Searching for the Electric Dipole Moment of the Neutron, the Holy Grail of Precision Measurements

Chen-Yu Liu
Indiana University

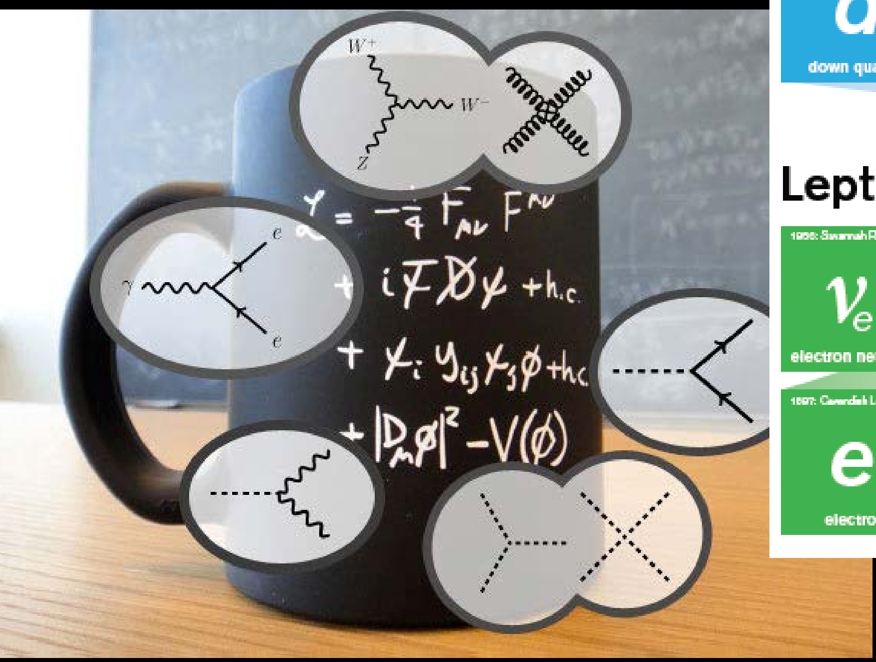
September 25, 2016

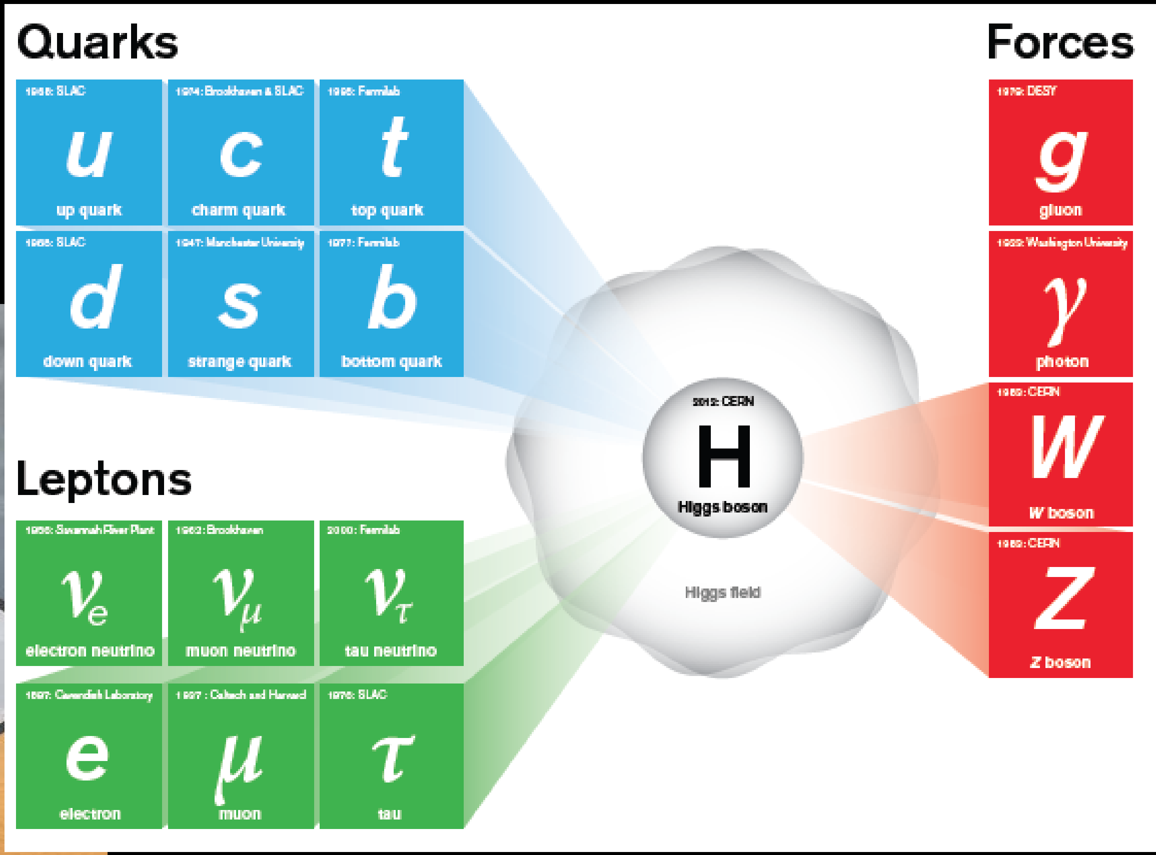
SPIN Conference

Physics in the late 19th century

Albert A. Michelson, in 1894, stated: "… it seems probable that most of the grand underlying principles have been firmly established … An eminent physicist remarked that *the future truths of physical science are to be looked for in the sixth place of decimals*."

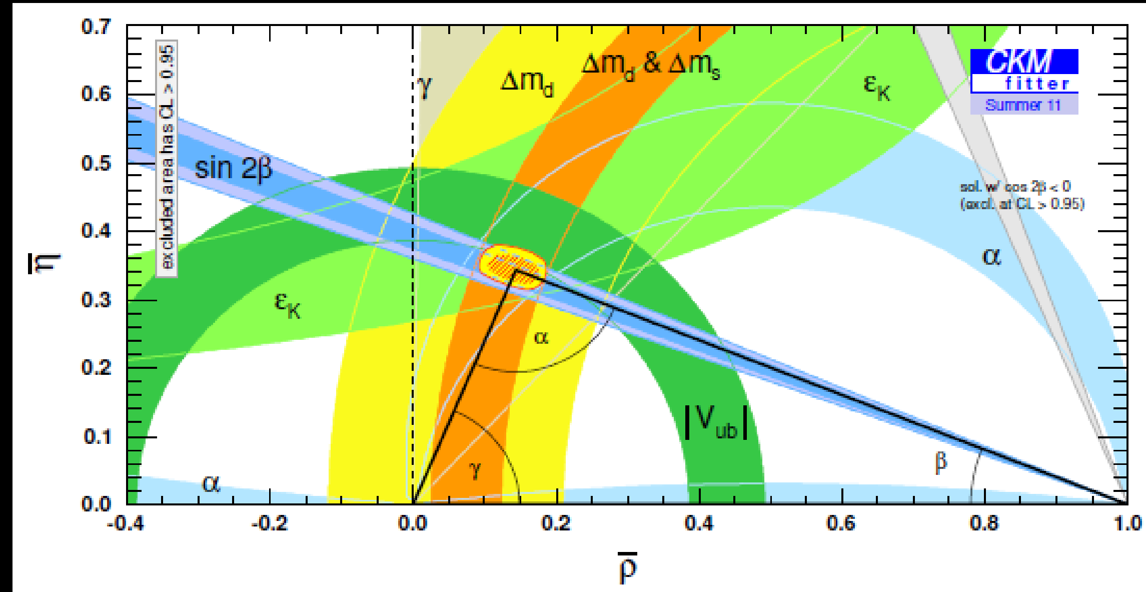
Standard Model of Particle Physics (the bright side)



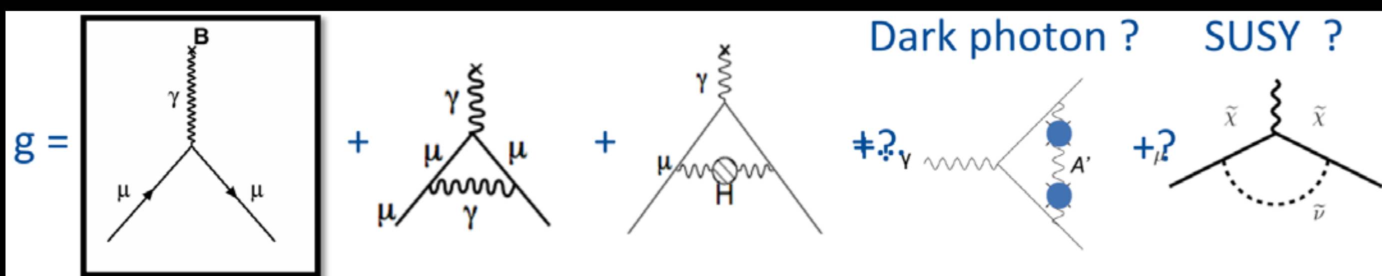


Standard Model of Particle Physics (the dark side)

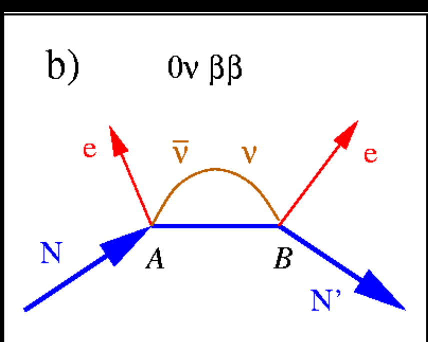
Precision Measurements



Muon Anomaly $\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 276(80)\times10^{-11}$



$g = 2 + \alpha/2\pi + 6\times10^{-8} + \ldots + ? \quad +?$



<u>MuLAN & FAST experiments at PSI</u>:

$\tau_{\mu+}$=2.1969803(22)x10^{-6}sec MuLAN 2010

(Most precise lifetime measurement ever!)

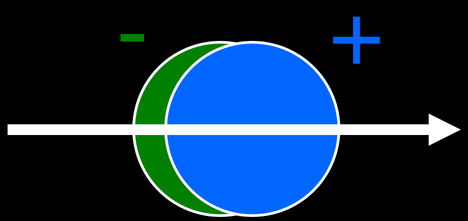
Improved Previous World Average by error/20!

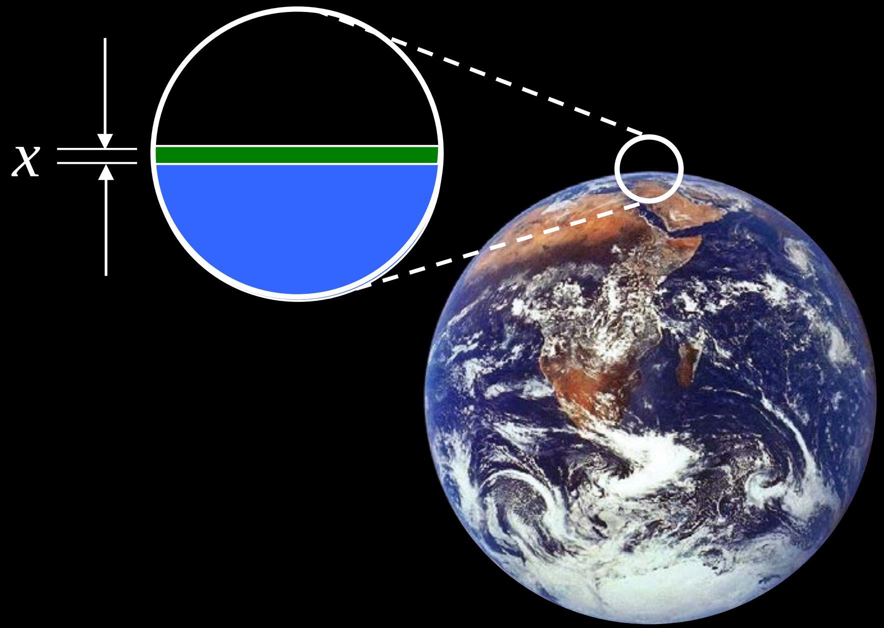
and many more…

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





- Current limit [1]:

  $d_E < 2.9 \times 10^{-26}$ e-cm

- First experiment (1957):

  $d_E < 5 \times 10^{-20}$ e-cm

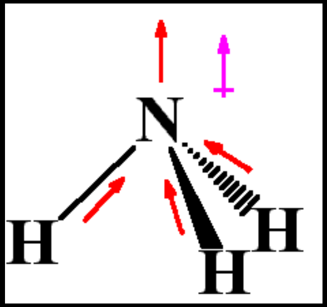
<u>Charge separation for an earth-size neutron</u>

Current limit: $\Delta x < 3 \times 10^{-13} r_E$ $(4\ \mu\mathrm{m})$

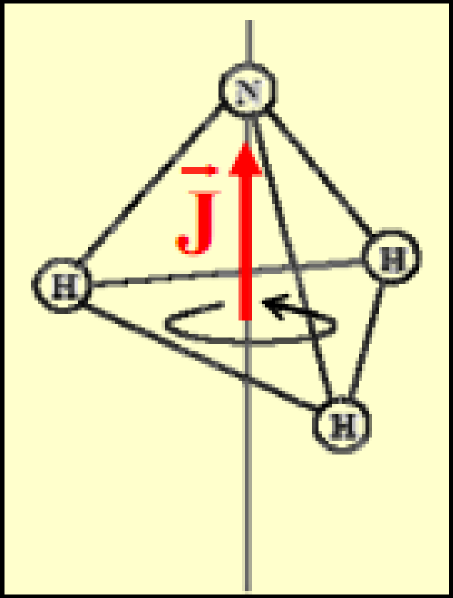
Goal sensitivity: $\Delta x < 3 \times 10^{-15} r_E$ $(40\ \mathrm{nm})$

[1] PRL 97 131801 (2006)

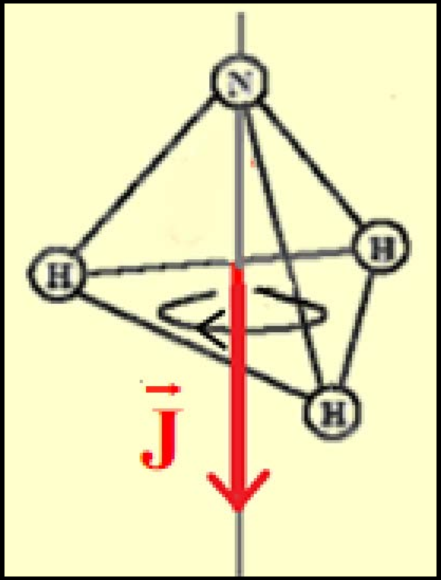
Electric Dipole Moment of polar molecules



NH_3 molecule has two (degenerate) ground states:

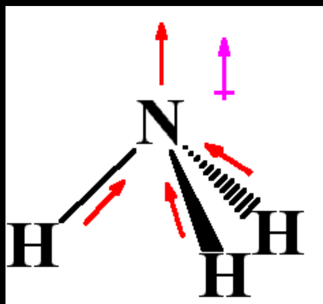


$$\vec{d} = d\,\frac{\vec{J}}{|J|}$$



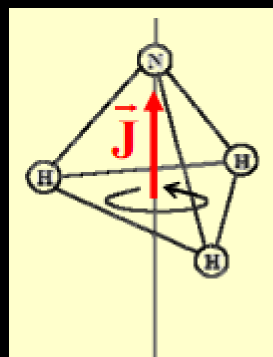
$$\vec{d} = -d\,\frac{\vec{J}}{|J|}$$

Electric Dipole Moment of polar molecules

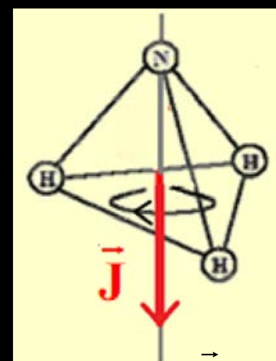


NH_3 molecule has two (degenerate) ground states:

$$|\varphi_G\rangle_1 = \frac{1}{\sqrt{2}}\Big\{$$

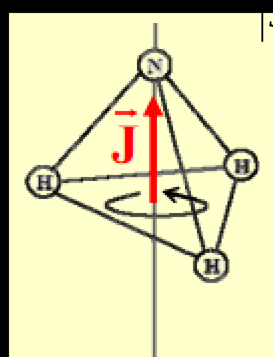


$$+$$

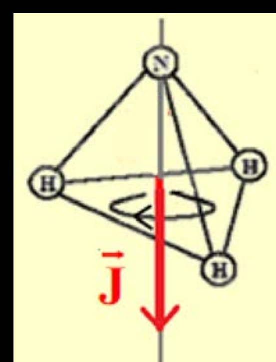


$$\Big\} \quad \xrightarrow{T} \quad |\varphi_G\rangle_1$$

$$|\varphi_G\rangle_2 = \frac{1}{\sqrt{2}}\Big\{$$



$$-$$



$$\Big\} \quad \xrightarrow{T} \quad -|\varphi_G\rangle_2$$

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

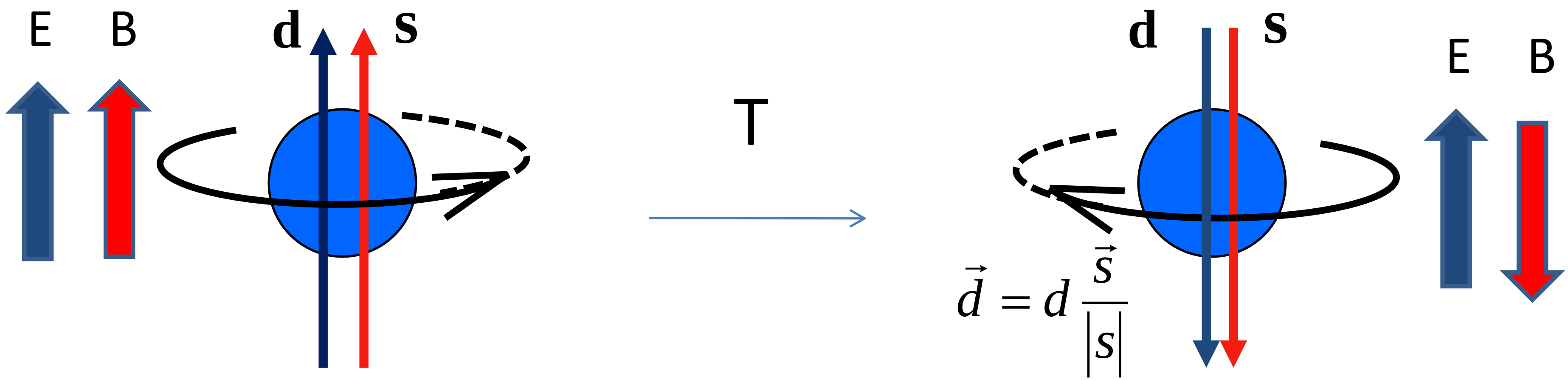
NH_3: d = 0.3 x 10^{-8} e-cm
$H_2 0$: d = 0.4 x 10^{-8} e-cm
NaCl: d= 1.8 x 10^{-8} e-cm

A permanent EDM is possible without violations in T (&P).

Electric Dipole Moment of fundamental particles

Fundamental particles don't have degenerate ground state, so $\vec{d} = d\hat{J}$.

Say, if the ground state (under fields) is



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

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

T-odd Pseudo-scalar

T-even scalar

	C	*P*	*T*
$\vec{E}$	-	-	+
$\vec{J}$	+	+	-
$d\hat{J}$	-	+	-

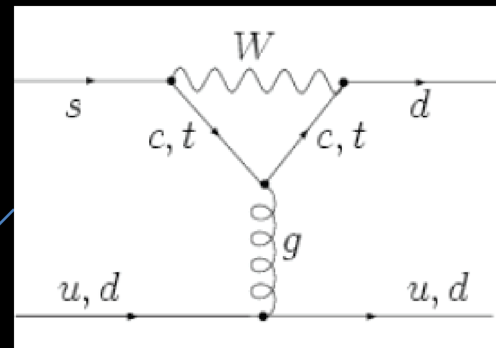
$$|\varphi_G\rangle \xrightarrow{T} |\varphi'\rangle$$

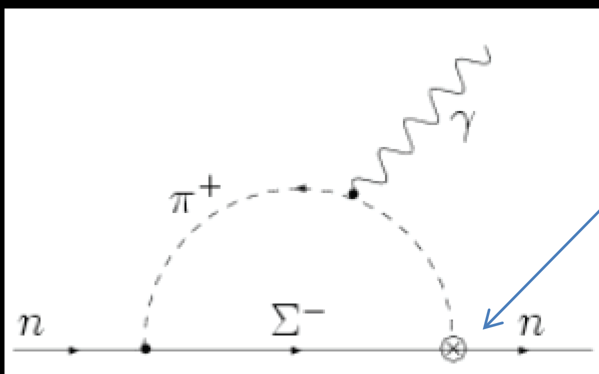
The ground state is not a T eigenstate!

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

EDM is a sensitive probe for symmetry-violating physics.

nEDM: violates P and T

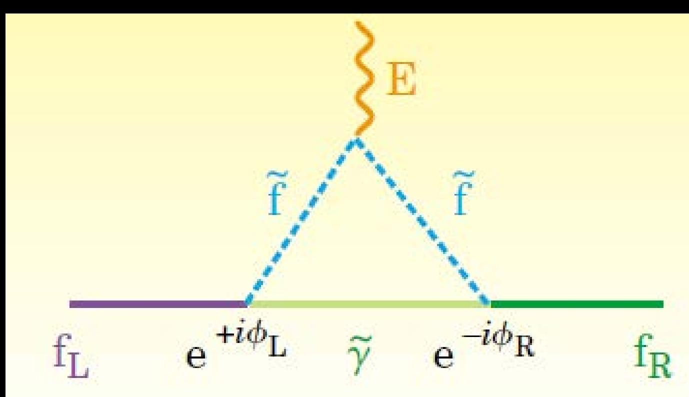


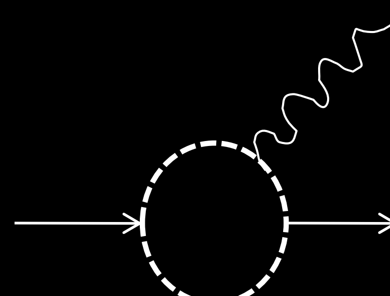


Suppressed 3-loop effect in the Standard Model

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

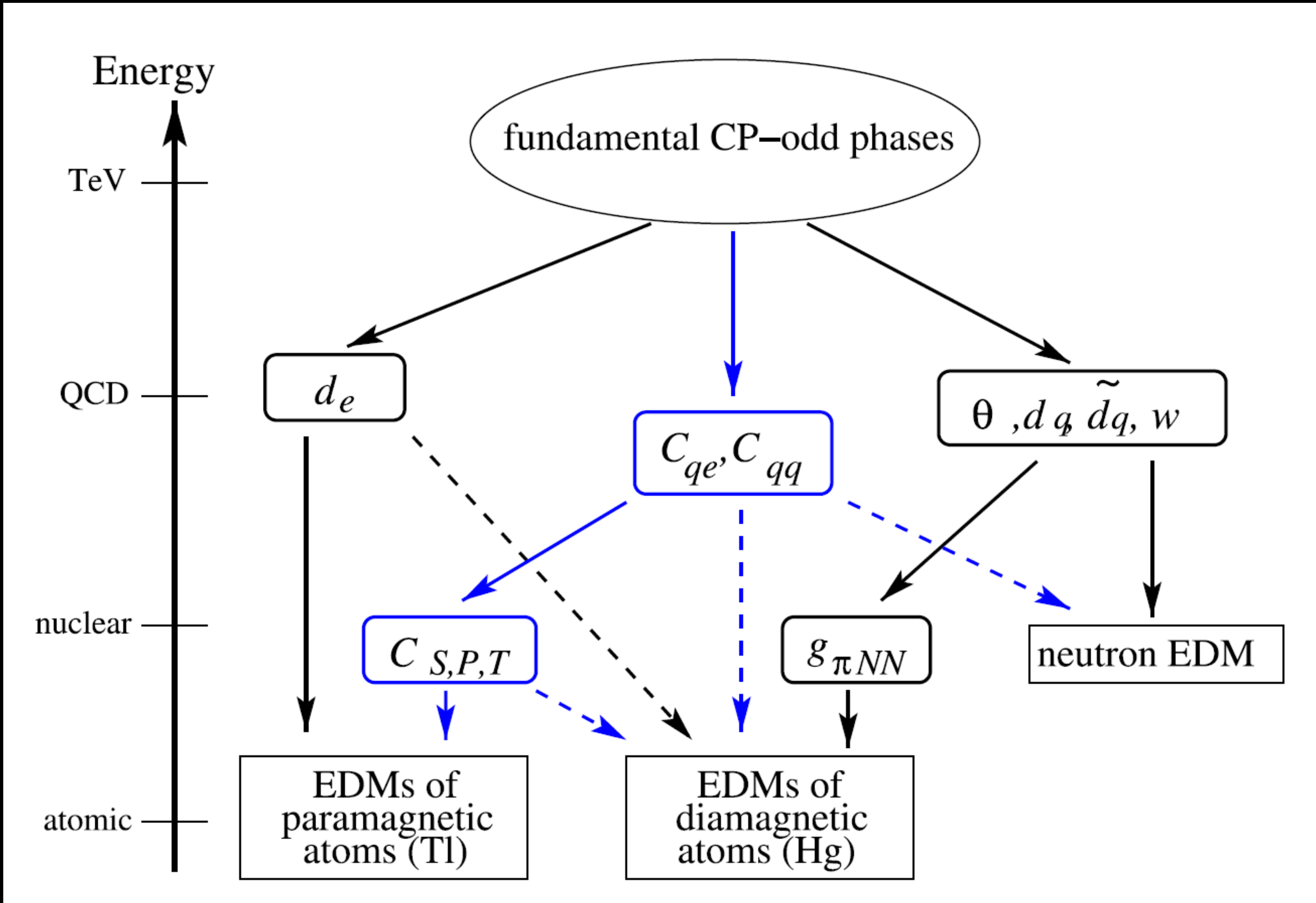
Large effect in more comprehensive theories





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

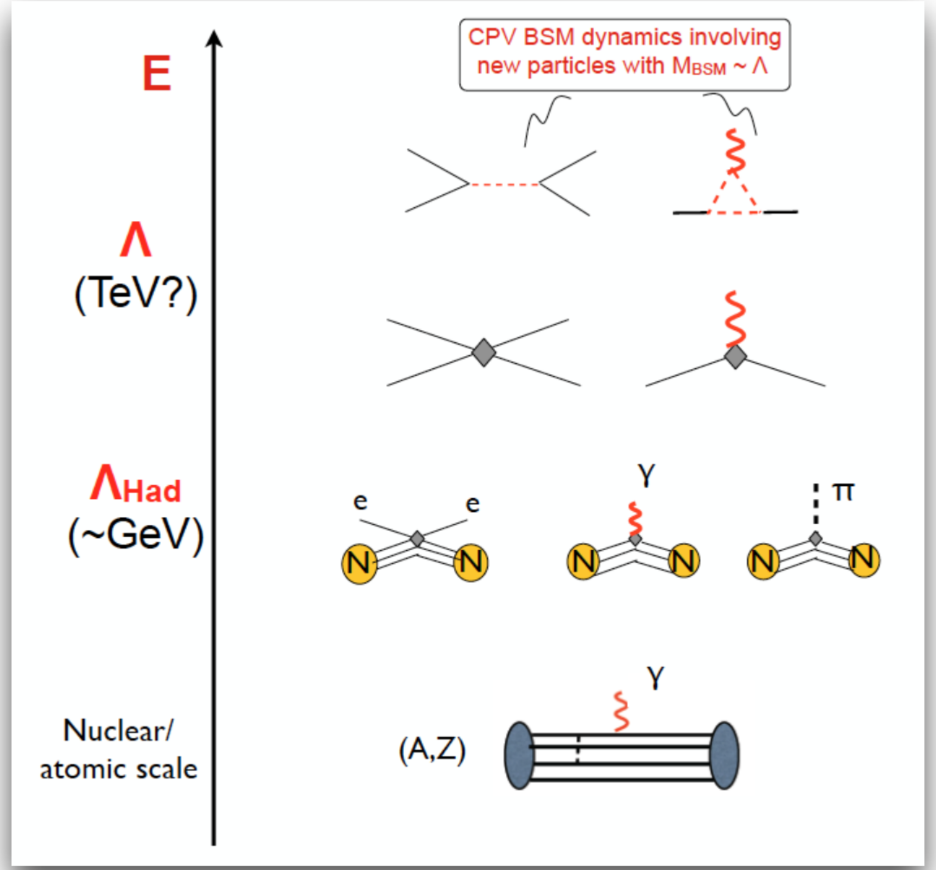
$d < 10^{-26}$ e-cm$\rightarrow \Lambda_{cp} = 1$ TeV



Pospelov, Ritz, Ann. Phy. 318 (2005) 119.

