The ACME Experiment

(an improved limit on the electric dipole moment of the electron)

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ACME Collaboration
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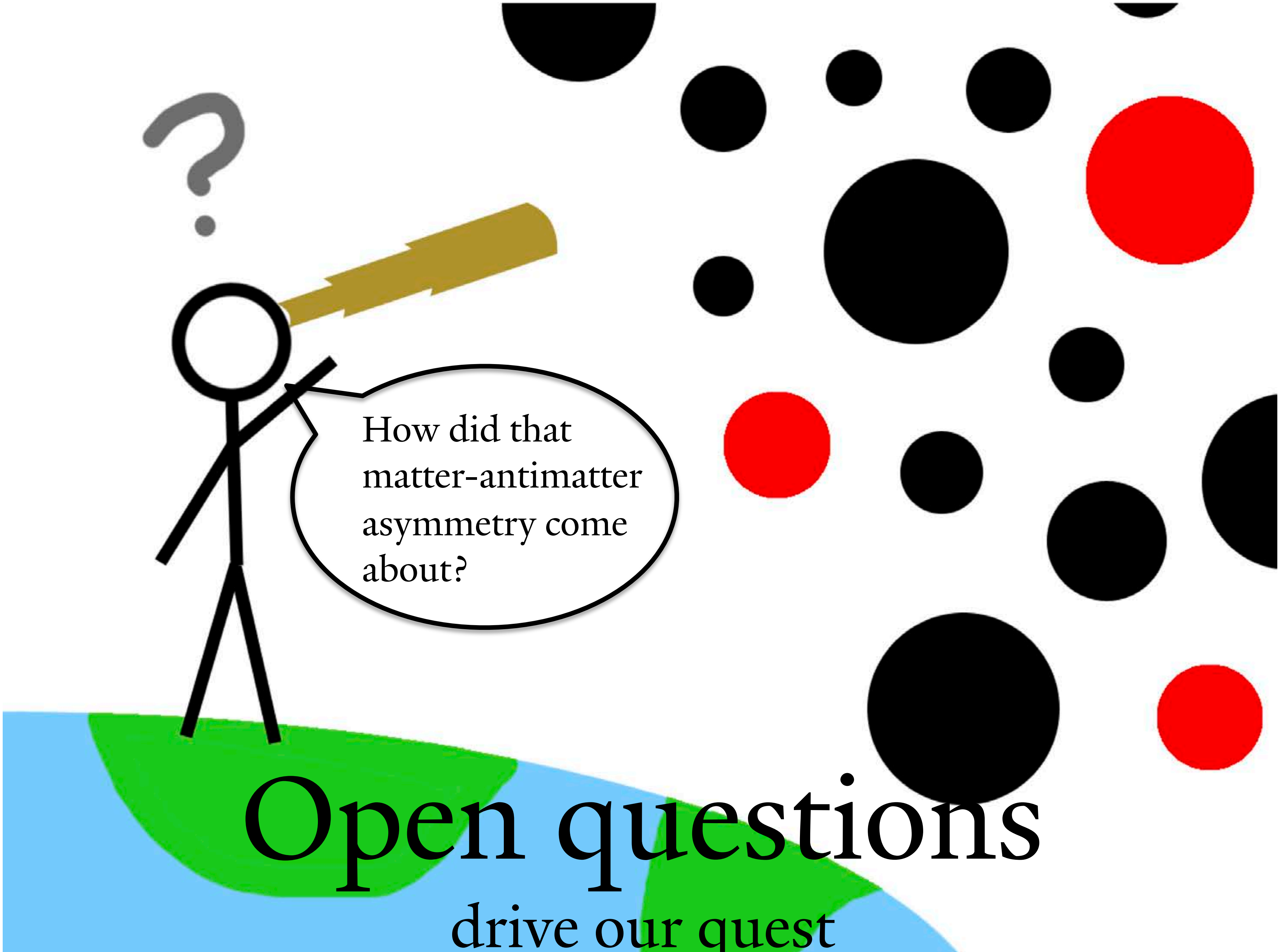
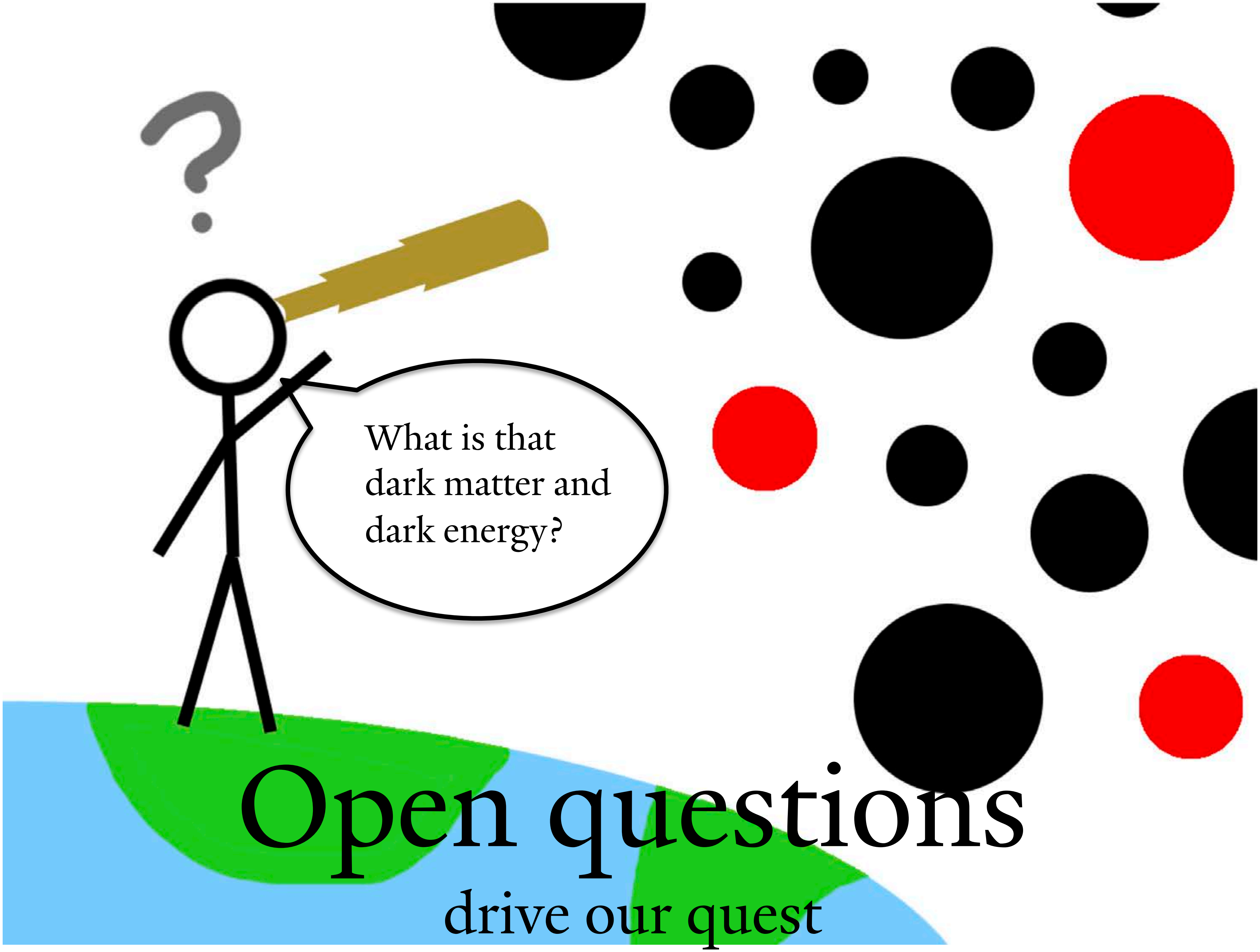
March 4, 2014



Open questions

drive our quest



Open questions

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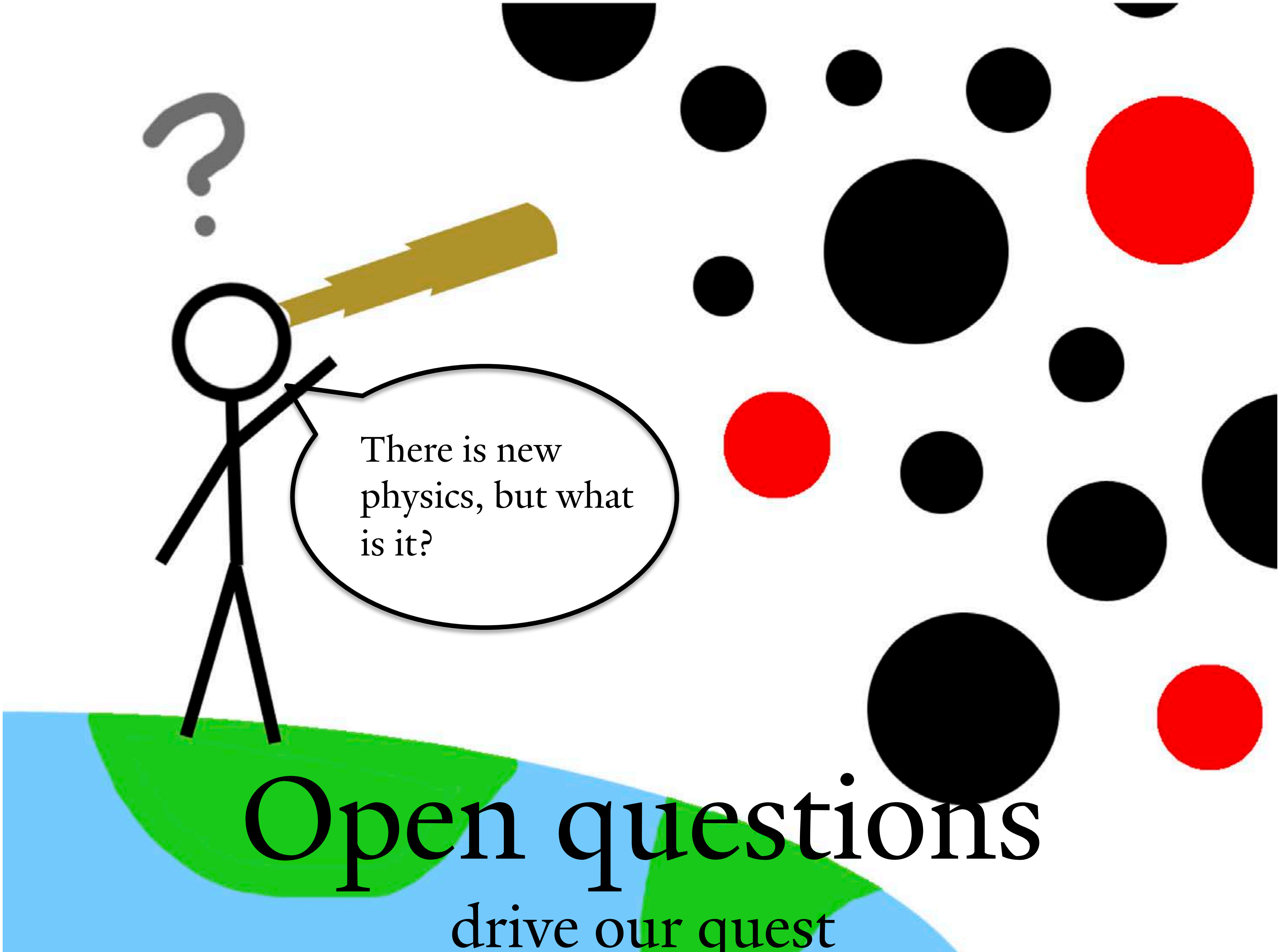


Open questions

drive our quest

Possible Solutions

(new particle theories beyond the standard model)

- What is that dark matter?

- How did that matter-antimatter asymmetry come about?

Possible Solutions

(new particle theories beyond the standard model)

- What is that dark matter?

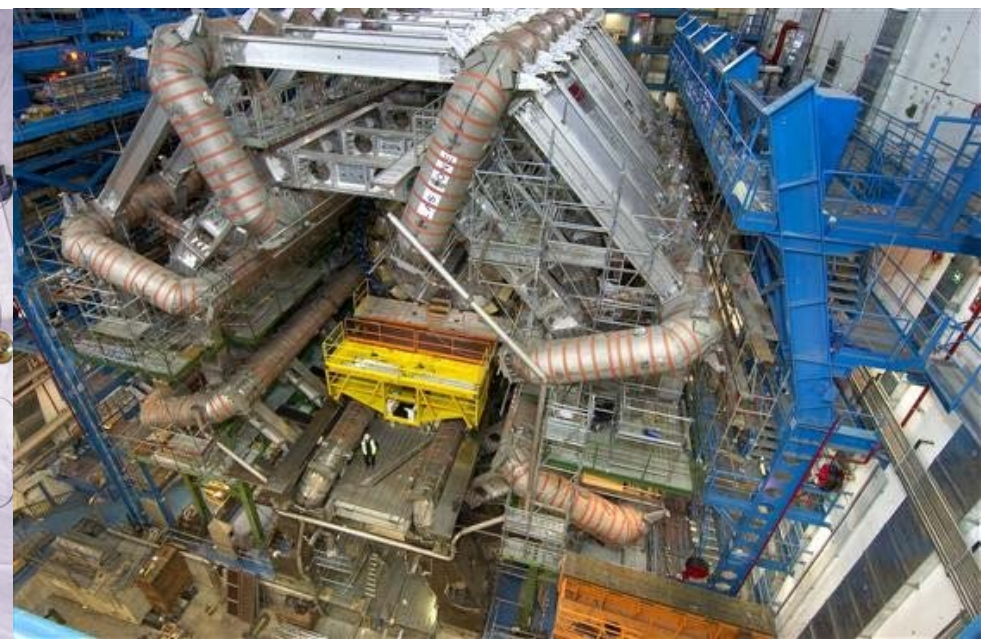
-heavy particles that we haven't discovered yet that interact weakly with known particles (WIMPs)?

LUX

Dark Matter Detection

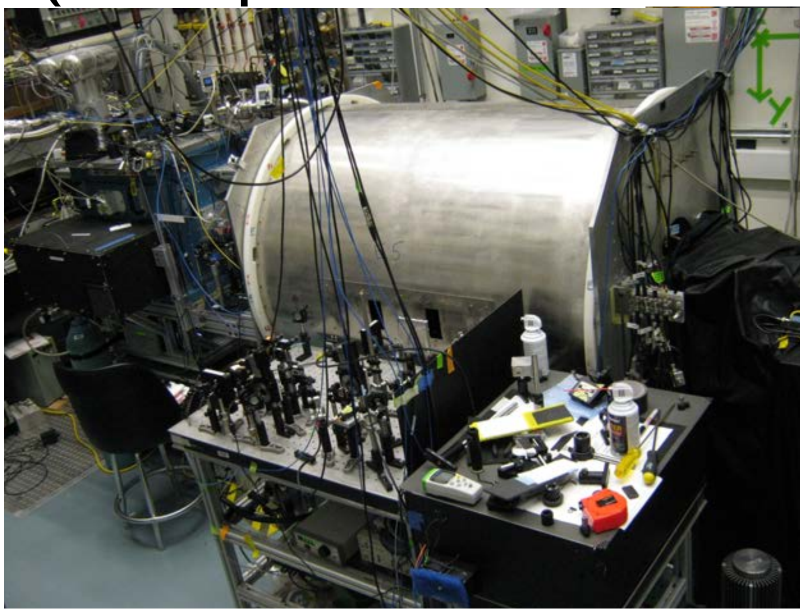
ATLAS

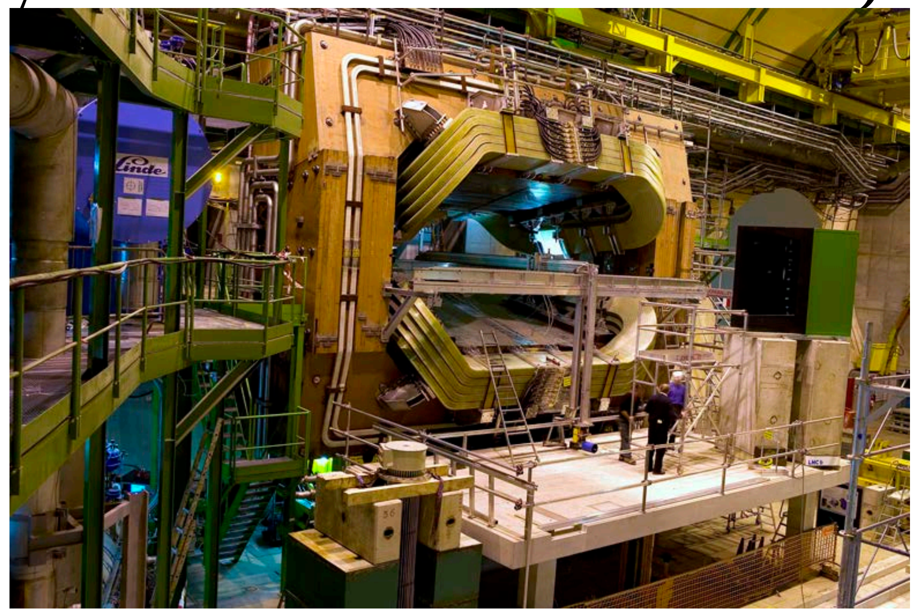
Massive Particle Creation



Possible Solutions

(new particle theories beyond the standard model)





- How did that matter-antimatter asymmetry come about?

  -Sakharov's conditions say that CP violating interactions are required for this to happen. New particles would mean new CP violating phases in weak mixing matrix.

ACME
EDM Experiment

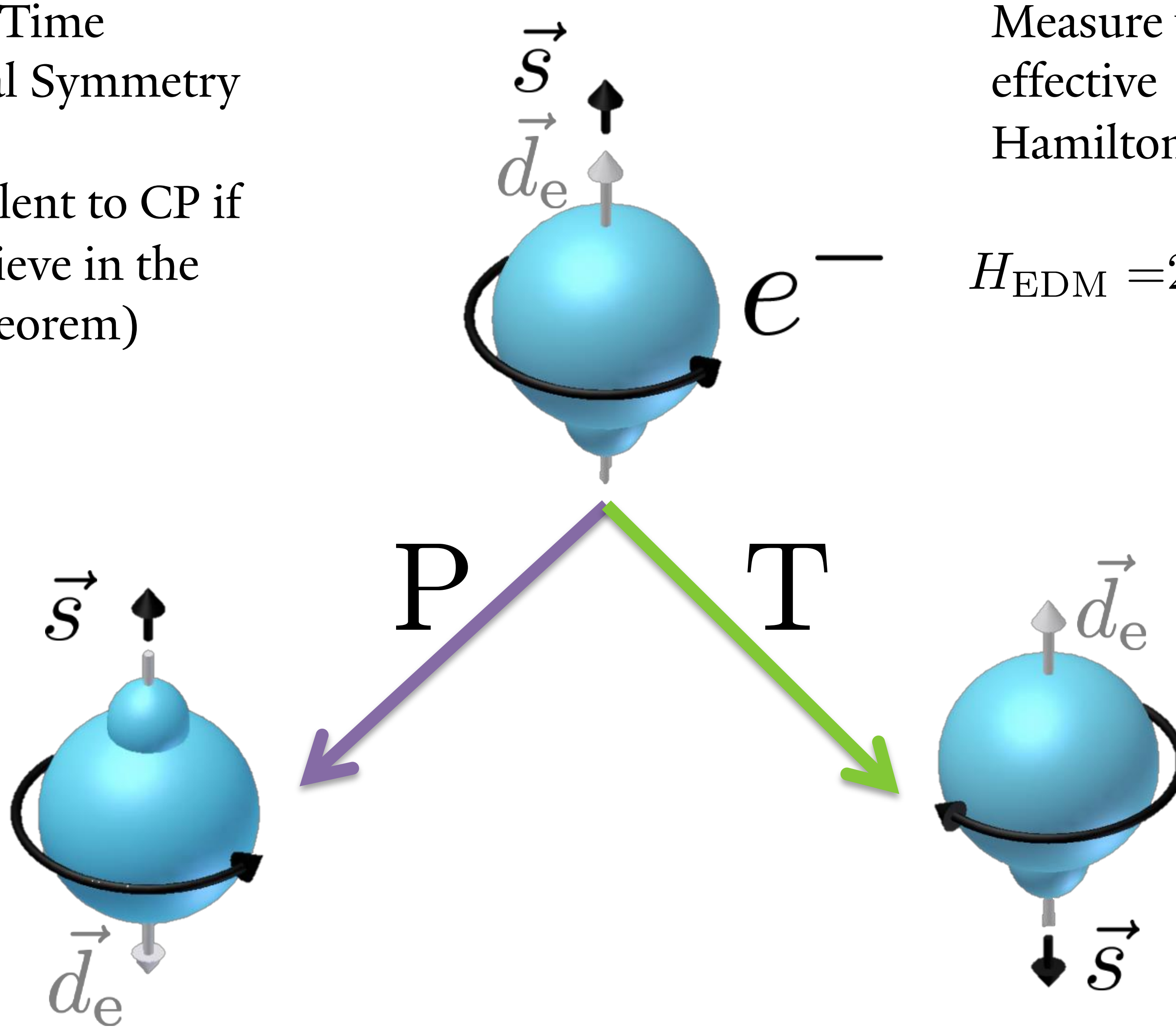
LHCb
CP-Violating Decays

A.D. Sakharov, 1967, JETP Lett. 6, 24
M. Dine, A. Kusenko. Rev. Mod. Phys. 76, 1 (2003)

Electric Dipole Moments

Violate Time Reversal Symmetry

(equivalent to CP if you believe in the CPT theorem)

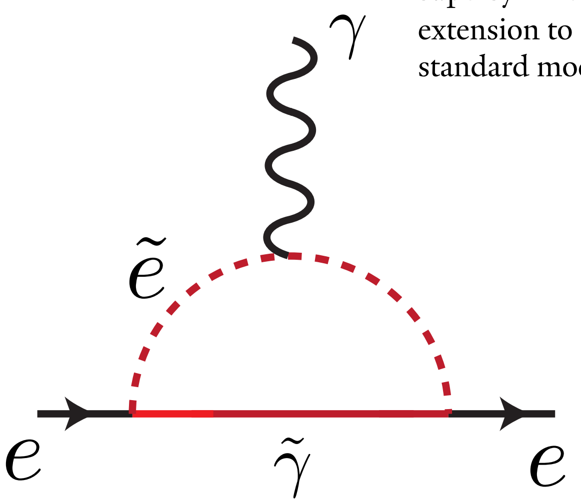


Measure via the effective Hamiltonian:

$$H_{\mathrm{EDM}} = 2 d_e \vec{S} \cdot \vec{\mathcal{E}}$$

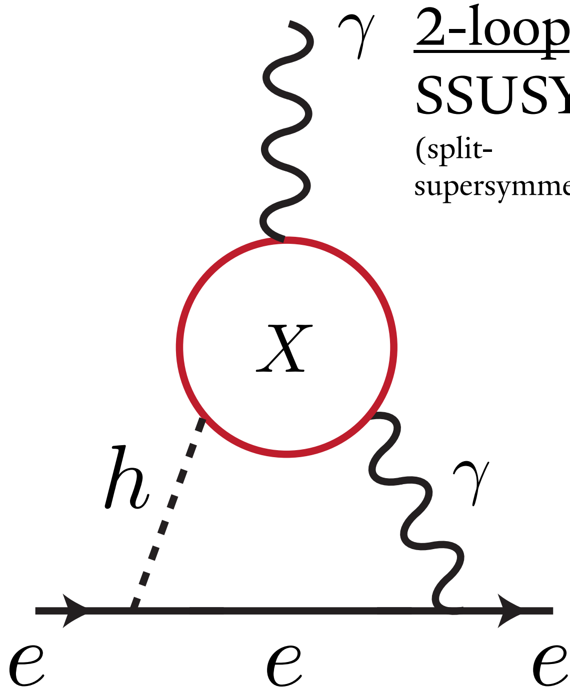
EDMs in Particle Theory

Our EDM sensitivity is at the level of $\delta d_e \approx 10^{-28}\ e \cdot cm$



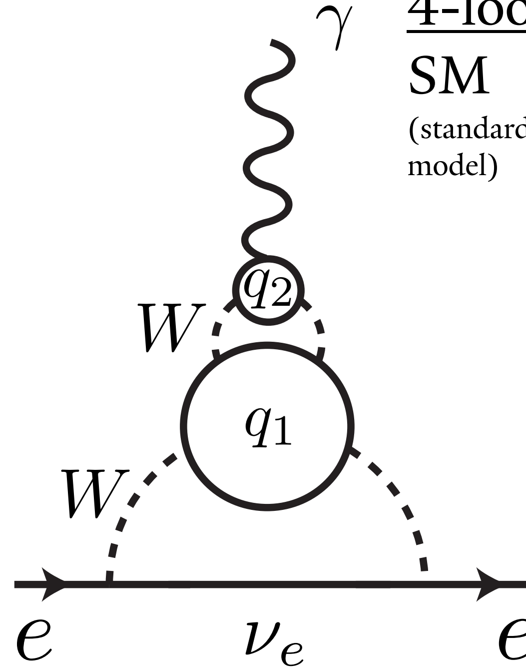
1-loop
MSSM
(minimal supersymmetric extension to the standard model)

10^{-25}-10^{-27} e cm
(ruled out or fine tuned)



2-loop
SSUSY
(split-supersymmetry)

10^{-27}-10^{-29} e cm
(probing this range)



4-loop
SM
(standard model)

10^{-40} e cm
(negligibly small: no SM background)

Any measured EDM must come from New Physics!

EDMs in Particle Theory

typical EDM diagram scaling:

number of loops

coupling between SM
and new particles
(assume g^2~.01)

CP violating phase
(assume ~.1-1)

$$d_e \approx \mu_B \left(\frac{g^2}{4\pi}\right)^n \left(\frac{m_e}{m_X}\right)^2 \sin\left(\phi_{\mathrm{CP}}\right)$$

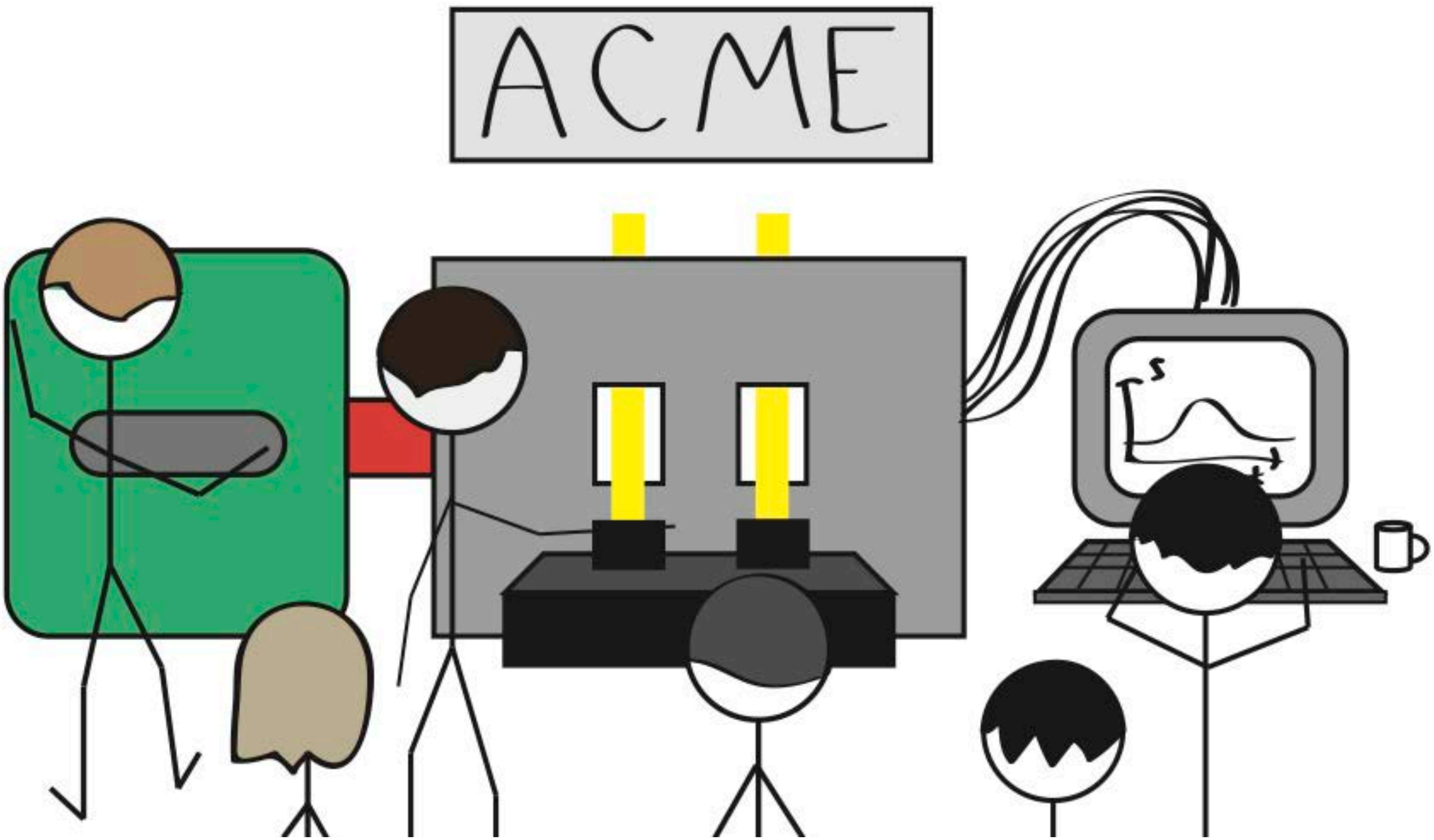
new particle mass scale

ACME experiment is sensitive to supersymmetric particles with ~TeV scale masses

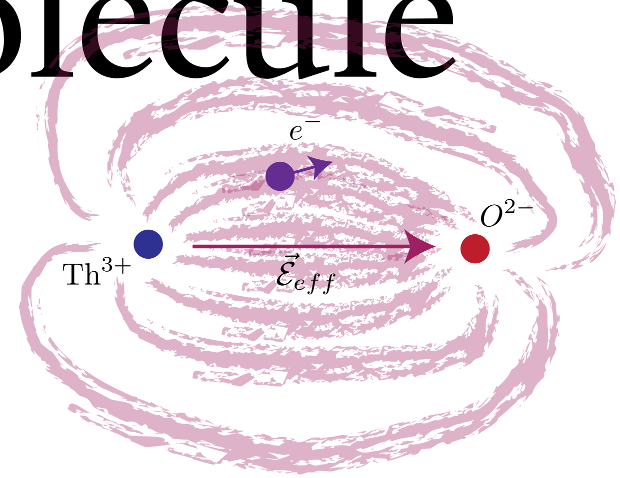
(with certain commonly made assumptions)

S. Barr, Int. J. Mod. Phys. A 08 (1993)
M. Pospelov, A. Ritz, Ann Phys. 318 (2005)
J. Engel, M.J. Ramsey-Musolf, U. van Kolck, Prog. Part. Nucl. Phys. 71 (2013)

The Measurement



Lets use a molecule

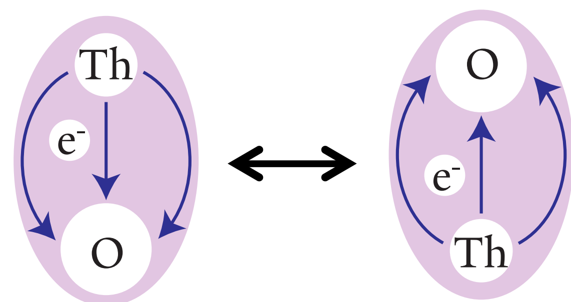


- Diatomic Molecules have large internal electric fields*:
  the molecule is our laboratory.

$$\mathcal{E}_{\text{eff}} \approx 85\ \text{GV/cm}$$

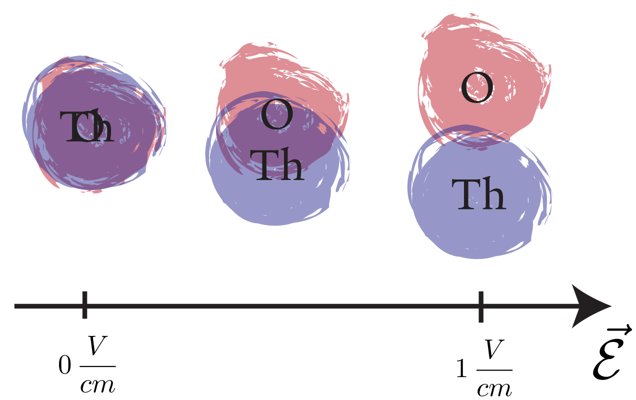
- Internal Co-magnetometer (omega doublet structure)

  Can spectroscopically flip the molecule with respect to applied fields,
  N=+1 is aligned, N=-1 is anti-aligned



- Easily Polarized

  Can align the molecules with small laboratory electric fields.



