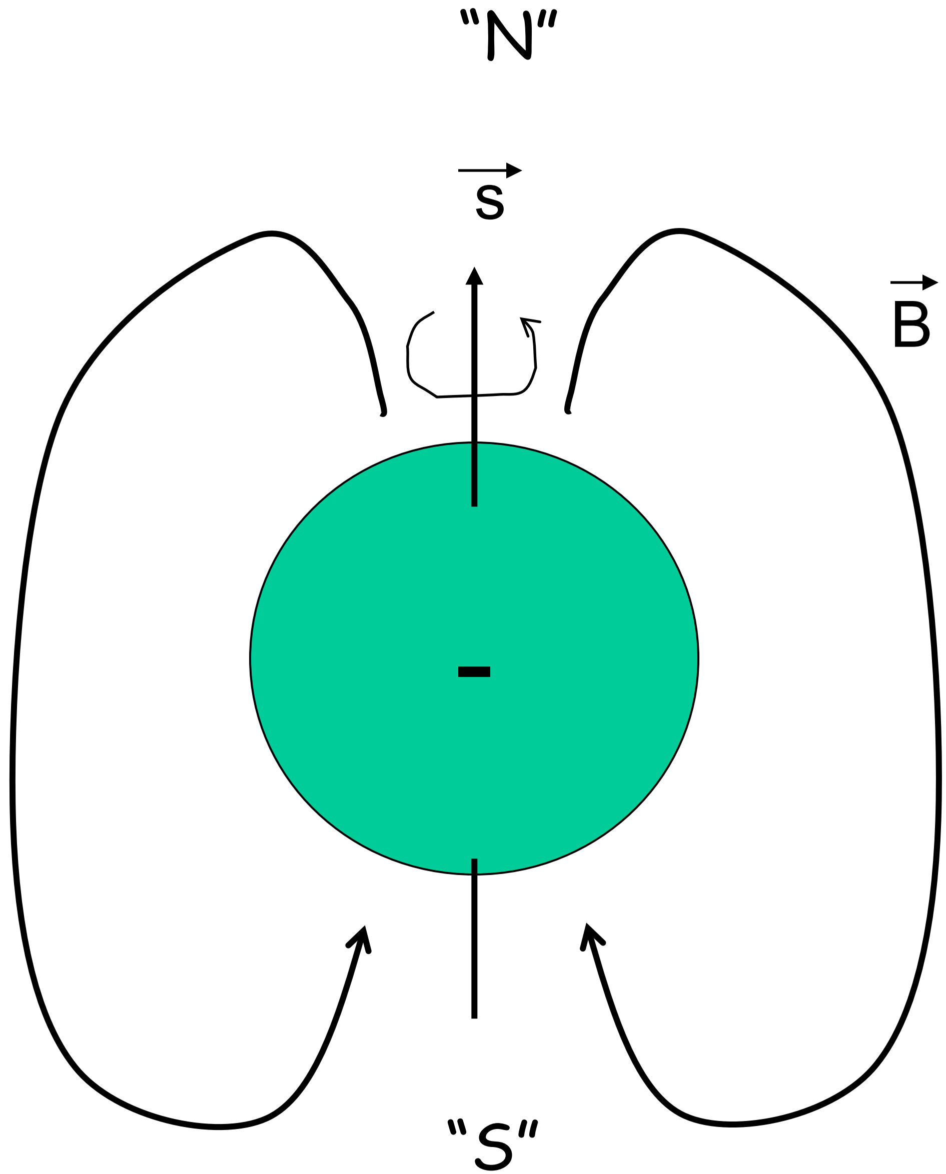
Meet Mr. Electron.

charge = $-q$
mass = m_e
spin = 1/2
magnetic moment
= μ_B

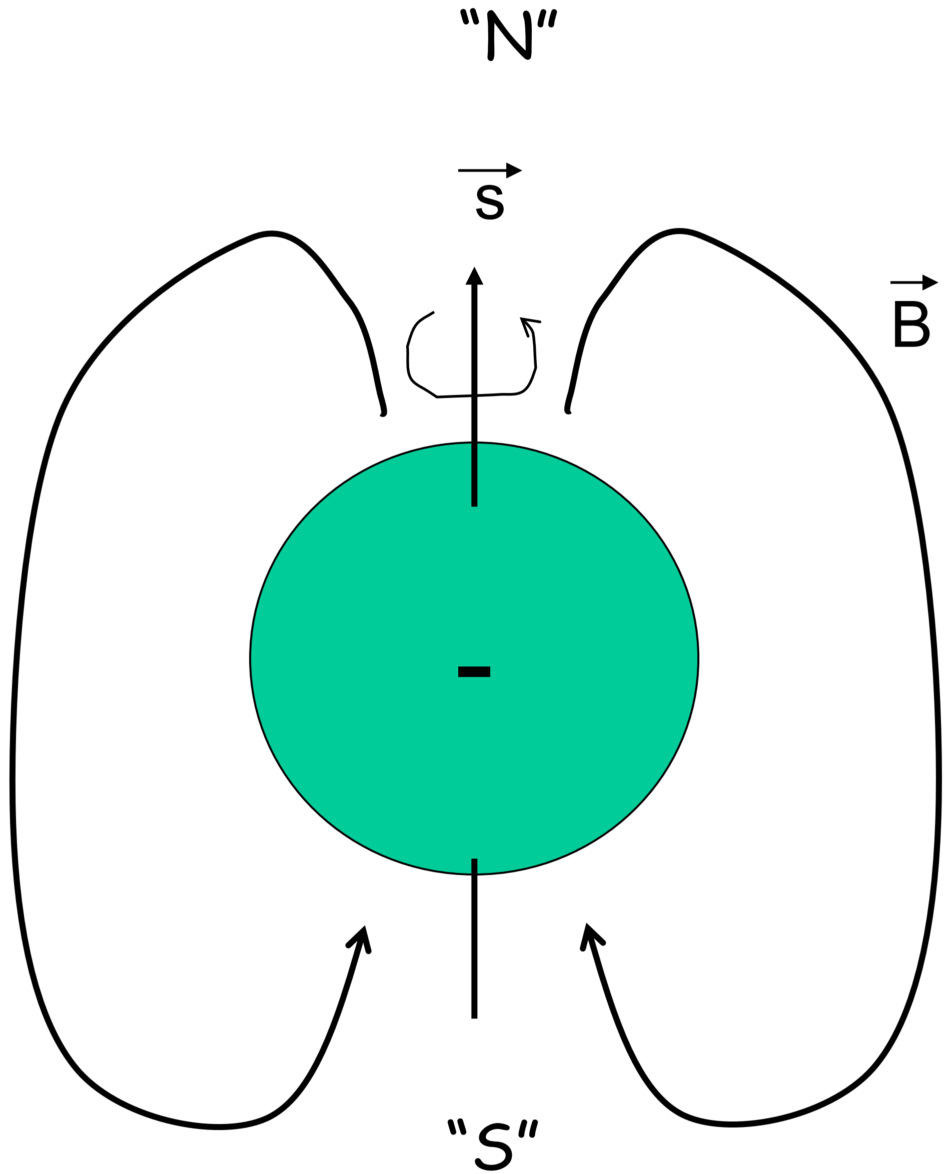


Meet Mr. Electron.

charge = $-q$
mass = m_e
spin = 1/2
magnetic moment
= μ_B

and that's pretty much it.

Or is it?



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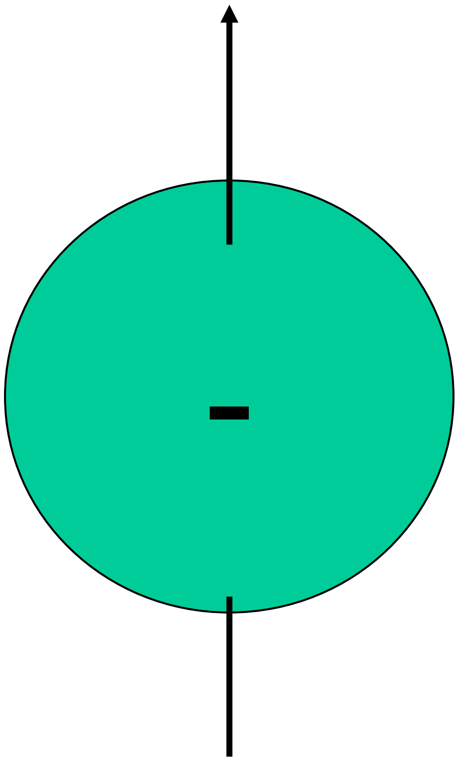

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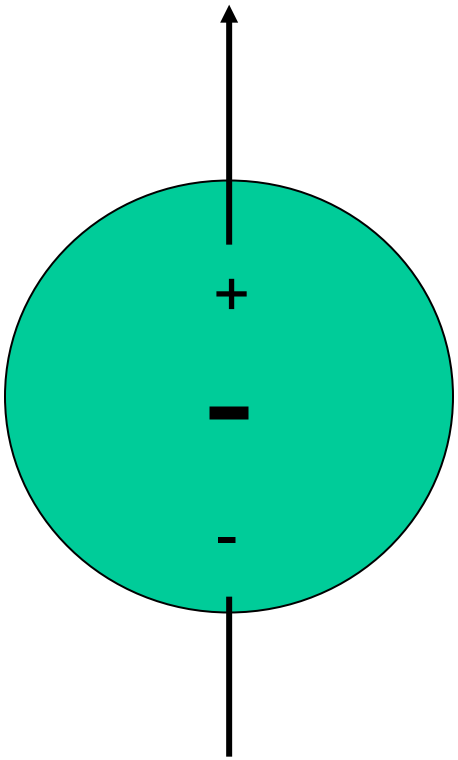
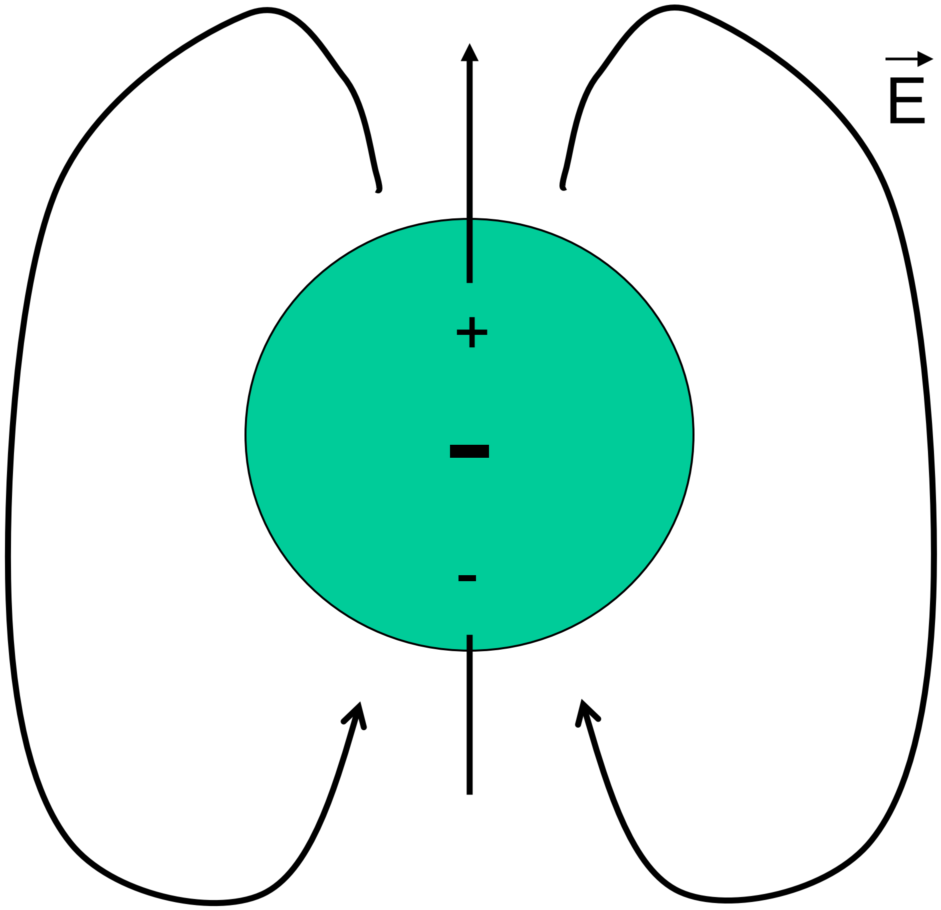


Meet Mr. Electron.

electron
Electric
Dipole
Moment
(eEDM)?



Meet Mr. Electron.

electron
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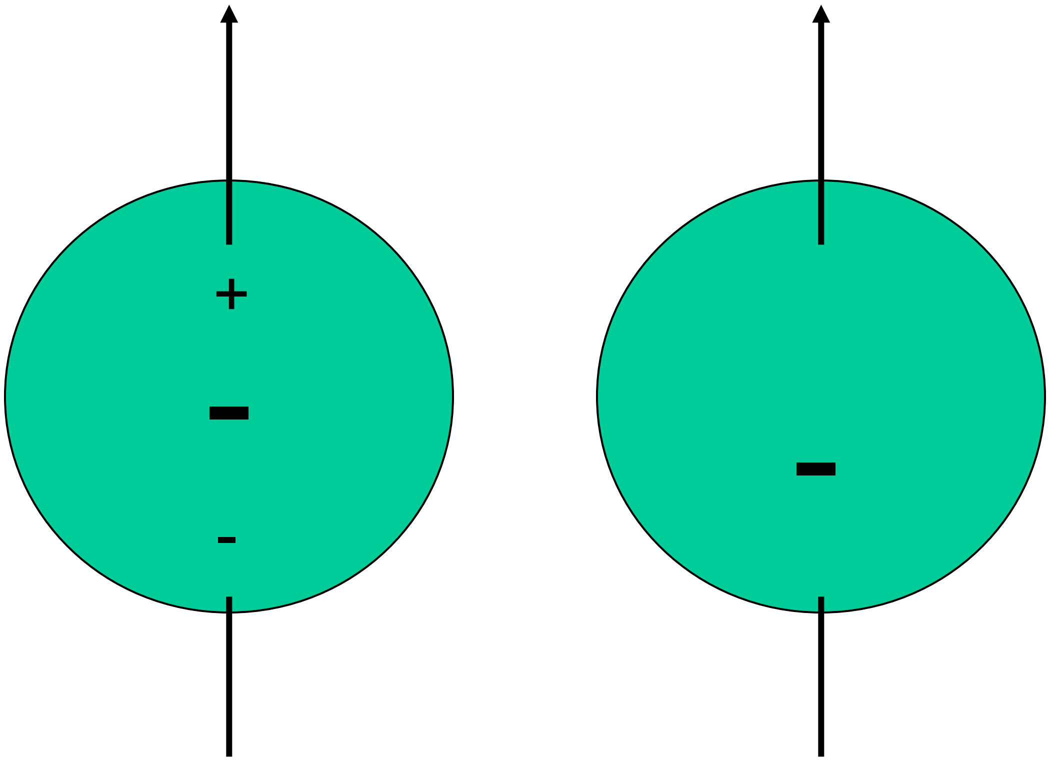
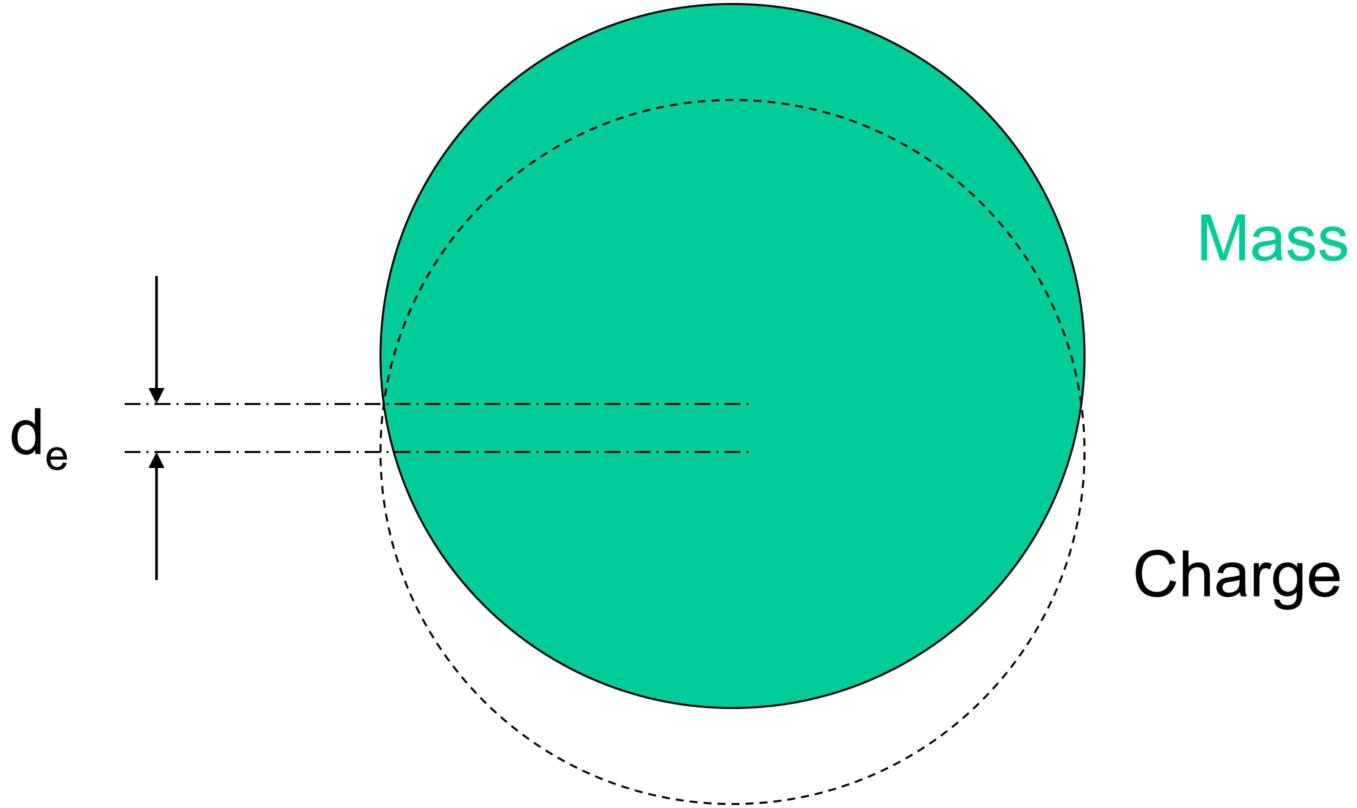
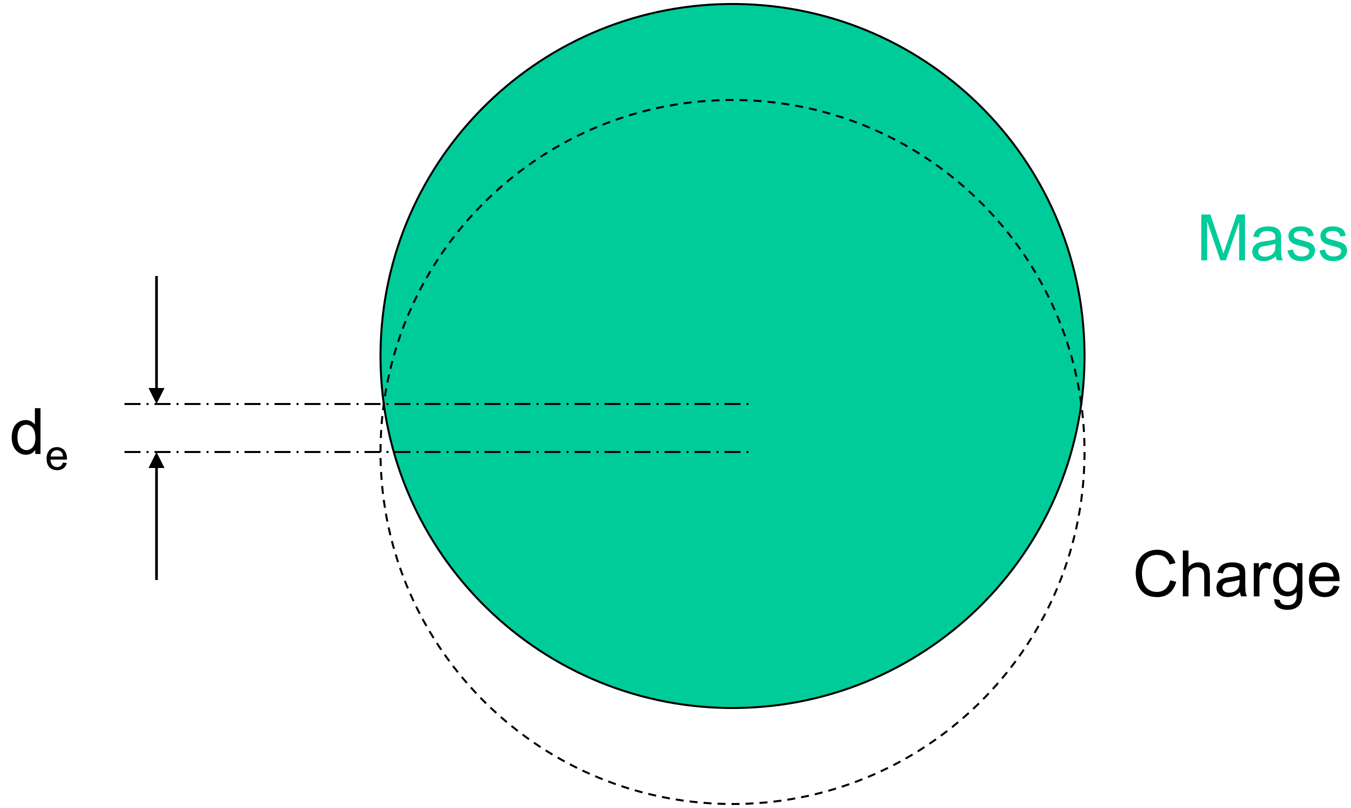


eEDM looks like offset between center of mass and center of charge!

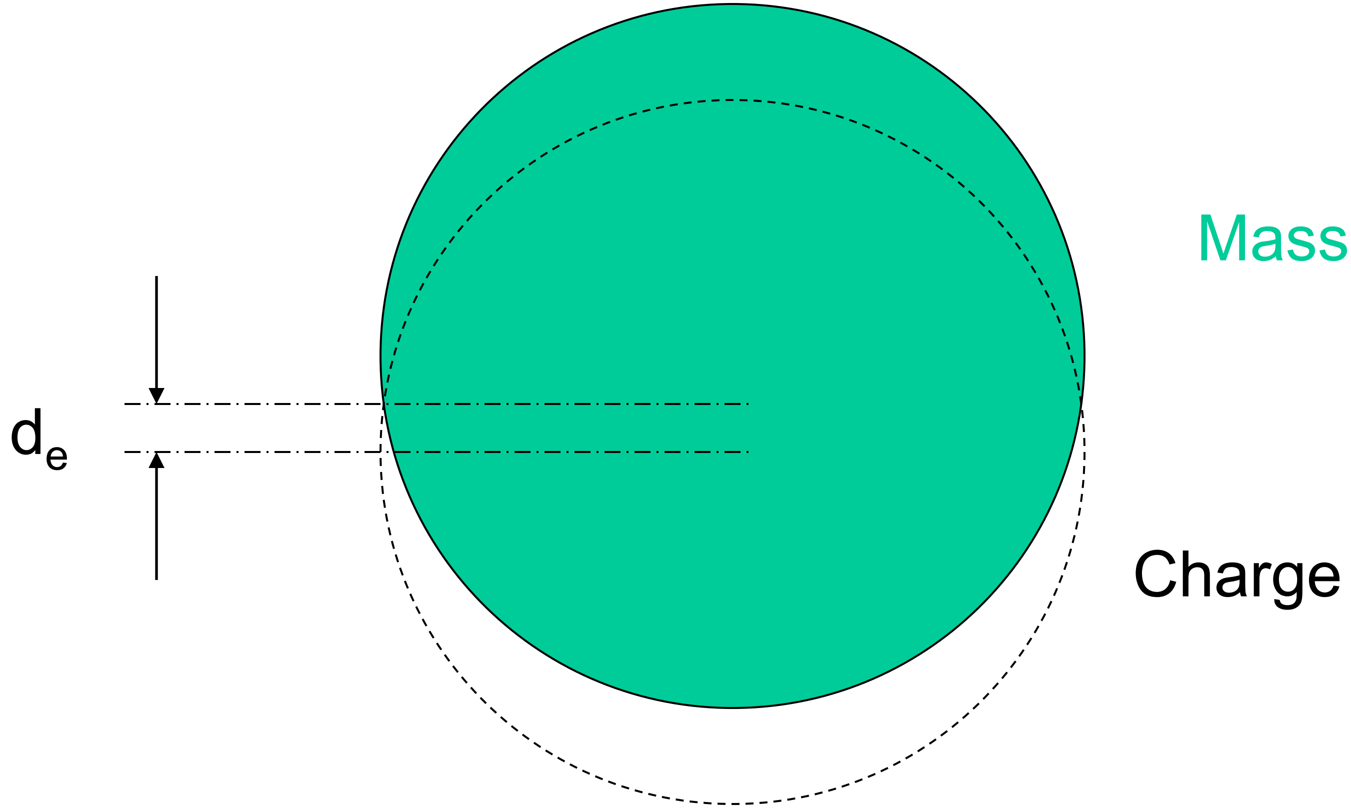


(In my world, [E]=[B] [d] = [μ] = distance-charge)



(In my world, [E]=[B] [d] = [μ] = distance-charge)

$d_e < 10^{-28}$ cm (ACME: Harvard/Yale)



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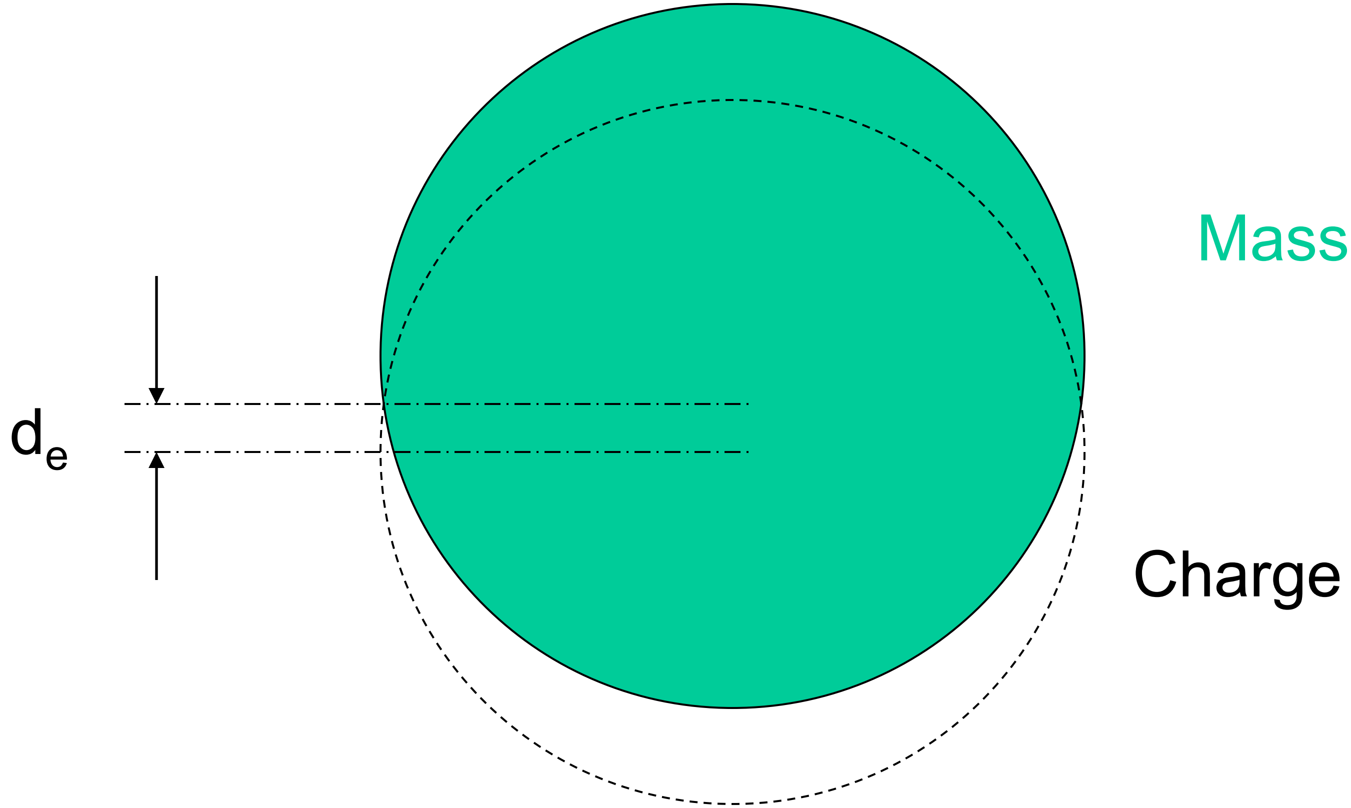
$d_e < 10^{-28}$ cm

Isn't that basically zero? Why do better?



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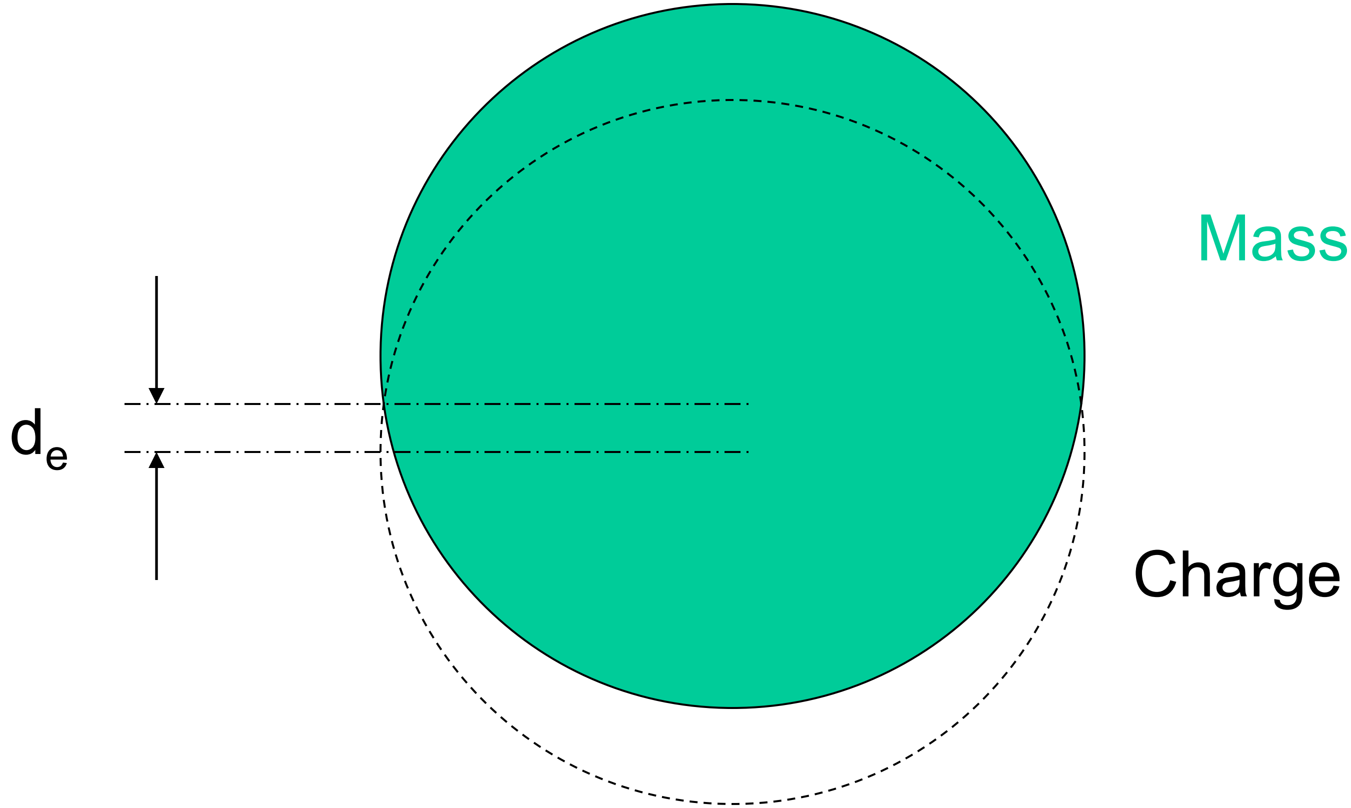
A1: Doing better is like building a bigger LHC!



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$$d_e < 10^{-28}\ \text{cm}$$

Isn't that basically zero? Why do better?

A1: Doing better is like building a bigger LHC!

A2: Doing better is like building a new telescope!

