Electric Dipole Moments and g-2 experiments

Yannis K. Semertzidis
Brookhaven National Lab

Organizing committee of WG3:
Andries van der Schaaf (exp.), YkS (exp.),
Martti Raidal (theory), Bigi Ikaros (theory)
and the main organizer of the workshops
Michelangelo Mangano

Flavour in the era of the LHC

a Workshop on the interplay of flavour and collider physics

First meeting:

CERN, November 7-10 2005

http://mlm.home.cern.ch/mlm/FlavLHC.html

- BSM signatures in B/K/D physics, and their complementarity with the high-pT LHC discovery potential
- Flavour phenomena in the decays of SUSY particles
- Squark/slepton spectroscopy and family structure
- Flavour aspects of non-SUSY BSM physics
- Flavour physics in the lepton sector
- g-2 and EDMs as BSM probes
- Flavour experiments for the next decade

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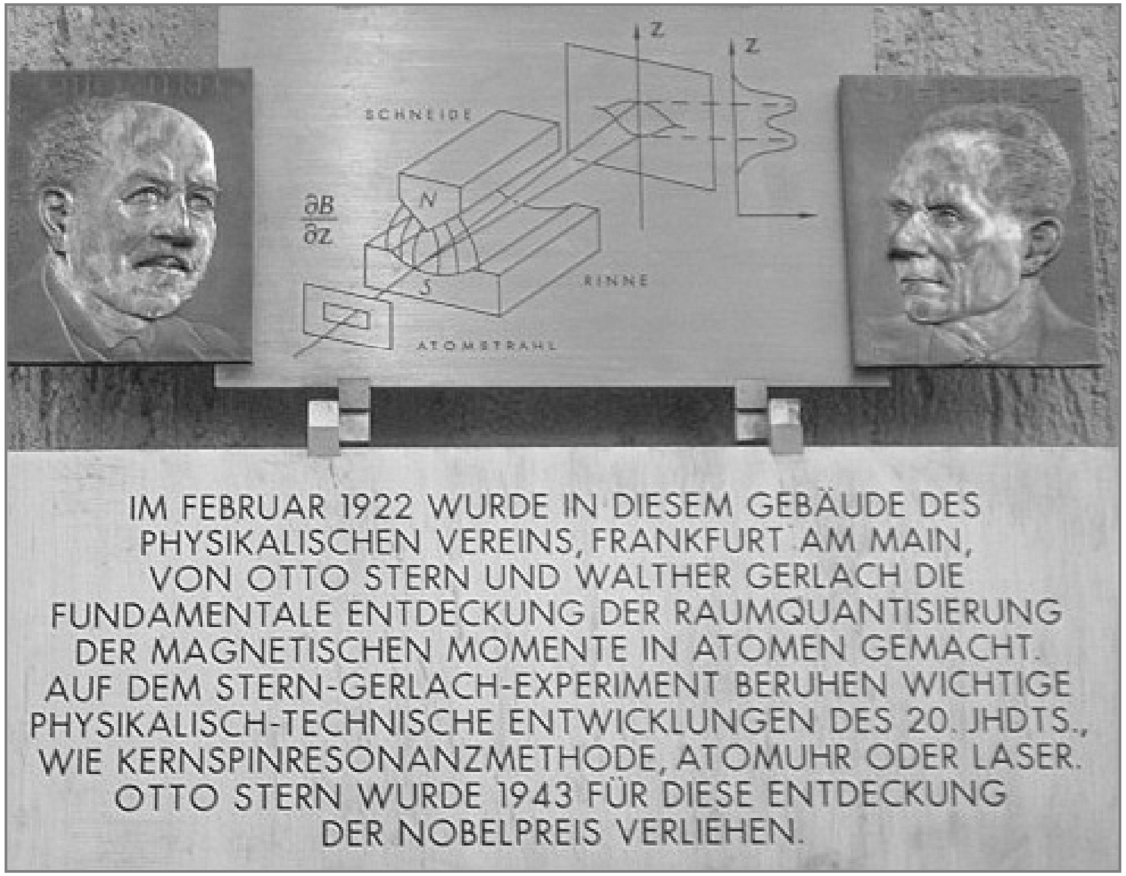
1922 Space Quantization discovery by Stern and Gerlach

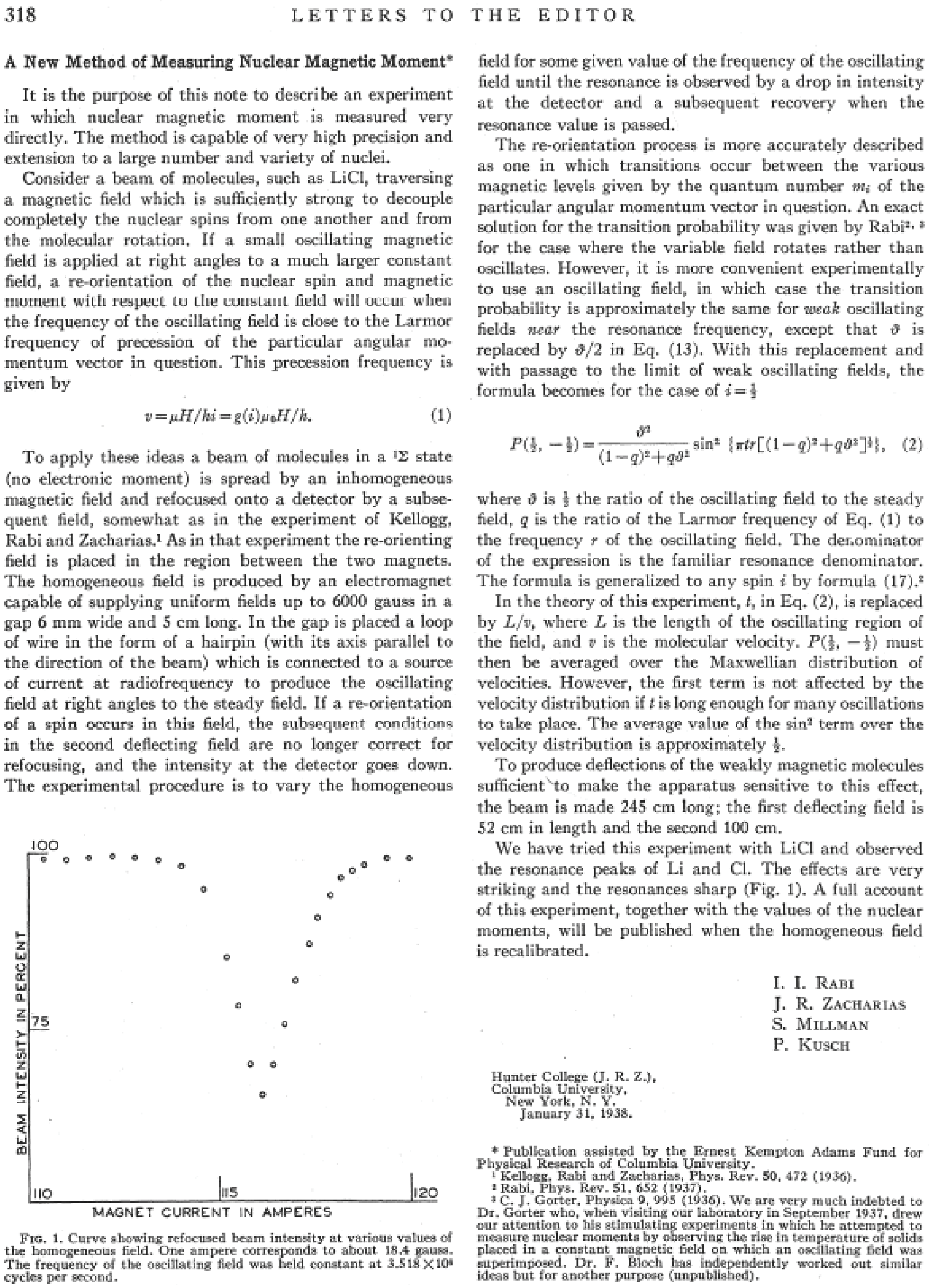


IM FEBRUAR 1922 WURDE IN DIESEM GEBÄUDE DES
PHYSIKALISCHEN VEREINS, FRANKFURT AM MAIN,
VON OTTO STERN UND WALTHER GERLACH DIE
FUNDAMENTALE ENTDECKUNG DER RAUMQUANTISIERUNG
DER MAGNETISCHEN MOMENTE IN ATOMEN GEMACHT.
AUF DEM STERN-GERLACH-EXPERIMENT BERUHEN WICHTIGE
PHYSIKALISCH-TECHNISCHE ENTWICKLUNGEN DES 20. JHDTS.,
WIE KERNSPINRESONANZMETHODE, ATOMUHR ODER LASER.
OTTO STERN WURDE 1943 FÜR DIESE ENTDECKUNG
DER NOBELPREIS VERLIEHEN.

II Rabi 1938

Magnetic Resonance

Nobel Prize 1944



318 LETTERS TO THE EDITOR

A New Method of Measuring Nuclear Magnetic Moment*

It is the purpose of this note to describe an experiment in which nuclear magnetic moment is measured very directly. The method is capable of very high precision and extension to a large number and variety of nuclei.

Consider a beam of molecules, such as LiCl, traversing a magnetic field which is sufficiently strong to decouple completely the nuclear spins from one another and from the molecular rotation. If a small oscillating magnetic field is applied at right angles to a much larger constant field, a re-orientation of the nuclear spin and magnetic moment with respect to the constant field will occur when the frequency of the oscillating field is close to the Larmor frequency of precession of the particular angular momentum vector in question. This precession frequency is given by

$$v=\mu H/hi=g(i)\mu_0 H/h. \qquad (1)$$

To apply these ideas a beam of molecules in a $^1\Sigma$ state (no electronic moment) is spread by an inhomogeneous magnetic field and refocused onto a detector by a subsequent field, somewhat as in the experiment of Kellogg, Rabi and Zacharias.[1] As in that experiment the re-orienting field is placed in the region between the two magnets. The homogeneous field is produced by an electromagnet capable of supplying uniform fields up to 6000 gauss in a gap 6 mm wide and 5 cm long. In the gap is placed a loop of wire in the form of a hairpin (with its axis parallel to the direction of the beam) which is connected to a source of current at radiofrequency to produce the oscillating field at right angles to the steady field. If a re-orientation of a spin occurs in this field, the subsequent conditions in the second deflecting field are no longer correct for refocusing, and the intensity at the detector goes down. The experimental procedure is to vary the homogeneous field for some given value of the frequency of the oscillating field until the resonance is observed by a drop in intensity at the detector and a subsequent recovery when the resonance value is passed.

The re-orientation process is more accurately described as one in which transitions occur between the various magnetic levels given by the quantum number m_i of the particular angular momentum vector in question. An exact solution for the transition probability was given by Rabi[2, 3] for the case where the variable field rotates rather than oscillates. However, it is more convenient experimentally to use an oscillating field, in which case the transition probability is approximately the same for *weak* oscillating fields *near* the resonance frequency, except that ϑ is replaced by $\vartheta/2$ in Eq. (13). With this replacement and with passage to the limit of weak oscillating fields, the formula becomes for the case of $i=\frac{1}{2}$

$$P(\tfrac{1}{2},-\tfrac{1}{2})=\frac{\vartheta^2}{(1-q)^2+q\vartheta^2}\sin^2\{\pi tr[(1-q)^2+q\vartheta^2]^{\frac{1}{2}}\}, \qquad (2)$$

where ϑ is $\frac{1}{2}$ the ratio of the oscillating field to the steady field, q is the ratio of the Larmor frequency of Eq. (1) to the frequency r of the oscillating field. The denominator of the expression is the familiar resonance denominator. The formula is generalized to any spin i by formula (17).[2]

In the theory of this experiment, t, in Eq. (2), is replaced by L/v, where L is the length of the oscillating region of the field, and v is the molecular velocity. $P(\frac{1}{2},-\frac{1}{2})$ must then be averaged over the Maxwellian distribution of velocities. However, the first term is not affected by the velocity distribution if t is long enough for many oscillations to take place. The average value of the $\sin^2$ term over the velocity distribution is approximately $\frac{1}{2}$.

To produce deflections of the weakly magnetic molecules sufficient to make the apparatus sensitive to this effect, the beam is made 245 cm long; the first deflecting field is 52 cm in length and the second 100 cm.

We have tried this experiment with LiCl and observed the resonance peaks of Li and Cl. The effects are very striking and the resonances sharp (Fig. 1). A full account of this experiment, together with the values of the nuclear moments, will be published when the homogeneous field is recalibrated.

I. I. Rabi
J. R. Zacharias
S. Millman
P. Kusch

Hunter College (J. R. Z.),
Columbia University,
New York, N. Y.
January 31, 1938.

Fig. 1. Curve showing refocused beam intensity at various values of the homogeneous field. One ampere corresponds to about 18.4 gauss. The frequency of the oscillating field was held constant at 3.518×10^6 cycles per second.

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* Publication assisted by the Ernest Kempton Adams Fund for Physical Research of Columbia University.

[1] Kellogg, Rabi and Zacharias, Phys. Rev. 50, 472 (1936).

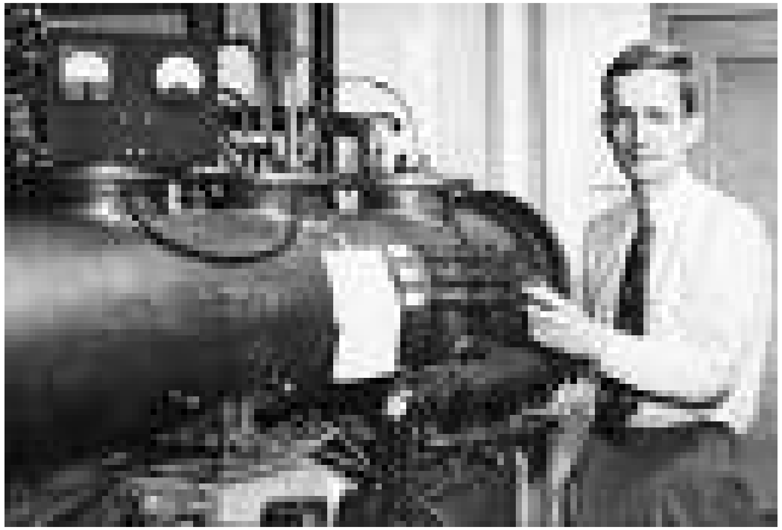
[2] Rabi, Phys. Rev. 51, 652 (1937).

[3] C. J. Gorter, Physica 9, 995 (1936). We are very much indebted to Dr. Gorter who, when visiting our laboratory in September 1937, drew our attention to his stimulating experiments in which he attempted to measure nuclear moments by observing the rise in temperature of solids placed in a constant magnetic field on which an oscillating field was superimposed. Dr. F. Bloch has independently worked out similar ideas but for another purpose (unpublished).

EDM, g-2 Experiments

EDMs

- leptonic
- hadronic



g-2

- muon
- electron

Norman Ramsey
Separated Oscillator Beam Resonance
Nobel Prize 1989 ***STANDARD OF TIME***

1950 Purcell & Ramsey [PR. **78**, 807],
Parity needed to be tested in nuclear forces.

In 1957 Ramsey et al., suggested to check T-reversal symmetry in nuclear forces.

