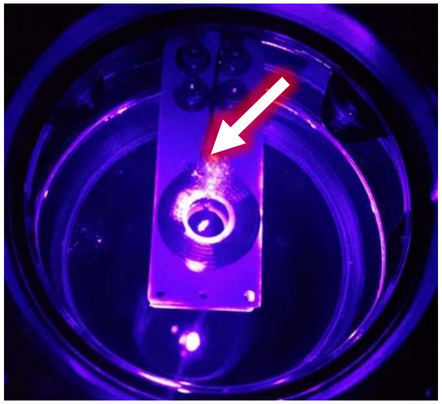
Physics Beyond the Standard Model with Polar Molecules

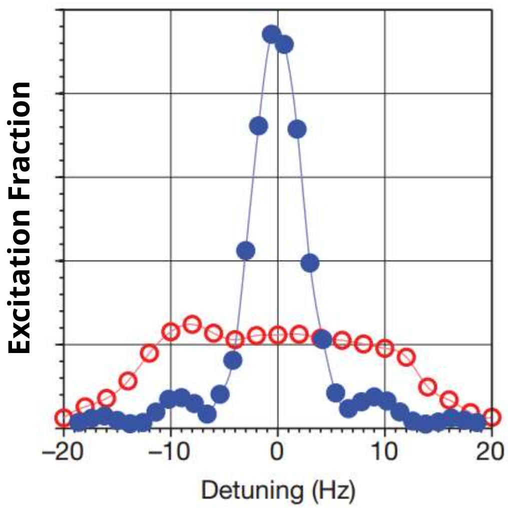
Nick Hutzler
Caltech

High precision

- Techniques to probe atoms and molecules enable extreme precision and control
  - Cooling/trapping
  - Long interaction times
  - Controlled environment

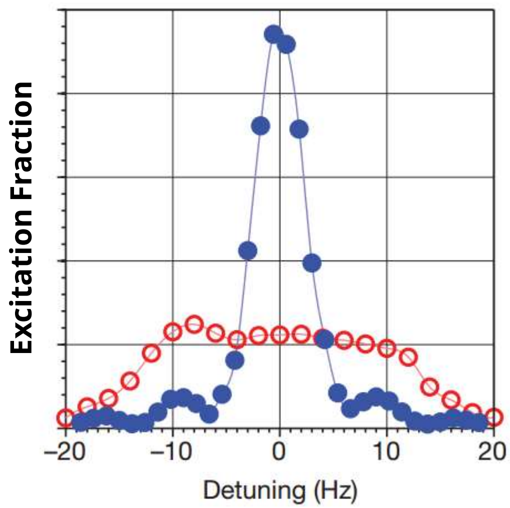


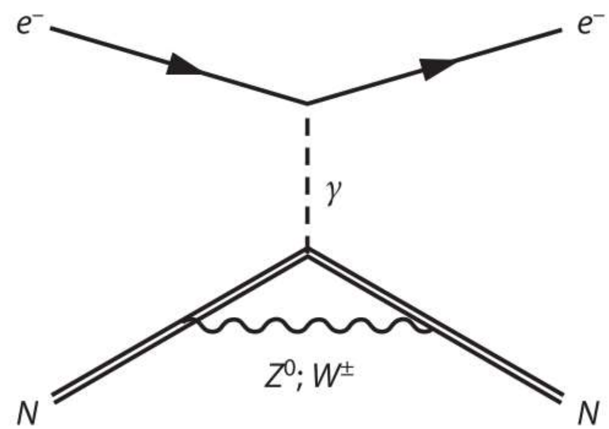
High precision…



B. J. Bloom *et al.,* Nature **506**, 71 (2014)

High precision… high energy





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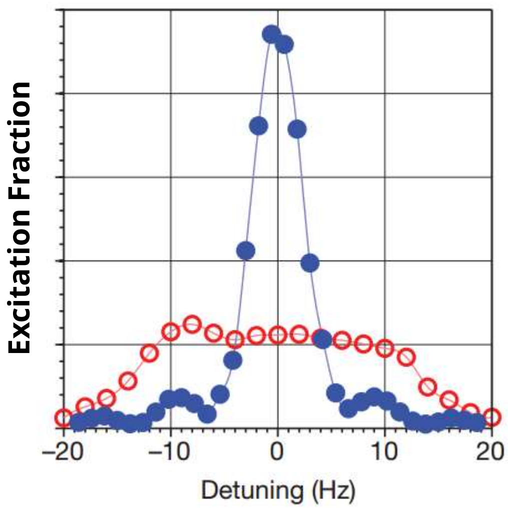
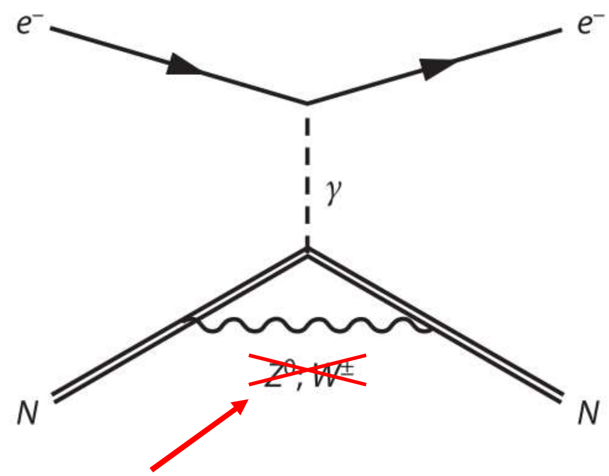




New physics?

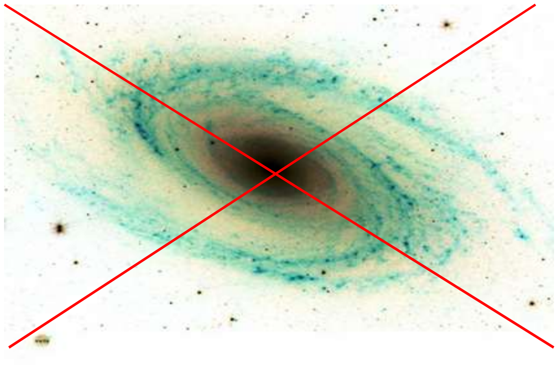
Supersymmetry, axions, Lorentz violation, new forces, …

B. J. Bloom *et al.*, Nature **506**, 71 (2014)

I. Introduction
II. Motivation
III. Experiments
IV. Implications
V. Future Work

Baryon Asymmetry

- The universe is made of matter
  - Which processes favor matter over anti-matter?
  - How can we study this?



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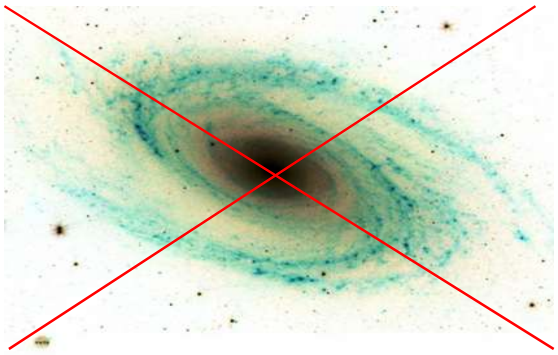

- One requirement: CP violation
  - C: $+q \leftrightarrow -q$
  - P: $+\vec{r} \leftrightarrow -\vec{r}$

A. D. Sakharov, JETP Lett. **5**, 27 (1967)

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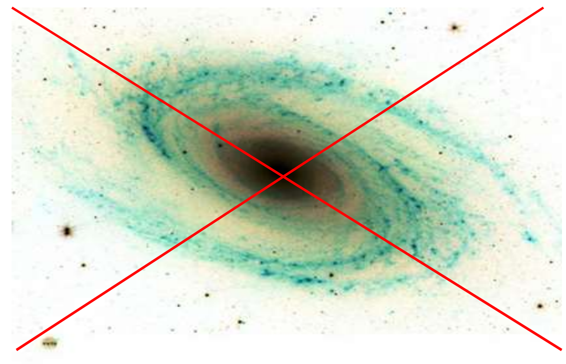

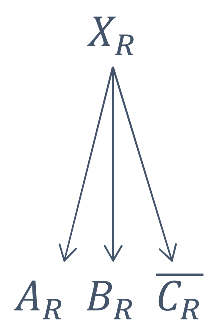

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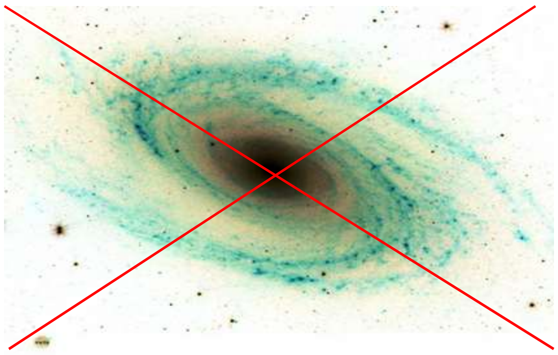

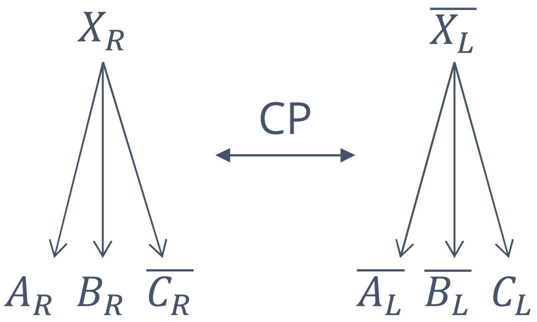

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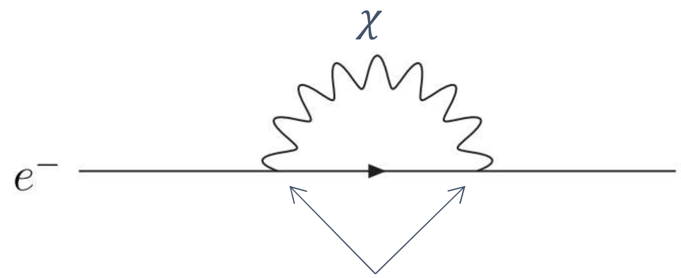
CP Violation

- CP violation exists in the Standard Model
  - Weak-quark interactions, mesons
  - Not enough!
- New particles, forces can violate CP



CP violating interaction

CP Violation

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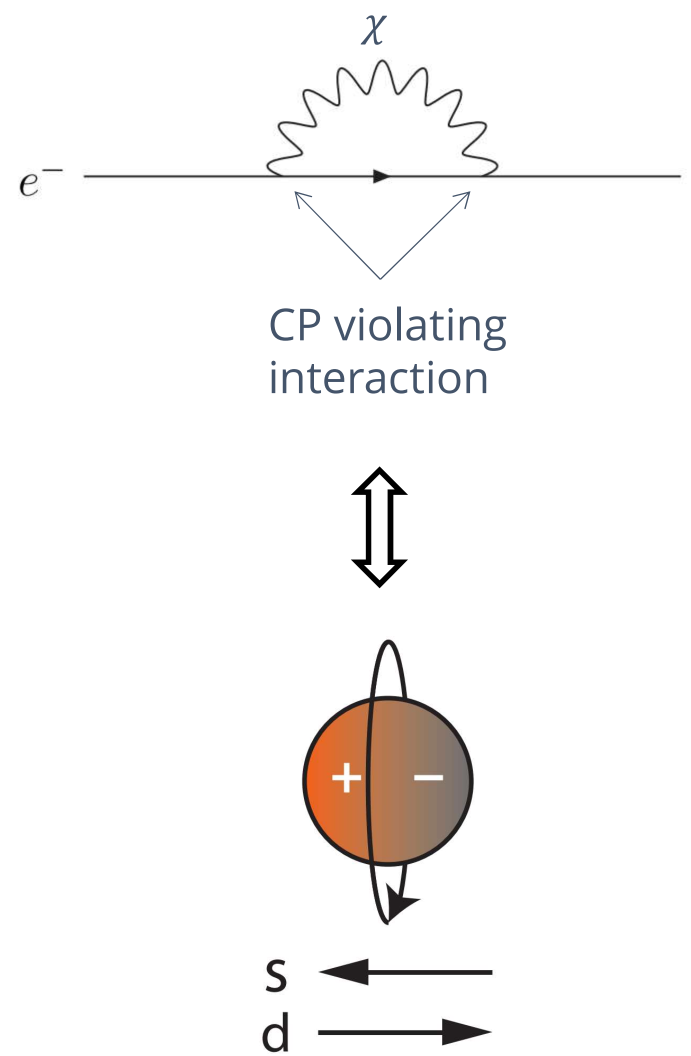
- Generates permanent electric dipole moments (EDMs)



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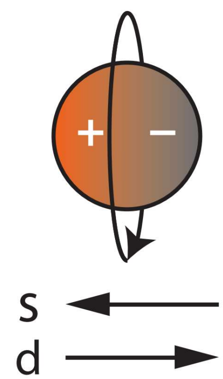

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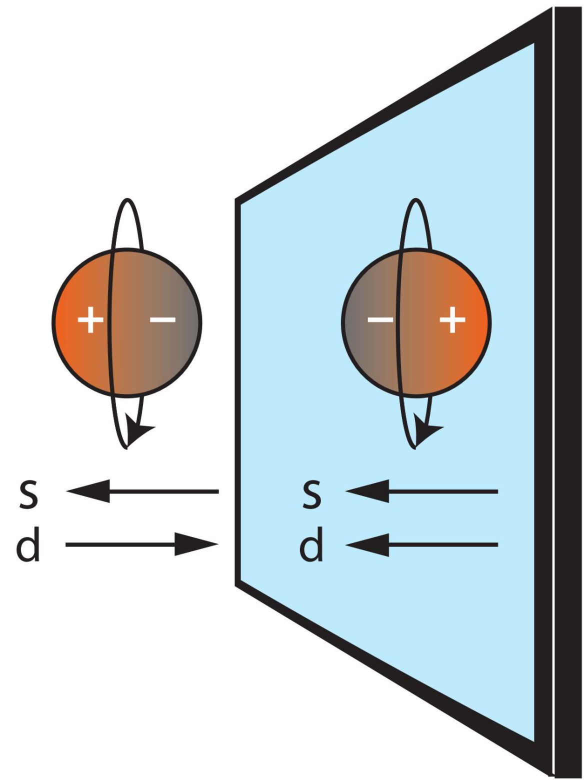

