High-Energy Physics from Low-Energy Symmetry Studies

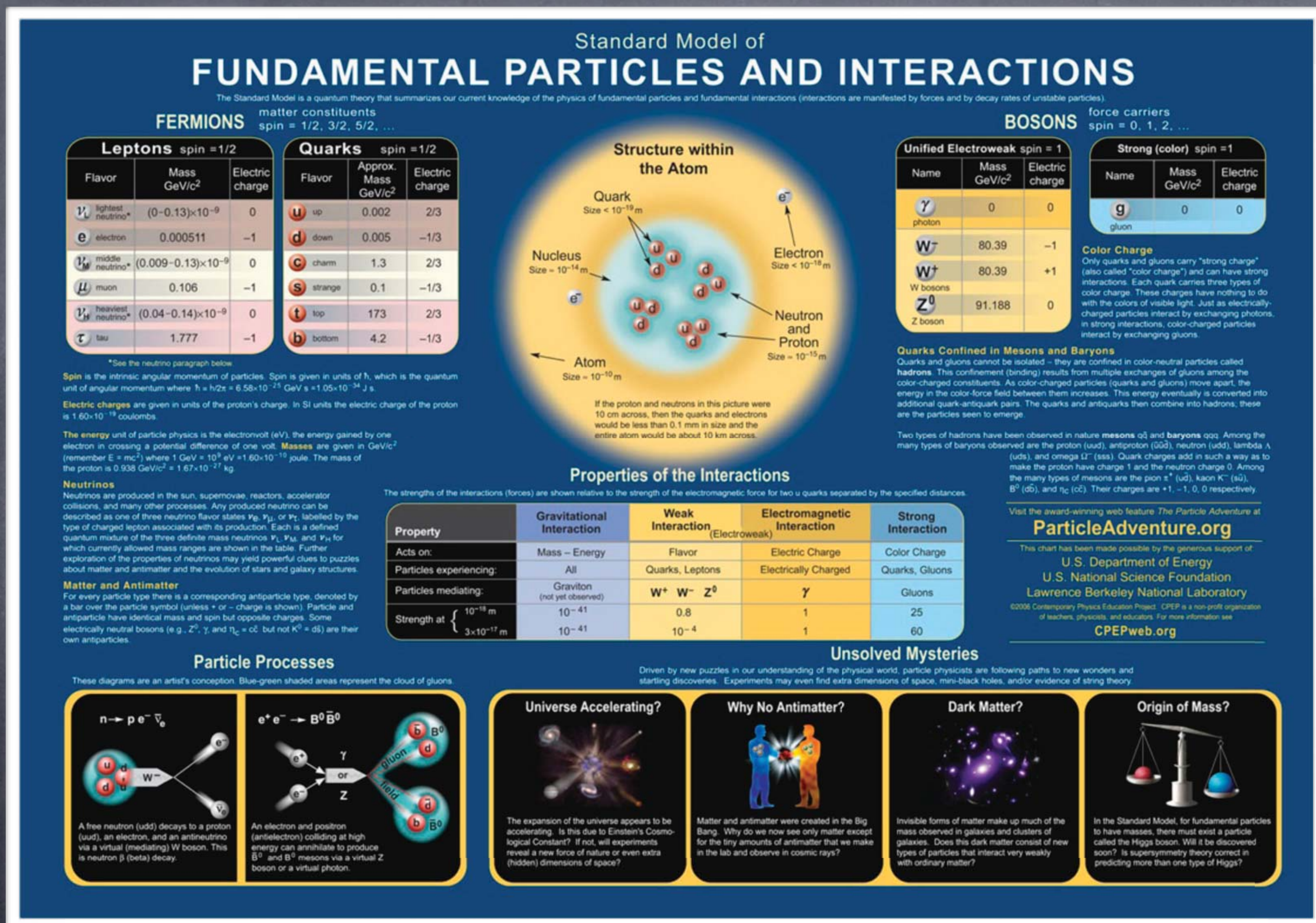
David Hanneke

Michelson Postdoctoral Prize Lectures

14 May 2010

High Energy Physics

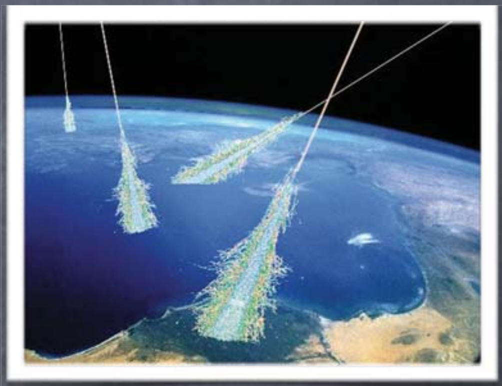
$E = mc^2 = hc/\lambda$

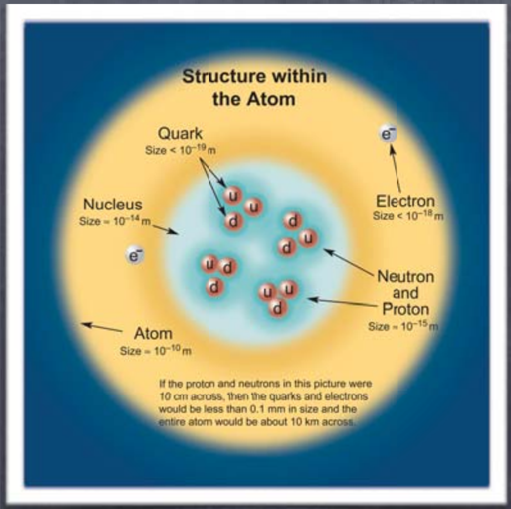


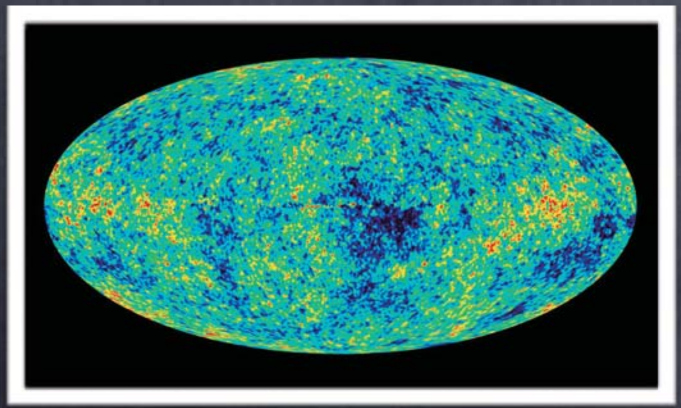
http://cpepweb.org

How to do high-energy physics

- Make high-energy particles
  - Accelerators
- Find high-energy particles
  - Cosmic rays
  - Dark matter searches
  - Astrophysics/cosmology
- Find high-energy virtual particles
  - Precision measurement

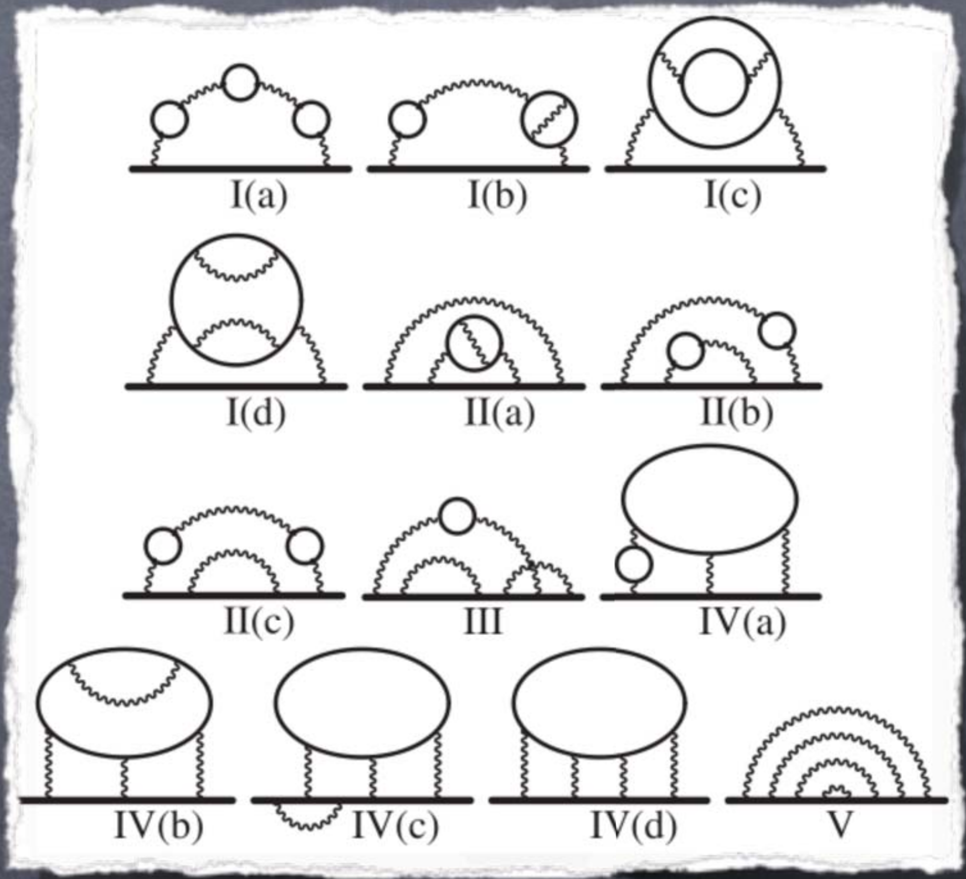






Precision Measurements

- Look for high-energy (vacuum) effects
- Cheap, small
- Fruitful ground: things that are forbidden in the low-energy theory



G. Gabrielse, D. Hanneke, T. Kinoshita, M. Nio, and B. Odom, Phys. Rev. Lett. **97**, 030802 (2006). Ibid. **99** 039902(E) (2007)

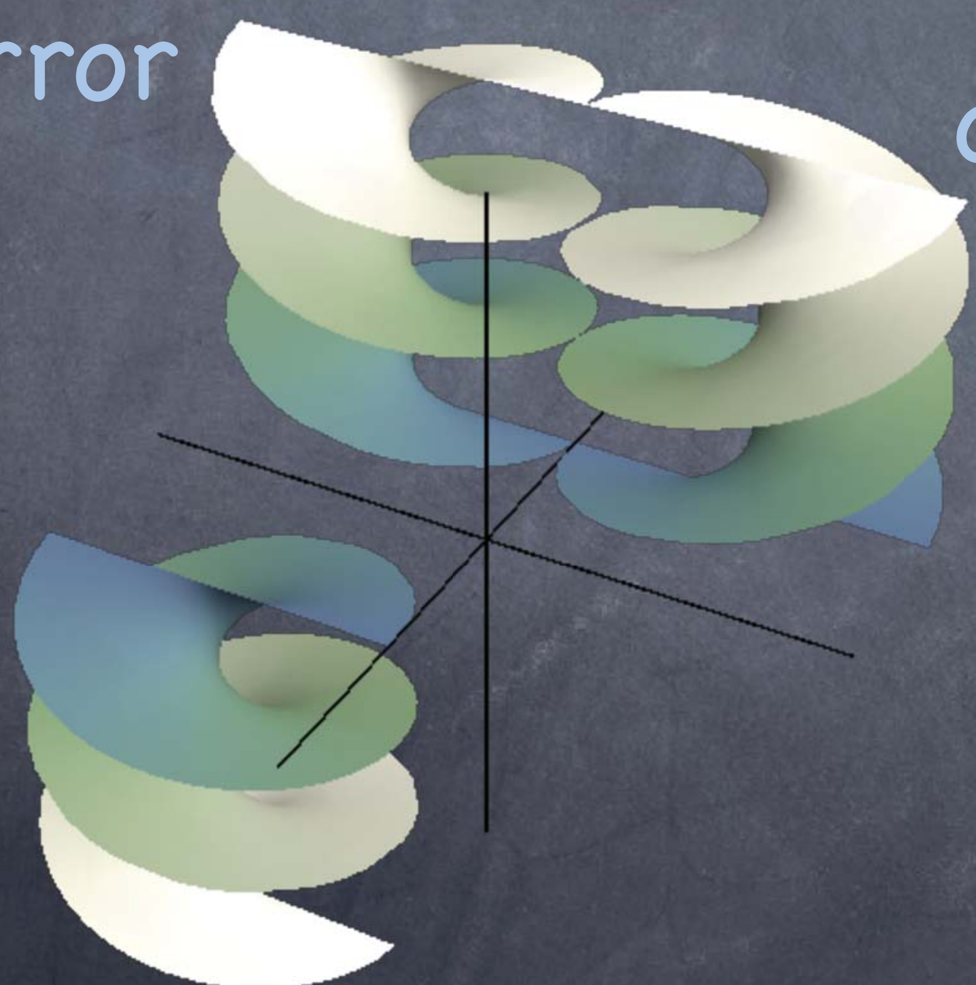
Symmetries

- Discrete
  - Charge conjugation $e^- \rightarrow e^+$
  - Parity $\vec{x} \rightarrow -\vec{x}$
  - Time-reversal $t \rightarrow -t$
- Continuous: Lorentz invariance

