Fundamental Neutron Physics III

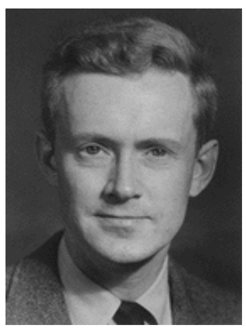
symmetry breaking and the neutron electric dipole moment

Geoffrey Greene
University of Tennessee / Oak Ridge National Laboratory

Parity Violation and Spontaneous Symmetry Breaking

"It is generally assumed on the basis of some suggestive theoretical symmetry arguments that nuclei and elementary particle can have no electric dipole moments. It is the purpose of this note to point out that although these theoretical arguments are valid when applied to molecular and atomic moments whose electromagnetic origin is well understood, their extension to nuclei and elementary particles rests on assumptions not yet tested"

E.M.Purcell and N.F.Ramsey,
Physical Review 78, 807 (1950)



Edward Purcell

Norman Ramsey

A Short History of Symmetry Violation

1863 (94 BP)	*Pasteur notes parity "violation" in organic molecules*
1950 (7 BP)	*Purcell and Ramsey suggest that parity violation must be subject to experimental confirmation (Ramsey gets 50-1 odds from Feynman)*
1951 (6 BP)	*First experiment specifically designed to look for a parity violation (neutron EDM at ORNL)*
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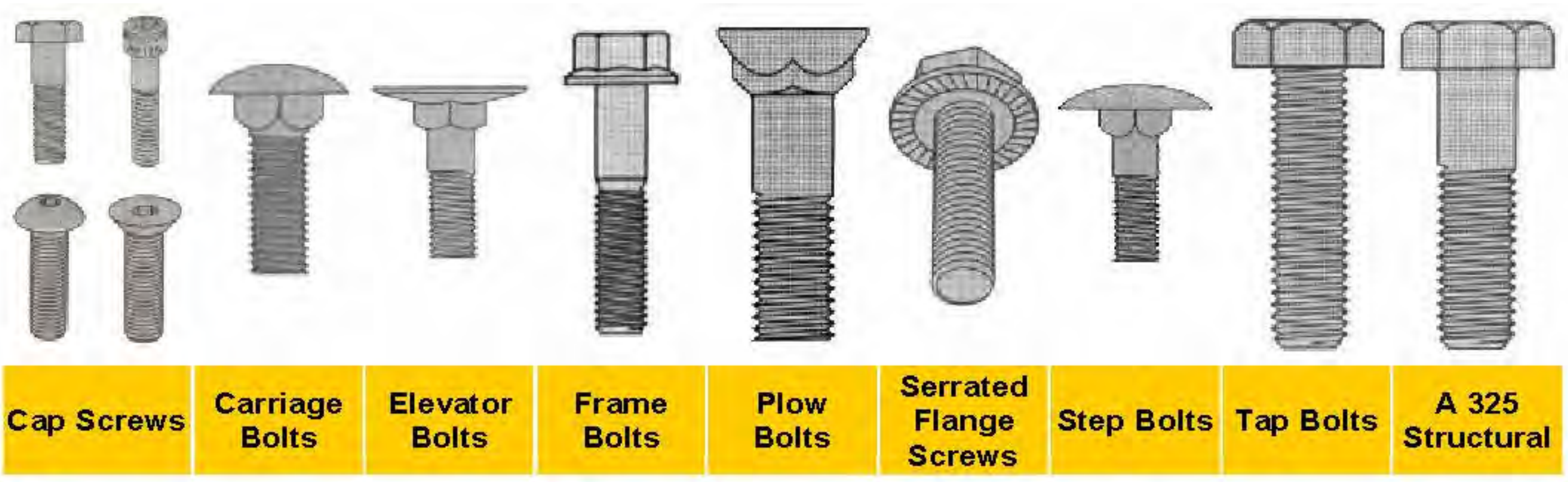
1957	*Wu, Ambler, et. al. and Garwin, et. al., Conclusively demonstrate that parity is violated in the weak interaction Landau suggests that CP is the "Real" symmetry*
1964	*Christianson, et. al., demonstrate that CP is violated in K-decay*

Brief Digression

Spontaneous Symmetry breaking

In the Universe of Nuts and Bolts



PARITY IS VIOLATED

If I randomly select a screw from the hardware bins At Home Depot…It will be RIGHT-HANDED

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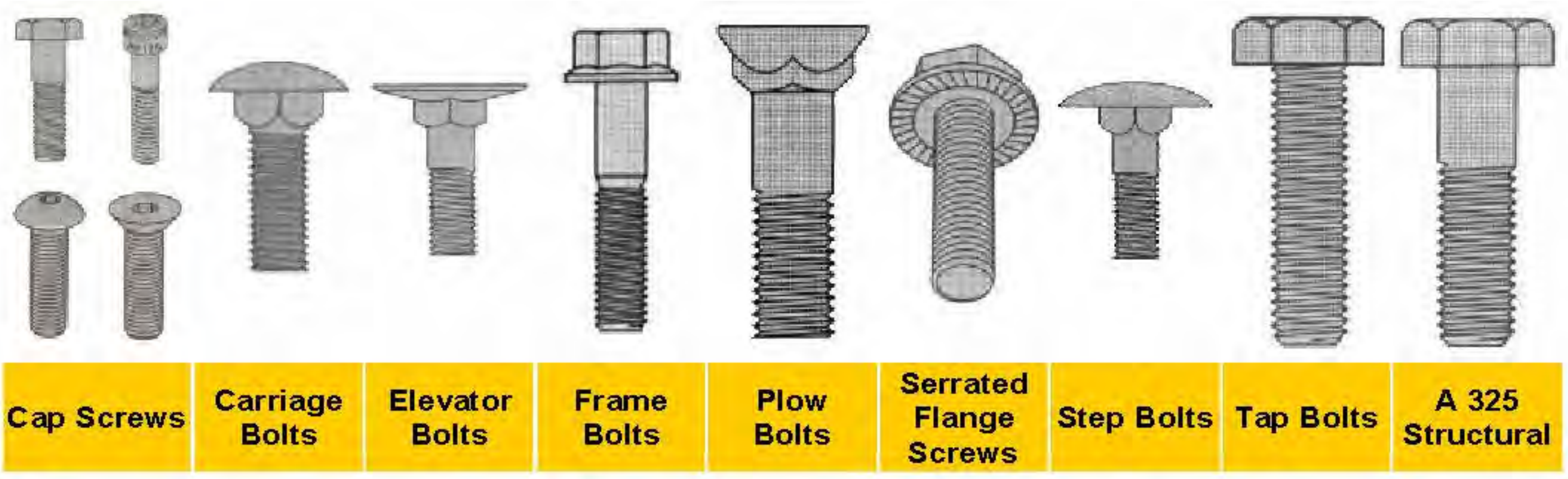

PARITY IS VIOLATED

This is an example of a "Broken Symmetry"

Broken Symmetry

A situation in which the ground state of a many-body system has a lower symmetry than the Hamiltonian which defines the system.*

**also may apply to the vacuum state of a relativistic quantum field theory*

Some Characteristics of "Spontaneous Symmetry Breaking"

- *There is an underlying symmetry to the system.*
- *The physical state has lower symmetry than the underlying symmetry*
- *The symmetry breaking may not be complete.*
- *Incomplete symmetry breaking may be manifested by a residue of other symmetry states or domains in which the other symmetry is manifested*

Incomplete Symmetry Violation is Often an Indication of Broken Symmetry

Threads on bicycle pedals come in symmetric pairs

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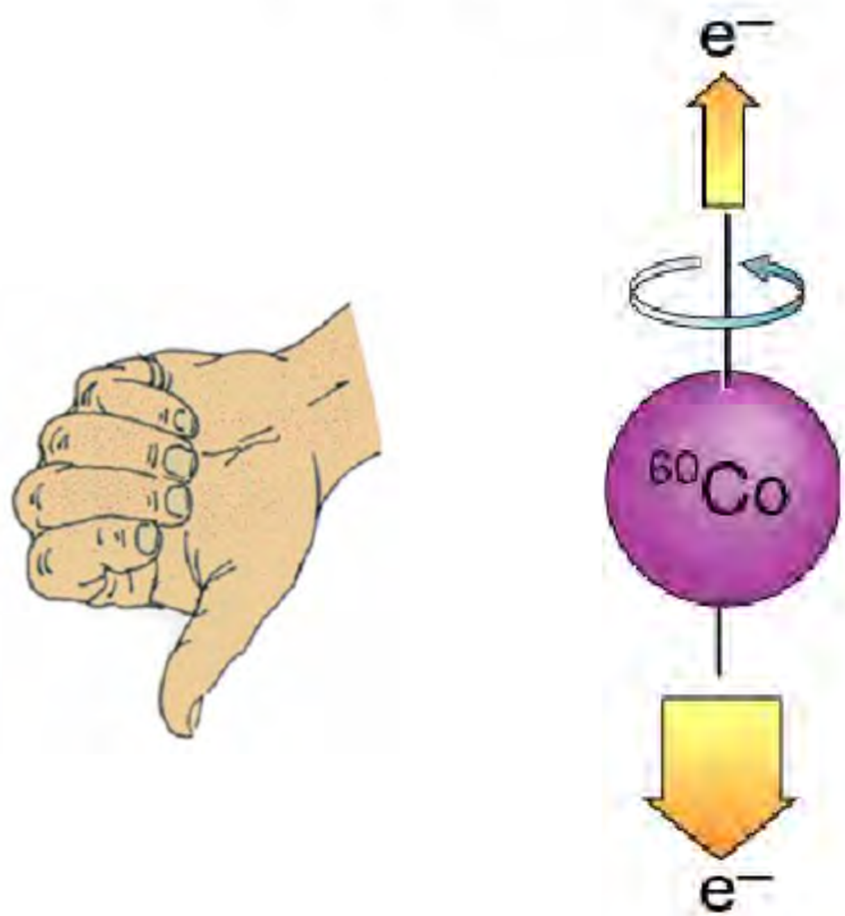
$$^{60}Co \rightarrow \ ^{60}Ni + e^- + \bar{\nu}_e$$



Wu, Ambler, Hudson, Hoppes, Hayward
(NBS) 1957

At the Fundamental Level,
the Nuclear Weak Force Violates Parity

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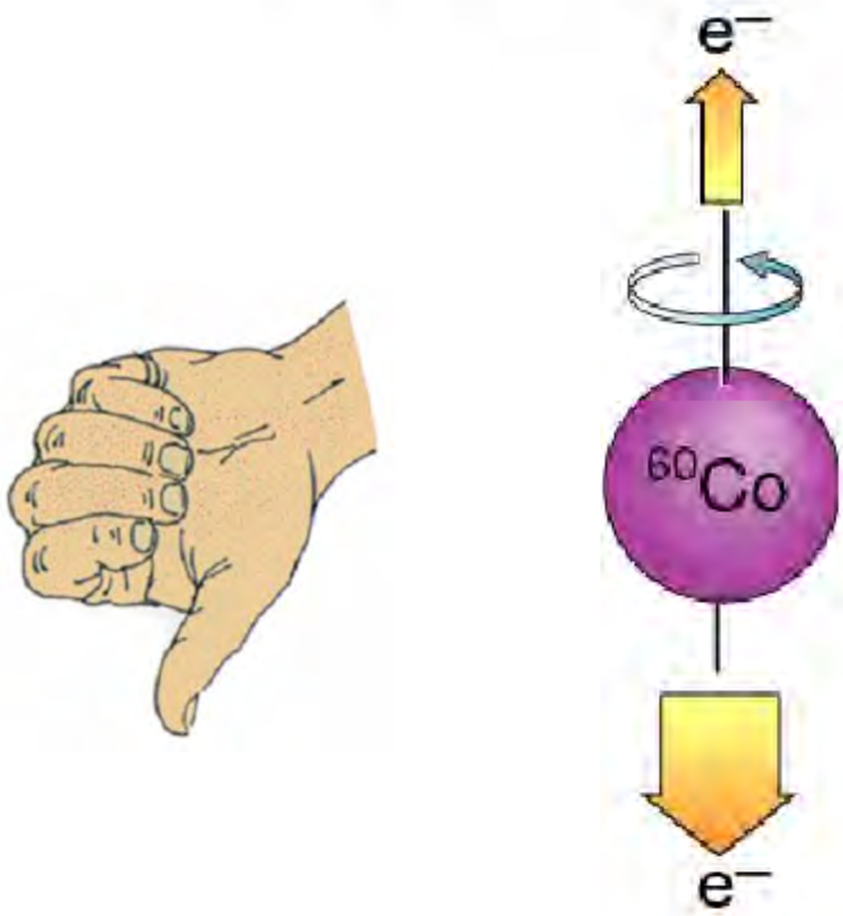

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Is This a Broken symmetry?

The Cosmic Baryon Asymmetry

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Observation:

As best we can determine, the universe consists of Matter.
There is essentially NO Antimatter.

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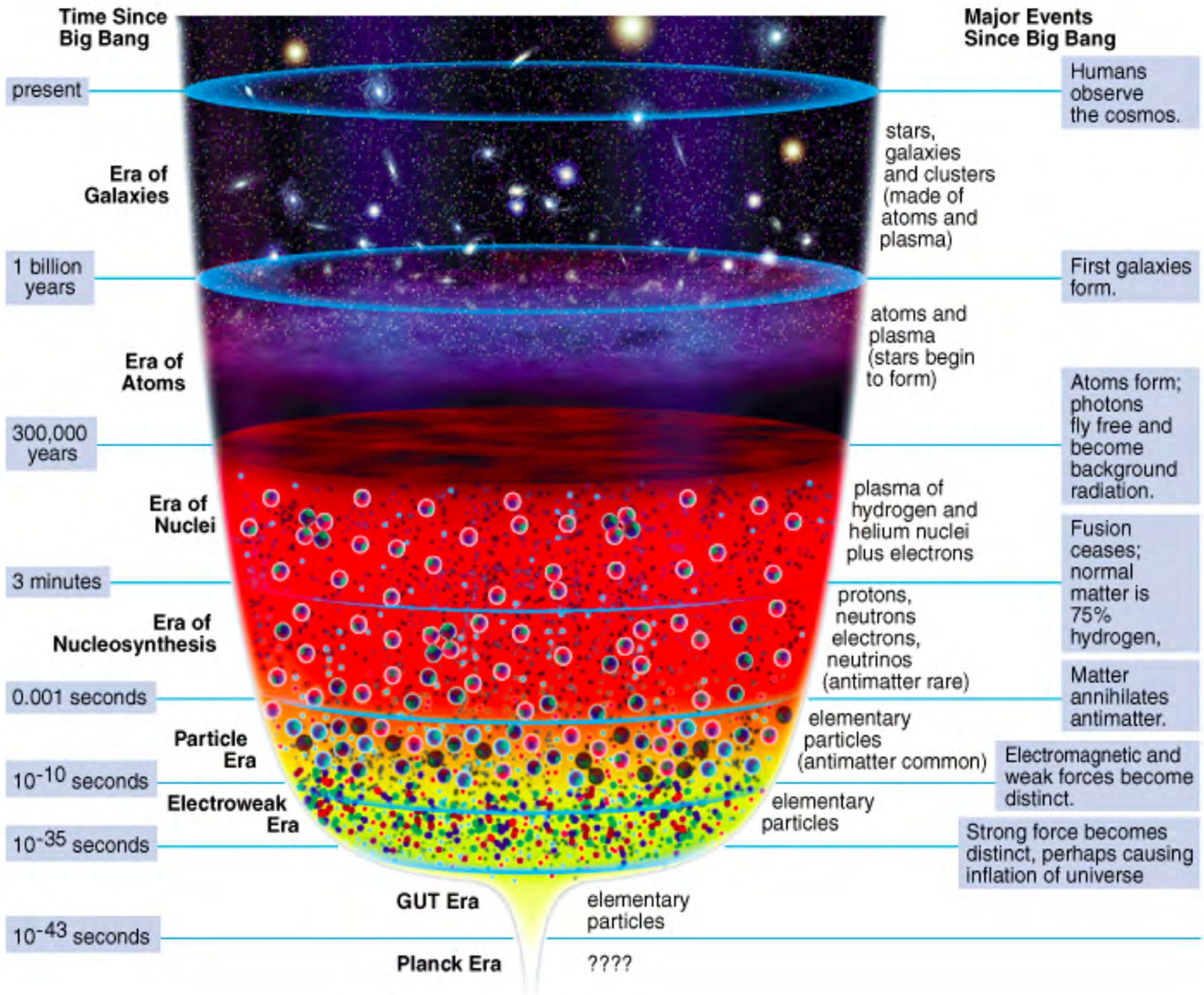

