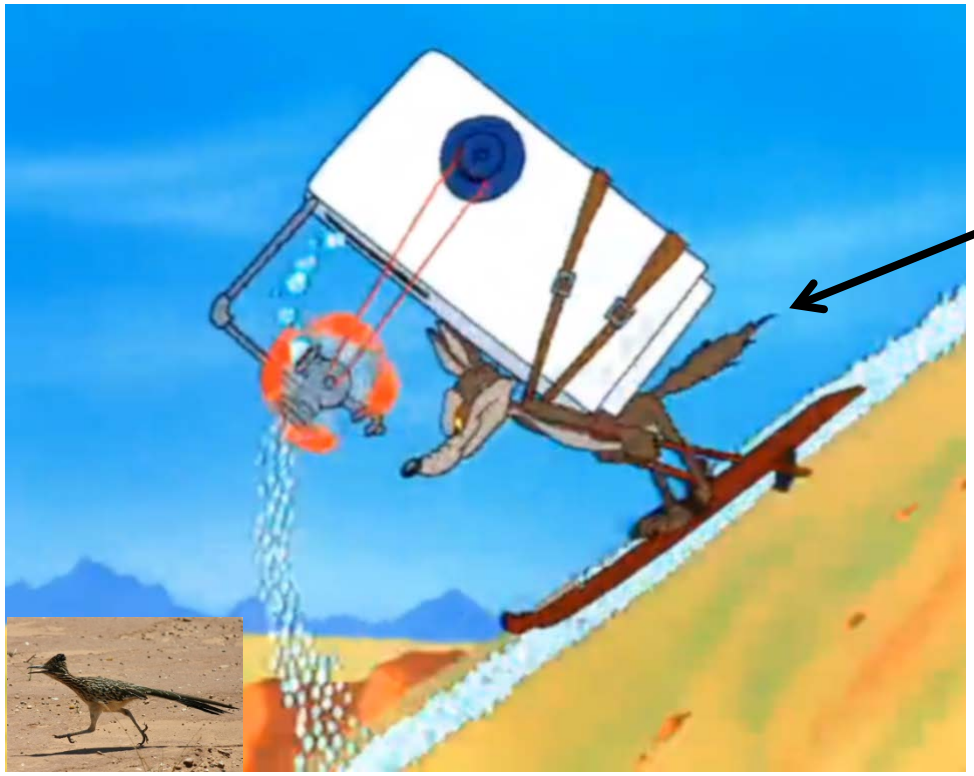
Improving the search for the electron's electric dipole moment in ThO



Zack Lasner
Advanced Cold Molecule Electron EDM (ACME) collaboration
WIDG, Yale University
9/22/15

Outline

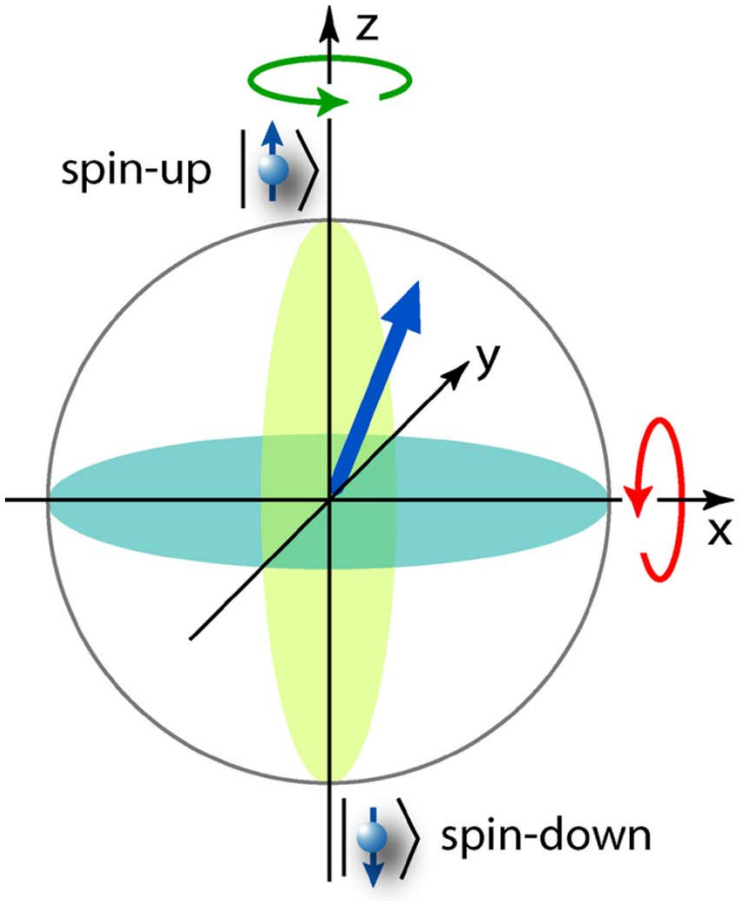
- Background
- Using ThO to measure the eEDM
- The ACME apparatus
- Data analysis
- Outlook

Outline

- **Background**
  - What is an EDM?
  - Why is the electron's EDM small?
  - Why are we trying to measure it anyway?
  - How are we trying to do that?
- Using ThO to measure the eEDM
- The ACME apparatus
- Data analysis
- Outlook

Electromagnetic moments of the electron

- The electron has spin $S = 1/2$.
- Can specify *one* axis (plus overall phase)
  - Bloch sphere representation
- Allows for only monopole, dipole moments
  - E.g., quadrupole has two axes
- Dipole parallel to spin axis: $\vec{d}$ c $\vec{S}$



Known and forbidden moments

- **Electric monopole** (charge):

$$H_q = \frac{1}{2m}\left(\vec{p} - q\vec{A}\right)^2 + q\phi$$

- **Magnetic dipole** (spin):

$$H_\mu = -\vec{\mu} \cdot \vec{B}$$

Forbidden:

- Magnetic monopole
- Toroidal moments (e.g., “anapole moment”)
- All higher-order moments (quadrupole, octupole, *etc*.)

Why is the electric dipole moment small*?

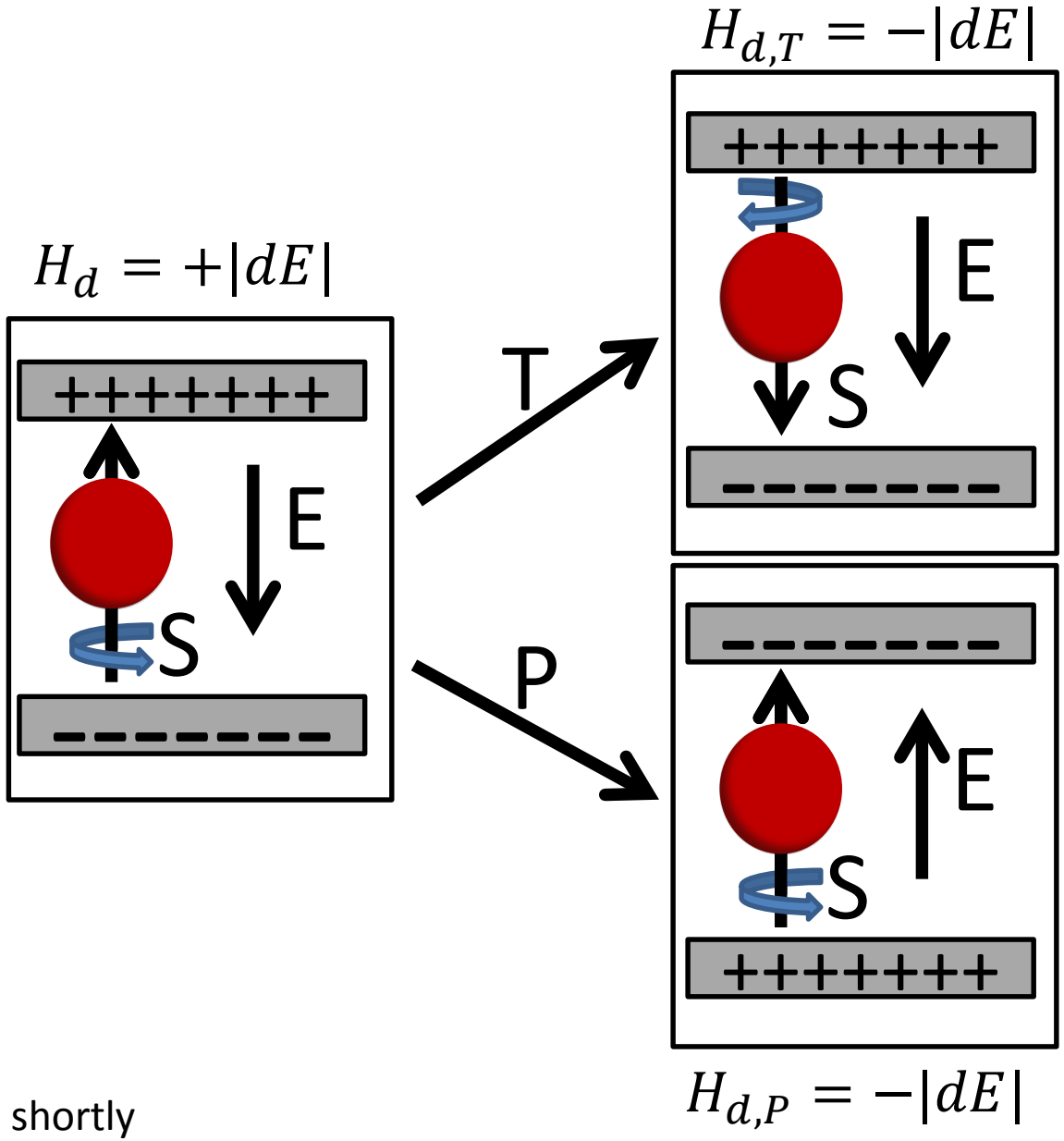
$H_d = -2d\vec{S} \cdot \vec{E}$

Symmetry transformations:

- $T: \vec{S} \rightarrow -\vec{S}$
- $T: \vec{E} \rightarrow \vec{E}$
- $P: \vec{S} \rightarrow \vec{S}$
- $P: \vec{E} \rightarrow -\vec{E}$

So:

$T: H_d \rightarrow -H_d$
$P: H_d \rightarrow -H_d$

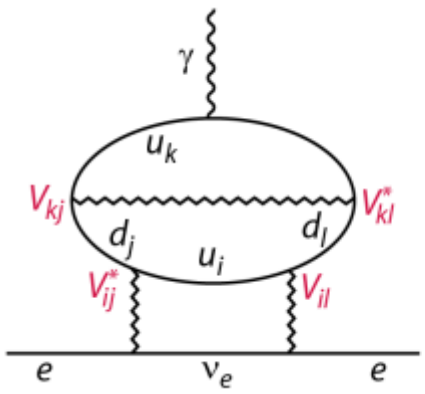


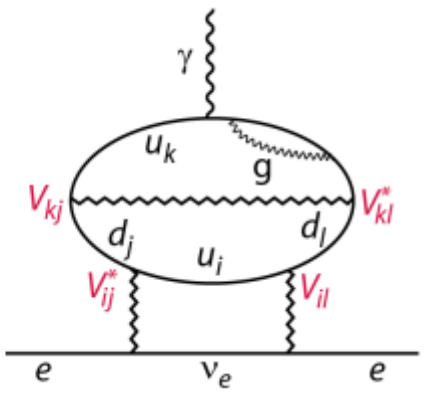
*I will say “small compared to what” shortly

eEDM in the Standard Model

- Non-zero, non-cancelling effects only appear at four-loop diagrams
- Resulting EDM:

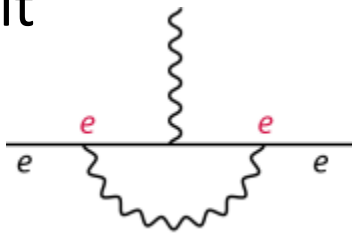
$$|d_e| \sim 10^{-38}\ e \text{ cm}.$$





…What does this mean? A few perspectives:

- Precession in 100 kV/cm field would take 10 ages of the universe
- 10 orders of magnitude smaller than experimental limit
- 24 orders of magnitude smaller than $(g-2)\mu_B/\mathrm{c}$

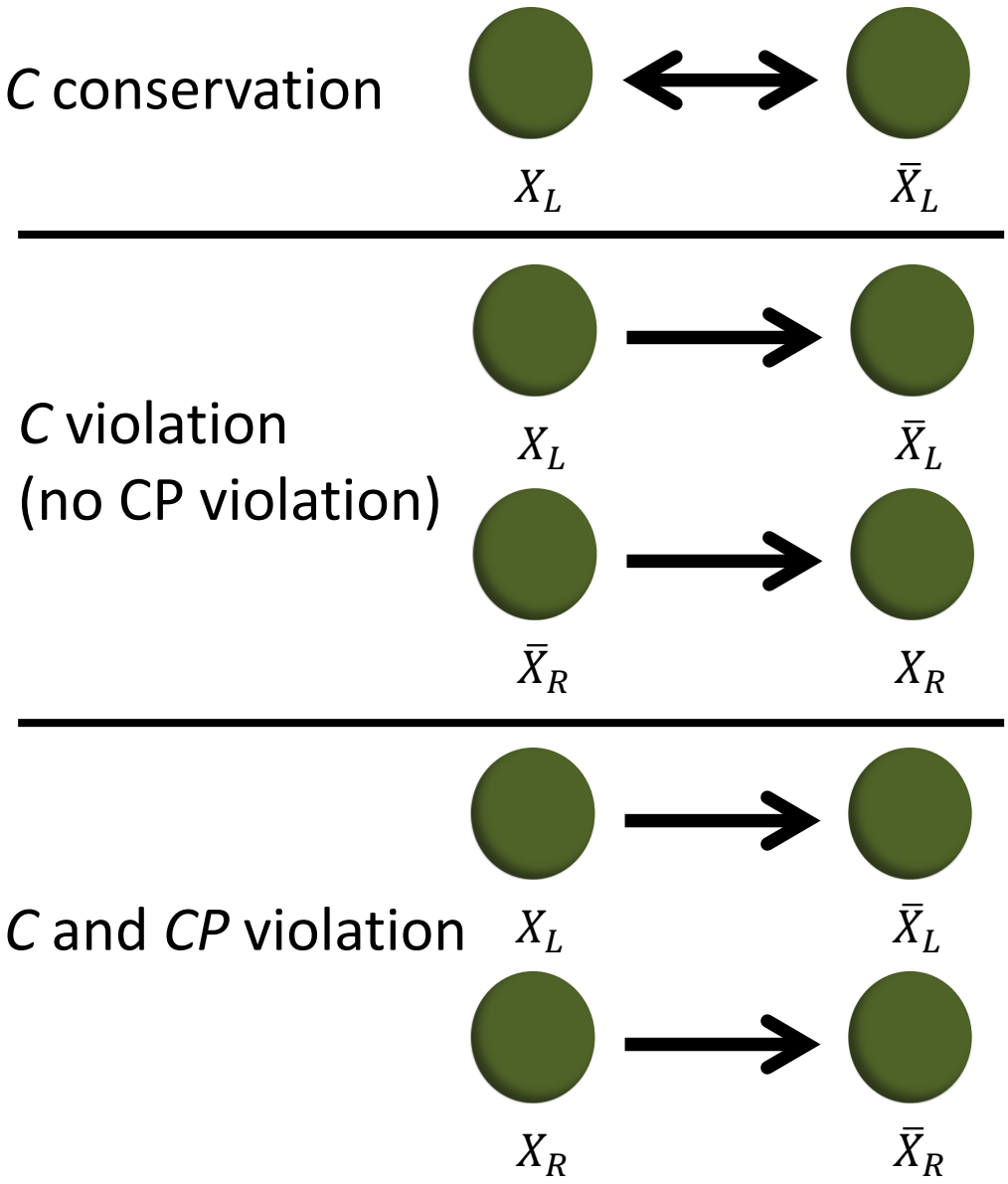


Answer, Jan. 2014:
Too round!

