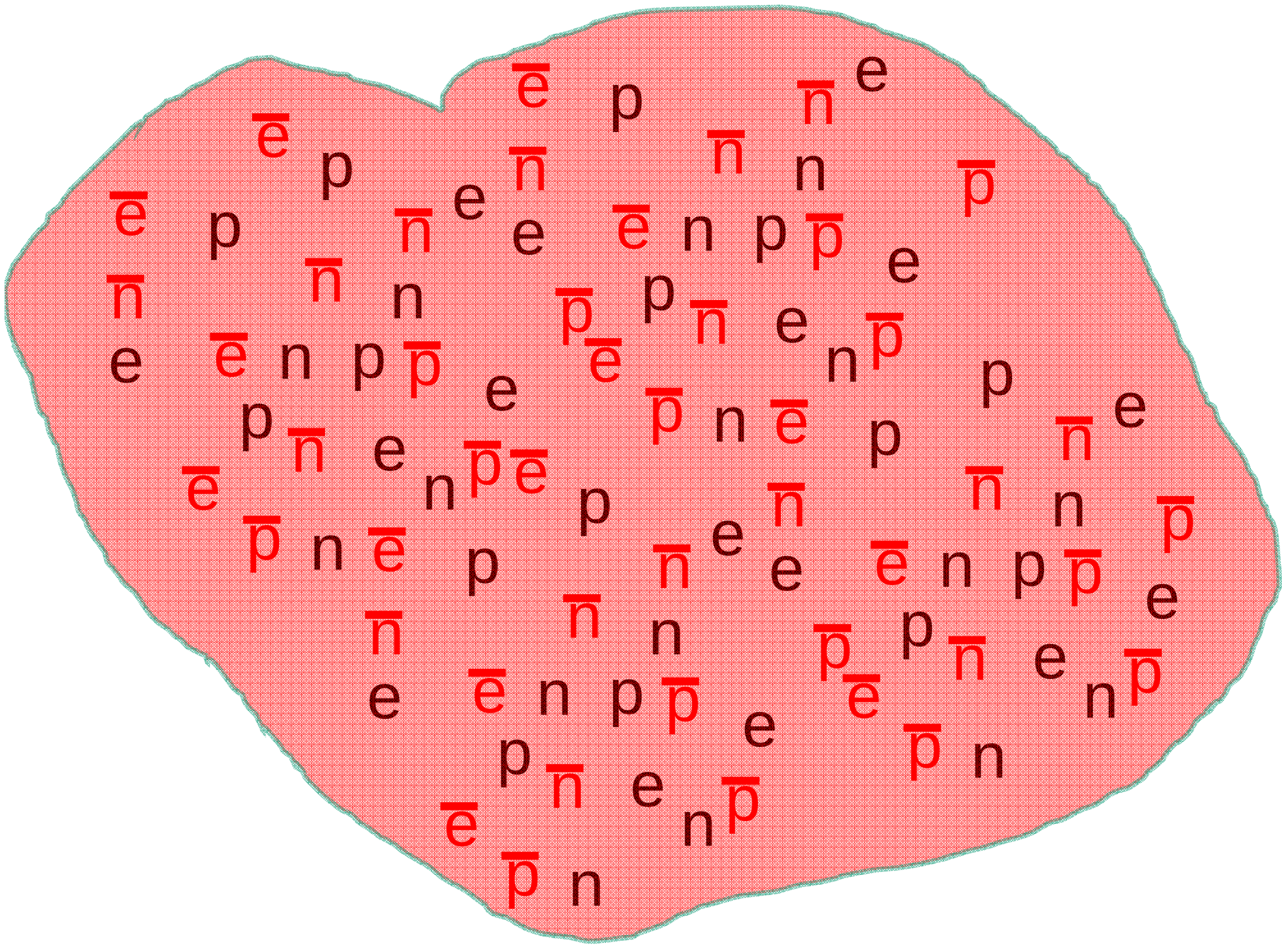
The situation, approximately
14 billion years before right now:

BANG

Then, shortly thereafter:



e = electron

p = proton

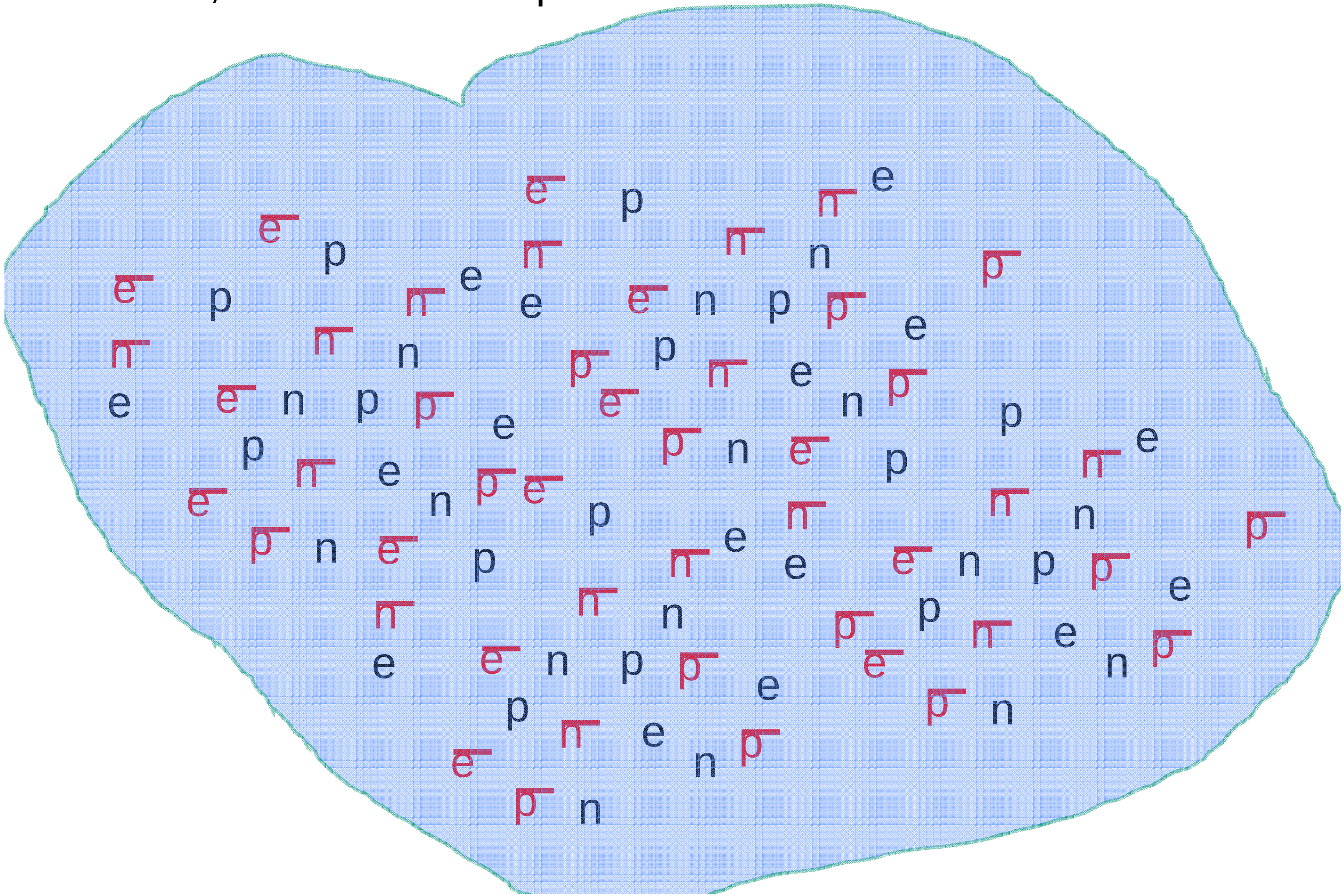
n = neutron

$\overline{e}$ = antielectron

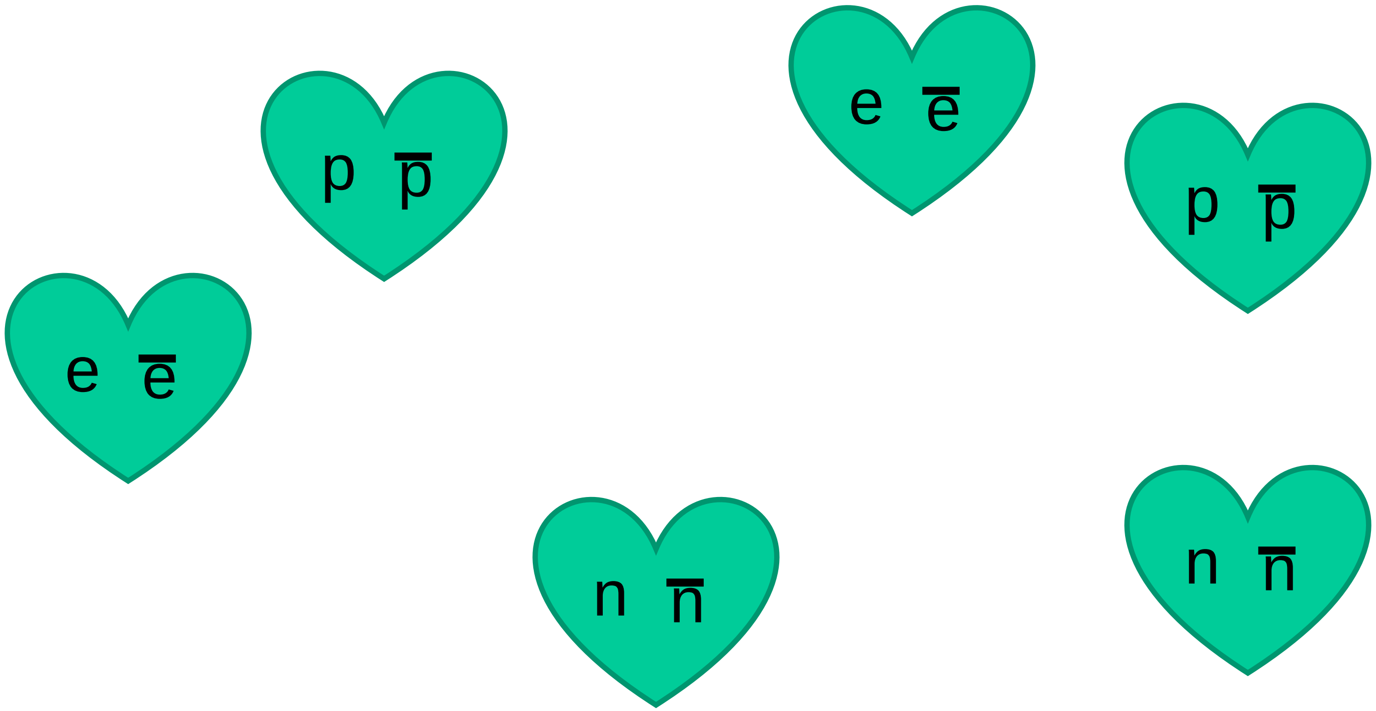
$\overline{p}$ = antiproton

$\overline{n}$ = antineutron

Then, the universe expanded and cooled:

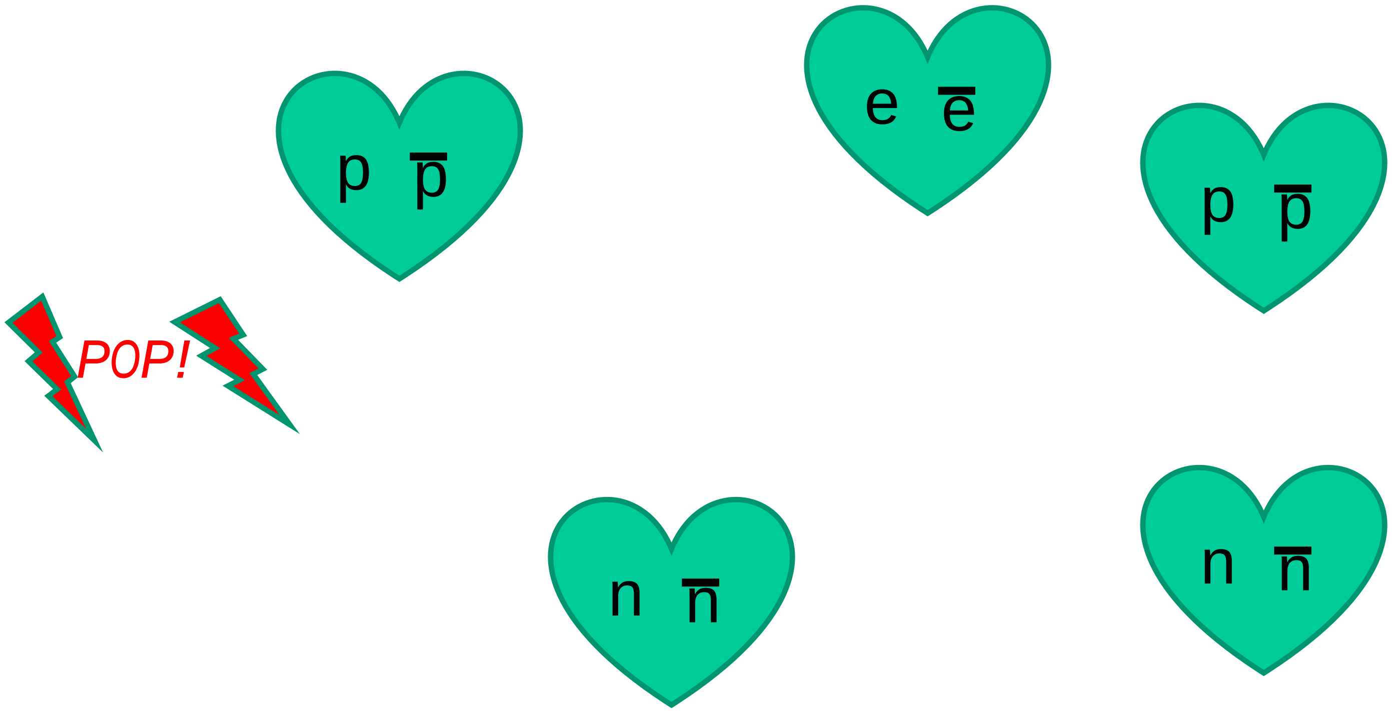


Then, True Love!



Each particle finds its “soul mate”.

Married life is passionate, but short.



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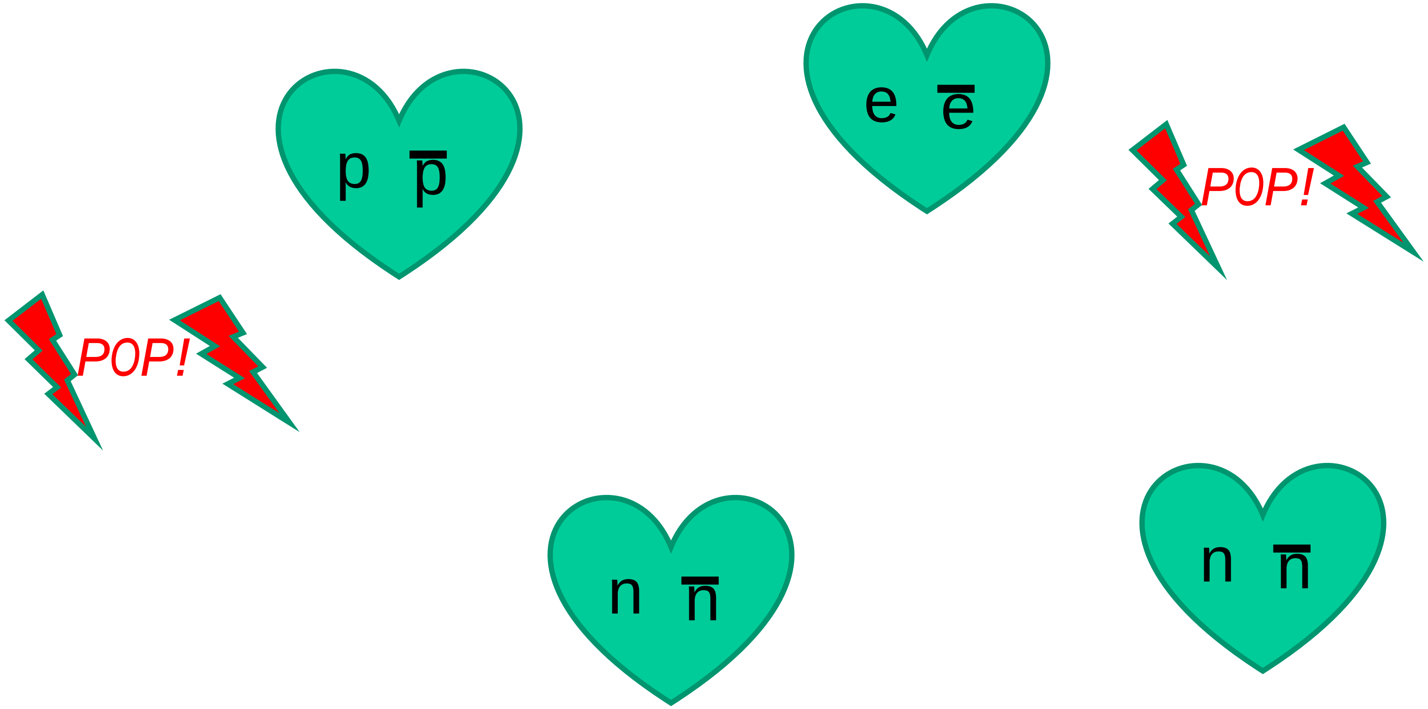
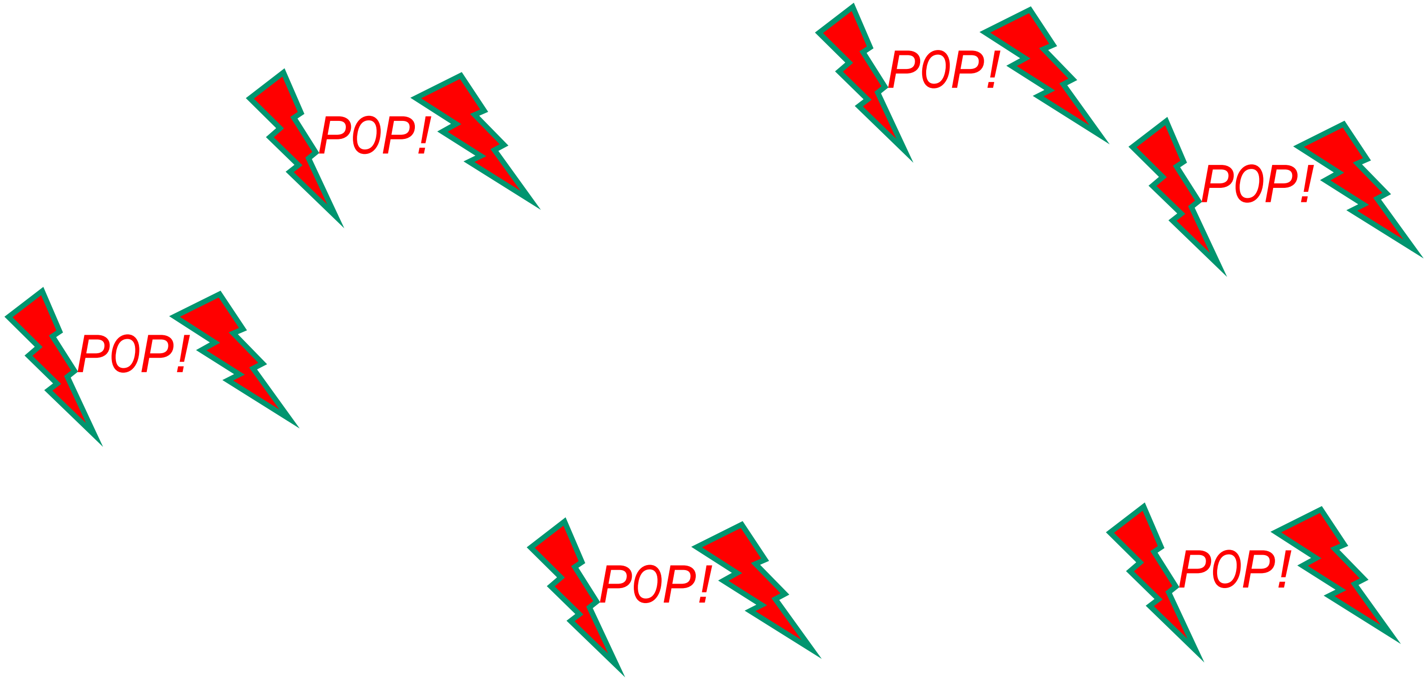
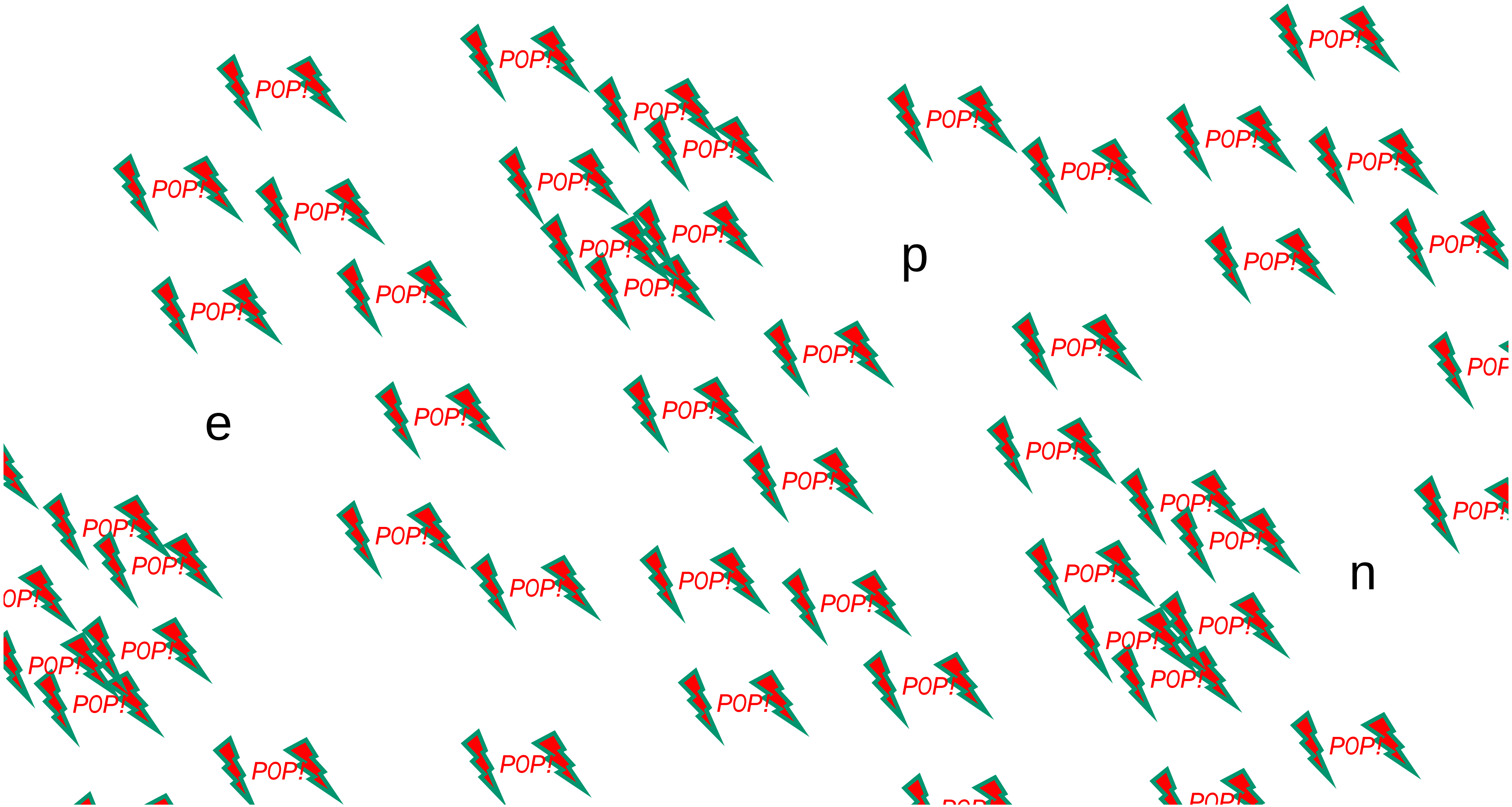


Married life is passionate, but short. Nothing is left but a pulse of light.

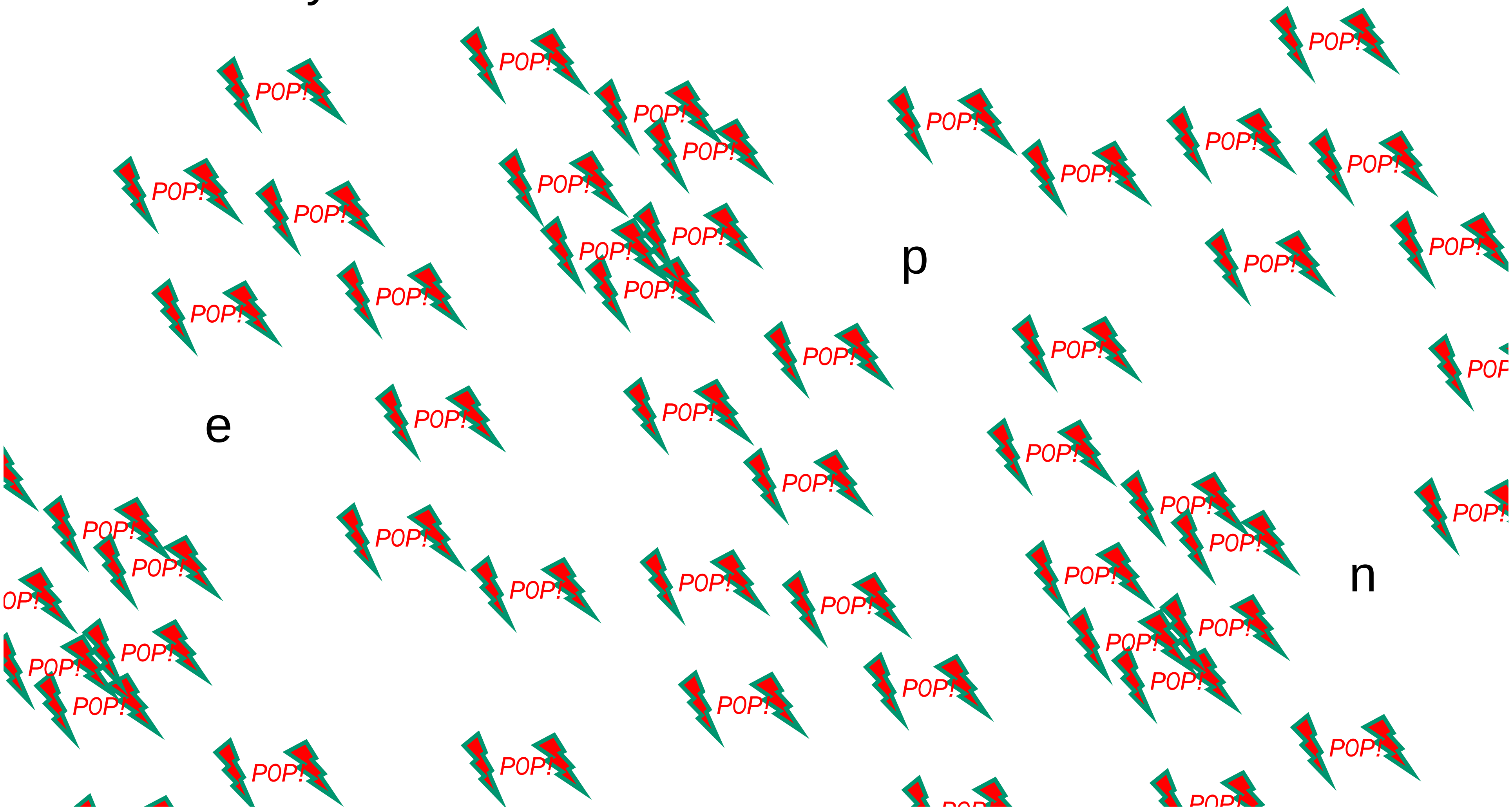


In the mass cosmic wedding,
there was somebody for everyone.



