Search for Hadronic CP Violation in Deformed Nuclei with Polyatomic Molecules

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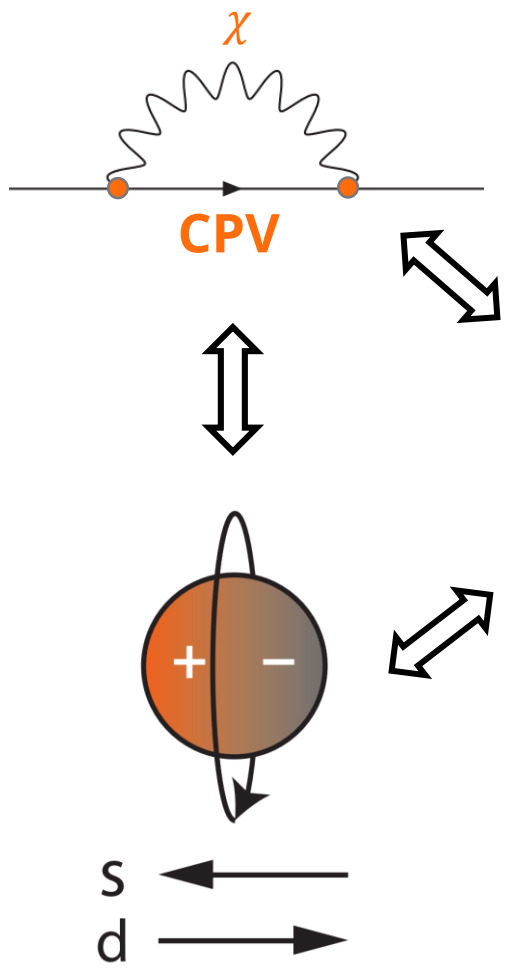
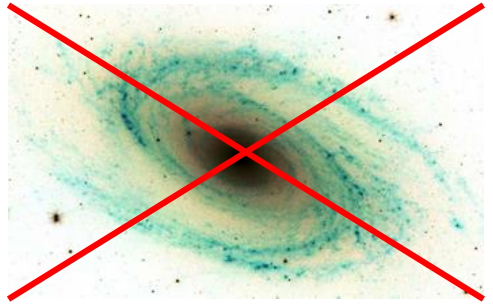
CP Violating Observables

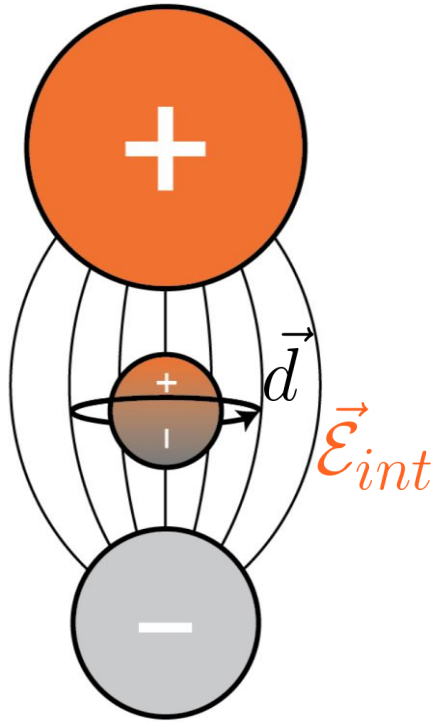
- The baryon asymmetry suggests new CPV physics beyond the Standard Model
- BSM CPV physics creates **low energy** observables
  - Classic example: permanent EDMs
  - EDMs violate CP
- Converse also true – New CPV at high energies creates EDMs

