The status and Future of the storage ring proton EDM experiment

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Workshop on Future Accelerators
Mon Repos, Corfu, May 19-26, 2024

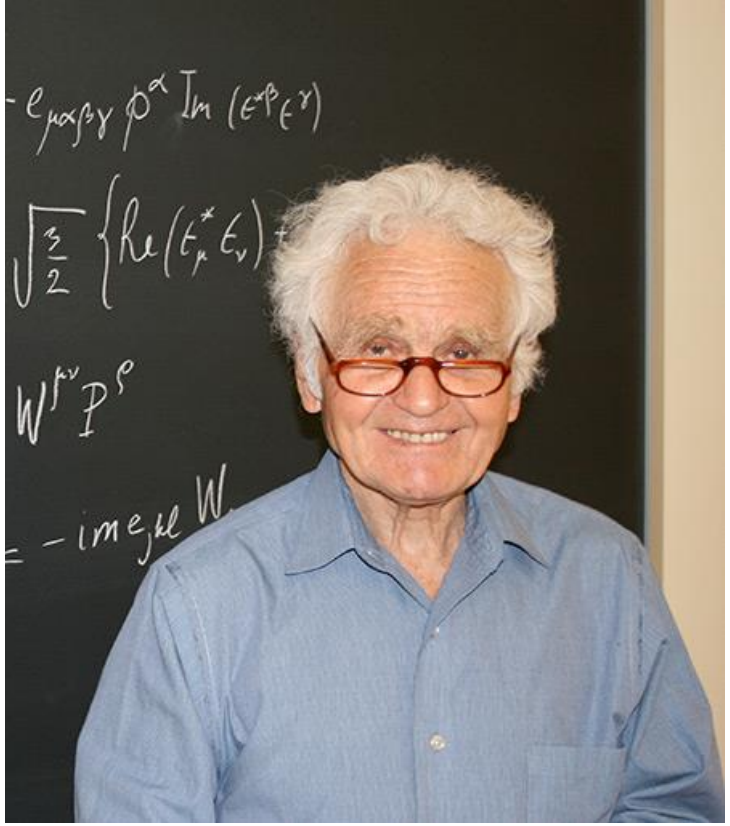
CAPP
Center for Axion and Precision Physics Research

- Statistics for better than 10^{-29} *e*-cm for pEDM, ~10^3 TeV New-Physics reach
- Matching systematic error levels, greatly reduced using symmetries
- Getting ready to go (technically), need more community support to build

Outline

- Motivation
- Status of EDMs
- Systematics with hybrid and hybrid-symmetric lattices
- Status of our srEDM project, conclusions

Yuri F. Orlov (1924-2020)



- First complete analysis of storage-ring EDM systematic errors in 1996 and with a contribution to AGS-2000 workshop. He set us on the right path.
- Non-linear analysis of beam and spin dynamics
  - Spin coherence time (SCT) estimation including three independent parameters (hor., vert., and longitudinal oscillations)
  - In electric rings with RF set the correct analysis of conserved parameters-verified by benchmarked simulations
- Geometrical phases, establishing superiority over neutron EDM case due to special geometry
- Wien-filter with partially frozen spin method
- Resonance EDM method for the deuteron case
- Comprehensive study of gravitational effects
- Invaluable contributions to muon g-2, pEDM exps.

Cornell University

Motivation of pEDM at 10^{-29} *e*-cm

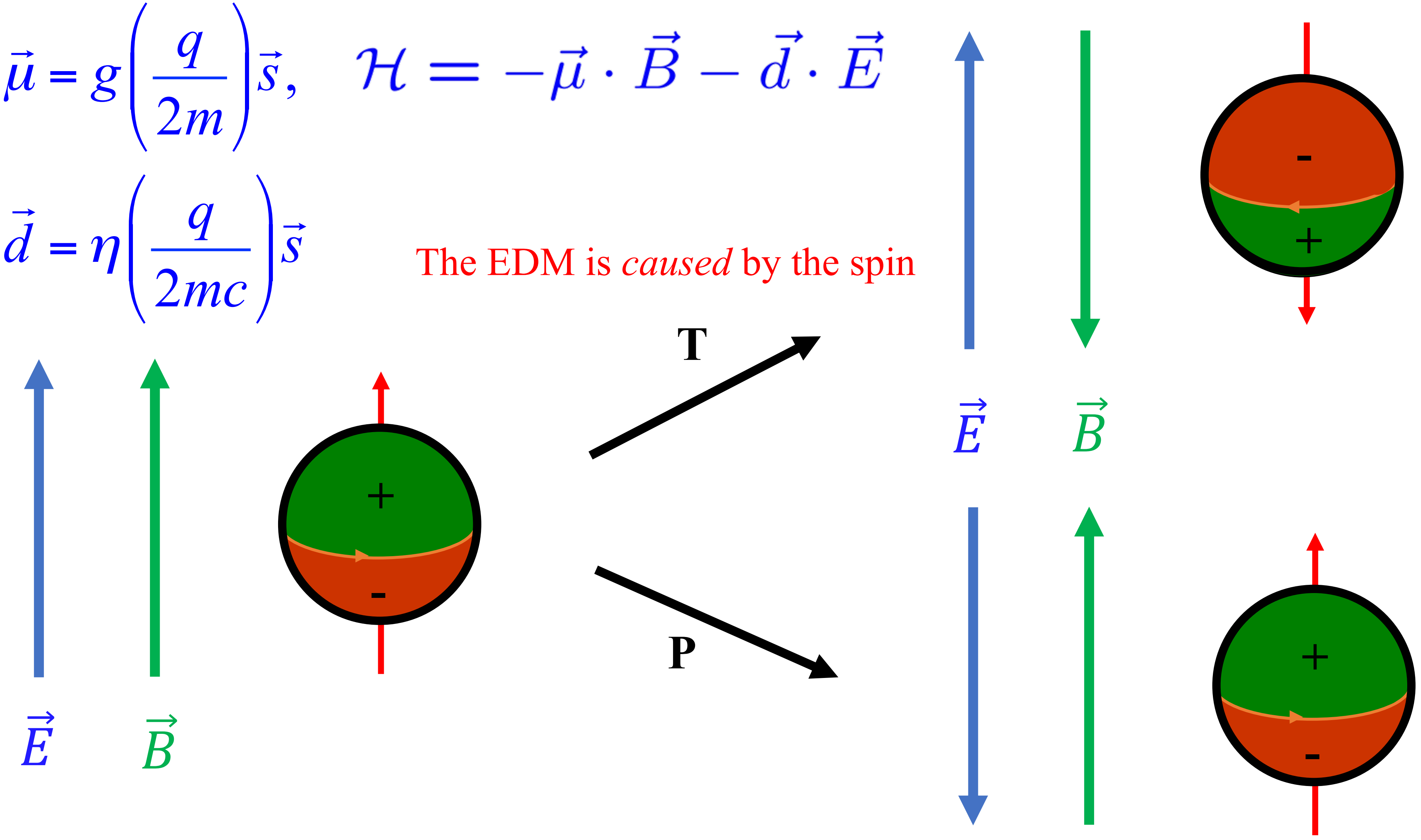
- Probe New Physics, at ~10^3 TeV mass scale, Higgs CPV
- Improve sensitivity to θ_{QCD} by three orders of magnitude
- Direct search for axion dark matter (axion-gluon coupling)

A Permanent EDM Violates both T & P Symmetries:

$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{s}, \quad \mathcal{H} = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

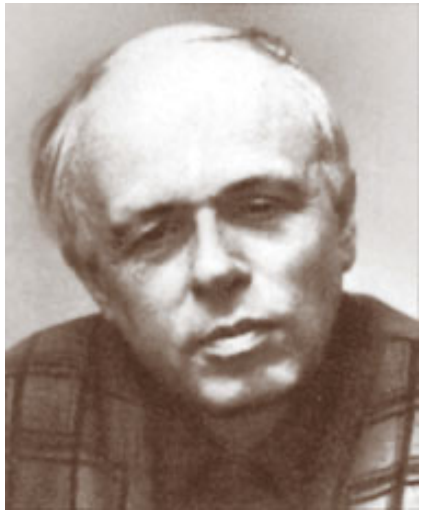
$$\vec{d} = \eta\left(\frac{q}{2mc}\right)\vec{s}$$

The EDM is *caused* by the spin



Reminder: batteries are allowed in the SM!

T-Violation $\xrightarrow{\text{CPT}}$ CP-Violation

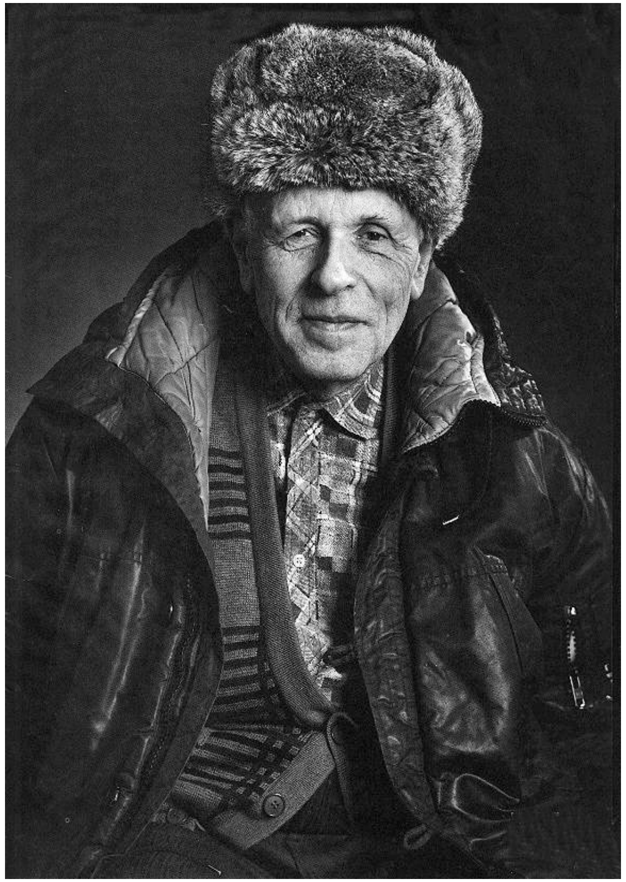


Andrei Sakharov 1967:

CP-Violation is one of three conditions to enable a universe containing initially equal amounts of matter and antimatter to evolve into a matter-dominated universe, which we see today....

Yuri F. Orlov in 4th Vernon W. Hughes Memorial Lecture, Brookhaven National Laboratory, 2009.

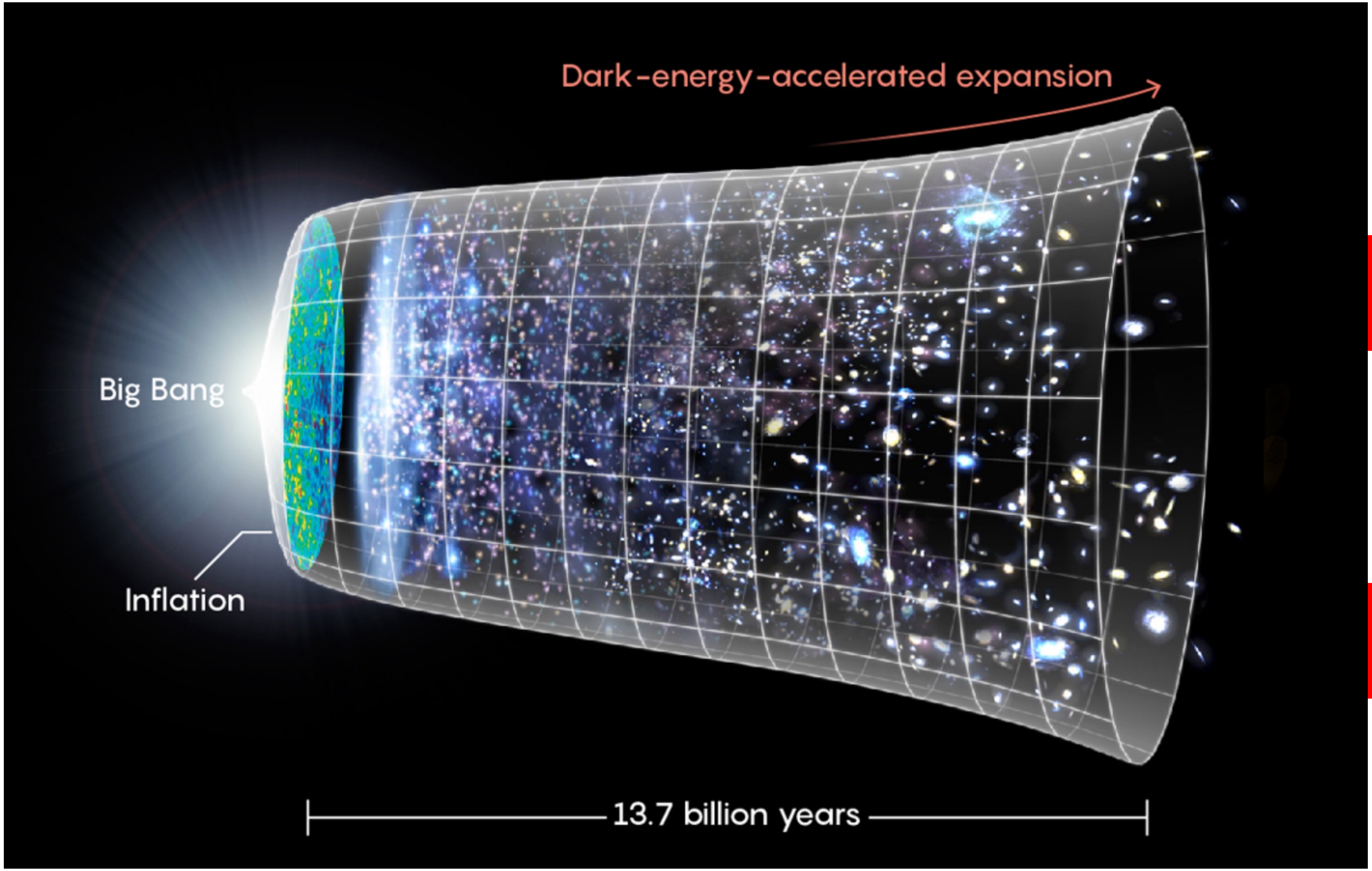
In 1973, Orlov wrote a letter to Brezhnev in defense of Sakharov and lost his job… Moved to Armenia and started work on storage rings and on ideas related to muon g-2 experiment.



A. SAKHAROV (1921-1989)

1968 was also the year of Sakharov's famous "Reflections on Progress, Peaceful Coexistence and Intellectual Freedom," arguing the necessary convergence of the opposite sides of the Cold War.

Why is there so much matter after the Big Bang:



We see:

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

From the SM:

$$\frac{n_B}{n_\gamma} \approx 10^{-18}$$

Purcell and Ramsey:

“The question of the possible existence of an electric dipole moment of a nucleus or of an elementary particle…becomes a purely experimental matter”

Phys. Rev. 78 (1950)

Bill Marciano
Snowmass Workshop,
September 15, 2020

Proton edm SR goal: $d_p \sim 10^{-29}$e-cm

Improvement by more than 4 orders!
Sensitivity similar to $d_e < 10^{-30}$e-cm

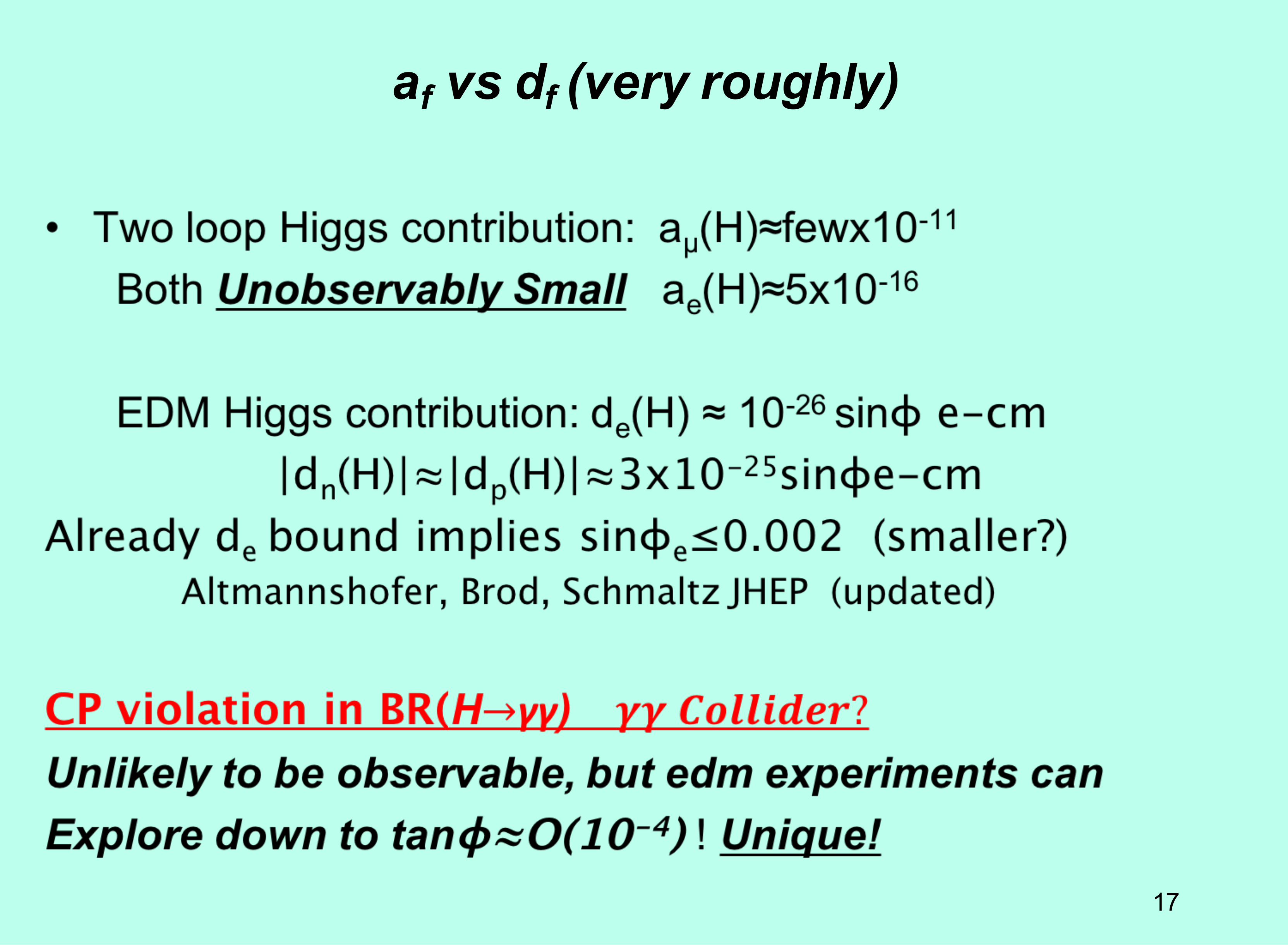
In a renormalizable quantum field theory, at lowest order $d_p=0$ (No dim. 5 operators)

$d_p \sim em/\Lambda_{NP}^2 \sin\phi^{NP}$ quantum loop induced
Λ_{NP} scale of “new physics”
ϕ^{NP} = Complex CP violation phase of New Physics
phase misalignment with m_p
$\sim 10^{-22}(1\mathrm{TeV}/\Lambda_{NP})^2 \sin\phi^{NP}$e-cm

If ϕ^{NP} is of O(1), $\Lambda_{NP} \sim$ 3000TeV Probed! (very roughly)
If $\Lambda_{NP} \sim$ O(1TeV), $\phi_{NP} \sim 10^{-6}$ Probed!

