Studying the Exact and Approximate Symmetries of Electroweak Interactions

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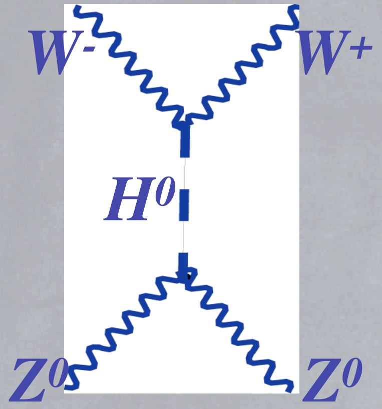
Unique Low Energy Probes of the Early Universe exploiting special properties of Leptons, Nucleons and Nuclei

Outline of Lectures

- Standard Model of Electroweak Interactions
- Searches for Violations of Discrete Symmetries
- Charged Lepton Flavor Violation and Precision Weak Neutral Current experiments
- Precision Weak Charged Current Experiments & Electroweak Probes of Hadron Structure

Discussion Point on Lecture #1

Something like this must occur



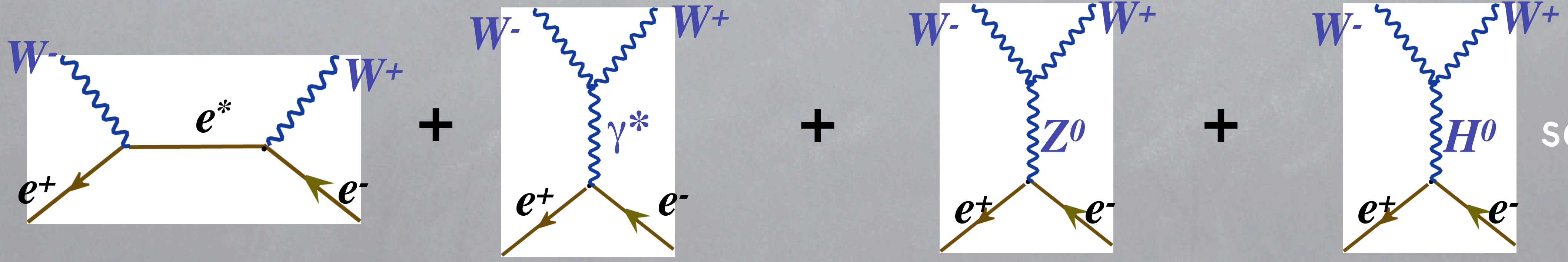
Scattering of longitudinal vector bosons (m=0)

- eeZ couplings depend on $\sin^2\theta_W$

$$\frac{m_W}{m_Z} = \cos\theta_W$$

$$e^+e^- \to W^+W^-$$

Scattering to longitudinal vector bosons (m=0)



scalar

For good high energy behaviour, Higgs must couple to m_e.

Why? Hint: if massless, helicity must be conserved

Outline of Lecture #2

- Symmetries and Conservation Laws
- Discrete and Continuous Symmetries
- Discoveries of P and CP violation
- T Violation and EDMs

Symmetries and Conservation Laws

Noether's Theorem: If Euler-Lagrange equation is invariant under any coordinate transformation, $\exists$ an integral of motion

Symmetry		conservation law
translation	⇔	momentum
time	⇔	energy
rotation	⇔	angular momentum

Not just space-time symmetries: Invariance of Lagrangian/Hamiltonian

e.g. Charge Conservation

$$[Q, H] = 0 \rightarrow \frac{d < Q >}{dt} = 0$$

$$Q|\Psi >= q|\Psi >$$

Conserved Quantities/Quantum Numbers

Symmetries and Groups

Symmetry operations:

Group of all operations: display closure & Associativity and have identity and inverse

Finite Group ⟺ Discrete Symmetry

Infinite Group ⟺ Continuous Symmetry

In Physics, group operations can be represented by matrices

SO(n): n-D rotations

SO(3) ⟺ SU(2)

Invariance under SU(2): Angular Momentum Conservation

Continuous Symmetries

Dirac free particle Lagrangian $\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi$

U(1) Invariance: conserved current $\partial_\mu J^\mu = 0$

Local U(1) Invariance: $A_\mu J^\mu$ Electromagnetic Interactions

Rotation in "Isospin Space"

$\begin{pmatrix} p \\ n \end{pmatrix}$ nucleon-nucleon interaction Hamiltonian invariant under SU(2) transformations in Isospin Space

$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$ the "massless" left-handed electron and electron-neutrino are part of a similar "weak isospin" doublet

SU(2) invariance yields 3 independent conserved currents

(there are 3 independent 2x2 Pauli spin matrices)

Symmetries of the Electroweak Lagrangian

$SU(2)_L \times U(1)_Y$

4 conserved currents

local gauge invariance yields 4 bosons: W^+, W^-, W^0, B^0

After spontaneous symmetry breaking via Higgs Mechanism:

$$SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$$

two weak charged currents	electromagnetic current	weak neutral current
$W^\pm$	γ	Z^0

SU(3)$_c$ and gluons ↔ Quantum Chromodynamics

Exact symmetries of nature: fully manifest in the early universe

Unbroken exact symmetries: massless mediator & infinite range force

Additive Conservation Laws

Are there other symmetries at low energies?

Are they exact?

If approximate, were they unbroken in the early universe?

Electric Charge is conserved

Charge is quantized

sum of initial charges = sum of final charges

$p \longrightarrow e^+\pi^0$

Proton Decay? Highly suppressed (lucky us!)

We know baryons are made of 3 quarks

Conserved quark current: consequence of $SU(3)_c$

quark (baryon) # violations suppressed on general grounds based on the symmetries of the electroweak Lagrangian

Baryon & Lepton Number

$n \rightarrow p e^- \bar{\nu}_e$ ⇒

$\bar{\nu}_e p \rightarrow e^+ n$ observed

$\bar{\nu}_e n \rightarrow e^- p$ not observed

Introduce Baryon B and Lepton number L: opposite sign for anti-particles

Are these exact conservation laws?

No fundamental reason: Certainly not as unbroken exact symmetries of nature ⇒ would lead to signals in Eotvos-style fifth force searches

Neutrino Mass leads to the speculation that neutrinos are their own anti-particles ⇒ Neutrino-less Double Beta Decay

If a process is not forbidden, it will occur!