Time Since Big Bang
Major Events Since Big Bang
present
Humans observe the cosmos.
stars, galaxies and clusters (made of atoms and plasma)
Era of Galaxies
1 billion years
First galaxies form.
atoms and plasma (stars begin to form)
Era of Atoms
Atoms form; photons fly free and become background radiation.
300,000 years
Era of Nuclei
plasma of hydrogen and helium nuclei plus electrons
Fusion ceases; normal matter is 75% hydrogen,
3 minutes
Era of Nucleosynthesis
protons, neutrons electrons, neutrinos (antimatter rare)
0.001 seconds
Matter annihilates antimatter.
Particle Era
elementary particles (antimatter common)
10^{-10} seconds
Electromagnetic and weak forces become distinct.
Electroweak Era
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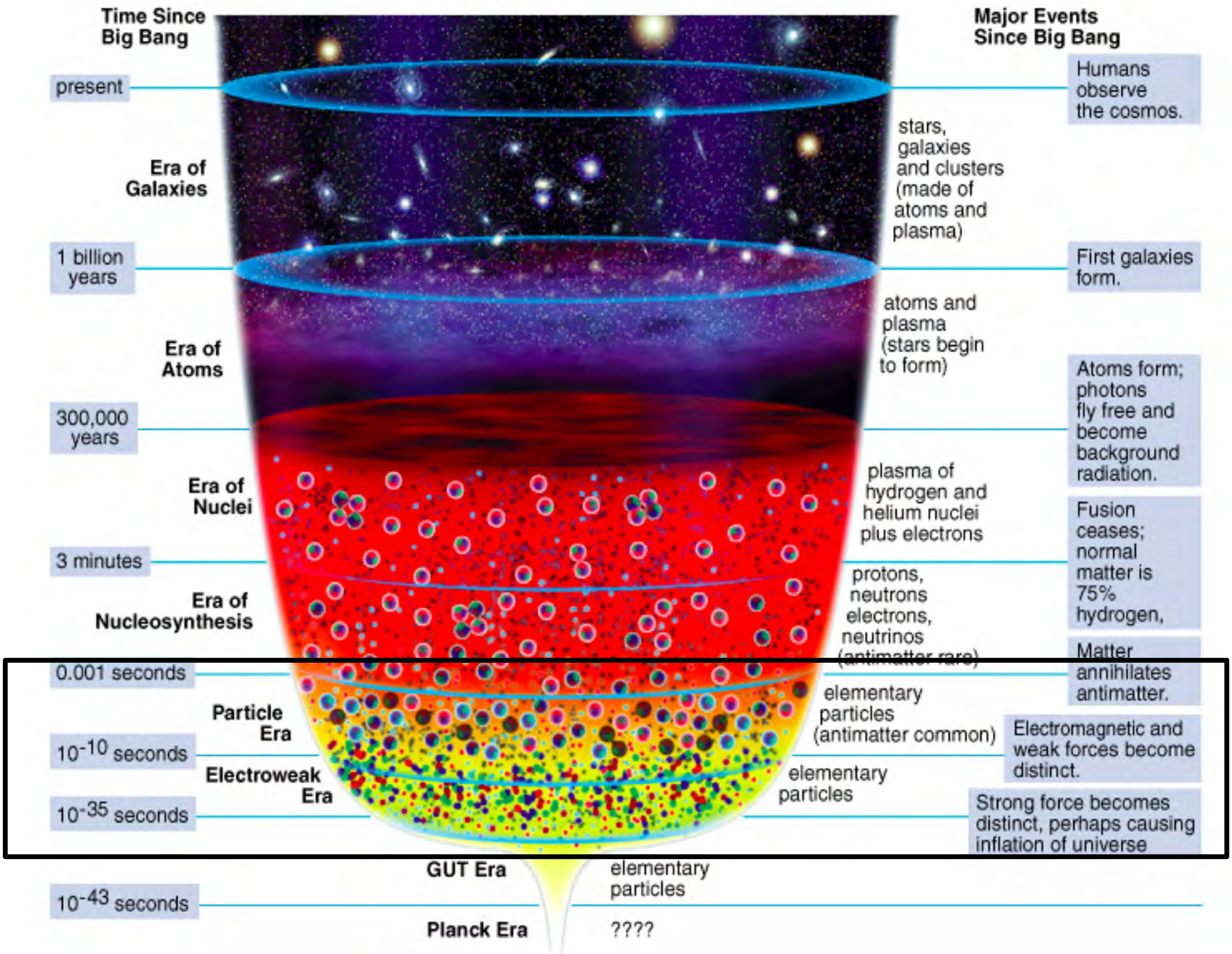
Strong force becomes distinct, perhaps causing inflation of universe
GUT Era
elementary particles
10^{-43} seconds
Planck Era
????



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Just after Inflation, there were equal amounts of Matter and Antimatter.

If nothing else happened, all matter and antimatter would annihilate leaving…

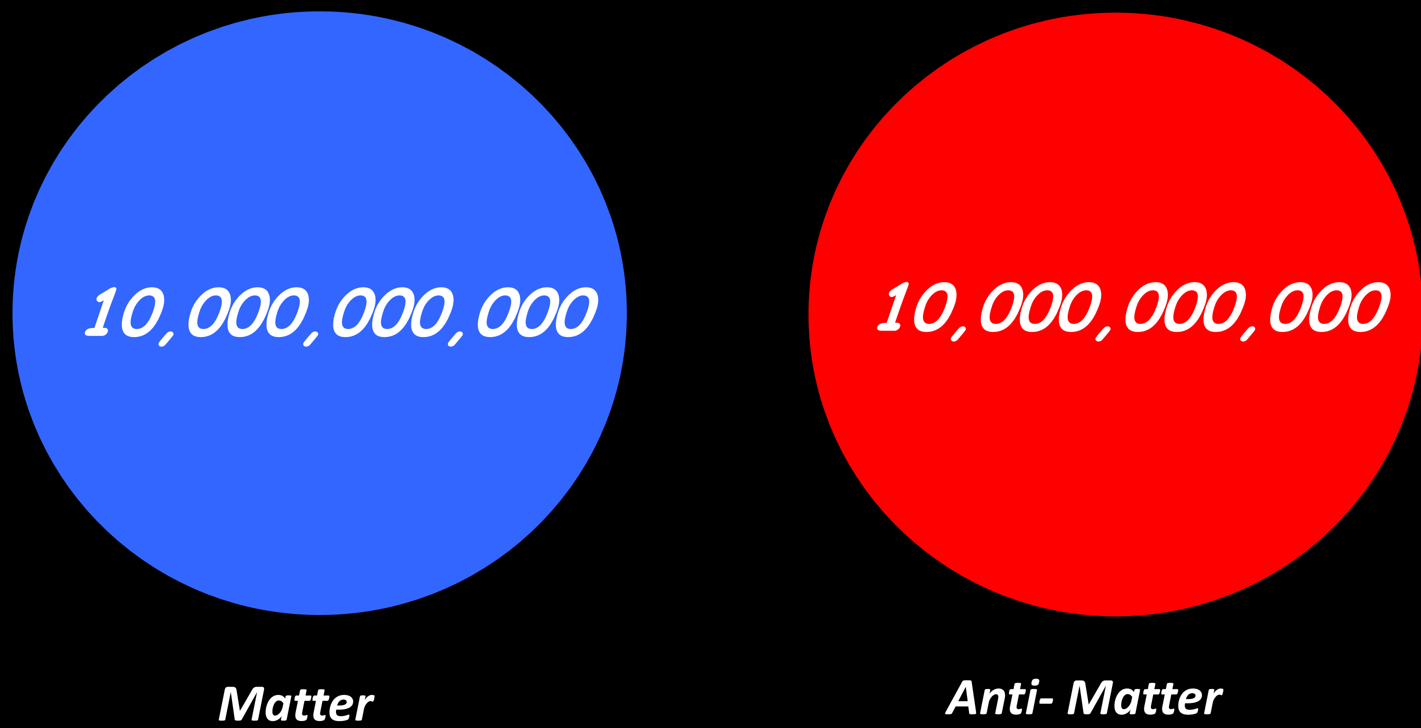
NOTHING!

Today, the Universe consists of matter and there is essentially NO anti-matter

This is the

"Baryon Asymmetry Problem"

Matter and Antimatter Just After Inflation



after Hitoshi Murayama

Matter and Antimatter
~10^{-6} s later

10,000,000,000

Matter

9,999,999,999

Anti- Matter

after Hitoshi Murayama

Matter and Antimatter
Now

1

Matter

Anti- Matter

after Hitoshi Murayama

Matter and Antimatter
Now

That's us…and everything we can see

1

Matter

Anti- Matter

after Hitoshi Murayama

Generating a Matter-Antimatter Asymmetry

A. D. Sakharov, JETP Lett. 5, 24 (1967)

A. Sakharov

Sakharov Process Requires Three Things:

1. The process must violate Baryon Number Conservation
2. There must be a period of Non-Thermal Equilibrium
3. The process must violate Time Reversal Non-Invariance

Question:

Can the T violation needed to generate the matter-antimatter asymmetry when the universe was 10^{-6}s old be related to an observable quantity today?

The Neutron Electric Dipole Moment

An example of T violaton

Discrete Symmetries

Parity: $\hat{P} \cdot \Psi(x, y, z) \Rightarrow \Psi(-x, -y, -z)$

Time Reversal: $\hat{T} \cdot \Psi(t) \Rightarrow \Psi(-t)$

Charge Conjugation: $\hat{C} \cdot \Psi_n \Rightarrow \Psi_{\bar{n}}$

Wigner-Eckhart Theorem Implies $\vec{\mu} = \mu \frac{\vec{J}}{J}$ *and* $\vec{d} = d \frac{\vec{J}}{J}$

Non-Relativistic Hamiltonian

$$H = \underbrace{\vec{\mu} \cdot \vec{B}}_{} + \underbrace{\vec{d} \cdot \vec{E}}_{}$$

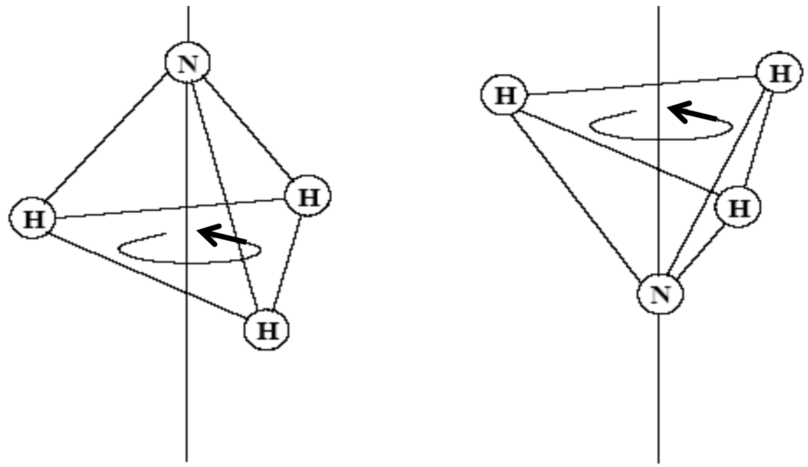
$\vec{\mu} \cdot \vec{B}$	$\vec{d} \cdot \vec{E}$
C-even	C-even
P-even	P-odd
T-even	T-odd

	C	P	T
$\vec{\mu}$	-	+	-
$\vec{d}$	-	+	-
$\vec{E}$	-	-	+
$\vec{B}$	-	+	-
$\vec{J}$	+	+	-

Non-zero d violates P,T, and CP

Slide curtesy B. Filippone

Non-Elementary Particles can have EDM's
Without Violating Parity and Time Reversal Symmetry



If the neutron was a composite object it could also have non-zero edm without P and T.

However, it would then have a degenerate ground state Which is incompatible with observed nuclear shell structure

Non-Elementary Particles can have EDM's <u>Without</u> Violating Parity and Time Reversal Symmetry

Theorem:

The observation of a non-zero, static, electric dipole moment for a non-degenerate elementary particle would be a direct violation of time reversal symmetry.

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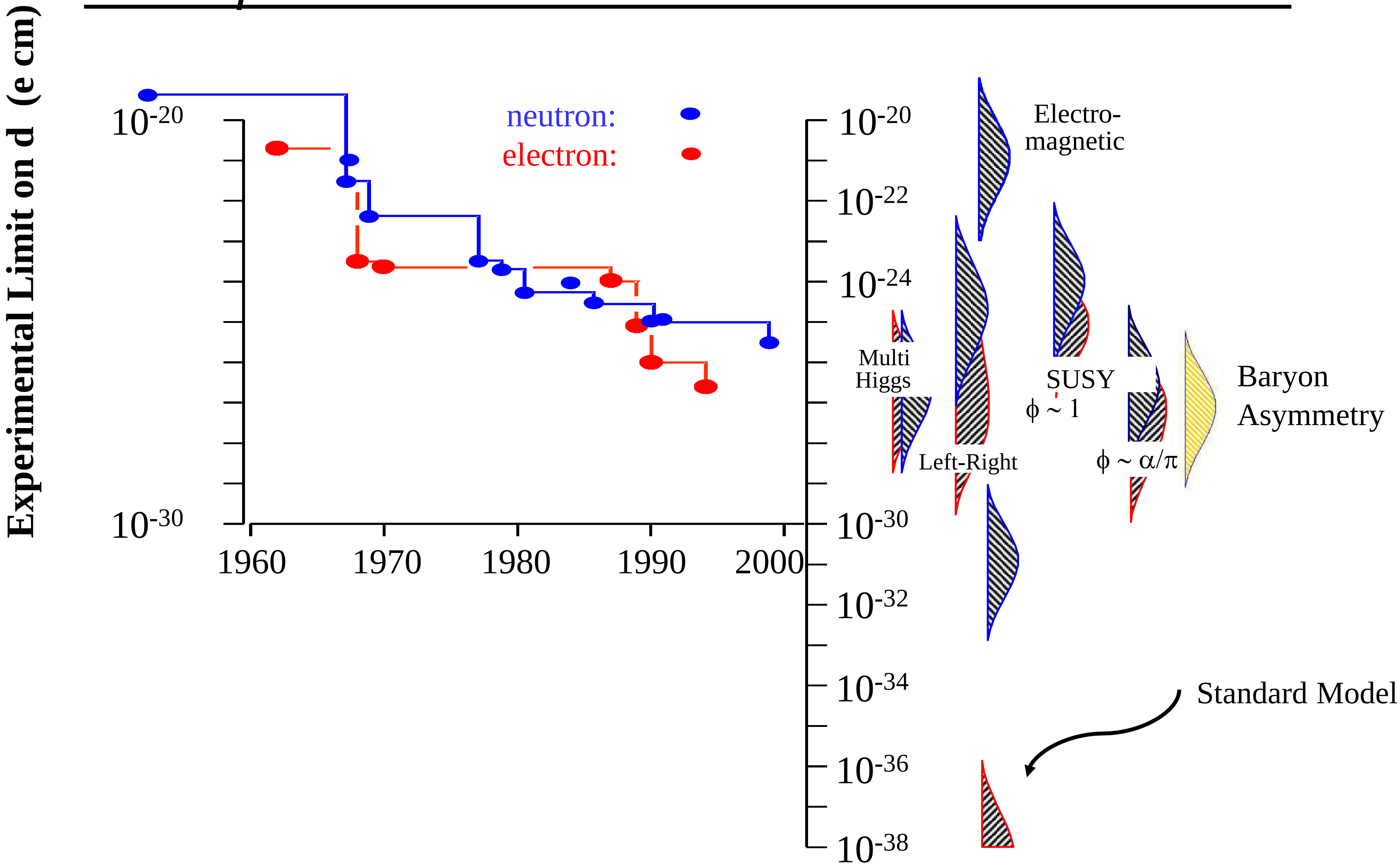
We expect a non-zero neutron EDM at some level