Parity

$$\vec{x} \rightarrow -\vec{x}$$

- "mirror" symmetry



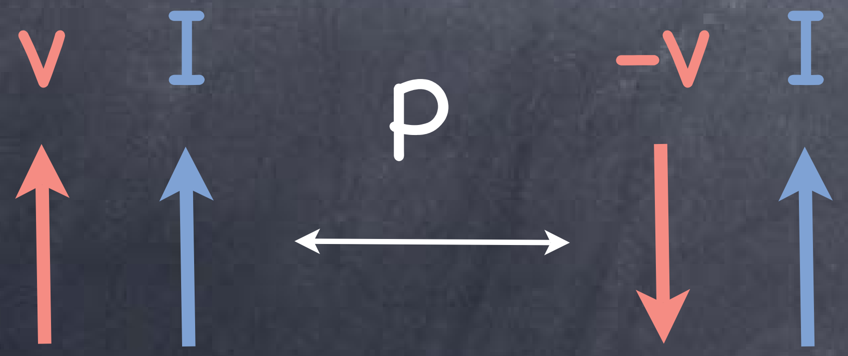
+ even	- odd
m	$\vec{x}$
q	$\vec{p}$
t	$\vec{E}$
$\vec{B}$	
$\vec{J}$	

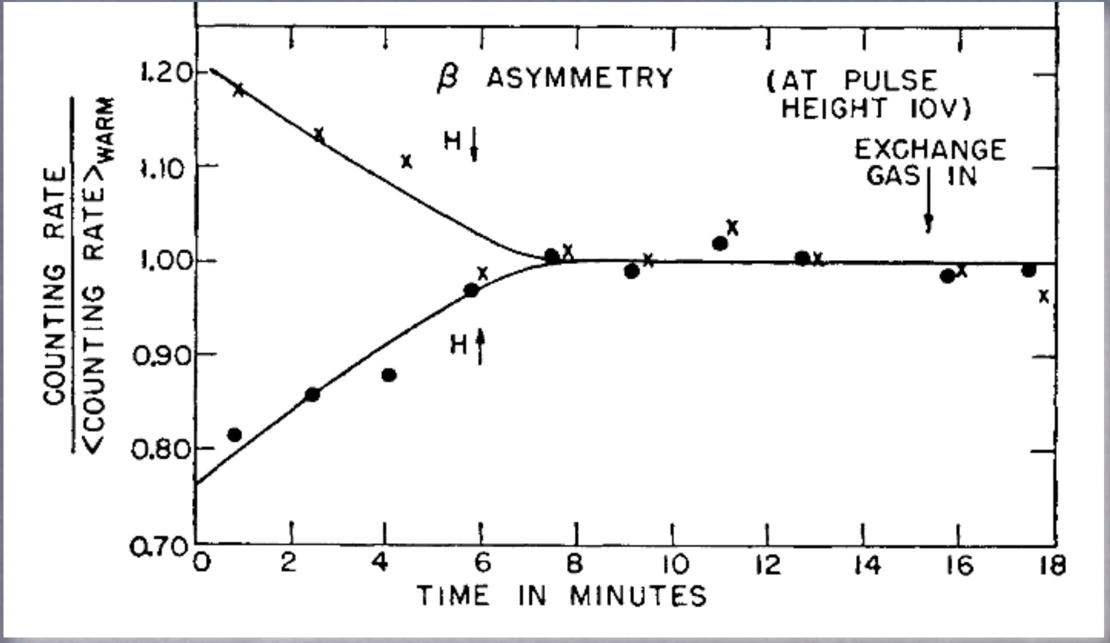
scalars, pseudovectors

vectors

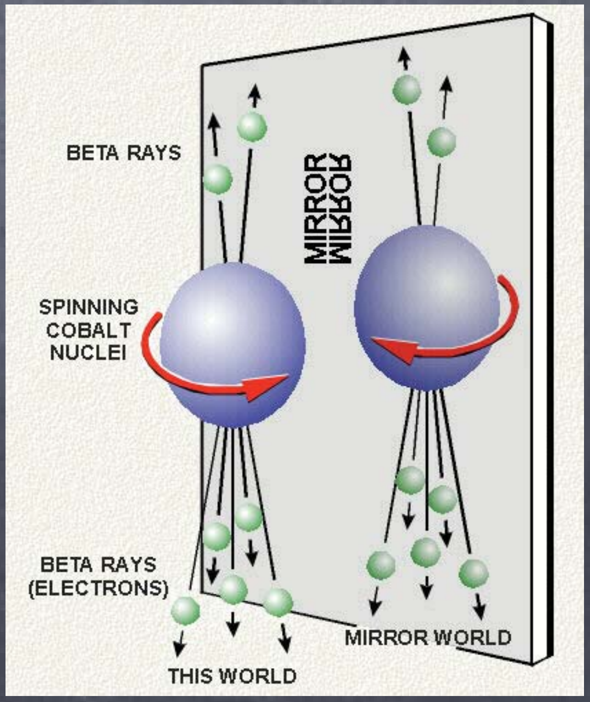
Parity in β-Decay

- Parity is violated in weak interactions
- Electrons are preferentially emitted antiparallel to the nuclear spin of ^{60}Co





C. S. Wu, et al., Phys. Rev. **105** 1413-1415 (1957)



http://www.nist.gov/physlab/general/parity

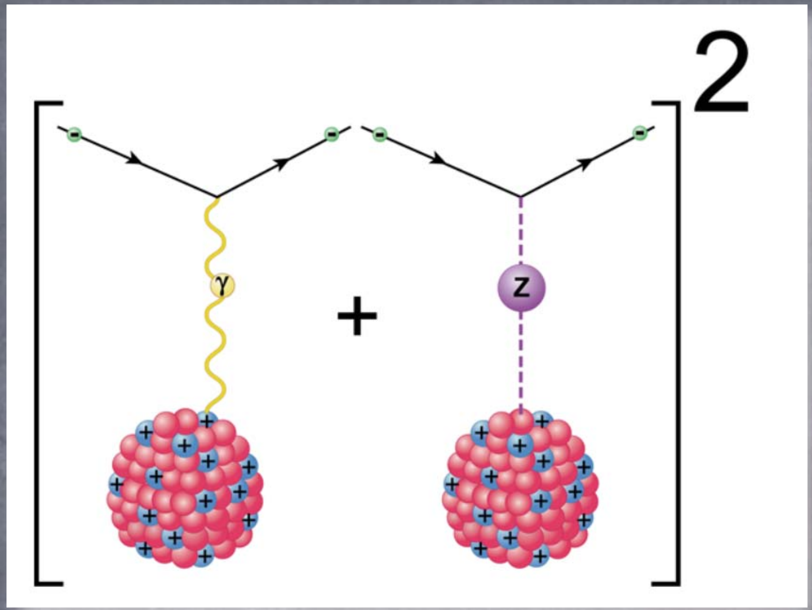
Parity in Atomic Transitions

- E1 transitions connects levels of opposite parity

$$A_{ba} \propto \langle \psi_b | \vec{x} | \psi_a \rangle$$

- PNC mixes levels of opposite parity

$$|P'_+\rangle = |P_+\rangle + \epsilon |P_-\rangle$$

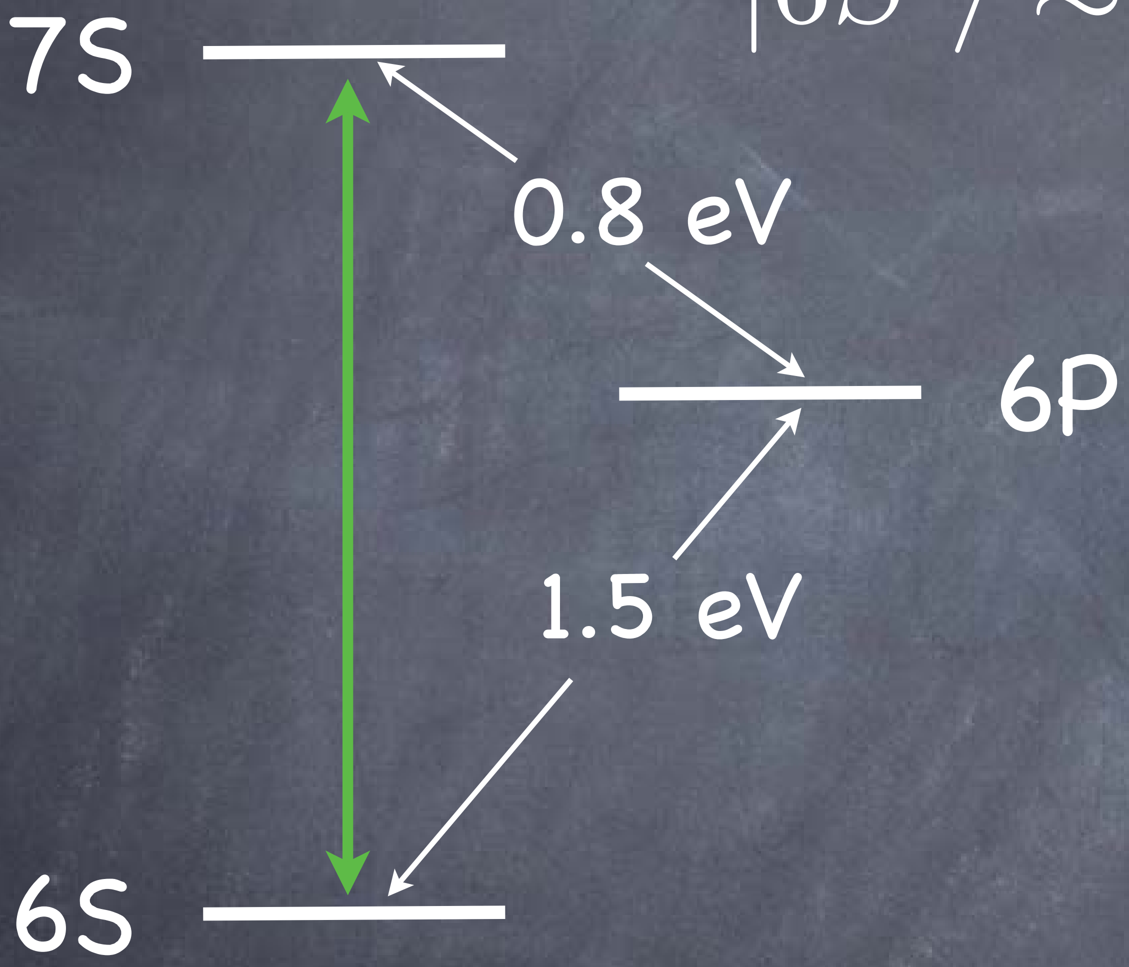


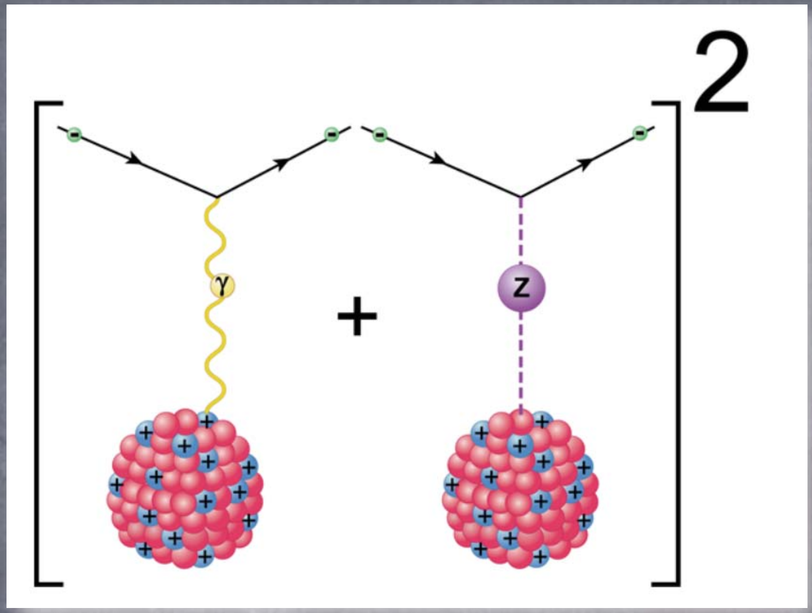
K. Jungmann, Physics **2** 68 (2009)

