2 March 2017
PBC meeting, CERN

PBC EDM subgroup

Yannis Semertzidis, CAPP/IBS and KAIST

Proton, deuteron, muon, ^{3}He (n-equivalent)

- Storage ring p,d EDMs @ $<10^{-29}$ e-cm level
- Probing New Physics ~10^3-10^4 TeV

- Storage ring EDMs: Great probe of New Physics AND θ_{QCD}

Core members

- Mike Lamont (CERN)
- Gianluigi Arduini (CERN)
- Christian Carli (CERN)
- Mei Bai (Juelich/GSI)
- Klaus Jungman (Groningen)
- YkS (CAPP/IBS & KAIST, Korea)
- Joerg Pretz (Aachen)
- Ed Stephenson (Ind. University)
- Hans Stroeher (Juelich)
- Paolo Lenisa (Ferara)
- Themis Bowcock (Liverpool), TBC

srEDM Collaboration

REVIEW OF SCIENTIFIC INSTRUMENTS **87**, 115116 (2016)

A storage ring experiment to detect a proton electric dipole moment

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JEDI

Jülich Electric Dipole Moment Investigations

≈ 100 members actual count: 126
(Aachen, Bonn, Daejeon, Dubna, Ferrara, Grenoble, Indiana, Ithaca, Jülich, Krakow, Michigan, Minsk, Novosibirsk, St. Petersburg, Stockholm, Tbilisi, . . .)
≈ 10 PhD students

Current spokespersons: **Paolo Lenisa** (INFN Ferrara), **Jörg Pretz** (FZJ)
Executive Board, PubCom, Bi-annual Collaboration Mtgs.

http://collaborations.fz-juelich.de/ikp/jedi/

JEDI

COSY at Forschungszentrum Jülich

… the only (operational) test facility for $\not{C}\not{P}$ **EDM**

JEDI & srEDM Collaborations

- Two very strong collaborations

Extensive experience in

- Hadronic physics, polarimeters
- Storage rings
- Muon g-2 systematic errors
- Polarized beams
- Beam/spin dynamics

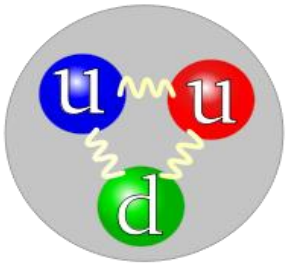
Together: CP EDM

Fundamental particle EDM: study of CP-violation beyond the Standard Model

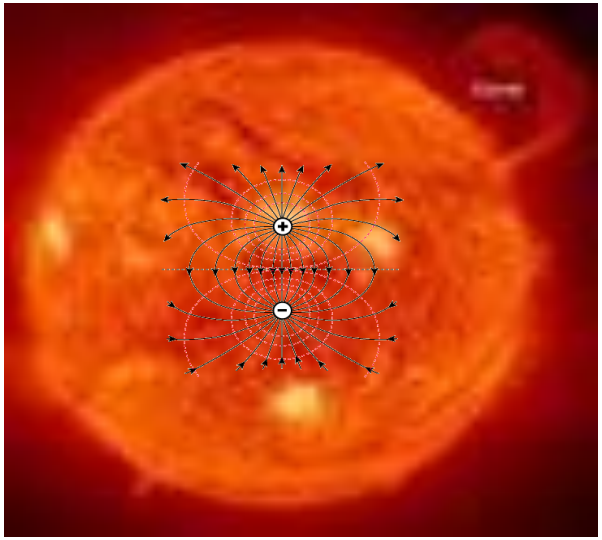
Proton EDM proposal: $d=10^{-29} e\cdot$cm

- High sensitivity experiment:
- Blowing up the proton to become as large as the sun, the sensitivity to charge separation along N-S would be r < 0.1 μm!