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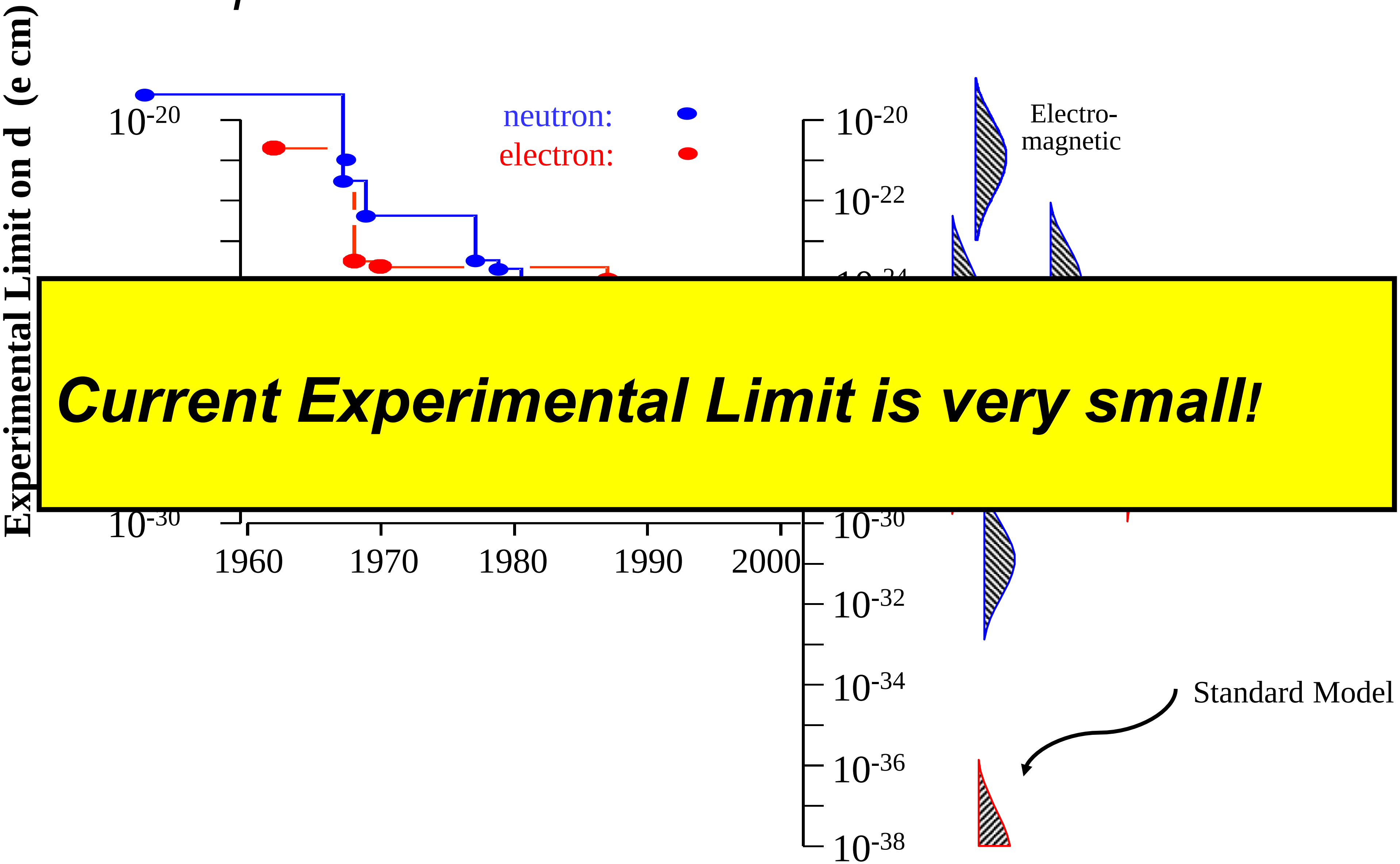
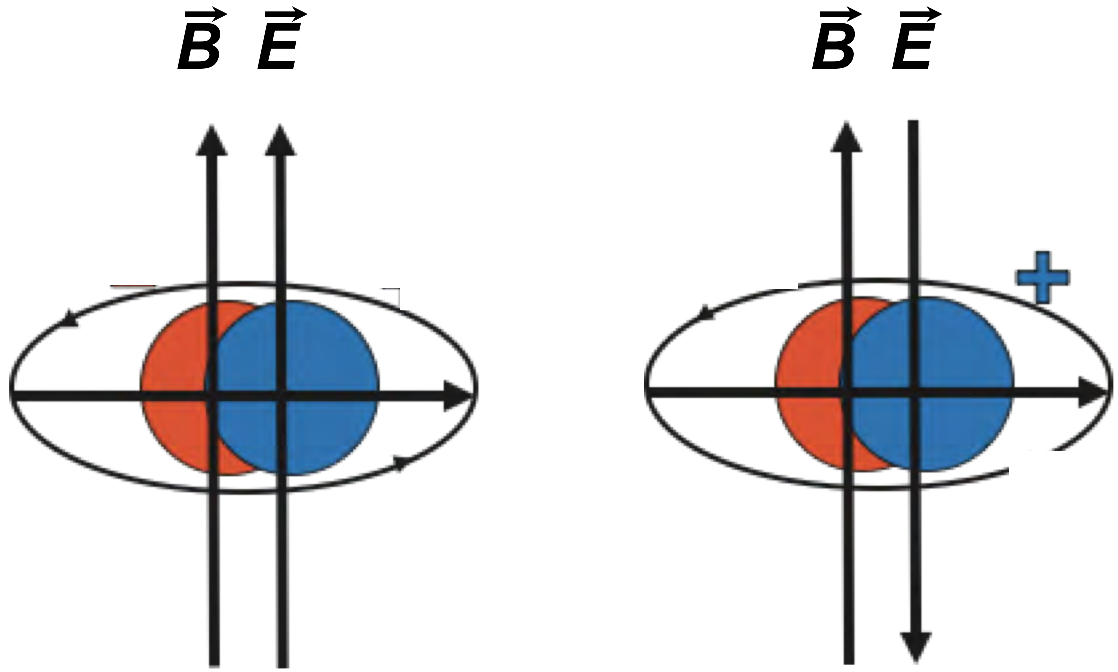


Current Experimental Limit is very small!

If a neutron were blown up to the size of the earth, the current limit on its EDM would correspond to a displacement of + and – electron charge by ~1 μm

Measuring the Electric Dipole Moment



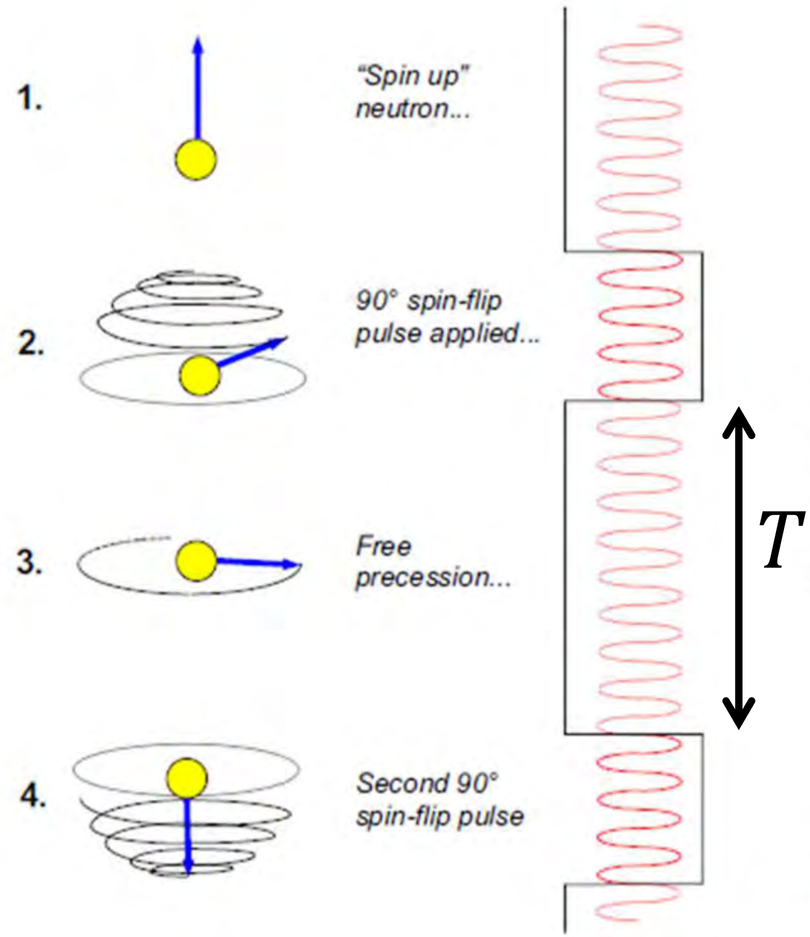
$$H = \vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}$$

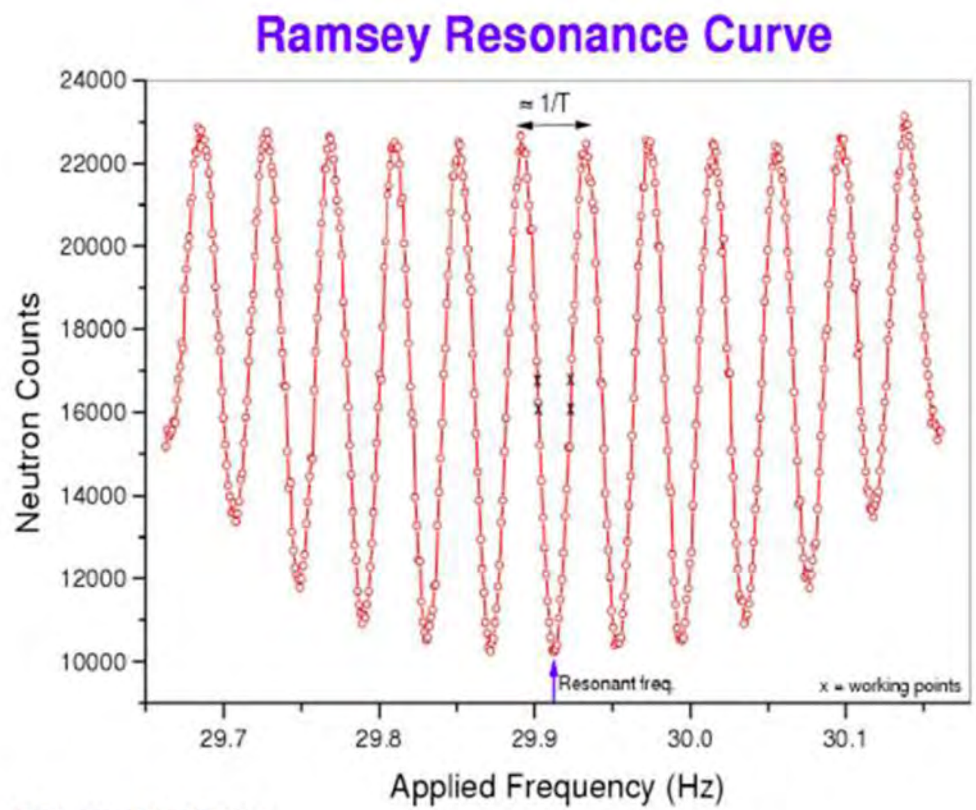
$$\omega = \frac{2\mu_n B}{\hbar} \pm \frac{2d_n E}{\hbar}$$

Look for a precession frequency $\hbar\omega = 2\mu_n B \pm 2d_n E$

A moment of 10^{-25} ecm in a 10 kV/cm electric field corresponds to a shift in frequency of 0.5 μHz!

*Ramsey's Method of Separated Oscillatory Fields**





PRL82(1999)904

$$\Delta\omega = \frac{1}{2T}$$

**cited for Nobel Prize 1989*

EDM Statistical Sensitivity

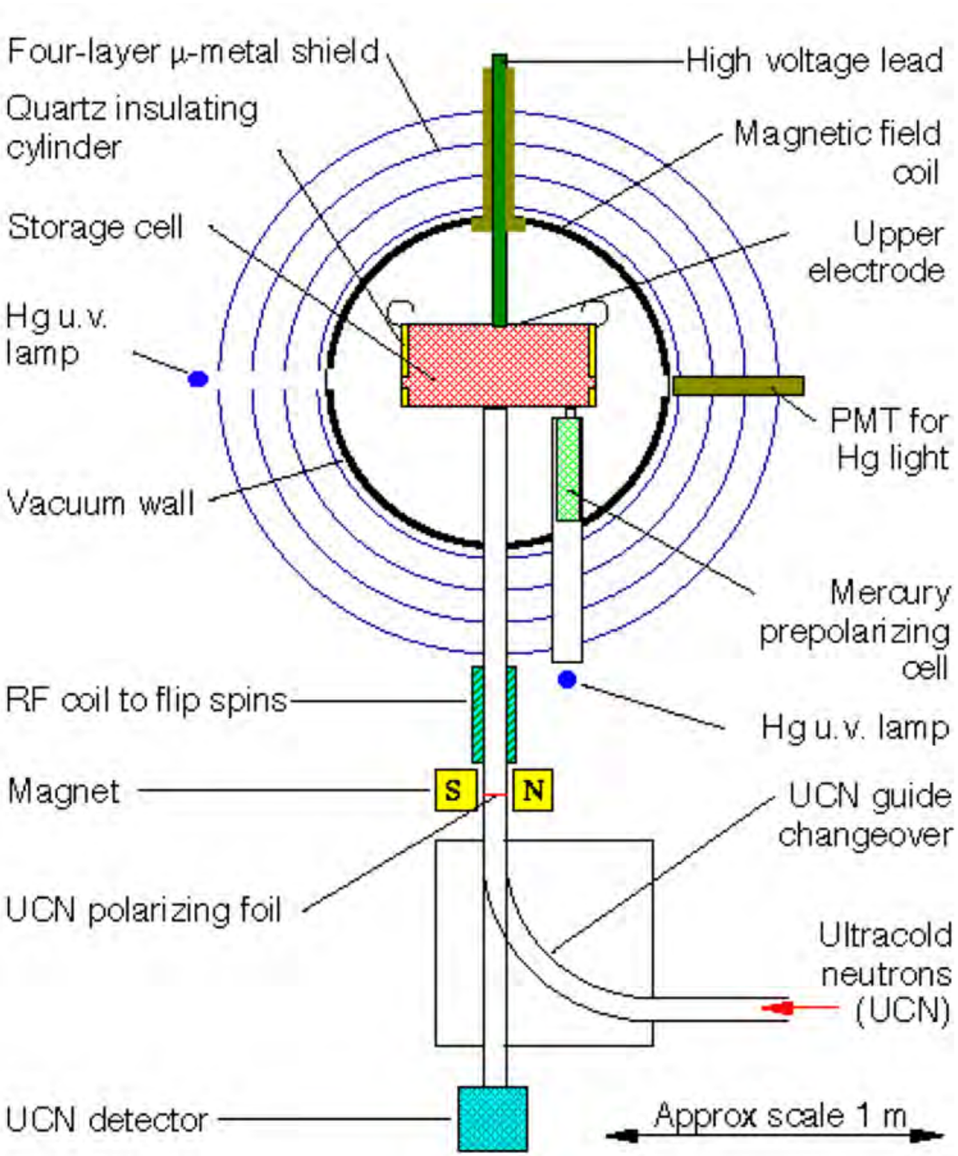
$$\sigma_{edm} \propto \frac{1}{ET\sqrt{N_n}}$$

$$E = Applied\ Electric\ Field$$
$$N_n = Number\ of\ neutrons\ observed$$
$$T = Observation\ Time$$

We want:

1. *Highest Possible Electric Field (Limited by breakdown)*
2. *More neutrons (limited by source strength)*
3. *Longest possible free precession time (ultimately limited by τ_n)*

*ILL- Sussex Neutron Electric Diopole Moment Experiment**

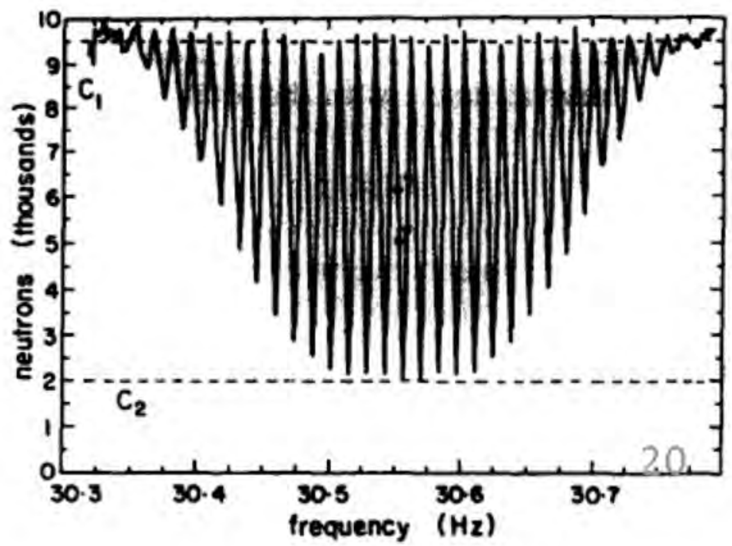


$$\boxed{d = (-0.21 \pm 1.82) \times 10^{-26}\ ecm}$$

J.M. Pendlebury et al., PR D92 09 (2003

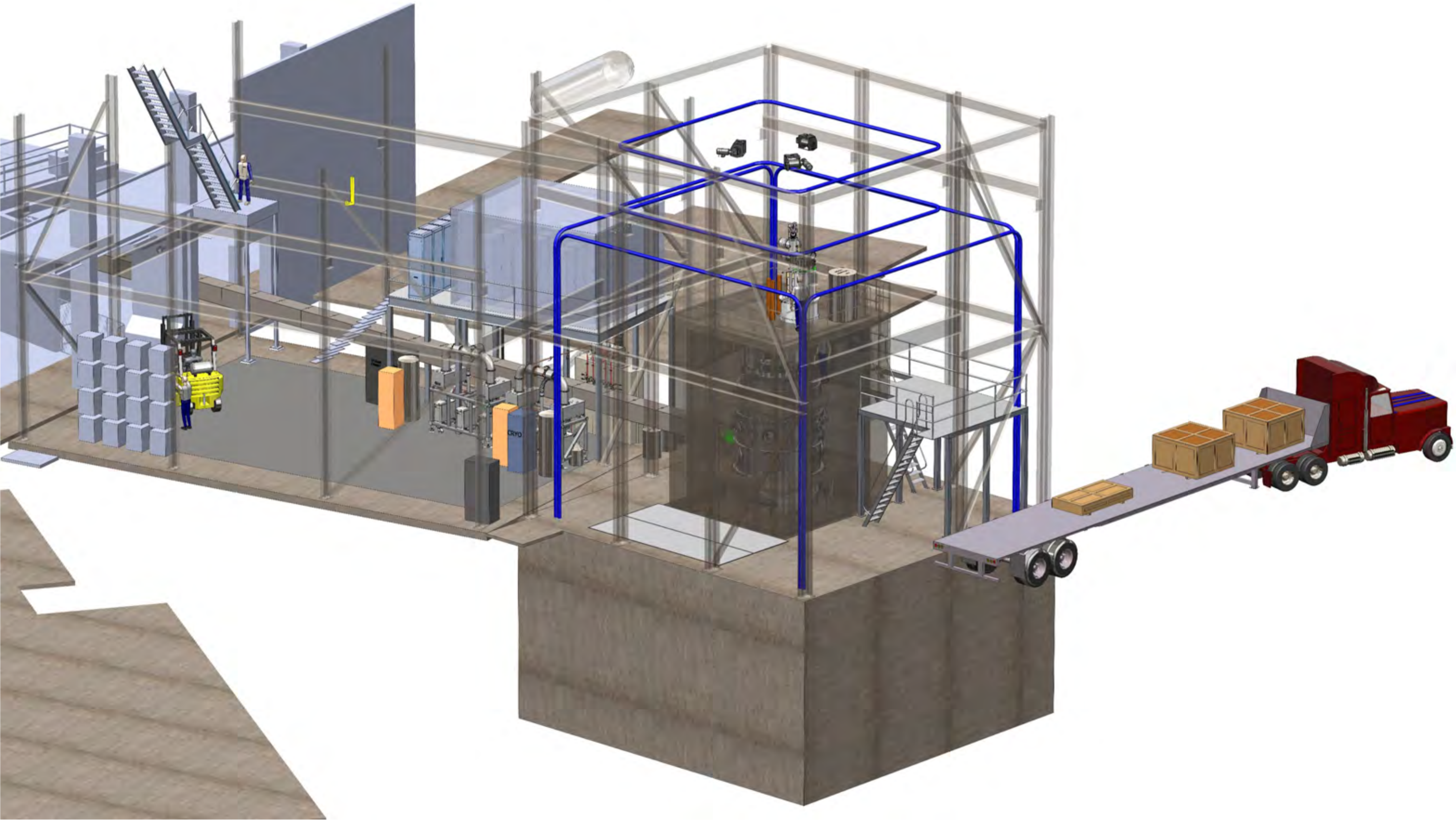
$T = 130\ s$

$E = 10kV/cm$



Experiment has been upgraded and installed at PSI. New result is pending.

