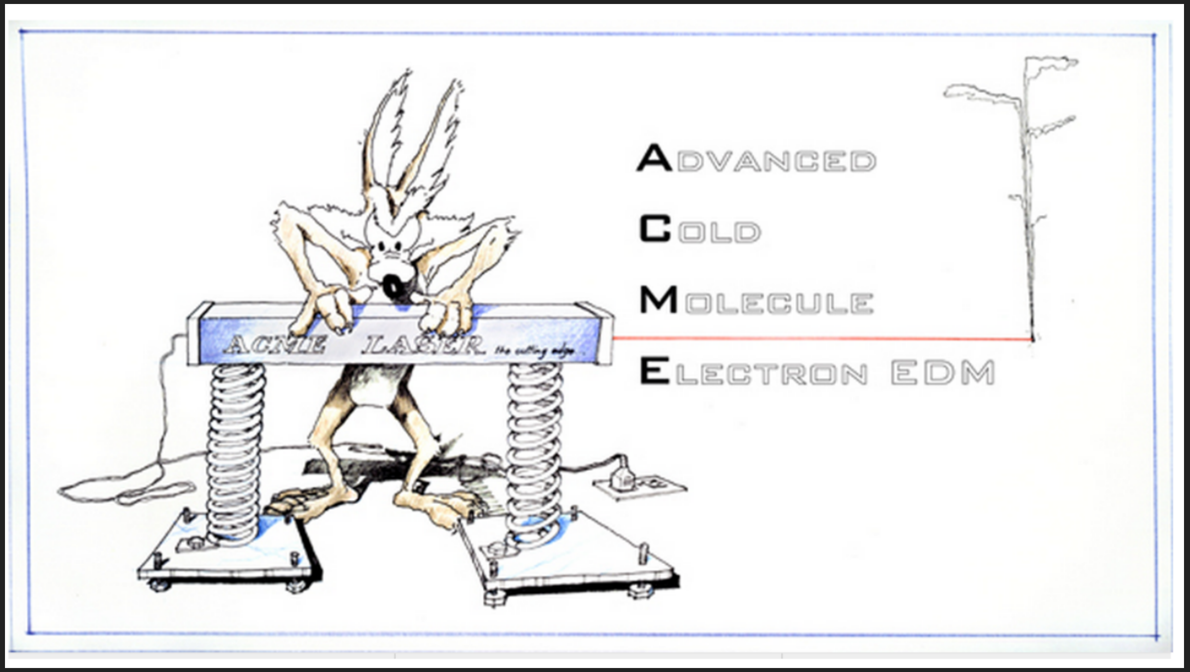


COLE MEISENHELDER

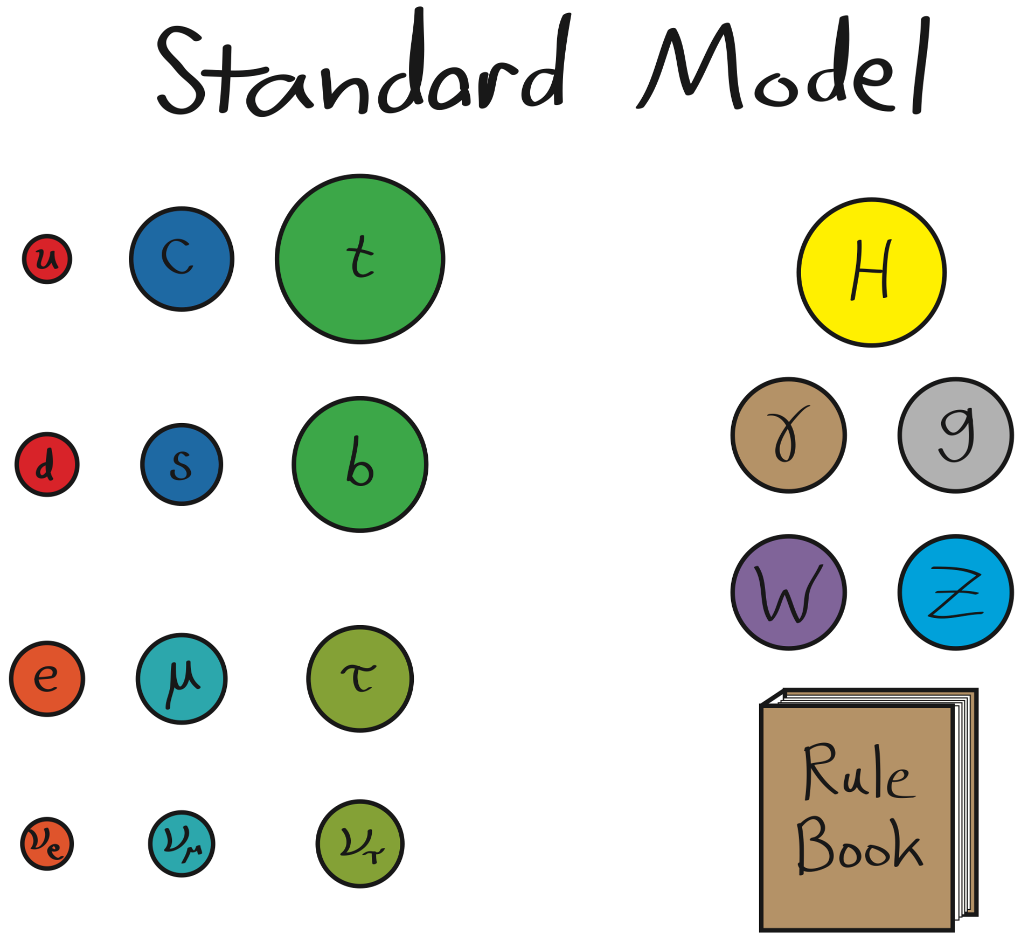
CUA PIZZA TALK

TOWARDS A NEW MEASUREMENT OF THE ELECTRON EDM

SECTION I: WHY ARE EDMS INTERESTING?

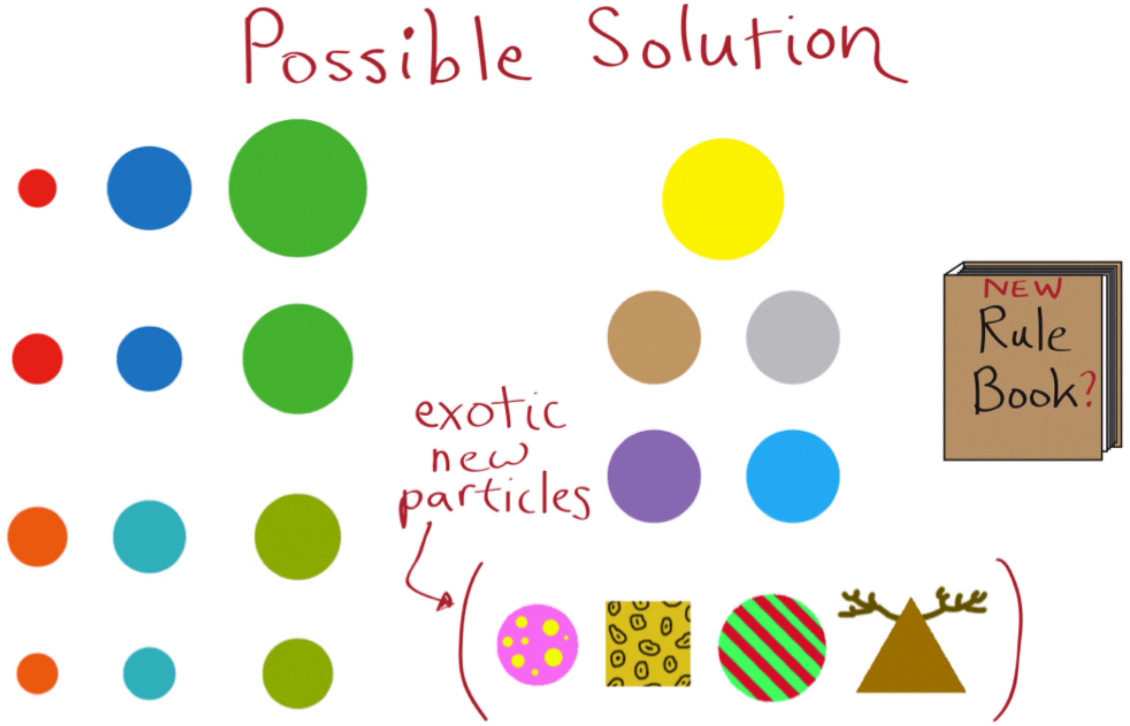
MOTIVATION

- The Standard Model cannot answer all questions
- Dark matter and dark energy remain unexplained
- Matter-Antimatter Asymmetry Problem