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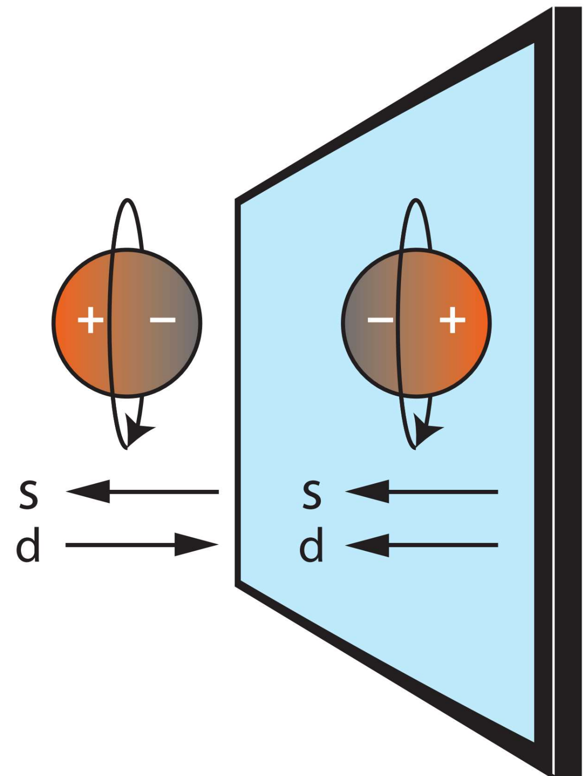

$\neq$

EDMs violate P, T, CP*

(*Assuming conservation of CPT…)

New Lab @ Caltech

Caltech, Downs/Lauritsen building, first floor

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- Sensitive, background-free probe for new physics
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B. Regan *et al.*, PRL **88**, 18 (2002)   J. J. Hudson *et al.*, Nature **473**, 493 (2011)

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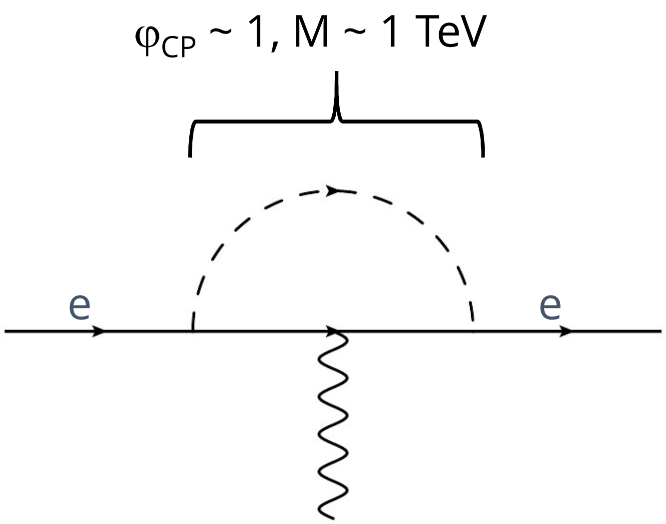

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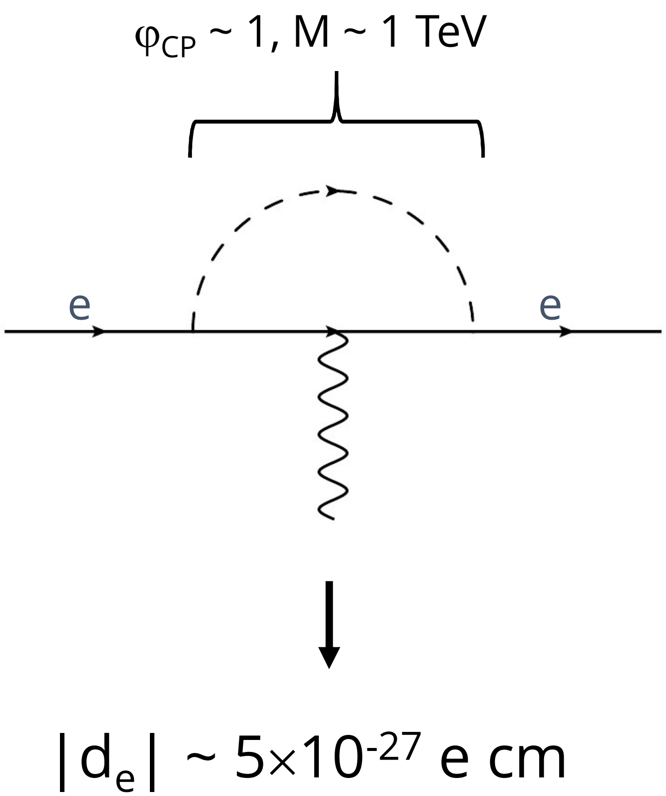

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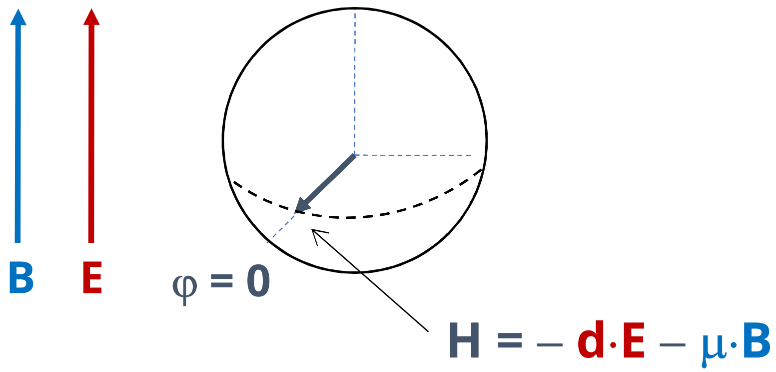

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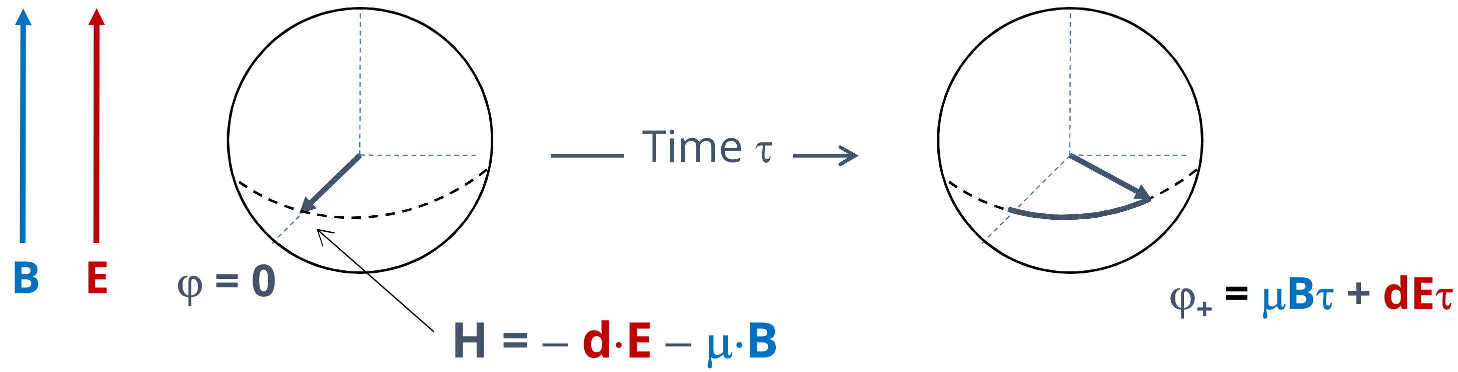

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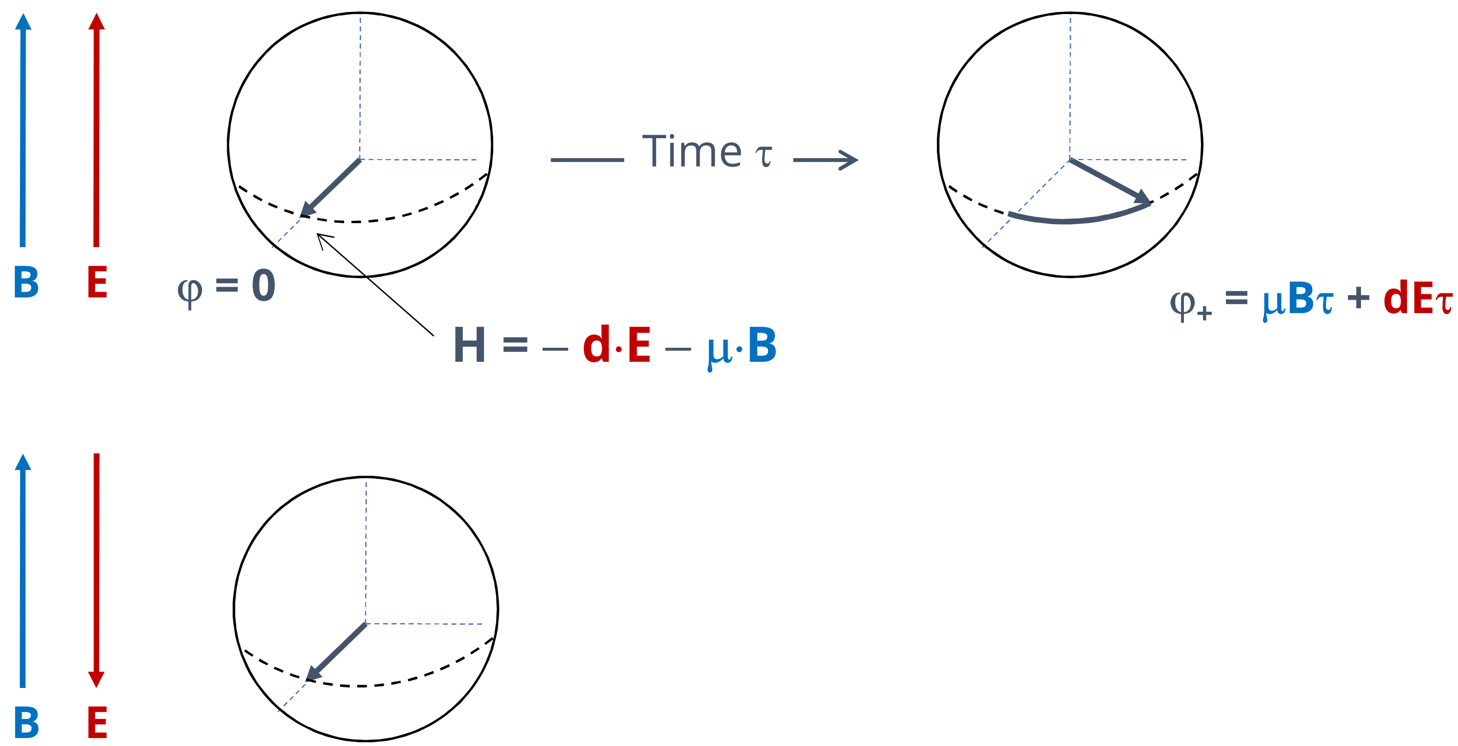

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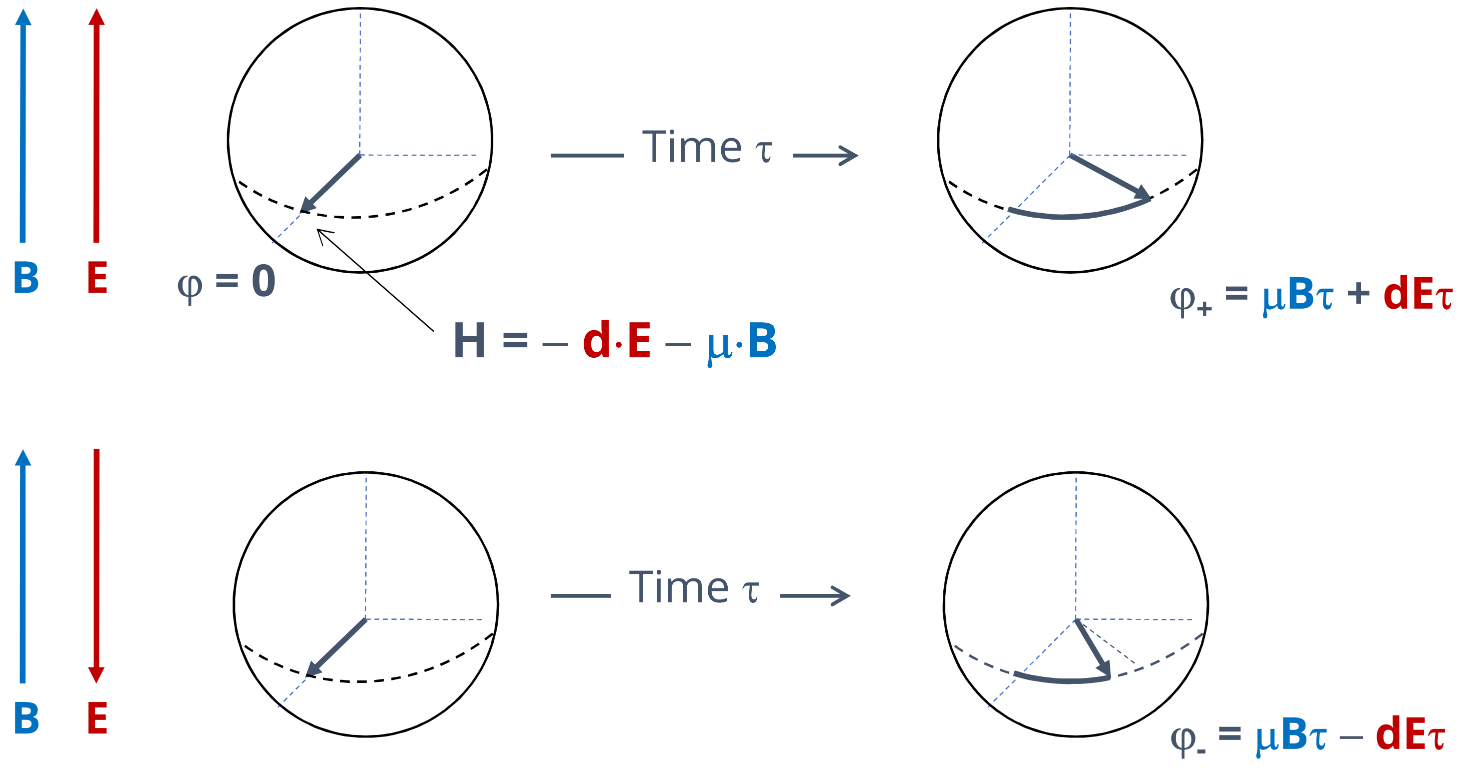