We hate EDMs because:

Theorists



RG EVOLUTION
(perturbative)

MATRIX ELEMENTS
(non-perturbative)

Connecting EDMs to new physics is a challenging multi-scale problem: need RG evolution of effective couplings & hadronic / nuclear / molecular calculations of matrix elements

Slide: Vincenzo Cirigliano

We love EDMs because:

Theorists

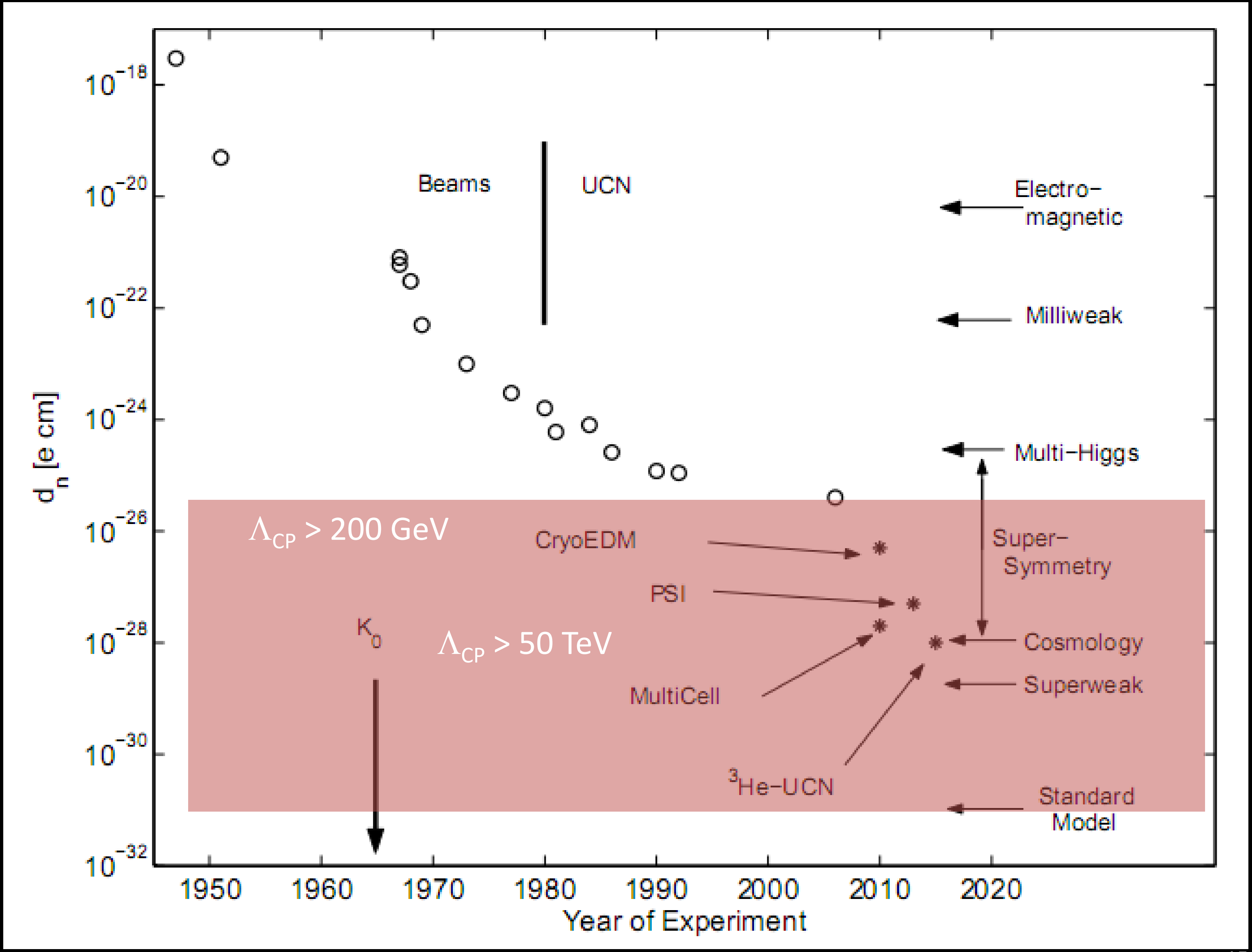
1. Essentially free of SM "background" (CKM)*
2. Probe very high-scales (Λ~10-100 TeV)

$$d_n \propto \frac{m_q}{\Lambda^2} e\, \phi_{CP}$$

3. Probe key ingredient for baryogenesis (CPV in SM is insufficient)

* Observation would signal new physics or a tiny QCD θ-term ($< 10^{-10}$).
Multiple measurements can disentangle the two effects

Slide: Vincenzo Cirigliano



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

Traditional technique: Nuclear Magnetic Resonance (NMR)

$$H = -\left(\mu\vec{B} + d_n\vec{E}\right)\cdot\frac{\vec{S}}{|S|}$$

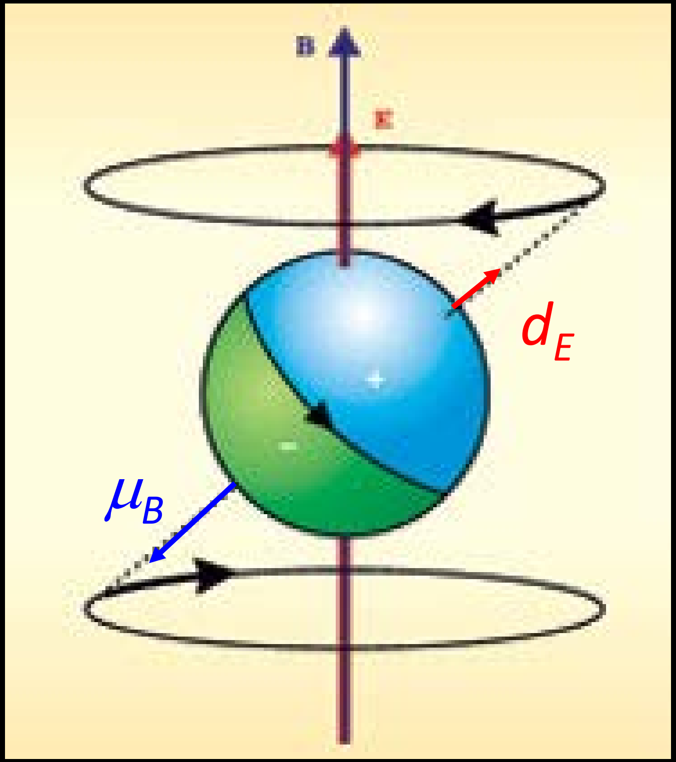


Figure: Physics Today 56 6 (2003) 33

- Larmor frequency: $\omega_B = -\frac{2\mu_B B}{\hbar}$

(~ 29.2 Hz for *B* ~ 0.1G)

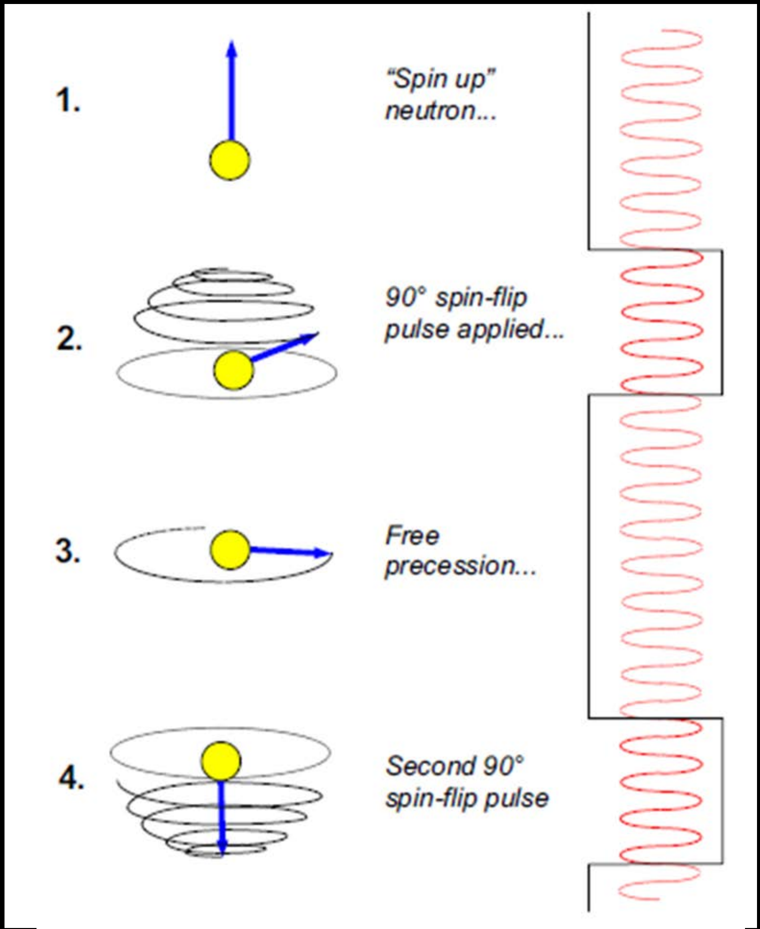
- d_n: additional precession: $\omega_E = \frac{2d_n E}{\hbar}$

$$\omega_{E\|B} - \omega_{E\,anti-\|B} \equiv \Delta\omega = \frac{4d_E E}{\hbar}$$

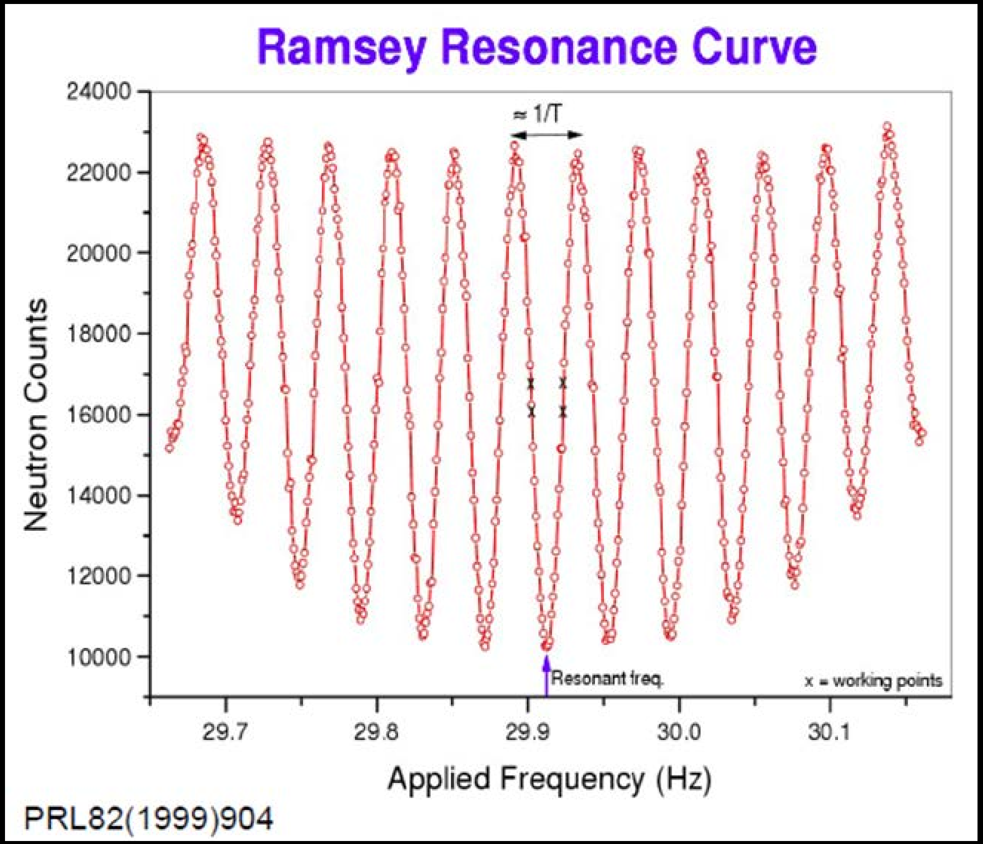
- Apply static *B*, *E*||*B*
- Look for $\Delta\omega$ on reversal of *E*

If $d_n = 5\times10^{-28}$ e cm, $\Delta\omega$=12nHz.

Technique:
The Ramsey's Separated Oscillatory Field Method



5. Spin analyzer (only allows "spin up" UCN through to be counted)



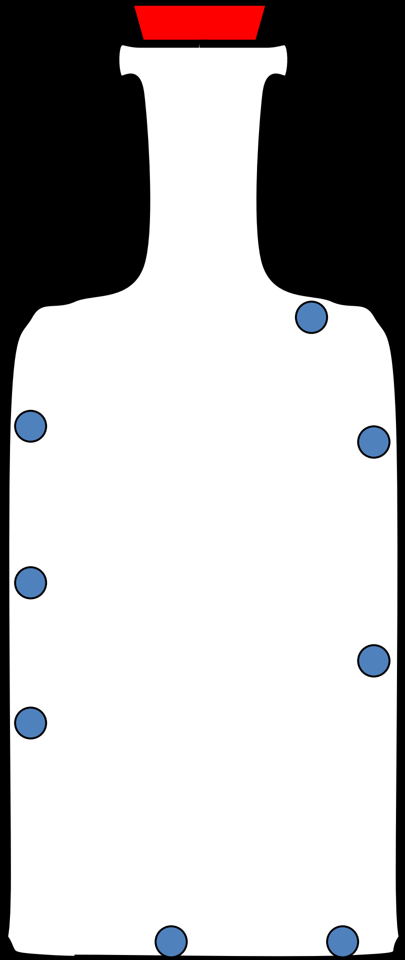
Ultra-Cold Neutrons (UCN)

What are UCN ?

Very slow neutrons

($v < 8$ m/s; $\lambda > 500$ Å)

that cannot penetrate into certain material.



