Electric Dipole Moment Experiments

Birmingham Particle Physics Seminar, Feb.13, 2019

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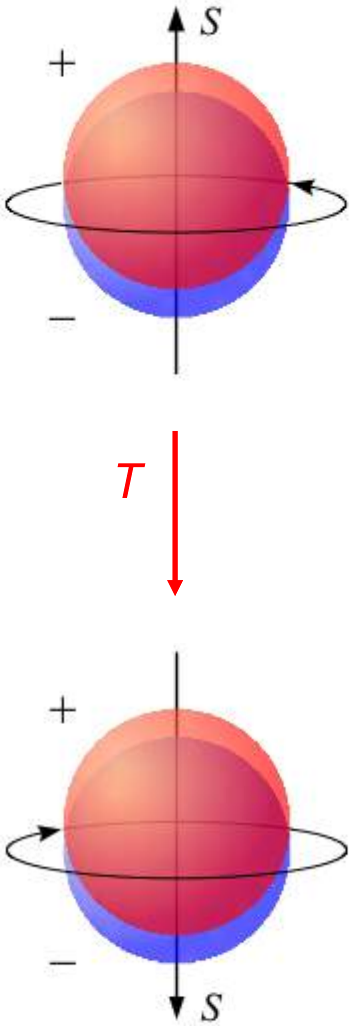
Outline

- what’s an EDM and how to measure it
  - different types of searches
- mercury EDM – nuclear CP violation
- polar molecules – electron EDM
- neutron EDM
  - PSI nEDM/n2EDM
  - cryogenic nEDM

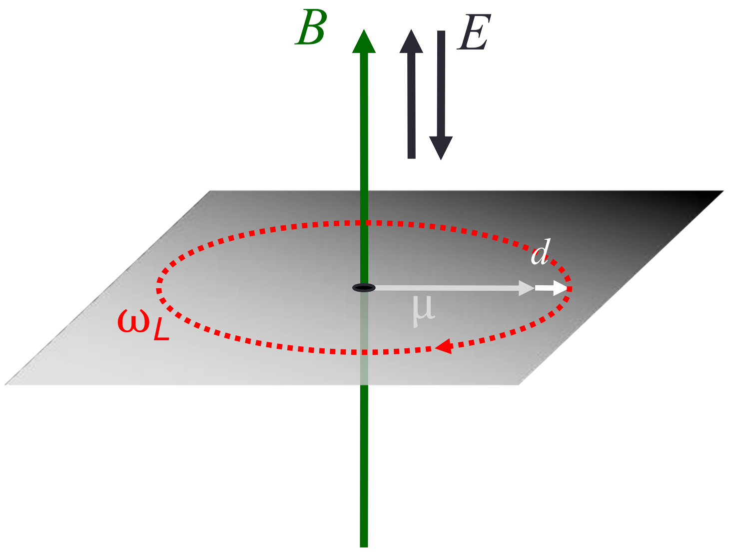
Electric Dipole Moments



- permanent EDM of a particle/atom/molecule violates T and P
  - with CPT theorem → implies CP violation
- Standard Model EDM predictions are vanishingly small
  - any nonzero measurement is a *background free* signal of CP violating *new physics!*
  - SM CP violation is too small to account for baryogenesis
    - BSM extensions preferably allow for new sources of of CP violation = *measurable EDMs*
- EDM experiments have an excellent potential for BSM *discovery*

Measuring an EDM via spin precession

$$H = -(\vec{\mu}\cdot\vec{B} + \vec{d}\cdot\vec{E})$$



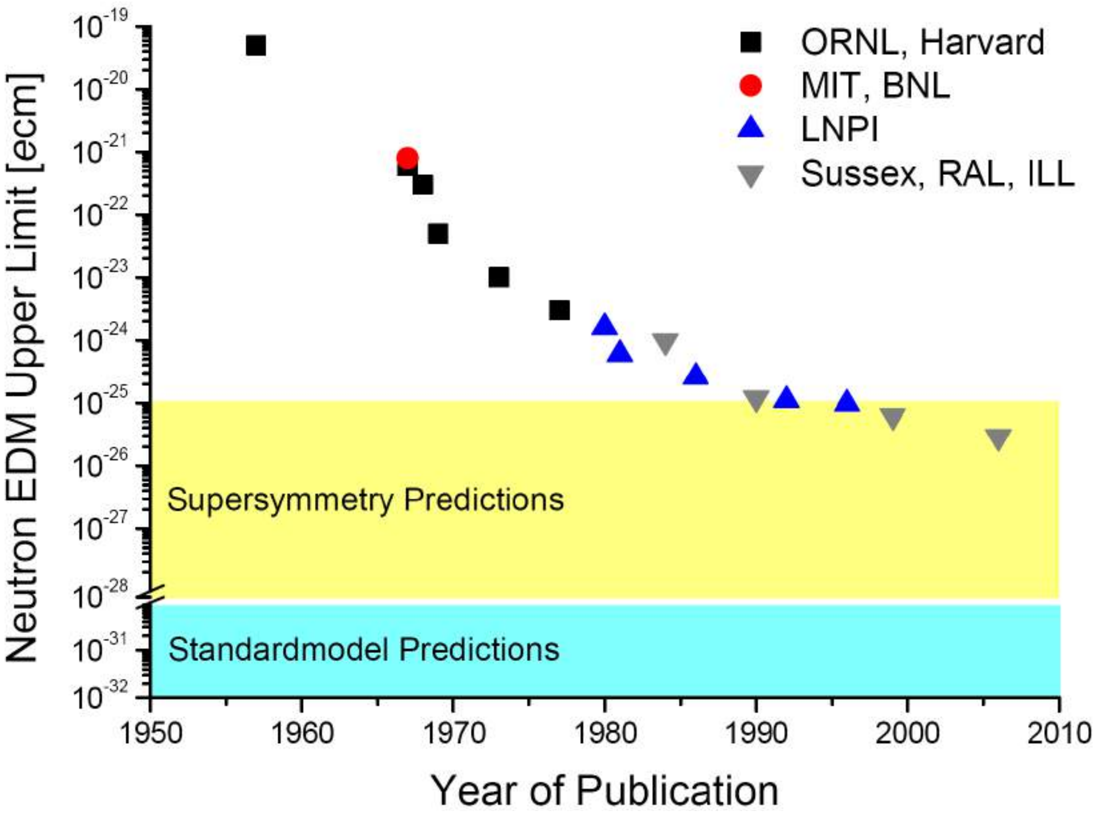
$$\omega_1 = \frac{2\vec{\mu}\cdot\vec{B} + 2\vec{d}\cdot\vec{E}}{\hbar}$$

$$\omega_2 = \frac{2\vec{\mu}\cdot\vec{B} - 2\vec{d}\cdot\vec{E}}{\hbar}$$

$$\Rightarrow \quad \boxed{\omega_1 - \omega_2 = \frac{4\,d\,E}{\hbar}}$$

larger E-fields give better sensitivity, need to control magnetic fields very well, guard against any B-fields correlated with E

EDM searches: neutron



$$d_n \approx \left(\frac{300\,\mathrm{GeV}}{\Lambda_{SUSY}} \right)^2 \sin\varphi_{CP} \times 10^{-24}\,\mathrm{e.cm}$$

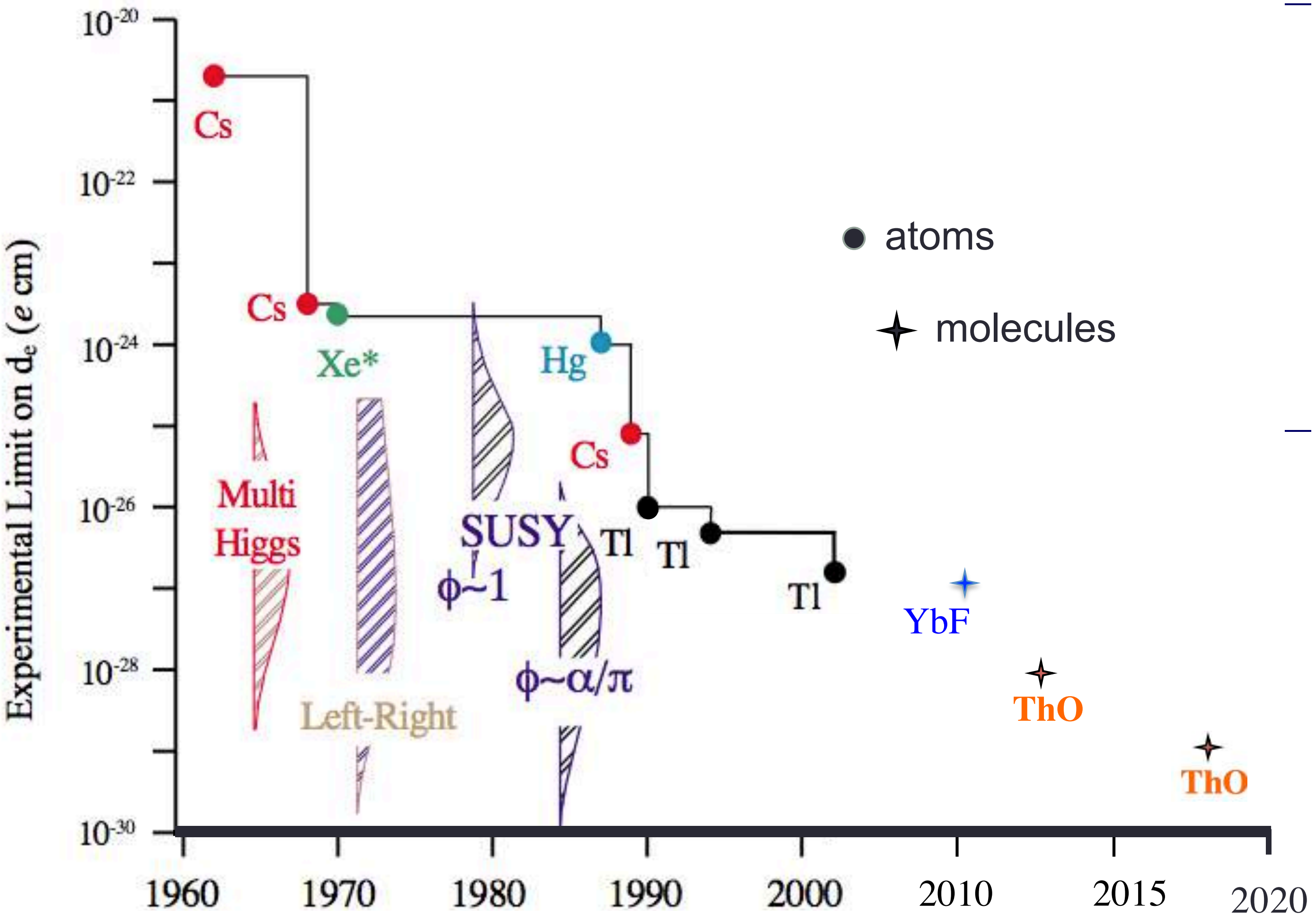
nEDM measurements utilise *UltraCold Neutrons* (UCN)
v = 0-6 m/s, can be stored in material bottles

$|d_n| < 3 \times 10^{-26}$ *e* cm

2006 result – Sussex/RAL/ILL reanalysed in 2015 accounting for gravitational depolarisation systematic

Sussex led experiment has had world lead since 1999

EDM searches: electron



- electron EDM is enhanced by relativistic effects in heavy paramagnetic atoms/molecules
- best atomic limit is from Berkeley Thallium beam experiment:

$$d_{\mathrm{Tl}} = -585\, d_e$$

$$|d_e| < 1.6 \cdot 10^{-27} \text{ e cm } (2002)$$

B.C. Regan, E.D. Commins, C.J. Schmidt, and D. DeMille, PRL **88**, 071805 (2002).

- polar molecules now give best limits

YbF at Imperial College:

$$d_{\mathrm{YbF}} \sim 10^6\, d_e$$

$$|d_e| < 1.05 \cdot 10^{-27} \text{ e cm } (2011)$$

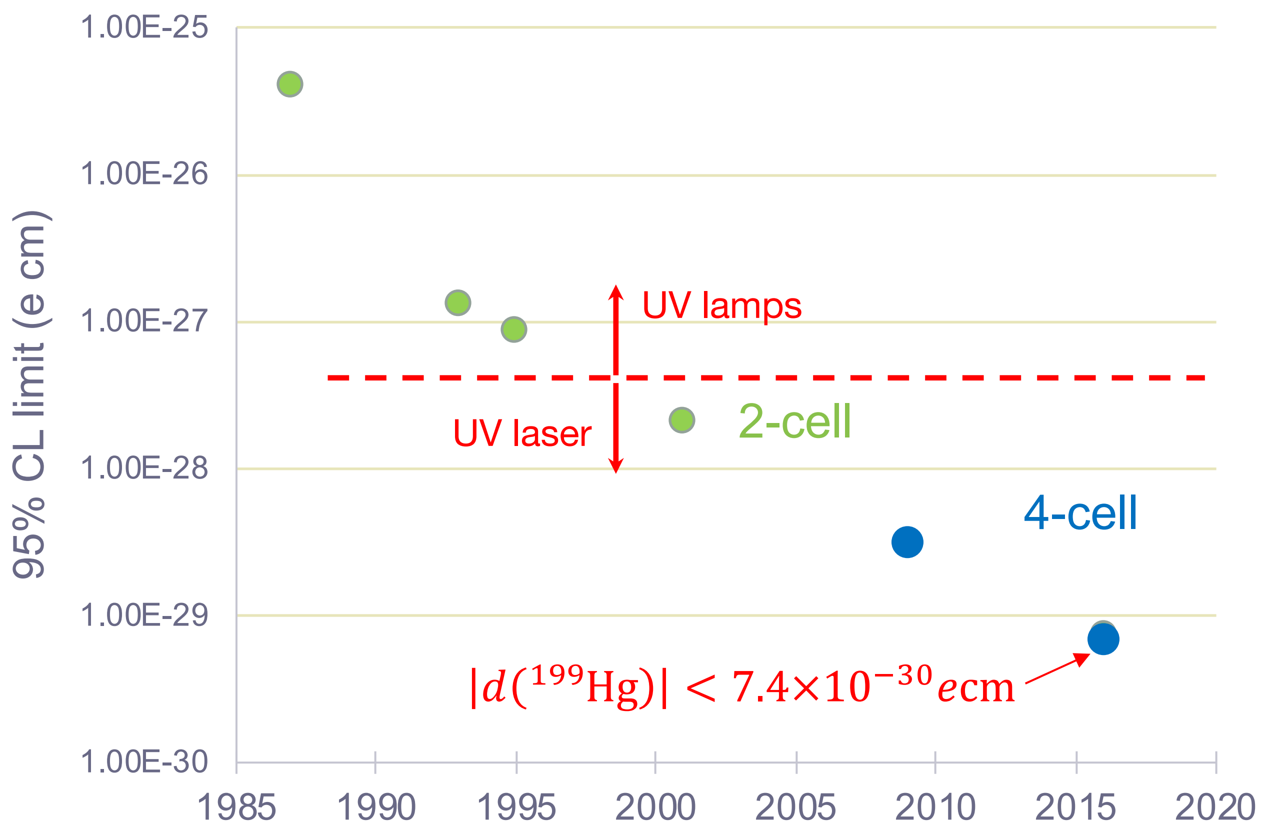
J.J. Hudson, D.M. Kara, I.J. Smallman, B.E. Sauer, M.R. Tarbutt, and E. A. Hinds, Nature **473**, 493 (2011).

ThO at Harvard/Yale:

$$|d_e| < 1.1 \cdot 10^{-29} \text{ e cm } (2018)$$

-ACME Collab. Nature **562**, 355 (2018)

EDM searches: diamagnetic atoms



$|d(^{199}\mathrm{Hg})| < 7.4\times10^{-30}\,ecm$

S.K. Lamoreaux, J.P. Jacobs, B.R. Heckel, F.J. Raab, and E.N. Fortson, PRL **59**, 2275 (1987).
J.P. Jacobs, W.M. Klipstein, S.K. Lamoreaux, B.R. Heckel, and E.N. Fortson, PRA **52**, 3521 (1995).
M.V. Romalis, W.C. Griffith, J.P. Jacobs, and E.N. Fortson, PRL **86**, 2505 (2001).
W.C. Griffith, M.D. Swallows, T.L. Loftus, M.V. Romalis, B.R. Heckel, and E.N. Fortson, PRL **102**, 101601 (2009).
B. Graner, Y. Chen, E.G. Lindahl, and B.R. Heckel, PRL **116**, 161601 (2016).