Bill Marciano

Snowmass Workshop,
September 15, 2020



a_f vs d_f (very roughly)

- Two loop Higgs contribution: $a_\mu(H) \approx \text{few} \times 10^{-11}$

  Both ***Unobservably Small*** $a_e(H) \approx 5 \times 10^{-16}$

EDM Higgs contribution: $d_e(H) \approx 10^{-26} \sin\phi$ e-cm

$|d_n(H)| \approx |d_p(H)| \approx 3 \times 10^{-25} \sin\phi$ e-cm

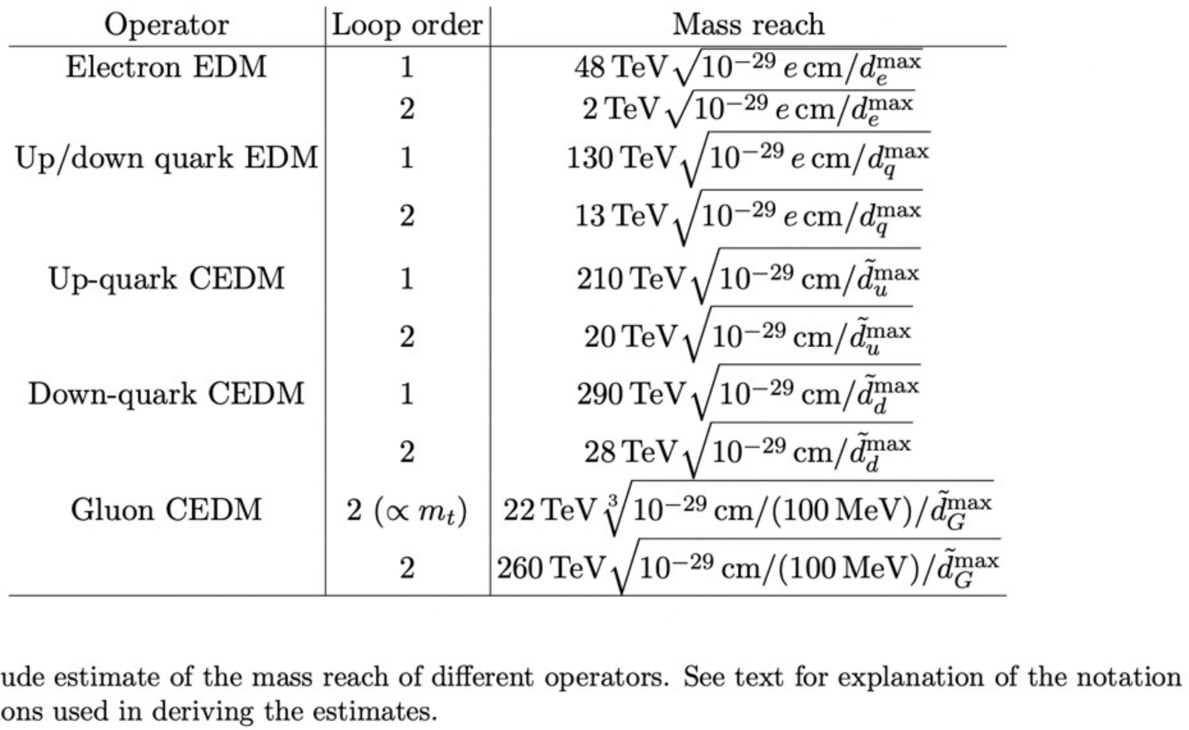
Already d_e bound implies $\sin\phi_e \leq 0.002$ (smaller?)

Altmannshofer, Brod, Schmaltz JHEP (updated)

CP violation in BR($H \to \gamma\gamma$) *$\gamma\gamma$ Collider?*

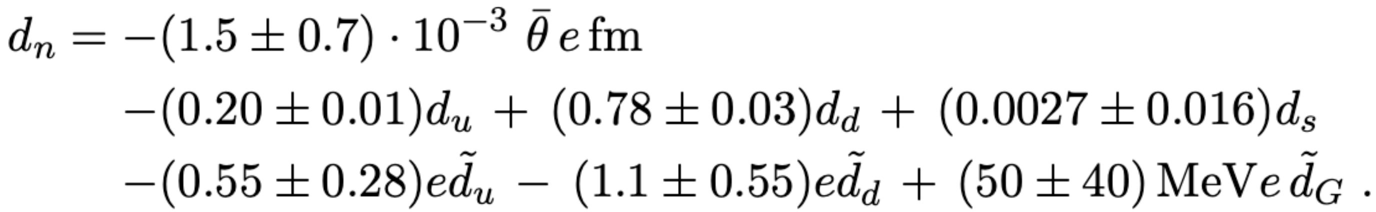
Unlikely to be observable, but edm experiments can Explore down to $\tan\phi \approx O(10^{-4})$! Unique!

Snowmass paper on EDMs, why many EDMs:



Operator	Loop order	Mass reach
Electron EDM	1	$48\,\mathrm{TeV}\sqrt{10^{-29}\,e\,\mathrm{cm}/d_e^{\max}}$
	2	$2\,\mathrm{TeV}\sqrt{10^{-29}\,e\,\mathrm{cm}/d_e^{\max}}$
Up/down quark EDM	1	$130\,\mathrm{TeV}\sqrt{10^{-29}\,e\,\mathrm{cm}/d_q^{\max}}$
	2	$13\,\mathrm{TeV}\sqrt{10^{-29}\,e\,\mathrm{cm}/d_q^{\max}}$
Up-quark CEDM	1	$210\,\mathrm{TeV}\sqrt{10^{-29}\,\mathrm{cm}/\tilde{d}_u^{\max}}$
	2	$20\,\mathrm{TeV}\sqrt{10^{-29}\,\mathrm{cm}/\tilde{d}_u^{\max}}$
Down-quark CEDM	1	$290\,\mathrm{TeV}\sqrt{10^{-29}\,\mathrm{cm}/\tilde{d}_d^{\max}}$
	2	$28\,\mathrm{TeV}\sqrt{10^{-29}\,\mathrm{cm}/\tilde{d}_d^{\max}}$
Gluon CEDM	2 ($\propto m_t$)	$22\,\mathrm{TeV}\sqrt[3]{10^{-29}\,\mathrm{cm}/(100\,\mathrm{MeV})/\tilde{d}_G^{\max}}$
	2	$260\,\mathrm{TeV}\sqrt{10^{-29}\,\mathrm{cm}/(100\,\mathrm{MeV})/\tilde{d}_G^{\max}}$

TABLE I. Crude estimate of the mass reach of different operators. See text for explanation of the notation and assumptions used in deriving the estimates.



$$
\begin{aligned}
d_n = &-(1.5 \pm 0.7) \cdot 10^{-3}\ \bar{\theta}\, e\,\mathrm{fm} \\
&-(0.20 \pm 0.01) d_u \ + \ (0.78 \pm 0.03) d_d \ + \ (0.0027 \pm 0.016) d_s \\
&-(0.55 \pm 0.28) e\tilde{d}_u \ - \ (1.1 \pm 0.55) e\tilde{d}_d \ + \ (50 \pm 40)\,\mathrm{MeV}\, e\, \tilde{d}_G \ .
\end{aligned}
$$

Electric dipole moments and the search for new physics

Ricardo Alarcon,[1] Jim Alexander,[2] Vassilis Anastassopoulos,[3] Takatoshi Aoki,[4] Rick Baartman,[5] Stefan Baeßler,[6,7] Larry Bartoszek,[8] Douglas H. Beck,[9] Franco Bedeschi,[10] Robert Berger,[11] Martin Berz,[12] Tanmoy Bhattacharya,[13,a] Michael Blaskiewicz,[14] Thomas Blum,[15,b] Themis Bowcock,[16] Kevin Brown,[14] Dmitry Budker,[17,18] Sergey Burdin,[16] Brendan C. Casey,[19] Gianluigi Casse,[20] Giovanni Cantatore,[21] Lan Cheng,[22] Timothy Chupp,[20] Vince Cianciolo,[23] Vincenzo Cirigliano,[13,24,c] Steven M. Clayton,[25] Chris Crawford,[26] B. P. Das,[27] Hooman Davoudiasl,[14] Jordy de Vries,[28,29,d] David DeMille,[30,31,e] Dmitri Denisov,[14] Milind V. Diwan,[14] John M. Doyle,[32] Jonathan Engel,[33] George Fanourakis,[34] Renee Fatemi,[35] Bradley W. Filippone,[36] Nadia Fomin,[37] Wolfram Fischer,[14] Antonios Gardikiotis,[38,3] R. F. Garcia Ruiz,[39] Claudio Gatti,[40] James Gooding,[16] Peter Graham,[41] Frederick Gray,[42] W. Clark Griffith,[43] Selcuk Haciomeroglu,[44] Gerald Gwinner,[45] Steven Hoekstra,[46,47] Georg H. Hoffstaetter,[2] Haixin Huang,[14] Nicholas R. Hutzler,[48,f] Marco Incagli,[10] Takeyasu M. Ito,[25,g] Taku Izubuchi,[49] Andrew M. Jayich,[50] Hoyong Jeong,[51] David Kaplan,[52] Marin Karuza,[53] David Kawall,[54] On Kim,[44] Ivan Koop,[55] Valeri Lebedev,[19] Jonathan Lee,[56] Soohyung Lee,[44] Kent K. H. Leung,[57] Chen-Yu Liu,[58,9,h] Joshua Long,[58,9] Alberto Lusiani,[59,10] William J. Marciano,[14] Marios Maroudas,[3] Andrei Matlashov,[44] Nobuyuki Matsumoto,[60] Richard Mawhorter,[61] Francois Meot,[14] Emanuele Mereghetti,[13] James P. Miller,[62] William M. Morse,[63,i] James Mott,[62,19] Zhanibek Omarov,[44,64] Chris O'Shaughnessy,[25] Cenap Ozben,[65] SeongTae Park,[44] Robert W. Pattie Jr.,[66] Alexander N. Petrov,[67,68] Giovanni Maria Piacentino,[69] Bradley R. Plaster,[26] Boris Podobedov,[14] Matthew Poelker,[70] Dinko Pocanic,[71] V. S. Prasannaa,[27] Joe Price,[16] Michael J. Ramsey-Musolf,[72,73] Deepak Raparia,[14] Surjeet Rajendran,[52] Matthew Reece,[74,j] Austin Reid,[58] Sergio Rescia,[14] Adam Ritz,[75] B. Lee Roberts,[62] Marianna S. Safronova,[76] Yasuhiro Sakemi,[77] Andrea Shindler,[78] Yannis K. Semertzidis,[44,64,k] Alexander Silenko,[79] Jaideep T. Singh,[80] Leonid V. Skripnikov,[67,68] Amarjit Soni,[14] Edward Stephenson,[58] Riad Suleiman,[81] Ayaki Sunaga,[82] Michael Syphers,[83] Sergey Syritsyn,[84] M. R. Tarbutt,[85] Pia Thoerngren,[86] Rob G. E. Timmermans,[87] Volodya Tishchenko,[14] Anatoly V. Titov,[67,68] Nikolaos Tsoupas,[14] Spyros Tzamarias,[88] Alessandro Variola,[40] Graziano Venanzoni,[10] Eva Vilella,[16] Joost Vossebeld,[16] Peter Winter,[89,l] Eunil Won,[51] Anatoli Zelenski,[14] Yan Zhou,[90] and Konstantin Zioutas[3]

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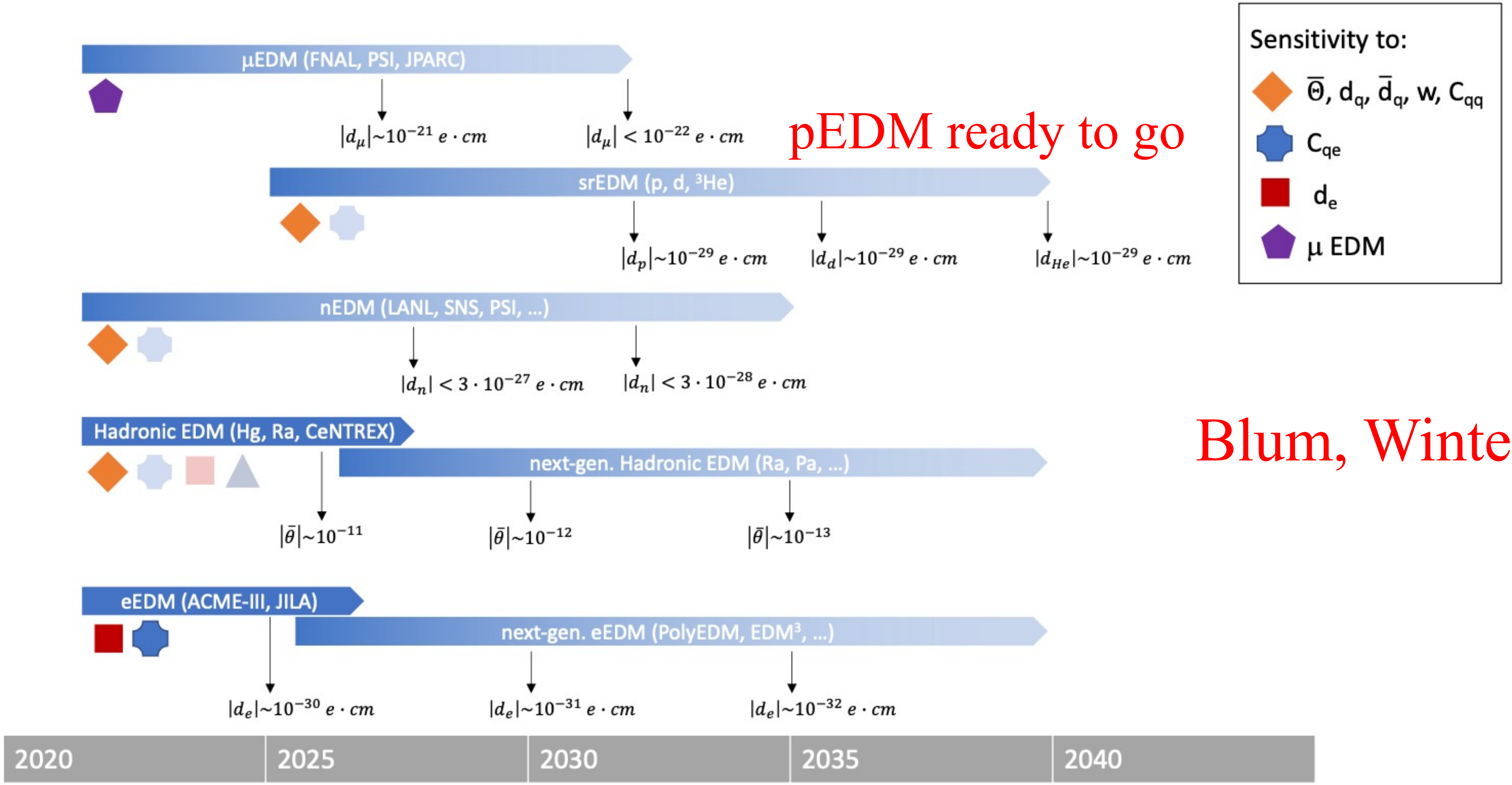
EDM timelines, from Snowmass 2021 (2022).



pEDM ready to go

Blum, Winter *et al.*

Figure 3-1. *Timelines for the major current and planned EDM searches with their sensitivity to the important parameters of the effective field theory (see Fig. 3-2 for details). Solid (shaded) symbols indicate each experiment's primary (secondary) sensitivities. Measurement goals indicated by the black arrows are based on current plans of the various groups.*

