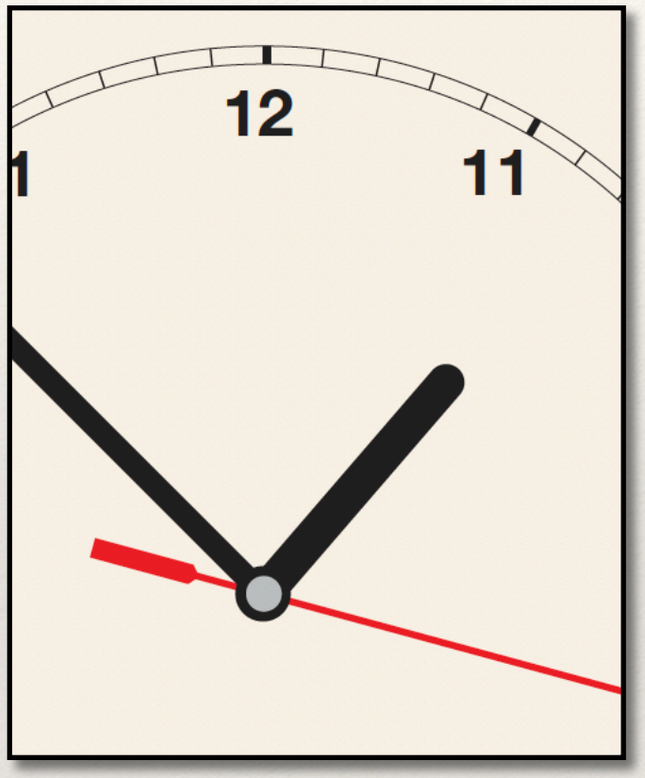
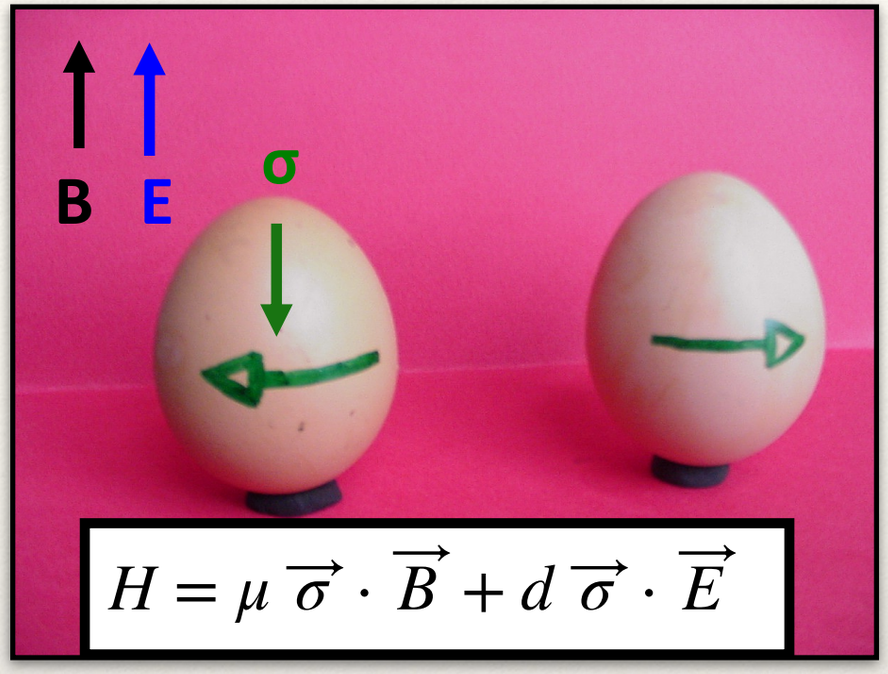
Why measure time-reversal violation in molecules ?