- Diamagnetic atoms ($^1S_0$ ground state) with finite nuclear spin (*I*) are sensitive to the EDM of the nucleus / CP-violating nuclear forces

Expected signal is larger for heavier atoms:

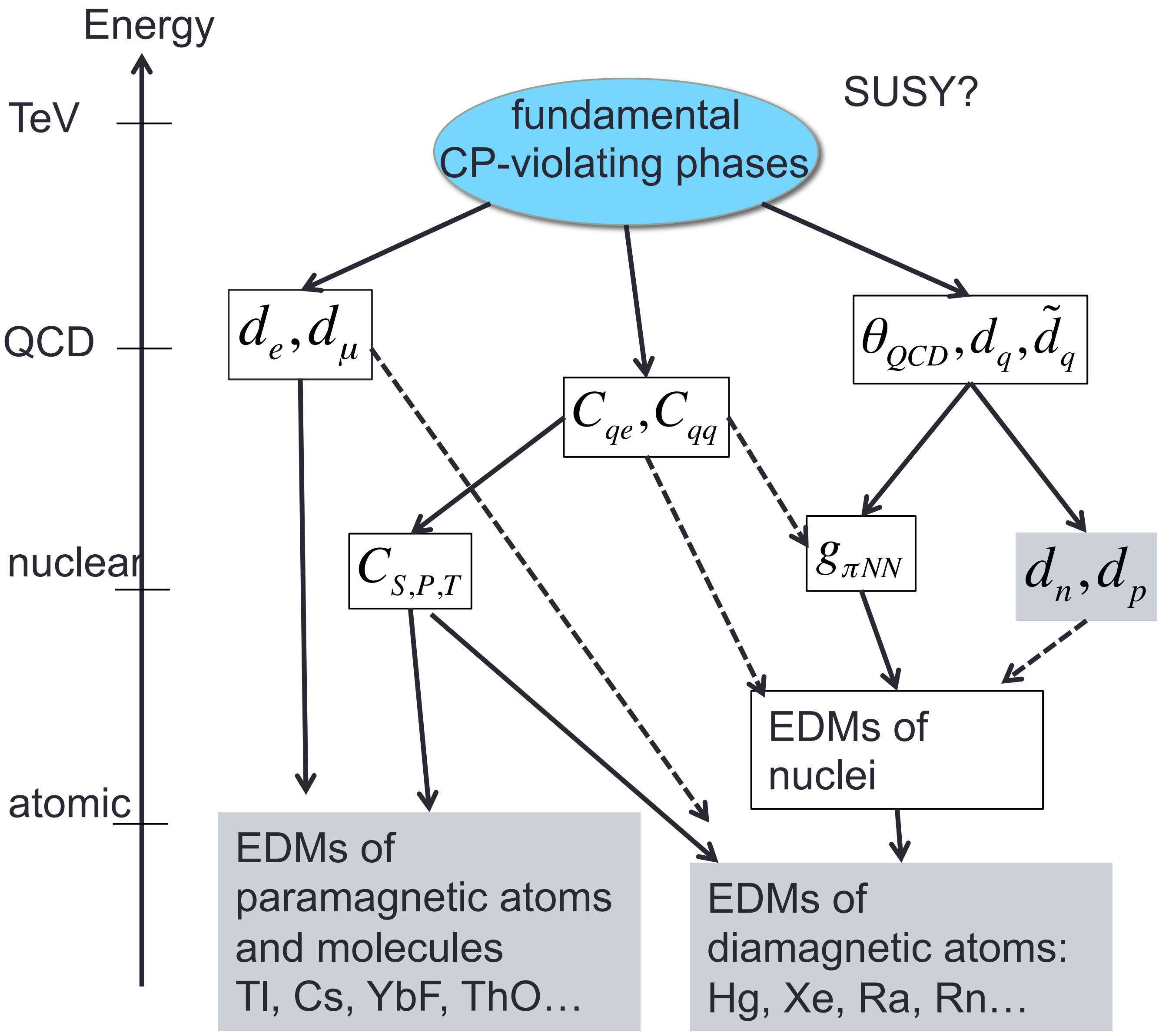
$$d_{atom} \propto d_{nuc} \underbrace{\left[Z^2\left(\frac{r_n}{a_0}\right)^2\right]}_{\approx 10^{-3}}$$

^{199}Hg is the heaviest, stable I=1/2 nucleus

other diamagnetic experiments:
Xe (Princeton, Tokyo, TUM, Mich.)
trapped Ra (Argonne,KVI)
Rn (Mich./TRIUMF)

EDM searches

- EDM limits from the neutron, paramagnetic, and diamagnetic atoms can set orthogonal bounds on CP-violation in SUSY and other standard model extensions
- It is important to improve EDM sensitivity in all 3 sectors


Energy

TeV

QCD

nuclear

atomic

SUSY?

fundamental CP-violating phases

d_e, d_μ

C_{qe}, C_{qq}

$\theta_{QCD}, d_q, \tilde{d}_q$

$C_{S,P,T}$

$g_{\pi NN}$

d_n, d_p

EDMs of nuclei

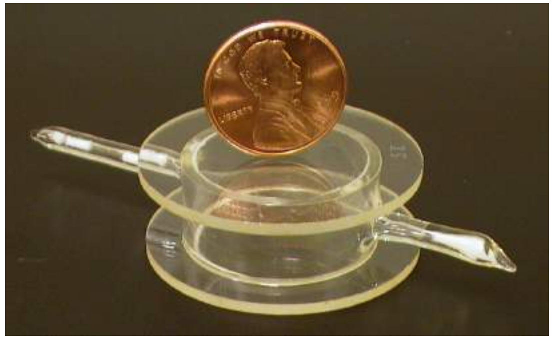
EDMs of paramagnetic atoms and molecules
Tl, Cs, YbF, ThO…

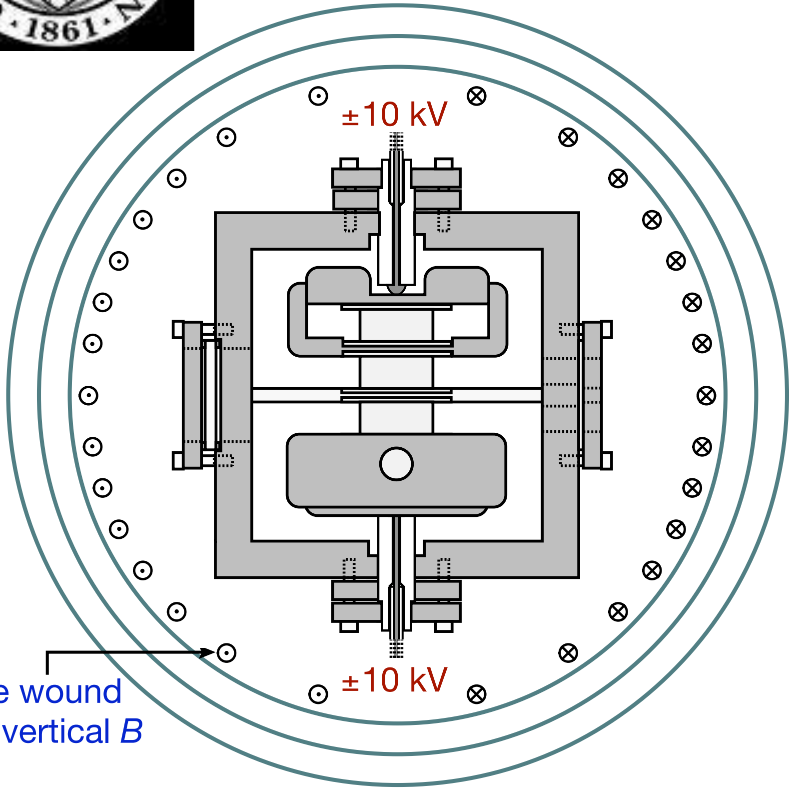
EDMs of diamagnetic atoms:
Hg, Xe, Ra, Rn…

Mercury EDM experiment

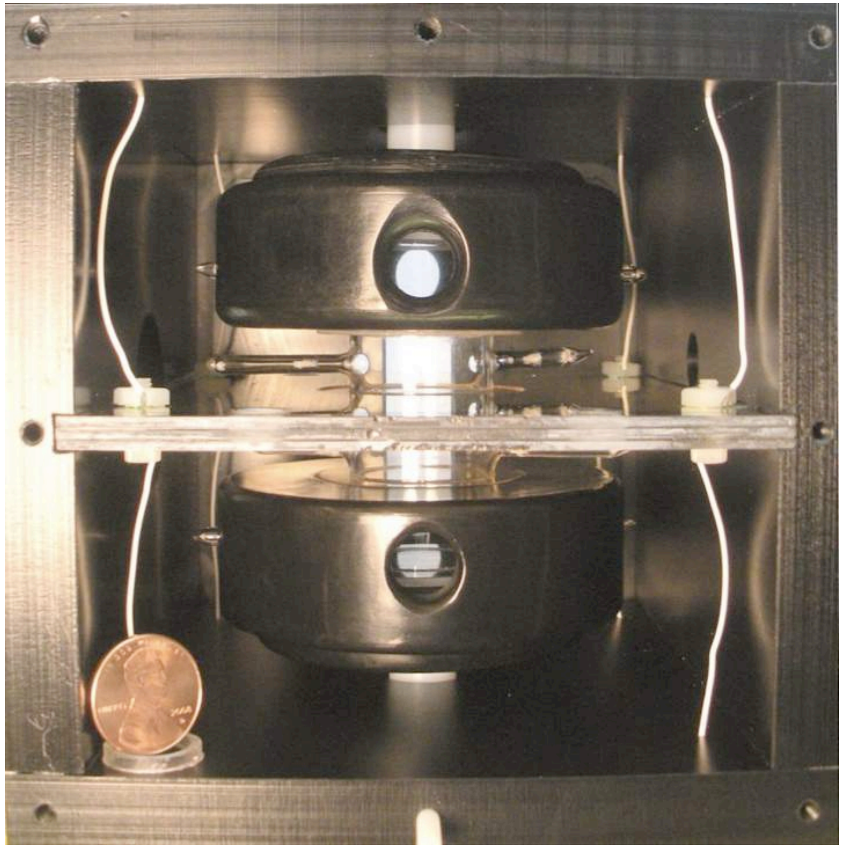
Univ. of Washington, Seattle, USA

a gas of Hg atoms is contained in a quartz vapor cell…



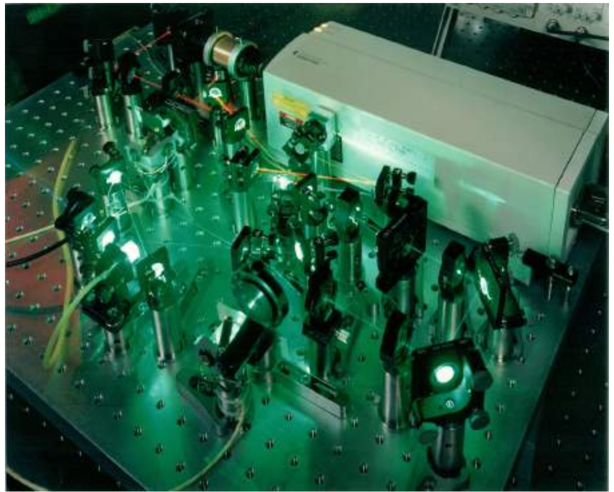


cosine wound coil for vertical *B*



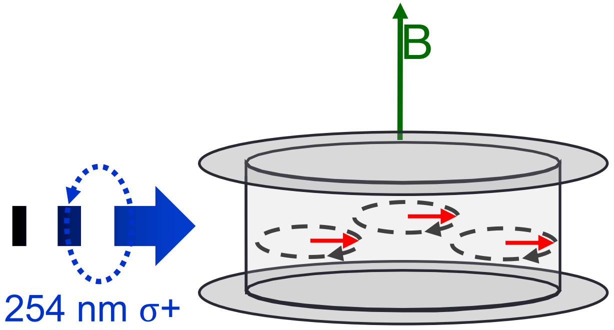
a stack of 4 cells is placed in a magnetic and electric field