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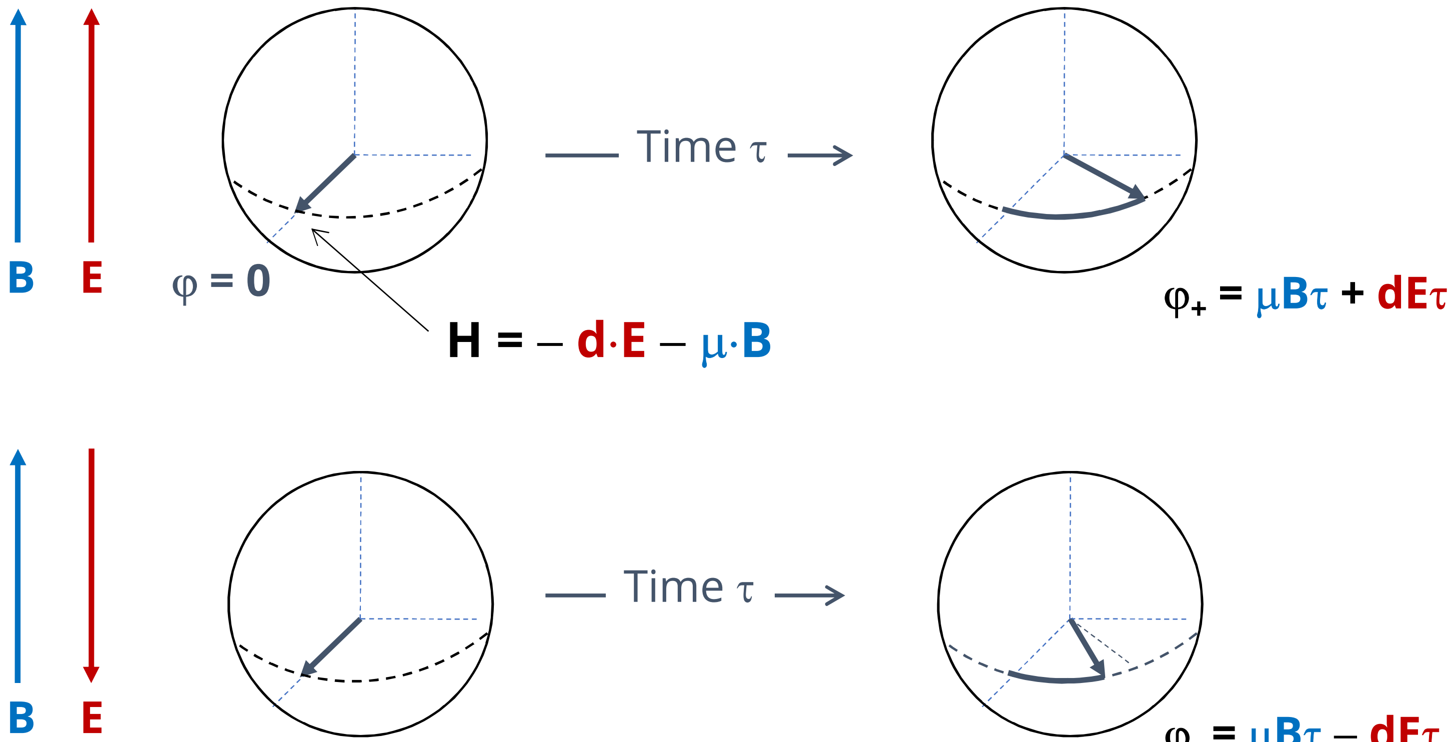

$$\Delta\varphi \propto dE\tau$$

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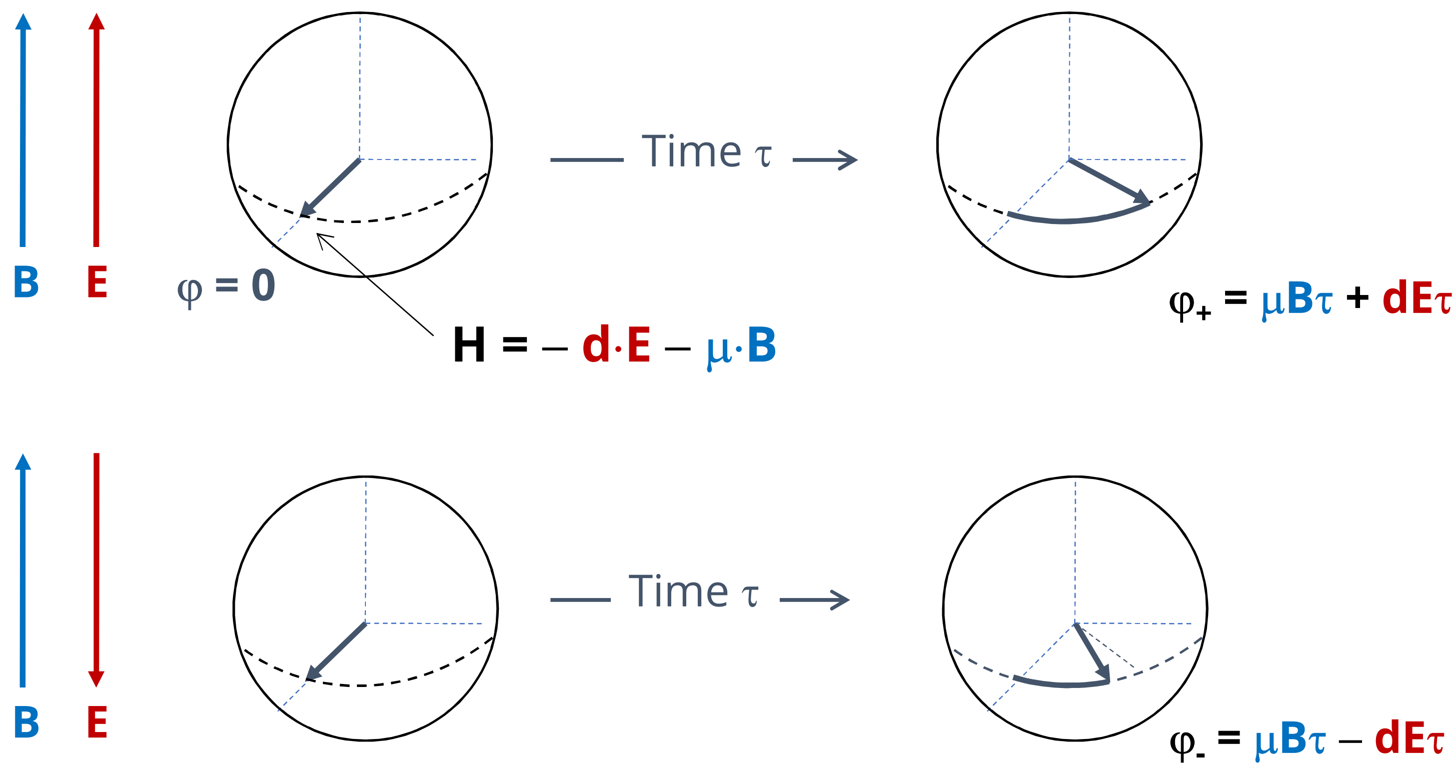


Spin precession!

$$\Delta\varphi \propto dE\tau$$

Sensitivity

- Measure $\Delta\varphi \propto dE\tau$
  - Want large E, large τ

Sensitivity

- Measure $\Delta\varphi \propto dE\tau$
  - Want large E, large τ
- Shot-noise limited uncertainty

$$\delta d_{\mathrm{e}} = \frac{\hbar}{2\mathcal{E}_{\mathrm{eff}}\tau\sqrt{N}}$$

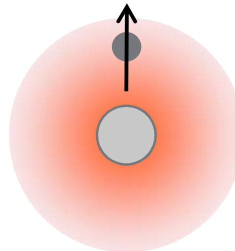
Total counts

Effective electric field

Coherence time

Electric field?

- Atoms/molecules have huge fields!
  - $e/4\pi\epsilon_0 a_0^2$ ~ GV/cm
  - Relativistic ~ Z^3 enhancement



Electric field?

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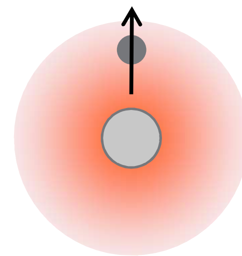

$$\langle \vec{d}_e \cdot \vec{\mathcal{E}} \rangle = 0$$

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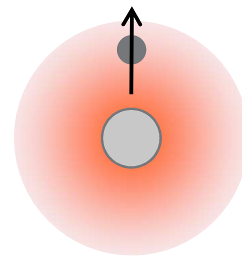
  - $H = -\vec{d}_e \cdot \vec{\mathcal{E}}_{eff}$



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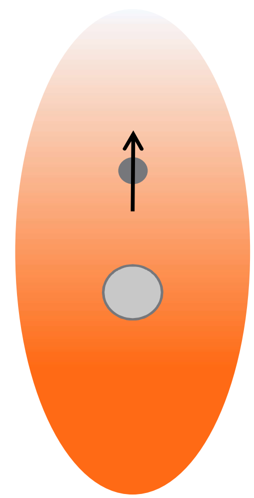

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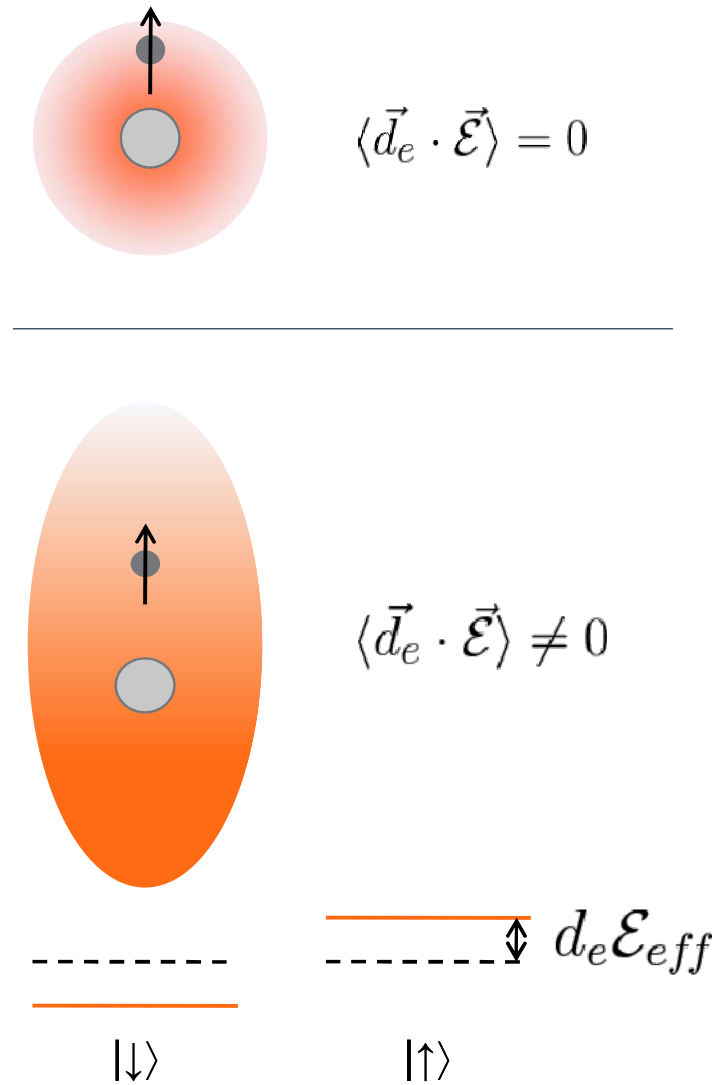