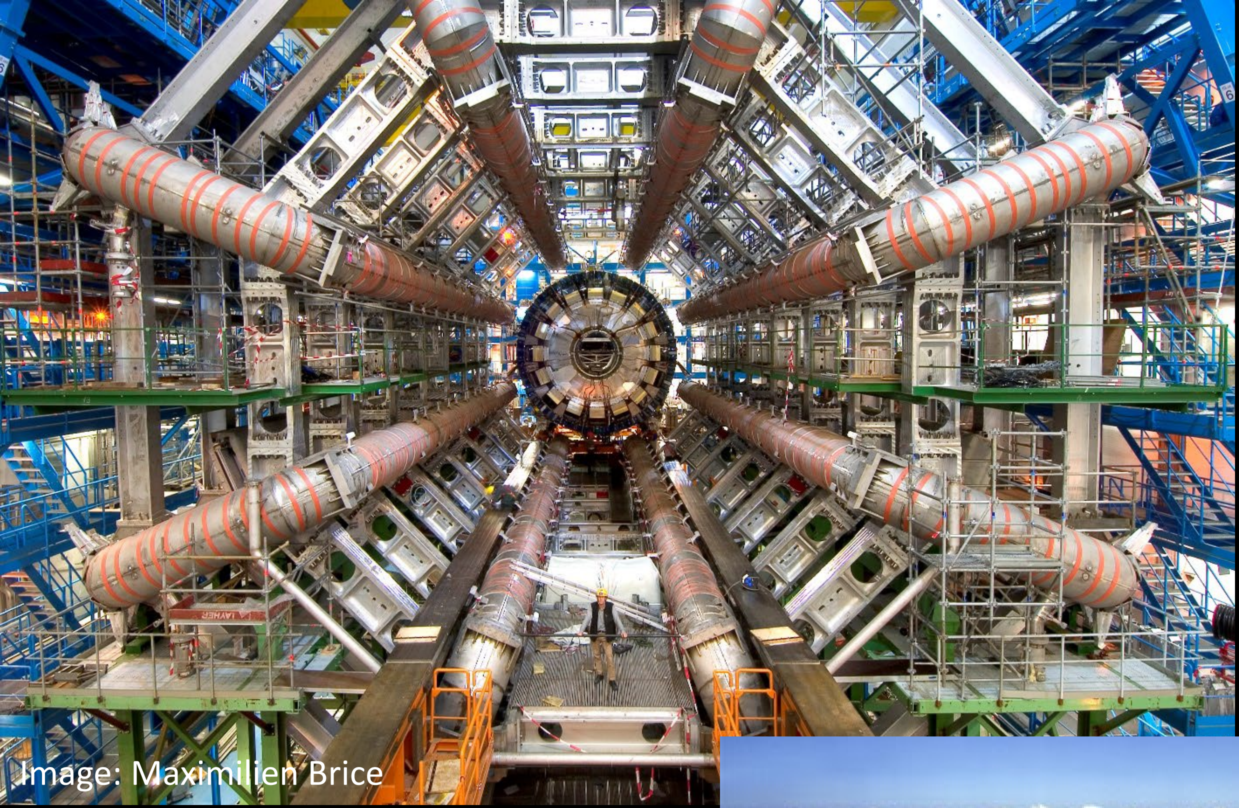

Image: Maximilien Brice

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

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

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

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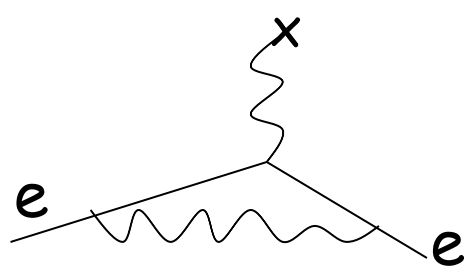

New particle physics from precision dipole moments ---- long tradition

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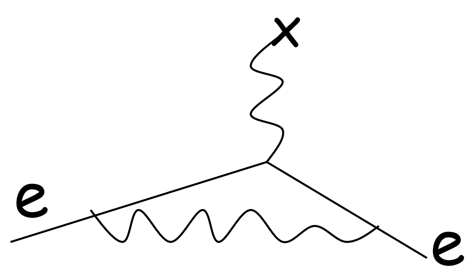
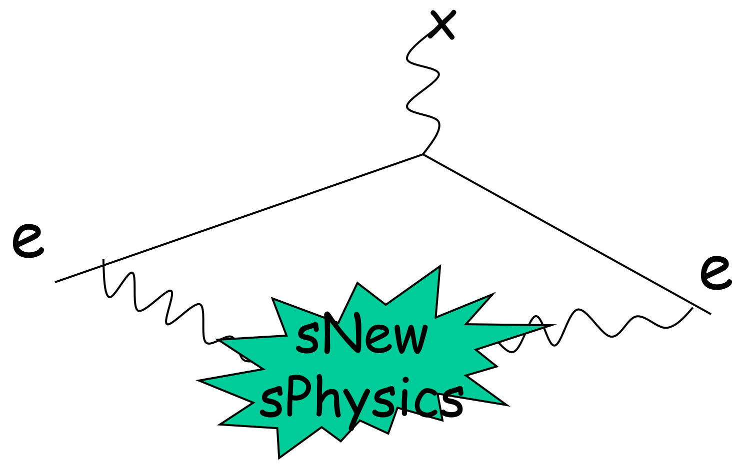


3. $g = 2 + a_1\alpha + a_2\alpha^2 + a_3\alpha^3 + a_4\alpha^4 + \ldots$

(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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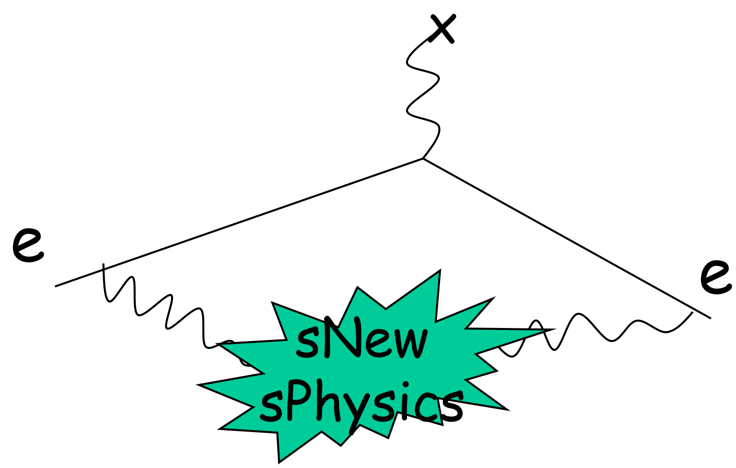
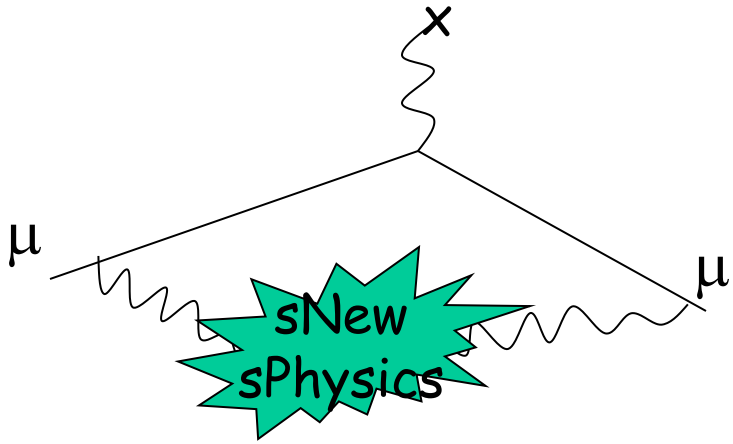


A: Probably not. m_e is too small.

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



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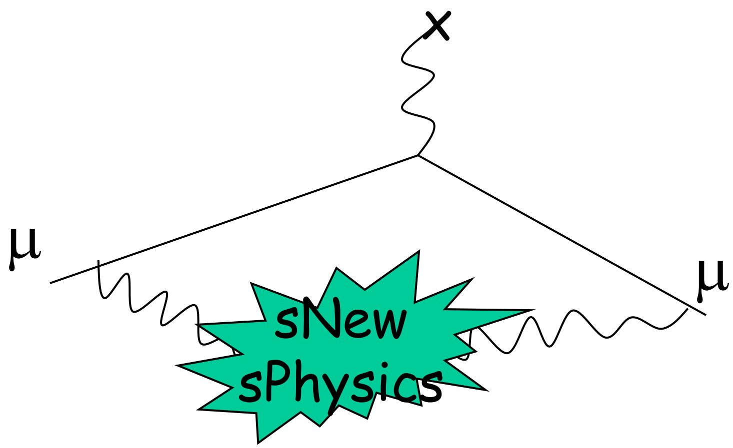
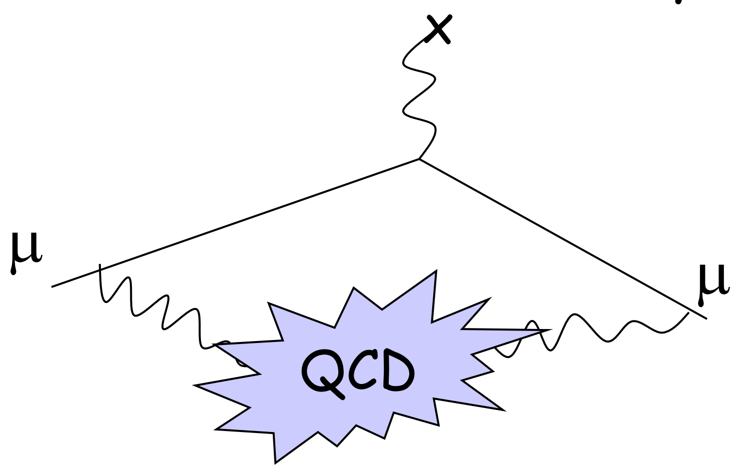


A: Maybe (there is a big effort) but difficult due to uncertainties in QCD "theory background".

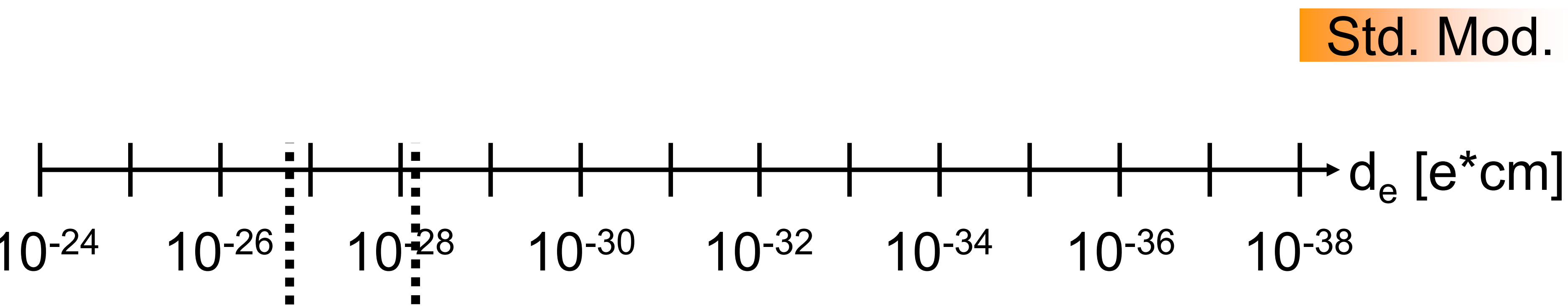


New particle physics from precision dipole moments

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 Berkeley [PRL **88**, 071805 (2002)]

$< 0.8 \times 10^{-28}$ e*cm Harvard/Yale (2014)

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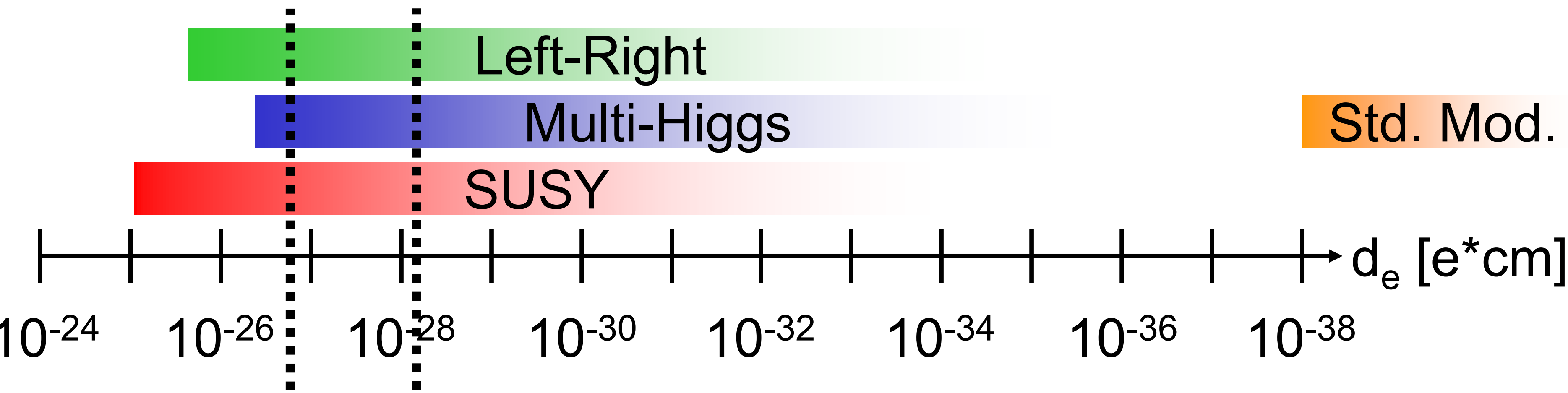

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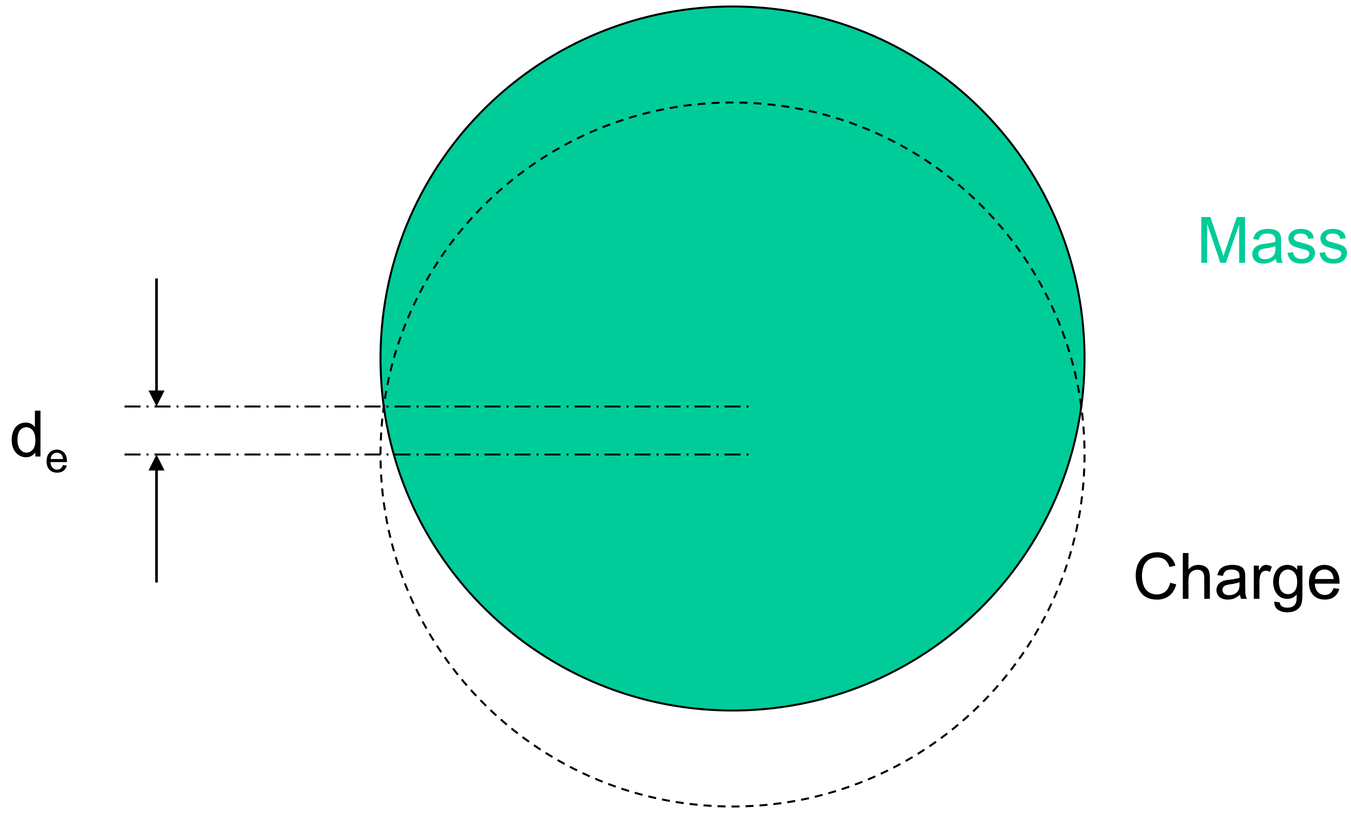


OK, so what might d_e be?

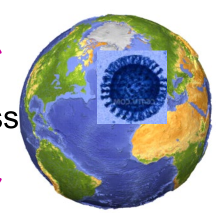
(In my world, [E]=[B]

[d] = [μ] = distance-charge)

$r_{class.} = e^2/mc^2$	$d_e = e\, r_{class.}$?	$\alpha^2\, e\, a_0$	3×10^{-13} e-cm	

Why
10^{-16} ??

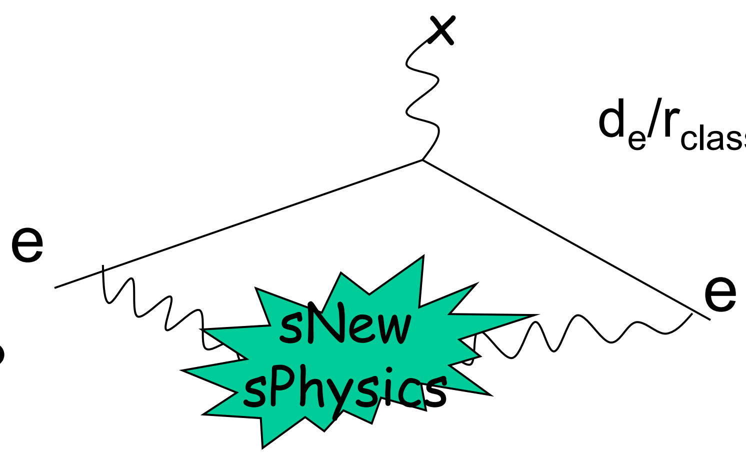
r_{class}



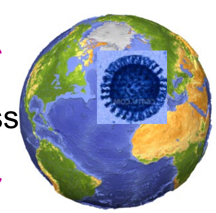
Future limit from proposed experiments (JILA, many other groups):	$< 10^{-29}$ e-cm	

$r_{class.} = e^2/mc^2$	$d_e = e\, r_{class.}$?	$\alpha^2\, e\, a_0$	$3\text{x}10^{-13}$ e-cm	

$$d_e/r_{class} = (1/24\pi)\ \text{“}(\sin\theta_{newcp})\text{”}(m_e/m_{new})^2$$



Why 10^{-16} ??

r_{class} 	Future limit from proposed experiments (JILA, many other groups):	$<10^{-29}$ e-cm	

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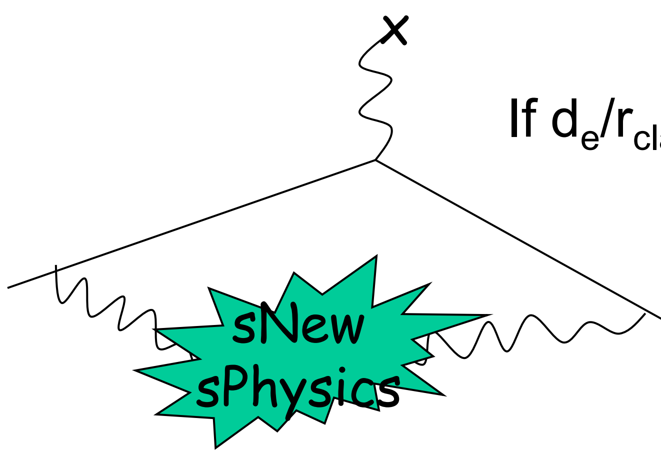
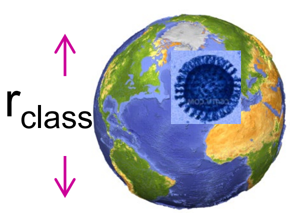


If $d_e/r_{class} = (1/24\pi)$ "$(\sin\theta_{newcp})$"$(m_e/m_{new})^2$
$=10^{-16}$
Then?



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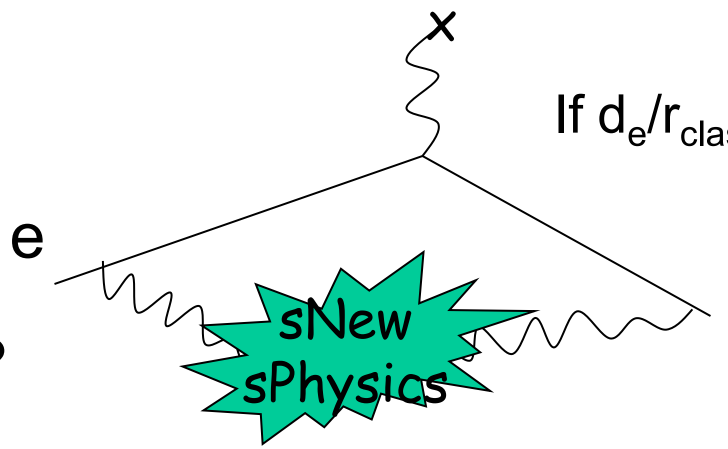
$r_{class.} = e^2/mc^2$	$d_e = e\, r_{class.}$?	$\alpha^2 e\, a_0$	$3x10^{-13}$ e-cm	

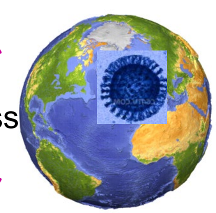
Why 10^{-16} ??



If $d_e/r_{class} = (1/24\pi)$ "($\sin\theta_{newcp}$)"$(m_e/m_{new})^2$ (0.1)

$=10^{-16}$

Then?

r_{class} 	Future limit from proposed experiments (JILA, many other groups):	$<10^{-29}$ e-cm	

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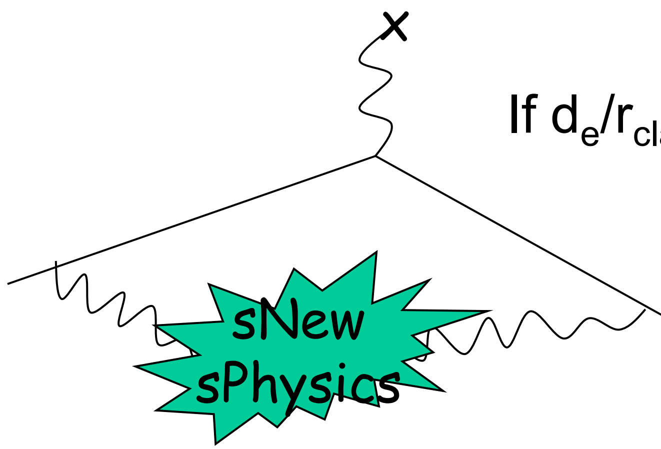
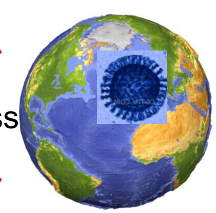


Why 10^{-16} ??

If $d_e/r_{class} = (1/24\pi)$ "$(\sin\theta_{newcp})$"$(m_e/m_{new})^2$ $=10^{-16}$ (0.1)

Then

$m_{new} = 2000$ GeV

$\uparrow$ r_{class} $\downarrow$ 	Future limit from proposed experiments (JILA, many other groups):	$<10^{-29}$ e-cm	

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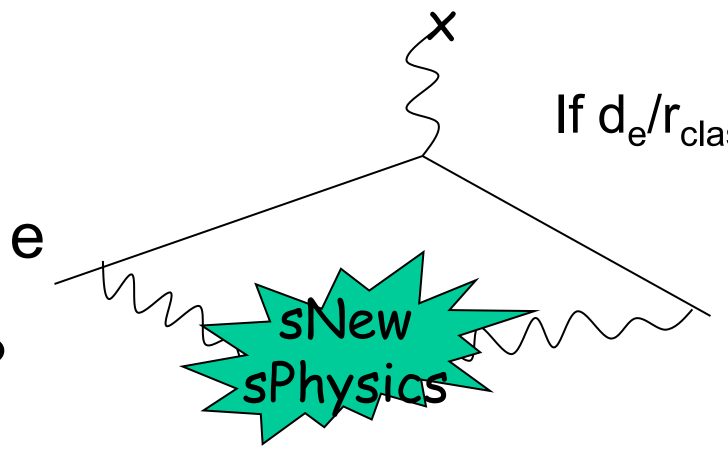

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Then

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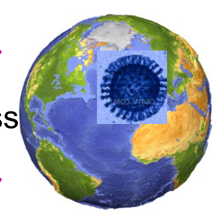
Compare with M_{Higgs} ~ 100GeV

 r_{class} ↑↓	Future limit from proposed experiments (JILA, many other groups):	$<10^{-29}$ e-cm

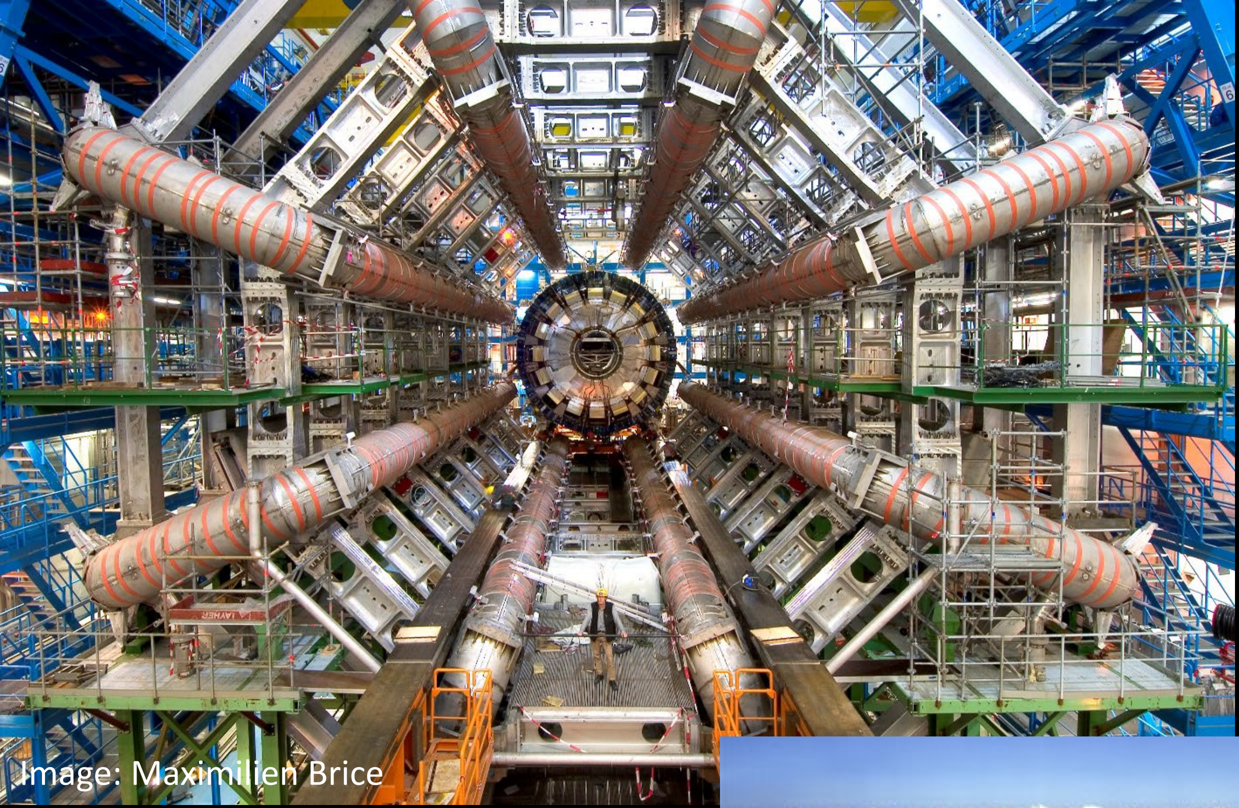


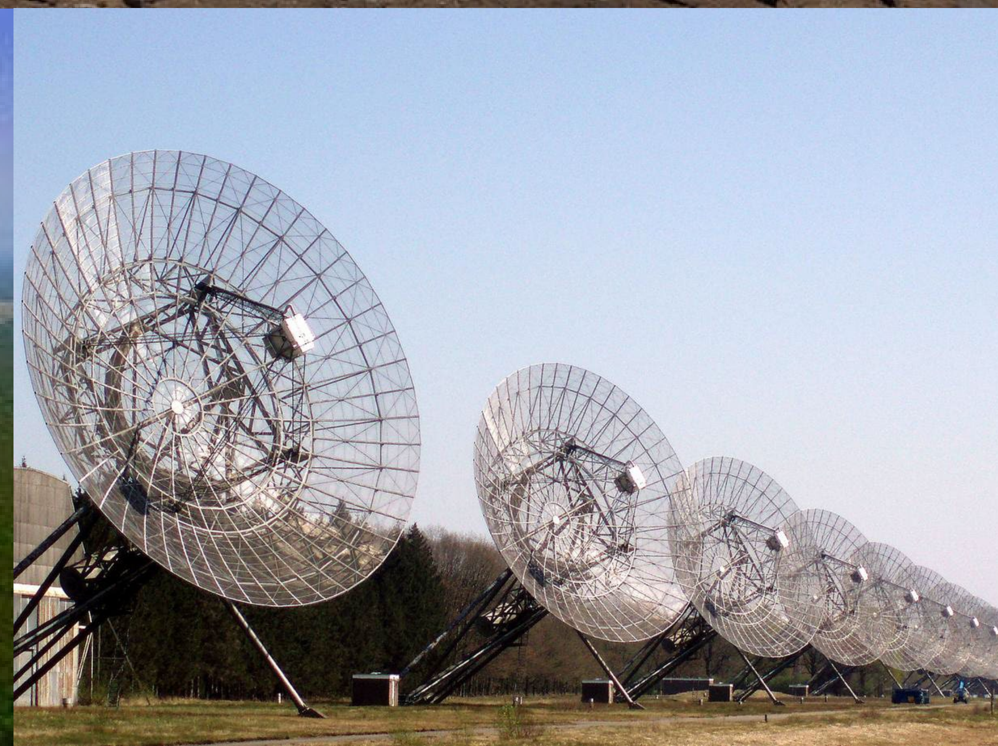
Image: Maximilien Brice

Motivation #2   (EDM like a big telescope)

The remnant of asymmetry.

The situation, approximately
14 billion years before right now:


16

The situation, approximately
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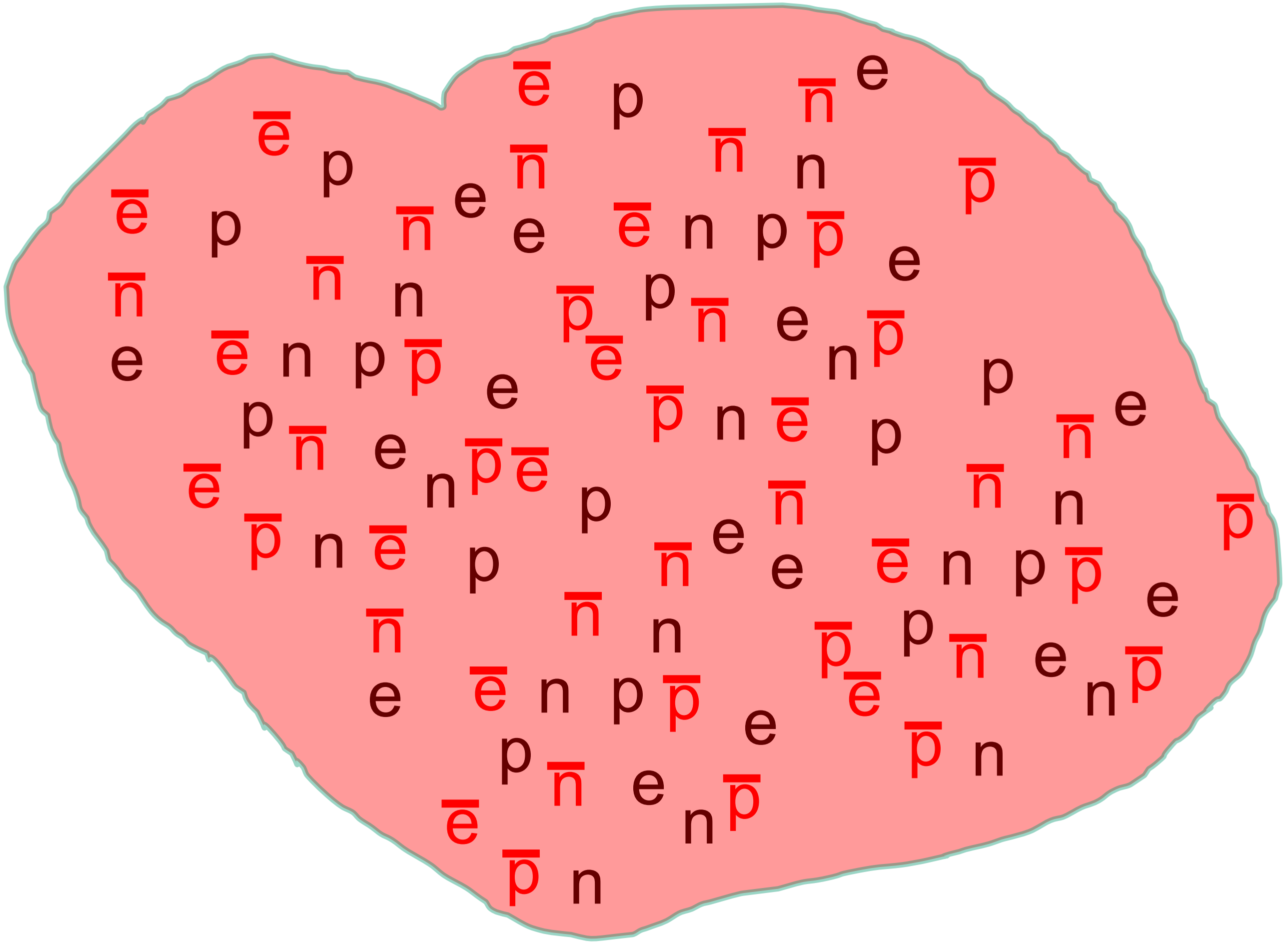
Then, shortly thereafter:



