T-violating electric dipole moments as probes for new physics at high scales

- Electric dipole moments (EDM)s and new particle physics
- How to detect an EDM
- Recent advances & relation to quantum science
- What it means, and where we go next

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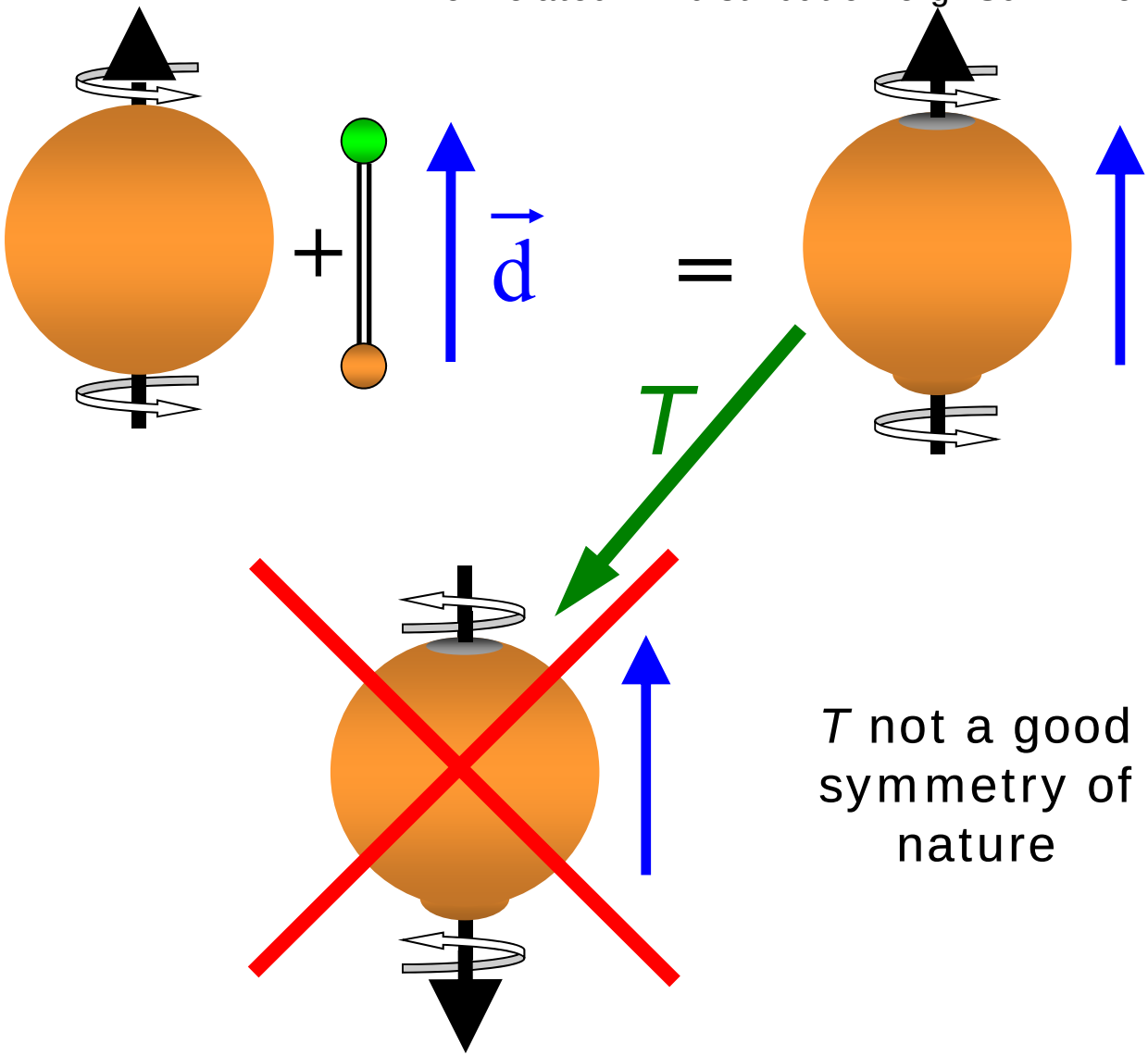
EDM along spin violates CP*

*or related EM distribution e.g. Schiff Moment



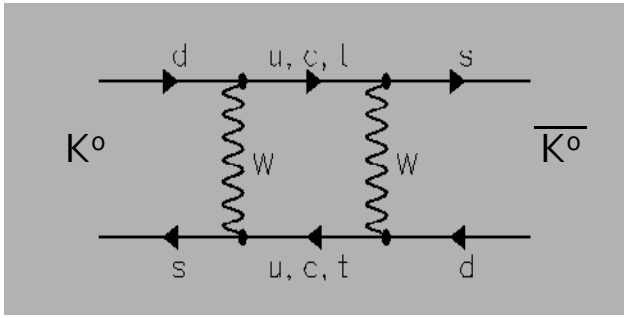
Purcell
Ramsey
Landau

T not a good symmetry of nature

CPT theorem ⇒ T-violation = CP-violation

CP-violation: a window to new physics

- CPV observed in K- and B-mesons
  ⇒ T ***NOT*** conserved in nature



- Observations consistent w/Std. Model CKM matrix
  but still allow new CPV from physics at higher scale

