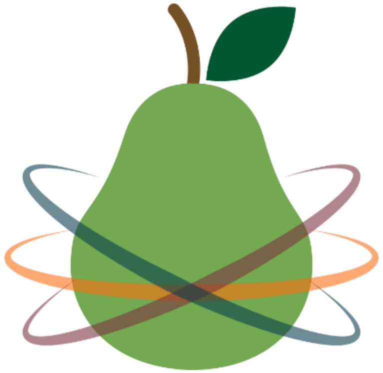
Precision Measurements with Radioactive Molecules

Nick Hutzler
Caltech



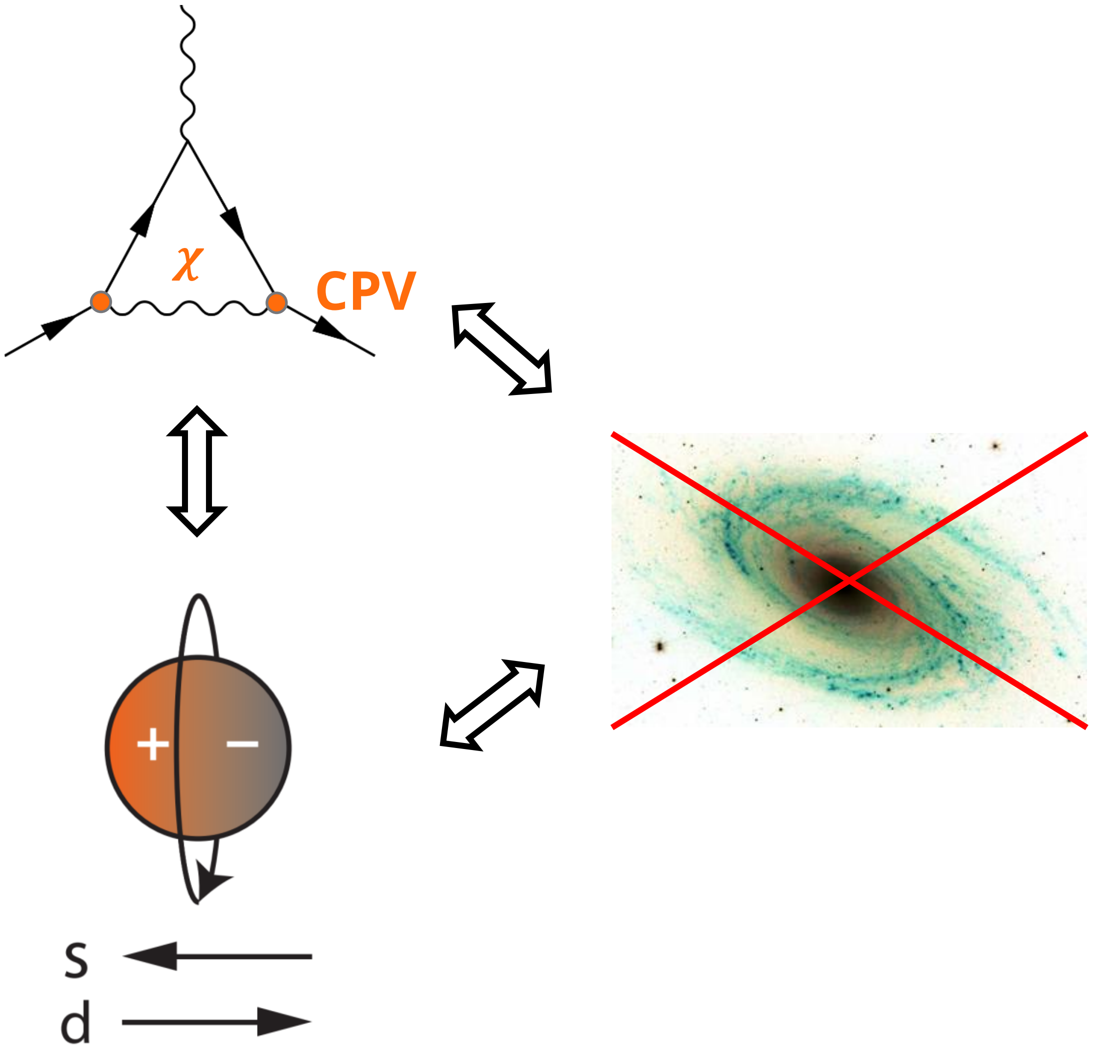
Outline

- **Brief review: atoms and molecules for CPV searches**
- **Advantages of quantum-controlled molecules**
- **Advantages of radioactive molecules**
- **Experimental developments**
- **Outlook and future directions**

Atoms and molecules for CPV searches

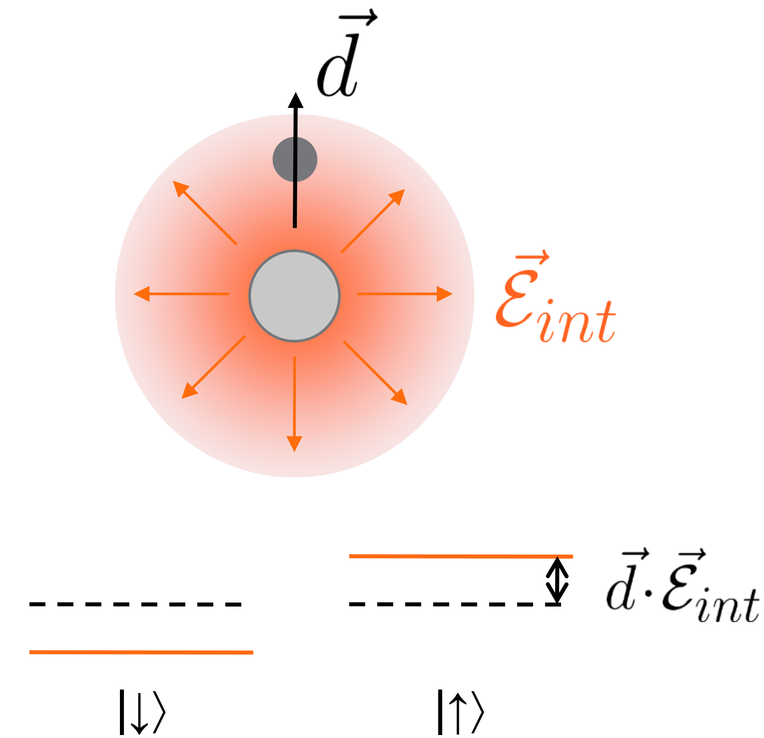
Low Energy Observables

- The baryon asymmetry suggests new CP-violating physics
- Leads to CPV electromagnetic moments of regular matter
  - Electric dipole moment (EDM)
  - Nuclear Schiff moment (NSM)
  - Magnetic quadrupole moment (MQM)
- Enables sensitive probes of new physics with tabletop scales



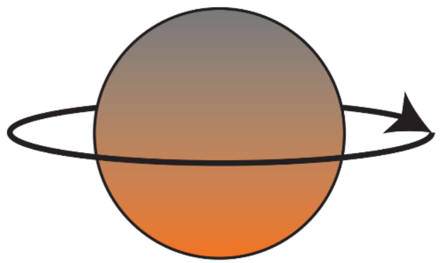
The basic idea

- Look for CPV spin precession in the internal fields in atoms/molecules
- CPV shifts generally ~(spin)·(internal E field)
  - We just say "EDM measurements" even though some are not
- Measure spin precession between time-reversed states
  - Coherent measurement



$$|\uparrow\rangle + |\downarrow\rangle \;\rightarrow\; |\uparrow\rangle + e^{i\tau\omega_{CP}}|\downarrow\rangle$$

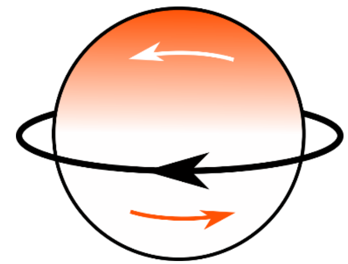
CP-Violating Observables



Electron electric dipole moment (EDM)

Sensitive to electron-coupled CPV

Enhanced in heavy species

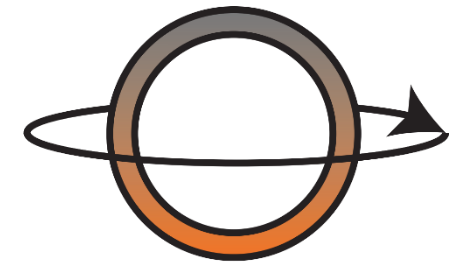


Nuclear magnetic quadrupole moment (MQM)

Sensitive to nuclear CPV

Enhanced in heavy species

Enhanced in quadrupole-deformed nuclei



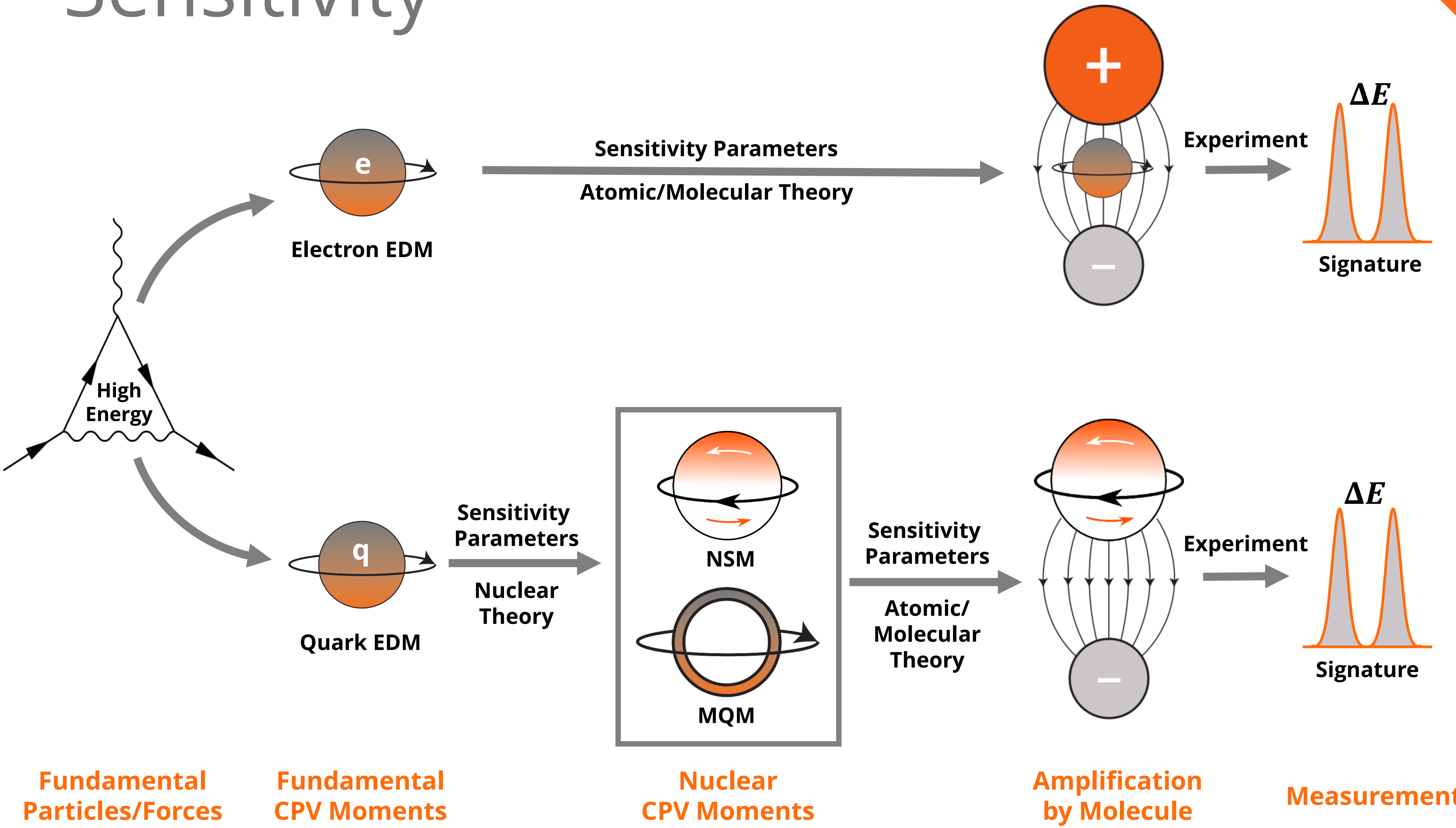
Nuclear Schiff moment (NSM)

Sensitive to nuclear CPV

Enhanced in heavy species

Enhanced in octupole-deformed nuclei

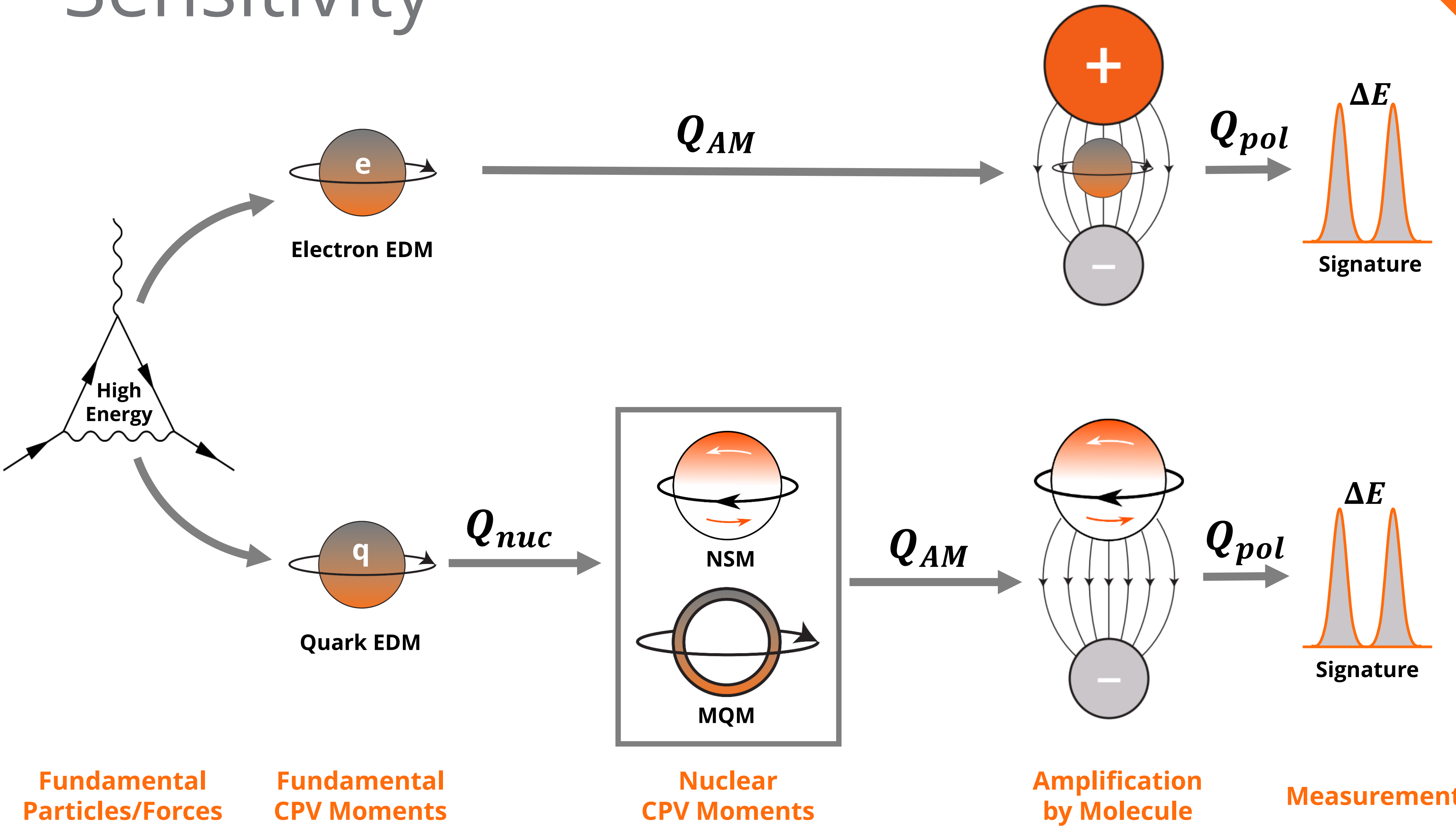
Sensitivity



Sensitivity

- Goal: measure some CPV electromagnetic moment in the electrons/nuclei
  - eEDM, NSM, or MQM
  - Ultimately arises from some CPV parameter $C = d_e, d_n, g_{\pi NN}^{(1)}, \ldots$
- Observable: energy shifts in an atom or molecules, ΔE
- Related by three factors: $\boldsymbol{\Delta E = C \times Q_{AM} \times Q_{nuc} \times Q_{pol} = C \times Q}$
  - Q_{AM} = sensitivity of atom/molecule to the effect
    - How much does the energy shift given the presence of this electromagnetic moment?
    - "Internal fields"
  - Q_{nuc} = sensitivity of the nucleus to the effect
    - How large of a CPV moment is induced in the nucleus given C?
  - Q_{pol} = polarization factor
    - What fraction of the "internal fields" in the atom/molecule can be aligned in the lab?
  - $\boldsymbol{Q = Q_{AM} \times Q_{nuc} \times Q_{pol}}$ = **overall sensitivity of species to CPV**
  - **Punchline: $\boldsymbol{Q}$ is maximized for radioactive molecules**
- See Snowmass EDM whitepaper 2203.08103 for even more details