The nEDM experiment at the Spallation Neutron Source



Features of the new SNS nEDM experiment:

- Double cell (common B, opposite E)

- Ultra-cold neutrons produced in-situ
  - in superfluid Helium below 0.7K to achieve long storage time (suppress phonon upscattering) **as a UCN source**

- Helium-3 as co-magnetometer
  - precession monitored by SQUID
  - long relaxation time in superfluid Helium **as a buffer gas**

- Neutron precession measured through the spin-dependent $n+^{3}He$ capture reaction **as a particle detector**
  - Use liquid helium as scintillating medium
  - Cell has to be optically transparent as a part of the light guide
  - PMT operated at cryogenic temperatures (4K)

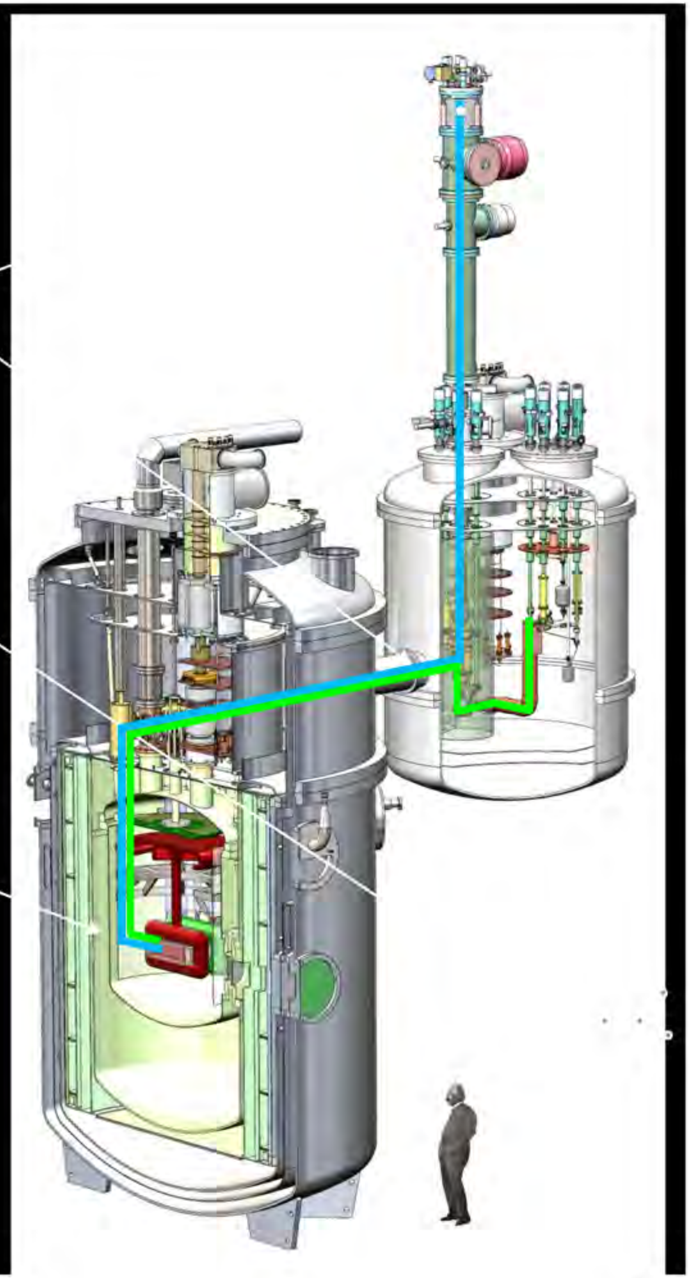
as a HV insulator

- High dielectric strength of superfluid helium (>50kV/cm)

Slide curtesy, Chen-Yu Lu

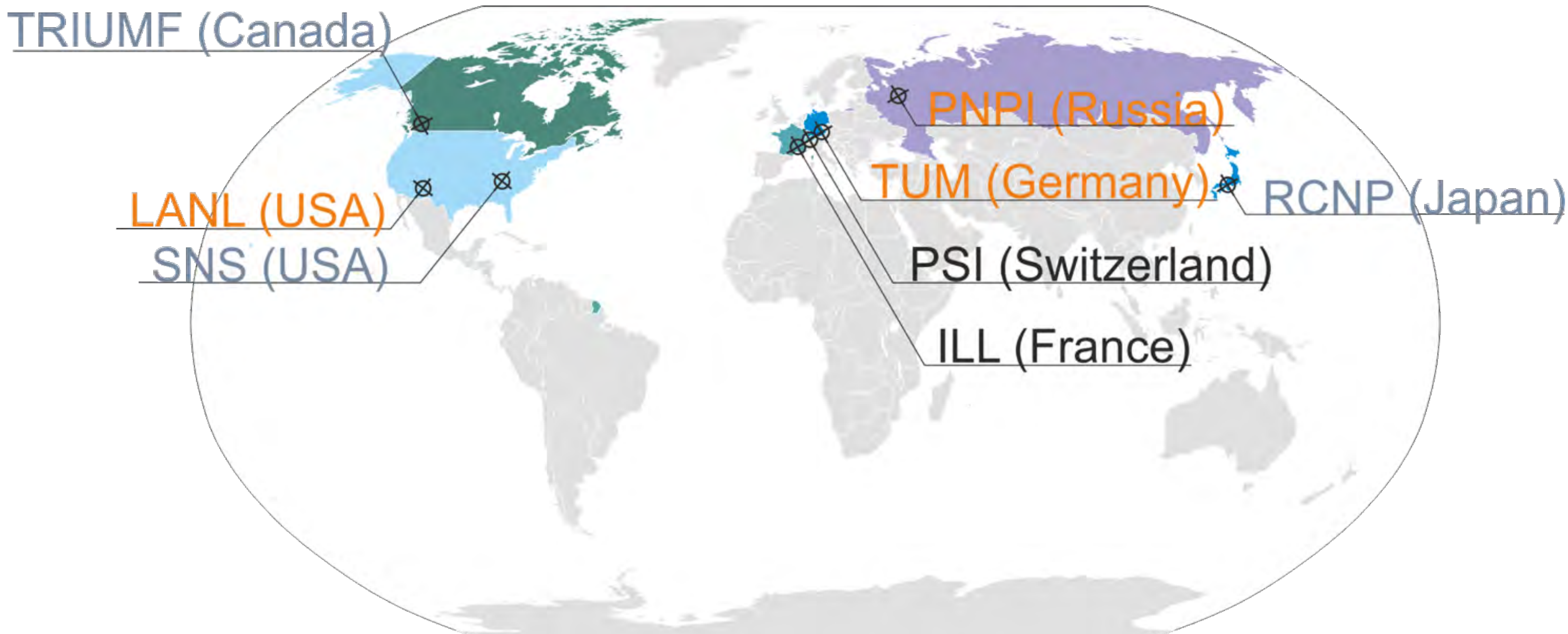
nEDM@SNS Measurement Cycle

1. Load collection volume with polarized ^{3}He atoms
2. Transfer polarized ^{3}He atoms into measurement cell
3. Illuminate measurement cell with polarized cold neutrons to produce polarized UCN
4. Apply a $\pi/2$ pulse to rotate spins perpendicular to B_0
5. Measure precession frequency
6. Remove reduced polarization ^{3}He atoms from measurement cell
7. Flip E-field & Go to 1.



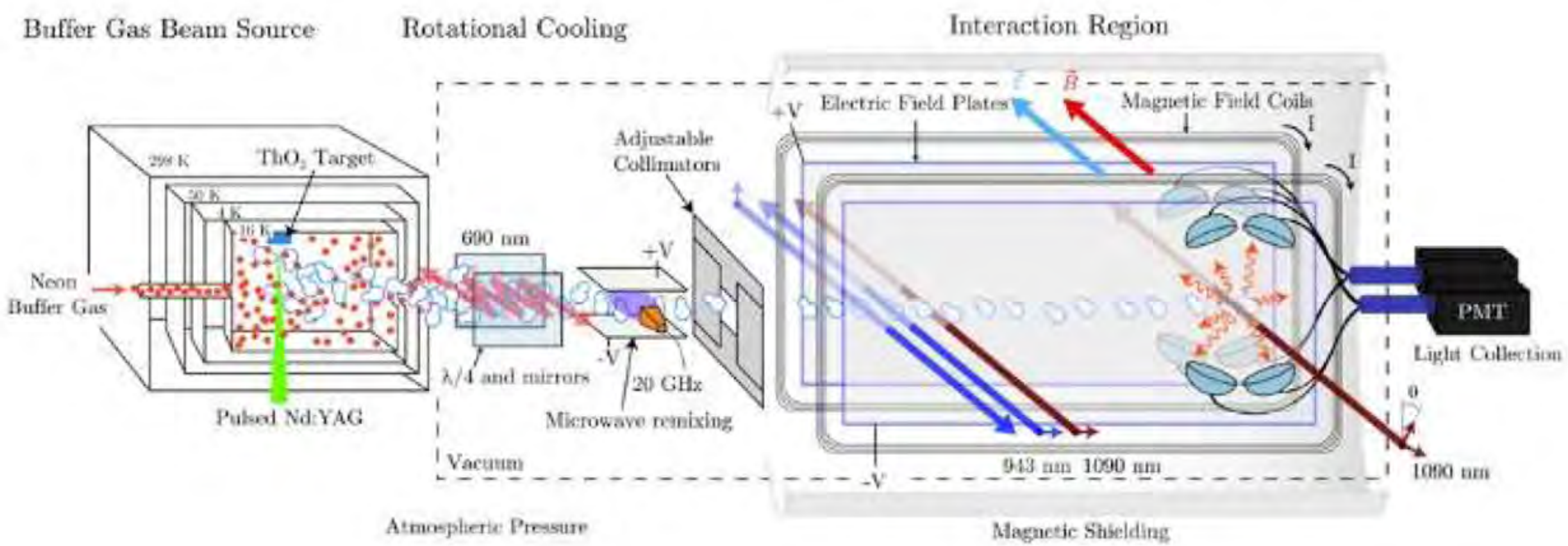
Slide thanks to Vince Cianciolo

Neutron EDM searches are in progress at many facilities world wide



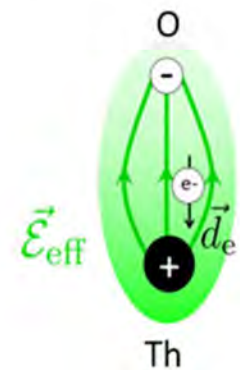
The Neutron EDM search is complementary to other types of EDM measurements

ACME experiment



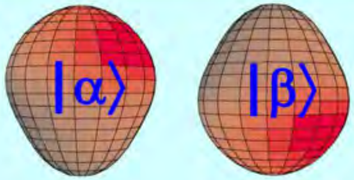
$d_e = (-2.1 \pm 3.7_{stat} \pm 2.5_{syst}) \times 10^{-29}$ $e\cdot$cm

Science 17 Jan 2014:
Vol. 343, Issue 6168, pp. 269-272



10 V/cm → 10*1e+9 V/cm,

Slide curtesy, Chen-Yu Lu



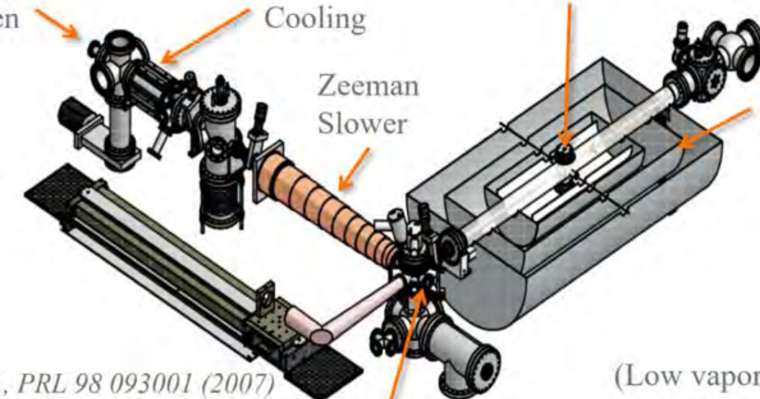
A large quadrupole and octupole deformation results In an enhanced Schiff moment
– Auerbach, Flambaum & Spevak (1996)

Enhancement Factor: EDM (^{225}Ra) / EDM (^{199}Hg)

Skyrme Model	Isoscalar	Isovector	Isotensor
SIII	300	4000	700
SkM*	300	2000	500
SLy4	700	8000	1000

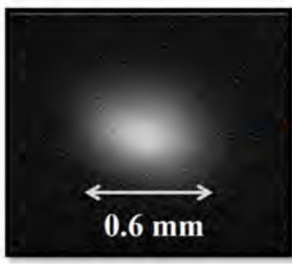
Collect Atoms in MOT

Radium-255
deformed nuclei



J. R. Guest et al., PRL 98 093001 (2007)

(Low vapor pressure)



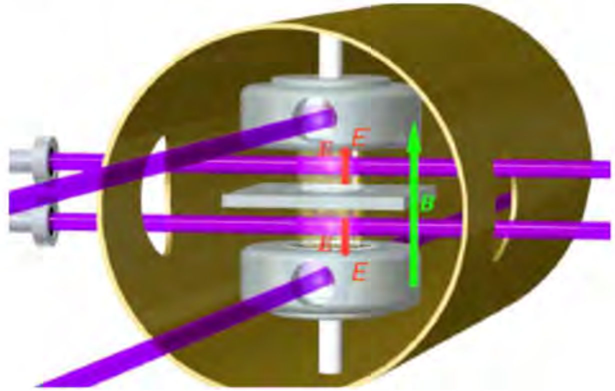
^{226}Ra MOT
20,000 atoms

For EDM:	For Testing:
Ra-225	Ra-226
I = 1/2, J = 0	I = 0, J = 0
$t_{1/2}$ = 15 days	$t_{1/2}$ = 1600 yrs

Slide curtesy, Chen-Yu Lu

The Seattle ^{199}Hg (atomic) EDM Measurement

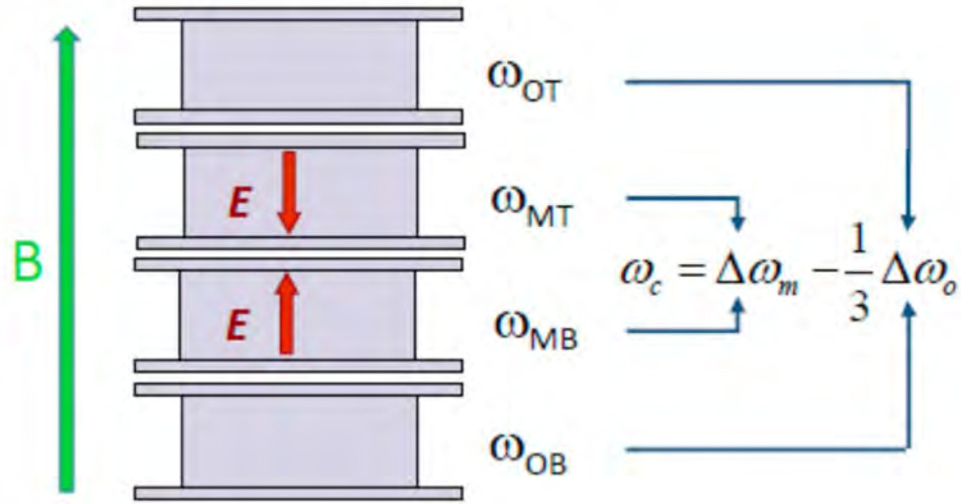
4 mercury vapor Cells:
2 with opposite E fields
2 for B field normalization



$$H = -(\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E})$$

$$\omega_c = \frac{\mu}{\hbar}\left(-\frac{8}{3}\frac{\partial^3 B}{\partial z^3}\Delta z^3\right) + \frac{4dE}{\hbar}$$

Cancels up to 2nd order gradient noise
Same EDM sensitivity as Middle Difference



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Why Do We Need So Many Experiments?