Snowmass paper on EDMs

Neutron EDM

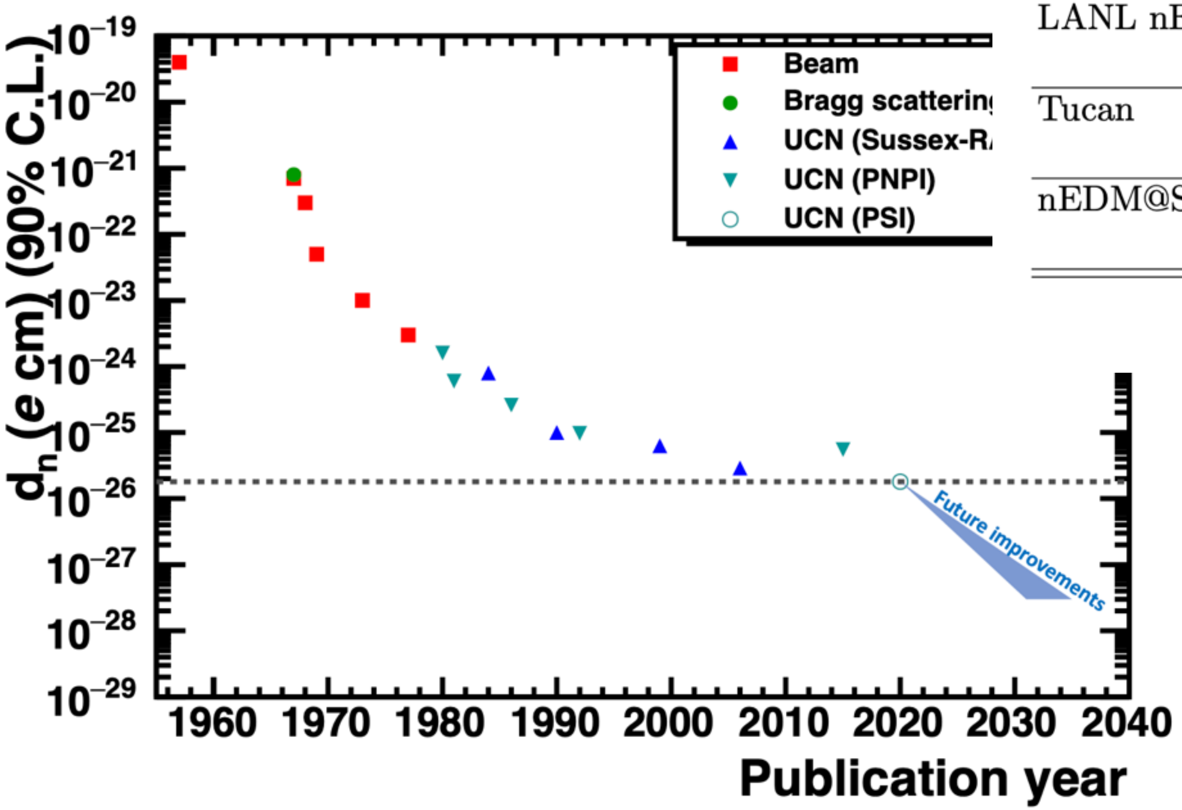
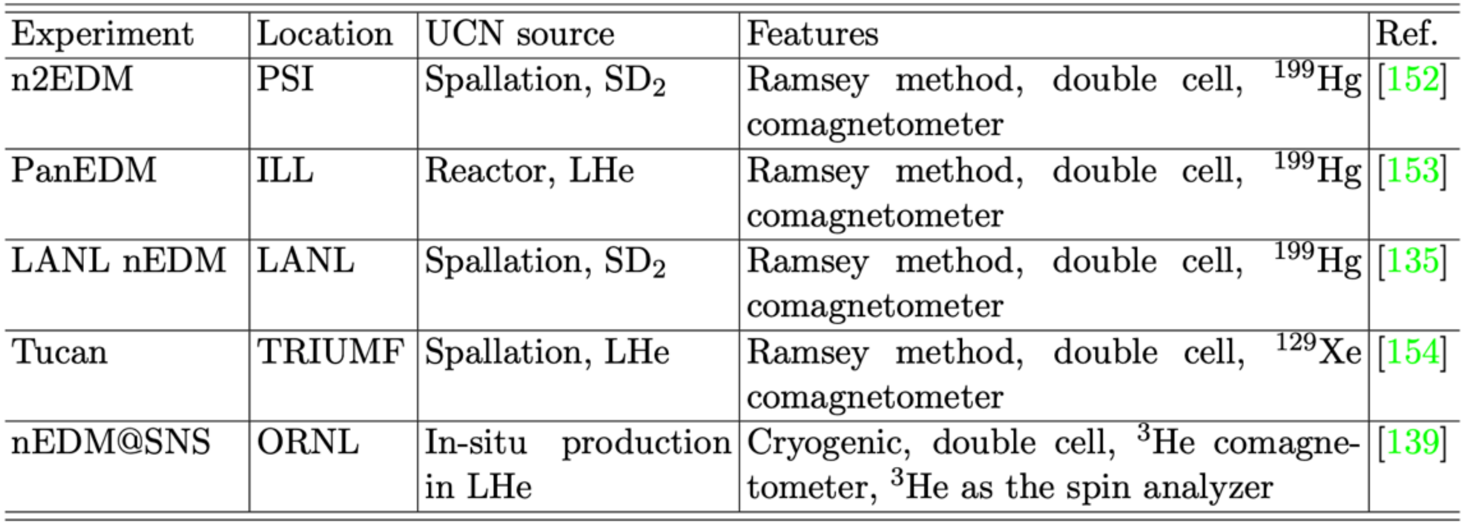


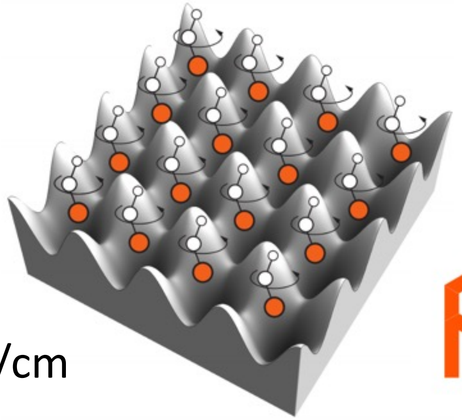
FIG. 3. Evolution of the nEDM results along with projected future results



Experiment	Location	UCN source	Features	Ref.
n2EDM	PSI	Spallation, SD_2	Ramsey method, double cell, ^{199}Hg comagnetometer	[152]
PanEDM	ILL	Reactor, LHe	Ramsey method, double cell, ^{199}Hg comagnetometer	[153]
LANL nEDM	LANL	Spallation, SD_2	Ramsey method, double cell, ^{199}Hg comagnetometer	[135]
Tucan	TRIUMF	Spallation, LHe	Ramsey method, double cell, ^{129}Xe comagnetometer	[154]
nEDM@SNS	ORNL	In-situ production in LHe	Cryogenic, double cell, ^{3}He comagnetometer, ^{3}He as the spin analyzer	[139]

TABLE III. A list of the nEDM experiments that are being developed

Snowmass paper on EDMs



PolyEDM

Effective E-field with polar molecules: order GV/cm

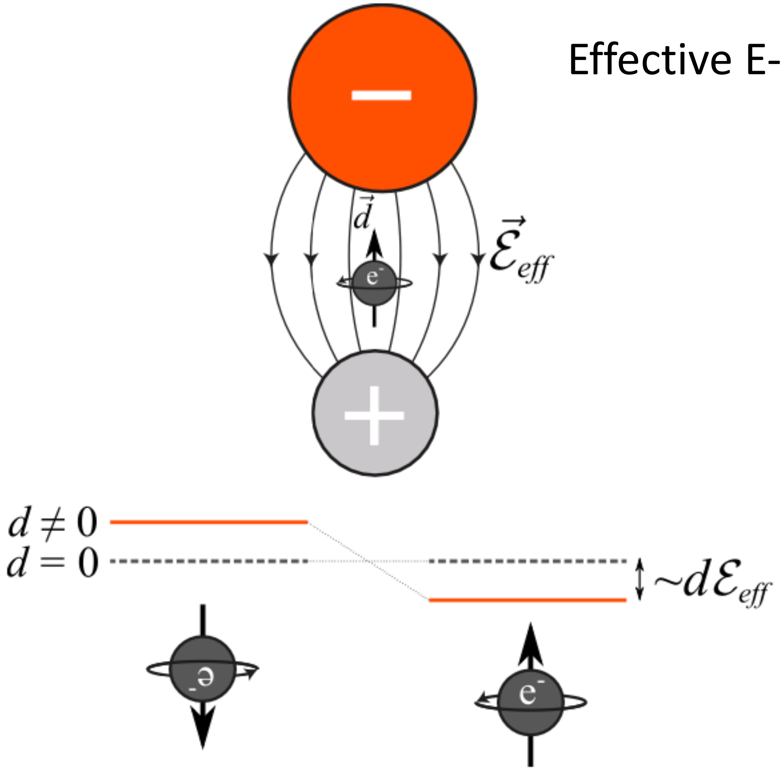


Figure: Laser-cooled polyatomic molecules, optically trapped, with full quantum control. Such a platform can be used to access new physics at the PeV scale.

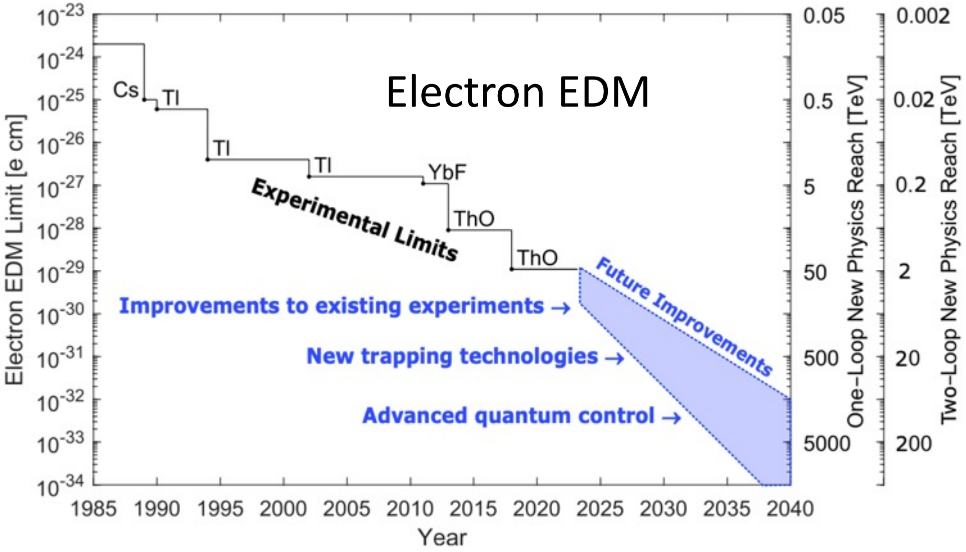
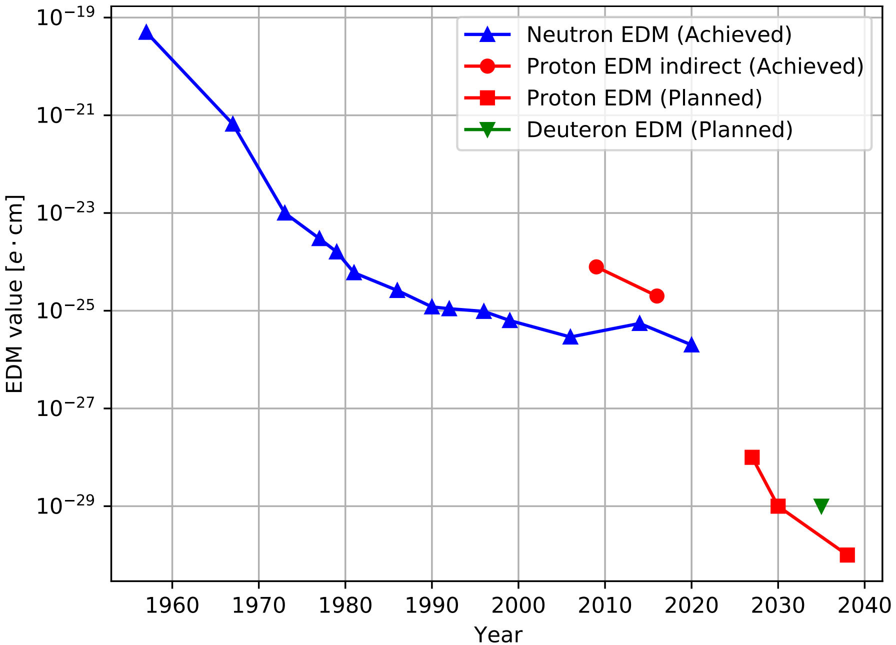


FIG. 5. Electron EDM limits versus time, along with new physics reach for one-loop and two-loop effects (see Eq. 2). All electron EDM experiments to date use AMO techniques. The solid line indicates the most sensitive experimental limit, including the species used. The shaded area indicates potential future improvements discussed in the text. Improvements in the next few years are driven largely by improvements to existing experiments and are quite likely, though as we go more into the future the projection becomes increasingly speculative and uncertain.

Storage ring EDM experiment

- Snowmass white paper: next steps - CDR, proposal, TDR
- 10^{-29} *e*-cm; fits in BNL AGS tunnel
    - World-class, high intensity polarized sources for protons, deuterons, ^{3}He, other nuclei
    - ring design PRD105:032001 (2022), storage ring experiment Rev.Sci.Instrum.87:115116 (2016)
- Possible interesting results within a decade (compatible with EIC schedule)
- Competitive EDM sensitivity:
    - New-Physics reach ~10^3 TeV.
    - Best probe on Higgs CPV, Marciano
        - proton is better than H→ $\gamma\gamma$
        - 30x better than electron with same EDM.
    - Three orders of magnitude improvement in θ_{QCD} sensitivity.
    - Direct axion dark matter reach (best exp. sensitivity at very low frequencies).



The storage ring proton EDM experiment

Jim Alexander[7], Vassilis Anastassopoulos[36], Rick Baartman[28], Stefan Baeßler[39,22], Franco Bedeschi[19], Martin Berz[17], Michael Blaskiewicz[4], Themis Bowcock[33], Kevin Brown[4], Dmitry Budker[9,31], Sergey Burdin[33], Brendan C. Casey[8], Gianluigi Casse[34], Giovanni Cantatore[38], Timothy Chupp[34], Hooman Davoudiasl[4], Dmitri Denisov[4], Milind V. Diwan[4], George Fanourakis[20], Antonios Gardikiotis[30,36], Claudio Gatti[18], James Gooding[33], Renee Fatemi[32], Wolfram Fischer[4], Peter Graham[26], Frederick Gray[23], Selcuk Haciomeroglu[6], Georg H. Hoffstaetter[7], Haixin Huang[4], Marco Incagli[19], Hoyong Jeong[16], David Kaplan[13], Marin Karuza[37], David Kawall[29], On Kim[6], Ivan Koop[5], Valeri Lebedev[14,8], Jonathan Lee[27], Soohyung Lee[6], Alberto Lusiani[25,19], William J. Marciano[4], Marios Maroudas[36], Andrei Matlashov[6], Francois Meot[4], James P. Miller[3], William M. Morse[4], James Mott[3,8], Zhanibek Omarov[15,6], Cenap Ozben[11], SeongTae Park[6], Giovanni Maria Piacentino[35], Boris Podobedov[4], Matthew Poelker[12], Dinko Pocanic[39], Joe Price[33], Deepak Raparia[4], Surjeet Rajendran[13], Sergio Rescia[4], B. Lee Roberts[3], Yannis K. Semertzidis [*6,15], Alexander Silenko[14], Amarjit Soni[4], Edward Stephenson[10], Riad Suleiman[12], Michael Syphers[21], Pia Thoerngren[24], Volodya Tishchenko[4], Nicholaos Tsoupas[4], Spyros Tzamarias[1], Alessandro Variola[18], Graziano Venanzoni[19], Eva Vilella[33], Joost Vossebeld[33], Peter Winter[2], Eunil Won[16], Anatoli Zelenski[4], and Konstantin Zioutas[36]

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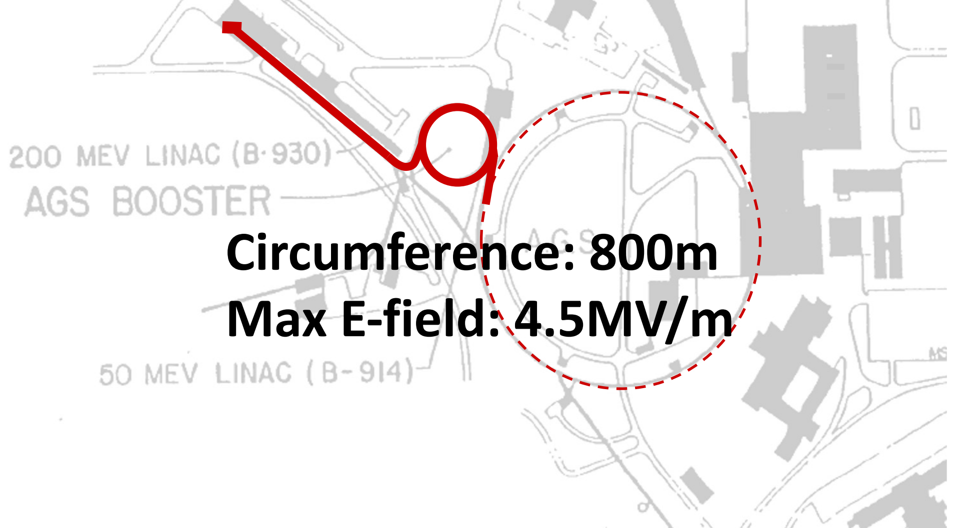
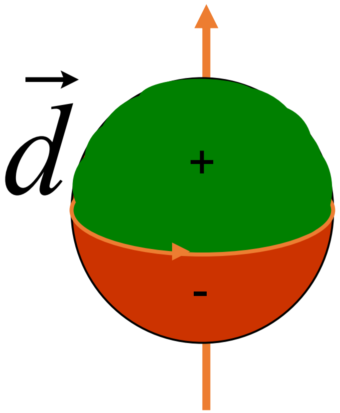