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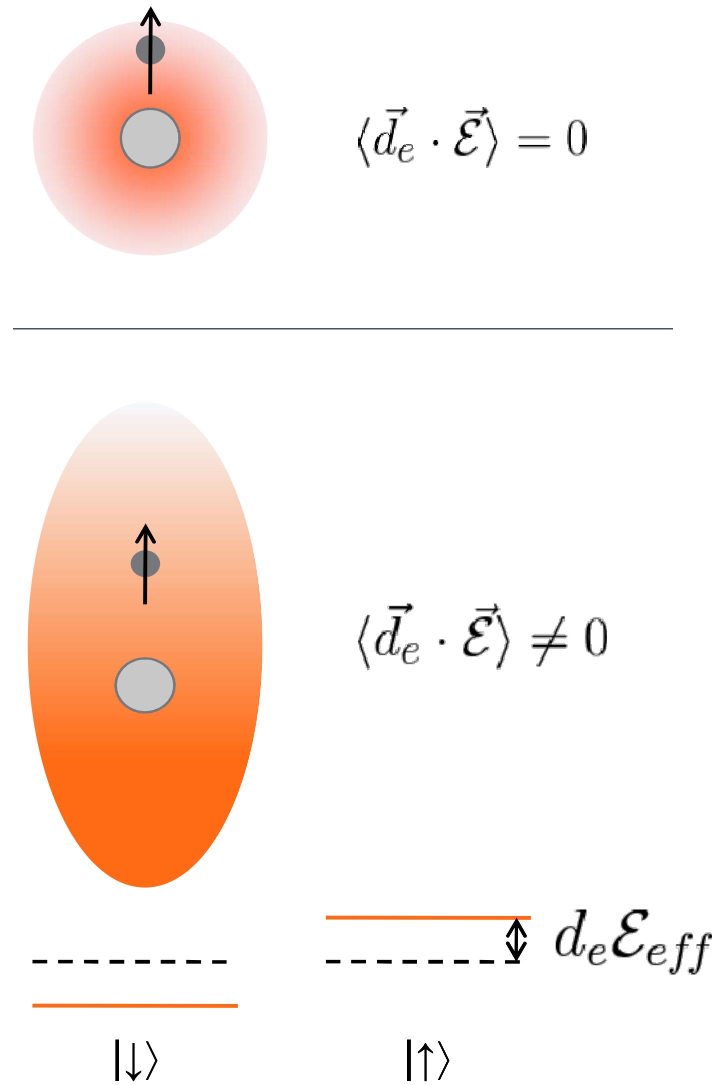
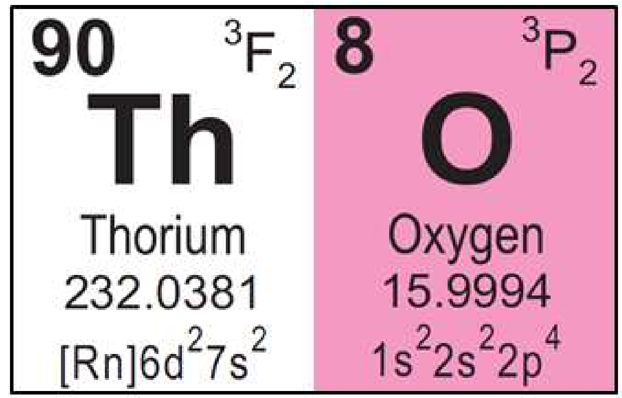
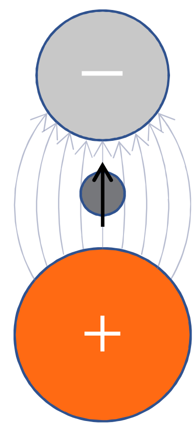
- Must be polarized!
  - Atoms ~ 10^{-3}
  - Molecules ~ 1



ACME Molecule: ThO

- Metastable, EDM-sensitive electronic state
  - $\tau \approx 2$ ms
  - $E_{eff} = 78$ GV/cm
  - Completely polarize with 10 V/cm
  - Internal co-magnetometer





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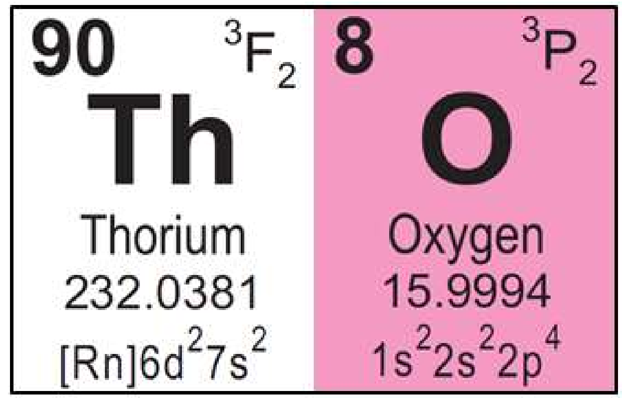

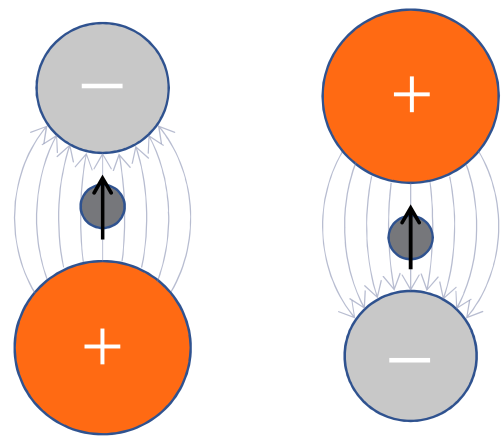

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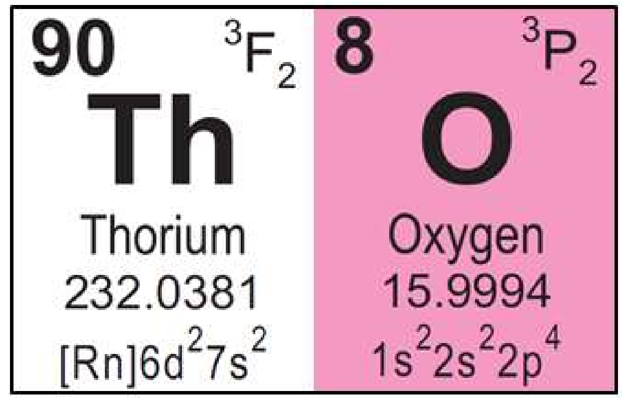
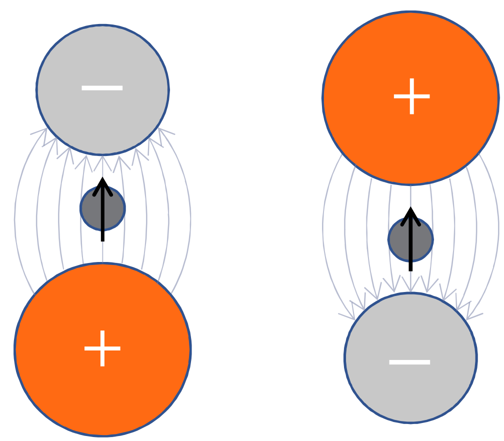
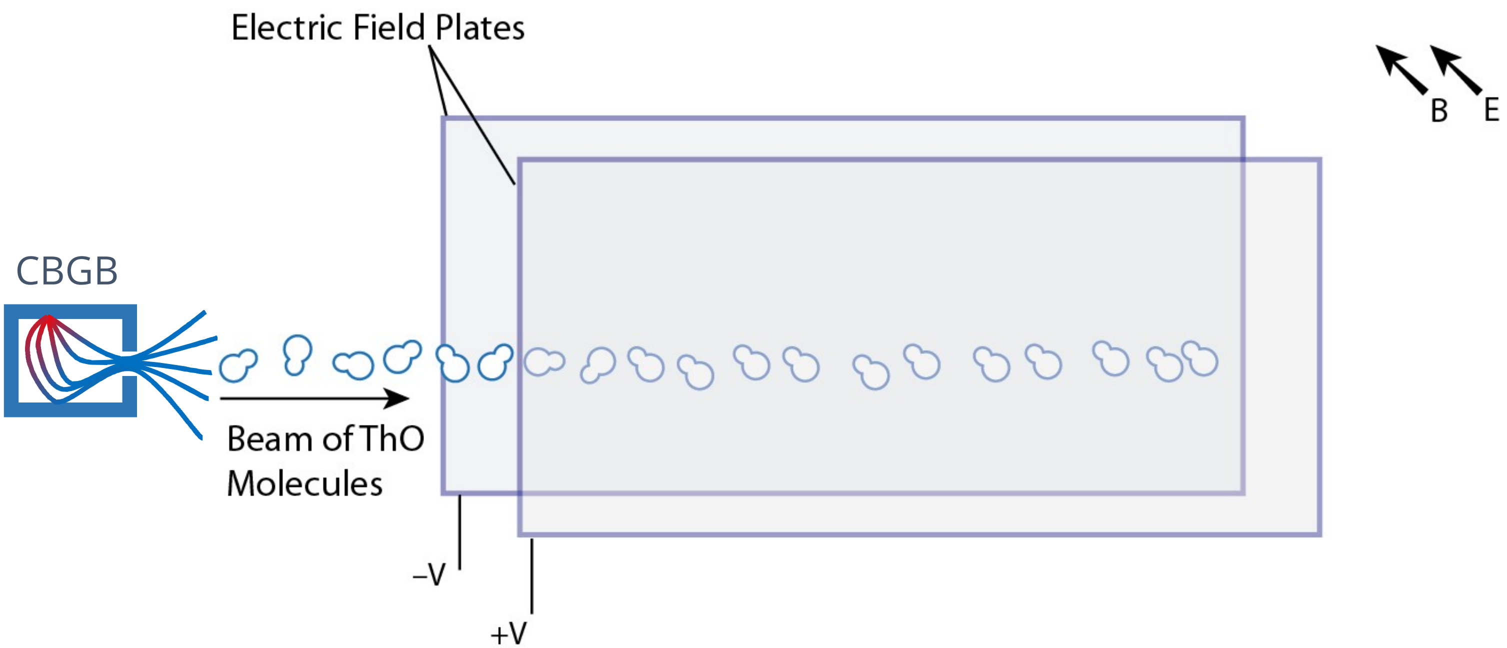
  - Internal co-magnetometer
- Refractory, reactive
  - $T_{melt} \sim 3{,}400\ ^{o}C$
  - Create with cryogenic buffer gas beam (CBGB)





N. R. Hutzler, H.-I. Lu, and J. M. Doyle, Chem. Rev. **112**, 4803 (2012)

Apparatus Overview



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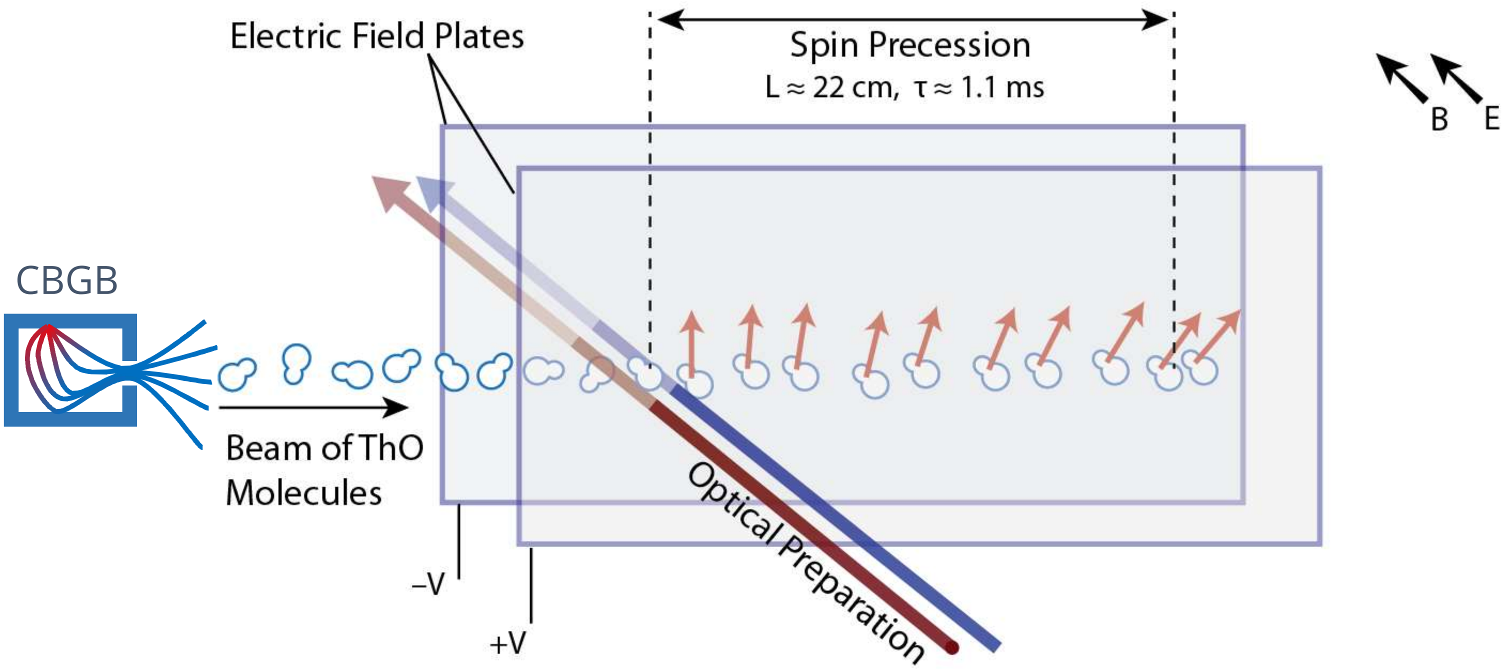

