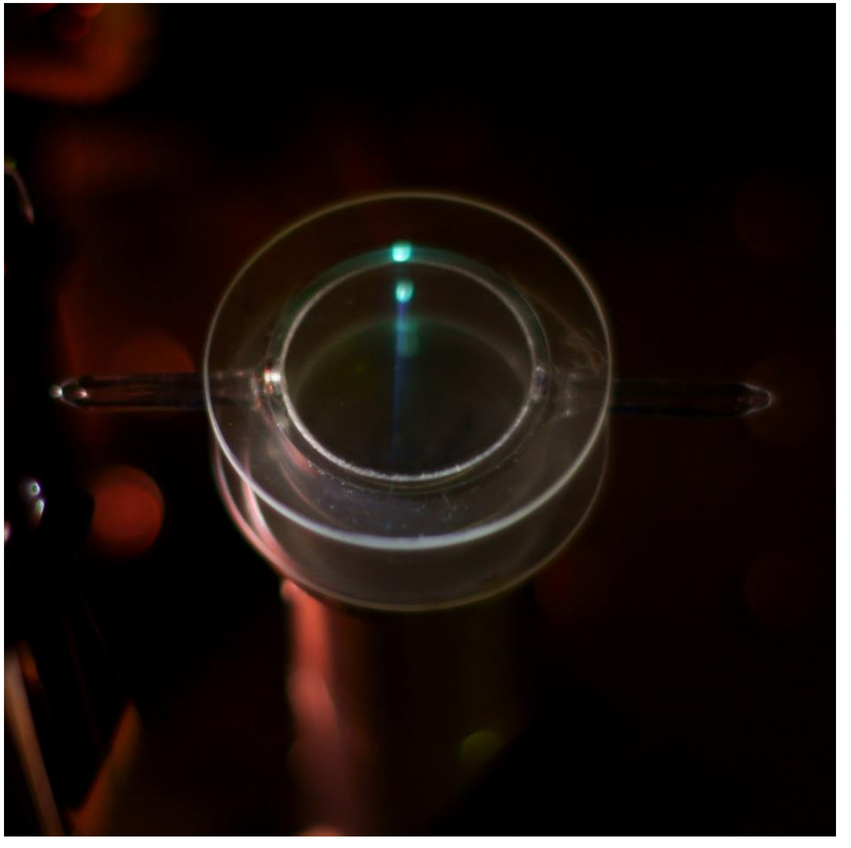
^{199}Hg EDM Measurement



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A time-reversal-sensitive atomic clock

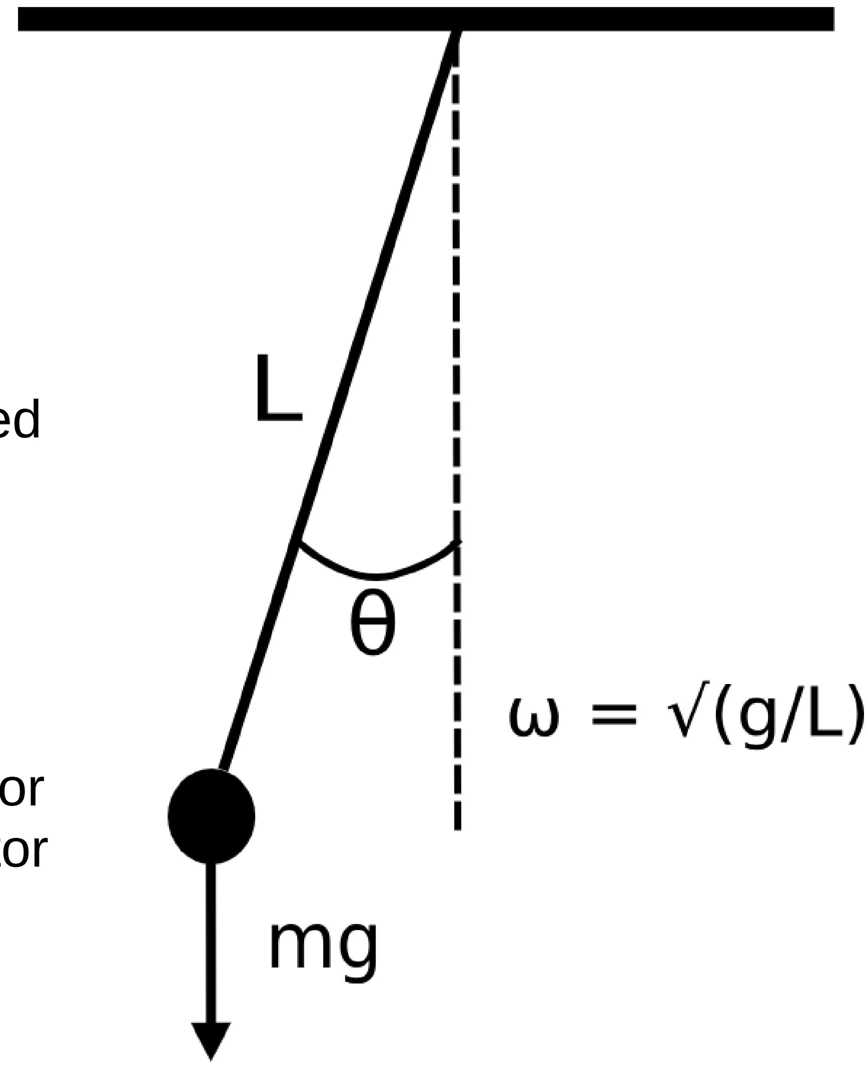
Traditional clocks consist of an oscillator and escapement (i.e. counter)

More precise clocks are made by:

1) Using oscillators with more well-defined frequency (atoms vs. pendulum)

2) Isolating the oscillator from external disturbances

3) Using a reference oscillator checked for phase deviation from the primary oscillator (Ramsey Method)

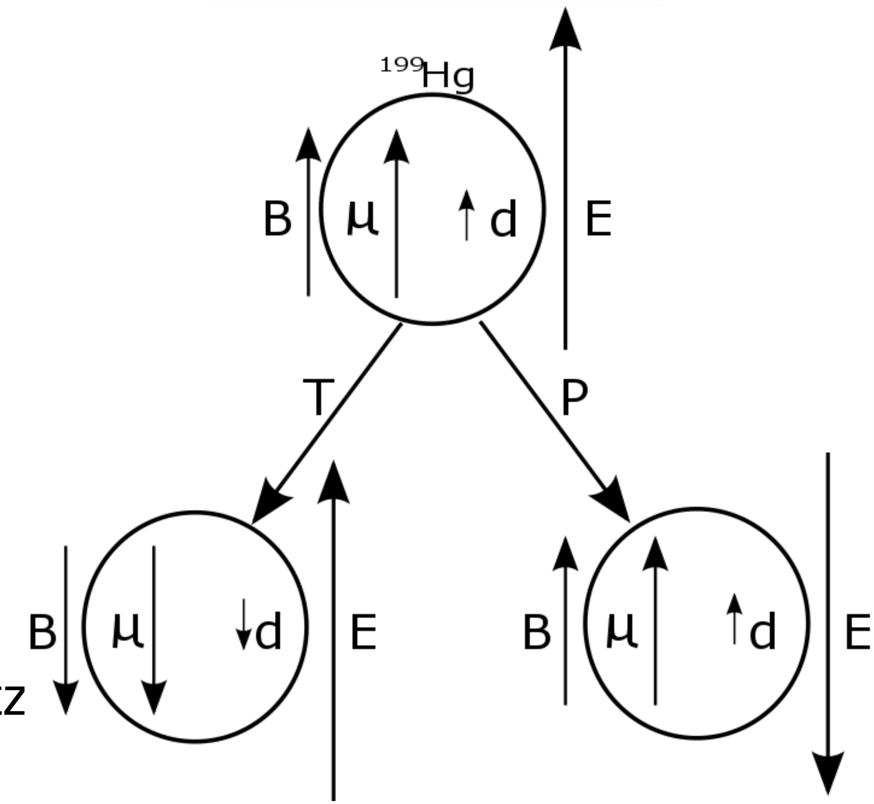


T and CP Symmetry Breaking

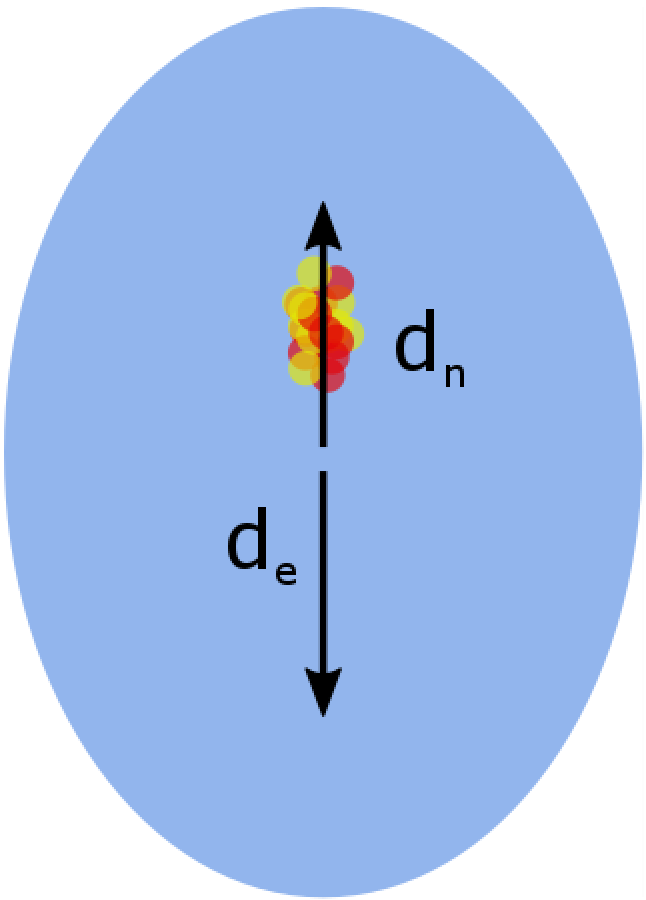
- •EDM represents charge separation
- •Units of e*cm
- •EDM must point along (nuclear) spin axis
- •Transforms like angular momentum (P-even, T-odd)
- •Breaks time-reversal (T) symmetry of the Hamiltonian
- •CPT conservation follows from Lorentz invariance

T violation is equivalent to CP violation

$$H = -\mu \cdot B - d \cdot E$$



Atomic vs. Neutron EDMs



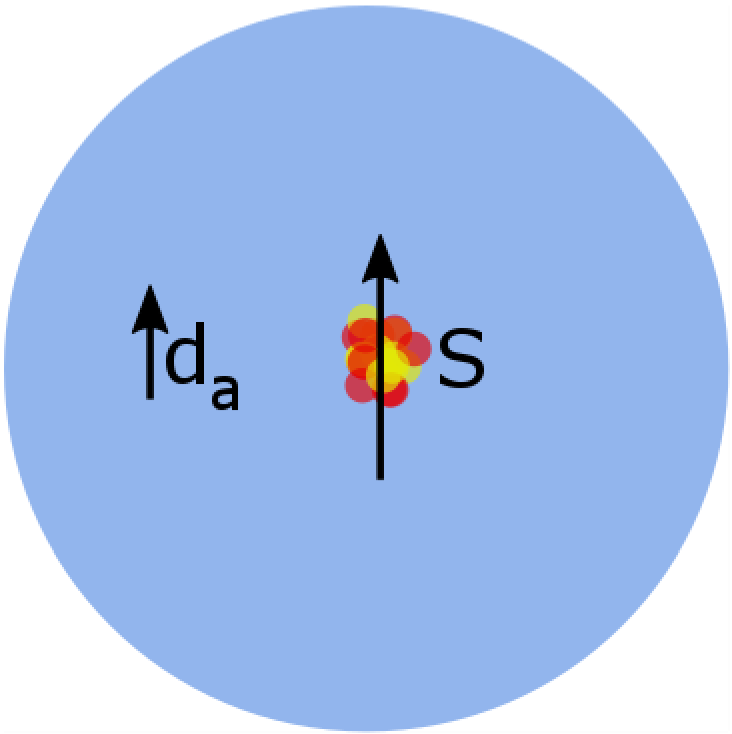
- Schiff's Theorem: An EDM of a point-like nucleus would be perfectly screened by non-relativistic electrons interacting electrostatically

- The EDM of an atomic system is due to the operator product of the EDMs of constituent particles and a P-odd, T-odd n-n or e-n interaction:

$$\mathbf{d}_{\text{atom}} = 2\sum_{M} \frac{\langle K|\hat{\mathbf{D}}|M\rangle\langle M|\hat{H}_{PT}|K\rangle}{E_K - E_M} = d_{\text{atom}}(\mathbf{F}/F)$$

- This P-even, T-odd “EDM” has a P,T-odd dipole interaction with electric field **E**

The Schiff Moment



- Schiff's Theorem has 3 assumptions:

1) **Point-like nucleus**

2) **Non-relativistic** electrons

3) **Electrostatic** interactions

- The Schiff moment **S** is the dominant P, T-odd nuclear moment (e fm^3):