- Reduced sensitivity to magnetic field imperfections

$$^3\Delta_1 \implies g \sim 10^{-2}$$

E. R. Meyer and J.L. Bohn, Phys. Rev. A 78, 010502(R) (2008).
L.V. Skripnikov, A.N. Petrov, A.V. Titov, J. Chem Phys. 139, 221103 (2013)
T. Fleig, M.K. Nayak, arXiv:1401.2284v2 (2014)

*Schiff's Theorem

$$H_{edm} = \vec{d}_e \cdot \vec{\mathcal{E}}$$

Classical Dipole Hamiltonian

$$\langle H_{edm} \rangle = \vec{d}_e \cdot \left\langle \vec{\mathcal{E}} \right\rangle = 0$$

Energy shift must be zero or else the electron would fly away!

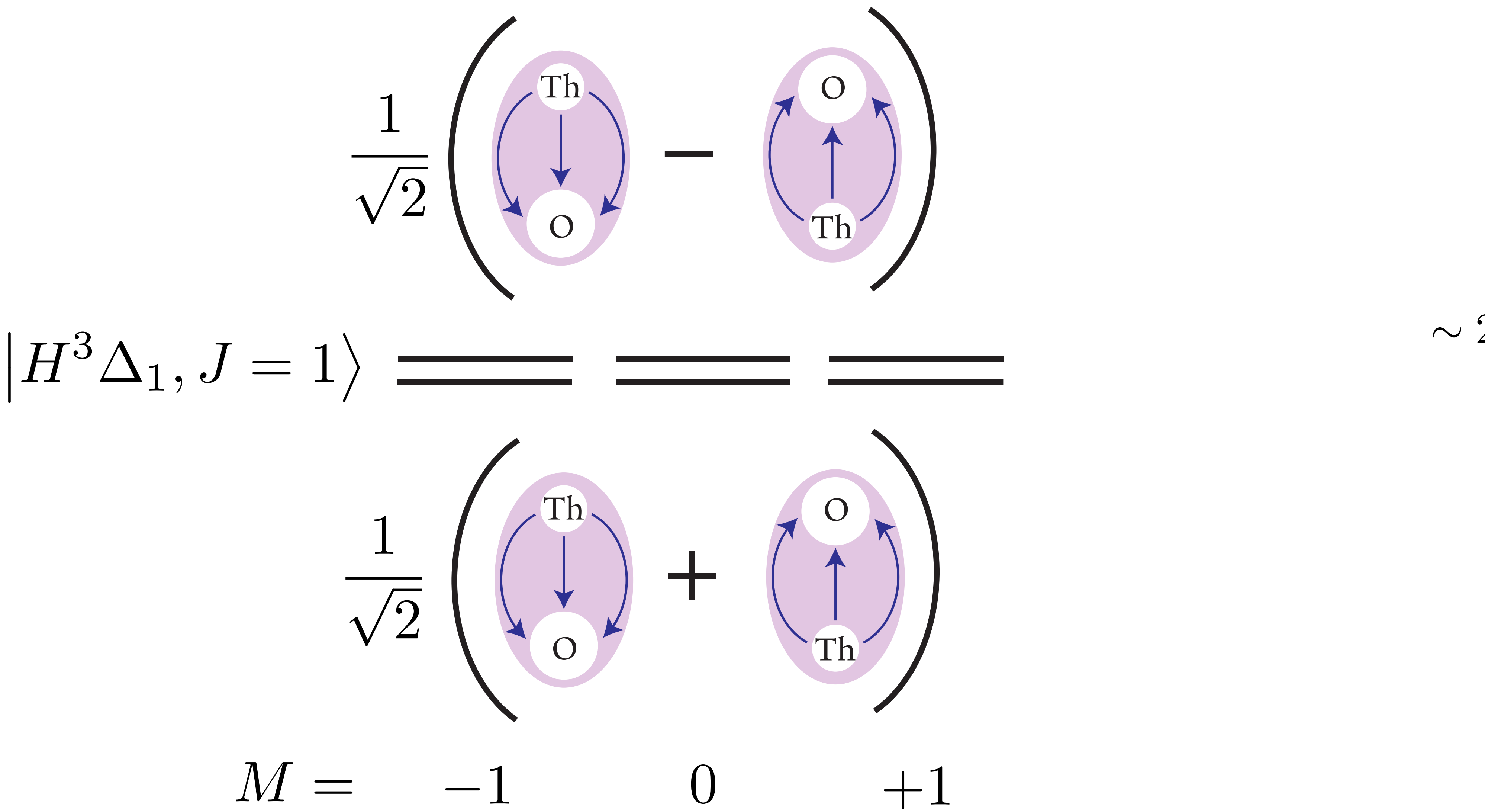
$$\vec{d}_e^{rel} = 2d_e \left[\vec{S} - \left(\frac{\gamma}{\gamma + 1} \right) \left(\vec{v} \cdot \vec{S} \right) \vec{v} \right]$$

Include relativistic length contraction

$$H_{edm} = 2d_e \vec{S} \cdot \vec{\mathcal{E}}_{mol} = \left\langle 2d_e \left(\frac{\gamma}{\gamma + 1} \right) \left(\vec{v} \cdot \vec{S} \right) \left(\vec{v} \cdot \vec{\mathcal{E}} \right) \right\rangle$$

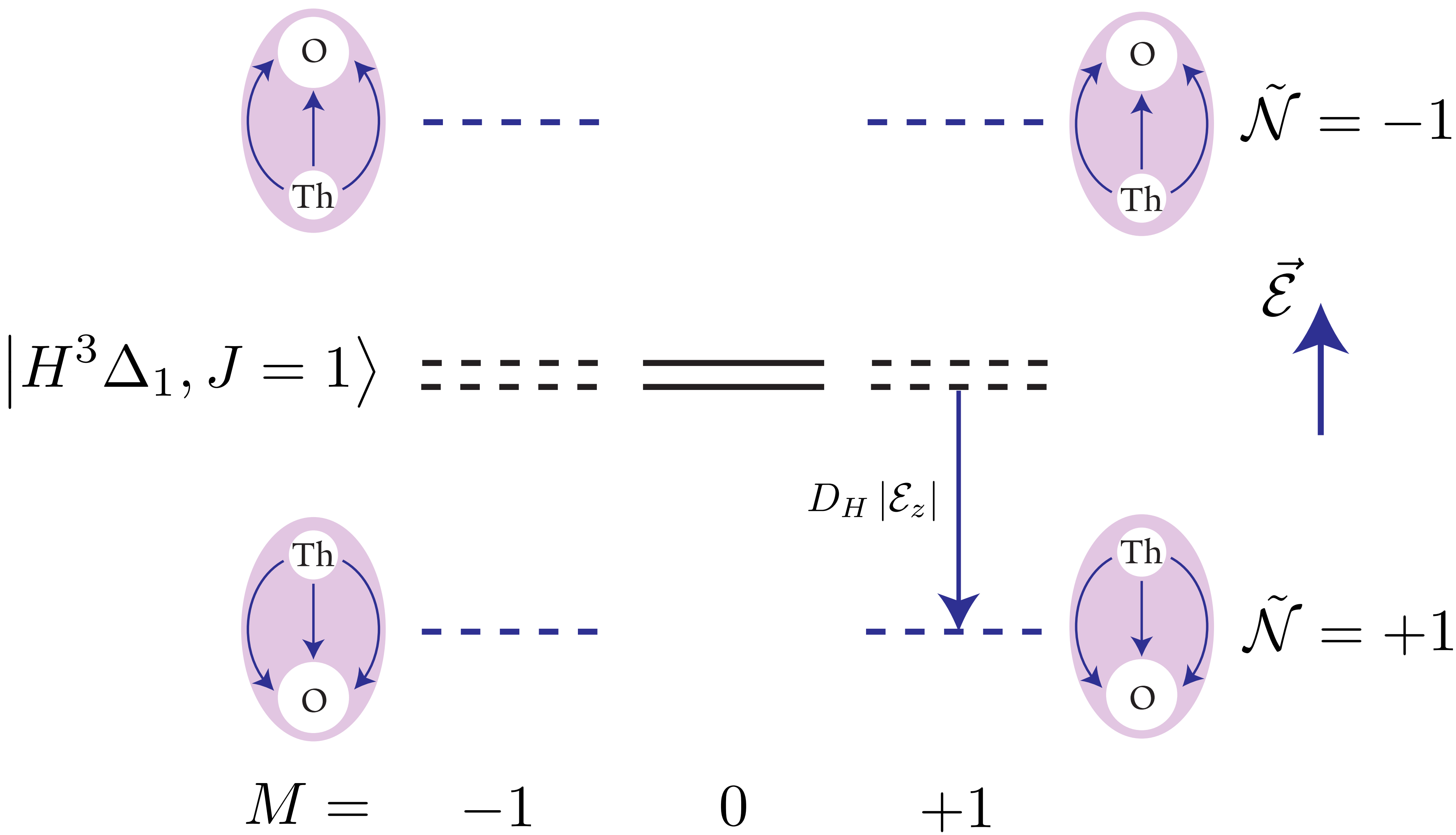
EDM shift comes from length contracted bit of EDM interacting with the internal electric field

L. I. Schiff, Phys. Rev. 132, 2194 (1963)
P. G. H. Sandars, Phys. Lett. 14, 194 (1965)
E. D. Commins, J. D. Jackson, and D. P. DeMille, Am. J. Phys. 75, 532(2007)

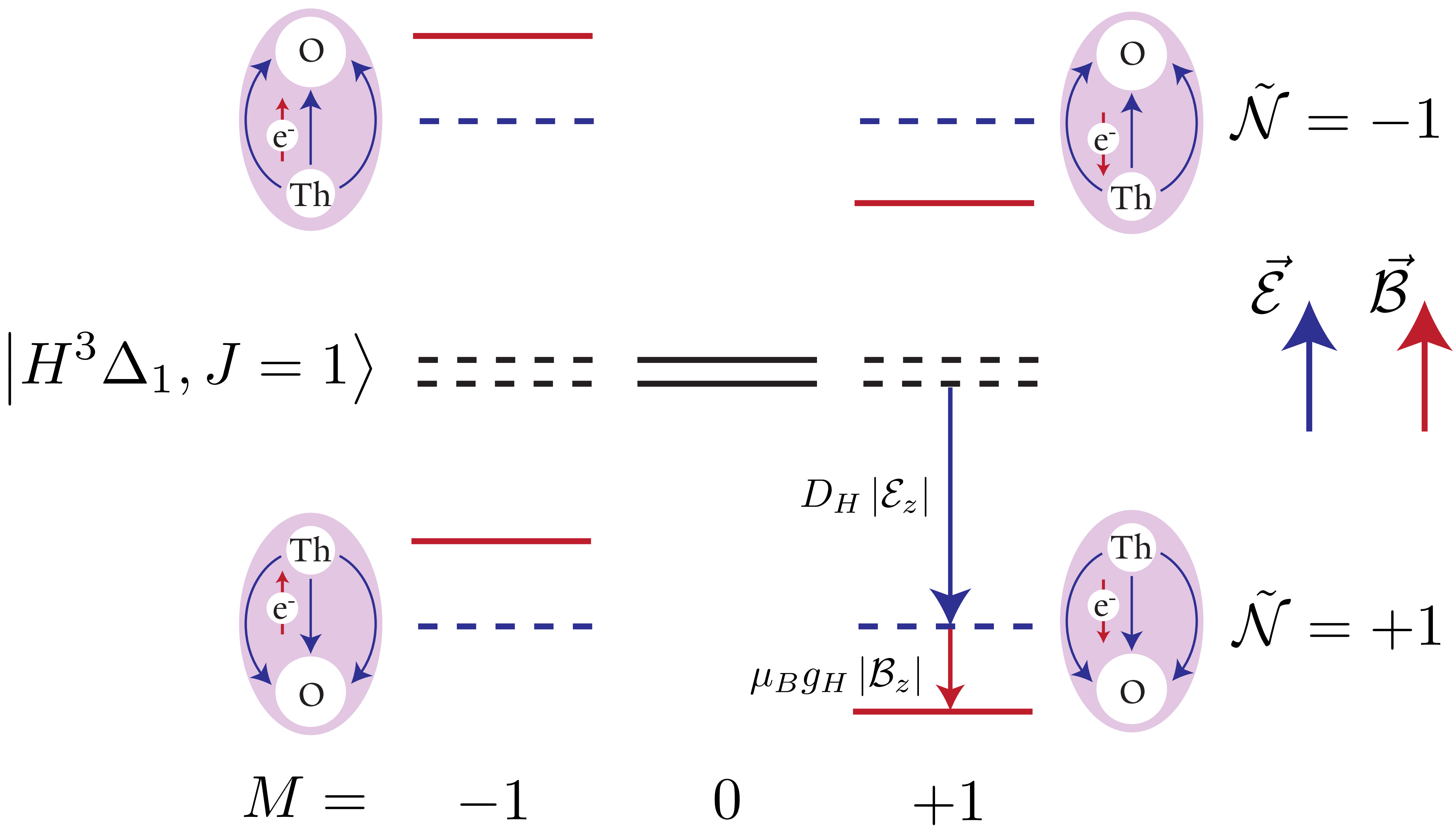


$\frac{1}{\sqrt{2}}$
Th
O
$-$
O
Th
$\left|H^3\Delta_1, J=1\right\rangle$
~ 2
$\frac{1}{\sqrt{2}}$
Th
O
$+$
O
Th
$M =$
-1
0
$+1$

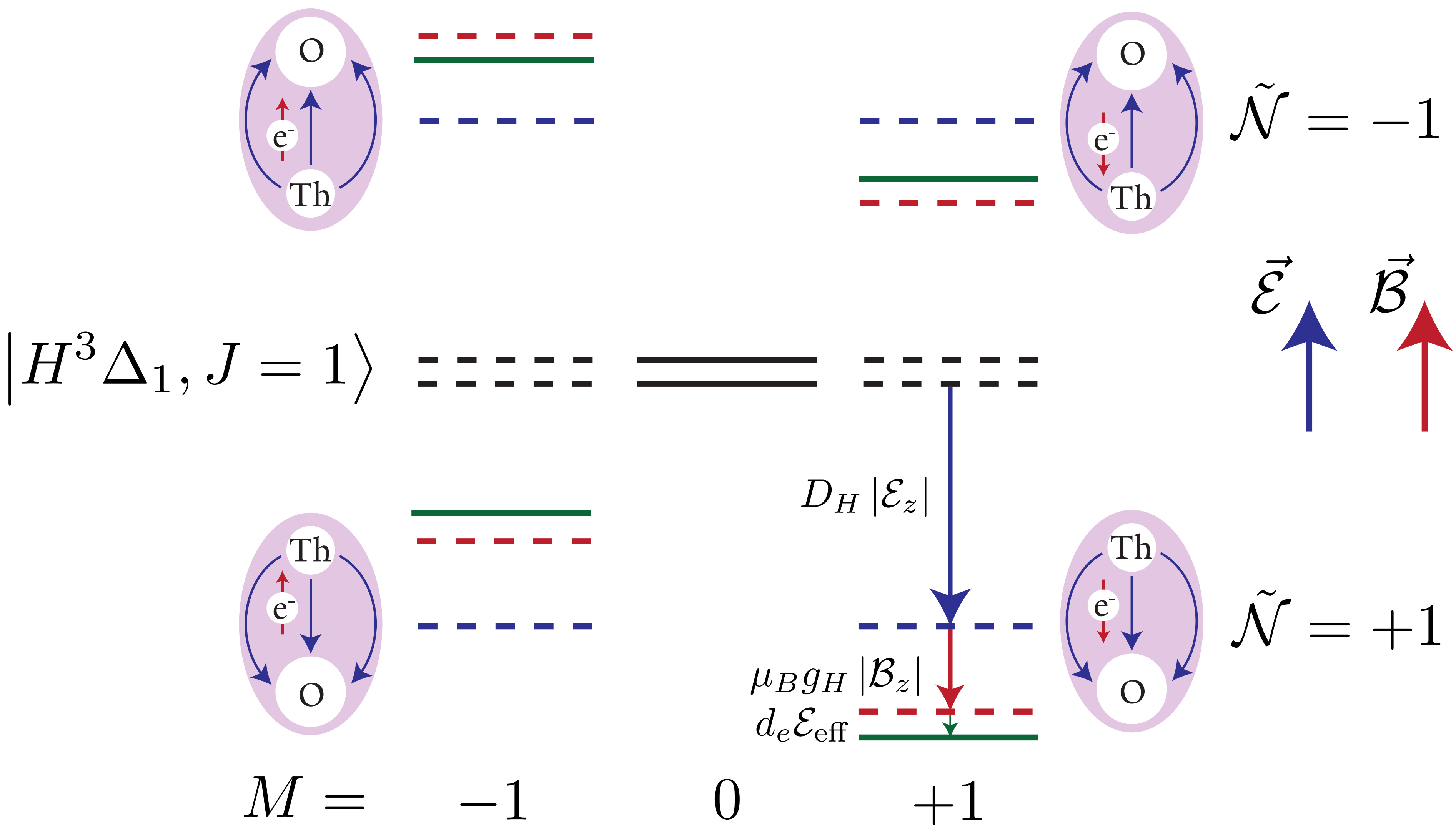
$$E\left(M,\tilde{\mathcal{N}},\tilde{\mathcal{E}},\tilde{\mathcal{B}}\right) = \boxed{-\tilde{\mathcal{N}}D_H\left|\mathcal{E}_z\right|}$$

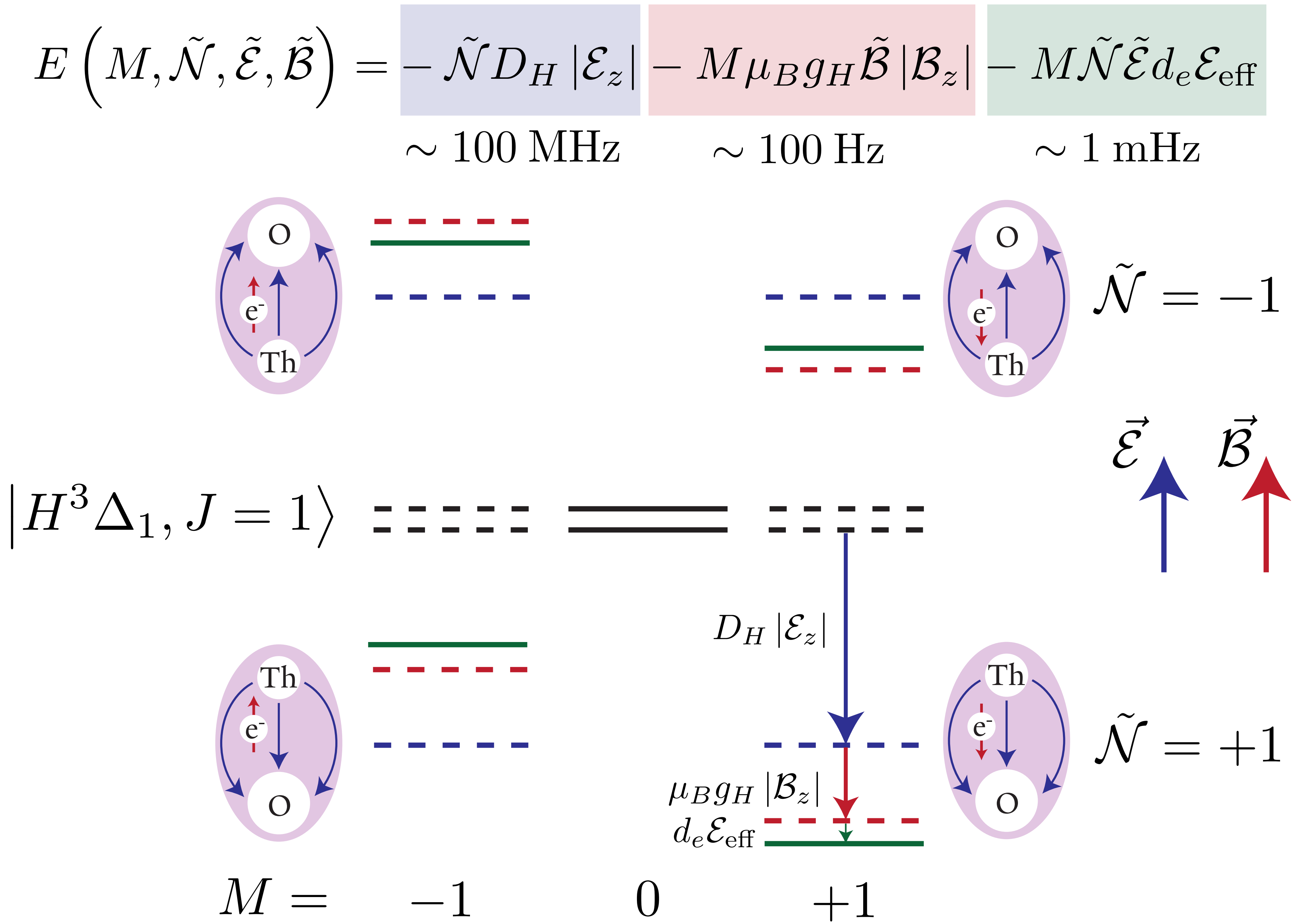


$$E\left(M, \tilde{\mathcal{N}}, \tilde{\mathcal{E}}, \tilde{\mathcal{B}}\right) = \boxed{-\tilde{\mathcal{N}} D_H \left|\mathcal{E}_z\right|} \boxed{-M \mu_B g_H \tilde{\mathcal{B}} \left|\mathcal{B}_z\right|}$$

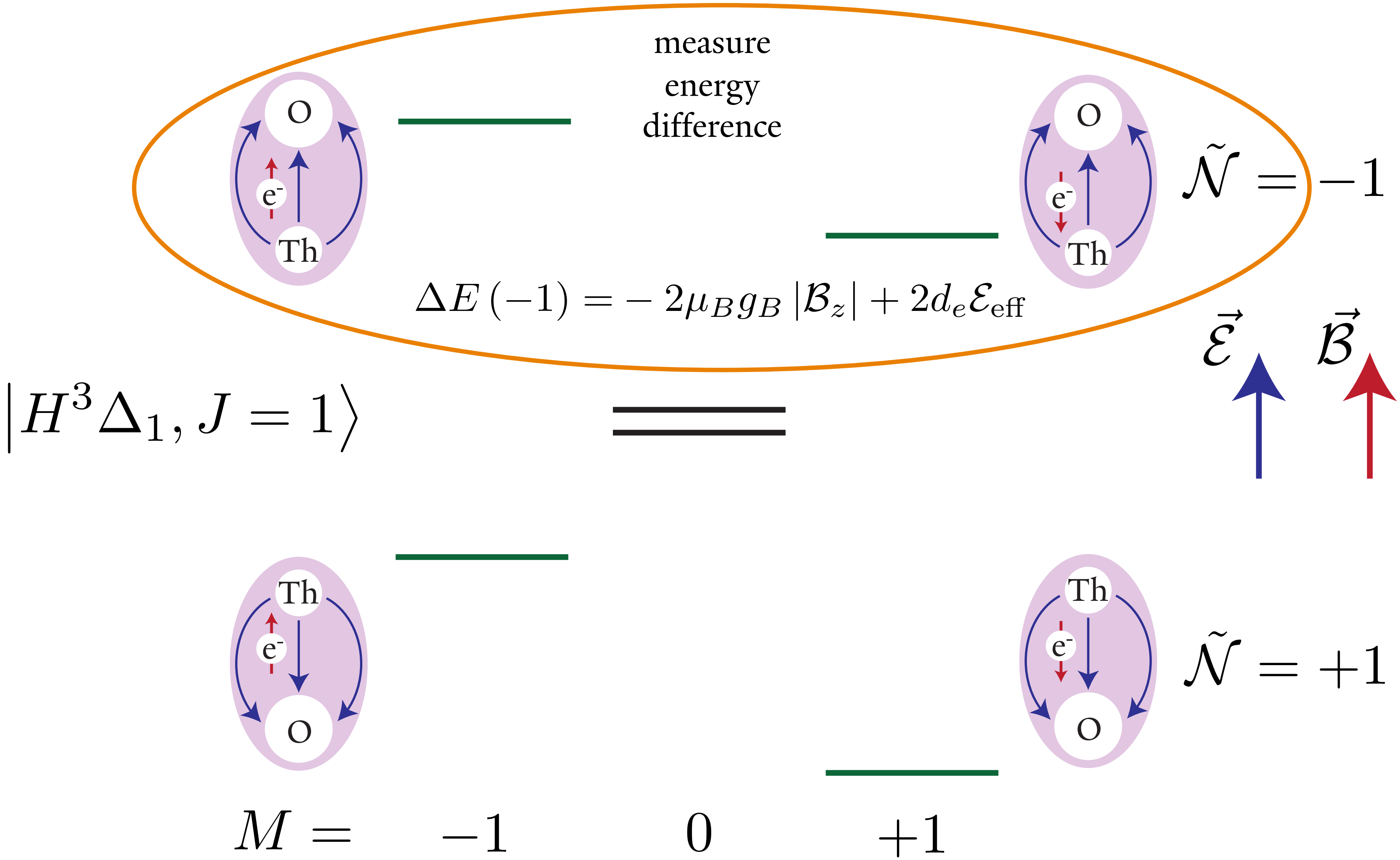


$$E\left(M,\tilde{\mathcal{N}},\tilde{\mathcal{E}},\tilde{\mathcal{B}}\right) = \boxed{-\tilde{\mathcal{N}} D_H |\mathcal{E}_z|} \boxed{-M\mu_B g_H \tilde{\mathcal{B}} |\mathcal{B}_z|} \boxed{-M\tilde{\mathcal{N}}\tilde{\mathcal{E}} d_e \mathcal{E}_{\text{eff}}}$$