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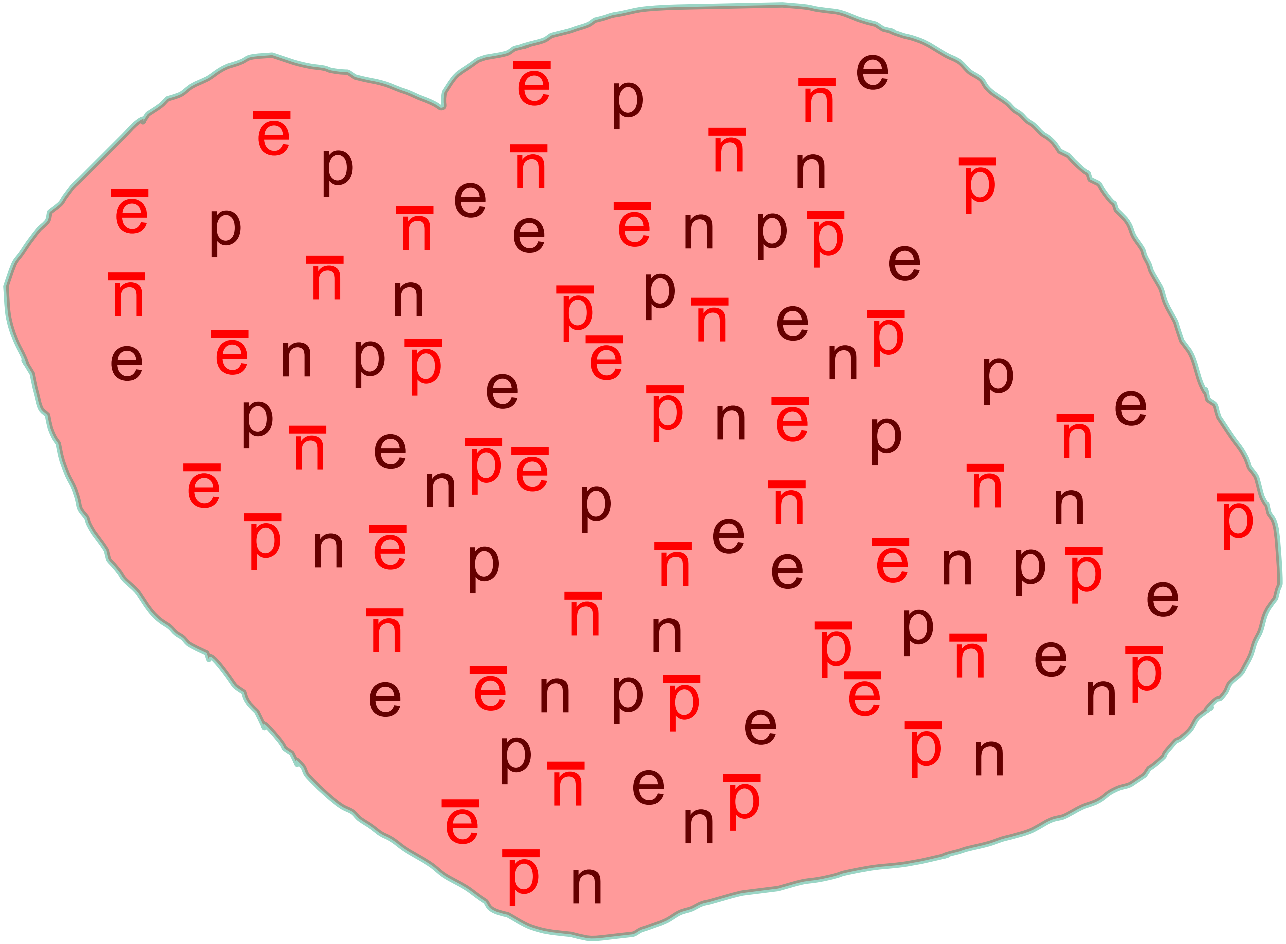
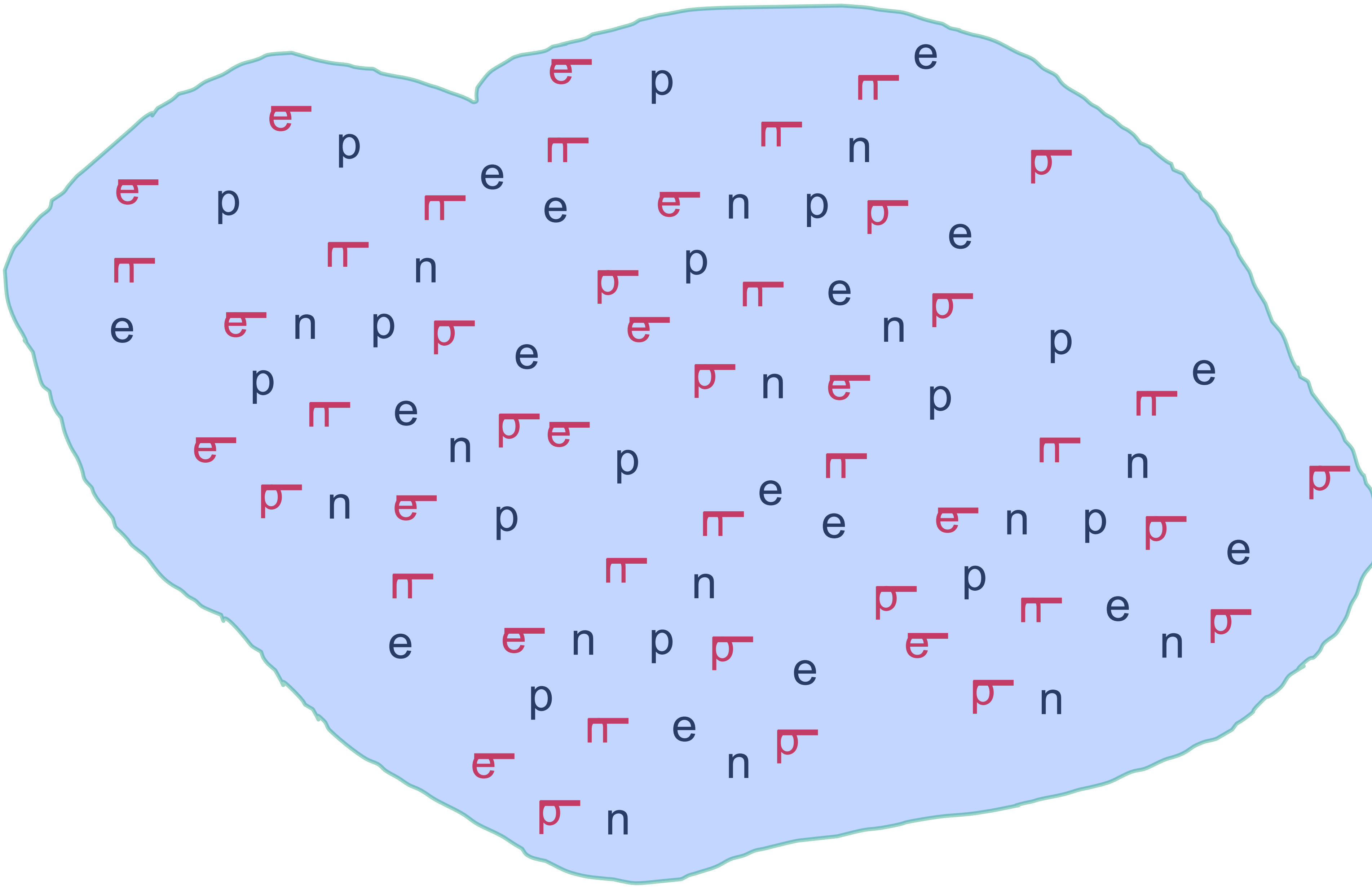
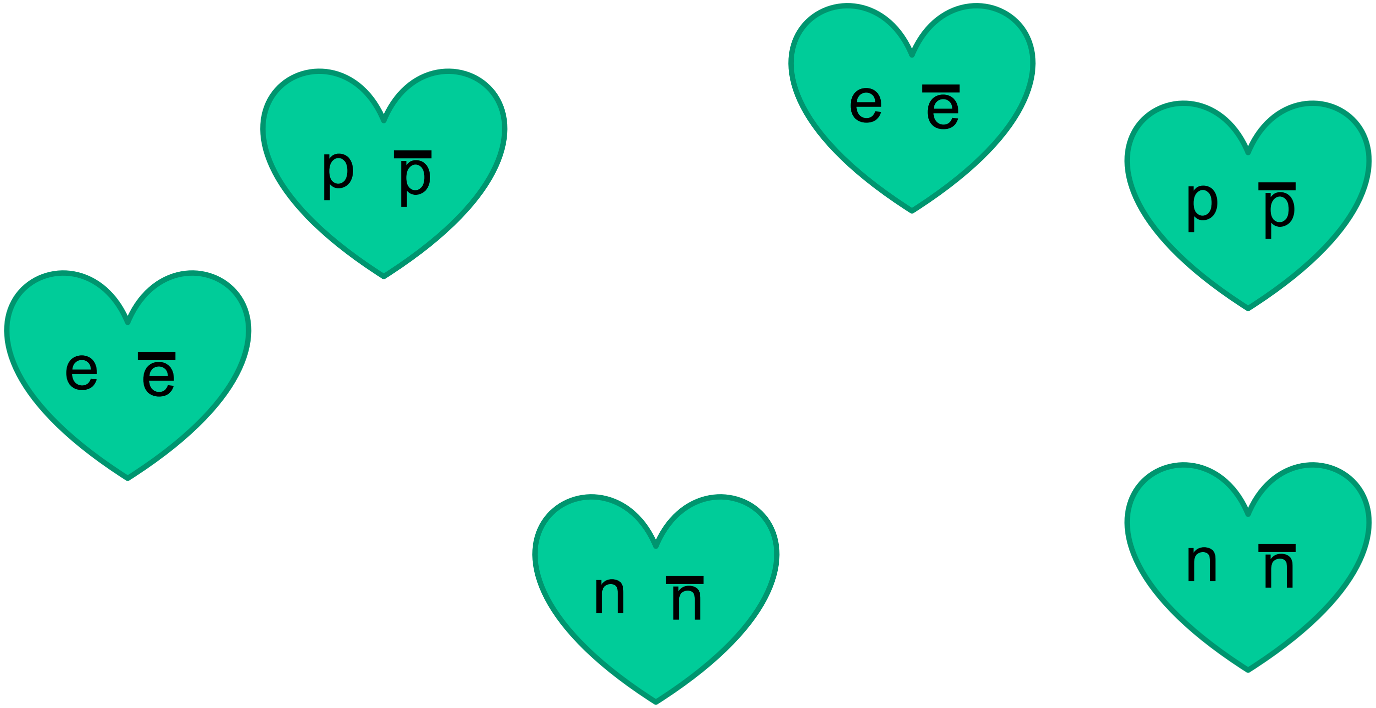
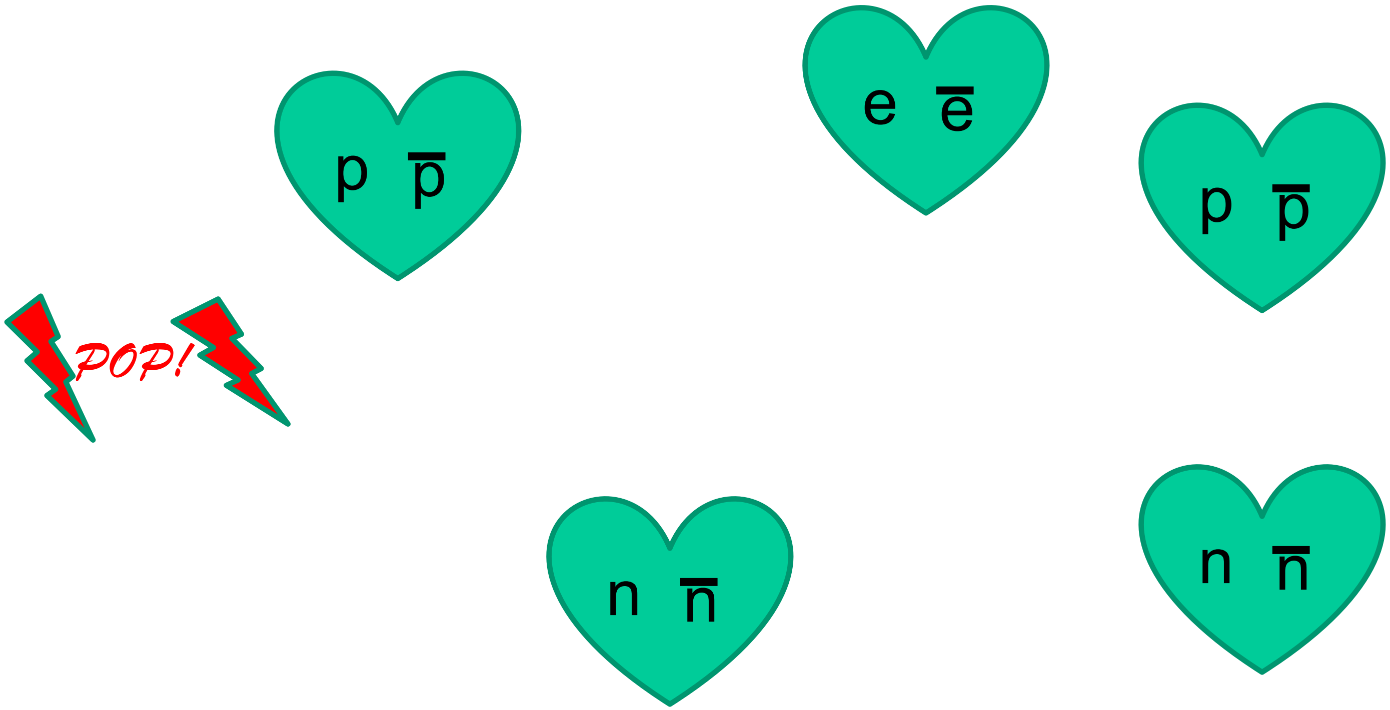


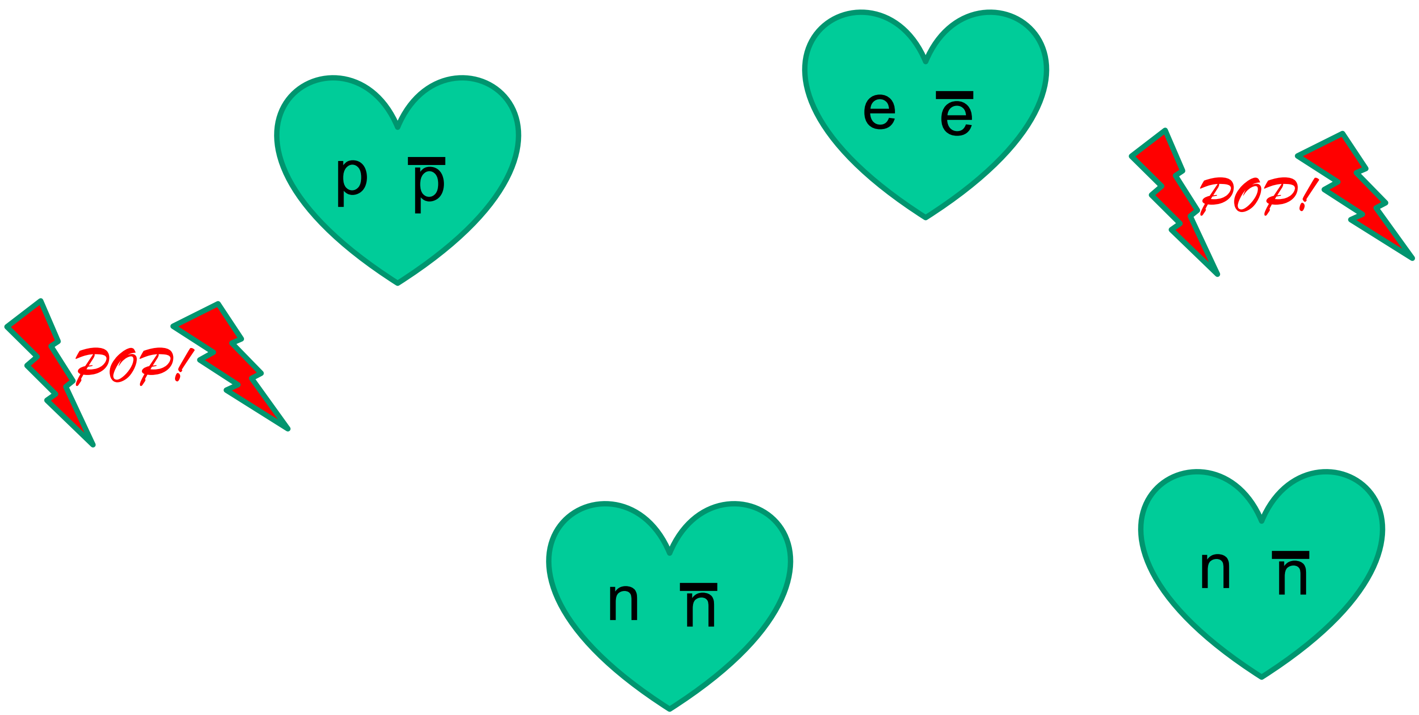
Then, the universe expanded and cooled:



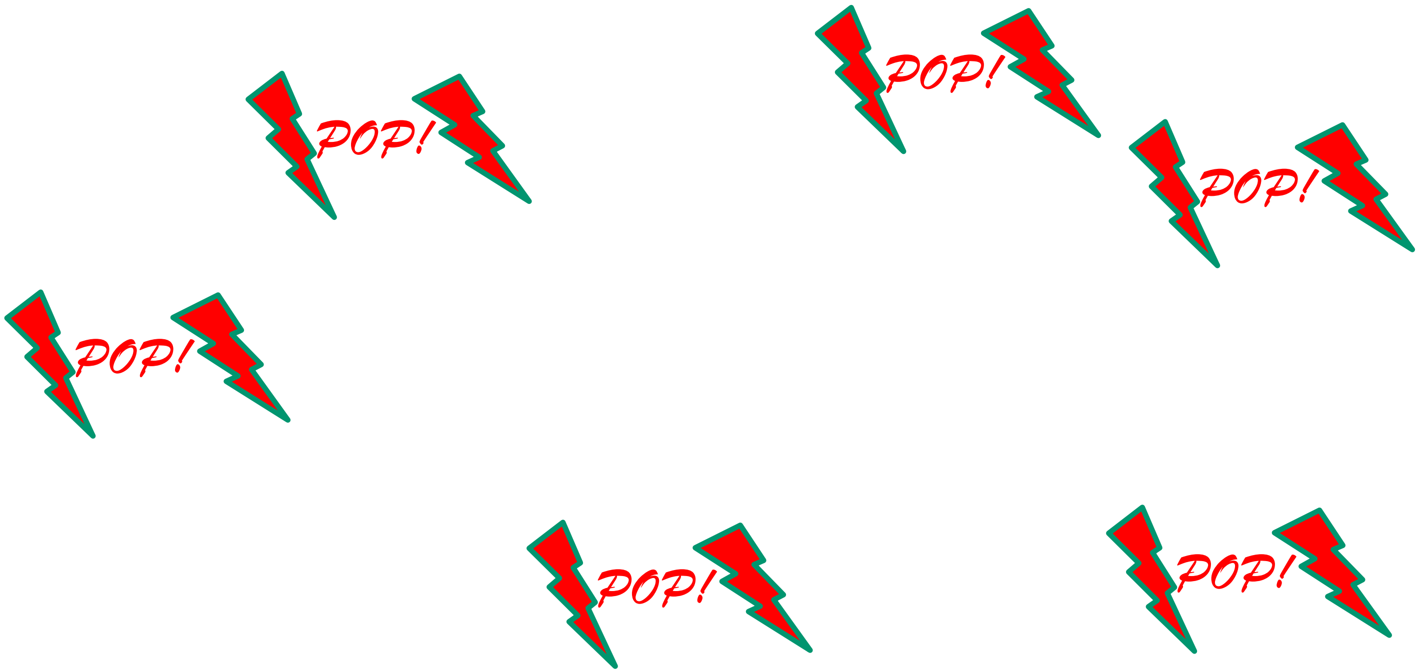
Then, true love!:




p $\bar{p}$
e $\bar{e}$
p $\bar{p}$
POP!
n $\bar{n}$
n $\bar{n}$



p $\bar{p}$
e $\bar{e}$
POP!
POP!
n $\bar{n}$
n $\bar{n}$

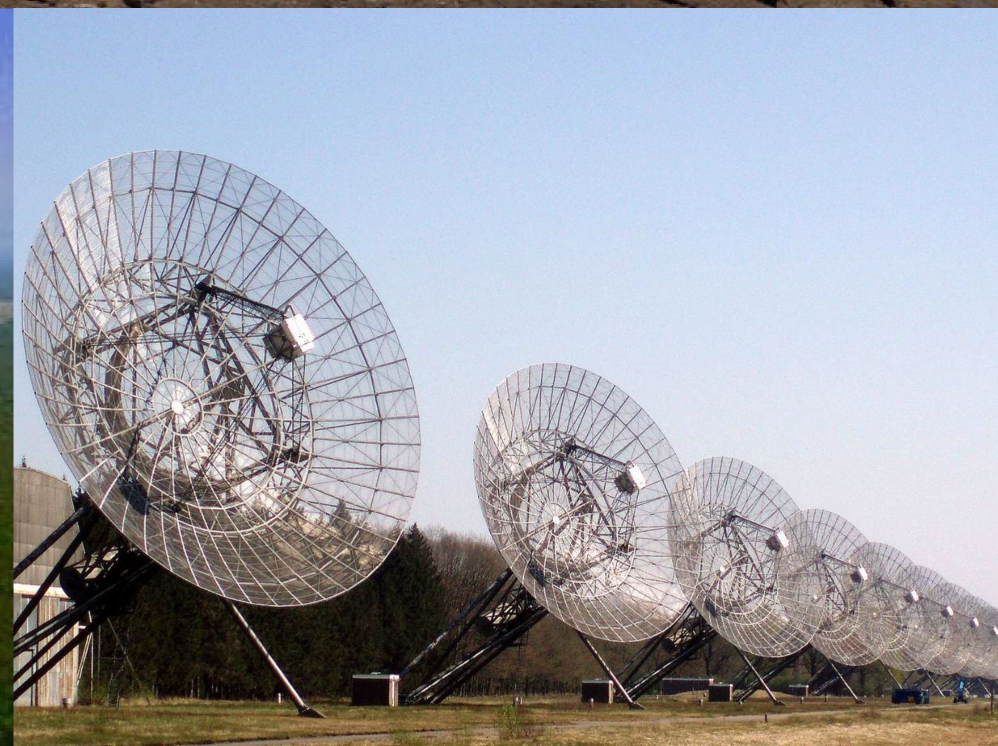

POP!
POP!
POP!
POP!
POP!
POP!

In the mass cosmic wedding,
there was somebody for everyone.

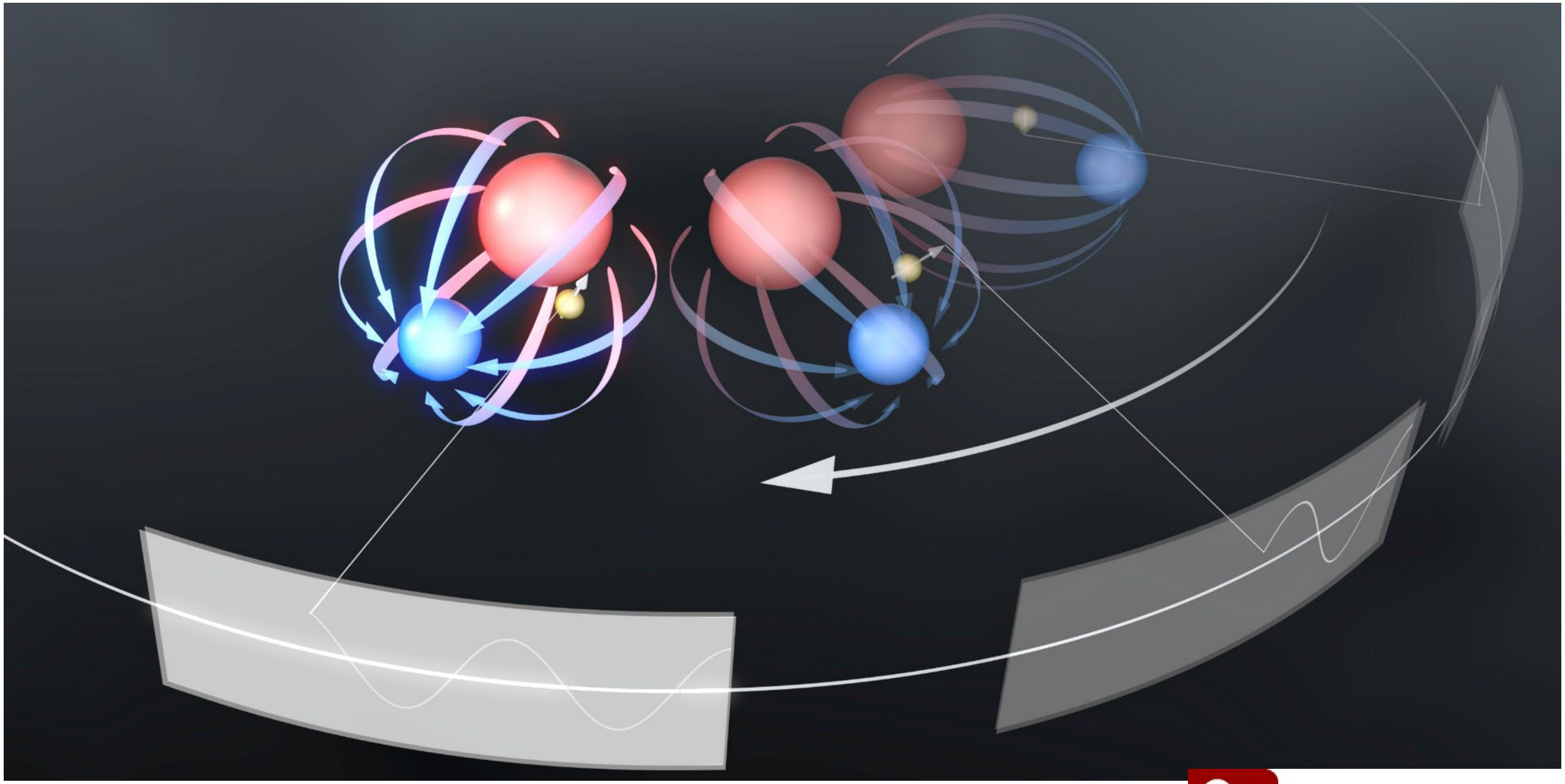
In the mass cosmic wedding,
there was somebody for everyone.
Except for you.



16



Measuring electron EDM using molecular ions



JILA eEDM collaboration

- *Dr. Yan Zhou*
- *Dr. Yuval Shagam*
- *Kia Boon Ng*
- *Will Cairncross*
- *Dan Gresh*
- *Tanya Roussy*
- *Fatemeh Abbasi-Razgaleh*
- *Jeff Meyers, Kevin Boyce*
- ***Jun Ye***
- *Eric Cornell*

Local theory: John Bohn

Non local Theory: Bob Field

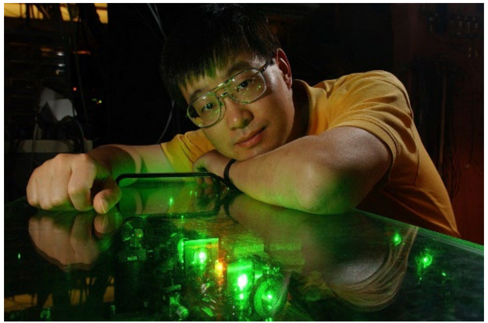
Still Less Local Theory

St. Petersberg quantum chemistry group

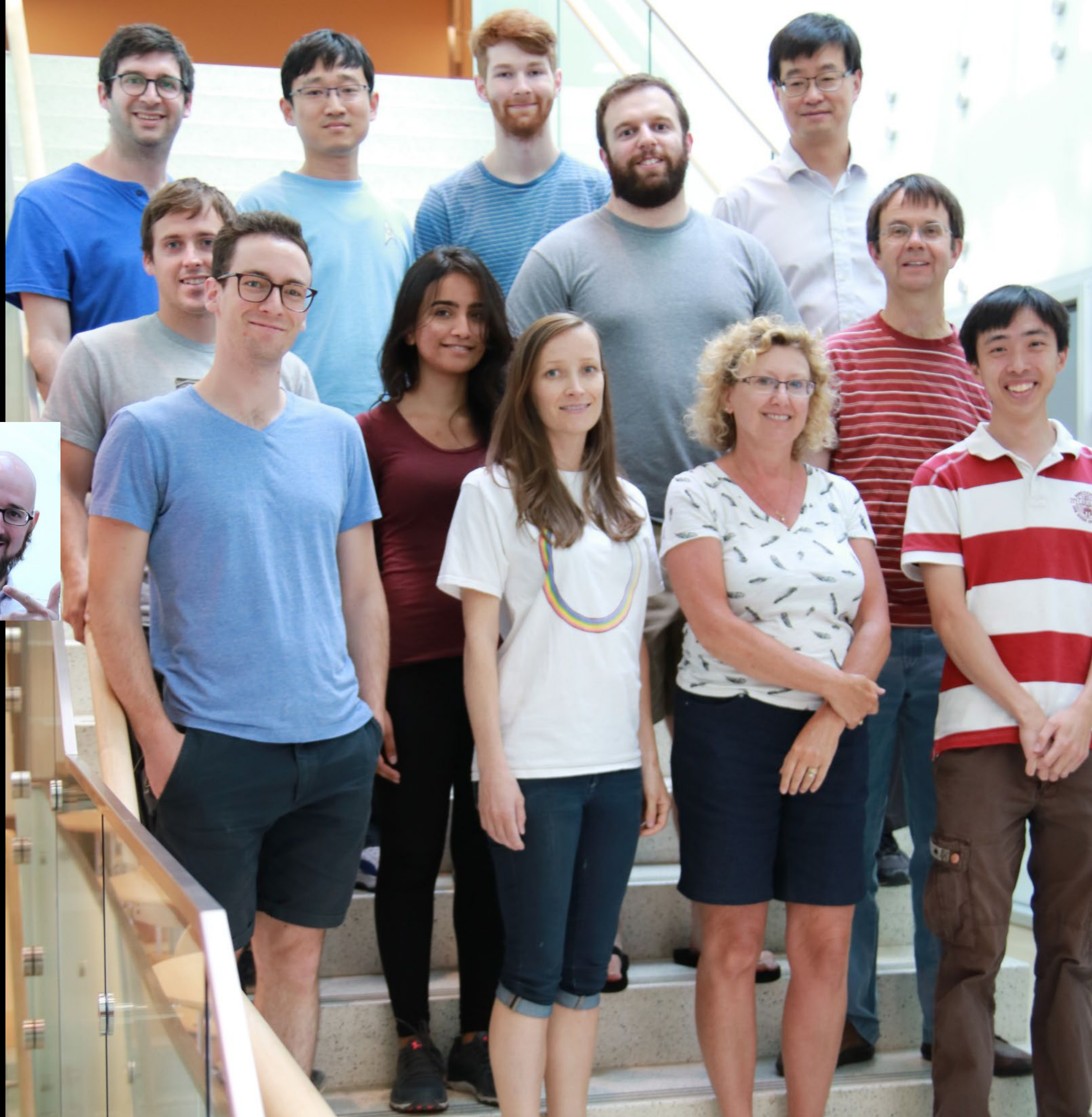
Past Group Members

- Laura Sinclair
- Kang-Kuen Ni
- Kevin Cossel
- Russ Stutz
- Aaron Leanhardt
- Yiqi Ni
- Huanqian Loh
- Matt Grau

Thanks: NSF/PFC, NIST, and Marsico Foundation

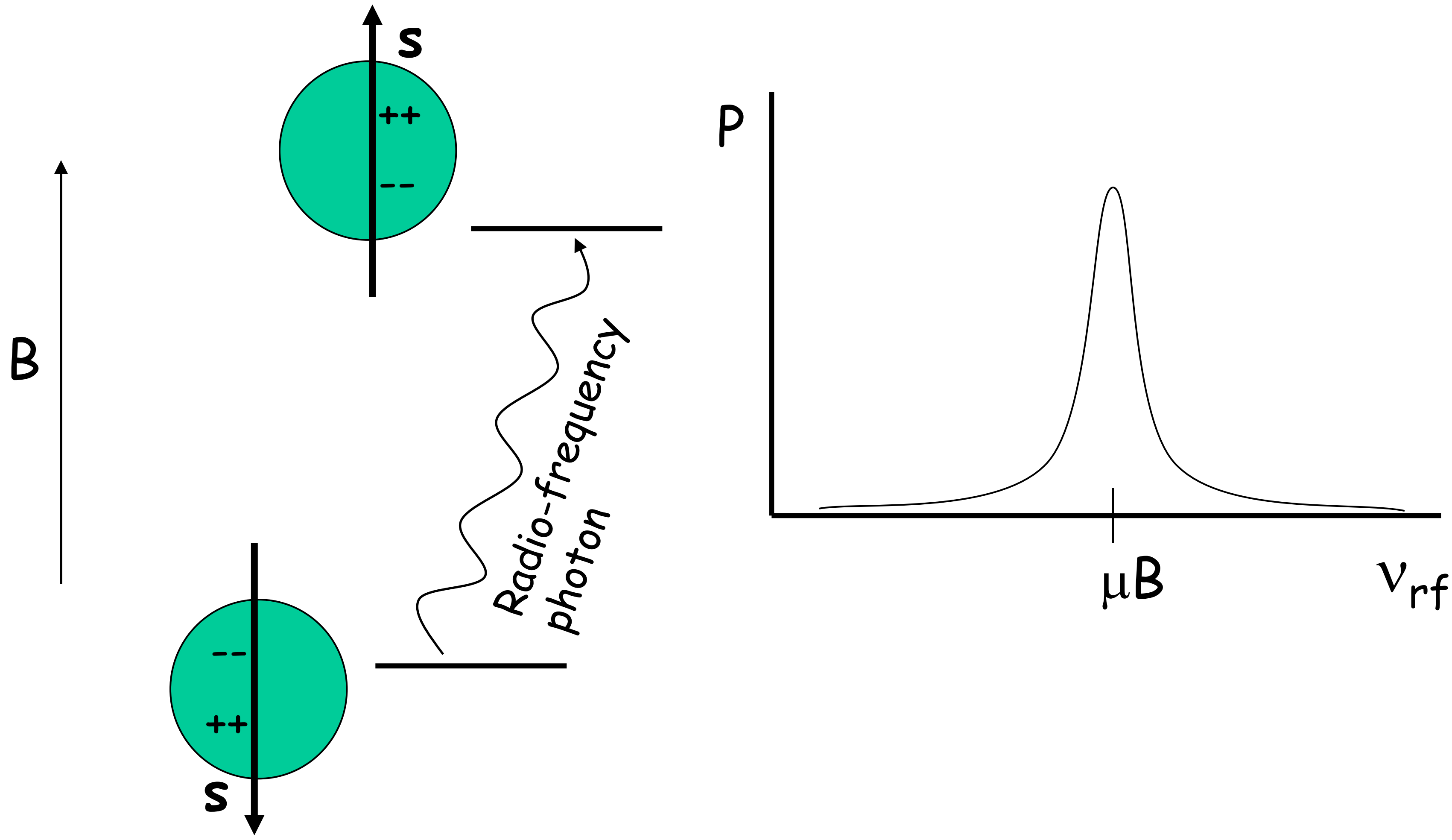




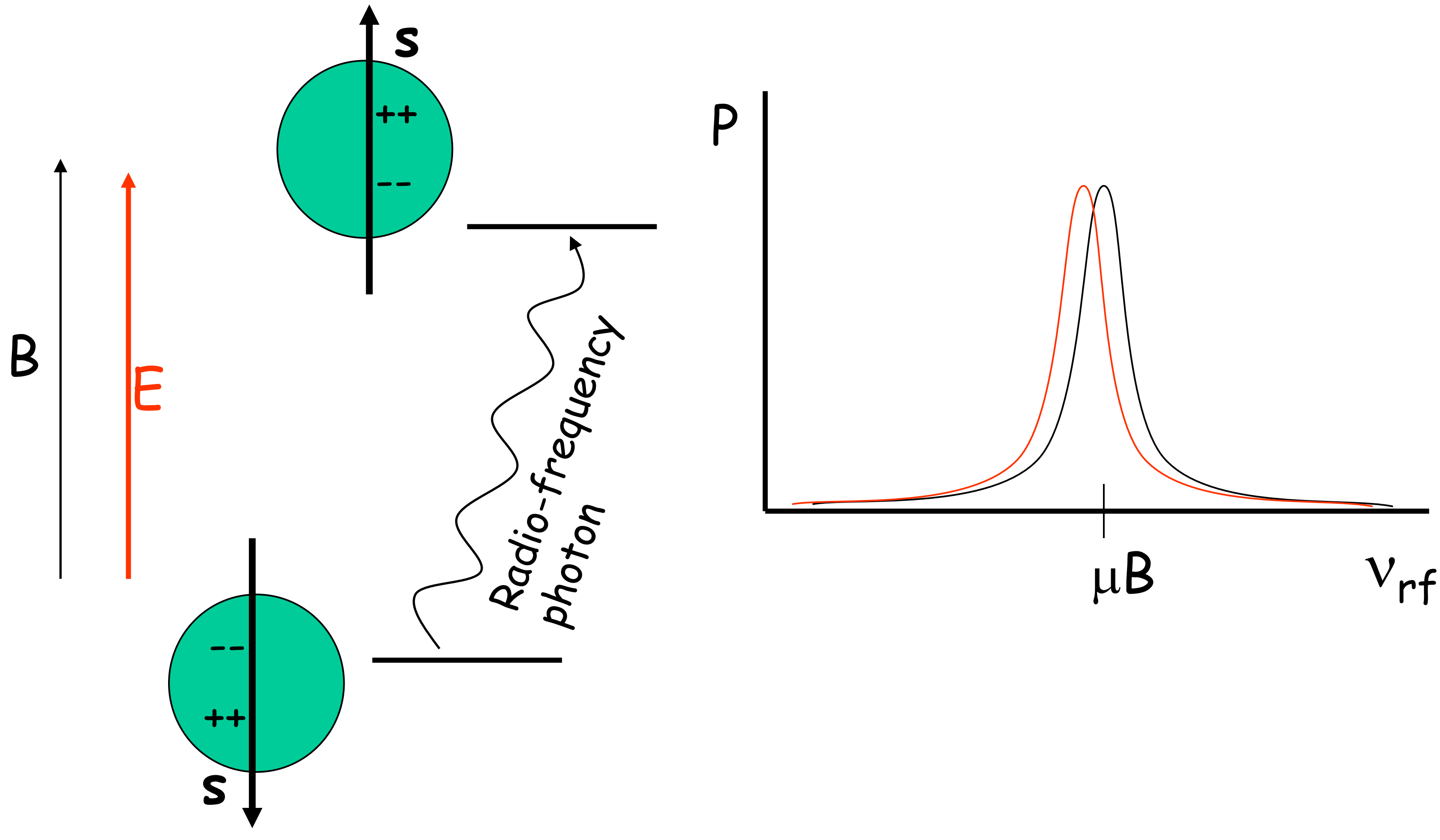



Q: How to measure an eEDM?

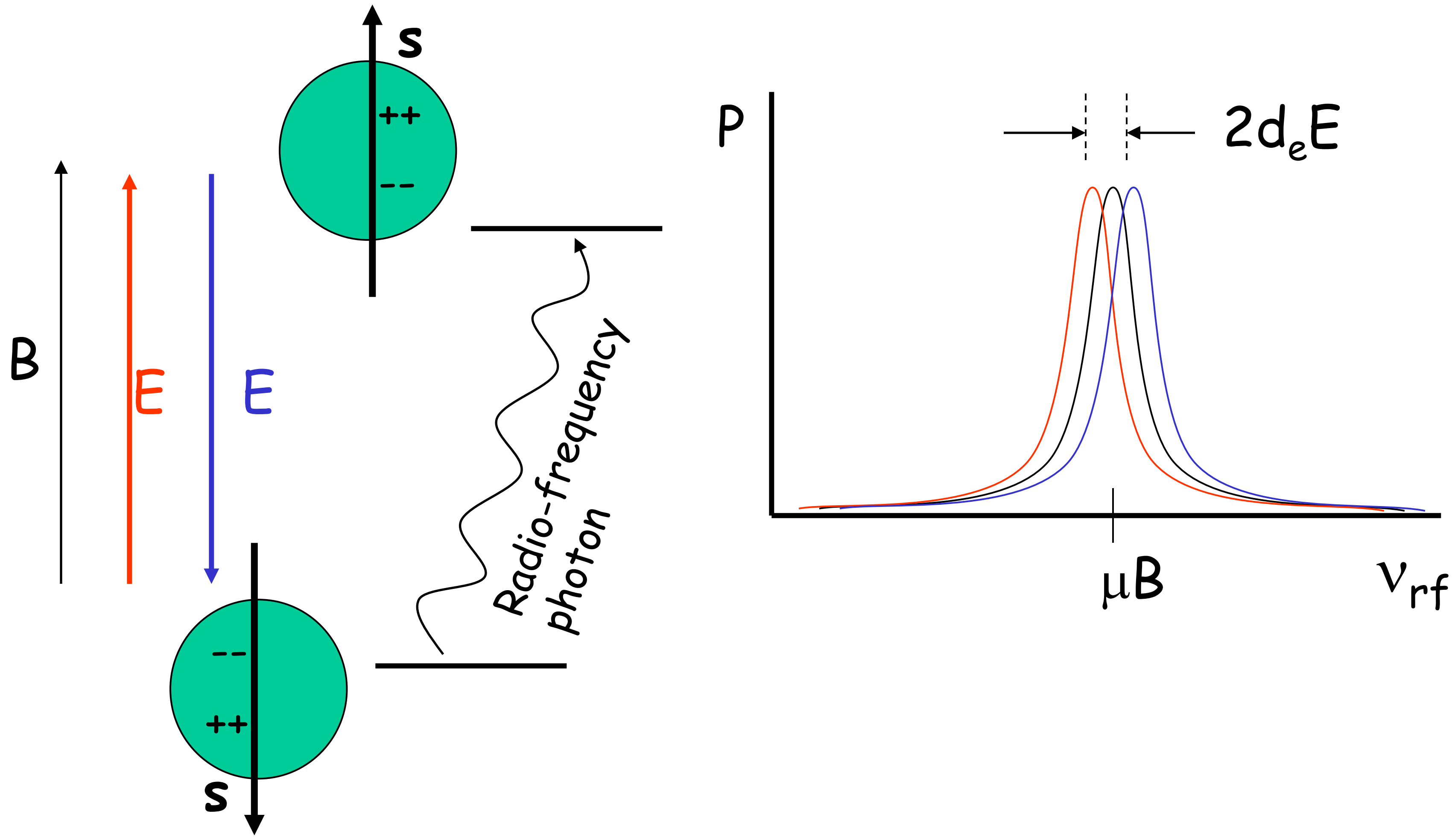
How to measure eEDM? First, how do we measure eMDM?



