The ACME search for the electron EDM

ACME

- Basic approach
- Measurement scheme
- Statistics
- Systematics
- Result: order of magnitude improvement in sensitivity
- 2nd generation: towards another order of magnitude

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Funding: NSF

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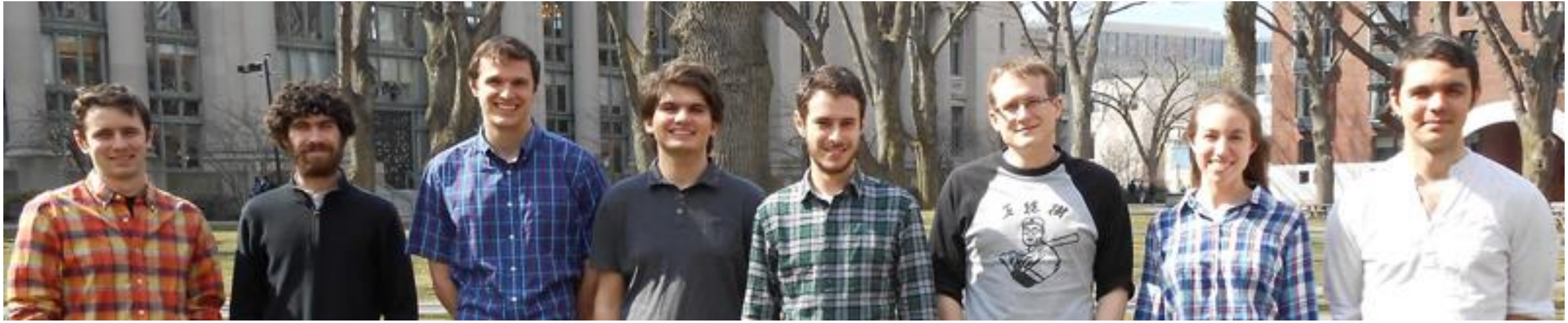
Science

HOW ROUND IS THE ELECTRON?

AAAS

The ACME team



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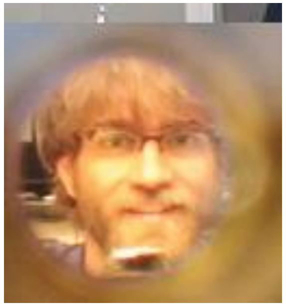

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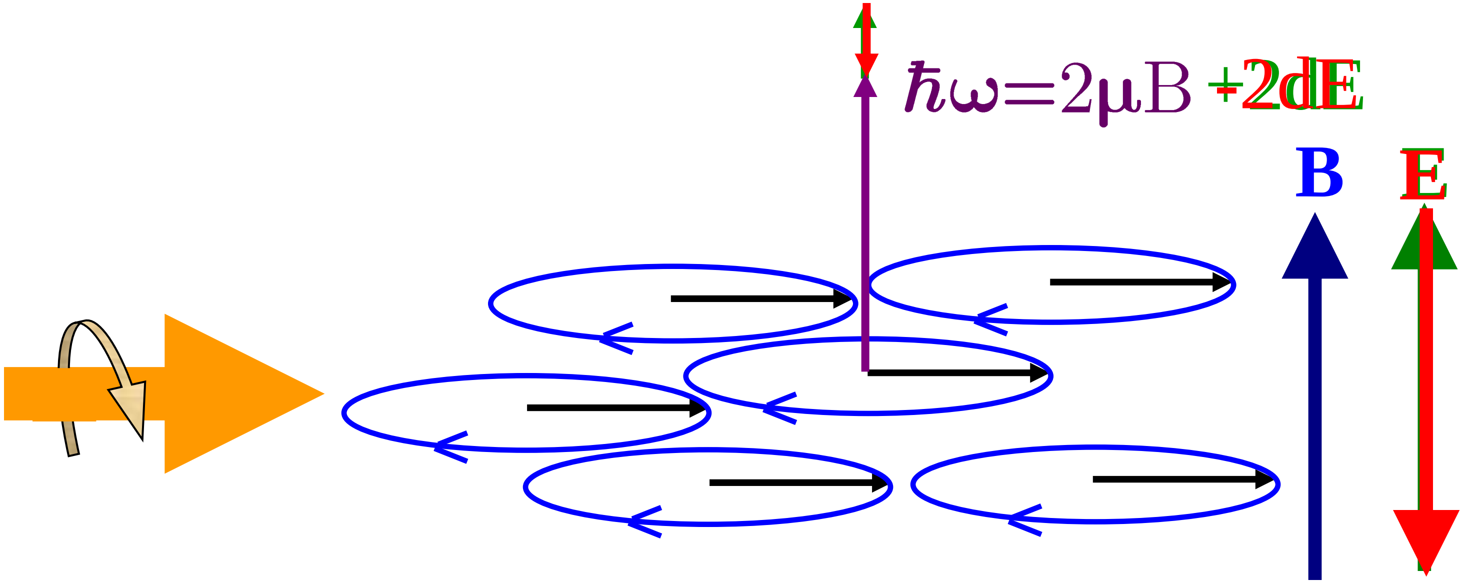
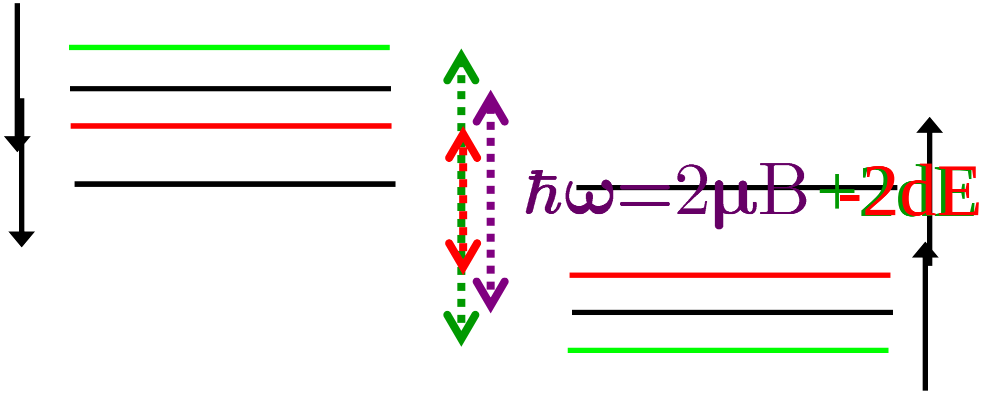
General method to detect an EDM



Energy level picture:



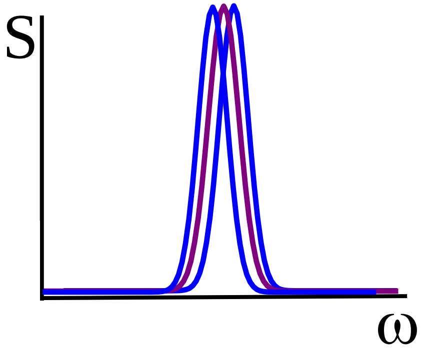
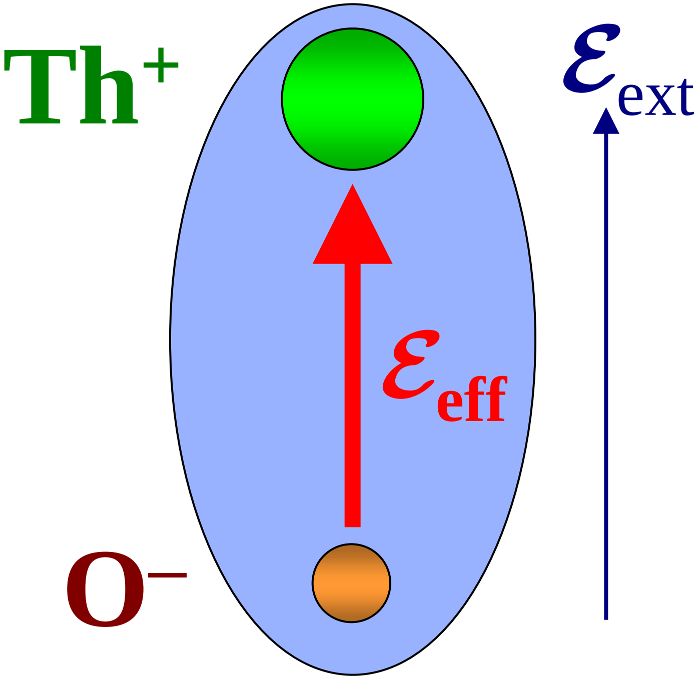


Figure of merit:

$$\frac{\textit{shift}}{\textit{resolution}} = \frac{d\mathrm{E}}{(\tau)^{-1}(S/N)^{-1}} \propto \mathrm{E}\cdot\tau\cdot\mathrm{C}\cdot\sqrt{\dot{N}\cdot T_{\mathrm{int}}}$$

Amplifying the electric field $\mathcal{E}$ with a polar molecule



Small energy splittings
in molecules
enable polarization $\mathcal{P}$ ~ 100%

($\mathcal{E}_{\text{ext}} \gtrsim$ 1 V/cm enough for ThO)

Inside molecule, eEDM acted on by
$\mathcal{E}_{\text{eff}} \sim \mathcal{P}\, \alpha^2 Z^3 e/a_0^2$ due to relativistic motion

P. Sandars
1965

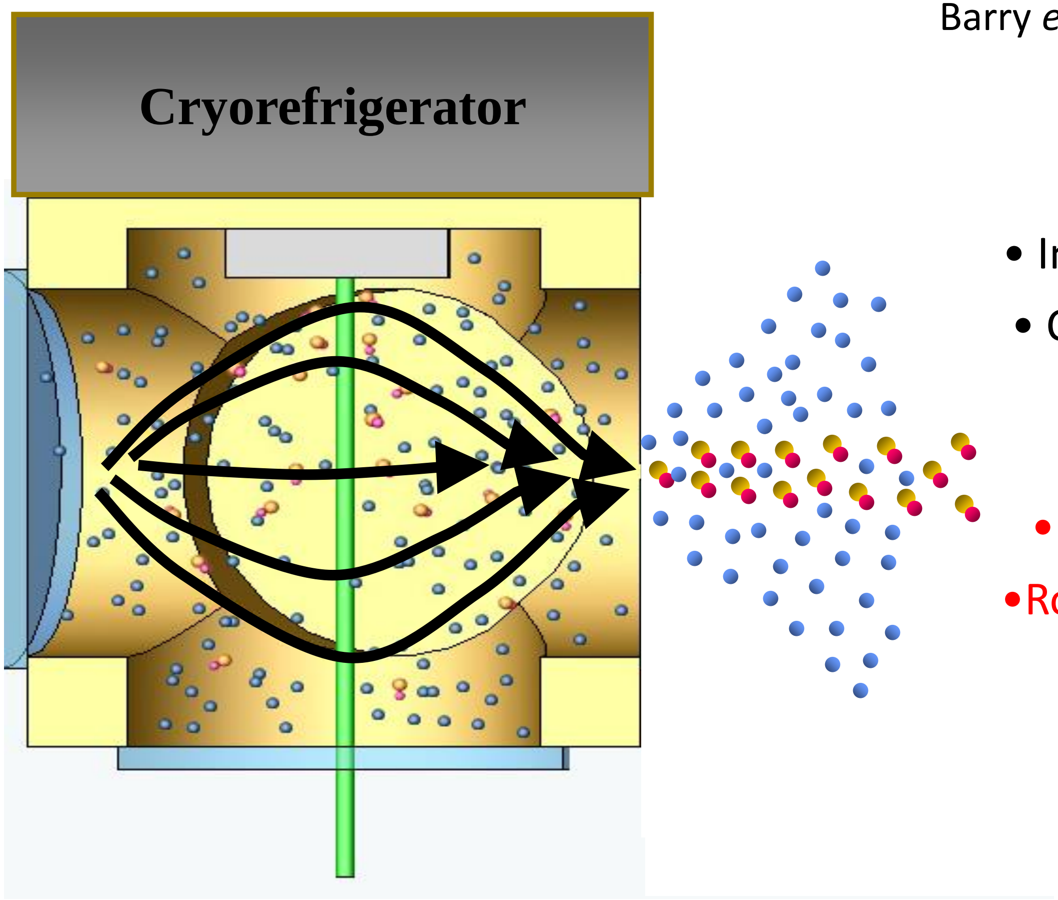
$\mathcal{E}_{\text{eff}} \cong$ 80 GV/cm for ThO*

Meyer & Bohn (2008);	Skripnikov, Petrov & Titov (2013);	Fleig & Nayak (2014)
104(26)	$\boxed{84(13)}$	75(2)

Requires unpaired electron spin(s)

New molecular beam technology: hydrodynamically enhanced cryogenic beams

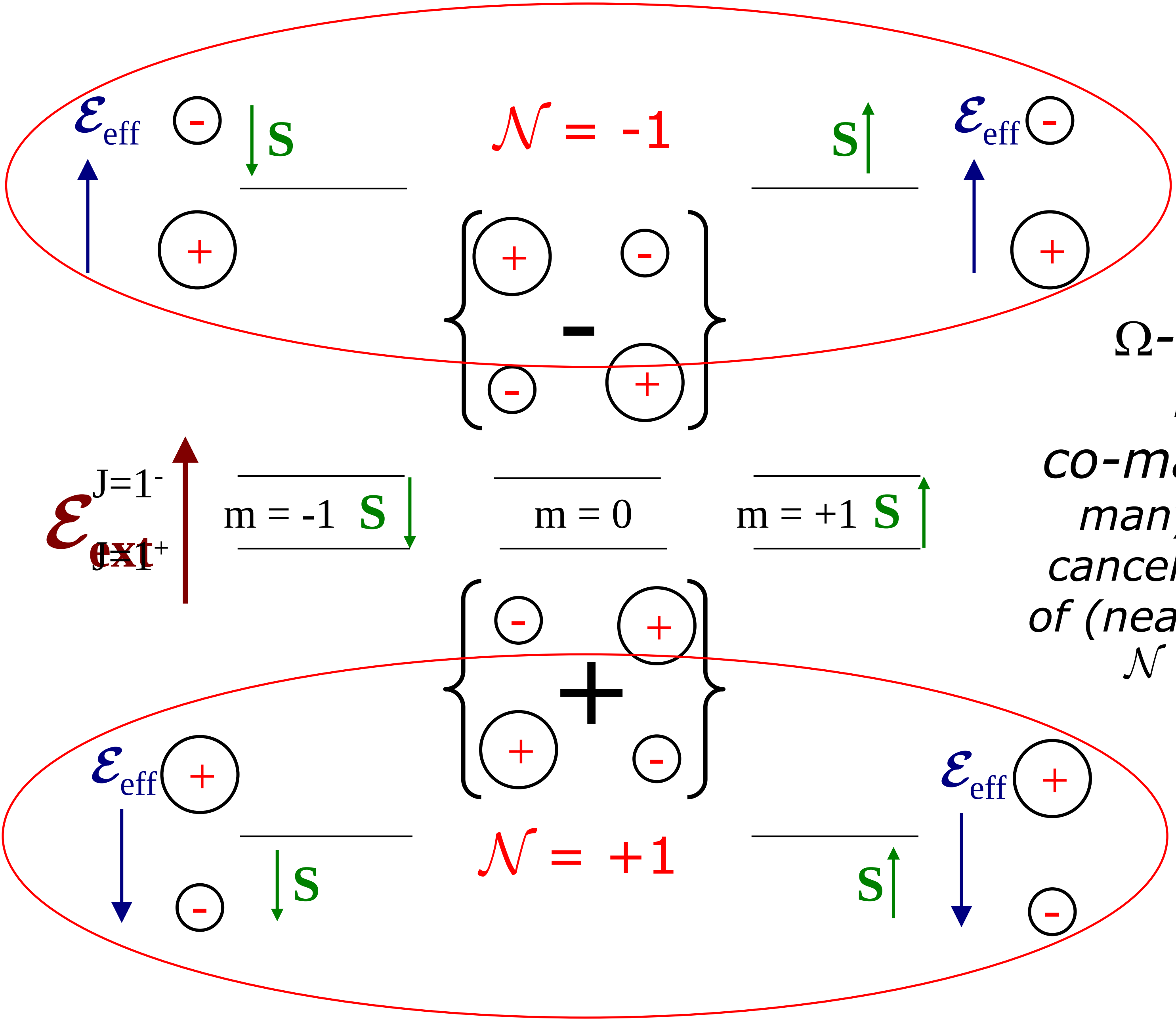
[Maxwell *et al.* PRL 2005; Patterson & Doyle JCP 2007;
Barry *et al.* PCCP 2011; Hutzler *et al.* PCCP 2011]



- Inject hot molecules (e.g. via laser ablation)
- Cool w/cryogenic buffer gas *@high density*
- **Efficient** extraction to beam via "wind" in cell: $10^{-3} \rightarrow >10\%$
- "Self-collimated" by extraction dynamics
- Rotationally cooled by supersonic expansion
- Cold (~4 K) & **moderately slow (*v* ~ 200 m/s)**

Beam brightness [=flux/divergence]
~ ***10^3 × larger*** than other sources
for refractory/free radical species

EDM measurement with Ω-doublet states



Ω-doublet = internal co-magnetometer

many systematics cancel in comparison of (near-) mirror image $\mathcal{N} = \pm1$ states

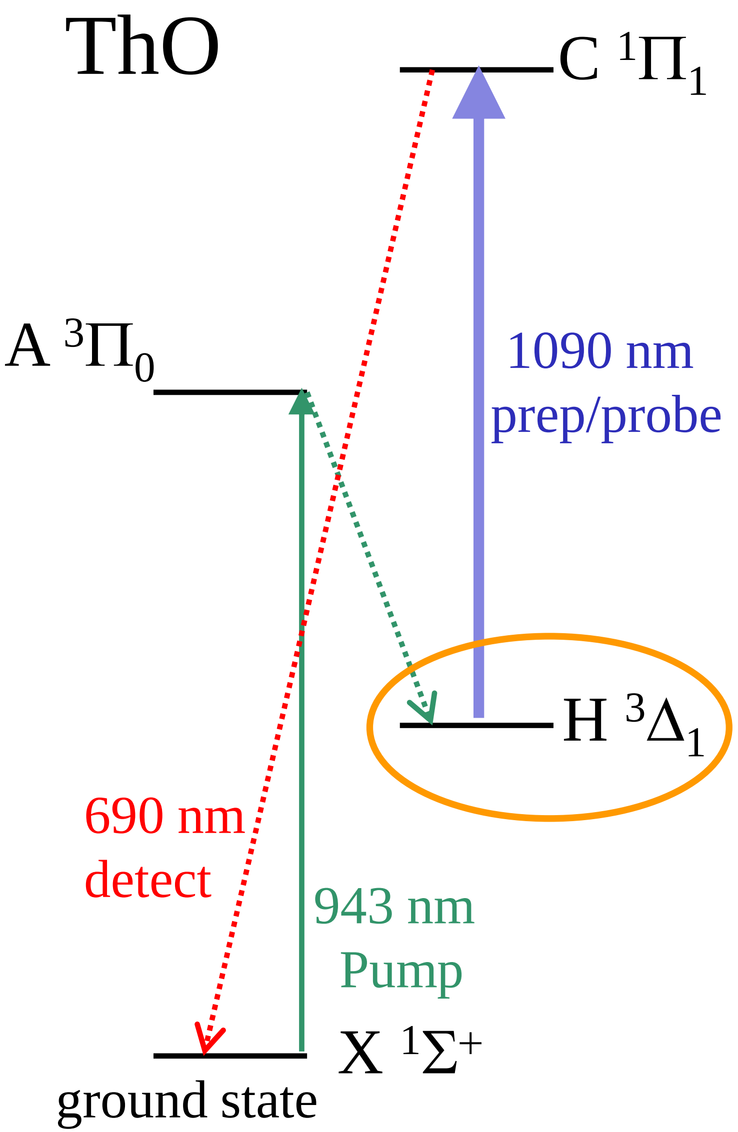
Spin triplet state

S=1

[DD *et al.*,
AIP Conf. Proc.
596, 2001]