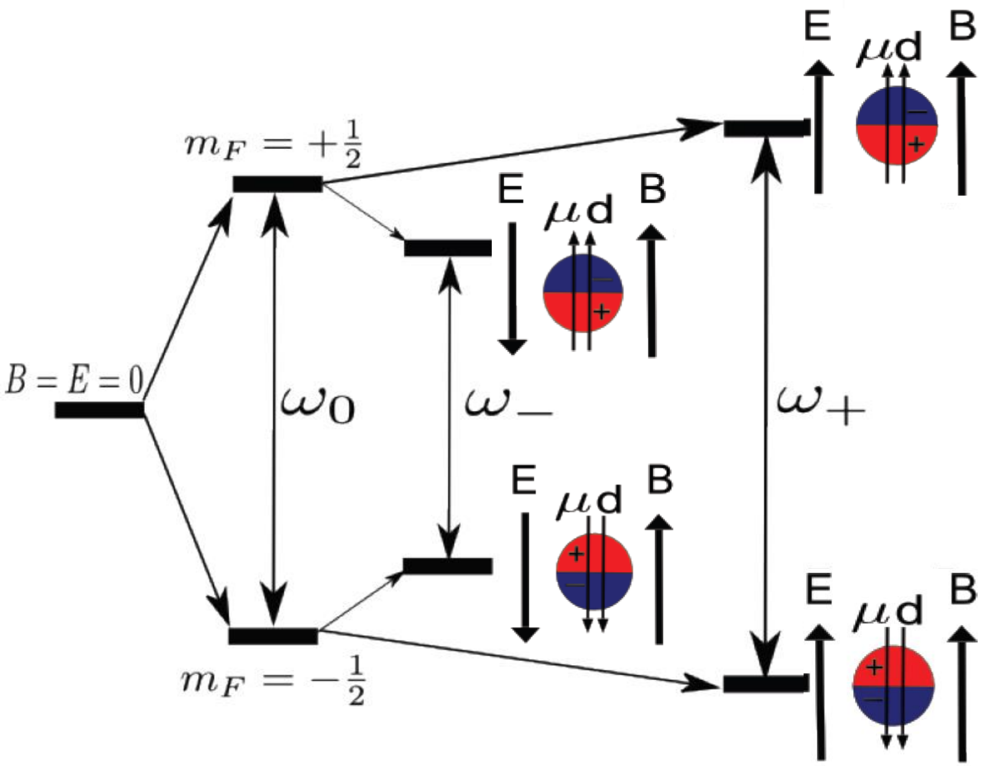
$$\mathbf{S} = \frac{1}{10}\left[\int e\rho(\mathbf{r})\mathbf{r}r^2\, \mathrm{d}^3r - \frac{5}{3}\mathbf{d}\frac{1}{Z}\int \rho(\mathbf{r})r^2\, \mathrm{d}^3r\right]$$

- **S** goes to 0 in the limit of a point nucleus

- Heavier nuclei give larger **S** values, larger atomic EDM/nuclear EDM ratios

Measurement principle: Larmor frequency observation

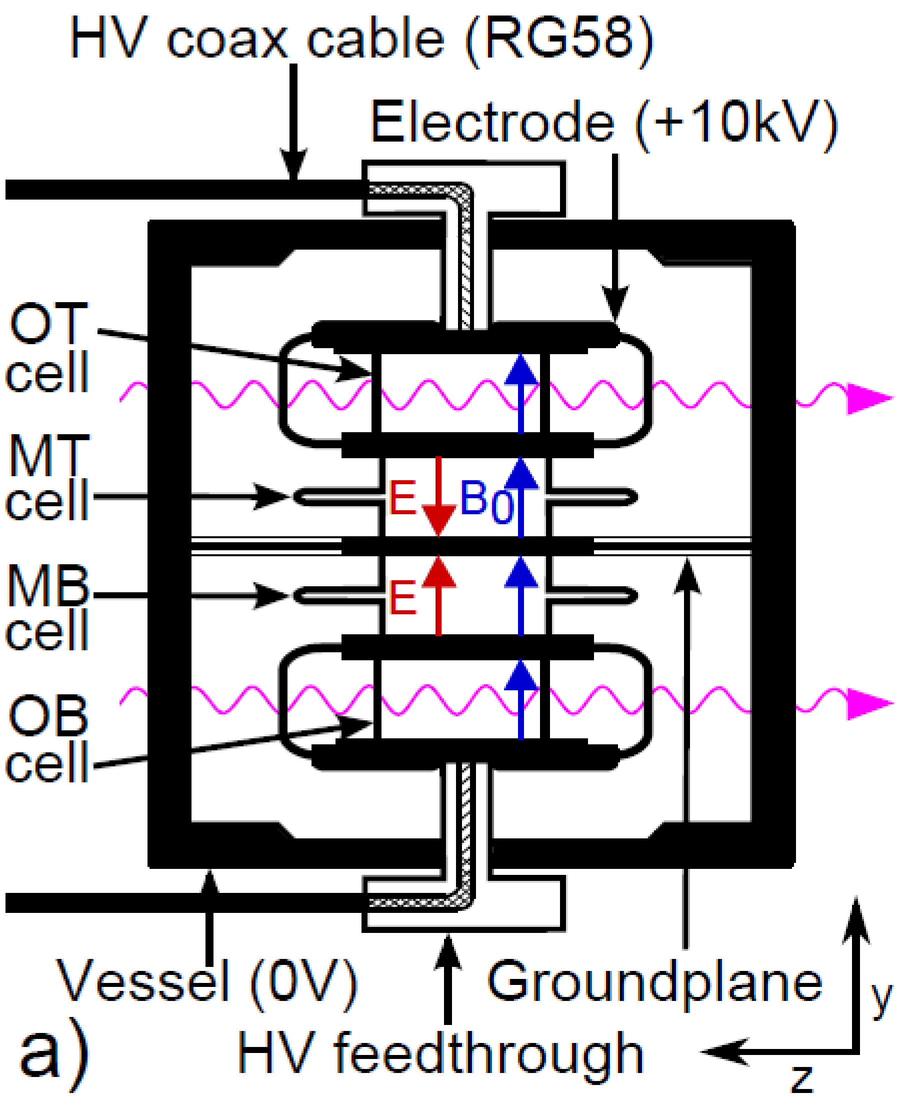
$$H = -\mu \cdot B - d \cdot E$$



Level diagram of ^{199}Hg ground state with parallel **μ** and **d**$_{atom}$ in parallel, antiparallel **E** and **B** fields

- Measurement is done on the ground state ($^1S_0$) hyperfine manifold with |**F**|=1/2
- **d**$_{atom}$ must always be parallel to **μ**
- The 2 energy levels will shift farther apart or closer together when **E** is applied
- For B = 15mG, E = 10kV/cm, we get $\Delta\omega/\omega < 10^{-10}$
- This gives $\Delta E < 3.1 \times 10^{-25}$ eV!

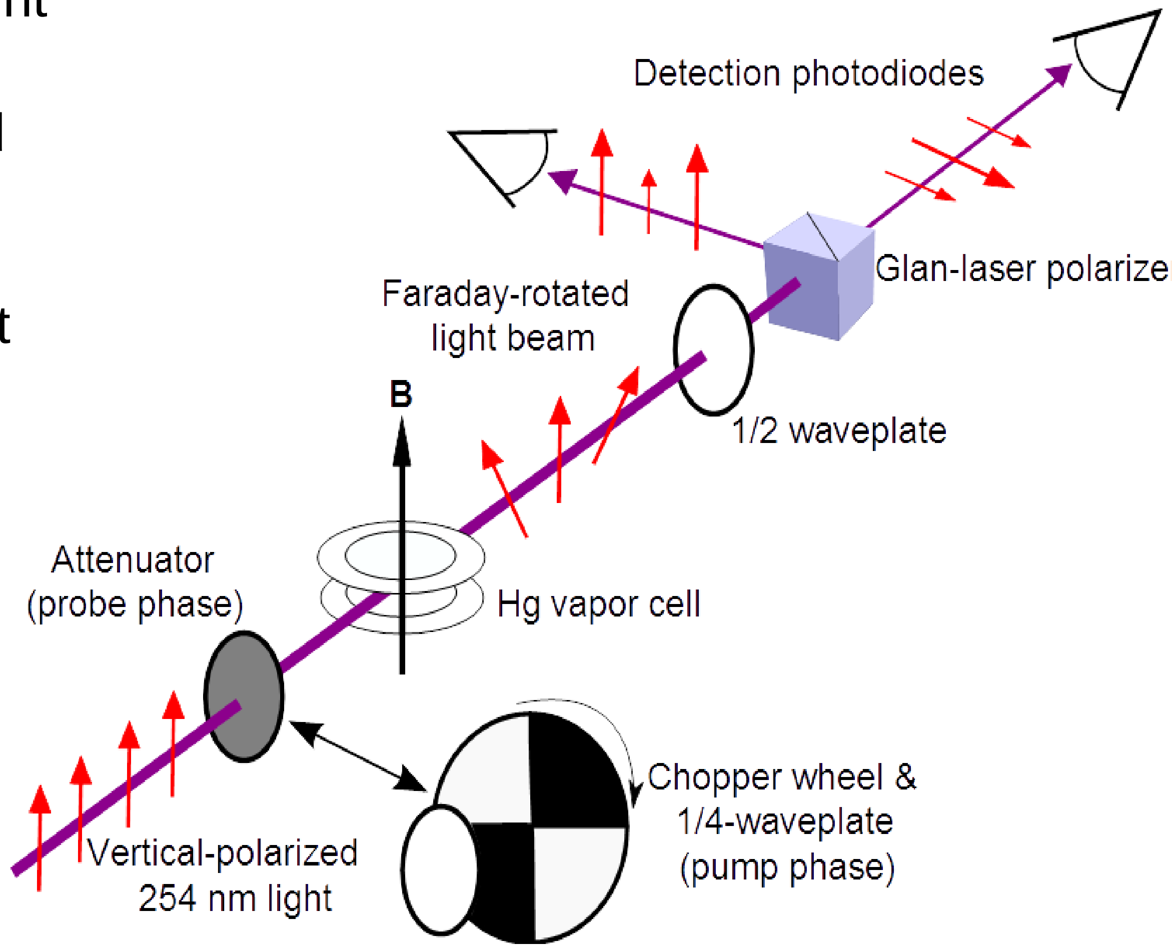
Measurement Technique



- Atoms are contained in a stack of 4 vapor cells in a common B field
- 2 conducting plastic electrodes at the same potential hold the 2 outer cells
- Opposite E field causes an EDM to shift the relative frequency of the 2 inner cells
- ^{199}Hg is pumped to align spins with laser beams
- Precession is observed by detecting Faraday rotation of weak, linear polarized light

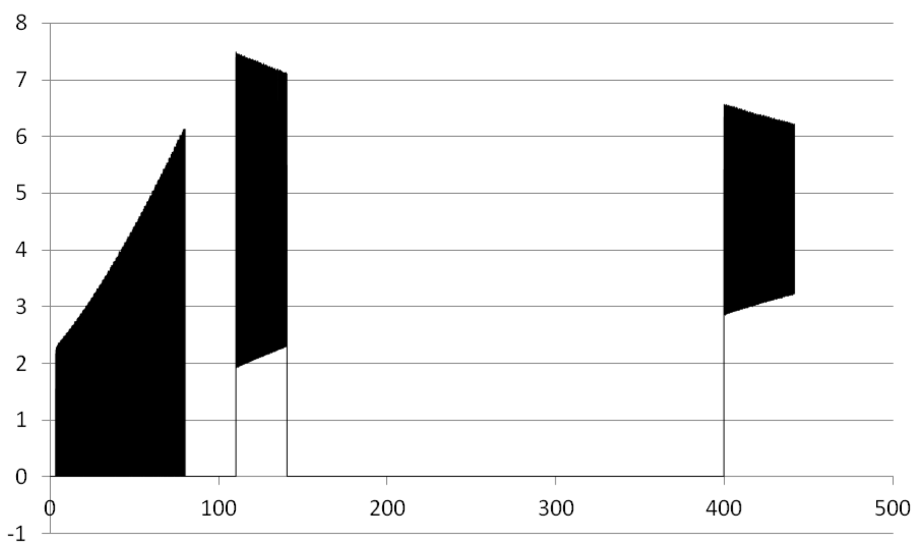
Faraday Rotation Detection

- Atomic polarization changes the index of refraction for σ_+ and σ_- light
- Incoming linearly polarized probe light is rotated
- Rotation angle oscillates at the Larmor frequency
- A polarizing beam splitter separates the beam into vertical, horizontal components
- Intensity of 2 orthogonal polarization states oscillate out of phase



