The electric dipole moment of the electron

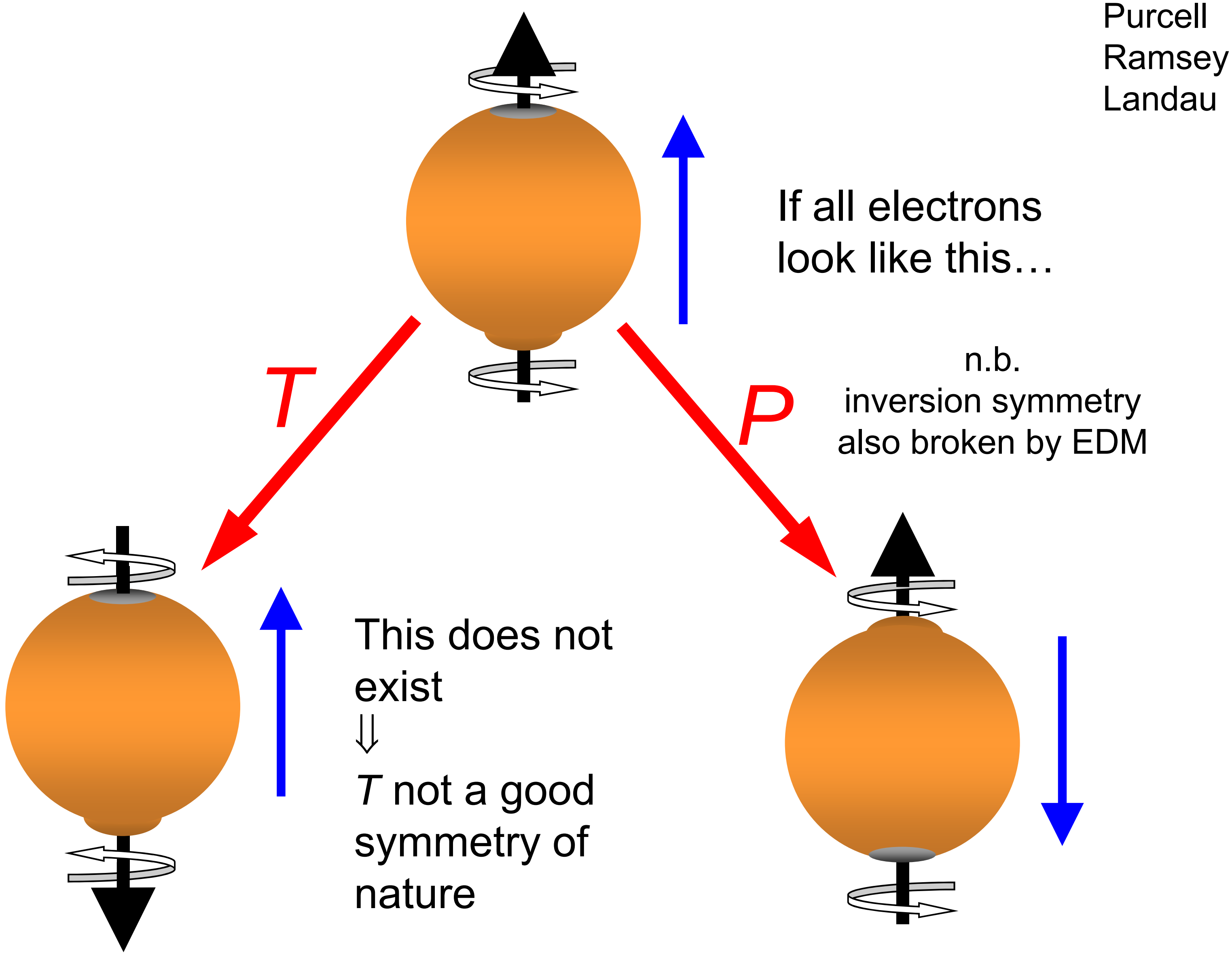
- Electric dipole moments (EDMs) and new particle physics
- How to detect an EDM
- Upper bound from the ACME experiment
- What it means, and where we go next

DeMille Group

Dave DeMille
Physics Department
Yale University

Funding
NSF

An EDM violates time-reversal symmetry



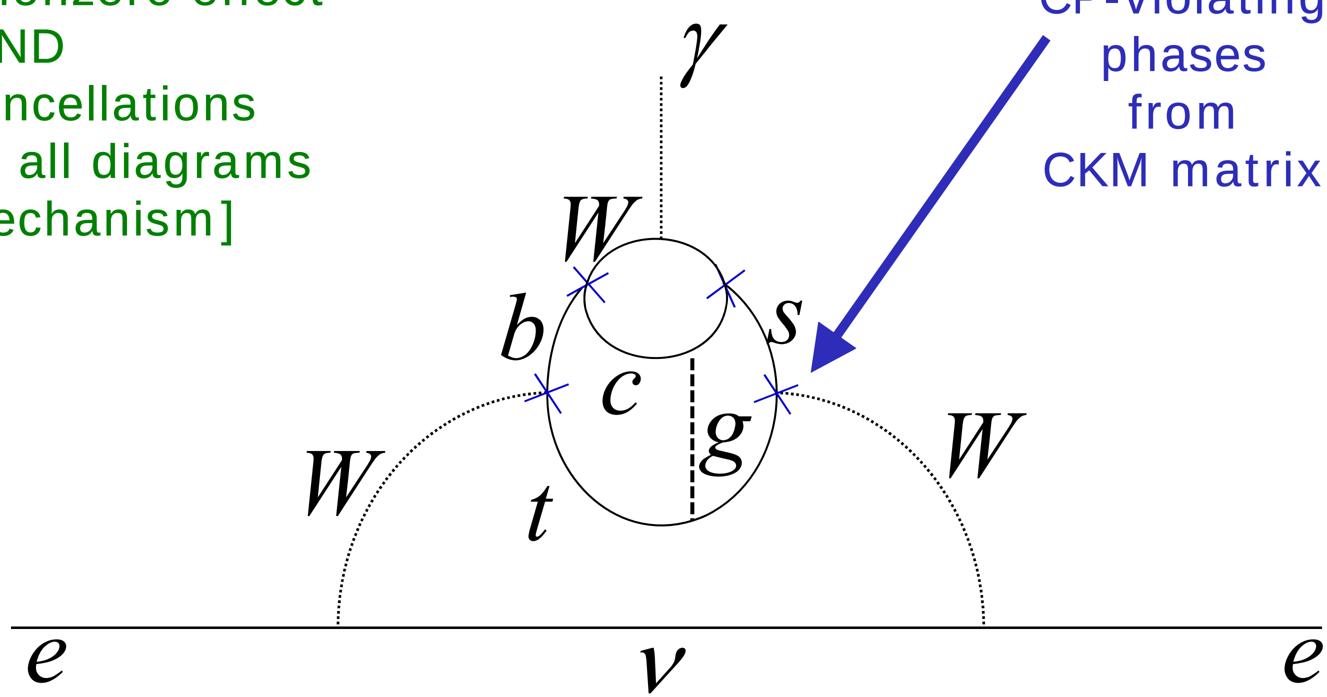
CPT theorem ⇒ T-violation = CP-violation

Q. How can a T-violating electron EDM arise?

A. From radiative corrections, with CP-violating interactions

Standard Model

4-loops for nonzero effect
AND
severe cancellations
in sum over all diagrams
[GIM mechanism]

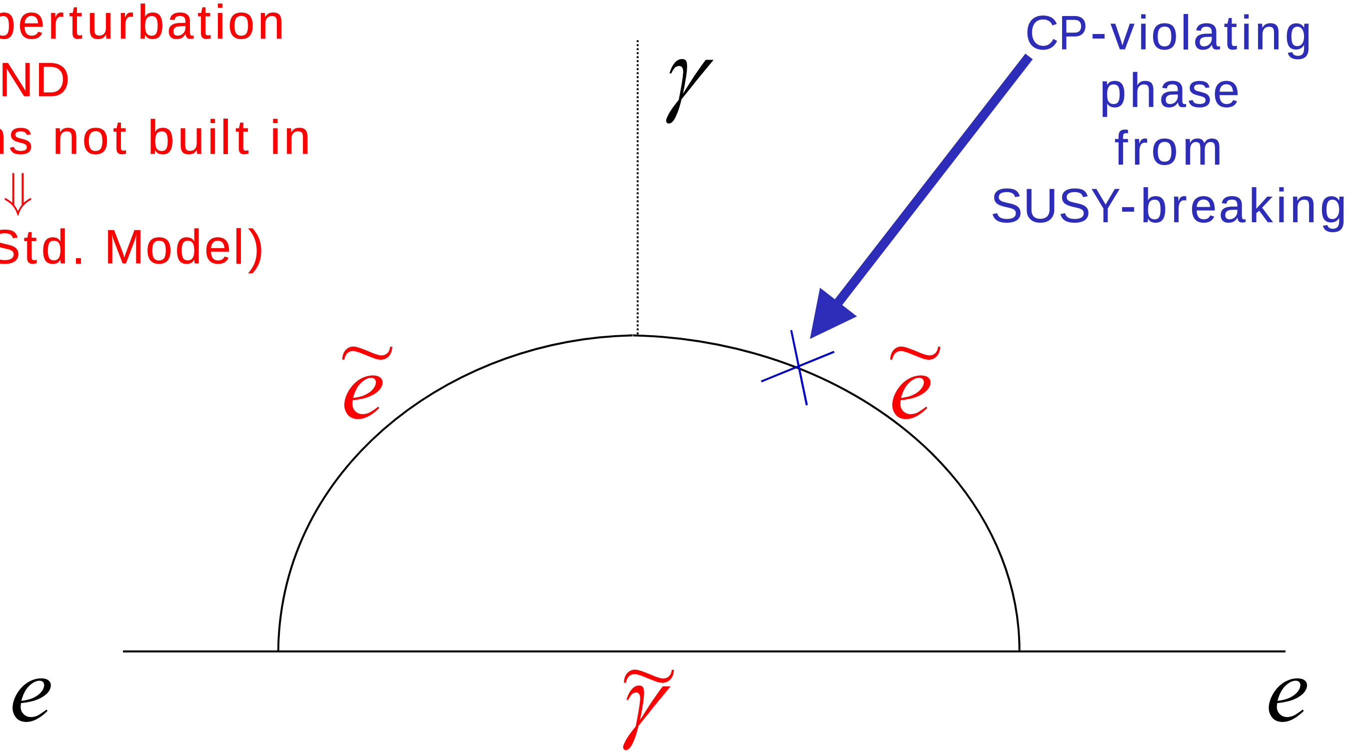


Q. How can a T-violating electron EDM arise?

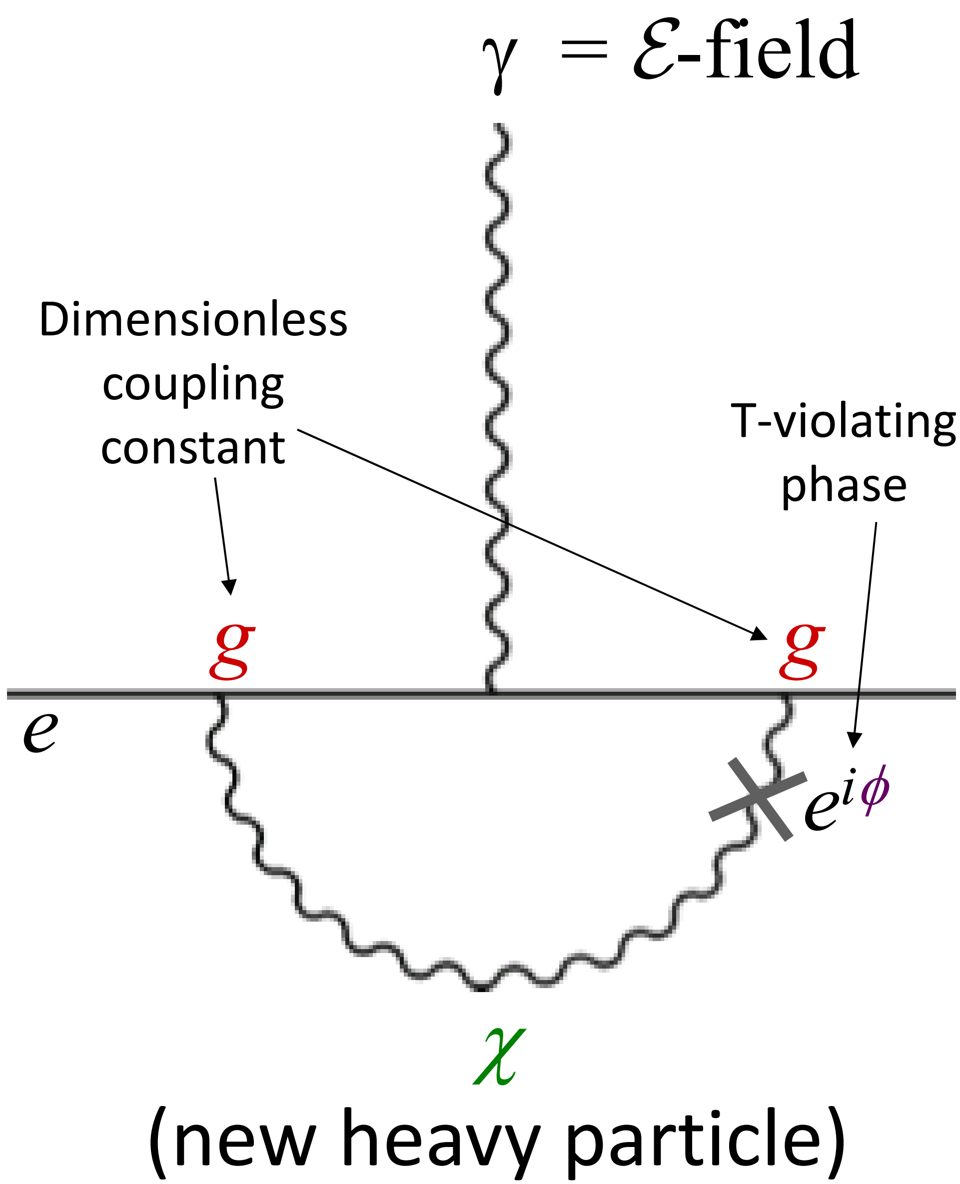
A. From radiative corrections, with CP-violating interactions