Discrete Symmetries
C, P & T

Parity P $x, y, z \rightarrow -x, -y, -z$ $P\psi(\vec{r}) = \psi(-\vec{r})$

$P^2 = I$ Group has 2 elements, P and I

$[H, P] = 0 \Rightarrow H\psi = E\psi$ & $P\psi = \pi\psi \Rightarrow \pi = \pm 1$

If hamiltonian is invariant under parity transformations, then π is conserved and observable

Charge Conjugation C $C|p> = |\bar{p}>$

All quantum numbers flip sign
except mass and spin

particles that are its own anti-particles are eigenstates of C

$C|\gamma> = -|\gamma> \Rightarrow \pi^0 \rightarrow \gamma\gamma \Rightarrow C|\pi^0> = +|\pi^0> \Rightarrow$ $\pi^0 \rightarrow \gamma\gamma\gamma$ forbidden

Time Reversal T $T\psi(t) = \psi^*(-t)$

reactions are reversible in
principle if T is conserved

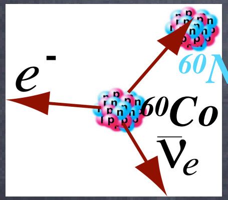
Discovery of Parity Violation

Particle Classification S^{π} e.g. pions: 0^{+} pseudoscalar mesons

Tau-theta puzzle (1956) $\theta^{+} \longrightarrow \pi^{+}\pi^{0}$ (P=+1) $\tau^{+} \longrightarrow \pi^{+}\pi^{0}\pi^{0}$ (P=-1)

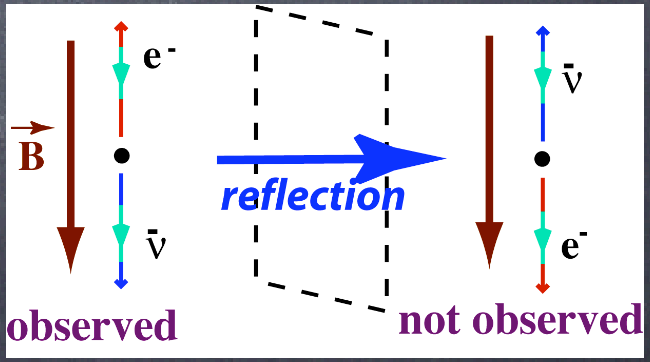
same mass but different parities! Lee and Yang propose:

The SAME particle is produced in strong interactions, but decays via weak interactions; P conserved in strong interactions, but not in weak interactions



Weak decay of ^{60}Co Nucleus

C.S. Wu et al: Beta's in decays of ^{60}Co nuclei aligned in a magnetic field showed anisotropy



Classic example: Puzzle in accelerator result; theorists propose a solution; test on a different process (table-top)

Neutral Kaon System

$\tau^+ = \theta^+ = K^+ \equiv \bar{s}u$ Also K^-: Opposite “strangeness” quantum numbers

$K^0 \equiv \bar{s}d$ & $\bar{K}^0 \equiv \bar{s}d$ Also opposite strangeness: are they distinct?

Gell-Mann and Pais propose a test assuming CP conservation

$$CP|\nu_{eL} >= |\bar{\nu}_{eR} >$$

$$|K_1 >= \frac{1}{\sqrt{2}}(|K^0 > +|\bar{K}^0 > \qquad CP|\bar{K}^0 >= |K^0 > \qquad CP|K_1 >= +|K_1 > \qquad CP|\pi\pi >= +|\pi\pi >$$

$$|K_2 >= \frac{1}{\sqrt{2}}(|K^0 > -|\bar{K}^0 > \qquad CP|K^0 >= |\bar{K}^0 > \qquad CP|K_2 >= -|K_2 > \qquad CP|\pi\pi\pi >= -|\pi\pi\pi >$$

If CP is conserved:

$K_1 \rightarrow \pi\pi$ $K_2 \rightarrow \pi\pi\pi$ allowed

$K_1 \rightarrow \pi\pi\pi$ $K_2 \rightarrow \pi\pi$ forbidden

Elegant Prediction:
Existence of K_2

two pion decay lifetime much shorter than three pion case

start with K0’s; have near and far detectors; 2 pions in near detector, 3 pions in far detector

Discovery of CP Violation

Christensen, Cronin, Fitch and Turlay

$$|K^0 >= \frac{1}{\sqrt{2}}(|K_1 > +|K_2 >)$$

$$|\bar{K}^0 >= \frac{1}{\sqrt{2}}(|K_1 > -|K_2 >)$$

start with K0's:
contains K1's and K2's

drift region
(vacuum)

K2's only:
antiK0's!

Anti-K0's have much larger cross-section to scatter off nuclei

K2's only:
antiK0's!

material

K1's again:
2 pion decays!

Startling observation: take material away and some residual 2 pion decays remain!!!!

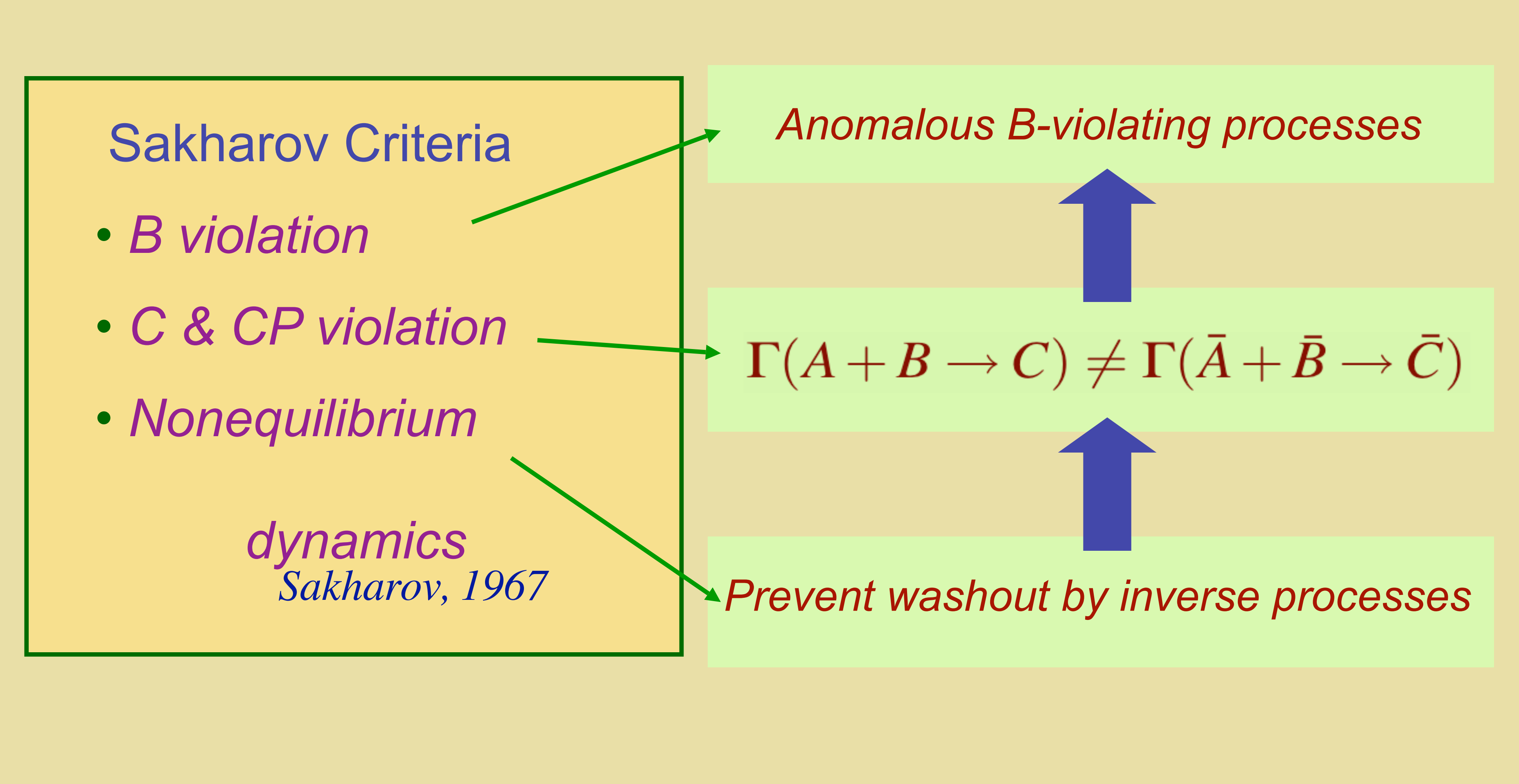
$$|K_L >= \frac{1}{\sqrt{1+\epsilon^2}}(|K_2 > +\epsilon|K_1 >)$$