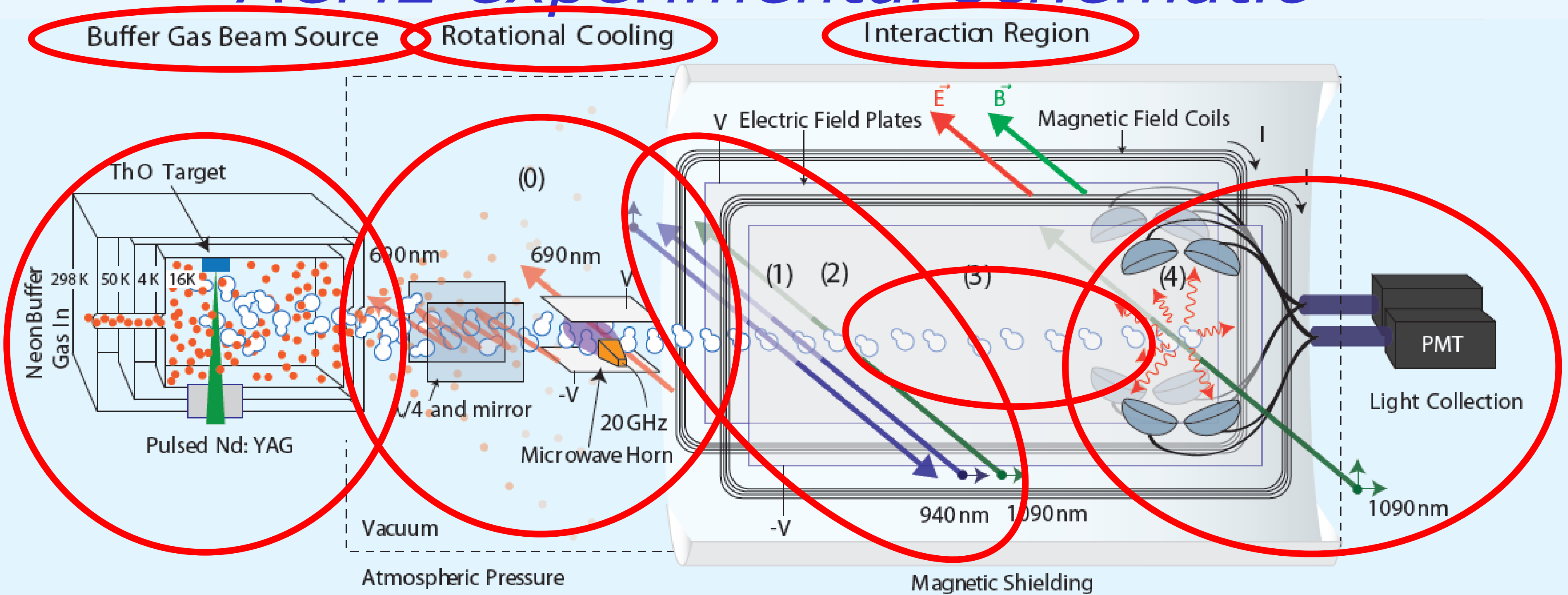
"New" molecular species: ThO*

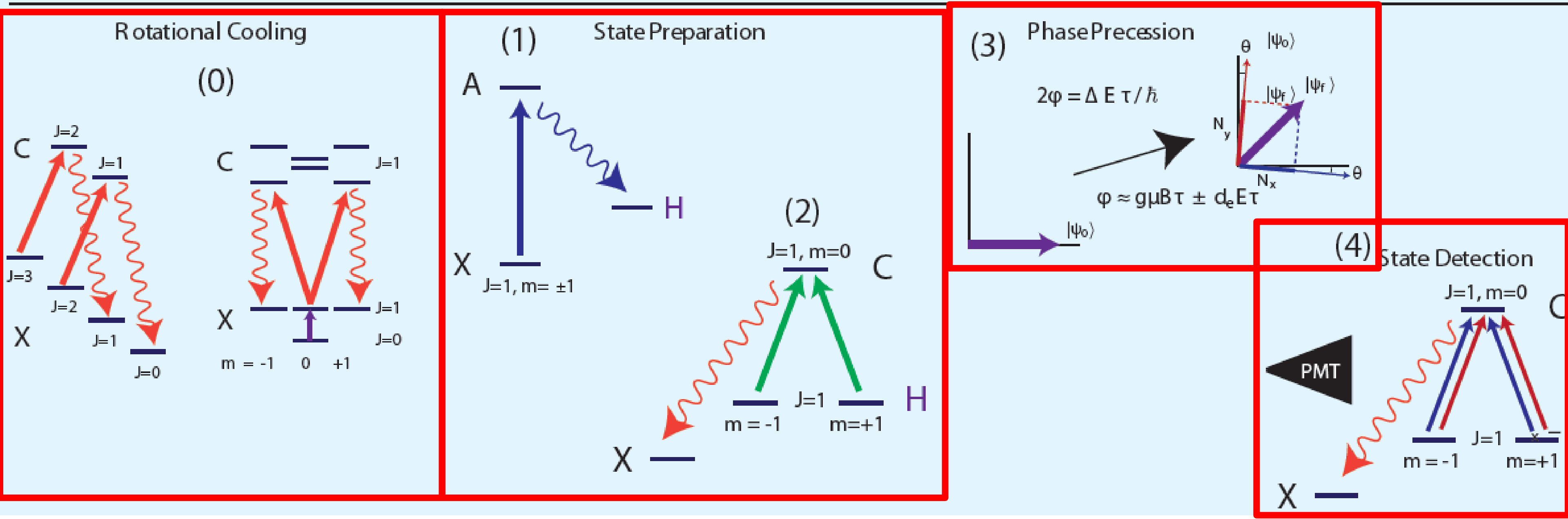
[A.C. Vutha *et al.* J. Phys B (2010)]



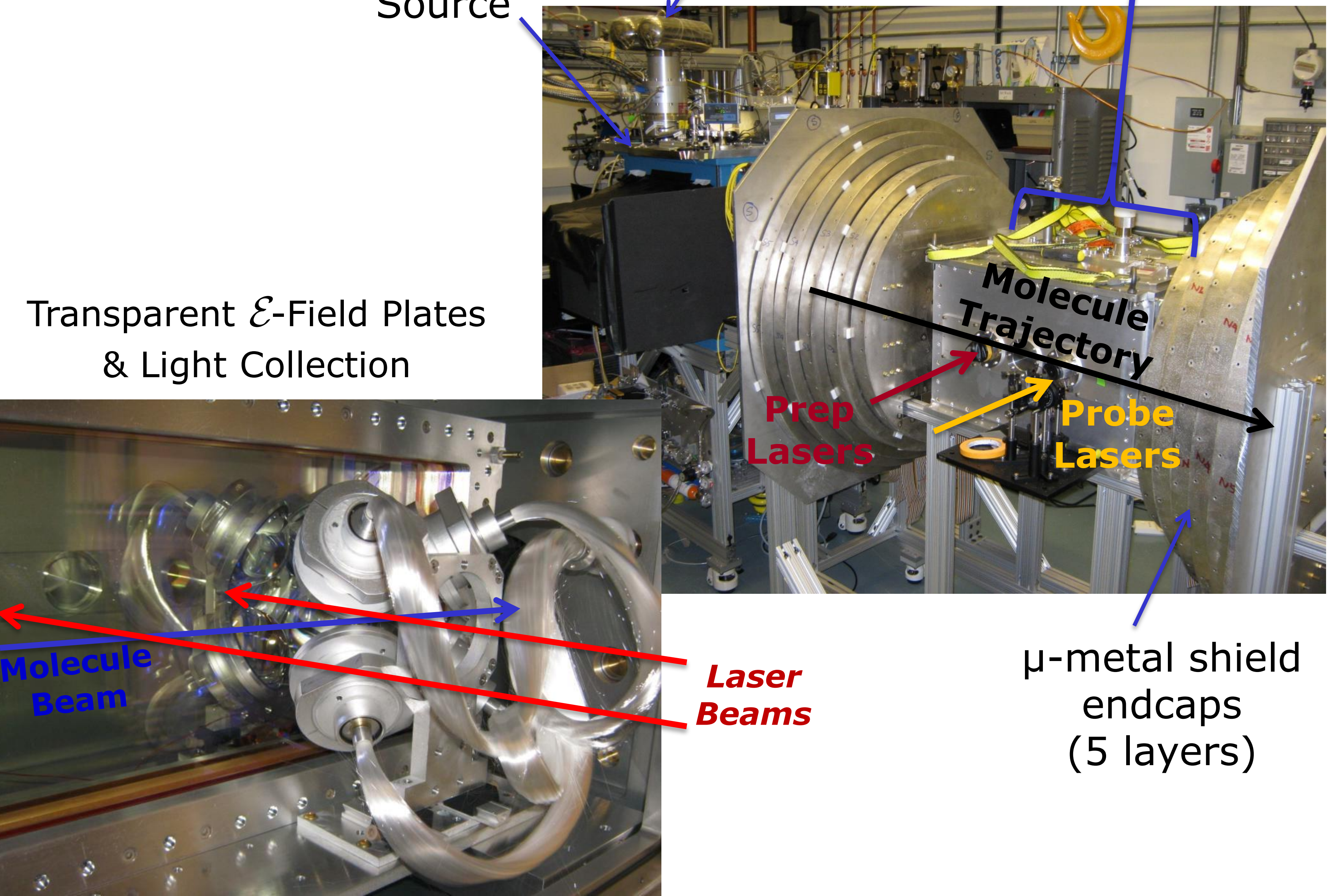
- **Large $\mathcal{E}_{\mathrm{eff}} \cong 80$ GV/cm in $H\,^3\Delta_1$ state**
  [Meyer & Bohn PRA 2008; Skripnikov et al. JCP 2013;
  Fleig & Nayak J. Mol. Spectrosc. 2014]
- **Ω-doublet structure in $H\,^3\Delta_1$ state**
  --very easily polarized
  --suppresses many possible systematics
- **Sufficient coherence time in $H\,^3\Delta_1$ state**
  metastable: $\tau \approx 1.9$ ms
- **Suppressed magnetic moment in $H\,^3\Delta_1$ state**
  $<0.01\ \mu_B$ in $H\,^3\Delta_1$ reduces *B*-field systematics
  [Idea: Meyer, Bohn, Cornell et al. (JILA);
  Measured: A.C. Vutha *et al.*, PRA 2011]
- All spectroscopic data previously known
- State preparation and readout
  w/standard, robust diode & fiber lasers
- Blue-shifted fluorescence from probe laser
  ⇒no problem with backgrounds
- **High beam source yield**

ACME experimental schematic





ACME apparatus



Molecular Beam Source

Pulse Tube Cryo Frig

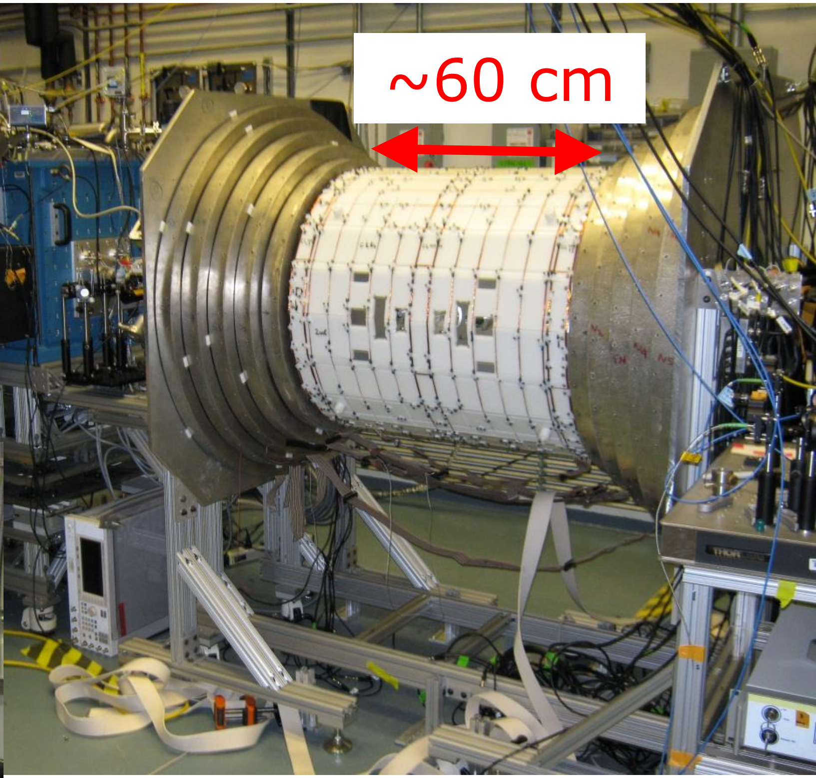
Interaction Region

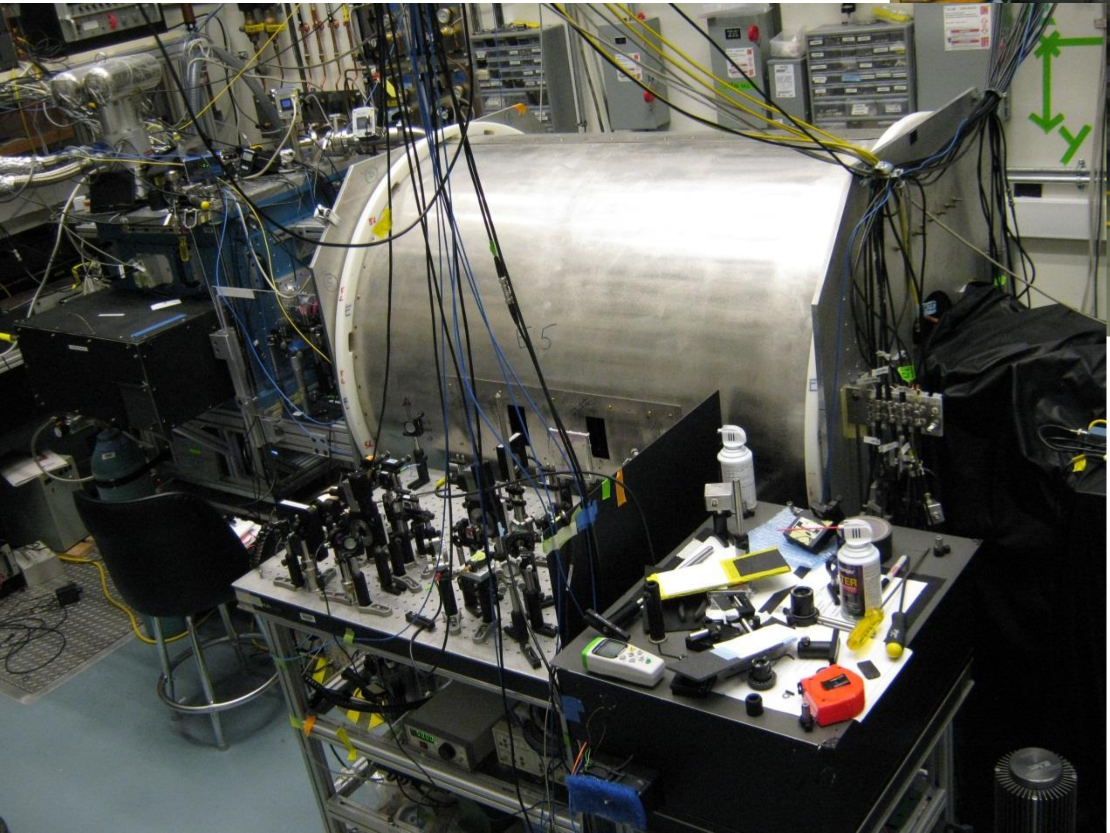
Transparent $\mathcal{E}$-Field Plates & Light Collection

μ-metal shield endcaps (5 layers)

ACME apparatus

Magnetic field coils
(3 orthogonal components
& all first-order gradients)

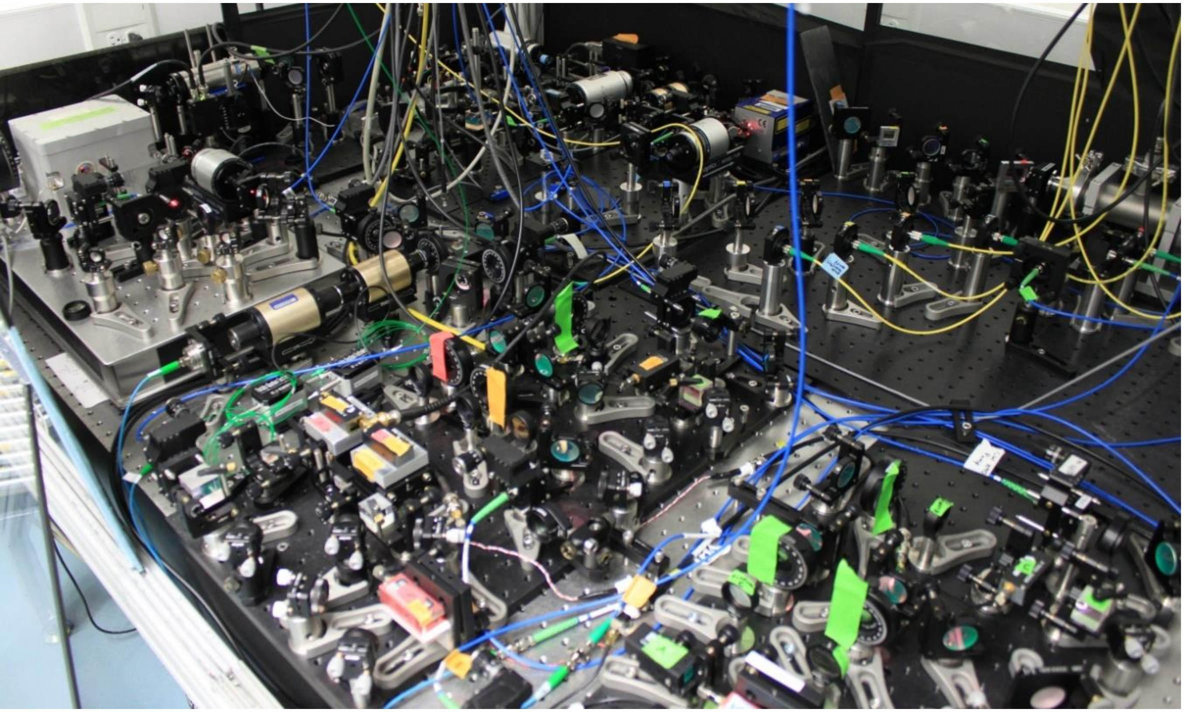




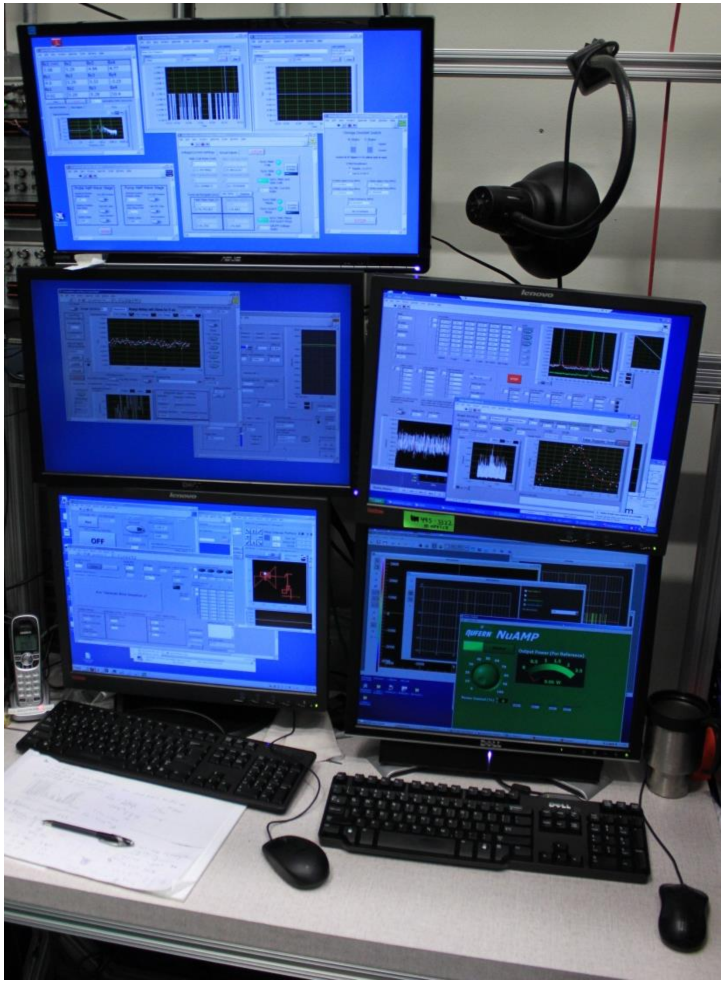
Complete
beam source
& magnetic shields
& last-stage optics