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}.$$

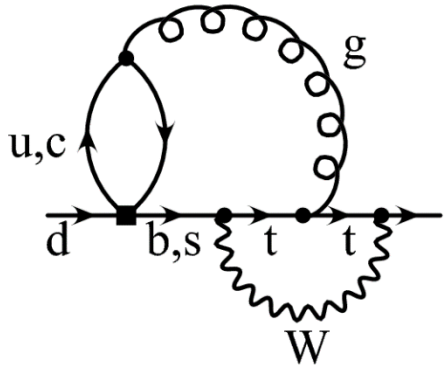
$$\begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{bmatrix}$$

- CP-violation in SM: peculiar & (in some sense) minimal
  SM extensions ***typically*** include new sources of CP-violation

- Observed baryon asymmetry of universe
  REQUIRES *new sources of CPV* beyond Std. Model

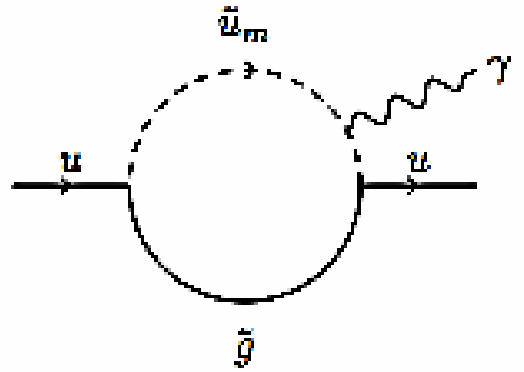
EDM from radiative corrections*

Quark EDM in Standard Model



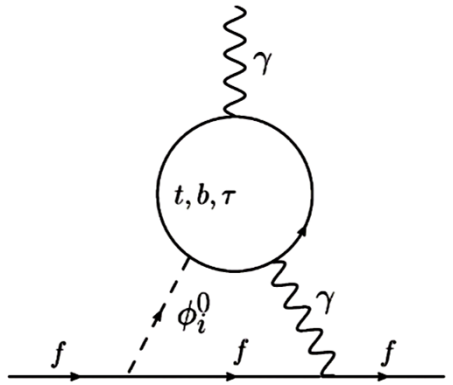
3 loops, highly suppressed by GIM mechanism

Quark EDM in SUSY



1 loop, no evident suppression (similar for electron)

Sensitivity to heavy-flavor CPV only slightly suppressed



Probes CPV in Higgs sector, split SUSY, etc. etc.

Similar in spirit to muon g-2 experiment at FNAL, *BUT*:

--no Standard Model background to subtract (at least in near future...)

--much higher mass reach even at current sensitivities (modulo CPV associated with new physics)

