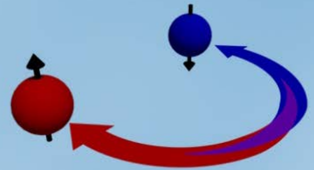
The ACME Electron EDM Search

Adam West, Yale (UCLA)

Disclaimer/Advert

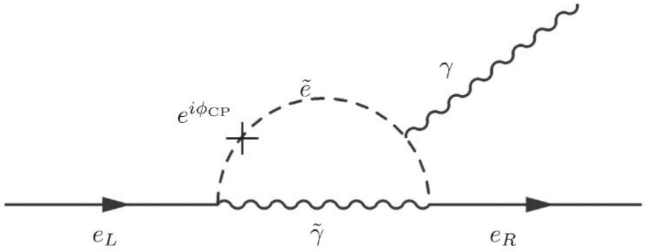
Rotation Sensing with Trapped Ions



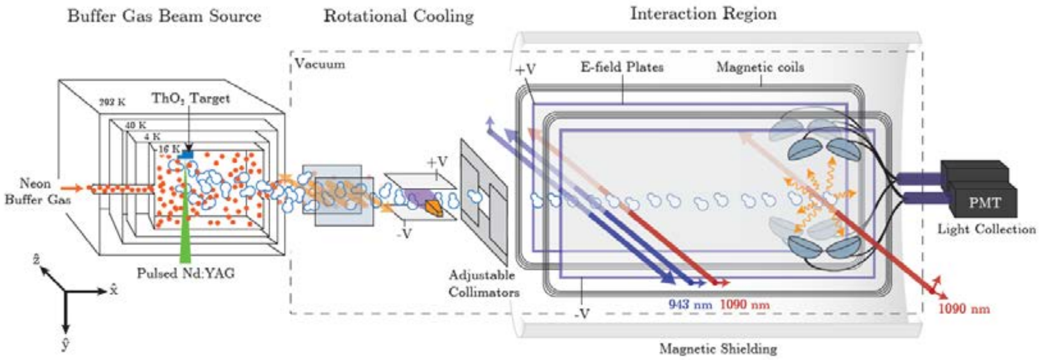
Hamilton Lab
UCLA

Outline

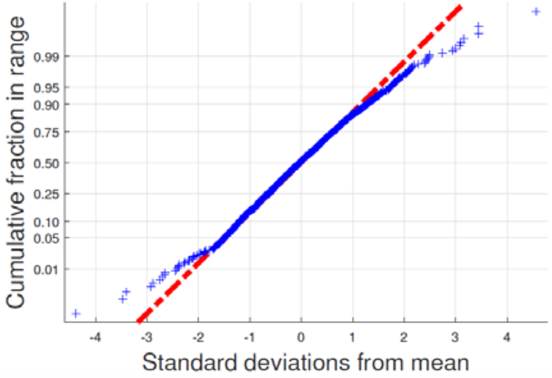
- Motivation



- Experimental method
  - Apparatus
  - Systematics

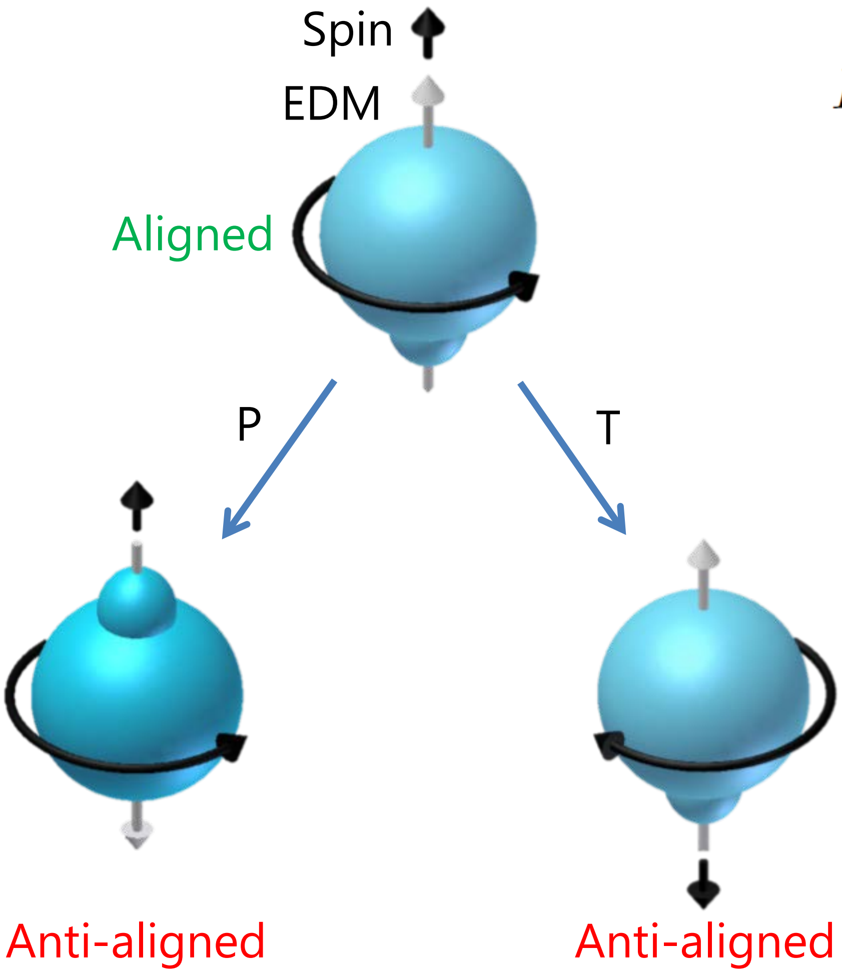


- Result
  - New limit on d_e
  - Impact



- Outlook

Motivation



$$H = -d_e \vec{\sigma} \cdot \vec{\mathcal{E}} \xrightarrow{P} -d_e \vec{\sigma} \cdot (-\vec{\mathcal{E}}) = -H$$

$$\xrightarrow{T} -d_e(-\vec{\sigma}) \cdot \vec{\mathcal{E}} = -H$$

EDMs of fundamental particles violate both P and T, and hence CP

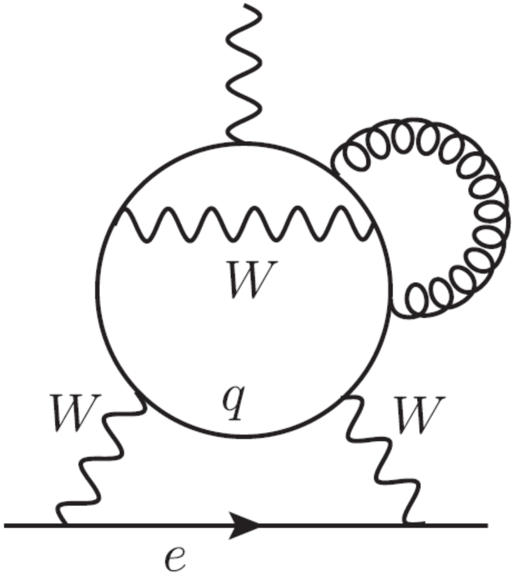
Baryogenesis needed to explain observed matter-antimatter asymmetry

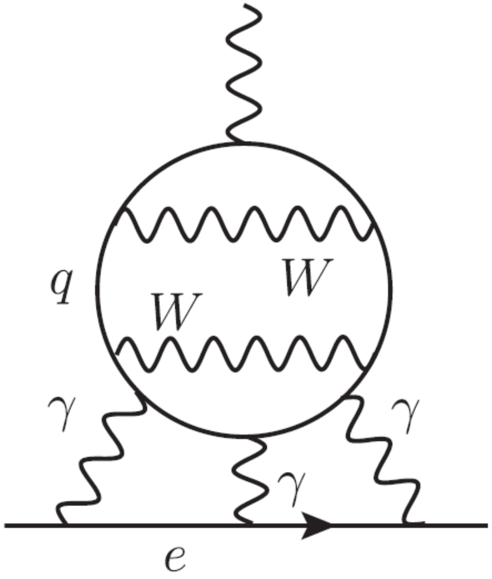
Sakharov showed this requires (beyond-SM) CP-violation

CP Violation

Standard Model:

eEDM contributions
at ≥4-loop level





CP-violation from CKM matrix predicts d_e of 10^{-44} e.cm[1]

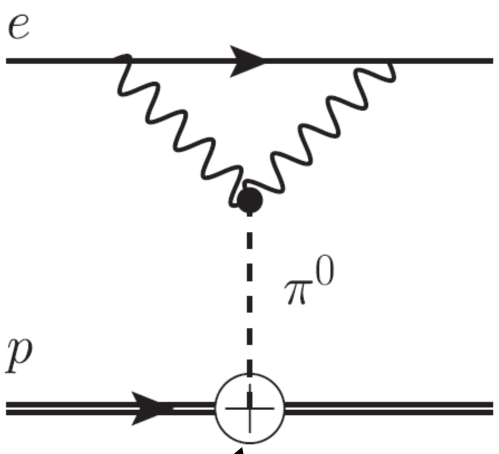
Our sensitivity is around 10^{-29} e.cm – SM background free

By contrast, CKM expected to generate neutron EDM of 10^{-31}-10^{-32} e.cm (current limit 3 x 10^{-26} e.cm)[2]

[1] Phys. Rev. D **89**, 056006 (2014)
[2] Phys. Rev. D **92**, 092003 (2015)

CP Violation

CKM CP-violation signal could also arise from SM electron-nucleon interaction.



CP-odd π^0NN vertex

Characterised by coupling constant:

$$C_S \sim 10^{-19}$$

Recasting as an 'equivalent' electron EDM:

$$d_e \sim 10^{-38}\ \text{e.cm}^1$$

Dominant SM CP-violating signal actually from this type of interaction

Still well below current experimental sensitivity

[1] Phys. Rev. D **89**, 056006 (2014)

CP Violation

θ_{QCD} is potential source of CP-violation, but neutron EDM much more sensitive

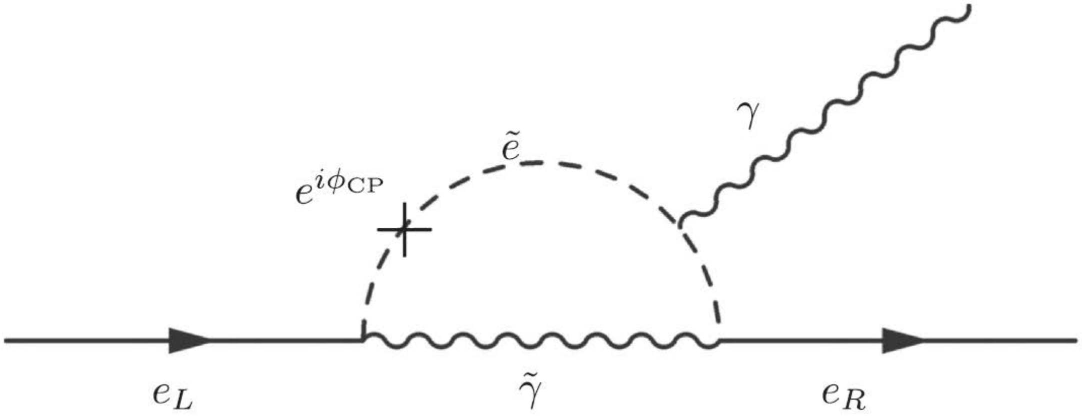
Current limits on θ_{QCD} give a contribution to d_e similar to those from CKM

SM + Majorana neutrinos can tune d_e to be much higher[1,2]

[1] Phys. Rev. D **70**, 073006
[2] Phys. Rev. D **89**, 091901(R)

CP Violation

SUSY:



In beyond-SM theories, CP violation can enter generically

The mass scale of BSM physics and d_e can be estimated via[1]