How to measure eEDM?



How to measure eEDM?



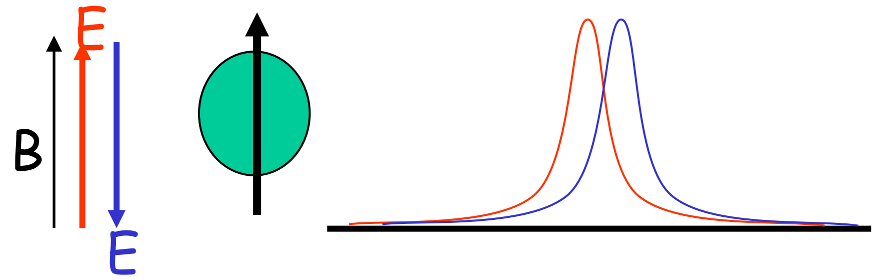
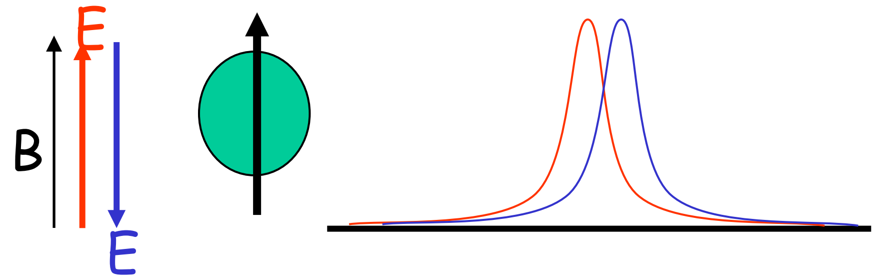

B
E
E

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



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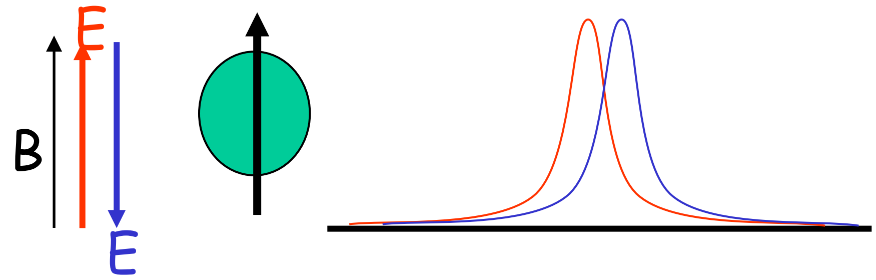
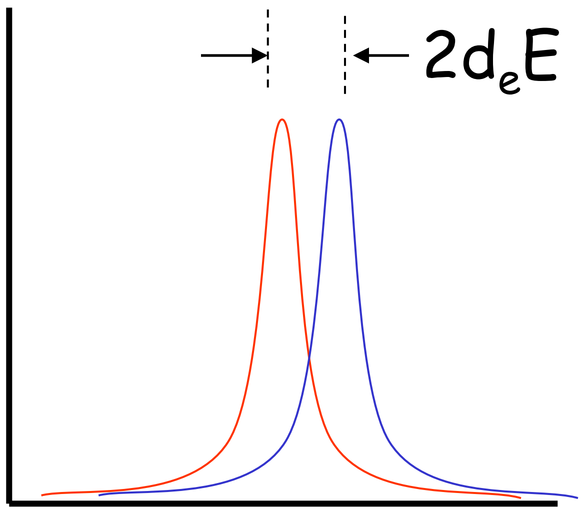
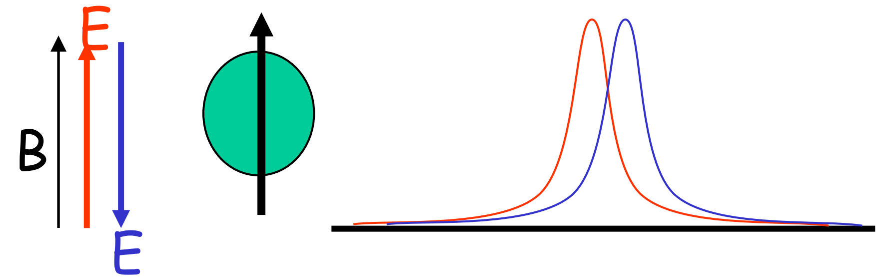
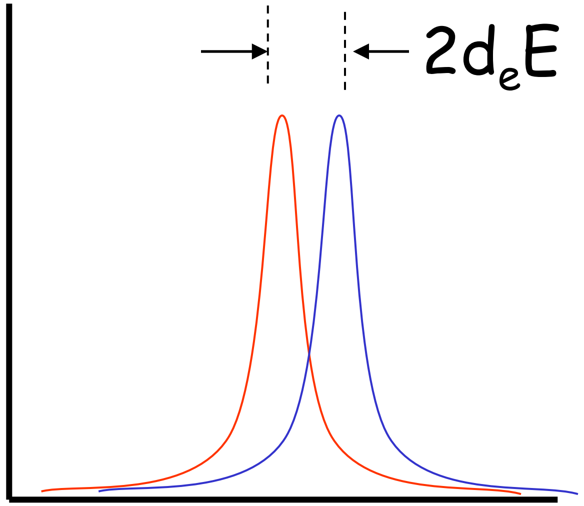




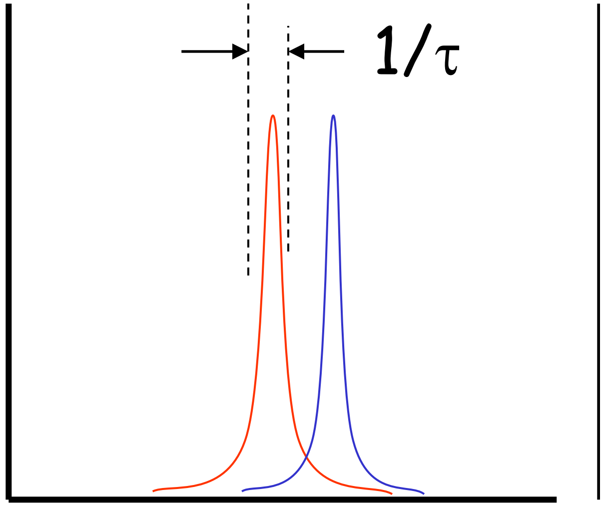
Big Electric Field!

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



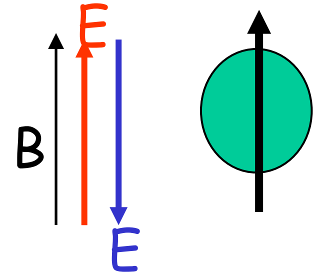


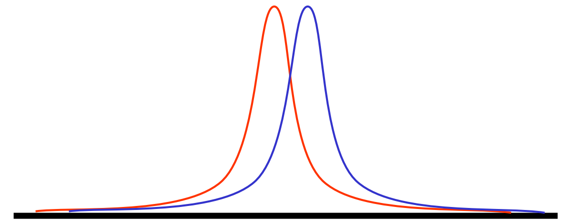
Big Electric Field!

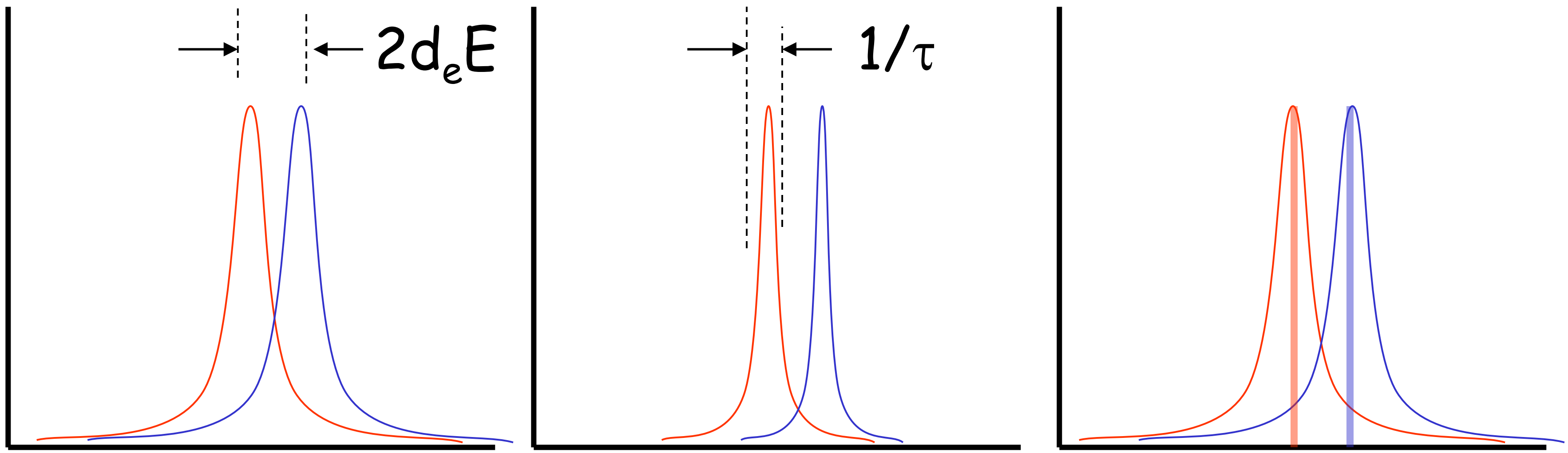


Long Coherence Time (narrow resonances)!

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







Big Electric Field!

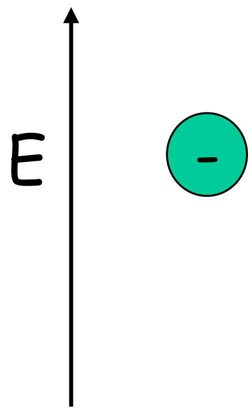
Long Coherence Time (narrow resonances)!

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

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

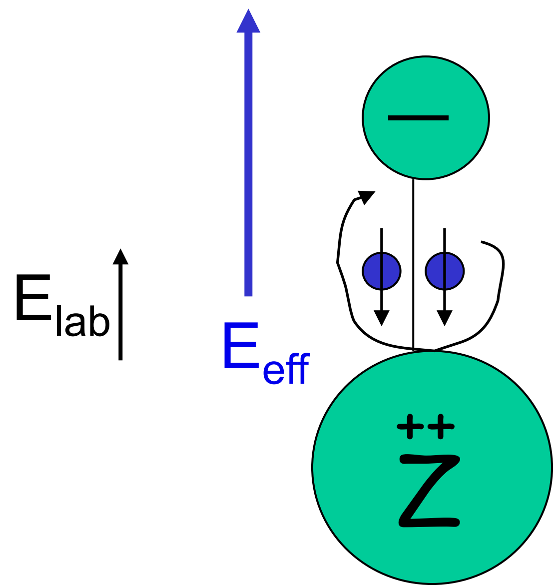
Problem:

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



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

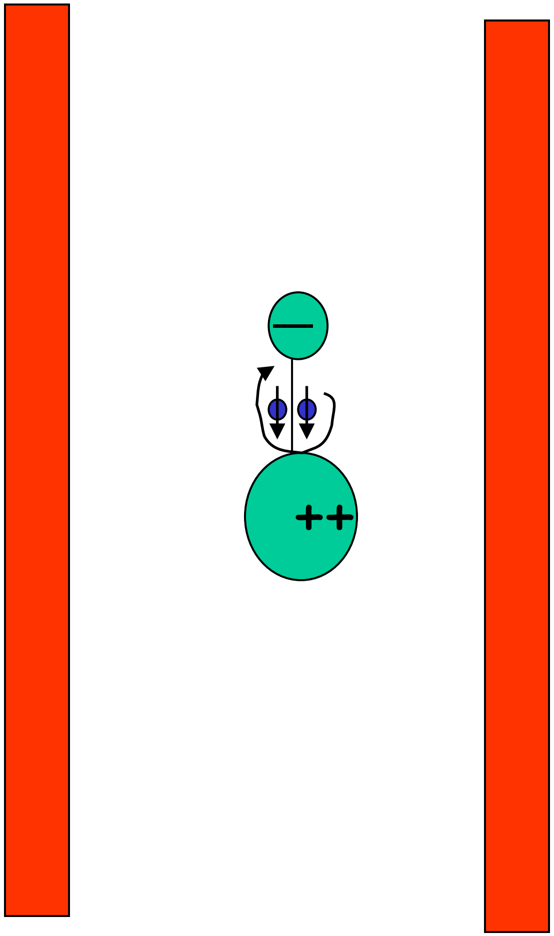
(we follow Hinds and Demille in this)



$E_{lab} = 10$ 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 an ion trap.

Comparison with previous and ongoing experiments

Figure-of-merit : $E_{eff}\tau\sqrt{N}$	E_{eff}(V/cm)	τ(msec)	N_{eff} (s^{-1})
Berkeley Tl beam, $d_e<1.6\times10^{-27}$ e.cm (2002)	6×10^7	2	1×10^9
Imperial YbF beam, $d_e<1.0\times10^{-27}$ e.cm (2011)	1.5×10^{10}	1	10^6
Penn State, (projected sensitivity $d_e < 10^{-28}$ e.cm)	$\sim10^8$	$\sim10^3$	?
ACME Collaboration (ThO), $d_e<9\times10^{-29}$ e.cm (2014)	8.4×10^{10}	1.1	2.5×10^4
JILA (projected sensitivity $d_e < 10^{-28}$ e.cm)	$3\text{-}9 \times 10^{10}$	1000	10

Also other experiments in atoms, Penn State, TRIUMF, Tokyo, etc.

Molecular Ions

$$\delta d_e \sim \frac{1}{|E_{eff}|\tau\sqrt{N}}$$

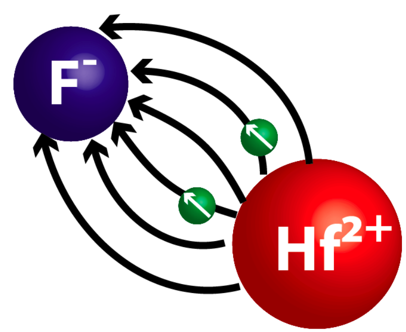
Molecules provide large effective electric fields

$E_{lab} = 10$ 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

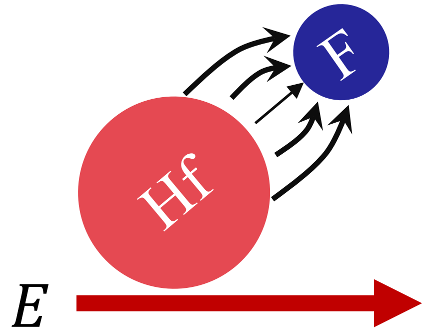


Our choice: HfF^+

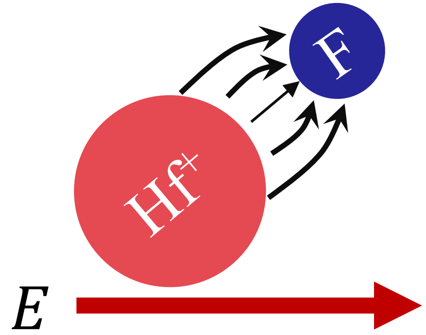
P. G. H. Sandars, Physics Letters **14**, 194 (1965).
E. A. Hinds, Physica Scripta **T70**, 34 (1997).
D. DeMille, *et al.*, Physical Review A **61**, 1 (2000).

Electric Field

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

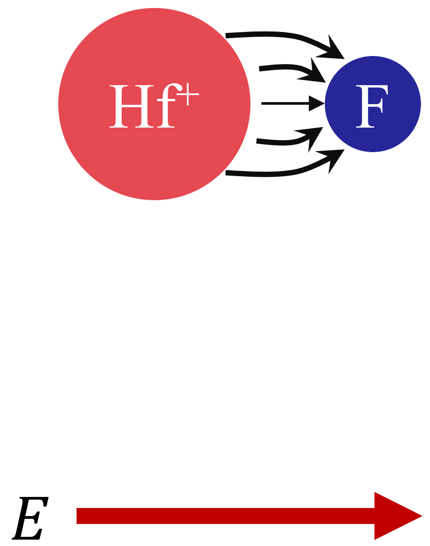


- But because the molecule is also an ion, this won't work



Rotating Electric Field

- Solution! Rotate the electric field

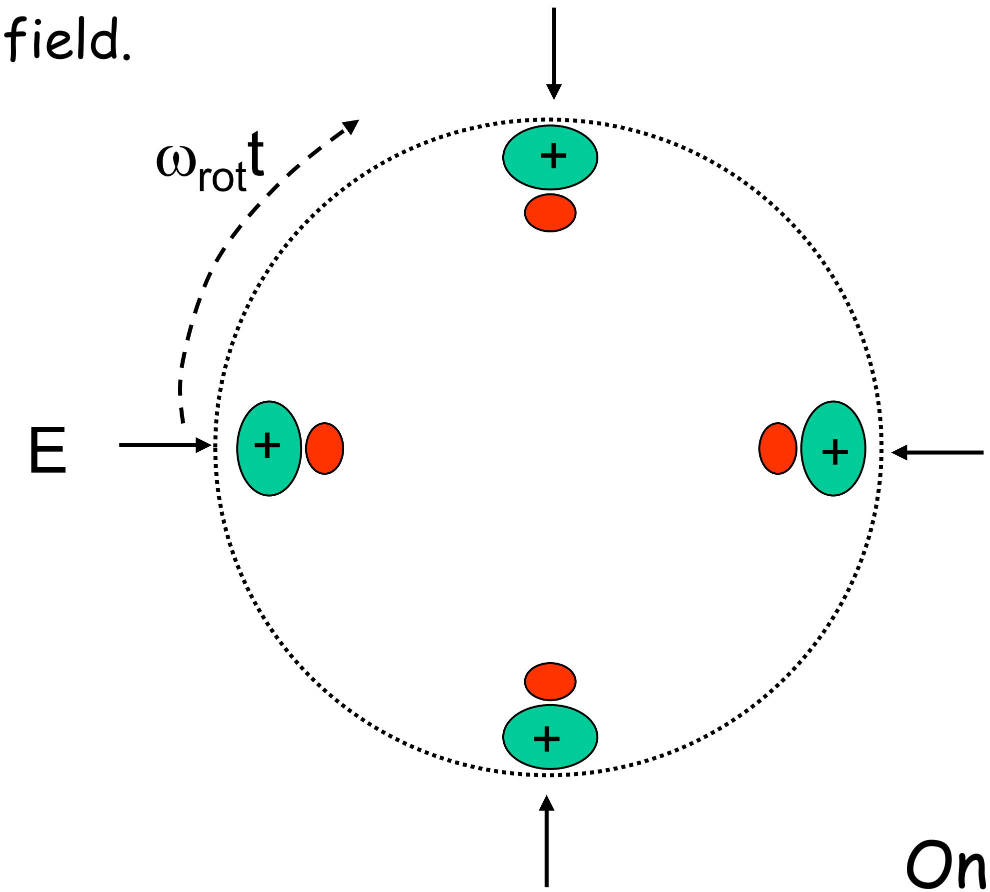


!!!!!Use rotating E-field bias!!!!!

-E-field defines quantization axis

-Excellent rejection of lab-frame residual

B-field.



ω_{rot} is:

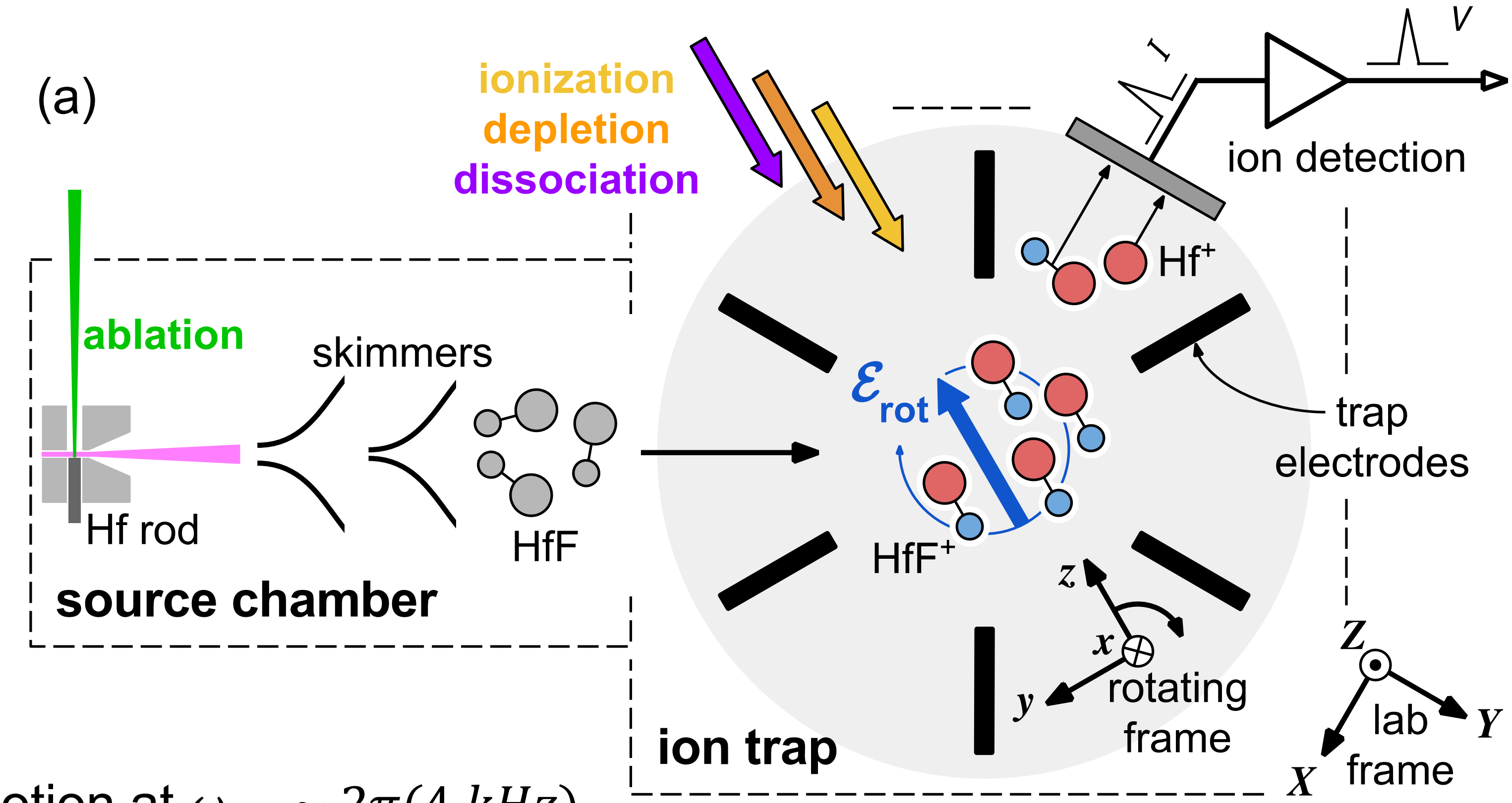
BIG enough that radius of "micromotion" circle is small compared to trap size.

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.

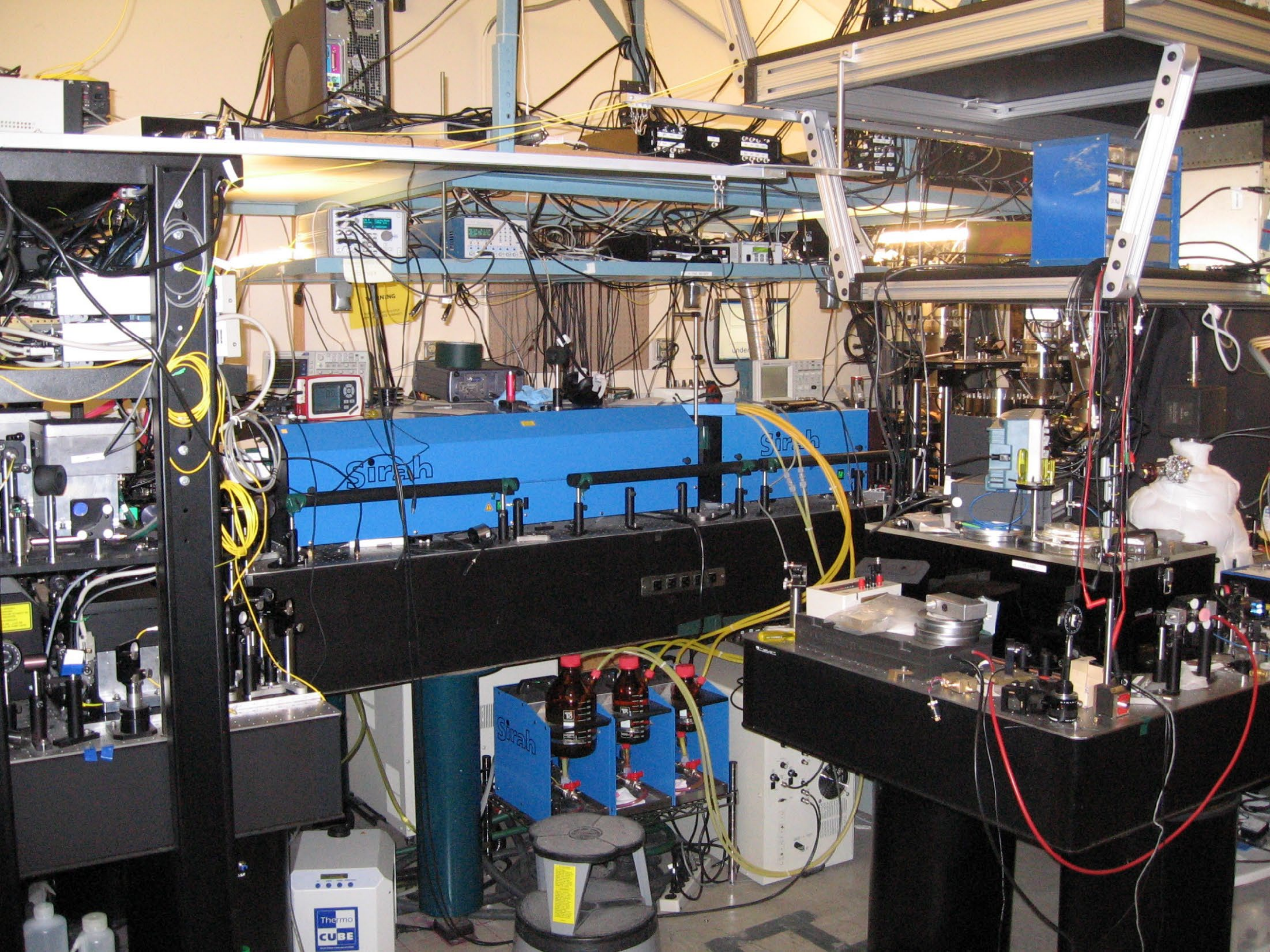
Leanhardt et al, J. Mol. Spec. (2011) [25 typeset pages]

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>

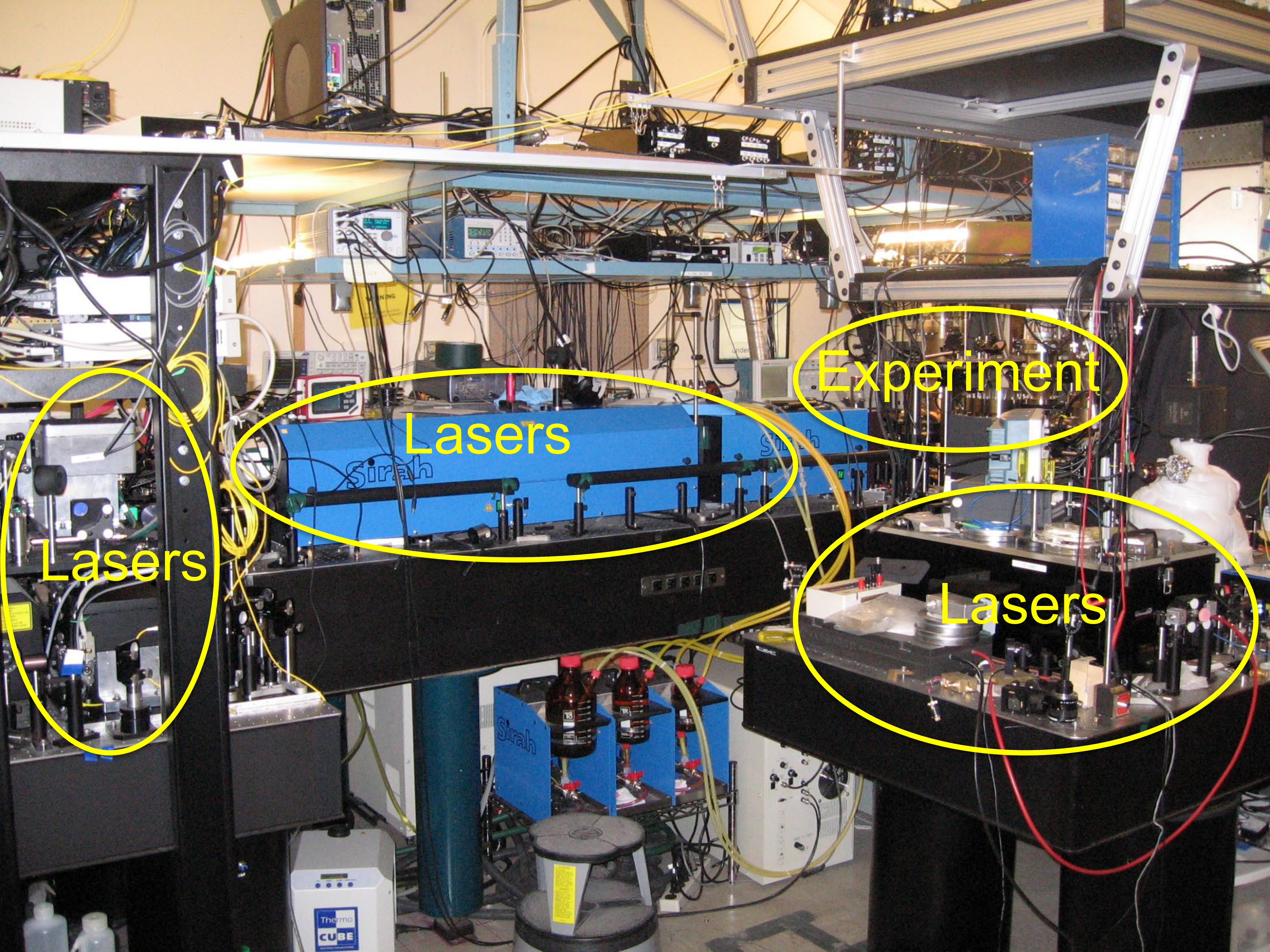

Sirah
Sirah
Sirah
Thermo
CUBE

Initial state preparation:

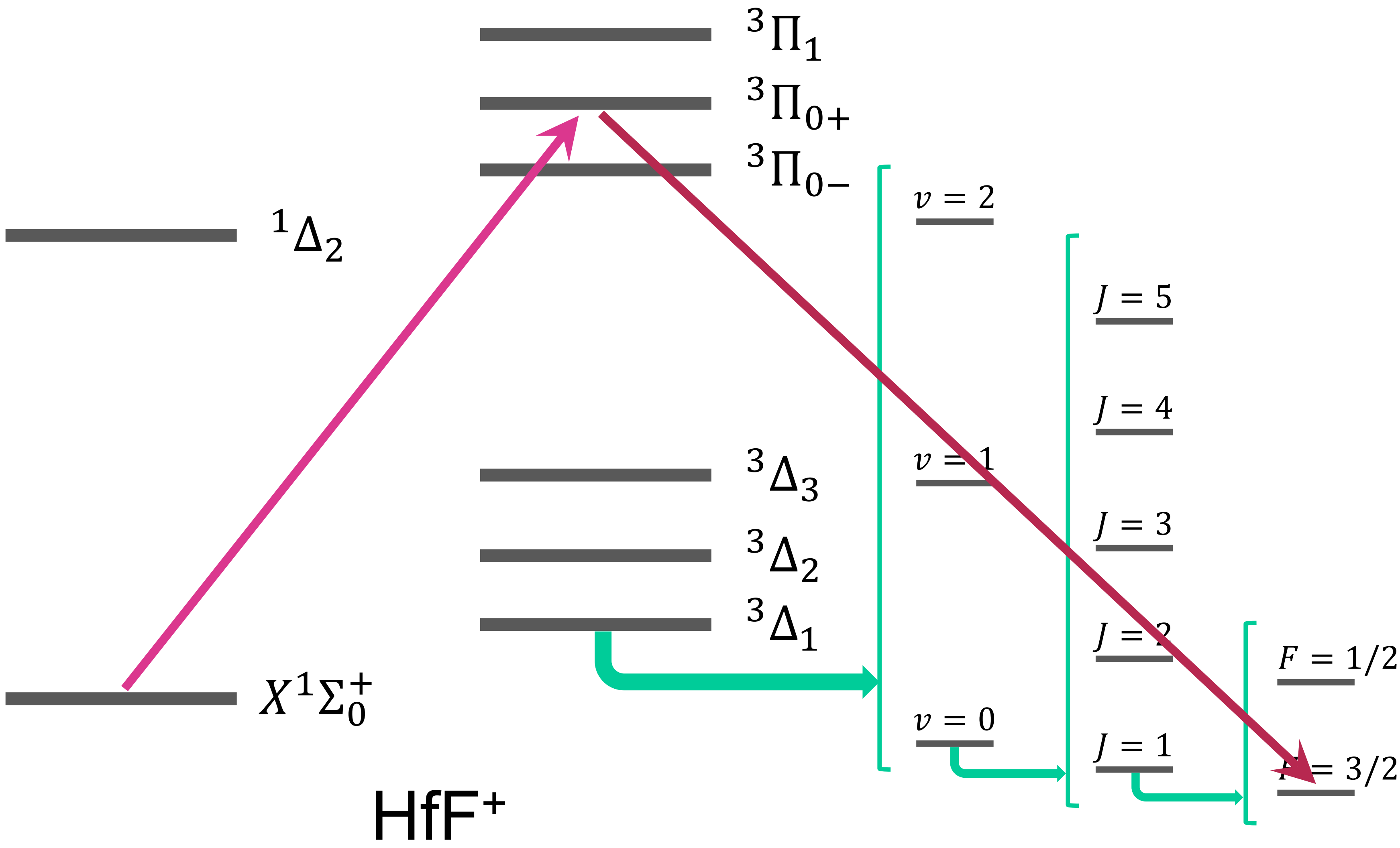
photo-ionization, coherent transfer,
m-level depletion.
(2 tunable UV lasers, 2 tunable IR)