$$|K_S >= \frac{1}{\sqrt{1+\epsilon^2}}(|K_1 > -\epsilon|K_2 >)$$

Impressive experimental challenges overcome:

only careful, methodical and confident experimentalists need apply!

Matter-Antimatter Asymmetry



Sakharov Criteria

- *B violation*
- *C & CP violation*
- *Nonequilibrium dynamics*

Sakharov, 1967

Anomalous B-violating processes

$$\Gamma(A+B \rightarrow C) \neq \Gamma(\bar{A}+\bar{B} \rightarrow \bar{C})$$

Prevent washout by inverse processes

CP violation in the weak interactions requires 3 generations of quarks:

Ensures quark mixing matrix has complex phase

However, electroweak CP phase explains Kaons; insufficient for consideration above

CPT Theorem and T Violation

The renormalizable field theories such as the ones that describe strong and electroweak interactions conserve CPT: e.g. masses and lifetimes of particle and anti-particle

CP violation therefore implies T violation

added impetus for new sources of CP & T violation: observed matter-anti-matter asymmetry

$$i\hbar\frac{\partial\Psi}{\partial t} = -\left(\frac{\hbar^2}{2m}\right)\frac{\partial^2\Psi}{\partial x^2} + V\Psi$$

If V is real then T is a good symmetry $\Psi(t)$ & $\Psi^*(-t)$ are solutions

If V is complex, then T is violated; quantified by a complex phase

Electric Dipole Moments

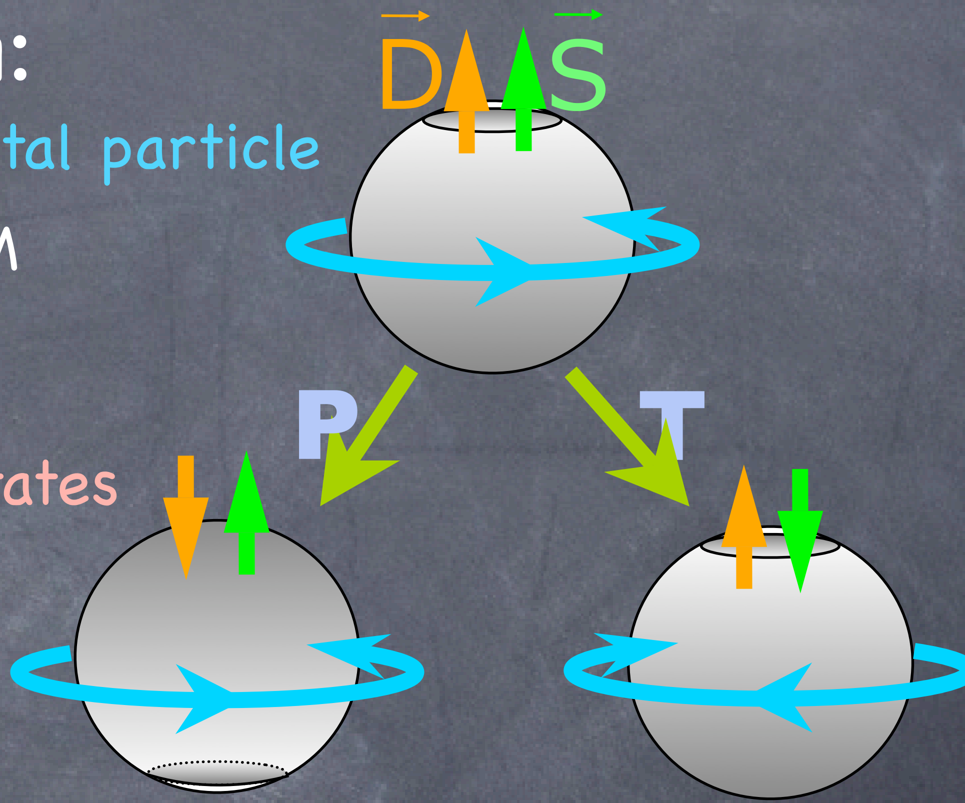
Most practical way to find T violation:

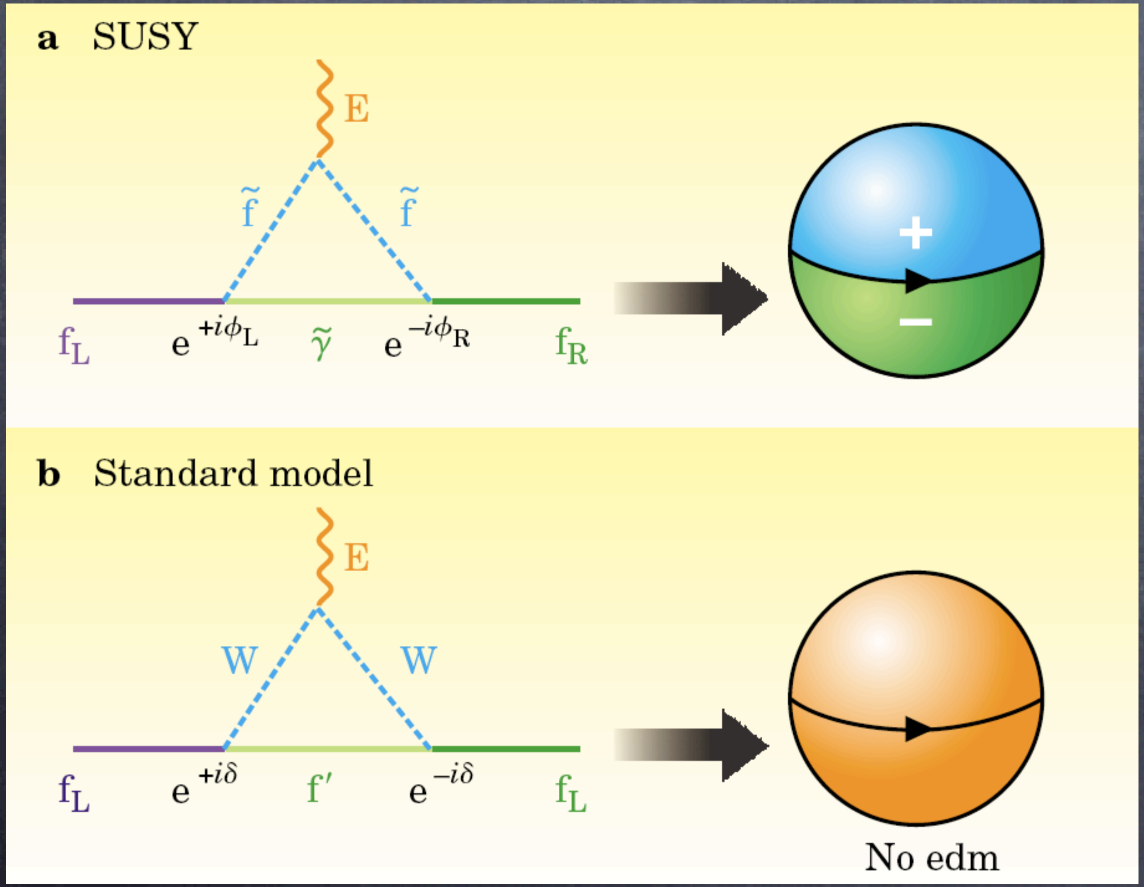
establish permanent electric dipole moment for a fundamental particle