Sensitivity



Sensitivity

- Observable is phase ϕ after free precession for time τ

$$\phi = \tau \Delta E/\hbar = CQ\tau/\hbar$$

- Repeated measurements:

$$\delta C = \hbar / Q\tau\sqrt{N}$$

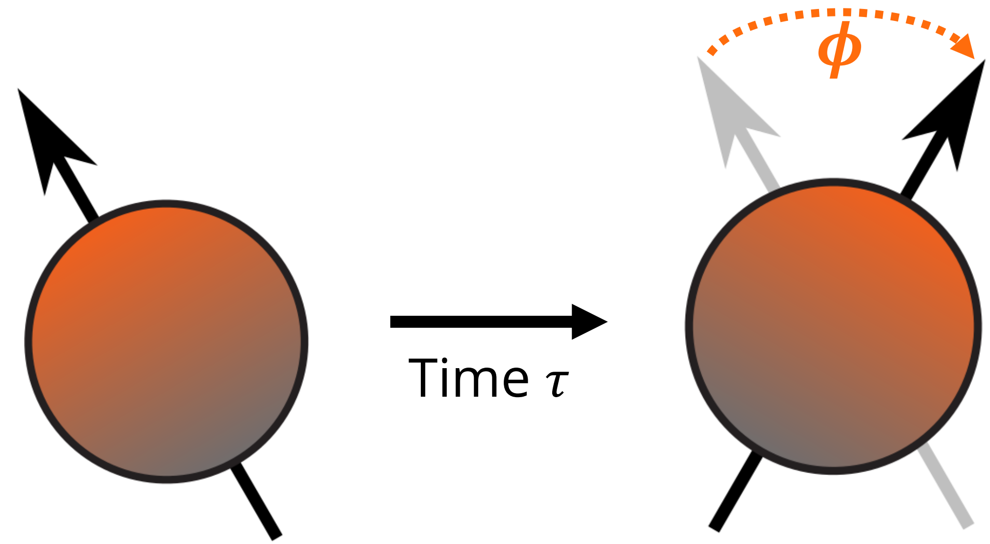
Total measurements

Coherence time

Sensitivity: $Q_{AM} \times Q_{nuc} \times Q_{pol}$

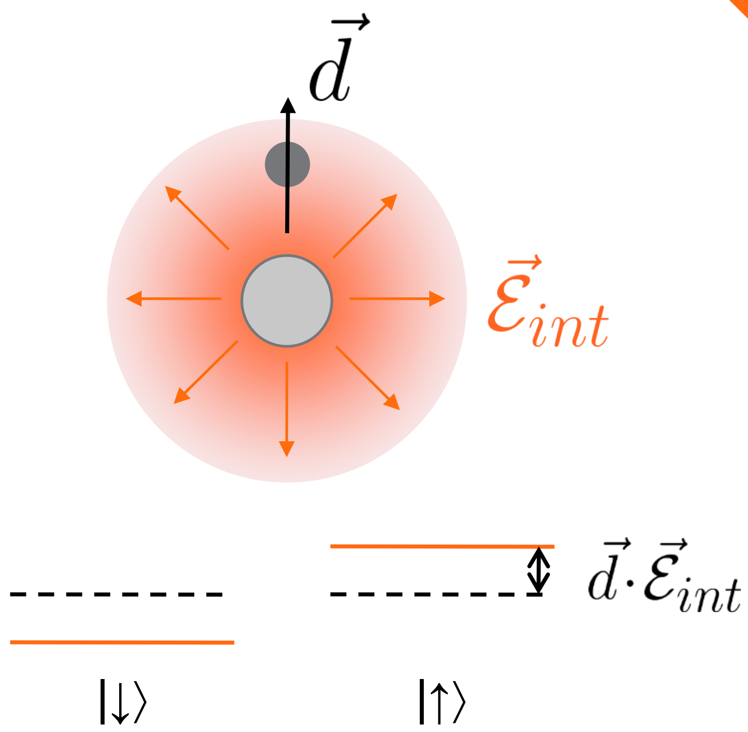
Make these large

Uncertainty in CPV parameter



Maximizing Q_{AM}

- Atoms/molecules have extreme internal electromagnetic environments
- Directly enhances electron EDM
  - Maximum lab field ~100 kV/cm
  - Q_{AM} given by effective field $\mathcal{E}_{eff}$
- Directly enhances NSM, MQM
  - More complicated than simple "internal field" picture… more later
  - Due to strong electron/nucleus interactions
- $Q_{AM} \sim Z^{2-3}$ generally
  - For species with similar electronic structure, e.g. periodic table columns

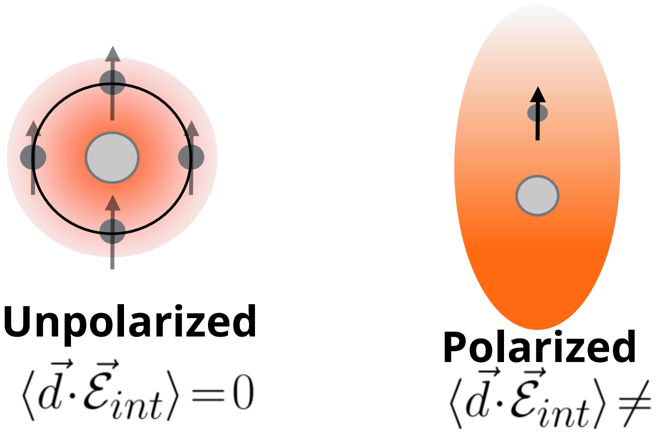


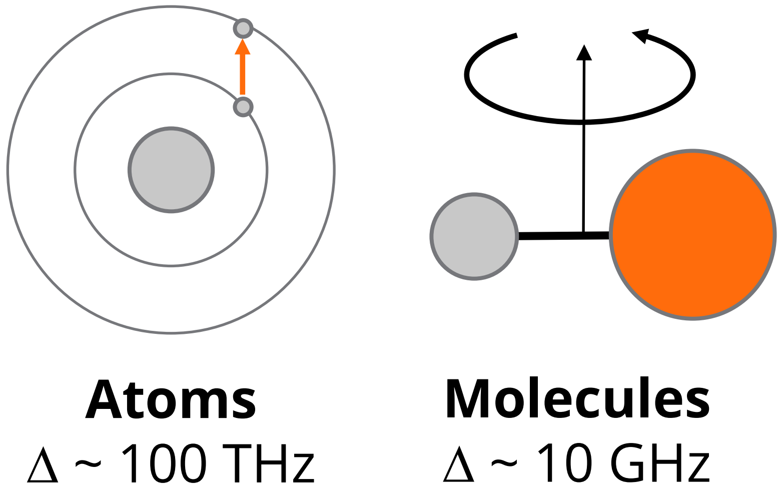
Molecule	Z	$\mathcal{E}_{eff}$ [GV/cm]
CaOH	20	0.3
SrOH	38	2.1
BaOH	56	6.6
YbOH	70	24
RaOH	88	56

K. Gaul and R. Berger, PRA 101, 012508 (2020)

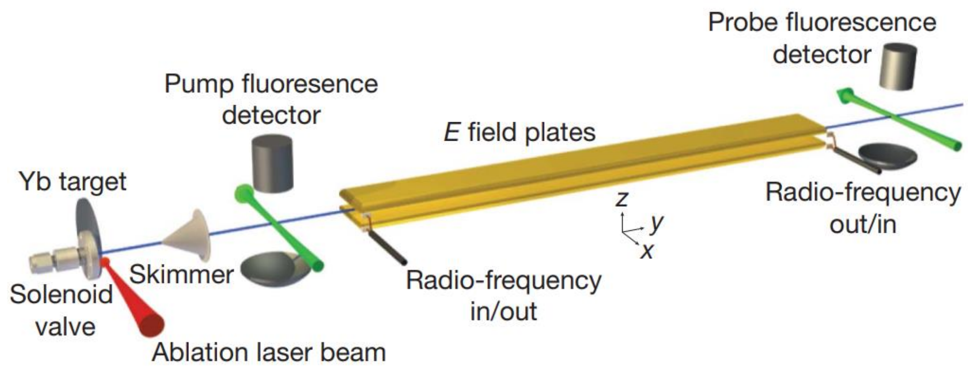
Maximizing Q_{pol}: Atoms vs. molecules

- Need to align internal fields in the lab frame
  - Otherwise, zero average direction → zero average energy shift
  - True for all static CPV effects
- Atoms
  - Δ ~ 100 THz (electronic)
  - Q_{pol} ~ 10^{-3} @ 100 kV/cm
- Molecules
  - Δ ~ 10 GHz (rotational)
    - Sometimes even smaller, more on that later
  - $Q_{pol} \gtrsim \mathcal{O}(1)$ @ 10 kV/cm
- **"Molecules are 1000x more sensitive than atoms"**
  - Q_{AM} ~ same, Q_{pol} much larger



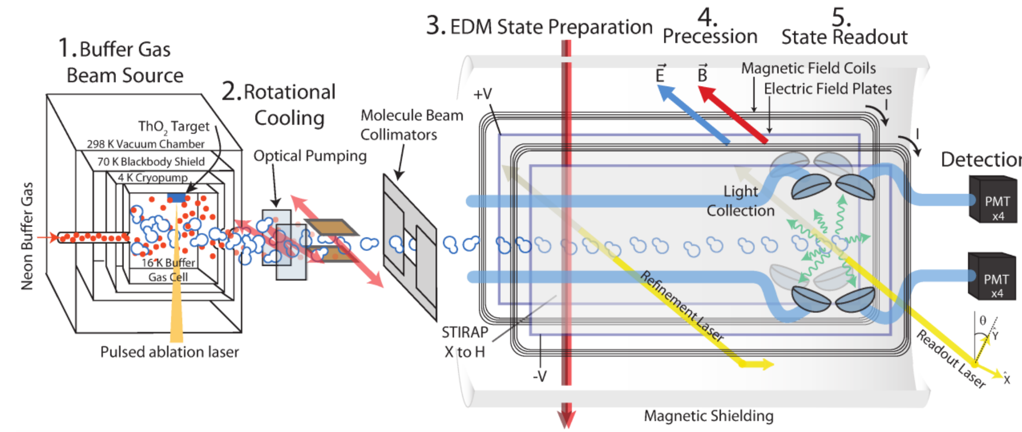


Molecular eEDM Searches



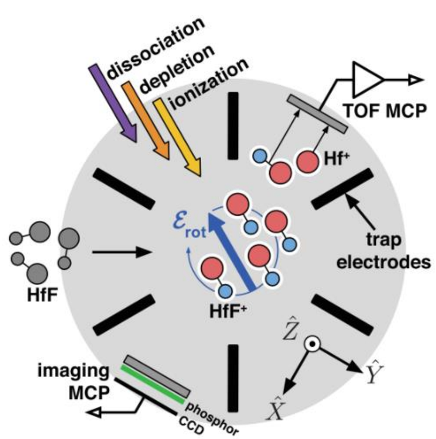
YbF, Imperial

- Spin precession in pulsed supersonic beam
- First to beat atomic Tl limits
- $|d_e| < 1.1 \times 10^{-27}$ e cm (2011)



ACME, ThO, Harvard/Chicago/Northwestern

- Spin precession in cryogenic beam
- $|d_e| < 8.7 \times 10^{-29}$ e cm (2014)
- $|d_e| < 1.1 \times 10^{-29}$ e cm (2018)

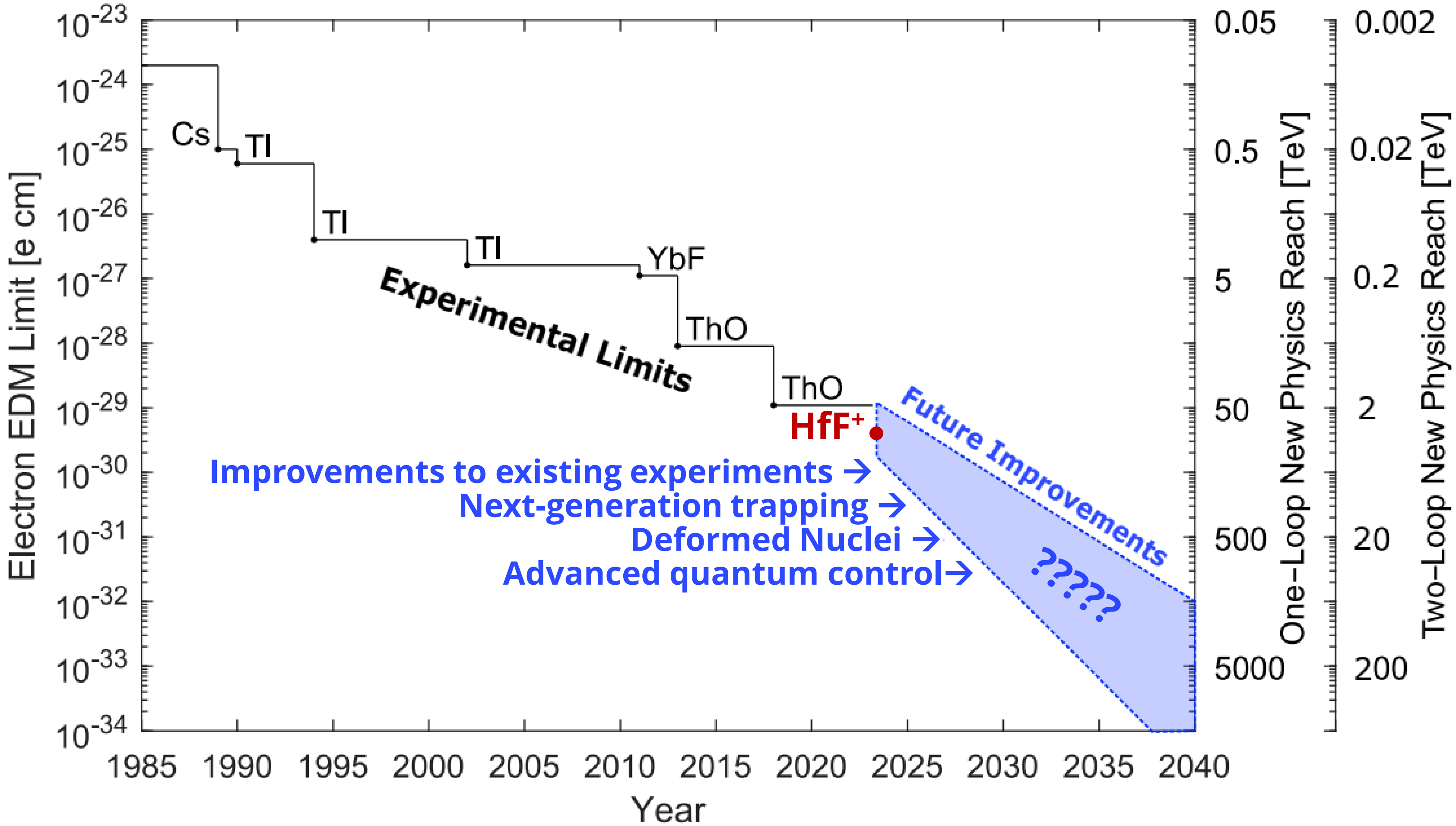


HfF⁺, JILA/Boulder

- Spin precession in ion trap
- $|d_e| < 1.3 \times 10^{-28}$ e cm (2017)
- **$|d_e| < 4.1 \times 10^{-30}$ e cm (2023)**

- **Electron CPV only**
- **100x in 10 years**
- **Each is being upgraded**
- **More are under way**
- **Methods are being extended to nuclear CPV**