ACME apparatus

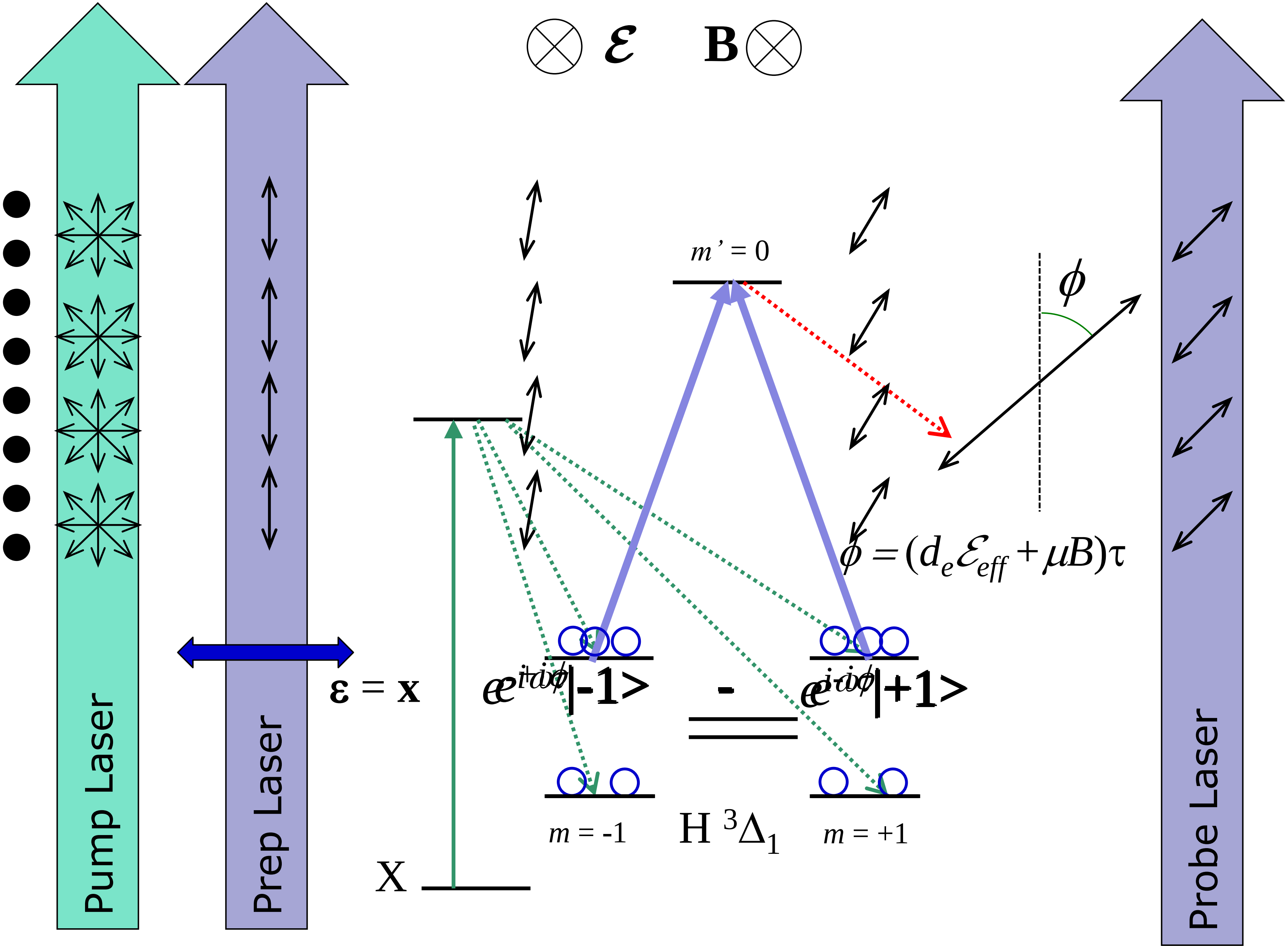
One of several optical tables w/
~ten lasers, dozens of modulators,
hundreds of meters of optical fiber, etc.
spread over two buildings



“control room”



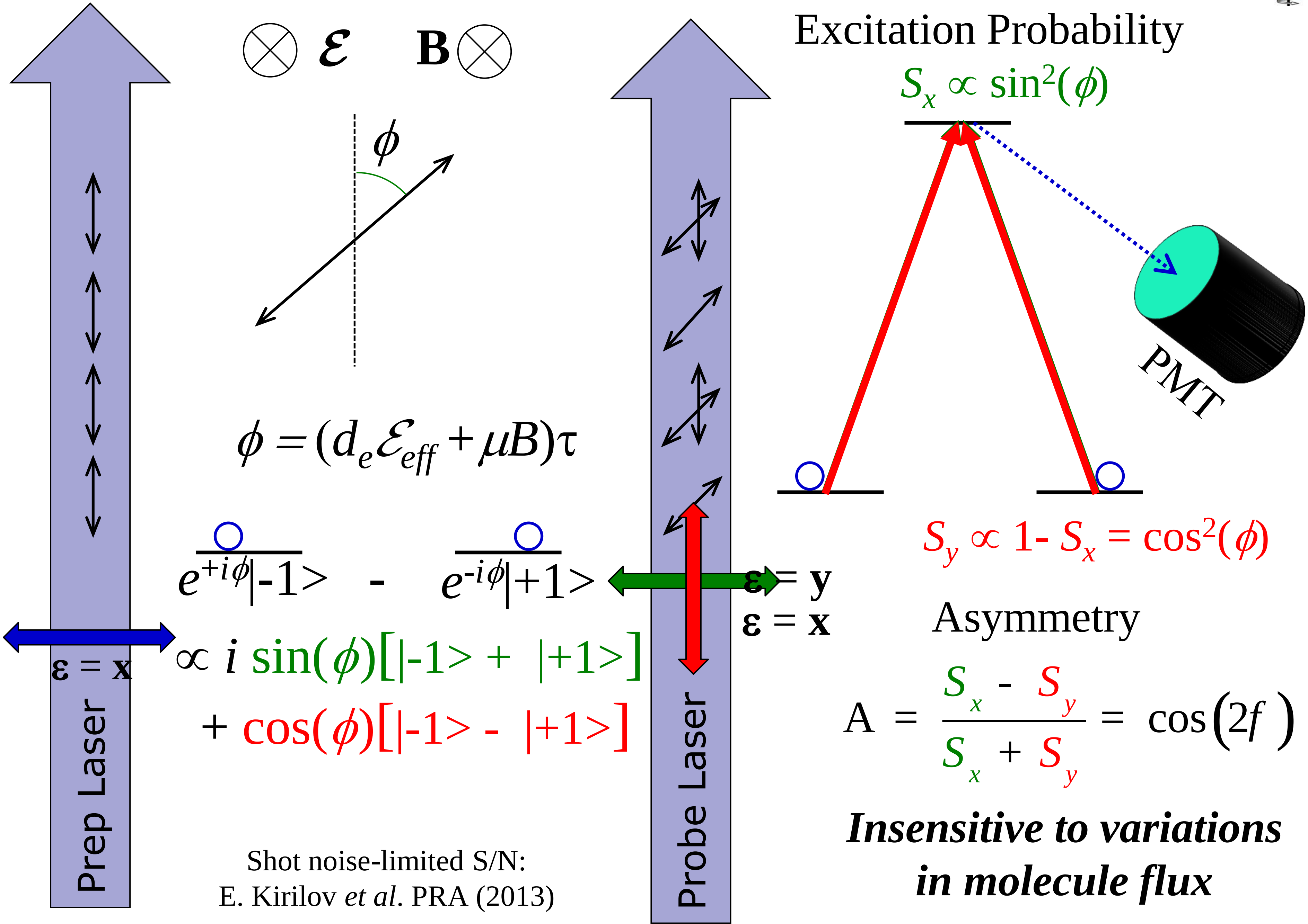
ACME spin-measurement protocol



$$e^{+i\phi}|-1\rangle - e^{-i\phi}|+1\rangle$$

$$\phi = (d_e\mathcal{E}_{eff} + \mu B)\tau$$

ACME spin-measurement protocol



$$\phi = (d_e \mathcal{E}_{eff} + \mu B)\tau$$

$$e^{+i\phi}|-1> \quad - \quad e^{-i\phi}|+1>$$

$$\propto i \sin(\phi)[|-1> + |+1>]$$

$$+ \cos(\phi)[|-1> - |+1>]$$

Excitation Probability

$$S_x \propto \sin^2(\phi)$$

$$S_y \propto 1 - S_x = \cos^2(\phi)$$

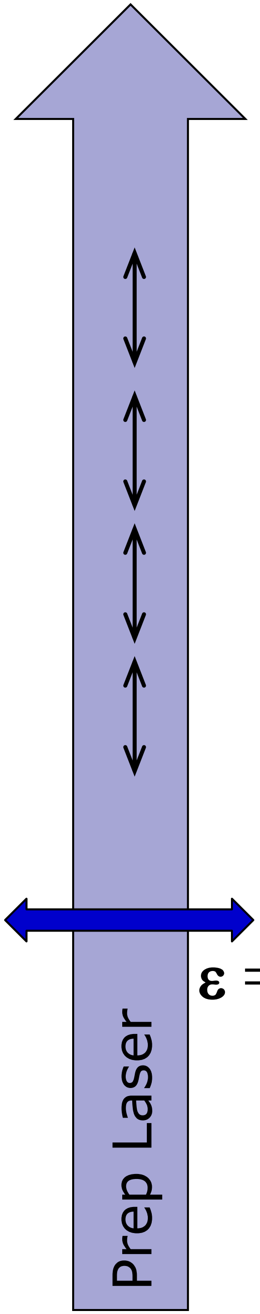
Asymmetry

$$A = \frac{S_x - S_y}{S_x + S_y} = \cos(2f)$$

Insensitive to variations in molecule flux

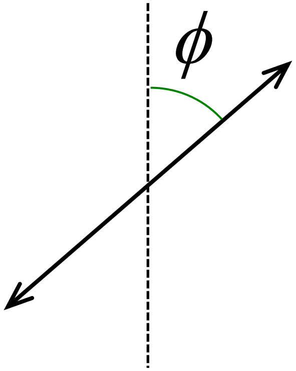
Shot noise-limited S/N:
E. Kirilov *et al*. PRA (2013)

Contrast measurement w/rotated basis



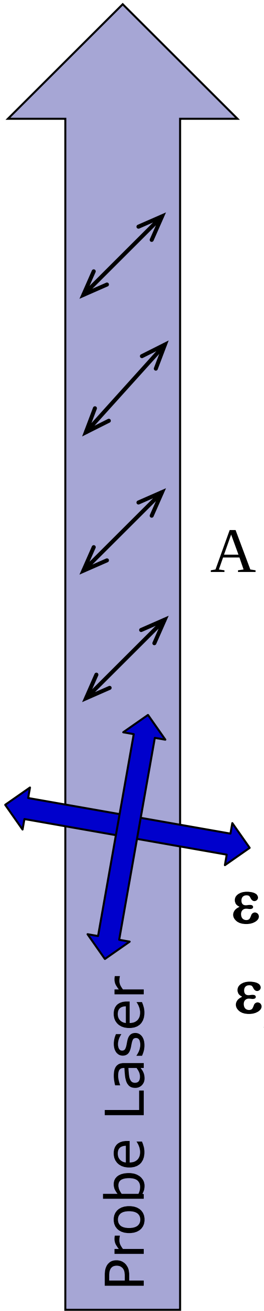
$\boldsymbol{\varepsilon} = \mathbf{x}$

$\otimes\ \mathcal{E}$ $\quad \mathbf{B}\otimes$



$$\phi = (d_e \mathcal{E}_{eff} + \mu B)\tau$$

$$e^{+i\phi}|-1> \quad + \quad e^{-i\phi}|+1>$$



$\boldsymbol{\varepsilon}_1 = \mathbf{y}\sin\theta + \mathbf{x}\cos\theta$

$\boldsymbol{\varepsilon}_2 = \mathbf{x}\sin\theta - \mathbf{y}\cos\theta$

Including backgrounds:

$$S_1 = S_0 \sin^2(\phi-\theta) + B$$

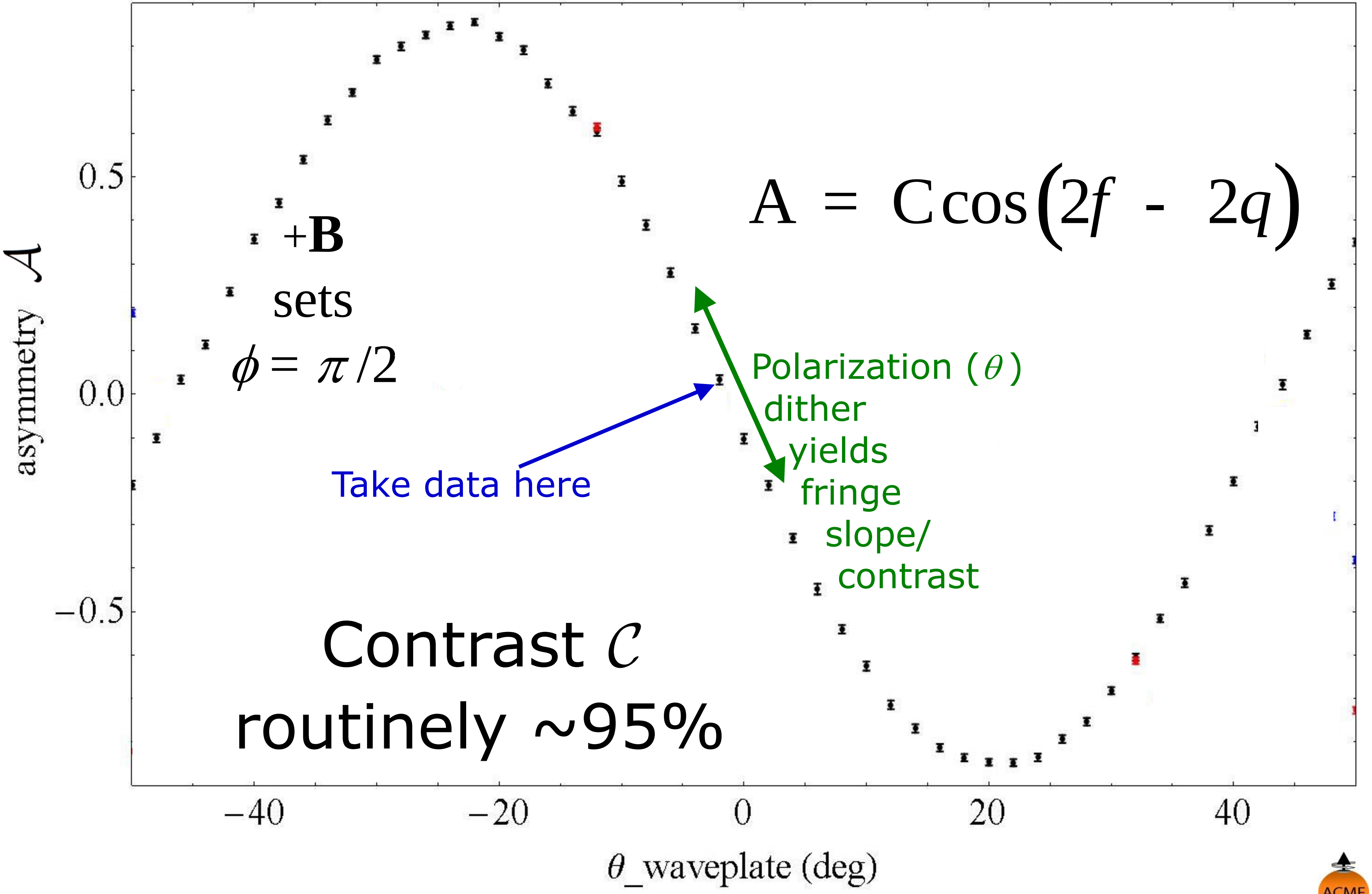
$$S_2 = S_0 \cos^2(\phi-\theta) + B$$

Asymmetry

$$A = \frac{S_1 - S_2}{S_1 + S_2} = C\cos(2\phi - 2\theta)$$

$$\left[\text{contrast } C = \frac{S_0}{S_0 + B}\right]$$

Contrast measurement & spin-rotation fringe



$$A = C\cos(2f - 2q)$$

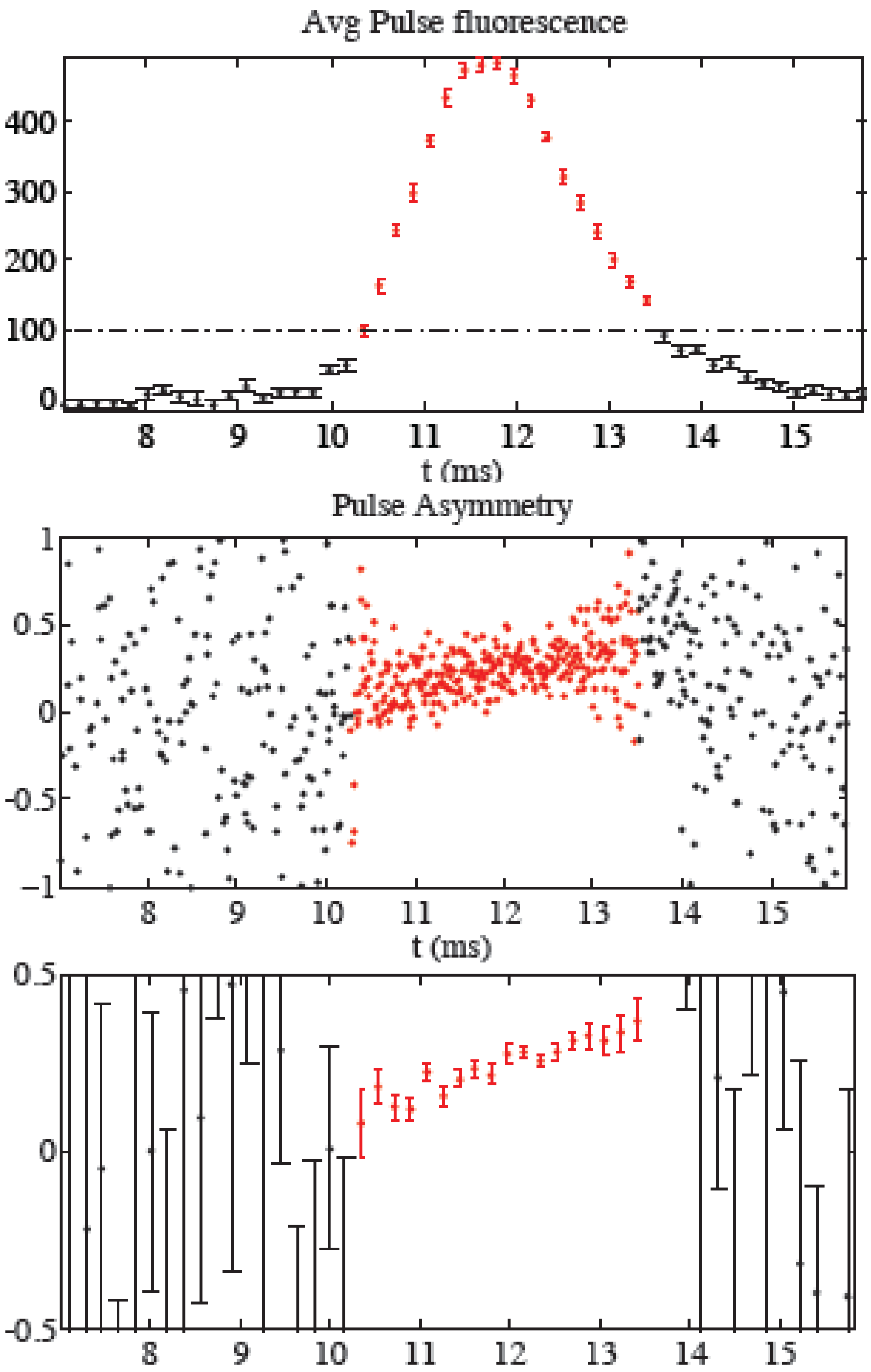
+**B** sets $\phi = \pi/2$

Take data here

Polarization (θ) dither yields fringe slope/ contrast

Contrast $\mathcal{C}$ routinely ~95%

Assigning statistical uncertainty



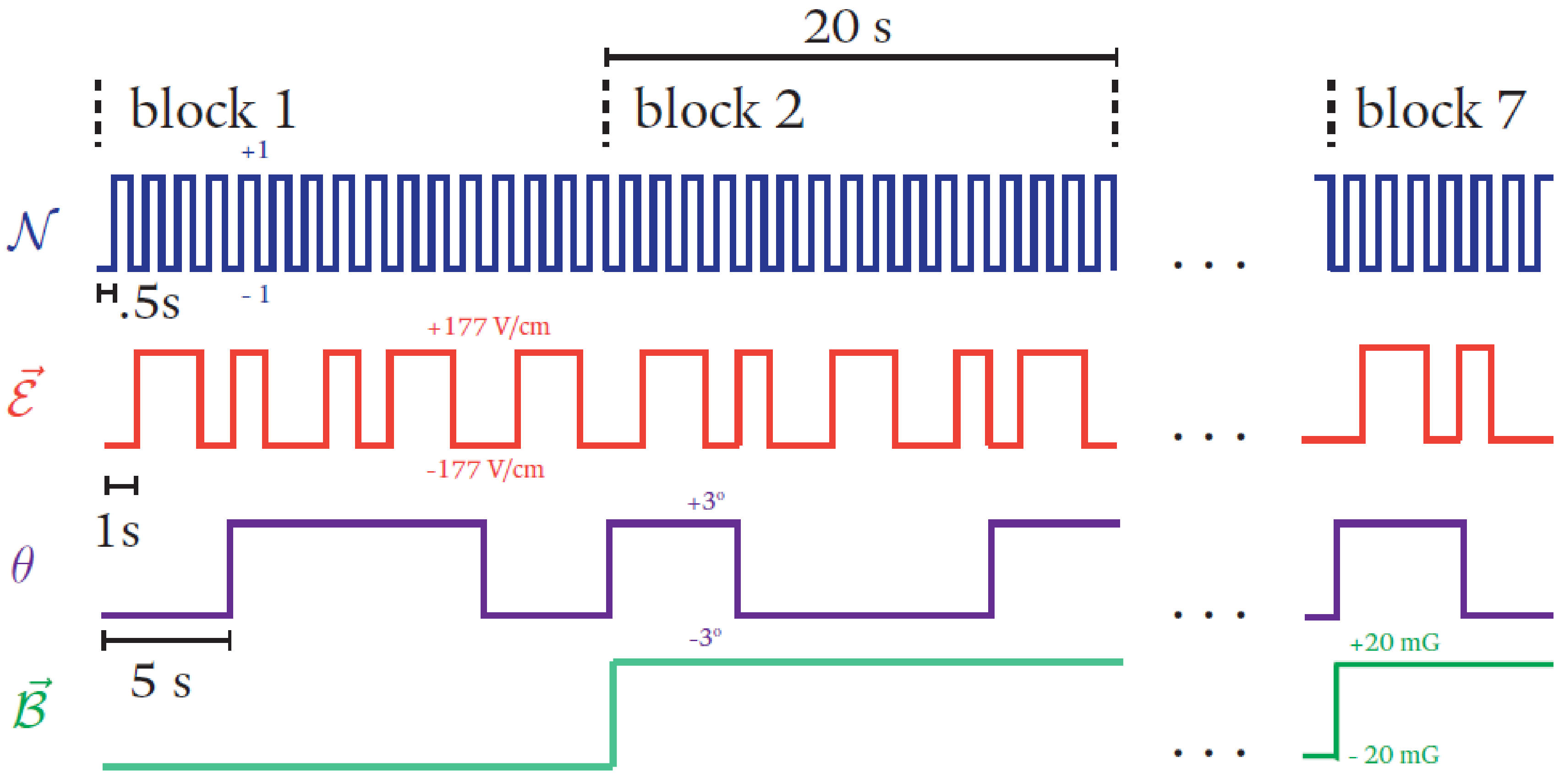
Cut on signal size
--avoids non-Gaussian stats.
--*only significant data cut*