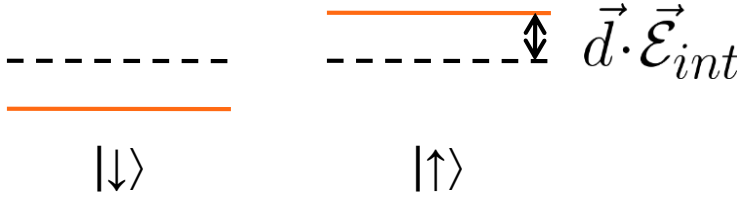




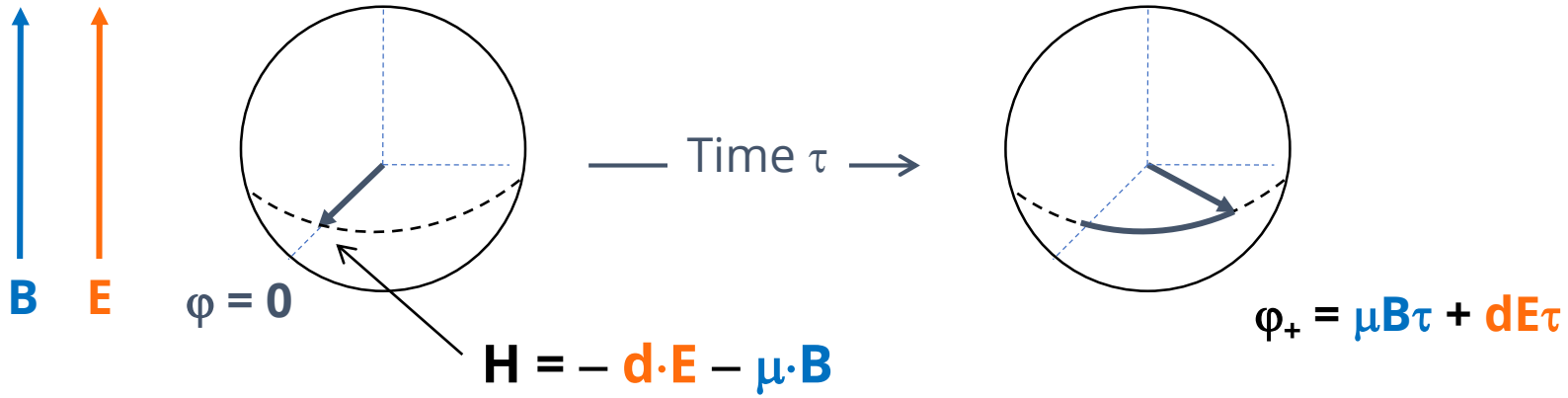
Molecular Internal Fields

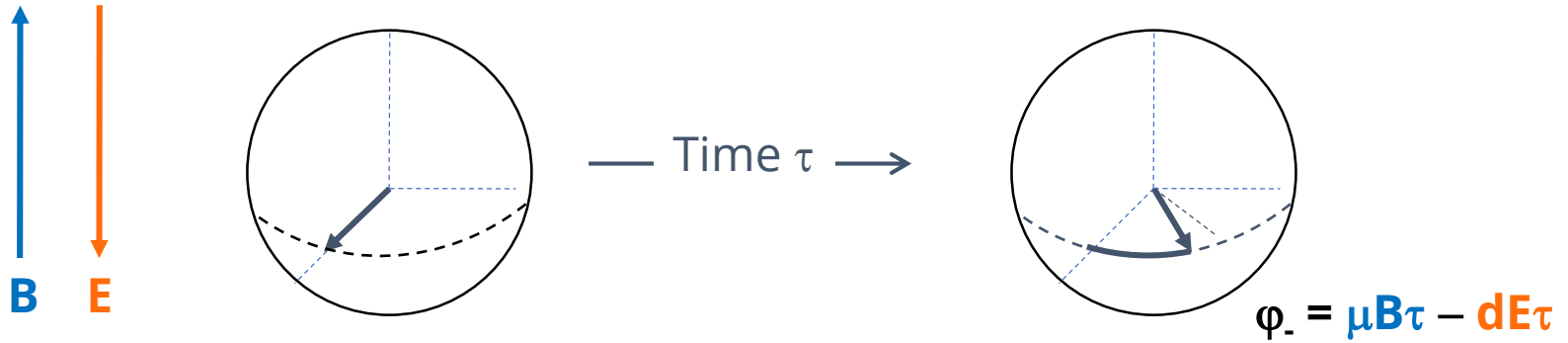
- Atoms/molecules have **extremely large** fields
  - $e/4\pi\epsilon_0 a_0^2$ ~ GV/cm
  - Relativistic ~Z^3 enhancement
  - 10-100 GV/cm for heavy species
  - Maximum lab field ~100 kV/cm
- CPV moments cause CPV energy shifts
  - Example: eEDM
  - $H = -\vec{d} \cdot \vec{\mathcal{E}}_{int}$
- Study effect of internal fields on molecular constituents