- Electron EDM
- TVPV pseudoscalar-scalar eN coupling
- TVPV tensor eN coupling
- Short-distance contribution to d_n
- Short distance contribution to d_p
- TVPV isoscalar πN coupling
- TVPV isovector πN coupling

$$d = \underbrace{\alpha_{d_e} d_e + \alpha_{C_S} C_S}_{\text{Paramagnetic Systems}} + \underbrace{\alpha_{C_T} C_T + \alpha_{\bar{d}_n} \bar{d}_n + \alpha_{\bar{d}_p} \bar{d}_p + \alpha_{g_\pi^0} \bar{g}_\pi^0 + \alpha_{g_\pi^1} \bar{g}_\pi^1,}_{\text{Diamagnetic Systems}}$$

T. Chupp, M. Ramsey-Musolf, Phys. Rev. **C91** 035502 (2015)

End of Lecture 3

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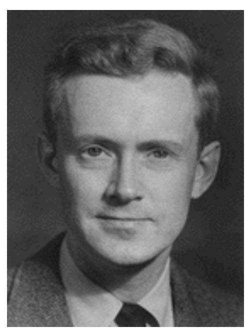

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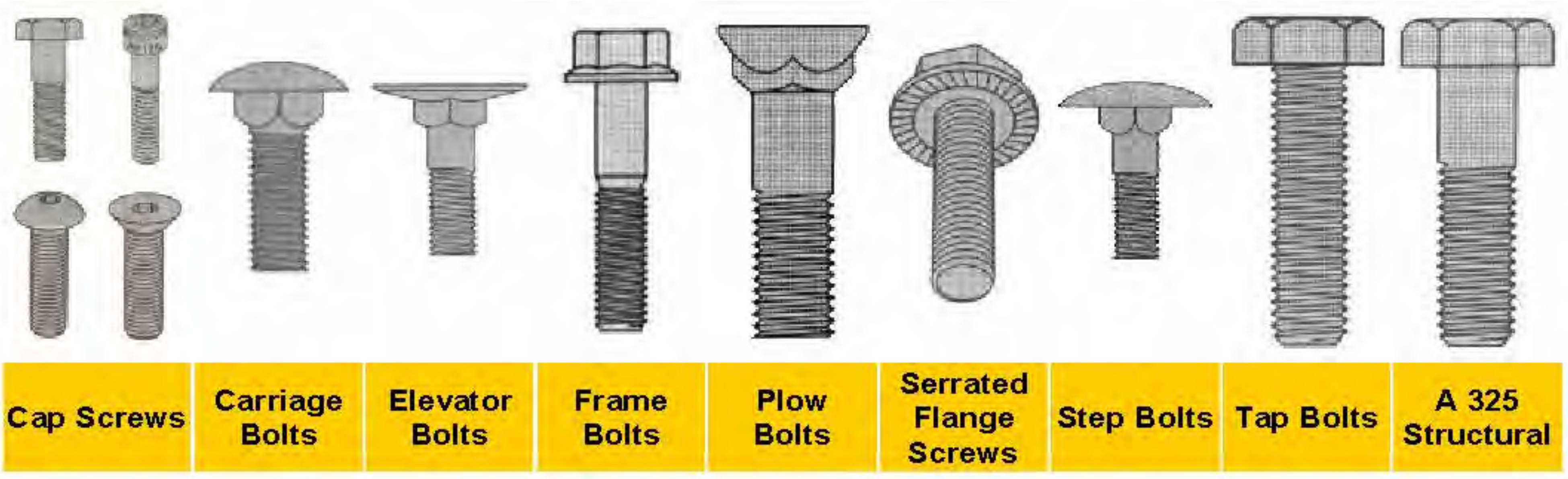

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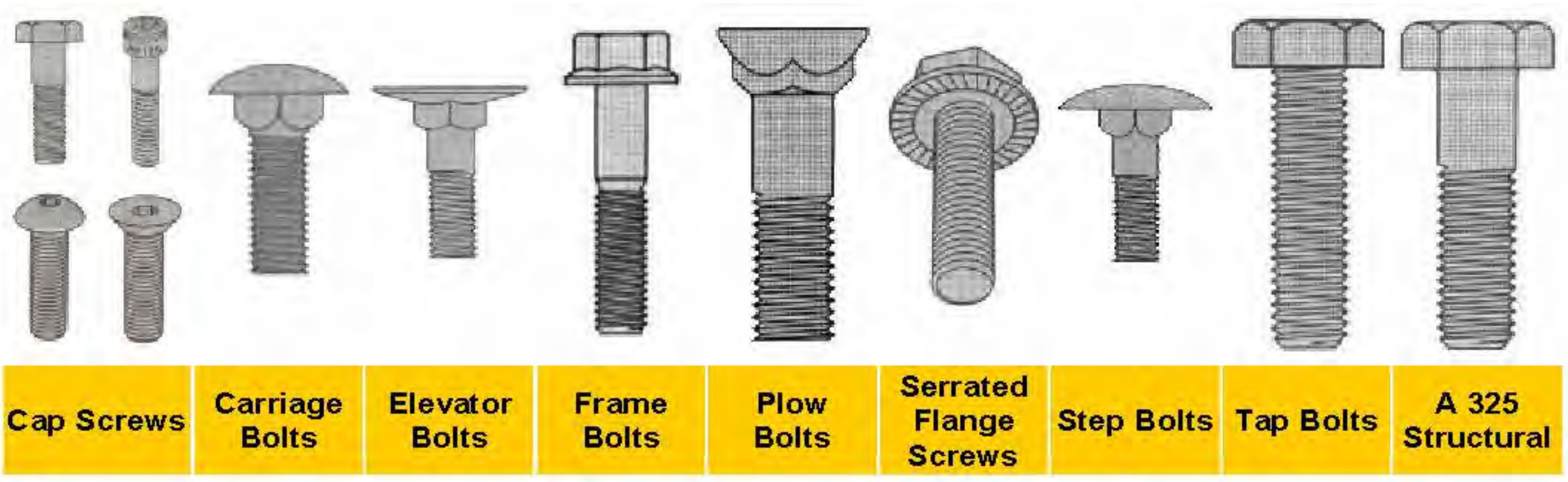

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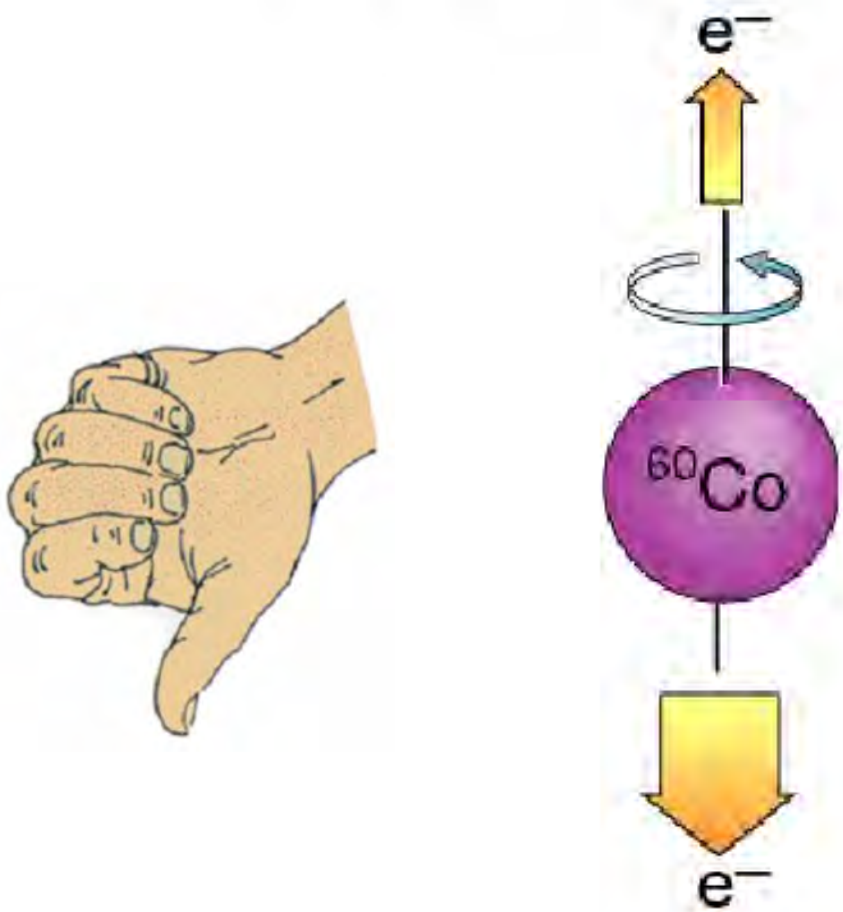

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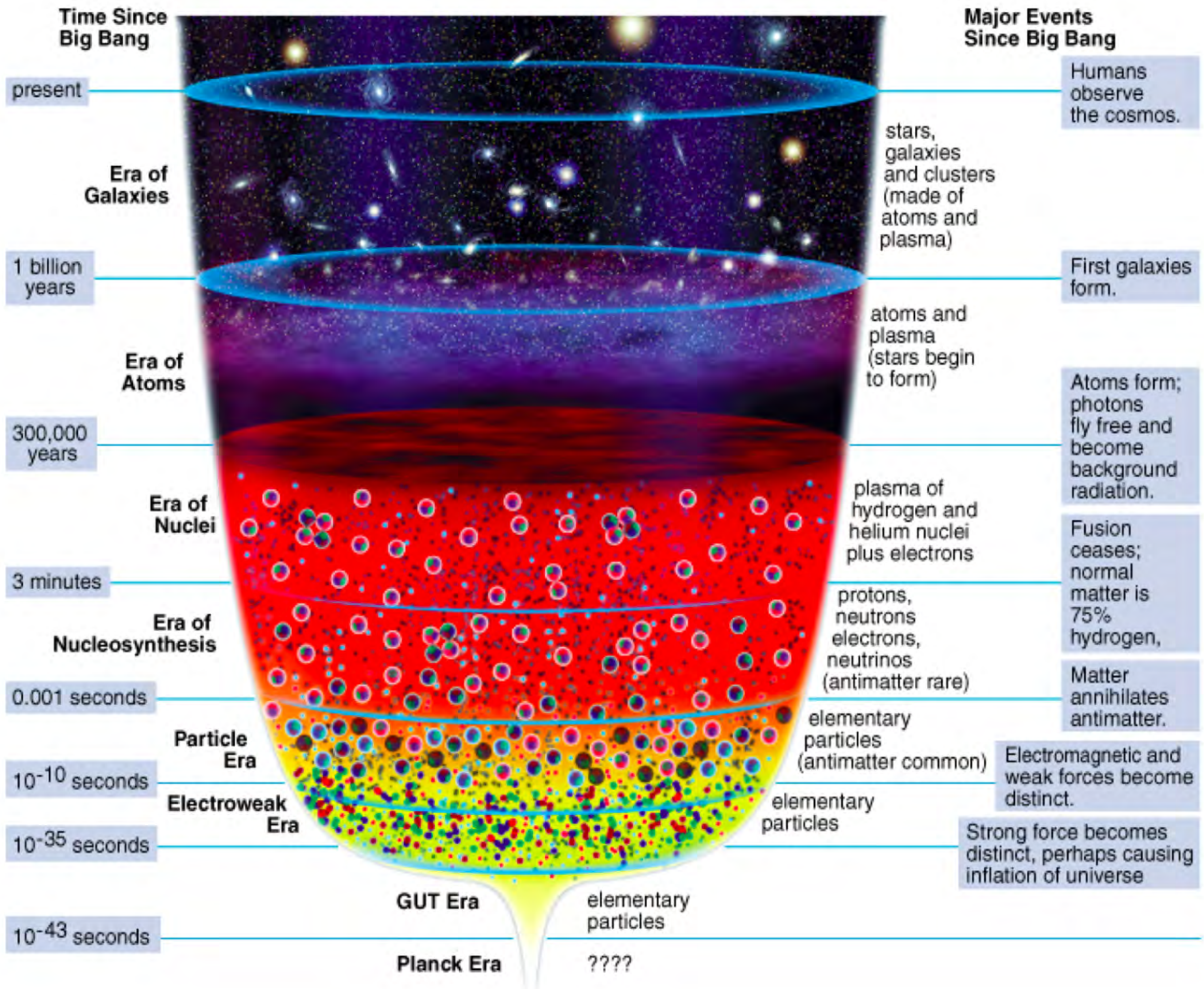

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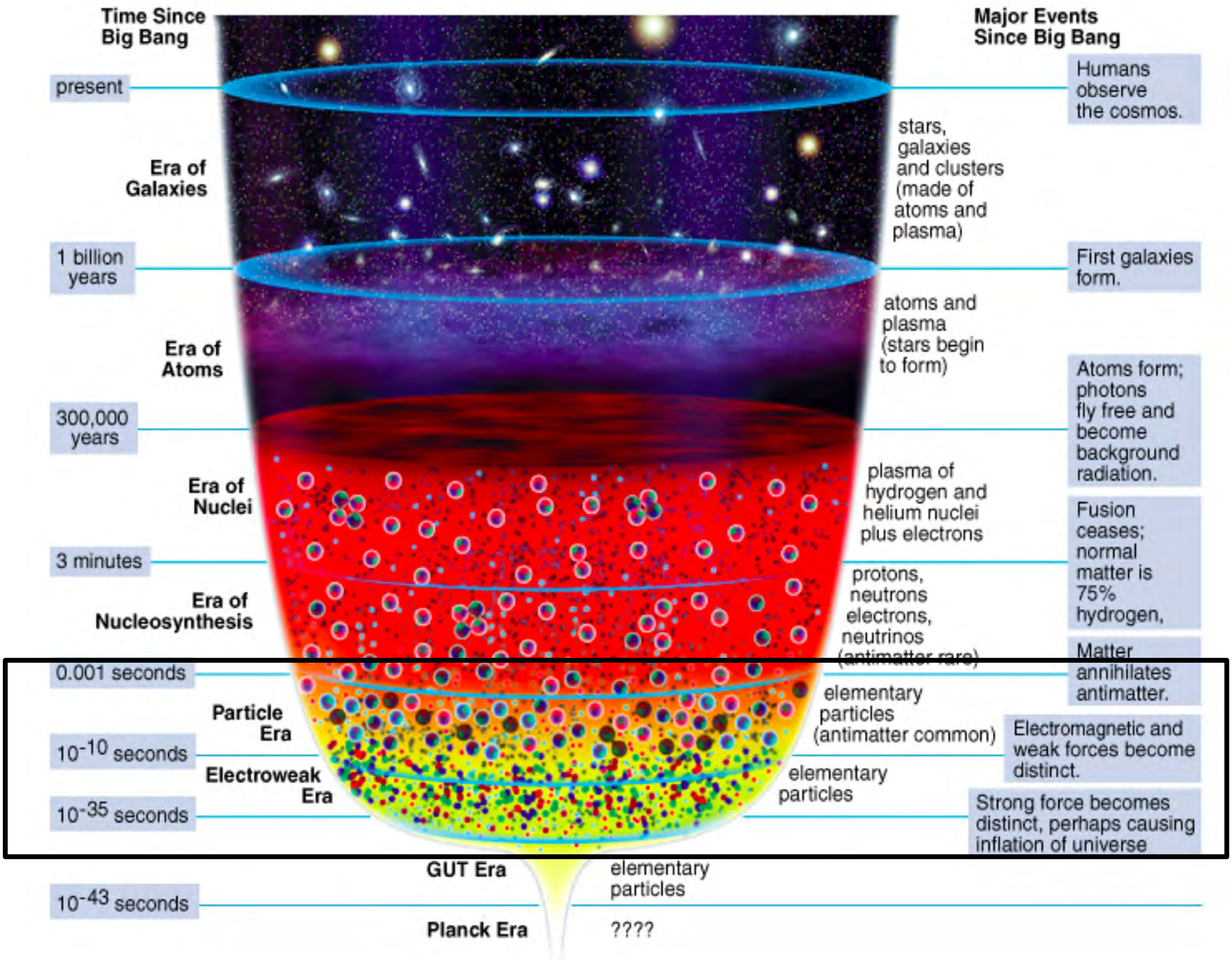
Planck Era
????



Time Since Big Bang
Major Events Since Big Bang
present
Humans observe the cosmos.
Era of Galaxies
stars, galaxies and clusters (made of atoms and plasma)
1 billion years
First galaxies form.
Era of Atoms
atoms and plasma (stars begin to form)
300,000 years
Atoms form; photons fly free and become background radiation.
Era of Nuclei
plasma of hydrogen and helium nuclei plus electrons
3 minutes
Fusion ceases; normal matter is 75% hydrogen,
Era of Nucleosynthesis
protons, neutrons electrons, neutrinos (antimatter rare)
0.001 seconds
Matter annihilates antimatter.
Particle Era
elementary particles (antimatter common)
10^{-10} seconds
Electromagnetic and weak forces become distinct.
Electroweak Era
elementary particles
10^{-35} seconds
Strong force becomes distinct, perhaps causing inflation of universe
GUT Era
elementary particles
10^{-43} seconds
Planck Era
????

Just after Inflation, there were equal amounts of Matter and Antimatter.