--Calculate Asymmetry $\mathcal{A}$
for each polarization chop

--Bin to find
average & std. error

--use standard
“error propagation”
for subsequent
combinations

Data taking strategy: primary



--psuedo-random (pair-wise), interleaved reversals

--calculate average asymmetry $\mathcal{A}$, contrast $\mathcal{C}$, & phase $\phi = \mathcal{A}/\mathcal{C}$ for each "machine state" $(\tilde{N}, \tilde{E}, \tilde{B})$

[tilde = signs of $\mathcal{N}$, $\mathcal{E}$, $\mathcal{B}$]

Data sorting & analysis

Rewrite phase as components correlated w/switches:

$$\phi = \phi^0 + \phi^{\boxed{\tilde{E}}} + \phi^{\tilde{B}} + \phi^{\tilde{N}} + \boxed{\phi^{\tilde{N}\tilde{E}}} + \boxed{\phi^{\tilde{N}\tilde{B}}} + \boxed{\phi^{\tilde{E}\tilde{B}}} + \boxed{\phi^{\tilde{N}\tilde{E}\tilde{B}}}$$

Superscipt means
“odd under this reversal”
&
“even under all others”

EDM phase

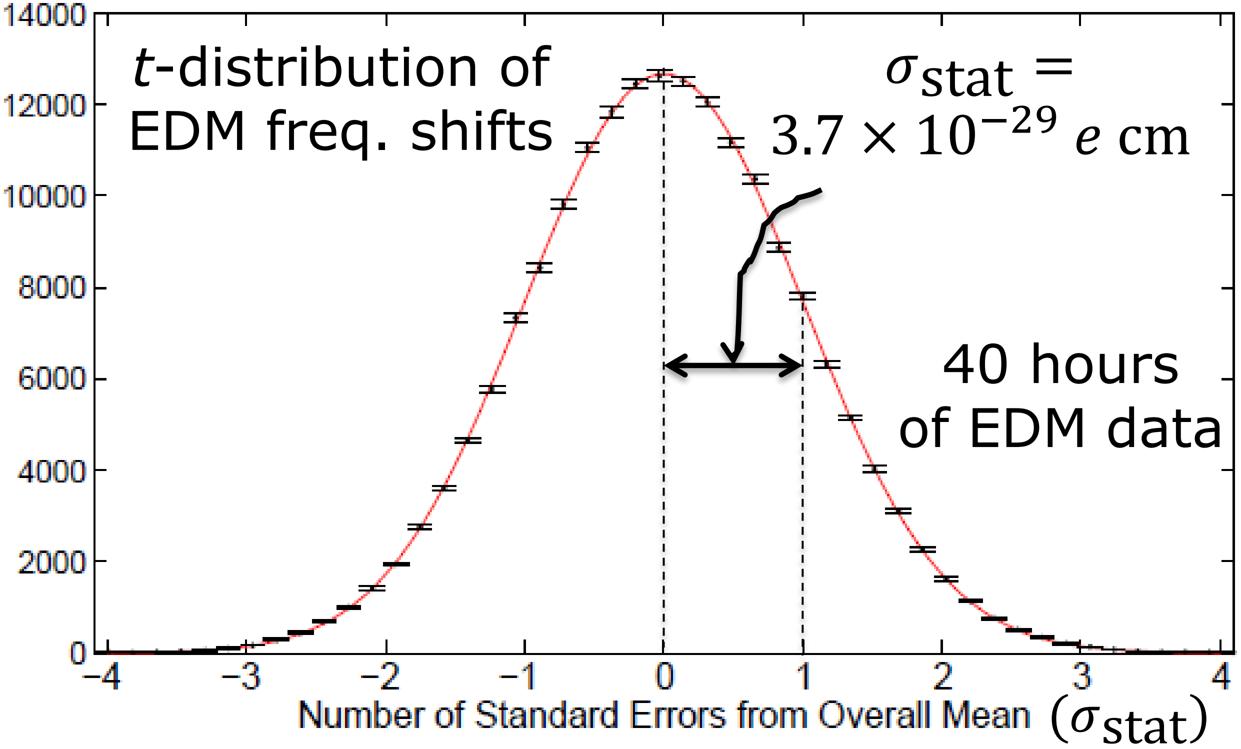
other phases to
diagnose systematics

Different “switch-correlated phases”
isolate different physical contributions

ACME EDM data: statistics

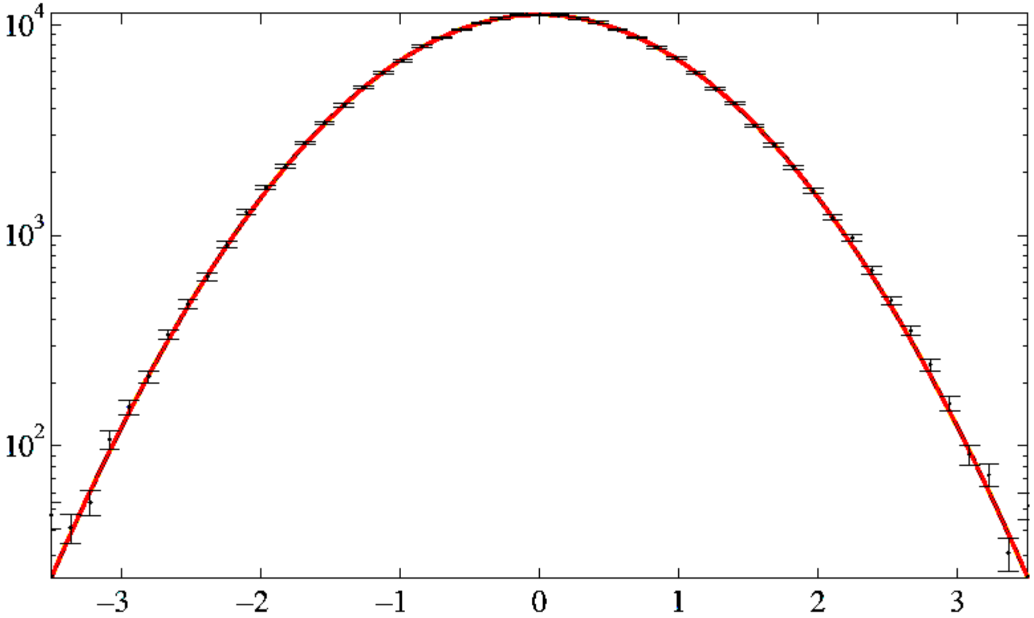
- **Blind analysis:** *hidden offset added to EDM* until final value & uncertainties fixed

- *t*-distribution Gaussian over full range, out to >3σ


t-distribution of EDM freq. shifts

$\sigma_{\text{stat}} = 3.7 \times 10^{-29}\, e\ \text{cm}$

40 hours of EDM data



Systematic error analysis

Rewrite phase as components correlated w/switches:

$$\phi = \phi^0 + \phi^{\tilde{E}} + \phi^{\tilde{B}} + \phi^{\tilde{N}} + \phi^{\tilde{N}\tilde{E}} + \phi^{\tilde{N}\tilde{B}} + \phi^{\tilde{E}\tilde{B}} + \phi^{\tilde{N}\tilde{E}\tilde{B}}$$

Superscipt means
"odd under this reversal"

EDM phase

other phases to
diagnose systematics

"Switch-correlated phases" contain physical contributions:

$$f^{\tilde{N}\tilde{E}} \mu\, d_e E_{eff} + \frac{1}{2} D g_N m_H B_{leak} + \frac{1}{2} D g_N m_H B_{nr} \frac{E_{nr}}{E_0} + \ldots$$

EDM

Systematics due to experimental imperfections e.g.
--leakage current-induced $\mathcal{B}$-field $\mathcal{B}_{leak} \propto \mathcal{E}$
--non-reversing $\mathcal{E}$-field $\mathcal{E}_{nr}$
--etc.

Data analysis: diagnosing imperfections

Switch-correlated phases isolate physical contributions:

$$\phi^{\tilde{N}\tilde{E}} \propto d_e \mathcal{E}_{eff} + \frac{1}{2}\Delta g_N \mu_H \mathcal{B}_{leak} + \frac{1}{2}\Delta g_N \mu_H \mathcal{B}_{nr}\frac{\mathcal{E}_{nr}}{\mathcal{E}_0} + \dots$$

EDM

Experimental imperfections

Most imperfections appear in other correlated phases BUT GREATLY AMPLIFIED

$$\phi^{\tilde{E}} \propto \frac{1}{2} g \mu_H \mathcal{B}_{leak}$$

$$g / \Delta g_N \sim 1000$$

$$\phi^{\tilde{N}\tilde{E}\tilde{B}} \propto \frac{1}{2}\Delta g_N \mu_H \mathcal{B}\frac{\mathcal{E}_{nr}}{\mathcal{E}_0}$$

$$\mathcal{B} / \mathcal{B}_{nr} \sim 1000$$

⇒“Other” correlated phases diagnose imperfections

Search strategy for systematic errors

Switch-correlated phases isolate physical contributions:

$$f^{\overset{\pm}{N}\overset{\%}{E}} \mu \; d_e E_{eff} + \frac{1}{2} D g_N m_H B_{leak} + \frac{1}{2} D g_N m_H B_{nr} \frac{E_{nr}}{E_0} + \ldots$$

EDM

Experimental imperfections

But… what about terms we don’t anticipate?

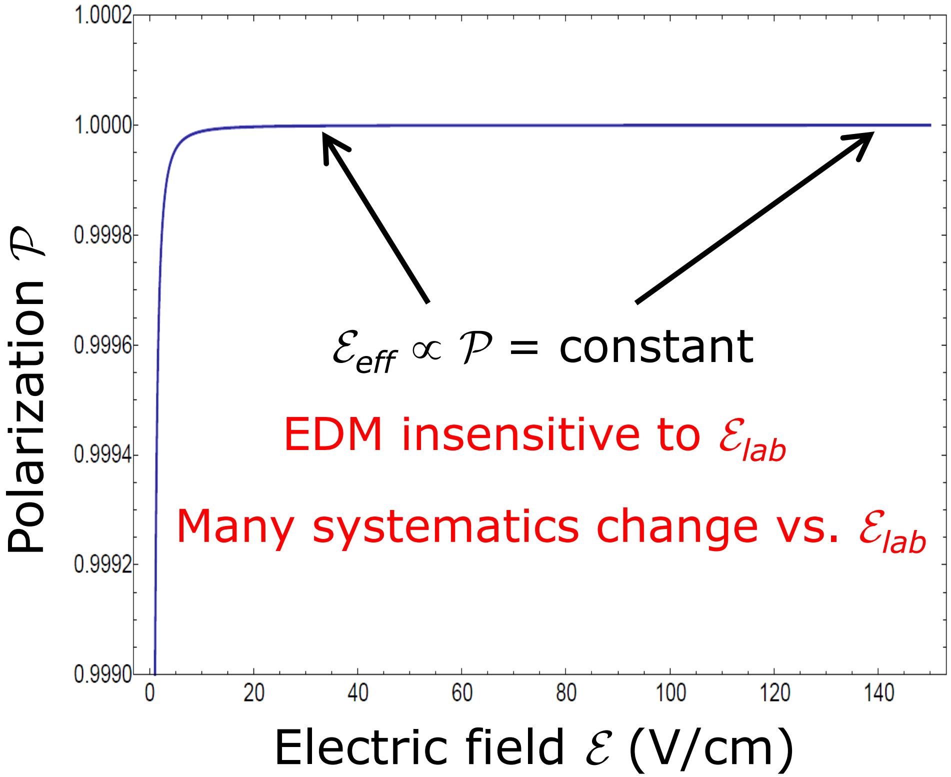
Strategies:

- Change parameters that should NOT affect EDM but MAY couple to unanticipated imperfections

- DELIBERATELY amplify imperfections, understand any changes in correlated phases

"Extra" reversals and variations

- Pump-probe Relative polarization
- Pump-probe Global polarization
- Swap $\mathcal{E}$-field plate Leads
- Magnitude of $\mathcal{B}$
- Laser propagation direction **k**
- Probe transition upper state Parity
- Magnitude of $\mathcal{E}$



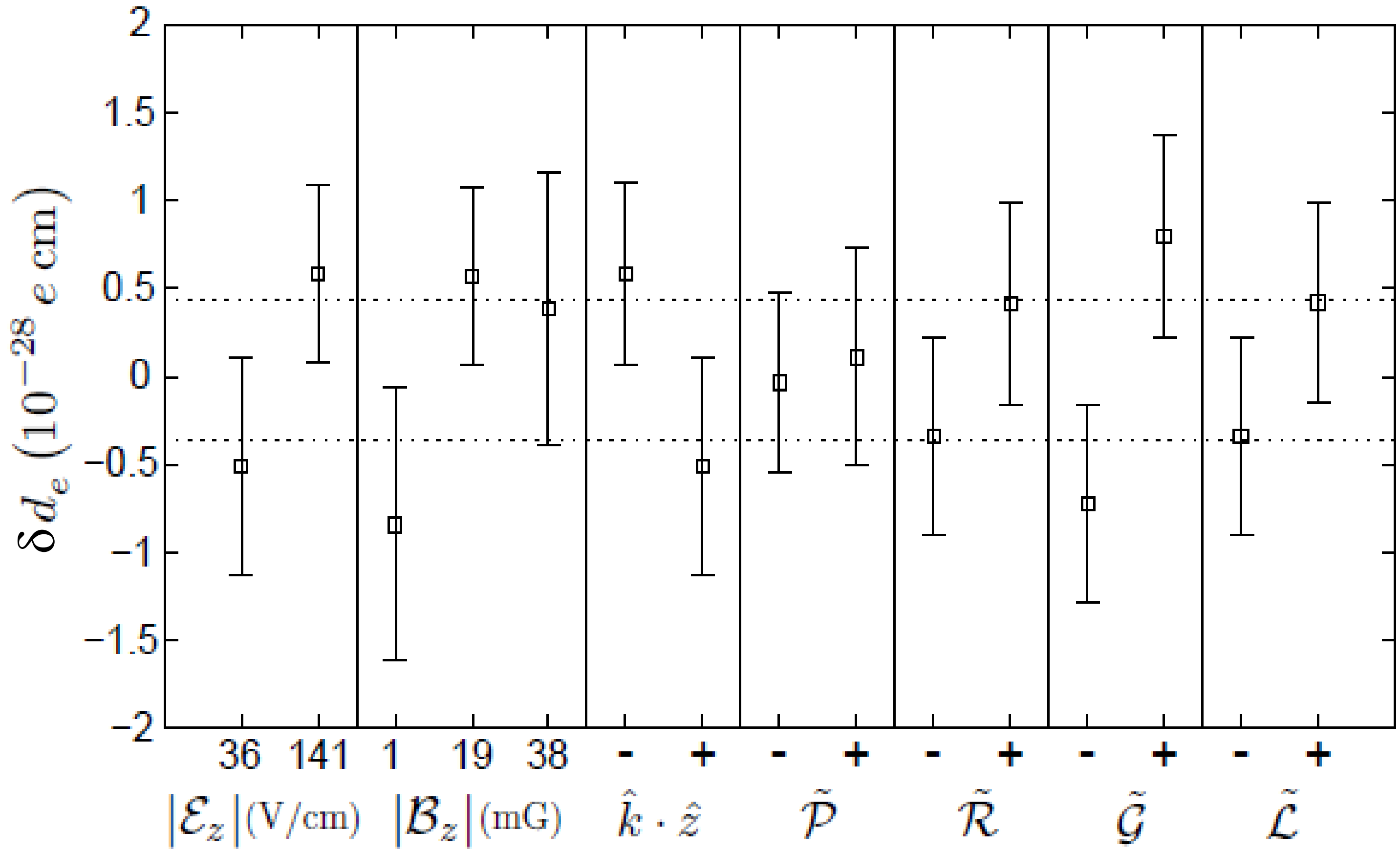
$\mathcal{E}_{eff} \propto \mathcal{P}$ = constant

EDM insensitive to $\mathcal{E}_{lab}$

Many systematics change vs. $\mathcal{E}_{lab}$

--Each changes effect of certain imperfections
but leaves EDM phase unchanged

Consistency under "extra" switches



No significant correlation with "extra" variations

as expected for EDM without systematic contamination

Intentionally amplified imperfections

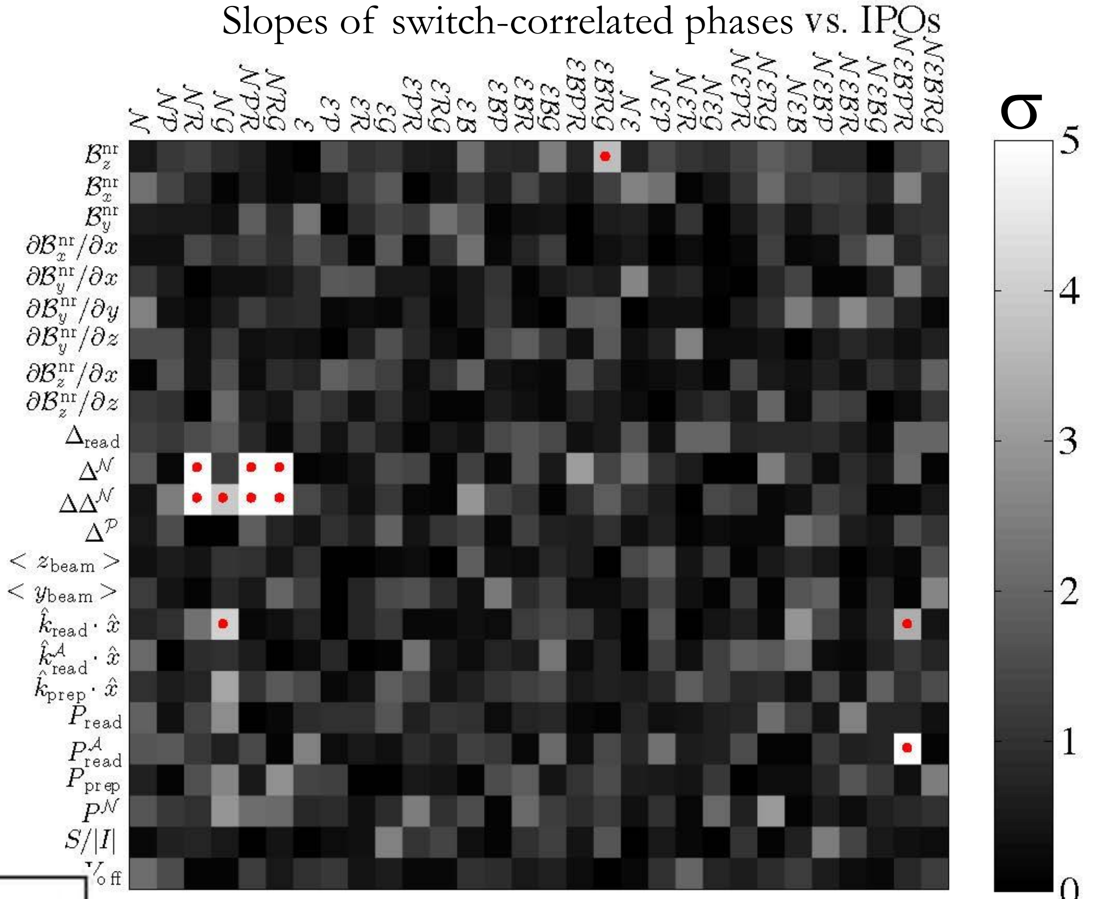
Non-reversing $\mathcal{E}$-field	Non-reversing $\mathcal{B}$-field
Ω-doublet reversal laser detuning	Relative detuning of Ω-doublet
Global laser detuning	Individual laser detuning
Laser beam spatial profile	Laser polarization/ellipticity gradients
Laser polarization/ellipticity	Probe laser power
Relative power/pointing of x/y probes	Pump laser power
Laser beam alignment	AOM settling time
Molecule beam pointing & position	Beam source variation
$\mathcal{B}$-field gradients	$\mathcal{B}$-field pointing
Non-reversing $\mathcal{B}$-field gradients	Non-reversing $\mathcal{B}$-field pointing
Simulated leakage current	