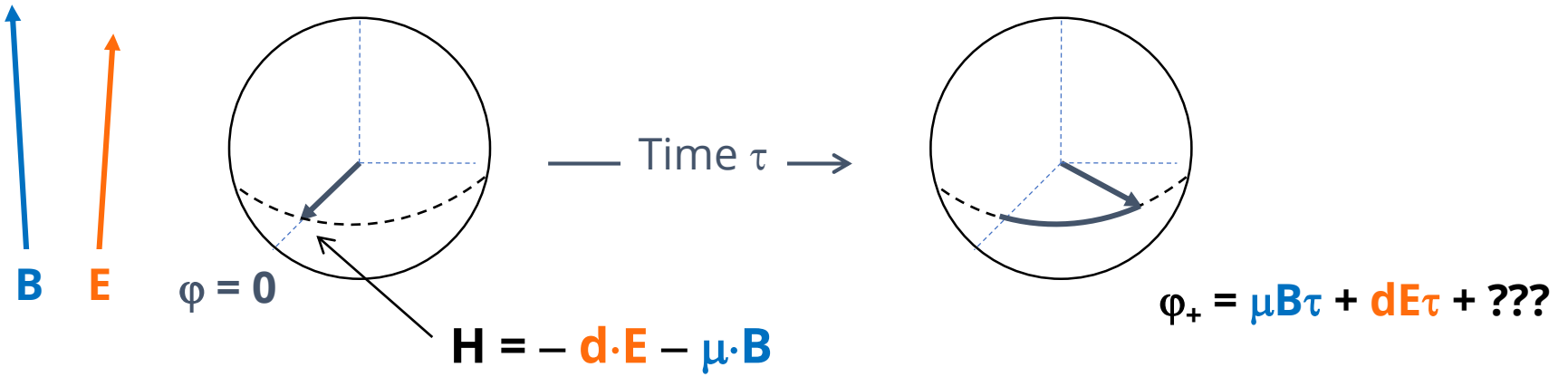
Spin precession





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

Nothing is perfect…

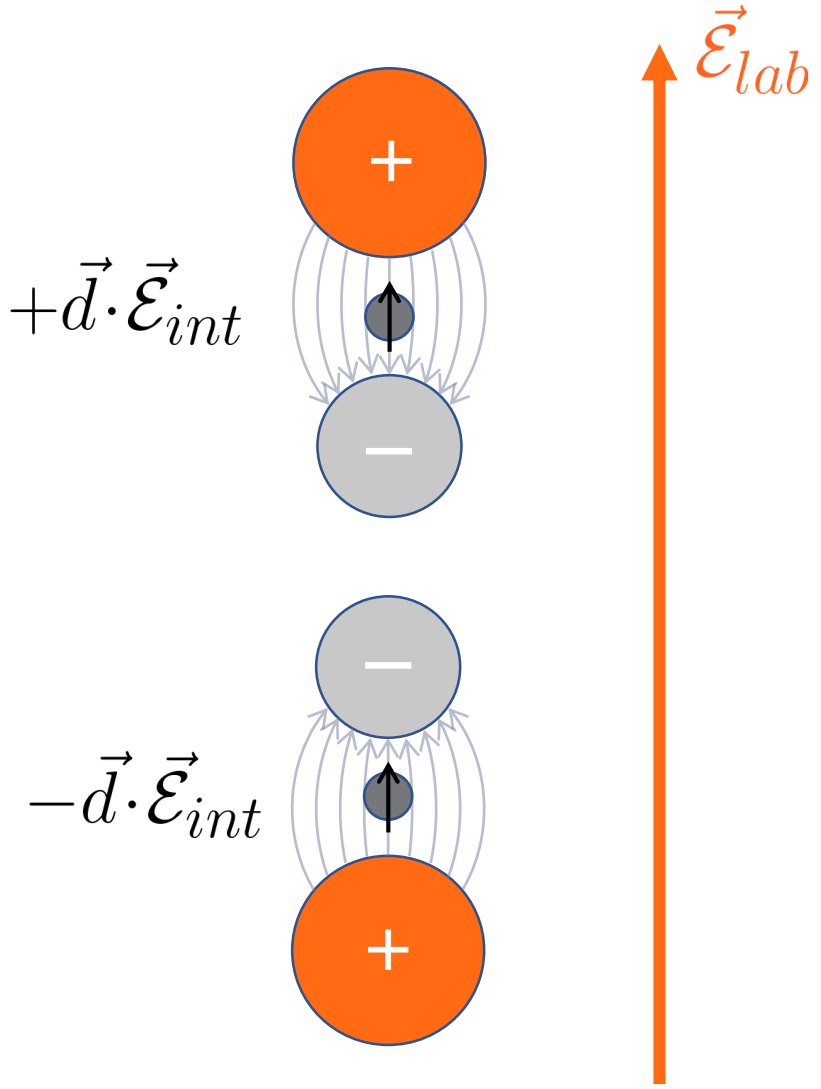


$dE / \mu B < 10^{-6}$

$\Delta\varphi \propto dE\tau + ???$

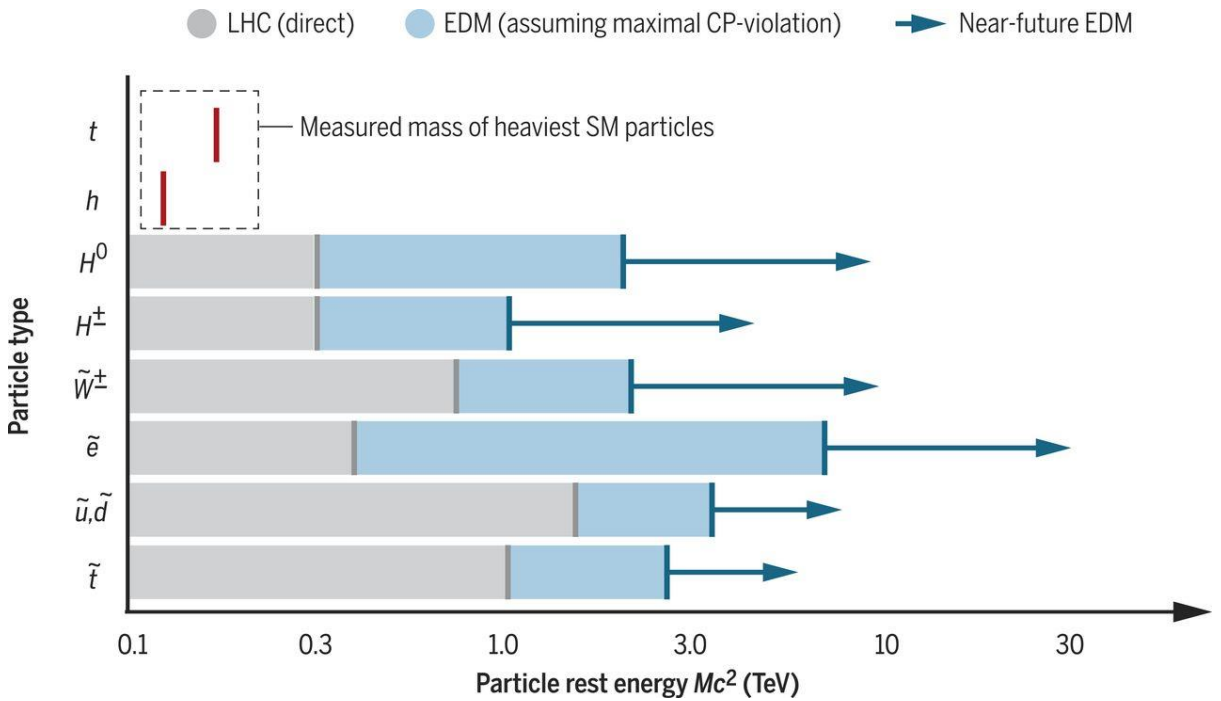
Internal Comagnetometers

- Some molecules can be fully polarized in the lab frame
  - Internal co-magnetometer (**ICM)**
  - Measure CPV in each state
- Non-CPV effects cancel
  - No external field change
  - Small fields (<1 kV/cm)
  - **Extreme suppression of motional fields, geometric phases, leakage currents, …**
- Requires particular, semi-exotic electronic structure



Sensitivity of Precision Measurements

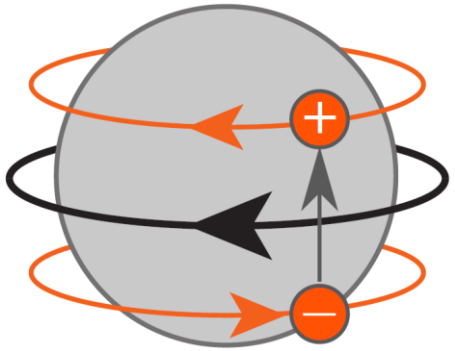
- Extremely sensitive probe for BSM CPV
  - Both generically, and for specific models
- Complements direct searches
  - LHC, flavor violation, neutrinos, …
- **Lots of room for improvement in sensitivity and breadth**



