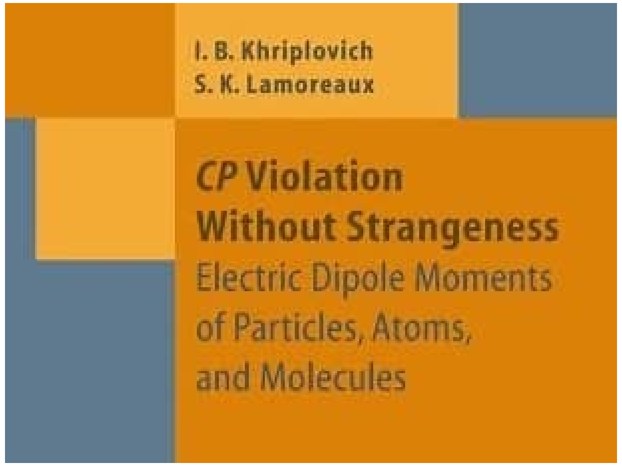
Searches for Neutron EDM: CP violation *without* Strangeness, Charm or Beauty



21st Conference on Flavor Physics & CP Violation

Chen-Yu Liu

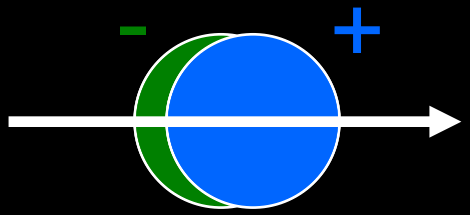
University of Illinois Urbana-Champaign

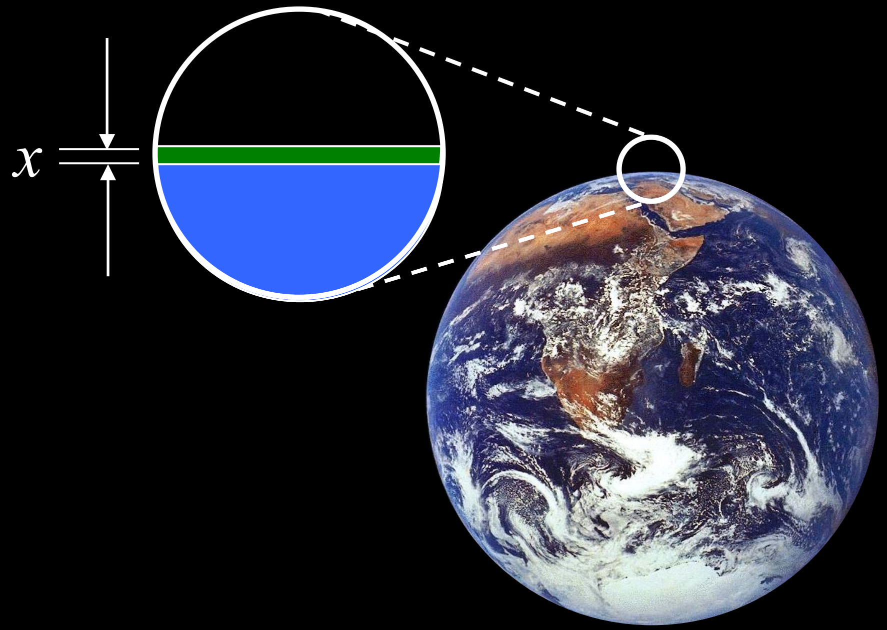
6/1/2023

Electric Dipole Moment (EDM) of the Neutron

Purcell and Ramsey, Phys. Rev. 78, 807 (1950)

- Neutron EDM (d_E) : Permanent, net charge separation within the neutron volume





- First experiment (1957): $d_E < 5 \times 10^{-20}$ e-cm

- Current limit [1]: $d_E < 1.8 \times 10^{-26}$ e-cm

__Charge separation for an earth-size neutron__

Current limit: $\Delta x < 1.8 \times 10^{-13} r_E$ (2 μm)

Goal sensitivity: $\Delta x < 1.8 \times 10^{-15} r_E$ (20 nm)

*[1] PRL **124** 081823 (2020)*

Electric Dipole Moment and Symmetry Violation

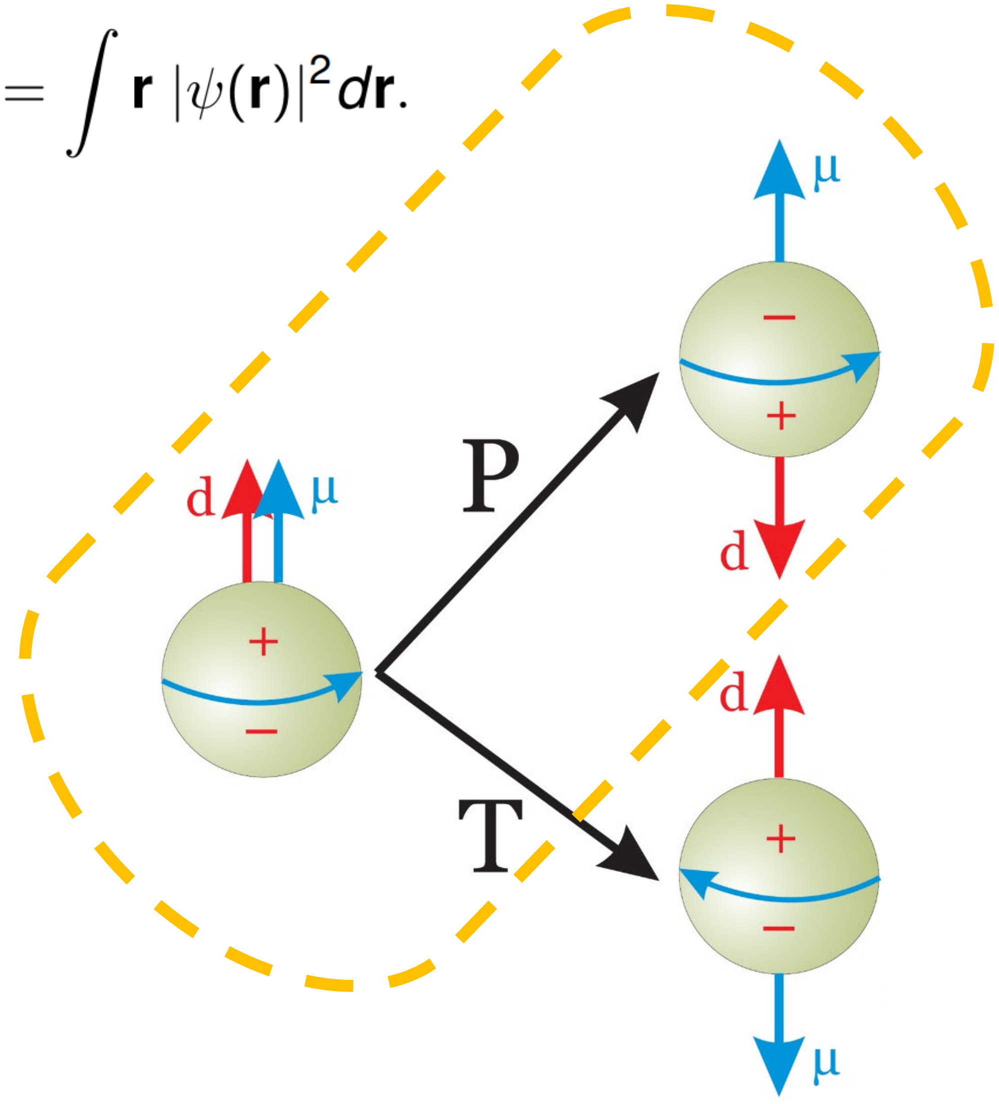
Electric Dipole Moment (EDM):

$$\mathbf{d} = \int \mathbf{r}\ \rho(\mathbf{r}) d\mathbf{r} = \int \mathbf{r}\ |\psi(\mathbf{r})|^2 d\mathbf{r}.$$

If parity is conserved,

$$\hat{P}\psi(\mathbf{r}) = \psi(-\mathbf{r}) = \pm\psi(\mathbf{r}),$$

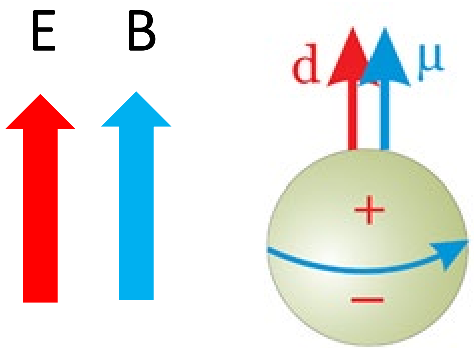
then EDM is zero.



Electric Dipole Moment implies Time Reversal Symmetry Violation

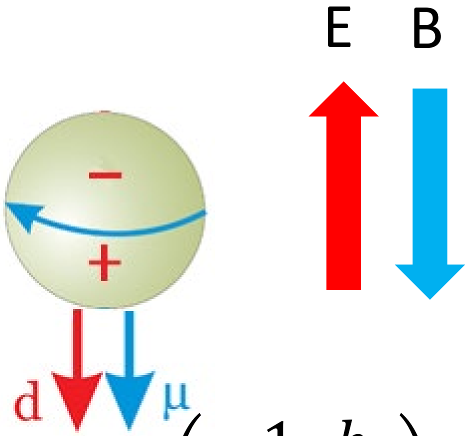
Fundamental particles do not have degenerate ground states, so $\vec{d} = d\hat{J}$.

We start with the ground state of



T →

$$\vec{d} = d\hat{J}$$



$$\varepsilon_{1/2} = dE + \left(\frac{1}{2}\frac{h}{2m}\right)B$$

$$\varepsilon_{1/2} = -dE + \left(-\frac{1}{2}\frac{h}{2m}\right)(-B)$$

T-odd T-even

The ground state is not a T eigenstate!

$$\Rightarrow [H,T] \neq 0$$

The Hamiltonian violates T symmetry.

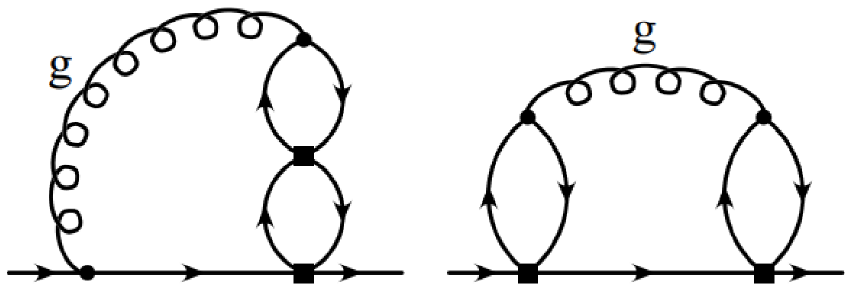
Electric Dipole Moment in the Standard Model

- Discovery of a non-zero EDM of neutrons, d_n , would be direct evidence of violation of both time reversal symmetry (T) and parity (P).
- If the symmetry under simultaneous charge conjugation, space inversion, and time reversal (CPT) is exact, T violation is equivalent to CP violation.
- In the electroweak sector of the SM, a complex phase of the Cabibbo-Kobayashi-Maskawa (CKM) matrix violates CP and, via loop effects, induces an EDM for all non-self conjugate particles with spin.

$$d_n = \frac{4}{3} d_d - \frac{1}{3} d_u$$

The quark EDM appears only at the three-loop level. The largest effect is due to the exchange of two W bosons and one gluon:

For quarks w/ mass < m_W



For top quarks in the loops,

Czarnecki & Krause, PRL.78:4339-4342,1997

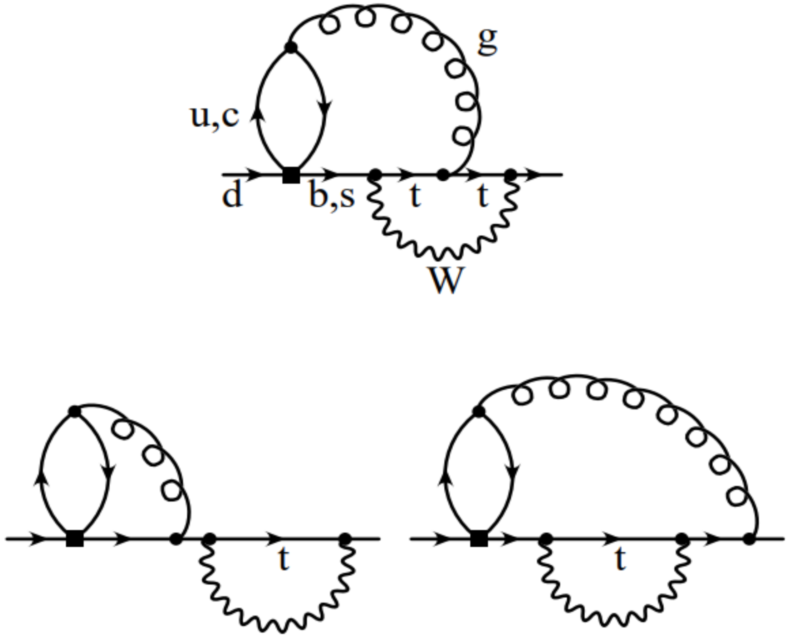


FIG. 3. Heavy top quark contributions to d_d.

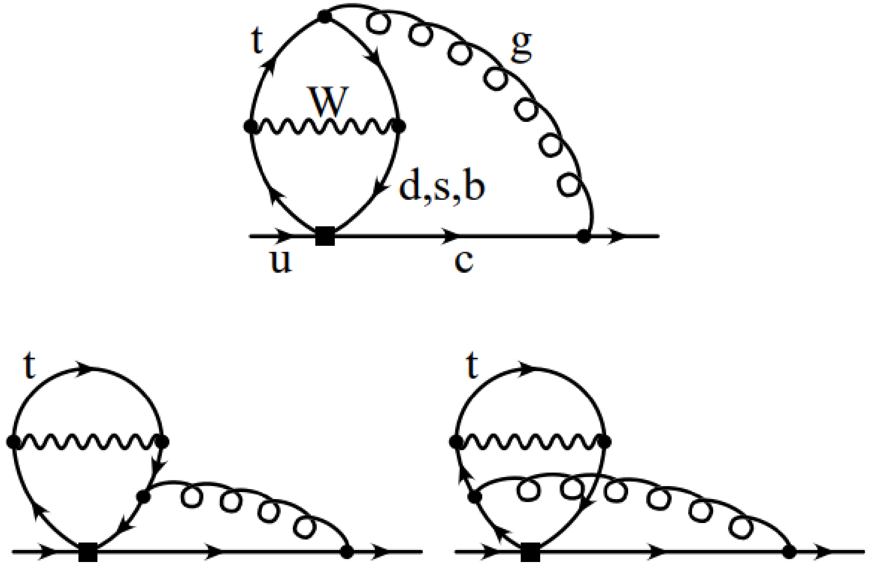


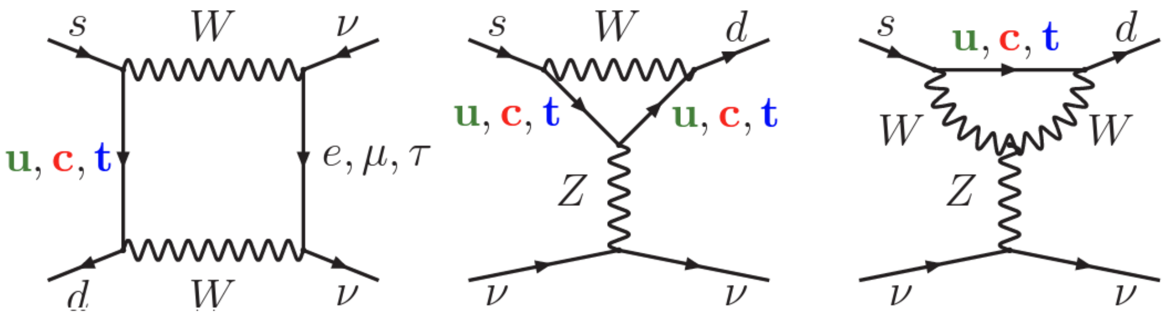
FIG. 4. Heavy top quark contributions to d_u.

the contribution to EDM is suppressed.