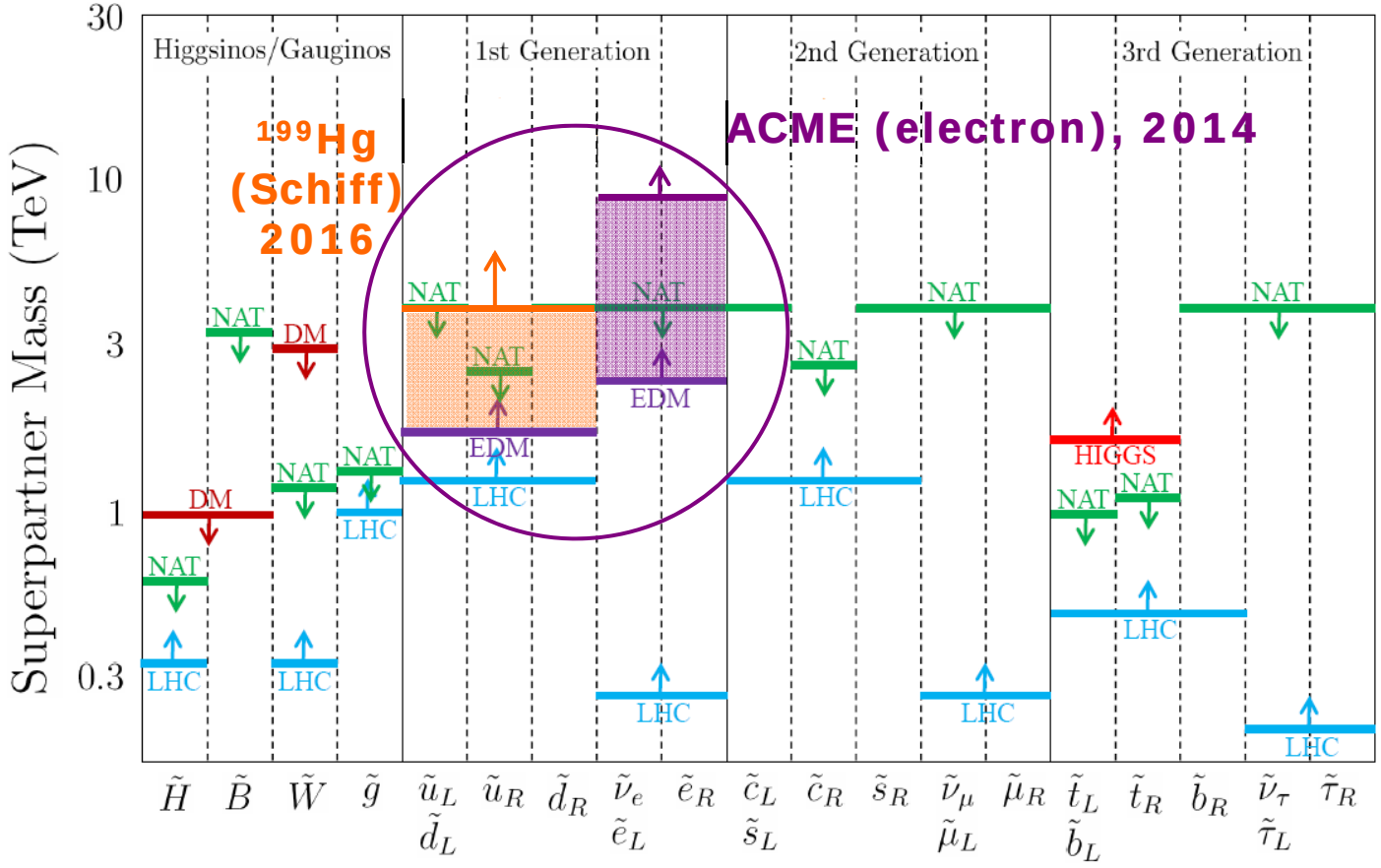
--progress by orders of magnitude seems feasible!

GRAND CHALLENGE:

search for new CPV physics at PeV scale

Particle physics relevance & impact

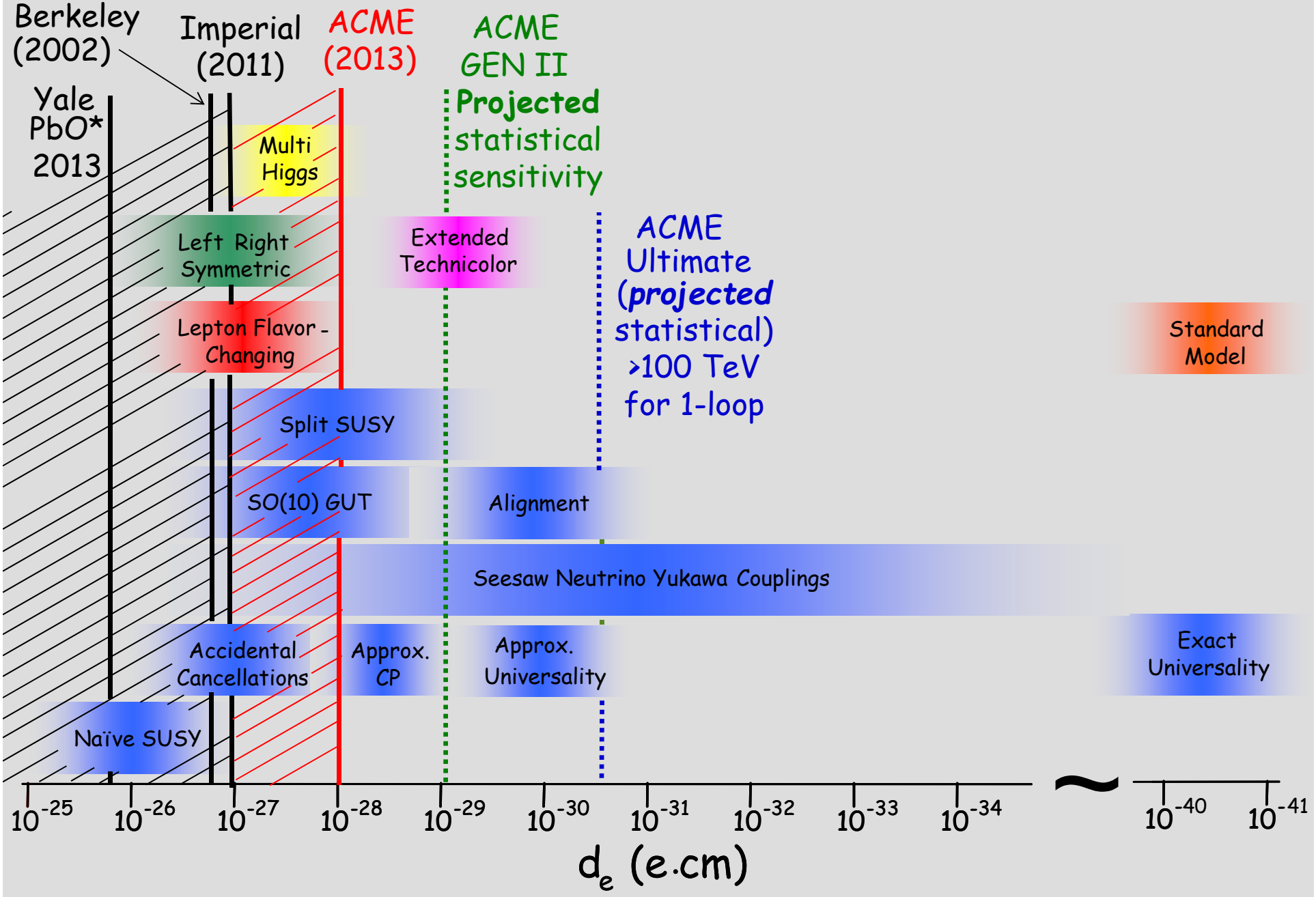
From: J. Feng, Annu. Rev. Nucl. Part. Sci. (2013) "Naturalness and the status of SUSY"