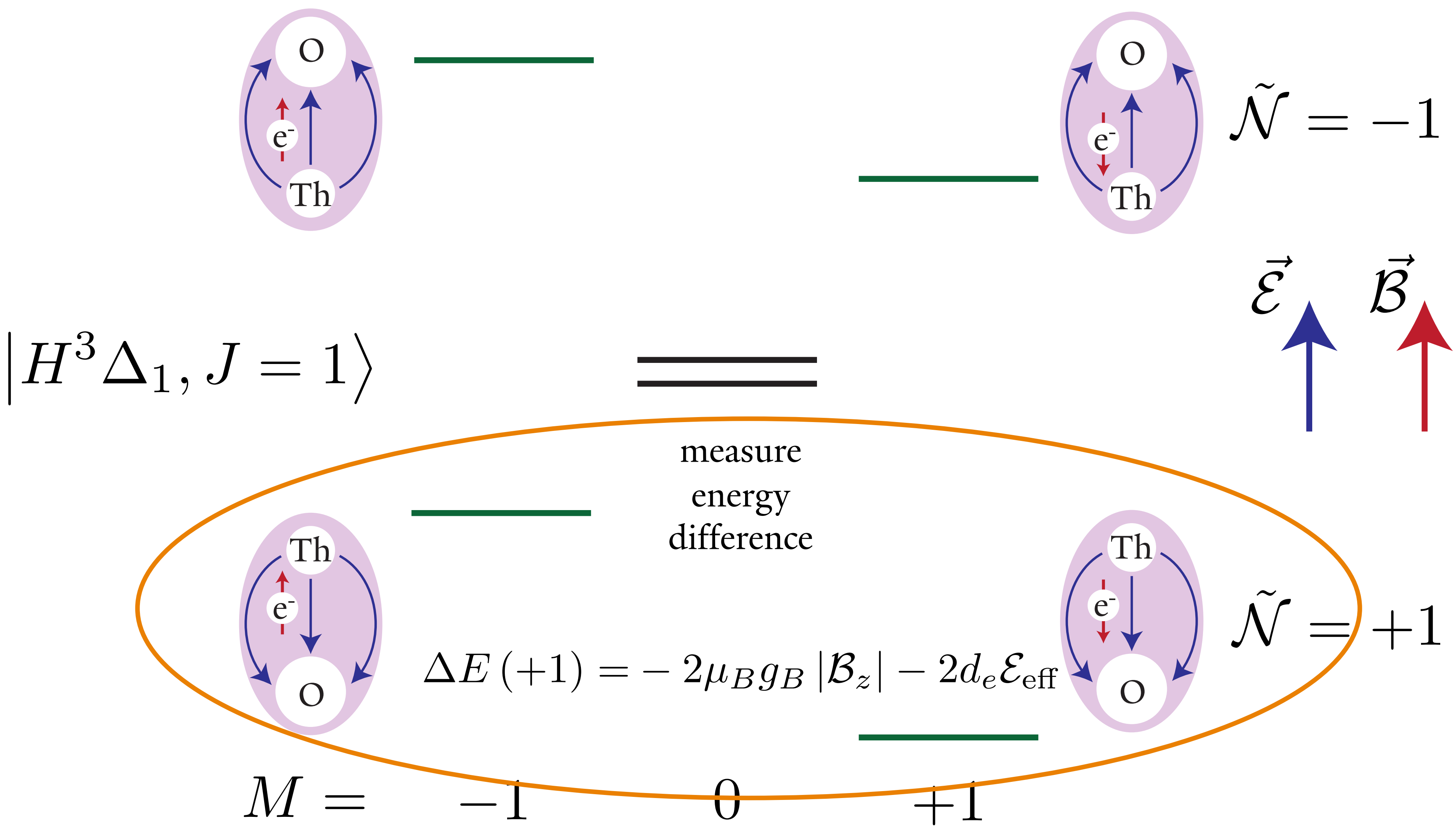



$E\left(M,\tilde{\mathcal{N}},\tilde{\mathcal{E}},\tilde{\mathcal{B}}\right) = -\tilde{\mathcal{N}}D_H\left|\mathcal{E}_z\right| - M\mu_B g_H\tilde{\mathcal{B}}\left|\mathcal{B}_z\right| - M\tilde{\mathcal{N}}\tilde{\mathcal{E}}d_e\mathcal{E}_{\text{eff}}$
~ 100 MHz
~ 100 Hz
~ 1 mHz
O
Th
e-
$\tilde{\mathcal{N}} = -1$
$\vec{\mathcal{E}}$
$\vec{\mathcal{B}}$
$\left|H^3\Delta_1, J = 1\right\rangle$
$D_H\left|\mathcal{E}_z\right|$
$\mu_B g_H\left|\mathcal{B}_z\right|$
$d_e\mathcal{E}_{\text{eff}}$
$\tilde{\mathcal{N}} = +1$
$M =$
-1
0
$+1$

$$E\left(M,\tilde{\mathcal{N}},\tilde{\mathcal{E}},\tilde{\mathcal{B}}\right) = -\tilde{\mathcal{N}}D_H\left|\mathcal{E}_z\right| - M\mu_B g_H\tilde{\mathcal{B}}\left|\mathcal{B}_z\right| - M\tilde{\mathcal{N}}\tilde{\mathcal{E}}d_e\mathcal{E}_{\text{eff}}$$



$$E\left(M,\tilde{\mathcal{N}},\tilde{\mathcal{E}},\tilde{\mathcal{B}}\right) = -\tilde{\mathcal{N}}D_H\left|\mathcal{E}_z\right| - M\mu_B g_H\tilde{\mathcal{B}}\left|\mathcal{B}_z\right| - M\tilde{\mathcal{N}}\tilde{\mathcal{E}}d_e\mathcal{E}_{\text{eff}}$$

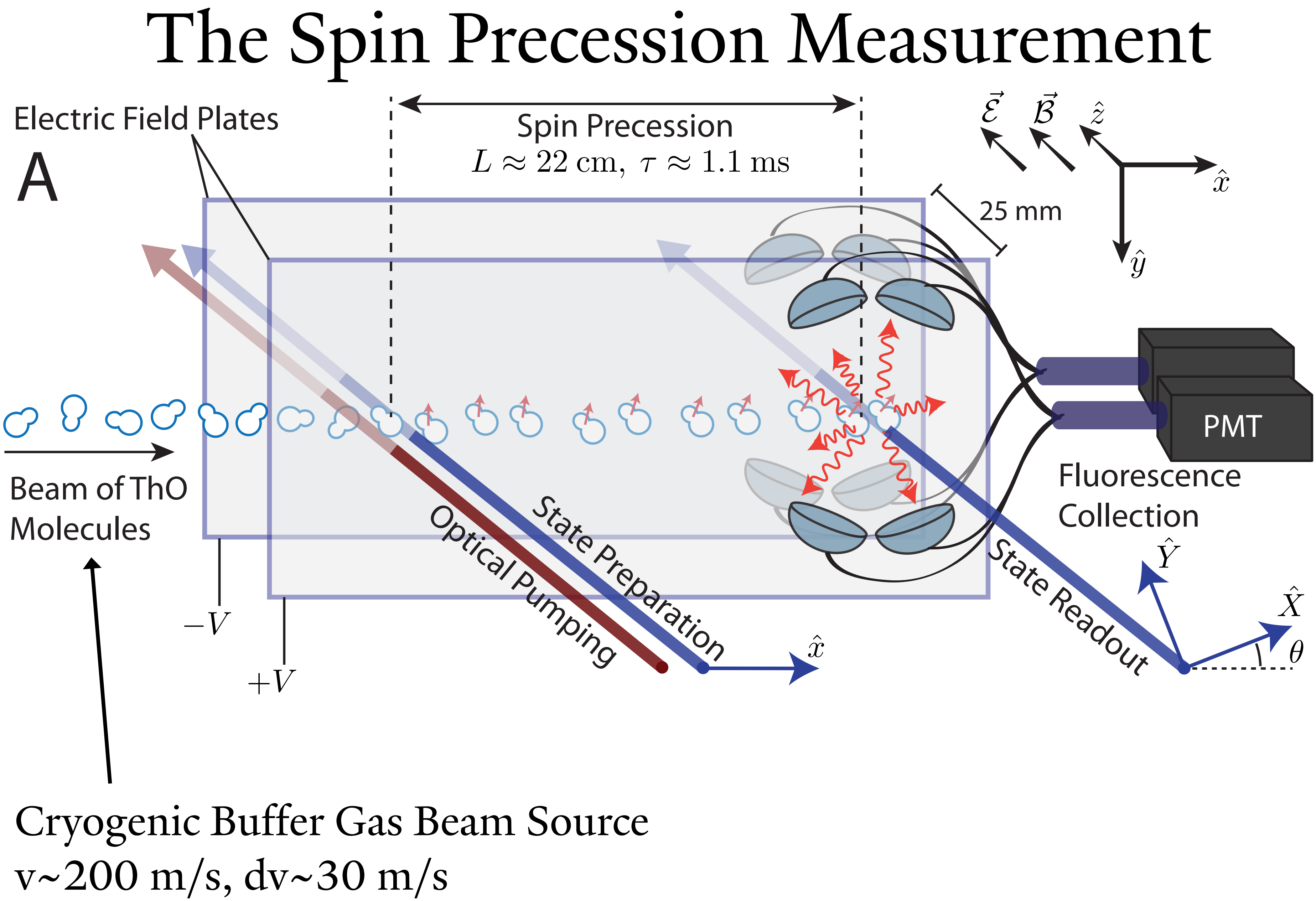


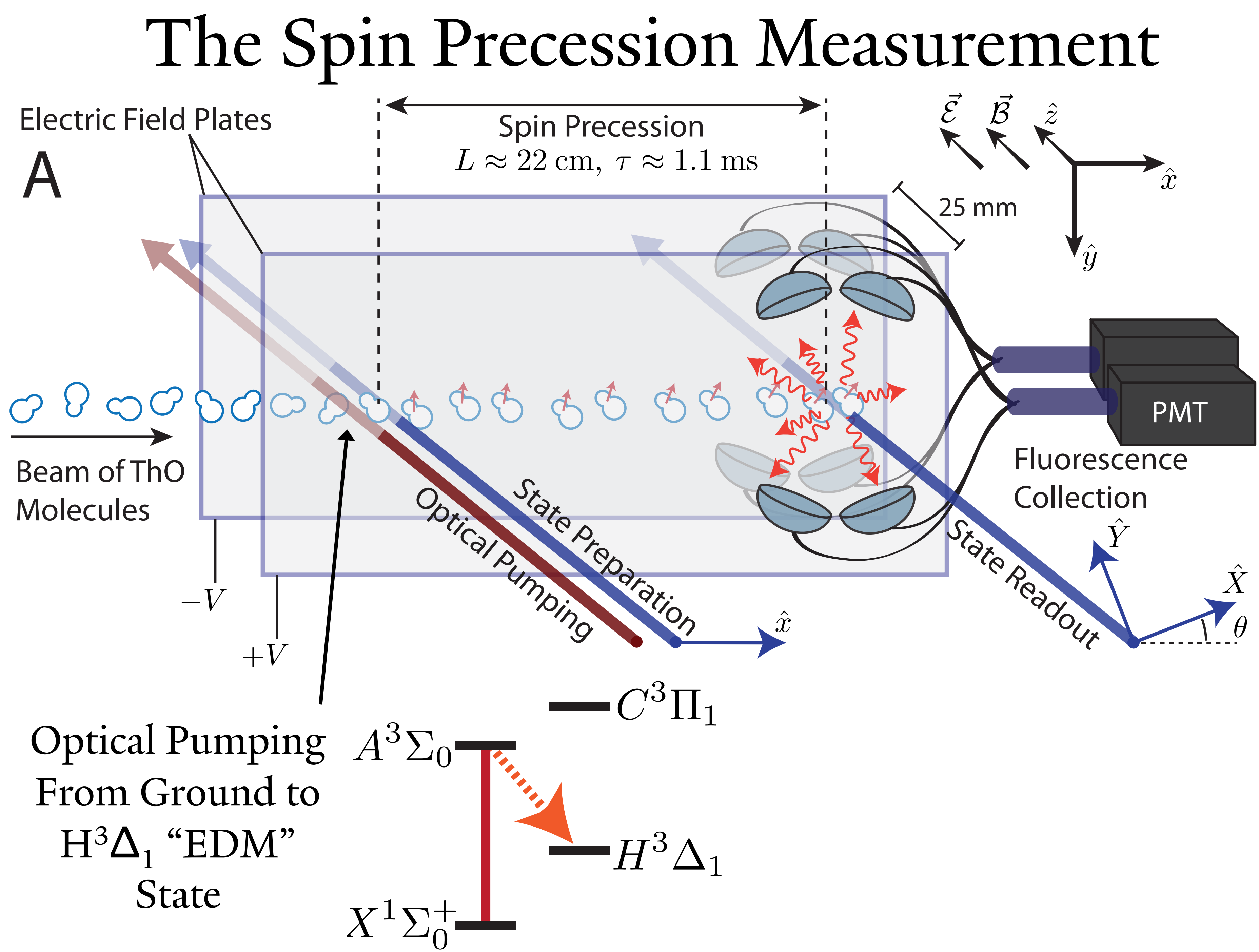
Extracting the EDM

$$\Delta E\,(-1) = -\,2\mu_B g_B\,|\mathcal{B}_z| + 2d_e\mathcal{E}_{\text{eff}}$$

$$-\quad \Delta E\,(+1) = -\,2\mu_B g_B\,|\mathcal{B}_z| - 2d_e\mathcal{E}_{\text{eff}}$$

$$\Delta E\,(-1) - \Delta E\,(+1) = \boxed{4d_e\mathcal{E}_{\text{eff}}}$$


The Spin Precession Measurement
Electric Field Plates
A
Spin Precession
$L \approx 22$ cm, $\tau \approx 1.1$ ms
$\vec{\mathcal{E}}$ $\vec{\mathcal{B}}$ $\hat{z}$
$\hat{x}$
$\hat{y}$
25 mm
PMT
Fluorescence Collection
Beam of ThO Molecules
$-V$
$+V$
Optical Pumping
State Preparation
$\hat{x}$
State Readout
$\hat{Y}$
$\hat{X}$
θ
Cryogenic Buffer Gas Beam Source
v~200 m/s, dv~30 m/s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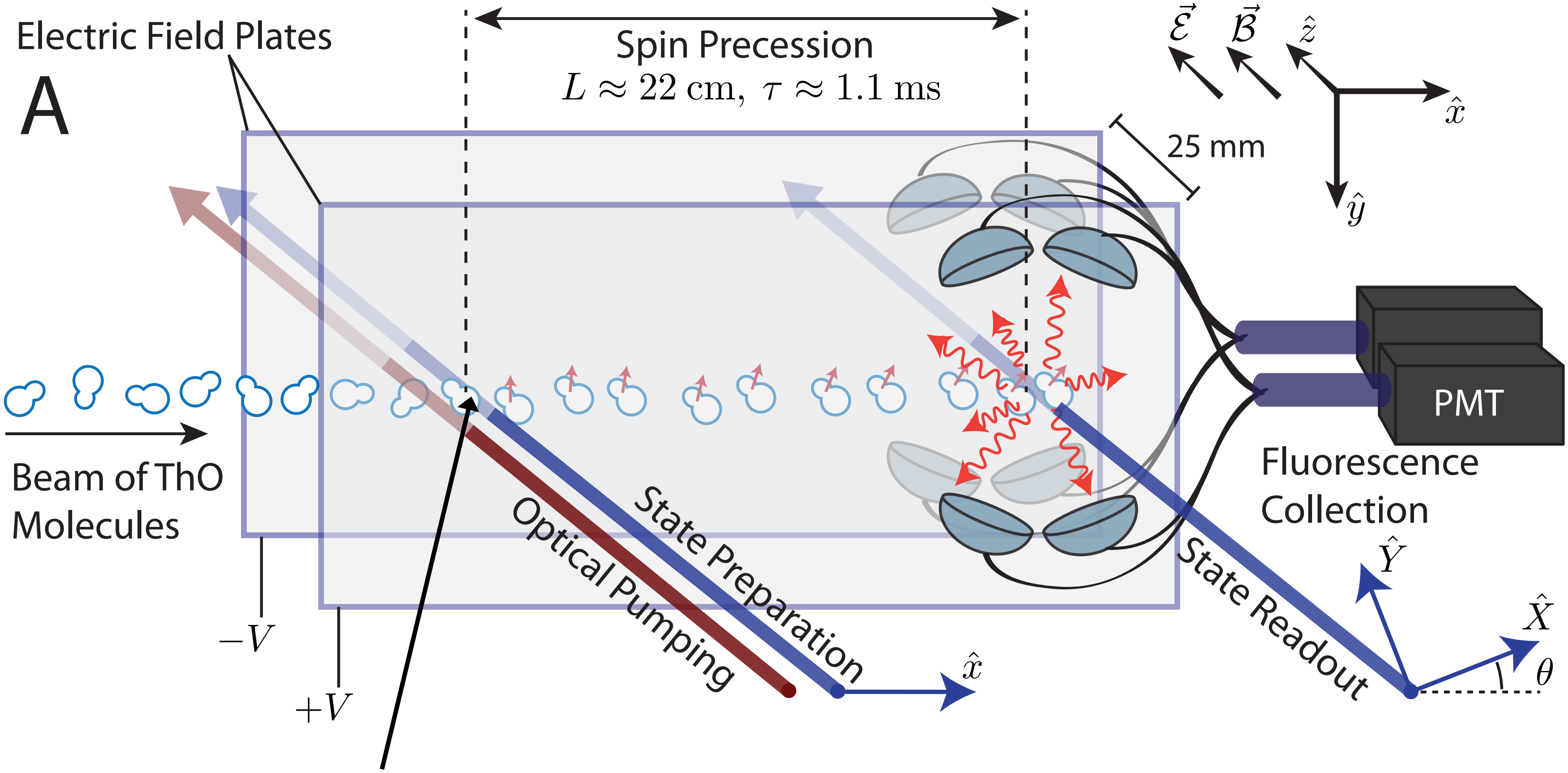
Beam of ThO Molecules
State Preparation
Optical Pumping
State Readout
$-V$
$+V$
$\hat{x}$
$\hat{Y}$
$\hat{X}$
θ
Optical Pumping From Ground to $H^3\Delta_1$ "EDM" State
$C^3\Pi_1$
$A^3\Sigma_0$
$H^3\Delta_1$
$X^1\Sigma_0^+$

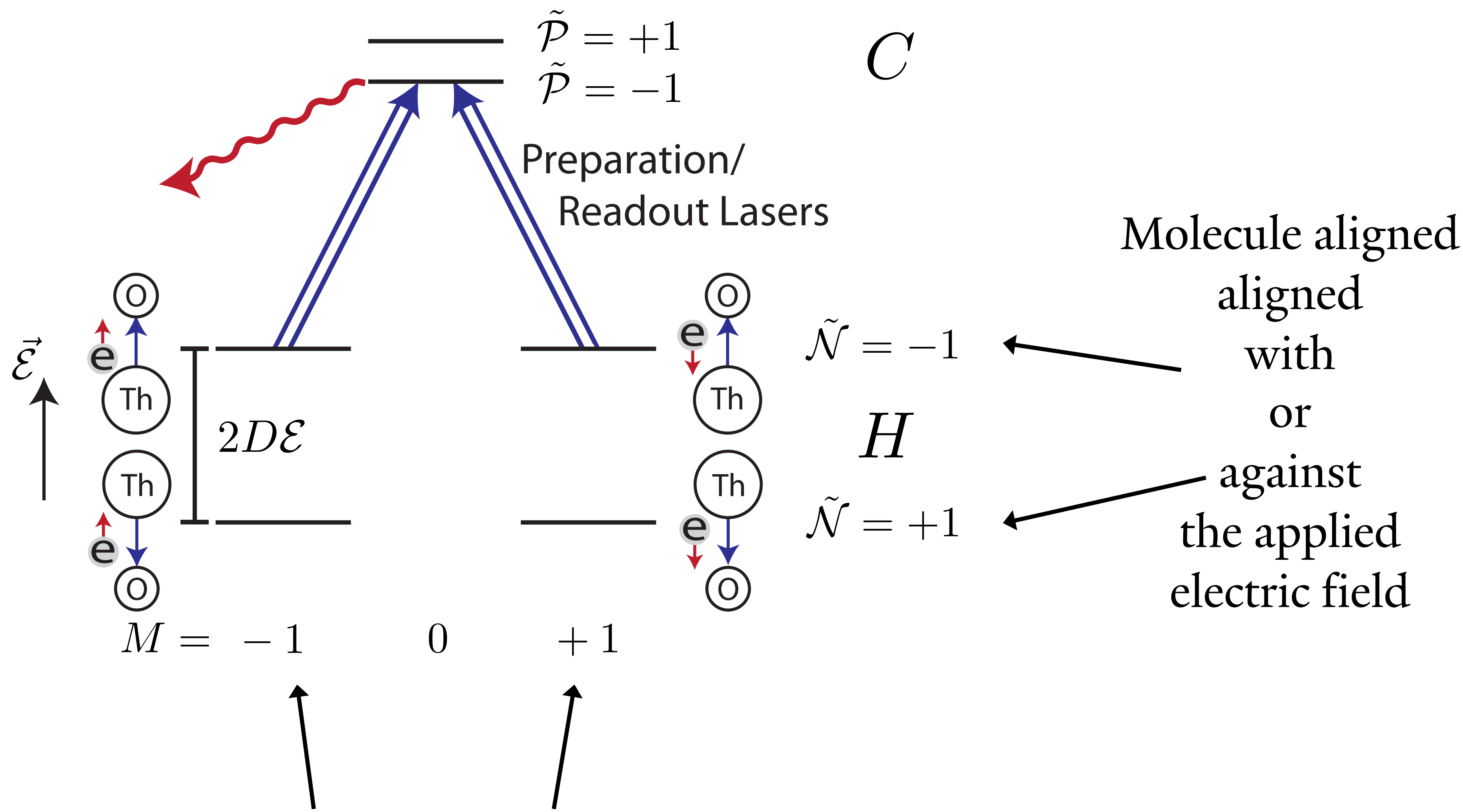
The Spin Precession Measurement



State preparation:

- Choose molecule alignment with frequency
- Choose electron spin alignment with polarization

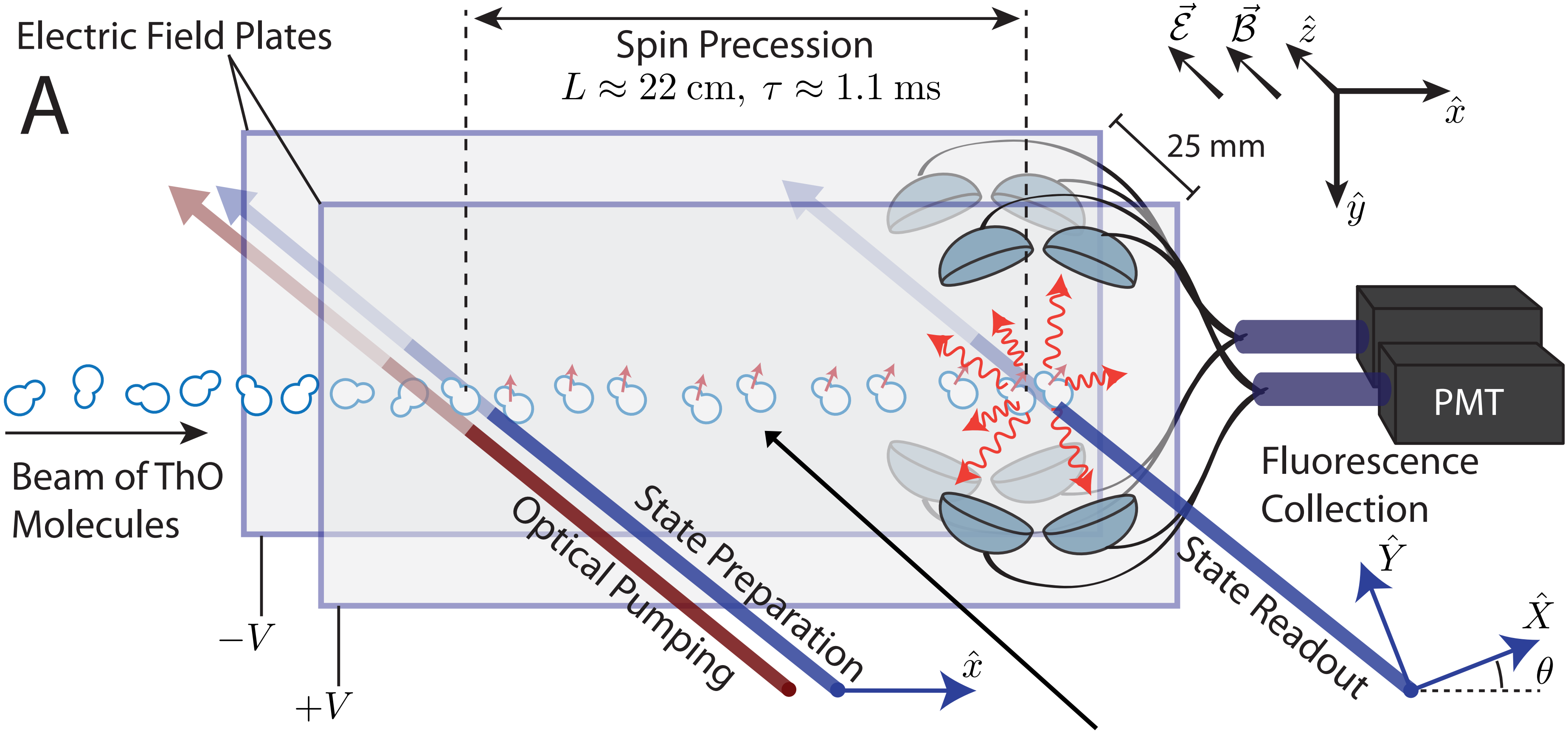
(optically pump out wrong electron alignment)



Electron spin aligned with or against the 'internal electric field'

We prepare a superposition of these two using linear laser polarization (electron spin in xy plane)

The Spin Precession Measurement

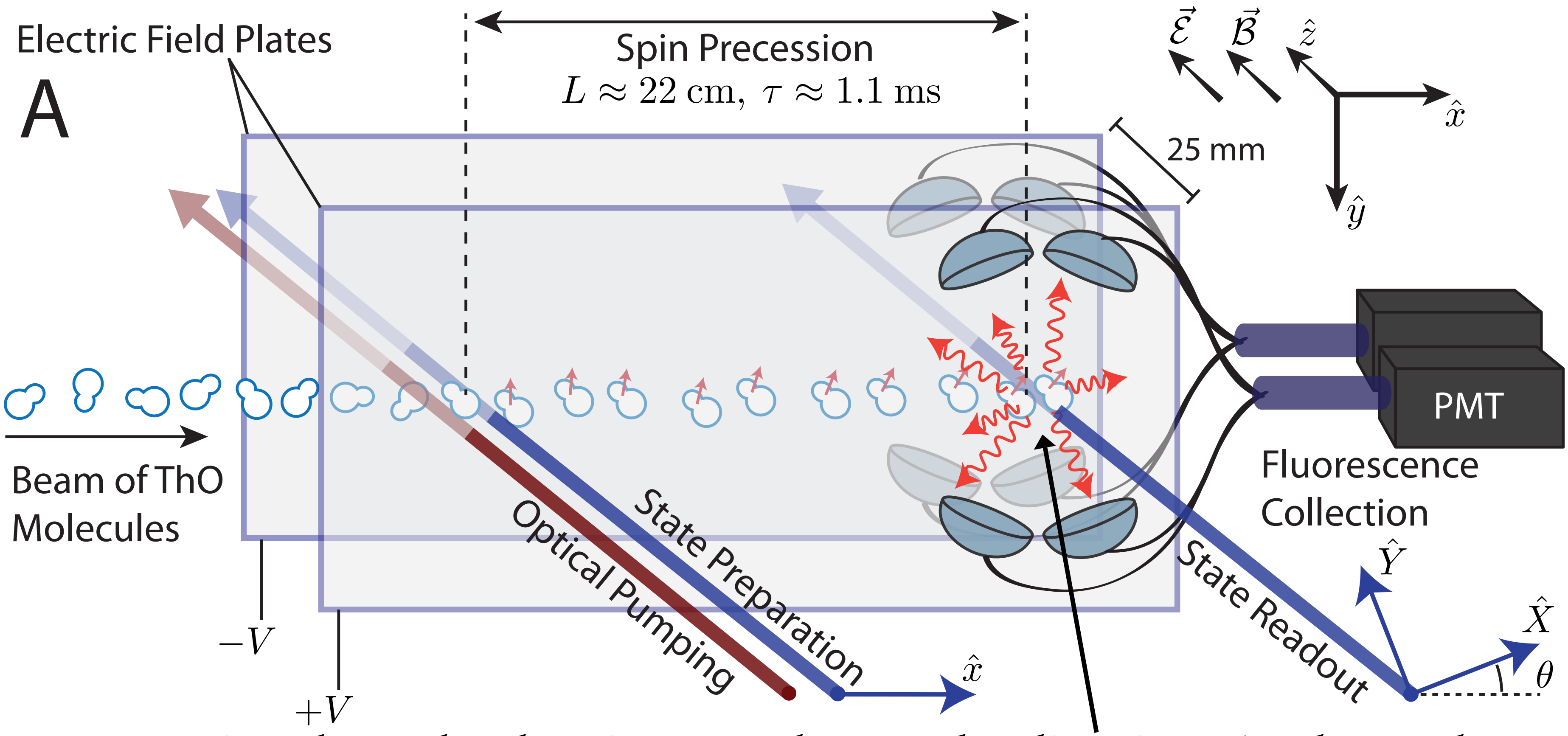


The electrons spins precess around the applied magnetic field

And the also precess around the molecules internal electric field if there is an EDM

$$\left|\psi\left(\tau\right),\tilde{\mathcal{N}}\right\rangle = \frac{1}{\sqrt{2}}\left(e^{-i\phi}\left|M=+1,\tilde{\mathcal{N}}\right\rangle - e^{+i\phi}\left|M=-1,\tilde{\mathcal{N}}\right\rangle\right)$$

The Spin Precession Measurement

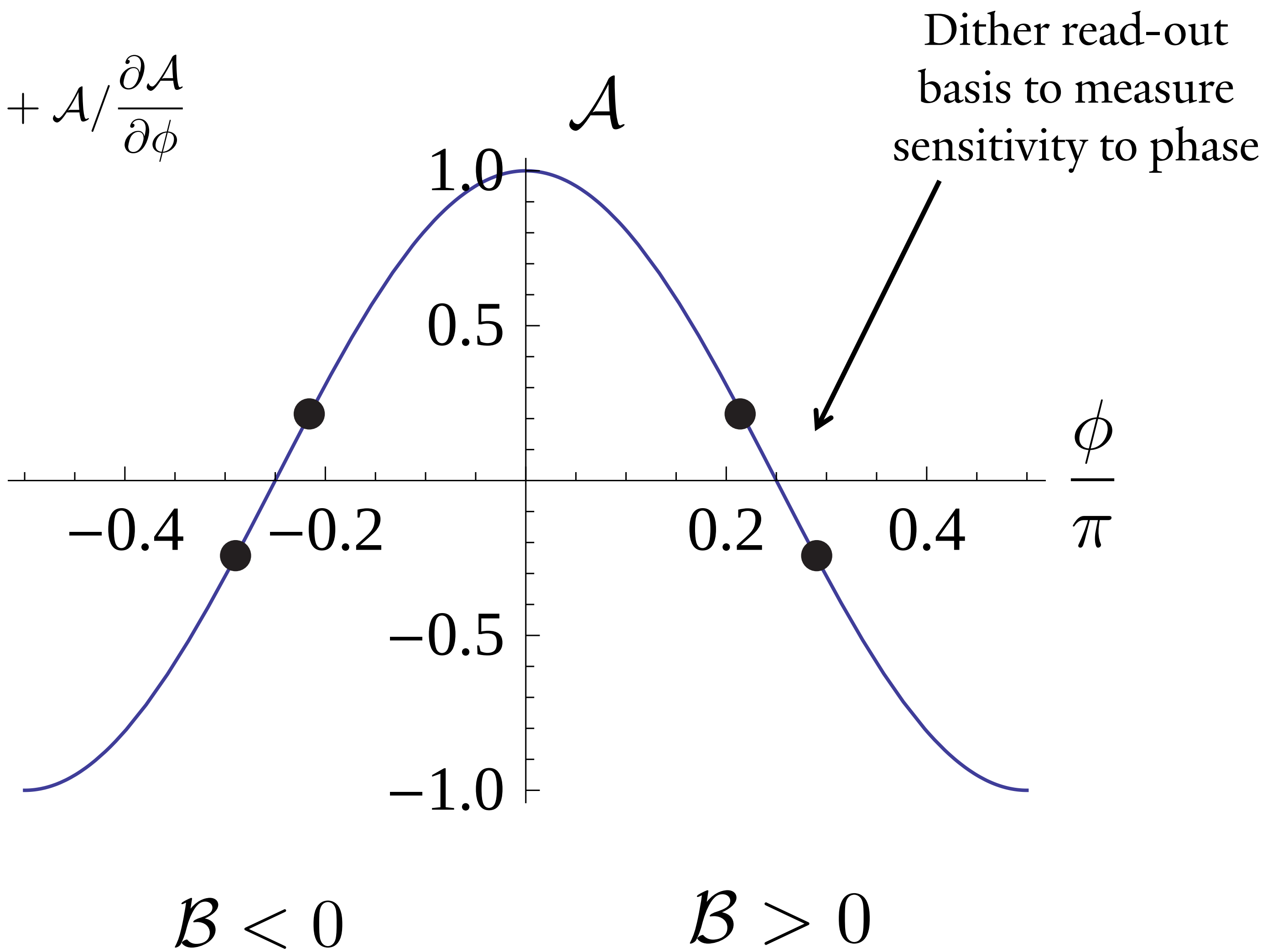


- We project the molecule spins onto the X and Y directions (set by our laser polarizations)
- We collect the resulting fluorescence from which we can determine the precession phase

$$\mathcal{A} = \frac{S_X - S_Y}{S_X + S_Y} = \mathcal{C}\cos\left(2\left(\phi - \theta\right)\right) \qquad \phi = -\left(\mu_{\mathrm{B}} g \tilde{\mathcal{B}} \left|\mathcal{B}_z\right| + \tilde{\mathcal{N}}\tilde{\mathcal{E}} d_e \mathcal{E}_{\mathrm{eff}}\right)\tau$$