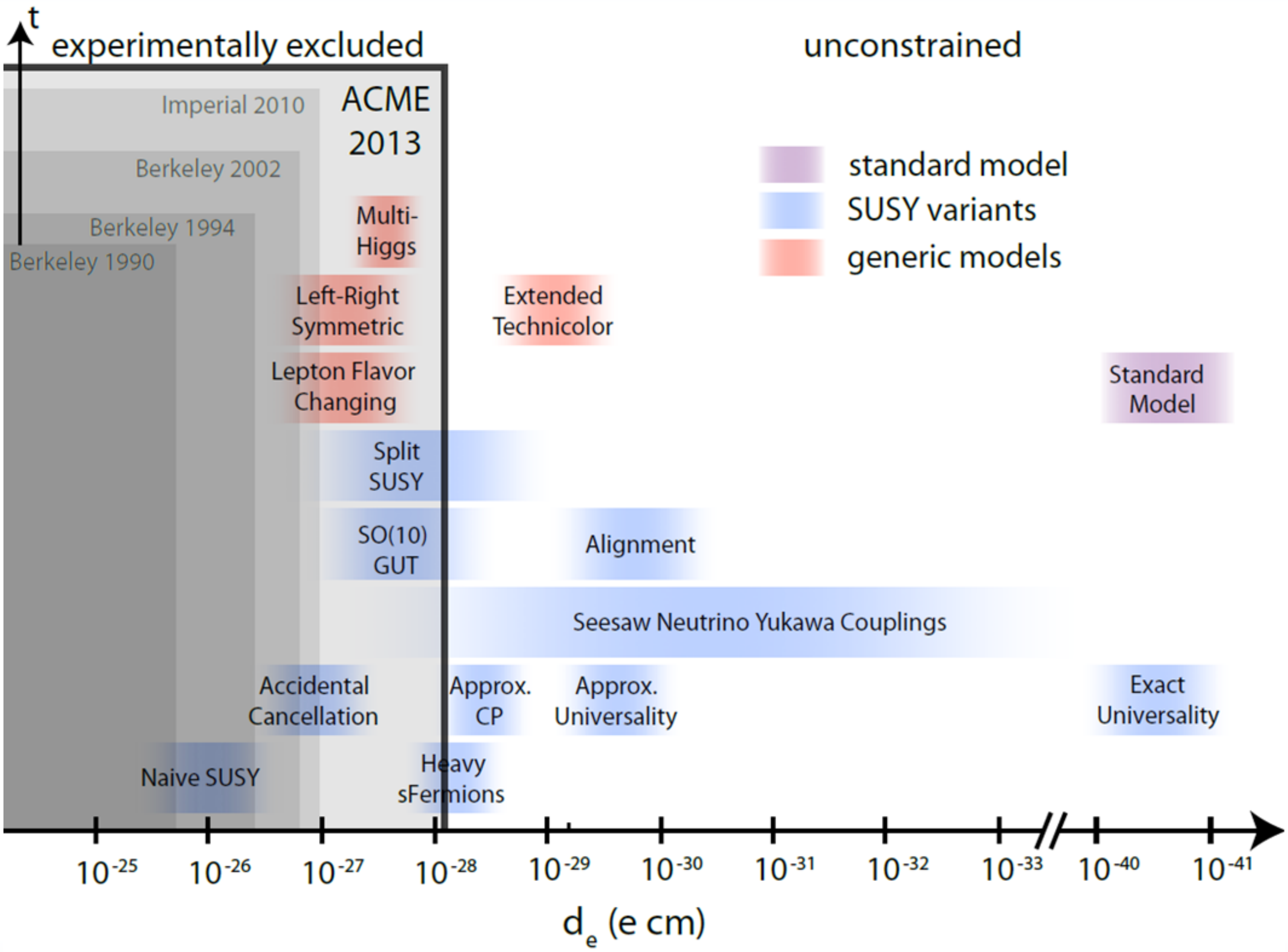
$$\Lambda^2 \sim e\frac{m_e}{d_e}\left(\frac{\alpha}{2\pi}\right)^n \sin\phi_{\mathrm{CP}}$$

ACME I: $|d_e| \leqslant 9.4 \times 10^{-29}\ e\ \mathrm{cm}$ (90% conf. level).

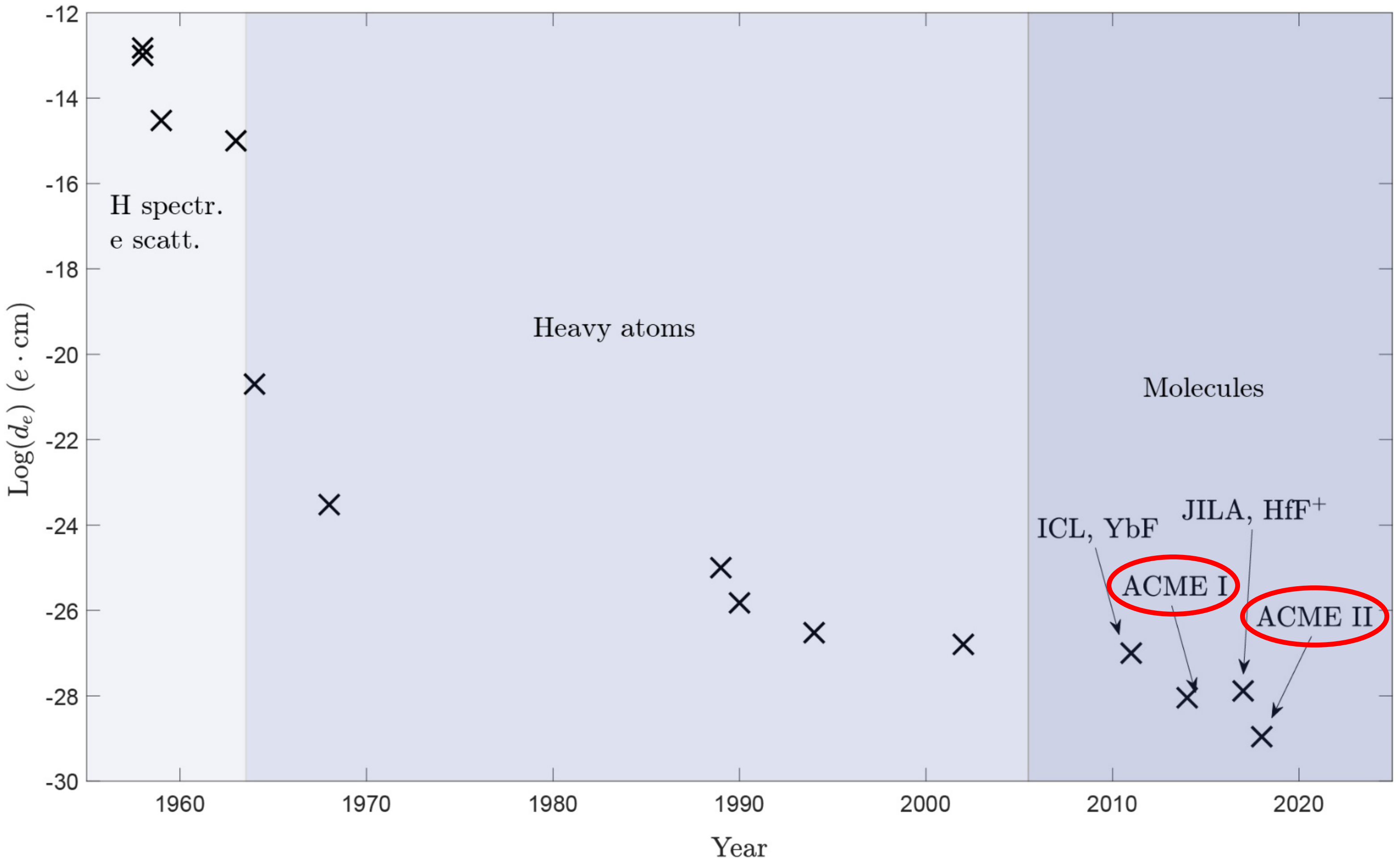
Probe of new physics at Λ~10 TeV (1 TeV) for 1 loop (2 loop)

[1] Prog. Part. Nucl. Phys. **71,** 21 (2013)

Motivation


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)

Work so far



Huge enhancement afforded by heavy atoms/molecules

ThO

In ACME, we use Thorium Monoxide (ThO) – why?

High Effective E-field

- Schiff's theorem implies zero E-field inside molecule
- Evaded in relativistic limit
- Heavy Th nucleus gives E_{eff} of 80 GV/cm[1,2]

'Omega Doublets'

- Closely spaced levels, separated by ~100 kHz
- Easily polarized by external E-field (energy shift ~100 MHz)
- Opposite levels have opposite E_{eff} – spectroscopic reversal of E_{eff}

Small Magnetic Moment

Long Coherence Time

- ~1 ms

High Flux

Statistical sensitivity:

$$\delta d_e = (2\tau \mathcal{E}_{\text{eff}} \sqrt{N})^{-1}$$

[1] J. Chem. Phys. **145**, 214301 (2016)
[2] J. Chem. Phys. **145**, 214307 (2016)

Extracting the Signal

$$H = -d_e \mathcal{E}_{\mathrm{eff}} + \mu_{\mathrm{B}} g B + \ldots$$

EDM <<<<<< MDM

Need to know/control B, g, … with 10^{-8} fractional uncertainty

We use switches to isolate the EDM interaction:

$$H = -d_e \mathcal{E}_{\mathrm{eff}} \tilde{\mathcal{N}} \tilde{\mathcal{E}} + \mu_{\mathrm{B}} g B \tilde{\mathcal{B}}$$

Molecule orientation

E-field direction

B-field direction

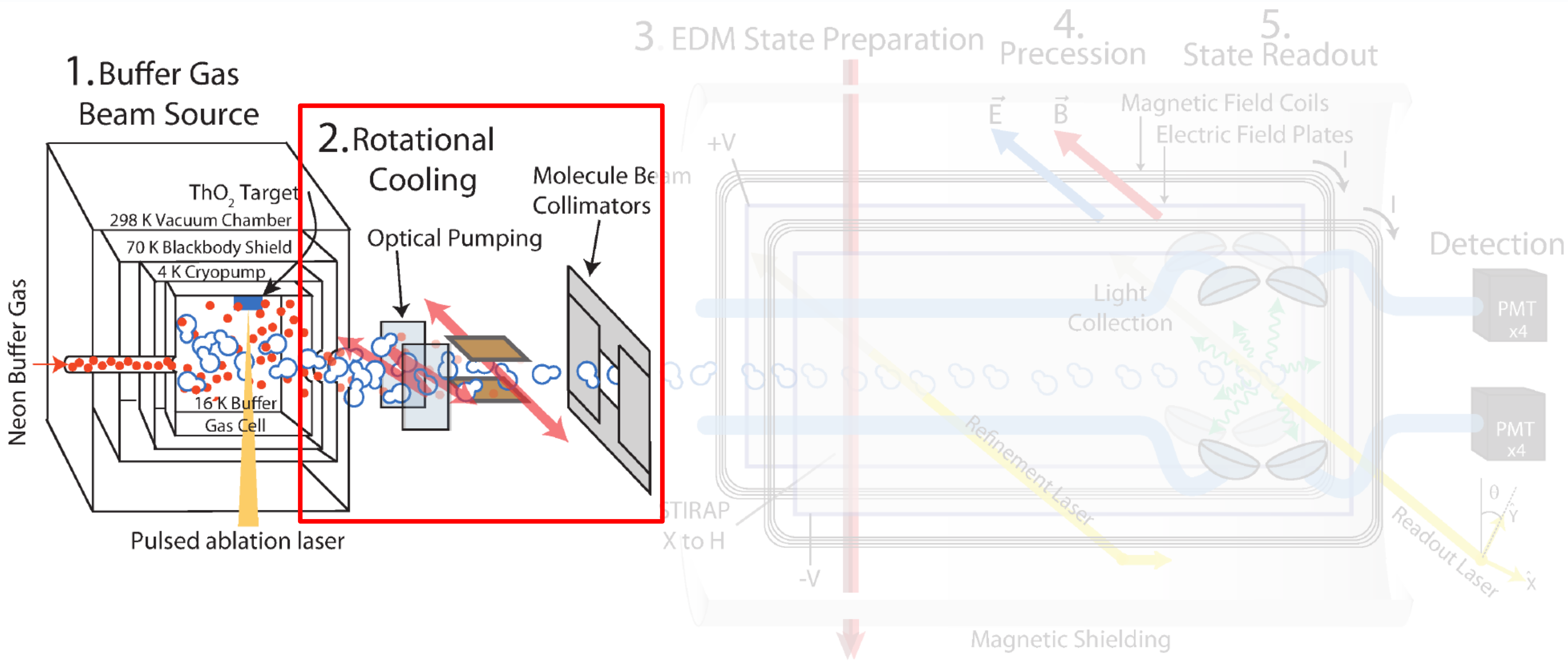
We look for an interaction that **only** changes with $\tilde{\mathcal{N}}$nd $\tilde{\mathcal{E}}$