- **Long storage time**
- **Low radiation background**
- **100% polarization**

→ Precision measurements

Magnetic Field Fluctuations Corrected by "Co-magnetometer"

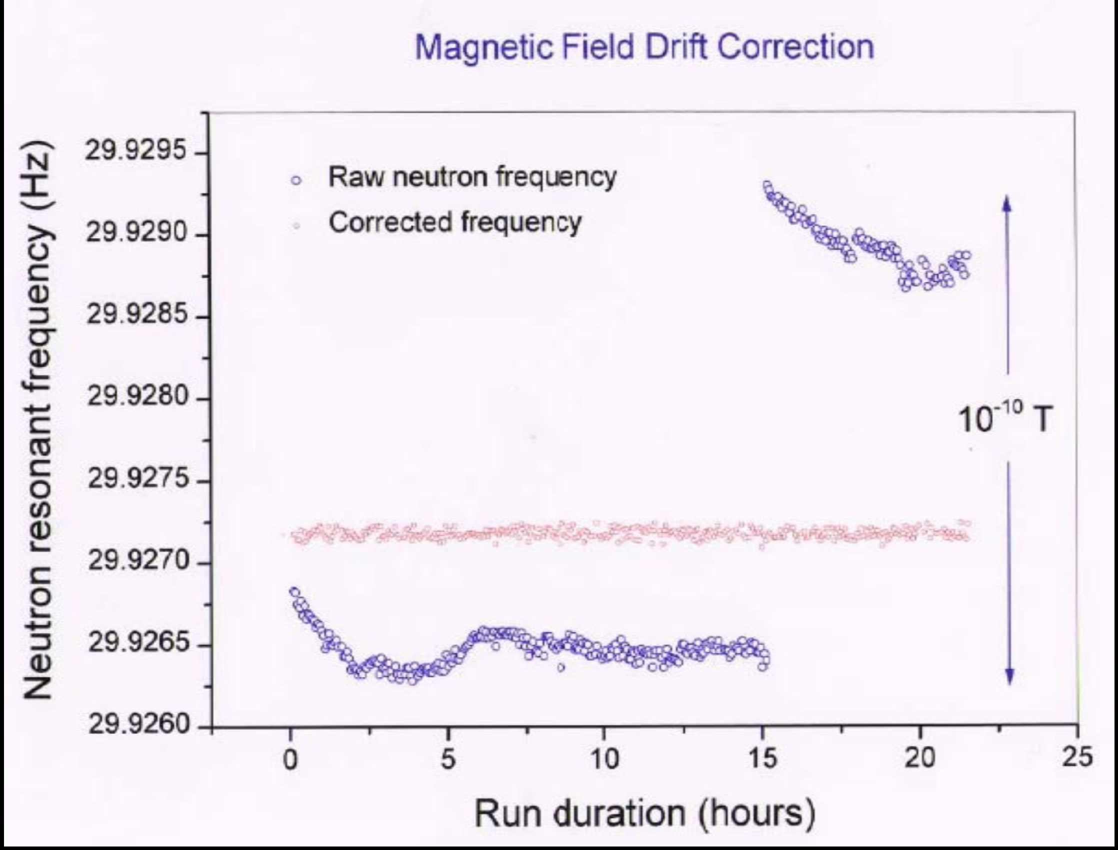
$$H = -\left(\mu\vec{B} + d_n\vec{E}\right)\cdot\frac{\vec{S}}{|S|}$$

If nEDM = 10^{-26} e·cm,

10kV/cm → 0.1 μHz shift

≅ B field of 2×10^{-15} T.

"Co-magnetometer"
Uniformly samples the B Field faster than its relaxation time.



Data: ILL nEDM experiment with ^{199}Hg co-magnetometer

EDM of ^{199}Hg < 10^{-28} e-cm (measured); atomic EDM ~ $\alpha^2 Z^2$ → ^{3}He EDM << 10^{-30} e-cm

Under gravity, the center of mass of He-3 is higher than UCN by $\Delta h \approx 0.13$ cm, sets ΔB = 30 pGauss (1nA of leakage current). $\Delta B/B$=0.001.

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	Solid D_2	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

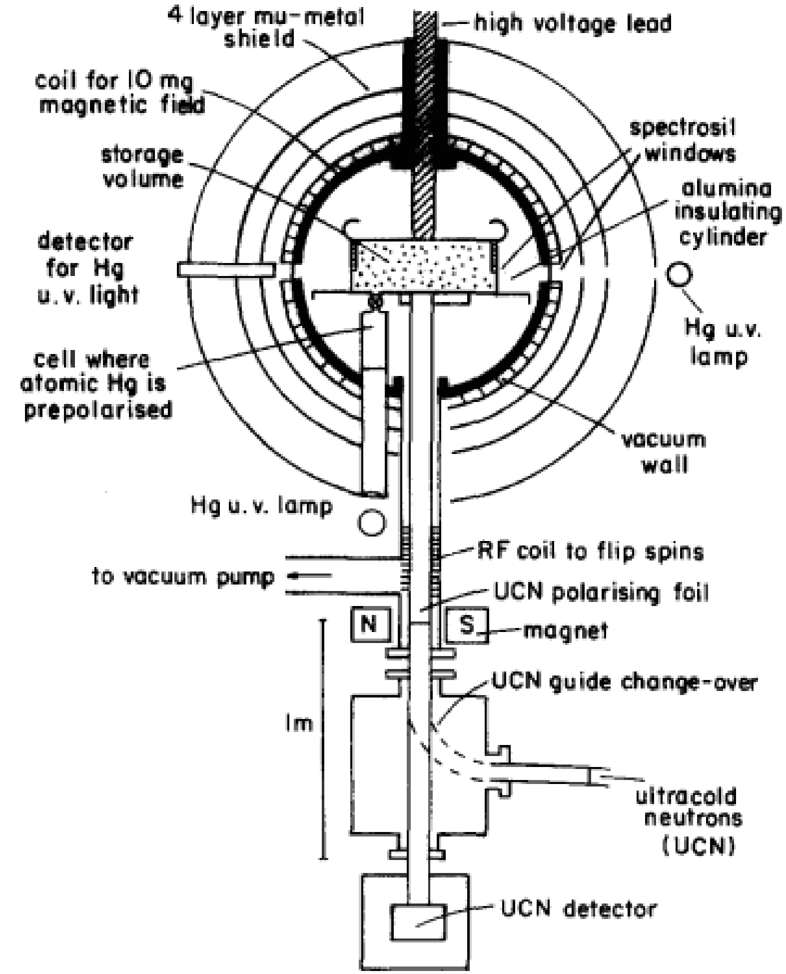
11

= sensitivity < 5 x 10^{-28} e-cm

Slide thanks to Brad Filippone

ILL Experiment:

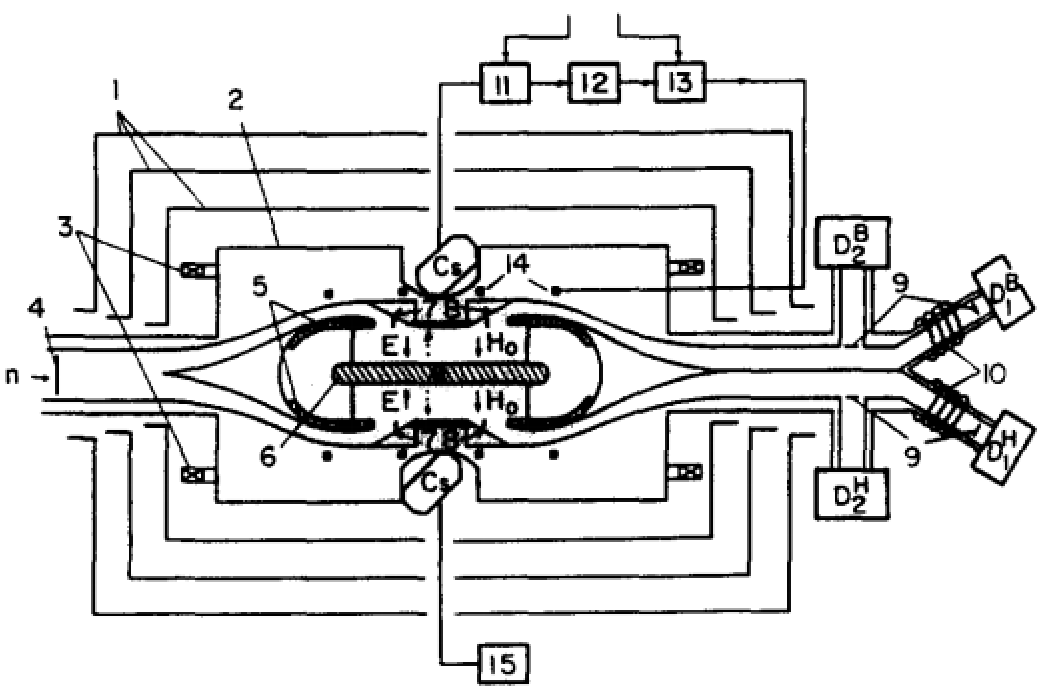
- UCN in storage cell (Be electrode, BeO dielectric cell wall) at room temperature
- Ramsey's separate oscillatory field method (interference in time domain)

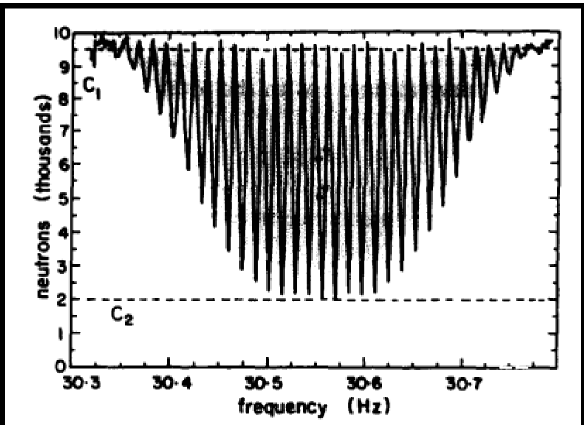


PNPI Experiment:

Double cell configuration

$\rightarrow$ double the signal and reduce the sensitivity to common mode magnetic field noise

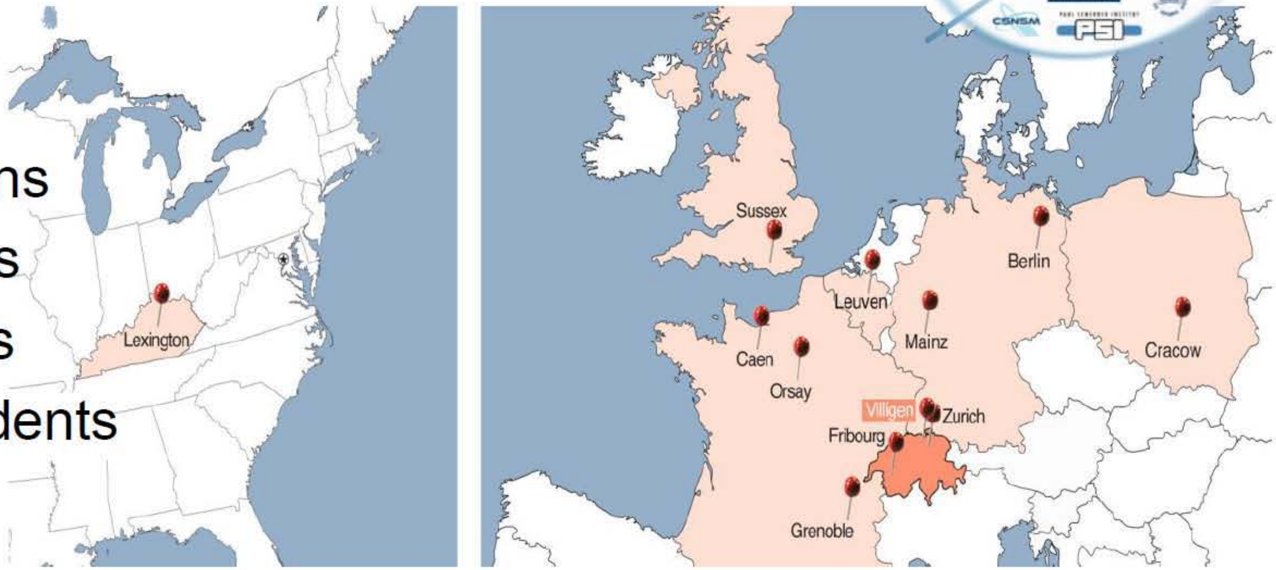




The nEDM@PSI collaboration

Presently:

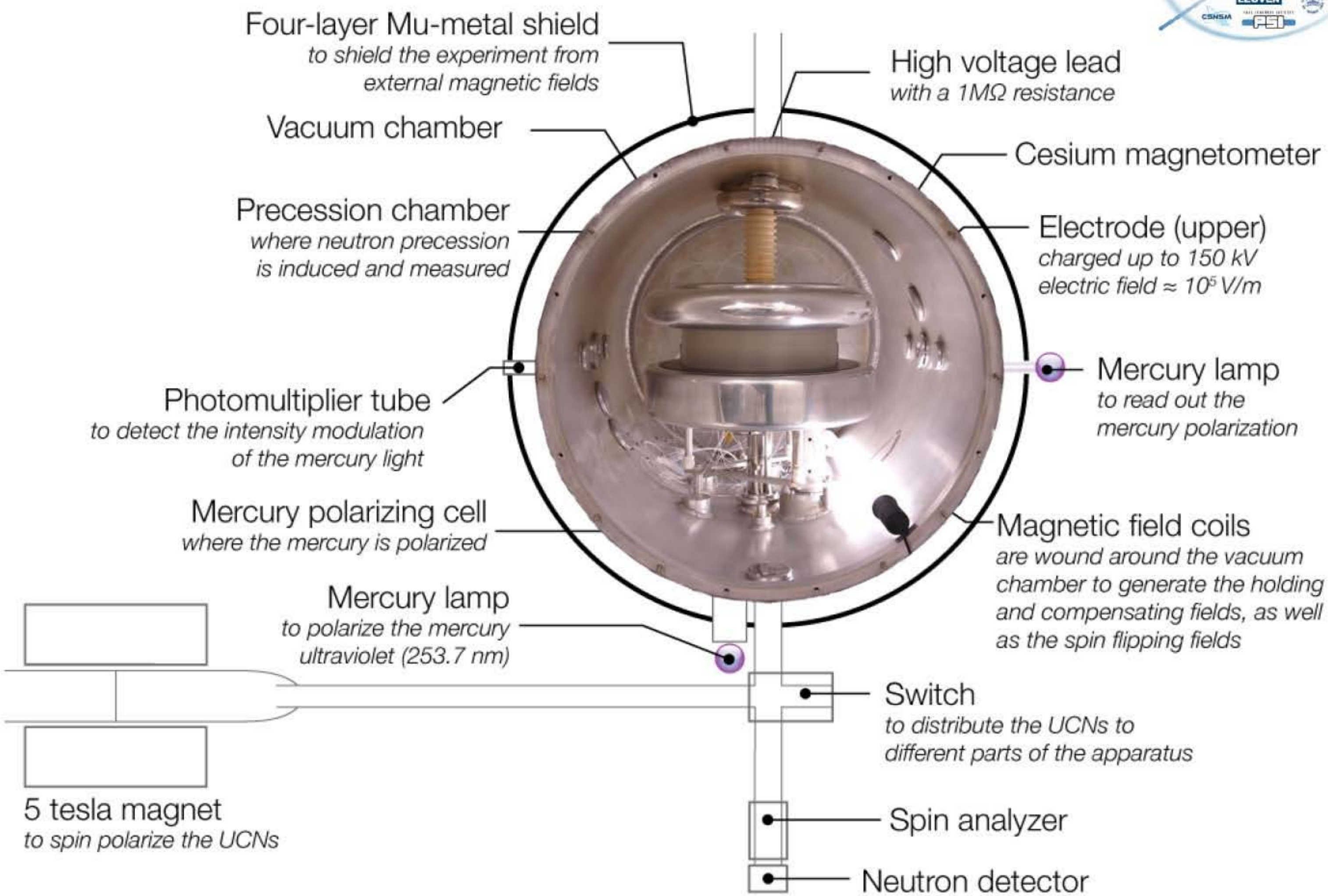
- 13 Institutions
- 7 Countries
- 48 Members
- 11 PhD students