Charge q displaced from -q by a distance r creates an EDM

$$\vec{d} = q\vec{r}$$

If T is conserved and d is non-zero: degenerate particle states





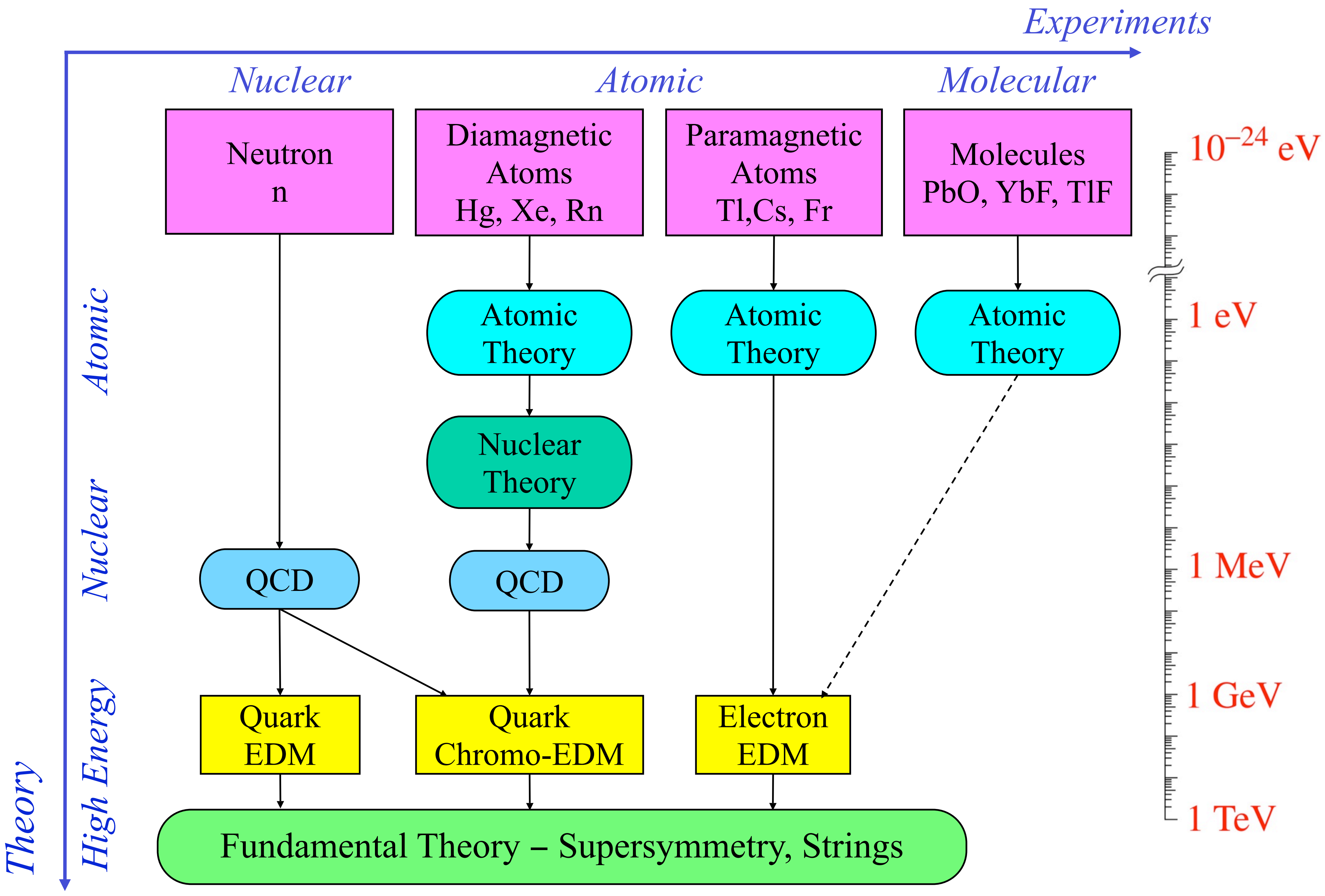
raw sensitivity:

$d \sim (m \times e)/\Lambda^2$

$d \sim 10^{-27}$: $\Lambda \sim 100$ TeV

M. Romalis

EDM Approaches



Experiments

Nuclear

Atomic

Molecular

Theory

Atomic

Nuclear

High Energy

Neutron
n

Diamagnetic
Atoms
Hg, Xe, Rn

Paramagnetic
Atoms
Tl,Cs, Fr

Molecules
PbO, YbF, TlF

Atomic
Theory

Atomic
Theory

Atomic
Theory

Nuclear
Theory

QCD

QCD

Quark
EDM

Quark
Chromo-EDM

Electron
EDM

Fundamental Theory – Supersymmetry, Strings

10^{-24} eV

1 eV

1 MeV

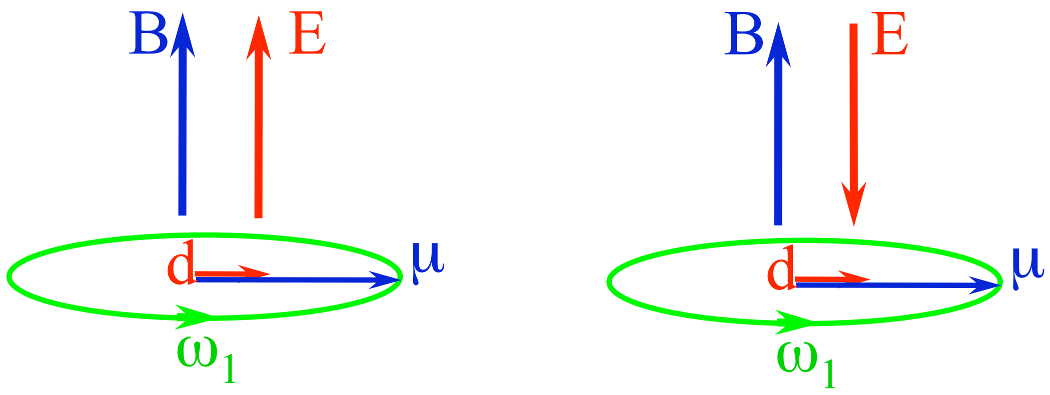
1 GeV

1 TeV

Experimental Concept

- Measure spin-precession frequencies

$$H = -\vec{\mu} \times \vec{B} - \vec{d} \times \vec{E}$$



$$\omega_1 = \frac{2\mu B + 2dE}{\hbar} \qquad \omega_2 = \frac{2\mu B - 2dE}{\hbar} \qquad \omega_1 - \omega_2 = \frac{4dE}{\hbar}$$

- Statistical Sensitivity:

Single atom with coherence time τ: $$\delta\omega = \frac{1}{\tau}$$

N uncorrelated atoms measured for time T >> τ: $$\delta d = \frac{\hbar}{2E}\frac{1}{\sqrt{2\tau T N}}$$

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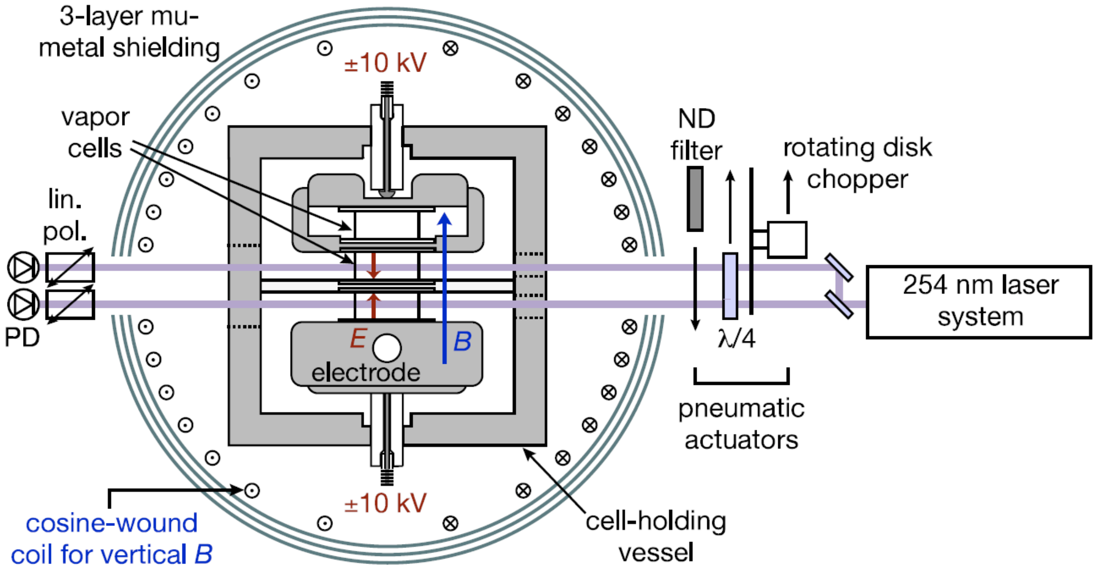
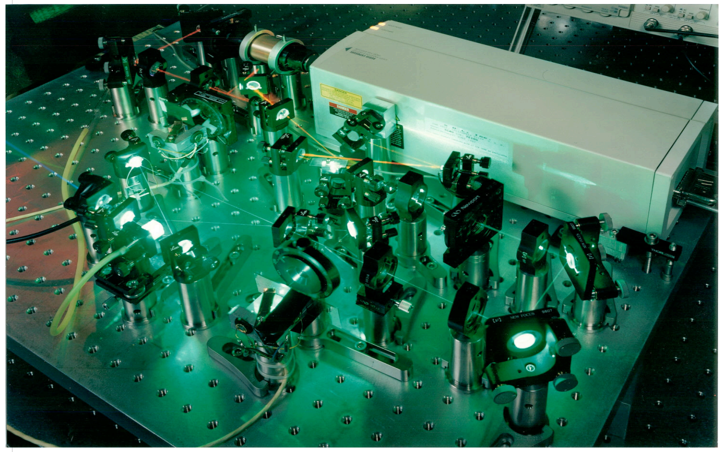
Hg EDM Experiment

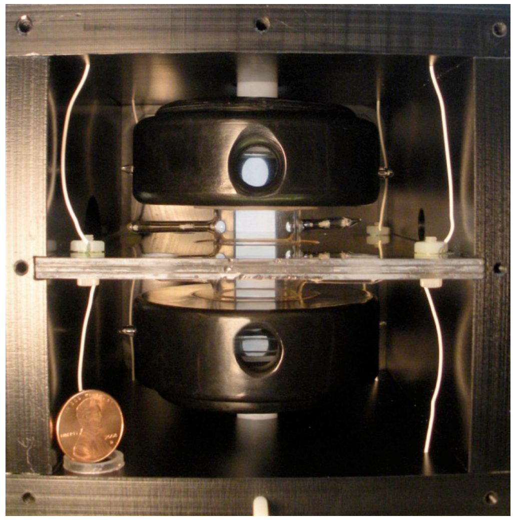


Solid-state Quadrupled UV laser



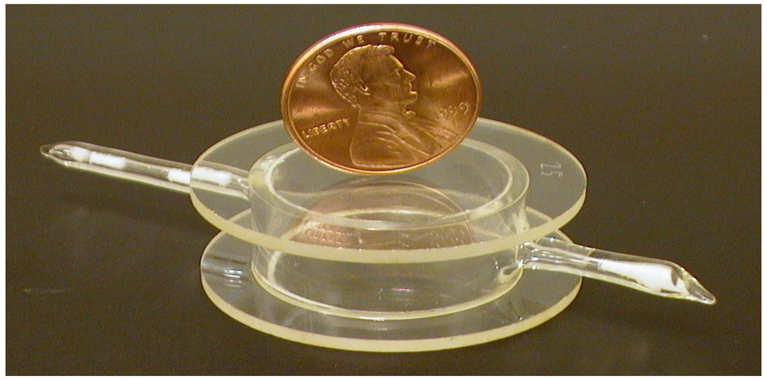
100,000 hours of operation

High purity non-magnetic vessel



All materials tested with SQUID

Hg Vapor cells



Spin coherence time: 300 sec
Electrical Resistance: $2\times10^{16}\ \Omega$

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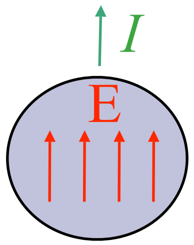
Interpretation of Hg EDM