Experimental Method

Ablation of ThO$_2$ target yields ThO in ground state, $|X\rangle$

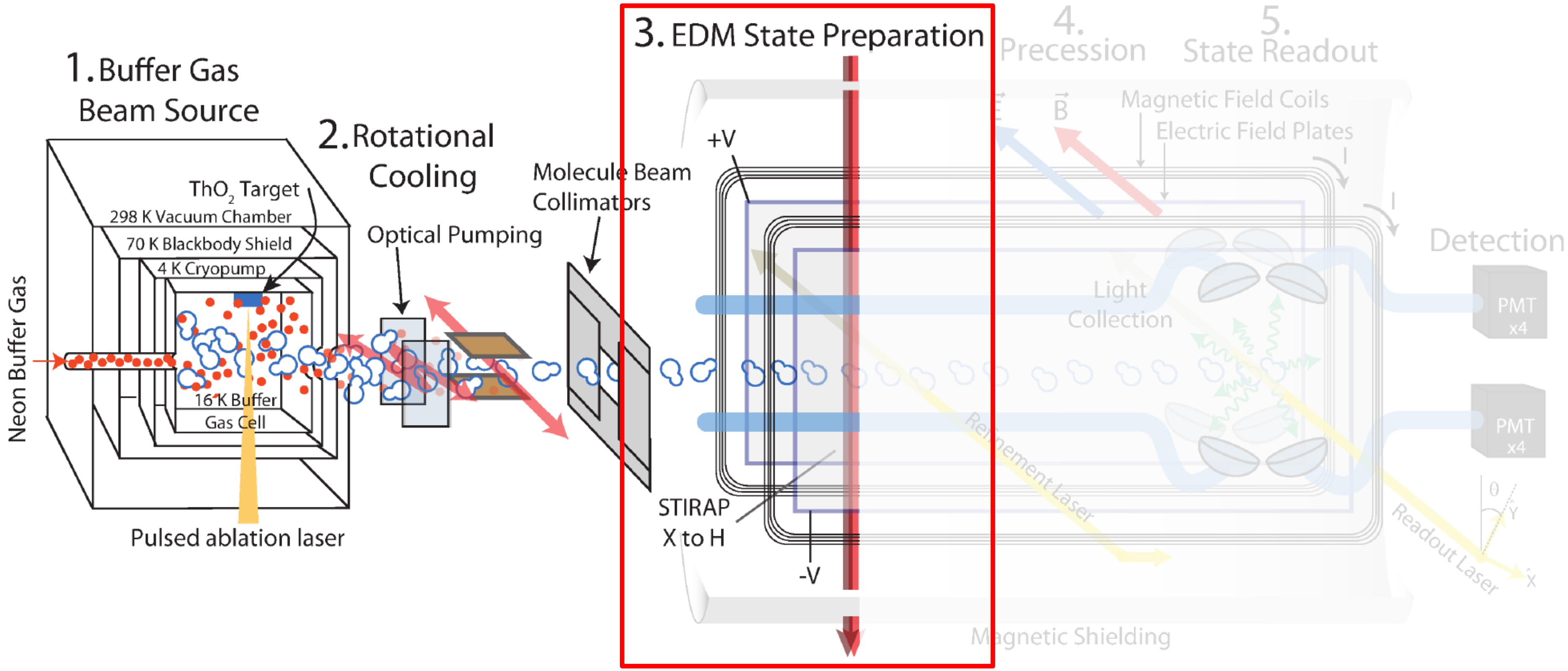
Cryogenic buffer gas beam produced

Experimental Method



Optically pumped into rotational ground state, $|X, J = 0\rangle$

Experimental Method

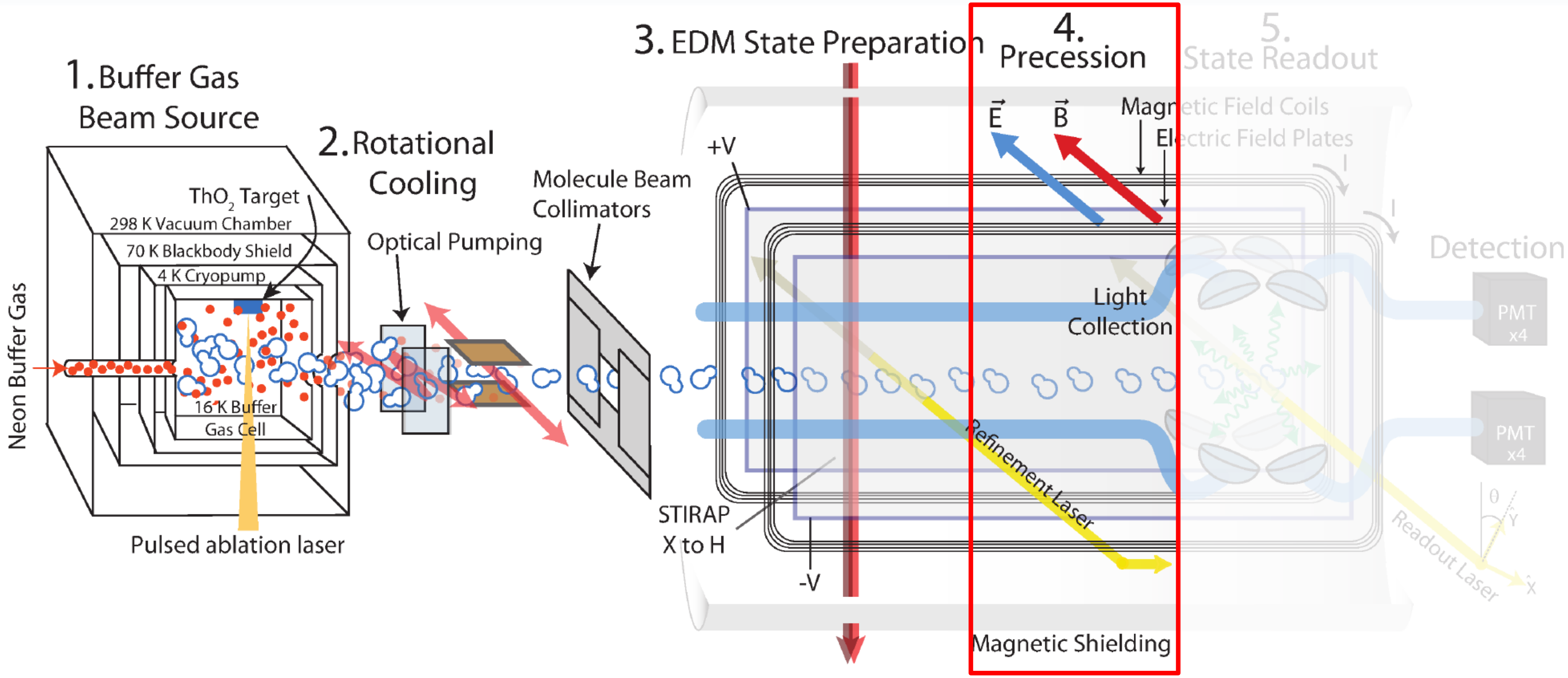


Coherently transferred with lasers to EDM-sensitive state, $|H\rangle$

Transfer is to particular $|H,\mathcal{N}\rangle$ defining orientation of $\mathcal{E}_{\text{eff}}$

Prepare spin-aligned state, $|M=-1\rangle + |M=+1\rangle$

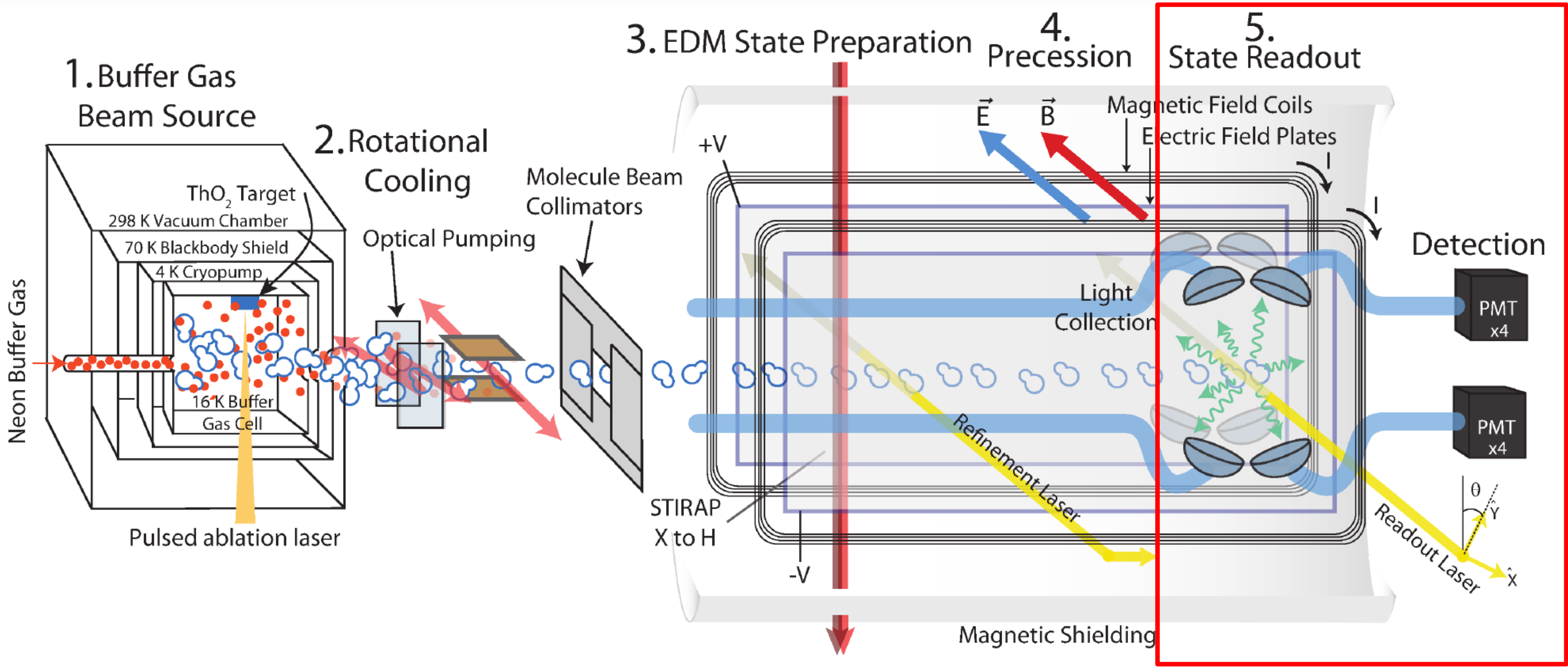
Experimental Method



Spin precesses in applied E- and B-fields:

$$e^{-i\phi/2}\,|M=-1\rangle \pm e^{i\phi/2}\,|M=+1\rangle$$

Experimental Method



Read out spin alignment via optical pumping

Laser polarization prescribes spin projection addressed,
e.g. 'X/Y' excite $|M=-1\rangle \pm |M=+1\rangle$ng fluorescence signals $S_{X/Y}$

Experimental Method

Rapidly alternate polarization:

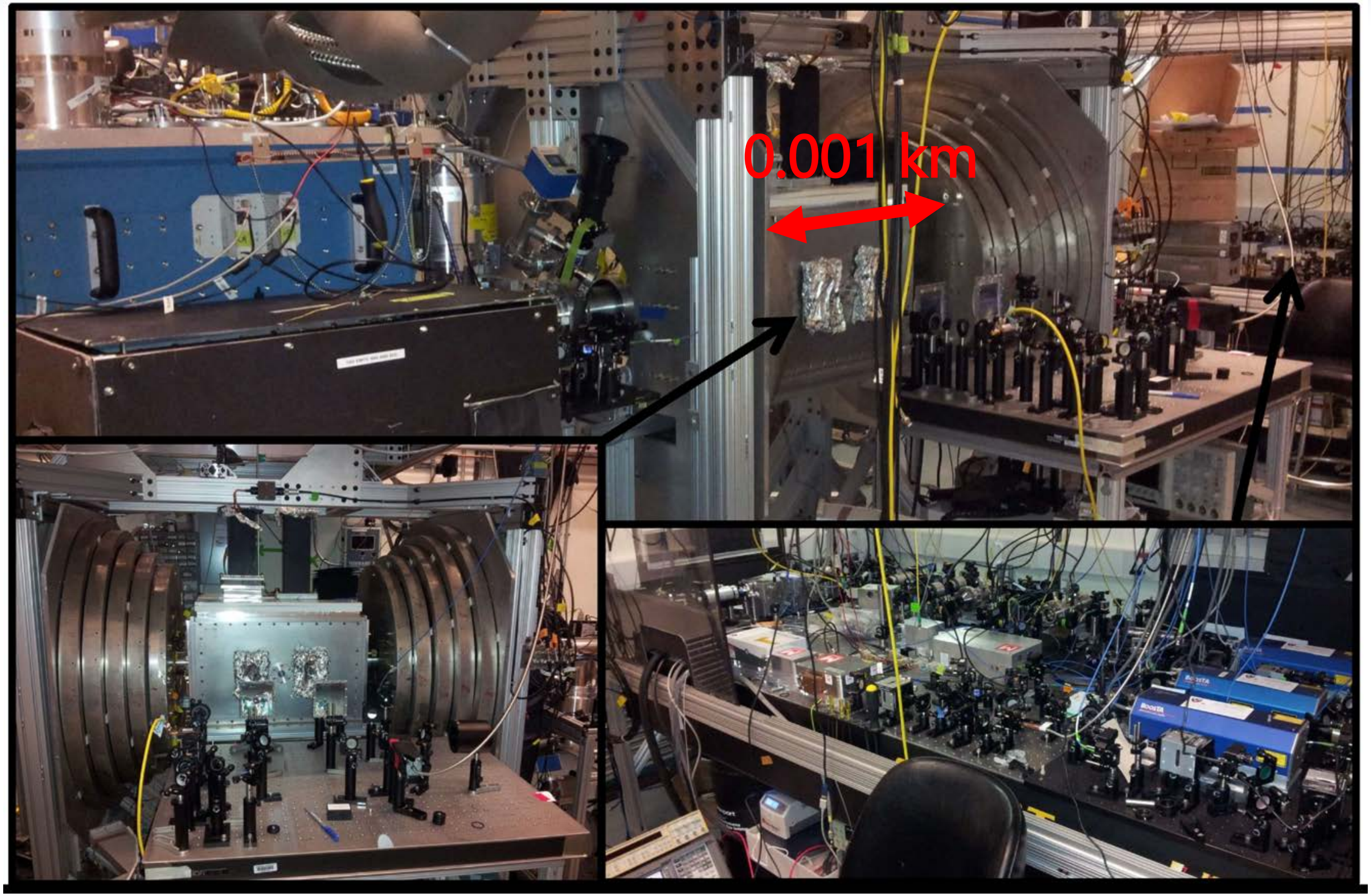
$$S_X \propto \cos^2(\phi - \theta), \quad S_Y \propto \sin^2(\phi - \theta)$$

Form asymmetry:

$$\mathcal{A} = \frac{S_X - S_Y}{S_X + S_Y} \propto \cos(2(\phi - \theta))$$

From the asymmetry we extract the phase ϕ.