Circumference: 800m
Max E-field: 4.5MV/m

The Electric Dipole Moment precesses in an Electric field



The EDM vector *d* is induced by the particle spin

$$\boxed{\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}}$$

Important attributes of an EDM Experiment

1. Polarization: state preparation, intensity of beams (statistics)

2. Interaction with an E-field: the higher the better (statistics)

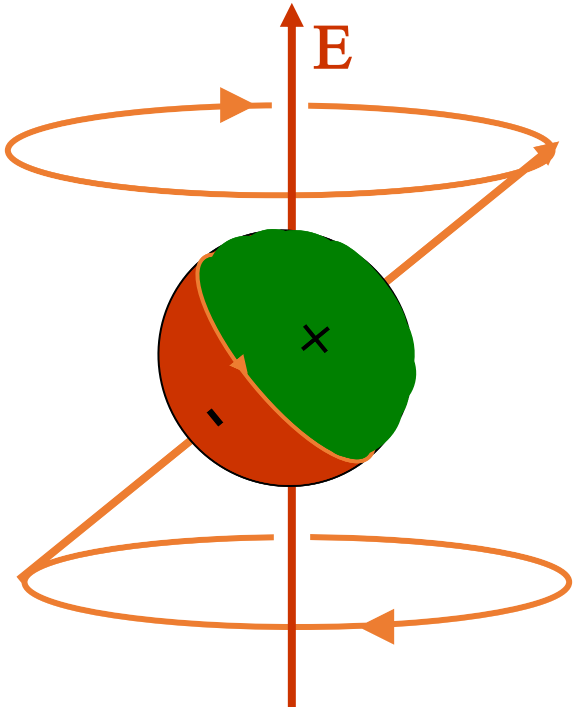
3. Analyzer: high efficiency analyzer (statistics)

4. Symmetry tools: combat systematic errors, critical!

5. Scientific Interpretation of Result! Easier for the simpler systems

Spin precession at rest

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



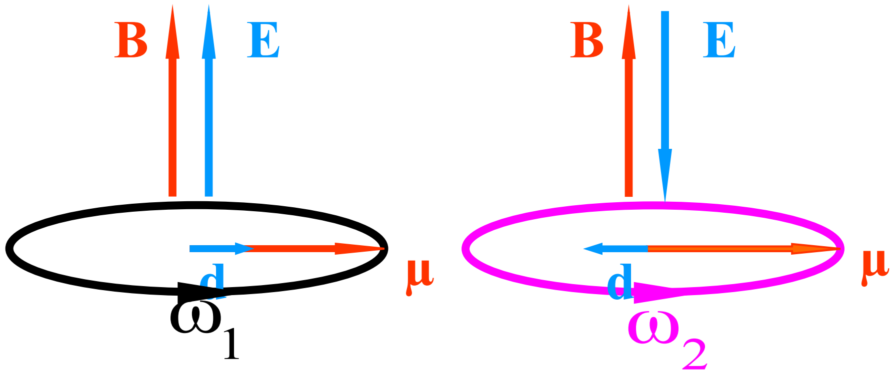
Compare the Precession Frequencies with E-field Flipped:

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

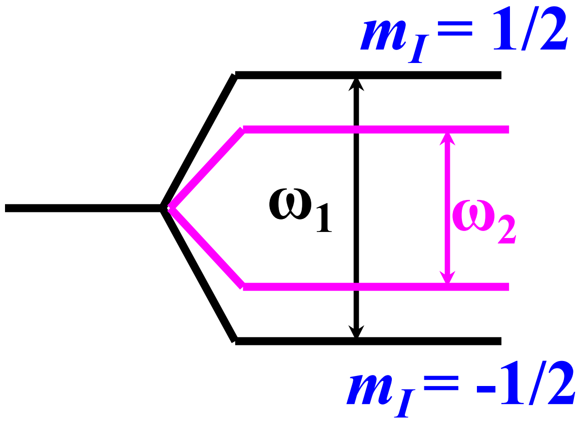
$$\boxed{\sigma_d \propto \frac{1}{EPA}\frac{1}{\sqrt{N\tau T}}}$$

Measuring an EDM of Neutral Particles

$$H = -(d\,\mathbf{E} + \mu\,\mathbf{B}) \bullet \mathbf{I}/I$$



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



$$d = \frac{\hbar(\omega_1 - \omega_2)}{4E}$$

$d = 10^{-28}$ e cm

$E = 20$ kV/cm

$\Rightarrow$ $\delta\omega = 10^{-8}$ rad/s

^{3}He Co-magnetometer

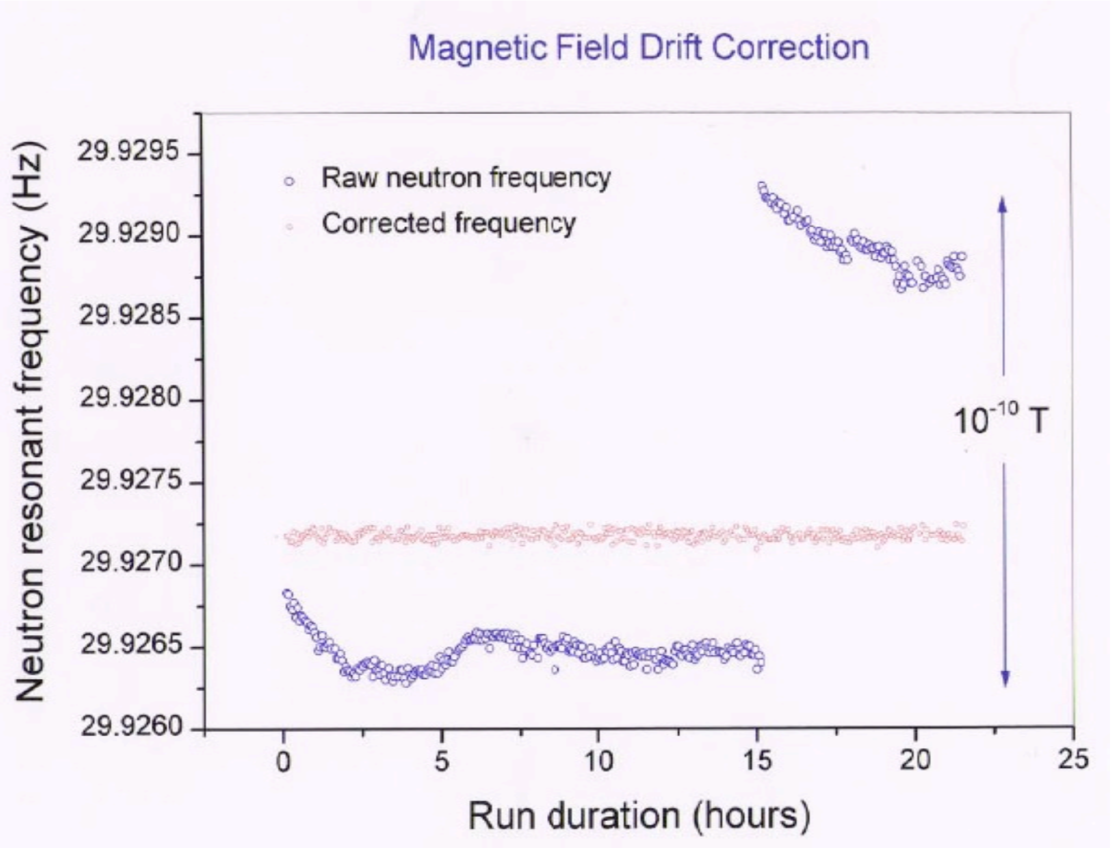
If nEDM = 10^{-26} e·cm,

10 kV/cm → 0.1 μHz shift

≅ B field of 2×10^{-15} T.

Co-magnetometer :

Uniformly samples the B Field faster than the relaxation time.



Data: ILL nEDM experiment with ^{199}Hg co-magnetometer

EDM of ^{199}Hg < 10^{-28} e-cm (measured); atomic EDM ~ Z^2 → ^{3}He EDM << 10^{-30} e-cm

Under gravity, the center of mass of He-3 is higher than UCN by $\Delta h \approx 0.13$ cm, sets ΔB = 30 pGauss (1 nA of leakage current). $\Delta B/B=10^{-3}$.

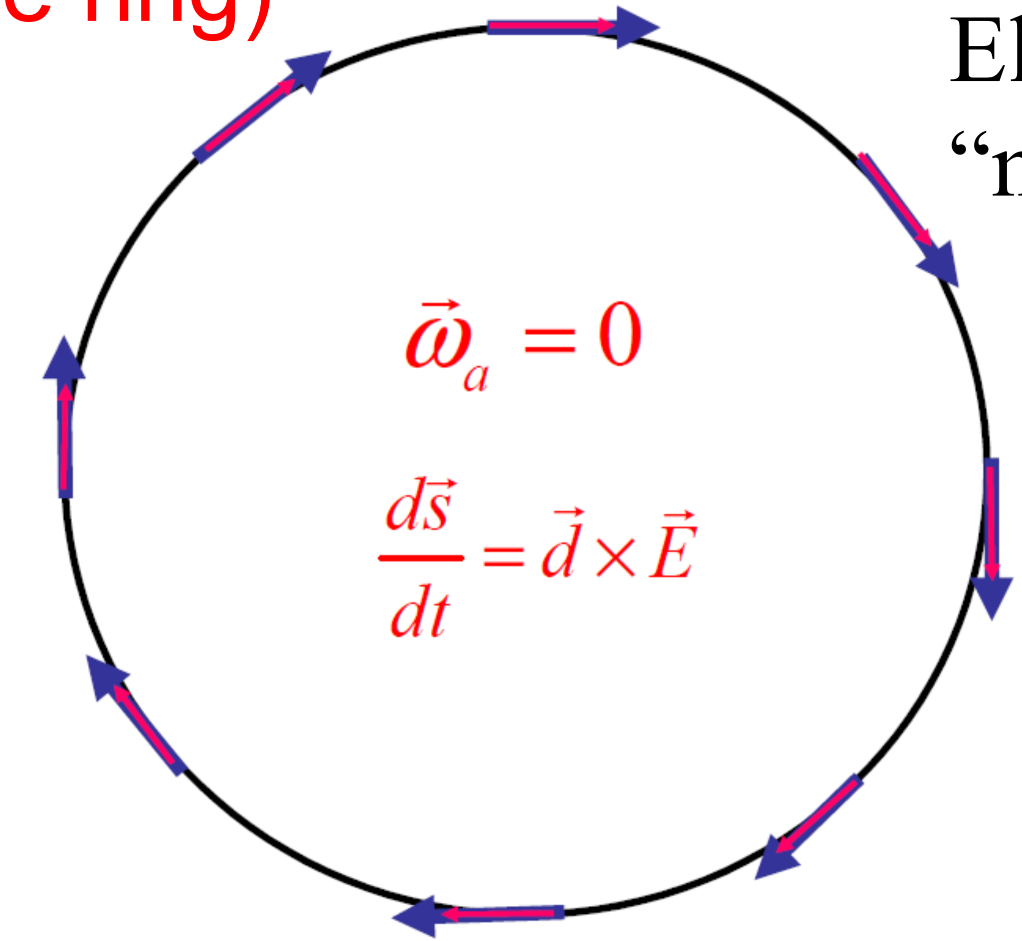
The next level in EDMs

- Neutrons still suffer from statistics
- Hg, Xe, etc. suffer from electron shielding of nucleus
- Ra is developing as a promising method
- ThO is successful in making progress in eEDM, smaller mass than quarks, no direct access to $\boldsymbol{\theta}_{\mathrm{QCD}}$

- Storage-ring proton EDM with a hybrid, symmetric ring lattice is the only one that can
  - Have high statistics for better than 10^{-29} *e*-cm
  - Eliminates primary systematic error sources at design level with present technology
  - A number of symmetry tools are available to combat all known systematic error sources

Storage Ring EDM experiments

(or how to create a Dirac-like particle in a storage ring)

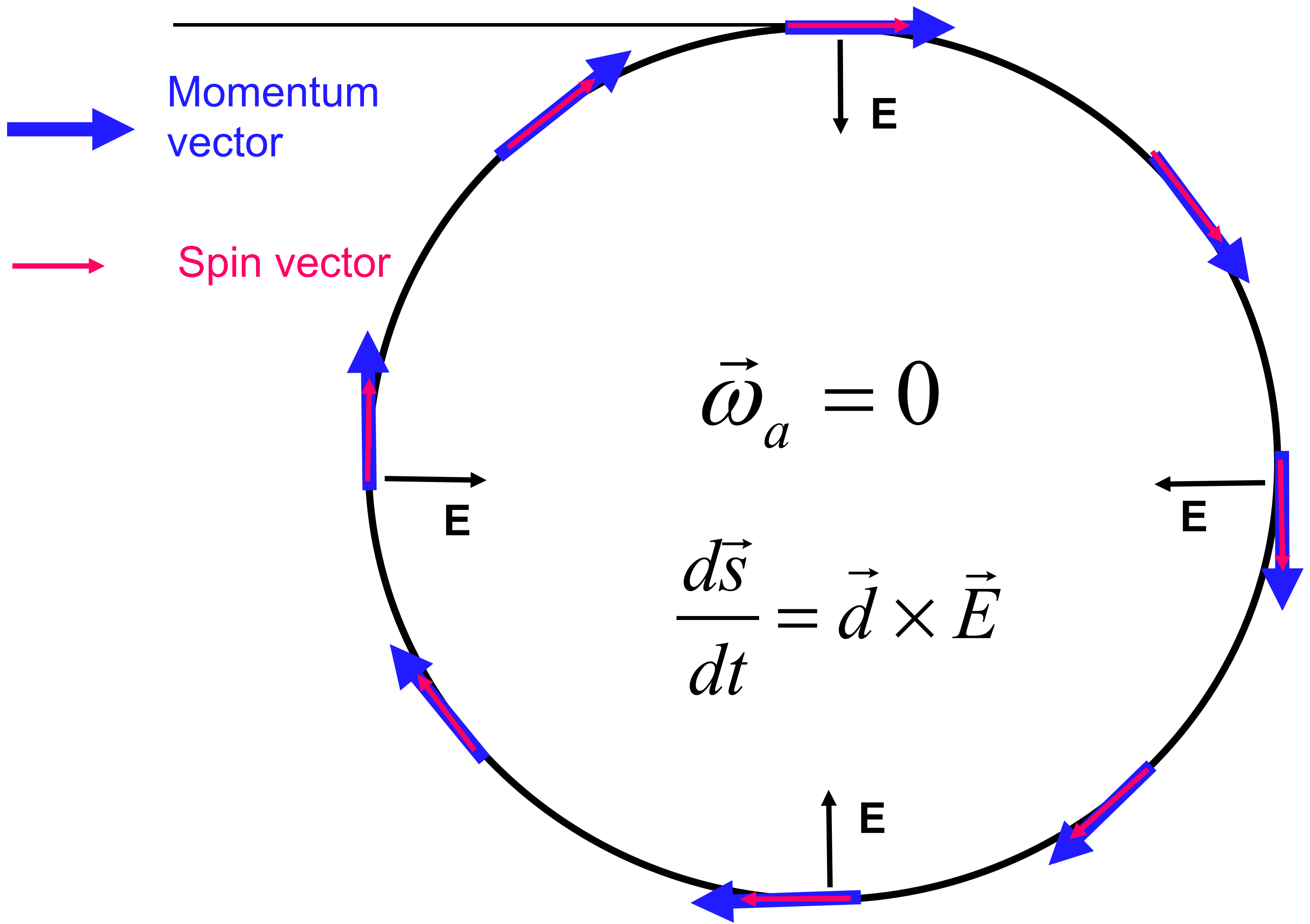


$$\vec{\omega}_a = 0$$

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

Electric bending, w/
“magic” momentum

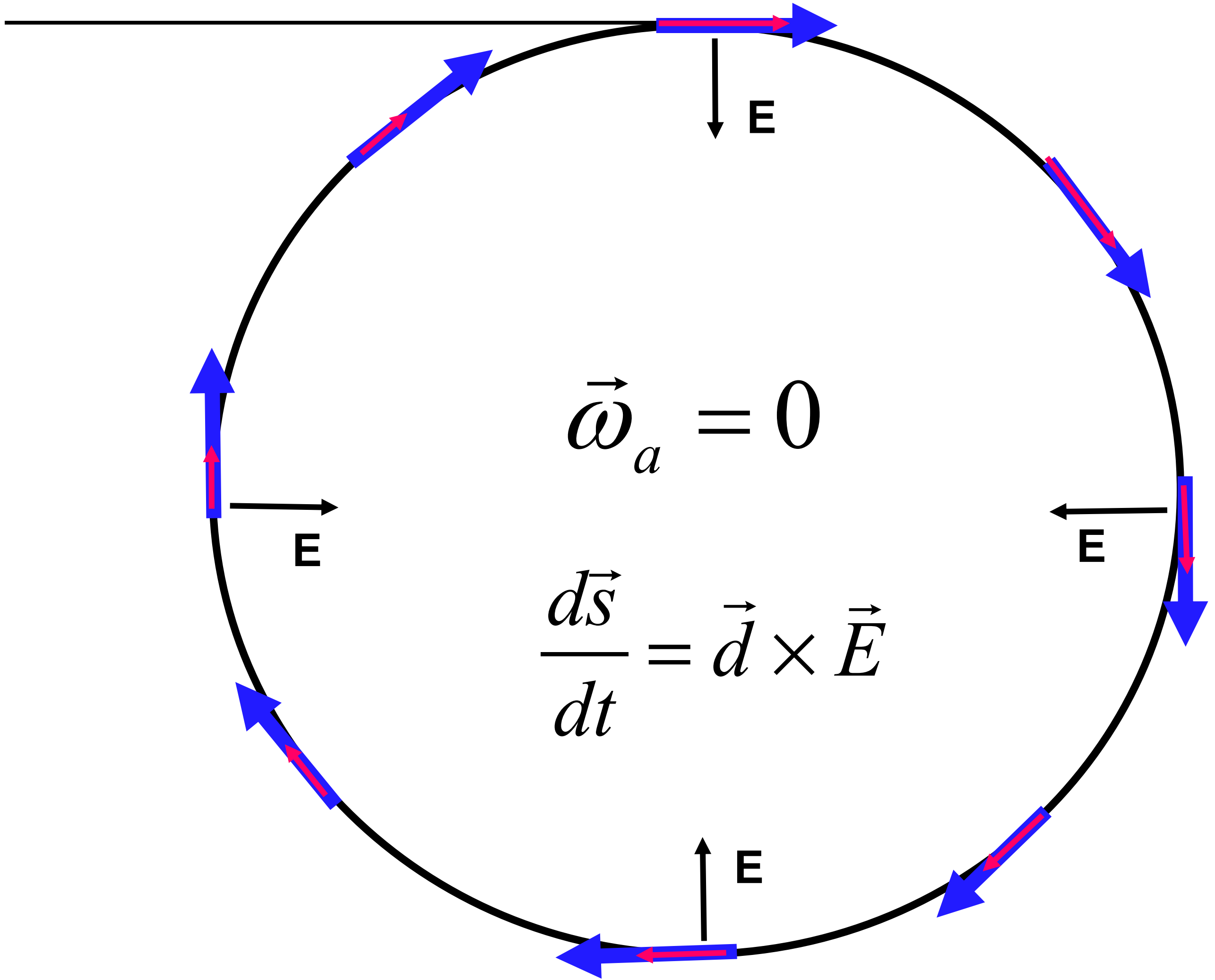
The sensitivity to EDM is optimum when the spin vector is kept aligned to the momentum vector



$$\vec{\omega}_a = 0$$

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

The spin precession relative to momentum in the plane is kept near zero. A vert. spin precession vs. time is an indication of an EDM (*d*) signal.



