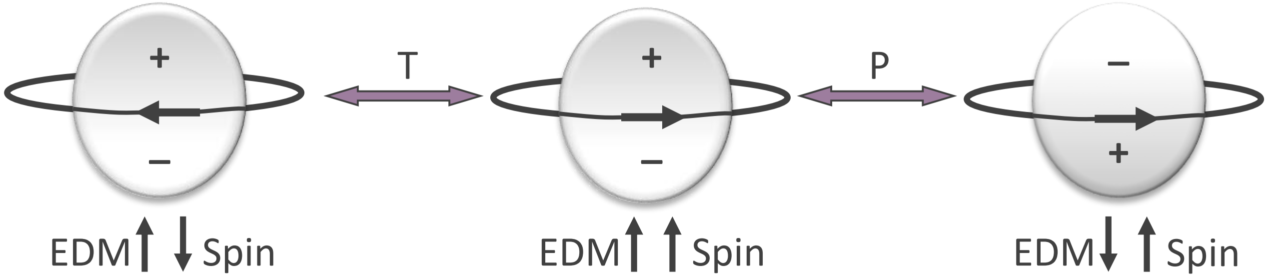


Progress and outlook in nuclear science on the search for new physics using EDMs

Roy J. Holt
Physics Division, Argonne National Laboratory

Outline

- Introduction
- The EDM experiments
  - leptonic
  - hadronic
- Summary

The big questions

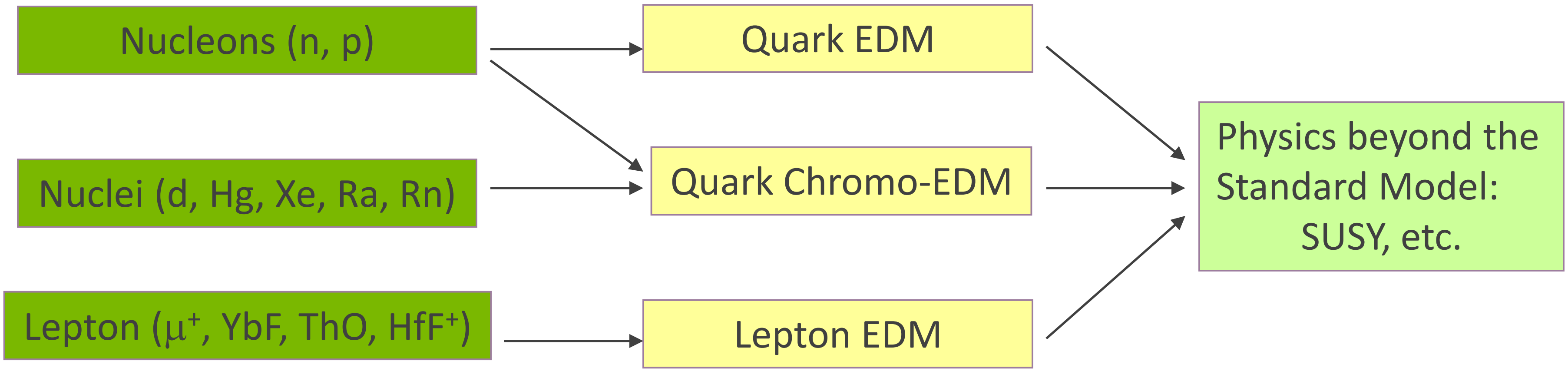
- Why do we exist?
  - Why is there more matter than antimatter?
  - Only 1 part in 10^9 of matter left from the big bang
- Sakharov's three conditions for a baryon asymmetry
  - Baryon number violation
  - Microscopic C, **CP** (or **T**) **violation**
  - Thermal non-equilibrium

"The observation of a nonzero EDM in any of the above searches would constitute a major discovery with significant implications for the origin of matter and the nature of new forces in the early universe."
(NSAC Long Range Plan, 2015)

Why EDMs?

- "… EDM searches shed light on one of the key questions for all of physics: why the present universe contains more visible matter than antimatter." *(NSAC Long Range Plan, 2015)*
- "Improved sensitivities by a factor of 10–100 would imply reach on the scale of CPV interactions in the 10–50 TeV range, inaccessible at high-energy colliders today ..." *(NSAC Long Range Plan, 2015)*
- Impacts cosmology as well as high energy, nuclear, atomic and molecular physics
- No Standard Model background

EDM Searches in Three Sectors


Nucleons (n, p)

Nuclei (d, Hg, Xe, Ra, Rn)

Lepton (μ^+, YbF, ThO, HfF^+)

Quark EDM

Quark Chromo-EDM

Lepton EDM

Physics beyond the Standard Model: SUSY, etc.

Sector	Exp Limit (e-cm)	Method	Standard Model
Electron	9×10^{-29}	ThO in a beam	10^{-38}
Neutron	3×10^{-26}	UCN in a bottle	10^{-31}
^{199}Hg	7.4×10^{-30}	Hg atoms in a cell	10^{-33}

Experiments worldwide

Leptonic EDMs

YbF	(beam)	Imperial College
HfF^+	(trapped)	JILA
ThO	(beam)	Harvard-Yale
^{210}Fr	(trapped)	CYRIC
^{210}Fr	(fountain)	TRIUMF
μ^+	(ring)	FNAL
μ^+	(ring)	J-PARC

Hadronic EDMs

n	(vac)	ILL-PNPI
n	(beam,solid)	ILL
n	(vac)	PSI
n	(vac)	Munich-(ILL)
n	(^{4}He)	RCNP-TRIUMF
n	(^{4}He)	SNS nEDM
n	(vac)	J-PARC
n	(vac)	LANL
p	(ring)	(CERN)
d	(ring)	COSY
^{129}Xe	(cell)	Mainz/Juelich
^{129}Xe	(cell)	Tokyo Tech.
^{129}Xe	(cell)	Munich
^{199}Hg	(cell)	U. Washington
^{223}Rn	(cell)	TRIUMF
^{225}Ra	(trapped)	ANL (FRIB)
TlF	(beam)	Harvard-Yale

Precision in EDM measurements

$$E = \hbar\omega = 2\vec{d}\cdot\vec{\mathrm{E}}$$

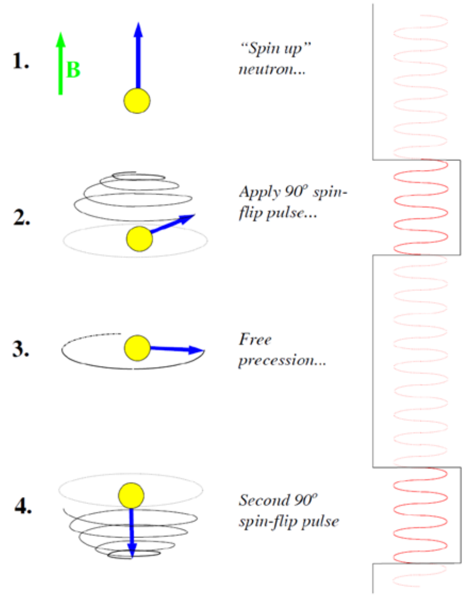
$$\sigma_d = \frac{\Delta E}{2|\vec{\mathrm{E}}|}$$

$$\Delta E \Delta t \sim \hbar$$

Measure a frequency

$$\nu = \frac{2\vec{\mu}\cdot\vec{B} \pm 2\vec{d}\cdot\vec{E}}{h}$$

Ramsey separated oscillatory fields



$$\sigma_d = \frac{\hbar}{2|\vec{E}|\tau\sqrt{N}}$$

E = electric field

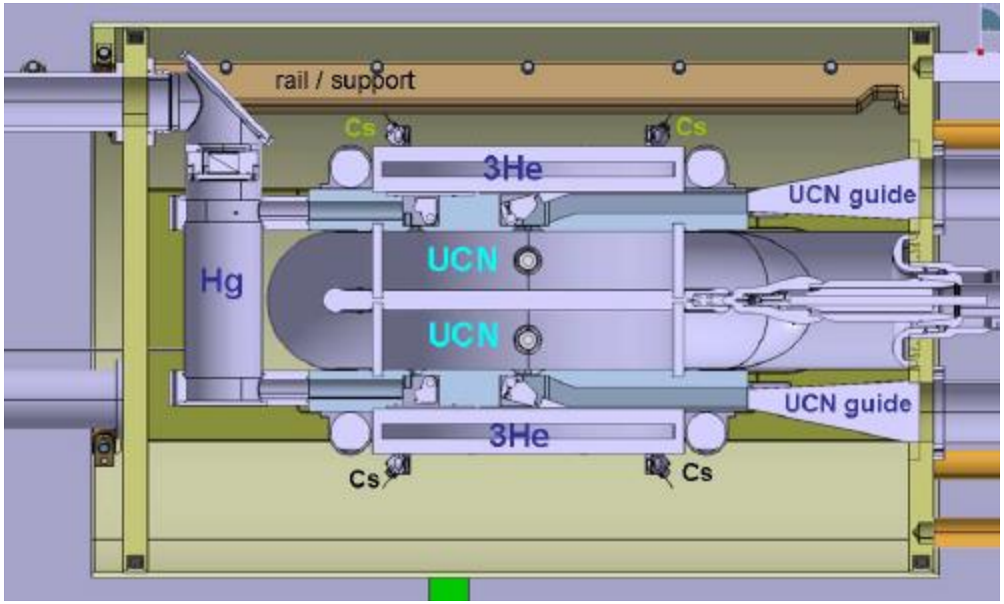
N = number of counts

τ = coherence time

Systematics in EDM measurements

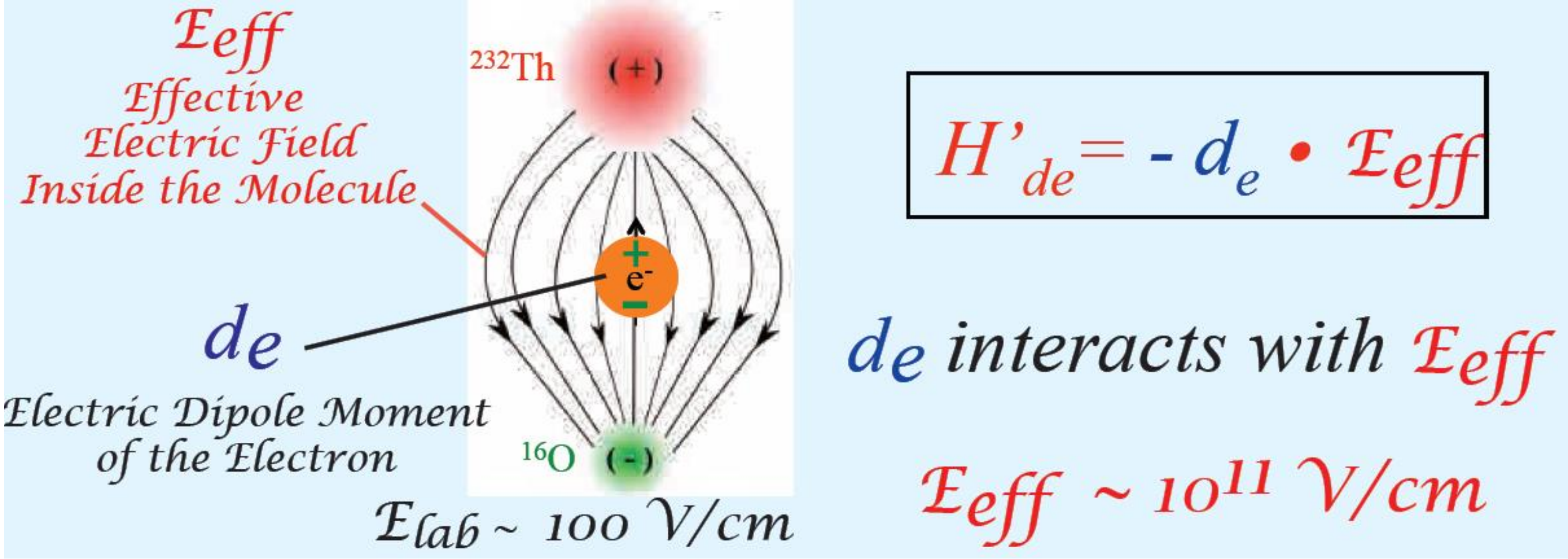
- Magnetic fields
  - shielding
  - Field gradients
  - (Co-)Magnetometry
- Correlations with E-field
- E x v effects
- Geometric phase effect
- …

PSI n2EDM science chamber



Leptonic EDMs

Molecules: highly polarizable
10 V/cm -> 10^{10} V/cm effective electric field



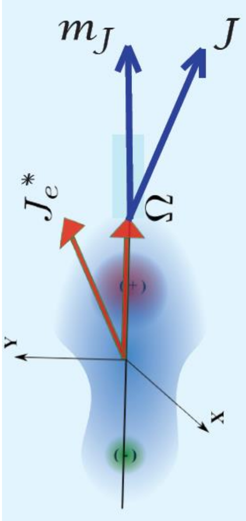
Thanks to J. Doyle

Yale

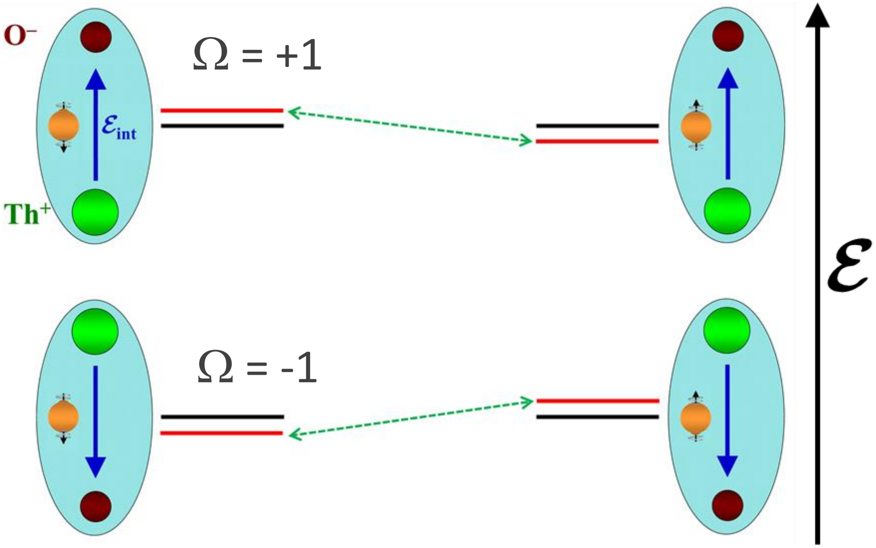
Harvard

ACME

Advanced Cold Molecule EDM

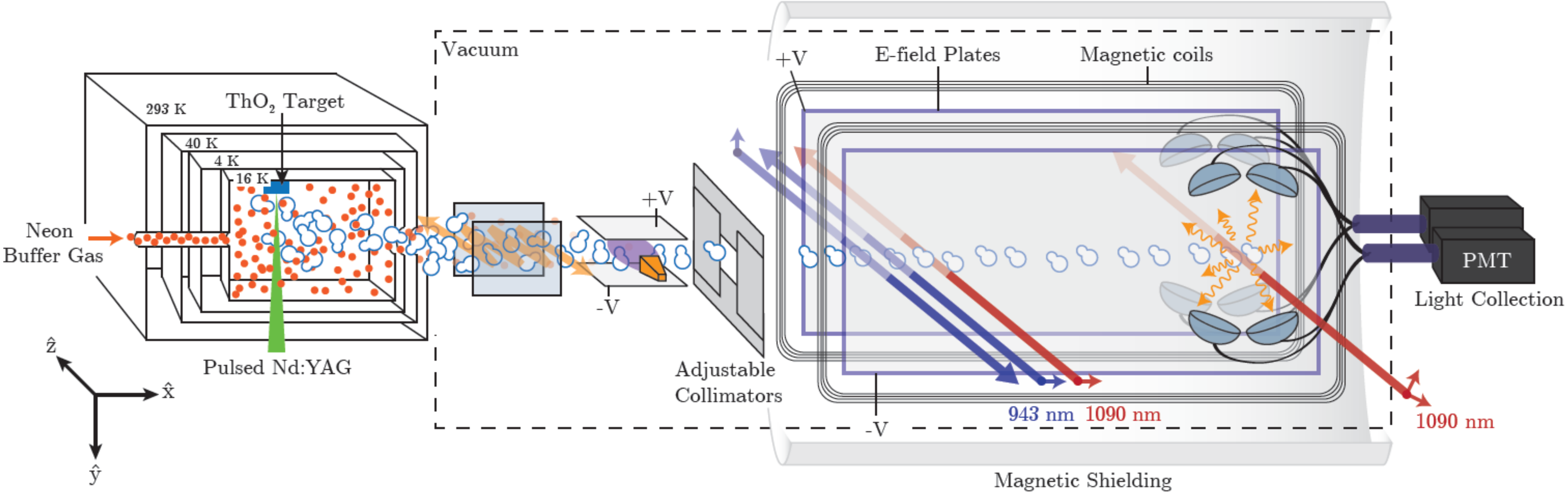


Polar molecule:
Large
internal
E-field (84 GV/cm)
+
Internal
co-magnetometer
to control
systematics



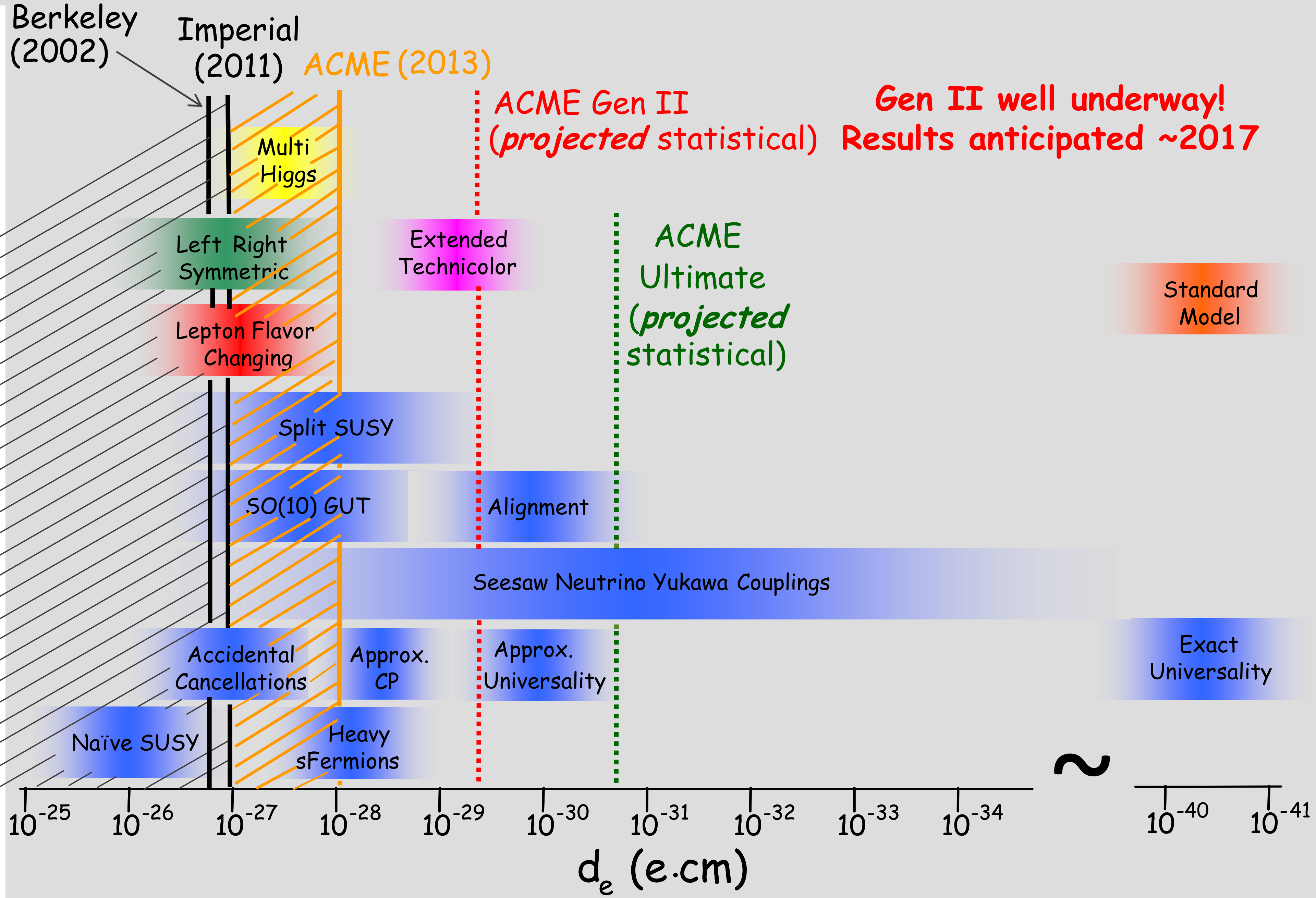
Cryogenic molecular beam: large flux, good statistics