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

Except for a very small number of lonely, left-over particles, that nobody wanted!



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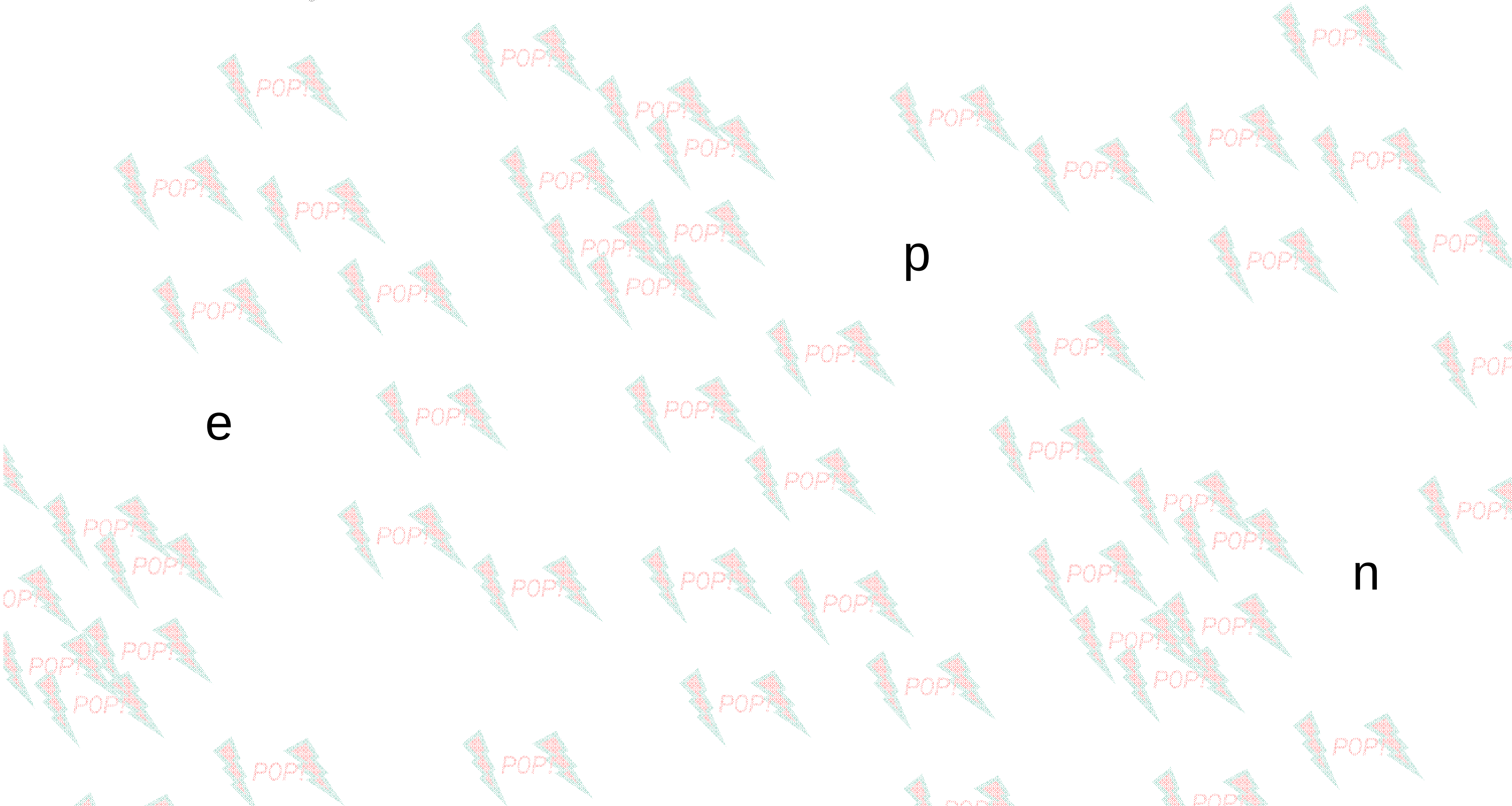
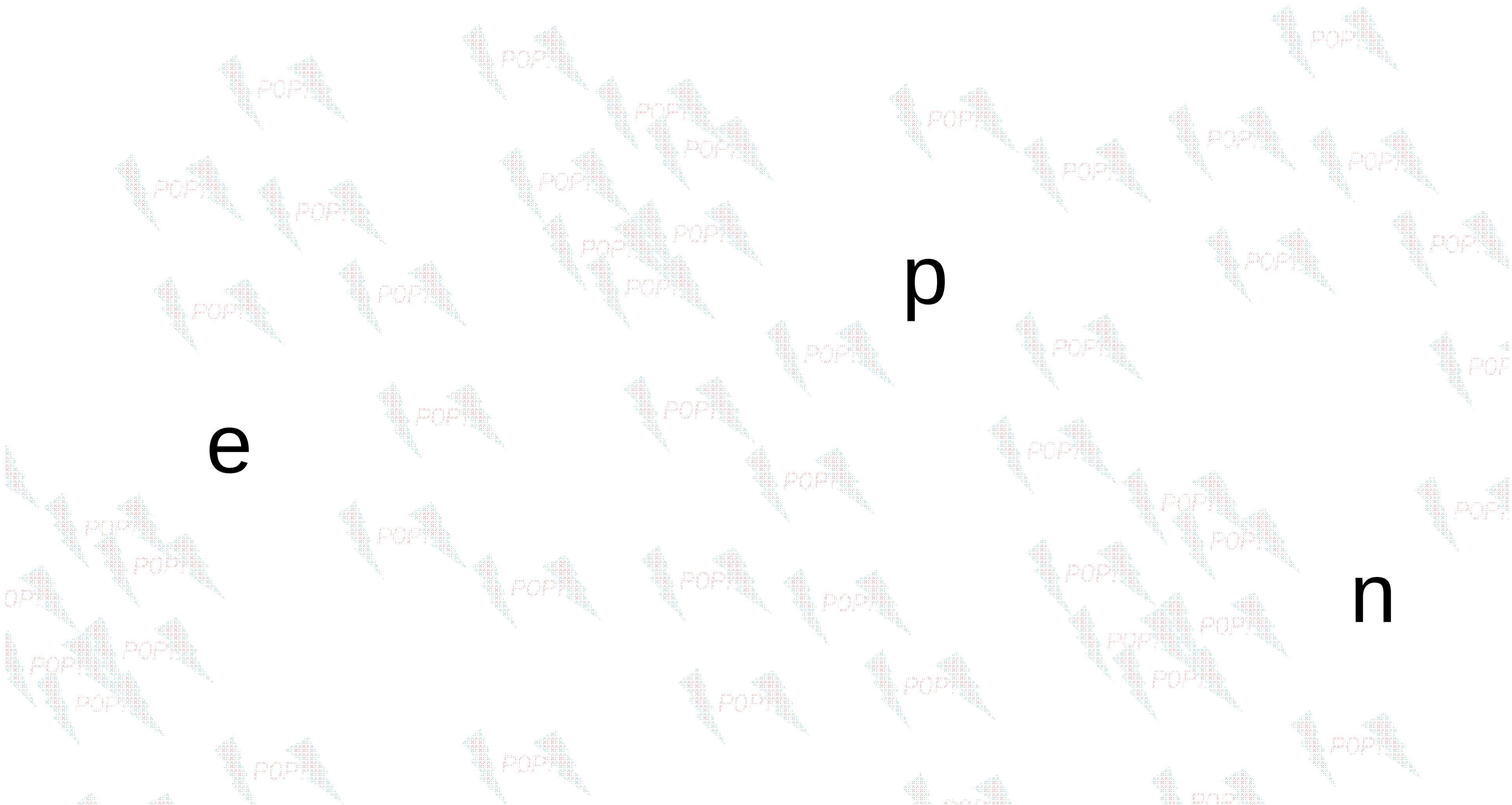
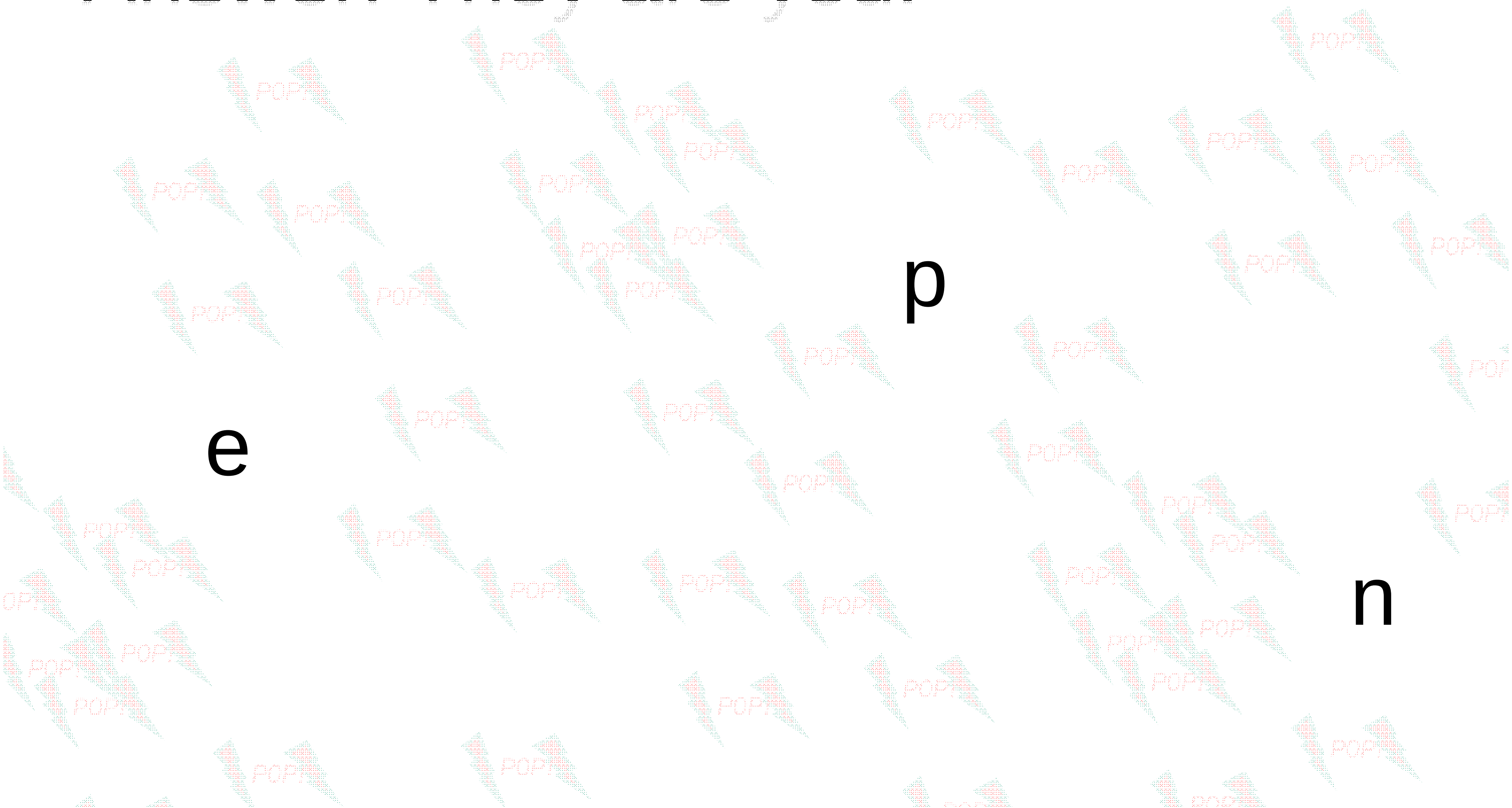


Question: Who are these final, few, lonely particles that no one wanted?



Question: Who are these final, few, lonely particles that no one wanted?
Answer: They are you.



Question: Why, right after the Big Bang, was there *just a tiny bit* more matter than antimatter? (How is it we can exist, today?)

p

e

n

Question: Why, right after the Big Bang, was there *just a tiny bit* more matter than antimatter? (How is it we can exist, today?)

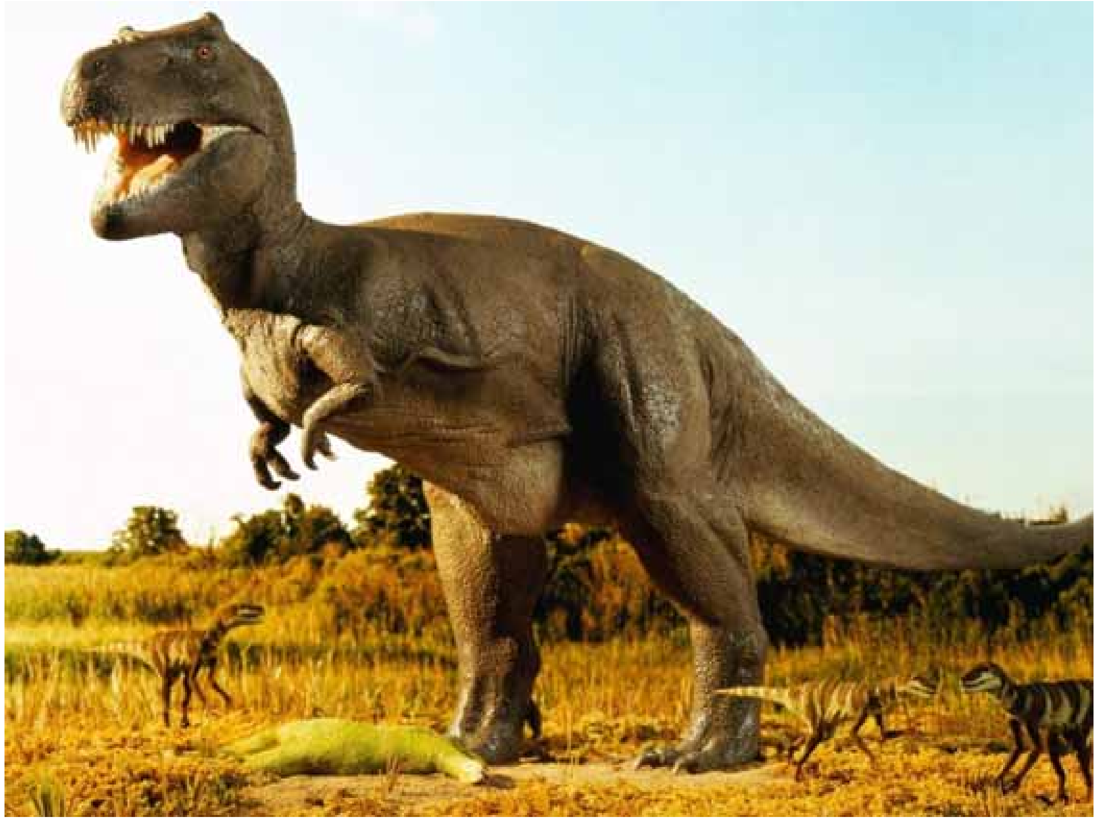
Answer: Physicists don't know! But we are trying to understand.

p

e

n

What does “electric dipole moment” have to do with
“a tiny bit more electron than antielectron 14 billion years
ago”?



What does “electric dipole moment” have to do with
“a tiny bit more electron than antielectron 14 billion years ago”?   Modern-day fossil of ancient asymmetry.

Symmetries:

What does “electric dipole moment” have to do with “a tiny bit more electron than antielectron 14 billion years ago”? Modern-day fossil of ancient asymmetry.
Symmetries

1. electrons act just like antielectrons.

What does “electric dipole moment” have to do with
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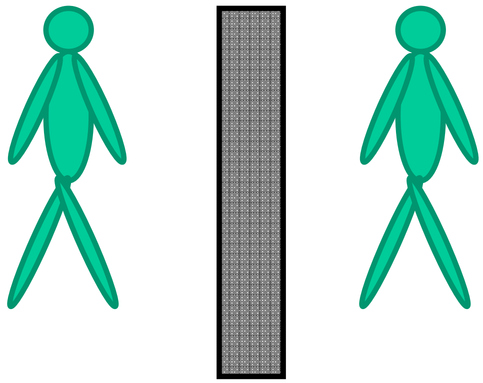
Symmetries

1.electrons act just like antielectrons.
2.electrons and other particles look the same in the mirror:



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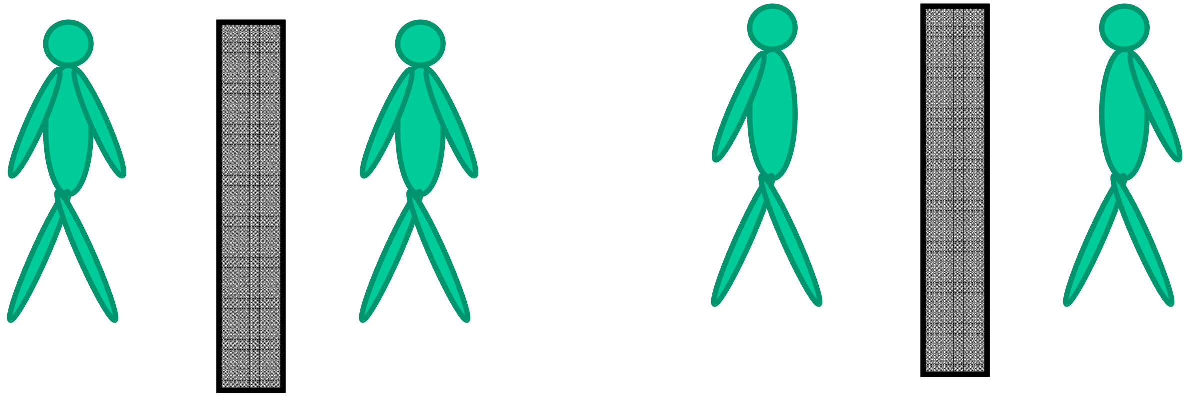

What does "electric dipole moment" have to do with
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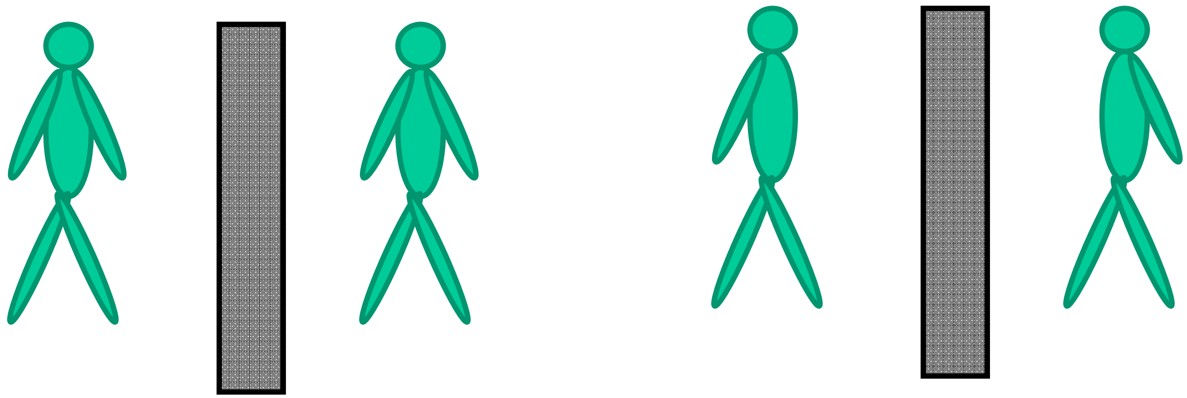
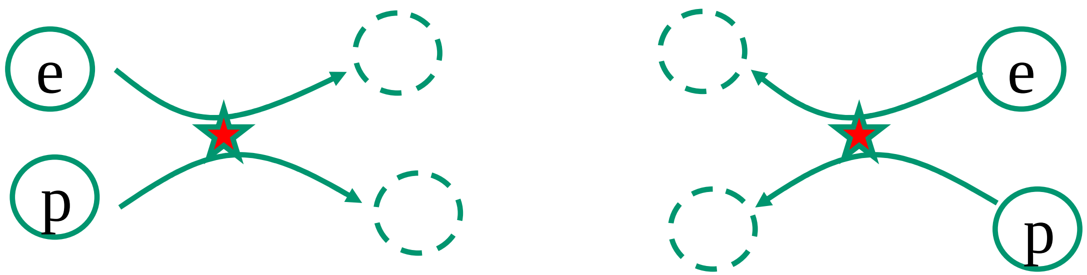


3. Particles look same if you
"run the movie backwards."



In nature, we see a lot of symmetry.

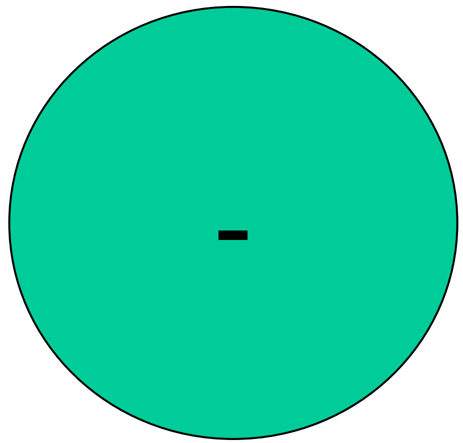
things look the same in the mirror.
things look same when time runs backwards. (little things.)
matter is same as antimatter

this is a little hard to explain: these different symmetries are *connected* by theoretical considerations.

Meet Mr. Electron.

charge = -q

mass = m_e

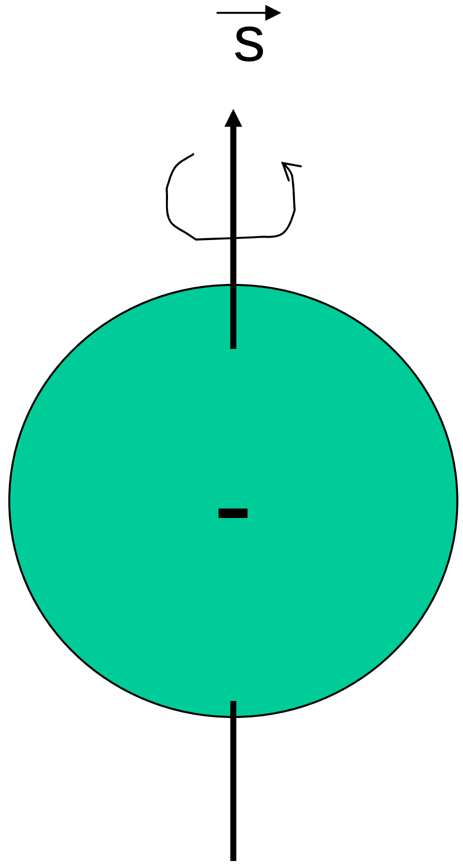


Meet Mr. Electron.

charge = -q

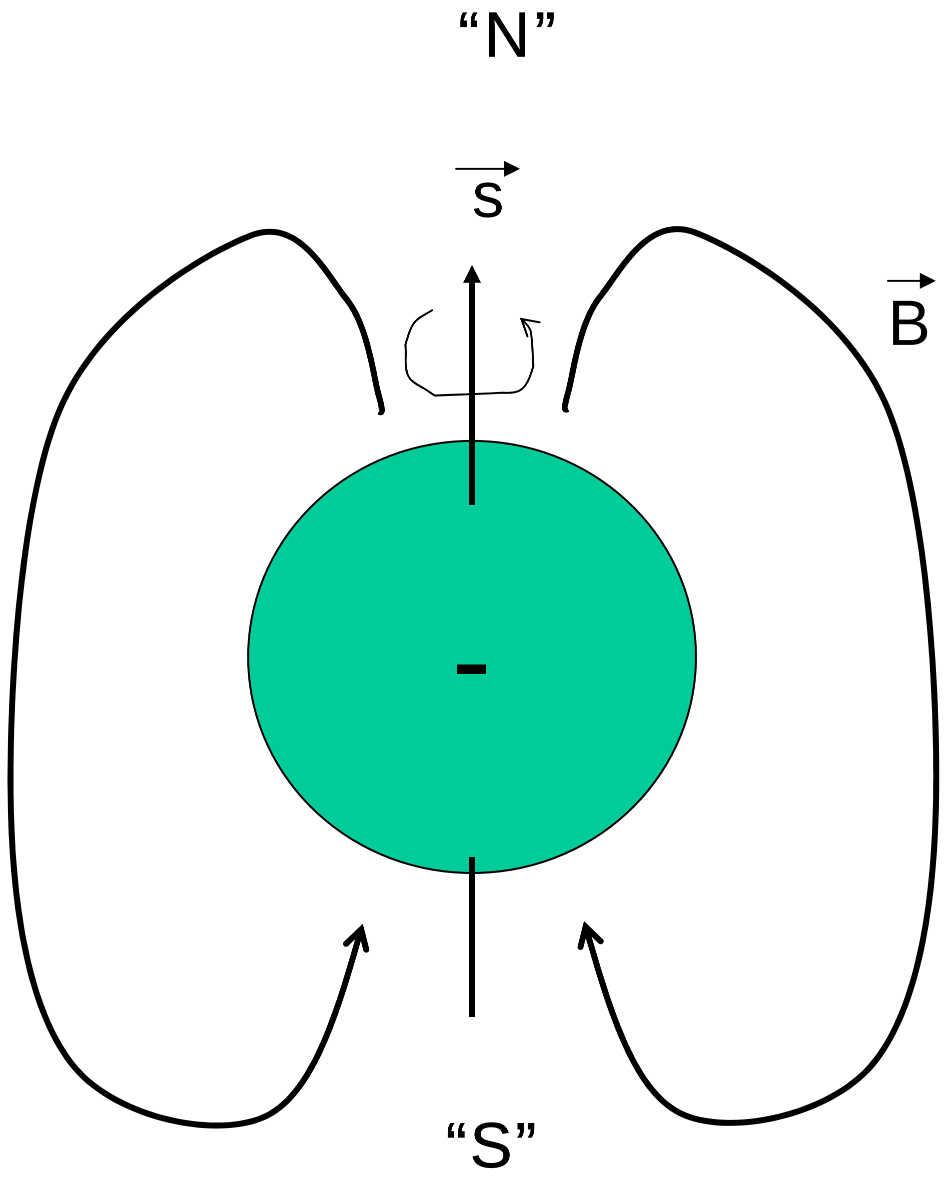
mass = m_e

It spins.