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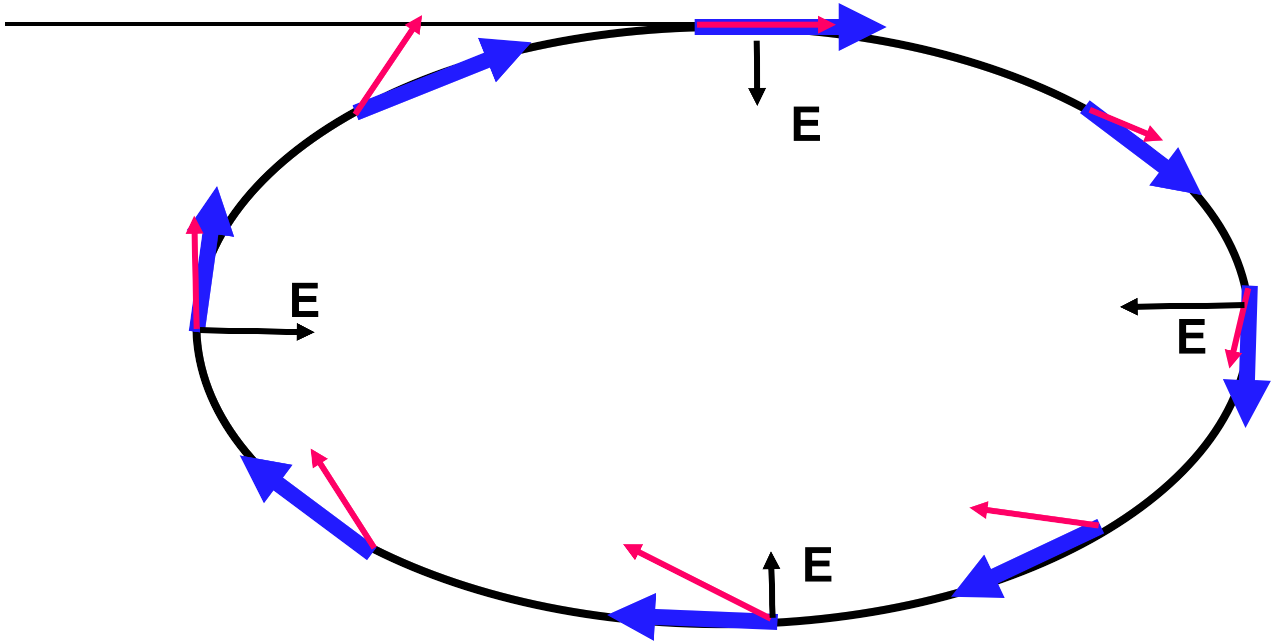


$$\vec{\omega}_a = 0 \qquad \frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

Freezing the horizontal spin precession

$$\vec{\omega}_a = -\frac{q}{m}\left[a - \left(\frac{mc}{p}\right)^2\right]\frac{\vec{\beta}\times\vec{E}}{c}$$

- The spin precession is zero at “magic” momentum (0.7 GeV/c for protons, 3.1GeV/c for muons,…)

$$p = \frac{mc}{\sqrt{a}}, with\ a = G = \frac{g-2}{2}, \gamma_m = \sqrt{1 + 1/a}$$

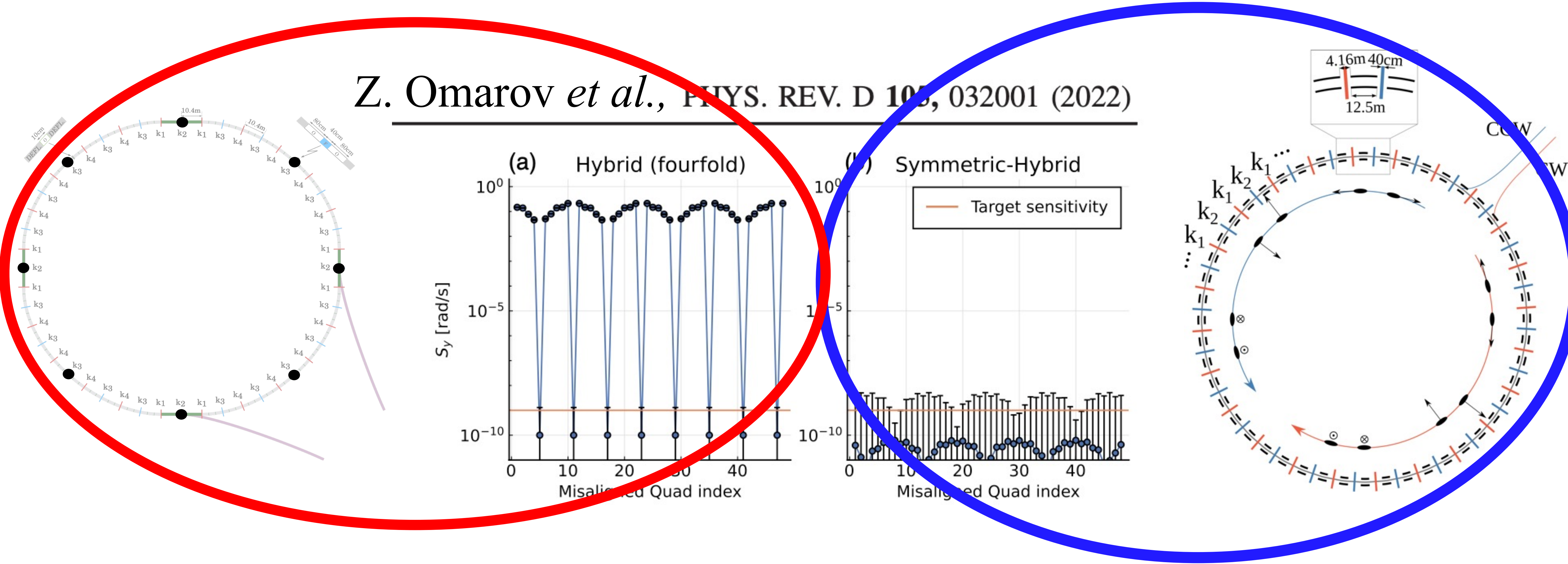
- The “magic” momentum concept was first used in the last muon g-2 experiment at CERN, at BNL & FNAL.

Proton Statistical Error (230MeV): 10^{-29} *e*-cm

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

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 : 4×10^{10}p/cycle Total number of stored particles per cycle (10^3s)
T_{Tot}: 10^7s Total running time per year
f : 1% Useful event rate fraction (efficiency for EDM)
E_R : 4.5 MV/m Radial electric field strength

Hybrid, symmetric lattice storage ring. Great for systematic error reduction.


Z. Omarov *et al.*, PHYS. REV. D 105, 032001 (2022)

Sensitivity of radially polarized beams (sensitive to V. Dark Matter/Dark Energy, P. Graham *et al.*, PRD, 055 010, 2021), most sensitive to vertical velocity problem

EDM is probed with longitudinally polarized beams, less sensitive to this effect by >10^3

Use radially polarized beams to align the ring (spin based alignment) and monitor background

Vertical velocity and geometrical phase effects:

Magnetic quadrupoles 0.2T/m, positioning accuracy dominates background B-fields

Mitigation by flipping quad polarity in ~10^5 separate beam injections

ZHANIBEK OMAROV *et al.* PHYS. REV. D **105,** 032001 (2022)

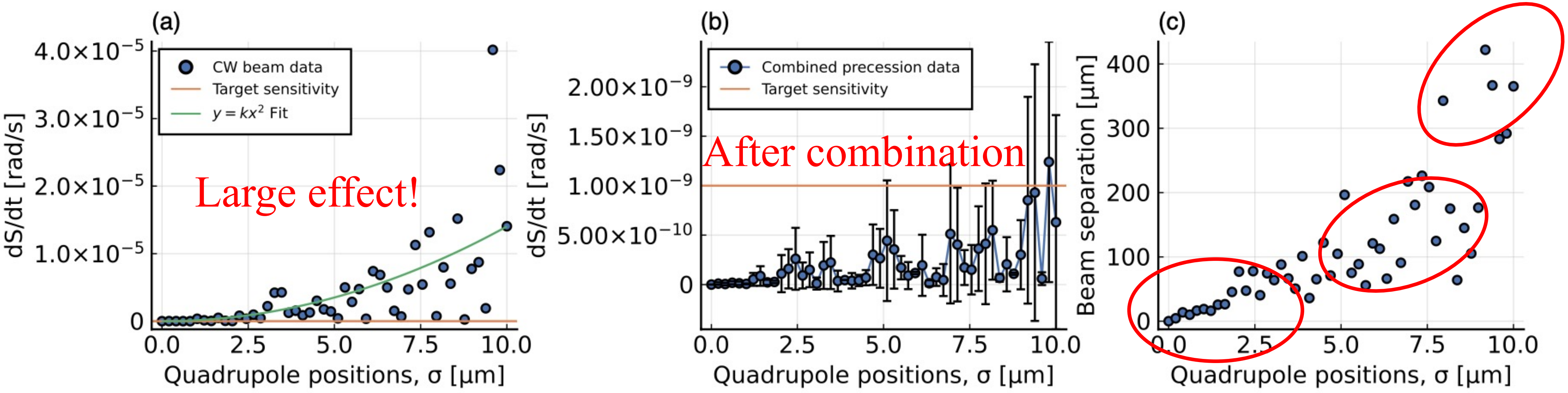


FIG. 9. (a) *Longitudinal polarization case, CW beam only*. Vertical spin precession rate (absolute) vs random misalignments of quadrupoles in both x, y directions by rms σ with different seeds per each point (when the same seeds are used everywhere, the $y = kx^2$ fit is perfect, meaning that every point can be extrapolated to any rms σ value using this functional form). Combination with CCW and quadrupole polarity switching achieves large cancellation—see part (b). (b) *CW and CCW beam and with quadrupole polarity switching*. Total combination as presented in Appendix C. Notably, the background vertical spin precession rate (absolute) stays below the target sensitivity. Irregularity of the points is discussed in Appendix B. (c) Correspondence between CR beam separation and rms σ quadrupole misalignments.

Hybrid, symmetric lattice storage ring

arXiv:2007.10332v2 [physics.acc-ph] 29 Dec 2020

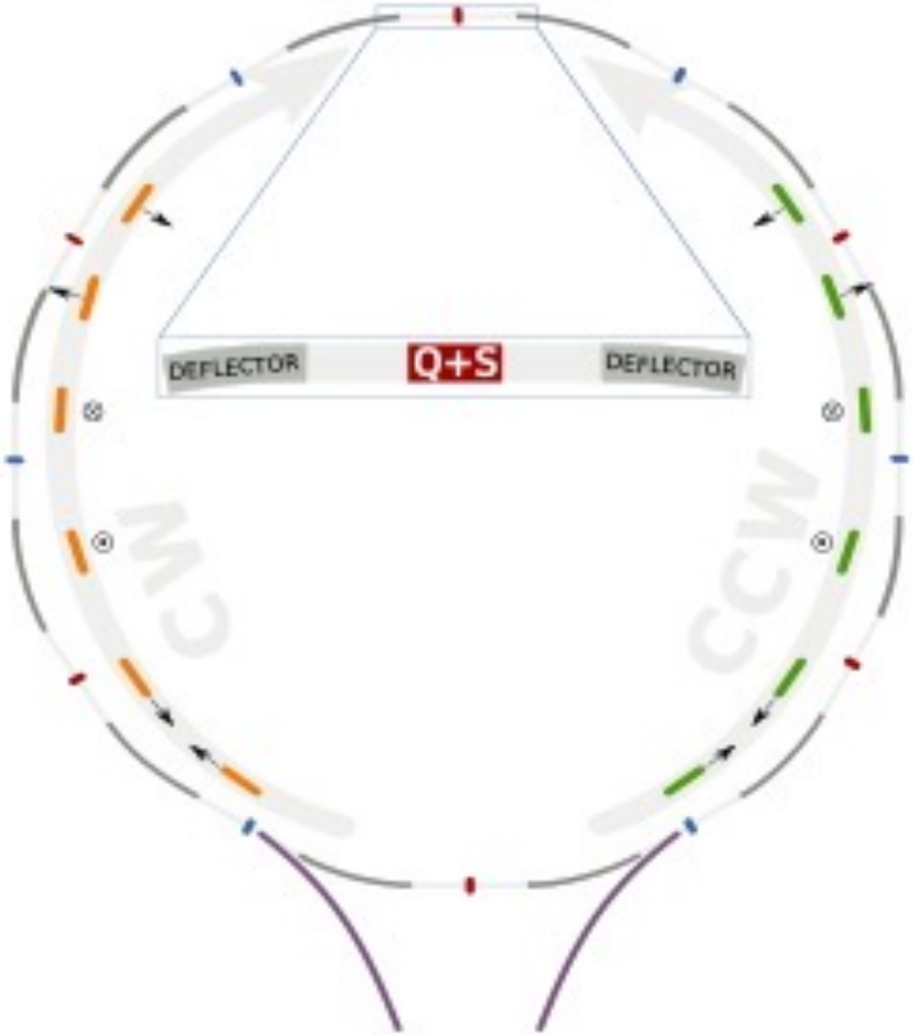


TABLE I. Ring and beam parameters for Symmetric Hybrid ring design

Quantity	Value
Bending Radius R_0	95.49 m
Number of periods	24
Electrode spacing	4 cm
Electrode height	20 cm
Deflector shape	cylindrical
Radial bending E-field	4.4 MV/m
Straight section length	4.16 m
Quadrupole length	0.4 m
Quadrupole strength	±0.21 T/m
Bending section length	12.5 m
Bending section circumference	600 m
Total circumference	799.68 m
Cyclotron frequency	224 kHz
Revolution time	4.46 µs
$\beta_x^{\max}$, $\beta_y^{\max}$	64.54 m, 77.39 m
Dispersion, $D_x^{\max}$	33.81 m
Tunes, Q_x, Q_y	2.699, 2.245
Slip factor, $\eta = \frac{dt}{t} / \frac{dp}{p}$	-0.253
Momentum acceptance, (dp/p)	5.2×10^{-4}
Horizontal acceptance [mm mrad]	4.8
RMS emittance [mm mrad], ϵ_x, ϵ_y	0.214, 0.250
RMS momentum spread	1.177×10^{-4}
Particles per bunch	1.17×10^{8}
RF voltage	1.89 kV
Harmonic number, h	80
Synchrotron tune, Q_s	3.81×10^{-3}
Bucket height, $\Delta p/p_{\text{bucket}}$	3.77×10^{-4}
Bucket length	10 m
RMS bunch length, σ_s	0.994 m

Low risk ←

Strong focusing ←

Input to hadronic EDM

- Theta-QCD (part of the SM)

- CP-violation sources beyond the SM

A number of alternative simple systems could provide invaluable complementary information (e.g. neutron, proton, deuteron,…).

- At 10^{-29}e•cm pEDM is at least an order of magnitude more sensitive than the current nEDM plans

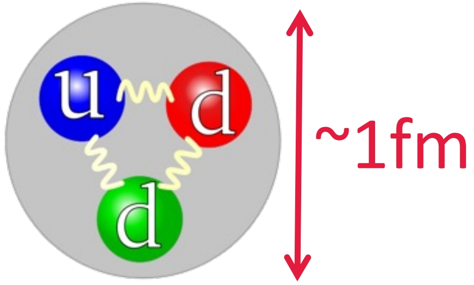
Strong CP-problem and neutron EDM

$$L_{QCD,\bar{\theta}} = \bar{\theta}\ \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

The QCD Lagrangian contains a theta-term violating both P-parity and T-time reversal symmetries.

