Electric Dipole Moment Searches

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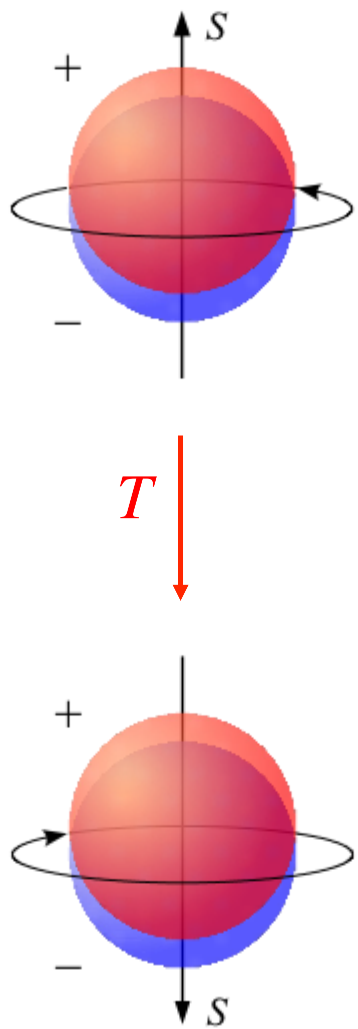
University of Sussex

The Search for an EDM

A permanent EDM
violates T :

with CPT theorem, implies CP violation



Standard Model CKM-CP violation generates EDMs far too small to measure.

Therefore, finding an EDM would be proof of new physics.

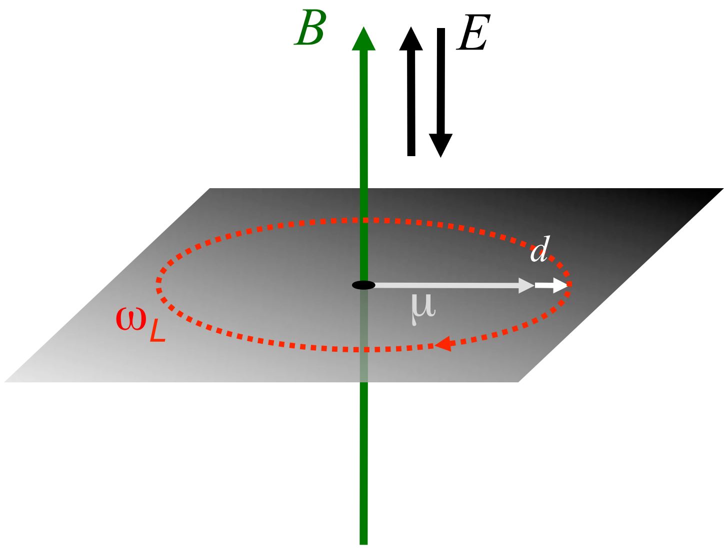
Search for an EDM of the neutron began 60 years ago, so far no luck.

Theories of physics beyond the Standard Model → easily giveEDMs large enough to see with current experiments.

Therefore, keep on looking!

Measuring an EDM via Larmor precession

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



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

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

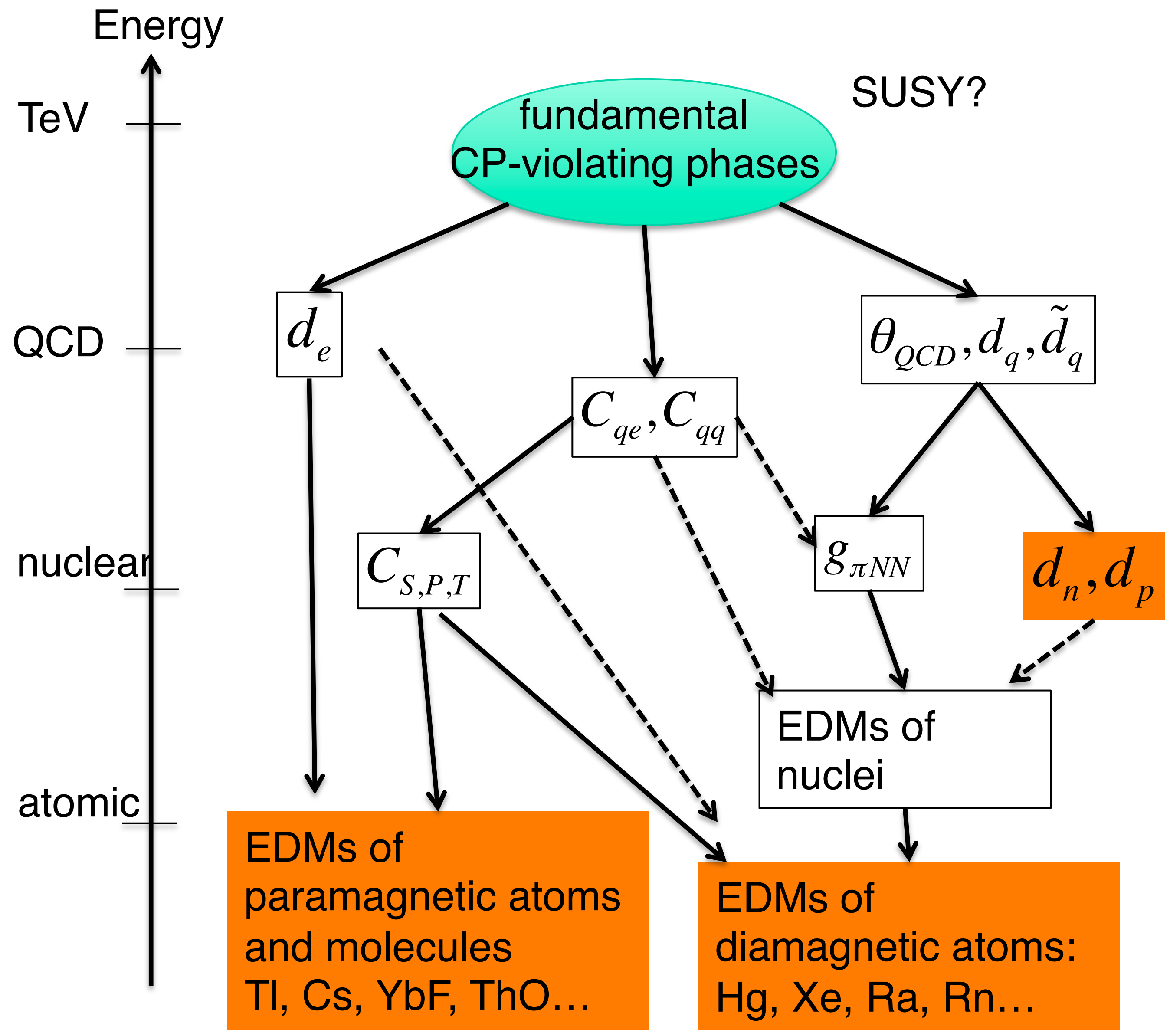
$$\Rightarrow \quad \boxed{\omega_1 - \omega_2 = \frac{4\,d\,E}{\hbar}}$$

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

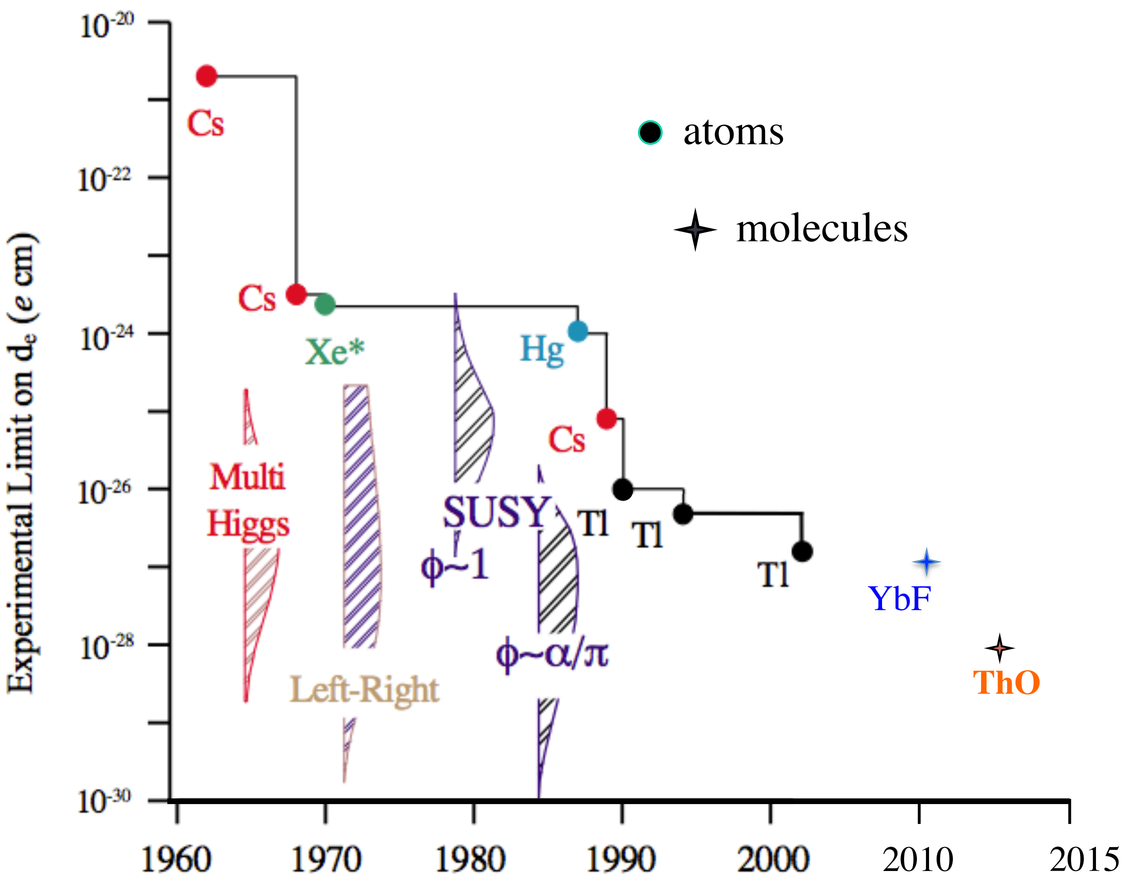
EDM searches

- neutron
  - first system to be looked at (1950s, Norman Ramsey) in beam experiments
  - current experiments all use ultracold neutrons (UCN), v < 7 m/s, can be stored for 100s of seconds in measurement cells
  - current limit: $d_n < 3\text{x}10^{-26}$ $e$cm
- electron
  - searched for mostly in heavy paramagnetic atoms – Cs, Tl
    - relativisitic enhancement: $d_{\mathrm{Tl}} \sim 600\ d_e$
  - newer measurements take advantage of even larger enhancements in polar molecules – YbF, ThO
  - current limit: $d_e < 9\text{x}10^{-29}$ $e$cm
- diamagnetic (Hg)
  - zero electronic spin, finite nuclear spin
  - could arise from nucleon EDMs, but most sensitive to CP-violating nuclear forces
  - current limit: $d_{\mathrm{Hg}} < 3\text{x}10^{-29}$ $e$cm