Rare processes in B, D, & K meson decays

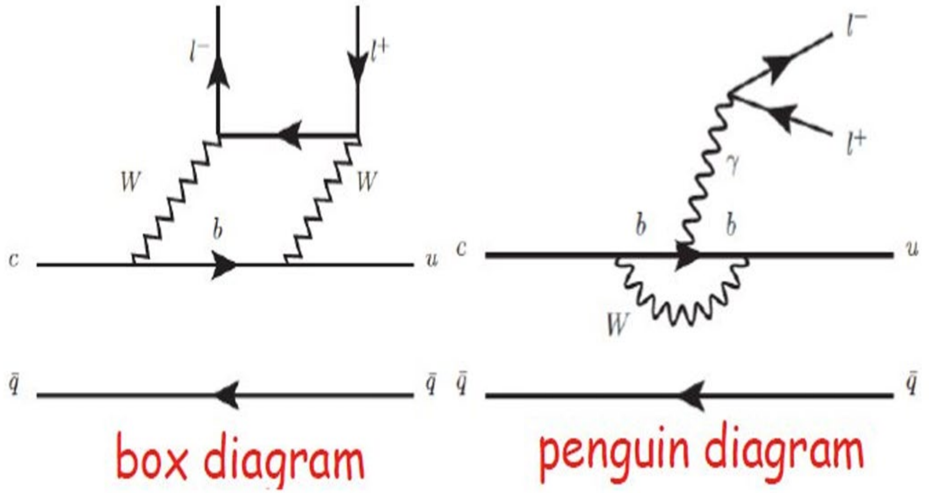
e.g.,

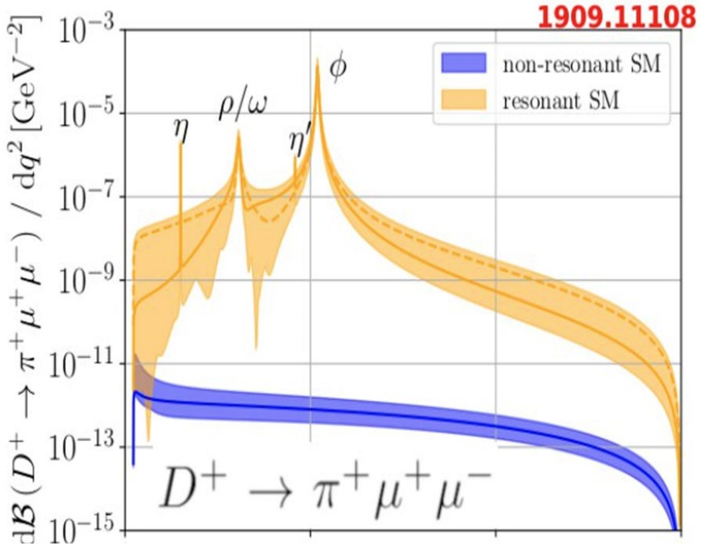
See Joachim Brod's talk (Tuesday)



$$K_L \to \pi^0 \nu \bar{\nu}$$

See Liang Sun's talk (Monday)



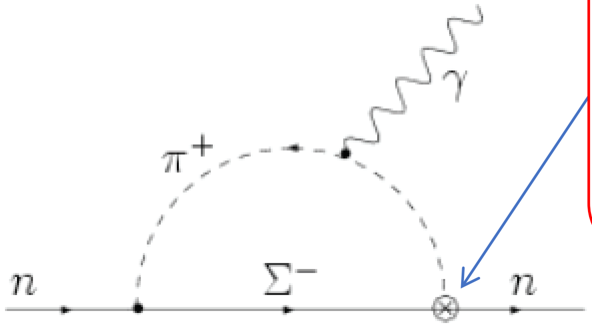


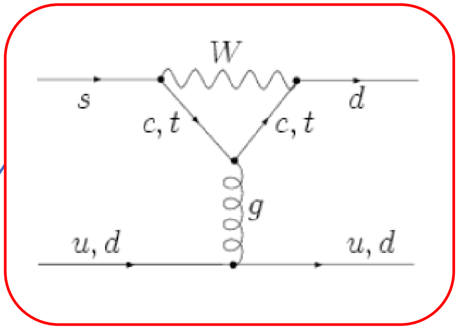
EDM searches could be contrasted to the many rare meson decay processes, which involve W bosons in loops, but EDM has no background from other SM processes.

EDM is a sensitive probe to search for BSM CP-violating physics

nEDM: violates P and T

In the Standard Model:



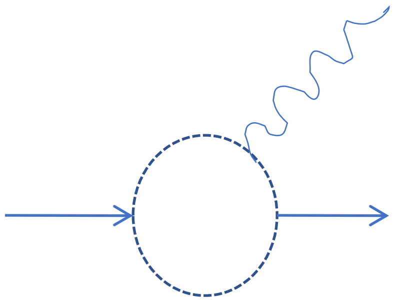


Suppressed 3-loop effect from the CKM phase in the Standard Model

$d_n \sim 10^{-32}$ e-cm (Khriplovich & Zhitnitsky 1986)

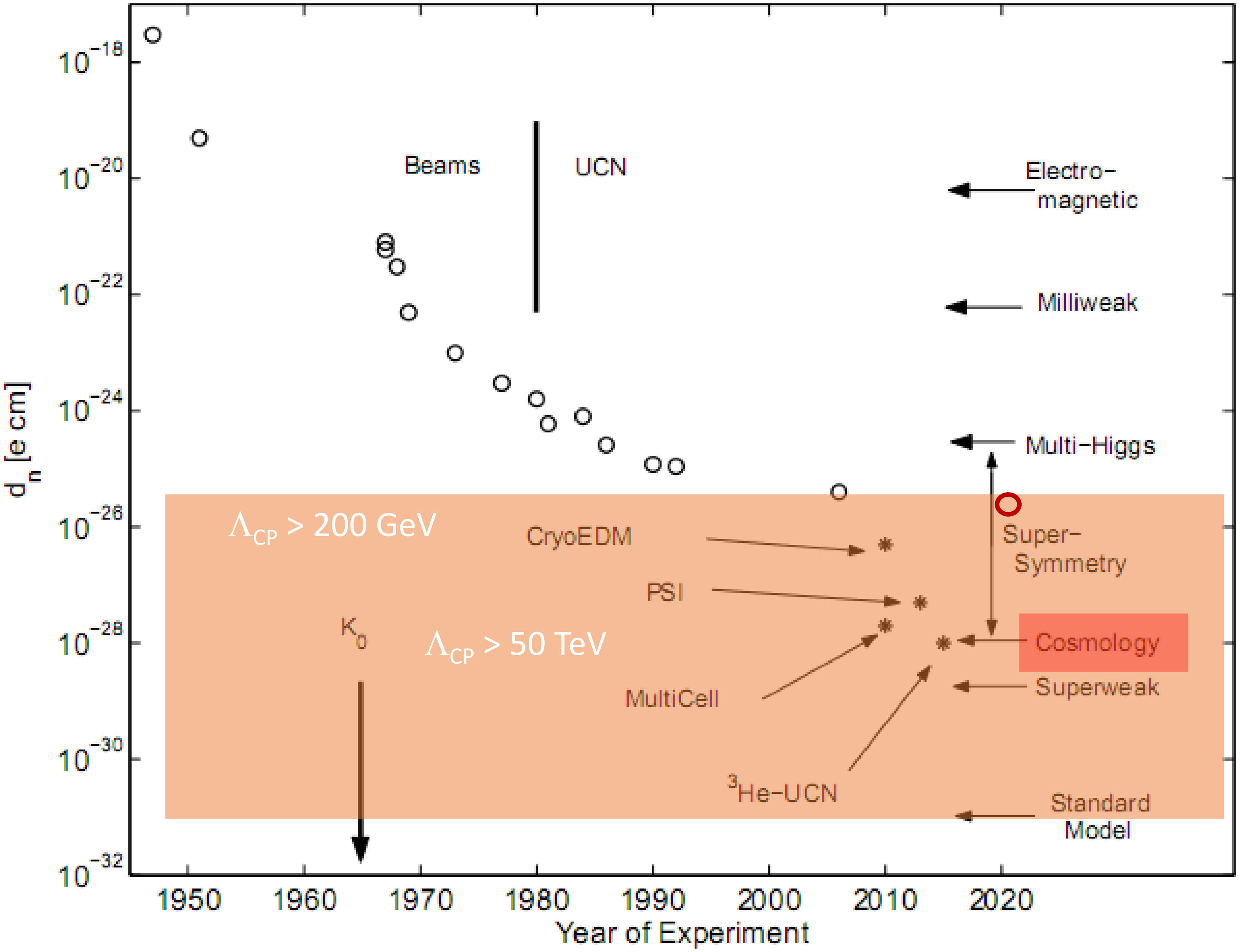
Large effect in more comprehensive theories:

In beyond the Standard Model (BSM) physics extensions:



$$d \sim (loop)\frac{m_f}{\Lambda_{cp}^2}$$

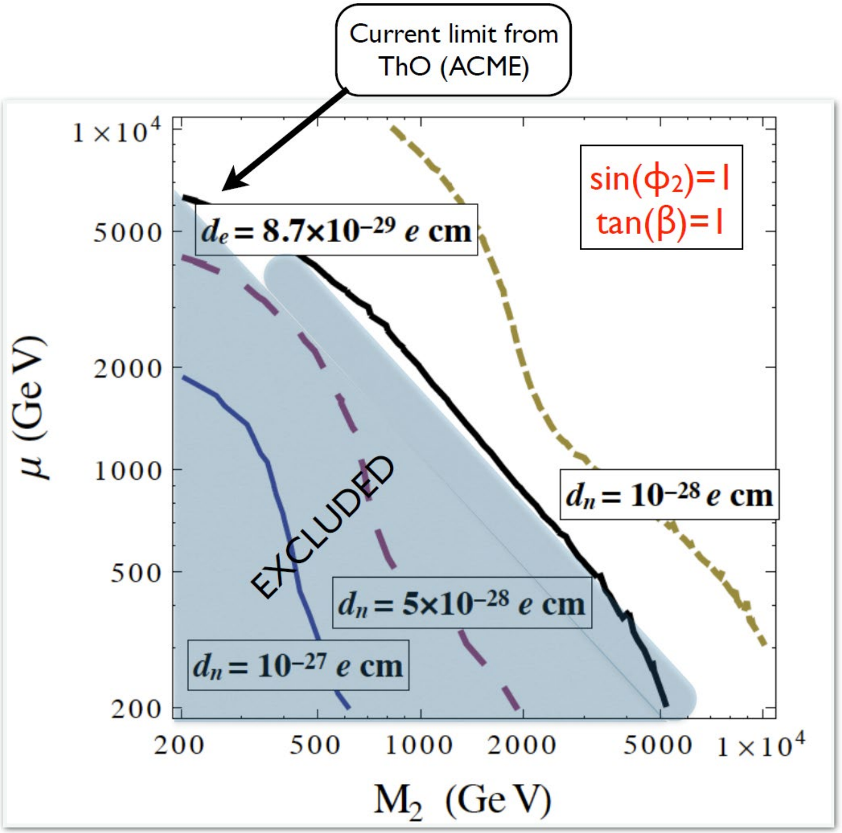
$d < 10^{-26}$ e-cm $\rightarrow \Lambda_{cp} = 1$ TeV



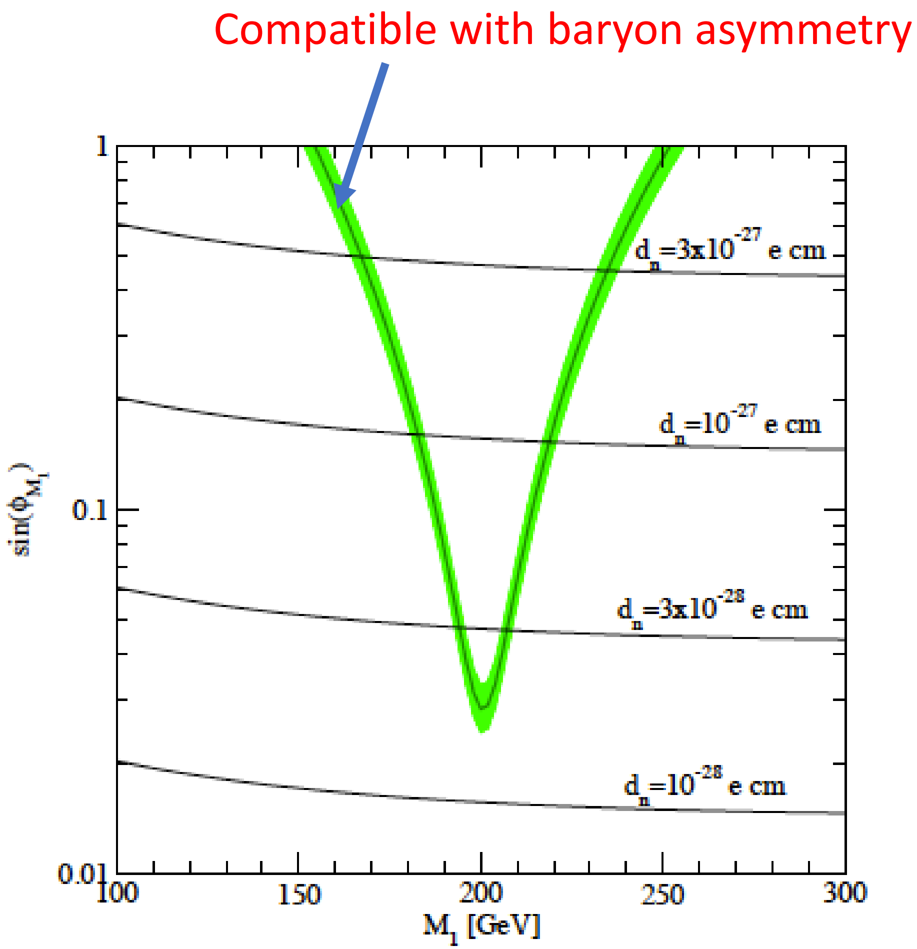
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-28}
10^{-30}
10^{-32}
d_n [e cm]
1950
1960
1970
1980
1990
2000
2010
2020
Year of Experiment
Beams
UCN
Electro-magnetic
Milliweak
Multi-Higgs
Super-Symmetry
Cosmology
Superweak
Standard Model
Λ_{CP} > 200 GeV
Λ_{CP} > 50 TeV
CryoEDM
PSI
MultiCell
^{3}He-UCN
K_0