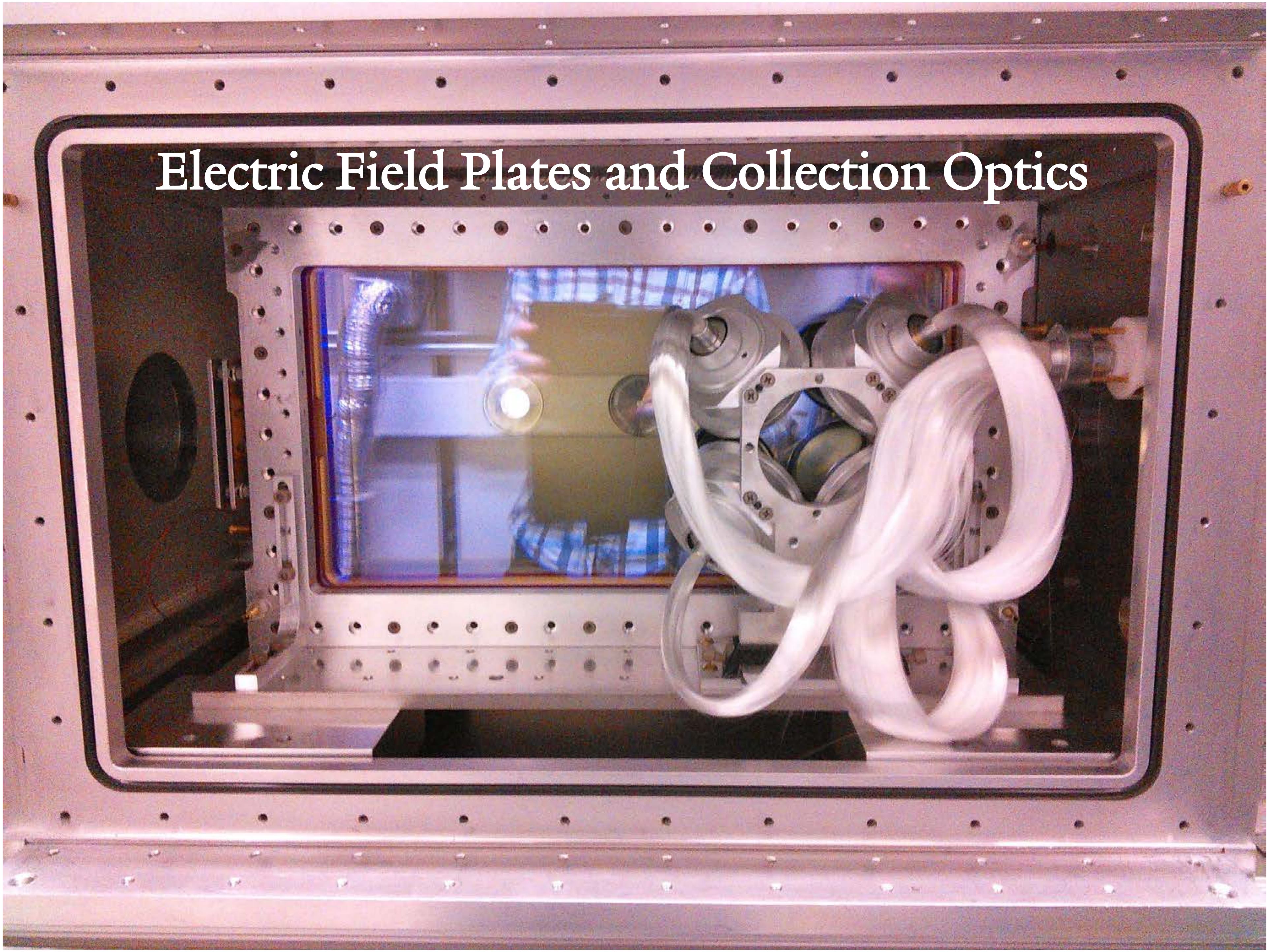
Precession Fringe

$$\phi \approx \mathrm{sgn}\,(\mathcal{B})\,\frac{\pi}{4} + \mathcal{A}/\frac{\partial \mathcal{A}}{\partial \phi}$$

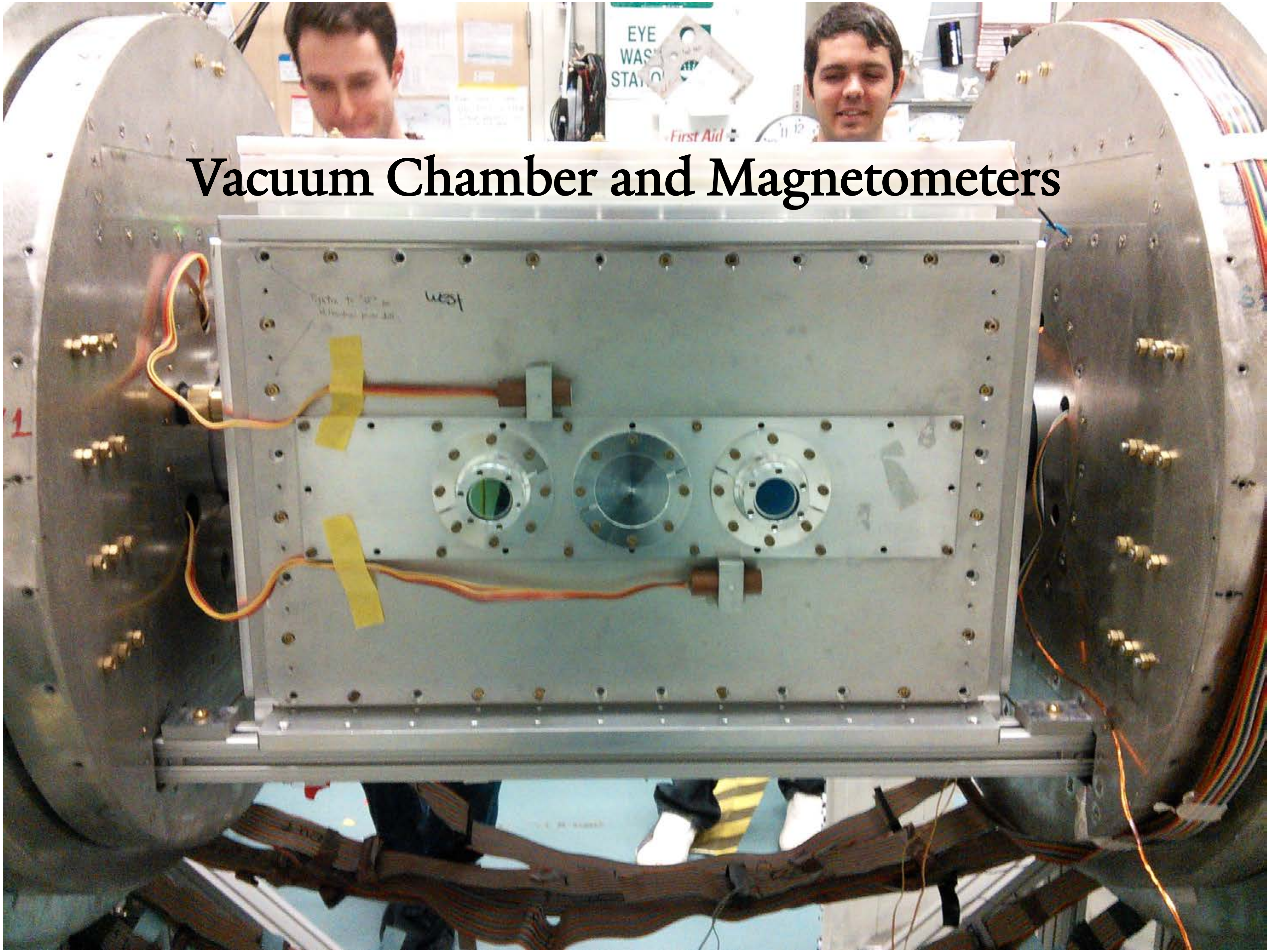


The Apparatus

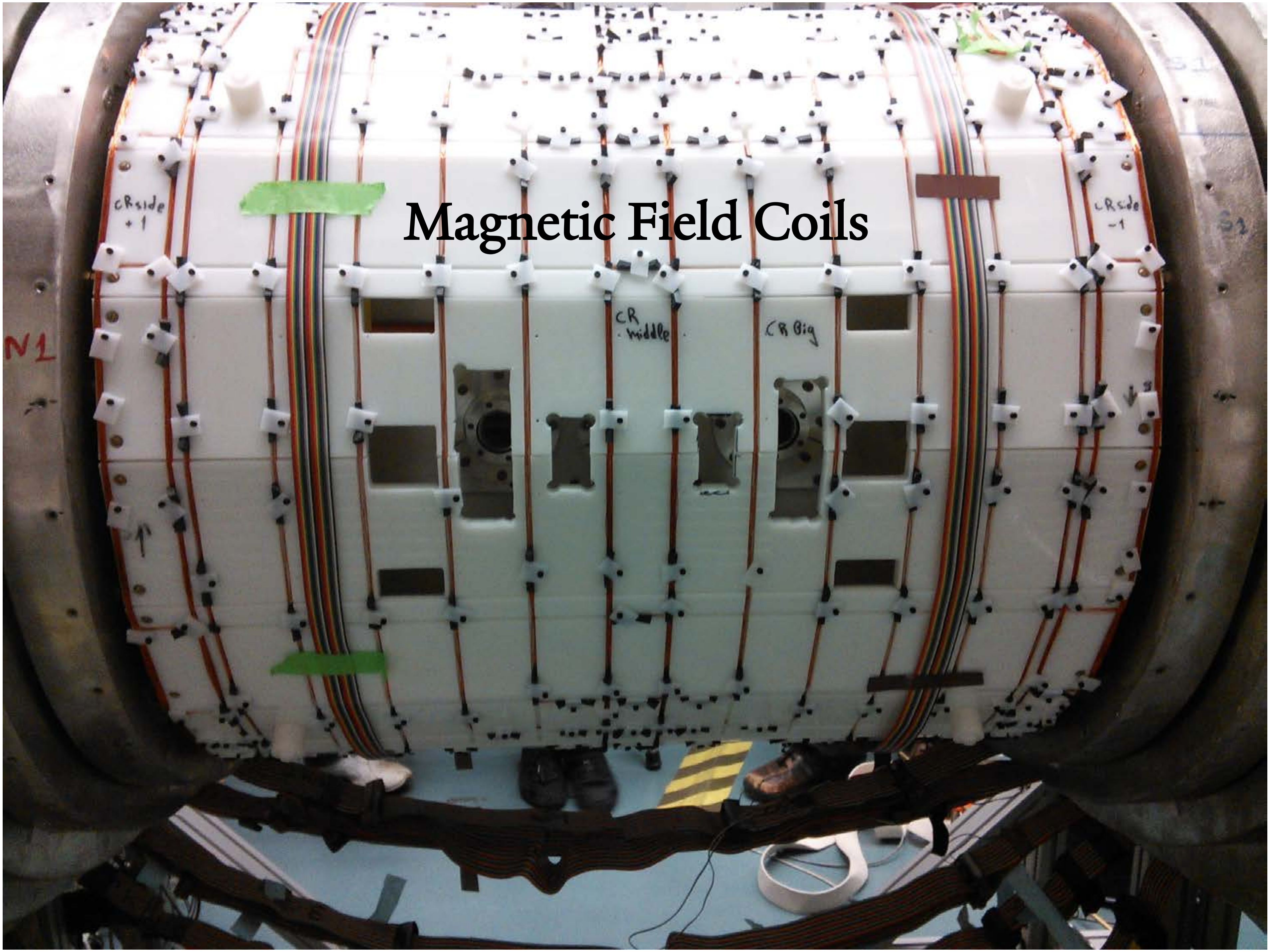
Electric Field Plates and Collection Optics



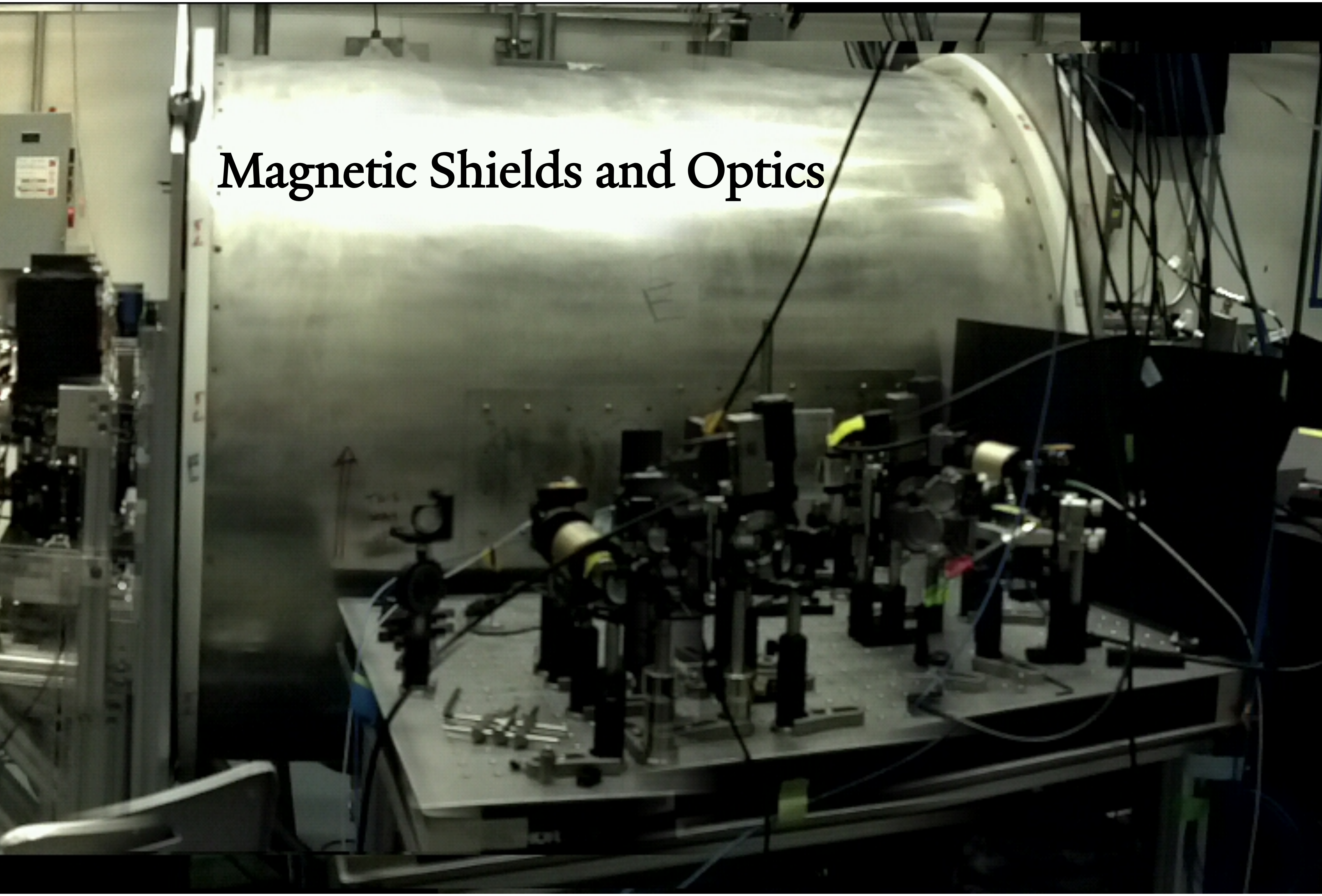
Vacuum Chamber and Magnetometers

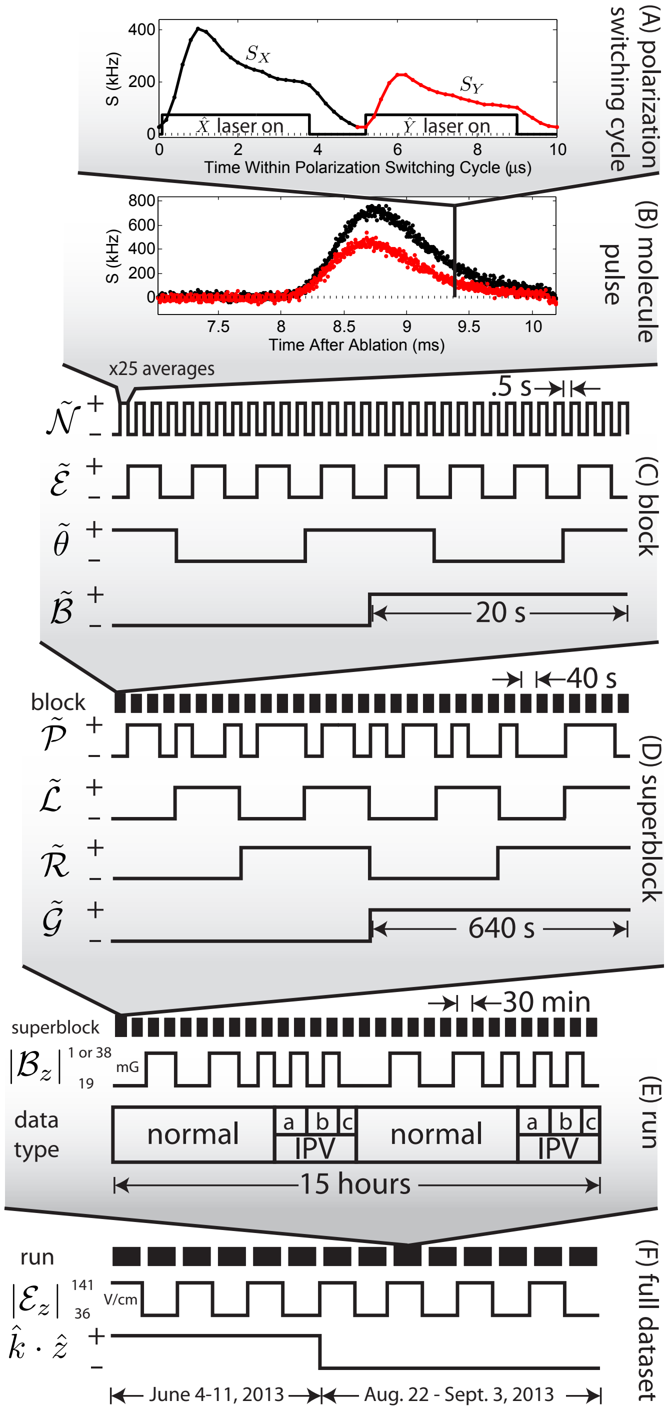


Magnetic Field Coils



Magnetic Shields and Optics





Switches and Timescales

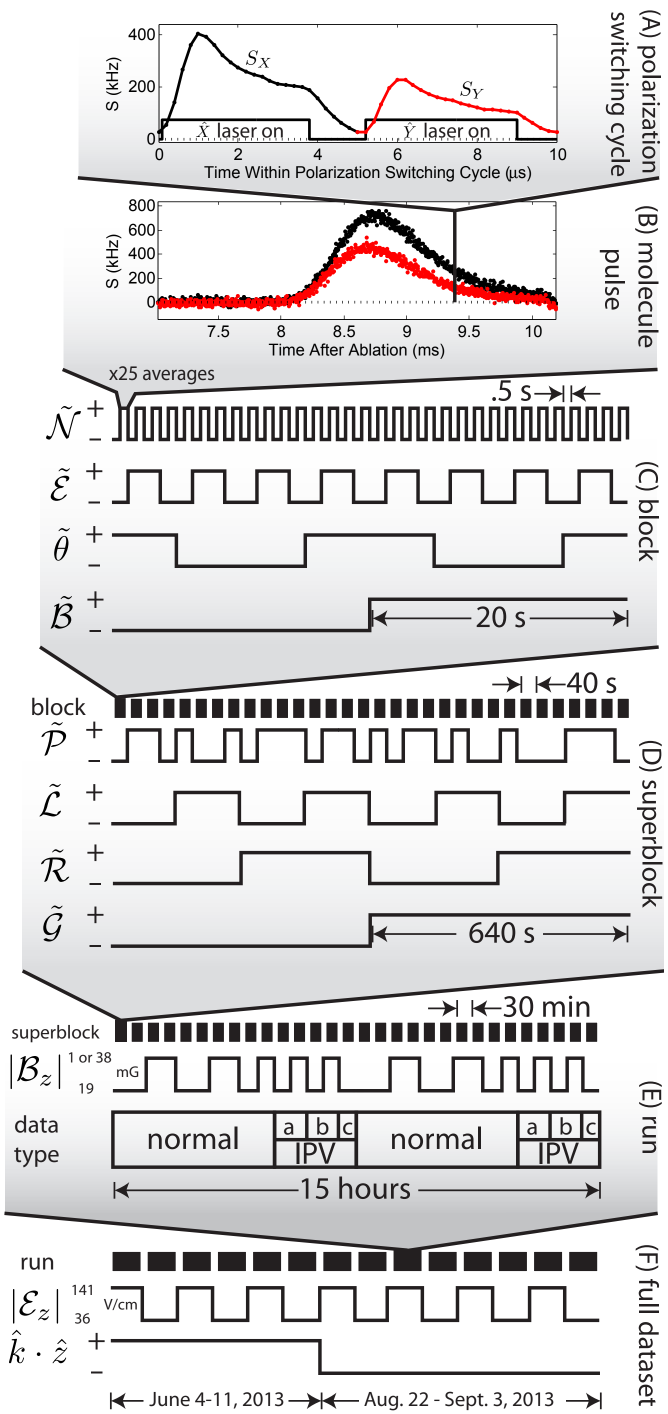
Switches = Changing the experimental configuration in a controlled way

Most of our switches are naturally binary (have two states) –

Look at effects that are even and odd with respect to these switches

Necessary to:

- Distinguish the EDM from background phases or fluorescence effects.
- Search for Unknown Systematic Errors and Monitor known ones.



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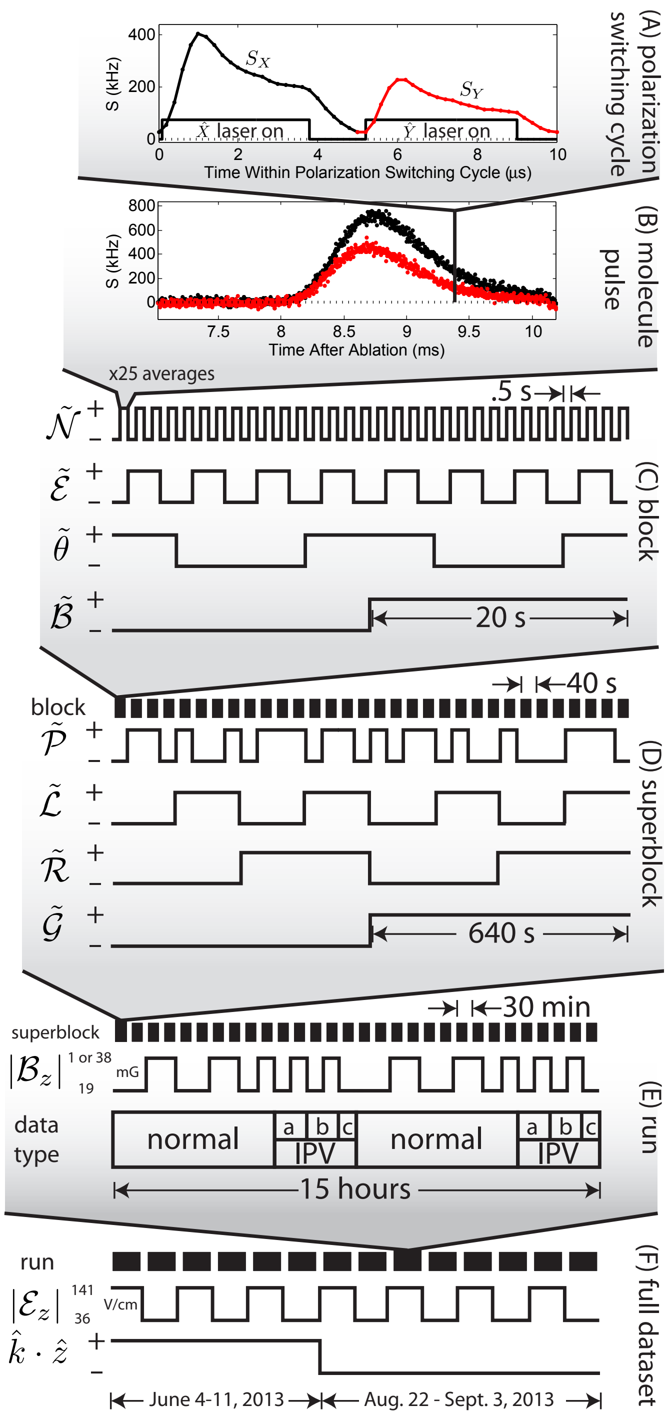