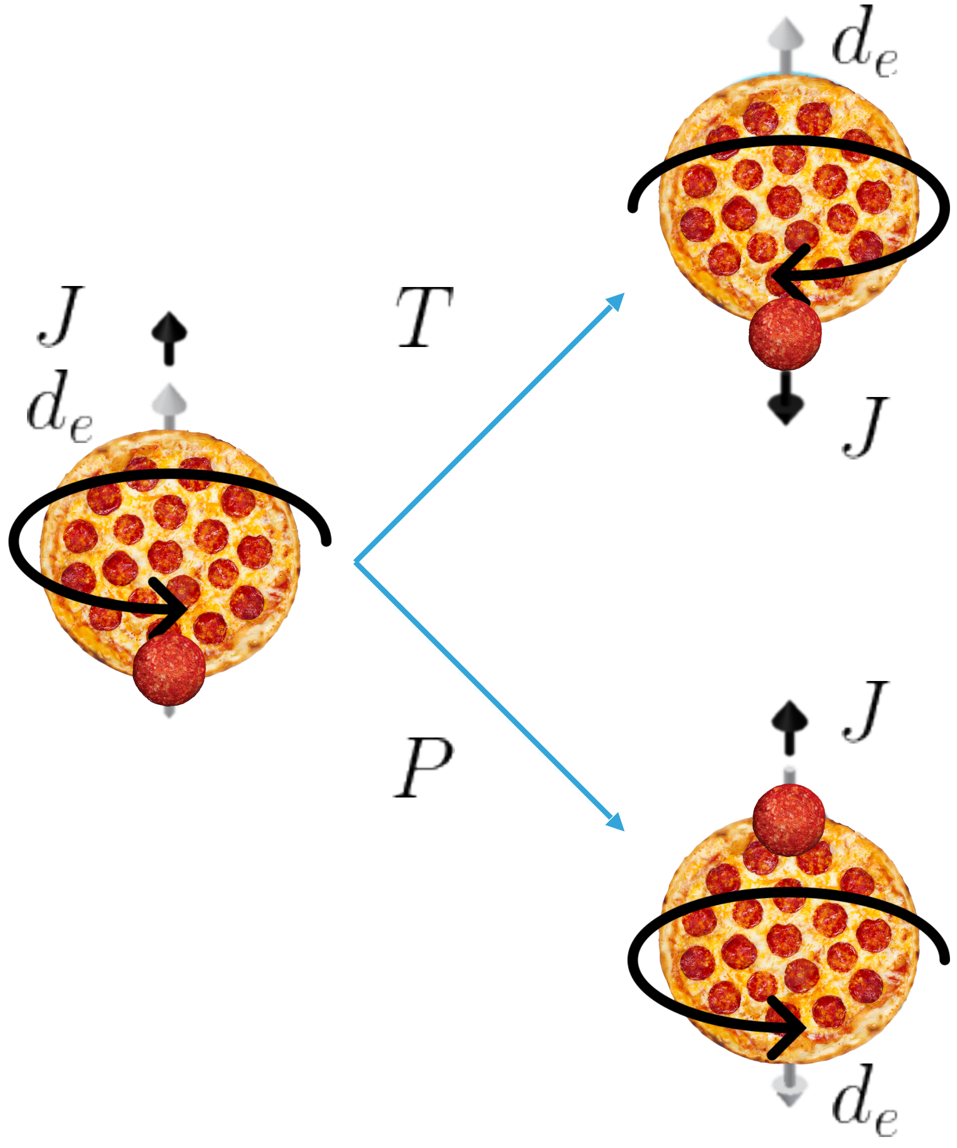
POSSIBLE SOLUTION TO BARYON ASYMMETRY

- Sakharov Conditions (1967) allow for Baryon Asymmetry
- CP Violation
  - Allowed in quark mixing
  - Standard Model does not account for the observed asymmetry
  - Need physics Beyond the Standard Model (BSM)
  - CPT theorem makes CP and T violations equivalent

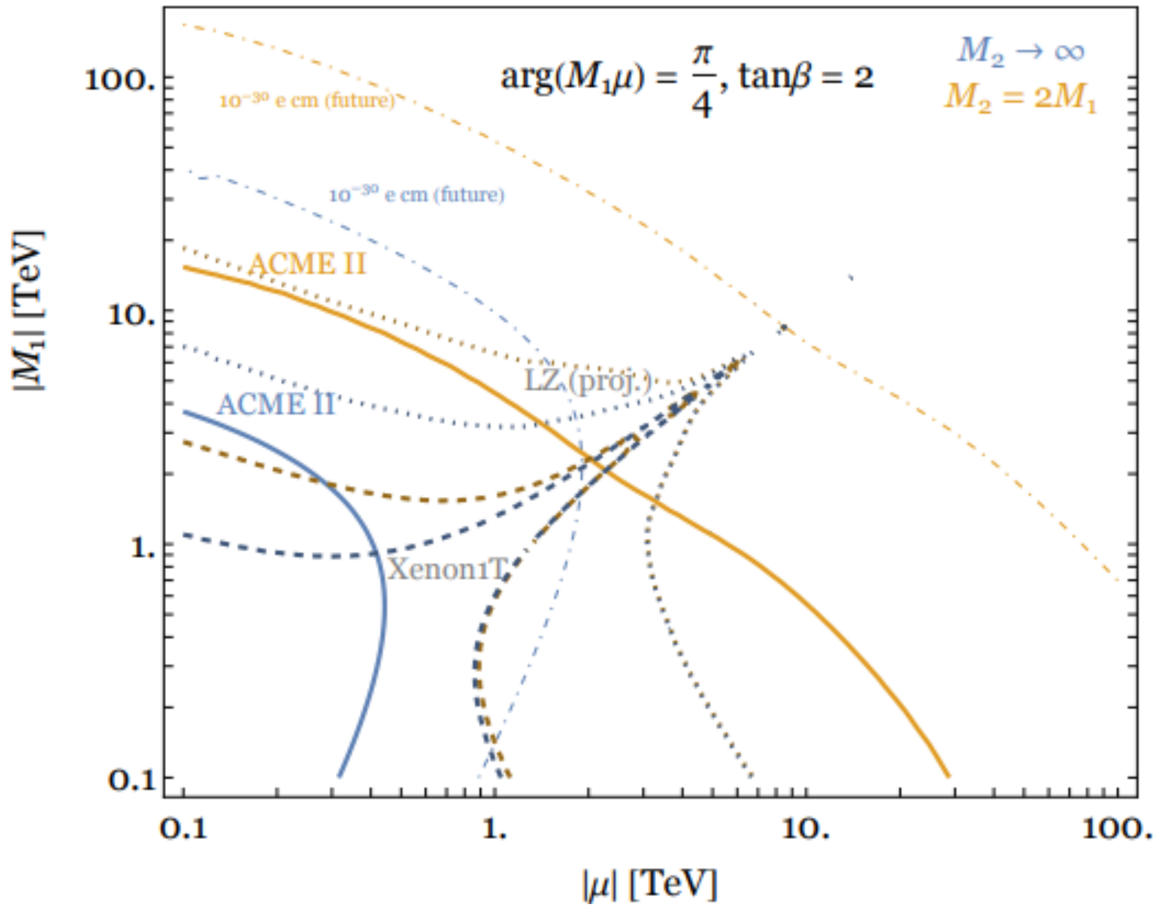


EDMS AND CP VIOLATION

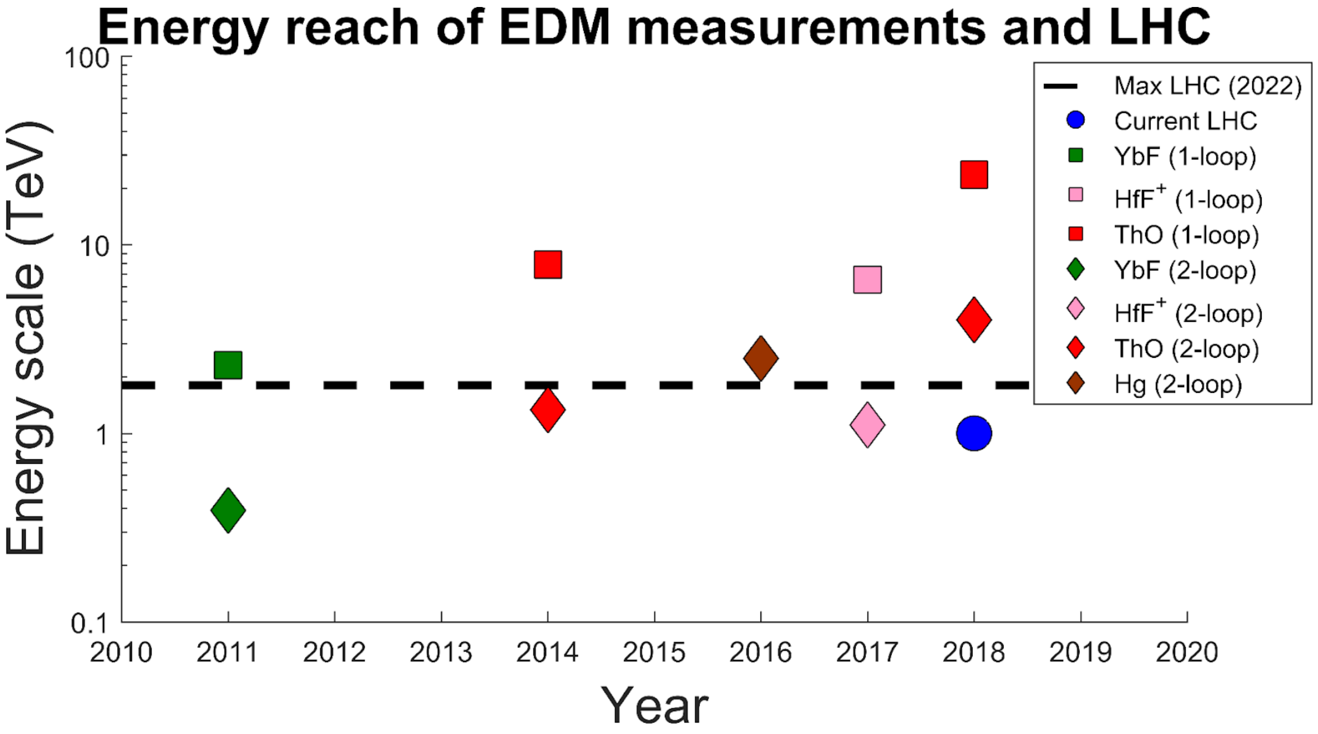
- Permanent EDMs inherently violate P and T
- Standard Model predicts electron EDM $< 10^{-38}\ e \cdot cm$
- Current limit: $|d_e| < 1.1 \times 10^{-29} e\ \mathrm{cm}$
- Many BSM theories predict nonzero eEDMs near our sensitivity



PLACING LIMITS ON NEW PHYSICS



SUSY particle bounds from the ACME II result. Fig. from Matt Reece (unpublished). ACME III projection (~10^{-30} e cm) dashed.