EDM searches



EDM searches: electron



- best atomic limit is from Berkeley Thallium beam experiment:

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

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

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

- polar molecules have recently eclipsed Tl

YbF at Imperial College:

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

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

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:

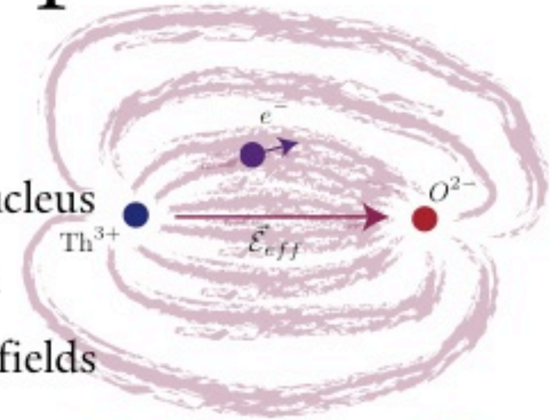
$$|d_e| < 0.9 \cdot 10^{-28}\, e\ \mathrm{cm}\ (2014)$$

-ACME Collab.. Science 343, 269 (2014)

- Other efforts:
  - polar molecules
    - WC (Mich.),
    - HfH^+ (JILA) ....
  - laser cooled Cs (Penn St., Texas)
  - solid state (Amherst, Indiana, Yale)

ACME electron EDM Experiment

System: molecule state - $H^3\Delta_1\mathrm{ThO}$

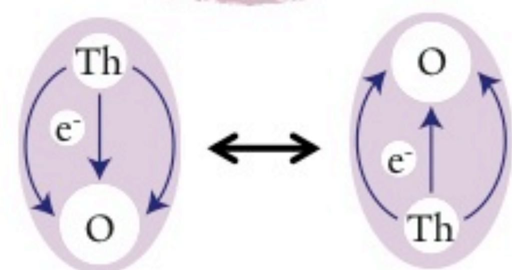


- High sensitivity[1] to the eEDM due to highly charged Th nucleus

$$|\Delta E_{\mathrm{EDM}}| = d_e \mathcal{E}_{\mathrm{eff}} \qquad \mathcal{E}_{\mathrm{eff}} = 85\ \mathrm{GV/cm}$$

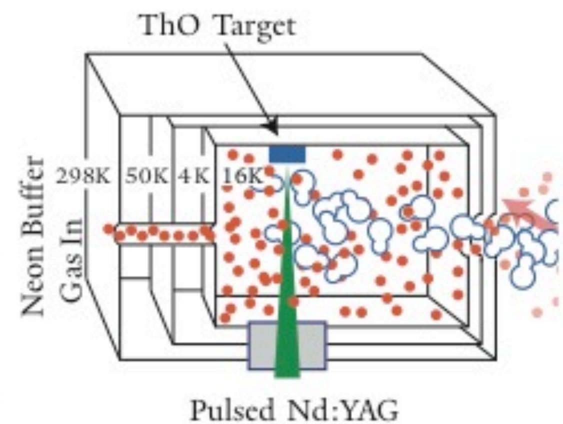
and molecule can be fully aligned with small laboratory $\mathcal{E}$-fields

- Conventional systematic errors are highly suppressed
  - Ω-doublet structure allows spectroscopic reversal of EDM energy shift
  - Small magnetic g-factor $^3\Delta_1 \implies g \sim 10^{-2}$



Source: Cryogenic Buffer Gas Beam

- Slow (200 m/s), high flux, molecular beam source.
- Works well for most species, including refractory species

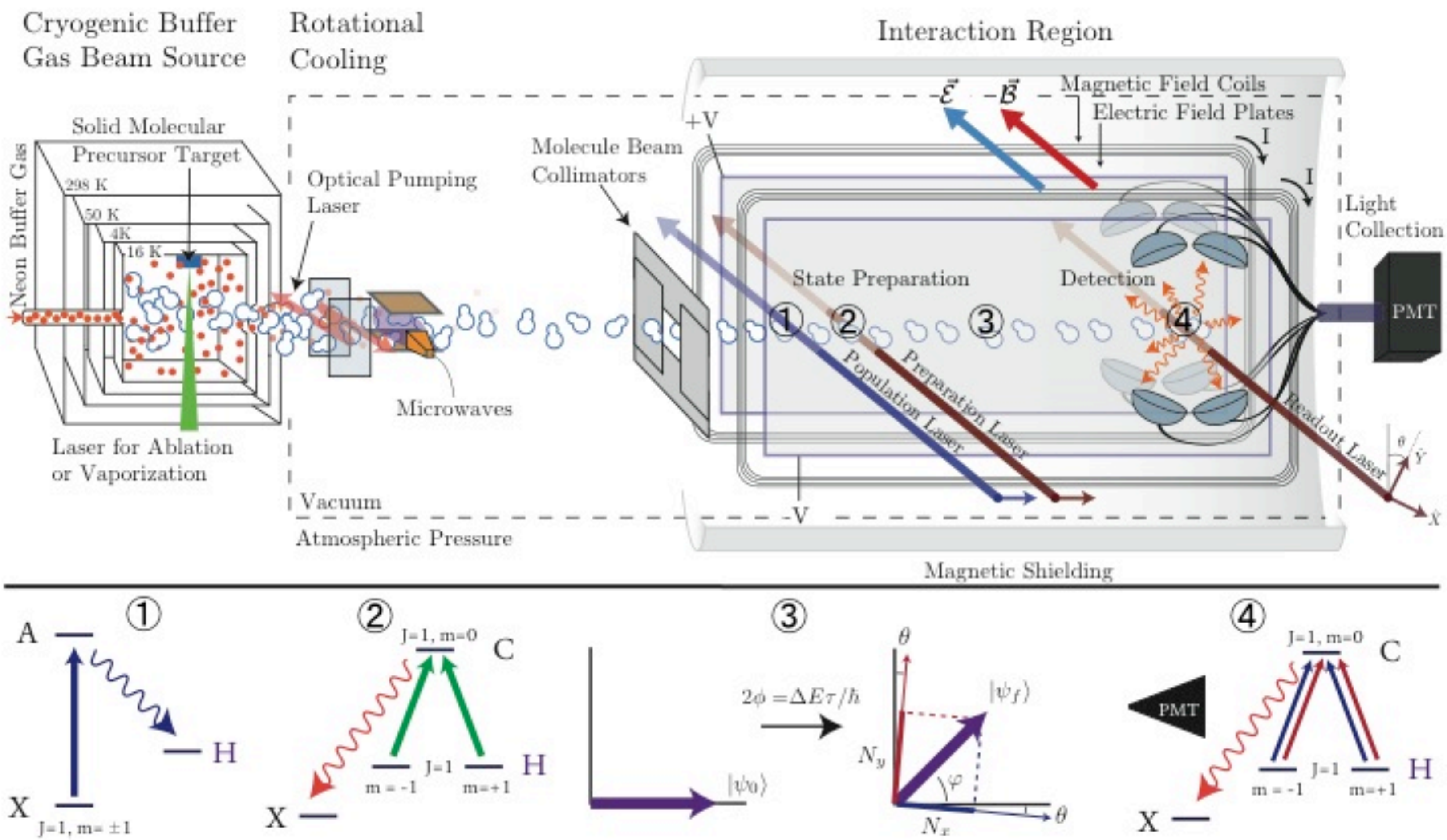


1 - L. V. Skripnikov, A. N. Petrov, A. V. Titov, J. Chem. Phys.139, 221103 (2013).

The ACME Experiment

Results[2]: Still no eEDM $|d_e| < 8.7 \times 10^{-29}\ e \cdot \mathrm{cm}$ @ 90% confidence

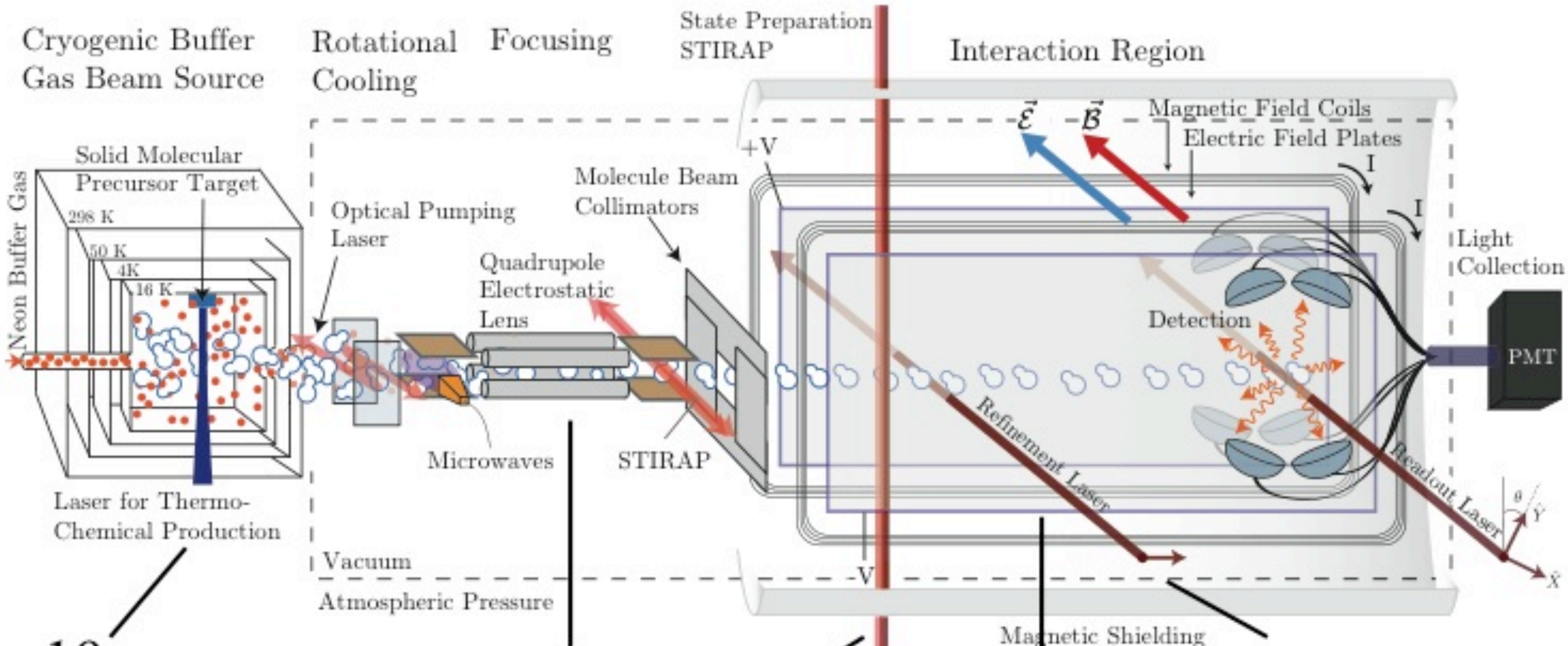
Order of magnitude improvement in upper limit constraining T-violating physics well into TeV scale