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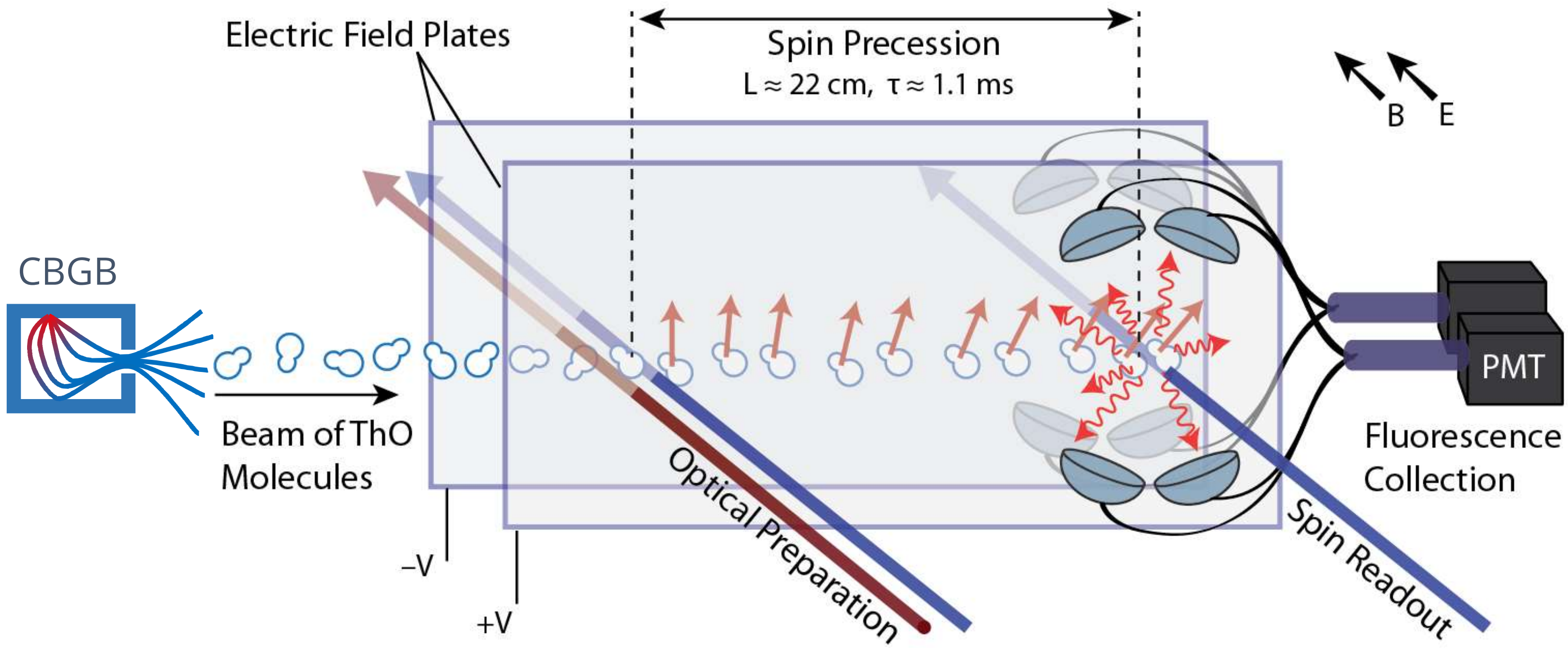
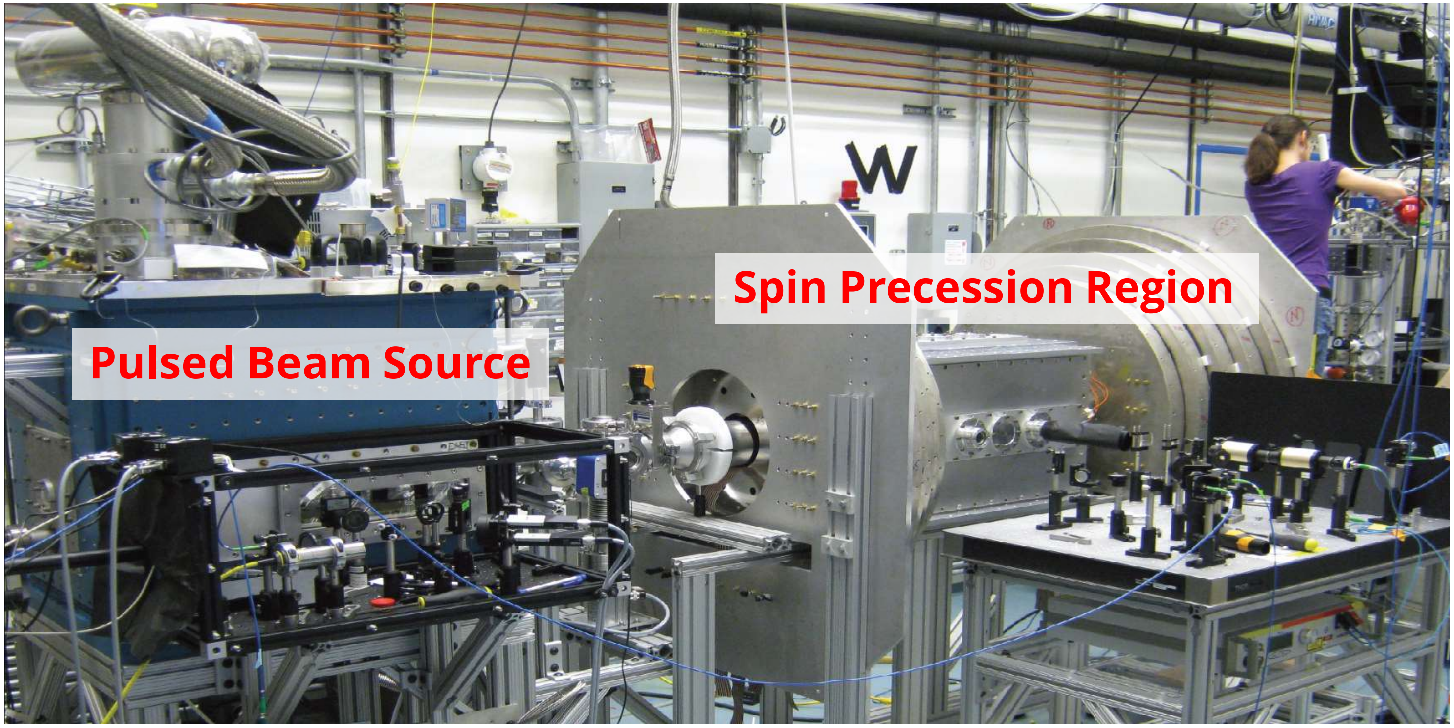
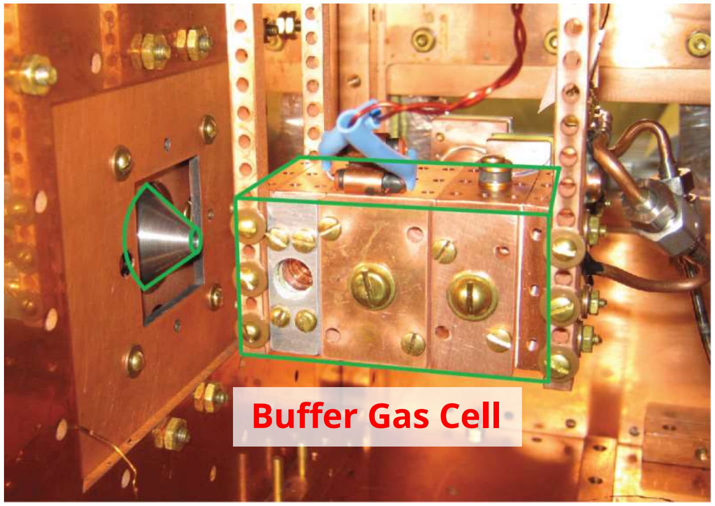
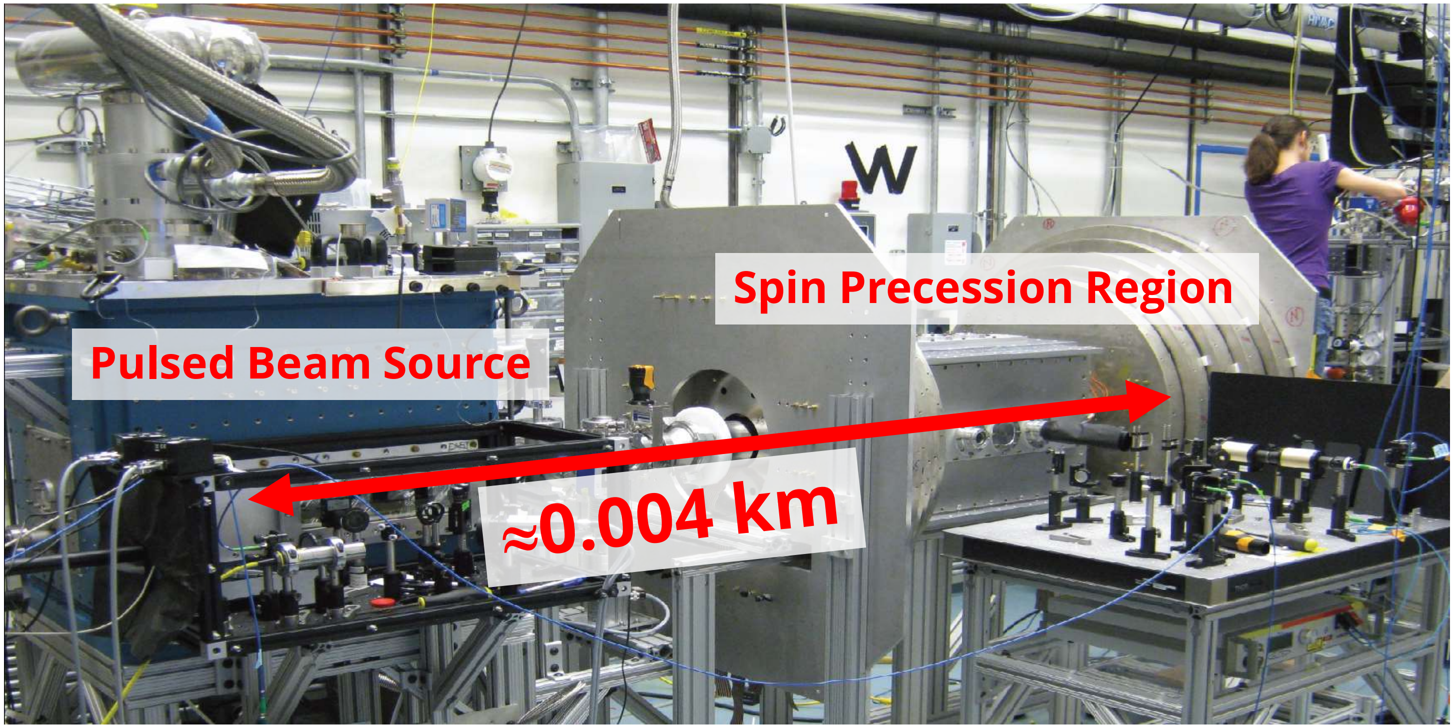
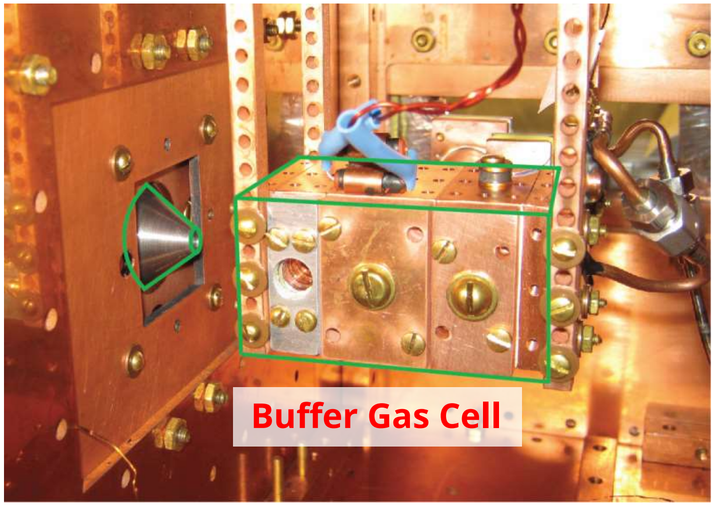



Pulsed Beam Source
Spin Precession Region


Buffer Gas Cell


Fluorescence Collection

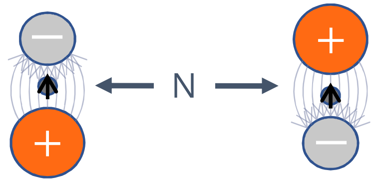

Spin Precession Region
Pulsed Beam Source
≈0.004 km


Buffer Gas Cell


Fluorescence Collection

Isolating the EDM – “Switches”

- All terms in the Hamiltonian (phases) have distinct behavior under reversal of:
  - N - Molecule dipole orientation
  - E - External electric field
  - B - External magnetic field



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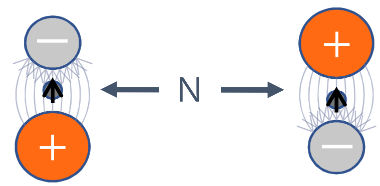

- Look for correlations between experiment states

Quantity	N-flip	E-flip	B-flip
Electron EDM	–	–	+
Applied B field	+	+	–

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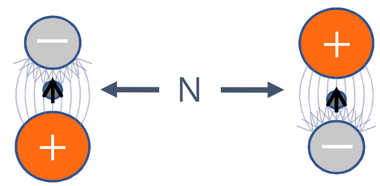

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Applied B field	+	+	–
Background B field	+	+	+
Leakage current/v x E/Geometric phases	+	–	+
etc…			

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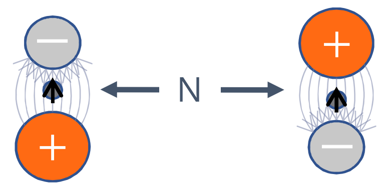

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Common source of experimental problems
Only available with co-magnetometer

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  - $|d_e| < 9.6 \times 10^{-29}$ e cm
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- Current status: working on generation II
  - Count rate up by ~500
  - Integrating and checking for systematics – stay tuned!