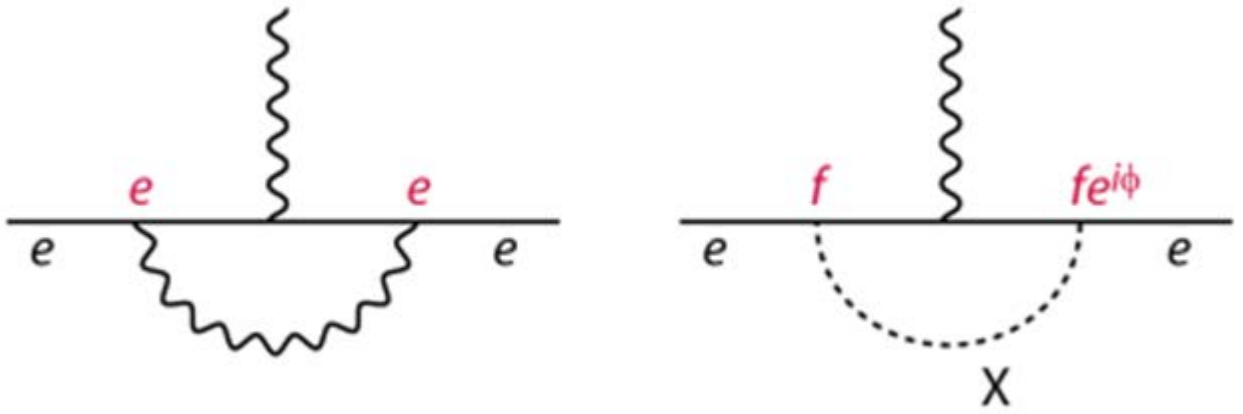
$|d_e| < 10^{-28}\ e$ cm

Sakharov's conditions

- Matter/antimatter imbalance requires both *C* and *CP* violation
- SM doesn't contain enough *CP* violation to account for observed imbalance
- Physics beyond the SM expected to have extra *CP* violation
- *CP = T*
- This means bigger EDMs!



eEDM beyond the Standard Model

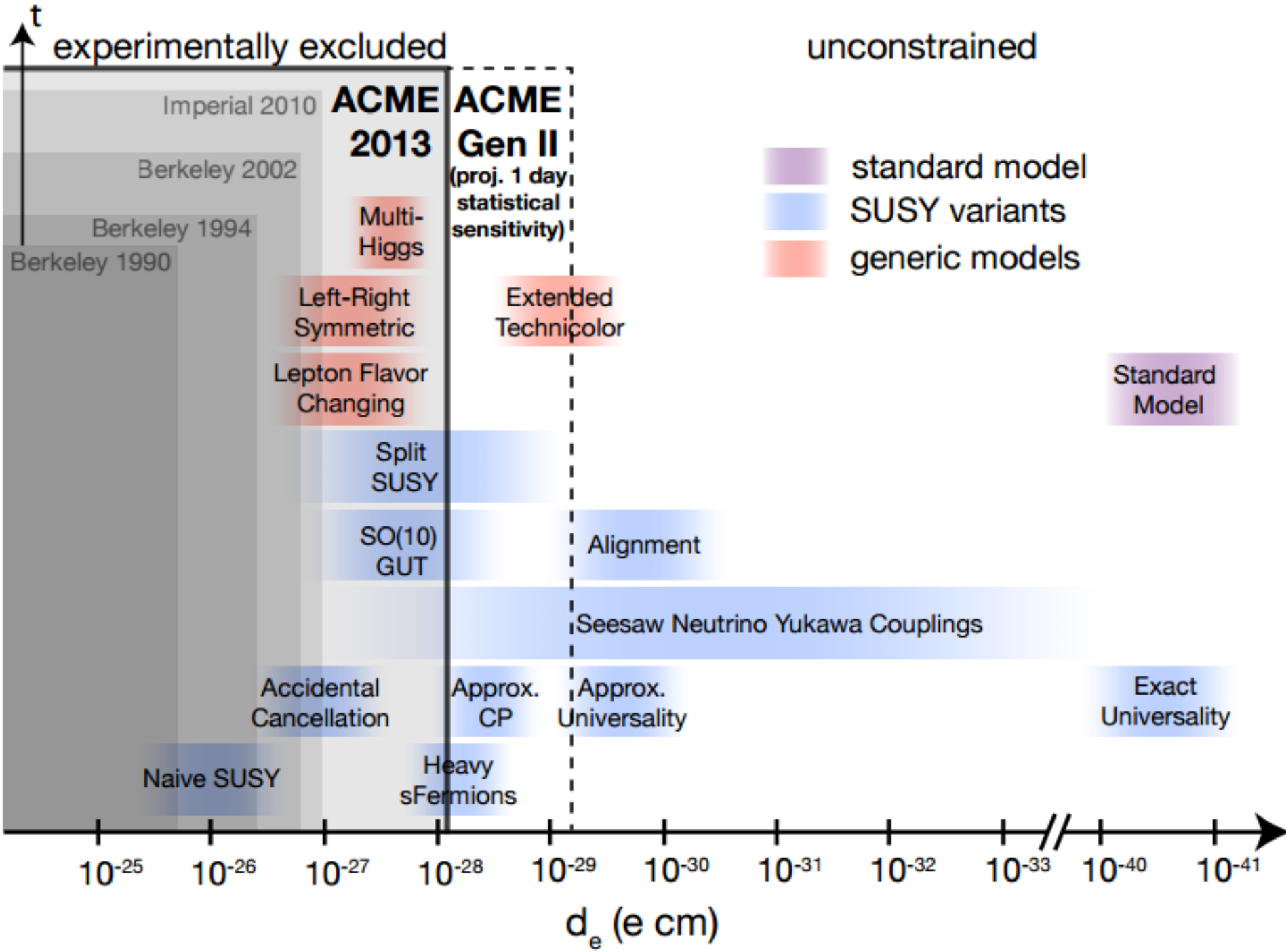


With a new particle *X* and *CP*-violating phase ϕ, a $(g-2)$-type Feynman diagram (above) gives:

$$d_e \sim \left[\left(\frac{f}{e}\right)^2 \sin\phi \left(\frac{m_e}{m_X}\right)^2\right]\left(\frac{\alpha}{2\pi}\right)\mu_B \sim 10^{-3}\left(\frac{m_e}{m_X}\right)^2 \mu_B$$

(assuming natural units with $f \sim e$ and $\phi \sim 1$)

With $m_X \sim 10$ TeV, obtain $d_e \sim 5 \times 10^{-29} e$ cm.

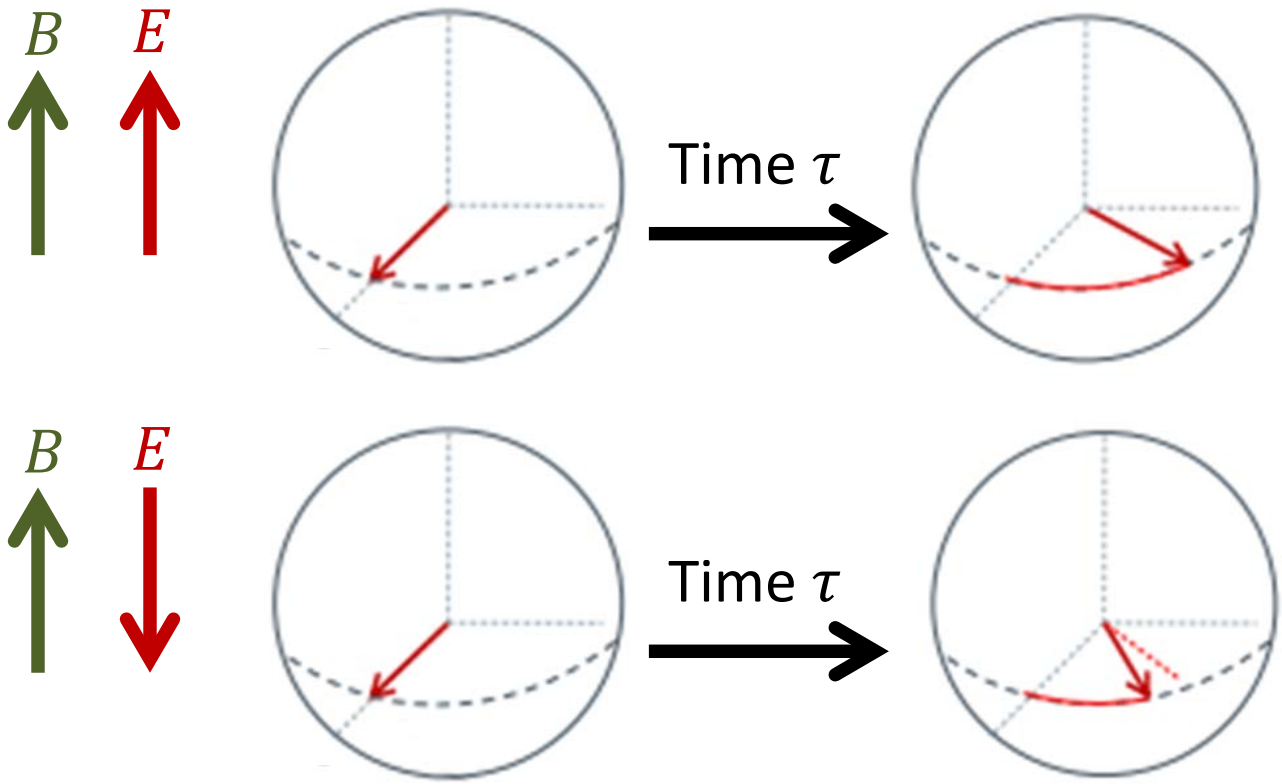

t
experimentally excluded
unconstrained
Imperial 2010
Berkeley 2002
Berkeley 1994
Berkeley 1990
ACME 2013
ACME Gen II (proj. 1 day statistical sensitivity)
standard model
SUSY variants
generic models
Multi-Higgs
Left-Right Symmetric
Extended Technicolor
Lepton Flavor Changing
Standard Model
Split SUSY
SO(10) GUT
Alignment
Seesaw Neutrino Yukawa Couplings
Accidental Cancellation
Approx. CP
Approx. Universality
Exact Universality
Naive SUSY
Heavy sFermions
10-25
10-26
10-27
10-28
10-29
10-30
10-31
10-32
10-33
10-40
10-41
de (e cm)

Outline

- Background
- **Using ThO to measure the eEDM**
  - Relativistic enhancement
  - Benefits of the Ω doublet and $^3\Delta_1$ structure
  - Other benefits of ThO
- The ACME apparatus
- Data analysis
- Outlook

EDM measurement scheme

$$H = -\mu \cdot B - d \cdot E$$



$$\phi_+ = \mu B\tau + dE\tau$$

$$\phi_- = \mu B\tau - dE\tau$$

$$d \propto \phi_+ - \phi_-$$

Figure of merit:

$$\frac{1}{\Delta d} \propto E\tau\sqrt{\dot{N}T}$$

E = electric field
τ = precession time
$\dot{N}$ = experiment repetition rate
T = integration time

Choosing a system

- Free electrons impractical (small τ)
- Schiff's theorem: electrostatically bound electrons have no observable EDM:

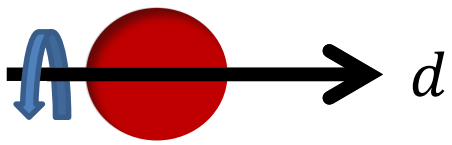
$$\langle H_d \rangle = -\langle 2d\, S \cdot E \rangle = -2d\, S \cdot \langle E(r) \rangle = 0$$

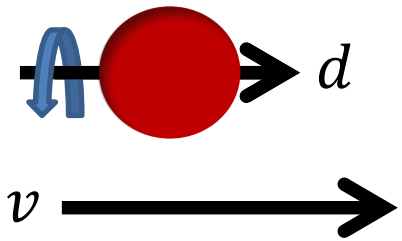
(otherwise, electron would accelerate away)

- Loophole: relativistic electron has length-contracted spin.

$$\langle H_d \rangle = -\langle 2d\, S \cdot E \rangle = -2d\, \langle S(r) \cdot E(r) \rangle \neq -2d \langle S \rangle \cdot \langle E \rangle$$

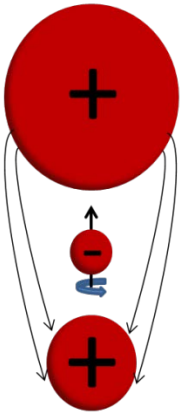
- Therefore, want relativistic bound electrons
  - Will use a molecule with a heavy atom: ThO ($Z_{Th} = 90$)