2-ACME Collaboration. Science 343, 269 (2014)

ACME: THE NEXT GENERATION

Upgrades: More Molecules, Smaller Systematics



x10
will require
characterization,
optimization

x10

x10 +new
systematic error

suppress
new systematic
x10^{-3}-10^{-4}

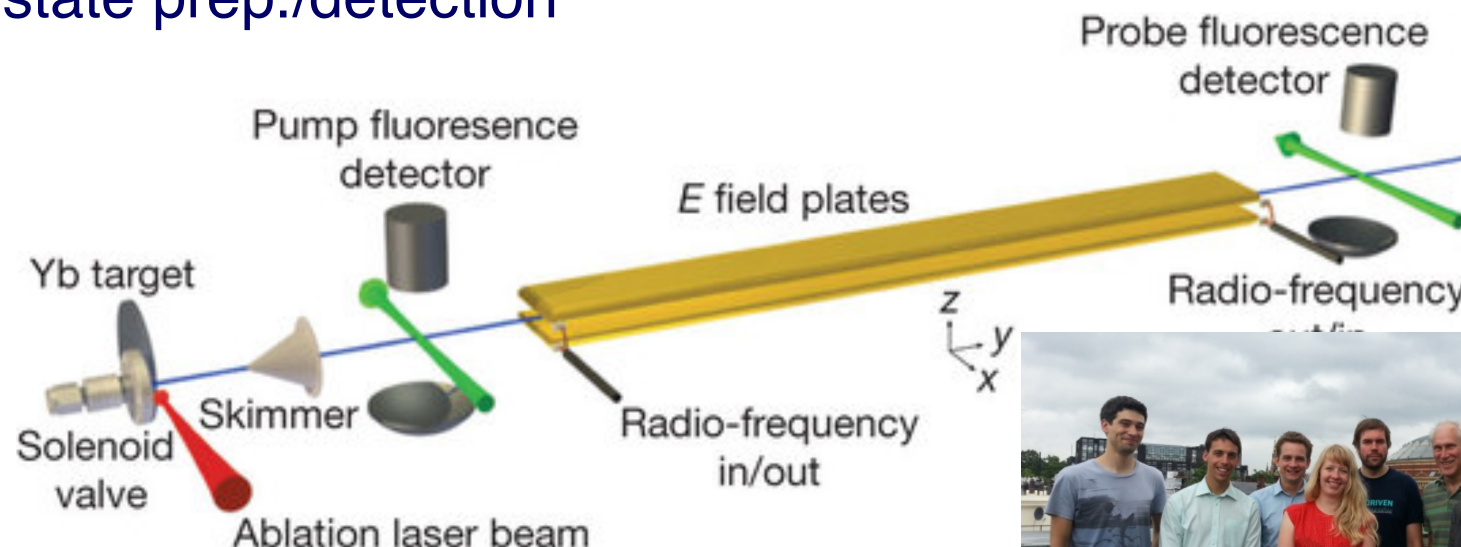
new field plates- suppress old systematic error by x10^{-2}

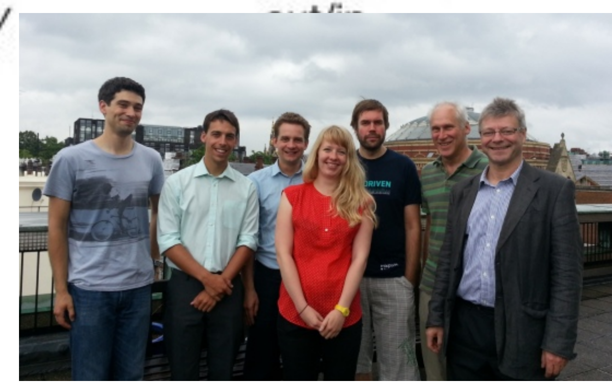
Anticipate an order of magnitude improvement in sensitivity

x10 improvement in 5 years, another 10-30x may be possible with method

electron EDM: YbF at Imperial College

- Result in 2011: $|d_e| < 1.05 \times 10^{-27}$ e cm
  - currently have 3x better sensitivity: improved mag. shielding and RF generation
  - further upgrades could reach 2 orders of magnitude: new buffer gas cold beam source, longer plates, improved state prep./detection

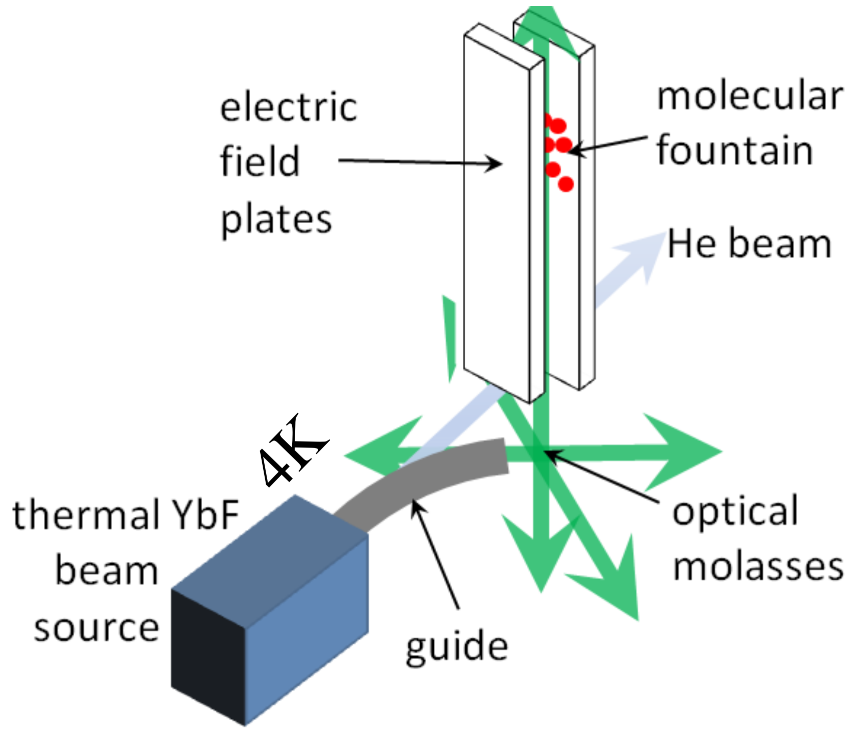




Royal Society, STFC, EPSRC, European Research Council
http://www3.imperial.ac.uk/ccm/research/edm
http://www.nature.com/nature/journal/v473/n7348/full/nature10104.html

electron EDM: YbF at Imperial College

Proposed YbF fountain:

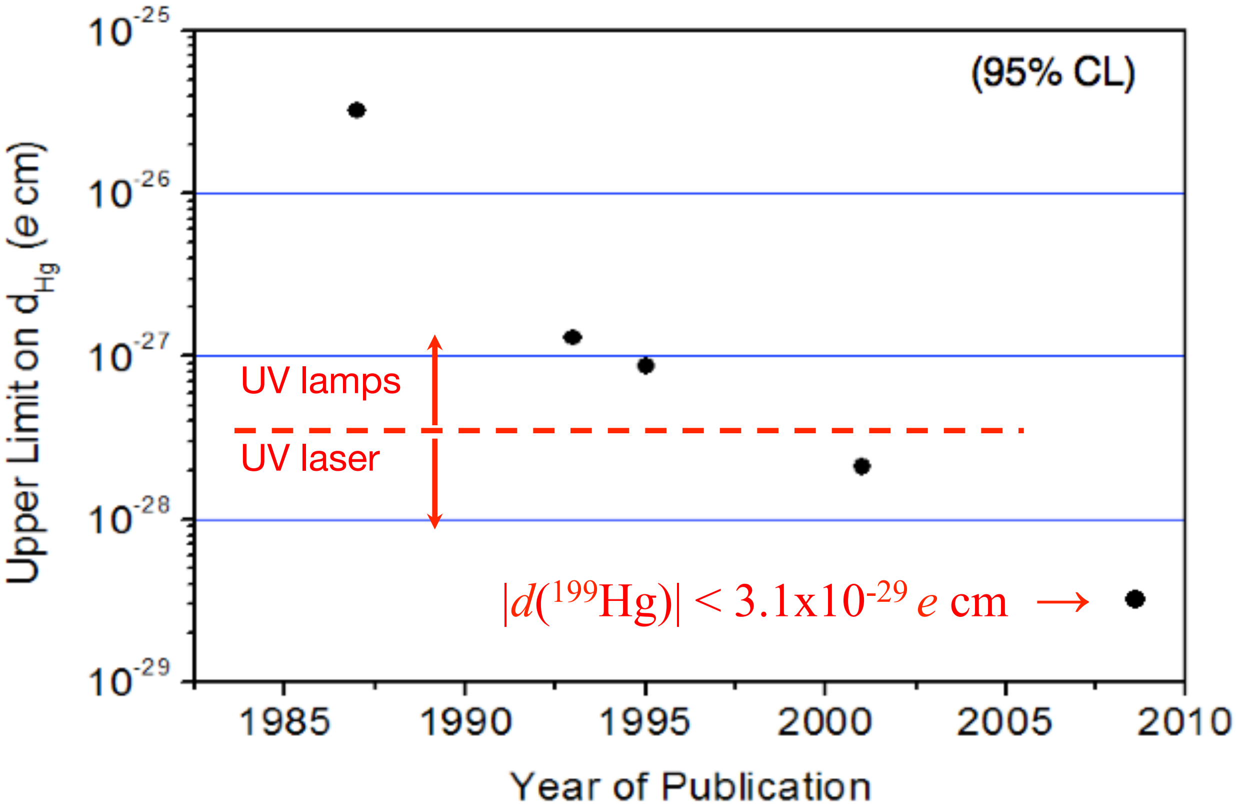


Design for a fountain of YbF molecules to measure the electron's electric dipole moment
M R Tarbutt, B E Sauer, J J Hudson and E A Hinds
New J. Phys. **15** (2013) 053034

Fantastically inefficient: 10^{-8} from cell to detector. But T = 300ms, so 60h of data gives $\sigma_d = 3\times10^{-31}$ e.cm!