Final spin state read-out:

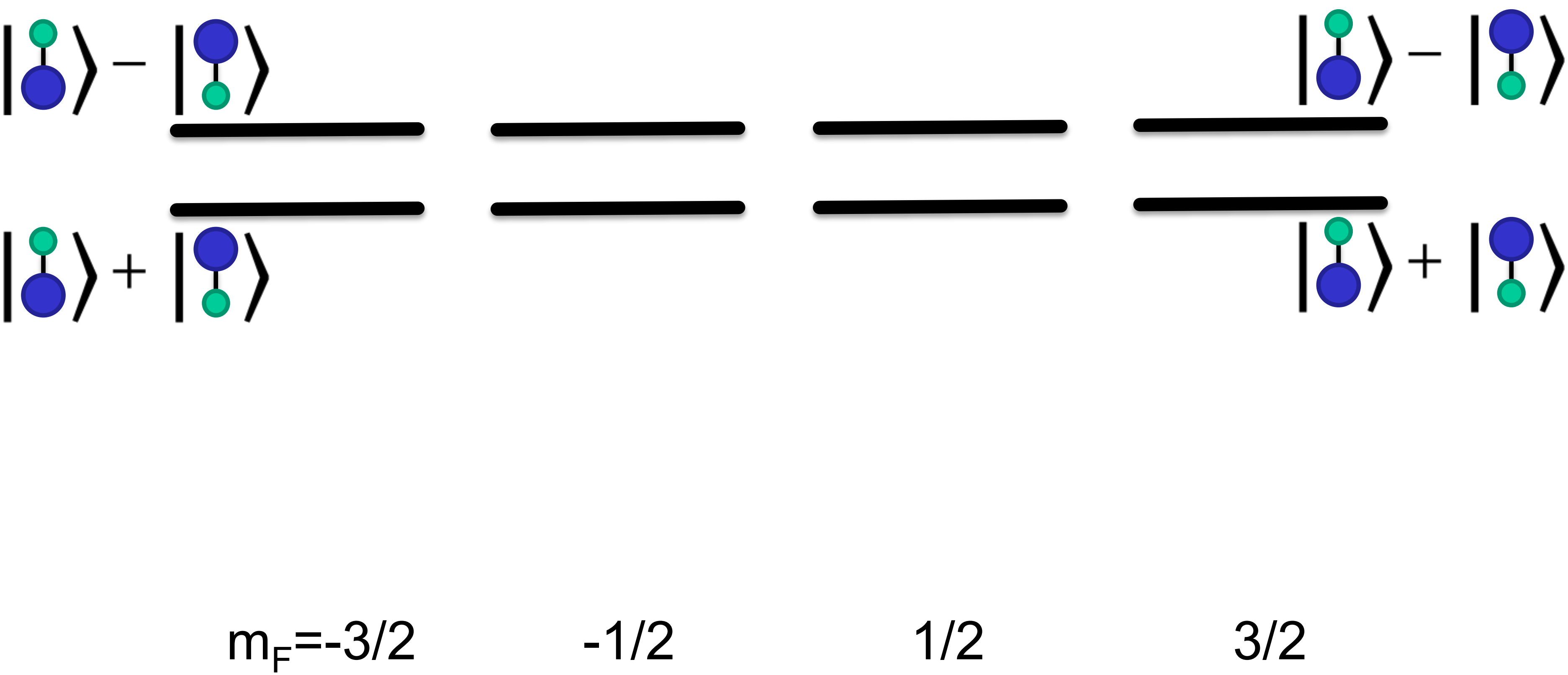
(another tunable UV laser and a fixed-freq UV laser

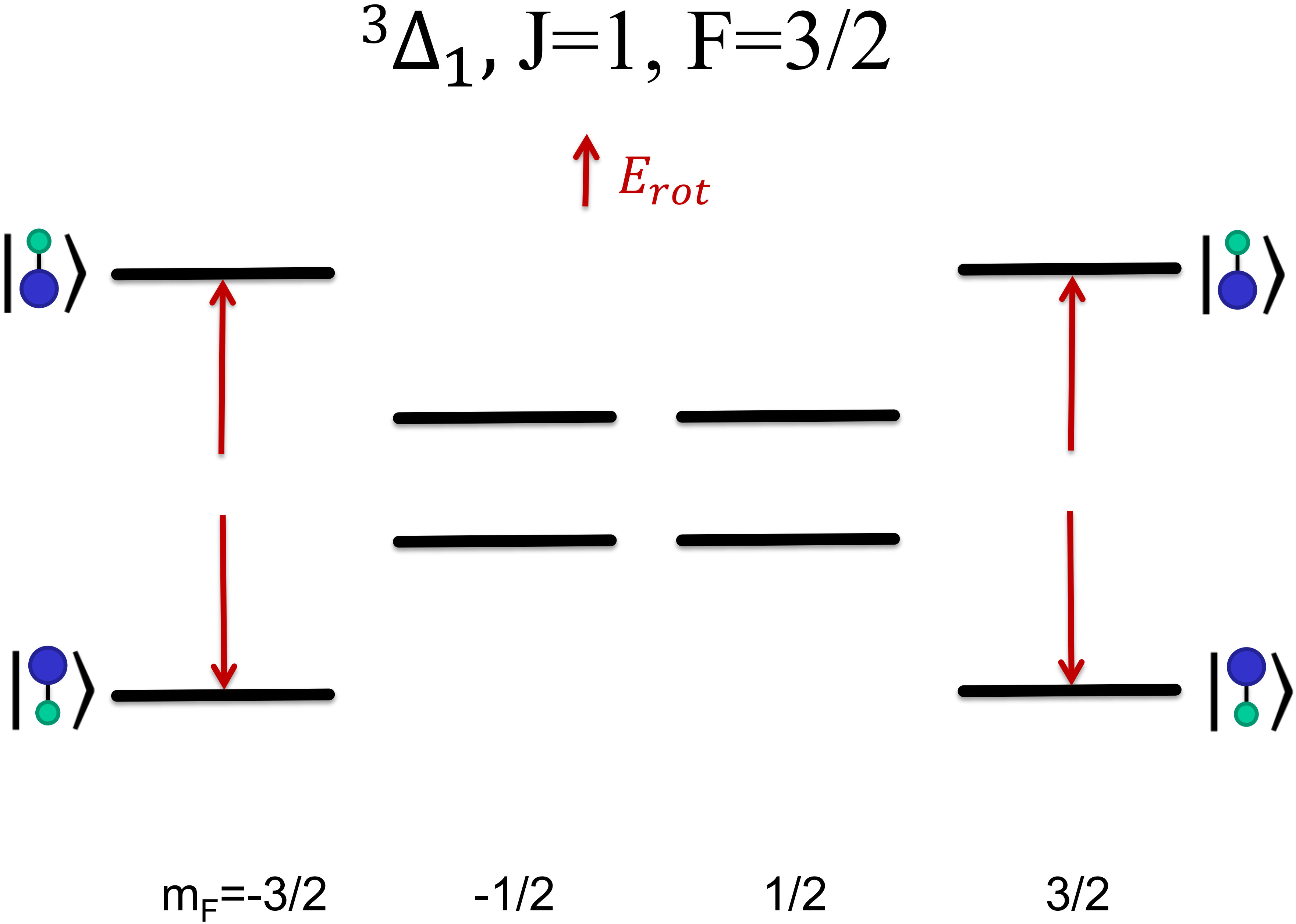

Experiment
Lasers
Lasers
Lasers

State Transfer



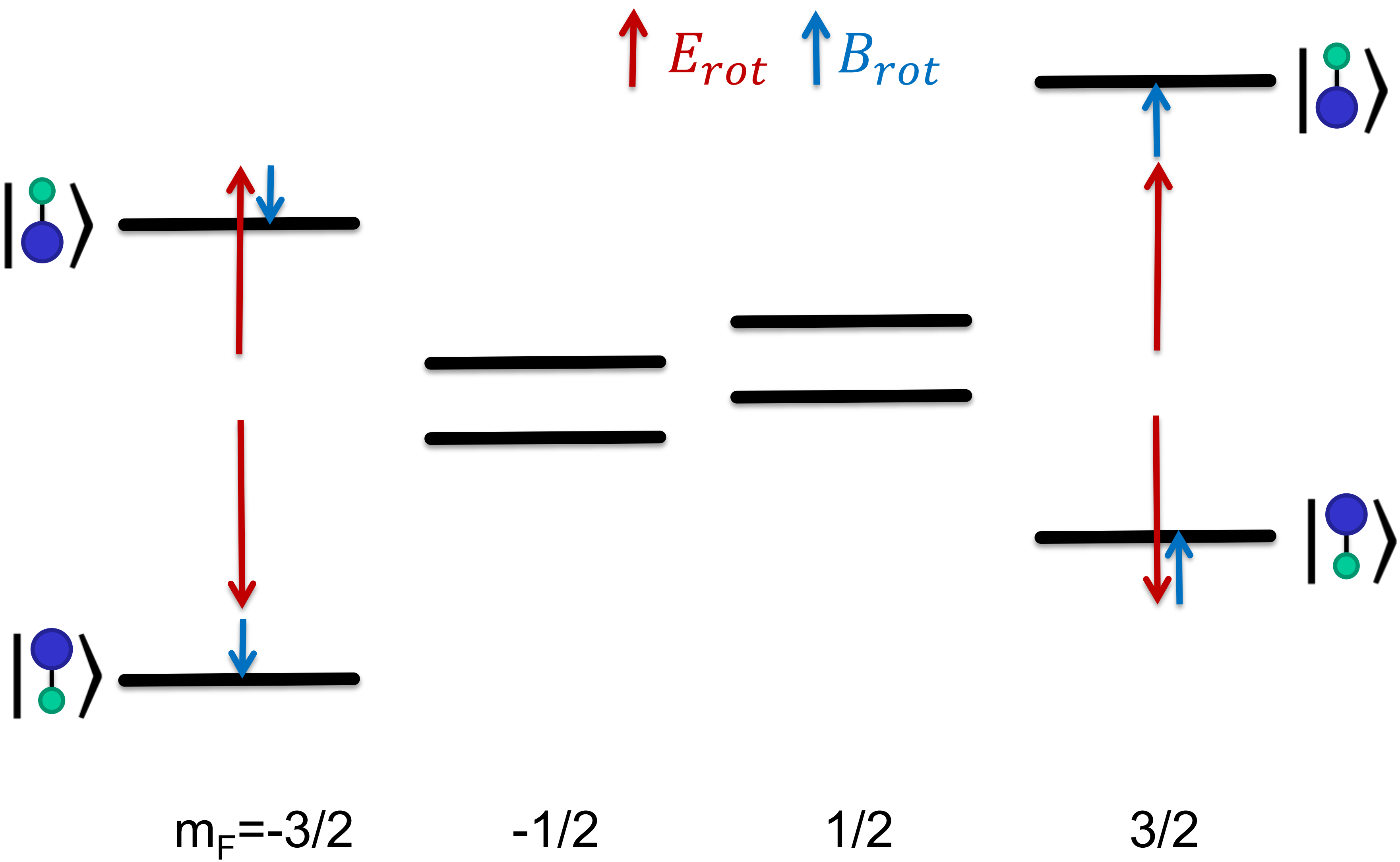
$^3\Delta_1$, J=1, F=3/2





$^3\Delta_1$, J=1, F=3/2
E_{rot}
m_F=-3/2
-1/2
1/2
3/2

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



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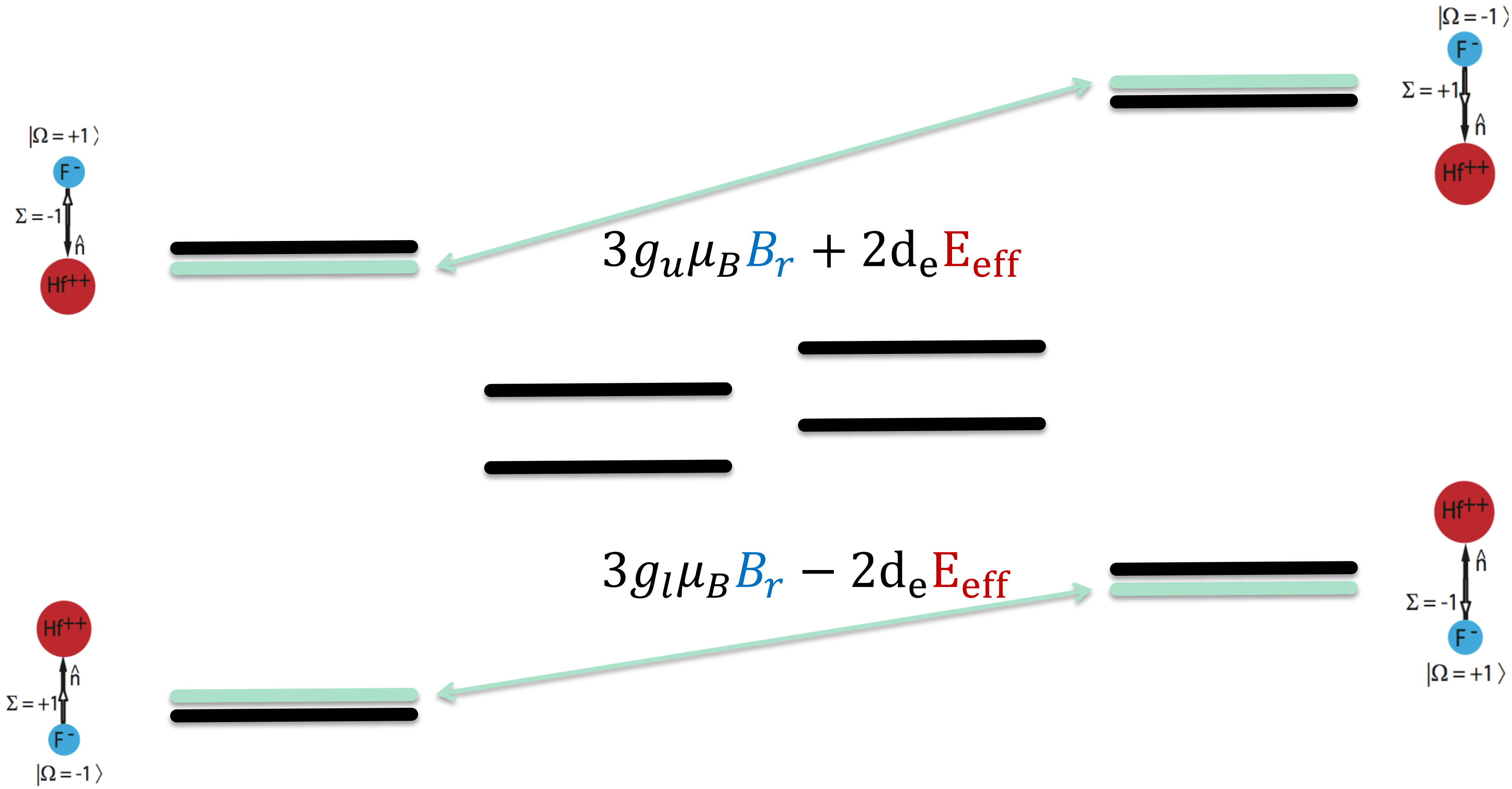
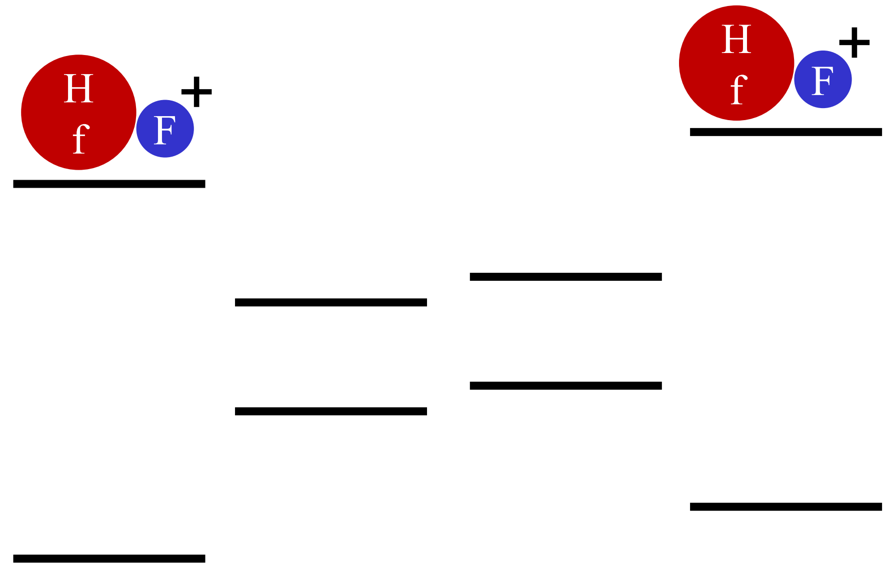


"The Demille Idea"

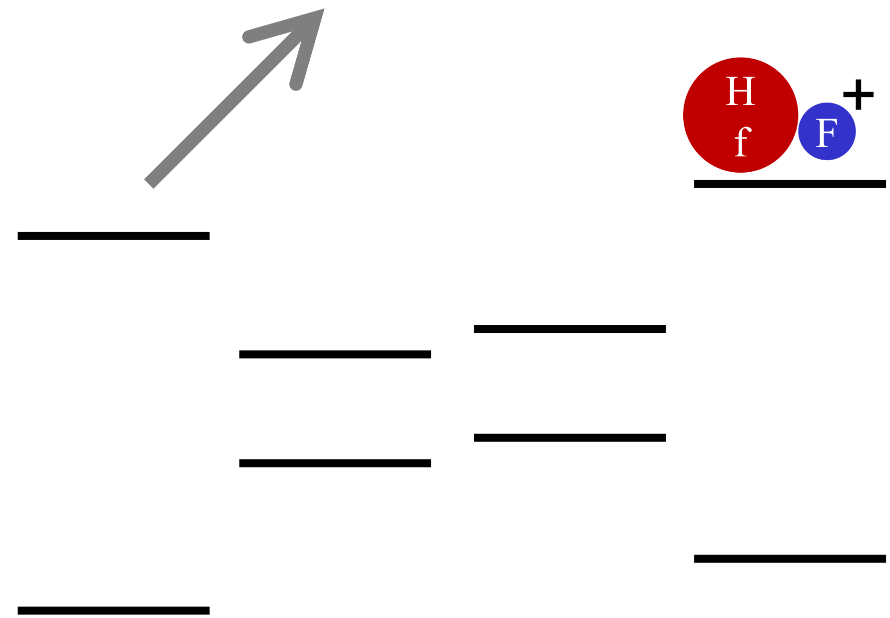
Ramsey Sequence

Transfer lasers prepare population in a single pair of Stark states



Ramsey Sequence

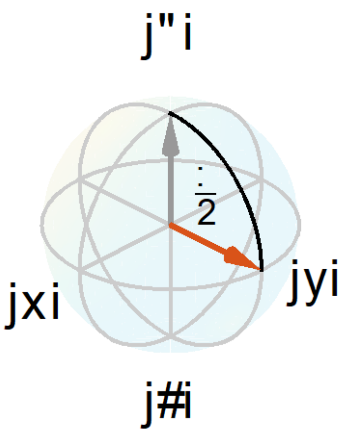
Optically deplete the population of one m_F level using strobed circularly polarized light

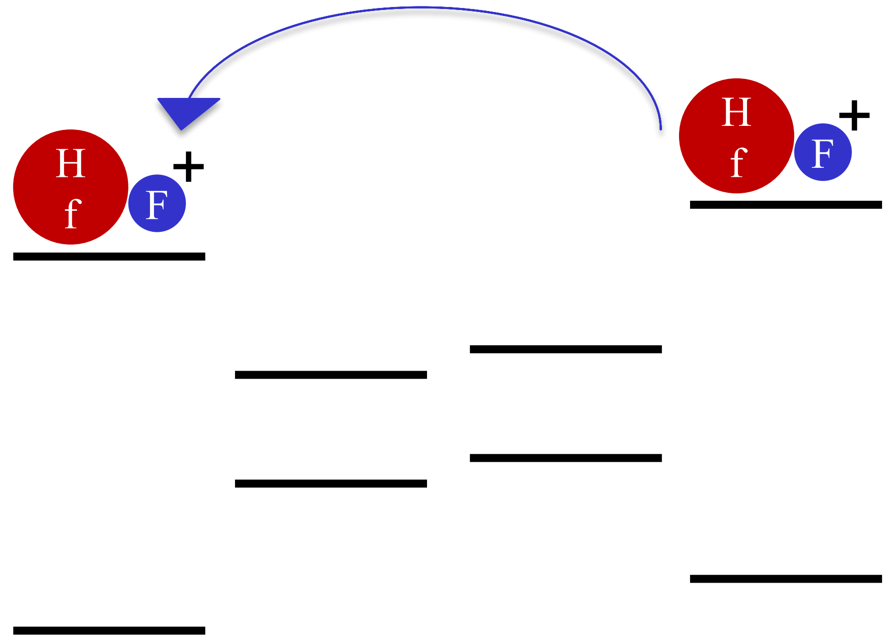


Ramsey Sequence

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

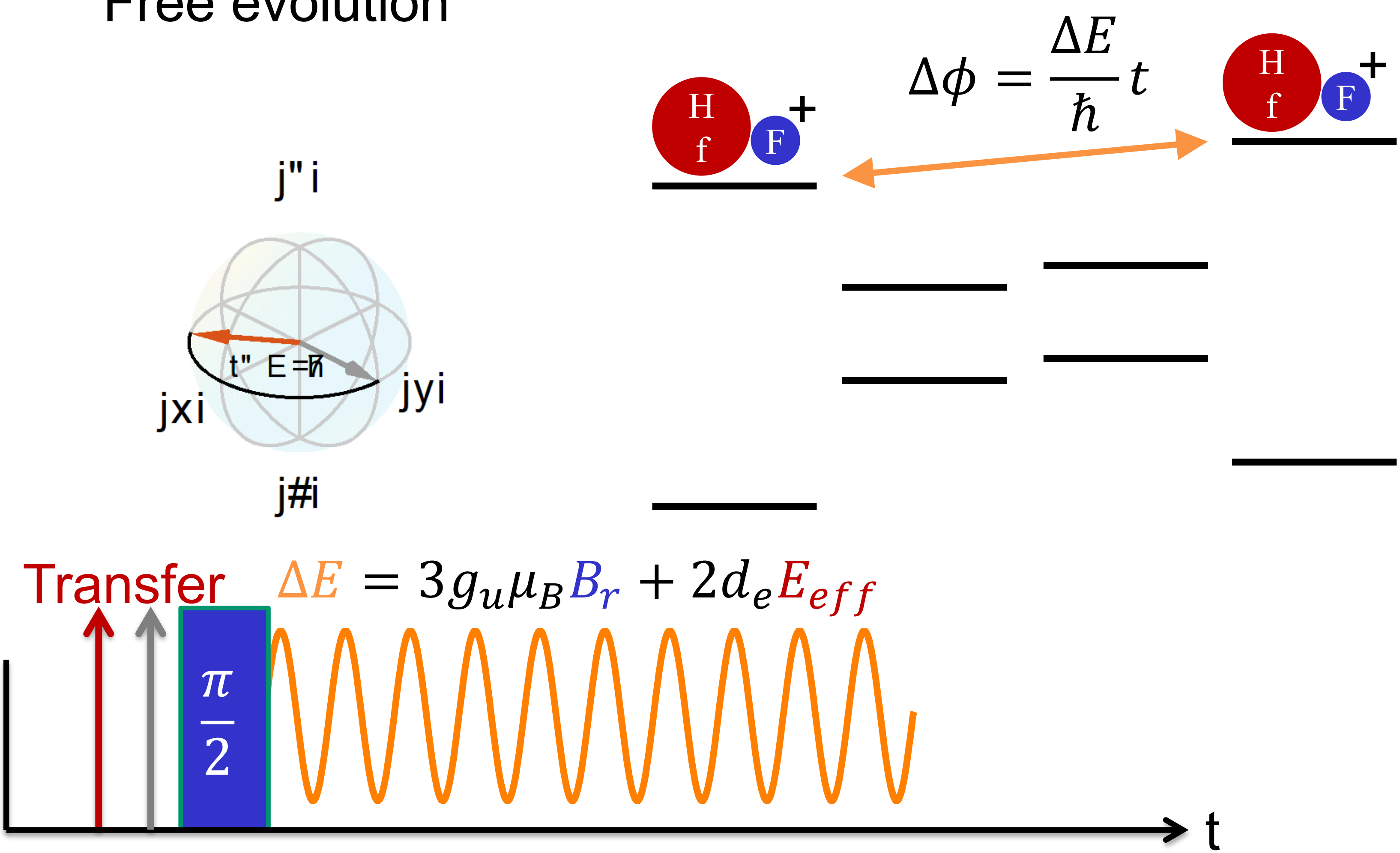
$$\left|m_F = -\frac{3}{2}\right\rangle + \left|m_F = +\frac{3}{2}\right\rangle$$





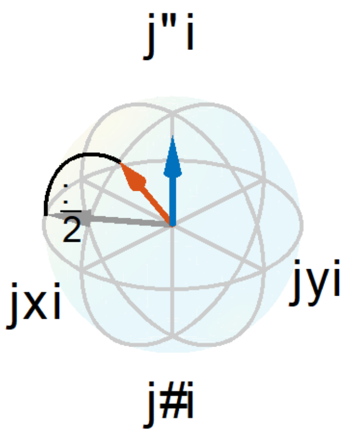
Ramsey Sequence

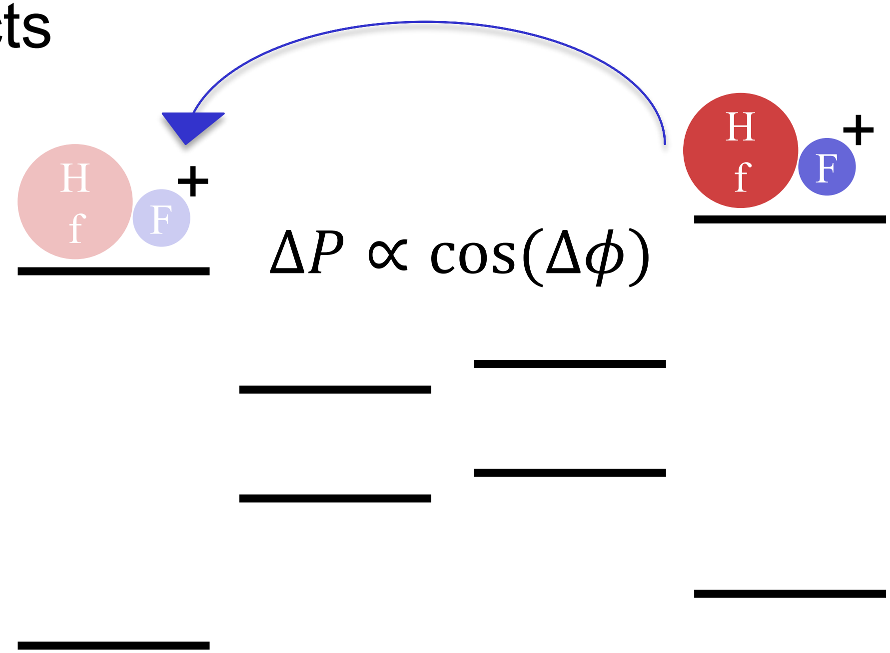
Free evolution

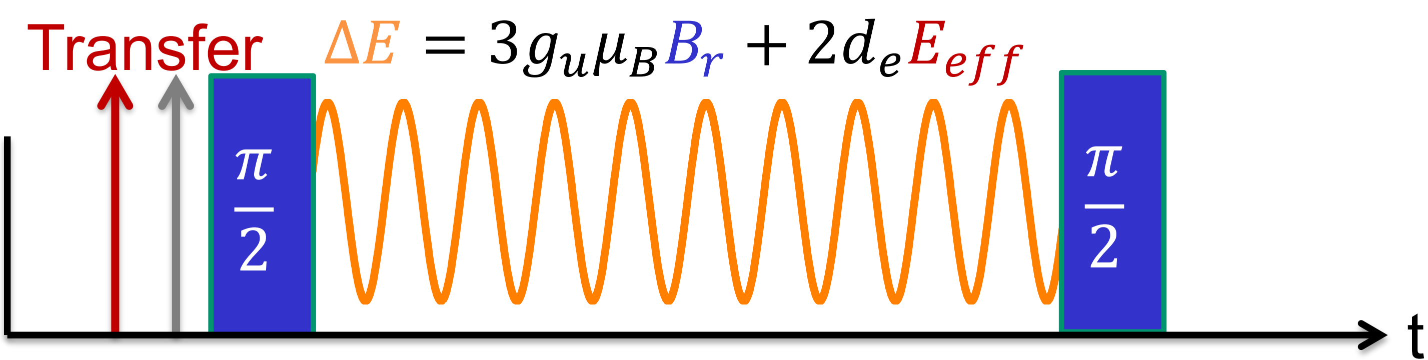


Ramsey Sequence

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

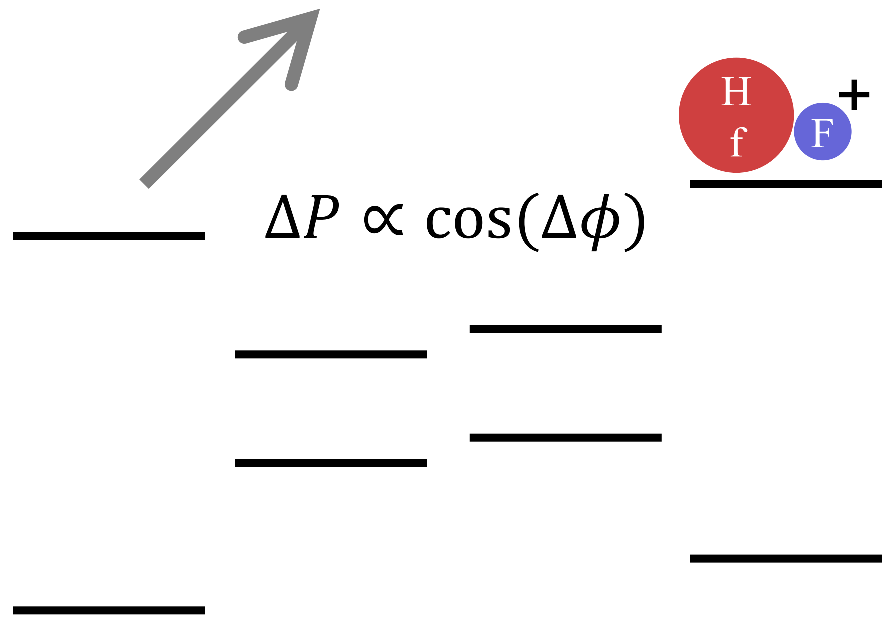


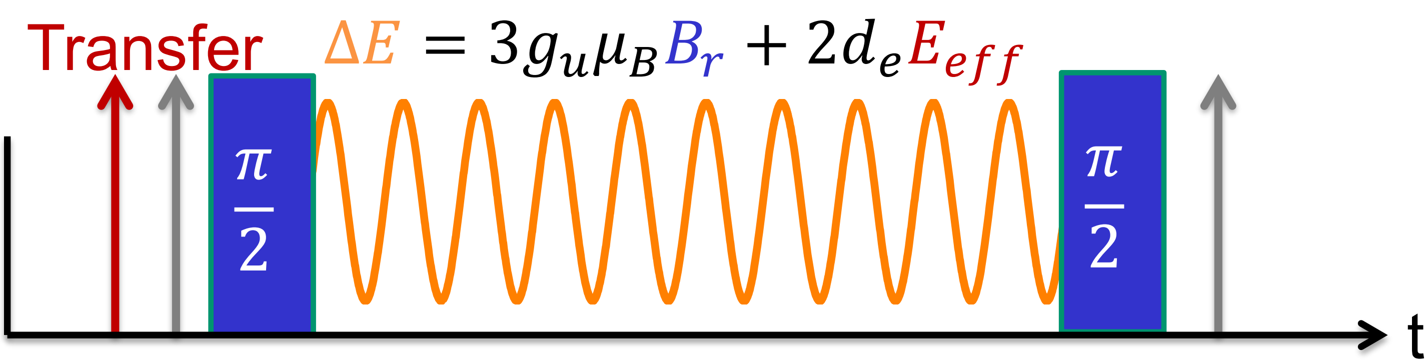




Ramsey Sequence

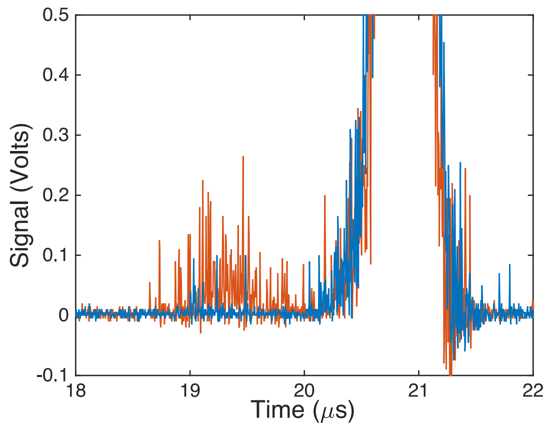
Optically deplete population out of one of the m_F levels