Apparatus



Experimental Method

Different contributions to the phase we measure behave differently when we perform switches:

$$\phi(\tilde{\mathcal{N}},\tilde{\mathcal{E}},\tilde{\mathcal{B}}) = \phi^{nr} + \phi^{\tilde{\mathcal{N}}}\tilde{\mathcal{N}} + \phi^{\tilde{\mathcal{E}}}\tilde{\mathcal{E}} + \phi^{\tilde{\mathcal{B}}}\tilde{\mathcal{B}} + \phi^{\tilde{\mathcal{N}}\tilde{\mathcal{E}}}\tilde{\mathcal{N}}\tilde{\mathcal{E}} + \phi^{\tilde{\mathcal{N}}\tilde{\mathcal{B}}}\tilde{\mathcal{N}}\tilde{\mathcal{B}} + \phi^{\tilde{\mathcal{E}}\tilde{\mathcal{B}}}\tilde{\mathcal{E}}\tilde{\mathcal{B}} + \phi^{\tilde{\mathcal{N}}\tilde{\mathcal{E}}\tilde{\mathcal{B}}}\tilde{\mathcal{N}}\tilde{\mathcal{E}}\tilde{\mathcal{B}}$$

Larmor precession

EDM phase, reverses with N and E

Six switches necessary for an EDM measurement:

N, E, B, θ, P, R

Molecule orientation

E-field direction

B-field direction

Laser polarization dither

Excited state parity

Laser polarisation

Many more switches/knobs to hunt for systematic effects

Systematics

$$H_{\mathrm{eEDM}} = -d_e \mathcal{E}_{\mathrm{eff}} \tilde{\mathcal{N}} \tilde{\mathcal{E}}$$

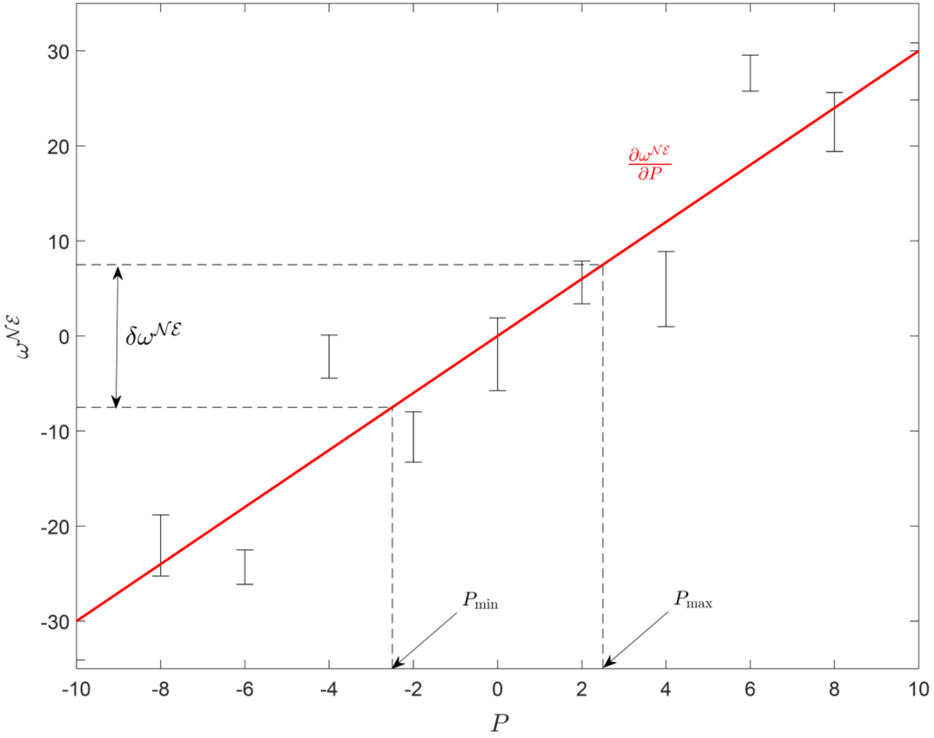
E-field direction

Molecule orientation

- Nothing we do should change $|d_e|$

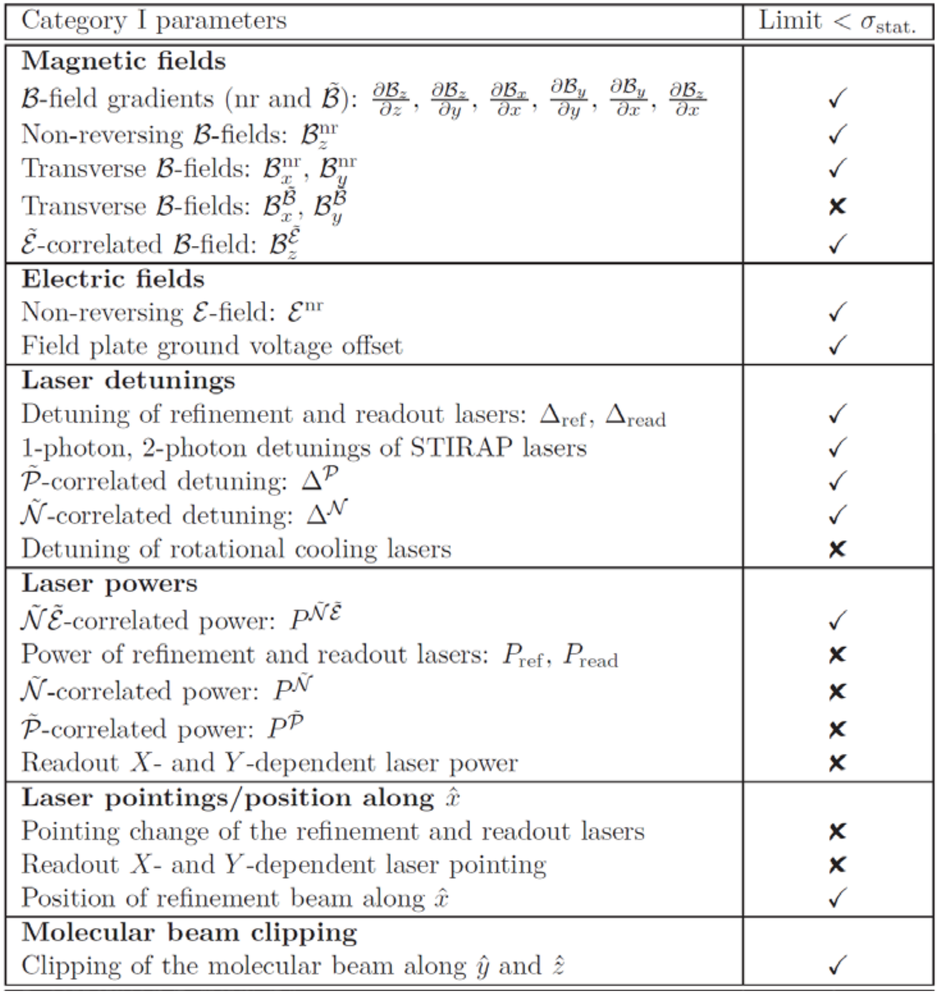
- Exaggerate some experimental parameter, *P*
- Measure the change of the eEDM channel
- Fit dependence
- Measure typical variation of *P*
- Compute corresponding uncertainty of eEDM channel

$$\delta\omega_P^{\mathcal{N}\mathcal{E}} = \sqrt{\left(\frac{\partial\omega^{\mathcal{N}\mathcal{E}}}{\partial P}\,\delta\bar{P}\right)^2 + \left(\bar{P}\,\delta\frac{\partial\omega^{\mathcal{N}\mathcal{E}}}{\partial P}\right)^2}$$



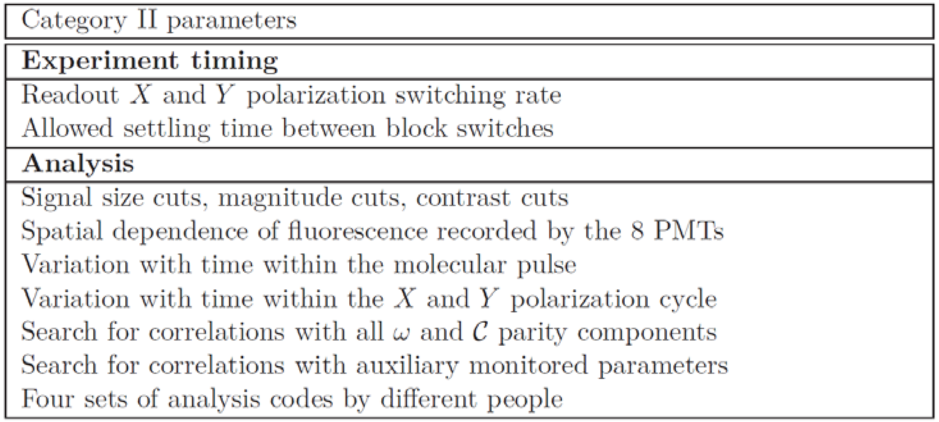
Systematics

Varied far from typical values



Category I parameters	Limit $< \sigma_{\text{stat.}}$
Magnetic fields	
$\mathcal{B}$-field gradients (nr and $\tilde{\mathcal{B}}$): $\frac{\partial \mathcal{B}_z}{\partial z}, \frac{\partial \mathcal{B}_z}{\partial y}, \frac{\partial \mathcal{B}_x}{\partial x}, \frac{\partial \mathcal{B}_y}{\partial y}, \frac{\partial \mathcal{B}_y}{\partial x}, \frac{\partial \mathcal{B}_z}{\partial x}$	✓
Non-reversing $\mathcal{B}$-fields: $\mathcal{B}_z^{\text{nr}}$	✓
Transverse $\mathcal{B}$-fields: $\mathcal{B}_x^{\text{nr}}, \mathcal{B}_y^{\text{nr}}$	✓
Transverse $\mathcal{B}$-fields: $\mathcal{B}_x^{\tilde{\mathcal{B}}}, \mathcal{B}_y^{\tilde{\mathcal{B}}}$	✗
$\tilde{\mathcal{E}}$-correlated $\mathcal{B}$-field: $\mathcal{B}_z^{\tilde{\mathcal{E}}}$	✓
Electric fields	
Non-reversing $\mathcal{E}$-field: $\mathcal{E}^{\text{nr}}$	✓
Field plate ground voltage offset	✓
Laser detunings	
Detuning of refinement and readout lasers: $\Delta_{\text{ref}}, \Delta_{\text{read}}$	✓
1-photon, 2-photon detunings of STIRAP lasers	✓
$\tilde{\mathcal{P}}$-correlated detuning: $\Delta^{\mathcal{P}}$	✓
$\tilde{\mathcal{N}}$-correlated detuning: $\Delta^{\mathcal{N}}$	✓
Detuning of rotational cooling lasers	✗
Laser powers	
$\tilde{\mathcal{N}}\tilde{\mathcal{E}}$-correlated power: $P^{\tilde{\mathcal{N}}\tilde{\mathcal{E}}}$	✓
Power of refinement and readout lasers: $P_{\text{ref}}, P_{\text{read}}$	✗
$\tilde{\mathcal{N}}$-correlated power: $P^{\tilde{\mathcal{N}}}$	✗
$\tilde{\mathcal{P}}$-correlated power: $P^{\tilde{\mathcal{P}}}$	✗
Readout X- and Y-dependent laser power	✗
Laser pointings/position along $\hat{x}$	
Pointing change of the refinement and readout lasers	✗
Readout X- and Y-dependent laser pointing	✗
Position of refinement beam along $\hat{x}$	✓
Molecular beam clipping	
Clipping of the molecular beam along $\hat{y}$ and $\hat{z}$	✓

No 'ideal' value



Category II parameters
Experiment timing
Readout X and Y polarization switching rate
Allowed settling time between block switches
Analysis
Signal size cuts, magnitude cuts, contrast cuts
Spatial dependence of fluorescence recorded by the 8 PMTs
Variation with time within the molecular pulse
Variation with time within the X and Y polarization cycle
Search for correlations with all ω and $\mathcal{C}$ parity components
Search for correlations with auxiliary monitored parameters
Four sets of analysis codes by different people

In general, require at least two simultaneous imperfections to mimic EDM

Systematics

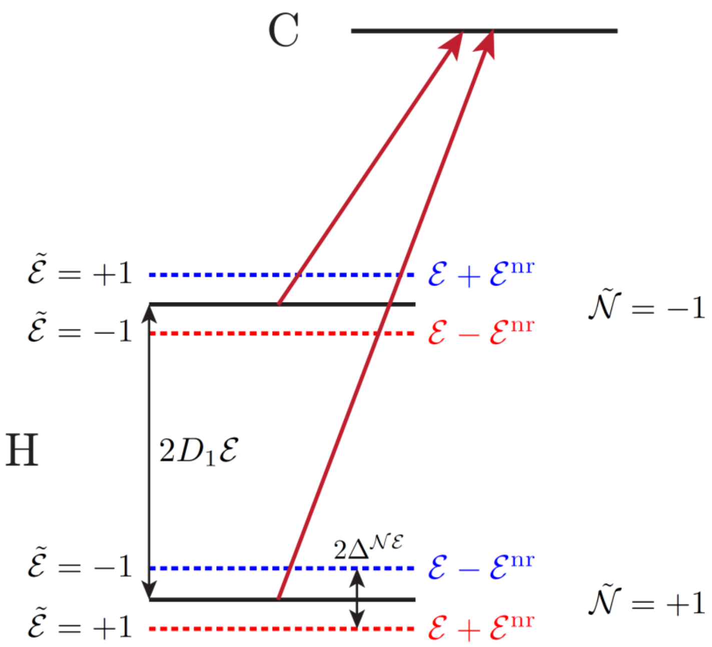
Example systematic

Recall, E-field splits the N states

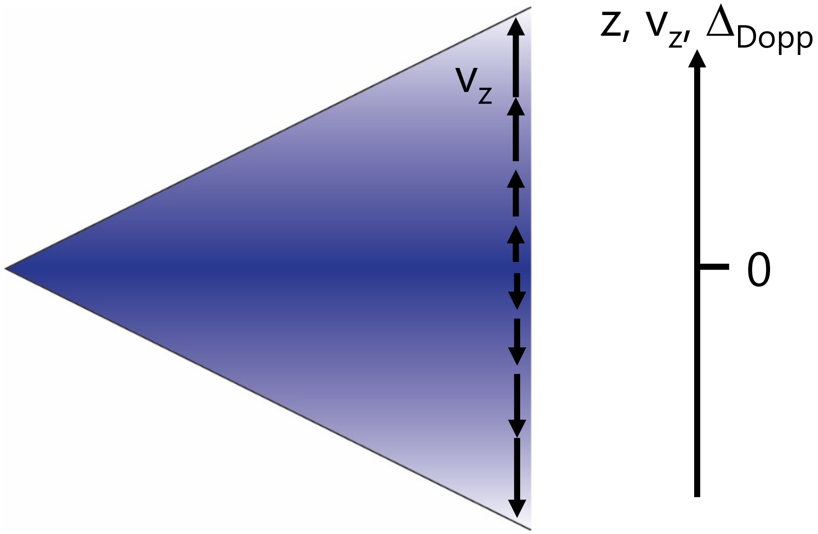
E^{nr} produces an E-field magnitude correlated with $\tilde{\mathcal{N}}$ and $\tilde{\mathcal{E}}$