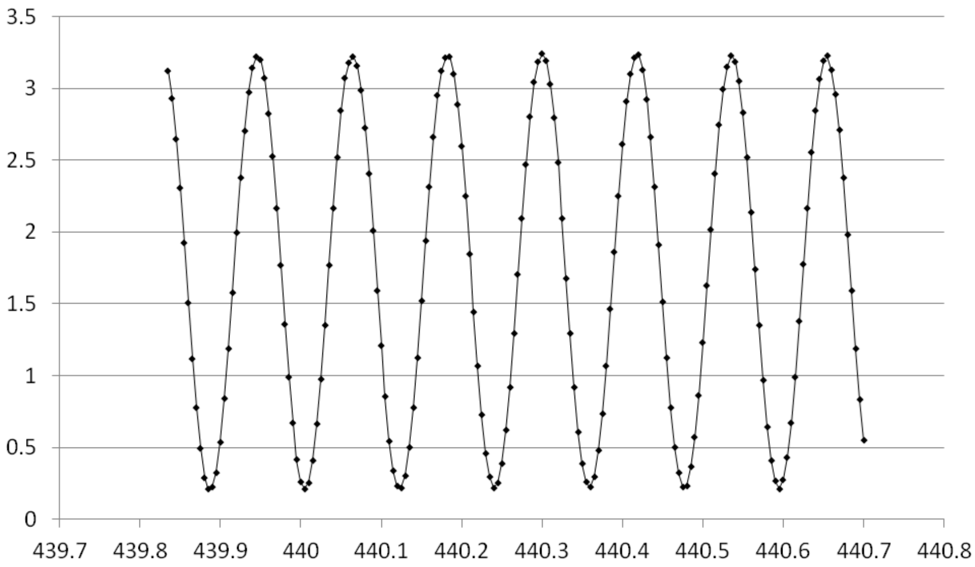
Phase Difference Analysis

^{199}Hg EDM raw data (run 16030, 5/29/2013)



Photodiode signal (V) vs. time (seconds)

^{199}Hg EDM run 16030 data excerpt (-3.0V offset)



Photodiode signal (V) vs. time (seconds)

- Instead of fitting a single long sample for **ω**, we can apply the Ramsey method: fit 2 samples for Δφ with light off in between for time Δt

- Freq. difference $(\omega_{MT} - \omega_{MB}) = \Delta\varphi_{MT\text{-}MB}(t_f) - \Delta\varphi_{MT\text{-}MB}(t_i)$

- $\mathbf{d}_{Hg}$ signal $= \Delta_{HV}[(\omega_{MT} - \omega_{MB}) - 1/3(\omega_{OT} - \omega_{OB})]$

Digital Phase Analysis

- For each pair of cells, we measure $\Delta\omega$ from $\Delta\varphi_{initial}$ and $\Delta\varphi_{final}$

- For cell a or b, our signal is proportional to $S_{a,b}(t) = \sin(t\omega \pm t\Delta\omega + \varphi \pm \Delta\varphi)$

- It can be shown that if $\omega\Delta t = \pi/2$, then

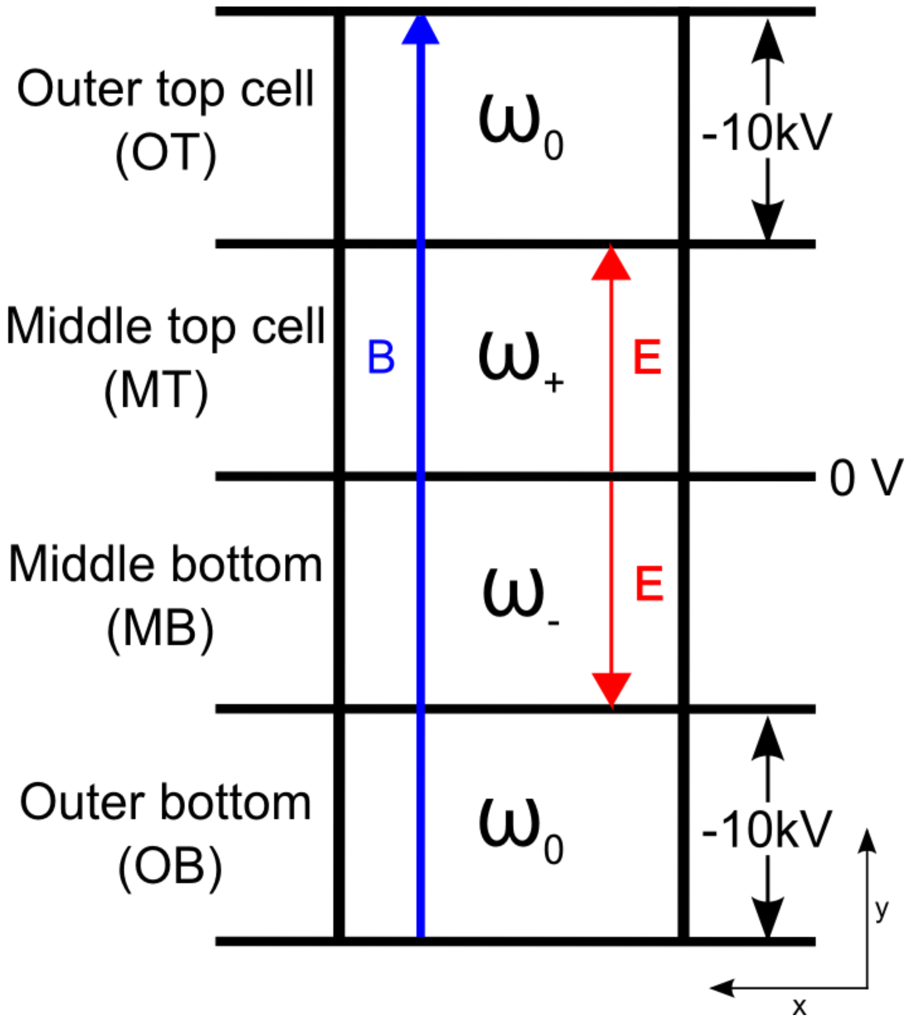
$$S_1(t) * (½)[S_2(t + \Delta t) – S_2(t - \Delta t)] – S_2(t) * (½)[S_1(t + \Delta t) – S_1(t - \Delta t)]$$
$$= \sin(2t\Delta\omega + 2\Delta\varphi) \approx 2t\Delta\omega + 2\Delta\varphi$$

- The data can then be fit to a straight line

- We tune our precession frequency ω_0 to match the condition $\omega\Delta t = \pi/2$ for our analog-to-digital conversion rate (2 kHz, 10 points averaged, Δt = 5 ms)

- $\Delta\varphi_{initial}$ is measured at the end of the first probe period, $\Delta\varphi_{final}$ is measured at the beginning of the second probe period

B Gradient Noise Reduction



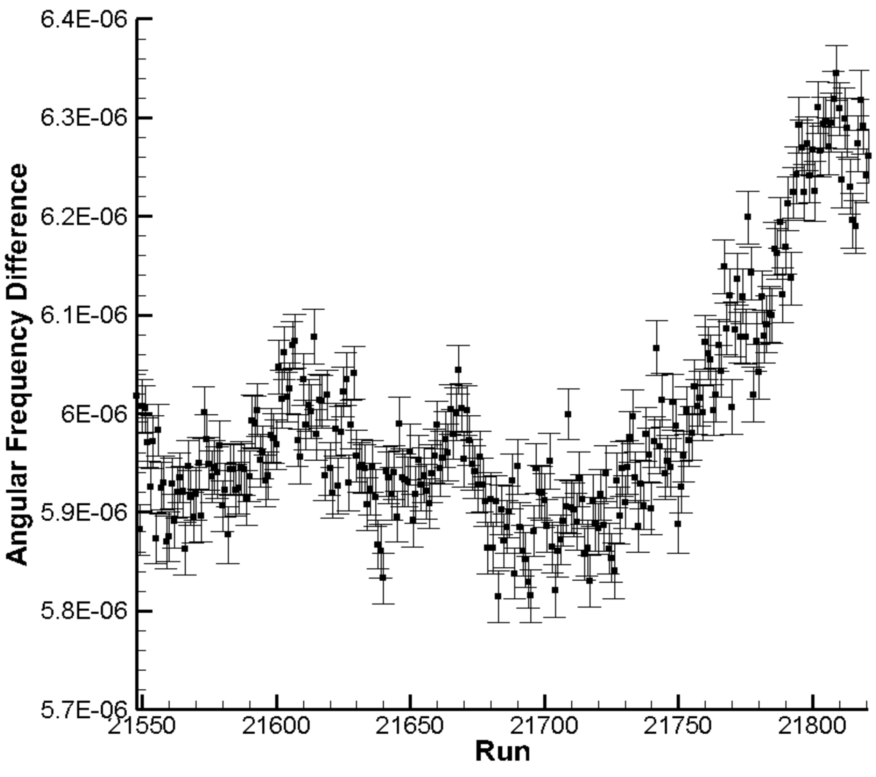
- With our 4-cell setup, outer 2 cells are used as magnetometers
- EDM signal is equivalent to a 3rd-order B_y field gradient correlated with **E:**

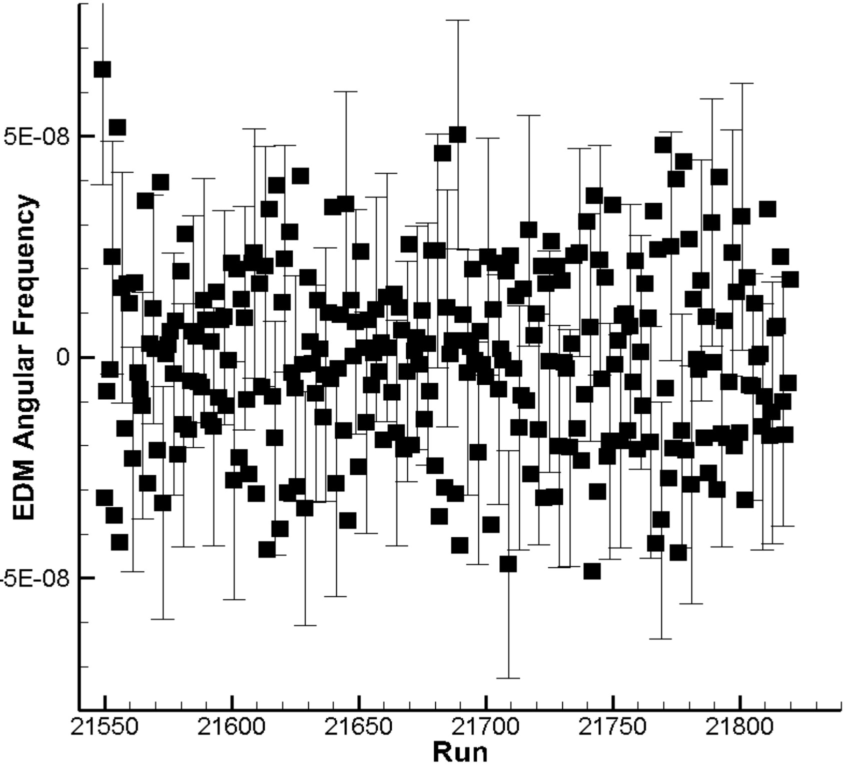
$$\mathbf{d}_{atom} = \Delta_{HV}[(\omega_{MT} - \omega_{MB}) - 1/3(\omega_{OT} - \omega_{OB})]$$

- In principle, this should cut down **B** field gradient noise
- In practice, outer cells are more useful for looking at potential systematics
- Blind offset is applied to EDM-sensitive channels