EDM searches: diamagnetic atoms

– 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:

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

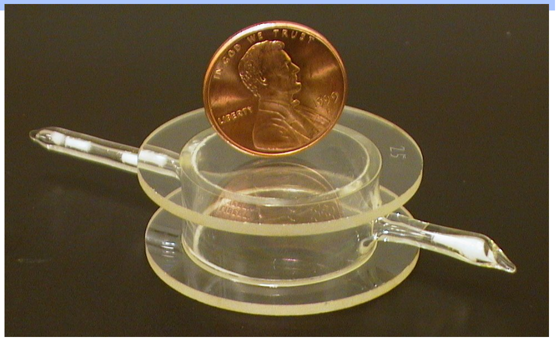
^{199}Hg is the heaviest, stable I=1/2 nucleus

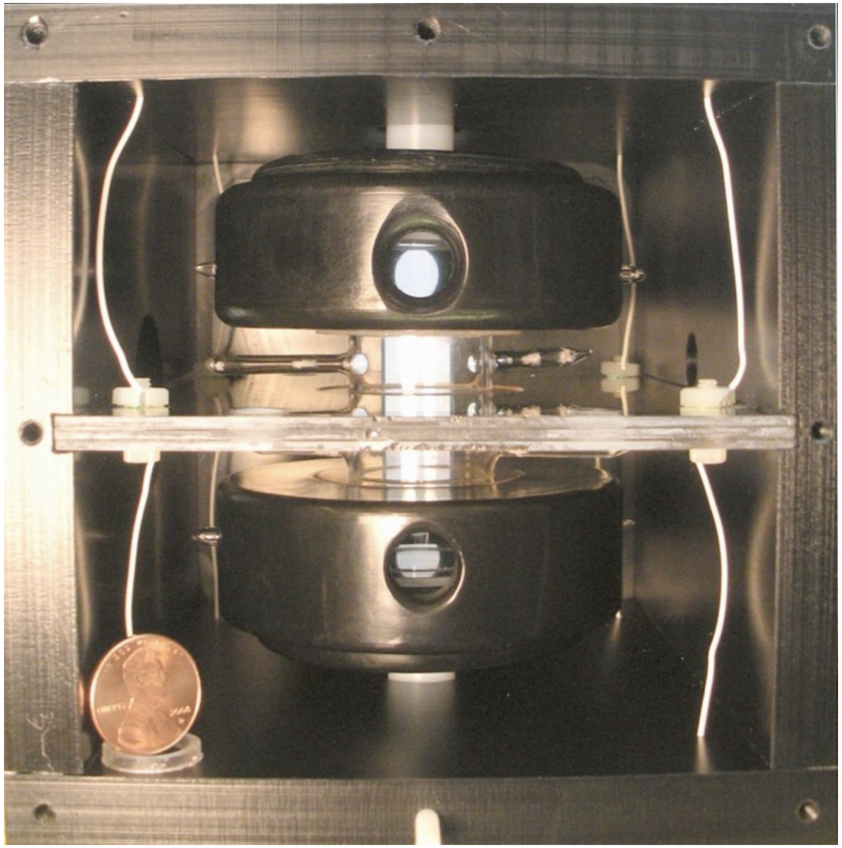
S.K. Lamoreaux, J.P. Jacobs, B.R. Heckel, F.J. Raab, and E.N. Fortson, PRL **59**, 2275 (1987).
J.P. Jacobs, W.M. Klipstein, S.K. Lamoreaux, B.R. Heckel, and E.N. Fortson, PRA **52**, 3521 (1995).
M.V. Romalis, W.C. Griffith, J.P. Jacobs, and E.N. Fortson, PRL **86**, 2505 (2001).
W.C. Griffith, M.D.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

Hg EDM experiment

Univ. of Washington
Seattle, USA

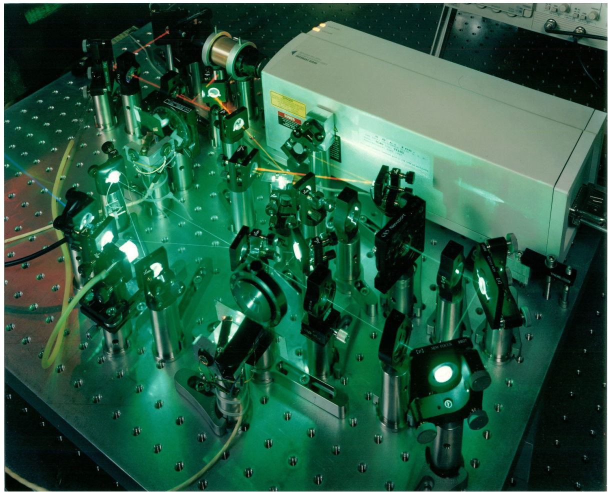
a gas of Hg atoms is contained in a quartz vapor cell…





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

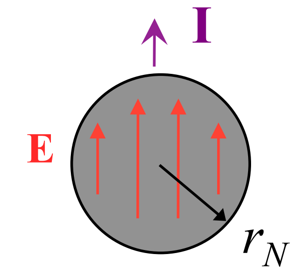


Theoretical interpretation: the Schiff moment

- Electric shielding is imperfect in a finite size nucleus if the nuclear EDM distribution does not match the nuclear charge distribution
  - parameterized by the *CP*-violating Schiff moment: $\vec{S} = S\vec{I}/I$
- $\mathbf{S}$ creates an electrostatic potential: $\varphi(\mathbf{r}) = -\dfrac{15\mathbf{S}\cdot\mathbf{r}}{r_N{}^5}n(\mathbf{r})$

  corresponding to a constant electric field inside the nucleus:

$$\mathbf{E} = -\nabla\varphi$$



- Electron wavefunctions are polarized by this potential leading to an atomic EDM,
  - from atomic calculations: $d_{\text{Hg}} = -2.8\times 10^{-4}\,S\ \text{fm}^{-2}$

Dzuba, Flambaum, Ginges and Kozlov (2002).

$$= -5.1\times 10^{-4}\,S\ \text{fm}^{-2}$$

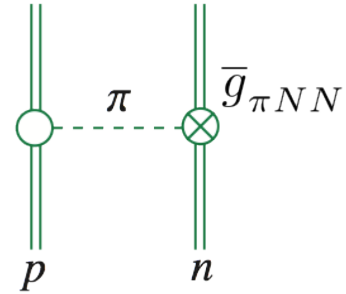
Latha, Angom, Das, Mukherjee (2009).

$$= -2.6\times 10^{-4}\,S\ \text{fm}^{-2}$$

Dzuba, Flambaum, and Porsev (2009).

Hg theoretical interpretation: nuclear calculation

- **S** can arise from nucleon EDMs or *CP*-violating internuclear forces
- Nucleon EDMs: $S(\mathrm{Hg}) = (1.9\, d_n + 0.2\, d_p)\ \mathrm{fm}^2$ Dmitriev and Sen'kov (2003).
  - $|d_n| < 6.3 \cdot 10^{-26}\ e\ \mathrm{cm}$ $|d_p| < 8.6 \cdot 10^{-25}\ e\ \mathrm{cm}$
- Schiff moment from nucleon-nucleon interactions:



  - $S(\mathrm{Hg}) = g(a_0 \bar{g}_\pi^{(0)} + a_1 \bar{g}_\pi^{(1)} + a_2 \bar{g}_\pi^{(2)})$
  - various calculations give: (a_i in units of $e\mathrm{fm}^3$)

	a_0	a_1	a_2	
schematic, contact int.	0.087	0.087	0.174	Flambaum, Khriplovich, and Sushkov (1986)
phenomenological RPA	0.00004	0.055	0.009	Dmitriev and Sen'kov(2003), arXiv:nucl-th/0304048
Skyrme QRPA	0.002-0.01	0.057-0.090	0.011-0.025	de Jesus and Engel (2005), arXiv:nucl-th/0507031
Odd-A Skryme MFT	0.009-0.041	–0.027-+0.005	0.009-0.024	Ban, Dobaczewski, Engel, and Shukla (2010), arXiv:1003.2598

isoscalar term can be related to θ_{QCD}: $g_\pi^{(0)} \approx 0.027\,\theta_{QCD}$

isovector can be generated by quark chromo-EDMs: $\bar{g}_\pi^{(1)} \approx 2\left(\tilde{d}_u - \tilde{d}_d\right) \times 10^{14}\,\mathrm{cm}^{-1}$

Hg EDM prospects

- Hg EDM limit from 2009 sets most precise upper bound on any EDM

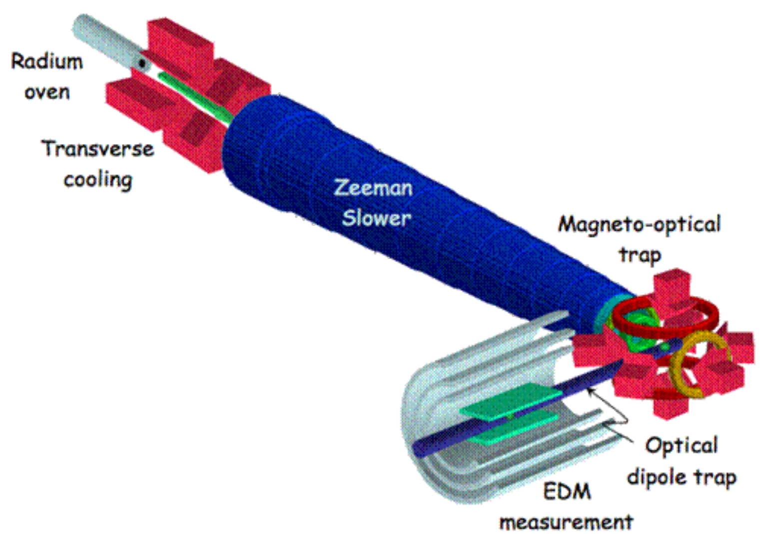
$$|d(^{199}\mathrm{Hg})| < 3.1 \times 10^{-29}\ e\ \mathrm{cm}\ (95\%\ \mathrm{CL})$$

  - provides extremely tight constraint on CP violating nuclear forces, proton EDM, and competitive bound on neutron EDM: $|d_p| < 7.9 \cdot 10^{-25}\ e\ \mathrm{cm}$, $|d_n| < 5.8 \cdot 10^{-26}\ e\ \mathrm{cm}$
- 4-cell data taking continues with 3-5x improvement in statistical sensitivity
  - improved Hg cell coherence times (500-1000 sec.)
  - precession in the dark measurement
  - improved magnetic noise
- Expect a factor of 3-4 improvement in limit by the end of 2014
  - current apparatus/technique can reach a x10 improvement in a few years ($\sim 10^{-30}\ e\ \mathrm{cm}$)
- Hopefully nuclear theory calculations will also improve...