Leads to detuning correlated with $\tilde{\mathcal{N}}$ and $\tilde{\mathcal{E}}$

$$\Delta^{\tilde{\mathcal{N}}\tilde{\mathcal{E}}}$$



Systematics



$v(z) \propto z$

- Molecule beam has correlated transverse velocity/position
- Doppler shift correlated with z
- Normally, beam centre (z=0) read out with higher probability
- Additional detuning shifts preferred position, $z \neq 0$
- B-field gradient gives position-dependent phase

Together with $\Delta^{\tilde{\mathcal{N}}\tilde{\mathcal{E}}}$ this produces an EDM-like systematic

Systematics

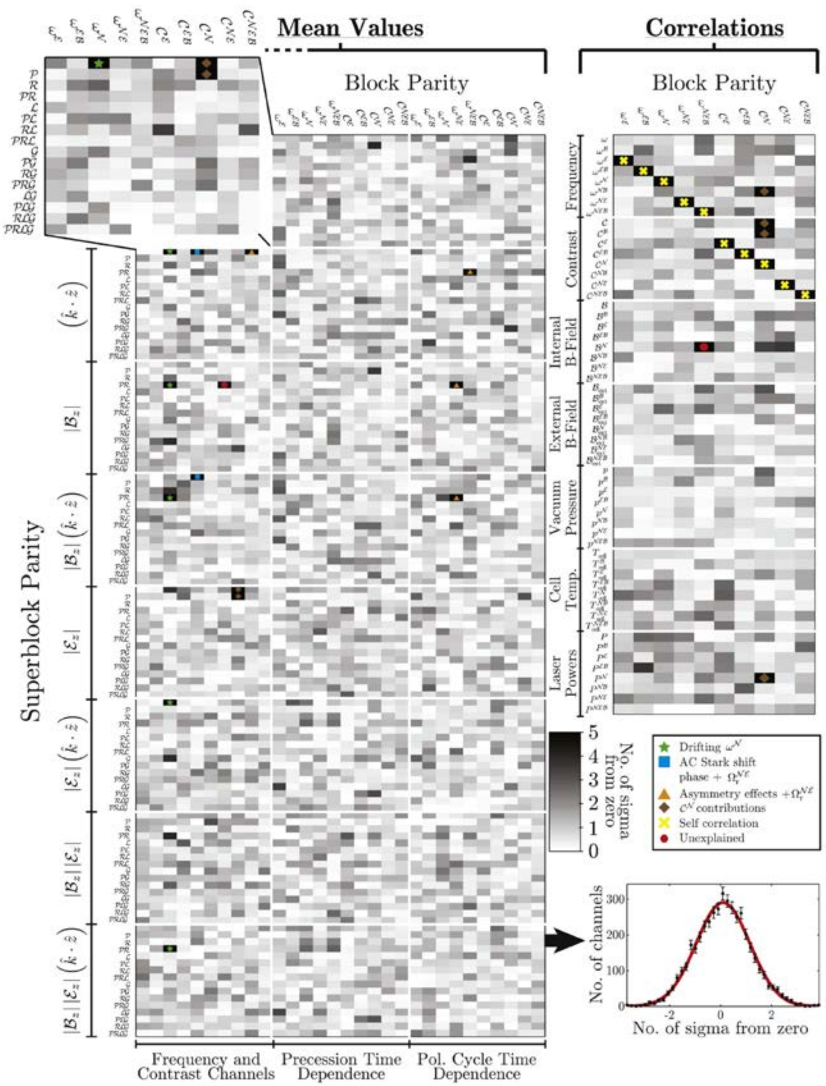
$$\frac{\partial \phi}{\partial B}$$

- Larmor precession phase
- B-field gradient
- Molecule beam correlations
- Doppler shift
- E-field induced detuning

$\partial B/\partial z$ produces a Larmor precession phase correlated with $\tilde{\mathcal{N}}$ and $\tilde{\mathcal{E}}$

This looks just like the EDM phase!

Systematics



Large number of data 'channels' examined

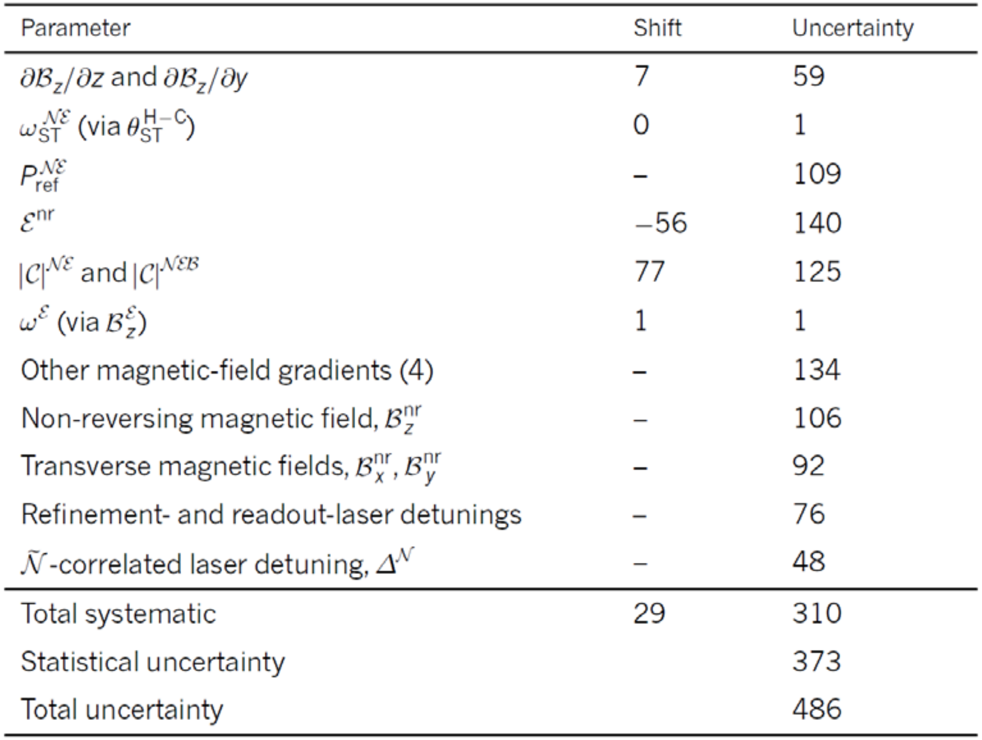
Systematics

B-field gradients →

Imperfect state prep. →

Non-reversing E →

…



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

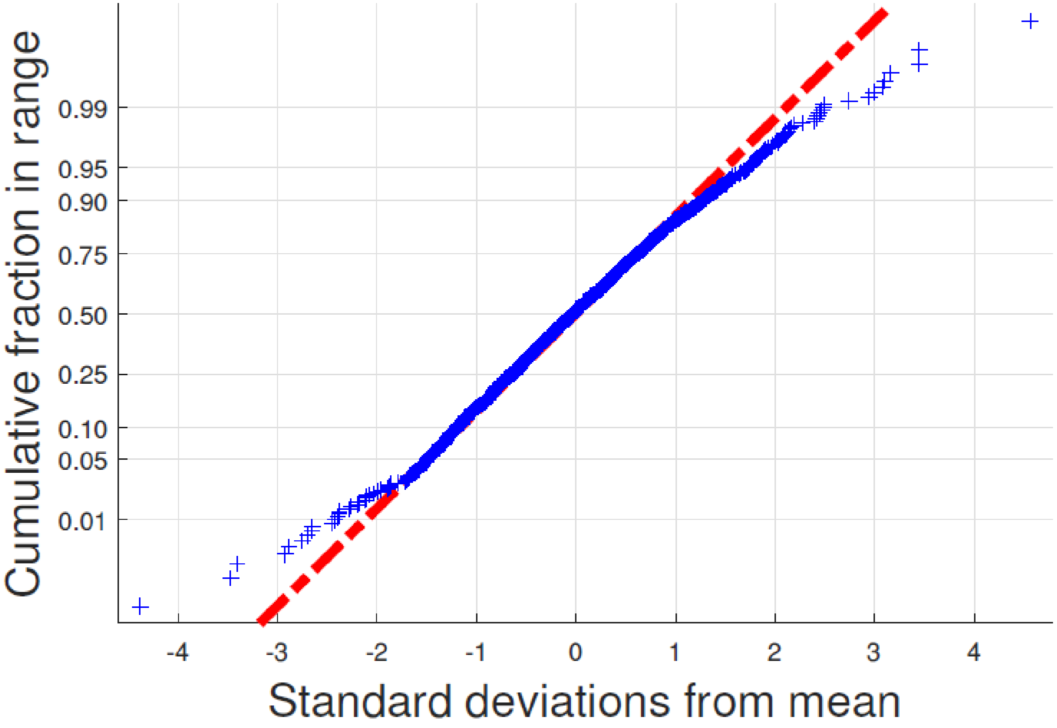
A couple of effects understood to shift EDM value – accounted for

Included uncertainties are directly or closely related to known systematic effects

Systematics at level of statistical uncertainty

Result

Entire dataset:



Non-Gaussian character in wings due to excess noise:

- Electrical pickup in DAQs
- Electrical pickup in PMTs
- Beam velocity variation

M-estimator analysis of mean

Bootstrapped sampling to determine uncertainty

Result

All data taking/analysis performed with blind

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

Feldman-Cousins construction of confidence interval yields

$$|d_e| < 1.1 \times 10^{-29} e\ \text{cm}$$ (90% C.L.)

CP-violation in ThO also possible from electron-nucleon interaction:

$$\hbar\omega^{\mathcal{NE}} = -d_e\mathcal{E}_{\text{eff}} + W_S C_S$$

Molecule specific, calculated[1,2]

$-2\pi\hbar \times 282\ \text{kHz}$

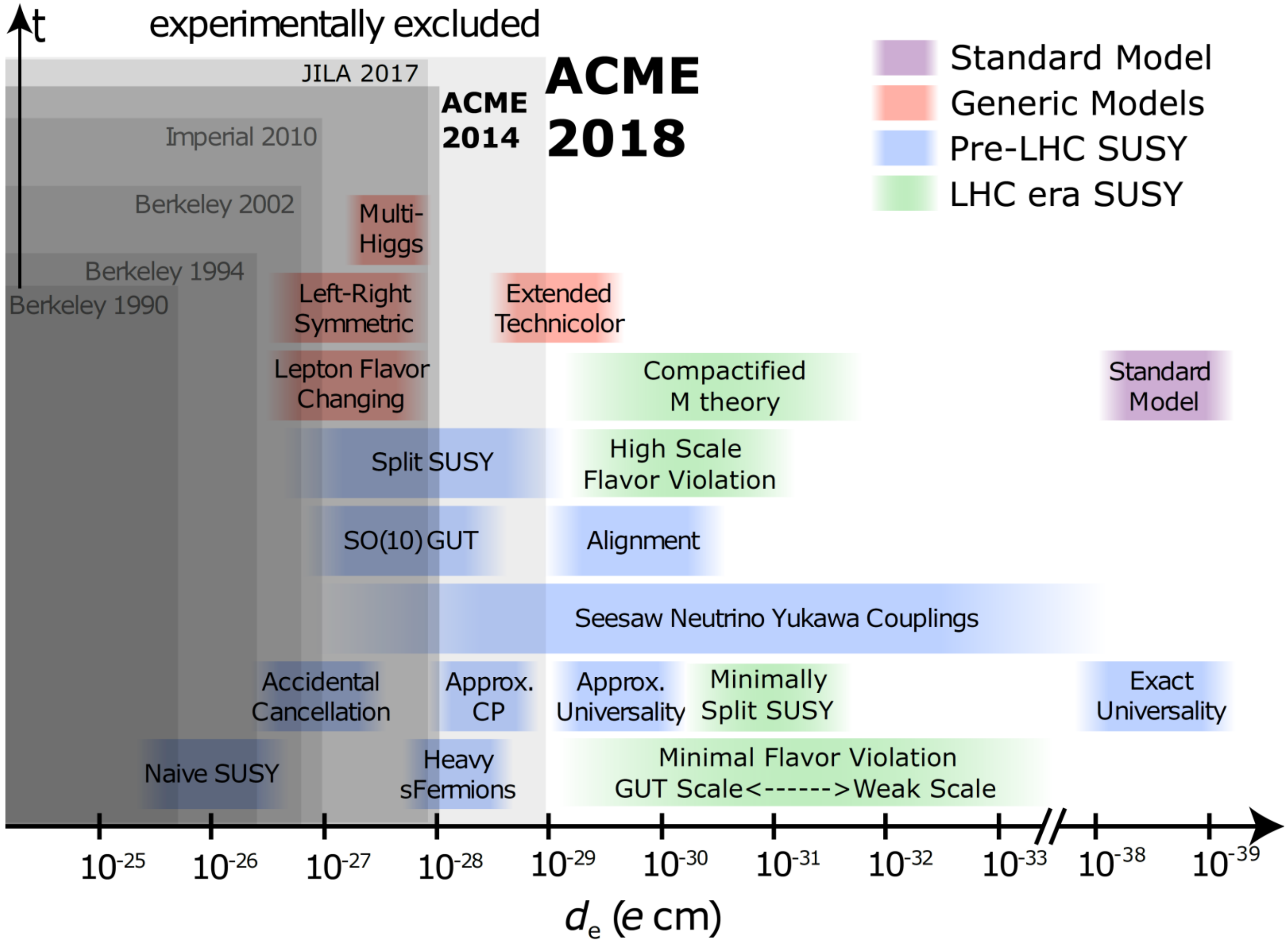
We assume $C_S = 0$ to compute d_e limit

Assuming $d_e = 0$ instead:

$$|C_S| < 7.3 \times 10^{-10}$$ (90% C.L.)