--Data with amplified imperfection not used for actual EDM limit

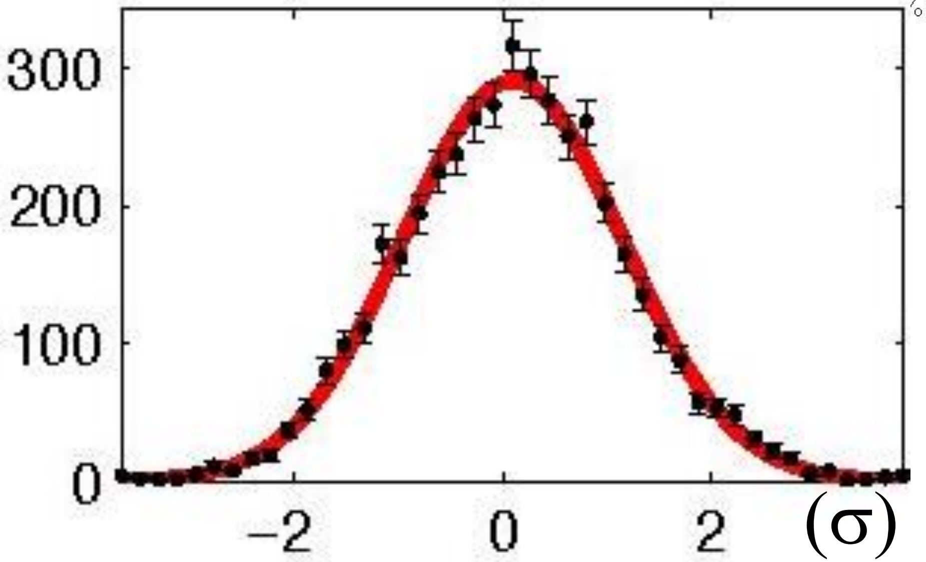
--also monitored data for correlations with drift of most parameters

Searching for systematic errors

“Pixel plots”
used to identify
significant correlations
between
switch-correlated
phase, contrast, etc.
vs. any varying
parameter or other signal



ω Parity Sums IPO Slopes
Red Dots: > 3.39σ. Expect 0.5 by chance



Statistical distribution of diagnostic signals for systematic errors

Few outliers;
all “close” to EDM channel
understood and/or controlled

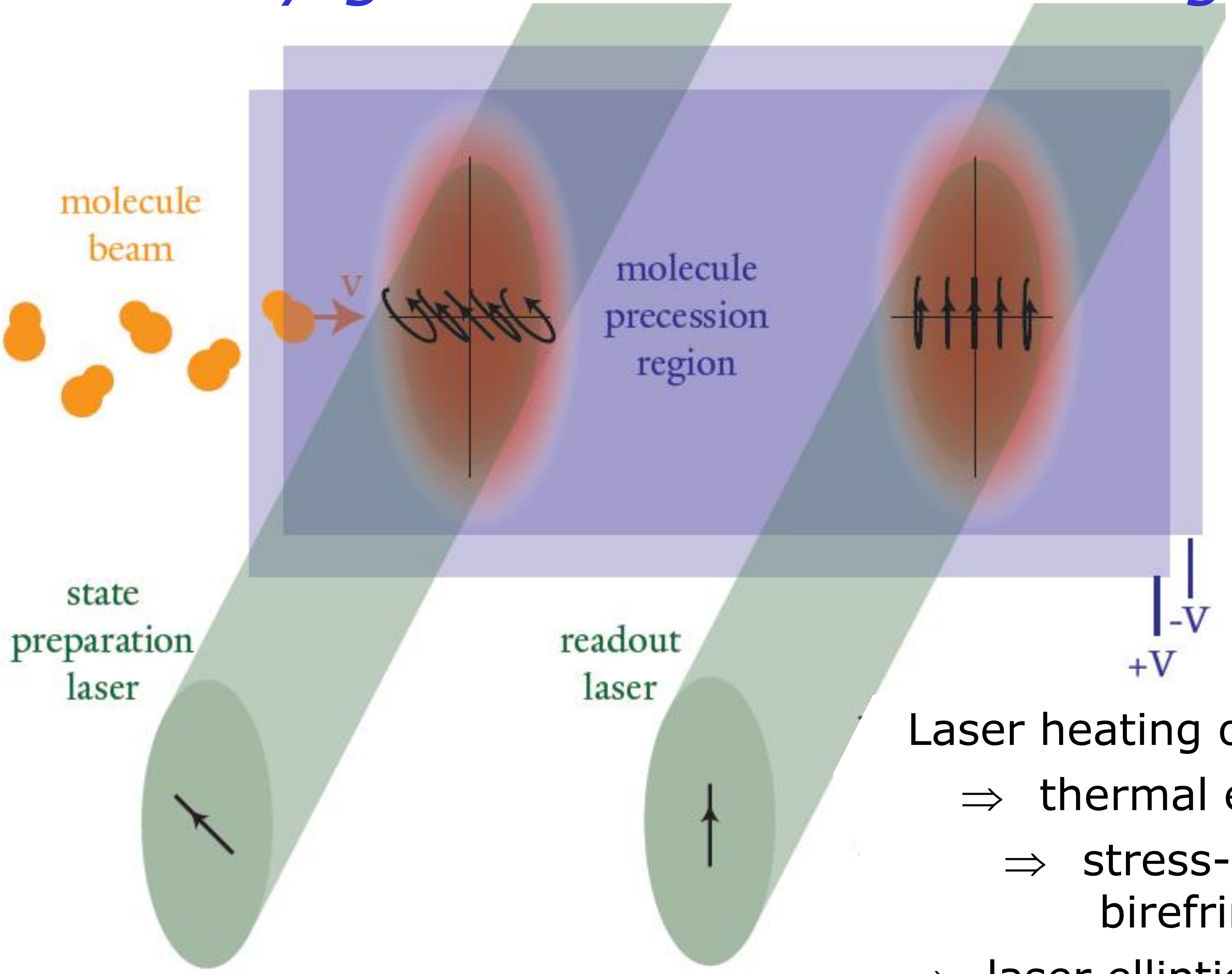
Case study: a nasty systematic error

Intentionally amplified imperfections

Non-reversing $\mathcal{E}$-field	Non-reversing $\mathcal{B}$-field
Ω-doublet reversal laser detuning	Relative detuning of Ω-doublet
Global laser detuning	Pump & Probe Laser detuning individually
Laser beam spatial profile	Laser polarization/ellipticity gradient
Laser polarization/ellipticity	Probe laser power
Relative power/pointing of x/y probes	Pump laser power
Laser beam alignment	AOM settling time
Molecule beam pointing & position	Beam source variation
$\mathcal{B}$-field gradients	$\mathcal{B}$-field pointing
Non-reversing $\mathcal{B}$-field gradients	Non-reversing $\mathcal{B}$-field pointing
Simulated leakage current	

Several months to investigate, understand, & suppress
one systematic involving these 3 imperfections simultaneously;
all previous EDM data discarded

Example systematic: ellipticity gradient + intensity gradient + non-reversing $\mathcal{E}$-field



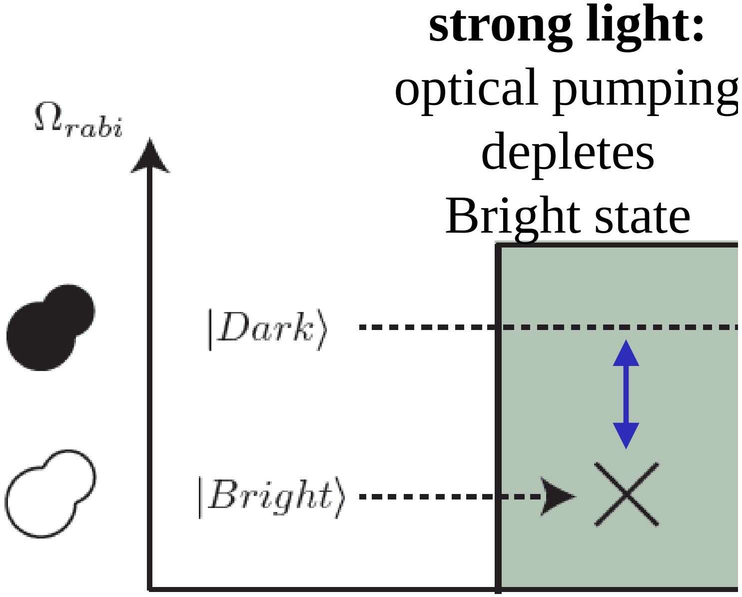
Laser heating of electrodes

⇒ thermal expansion

⇒ stress-induced birefringence

⇒ laser ellipticity gradient

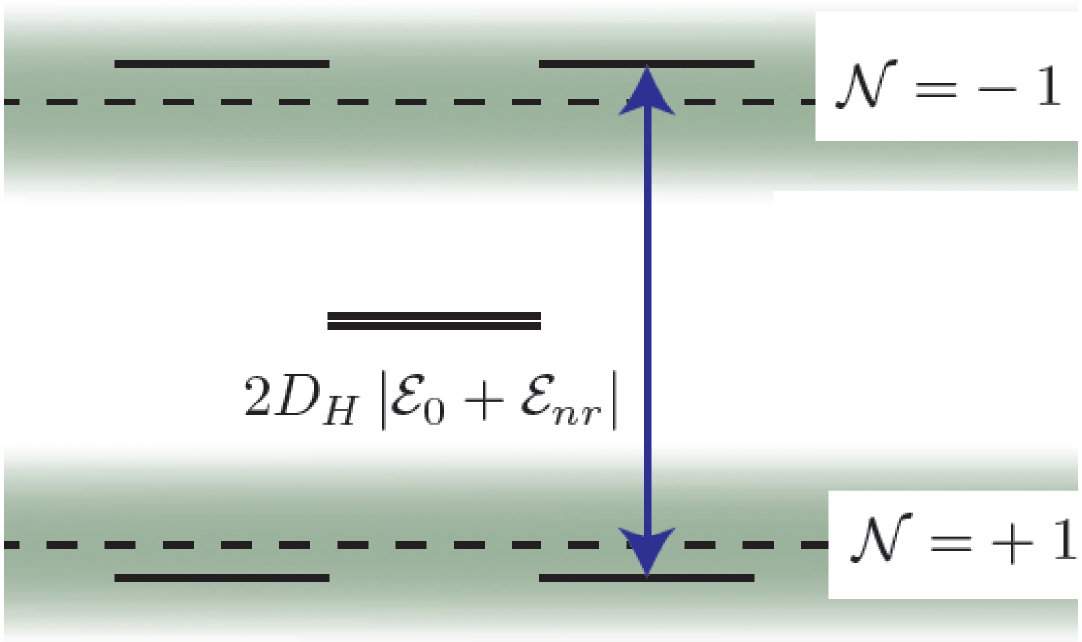
Example systematic: ellipticity gradient + intensity gradient + non-reversing $\mathcal{E}$-field



Laser ellipticity gradient ⇒ time-dependent dark states + laser intensity gradient ⇒ nonadiabatic evolution

⇒ detuning-dependent AC Stark shift in molecule phase

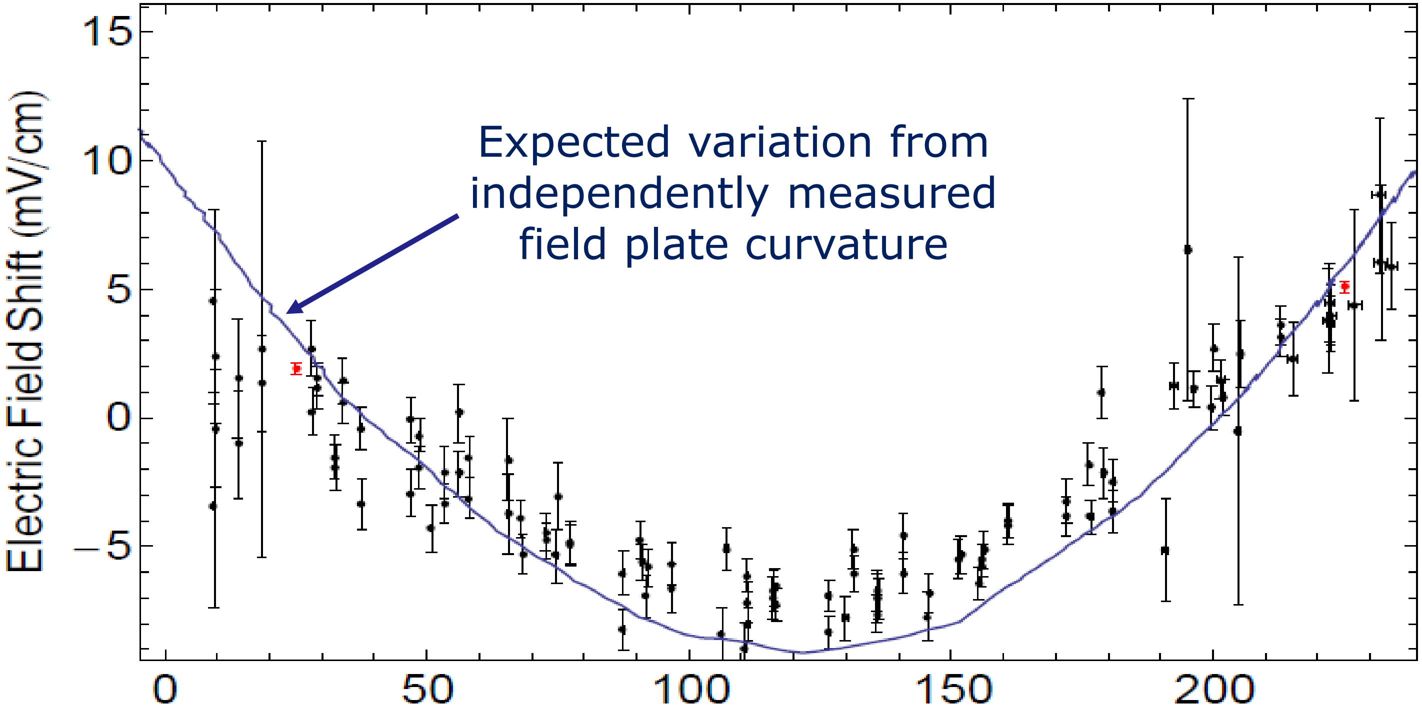
Example systematic: ellipticity gradient + intensity gradient + non-reversing $\mathcal{E}$-field



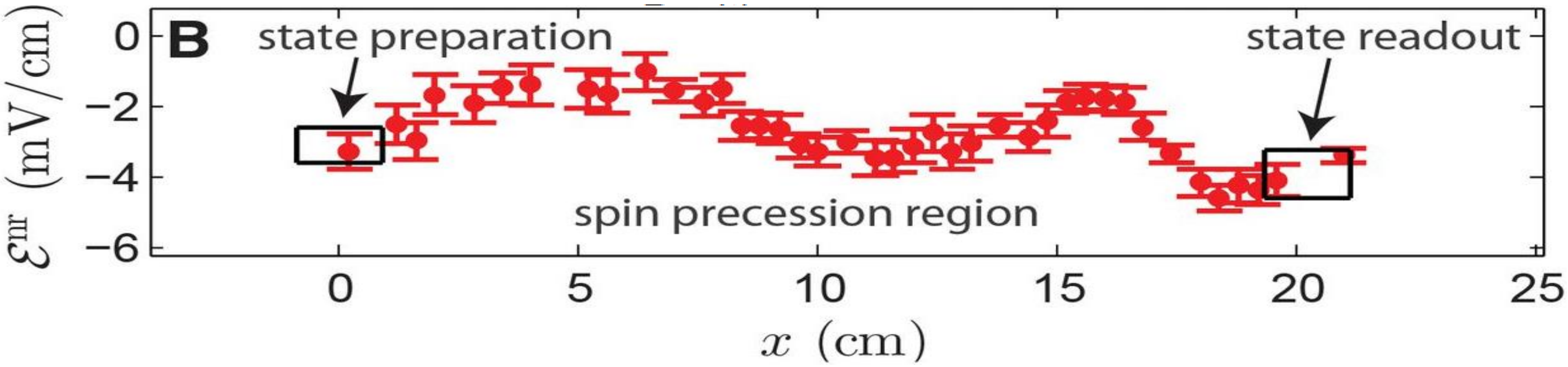
non-reversing $\mathcal{E}$-field component
$\Rightarrow$ DC Stark shift changes when $\mathcal{E}$-field reverses
$\Rightarrow$ $\mathcal{N}$, $\mathcal{E}$-odd detuning changes

+detuning-dependent AC Stark shift from laser
$\Rightarrow$ EDM-like signal in precession phase