Key EDM results since 2010. Two-loop sensitivity from Nakai & Reece (2017). One-loop sensitivity from Feng (2013). LHC scale gives stop mass sensitivity.

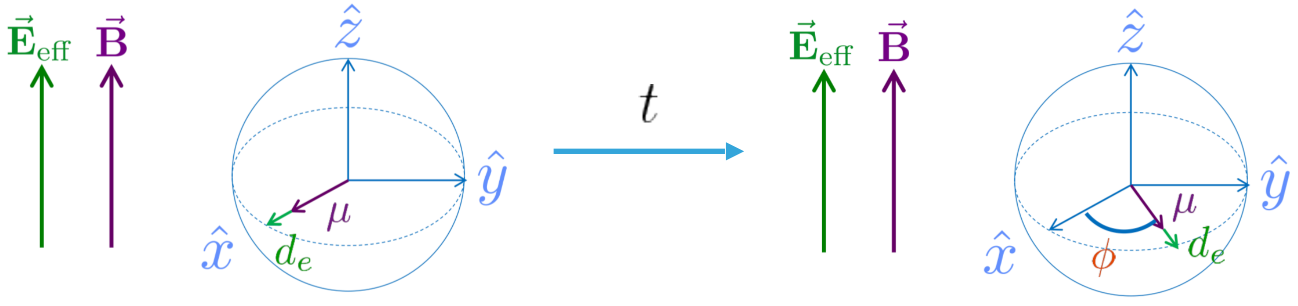
SECTION II: HOW CAN WE MEASURE AN ELECTRON EDM?

HOW DO WE MEASURE AN EDM?

- An eEDM will precess in both electric and magnetic fields

$$E = -\vec{d}_e \cdot \vec{\mathcal{E}} - \vec{\mu} \cdot \vec{B}$$

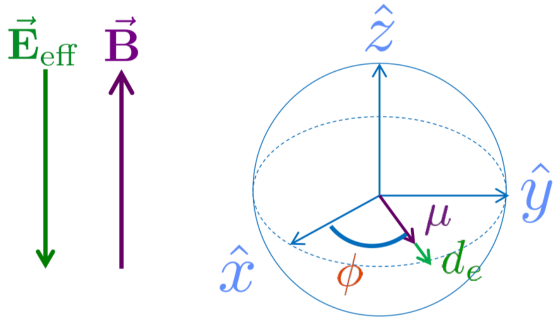
$$\phi(\vec{\mathcal{E}}) = E\tau/\hbar = -(\vec{d}_e \cdot \vec{\mathcal{E}} + \vec{\mu} \cdot \vec{B})\tau/\hbar$$



- Reverse E field for differential measurement

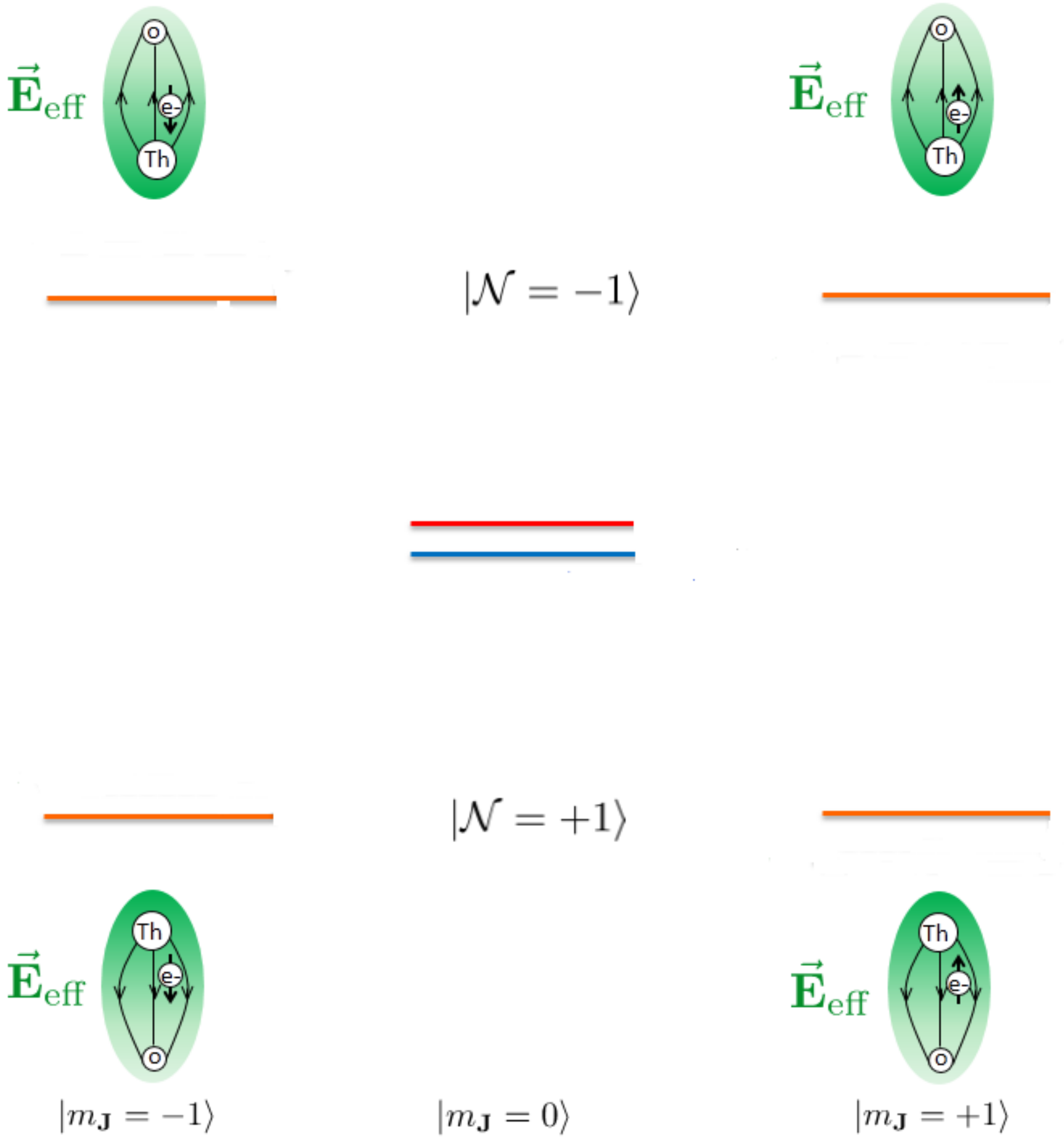
$$\phi_{EDM} = (\phi(\vec{\mathcal{E}}) - \phi(-\vec{\mathcal{E}}))/2$$

$$\phi_{EDM} = -(\vec{d}_e \cdot \vec{\mathcal{E}})\tau/\hbar$$



AN EDM IN THO

- Molecules can provide strong internal electric fields
    - ThO has E_{eff} ~ 80 GV/cm
- We can flip this electric field by probing different states
    - Powerful method for eliminating systematic errors
    - ThO only requires a small applied field



MOLECULAR EDMS

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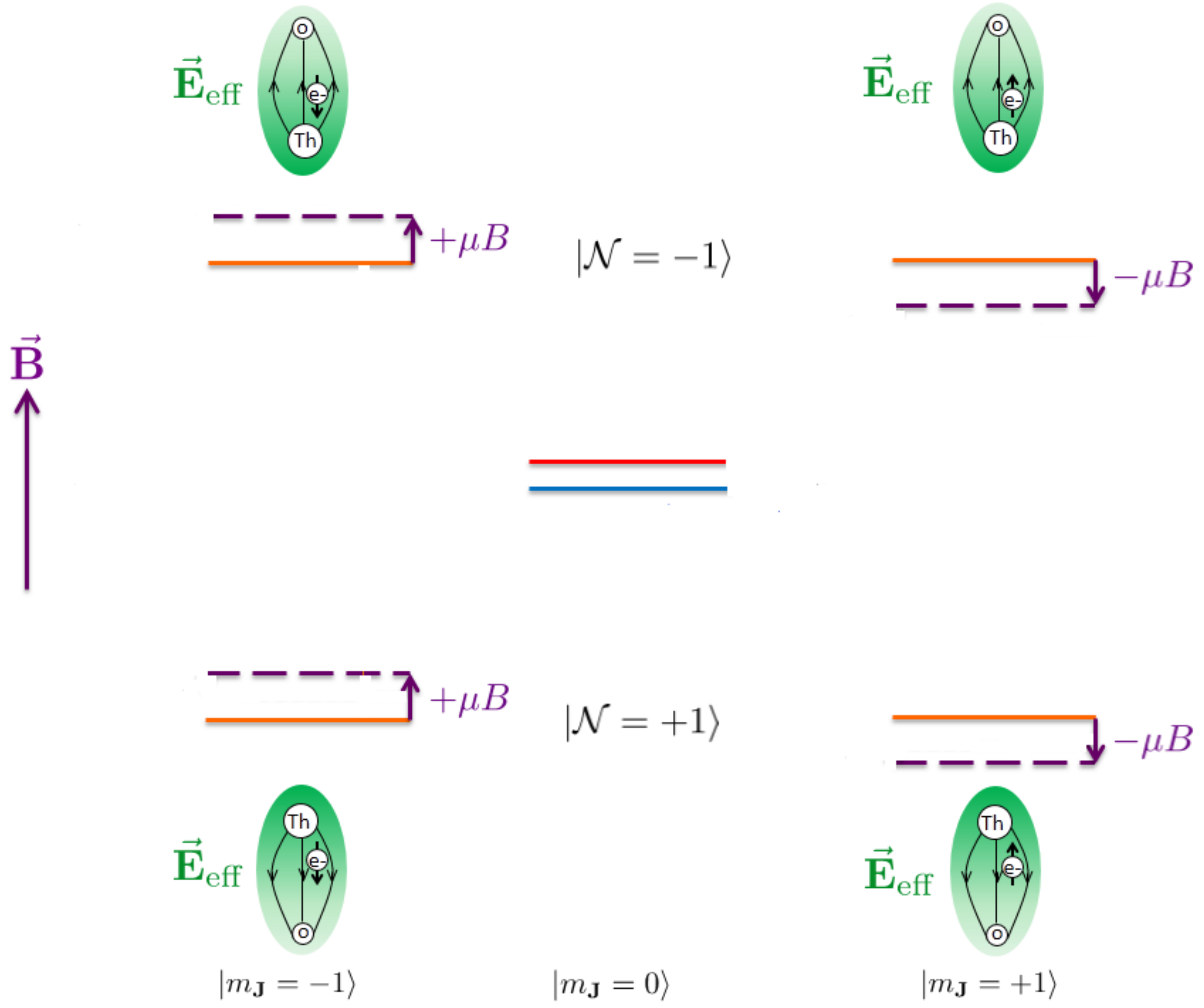