EDMs test SuperSymmetry

$$d \approx (10^{-16}\ e\ \mathrm{cm}\ ) \left(\frac{v}{\Lambda}\right)^2\ (\sin\phi_{\mathrm{CPV}})(y_f\ F)$$

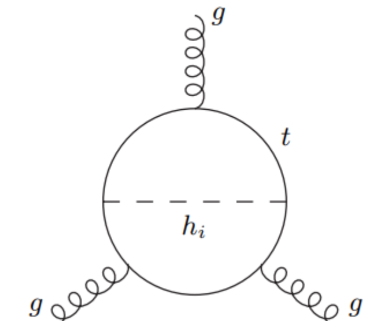


Bhattacharya, VC, Gupta, Lin, Yoon
Phys. Rev. Lett. 115 (2015) 212002 [1506.04196]

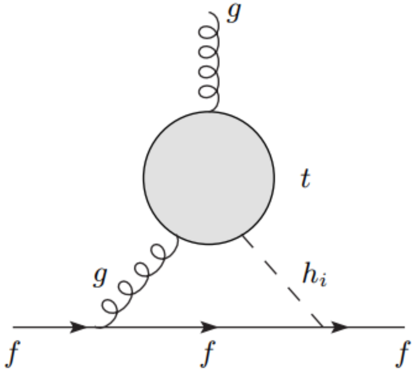


Li, Profumo, Ramsey-Musolf 2009-10

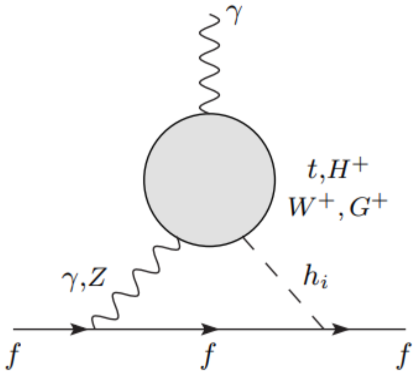
EDMs test the Two-Higgs Doublet Model



CPV neutral Higgs mixing

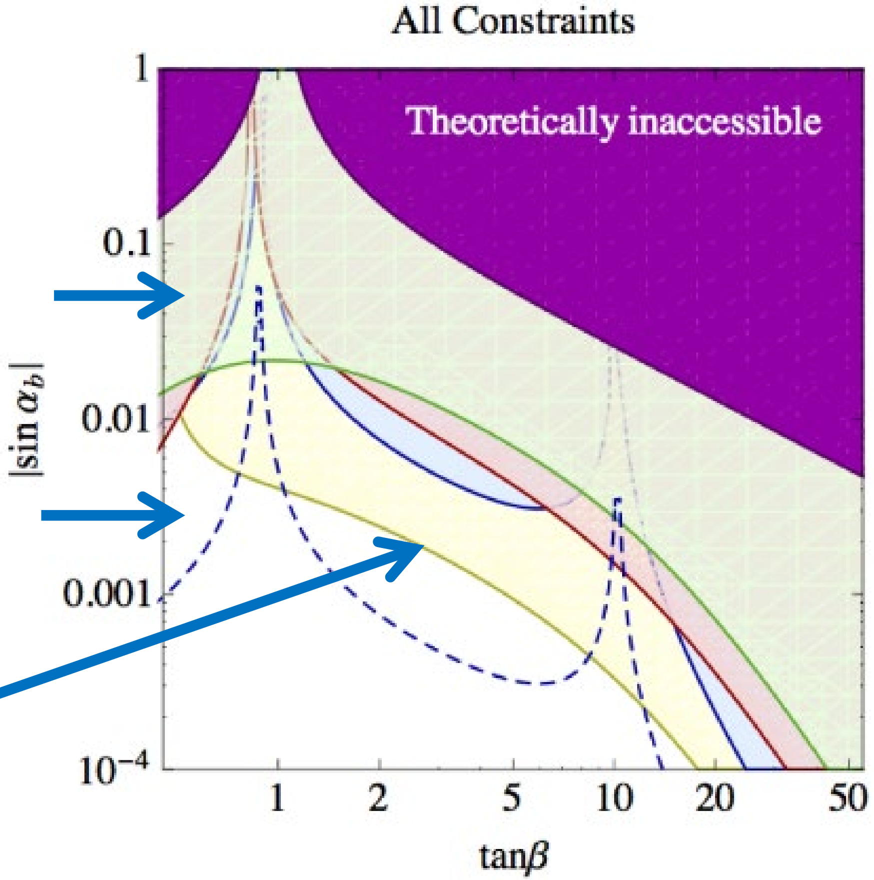


Chromo-edm



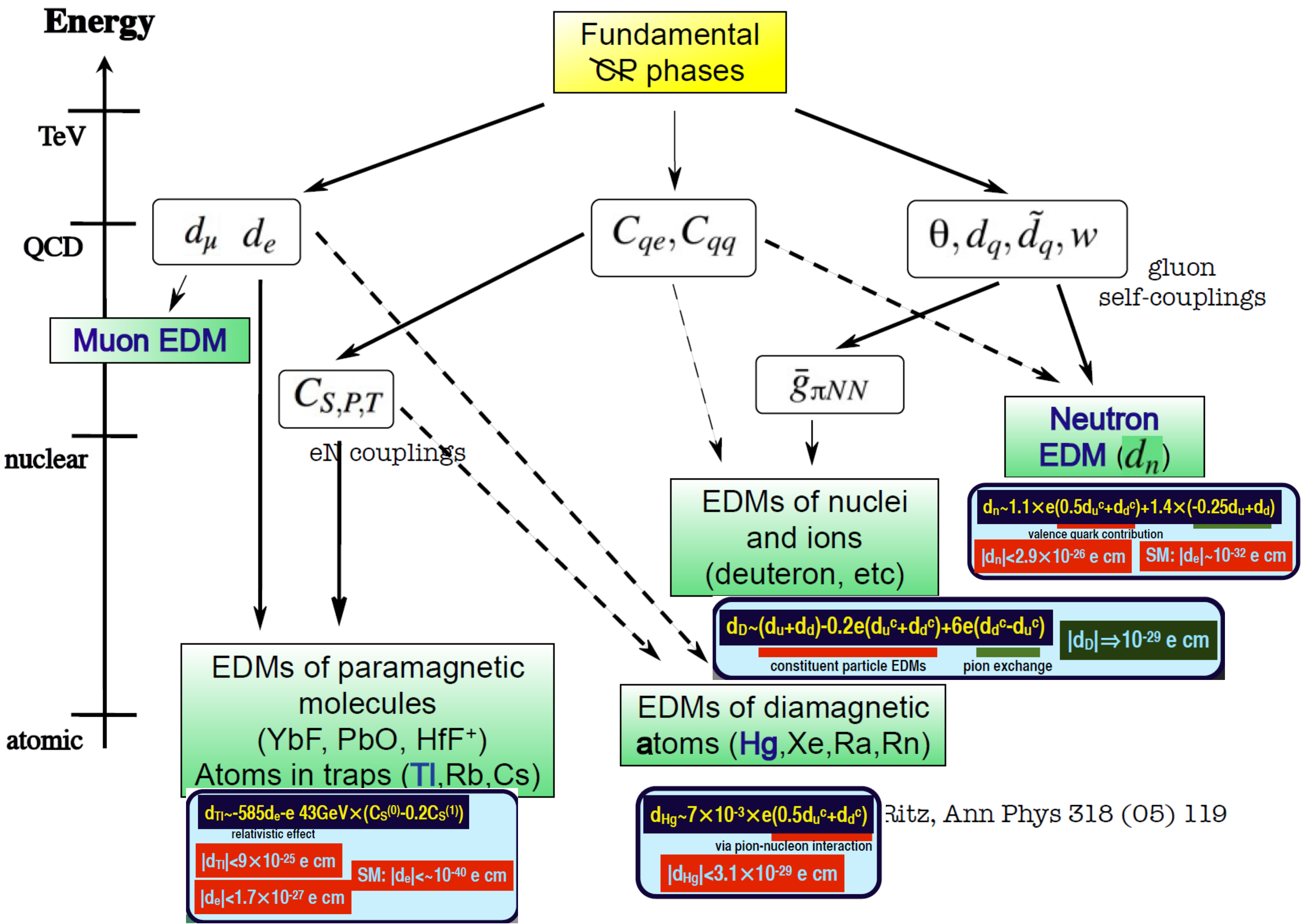
Quark edm

neutron EDM (Green)
Mercury EDM (red)
electron EDM (blue)
Radium (yellow)

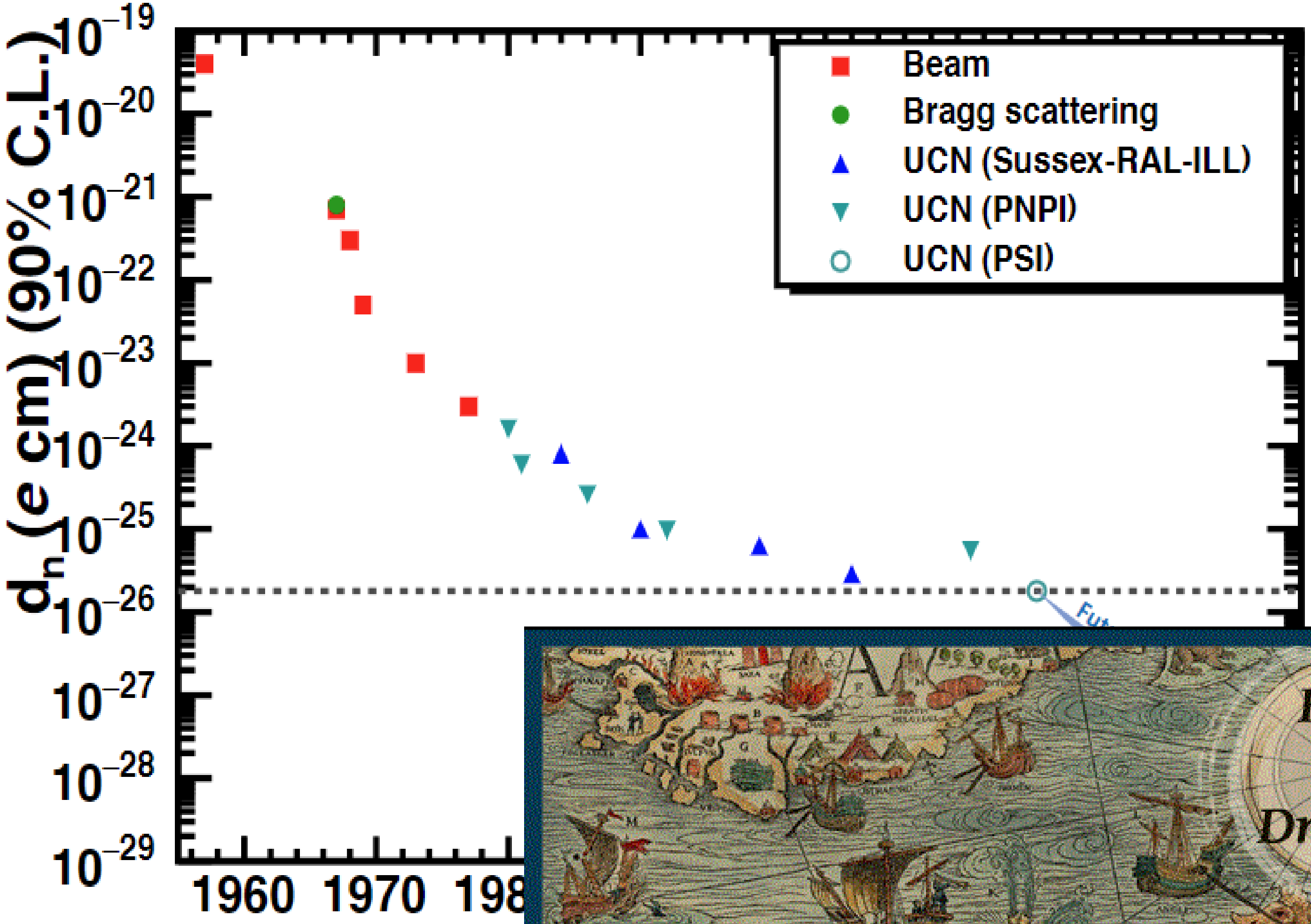


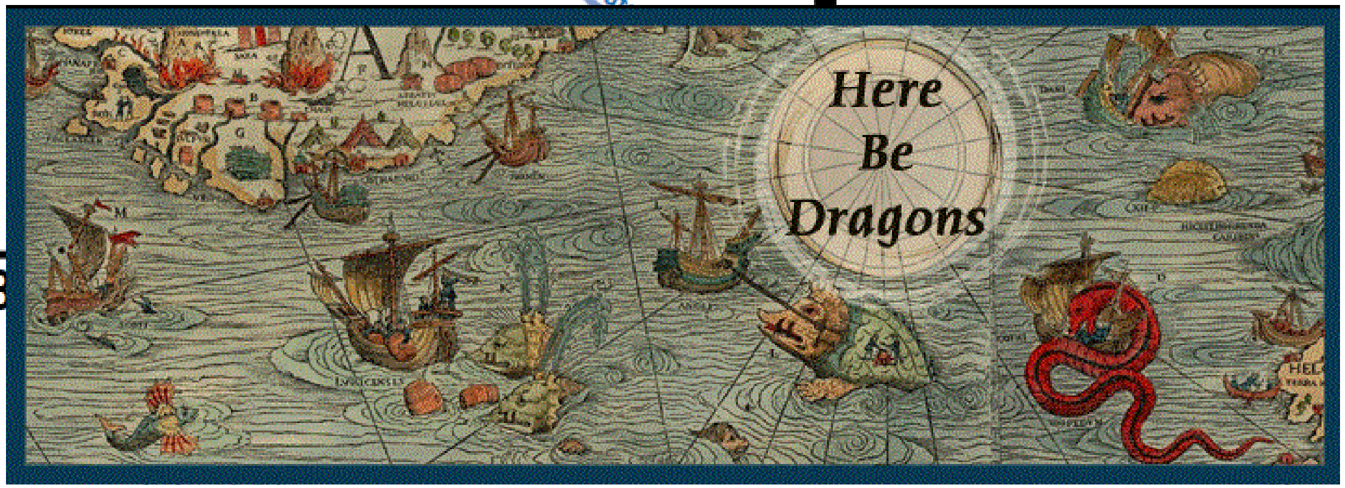
S. Inoue, M. J. Ramsey-Musolf, Y. Zhang Phys. Rev. D 89, 115023 (2014)
C.-Y Chen, H.-L Li, M. J. Ramsey-Musolf, Phys. Rev. D 97, 015020 (2018)

CP-violation in Low Energy Phenomena



nEDM experimental limits





Why neutron EDM?