Other diamagnetic approaches

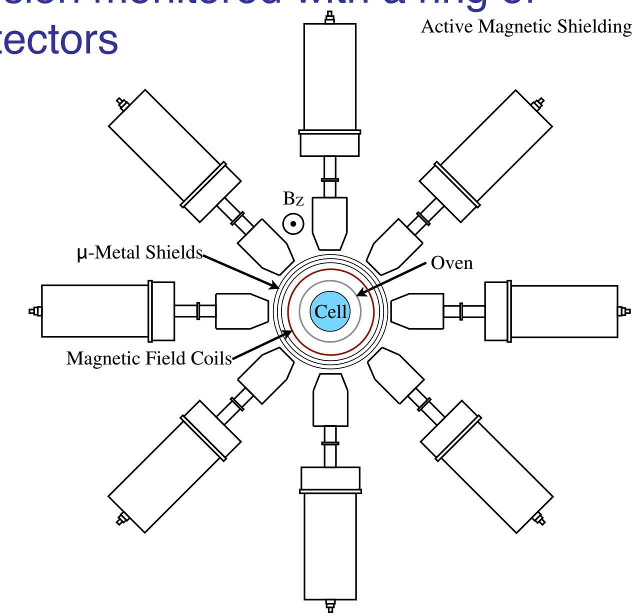
- Octupole deformed nuclei potentially 2-3 orders of magnitude more sensitive to fundamental CP violation than ^{199}Hg
  - nuclear calculations may also be more robust than Hg

Argonne National Lab:
laser trapped ^{225}Ra



https://www.phy.anl.gov/mep/atta/research/radiumedm.html

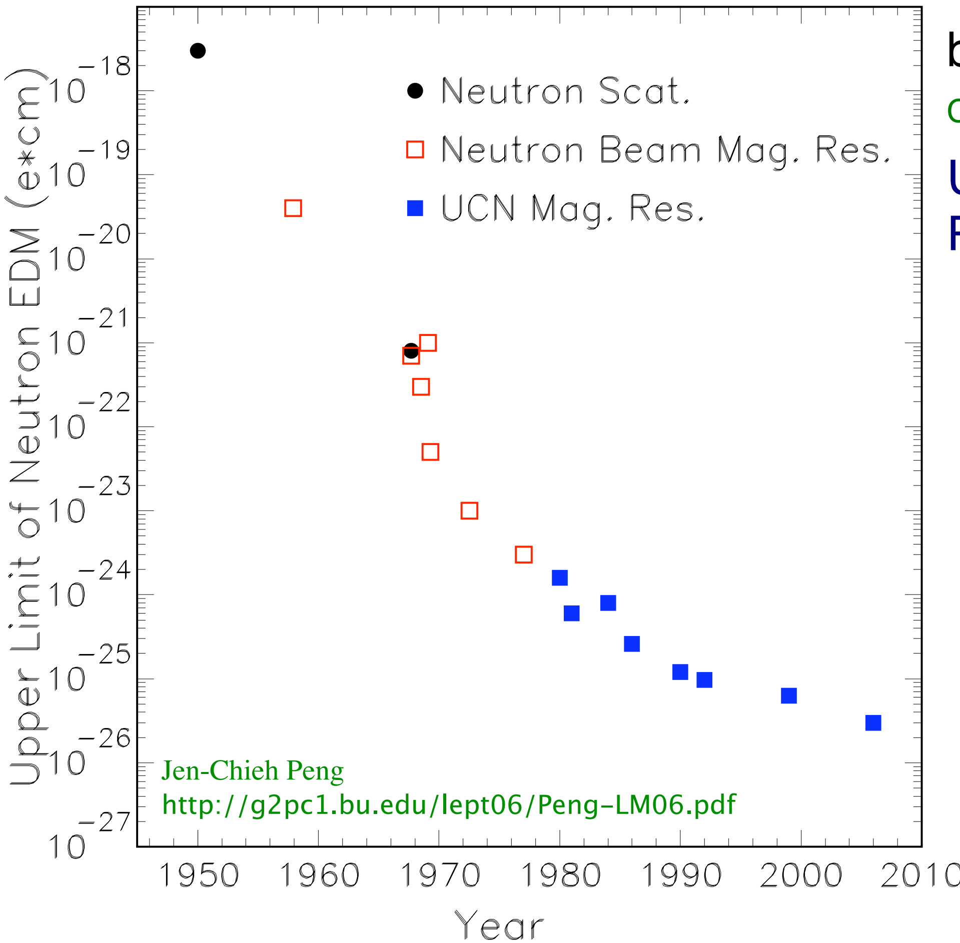
TRIUMF-ISAC: Rn in a vapor cell, precession monitored with a ring of Ge detectors



E.R. Tardiff et al, *Hyperfine Int.*, **225**, 197 (2014).

- ^{129}Xe – spherical nuclei, lighter than Hg, but can achieve >1000s coherence times (Munich, Mainz, Princeton, Tokyo Tech.)
  - also of interest for neutron EDM comagnetometer

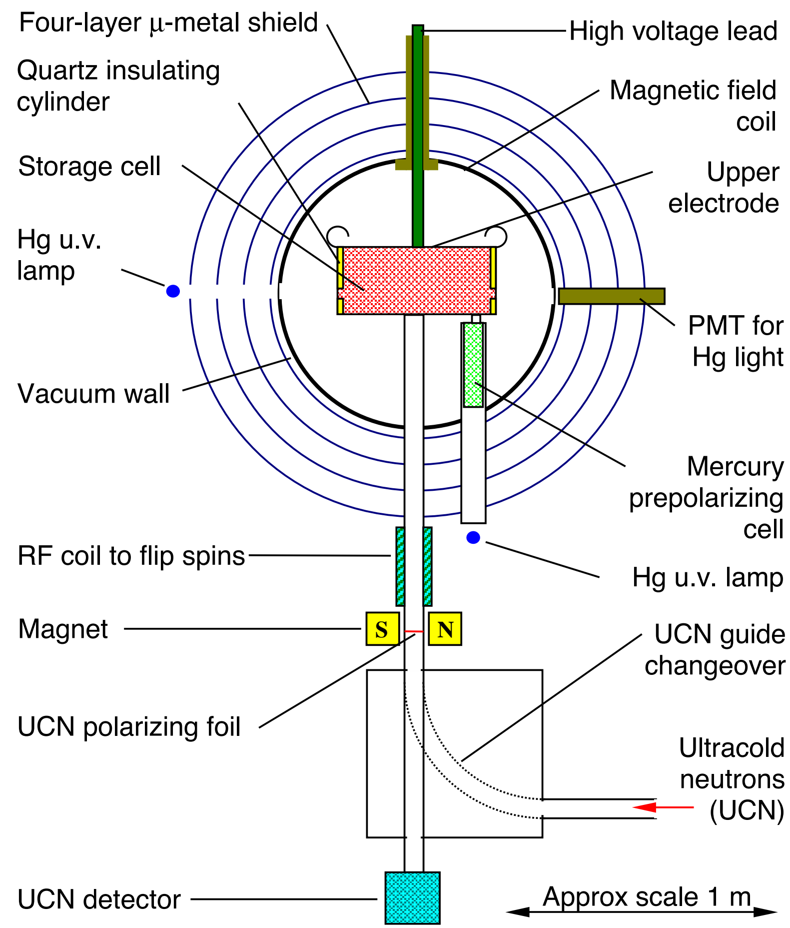
EDM searches: neutron



best limit: $|d_n| < 3.0 \times 10^{-26}$ e cm (2006)

C. A. Baker *et al*, PRL **97**, 131801 (2006).

UCN+^{199}Hg comagnetometer (Sussex/RAL/ILL)

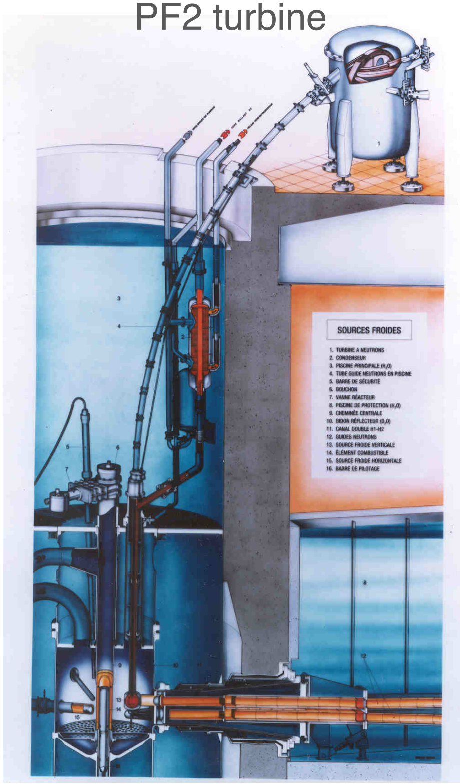


UCN: ultracold neutrons
v = 0-6 m/s, can be stored in material bottles

neutron EDM challenges: UCN source

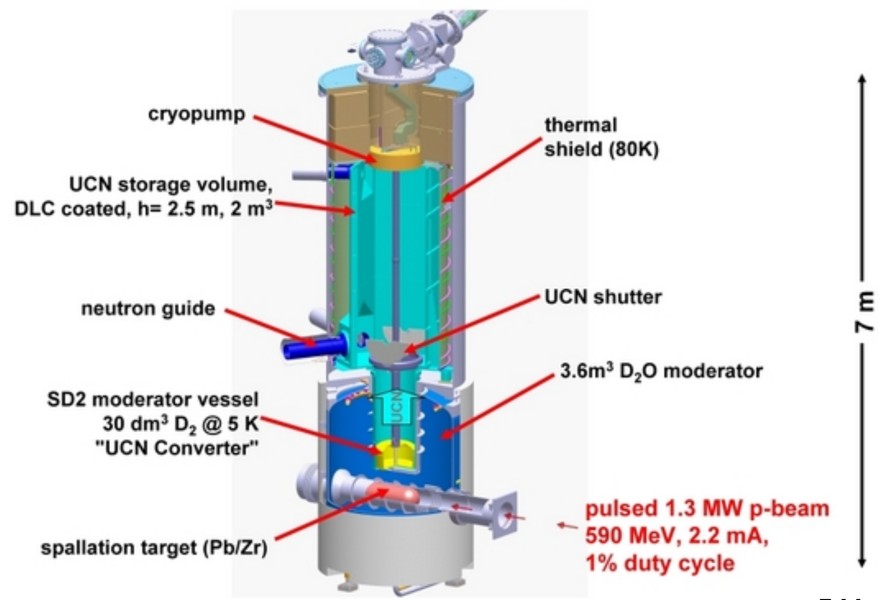
- to improve nEDM sensitivity, need higher UCN densities
  - ILL/Steyerl turbine source has been the main source of UCN for 3 decades, provides ~ 50 UCN/cc

PF2 turbine



  - next generation sources hope to achieve 10-100x greater dens. by superthermal-production from downscattering cold neutrons from phonons in
    - LHe (ILL,SNS,RCNP,PNPI)
    - or solid D2 (LANL,PSI,FRM-II,NCSU)