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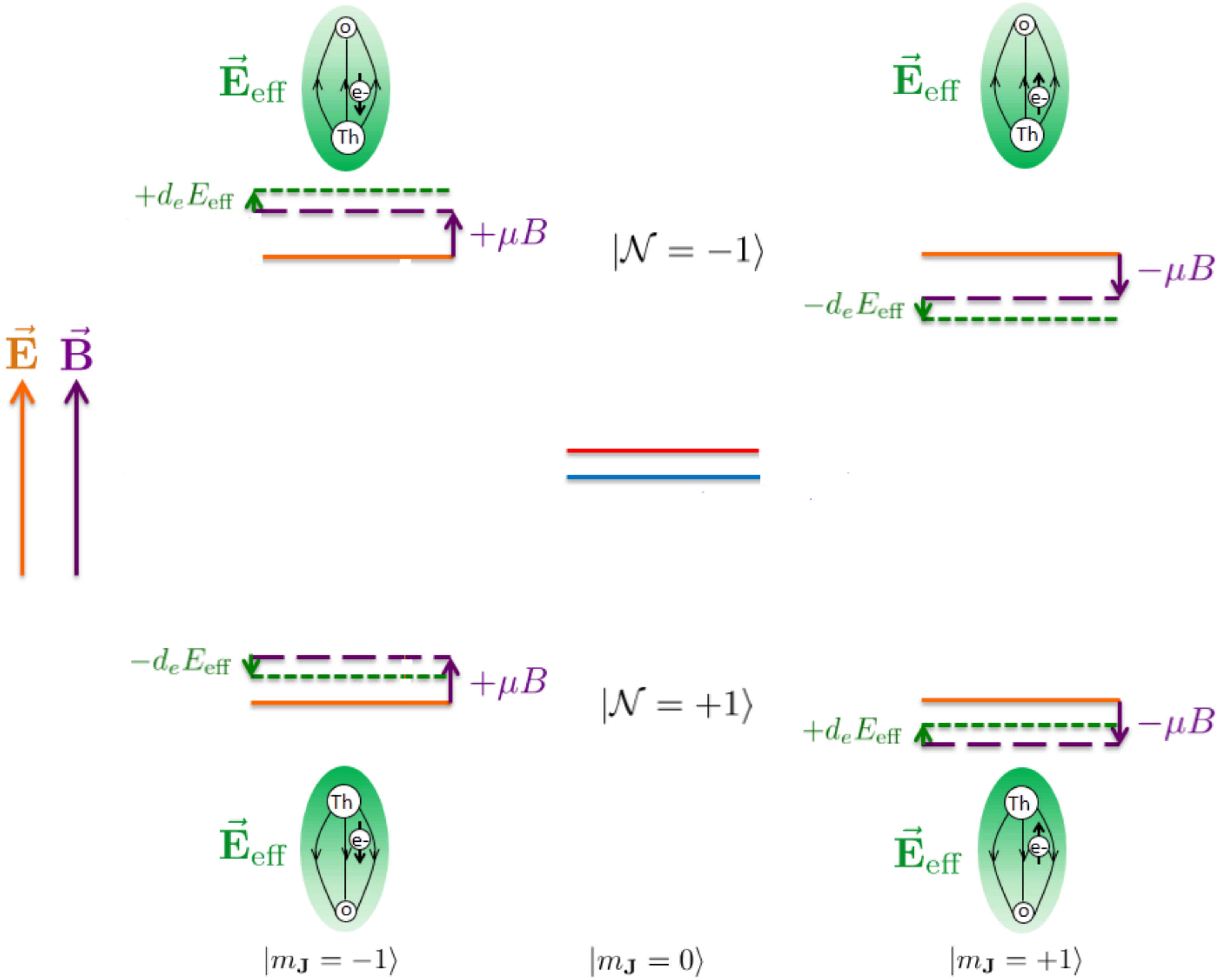


EXPERIMENTAL SENSITIVITY

- For a shot noise limited measurement we

$$\delta\omega \propto \frac{1}{\tau\sqrt{\dot{N}T}}$$

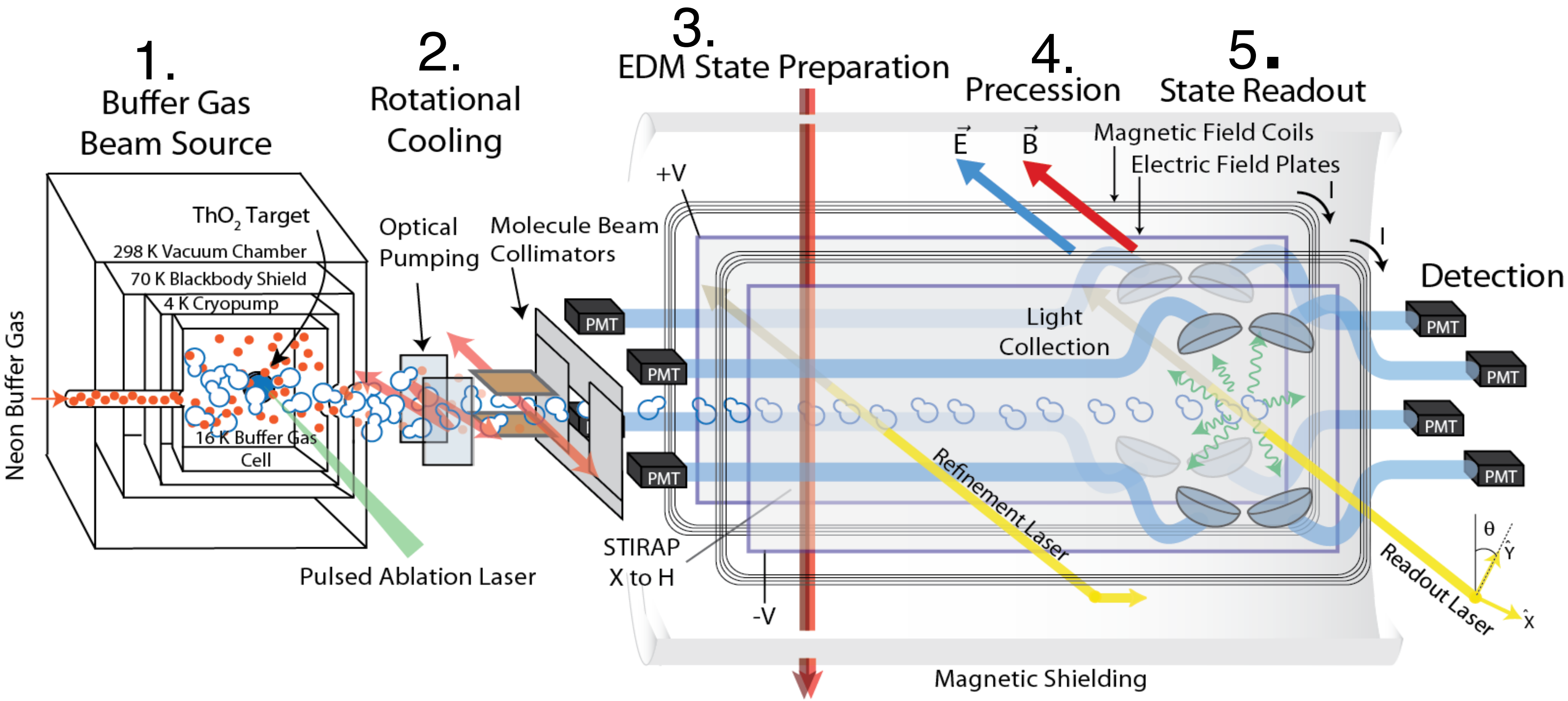
$\tau =$ Coherence time
$\dot{N} =$ Count rate
$T =$ Averaging time