Supersymmetry

1st order perturbation
AND
cancellations not built in
⇓
$d_e \gg d_e$ (Std. Model)



Dimensional estimate for size of EDM



typical e-*EDM*

$$d_e \sim \mu_B \left(\frac{g^2}{2\pi}\right)^N \left(\frac{m_e}{m_\chi}\right)^2 \sin\phi$$

N = # loops

"natural" assumptions

$g^2/\hbar c \approx \alpha$

$\sin(\phi) \sim 1$

$m_\chi \sim 1\ \mathrm{TeV}$

$\Downarrow$

$d_e \sim 30\times$ current limit

(for *N* = 1 loop)

Artist's impression of an electron EDM...

Note the resemblance to 0…

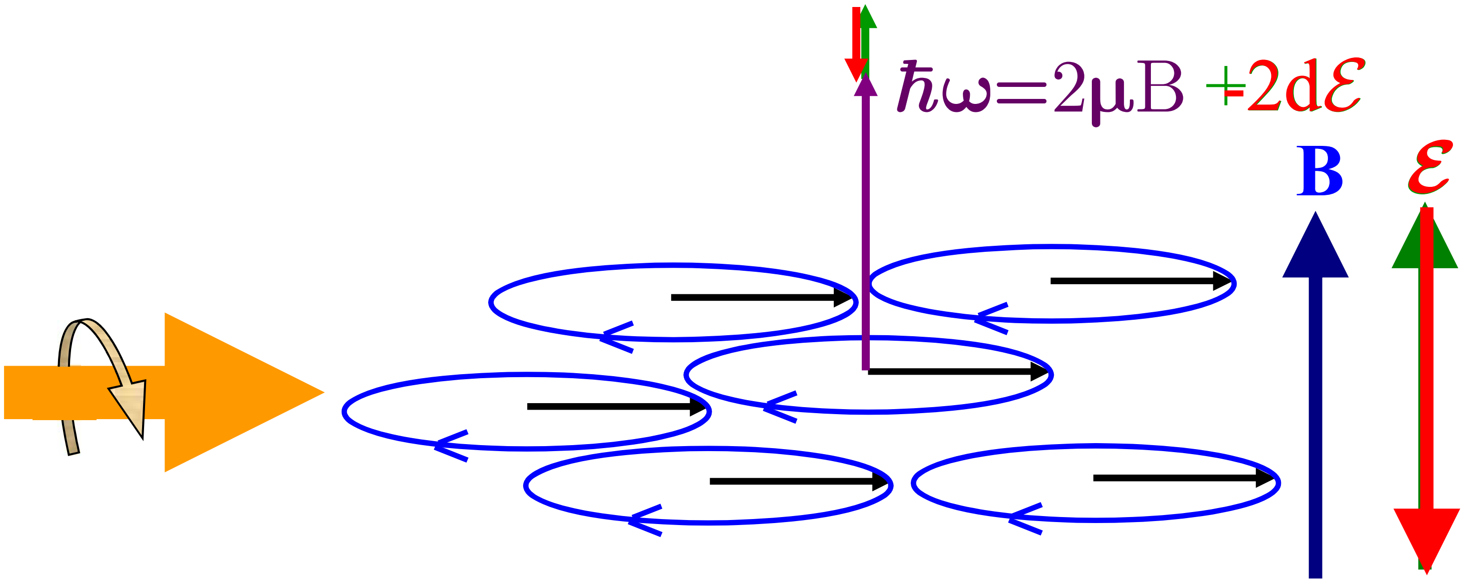
any EDM must be VERY small

QED radiative correction scale
$[\alpha/2\pi]\ \mu_B/e \sim 10^{-13}$ cm
:
Size of earth ~10^4 km

::

eEDM charge displacement
:
<20 nanometers

General method to detect an EDM



Energy level picture:

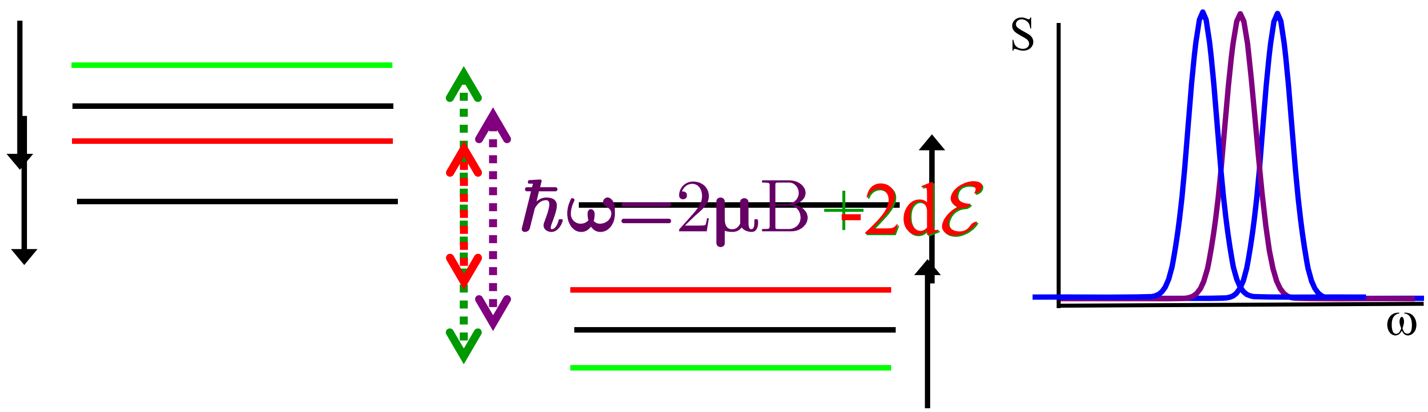
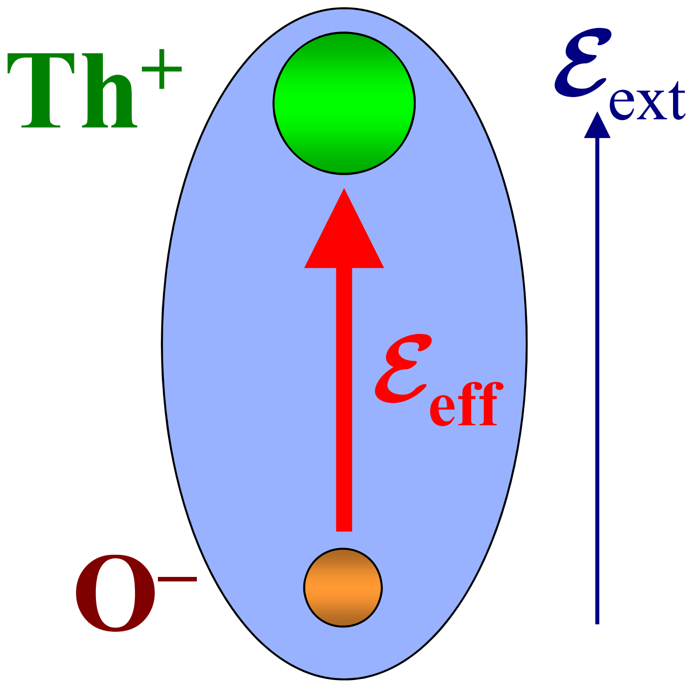


Figure of merit:

$$\frac{shift}{resolution} = \frac{d\mathcal{E}}{(1/\tau_{coh})(S/N)^{-1}} \propto \mathcal{E}\cdot\tau_{coh}\cdot\sqrt{\dot{N}\cdot T_{\text{int}}}$$

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



Small energy splittings
(rotational levels)
enables polarization $\mathcal{P}$ ~ 100%
with $\mathcal{E}_{ext}$ ~ 10 V/cm

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

P. Sandars
1965

$\mathcal{E}_{eff} \cong$ 80 GV/cm for ThO* [near theoretical maximum]

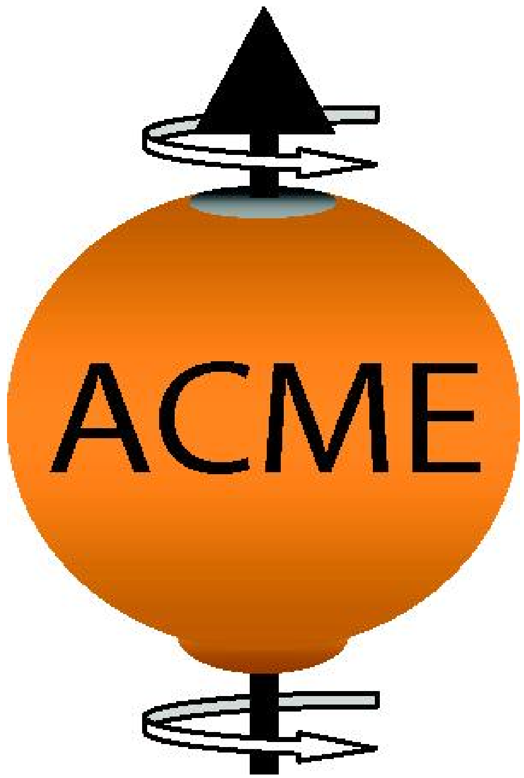
Meyer & Bohn (2008); Skripnikov, Petrov & Titov (2013, 2015); Fleig & Nayak (2014)