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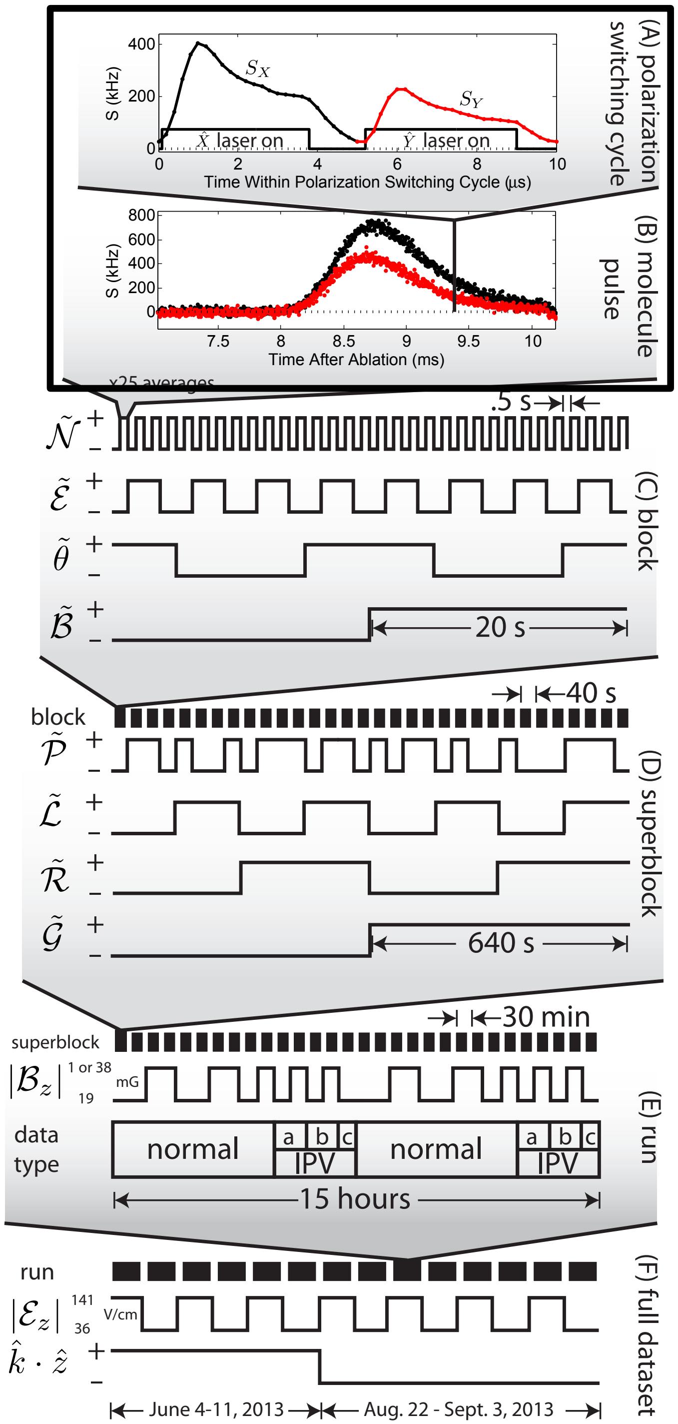
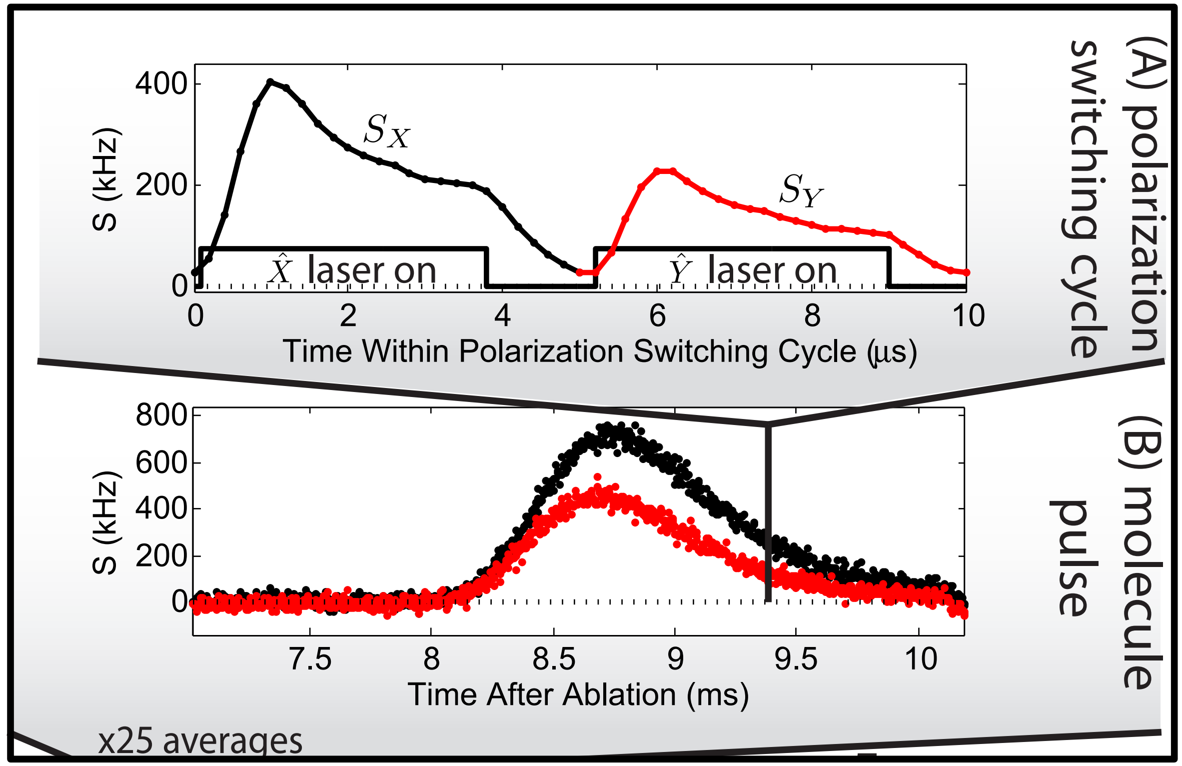
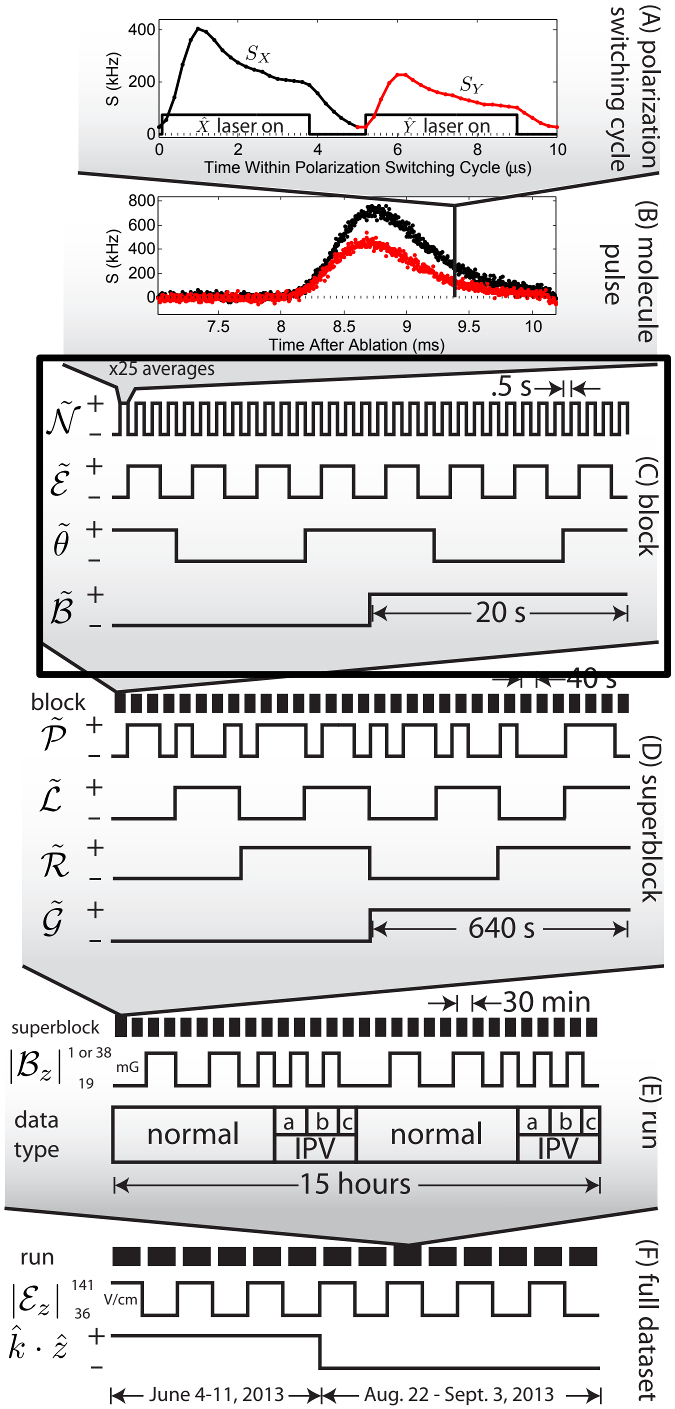


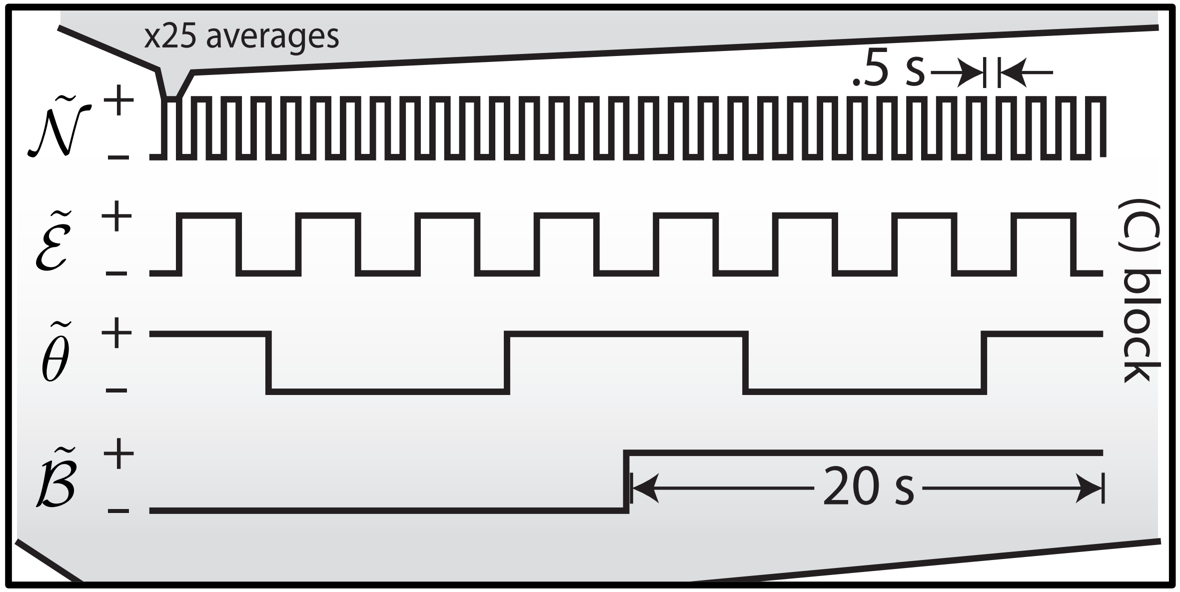


- Switch between read-out polarizations on the microsecond timescale.
(to normalize out molecule number fluctuations)

$$\mathcal{A} = \frac{S_X - S_Y}{S_X + S_Y} = \mathcal{C}\cos\left(2\left(\phi - \theta\right)\right) \approx 2\mathcal{C}\left(\phi - \theta\right)$$

Switches and Timescales



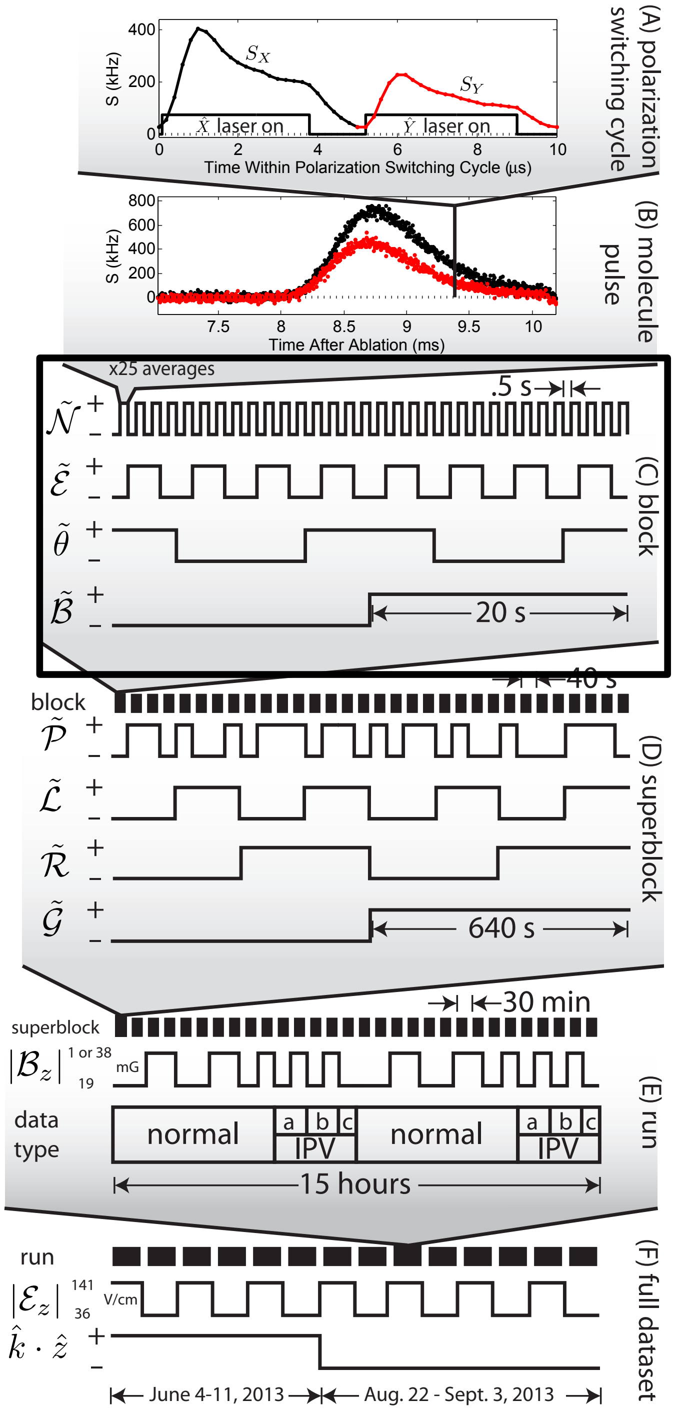


$\tilde{\mathcal{N}}$: Molecule alignment with respect to applied E-field

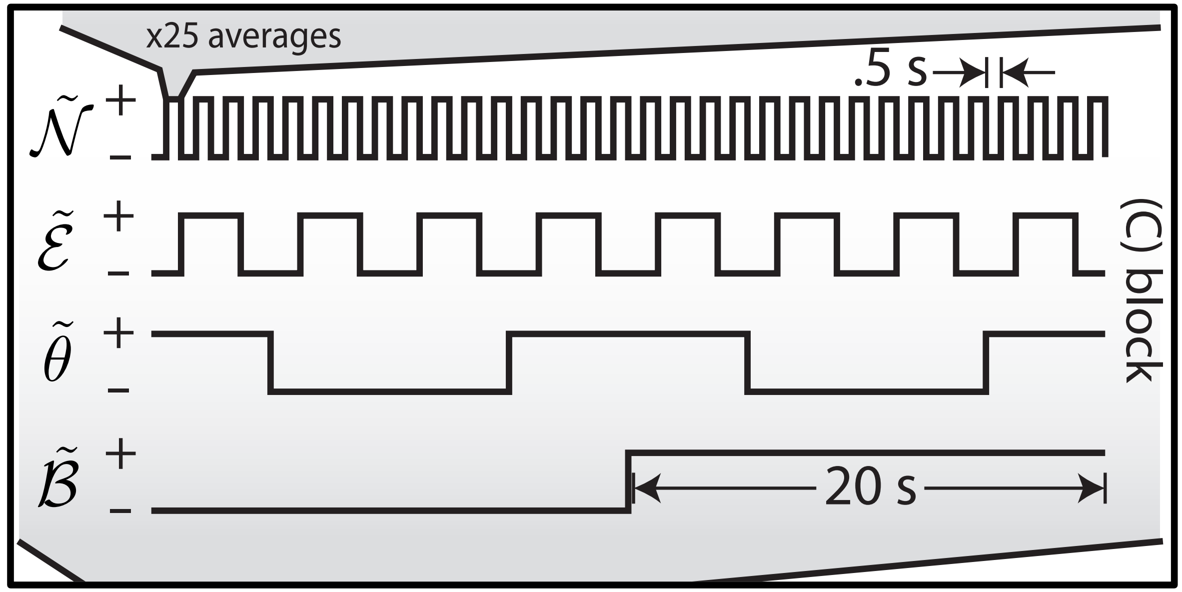
$\tilde{\mathcal{E}}$: Direction of applied electric field in laboratory

$\tilde{\theta}$: Dither state of the Read-out laser polarization basis

$\tilde{\mathcal{B}}$: Direction of applied magnetic field in laboratory



Switches and Timescales



- Extract contrast using $\tilde{\theta}$ switch to compute phase:

$$\mathcal{C} = \frac{1}{\Delta\theta}\left[\mathcal{A}\left(\tilde{\theta} = +1\right) - \mathcal{A}\left(\tilde{\theta} = -1\right)\right] \longrightarrow \phi \approx \mathcal{A}/2\mathcal{C}$$

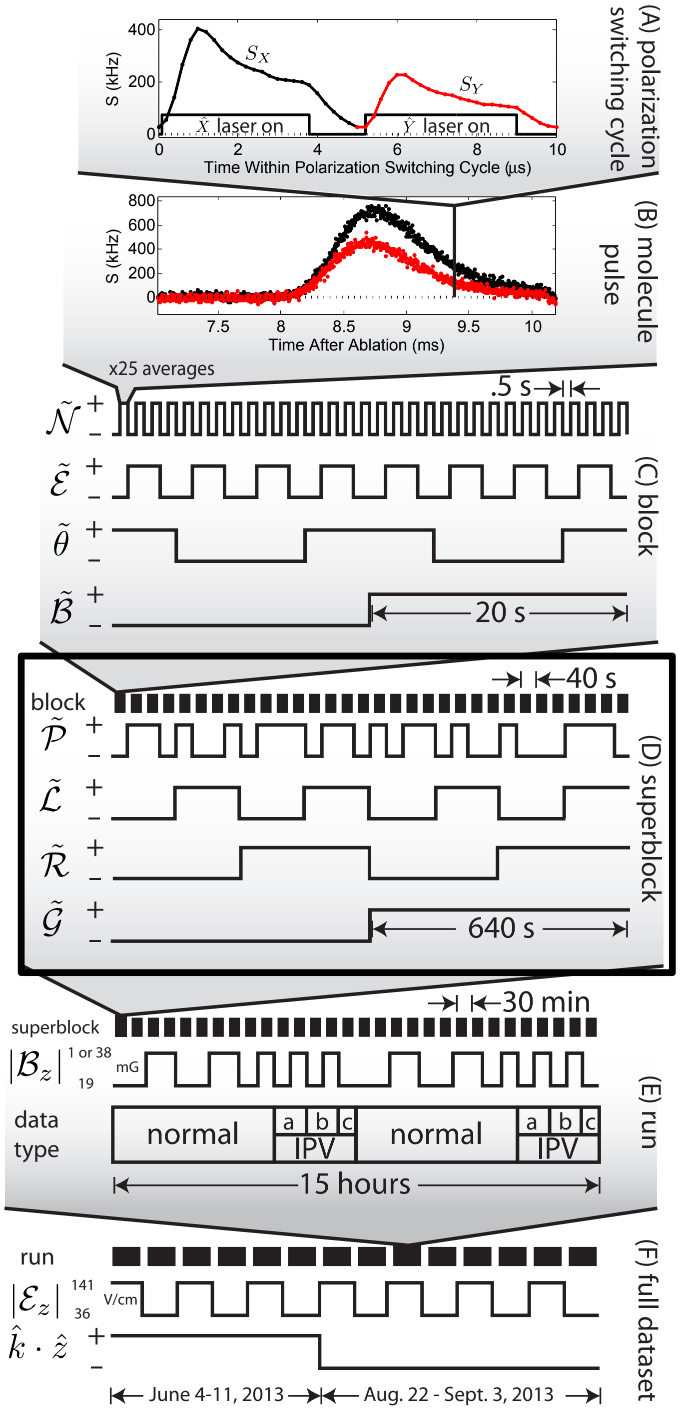
- Use the $\tilde{\mathcal{B}}$ switch to extract the precession time and compute energy shifts:

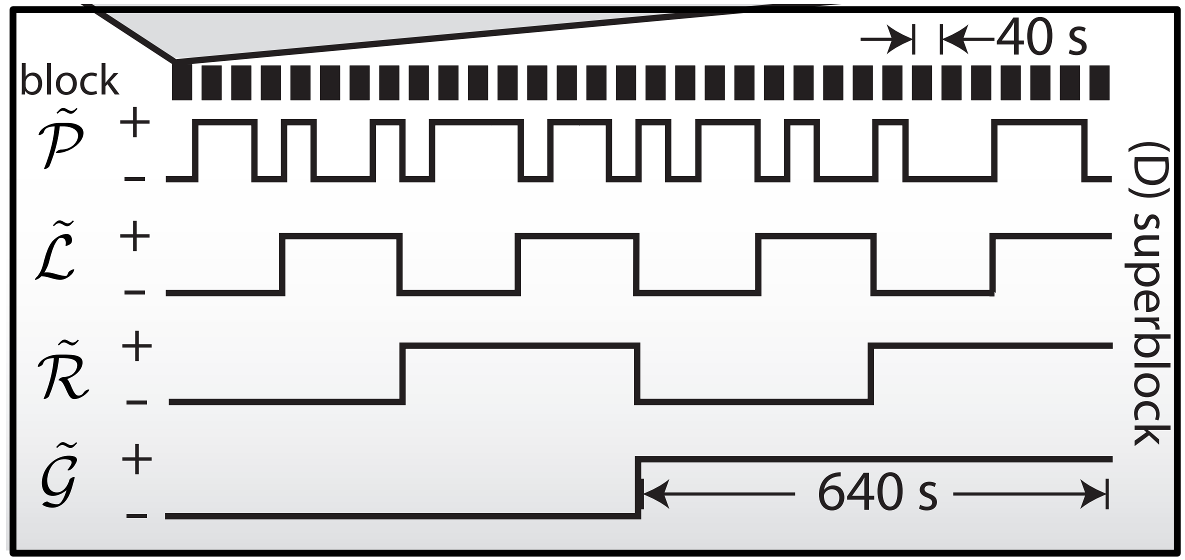
$$\phi^{\mathcal{B}} = \mu_{\mathrm{B}} g \left|\mathcal{B}_z\right| \tau \longrightarrow \omega = \phi/\tau$$

- Use the $\tilde{\mathcal{N}}\tilde{\mathcal{E}}$ switches to distinguish between the energy shift from an EDM:

$$\omega^{\mathcal{N}\mathcal{E}} = d_e \mathcal{E}_{\mathrm{eff}}$$

Switches and Timescales





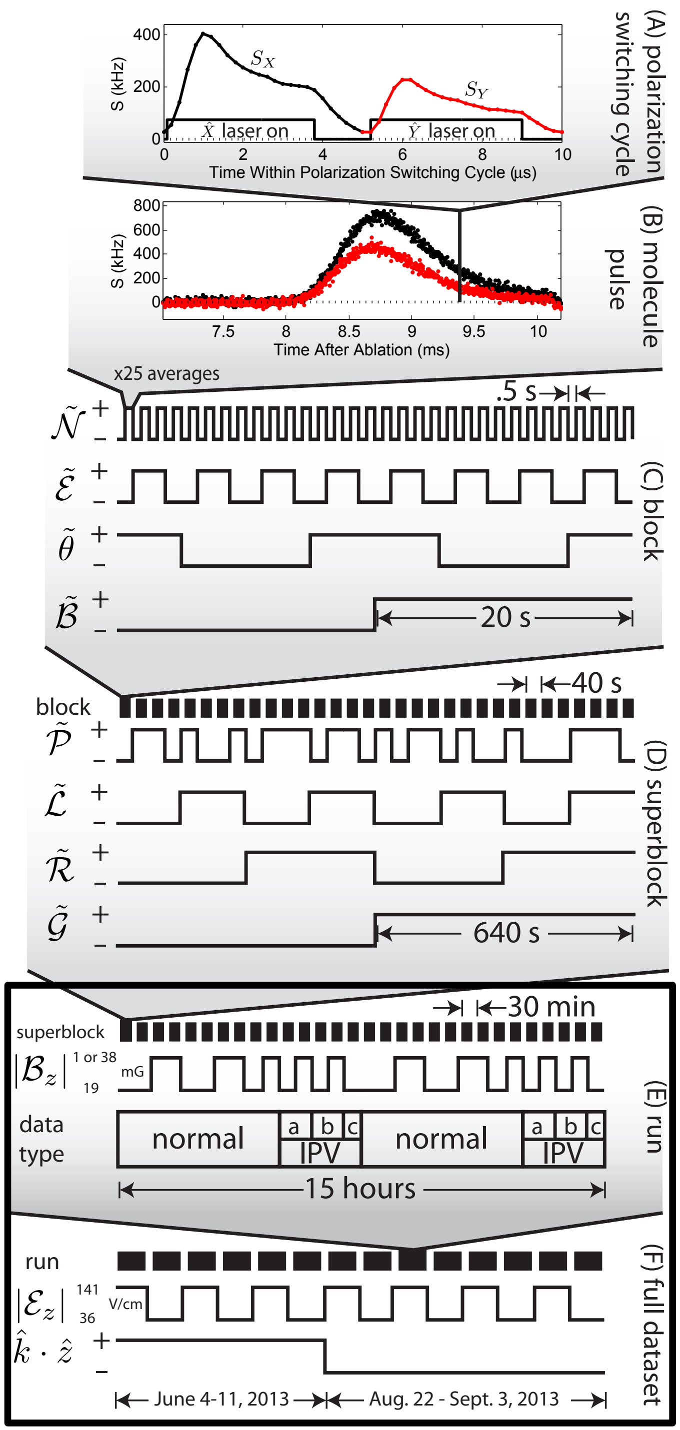
$\tilde{\mathcal{P}}$: Parity of the Excited State

$\tilde{\mathcal{L}}$: Reversal of Electric field leads

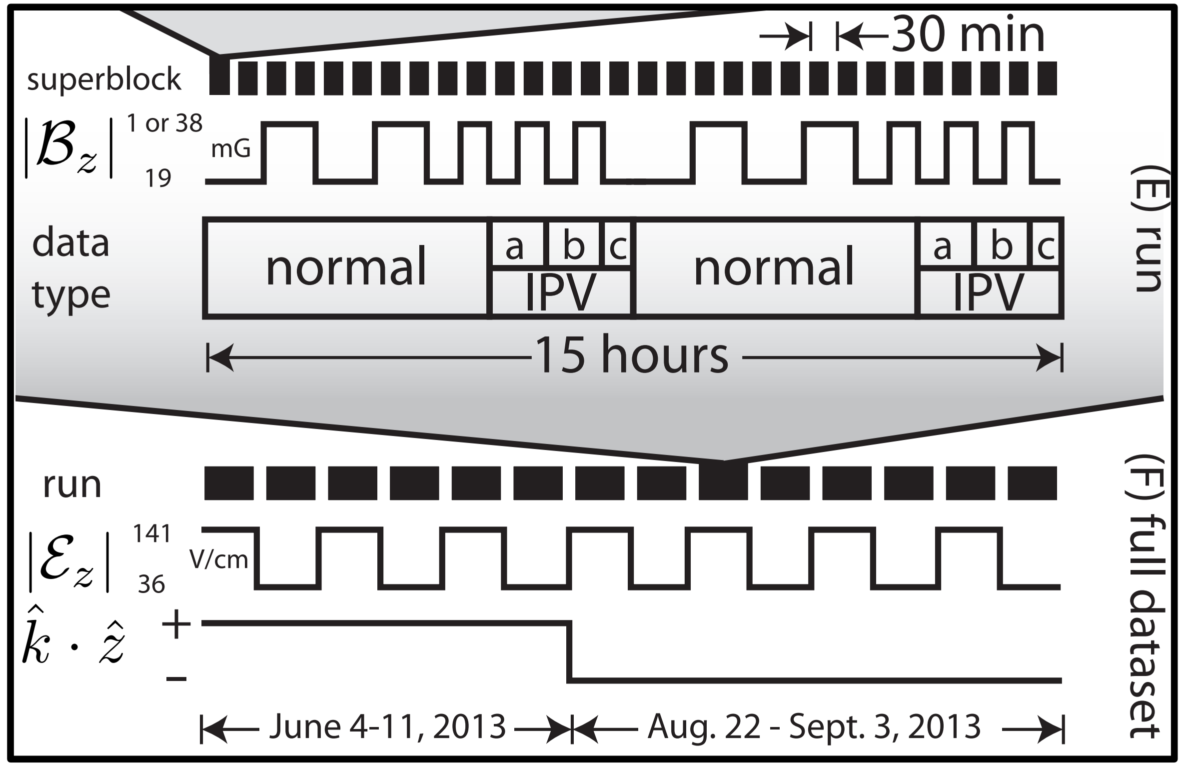
$\tilde{\mathcal{R}}$: Reversal of X and Y read-out laser beams

$\tilde{\mathcal{G}}$: Rotation of all laser polarizations in sync

- Systematic errors that depend on differences between X and Y read-out beams are odd under $\tilde{\mathcal{P}}\tilde{\mathcal{R}}$
- An offset voltage in the E-field power supply is canceled by $\tilde{\mathcal{L}}$
- $\tilde{\mathcal{G}}$ states are chosen to minimize a systematic error coupling to ellipticity of the laser light



Switches and Timescales



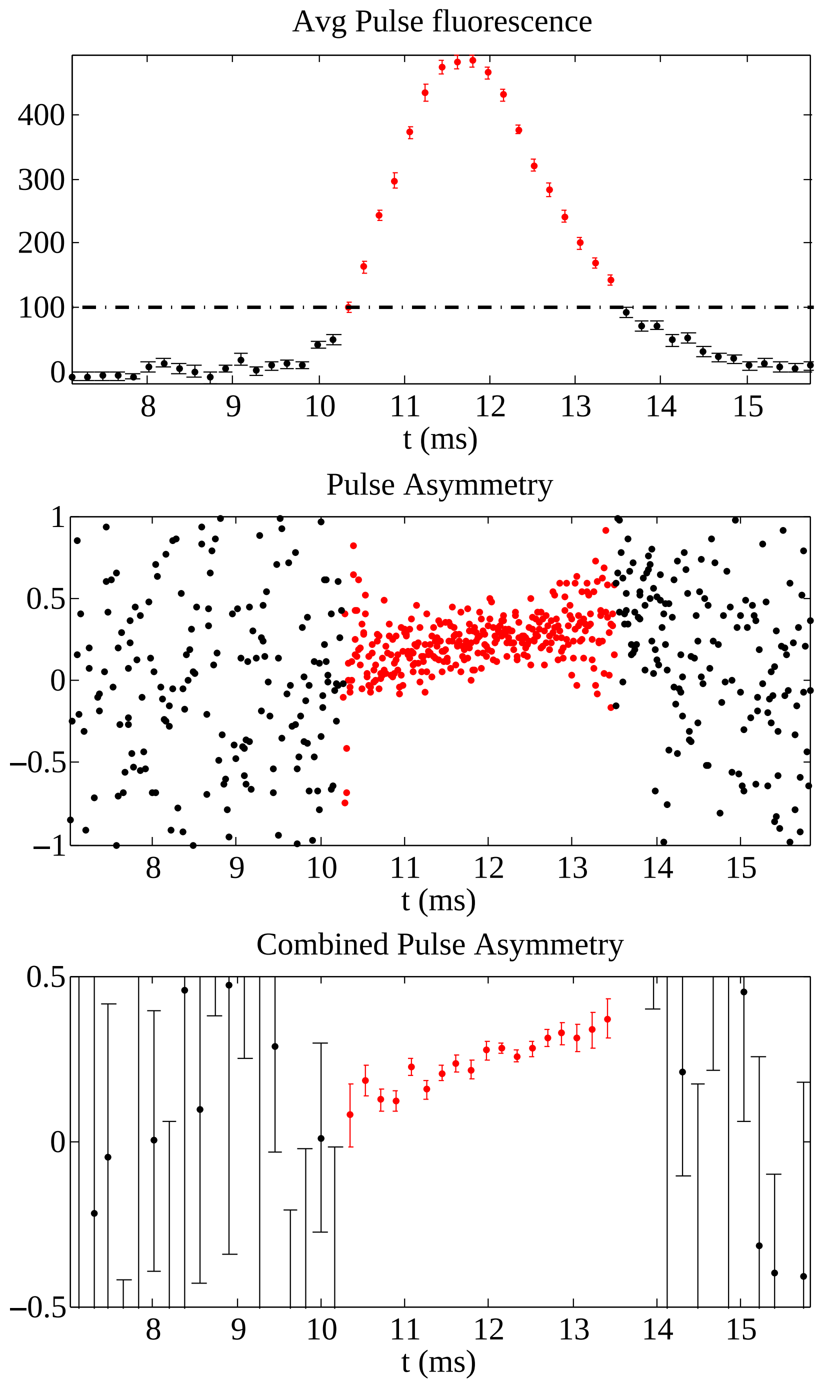
$|\mathcal{B}_z|$: Magnetic field magnitude

$|\mathcal{E}_z|$: Electric field magnitude

$\hat{k} \cdot \hat{z}$: Propagation direction of lasers

EDM data is interwoven with Intentional Parameter Variations to carefully monitor quantities that couple to known systematic errors.