If nothing else happened, all matter and antimatter would annihilate leaving…

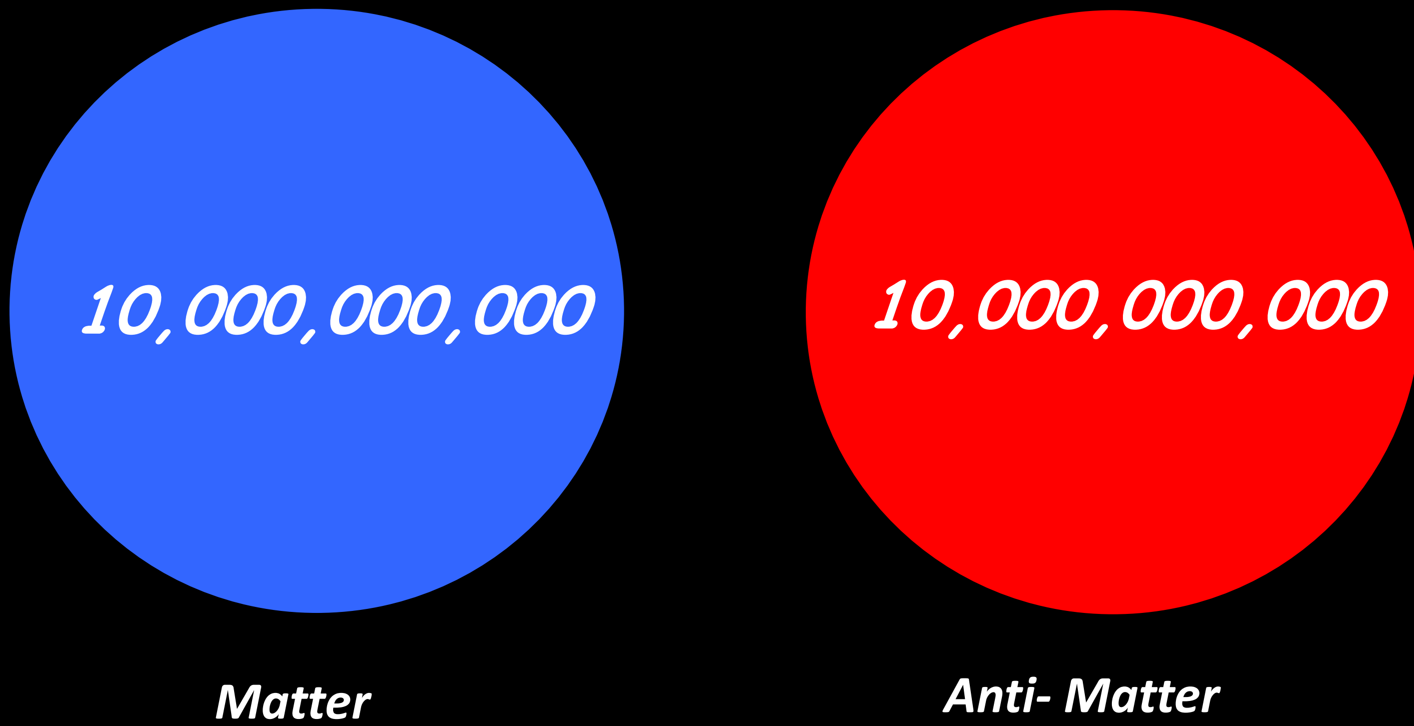
NOTHING!

Today, the Universe consists of matter and there is essentially NO anti-matter

This is the

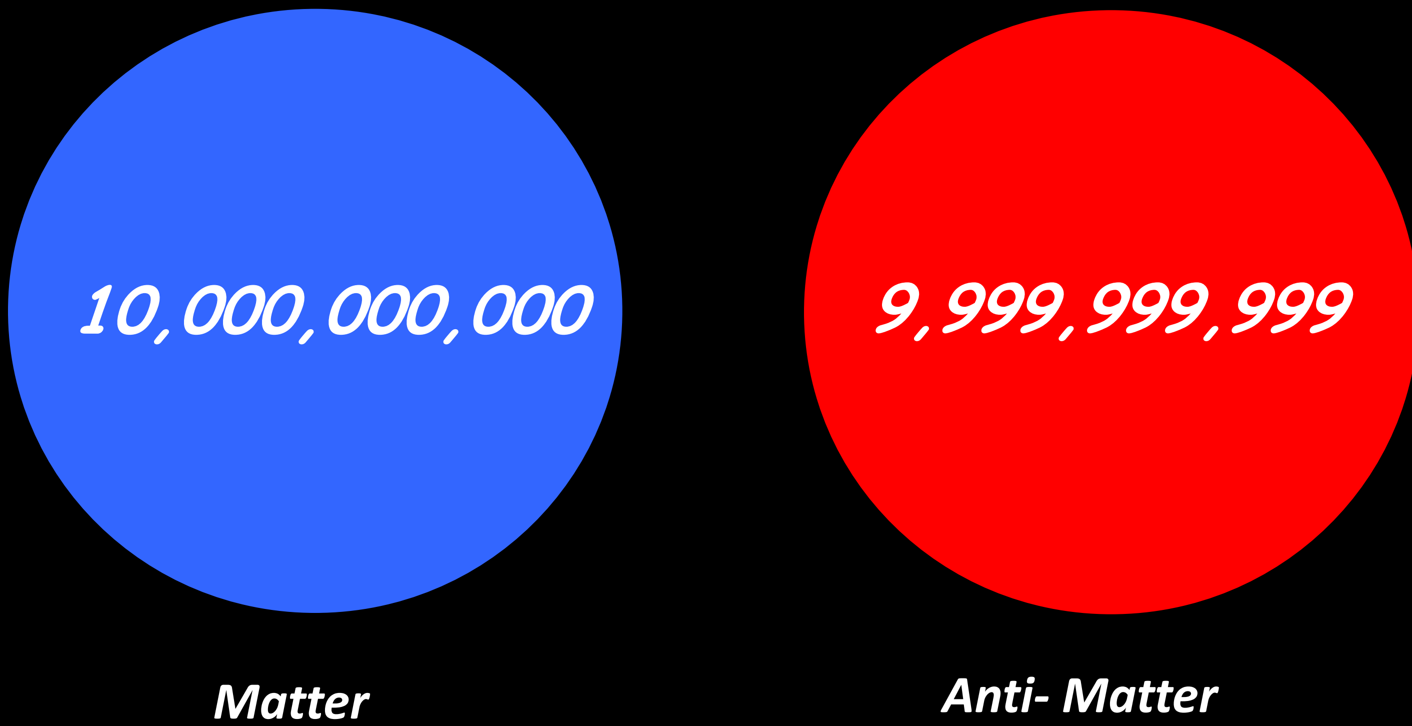
"Baryon Asymmetry Problem"

Matter and Antimatter
Just After Inflation



after Hitoshi Murayama

Matter and Antimatter
~10^{-6} s later



after Hitoshi Murayama

Matter and Antimatter

Now

1

Matter

Anti- Matter

after Hitoshi Murayama

Matter and Antimatter

Now

That's us…and everything we can see

1

Matter

Anti- Matter

after Hitoshi Murayama

Generating a Matter-Antimatter Asymmetry

A. D. Sakharov, JETP Lett. 5, 24 (1967)

A. Sakharov

Sakharov Process Requires Three Things:

1. The process must violate Baryon Number Conservation
2. There must be a period of Non-Thermal Equilibrium
3. The process must violate Time Reversal Non-Invariance

Question:

Can the T violation needed to generate the matter-antimatter asymmetry when the universe was 10^{-6}s old be related to an observable quantity today?

The Neutron Electric Dipole Moment

An example of T violaton

Discrete Symmetries

Parity: $\hat{P} \cdot \Psi(x, y, z) \Rightarrow \Psi(-x, -y, -z)$

Time Reversal: $\hat{T} \cdot \Psi(t) \Rightarrow \Psi(-t)$

Charge Conjugation: $\hat{C} \cdot \Psi_n \Rightarrow \Psi_{\bar{n}}$

Wigner-Eckhart Theorem Implies $\vec{\mu} = \mu \frac{\vec{J}}{J}$ *and* $\vec{d} = d \frac{\vec{J}}{J}$

Non-Relativistic Hamiltonian

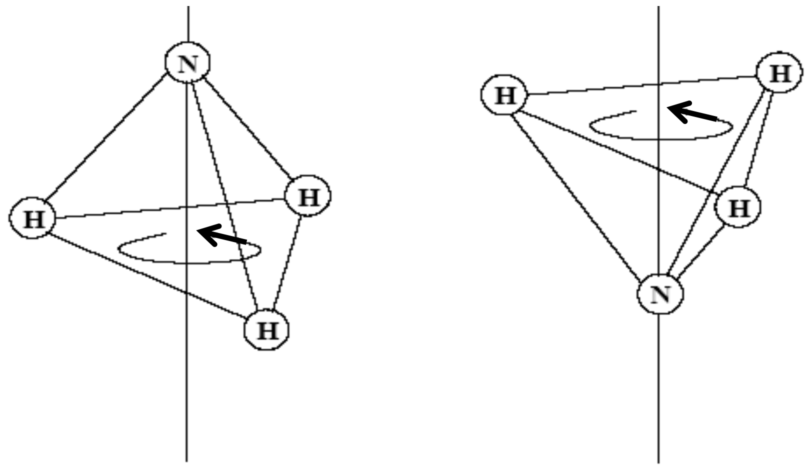
$$H = \underbrace{\vec{\mu} \cdot \vec{B}}_{\substack{\text{C-even} \\ \text{P-even} \\ \text{T-even}}} + \underbrace{\vec{d} \cdot \vec{E}}_{\substack{\text{C-even} \\ \text{P-odd} \\ \text{T-odd}}}$$

	C	P	T
$\vec{\mu}$	-	+	-
$\vec{d}$	-	+	-
$\vec{E}$	-	-	+
$\vec{B}$	-	+	-
$\vec{J}$	+	+	-

Non-zero d violates P,T, and CP

Slide curtesy B. Filippone

Non-Elementary Particles can have EDM's <u>Without</u> Violating Parity and Time Reversal Symmetry



If the neutron was a composite object it could also have non-zero edm without P and T.

However, it would then have a degenerate ground state Which is incompatible with observed nuclear shell structure

Non-Elementary Particles can have EDM's <u>Without</u> Violating Parity and Time Reversal Symmetry

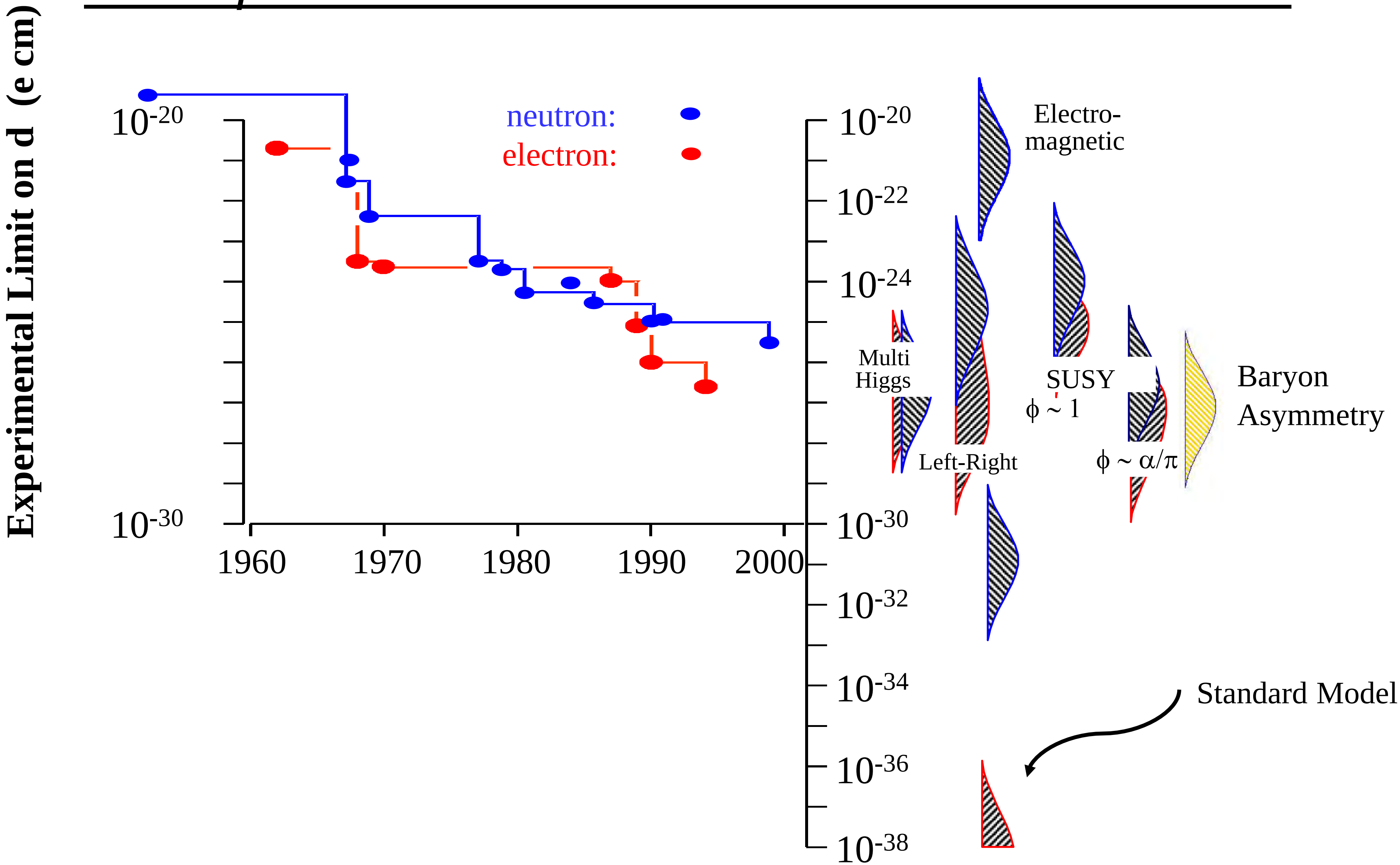
Theorem:

The observation of a non-zero, static, electric dipole moment for a non-degenerate elementary particle would be a direct violation of time reversal symmetry.

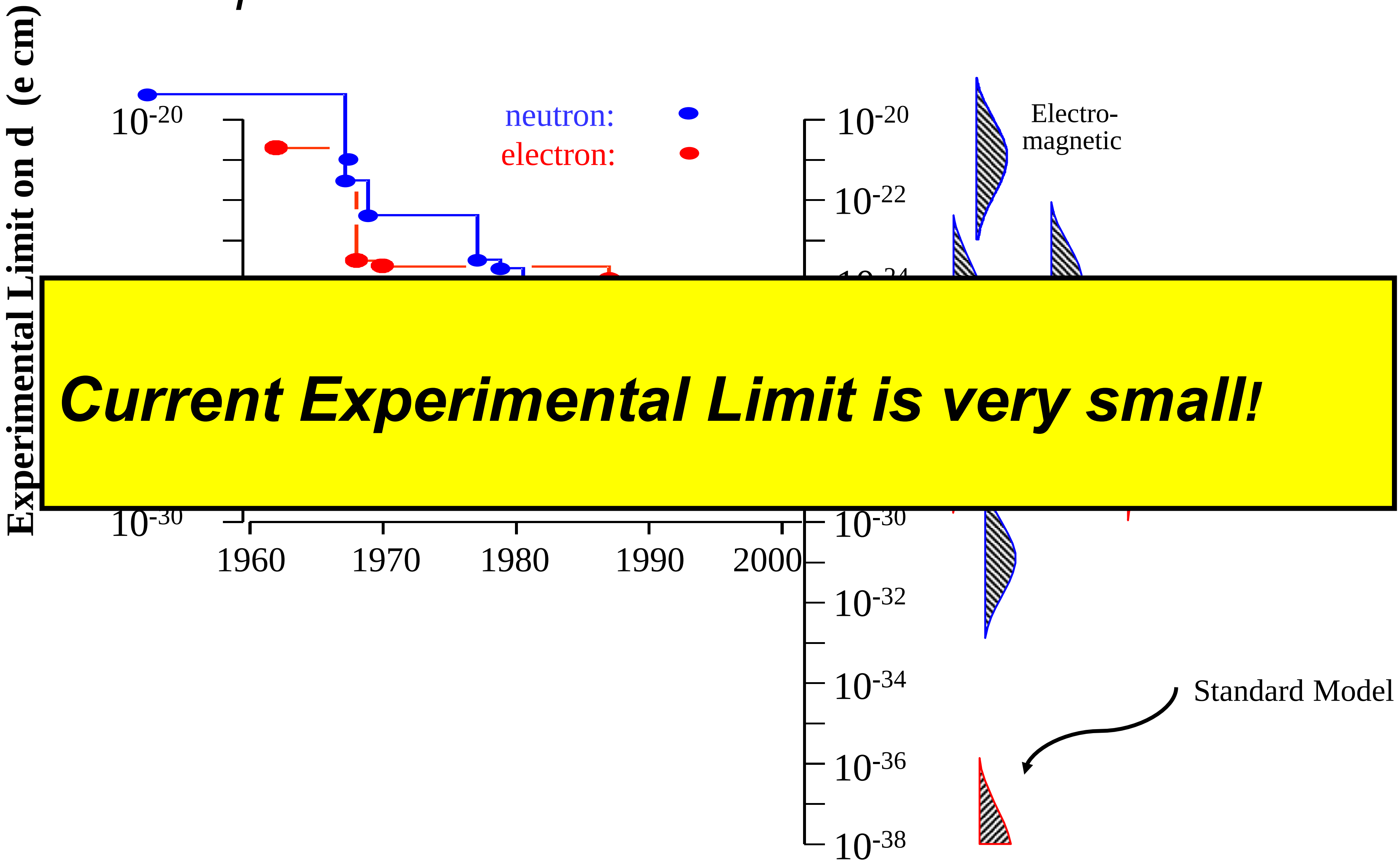
If the neutron was a composite object it could also have non-zero edm without P and T.