Paul Scherrer Institute
Pulsed UCN-Source



  - but so far have only ~ matched the turbine source performance
  - also difficult to maintain densities while transferring to the experiment region

neutron EDM challenges: magnetic fields

- If larger UCN densities are achieved, need to also improve theunderstanding of magnetic fields in apparatus
  - geometric phase systematic effect: magnetic field gradients coupled to $\boldsymbol{v}\times\boldsymbol{E}$ gives electric field correlated frequency shifts
  - 1 μG/cm mag. gradient requirements for 10^{-28} $e$cm sensitivity
- Comagnetometer: use an atomic magnetometer sampling the same region, at the same time as the UCN
  - gives real time readout of the B field that the UCN experience
  - ^{199}Hg, ^{129}Xe, ^{3}He
  - but, sampling volume tends to be slightly different due to different mass/velocity

neutron EDM: PSI

- using Sussex/RAL room temperature UCN/Hg comagnetometer apparatus on PSI UCN source
  - state of the art Cs atom magetometry to evaluate magnetic uniformity, control systematic effects
  - 254 nm laser system replaces discharge lamps for Hg polarization/ readout, and other technology upgrades…

PAUL SCHERRER INSTITUT

neutron EDM: PSI status

$$\sigma = \frac{h}{2\alpha T E \sqrt{N}}$$

UCN source has not performed as well as expected, but output has increased every year of operation…

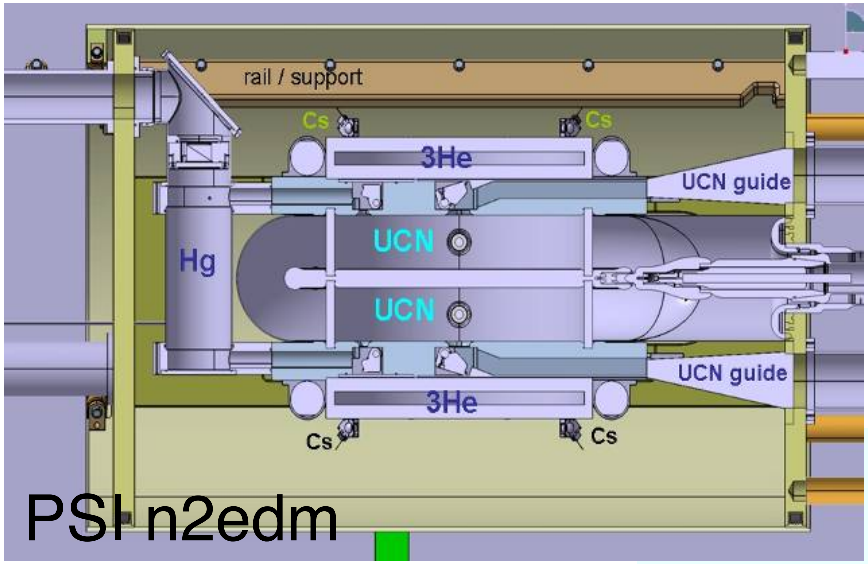
	RAL/Sx/ILL*		PSI 2012		PSI 2013	
	best	avg	best	avg	best	avg
E-field	8.8	8.3	8.33	7.9	12	10.3
Neutrons	14 000	14 000	9 000	5 400	10 500	6 500
T_{free}	130	130	200	200	200	180
T_{duty}	240	240	360	360	340	340
α	0.6	0.453	0.65	0.57	0.62	0.57
day (10^{-25}ecm)	2.3	3.0	2.3	3.5	1.5	2.8

systematics controlled well below 2006 result.
Hope to take 100 days nEDM data in 2014
reach ~10^{-26} e cm in a few years,

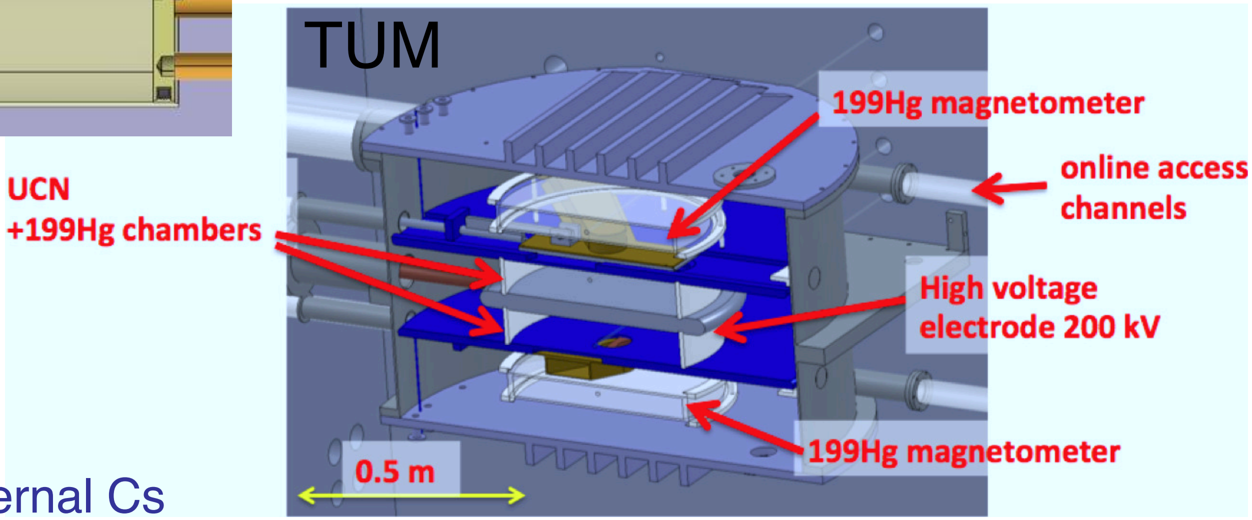
* Best nedm limit:
Baker *et al*., PRL**97**(2006)

then change to upgraded n2edm apparatus: double Ramsey chambers, expected 5-7x improvement in sensitivity

room temperature neutron EDM



both have 2 UCN chambers, Hg comag, additional outer magnetometry cells, additional external Cs magnetometers



Currently running:
– PNPI, double chamber, external Cs mag, no comag, currently on ILL turbine

Other under development:
– RCNP/TRIUMF, Xe comag.
– LANL, Hg comag.

Cryogenic nEDM

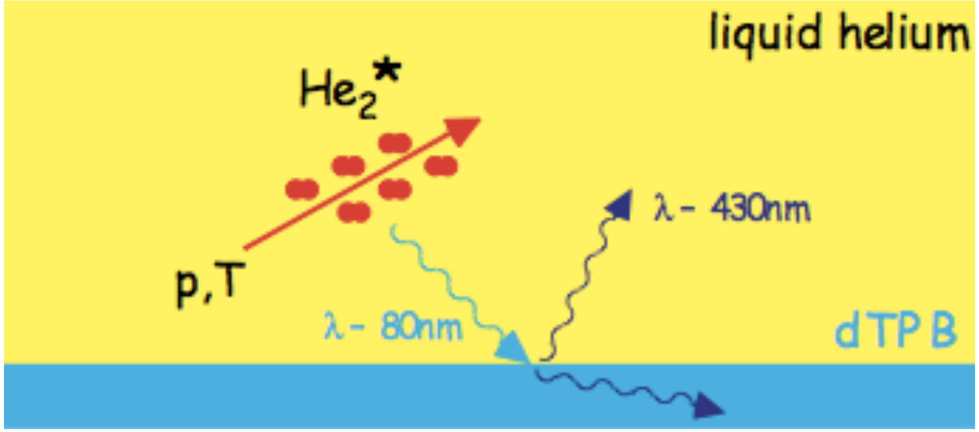
- create high UCN density by superthermal production in LHe
- high electric field breakdown strength in LHe (> 30kV/cm)
  - room temperature experiments generally limited to 10 kV/cm
- superconducting magnetic shielding and magnetic coils give higher stability field environment
  - can also use low T_C SQUID sensors
- longer UCN storage times at low temperatures, leakage currents tend to be smaller
- but… very difficult experimental challenges in building a cryogenic UCN apparatus
  - UCN lost in gaps – need to carefully design guides and transfer valves that will still work after thermal contraction
  - long thermal cycle times to make changes to the apparatus

SNS nEDM measurement at Oak Ridge

- UCN generated by superthermal production in LHe by cold neutron beam directly inside measurement cell
  - no UCN transport issues
  - need to deal with higher backgrounds in measurement cell, though

- superfluid ^{4}He with small amount of polarized ^{3}He ($\rho_3/\rho_4 \sim 10^{-10}$)
  - 3He acts as neutron spin analyzer
    - UV scintillation light shifted to visible by tetraphenyl butadiene (TPB) on cell walls, cell walls act as light guides to PMTs
  - detection of ^{3}He precession with SQUIDs gives comagnetometer signal

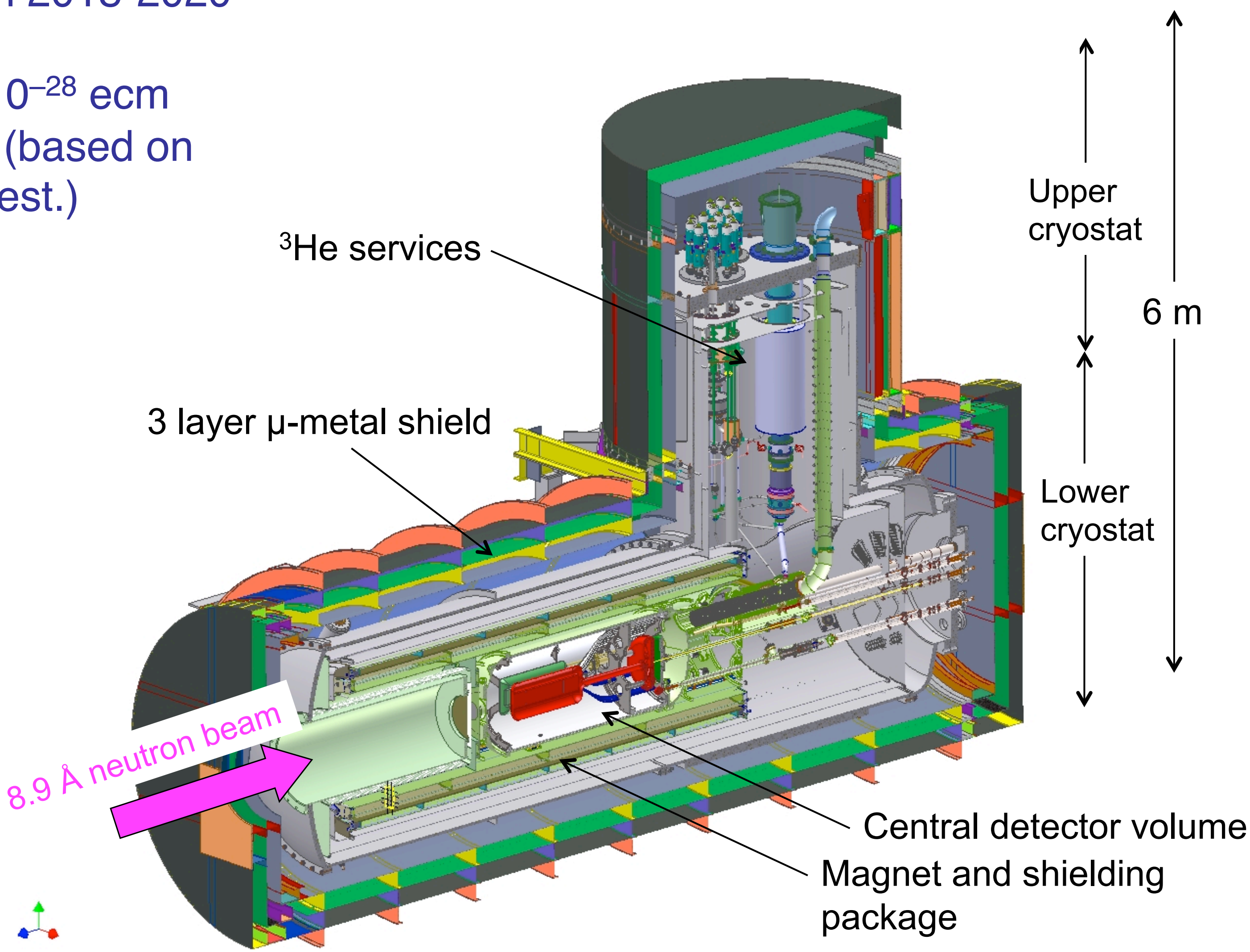
$$\vec{n} + {}^3\vec{\mathrm{He}} \rightarrow \mathrm{p} + \mathrm{t} + 764\ \mathrm{keV} \quad (\sigma_{\uparrow\downarrow} \gg \sigma_{\uparrow\uparrow})$$