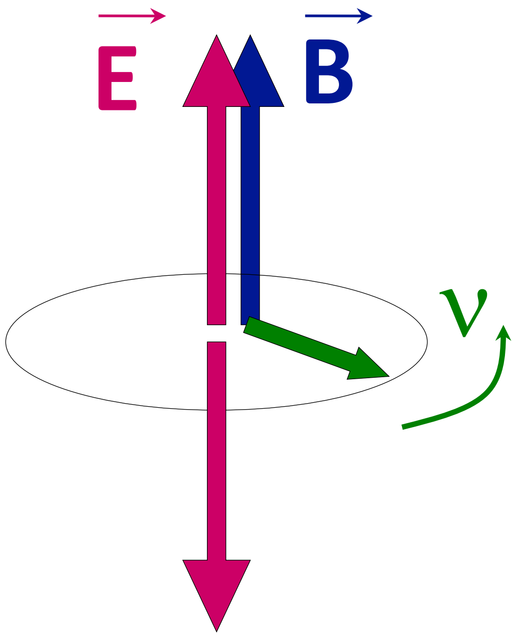
- Neutral particle (no net force in E-field)
  - Particle motion not affected by E field
  - No Schiff's shielding

- Long measurement/coherence times possible
  - 200 – 1000 s → limited by neutron lifetime

- Because it's the simplest Z=0 "nucleus"
  - Lattice QCD calculations can connect measured EDM to fundamental hadronic CP violation

- Directly addressing the 'Strong CP problem'

Principle of nEDM experiments



$$\nu = \left(2\mu_n B \pm 2 d_n E\right)/h$$

$$\Delta\nu = 4 d_n E/h$$

$$\delta d_n = h\frac{\delta\Delta\nu}{4E}$$

- For B ~ 10 mG, ν = 30 Hz
- For E = 10 kV/cm and d_n= 3 x 10^{-27} e·cm, $\delta\nu$ = 30 nHz

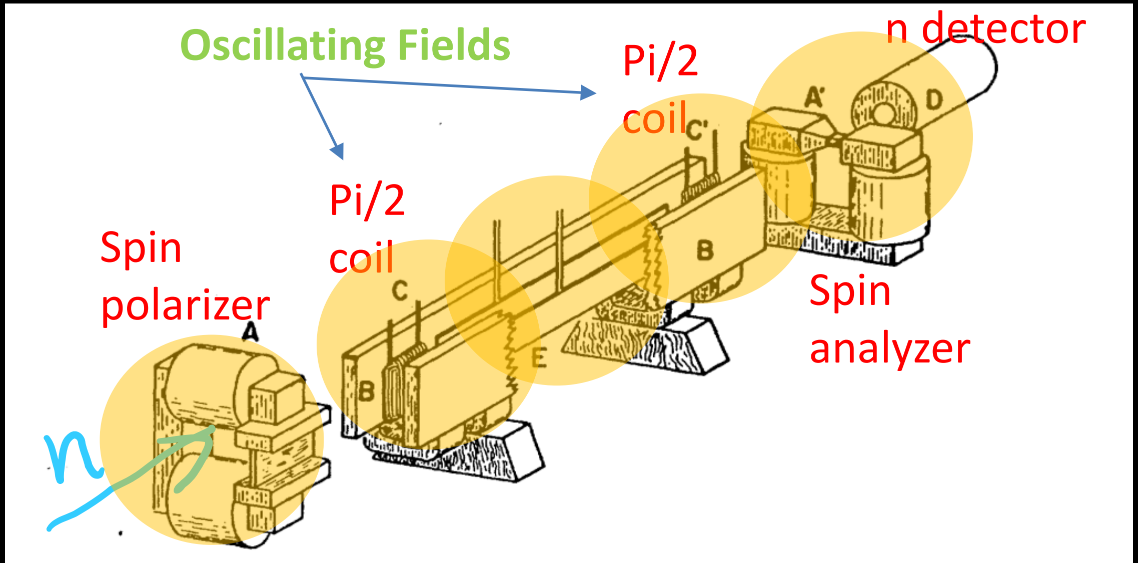
One part per billion precision!

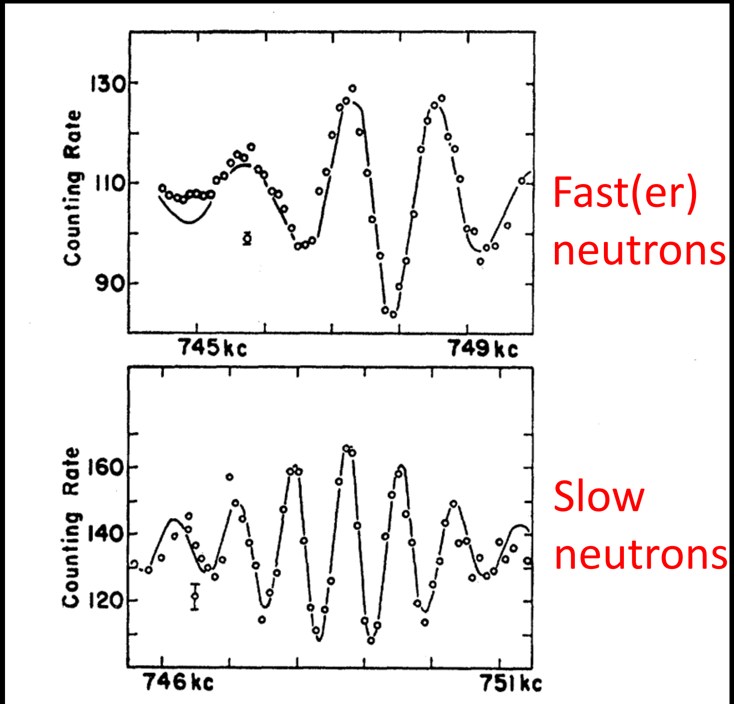
Ramsey's method of Separated Oscillatory Fields

A particular arrangement that is more advantageous in many cases is one in which the oscillating field is confined to a small region at the beginning of the space in which the energy levels are being studies and to another small region at the end, there being no oscillating field in between.

-- N. Ramsey (1950)

Smith, Purcell, Ramsey, Phys. Rev. 108, 120 (1957)



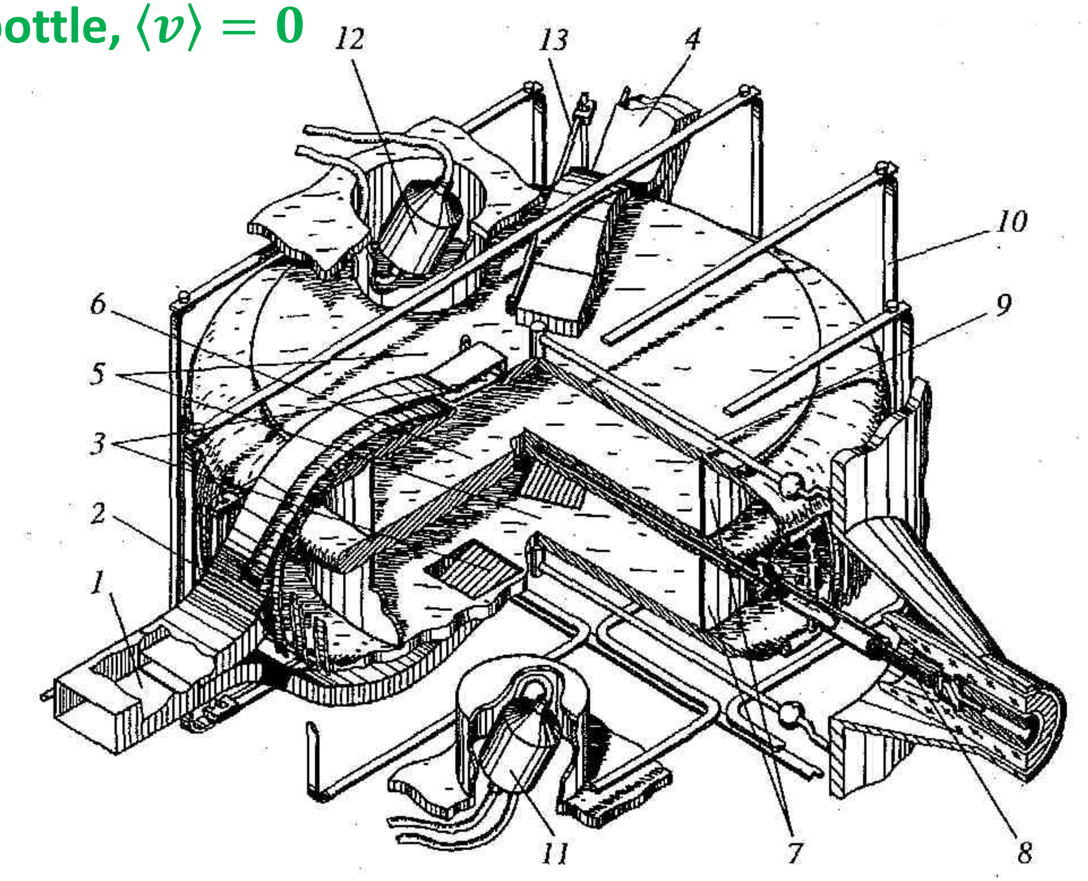


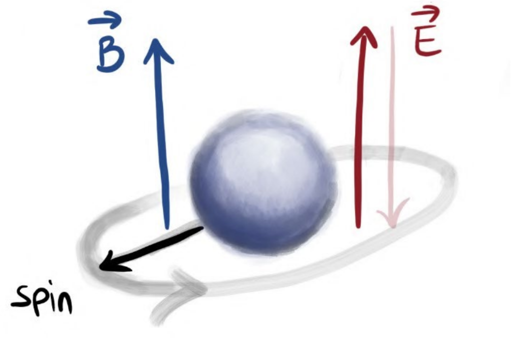
This separated oscillatory fields give
1. Narrow fringes
2. Not sensitive to the field uniformity.

UCN Bottle nEDM experiments

Problem: $v \times E$ motional field

Mitigation: UCN in a bottle, $\langle v \rangle = 0$





$$2\pi f = \frac{2\mu}{\hbar} B \pm \frac{2d}{\hbar} E$$

$$f(\uparrow\uparrow) - f(\uparrow\downarrow) = \frac{4}{2\pi\hbar} dE$$

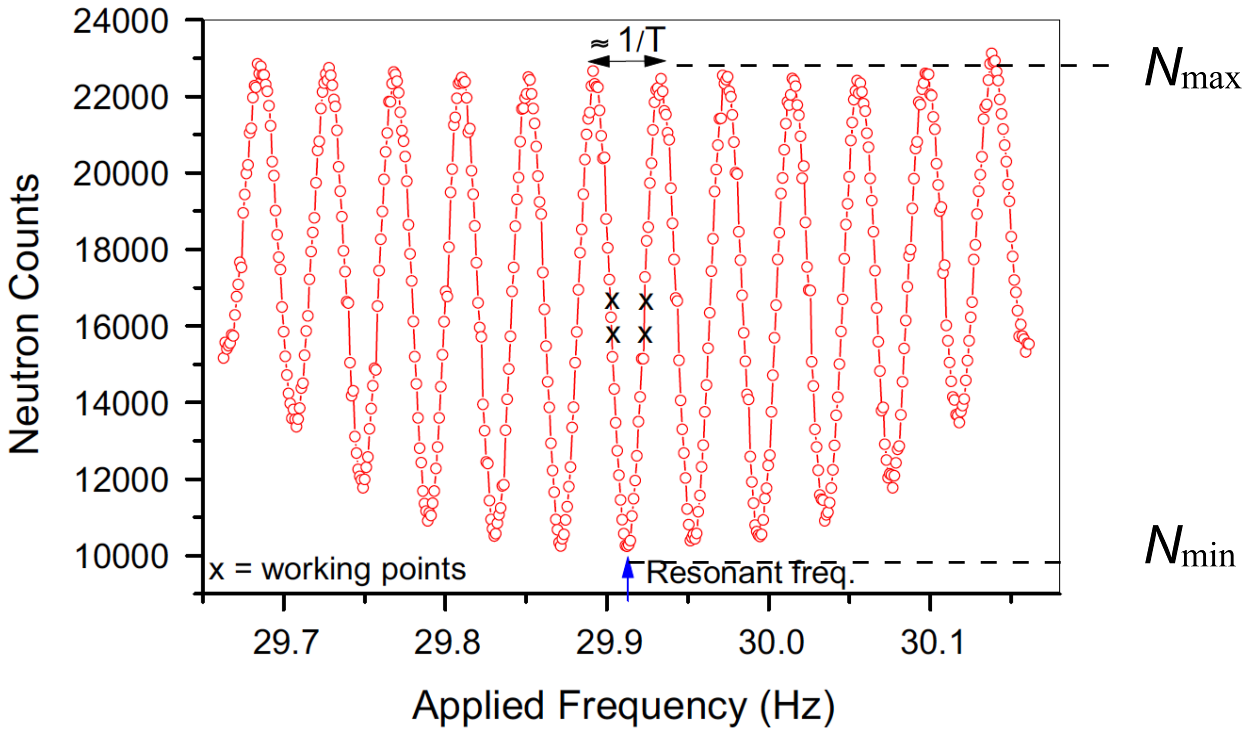
Double-cell configuration:

In one load, the EDM is extracted by the frequency difference between the two cells.

→ Less sensitive to *temporal drifts* of the background B fields.

nEDM sensitivity:

The principle is to measure frequency of spin precession, but in practice we are still counting neutrons.



