The situation, approximately 14 billion years before right now:
Then, shortly thereafter:

e = electron
p = proton
n = neutron

\( \bar{e} \) = antielectron
\( \bar{p} \) = antiproton
\( \bar{n} \) = antineutron
Then, the universe expanded and cooled:
Then, True Love!

Each particle finds its “soul mate”.
Married life is passionate, but short.
Married life is passionate, but short.
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!
In the mass cosmic wedding, there was somebody for everyone.
Except for a very small number of lonely, left-over particles, that nobody wanted!
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?)
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.
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 “a tiny bit more electron than antielectron 14 billion years ago”? Modern-day fossil of ancient asymmetry.

Symmetries

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

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?
Meet Mr. Electron.

“N”

“S”
Meet Mr. Electron.
Meet Mr. Electron.

electron
Electric Dipole Moment (eEDM)?
Meet Mr. Electron.

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. Petersburg 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 one part in $1,000,000,000,000,000$ (10^{-15}).
Ex #2: How strong is the magnet?

A compass.
Ex #2: How strong is the magnet?

A compass.
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A compass.
Ex #2: How strong is the magnet?

A compass.
Ex #2: How strong is the magnet?

A compass.
Ex #2: How strong is the magnet?

A compass.
Ex #2: How strong is the magnet?

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!
Ex #2: How strong is the magnet? 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.
Ex #3: Forget about proton! Forget about magnet! What about electron electric dipole moment?

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

A compass.

An electron with, maybe! electric dipole moment (EDM)
Ex #3: Forget about proton! Forget about magnet! What about electron electric dipole moment?

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An electron with, maybe! electric dipole moment (EDM)
If electron EDM exists at all, it is very small. We must apply a VERY large electric field. Two problems!
If electron EDM exists at all, it is very small. We must apply a VERY large electric field. Two problems!

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

Example: NaCl (Sodium Chloride). Plain salt.

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…”
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.”
Scan-ramsey-1  2  3  4  5: $S = 47 \text{mHz/h}\cdot\text{r}^{-1/2}$

$23.4 \text{ V/cm, } B_{\text{Hall}} = +0.033 \text{ V, } E_{\pi/2} = 6 \text{ V/cm, upper doublet, } \pi/2 \text{ duration } = 1.07 \text{ ms,}$

Depletion Contrast

$\phi: (2\pi)0.4898(85); \text{ offset: } 0.0167(71); \text{ Contrast: } 0.613(38); \tau: 860(\pm 20)$

$T (\text{ms})$

$0 100 200 300 400 500 600 700 800 900$

$\text{Depletion Contrast}$
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
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+ $^1\Sigma^+$ v=1

$^1\Sigma^+$

$^1\Sigma^+$

$^1\Sigma^+$

180HfF+ $^1\Sigma^+$ v=0
30% N=0, m_N=0
m_l = +/-1/2,
mean occ. =15%

neutral $^{180}$HfF $\Omega=1/2$ J=1/2
Single internal quantum level.
An electron with North pole, south pole and, maybe! electric dipole moment (EDM)
A compass.

An electron with, North pole, south pole and, maybe! electric dipole moment (EDM)
A precision measurement of the electron EDM using trapped molecular ions

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

\[d_e < 8 \times 10^{-27} e \text{ cm}\]

Upper Doublet

Lower Doublet
Sensitivity Estimate

\[ |d_e| < \frac{h}{2 E_{\text{eff}} \tau \sqrt{N}} \]

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

proj. sensitivity: \( |d_e| \sim 10^{-28} \) 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.

<table>
<thead>
<tr>
<th>Chop:</th>
<th>B</th>
<th>E</th>
<th>(E/E_{\text{eff}})</th>
<th>(\nu)</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tl beam</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>YbF beam</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N*</td>
<td></td>
</tr>
<tr>
<td>PbO vapor cell</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N*</td>
<td></td>
</tr>
<tr>
<td>trapped Cs</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Trap</td>
<td></td>
</tr>
<tr>
<td>Cs fountain</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td></td>
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<tr>
<td>ThO beam</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N*</td>
<td></td>
</tr>
<tr>
<td>Trapped MF+</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Rotation sense</td>
<td></td>
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</table>
Systematic Error Rejection. Key Chops.