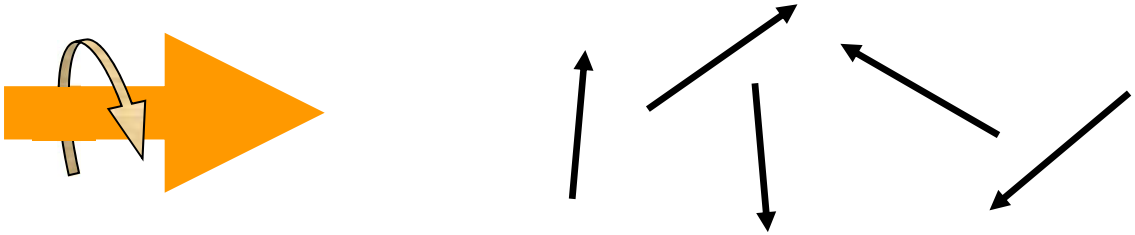
- *EDMs can **surpass LHC reach** in many models (not just SUSY)*

- *With LHC data, definitive test of electroweak baryogenesis...?*

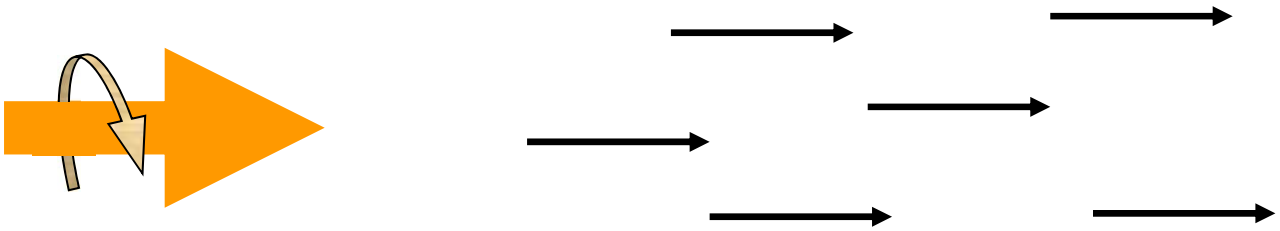
Example: projected improvements in e-EDM