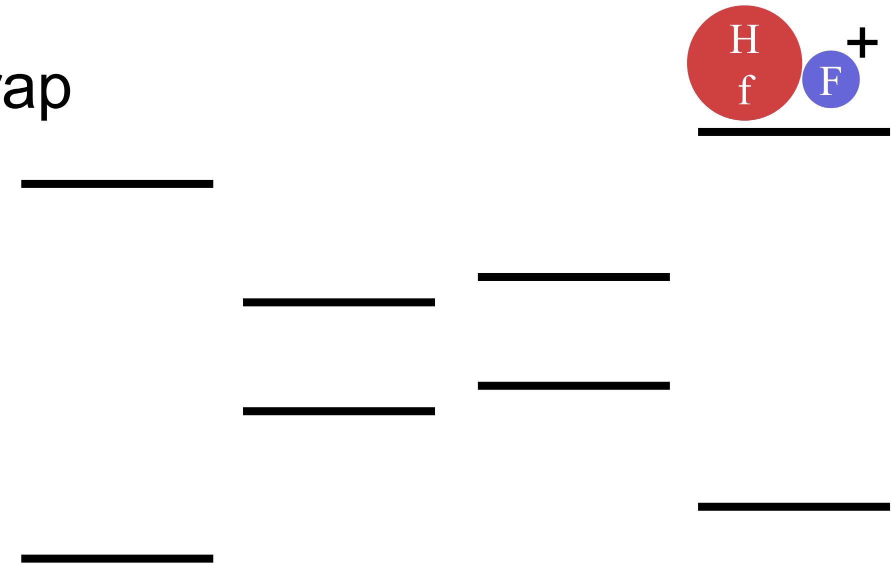




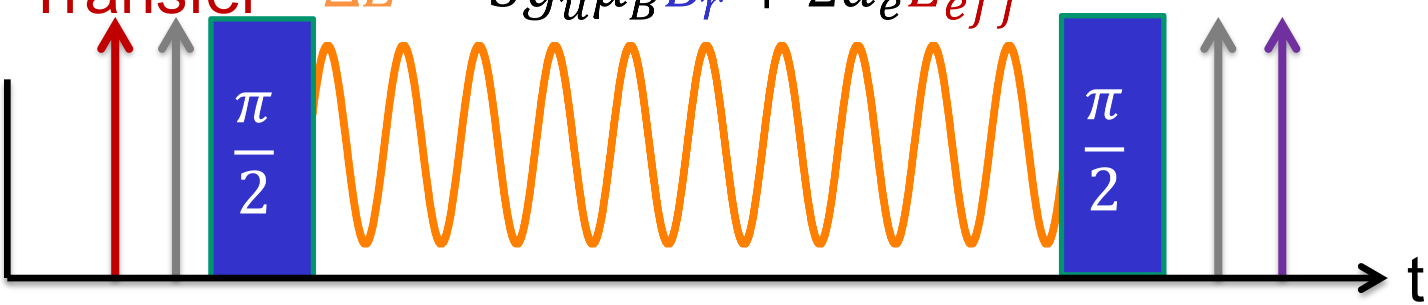
Ramsey Sequence

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

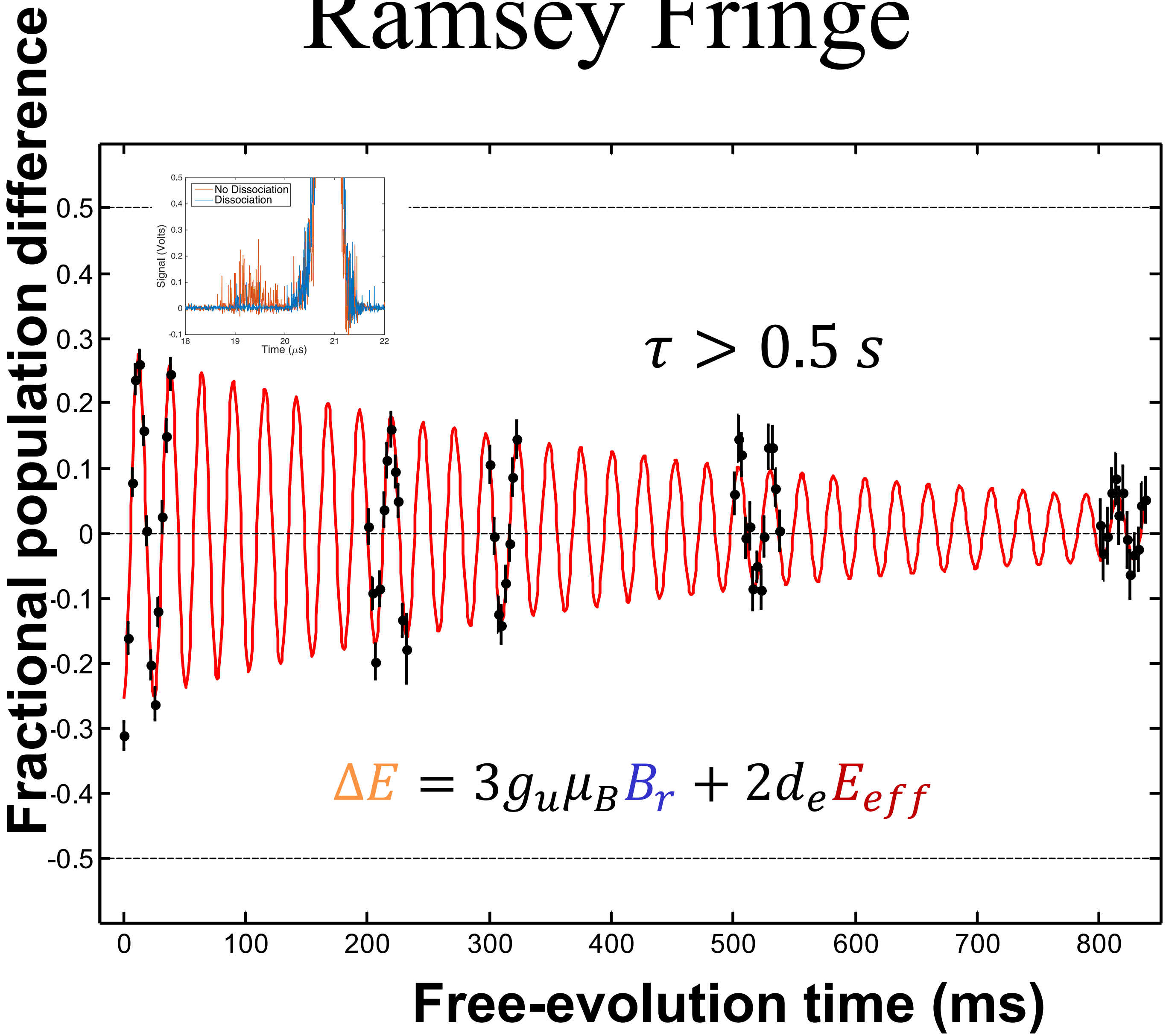




Transfer $\Delta E = 3 g_u \mu_B B_r + 2 d_e E_{eff}$

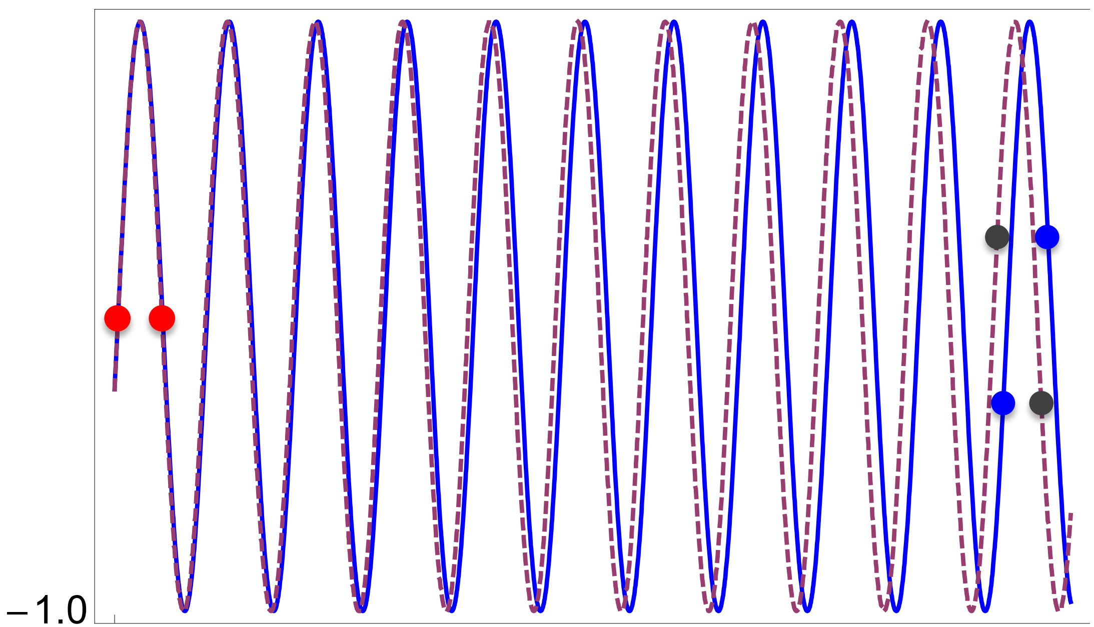


Ramsey Fringe

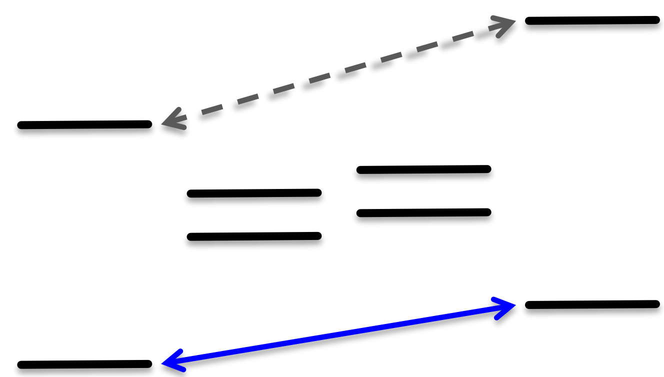


eEDM measurement

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



$$3 g_u \mu_B B_r + 2 \mathrm{d_e} \mathrm{E_{eff}}$$



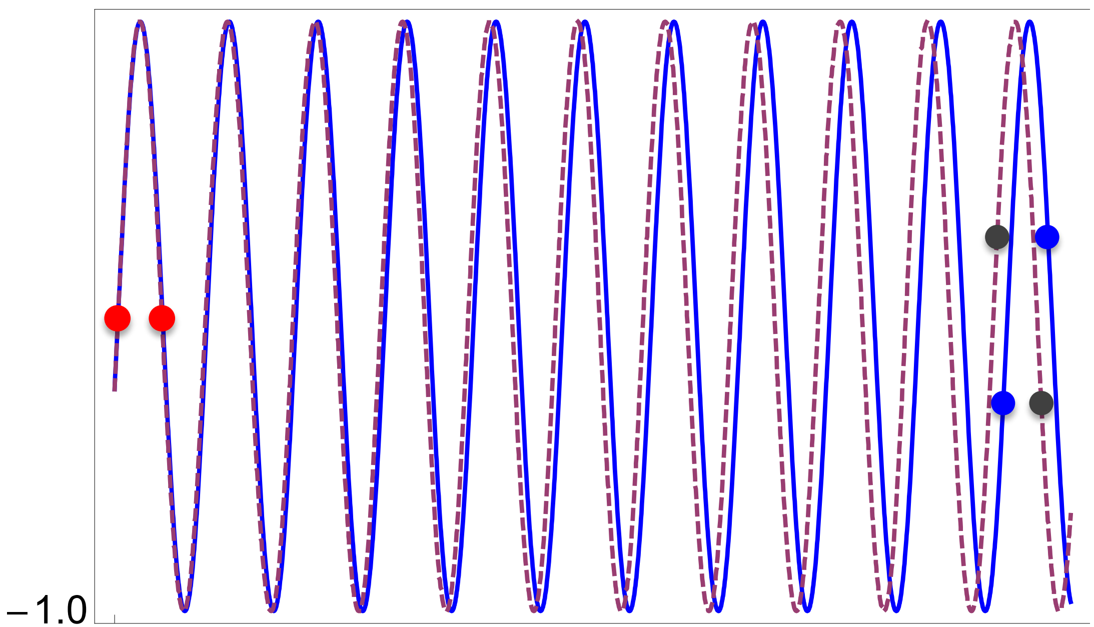
$$3 g_l \mu_B B_r - 2 \mathrm{d_e} \mathrm{E_{eff}}$$

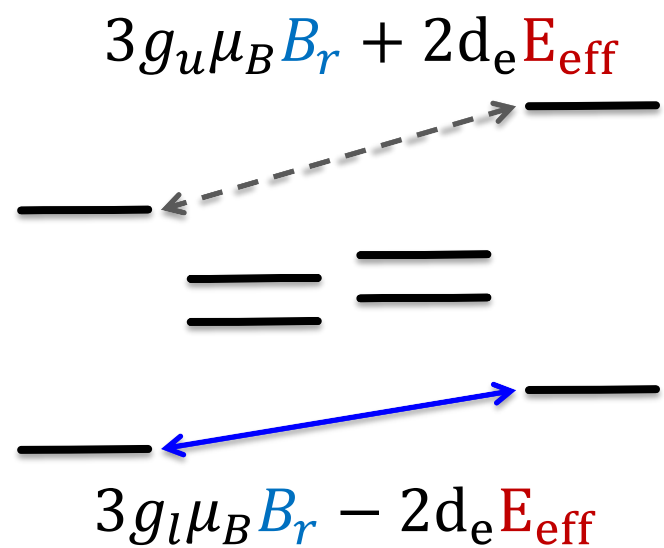
Systematics

How to make sure you're actually measuring something

eEDM measurement

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





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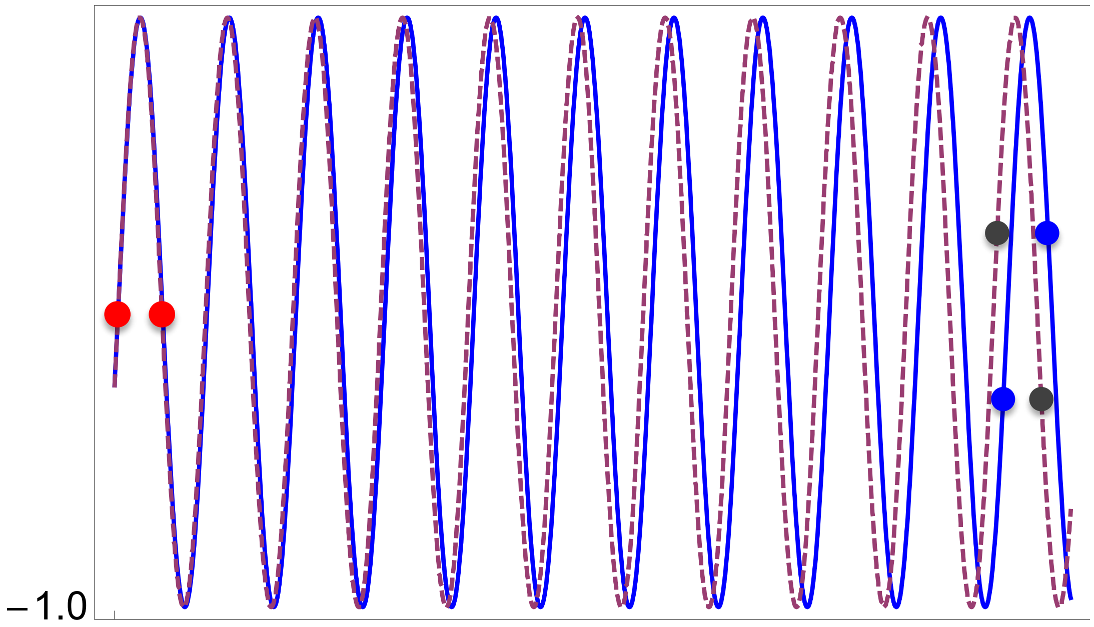

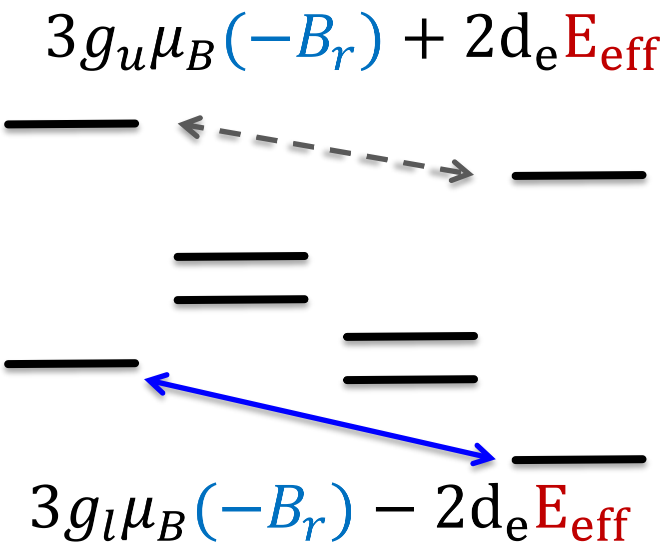

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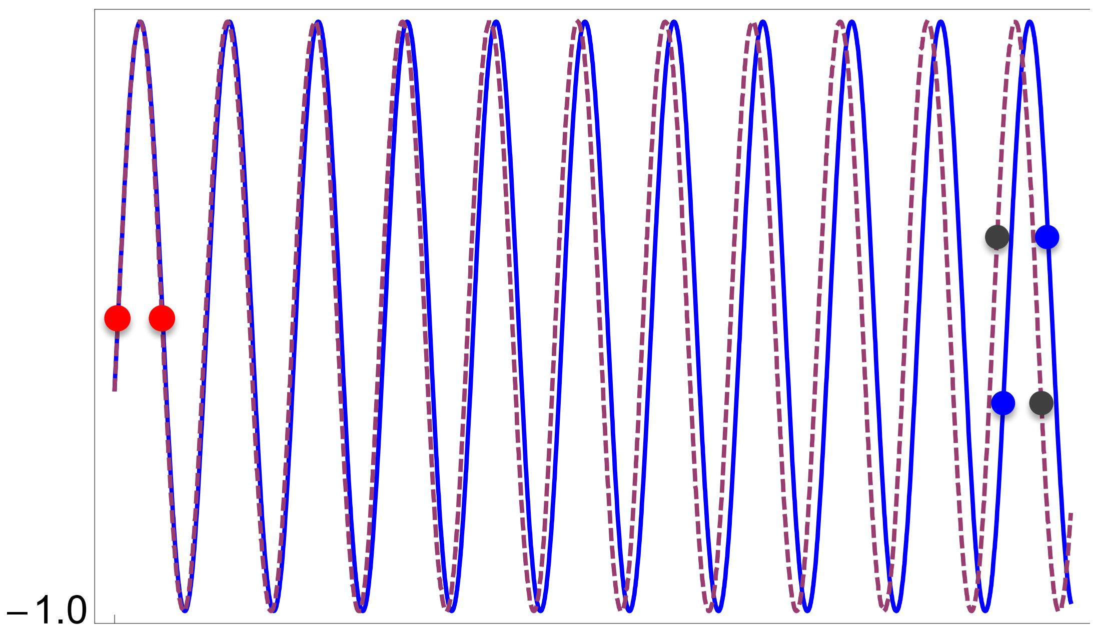

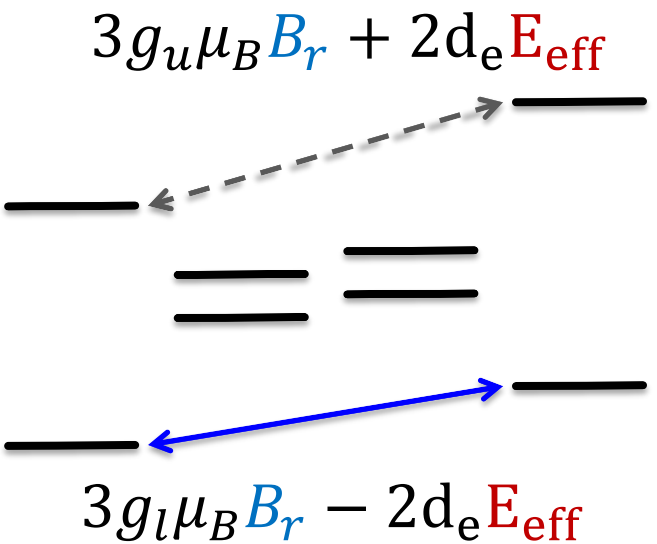

eEDM measurement

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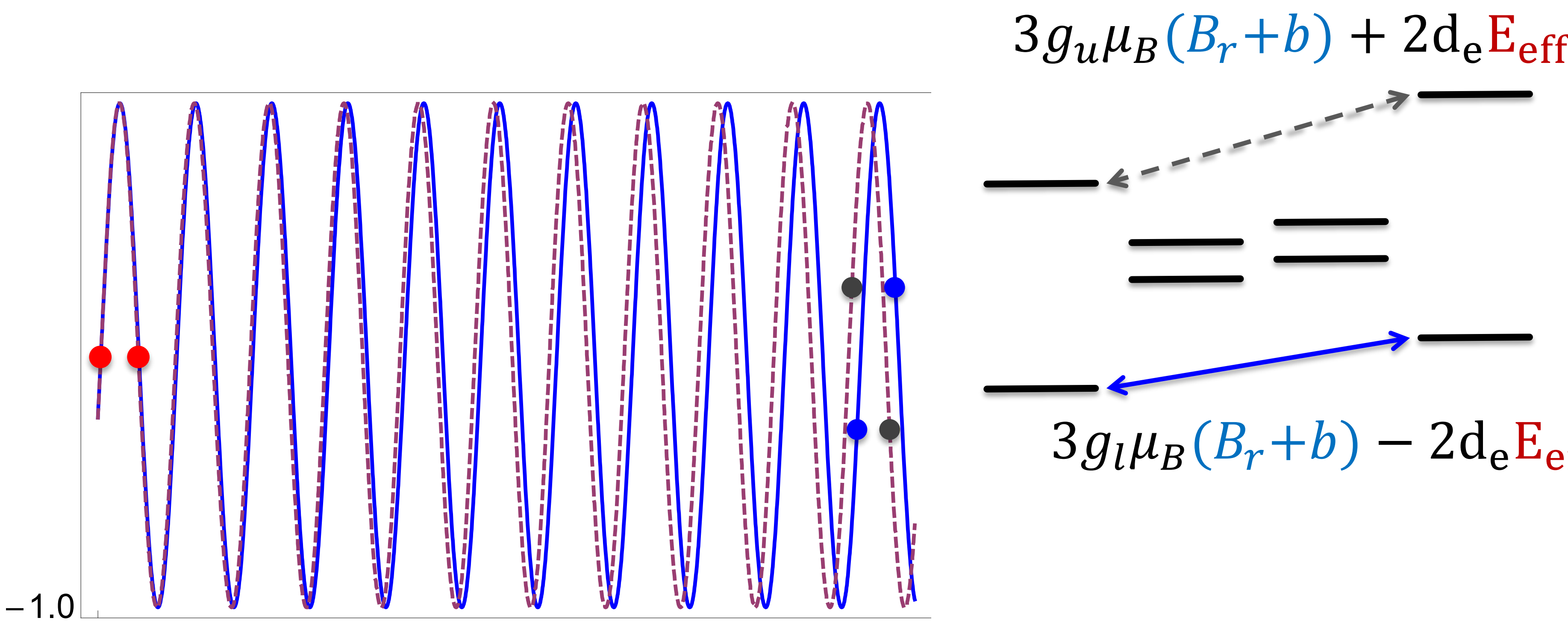
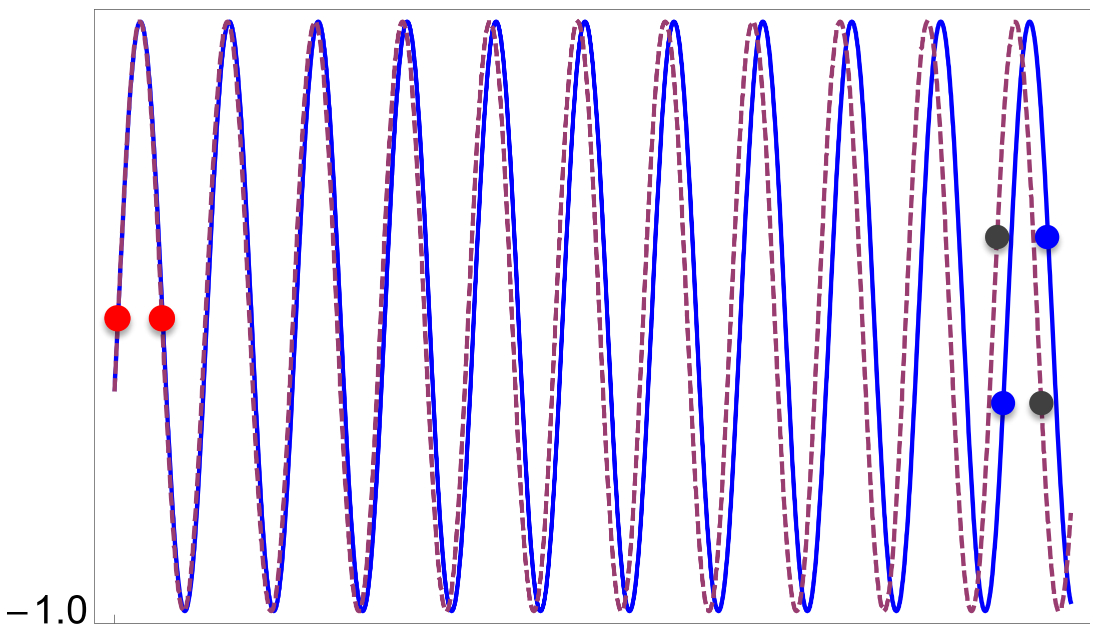
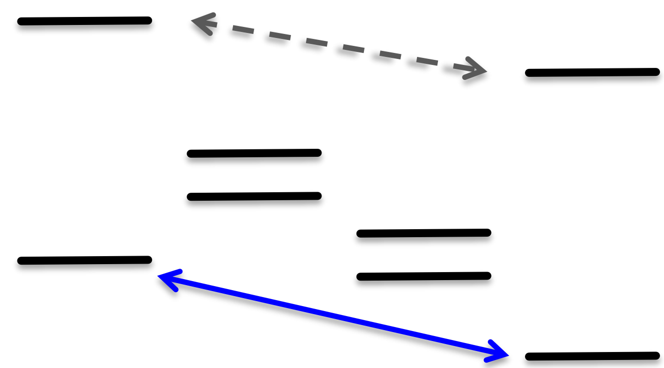


eEDM measurement

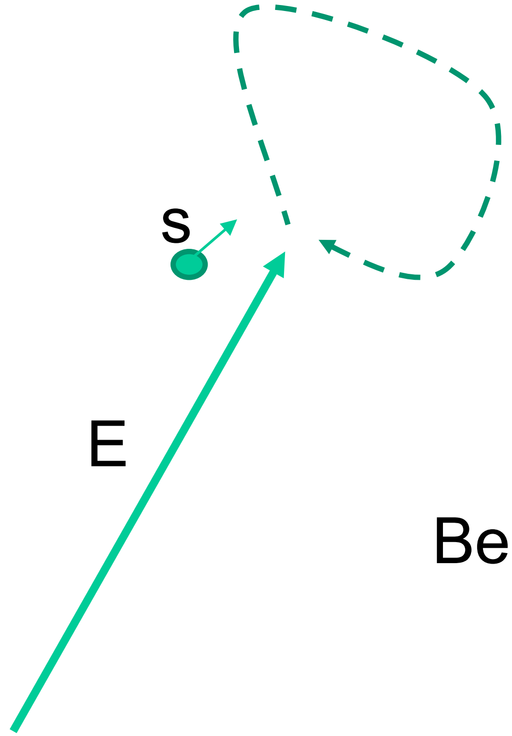
1. Measure initial phase and phase at long time
2. Compare upper and lower transitions
3. Switch B field sign

$3g_u\mu_B(-B_r+b) + 2\mathrm{d_e}\mathrm{E}$





$3g_l\mu_B(-B_r+b) - 2\mathrm{d_e}\mathrm{E_{ef}}$



$\mathcal{A}$ = solid angle swept out by changing bias field.

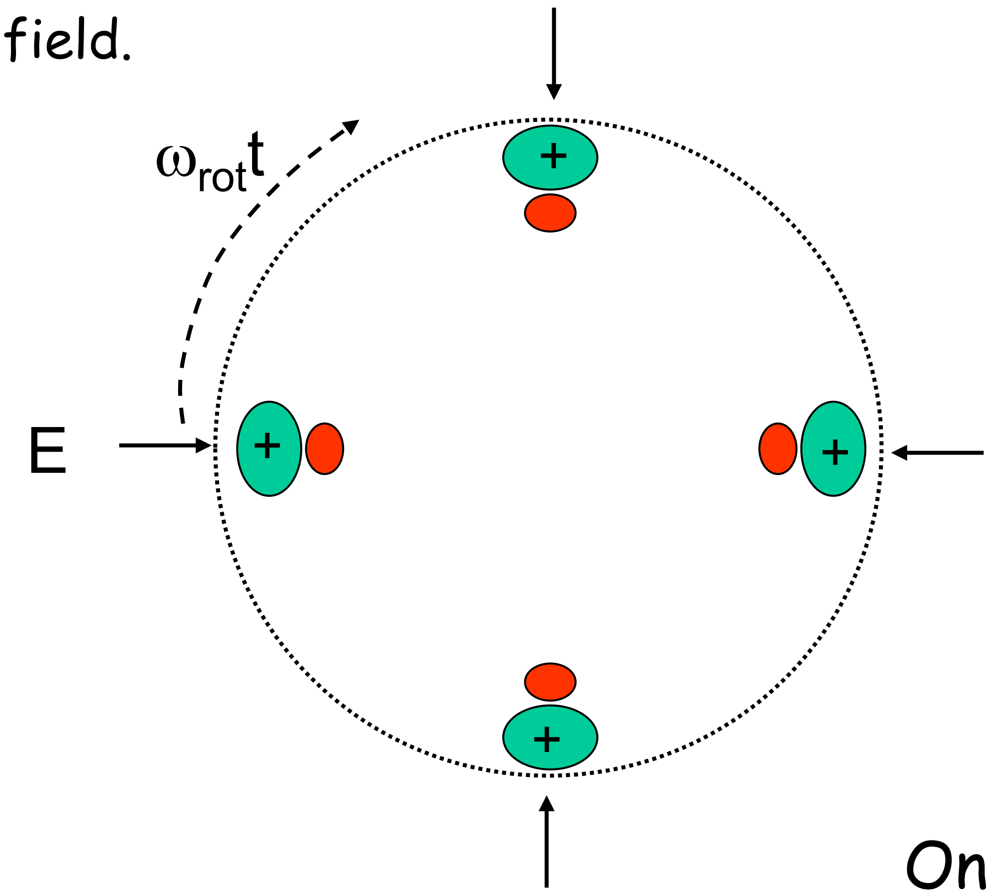
Berry's phase after one cycle:

$$\delta\phi = m\,\mathcal{A}$$

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

-E-field defines quantization axis

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



Leanhardt et al, J. Mol. Spec. (2011) [25 typeset pages]

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

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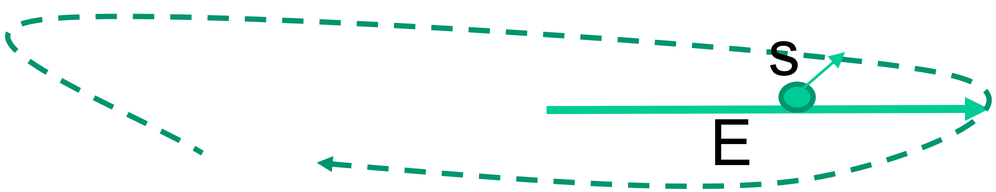
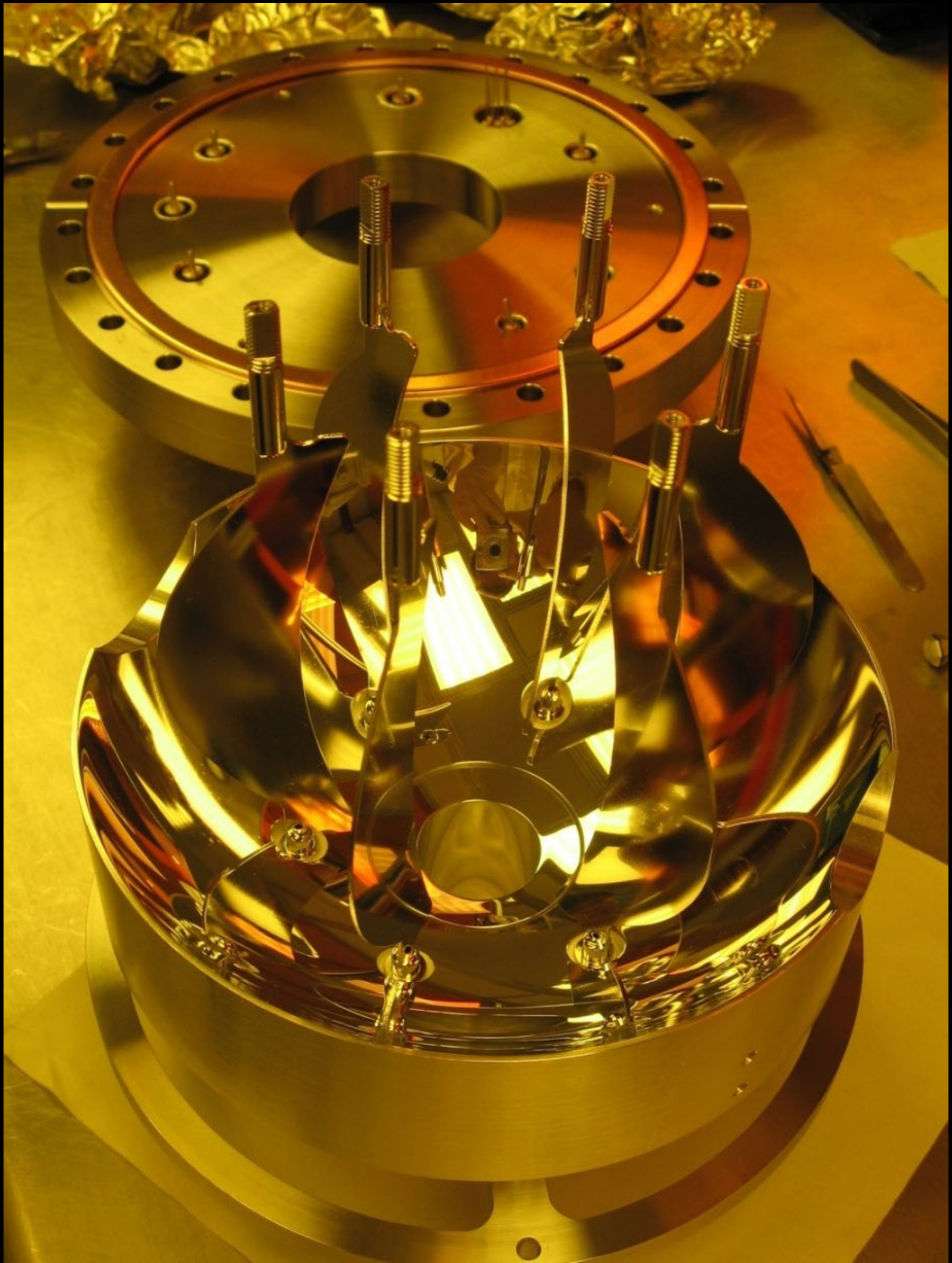
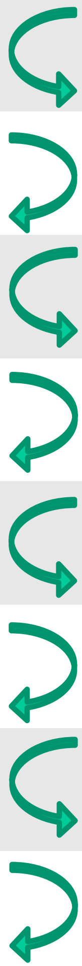
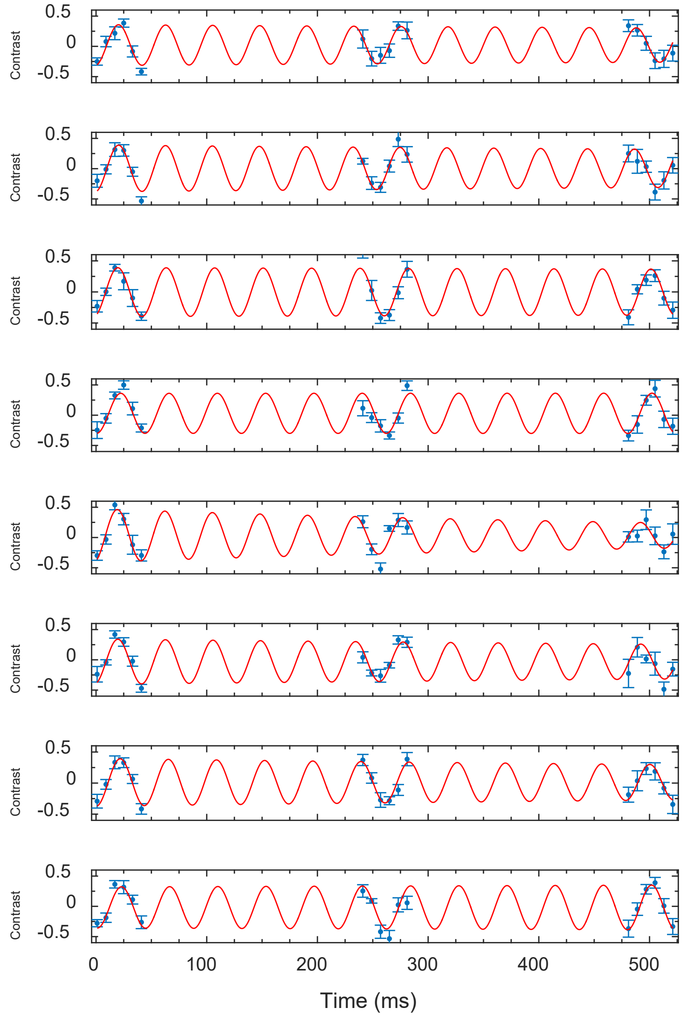


Basic scale of Berry's phase related freq shift in our experient: 750 kHz. Rough place to do 1 mHz spectroscopy?