We've got the chops, and:

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

<table>
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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.”
$^{180}\text{HfF}^+ \ 1,3 \Pi_0$

$^{180}\text{HfF}^+ \ 1\Sigma^+ \ v=0$

$N=0, \ m_N=0$

$m_I = +/-1/2,$
\[ ^{180}\text{HfF}^+  \]  $\Sigma$ $\sum_{v=0}^{\infty}$ $N=0, m_N=0$

$m_l = +/-1/2,$
$^{180}\text{HfF}^+ \, 1\Sigma_v^+ \, v=0$

$N=0, \ m_N=0$

$m_l = +/-1/2,$

$1\Sigma_0^+$

$^{1\Sigma_1 1}\, J=1$

ir laser #1

ir laser #2
$^{180}\text{HfF}^+ \quad 1,3\Pi_0$

$^{180}\text{HfF}^+ \quad 1\Sigma^+ \quad v=0$

$N=0, \quad m_N=0$

$m_I = +/-1/2,$

ir laser

#1

ir laser

#2

$\quad 3\Delta_1 \quad J=1$
Linear Paul trap.

\[ \omega_z/2\pi = 800 \text{ Hz} \]

15 cm
Linear Paul trap.

\[ \frac{\omega_z}{2\pi} = 800 \text{ Hz} \]

15 cm

\[ V_z \]

Linear quadrupole Paul trap.

\[ V_{rf} = A_{rf} \cos \omega_{rf} t \]

\[ \frac{\omega_{rf}}{2\pi} \approx 50 \text{ kHz} \]

\[ \frac{\omega_x}{2\pi} \approx \frac{\omega_y}{2\pi} \approx 3 \text{ kHz} \]
Linear Paul trap.

\[ \omega_z/2\pi = 800 \text{ Hz} \]

\[ V_z \]

15 cm

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\[ V_{rf} = A_{rf} \cos \omega_{rf} t \]

\[ +V_{rf} \]

\[ +V_{rf} \]

\[ +V_{rf} \]

\[ +V_{rf} \]

\[ -V_{rf} \]

\[ -V_{rf} \]

\[ \omega_{rf}/2\pi \approx 50 \text{ kHz} \]

\[ \omega_x/2\pi, \omega_y/2\pi \approx 3 \text{ kHz} \]

Linear quadrupole Paul trap, with rotating electric bias field...

\[ \phi = 300^\circ \]

\[ \phi = 240^\circ \]

\[ \phi = 0^\circ \]

\[ \phi = 180^\circ \]

\[ \phi = 60^\circ \]

\[ \phi = 120^\circ \]

\[ V_{rot} = A_{rot} \cos \omega_{rot} + \phi \]

\[ \omega_{rot}/2\pi \approx 200 \text{ kHz} \]

\[ E_{rot} \approx 20 \text{ V/cm} \]

\[ r_{rot} \approx 0.5 \text{ mm} \]
Linear Paul trap.

\[ V_z \]

\[ \omega_z / 2\pi = 800 \text{ Hz} \]

15 cm

Linear quadrupole Paul trap.

\[ V_{rf} = A_{rf} \cos \omega_{rf} t \]

\[ +V_{rf} \]

\[ -V_{rf} \]

\[ \omega_{rf} / 2\pi \approx 50 \text{ kHz} \]

\[ \omega_x / 2\pi, \omega_y / 2\pi \approx 3 \text{ kHz} \]

Linear quadrupole Paul trap, with rotating electric bias field...

\[ V_{rot} = A_{rot} \cos \omega_{rot} + \phi \]

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\[ \phi = 180^\circ \]

\[ \phi = 0^\circ \]

\[ \phi = 60^\circ \]

\[ \phi = 120^\circ \]

\[ \omega_{rot} / 2\pi \approx 200 \text{ kHz} \]

\[ E_{rot} \sim 20 \text{ V/cm} \]

\[ r_{rot} \sim 0.5 \text{ mm} \]

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

Transition freq. is immune to uniform dc B-fields: no mu-metal shielding necessary!
$^{180}\text{HfF}^+ \, 1,3\Pi_0$

$^{180}\text{HfF}^+ \, 1\Sigma^+ \, v=0$

$N=0, \, m_N=0$

$m_l= +/-1/2,
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$^3\Delta_1 \ J=1$
$^{180}\text{HfF}^+ \, 1,3\Pi_0$

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

$^3\Delta_1 J=1$
Arrival time (us)

Ion count (arb.)

Arrival time (us)

180HfF+ 1^3Π_0  HfF+

ir laser #2

180HfF+

J=0  Ω=0

ir laser #2

Detect LIF?

HfF+ + F

HfF+ ?

Hf+?

uv laser #4

γ

3^3Δ_1 J=1

180HfF+  Ω=0

J=0

HfF+

uv laser #3

3^3Δ_1

?
Q: What about systematic errors?
Coherent transfer

difficulty: large doppler width

\[ W^u = 2g_F\mu_B B + d_e\varepsilon_{\text{eff}} \]

\[ W^l = 2g_F\mu_B B - d_e\varepsilon_{\text{eff}} \]

\[ m_J = -1 \quad 0 \quad 1 \]
Rethinking Ion Trap Loading

Create pre-polarized sample of ions via 2 photon process

- 1064 nm ablation pulse
- Pulse valve
- Skimmer
- Deflection plate
- 2 photon ionization
- Microchannel plate
- Total length ~1.5 m

~ 100 psig He + 1% SF₆
Hf rod

Not to Scale