Future Improvements

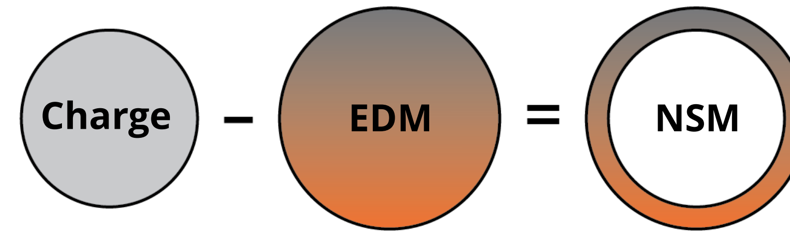


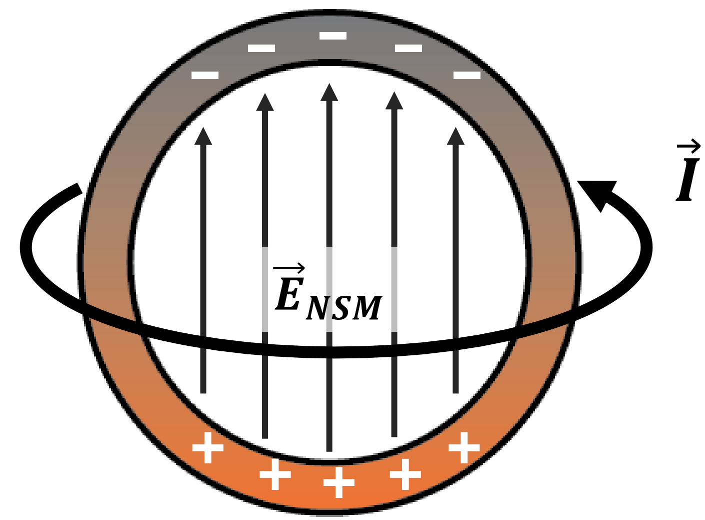
Similar improvements in hadronic CPV are also anticipated

From 2022 Snowmass EDM whitepaper, arXiv:2203:08103 **– Already out of date**

Nuclear Schiff Moments

- Non-overlap of charge, spin in nucleus creates Nuclear Schiff Moment (NSM)
  - Electric field $\vec{E}_{NSM} \propto \vec{I}$ confined within the nucleus
  - Mixes core-penetrating, opposite parity atomic orbitals
- Need atomic *s,p* orbitals to penetrate nuclear core
- Need $\vec{I} > 0$ to align $\vec{E}_{NSM}$



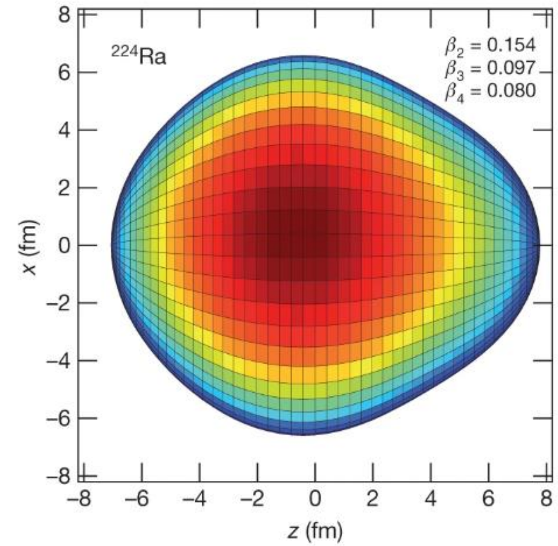


$$\langle S_0 \rangle \propto \sum_p \left(r_p^3 - \frac{5}{3} r_p \overline{r_{ch}^2} \right) z_p$$

V. V. Flambaum and J. S. M. Ginges, PRA 65, 032113 (2002)

Octupole Deformations

- NSMs can be enhanced in octupole-deformed (β_3) nuclei
  - Increases Q_{nuc} by **100-1,000**
- Combines with molecular Q_{pol} enhancements → **~10^6** sensitivity gain vs. atoms with spherical nuclei
- **The ability to trap and probe one molecule at a time would reach the frontiers of hadronic CPV**
  - Atomic experiments are very advanced, continue to advance, are hard to beat
- ^{229}Pa might have a further Q_{nuc} enhancement of $\sim 10^3$



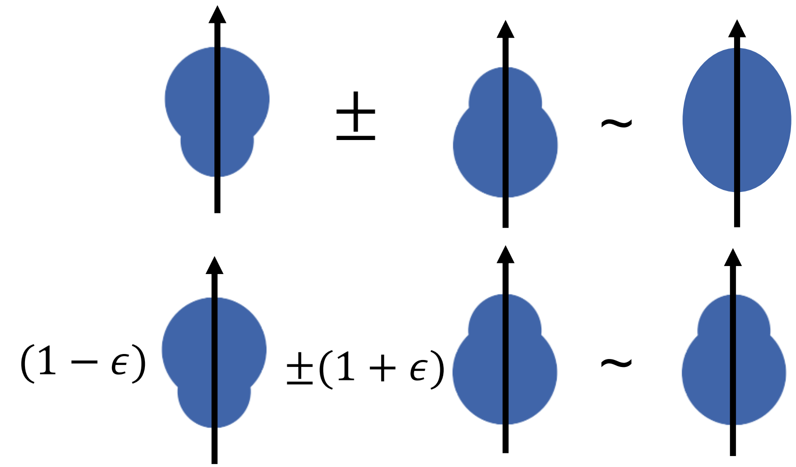
L. P. Gaffney et al., Nature 497, 199 (2013)

Z	Atom	S $[e\,\mathrm{fm}^3\bar{\theta}]$	$d_A[e\,\mathrm{cm}]$ $10^{-17}S[e\,\mathrm{fm}^3]$	$10^{-17}\bar{\theta}$
80	^{199}Hg	0.005	−2.50	−0.013
88	^{225}Ra	−1	−8.25	8
		Q_{nuc}	Q_{AM}	$Q_{nuc} \times Q_{AM}$

V. V. Flambaum and V. A. Dzuba, PRA 101, 042504 (2020)

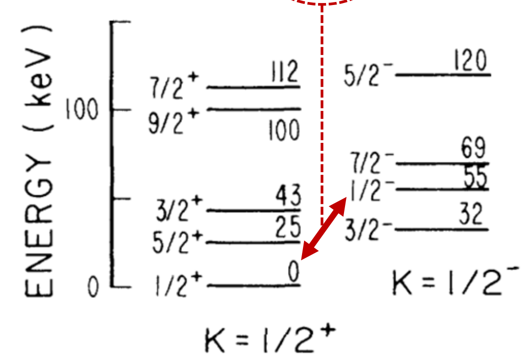
Why Octupole?

- In absence of symmetry violation, nucleus should be in superposition → octupole shape averages away
- PV, TV nuclear forces can mix these states
- Large charge, mass mismatch from asymmetric shape
- Deformed nuclei often have low-lying opposite parity states, ≲ 100 keV
    - Makes theory much more tractable → only few relevant states



$$\propto \sum_i \left(r_i^3 - \frac{5}{3} r_i \langle r_{ch}^2 \rangle\right) z_i$$

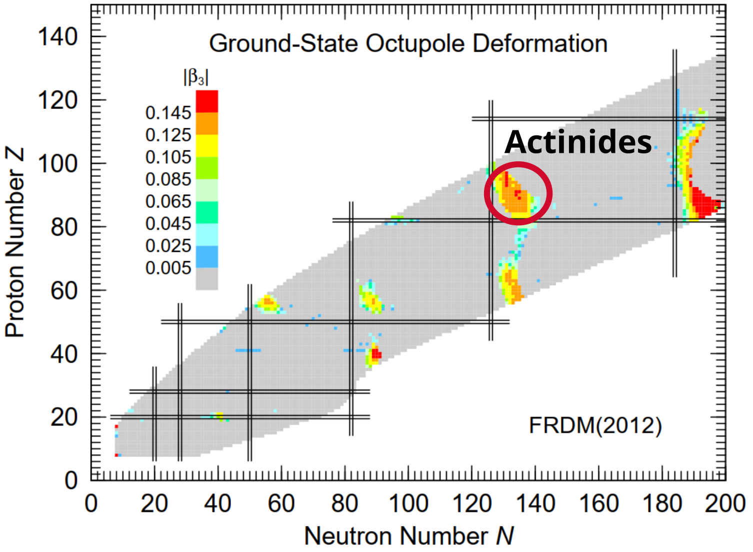
$$S \approx -2 \frac{\langle \Psi_0 | \hat{S}_0 | \bar{\Psi}_0 \rangle \langle \bar{\Psi}_0 | \hat{V}_{PT} | \Psi_0 \rangle}{\Delta E}$$



N. Auerbach, V. V. Flambaum, & V. Spevak, PRL 76, 4316 (1996)
J. Dobaczewski, J. Engel, M. Kortelainen & P. Becker, PRL 121, 232501 (2018), J. Engel et al., PRC 35, 1973R (1987)

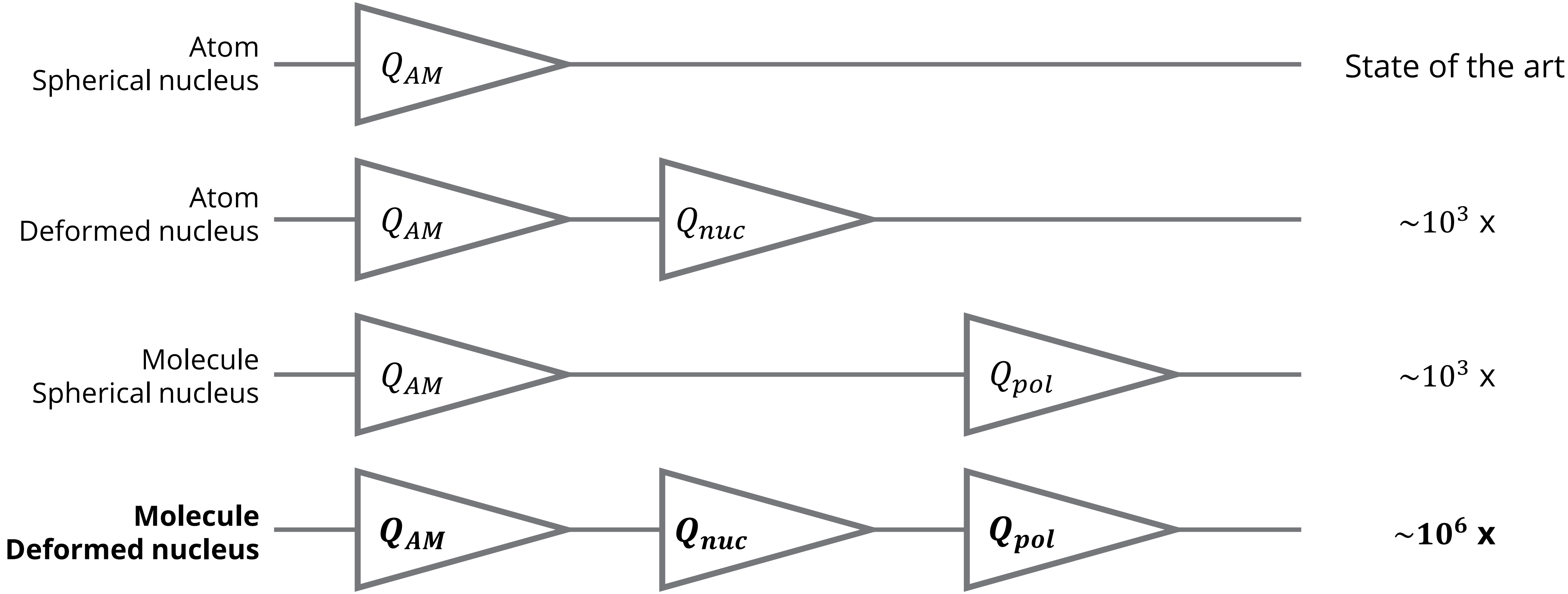
Radioactive Nuclei

- Heavy, spinful, octupole-deformed nuclei are radioactive
- Nuclei must be in a molecule amenable to quantum control
  - Synthesis, spectroscopy, measurement protocol development, …
- All of these pieces are coming together



Isotope	Half-life
^{223}Fr	22 min
^{225}Ra	15 d
^{223}Ra	11 d
^{227}Ac	22 yr
^{229}Th	7,900 yr
^{229}Pa	2 d

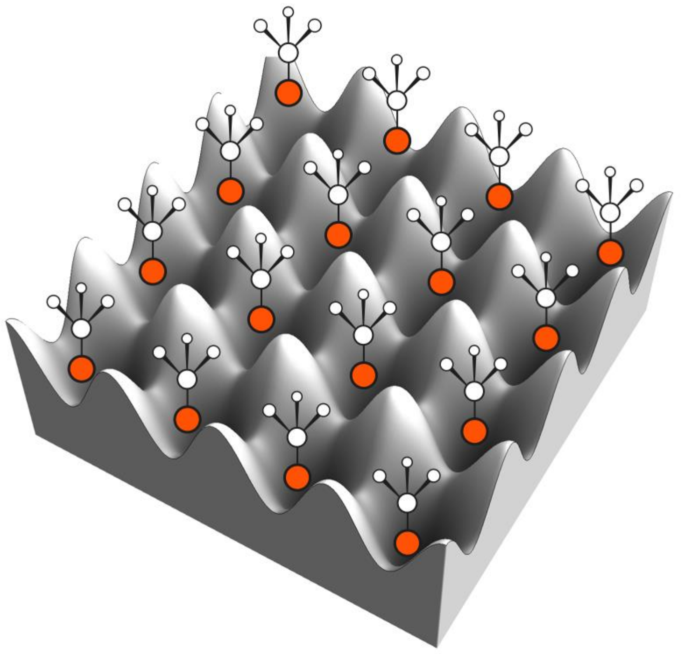
Combining Enhancements



Radioactive molecules offer a unique opportunity to probe far beyond the current frontiers of fundamental symmetries

10^6 molecules
100 s coherence time
Heavy, deformed nucleus
Quantum control
Robust error rejection

>PeV-scale CP-violating physics @ 1 loop
>100 TeV-scale CP-violating physics @ 2 loops
Both leptonic and hadronic sectors
Extreme precision, $\theta_{QCD} < 10^{-14}$
Near Standard Model limit for NSMs



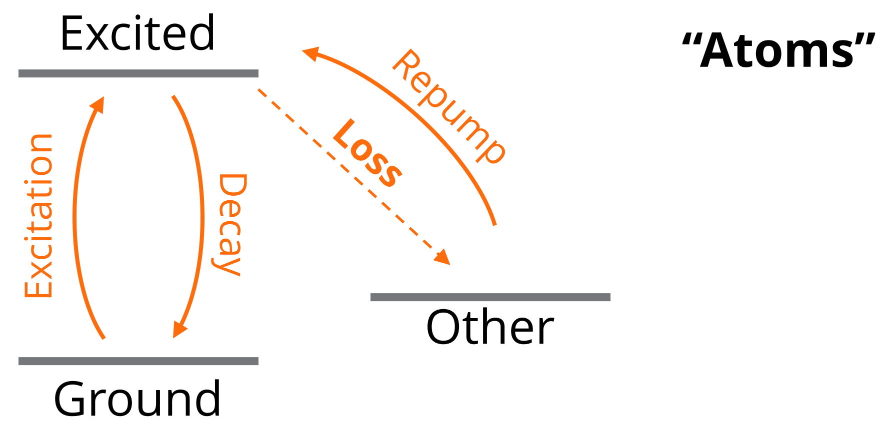
Future orders-of-magnitude improvements from quantum-enhanced metrology, highly exotic nuclei, ...

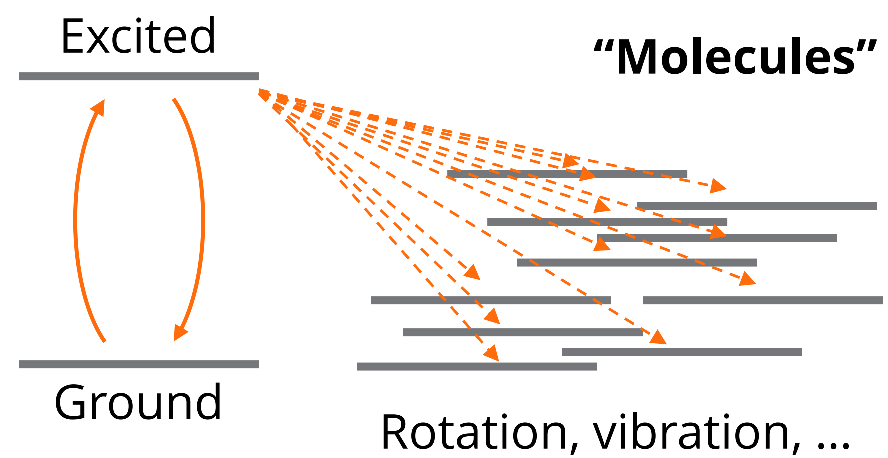
How can we implement advanced quantum control in CPV-sensitive molecules?