$$\epsilon \propto \frac{Z^3}{\Delta E}$$

Parity Violation in Cs

$$|6S'\rangle \approx |6S\rangle - i10^{-11}\,|6P\rangle$$





K. Jungmann, Physics **2** 68 (2009)

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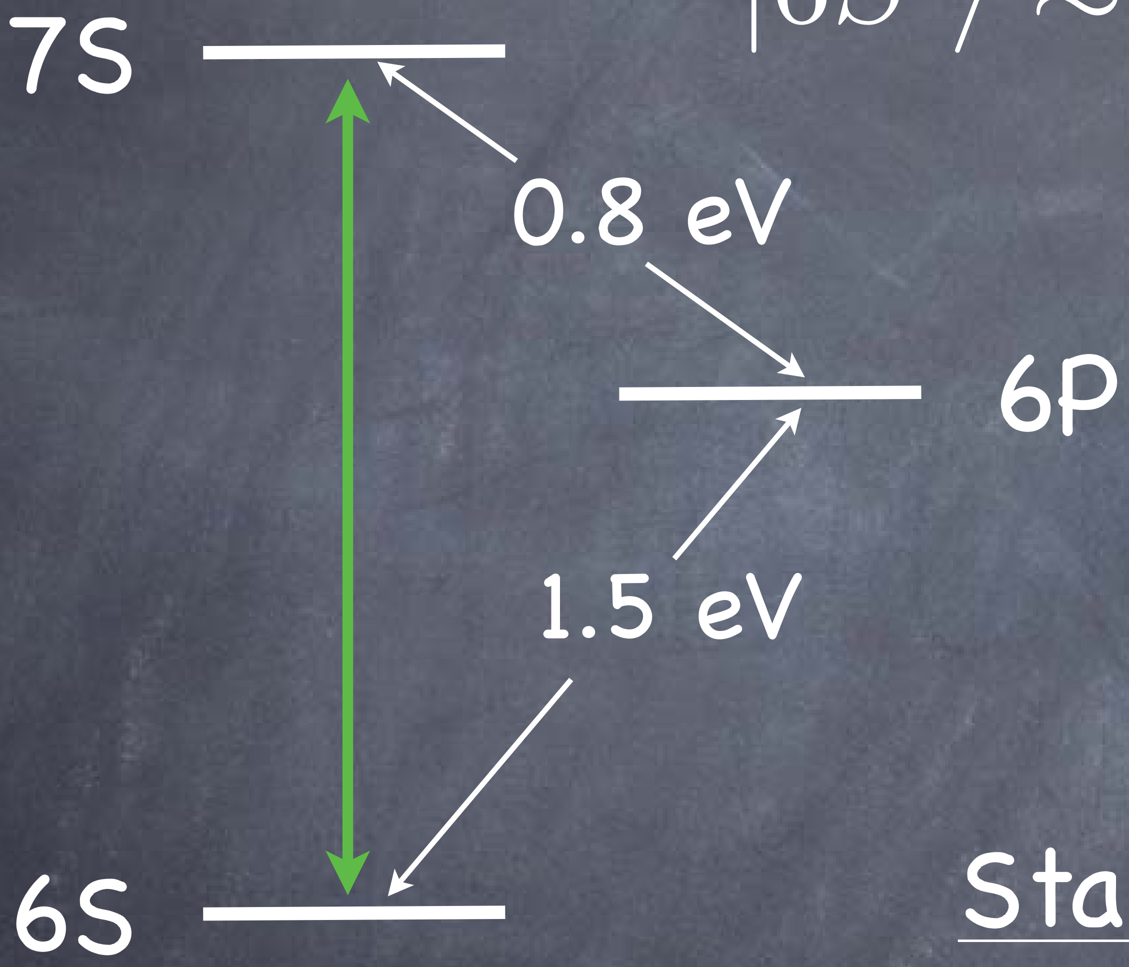
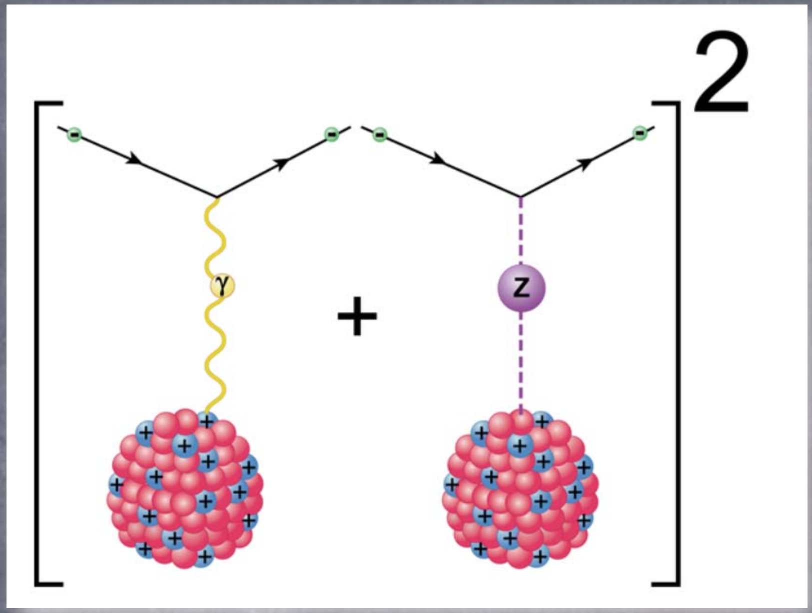




K. Jungmann, Physics **2** 68 (2009)

Stark-induced transition

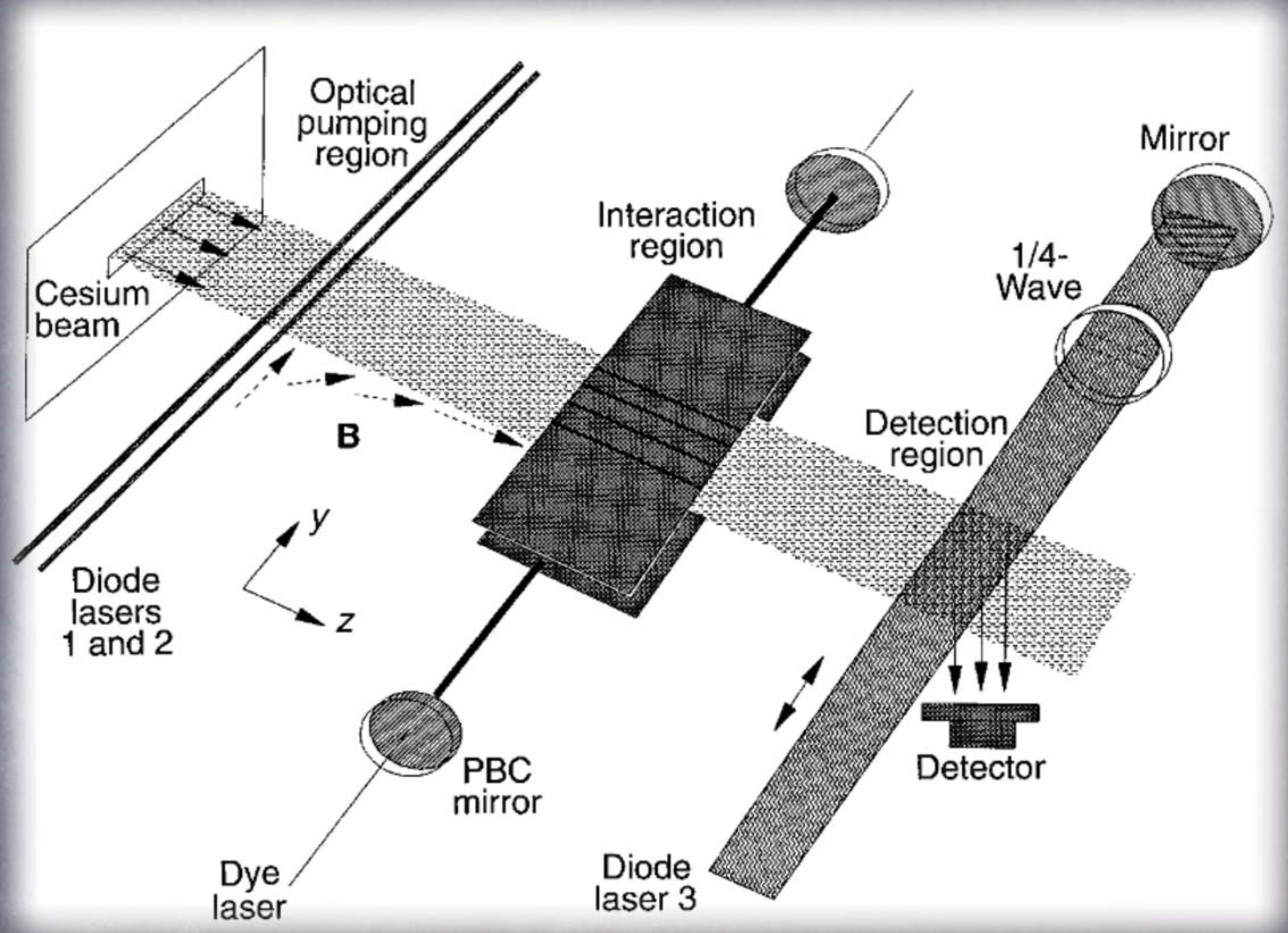
Electric field mixes levels of opposite parity

$$R = |A_{\mathrm{E}} + A_{\mathrm{PNC}}|^2 = |A_{\mathrm{E}}|^2 + 2\,\mathrm{Re}[A_{\mathrm{E}}A^*_{\mathrm{PNC}}] + |A_{\mathrm{PNC}}|^2$$