General method to detect an EDM



General method to detect an EDM



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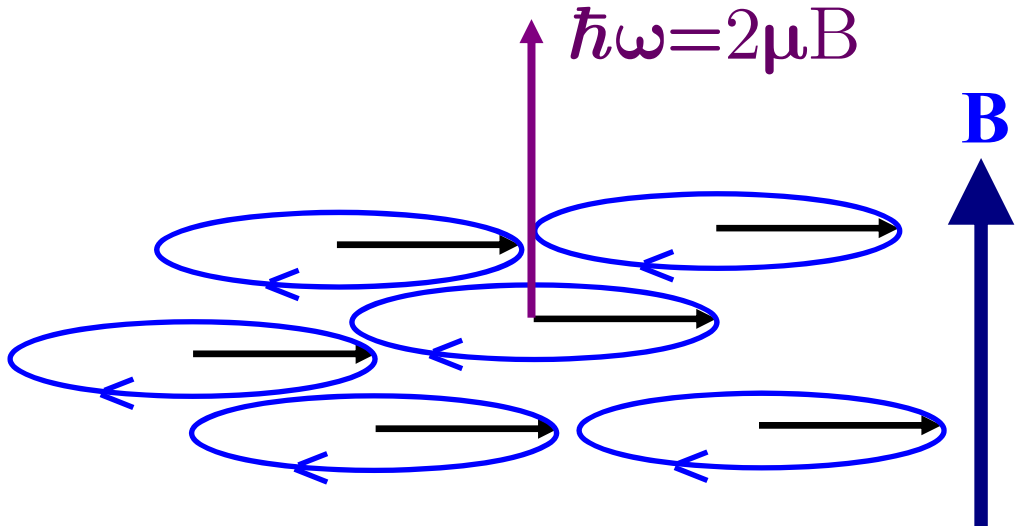
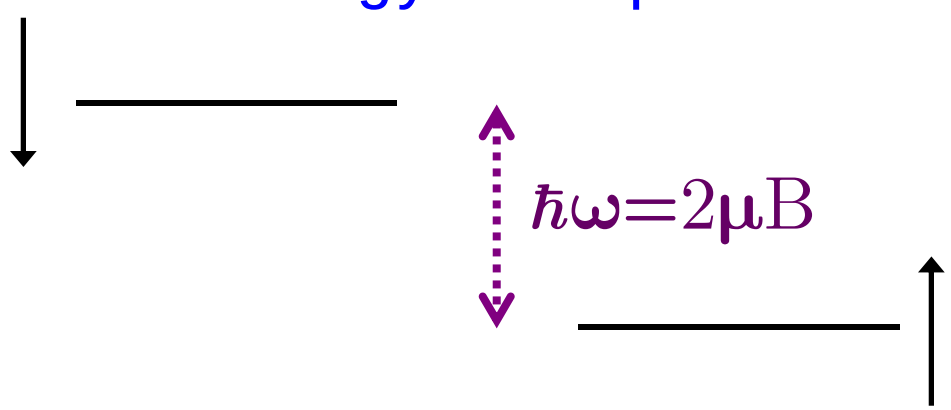
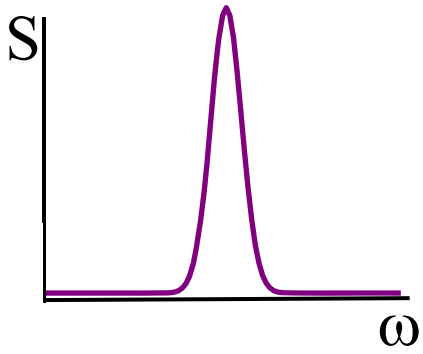


Energy level picture:





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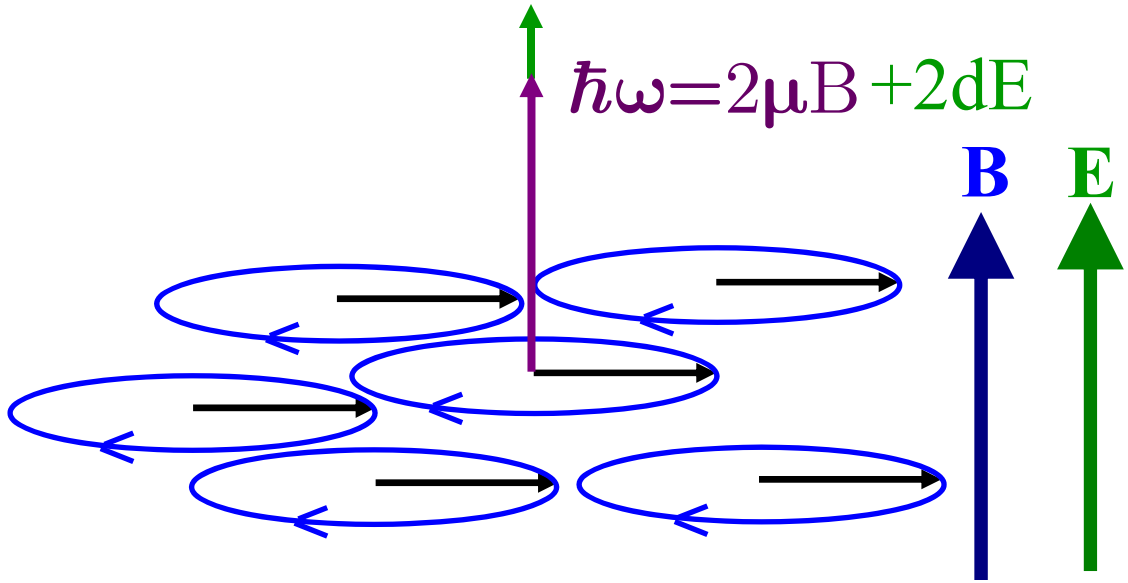