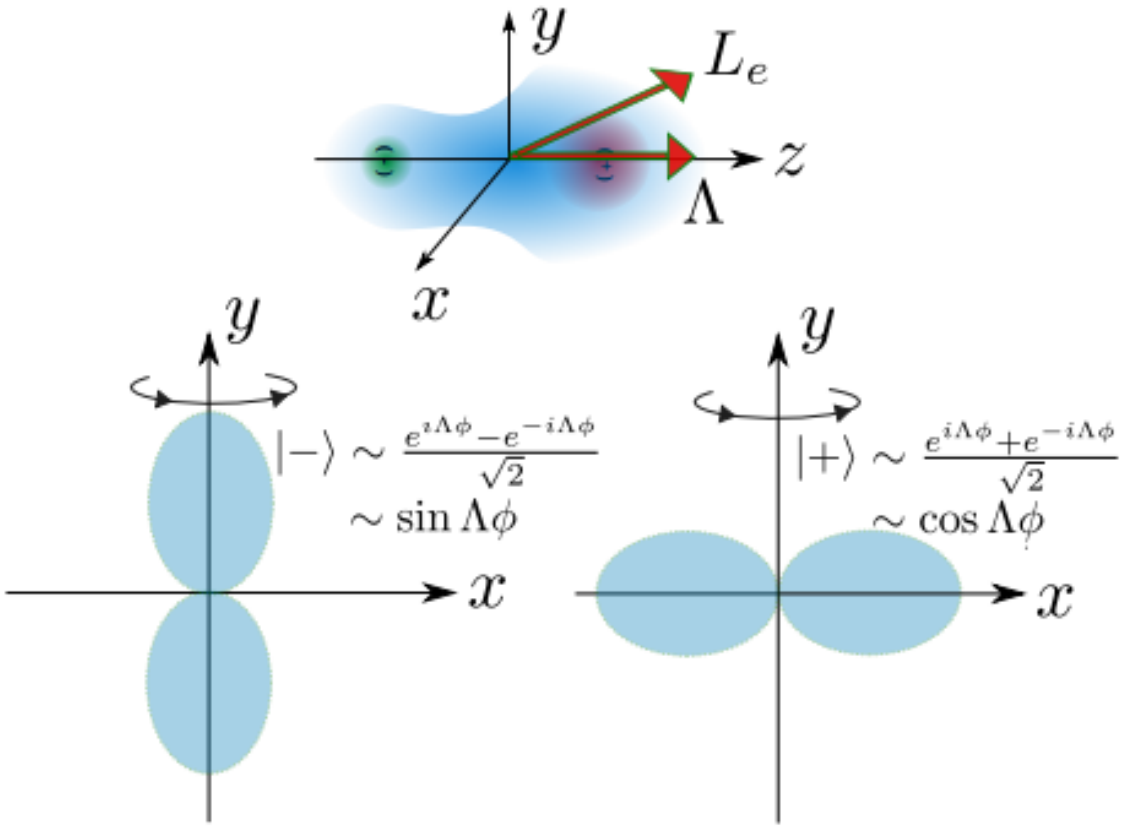




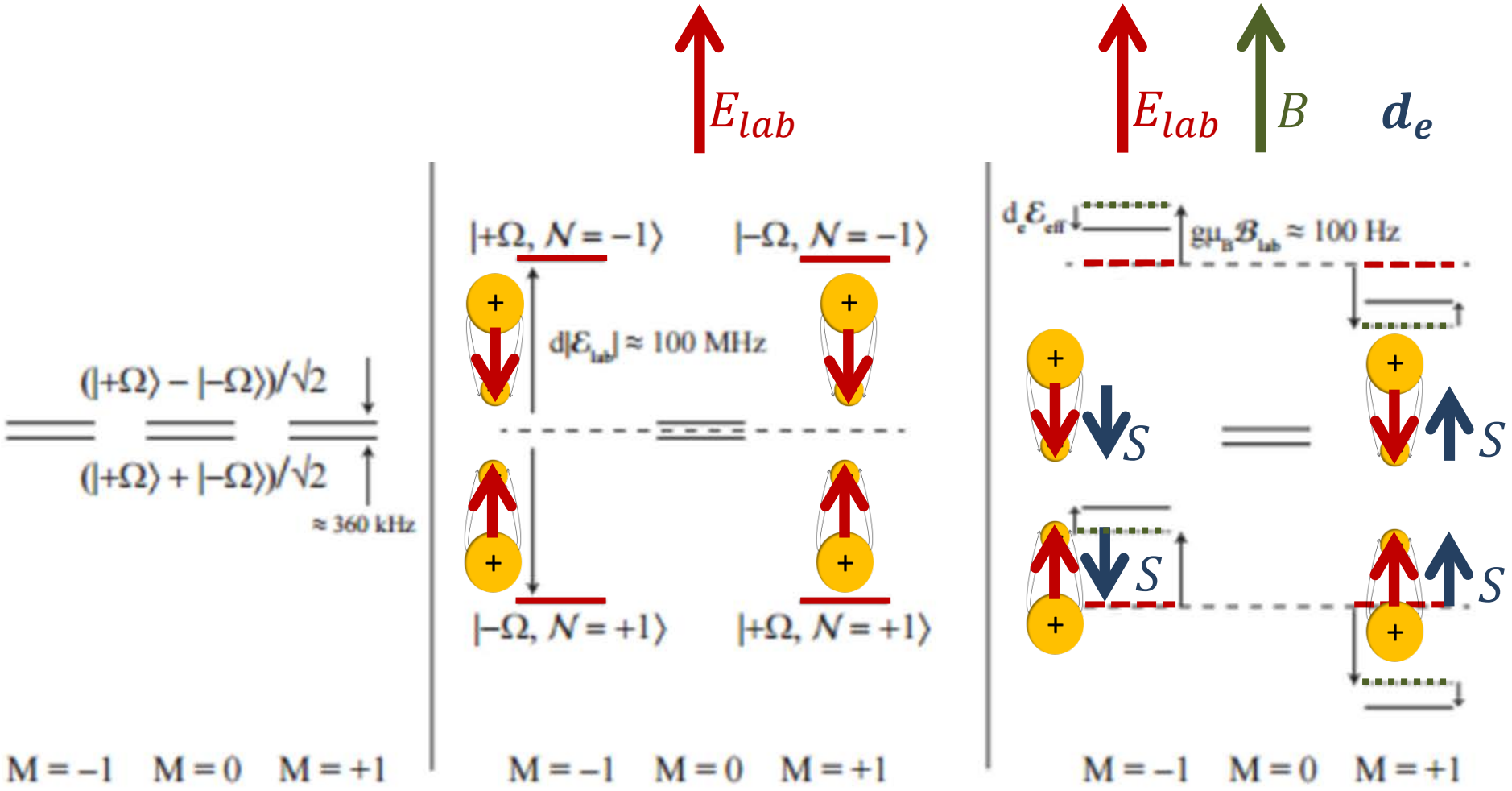
Ω doublets in molecules

- Molecules have large internal electric fields
- Easily polarized due to nearby opposite-parity states
  - Rotational levels: $\sim 10^{-5}$ eV $\rightarrow$ ~ 100 kV/cm
  - Ω doublets: $\sim 10^{-9}$ eV $\rightarrow$ ~ 10 V/cm





Ω doublet structure



Takeaway: can reverse effective electric field spectroscopically!

$^3\Delta_1$ structure

Choose a state with:

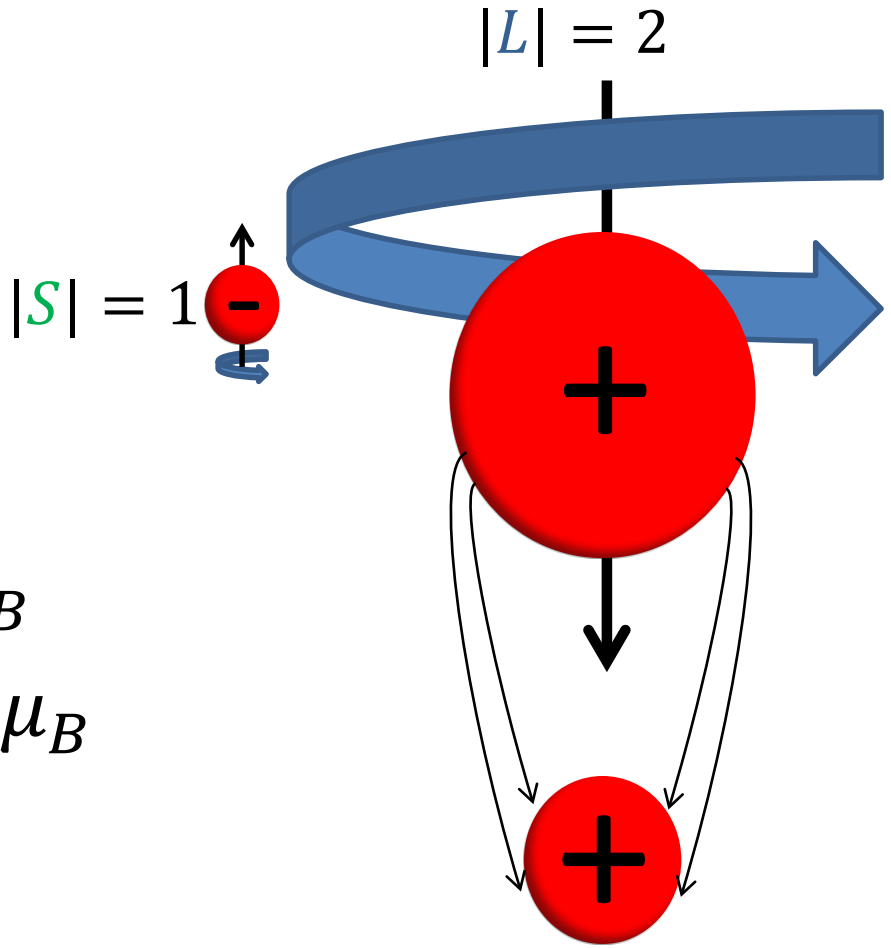
- $|S_z| = 1$
- $|L_z| = 2$
- $\hat{S} = -\hat{L}$

$\rightarrow |\mu_{tot}| = |g_s S_z + g_L L_z|\mu_B$

$\approx |2 \times 1 + 1 \times (-2)|\mu_B$

$= 0.$

(Actually, $g_{tot} \approx 10^{-2}$.)



Criteria favorable to ThO

- Large effective electric field (relativistic; heavy nucleus)
- Polarizable (omega doublet)
- Orientations in applied field spectroscopically resolvable

- Diatomic (simple spectra)
- Transitions accessible by lasers
- Spectroscopy worked out before our experiment

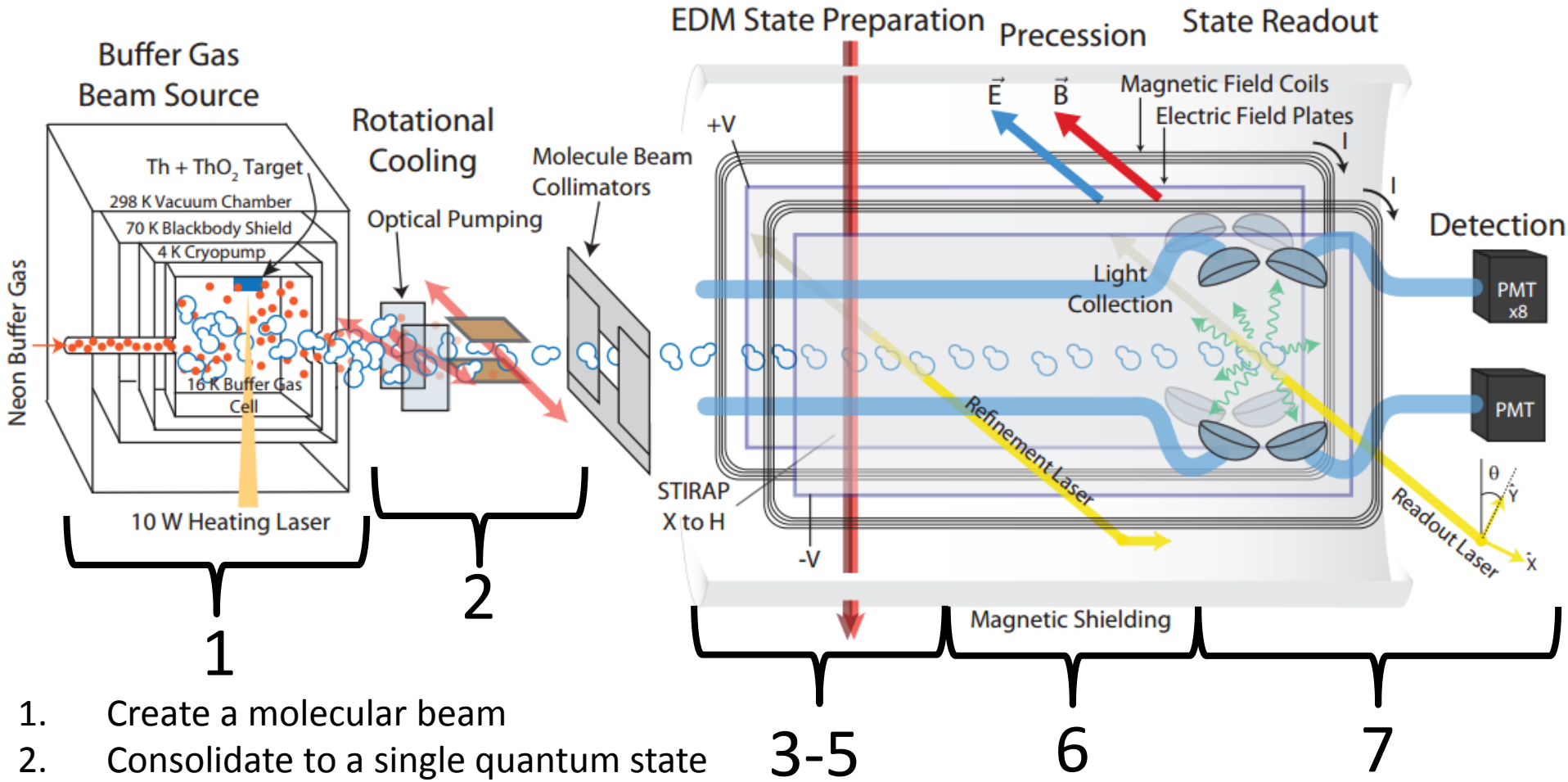
- Magnetically insensitive (systematic error rejection)
- “Long” lifetime (precession time) in science state: ~1 ms

