Proposal to measure the muon electric dipole moment with a compact storage ring at PSI

Klaus Kirch

in collaboration with

A. Adelmann, G. Onderwater*, T. Schietinger, A. Streun

PAUL SCHERRER INSTITUT

PSI

*Rijksuniversiteit Groningen

Seattle, March 2007

Contents

- **Lepton dipole moments**
- **Muon spin precession in *B* and *E* fields**
- **Measurement of $(g–2)_\mu$ and μEDM at storage rings**
- **Motivations to go below 10^{-19} *e cm***
- **The "frozen spin" technique**
- **A possible layout for PSI**
- **Sensitivity estimate**
- **Status of the project**

Lepton dipole moments

Hamiltonian: $$\mathcal{H} = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E} \qquad \vec{\mu},\vec{d}\,||\,\vec{\sigma}$$

Define *g* and η as dimension-less quantities describing magnetic and electric dipole moments, respectively:

$$\mu = \frac{g}{2}\frac{e\hbar}{2m} \qquad d = \frac{\eta}{2}\frac{e\hbar}{2mc}$$

For a Dirac particle (i.e. lepton):
g = 2 (+ corrections) and
η = 0 (+ super-tiny corrections from CP-violating interactions)

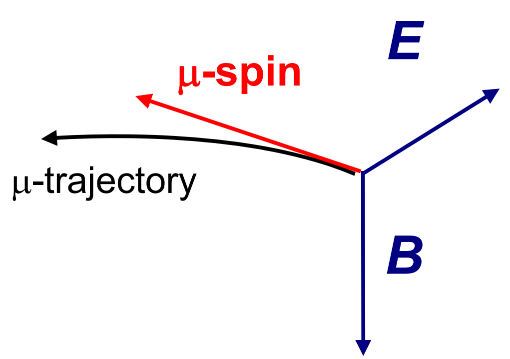
⇨ convenient to define: $$\mu = (1+a)\frac{e\hbar}{2m} \qquad a = \frac{g-2}{2}$$

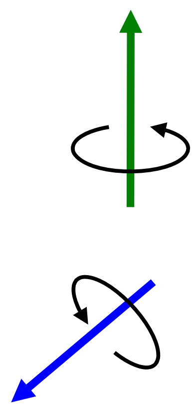
Muon spin precession in *B* and *E* field

Muon spin precession in the presence of *B* and *E* field,
perpendicular to each other and to the muon momentum:

$$\vec{\omega} = -\frac{e}{m}\left\{ \underbrace{a\vec{B} + \left(\frac{1}{1-\gamma^2} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}}_{\vec{\omega}_a} + \underbrace{\frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)}_{\vec{\omega}_e} \right\}$$

Example:
B-field pointing down,
E-field radially outward:





$\vec{\omega}_a$: spin precession in orbital plane
("*g*–2" precession)

$\vec{\omega}_e$: spin precession out of orbital plane

$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_e$ tilts the precession plane out of the orbital plane

Muon spin precession in *B* and *E* field

$$\vec{\omega} = -\frac{e}{m}\left\{ a\vec{B} + \left(\frac{1}{1-\gamma^2} - a\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right\}$$

$\vec{\omega}_a$ $\vec{\omega}_e$

Strategy for (recent) *g*–2 measurement at storage rings:

- run at **"magic γ"**, $\gamma = 29.3$ ($p_\mu = 3.1$ GeV)

  □ no effect from electric fields, can use **electric focusing**
  (need for uniform *B* field precludes magnetic focusing)

- assume η small for measurement of a
  direct access to a if *B* is known

$$\vec{\omega} = -\frac{e}{m}a\vec{B}$$

- look for small vertical oscillation to put a limit on η.
  - All recent limits have been obtained in this way (CERN, Brookhaven)
  - Plagued by systematics: *g*–2 precession interferes strongly!

μEDM at g–2 storage rings

- Search for a **vertical oscillation signal** in *g*–2 data (vertical segmentation of some of the electron detectors)

- Seriously limited by two effects:

  1) ***g*–2 rotation** of spin strongly suppresses the effect of ω_e

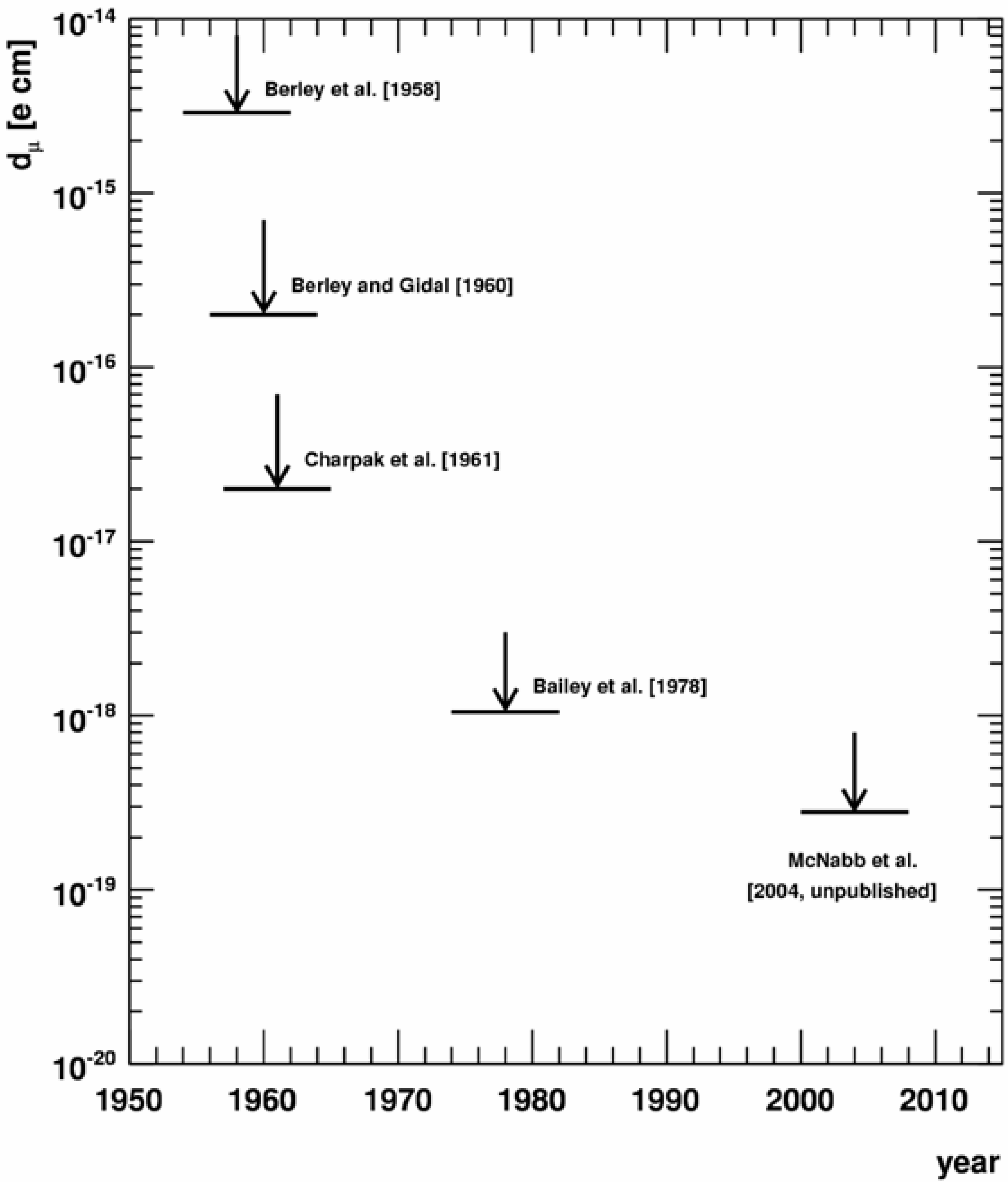
  2) **Trajectories** of the decay electrons are **very different** at the two extremes of vertical oscillation, leading to large systematic effects.

- Best current limit from **Brookhaven E821**: $d_\mu < 2.4 \times 10^{-19}\ e\ \mathrm{cm}$

  R. McNabb et al.:
  hep-ex/0407008, unpublished

  – Only preliminary, but soon to be published (L. Roberts).

  – Only **modest improvement** with respect to previous (CERN) experiment.