Strong CP-problem and neutron EDM

$$L_{QCD,\bar{\theta}} = \bar{\theta} \, \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$



Dimensional analysis (naïve) estimation of the neutron EDM:

$$d_n(\bar{\theta}) \sim \bar{\theta} \, \frac{e}{m_n} \frac{m_*}{\Lambda_{QCD}} \sim \bar{\theta} \cdot \left(6 \times 10^{-17}\right) \mathrm{e} \cdot \mathrm{cm}, \quad m_* = \frac{m_u m_d}{m_u + m_d}$$

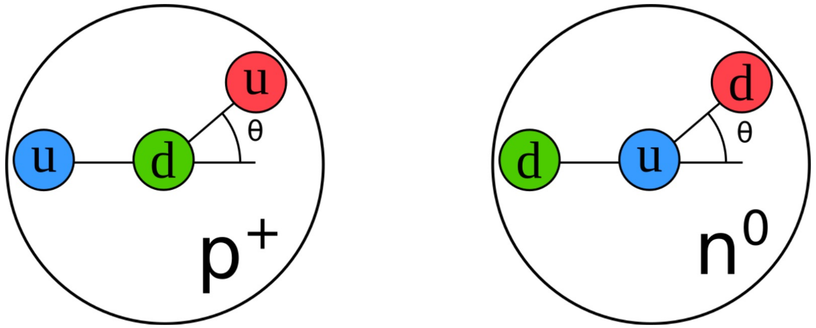
$$d_n(\bar{\theta}) \approx -d_p(\bar{\theta}) \approx 3.6 \times 10^{-16} \bar{\theta} \ \mathrm{e} \cdot \mathrm{cm}$$

M. Pospelov,
A. Ritz, Ann. Phys.
318 (2005) 119.

$$\text{Exp.: } d_n < 3 \times 10^{-26} e \cdot \mathrm{cm} \rightarrow \bar{\theta} < 10^{-10}$$

In simple terms: the theory of strong interactions demands a large neutron EDM. Experiments show it is at least ~9-10 orders of magnitude less! WHY?

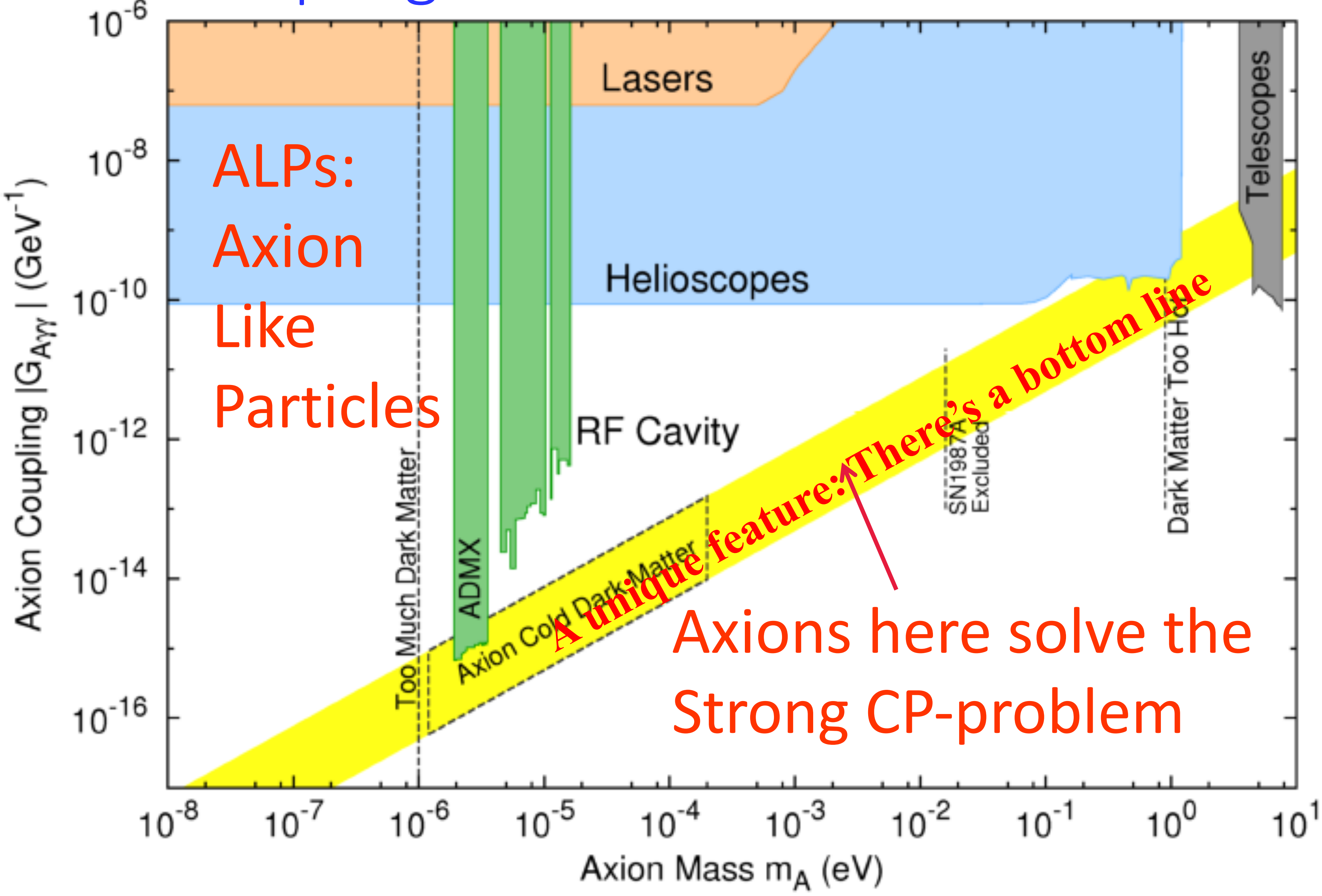
Strong CP-problem: the neutron EDM is too small…



$$L_{QCD,\bar{\theta}} = \left(\bar{\theta} - \frac{a(x)}{f_a} \right) \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

- Peccei-Quinn: θ_{QCD} is a dynamical variable (1977), *$a(x)/f_a$*. It goes to zero naturally.
- Weinberg and Wilczek pointed out that a new particle must exist, axion.

Axion coupling vs. axion mass

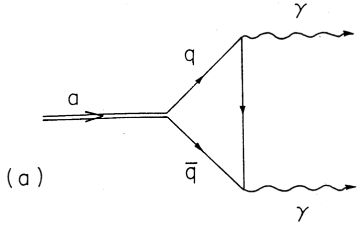


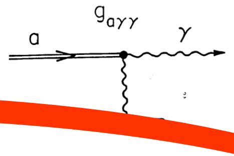
ALPs:
Axion
Like
Particles

A unique feature: There's a bottom line

Axions here solve the Strong CP-problem

Axion Couplings





- Gauge fields:
  - Electromagnetic fields
  -
  - Gluon Fields (Oscillating EDM,…)

$$L_{\text{int}} = -\frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

$$L_{\text{int}} = \frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

- Fermions (coupling with axion field gradient, pseudomagnetic field)

$$L_{\text{int}} = \frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

Dark Matter and Isaac Newton (1642-1726)

Isaac Newton unified the Physics phenomena: falling of an apple with the planet, moon, star, sattelite, comet motions, under Gravity!

He clarified the view of Heavens for Humanity!

He also gave us the ability to see what cannot be seen with ordinary methods. Looking from deviations from his rules we are able to sense the presence of Dark Matter.

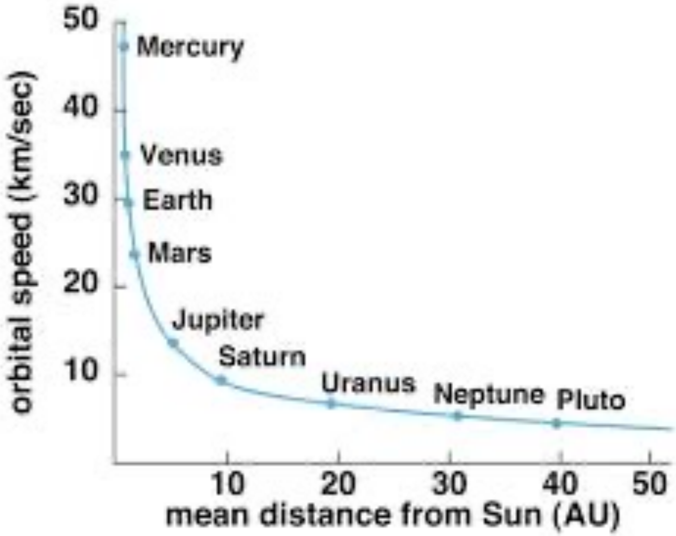
Newton's laws: "observing" the unseen

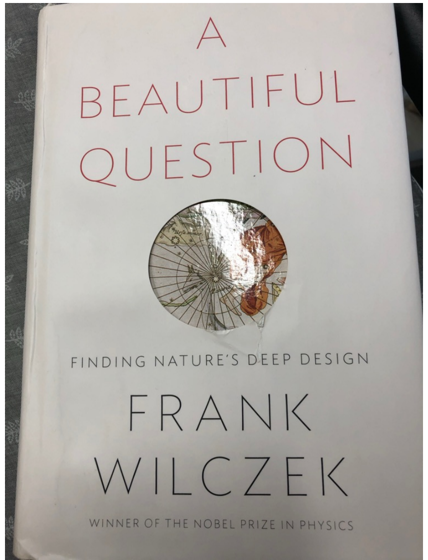
- Gravitational law applied to the planets: by measuring the planet velocity and its distance from the center, we can estimate the enclosed mass.

$$F = \frac{GM_\odot m}{r^2} = \frac{mv^2}{r}$$

$$v = \sqrt{\left(\frac{GM_\odot}{r}\right)}$$

1915, Einstein's General Relativity
Resolved the issue with Mercury's precession



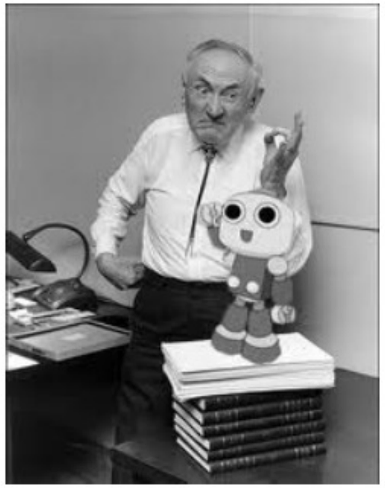


1846, Adams and Le Verrier suggested the existence of Neptune: First discovery of "Dark Matter". Frank Wilczek in "A Beautiful Question"

For gravitational attraction, n equals −1 and the average kinetic energy equals half of the average negative potential energy

$$\langle T\rangle_\tau = -\frac{1}{2}\langle V_{\mathrm{TOT}}\rangle_\tau .$$

Origins of dark-matter: Zwicky (Coma cluster) & Smith (Virgo cluster)



Coma Cluster

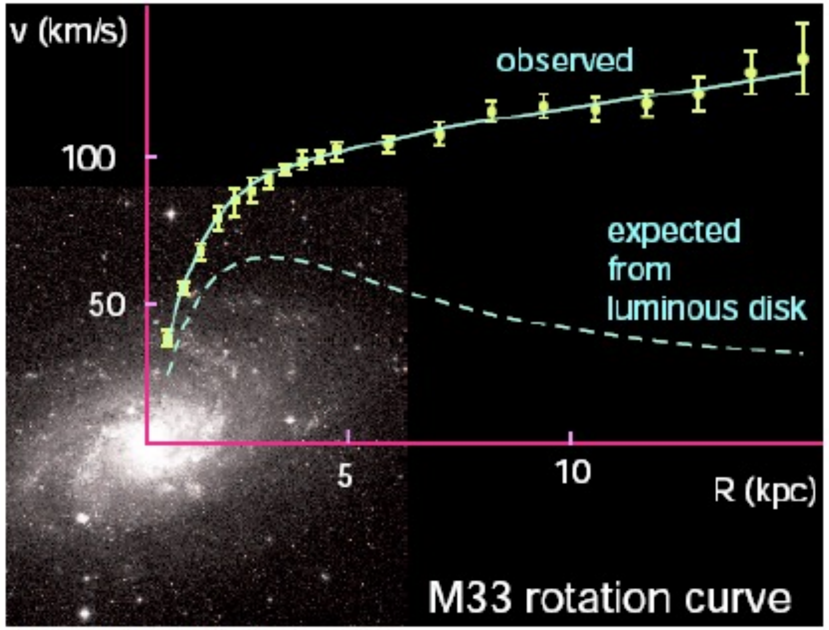
Virial motions within galaxy clusters:

"The difference between this result and Hubble's value for the average mass of a nebula must remain unexplained until further information becomes available."

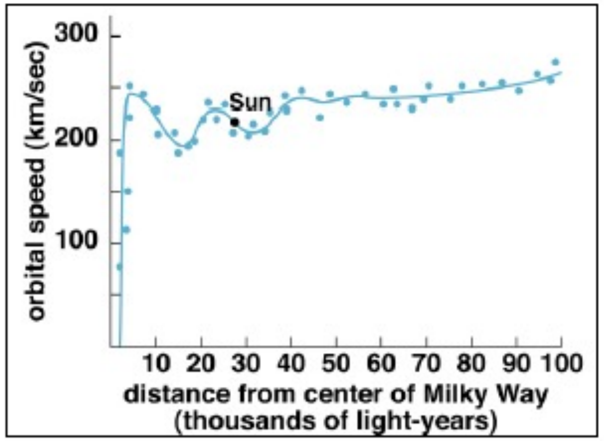
The "dunkelmaterie" of Zwicky 1936

Origins of dark matter: Rubin, Gallagher, Faber et al.

Flat galactic rotation curves
Rubin, “1970’s: The decade of seeing is believing.”



Paolo Saluchi



Vera Rubin

- Her findings were cross checked and found to be correct.
- More galaxies were checked, most of them found to be part of extended halos
- Vera Rubin started a field in Astronomy that firmly established the idea of DM.

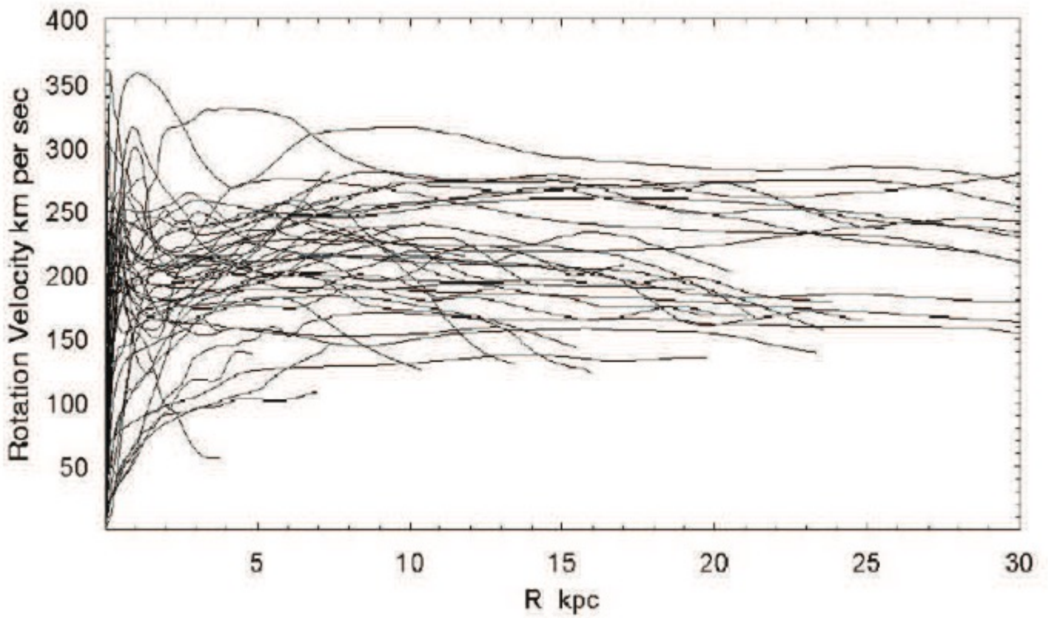


Figure 4: Rotation curves of spiral galaxies obtained by combining CO data for the central regions, optical for disks, and HI for outer disk and halo (Sofue et al. 1999).

[https://www.nature.com/articles/nature25767].

A Galaxy without Dark Matter, effectively confirming Dark Matter!

A Galaxy Without Dark Matter

Press Release - Source: Yale University   Posted March 28, 2018 10:34 PM   0 Comments

NGC 1052-DF2

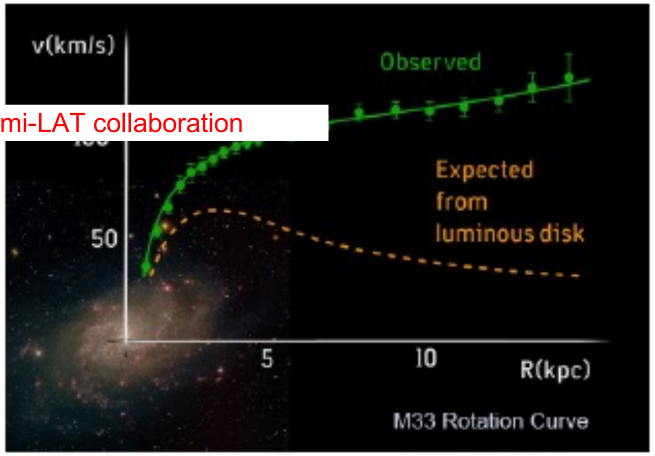
©YALE/NASA

A Yale-led research team has discovered a galaxy that contains no dark matter -- a finding that confirms the possibility of dark matter as a separate material elsewhere in the universe.