- Efficiently produced in a beam

Outline

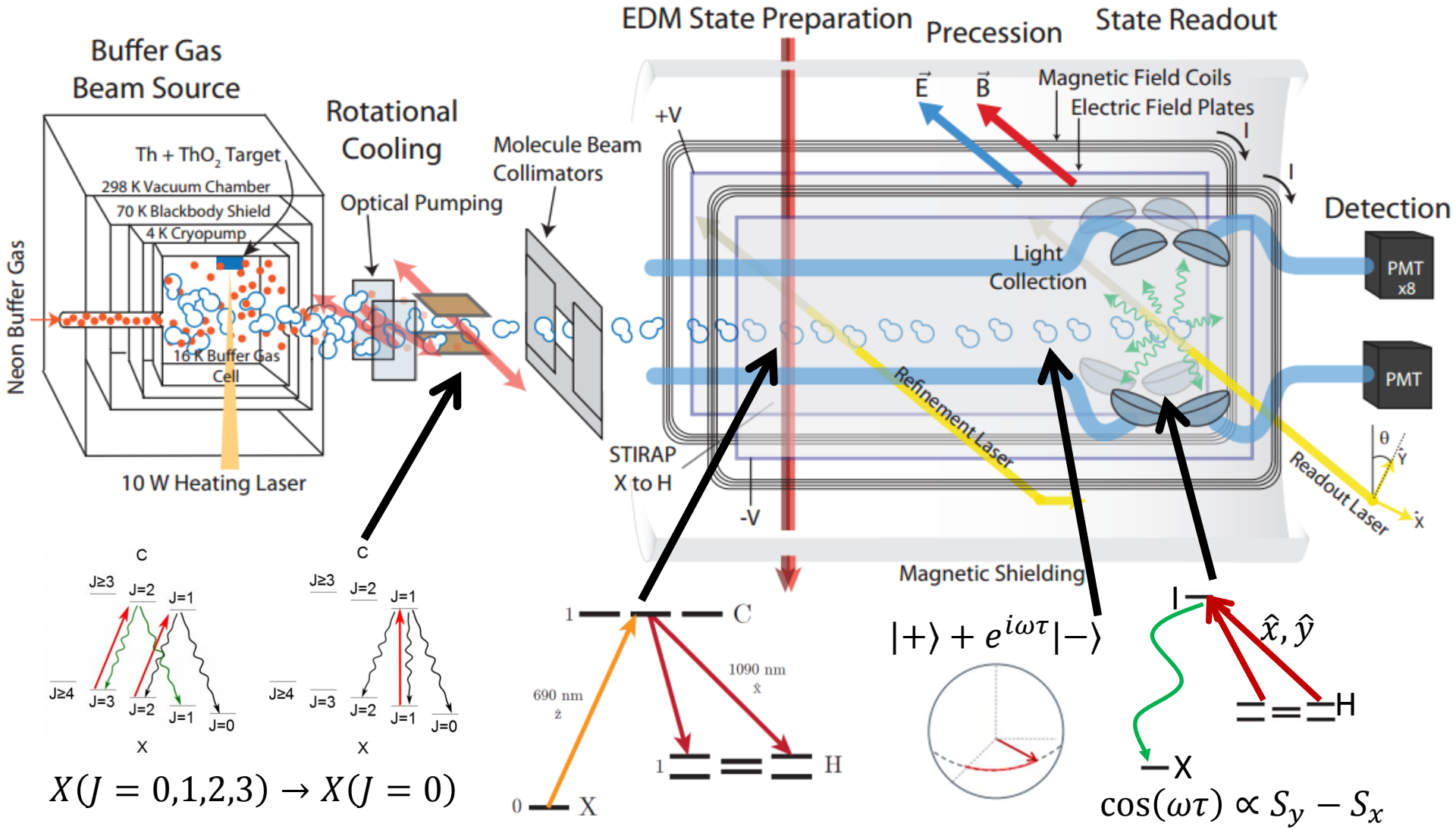
- Background
- Using ThO to measure the eEDM
- **The ACME apparatus**
  - Beam source
  - Rotational cooling
  - State preparation
  - State readout
  - Parameter switches
- Data analysis
- Outlook

Doing the measurement

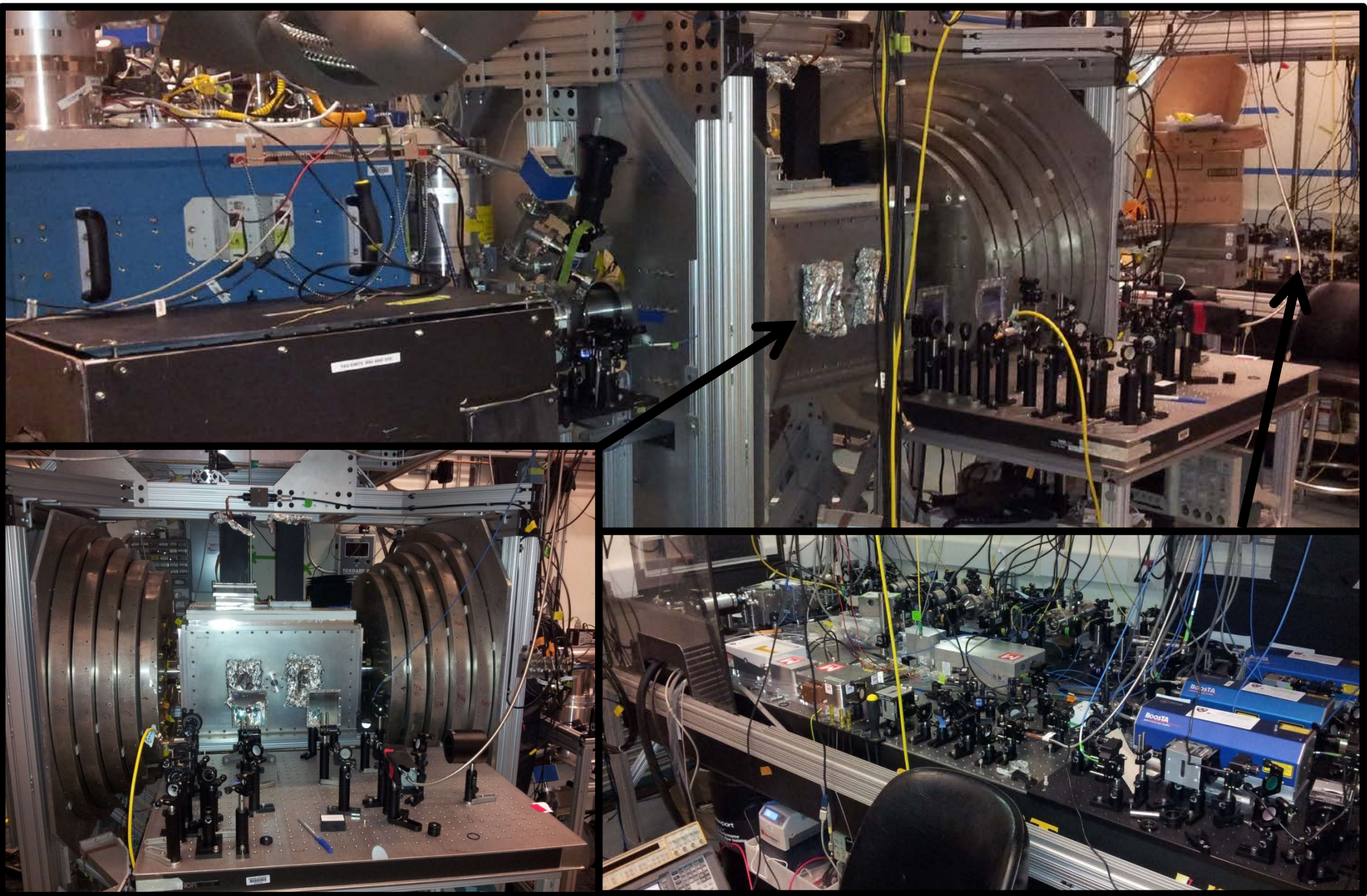


1. Create a molecular beam
2. Consolidate to a single quantum state
3. Transfer to the $^3\Delta_1$ science state
4. Polarize the molecule
5. Orient the spin
6. Wait for precession
7. Read out the spin precession

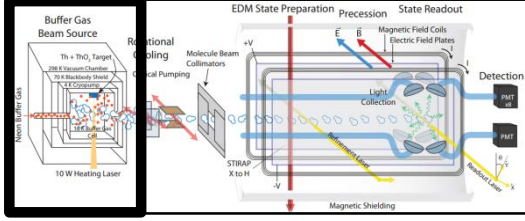
Doing the measurement



…and actually doing the measurement



Closer look: beam source



Buffer Gas Beam Source

Th + ThO_2 Target

298 K Vacuum Chamber

70 K Blackbody Shield

4 K Cryopump

Neon Buffer Gas

16 K Buffer Gas Cell

10 W Heating Laser

Rotational Cooling

Optical Pumping

Molecule Beam Collimators

EDM State Preparation

Precession

State Readout

+V

$\vec{E}$ $\vec{B}$

Magnetic Field Coils

Electric Field Plates

I

Detection

Light Collection

PMT x8

PMT

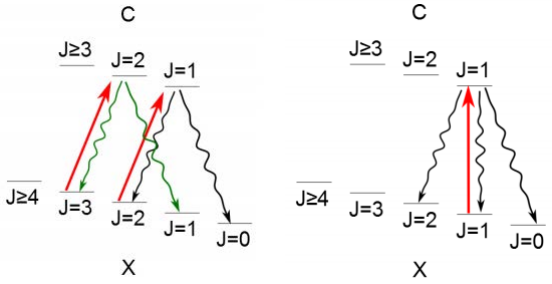
STIRAH X to H

Refinement Laser

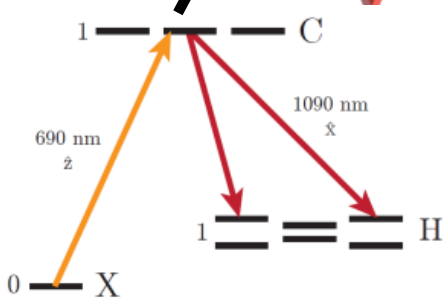
Readout Laser

-V

Magnetic Shielding

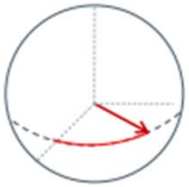


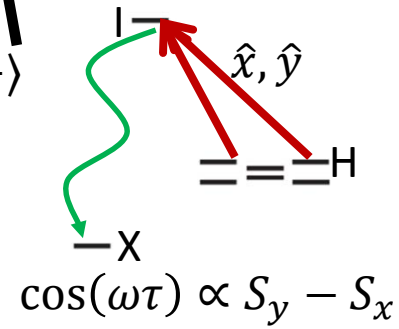
$X(J = 0,1,2,3) \rightarrow X(J = 0)$



$X(J = 0) \rightarrow H(J = 1)(|+\rangle + |-\rangle)$

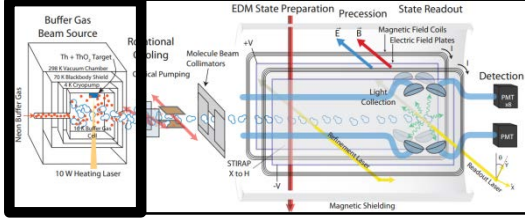
$|+\rangle + e^{i\omega\tau}|-\rangle$



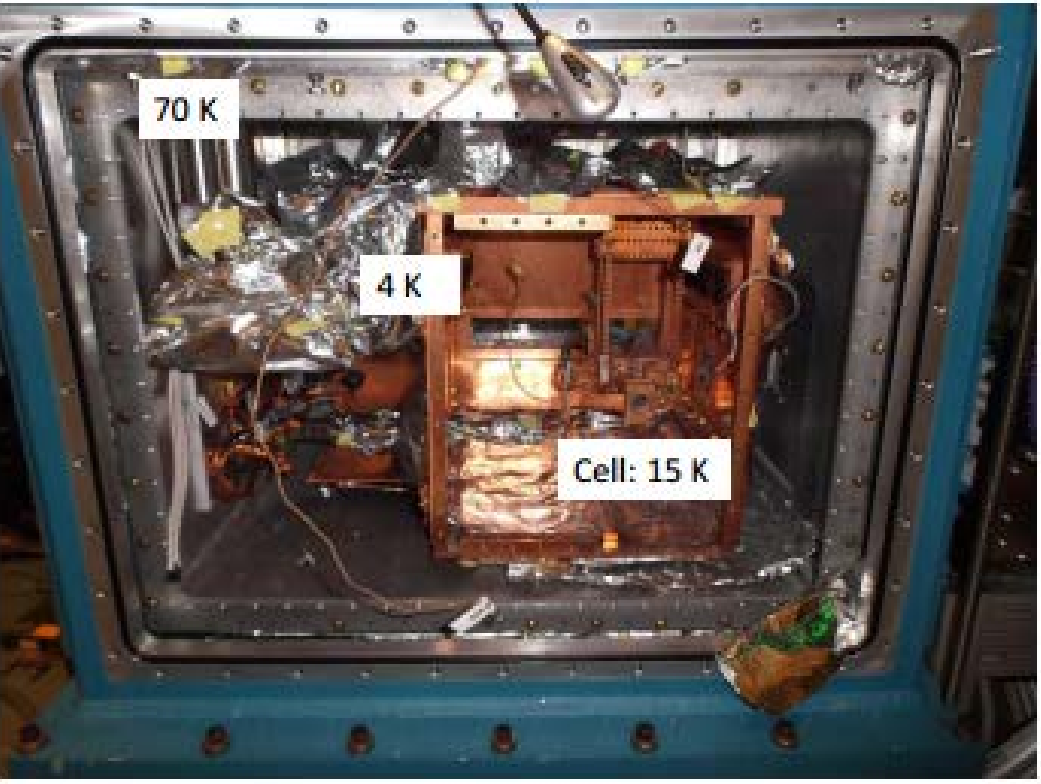


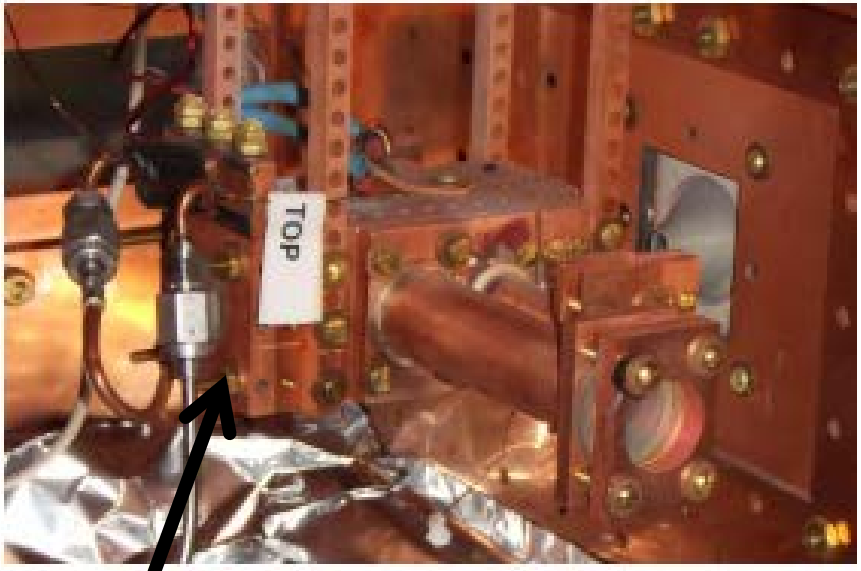
$\cos(\omega\tau) \propto S_y - S_x$

Beam source: laser ablation



- ThO_2 ablated by pulsed Nd:YAG laser
- Some of the ablation plume is ThO
- The plume is entrained in a flow of cold neon buffer gas