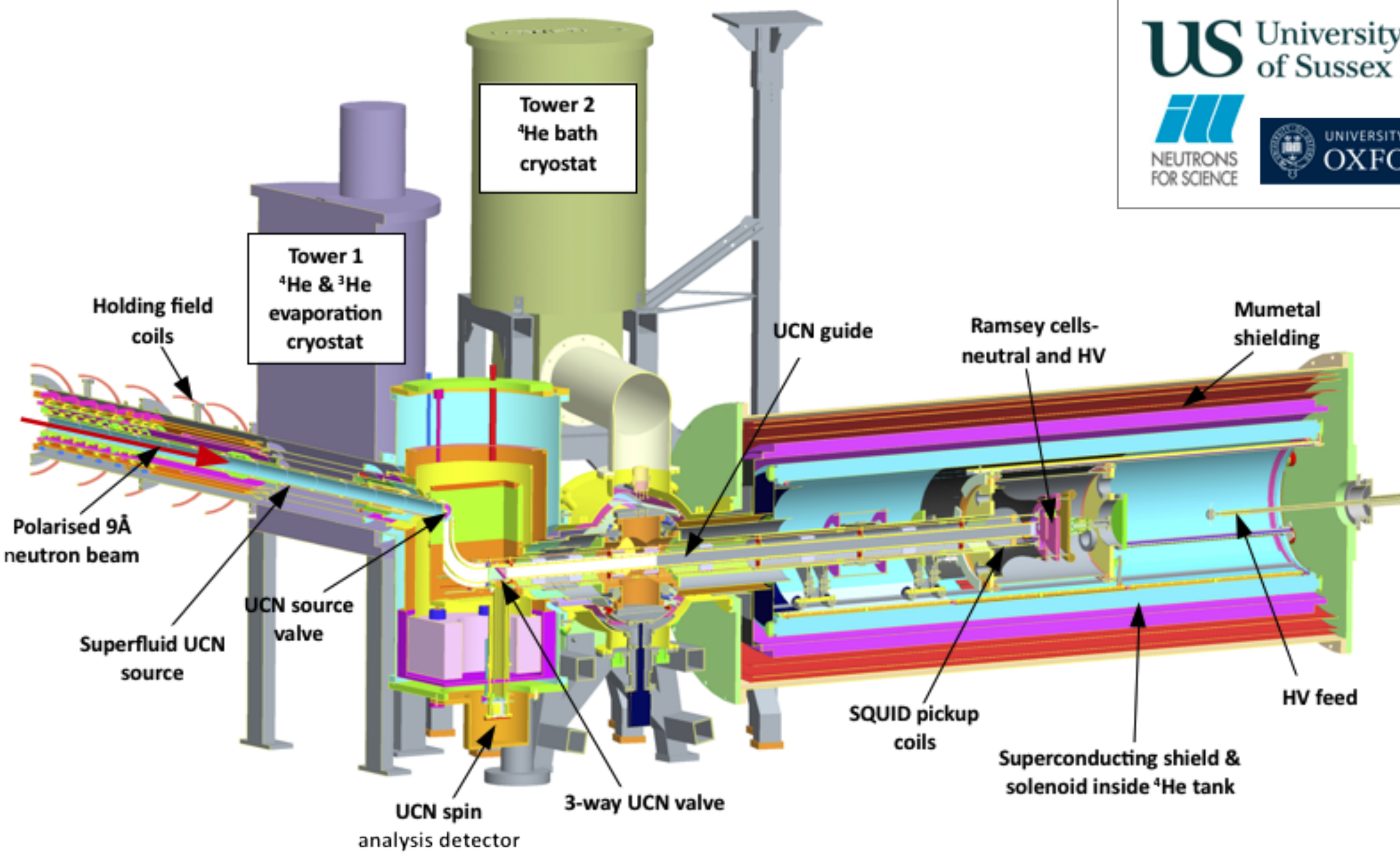
SNS nedm

– working towards starting to install at Oak Ridge in 2018-2020

– sensitivity goal: 5×10^{-28} ecm after 3 years running (based on extensive simulation est.)



CryoEDM



- Superthermal LHe UCN source
- Fill separate measurement cells through UCN guides (all in SF He)
- Ramsey separated oscillatory fields technique to measure nEDM (as was used in room temperature experiment)

CryoEDM RIP...

- December 2013 Science Board decision: “managed withdrawal” from CryoEDM
  - scale of program required to reach a new physics result in a competitive timescale outside of STFC’s anticipated available resource levels

- CryoEDM accomplishments:
  - Multiple operations of cryostat at 0.6 K base temperature, 300 L superfluid He volume
  - Superthermal UCN production at expected rate
  - Demonstrated transport to Ramsey cells and to detectors
  - Development/operation of solid-state UCN detectors in LHe
  - Implementation of SQUID magnetometry system for nEDM

- But …consistently low on manpower, apparatus very difficult to implement changes, slow+expensive to cool down (>2 months), still at least 3 years from competitive nEDM data…

Path forward for UK in nEDM

- Short-mid term: Sussex will increase involvement with PSI room temperature experiment

- Longer term: greatest nEDM sensitivity is achievable in a fully cryogenic experiment
  - superthermal LHe UCN source on new ILL 9Å cold neutron beamline
    - must be much more efficient/shorter turnaround time than CryoEDM source – O. Zimmer group at ILL has made many advances in this area, will build new SuperSun UCN source in 2-4 years
    - P. Fierlinger at TUM is planning to bring his nEDM apparatus to ILL to utilize this UCN source
  - RAL/Sussex/Lancaster plans to develop a cryogenic “insert” to go inside the TUM magnetic shield+coil, attach to SuperSun UCN source
    - allow E field > 30 kV/cm, several hundred second UCN storage time, superconducting magnetic shielding, separate source and measurement allow modular access and optimization of each separately
    - utilize UK’s existing expertise/experience from CryoEDM, continued development of cryogenic nEDM techniques

Storage ring EDM measurements

- enables EDM measurements on charged particles
- muon EDM can be extracted from g-2 data
  - from BNL E821, $d_\mu < 2 \times 10^{-19}$ e.cm
  - expected improvement at FNAL, $\sigma(d_\mu) \sim 10^{-21}$ e.cm
- Storage Ring EDM Collaboration (BNL) have proposed:
  - measuring the bare ^2H or ^3He nuclei EDM: sensitive to same CP violating nucleon-nucleon interaction as Hg, but not nearly as difficult to calculate, and no Schiff shielding.
  - measuring the proton EDM to 10^{-29} e.cm

Current and projected sensitivities

	current limit	projected sens. from planned exp.	standard model CKM prediction
n	3×10^{-26}	10^{-28}	$10^{-31} - 10^{-33}$
e	9×10^{-29}	10^{-30}	$\sim 10^{-38}$
Hg	3×10^{-29}	10^{-30}	$< 10^{-35}$

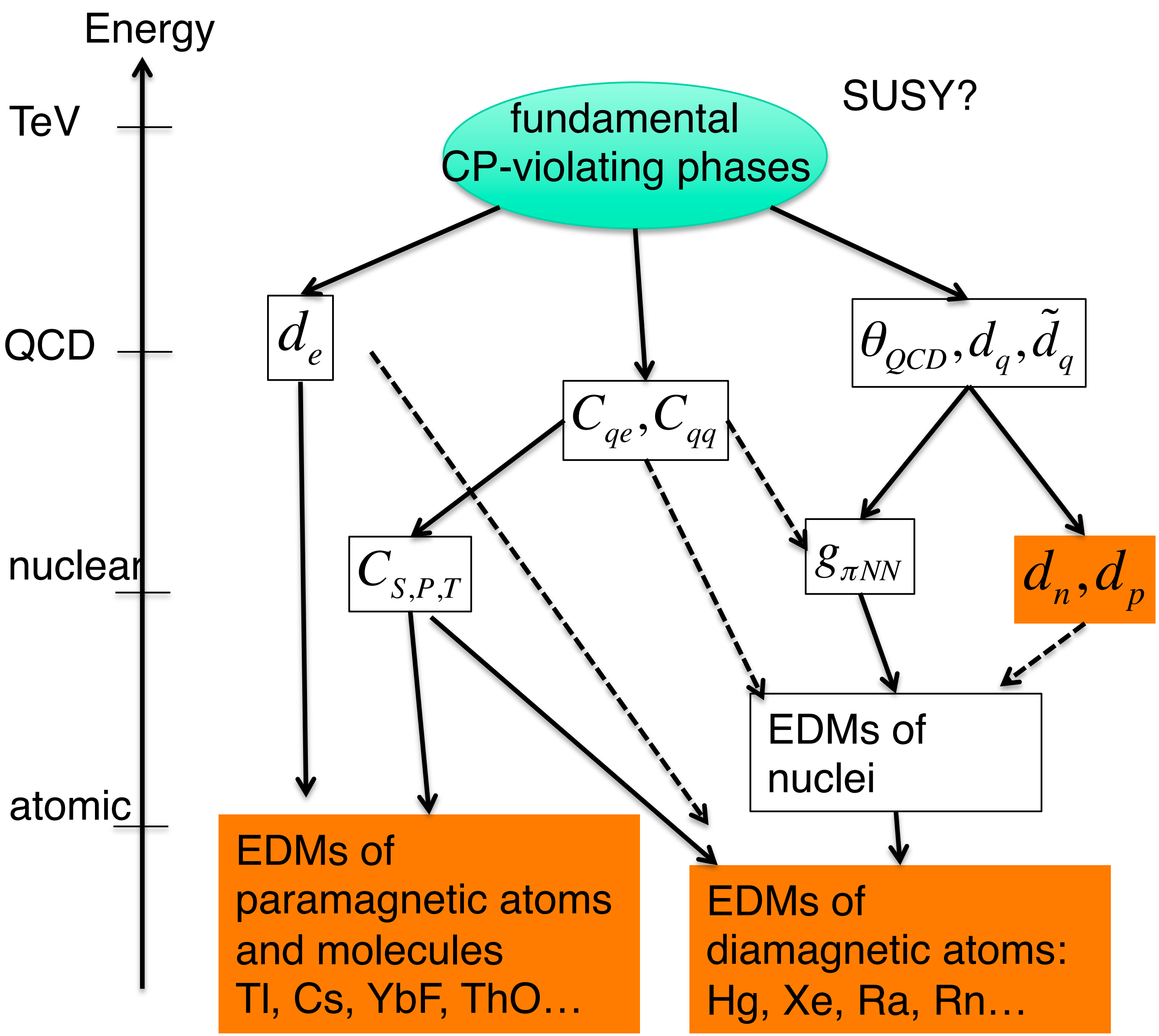
(units are in e.cm)