spin precession of the Hg atoms is interrogated by a UV laser

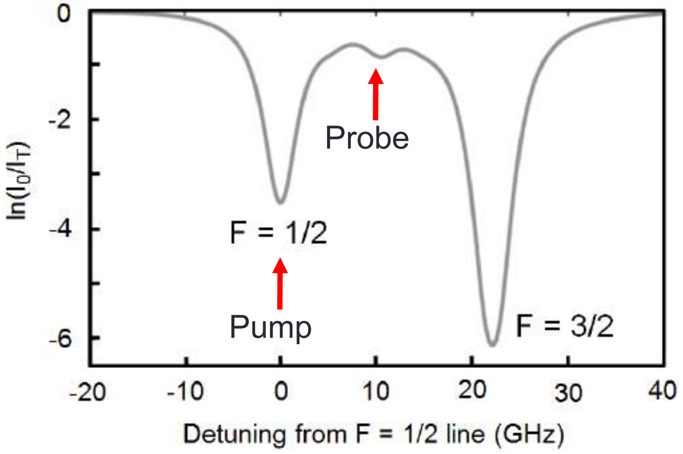


Hg spin precession measurement

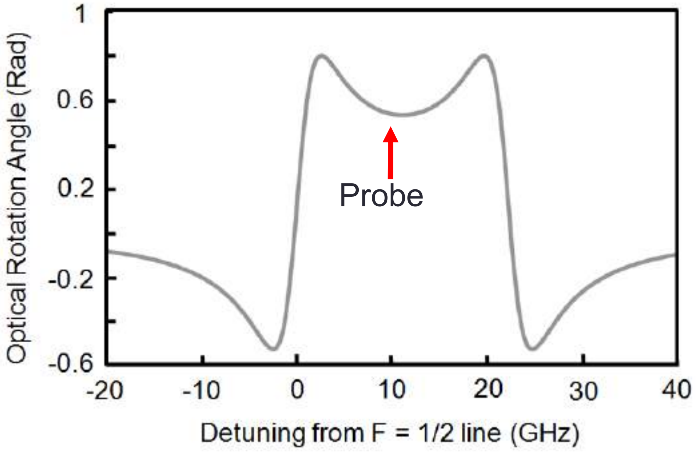
Transverse Optical Pumping



Absorption

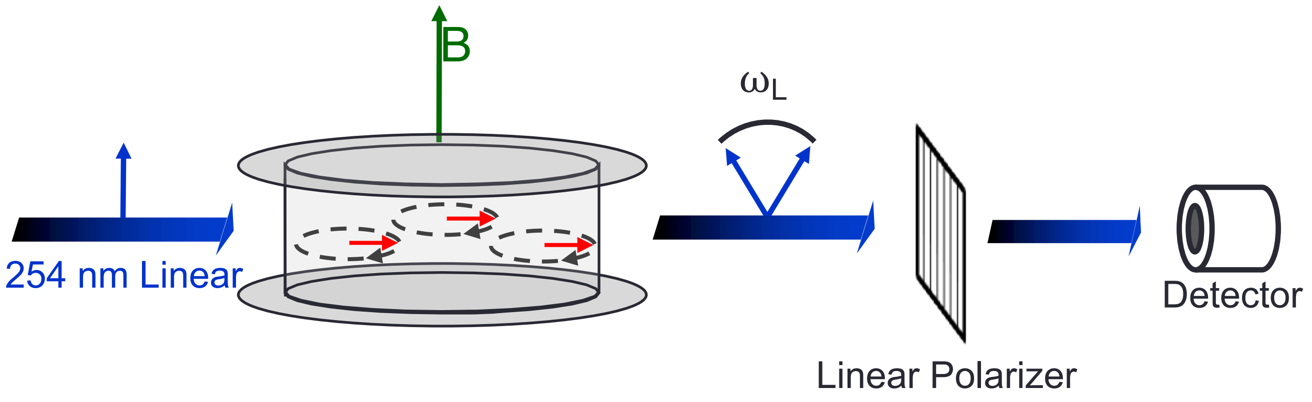


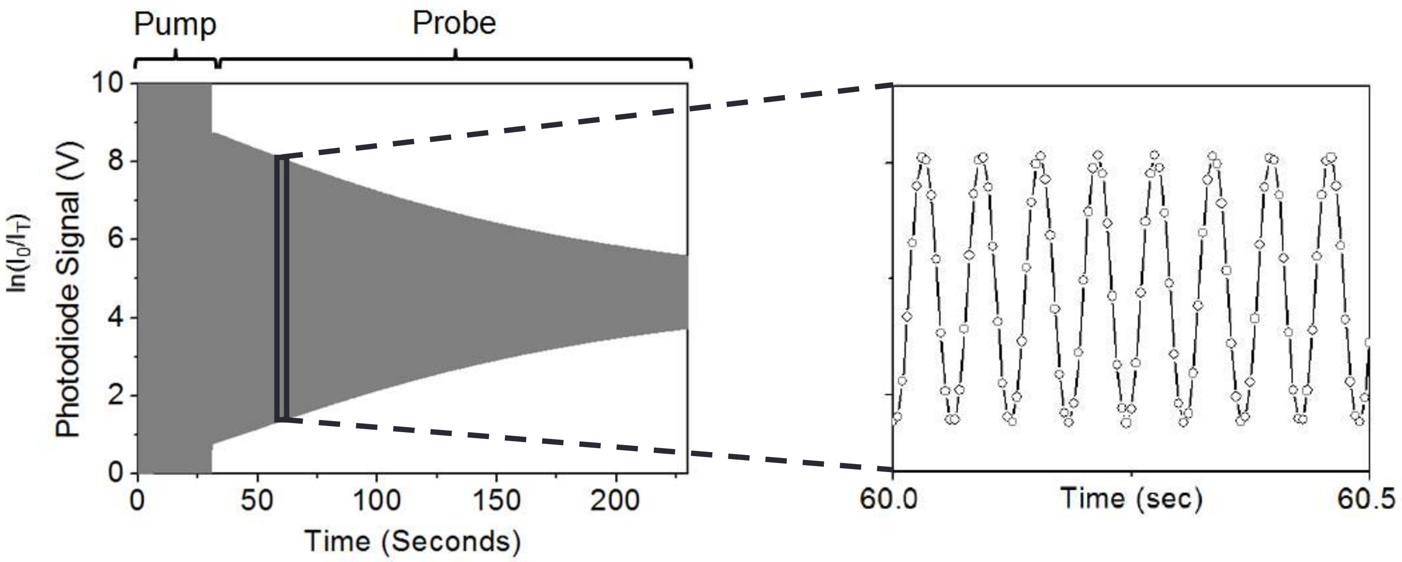
Optical Rotation Angle



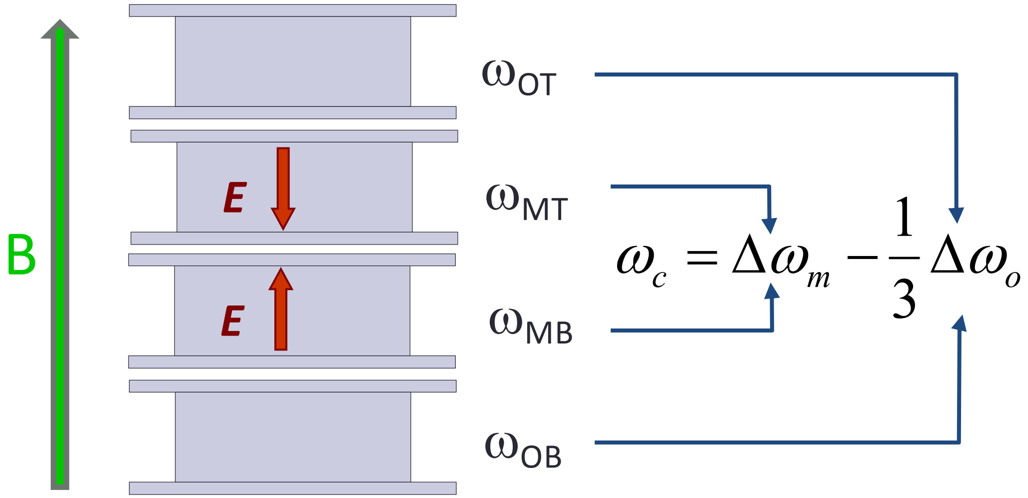
Hg spin precession measurement

Measure ω_L via Optical Rotation





4 cell, ^{199}Hg magnetometer



$$\omega_c = \Delta\omega_m - \frac{1}{3}\Delta\omega_o$$

EDM sensitive frequency combination

$$\omega_c = \frac{\mu}{\hbar}\left(-\frac{8}{3}\frac{\partial^3 B}{\partial z^3}\Delta z^3\right) + \frac{4dE}{\hbar}$$

Cancels up to 2nd order gradient noise

EDM insensitive channels: $\omega_{OT} - \omega_{OB}$ and $(\omega_{OT} + \omega_{OB}) - (\omega_{MT} + \omega_{MB})$ monitor for E field correlations odd and even in z, respectively.

The EDM of mercury atoms…

- ... is still consistent with zero, $|d_{Hg}| < 7.4 \times 10^{-30}$ *e* cm

  smallest EDM upper bound achieved in any measurement!

- ...is associated with the mercury nuclear spin
  - might arise from the neutron EDM $|d_n| < 1.6\times10^{-26}\ ecm$
  - or the proton EDM $|d_p| < 2\times10^{-25}\ ecm$
  - T-violating nuclear forces $|\theta_{QCD}| < 1.5\times10^{-10}$ $|\tilde{d}_q| < 10^{-27}\ \mathrm{cm}$

Caveats: *assumes single source for* d_{Hg}

very large uncertainties in nuclear calculations

Electron EDM

- EDM measurements in atoms with unpaired electron spins tend to be sensitive to the electron EDM
  - how spherical is the electron?
- In heavy atoms, the atomic EDM is enhanced relative to the electron EDM

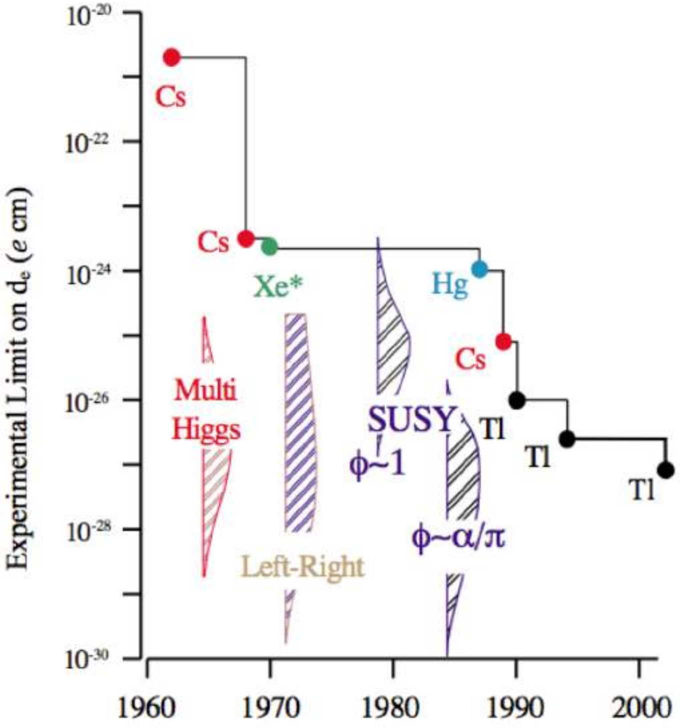
best limit is from Thallium:

$$d_{\mathrm{Tl}} = -585\, d_e$$

$$|d_e| < 1.6 \cdot 10^{-27}\ e\ \mathrm{cm}\ (2002)$$

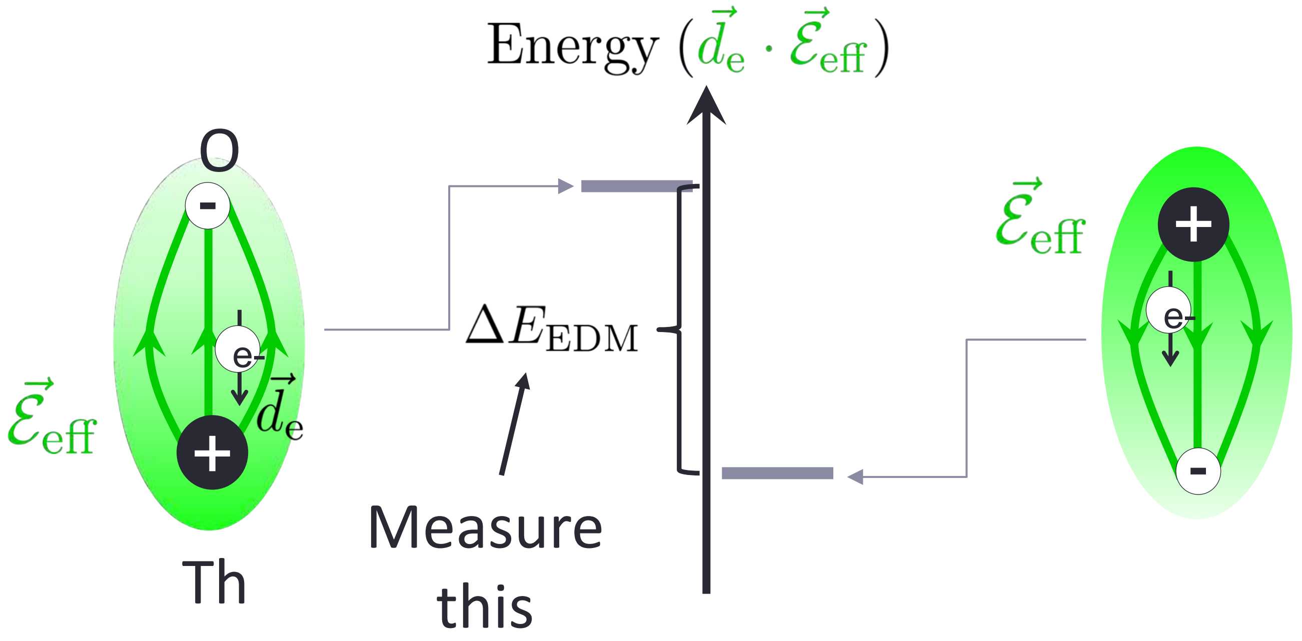
U. California, Berkeley

B.C. Regan, E.D. Commins, C.J. Schmidt, and D. DeMille, PRL **88**, 071805 (2002).



Electron EDM – molecular enhancement

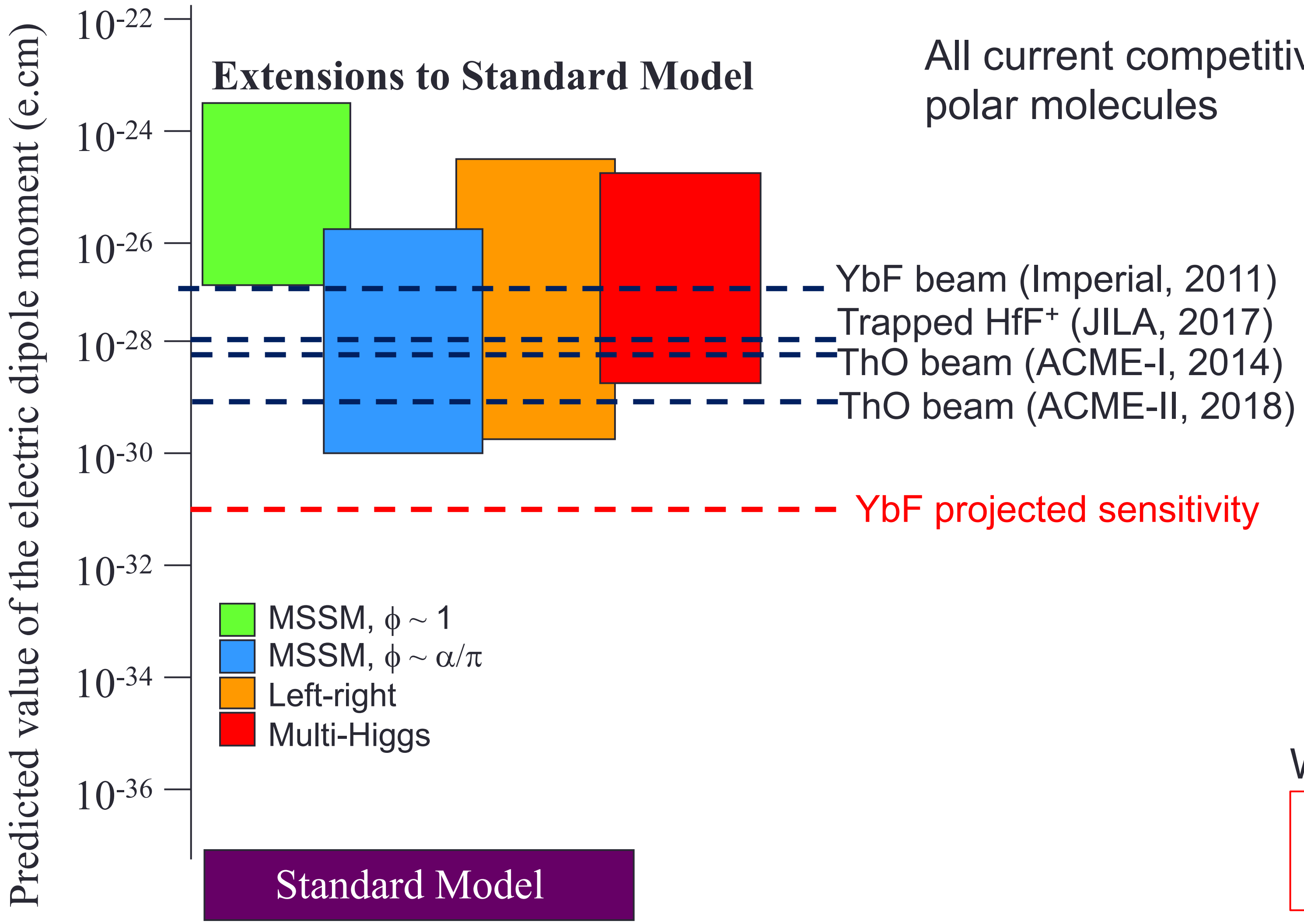
- With a relatively modest laboratory electric field, the unpaired electron in paramagnetic systems experiences a much larger internal electric field
- Gives a large enhancement of d_e relative to the atomic or molecular EDM
  - x10^3 in heavy atoms (Tl,Fr)
  - x10^6 in molecules



http://laserstorm.harvard.edu/edm/

Electron EDM – current status

All current competitive experiments are done using polar molecules



n-loop diagram

CP-violating phases

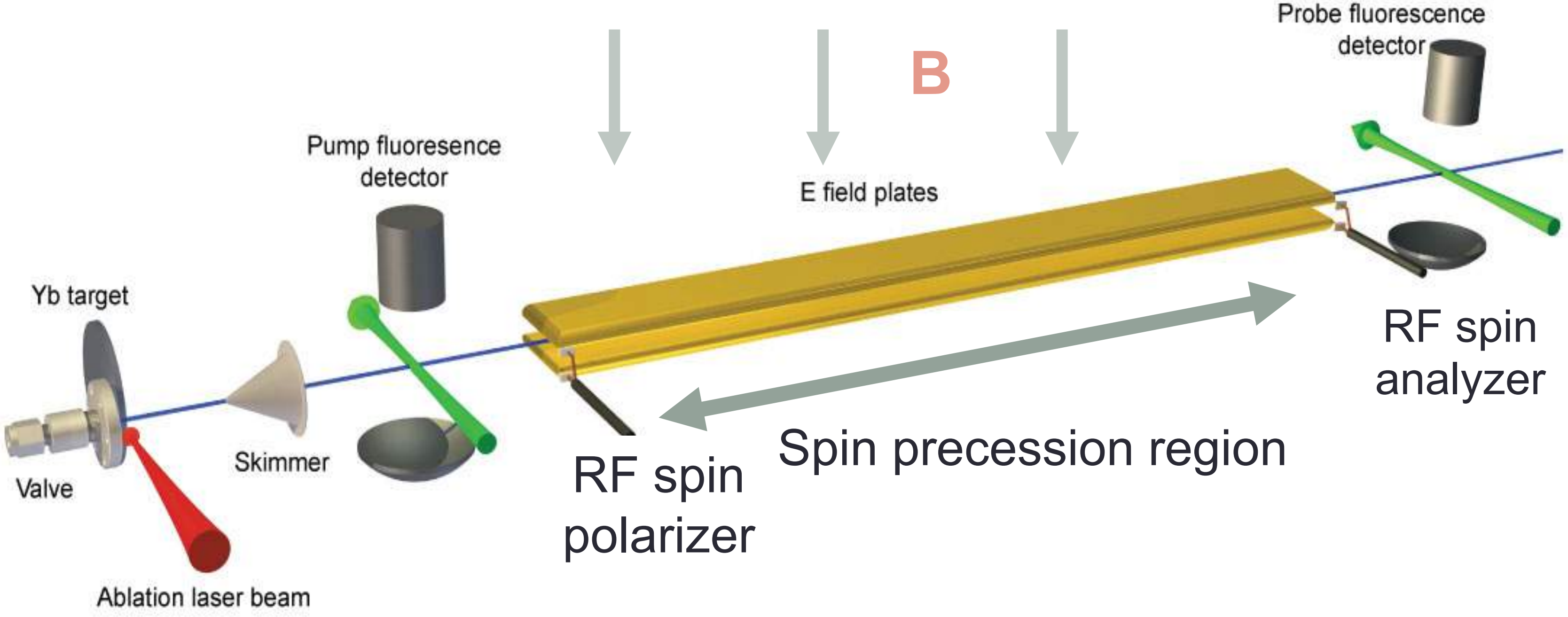
$$\frac{d_e}{e} \sim h\,c \left(\frac{\alpha}{4\pi}\right)^{n} \left(\frac{m_e c^2}{\Lambda^2}\right) \sin(\phi_{cp})$$