ACME Collaboration: Baron et al., Science **343**, 269 (2014)

www.electronedm.info

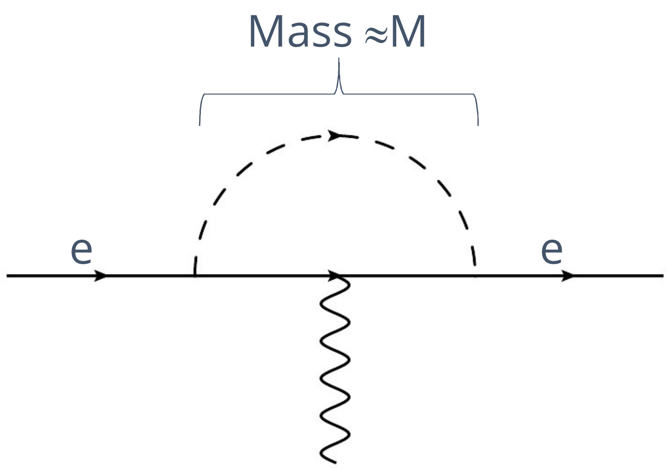
ACME Collaboration (Gen I)

- Harvard University
  - Jacob Baron [→ Harvard]
  - Wes Campbell [→ UCLA]
  - Yulia Gurevich [→ Heidelberg]
  - Paul Hess [→ Middlebury]
  - NH [→ Caltech]
  - Cris Panda
  - Max Parsons [→ Oculus]
  - Elizabeth Petrik-West [→ UCLA]
  - Ben Spaun [→ Honeywell]
  - **Prof. John Doyle**
  - **Prof. Gerald Gabrielse**

- Yale University
  - Emil Kirilov [→ Innsbruck]
  - Ivan Kozyryev [→ Harvard]
  - Brendon O'Leary [→ SeatGeek]
  - Adam West [→ UCLA]
  - Amar Vutha [→ Toronto]
  - **Prof. David DeMille**

- Funding
  - NSF
  - NIST Precision Measurement Grant

What does this mean?



J. Engel, M. J. Ramsey-Musolf, and U. van Kolck, Prog. Part. Nucl. Phys. **71**, 21 (2013)

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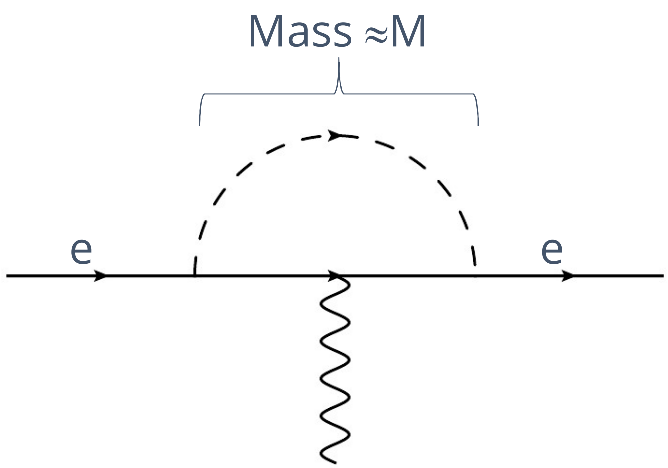

$$d_e \approx \sin(\phi_{CP}) \left(\frac{1\,TeV}{M}\right)^2 \times 5 \times 10^{-27} e\ cm$$

$$\Rightarrow \mathbf{M} \gtrsim (\mathbf{7\ TeV}) \times \sqrt{\mathbf{sin}(\boldsymbol{\phi}_{\boldsymbol{CP}})}$$

Probing ~few TeV energy scales
for ***generic*** CPV particles

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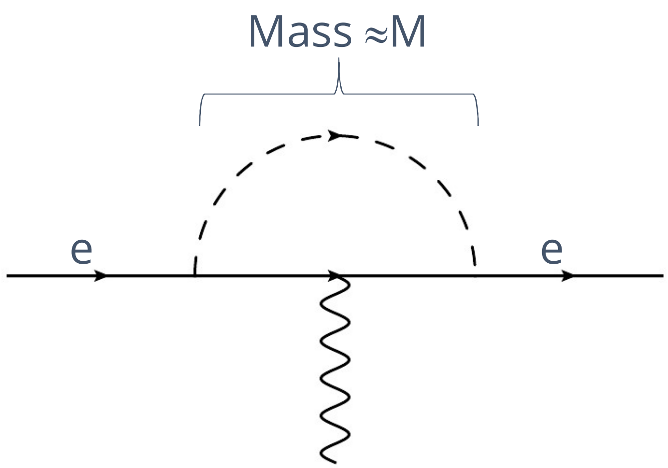

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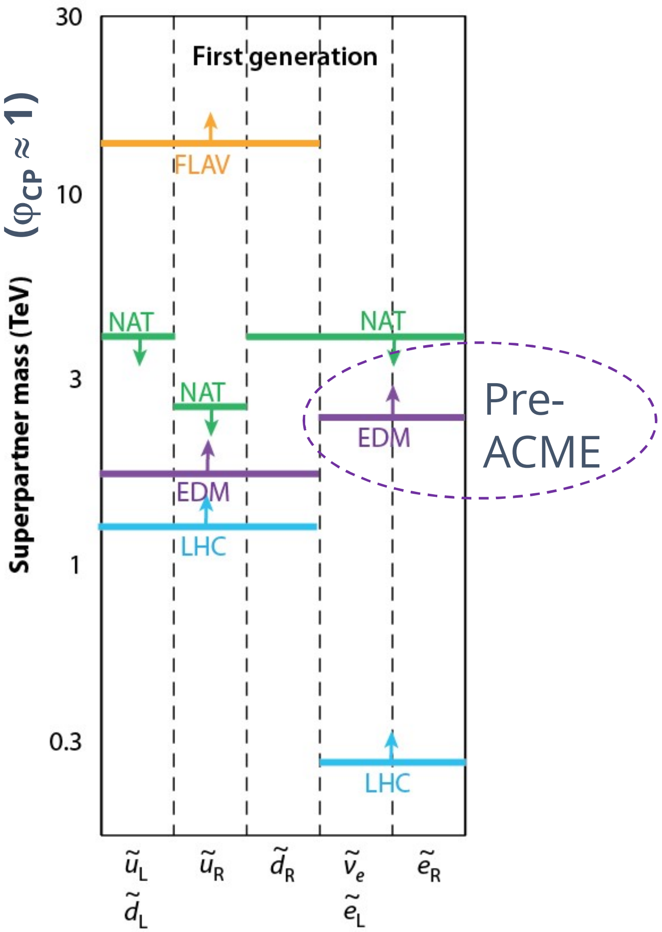

J. L. Feng, Annu. Rev. Nucl. Part. Sci. **63**, 351 (2013)
J. Engel, M. J. Ramsey-Musolf, and U. van Kolck, Prog. Part. Nucl. Phys. **71**, 21 (2013)

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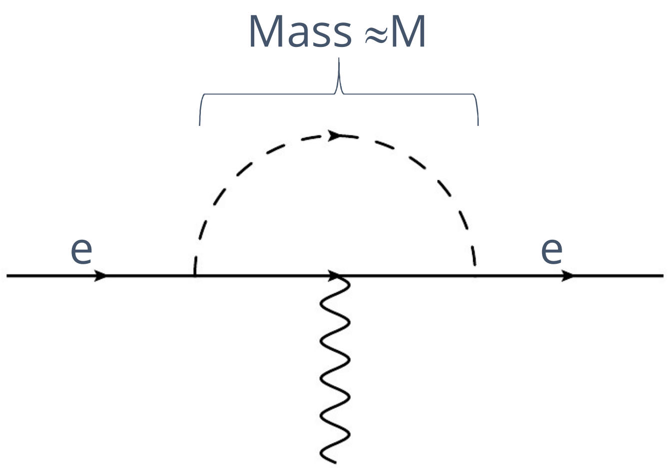

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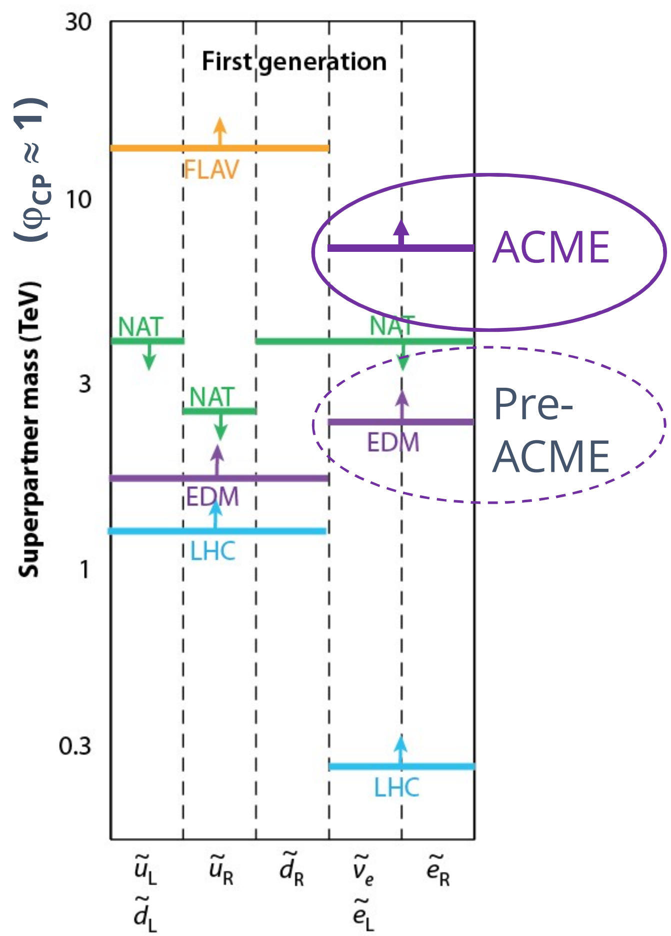
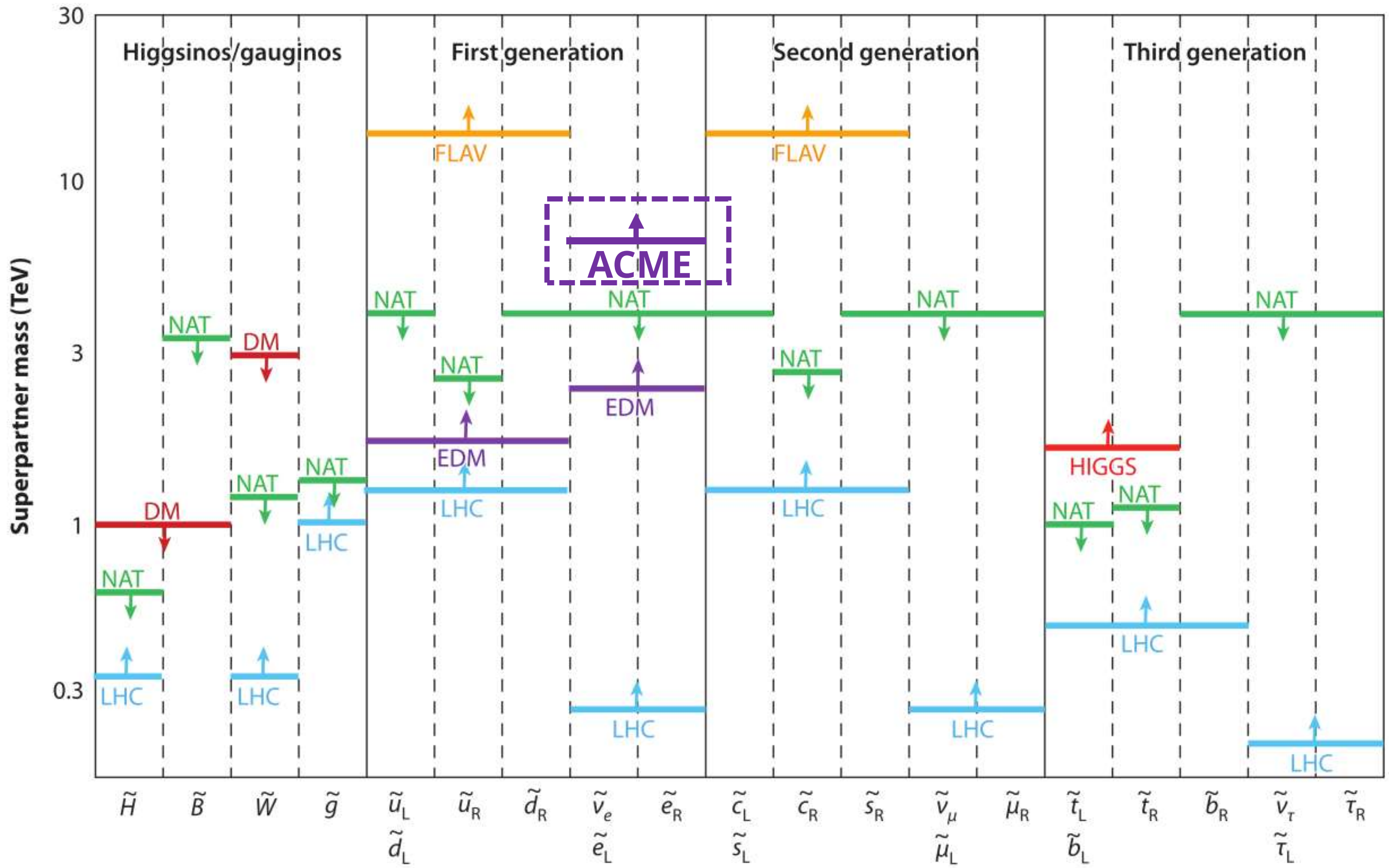