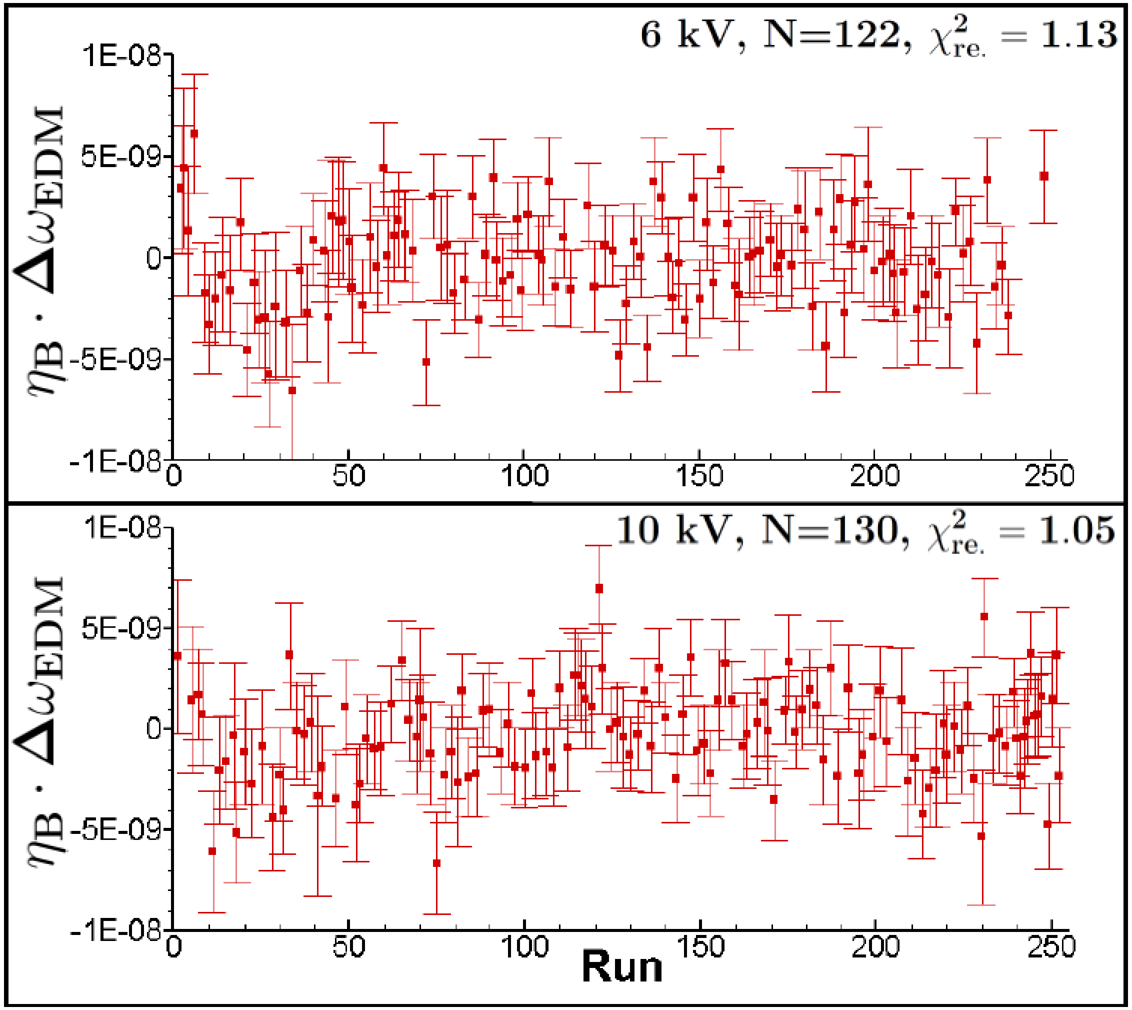
HV Correlation Analysis

- Raw frequency difference measurements are dominated by low-frequency noise on B-field gradient
- Take the HV-correlated signal: $(-1)^i \{(1/2)(\Delta\omega_{i-1} + \Delta\omega_{i+1}) - \Delta\omega_i\}$
- Resulting signal is insensitive to slow drifts in the 3rd-order $\mathbf{B}_y$ gradient



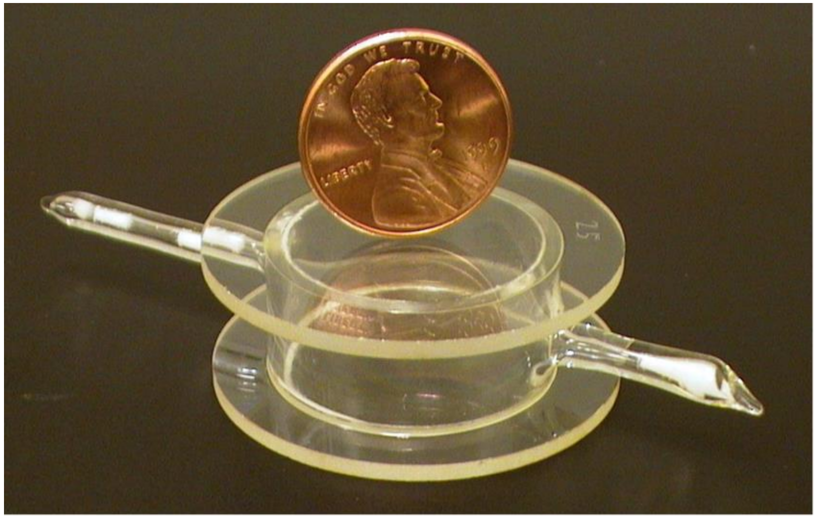


Statistical Performance



- 2009 EDM paper had statistical sensitivity of 6.43 $*10^{-10}$ s^{-1}
- New data set has an avg. daily error bar 2.0 $*10^{-9}$ s^{-1}
- 252 runs remain after cuts
- New EDM data set has a stat. error of 1.45 $*10^{-10}$ s^{-1}

Performance Improvements

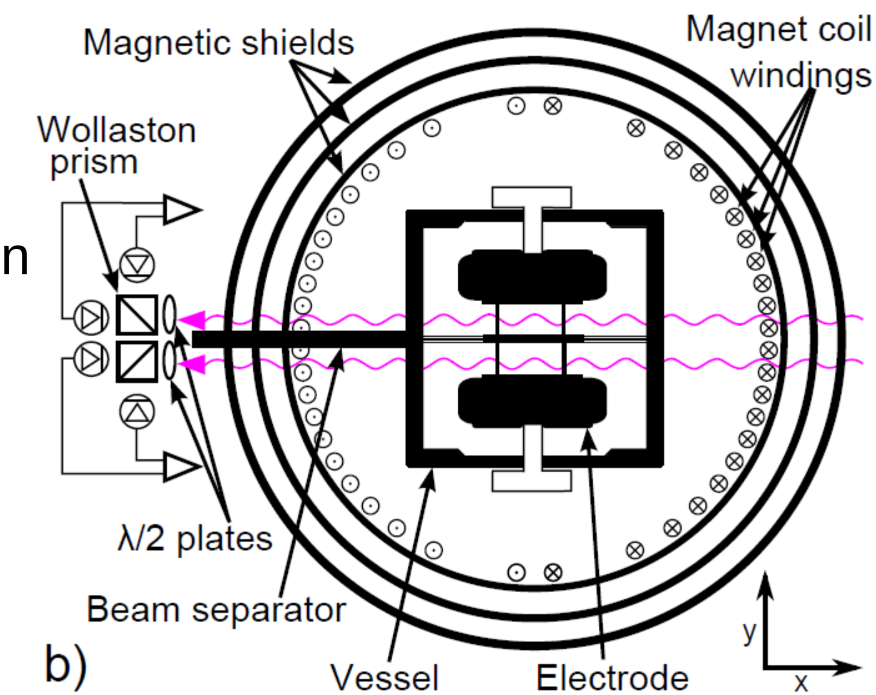


•New generation of vapor cells have coherence lifetimes of 500-1000s (up from 100-200s)

•New cells do not lose coherence time with UV exposure

•New data analysis technique eliminates frequency shifts, relaxation due to probe light

•New magnet coil allows for better trimming of **B**-field gradients, less eddy-current magnetic noise



b)

Vapor Cell Development

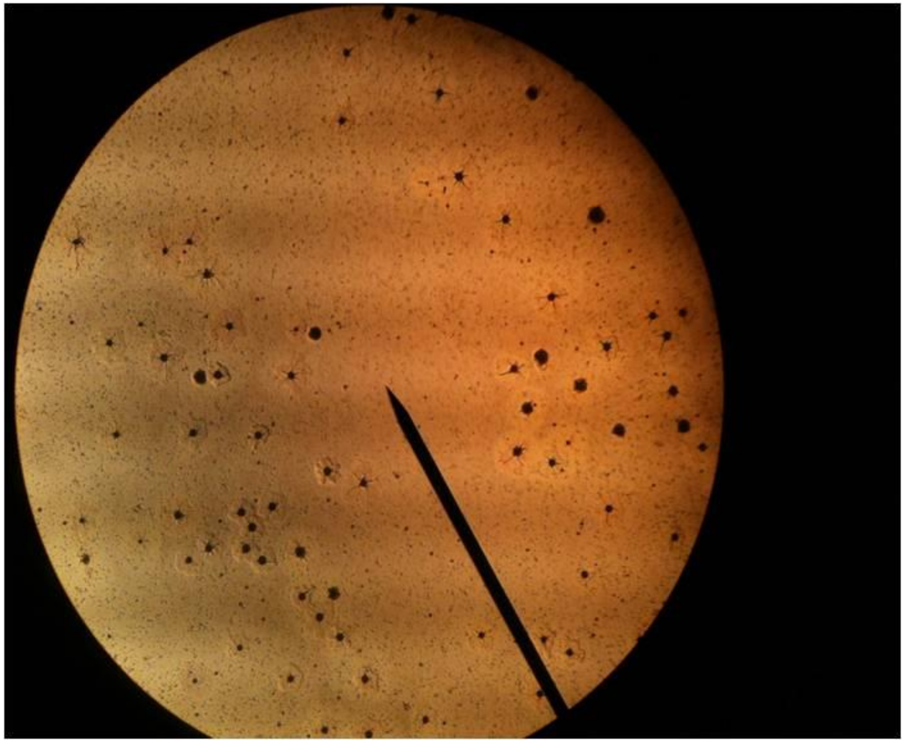
•UV curing epoxy contains sulfur, can outgas and react with Hg

•New cells are bonded with Lesker KL-5 vacuum leak sealant

•Droplets of Hg can be found on waxed inner cell surfaces

•Liquid Hg in droplets or films exchanges unpolarized atoms with polarized vapor

•Resonant UV light promotes nucleation in saturated Hg vapor

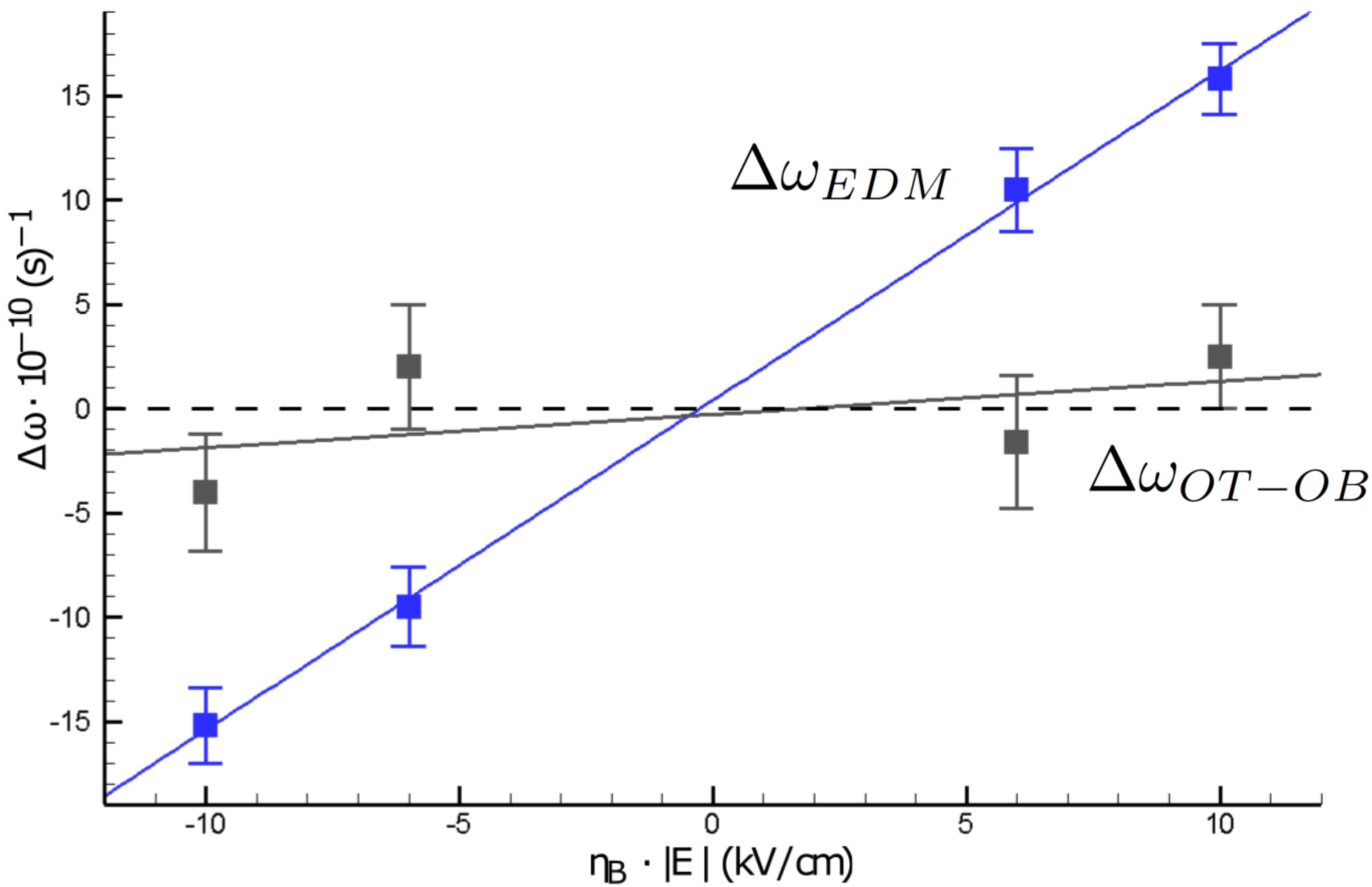


Systematic Performance

Source	**Error (10^{-31} e cm)**
Axial Cell Motion	12.6
Leakage Currents	5.02
Radial Cell Motion	3.36
E^2 effects	3.04
Parameter Correlations	2.33
v x **E B** fields	2.29
Charging Currents	1.83
Geometric Phase	0.06
Quadrature sum	**14.8**