N. Ramsey:
History of EDM

1964	Failure of CP in K^0_L so T symmetry fail if CPT conserved
1967	$d_n < 4x10^{-23}$ e cm. Beam Oak Ridge
1973	Beam Grenoble $d_n < 4x10^{-24}$ e cm
1984	$d_n < 3x10^{-25}$ e cm. Bottle expts. St Peters, Grenoble
1999	$d_n < 6.3x10^{-26}$ e cm St Peters, Grenoble
2006	$d_n < 3.0x10^{-26}$ e cm Grenoble [geom. phase]

A Permanent EDM Violates both T & P Symmetries:

$$H = -d\vec{\sigma}\cdot\vec{E} \xrightarrow{\mathbf{T}} H = -d\left(-\vec{\sigma}\right)\cdot\vec{E} = d\vec{\sigma}\cdot\vec{E}$$

$$H = -d\vec{\sigma}\cdot\vec{E} \xrightarrow{\mathbf{P}} H = -d\vec{\sigma}\cdot\left(-\vec{E}\right) = d\vec{\sigma}\cdot\vec{E}$$

How about Induced EDMs?

$$\vec{d} \propto d\vec{E}$$

$$H = -d\vec{E}\cdot\vec{E} \xrightarrow{\textbf{T}} \textbf{OK}$$

$$H = -d\vec{E}\cdot\vec{E} \xrightarrow{\textbf{P}} \textbf{OK}$$

$$H = -d\vec{\sigma}\cdot\vec{E}$$

1st order Stark effect. T, P Violation!

$$H = -d\vec{E}\cdot\vec{E}$$

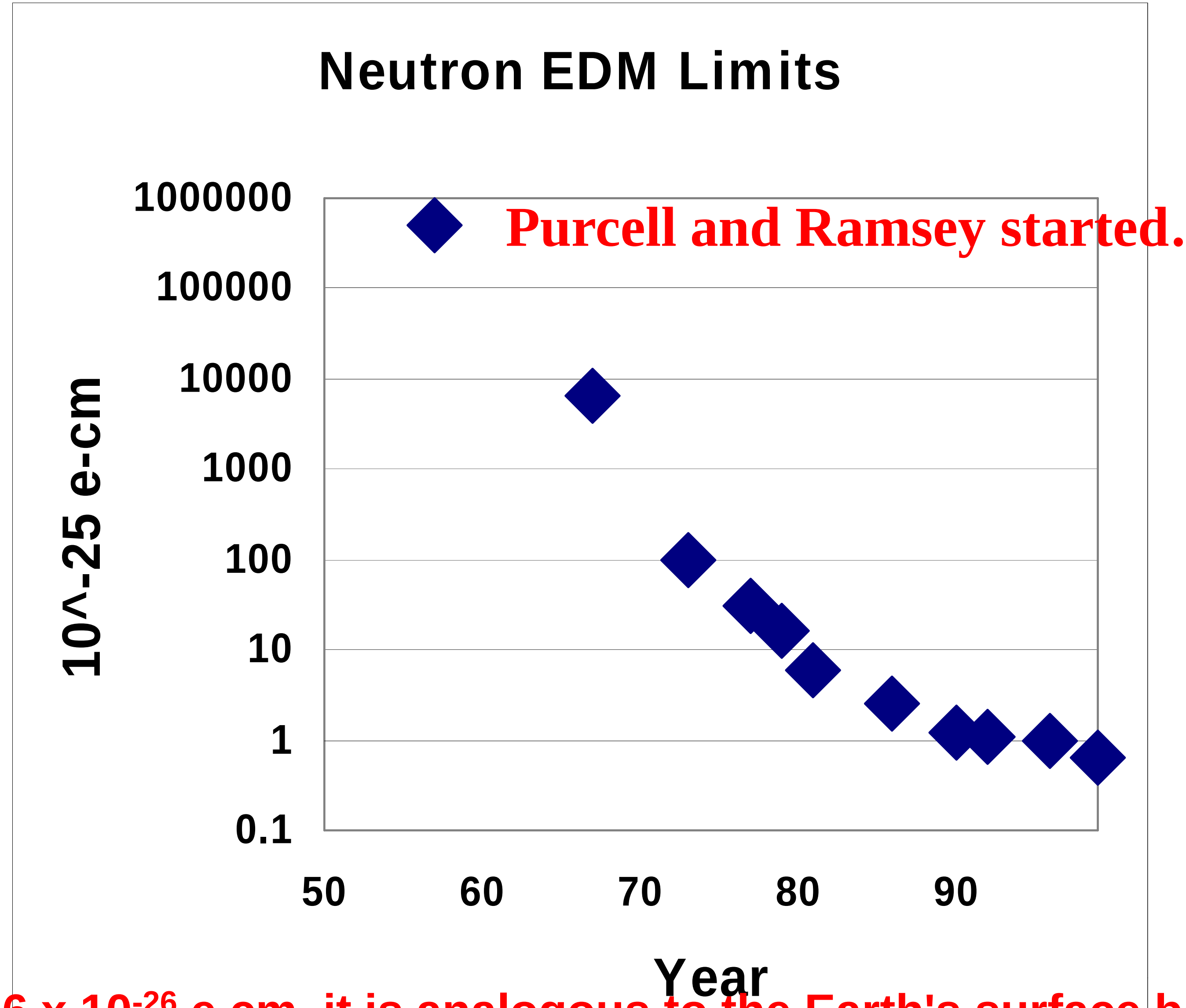
2nd order Stark effect. Allowed!
Of course, batteries are also allowed!

MDMs are Allowed…

$$H = -\mu\vec{\sigma}\cdot\vec{B} \xrightarrow{\mathbf{T}} H = -\mu\left(-\vec{\sigma}\right)\cdot\left(-\vec{B}\right) = -\mu\vec{\sigma}\cdot\vec{B}$$

$$H = -\mu\vec{\sigma}\cdot\vec{B} \xrightarrow{\mathbf{P}} H = -\mu\left(\vec{\sigma}\right)\cdot\left(\vec{B}\right) = -\mu\vec{\sigma}\cdot\vec{B}$$

Neutron EDM Vs Year



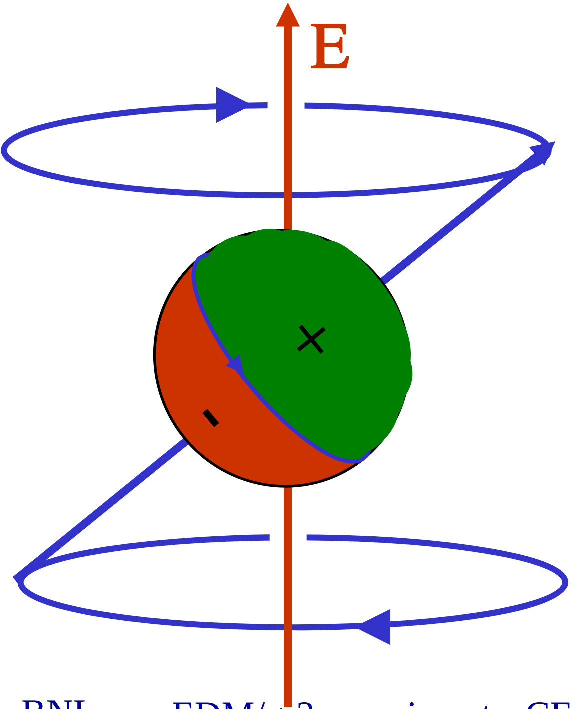
Purcell and Ramsey started…

“…at 6 x 10^{-26} e cm, it is analogous to the Earth's surface being smooth and symmetric to less than 1 μm” (John Ellis).

Usual Experimental Method

$$\frac{d\vec{s}}{dt} = \vec{\mu}\times\vec{B} + \vec{d}\times\vec{E}$$

Small Signal



Compare the Larmor Frequencies when E-field is Flipped:

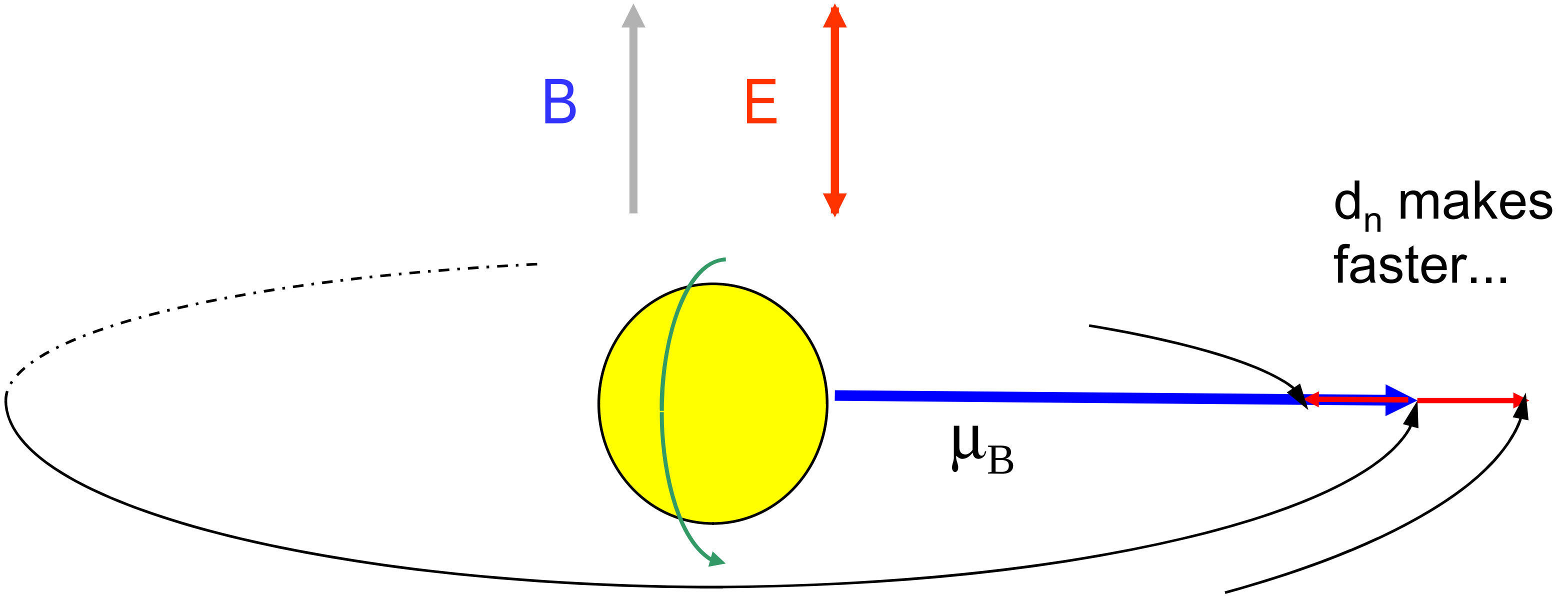
$$\hbar\left(\omega_1 - \omega_2\right) = 4dE$$

$$\boxed{\sigma_d \propto \frac{1}{E}\frac{1}{\sqrt{N\tau T}}}$$

Measurement principle

P. Harris

Measure Larmor spin precession freq in parallel & antiparallel **B** and **E** fields



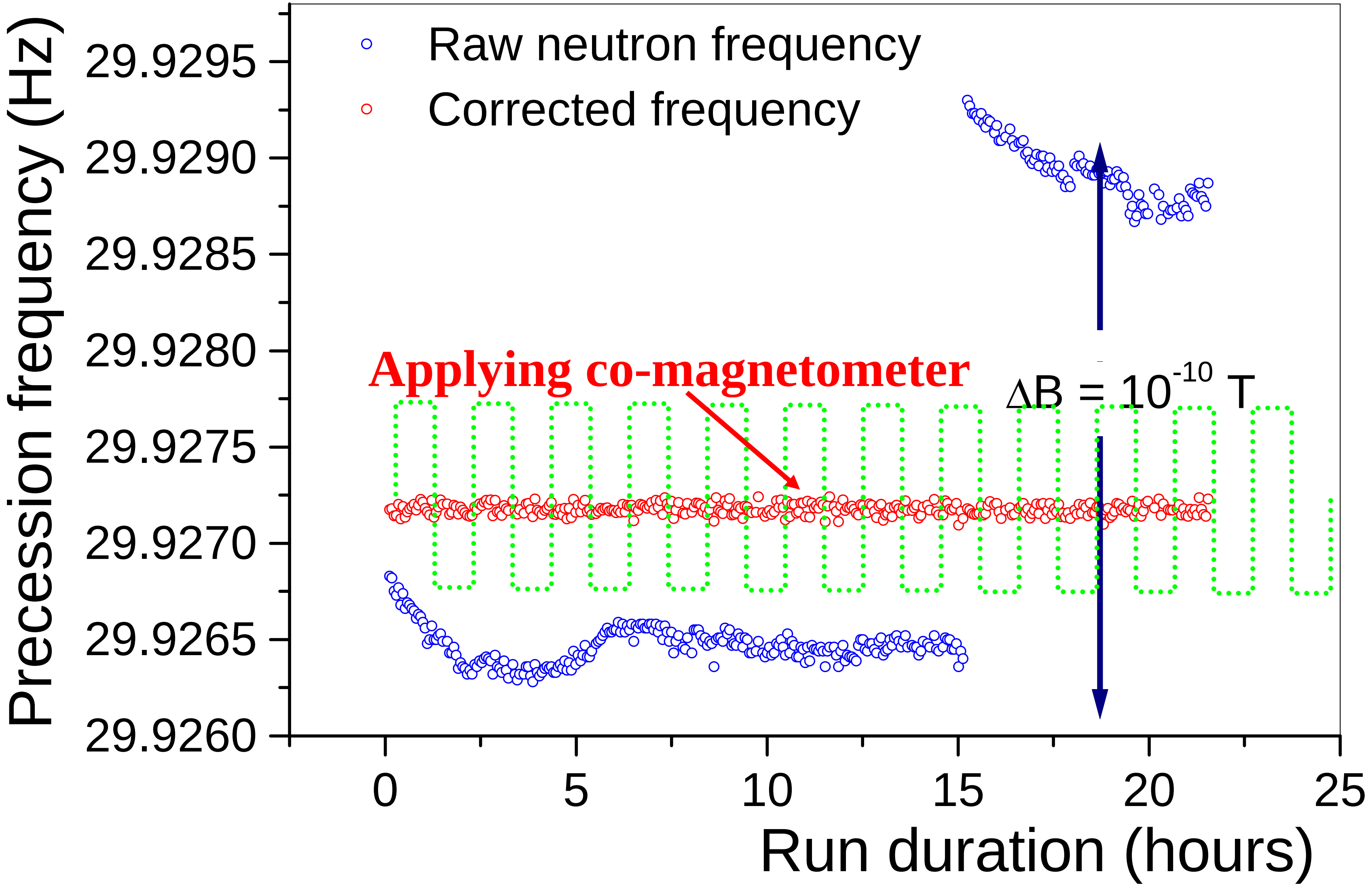
d_n makes precession faster...

... or slower.

Reverse E relative to B, look for freq shift.