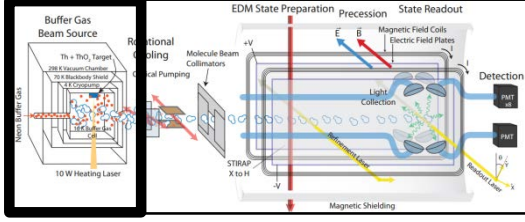


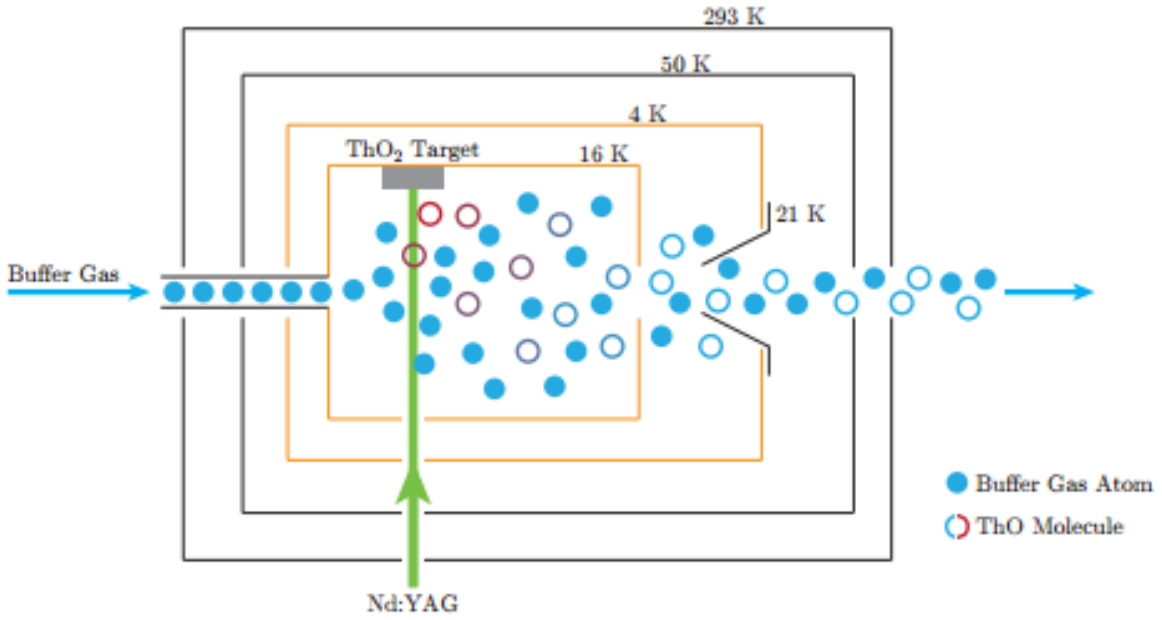


Ceramic ThO_2 target (white) on bottom, pressed and sintered. Used for ablation.

Mixed ThO+ThO_2 target (gray) pressed and used for thermochemical source.

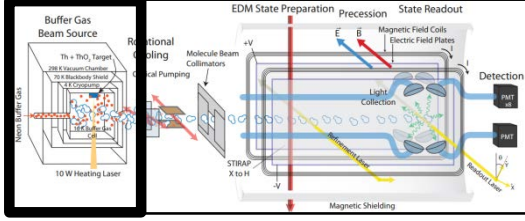
Buffer-gas beam source





- Slow (180 m/s)
- Cold (~all ThO molecules in vibronic ground state, T_{rot}~4 K)
- Relatively high flux. ThO ablation source: 5×10^{12} mol/sec

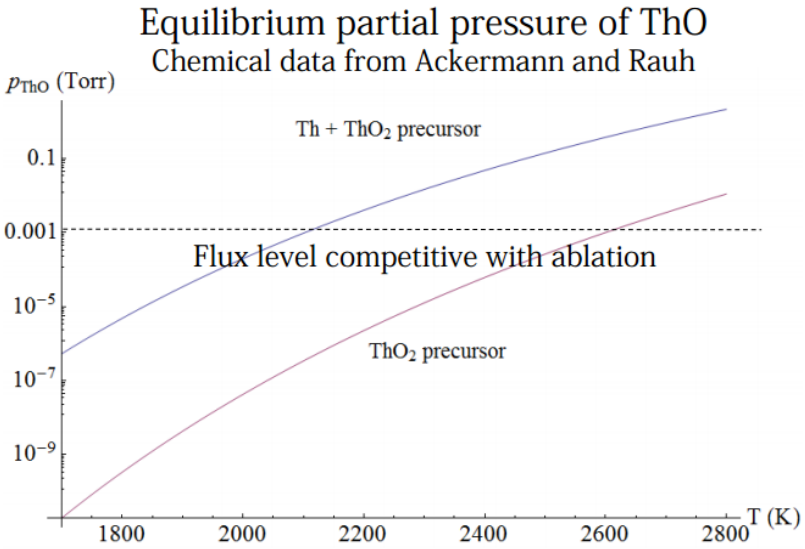
Thermochemical source

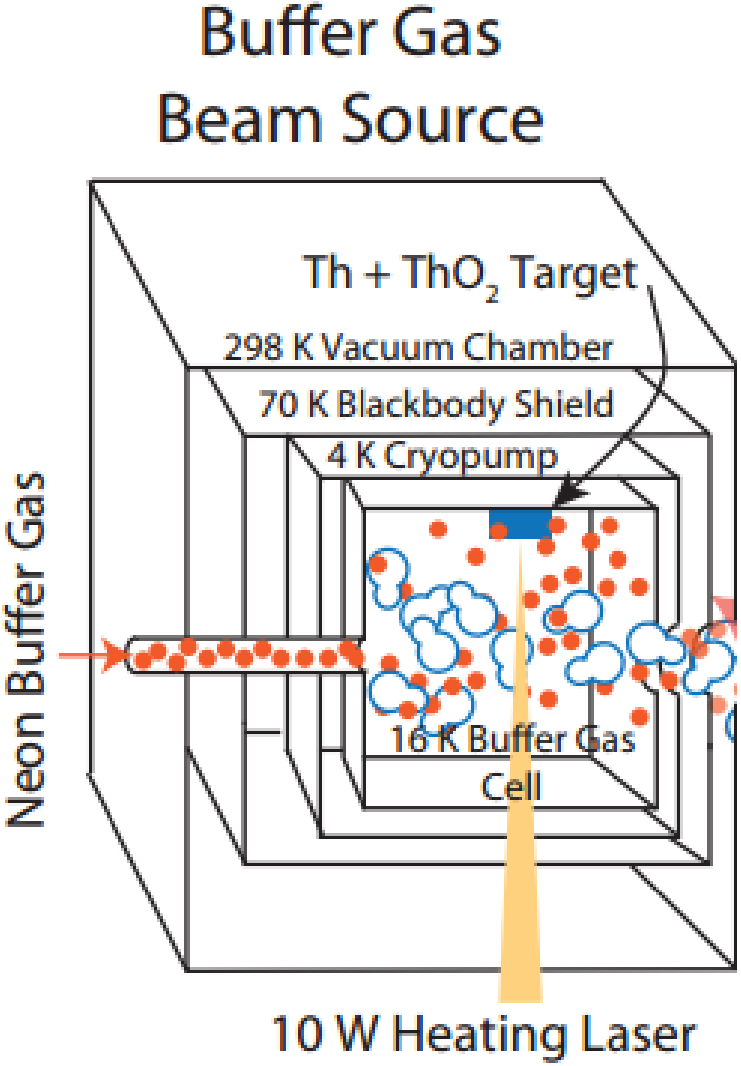


- Drive reaction by heating:

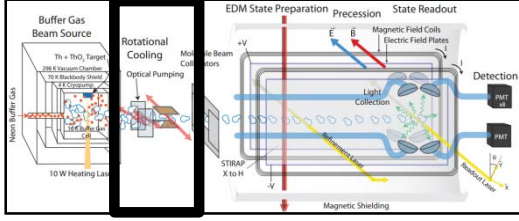
$$ThO_2\,(s) + Th(s) \rightarrow 2ThO(g)$$

- Use 10 W fiber laser
- 10x higher flux!
- Radioactive dust high
- Target lifetimes low