Thanks to D. DeMille



2^{nd} generation upgrades now in place: >600x increase in count rate observed

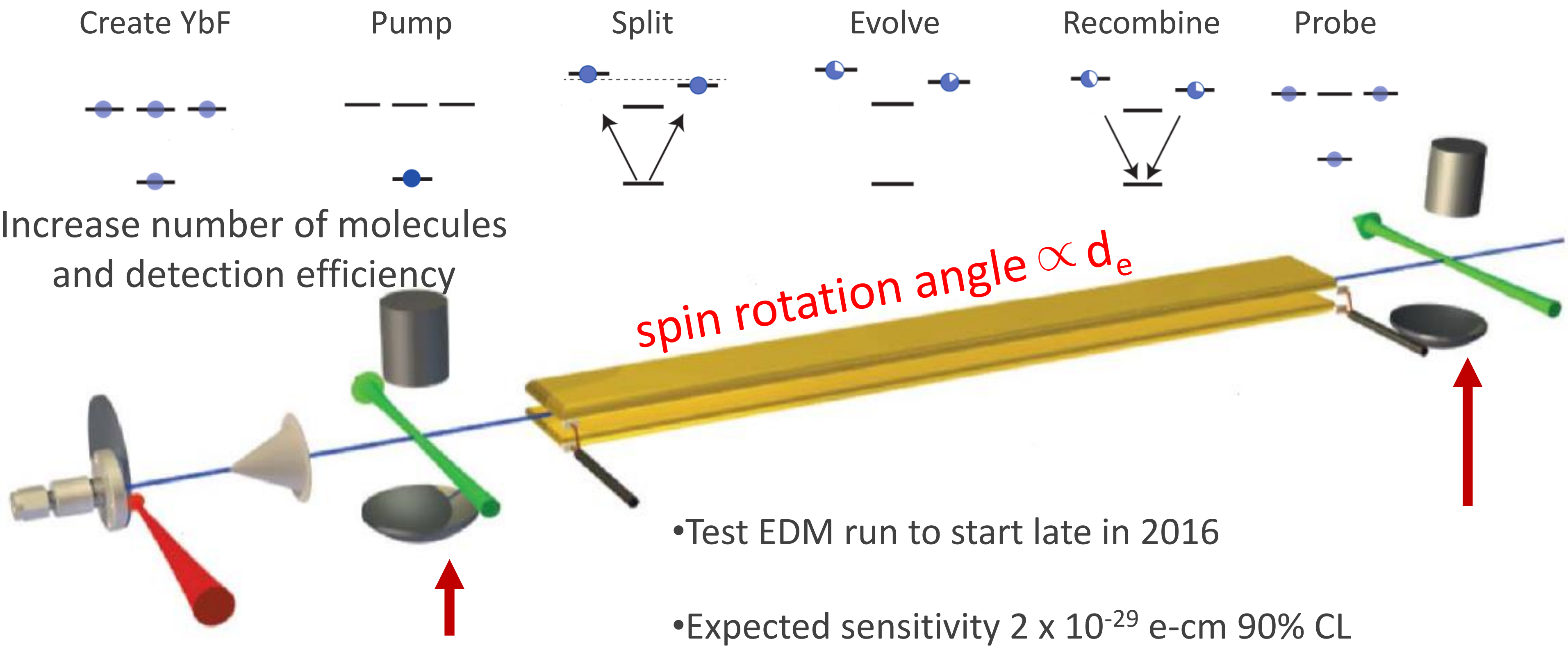
Continuing search for new physics with ACME



YbF Electron EDM Measurement

Imperial College

Thanks to E Hinds



Increase number of molecules and detection efficiency

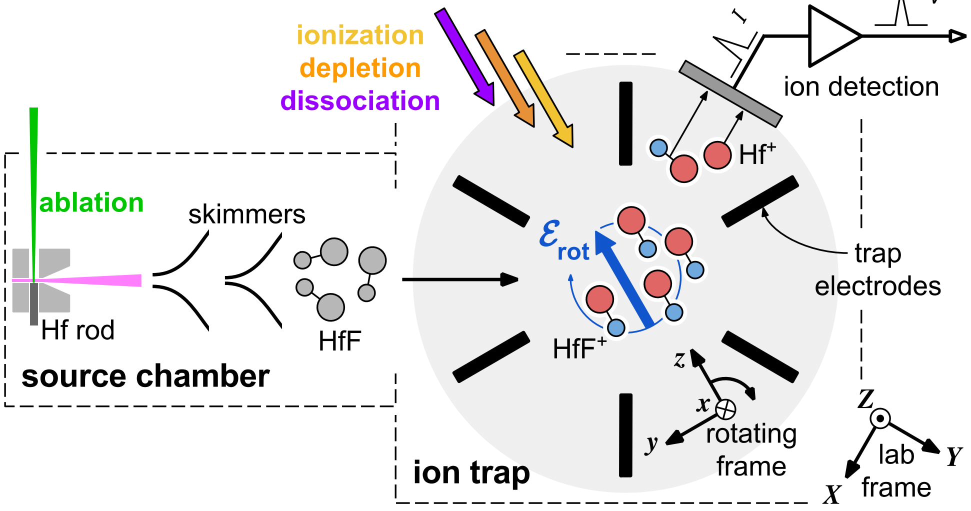
- Test EDM run to start late in 2016
- Expected sensitivity 2×10^{-29} e-cm 90% CL
- Current limit $|d_e| < 9 \times 10^{-29}$ e-cm 90% CL
- Goal: intense slow beams 10^{-30} e-cm/day

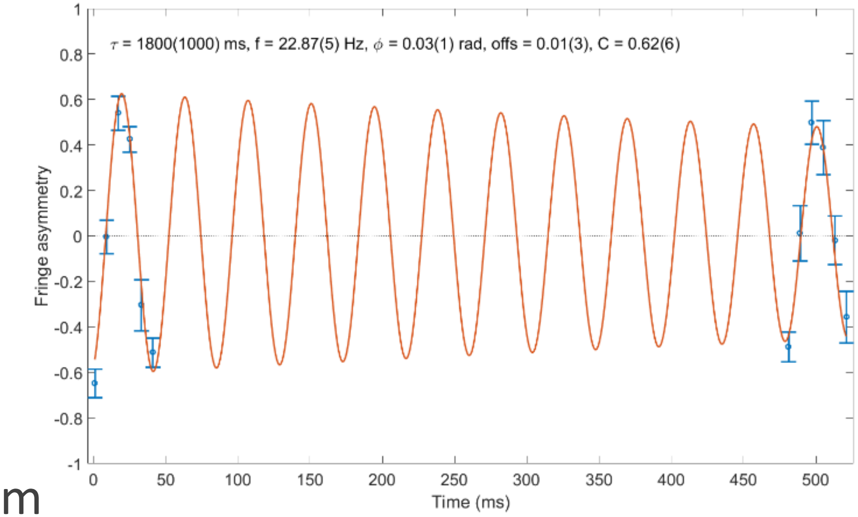
E = 10 kV/cm →
$|E_{int}|$ = 14.5 GV/cm

JILA eEDM Project

HfF^+: $^3\Delta_1$ in an ion trap

- Effective E-field = 23.3 GV/cm
- Coherence time > 0.5 s
- Count rate = 5 /s





Data still blinded!

EDM = ? ± 1.5(stat) ± 0.025(syst) 10^{-28} e·cm

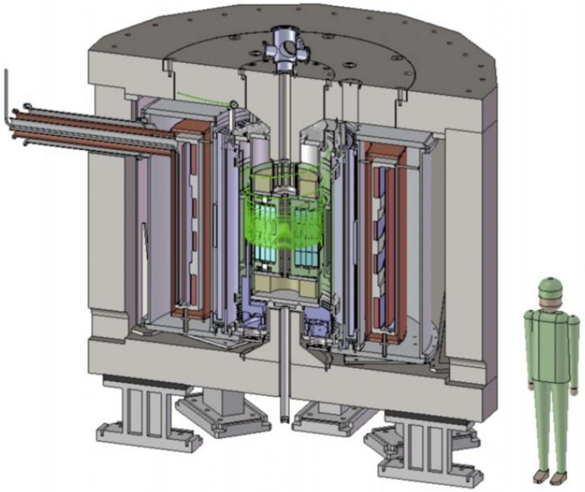
Expect x10 over next 2 years

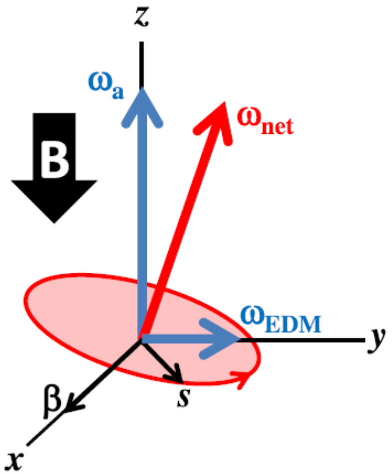
Longer term: switch to ThF^+

Thanks to E. Cornell

Muon EDM

- Present limit: $|d_\mu| < 1.8 \times 10^{-19}$ e-cm CL=95%
- induced motional E-field: $\vec{E}_m \propto \vec{\beta} \times \vec{B}$ $\gamma = 29.3$ → E ~ 13 GV/m
- Measure up and down slopes of muon decays: tracking detectors
- FNAL (2020) and J-PARC (2022): sensitivity ~ O(10^{-21} e-cm)





EDM

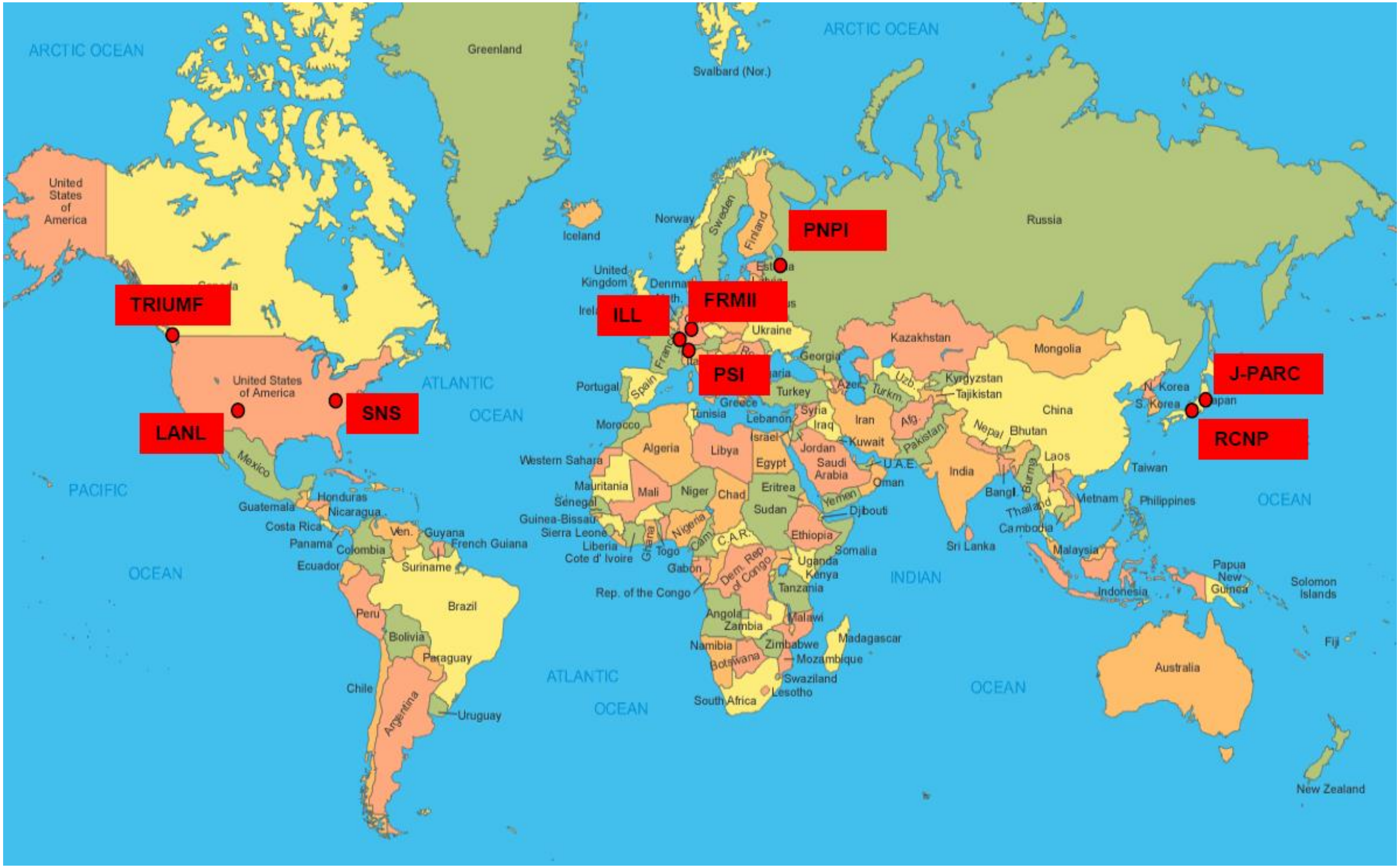
$$\vec{\omega}_{\rm net} = -\frac{q}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

Thanks to D. Hertzog

T. Gorringe, D. Hertzog, Prog. Part. Nuc. Phys. (2015)

Hadronic EDMs

Neutron EDM experiments



Thanks to B. Filippone

Neutron EDM searches

Experiment	UCN source	cell	Measurement techniques	σ_d Goal (10^{-28} e-cm)
			Present neutron EDM limit < 300	
ILL-PNPI	ILL turbine PNPI/Solid D_2	Vac.	Ramsey technique for ω E=0 cell for magnetometer	Phase1<100 < 10
ILL Crystal	Cold n Beam	solid	Crystal Diffraction Non-Centrosymmetric crystal	< 100
PSI EDM	Solid D_2	Vac.	Ramsey for ω, external Cs & Hg comag. Xe or Hg comagnetometer	Phase1 ~ 50 Phase 2 < 5
Munich ~~FRMII~~ ILL	Solid D_2 SUN	Vac.	Room Temp. , Hg Co-mag., also external 3He & Cs mag.	< 5
RCNP/TRIUMF	Superfluid ^{4}He	Vac.	Small vol., Xe co-mag. @ RCNP Then move to TRIUMF	< 50 < 5
SNS nEDM	Superfluid ^{4}He	^{4}He	Cryo-HV, ^{3}He capture for ω, ^{3}He co-mag. with SQUIDS & dressed spins, supercond.	< 5
JPARC	Solid D_2	Vac.	Under Development	< 5
JPARC	Solid D_2	Solid	Crystal Diffraction Non-Centrosymmetric crystal	< 10?
LANL	Solid D_2	Vac.	R & D, Ramsey SOF, Hg co-mag.	~ 30

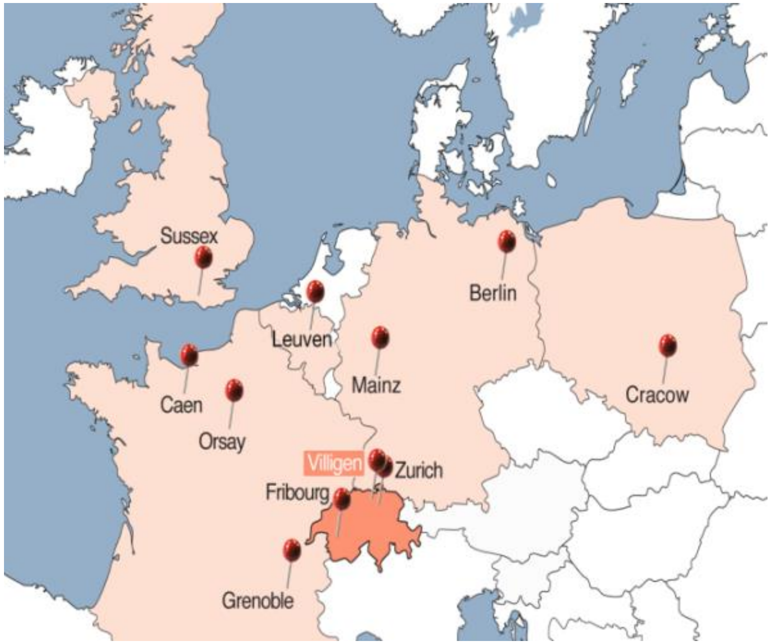
Thanks to B. Filippone

The collaboration

PSI nEDM

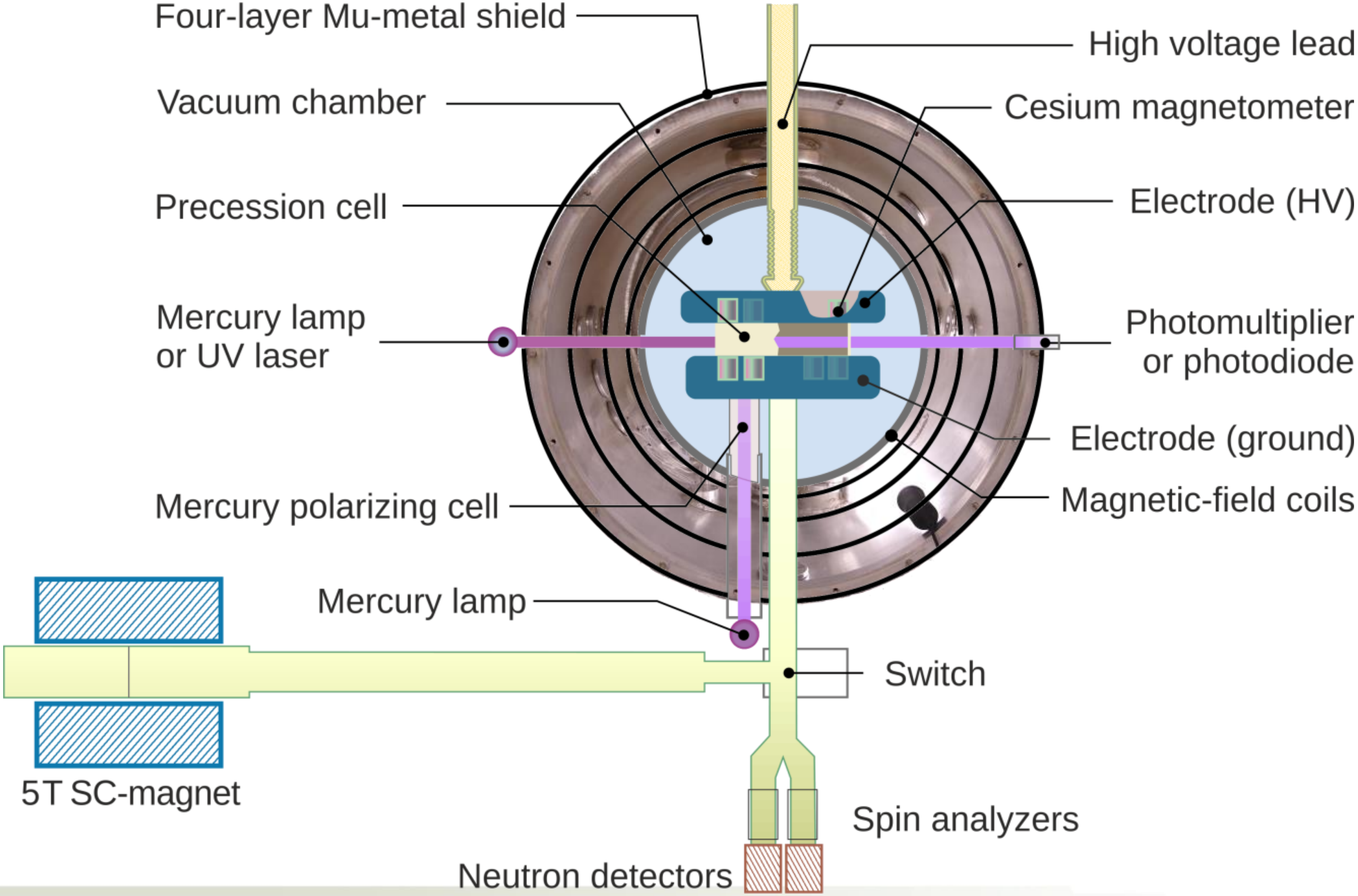
Thanks to K. Kirch, P. Schmidt-Wellenburg