The discovery has broad implications for astrophysics, the researchers said. It shows for the first time that dark matter is not always associated with traditional matter on a galactic scale, ruling out several current theories that dark matter is not a substance but merely a manifestation of the laws of gravity on cosmic scales.

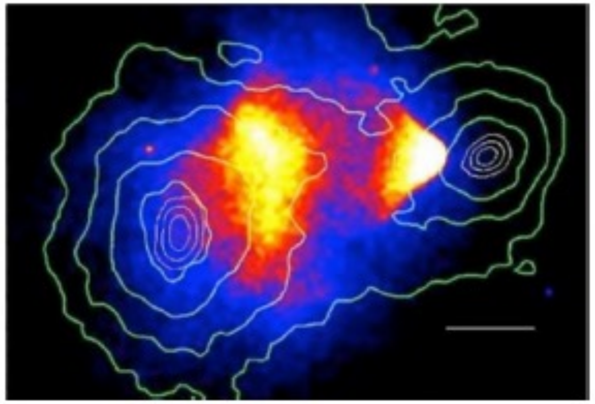
Evidence for / Salient Features of Dark Matter

*Comprises **majority** of **mass** in Galaxies*
Missing mass on Galaxy Cluster scale
Zwicky (1937)

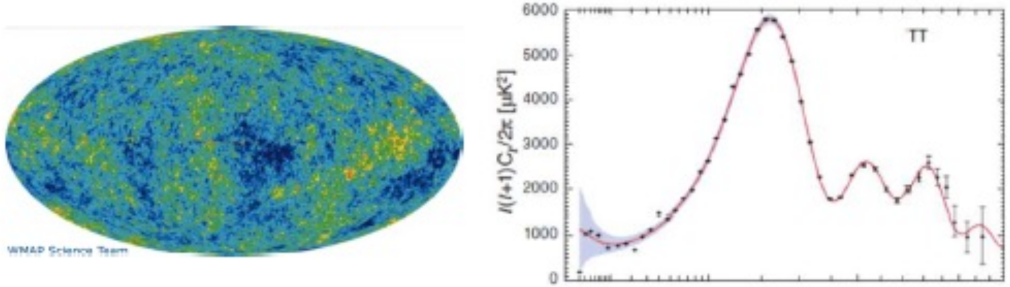


Eric Charles, Fermi-LAT collaboration

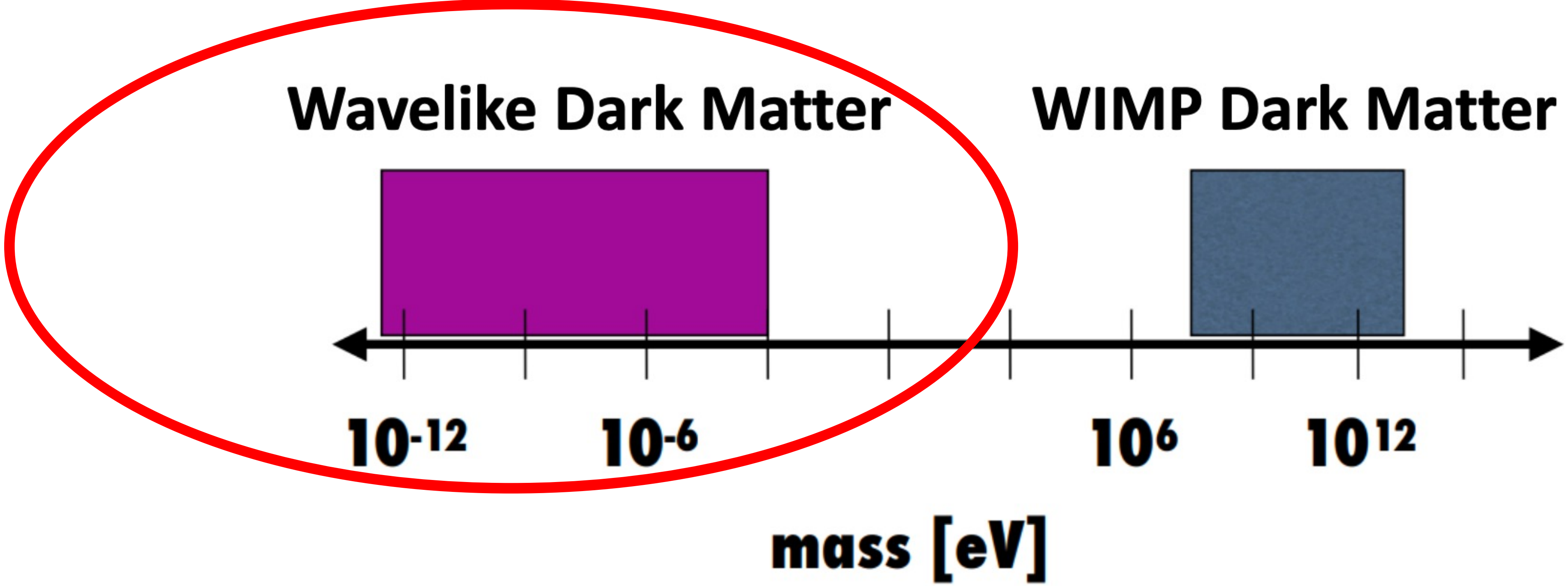
*Large **halos** around Galaxies*
Rotation Curves
Rubin+(1980)



*Almost **collisionless***
Bullet Cluster
Clowe+(2006)



Non-Baryonic
Big-bang Nucleosynthesis,
CMB Acoustic Oscillations
WMAP(2010)



de Broglie Wavelength - $\lambda_{dB} \approx \frac{2\pi}{mv}$

Occupancy Number - $N \approx \frac{\rho_{DM}}{m}\lambda_{dB}^3$

- Axion ($m \sim 10^{-9}$ eV): $\lambda_{dB} \sim 10^4$ km with $N \sim 10^{44}$
- WIMP ($m \sim 100$ GeV): $\lambda_{dB} \sim 10^{-16}$ km with $N \sim 10^{-36}$

where $\rho_{DM} = 0.4$ GeV/cm^3

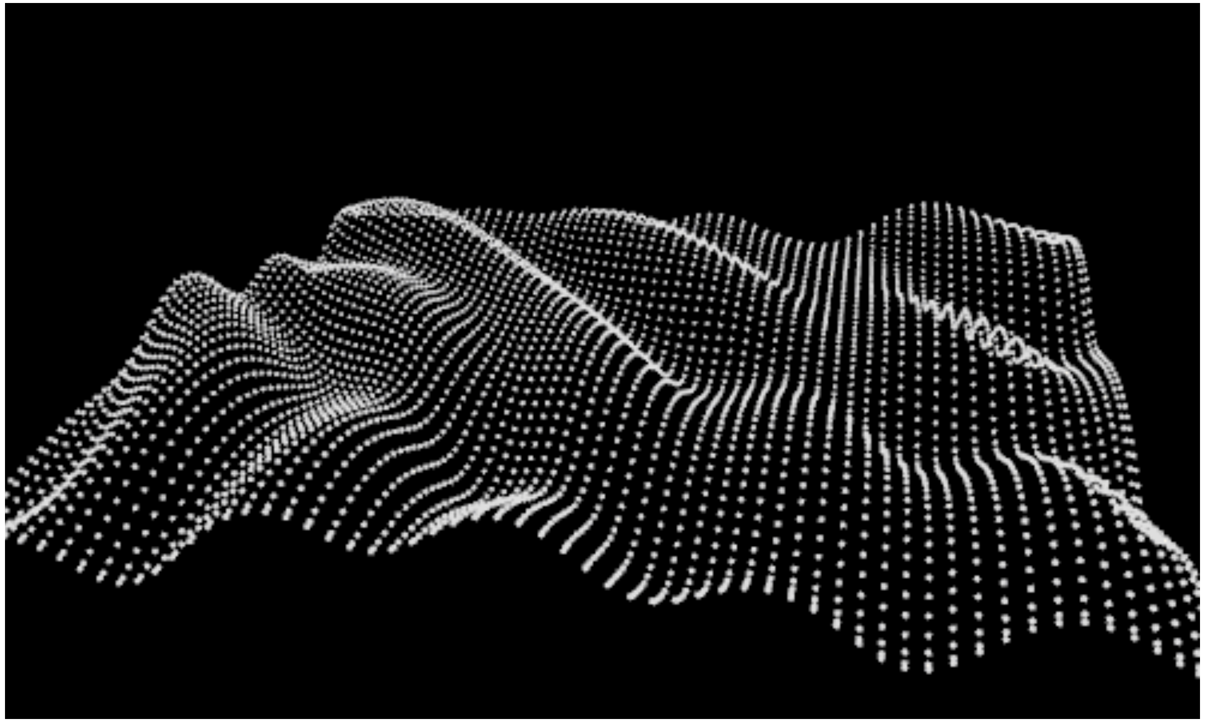
Adapted from B. Safdi

Axion Dark Matter: a Cosmic MASER

De Broglie wavelength of axions

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

$$\lambda \approx 300\mathrm{m} \times \left(\frac{1\mu\mathrm{eV}}{m_a}\right)$$



World map of current experiments on wavy dark matter

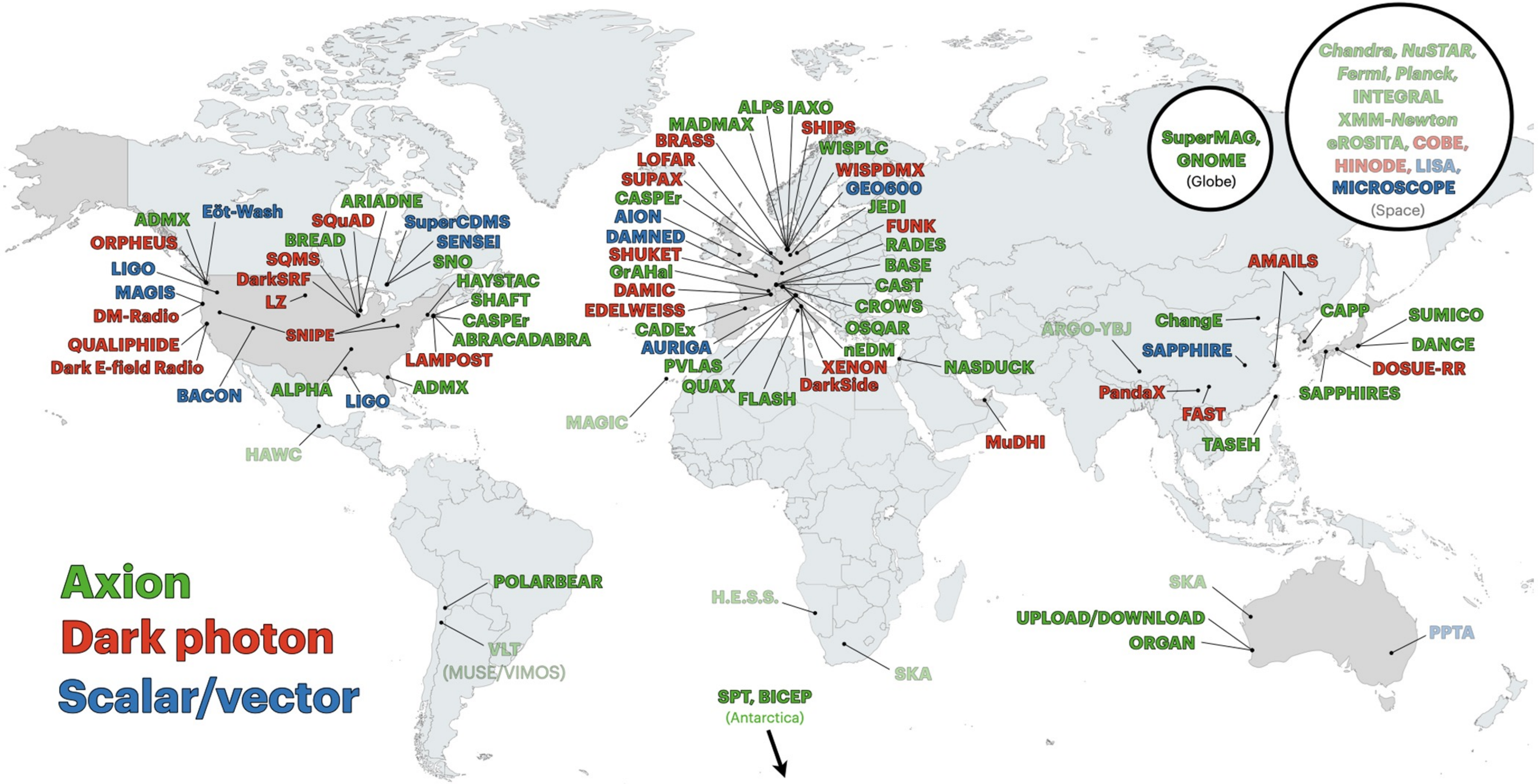
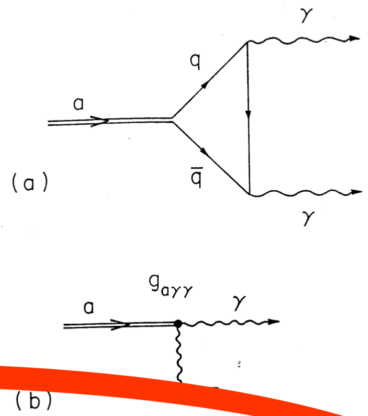


Figure 6: World map displaying current experiments searching for wavy dark matter [9].

Axion Couplings



- Gauge fields:
  - Electromagnetic fields
  -
  - Gluon Fields (Oscillating EDM,…)

$$L_{\text{int}} = -\frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

Cavity experiments at IBS-CAPP, Korea

$$L_{\text{int}} = \frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

- Fermions (coupling with axion field gradient, pseudomagnetic field)

$$L_{\text{int}} = \frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

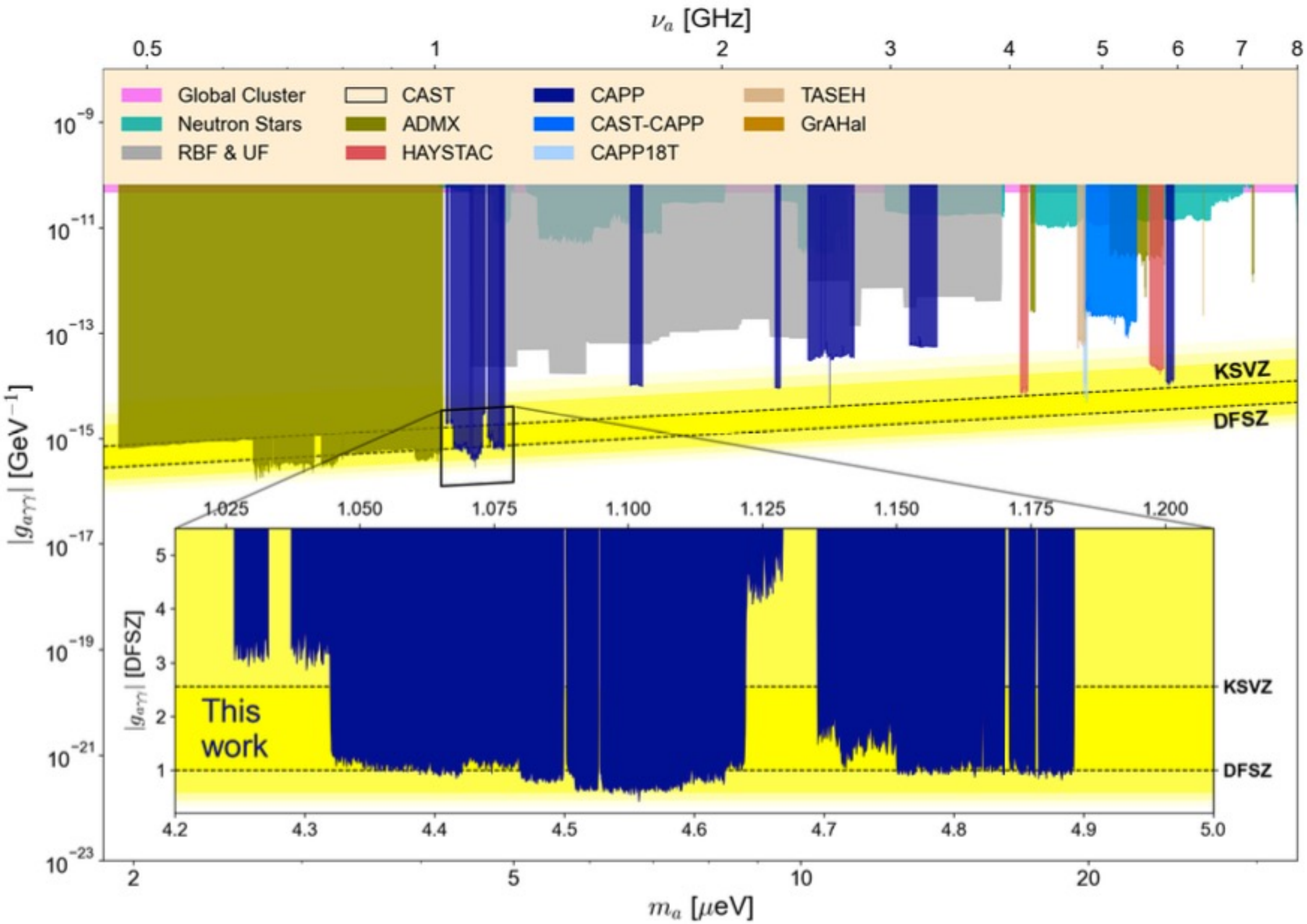
Institute for Basic Science, South Korea
2011: Major Investment in Basic Sciences

- IBS-CAPP is scanning at DFSZ sensitivity for axions over 1 GHz. (It seemed impossible at CAPP's establishment time, October 2013.)