$\mathcal{E}$ and $\mathcal{E}_{nr}$ from microwave spectroscopy

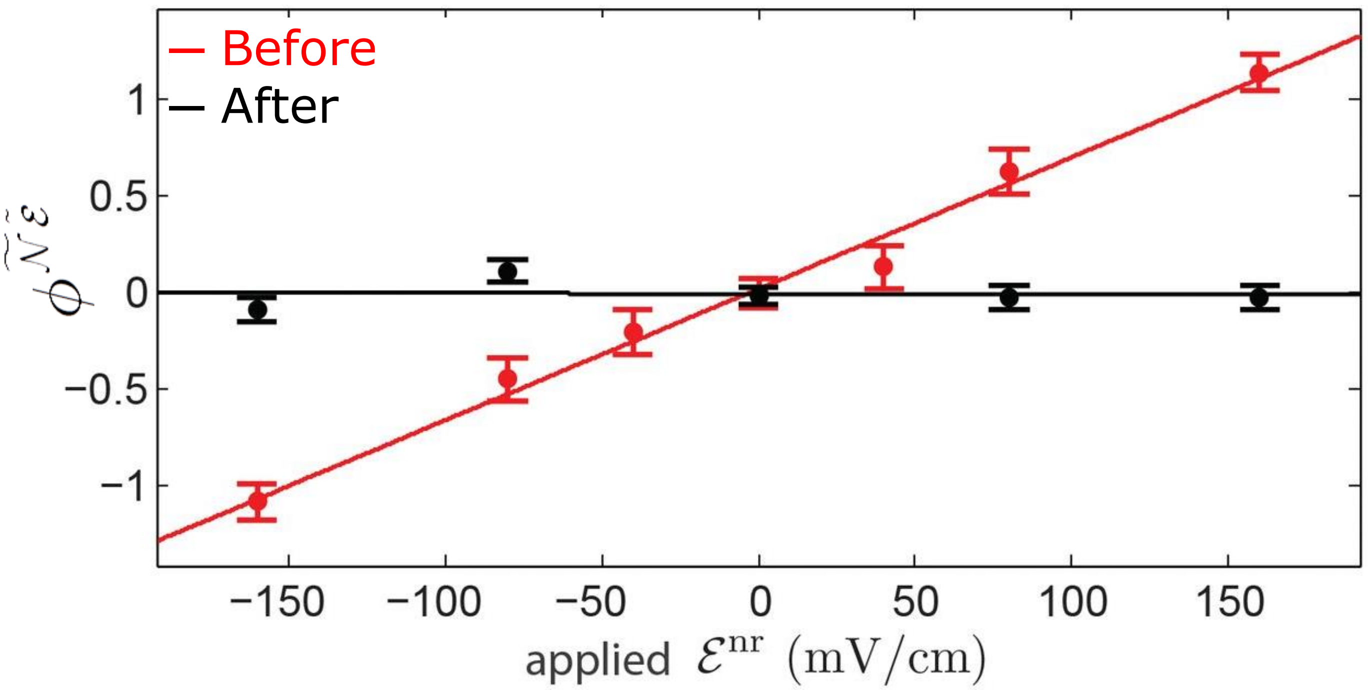


Expected variation from independently measured field plate curvature



--Measured $\mathcal{E}_{nr}$ <5 mV/cm out of ~100 V/cm everywhere

Suppressing the ellipticity + $\mathcal{E}_{nr}$ systematic

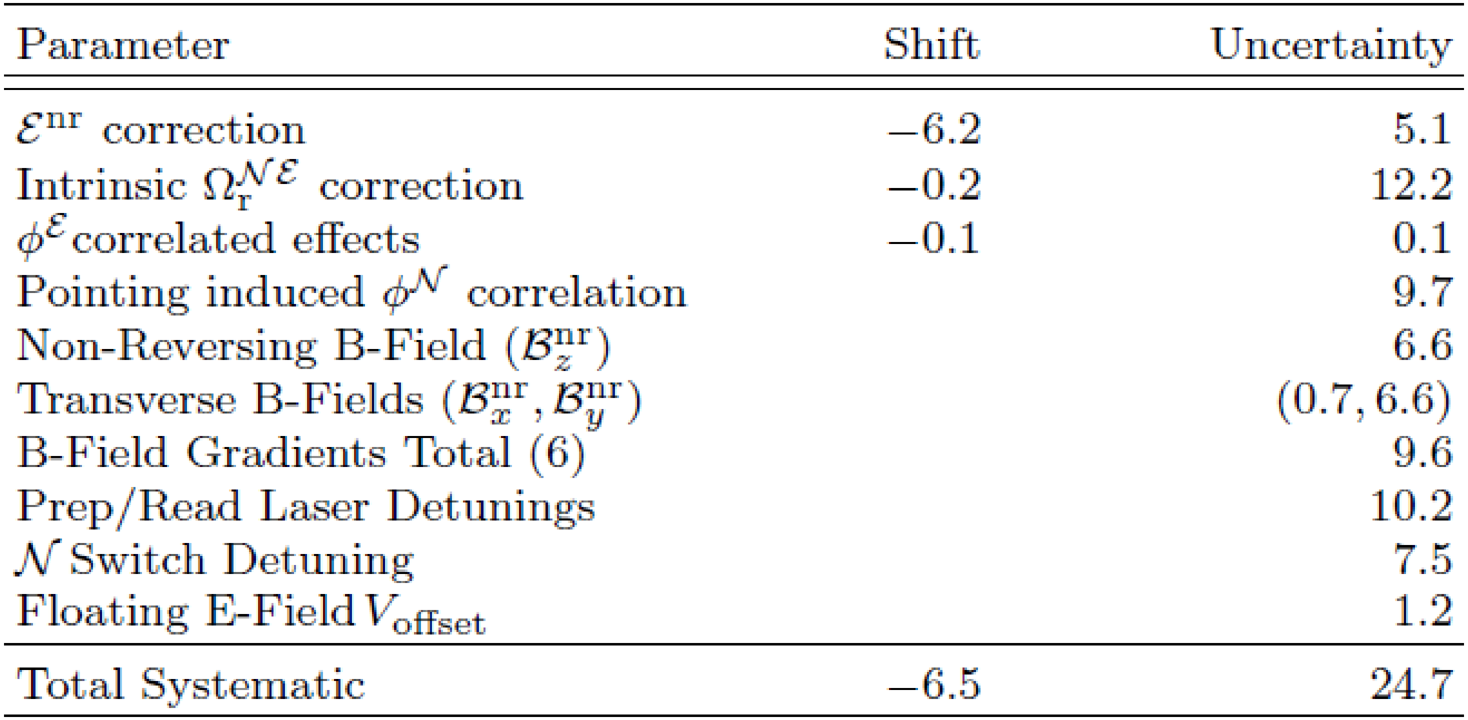


- Reduce laser-induced heat load on field plates (optical chopper)
- Reduce weak optical field region (laser beam shape)
- Align polarization w/birefringence axis

With precise measurement of $\mathcal{E}_{\text{nr}}$ (<5 mV/cm), small residual uncertainty: $\delta d_e \sim 0.5\times10^{-29}$ e·cm

Systematic Error Budget

$(d_e \times 10^{-30} e \text{ cm})$



Parameter	Shift	Uncertainty
$\mathcal{E}^{\mathrm{nr}}$ correction	-6.2	5.1
Intrinsic $\Omega_{\mathrm{r}}^{\mathcal{N}\mathcal{E}}$ correction	-0.2	12.2
$\phi^{\mathcal{E}}$ correlated effects	-0.1	0.1
Pointing induced $\phi^{\mathcal{N}}$ correlation		9.7
Non-Reversing B-Field ($\mathcal{B}_z^{\mathrm{nr}}$)		6.6
Transverse B-Fields ($\mathcal{B}_x^{\mathrm{nr}}, \mathcal{B}_y^{\mathrm{nr}}$)		$(0.7, 6.6)$
B-Field Gradients Total (6)		9.6
Prep/Read Laser Detunings		10.2
$\mathcal{N}$ Switch Detuning		7.5
Floating E-Field V_{offset}		1.2
Total Systematic	-6.5	24.7

$(\sigma_{stat} = 37)$

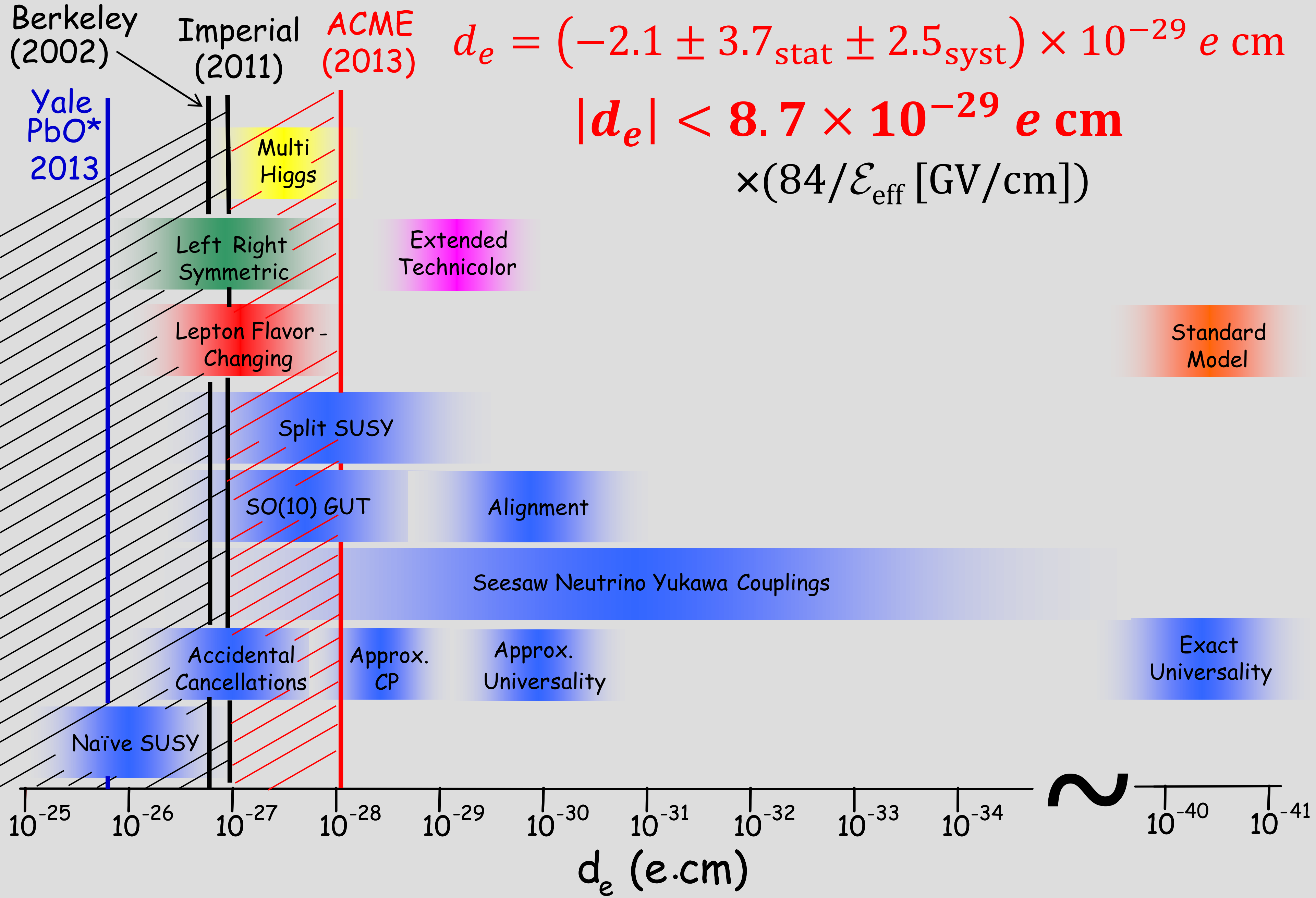
- Systematic *shifts* applied only from effects observed to move EDM channel
- Applied shift small compared to uncertainties

New electron EDM limit from ACME

$$d_e = \left(-2.1 \pm 3.7_{\text{stat}} \pm 2.5_{\text{syst}}\right) \times 10^{-29}\ e\ \text{cm}$$

$$\boldsymbol{|d_e| < 8.7 \times 10^{-29}\ e\ \text{cm}}$$

$$\times(84/\mathcal{E}_{\text{eff}}\,[\text{GV/cm}])$$



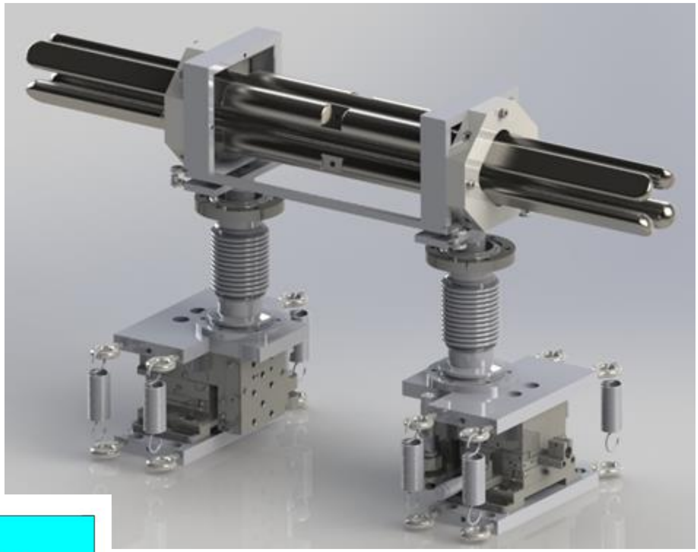
Many upgrades planned for ACME signal size

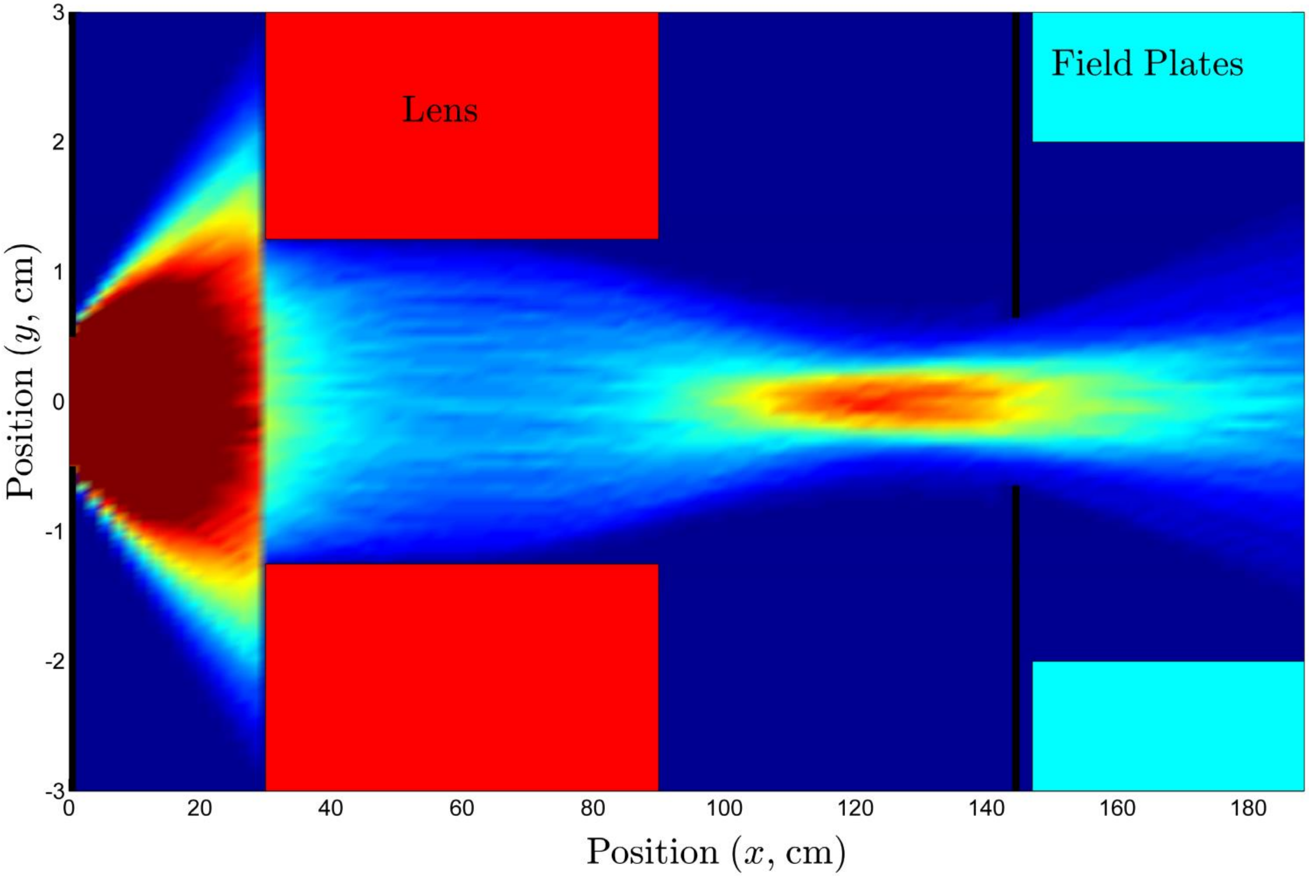
• Electrostatic focusing of molecular beam:	~20x (***)
• Stimulated vs. spontaneous state prep:	~8x (***)
• Thermochemical beam source	~10-50x (**)
• New fluorescence collection & detectors	~4-10x (*)
• Cycling fluorescence	~3-10x (*)
• Longer integration time	~10-100x

(***) = fully characterized in auxiliary tests
(**) = partially characterized
(*) = preliminary observations and/or theory estimates

>300x gain in $\sqrt{N}$ appears feasible ultimately

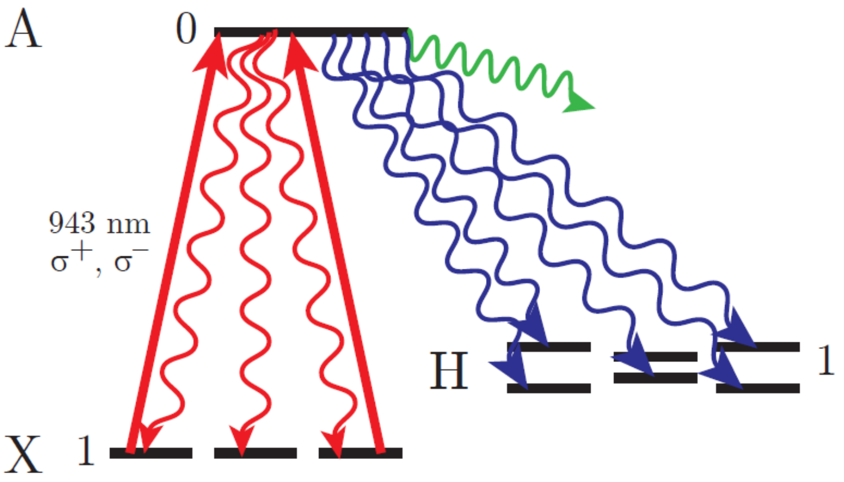
Electrostatic Quadrupole Lens: Focused Molecular Beam



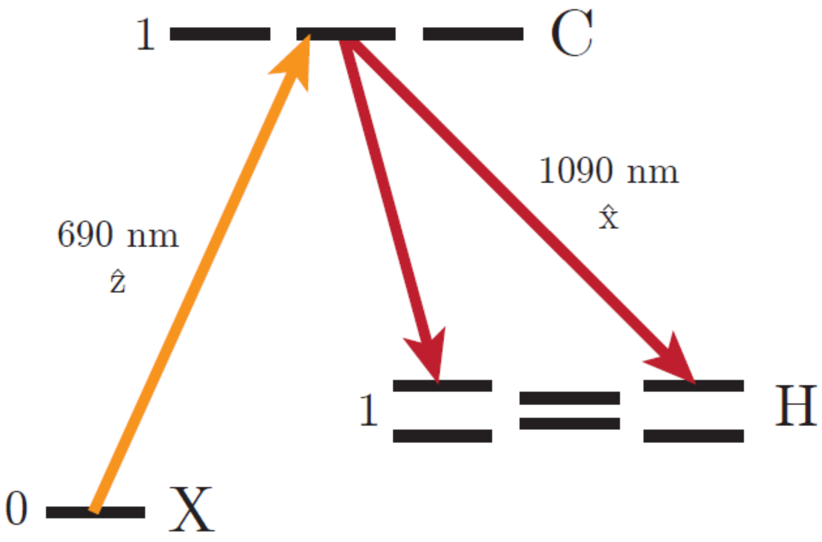


- Well-understood
- ~20× signal (simulation)
- Validated in test apparatus
- Increased transverse acceptance is OK
- Requires efficient state transfer before & after

Coherent state prep: STIRAP vs. optical pumping

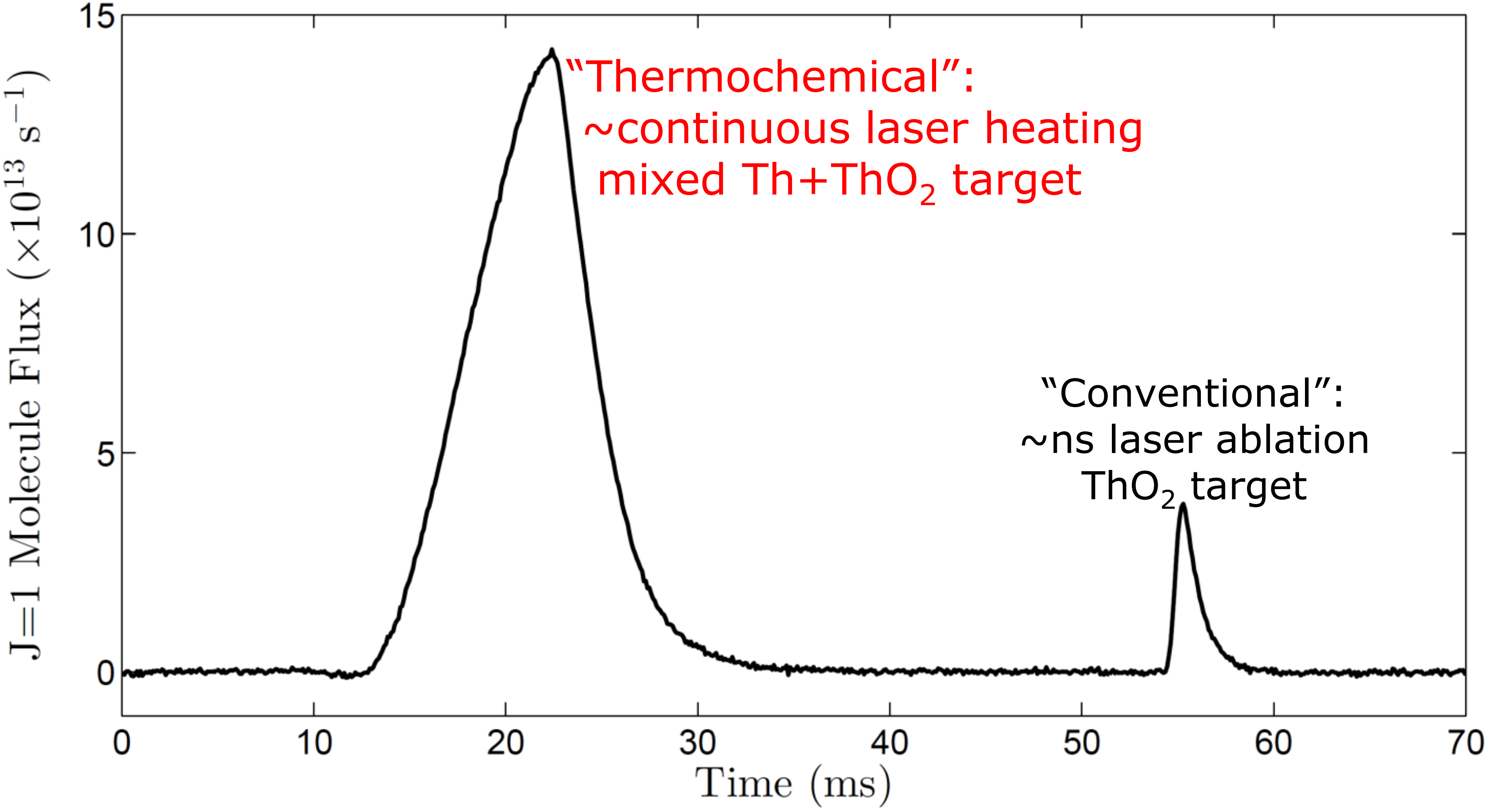


- Optical pumping via spontaneous emission
- ~1/8 of J=1 population pumped into final state



- Stimulated drive into final state
- Can be ~100% efficient (60% in test setup)
- Requires narrow (~kHz) lasers
- Requires new, orthogonal laser beam path
- New systematics seem controllable
- Scattered 690 nm laser light…?