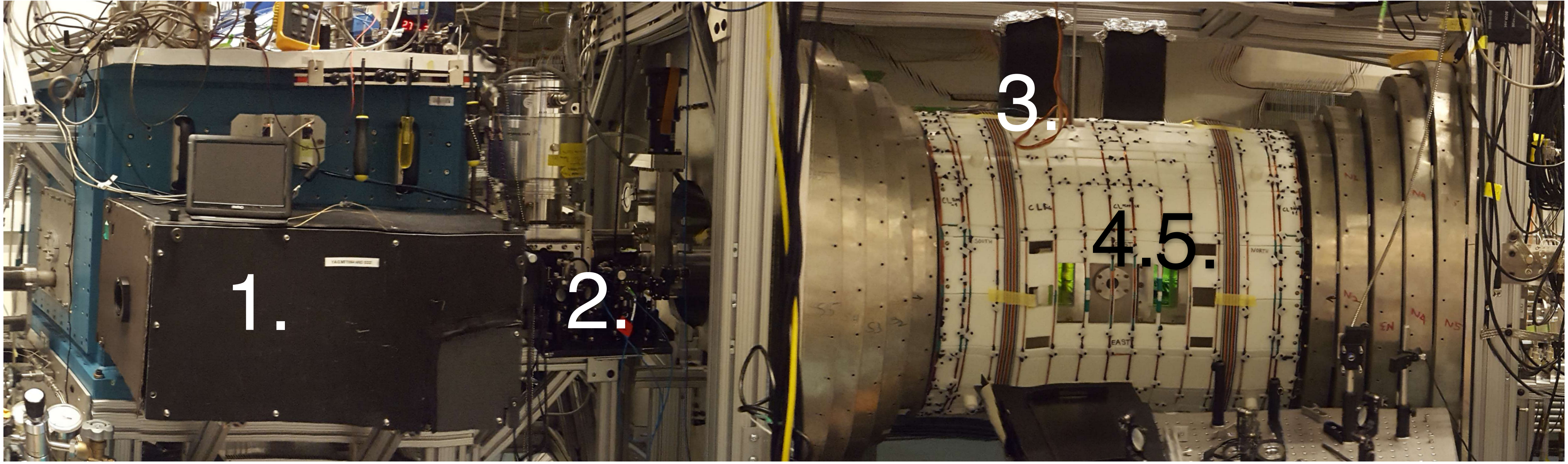
- For our experiment we have $\mathcal{H}_{EDM} = -\vec{d_e} \cdot \vec{\mathcal{E}_{eff}}$

$$\delta d_e \propto \frac{1}{\mathcal{E}_{eff}\tau\sqrt{\dot{N}T}}$$

$\mathcal{E}_{eff} =$ Electric field

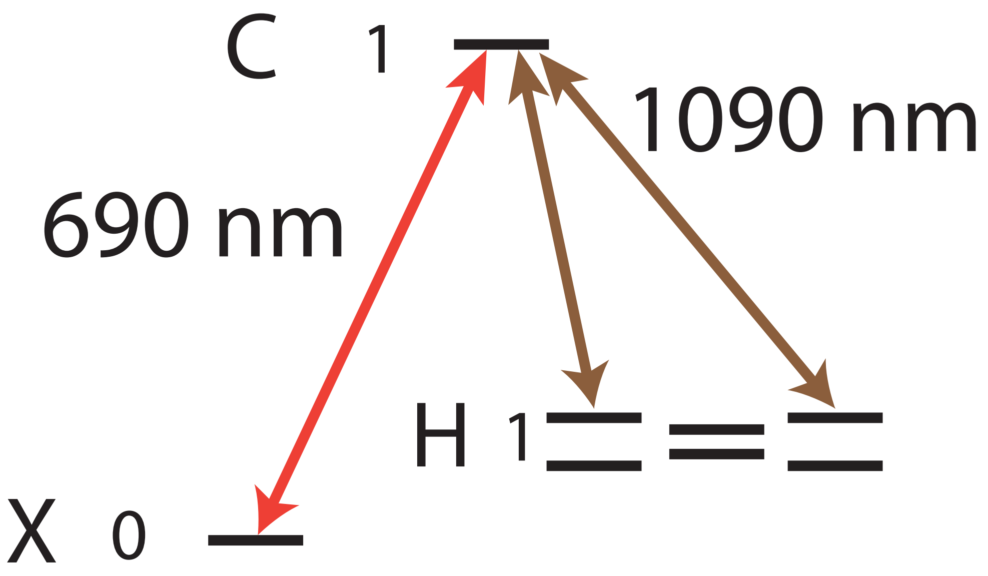
EXPERIMENT STRUCTURE

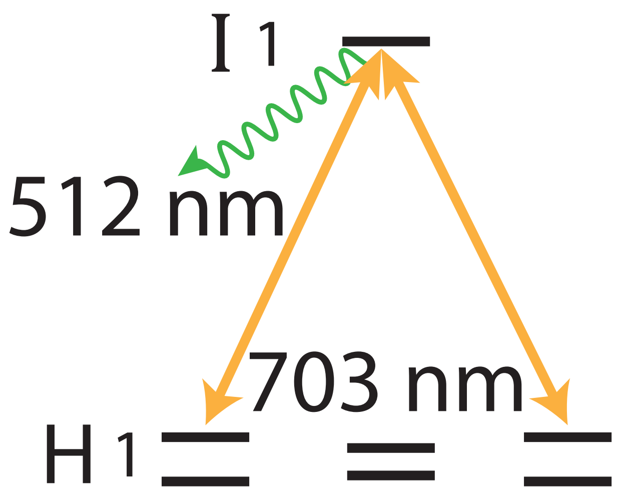


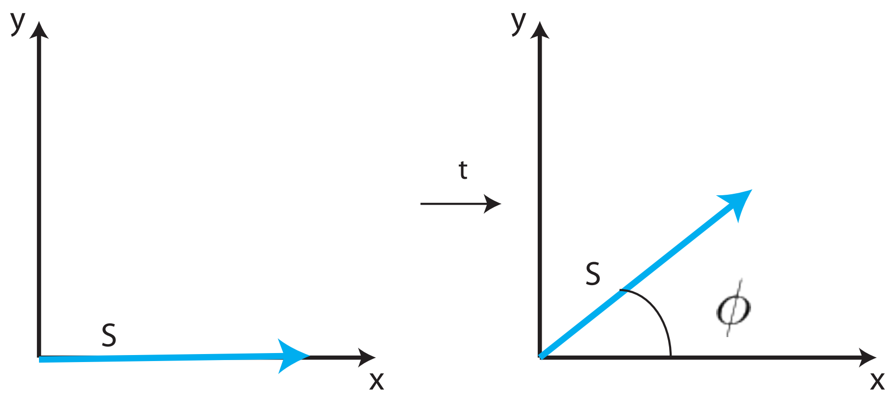


STATE PREPARATION

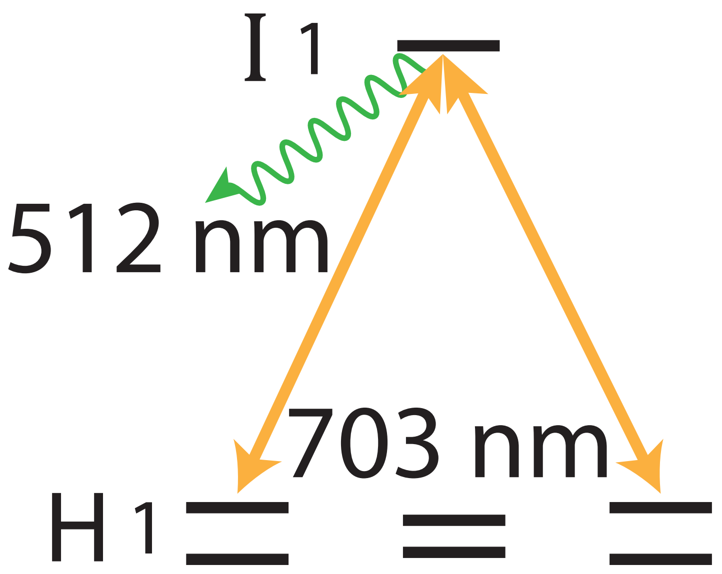
- Stimulated Raman Adiabatic Passage (STIRAP)
  - Coherent population transfer from X to H
  - ~75% transfer efficiency
- State Refinement
  - Optically pump into dark state with desired polarization
  - Suppress residual STIRAP phases



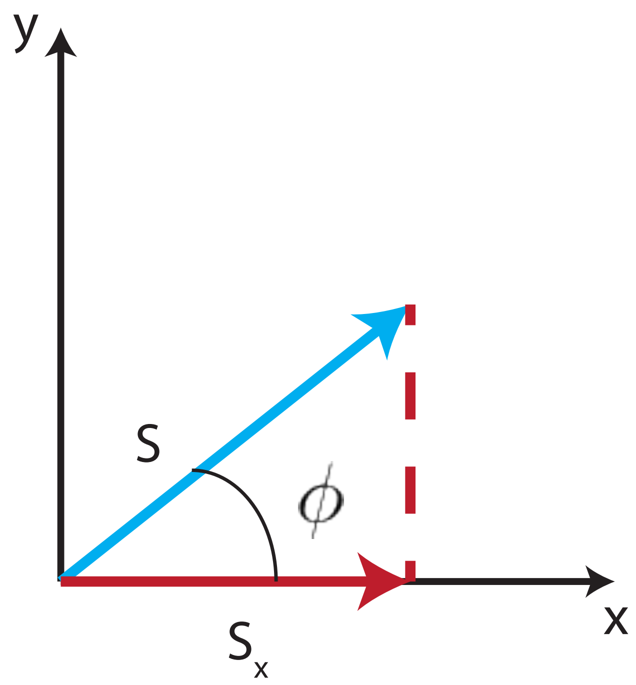


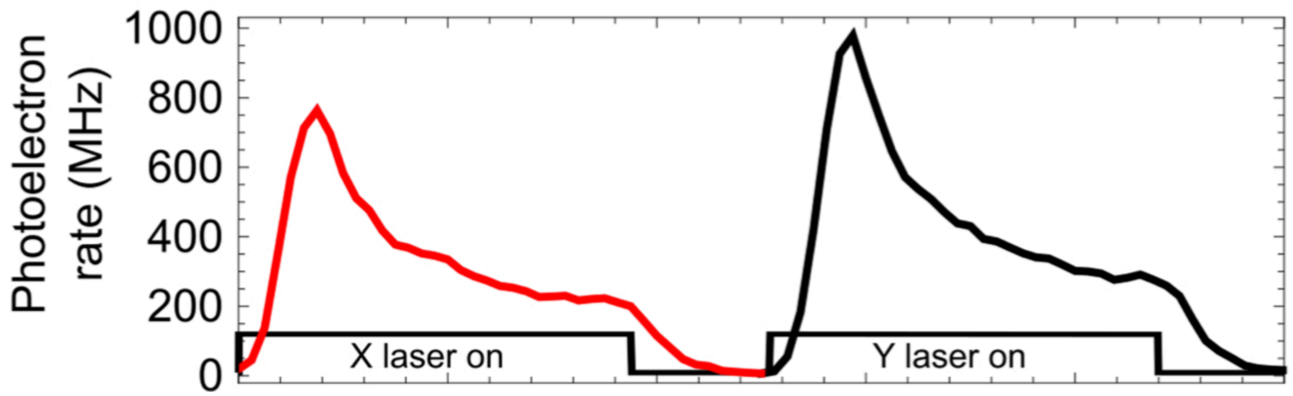


STATE READOUT



- Project phase onto orthogonal polarizations
- Rapidly switch polarization at 200 kHz
  - AOMs allow rapid switching
- Detect fluorescence with 8 PMTs