P. Harris

nEDM measurement



P. Harris

Statistical limits

$$\sigma_d = \frac{\hbar / 2}{\alpha\, E\, T \sqrt{N}}$$

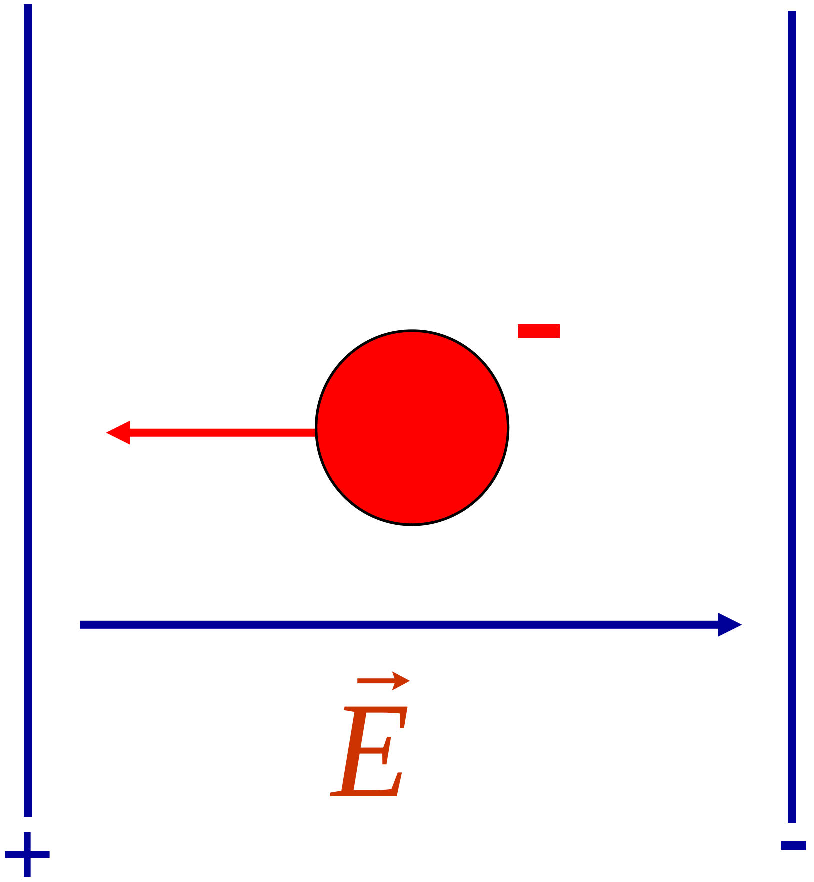
Parameter	Room-tmpr. expt	Sensitivity
• Polarisation+detection:	α = 0.75	x 1.2
• Electric field:	$E = 10^6$ V/m	x 4
• Precession period:	T = 130 s	x 2
• Neutrons counted:	$N = 6 \times 10^6$ /day	x 4.5
(with new beamline)		x 2.6

Total increase approx factor 100 with UCN is expected

Neutron EDM Timeline

2005	Exp begin data taking	Exp goal
2007		
2008	PSI	10^{-27}e·cm
2009	UCN-ILL	2×10^{-28}e·cm/yr
2011	UCN-LANL/SNS	1×10^{-28}e·cm

A charged particle in an Electric Field…



How about an electron in an atom…

(anti)Schiff Theorem:

A Charged Particle at Equilibrium Feels no Force… …An Electron in a Neutral Atom Feels no Force Either:

$$\left\langle \vec{F}_{Total} \right\rangle = q\left\langle \vec{E}_{Total} \right\rangle = q\left\langle \vec{E}_{ext} + \vec{E}_{\text{int}} \right\rangle = 0$$

…Otherwise it Would be Accelerated…

Schiff Theorem:

A Charged Particle at Equilibrium Feels no Force…

…An Electron in a Neutral Atom Feels no Force Either. However:

$$\left\langle \vec{F}_{Tot} \right\rangle = \left\langle q\vec{E}_{ext} + q\vec{E}_{\text{int}} + Other\ Forces \right\rangle = 0$$

…the net E-field is not zero!

Current Atomic EDM Limits

- **Paramagnetic Atoms, ^{205}Tl: electron $|d_e| < 1.6\times10^{-27}$e·cm (90%CL)**
  PRL 88, 071805 (2002)

- **Diamagnetic Atoms, ^{199}Hg Nucleus: $|d(^{199}Hg)| < 2.1\times10^{-28}$e·cm (95%CL)**
  PRL 86, 2505 (2001)

Estimate of atomic EDM
[Sandars 1965, Flambaum 1976]

M. Kozlov

The estimate of the atomic energy shift due to eEDM:

$$\delta\varepsilon \sim d_e E \, (\alpha Z)^2 \, \psi^2(0) \, \left(\nabla\phi|_{r\sim 1/Z} V\right) \sim \alpha^2 Z^3 d_e E.$$

If we define atomic EDM so that:

$$\delta\varepsilon \equiv d_{\mathrm{at}} E,$$

we see that $d_{\mathrm{at}} = k_{\mathrm{at}} d_e \sim \alpha^2 Z^3 d_e$ and atomic enhancement factor

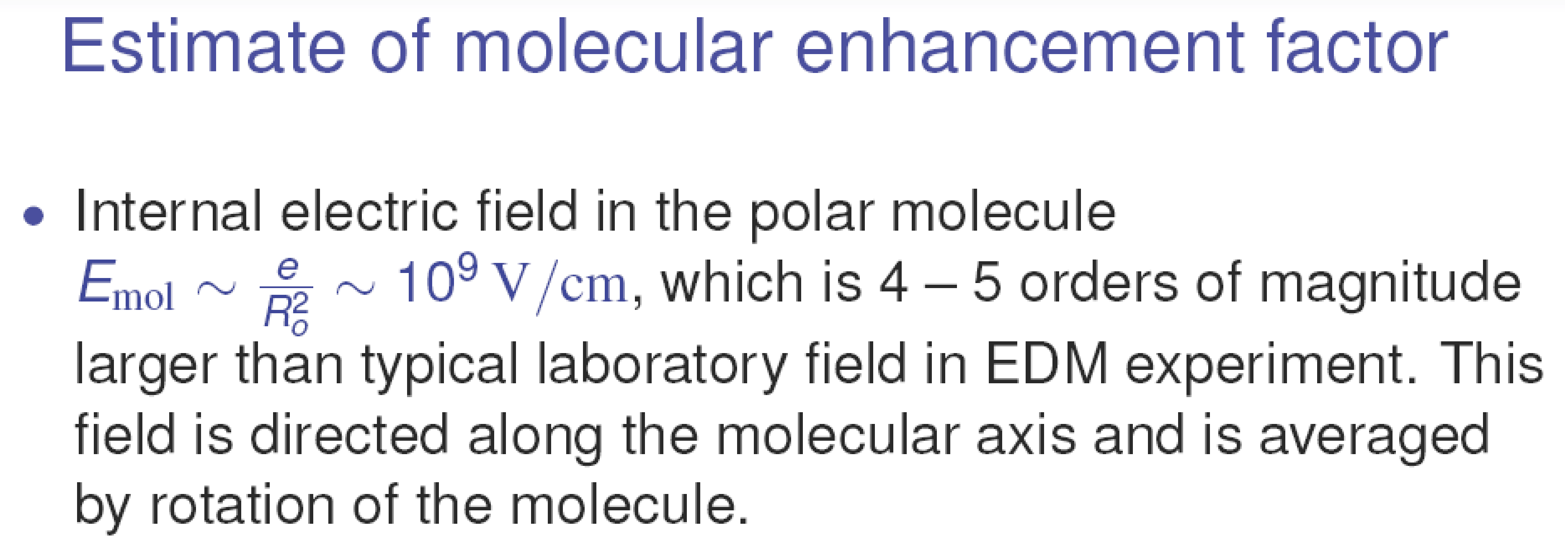
$$\boxed{k_{\mathrm{at}} \sim \alpha^2 Z^3.}$$

M. Kozlov

Summary for atoms

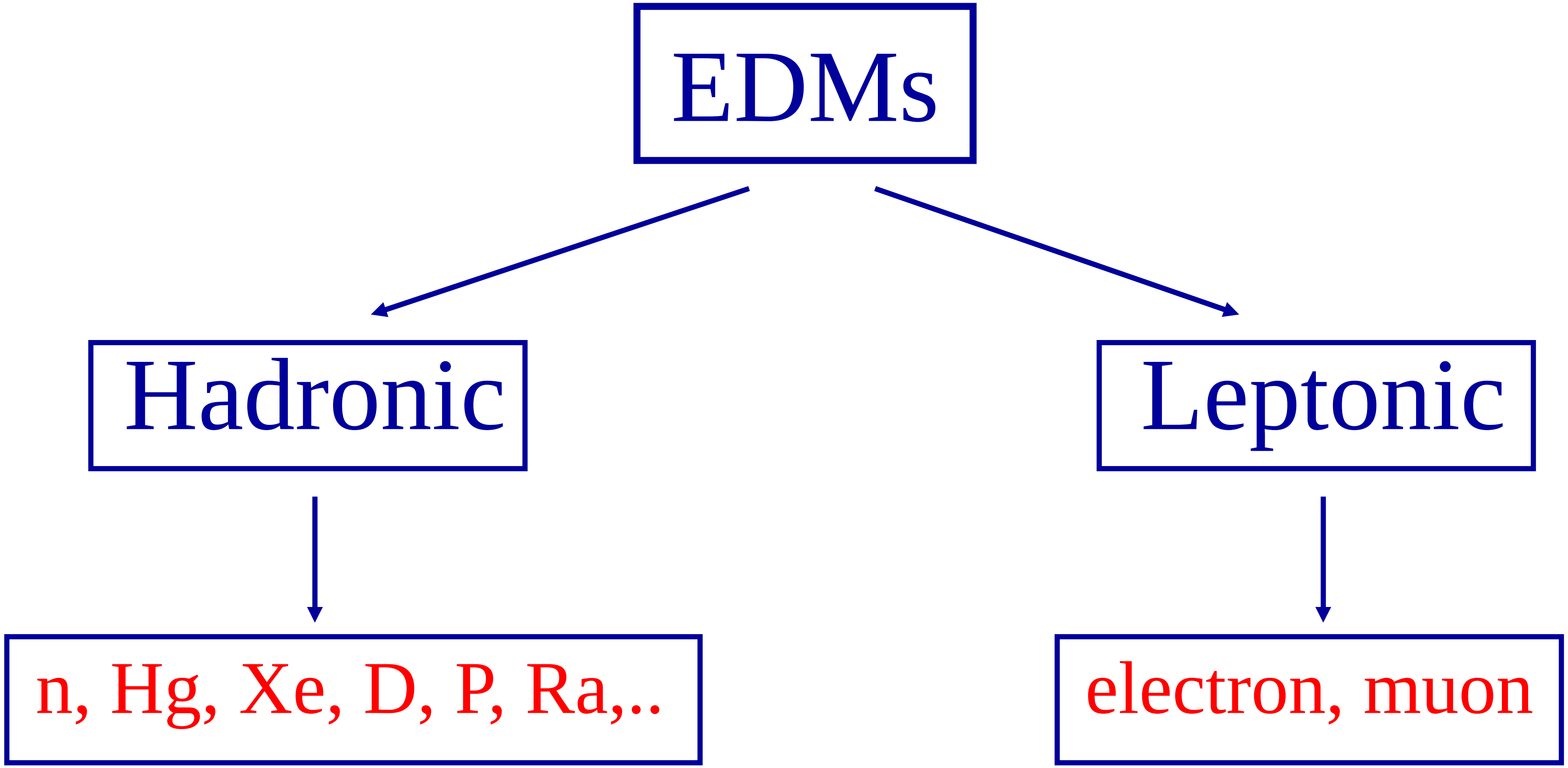
- Atomic EDM scales as $10\alpha^2 Z^3 \times d_e$ when valence electron has $j = \frac{1}{2}$ and is much smaller otherwise.
- The sign of $d_{\rm at}$ depends on the valence configuration.
- Atomic enhancement factor $k_{\rm at}$ is very sensitive to electron correlations, in particular for the case of $j > \frac{1}{2}$.
- Modern atomic theory allows reliable calculations of $k_{\rm at}$ for most heavy atoms of interest.

M. Kozlov



Estimate of molecular enhancement factor

- Internal electric field in the polar molecule $E_{\mathrm{mol}} \sim \frac{e}{R_o^2} \sim 10^9\,\mathrm{V/cm}$, which is 4 – 5 orders of magnitude larger than typical laboratory field in EDM experiment. This field is directed along the molecular axis and is averaged by rotation of the molecule.



EDMs

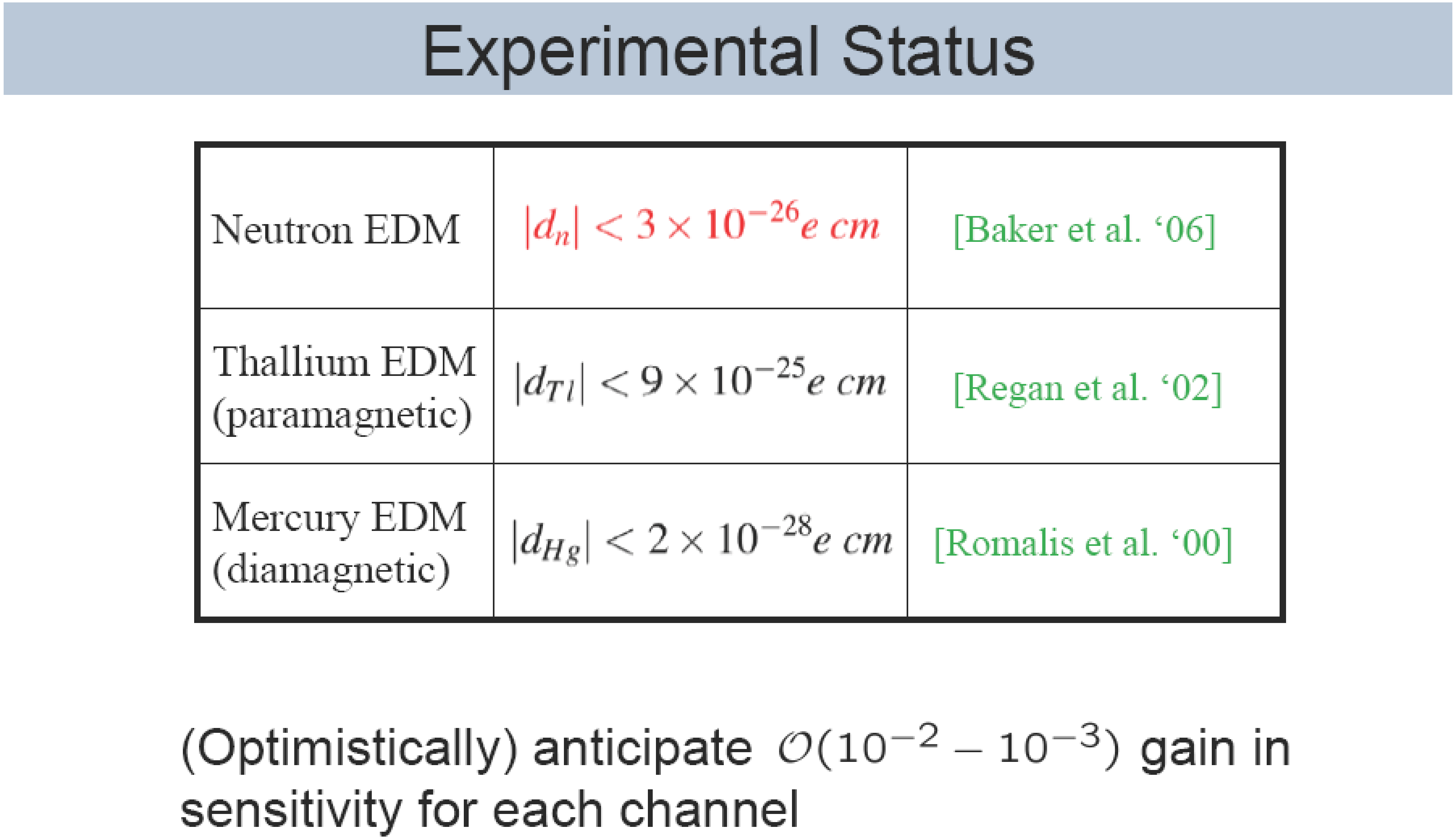
Hadronic

Leptonic

n, Hg, Xe, D, P, Ra,..