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

α: fringe visibility

E: Electric field

T: Free precession time

N: number of neutrons counted

M: number of repeats

The best nEDM limit: PSI (2020)

$$\sigma(d_n) \geq \frac{\hbar}{2\alpha ET\sqrt{N}\sqrt{M}}$$

$$\alpha = 0.76$$
$$E = 11\ \text{kV/cm}$$
$$T = 180\ \text{s}$$
$$N = 11{,}400$$

$$M = 288\ \text{cycles/day}$$

2005-2015: improving OILL apparatus @ PSI
2015-2016: physics data taking
2017: field mapping

- Previous Measurement: $(-0.2 \pm 1.5_{stat} \pm 1.0_{sys}) \times 10^{-26}$ e cm
  - Infer $|d_n| < 3 \times 10^{-26}$ e cm (90% CL)
  - J. M. Pendlebury *et al.* Phys. Rev. D **92**, 092003 (2015)
- New Measurement: $(0.0 \pm 1.1_{stat} \pm 0.2_{sys}) \times 10^{-26}$ e cm
  - Infer $|d_n| < 1.8 \times 10^{-26}$ e cm (90% CL)
  - C. Abel *et al.* PRL **124**, 081803 (2020)

Additional Systematics

Effect	Shift (x10^{-28} e cm)	Error (x10^{-28} e cm)
Error on $\langle z \rangle$	···	7
Higher-order gradients $\hat{G}$	69	10
Transverse field correction $\langle B_T^2 \rangle$	0	5
Hg EDM [8]	−0.1	0.1
Local dipole fields	···	4
$v \times E$ UCN net motion	···	2
Quadratic $v \times E$	···	0.1
Uncompensated G drift	···	7.5
Mercury light shift	···	0.4
Inc. scattering ^{199}Hg	···	7
TOTAL	69	18

Included in Crossing Lines Fit (first three rows)

Dedicated mapping measurements (Higher-order gradients, Transverse field correction)

Constrained with measurement at PTB Berlin (Local dipole fields)

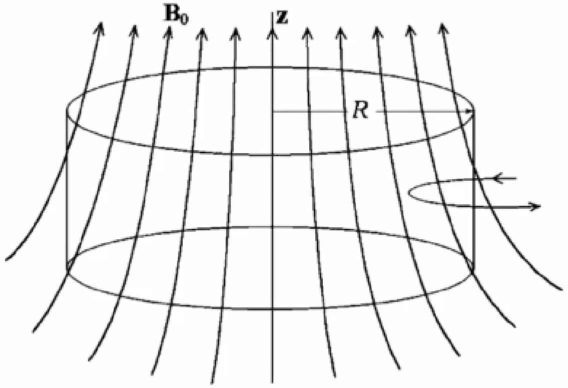
Cs Magnetometers (Uncompensated G drift)

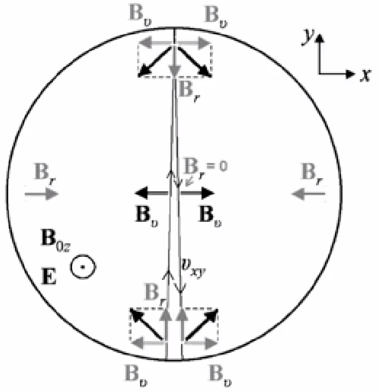
Not anticipated at design, bear in mind for next time (Inc. scattering ^{199}Hg)

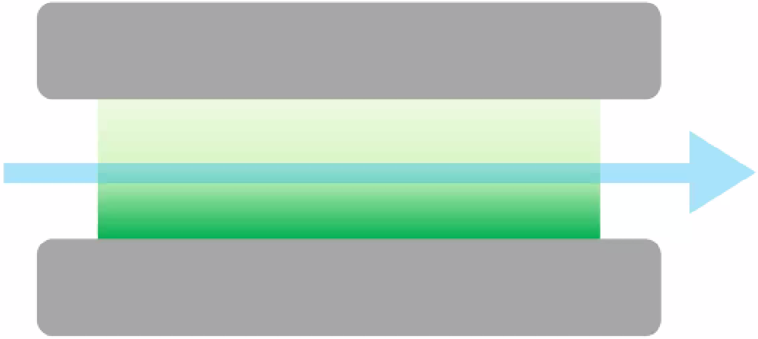
Total systematic error **0.18 x 10^{-26} e cm**
Factor 5 improvement on previous measurement
Only 20% of statistical error

From N. Ayres, nEDM2022

Leading Systematic: False EDMs and Gravitational Shift







Conspiracy between vertical gradient and motional magnetic field from Lorentz transform of *E* into Hg atom frame causes *E*-correlated frequency shift

$$d^{\text{false}}_{\text{n}\leftarrow\text{Hg}} = \frac{G_{1,0}}{1\ \text{pT/cm}} * 4.4 * 10^{-27} \text{e cm}$$

Slow UCN hang at the bottom of the chamber
Shifts $\mathcal{R}$ shift proportional to vertical gradient

$$\mathcal{R} = \mathcal{R}_0 \left(1 + G_{1,0} \frac{\Delta h}{B_0}\right) \qquad \Delta h \approx 0.35 \text{ cm}$$

To first order these are proportional, but more complicated fields can cause a “phantom” effect

PRA **99**, 042112 (2019)

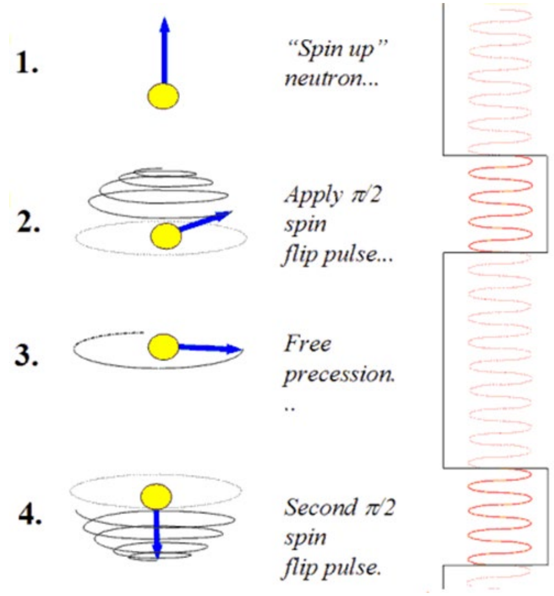
From N. Ayres, nEDM2022

Study the Systematic Effects below 1e-26 e-cm

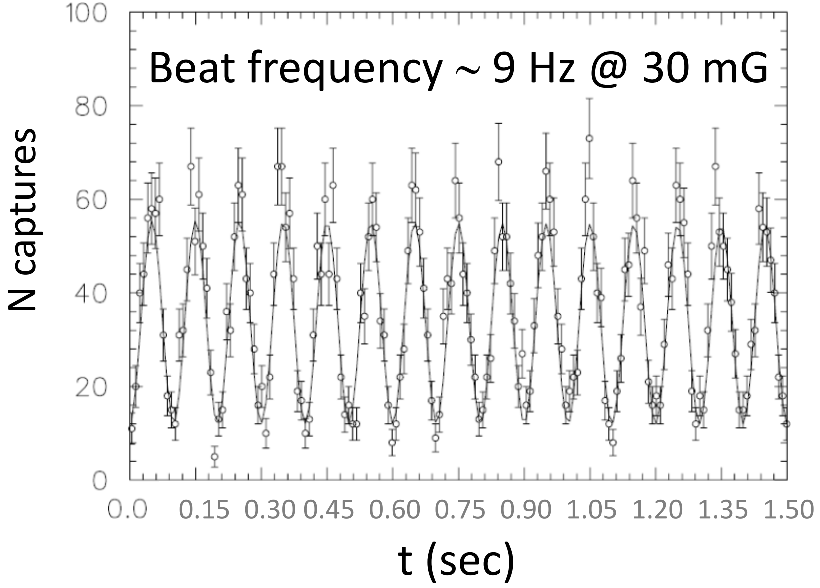
- Low-frequency field drift
  - Cancelled by Hg signal
- Leakage current
- Geometric Phase Effects
  - The field gradient coupled to the motion of UCN
- Gravitational induced frequency shift
  - Different velocity of UCN and Hg
- Earth rotation
  - Frequency shift in an accelerating frame.
- Pseudo magnetic field
  - Spin-dependent scattering between UCN & Hg
- …….

Techniques for measuring $\Delta\omega$

- Classic `Ramsey's Separated Oscillatory Fields' method
  - Precess for long time Δt accumulating $\omega_{EDM}\Delta t$ phase
  - Accumulated phase leads to different final polarization



- Comagnetometers
  - Optically pumped ^{199}Hg vapors (Room temperature exp'ts)
  - Free Precession with n-^{3}He capture (cryogenic exp'ts)



- Critical Spin Dressing
  - Golub & Lamoreaux, Phys. Rep. 237, 1 (1994)
  - Additional AC B-field matches n&^{3}**He precession frequency for E=0**
  - $d_n \neq 0$ **changes capture rate**

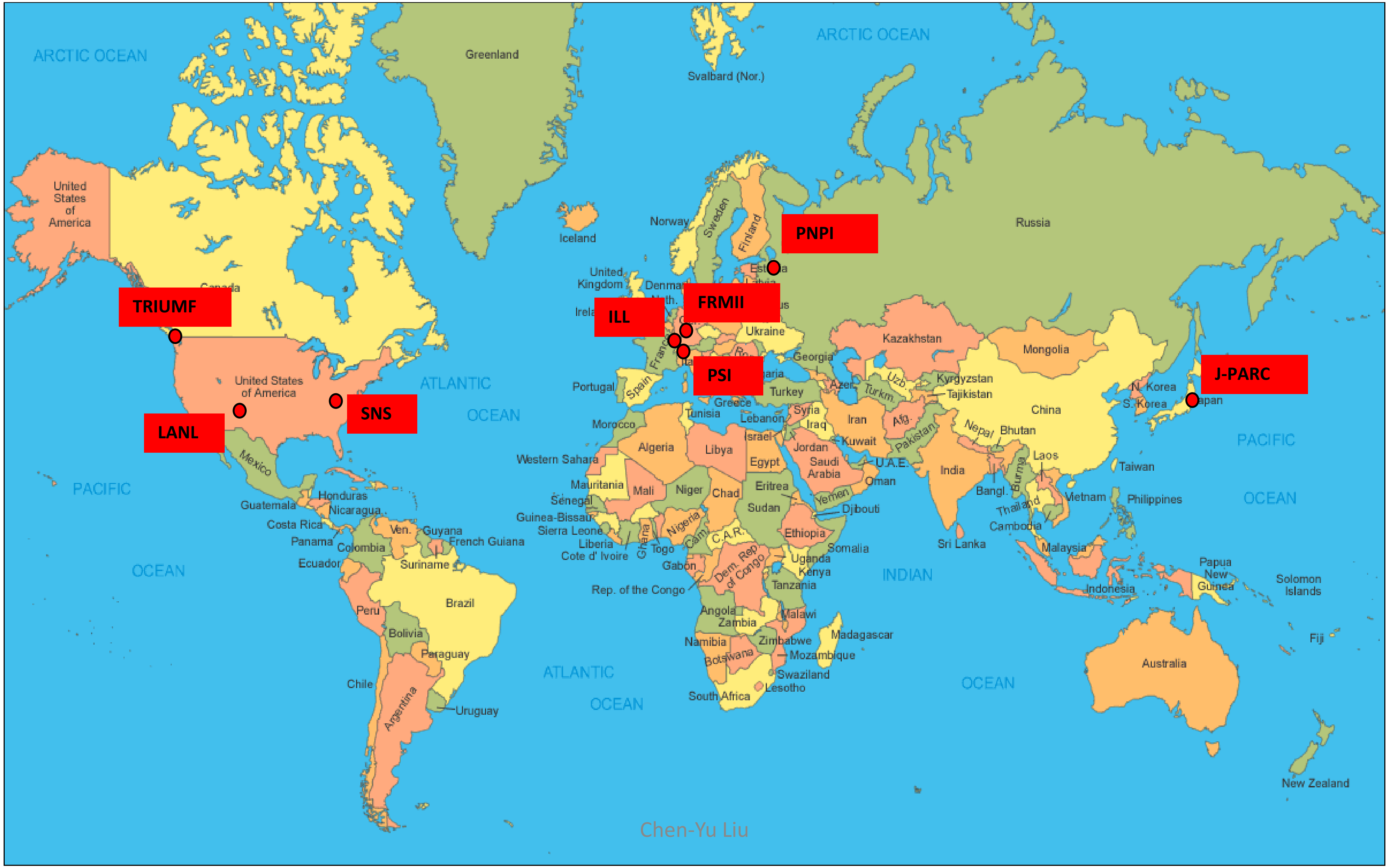
How to Improve Sensitivity

Figure of Merit $\sim \frac{1}{|\vec{E}|\tau\sqrt{N}}$

- New sources of Ultra-Cold Neutrons providing more N
  - Solid Deuterium, Superfluid LHe

- New technologies for higher $|\vec{E}|$, τ
  - Vacuum (~10kV/cm)→ Superfluid LHe (~75 kV/cm)

Neutron EDM Experiments Underway



Beyond 1e-26 e-cm…

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

Present 90% limit:
1.8 x 10^{-26} e-cm
Abel et al., PRL. 2020; 124(8): 081803

Experiment	Facility	α	E (kV/cm)	T (s)	N	neutron density (1/c.c.)	Chamber D (cm) or volume	Coating	σ(d) per day (e-cm)	σ(d) (e-cm)
OILL	PSI-sD2	0.76	11	180	11,400	2	47	DLC + dPS	11e-26	1.5e-26
n2EDM	PSI-sD2	0.8	15	180	121,000	2	80	DLC + dPS	2.6e-26	
LANL	LANL-sD2	0.8	12	180	80,000	15	47	dPS	4 e-26	3.4e-27 (1y)
TUCAN	TRIUMF-lHe				600,000-2,000,000	200-400	30,000 c.c.	dPS		1e-27 (400d)
PanEDM	ILL—lHe					3.9 40		dPE	3.8e-26 (I) 7.9e-27 (II)	3.8e-27 (100d) 7.9e-28 (100d)
PNPI	PIK—lHe		12→ 27			200			1.5e-26	1e-27 (1y)
SNS	SNS—lHe		75	500	380,000	120	3,000 c.c.	dTPB-dPS		3e-28 (3y)
BeamEDM	ILL/ESS		40	4e-2			FP=50m		5e-26	

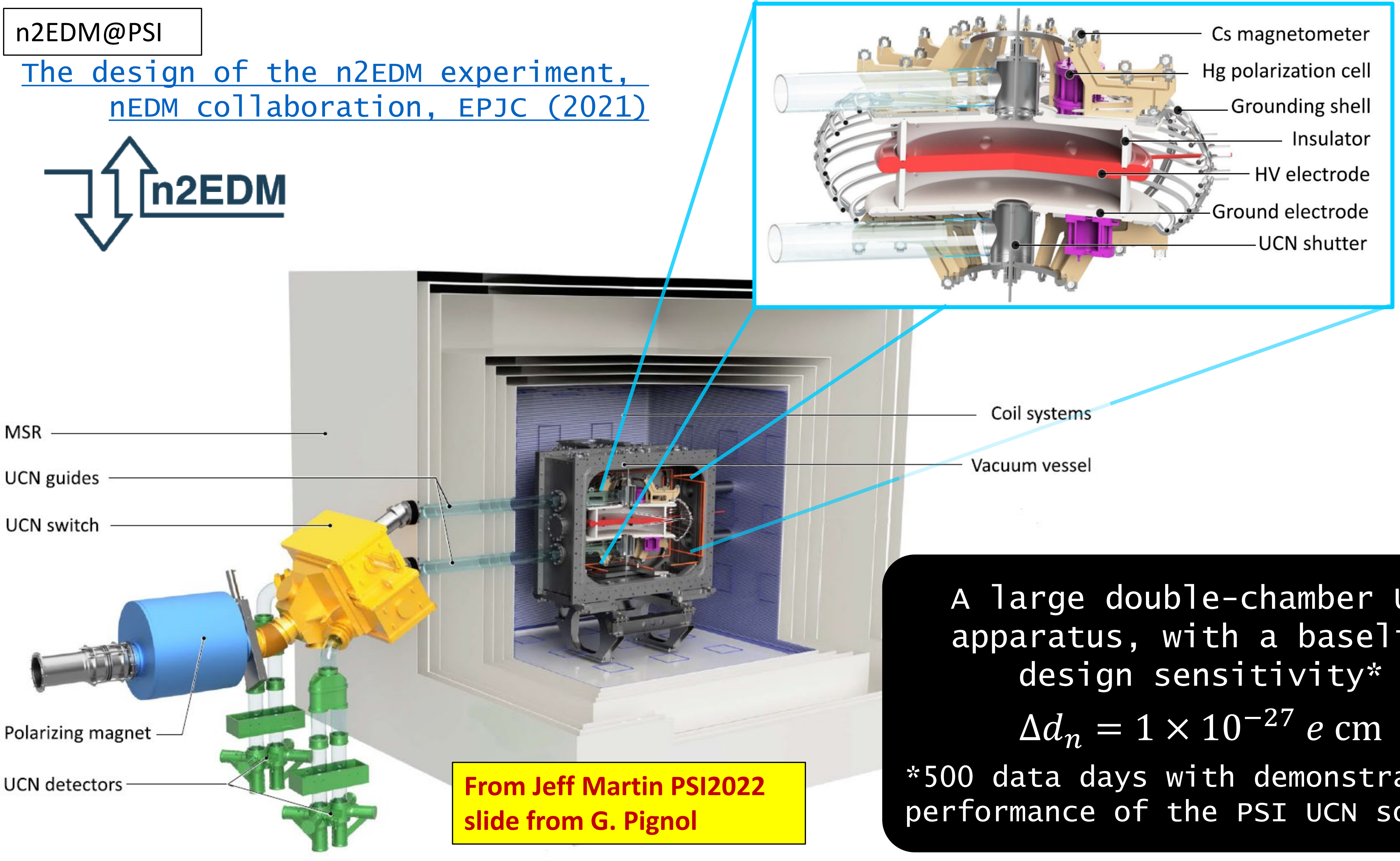
$$\sigma(d_n) \geq \frac{\hbar}{2\alpha E T \sqrt{N}\sqrt{M}}$$

nEDM sensitivity is still limited by the UCN counting statistics → continuing efforts to make more intense UCN sources