Closer look: Optical pumping



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Molecule Beam Collimators

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Precession

State Readout

+V

$\vec{E}$ $\vec{B}$

Magnetic Field Coils

Electric Field Plates

I

I

Detection

Light Collection

PMT x8

PMT

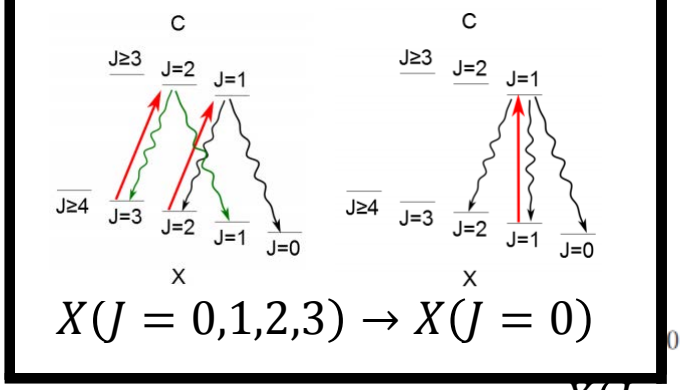
STIRAP X to H

-V

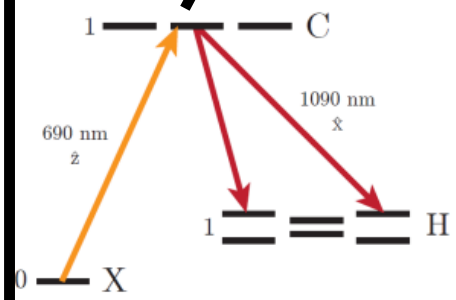
Refinement Laser

Readout Laser

Magnetic Shielding

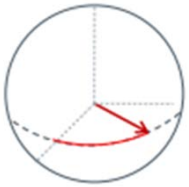


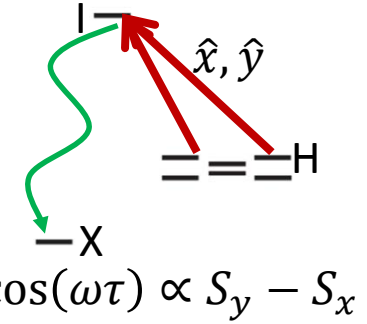
$X(J = 0,1,2,3) \rightarrow X(J = 0)$



$X(J = 0) \rightarrow H(J = 1)(|+\rangle + |-\rangle)$

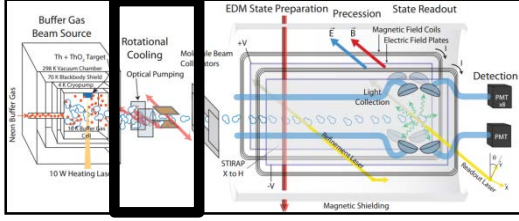
$|+\rangle + e^{i\omega\tau}|-\rangle$



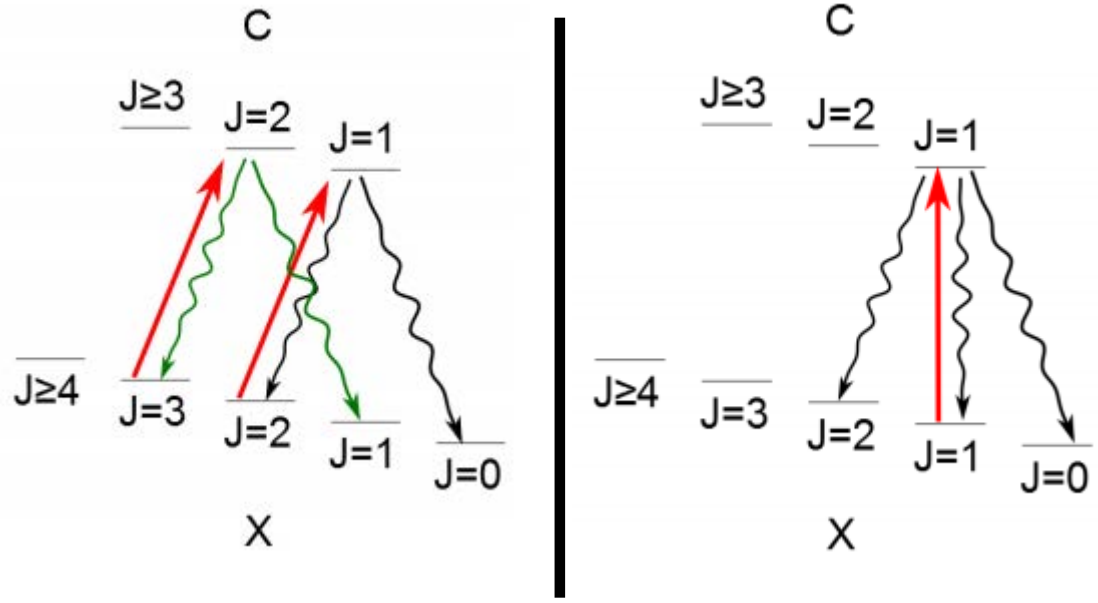


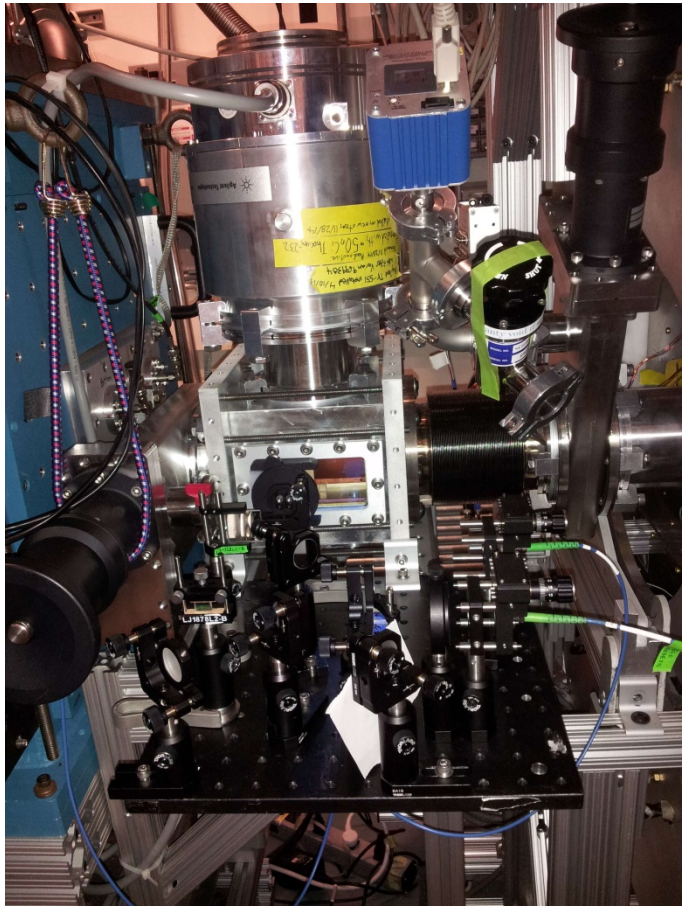
$\cos(\omega\tau) \propto S_y - S_x$

Rotational cooling

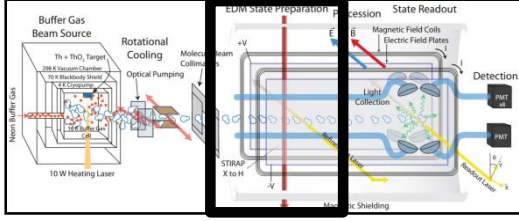


- Rotational temperature ~4 K
- Drive population to $J = 0$
- Increase population by ~ 4x
- No gain relative to Gen. I





Closer look: STIRAP



Buffer Gas Beam Source

Th + ThO_2 Target

298 K Vacuum Chamber

70 K Blackbody Shield

4 K Cryopump

Neon Buffer Gas

16 K Buffer Gas Cell

10 W Heating Laser

Rotational Cooling

Optical Pumping

Molecule Beam Collimators

EDM State Preparation

Precession

State Readout

$\vec{E}$

$\vec{B}$

+V

-V

Magnetic Field Coils

Electric Field Plates

I

I

Detection

Light Collection

PMT x8

PMT

STIRAP X to H

Refinement Laser

Readout Laser

Magnetic Shielding

C

J≥3

J=2

J=1

J≥4

J=3

J=2

J=1

J=0

X

$X(J = 0,1,2,3) \rightarrow X(J = 0)$

1

C

690 nm

ẑ

1090 nm

x̂

1

H

0

X

$X(J = 0) \rightarrow H(J = 1)(|+\rangle + |-\rangle)$

$|+\rangle + e^{i\omega\tau}|-\rangle$

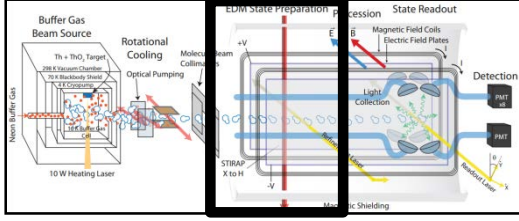
$\hat{x}, \hat{y}$

H

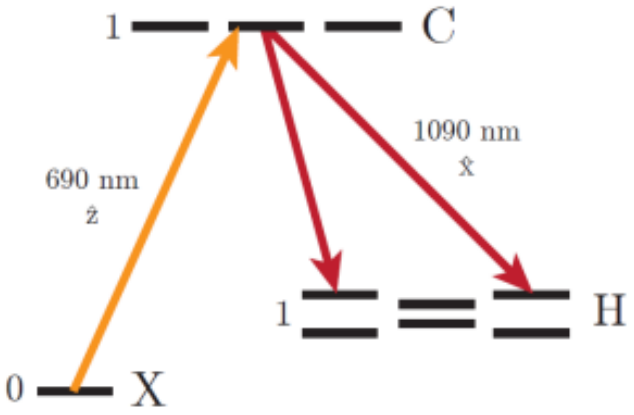
X

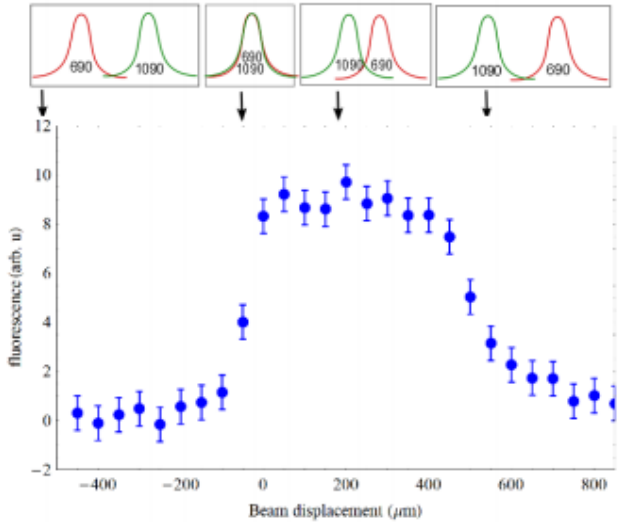
$\cos(\omega\tau) \propto S_y - S_x$

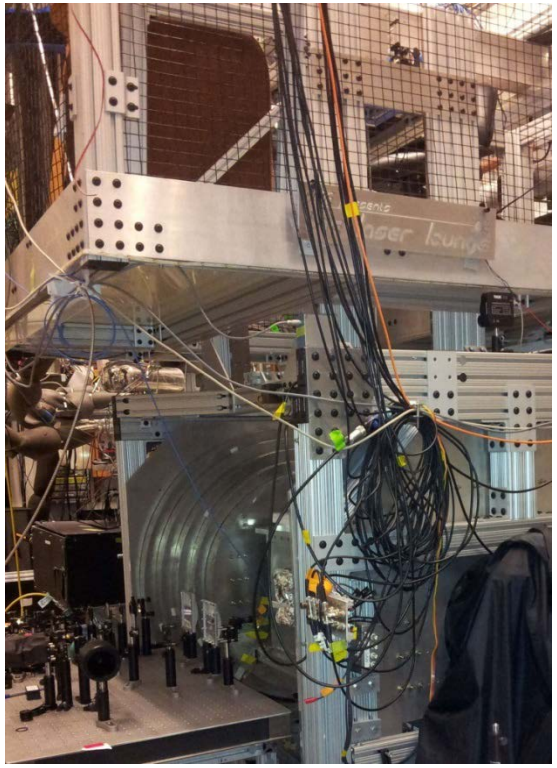
State preparation: STIRAP



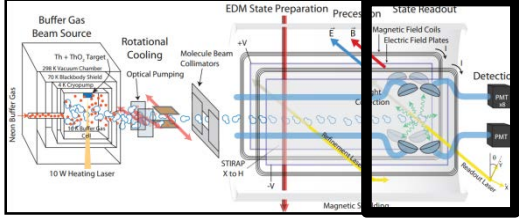
- Gen. I state preparation via optical pumping
  - ~5% efficiency
- Gen. II: counter-intuitive pulse sequence coherently transfers 80-100% of population to target state
- Demonstrated 40%; improvements ongoing







Closer look: state readout



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STIRAP X to H

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Refinement Laser

Readout Laser

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PMT x8

PMT

Magnetic Shielding

C

J≥3 J=2 J=1

J≥4 J=3 J=2 J=1 J=0

X

$X(J = 0,1,2,3) \rightarrow X(J = 0)$

1 C

690 nm ẑ

1090 nm x̂

0 X

1 H

$X(J = 0) \rightarrow H(J = 1)(|+\rangle + |-\rangle)$

$|+\rangle + e^{i\omega\tau}|-\rangle$

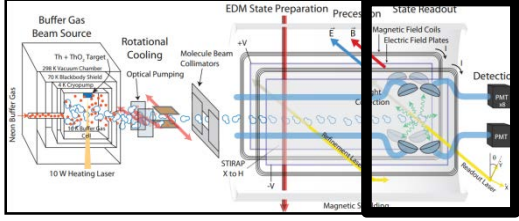
$\hat{x}, \hat{y}$

H

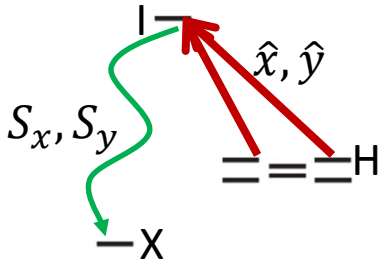
X

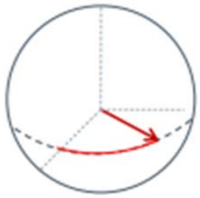
$\cos(\omega\tau) \propto S_y - S_x$

Projective measurement

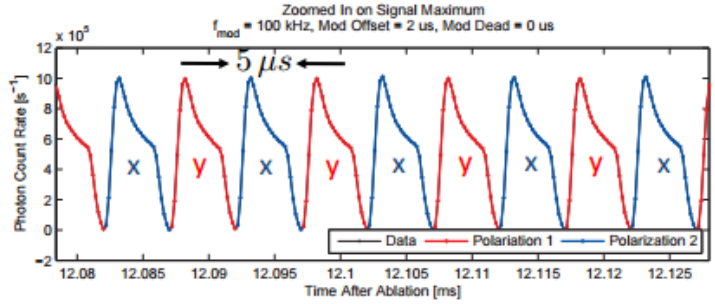


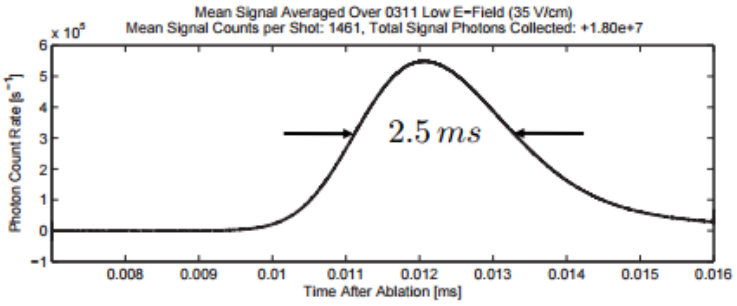
- Alternately project spin along $\hat{x}$ and $\hat{y}$
- Detect fluorescence signals S_x and S_y
- Phase given by $\cos(\phi) \propto A = \frac{S_y - S_x}{S_y + S_x}$
- Dither readout basis to measure "contrast," sensitivity to $\Delta\phi$

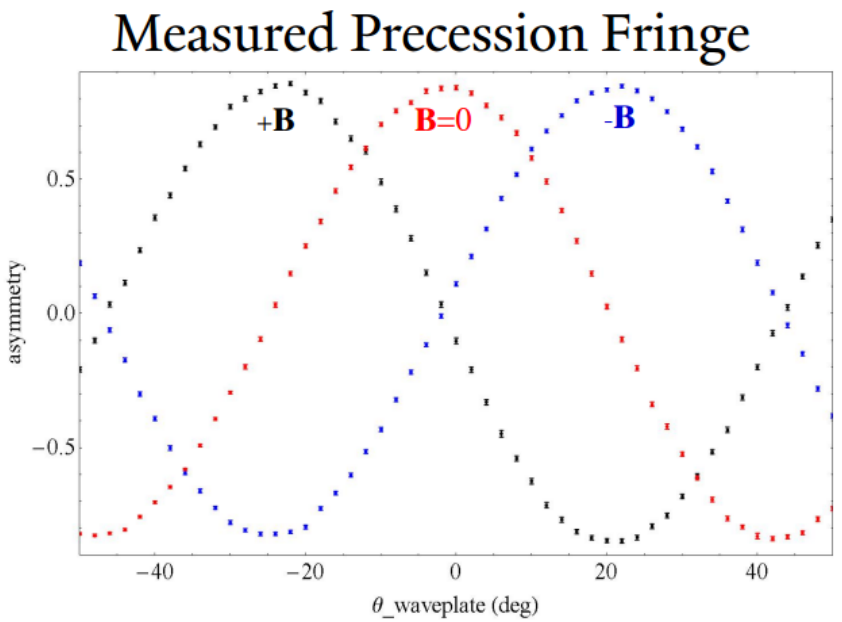




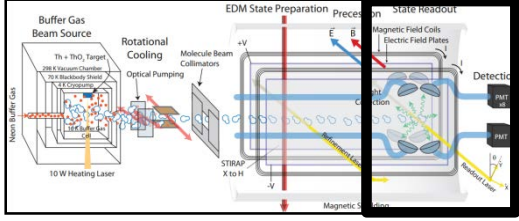
$$\cos(\omega\tau) \propto \frac{S_y - S_x}{S_y + S_x}$$