Energy scale for new particles

When $n = 1$ and $\sin(\phi_{\mathrm{CP}}) \sim 1$:

$d_e = 10^{-30}$ e.cm corresponds to $\Lambda \approx 100$ TeV

Current eEDM experiment at Imperial



B

RF spin analyzer

Spin precession region

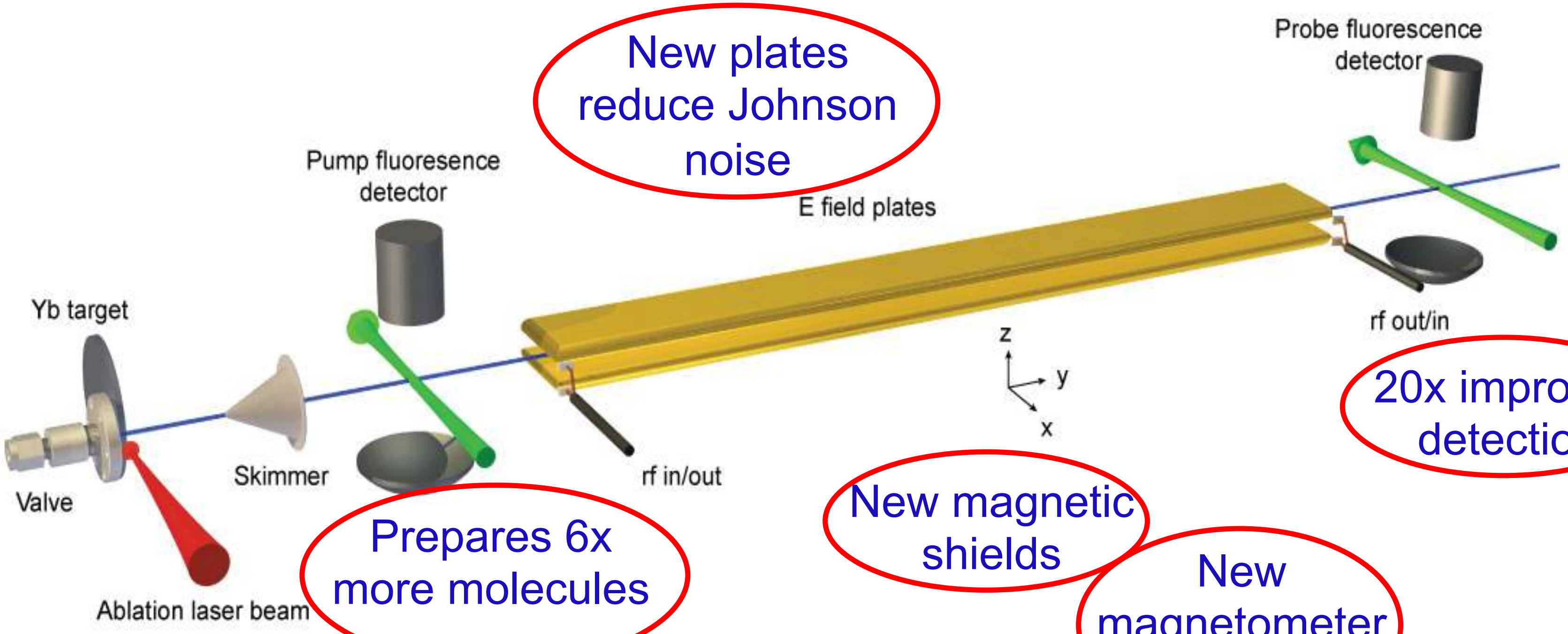
RF spin polarizer

Supersonic YbF beam
Temperature: 4 K
Speed: 590 m/s

To increase precision:

(1) Increase number of detected molecules
(2) Reduce magnetic noise
(3) Increase spin-precession time

More molecules and reduced magnetic noise



New plates reduce Johnson noise

Prepares 6x more molecules

New magnetic shields

New magnetometer array

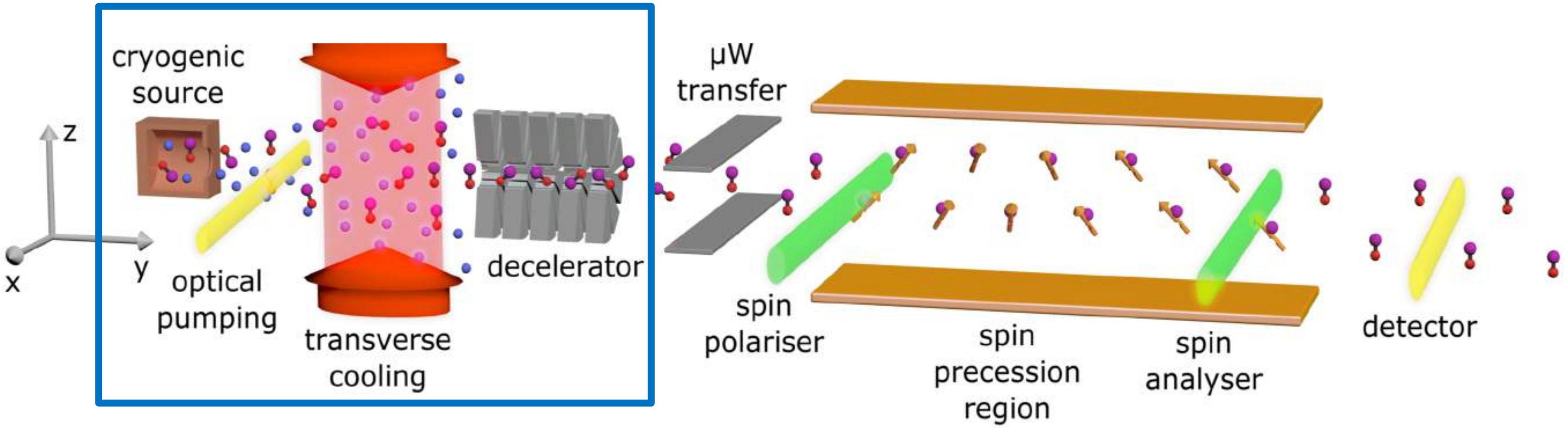
20x improved detection

- x20 improved eEDM sensitivity relative to 2011 result
- 2019: aim for new measurement with uncertainty of 5×10^{-29} e.cm
- 2020: improve limit to 2×10^{-29} e.cm
- This is limit of current method - to go further, must increase spin precession time

New YbF experiment

- Spin precession time limited by thermal expansion of beam – need ultracold molecules
- Have recently demonstrated laser cooling of YbF molecules to 100 μK

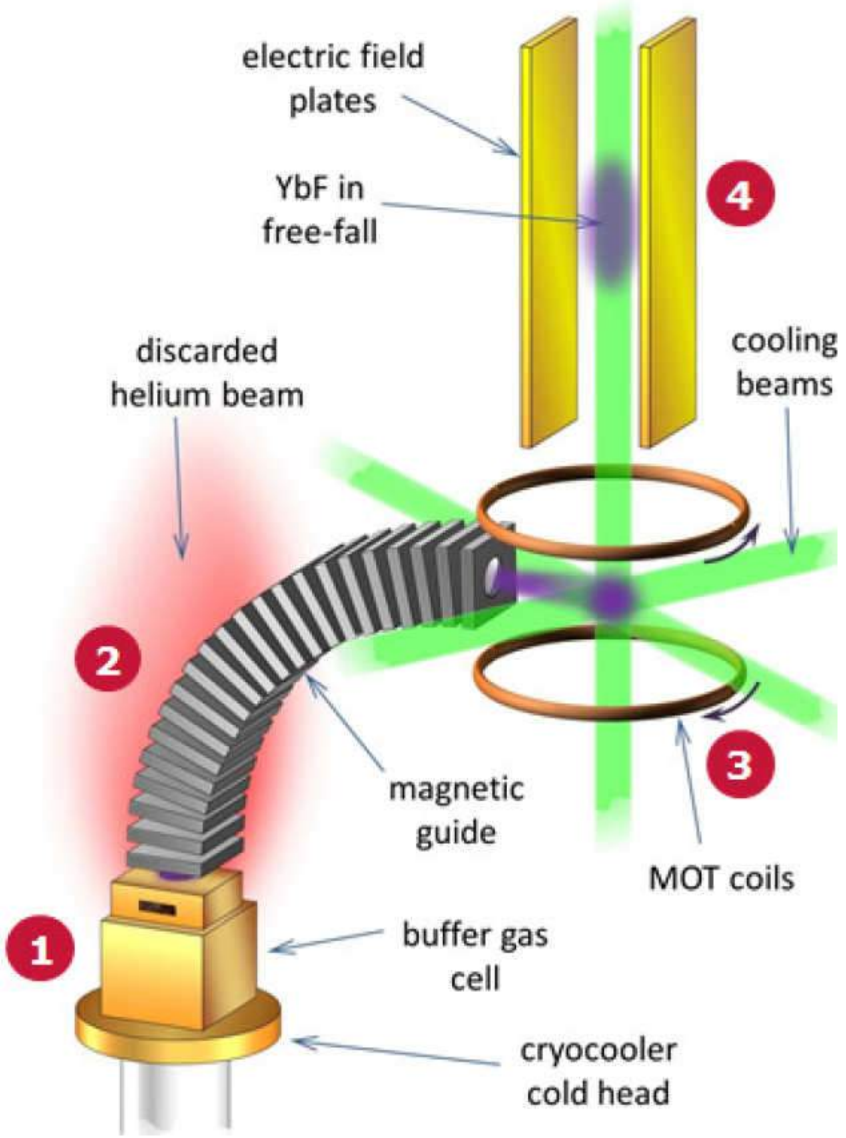
> 300x improvement



- 2019-2022: build this apparatus and demonstrate eEDM sensitivity at 10^{-30} e.cm level
- Longer term: use the apparatus to measure eEDM with uncertainty below 10^{-31} e.cm

YbF next-next-generation

- full 3D laser cooling/trapping of YbF
- launched 10 cm up into E and B field region, fall back down for detection
- will have many less molecules than in a beam, but much longer coherence time
  - beam: ~ 0.001 sec
  - fountain: ~ 1 sec



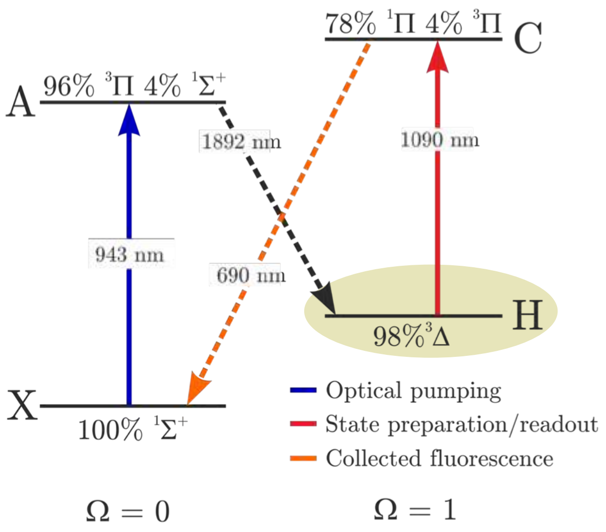
Design for a fountain of YbF molecules to measure the electron's electric dipole moment

M R Tarbutt, B E Sauer, J J Hudson and E A Hinds
New J. Phys. **15** (2013) 053034

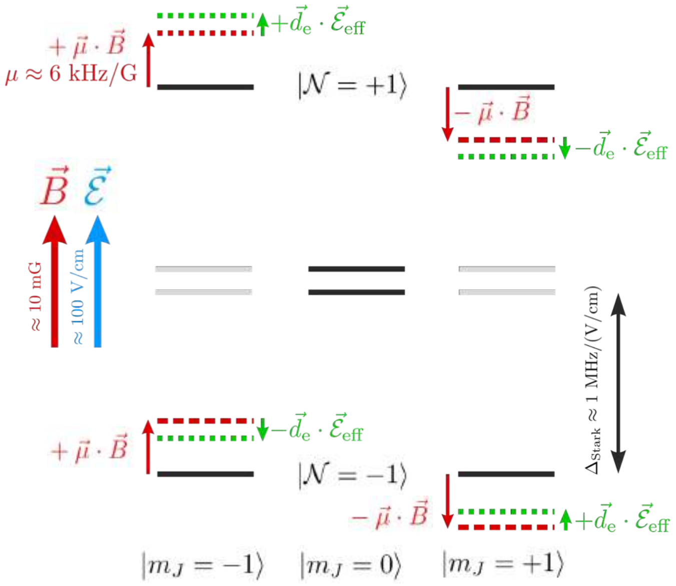
ACME electron EDM experiment

- **A**dvanced **C**old **M**olecule **E**lectron edm
- Collaboration between Harvard (John Doyle, Gerald Gabrielse) and Yale (David Demille)
- uses ThO molecules
  - with ~100 V/cm laboratory electric field, electron sees internal field ~ 85 GV/cm
  - Ω-doublet molecular state structure allows spectroscopic reversal of EDM signal
    - a powerful tool for ruling out systematic effects
  - small magnetic g-factor: $^3\Delta_1 \Longrightarrow g \sim 10^{-2}$