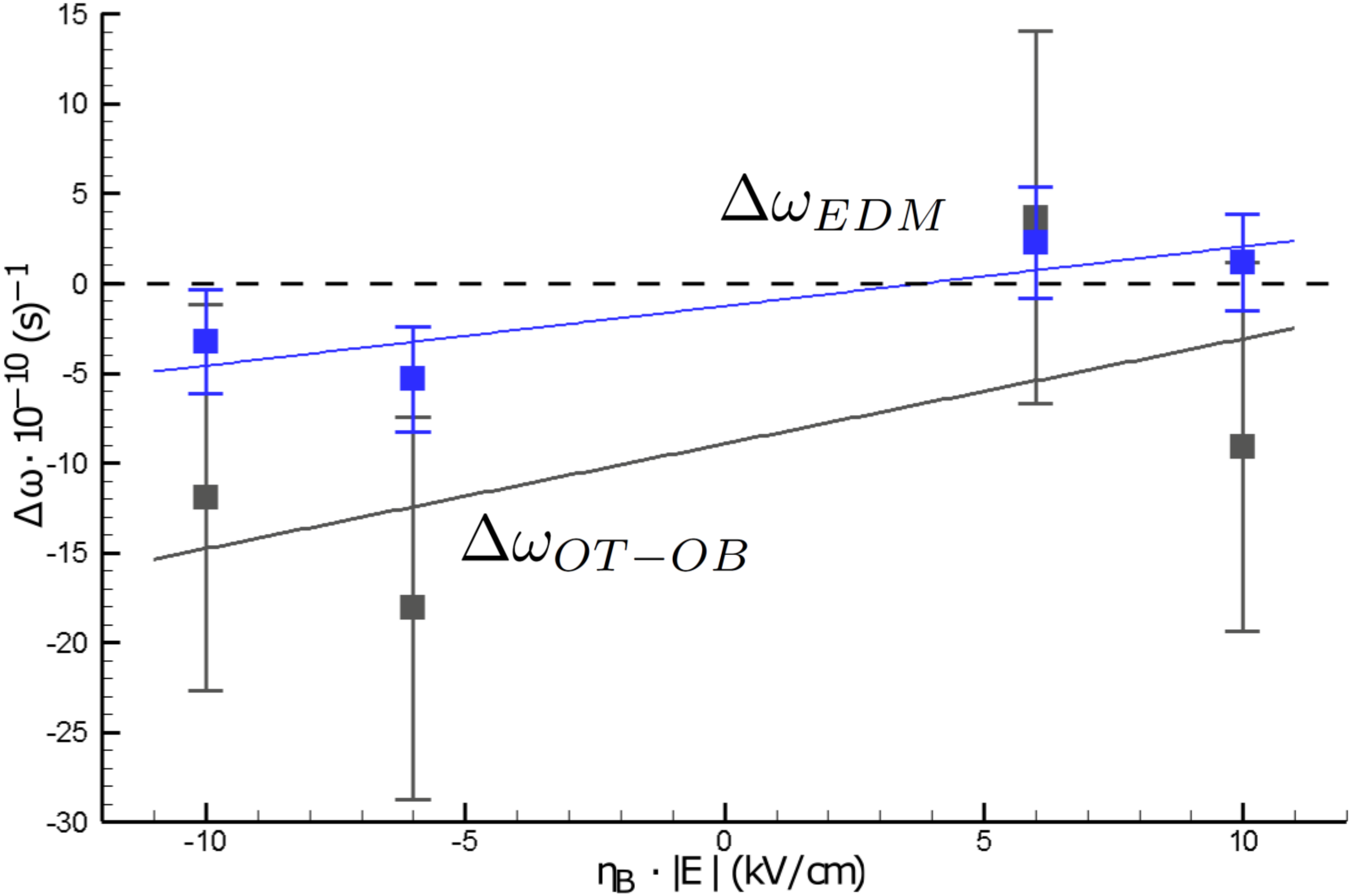
EDM Field Dependence

- A substantial nonzero EDM signal would be linear, with no outer cell HV correlation

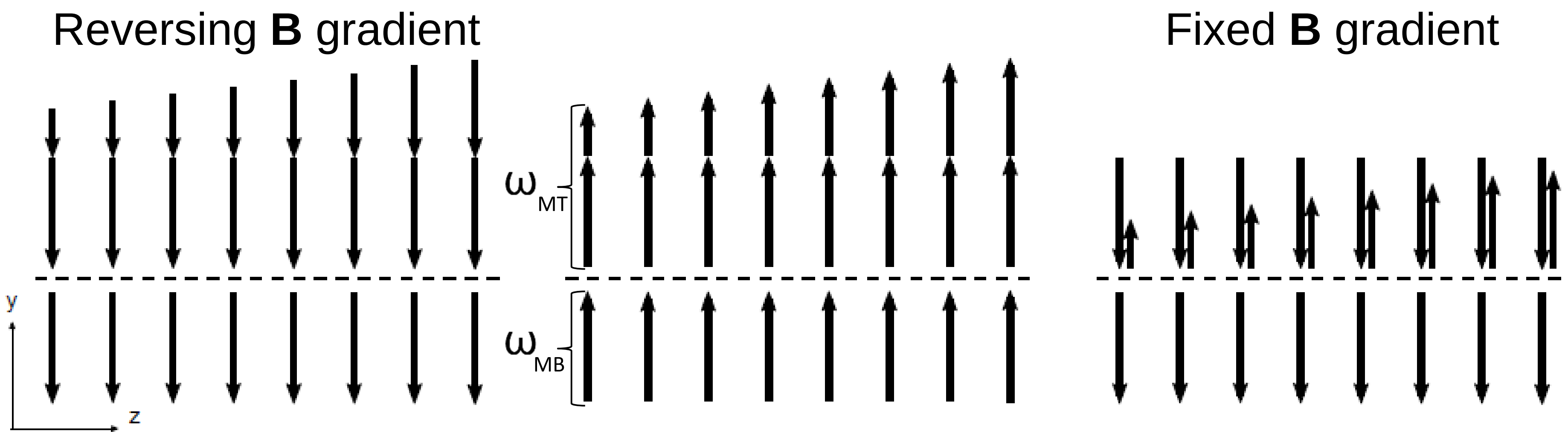


Systematics: Cell Motion

- Latest EDM data has a HV-correlated outer cell difference
- Errors and field dependence suggest this is driven by linear gradients



Systematics: Cell Motion



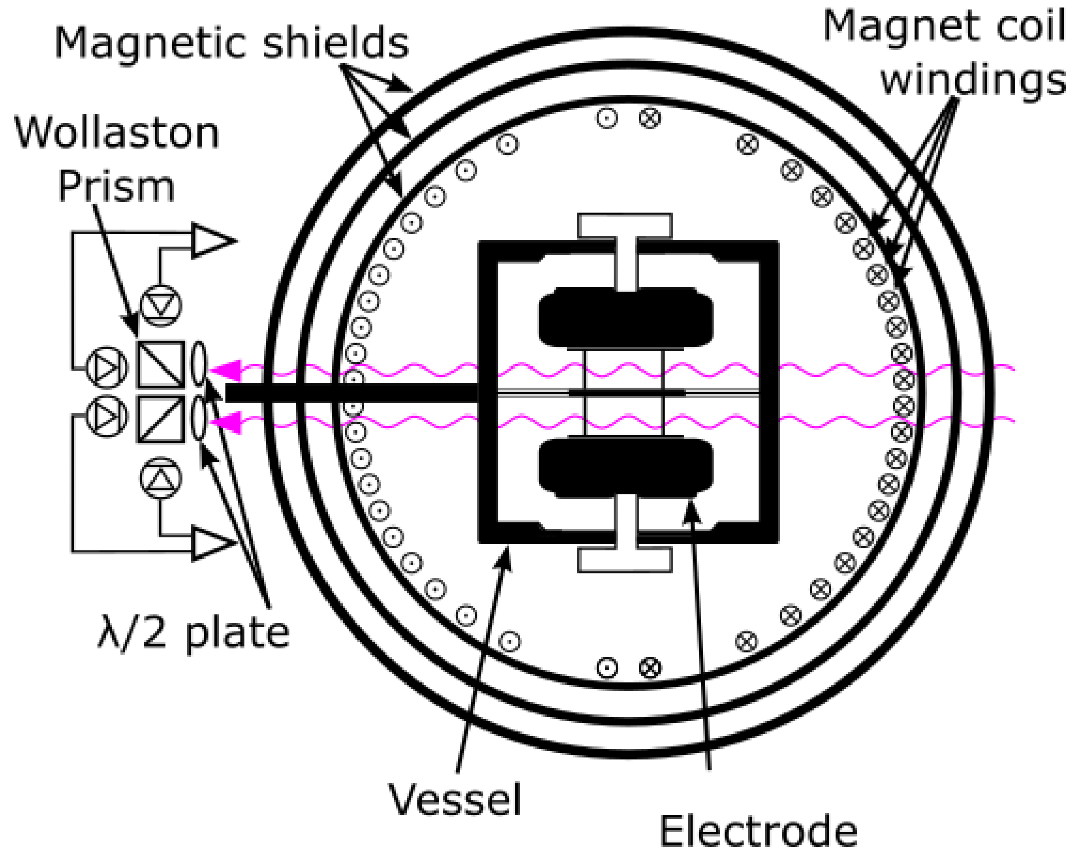
- HV-correlated cell motion through **B** gradients generates frequency shifts
- Gradients that reverse with $\mathbf{B_0}$ will give a fixed freq. shift
- Fixed gradients give a reversible freq. shift-mimics EDM behavior
- Gradients perpendicular to the shield axis reverse to within 5%

Systematics: Cell Motion

- Gradients perpendicular to the shield axis reverse to within 5%

- 5% of the part of the EDM frequency shift signal that does not reverse with $\mathbf{B_0}$ is the Radial Cell Motion systematic

- Measured **B** gradients suggest this motion is approximately 2 nm



Source	Error (10^{-31} e cm)
Axial Cell Motion	12.6
Radial Cell Motion	**3.36**

Axial Motion Constraints From Cut Data

- We have 285 completed days (runs) in the data set
- 32 days were excluded from the set b/c of HV-correlated (ω_{OT} - ω_{OB})
- Cut criteria:

$$1.\ |\Delta\omega_{OT-OB}| > 2.0\sigma \text{ or } 2.0 \times 10^{-8}\ \text{s}^{-1}$$

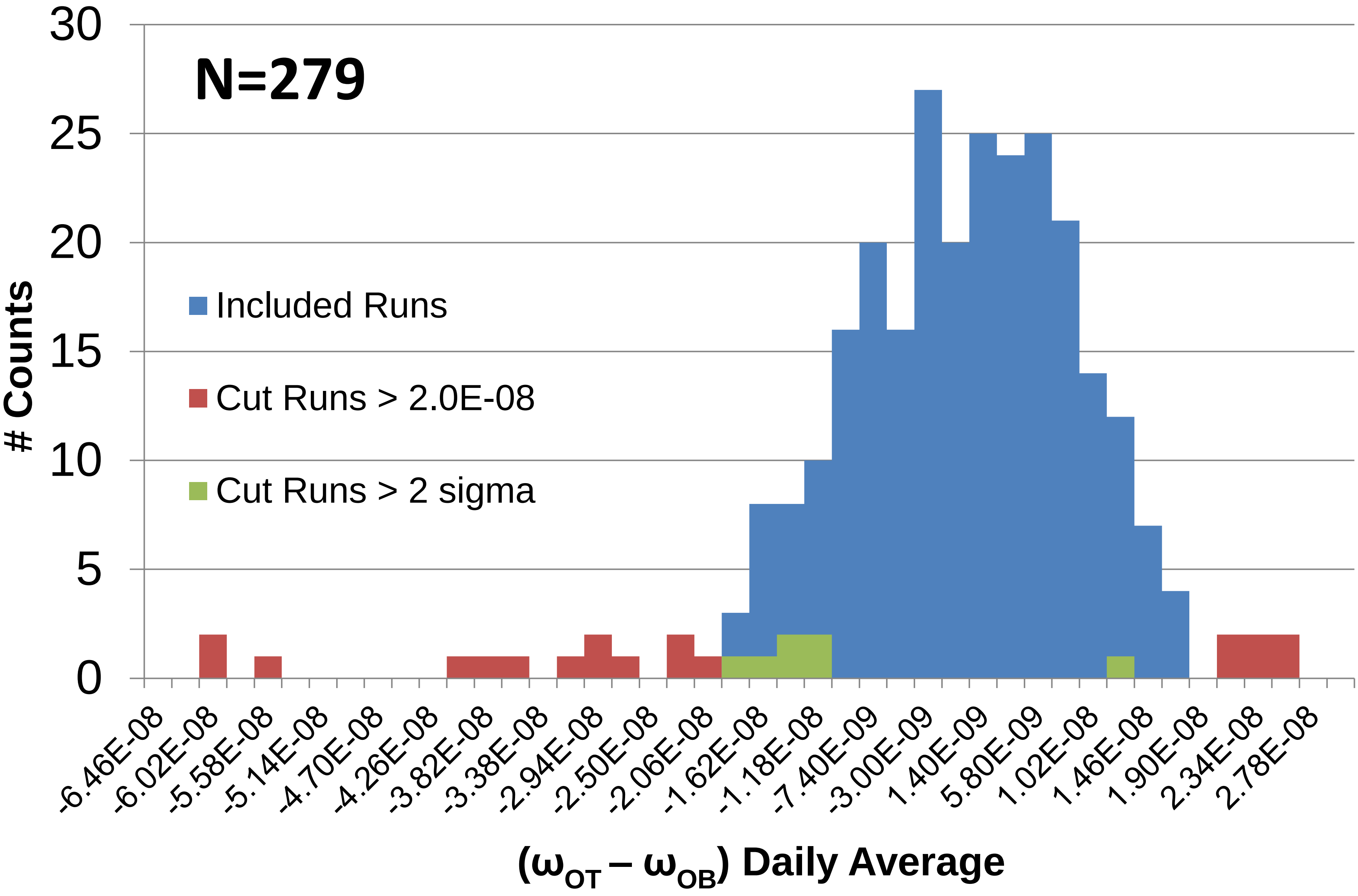
$$2.\ |\Delta\omega_{(OT-MT)+(OB-MB)}| > 3.0\sigma \text{ or } 1.5 \times 10^{-8}\ \text{s}^{-1}$$