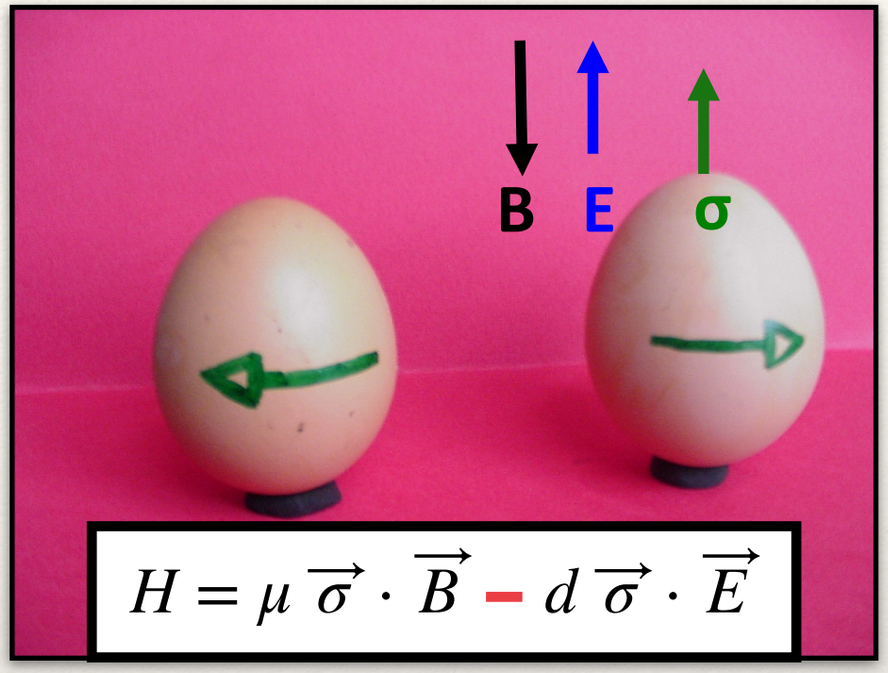


Jordy de Vries and the NL-eEDM collaboration

What are electric dipole moments?



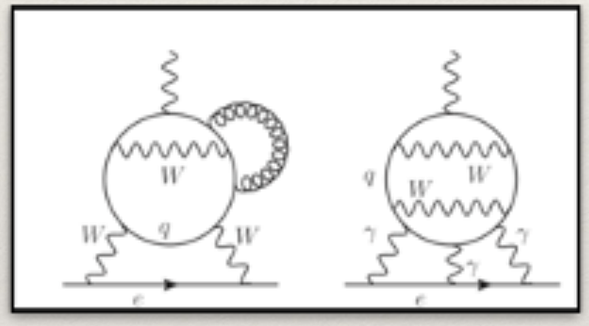
Flip time



- Electric dipole moment (interaction between **spin** and **E-field**) implies T violation
- CPT-theorem: EDMs violate **CP symmetry**
- EDMs are not zero in the Standard Model since **CP is violated**

Let's talk about small numbers

- 2 sources of CP violation in the Standard Model, but only 1 is confirmed
- Kobayashi/Maskawa: Nobel prize for **prediction of third generation**
- **Extremely inefficient to generate EDMs. Electron EDM at 4 loops !**



Electric dipole moment

$$d_e \sim 10^{-44} e\,\mathrm{cm} \sim \frac{1}{10^{30}\,\mathrm{GeV}}$$

Magnetic dipole moment

$$\mu_e \sim 10^{-11} e\,\mathrm{cm} \sim \frac{1}{\mathrm{MeV}}$$

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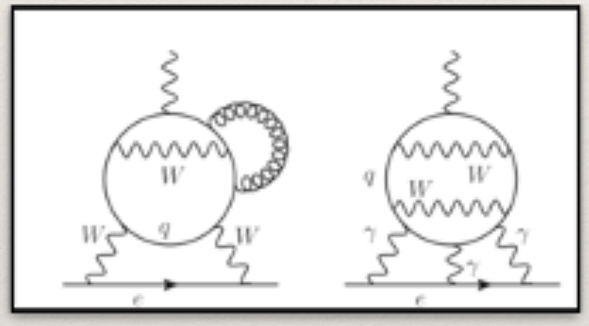