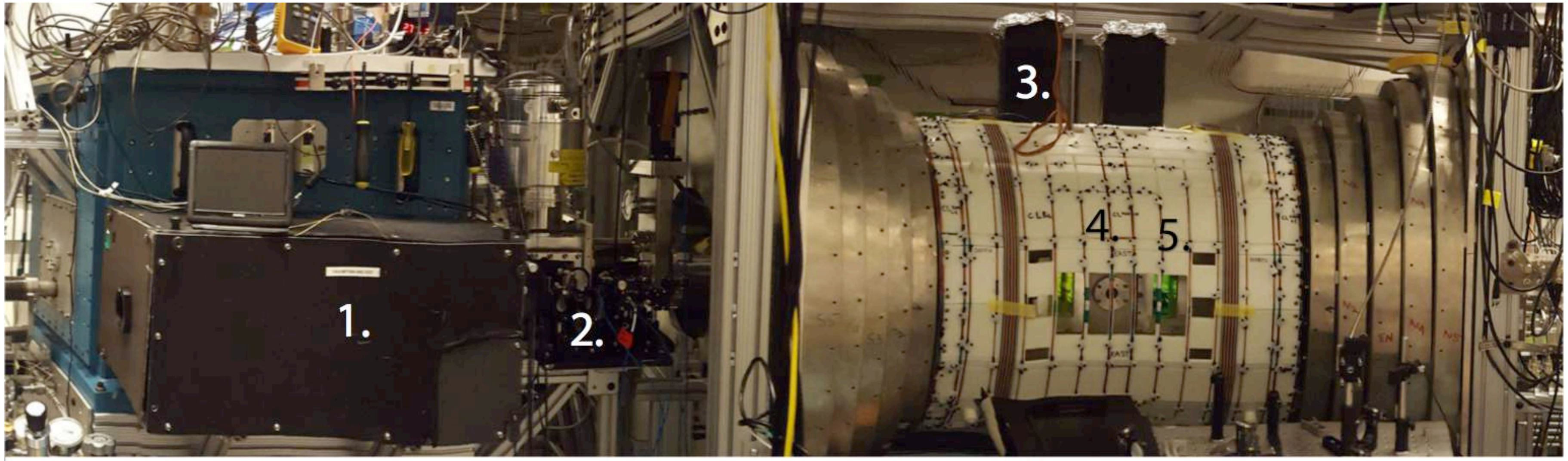
ThO level diagram

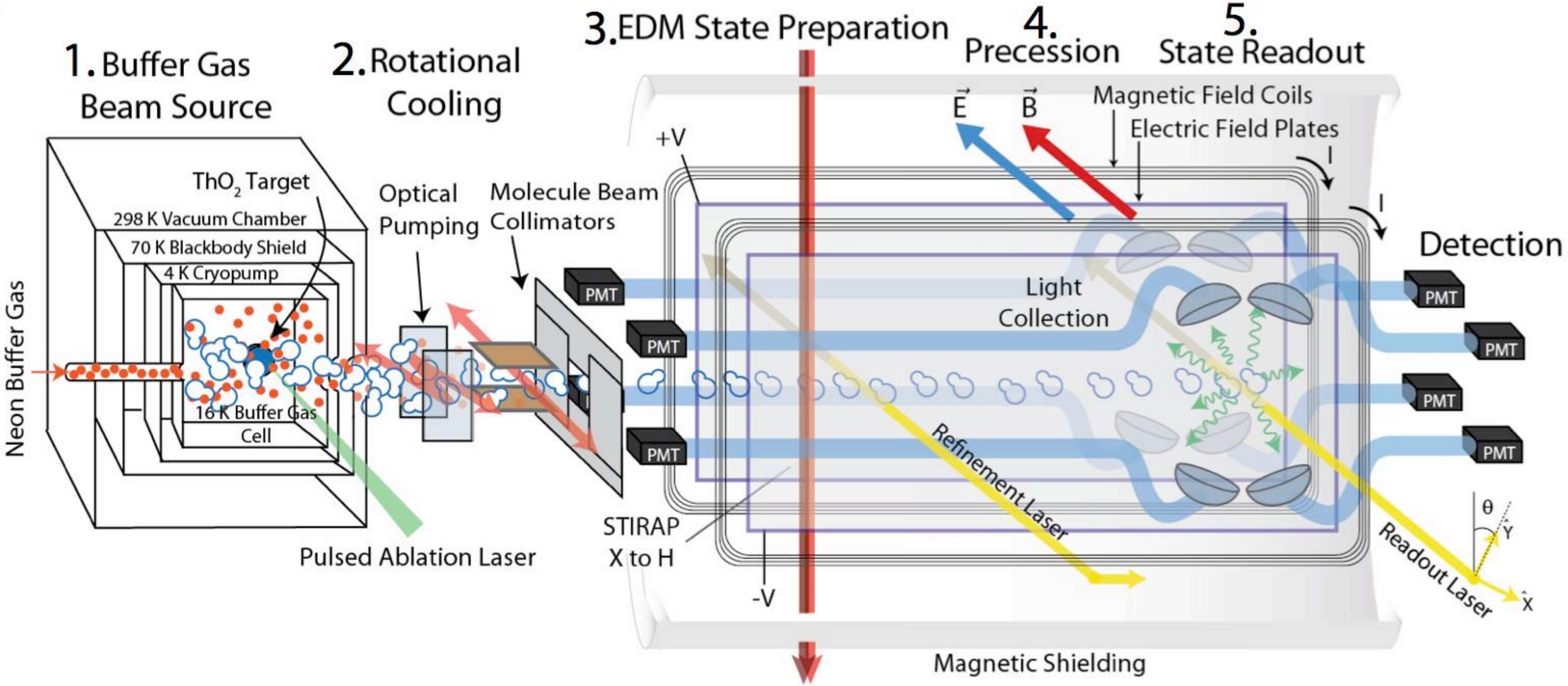


H state diagram



ACME apparatus





http://laserstorm.harvard.edu/edm/gallery.html

ACME results

- 2014: $|d_e| < 9.3\times10^{-29}\ e\mathrm{cm}$ (90% C.L.)
- 2018: $|d_e| < 1.1\times10^{-29}\ e\mathrm{cm}$
  - improvements to molecular flux, state preparation, and light collection efficiency
- project that another x10 improvement possible in next 5 years
  - molecular beam focusing
  - SiPMs for improved quantum efficiency
  - improved magnetic shielding
  - ...

Zack Lasner, Yale PhD thesis (2019).

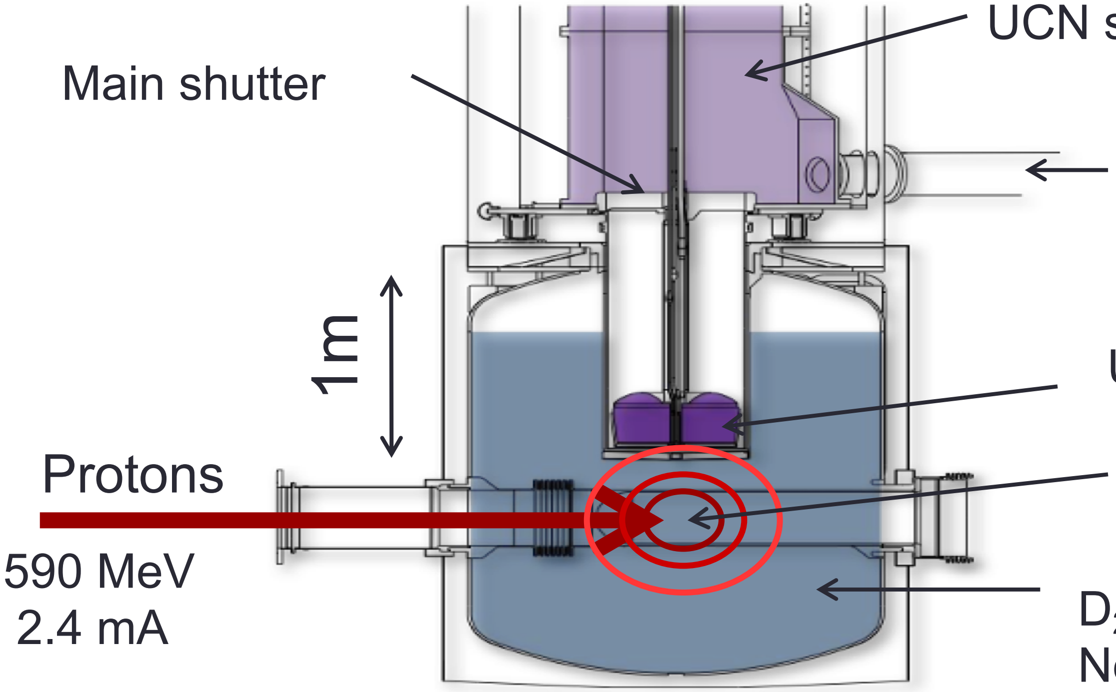
note: the ThO eEDM state is metastable, so limits the coherence time

$\Longrightarrow$ little benefit from laser cooling techniques (unlike YbF)

neutron EDM searches: PSI

- collaboration: 50 members from 15 institutions in 7 countries
- using Sussex/RAL room temperature UCN/Hg comagnetometer apparatus on PSI UCN source
  - + state of the art Cs atom magnetometry to evaluate magnetic uniformity, control systematic effects
  - + 254 nm laser system replaces discharge lamps for Hg polarization/readout, and other technology upgrades…

PSI UCN source



Main shutter

UCN storage volume

Neutron guide to experiments

1m

UCN convertor (solid D_2 @ 5K)

Spallation target
E_n~MeV

Protons

590 MeV
2.4 mA

D_2O moderator
Neutrons thermalized to 25 meV

Ultracold neutrons: neutrons moving slow enough to undergo total internal reflection on (some) surfaces

$\lambda_n \approx 800$ Å;

$v_n \approx 5$ m/s;

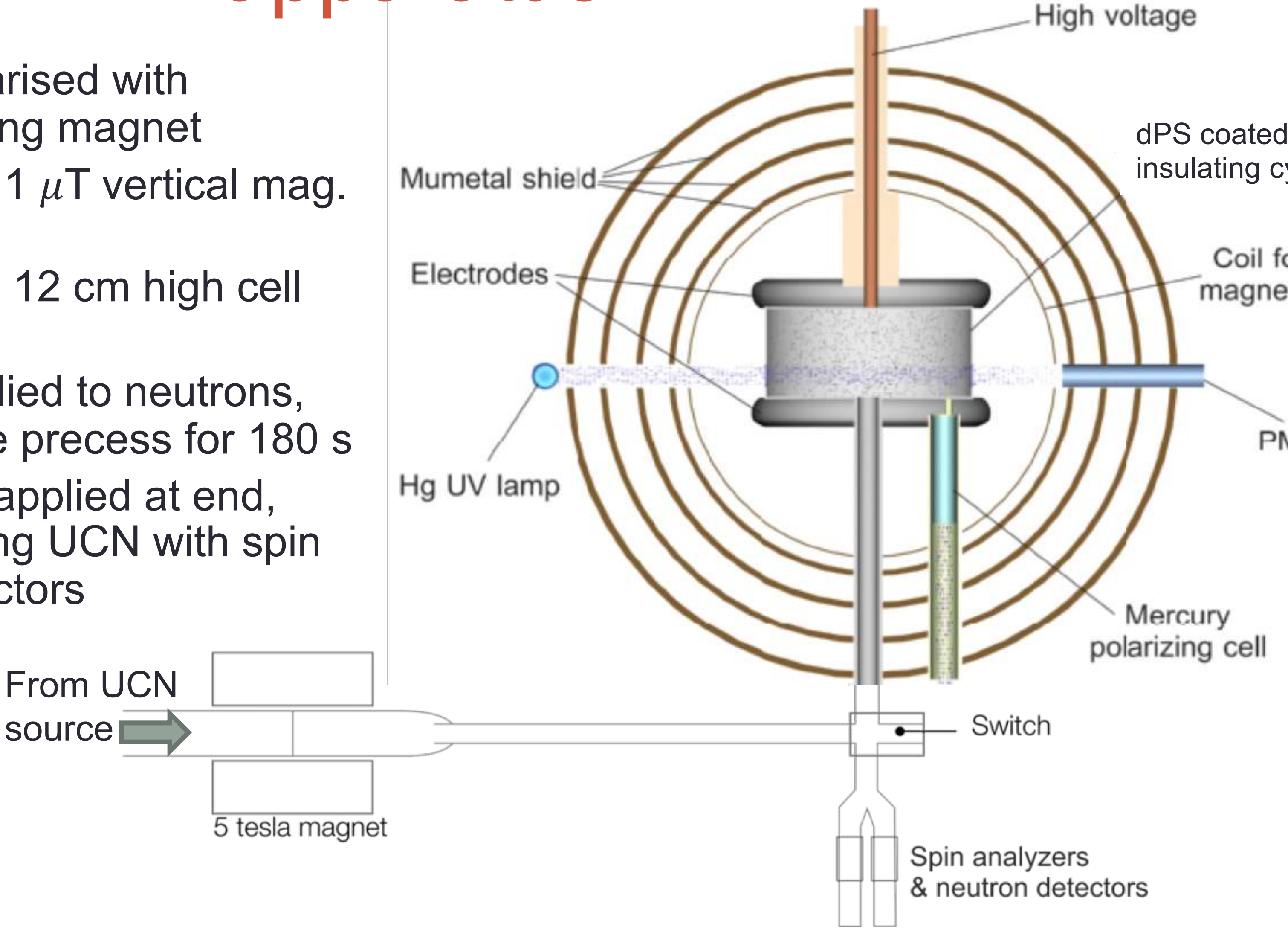
$T_n \approx 2$ mK ;

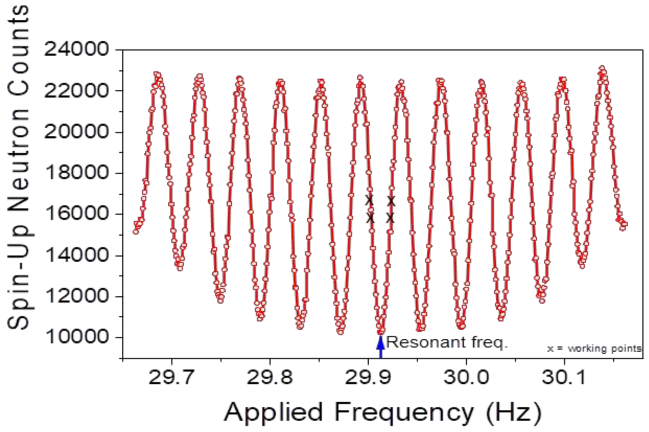
$E_n \approx 130$ neV

Golub, R. & Pendlebury, J. M, *PLA* (**1975**)133
Anghel, *et. al NIMA* **(2009)** 272
Lauss B., Phys. Proc. **(2013)**

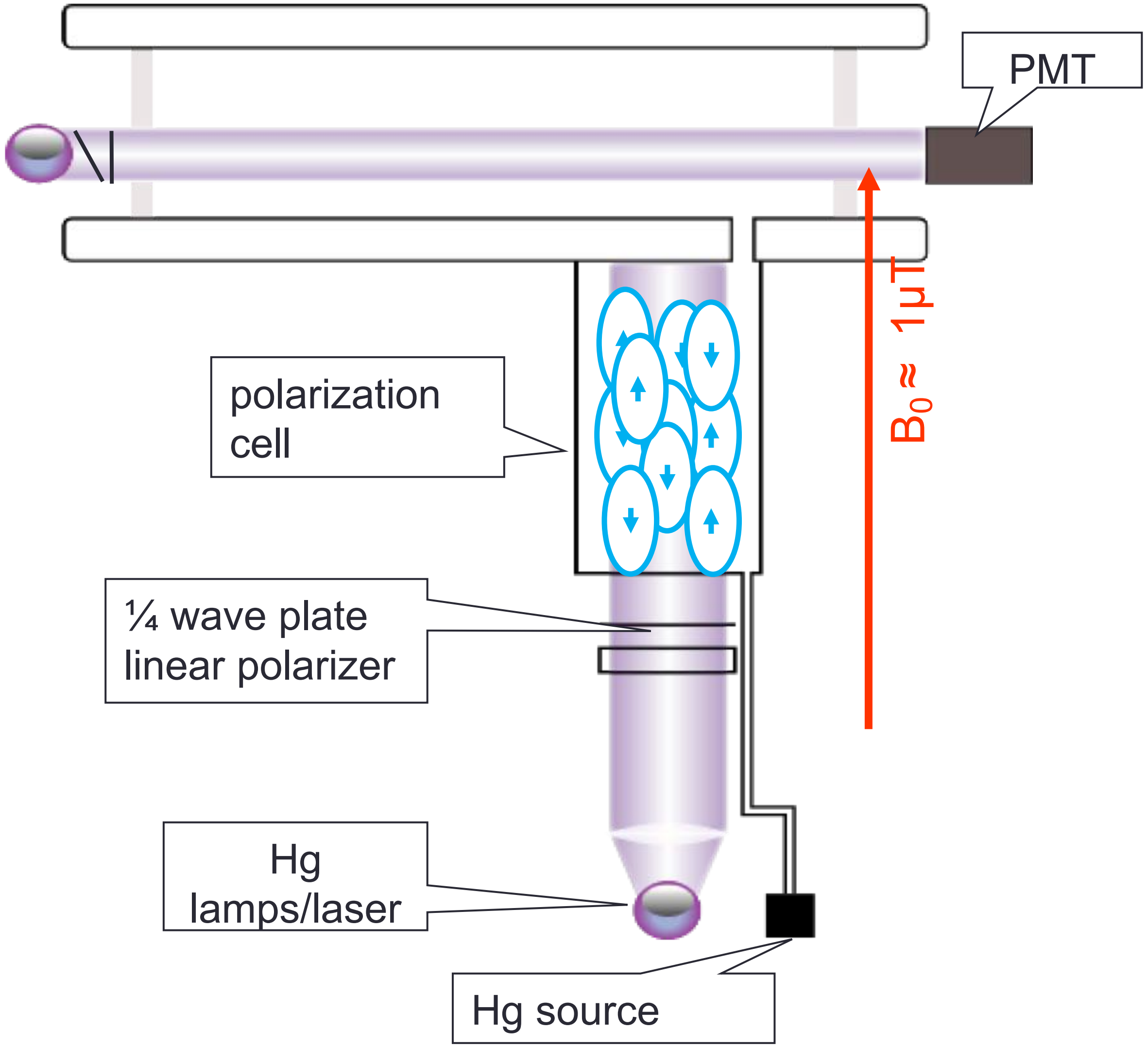
PSI nEDM apparatus

- UCN spin polarised with superconducting magnet
- enter cell with 1 μT vertical mag. field
- 132 kV across 12 cm high cell (11 kV/cm)
- pi/2 pulse applied to neutrons, allowed to free precess for 180 s
- 2nd pi/2 pulse applied at end, count remaining UCN with spin sensitive detectors