- No atomic EDM due to EDM of the nucleus – Schiff's Theorem

  ⇒Electrons screen applied electric field

- d(Hg) is due to finite nuclear size

  ⇒ nuclear Schiff moment S – Difference between mean square radius of the charge distribution and electric dipole moment distribution



$$\vec{S} = \frac{2\pi}{5}\int dx^3 \rho(x)\left(x^2\vec{x} - \frac{5}{3}\langle r^2\rangle_{ch}\vec{x}\right)$$

⇒Schiff moment induces parity mixing of atomic states, giving an atomic EDM:

$$d_a = R_A\, S$$

⇒R_A - from atomic wavefunction calculations, uncertainty 20%

Ra-225 Experiment

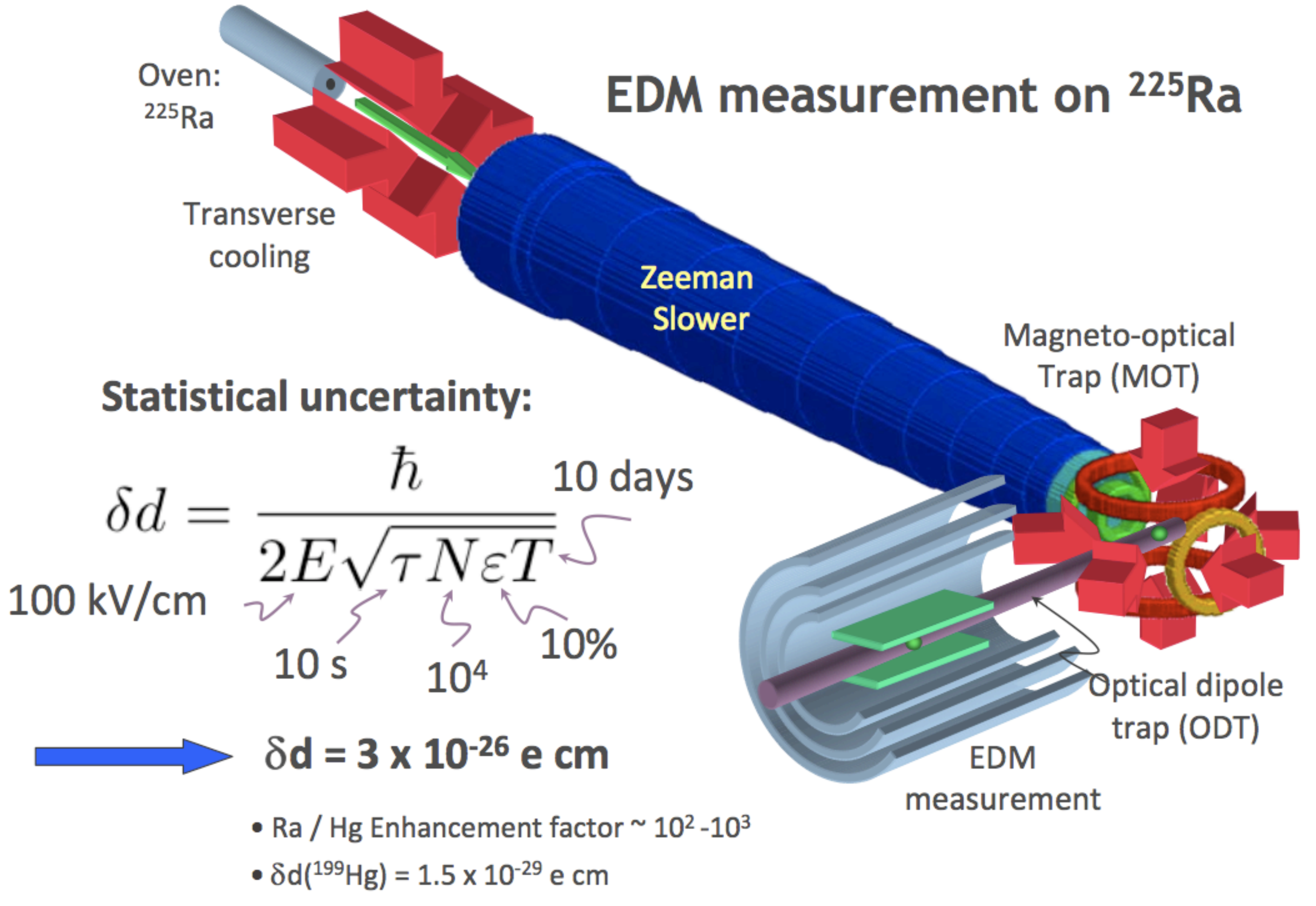
EDM of ^{225}Ra enhanced:

- Large intrinsic Schiff moment due to octupole deformation;
- Closely spaced parity doublet;
- Relativistic atomic structure.

Z-T Lu, ANL
Atom Trap Program

Future:

Improve sensitivity by 2 orders of magnitude



EDM measurement on ^{225}Ra

Statistical uncertainty:

$$\delta d = \frac{\hbar}{2E\sqrt{\tau N \varepsilon T}}$$

10 days

100 kV/cm

10 s

10^4

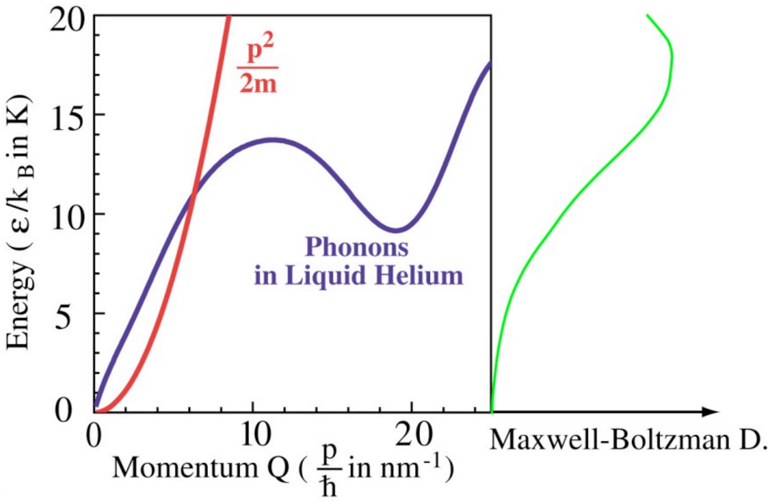
10%

$\delta d = 3 \times 10^{-26}$ e cm

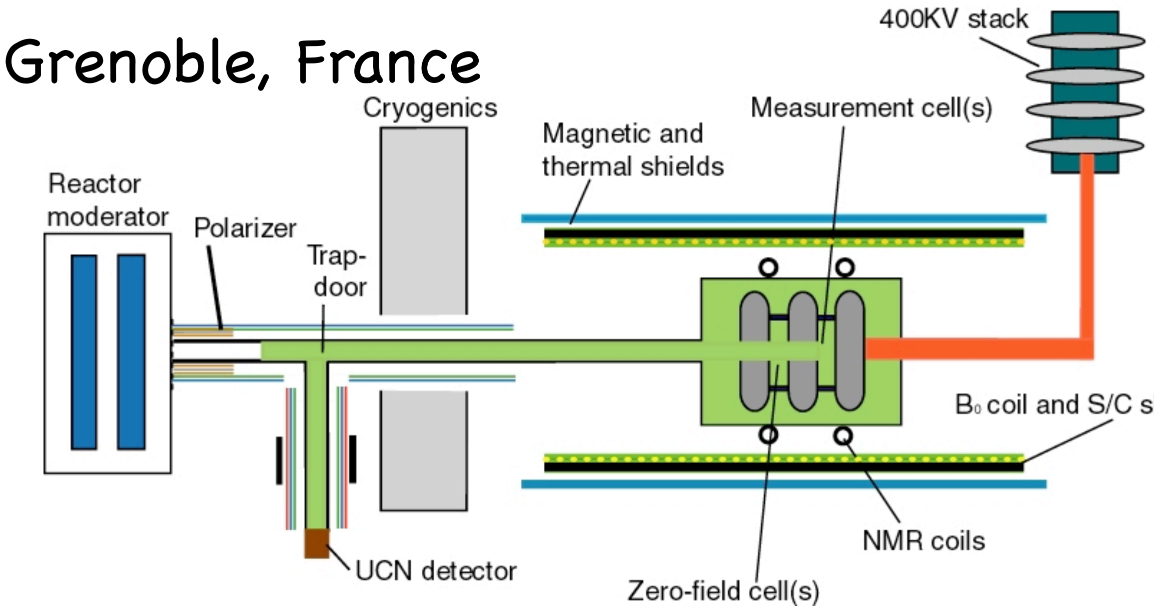
- Ra / Hg Enhancement factor ~ 10^2 - 10^3
- $\delta d(^{199}\mathrm{Hg}) = 1.5 \times 10^{-29}$ e cm

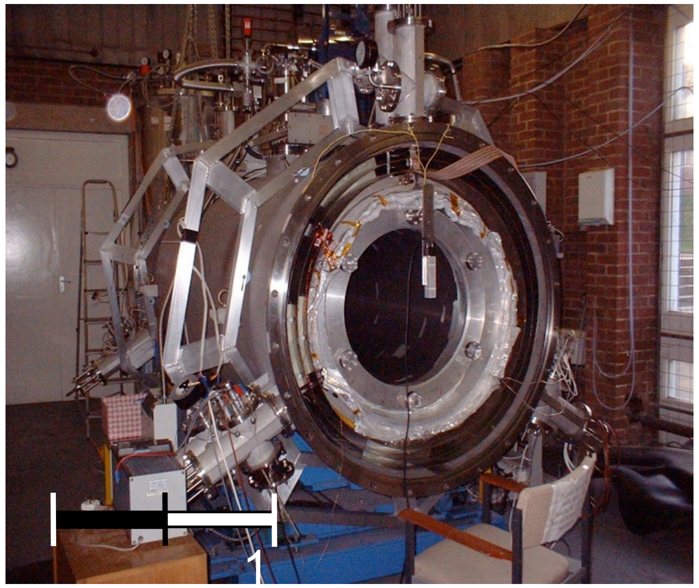
Neutron EDM

- Superthermal production in superfluid ^{4}He
  - ⇒N increased by 100 – 10000
- He-4 good isolator, low temperature
  - ⇒E increased by 5
- Superconducting magnetic shields
- SQUID magnetometers



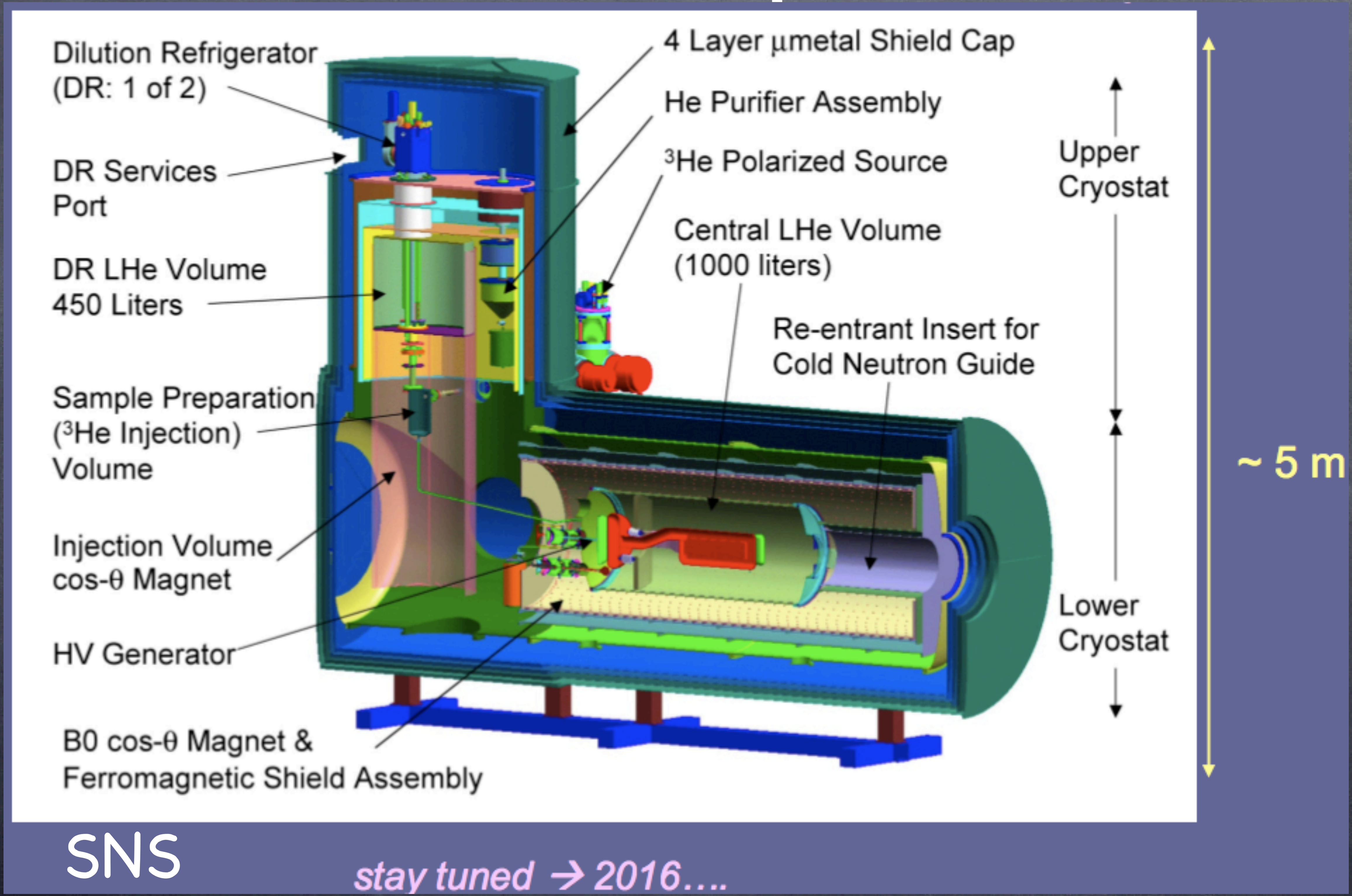
ILL, Grenoble, France





New Concept: ^{3}He co-magnetometer

US nEDM experiment



SNS

stay tuned → 2016….