PAUL SCHERRER INSTITUT

Slide thanks to Klaus Kirch

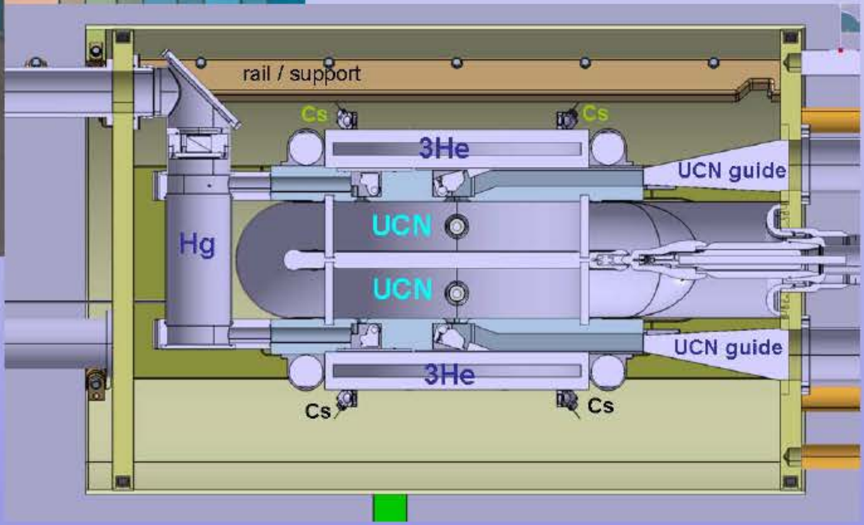
The nEDM spectrometer



Slide thanks to Klaus Kirch

Towards n2EDM

Status/Prospects:
Taking data at δdn~ 1x10-26e-cm/yr
n2EDM hopes to reach δdn~ 4 x10-27e-cm/yr



- **Two UCN precession chambers with opposite electric field directions**
- **Improved magnetometry Hg – laser read out of Hg-FID to avoid light shift**
  Cs – vectorial
  3He – free from geometrical phase shift

Slide thanks to Klaus Kirch

Optimistic (but in principle possible) plan towards a physics result

Move Inner Shield to ILL (2016)
Adapt/build new UCN components, mobile Cs magnetometers
No RF shield, only manual alignment control

Installation at new Super-SUN Stage 1 w/o magnet (2017+), no co-magnetometer
Best possible results ~ 3.10^{-27} ecm (stat, 1)

EDM runs at Super-SUN Stage 2 with magnet (2019+)
Best possible result ~ 8.10^{-28} ecm (stat, 1

Outer Shield at TUM
Outer magnetic shield
External field compensation
HV R&D and assembly

Magnetometer development
Magnetometer comparisons
Spin-clocks with polarized noble gases
Component optimization

Development of cryogenic chambers

Options
(i) Assembly of Inner and Outer shield with RT chamber
(ii) Cryogenic chambers with Inner Shield
(iii) Cryogenic chambers with Outer and Inner Shield
(before ~ 2022 no UCN at FRM-II EDM position)

Slide thanks to Peter Fierlinger

Sensitivity potential of nEDM @ Super-SUN at ILLP

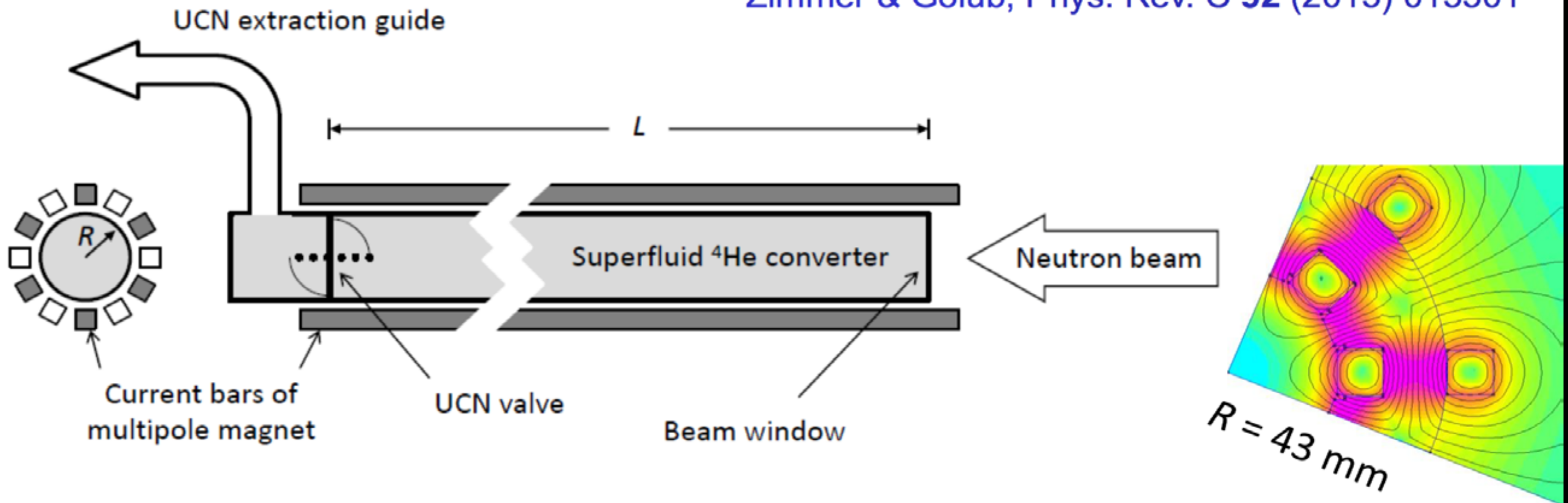
	SuperSun stage I		SuperSun stage II	
UCN density	333	1/cm3	1670	1/cm3
Diluted density	80	1/cm3	400,8	1/cm3
Transfer loss factor	3		1,5	
Source saturation loss factor	2		2	
Polarization loss factor	2		1	
Density in cells	6,7	1/cm3	133,6	1/cm3
2 EDM chamber volume	33,2	l	33,2	l
Neutrons per chamber	110556		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**

Slide thanks to Peter Fierlinger

The nextversion: Super-SUN (funded+ underconstruction @ ILL)

For calculations of UCN storage see:

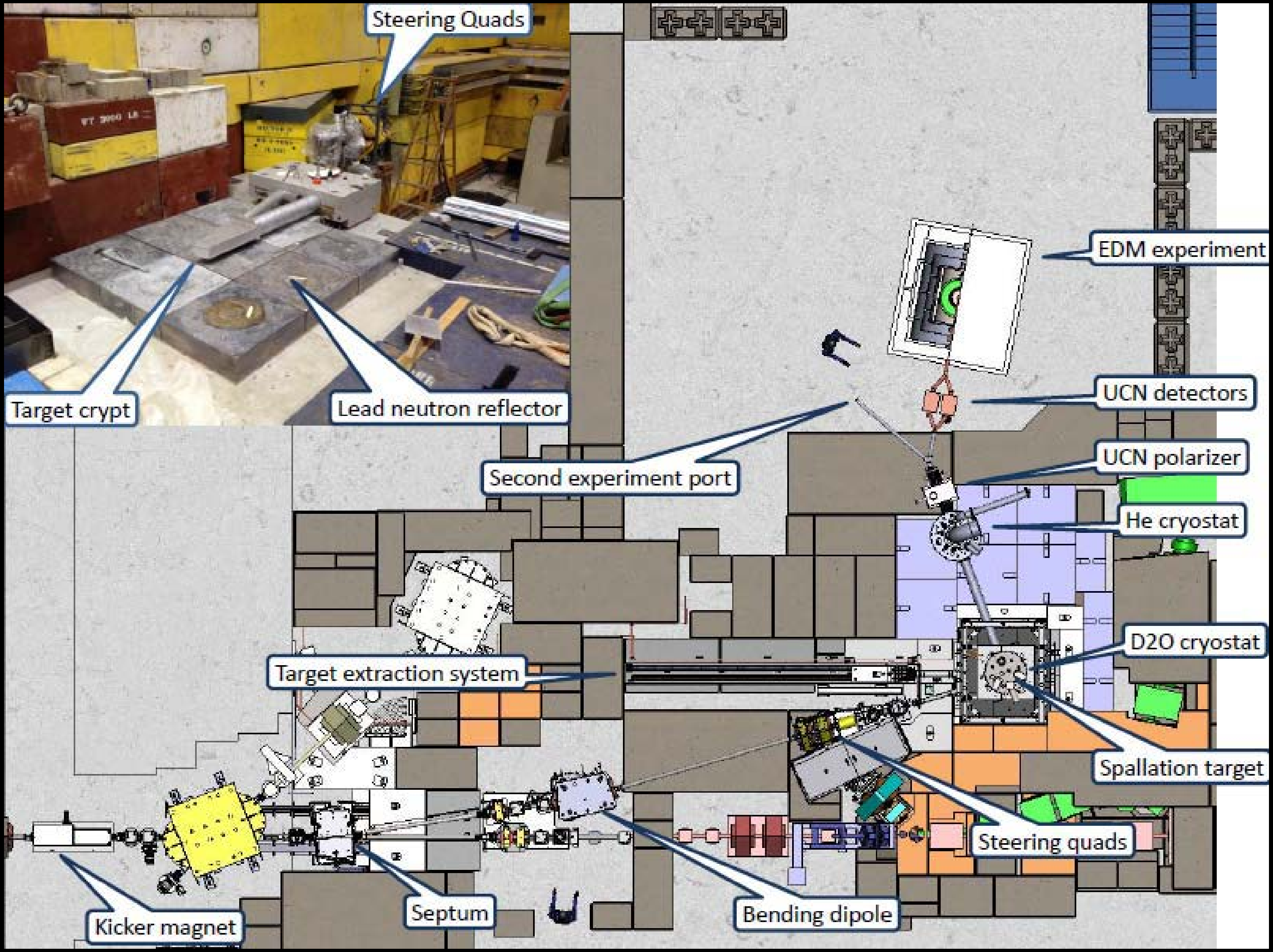
Zimmer & Golub, Phys. Rev. C **92** (2015) 015501



- Single-user facility
- Converter volume: 12 litres
- UCN production rate: 10^5 s^{-1} (E < 230 neV)
- UCN saturation number: 4×10^6 (2017, fomblin spectrum)
  2×10^7 (2019, polarised, E < 230 neV)

Slide thanks to Peter Fierlinger

TRIUMF UCN Facility

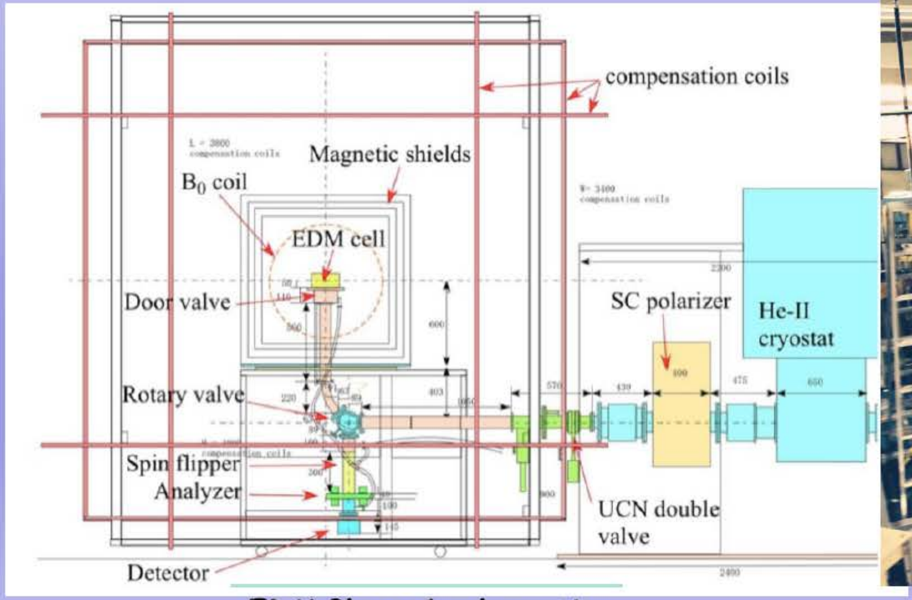


Slide thanks to Jeff Martin

"Phase 1" – what will exist in 2017

- use **existing** EDM Ramsey **apparatus** from RCNP, Osaka
- exploit **higher UCN density** at TRIUMF (also more beamtime available)
- room temperature, **1 small cell**, vertical loading, spherical B_0 coil
- small incremental improvements until replaced by Phase 2
  - **Active magnetic compensation system**
  - **high voltage**
  - **comagnetometer**
  - **high-flux detector**

Slide thanks to J. Martin

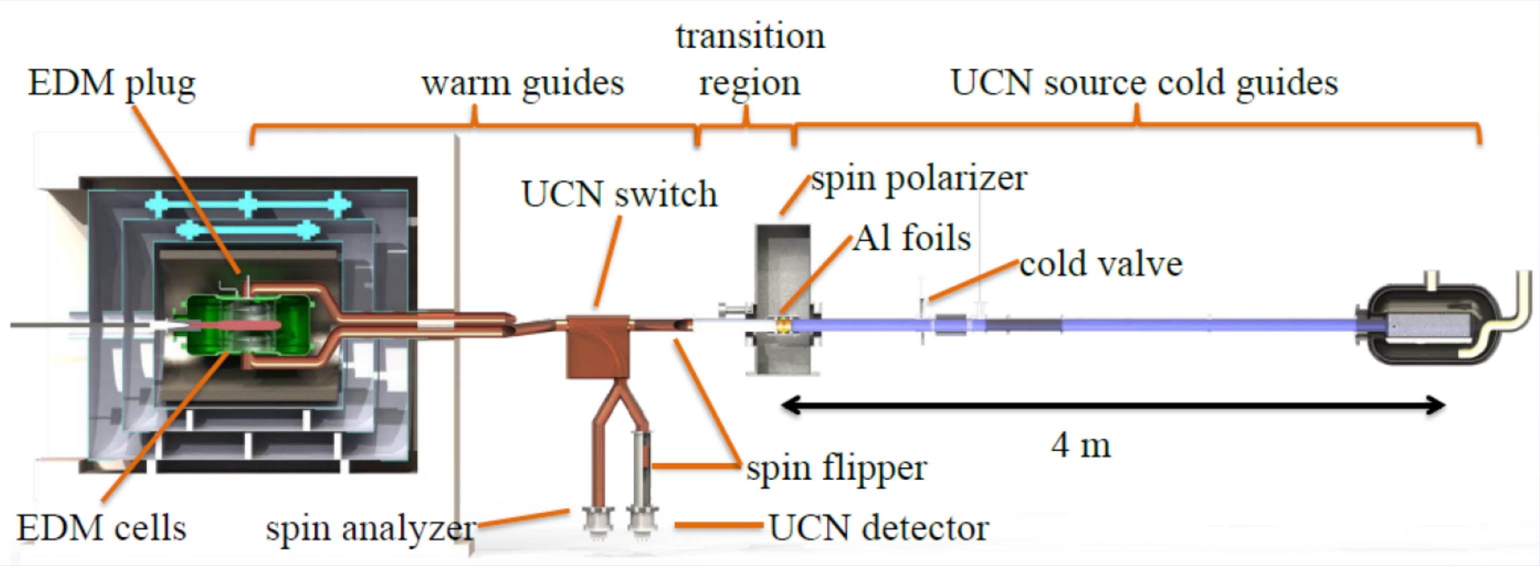


EDM Phase 1 schematic

EDM Phase 1 at RCNP

"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 Jeff Martin

Concept for nEDM experiment at LANL

- A neutron EDM experiment with a sensitivity of $\delta d_n \sim O(10^{-27})$ e-cm based on already proven room temperature Ramsey's separated oscillatory field method could take advantage of the existing LANL SD_2 UCN source
  - nEDM measurement technology for $\delta d_n \sim O(10^{-27})$ e-cm exists. What is holding up the progress is the lack of UCN density.
  - The LANL UCN source currently provides a UCN density of ~ 60 UCN/cc at the exit of the biological shield
  - A 5-10 fold improvement in the delivered UCN density is required for an nEDM experiment with $\delta d_n \sim O(10^{-27})$ e-cm
- Such an experiment could provide a 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.