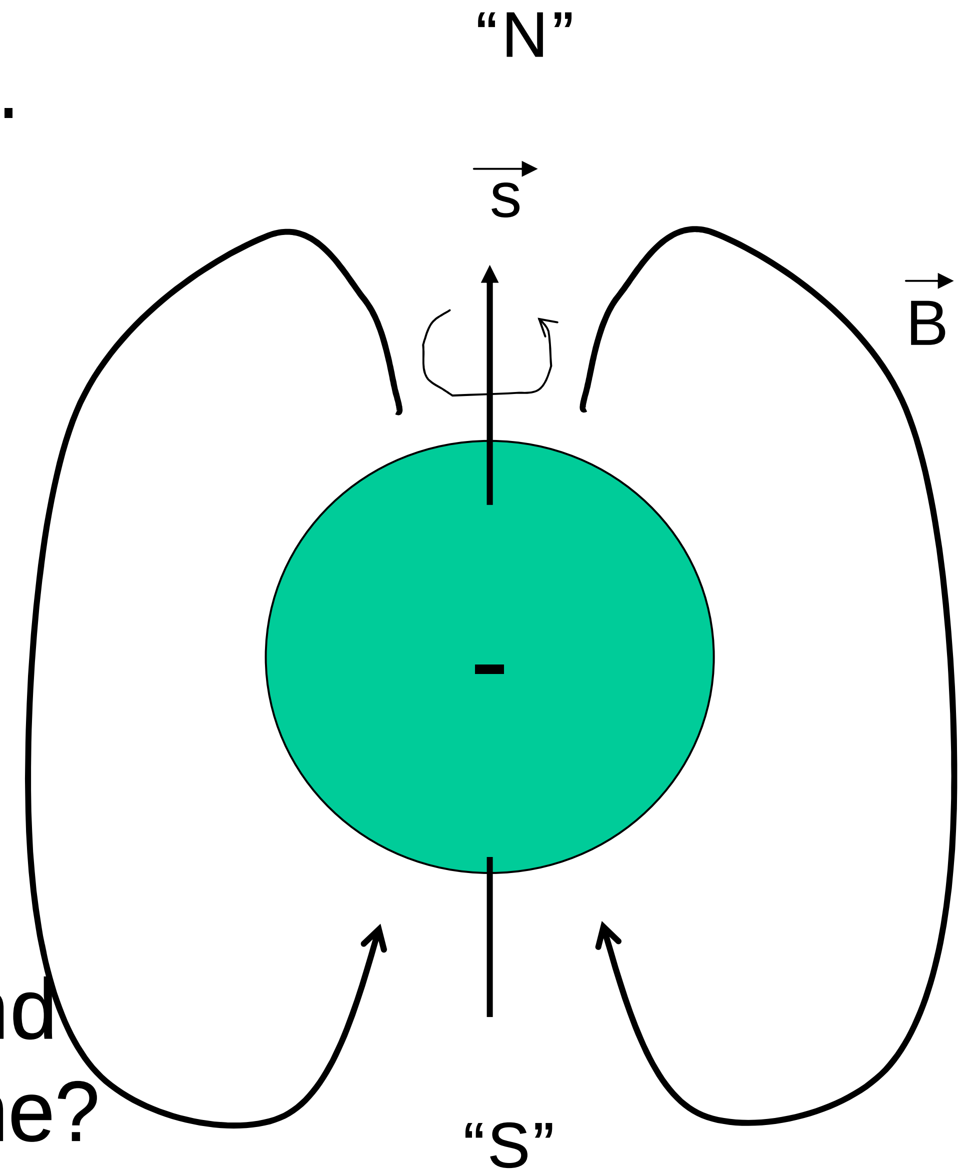
Meet Mr. Electron.

charge = -q
mass = m_e
It spins.
It has a magnetic north pole and south pole.



Meet Mr. Electron.

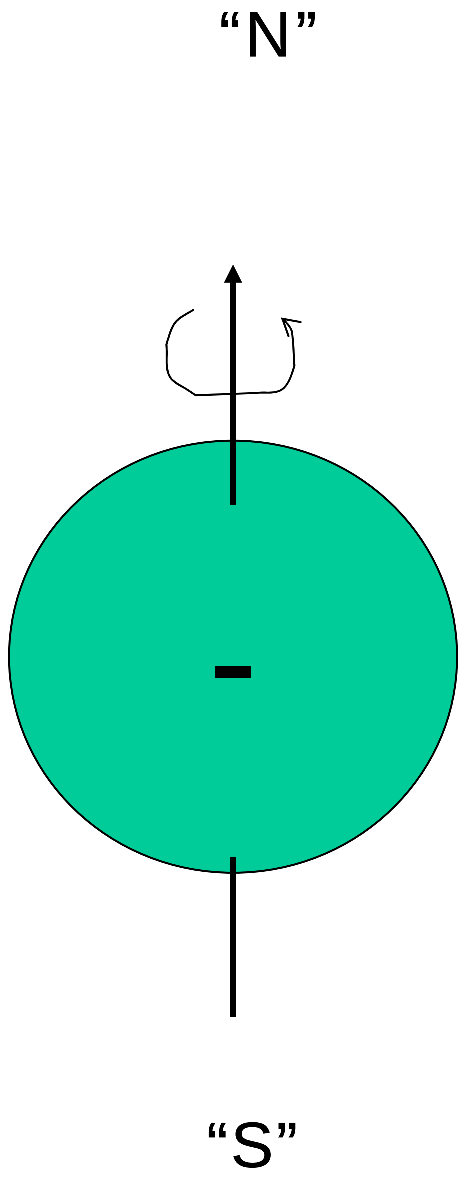
charge = -q
mass = m_e
It spins.
It has a magnetic north pole and south pole.
Symmetry
Question: north and south pole the same?



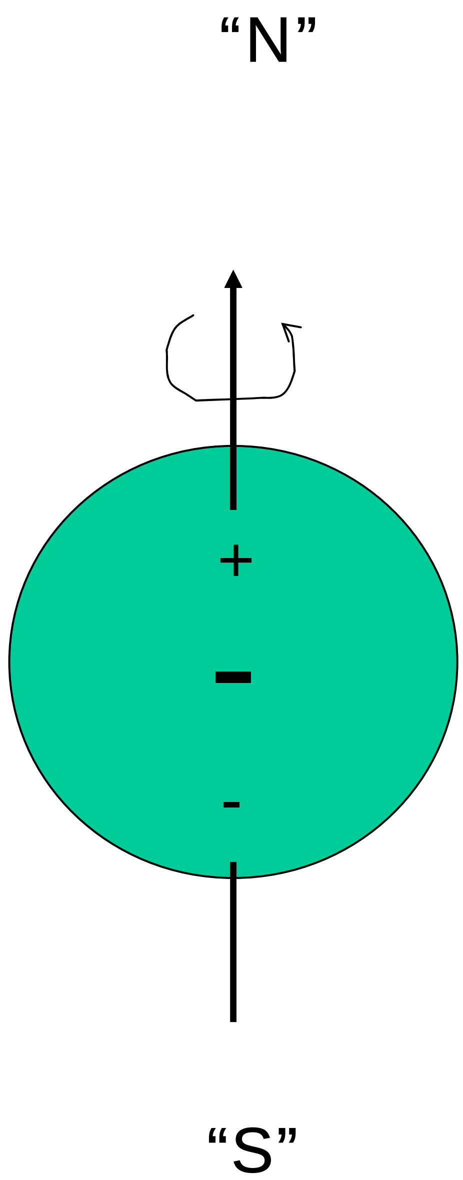
North Pole, Earth

South Pole, Earth

Meet Mr. Electron.

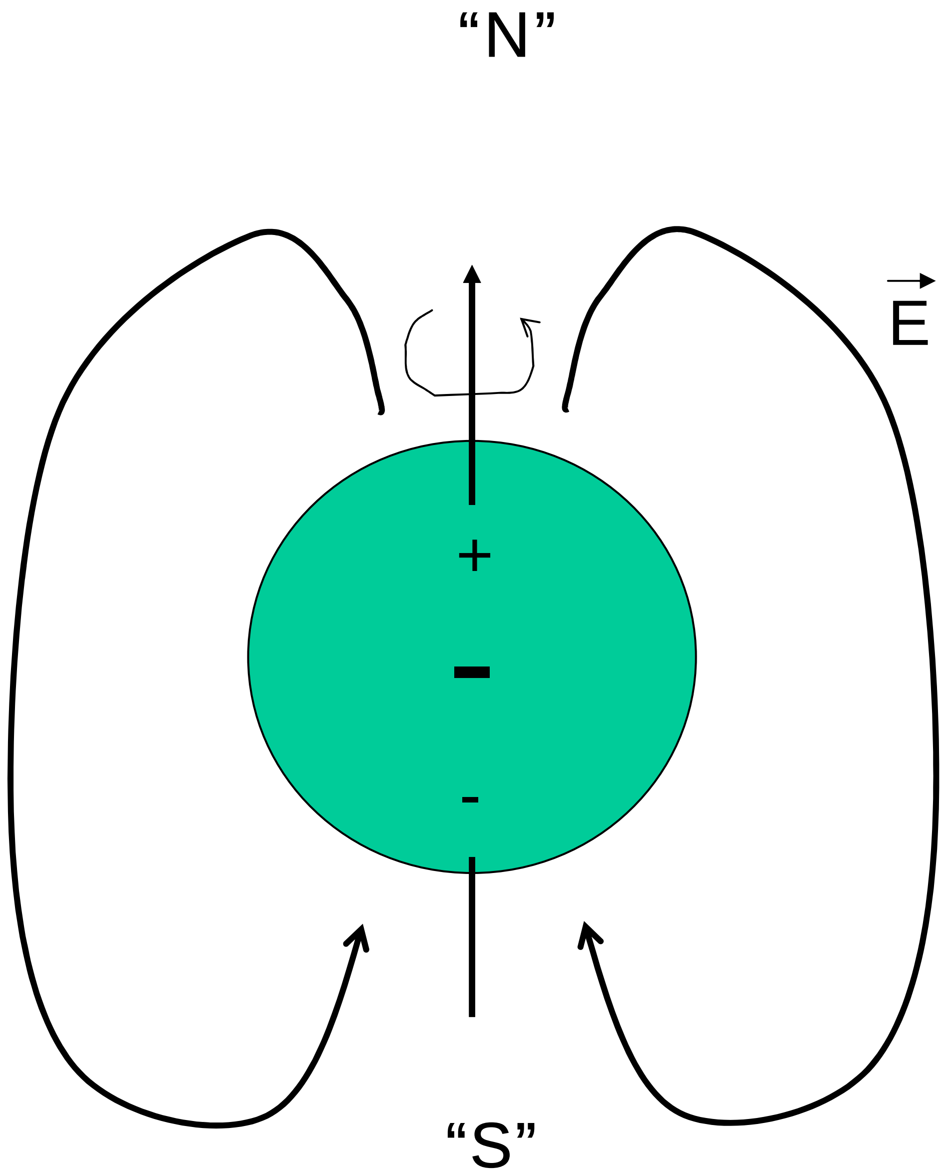


Meet Mr. Electron.



Meet Mr. Electron.

electron
Electric
Dipole
Moment
(eEDM)?



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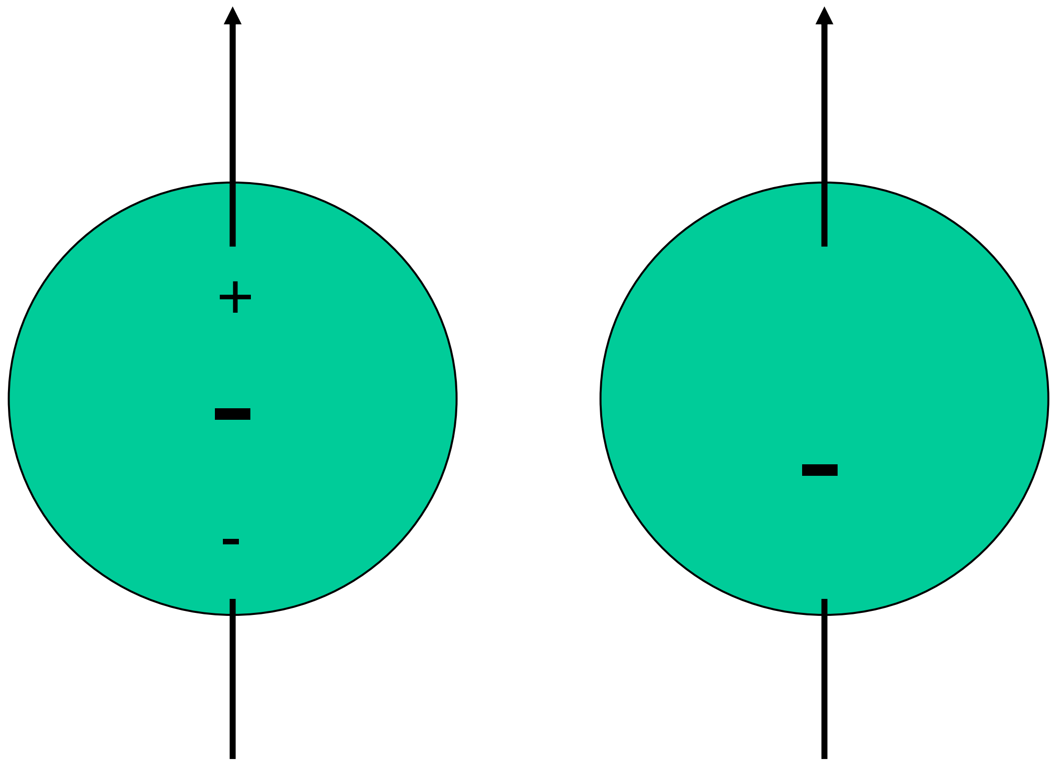
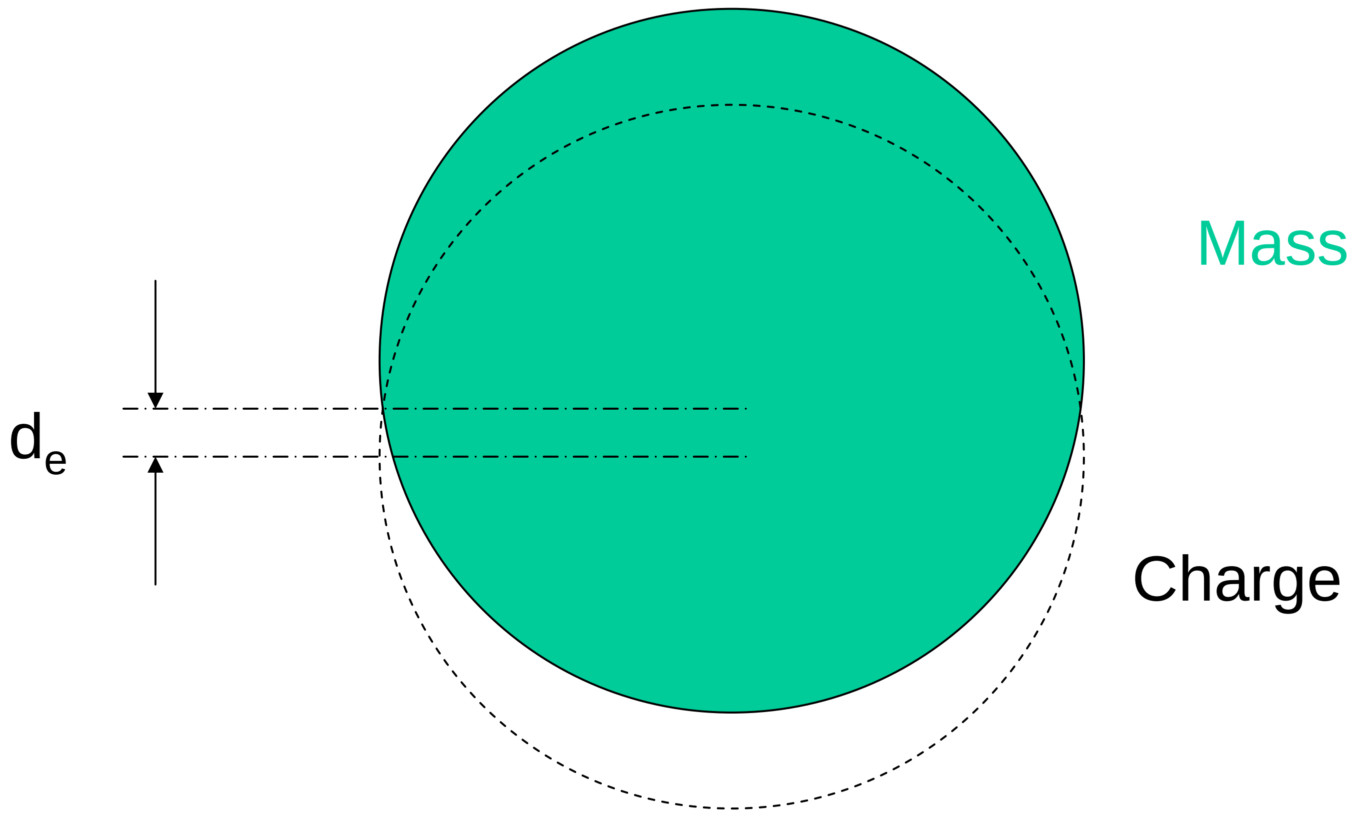
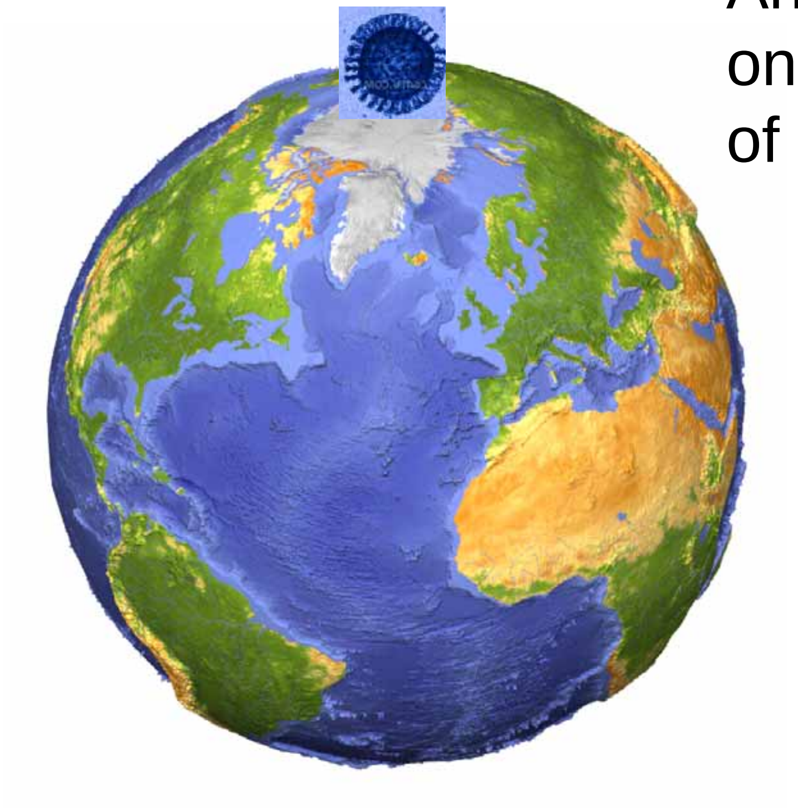


eEDM looks like offset between center of mass and center of charge!



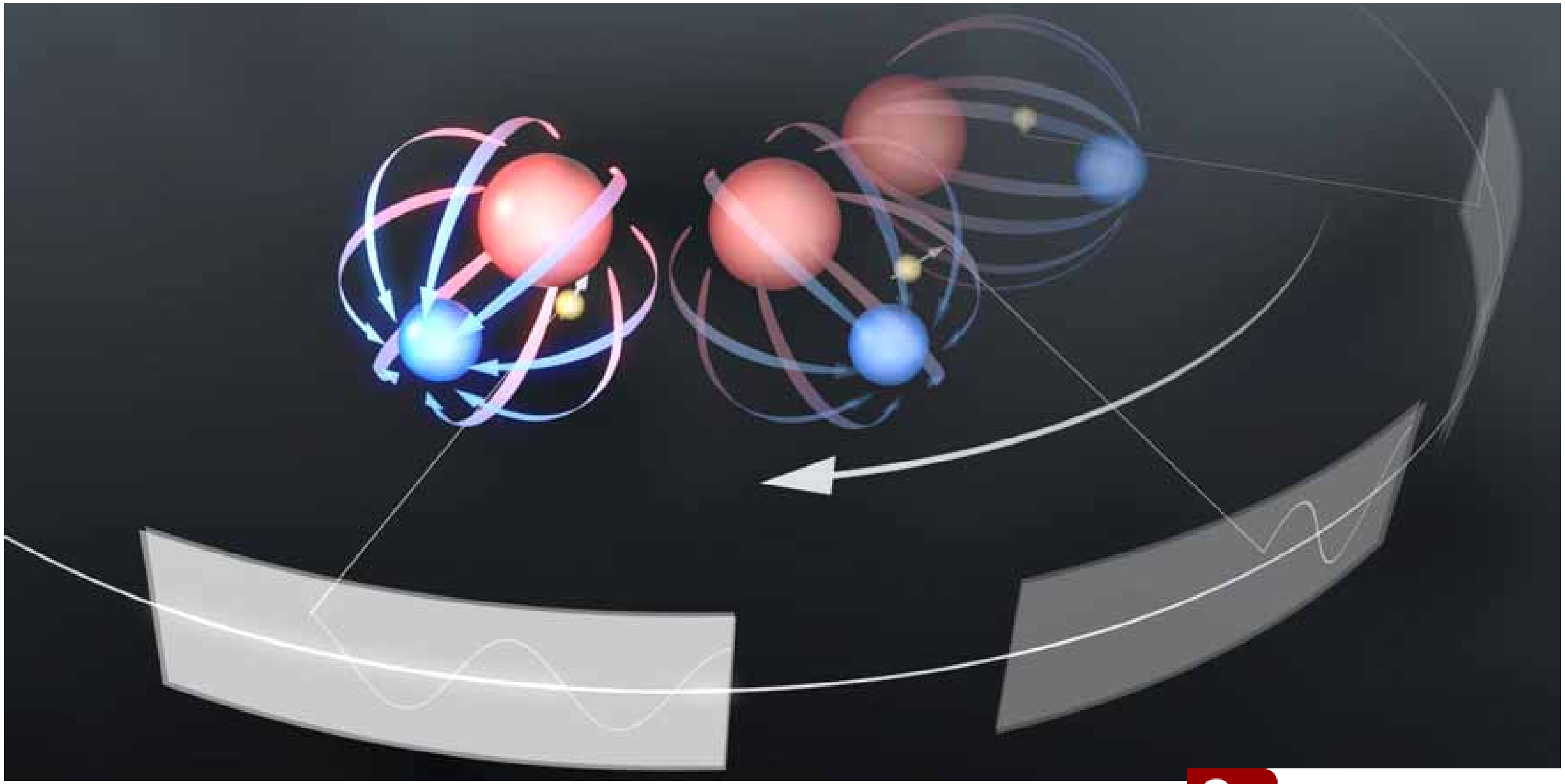
$d_e < 10^{-28}$ cm



An extra thickness of electric charge on north pole, in proportion to the size of the earth, thickness of a virus.

If the electron has an asymmetry of this tiny size, a very small “electric dipole moment”, that would be a *very important* “fossil”, a big clue to help explain the more important asymmetry, the asymmetry that asks “why are we here?”