Requires unpaired electron spin(s): chemical free radical

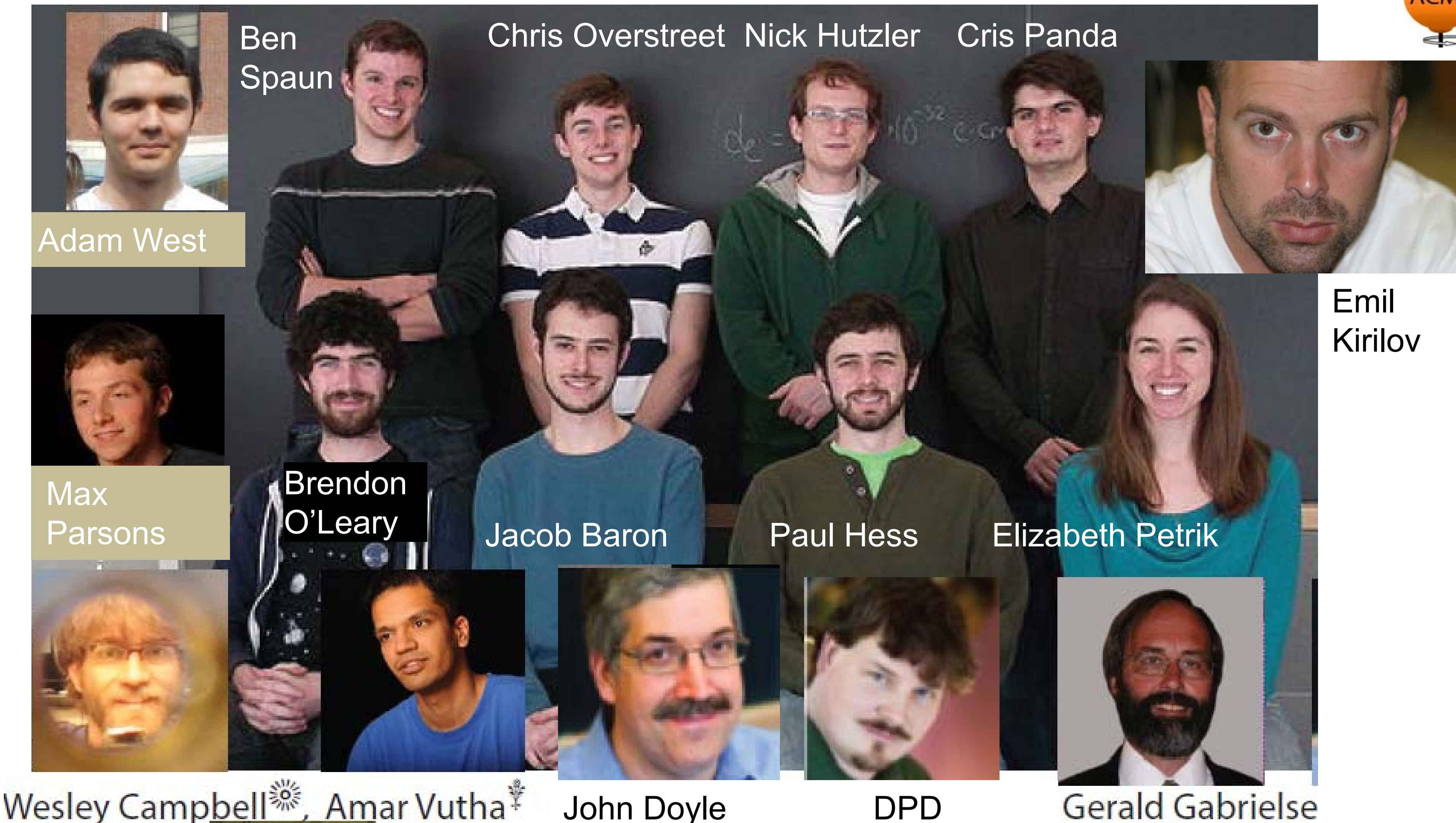
Advanced Cold-Molecule Electron EDM

Yale University

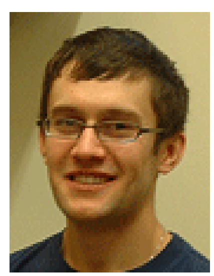
Harvard University



The ACME team 2009-2014



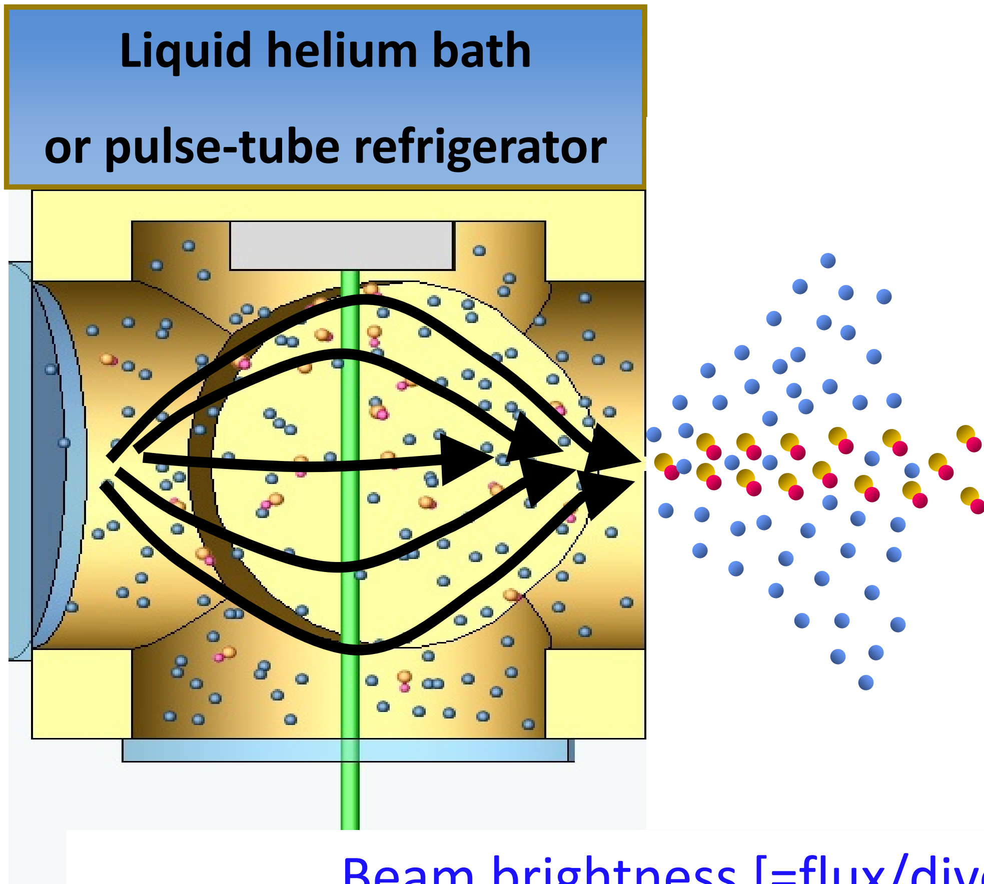
Yulia Gurevich



Ivan Kozyryev

New molecular beam technology: Cryogenic Buffer Gas-cooled Beam (CBGB)

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



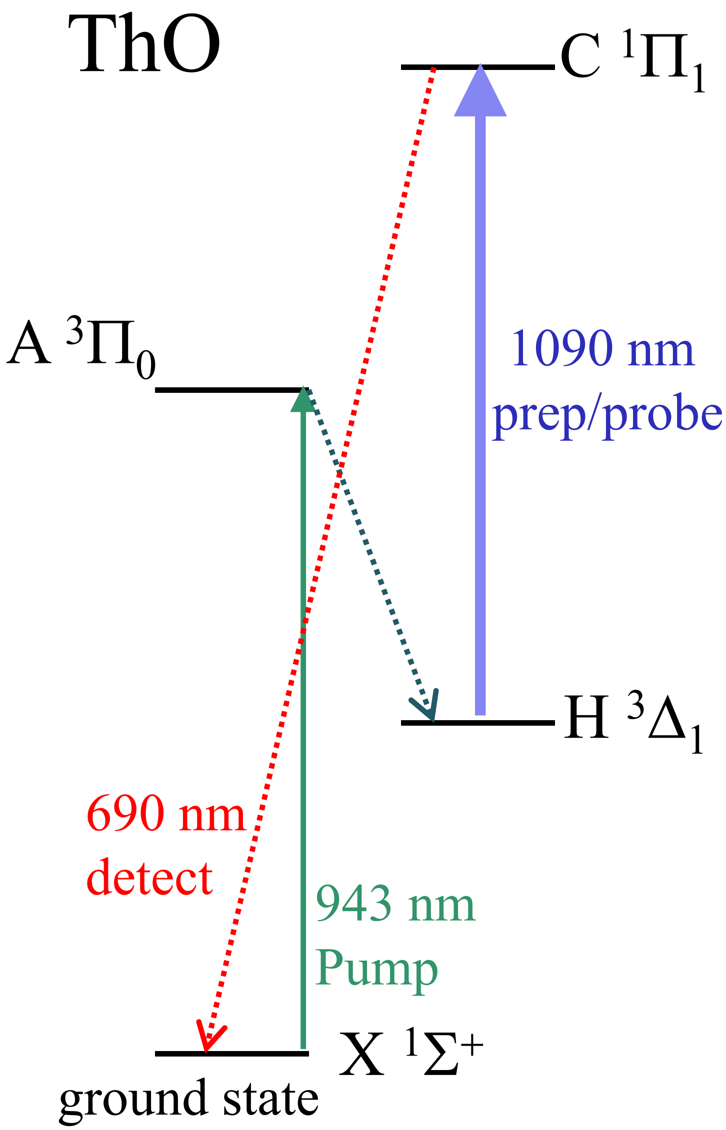
- Inject hot molecules (e.g. via laser ablation)
- Cool w/cryogenic buffer gas *@high density*
- **Efficient** extraction to beam via "wind" in cell: $10^{-4} \rightarrow$ 10%-40%
- "Self-collimated" by extraction dynamics
- **Rotational cooling** in expansion: T ~ 1 - 4K
- **Moderately slow:** $v \sim$ 130-180 m/s

Beam brightness [=flux/divergence] ~ ***10^3 -10^4 × larger***
vs. other sources for refractory/free radical species
typically ~ 2×10^{11} mol/sr/state/pulse @ $\gtrsim$10 Hz rep. rate

Used for **SrF**, **ThO**, BaF, YO, CaF, O_2, NH_3, Yb, …

"New" molecular species: ThO*

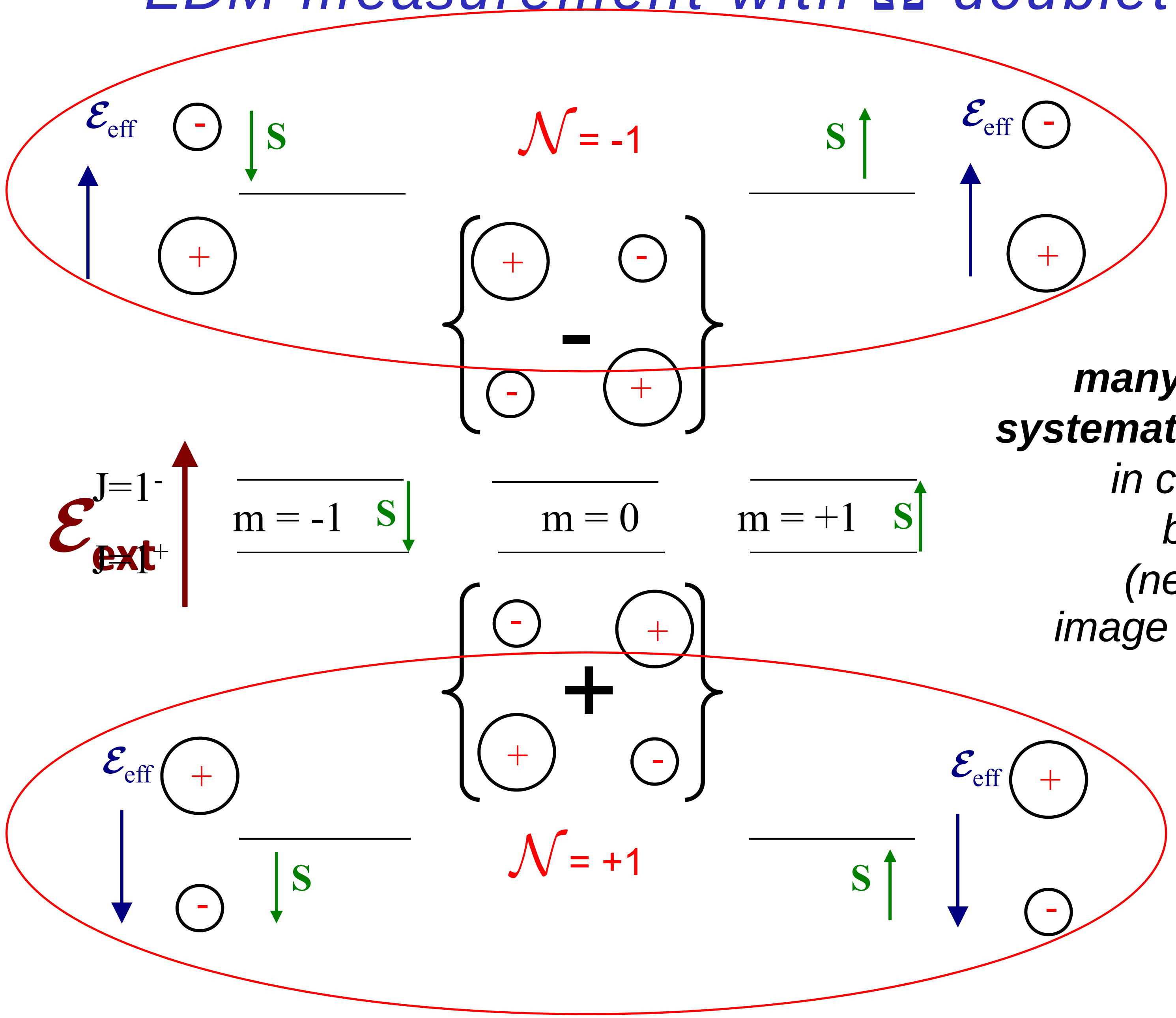
[A.C. Vutha *et al.* J. Phys B 2010]



- **Largest effective internal $\mathcal{E}$:** ~80 GV/cm
  [Titov *et al.* 2013/2015, Fleig *et al.* 2014]
- **Sufficient coherence time** (~1.9 ms max)
  lifetime of metastable state $H\ ^3\Delta_1$
- **Suppressed magnetic moment**
  <0.01 μ_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]
- **Omega-doublet co-magnetometer**
  suppresses many possible systematics
- 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