electron, muon

A. Ritz



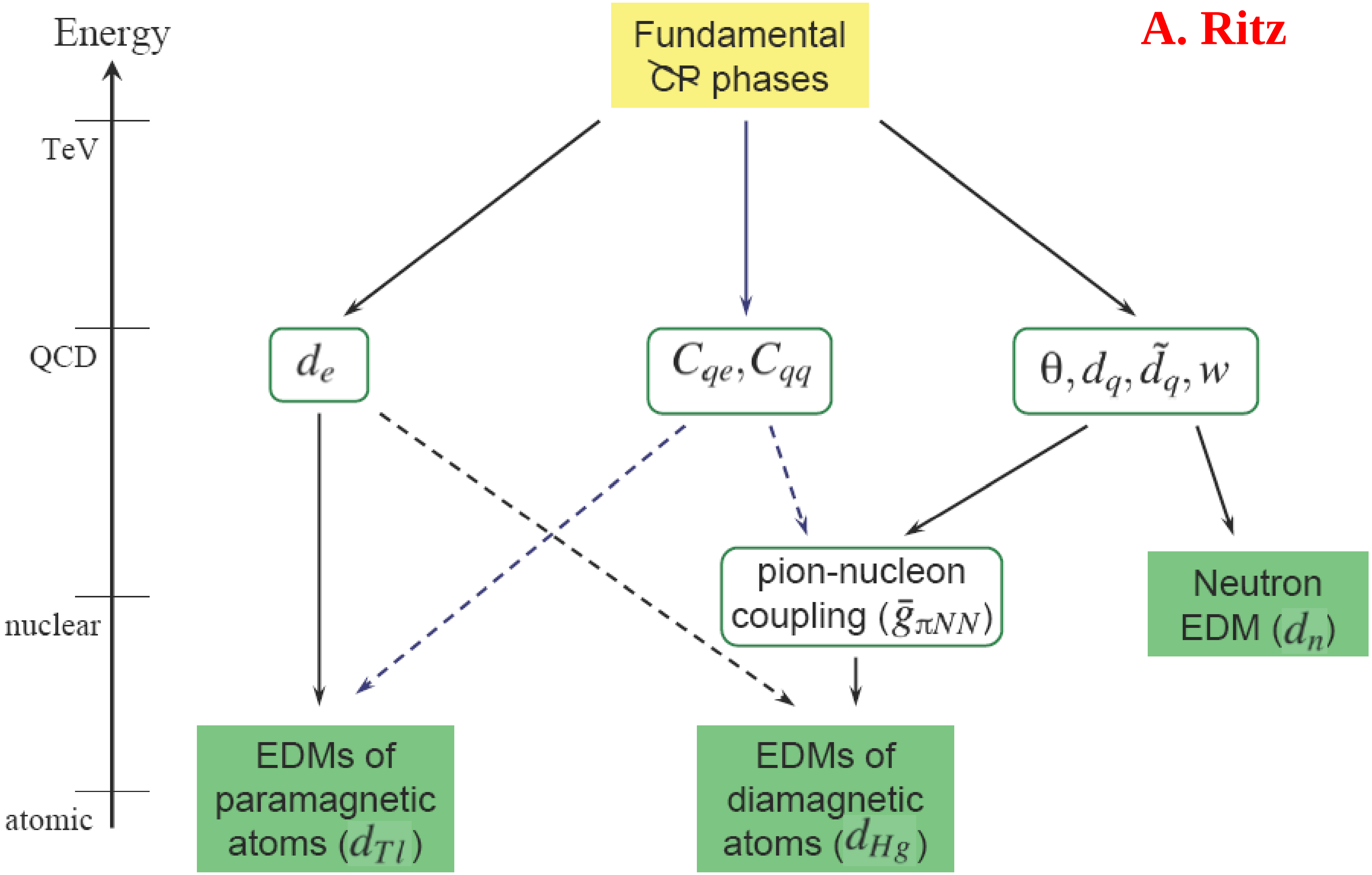
Experimental Status

Neutron EDM	$\lvert d_n \rvert < 3 \times 10^{-26} e\ cm$	[Baker et al. '06]
Thallium EDM (paramagnetic)	$\lvert d_{Tl} \rvert < 9 \times 10^{-25} e\ cm$	[Regan et al. '02]
Mercury EDM (diamagnetic)	$\lvert d_{Hg} \rvert < 2 \times 10^{-28} e\ cm$	[Romalis et al. '00]

(Optimistically) anticipate $\mathcal{O}(10^{-2} - 10^{-3})$ gain in sensitivity for each channel

Origin of the EDMs

A. Ritz



Energy

TeV

QCD

nuclear

atomic

Fundamental $\not{C}\not{P}$ phases

d_e

C_{qe}, C_{qq}

$\theta, d_q, \tilde{d}_q, w$

pion-nucleon coupling ($\bar{g}_{\pi NN}$)

Neutron EDM (d_n)

EDMs of paramagnetic atoms (d_{Tl})

EDMs of diamagnetic atoms (d_{Hg})

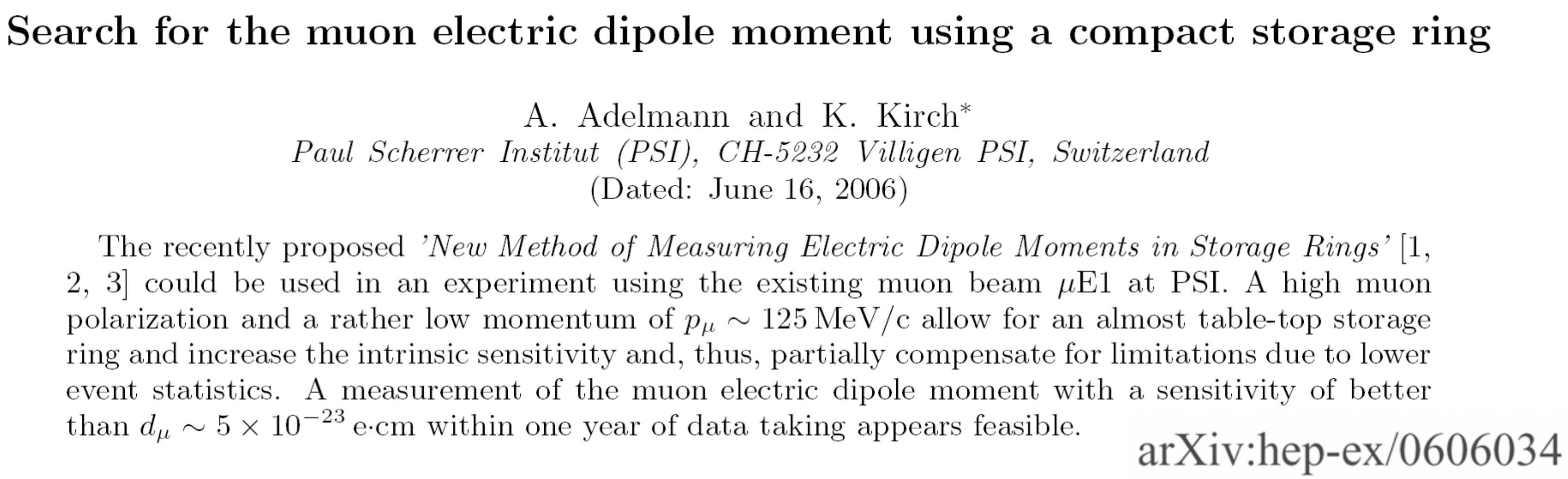
A. Ritz

Resulting Bounds on fermion EDMs & CEDMs

Tl EDM (20%)	$\left\lvert d_e + e(26MeV)^2\left(3\frac{C_{ed}}{m_d}+11\frac{C_{es}}{m_s}+5\frac{C_{eb}}{m_b}\right)\right\rvert < 1.6\times10^{-27}\, e\ cm$
Neutron EDM (50 %)	$\left\lvert e(\tilde{d}_d+0.5\tilde{d}_u)+1.3(d_d-0.25d_u)+O(\tilde{d}_s, w, C_{qq})\right\rvert < 2\times10^{-26}\, e\ cm$
Hg EDM (+200%)	$e\lvert\tilde{d}_d-\tilde{d}_u+O(d_e,\tilde{d}_s,C_{qq},C_{qe})\rvert < 2\times10^{-26}\, e\ cm$

Sensitivity: $d_f \sim e\frac{m_f}{M_{CP}^2} \Rightarrow \boxed{M_{CP} \geq \mathcal{O}(10-50)\, TeV}$

K. Kirch



Search for the muon electric dipole moment using a compact storage ring

A. Adelmann and K. Kirch*
Paul Scherrer Institut (PSI), CH-5232 Villigen PSI, Switzerland

(Dated: June 16, 2006)

The recently proposed *'New Method of Measuring Electric Dipole Moments in Storage Rings'* [1, 2, 3] could be used in an experiment using the existing muon beam μE1 at PSI. A high muon polarization and a rather low momentum of $p_\mu \sim 125\,\mathrm{MeV/c}$ allow for an almost table-top storage ring and increase the intrinsic sensitivity and, thus, partially compensate for limitations due to lower event statistics. A measurement of the muon electric dipole moment with a sensitivity of better than $d_\mu \sim 5 \times 10^{-23}\,e\cdot\mathrm{cm}$ within one year of data taking appears feasible.

arXiv:hep-ex/0606034

Since then:

- work with **G. Onderwater** on systematic issues
- encouraging discussions with both, experimentalists and theoreticians
- work with **A. Adelmann** on realistic injection schemes

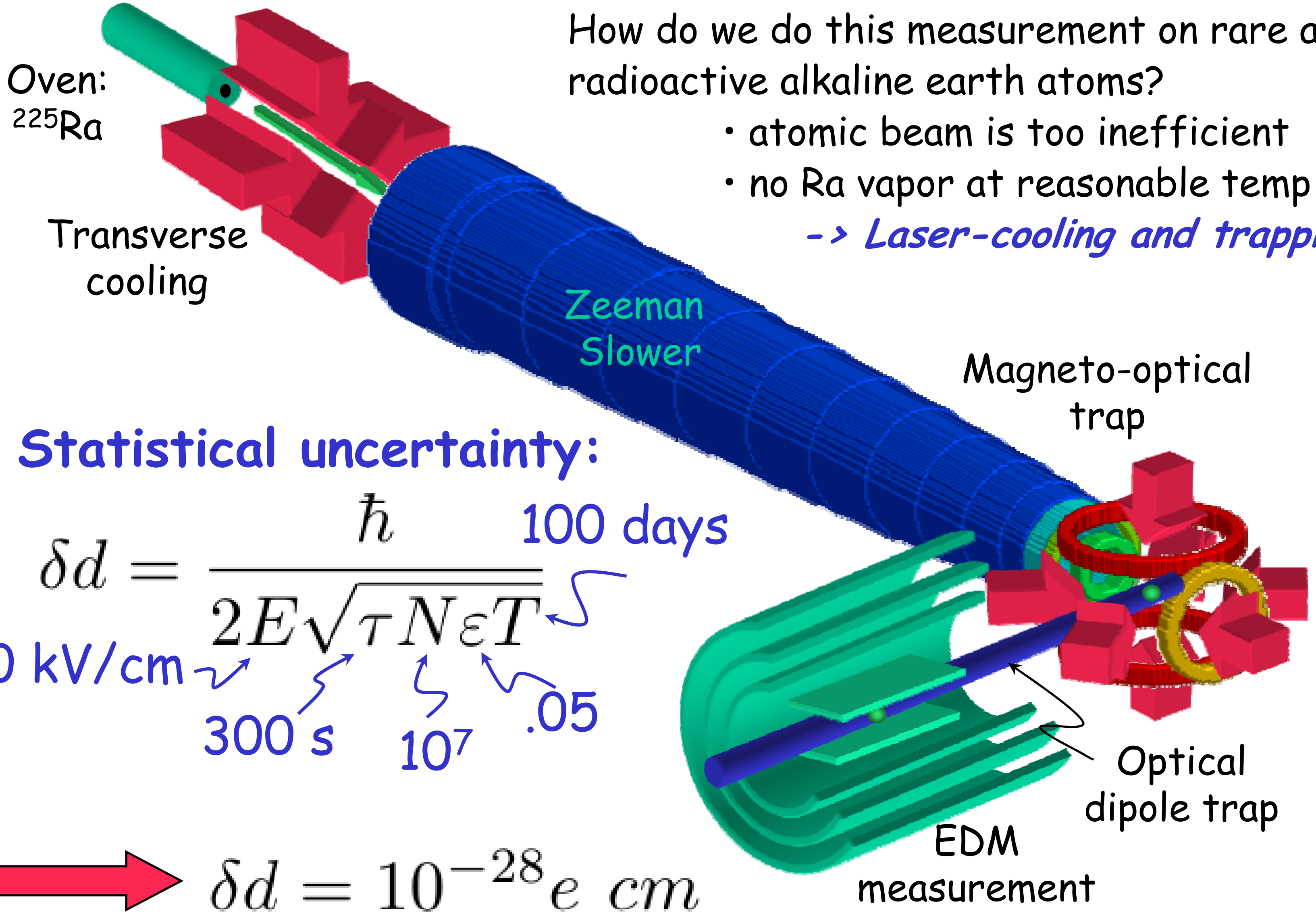
→ Can soon update the paper and perhaps undertake steps towards a LOI in case we can bring together a sufficiently strong group

EDM measurement on Ra-225

How do we do this measurement on rare and radioactive alkaline earth atoms?