Parity Violation in Cs

$$\frac{A_{\mathrm{PNC}}}{A_{\mathrm{E}}} \sim 10^{-5}$$

0.5% accuracy, statistics limited



C. S. Wood, et al., Science **275** 1759-1763 (1997)

Weak Mixing Angle

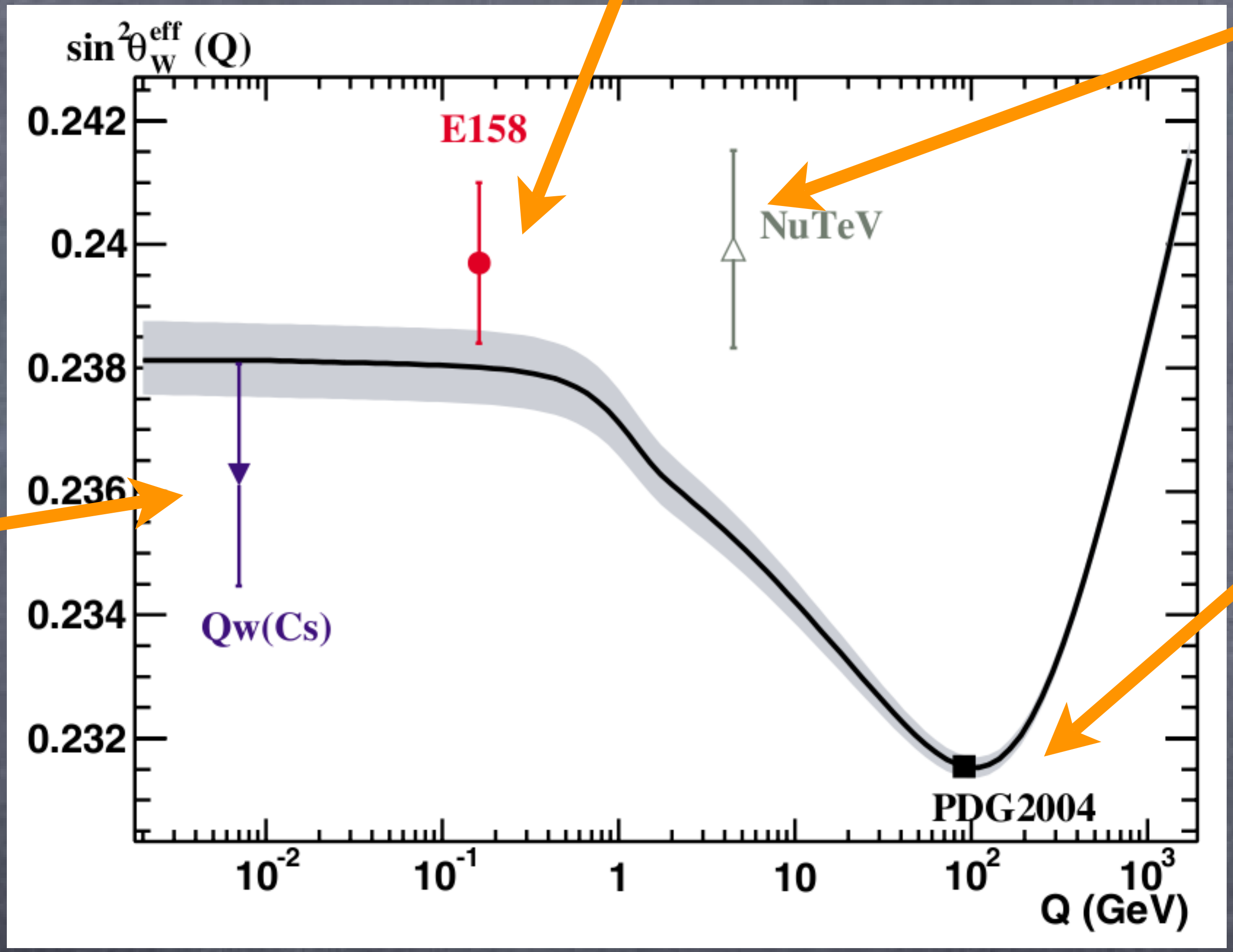
$$\cos\theta_W = \frac{M_W}{M_Z}$$

e⁻/e⁻ scattering

ν/nucleon scattering

e⁺/e⁻ collisions

atomic Cs



P. L. Anthony, et al, Phys. Rev. Lett. **95** 081601 (2005)

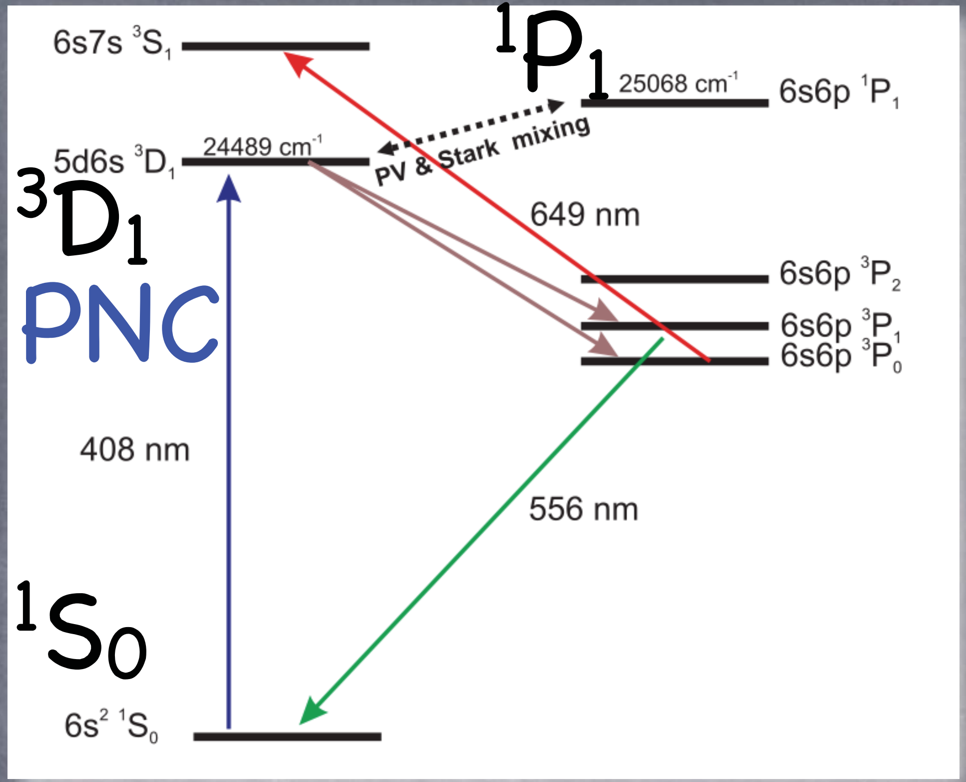
$$Q_w = -N + \left(1 - 4\sin^2\theta_W\right) Z$$

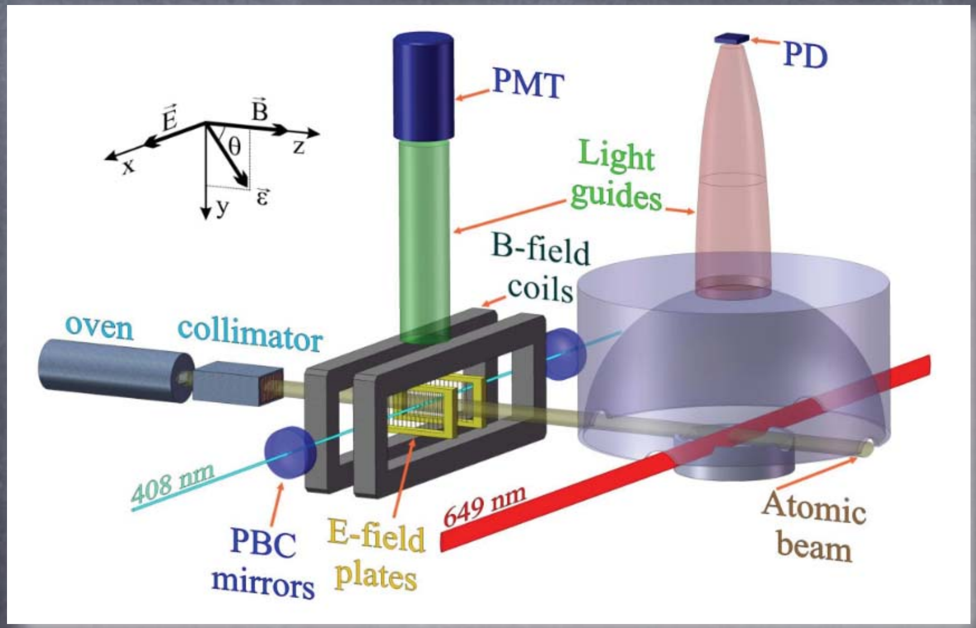
Current P-violation Efforts

- Yb: 100x larger PNC amplitude than Cs
  - Measured to 16%
  - 7 stable isotopes

$$Q_w = -N + \left(1 - 4\sin^2\theta_W\right) Z$$

- Other ongoing efforts: Fr, Ba^+, Ra^+



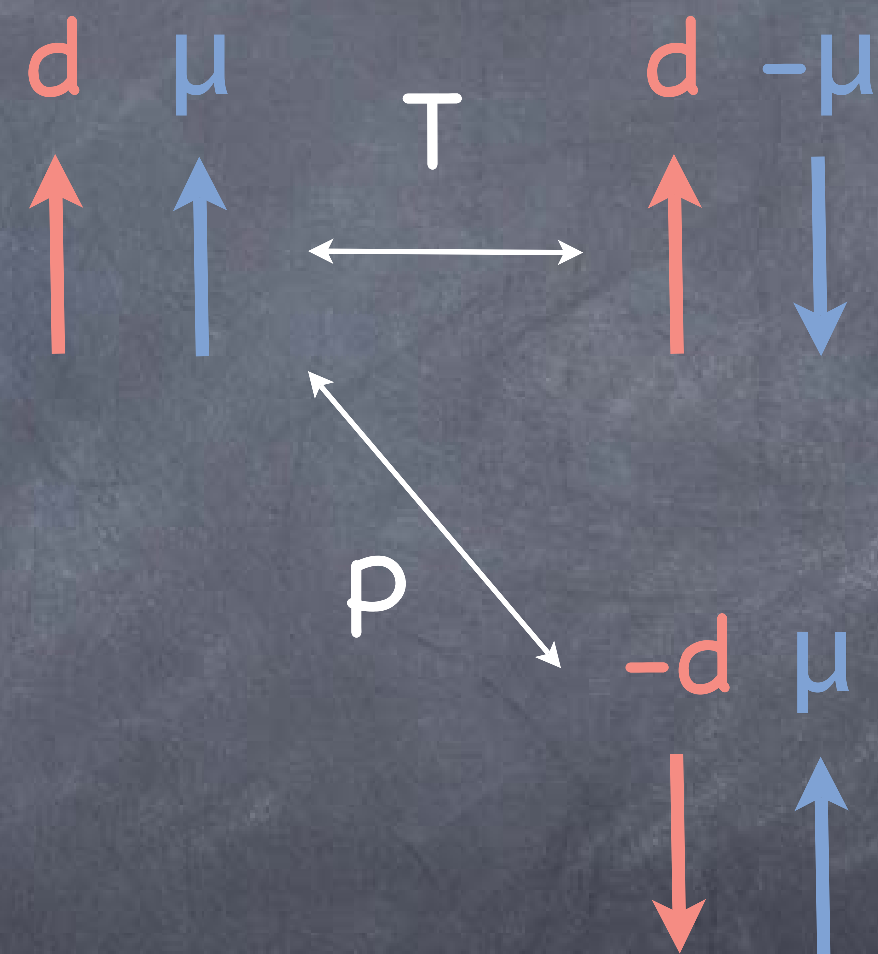


K. Tsigutkin, et al, Phys. Rev. Lett. **103** 071601 (2009)
K. Tsigutkin, et al, Phys. Rev. A **81** 032114 (2010)

Time-Reversal

$$t \rightarrow -t$$

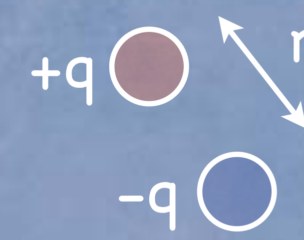
- Related to CP-violation (and hence matter/antimatter asymmetry)
- Intrinsic electric dipole moments are forbidden



+ even	- odd
m	t
q	$\vec{p}$
$\vec{x}$	$\vec{B}$
$\vec{E}$	$\vec{J}$
$\vec{d}$	$\vec{\mu}$

Electric Dipole Moments

Classical EDM



$$d = qr$$

Experimental limits

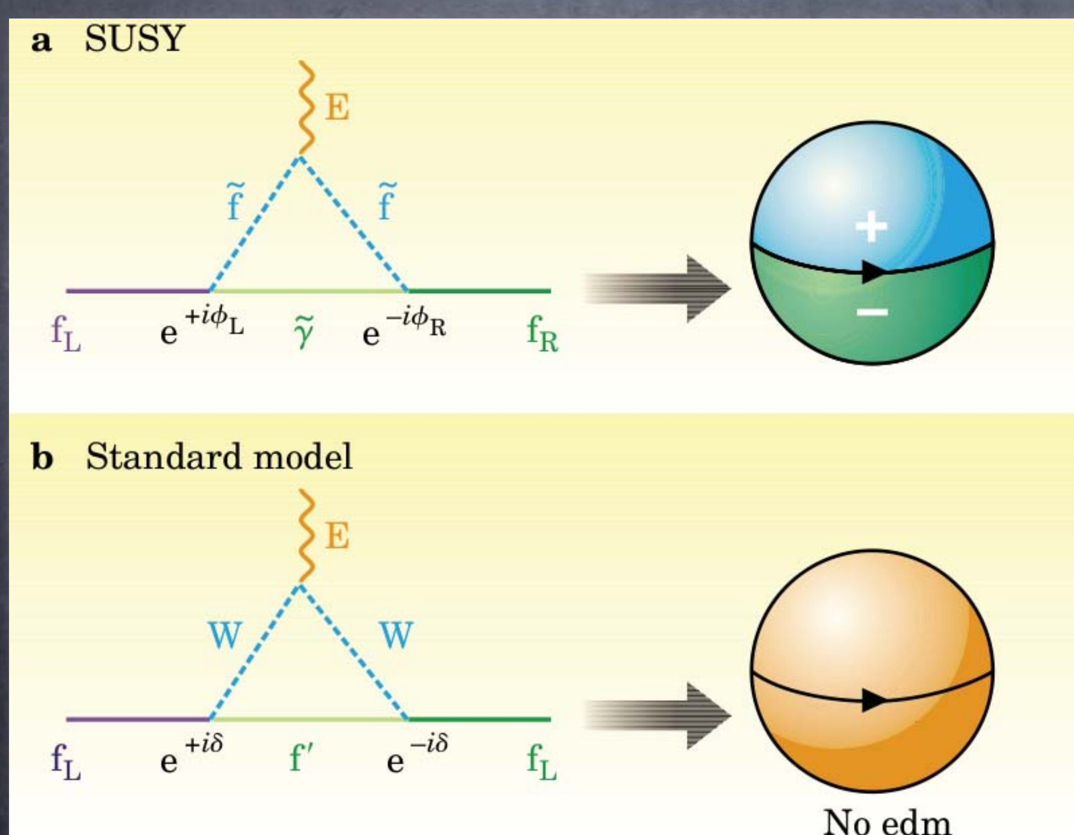
$$|d(e)| \leq 1.6 \times 10^{-27} e \cdot \mathrm{cm}$$

$$|d(n)| \leq 2.9 \times 10^{-26} e \cdot \mathrm{cm}$$

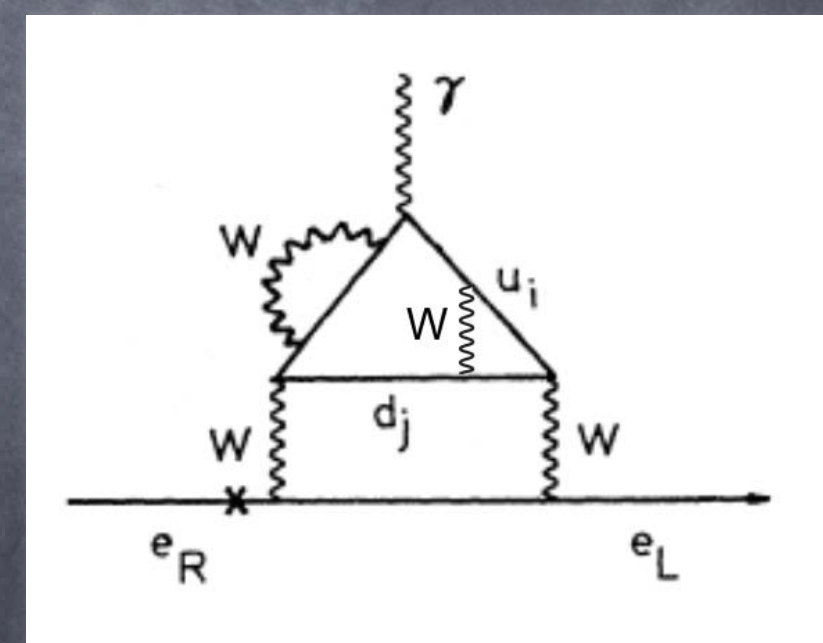
$$|d(^{199}\mathrm{Hg})| < 3.1 \times 10^{-29} e \cdot \mathrm{cm}$$