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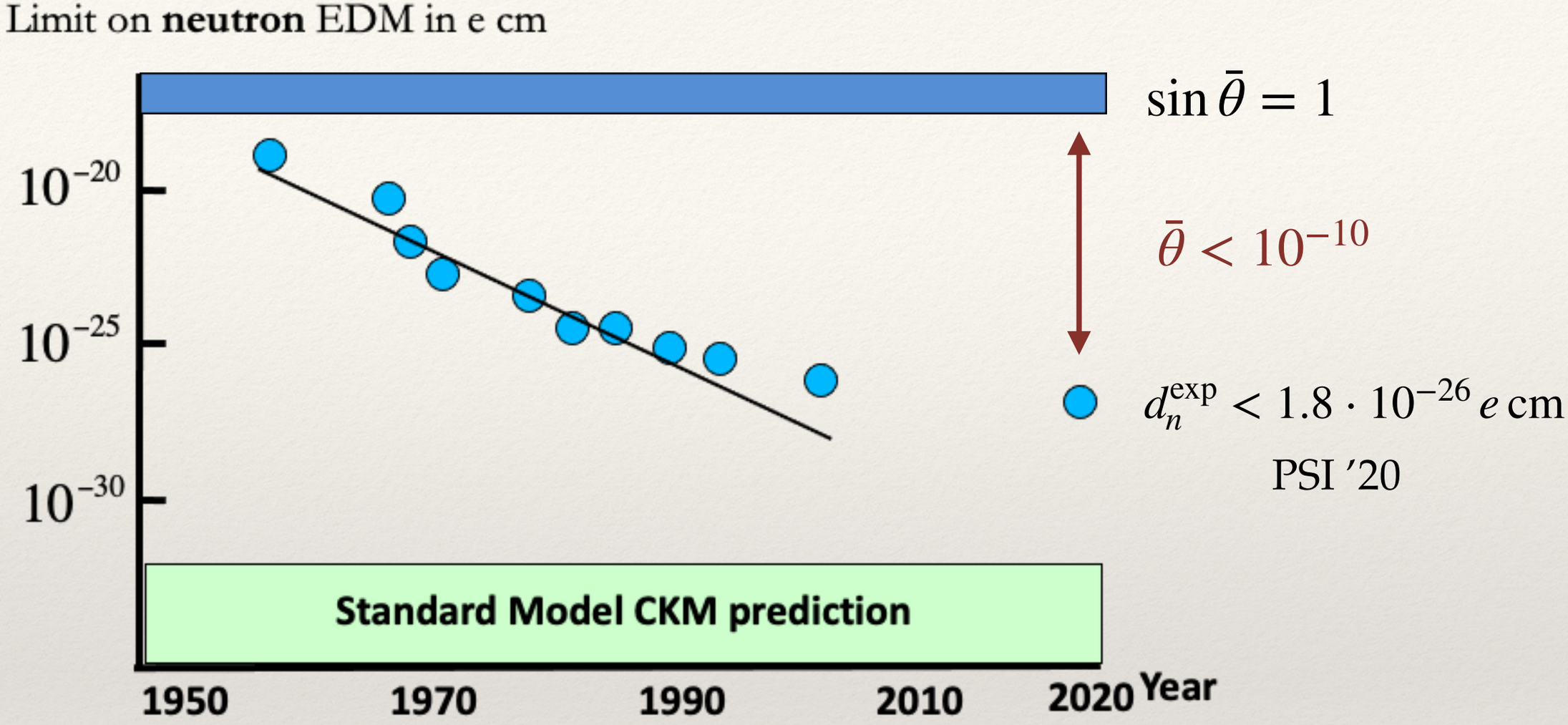
- **Second source of CP violation in Quantum Chromo-Dynamics**

$$\mathscr{L}_\theta \sim \sin\bar{\theta}\left(\epsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta}\right) \longrightarrow$$