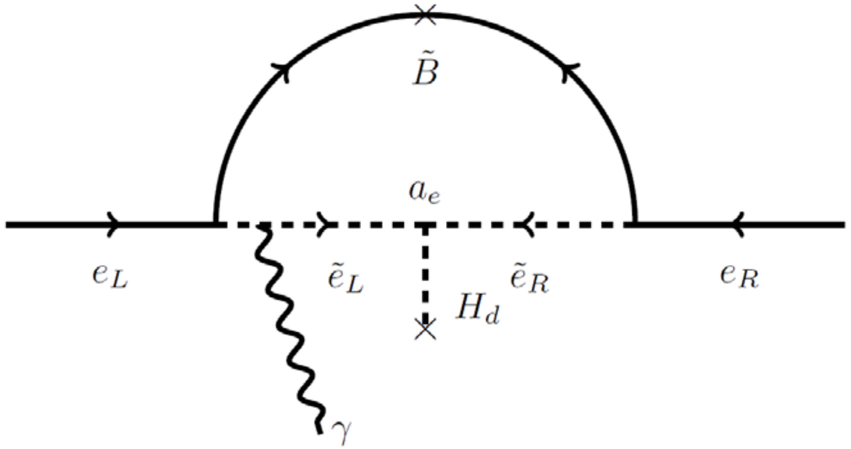
[1] J. Chem. Phys. **145**, 214301 (2016)
[2] J. Chem. Phys. **145**, 214307 (2016)

Result

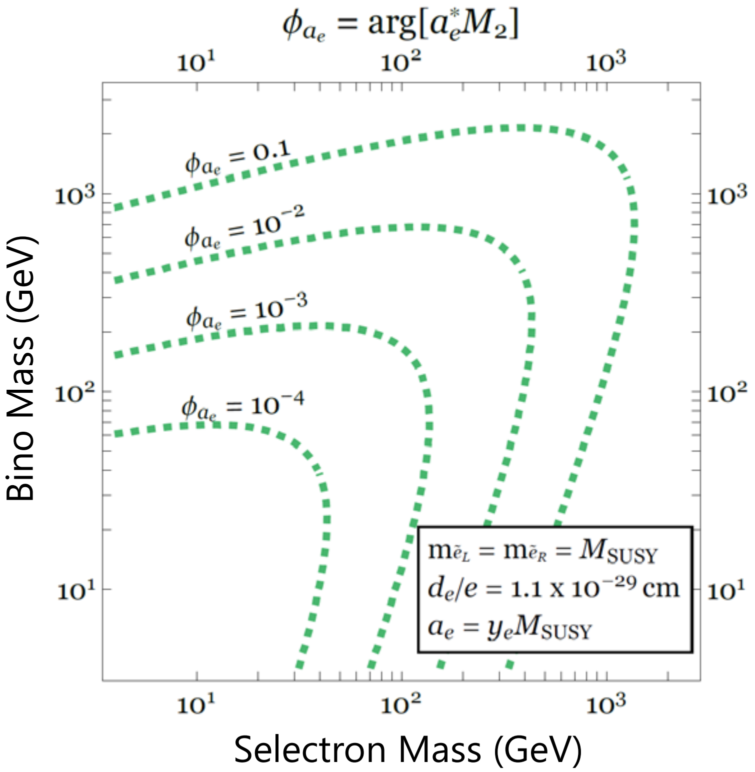

t
experimentally excluded
JILA 2017
ACME 2014
ACME 2018
Imperial 2010
Berkeley 2002
Berkeley 1994
Berkeley 1990
Standard Model
Generic Models
Pre-LHC SUSY
LHC era SUSY
Multi-Higgs
Left-Right Symmetric
Extended Technicolor
Lepton Flavor Changing
Compactified M theory
Standard Model
Split SUSY
High Scale Flavor Violation
SO(10) GUT
Alignment
Seesaw Neutrino Yukawa Couplings
Accidental Cancellation
Approx. CP
Approx. Universality
Minimally Split SUSY
Exact Universality
Naive SUSY
Heavy sFermions
Minimal Flavor Violation GUT Scale<------>Weak Scale
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-38}
10^{-39}
d_e (e cm)

Impact

1-loop SUSY: Selectron



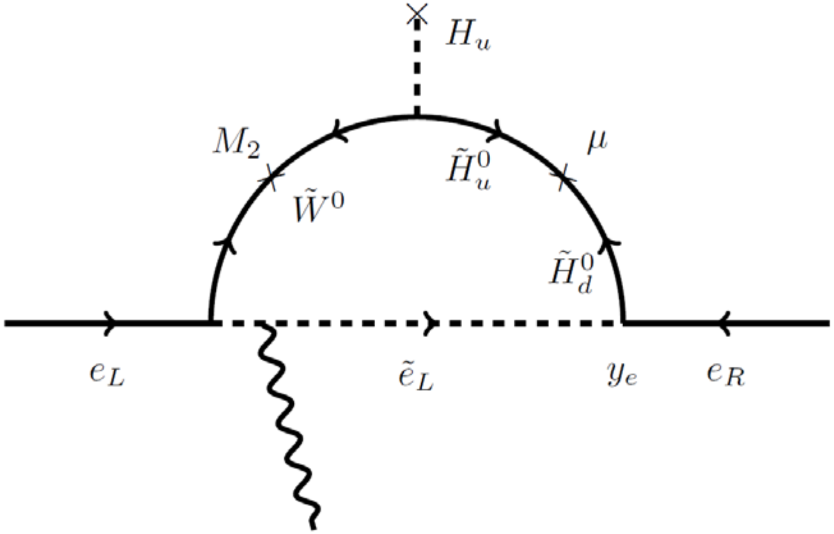
Order unity phases imply several TeV masses