- 13 Institutions
- 7 Countries
- 48 Members
- 10 PhD students

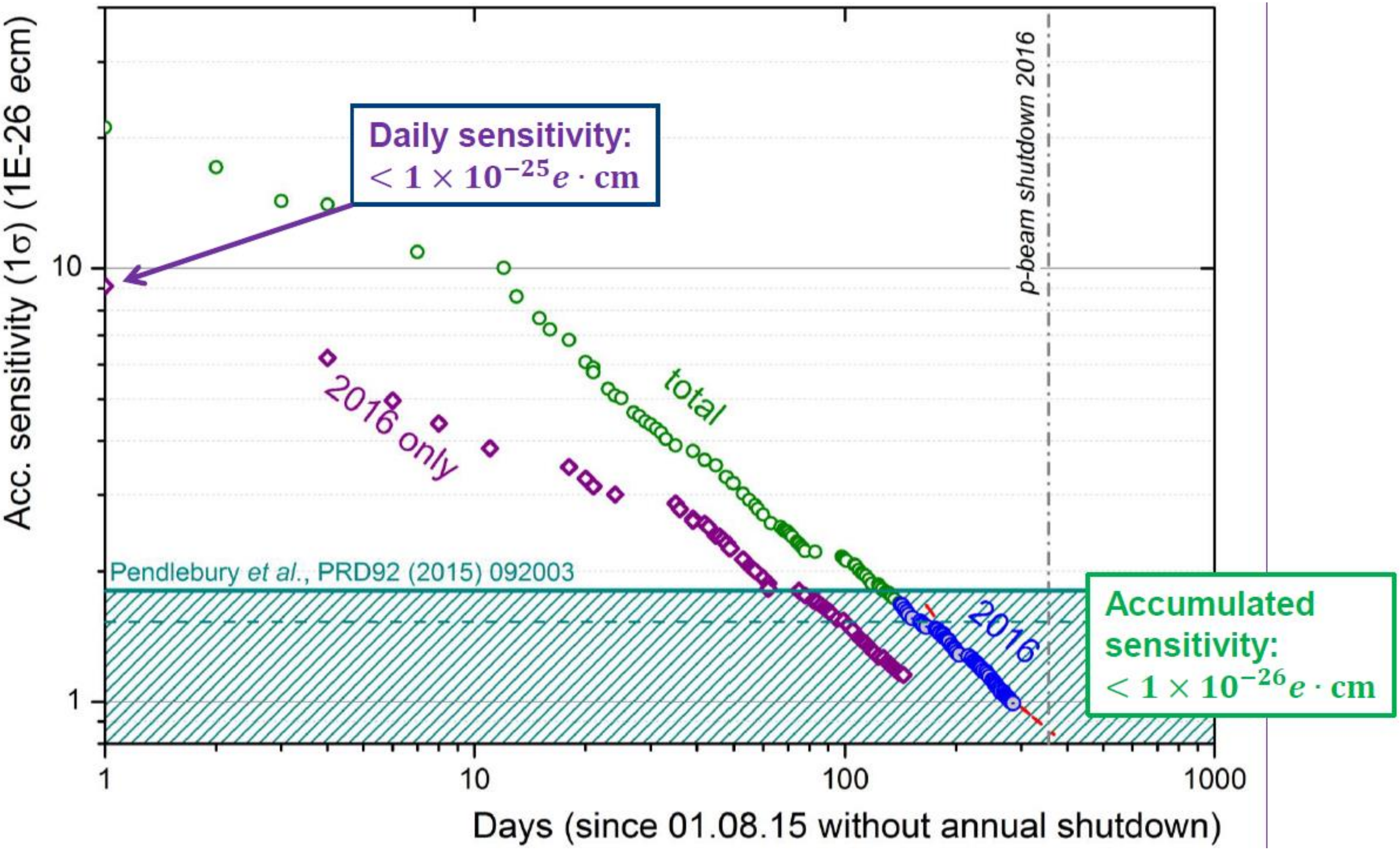


The PSI nEDM spectrometer

Thanks to K. Kirch, P. Schmidt-Wellenburg



nEDM@PSI statistical sensitivity



Daily sensitivity:
$< 1 \times 10^{-25} e \cdot \mathrm{cm}$

Accumulated sensitivity:
$< 1 \times 10^{-26} e \cdot \mathrm{cm}$

Thanks to K. Kirch, P. Schmidt-Wellenburg

Schedule of nEDM@PSI

Thanks to K. Kirch, P. Schmidt-Wellenburg

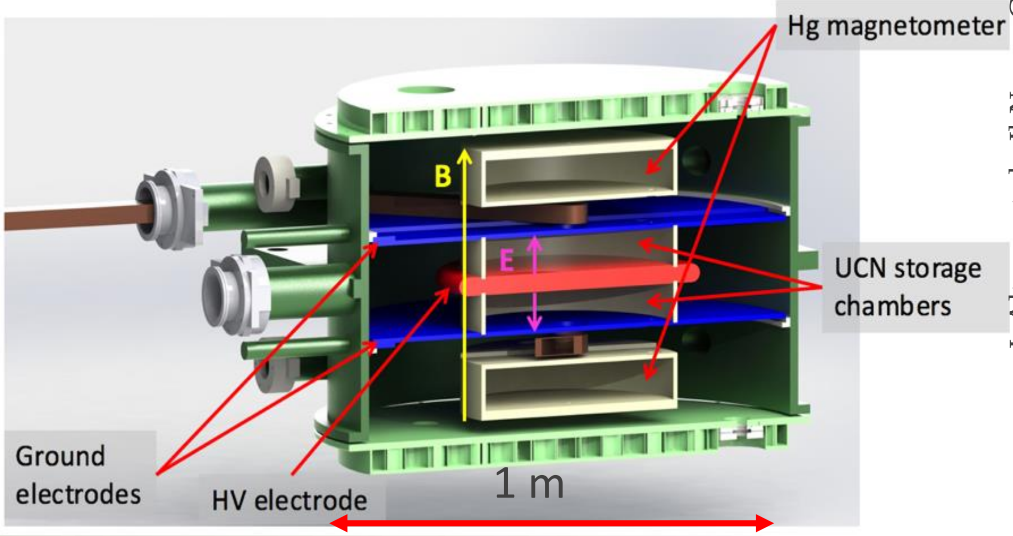
- nEDM online sensitivity per day presently approaching 1x10^{-25} *e*cm
- nEDM operation will come to an end in 2017
- n2EDM sensitivity will intrinsically be more than 5 times better than that of nEDM, plus additional gains from UCN source improvements
- n2EDM will be installed and commissioned in 2018/19
- n2EDM will start production data taking in 2020 and cut into the low 10^{-27} *e*-cm region

The TUM EDM experiment

- Contributions from Berkeley/Mainz, ILL, Jülich, LANL, Michigan, MSU, NCSU, PTB, RAL, TUM (FRM, Cluster), UIUC, Yale
- Ramsey experiment with UCN trapped at room temperature, ultimately cryogenic. Room temperature option already available.
- Double chamber with co-magnetometers as option (if needed)
- ^{199}Hg, Cs, ^{129}Xe, ^{3}He, SQUID magnetometers with sufficient precision developed

The new flagship experiment at Super-SUN UCN source at ILL!

Projected sensitivity at ILL:
Super-SUN Stage I (2018)
$\sigma = 2 \cdot 10^{-27}$ ecm
Super-SUN Stage II (2019)
$\sigma = 4.2 \cdot 10^{-28}$ ecm (100 days)

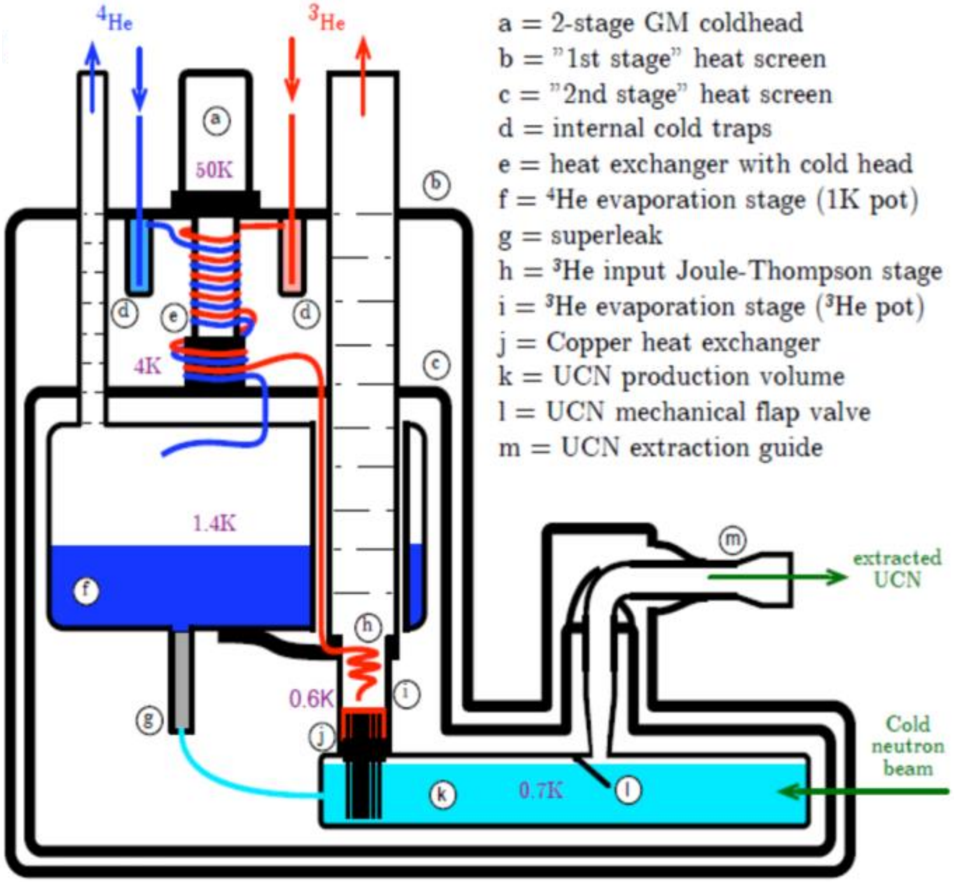


I. Altarev et al., Il Nuovo Cimento 35 C 122 (2012)

Thanks to P. Fierlinger

Super-SUN superfluid helium source:

- Stage I: 4x10^6 UCN with Fomblin spectrum (2018)
- Stage II: 2x10^7 UCN with 230 neV polarized (2019)



a = 2-stage GM coldhead
b = "1st stage" heat screen
c = "2nd stage" heat screen
d = internal cold traps
e = heat exchanger with cold head
f = ^{4}He evaporation stage (1K pot)
g = superleak
h = ^{3}He input Joule-Thompson stage
i = ^{3}He evaporation stage (^{3}He pot)
j = Copper heat exchanger
k = UCN production volume
l = UCN mechanical flap valve
m = UCN extraction guide

O. Zimmer et al., Phys. Rev. Lett. **107** (2011) 134801

Thanks to P. Fierlinger

nEDM Collaboration

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Valparaiso University

S. Baeβler
University of Virginia

S. Lamoreaux
Yale University

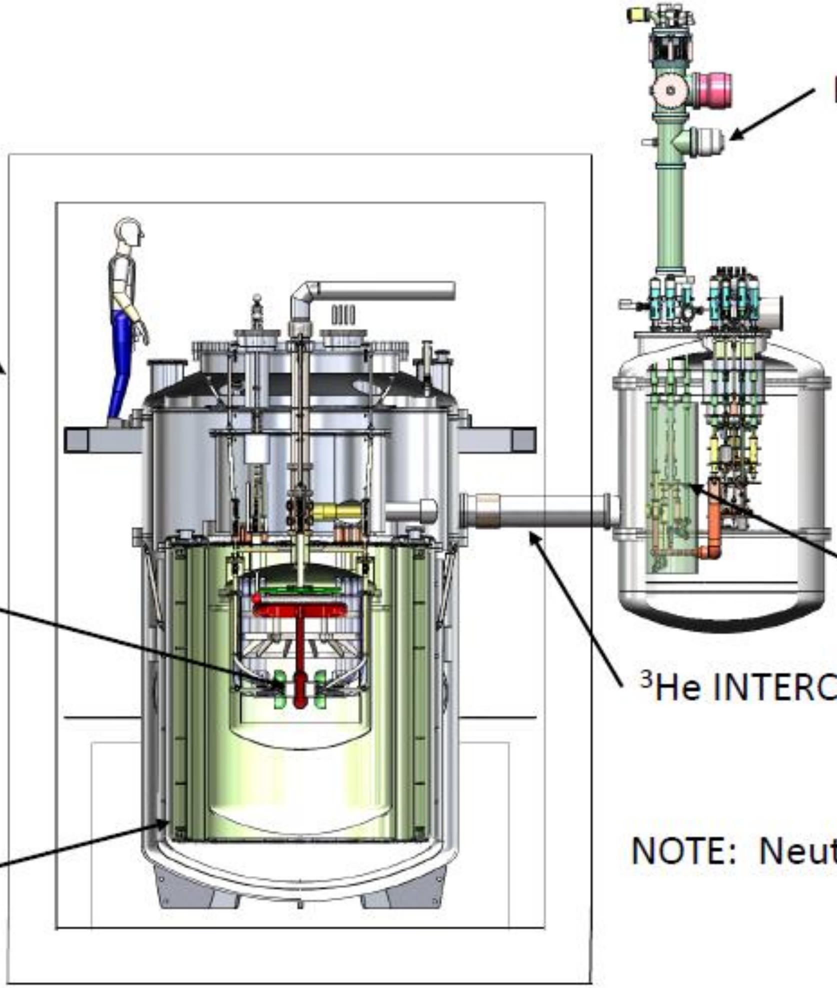
Thanks to B. Filippone

Key Features of nEDM@SNS

- Sensitivity: ~2×10^{-28} e-cm, 100 times better than existing limit
- In-situ Production of UCN in superfluid helium (no UCN transport)
- **Polarized ^{3}He co-magnetometer**
  - Also functions as neutron spin precession monitor via spin-dependent n-^{3}He capture cross section using wavelength-shifted scintillation light in the LHe
  - Ability to vary influence of external B-fields via "dressed spins"
    - Extra RF field allows synching of n & ^{3}He relative precession frequency
- Superconducting Magnetic Shield
- Two cells with opposite E-field
- Control of central-volume temperature
  - Can vary ^{3}He diffusion (mfp)- big change in geometric phase effect on ^{3}He that allows minimization of this systematic effect

Thanks to B. Filippone

nEDM @ SNS



MAGNETIC SHIELD HOUSE

POLARIZED 3He SOURCE

MEASUREMENT CELLS

INJECTION MODULE

^{3}He INTERCONNECT

MAGNET PACKAGE

NOTE: Neutron beam goes into page

Thanks to B. Filippone

Status of nEDM@SNS

- 2014-2017: Critical Component Demonstration (CCD) phase is underway
  - Build working, full-scale, prototypes of technically-challenging subsystems (can use these in the full experiment)
  - 4yr National Science Foundation funds 5.5M$ for CCD
  - Department of Energy commitment of 1.8M$/yr for CCD
- 2018-202~~0~~21: Large Sale Integration (LSI) and Conventional Component Procurement (CCP)
  - LSI – Integrate Central Detector, Magnets and ^{3}He systems
  - CCP – Includes Neutron Guide, Magnetic Shield, He Liquefier, etc
- 202~~1~~22: Begin Commissioning and Data-taking

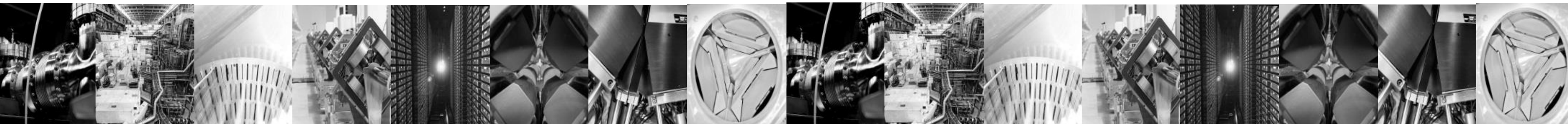
Thanks to B. Filippone

Neutron EDM collaboration

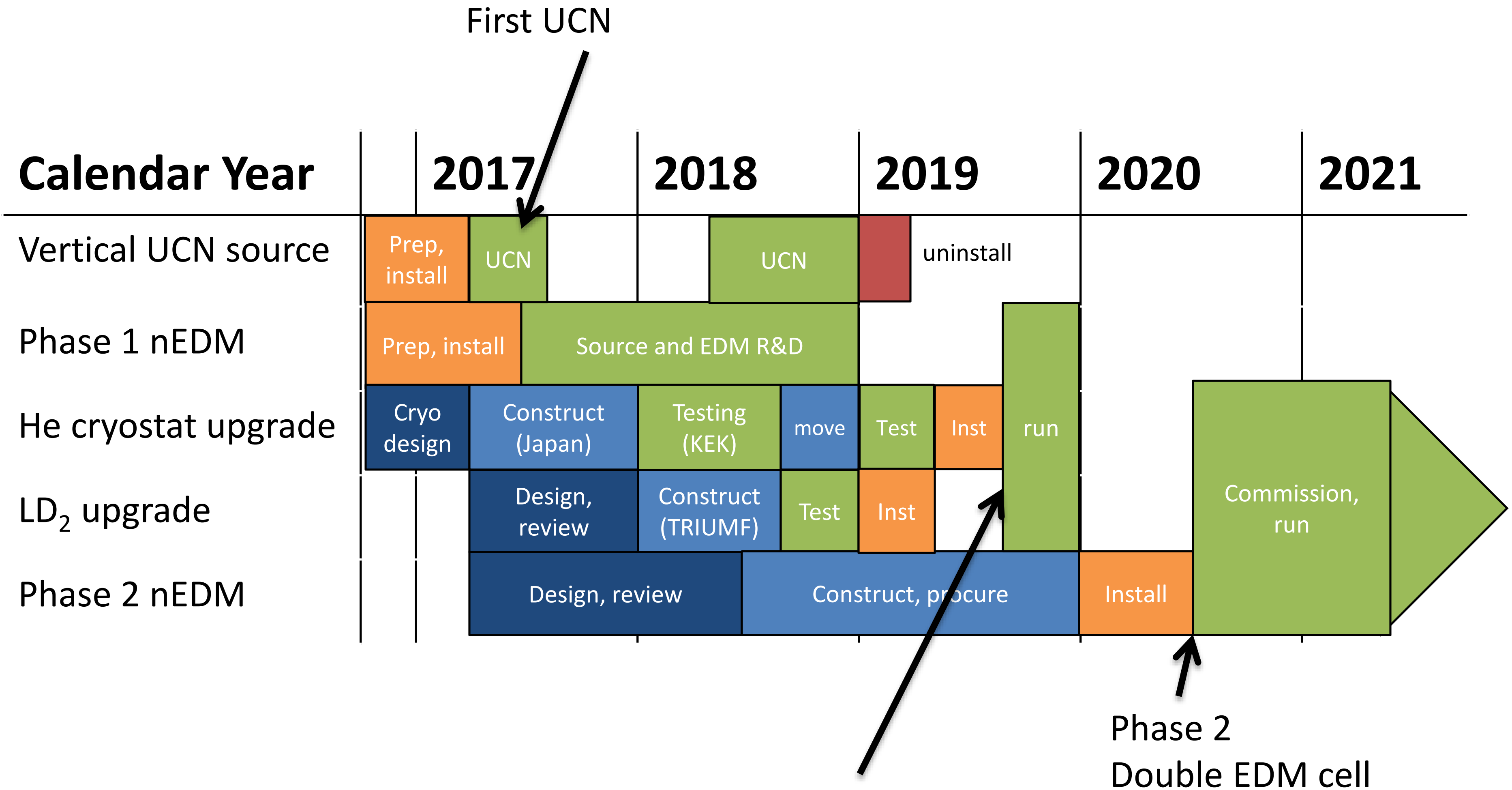
- *KEK:* T. Adachi, S. Jeong, S. Kawasaki, Y. Watanabe
- *RCNP Osaka:* K. Hatanaka, I. Tanihata, R. Matsumiya, E. Pierre (also TRIUMF)
- *UBC:* E. Altiere, D. Jones, K. Madison, E. Miller, T. Momose, J. Weinands, T. Hayamizu
- *U Winnipeg:* C. Bidinosti, B. Jamieson, R. Mammei (also TRIUMF), J. Martin
- *U Manitoba:* T. Andalib, J. Birchall, M. Gericke, M. Lang, J. Mammei, S. Page, L. Rebenitsch, S. Hansen-Romu, S. Ahmed
- *TRIUMF:* C. Davis, B. Franke, K. Katsika, T. Kikawa, A. Konaka (also UVic and Osaka U.), F. Kuchler, L. Lee (also U. Manitoba), R. Picker (also SFU), W. Ramsay, W. van Oers (also U. Manitoba), T. Lindner (also UW)
- *UNBC:* E. Korkmaz
- *SFU:* J. Sonier

We are an open collaboration and are accepting new membership requests/

33 PhD members, 7 student members



Schedule



Calendar Year		2017	2018	2019	2020	2021
Vertical UCN source	Prep, install	UCN	UCN	uninstall		
Phase 1 nEDM	Prep, install	Source and EDM R&D		run		
He cryostat upgrade	Cryo design	Construct (Japan)	Testing (KEK) move	Test Inst run		
LD_2 upgrade		Design, review	Construct (TRIUMF) Test	Inst run		
Phase 2 nEDM		Design, review	Construct, procure		Install Commission, run	Commission, run

First UCN

Phase 1
KEK apparatus

Phase 2
Double EDM cell
4-layer shield
Hg comag., dual Hg/Xe
O(10^{-27} e-cm)

Thanks to R. Picker

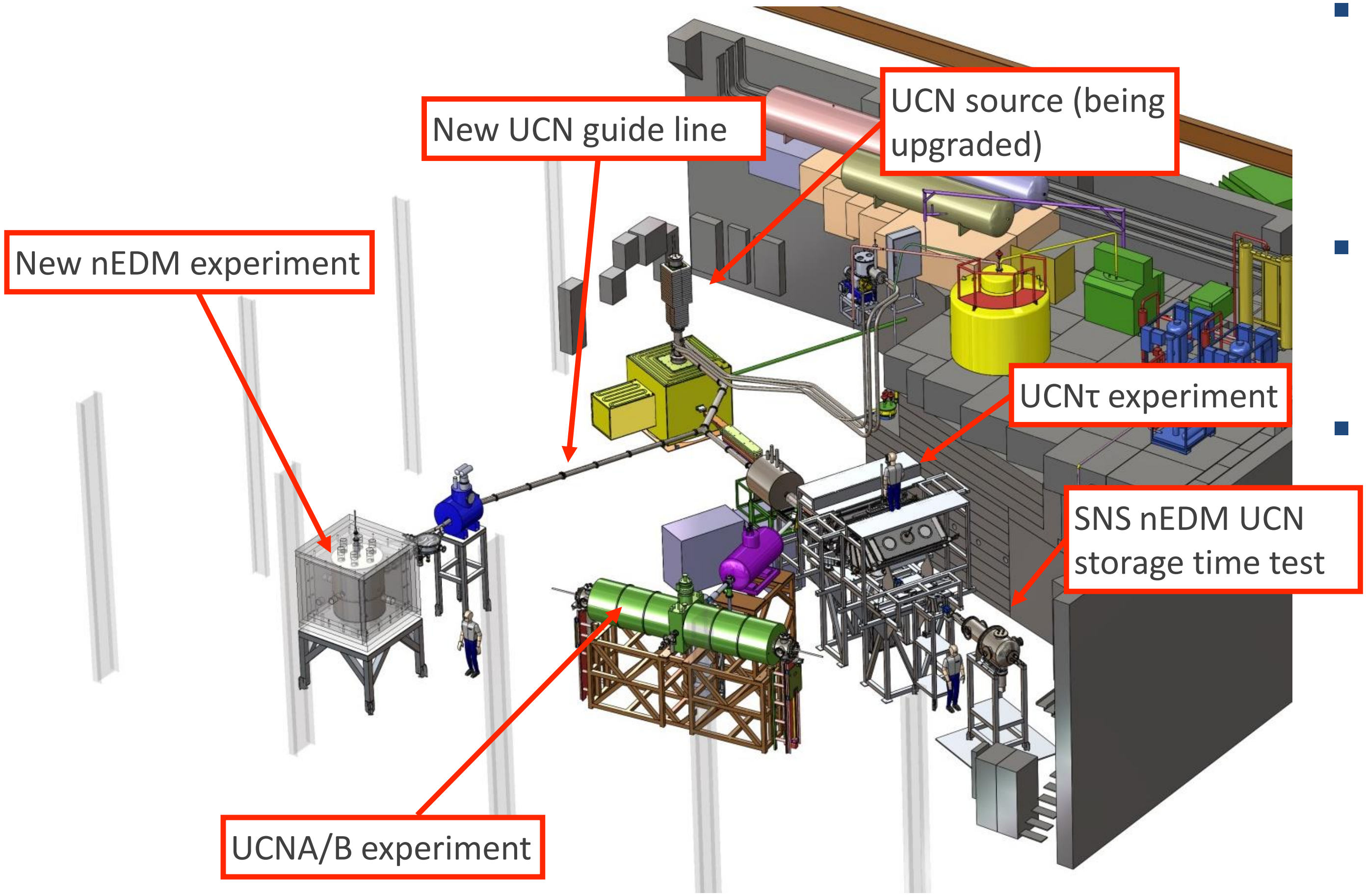
R&D Toward a new nEDM Experiment at LANL

S. Clayton, S. Currie, T. Ito, M. Makela, C. Morris, R. Pattie, J. Ramsey, A. Saunders, Z.Tang
Los Alamos National Laboratory
C.-Y. Liu, J. Long, W. Snow
Indiana University
A. Aleksandrova, J. Dadisman, B. Plaster
University of Kentucky
T. Chupp
University of Michigan
S. Lamoreaux
Yale University
E. Sharapov
Joint Institute of Nuclear Research

- Conventional room temperature Ramsey separated oscillatory field method
- Existing LANL SD_2 UCN source
- Sensitivity: O(10^{-27} e-cm)
- Relatively fast implementation and low cost

Thanks to T. Ito

Area B layout with proposed nEDM Experiment



- UCN density achievable with the previous source was already competitive with PSI.
- The new UCN source is about to be commissioned.
- If the expected performance (x 5-10) is achieved, it could provide a sensitivity of a few x 10^{-27} e–cm with existing technology.