Measuring electron EDM using molecular ions



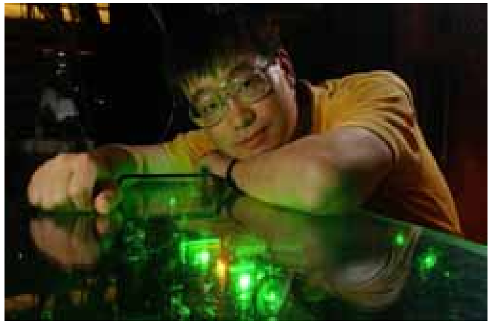
JILA eEDM collaboration

- Kevin Cossel (now Dr.)
- Matt Grau
- Laura Sinclair
- Huanqian Loh
- Dr. Kang-Kuen Ni (now Prof.)
- Will Cairncross
- Dan Gresh
- Yiqi Ni
- Prof. Jun Ye
- Prof. Eric Cornell

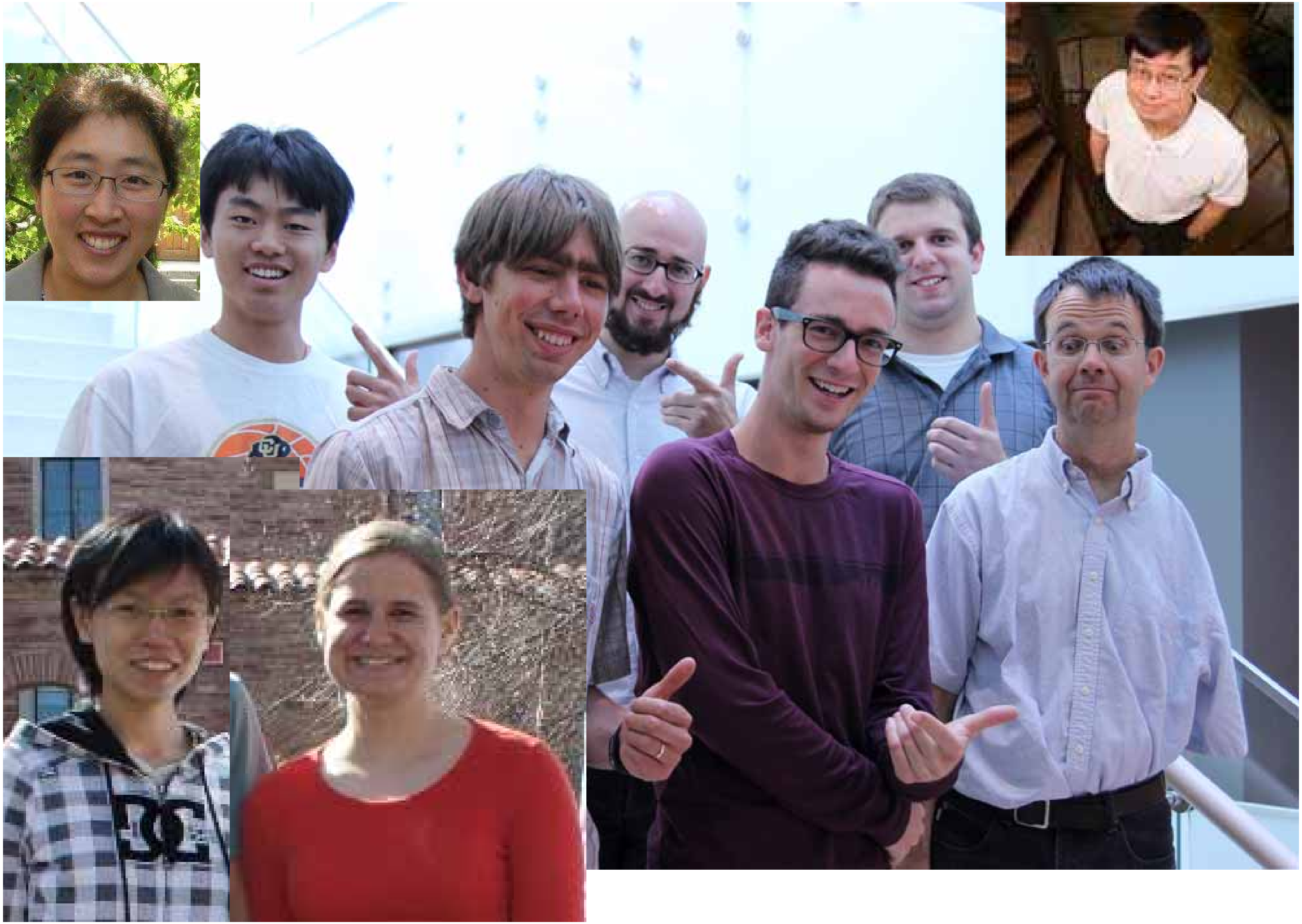
•Bob Field

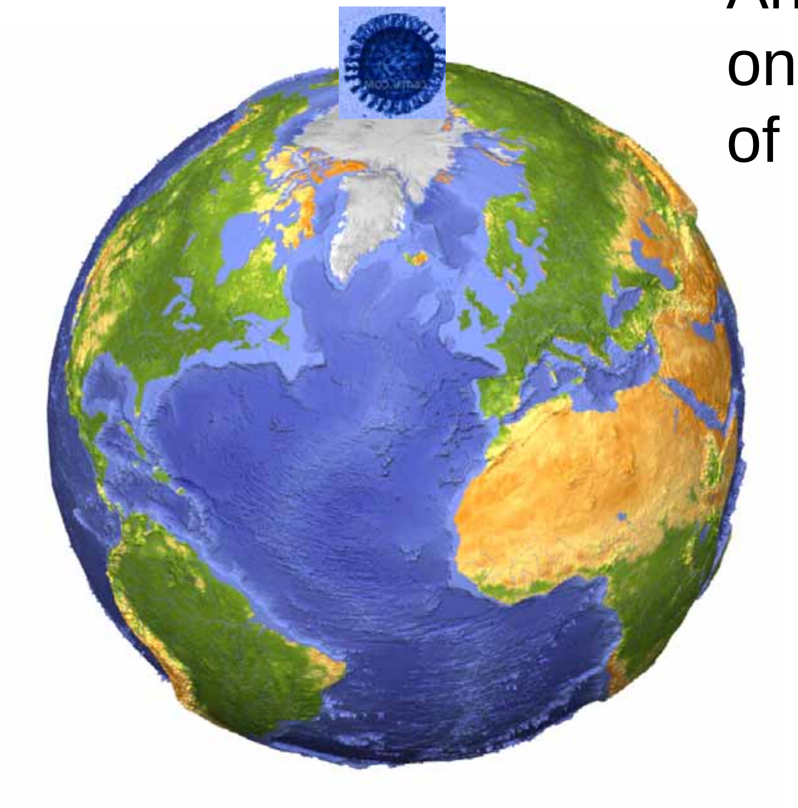
•John Bohn
•Ed Meyer
•Chris Greene
•Jia Wang

•St Petersberg Theory



Thanks: NSF/PFC, NIST,
and Marsico Foundation

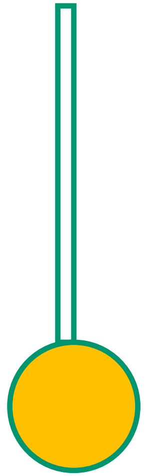


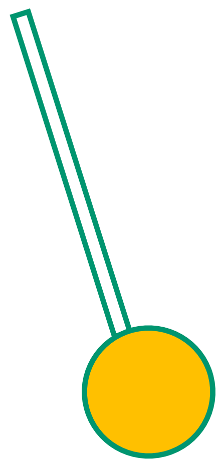


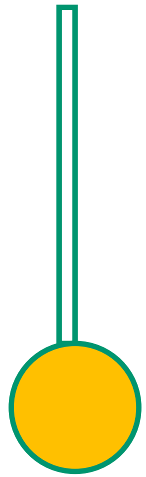
An extra thickness of electric charge on north pole, in proportion to the size of the earth, thickness of a virus.

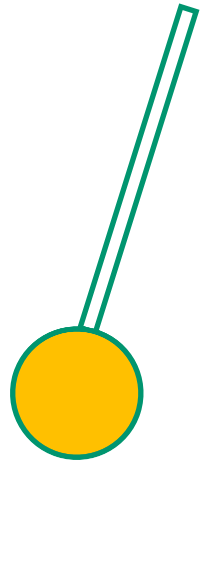
How to measure something so very small?

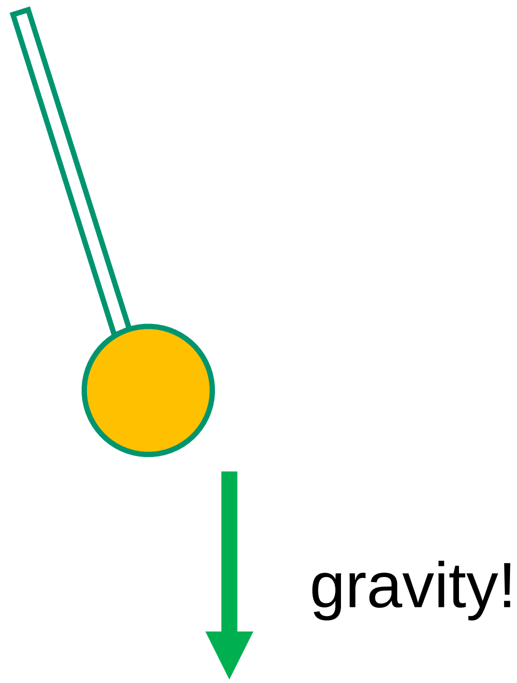
#1 Rule of experimental physics: if you want to measure something very carefully, change the thing you want to measure into a frequency, and measure that!

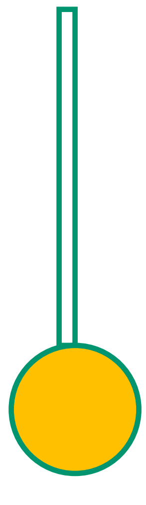



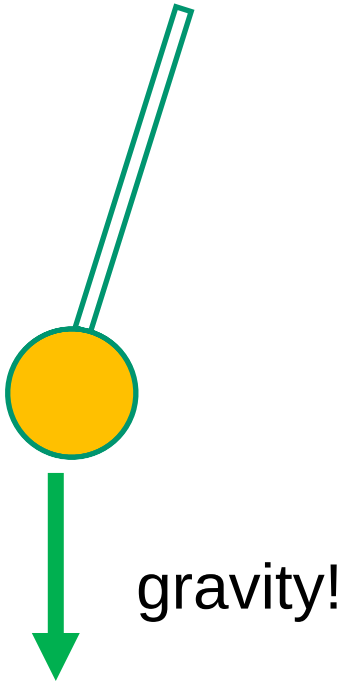






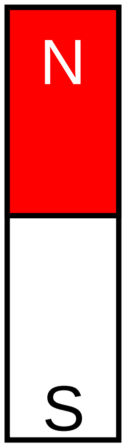

gravity!



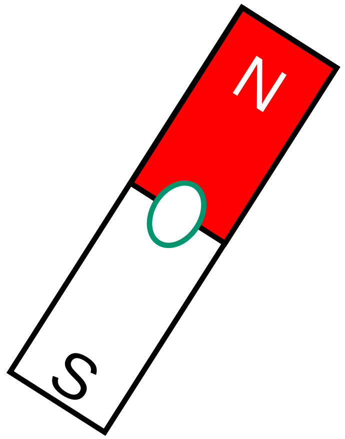


This is a very good way to measure gravity. If it gets even a very small amount stronger or weaker, the clock will "tick" a little faster or a little slower.   Physicists can measure changes in clock as small as on part in 1,000,000,000,000,000   (10^{-15})

Ex #2: How strong is the magnet?



A compass.



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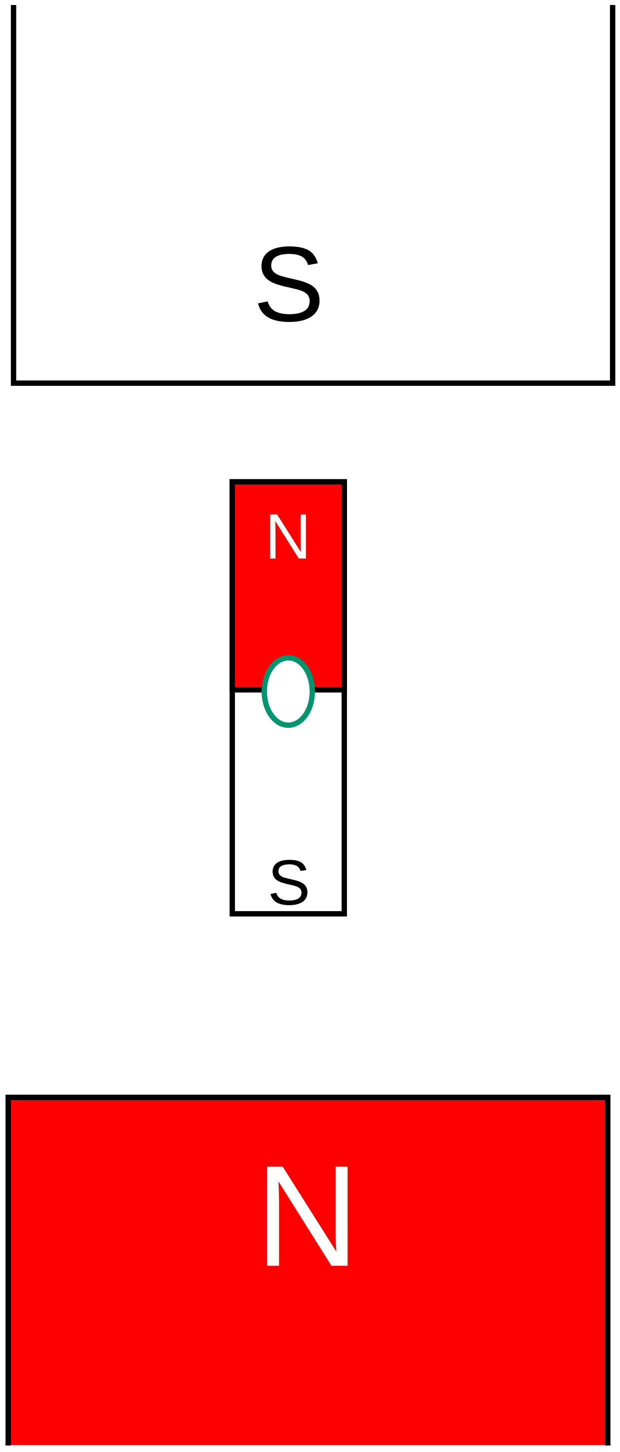

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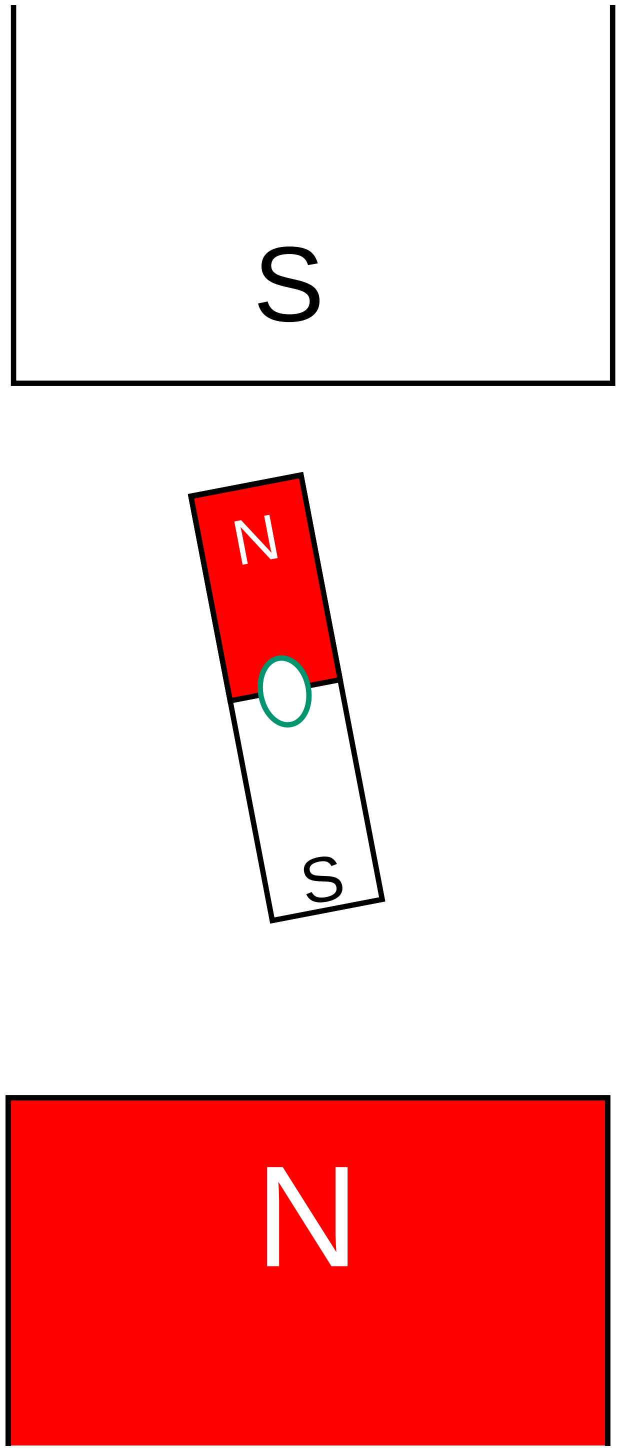

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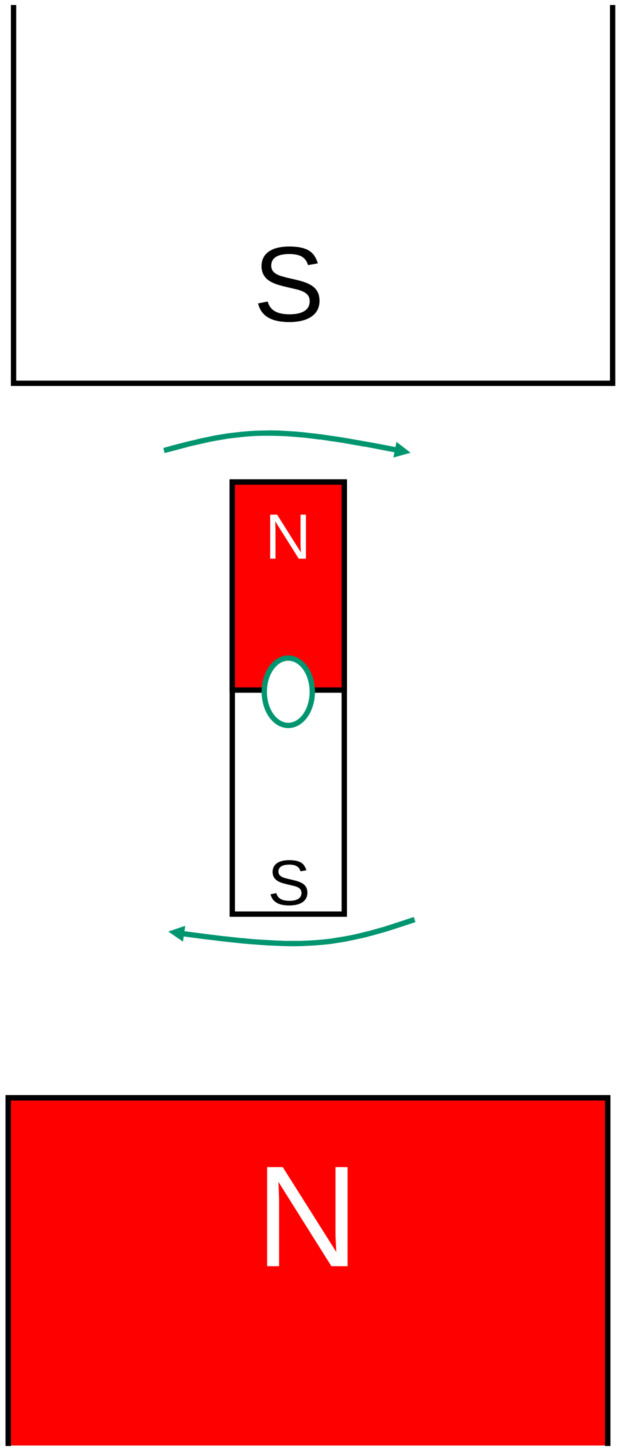

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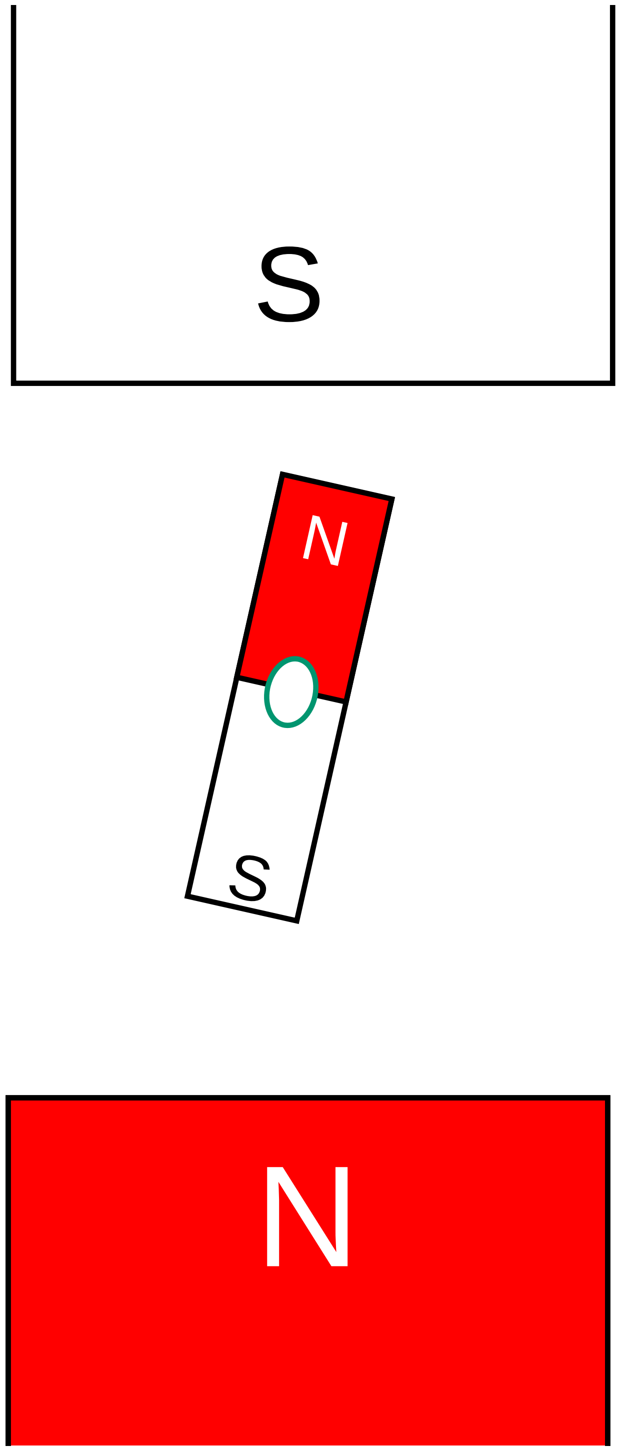
A compass.



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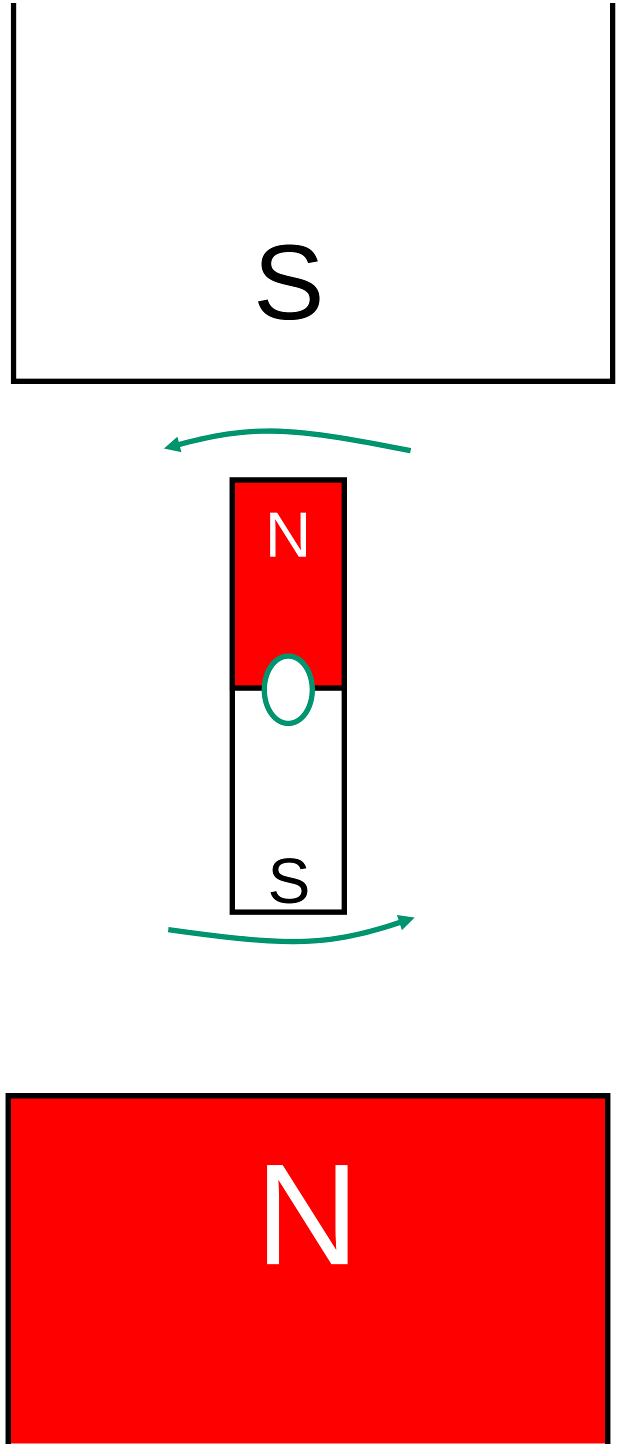

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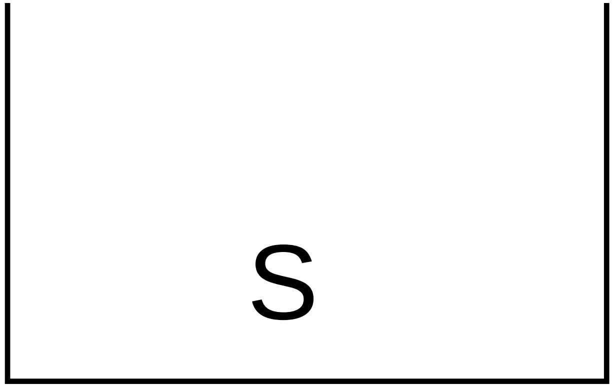
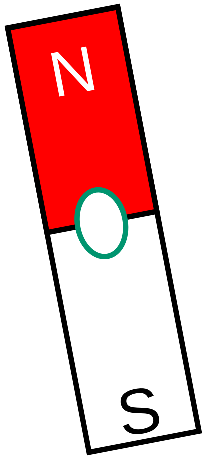
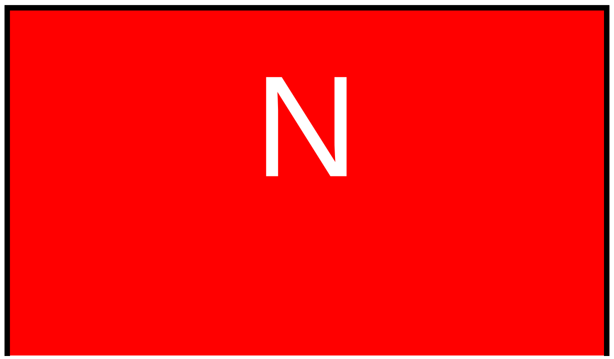


A compass.

If our little magnet is weak, it wiggles slowly (low frequency), if it is strong, it wiggles quickly (high frequency).
Measure the frequency measure the magnet!