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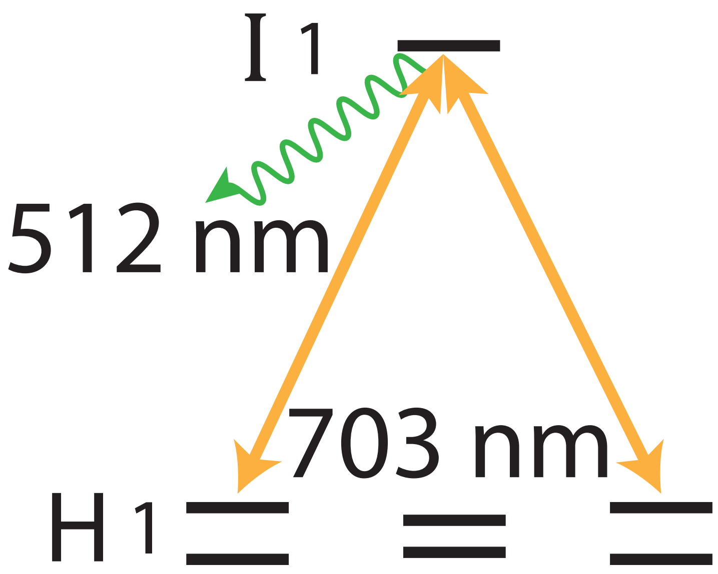
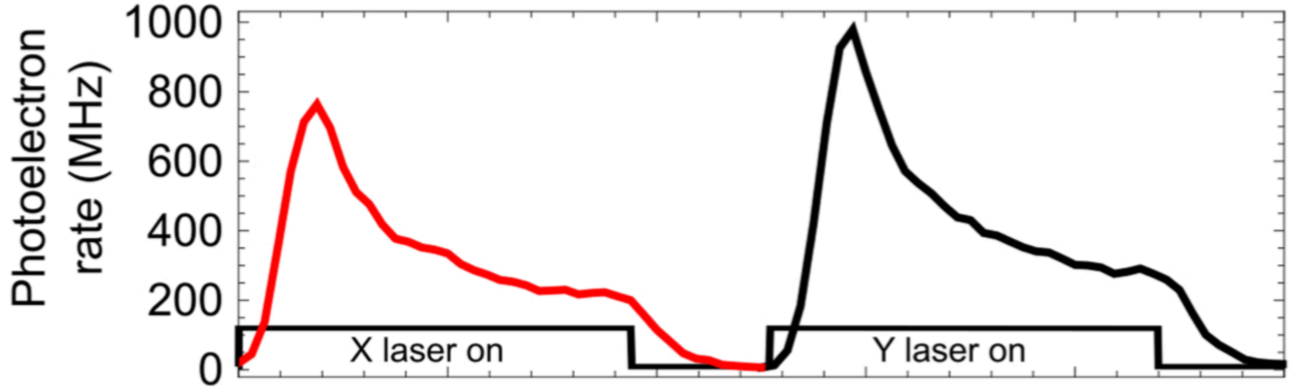
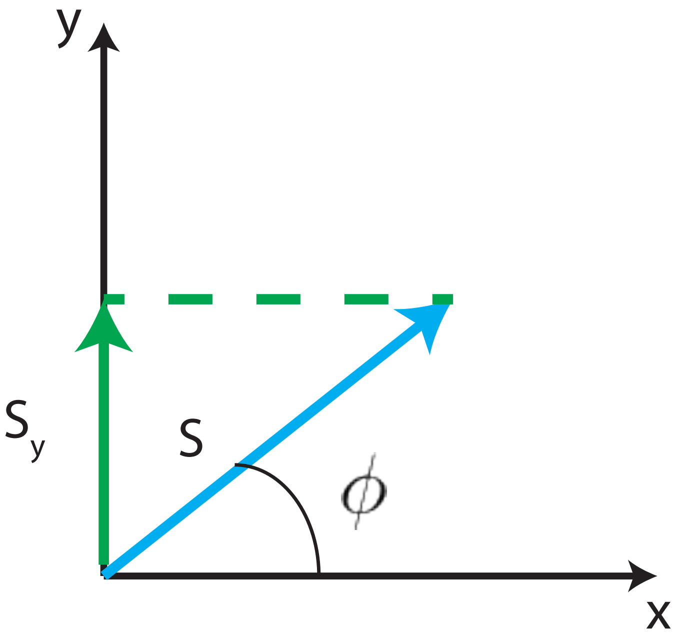






ACME II RESULT

- ACME Collaboration et al., *Nature* (2018):

$$d_e = (4.3 \pm 3.1_{stat} \pm 2.6_{syst}) \times 10^{-30} e \text{ cm}$$

- Implies a 90% C. L. upper limit of:

$$|d_e| < 1.1 \times 10^{-29} e \text{ cm}$$

- Probes new physics up to ~30 TeV at 1-loop level

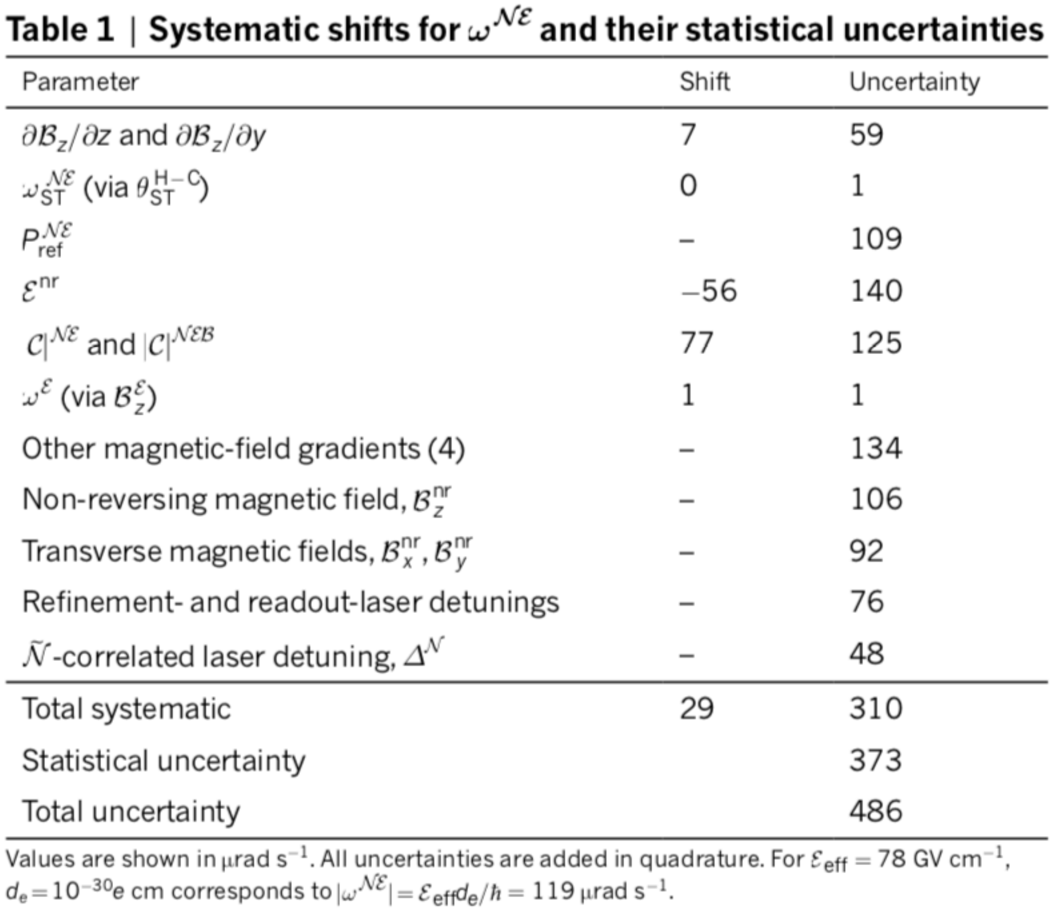


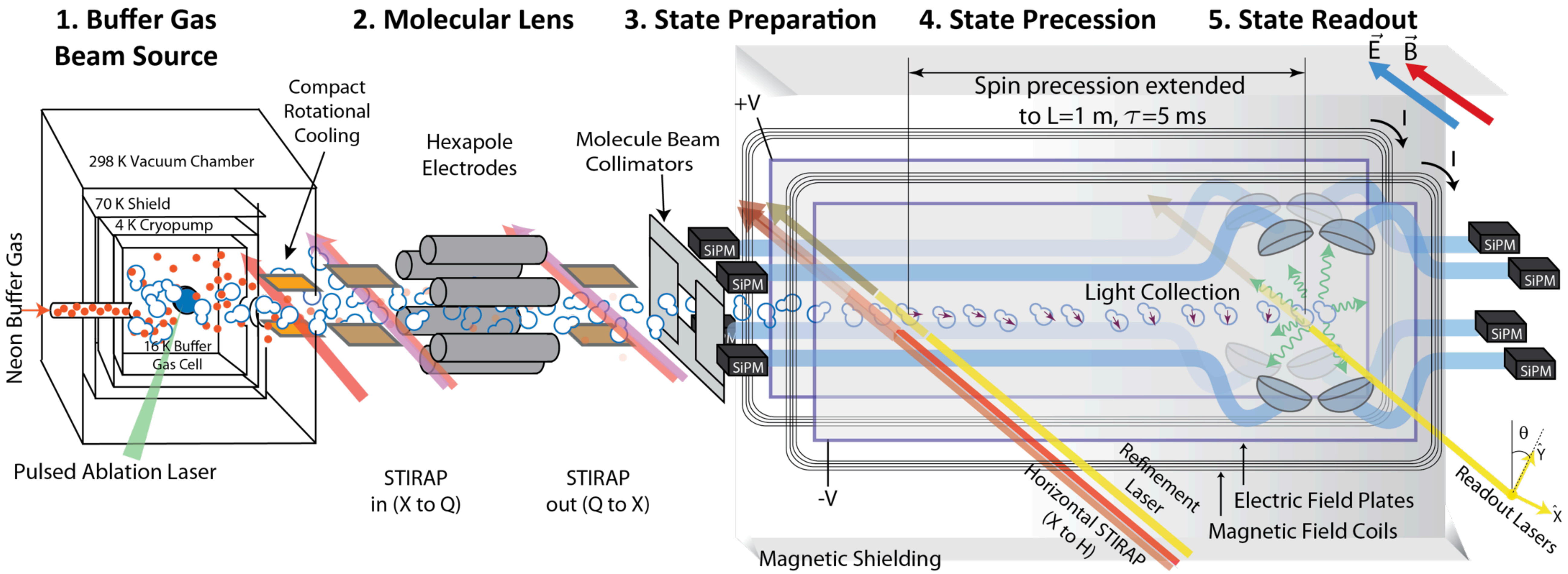
Table 1 | Systematic shifts for $\omega^{\mathcal{N}\mathcal{E}}$ and their statistical uncertainties

Parameter	Shift	Uncertainty
$\partial\mathcal{B}_z/\partial z$ and $\partial\mathcal{B}_z/\partial y$	7	59
$\omega_{\mathrm{ST}}^{\mathcal{N}\mathcal{E}}$ (via $\theta_{\mathrm{ST}}^{\mathrm{H-C}}$)	0	1
$P_{\mathrm{ref}}^{\mathcal{N}\mathcal{E}}$	–	109
$\mathcal{E}^{\mathrm{nr}}$	–56	140
$\mathcal{C}\|^{\mathcal{N}\mathcal{E}}$ and $\|\mathcal{C}\|^{\mathcal{N}\mathcal{E}\mathcal{B}}$	77	125
$\omega^{\mathcal{E}}$ (via $\mathcal{B}_z^{\mathcal{E}}$)	1	1
Other magnetic-field gradients (4)	–	134
Non-reversing magnetic field, $\mathcal{B}_z^{\mathrm{nr}}$	–	106
Transverse magnetic fields, $\mathcal{B}_x^{\mathrm{nr}}, \mathcal{B}_y^{\mathrm{nr}}$	–	92
Refinement- and readout-laser detunings	–	76
$\tilde{\mathcal{N}}$-correlated laser detuning, $\Delta^{\mathcal{N}}$	–	48
Total systematic	29	310
Statistical uncertainty		373
Total uncertainty		486

Values are shown in μrad s^{-1}. All uncertainties are added in quadrature. For $\mathcal{E}_{\mathrm{eff}} = 78$ GV cm^{-1}, $d_e = 10^{-30} e$ cm corresponds to $|\omega^{\mathcal{N}\mathcal{E}}| = \mathcal{E}_{\mathrm{eff}} d_e/\hbar = 119$ μrad s^{-1}.