- atomic beam is too inefficient
- no Ra vapor at reasonable temp

-> Laser-cooling and trapping



Statistical uncertainty:

$$\delta d = \frac{\hbar}{2\underset{100\text{ kV/cm}}{E}\sqrt{\underset{300\text{ s}}{\tau}\,\underset{10^{7}}{N}\,\underset{.05}{\varepsilon}\,\overset{100\text{ days}}{T}}}$$

$$\Rightarrow \quad \delta d = 10^{-28} e\ cm$$

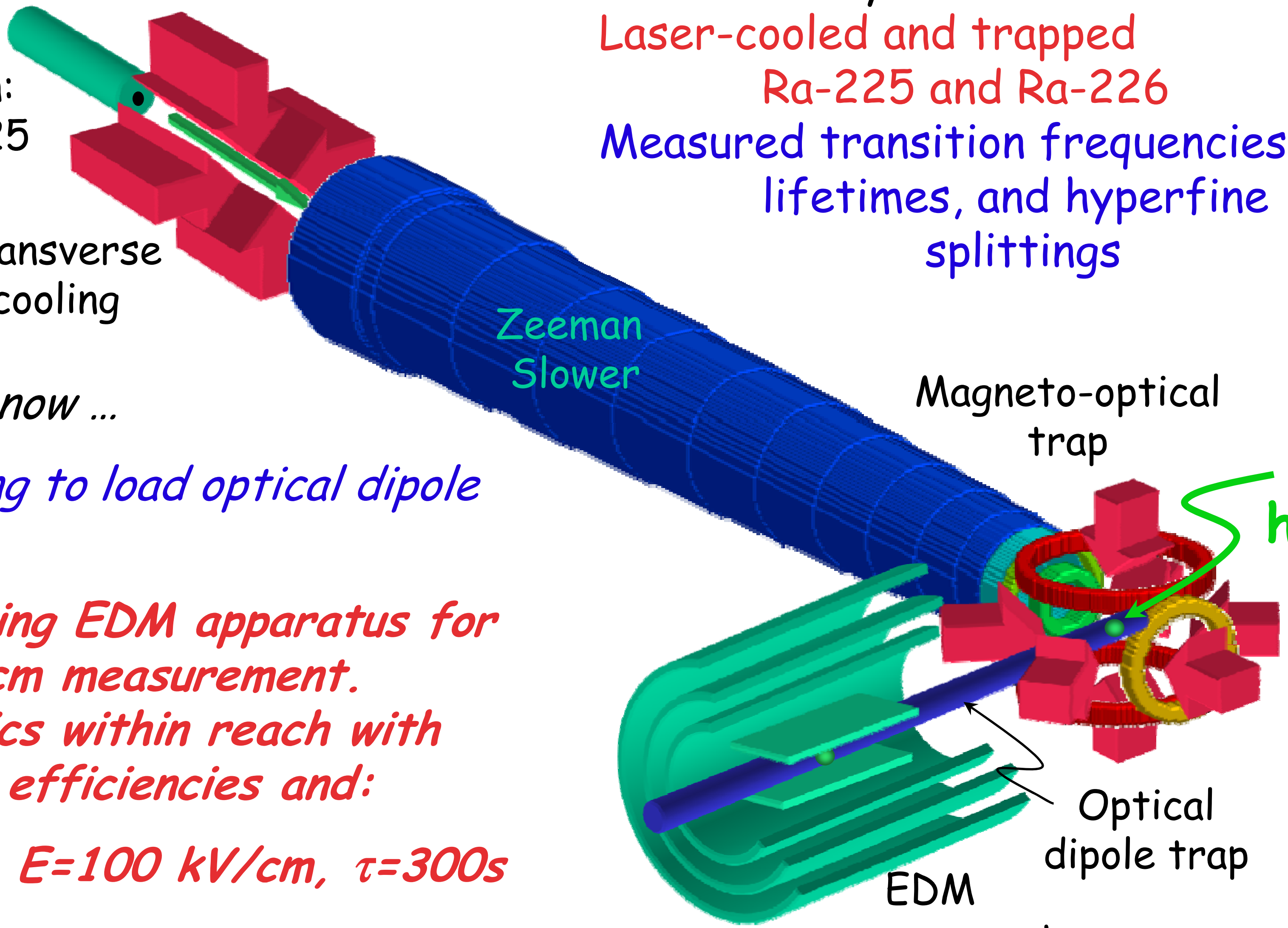
J. Guest

Where we are and where we're going …

We have successfully …

Laser-cooled and trapped Ra-225 and Ra-226

Measured transition frequencies, lifetimes, and hyperfine splittings



We are now …

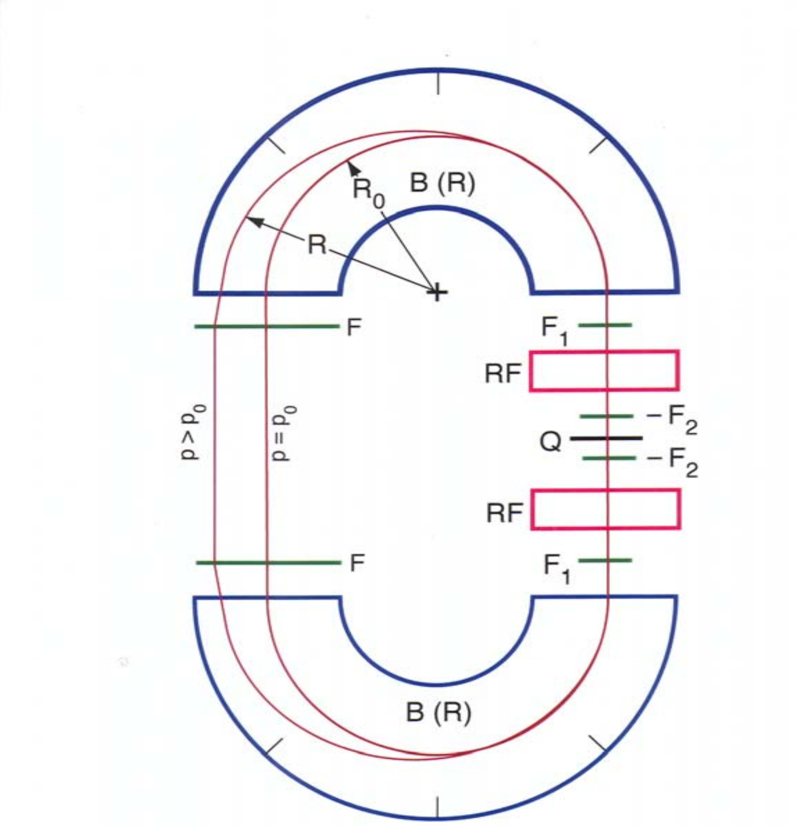
Preparing to load optical dipole trap

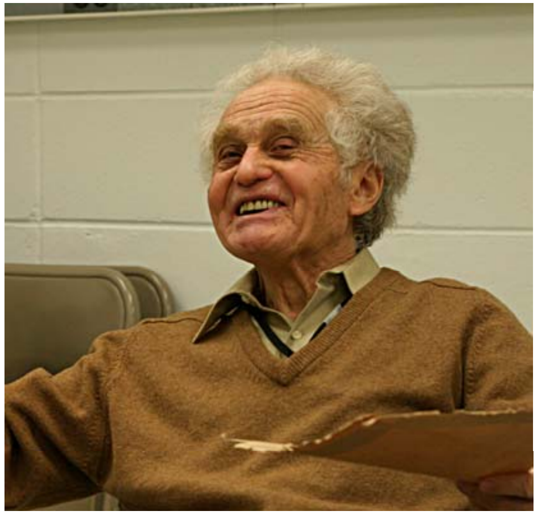
Developing EDM apparatus for 10^{-26} ecm measurement. Statistics within reach with current efficiencies and:

10 mCi, E=100 kV/cm, τ=300s

J. Guest

Resonance Electric Dipole Moment Method: Deuteron at 10^{-29}e·cm!





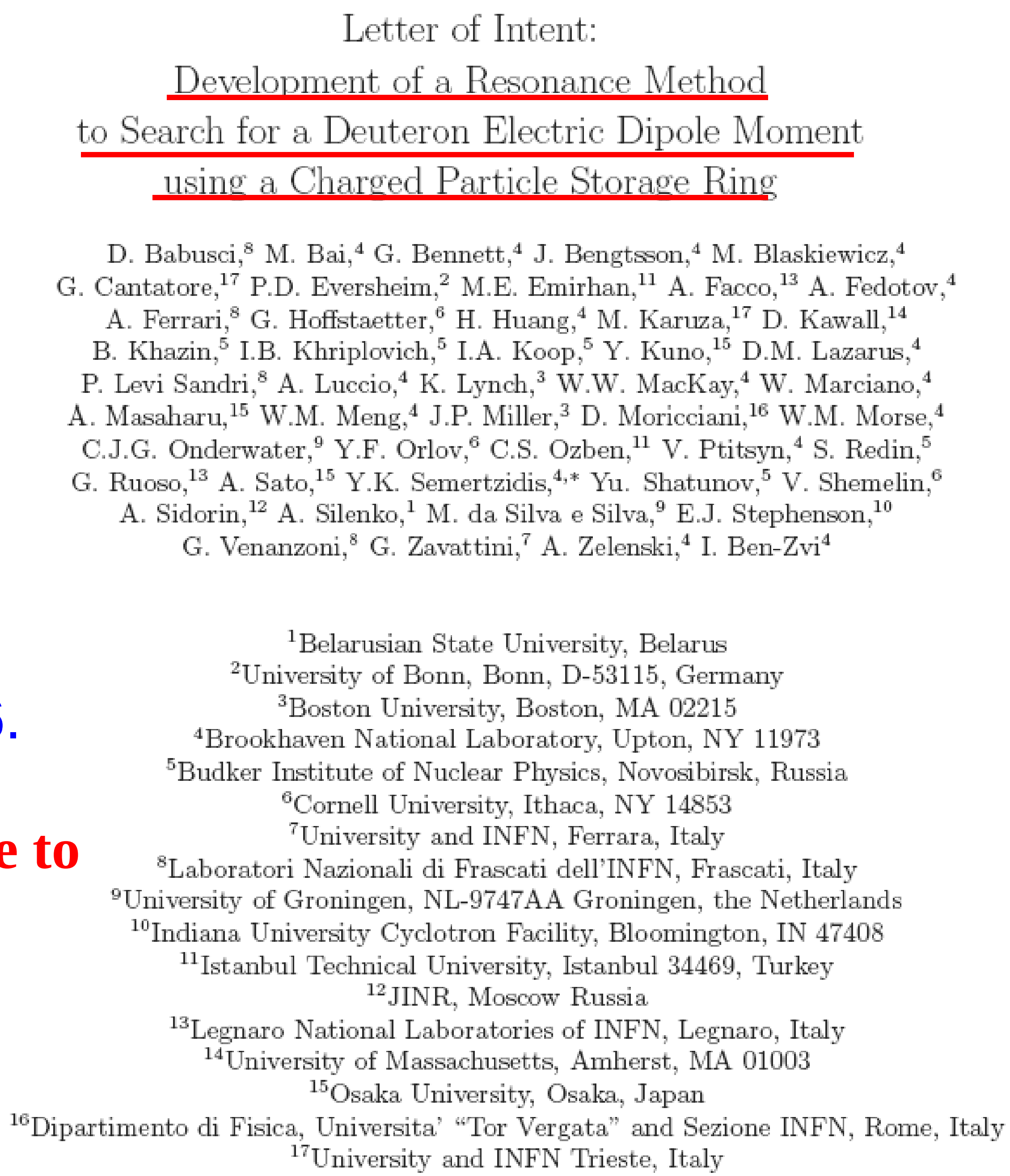
Yuri Orlov

September 2006: BNL PAC …is enthusiastic about this ingenious new idea. The collaboration must study systematics…

Members of the Storage Ring EDM Collaboration and friends…

Deuteron,
Proton (B. Morse)

Storage
Ring
EDM
Collaboration



Letter of Intent:
Development of a Resonance Method
to Search for a Deuteron Electric Dipole Moment
using a Charged Particle Storage Ring

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A. Ferrari,[8] G. Hoffstaetter,[6] H. Huang,[4] M. Karuza,[17] D. Kawall,[14]
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P. Levi Sandri,[8] A. Luccio,[4] K. Lynch,[3] W.W. MacKay,[4] W. Marciano,[4]
A. Masaharu,[15] W.M. Meng,[4] J.P. Miller,[3] D. Moricciani,[16] W.M. Morse,[4]
C.J.G. Onderwater,[9] Y.F. Orlov,[6] C.S. Ozben,[11] V. Ptitsyn,[4] S. Redin,[5]
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[17]University and INFN Trieste, Italy

Presented to the BNL PAC, September 2006.

An effort is being made to include it in the N.P. Long Range Plan…

G. Onderwater

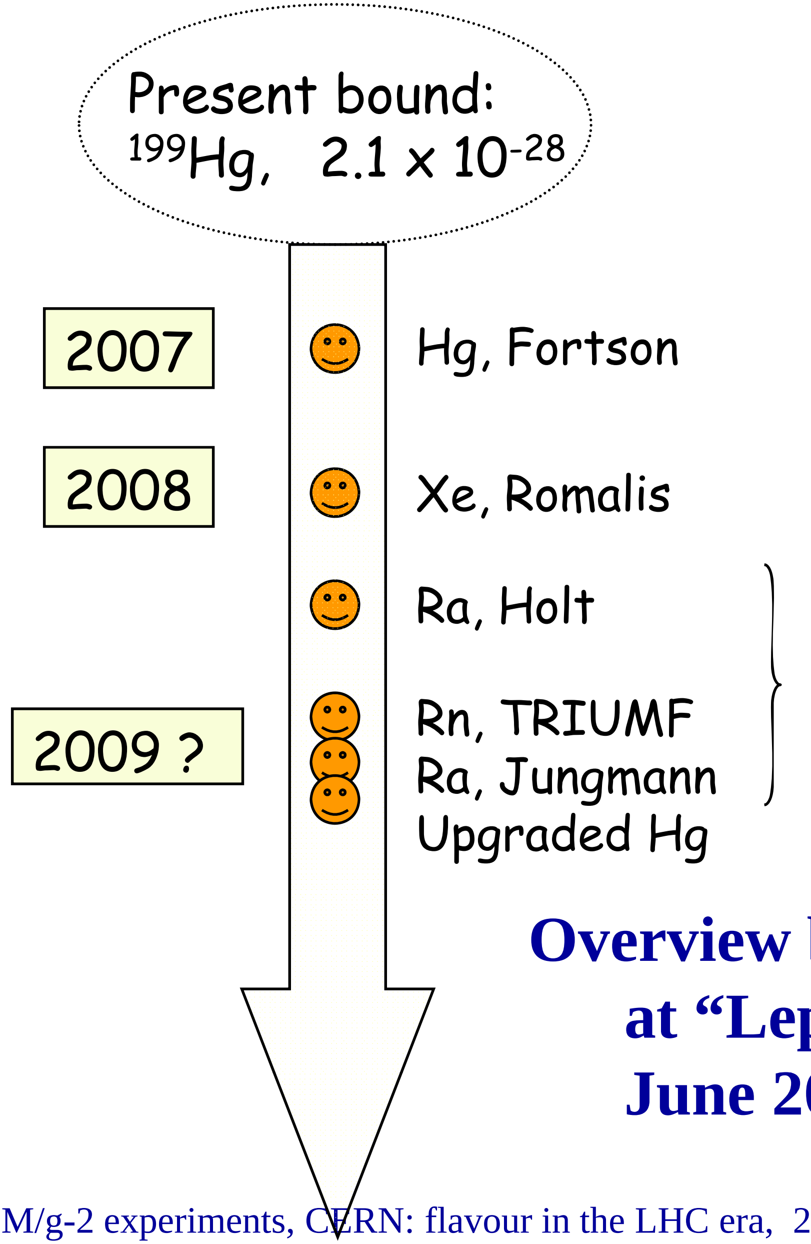
Deuteron EDM talk

Lepton and hadron EDM searches are exciting and complementary

- Next two to three orders of magnitude will be defining (A. Ritz, I. Masina)

- Need to do both neutrons/hadrons and leptons since their relative sensitivity might be a ratio of 10-100 or 100-10000 in non-universal SUSY models (O. Lebedev)

Diamagnetic atoms: a forecast



Present bound:
^{199}Hg, 2.1 x 10^{-28}

2007 Hg, Fortson

2008 Xe, Romalis

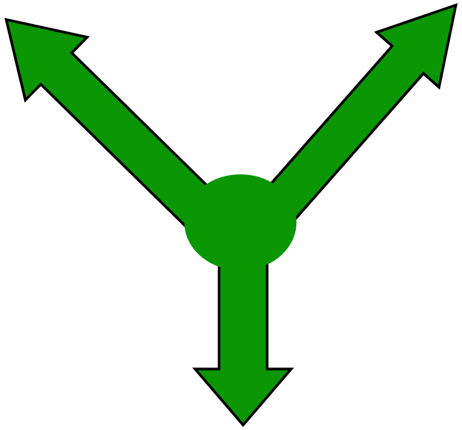
Ra, Holt

2009 ?
Rn, TRIUMF
Ra, Jungmann
Upgraded Hg

octupole deformation

Overview by A. Czarnecki at "Lepton Moments" June 2006

A road-map to the electron EDM



Atoms

Well-known enhancement factors
Well-studied spectroscopy
Routine technology
Long measurement times

Molecules

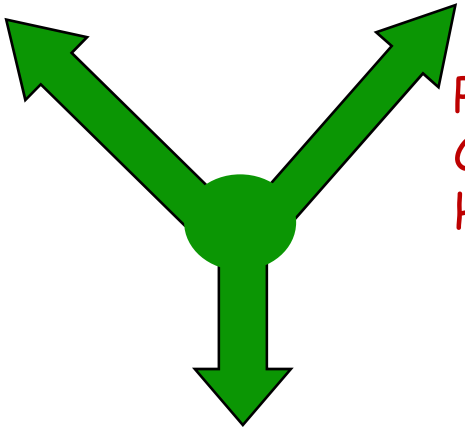
Very large enhancement factors
Some systematic issues easier:
- magnetic field
- v x E

Solid state (garnets)

Huge number of spins
VERY long coherence time

A. Czarnecki

A road-map to the electron EDM



Atoms

Well-known enhancement factors
Well-studied spectroscopy
Routine technology
Long measurement times

Small enhancement
Very large E-field needed

Molecules

Very large enhancement factors
Some systematic issues easier:
- magnetic field
- v x E

Poorly known spectra
Can't get them "in bottles"
How to cool?