Predicts large hadronic EDMs

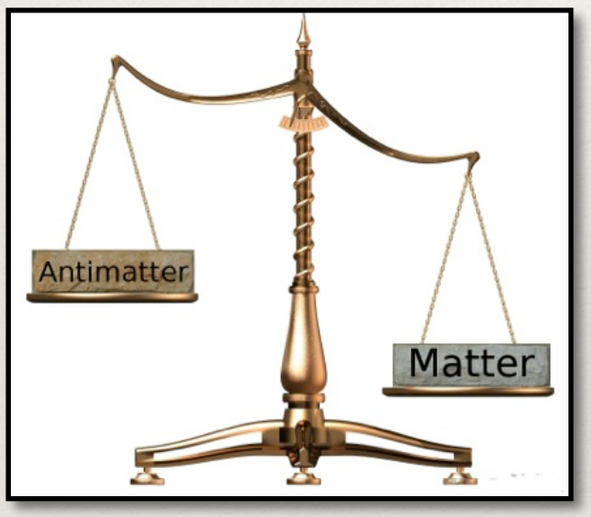
Strong CP problem



- Only term in Standard Model that seems to be missing !
- **Strong CP problem** is driven by EDM experiments
- Many proposed solutions —> axions? Could also be Dark Matter

Can there be larger EDMs ?

- Main reasons to think (hope?) EDMs are bigger than predicted from CKM phase



$$10^{-10} > \sin\bar{\theta} > 0$$

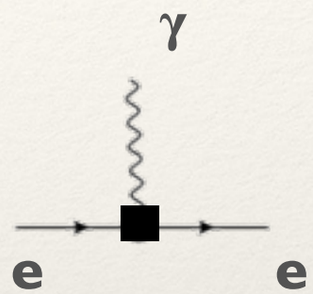
- **Standard Model CP violation not sufficient**
- Caveat: more CP violation is not sufficient. Not all cosmological scenarios predict large EDMs.

- **CP violation is a broken symmetry**
- Almost any Standard Model extension has new sources of CP violation
- **~1/2 of SMEFT operators break CP**

How sensitive are EDM experiments ?

- EDMs are **low-energy experiments** that are **indirect** probes of new CP violation
- Similar in spirit to BSM searches at, for example, **LHCb**
- Electron EDM appears as a dimension-six operator in the SM-EFT

$$\mathscr{L} = C_e\, \bar{e}_L \sigma^{\mu\nu} \varphi e_R F_{\mu\nu} \qquad d_e \sim v\, \mathrm{Im}\, C_e \sim \frac{v}{\Lambda^2}$$



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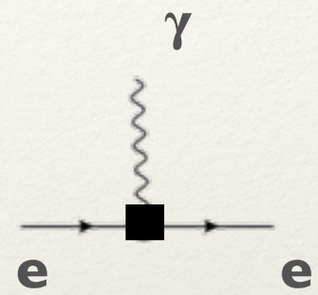