Data Analysis

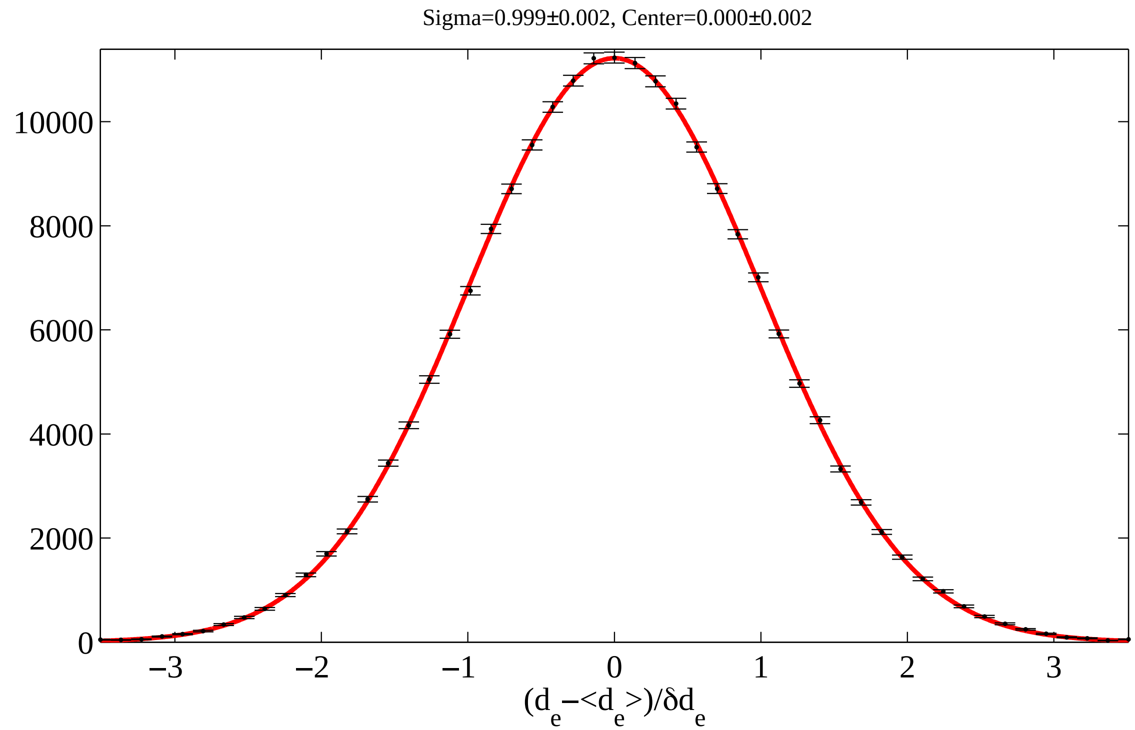


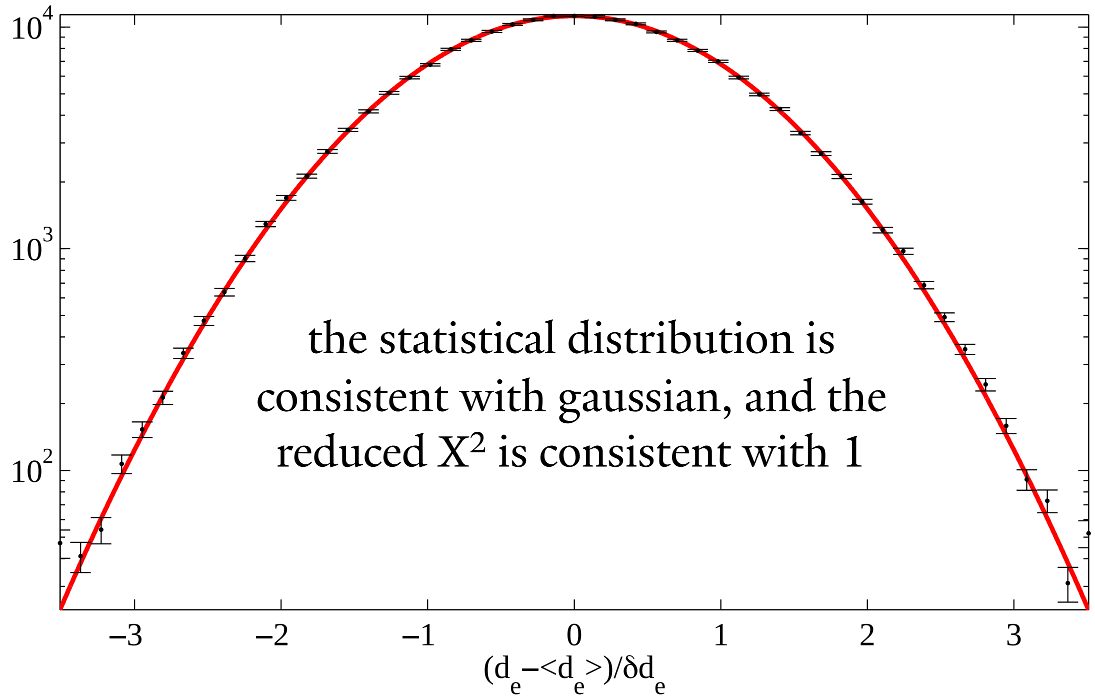
signal threshold cut ensures gaussian asymmetry

binning of asymmetries (18-30 pts)

- Computation of Uncertainty
- Uncertainty propagation
- Statistical Distribution
- Blind Offset
- Feldman-Cousins Confidence Intervals

compute the standard error in the mean, and use standard error propagation to obtain the result.





Data Analysis

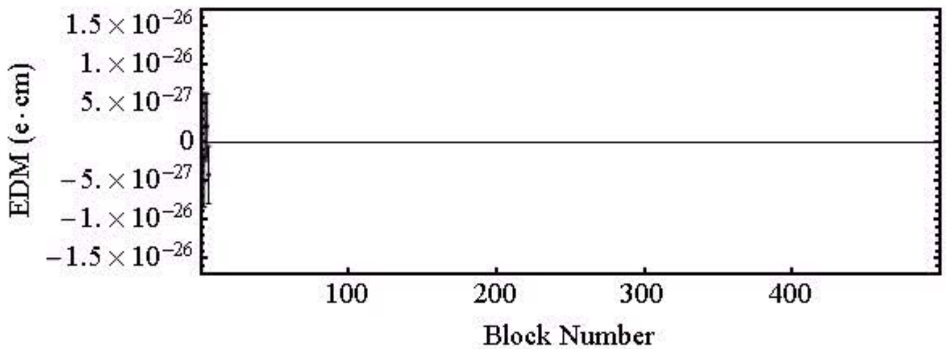
- Computation of Uncertainty
- Uncertainty propagation
- **Statistical Distribution**
- Blind Offset
- Feldman-Cousins Confidence Intervals

the uncertainty is limited by photon shot noise in the photodetectors,

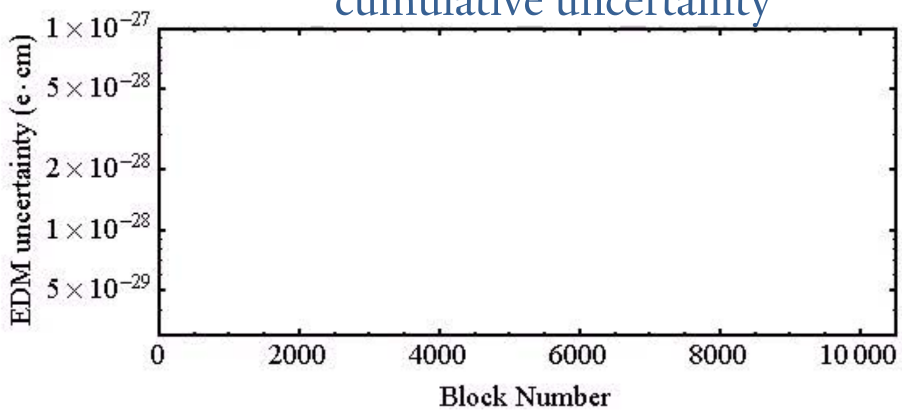
$$\delta\omega^{\mathcal{N}\mathcal{E}} \approx 1.15 \times \frac{1}{\mathcal{C}\tau\sqrt{N}}$$

Visualization of the Statistics

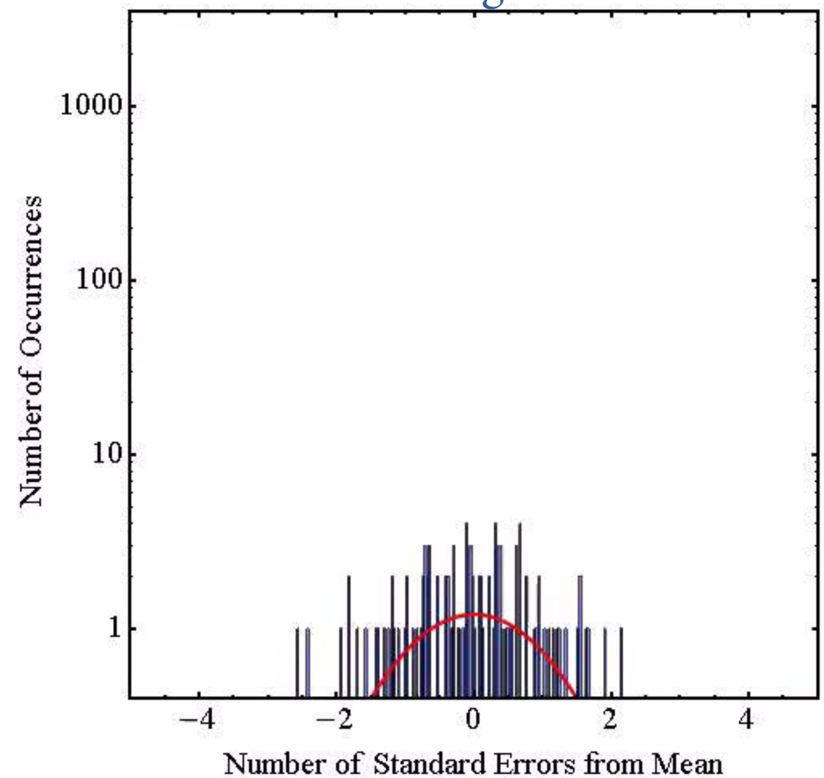
measurements



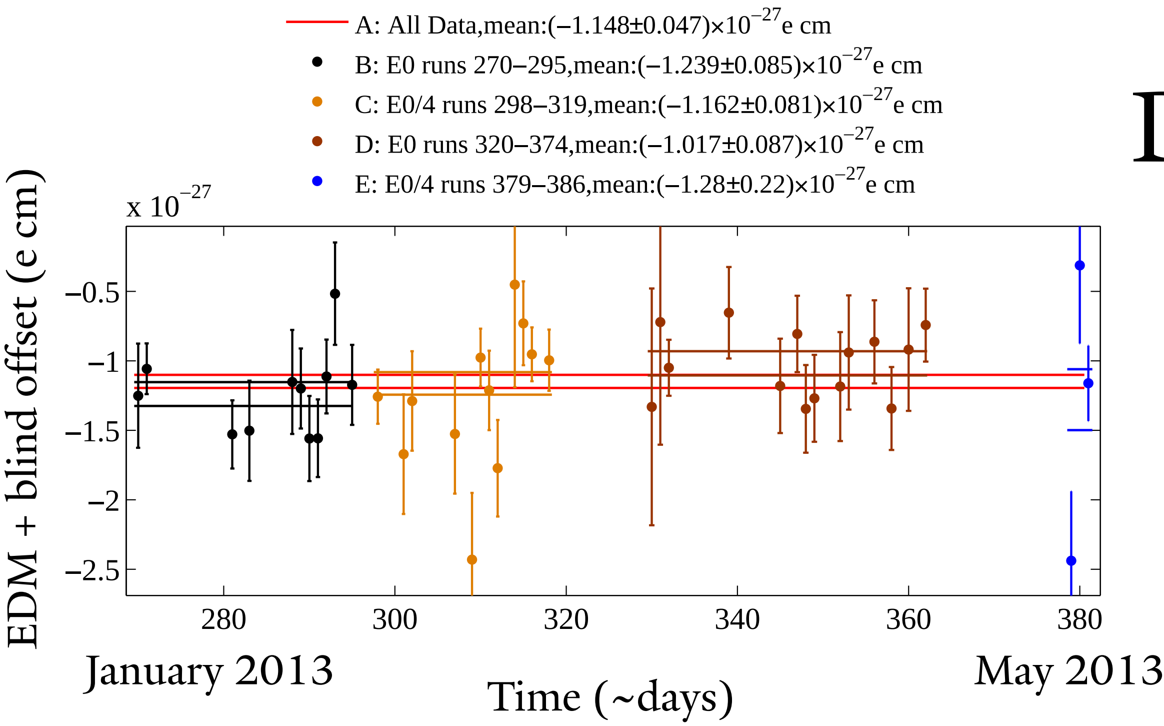
cumulative uncertainty



histogram



Data Analysis

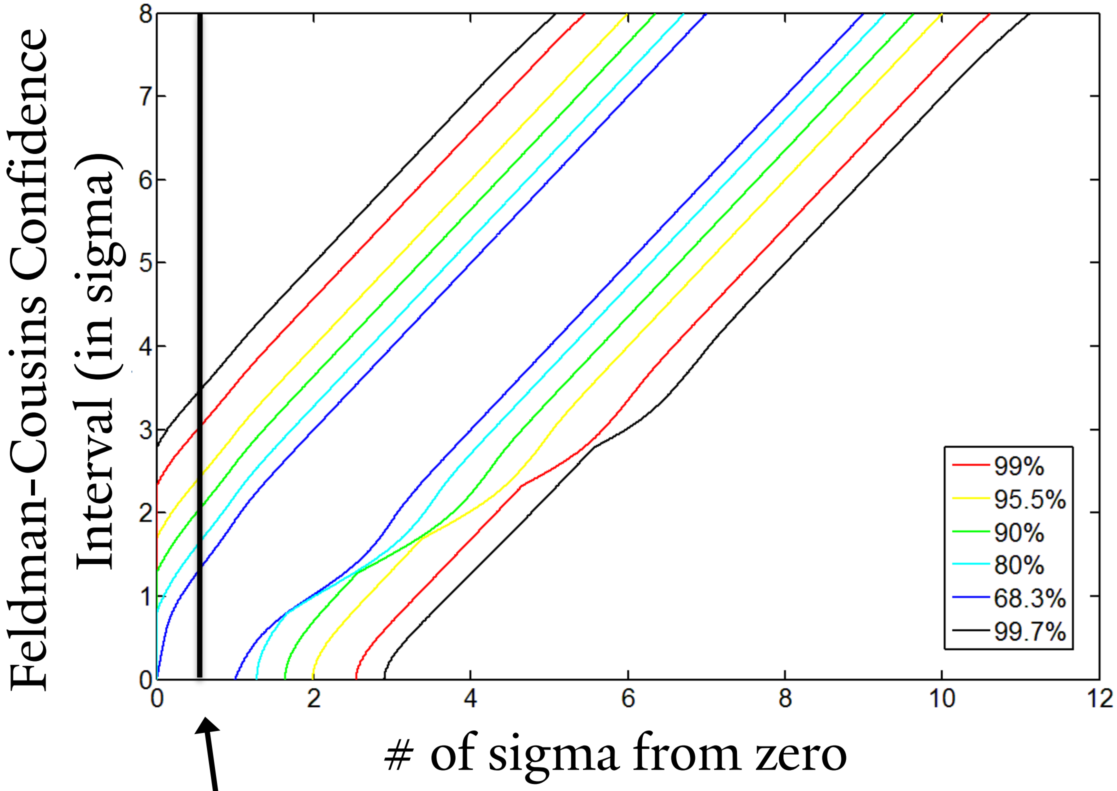


- Computation of Uncertainty
- Uncertainty propagation
- Statistical Distribution
- **Blind Offset**
- Feldman-Cousins Confidence Intervals

Blind Offset was a randomly chosen number selected from a Gaussian distribution

- centered on zero
- 1 sigma width equal to the previous best limit (at 90% confidence)

Data Analysis



measured center value for EDM (corresponds to an upper limit in this case for all reasonable confidence levels)

Avoids overconfidence that results from flipping between reporting a center value or upper limit contingent on the result.

- Computation of Uncertainty
- Uncertainty propagation
- Statistical Distribution
- Blind Offset
- Feldman-Cousins Confidence Intervals

How to Perform a Systematic Search

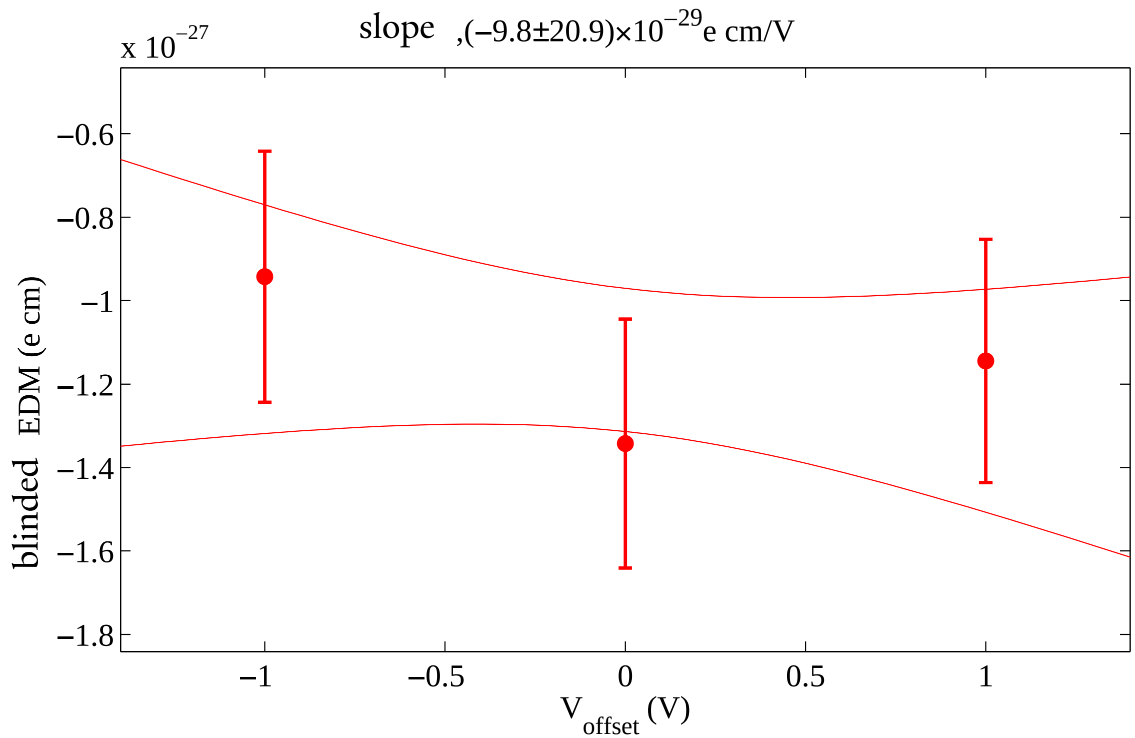
1.) Vary some experiment parameter

(in this case an offset voltage of field plates relative to vacuum chamber)

2.) Measure the EDM channel

3.) Choose a model for a systematic to enter into the EDM channel

(usually we fit to a line)



4.) Measure the value that was varied under normal conditions

$$\frac{\partial d_e}{\partial V_{offset}} \sim (-1 \pm 2) \times 10^{-28}\, e \cdot cm/V$$

(in this case with a volt-meter)

$$V_{offset} \sim (0 \pm 5)\ mV$$

5.) Derive a systematic errorbar

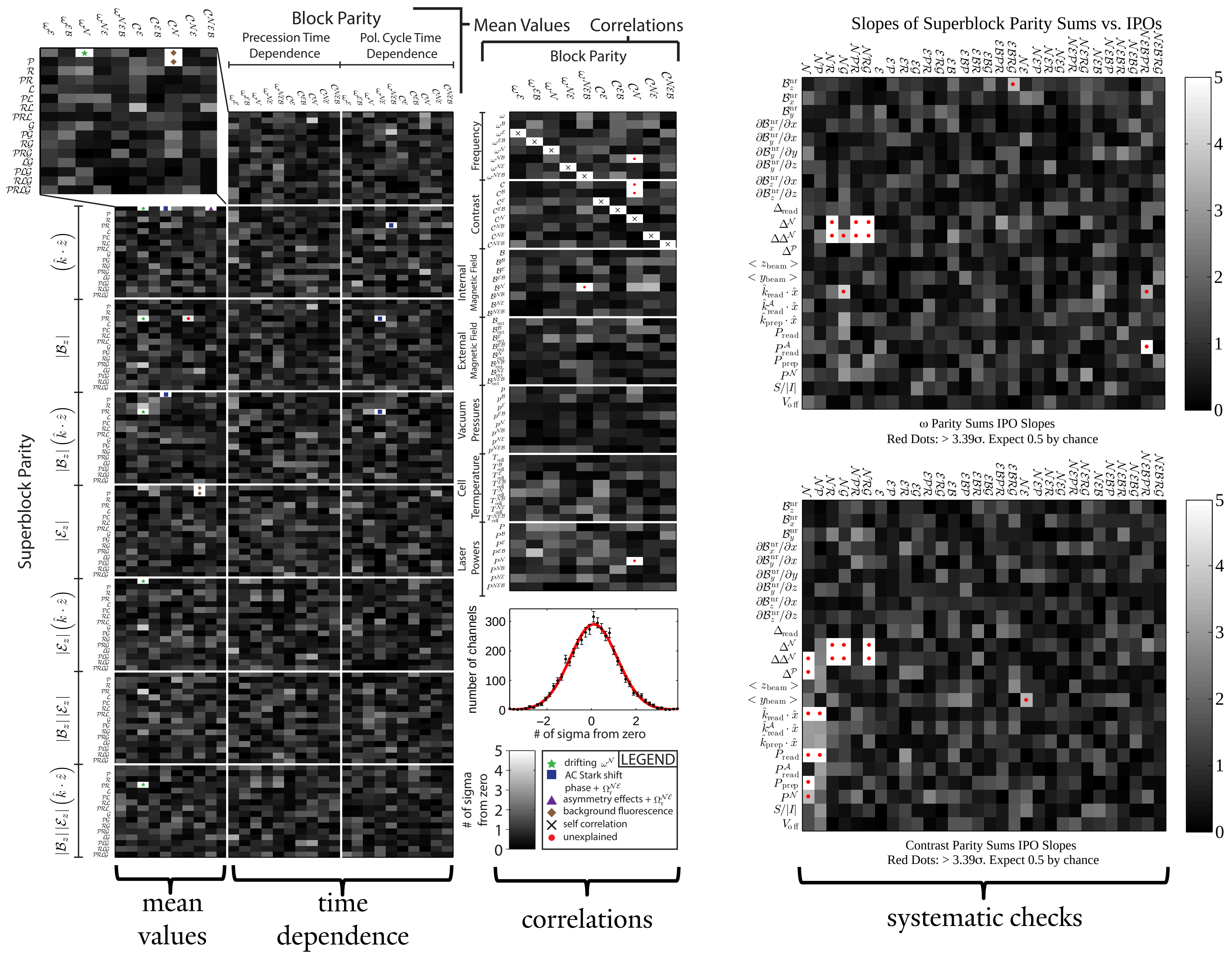
$$\delta d_{e,\,syst} \sim \frac{\partial d_e}{\partial V_{offset}} \delta V_{offset} \approx 10^{-30}\, e \cdot cm$$

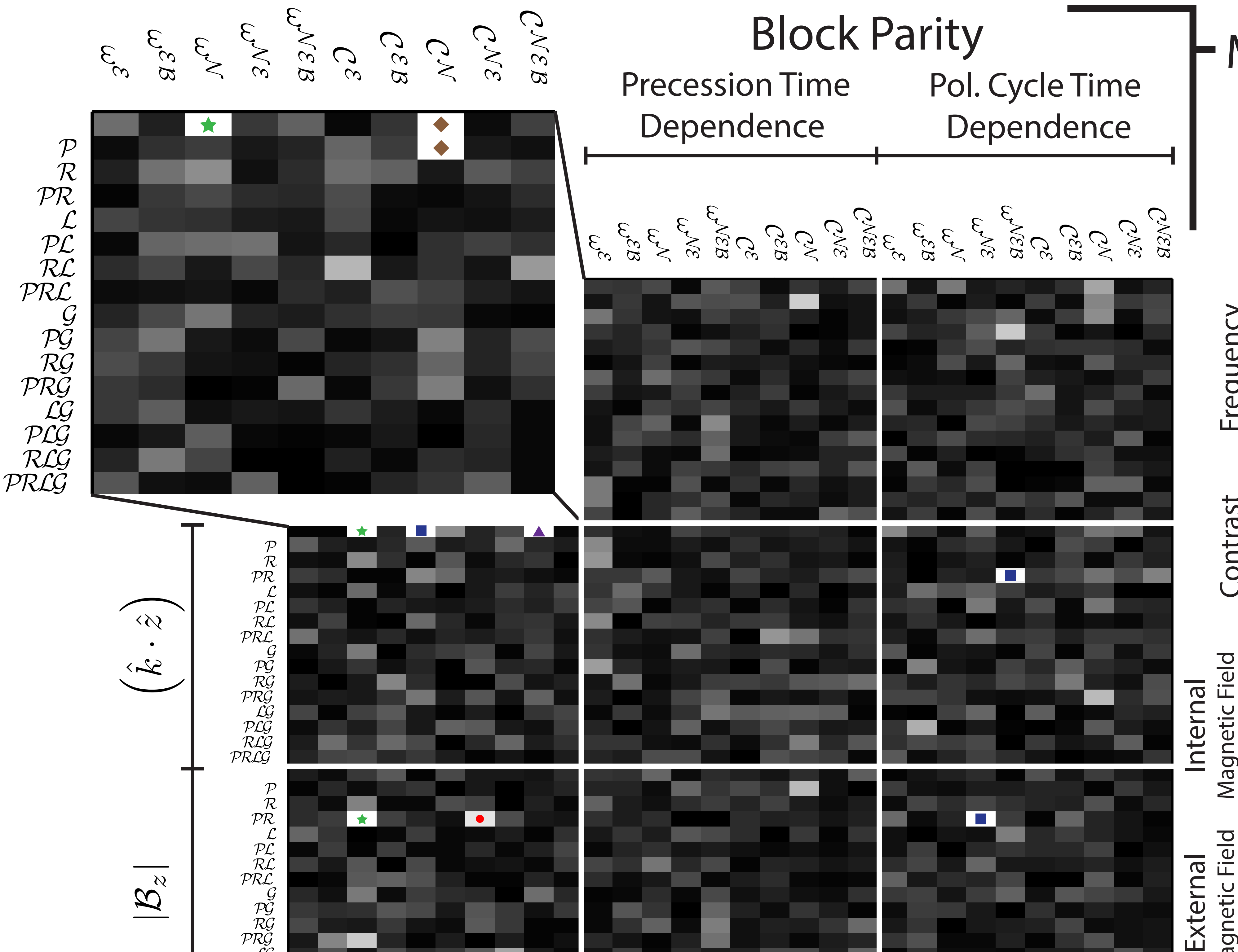
Category I Parameters
Magnetic Fields
- Non-Reversing $\mathcal{B}$-Field: $\mathcal{B}_z^{\mathrm{nr}}$
- Transverse $\mathcal{B}$-Fields: $\mathcal{B}_x, \mathcal{B}_y$ (even and odd under $\tilde{\mathcal{B}}$)
- Magnetic $\mathcal{B}$-Field Gradients:
$\frac{\partial \mathcal{B}_x}{\partial x}, \frac{\partial \mathcal{B}_y}{\partial x}, \frac{\partial \mathcal{B}_y}{\partial y}, \frac{\partial \mathcal{B}_y}{\partial z}, \frac{\partial \mathcal{B}_z}{\partial x}, \frac{\partial \mathcal{B}_z}{\partial z}$ (even and odd under $\tilde{\mathcal{B}}$)
- $\tilde{\mathcal{E}}$ correlated $\mathcal{B}$-field: $\mathcal{B}^{\mathcal{E}}$ (to simulate
$\vec{v} \times \vec{\mathcal{E}}$/geometric phase/leakage current effects)
Electric Fields
- Non-Reversing $\mathcal{E}$-Field: $\mathcal{E}^{\mathrm{nr}}$
- $\mathcal{E}$-Field Ground Offset
Laser Detunings
- Detuning of the Prep/Read Lasers: Δ_{prep}, Δ_{read}
- $\tilde{\mathcal{P}}$ correlated Detuning: $\Delta^{\mathcal{P}}$
- $\tilde{\mathcal{N}}$ correlated Detunings: $\Delta^{\mathcal{N}}$, $\Delta\Delta^{\mathcal{N}}$
Laser Pointings along $\hat{x}$
- Change in Pointing of Prep/Read Lasers
- Readout laser $\hat{X}/\hat{Y}$ dependent pointing
- $\tilde{\mathcal{N}}$ correlated laser pointing
- $\tilde{\mathcal{N}}$ and $\hat{X}/\hat{Y}$ dependent laser pointing
Laser Powers
- Power of Prep/Read Lasers: P_{prep}, P_{read}
- $\tilde{\mathcal{N}}\tilde{\mathcal{E}}$ correlated power, $P^{\mathcal{N}\mathcal{E}}$ (simulating $\Omega_r^{\mathcal{N}\mathcal{E}}$)
- $\tilde{\mathcal{N}}$ correlated power, $P^{\mathcal{N}}$
- $\hat{X}/\hat{Y}$ dependent Readout laser power
Laser Polarization
- Preparation Laser Ellipticity
Molecular Beam Clipping
- Molecule Beam Clipping along the $\hat{y}$ and $\hat{z}$
(changes $\langle v_y \rangle$,$\langle v_z \rangle$,$\langle y \rangle$,$\langle z \rangle$ for molecule ensemble)

Category II Parameters
Experiment Timing
- $\hat{X}/\hat{Y}$ Polarization Switching Rate
- Number of Molecule Pulse Averages
contributing to an Experiment State
Analysis
- Signal size cuts, Asymmetry magnitude
cuts, Contrast cuts
- Difference between two PMT detectors
(checking spatial fluorescence region dependence)
- Variation with time within molecule pulse
(serves to check v_x dependence)
- Variation with time within polarization
switching cycle
- Variation with time throughout the
full dataset (autocorrelation)
- Search for correlations with all ϕ, $\mathcal{C}$, and S
switch-parity components
- Search for correlations with auxiliary measurements
of $\mathcal{B}$-fields, laser powers, and vacuum pressure
- 3 individuals performed independent
analyses of the data

We looked at many things

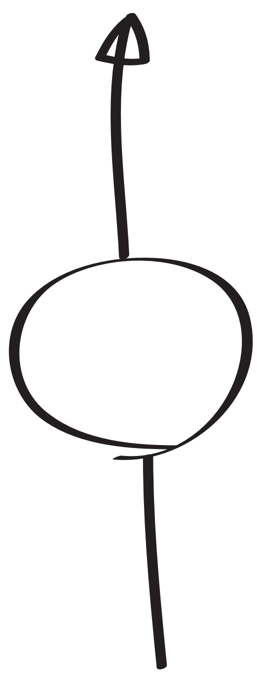
EDM Measurement=
(1 year of systematic checks)+
(2 weeks of EDM data)


Block Parity
Precession Time Dependence
Pol. Cycle Time Dependence
Mean Values
Correlations
Block Parity
Superblock Parity
Frequency
Contrast
Internal Magnetic Field
External Magnetic Field
Vacuum Pressures
Cell Temperature
Laser Powers
number of channels
# of sigma from zero
# of sigma from zero
LEGEND
drifting $\omega^{\mathcal{N}}$
AC Stark shift phase + $\Omega_r^{\mathcal{NE}}$
asymmetry effects + $\Omega_r^{\mathcal{NE}}$
background fluorescence
self correlation
unexplained
Slopes of Superblock Parity Sums vs. IPOs
ω Parity Sums IPO Slopes
Red Dots: > 3.39σ. Expect 0.5 by chance
Contrast Parity Sums IPO Slopes
Red Dots: > 3.39σ. Expect 0.5 by chance
mean values
time dependence
correlations
systematic checks



Block Parity
Precession Time Dependence
Pol. Cycle Time Dependence
Frequency
Contrast
Internal Magnetic Field
External Magnetic Field
$(\hat{k}\cdot\hat{z})$
$|\mathcal{B}_z|$

Systematic Errors



vs

Phase Dependence on Δ, Ω_r?