History of *μEDM* measurements

D. Berley et al.,
Phys. Rev. Lett. 1 (1960) 144

D. Berley, G. Gidal,
Phys. Rev. 118 (1960) 1086

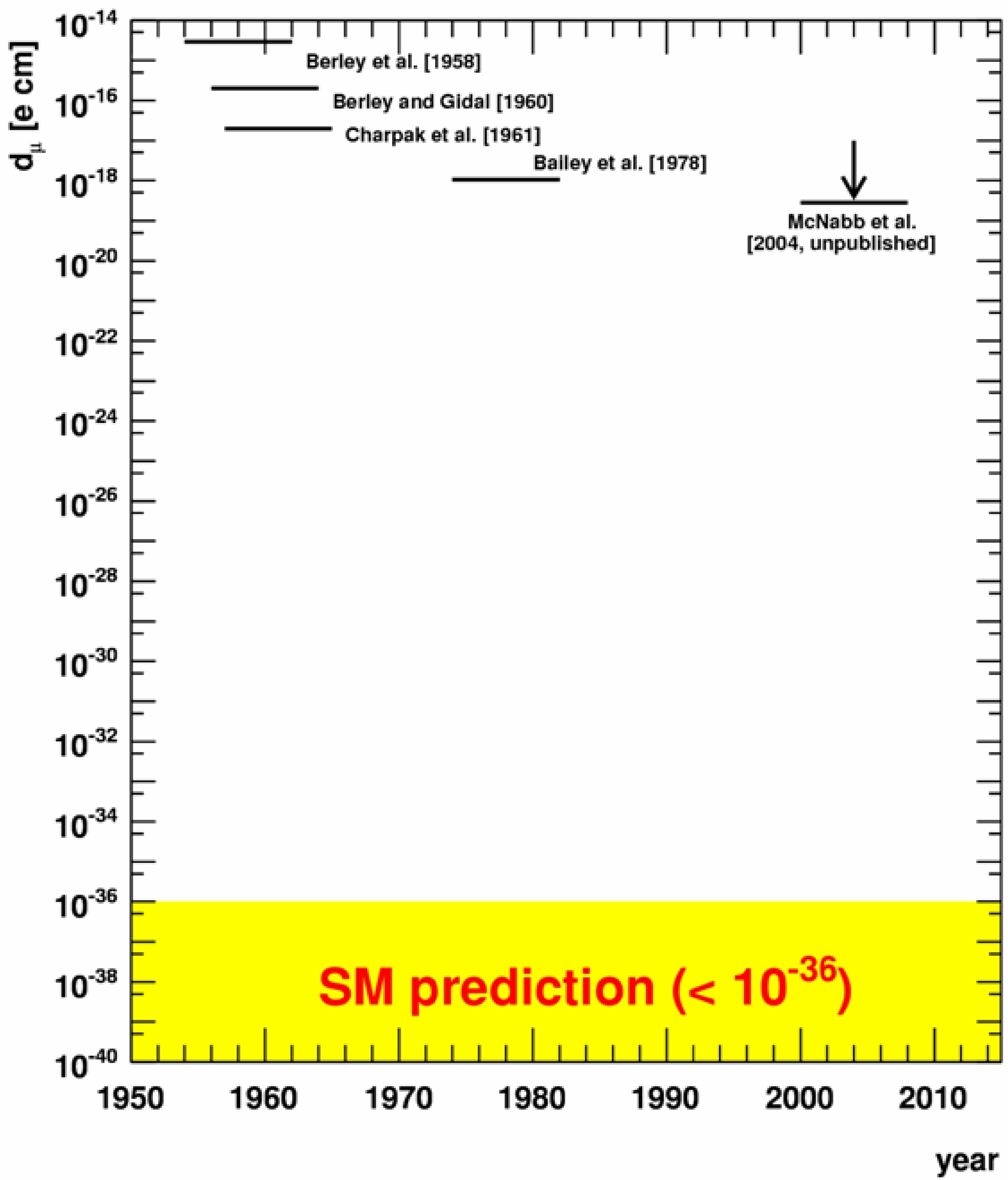
G. Charpak et al.,
Nuovo Cim. 22 (1961) 1043

J. Bailey et al.,
J. Phys. G: Nucl. Phys. 4 (1978) 345

R. McNabb et al.,
hep-ex/0407008, unpublished

Stalling progress with conventional storage ring method...

… need new method,
but first look at motivations



What is the motivation to go below 10^{-19} e cm?

Various:

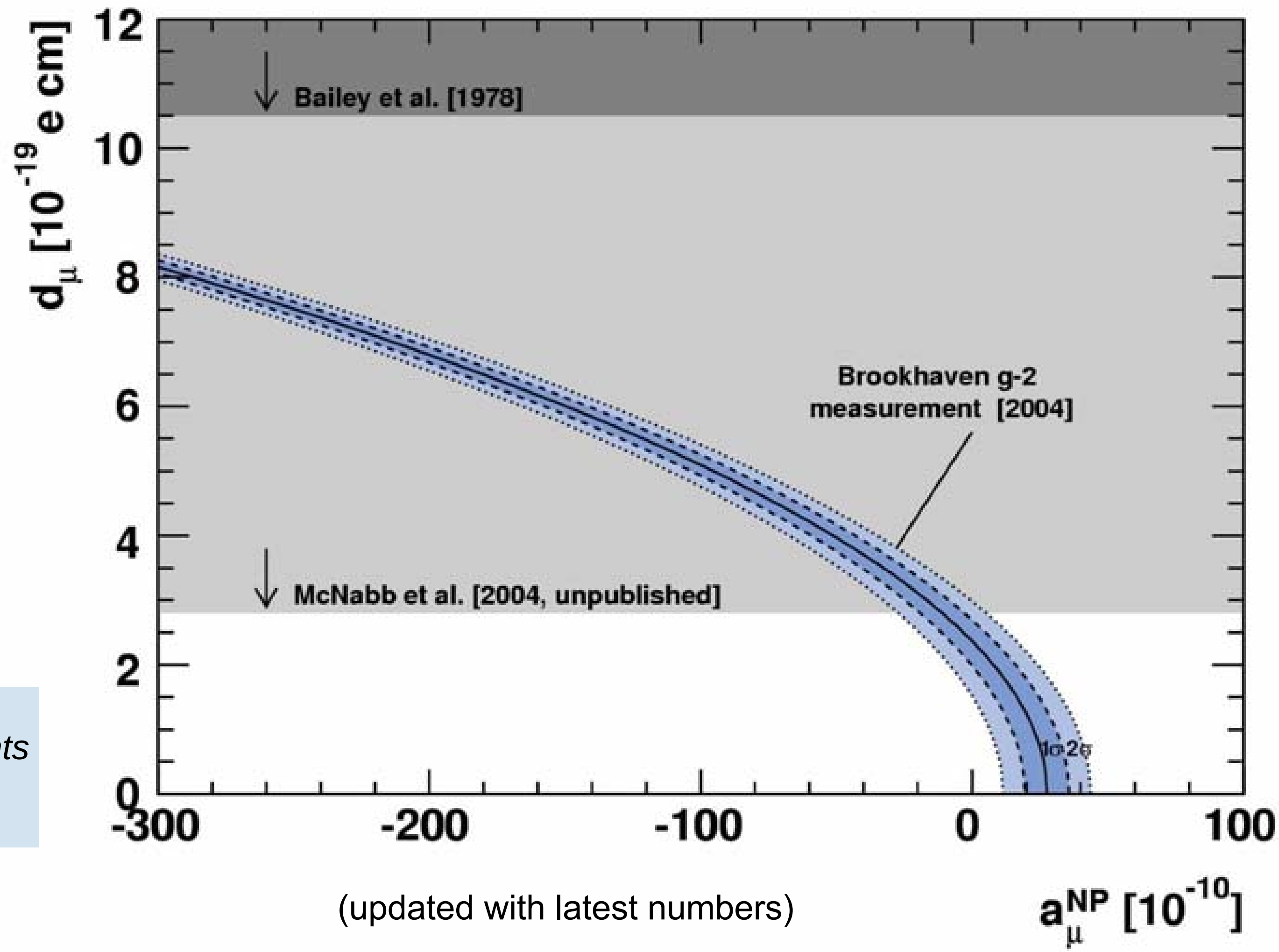
- model independent …
- model dependent …
- forget models …

The g–2 anomaly isn't?