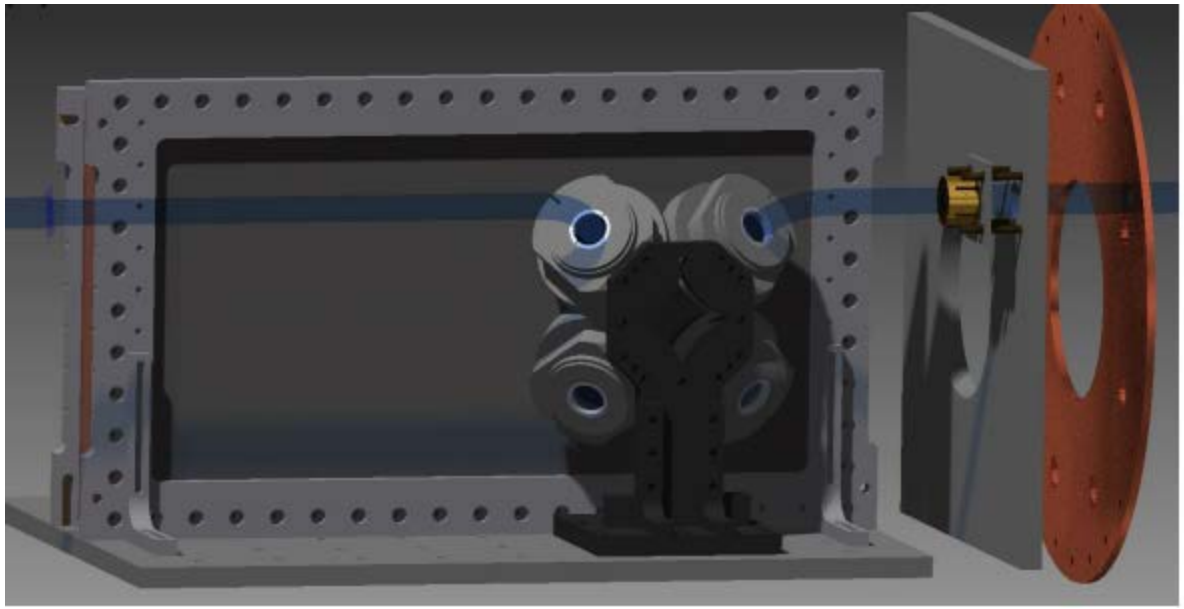


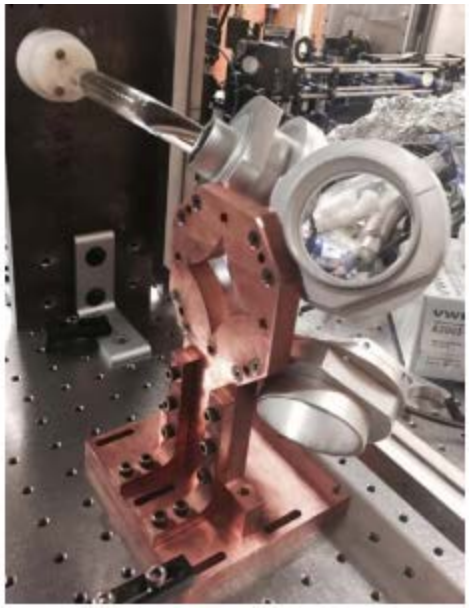


Fluorescence collection

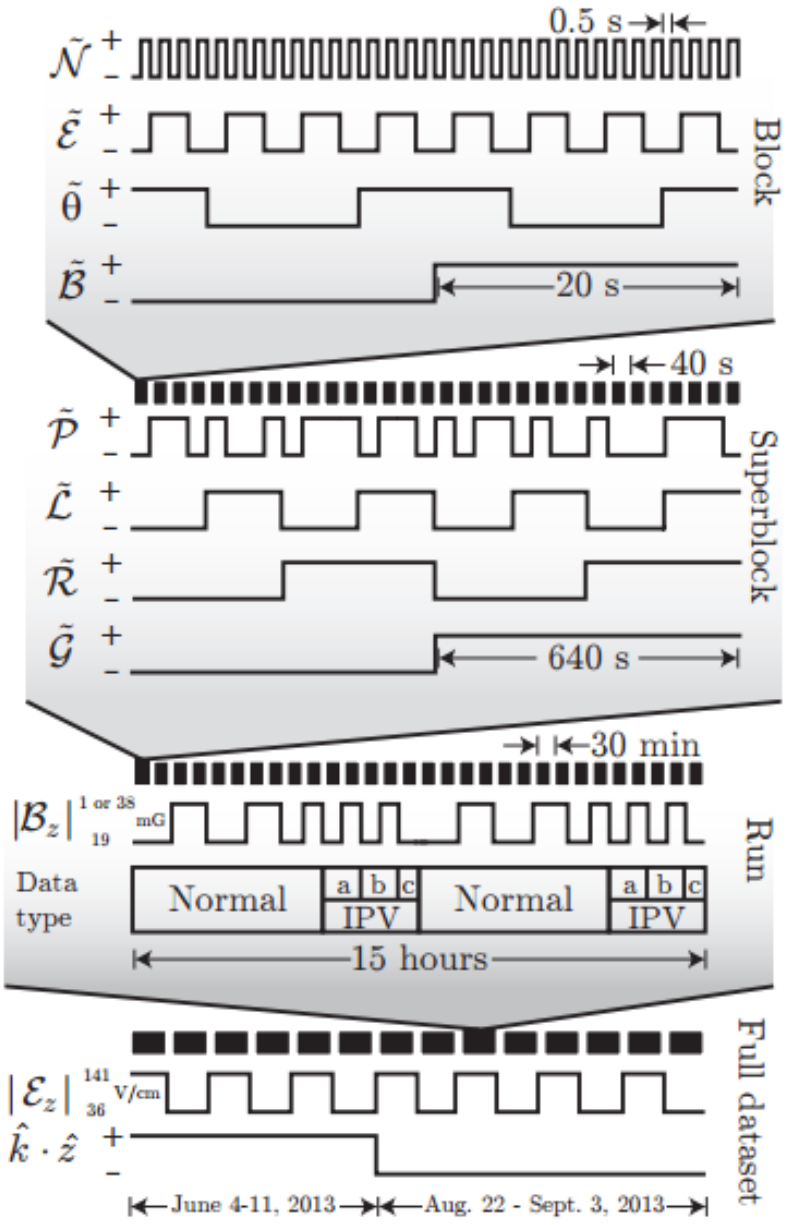


- Collect 512 nm fluorescence using lenses and light pipes
  - 10-20% photon collection efficiency
- Quantum efficiency with photomultiplier tubes: 20-25%
  - Overall efficiency: 2-5%
- Very preliminary: switch to silicon photomultipliers? (QE ~40%)





Repeat under different conditions



- 1 min: A “block” of data contains all switches for an independent “EDM experiment”
- 30 mins: A “superblock” contains auxiliary switches for systematic checks
- 1 hr: The magnetic field magnitude is varied across superblocks
- 5 hrs: Some superblocks are performed with parameters intentionally varied (IPV)
- 1 day: The electric field magnitude is changed between “runs”
- 1 wk: The propagation direction of lasers for state preparation and readout is reversed
- 2 wks: All data for the Jan. 2014 result

Before this: 1 year of systematic checks!

Outline

- Background
- Using ThO to measure the eEDM
- The ACME apparatus
- **Data analysis**
  - Extracting the eEDM
  - Checking for systematic errors
- Outlook

Extracting the eEDM

Decompose phase according to parity under experimental switches:

$$\phi = \phi^0 + \phi^N + \phi^E + \phi^B + \phi^{NE} + \phi^{NB} + \phi^{EB} + \phi^{NEB}$$

$N = \hat{E}_{mol} \cdot \hat{E}_{lab}$

$E = \hat{E}_{lab} \cdot \hat{z}$

$B = \hat{B}_{lab} \cdot \hat{z}$

EDM here! (Or not.)

- Reverses with N and E
- Doesn't reverse with B

$$\phi^{NE} = 2(dE_{mol})\tau + \phi^{NE}_{syst}$$

Many other terms in the Hamiltonian…

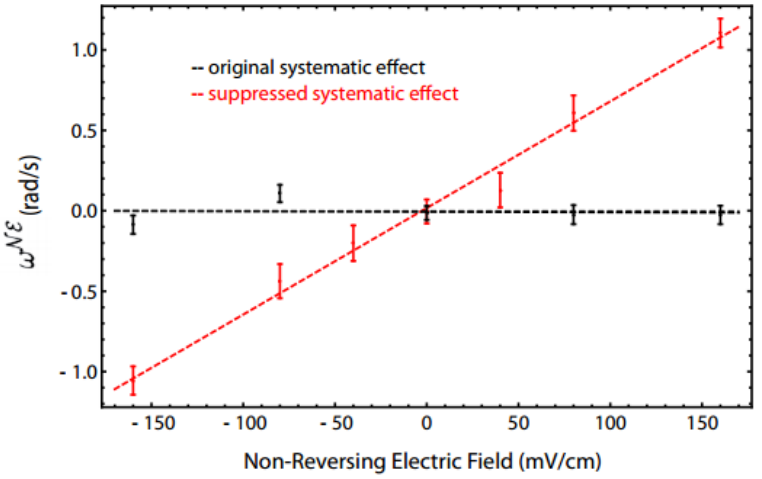
$\mathcal{NEB}$ parity	$\phi^p(\mathcal{N},\mathcal{E},\mathcal{B})$
$+++$	$\Theta_{nr} + \mu g \mathcal{B}_{nr}\tau + \alpha\Delta_0 + \beta\Delta_0^2\mathcal{B}_{nr} + \ldots$
$++-$	$\mu g \delta \mathcal{B}_0 \tau + \beta\Delta_0^2\mathcal{B}_0 + \ldots$
$+-+$	$\mu g \mathcal{B}_{\mathcal{E}}\tau + \beta\Delta_0^2\mathcal{B}_{\mathcal{E}} + \ldots$
$+--$	$\beta\Delta_0\mathcal{B}_0 D_H \mathcal{E}_{nr} + \ldots$

$\mathcal{NEB}$ parity	$\phi^p(\mathcal{N},\mathcal{E},\mathcal{B})$
$-++$	$\mu\frac{\Delta g}{2}\mathcal{B}_{nr}\tau + \alpha\Delta_{\mathcal{N}} + \beta\Delta_0\Delta_{\mathcal{N}}\mathcal{B}_{nr} + \ldots$
$-+-$	$\mu\frac{\Delta g}{2}\mathcal{B}_0\tau + \beta\Delta\Delta_{\mathcal{N}}\mathcal{B}_0 + \ldots$
$--+$	$\boxed{d_e\mathcal{E}_{mol}\tau} + \alpha D_H\mathcal{E}_{nr} + \mu\frac{\Delta g}{2}\mathcal{B}_e\tau + \ldots$
$---$	$\beta\Delta D_H\mathcal{E}_{nr}\mathcal{B}_0 + \ldots$

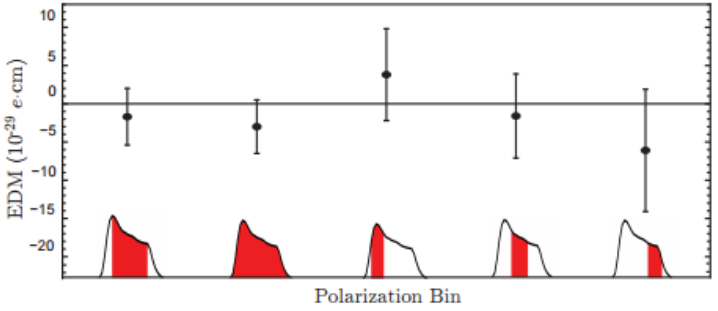
Non-EDM channels used to understand systematic errors

Checking for systematic errors

1. Exaggerate parameter variation
2. Check effect on ϕ^{NE}
3. Measure normal parameter variation
4. Infer normal effect on ϕ^{NE}



- Repeat for many parameters…
  - Laser detuning, power, pointing, polarization
  - Field plate voltage offset
  - Molecular beam shape (via clipping)
  - Magnetic field gradients
  - Non-reversing electric and magnetic field
  - Polarization switching rate



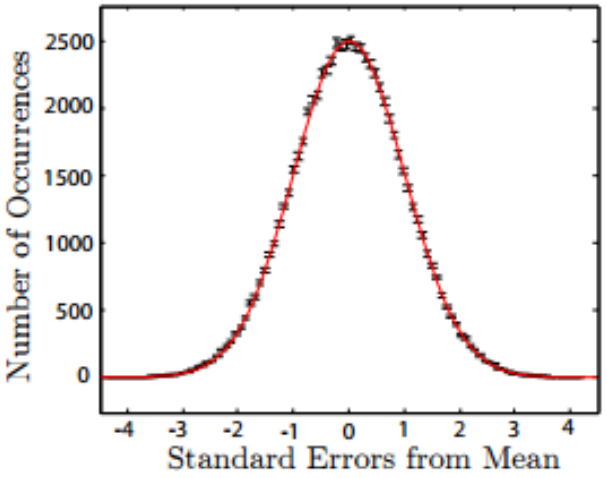
- In analysis, vary:
  - Data cut thresholds, time within molecular pulse profile, correlations with auxiliary parameters like vacuum pressure, time over dataset…

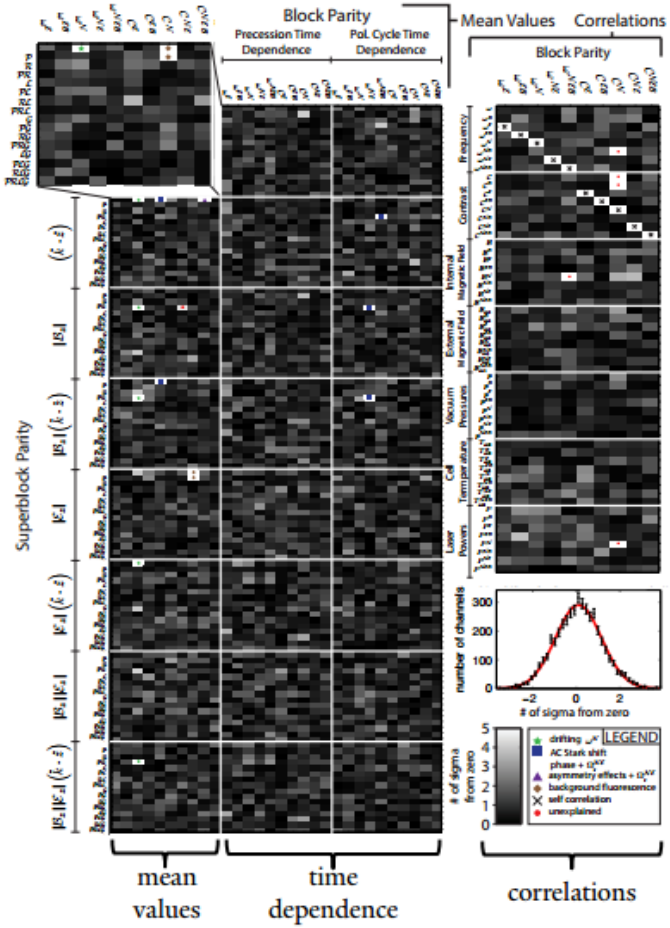
Outline

- Background
- Using ThO to measure the eEDM
- The ACME apparatus
- Data analysis
- **Outlook**