Thanks to T. Ito

^{199}Hg collaboration

The Team

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Brent Graner*

Scientific Glassblower
Eric Lindahl

Faculty
B. R. Heckel

Primary support from NSF
* Supported by DOE Office of Nuclear Science

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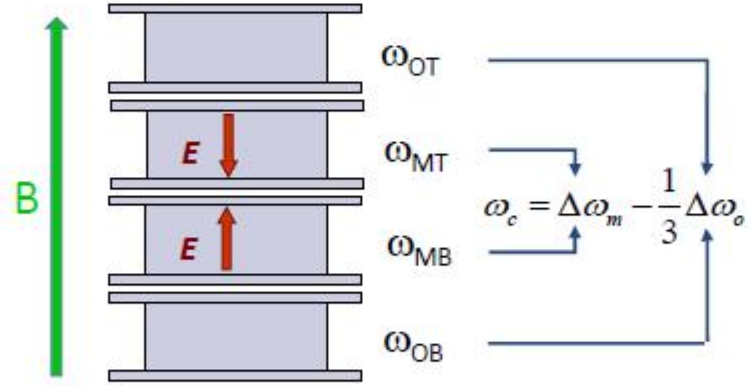
B. Klipstein (JPL)
W. C. Griffith (U. Sussex)
M. D. Swallows (AOSense)
T. H. Loftus (AOSense)

CENPA
Center for Experimental Nuclear Physics and Astrophysics

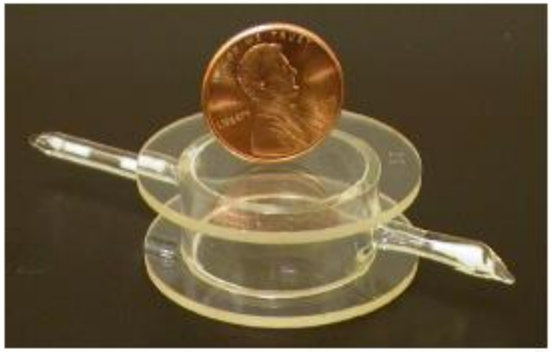
Thanks to B. Heckel

Current EDM Experiment

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



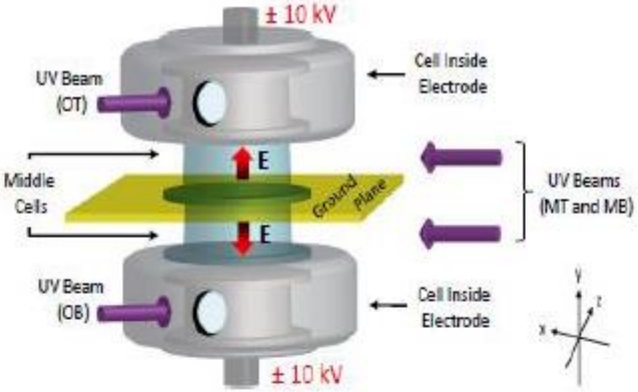
$$\omega_c = \Delta\omega_m - \frac{1}{3}\Delta\omega_o$$



T_2 Spin Relaxation: 300 - 600 sec

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

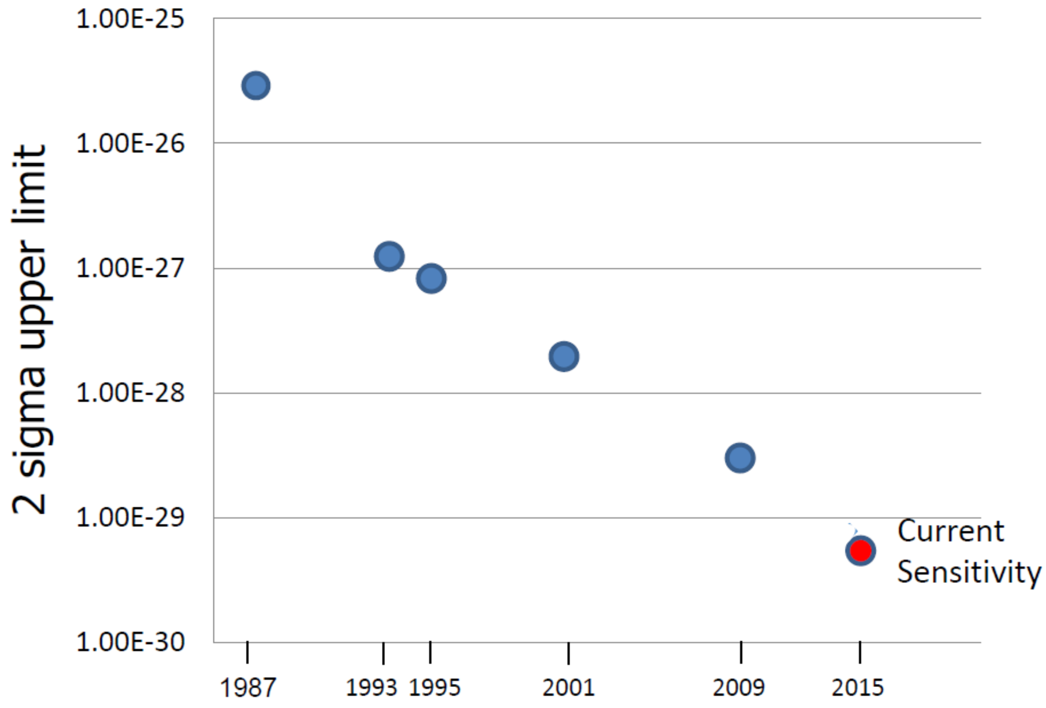
Cancels up to 2nd order gradient noise
Same EDM sensitivity as Middle Difference



Thanks to B. Heckel

^{199}Hg EDM search

Final EDM Data Set



$$d_{Hg} = (2.20 \pm 2.75_{stat} \pm 1.59_{sys}) \times 10^{-30} e \cdot cm$$

$$|d_{Hg}| < 7.5 \times 10^{-30} e \cdot cm$$

at 95% C.L.

(B. Graner, et al, PRL 116, 161601, 2016)

SM limit ~ 2045

Expect factor of 2-3 improvement with existing apparatus

CENPA Center for Experimental Nuclear Physics and Astrophysics

Thanks to B. Heckel

The HeXe experiment

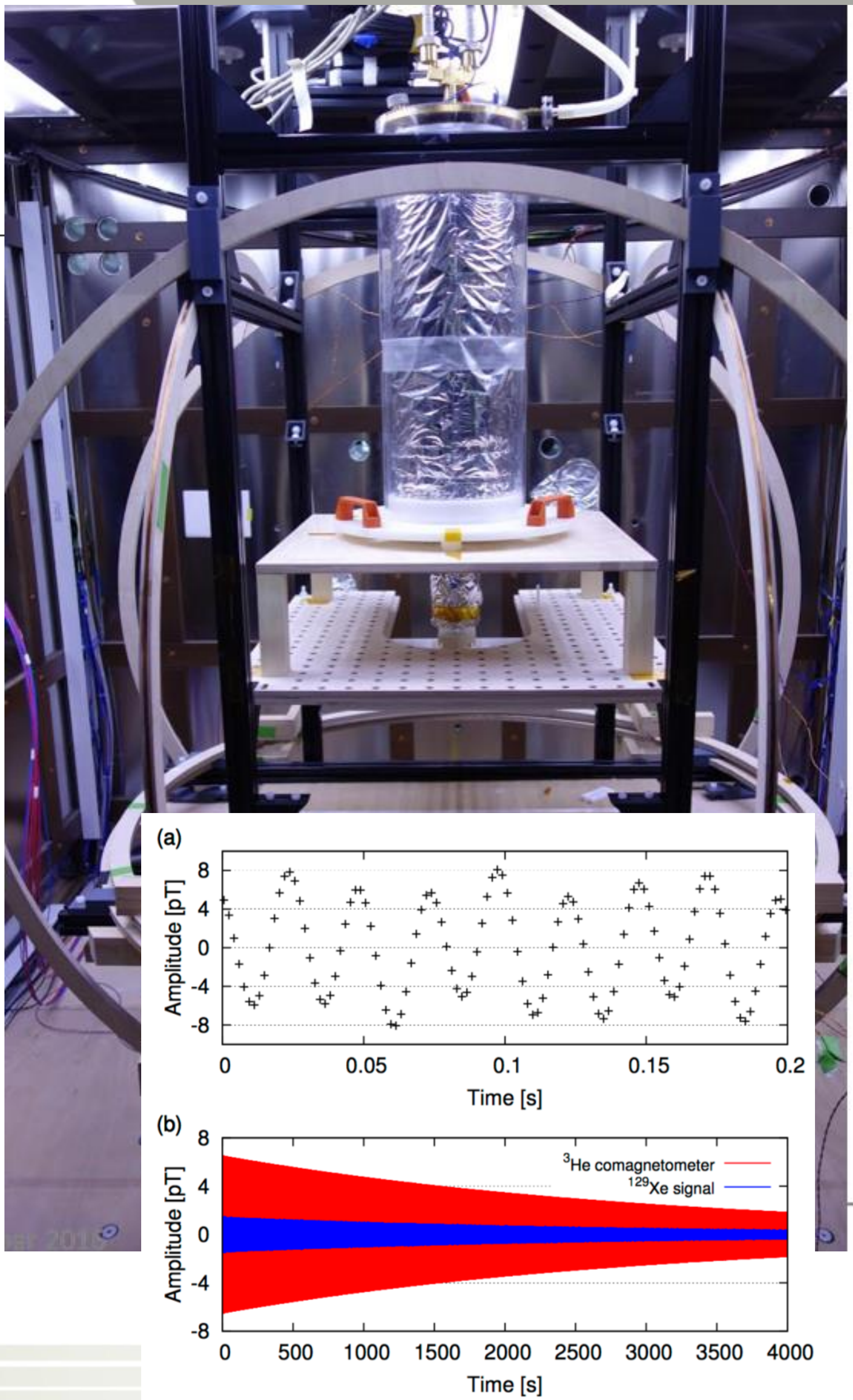
Collaboration of Jülich, MSU, PTB, TU Munich, U.Mich.

- SEOP polarized ^{3}He and ^{129}Xe simultaneously placed in a cell
- Coherent precession of spins causes rotating magnetic dipole field
- Detection using SQUIDs
- fT noise vs. ~ 10^4 fT signal
- Cylindrical cells with Si electrodes
- projected EDM sensitivity:

-10^3 s T_2* while 5 kV applied to cell

-Investigation of systematics ongoing

-Goal with current setup: < 10^{-29} ecm



Thanks to P. Fierlinger

MIXe$\vec{d}$

Measurement and Investigation of the Xenon-129 electric dipole moment

university of groningen

J.O. Grasdijk

K. Jungmann

L. Willmann

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U

M. Doll

W. Heil

S. Karpuk

Y. Sobolev

K. Tullney

S. Zimmer

RUPRECHT-KARLS-UNIVERSITÄT HEIDELBERG

F. Allmendinger

U. Schmidt

JÜLICH FORSCHUNGSZENTRUM

H.-J. Krause

A. Offenhäusser

FOM DFG PRiSMA

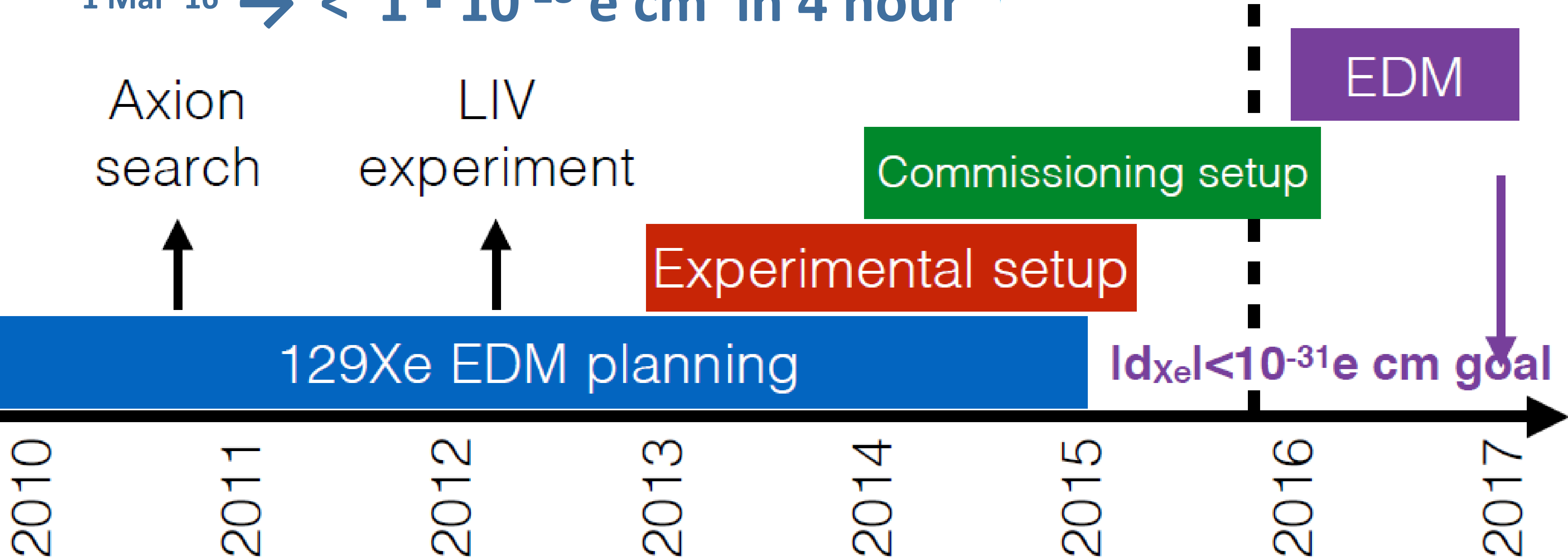
Progress

- measure with E field
- realistic expectation
  - δϕ ≈ 10 μrad in a day
  - δυ ≈ 18pHz in a day

$< 4.1 \times 10^{-27}$ e-cm M. Rosenberry et al PRL (2001)

$$|d_{Xe}| < \frac{\pi\hbar}{2E\left(\gamma_{He}/\gamma_{Xe}\right)}\delta\nu$$

1 Mar '16 → $< 1 \cdot 10^{-28}$ e cm in 4 hour



Axion search

LIV experiment

EDM

Commissioning setup

Experimental setup

129Xe EDM planning

$|d_{Xe}|<10^{-31}$e cm goal

Thanks to K. Jungmann

Progression of the Radium EDM Search

- 2006 – Atomic transitions identified and studied;
- 2007 – Magneto-optical trap (MOT) of radium realized;
- 2010 – Optical dipole trap (ODT) of radium realized;
- 2011 – Atoms transferred to the measurement trap;
- 2012 – Spin precession of Ra-225 in ODT observed;
- 2014 – First measurements of EDM of Ra-225;
- 2015 - Sensitivity improved by a factor of 36.

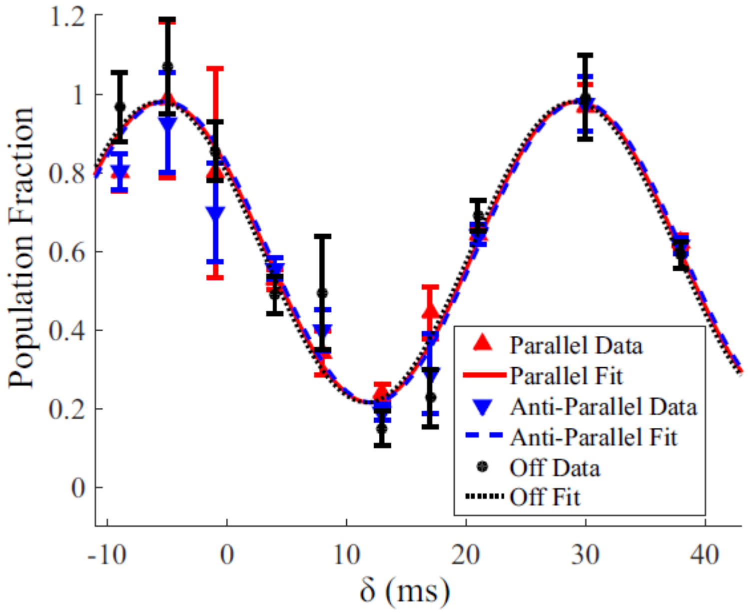
N.D. Scielzo *et al.*, PRA Rapid **73**, 010501 (2006)

J.R. Guest *et al.*, PRL **98**, 093001 (2007)

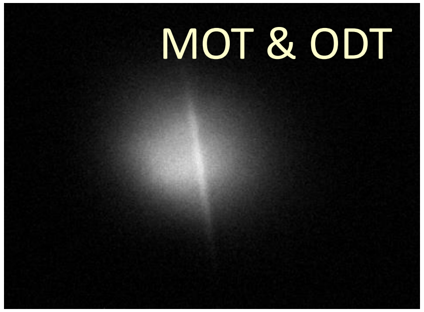
R.H. Parker *et al.*, PRC **86**, 065503 (2012)

R.H. Parker *et al.*, PRL 114, 233002 (2015)

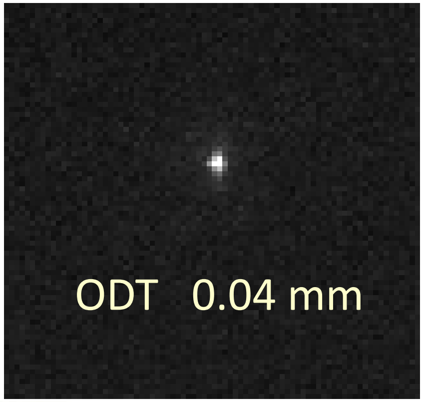
M. Bishof *et al.*, PRC **94**, 025501 (2016)



Sideview



Head-on view

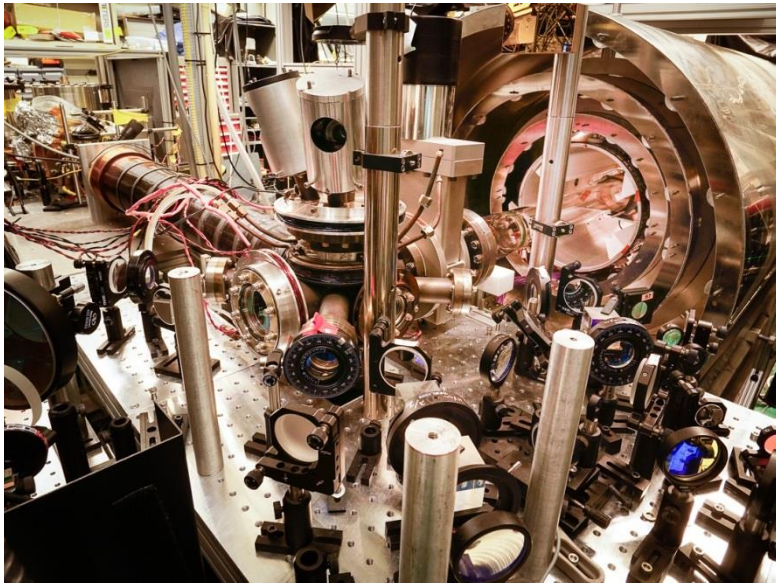


The Search for the Electric Dipole Moment of Radium-225

ANL/Kentucky/MSU/USTC

Radium Upper Limit (ANL 2016)	1.4×10^{-23} e-cm
Radium/Blue Slower (3 year)	10^{-26} e-cm
New Radium Source (with FRIB)	10^{-28} e-cm

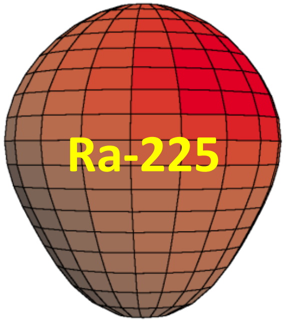
R. Parker *et al.* PRL (2015), M. Bishof *et al.* PRC (2016)



Due to its nuclear octupole deformation, radium-225 is expected have an EDM of about 100 to 1000 times greater than that of other species.