D. DeMille, J. M. Doyle, and A. O. Sushkov, Science **357**, 990 (2017)

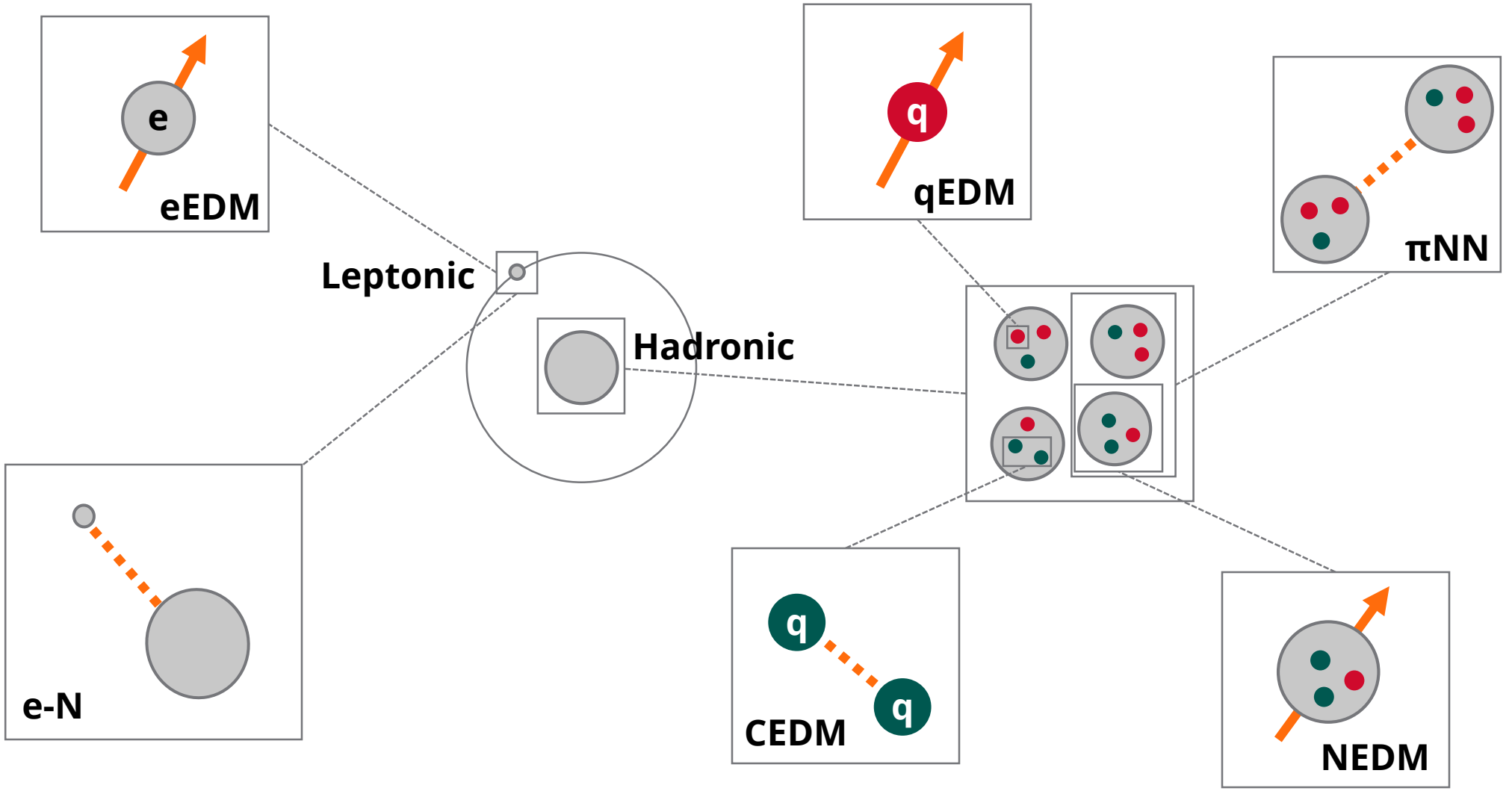
Research at Caltech

Extend molecular CPV searches to the hadronic sector

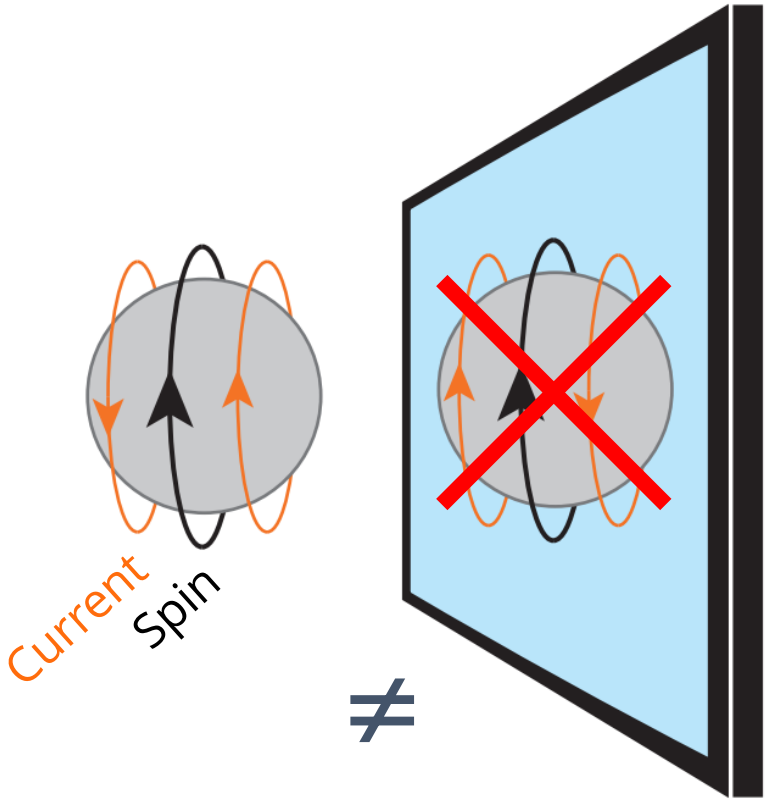


Extend sensitivity to much higher energy scales

Many Sources



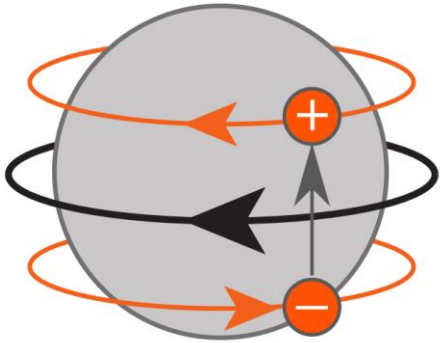
Magnetic quadrupole moment (MQM)



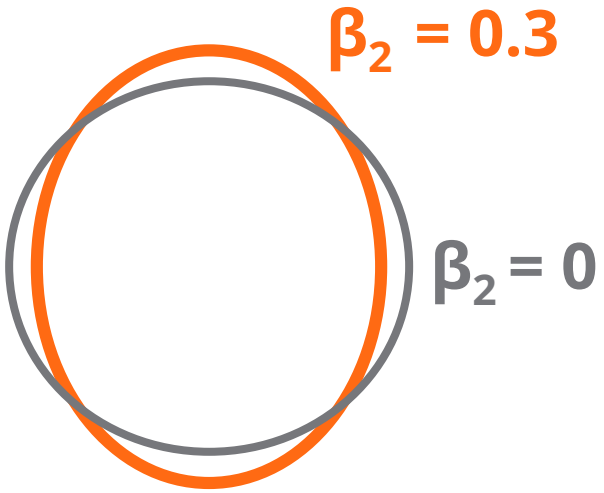
MQMs violate P, T, CP

Physical Origin

- Arises from hadronic sources
  - Nucleon EDM
  - quark EDM/chromo-EDM
  - CPV nuclear forces
  - Strong CPV (θ_{QCD})
  - …
- Quadrupole deformation (β_2) enhances MQM
  - Collective enhancement
  - Typically $\beta_2 Z \sim 10$
  - Ta, Yb, Hf, Lu, …



Rotating EDM produces MQM



nEDM, NSM, MQM – Complementarity

- No current search is sensitive to MQM (needs $I \geq 1$)
- nEDM, Nuclear Schiff Moments (Hg, Ra, TlF) have complementary sensitivity
  - Hadronic parameter space is complex!
- MQM has some advantages as well