strong CP problem

$$|d(e)|_{\mathrm{SM}} < 10^{-40} e \cdot \mathrm{cm}$$



N. Fortson, et al, Phys. Today, June 2003, 33-39

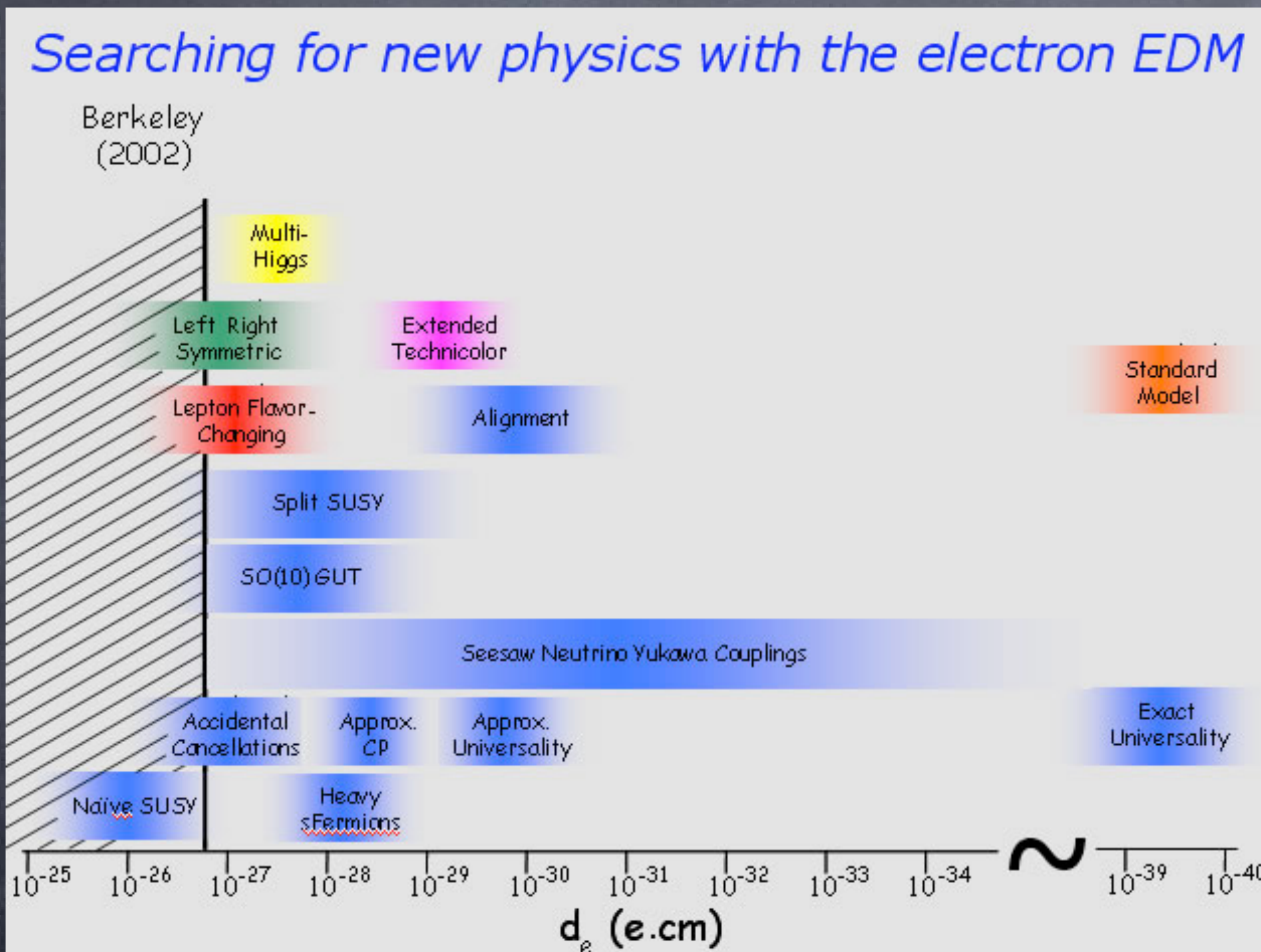


W. Bernreuther & M. Suzuki,
Rev. Mod. Phys. **63** 313-340 (1991)

S. Bickman, Yale Ph.D. Thesis (2007)

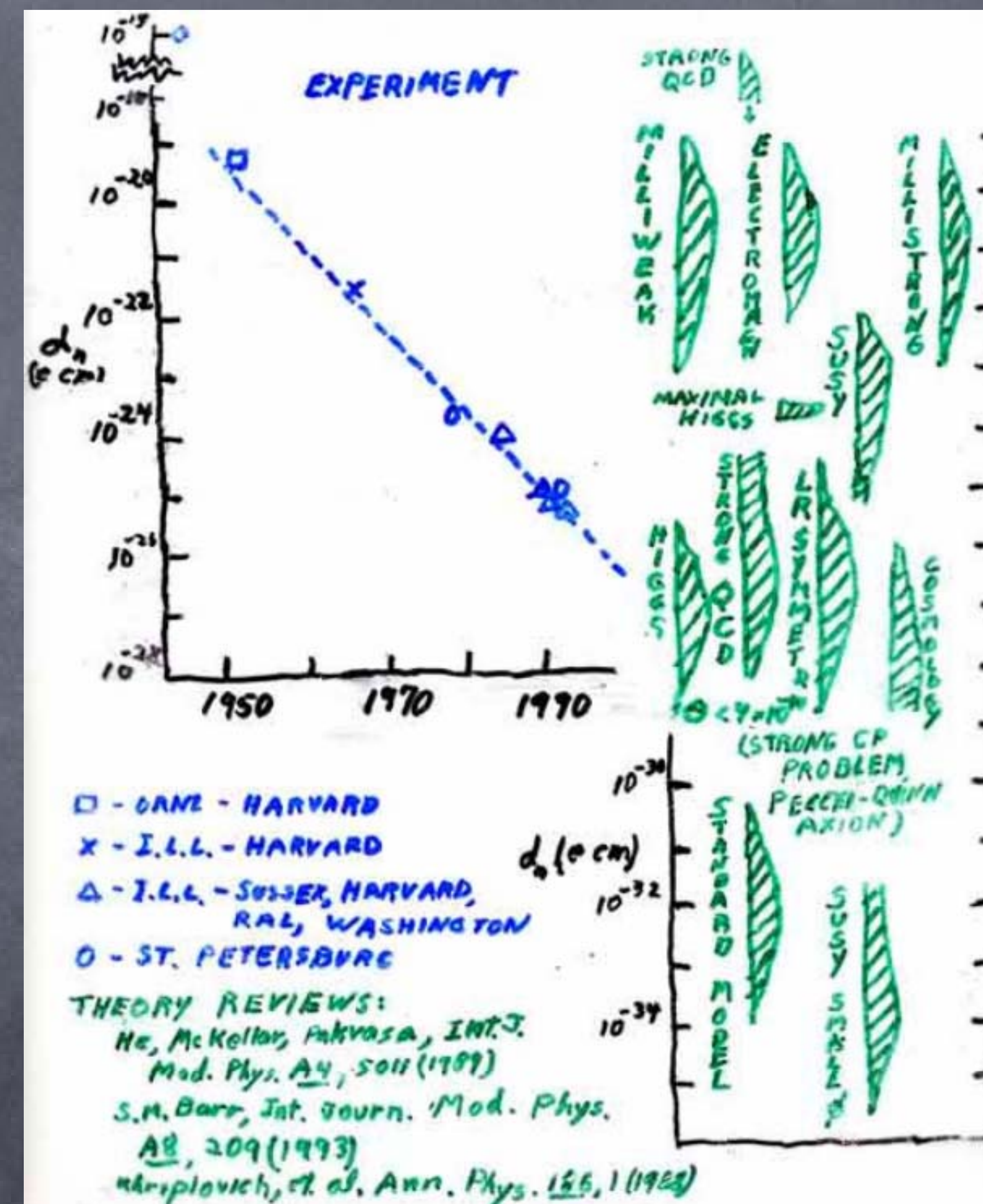
EDM constraints

electron



Data compiled by D. DeMille, Yale
Plot from http://hussle.harvard.edu

neutron



Data compiled by N. Ramsey, Harvard

EDM Searches

- Use something with a MDM and no electric monopole moment
- Constant B, modulate (a large!) E

$$\nu_+ = 2\left(\mu B + dE\right)/h$$
$$\nu_- = 2\left(\mu B - dE\right)/h$$

- Spend years on the systematics
- Atomic EDM
  - Relativistic effects enhance an electron EDM for high-Z atoms
  - Suppressed relative to nuclear EDM by 10^{-3} - 10^{-4}

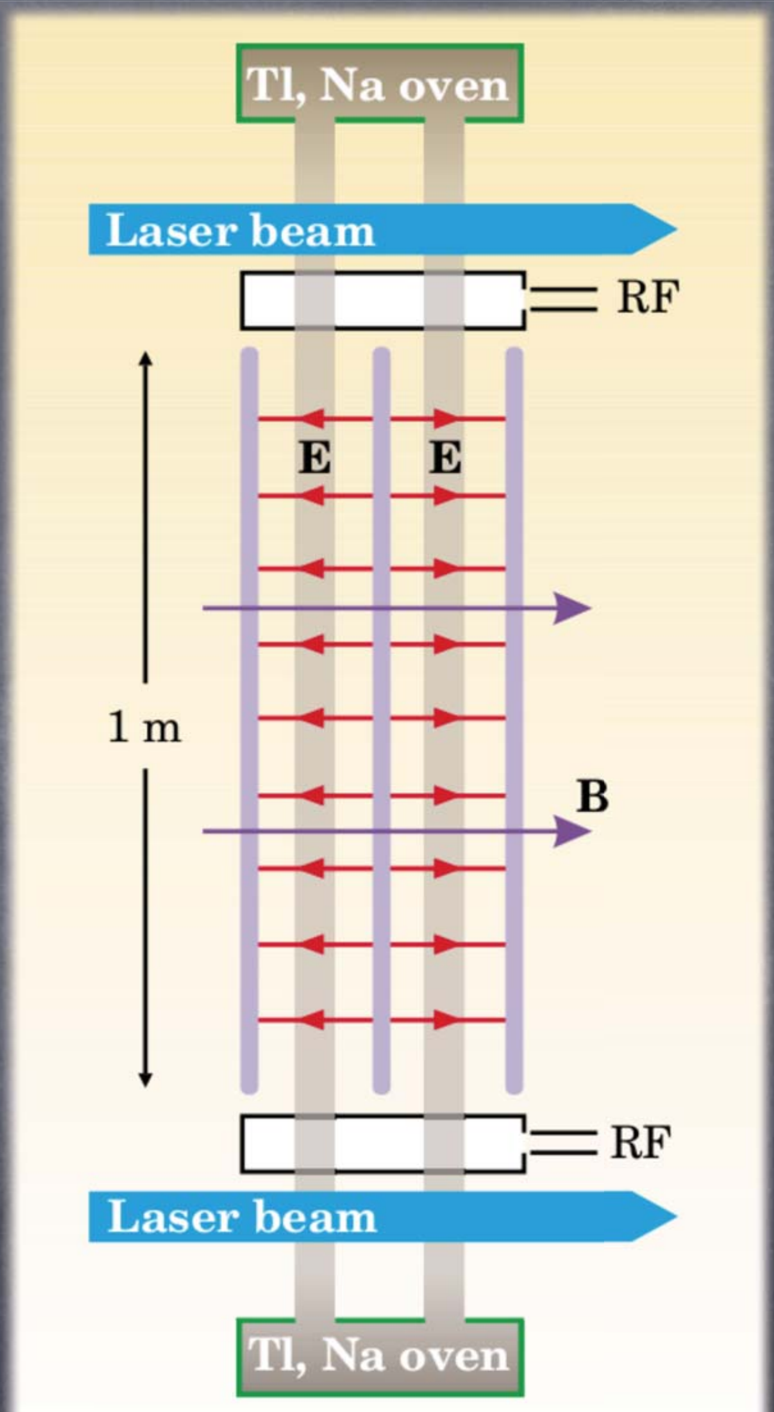
e.g. atom, neutron

Electron EDM

B. C. Regan, et al, Phys. Rev. Lett. **88** 071805 (2002)

- Thallium EDM
- Ramsey interference with optical state prep/measurement
- 8 atomic beams
  - Th +E/-E for differential **d·E**
  - Th up/down for differential **v** x **E**
  - Sodium as co-magnetometer
- 256 apparatus configurations