BSM parameter	C_T	$g_\pi^{(0)}$	$g_\pi^{(1)}$	$đ_n$ (e cm)
Current limits (95% CL)	2×10^{-6}	8×10^{-9}	1.2×10^{-9}	1.2×10^{-22}
Improvement Factor (over current limit)				
Current + ^{225}Ra [10^{-25} e cm]	40	2	1.2	20
Current + ^{225}Ra [10^{-26} e cm]	200	8	4	60

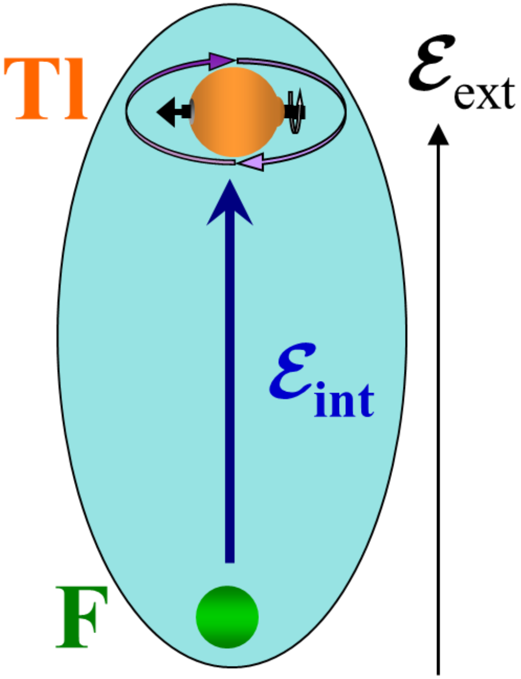
T. Chupp, M. Ramsey-Musolf, PRC (2015)



CeNTREX:
Cold molecule Nuclear Time-Reversal EXperiment

(D. DeMille [Yale], D. Kawall [UMass], S. Lamoreaux [Yale], T. Zelevinsky [Columbia])

New TlF molecule-based search for nuclear Schiff moment



complementary to ^{199}Hg and n EDMs:
^{205}Tl primarily sensitive to *proton* EDM & θ QCD

Similar to *e*-EDM, enhanced by intra-molecular E-field
⇒spin precession rate due to Schiff moment
~10^4× larger than in ^{199}Hg atoms
for similar underlying physics contributions

+ internal co-magnetometer for systematics control

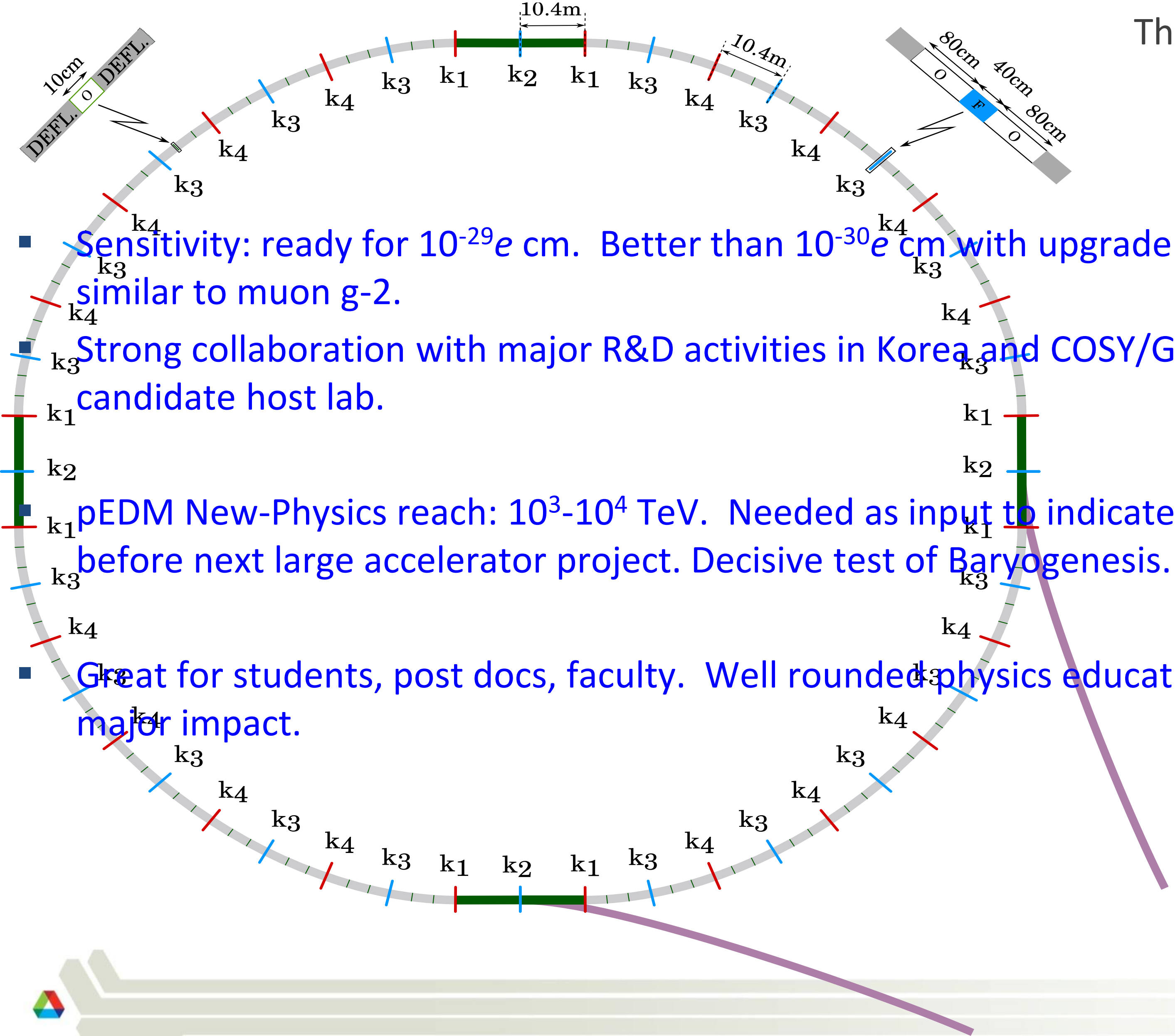
GOAL: use molecular "enhancement" + cycling detection & cooling to obtain improved sensitivity to ***hadronic*** CP-violating interactions

1st generation target (est. ~2022): 30x improvement vs. ^{199}Hg

Thanks to D. DeMille

Storage ring Proton EDM experiment

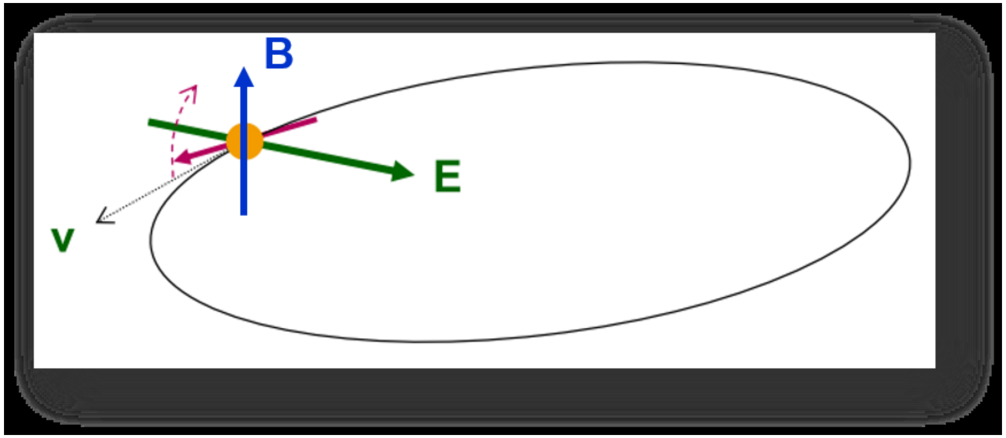
Thanks to Y. Semertzidis



- Sensitivity: ready for $10^{-29}e$ cm. Better than $10^{-30}e$ cm with upgrade. Method/technique similar to muon g-2.
- Strong collaboration with major R&D activities in Korea and COSY/Germany. CERN is a candidate host lab.
- pEDM New-Physics reach: 10^3-10^4 TeV. Needed as input to indicate New-Physics level before next large accelerator project. Decisive test of Baryogenesis.
- Great for students, post docs, faculty. Well rounded physics education, opportunities for major impact.

Deuteron EDM (JEDI Collaboration at COSY)

- Ions have the advantage of no Schiff shielding
- 2017:Use COSY ring as proof of principle and make initial measurement of d EDM
- 10^{-19}-10^{-20} e-cm
- 2019: Conceptual design for dedicated EDM ring at 10^{-29} e-cm
- For deuteron, both E and B fields required for "frozen spin" condition
- Align spin along direction of flight at magic momentum
- Search for time development of vertical polarization



Tune for magic energy

Thanks to Frank Rathmann

EDM measurements for multiple systems are necessary

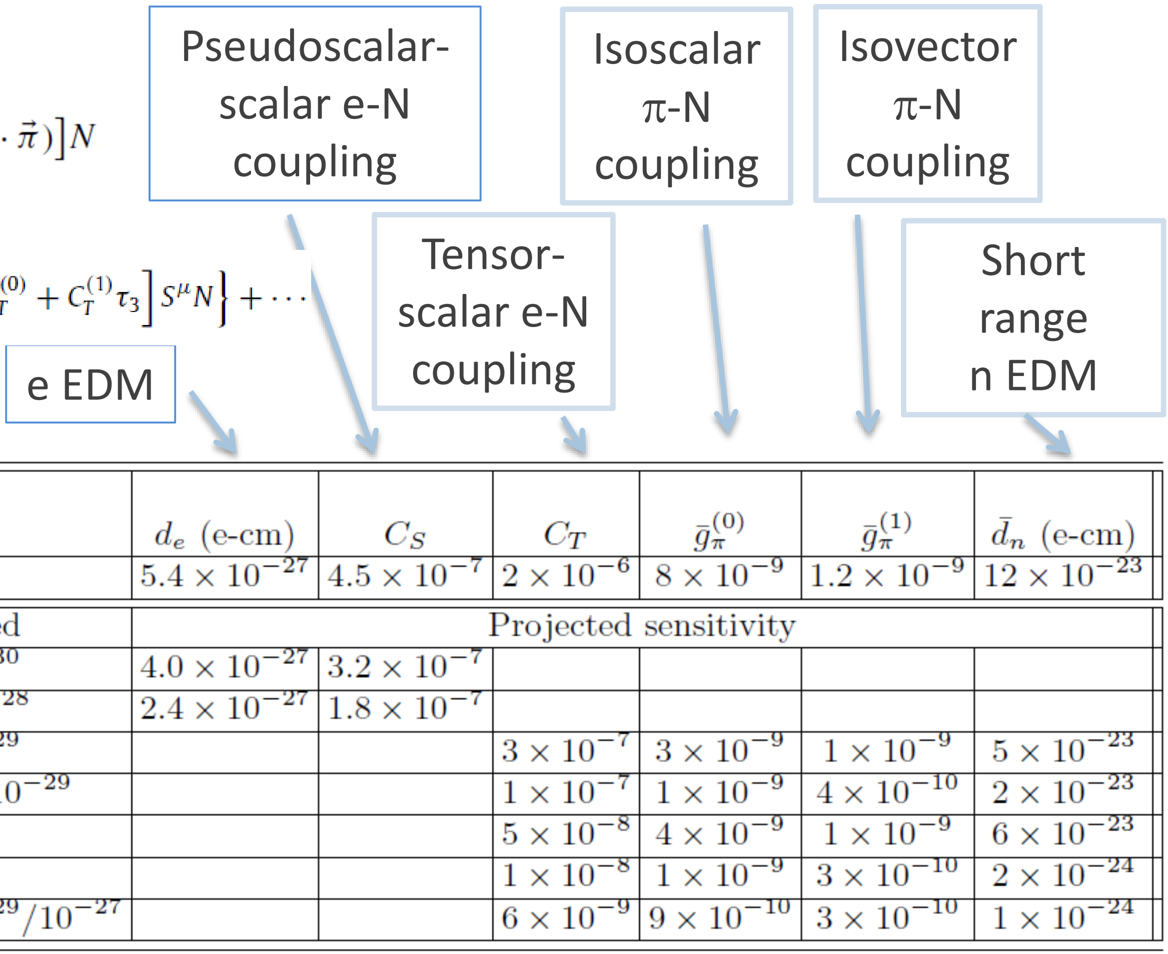
Global model independent analysis: **6 parameters**

TVPV π-N interaction:

$$\mathcal{L}_{\pi NN}^{\mathrm{TVPV}} = \bar{N}\left[\bar{g}_\pi^{(0)}\vec{\tau}\cdot\vec{\pi} + \bar{g}_\pi^{(1)}\pi^0 + \bar{g}_\pi^{(2)}\left(3\tau_3\pi^0 - \vec{\tau}\cdot\vec{\pi}\right)\right]N$$

TVPV e-N interaction:

$$\mathcal{L}_{eN}^{\mathrm{eff}} = -\frac{G_F}{\sqrt{2}}\left\{\bar{e}i\gamma_5 e\,\bar{N}\left[C_S^{(0)} + C_S^{(1)}\tau_3\right]N - 8\,\bar{e}\sigma_{\mu\nu}e\,v^\nu\bar{N}\left[C_T^{(0)} + C_T^{(1)}\tau_3\right]S^\mu N\right\} + \cdots$$



e EDM

Pseudoscalar-scalar e-N coupling

Tensor-scalar e-N coupling

Isoscalar π-N coupling

Isovector π-N coupling

Short range n EDM

			d_e (e-cm)	C_S	C_T	$\bar{g}_\pi^{(0)}$	$\bar{g}_\pi^{(1)}$	$\bar{d}_n$ (e-cm)
Current Limits (95%)			5.4×10^{-27}	4.5×10^{-7}	2×10^{-6}	8×10^{-9}	1.2×10^{-9}	12×10^{-23}
System	Current (e-cm)	Projected	Projected sensitivity					
ThO	5×10^{-29}	5×10^{-30}	4.0×10^{-27}	3.2×10^{-7}				
Fr		$d_e < 10^{-28}$	2.4×10^{-27}	1.8×10^{-7}				
^{129}Xe	3×10^{-27}	3×10^{-29}			3×10^{-7}	3×10^{-9}	1×10^{-9}	5×10^{-23}
Neutron/Xe	2×10^{-26}	$10^{-28}/3\times10^{-29}$			1×10^{-7}	1×10^{-9}	4×10^{-10}	2×10^{-23}
Ra		10^{-25}			5×10^{-8}	4×10^{-9}	1×10^{-9}	6×10^{-23}
”		10^{-26}			1×10^{-8}	1×10^{-9}	3×10^{-10}	2×10^{-24}
Neutron/Xe/Ra		$10^{-28}/3\times10^{-29}/10^{-27}$			6×10^{-9}	9×10^{-10}	3×10^{-10}	1×10^{-24}

T. Chupp and M. Ramsey-Musolf, PRC 91 (2015) 035502

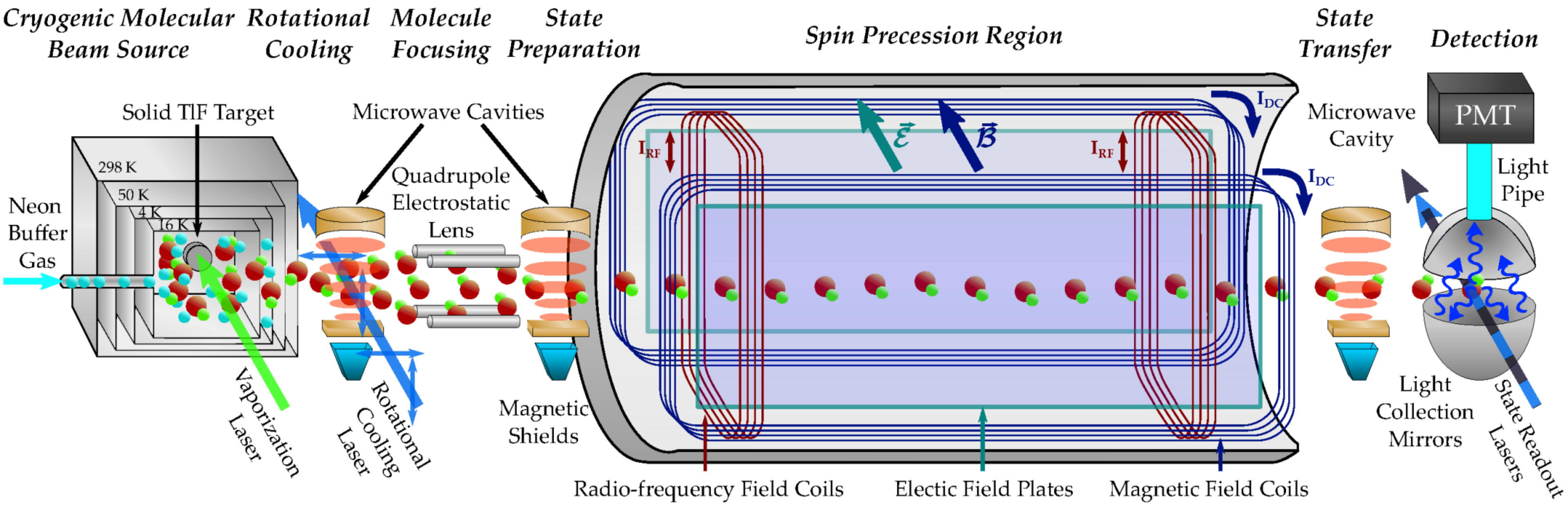
Summary

- Many new technologies are being developed
- My expectation
  - New best sensitivities (n, d, Ra, Xe, Hg, ThO, YbF, HfF^+)within 1-2 years
  - Factor of 5-10 improvement (μ, n, Ra, Xe, Rn, ThO, YbF, HfF^+/ThF^+) within 5 years
  - Factor of 50-100 improvement (n, p, d, Ra, Rn, TlF, ThO, YbF, ThF^+) within 10 years

Extra slides

CENTREX 1st generation proposed schematic

Incorporates many methods from ACME & laser cooling experiments
(slow molecular beam, rotational cooling, cycling fluorescence for detection, etc.)