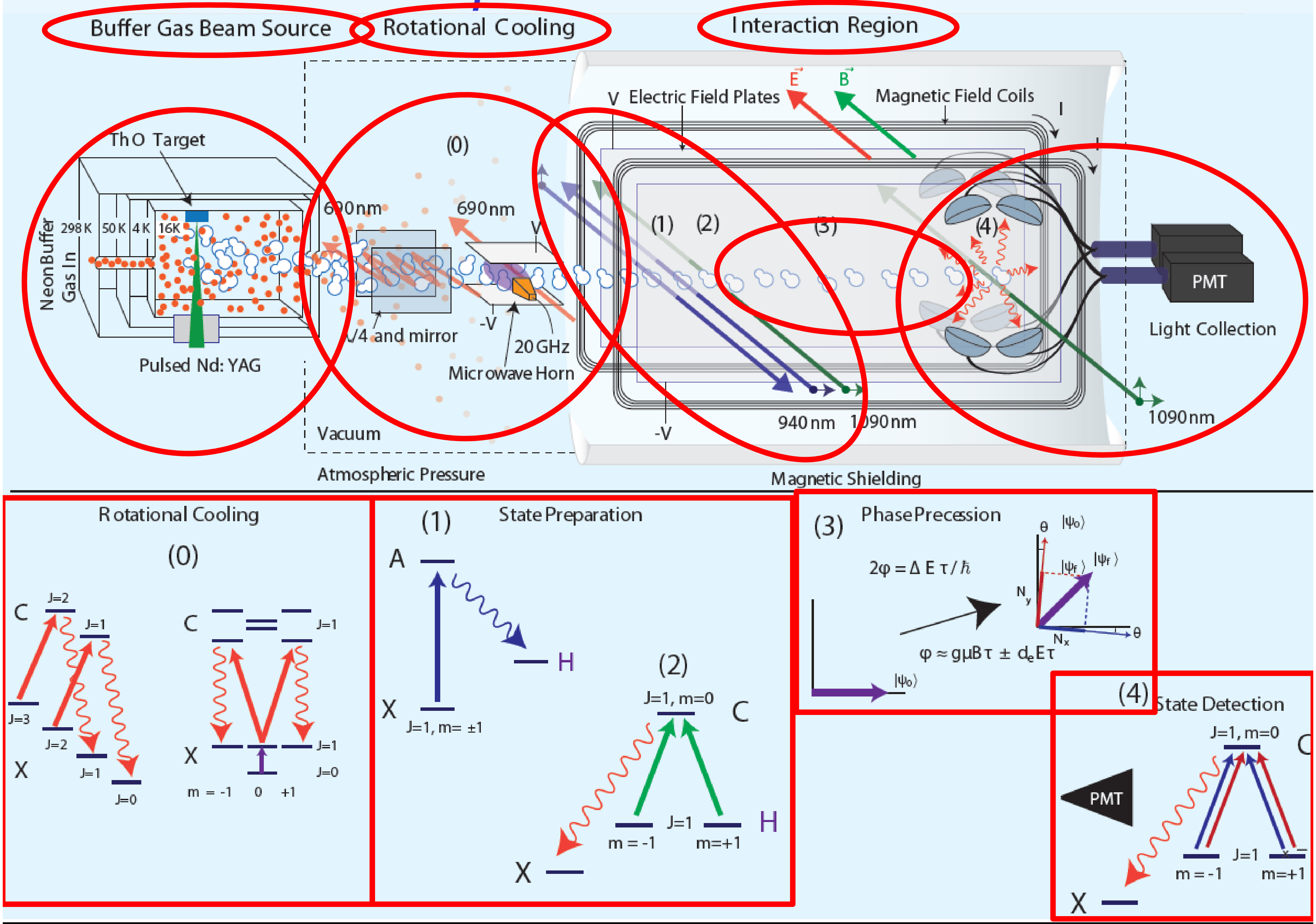
EDM measurement with Ω-doublet states



many dangerous systematic errors cancel
in comparison between (near-)mirror image $\mathcal{N}$ = ±1 states

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

ACME experimental schematic



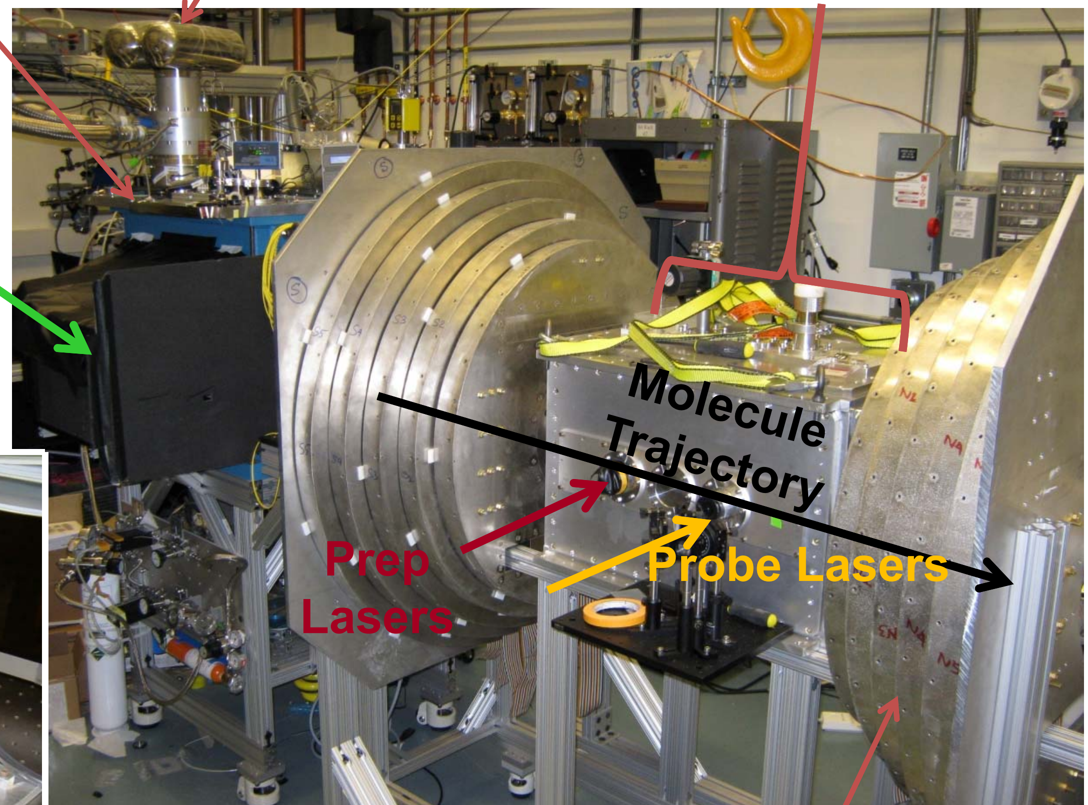
ACME apparatus

Molecular Beam Source

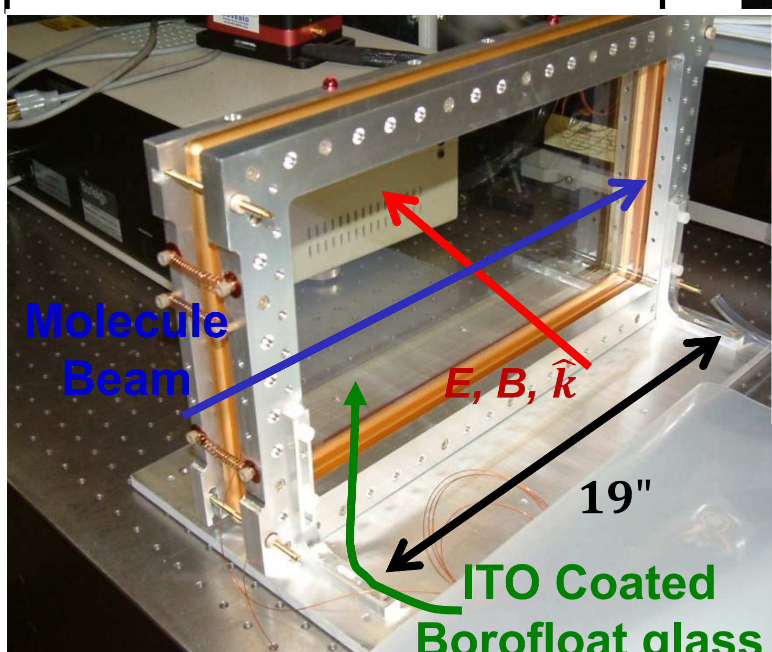
Pulse Tube Cryo Frig

Interaction Region:
internal $\mathcal{E}$-field plates & external *B*-field coils
(not shown here)

Pulsed ablation laser



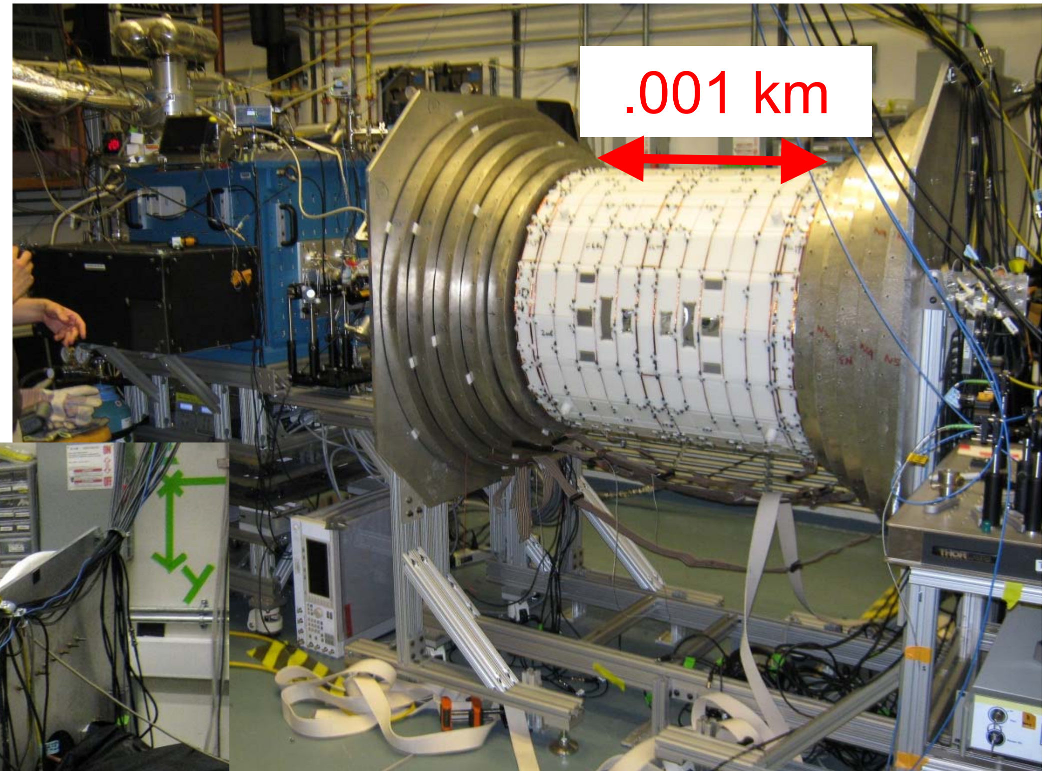
Transparent Field Plates

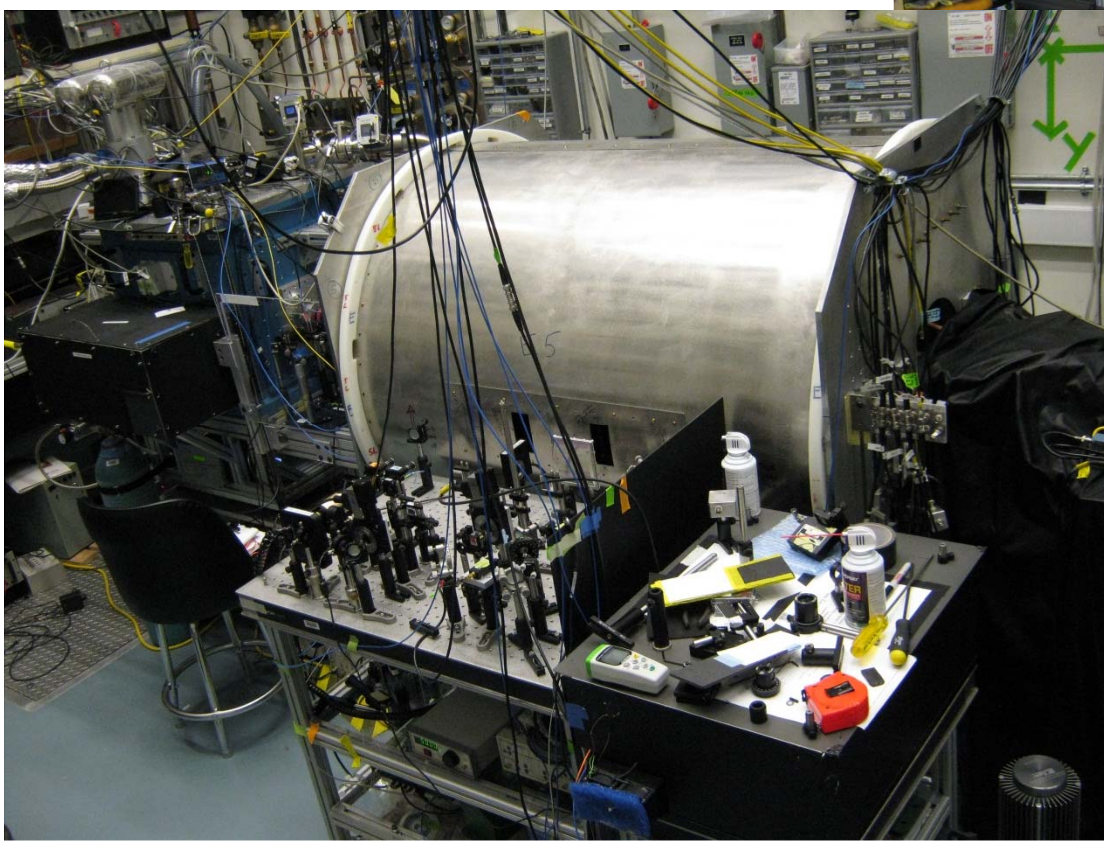


μ-metal shield endcaps
(5 layers)