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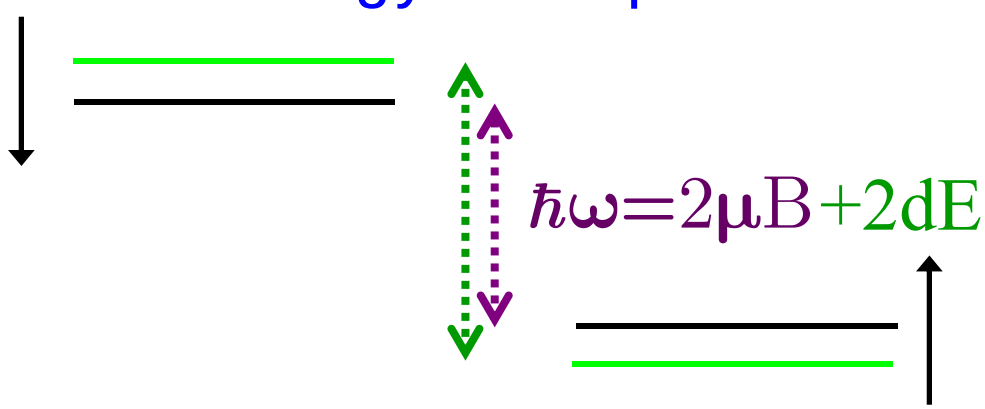

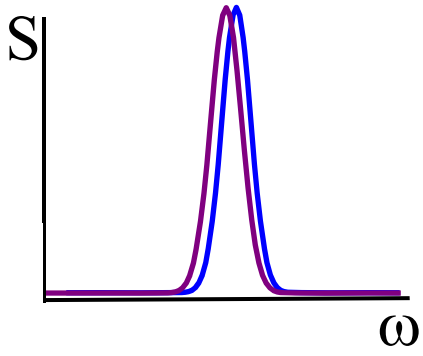

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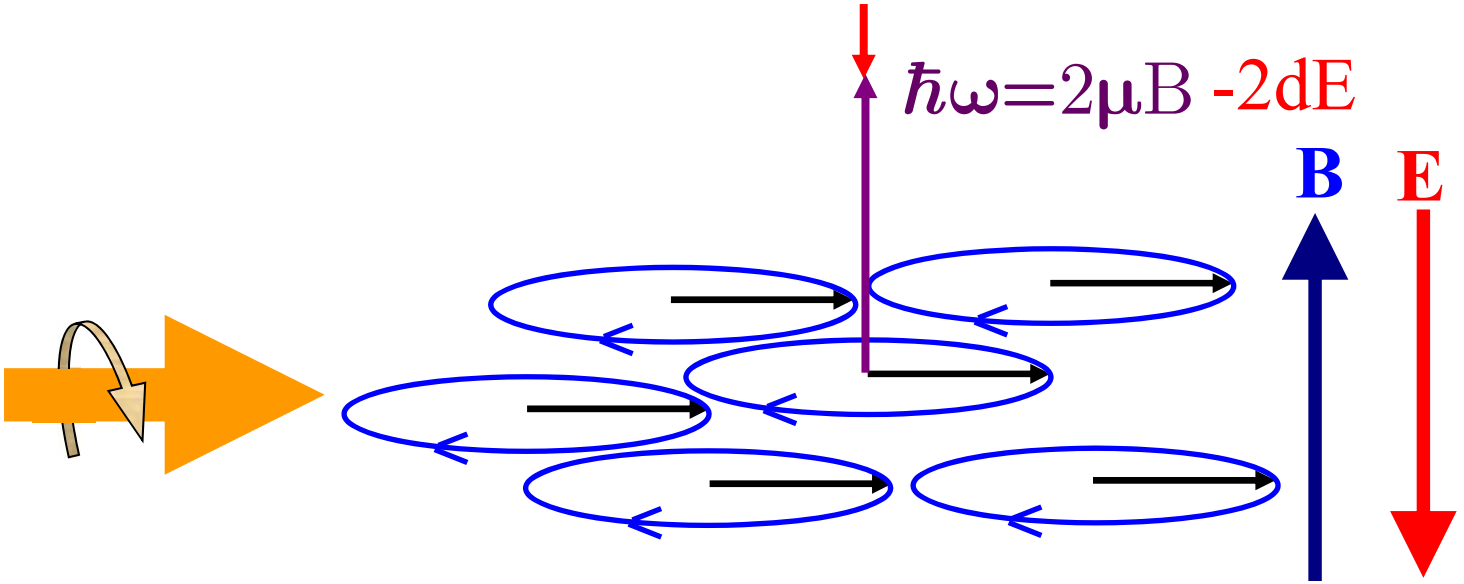