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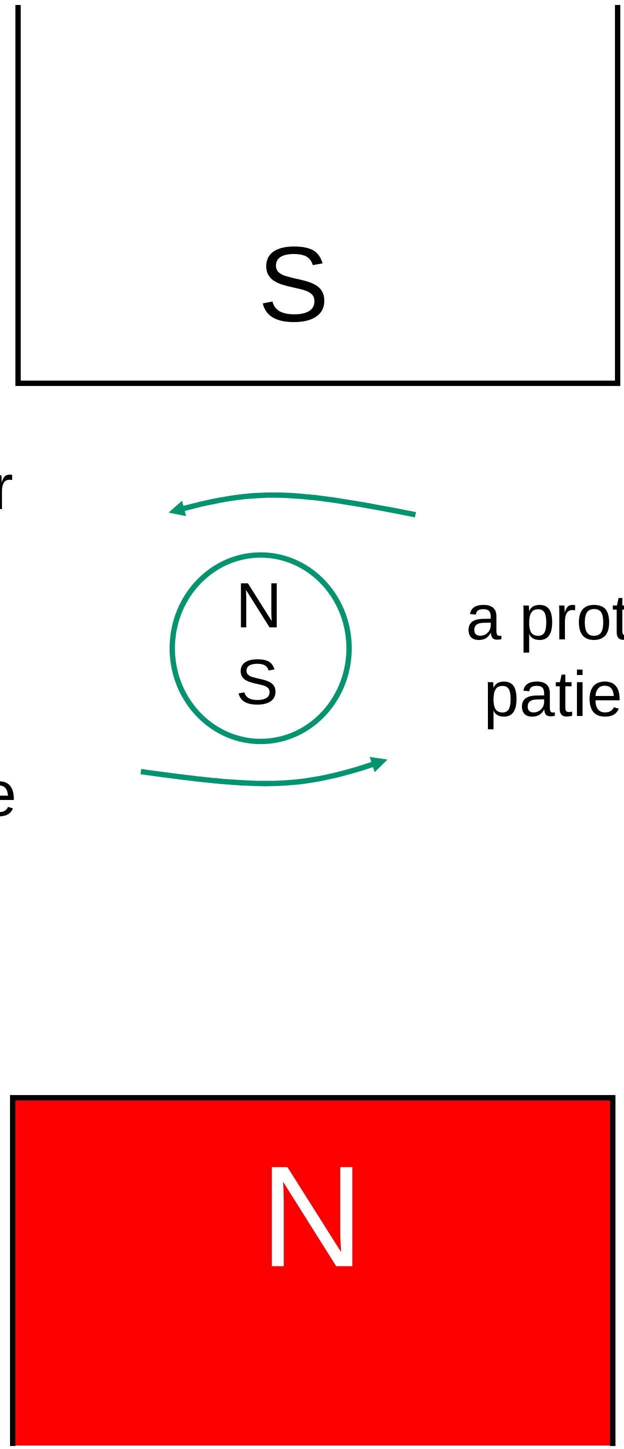
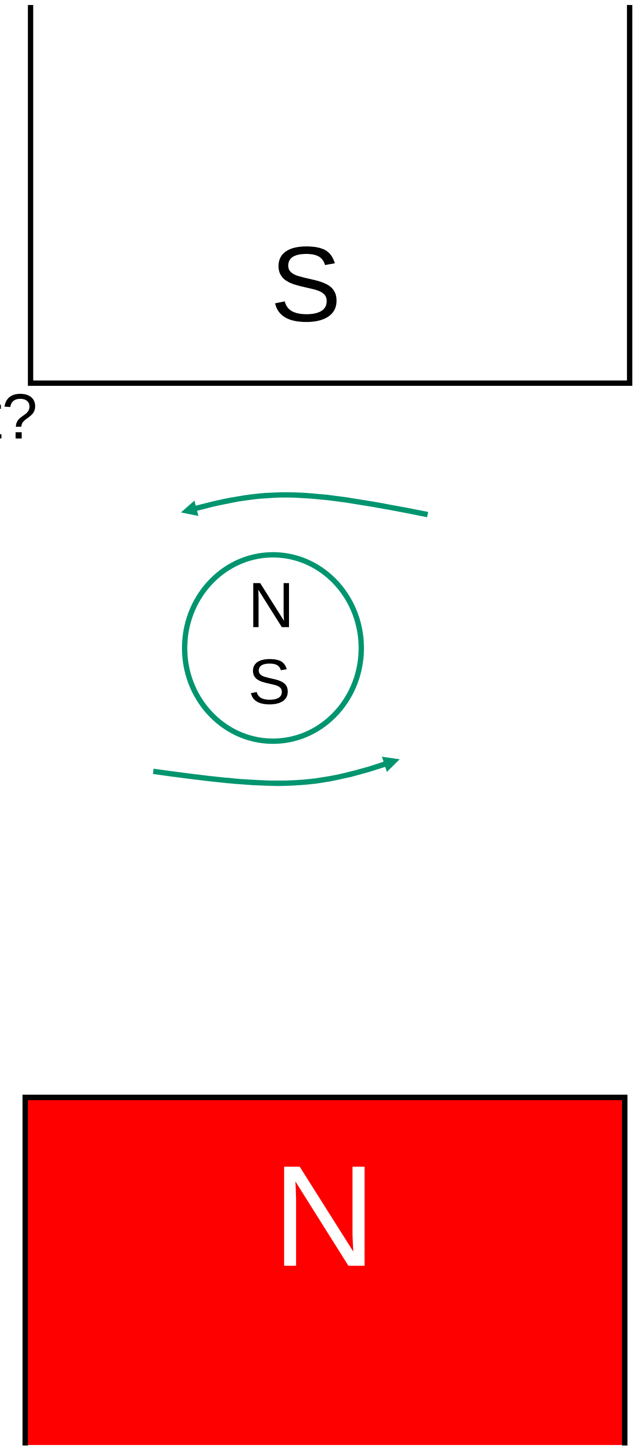
A compass.



The proton (inside your body, inside the NMR scanner) is a very small magnet. To make the proton wiggle strongly we need the biggest lab magnet possible.

a proton inside patient's body.

Ex #3: Forget about proton! Forget about magnet!
What about electron electric dipole moment?



A compass.

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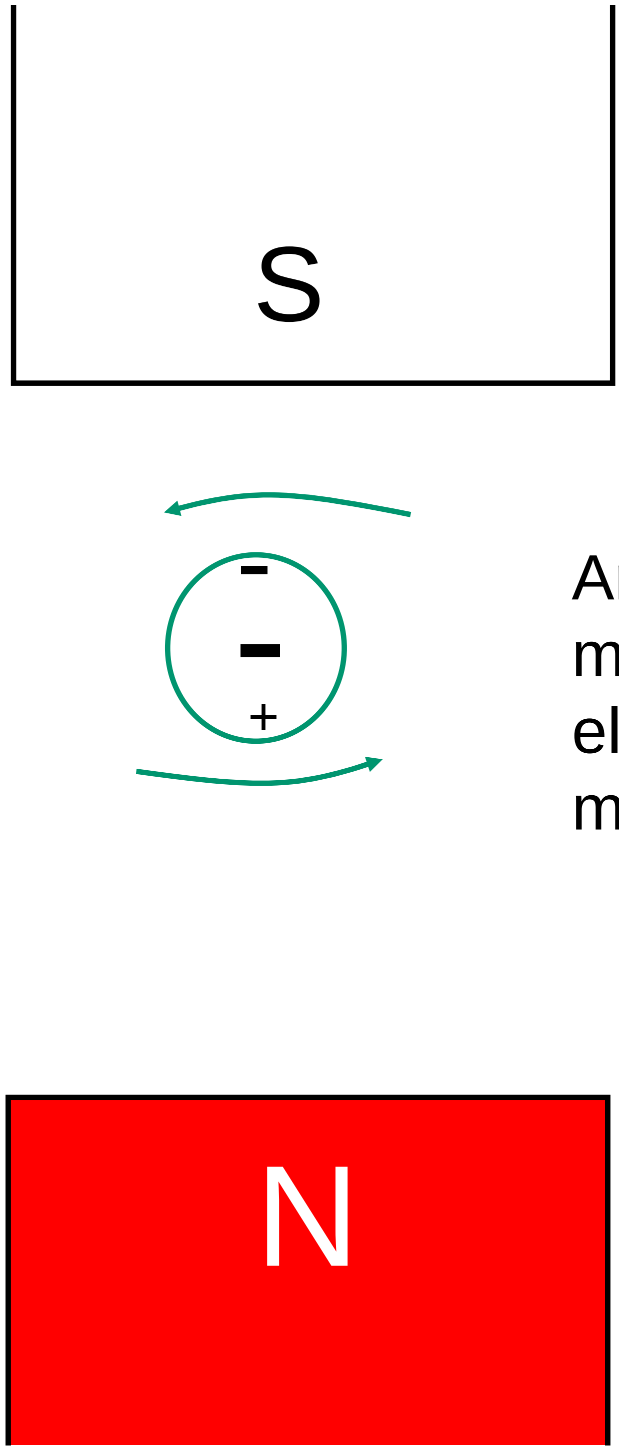

A compass.

An electron with, maybe!
electric dipole moment (EDM)

Ex #3: Forget about proton! Forget about magnet!
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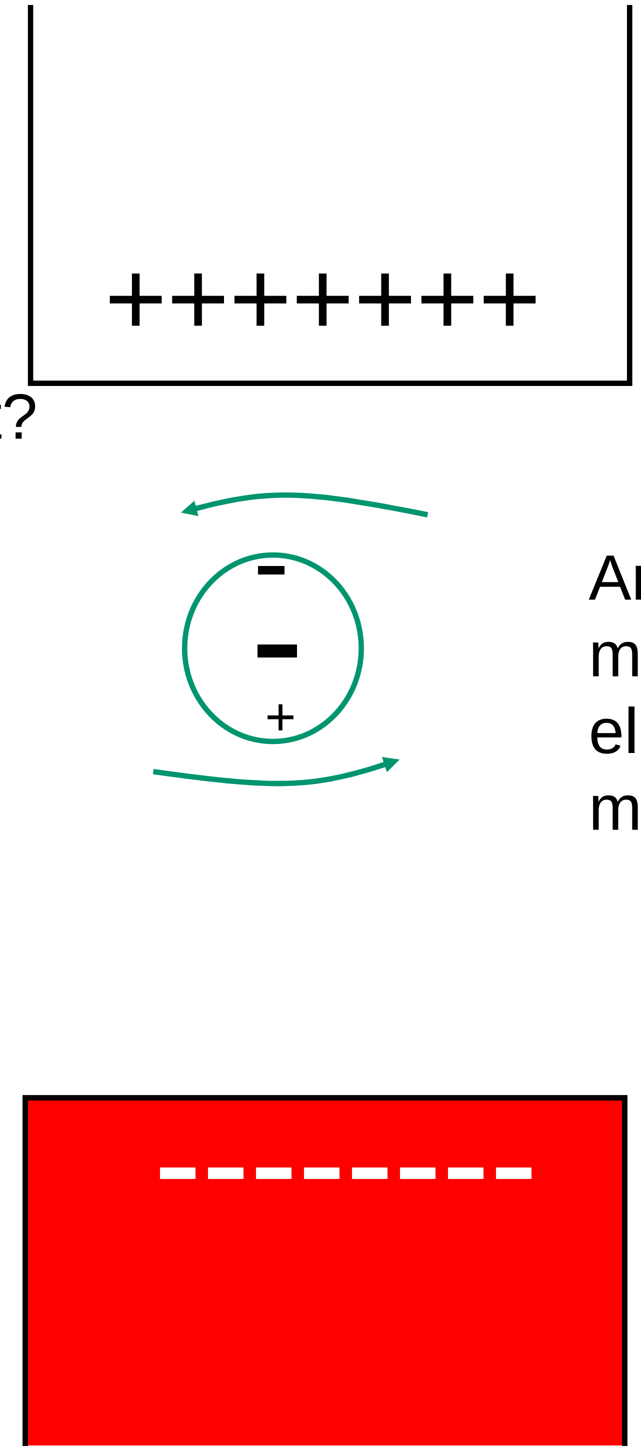
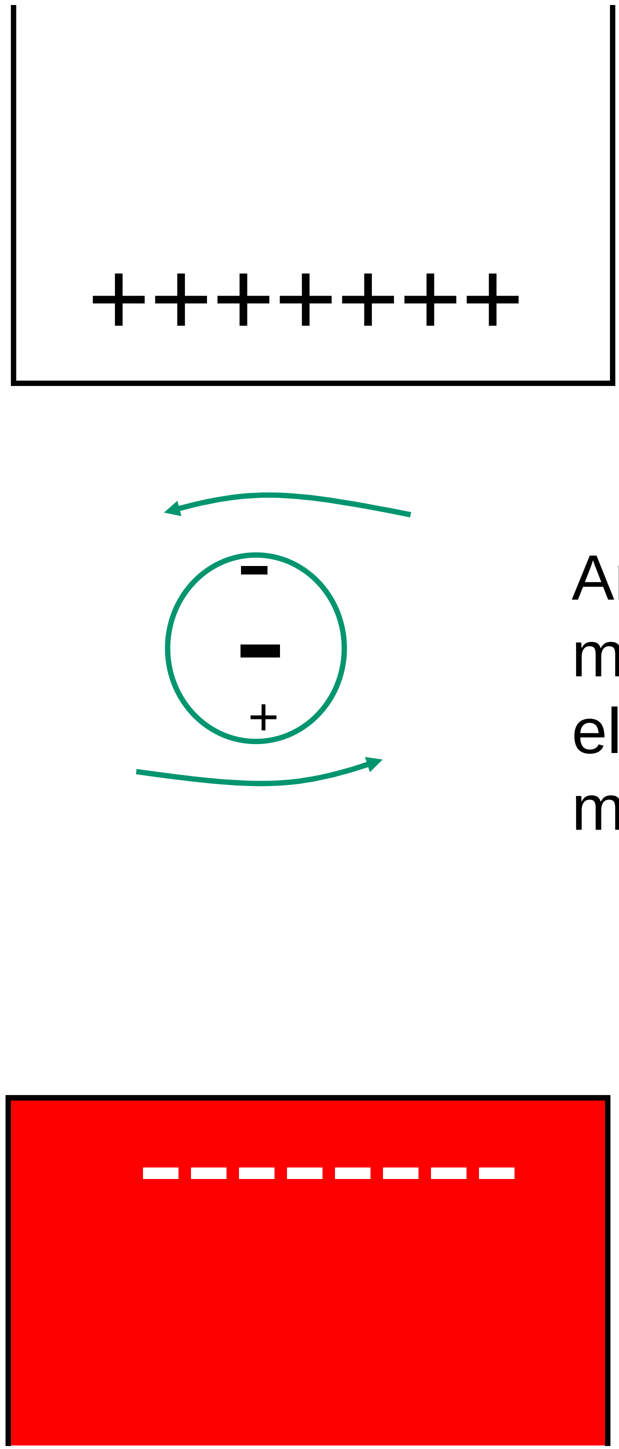
A compass.



An electron with, maybe!
electric dipole moment (EDM)

A compass.

If electron EDM exists at all, it is very small. We must apply a VERY large electric field. Two problems!



An electron with, maybe! electric dipole moment (EDM)

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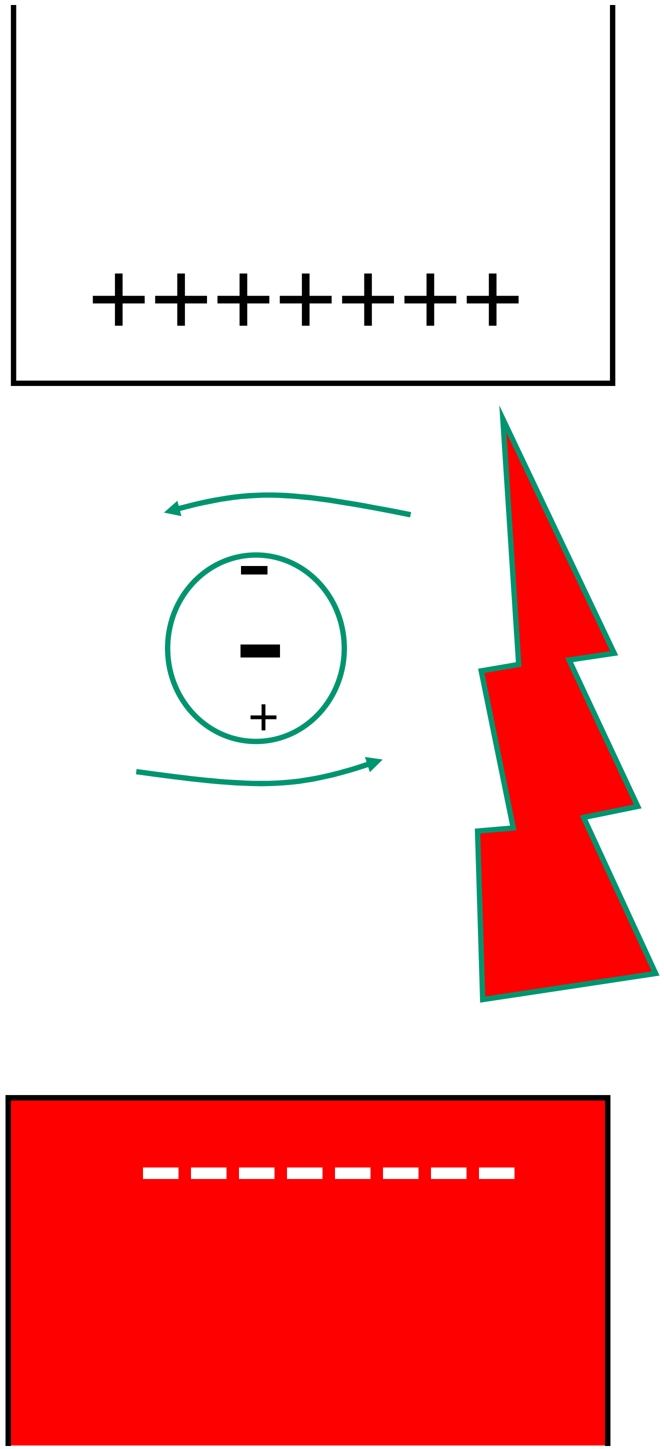
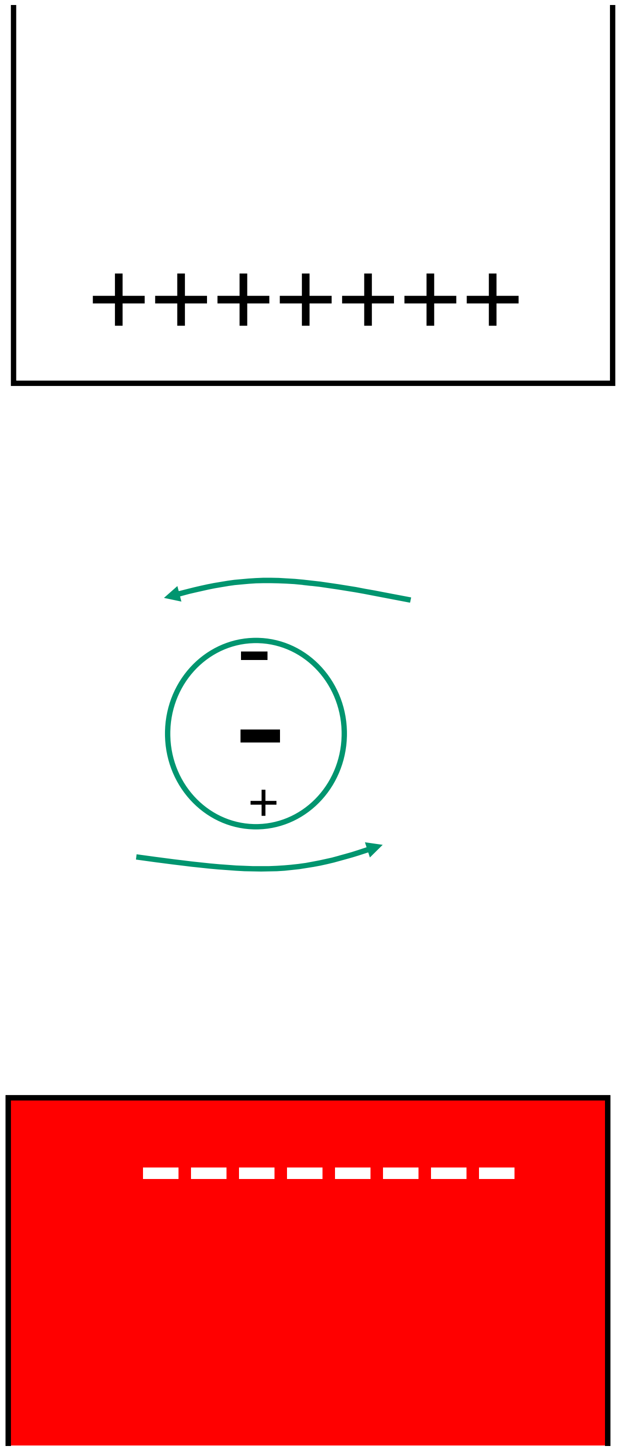


Problem 1:
Lightning!
Spark!
(If electric field
is too big.)

If electron EDM exists at all, it is very small. We must apply a VERY large electric field. Two problems!

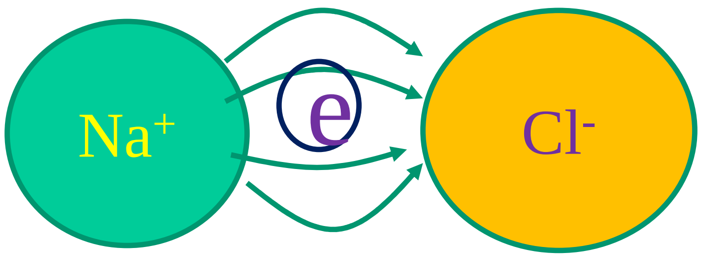


Problem 2: Electron gets pulled away by electric field.

Q: Where in nature can we find a REALLY STRONG electric field?

Q: Where in nature can we find a REALLY STRONG electric field?
A: Inside a molecule!

Example: NaCl (Sodium Chloride). Plain salt.



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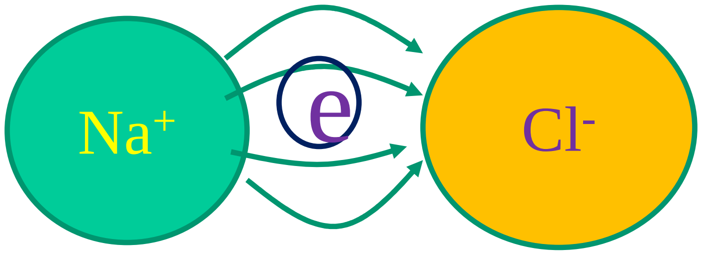
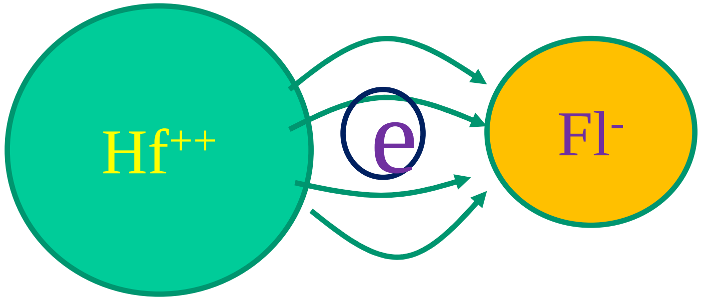
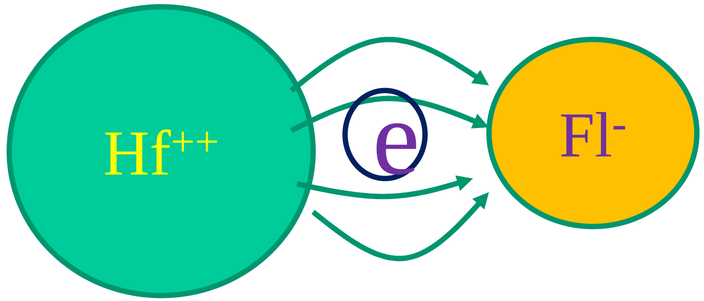




We use HfF^+
"Hafnium Fluoride plus"

Big electric field is good –
it helps electron wiggle faster!
What else do we need to compare
time really well?



We use HfF^{+}
"Hafnium Fluoride plus"

Grandfather #1: “tick, tick, tick…”

Grandfather #2: “tick, tick, tick…”

Grandfather #1: “tick, tick, tick…”

Grandfather #2: “tick, tick, tick…”

Which clock is faster? Let’s count the “ticks”.
After one min,
#1: 60 ticks. #2: 60 ticks.
Are they the same?

Grandfather #1: “tick, tick, tick…”

Grandfather #2: “tick, tick, tick…”

Which clock is faster? Let’s count the “ticks”.
After one min,
#1: 60 ticks. #2: 60 ticks.
Are they the same?
Let’s count for one hour.
#1: 3600. #2 3600.

Grandfather #1: “tick, tick, tick…”

Grandfather #2: “tick, tick, tick…”

Which clock is faster? Let’s count the “ticks”.
After one min,
#1: 60 ticks. #2: 60 ticks.
Are they the same?
Let’s count for one hour.
#1: 3600. #2 3600.
Wow. They are really the same. Let’s count for one day:
#1: 86398. #2: 86399.

Grandfather #1: “tick, tick, tick…”

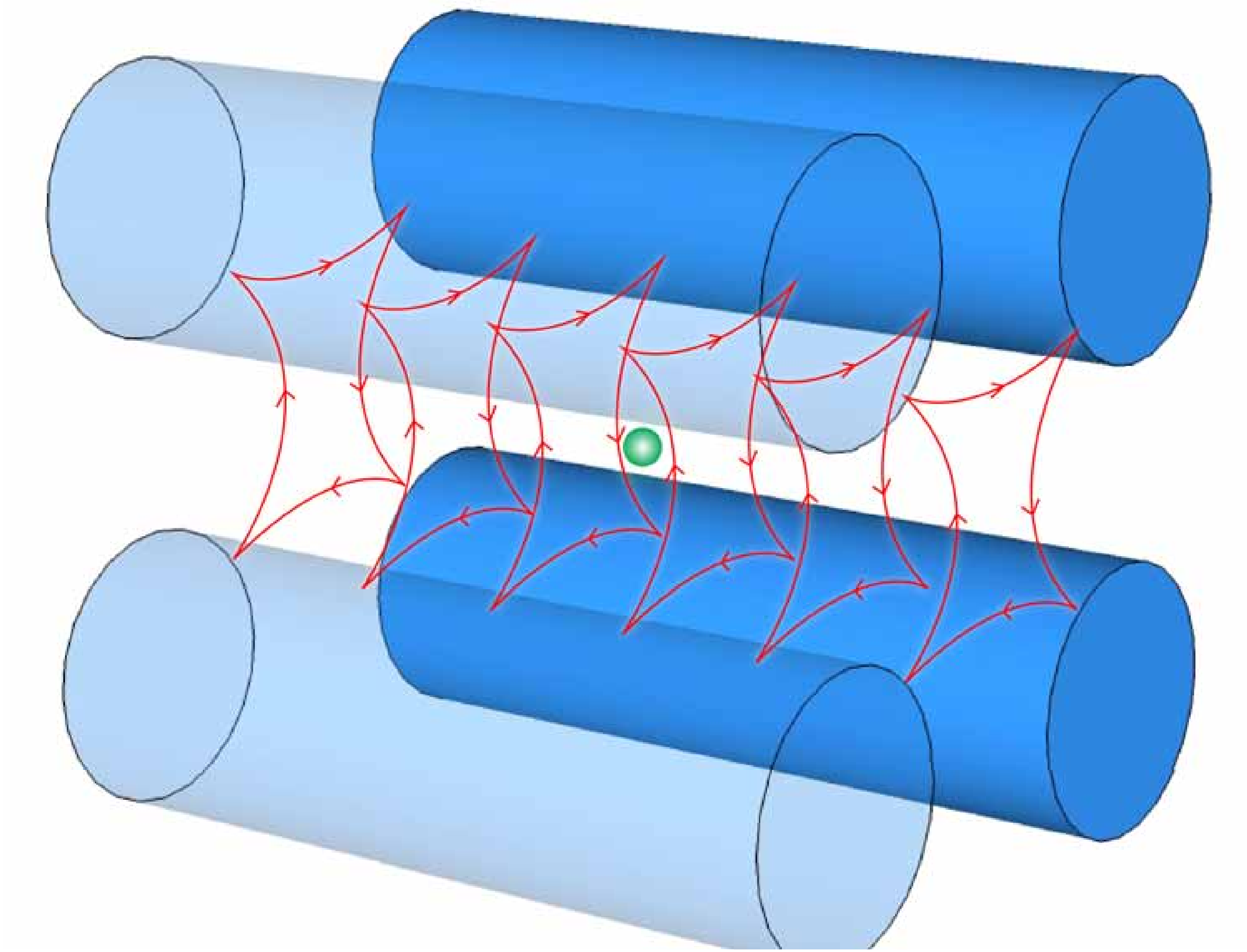
Grandfather #2: “tick, tick, tick…”

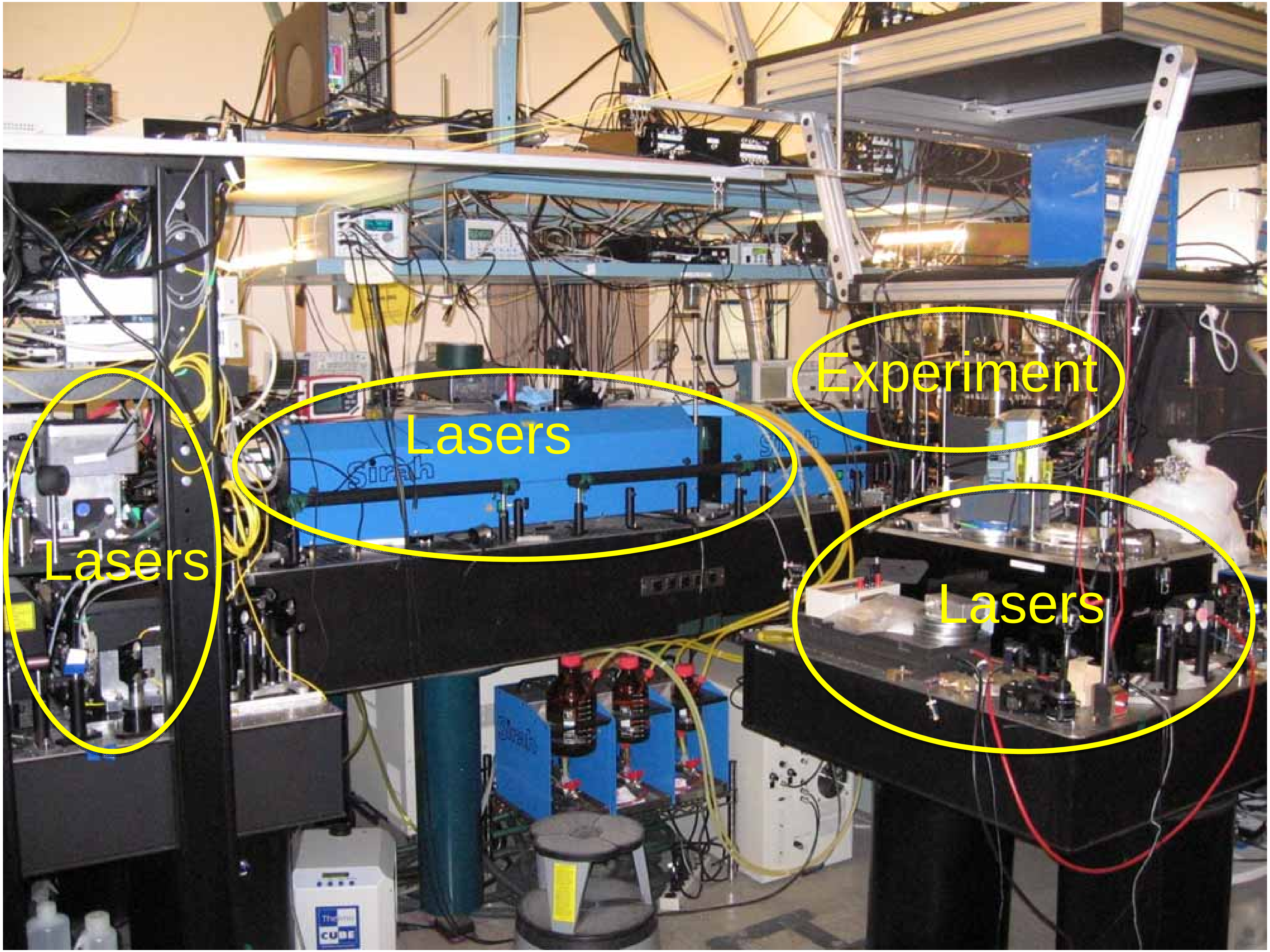
Which clock is faster? Let’s count the “ticks”.
After one min,
#1: 60 ticks. #2: 60 ticks.
Are they the same?
Let’s count for one hour.
#1: 3600. #2 3600.
Wow. They are really the same. Let’s count for one day:
#1: 86398. #2: 86399.