Advanced Quantum Control

Photon cycling in molecules

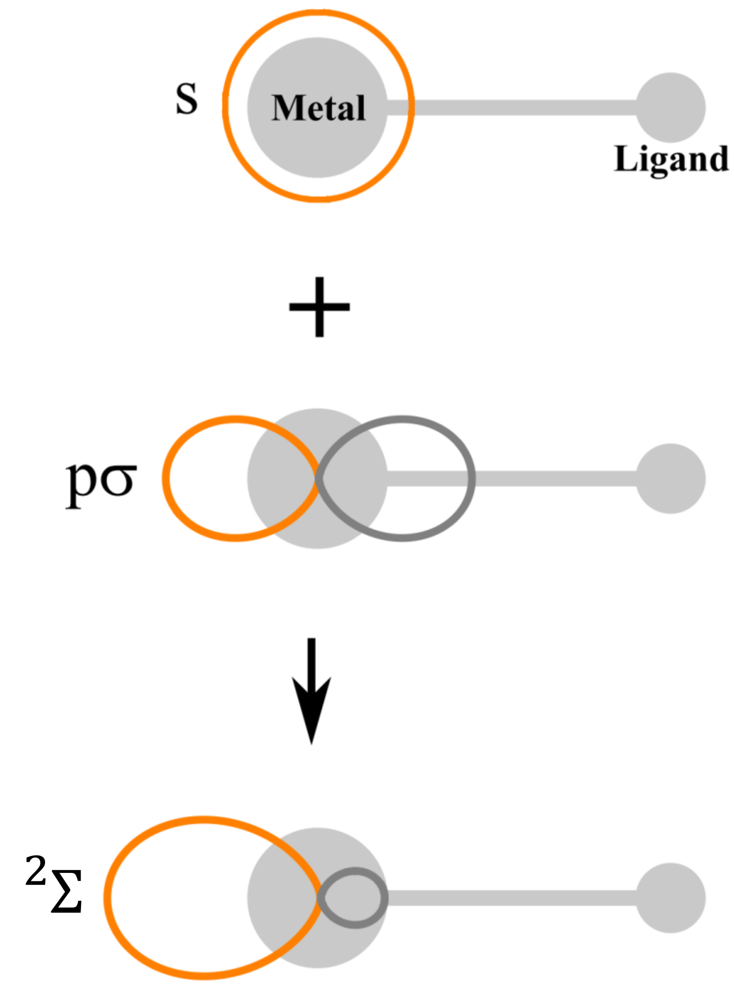
- The ability to scatter many photons is useful for quantum control in gas phase molecules
  - Efficient state control through optical pumping
  - Efficient detection
  - Optical forces/ cooling/trapping
  - Critical ingredient in ultracoherent atomic experiments (clocks)
- Decay to other states stops the cycling process
  - Vibration is limiting factor
  - Rotation, hyperfine → "solved"





Electronic structure for optical cycling

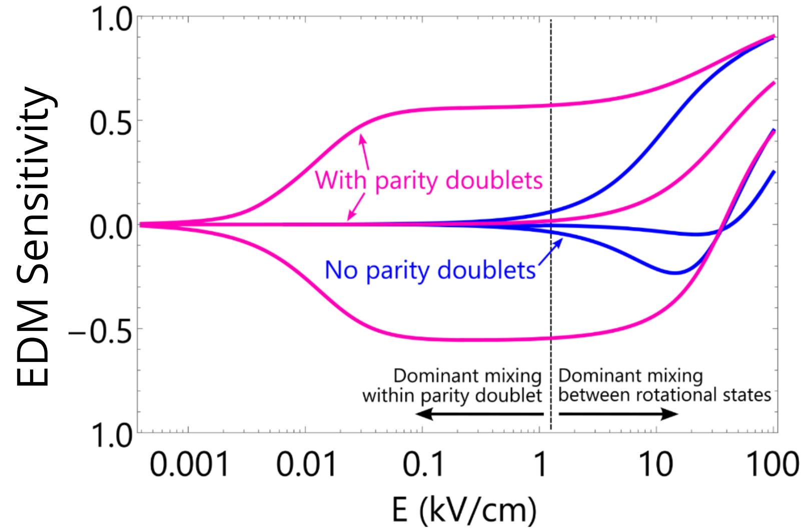
- Generally works for single, metal-centered s orbital
  - Alkaline-earth (s^2)
  - Single bond to halogen (F)
- Orbital hybridization pushes electron away from bond
  - Decouples electronic structure from molecular excitations
- CaF, SrF, BaF, YbF, RaF,…
- Generally holds for pseudohalogens
  F → OH, CCH, OCH_3, …
- This structure also gives good CPV sensitivity
  - Core-penetrating electrons

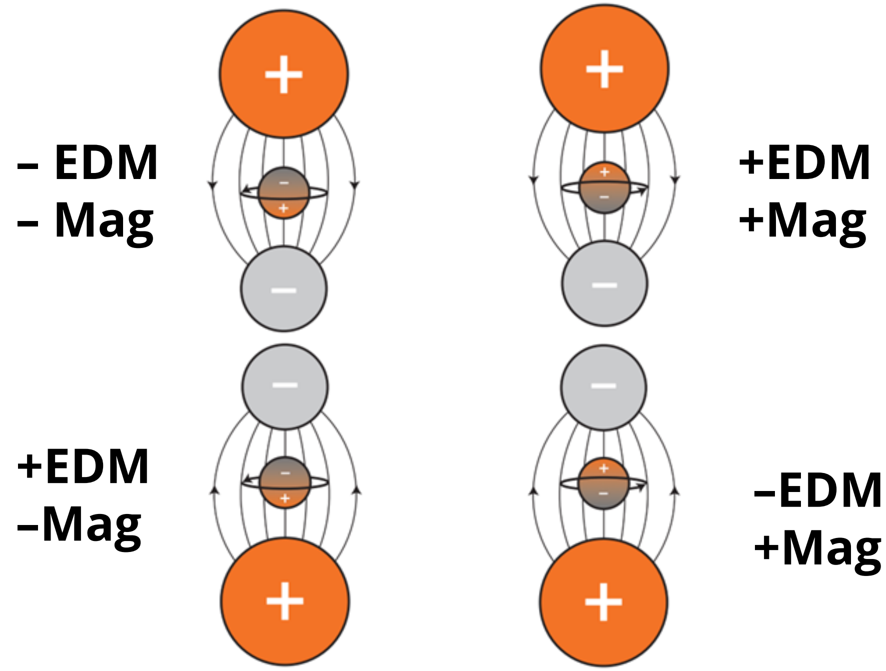


Parity Doublets

- Challenge: CPV experiments also rely on high polarizability
  - CPV sensitivity ∝ polarization
- Current best experiments utilize "parity doublets"
  - Each level in rotational ladder is split into a doublet
- Large polarization, small fields
  - Typically $\mathcal{O}(1)$ in $\lesssim$100 V/cm
  - Significantly easier engineering
  - Many systematics are ∝ E field
- Suppresses E,B systematics
  - States with oppose EDM, magnetic energy shifts
  - "Internal co-magnetometers"
  - Critical for leading experiments
- Laser coolable $^2\Sigma$ diatomics don't have these

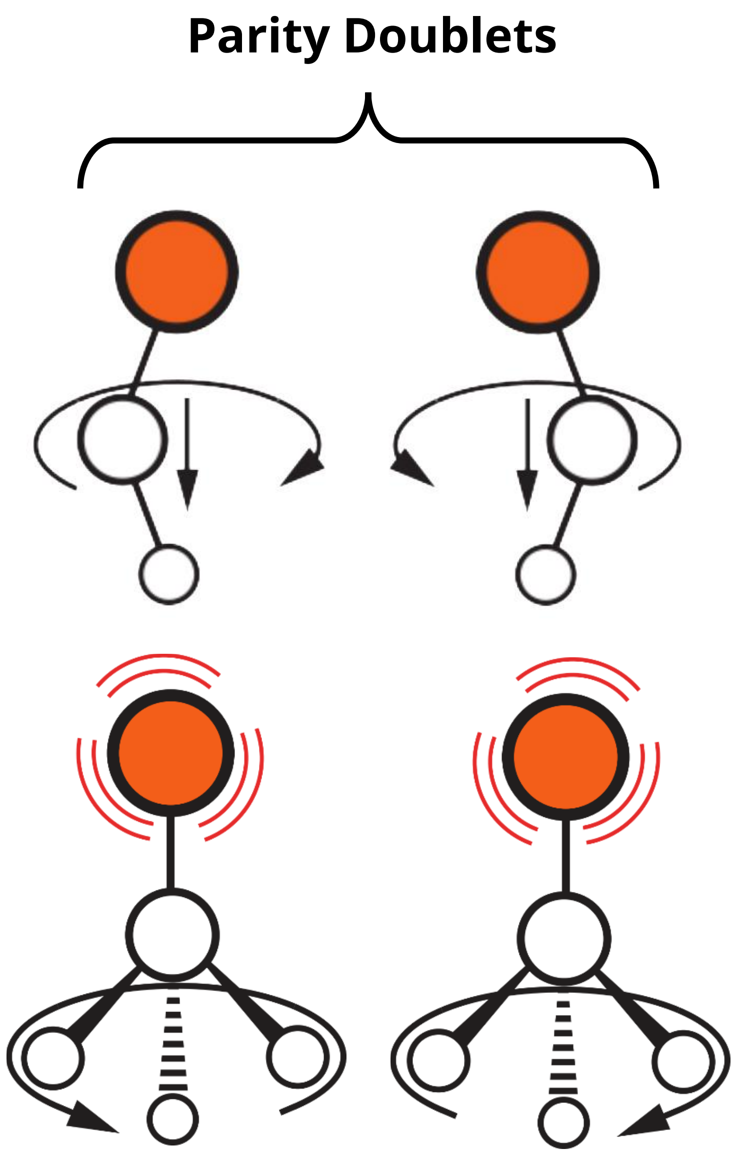
Augenbraun et al., Adv. AMO Phys. 72, 89 (2023)





Polyatomic Molecules

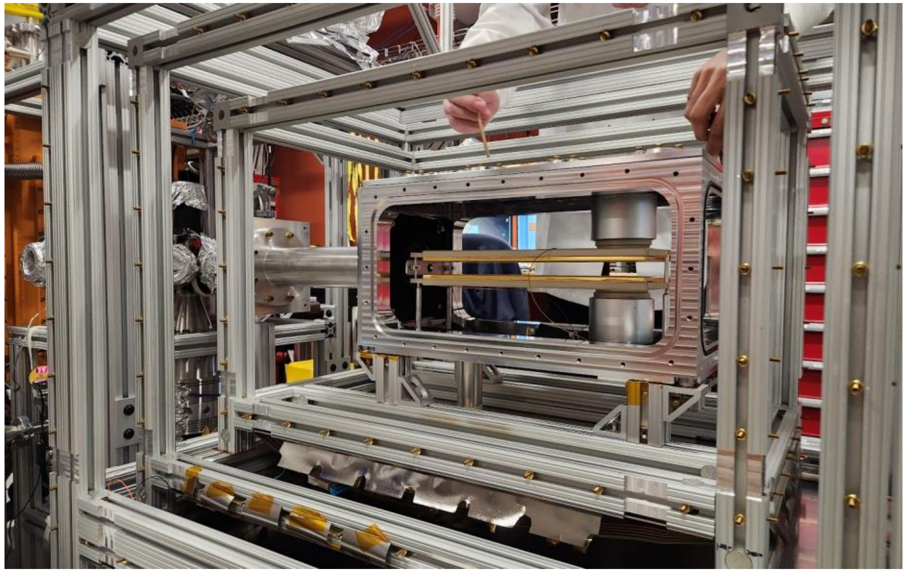
- One solution: polyatomics generically have parity doublets
  - Arise from symmetry-lowering mechanical motions
- Use ligand as a resource to engineer molecule
  - Maintains laser cooling (usually)
  - Gives parity doublets
  - Tune electromagnetic sensitivity
- Solves two important limitations with laser-coolable diatomics
  - No doublets → hard to polarize
  - Unpaired electron → magnetic

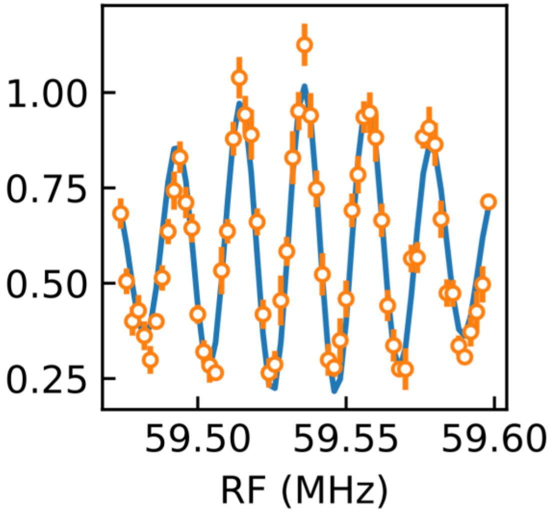


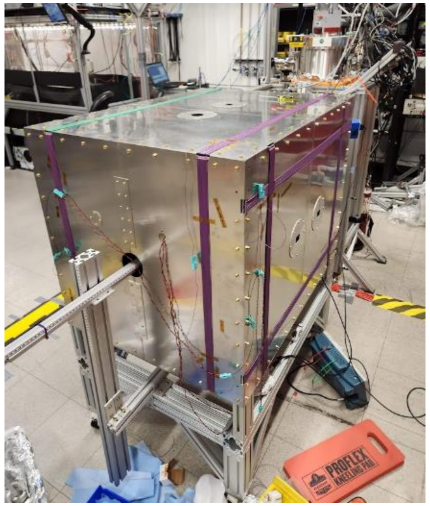
I. Kozyryev and NRH, PRL 119, 133002 (2017)

^{173}YbOH NMQM @ Caltech

- MQM search in ^{173}YbOH
- ^{173}Yb has large MQM sensitivity
- Cryogenic buffer gas beam
- Laser cooling in future generations
- Parity doubling due to vibrational bending
  - Polarize in ~100 V/cm
  - Internal co-magnetometers
- All-optical spin precession and readout

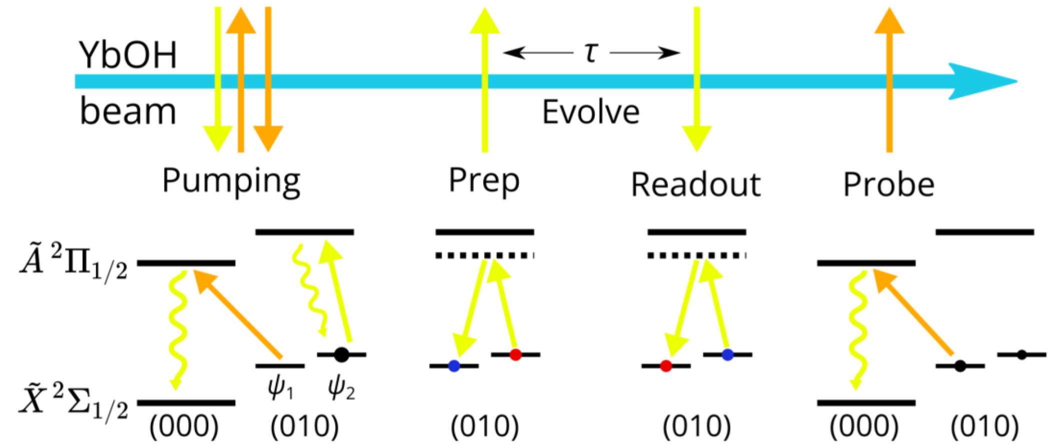


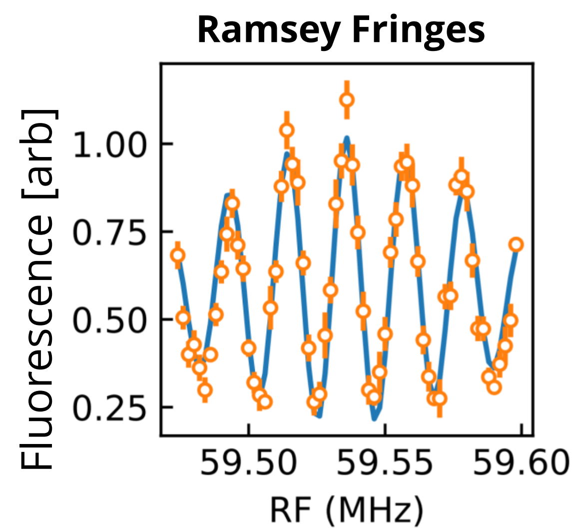




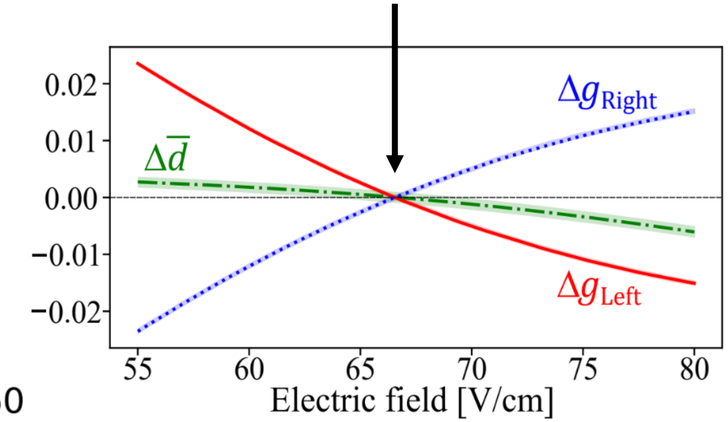
Spin Precession

- Observed electron spin precession in bending mode
- Use two-photon transition to prepare, read superposition
- Can engineer field-insensitive clock transitions to suppress decoherence
  - Generally useful for a wide range of species
  - Helps address problems from large nuclear hyperfine structure (relevant!)