proton

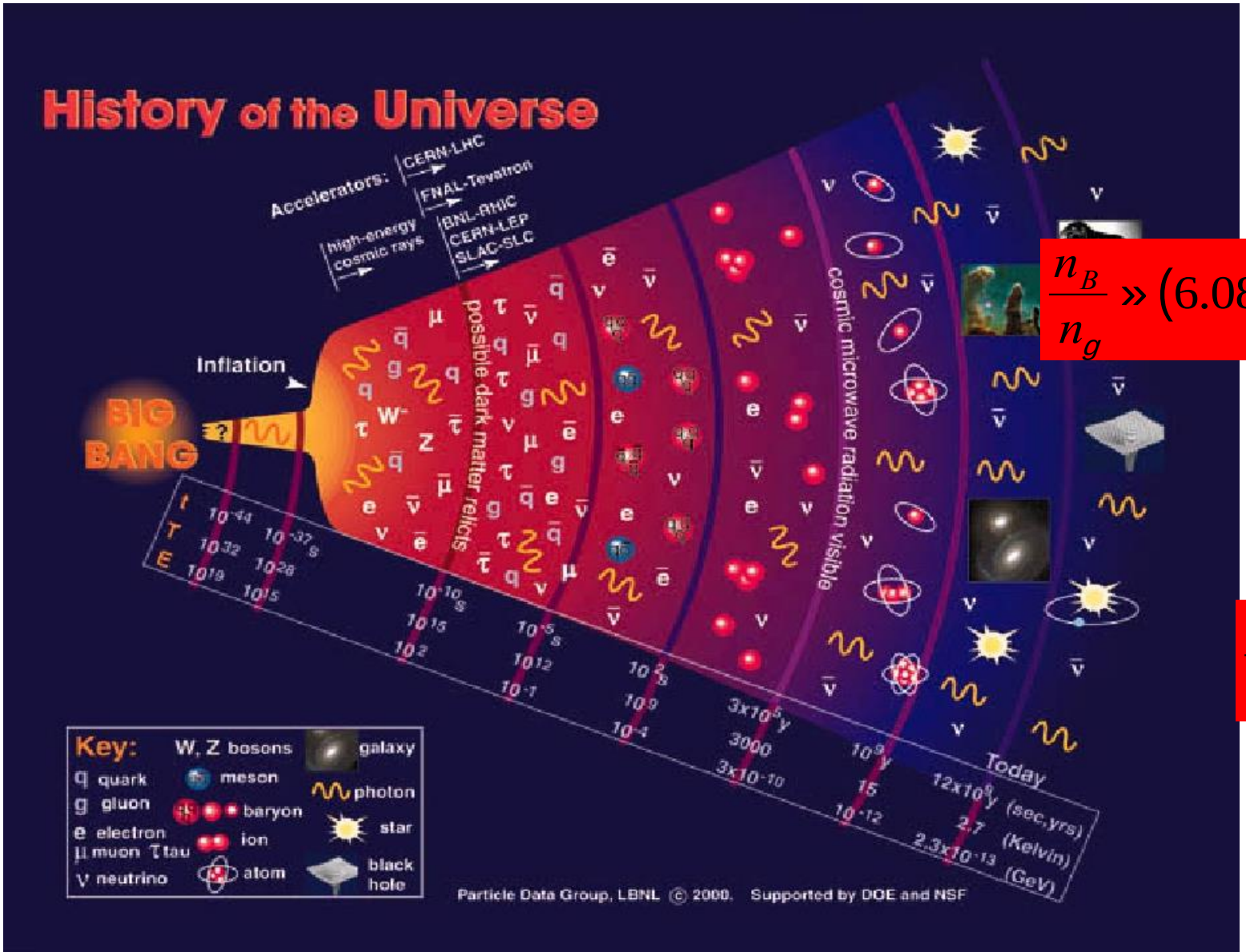


Sun



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

Why is there so much matter after the Big Bang:



We see:

$$\frac{n_B}{n_g} \approx (6.08 \pm 0.14) \times 10^{-10}$$

From the SM:

$$\frac{n_B}{n_g} \approx 10^{-18}$$

Storage Ring Electric Dipole Moments

Fields	Example	EDM term	Comments
Dipole magnetic field **(B)**	Muon g-2	Tilt of the spin precession plane. (Limited sensitivity due to spin precession)	Eventually limited by geometrical alignment. Requires CW and CCW injection to eliminate systematic errors
Combination of electric and magnetic fields **(E, B)**	Deuteron, ^{3}He, proton, etc.	Mainly: $\frac{d\vec{s}}{dt} = \vec{d} \times \left(\vec{v} \times \vec{B}\right)$	Most powerful. Small ring. Need to build combined B and E-field system. Reduce vertical E-field.
Radial Electric field **(E)**	Proton, etc.	$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$	Large ring, CW & CCW storage. Simplest to achieve. Reduce radial B-field.

What has been accomplished?

- ✓ Polarimeter systematic errors (with beams at KVI, and stored beams at COSY).
- ✓ Precision beam/spin dynamics tracking.
- ✓ Stable lattice, IBS lifetime: ~10^4s (Lebedev, FNAL)
- ✓ Spin coherence time 10^3 s; role of sextupoles understood (using stored beams at COSY).
- ✓ Feasibility of required electric field strength >10 MV/m, 3cm plate separation (JLab)
- ✓ Analytic estimation of electric fringe fields and precision beam/spin dynamics tracking. Stable!