ACME apparatus

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

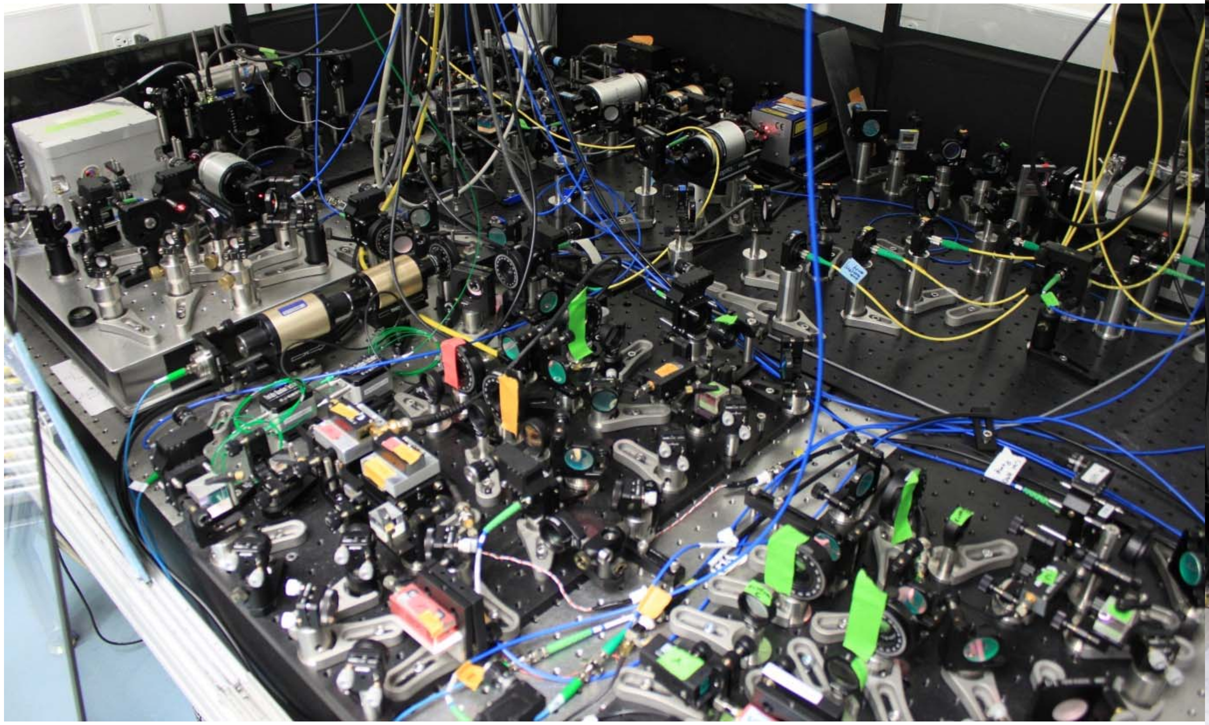




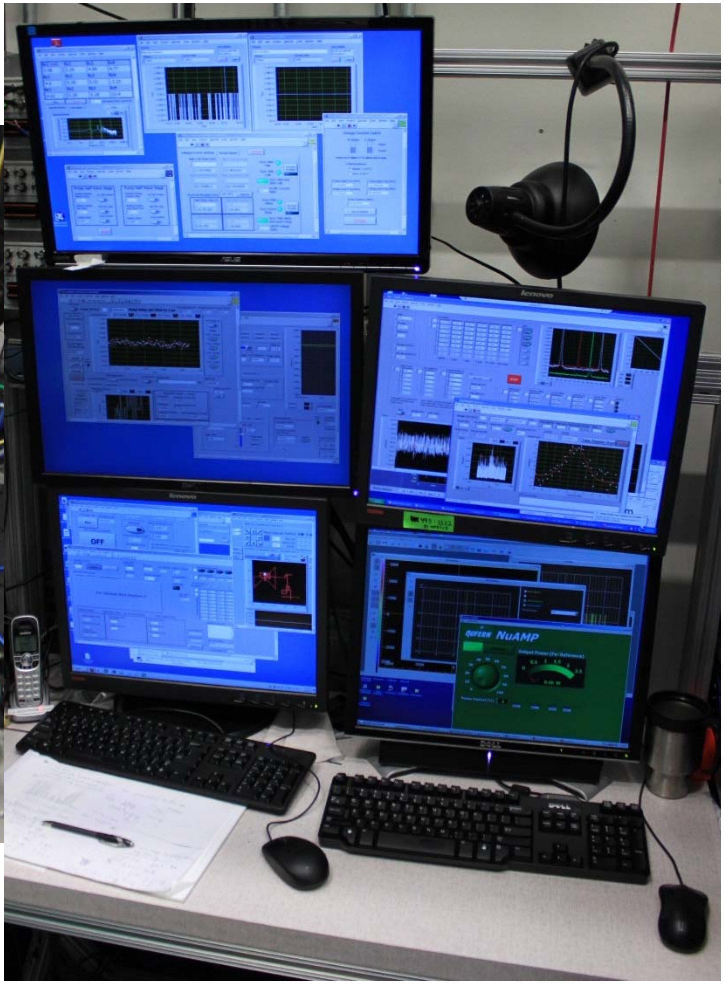
Complete
beam source
& magnetic shields
& last-stage optics

ACME apparatus

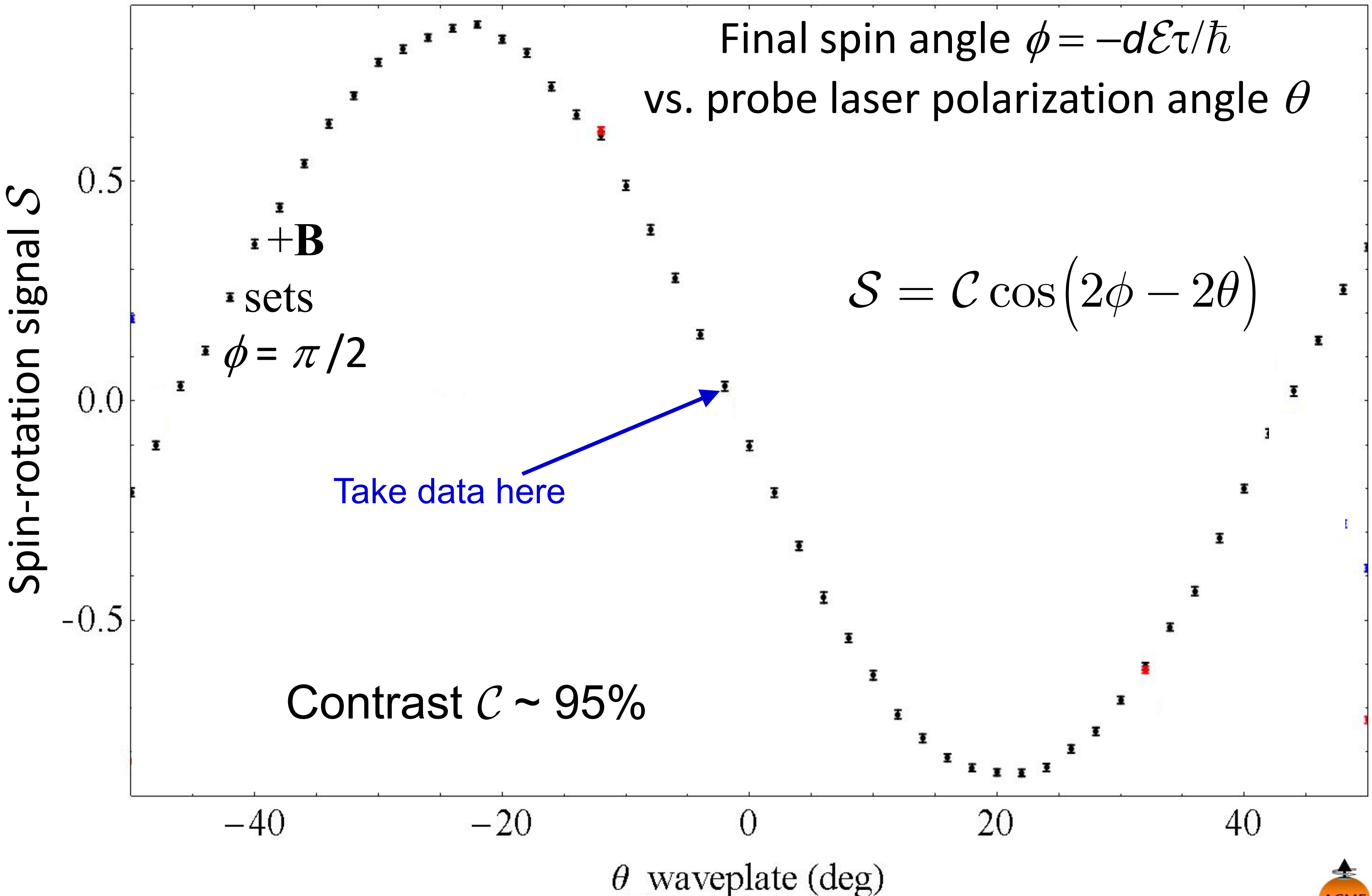
One of several optical tables w/
~ten lasers, dozens of modulators,
hundreds of meters of optical fiber, etc.
spread over two buildings



"control room"



Typical spin-rotation fringe signal



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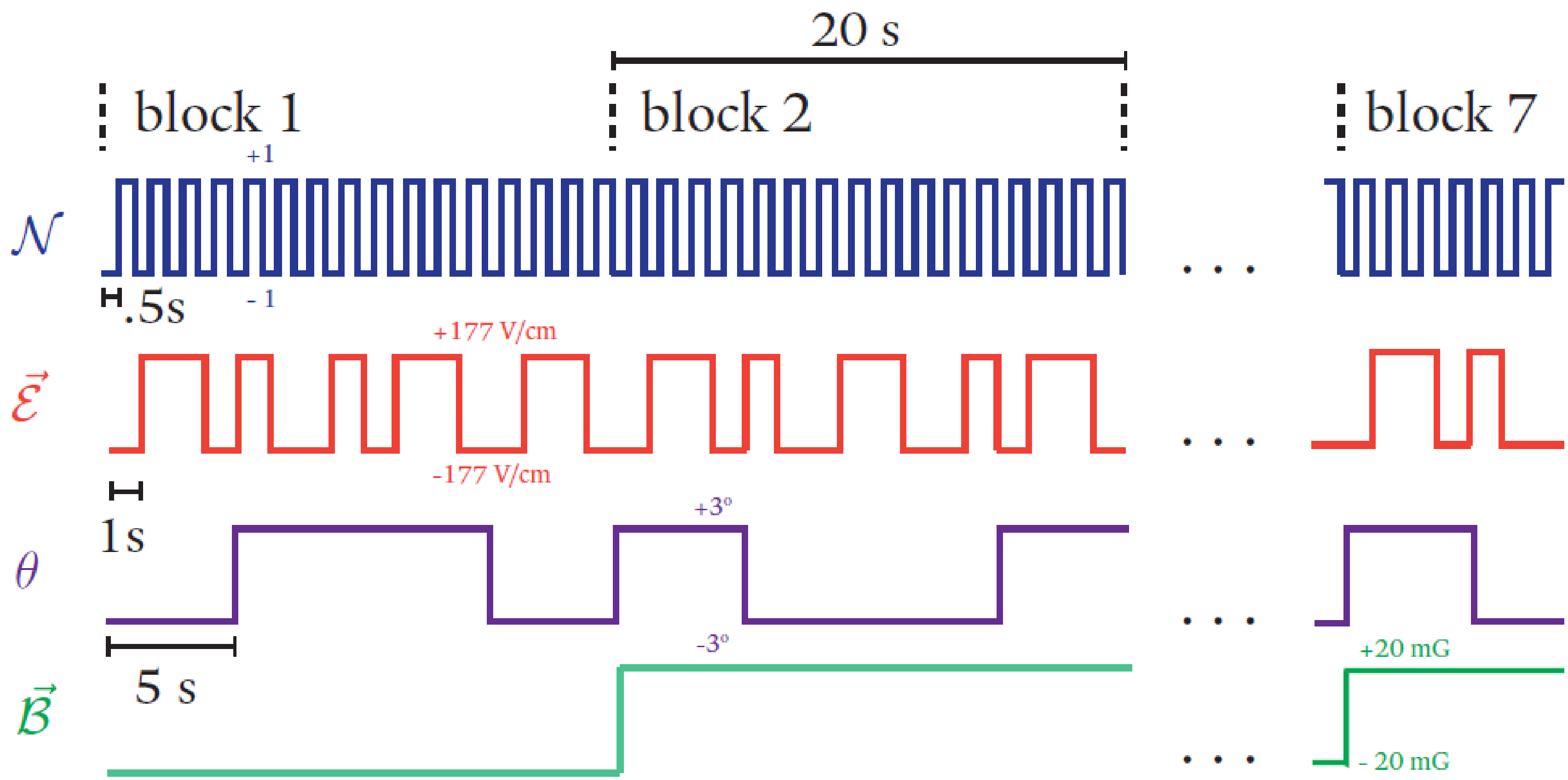
Primary machine settings to extract the EDM