Slide thanks to Takeyasu Ito

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^{-25} e-cm)	**0.93**
σ/year/cell (10^{-27} e-cm)	**4.8**
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:

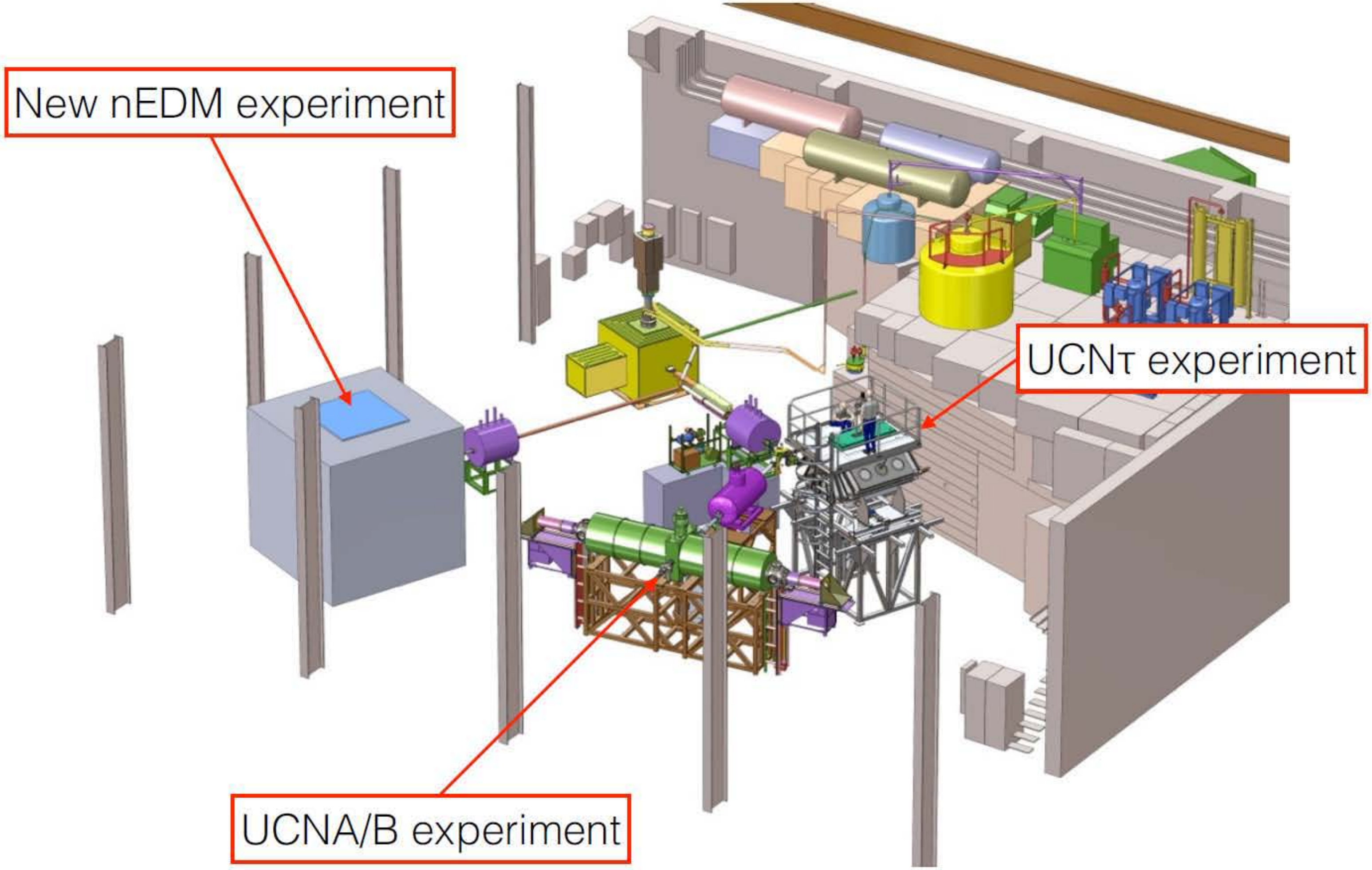
- The estimate for N is based on the results of the UCN storage test performed in January 2016 and **is not assuming the source upgrade.**
- The estimate for E, T_{free}, T_{duty}, and α is based on what has been achieved by other experiments.

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

- Present - August 2016: Installation of the new UCN source and guides
- September 2016-January 2017: Commissioning and operation of the new UCN source

Slide thanks to Takeyasu Ito

Area B layout with the proposed nEDM Experiment



Slide thanks to Takeyasu Ito

nEDM@SNS

Neutron electric-dipole moment, ultracold neutrons and polarized ^3He**

R. Golub[a] and Steve K. Lamoreaux[b]

[a]Hahn–Meitner Institut, Postfach 39 01 28, Glienicker Strasse 100, 14109 Berlin, Germany
[b]University of Washington, Department of Physics FM-15, Seattle, WA 98 195, USA

Physics Reports **237**, 1 (1994)

** "The Miracle of Helium"

$$\sigma \propto \frac{1}{E\sqrt{N\tau}}$$

Improve statistical precision by x100.

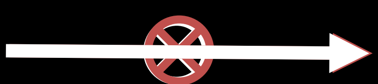
- *Increase E*: LHe permits very large electric fields; ~70 kV/cm in our measurement cell
- *Increase N*: LHe allows production of a high density of "ultracold" neutrons (UCN); ~few 10^2 UCN/cc
- *Increase t*: With T < 0.5K UCN can be stored for ~ a thousand seconds

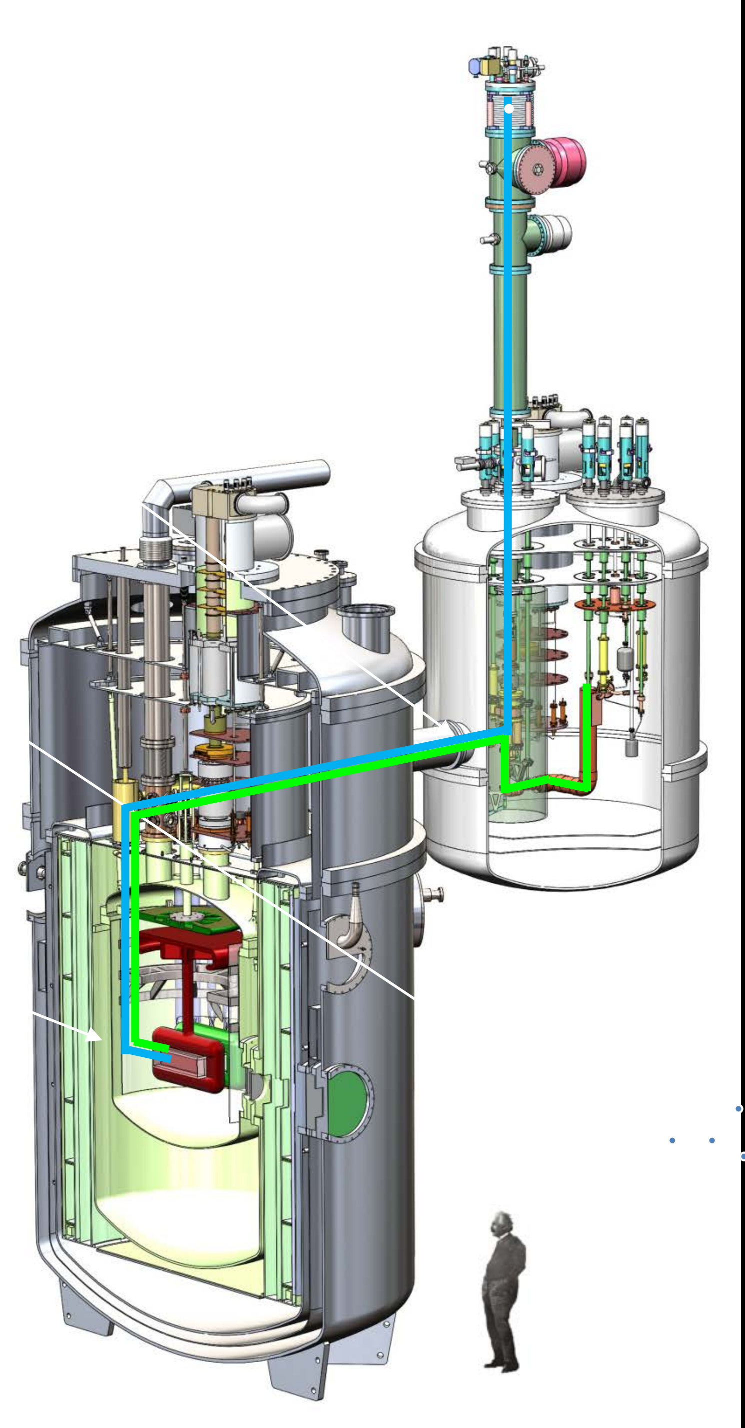
Additionally allows use of Helium-3 as a:

- *Spin analyzer*, providing continual measurement of the precession frequency
- *Co-magnetometer*, providing exquisite monitoring of the magnetic field

nEDM@SNS Measurement Cycle

1. Load collection volume with polarized ^{3}He atoms
2. Transfer polarized ^{3}He atoms into measurement cell
3. Illuminate measurement cell with polarized cold neutrons to produce polarized UCN
4. Apply a $\pi/2$ pulse to rotate spins perpendicular to B_0
5. Measure precession frequency
6. Remove reduced polarization ^{3}He atoms from measurement cell
7. Flip E-field & Go to 1.





Slide thanks to Vince Cianciolo

C. Crawford, T. Gorringe, W. Korsch, E. Martin, N. Nouri, B. Plaster
University of Kentucky
S. Clayton, S. Currie, T. Ito, Y, Kim, M. Makela, J. Ramsey, W.Sondheim. Z, Tang, W. Wei
Los Alamos National Lab
K. Dow, D. Hasell, E. Ihloff, J. Kelsey, J. Maxwell, R. Milner, R. Redwine, E. Tsentalovich, C. Vidal
Massachusetts Institute of Technology
D. Dutta, E. Leggett
Mississippi State University
R. Golub, C. Gould, D. Haase, A. Hawari, P. Huffman, E. Korobkina, K. Leung, A. Reid, A. Young
North Carolina State University
R. Allen, V. Cianciolo, Y. Efremenko, P. Mueller, S. Penttila, W. Yao
Oak Ridge National Lab
M. Hayden
Simon Fraser University
G. Greene, N. Fomin
University of Tennessee
S. Stanislaus
Valparaiso University
S. Baeßler
University of Virginia
S. Lamoreaux
Yale University

R. Alarcon, R. Dipert
Arizona State University
G. Seidel
Brown University
D. Budker
UC Berkeley
M. Blatnik, R. Carr, B. Filippone, C. Osthelder, S. Slutsky, X. Sun, C. Swank
California Institute of Technology

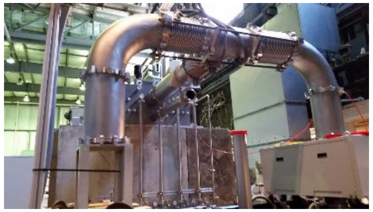
M. Ahmed, M. Busch, P. -H. Chu, H. Gao
Duke University
I. Silvera
Harvard University
M. Karcz, C.-Y. Liu, J. Long, H.O. Meyer, M. Snow
Indiana University
L. Bartoszek, D. Beck, C. Daurer, J.-C. Peng, T. Rao, S. Williamson, L. Yang
University of Illinois Urbana-Champaign

Project Manager: V. Cianciolo
Spokesperson: BWF

29

75 scientists from 19 institutions

UIUC Responsibilities



- Test bed:
  - 1K pot pump system,
  - ^{3}He circulation pump stack,
  - Room-temperature vacuum plumbing,
  - Gas service plumbing,
  - Vibration-damping anchor block and wall,
  - Cryostat outer vacuum can,
  - Aluminum personnel support frame,
  - Vacuum can (and shield) lift mechanism.
  - ^{3}He gas panel

- Cryostat:
  - Top flange
  - Insulating vacuum pump system
  - Heat shields (on order)

- Slow Controls: National Instruments “cDAQ” front end
  - Windows based
  - Autonomous
  - Data logged to “network shared variable” mechanism to server
  - Compatible with EPICS

- 500 l Helium Dewar
  - Tried “value engineering” (old Dewar from ORNL/U. Mich) – no.
  - New standard Dewar on order.

Look at me!
Look at me!
Look at me NOW!
It is fun to have fun
but you have to know how.