Solid state (garnets)

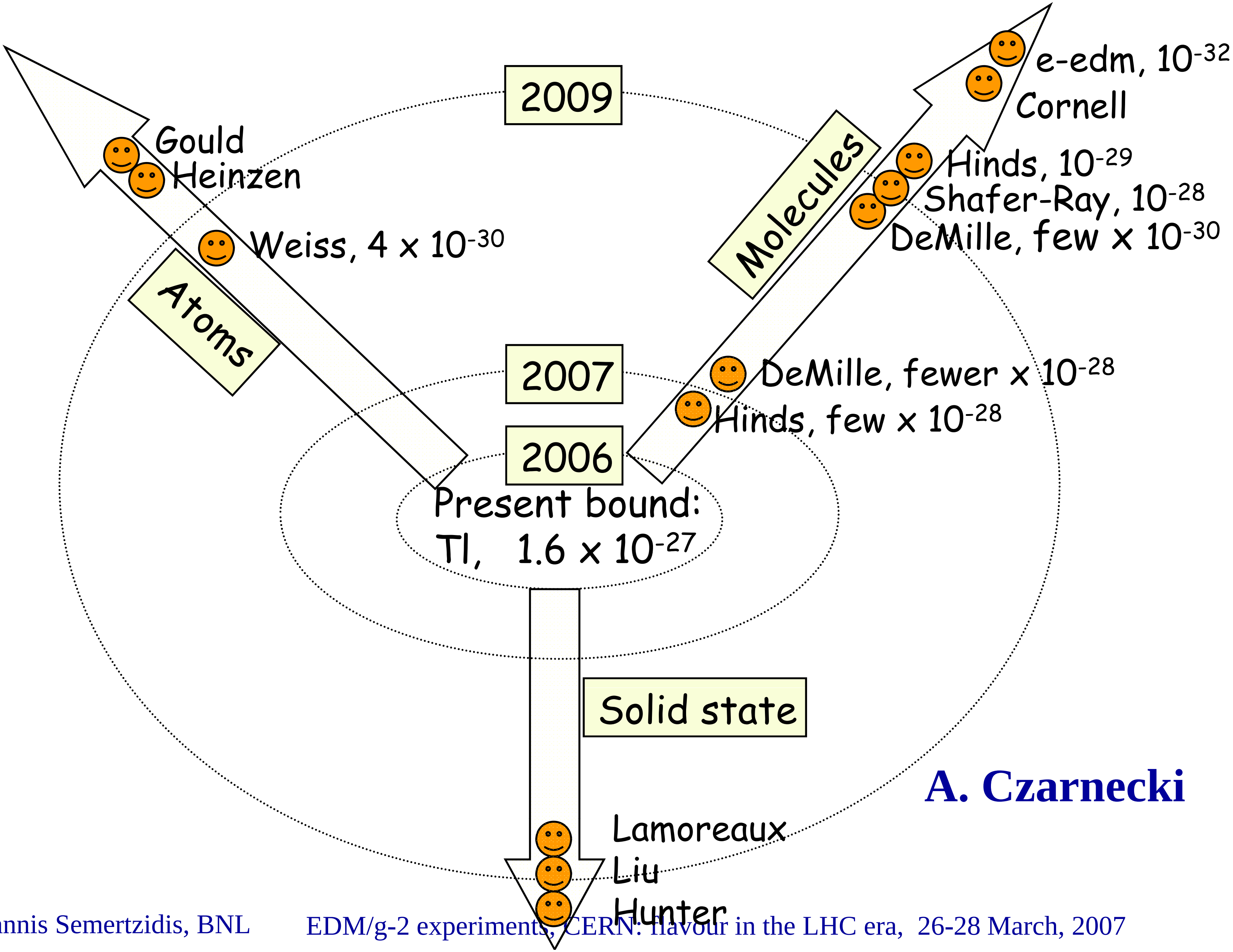
Huge number of spins
VERY long coherence time

Systematics?

A. Czarnecki

Thanks to
Sarah Bickman
and Dan Farkas

A forecast: electron EDM



2009

2007

2006

Present bound:
Tl, 1.6 x 10^{-27}

Atoms

Gould
Heinzen

Weiss, 4 x 10^{-30}

Molecules

e-edm, 10^{-32}
Cornell

Hinds, 10^{-29}
Shafer-Ray, 10^{-28}
DeMille, few x 10^{-30}

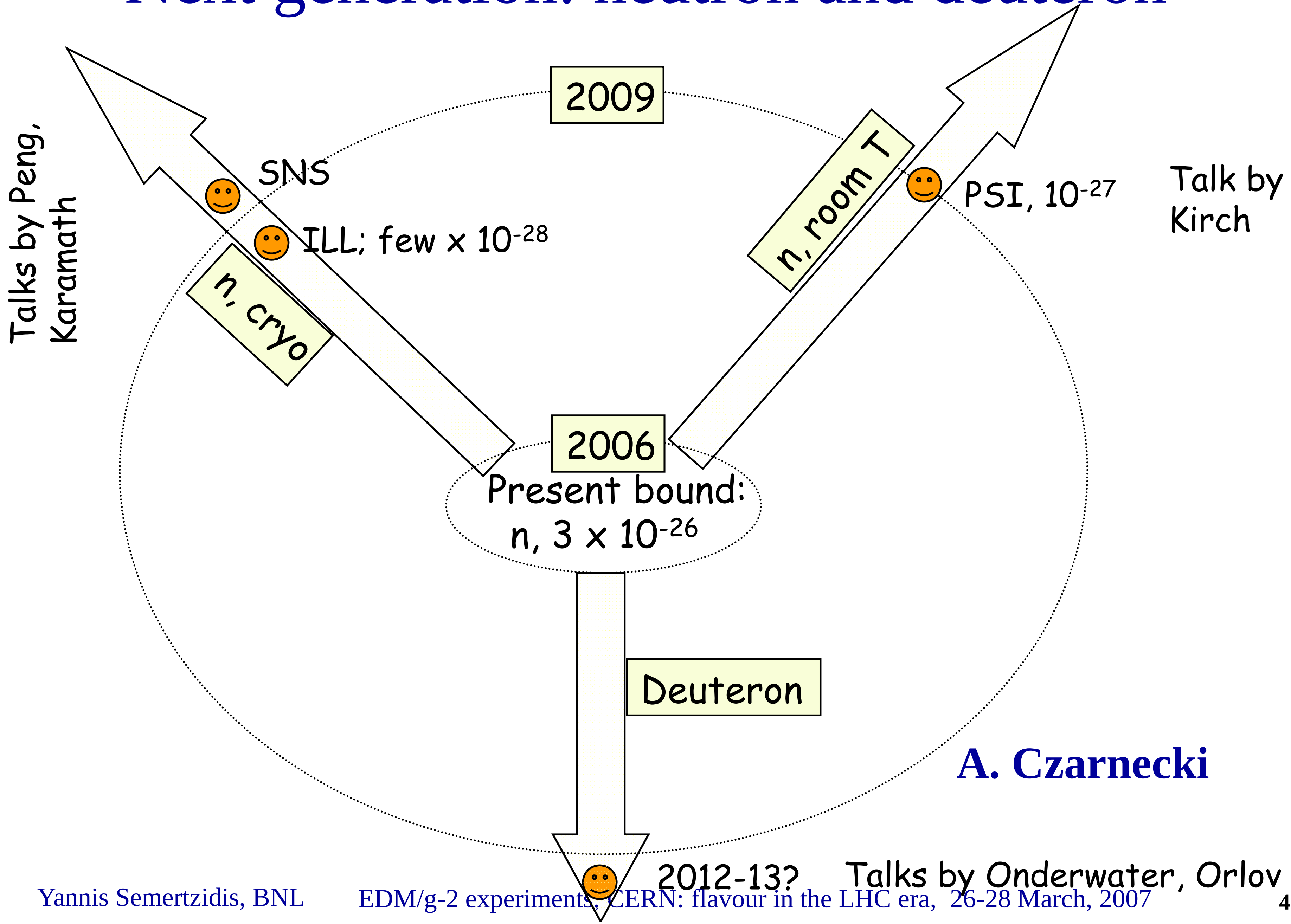
DeMille, fewer x 10^{-28}
Hinds, few x 10^{-28}

Solid state

Lamoreaux
Liu
Hunter

A. Czarnecki

Next generation: neutron and deuteron



Talks by Peng, Karamath

2009

SNS

ILL; few x 10^{-28}

n, cryo

n, room T

PSI, 10^{-27}

Talk by Kirch

2006

Present bound:
n, 3 x 10^{-26}

Deuteron

A. Czarnecki

2012-13?

Talks by Onderwater, Orlov

Muon (g-2) to 0.25 ppm

James Miller
(For the new Muon (g-2) Collaboration, E969)
Department of Physics
Boston University

Summary

J. Miller

- E821 Achieved a precision of ± 0.5 ppm
- There appears to be a discrepancy between experiment and e^+e^- based theory –> hint of new physics?
- E969 proposes to achieve a precision down to ± 0.25 ppm (factor of 2 improvement) with 4x as many muons
- Lots of continuing work worldwide on the hadronic theory piece, both experimental and theoretical.

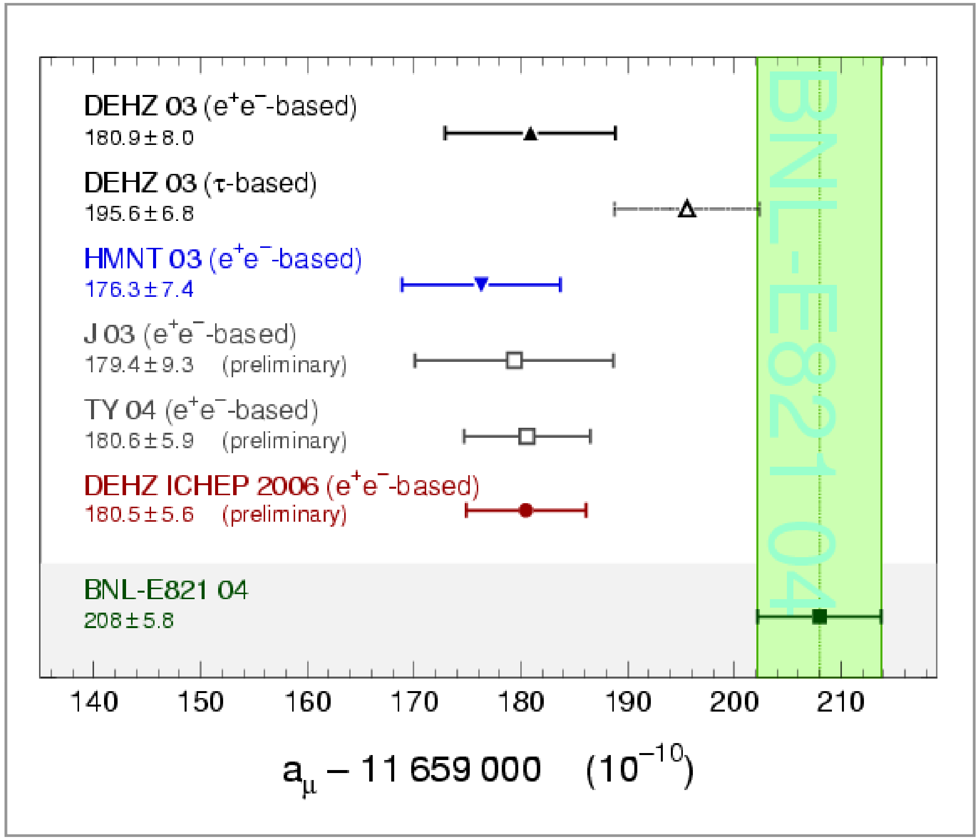
Outlook:

- E969 was one of the four recommendations of the Particle Physics Project Prioritization Panel (P5)!
- An effort is being made to include full funding for E969 in the Nuclear Physics Long Range Plan.
- If both theory and experiment can improve by a factor of 2, the stage is set for another potential confrontation between theory and experiment.