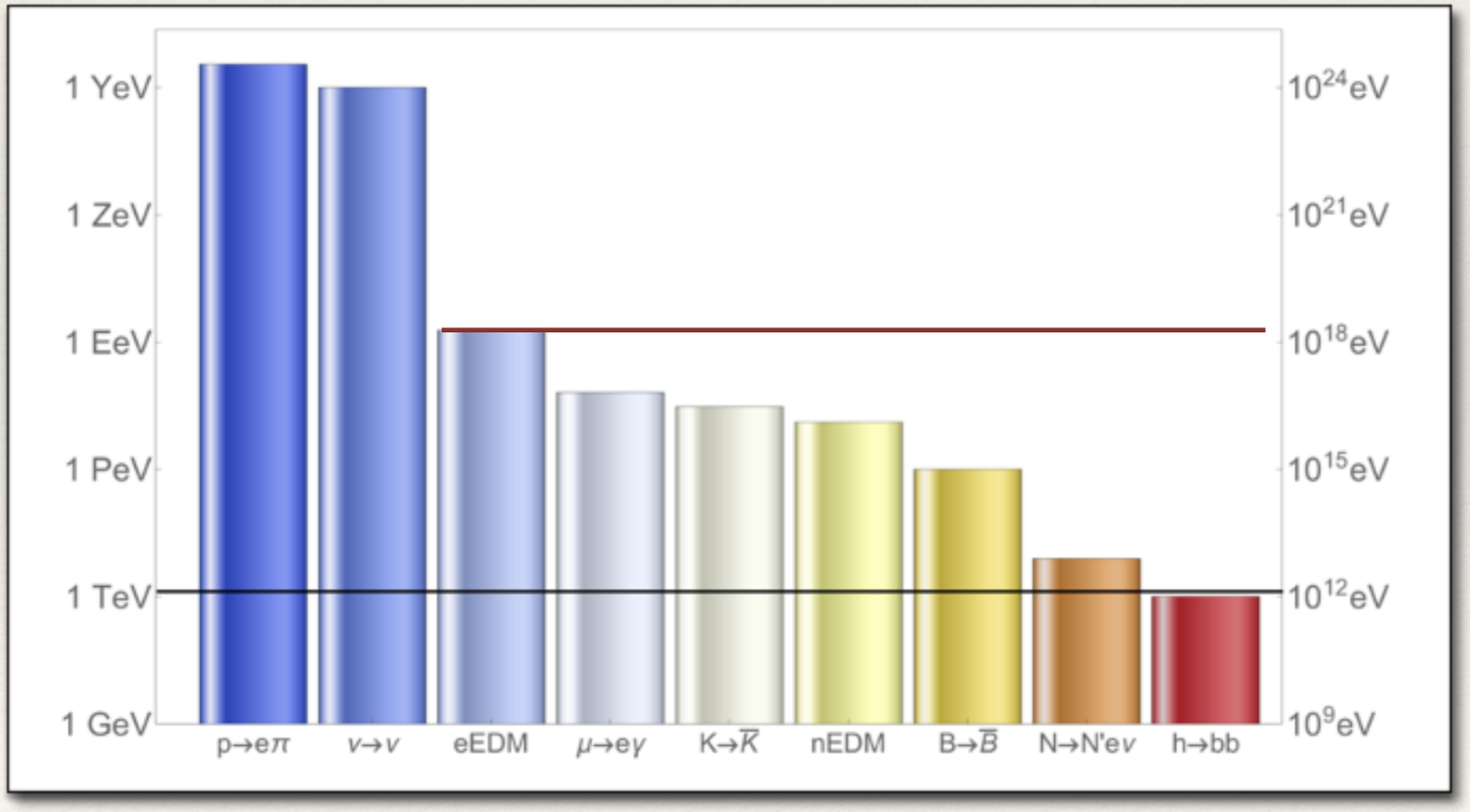

$$\Lambda_{EDM} \simeq 10^6\,\mathrm{TeV}$$

- **Ask me about the fine print !**

Picture from Adam Falkowski

Why do we use molecules ?

- You can measure EDM by studying spin precession in external E field
- But a free electron would be expelled by the same E field !
- Or store electron in a **neutral system** (an atom for example)