However, it would then have a degenerate ground state Which is incompatible with observed nuclear shell structure

We expect a non-zero neutron EDM at some level



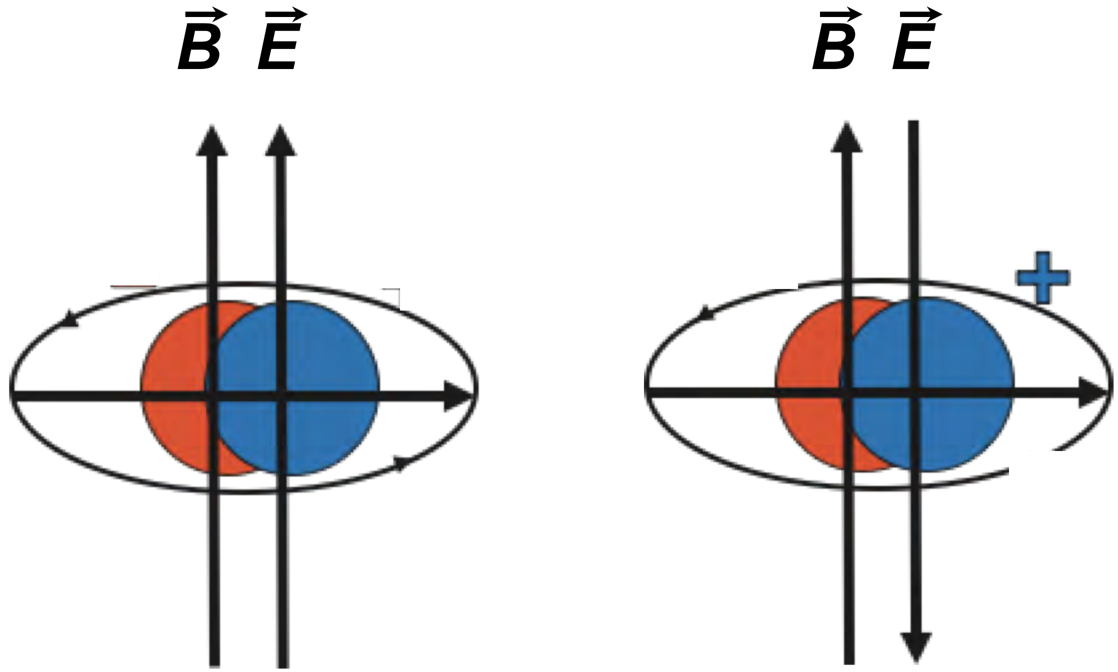
We expect a non-zero neutron EDM at some level



Current Experimental Limit is very small!

If a neutron were blown up to the size of the earth, the current limit on its EDM would correspond to a displacement of + and – electron charge by ~1 μm

Measuring the Electric Dipole Moment



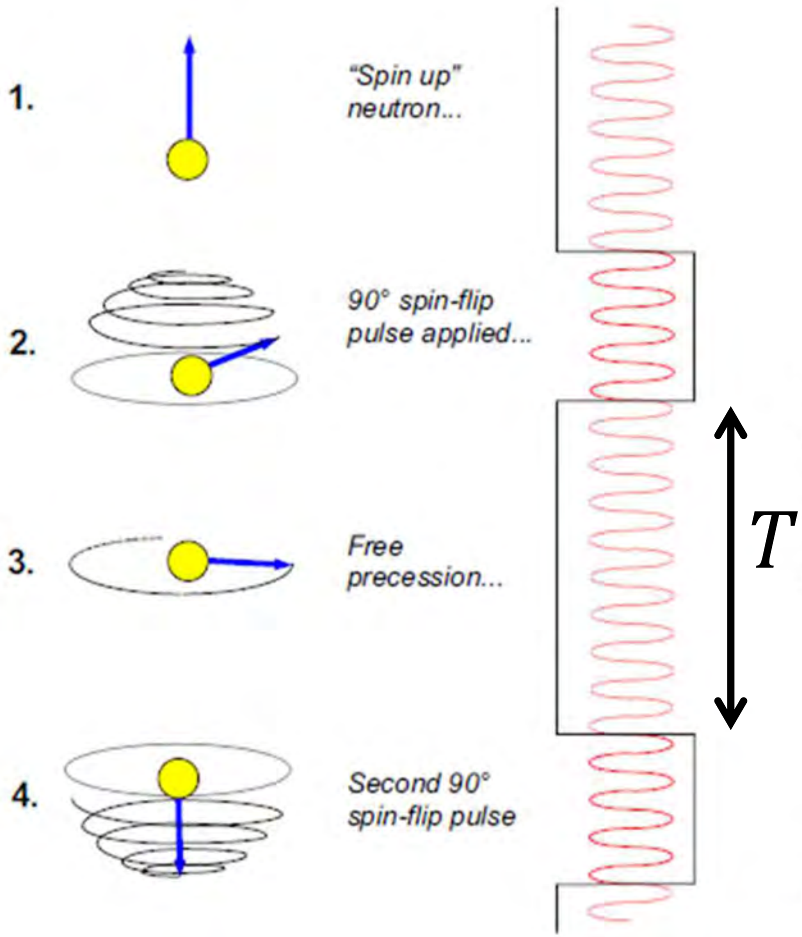
$$H = \vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}$$

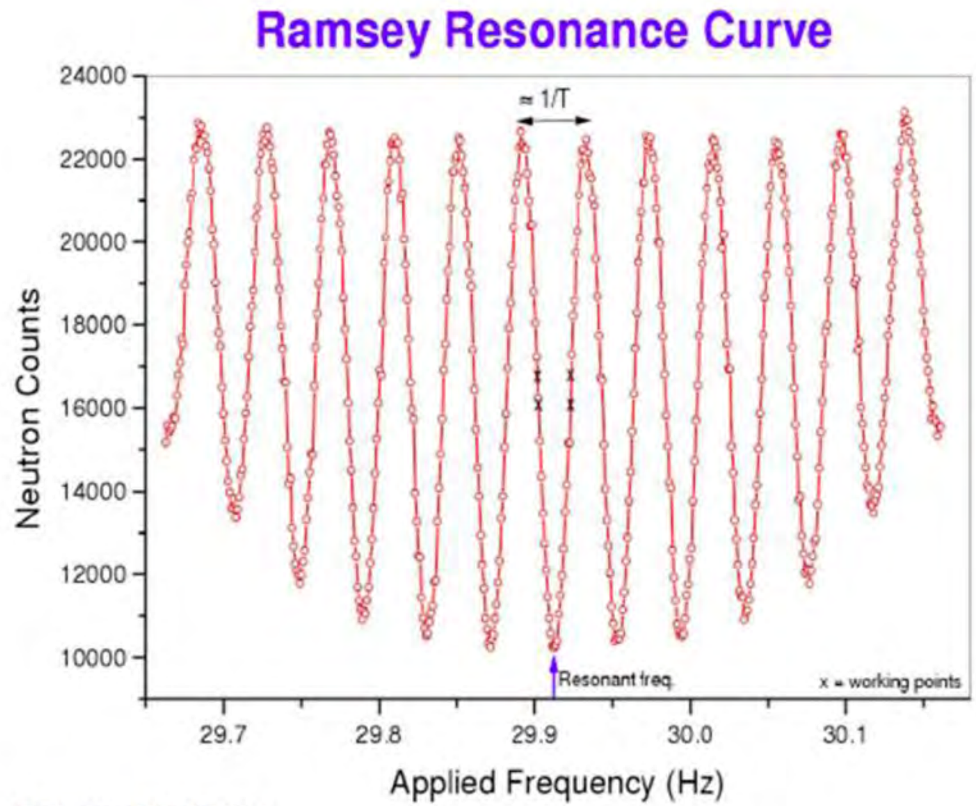
$$\omega = \frac{2\mu_n B}{\hbar} \pm \frac{2d_n E}{\hbar}$$

Look for a precession frequency $\hbar\omega = 2\mu_n B \pm 2d_n E$

A moment of 10^{-25} ecm in a 10 kV/cm electric field corresponds to a shift in frequency of 0.5 μHz!

*Ramsey's Method of Separated Oscillatory Fields**





PRL82(1999)904

$$\Delta\omega = \frac{1}{2T}$$

**cited for Nobel Prize 1989*

EDM Statistical Sensitivity

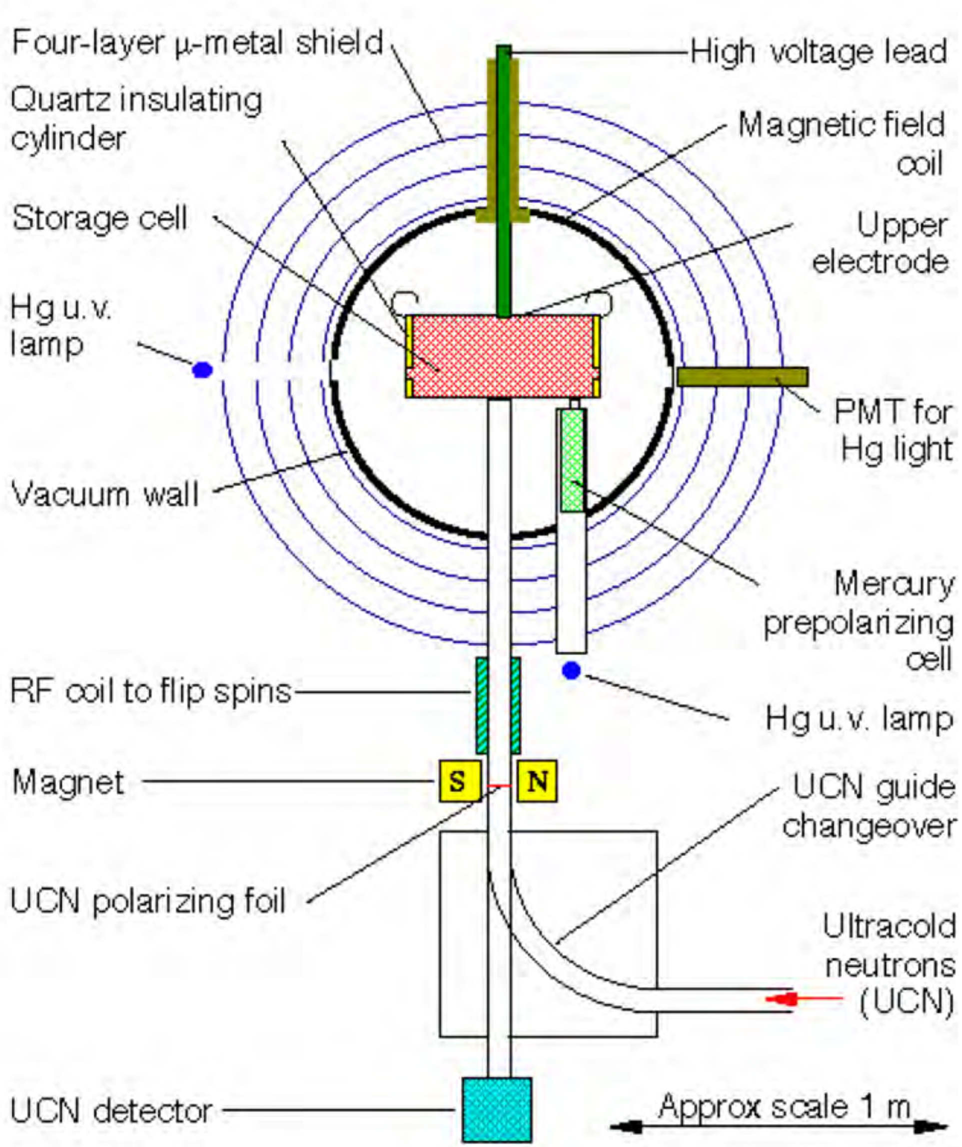
$$\sigma_{edm} \propto \frac{1}{ET\sqrt{N_n}}$$

$$\begin{aligned} E \quad &= \text{Applied Electric Field} \\ N_n \quad &= \text{Number of neutrons observed} \\ T \quad &= \text{Observation Time} \end{aligned}$$

We want:

1. Highest Possible Electric Field (Limited by breakdown)
2. More neutrons (limited by source strength)
3. Longest possible free precession time (ultimately limited by τ_n)

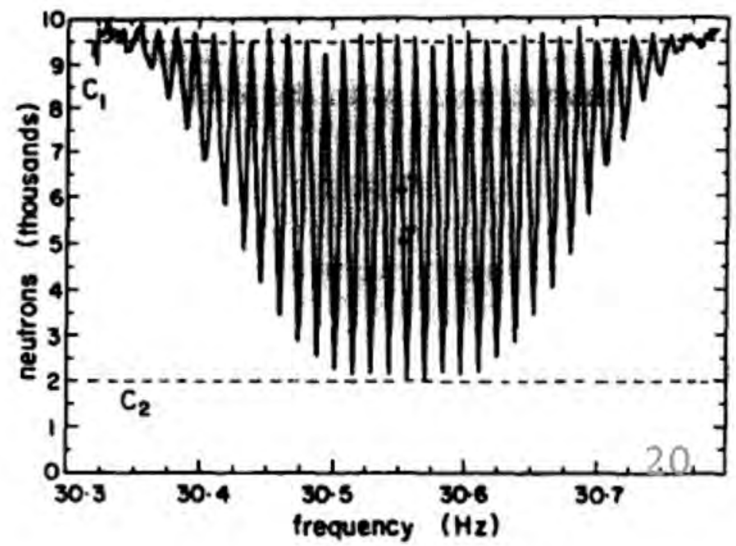
*ILL- Sussex Neutron Electric Diopole Moment Experiment**



$$\boxed{d = (-0.21 \pm 1.82) \times 10^{-26}\ ecm}$$

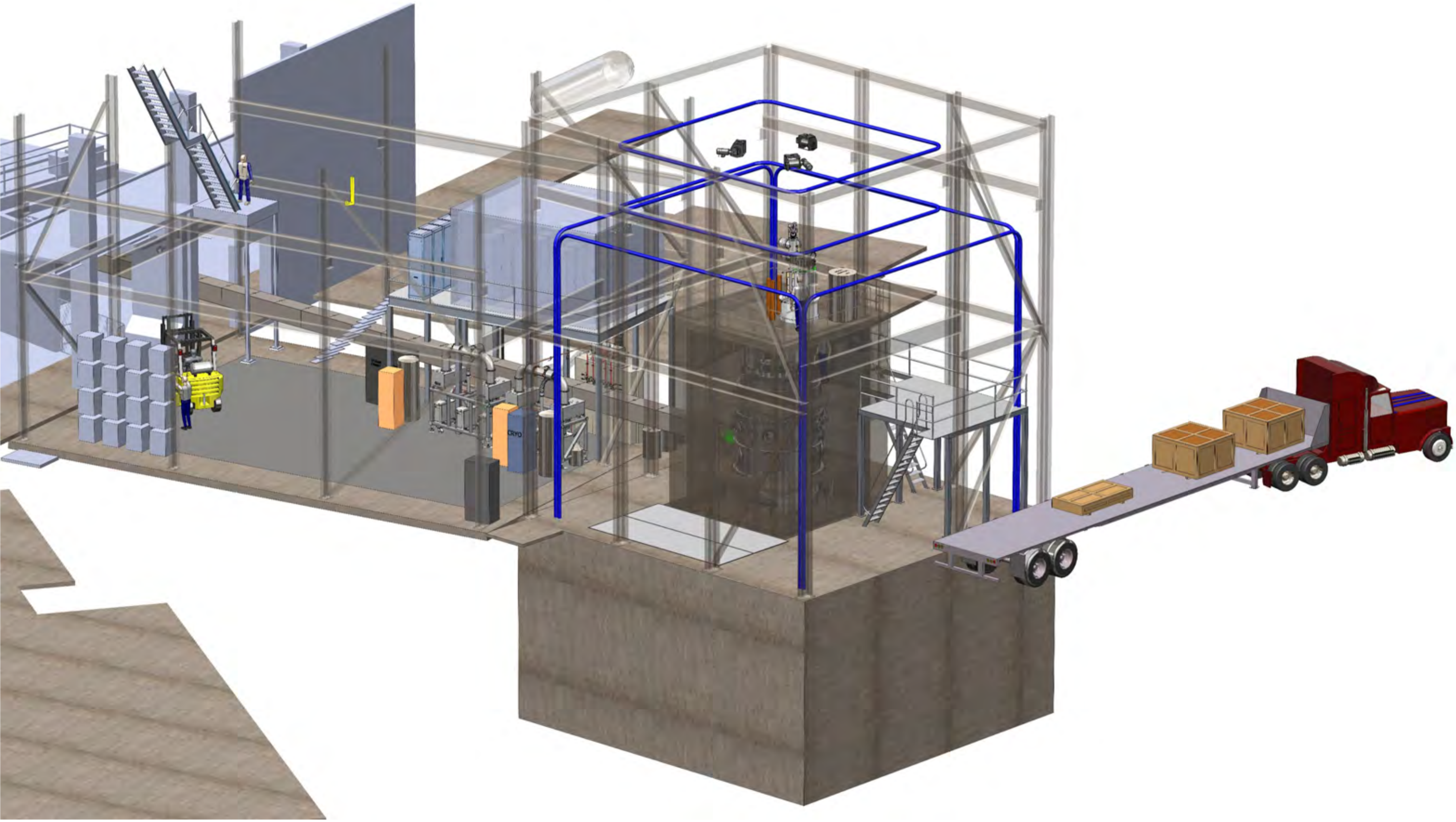
J.M. Pendlebury et al., PR D92 09 (2003

$T = 130\ s$
$E = 10kV/cm$



Experiment has been upgraded and installed at PSI. New result is pending.