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





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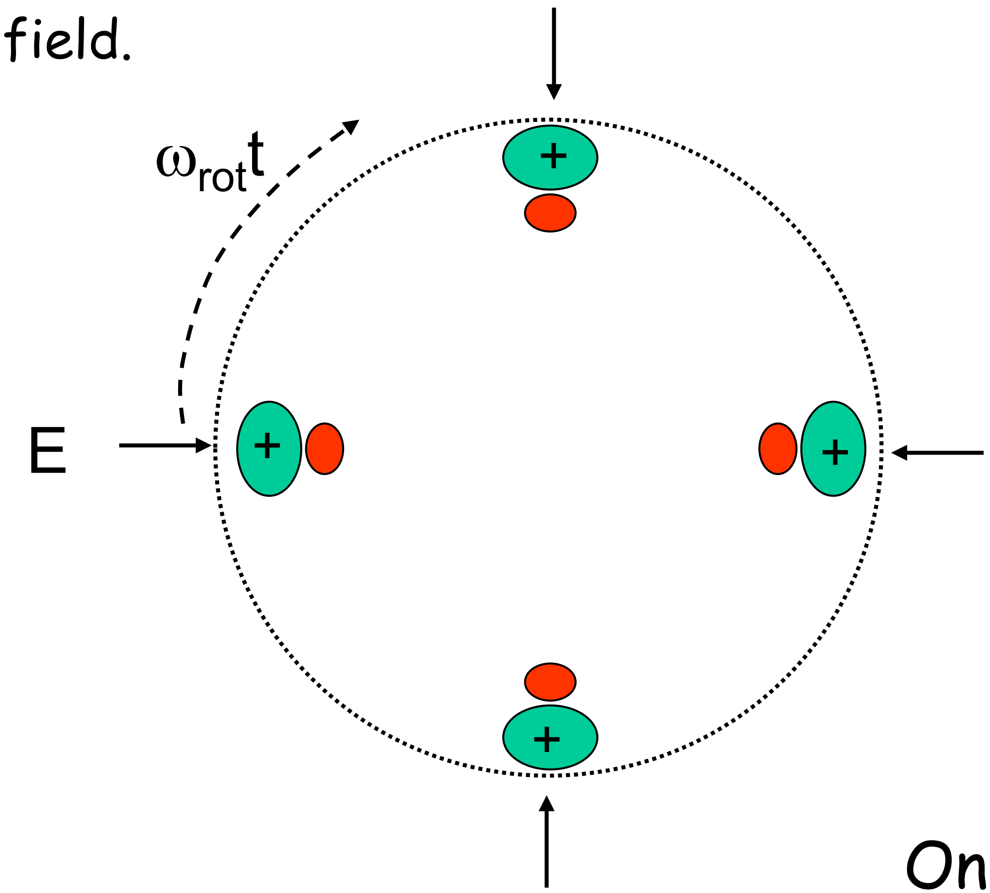

Leanhardt et al, J. Mol. Spec. (2011) [25 typeset pages]

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

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

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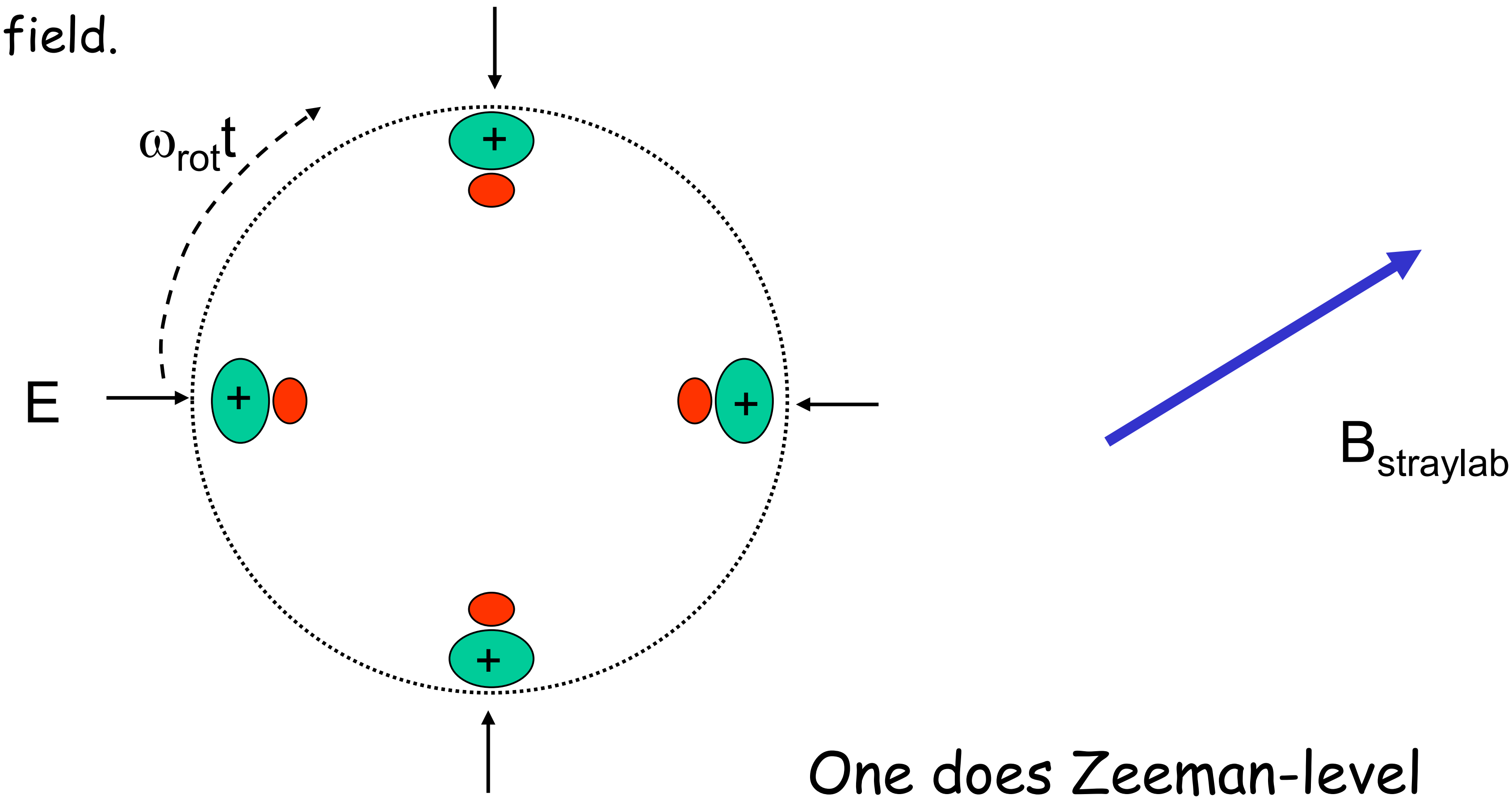
B-field.



Leanhardt et al, J. Mol. Spec. (2011) [25 typeset pages]

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

Two boasts from the early days of the experiment:

1. We won’t even need magnetic shielding!

2. Changing the direction of rotation will be superfluous!

Two boasts from the early days of the experiment:

1. We won’t even need magnetic shielding!

True!

2. Changing the direction of rotation will be superfluous!

Two boasts from the early days of the experiment:

1. We won’t even need magnetic shielding!

True! (or, mostly true)

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Two boasts from the early days of the experiment:

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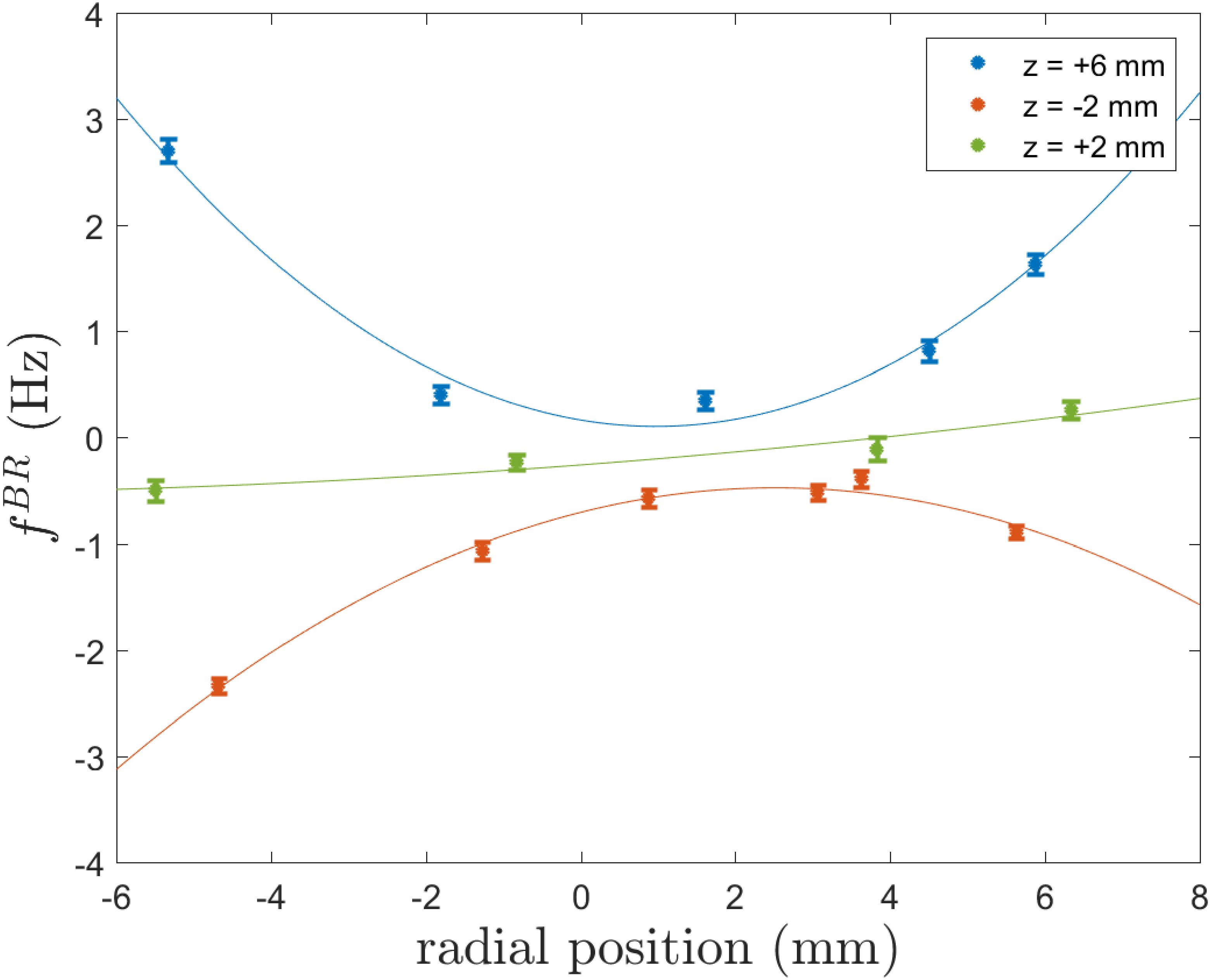
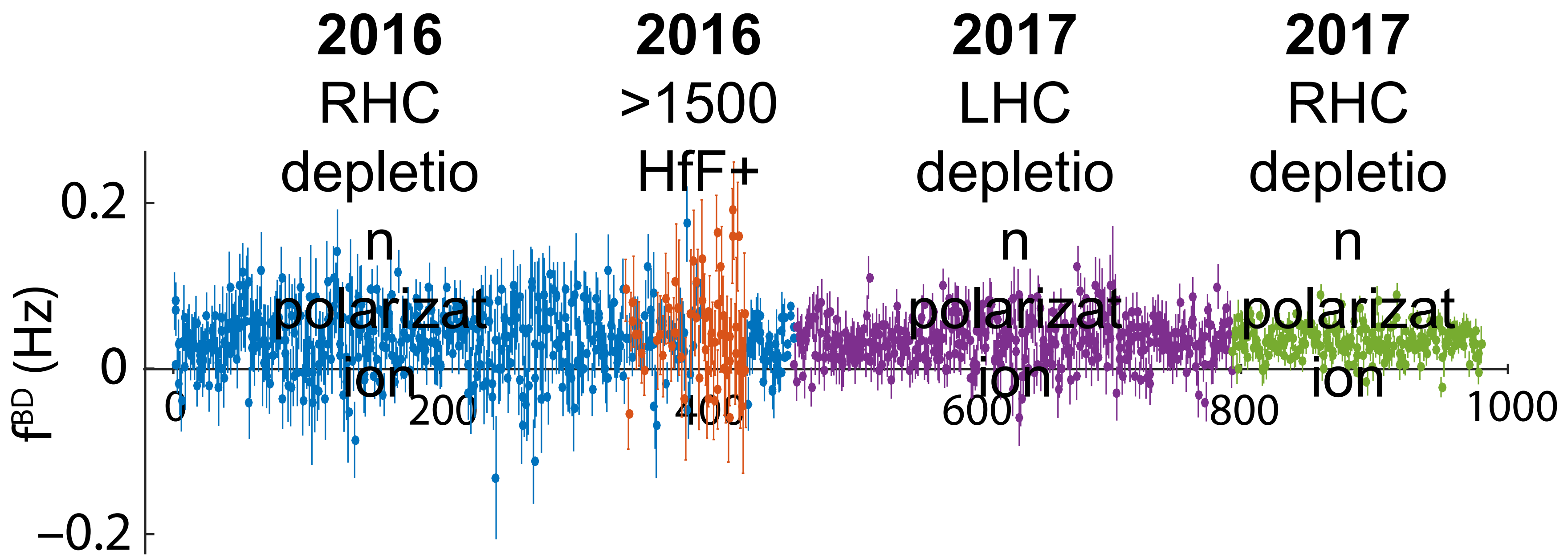
True! (or, mostly true)

2. Changing the direction of rotation will be superfluous!

True! (or, true, except…)



z = +6 mm
z = -2 mm
z = +2 mm
f^{BR} (Hz)
radial position (mm)
4
3
2
1
0
-1
-2
-3
-4
-6
-4
-2
0
2
4
6
8



Frequency channel	All data	2017 only
f^{R}	2.6(9) mHz	3(1) mHz
f^{DR}	–0.6(8) mHz	–1(1) mHz
f^{BD}	34.5(8) mHz	34.4(1.0) mHz
f^{BDR}	0.4(9) mHz	–0.3(1.0) mHz

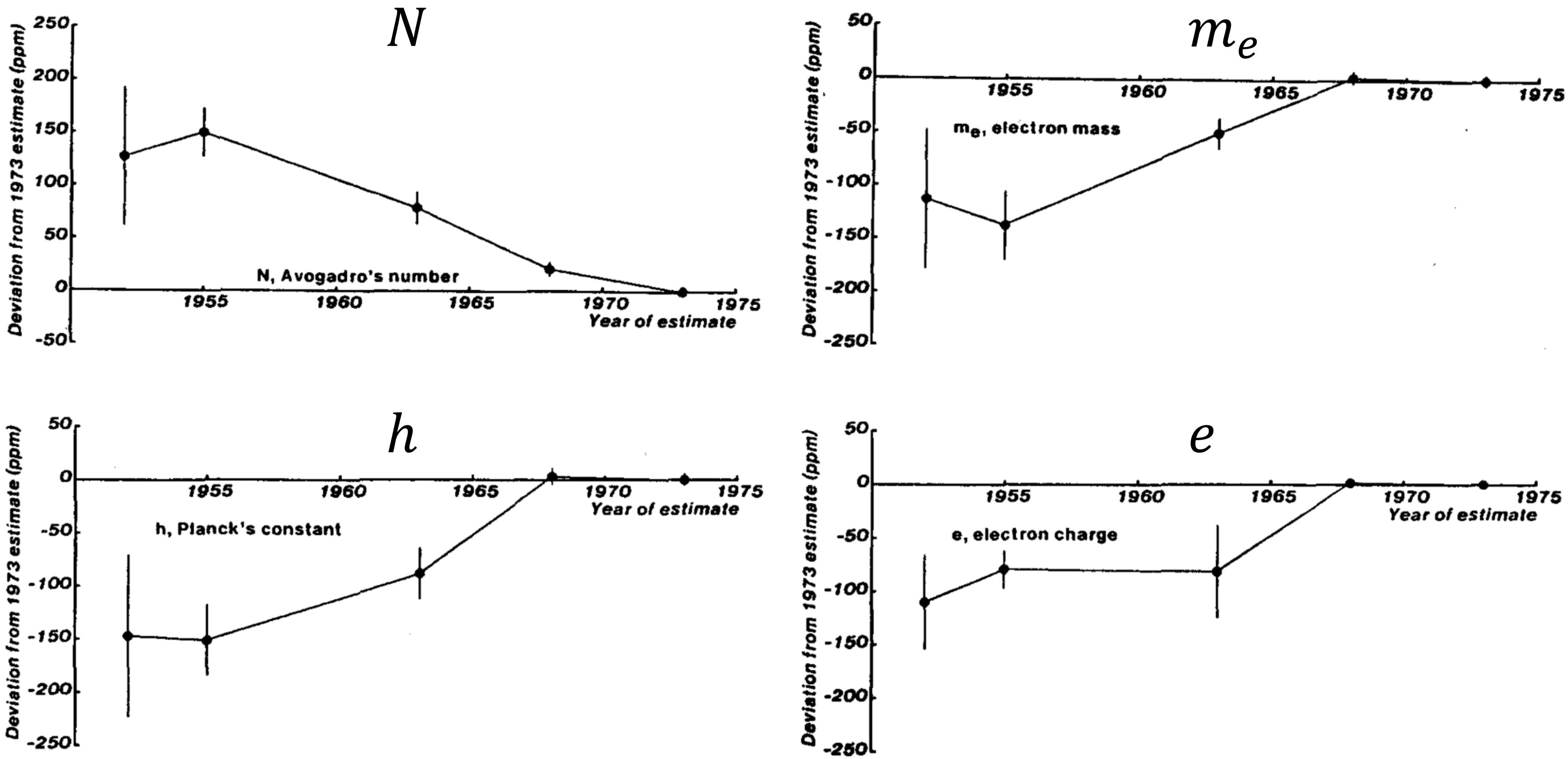
We are taking data “blind”!

Current EDM number:

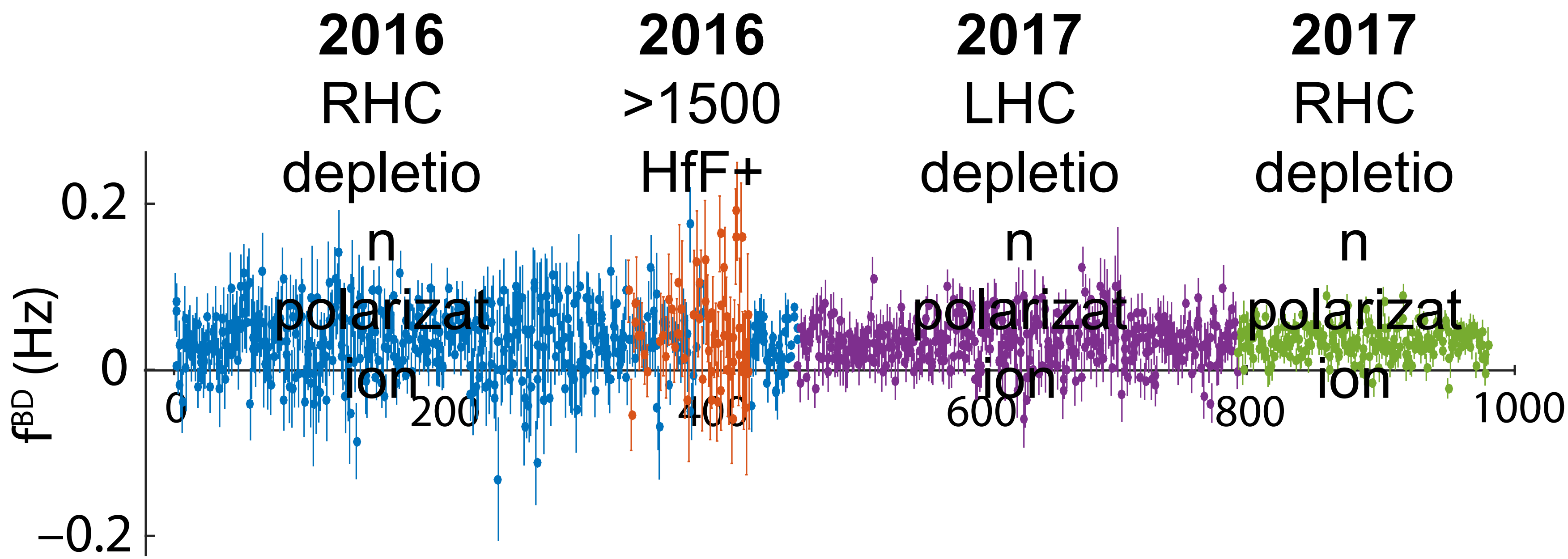
EDM = -8.3 +/- 1.5(stat) +/- 0.02(syst) +/- 5.0(blind) 10^-28 e cm

Best limit:
$|d_e| < 0.87 \times 10^{-28}\ e\ cm$

Blinding data



M. Henrion, B. Fischhoff, American Journal of Physics **54**, 791 (1986)



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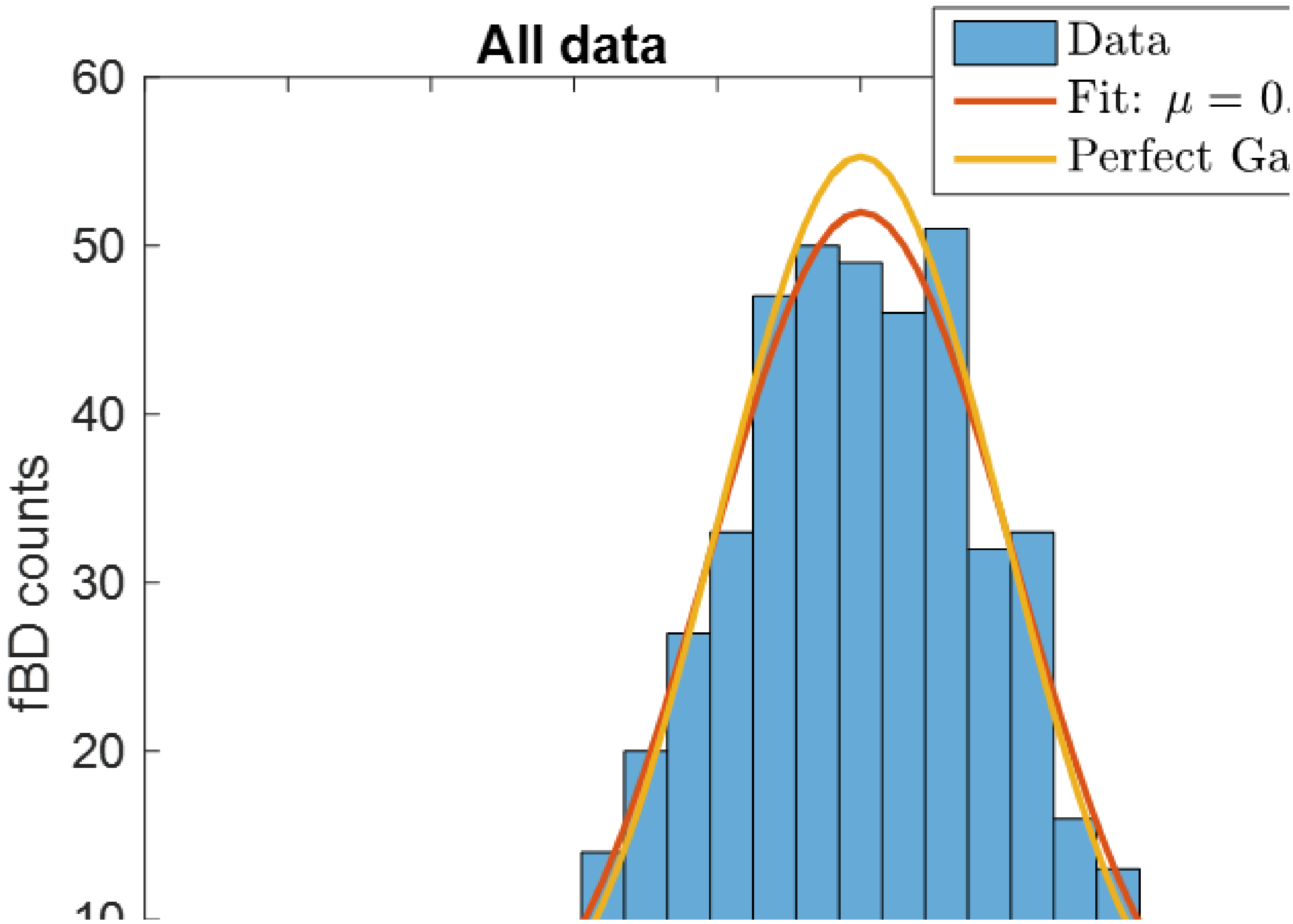
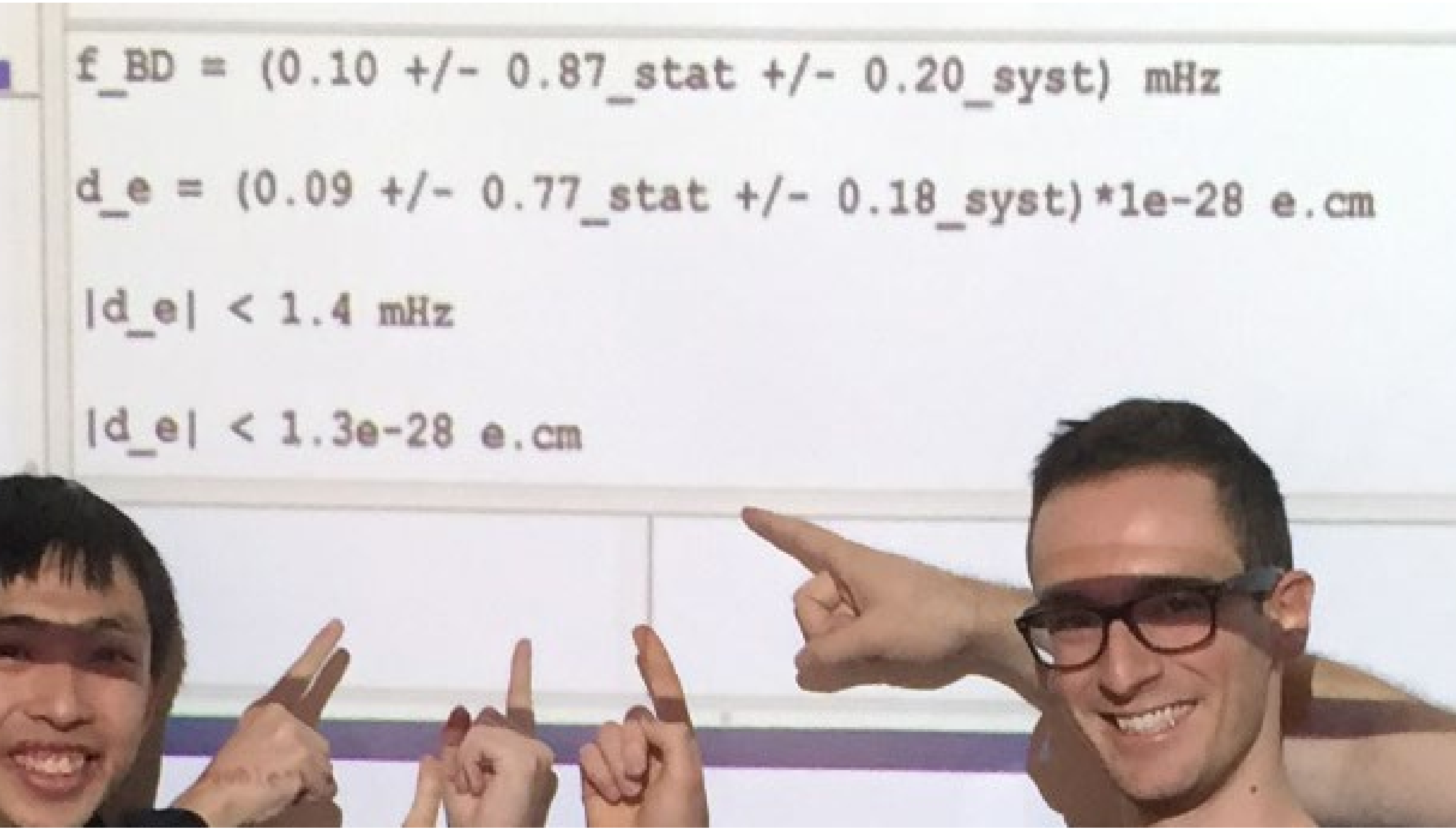


All data
Data
Fit: $\mu = 0.$
Perfect Ga
fBD counts
60
50
40
30
20


f_BD = (0.10 +/- 0.87_stat +/- 0.20_syst) mHz
d_e = (0.09 +/- 0.77_stat +/- 0.18_syst)*1e-28 e.cm
|d_e| < 1.4 mHz
|d_e| < 1.3e-28 e.cm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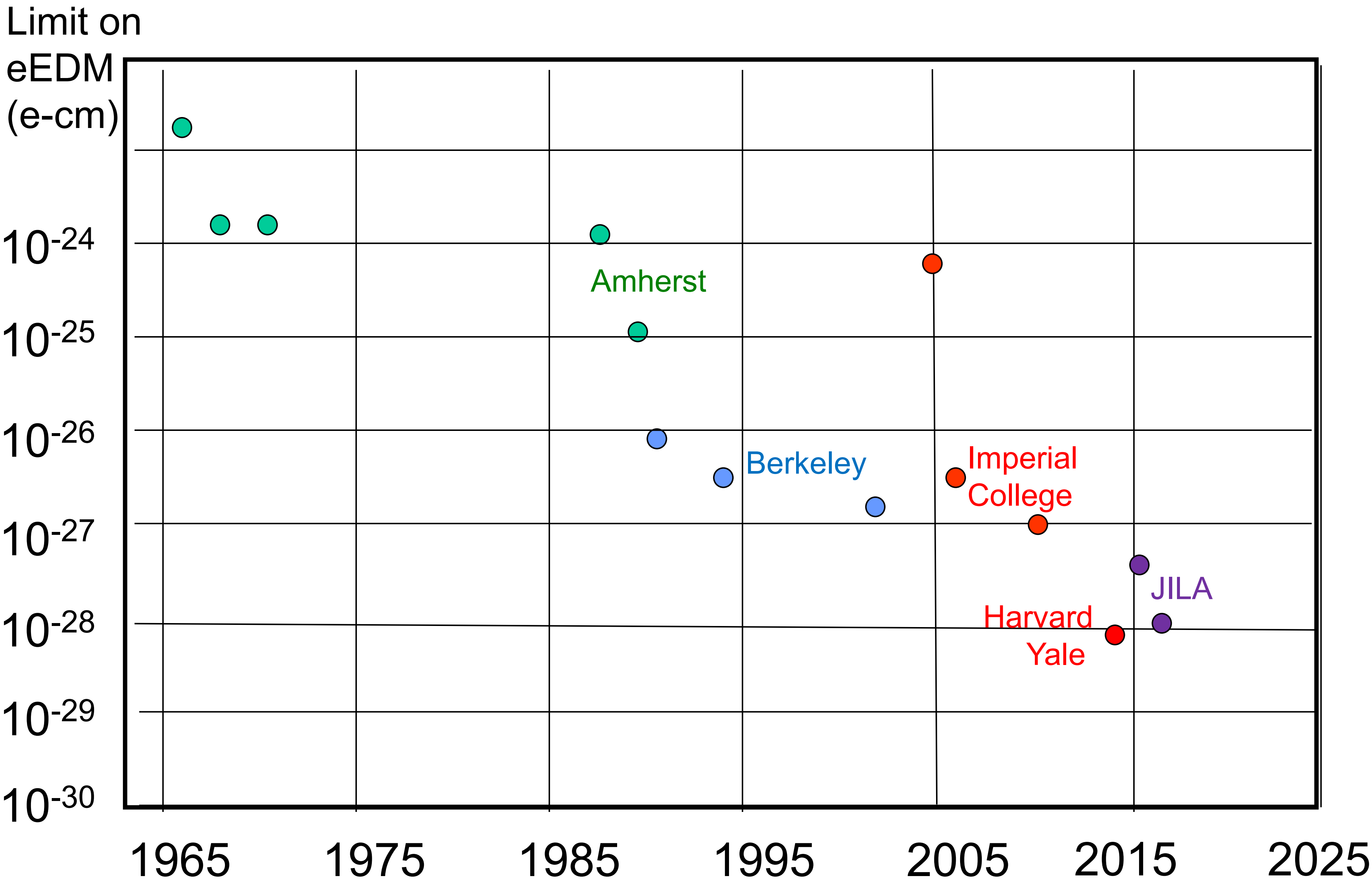
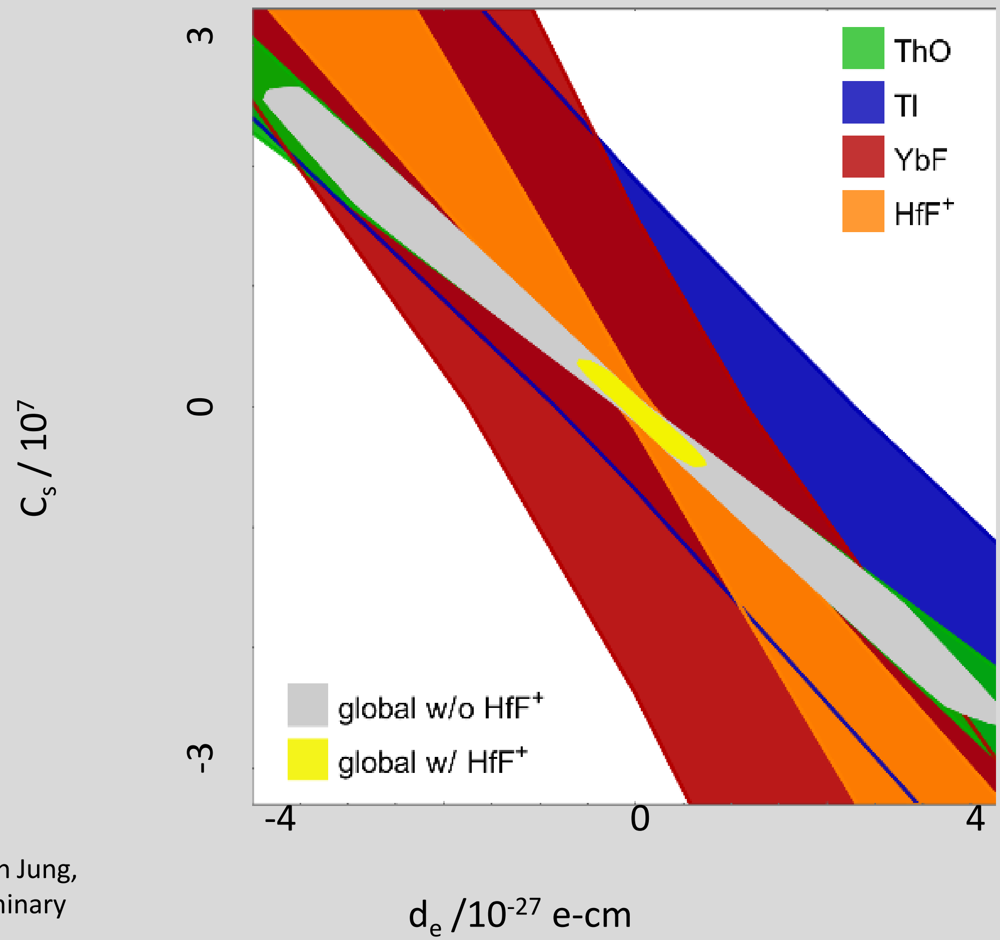
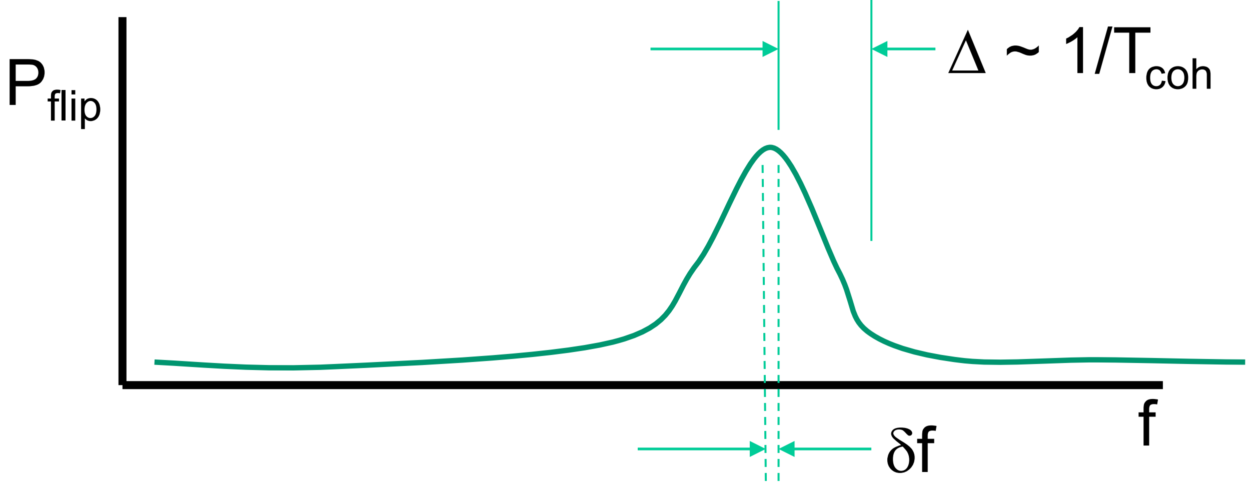
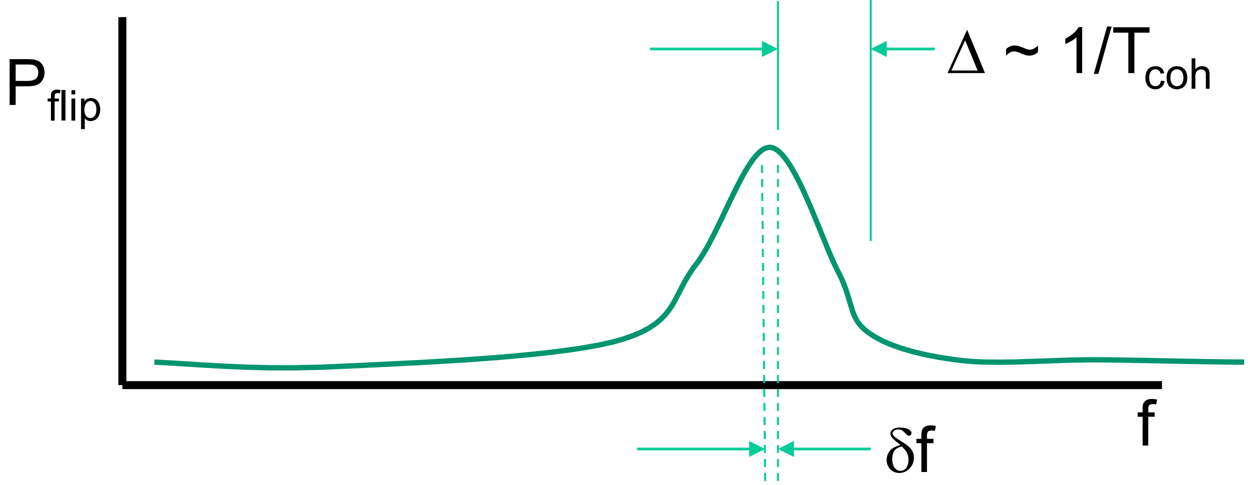