Finishing up

- SQUID-based beam position monitors
- Magnetic field shielding: develop a cost effective mu-metal shielding
- Define the B and E-field specifications (geometrical phases)
- High efficiency precision beam/spin dynamics simulations

P5: Particle Physics Project Prioritization Panel setup by DOE and NSF. It took more than a year for the HEP community to come up with the report.

In 2014 we have received the P5 endorsement for the proton EDM experiment under all funding scenarios!

Possible candidate particles

- Proton EDM (θ_{QCD}, quark-gluon EDM)
- Deuteron EDM (T-odd nuclear forces)

- ^{3}He (equivalent to nEDM)
- Electron EDM?
- Muon EDM?

Storage ring EDM program

- Proton, Deuteron and neutron (or ^{3}He) together can help pin-point the source of CP-violation should one is found to be non-zero!

- Possible sources: θ_{QCD} or (e.g., SUSY-like) New Physics or (most likely) a combination.

- Which one first? To be decided by the experimental working group. Both is a must!

EDM status

- The EDM experiments are gearing up, getting ready:

- ^{199}Hg EDM $<10^{-29}$ e-cm sensitivity

- nEDM at PSI 10^{-26} e-cm sensitivity, 2015 - 2017
- nEDM at PSI 10^{-27} e-cm sensitivity, 2018 - …

- nEDM at SNS $\sim 2 \times 10^{-28}$ e-cm starting data taking 2021

EDM status (cont'd)

- ThO, current limit on eEDM: 10^{-28} e-cm, next $\times 10$ improvement.

- TUM nEDM effort, making progress in B-field shielding, met B-field specs. It moves to ILL in 2015, goal: 10^{-28} e-cm, staged approach, starting in 2016.
- ^{225}Ra EDM, ~5×10^{-22} e-cm now, ~3×10^{-28} e-cm w/ FRIB

- Storage ring EDM: p,dEDM goals ~10^{-29} e-cm Strength: statistics. Proton w/ upgrade ~10^{-30} e-cm

Marciano, CM9/KAIST/Korea, Nov 2014

Generic Physics Reach of $d_p \sim 10^{-29}$e-cm

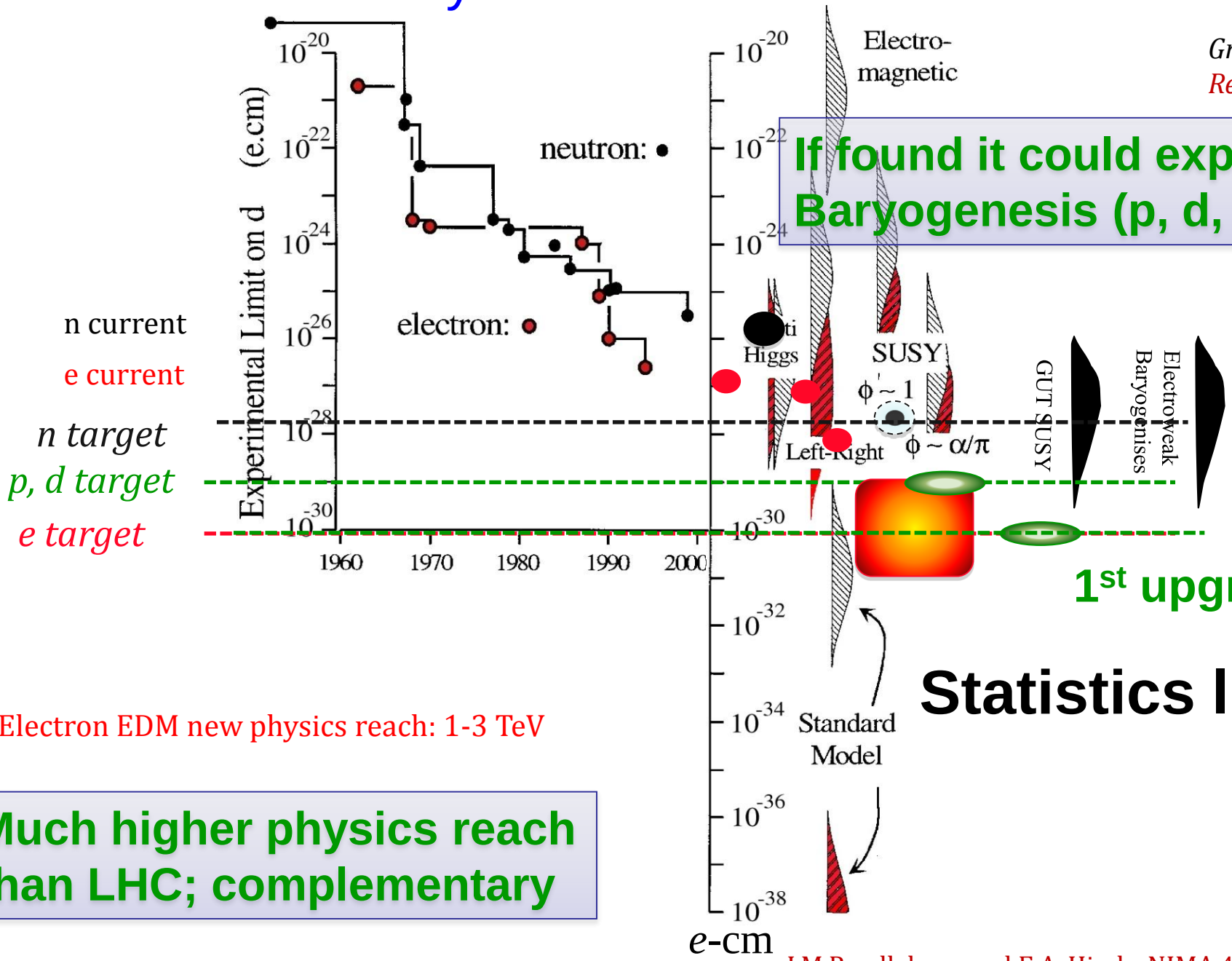
$$d_p \sim 0.01(m_p/\Lambda_{NP})^2 \tan\phi^{NP} e/2m_p$$
$$\sim \mathbf{10^{-22}(1TeV/\Lambda_{NP})^2 \tan\phi^{NP} e\text{-}cm}$$