Wilson coefficient	Operator (dimension)	Number	Systems
$\bar{\theta}$	Theta term (4)	1	Hadronic & diamagnetic atoms
δ_e	Electron EDM (6)	1	Paramagnetic atoms & molecules
$\mathrm{Im}\, C_{\ell equ}^{(1,3)}$, $\mathrm{Im}\, C_{\ell eqd}$	Semi-leptonic (6)	3	
δ_q	Quark EDM (6)	2	Hadronic & diamagnetic atoms
$\tilde{\delta}_q$	Quark chromo EDM (6)	2	
$C_{\tilde{G}}$	Three-gluon (6)	1	
$\mathrm{Im}\, C_{quqd}^{(1,8)}$	Four-quark (6)	2	
$\mathrm{Im}\, C_{\varphi ud}$	Induced four-quark (6)	1	
Total		13	

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

Where can we improve?

- Let's also work in a system that offers significant room for improvement
- Shot noise limited sensitivity:

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

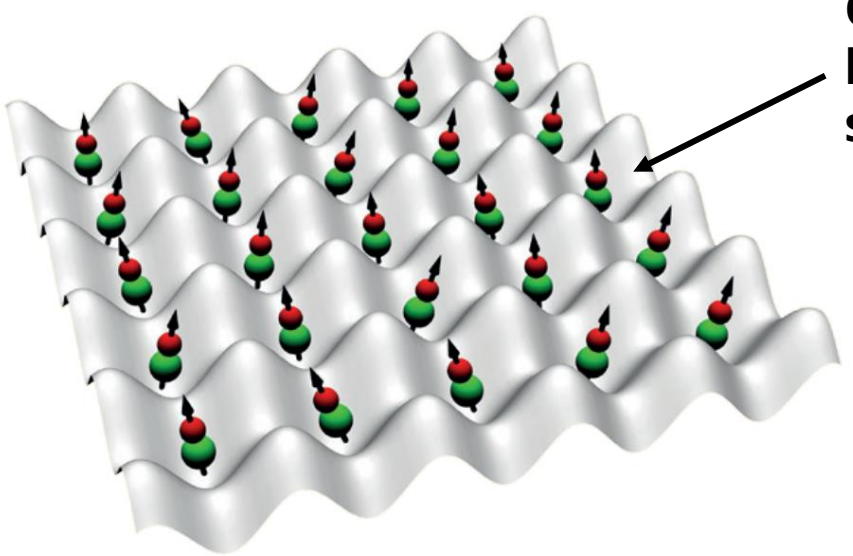
Beams have τ ~ 1 ms …

Traps can have τ > 1 s

Reaching Higher Energies

- 10^6 molecules
- 10 s coherence
- Large internal fields
- Robust error rejection
- 1 week averaging