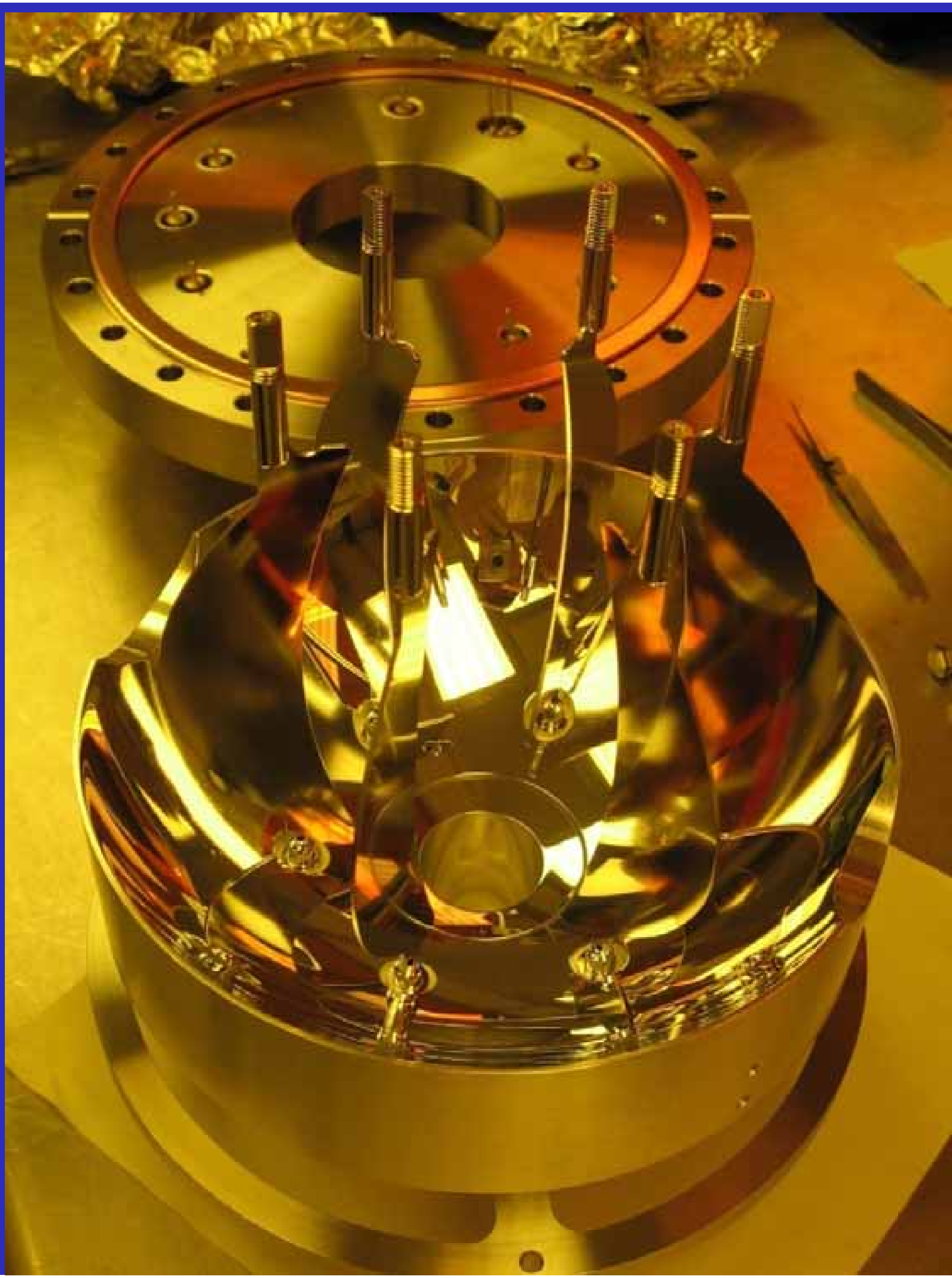
Aha. Grandfather #2 is a little bit faster!
But we had to watch them for a long time, to know.

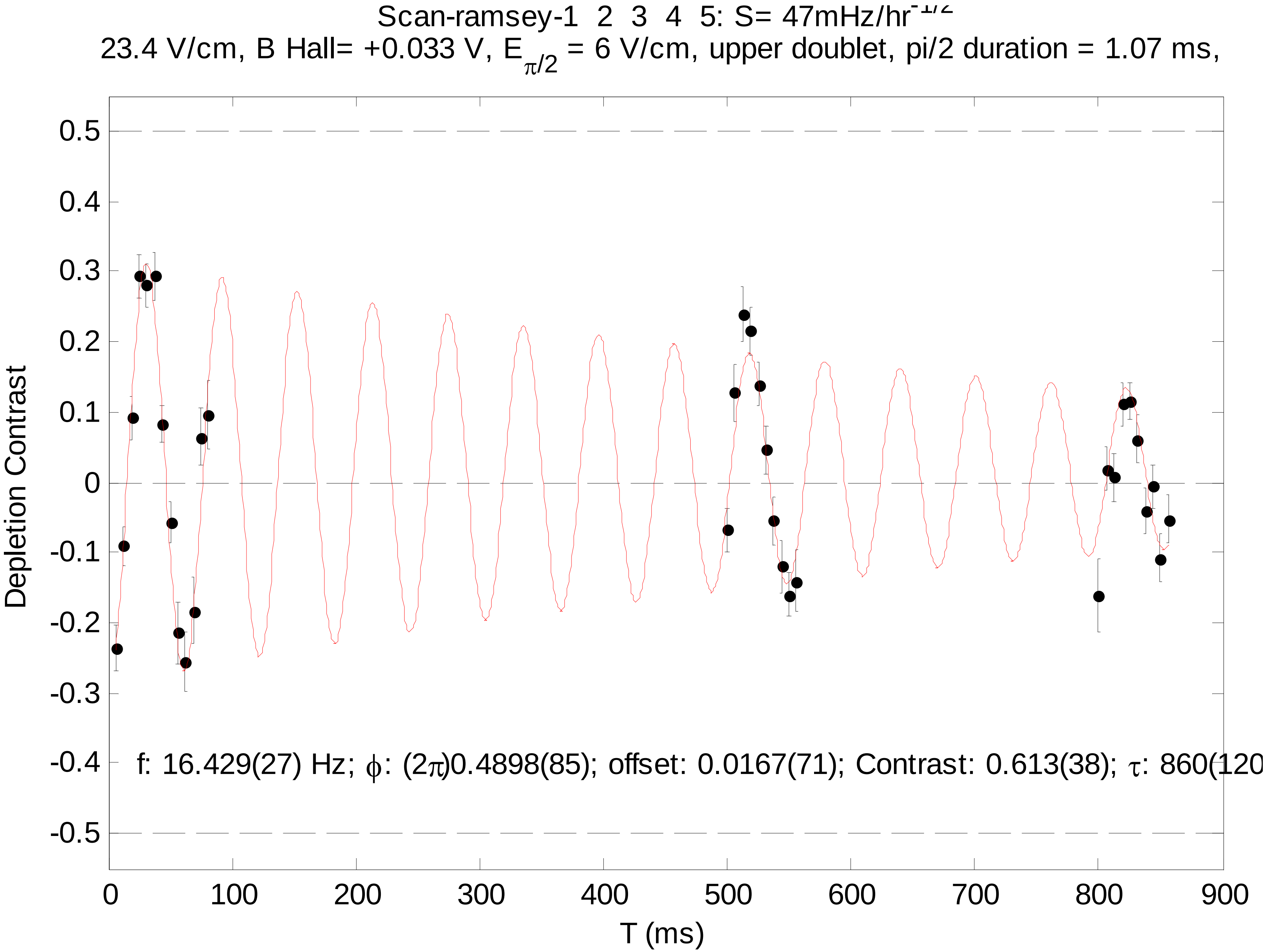
In order to listen to the electron "tick" for a long time, we keep the molecule, HfF^+, in an "ion trap".

A box to keep ions in so we can measure them a long time.
An “ion trap.”




Experiment
Lasers
Lasers
Lasers

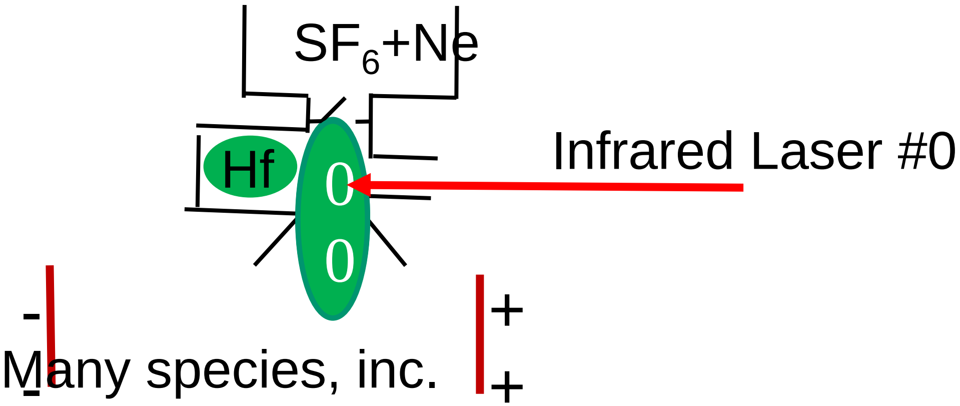




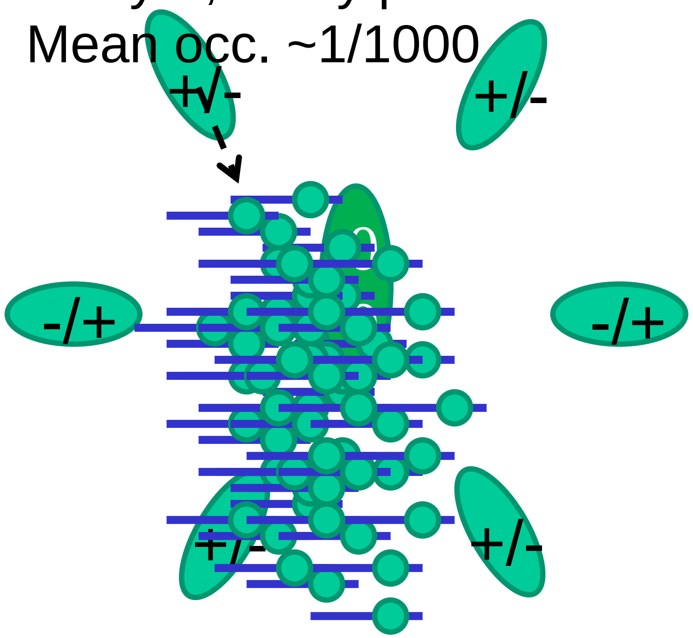
Scan-ramsey-1 2 3 4 5: S= 47mHz/hr^-1/2
23.4 V/cm, B Hall= +0.033 V, E_π/2 = 6 V/cm, upper doublet, pi/2 duration = 1.07 ms,
Depletion Contrast
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
f: 16.429(27) Hz; φ: (2π)0.4898(85); offset: 0.0167(71); Contrast: 0.613(38); τ: 860(120
0
100
200
300
400
500
600
700
800
900
T (ms)

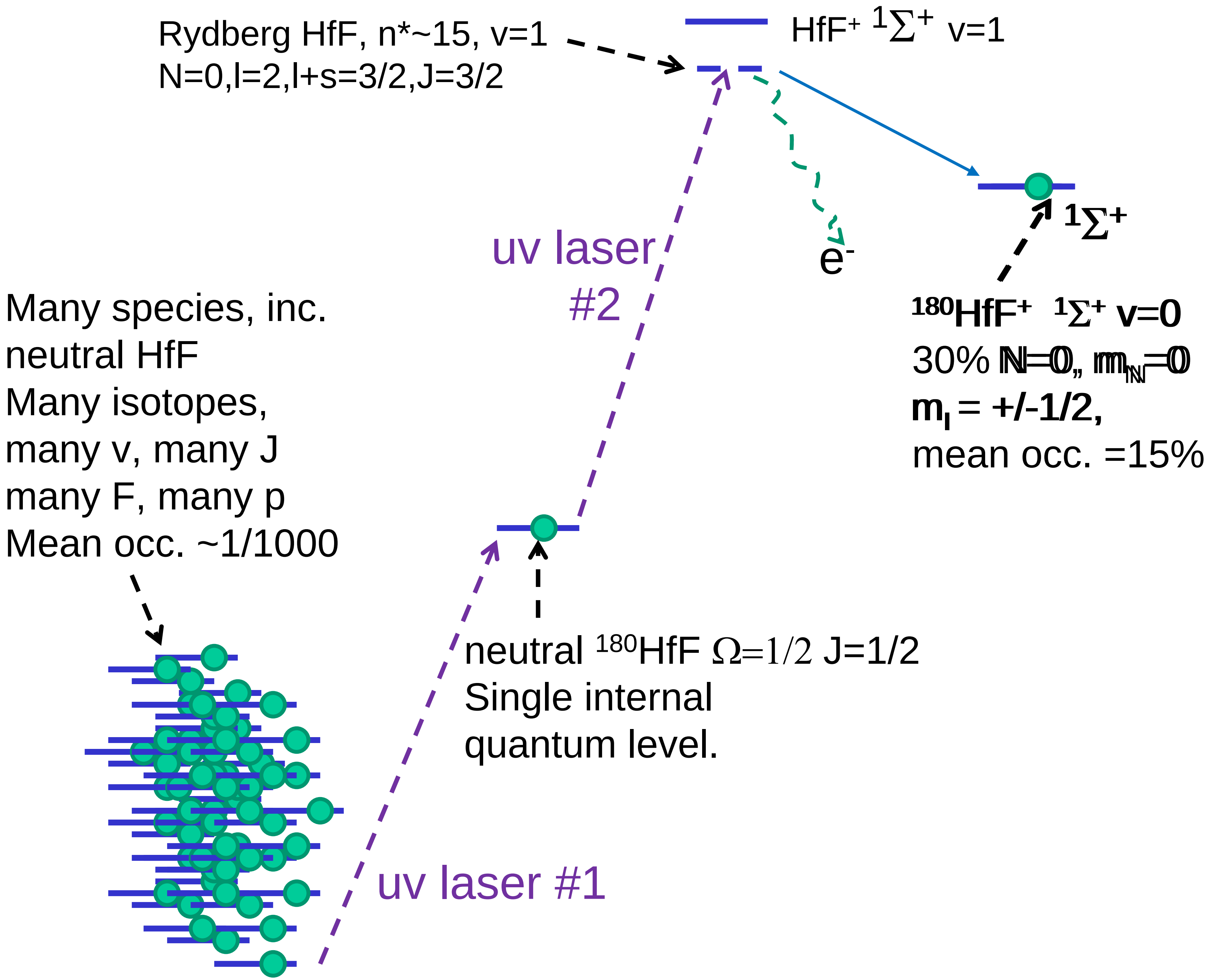
Q #1: How to we make the electron, in the molecule, “tick”?
Q #2: How do we “listen” to it tick?

A: We use lasers.

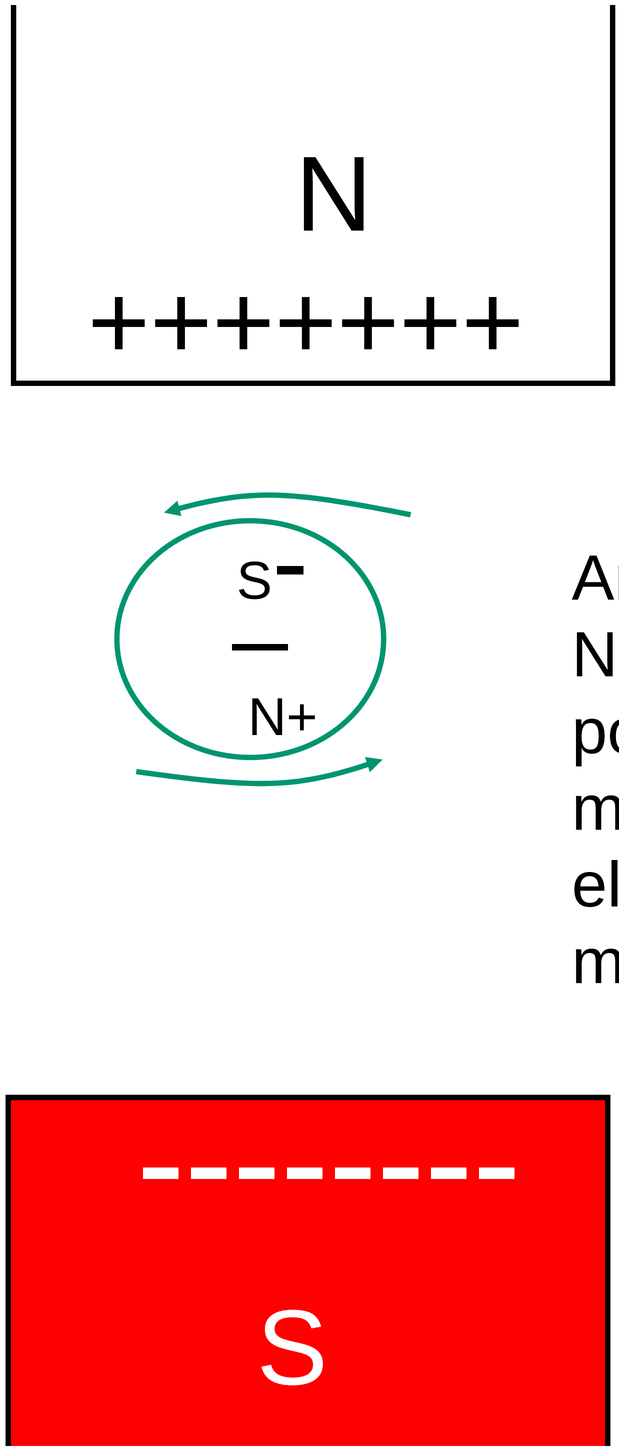


Many species, inc.
neutral HfF
Many isotopes,
many v, many J
many F, many p
Mean occ. ~1/1000



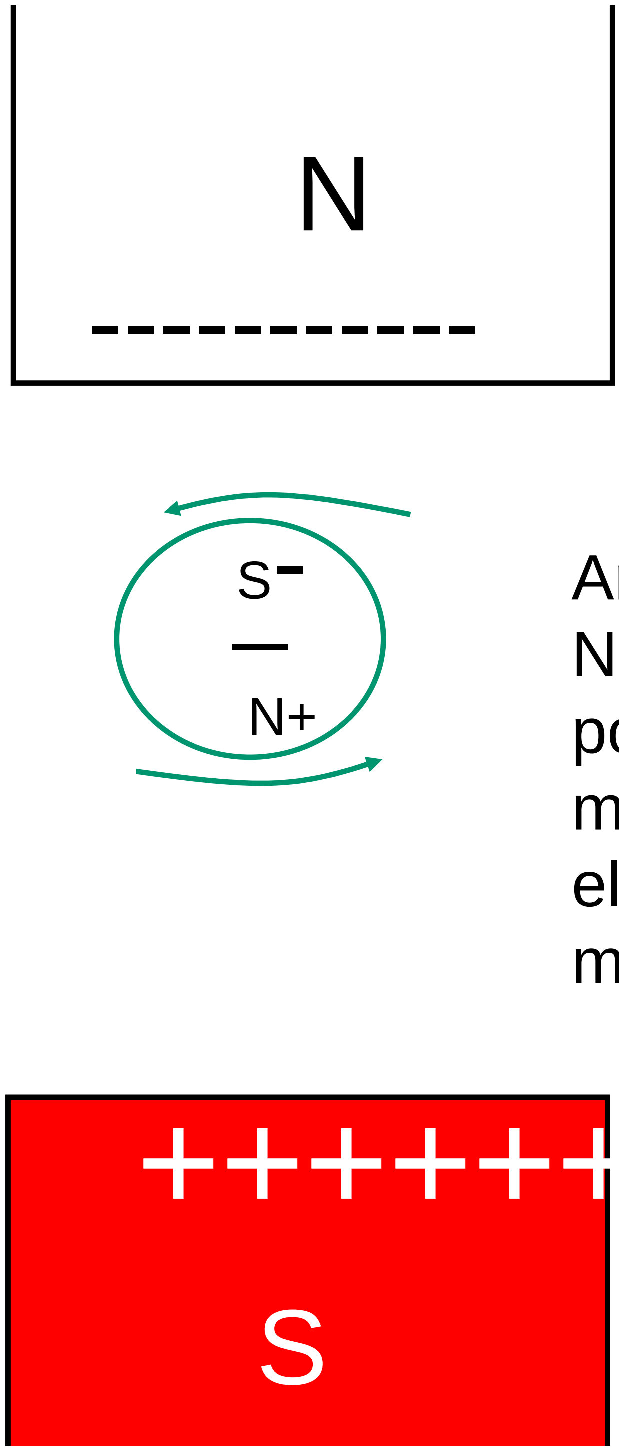


Rydberg HfF, n*~15, v=1
N=0,l=2,l+s=3/2,J=3/2
HfF+ 1Σ+ v=1
uv laser
#2
e-
1Σ+
180HfF+ 1Σ+ v=0
30% N=0, mN=0
mI = +/-1/2,
mean occ. =15%
Many species, inc.
neutral HfF
Many isotopes,
many v, many J
many F, many p
Mean occ. ~1/1000
neutral 180HfF Ω=1/2 J=1/2
Single internal
quantum level.
uv laser #1



A compass.

An electron with,
North pole, south pole and,
maybe!
electric dipole moment (EDM)



A compass.

An electron with,
North pole, south
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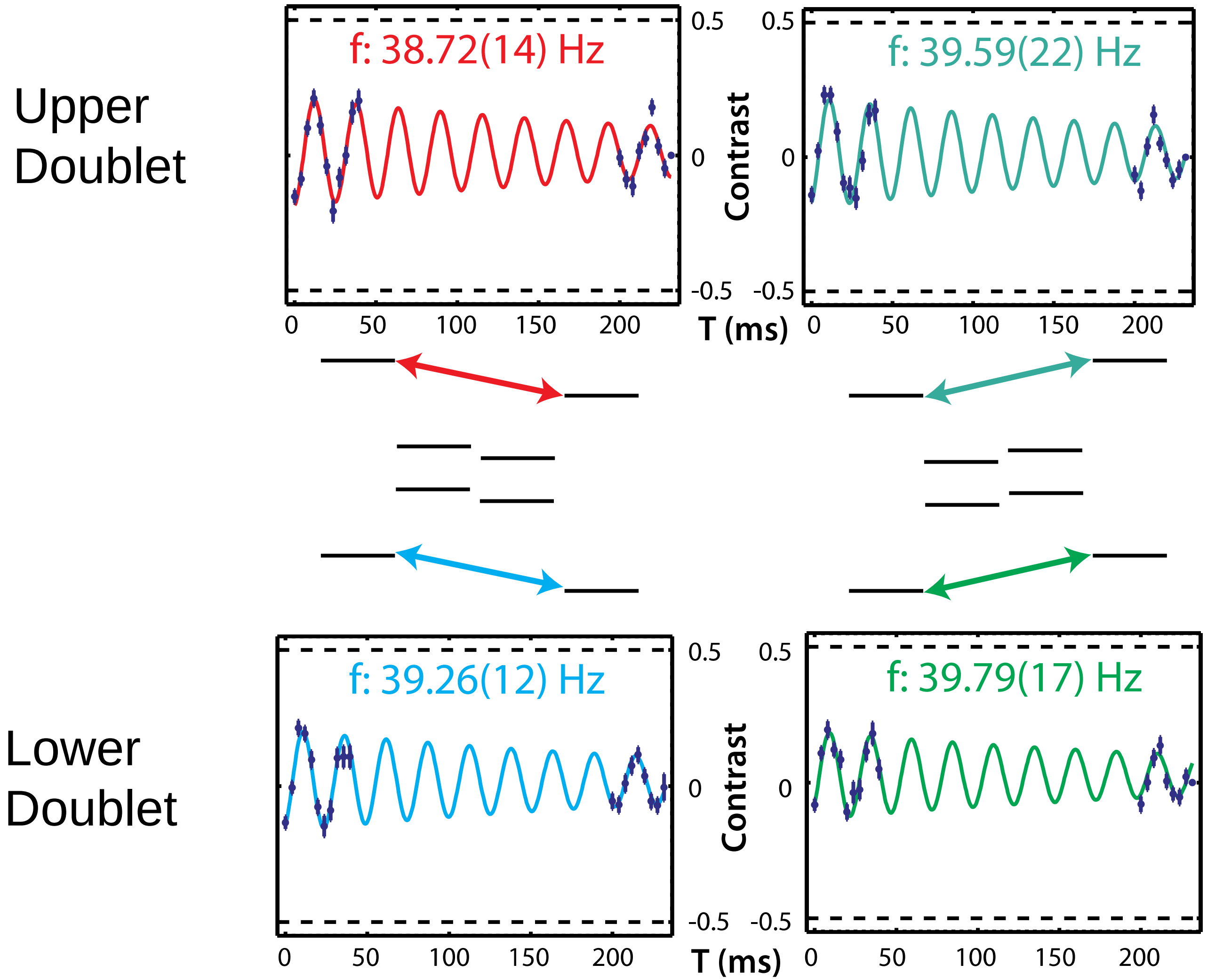
electric dipole
moment (EDM)

$$(f^u(B) - f^u(-B)) - (f^l(B) - f^l(-B)) = 0.34(33)\ \text{Hz}$$

$$d_e < 8 \times 10^{-27} e\ cm$$



Sensitivity Estimate

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

- N = 4 ions/shot (~10^6 counts/day)
- E_{eff} = 5x10^{10} V/cm
- τ = 0.4 second

proj. sensitivity: $|d_e|$ ~ 10^{-28} e*cm with 1 day of data

So far, all measurements are consistent with zero. The most accurate so far is the Harvard/Yale group, our competition, who see that it must be smaller than 10^{-28} e*cm.   We hope to pass them, soon!