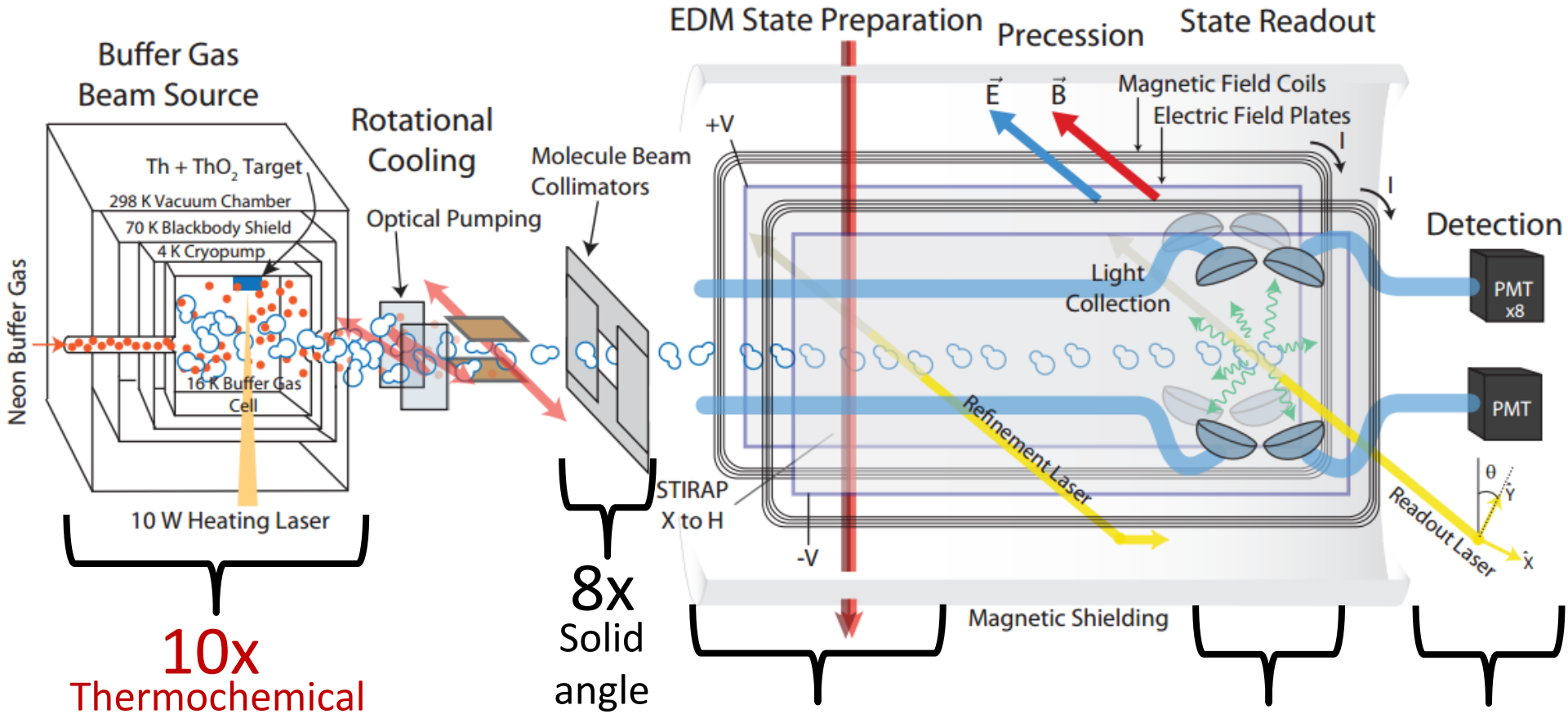
Outlook

- Gen. I:
  - good Gaussian statistics
  - Found $\Delta d_{syst} < \Delta d_{stat}$
- Gen. II statistical improvements (250-500x):
  - State preparation: 8x (16x?)
  - Fluorescence collection in light pipes: 2x
  - Detection at 512 nm: 2x
  - Beam solid angle: 8x
- Gen. III improvements (with above, >10^4x):
  - Thermochemical beam source: 10x?
  - Detection with silicon photomultipliers: 2x?
  - Electrostatic lens: 3x?
  - Optical cycling: 6x??





Projected Gen. II improvements



10x
Thermochemical beam source

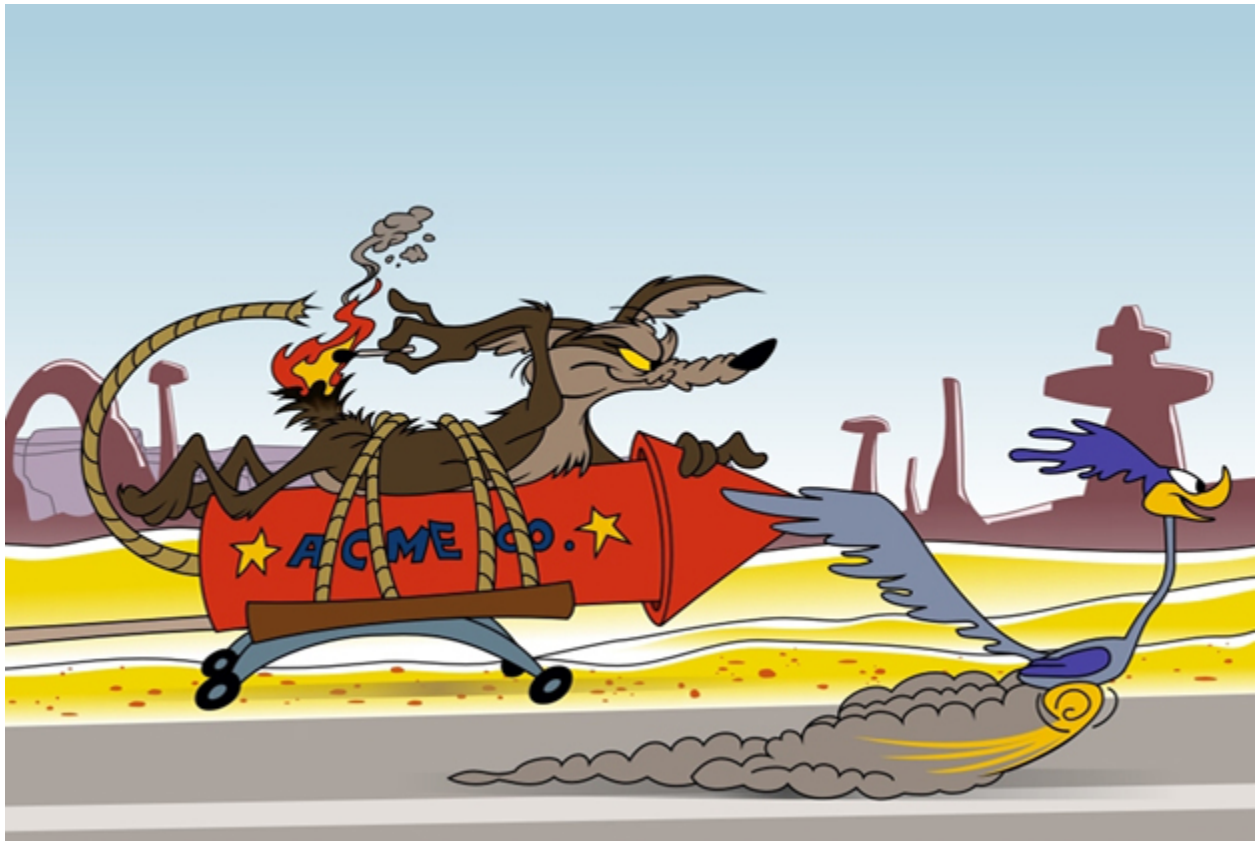
8x
Solid angle

8x-16x
STIRAP state preparation

2x
Fluorescence collection

2x
PMTs @512 nm

What could go wrong?



Systematics not expected to be limiting
…but needs to be thoroughly checked

Front: Elizabeth Petrik (J.D.), Jacob Baron (J.D.), Cris Panda (G.G.), Brendon O'Leary (D.D.), Zack Lasner (D.D.), Adam West (D.D.)

Middle (PIs): John Doyle, Gerald Gabrielse, David DeMille

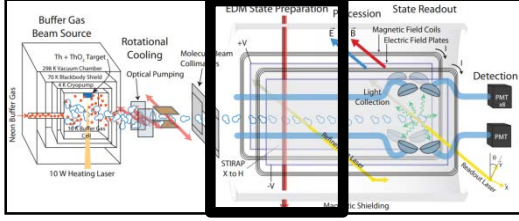
Back: Daniel Ang (G.G.), Vitaly Andreev (G.G.), Grey Wilburn (J.D.), Christian Weber (D.D.)

…And many former members!

Questions?

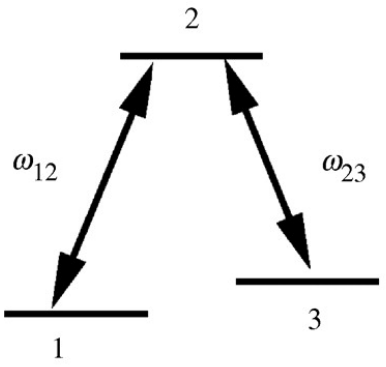
Extra slides

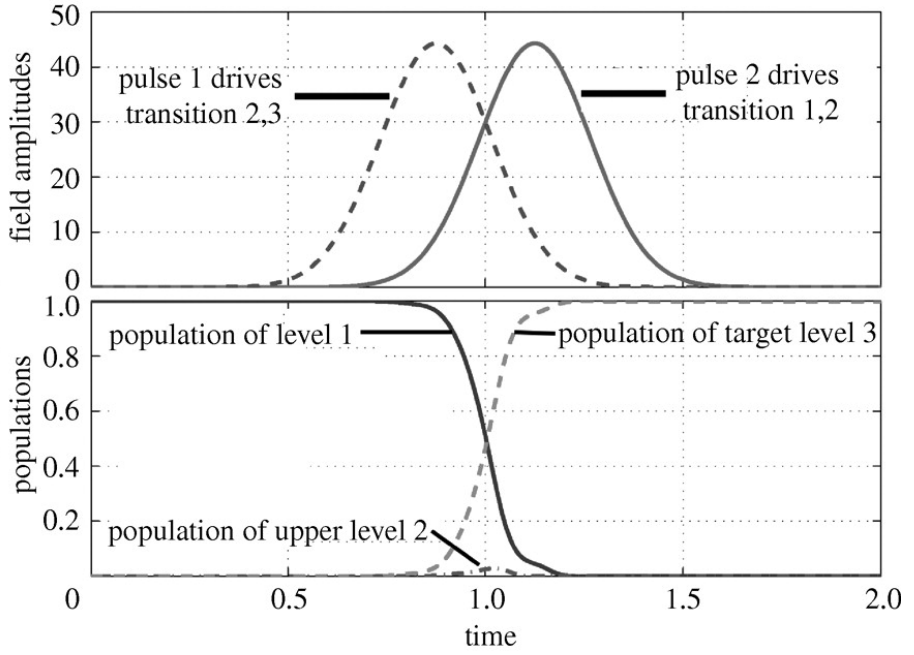
How STIRAP works



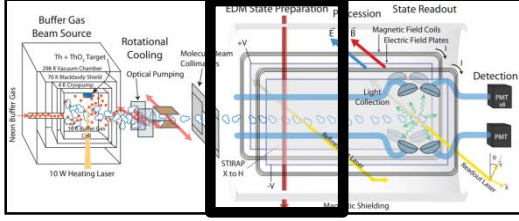
- Foolproof method:
  1. Write down Hamiltonian.
  2. Diagonalize.
  3. Look at answer.
- More intuitive example:
  1. Imagine $|1\rangle$ and $|2\rangle$ have orthogonal spin projections; each couples to only one laser polarization, $\hat{x}$ or $\hat{y}$. Population initially in $|1\rangle$.
  2. Turn on laser driving $|2\rangle \leftrightarrow |3\rangle$.
  3. Slowly rotate polarization. Population stays in "dark" state (adiabatic theorem).
  4. Once polarization is rotated, the "dark" state is $|2\rangle$.
  5. Ramp down laser.

three-level system in
lambda configuration





STIRAP in the lab



Lasers propagate between field plates

- "Laser lounge" allows for vertical propagation

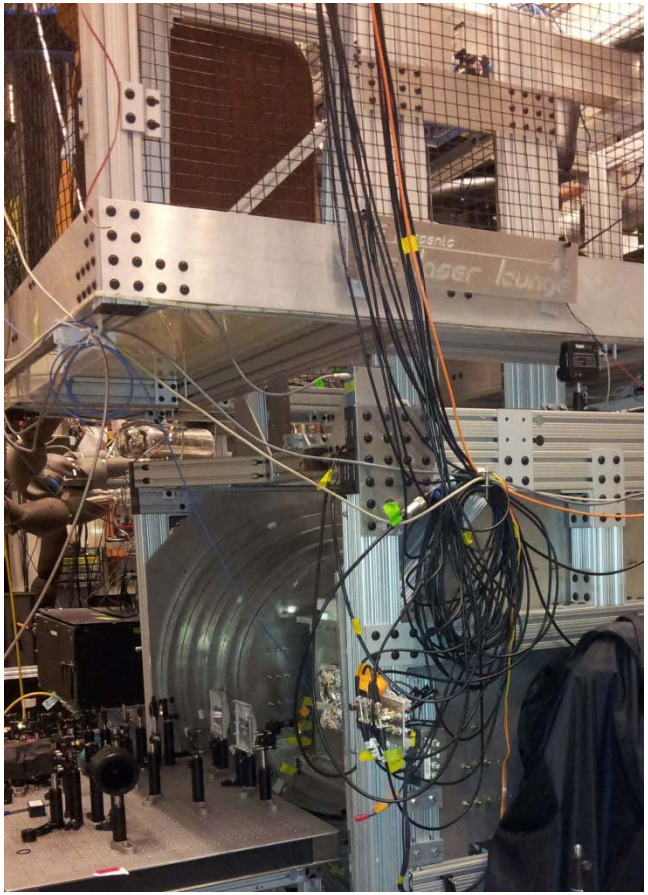
Technically challenging:

- Lasers must be narrow-linewidth (1 kHz)
- Efficiency depends on beam shaping, pointing, etc.
- Long path length

Demonstrated:

- 40% for $X \rightarrow C \rightarrow H$
- 80% for $X \rightarrow C \rightarrow X$ (won't be used)

Improvements ongoing.



Forbidden electromagnetic moments

- **Magnetic monopole**: $\nabla \cdot \vec{B} = 0$
- **Toroidal monopole**: (Static limit) $\nabla \cdot \vec{J} = 0$
- **Toroidal dipole**: Not invariant under electroweak gauge transformations; not physically meaningful in SM.
- **Quadrupole, octupole, *etc.***: $S = 1/2$ for the electron