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



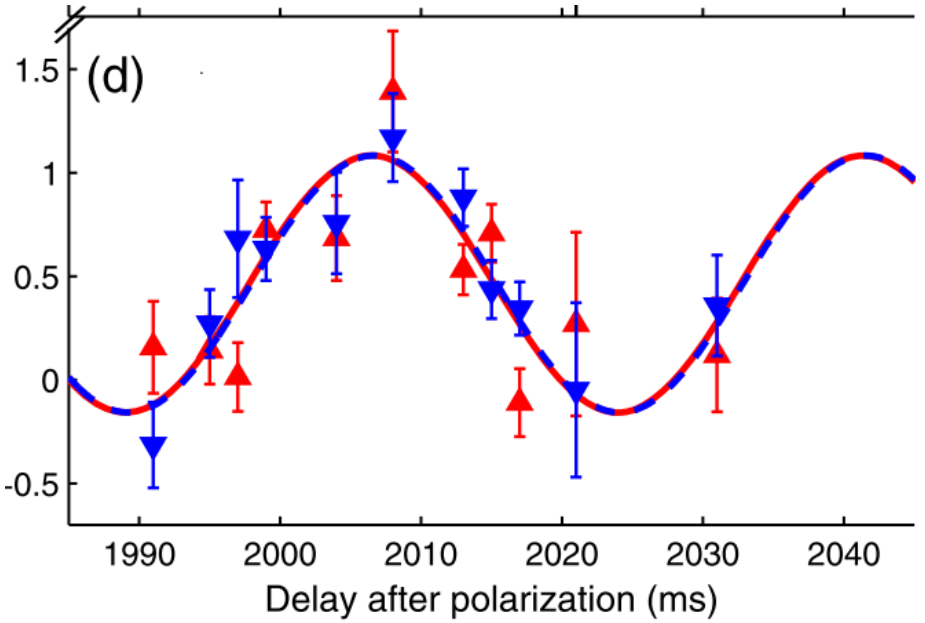
Optically trapped, heavy, polar molecule sensitive to new physics

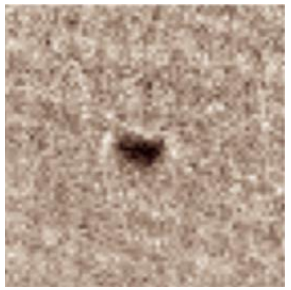
So… how to build this?

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

Laser cooling/trapping

- Lasers can be used to cool and trap < mK gases
  - Critical feature of Ra EDM experiment at ANL
- Let's laser cool molecules for CP-violation searches!



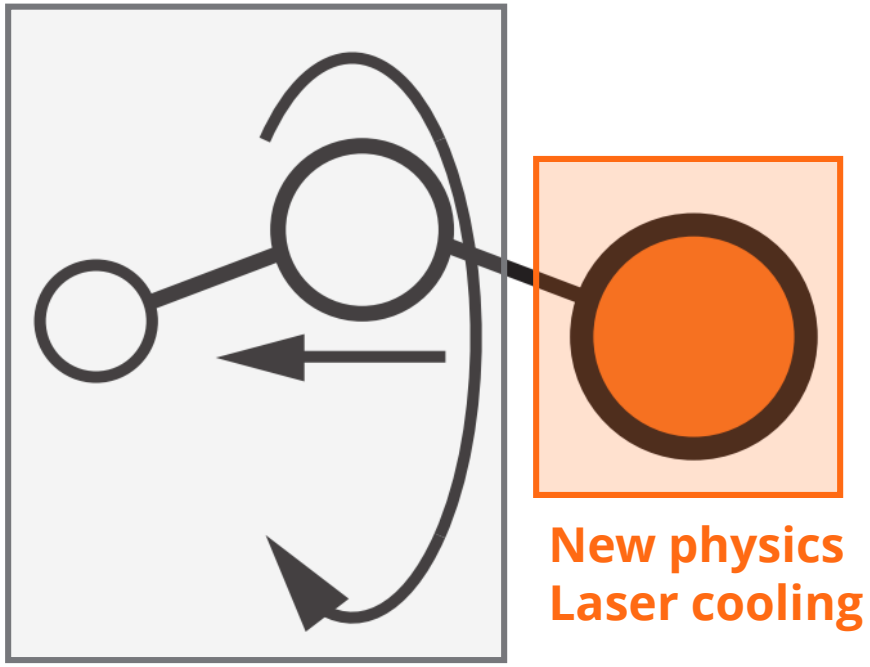


Laser cooled and trapped Ra atoms

R. H. Parker, M. R. Dietrich, M. R. Kalita, N. D. Lemke, K. G. Bailey, M. Bishof, J. P. Greene, R. J. Holt, W. Korsch, Z.-T. Lu, P. Mueller, T. P. O'Connor, and J. T. Singh. Phys. Rev. Lett. **114**, 233002 (2015)

Polyatomic molecules

- Problem: in *diatomic* molecules, laser cooling and internal co-magnetometers conflict
  - Incompatible electronic structure requirements
- Solution: use polyatomic molecules!
  - Only option to get all of these features at once
  - Realistic pathway to PeV scale CPV (?)