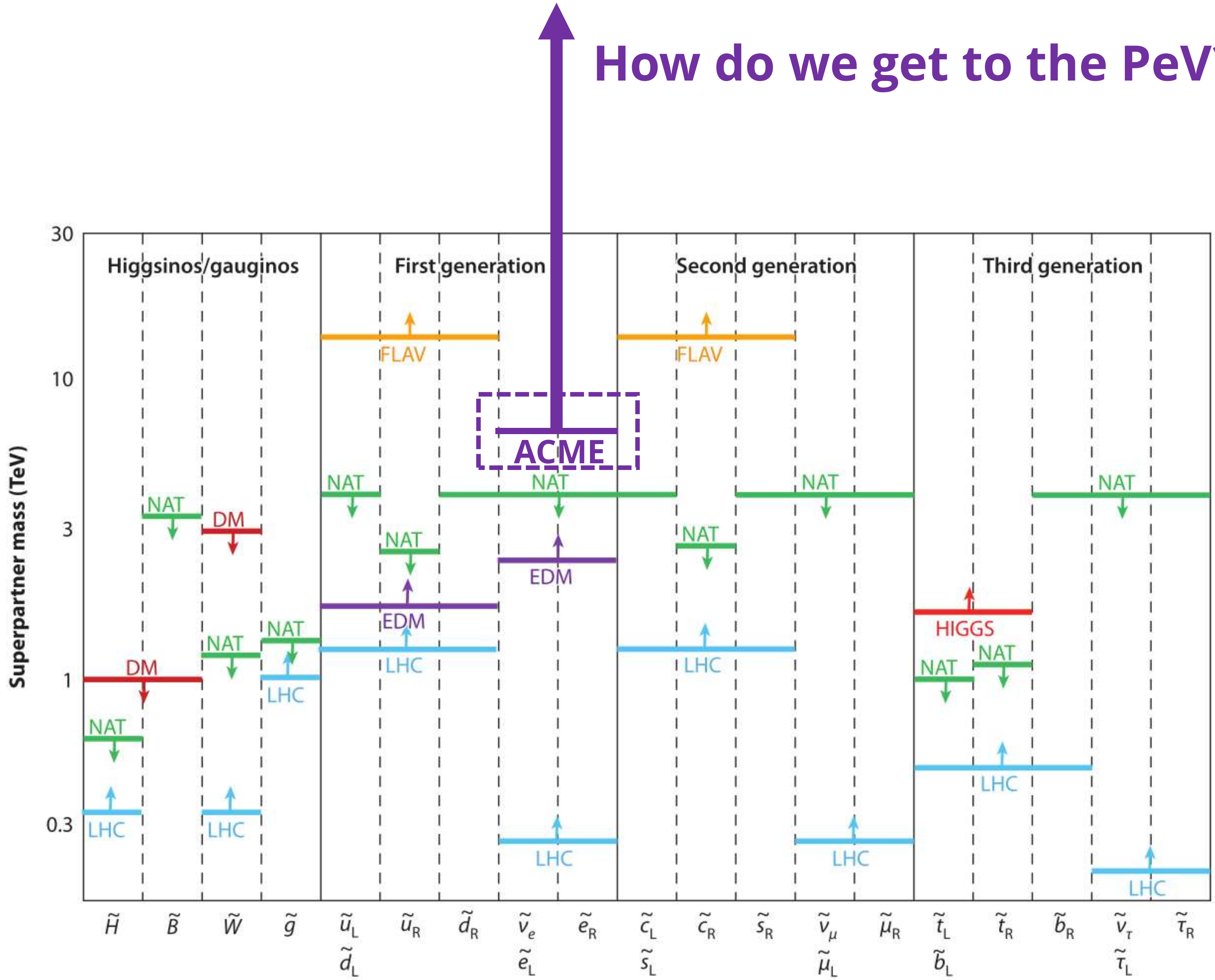
J. L. Feng, Annu. Rev. Nucl. Part. Sci. **63**, 351 (2013)
J. Engel, M. J. Ramsey-Musolf, and U. van Kolck, Prog. Part. Nucl. Phys. **71**, 21 (2013)

Many ingredients…

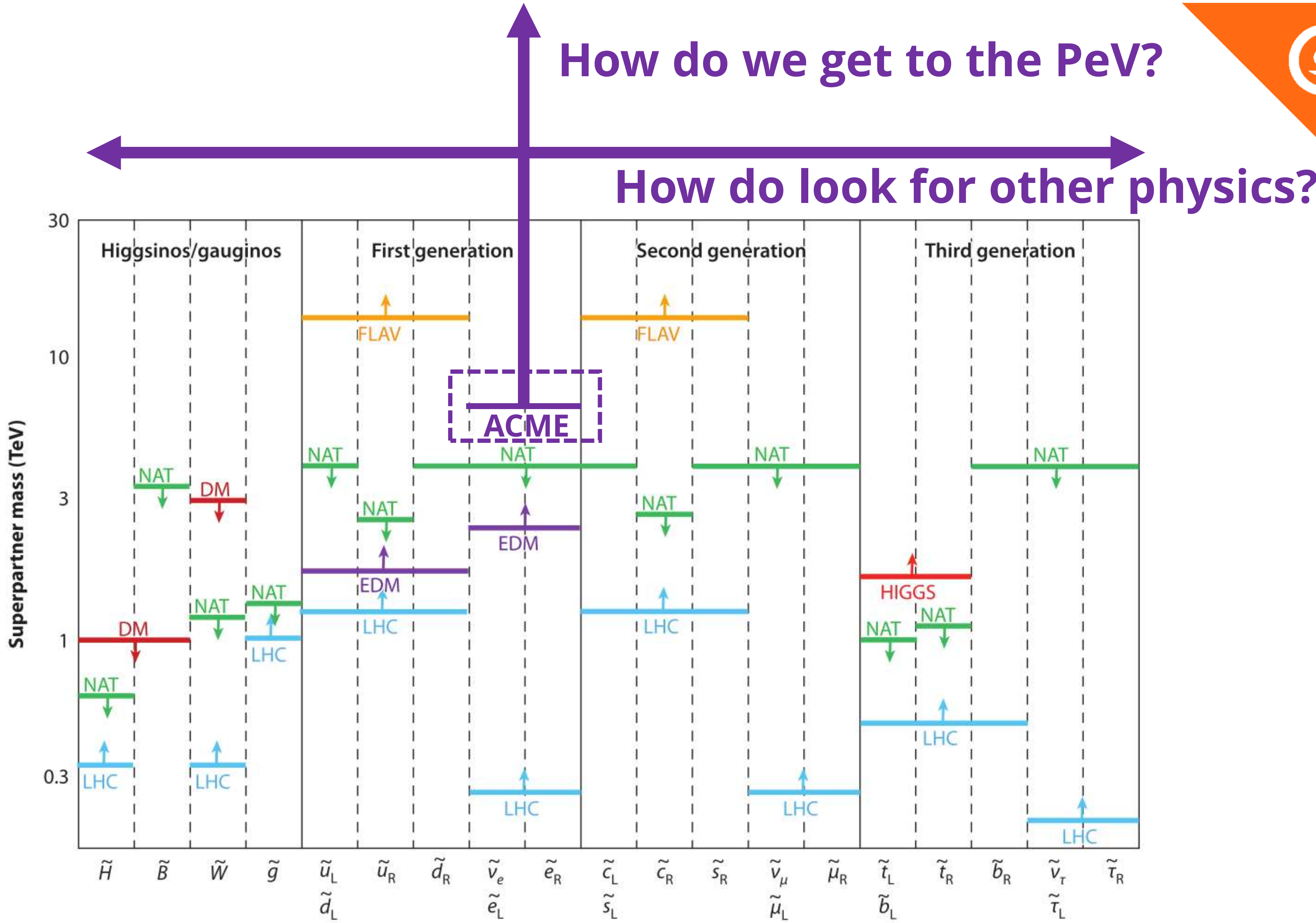


J. L. Feng, Ann. Rev. Nucl. Part. Sci. **63**, 351 (2013)

How do we get to the PeV?



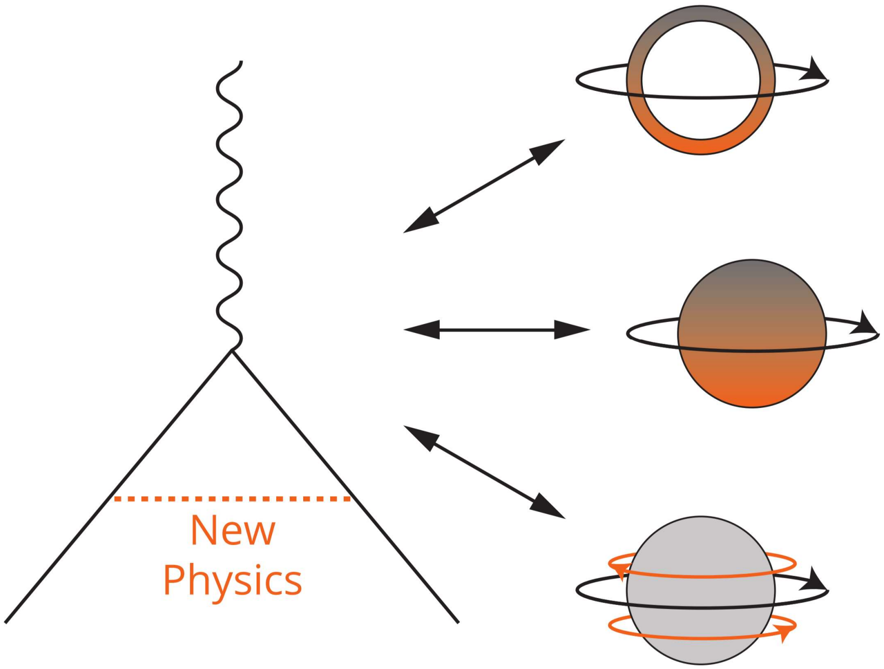
J. L. Feng, Ann. Rev. Nucl. Part. Sci. **63**, 351 (2013)



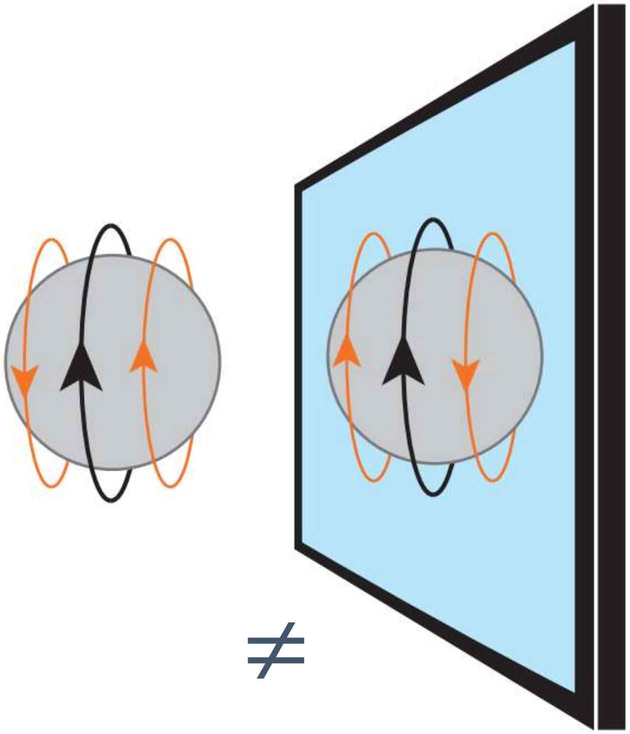
J. L. Feng, Ann. Rev. Nucl. Part. Sci. **63**, 351 (2013)

Symmetry violation in Molecules

- Molecules have enhanced sensitivity to *many* BSM sources
  - Electron EDM
  - Nuclear Schiff moment
  - Nuclear magnetic quadrdupole moment (MQM)
  - PV/anapole moments
  - … and more!
- Let's apply our methods to new sources



Magnetic quadrupole moment (MQM)

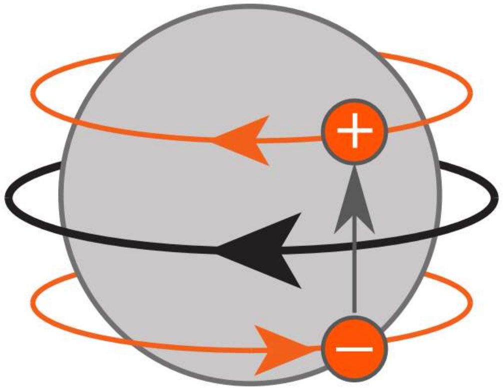


MQMs violate P, T, CP*

(*Assuming conservation of CPT…)

Physical Origin

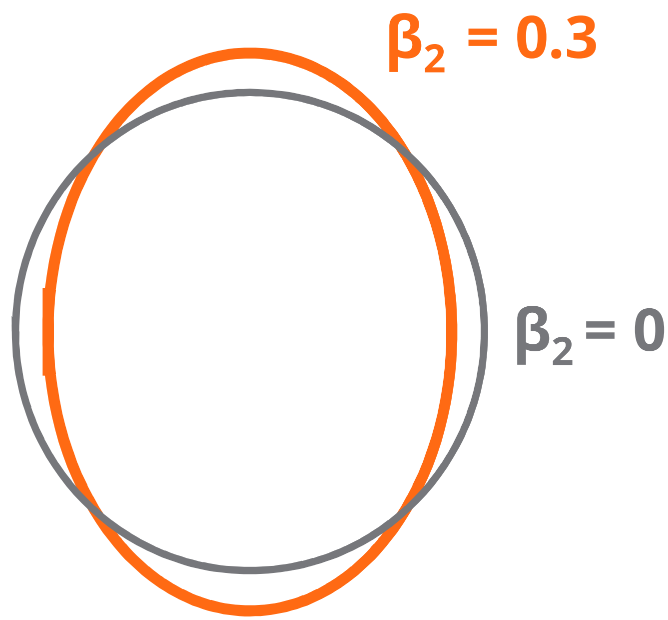
- Arises from physics *inside* the nucleus
  - Nucleon EDM
  - quark EDM/chromo-EDM
  - CPV nuclear forces
  - Strong CPV (θ_{QCD})
  - …
- Orthogonal to eEDM



A rotating EDM produces an MQM

Nuclear Deformation

- Quadrupole deformation enhances MQM
  - Collective enhancement
  - $\approx \beta_2 Z$
- Net MQM most sensitive to CPV nuclear forces



$$R(\theta)/R_0 = 1 + \beta_2 Y_2^0(\theta) + \cdots$$

V. V. Flambaum *et al.*, Phys. Rev. Lett. **113**, 103003 (2014)

Flambaum, V. V., Phys. Lett. B **320**, 211–215 (1994)

Which species?