J. Feng, T.M. Matchev, Y. Shadmi:
The Measurement of the Muon's Anomalous Magnetic Moment Isn't,
Phys. Lett. B 555 (2003) 89

$$\omega_{\text{obs}} = \sqrt{\omega_a^2 + \omega_e^2}\ !$$

See already: **J. Bailey et al.:**
New limits on the electric dipole moments of positive and negative muons,
J. Phys. G: Nucl. Phys. 4 (1978) 345



(updated with latest numbers)

Generic new-physics dipole moment

If one assumes that both non-SM MDM (a_μ^{NP}) and EDM (d_μ) are manifestations of the same **new-physics object:**

$$a_\mu^{\mathrm{NP}} \frac{e}{2m_\mu} = \mathrm{Re}D \quad \text{and} \quad d_\mu^{\mathrm{NP}} = \mathrm{Im}D$$

with D a **general dipole operator** (W. Marciano),

$$D = |D| \exp(i\phi_{\mathrm{CP}})$$

then the Brookhaven measurement can be interpreted as

$$d_\mu^{\mathrm{NP}} = 2.7 \times 10^{-22} e\,\mathrm{cm} \frac{a_\mu^{\mathrm{NP}}}{27.6 \times 10^{-10}} \tan\phi_{\mathrm{CP}}$$

i.e. either d_μ is **of order 10^{-22} e cm**,
or the CP phase is strongly suppressed!

J.L. Feng, K.T. Matchev, Y. Shadmi:
Theoretical Expectations for the Muon's Electric Dipole Moment,
Nucl. Phys. B 613 (2001) 366

PAUL SCHERRER INSTITUT PSI

Model-specific predictions

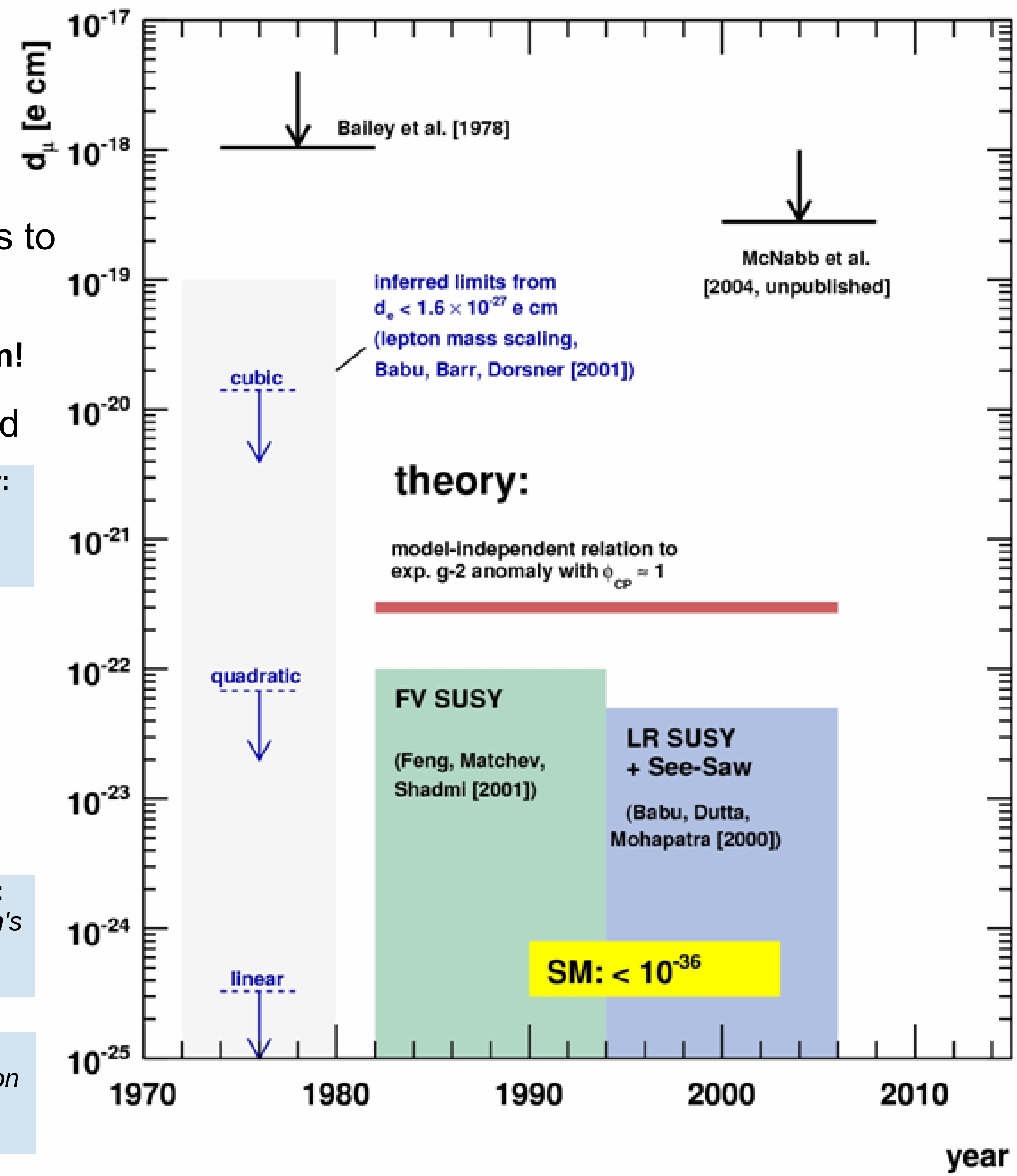
- Most reasonable models predict lepton EDMs to scale **linearly with mass**.
  - Strong bound on d_μ from $d_e < 1.6 \times 10^{-27}$ *e* cm!
- Some models, however, predict quadratic and cubic mass scaling

K.S. Babu, S.M. Barr, I. Dorsner:
Scaling of lepton dipole moments with lepton mass,
Phys. Rev. D 64 (2001) 053009

- Some SUSY variants can give up to 10^{-22} *e* cm, but this involves a lot of tuning
  - Flavour-violating SUSY a good candidate (but new Belle bound on $\tau \to \mu\gamma$ probably has a severe impact)

J.L. Feng, K.T. Matchev, Y. Shadmi:
Theoretical Expectations for the Muon's Electric Dipole Moment,
Nucl. Phys. B 613 (2001) 366

K.S. Babu, B. Dutta, R.N. Mohapatra:
Enhanced Electric Dipole Moment of the Muon in the Presence of Large Neutrino Mixing,
Phys. Rev. Lett. 85 (2000) 5064



Muon spin precession in *B* and *E* field

$$\vec{\omega} = -\frac{e}{m}\left\{a\vec{B} + \left(\frac{1}{1-\gamma^2} - a\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right\}$$

(The first two terms, $\vec{\omega}_a$, are crossed out; the last term is $\vec{\omega}_e$.)

New method for EDM measurement: the "frozen spin" technique!

- Go to lower momentum, install a **"magic *E* field"** (radially), such that ω_a vanishes completely: $E \approx aBc\beta\gamma^2$
- The spin remains parallel to the momentum along the orbit ("frozen spin")
- In the presence of an EDM ($\eta\neq0$) the spin is slowly rotated out of the orbital plane.
- **Much superior sensitivity** than with parasitic approach!

$$\vec{\omega} = -\frac{e}{m}\frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)$$