- We use the set of excluded data (32 cut runs + 63 systematic runs) to estimate the EDM dependence on outer cell Δω due to axial motion:

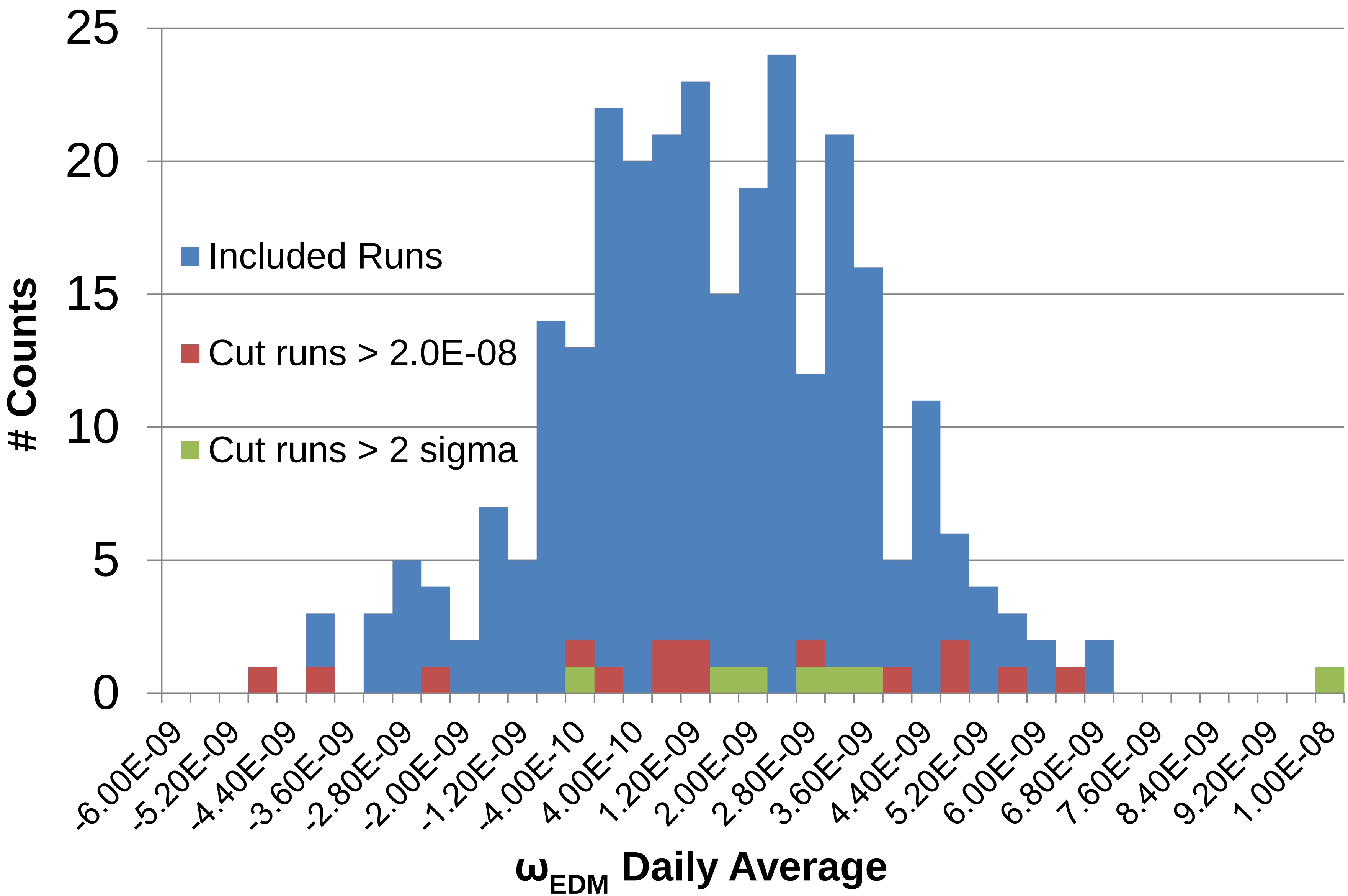
$$\frac{\eta_{\mathbf{B}} \cdot (\Delta\omega^{ex.}_{EDM} - \Delta\omega_{EDM})}{\eta_{\mathbf{B}} \cdot (\Delta\omega^{ex.}_{OT-OB} - \Delta\omega_{OT-OB})} = (1.6 \pm 5.7) \times 10^{-2}$$

- Excluded runs show that 7% of the outer cell freq. difference feeds through onto EDM channel

Outer Cell Daily Avg. Freq. Difference



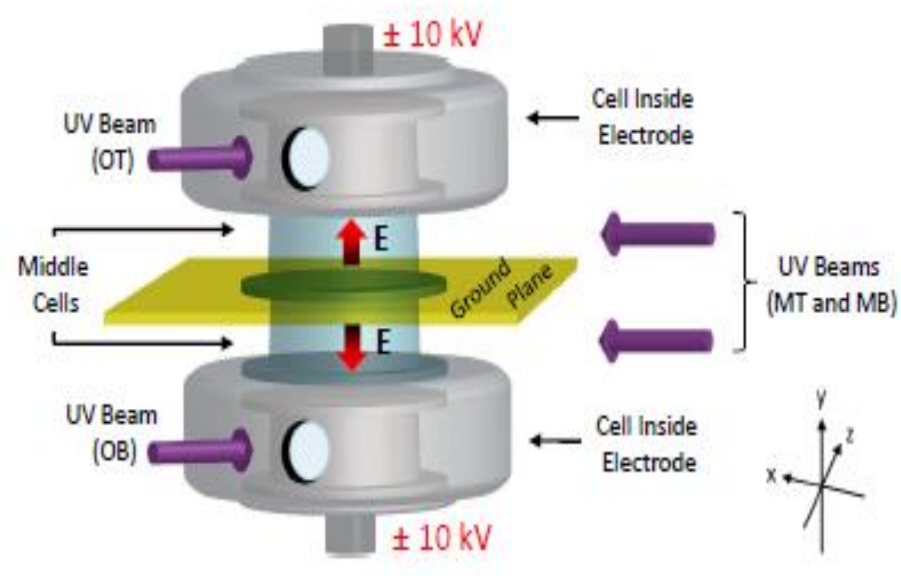
EDM Result Bias



Systematics: Leakage Currents

- '09 EDM data leakage current correlation = 0.42 pA
- Flowing dry N_2 continuously helps reduce leakage
- Field emission from sharp points on electrode surfaces can be reduced by polishing
- Ground plane coating of SnO_2 instead of Au eliminates photoelectric currents
- New measurement has 5 or 10x less leakage current than prev. measurement

Source	Error (10^{-31} e cm)
Leakage Currents	5.0
Quadrature sum	**14.8**



Systematics: Parameter Correlations

- Signals correlated with EDM and HV are treated as potential systematics

- Each parameter contribution is the product of correlations + 1σ

- Total systematic $\Delta\omega = 1.41 \times 10^{-11}$ (*cf*. statistical error $\Delta\omega = 1.45 \times 10^{-10}$)

Parameter	HV correlation	error	EDM Sig. correlation	error	Systematic
Avg. Lifetime	-2.72E-05	5.57E-04	-1.50E-09	7.97E-10	1.17E-12
Avg. Amplitude	2.45E-06	1.50E-06	-6.51E-07	6.02E-07	3.33E-12
Transmission	-3.40E-06	6.14E-06	2.83E-08	2.78E-08	2.96E-13
Laser Int.	-3.06E-07	7.91E-07	9.54E-08	9.93E-08	1.11E-13
Diode Current	6.72E-09	4.62E-08	8.82E-06	7.42E-06	4.70E-13
Green Piezo	5.18E-08	3.55E-06	6.36E-10	3.93E-09	2.30E-15
UV Piezo	2.29E-07	3.12E-07	-5.36E-10	2.62E-09	7.45E-16
Grad Coil 1	2.12E-10	1.64E-09	-5.74E-05	3.34E-04	1.30E-13
Grad Coil 2 (endcaps)	1.71E-09	2.81E-09	-3.89E-05	1.12E-04	2.87E-13
Grad Coil 3	8.60E-11	1.37E-09	1.04E-04	2.65E-04	1.53E-13
Main Coil	-1.30E-09	3.40E-09	1.89E-05	1.37E-04	2.14E-13
dBy/dx Coil	1.09E-10	2.85E-09	3.53E-05	2.69E-05	1.04E-13
Bx	-2.41E-05	2.46E-05	-1.36E-07	1.83E-08	6.66E-12
By	5.06E-08	1.60E-07	-2.37E-08	6.62E-09	5.01E-15
Bz	-1.35E-05	5.96E-06	-4.10E-07	4.49E-08	8.05E-12
Fluxgate (By)	2.69E-09	2.36E-08	6.47E-07	4.69E-07	1.71E-14
Normalized Vertical quad PD	1.17E-07	9.62E-08	-6.89E-07	1.27E-06	2.43E-13
Normalized Horizontal quad PD	6.70E-08	9.78E-08	-6.89E-07	1.27E-06	1.55E-13
Slab Temperature	-3.57E-25	1.50E-15	-1.38E-06	8.59E-07	2.08E-21
Table Temperature	3.24E-25	1.50E-15	-2.83E-07	5.52E-07	4.26E-22
Air Temperature	-1.95E-05	1.62E-05	-4.72E-08	4.20E-08	2.04E-12
Chopper Frequency	2.21E-06	4.19E-06	6.19E-07	3.56E-07	4.08E-12

Systematics: **E**^{2} Effects

Source	Error (10^{-31} e cm)
Axial Cell Motion	12.6
Leakage Currents	5.02
Radial Cell Motion	3.36
E^2 effects	3.04
Parameter Correlations	2.33
v x **E** **B** fields	2.29
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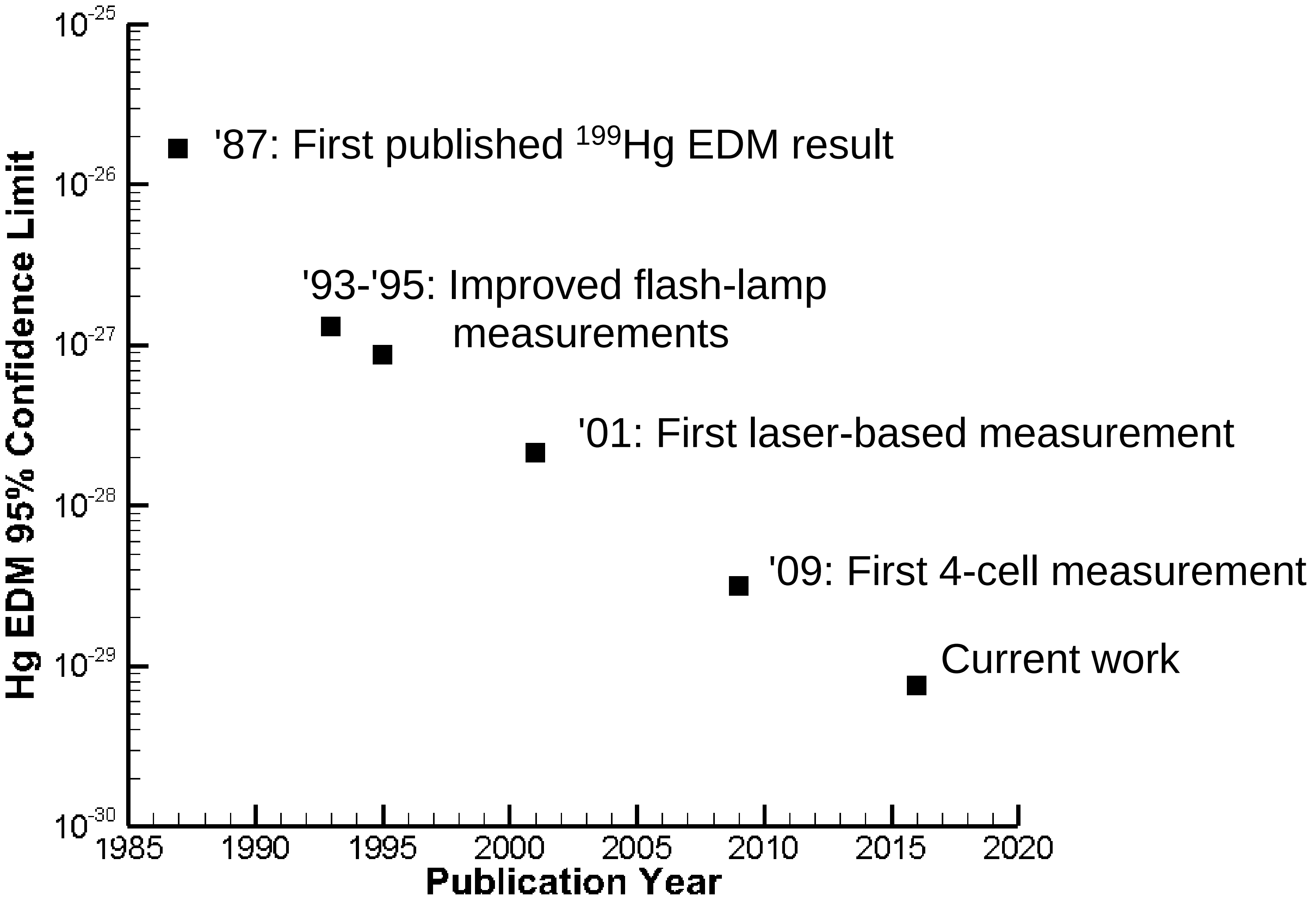
Quadrature sum	**14.8**