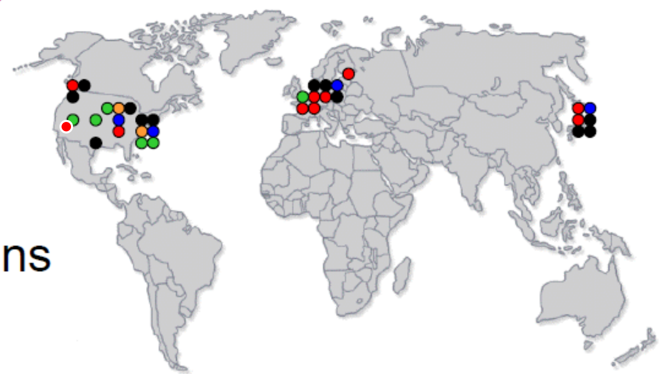
I can hold up the cup
and the milk and the cake!
I can hold up these books!
and the fish on a rake!
I can hold the toy ship
and a little toy man!
And look! With my tail
I can hold a red fan!
I can fan with the fan
As I hop on the ball!
but that is not all.
Oh, no
That is not all…

EDMs Worldwide

- Neutrons ~200
  - @ILL
  - @ILL,@PNPI
  - @PSI
  - @FRM-2
  - @RCNP,@TRIUMF
  - @SNS
  - @J-PARC
  - @LANSCE
- Molecules ~50
  - YbF@Imperial
  - PbO@Yale
  - ThO@Harvard
  - HfF+@JILA
  - WC@UMich
  - PbF@Oklahoma

Rough estimate of numbers of researchers, in total ~500 (with some overlap)

- Atoms ~100
  - Hg@UWash
  - Xe@Princeton
  - Xe@TokyoTech
  - Xe@TUM
  - Xe@Mainz
  - Cs@Penn
  - Cs@Texas
  - Fr@RCNP/CYRIC
  - Rn@TRIUMF
  - Ra@ANL
  - Ra@KVI
  - Yb@Kyoto



- Ions-Muons ~200
  - @BNL
  - @FZJ
  - @FNAL
  - @JPARC
- Solids ~10
  - GGG@Indiana
  - ferroelectrics@Yale

K. Kirch, Proceedings CIPANP 2012
http://nedm.web.psi.ch/EDM-world-wide/

Why Do We Need So Many Experiments?

Electron EDM

TVPV pseudoscalar-scalar eN coupling

TVPV tensor eN coupling

Short-distance contribution to d_n

Short distance contribution to d_p

TVPV isoscalar πN coupling

TVPV isovector πN coupling

$$d = \underbrace{\alpha_{d_e} d_e + \alpha_{C_S} C_S}_{\text{Paramagnetic Systems}} + \underbrace{\alpha_{C_T} C_T + \alpha_{\bar{d}_n} \bar{d}_n + \alpha_{\bar{d}_p} \bar{d}_p + \alpha_{g_\pi^0} \bar{g}_\pi^0 + \alpha_{g_\pi^1} \bar{g}_\pi^1,}_{\text{Diamagnetic Systems}}$$

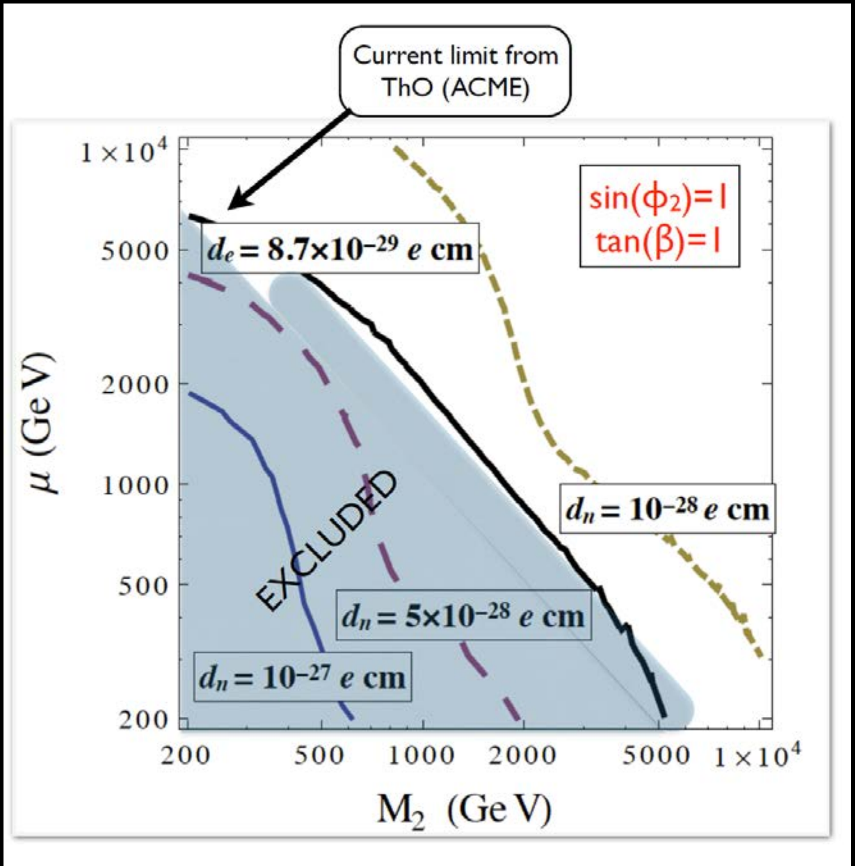
Paramagnetic Systems

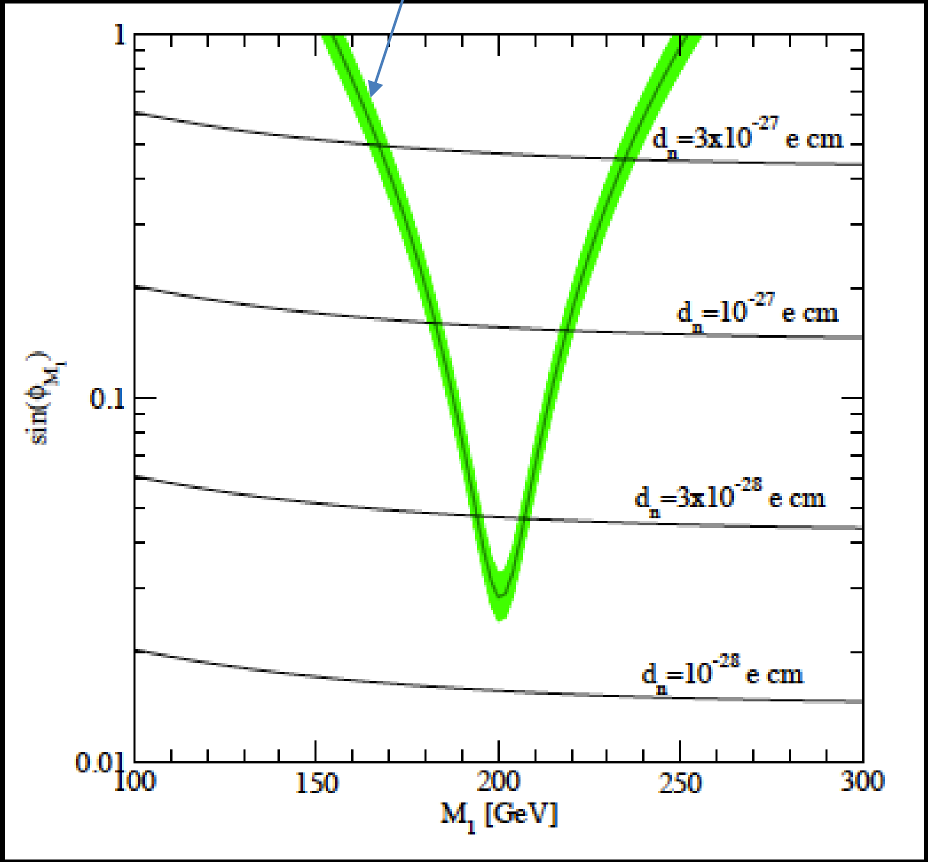
Diamagnetic Systems

T. Chupp, M. Ramsey-Musolf, Phys. Rev. **C91** 035502 (2015)

EDMs in SUSY

Compatible with baryon asymmetry





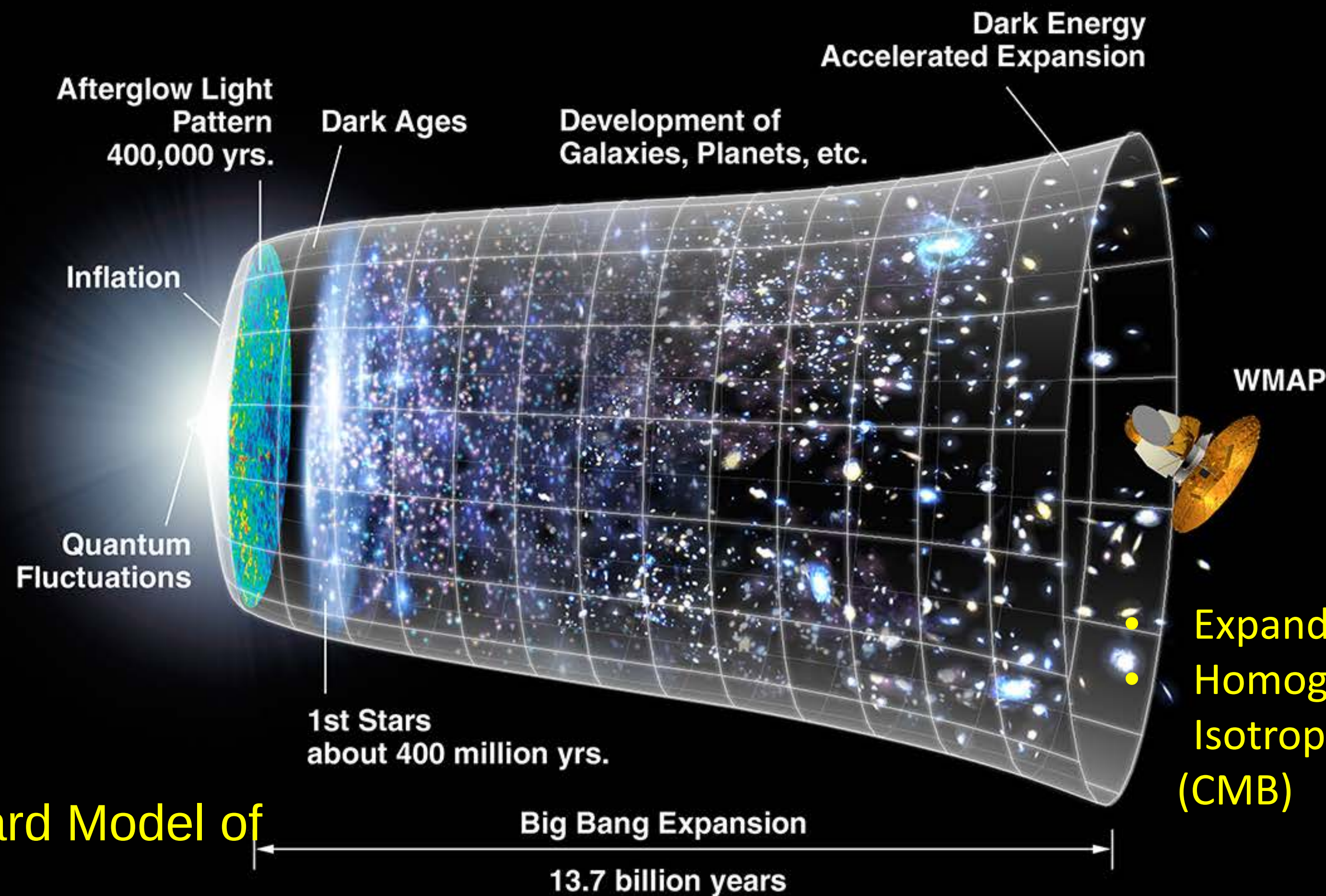
Bhattacharya, VC, Gupta, Lin, Yoon
Phys. Rev. Lett. 115 (2015) 212002 [1506.04196]

Li, Profumo, Ramsey-Musolf 2009-10

Where Do We Come From? What Are We? Where Are We Going?

Paul Gauguin, 1897

Where Do We Come From? What Are We? Where Are We Going

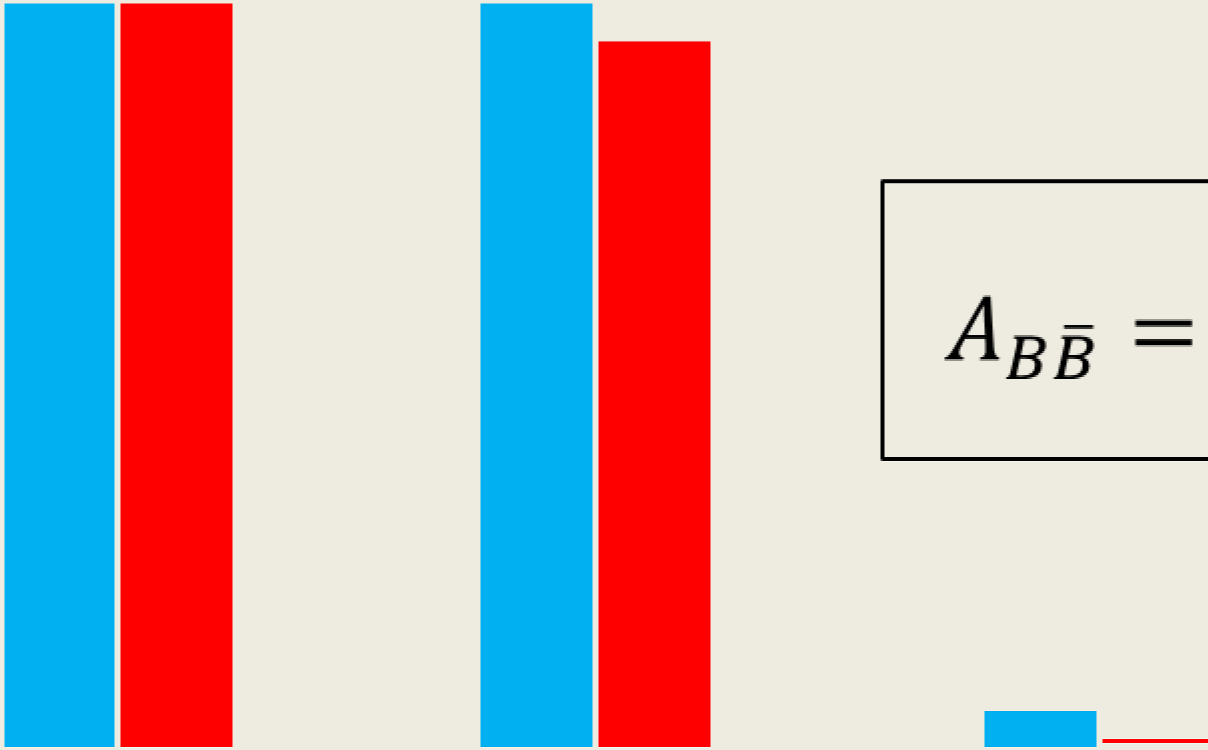


- Expanding
- Homogeneous & Isotropic (CMB)

The Standard Model of Cosmology

- The start: Big Bang Explosion
- The stage: Inflation
- Ingredients: Baryogenesis
- Cooking: Big Bang Nucleosynthesis (BBN); Stellar Nucleosynthesis

Big Bang Baryogenesis Today



$$A_{B\bar{B}} = \frac{B - \bar{B}}{B + \bar{B}}$$

$A_{B\bar{B}} = 0$ $A_{B\bar{B}} \sim 10^{-10}$ $A_{B\bar{B}} \sim 1$

Baryogenesis created more matter than anti-matter

- Sakharov's criteria

A.D. Sakharov, JETP **5** 24 (1967).