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

Data sorting & 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 measure physical contributions:

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

EDM

Spurious terms

Symmetries ensure systematic errors due ONLY 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:

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

EDM

Experimental imperfections

Most imperfections also appear in *other* correlated phases

BUT GREATLY AMPLIFIED

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

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

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

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

$\Rightarrow$"Other" correlated phases diagnose imperfections

ACME

Search strategy for systematic errors

Switch-correlated phases isolate physical contributions:

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

EDM

Experimental imperfections

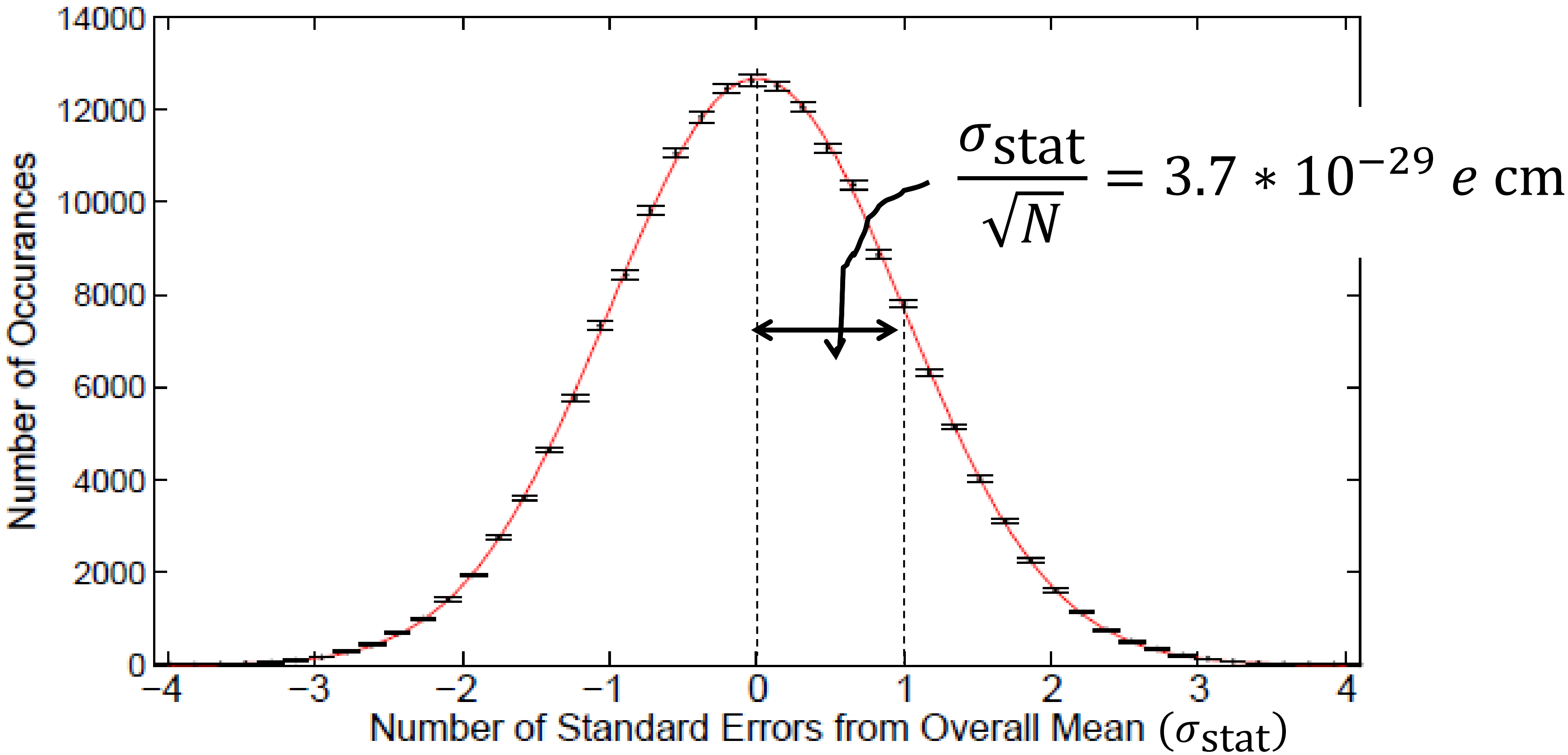
But… what about terms we don’t anticipate?

Strategies:

- **Change all possible parameters** that shouldn’t affect EDM ($\mathcal{E}$ magnitude, $\mathcal{B}$ magnitude, global polarization, etc. etc.) but *might* couple to unanticipated imperfections

- **Deliberately amplify imperfections**, understand any changes in correlated phases

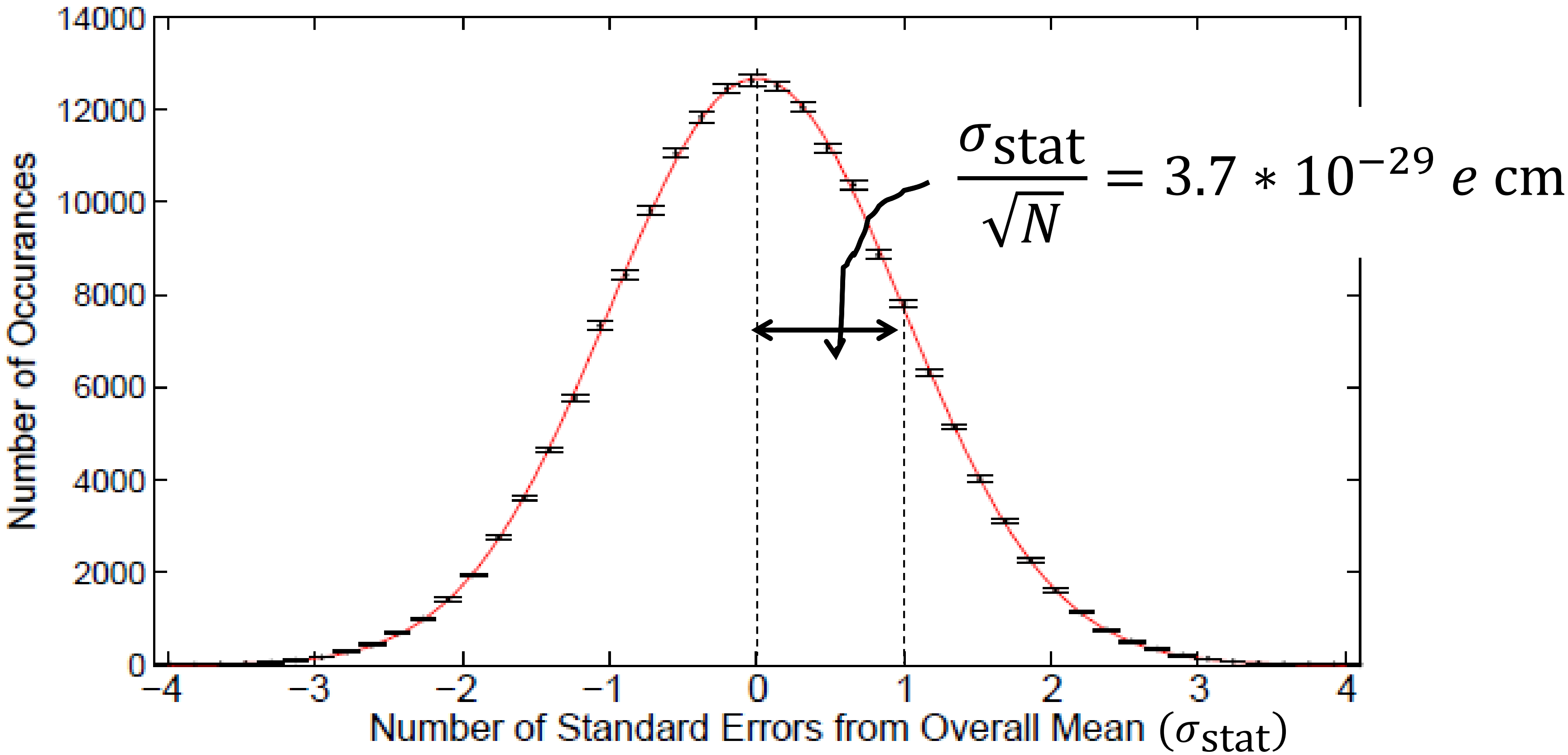
ACME electron EDM data



Blind analysis: randomly chosen offset added to data until analysis complete

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

ACME electron EDM data



Blind analysis: randomly chosen offset added to data until analysis complete

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

Consistent with zero
$\Rightarrow$ set upper limit

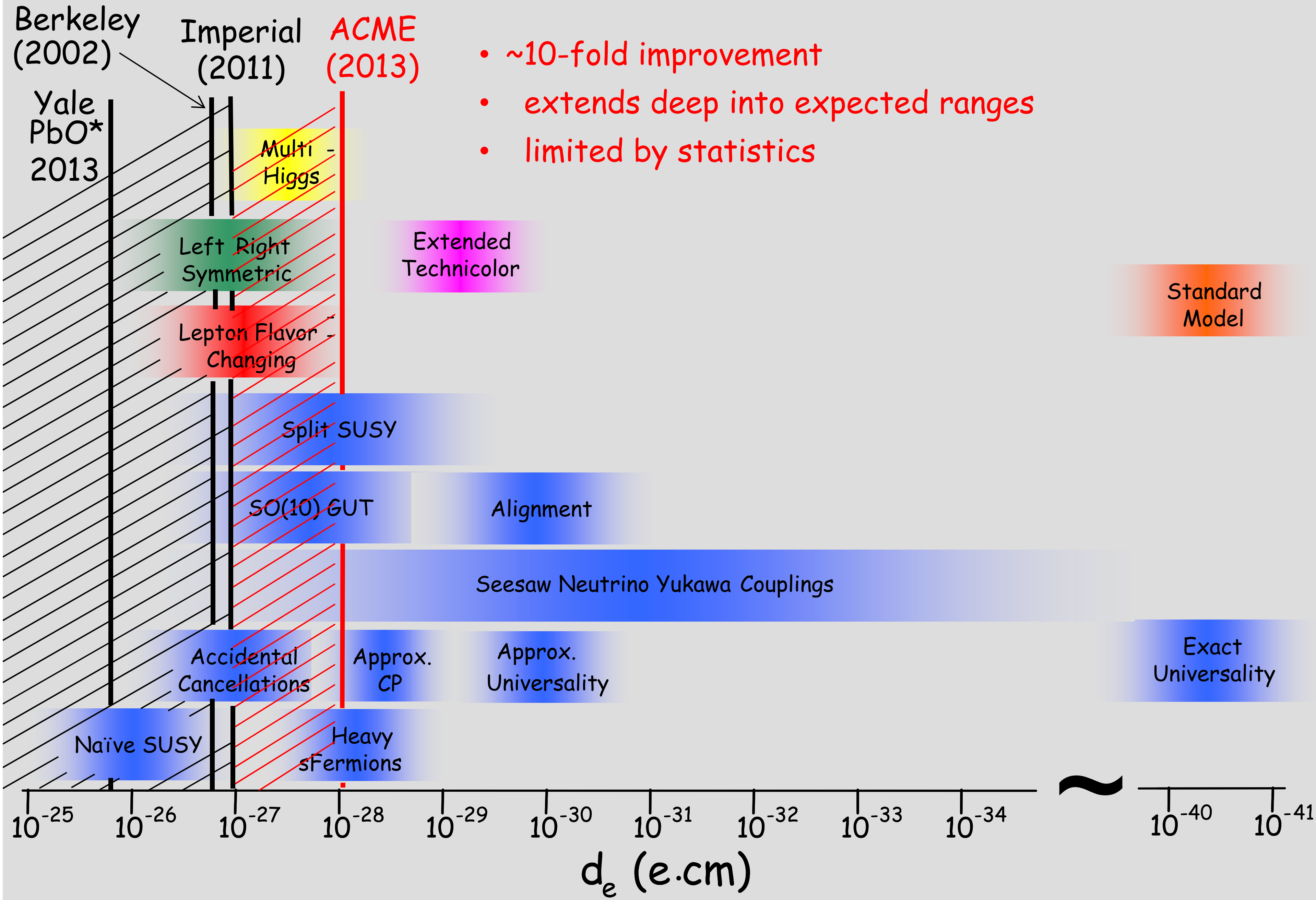
$$|d_e| < 9 \times 10^{-29}\ e\ \mathrm{cm}$$