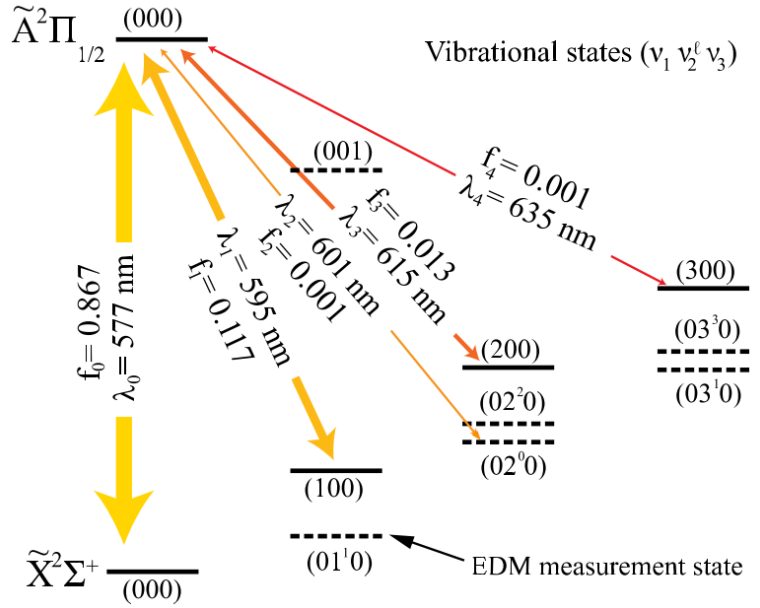


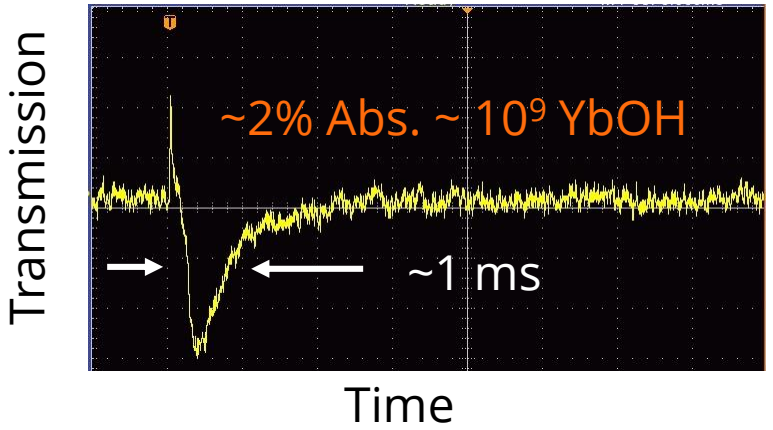
I. Kozyryev and NRH, Phys. Rev. Lett. **119**, 133002 (2017)

YbOH

- YbOH is ideal candidate for first experiment
  - Existing spectroscopy
  - Laser-coolable
  - Multiple isotopes
    - eEDM, NSM, MQM
  - ^{173}Yb ($I = 5/2\,, \beta_2 \approx 0.3$) for NMQM search
- We recently started making cryogenically cooled YbOH molecules at Caltech
  - Gen I: Beam