- Standard model CKM generated EDMs are generated at least at 3-loop level for n/Hg, 4-loop for the electron
  - see Pospelov and Ritz arXiv:1311.5537 for a recent examination of CKM generated EDMs
- Assuming some beyond the standard model source of CPV entering at one loop, we expect

$$d_f \sim e\left(\frac{m_f}{\Lambda^2}\right)\frac{\alpha}{4\pi}\sin\phi_{CPV}$$

with the current ThO limit, we are probing $\Lambda^2 \gtrsim (7\ \mathrm{TeV})^2 \left|\sin\phi_{CPV}\right|$

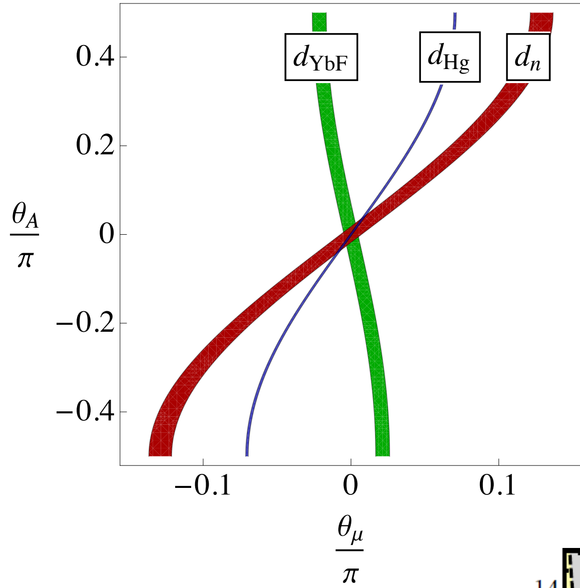
Interpretation of EDMs



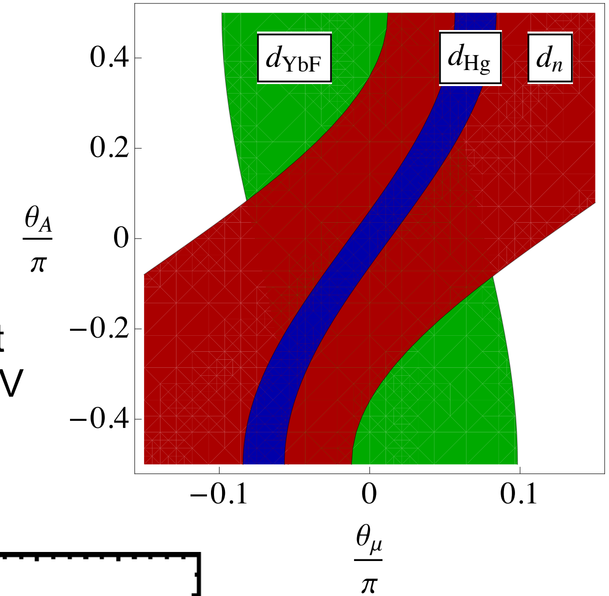
Note: oscillating EDMs at ~MHz could be generated by axion-like dark matter, see Graham and Rajendran, arXiv: 1306.6088

EDMs in MSSM

pre-LHC: M_{susy} = 500 GeV



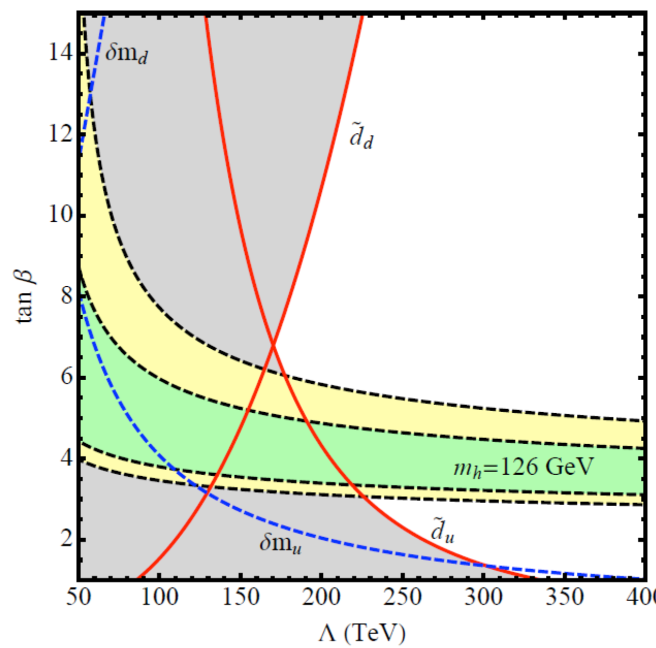
now: M_{susy} = 2 TeV



1st gen squarks excluded by direct searches at ~1 TeV

in minimal SUSY, $m_h \gg m_Z$ points to PeV scale s-partners, log-enhanced quark CEDMs

grey is ruled out by quark chromo-EDM limit from ^{199}Hg



McKeen,Pospelov&Ritz
hep-ph 1303.1172
Heavy sfermions >50 TeV
1 TeV gauginos
Present EDM Limits

from A. Ritz
http://www.psi.ch/psi2013/

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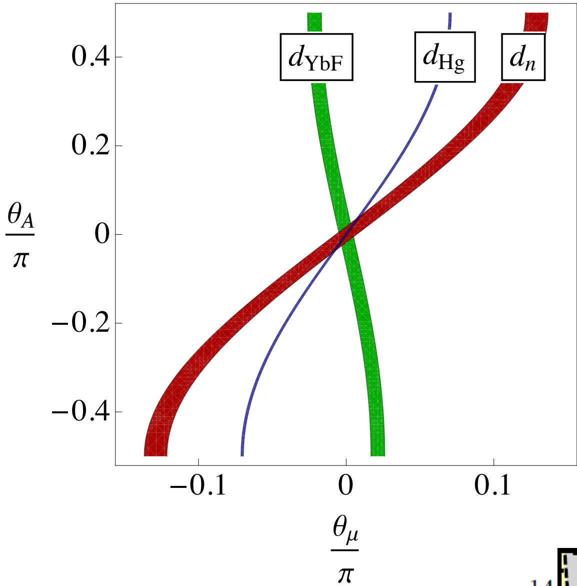

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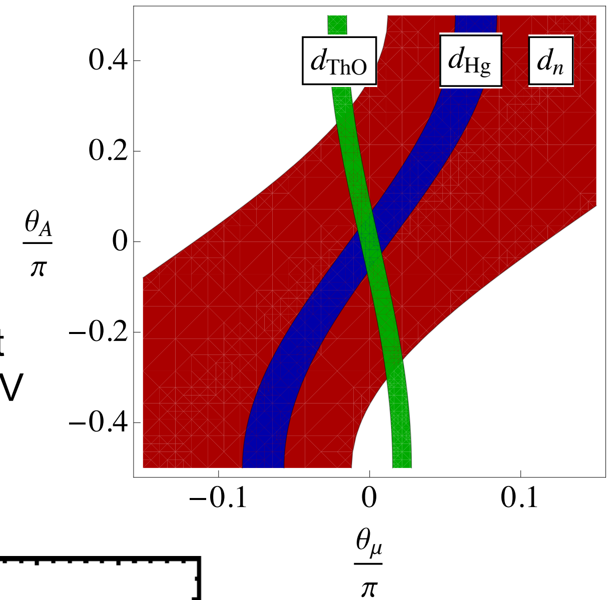

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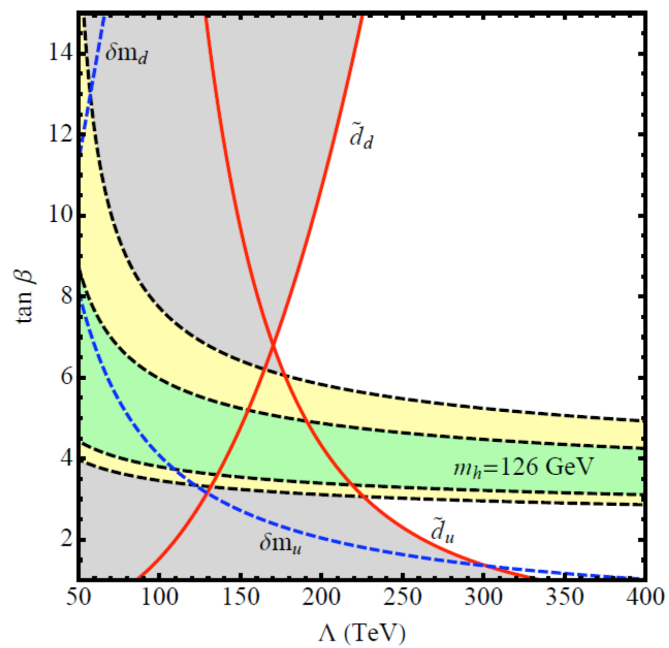

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Summary

- EDM searches in the neutron, leptonic, and diamagnetic systems provide a valuable test for new sources of *CP*-violation at TeV and beyond.
- Expect 10^{-30} e cm EDM sensitivity in the next few years from Hg, and the electron (YbF, ThO)
- neutron EDM limit still at 2006 Sussex/RAL level
  - likely will be surpassed within a few years at PSI
  - cryogenic techniques will ultimately give the greatest sensitivity gains

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