If ϕ^{NP} is of O(1), Λ_{NP}~<u>3000TeV</u> Probed!

If Λ_{NP}~O(1TeV), ϕ_{NP}~10^{-7} Probed!

<u>Unique Capabilities!</u>

Sensitivity to Rule on Several New Models



If found it could explain Baryogenesis (p, d, n, ^{3}He)

1st upgrade

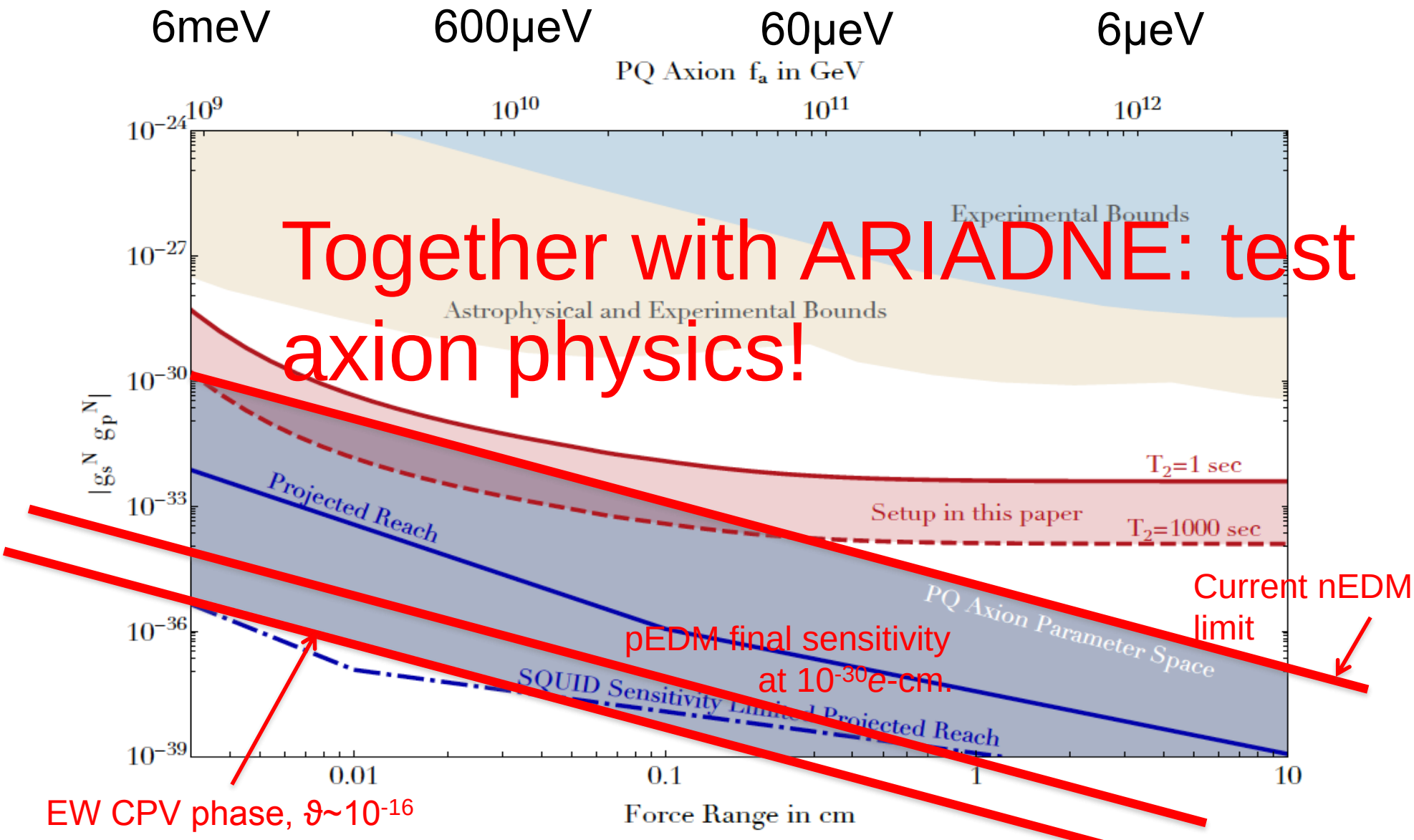
Statistics limited

Electron EDM new physics reach: 1-3 TeV