And the Complete Result

$$a_\mu^{SM}[e^+e^-] = (11\,659\,180.5 \pm 4.4_{\text{had,LO}} \pm 3.5_{\text{LBL}} \pm 0.2_{\text{QED+weak}}) \times 10^{-10}$$

DEHZ (Tau 2006)



A. Hoecker

BNL E821 (2004):

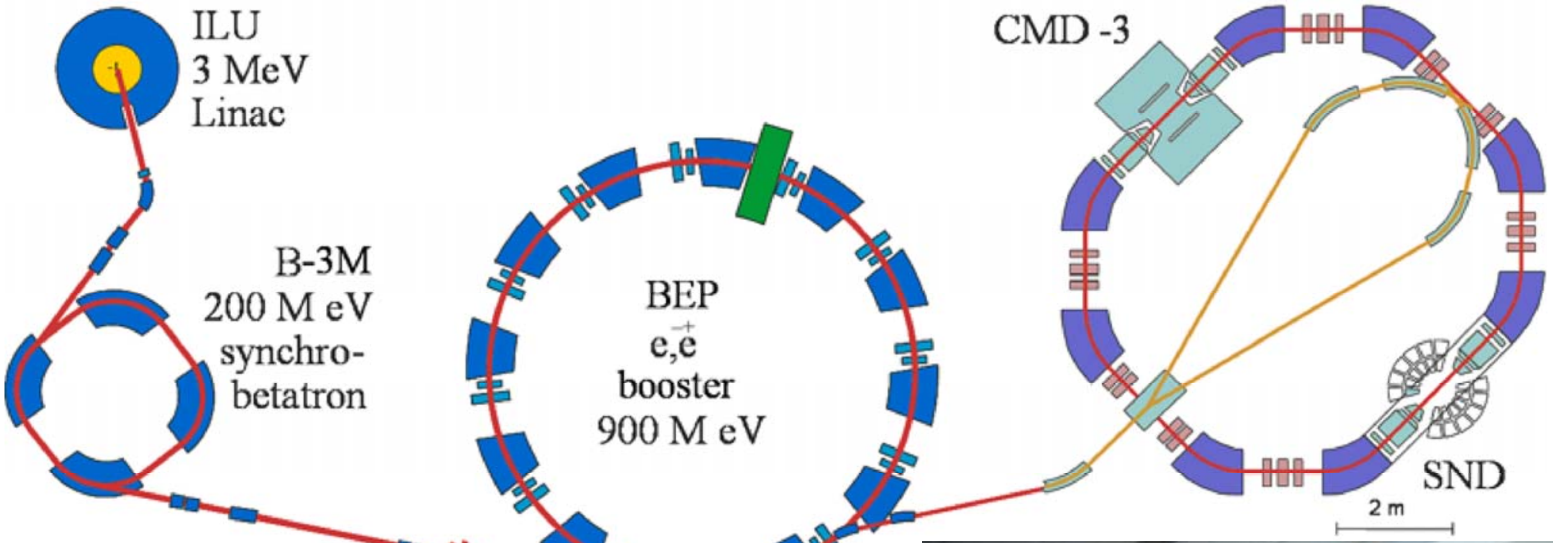
$a_\mu^{\text{exp}} = (11\,659\,208.0 \pm 6.3)\ 10^{-10}$

Observed Difference with Experiment:

$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (27.5 \pm 8.4) \times 10^{-10}$$

➡ 3.3 ”standard deviations“

Future measurements at VEPP-2000



S. Redin

Under construction. Data taking is expected to start is 2007-2008.

Small angle analysis (2002 data)

D. Leone/KLOE

A **new analysis** is carried out at small photon angles using 2002 data (240 pb^{-1})
With improved machine background and calibration conditions
Goals : - reduction of the total systematic error < 1%
- measure the R-ratio = $\sigma_{\pi\pi}/\sigma_{\mu\mu}$

Acceptance	0.3 %
Trigger	~~0.3 %~~
Tracking *	0.3%
Vertex *	0.3%
Offline reconstruction filter	~~0.6%~~
Particle ID	0.1%
Trackmass cut	0.2%
Background subtraction	0.3%
Unfolding effects	0.2%
Exp. Systematic with 2001 data:0.9 %	

No more losses due to cosmic veto trigger: **no cosmic veto inefficiency anymore**

Improved filter, less sensitive to Machine background:
error reduced to <0.1%

* Larger data set (2002 data) allows more precise determination.

Heated discussions…

Proposal for 10 times improvement on a_μ by F. Farley

$B = 4.5$ T $\langle B \rangle = 3.8$ T

bend radius   12 m

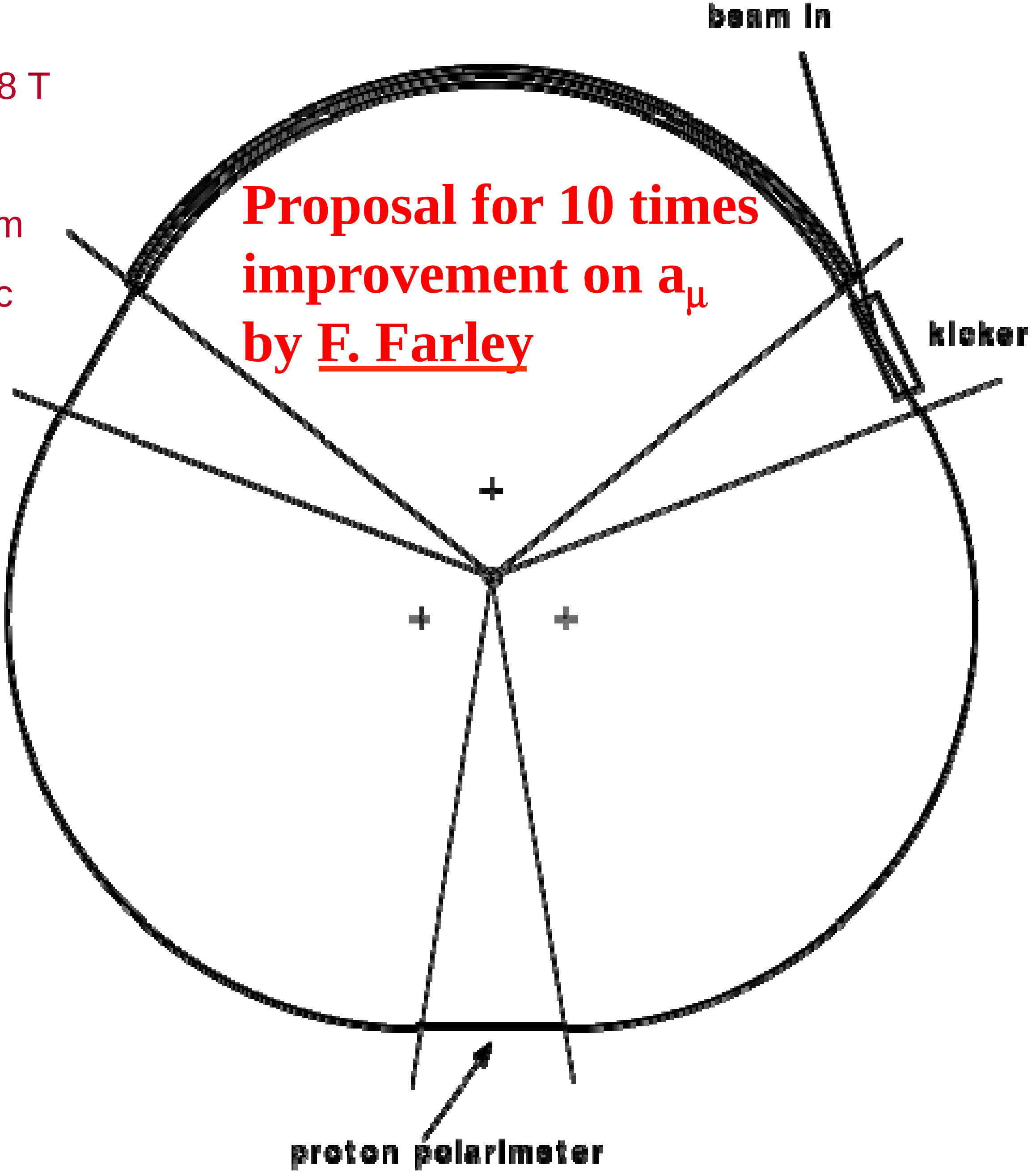
straight sections   4.3 m

momentum   15 GeV/c

Q_h 1.025

Q_v 0.4

Think about it



F. Farley &
E. Picaso discuss
a new g-2 exp.?

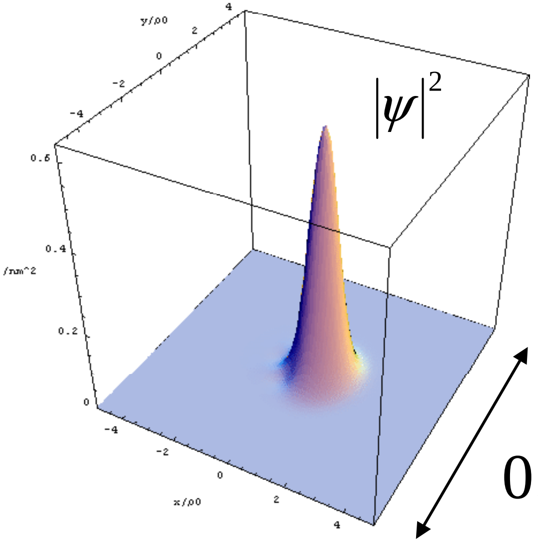
New Measurement
of the Electron Magnetic Moment
and the Fine Structure Constant

Gerald Gabrielse
Leverett Professor of Physics
Harvard University

20 years
6.5 theses

Almost finished student: David Hanneke
Earlier contributions: Brian Odom,
Brian D'Urso,
Steve Peil,
Dafna Enzer,
Kamal Abdullah
Ching-hua Tseng
Joseph Tan

2006 DAMOP Thesis
Prize Winner

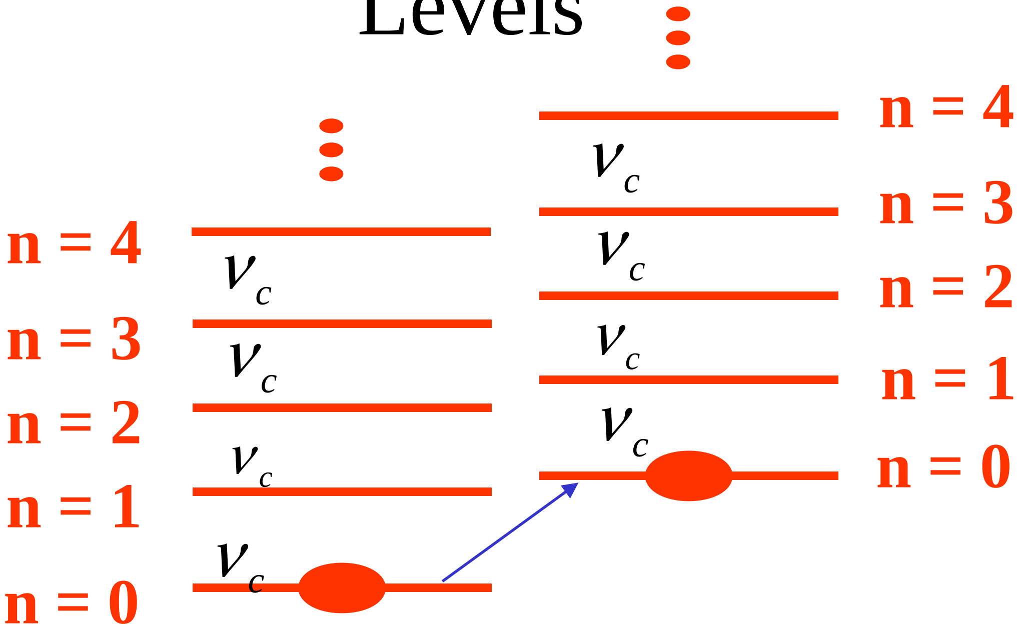


N$F

Spin → Two Cyclotron Ladders of Energy Levels

Cyclotron frequency:

$$\nu_c = \frac{1}{2\pi}\frac{eB}{m}$$



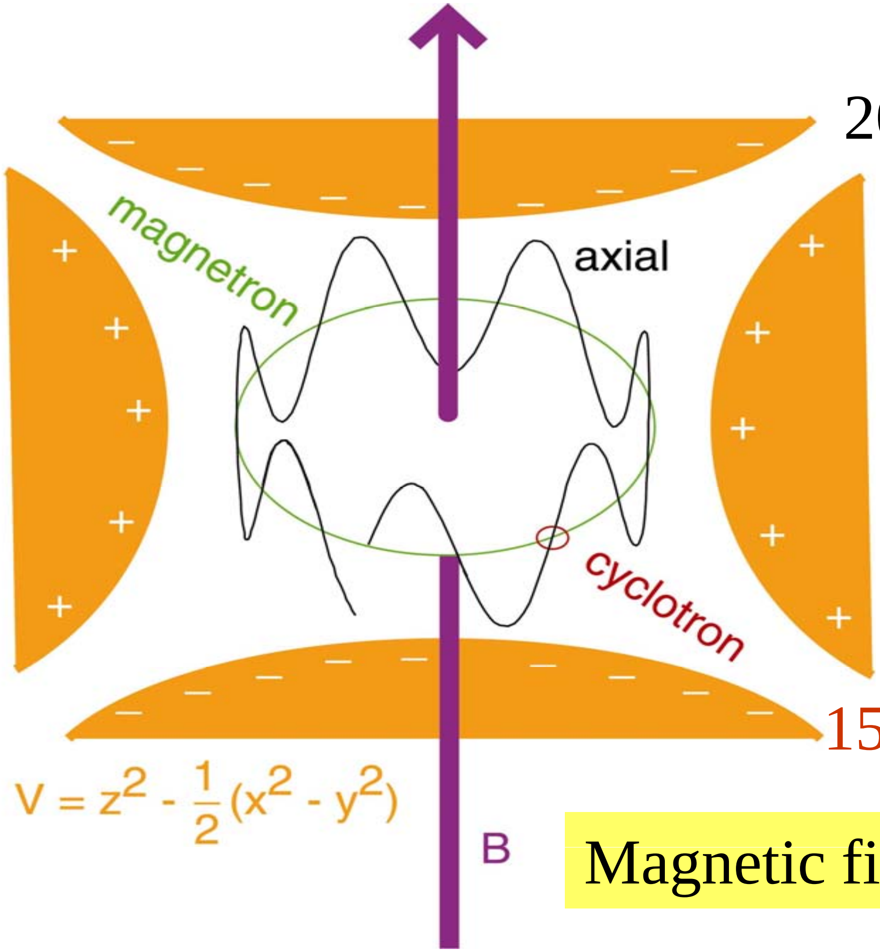
$m_s = -1/2$ $m_s = 1/2$

Spin frequency:

$$\nu_s = \frac{g}{2}\nu_c$$

One Electron in a Penning Trap

- very small accelerator
- designer atom



cool 12 kHz

200 MHz detect

153 GHz

need to measure for g/2

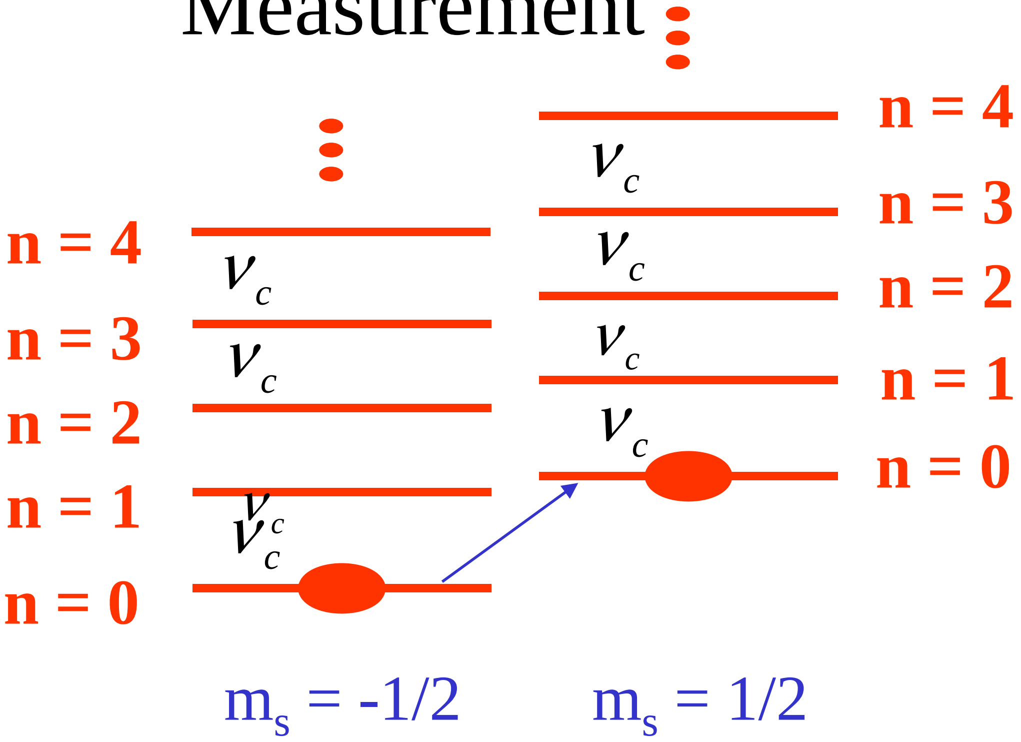
Electrostatic quadrupole potential

Magnetic field

Basic Idea of the Fully-Quantum Measurement

Cyclotron frequency:

$$\nu_c = \frac{1}{2\pi}\frac{eB}{m}$$



Spin frequency:

$$\nu_s = \frac{g}{2}\nu_c$$

Measure a ratio of frequencies:

$$\frac{g}{2} = \frac{\nu_s}{\nu_c} = 1 + \frac{\nu_s - \nu_c}{\nu_c}$$

B in free space

- almost nothing can be measured better than a frequency
- the magnetic field cancels out (self-magnetometer)