F. Farley et al.:
New Method of Measuring Electric Dipole Moments in Storage Rings,
Phys. Rev. Lett. 93 (2004) 052001

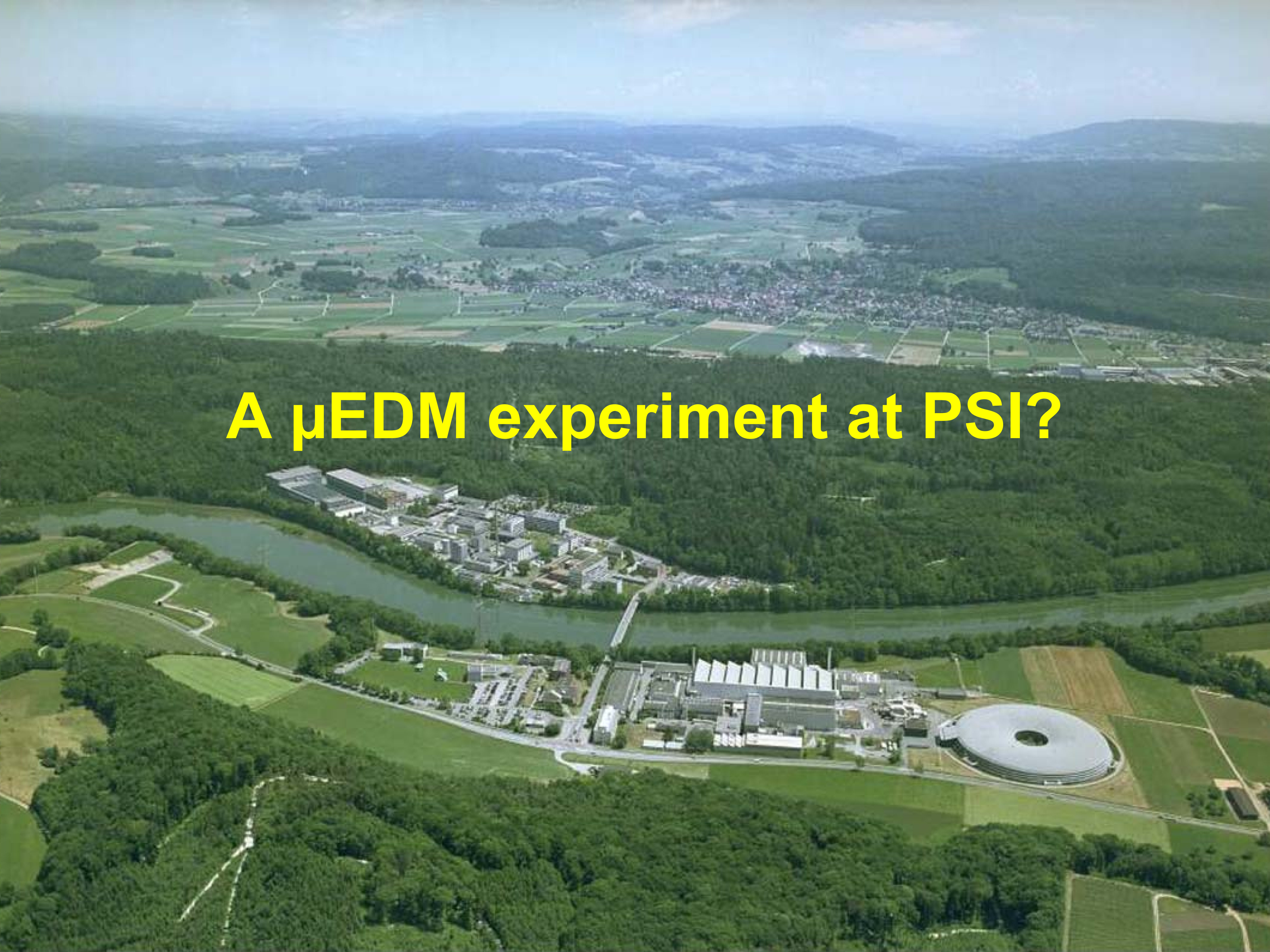
J-PARC letter of intent

A. Silenko et al.:
J-PARC Letter of Intent: Search for the Permanent Muon Electric Dipole Moment at the 10^{-24} e cm Level.

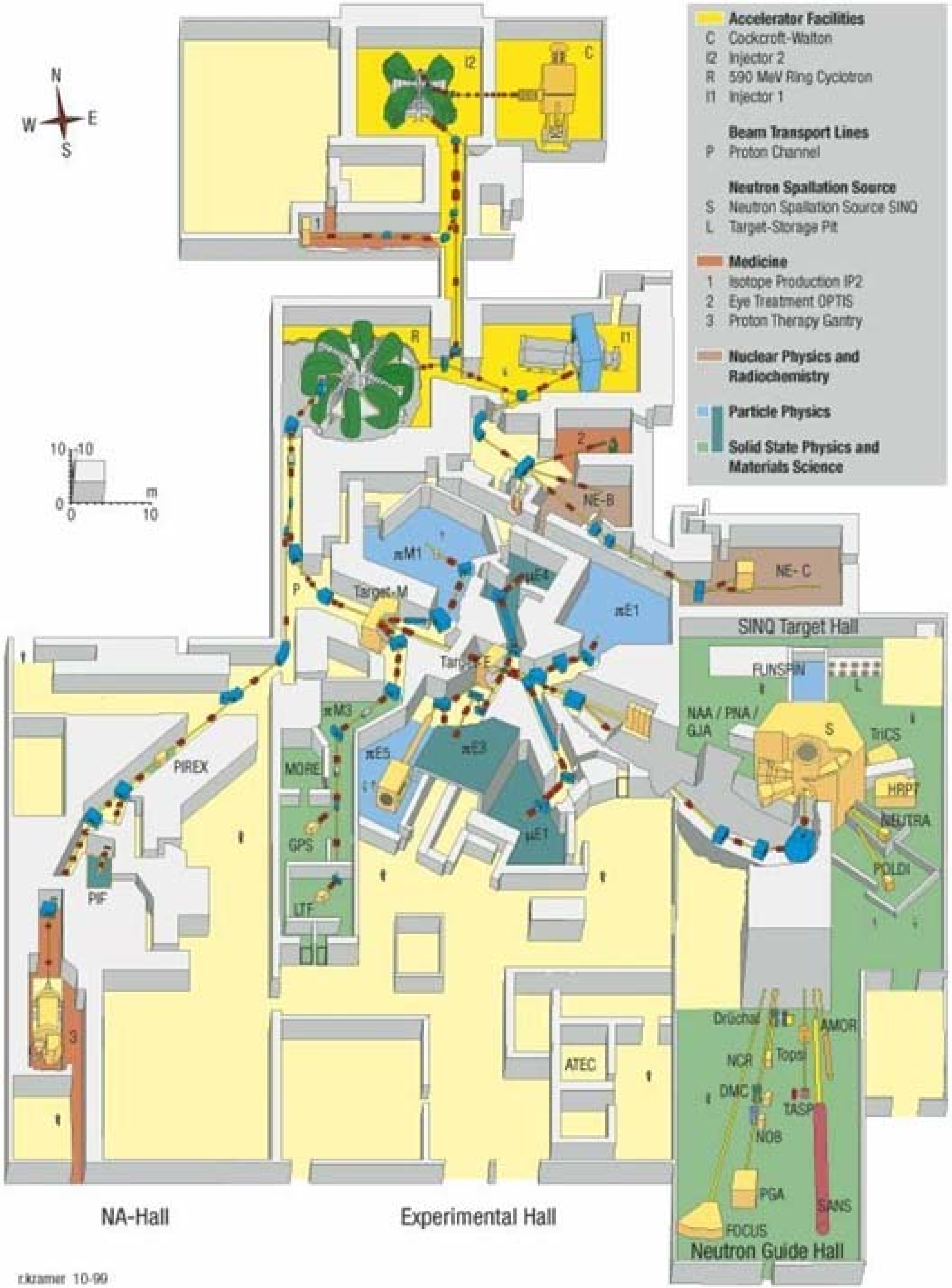
- Semertzidis, Farley et al. in 2003 proposed an experiment exploiting the frozen spin technique at **J-PARC** (PRISM-II FFAG).
- Design: **7-m radius ring**, with B = 0.25 T, E = 2 MV/m and p = 500 MeV/c ($\gamma\tau$ = 11 μs).

- Estimated sensitivity is around **10^{-24} e cm**
- So far a "virtual project", realization not likely before 2015.

Could we do this at PSI with lower energy muons?