Hg comagnetometer



PMT

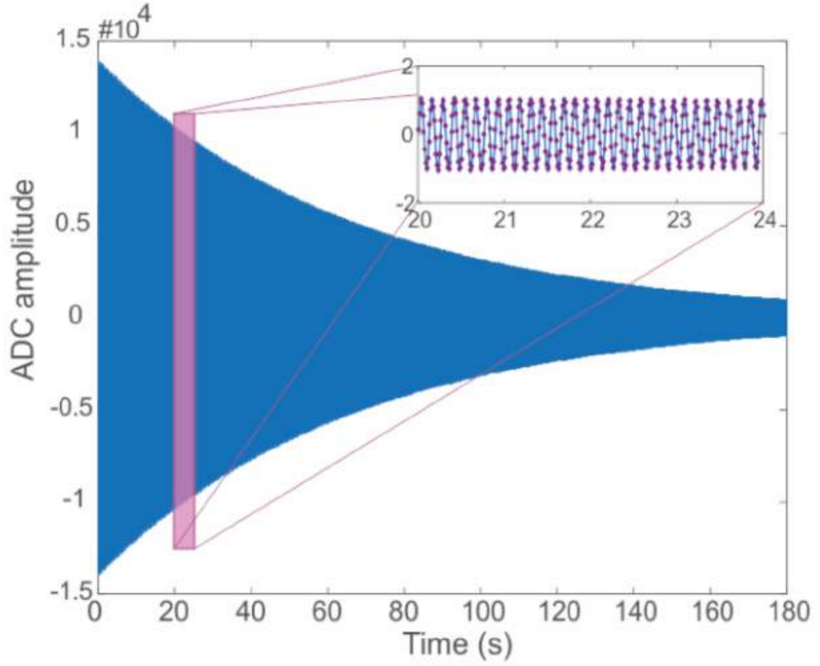
$B_0 \approx 1\mu T$

polarization cell

¼ wave plate
linear polarizer

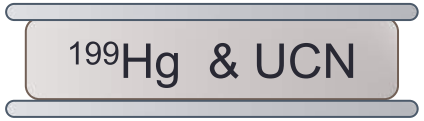
Hg lamps/laser

Hg source

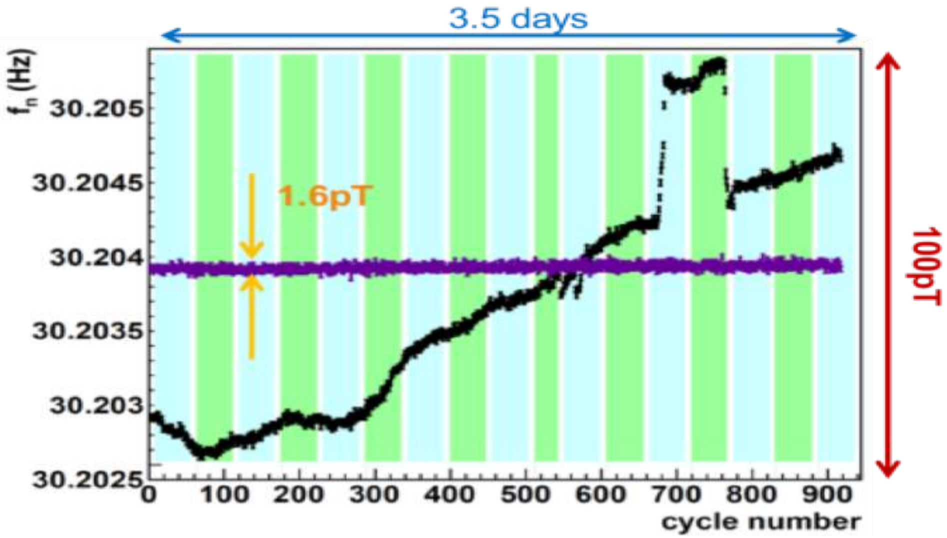


Accuracy: $< 200\text{fT}\ (0.2\text{ppm})$

Analysis: frequency ratio $R = f_n / f_{Hg}$



$\langle z \rangle$



$\frac{\gamma_n}{2\pi} \approx 30\ \mathrm{Hz/\mu T}$ $\frac{\gamma_{Hg}}{2\pi} \approx 8\ \mathrm{Hz/\mu T}$

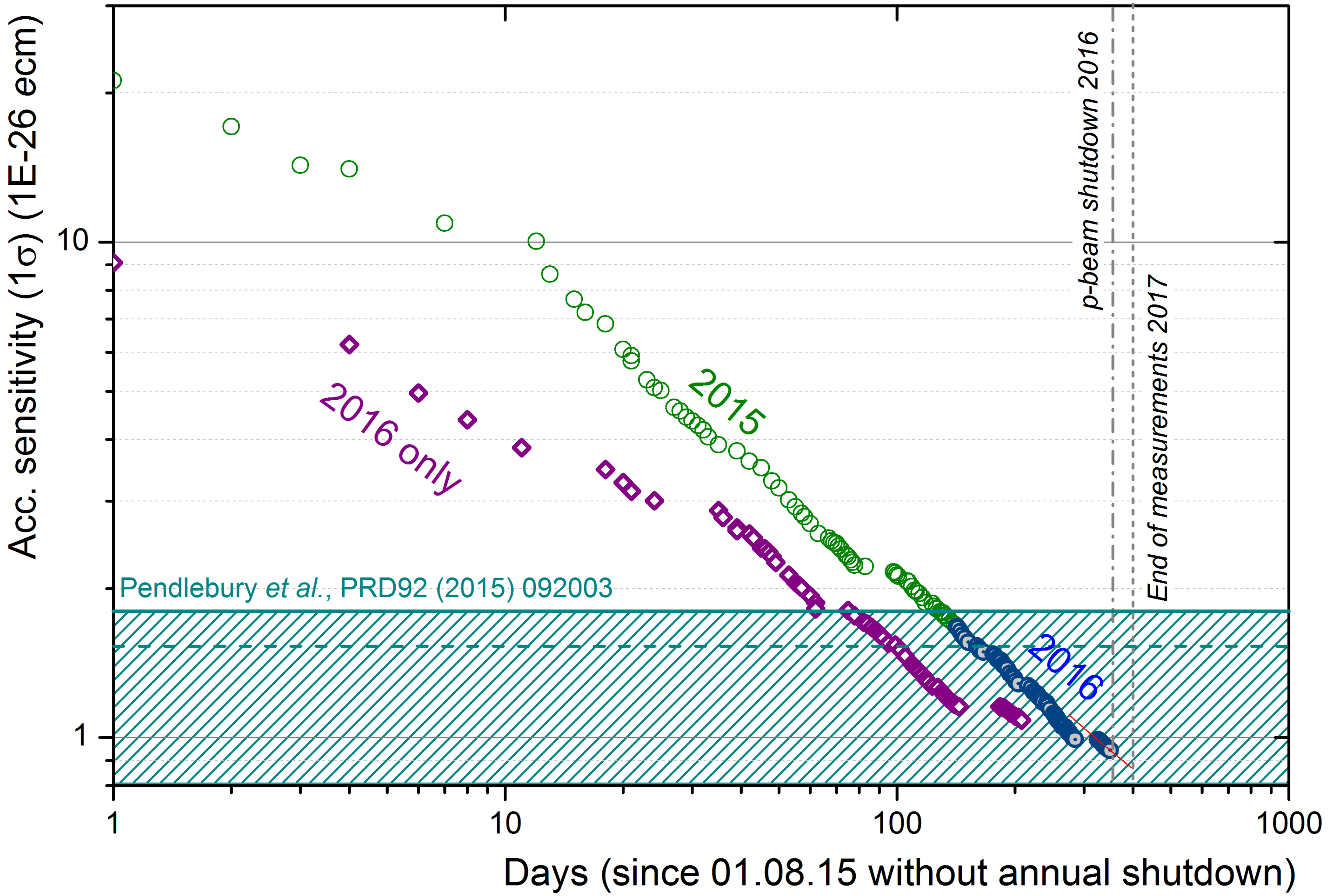
$\bar{v}_{Hg} \approx 160\ m/s$ vs. $\bar{v}_{UCN} \approx 4 m/s$

→ center of mass difference $\langle z \rangle$ & term $\langle B^2{}_\perp \rangle$ due to non-adiabaticity of Hg

$$R = \frac{\langle f_{UCN} \rangle}{\langle f_{Hg} \rangle} = \frac{\gamma_n}{\gamma_{Hg}} \left(1 + \delta_{EDM} \mp \frac{\partial B}{\partial z} \frac{\langle z \rangle}{|B_0|} + \frac{\langle B^2{}_\perp \rangle}{|B_0|^2} \mp \delta_{Earth} + \delta_{Hg-lightshift} + \cdots \right)$$

Analysis: based on R as function of dB/dz extrapolate to 0

PSI nEDM sensitivity



54362 cycles
(excluding runs with issues)

$$\sigma = 0.94\times10^{-26}\mathrm{ecm}$$

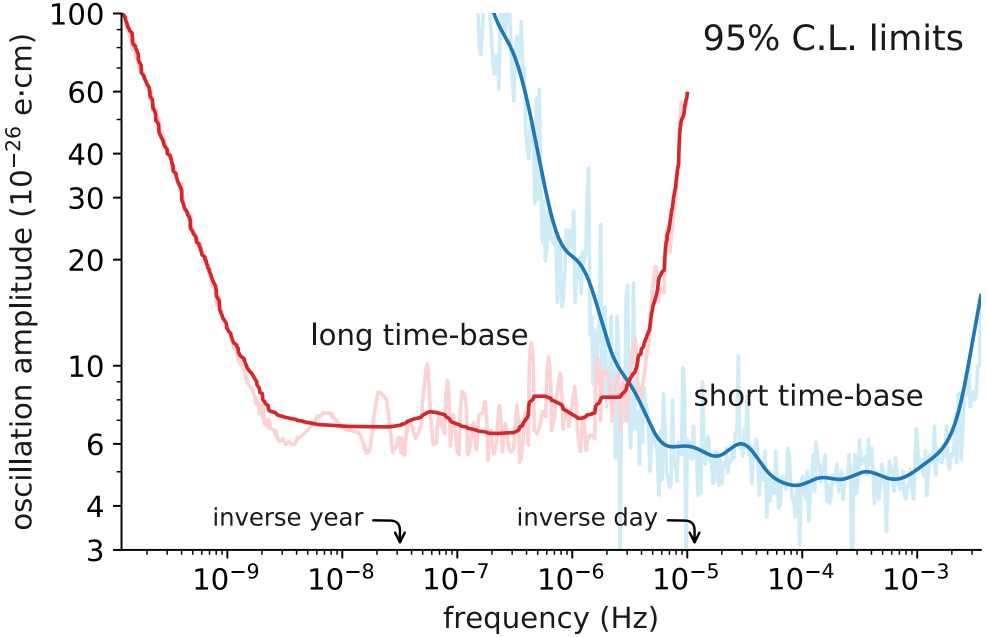
Analysis ongoing:

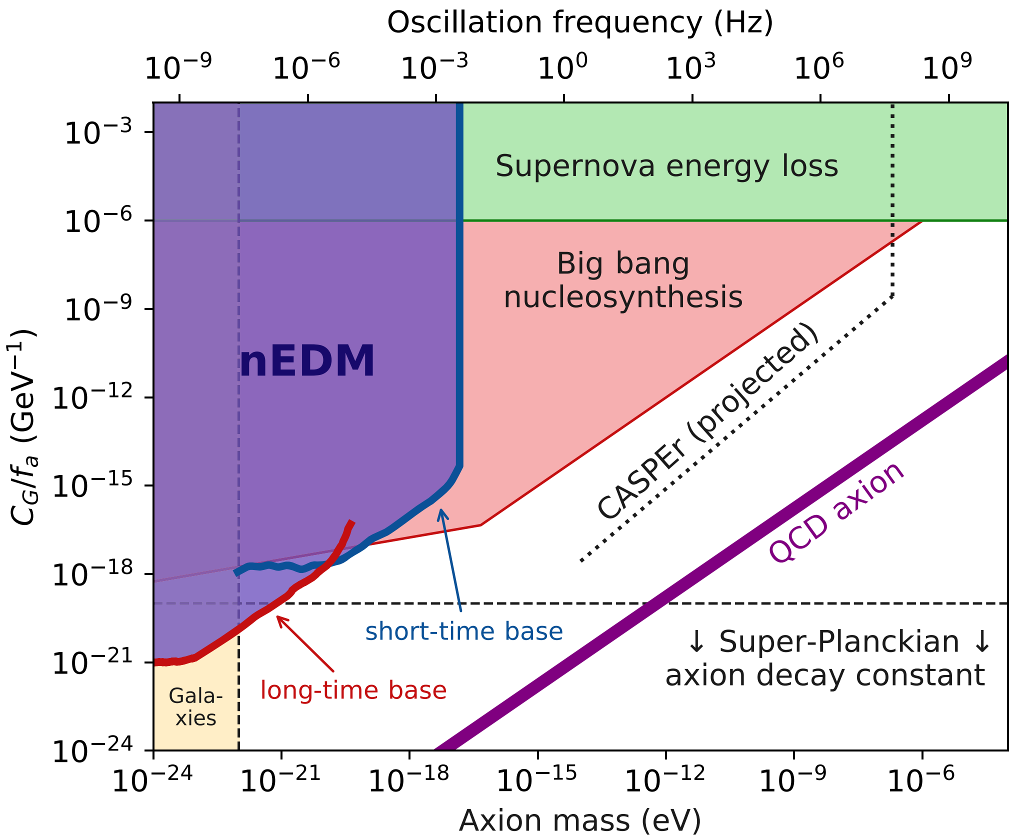
- Blinded data
- Two independent groups

nEDM: dark matter detector

- Axion like particles (possible DM candidate) generate a time varying EDM
- Existing nEDM data analysed for oscillating signals
  - Sussex-RAL-ILL: long-time base
  - PSI: short-time base (still blinded)
  - gives best constraints on axions over a range of masses
    - first laboratory based constraints on axion-quark coupling

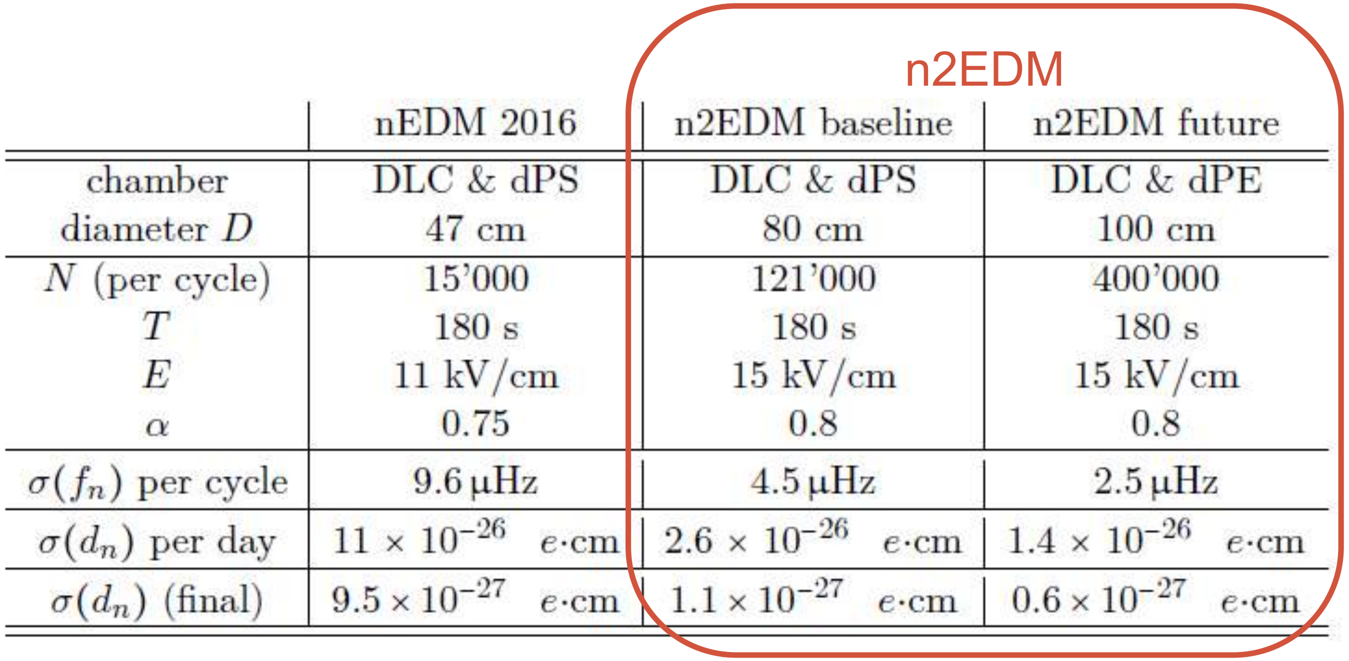
Phys Rev X, **7**, 041034 (2017)