Much higher physics reach than LHC; complementary

J.M.Pendlebury and E.A. Hinds, NIMA 440 (2000) 471

Axion mediated long range forces

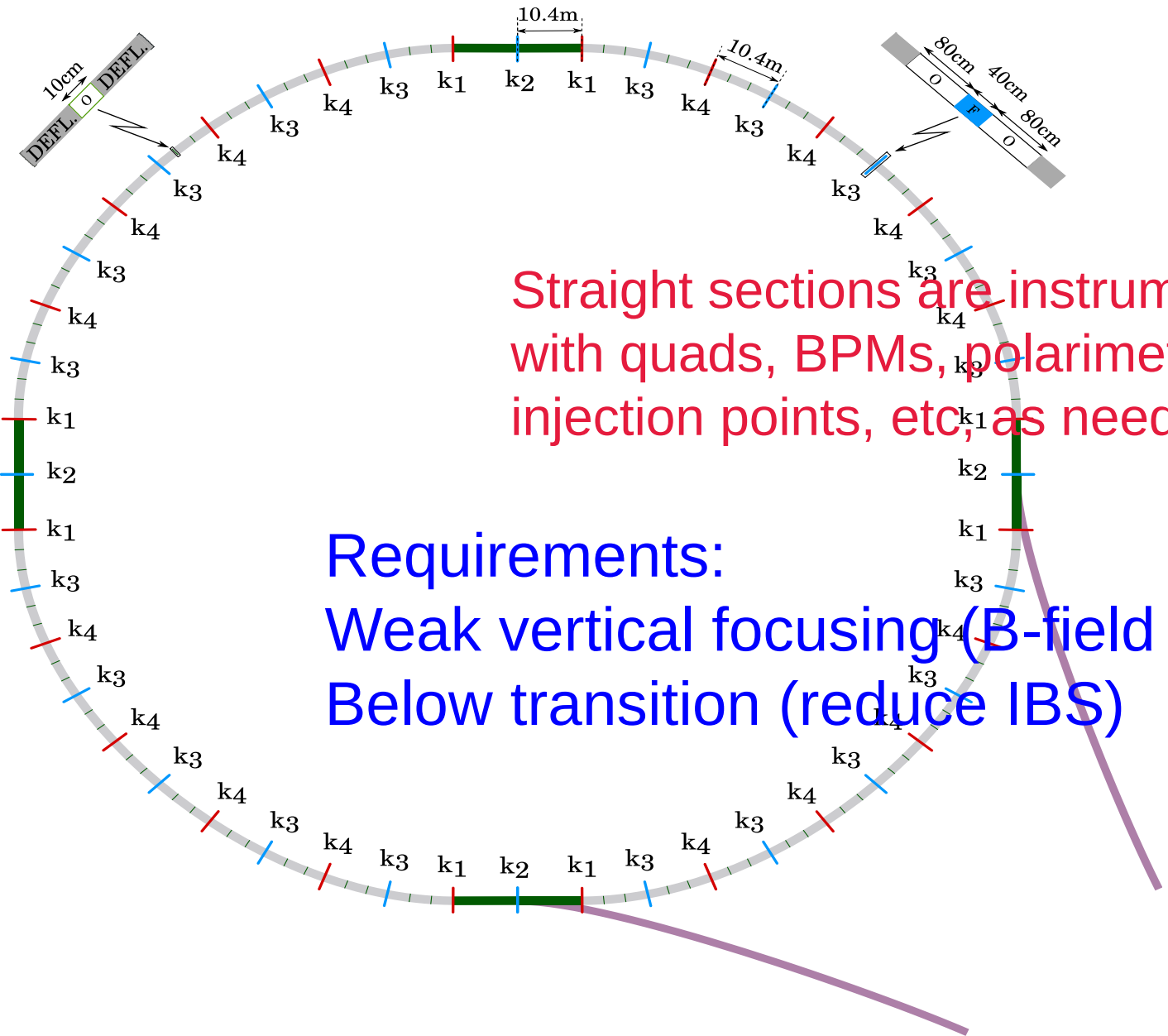


Summary

- Storage ring EDM effort is timely.
- Ultimate sensitivity for p,dEDM < 10^{-29} e-cm
- Great probe of New Physics AND θ_{QCD}