Systematics

How to make sure you're actually measuring something

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	
ThO beam	Y	Y	Y	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.

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In the end, we've got to try it, because we are fossil hunters

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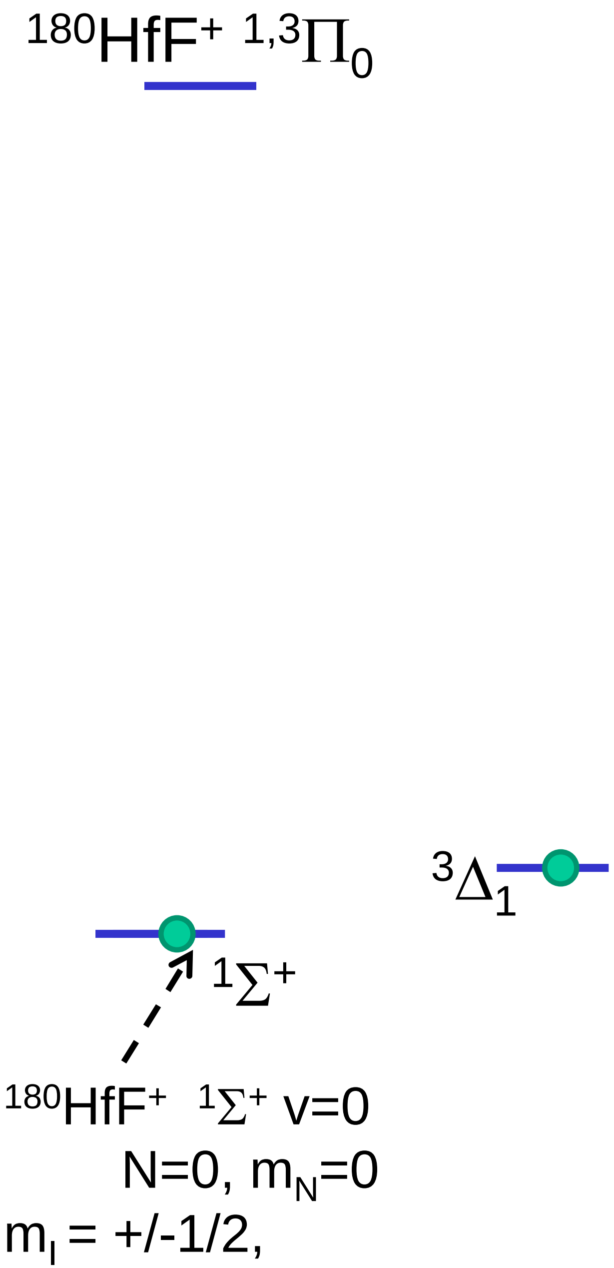
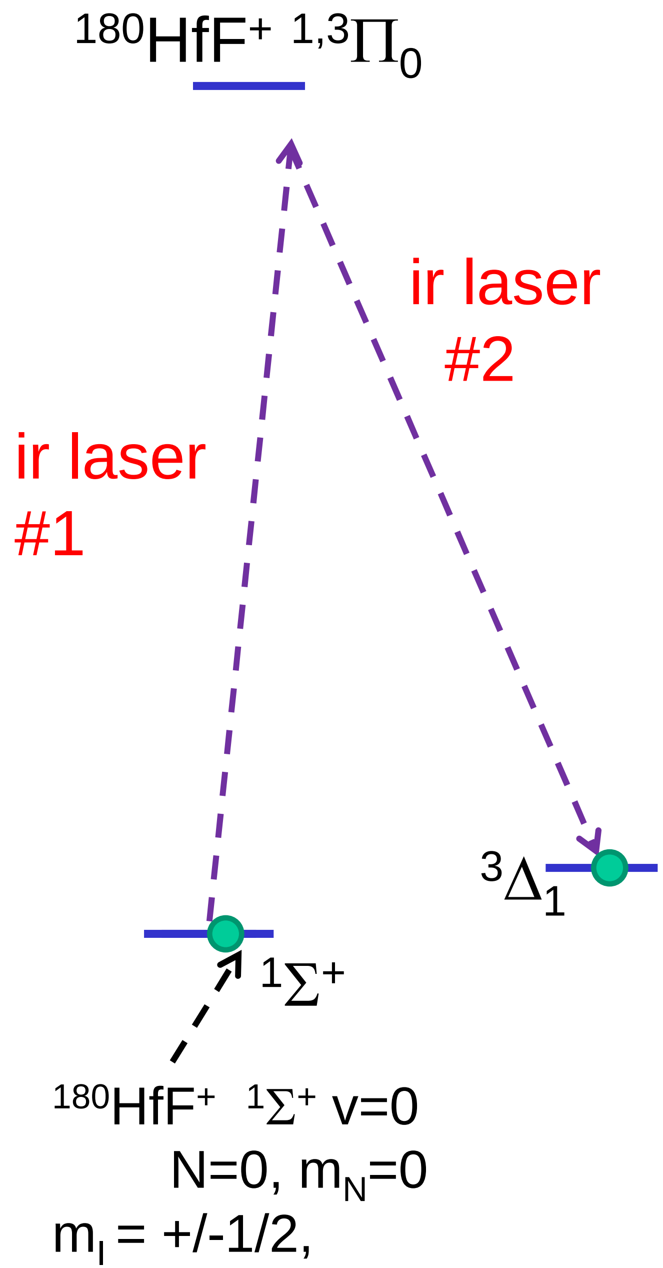
We haven't thought of a killer systematic at the 10^{-28} level yet. We will have a number of powerful techniques for smoking out unforeseen ones.

In the end, we've got to try it, because we are fossil hunters

and "hunters got to hunt."


$^{180}HfF^{+}$ $^{1,3}\Pi_0$
$^{3}\Delta_1$
$^{1}\Sigma^{+}$
$^{180}HfF^{+}$ $^{1}\Sigma^{+}$ v=0
N=0, m_N=0
m_I = +/-1/2,


$^{180}HfF^{+}$ $^{1,3}\Pi_0$
ir laser #2
ir laser #1
$^3\Delta_1$
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$^{180}HfF^{+}$ $^1\Sigma^+$ v=0
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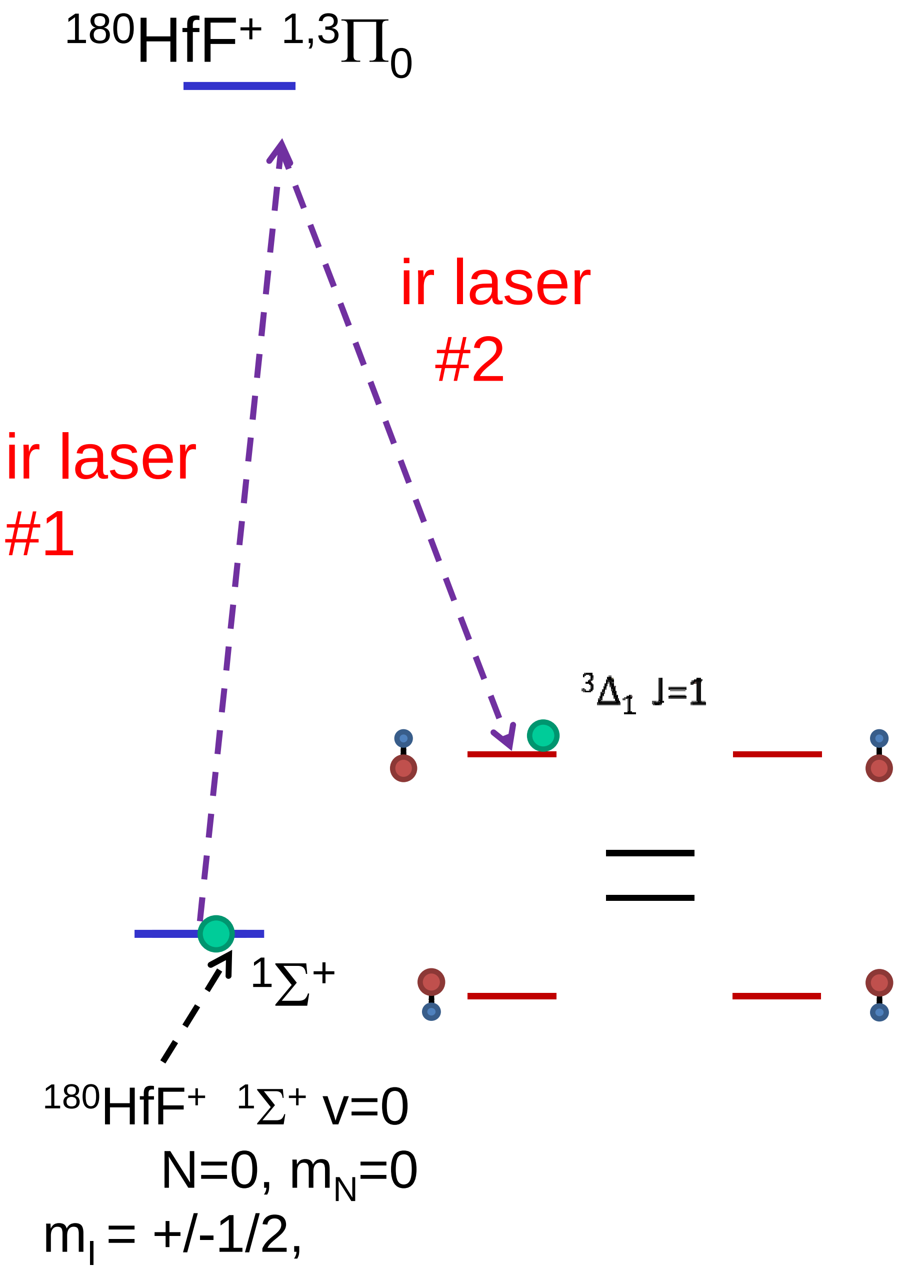

$^{180}HfF^{+}$ $^{1,3}\Pi_0$
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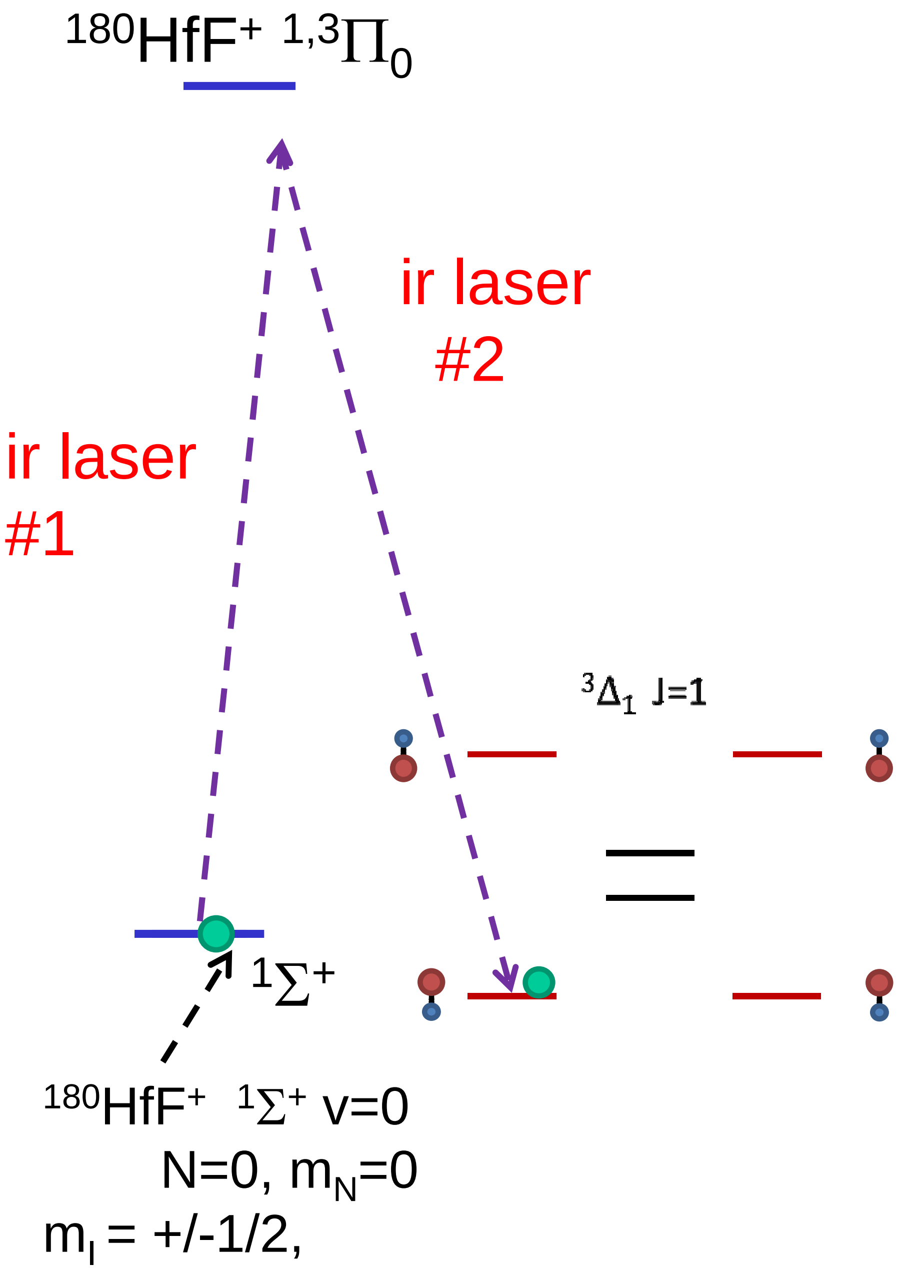
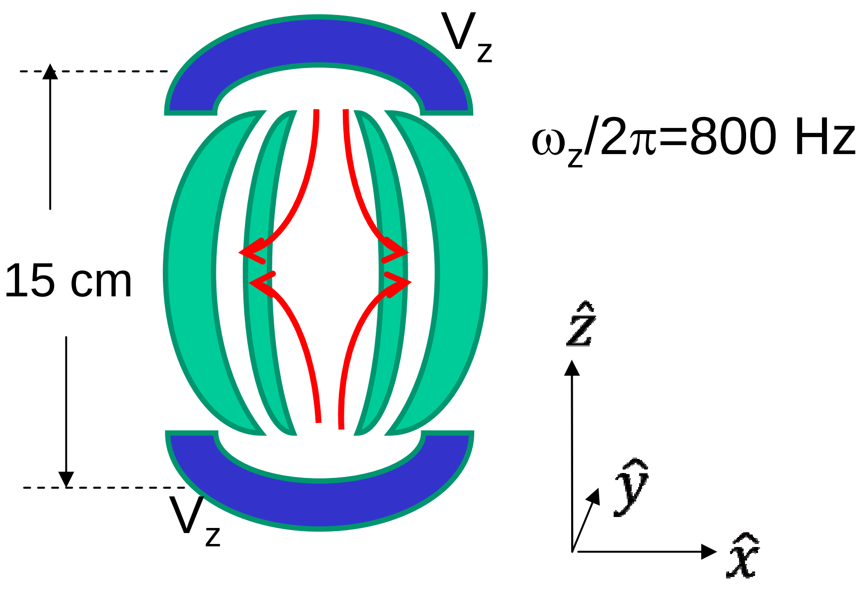
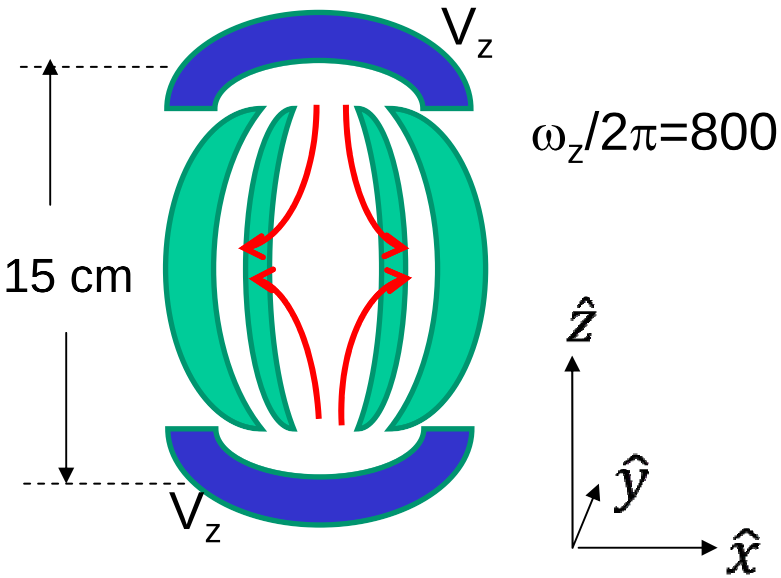


$^{180}HfF^+ \; ^{1,3}\Pi_0$
ir laser #2
ir laser #1
$^3\Delta_1$ J=1
$^1\Sigma^+$
$^{180}HfF^+ \; ^1\Sigma^+$ v=0
N=0, m_N=0
m_I = +/-1/2,

Linear Paul trap.

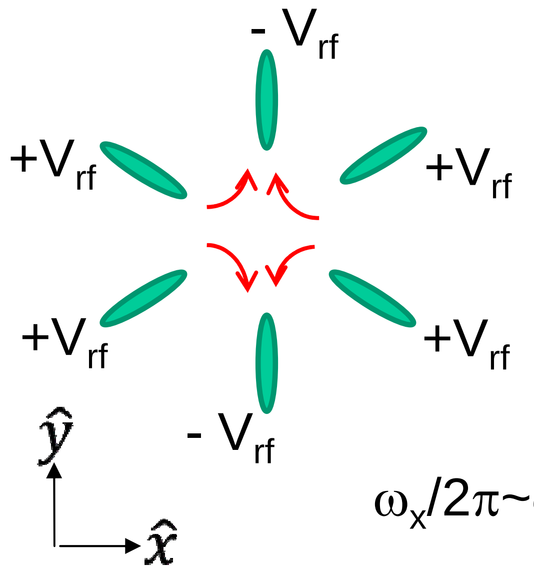


Linear Paul trap.



$\omega_z/2\pi$=800 Hz

Linear quadrupole Paul trap.

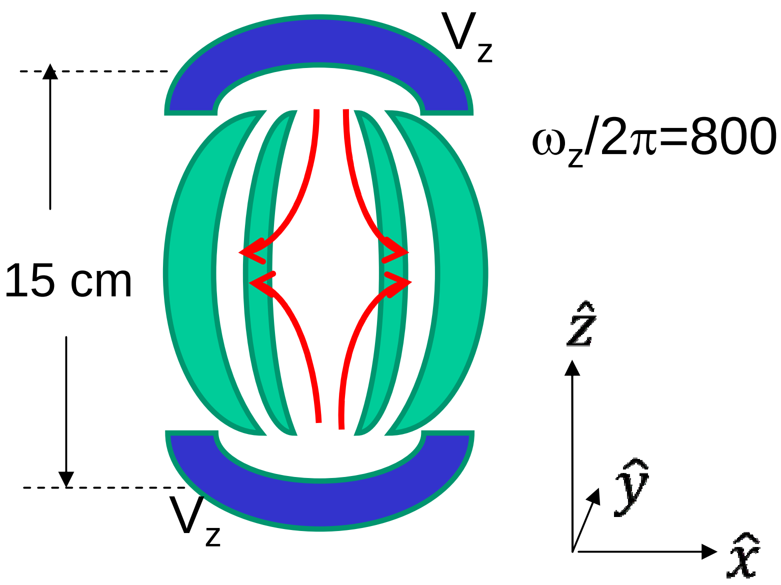


$V_{rf} = A_{rf} \cos \omega_{rf} t$

$\omega_{rf}/2\pi \sim$ 50 kHz

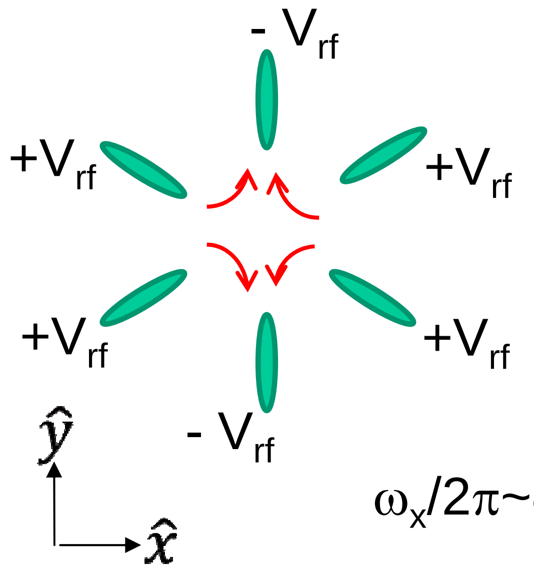
$\omega_x/2\pi \sim \omega_y/2\pi \sim$ 3 kHz

Linear Paul trap.



$\omega_z/2\pi$=800 Hz

Linear quadrupole Paul trap.

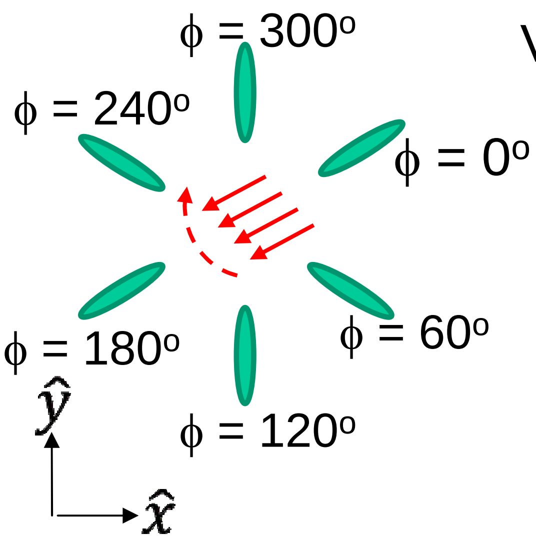


$V_{rf} = A_{rf} \cos \omega_{rf} t$

$\omega_{rf}/2\pi$~ 50 kHz

$\omega_x/2\pi$~$\omega_y/2\pi$~ 3 kHz

Linear quadrupole Paul trap, with rotating electric bias field…



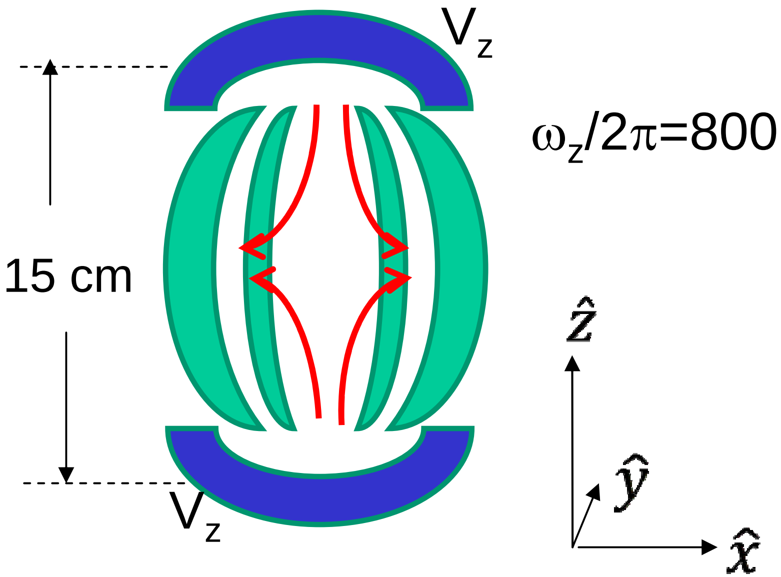
$V_{rot} = A_{rot} \cos \omega_{rot} + \phi$

$\omega_{rot}/2\pi$~ 200 kHz

E_{rot} ~ 20 V/cm

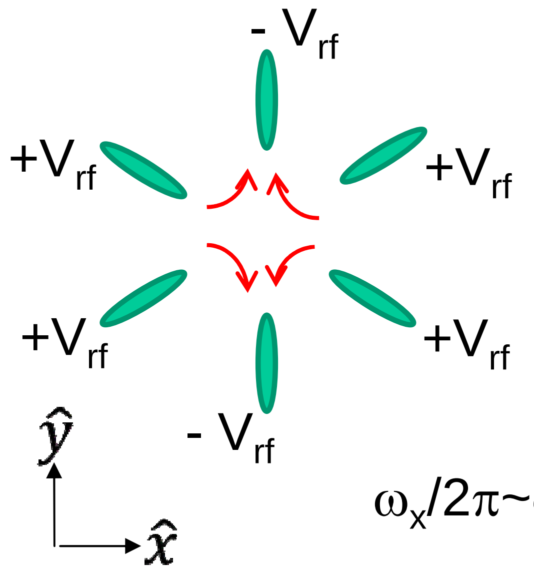
r_{rot} ~ 0.5 mm

Linear Paul trap.



$\omega_z/2\pi=800$ Hz

Linear quadrupole Paul trap.