$$\nu_+ = 2\left(\mu B + dE\right)/h$$
$$\nu_- = 2\left(\mu B - dE\right)/h$$

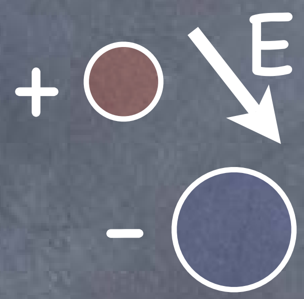


$d(e) < 1.6 \times 10^{-27}\, e$ cm

Figure from N. Fortson, et al, Phys. Today, June 2003, 33-39

Ongoing Searches for T-violation

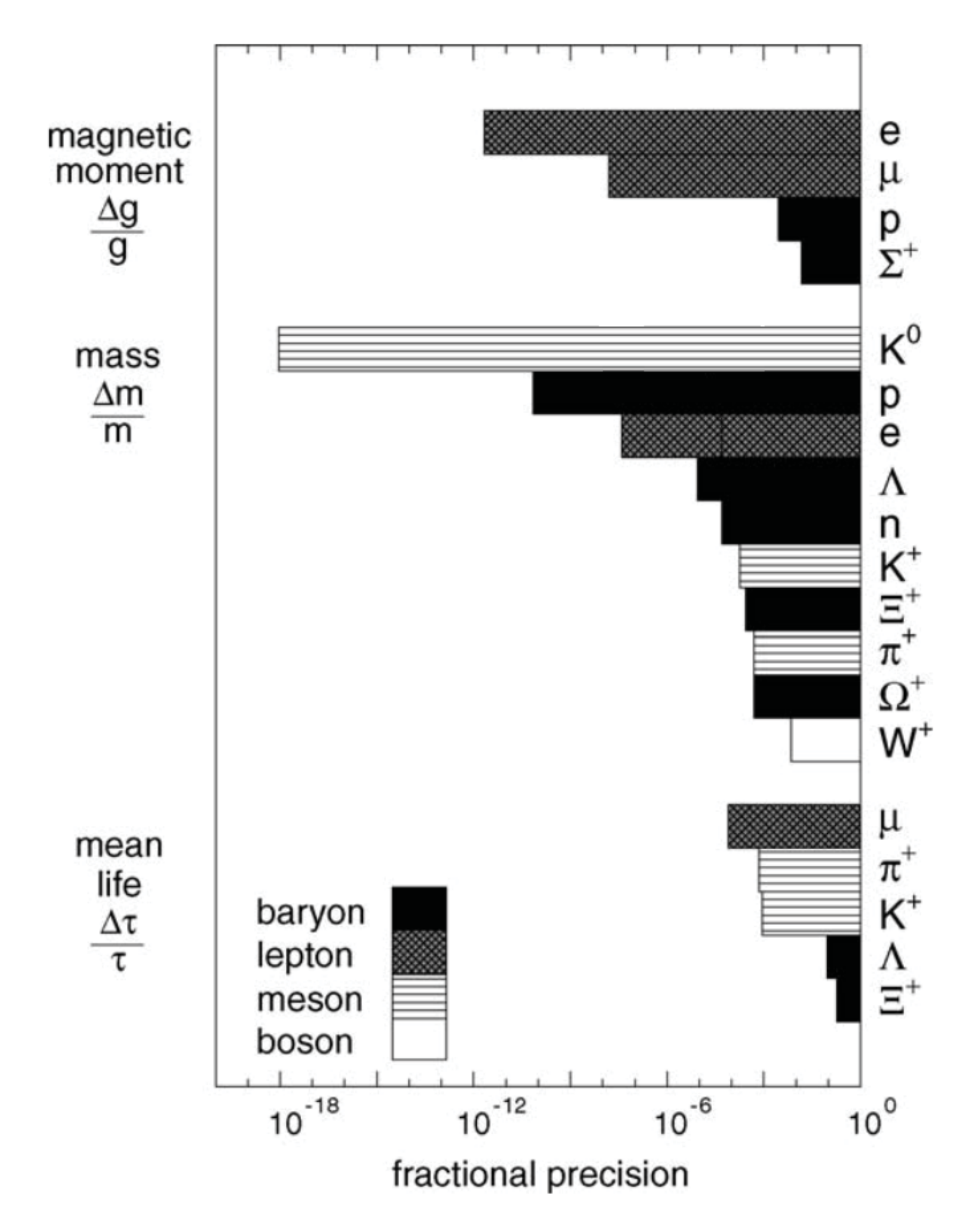
- Ultracold atoms
  - Increase the coherence times
- Polar molecules
  - 100 GV/cm
  - Flip spin instead of **E** (Ω-doublet)



- Solid-state
  - Statistics advantage (lots of e^-)
  - Apply **E**, look for magnetization

Cs: U. Texas, Penn State, Princeton, Berkeley
Fr: Osaka U.
YbF: Imperial College
PbF: U. Oklahoma
HfF^+: JILA
ThO: Harvard/Yale
PbO*: Yale
$Gd_3Ga_5O_{12}$: Yale, Indiana
$Gd_3Fe_5O_{12}$: Amherst

CPT Violation



Data from PDG
Figure from G. Gabrielse, Int. J. Mass Spec. **251** 273-280 (2006)

+ even	- odd
m	q
$\vec{p}$	t
$\vec{E}$	$\vec{x}$
$\vec{B}$	$\vec{J}$

CPT is a symmetry of any Lorentz-invariant, local QFT with a Hermitian Hamiltonian

Electron/positron g-values

Positrons from beta decay

$$^{22}Na \rightarrow\ ^{22}Ne + e^+ + \nu_e$$

VOLUME 59, NUMBER 1 PHYSICAL REVIEW LETTERS 6 JULY 1987

New High-Precision Comparison of Electron and Positron *g* Factors

Robert S. Van Dyck, Jr., Paul B. Schwinberg, and Hans G. Dehmelt
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 23 March 1987)

Single electrons and positrons have been alternately isolated in the same compensated Penning trap in order to form the geonium pseudoatom under nearly identical conditions. For each, the *g*-factor anomaly is obtained by measurement of both the spin-cyclotron difference frequency and the cyclotron frequency. A search for systematic effects uncovered a small (but common) residual shift due to the cyclotron excitation field. Extrapolation to zero power yields e^+ and e^- g factors with a smaller statistical error and a new particle-antiparticle comparison: $g(e^-)/g(e^+) = 1 + (0.5 \pm 2.1) \times 10^{-12}$.

PACS numbers: 14.60.Cd, 06.30.Lz, 12.20.Fv, 32.30.Bv

$$g_{e^-}/g_{e^+} = 1 + (0.5 \pm 2.1) \times 10^{-12}$$

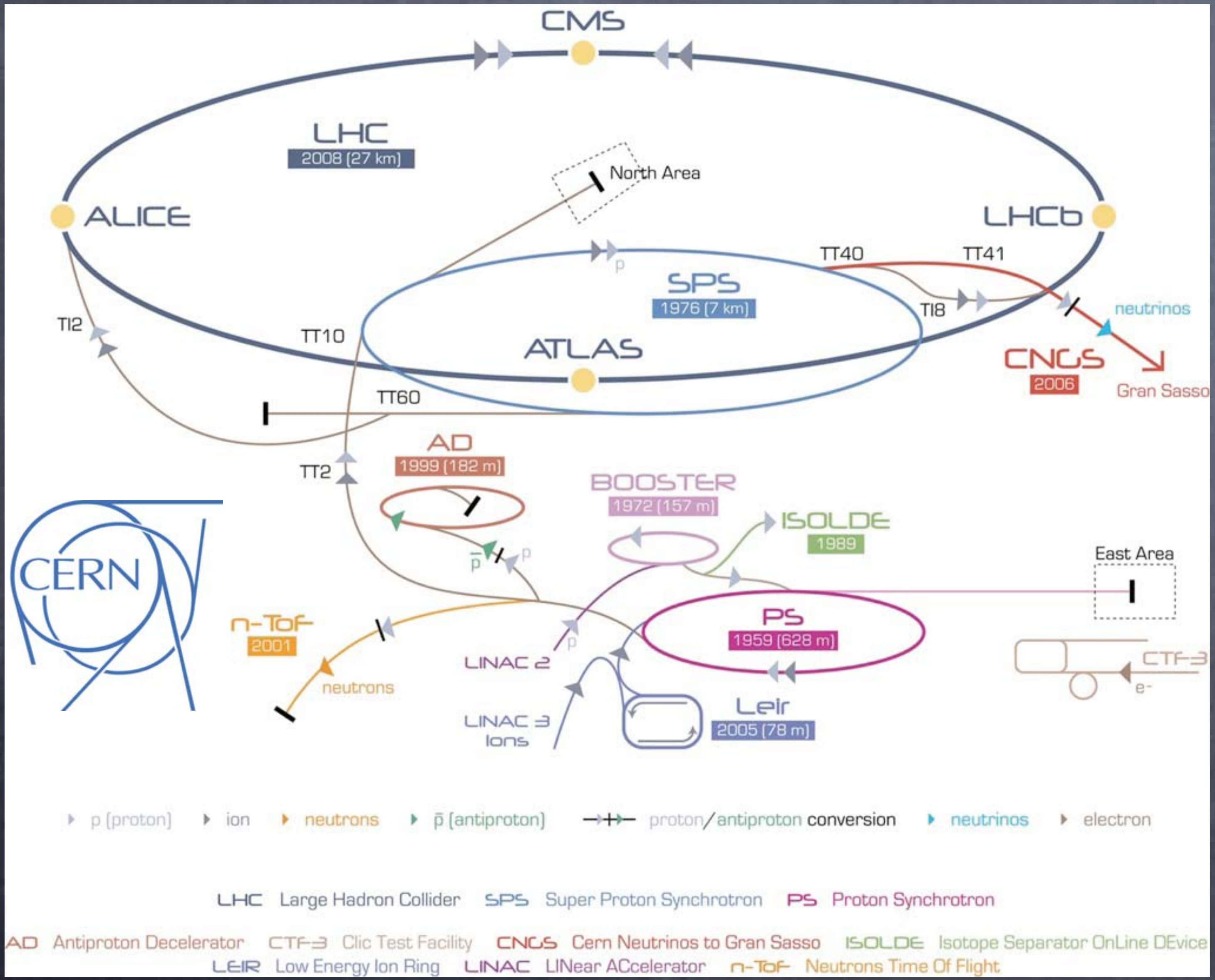
Ongoing work for 15x improvement

Antiprotons

Low-Energy Antiproton Ring (LEAR, at CERN): 1982-1996

Antiproton Decelerator (AD, at CERN): 2000-present

Facility for Antiproton and Ion Research (FAIR, at GSI): 2014?



PS: 10^{13} p @ 26 GeV

iridium wire target:

3×10^7 pbar @ 2.75 GeV

AD slows them to 5.3 MeV

Slow with matter

(He/SF_6 gases): 3.5 MeV

Slow with matter

(Be foil): few keV

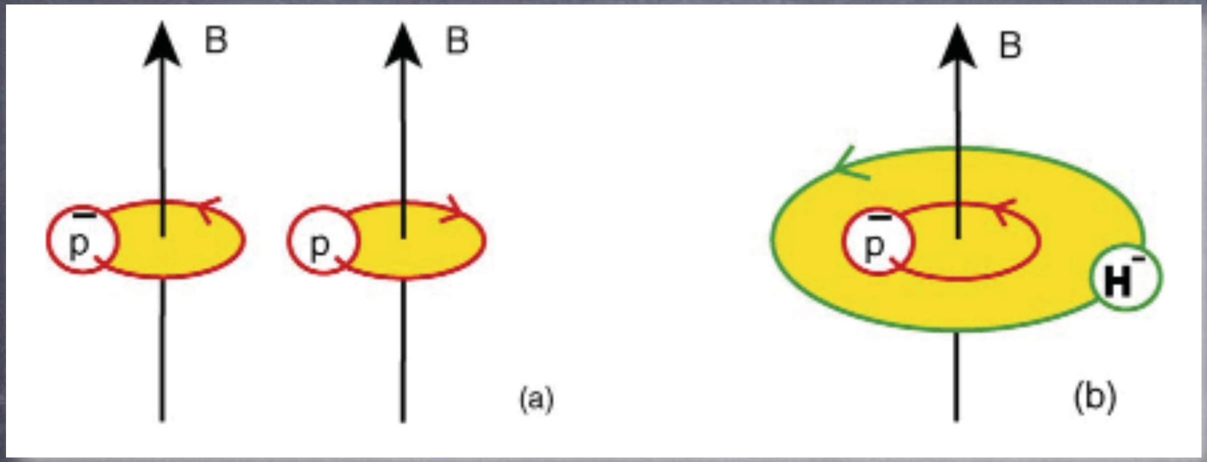
"Catch" 10^4 in an ion trap

Cool with e^- to 4.2 K (0.3 meV)