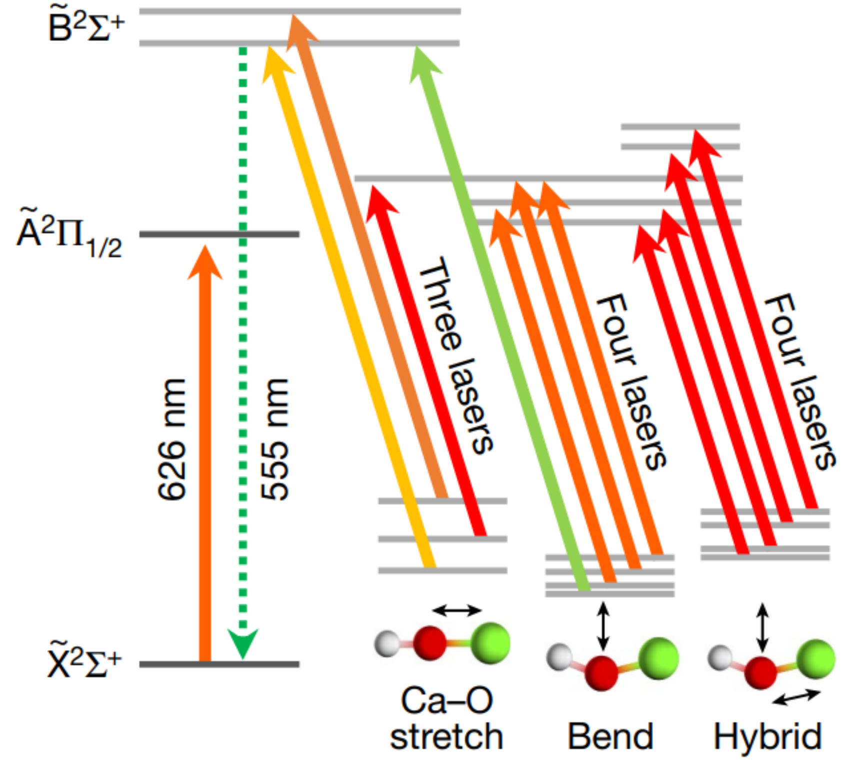
>100x suppression of field sensitivity



Y. Takahashi, C. Zhang, A. Jadbabaie, NRH, PRL 131, 183003 (2023)

EDM Pathfinder

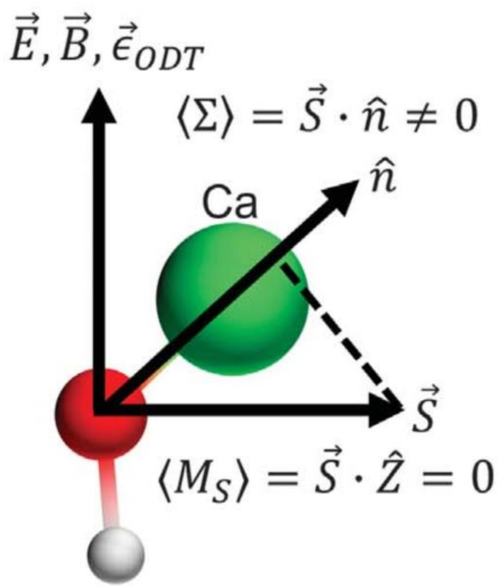
- Pathfinder experiment using trapped, ultracold **CaOH @ Harvard with John M. Doyle**
  - Trapped at tens of μK
  - EDM sensitivity is small
  - Science state X(010) structure is identical to other [AE]-OH
- Demonstrated PolyEDM
  - Full EDM protocol
  - Directly applicable to similar species (Sr, Ba, Yb, Ra)OH
  - PolyEDM science species: **SrOH**

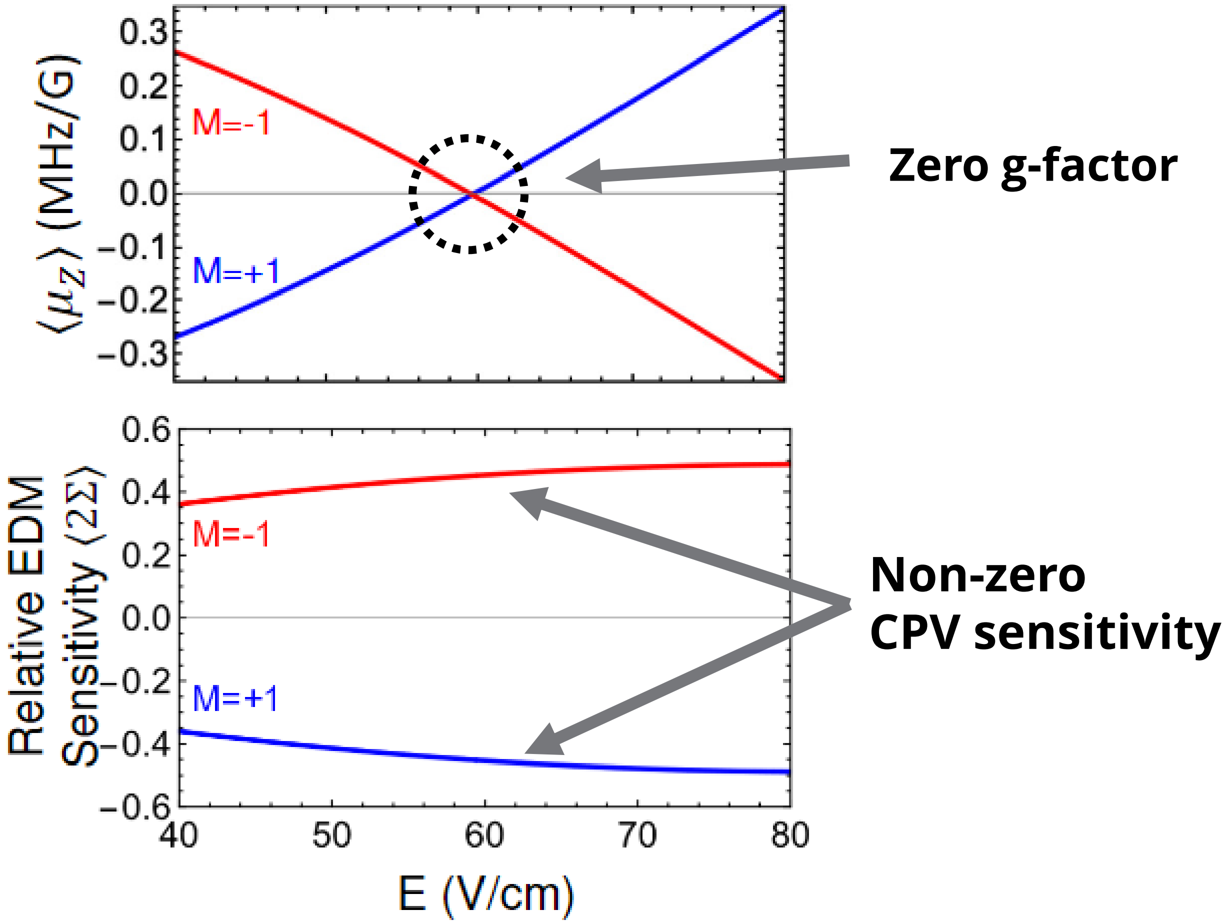


Loïc Anderegg
Harvard University

Engineering Coherence

- Able to tune-out magnetic sensitivity
- Tune magnetic projection via E field

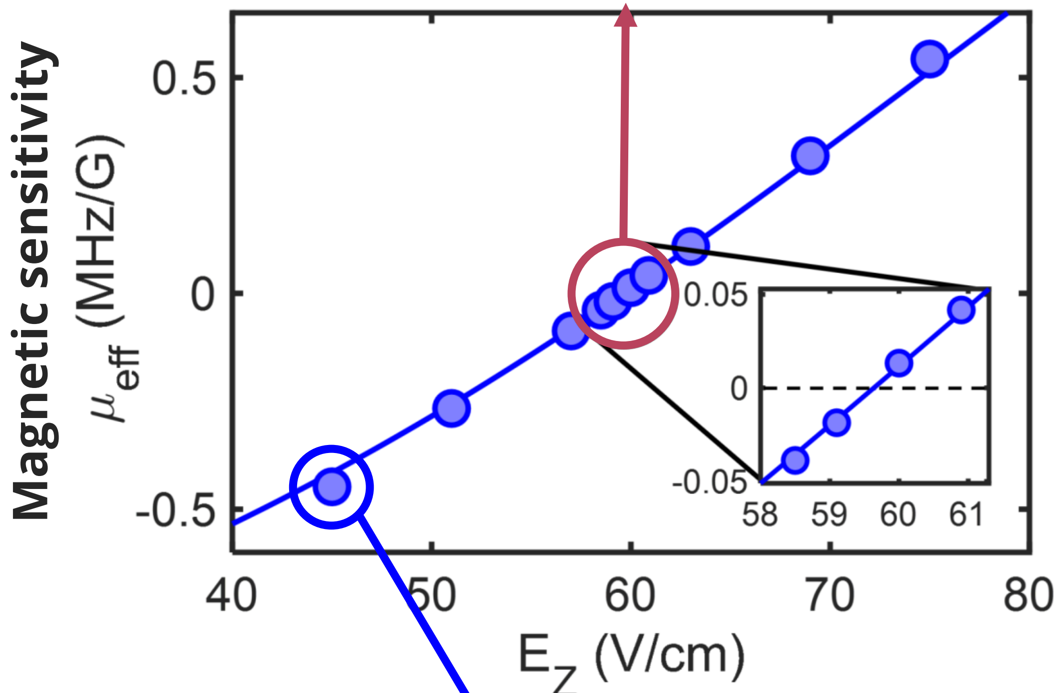


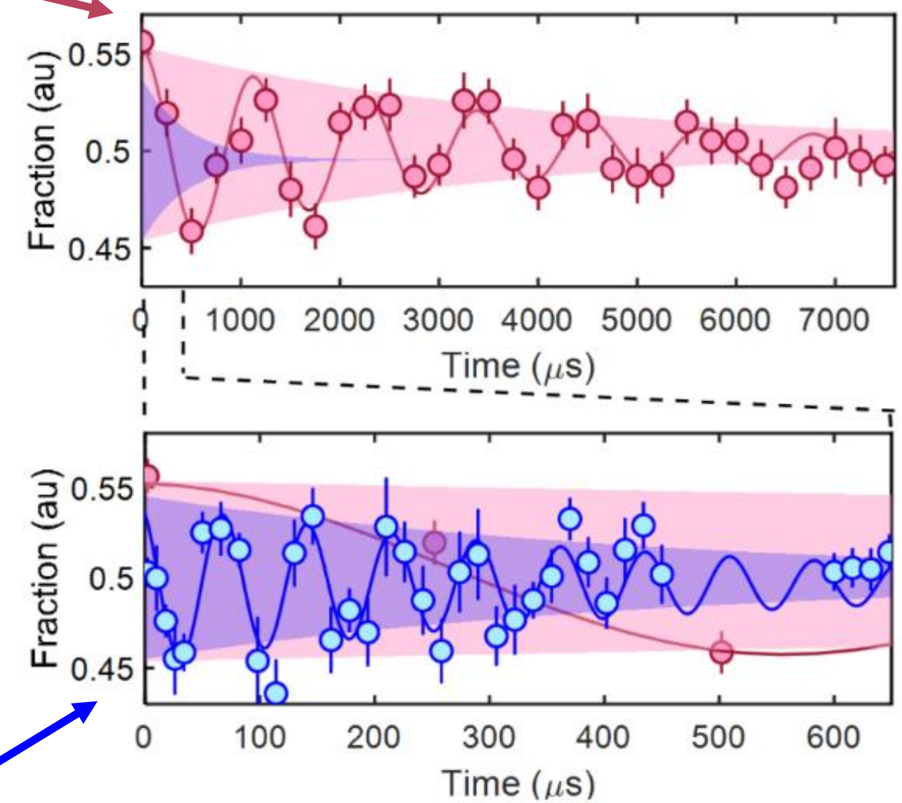


L. Anderegg, N. B. Vilas, C. Hallas, P. Robichaud, A. Jadbabaie, J. M. Doyle, and NRH, Science 382, 665 (2023)

Engineering Coherence

Long coherence, up to 30 ms
>1s with quieter apparatus
(stainless chamber, no shielding, etc.)





Short coherence, <1 ms

L. Anderegg, N. B. Vilas, C. Hallas, P. Robichaud, A. Jadbabaie, J. M. Doyle, and NRH, Science 382, 665 (2023)

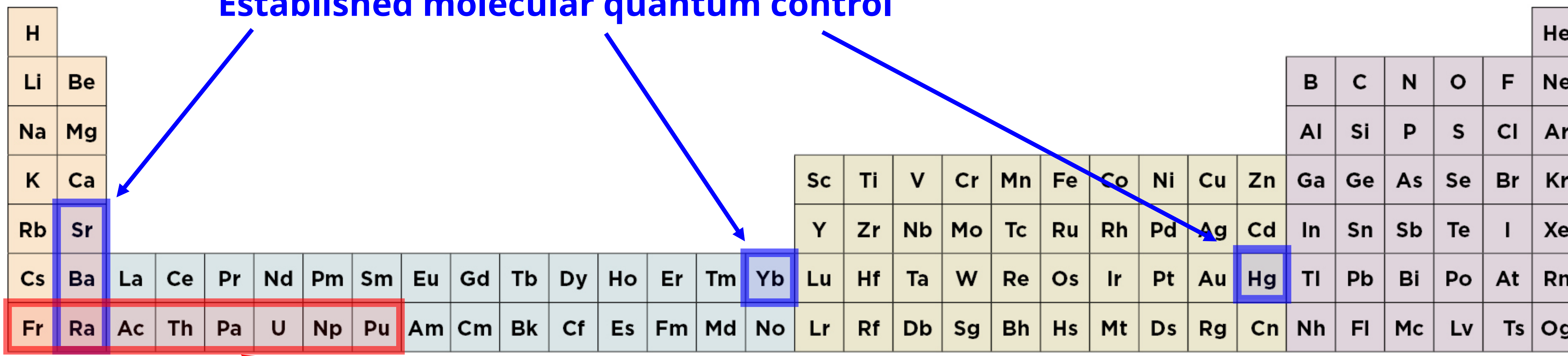
Radioactive Molecules

Can we find a species which combines everything I have discussed?

- Heavy, octupole nucleus → NSM enhancements
- Laser coolable → Advanced quantum control
- Polyatomic structure → Systematic error control

Where to start?