What if.... $\phi = \phi(\Delta, \Omega_r)$

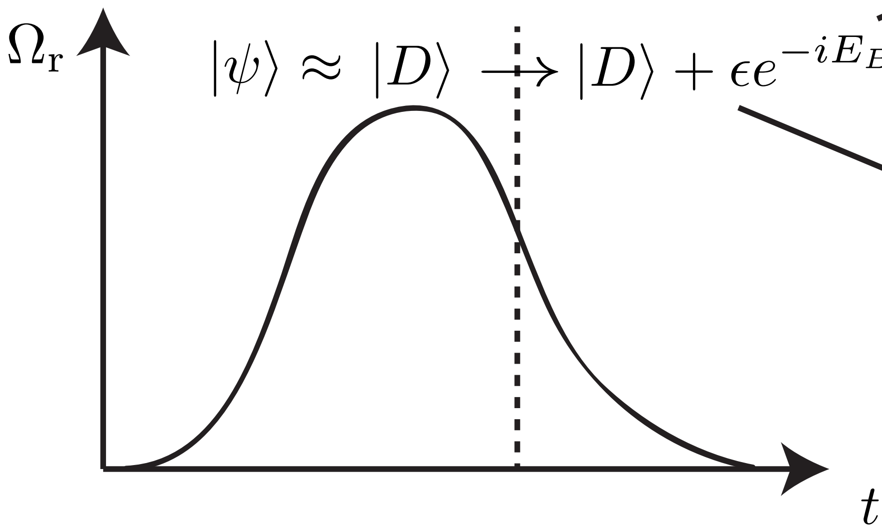
The measured phase depends on the laser parameters?

Δ : Laser Detuning from Resonance

Ω_r : Rabi Frequency

Phase Dependence on Δ, Ω_r?

$$|\psi\rangle \approx |D\rangle \longrightarrow |D\rangle + \epsilon e^{-iE_B t}|B\rangle$$

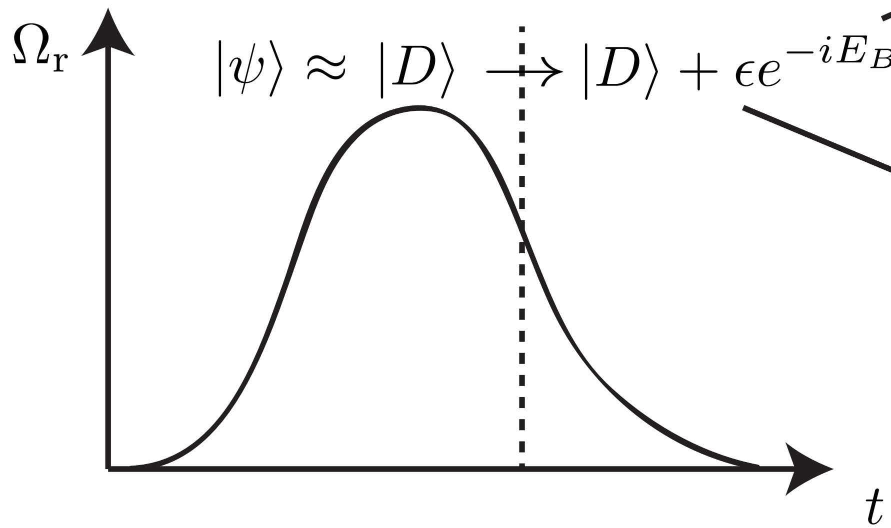


Phase that depends
on laser parameters

-non adiabatic transfer
from polarization gradients

-mixing from two-photon detuning
from Zeeman shift

Phase Dependence on Δ, Ω_r?



$$|\psi\rangle \approx |D\rangle \longrightarrow |D\rangle + \epsilon e^{-iE_B t}|B\rangle$$

Phase that depends on laser parameters

-non adiabatic transfer from polarization gradients

-mixing from two-photon detuning from Zeeman shift

Taylor Expansion about normal conditions:

$$\phi\left(\Omega_r, \Delta\right) \approx \overbrace{\left(a_1\Delta + a_2\Delta d\Omega_\mathrm{r}\right)}^{\text{Ellipticity Gradient}} + \overbrace{\left(a_3\Delta^2 + a_4 d\Omega_\mathrm{r}\right)}^{\text{Linear Polarization Gradient}}$$

$$+ \left|\mathcal{B}_z\right| \tilde{\mathcal{B}} \underbrace{\left(a_5\Delta^2 + a_6 d\Omega_\mathrm{r}\right)}_{\text{Magnetic Field = 2 photon detuning}} + \ldots$$

Light Shift Systematic Errors

Then…

We could have the following systematic errors:

$$d_e^{\text{syst}}\left(\Delta^{\mathcal{N}\mathcal{E}}\right) = \frac{1}{\mathcal{E}_{\text{eff}}\tau}\frac{\partial\phi}{\partial\Delta}\Delta^{\mathcal{N}\mathcal{E}}$$

Requires parameters correlated like an EDM

$$d_e^{\text{syst}}\left(\Omega_r^{\mathcal{N}\mathcal{E}}\right) = \frac{1}{\mathcal{E}_{\text{eff}}\tau}\frac{\partial\phi}{\partial\Omega_r}\Omega_r^{\mathcal{N}\mathcal{E}}$$

Light Shift Systematic Errors

Then…

We could have the following systematic errors:

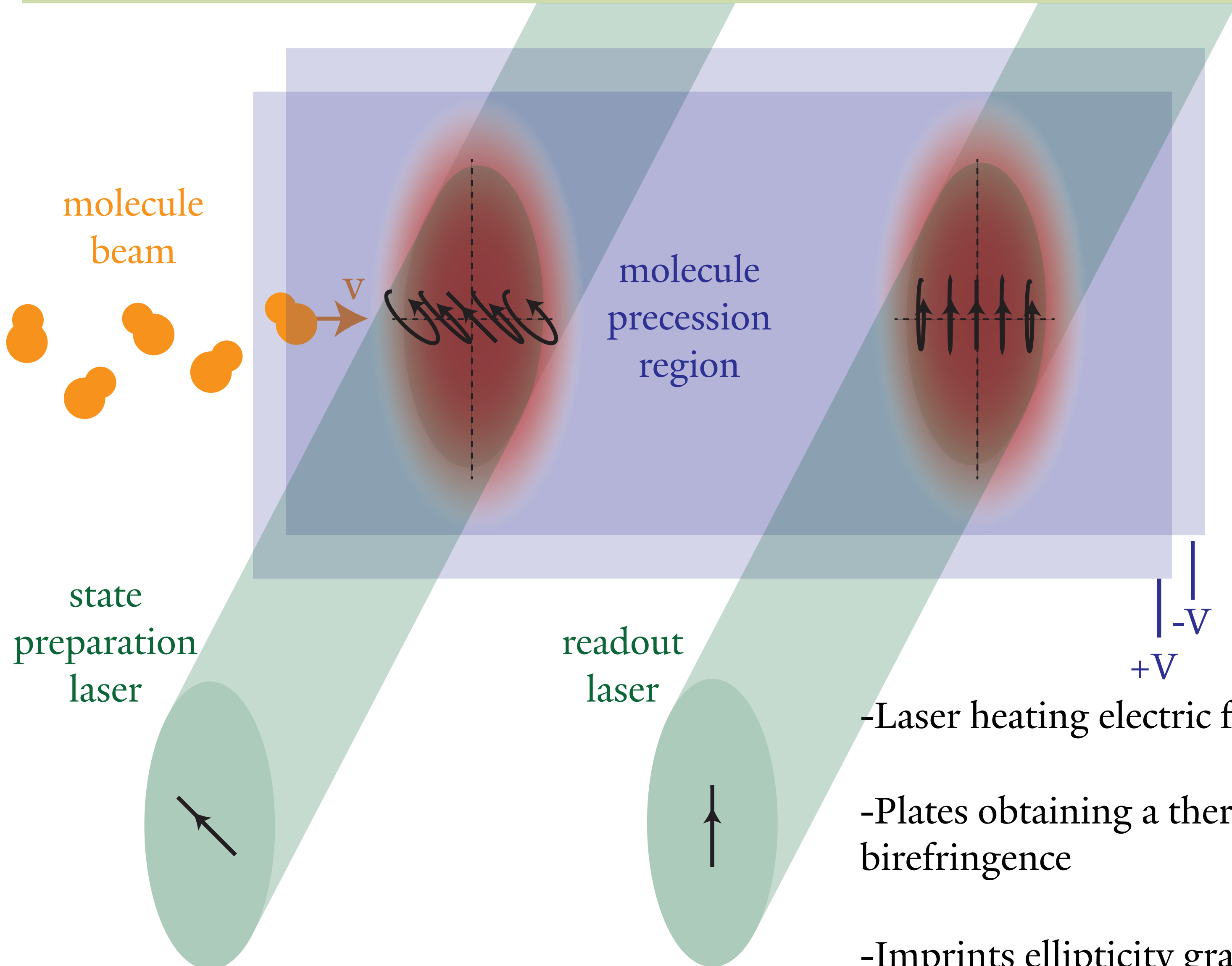
comes from ellipticity gradient
(we have one of these)

$$d_e^{\mathrm{syst}}\left(\Delta^{\mathcal{N}\mathcal{E}}\right) = \frac{1}{\mathcal{E}_{\mathrm{eff}}\tau}\frac{\partial\phi}{\partial\Delta}\Delta^{\mathcal{N}\mathcal{E}}$$

$$d_e^{\mathrm{syst}}\left(\Omega_r^{\mathcal{N}\mathcal{E}}\right) = \frac{1}{\mathcal{E}_{\mathrm{eff}}\tau}\frac{\partial\phi}{\partial\Omega_r}\Omega_r^{\mathcal{N}\mathcal{E}}$$

comes from a linear polarization
gradient (<1^0/cm)

Light Shift Systematic Errors



-Laser heating electric field plates

-Plates obtaining a thermal-stress birefringence

-Imprints <u>ellipticity gradient</u> across laser

Light Shift Systematic Errors

Then…

We could have the following systematic errors:

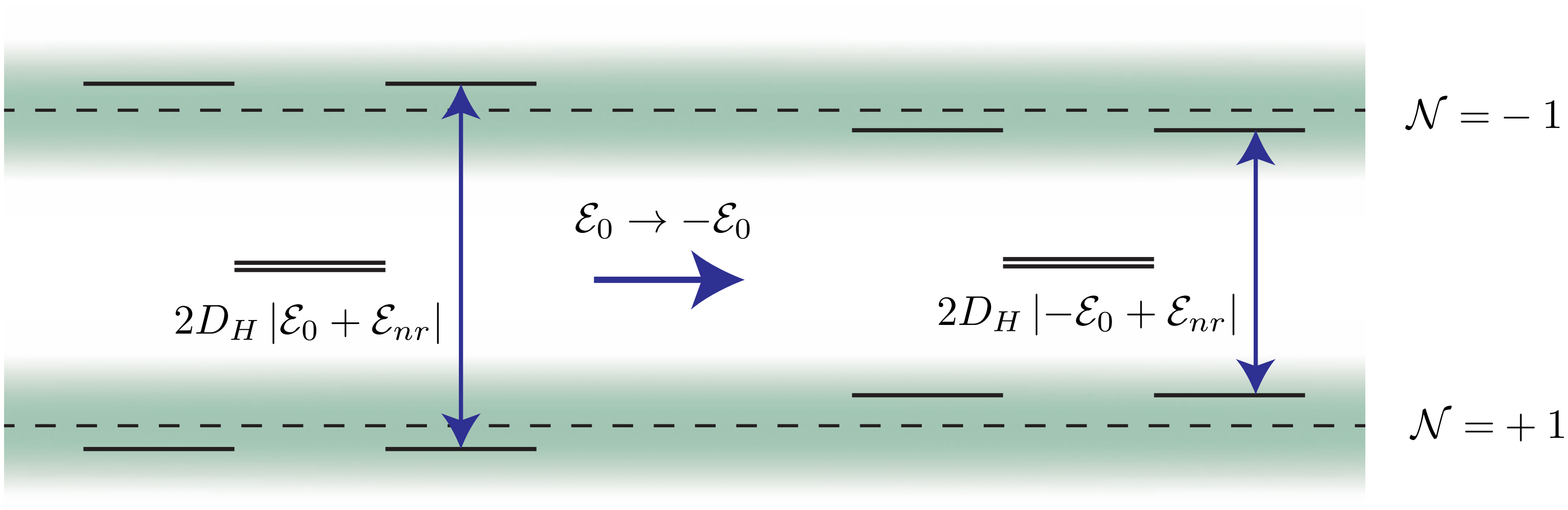
$$d_e^{\mathrm{syst}}\left(\Delta^{\mathcal{N}\mathcal{E}}\right) = \frac{1}{\mathcal{E}_{\mathrm{eff}}\tau}\frac{\partial\phi}{\partial\Delta}\Delta^{\mathcal{N}\mathcal{E}}$$

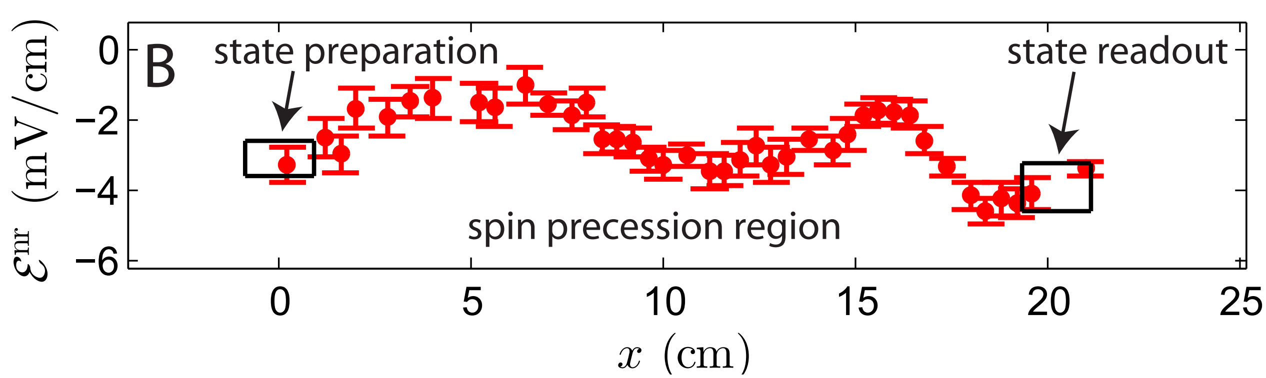
comes from a non-reversing component of the applied electric field
(we have one of these)

$$d_e^{\mathrm{syst}}\left(\Omega_r^{\mathcal{N}\mathcal{E}}\right) = \frac{1}{\mathcal{E}_{\mathrm{eff}}\tau}\frac{\partial\phi}{\partial\Omega_r}\Omega_r^{\mathcal{N}\mathcal{E}}$$

Non-Reversing Electric Fields

A Non-Reversing Electric Field Component Leads to a Detuning Correlation, $\Delta^{\mathcal{N}\mathcal{E}} = D_H \mathcal{E}^{\mathrm{nr}}$





We have measured and studied this detuning correlation over time and space (using 3 methods)

Light Shift Systematic Errors

Then…

We could have the following systematic errors:

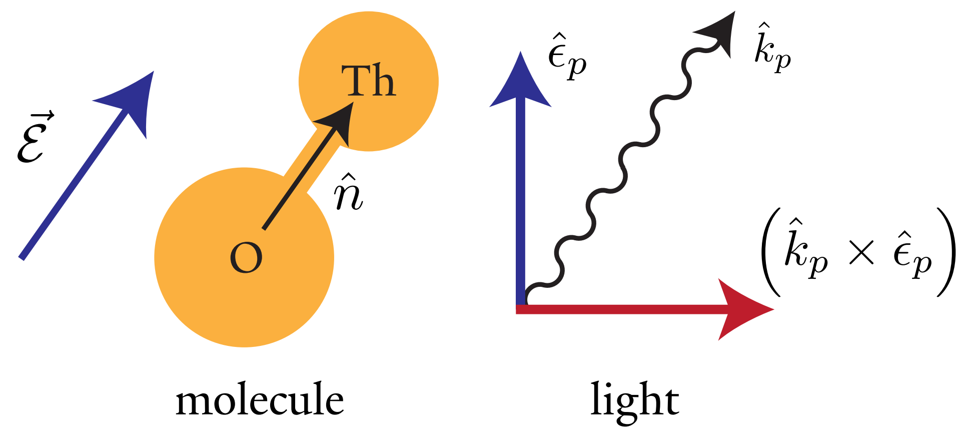
$$d_e^{\text{syst}}\left(\Delta^{\mathcal{N}\mathcal{E}}\right) = \frac{1}{\mathcal{E}_{\text{eff}}\tau}\frac{\partial\phi}{\partial\Delta}\Delta^{\mathcal{N}\mathcal{E}}$$

$$d_e^{\text{syst}}\left(\Omega_r^{\mathcal{N}\mathcal{E}}\right) = \frac{1}{\mathcal{E}_{\text{eff}}\tau}\frac{\partial\phi}{\partial\Omega_r}\Omega_r^{\mathcal{N}\mathcal{E}}$$

Comes from interference between the E1 and M1 amplitudes on the H to C transition

E1/M1 Interference

Operators $O_{E1} = -\,im\omega\left(\hat{\epsilon}_p \cdot \vec{r}\right)$ $O_{\mathrm{M1}} = -i\frac{\omega}{2c}\left(\hat{k}_{\mathrm{p}} \times \hat{\epsilon}_{\mathrm{p}}\right) \cdot \left(g_L \vec{L} + g_S \vec{S}\right)$



- For this geometry, the E1 and M1 operators connect the to the same superposition state. Relative sign is correlated like an EDM.

Rabi Frequency Correlation $\frac{\Omega^{\mathcal{N}\mathcal{E}}}{\Omega^{(0)}} = \mathrm{Im}\left(\frac{c_{\mathrm{M1}}}{c_{\mathrm{E1}}}\right)\left(\hat{k} \cdot \hat{z}\right) = -\,(8.0 \pm 0.8) \times 10^{-3}\left(\hat{k} \cdot \hat{z}\right)$

ratio of molecule frame matrix elements

measured from from its coupling to the B-field in another channel, $\omega^{\mathcal{N}\mathcal{E}\mathcal{B}}$

Constructing the Systematic Error

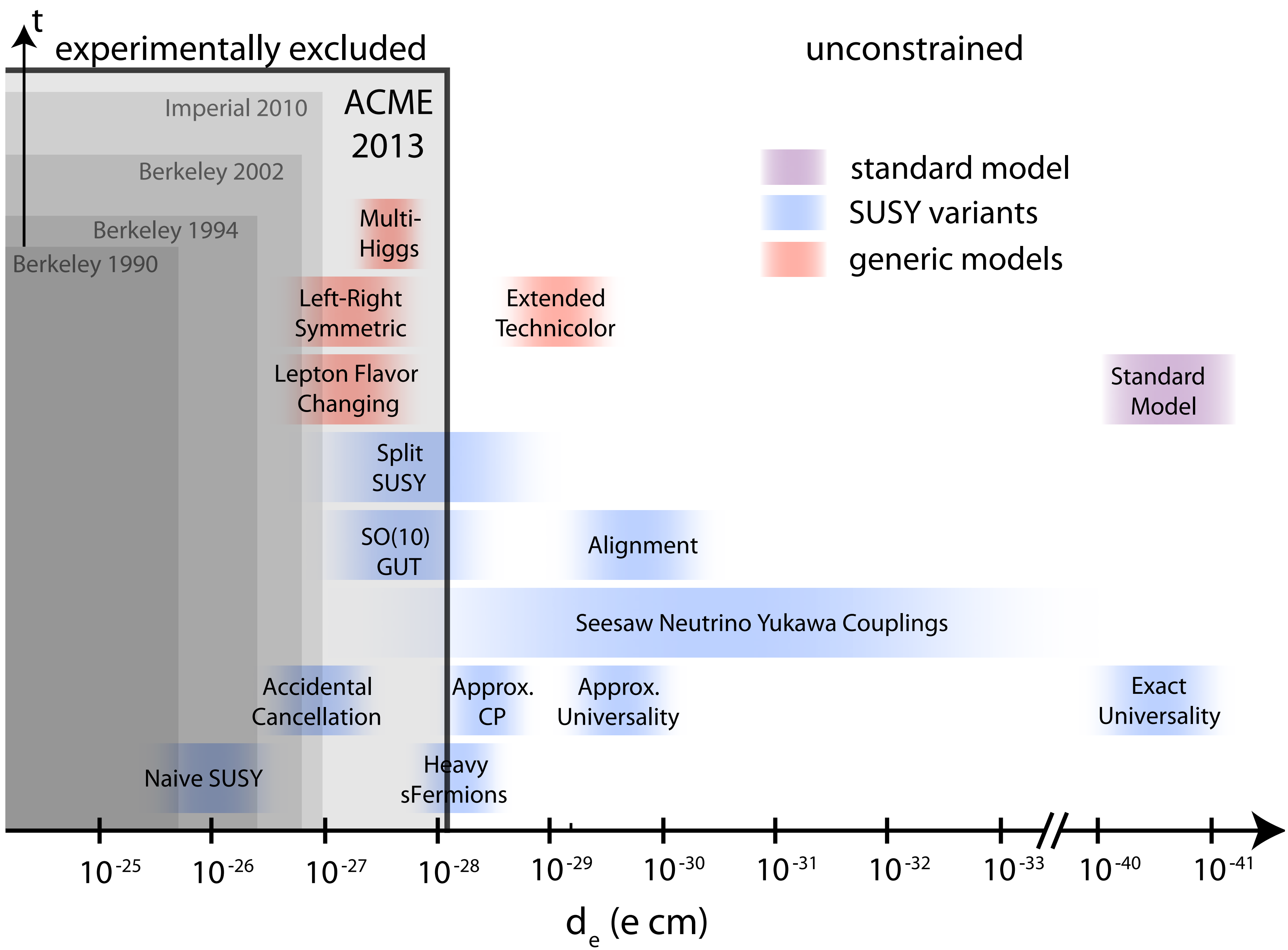
Parameter	Shift	Uncertainty
$\mathcal{E}^{\rm nr}$ correction	-0.81	0.66
$\Omega_{\rm r}^{\mathcal{N}\mathcal{E}}$ correction	-0.03	1.58
$\phi^{\mathcal{E}}$ correlated effects	-0.01	0.01
$\phi^{\mathcal{N}}$ correlation		1.25
Non-Reversing $\mathcal{B}$-field ($\mathcal{B}_z^{\rm nr}$)		0.86
Transverse $\mathcal{B}$-fields $\left(\mathcal{B}_x^{\rm nr}, \mathcal{B}_y^{\rm nr}\right)$		0.85
$\mathcal{B}$-Field Gradients		1.24
Prep./Read Laser Detunings		1.31
$\tilde{\mathcal{N}}$ Correlated Detuning		0.90
$\mathcal{E}$-field Ground Offset		0.16
Total Systematic	-0.85	3.24
Statistical		4.80
Total Uncertainty		5.79

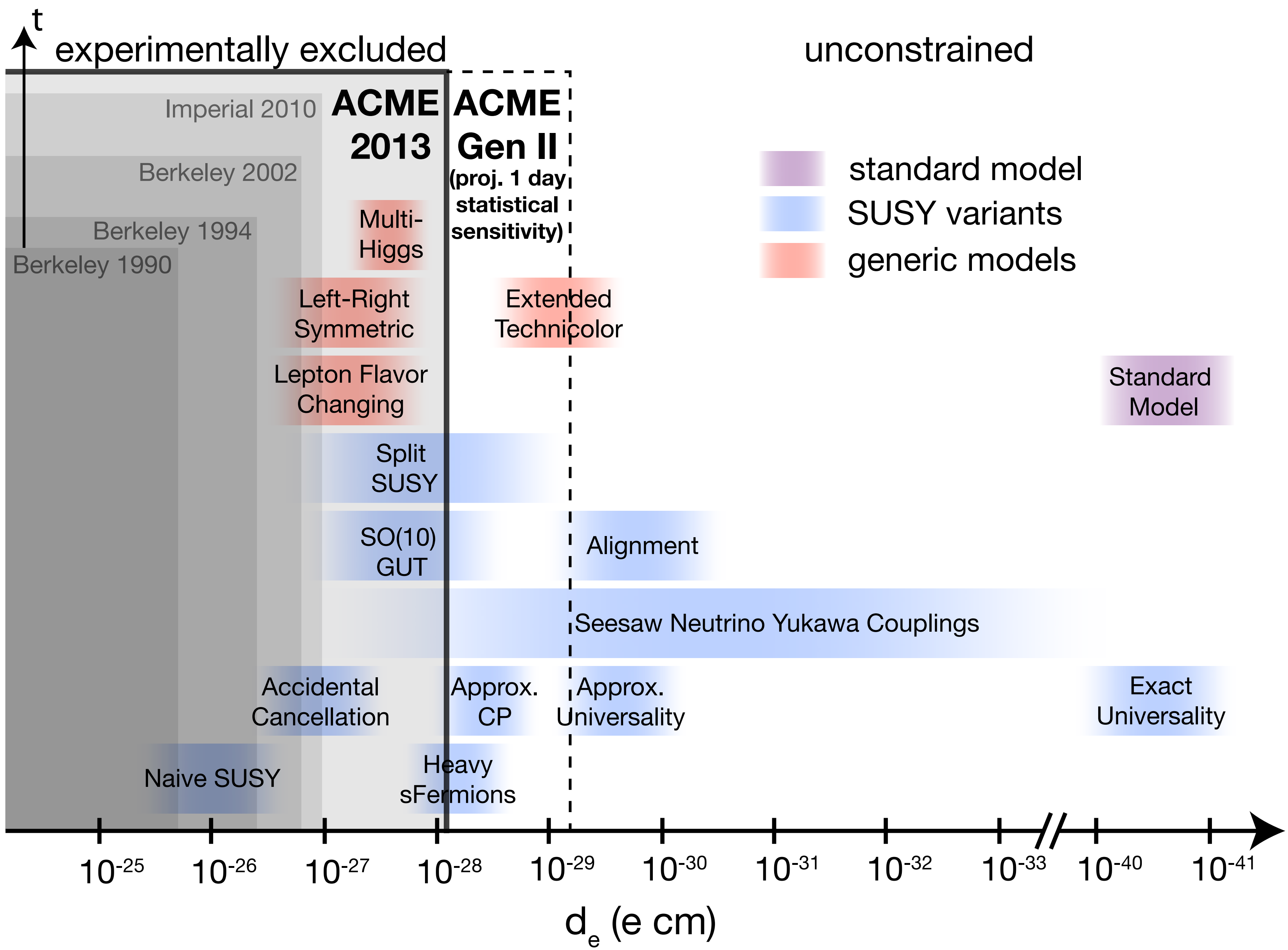
Nonzero Systematics Errors
Systematics errors that we have observed and carefully quantified

Unexplained Phenomena
Upper limits on possible systematic errors that are correlated with unexplained phenomena in the data

Historic Systematics:
Upper limits on possible systematic errors proportional to parameters that caused systematics in experiments similar to ours in the past