J. Baron *et al.*, Science (2014)

ACME

New upper bound on electron EDM from ACME

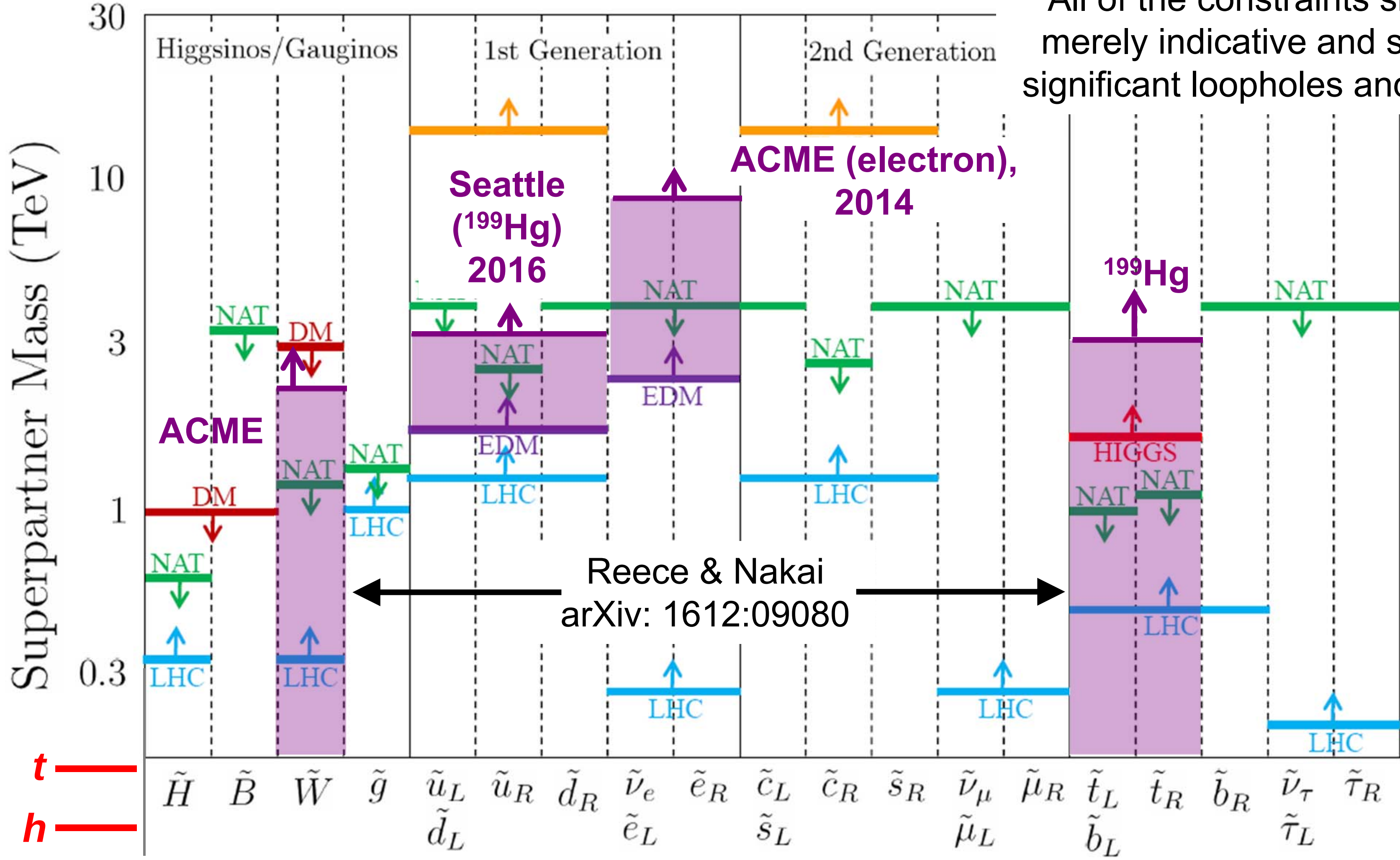
- ~10-fold improvement
- extends deep into expected ranges
- limited by statistics



Impact of EDMs in particle physics

J. Feng: "Naturalness and the status of SUSY", Annu. Rev. Nucl. Part. Sci. (2013)

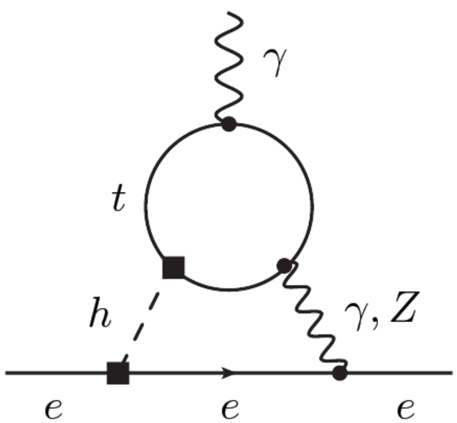
"All of the constraints shown are merely indicative and subject to significant loopholes and caveats"



EDM results push SUSY scale into "unnatural" regions
--potential for imminent discovery...?

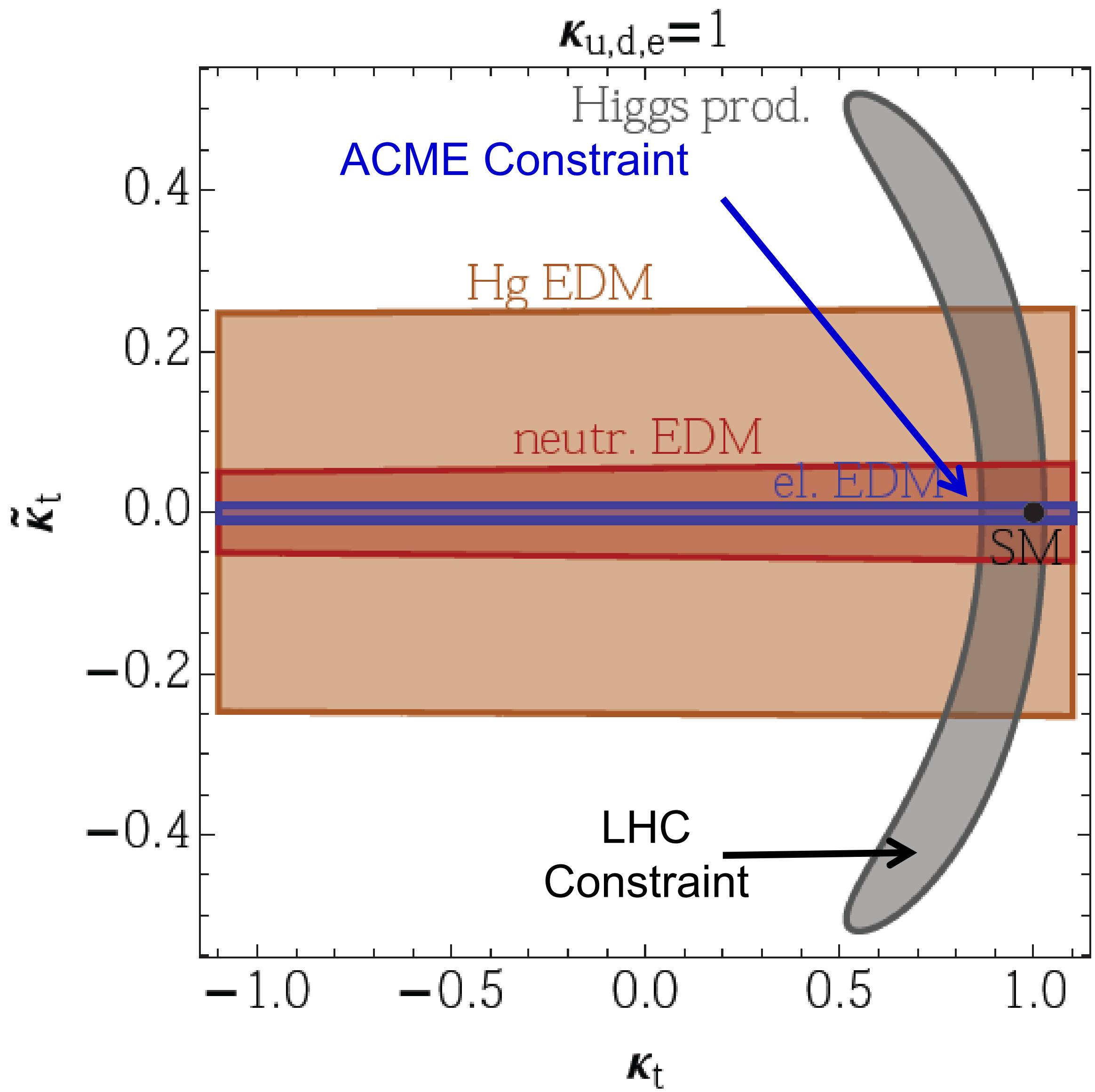
What does the eEDM limit mean for particle physics?