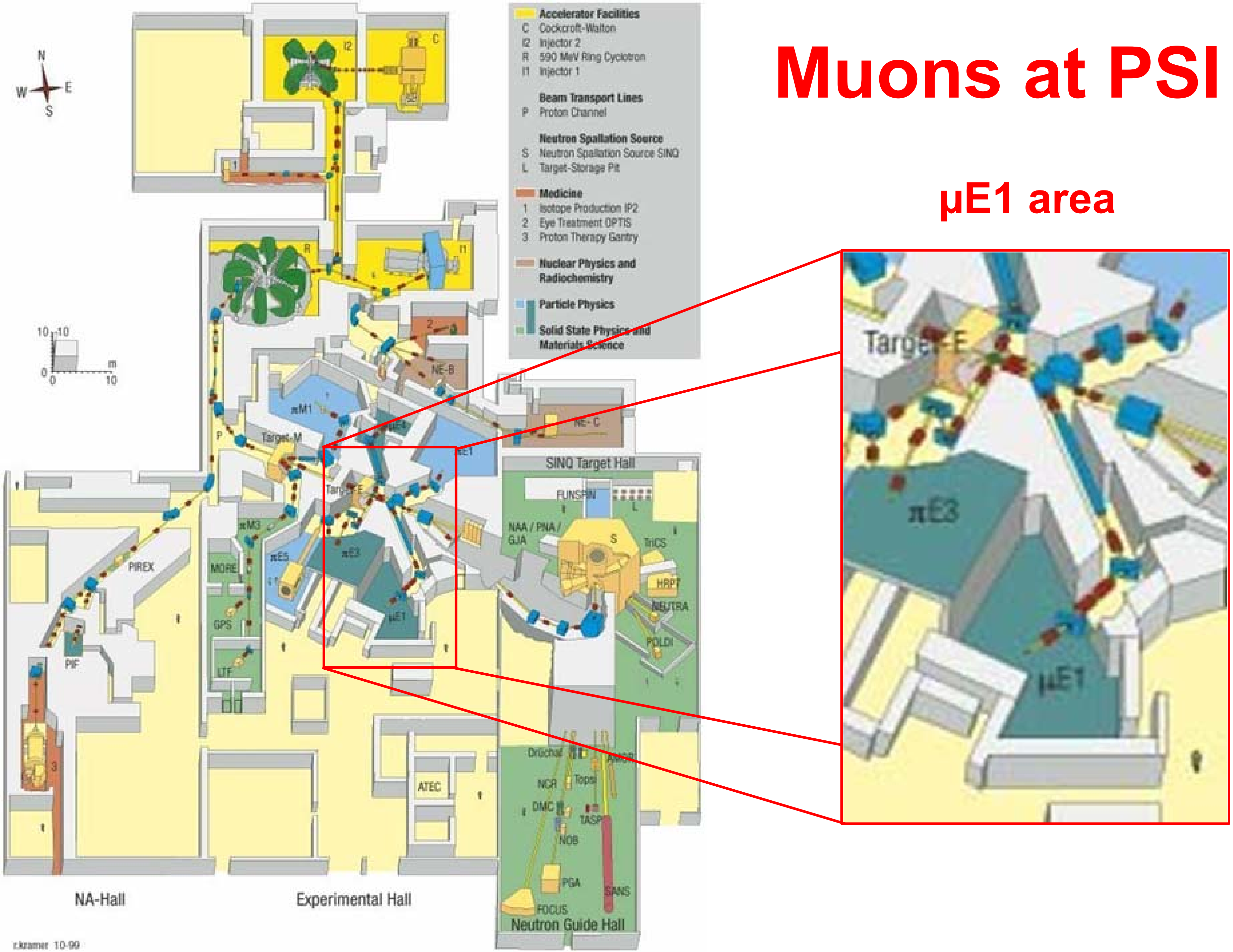

A μEDM experiment at PSI?

Muons at PSI



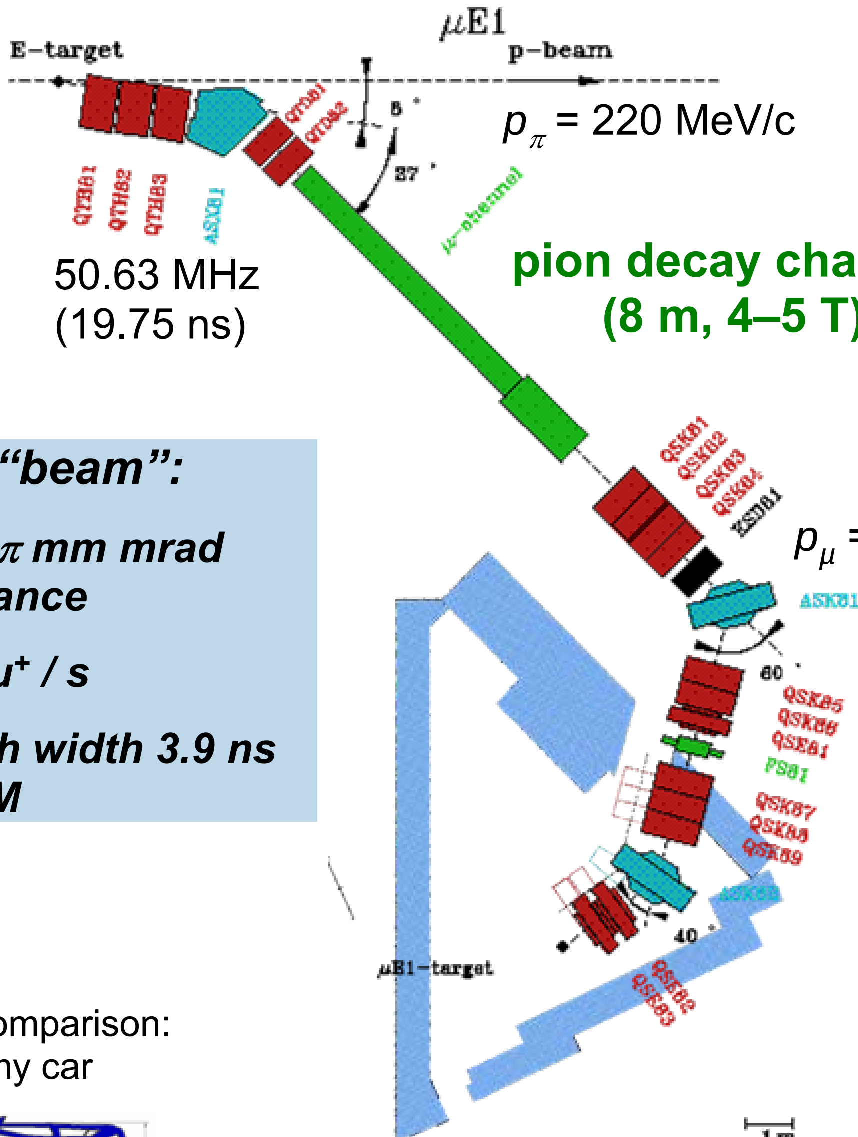
Accelerator Facilities
C Cockcroft-Walton
I2 Injector 2
R 590 MeV Ring Cyclotron
I1 Injector 1
Beam Transport Lines
P Proton Channel
Neutron Spallation Source
S Neutron Spallation Source SINQ
L Target-Storage Pit
Medicine
1 Isotope Production IP2
2 Eye Treatment OPTIS
3 Proton Therapy Gantry
Nuclear Physics and Radiochemistry
Particle Physics
Solid State Physics and Materials Science
NE-B
NE-C
SINQ Target Hall
πM1
Target-M
πE1
πE4
Target-E
πM3
πE5
πE3
μE1
PIREX
MORE
GPS
LTF
PIF
FUNSPIN
NAA / PNA / GJA
TriCS
HRPT
NEUTRA
POLDI
Drüchal
AMOR
NCR
Topsi
DMC
TASP
NOB
PGA
SANS
FOCUS
ATEC
NA-Hall
Experimental Hall
Neutron Guide Hall
r.kramer 10-99

Muons at PSI

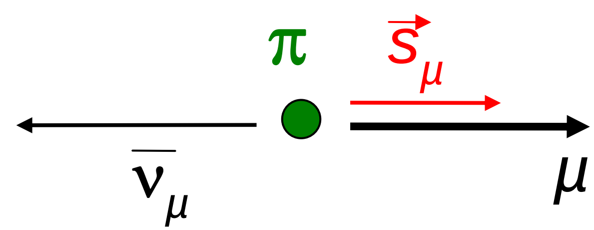


Accelerator Facilities
C Cockcroft-Walton
I2 Injector 2
R 590 MeV Ring Cyclotron
I1 Injector 1
Beam Transport Lines
P Proton Channel
Neutron Spallation Source
S Neutron Spallation Source SINQ
L Target-Storage Pit
Medicine
1 Isotope Production IP2
2 Eye Treatment OPTIS
3 Proton Therapy Gantry
Nuclear Physics and Radiochemistry
Particle Physics
Solid State Physics and Materials Science
N
W
E
S
Target-M
Target-E
SINQ Target Hall
NE-B
NE-C
PIREX
PIF
MORE
GPS
LTF
ATEC
FUNSPIN
NAA / PNA / GJA
TriCS
HRPT
NEUTRA
POLDI
Drüchal
NCR
DMC
Topsi
TASP
NOB
PGA
SANS
FOCUS
NA-Hall
Experimental Hall
Neutron Guide Hall
r.kramer 10-99
μE1 area
πE3
μE1

μE1 beamline and area



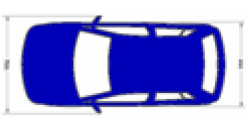
Existing infrastructure



Muon "beam":

- ***~400 π mm mrad emittance***
- ***~10^8 μ^+ / s***
- ***Bunch width 3.9 ns FWHM***

For comparison:
my car



I.C. Barnett et al. :
Nucl. Instr. and Meth. A 455 (2000) 329;
also: http://ltp.web.psi.ch

Concept for an experiment at PSI

Apply frozen spin technique at **lower momentum** than JPARC:

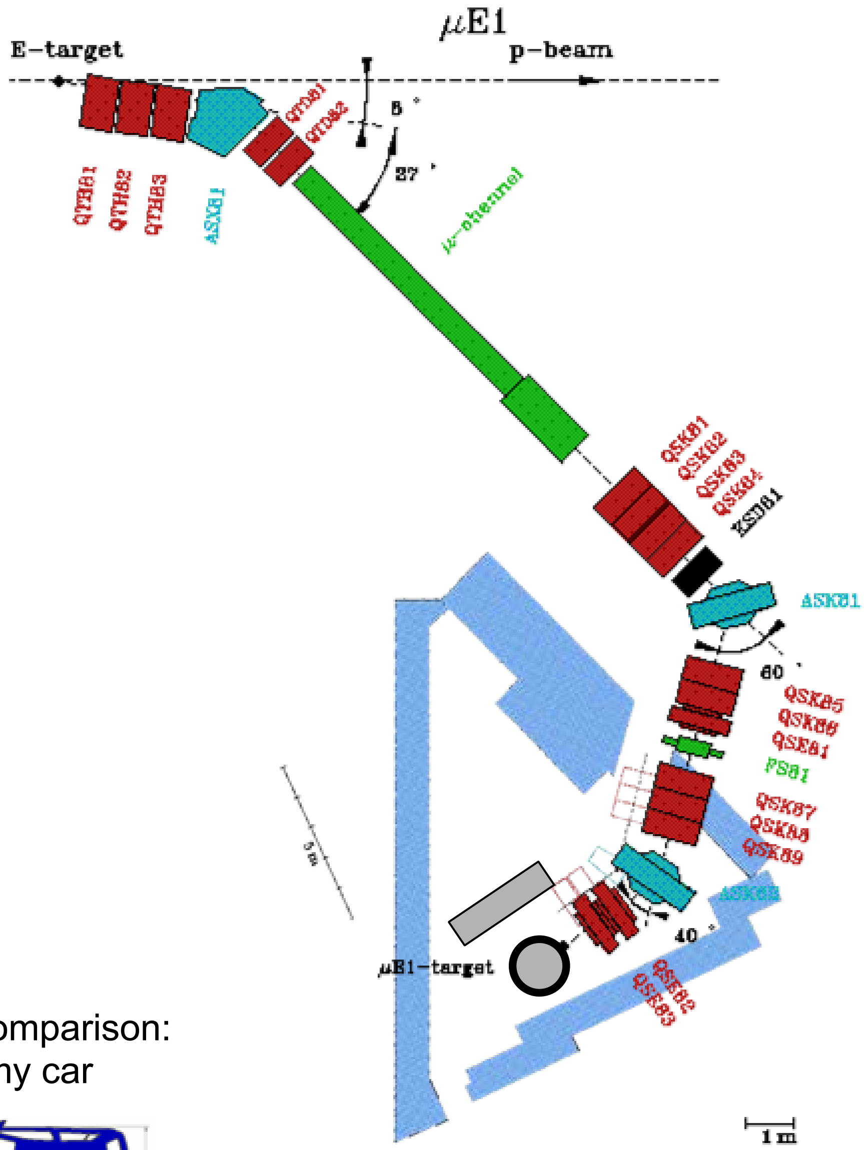
- *PSI μE1:* p_μ=125 MeV/c (β = 0.76, γ= 1.55), P_μ = 92%
- Choose B = 1 T (conventional magnet, straightforward change of polarity)

  ⇨ **42 cm orbit radius**, radial E-field 0.64 MV/m (64kV/10cm gap).

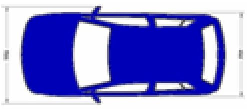
Trade off high intensity of muon beam for **beam quality**, selecting the muons to be injected into the ring:

- Reduce from 100 MHz to ~200 kHz
- **One muon at a time!** Average measurement time $\approx \gamma\tau_\mu$ = 3.4 μs.
- Assume run-time of 2 × 10^7 s, times 200 kHz gives 4 × 10^{12} electron decays (per year)
- Clockwise and counter-clockwise operation (systematics)
- Positively and negatively charged muons can be injected (systematics)

μE1 beamline and area

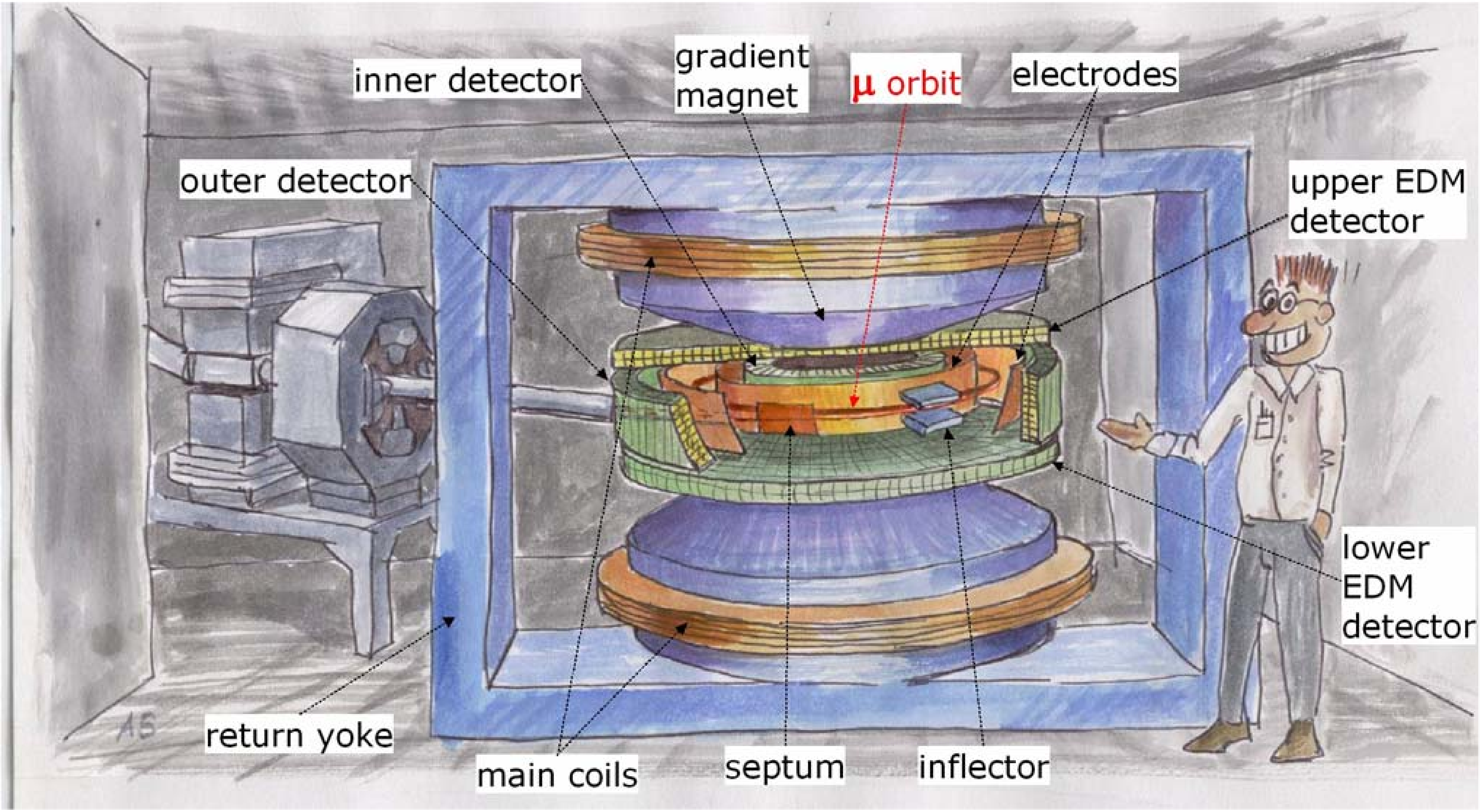


For comparison: my car



A ~1-m-diameter storage ring with support fits in comfortably

Artist's impression (A. Streun)



Sensitivity estimate

F. Farley et al.:
New Method of Measuring Electric Dipole Moments in Storage Rings,
Phys. Rev. Lett. 93 (2004) 052001

Uncertainty on η from a simple asymmetry counting experiment with *N* decays:

$$\sigma_\eta = \frac{\sqrt{2}}{\gamma\tau(e/m)\beta BAP\sqrt{N}}$$

$$d_\mu = \frac{\eta}{2}\frac{e\hbar}{2m_\mu c} \simeq \eta \times 4.7 \times 10^{-14} e\,\mathrm{cm}$$

A : electron asymmetry, assume *A* = 0.3
P : polarization of muons

J-PARC proposal: $\gamma\tau$ = 11 μs, β = 0.978, *P* = 50%, *B* = 0.25 T

⇨ $\sigma_\eta = 4 \times 10^{-3}/\sqrt{N}$; $N = 4 \times 10^{16}$ □ $\sigma_\eta = 2 \times 10^{-11}$

$d_\mu < 10^{-24}$ *e* cm

PSI proposal: $\gamma\tau$ = 3.4 μs, β = 0.76, *P* = 90%, *B* = 1.0 T

⇨ $\sigma_\eta = 2.4 \times 10^{-3}/\sqrt{N}$; $N = 4 \times 10^{12}$ □ $\sigma_\eta = 10^{-9}$

$$\sigma_\eta = \frac{\sqrt{2}ac\gamma}{\tau(e/m)EAP\sqrt{N}}$$

$d_\mu < 5 \times 10^{-23}$ e cm

PAUL SCHERRER INSTITUT PSI

Muon statistics is the dominant factor!