Facility		Current	Power	UCN converter	Production volume (L)	UCN rate (1/s)	Storage (s)	Temperature (K)	Heat load in target (W)	Neutron density (1/c.c.)
PSI	590 MeV p	2.4 mA (1%)	1.4 MW	sD2	30			5		2
LANL	800 MeV p	9 µA	7.2 kW	sD2	2		40	5		15
TRIUMF	480 MeV p	40 µA	20 kW	lHe	27	1.4-1.6e+7	30	1.1	8.1+1.5	200-400
ILL	9A n flux			lHe	12			0.6		200
PNPI—PIK reactor	9A n flux	5e+8 (/cm^2-s-A)		lHe				1.15	3.85	350
SNS	9A n flux	5e+8 /s		lHe	3	0.31/c.c.		0.5		

n2EDM@PSI

[The design of the n2EDM experiment, nEDM collaboration, EPJC (2021)]



From Jeff Martin PSI2022 slide from G. Pignol

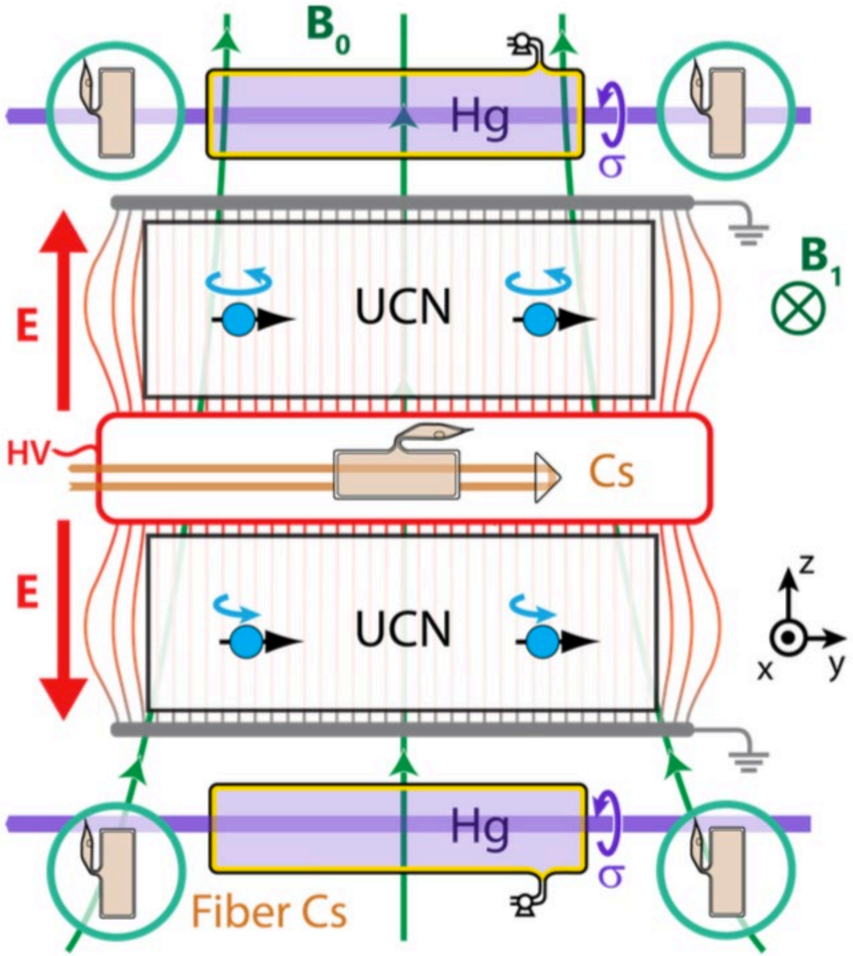
A large double-chamber UCN apparatus, with a baseline design sensitivity*

$$\Delta d_n = 1 \times 10^{-27}\, e\, \mathrm{cm}$$

*500 data days with demonstrated performance of the PSI UCN source

ILL/Munich
PanEDM

The PanEDM Experiment @ ILL



From Jeff Martin PSI2022
Adapted from P. Fierlinger

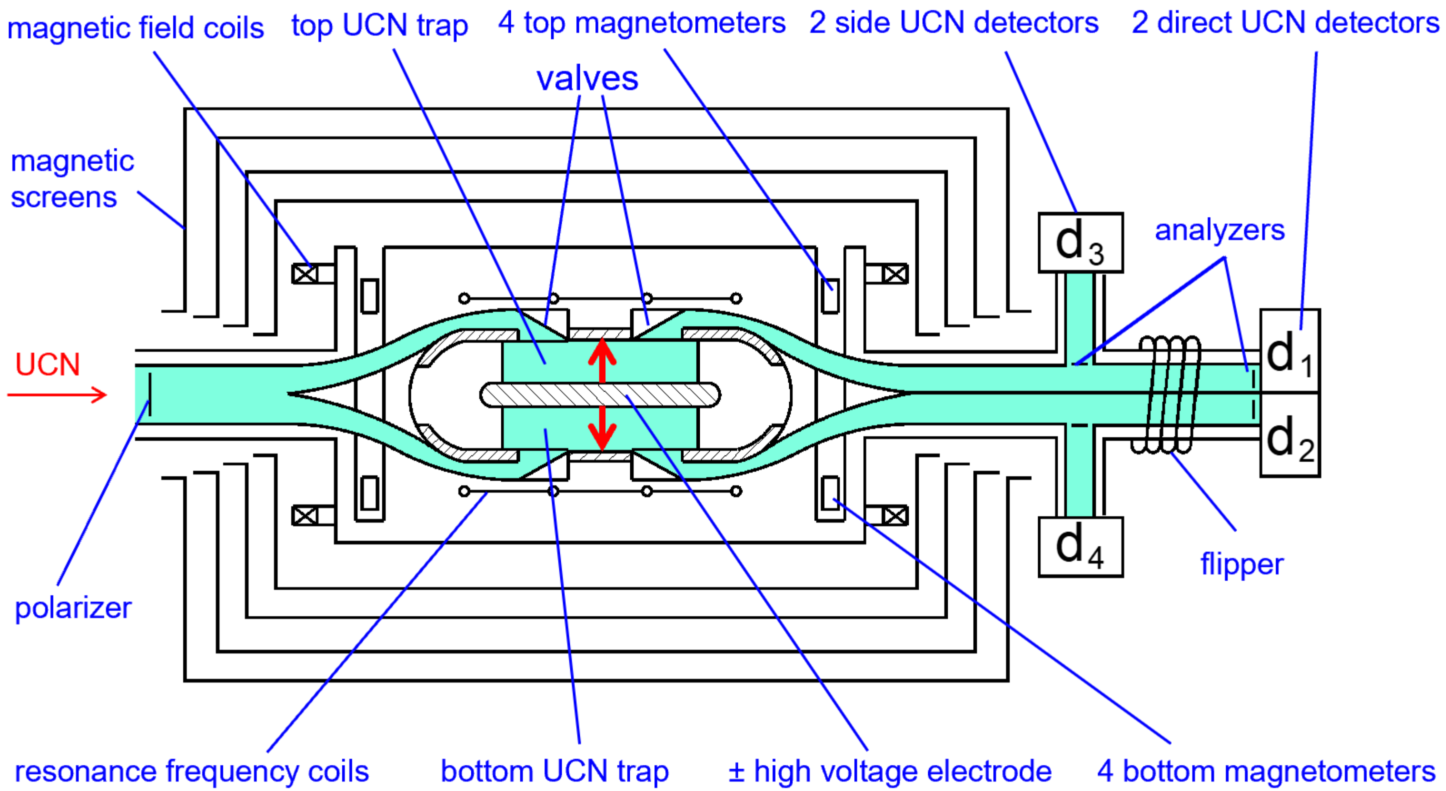
- Double chamber Ramsey experiment at room temperature
- ^{199}Hg magnetometers with few fT resolution
- Cs magnetometers also at HV
- Magnetic shield with SF 6.10^{6} at 1 mHz
- Simultaneous spin detection
- SuperSUN UCN source at ILL

  Two stages –
  - 1: unpolarized UCN with 80 neV peak
  - 2: polarized UCN, magnetic storage

Adapted from P. Fierlinger

ILL/PNPI

nEDM @ ILL/PNPI



Spectrometer used

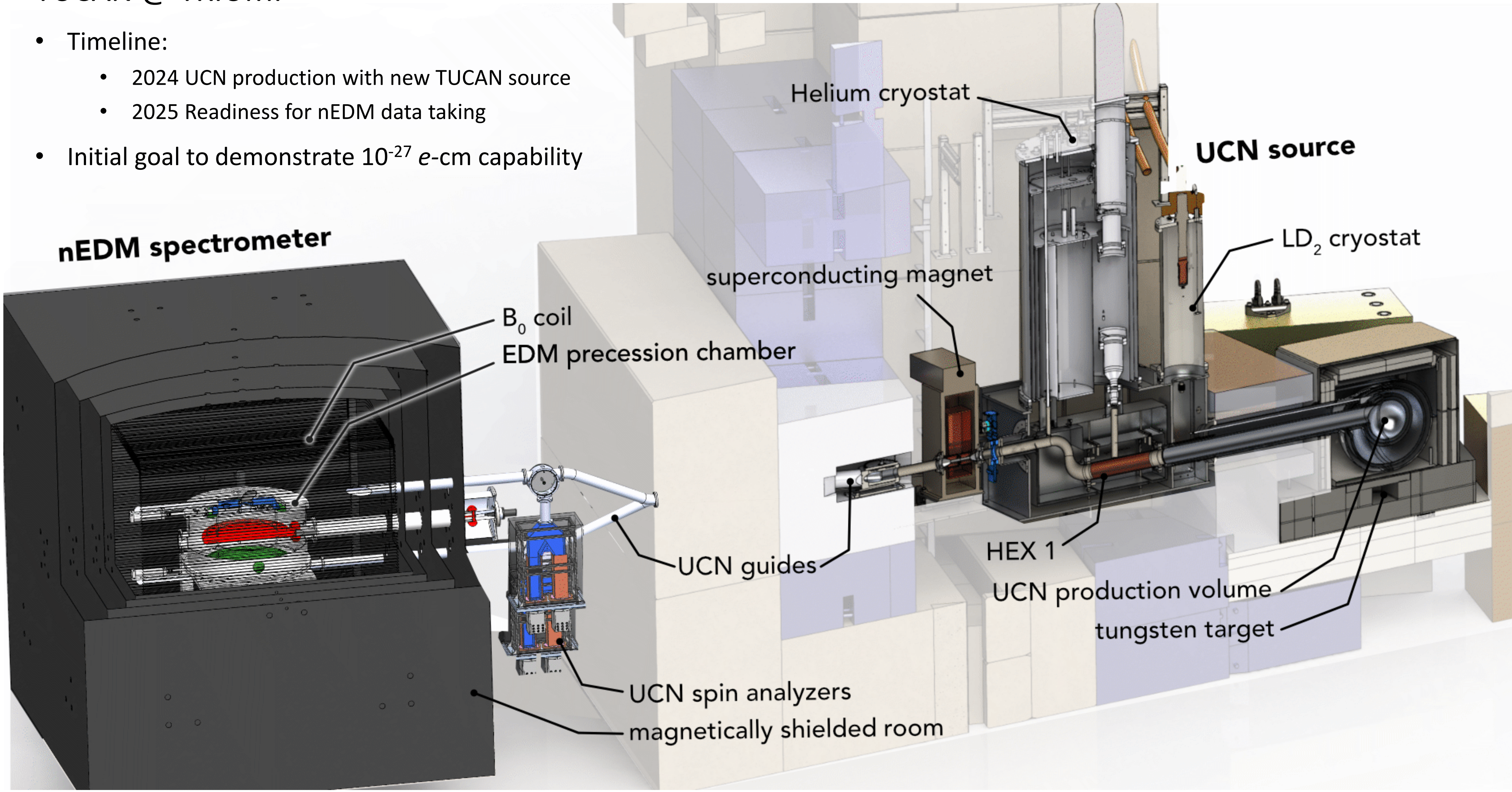
- 1985 – 1996 at PNPI
- 2008 – 2013 at ILL
- Plan to move to PNPI (Gatchina) to a new He-II UCN source

From Jeff Martin PSI2022
Adapted from A. Serebrov

TUCAN

TUCAN @ TRIUMF

- Timeline:
  - 2024 UCN production with new TUCAN source
  - 2025 Readiness for nEDM data taking
- Initial goal to demonstrate 10^{-27} *e*-cm capability