Diagrams with ***known*** SM particles can rule out non-SM couplings



Example:
CP-violating
Higgs-top coupling

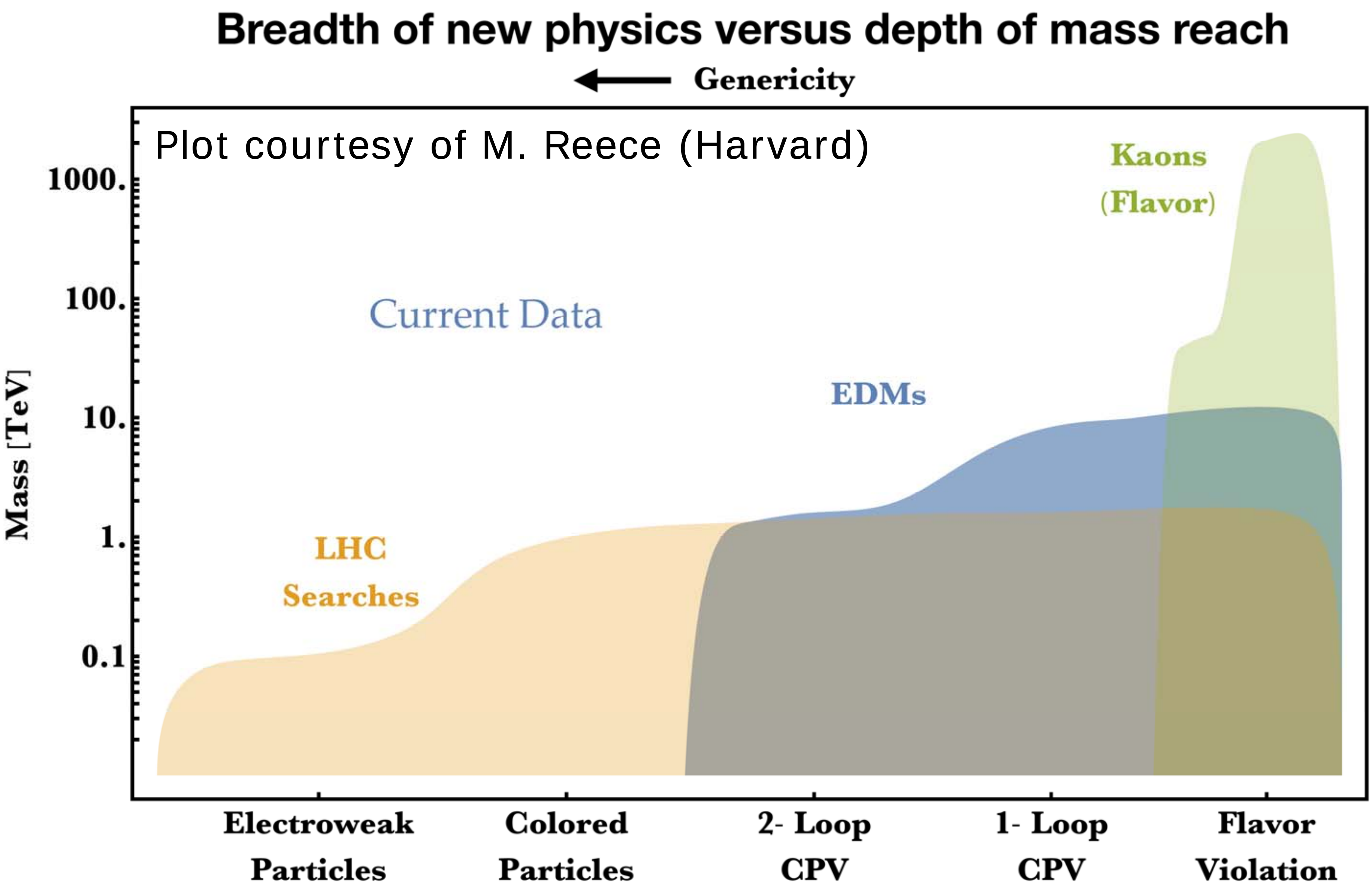
Brod *et al.*,
arXiv: 1310.1385



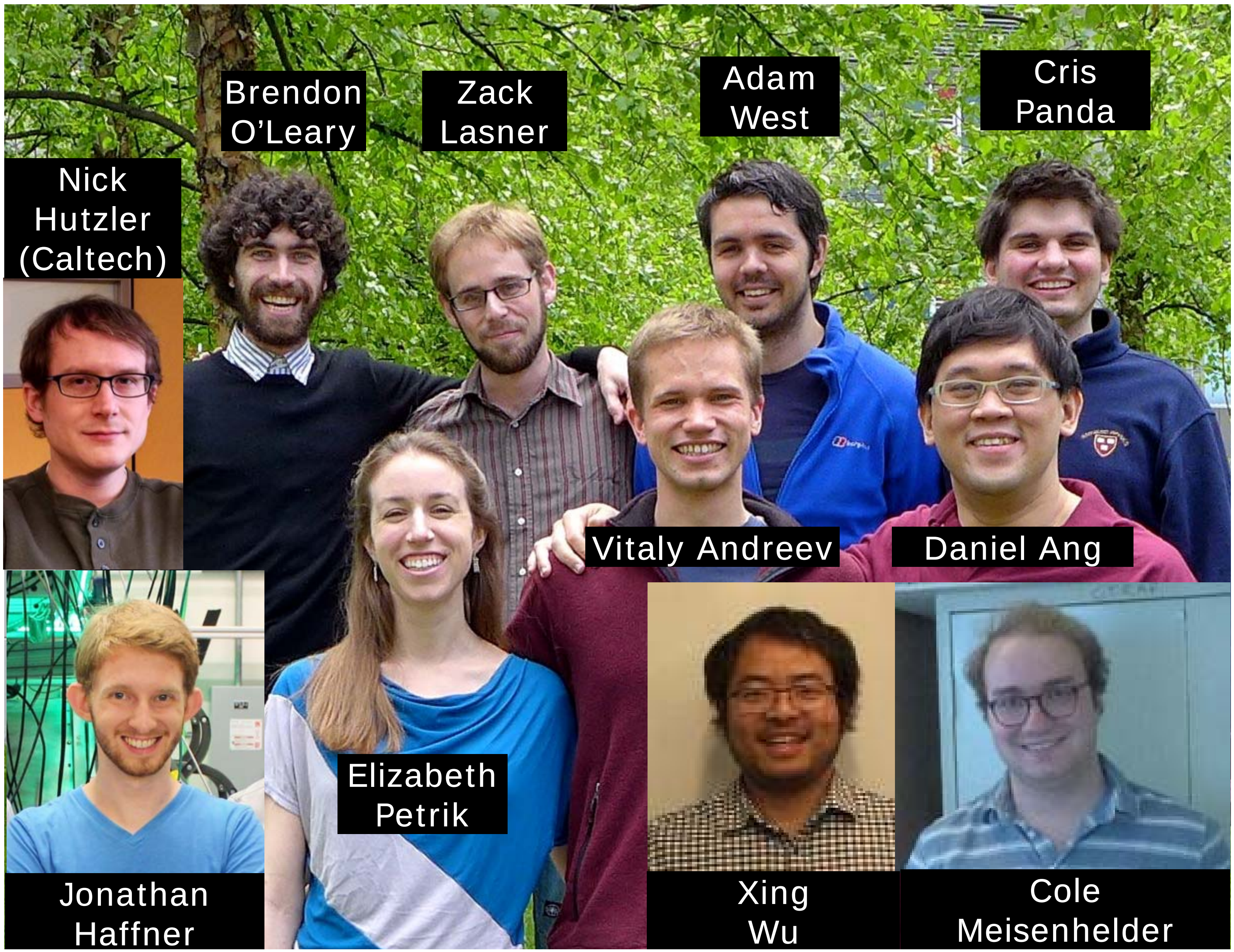
CP-odd/CP-even Higgs-top coupling <1% from ACME

Impact of EDMs in particle physics

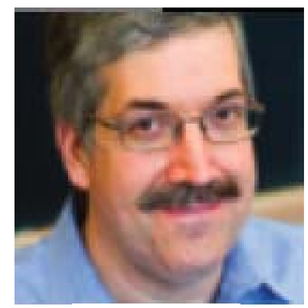
(A very generic view)



The ACME II team



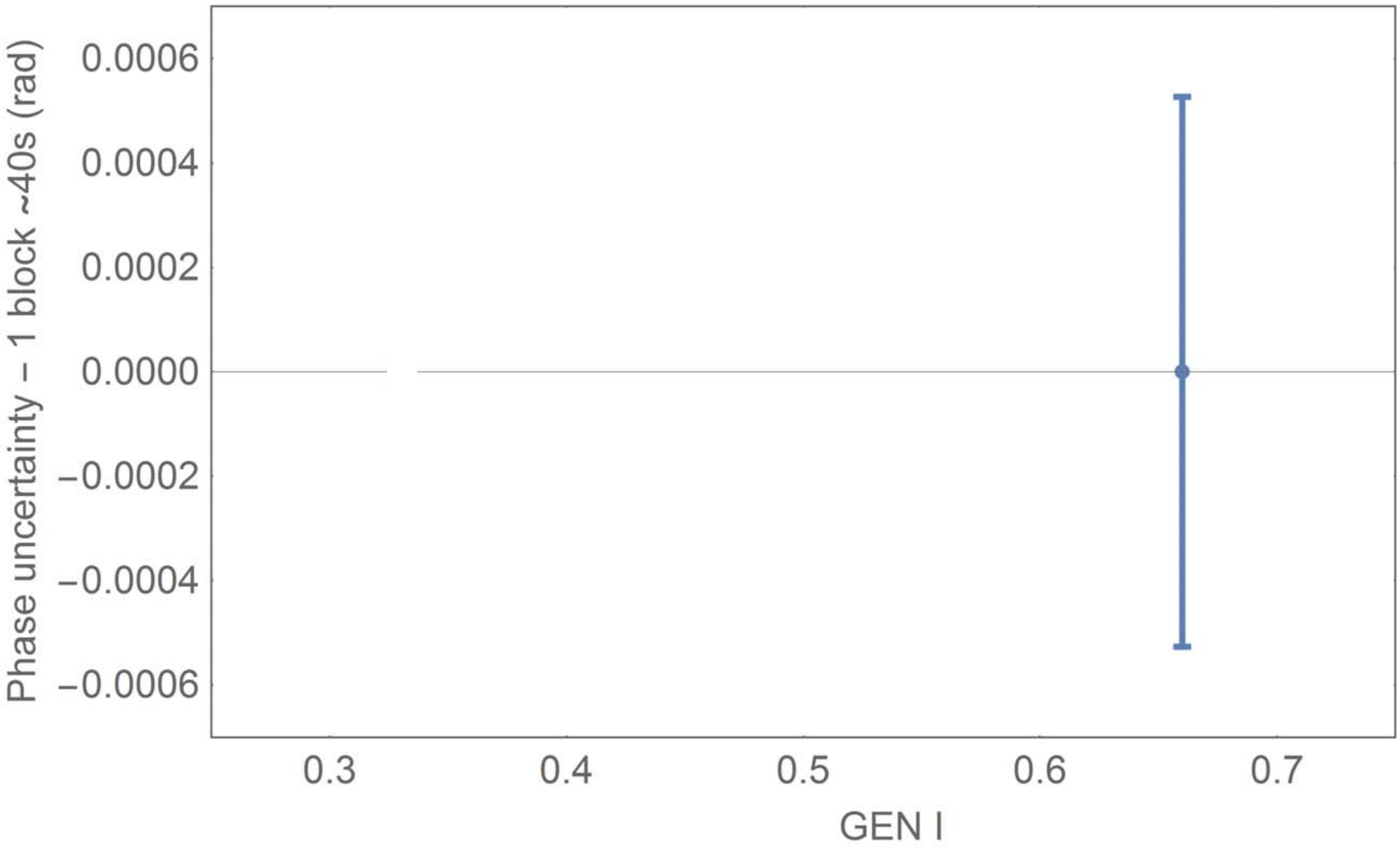
Gerald Gabrielse



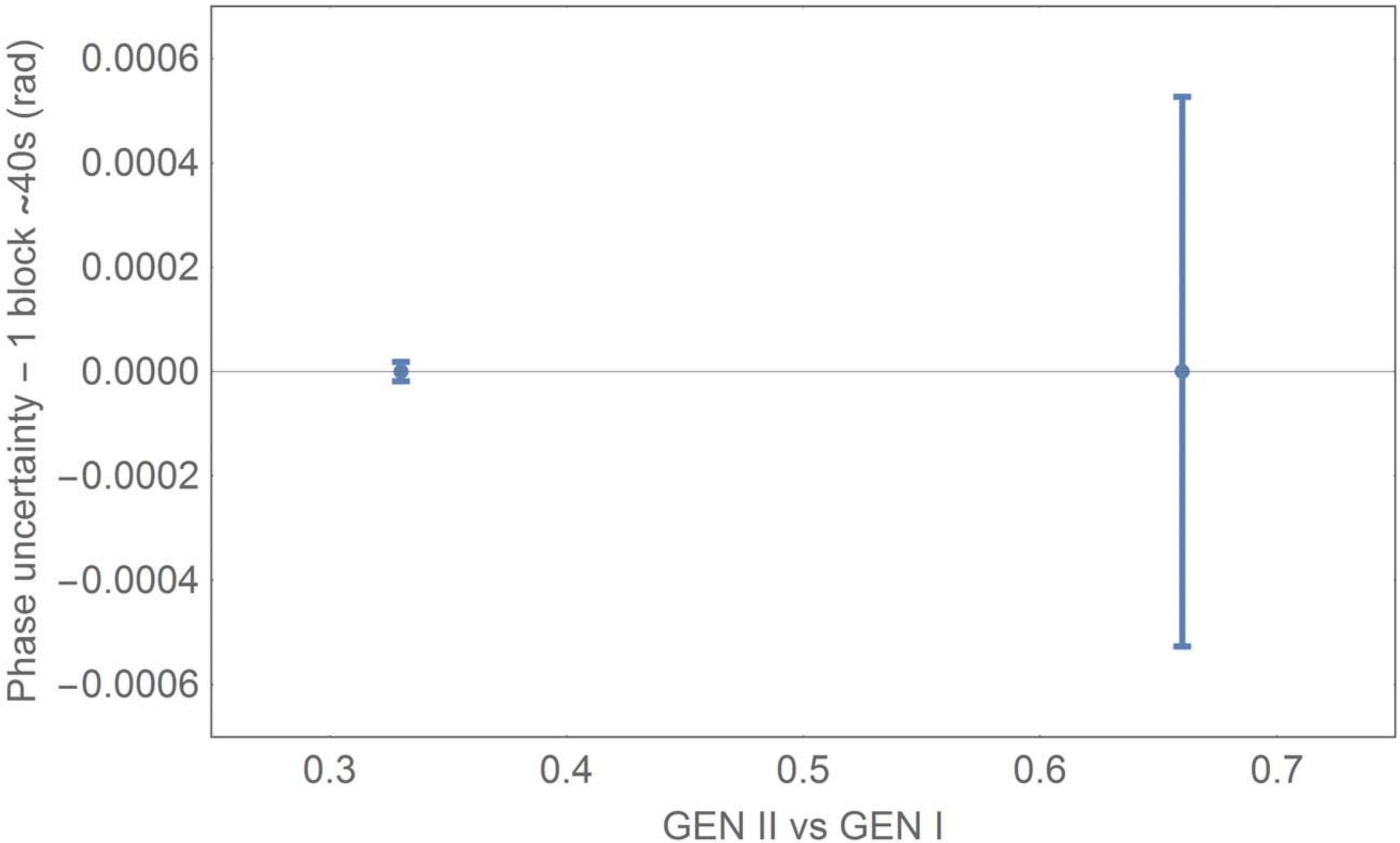
John Doyle

DD

ACME II statistical sensitivity



ACME II statistical sensitivity



~10x improved EDM statistical sensitivity/unit time

Systematic error studies ~complete, final data taking underway

Near-future discovery potential with the electron EDM