New method for producing ThO vapor for beam

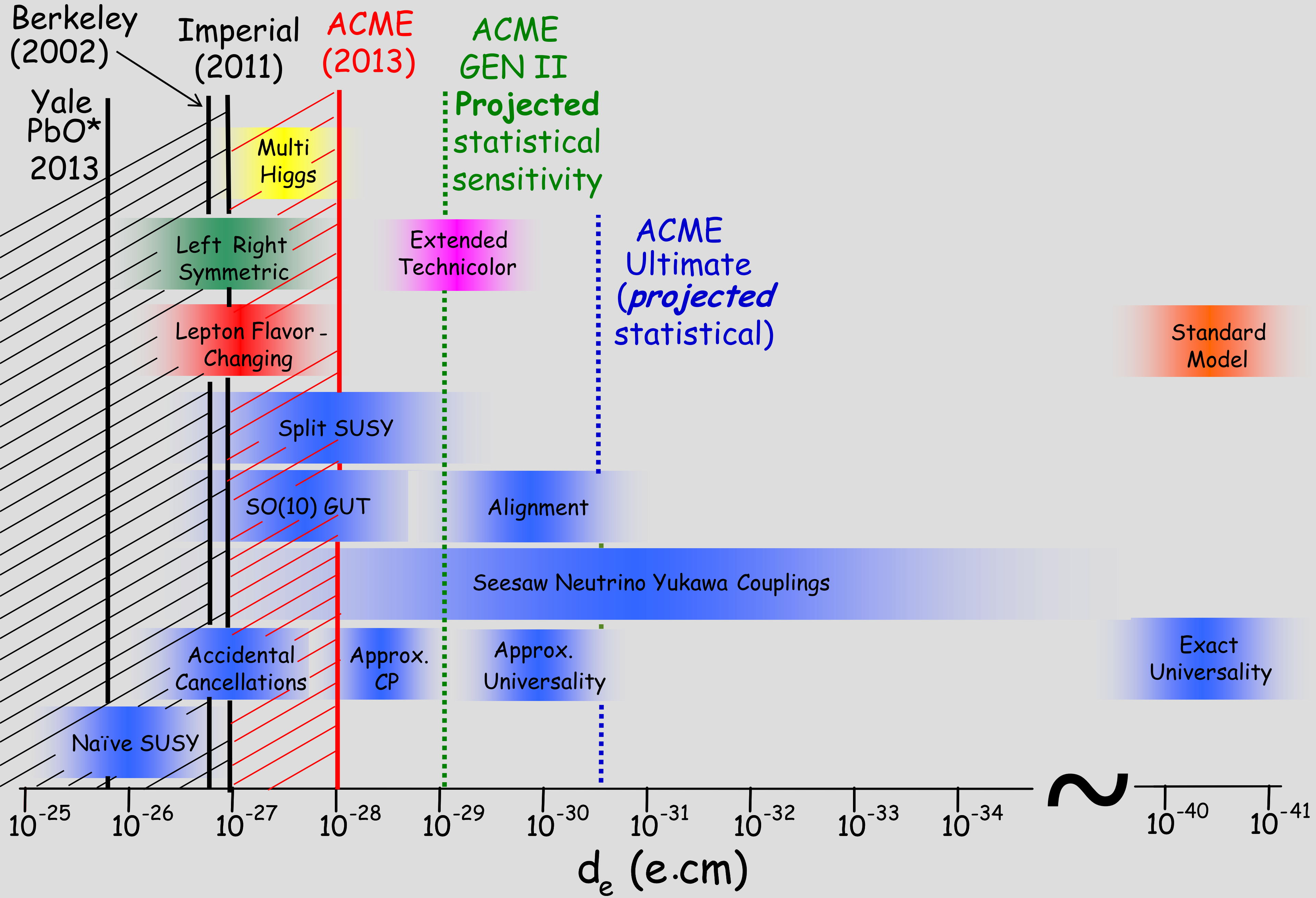


"Thermochemical":
~continuous laser heating
mixed Th+ThO_2 target

"Conventional":
~ns laser ablation
ThO_2 target

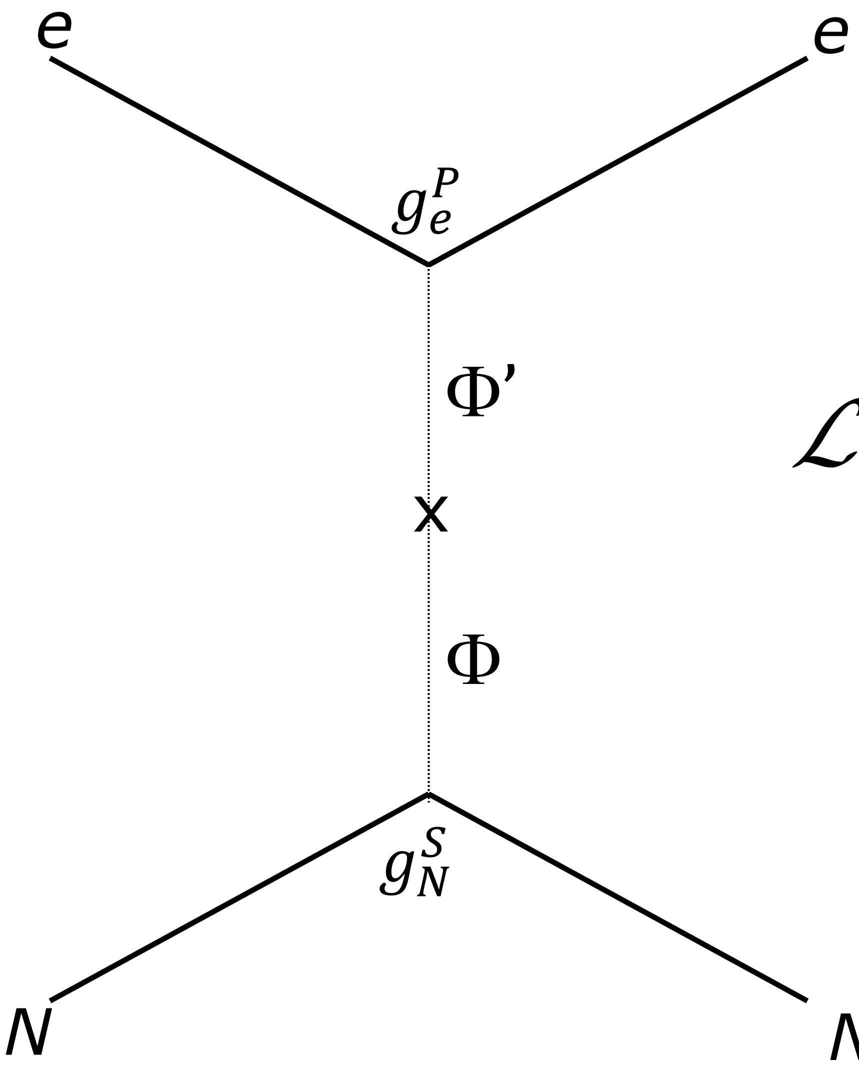
New source chamber with better cryocooling under construction; target development needed for dust control

New electron EDM limit from ACME



Extra Slides

New limit on electron-nucleon psuedoscalar-scalar interaction

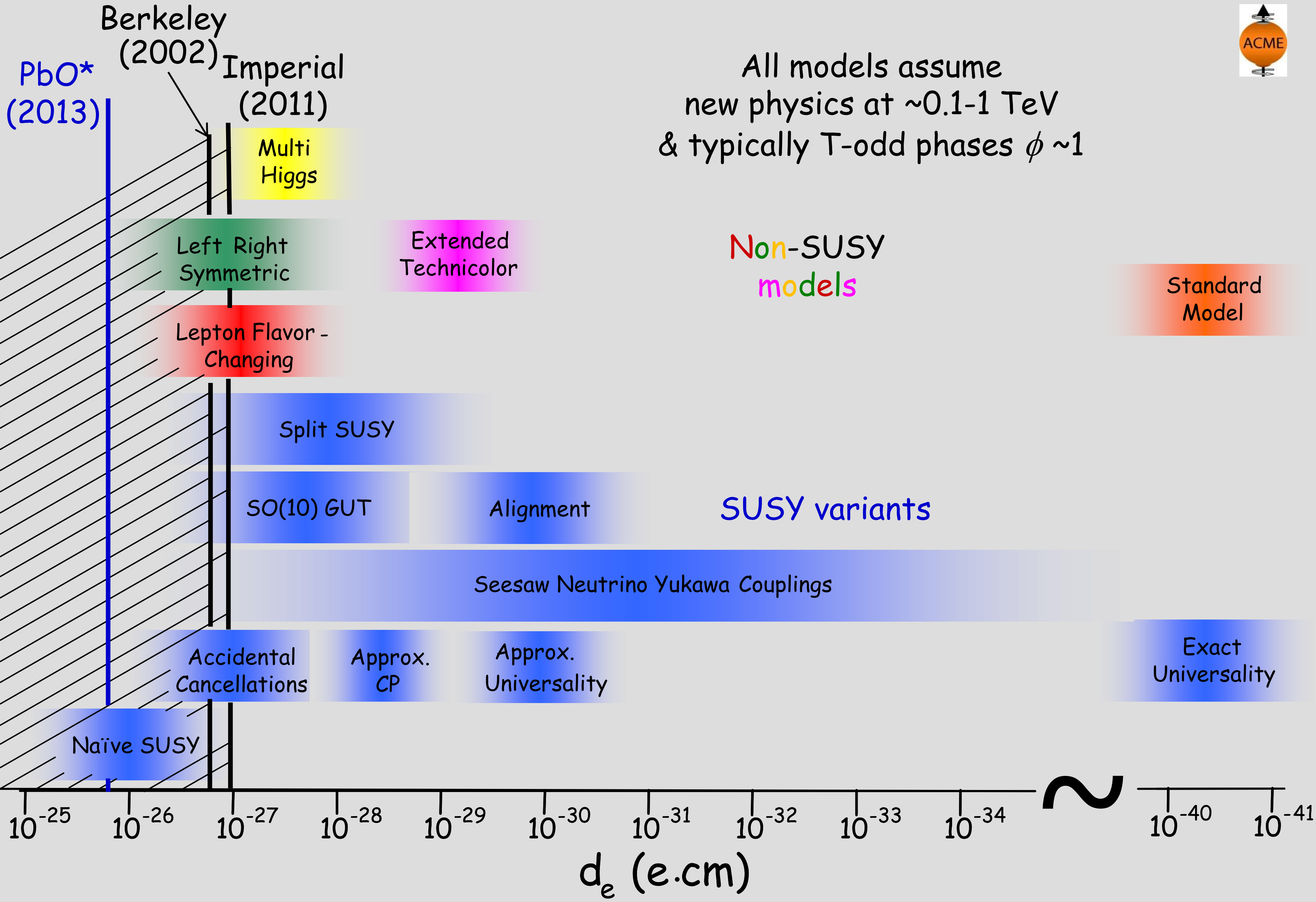


Parameterized with effective 4-fermion interaction:

$$\mathcal{L}_{eff} = C_S \frac{G_F}{\sqrt{2}} \bar{\psi}_e \gamma_5 \psi_e \bar{\psi}_N \psi_N$$