Result: $d_e < 1 \times 10^{-28} e \cdot \mathrm{cm}$ @ 90% confidence


t
experimentally excluded
unconstrained
Imperial 2010
ACME 2013
Berkeley 2002
Berkeley 1994
Berkeley 1990
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}
d_e (e cm)



t
experimentally excluded
unconstrained
Imperial 2010
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standard model
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10^{-25}
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10^{-28}
10^{-29}
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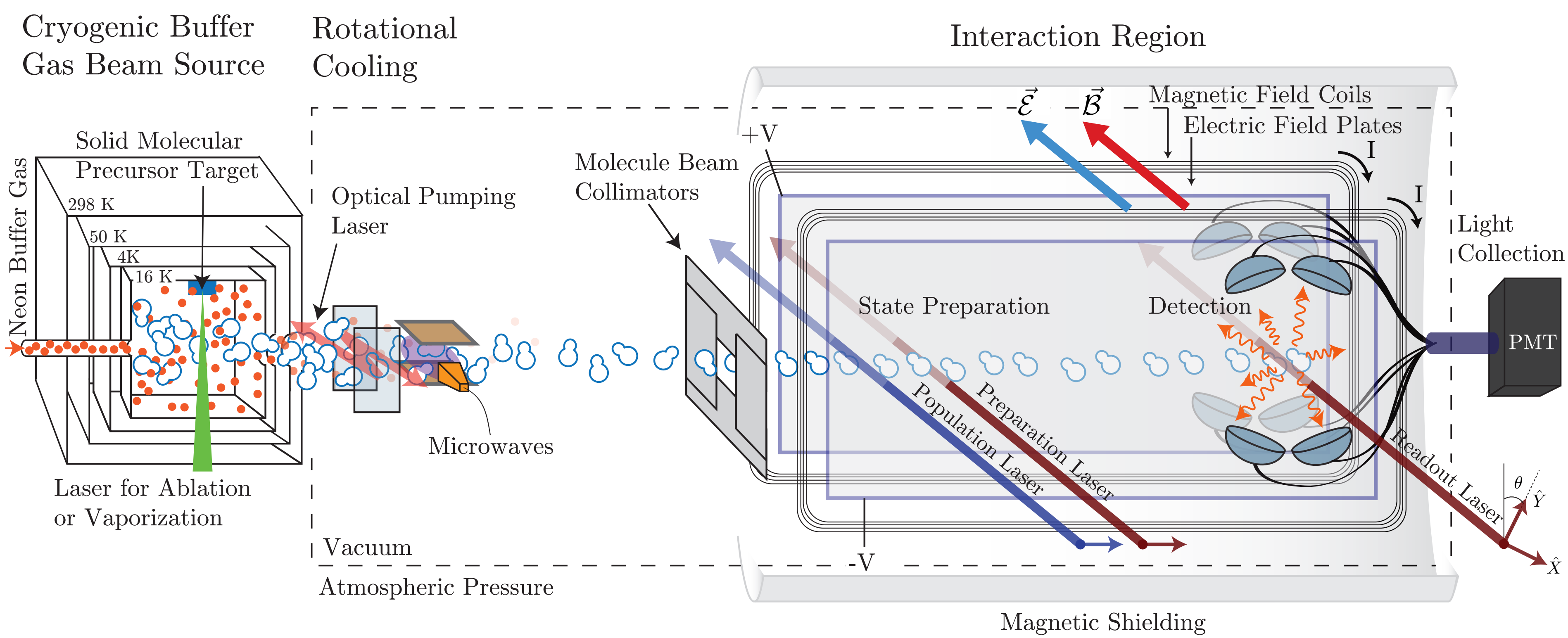
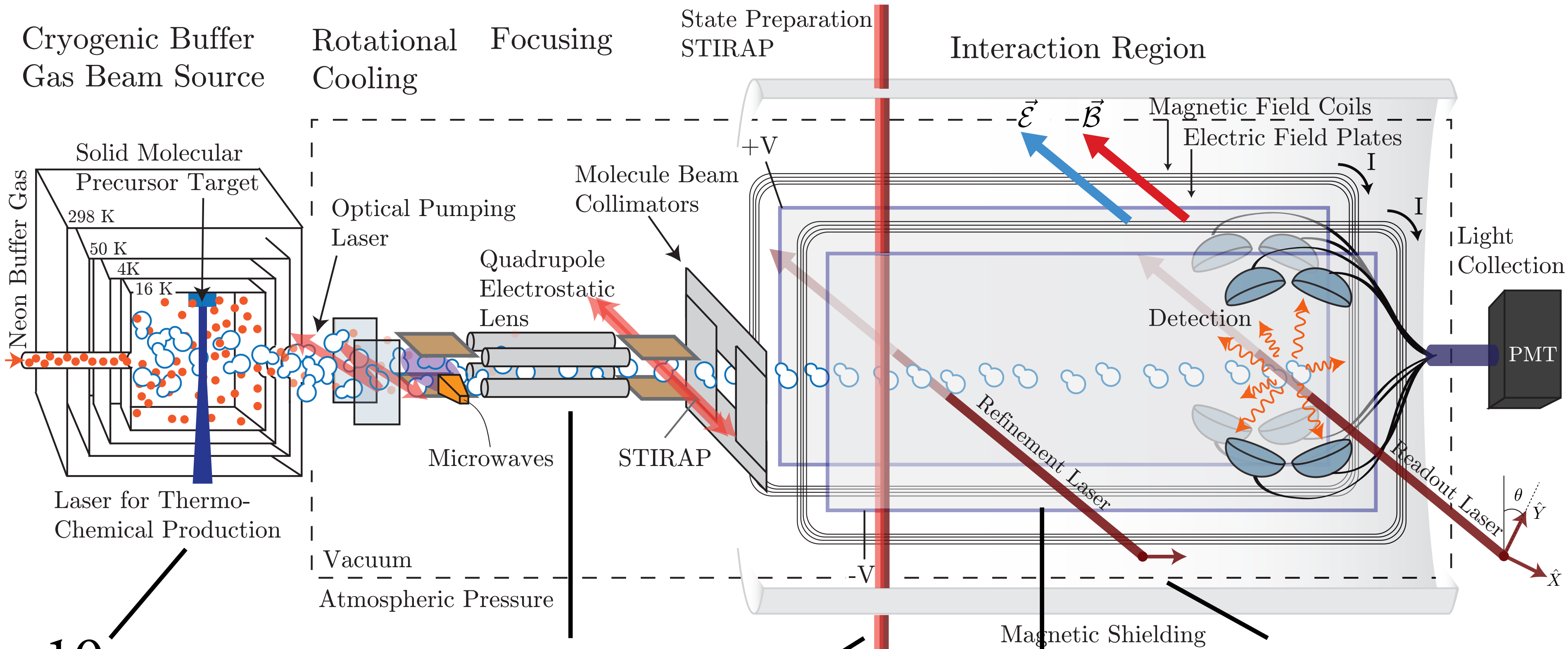
10^{-32}
10^{-33}
10^{-40}
10^{-41}
d_e (e cm)

The ACME Experiment



ACME: THE NEXT GENERATION



x10 will require characterization, optimization

x10

x10 +new systematic error

suppress new systematic error $\times 10^{-3}$-10^{-4}

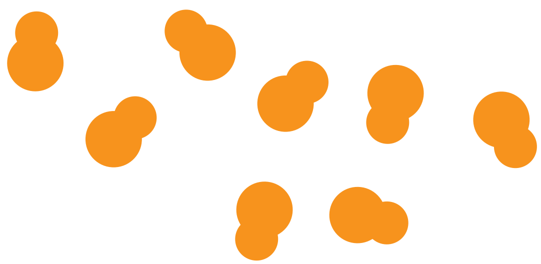
new field plates- suppress old systematic error by $\times 10^{-2}$

Anticipate an order of magnitude improvement in sensitivity

ACME: THE NEXT GENERATION

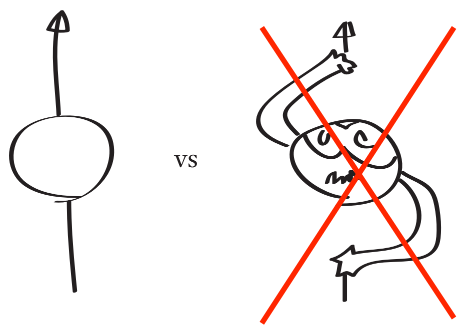
MORE MOLECULES -

-Thermochemical Beam Source
-Electrostatic Lens
-Efficient State Preparation



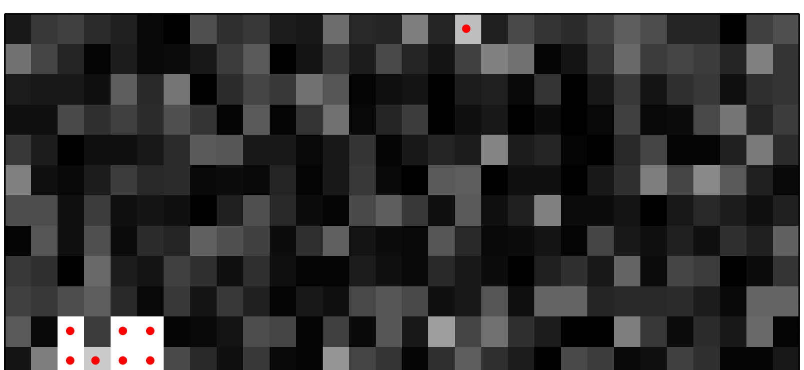
SMALLER SYSTEMATICS –

-Smaller Polarization Gradients
(Electric Field Plates with Better Thermal Properties)
-Reduction in Light Shift Phases
(Retroreflection of lasers, spectral broadening)



MORE DATA -

-Better Polarimetry
-Better Magnetometry
-EDM dependence on Rotational State
-Longer Integration Time?



ACME Collaboration

Red= Harvard
Blue= Yale
* = Now Elsewhere

J. Baron, W. C. Campbell*, D. DeMille, J. M. Doyle, G. Gabrielse, Y. V. Gurevich*, P. W. Hess, N. R. Hutzler, E. Kirilov*, I. Kozyryev*, B. R. O'Leary, C. D. Panda, M. F. Parsons*, E. S. Petrik, B. Spaun, A. C. Vutha*, A. D. West

Extra Slides!

(Our Method for) Constructing the Systematic Error Budget

To what extent do we trust our result? A systematic error budget can help quantify the answer.

- What is a systematic error?

a quantification of the offset in the measurement channel caused by spurious effects…

1. that exist, that we understand and that we can quantify well.

2. that may or may not exist but we are paranoid that such a thing might exist because of:

    a. some unexplained behavior in the data

    b. past experience

Un-included errors can still be present.
Including more effects in the error budget increase our personal estimate of the probability that we missed a systematic error above our level of sensitivity.


17 January 2014 | $10
Science
HOW ROUND IS THE ELECTRON?
AAAS

Order of Magnitude Smaller Limit on the Electric Dipole Moment of the Electron

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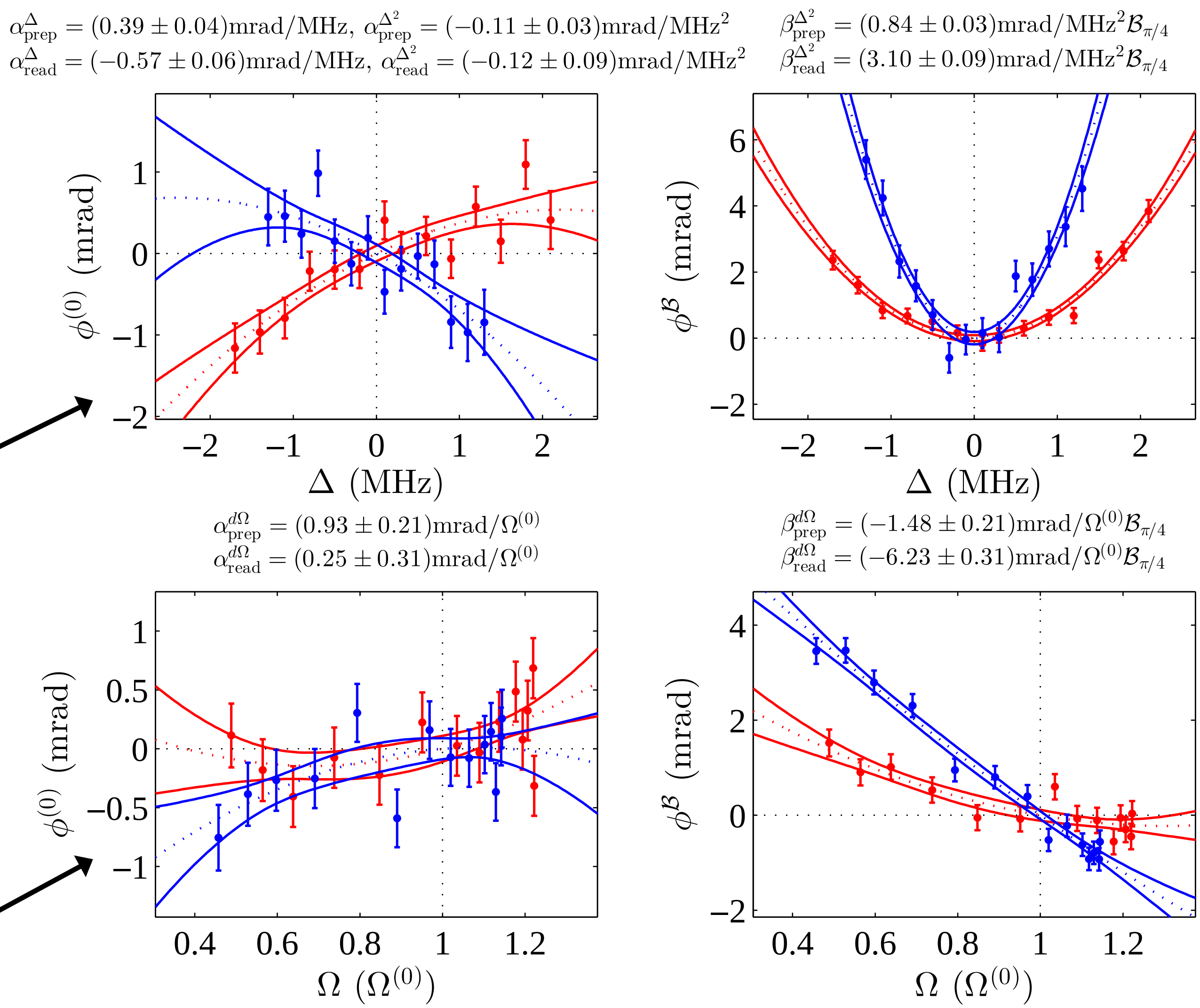
The Standard Model of particle physics is known to be incomplete. Extensions to the Standard Model, such as weak-scale supersymmetry, posit the existence of new particles and interactions that are asymmetric under time reversal (T) and nearly always predict a small yet potentially measurable electron electric dipole moment (EDM), d_e, in the range of 10^{-27} to 10^{-30} $e \cdot$cm. The EDM is an asymmetric charge distribution along the electron spin ($\vec{S}$) that is also asymmetric under T. Using the polar molecule thorium monoxide, we measured $d_e = (-2.1 \pm 3.7_{stat} \pm 2.5_{syst}) \times 10^{-29}$ $e \cdot$cm. This corresponds to an upper limit of $|d_e| < 8.7 \times 10^{-29}$ $e \cdot$cm with 90% confidence, an order of magnitude improvement in sensitivity relative to the previous best limit. Our result constrains T-violating physics at the TeV energy scale.

AC Stark Shift Systematic Errors

Non-adiabatic polarization changes in the laser can lead to a small bright state component in the prepared state. This bright state component acquires an AC stark shift phase that depends on laser detuning and laser power.

couples residual electric field to to contribute as a systematic error.

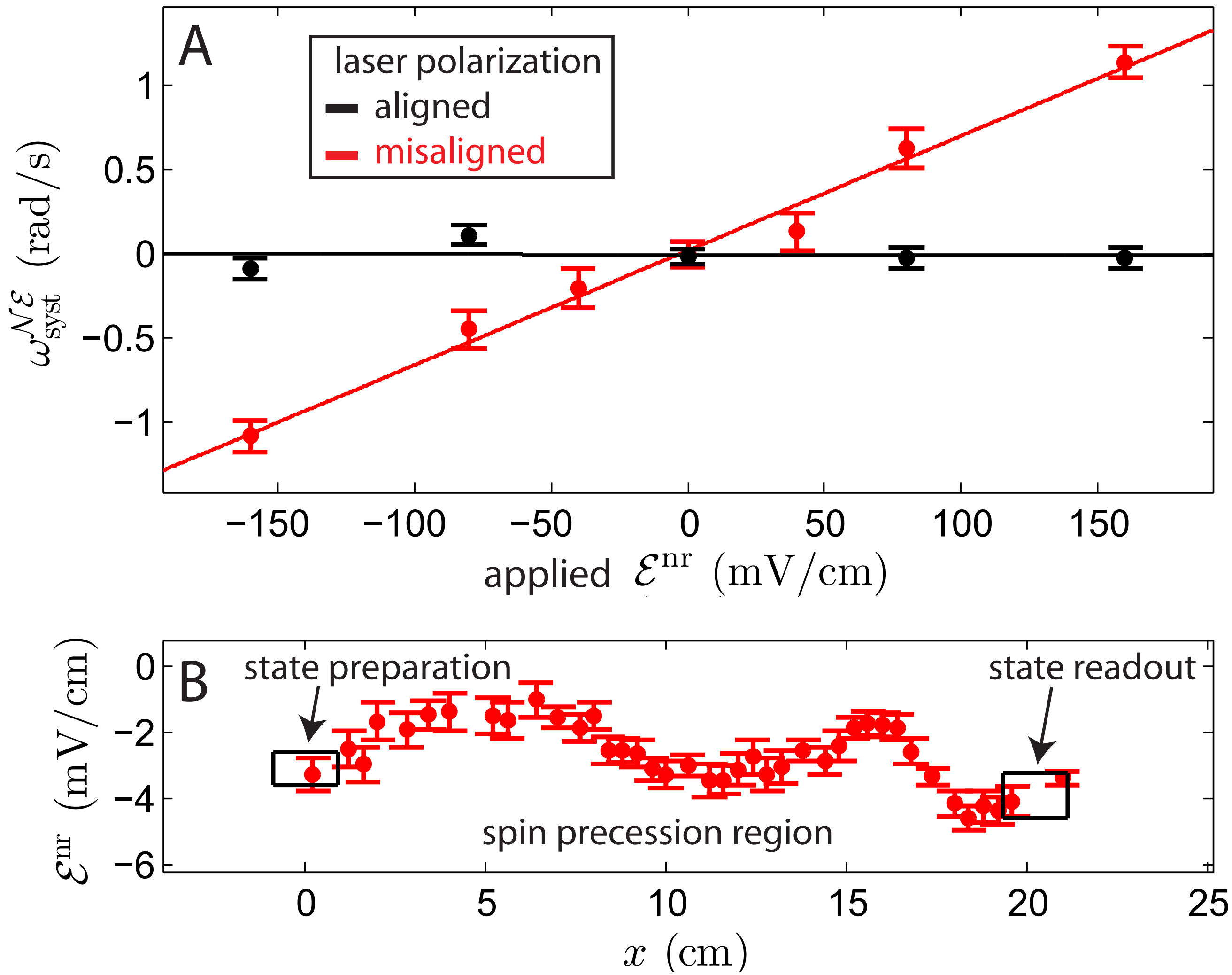
couples to E1/ M1 interference to contribute as a systematic error.



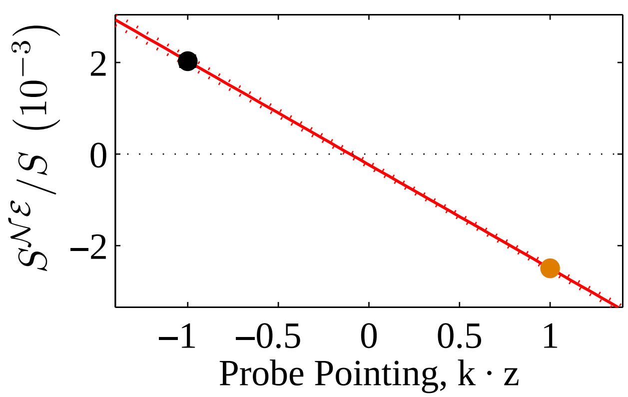
AC Stark Shift Systematic Errors

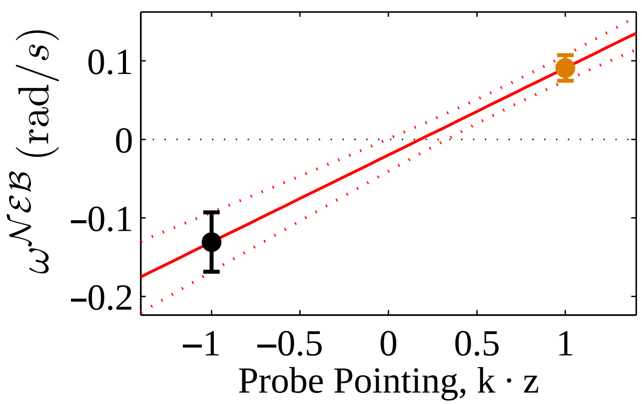
We were able to verify the model and were able to suppress the systematic error by tuning the laser polarization

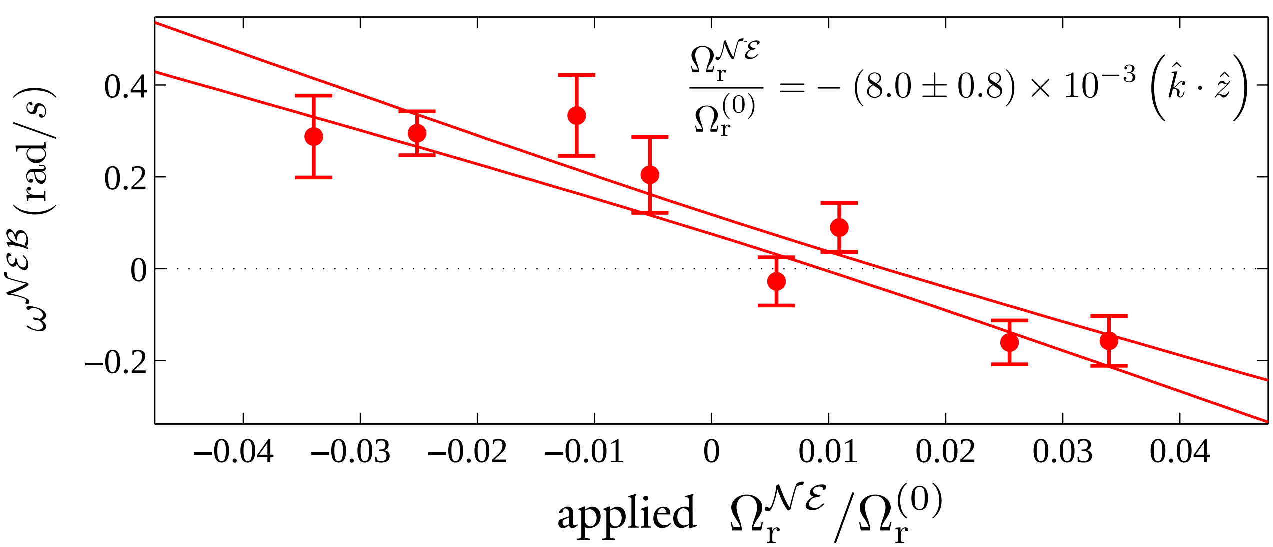
We were also able to very precisely measure the residual electric field and its spatial variation



$\Omega_r^{\mathcal{N}\mathcal{E}}$: Measurement



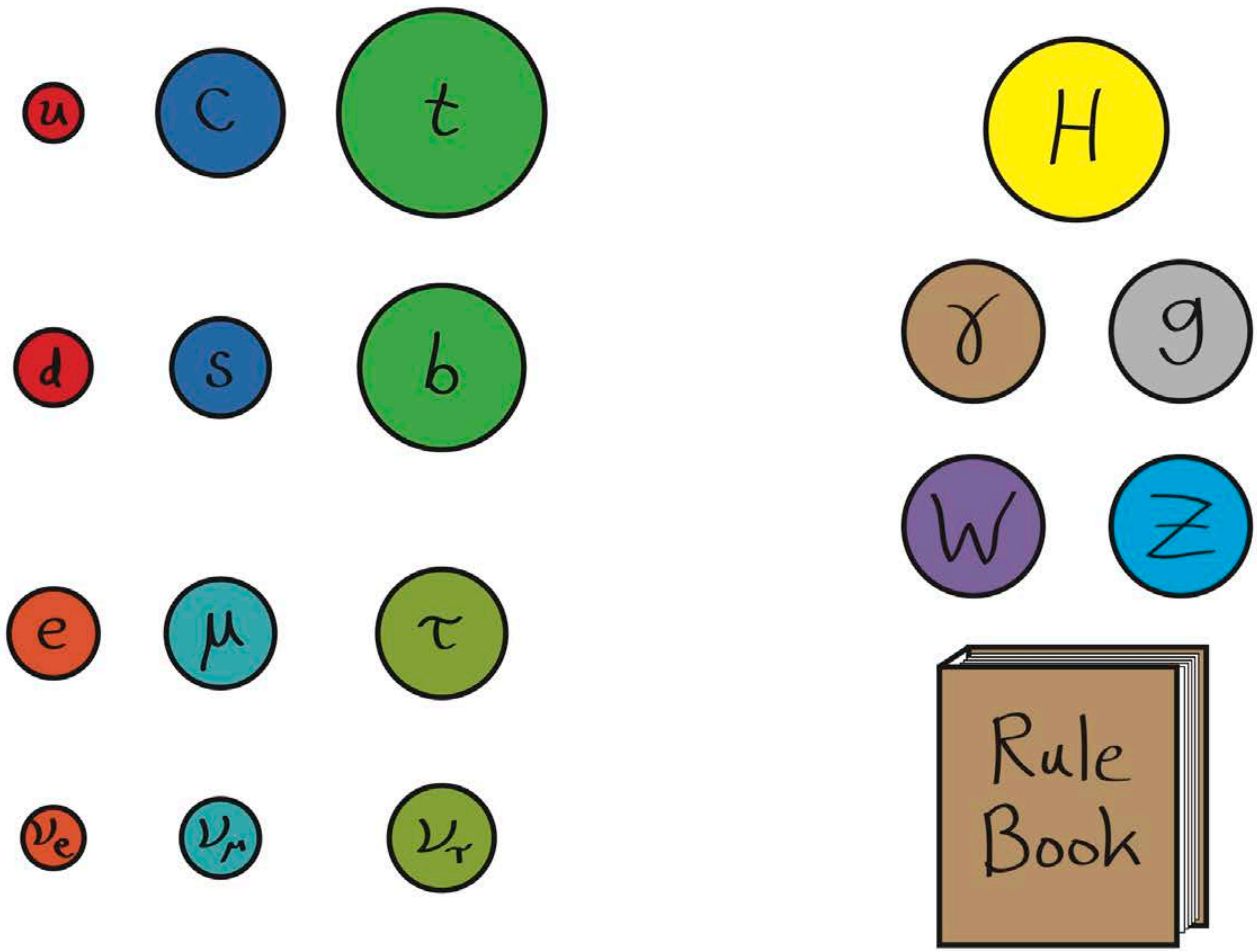




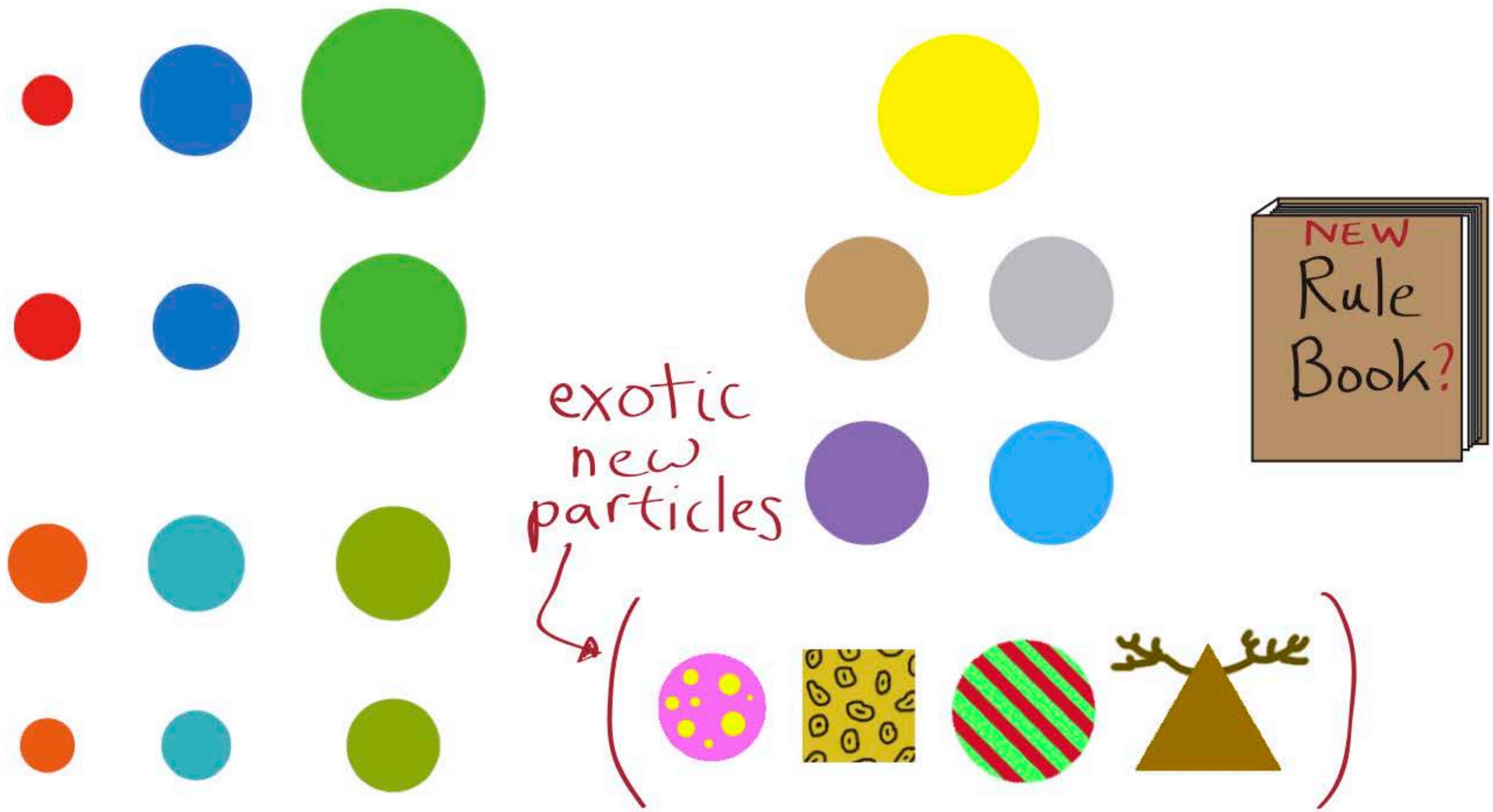
Verified that the expected measurement channels changed sign with laser pointing

Extract $\Omega_r^{\mathcal{N}\mathcal{E}}$ from data with an intentionally applied $\Omega_r^{\mathcal{N}\mathcal{E}}$

Standard Model



Possible Solution



Report Card

Model Name: *Standard Model* Term: *Spring 2014*

Subject	Grade	Comments
Explaining Physical Phenomena	B	Generally does an excellent job. Has difficulty with dark matter/energy problems. Needs improvement in explaining Matter/Antimatter asymmetry.
Performing Well in Experimental Tests	A	Has answered every question correctly. Outstanding job on the prediction of the electron g-2.
Getting Along with Peers	C	Does not get along well with gravity. Is generally disliked by peers.

Report Card

Model Name: SUSY Term: Spring 2014

Subject	Grade	Comments
Explaining Physical Phenomena	A	Has a witty answer for everything. Invented New Particles to account for Dark Energy and Dark Matter. New particles have CP violating phases that help explain Matter/Antimatter asymmetry
Performing Well in Experimental Tests	C	Needs improvement. Answers are not explicitly wrong, but are not explicitly right either.
Getting Along with Peers	B	One of the most popular models in class. Maybe falling from popularity due to poor behavior in experimental tests.