Main challenges

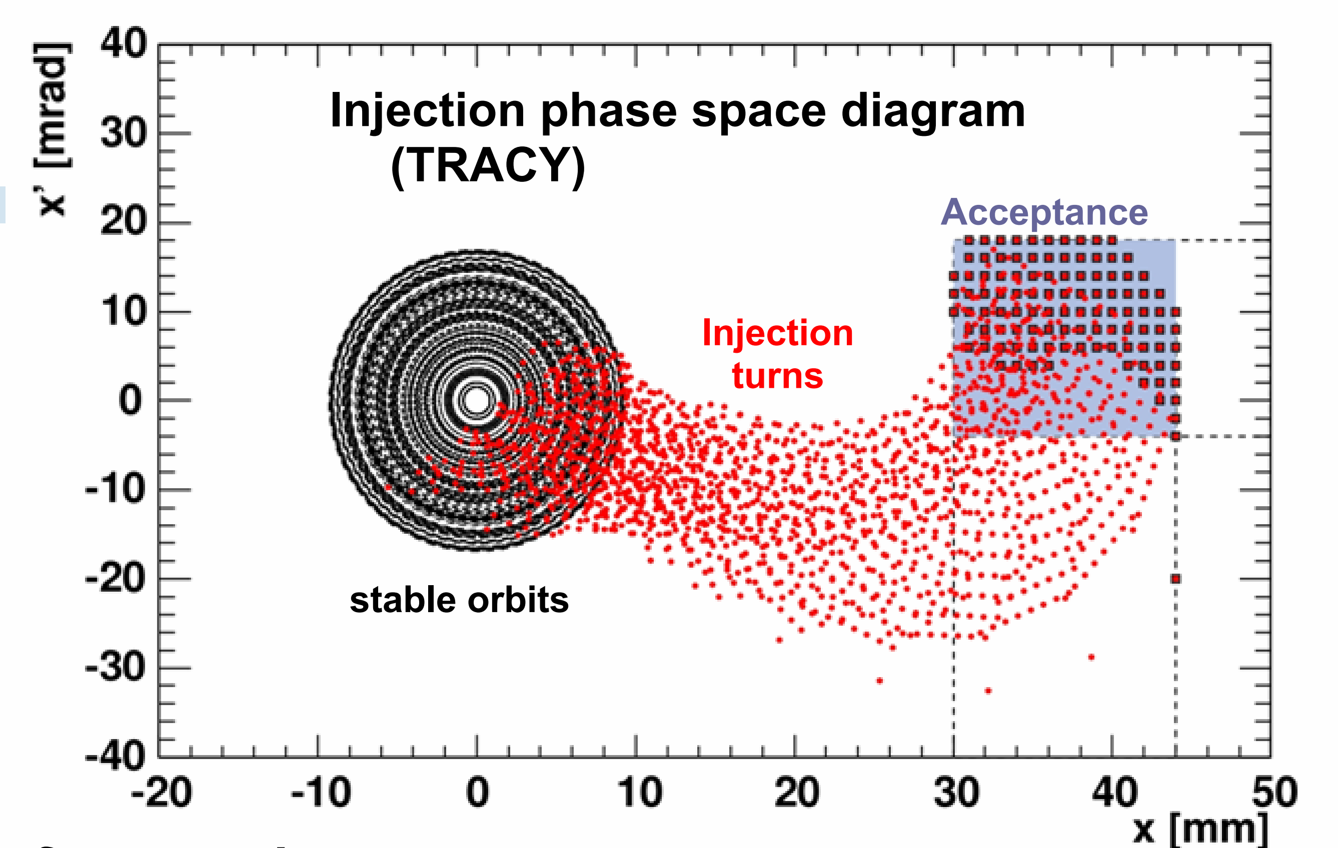
- **Injection**
  - Conventional kicker too slow, very short revolution time (11.6 ns)
  - Possible solution: **resonance injection** at half-integer tune using a non-linear field perturbator (inflector)
- **Injection trigger**
  - Minimal latency between detection of “good muon” and ramp-up of inflector
- ***E, B*-field setup, alignment and control**
- **Detector**
  - *E, B*-field, limited space, systematics issues
- **Data processing / storage**
  - O(10^{12}) muon decays, almost all of them carry interesting information

Injection study for µEDM project

- *Andreas Adelmann, using TRACY program*

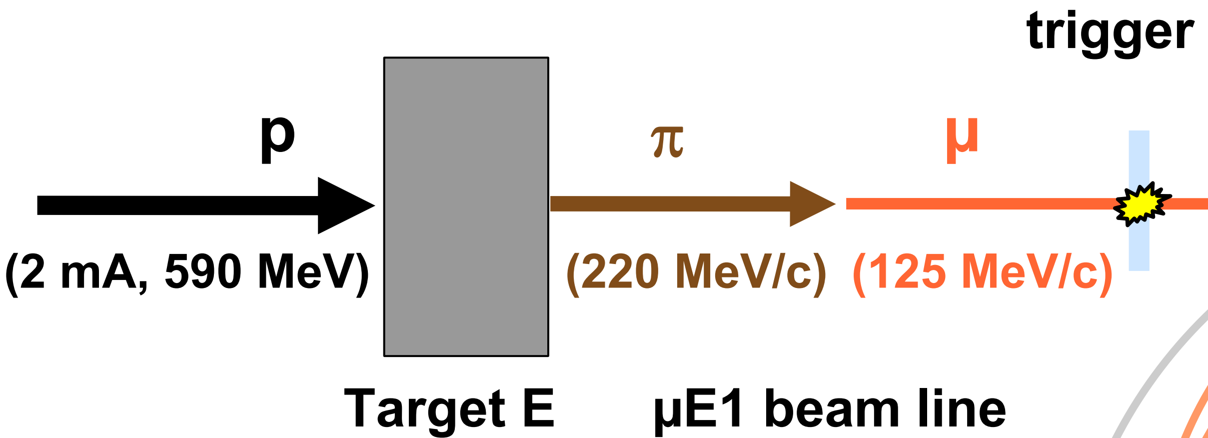
  http://slsbd.psi.ch/pub/slsnotes/tmeta9902/

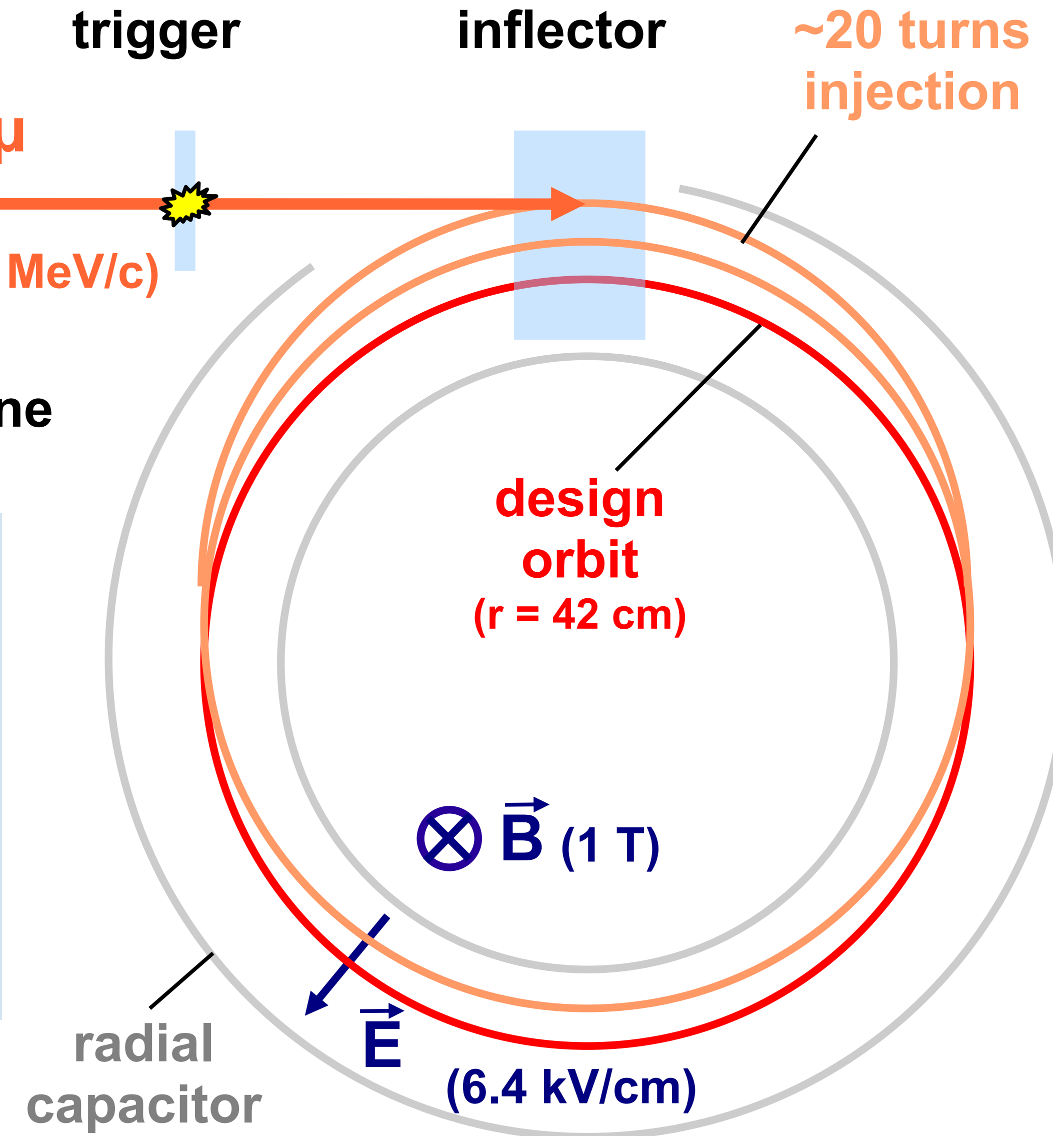
- *20 turns ramp of non-linear perturbator*
- *Acceptance ±7 mm / ±11 mrad, average latency for acceptable µ: ~1.2 µs*
- *Average measurement time $\gamma\tau_\mu$= 3.4 µs*