Molecule	I_t	State	$\lvert W_M \rvert$ 10^{33} Hz/ $e \cdot cm^2$	$\lvert W_M M S \rvert$ (μHz) $10^{25} d_p / e \cdot cm$	$10^{10} \tilde{\theta}$	$10^{27} (\tilde{d}_u - \tilde{d}_d)/$ cm
^{135,137}BaF	$\frac{3}{2}$	$^2\Sigma_{1/2}$	0.83[a]	~0.1	1	0.6
^{173}YbF	$\frac{5}{2}$	$^2\Sigma_{1/2}$	2.1[b]	22	42	25
^{201}HgF	$\frac{3}{2}$	$^2\Sigma_{1/2}$	4.8[a]	~1	10	6
^{177}HfF$^+$	$\frac{7}{2}$	$^3\Delta_1$	0.5	20	33	20
^{179}HfF$^+$	$\frac{9}{2}$	$^3\Delta_1$	0.5	14	26	16
^{181}TaN	$\frac{7}{2}$	$^3\Delta_1$	~1	30	50	30
^{229}ThO	$\frac{5}{2}$	$^3\Delta_1$	1.9	~10	72	44
^{229}ThF$^+$	$\frac{5}{2}$	$^3\Delta_1$	1.7	~10	65	39

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Fully polarize, internal co-magnetometer

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???

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V. V. Flambaum *et al.*, Phys. Rev. Lett. **113**, 103003 (2014)

Where can we improve?

- Shot noise limited EDM sensitivity

$$\delta d_{\mathrm{e}} = \frac{\hbar}{2\mathcal{E}_{\mathrm{eff}}\tau\sqrt{N}}$$

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Beams have $\tau \sim 1$ ms

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Beams have $\tau \sim 1$ ms

Traps can have $\tau > 1$ s…

Where are we going…

- 10^6 molecules
- 10 s coherence
- Large enhancement(s)
- 1 day averaging

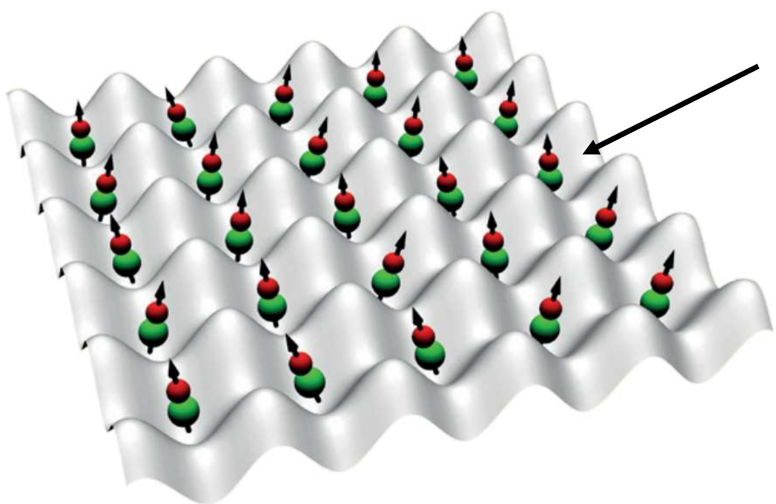

Figure adapted from A. J. Daley, Nature **501**, 497 (2013)

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$M_{new\ phys}$ ~ 1,000 TeV

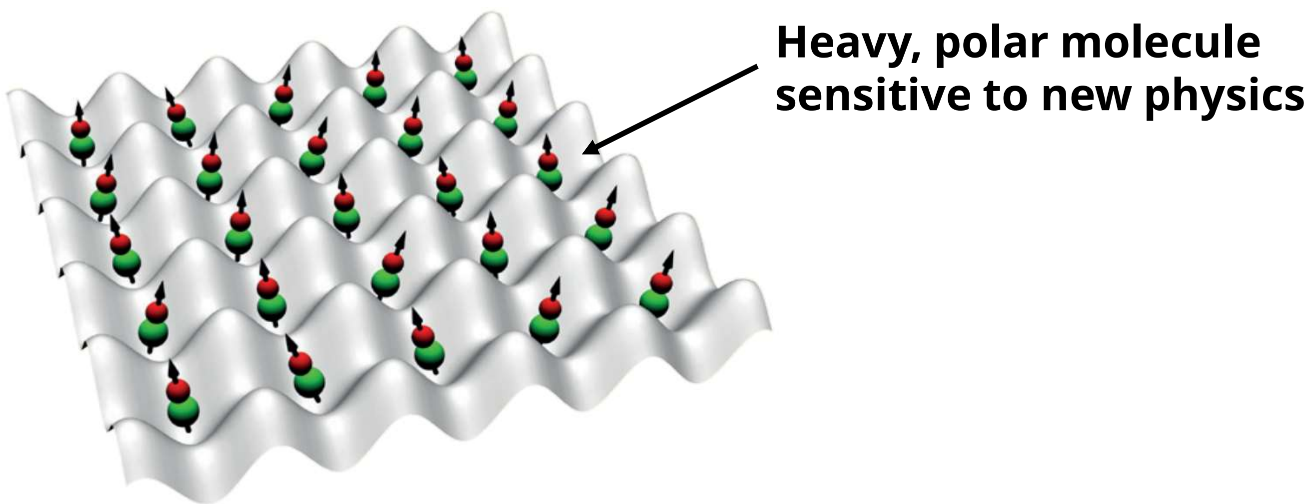
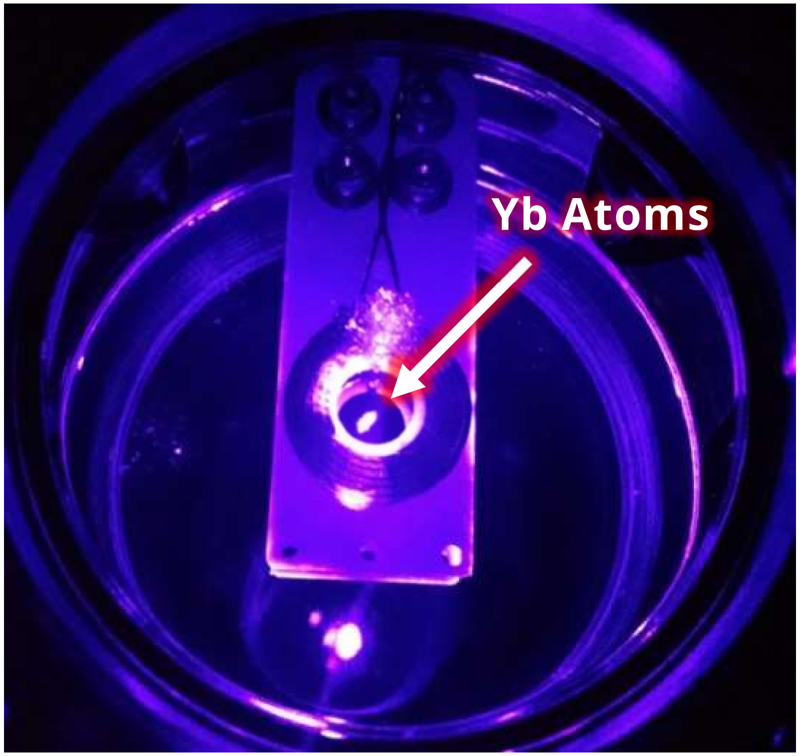


Figure adapted from A. J. Daley, Nature **501**, 497 (2013)

How do we get there?

- Laser cooling!
  - Only *demonstrated* technology
  - Only recently applied to molecules (difficult!)
  - Full polarization, co-magnetometers *destroy* laser cooling (d shells)

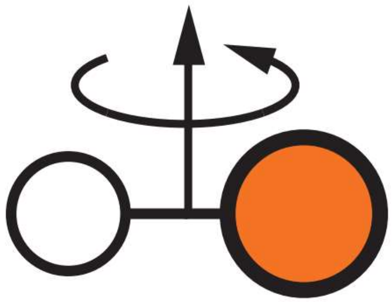


Incompatible features

Feature	ThO, TaN	WC	(Hf,Th)F$^+$	(Yb,Ba,Ra)F	Hg/Ra	?????????
Laser cooling	✗	✗	✗	✓	✓	✓
Full polarization	✓	✓	✓	✗	✗ ✗	✓
Internal co-mag.	✓	✓	✓	✗	✗	✓
>1 s lifetime	✗	✓	✓	✓	✓	✓
Scalable (Large #)	✓	✓	✗	✓	✓	✓

Decoupling features

- Polarization provides a “handle” to orient the molecule



I. Kozyryev and NRH, arXiv:1705.11020 (2017), to appear in PRL

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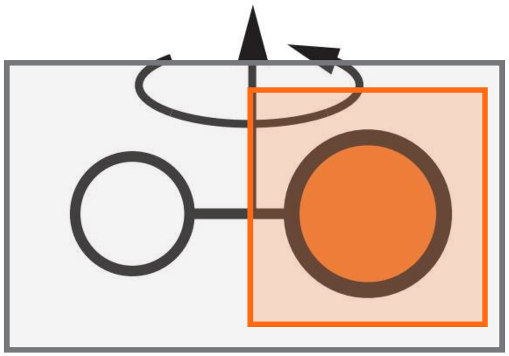

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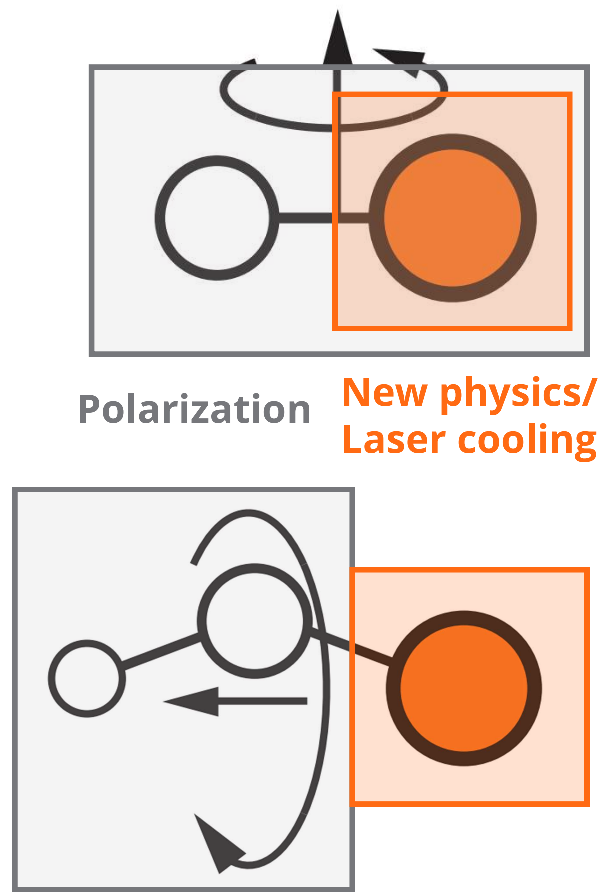
- Polarization provides a "handle" to orient the molecule
- In polyatomics, these features can be decoupled
  - Get laser cooling, full polarization, co-magnetometers, etc.



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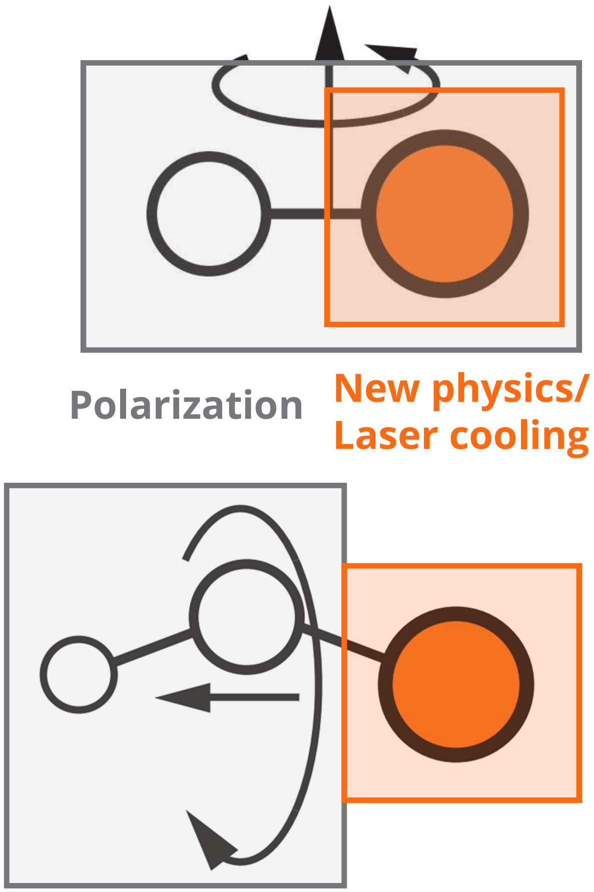
Decoupling features

- Polarization provides a “handle” to orient the molecule
- In polyatomics, these features can be decoupled
  - Get laser cooling, full polarization, co-magnetometers, etc.
- Realistic pathway to PeV-scale physics!



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Pathway to PeV Physics

Feature	ThO, TaN	WC	(Hf,Th)F^+	(Yb,Ba,Ra)F	Hg/Ra	**Polyatomics**
Laser cooling	✗	✗	✗	✓	✓	✓
Full polarization	✓	✓	✓	✗	✗ ✗	✓
Internal co-mag.	✓	✓	✓	✗	✗	✓
>1 s lifetime	✗	✓	✓	✓	✓	✓
Scalable (Large #)	✓	✓	✗	✓	✓	✓

New Lab

- Precision measurements in neutral polar molecules
  - NMQM search to look for BSM hadronic physics
  - Polyatomics to extend AMO BSM searches into the PeV regimes
- www.hutzlerlab.com
- Please come visit!

Thanks for your attention!

Let’s stay in touch – hutzler@caltech.edu