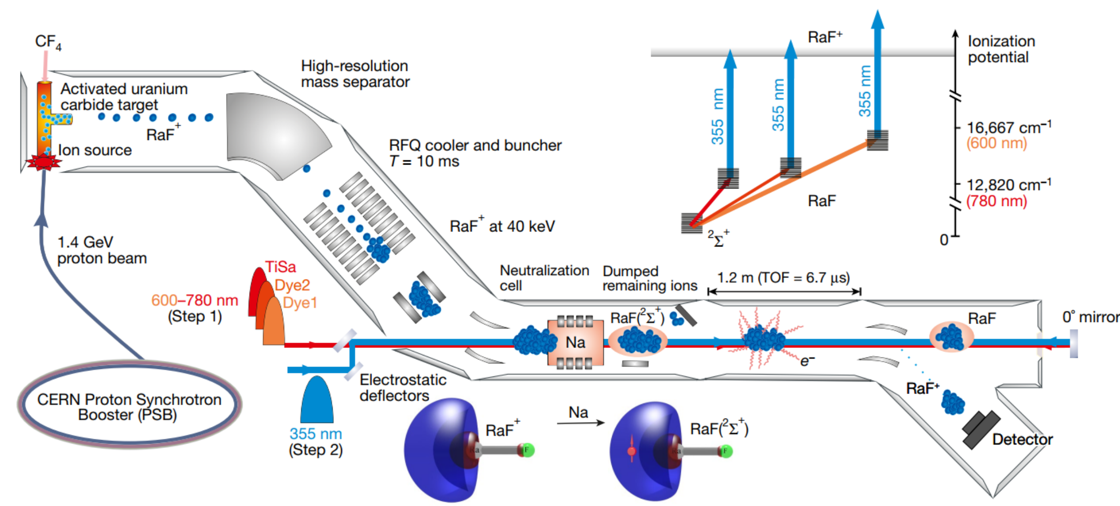
Established molecular quantum control



Octupole nucleus

Radium

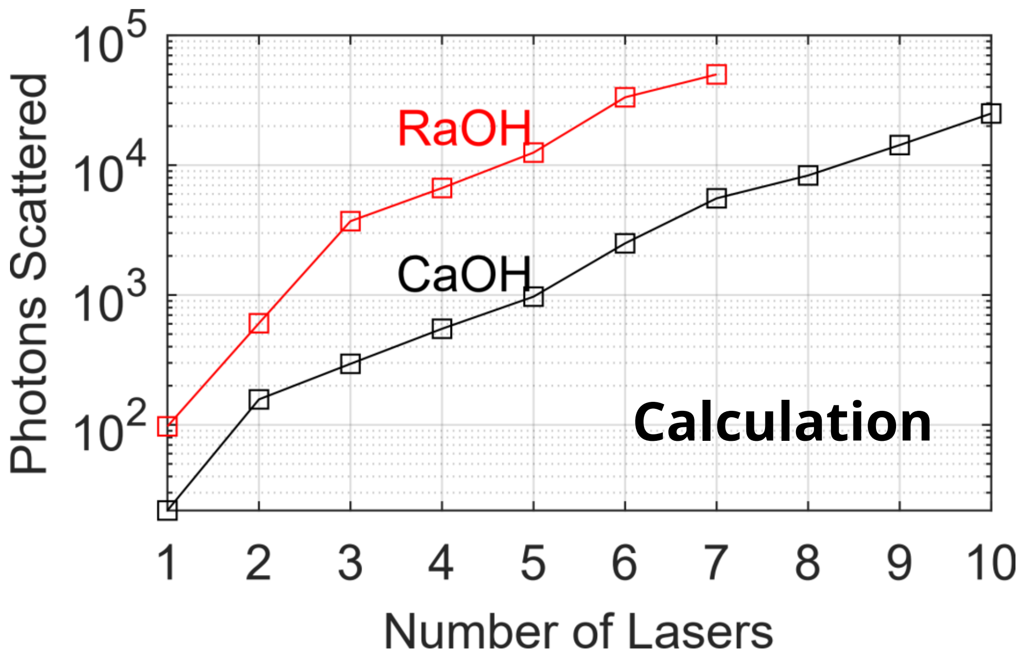
This contributed to motivation for groundbreaking RaF work



R. F. Garcia Ruiz *et al.*, Nature 581, 396 (2020)
T. A. Isaev, S. Hoekstra, and R. Berger, PRA 82, 052521 (2010)

Neutral Radium Polyatomics

- RaOH is the simplest molecule combining everything I have discussed
  - Laser cooling
  - Molecular enhancement
  - Octupole deformed nucleus
  - High polarizability
  - Tunable magnetic moments
  - Advanced quantum control
  - …
  - **Demonstrated protocols**
- Predicted to be *very* laser-coolable
  - Periodic trends help the ability to cycle photons in this case
- More complex ligands in future
- Could probe boundaries of leptonic and hadronic CPV with only a few trapped molecules
- **Need to produce and cool to ~few K to apply the methods I discussed**

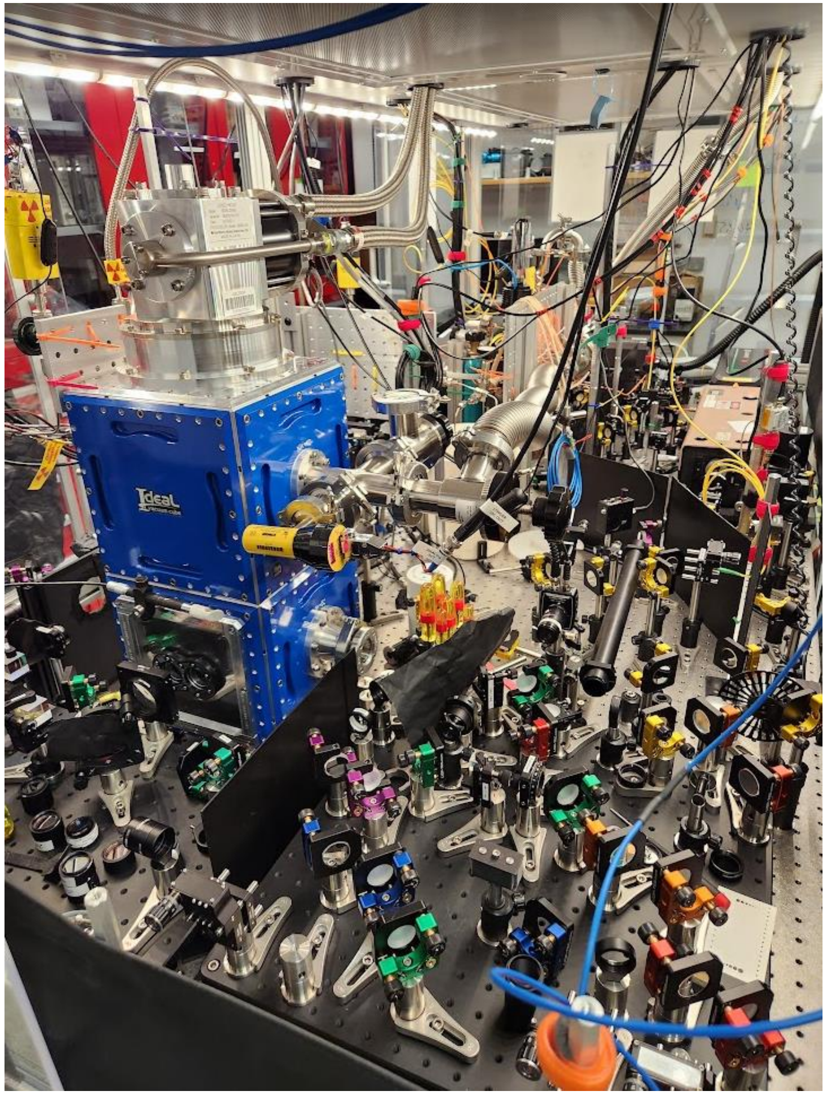


C. Zhang, NRH, L. Cheng, J. Chem. Theory Comput. 19, 4136 (2023)

See also:
T. A. Isaev, A. V. Zaitsevskii, E. Eliav, J. Phys. B. 50, 225101 (2017)
I. Kozyryev and NRH, Phys. Rev. Lett. 119, 133002 (2017)

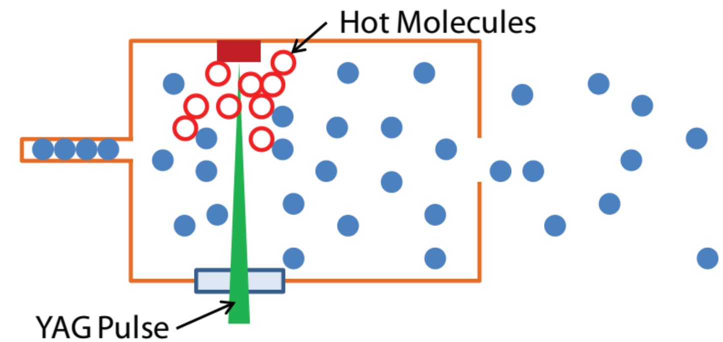
RaOH Spectroscopy

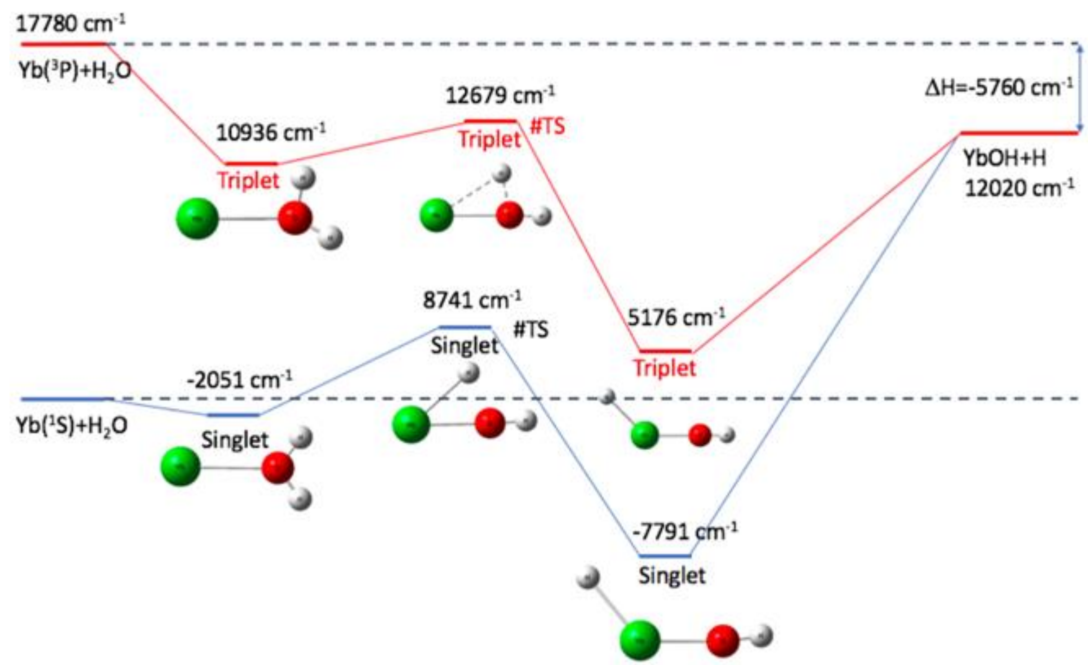
- Recently started studying $^{226}RaOH$ at Caltech
- Tabletop apparatus
- Cooled to 4 K
- Main challenge: quantity
  - (Obviously)
- Once the quantity problem is addressed, we can use the full quantum control toolbox



Molecular production

- MOH are free radicals
  - M=Ca, Sr, Ba, Yb, Ra
- Create via cryogenic buffer gas cooling
- Vaporize solid targets with pulsed laser
  - Some combination of M, O, H
  - We have tried many, many things
- Cool to 4 K with cryogenic helium
  - Translationally and internally
- Optically drive chemical reactions to create desired species
  - Excited M can overcome reaction barriers
  - Increase yield ~10x
  - Has been demonstrated in all of these different species
- Can make cold, slow, intense beams with an aperture in the gas cell





A. Jadbabaie, N. Pilgram, J. Kłos, S. Kotochigova, NRH, New J. Phys. 22, 022002 (2020)
NRH, H. Lu, and J. M. Doyle, Chem Rev 112, 4803 (2012)

Target Production

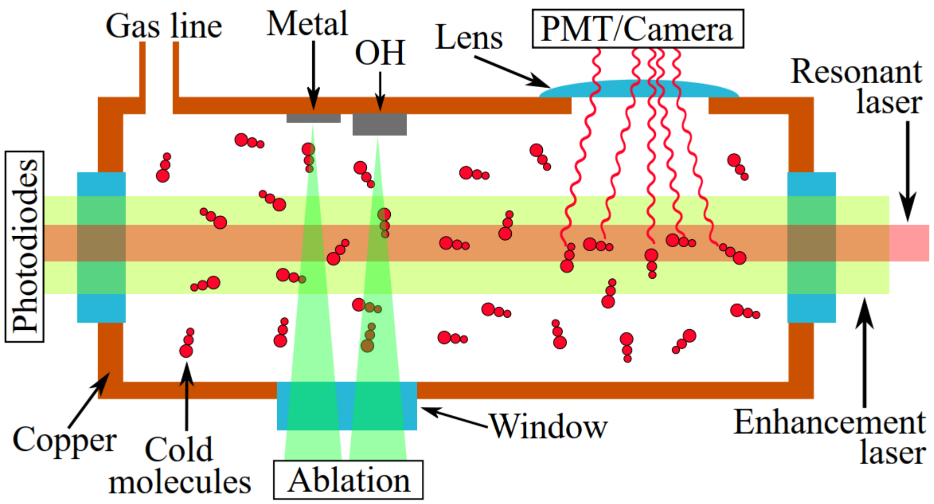
- Currently fabricating ablation targets in-house
- 10 μCi ^{226}RaCl solution from Eckert & Ziegler
  - 370 kBq, 10 μg, ~3 x 10^{16} atoms
- Pipette ("dropcast") solution onto substrate to evaporate
- Surround with (something)$_x$(OH)$_y$
  - We tried several things
- This is an area of major potential improvement
  - More later

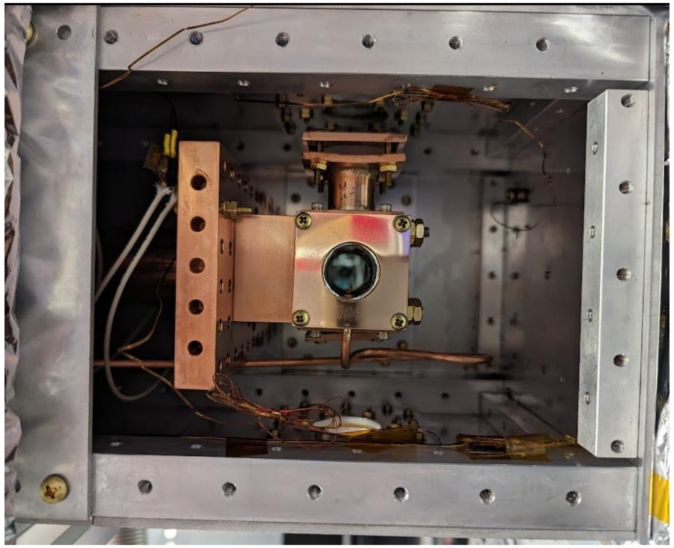
Isotope Lab @ Caltech

$RaCl_2$ surrounded by reaction precursors

Synthesis and Detection

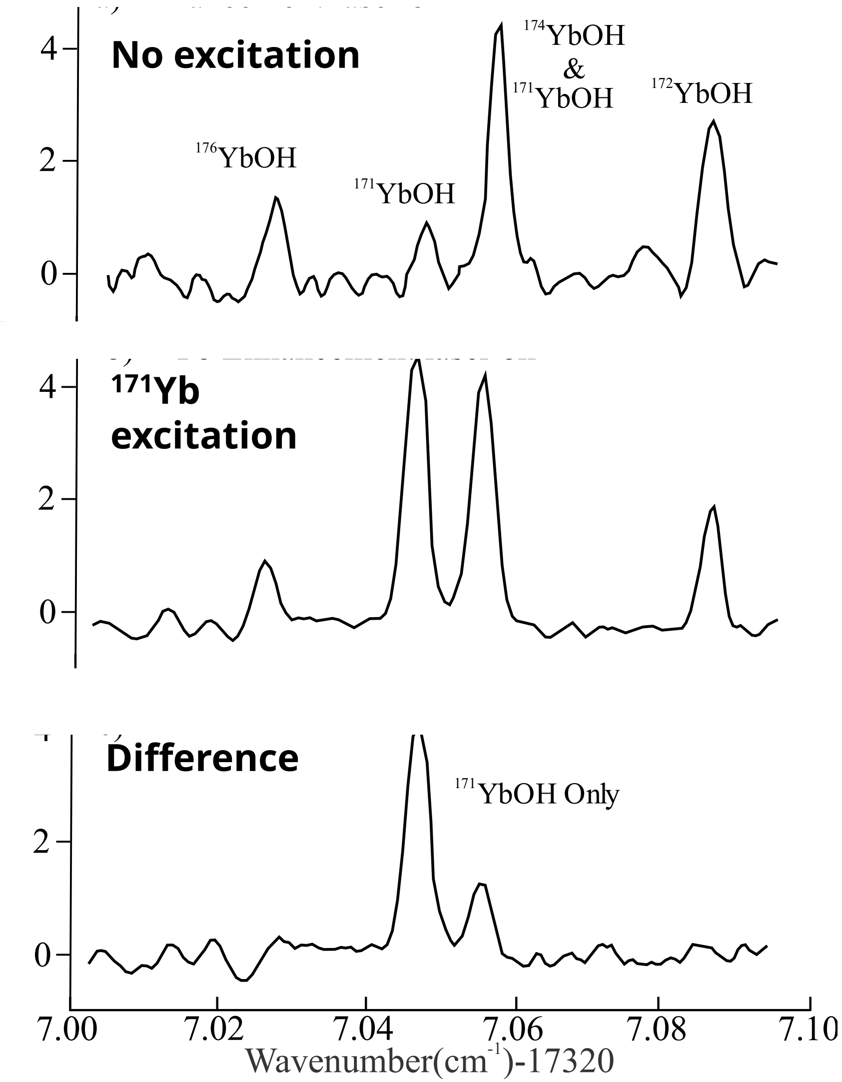
- Vaporize Ra and $Al(OH)_3$ with pulsed YAG
- $Ra^{*}+H_2O \rightarrow RaOH+H$
  - Excite Ra to metastable state
  - ${}^1S_0 - {}^3P_1$, 714 nm
- Cool RaOH with 4 K He
  - Molecules are cold, stopped
  - **Same starting point as other molecular precision measurement, laser cooling experiments**
  - Engineering challenges remain
- Detect RaOH through resonant fluorescence spectroscopy
- Also produced and detected RaOD with deuterated targets