PSI nEDM – current status

- Data taking complete in Oct. 2017
- Analysis in progress
  - unblinding expected in the next few months
    - 1σ sensitivity at 10^{-26} ecm
- As of early 2018, apparatus disassembled to make way for n2EDM



n2EDM

	nEDM 2016	n2EDM baseline	n2EDM future
chamber	DLC & dPS	DLC & dPS	DLC & dPE
diameter D	47 cm	80 cm	100 cm
N (per cycle)	15’000	121’000	400’000
T	180 s	180 s	180 s
E	11 kV/cm	15 kV/cm	15 kV/cm
α	0.75	0.8	0.8
$\sigma(f_n)$ per cycle	9.6 µHz	4.5 µHz	2.5 µHz
$\sigma(d_n)$ per day	11×10^{-26} $e{\cdot}$cm	2.6×10^{-26} $e{\cdot}$cm	1.4×10^{-26} $e{\cdot}$cm
$\sigma(d_n)$ (final)	9.5×10^{-27} $e{\cdot}$cm	1.1×10^{-27} $e{\cdot}$cm	0.6×10^{-27} $e{\cdot}$cm

$$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

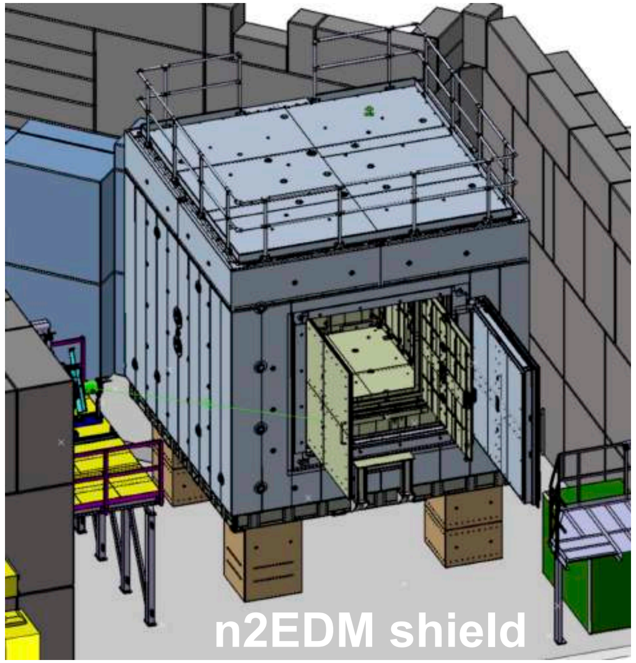
PSI – transition to n2EDM


Sept 2017


June 2018

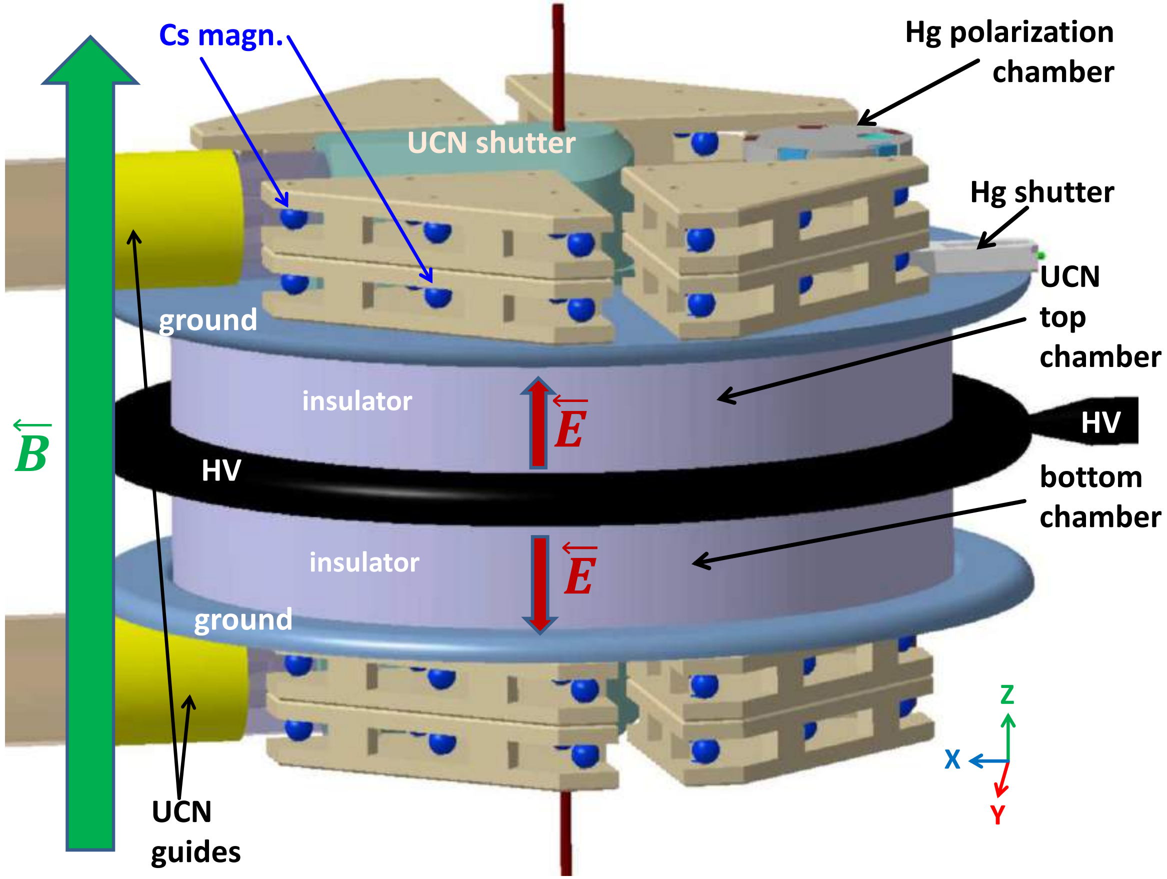

Jan 2019

- nEDM apparatus removed late 2017
- First n2EDM installation: magnetic shield
  - 5x5x5 m^3 external dim., 6 layers mu-metal, ~10^5 shielding factor
  - large internal space, 3x3x3 m^3 for B field coils and vac. tank

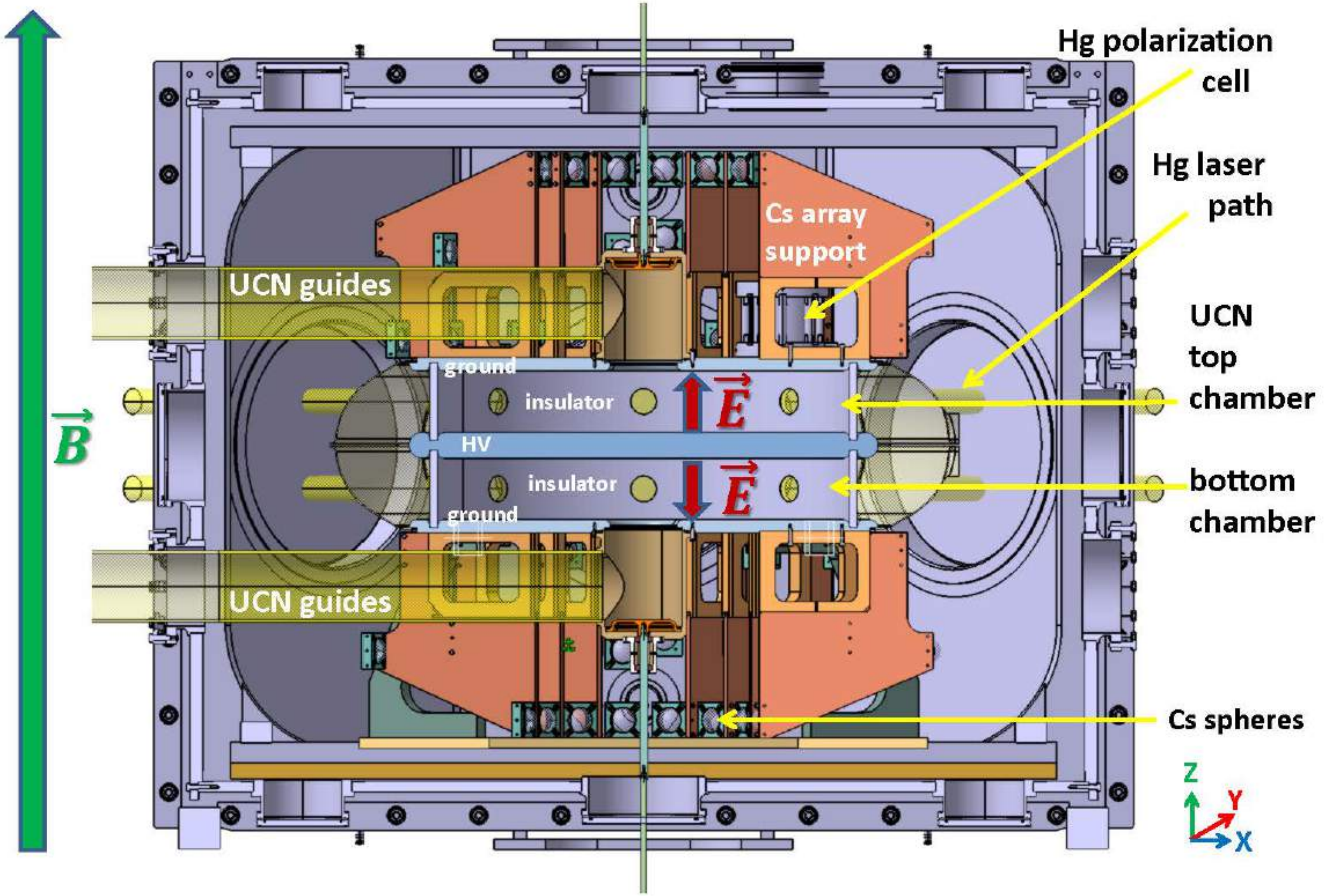

n2EDM shield

PSI – n2EDM

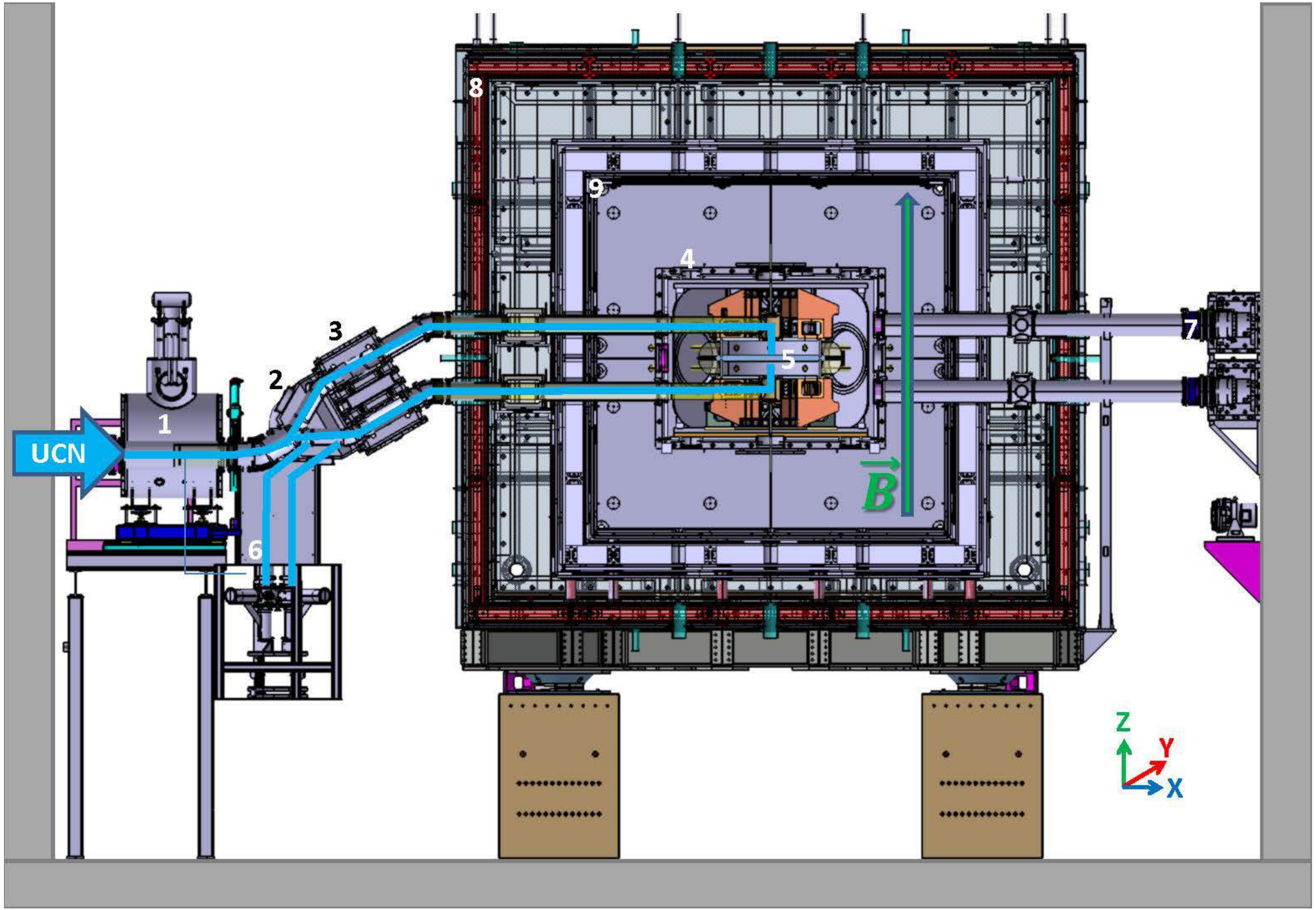
- based on well established techniques and technology
  - *mostly previously tested in PSI-nEDM*
- large double precession chambers, 80 cm diam.
- Hg comagnetometer with 254 nm laser readout
- ~100 sensor Cs magnetometer array
- Plan to have first data w/UCN in 2020
- Designed to reach ~1×10^{-27} *ecm* stat. sensitivity in a few years
- Further upgrades can push to 6×10^{-28} *ecm*
  - larger precession chambers, improved wall coatings to store higher energy UCN