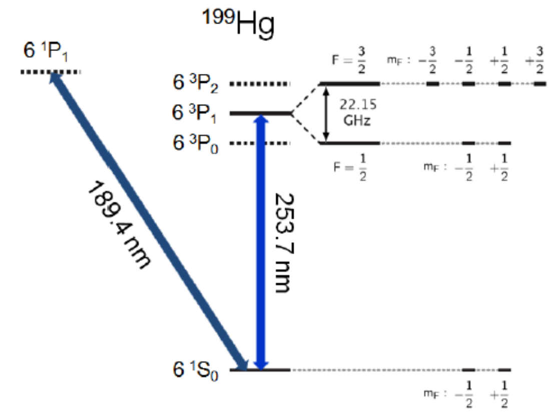


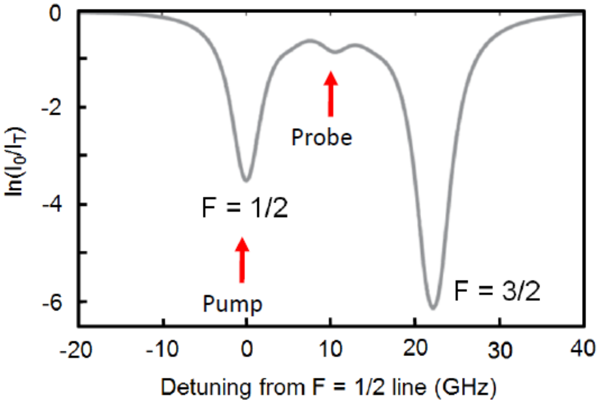
Design/construction phase
recently funded by Templeton Foundation & Heising-Simons Foundation

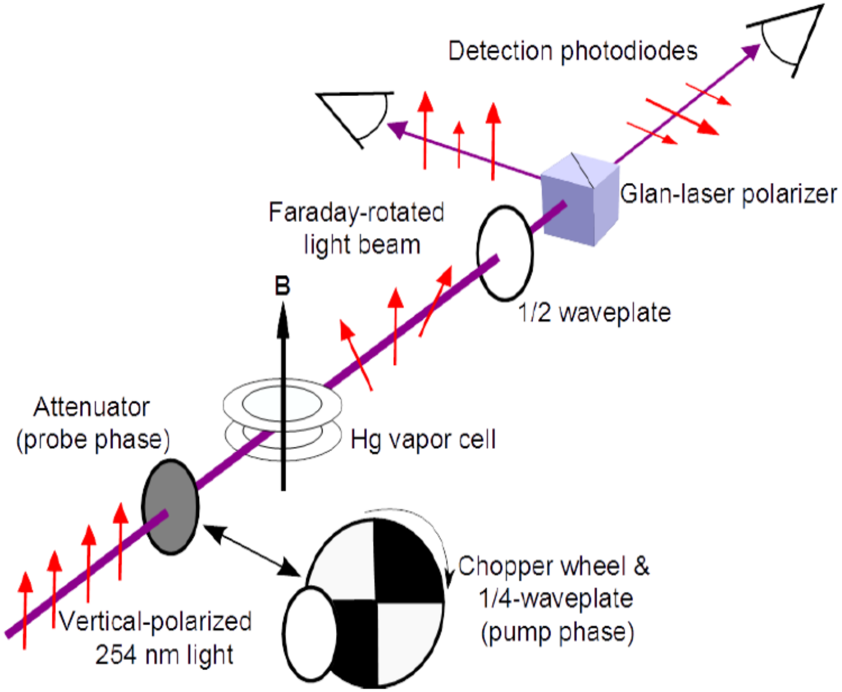
Future generations of CENTREX will also incorporate
--transverse laser cooling for increased flux
--laser slowing and/or trapping for increased interaction time

Thanks to D. DeMille

Faraday Rotation Detection







Thanks to B. Heckel

YbF Electron EDM Imperial College

Increasing the number of molecules in the experiment

Put more molecules into the initial state

- Achieved x 9 population in initial state

Detect the molecules better at the final stage

- Achieved x 24 increase

Total signal increase (expected): 216

- Test EDM run to start late in 2016
- Expected sensitivity 2 x 10^{-29} e-cm 90% CL
- Current limit $|d_e|<9 \times 10^{-29}$ e-cm 90% CL
- Goal: intense slow beams 10^{-30} e-cm/day

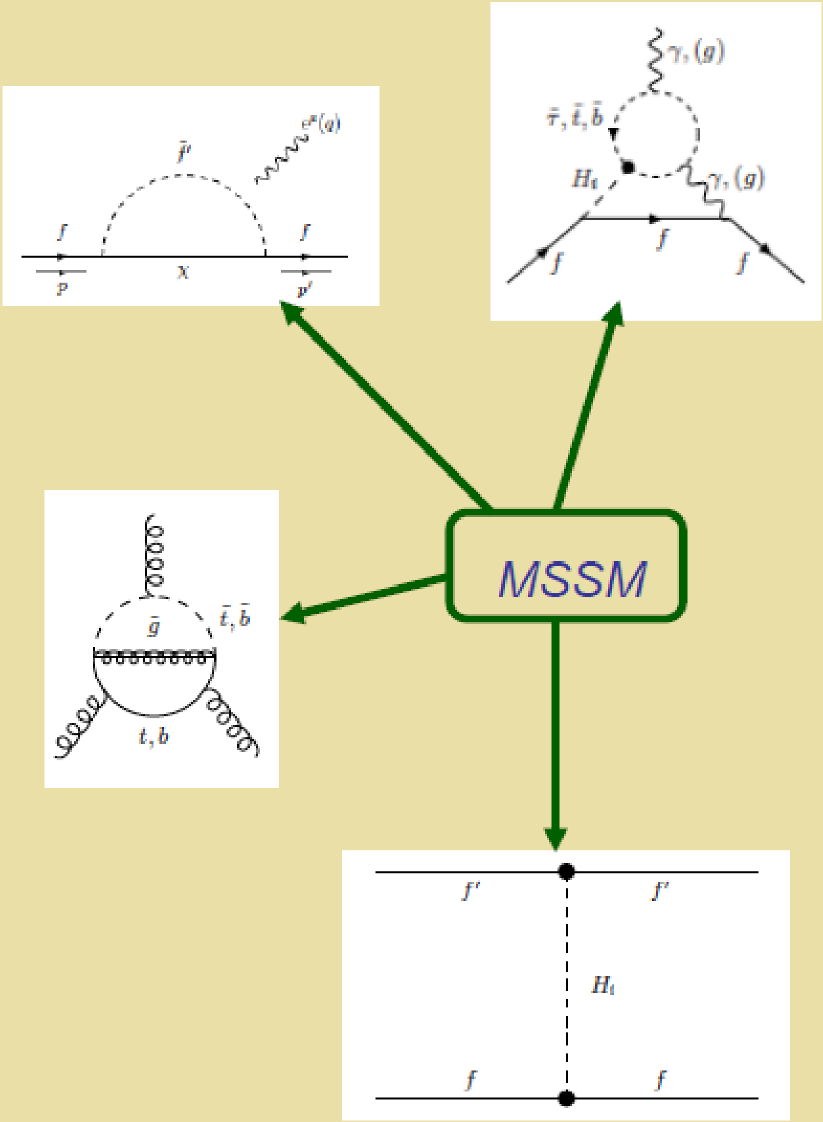
Thanks to E Hinds

EDM: γff

CEDM: gff

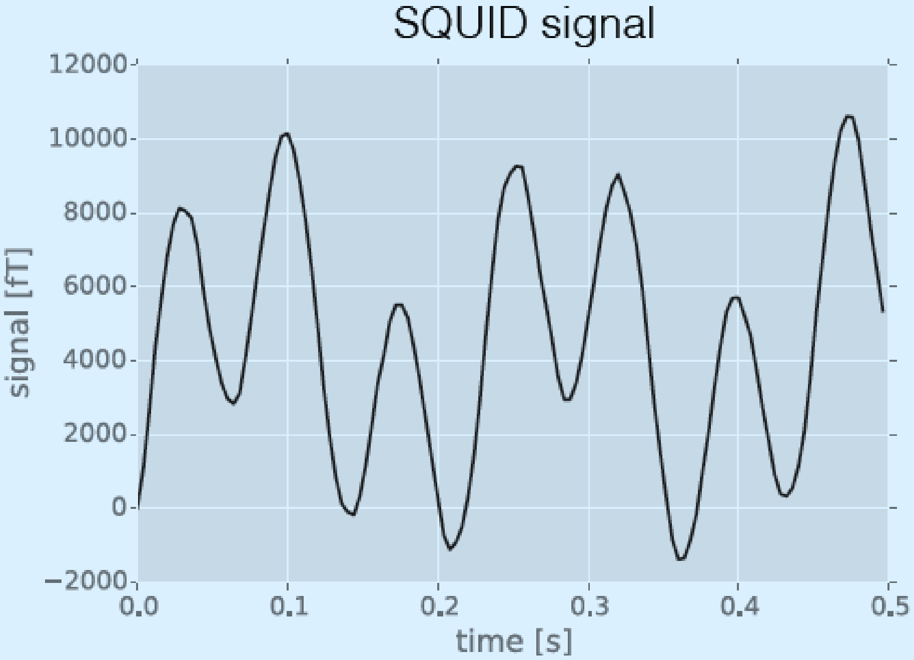
Weinberg ggg:

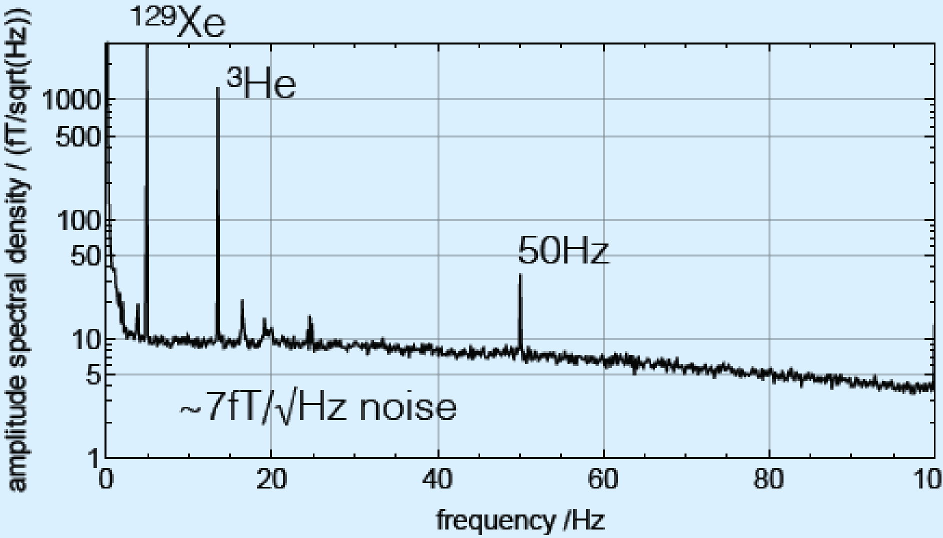
Four fermion


MSSM

^{3}He/^{129}Xe Measurement

October 2015



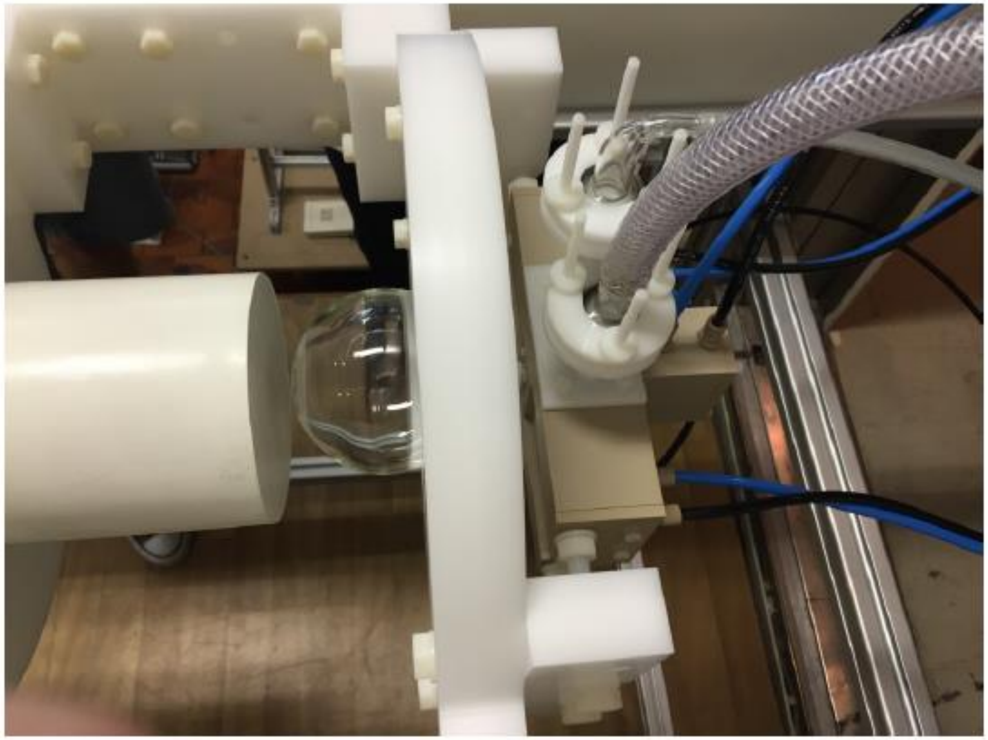


- polarized ^{3}He and ^{129}Xe transported from Mainz by car
- T_1 (^{129}Xe) transport cell ~7h

M. Repetto et al, J Mag. Reson. 252, 163(2015)

Thanks to K. Jungmann

Experiment

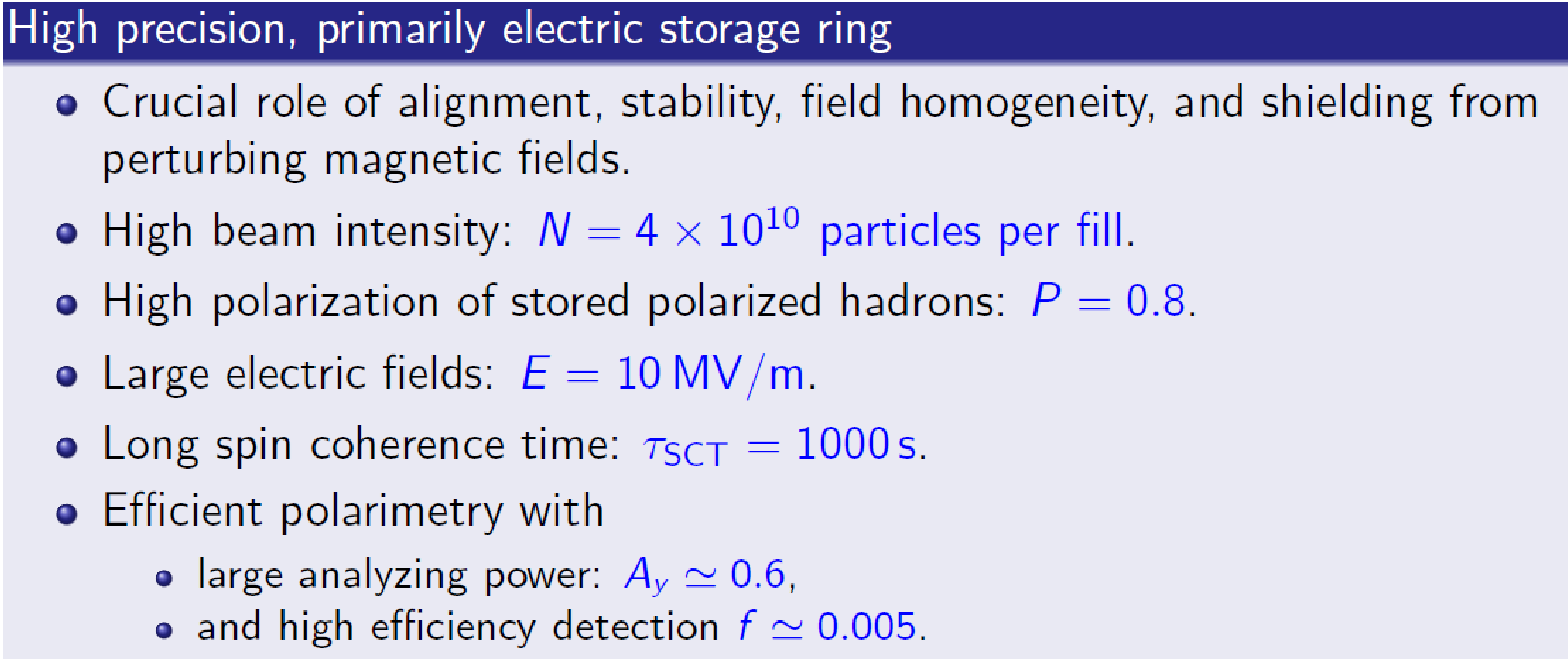


$$\delta \mathrm{d} = \frac{\hbar}{\mathrm{EP}\epsilon\sqrt{\tau \mathrm{TN}}}$$

E	2kV/cm
P	50%
ϵ	10^{-5}
τ	several 10^{4}s
T	~month
N	10^{22}

- spin polarized ^{3}He and ^{129}Xe loaded in cell
- spin precession measured with SQUIDs

Storage ring proton EDM experiment



High precision, primarily electric storage ring

- Crucial role of alignment, stability, field homogeneity, and shielding from perturbing magnetic fields.
- High beam intensity: $N = 4 \times 10^{10}$ particles per fill.
- High polarization of stored polarized hadrons: $P = 0.8$.
- Large electric fields: $E = 10\,\mathrm{MV/m}$.
- Long spin coherence time: $\tau_{\mathrm{SCT}} = 1000\,\mathrm{s}$.
- Efficient polarimetry with
  - large analyzing power: $A_y \simeq 0.6$,
  - and high efficiency detection $f \simeq 0.005$.

- $1\mathrm{x}10^{-29}$ e-cm achievable, statistically

"Magic" momentum

Spin precession frequency of particle *relative* to direction of flight:

$$\begin{aligned}\vec{\Omega} &= \vec{\Omega}_{\text{MDM}} - \vec{\Omega}_{\text{cyc}} \\ &= -\frac{q}{\gamma m}\left[G\gamma\vec{B}_{\perp} + (1+G)\vec{B}_{//} - \left(G\gamma - \frac{\gamma}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right].\end{aligned}$$

$\Rightarrow$ $\vec{\Omega} = 0$ **called frozen spin, because momentum and spin stay aligned.**

- In the absence of magnetic fields ($B_{\perp} = \vec{B}_{//} = 0$),

$$\vec{\Omega} = 0, \text{ if } \left(G\gamma - \frac{\gamma}{\gamma^2-1}\right) = 0.$$

$$G - \frac{1}{\gamma^2-1} = 0 \Leftrightarrow G = \frac{m^2}{p^2} \quad \Rightarrow \quad \boxed{p = \frac{m}{\sqrt{G}} = 700.740\ \text{MeV c}^{-1}}$$

YbF Electron EDM
Signal:noise increases (√signal)

Imperial College

Upgrade	Increase in signal:noise	Status
Pumping	2.2	Achieved
Optics	2	Achieved
Longer interaction time	1.5	Achieved
Shorter rf pulses	1.25	Achieved
Detection	3.5	In progress
Total	28.9	

- Test EDM run to start late in 2016
- Expected d_e sensitivity 2 x 10^{-29} e.cm (90% conf.)
- Current limit $|d_e|<9 \times 10^{-29}$ e.cm (90% conf.)
- Longer term: intense slow beams ~ 10^{-30} e-cm/day

Thanks to E Hinds

Expected achievable statistical sensitivity with the current LANL UCN source **without the upgrade**

Parameters	Values
E (kV/cm)	12.0
N (per cell)	14,700
T_{free} (s)	180
T_{duty} (s)	300
α	0.80
σ/day/cell (10^{-26} e-cm)	**9.3**
σ/day (10^{-26} e-cm) (for double cell)	**6.5**
σ/year* (10^{-27} e-cm) (for double cell)	**3.4**
90% C.L./year* (10^{-27} e-cm) (for double cell)	**5.6**

This estimate is based on the following:

- The estimate for N is based on the results of the UCN storage test performed in January 2016 and **is not assuming the source upgrade.**
- The estimate for E, T_{free}, T_{duty}, and α is based on what has been achieved by other experiments.

*** "year" = 365 live days. In practice it will take 3+ years to achieve this.**

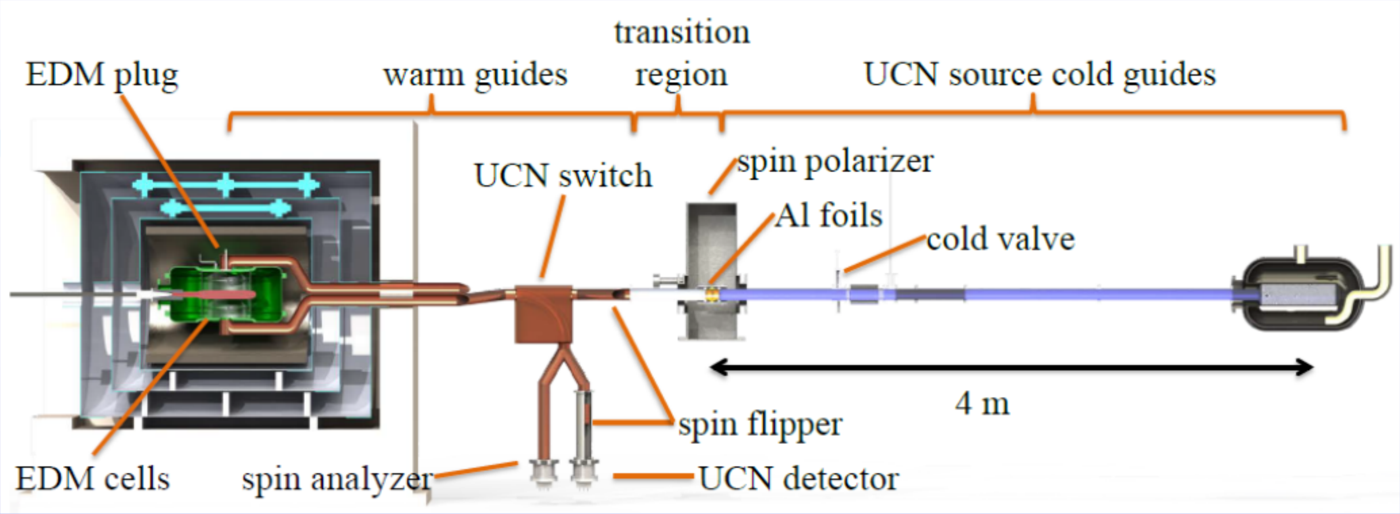
Thanks to T. Ito

Strategy, Goal etc

- Beamline and target commissioning fall 2016
- First UCN at TRIUMF summer 2017
- We will start with a prototype EDM apparatus from Japan (Phase 1), upgrade it as possible and develop techniques with it
- Source upgrades necessary for 10^{-27} ecm statistics shall come online 2019
- Our Phase 2 aparatus in 2020
  - Double EDM cell, room temperature, Ramsey technique
  - 4-layer magnetically shielded room
  - Self shielded $B_{0,1}$ coil
  - Start with ^{199}Hg comag, then implement dual ^{199}Hg/^{129}Xe comag to measure field and gradient simultaneously

"Phase 2" – to implement by 2020

R&D on Hg and Xe co-magnetometers is underway



Phase 2 sensitivity $\delta d_n \sim 10^{-27}$ e-cm

- LD_2 moderator, to increase cold flux entering the superfluid
- New high-quality guides.
- World-competitive nEDM experiment apparatus

CFI Innovation Fund application in progress, in Canada. Scale $16M.