The nEDM experiment at the Spallation Neutron Source



Features of the new SNS nEDM experiment:

- Double cell (common B, opposite E)

- Ultra-cold neutrons produced in-situ
  - in superfluid Helium below 0.7K to achieve long storage time (suppress phonon upscattering) **as a UCN source**

- Helium-3 as co-magnetometer
  - precession monitored by SQUID
  - long relaxation time in superfluid Helium **as a buffer gas**

- Neutron precession measured through the spin-dependent n+^{3}He capture reaction **as a particle detector**
  - Use liquid helium as scintillating medium
  - Cell has to be optically transparent as a part of the light guide
  - PMT operated at cryogenic temperatures (4K)

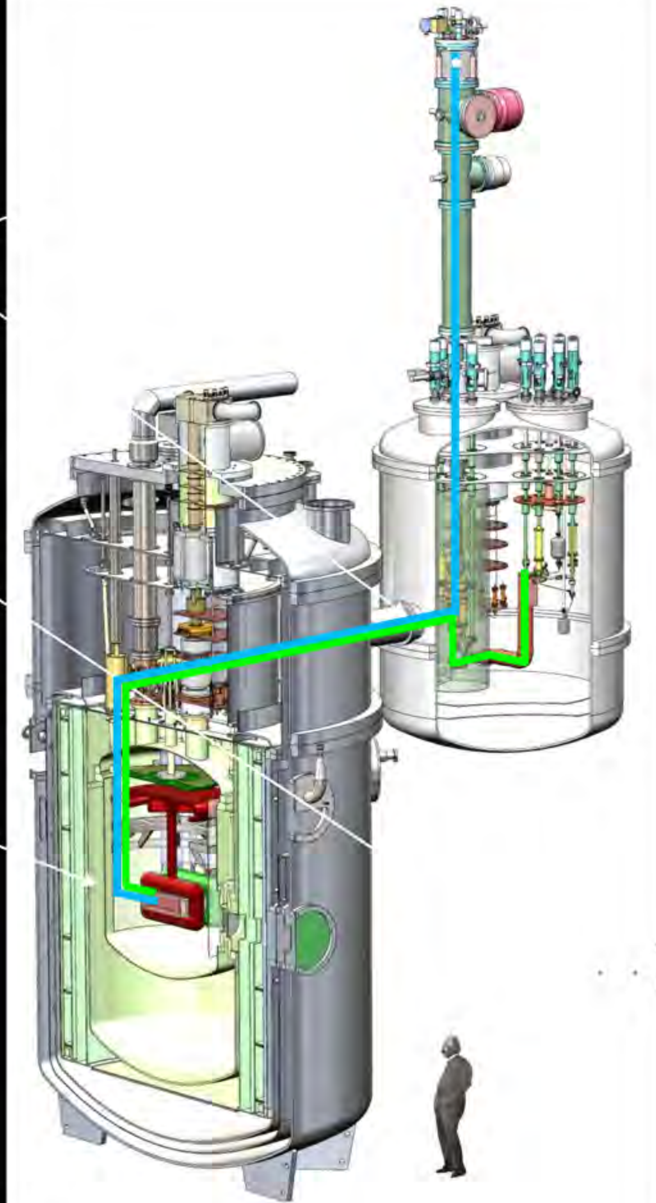
as a HV insulator

- High dielectric strength of superfluid helium (>50kV/cm)

Slide curtesy, Chen-Yu Lu

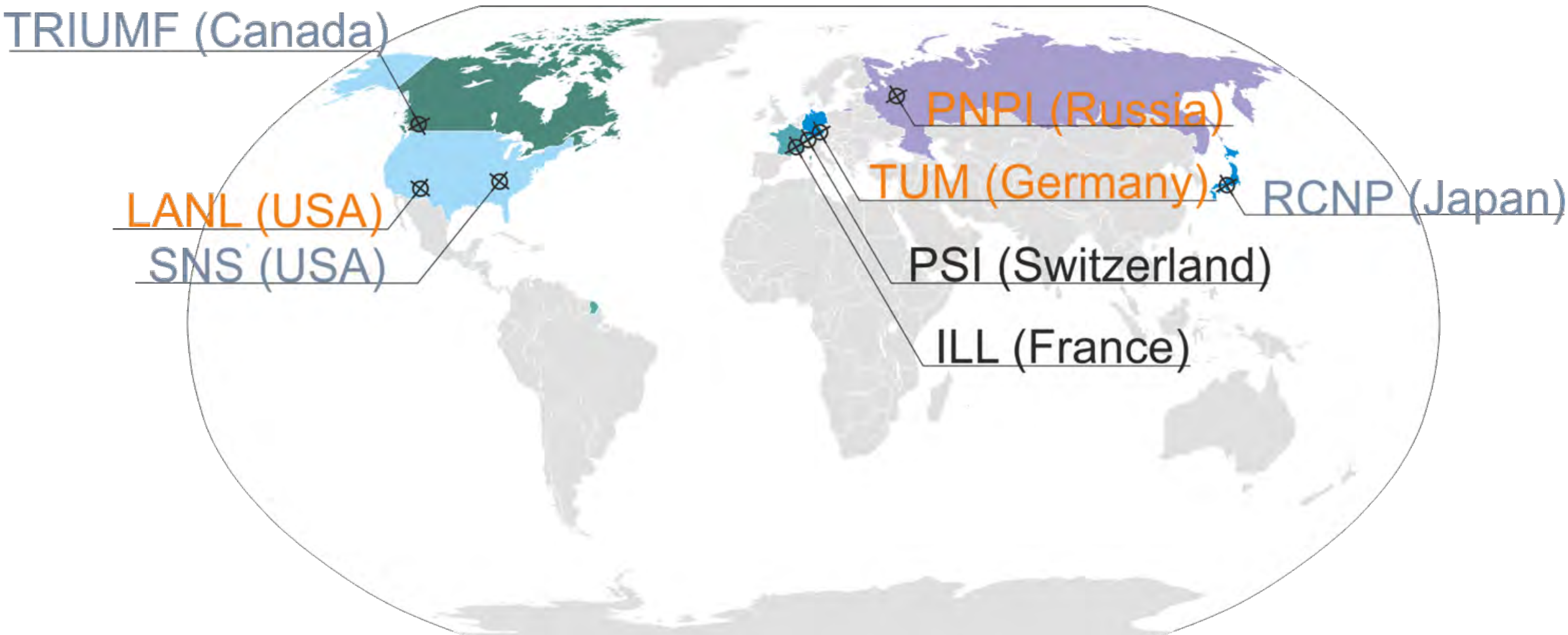
nEDM@SNS
Measurement Cycle

1. Load collection volume with polarized ^{3}He atoms
2. Transfer polarized ^{3}He atoms into measurement cell
3. Illuminate measurement cell with polarized cold neutrons to produce polarized UCN
4. Apply a $\pi/2$ pulse to rotate spins perpendicular to B_0
5. Measure precession frequency
6. Remove reduced polarization ^{3}He atoms from measurement cell
7. Flip E-field & Go to 1.



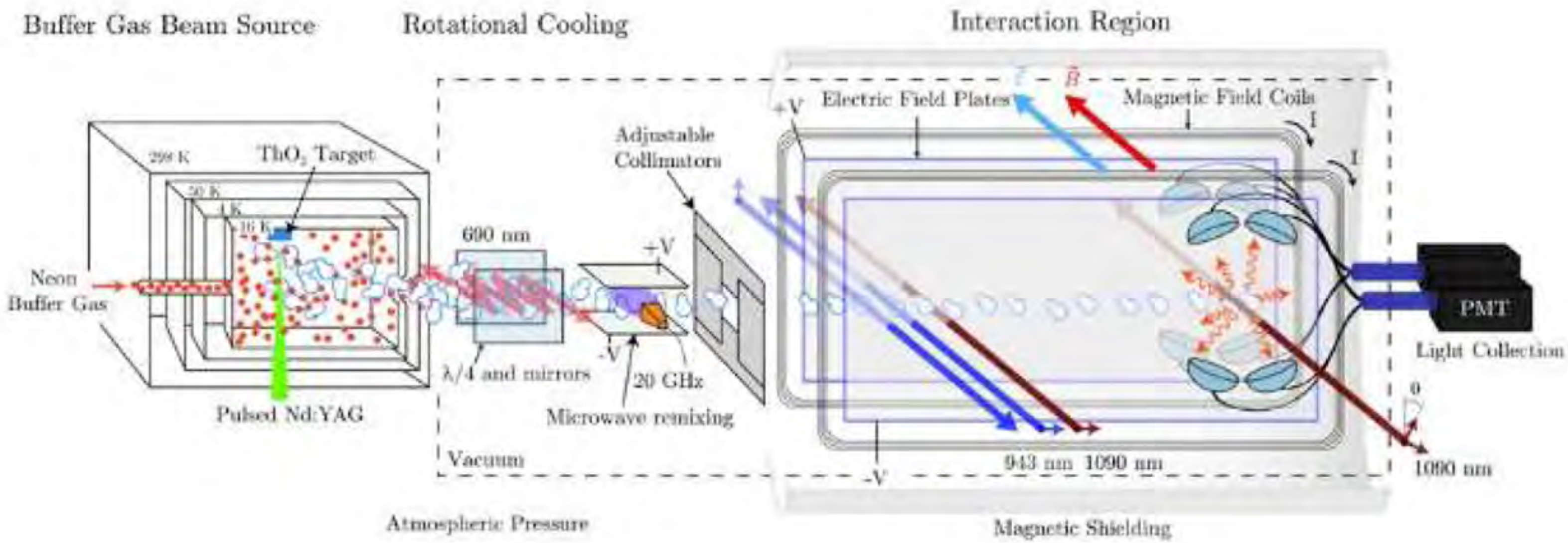
Slide thanks to Vince Cianciolo

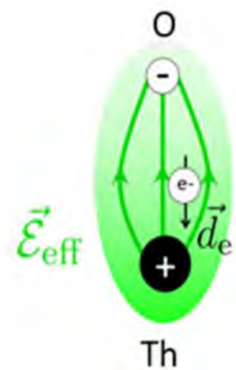
Neutron EDM searches are in progress at many facilities world wide



The Neutron EDM search is complementary to other types of EDM measurements

ACME experiment



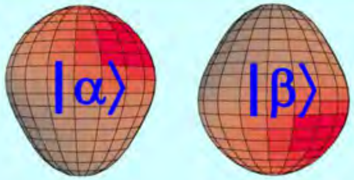


10 V/cm → 10*1e+9 V/cm,

$d_e = (-2.1 \pm 3.7_{\text{stat}} \pm 2.5_{\text{syst}}) \times 10^{-29}\ e\cdot\text{cm}$

Science 17 Jan 2014:
Vol. 343, Issue 6168, pp. 269-272

Slide curtesy, Chen-Yu Lu



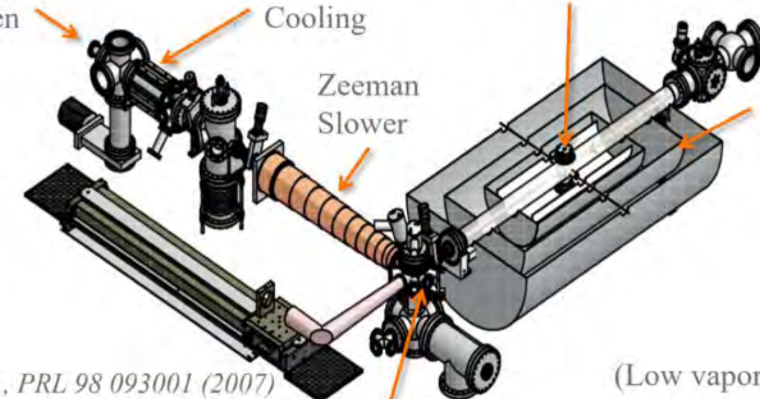
A large quadrupole and
octupole deformation results
In an enhanced Schiff moment
– Auerbach, Flambaum & Spevak (1996)

Enhancement Factor: EDM (^{225}Ra) / EDM (^{199}Hg)

Skyrme Model	Isoscalar	Isovector	Isotensor
SIII	300	4000	700
SkM*	300	2000	500
SLy4	700	8000	1000

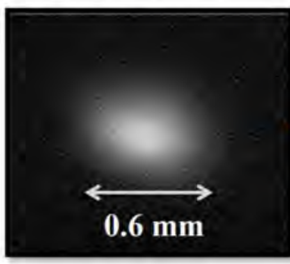
Collect Atoms in MOT

Radium-255
deformed nuclei



J. R. Guest et al., PRL 98 093001 (2007)

(Low vapor pressure)

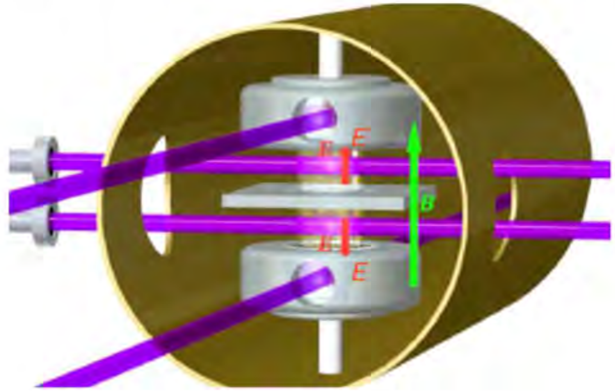


^{226}Ra MOT
20,000 atoms

For EDM:	For Testing:
Ra-225	Ra-226
$I = 1/2, J = 0$	$I = 0, J = 0$
$t_{1/2}$ = 15 days	$t_{1/2}$ = 1600 yrs

Slide curtesy, Chen-Yu Lu

The Seattle ^{199}Hg (atomic) EDM Measurement

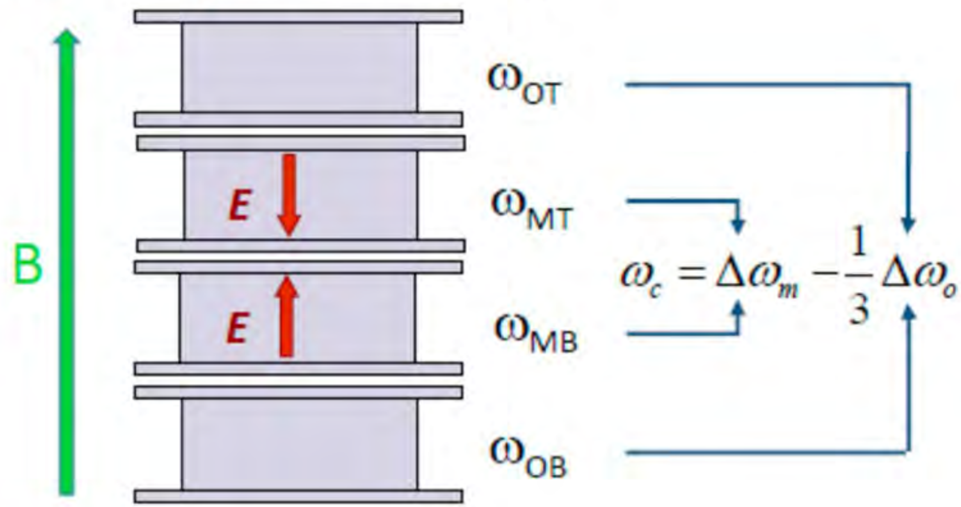


4 mercury vapor Cells:
2 with opposite E fields
2 for B field normalization

$$H = -(\vec{\mu}\cdot\vec{B} + \vec{d}\cdot\vec{E})$$

$$\omega_c = \frac{\mu}{\hbar}\left(-\frac{8}{3}\frac{\partial^3 B}{\partial z^3}\Delta z^3\right) + \frac{4dE}{\hbar}$$

Cancels up to 2nd order gradient noise
Same EDM sensitivity as Middle Difference



Slide curtesy, Chen-Yu Lu

Why Do We Need So Many Experiments?

Electron EDM

TVPV pseudoscalar-scalar eN coupling

TVPV tensor eN coupling

Short-distance contribution to d_n

Short distance contribution to d_p

TVPV isoscalar πN coupling

TVPV isovector πN coupling

$$d = \underbrace{\alpha_{d_e} d_e + \alpha_{C_S} C_S}_{\text{Paramagnetic Systems}} + \underbrace{\alpha_{C_T} C_T + \alpha_{\bar{d}_n} \bar{d}_n + \alpha_{\bar{d}_p} \bar{d}_p + \alpha_{g_\pi^0} \bar{g}_\pi^0 + \alpha_{g_\pi^1} \bar{g}_\pi^1}_{\text{Diamagnetic Systems}},$$

T. Chupp, M. Ramsey-Musolf, Phys. Rev. **C91** 035502 (2015)

End of Lecture 3