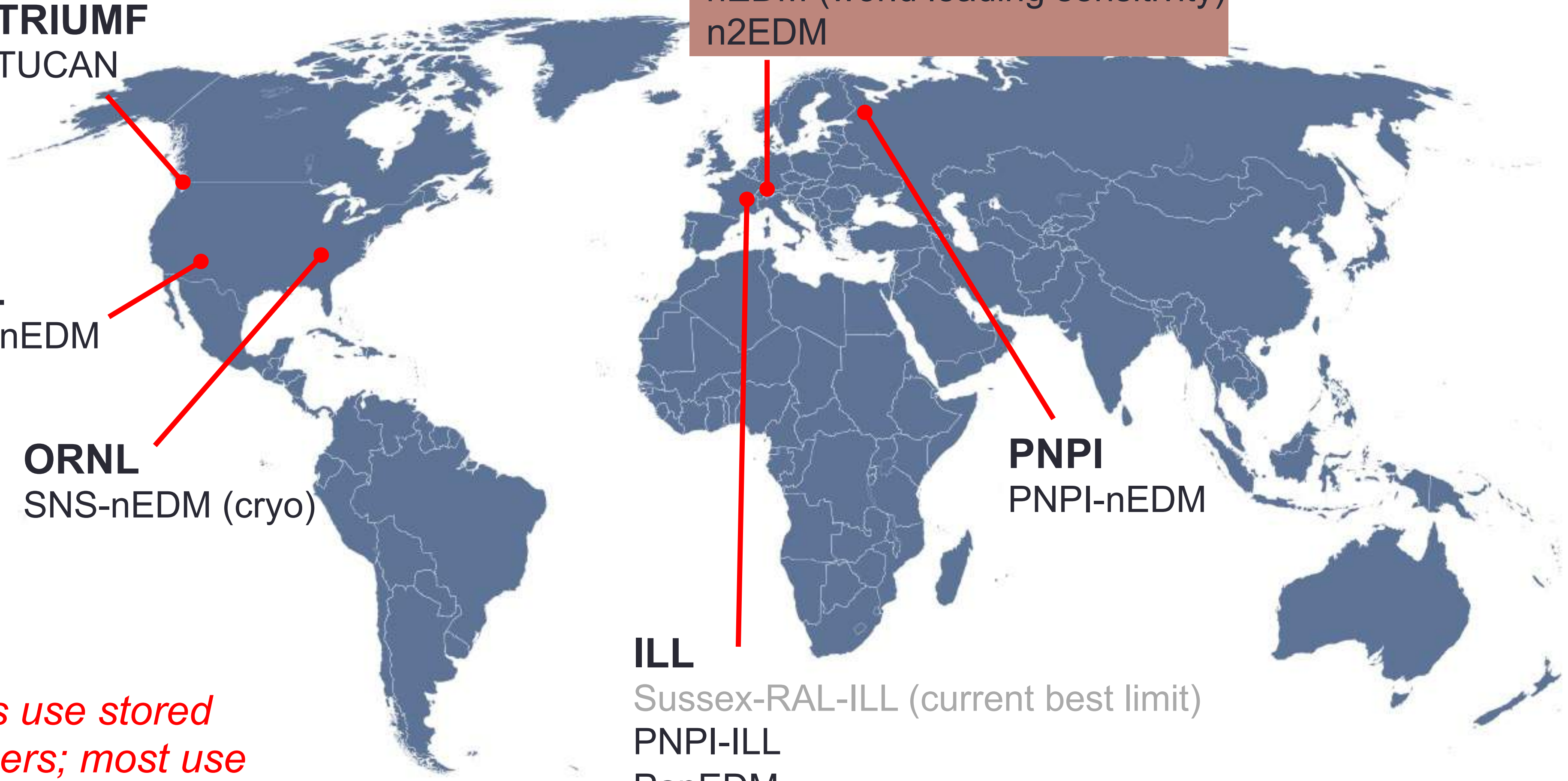
n2EDM apparatus



n2EDM apparatus



Neutron EDM – worldwide efforts



TRIUMF
TUCAN

PSI
nEDM (world leading sensitivity)
n2EDM

LANL
LANL-nEDM

ORNL
SNS-nEDM (cryo)

PNPI
PNPI-nEDM

ILL
Sussex-RAL-ILL (current best limit)
PNPI-ILL
PanEDM

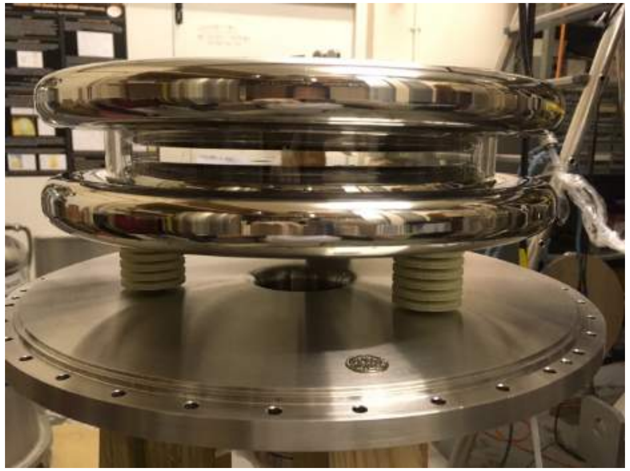
All current approaches use stored UCN in double chambers; most use an atomic comagnetometer

nEDM searches: future prospects

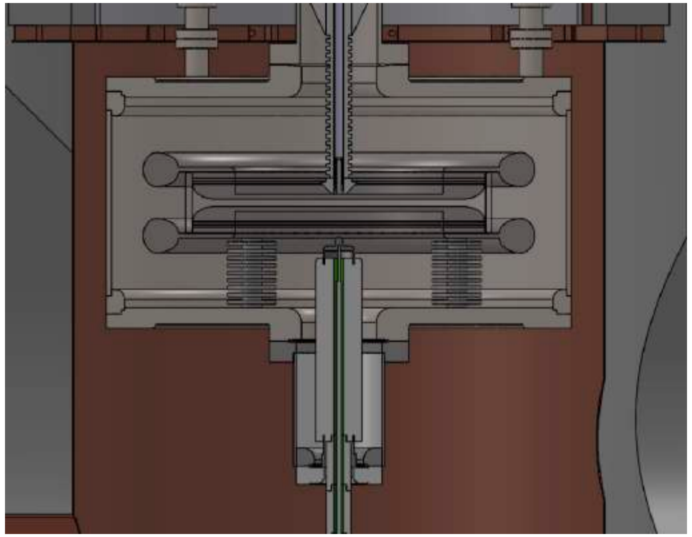
n2EDM (and other double chamber experiments) will likely reach the limits of the room temperature stored UCN approach in the next decade ($\sigma(d_n) \sim 5 - 10 \times 10^{-28}\ e\mathrm{cm}$)

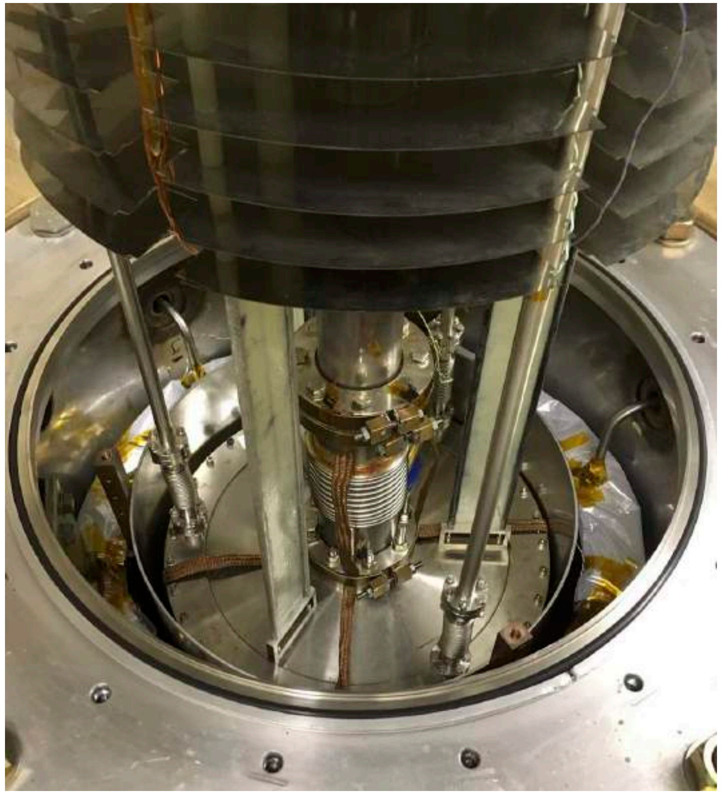
- Cryogenic
  - superfluid He has its benefits
    - higher *E* fields (10 kV/cm → 100 kV/cm)
    - potentially high UCN density (for in-situ production **transport losses a big issue**)
    - longer UCN storage times
    - superconducting mag. shields and persistent currents for *B* generation
  - CryoEDM (2003-2013) demonstrated the daunting technical challenges of cryogenic nEDM
  - USA SNS cryogenic experiment hopes to begin construction at Oak Ridge in the next few years
    - many technical challenges overcome, many remain
    - hope to reach $\sigma(d_n) \sim 2 \times 10^{-28}\ e\mathrm{cm}$
- Beam nEDM revisited
  - beam experiments abandoned previously due to $\vec{v} \times \vec{E}$ systematic
  - use pulsed beam (ESS) for velocity dependence, potential for ~$5\mathrm{x}10^{-28}$ *e*cm stat. sens. (100 days)
    - F. Piegsa, U. Bern, Phys Rev C 88 045502 (2013)

UK cryogenic nEDM R&D



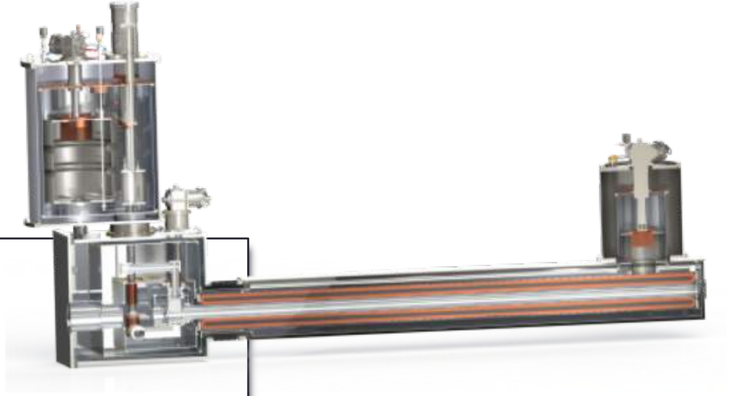
- while room temperature experiments expected to lead the field well into the next decade...
- UK groups maintaining cryogenic R&D efforts
  - RAL: cryogenic UCN guide and source development
    - involvement in the PanEDM collaboration
  - Sussex: electric fields in cryogenic liquids
    - have demonstrated > 60 kV/cm E fields in LHe in a mock cryogenic nEDM precession chamber
      - storage volume: 24 cm diam, 1.6 cm height





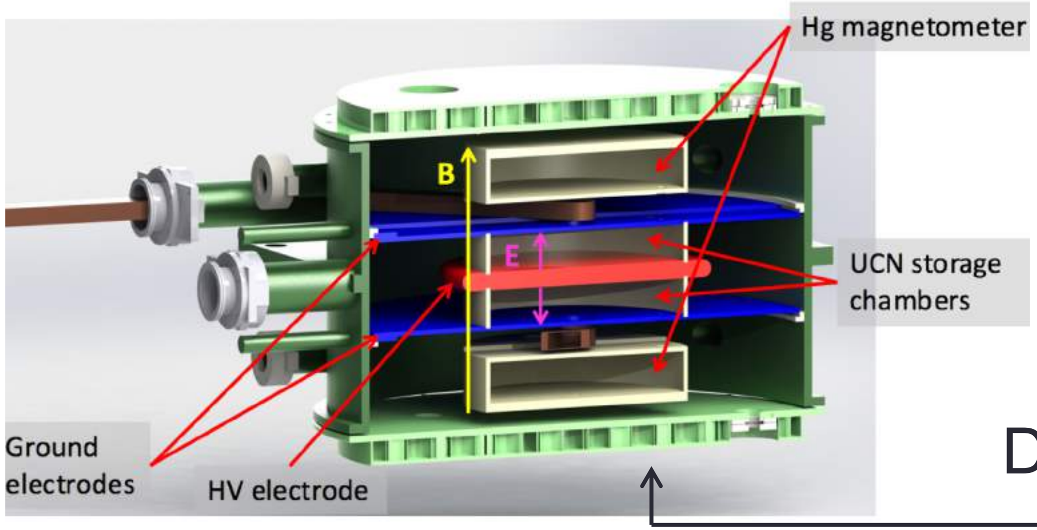
Jacob Thorne PhD thesis, w/ Mike Hardiman, Ian Wardell

Cryogenic nEDM R&D at ILL



PanEDM

- Dedicated cold n beamline at ILL installed
- SuperSUN LHe UCN source commissioning in 2019
- first will be coupled to TUM developed room temperature nEDM apparatus
- R&D starting for a fully cryogenic later stage



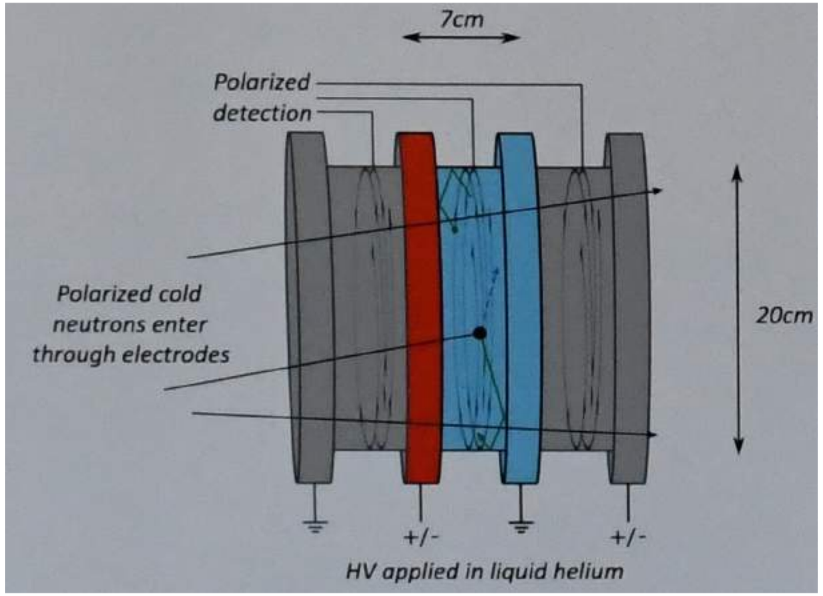
EDM chambers
Design - Manufacture

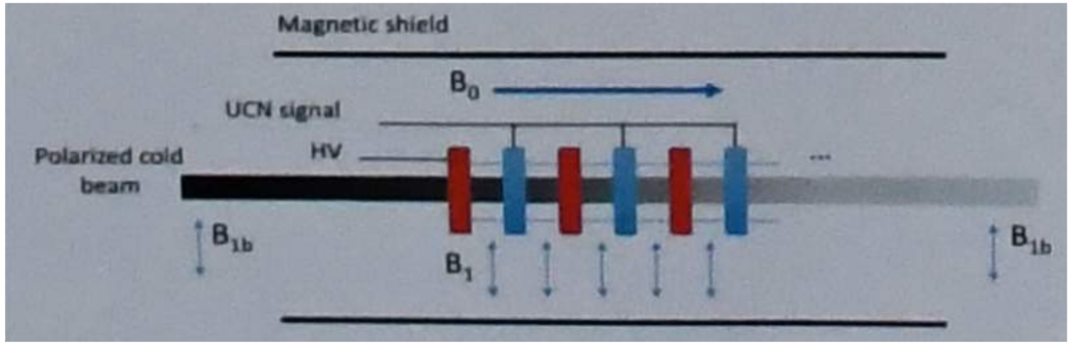
Cryogenic nEDM R&D at ILL

Skyler Degenkolb, Oliver Zimmer (ILL)
Peter Fierlinger (TUM)

Concept:

- in-situ spin sensitive UCN detection
  - superconducting wire draws high field seekers to an absorbing layer
  - no transport losses!
- many cells stacked along polarised cold beam with alternating E field directions
  - scalable! start small – optimise a single cell
  - with several meters of cells, potential to reach < $10^{-28}\ e\text{cm}$





International Workshop on Particle Physics at Neutron Sources 2018, ILL/LPSC Grenoble

Summary

- EDMs will continue to be an extremely important background free probe for new CP violating physics at $\gg$ TeV energy scales.
- Critical to keep pushing sensitivity in multiple systems
  - **neutron**, **electron**, *proton*, *muon*, nuclear (^{199}Hg, ^{225}Ra, ^{129}Xe, *deuteron*) *storage rings*
  - allows deciphering of underlying CP violation in case a signal is found
    - e.g. QCD θ or SUSY
- **mercury**
  - smallest EDM limit in any system, can set best limits on many CP violating parameters, but nuclear calculations a big problem for interpretation.
- **electron**
  - polar molecules will continue to be most sensitive – big key for advances is ultracold molecules
- **neutron**
  - room temperature stored UCN experiments *(n2EDM)* will continue to dominate well into next decade, but will then likely reach their limit
  - next generation will require a change in approach: cryogenic?

Thank You!

- Sussex nEDM collaborators: Chris Abel, Nick Ayres, Mike Hardiman, Phil Harris, Jacob Thorne, Ian Wardell.
- PSI collaboration
- Hg: Blayne Heckel, Brent Graner, Norval Fortson
- YbF slides: Michael Tarbutt (Imperial College).
  http://www.imperial.ac.uk/centre-for-cold-matter/research/edm/
- ACME: David DeMille
  http://laserstorm.harvard.edu/edm
- PanEDM: Maurits van der Grinten, Skyler Degenkolb