arXiv:1810.07736

Impact

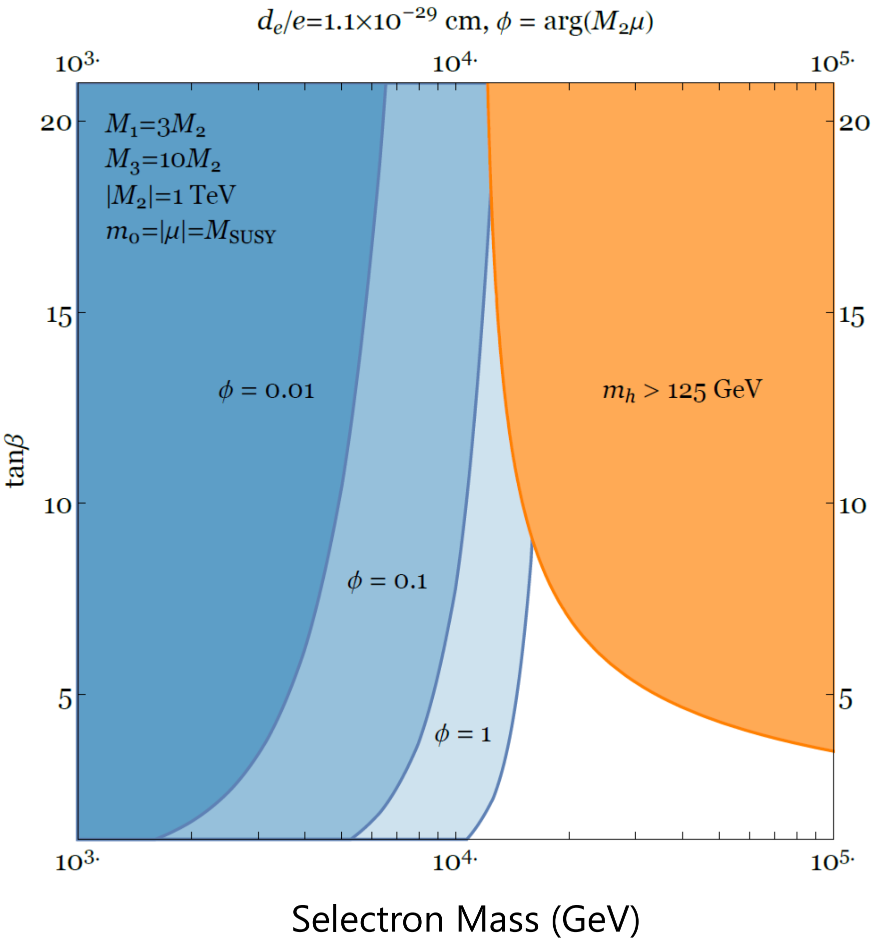
1-loop SUSY: Selectron



EDM constrains selectron mass and tanβ

Measured Higgs mass also constrains

Hint of tension between these data



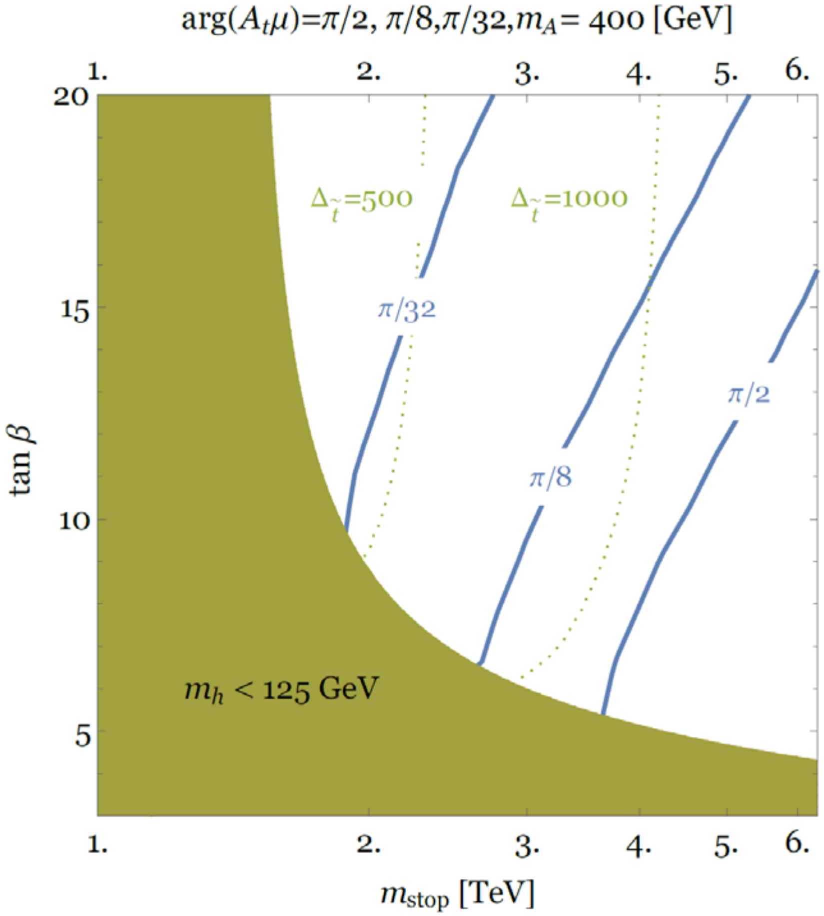
arXiv:1810.07736

Impact

Natural SUSY: Stop

Stop mass constrained to several TeV with reasonably natural phases

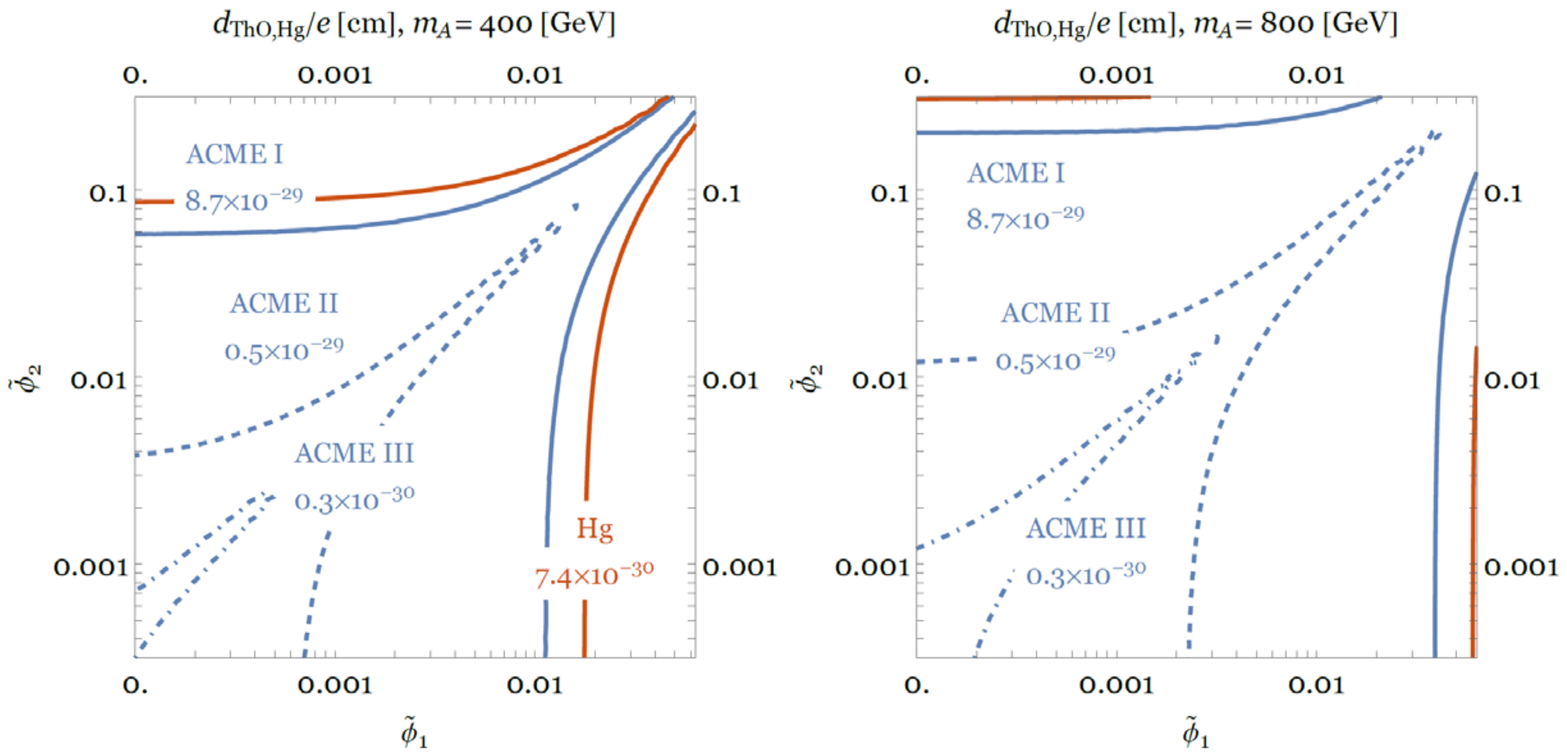
Higgs measurement provides complimentary constraint



arXiv:1810.07736

Impact

BMSSM



Significant constraint of CP-violating phases in BMSSM

Degree of constraint depends on Higgs mass, m_A

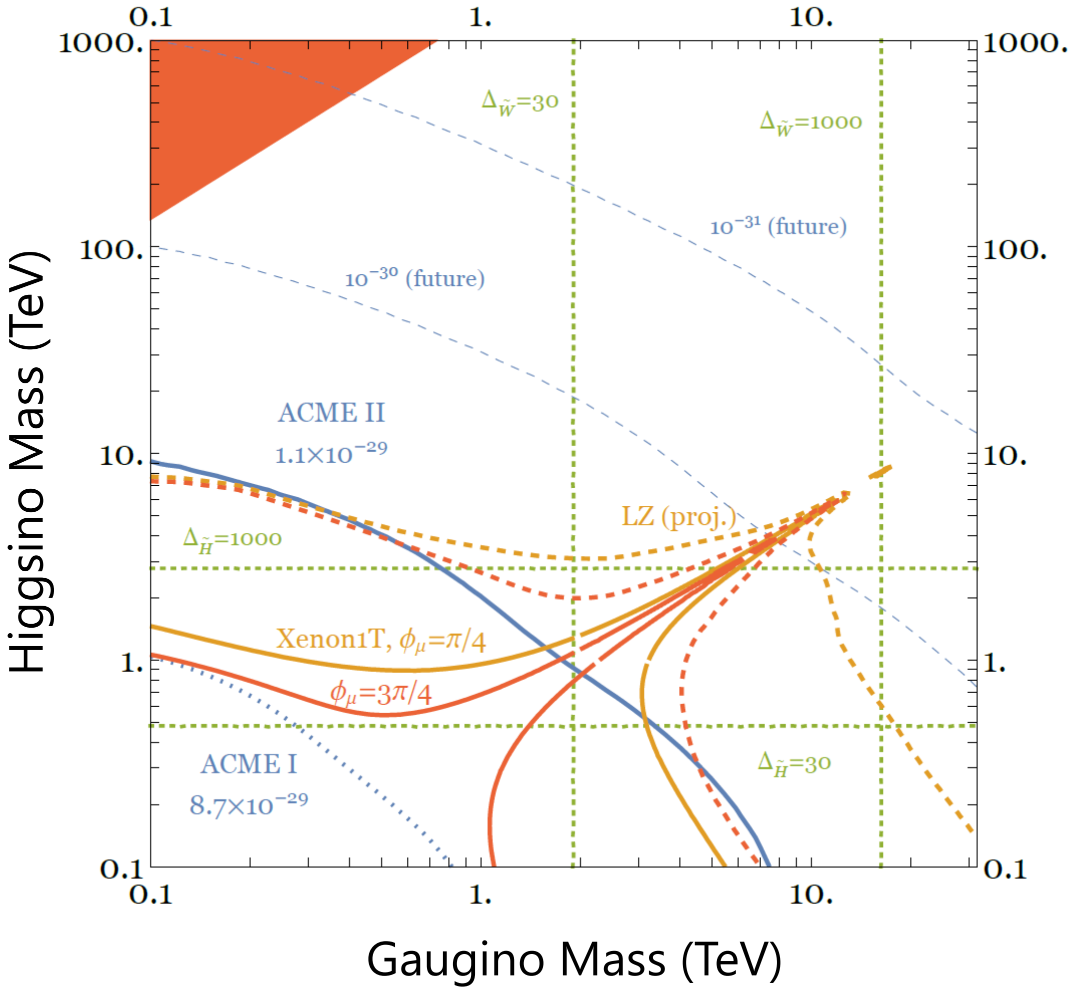
J. High Energ. Phys. (2017) 2017: 31

Impact

Split SUSY:

Constraints up to the 10 TeV level

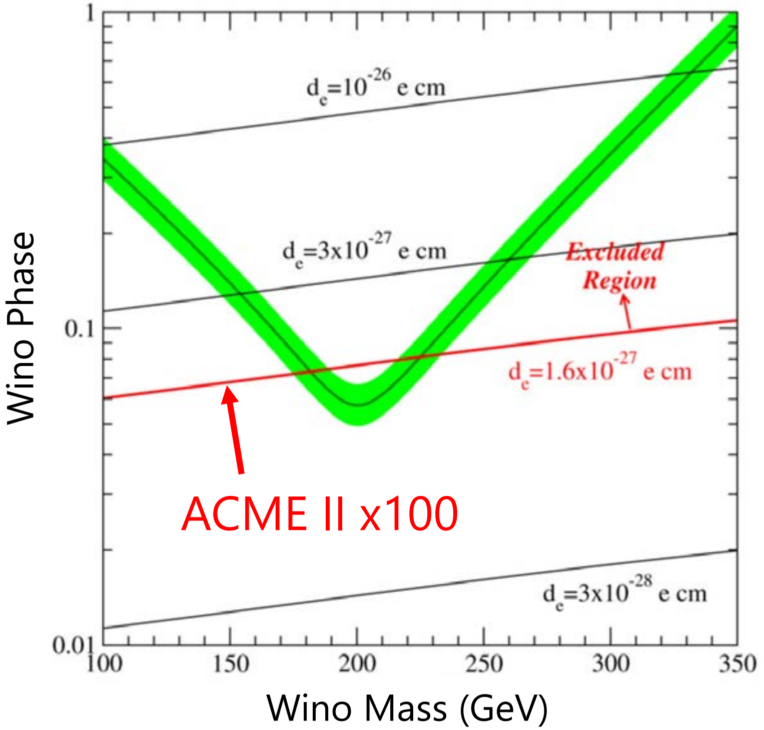
Broader coverage than dark matter experiments (assuming neutralino DM)

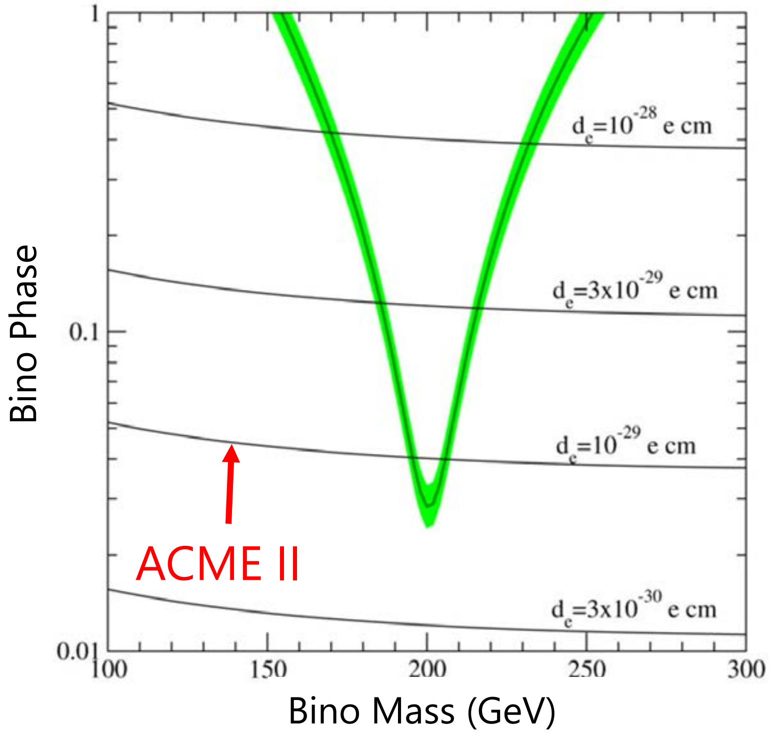


arXiv:1810.07736

Impact

Baryogenesis in MSSM:





Electroweak baryogenesis in MSSM severely constrained by eEDM[1]

Would also require stop to be reasonably light

Axionic baryogenesis much less constrained by eEDM[2]

[1] Phys. Lett. B **673**, 95 (2009)
[2] Phys. Lett. B **790**, 326 (2019)

Impact

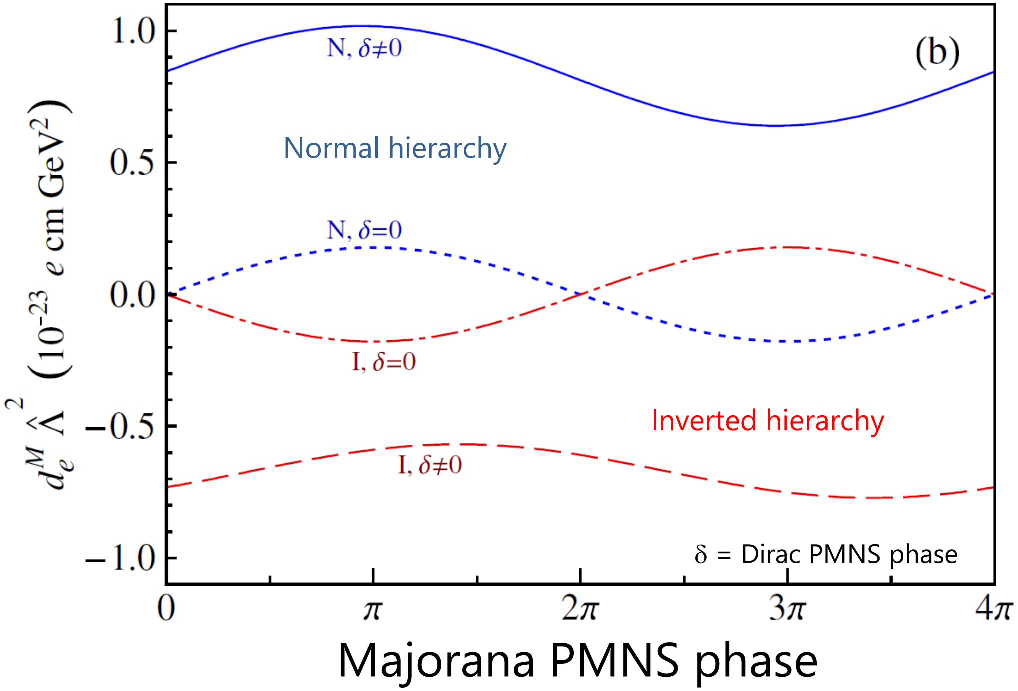
Majorana Neutrinos:

eEDM already constrains Majorana neutrinos within Minimum Flavour Violation framework:

ACME measurement constrains MFV energy scale, Λ to ~>1 TeV

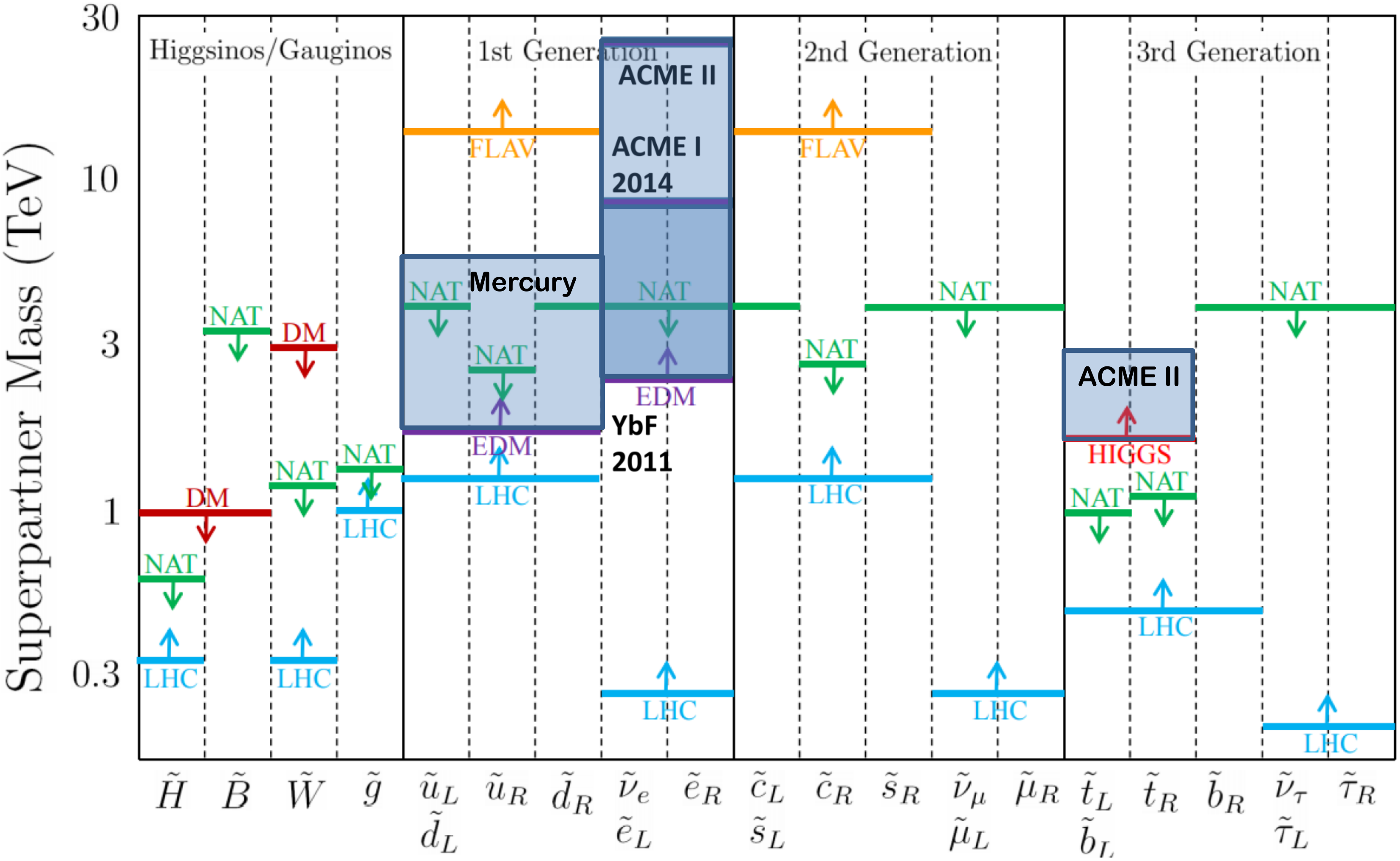
'd_e provides best CP-violating probe for Λ'[1]

Dirac neutrinos produce negligible d_e



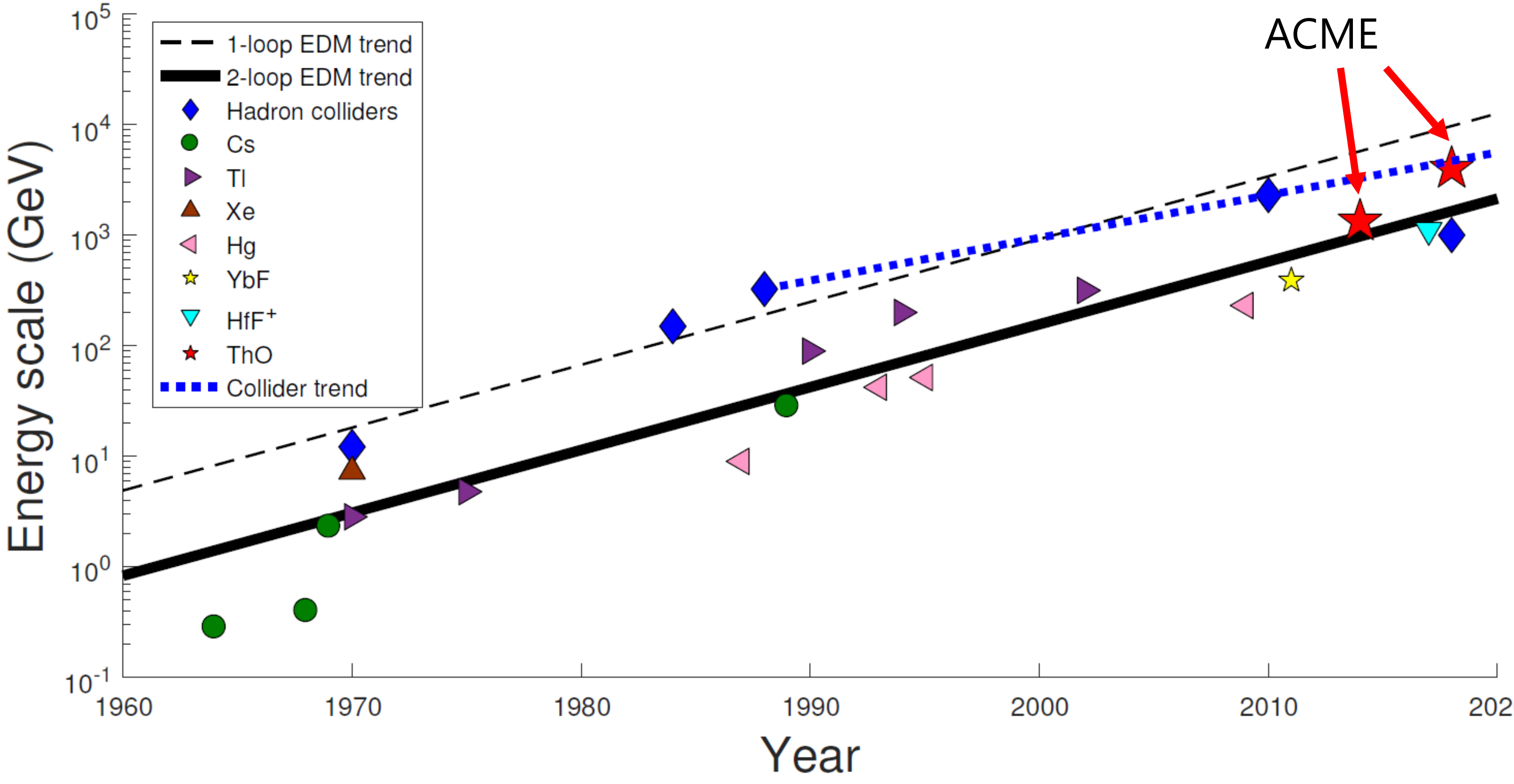
[1] Phys. Rev. D **89**, 091901(R)

Impact



Modified from Ann. Rev. Nucl. Part. Sci. **63**, 351 (2013)

Impact

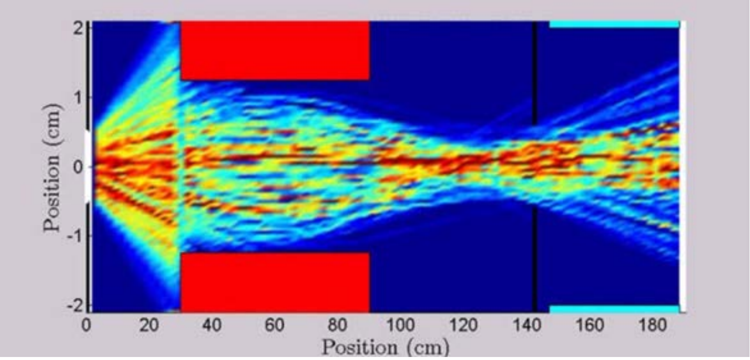


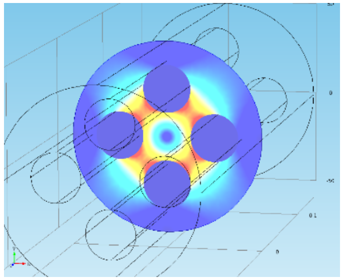
ACME
1-loop EDM trend
2-loop EDM trend
Hadron colliders
Cs
Tl
Xe
Hg
YbF
HfF+
ThO
Collider trend
Energy scale (GeV)
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
1960
1970
1980
1990
2000
2010
2020
Year

Future work

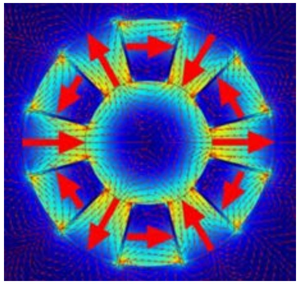
Improve statistical sensitivity:

Beam source highly divergent – focus with lens





Electrostatic

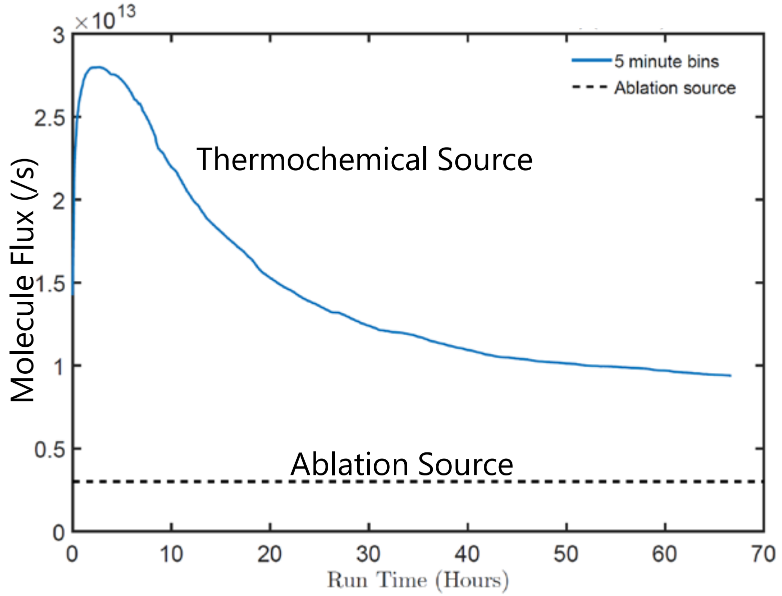


Magnetostatic

x7

Future work

Increase molecule flux with 'thermochemical' source



x5

Currently near photoelectron shot noise limit
Use optical cycling to reach molecule shot noise limit

x6

Total (optimistic!) gain:

7 x 5 x 6 = 210

Future work

Conservative estimate of x100 signal would give x10 sensitivity, x3 in energy reach

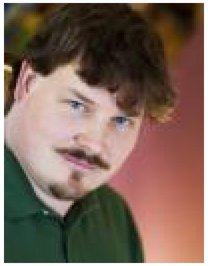
Need commensurate control over systematics and excess noise

Maybe ~100 TeV will be in reach?...

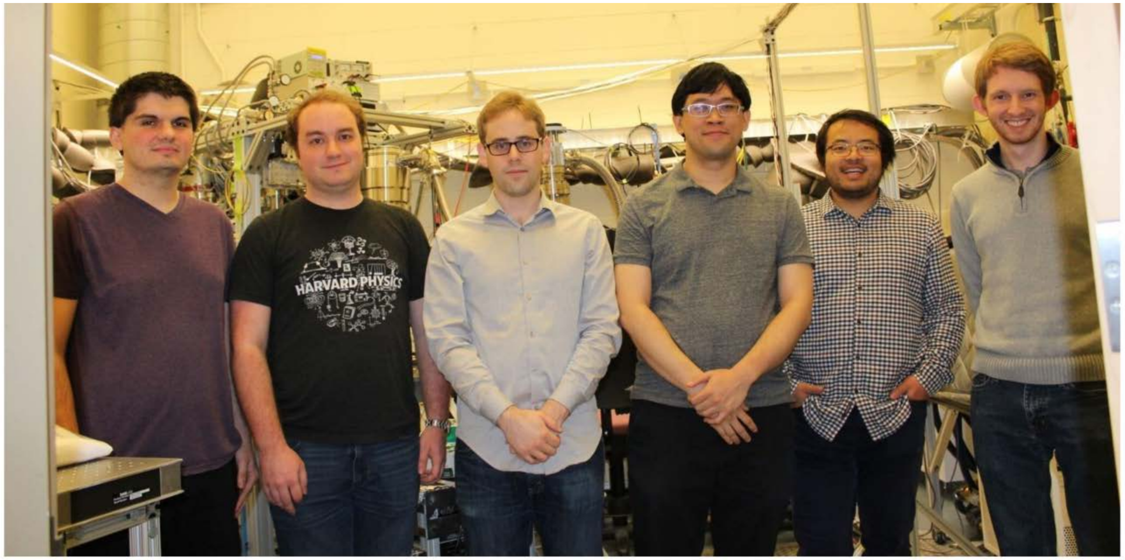
The Team


John Doyle


Jerry Gabrielse


David DeMille

Funding: NSF



Cris Panda
Cole Meisenhelder
Zack Lasner
Daniel Ang
Xing Wu
Jonathan Haefner

ACME II Alumni:
Vitaly Andreev (MPQ)
Nick Hutzler (Caltech)
Brendon O’Leary (SeatGeek)
Adam West (UCLA)
Elizabeth West (UCLA)