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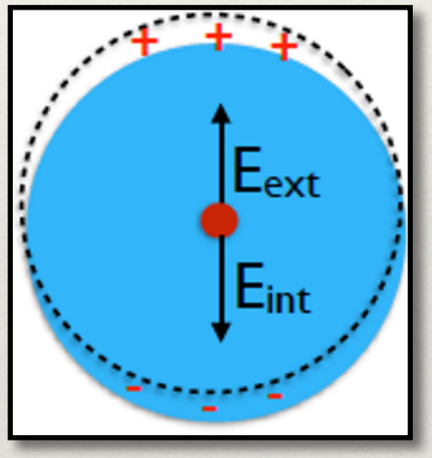
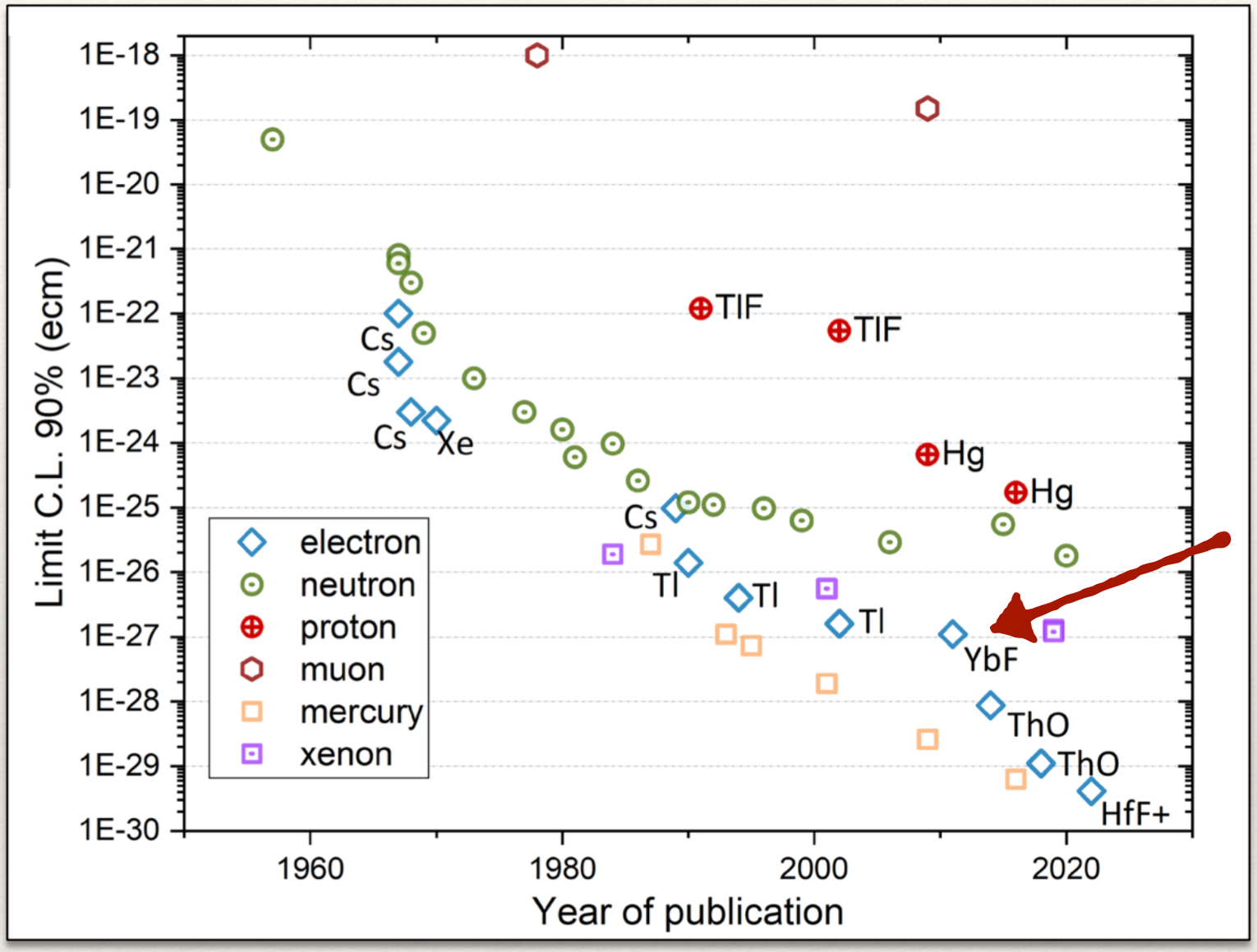
Schiff Theorem: EDMs of charged constituents are screened in a neutral atom



- Using hydrogen is therefore a bad idea. But Schiff's theorem breaks down for **relativistic electrons ! Enhancement in large systems !**

$$d_A \sim \alpha_{em}^2 Z^3 d_e \qquad d_{BaF} \sim 10^5 d_e$$

The molecular revolution



First molecular measurement

$d_e < 4.1 \cdot 10^{-30}\, e\,\mathrm{cm}$

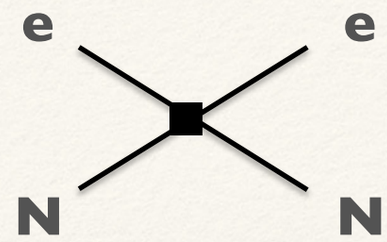
Boulder group ‘23

- **But it’s not just about the best limit**
- **We need different systems to unravel the source**