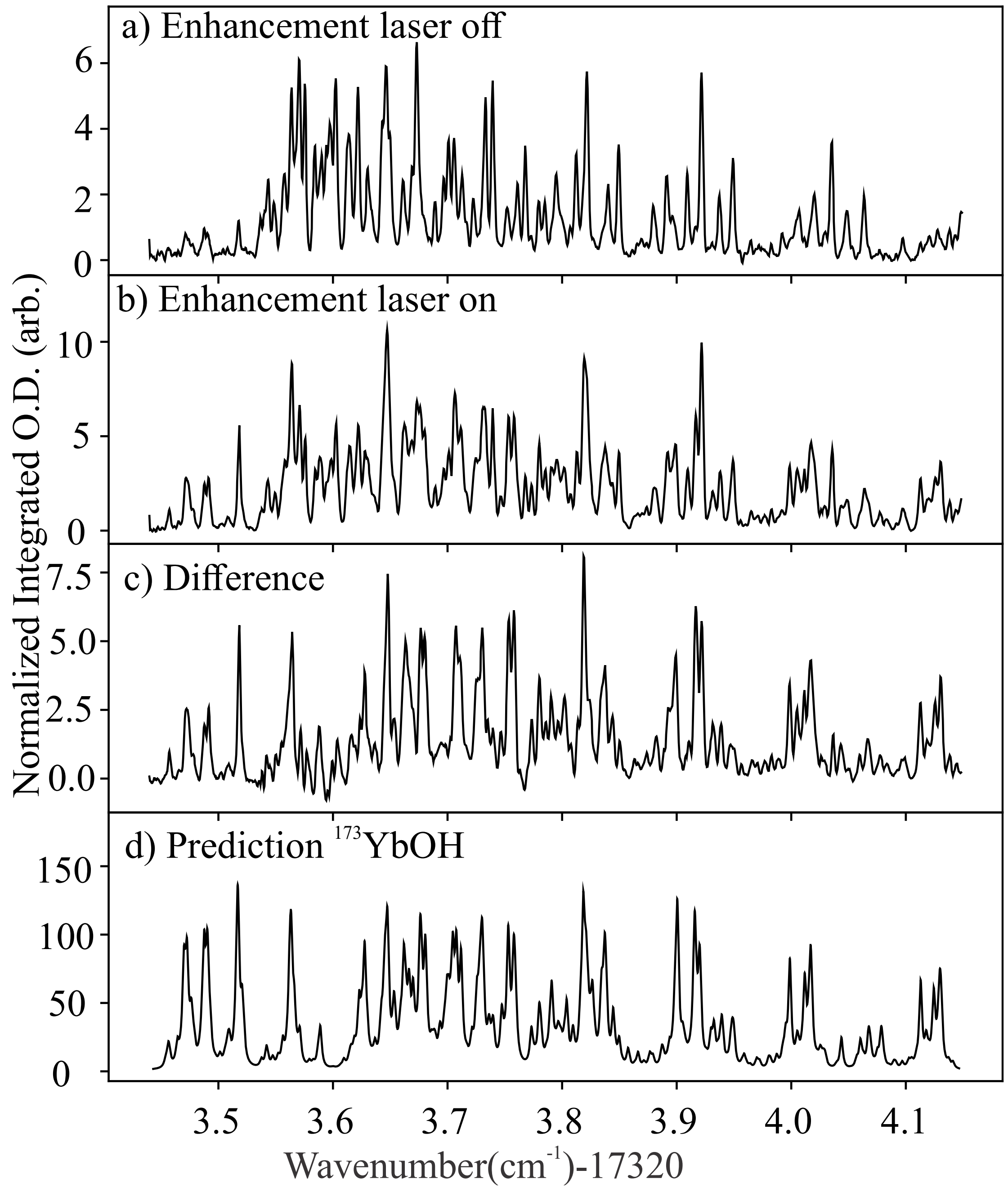
Species selectivity

- Ablation creates many species uncontrollably
  - How can we distinguish RaOH vs. ???
- Optically-driven M*+H_2O chemistry is ***resonant*** with metal M
  - M-containing molecules will change
  - Others will not
- Can even use to disentangle isotopologues since 4 K Doppler < Isotope shifts
- First demonstrated with YbOH spectroscopy
  - Very congested since multiple isotopes and isotope ~ hyperfine ~ rotation



N. H. Pilgram, A. Jadbabaie, Y. Zeng, NRH, T. C. Steimle. J. Chem Phys. 154, 244309 (2021)

Robust spectroscopy with dense and contaminated spectra



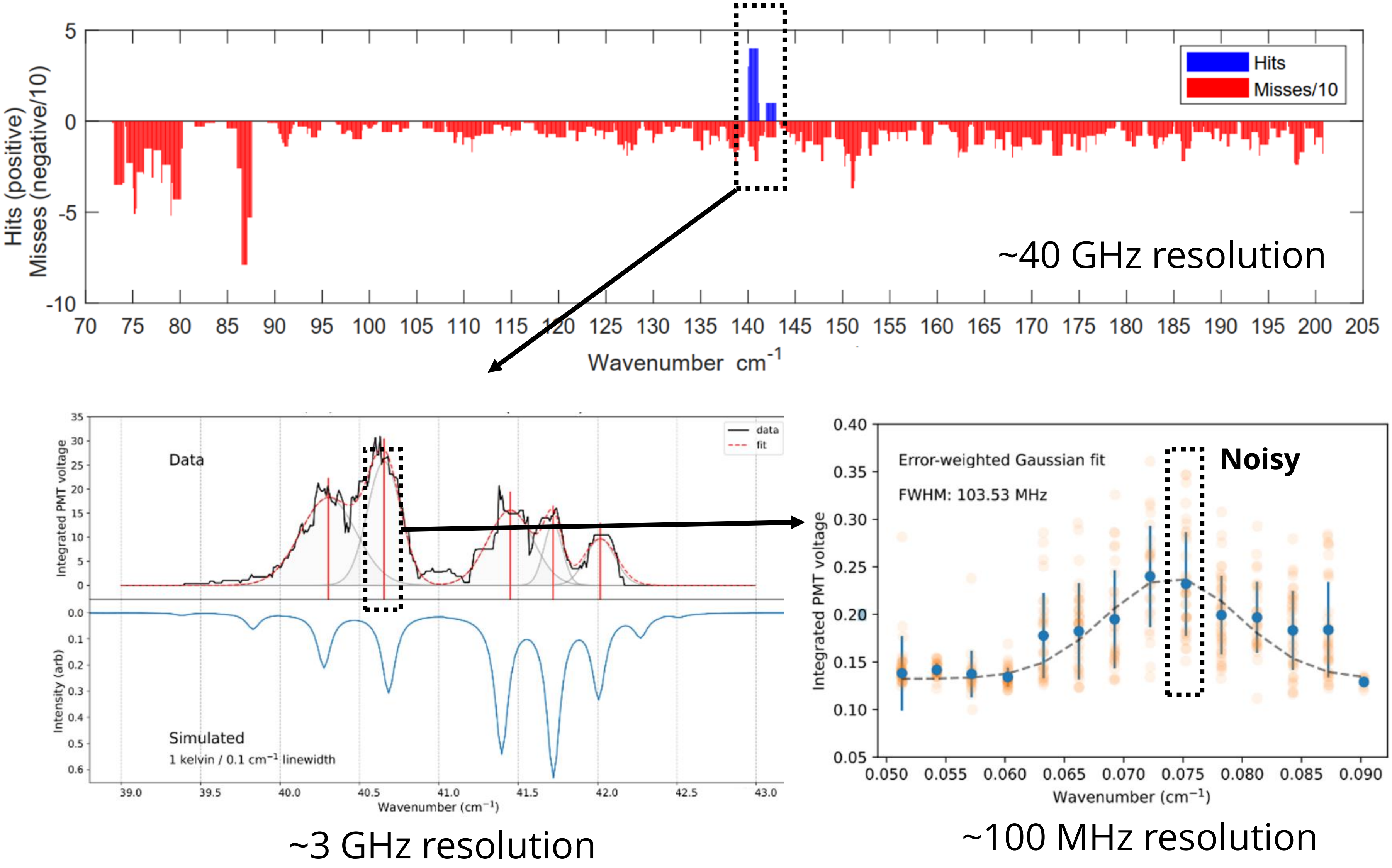
N. H. Pilgram, A. Jadbabaie, Y. Zeng, NRH, T. C. Steimle. J. Chem Phys. 154, 244309 (2021)

Search Approach

- Small quantity and theoretical uncertainties are challenges
  - 10 μCi → few thousand shots
  - Theory uncertainty → ~10 THz
  - Linewidth ~100 MHz
  - (10 THz)/(100 MHz) ~ 10^5
- Solution: phased search
  - ~40 GHz → ~3 GHz → ~100 MHz
  - This is common, but adapting to our system took work
  - (Typical ns pulsed lasers present challenges)

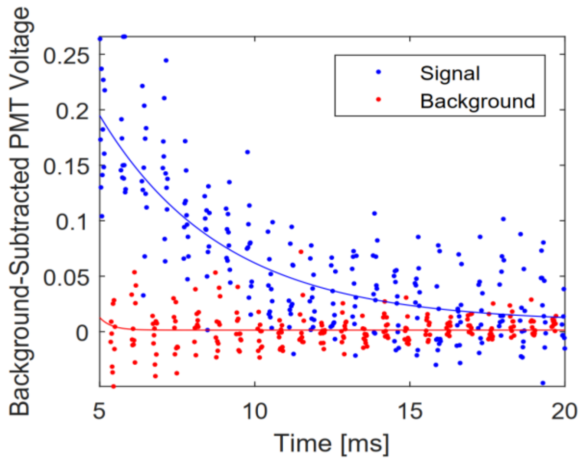
Partially depleted Ba target

Cold RaOH Spectroscopy - Preliminary

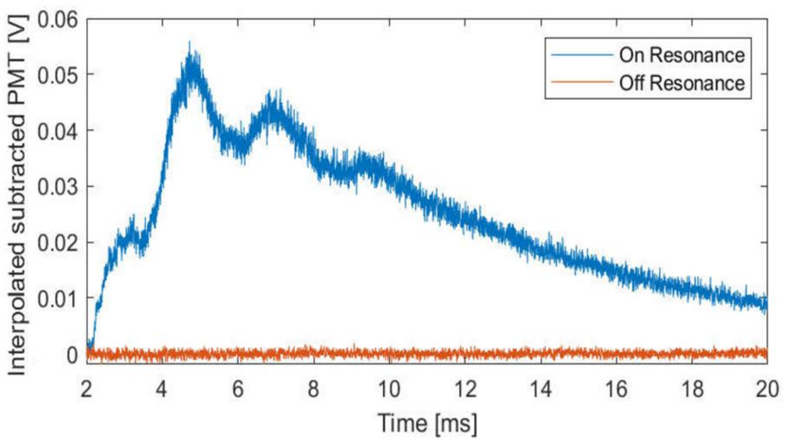


Improvements

- Previously: resolution limited by inconsistent production
  - Large shot-to-shot fluctuations
  - → too many averages needed
- Improvements in last few months
  - Mostly with BaOH, handled in equivalent forms and amounts, as a proxy
  - Improved atomic production via dropcasting tweaks
  - Atomic normalization via strong $^1S_0 - {}^1P_1$ line (483 nm in Ra, 553 nm in Ba)
  - Optimized multi-pulse ablation
  - Aggressive background/noise reduction
    - Better amplifiers/digitizer
    - Lock-in detection
    - Helium cryoplasma mitigation
- Now: consistent single-shot BaOH fluorescence with signal/noise > 100
  - With old methods, never saw BaOH on a single shot
- Next radium run starting on Thursday!



RaOH
10 μCi
Last year
SNR ~ few
Inconsistent

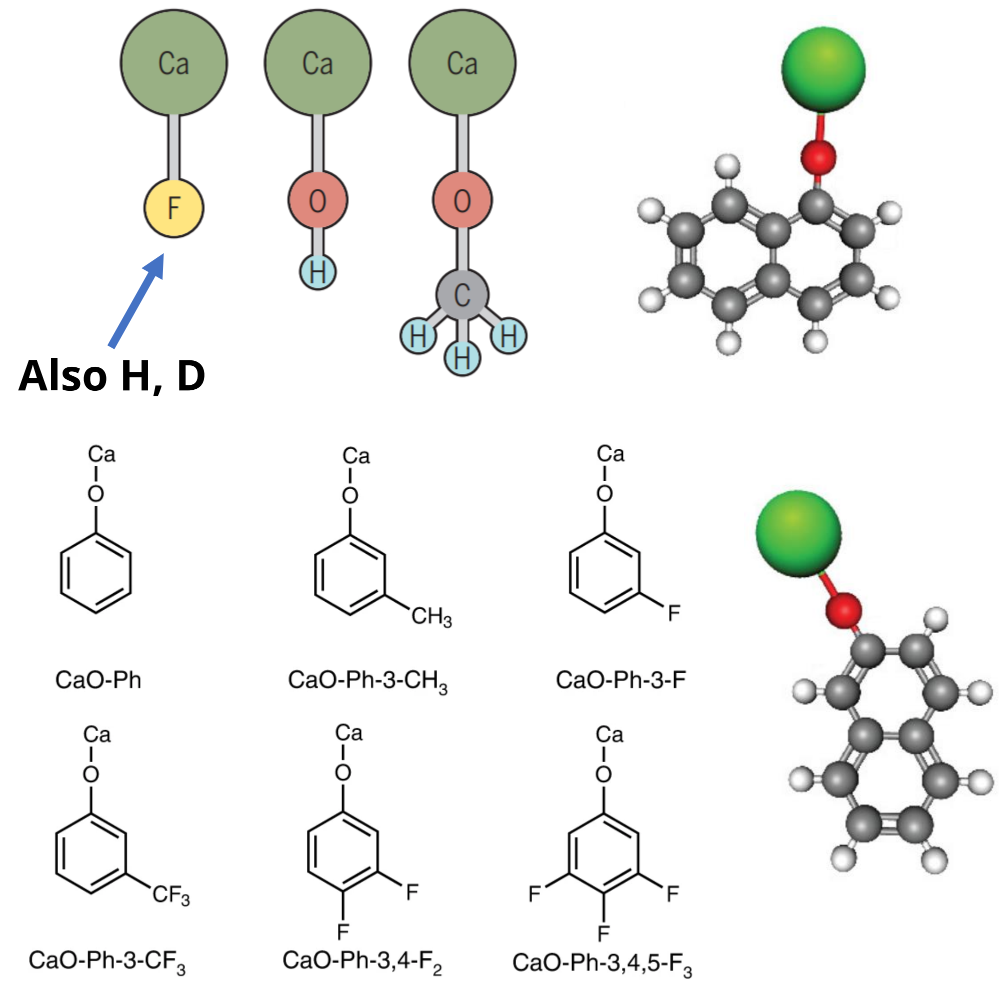


BaOH
10 μCi equiv.
Last week
SNR ~260
Consistent

Going Forward

- Improved ablation target production
  - Time consuming (hand pipetting)
    - Drop-on-demand?
    - Electrochemistry?
    - Something else?
  - Too expensive, pre-made RaCl $$$
    - Buy from DOE
    - Use other forms?
- Other ligands
  - Straightforward to change ligand
  - “We do this all the time”
  - Optimizing production still takes work
  - Can vary solid precursor or flow reactive gas
- Other species entirely?
  - Nuclear structure, nuclear astrophysics, exotic chemistry, … ?
  - In general, if we can get ≳ 10 ug of material we can probably make molecules out of it
  - Smaller quantities in the future as we push on the optimization
- **Combine with radioactive beam methods**
- **Shorter lived isotopes**
- **This method would benefit greatly from increased interactions with the community!**

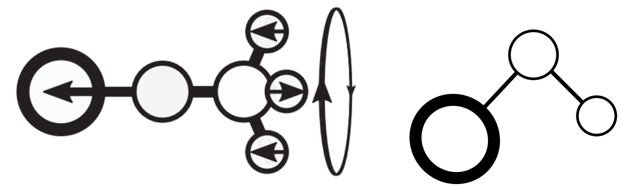
Calcium-containing molecules which have been buffer gas cooled