Extra slides

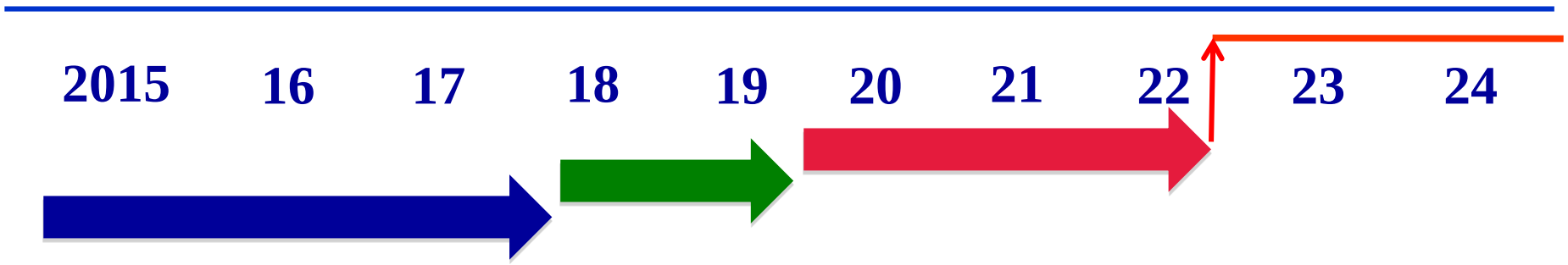
The proton EDM ring (alternate gradient)



Straight sections are instrumented with quads, BPMs, polarimeters, injection points, etc, as needed.

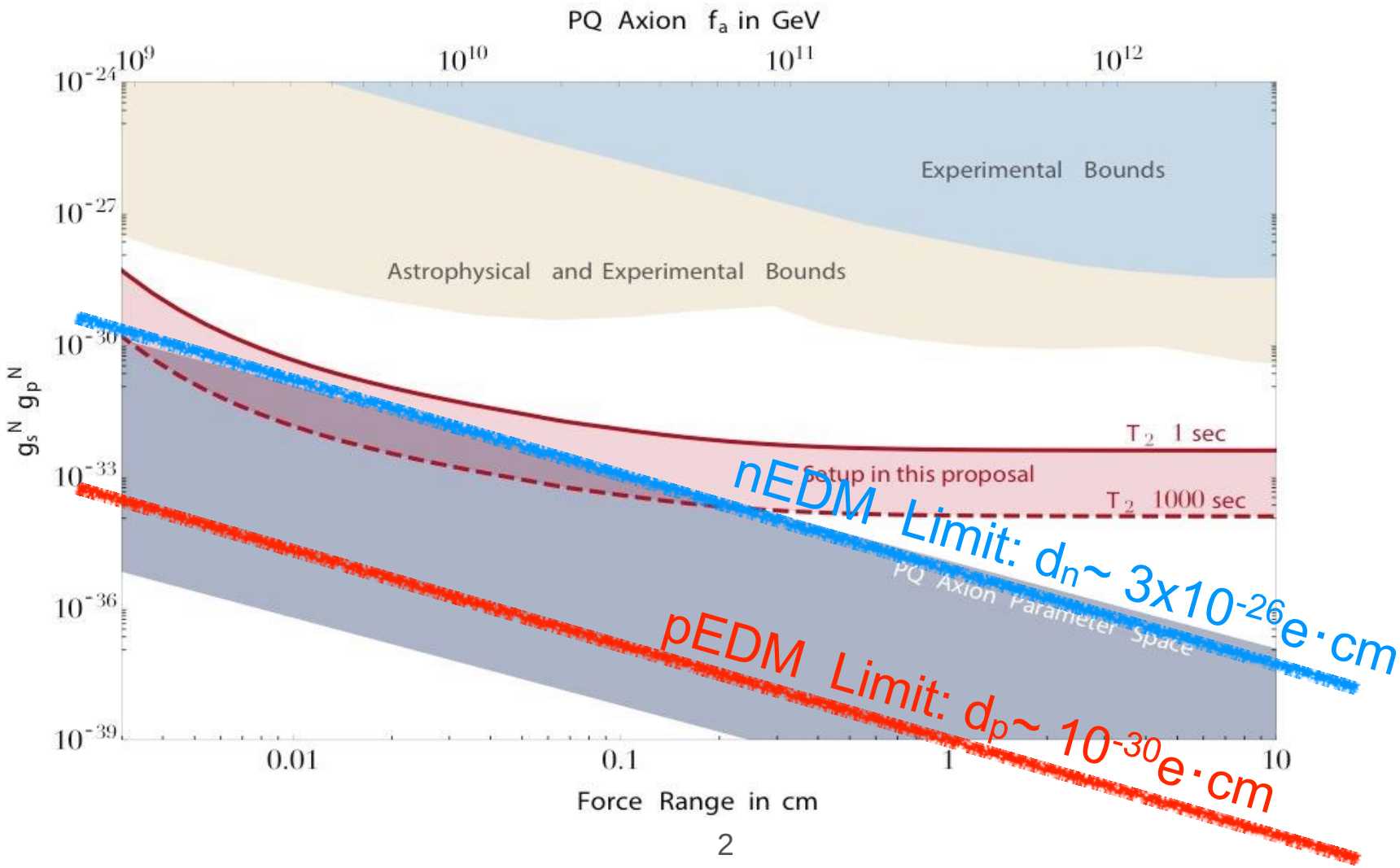
Requirements:
Weak vertical focusing (B-field sensitivity)
Below transition (reduce IBS)