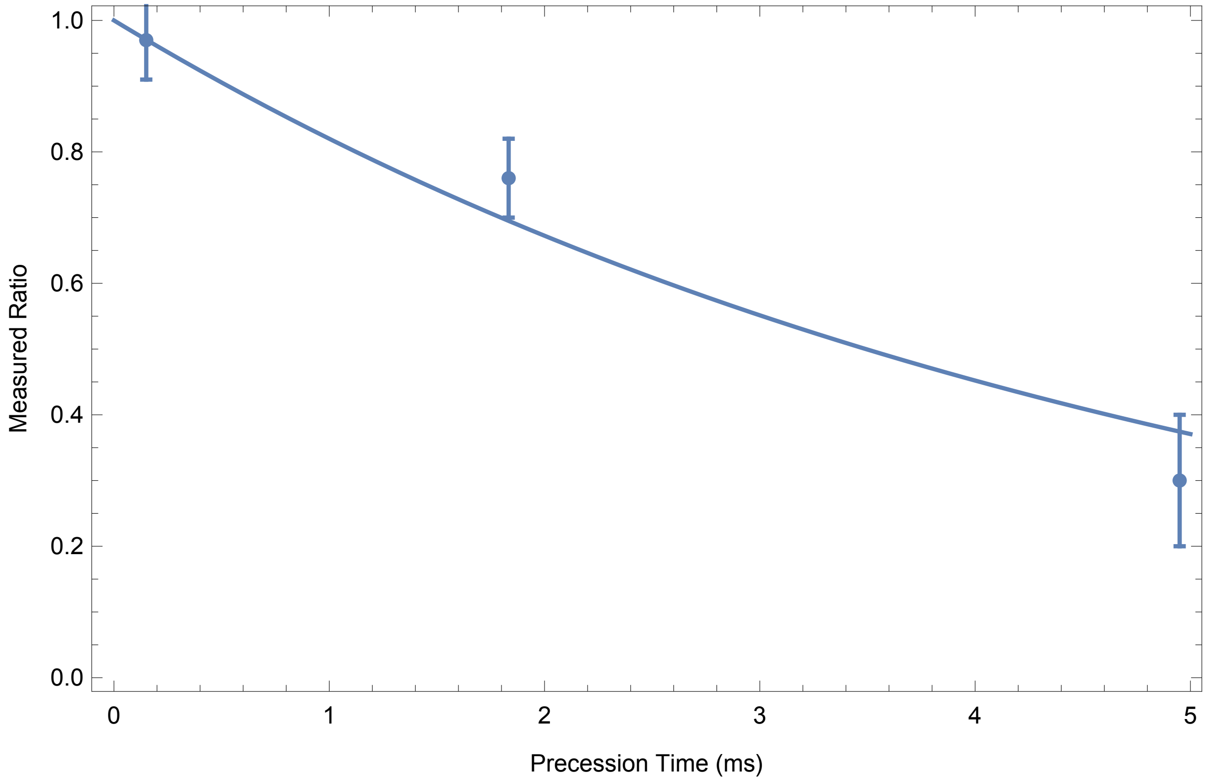
SECTION III: A NEW ACME MEASUREMENT

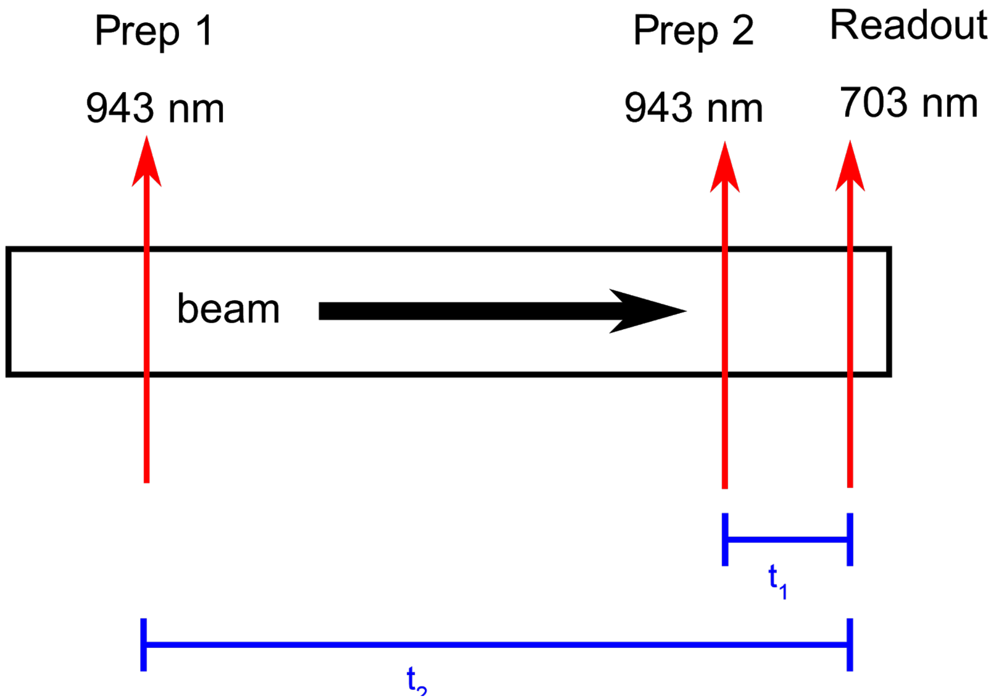
ACME III OVERVIEW



INCREASED H-STATE LIFETIME

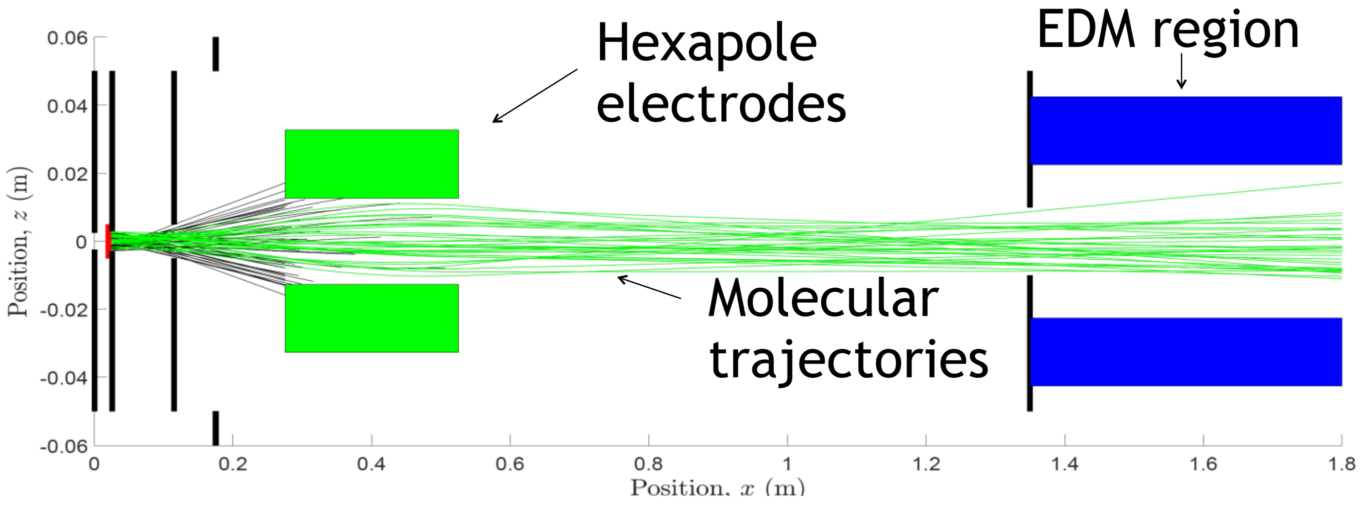
- In January measured H-state lifetime to be **5.3 ms**
- Last lifetime measurement showed a lower bound of just 1.8 ms
- ACME II used only 1 ms (20 cm) precession time
- Currently working on measurement to reduce uncertainty of H-state lifetime

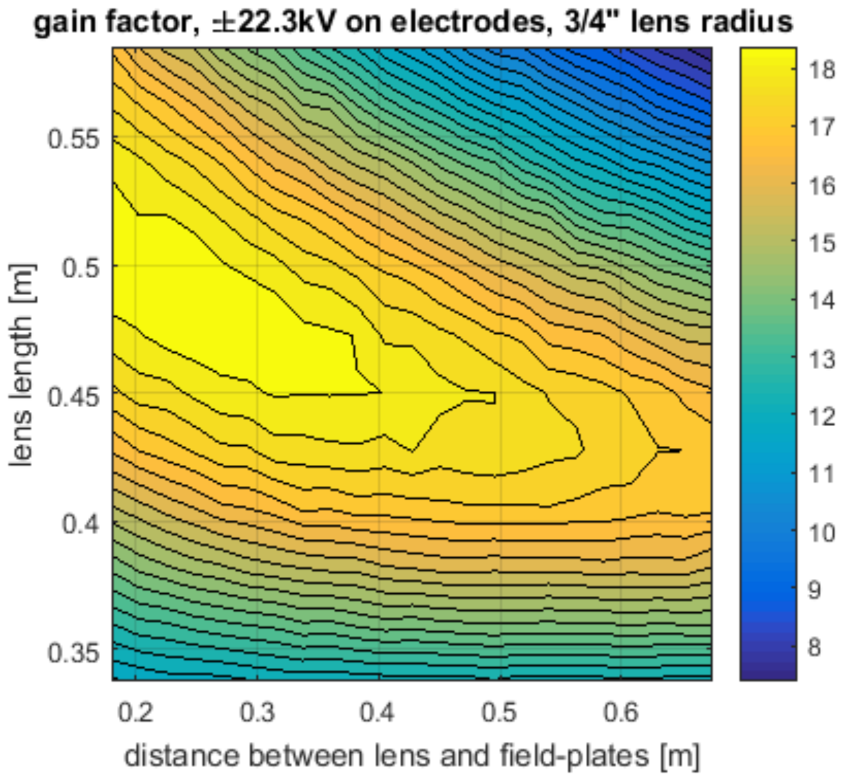




ELECTROSTATIC LENS FOR THO MOLECULES

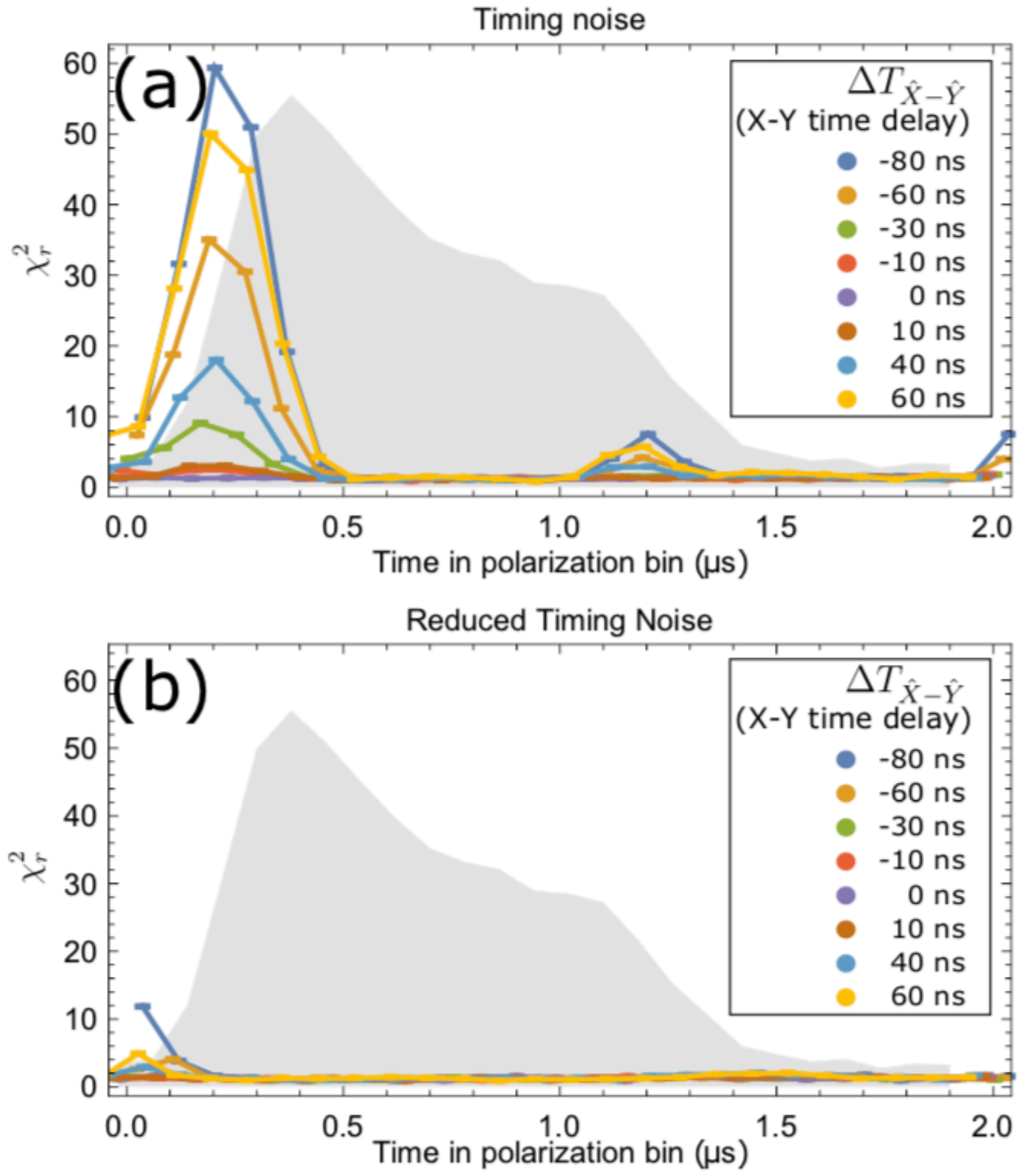
- Without a lens, fewer than .04% of molecules reach the detector
- Electrostatic lens focuses molecules into the EDM region, giving **~20x** gain in signal (including the efficiency of double-STIRAP)
- Efficient STIRAP into the Q state allows for strong focusing





CONTROLLING EXCESS NOISE FOR ACME III

- ACME II had 1.7 times more noise than expected from the shot noise limit
- Noise came from 2 effects:
  - Large scale timing jitter
  - Timing offset between X and Y polarization bins
  - We can now control both parameters to reduce this noise



See: C. Panda et al., Attaining the shot-noise-limit in the ACME measurement of the electron electric dipole moment, *J. Phys. B* (2019).

DETECTION UPGRADES

- SiPMs provide a significant gain over the PMTs used in ACME II
- Increased light pipe diameter improves our geometric collection efficiency

	Requirement	Measured	Comment
Photon detection efficiency	~ 50%	PMT × 2.5	Absolute value is unknown.
Dark count rate	< 10 Mcps	< 10 Mcps	Cooled down to -10°C
Cross talk & After pulse	< 25%	~ 20%	Array type package.
3dB Bandwidth	5 MHz	8.5 MHz	w/ Pole-Zero Cancellation
Electrical noise	$< 10\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$	$< 10\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$	

ACME III PROPOSED GAINS

$$\delta d_e = \frac{1}{2T\mathcal{E}_{eff}\sqrt{N}}$$

Improvement	Signal Gain	EDM Sensitivity Gain
Increased Precession Time	0.20	2.3
Electrostatic Lens	20.5	4.5
SiPM Detector Upgrade	2.3	1.5
Timing Jitter Noise Reduction	1	1.7
Total	**9.4**	**26.4**

OUTLOOK

- EDM searches are a powerful tool for studying BSM physics
- The ACME II measurement placed the strongest limit on the eEDM to date
- Promising path towards a new measurement with an order of magnitude improvement in sensitivity

THE ACME COLLABORATION

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James Chow (grad student)
Zhen Han (grad student)
Peiran Hu (grad student)

Harvard
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Xing Wu (postdoc)

Northwestern
Gerald Gabrielse (PI)
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Okayama University

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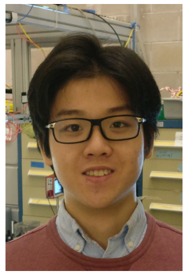
David DeMille


James Chow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