Proton/antiproton

Charge-to-mass ratio

$$\frac{(q/m)[\bar{p}]}{(q/m)[p]} = 1 - (1.6 \pm 0.9) \times 10^{-10}$$



$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

G. Gabrielse, et al, Phys. Rev. Lett. **82** 3198 (1999)

G. Gabrielse, Int. J. Mass Spec. **251** 273-280 (2006)

Proton/antiproton

Magnetic Moment

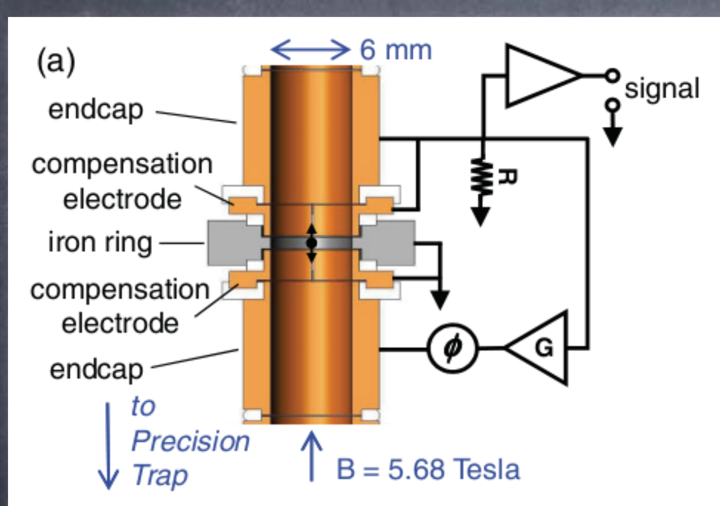
exotic atoms ($\bar{p}\ ^{208}\mathrm{Pb}$) ⟶
hydrogen spectroscopy ⟶

$$\left|\frac{\mu_{\bar{p}}}{\mu_p}\right| = 1.0026 \pm 0.0029$$

$$\frac{\mu_e}{\mu_p} \sim 650$$

Competition for million-fold improvement

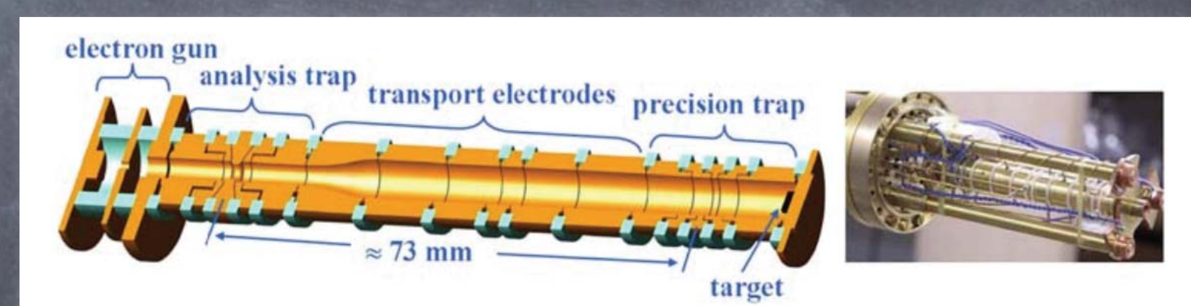
Harvard, Gerald Gabrielse



60 mHz on 553 kHz

N. Guise, et al, Phys. Rev. Lett. **104** 143001 (2010)

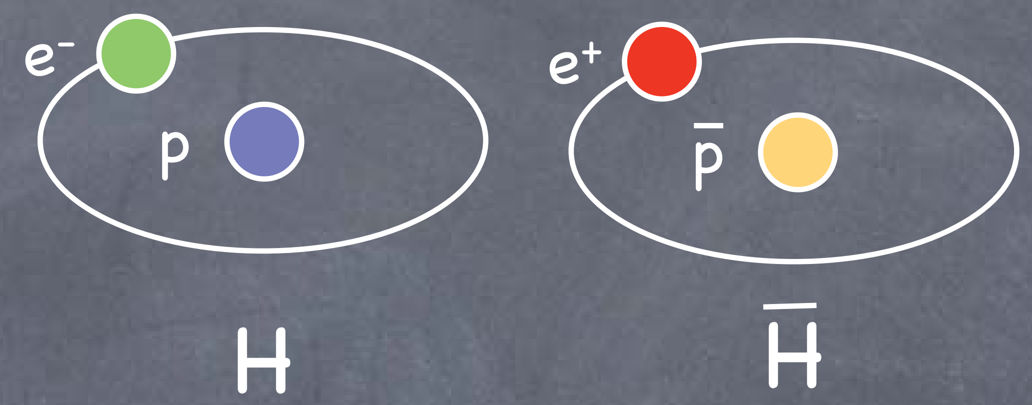
MPIK, GSI, J. Gutenberg U.
Klaus Blaum, Wolfgang Quint, Jochen Walz



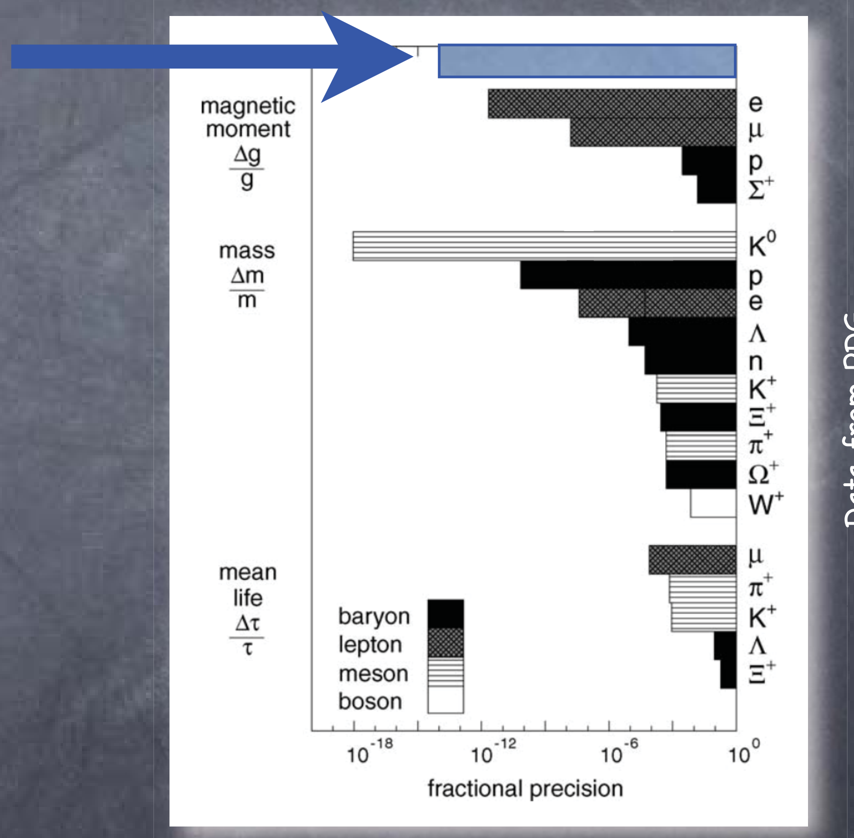
252 mHz on 692 kHz

C. C. Rodegheri, et al, Hyperfine Interactions **194** 93-98 (2009)

Antihydrogen



- combined lepton/baryon system
- Goal: 1S-2S (121 nm)
  - measured to 10^{-14} in hydrogen
- Making $\bar{H}$ is now “routine”
- Four main collaborations: ATRAP, ALPHA (formed from ATHENA), ASACUSA, AEGIS

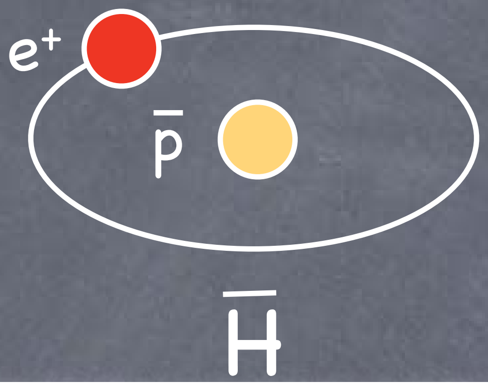


Data from PDG

Figure from G. Gabrielse, Int. J. Mass Spec. **251** 273-280 (2006)

$$\frac{R_\infty[\bar{H}]}{R_\infty[H]} = \frac{1+m[e^-]/M[p]}{1+m[e^+]/M[\bar{p}]}\left(\frac{m[e^+]}{m[e^-]}\right)\left(\frac{q[\bar{p}]}{q[p]}\right)^2\left(\frac{q[e^+]}{q[e^-]}\right)^2$$

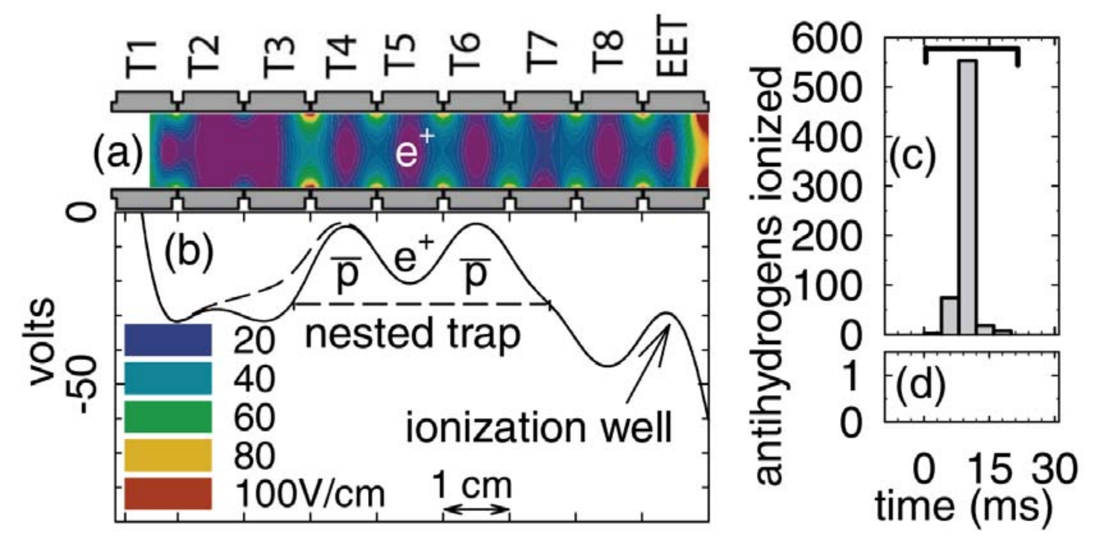
Antihydrogen Production



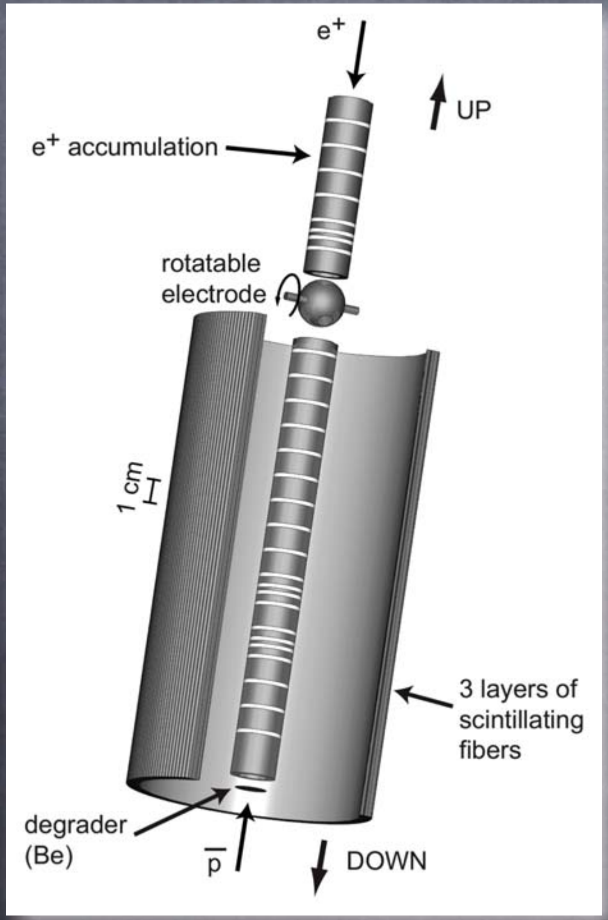
- Need to trap $\bar{p}$ and e^+ simultaneously
- Three-body recombination