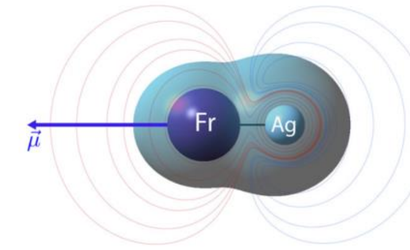
D. Mitra et al., J. Phys. Chem. Lett. 13, 7029 (2022), G. Lao et al., J. Phys. Chem. Lett. 13, 11029 (2022), G.-Z. Zhu et al., Nat. Chem. 14, 995 (2022)

Many other approaches

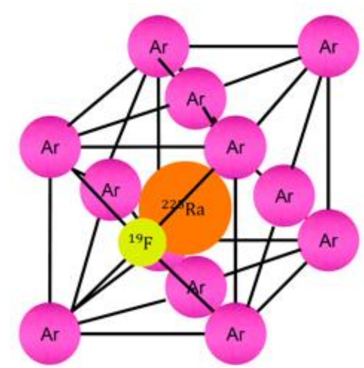
- See 2302.02165
- Other neutral molecules
  - RaF, AcX, ThX, FrX, PaX, …
- Photoassociated neutrals
  - FrAg, RaAg, …
- Molecular ions
  - RaX^+, ThF^+, $AcOH^+$, PaF_3^+, …
- Cryogenic matrices
  - RaX, Pa, …
- Atoms
  - Ra, Rn, …
- **We need experiments in multiple systems**
  - There is no best approach



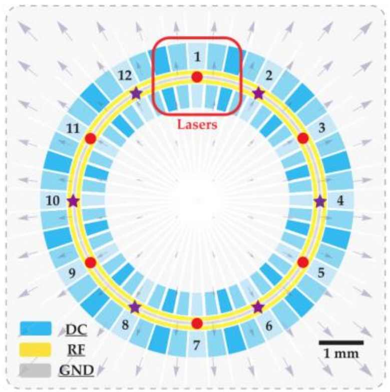
Radium polyatomic ions



FrAg



Solids

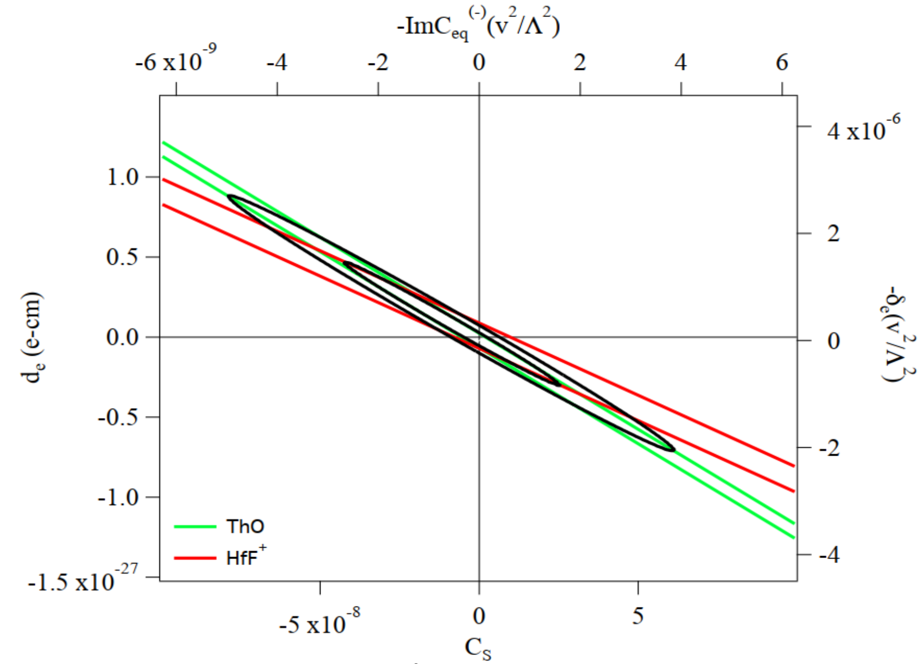


ThF^+

EDM, NSM, MQM – Complementarity

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

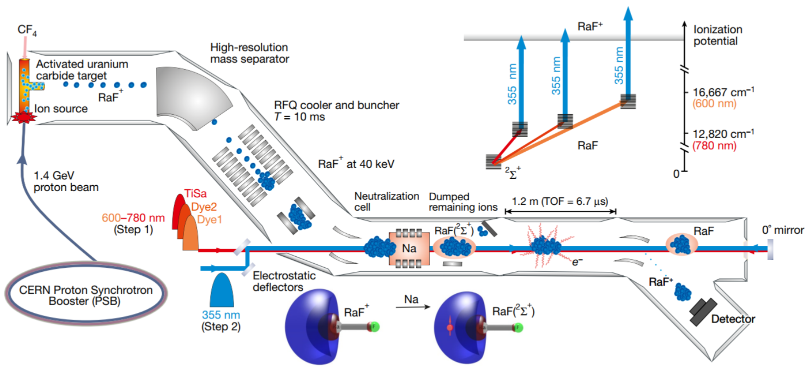
J. Engel, M. J. Ramsey-Musolf, and U. van Kolck, Prog. Part. Nucl. Phys. 71, 21 (2013)



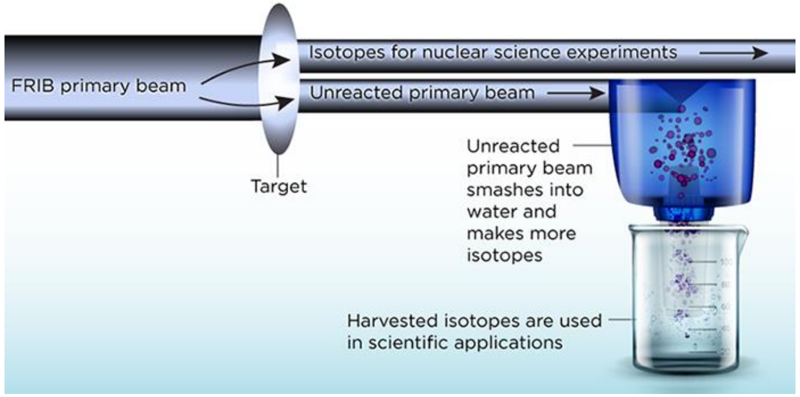
Snowmass EDM white paper, arXiv:2203.08103

- **Complex CPV parameter space <u>requires</u> multiple systems to obtain physically meaningful values**
  - Atom/molecule CPV measures a sum of sources
  - Need >1 eEDM and NSM and MQM, but also nucleon EDM
  - Dependencies are generally complementary

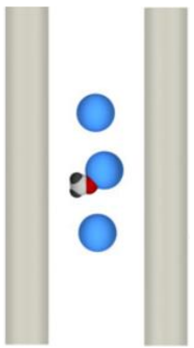
An exciting time – everything is coming together



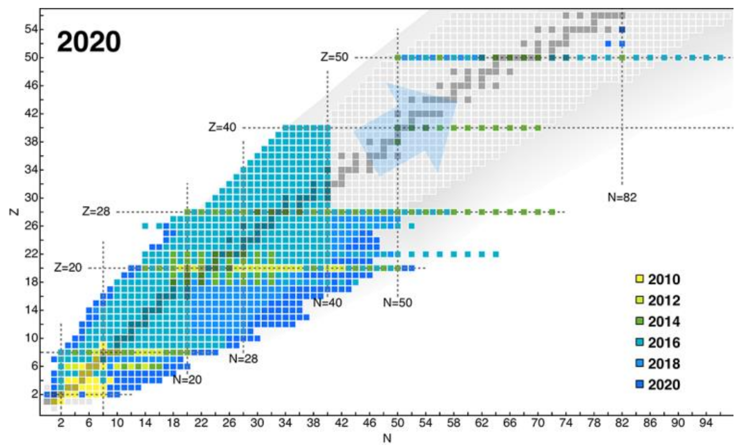
Radioactive beam spectroscopy



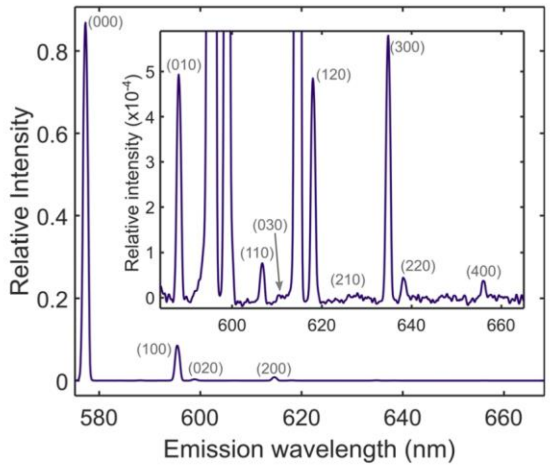
Radiochemistry, isotope access



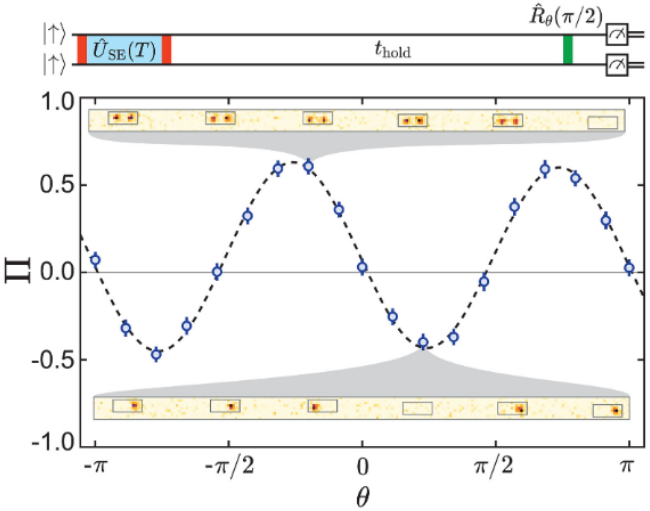
Trapping/control



Advances in theory



Rapid broadband spectroscopy

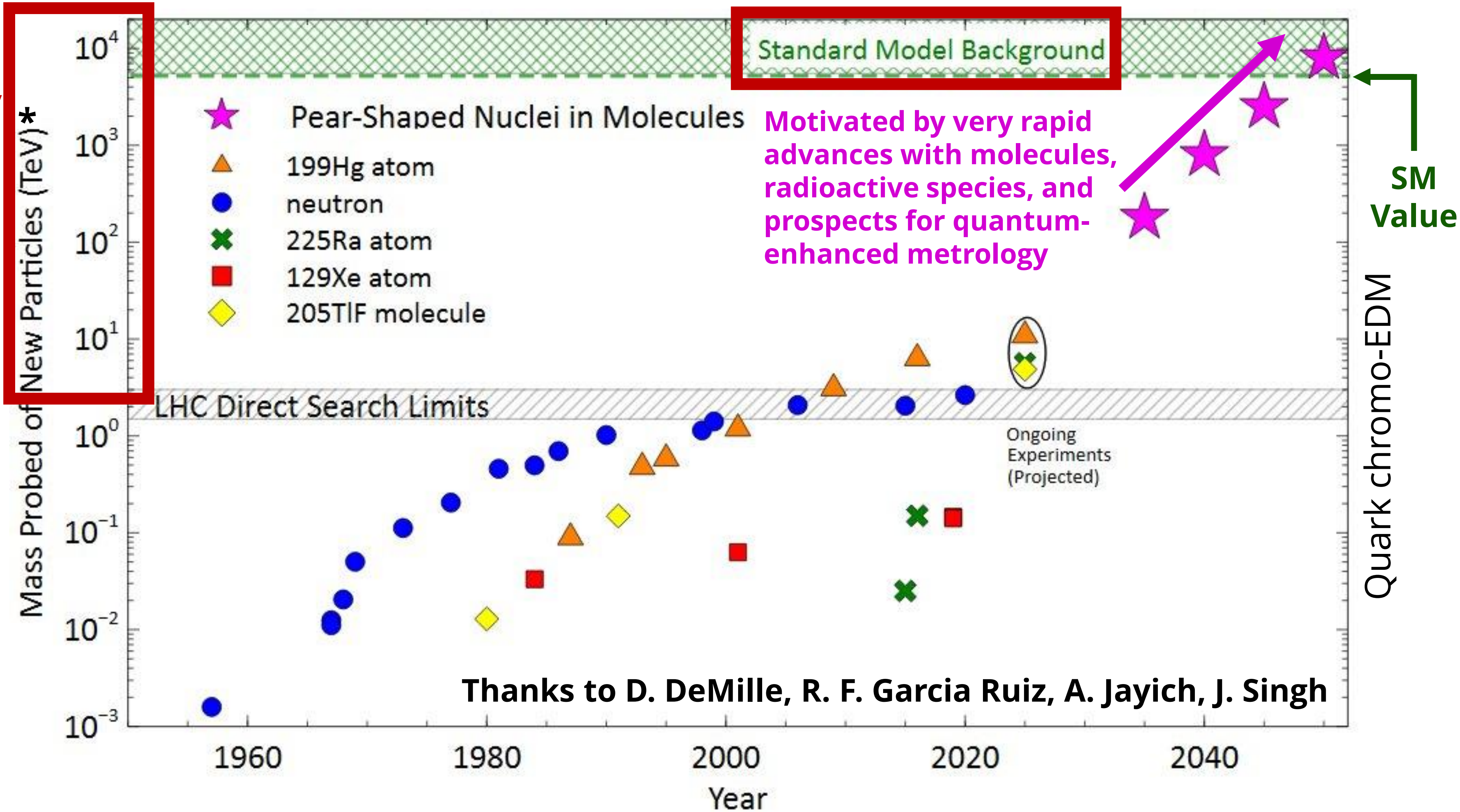


Advanced quantum control

Sensitivity Outlook

Pathway to seeing hadronic CKM physics

Pathway to extreme energy scales



Thanks to D. DeMille, R. F. Garcia Ruiz, A. Jayich, J. Singh

*** One-loop mass reach through quark chromo-EDMs. Different species have different mass reach for different hadronic CPV sources.**

Thanks for your attention!

Please get in touch, or learn more at:

Hutzler Lab
www.hutzlerlab.com

PolyEDM Collaboration
www.polyedm.com

SLAM! Community
www.slamcommunity.com

Caltech

Hutzler Lab, Summer 2023
Standing: Daniel, Phelan, Yi, Nick, Chandler
Sitting: Ashay, Arian, Madison, Taz, Adele
Hovering: Tim, Chi, Yuiki

Collaborators

PolyEDM
John M. Doyle (Harvard)
Tim Steimle (ASU/Caltech)
Amar Vutha (Toronto)

Molecular Theory
Anastasia Borschevsky (Groningen)
Bill Goddard (Caltech)

SLAM!
Lan Cheng (JHU)
Alyssa Gaiser (MSU)
Ronald Garcia Ruiz (MIT)
Andrew Jayich (UCSB)
Jaideep Singh (MSU/FRIB)

GORDON AND BETTY MOORE FOUNDATION

NSF

ALFRED P. SLOAN FOUNDATION

HEISING-SIMONS FOUNDATION

Caltech DeLogi Science and Technology Grant

Backup Slides

RaX vs. Hg

- Nuclei have different sensitivity to underlying sources of new physics
  - Makes comparing "how much more sensitive" difficult
- One metric: what is ΔE for NSM induced by CKM?
  - Disclosure: the theory uncertainties on these is large/unknown
  - Disclosure: this involved combining many different units and conventions
- Hg
  - CKM predicts NSM-induced atomic EDM $\left|d_{Hg}^{S}\right| = 4.2 \times 10^{-35}\ e\ cm$
  - Experiment uses 10 kV/cm → $|\Delta E/h| \approx 1 \times 10^{-16}\ Hz$
- RaX (X=F, OH, OH, … all fairly similar)
  - CKM predicts $\left|d_{Ra}^{S}\right| = 7.4 \times 10^{-32}\ e\ cm$
  - Atomic sensitivity $\left|K_{a}^{S}\right| = 8.8 \times 10^{-17}\ cm/(fm)^3$
  - CKM predicts $|S_{Ra}| = 8.3 \times 10^{-16}\ e\ (fm)^3$
  - RaX sensitivity $\Delta E/S_{Ra} \approx 2.5 \times 10^{4}\ e/4\pi\epsilon_0 a_0^4$
  - Energy shift $|\Delta E/h| \approx 1 \times 10^{-9}\ Hz$
- $|\Delta E_{RaX,CKM}/\Delta E_{Hg,CKM}| \approx 10^{7}$

See V. V. Flambaum, Phys. Rev. C 99, 035501 (2019), N. Yamanaka and E. Hiyama, J. High Energy Phys. 2016, 67 (2016), and references contained therein