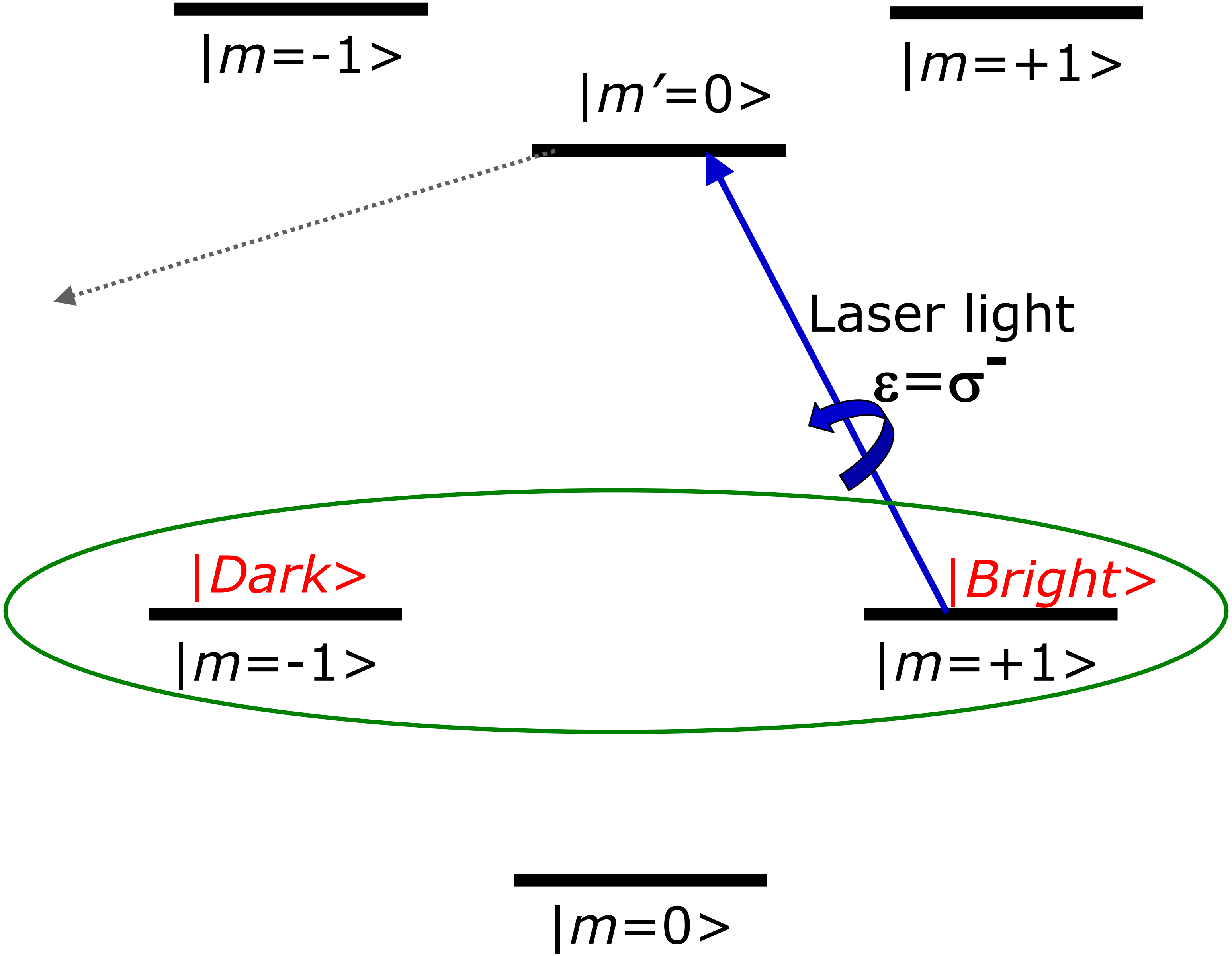
$$|C_S| < 6 \times 10^{-9}$$

Searching for new physics with electron EDM



All models assume
new physics at ~0.1-1 TeV
& typically T-odd phases ϕ ~1

Spin detection via dark & bright states



|*m*=-1>

|*m*′=0>

|*m*=+1>

Laser light

$\varepsilon=\sigma^-$

|*Dark*>

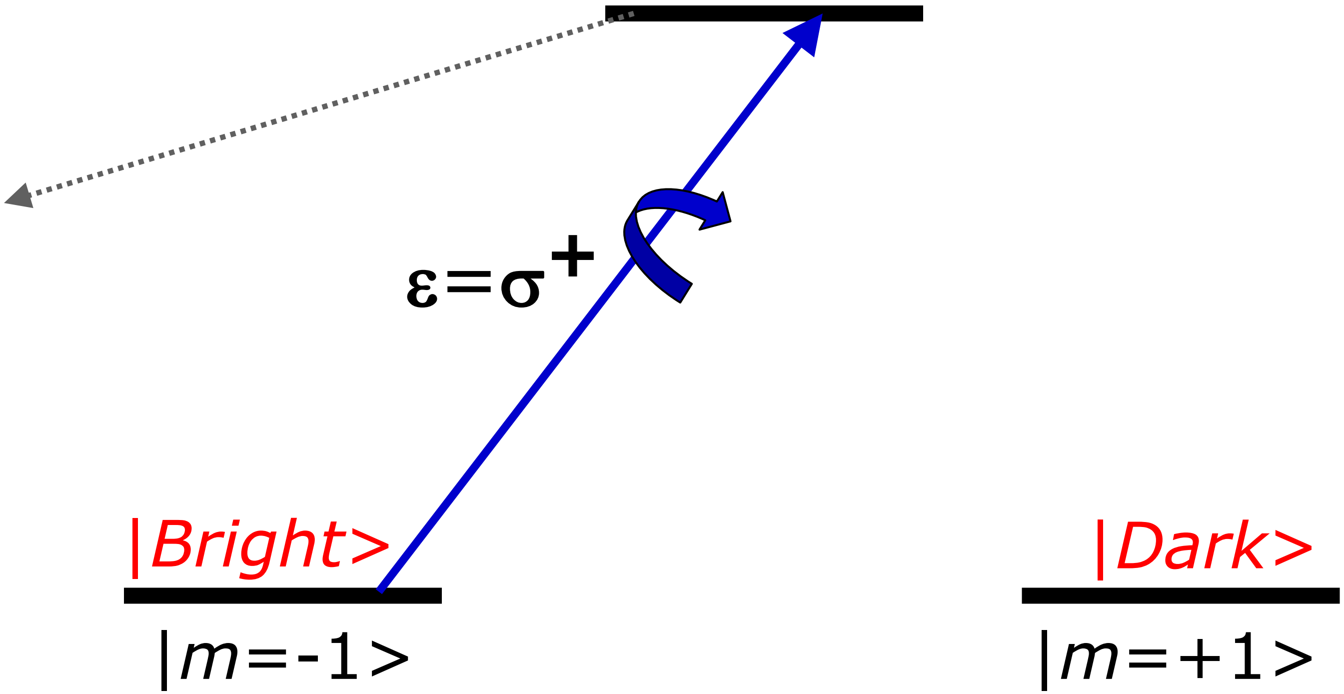
|*Bright*>

|*m*=-1>

|*m*=+1>

|*m*=0>

Spin detection via dark & bright states



$\varepsilon=\sigma^+$

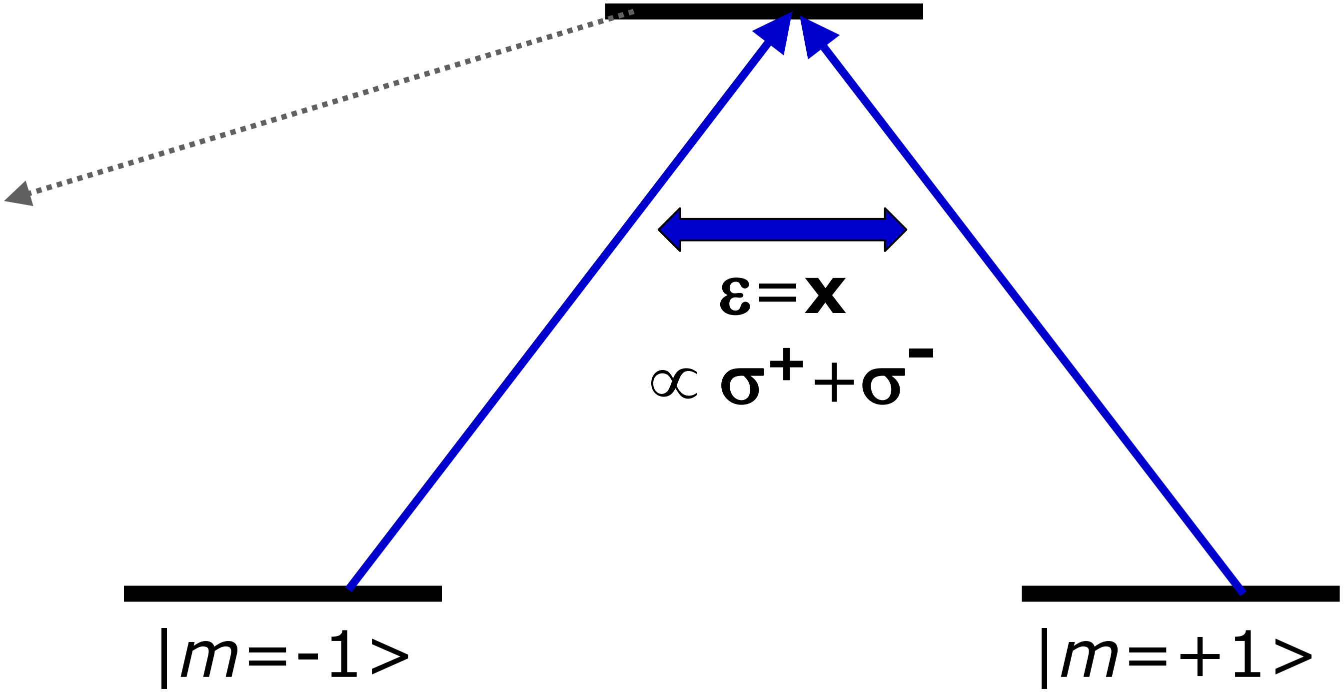
|*Bright*>

|*Dark*>

|*m*=-1>

|*m*=+1>

Spin detection via dark & bright states



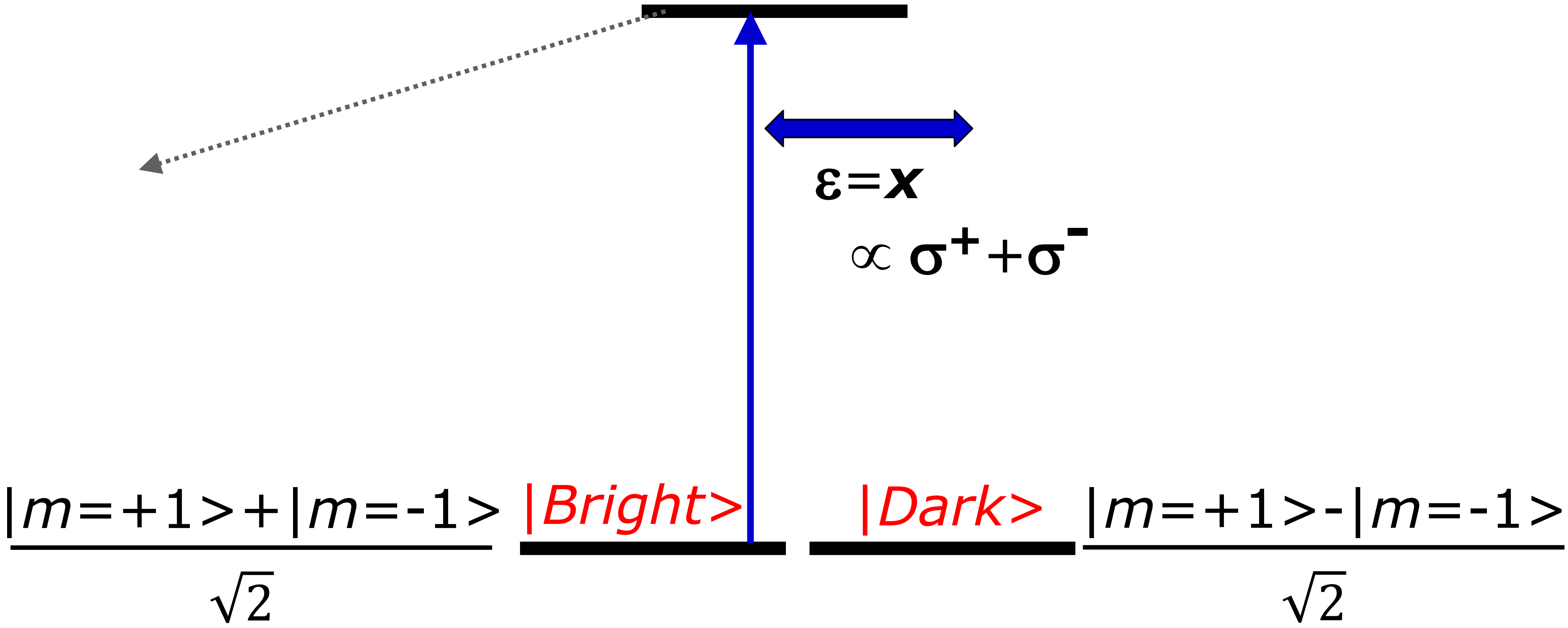
$\boldsymbol{\varepsilon} = \mathbf{x}$

$\propto \boldsymbol{\sigma}^{+} + \boldsymbol{\sigma}^{-}$

$|m=-1\rangle$

$|m=+1\rangle$

Spin detection via dark & bright states



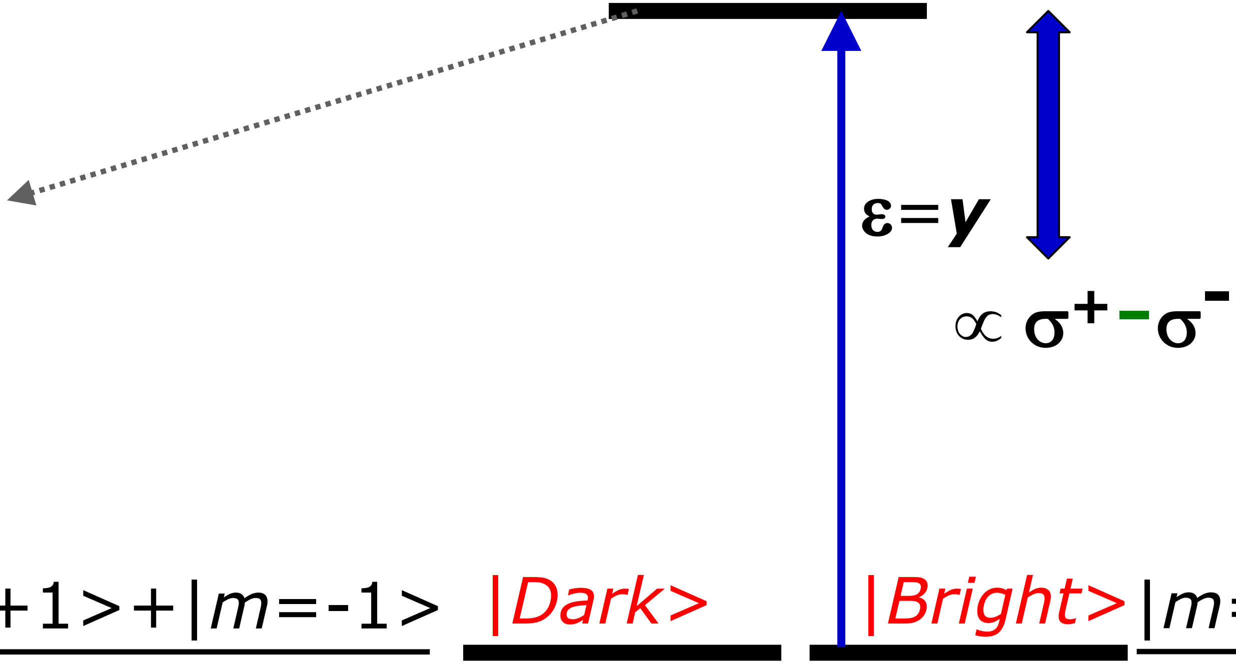
$\varepsilon = \boldsymbol{x}$

$\propto \sigma^{+} + \sigma^{-}$

$\frac{|m=+1>+|m=-1>}{\sqrt{2}}$ |*Bright*>

|*Dark*> $\frac{|m=+1>-|m=-1>}{\sqrt{2}}$

Spin detection via dark & bright states



$\varepsilon = \boldsymbol{y}$

$\propto \sigma^{+} - \sigma^{-}$

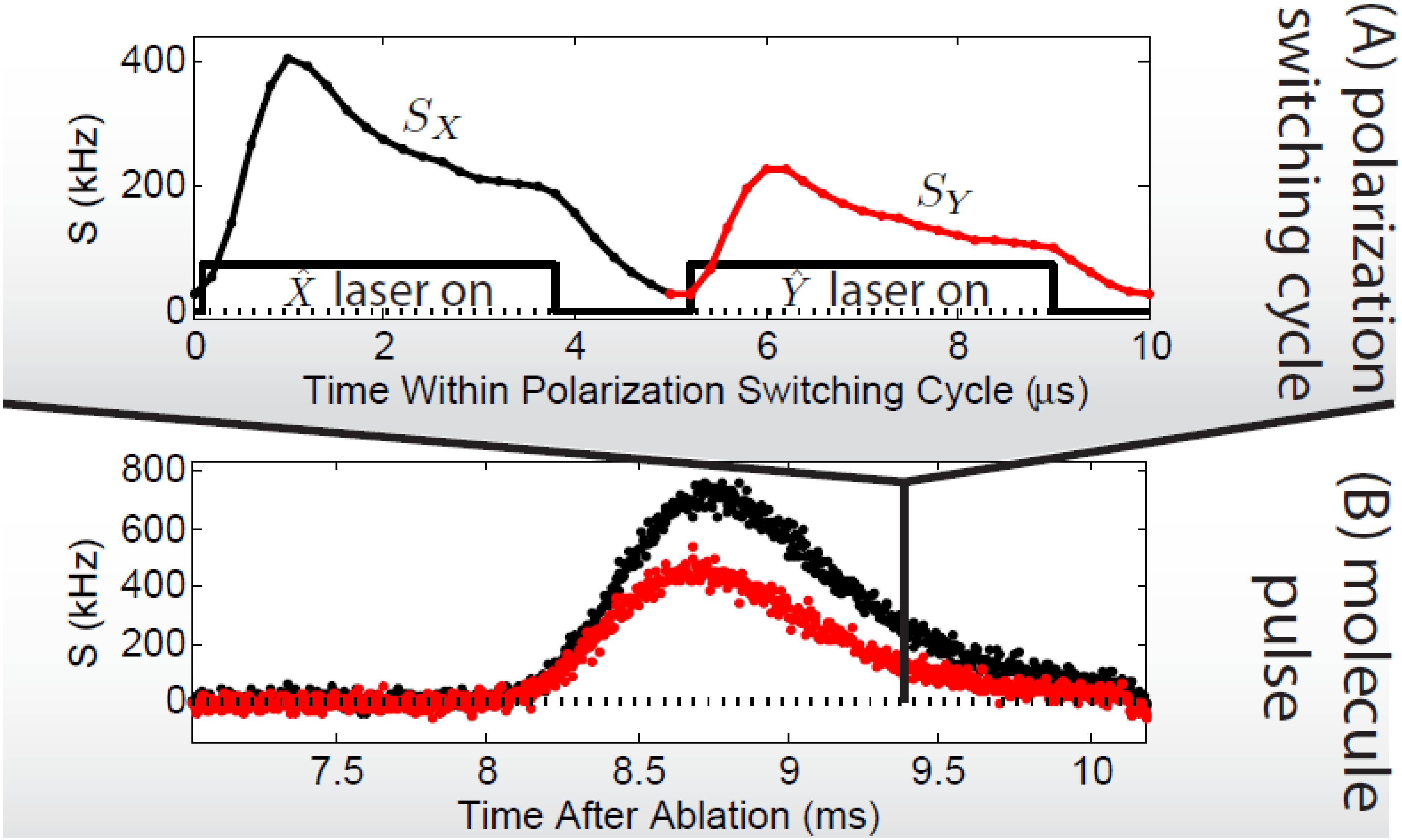
$$\frac{|m=+1\rangle + |m=-1\rangle}{\sqrt{2}}$$

|Dark>

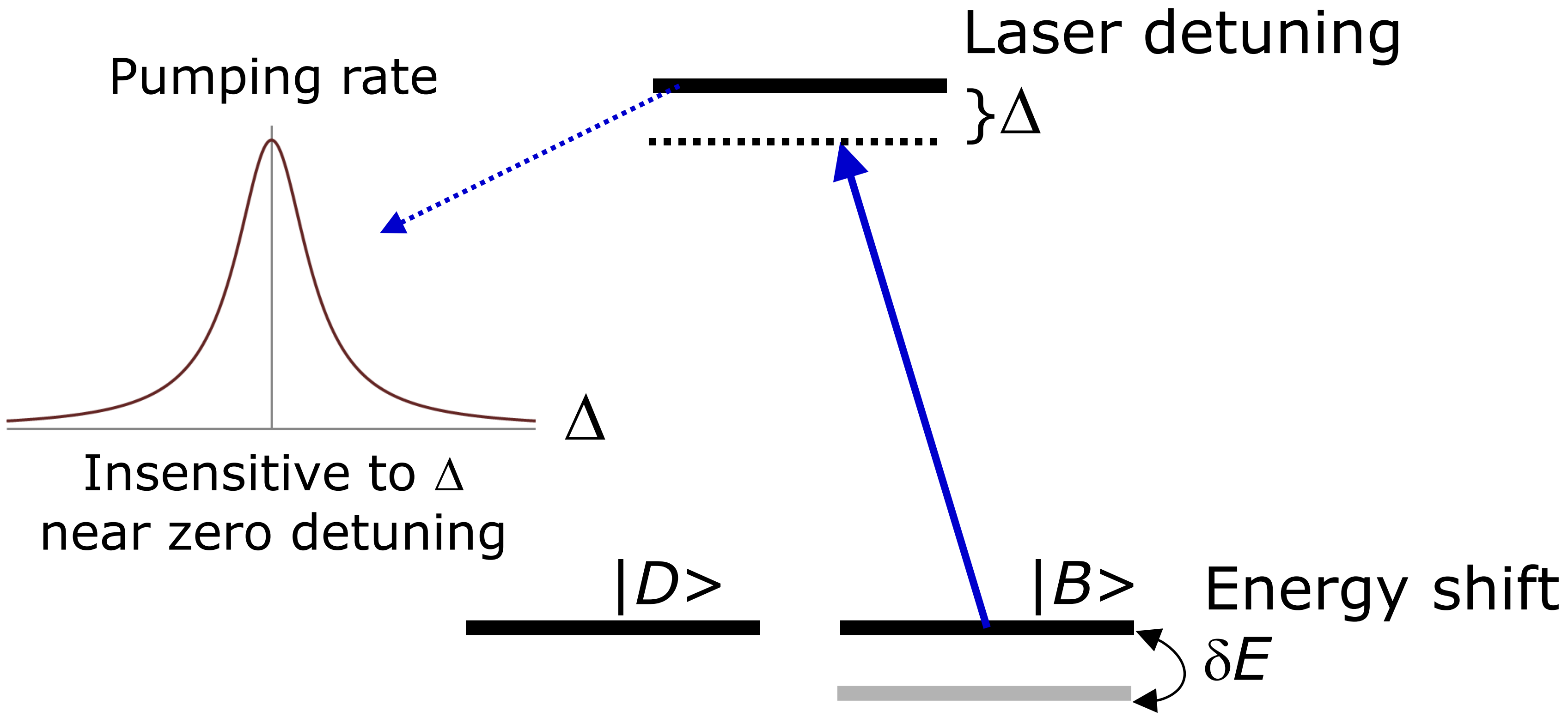
|Bright>

$$\frac{|m=+1\rangle - |m=-1\rangle}{\sqrt{2}}$$

Spin detection signal time scales

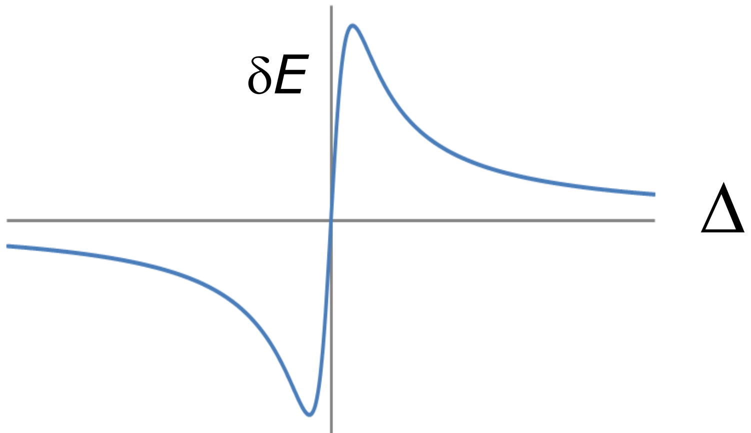


AC Stark shift in near-resonant light



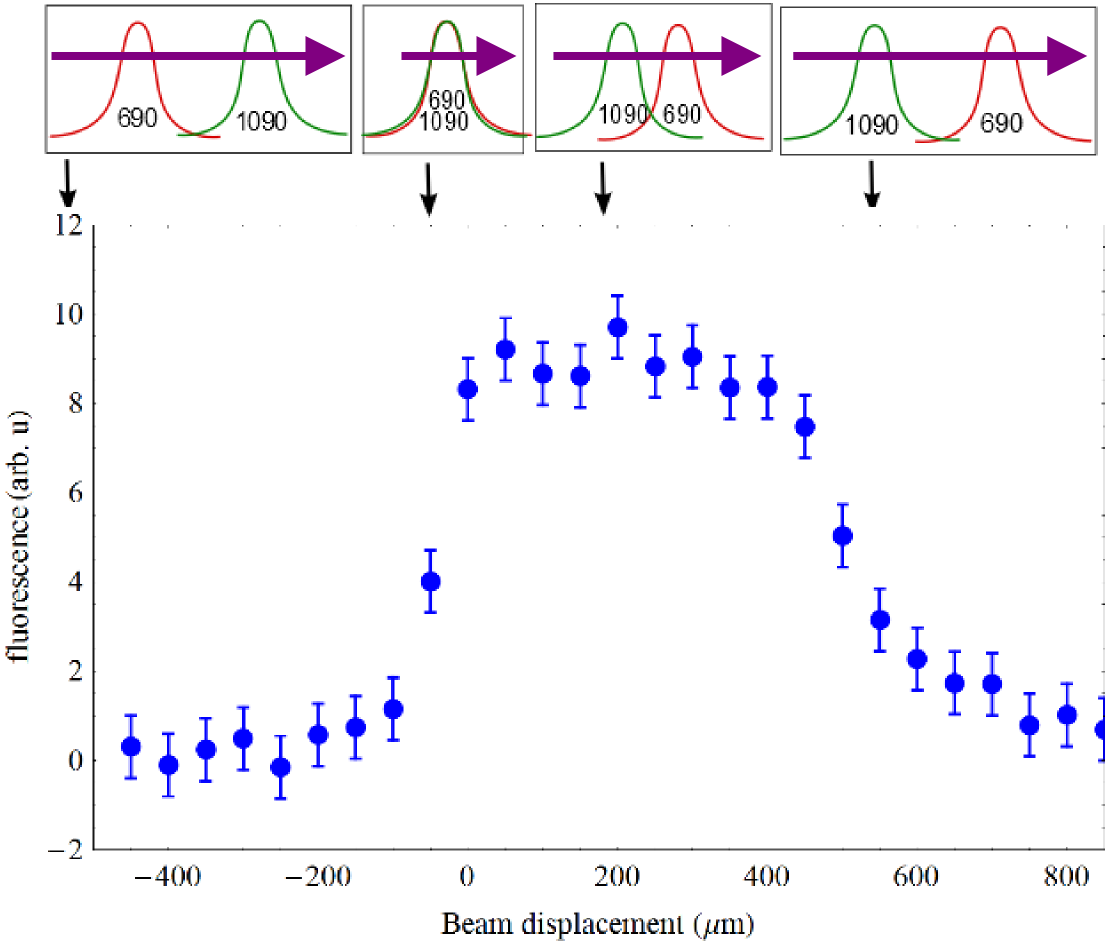
Insensitive to Δ
near zero detuning

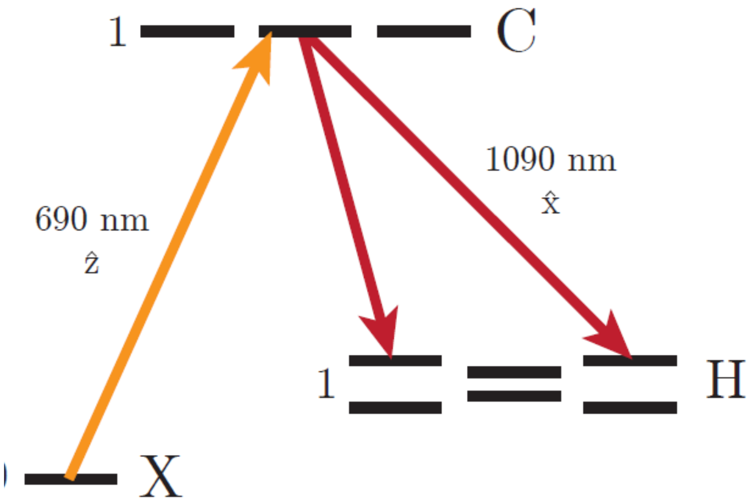
Vanishes at resonance
BUT:
Large slope vs. Δ
near zero detuning



Coherent state prep: STIRAP vs. optical pumping

Molecule motion through laser beams provides
“counter-intuitive” pulse sequence





Recent test data shows expected behavior for STIRAP

ACME 2nd Generation: Under construction