$$\bar{p} + e^+ + e^+ \rightarrow \bar{H}^* + e^+$$

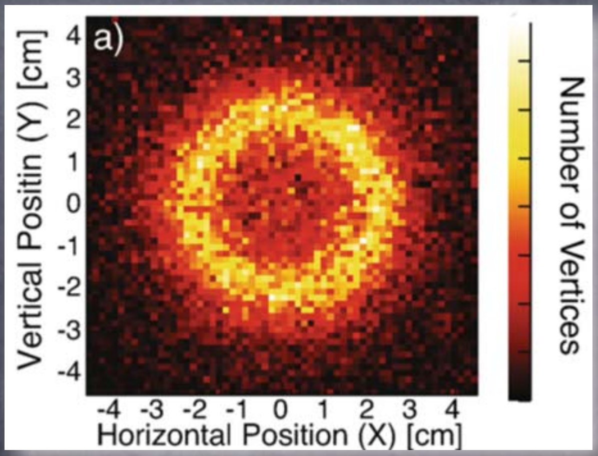
- Annihilation detection



G. Gabrielse, et al, (ATRAP) Phys. Rev. Lett. **89** 213401 (2002)



A. Speck, Ph.D. Thesis, Harvard 2005



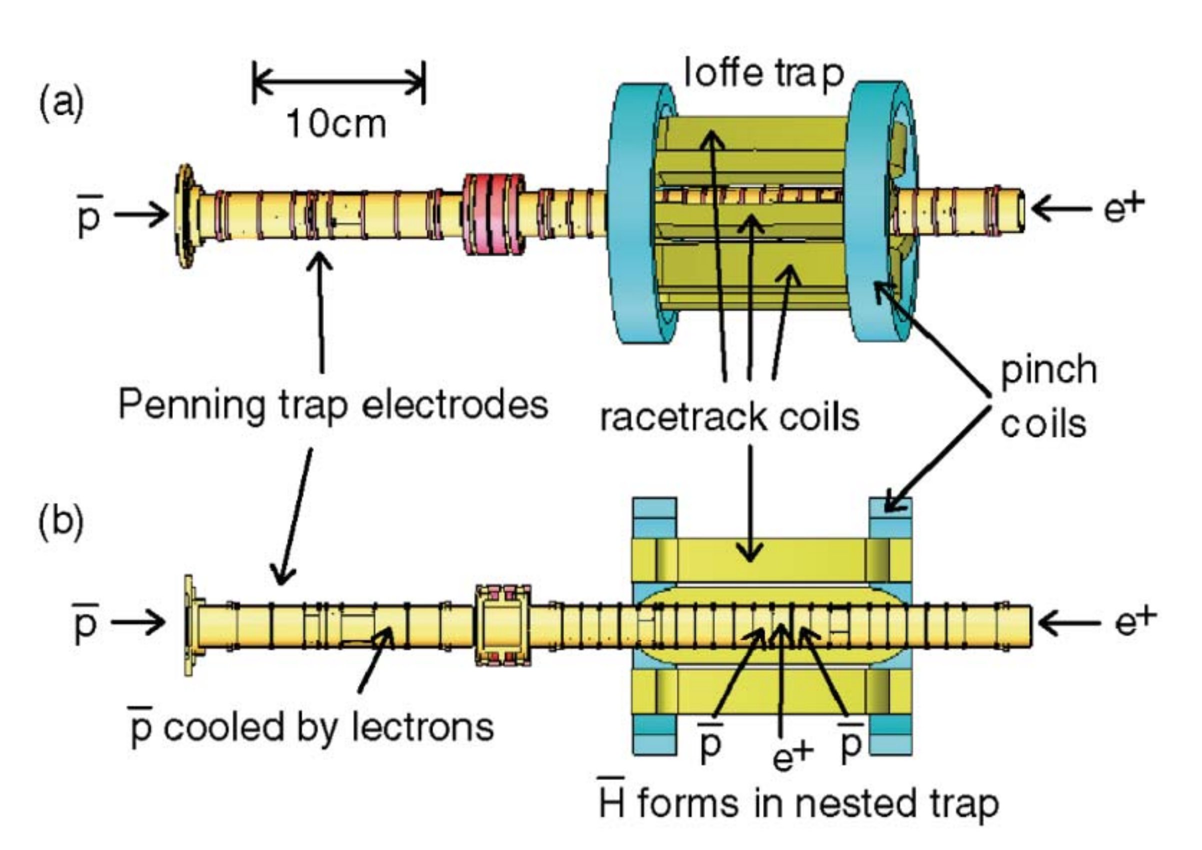
G. B. Andresen, et al, (ALPHA), Phys. Lett. B **685** 141 (2010)

See also, M. Amoretti, et al, (ATHENA) Nature **419** 456-459 (2002)

Trapping Antihydrogen

- Combined Penning-Ioffe trap
- $\bar{H}$ has been produced in such a trap
- No trapping demonstration...yet

$$U = -\vec{\mu} \cdot \vec{B}$$



G. Gabrielse, et al, (ATRAP), Phys. Rev. Lett. **100** 113001 (2008)
See also, G. Gabrielse, Physics Today, March 2010, 68-69
See also, G. B. Andresen, et al, (ALPHA), Phys. Lett. B **685** 141 (2010)

What could break CPT?

CPT is a symmetry of any Lorentz-invariant, local QFT with a Hermitian Hamiltonian

Standard Model Extension

- Phenomenological "low-energy" framework
- Spontaneous Lorentz violation (and some CPT violation)
- Preserves gauge structure, coordinate invariance, etc.

$$\mathcal{L}^{\mathrm{QED}} = \bar{\psi}\gamma^{\mu}\left(i\hbar c\partial_{\mu} - qcA_{\mu}\right)\psi - mc^2\bar{\psi}\psi - \frac{1}{4\mu_0}F^{\mu\nu}F_{\mu\nu}$$

$$\begin{aligned}\mathcal{L}^{\mathrm{SME}} &= -a_{\mu}\bar{\psi}\gamma^{\mu}\psi - b_{\mu}\bar{\psi}\gamma_5\gamma^{\mu}\psi + c_{\mu\nu}\bar{\psi}\gamma^{\mu}\left(i\hbar c\partial^{\nu} - qcA^{\nu}\right)\psi \\ &+ d_{\mu\nu}\bar{\psi}\gamma_5\gamma^{\mu}\left(i\hbar c\partial^{\nu} - qcA^{\nu}\right)\psi - \frac{1}{2}H_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi \\ &+ \frac{1}{2\hbar}\left(k_{\mathrm{AF}}\right)^{\kappa}\epsilon_{\kappa\lambda\mu\nu}\sqrt{\frac{\epsilon_0}{\mu_0}}A^{\lambda}F^{\mu\nu} - \frac{1}{4\mu_0}\left(k_{\mathrm{F}}\right)_{\kappa\lambda\mu\nu}F^{\kappa\lambda}F^{\mu\nu}\end{aligned}$$

D. Colladay & A. Kostelecký, Phys. Rev. D **58** 116002 (1998)

Michelson-Morley Experiment

THE

AMERICAN JOURNAL OF SCIENCE.

[THIRD SERIES.]

ART. XXXVI.—*On the Relative Motion of the Earth and the Luminiferous Ether;* by ALBERT A. MICHELSON and EDWARD W. MORLEY.*

PRL **103,** 090401 (2009) PHYSICAL REVIEW LETTERS week ending 28 AUGUST 2009

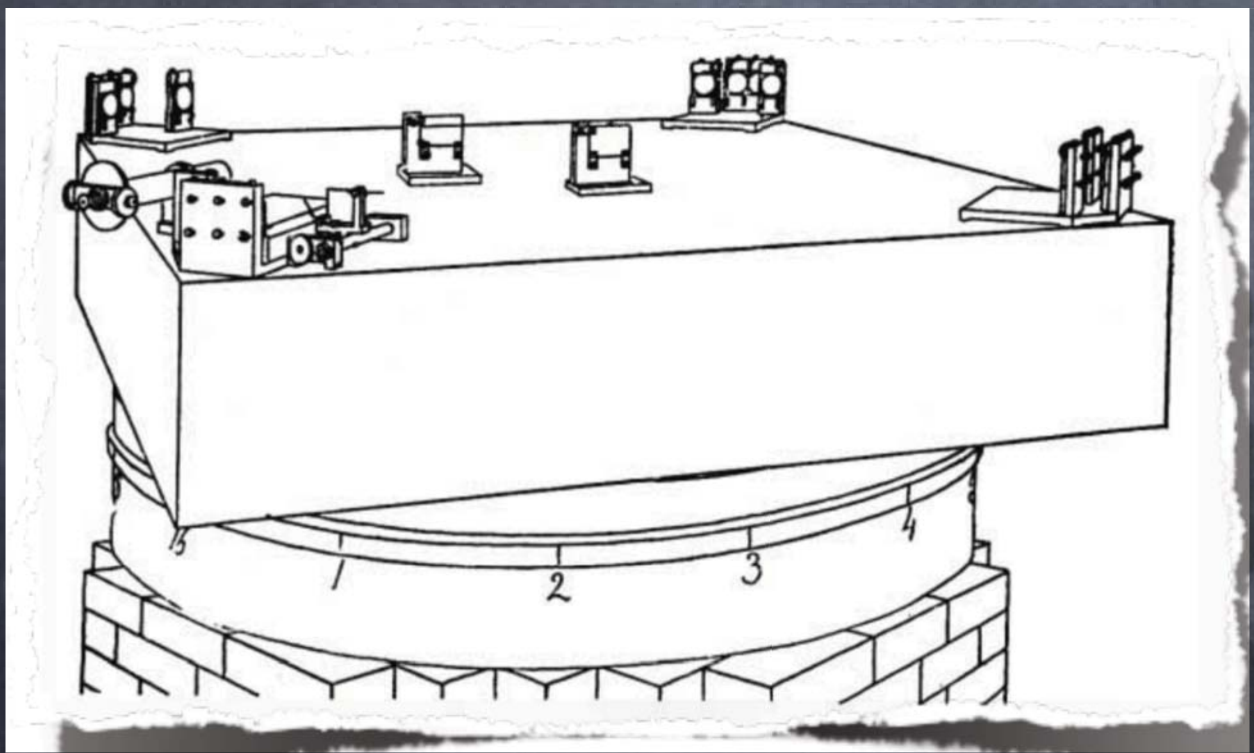
Laboratory Test of the Isotropy of Light Propagation at the 10^{-17} Level

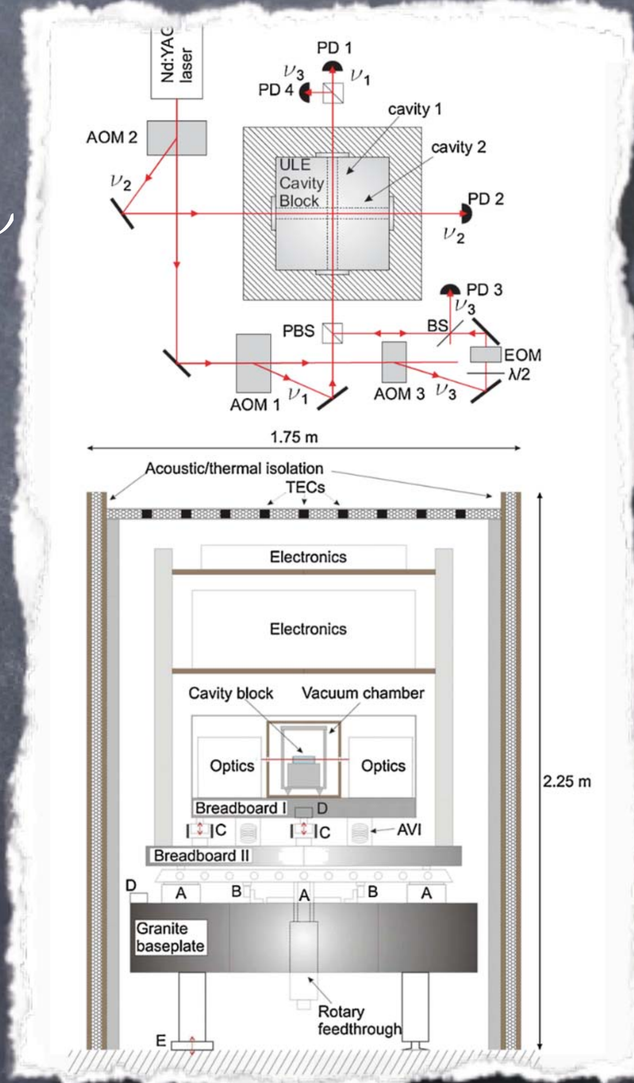
Ch. Eisele, A. Yu. Nevsky, and S. Schiller

Institut für Experimentalphysik, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany

revised manuscript received 7 August 2009;

$$\mathcal{L} = -\frac{1}{4\mu_0} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4\mu_0} (k_F)_{\kappa\lambda\mu\nu} F^{\kappa\lambda} F^{\mu\nu}$$





A. A. Michelson & E. W. Morley, Am. J. Sci. **XXXIV** 333-345 (1887)

Conclusions

- P: study weak interaction at low energies
- T, CPT, Lorentz: search for physics beyond SM
- Low-energy, precision measurements can do high-energy physics

Thank you for a great week!