- Any effect that couples $\Delta\omega_{EDM}$ to |**E**| is a systematic if |$\mathbf{E}_+$| is different from |$\mathbf{E}_-$|
- We measure |$\mathbf{E}_+$| - |$\mathbf{E}_-$| using the quad. Stark shift
- Measure $\Delta\omega_{EDM}$ (|**E**|) by taking ~10 scans each day at 0 kV between +/- 10 kV or +/- 6 kV

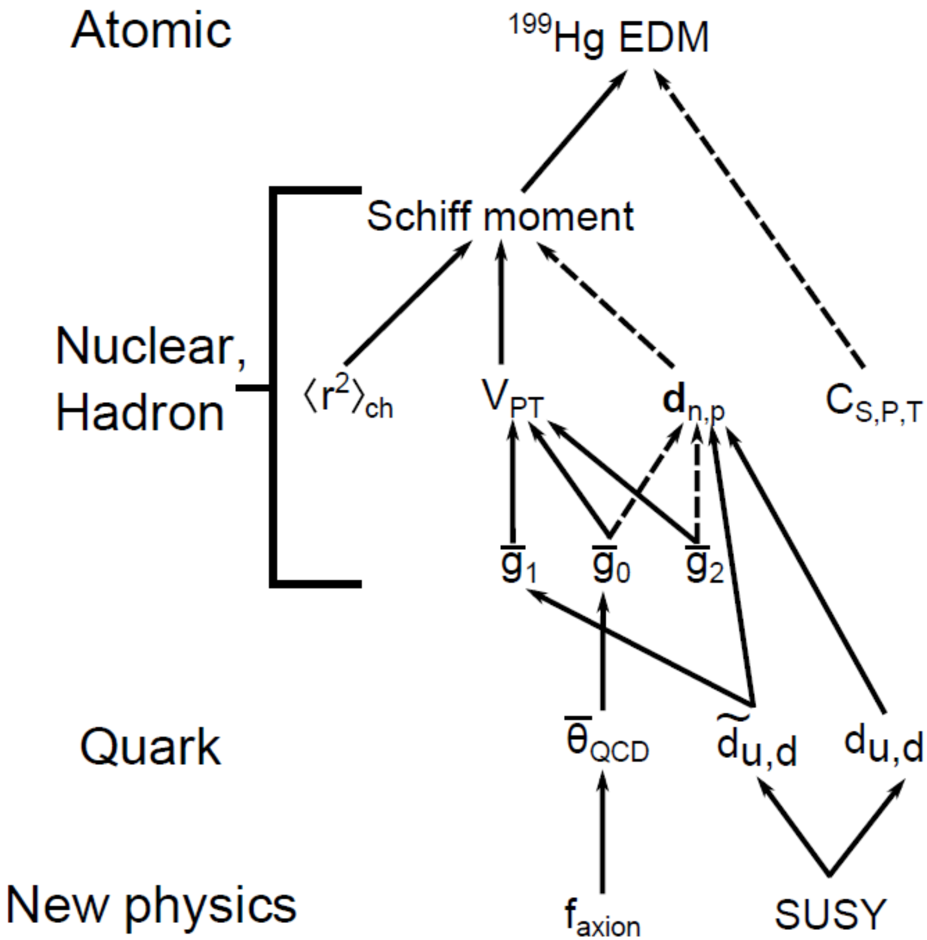
Null Result and New Limits

- We find ^{199}Hg EDM $d_{Hg} = (2.20 \pm 2.75_{stat} \pm 1.48_{syst}) \times 10^{-30} e \cdot \mathrm{cm}$
- Combined error bar $\sigma = 3.123 \times 10^{-30} e \cdot \mathrm{cm}$
- Set a 95% confidence limit by solving $\frac{1}{\sigma\sqrt{2\pi}} \int_{-L}^{L} e^{-(\mu - x)^2/2\sigma^2} dx \geq 0.95$
- New upper limit on $|d_{Hg}| < 7.4 \times 10^{-30} e \cdot \mathrm{cm}$
- Improves our 2009 limit $|d_{Hg}| < 3.1 \times 10^{-29} e \cdot \mathrm{cm}$ by a factor of 4
- If theoretical calculations are correct, $|d_{Ra}| < 7.5 \times 10^{-27} e \cdot \mathrm{cm}$

Hg EDM Limits vs. Time



Hg EDM Limits on CP-odd Parameters



- Hg EDM results can be used to put limits on CP-odd parameters
- It is necessary to assume the EDM has only 1 contribution
- $d_{Hg} < 7.4*10^{-30}$ e cm
- → $\theta_{QCD} < 8.5 *10^{-11}$
- $d_n < 1.6*10^{-26}$ e cm

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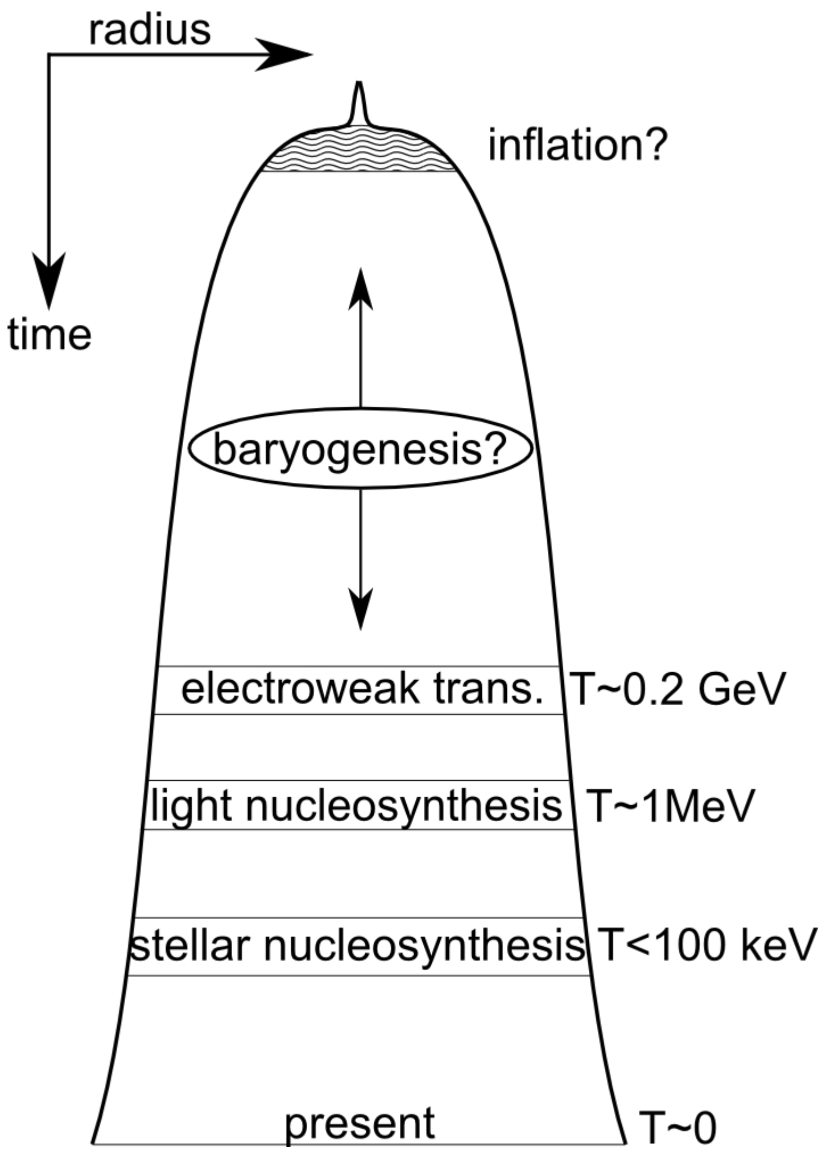
CP violation and baryogenesis



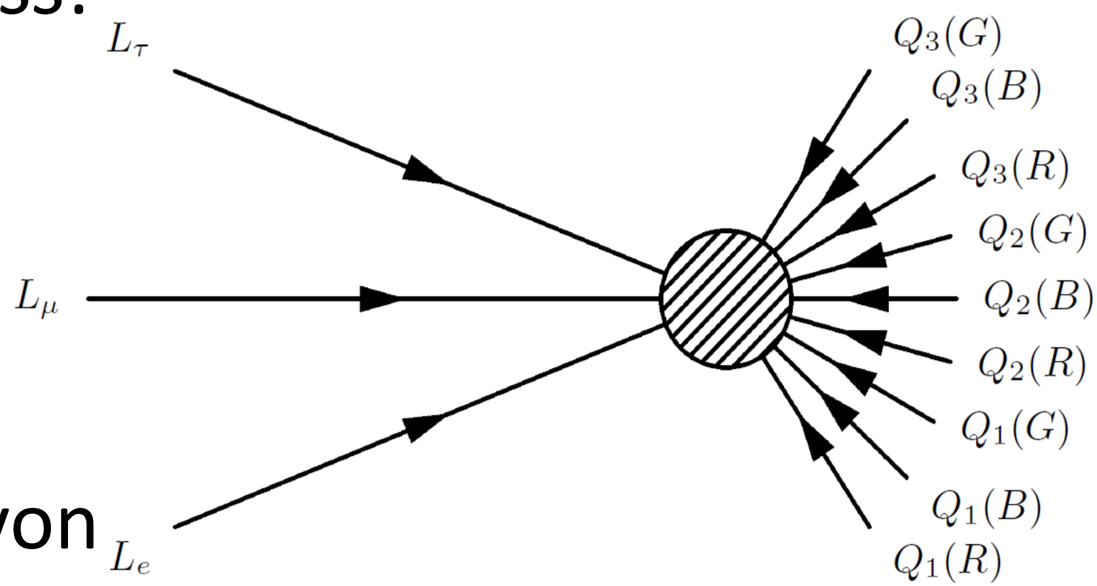
- No theory explains the ‘excess’ of matter over antimatter:

$$\eta = \frac{n_B - n_{\overline{B}}}{\gamma} = (6.14 \pm 0.25) \cdot 10^{-10}$$

- Any baryogenesis model needs to satisfy the Sakharov conditions:
  - 1. Baryon number violation
  - 2. CP symmetry violation
  - 3. Departures from thermal equilibrium
- Higgs is too massive for a workable theory based in standard model physics

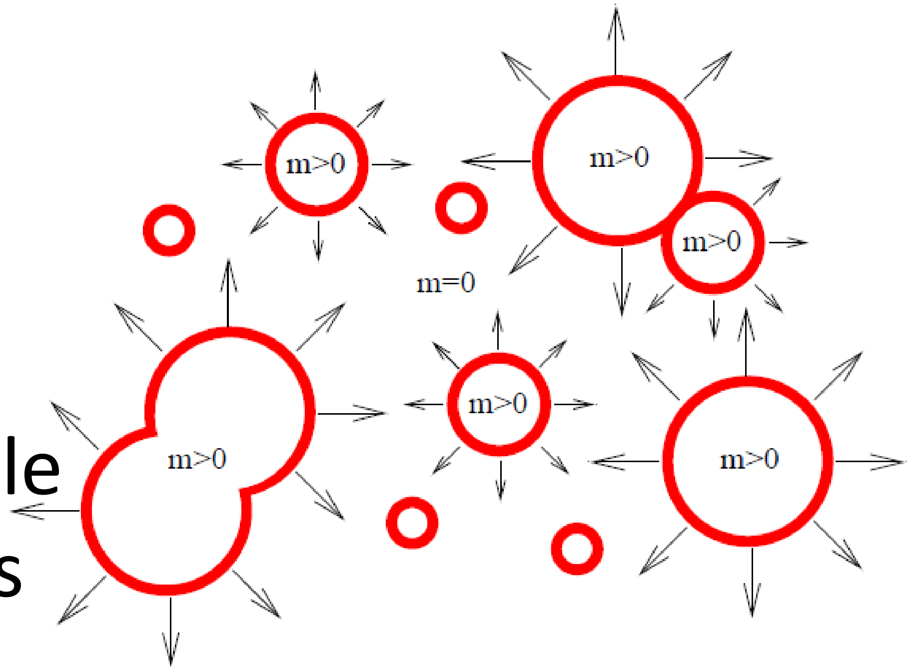
What does a B-violating process look like?