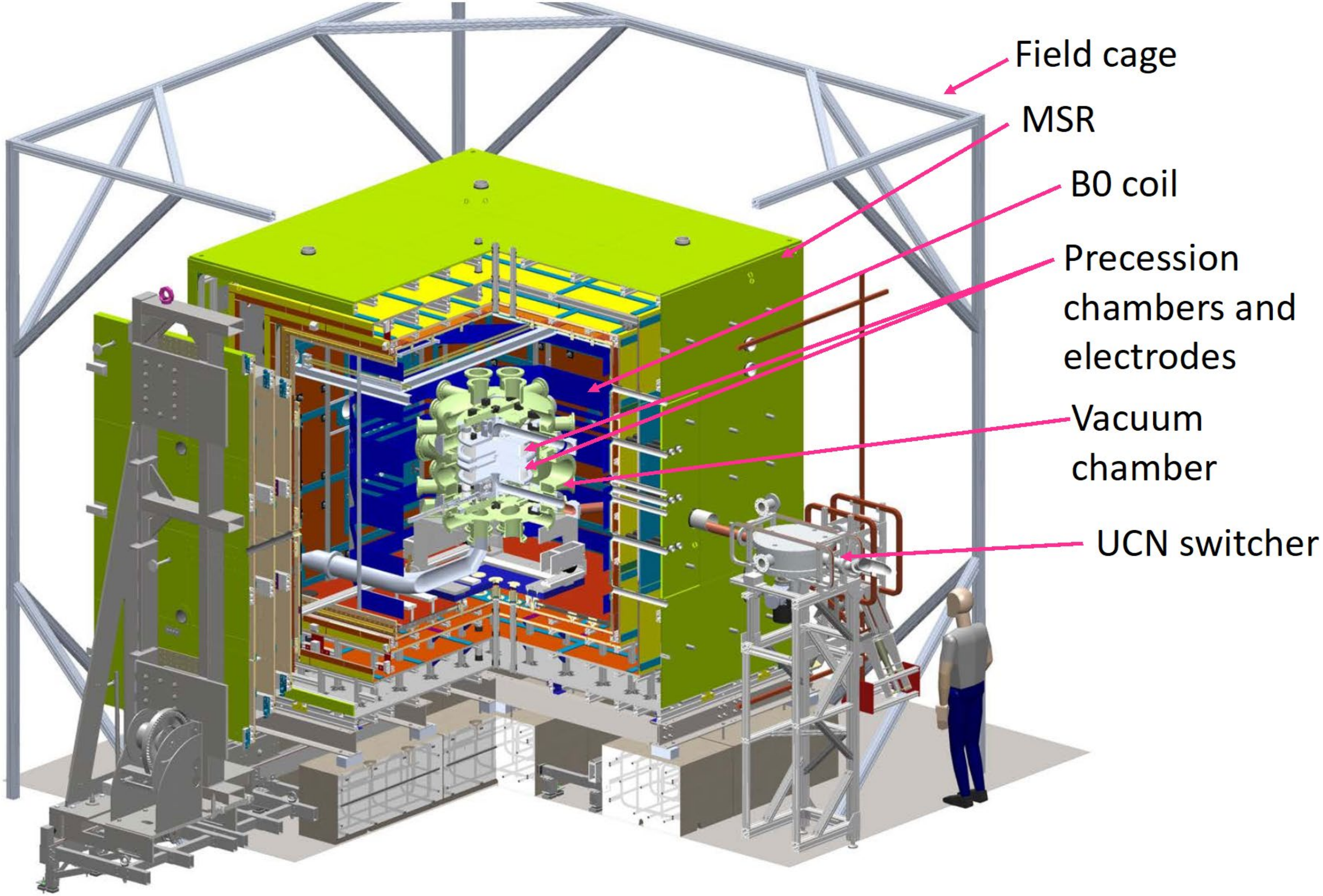


From Jeff Martin PSI2022

LANL nEDM

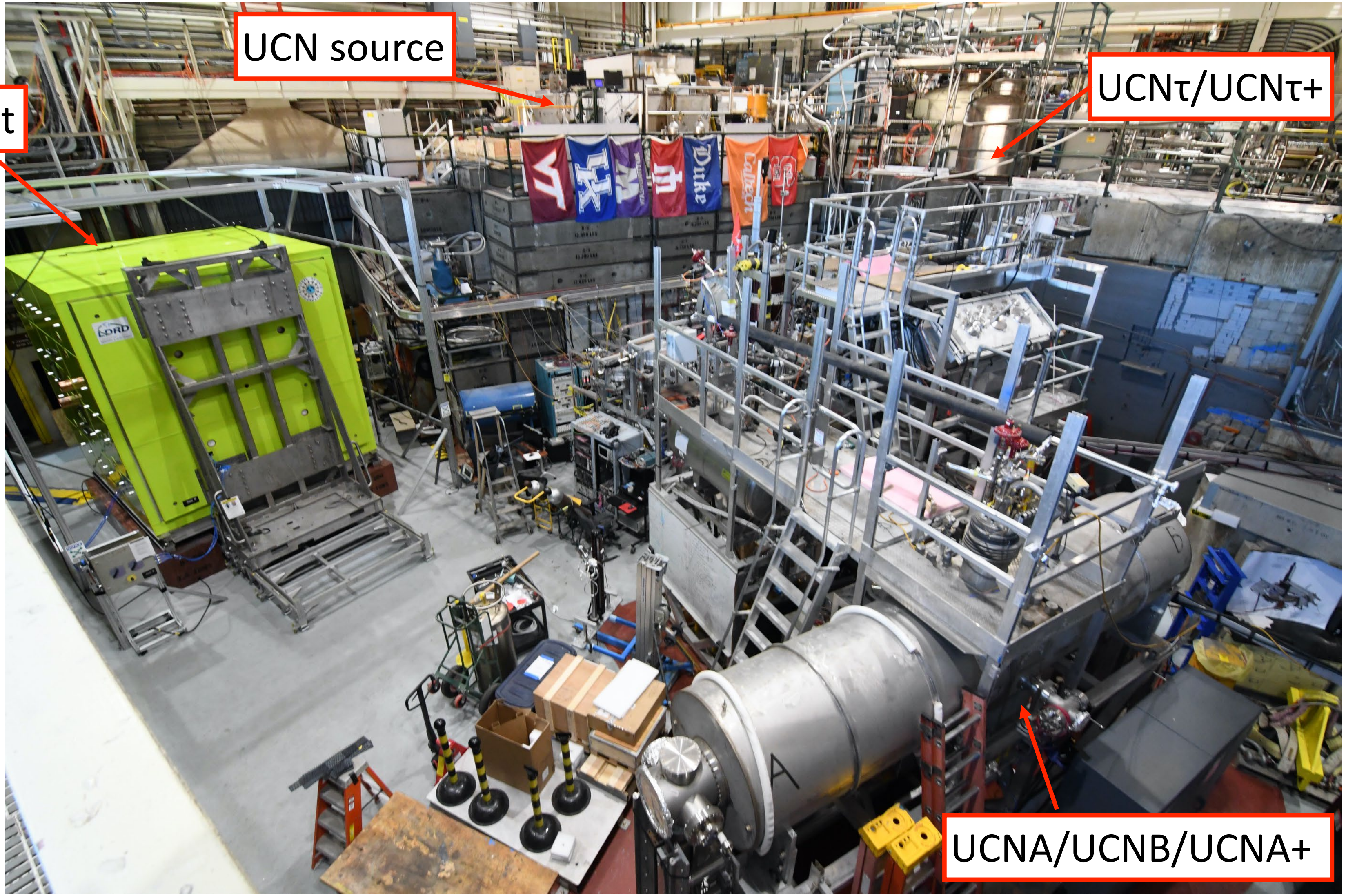
LANL nEDM experiment

- Successfully upgraded LANL UCN source has demonstrated the UCN density required for an nEDM experiment with $\delta d_n \sim O(10^{-27})$ *e*-cm
- Venue for the US nEDM community to obtain physics results, albeit less sensitive, in a shorter time scale with much less cost while development for the SNS nEDM experiment continues.
- Based on the measured stored polarized UCN density, we expect to achieve a statistical sensitivity of 2×10^{-27} *e*-cm in one live-year of running.



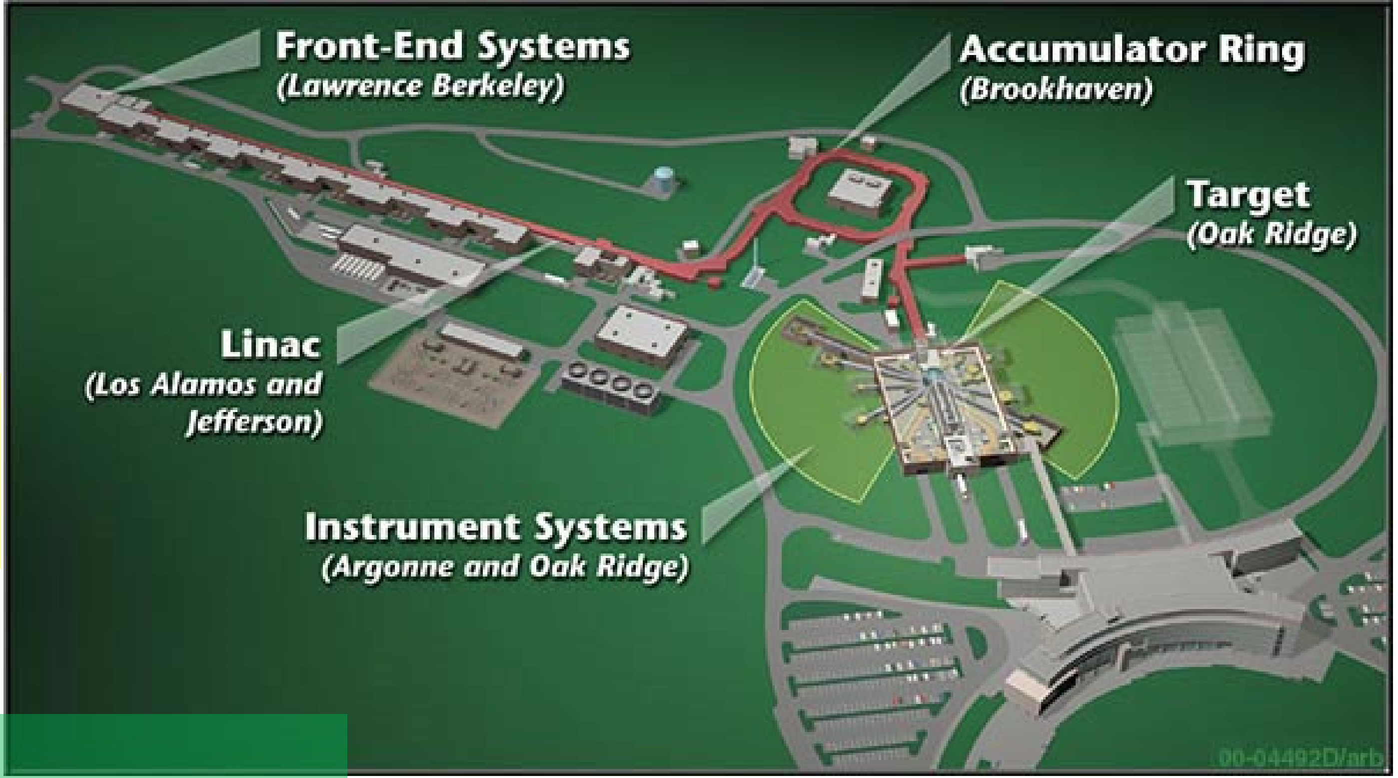
LANL UCN Experimental Hall

- MSR has been installed. It has been shown to meet the specs on both the shielding factor (10^5 @ 0.01 Hz) and the residual field ($\lesssim$ 0.5 nT).
- Assembled the precession chambers and UCN valves.
- Started engineering run w/ UCN in CY2022.
- Integrating Hg comagnetometer system in CY2023



nEDM@SNS

Spallation Neutron Source at ORNL



Concept:
R. Golub & S. K. Lamoreaux, Phys. Rep. 237, 1 (1994)

- High trapped neutron densities
  Superfluid Helium moderator
- LHe as HV insulator
  > 70 kV/cm vs 10 kV/cm
- Use of a $^{3}\vec{\mathrm{He}}$ co-magnetometer and superconducting shield
  Control of systematics
- Variation of LHe temperature to study v x E systematics
  Monitor of systematics
- Precession frequency measurement via two techniques
  Cross-check of non-zero signal
- Unprecedented sensitivity reach
  $d_n < 3 \times 10^{-28}$ e-cm (in 3 calendar yrs)

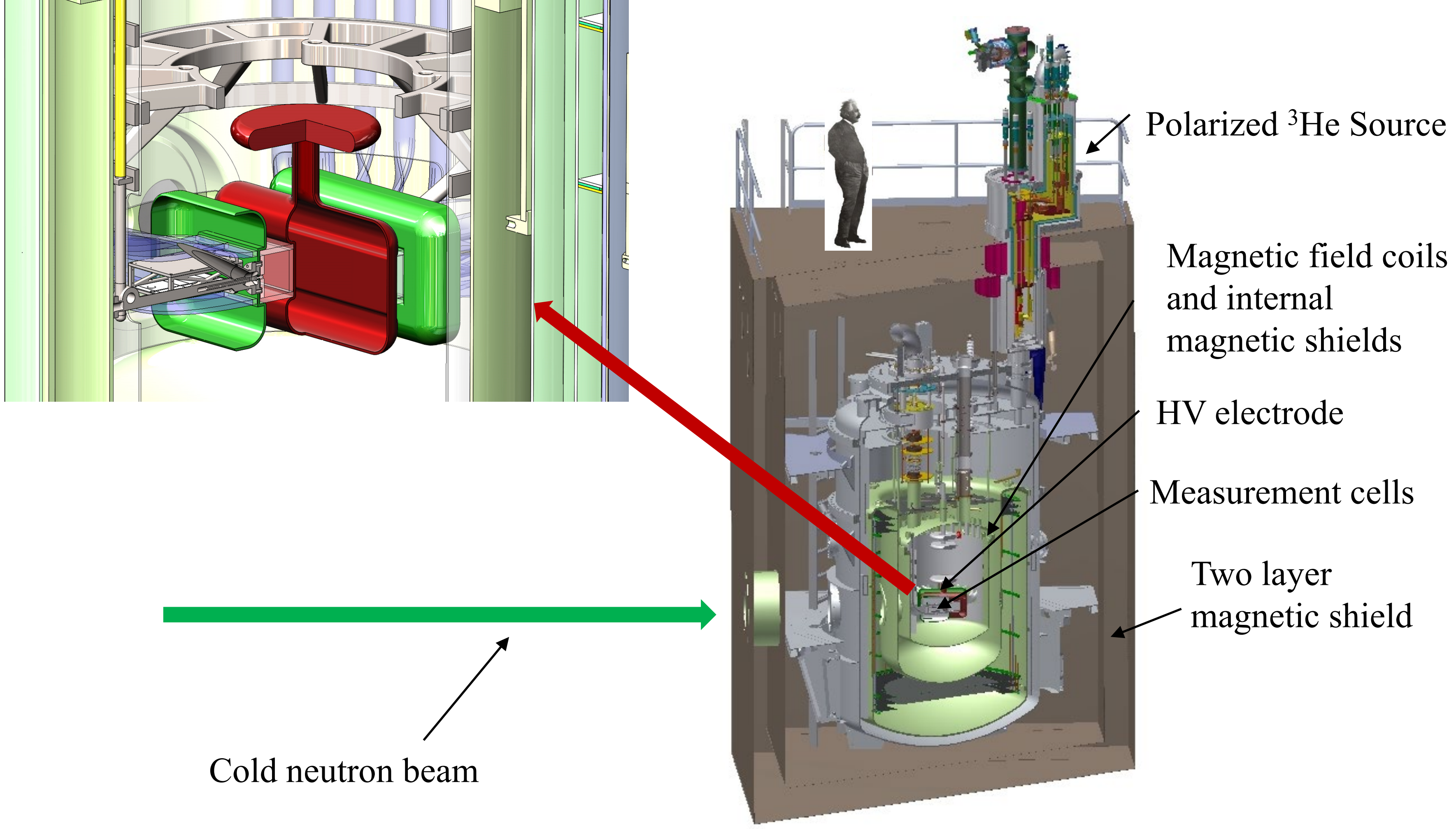
All unique to nEDM@SNS

"Most ambitious nEDM experiment that is currently underway"
nEDM@SNS Review Committee

Slide credit: B. Filippone (FSNN Townhall, 2022)