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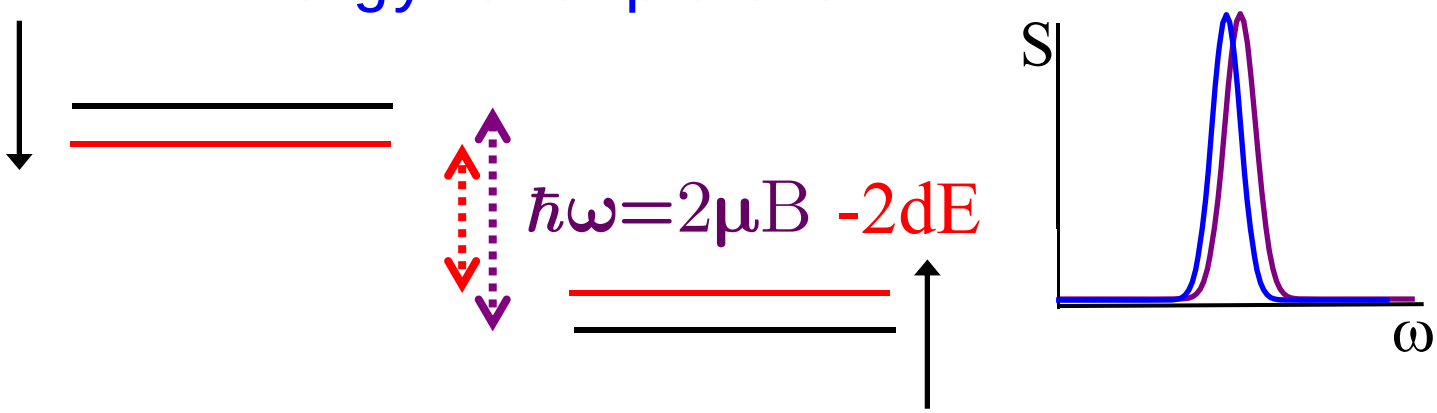

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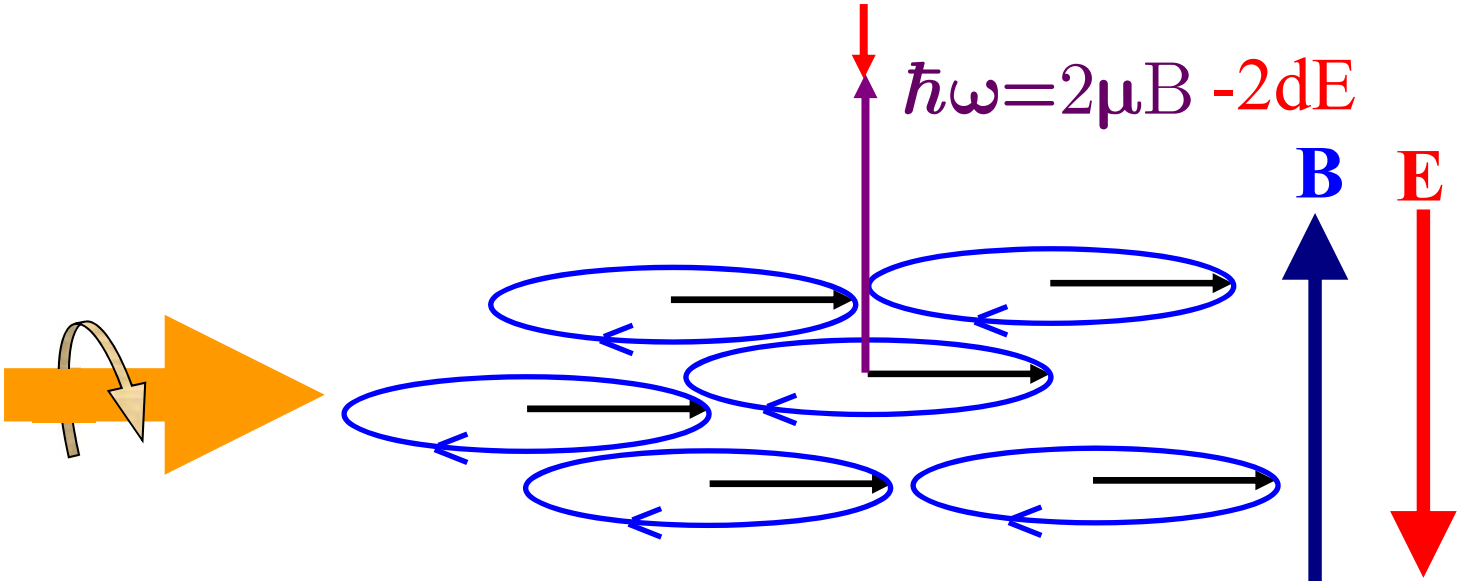