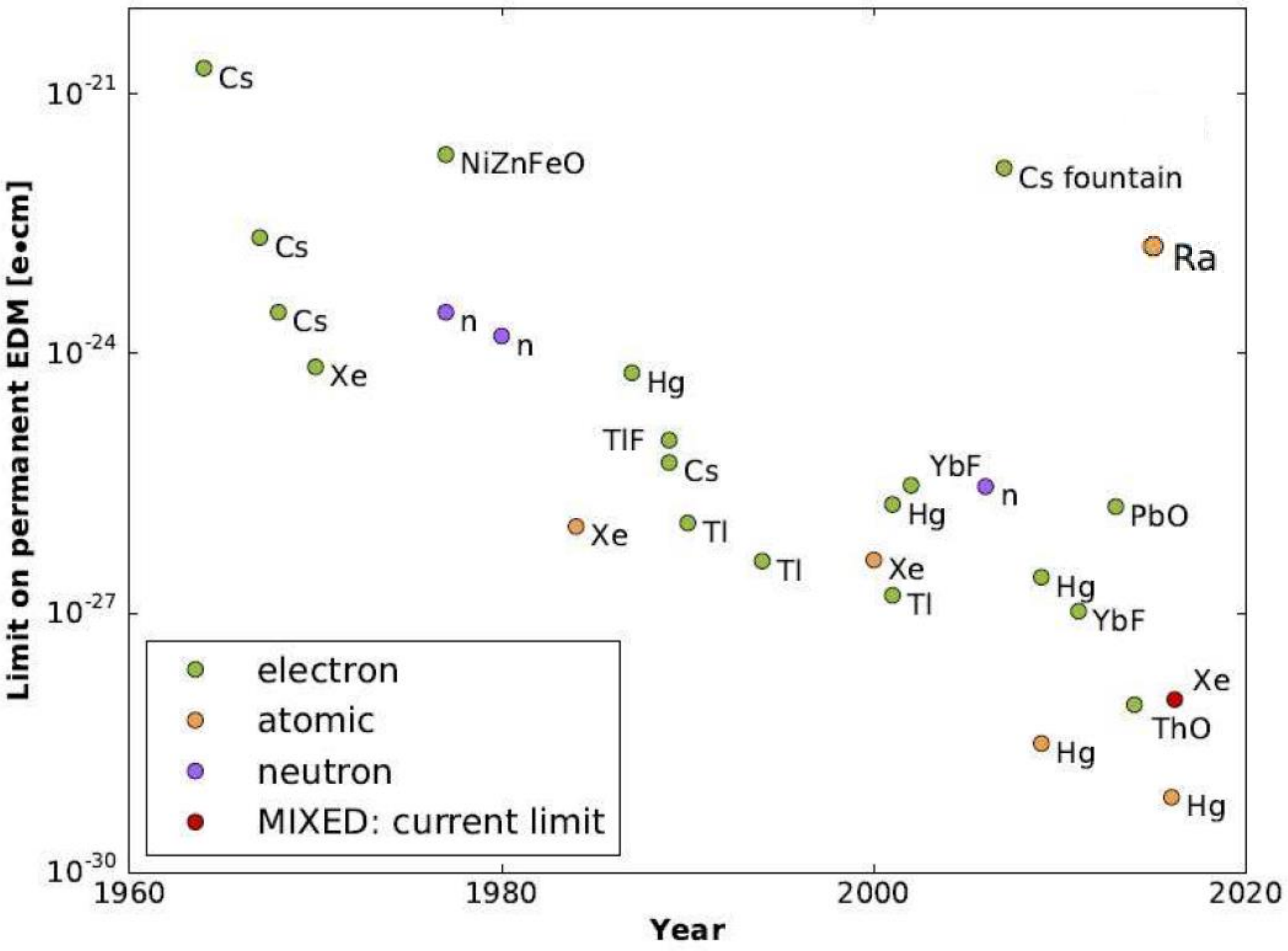
Slide thanks to J. Martin

Technical Challenges for nEDM@SNS

- 1200 L of superfluid Helium @ T = 0.5K
  - Must minimize heat sources
    - Eddy-current heating from AC B-fields → minimal conducting material
  - Large cooling plant required
- Highly sensitive to magnetic field variations and gradients
  - Significant magnetic shielding required
  - B-field uniformity of ppm/cm over measurement volume
  - Low-field operation: $B = 3\ \mu T$
- High electric fields: $E = 75$ kV/cm
  - Producing and maintaining $V > 600$ kV in cryogenic environment

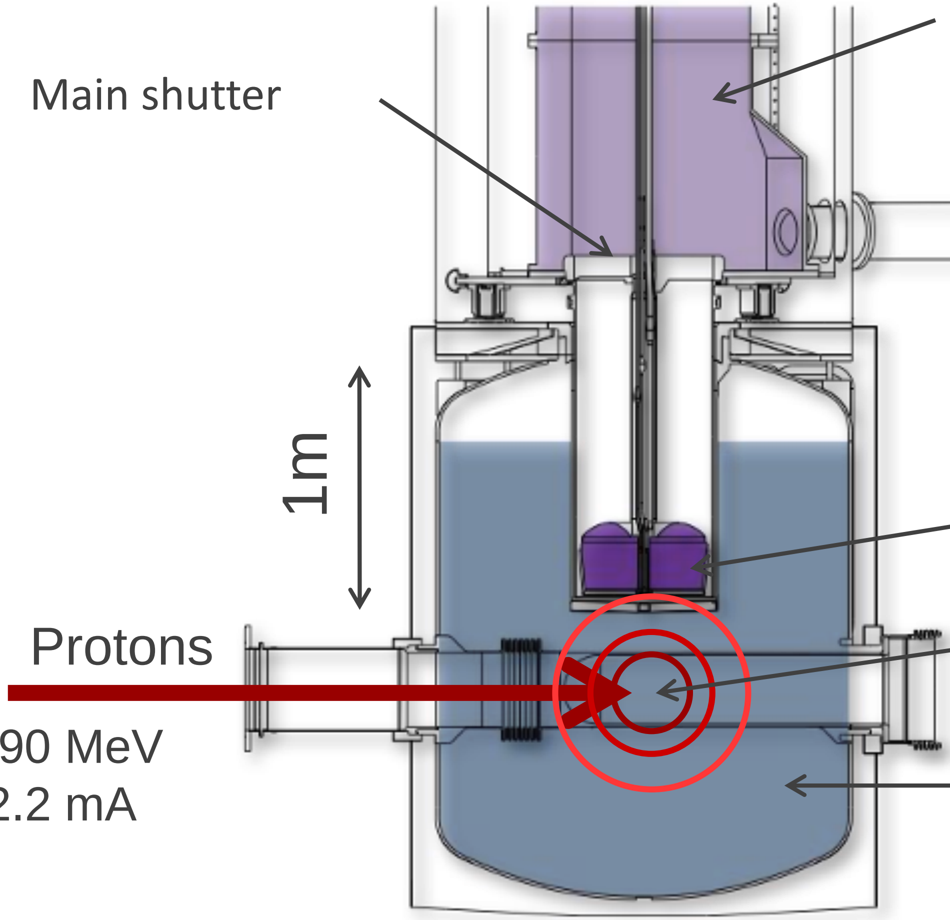
Thanks to B. Filippone

Summary


Limit on permanent EDM [e•cm]
Year
10^{-21}
10^{-24}
10^{-27}
10^{-30}
1960
1980
2000
2020
Cs
NiZnFeO
Cs fountain
Cs
Ra
Cs
n
n
Xe
Hg
TlF
Cs
YbF
n
Hg
PbO
Xe
Tl
Tl
Xe
Tl
Hg
YbF
Xe
ThO
Hg
Hg
electron
atomic
neutron
MIXED: current limit

PSI UCN source

Thanks to K. Kirch, P. Schmidt-Wellenburg



UCN storage volume

Main shutter

Neutron guide to experiments

UCN convertor (solid D_2 @ 5K)

Protons

590 MeV
2.2 mA

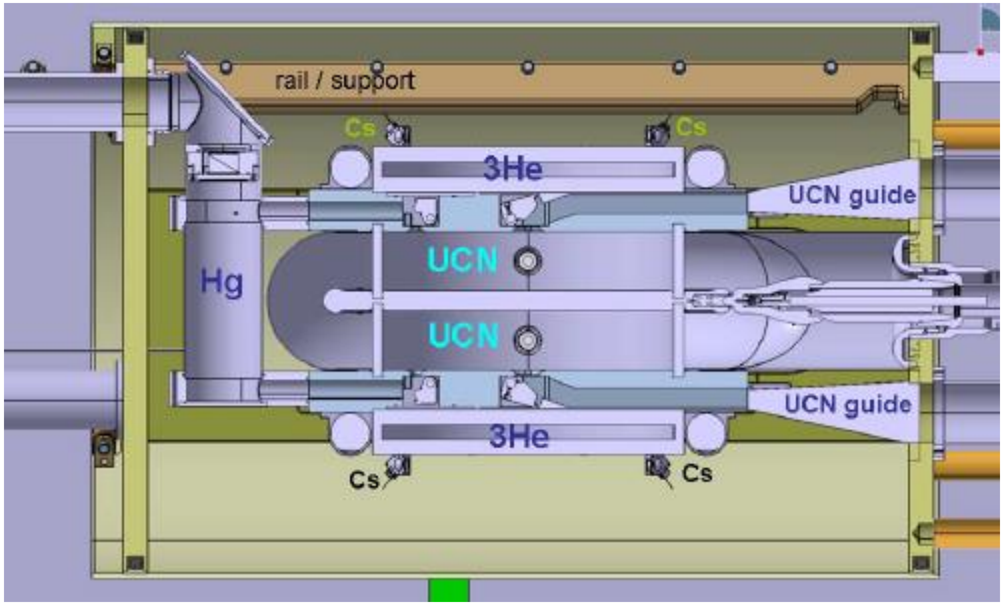
Spallation target
E_n~MeV

D_2O moderator
Neutrons thermalized to 25 meV

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

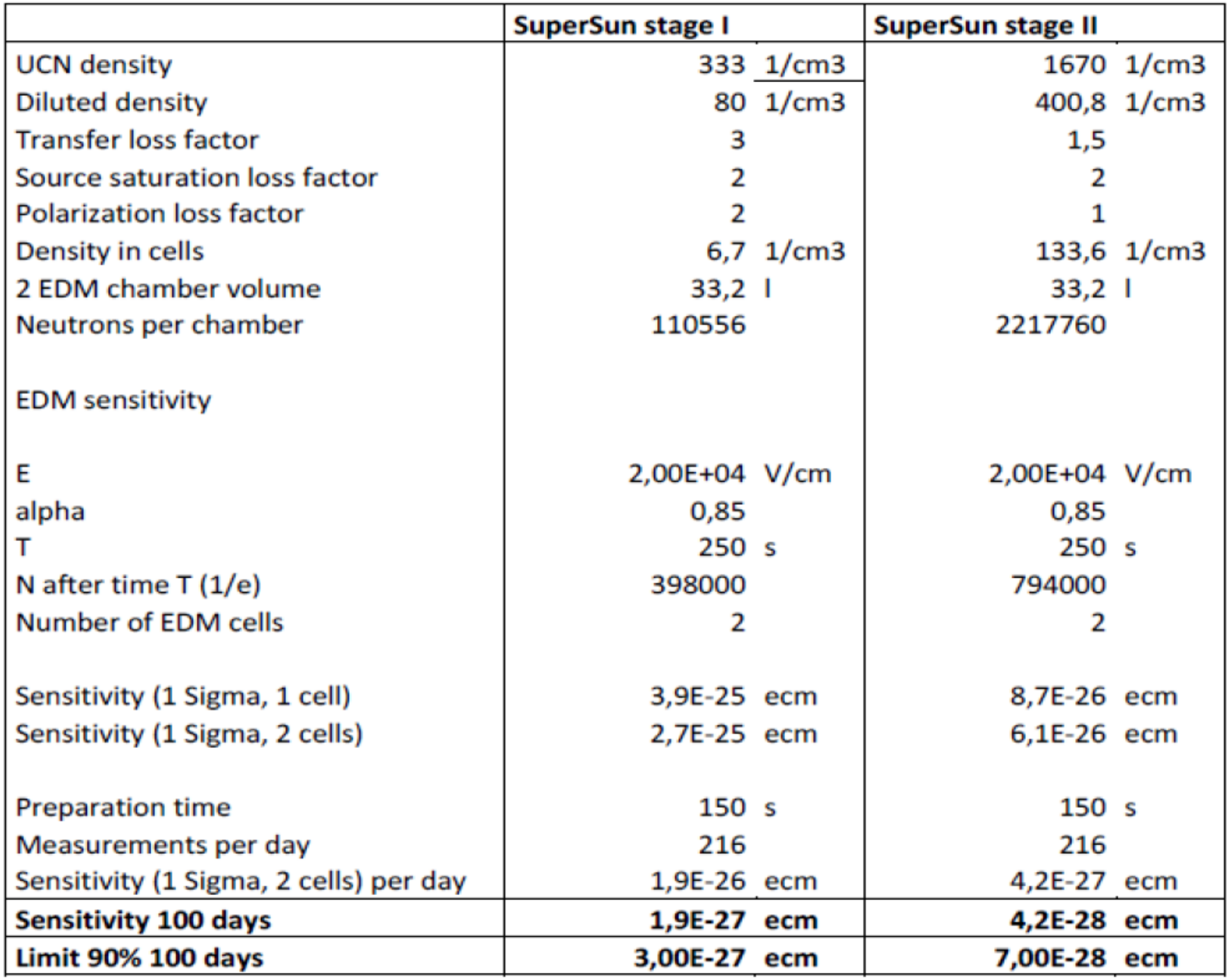
Presently up to 30 UCN/cm^3 in experiments

n2EDM at PSI



- Two UCN precession chambers with opposite E fields
- Improved magnetometry
    - Hg – laser readout
    - Cs
    - ^{3}He

Neutron EDM with Super-SUN at ILL



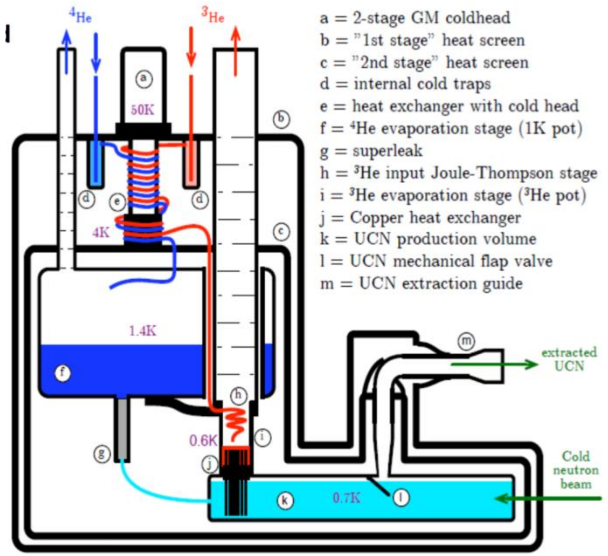
	SuperSun stage I		SuperSun stage II	
UCN density	333	1/cm3	1670	1/cm3
Diluted density	80	1/cm3	400,8	1/cm3
Transfer loss factor	3		1,5	
Source saturation loss factor	2		2	
Polarization loss factor	2		1	
Density in cells	6,7	1/cm3	133,6	1/cm3
2 EDM chamber volume	33,2	l	33,2	l
Neutrons per chamber	110556		2217760	
EDM sensitivity				
E	2,00E+04	V/cm	2,00E+04	V/cm
alpha	0,85		0,85	
T	250	s	250	s
N after time T (1/e)	398000		794000	
Number of EDM cells	2		2	
Sensitivity (1 Sigma, 1 cell)	3,9E-25	ecm	8,7E-26	ecm
Sensitivity (1 Sigma, 2 cells)	2,7E-25	ecm	6,1E-26	ecm
Preparation time	150	s	150	s
Measurements per day	216		216	
Sensitivity (1 Sigma, 2 cells) per day	1,9E-26	ecm	4,2E-27	ecm
Sensitivity 100 days	**1,9E-27**	**ecm**	**4,2E-28**	**ecm**
Limit 90% 100 days	**3,00E-27**	**ecm**	**7,00E-28**	**ecm**

Thanks to P. Fierlinger

Sensitivity and systematics

Super-SUN superfluid helium source:

- Stage I: 4×10^6 UCN with Fomblin spectrum (2018)
- Stage II: 2×10^7 UCN with 230 neV polarized (2019)

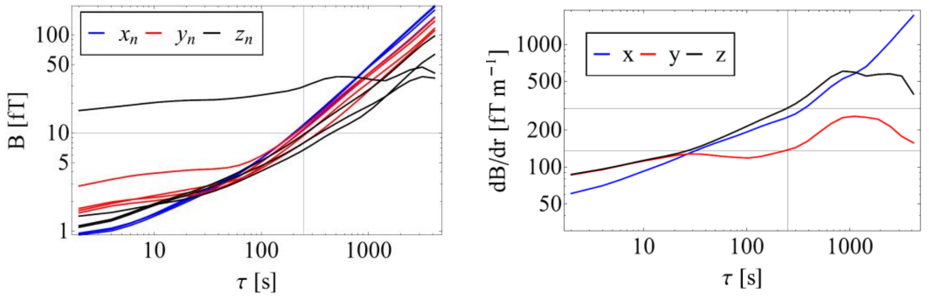


O. Zimmer et al., Phys. Rev. Lett. **107** (2011) 134801

Thanks to P. Fierlinger

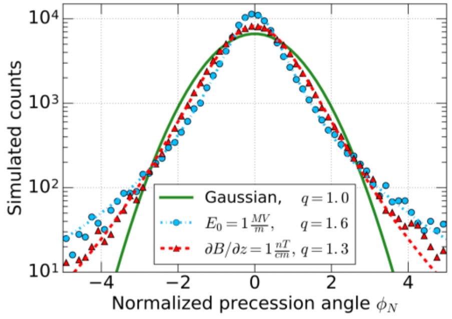
Control of systematics:

- < 100 pT/m B gradient over cell volume, < 10 fT/250 s drift : sufficient for 10^{-28} ecm level, even without comagnetometer



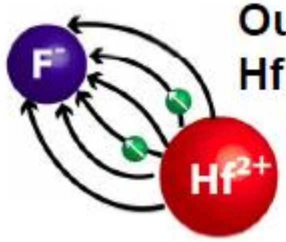
Potentially new class of systematics identified:

- Non-gaussian spin distributions in traps with gradients or E-fields
- Time-dependent shape of distributions



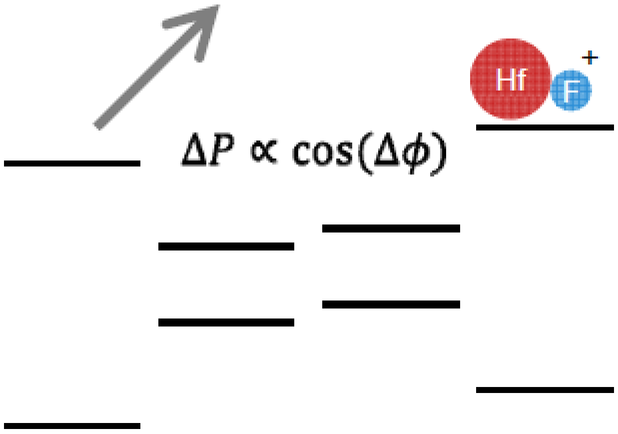
EDM search in HfF^+ molecular ion

NIST



Our choice: HfF^+

Optically deplete population out of one of the m_F levels

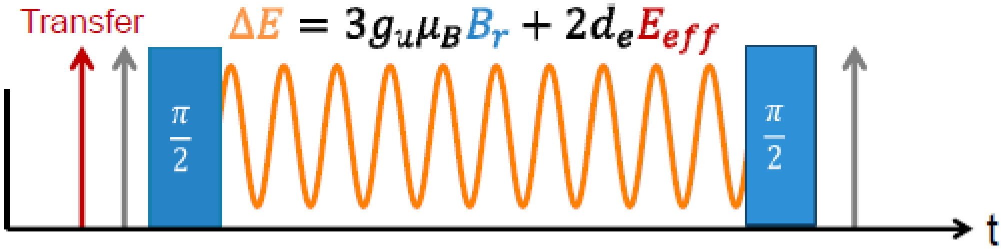


$\Delta P \propto \cos(\Delta\phi)$

Molecules provide large effective electric fields

$E_{lab} = 10$ V/cm

$|E_{eff}| > 10^{10}$ V/cm



$\Delta E = 3 g_u \mu_B B_r + 2 d_e E_{eff}$

1.5 x 10^{-28} e-cm

Expect x10 over next 2 years

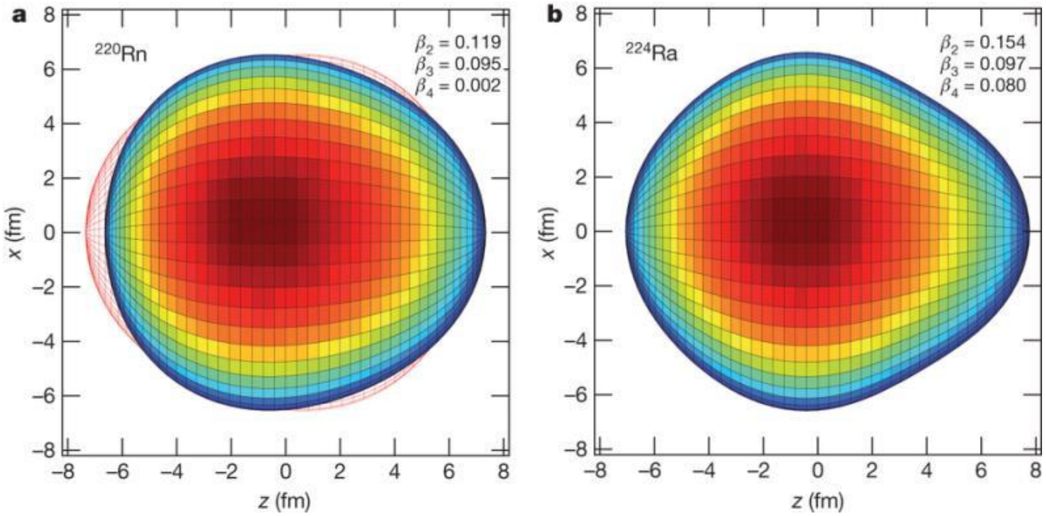
Longer term: switch to ThF^+

Thanks to E. Cornell and J. Ye

Radium-224 exhibits properties of octupole deformation

nature

GOING PEAR-SHAPED



REX-ISOLDE (CERN)

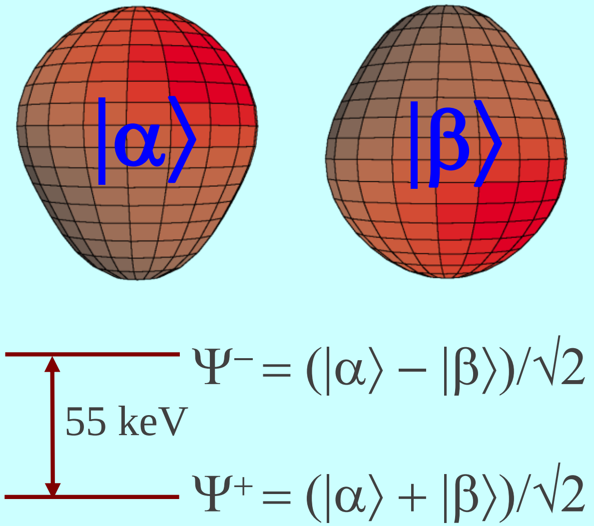
Measured B(E3, $0^+ \rightarrow 3^-$) in ^{224}Ra

L. P. Gaffney et al, **Nature 497 ,157 (2013)**

EDM of ^{225}Ra enhanced

- Closely spaced parity doublet – Haxton & Henley, PRL (1983)
- Large Schiff moment due to octupole deformation – Auerbach, Flambaum & Spevak, PRL (1996)
- Relativistic atomic structure (^{225}Ra / ^{199}Hg ~ 3) – Dzuba, Flambaum, Ginges, Kozlov, PRA (2002)

Parity doublet



$$\Psi^- = (|\alpha\rangle - |\beta\rangle)/\sqrt{2}$$

$$\Psi^+ = (|\alpha\rangle + |\beta\rangle)/\sqrt{2}$$

$$Schiff\_moment = \sum_{i \neq 0} \frac{\langle \psi_0 | \hat{S}_z | \psi_i \rangle \langle \psi_i | \hat{H}_{PT} | \psi_0 \rangle}{E_0 - E_i} + c.c.$$

Enhancement Factor: EDM (^{225}Ra) / EDM (^{199}Hg)

	Isoscalar	Isovector
Skyrme SIII	300	4000
Skyrme SkM*	300	2000
Skyrme SLy4	700	8000

Schiff moment of ^{225}Ra, Dobaczewski, Engel, PRL (2005)
Schiff moment of ^{199}Hg, Dobaczewski, Engel *et al.*, PRC (2010)

“[Nuclear structure] calculations in Ra are almost certainly more reliable than those in Hg.”