Technically driven pEDM timeline



- Research and systems development (R&D); CDR; final ring design, TDR, installation
- CDR by fall of 2018
- Proposal to a lab: fall 2018

Expected reach



Proton Statistical Error (230MeV):

$$\sigma_d = \frac{2\hbar}{E_R P A \sqrt{N_c f \tau_p T_{tot}}}$$

τ_p : 10^3s Polarization Lifetime (Spin Coherence Time)

A : 0.6 Left/right asymmetry observed by the polarimeter

P : 0.8 Beam polarization

N_c : 10^{11}p/cycle Total number of stored particles per cycle

T_{Tot}: 10^7s Total running time per year

f : 1% Useful event rate fraction (efficiency for EDM)

E_R : 7 MV/m Average radial electric field strength

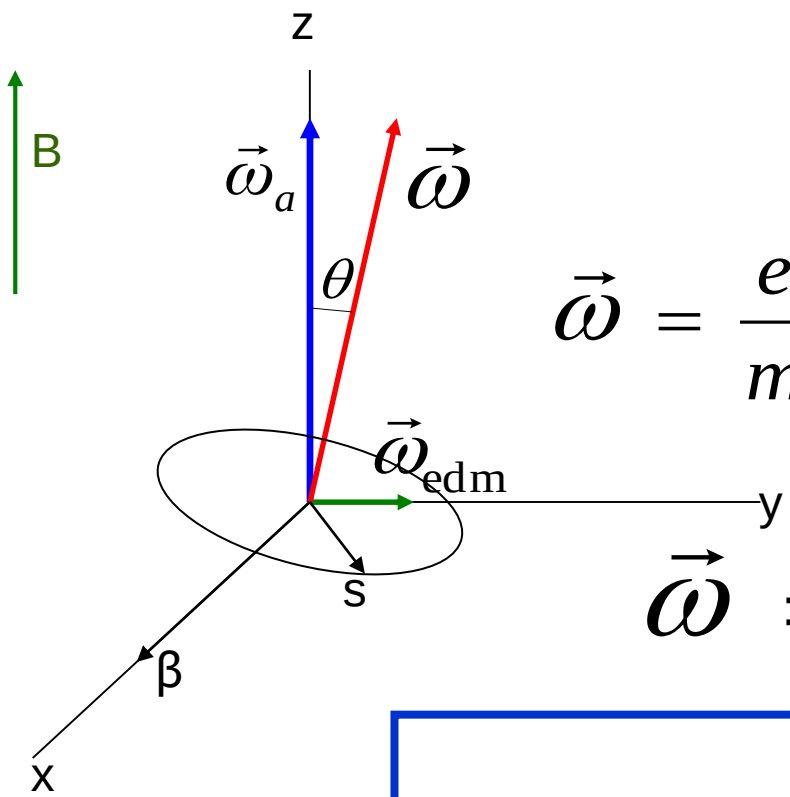
$\sigma_d = 1.0 \times 10^{-29}$ e-cm / year