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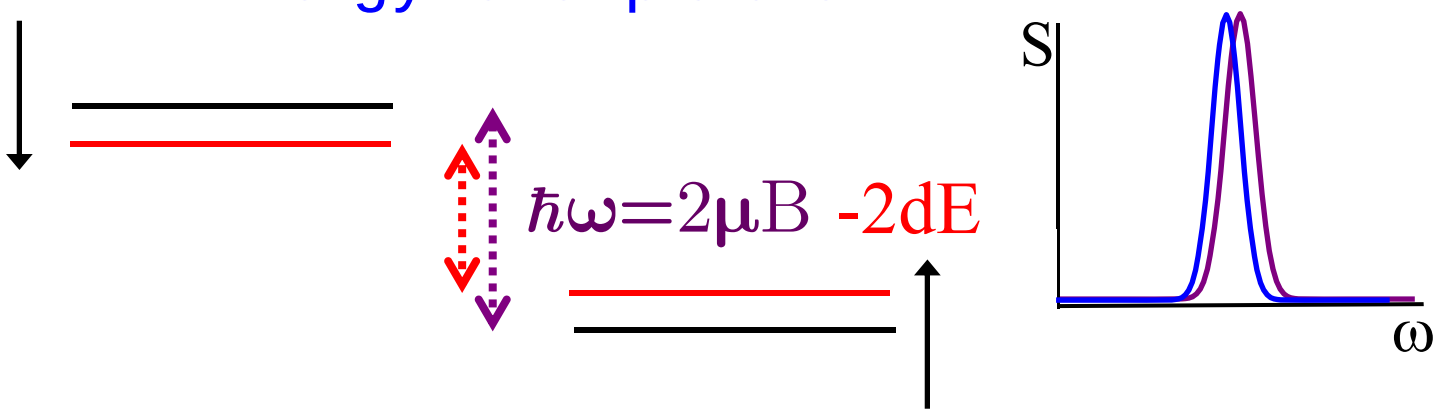

Figure of merit: $\dfrac{shift}{resolution} = \dfrac{d\mathcal{E}}{(\tau_{coh})^{-1}(S/N)^{-1}} \propto \mathcal{E}\cdot\tau_{coh}\cdot\mathcal{C}\cdot\sqrt{\dot{N}\cdot T_{\text{int}}}$

EDMs in the context of quantum science

--**Most EDM experiments use AMO systems & methods:**
tabletop-scale apparatus, modest budget (<$2M)
(EXCEPTION: neutron EDM)

--**EDM spin precession measurements**
have much in common with magnetometric sensors:
broad synergy between these types of experiments

--**EDM frequency measurements**
have much in common with atomic clocks:
broad synergy between these types of experiments

Recent advances & current trends in EDMs

RECENT NEW RESULTS

--Ultra-long spin coherence time for ^{199}Hg Schiff Moment (U. Wash.)
("quark chromo-EDM")

--Enhanced E-field in polar molecules for electron EDM
(Imperial Coll. UK, Yale/Harvard **ACME--ONGOING**)

ONGOING NEW EFFORTS

--Enhanced Schiff Moment with radioactive nuclei
needs ultra-long coherence time, high statistics (ANL, TRIUMF, FRIB)

--Ultra-long coherence time in atoms for e-EDM
laser-cooled & trapped atoms (Penn State)

--Long coherence time AND polar molecules for e-EDM
trapped molecular ions (JILA/U. Colorado)
laser-cooled neutral molecules (Imperial College)

[Also: neutron EDM, not discussed in this context]

Observation/comments about EDMs

Best experiments still "classical" in most respects

--Example: no leading EDM experiment uses laser cooling/trapping!

--Bigger wins so far from "classical" scaling up of statistics/signal size

An opportunity:
Possible advantages from scaling up EDM experiment size
(a la history of experimental particle physics)

--Growing experiment complexity stretches capabilities of historically typical single-PI group efforts

--Example: ACME went from concept to leading result in record time by pooling resources & expertise of 3 PIs
(most other leading experiments now 2+ PIs)

--*Possible advantages to pairing with national labs?*
Complex engineering & design now done by Ph.D. students,
automation insufficient to run for more than weeks,
better statistics or coherence time from brute size scaling, etc.

Observations/comments about EDMs

Intriguing opportunities from ongoing advances in quantum science

***Possible* big improvements from:**

- **laser cooled & trapped molecules** [e-EDM, Schiff]
  to combine ultra-long coherence time & enhanced E-field
- **Spin squeezing for sub-shot noise sensitivity** [e-EDM, Schiff]
  [a la recent advances in atomic clock systems: $\propto N$ vs. $\propto\sqrt{N}$]
- **Laser cooled & trapped molecules with deformed nuclei**
  enhancement^2...! [Schiff]

Technical & conceptual synergies with other related "quantum"-style fundamental experiments

- Light axion searches
- Tests for dynamic scalar fields from varying "constants", etc.

Summary: challenges and opportunities for EDM experiments*

GRAND CHALLENGE:

improved sensitivity EDM experiments to search for new CP-violating physics at PeV scale

OPPORTUNITIES:

--partnering with national labs to scale up experiments

--invest in application of quantum technologies to EDM-sensitive systems:

- Spin squeezing
- Laser cooling & trapping of “exotic” species
- Large-volume traps
- Etc.