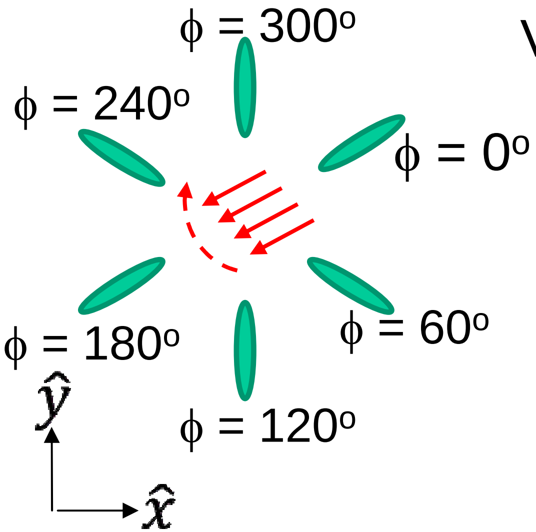


$V_{rf} = A_{rf} \cos \omega_{rf} t$

$\omega_{rf}/2\pi \sim 50$ kHz

$\omega_x/2\pi \sim \omega_y/2\pi \sim 3$ kHz

Linear quadrupole Paul trap, with rotating electric bias field…



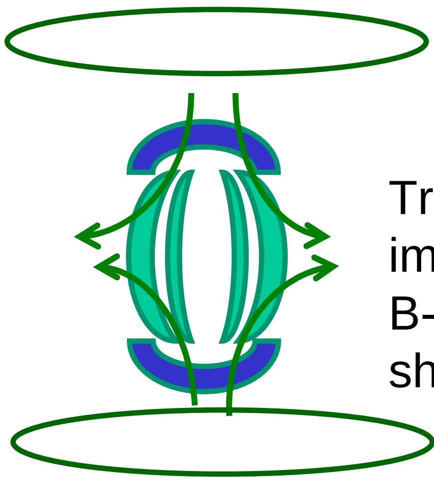
$V_{rot}=A_{rot} \cos \omega_{rot} + \phi$

$\omega_{rot}/2\pi \sim 200$ kHz

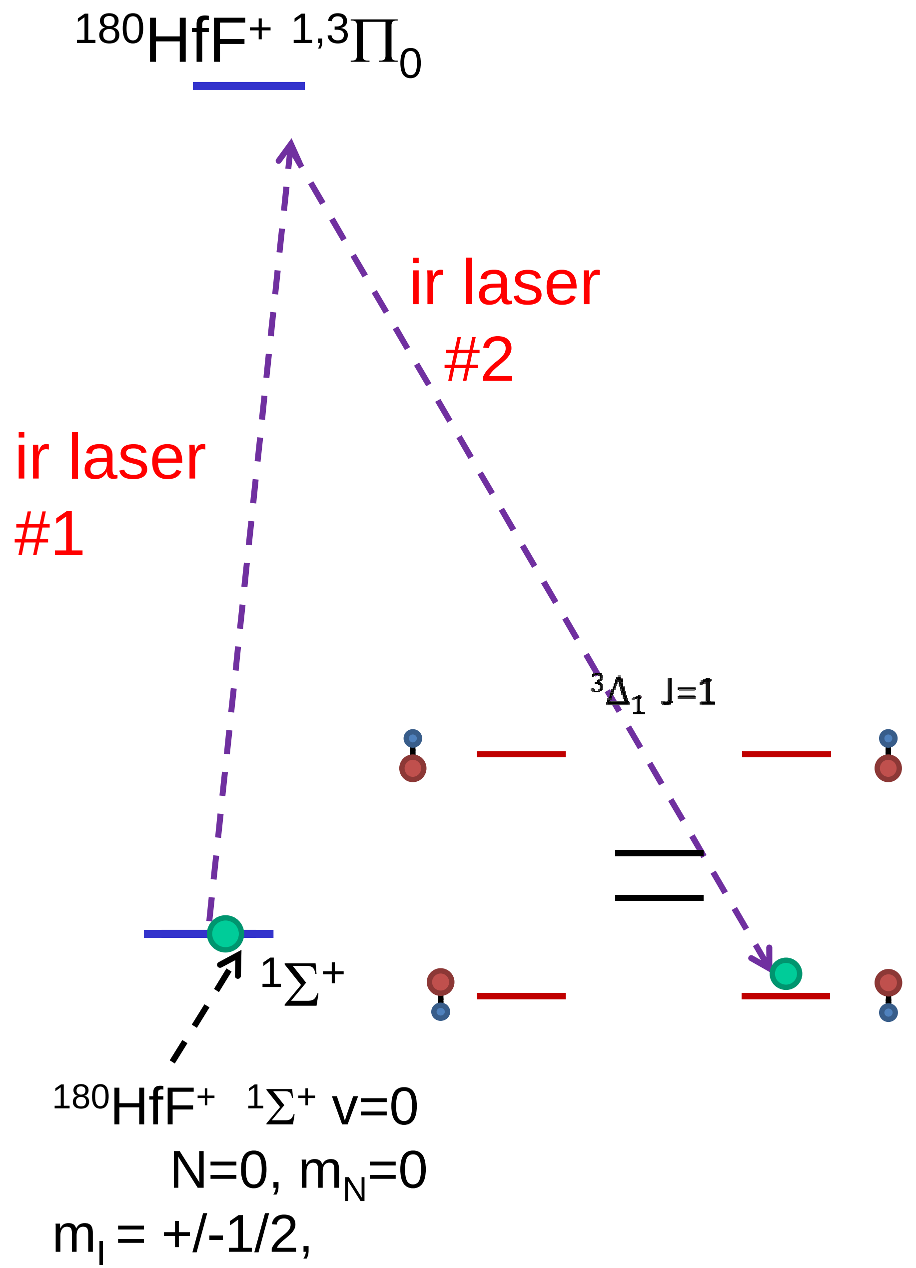
$E_{rot} \sim 20$ V/cm

$r_{rot} \sim 0.5$ mm

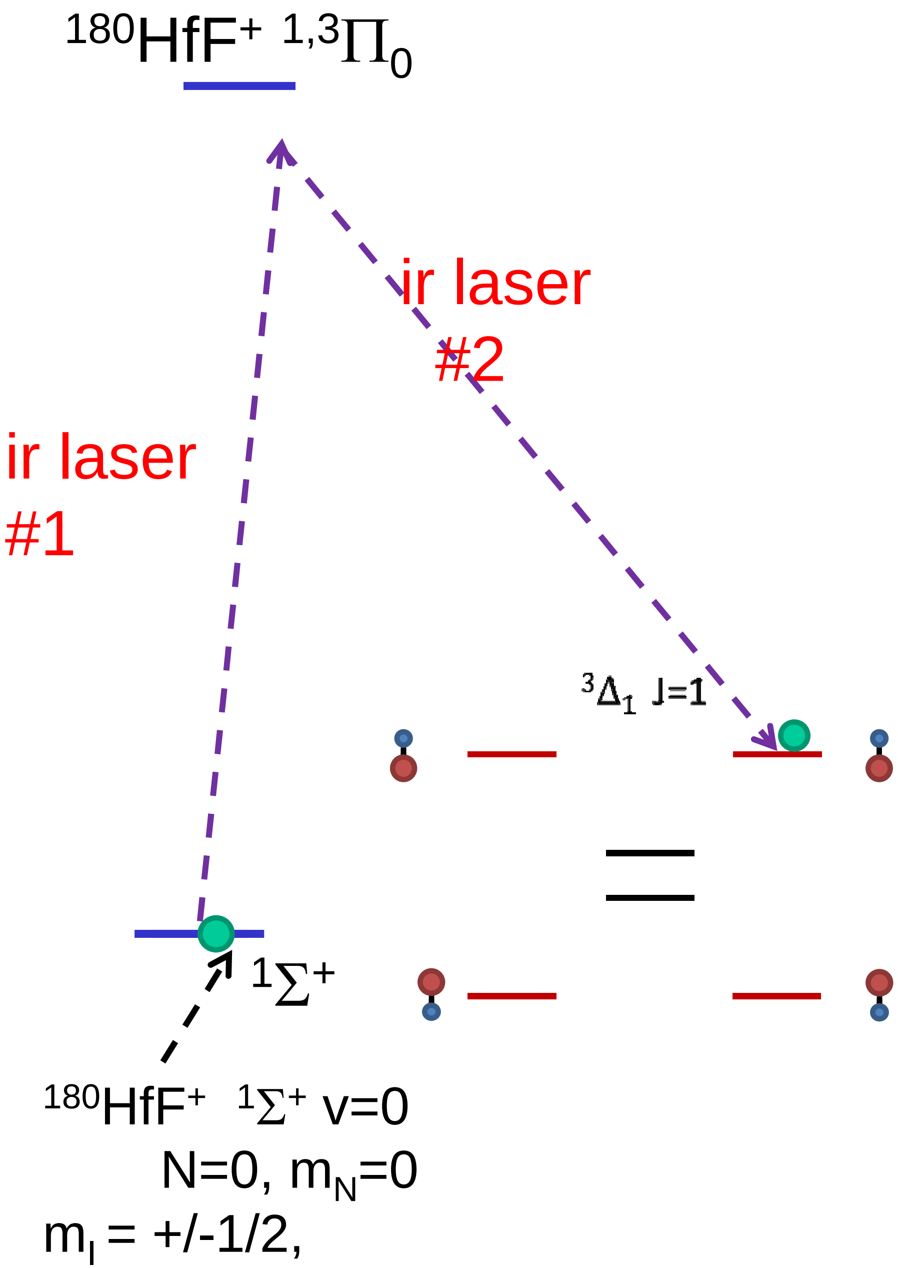
…..and with a magnetic gradient field to provide bias.



Transition freq. is immune to uniform dc B-fields: no mu-metal shielding necessary!



$^{180}HfF^{+}$ $^{1,3}\Pi_0$
ir laser #2
ir laser #1
$^3\Delta_1$ J=1
$^1\Sigma^+$
$^{180}HfF^{+}$ $^1\Sigma^+$ v=0
N=0, m_N=0
m_I = +/-1/2,



$^{180}HfF^{+}$ $^{1,3}\Pi_0$
ir laser #2
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$^3\Delta_1$ J=1
$^1\Sigma^+$
$^{180}HfF^{+}$ $^1\Sigma^+$ v=0
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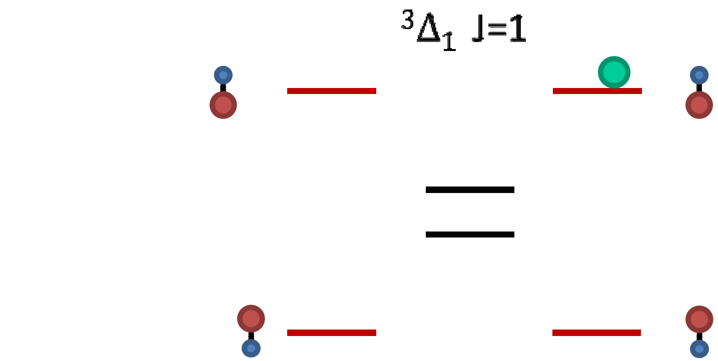
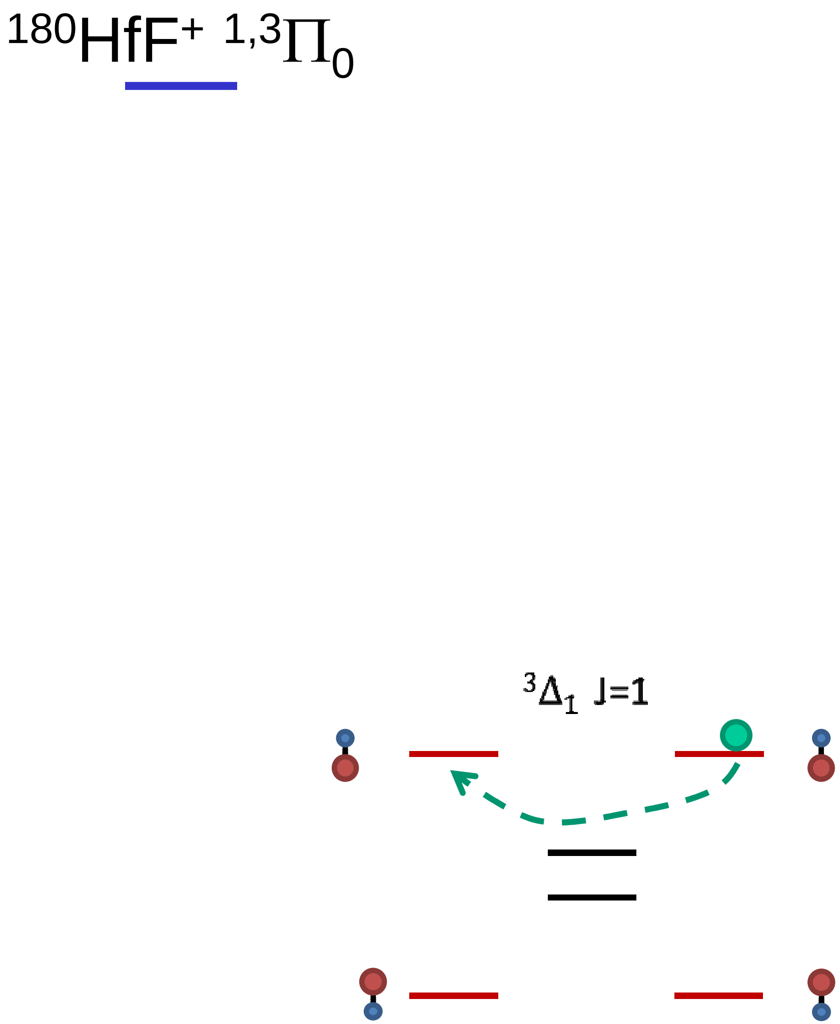
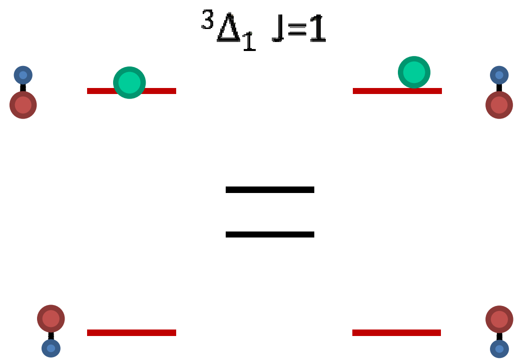
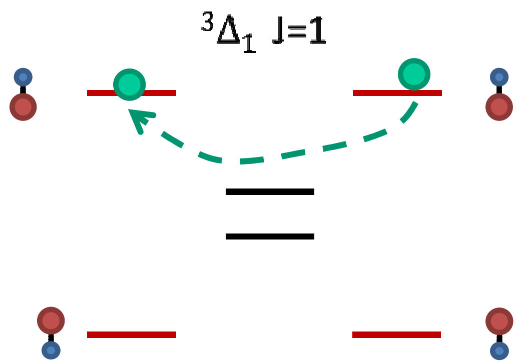



$^{180}HfF^+$ $^{1,3}\Pi_0$
$^3\Delta_1$ J=1

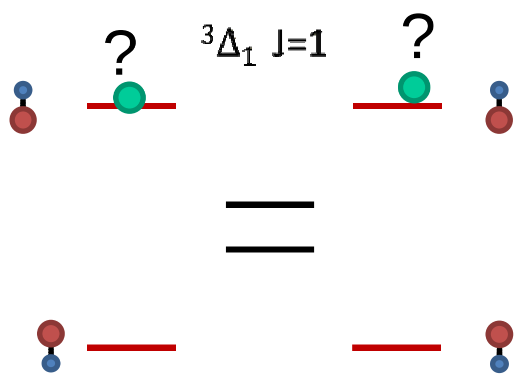
$^{180}HfF^+$ $^{1,3}\Pi_0$

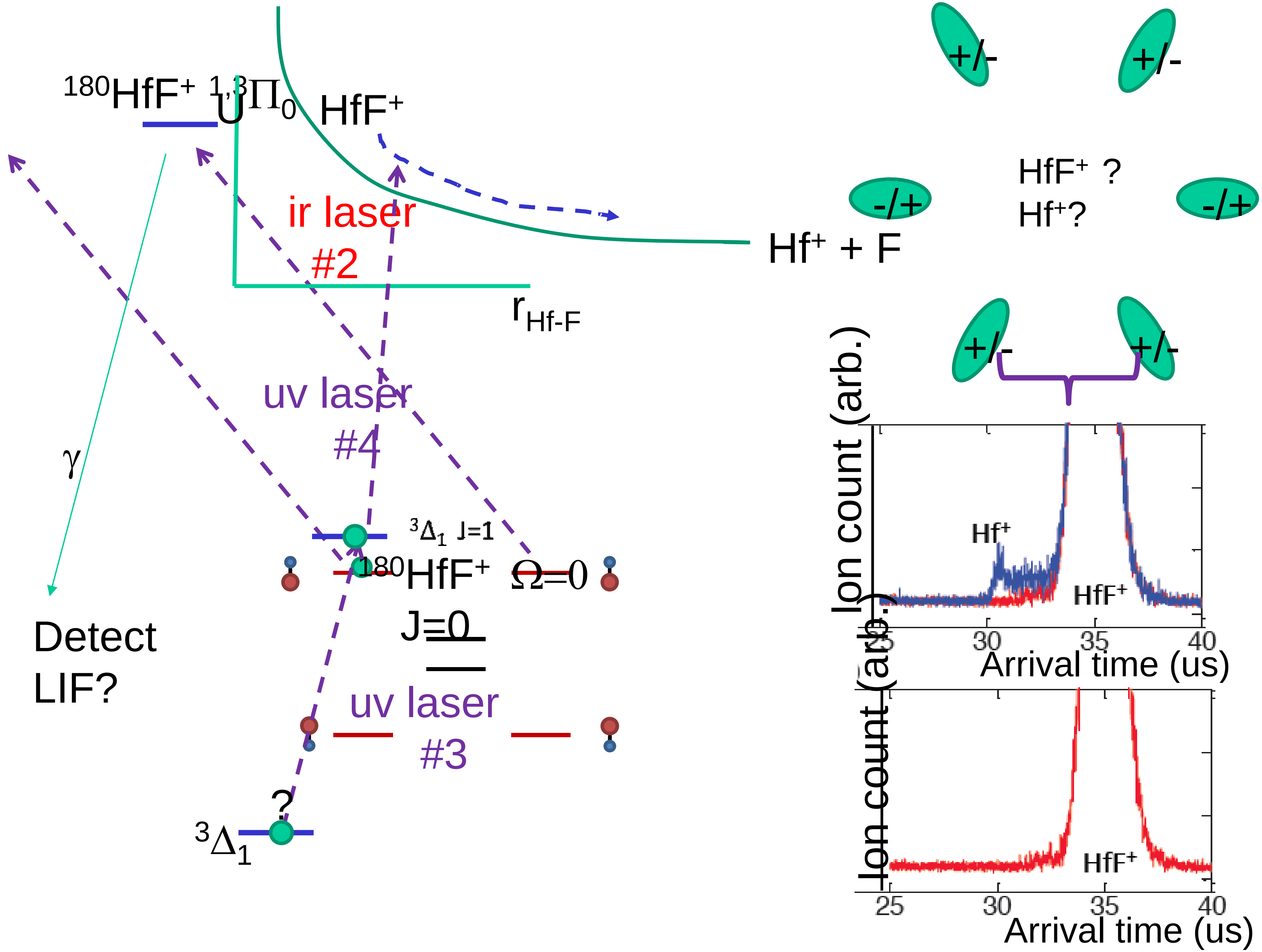


$^{180}\mathrm{HfF}^{+}$ $^{1,3}\Pi_0$



$^{180}HfF^{+}$ $^{1,3}\Pi_0$



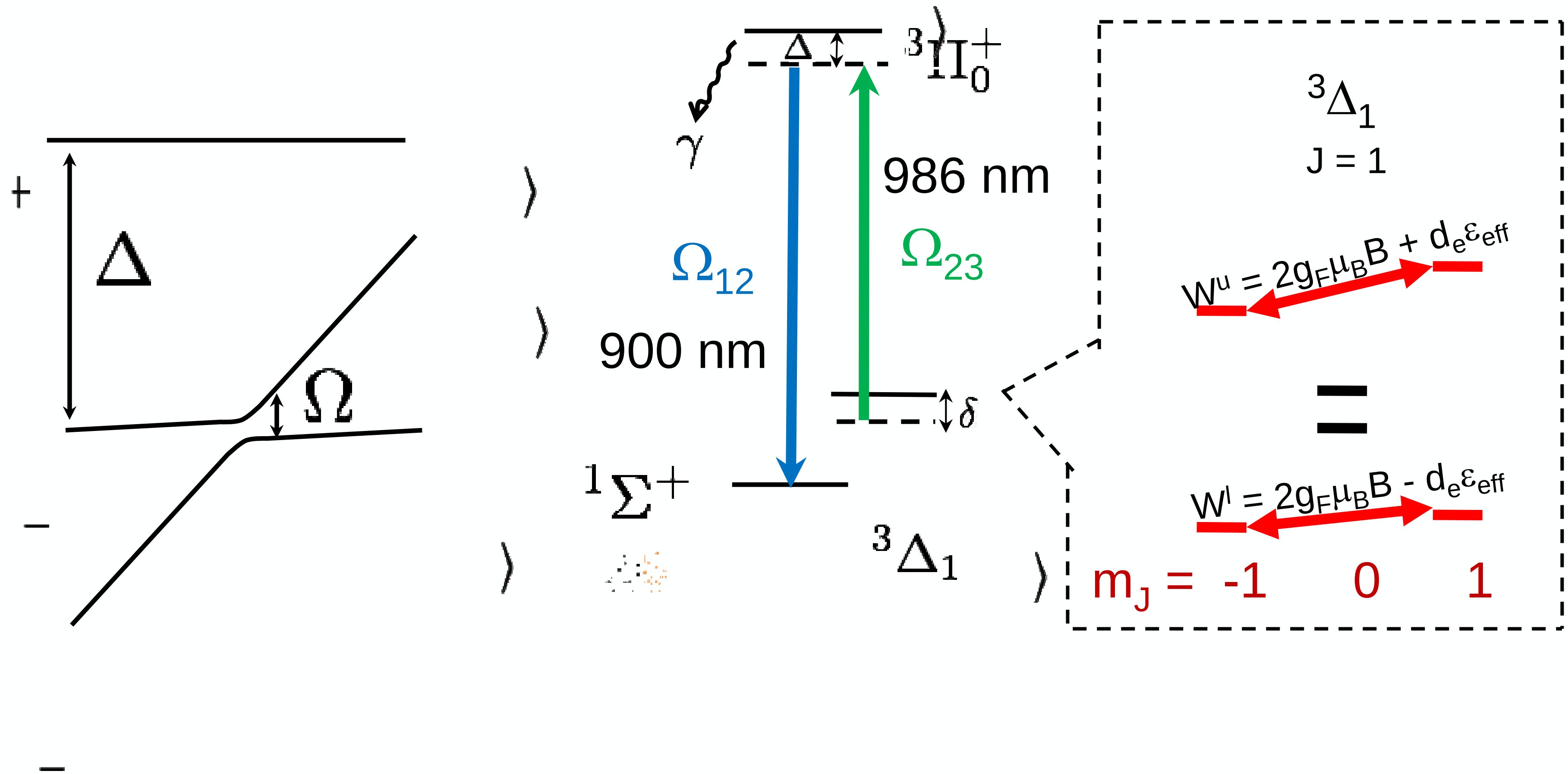


^{180}HfF$^+$ $^{1,3}\Pi_0$
U
HfF$^+$
ir laser
#2
r_{Hf-F}
Hf$^+$ + F
uv laser
#4
$^3\Delta_1$ J=1
^{180}HfF$^+$ Ω=0
J=0
uv laser
#3
?
$^3\Delta_1$
γ
Detect
LIF?
+/-
-/+
HfF$^+$?
Hf$^+$?
Ion count (arb.)
Hf$^+$
HfF$^+$
25
30
35
40
Arrival time (us)

Q: What about systematic errors?

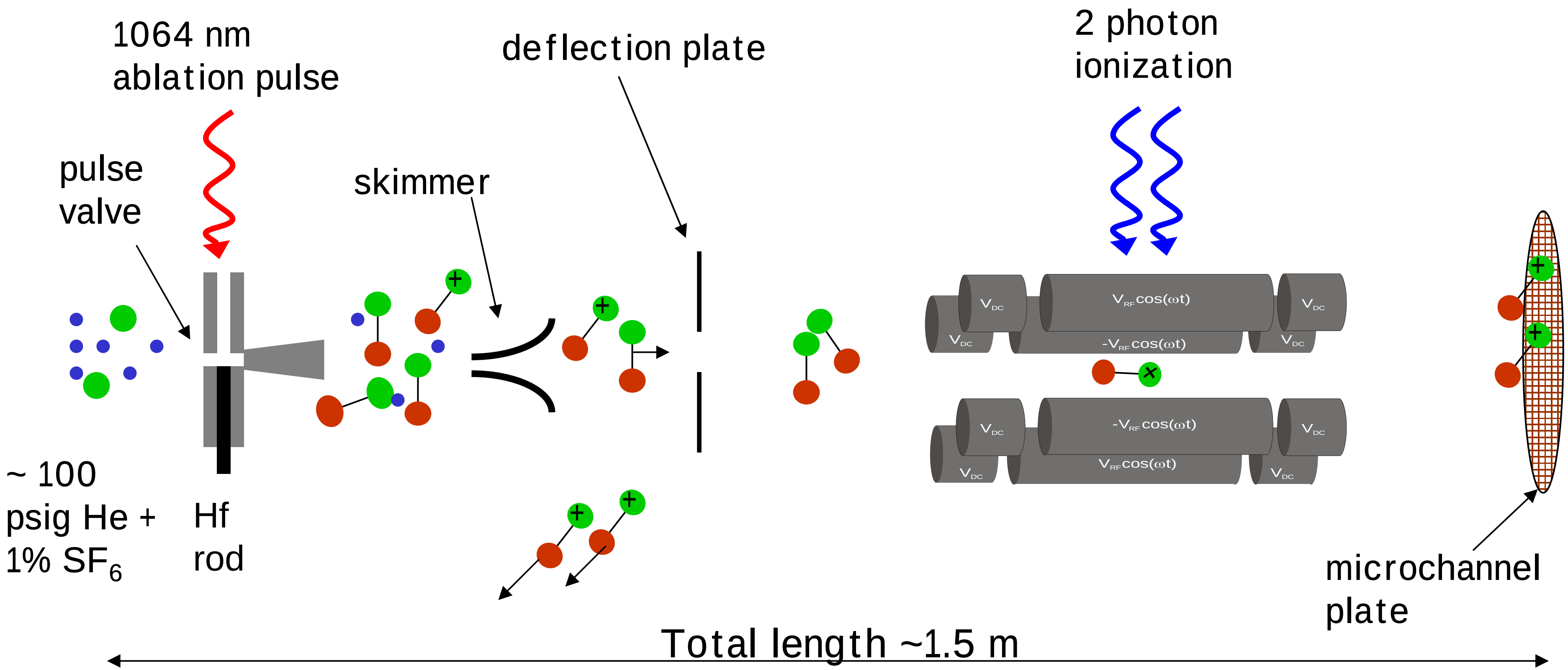
Coherent transfer

difficulty: large doppler width



Rethinking Ion Trap Loading

Create pre-polarized sample of ions via 2 photon process



Not to Scale