- Baryon number violation

$$\phi \to B; \phi \to \overline{B} \qquad \Delta B \neq 0$$

- CP violation and C violation

$$R(\phi \to B) > R(\phi \to \overline{B})$$

EDM

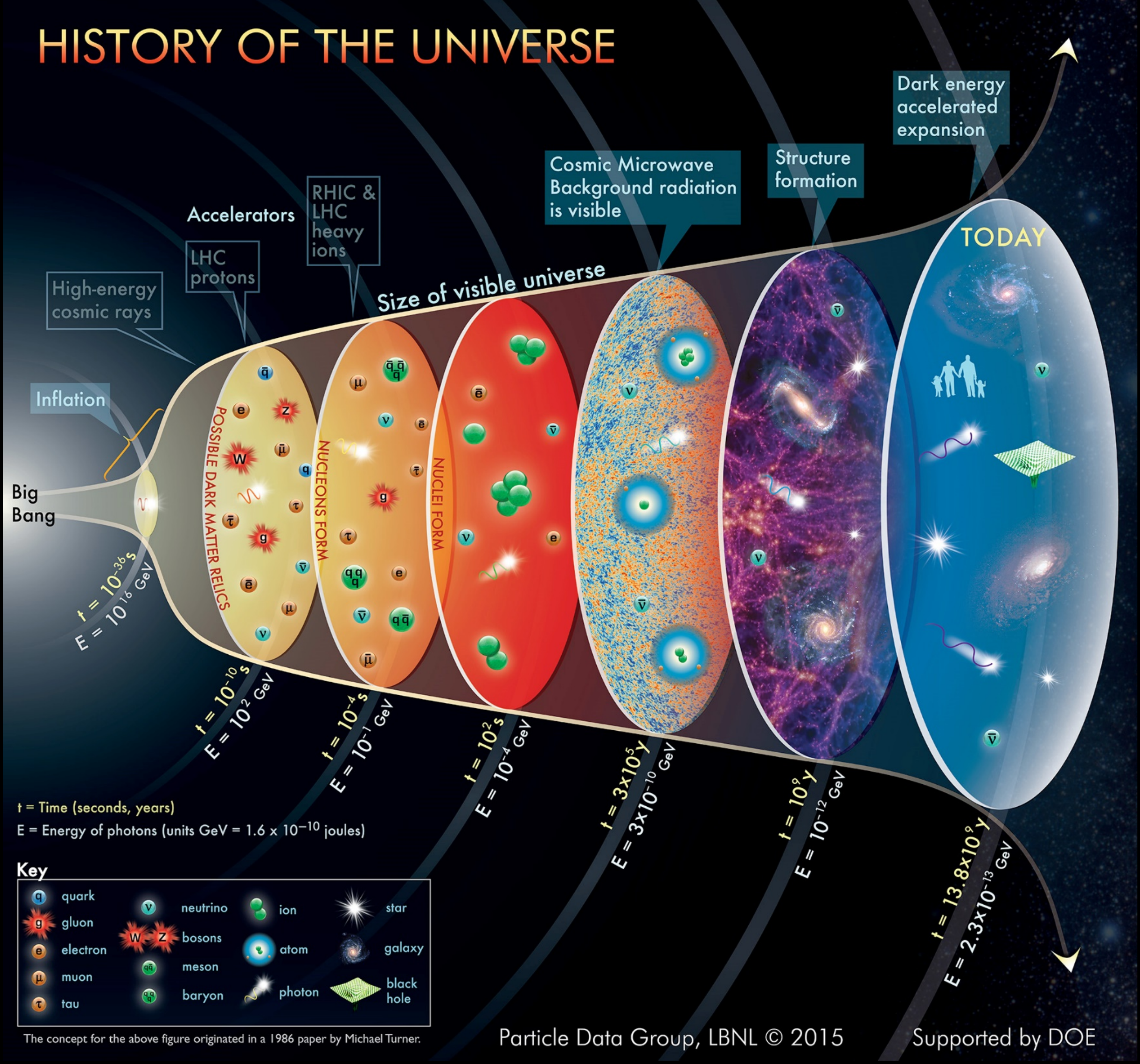
- Departure from thermal equilibrium

$$R(\phi \to B) > R(B \to \phi)$$

left-handed particle

under C → left-handed antiparticle

then P → **right-handed antiparticle**

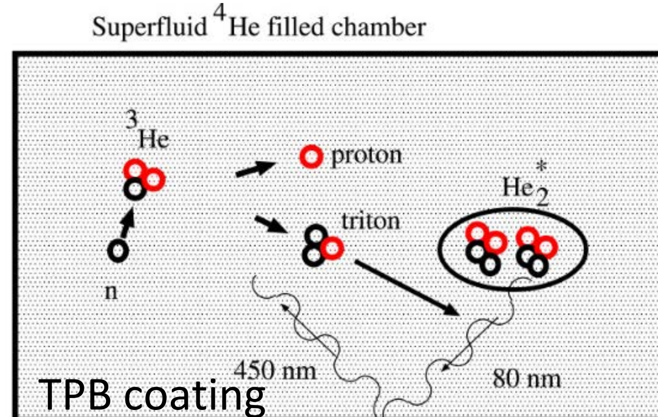

HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE

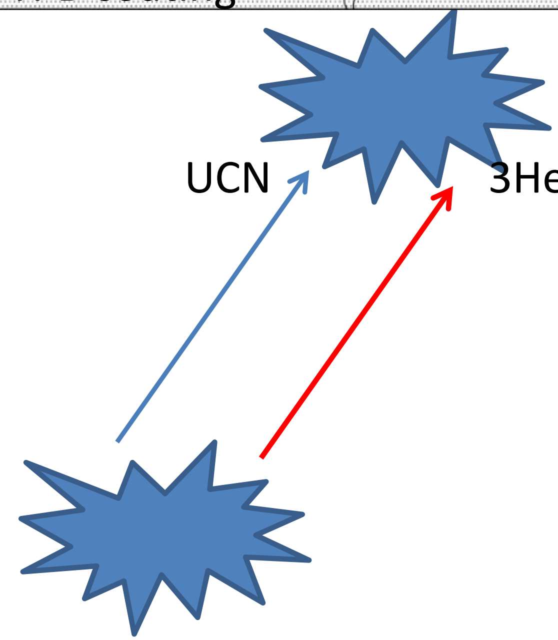
Backup Slides

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





- 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

Other Systematic Effects

Geometric Phase

In a rotating frame

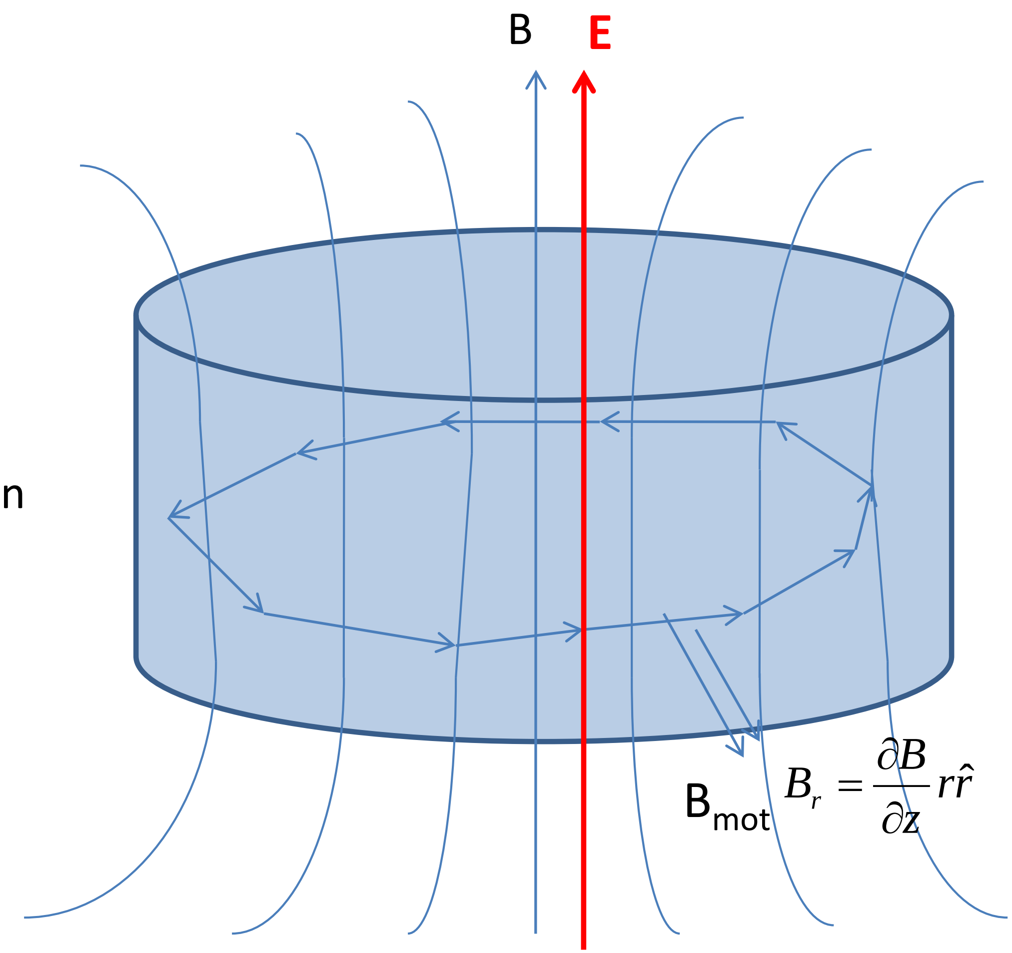
$$\delta\omega = -\frac{\omega_1^{\;2}}{\gamma B_0 - \omega_r}$$

UCN rotates due to specular reflection

$$\omega_r \approx \frac{v}{R}$$

$$\omega_1 = \gamma\left(B_{mot} + B_r\right)$$

$$\frac{\delta\omega}{\gamma^2} = -\frac{B_m B_r}{\omega_o - \omega_r} = -\frac{B_r v E}{c\left(\omega_o - v/R\right)}$$



$$B_r = \frac{\partial B}{\partial z} r\hat{r}$$

Sum UCNs moving in both clockwise & counterclockwise directions:

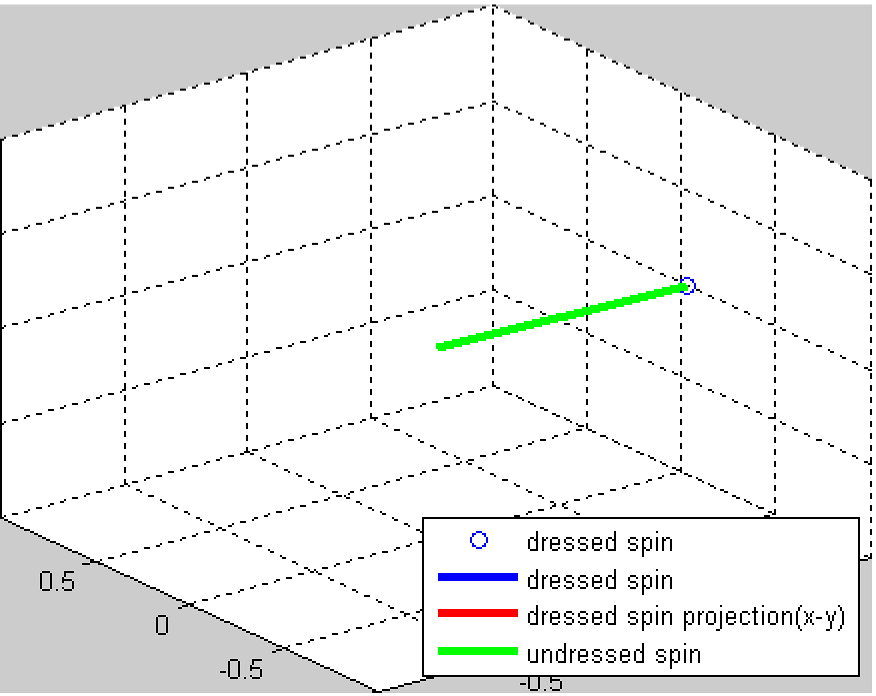
$$\delta\omega = -\frac{\gamma^2}{2}\frac{\left(\partial B_o/\partial z\right)E}{c}\frac{v^2}{\omega_o^2 - \omega_r^2}$$

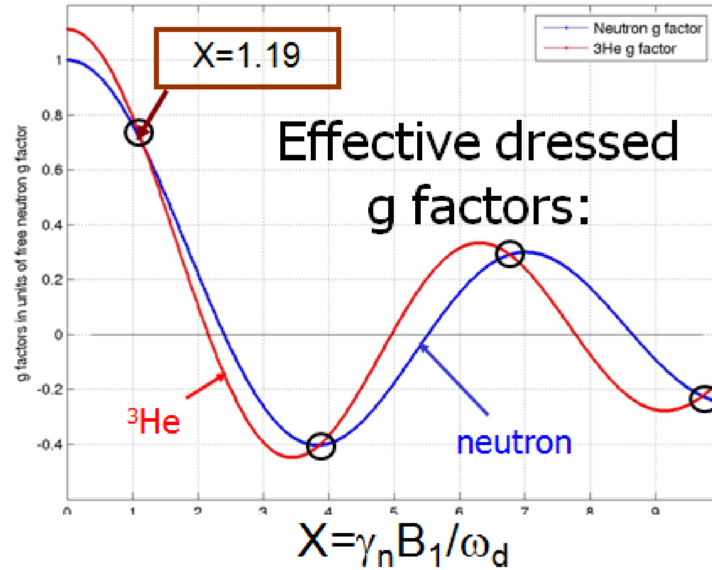
Geometric Phase effect is significant at the level of 10^{-28} e·cm.

Dressed Spin Magnetometry

$$\gamma' = \gamma J_0(\gamma B_{RF}/\omega_{RF}) = \gamma J_0(x)$$

The magnetic moment of 3He can be altered through "spin dressing" with applied RF:





The difference in the precession frequency between neutron and 3He:

$$\delta\omega = \left[\gamma_n J_0(\gamma_n x) - \gamma_3 J_0(\gamma_3 x)\right]$$

= 0 with appropriate x

1kHz, 100 mG RF field

All systematic effects and noises associated with the external magnetic field disappear!

EDM observable:

$$\delta\omega = 2d_n E J_0(\gamma_n x)$$

modulate *X* to look for X_c which leads to δω=0