- Best-known example is the *sphaleron process*:
  - $\Delta B = +/-3$
  - Conserves B-L
  - Suppressed below ~100 GeV
- Could generate baryon excess from lepton excess (*leptogenesis*)



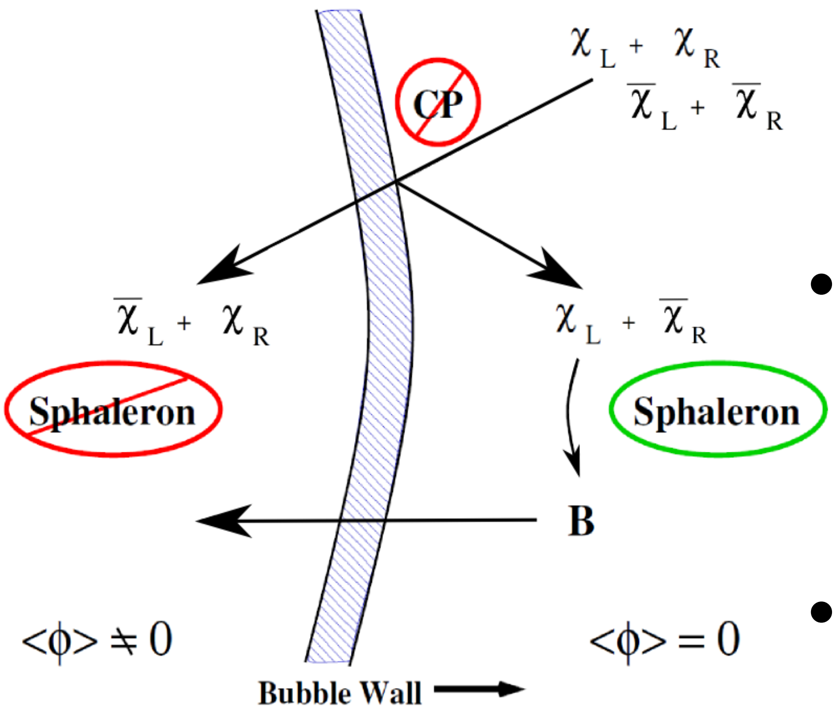
Out-of equilibrium decay: Electroweak baryogenesis (EWBG)

- Popular baryogenesis models focus on the EW symmetry breaking
- Higgs field acquires multiple vacuum expectation values



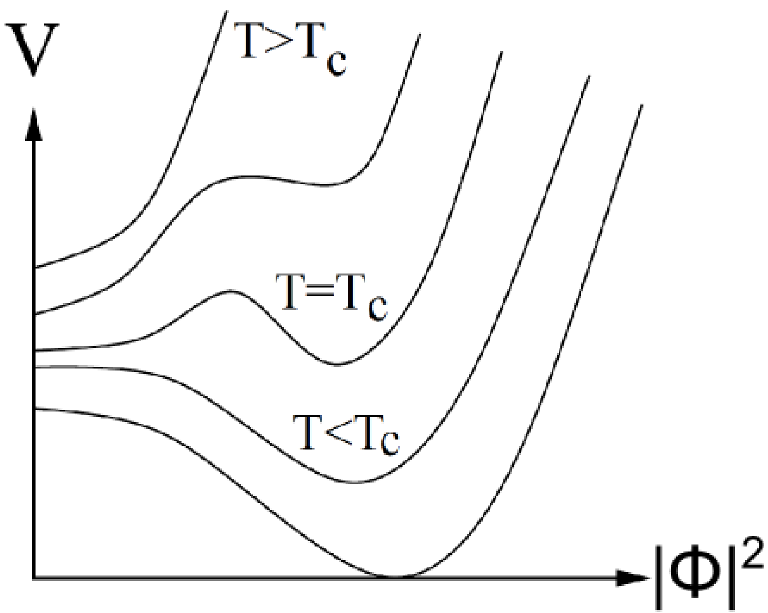
- Regions of broken EW symmetry can expand like bubbles
- Interactions at the walls violate CP, are out of eq.

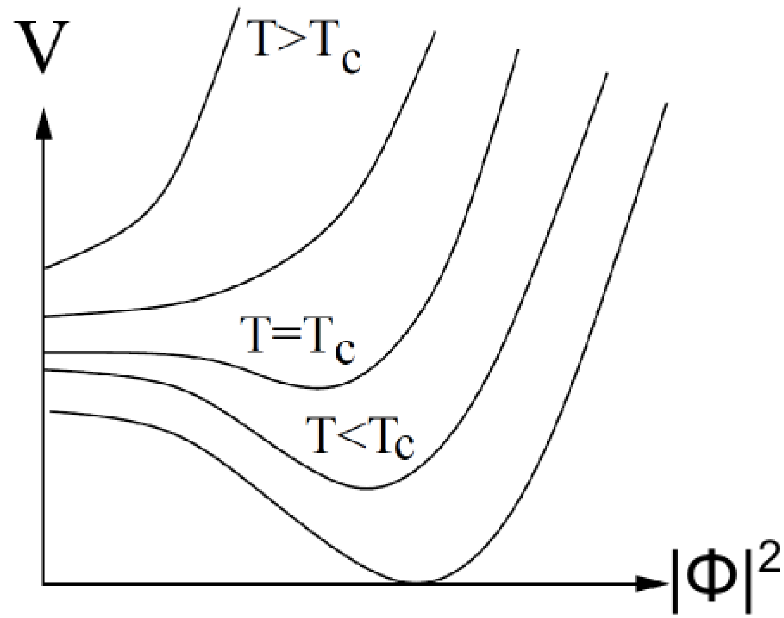
Where do the baryons actually come from?



- CP-violating interactions at the wall reflect LH particles, RH antiparticles
- Sphaleron process does not couple to RH (anti)particles, is frozen out by large $M_{W,Z}$
- Net flux of baryons outside diffuses in before eq. is established

First-order phase transitions in EWBG





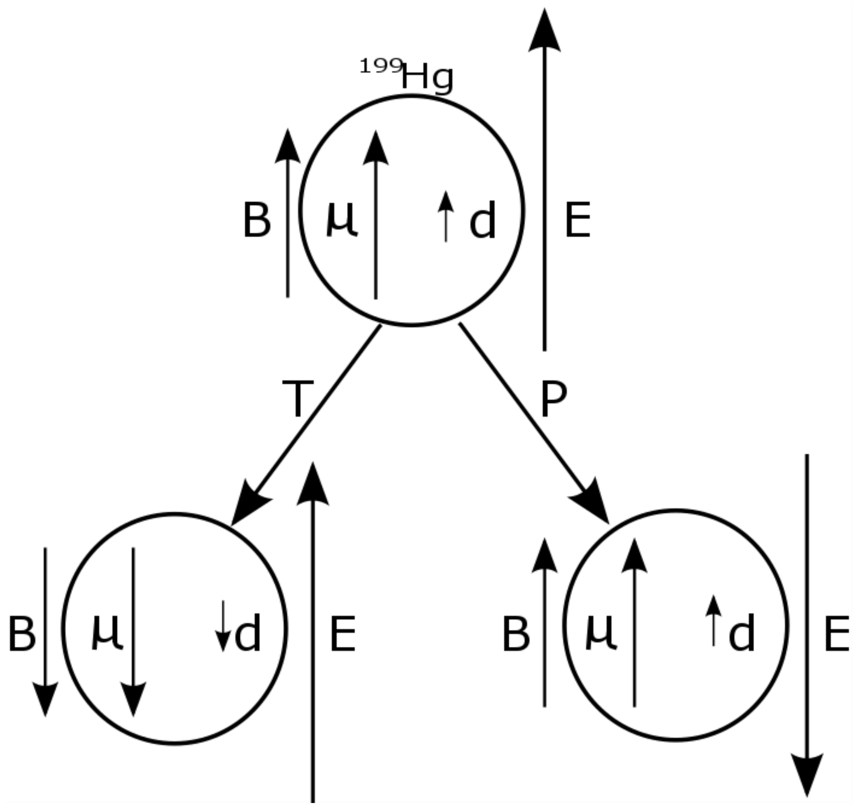
- For bubble nucleation, the electroweak symmetry breaking must be a first-order phase transition
- The effective Higgs potential at high temp. must have degenerate minima ($T=T_c$, left diagram)

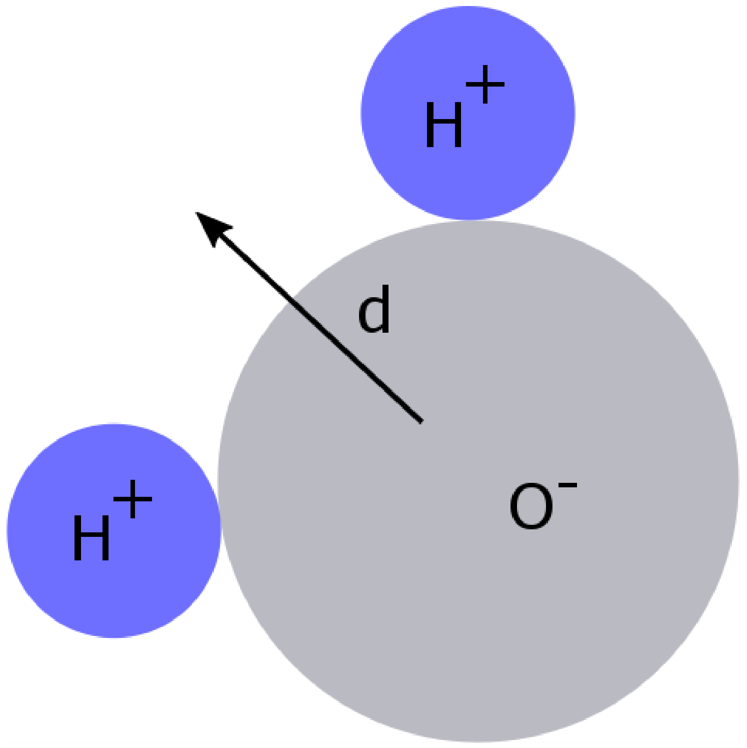
Can this happen under the Standard Model?

- No.
- CP-violation in the CKM matrix is insufficient to create large enough particle number asymmetries outside the bubbles of non-zero Higgs VEV
- Electroweak symmetry-breaking transition in the SM cannot involve bubble nucleation with $M_{Higgs} > 75$ GeV

Atomic vs. Molecular EDMs

- Parity violation requires a fixed EDM projection onto spin axis
- Molecules have additional degrees of freedom-EDMs have no definitive spin projection





Cell Motion Causes

- Magnetic shielding defects may cause gradients
- HV-correlated quadratic gradients appear larger on top
- Welded shield seam is nearest outer top cell
- Effect of cell motion changes from sequence to sequence

Sequence	MT cell	MT$\Delta\omega(10^{-10}\text{s}^{-1})$	MB cell	MB$\Delta\omega(10^{-10}\text{s}^{-1})$
1	IV	(-6.82 ± 7.7)	II	(-7.32 ± 7.7)
2	II	(-31.70 ± 7.5)	IV	(17.20 ± 8.3)
4	V	(-8.05 ± 9.0)	IV	(-5.20 ± 8.7)
5	IV	(-5.17 ± 8.2)	V	(1.28 ± 7.1)
6	II	(-7.35 ± 6.9)	V	(-2.29 ± 6.6)
7	II	(2.16 ± 5.8)	V	(10.00 ± 5.5)
8	V	(2.50 ± 6.5)	II	(-2.05 ± 6.1)
9	II	(13.10 ± 6.8)	V	(-15.6 ± 6.6)
10	IV	(6.28 ± 7.9)	V	(-7.33 ± 7.4)
11	V	(7.52 ± 8.8)	IV	(-6.49 ± 8.8)
12	IV	(-9.45 ± 9.4)	II	(-0.98 ± 9.2)
13	II	(-4.04 ± 7.2)	IV	(-7.48 ± 7.2)
14	V	(-27.30 ± 8.3)	II	(28.50 ± 8.3)
Average:		(-4.24 ± 2.1)		(-0.02 ± 2.0)