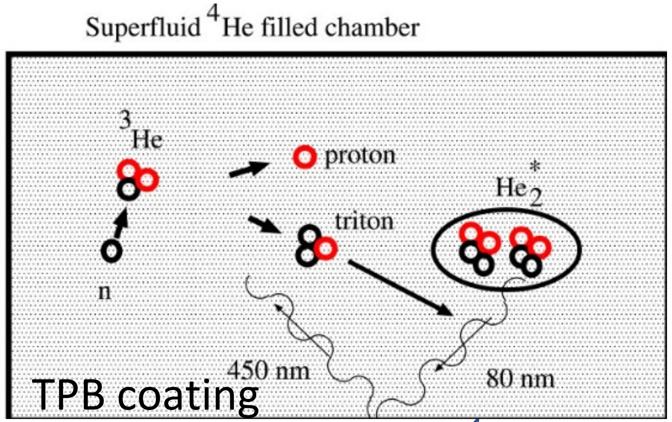
nEDM@SNS Experimental Design

Details: M.W. Ahmed at al 2019 JINST 14 P11017



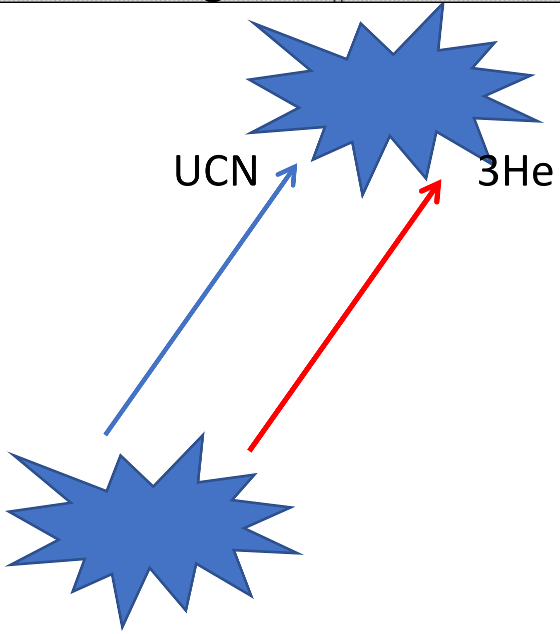
Experiment uses ^{3}He as detector

R. Golub and S. K. Lamoreaux, Phys. Rep. 237 (1994) 1



- UCN too dilute to detect with magnetometer (SQUID)
- Inject small concentration (~ 10^{-11}) of polarized ^{3}He
- Look for reaction: n + ^{3}He → t + p + 764 keV
  - t, p scintillate in ^{4}He
  - Pipe through light guides and detect with PMT

To measure spin precession:



- n + ^{3}He → t + p:

  σ (^{3}He, n: ↑↓singlet) ~ 10^7 b

  σ (^{3}He, n: ↑↑ triplet) < 10^4 b

- $\mu_{He}/\mu_n = 1.11$

  ^{3}He spins will rotate ahead of n spins in same *B*

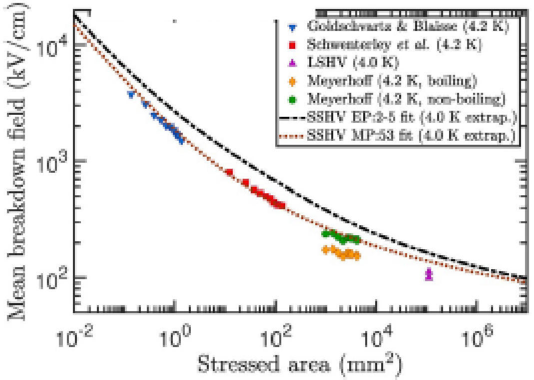
Scintillation light according to $\Phi = \Phi_0 \sin(\omega_{He} - \omega_n)\, t \sim 1 - P_n P_3 \cos(\omega_{He} - \omega_n) t$

- Independent monitor of ^{3}He spins with SQUIDs

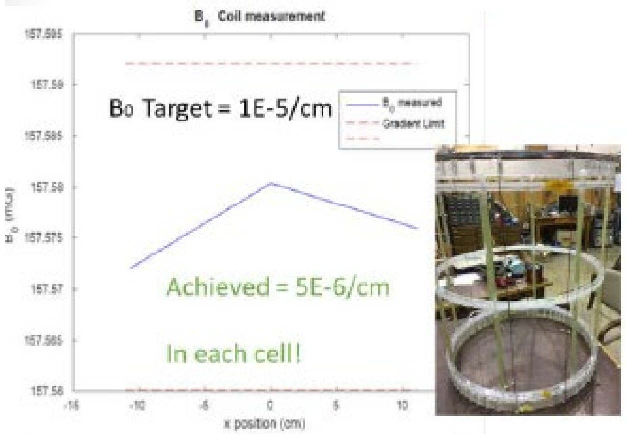
Major R&D Progress: Pre-2021

1/5-Scale High Voltage System Achieved 85 kV/cm with PMMA Electrodes with Copper Implantation

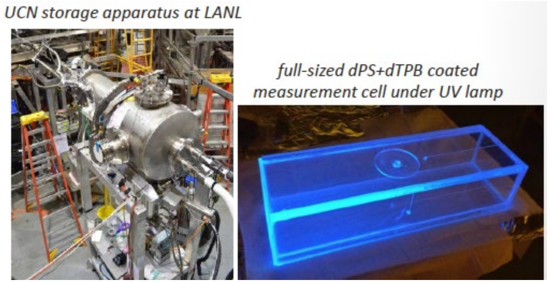
High Voltage Studies Revealed Key (Area) Scaling Laws



1/3-Scale Magnet System Demonstrated Field Gradient Requirements

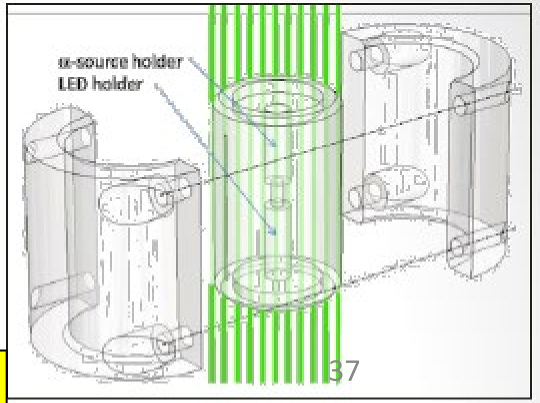


Measured 1800 s UCN Wall Loss Time in Cryogenic Environment



^{3}He System Constructed Full-Scale Non-Magnetic Dilution Refrigerator

Light Collection Prototype Extrapolates to 17 PE in Final Apparatus



From Brad Plaster PSI2022

Summary

- EDMs provide significant reach for BSM physics via new CP-violation
    - nEDM offers a particularly strong constraint when new physics couples to quarks/gluons.

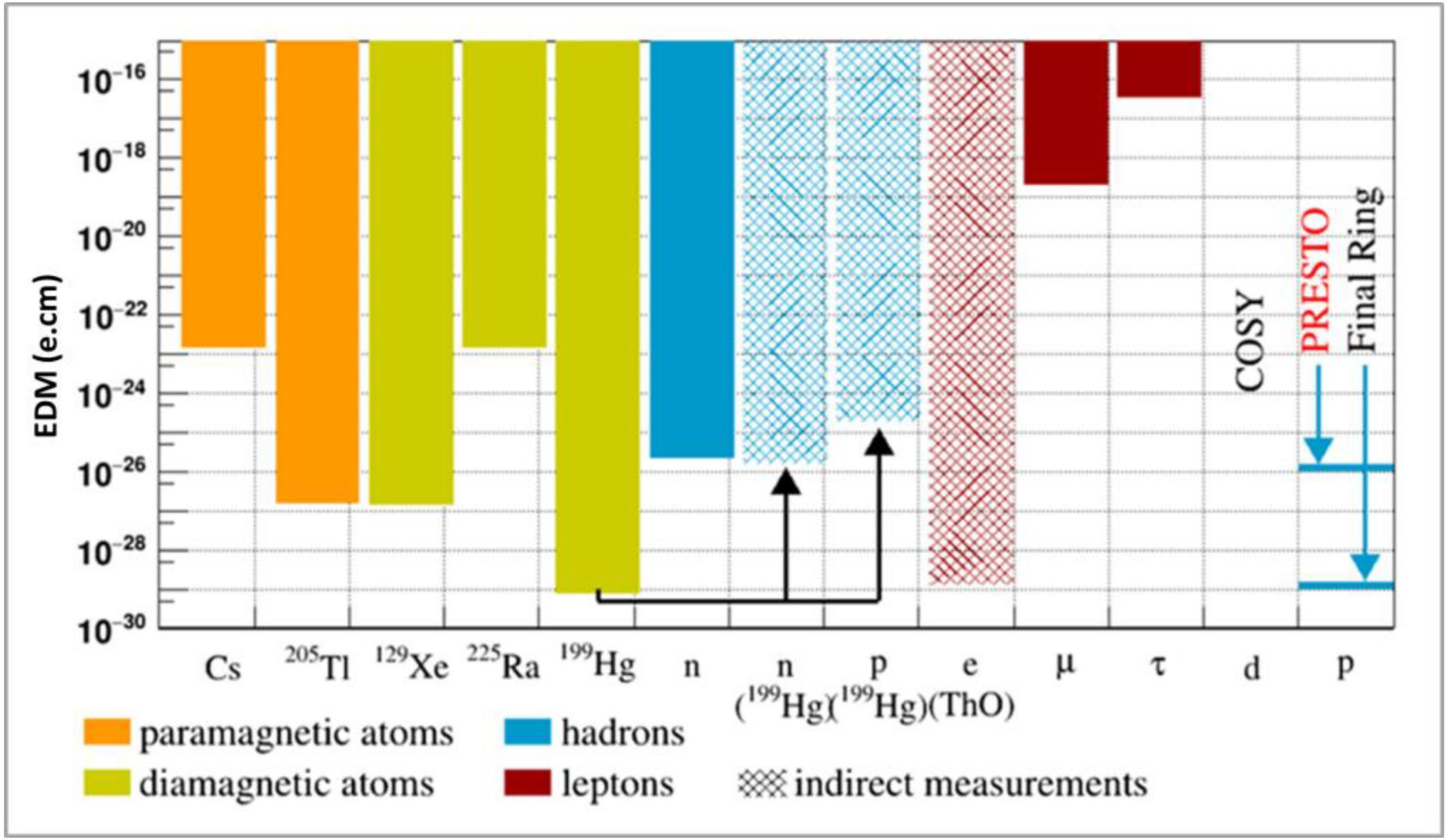
- Neutron EDM measurements are underway to extend sensitivity up to 2 orders-of-magnitude
    - Next generation of experiments aims at 10^{-27} e-cm uncertainty, order of magnitude improvement mostly arising from UCN source increase.
    - Experiments developing innovative techniques to achieve 10^{-28} e-cm.

- Multiple International efforts (PSI, ILL, TRIUMF) are underway

- Two competitive/world-leading efforts are underway in the US

EDM limit comparison

Particles **2023**, *6*(1), 385-398



Recent Hardware Progress

- Full-scale Cryogenic Magnet System being assembled at SNS
  - Preparing for polarized neutron beam through system to test for polarization loss and transmission issues
- New HV scaling studies indicate low-breakdown probability
- Potential additional electrode material recently identified
- Spin-dressing studies beginning at NCSU PULSTAR Systematics and Operational Studies (SOS) apparatus
- Recently completed large $4x4x7m^3$ 2-layer Magnetic Shield Enclosure meets specs

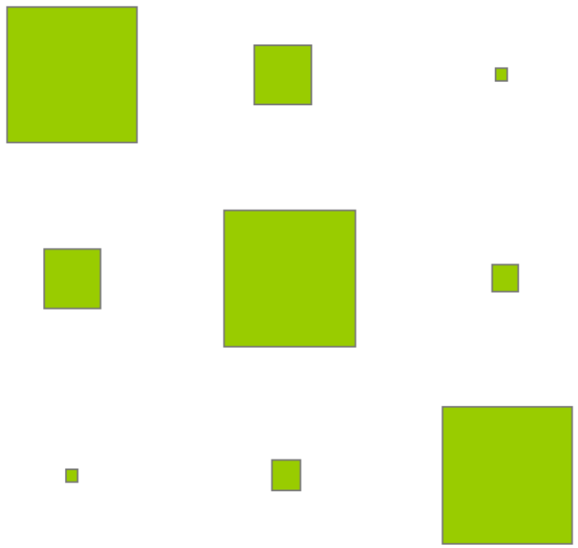
Slide credit: B. Filippone (FSNN Townhall, 2022)

The CKM matrix quantifies the quark flavor mixing.

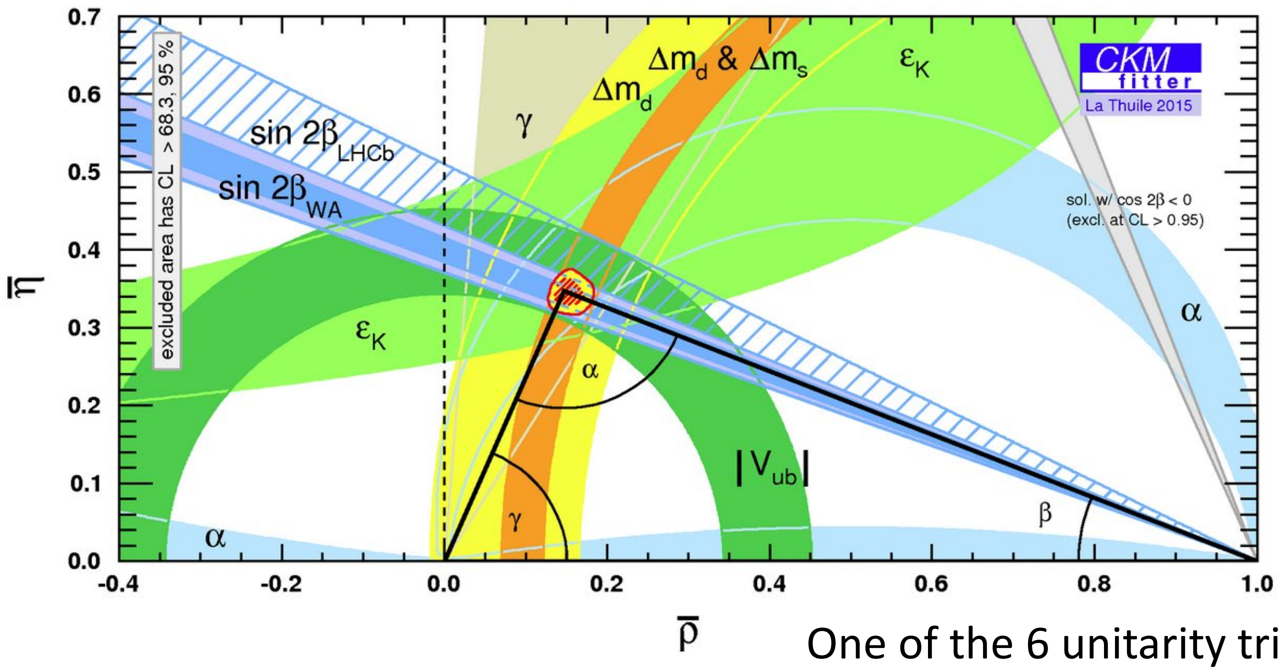
$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

Wolfenstein parameterization – expansion in λ = sin θ_C ~0.22

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$



V_{us}=λ=sin Θ_c



One of the 6 unitarity triangles

Area of the triangle → CP-violating phase