I. Kozyryev and NRH, Phys. Rev. Lett. **119**, 133002 (2017)

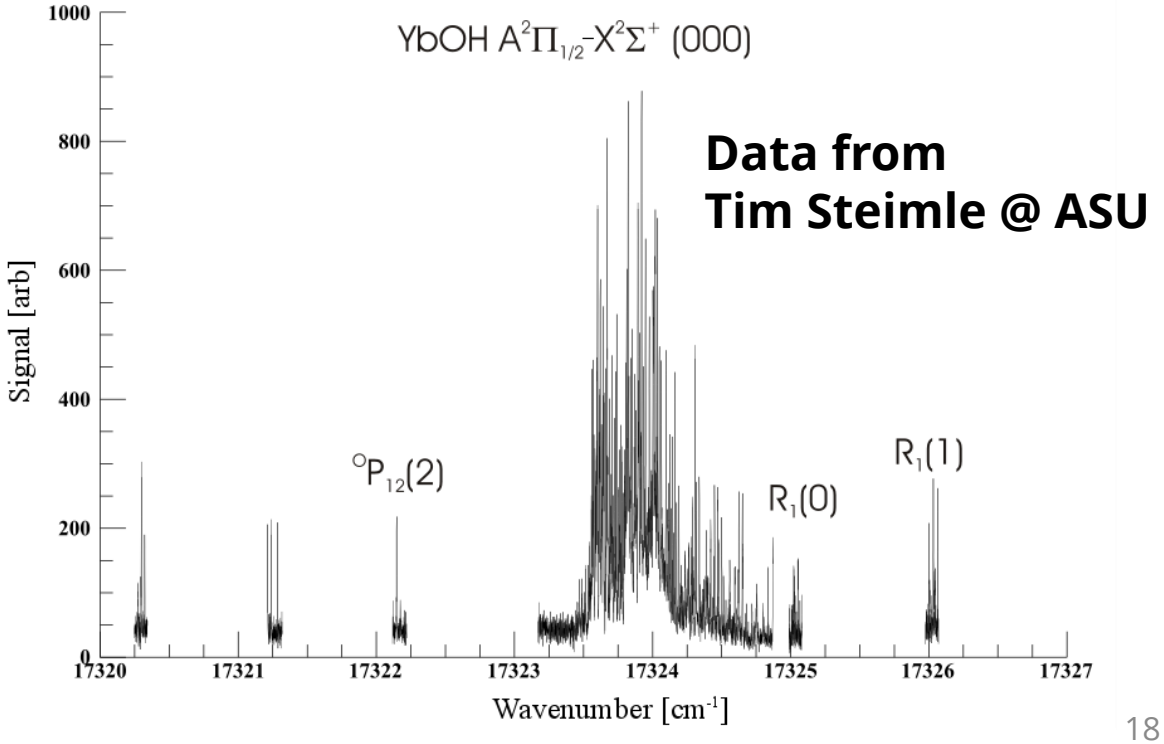




Polyatomic eEDM Experiment

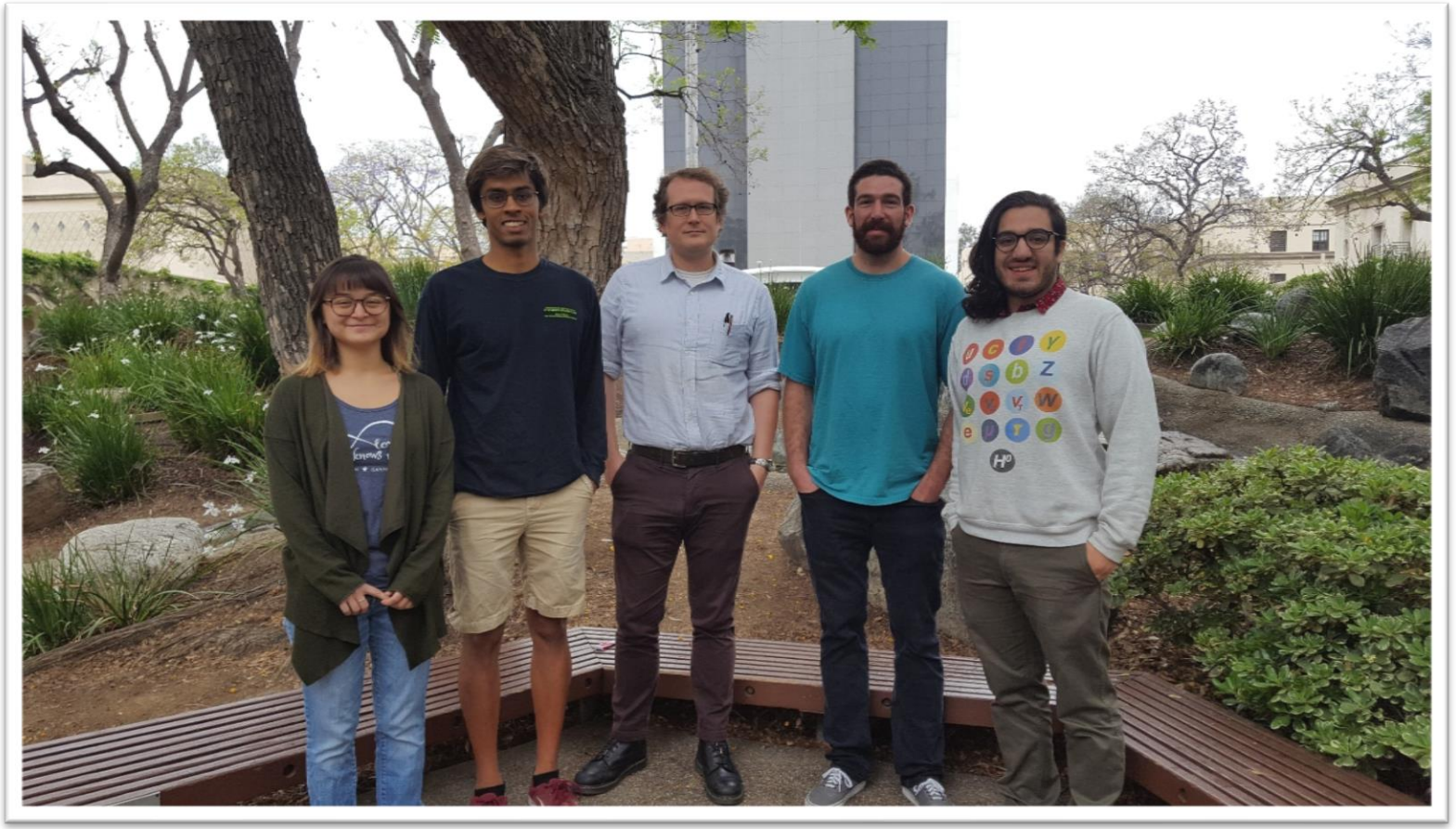
- Electron EDM search in laser cooled and trapped polyatomic molecules
- Just getting started!
  - Spectroscopy underway
    - **Steimle @ ASU**
    - Thanks for the line positions!
  - CBGB precision measurement under construction
    - NRH @ Caltech
  - Laser slowing, cooling, trapping gearing up
    - **Doyle @ Harvard**
- *Stay tuned!*

pEDM



Data from Tim Steimle @ ASU

The Group

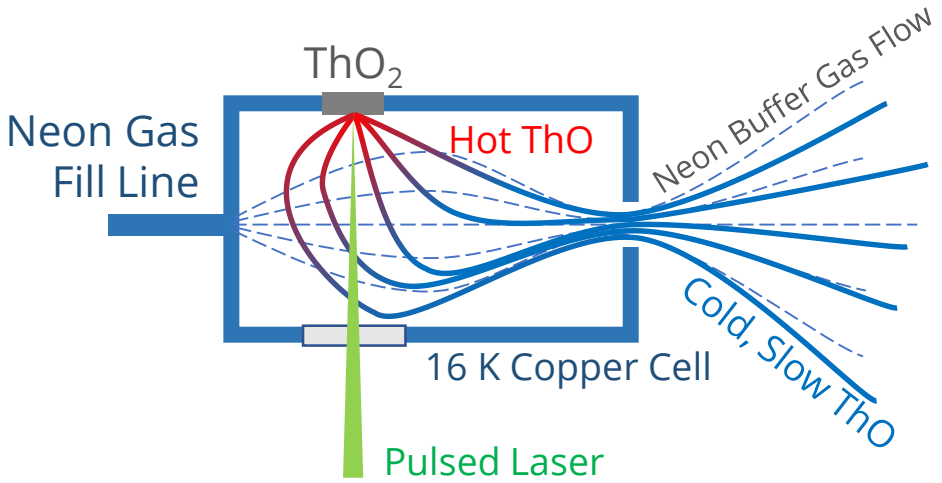


Avikar Periwal Nick Pilgram

Alicia Tirone Arian Jadbabaie

Searches with exotic nuclei?

- This approach is compatible with exotic nuclei
  - Can make cold beams of "just about anything"
- Molecular precision measurements are sensitive to lots of HEP/NP/BSM
- Let's talk!



N. R. Hutzler, H.-I. Lu, and J. M. Doyle, Chem. Rev. **112**, 4803 (2012)
N. R. Hutzler, *et al.*, Phys. Chem. Chem. Phys. **13**, 18976 (2011)

Summary

Polyatomic molecules offer laser cooling and internal co-magnetometers for sensitive, robust searches for physics beyond the Standard Model

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HEISING-SIMONS FOUNDATION

PMA

Division of Physics, Mathematics, and Astronomy

Thanks for your attention!