- *~200 kHz repetition rate for perturbator*
  - *Challenging, in particular for "random" ramp-up*
  - *Can we trigger the perturbator in time to catch the "good" muon?*

Beam schematic





- *Pions produced in thick target*
- *Capture muons from backward decay of pions   polarized muons (P_μ = 92%)*
- *Upon "good muon"-trigger, inflector ramps down non-linear perturbation field over a period of 20 turns*
- *Resonance injection at half-integer*

Various systematics issues...

- **Vertical *E* field** component: $E_\perp < 10^{-4} E_{rad}$.
- Rotational **misalignments** and residual *g*–2 precession
- **Instabilities** of *E*, *B* fields, detector,...

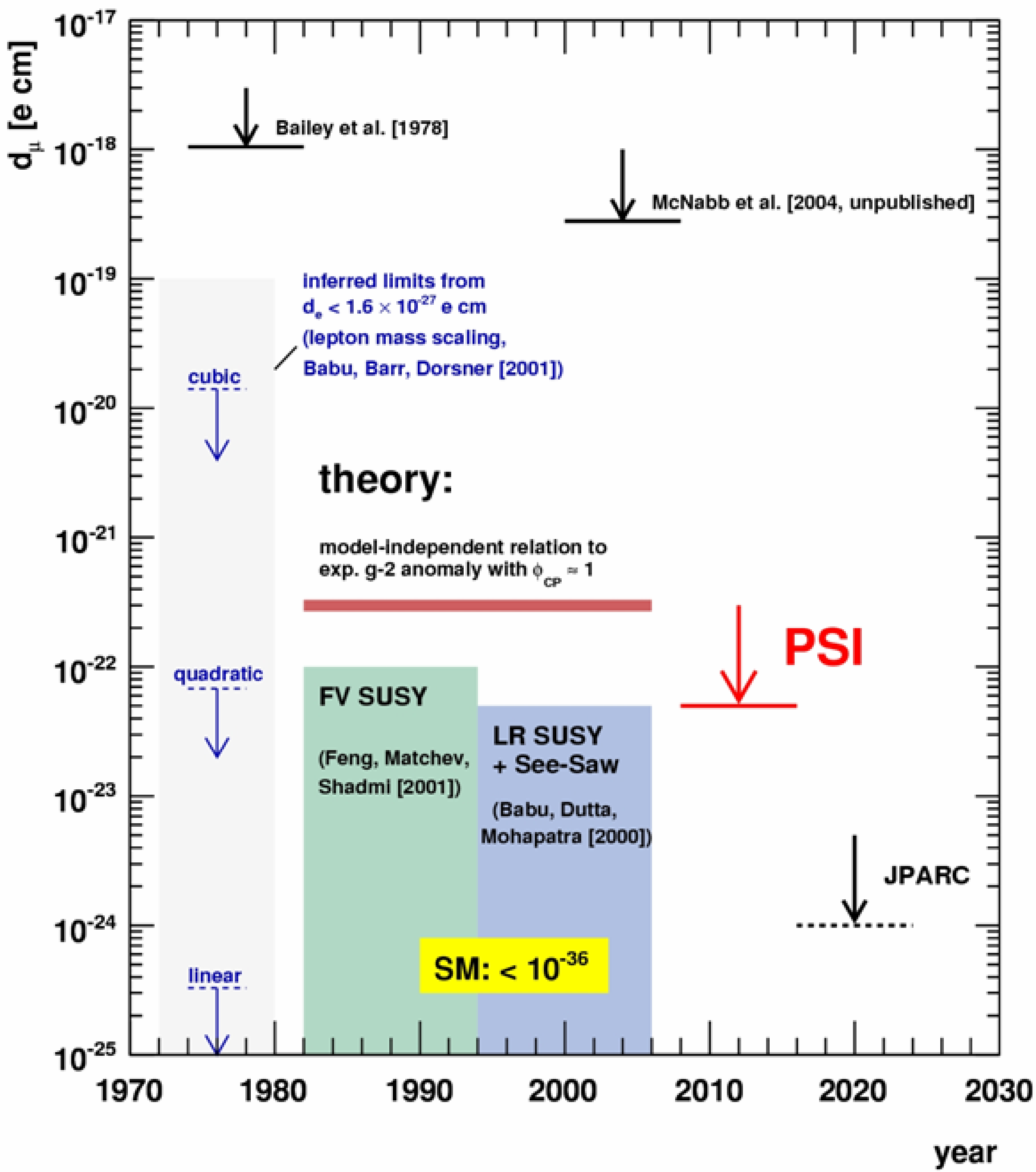
...but many ways to control them:

- Injection of μ^+ and μ^-
  - Factor 3 less statistics for μ^-
- Clockwise and counter-clockwise orbit
- *g*–2 precession for calibration
- Spin rotation?

F. Farley et al.:
New Method of Measuring Electric Dipole Moments in Storage Rings,
Phys. Rev. Lett. 93 (2004) 052001

Impact of a PSI measurement

- Rule out (or confirm) EDM explanation for Brookhaven MDM anomaly
- Rule out (or confirm) naïve relation between new physics MDM and EDM for the case $\phi_{CP} \approx 1$.
- Explore the region down to 5 **× 10^{-23} e cm**
- **... long before J-PARC** (or anyone else) can get there.
- Proof of principle for new technique at relatively low cost



Current status of the project

- Paper presenting the compact storage ring method in more detail is in preparation (follow-up of arXiv:hep-ex/0606034).
- **Poster presentation** at PSI workshop (pmle.web.psi.ch) was **met with enthusiasm:**
  - C. Petitjean: **“the highlight of the workshop”**
  - K. Jungmann: “for just 0.25% of its annual budget, PSI could have a **profound impact on muon physics**”
- PSI management encourages submission of LOI, however clear priority for MEG and nEDM. Need strong external collaborators.
- Strong interest to collaborate from
  - **Boston** (Lee Roberts, see g2pc1.bu.edu/~roberts/muonEDM/index.html)
  - **Groningen** (Gerco Onderwater)
  - Others !?
- Next steps:
  - Look for interested parties world wide (and in particular from Switzerland)
  - **Meeting at PSI** envisaged for **June 07**
  - With a **proto-collaboration**, we envisage writing a **LOI** for the next PSI user meeting (02/2008).

Thanks …

- ➔ for your attention !
- ➔ to my collaborators from PSI and Groningen: Andreas Adelmann, Gerco Onderwater, Thomas Schietinger, Andreas Streun
- ➔ to Thomas Schietinger who created many of the transparencies; for a longer talk by him, see: g2pc1.bu.edu/~roberts/muonEDM/index.html
- ➔ for various input and fruitful discussions with Francis Farley, Klaus Jungmann, Jim Miller, Lee Roberts, Stefan Ritt, Yannis Semertzidis, …

… **and** maybe you want to get involved ?