– Engel, Ramsey-Musolf, van Kolck, Prog. Part. Nucl. Phys. (2013)

^{225}Ra:

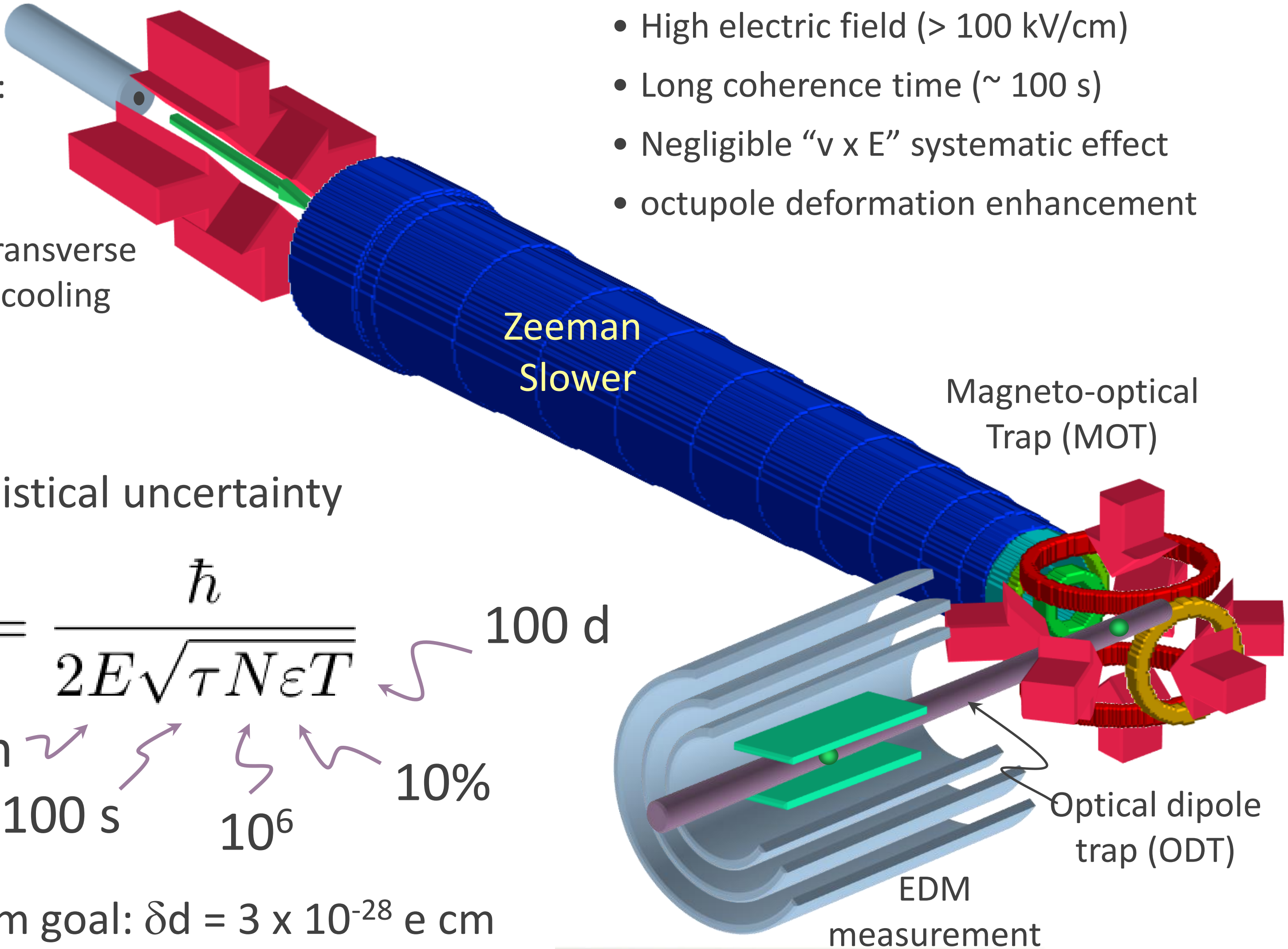
I = ½

$t_{1/2}$ = 15 d

EDM measurement on ^{225}Ra in a trap

Collaboration of Argonne, Kentucky, Michigan State, Northwestern

- Efficient use of the rare ^{225}Ra atoms
- High electric field (> 100 kV/cm)
- Long coherence time (~ 100 s)
- Negligible “v x E” systematic effect
- octupole deformation enhancement



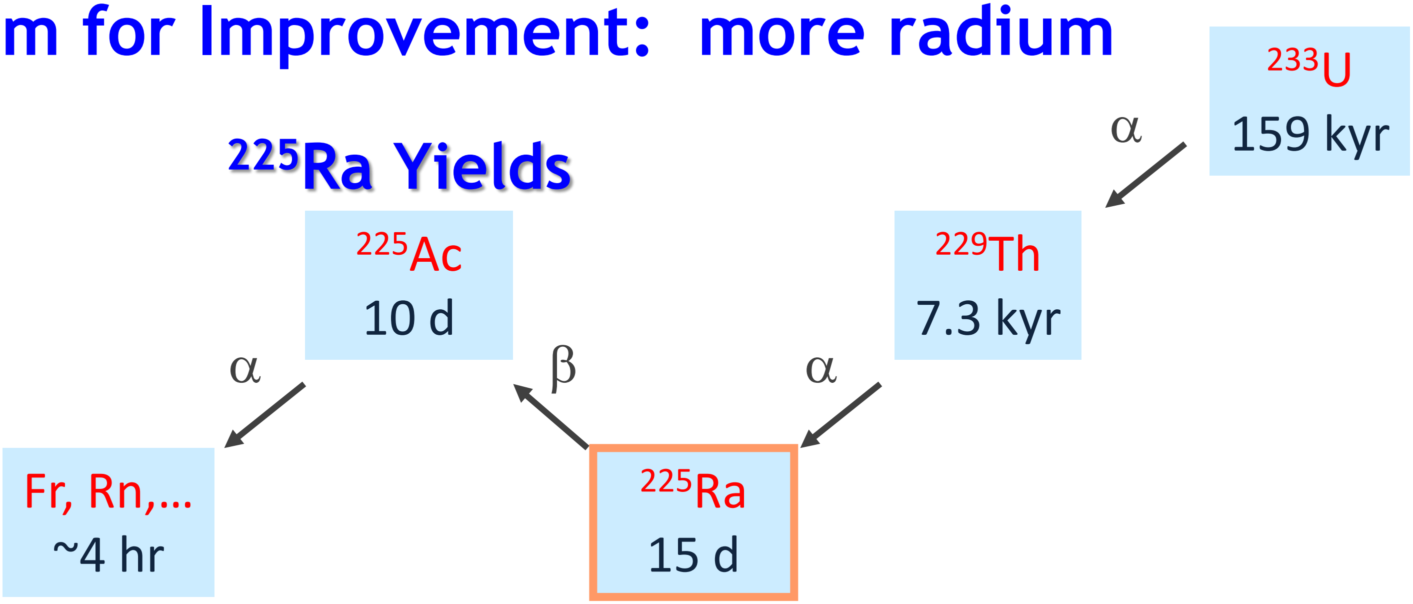
Statistical uncertainty

$$\delta d = \frac{\hbar}{2\underset{100\text{ kV/cm}}{E}\sqrt{\underset{100\text{ s}}{\tau}\,\underset{10^{6}}{N}\,\underset{10\%}{\varepsilon}\,\underset{100\text{ d}}{T}}}$$

Long-term goal: $\delta d = 3 \times 10^{-28}$ e cm

Room for Improvement: more radium

^{225}Ra Yields



Presently available

- National Isotope Development Center, ORNL
  - Decay daughters of ^{229}Th ---------------------------------- ^{225}Ra: 10^8 /s

Projected

- FRIB (B. Sherrill, MSU)
  - Beam dump recovery with a ^{238}U beam -------------------- 6×10^9 /s
  - Dedicated running with a ^{232}Th beam ---------------------- 5×10^{10} /s

- ISOL@FRIB (I.C. Gomes and J. Nolen, Argonne)
  - Deuterons on thorium target, 1 mA x 400 MeV = 400 kW 10^{13} /s

- MSU K1200 (R. Ronningen and J. Nolen, Argonne)
  - Deuterons on thorium target, 10 uA x 400 MeV = 4 kW 10^{11} /s

The Radium Team

Argonne: Kevin Bailey, Michael Bishof, John Greene, Roy Holt, Nathan Lemke, Zheng-Tian Lu, Peter Mueller, Tom O'Connor, Richard Parker;

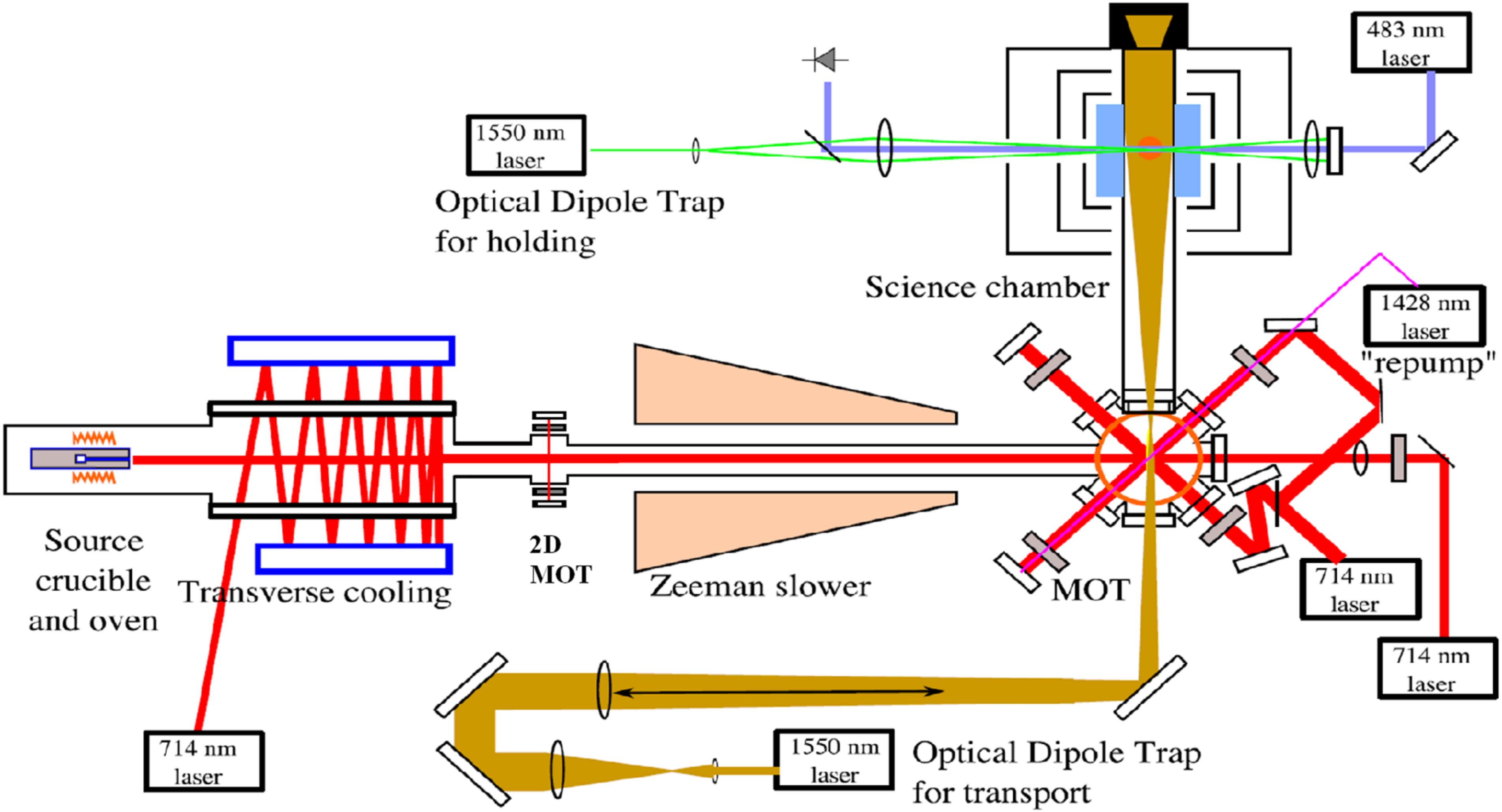
Kentucky: Mukut Kalita, Wolfgang Korsch;

Michigan State: Jaideep Singh;

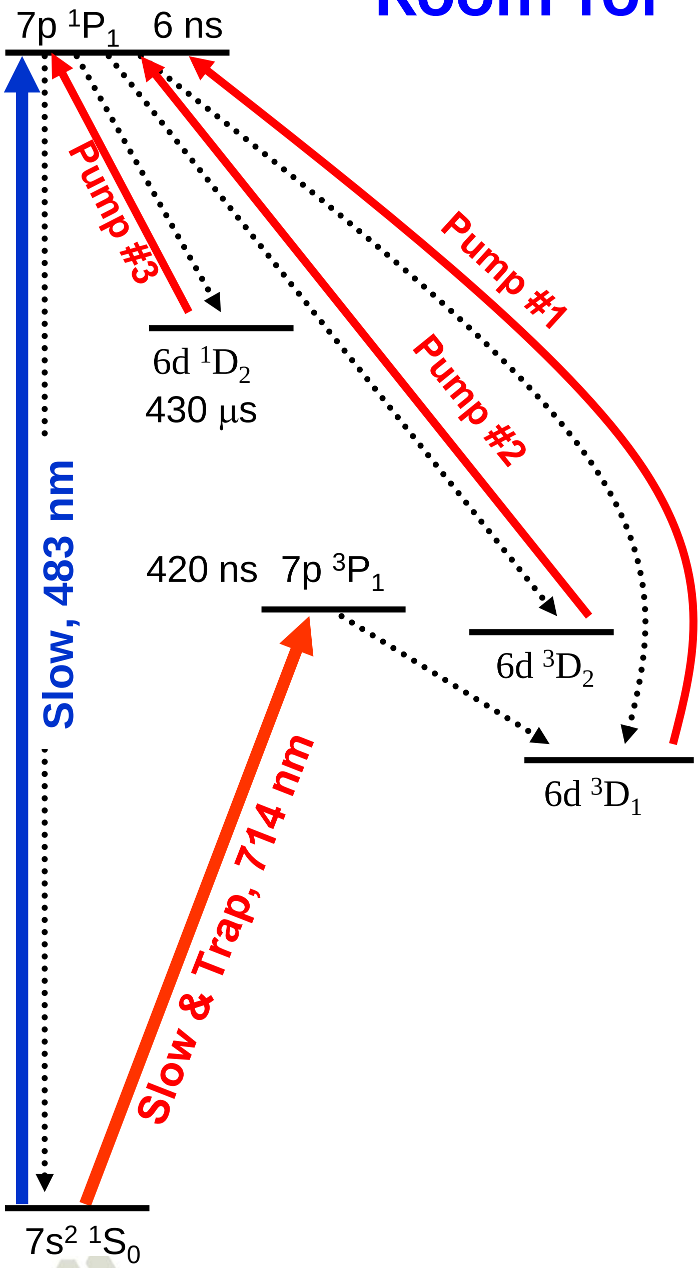
Northwestern: Matt Dietrich.

Special Thanks To: Irshad Ahmad, Dave Potterveld

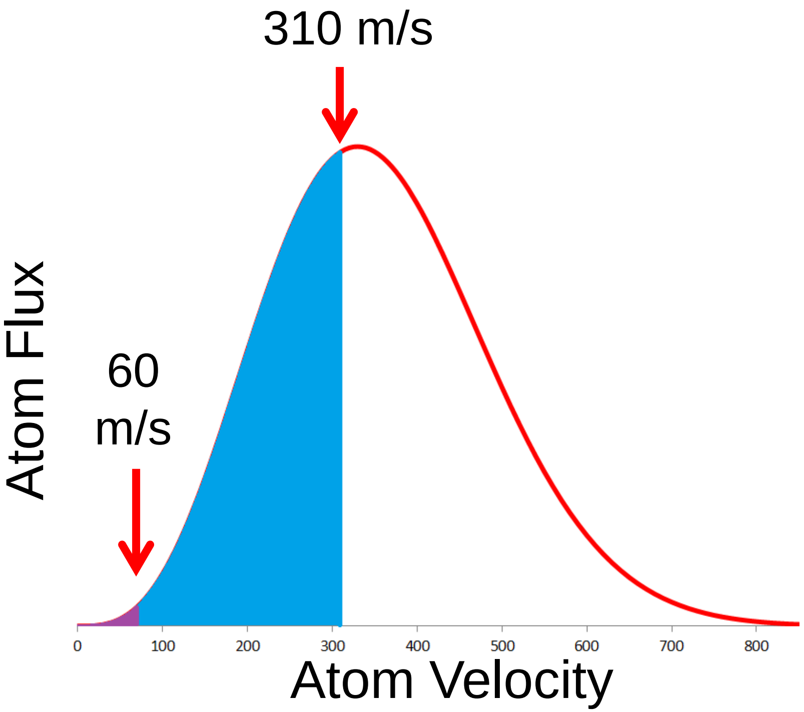
What does it take to measure the radium EDM?



Room for improvement: Blue Trap Upgrade



100x increase in N



Jon Engel Calculations

2010

Enhancement Factor: EDM (^{225}Ra) / EDM (^{199}Hg)

Skyrme Model	Isoscalar	Isovector	Isotensor
SIII	300	4000	700
SkM*	300	2000	500
SLy4	700	8000	1000

Schiff moment of ^{225}Ra, Dobaczewski, Engel (2005)
Schiff moment of ^{199}Hg, Ban, Dobaczewski, Engel, Shukla (2010)

2005

Enhancement Factor: EDM (^{225}Ra) / EDM (^{199}Hg)

Skyrme Model	Isoscalar	Isovector	Isotensor
SkM*	1500	900	1500
SkO’	450	240	600

Schiff moment of ^{199}Hg, de Jesus & Engel, PRC72 (2005)
Schiff moment of ^{225}Ra, Dobaczewski & Engel, PRL94 (2005)

Outlook

- 2016-2017
  - Implement STIRAP – more efficient way to detect spin;
  - Longer trap lifetime;
- 2018-2020, blue upgrade – more efficient trap;
- Five-year goal (before FRIB): 10^{-26} e cm;
- 2021 and beyond (at FRIB): 3×10^{-28} e cm;
- Far future: search for EDM in diatomic molecules
  - Effective E field is enhanced by a factor of 10^3;
  - Reach the Standard Model value of 10^{-30} e cm.