Electron g-2: theory, data, and a new alpha

$$\frac{g}{2} = 1 + C_1\left(\frac{\alpha}{\pi}\right)$$

$$+ C_2\left(\frac{\alpha}{\pi}\right)^2$$

$$+ C_3\left(\frac{\alpha}{\pi}\right)^3$$

$$+ C_4\left(\frac{\alpha}{\pi}\right)^4$$

$$+ \ldots\ \delta a$$

$$g/2 = 1.001\,159\,652\,180\,85$$

$$\pm 0.000\,000\,000\,000\,76$$

$$\left(7.6\times 10^{-13}\right)$$

Together:

$$\alpha^{-1} = 137.035\,999\,710(96) \qquad 7.0\times 10^{-10}$$

Independent measurement of alpha is urgently needed!

- A factor of ~100 in alpha
- Then a factor of ~20 in a_e will test the 3.3 sigma of the muon g-2 result!!

Summary

- The GREAT physics reach of the EDM, and g-2 exps was shown

- The physics reach of new exps are at the 10^3 TeV or (with new physics at LHC) at 10^{-5} rad for CP violating phases.

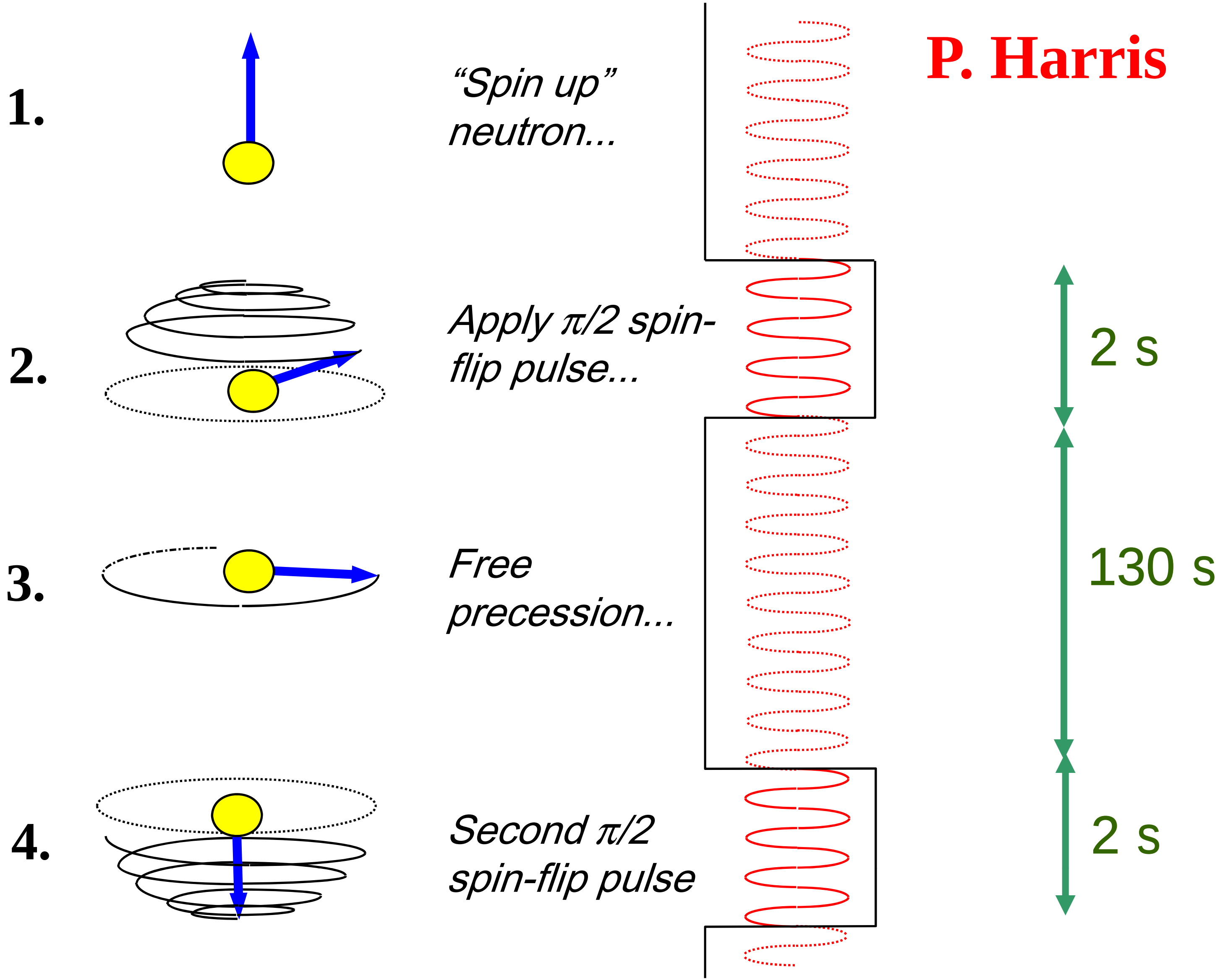
- The present is exciting and the future promises to be even more so!!

- We enjoyed the meetings!

Many thanks to both N. Ramsey for his contributions to EDM and NMR and M. Mangano for running a first class series of meetings. Many thanks to all the contributors…

Extra slides

Ramsey method of Separated Oscillating Fields



P. Harris

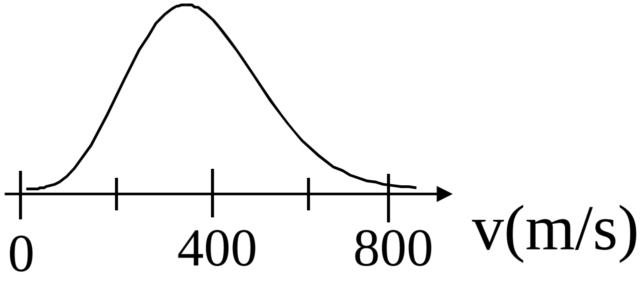
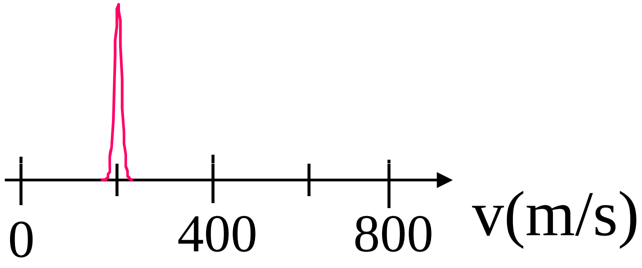
1. *"Spin up" neutron...*

2. *Apply $\pi/2$ spin-flip pulse...*

3. *Free precession...*

4. *Second $\pi/2$ spin-flip pulse*

Differences between an atomic beam and a beam of paramagnetic molecules

Beam	Expected Flux	Speed Distribution
Tl(F=1,|M|=1) (from oven)	8×10^{15}/str/sec	
YbF(J=1/2, F=1,|M|=1) (from supersonic expansion)	6×10^{10}/str/sec	

Easy to lose in statistics what one gains in intrinsic sensitivity.

Neil Shafer-Ray, O.U.

conclusions

A. Hoecker/hadronic corrections

- Phenomenal experimental progress from BNL (E821) $g-2$ measurement
- Improved theory prediction due to new CMD-2 and SND data
- Hadr. part dominates SM uncertainty (5.6), but more precise than experiment (6.3)
- Disagreement between SND/CMD-2 and KLOE data sets; so far KLOE not incl.
- Tau data in agreement (but Belle); revised SND data confirm τ / e^+e^- discrepancy
- What is behind the 4.5σ τ / e^+e^- discrepancy of the CVC BR ?
- KLOE will publish cross sections based on pion/muon ratios
- BABAR ISR: $\pi^+\pi^-$ spectral function over full mass range, multihadron channels
- Difference between experiment and $\mathrm{SM}_{[e+e-]}$ within range of possible New Physics

Final Remarks on Main $\pi^+\pi^-$ Contribution

The problem of the $\pi^+\pi^-$ contribution: **A. Hoecker/hadronic corrections**

- Experimental situation:
  - revised SND results in agreement with CMD-2
  - τ data without $m(\rho)$ and $\Gamma(\rho)$ corr. in strong disagreement with both data sets
  - ALEPH, CLEO and OPAL τ data in ok agreement, preliminary Belle less so
  - *e^+e^- spectral functions have now reached the precision of τ data*
- Concerning the remaining line shape discrepancy (0.7- 0.9 GeV^2):
  - SU(2) corrections: basic contributions identified and stable since long; overall correction applied to τ is (–2.2   0.5) %, dominated by uncontroversial short distance piece; additional long-distance corrections found to be small
  - ρ lineshape corrections can improve the situation, but cannot account for the difference above 0.7 GeV^2

- The agreement between SND and CMD-2 invalidates the use of τ data until a better understanding of the discrepancies is achieved (an interesting question as such)
- Discrepancy between KLOE and CMD-2/SND results: not safe to take advantage of decreased error when including KLOE

$p \rightarrow K^+ \nu$ VS d_e

I. Masina

From d=5 op generated by TRIPLET exchange
['82: Weinberg, Sakai, Yanagida, ...]

τ_p depends A LOT on M_T -structure

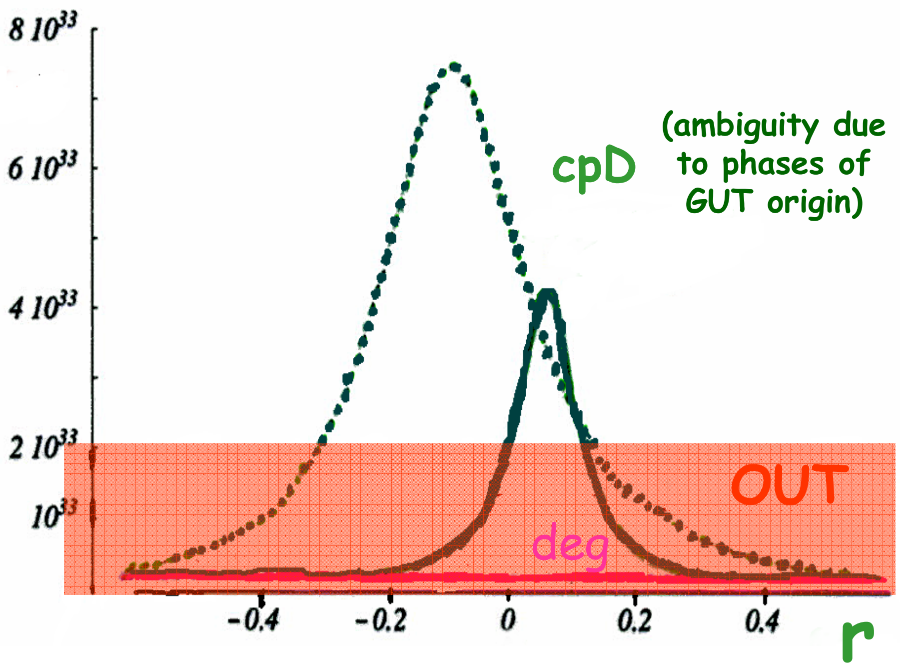
deg: KO cpD: SAFE

From RGE where contributions of the many heavy states sum up

d_e INSENSITIVE to M_T -structure

g_μ region& tgβ=3

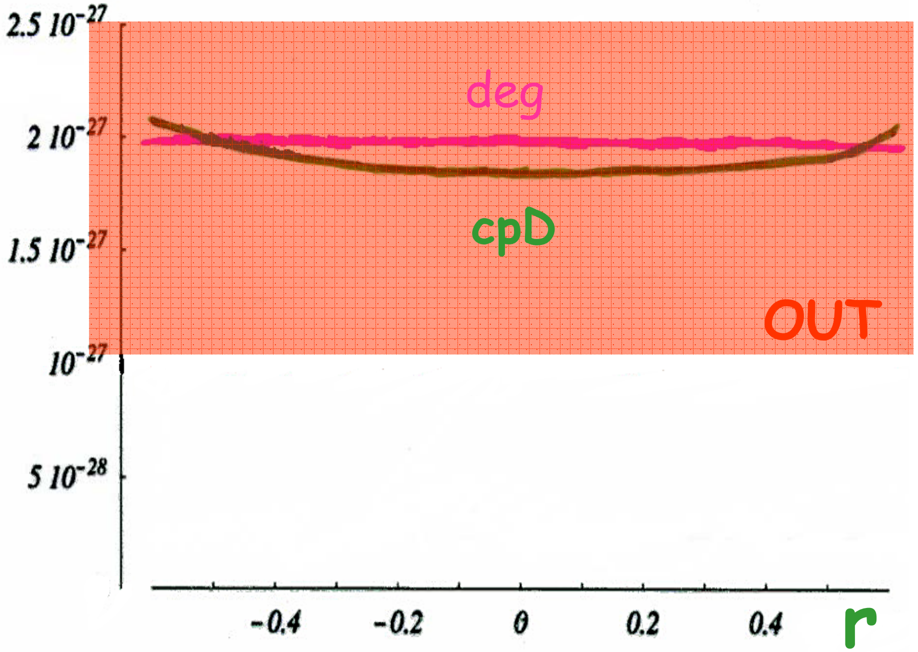
τ_p [yrs]



(ambiguity due to phases of GUT origin)

d_e [ecm]

With (naturally) O(1) phase:



Complementary in constraining SUSY GUTs

Outlook

I. Masina

EDMs are effective probes of TeV-scale NP beyond SM
in particular SUSY

Even thought it is interesting to compare their sensitivities by considering just ONE CPV source (like Argμ in SUSY) in general EDMs probe many different CPV sources

➡ This is the case for RGE-induced LEDMs
where CPV sources are Heavy State's Yukawas

See-Saw: EDMs generically below exp sensitivity
GUTs: EDMs possibly at hand

Planned EDM exp's have a strong impact on susy/seesaw/GUTs