Summary of EDM Experiments

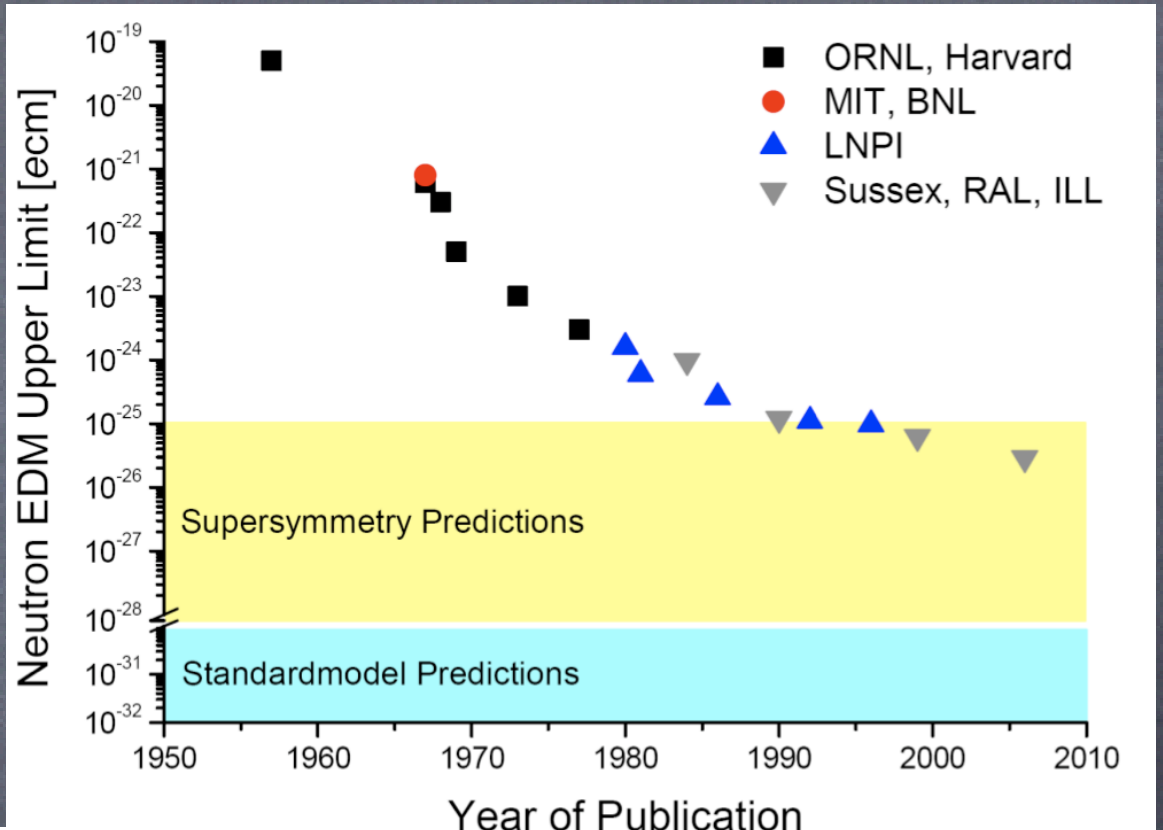
Area of Intense Activity

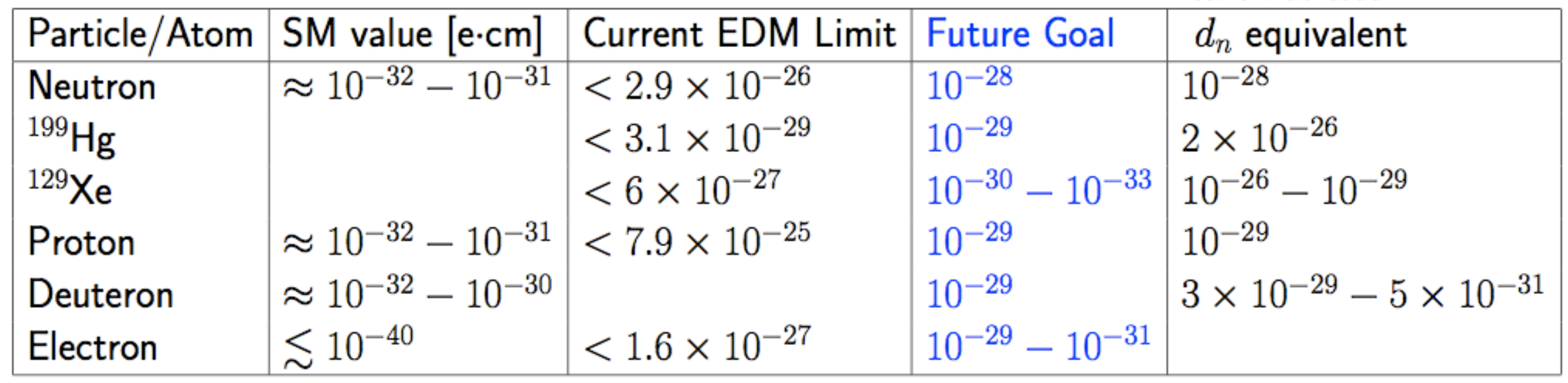
Both theory and experiment

Atomic experiments,

cryogenic experiments,

storage rings.....





Particle/Atom	SM value [e·cm]	Current EDM Limit	Future Goal	d_n equivalent
Neutron	$\approx 10^{-32} - 10^{-31}$	$< 2.9 \times 10^{-26}$	10^{-28}	10^{-28}
^{199}Hg		$< 3.1 \times 10^{-29}$	10^{-29}	2×10^{-26}
^{129}Xe		$< 6 \times 10^{-27}$	$10^{-30} - 10^{-33}$	$10^{-26} - 10^{-29}$
Proton	$\approx 10^{-32} - 10^{-31}$	$< 7.9 \times 10^{-25}$	10^{-29}	10^{-29}
Deuteron	$\approx 10^{-32} - 10^{-30}$		10^{-29}	$3 \times 10^{-29} - 5 \times 10^{-31}$
Electron	$\lesssim 10^{-40}$	$< 1.6 \times 10^{-27}$	$10^{-29} - 10^{-31}$	

Summary

- Symmetries have played and continue to play a profoundly important role in shaping theoretical and experimental research in the search for physics beyond the standard model
- A very important complementary experimental approach that involve nuclear theorists and experimentalists is the search for a permanent electric dipole moment of an elementary particle