We need to understand CP-odd forces

- **Molecular EDMS depend on more than the electron EDM**

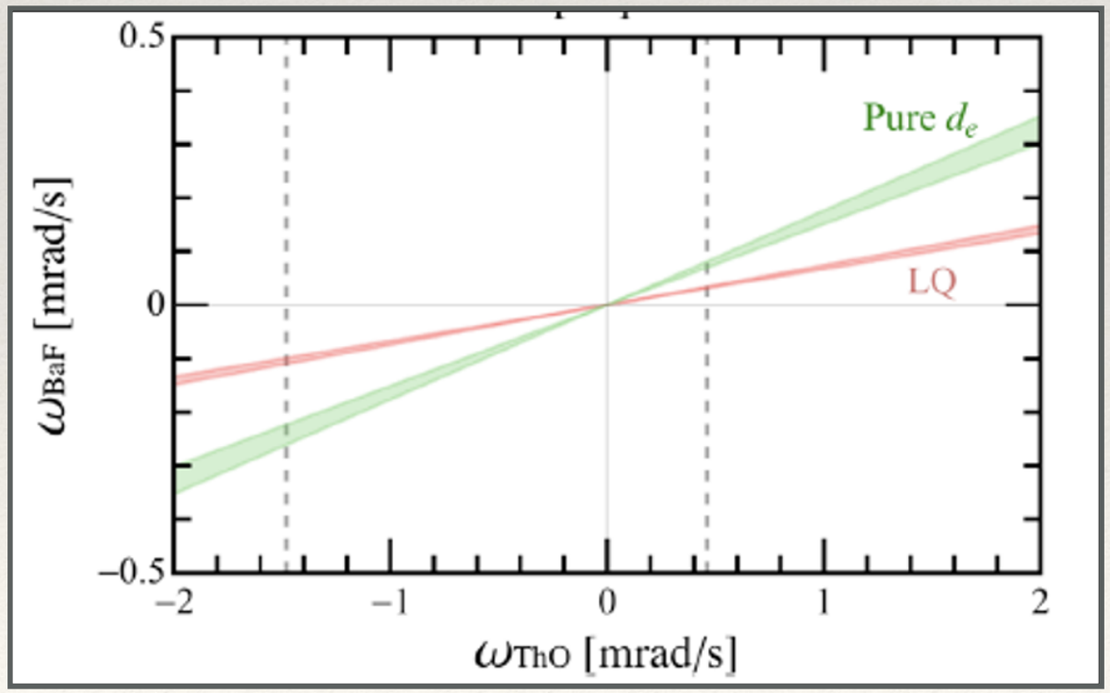
$$\mathscr{L}_{eN} = \bar{C}_S G_F \bar{N} N \bar{e} i\gamma^5 e$$



- Induces additional contributions to the energy shift we try to measure

$$\omega_X \sim (d_e + r_X \bar{C}_S)$$

- The interpretation requires many-body molecular computations
- **And a theoretical framework to connect to fundamental CP violation**

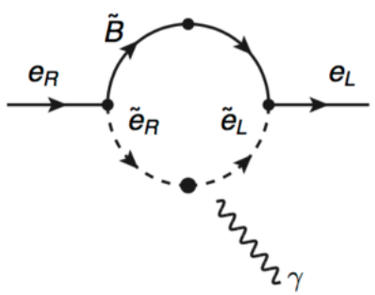


- Many open challenges to understand mechanisms to generate molecular EDMs

Back up

The BSM CP problem

Example 1:
Bino-Higgsino loop contribution
to the electron EDM



$$d_e \sim \left(\frac{\alpha_{em}}{\pi}\right)^n \frac{m_e}{\Lambda^2} \sin\phi$$

If phase = O(1): $\Lambda > 30$ TeV (n=1)

- This is generic: add more particles → no EDM protection mechanism