Electric Dipole Moments in Magnetic Storage Rings

$$\frac{d\vec{s}}{dt} = \vec{d} \times \left(\vec{v} \times \vec{B} \right)$$

e.g. 1 T corresponds to 300 MV/m for relativistic particles

Indirect Muon EDM limit from the g-2 Experiment



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

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{\mathrm{edm}}$$

$$\boxed{\tan\theta = \frac{\omega_{edm}}{\omega_a}}$$

Ron McNabb's Thesis 2003: $< 2.7\times10^{-19}\,\mathrm{e}\cdot\mathrm{cm}$ 95% C.L.

The proton EDM ring evaluation Val Lebedev (Fermilab)

Beam intensity 10^{11} protons limited by IBS

	Soft focusing	Strong focusing
Circumference, m	263	300
Qx/Qy	1.229/0.456	2.32/0.31
Particle per bunch	$1.5 \cdot 10^{8}$	$7 \cdot 10^{8}$
Coulomb tune shifts, $\Delta Q_x/\Delta Q_y$	0.0046/0.0066	0.0146/0.0265
Rms emittances, x/y, norm, μm	0.56/1.52	0.31/2.16
Rms momentum spread	$1.1 \cdot 10^{-4}$	$2.9 \cdot 10^{-4}$
IBS growth times, x/y/s, s	300/(-1400)/250	7500
RF voltage, kV	13	10.3
Synchrotron tune	0.02	0.006

Storage ring proton EDM method

- All-electric storage ring. Strong radial E-field to confine protons with “magic” momentum. The spin vector is aligned with momentum horizontally.

- High intensity, polarized proton beams are injected Clockwise and Counter-clockwise with positive and negative helicities. Great for systematics (e.g., geometrical phases).

- Great statistics: up to ~10^{11} particles with primary proton beams and small phase-space parameters.

Physics strength comparison (Marciano)

System	Current limit [e cm]	Future goal	Neutron equivalent
Neutron	$<1.6\times10^{-26}$	$\sim10^{-28}$	10^{-28}
^{199}Hg atom	$<10^{-29}$		10^{-25}-10^{-26}
^{129}Xe atom	$<6\times10^{-27}$	$\sim10^{-30}$-10^{-33}	10^{-26}-10^{-29}
Deuteron nucleus		$\sim10^{-29}$	3×10^{-29}-5×10^{-31}
Proton nucleus	$<7\times10^{-25}$	$\sim10^{-29}$-10^{-30}	10^{-29}-10^{-30}

CP-violation phase from Higgs

EDMs will eventually be discovered: $d_e, d_n, d_p \ldots d_D$

Magnitudes of ≈ -10^{-28} expected for Baryogenesis

Atomic, Molecular, Neutron, ***Storage Ring*** (All important)

Marciano

CP violation phase in***: Hee, Hγγ, Htt, 2HD Model…***

Uniquely explored by 2 loop edms! Barr-Zee effect

May be our only window to Hee, Huu and Hdd couplings

Guided by experiment: *H→γγ* *(H→τ⁺τ⁻, μ⁺μ⁻) etc.*

Updates Anxiously Anticipated!

The Higgs may be central to our existence!

Anomalous magnetic moment factors

$$\frac{1}{\gamma^2 - 1} - G = 0 \rightarrow \gamma = \sqrt{\frac{1}{G} + 1}$$

→ $G > 0$ for $\gamma > 1$, if only electric fields are applied

$$\gamma = \sqrt{\frac{1}{G} + 1} \Leftrightarrow p = \frac{m}{\sqrt{G}}$$

μ_p / μ_N = **2.792 847 356 (23)** → G_p = 1.7928473565
μ_d / μ_N = **0.857 438 2308 (72)** → G_d = -0.14298727202
$\mu_{He\text{-}3} / \mu_N$ = **-2.127 497 718 (25)** → G_{3He} = -4.1839627399

Nuclear magneton: $\mu_N = e\hbar / (2m_p c)$ = **5.050 783 24 (13) · 10^{-27} J T^{-1}**

→ Magic momentum for protons: p = 700.74 MeV/c
→ Deuterons, He-3:

$$E_r = \frac{GBc\beta\gamma^2}{1 - G\beta^2\gamma^2} \approx GBc\beta\gamma^2$$