Limit on eEDM (e-cm)
10^-24
10^-25
10^-26
10^-27
10^-28
10^-29
10^-30
Amherst
Berkeley
Imperial College
JILA
Harvard Yale
1965
1975
1985
1995
2005
2015
2025



Martin Jung,
Preliminary



Generic
"new physics"
resonance
experiment



Generic
"new physics"
resonance
experiment

δPhysics = δf / ($\mathcal{E}$ / h)

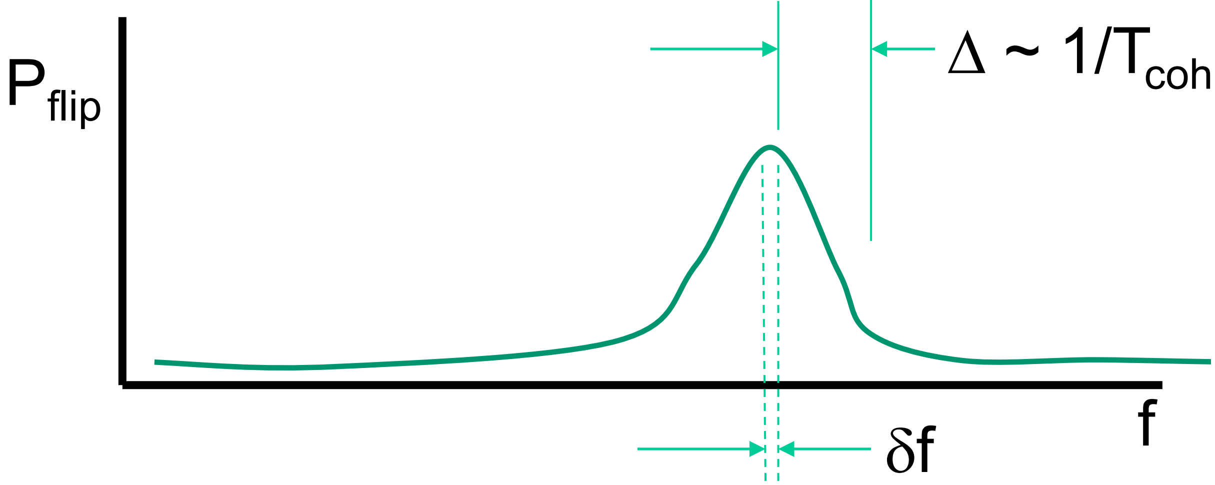
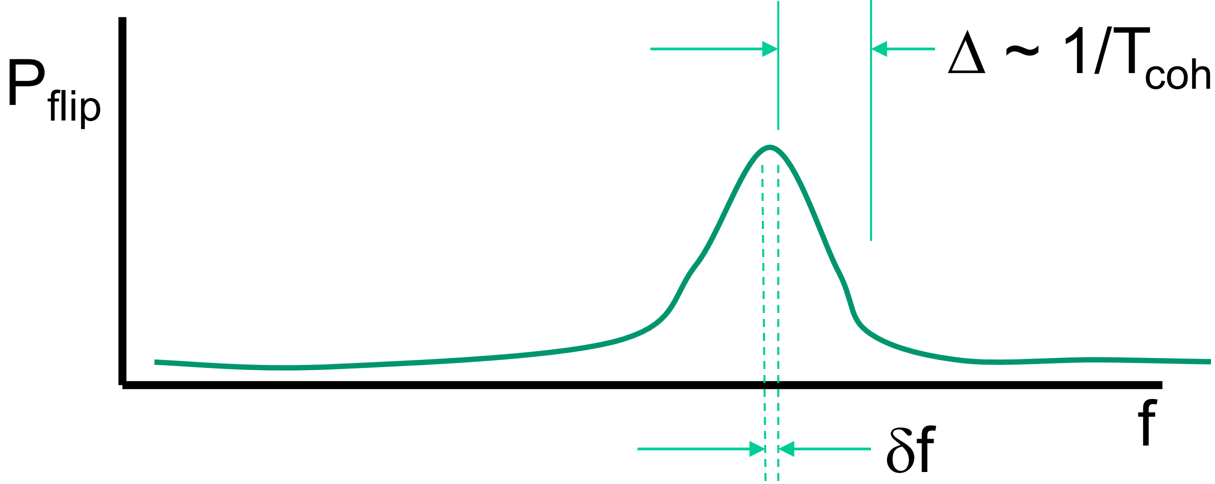


Table of “physics sensitivity”,

Experiment	$\mathcal{E}$
JILA eEDM	2.5×10^{10} V/cm
ACME eEDM	7×10^{10}
UWash eEDM	1×10^{4}

$$\delta\text{Physics} = \delta f / (\mathcal{E} / h)$$



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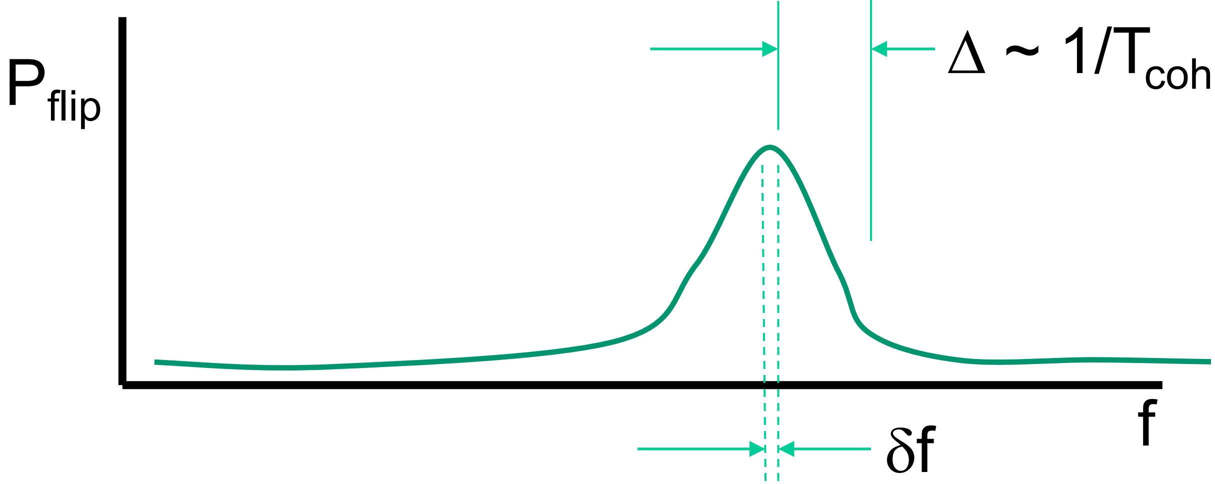
$$= (\delta f/\Delta)\,(1/T_{coh})\,(\mathcal{E} / h)$$



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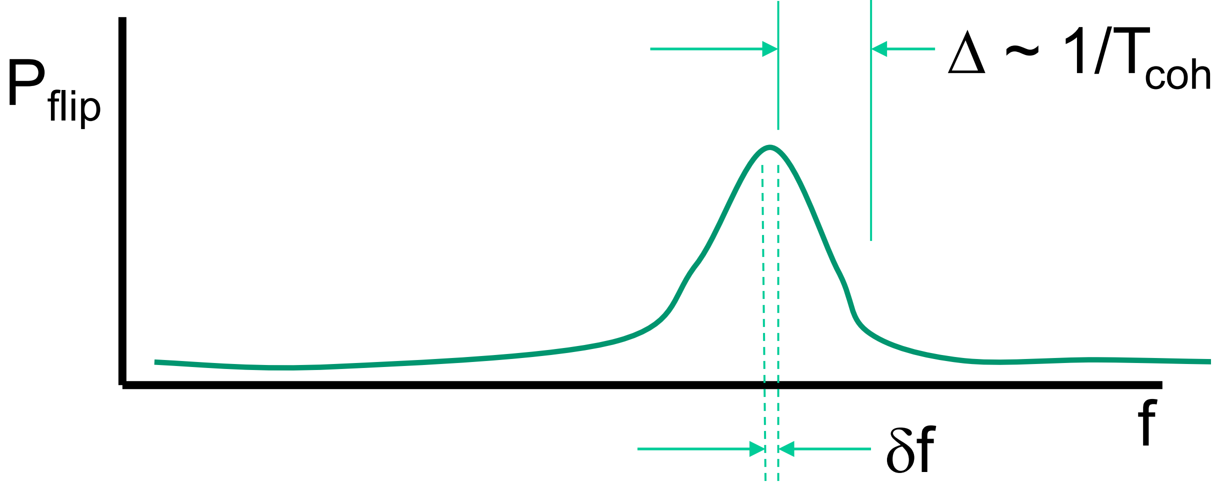
Sensitivity of resonance line to physics



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effective coherence time

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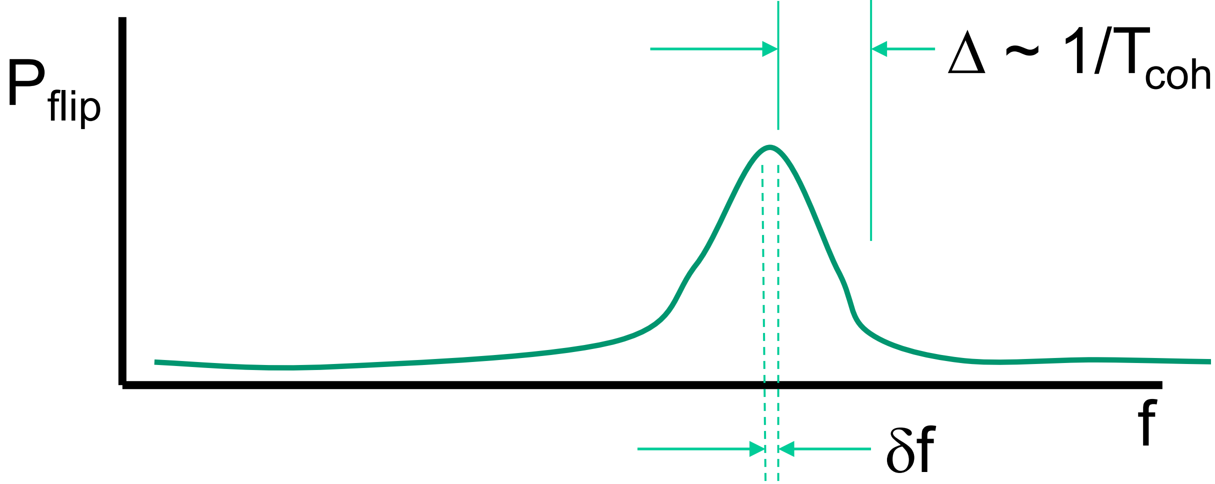

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how well you can "split the line" = 1/(Signal-to-noise) + systematic errors

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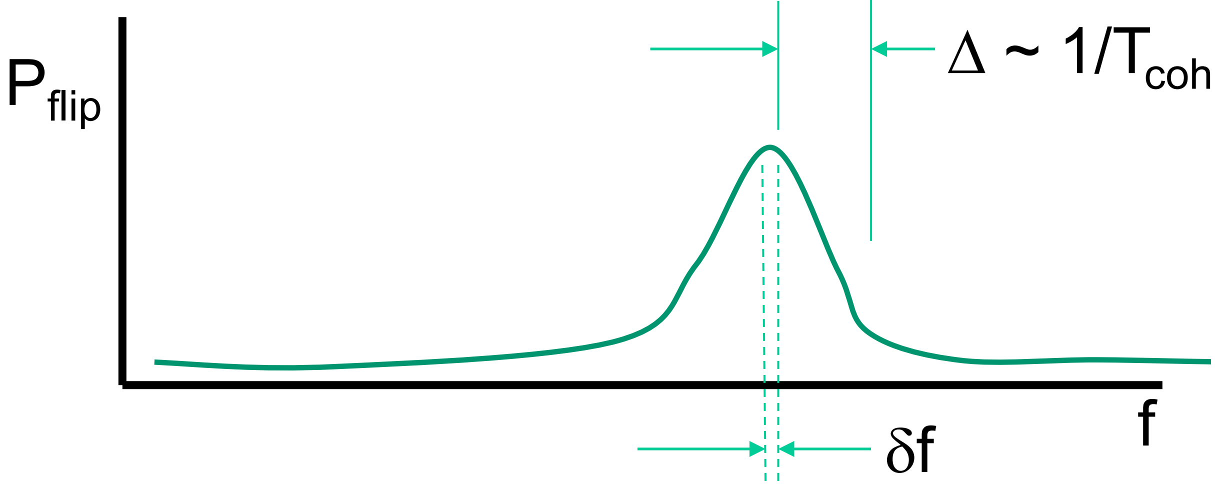

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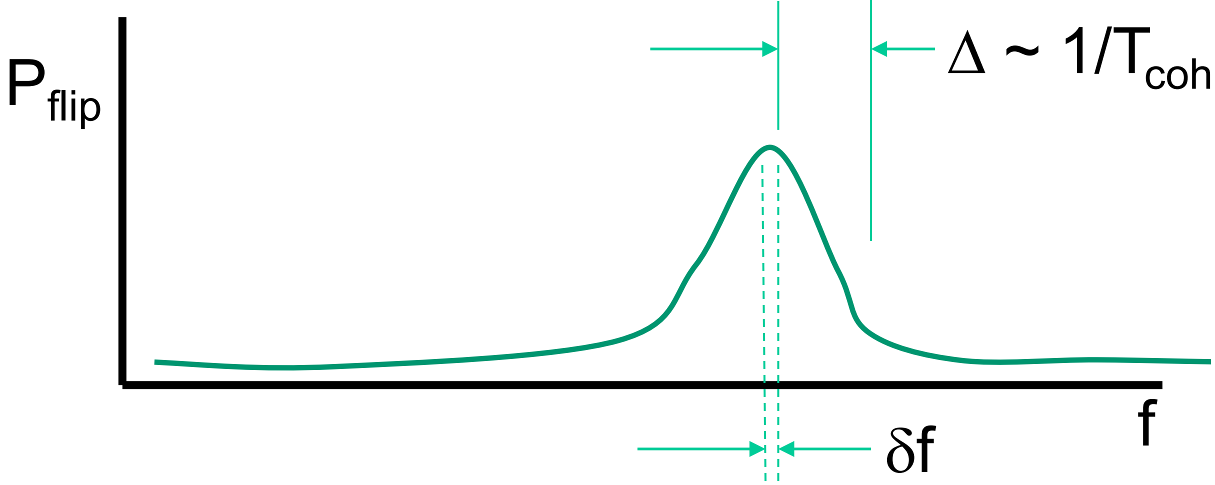
Sensitivity of resonance line to physics

Comes for Free!

(OK, not really, if you have to use radium, or prepare state of exotic molecule)



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effective coherence time

Glamorous AMO!
Traps, de-accelerators, cryo-buffer gas, laser cooling!

Sensitivity of resonance line to physics

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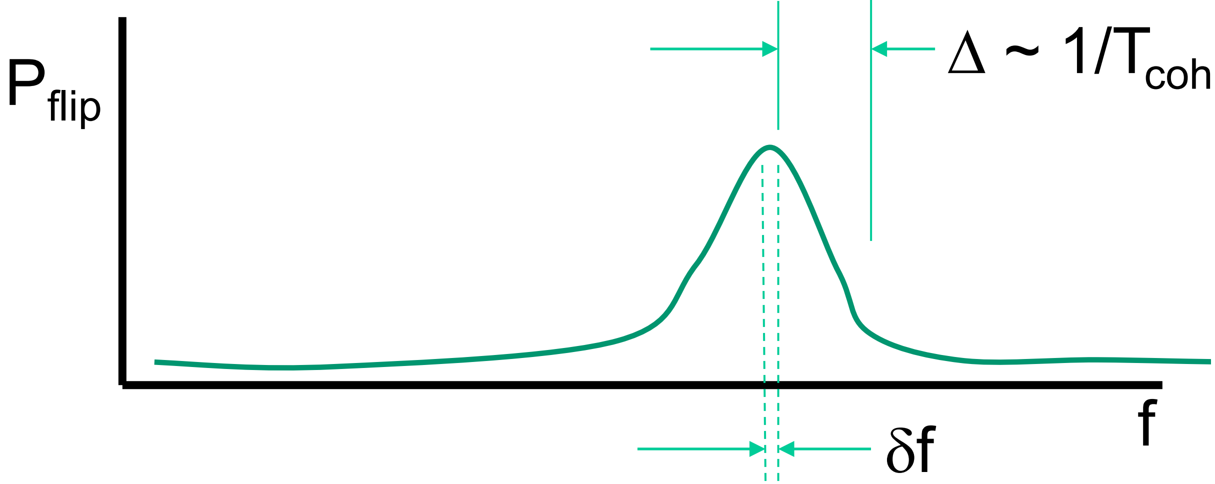

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Blood, Sweat, and Tears

Risky, thankless, back-breaking work!

effective coherence time

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Sensitivity of resonance line to physics

Comes for Free!

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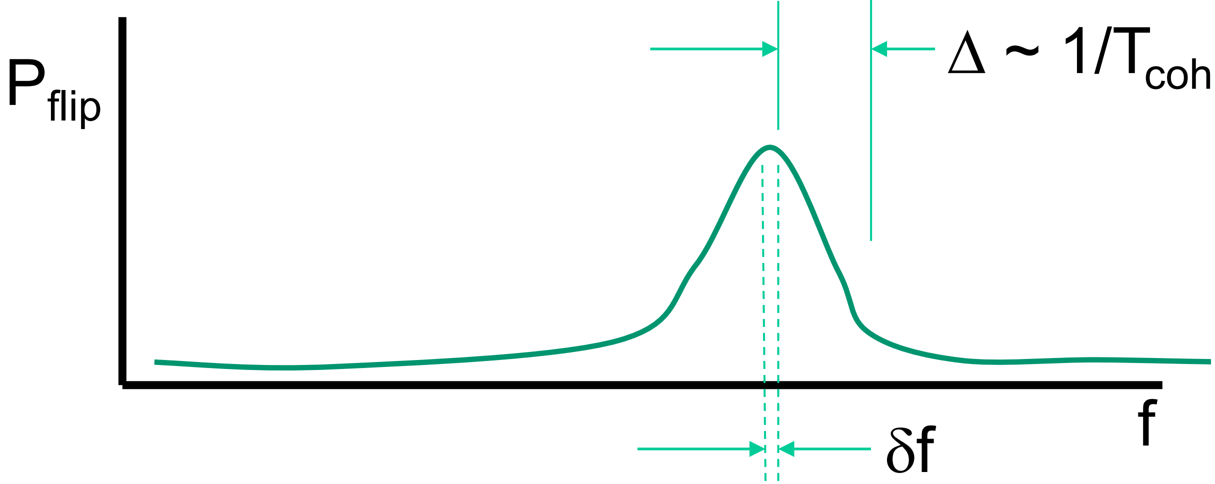

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how well you can "split the line" = 1/(Signal-to-noise) + systematic errors

Blood, Sweat, and Tears

Risky, thankless, back-breaking work! (i.e. "precision metrology")

effective coherence time

Glamorous AMO!

Traps, de-accelerators, cryo-buffer gas, laser cooling!

Sensitivity of resonance line to physics

Comes for Free!

(OK, not really, if you have to use radium, or prepare state of exotic molecule)

Blood, Sweat and Tears. Splitting the Line

Experiment	$1/(\delta f/\Delta)=1/(\delta f\ T)$	Qualitative Judgement

Blood, Sweat and Tears. Splitting the Line

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HgEDM (U.W.)	$3x10^7$	Very, very serious guys.

Blood, Sweat and Tears. Splitting the Line

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Cesium Beams Clock	1×10^6	Professional metrologists

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eEDM (ACME)	1×10^{5}	Appears to be room to improve

Blood, Sweat and Tears. Splitting the Line

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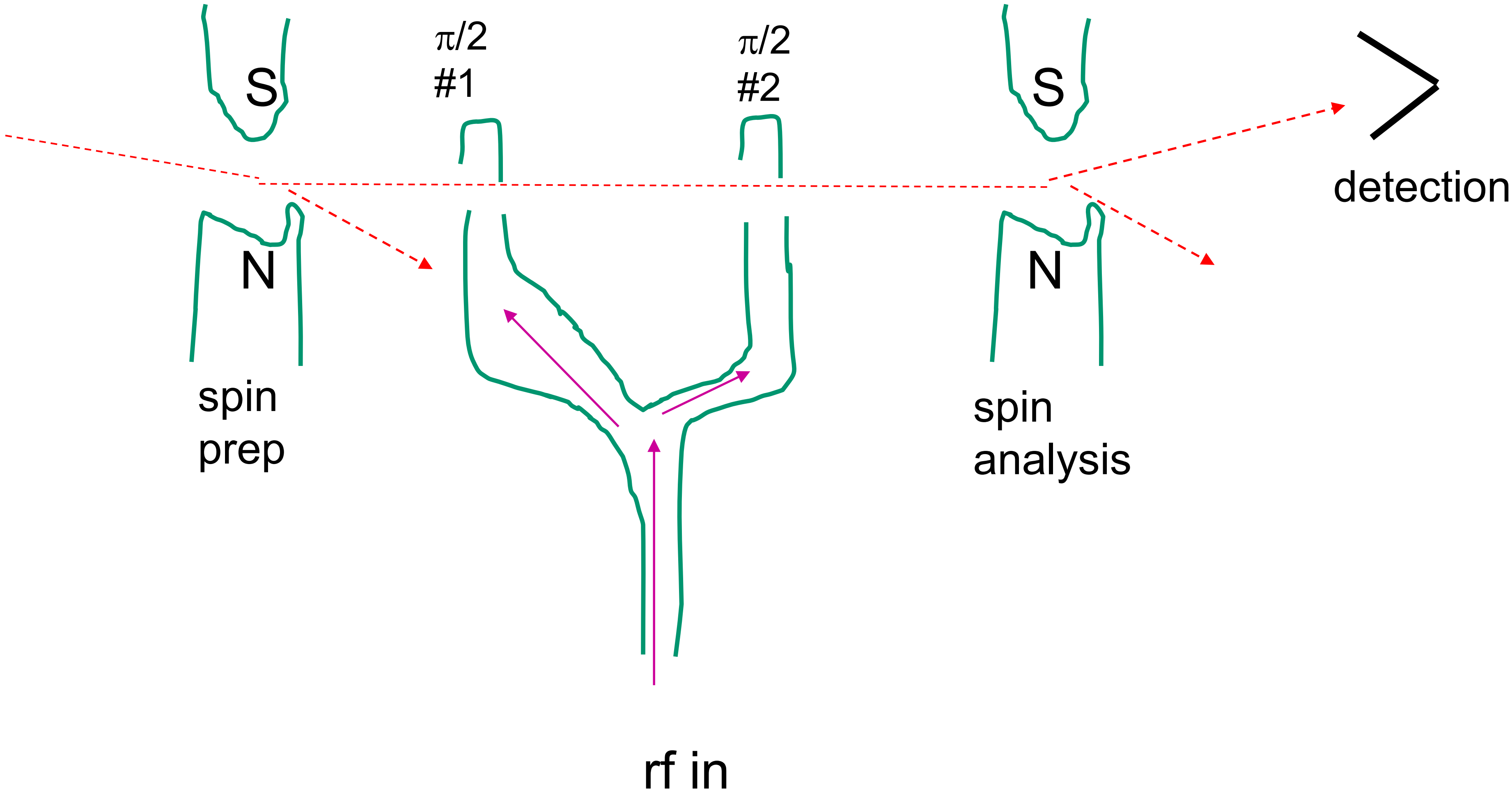
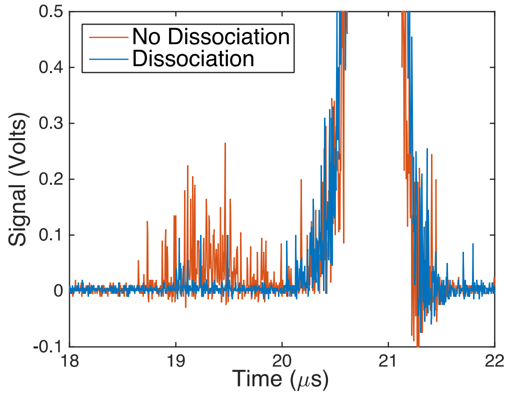
Cesium Beams Clock	1×10^6	Professional metrologists
eEDM (ACME)	$1\text{x}10^5$	Appears to be room to improve
eEDM (JILA)	$3\text{x}10^2$	Still in kindergarten

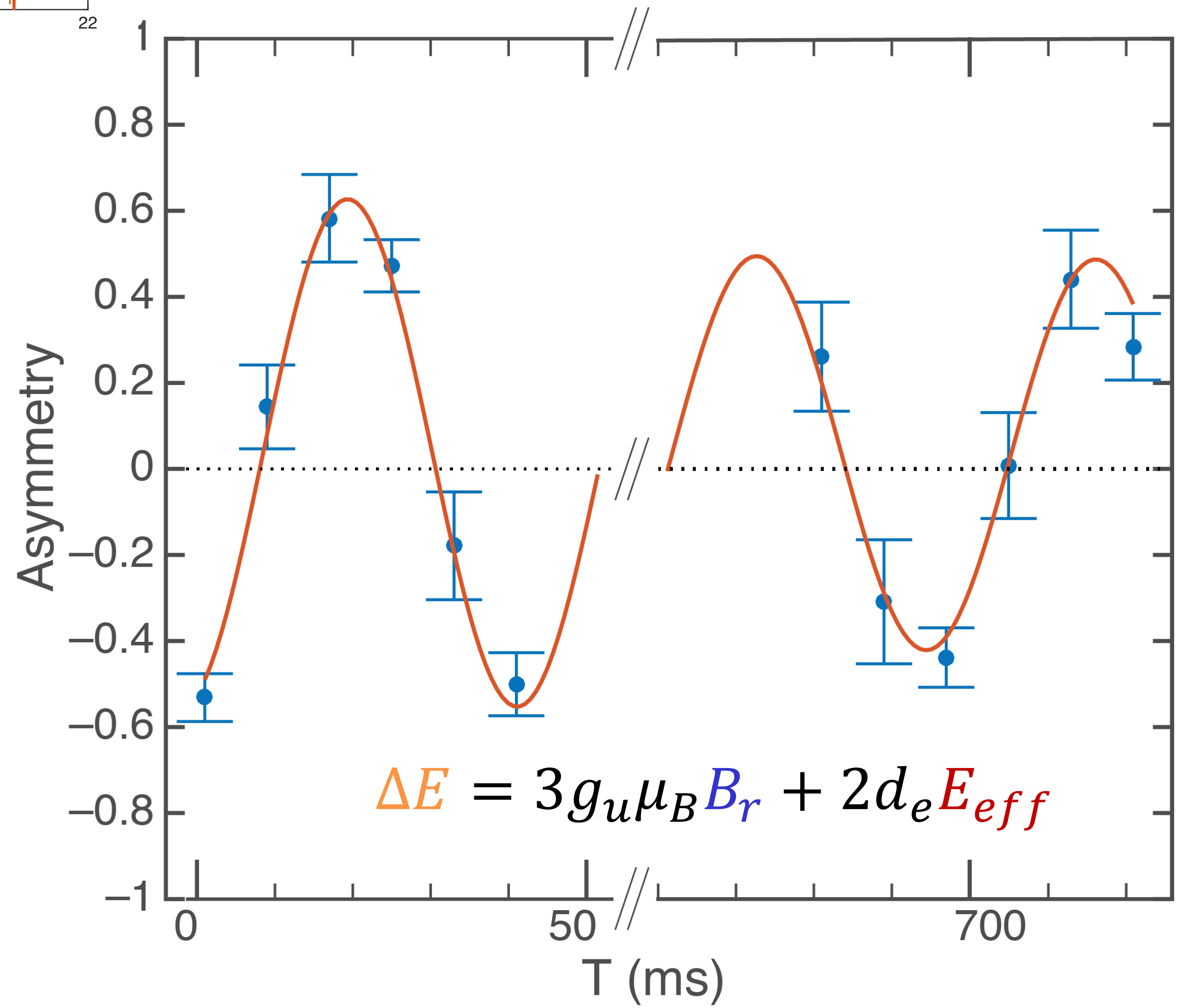
Old-school Atomic-Beam Clock



Problems if phase of rf at site #1 and #2 are different.
Time between p/2 pulses, T, is stuck at its largest value.

Ramsey Fringe

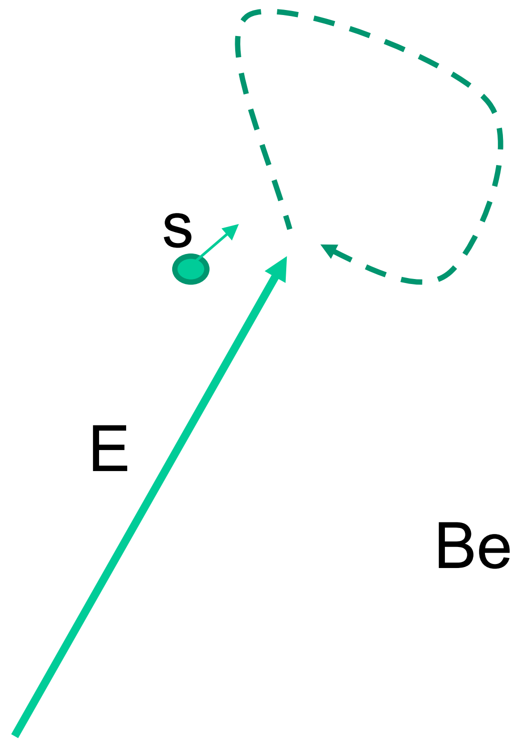




How will we do better?

1. Several incremental things, factors of root-2 here and there.

2. Improve count rate by trapping more ions. (increasing ion number is actually easy for us.)

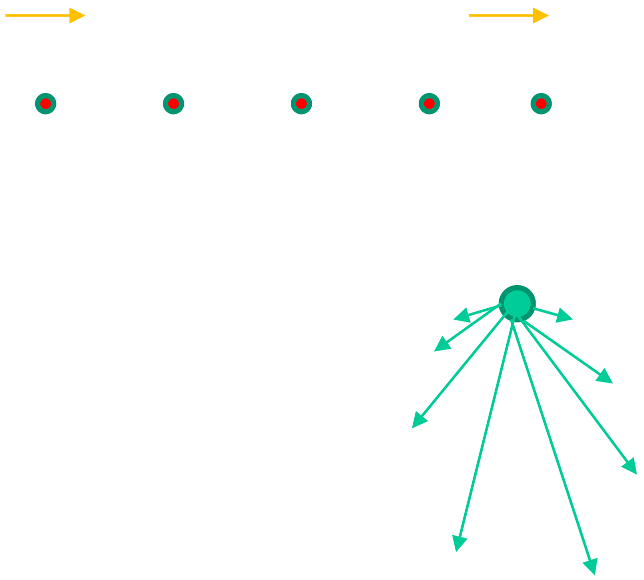


$\mathscr{A}$ = solid angle swept out
by changing bias field.

Berry's phase after one cycle:

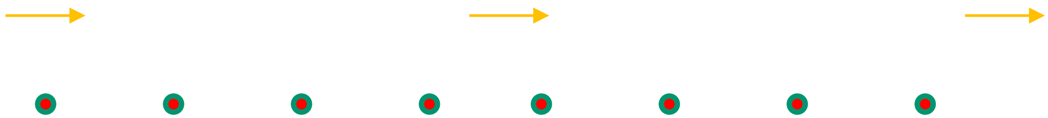
$\delta\phi = m\,\mathscr{A}$

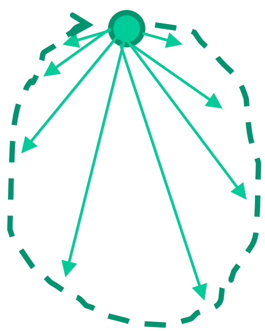
Ion-ion close-pass



Resultant electric field at ion #2

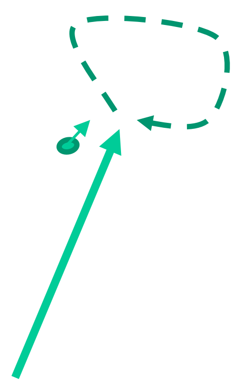
Ion-ion close-pass





Resultant electric field at ion #2

And imagine E_{rot} is out of the page, then viewed from the side:



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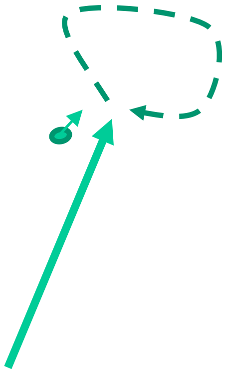
Berry's phase after one cycle:
$\delta\phi = m\,\mathcal{A}$



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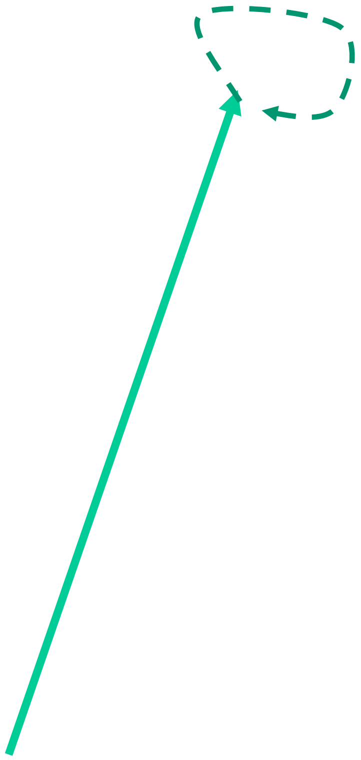
And the effect of many ion-ion close-pass events is to cause the phase between m=3/2 and m=-3/2 states to random-walk into decoherence.

But! If we double magnitude of E_{rot}…



$\mathcal{A}$ = solid angle swept out by changing bias field.

Berry's phase after one cycle:

$\delta\phi = m\,\mathcal{A}$

And the effect of many ion-ion close-pass events is to cause the phase between m=3/2 and m=-3/2 states to random-walk into decoherence (when accumulated $\delta\pi \sim \pi/2$)

But! If we double magnitude of E_{rot}… then same close-pass even yield only ¼ the subtended area, and time required to decohere increases by 2^4.

In Mark 2 machine, we hope to have 10 times more ions even while decoherence rate lower by 1.6.