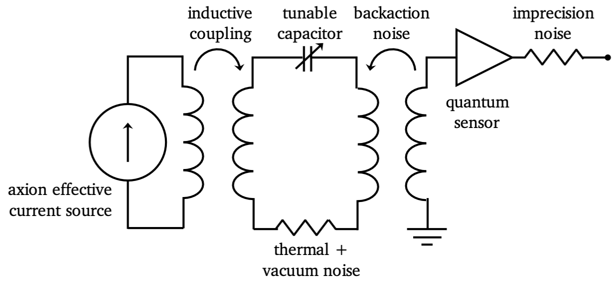
- **IBS-CAPP** with its many innovations including its HTS-cavities ($Q>10^7$ at 8T) is currently on **top of its field internationally in less than ten years** since its establishment!

- IBS-CAPP can be a leader in scanning the 1-8 GHz range for axions with DFSZ sensitivity. Even if axions are only 10% of the local dark matter density.

IBS-CAPP at DFSZ sensitivity, scanning 1-8 GHz



Dark Matter Radio, 2203.11246



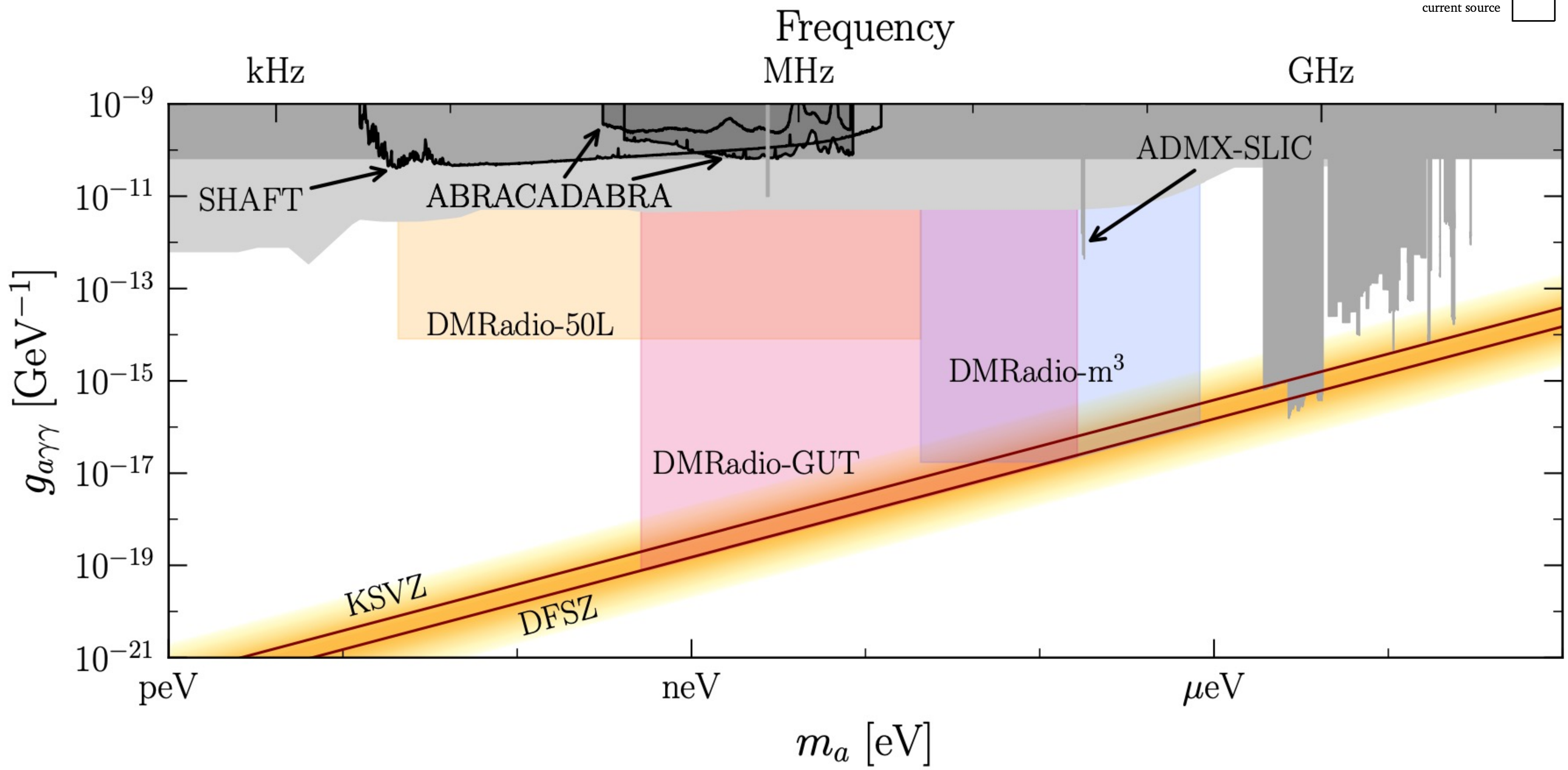
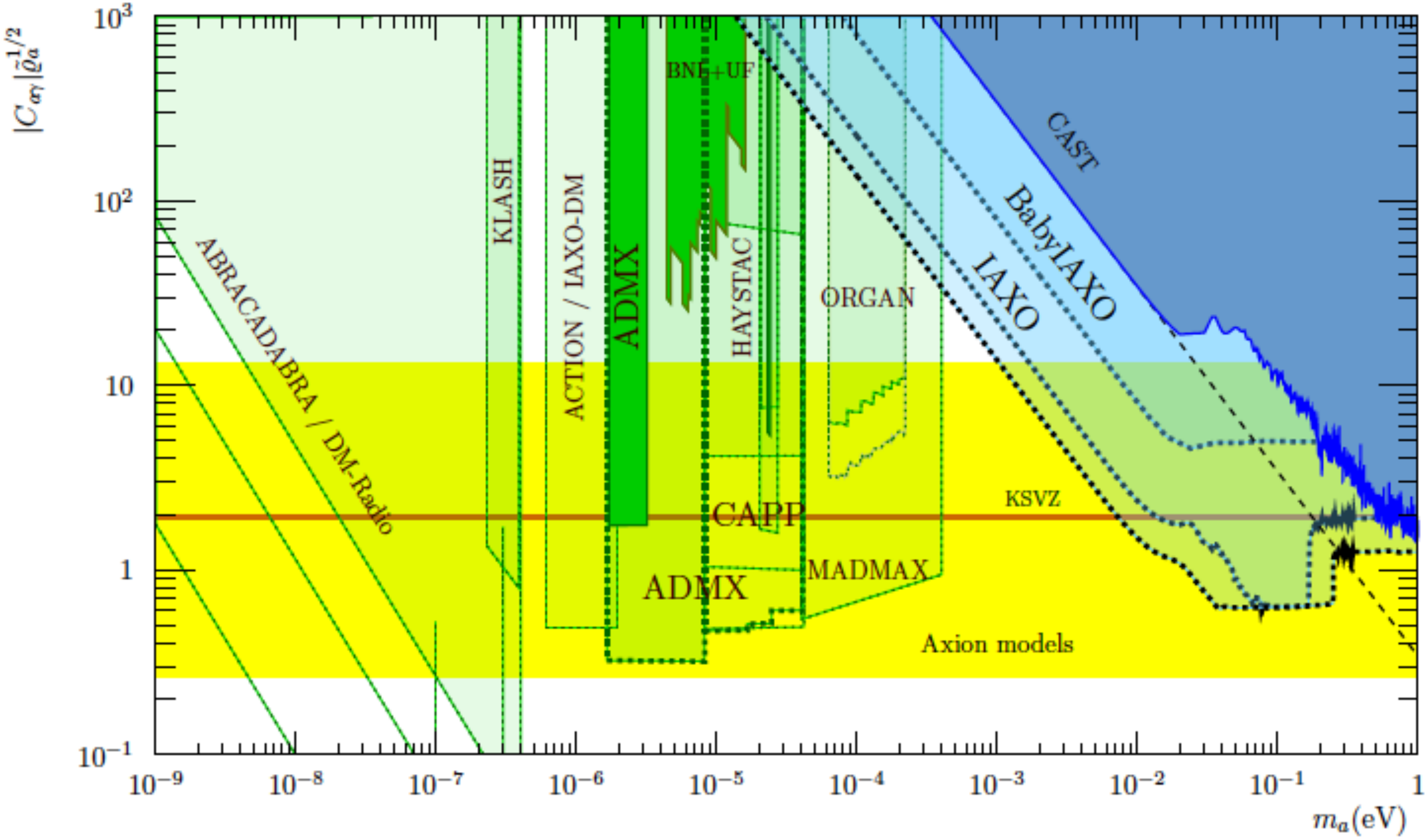


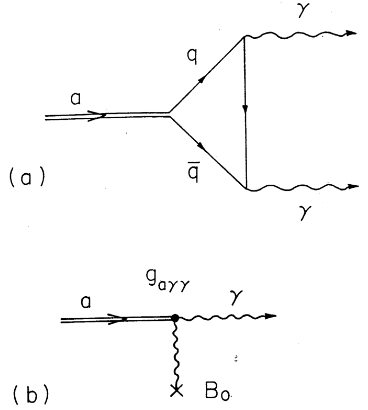
FIG. 4. Projected sensitivity for DMRadio-GUT in pink. The total scan time to cover this reach is ∼ 6 years, depending on R&D outcomes. Various scenarios are outlined in Table II. Existing limits are shown in grey.

Actively planned axion exps.



Irastorza, Redondo 1801.08127v2

Axion Couplings



- Gauge fields:
  - Electromagnetic fields
  -
  - Gluon Fields (Oscillating EDM,…)

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$$\boxed{L_{\text{int}} = \frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}}$$

- Fermions (coupling with axion field gradient, pseudomagnetic field)

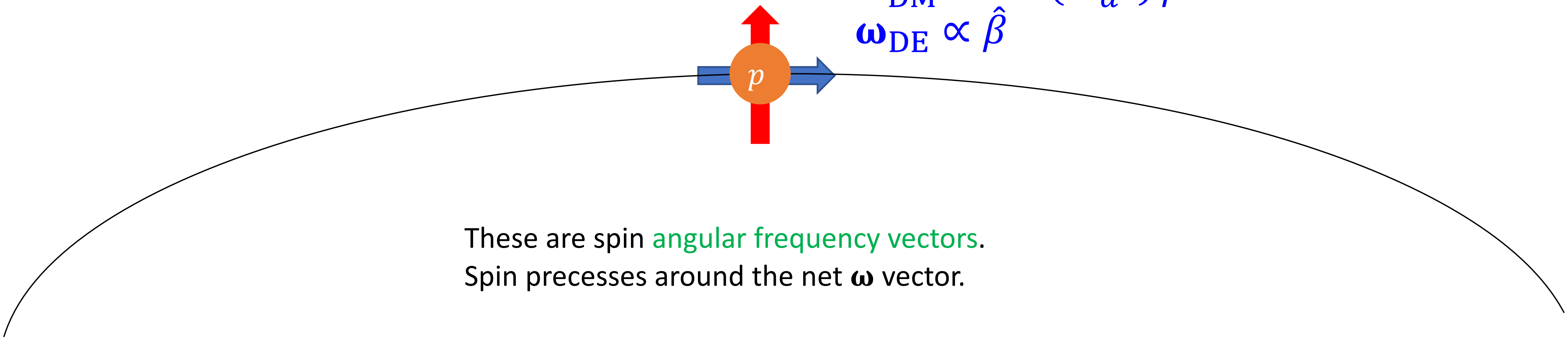
$$\boxed{L_{\text{int}} = \frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f}$$

Storage ring pEDM experiment at BNL

Storage ring probes of DM/DE

P. Graham and S. Rajendran, PRD **88**, 035023 (2013)
P. Graham et al., PRD **103**, 055010 (2021)

- Couplings with dark matter (DM) and dark energy (DE)
  - ALP DM-EDM ($g_{aN\gamma} a \hat{\sigma}_N \cdot \mathbf{E}$) ⇒ oscillating EDM at m_a. For the QCD axion: $d_N^{\mathrm{QCD}} \approx 10^{-34} \cos(m_a t)\ e \cdot \mathrm{cm}$.
  - ALP or vector DM wind ($g_{aNN} \nabla a \cdot \hat{\sigma}_N$) ⇒ anomalous longitudinal oscillating B field.
  - DE wind ⇒ anomalous longitudinal B field.



$\boldsymbol{\omega}_{\mathrm{axion-EDM}} \propto \cos(m_a t)\, \hat{x}$

$\boldsymbol{\omega}_{\mathrm{DM}} \propto \cos(m_a t)\, \hat{\beta}$
$\boldsymbol{\omega}_{\mathrm{DE}} \propto \hat{\beta}$

These are spin angular frequency vectors.
Spin precesses around the net $\boldsymbol{\omega}$ vector.

Storage ring probes of DM/DE

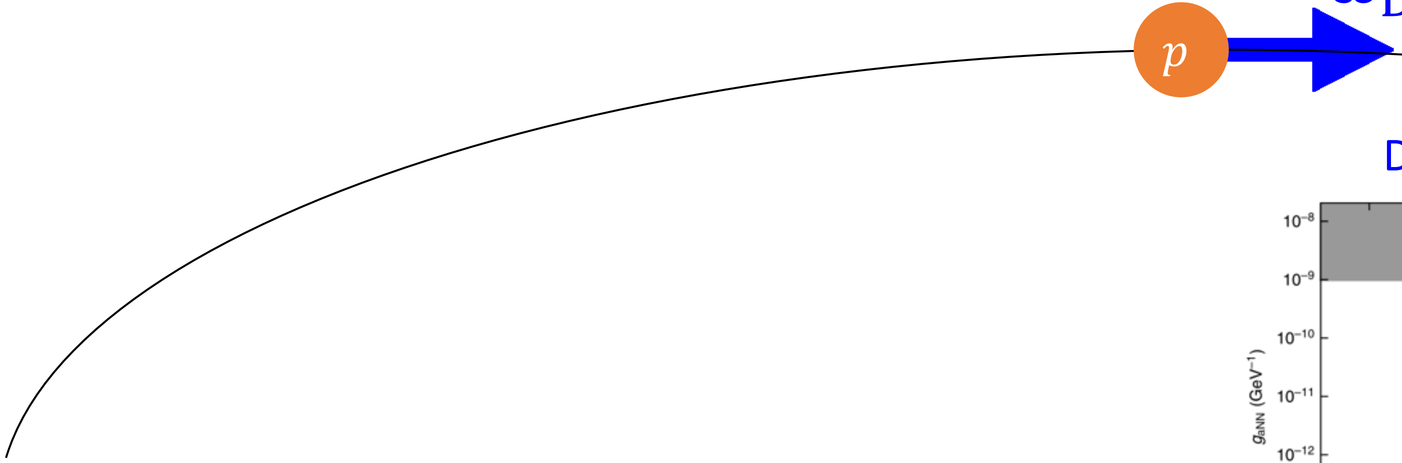
- Couplings with dark matter (DM) and dark energy (DE)

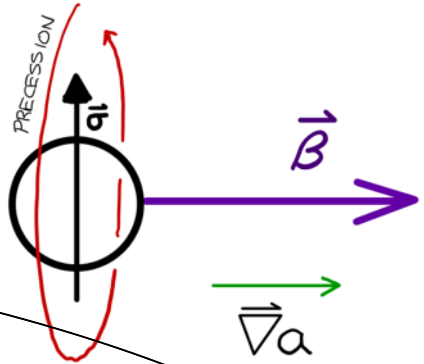
P. Graham and S. Rajendran, PRD **88**, 035023 (2013)
P. Graham et al., PRD **103**, 055010 (2021)

  - ALP or vector DM wind ($g_{aNN}\nabla a \cdot \hat{\sigma}_N$) ⇒ anomalous longitudinal oscillating B field.
  - DE wind ⇒ anomalous longitudinal B field.

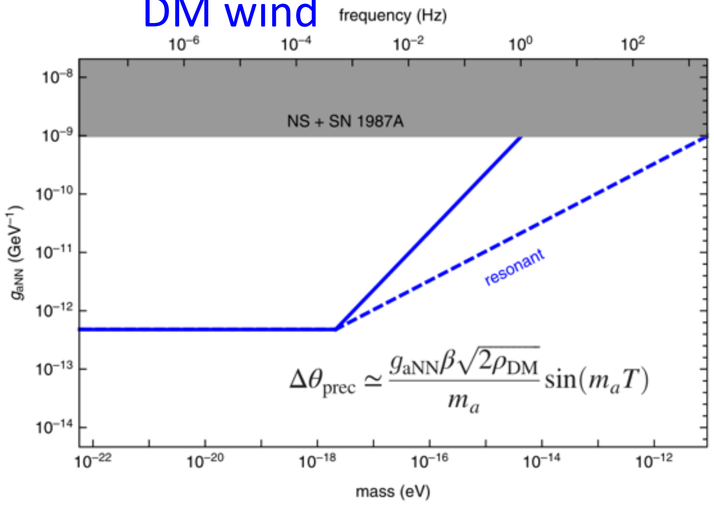
Storage ring is an optimal probe for wind coupling since β is large!

$$\boldsymbol{\omega}_{\mathrm{DM}} \propto \cos(m_a t)\,\hat{\beta}$$
$$\boldsymbol{\omega}_{\mathrm{DE}} \propto \hat{\beta}$$





DM wind

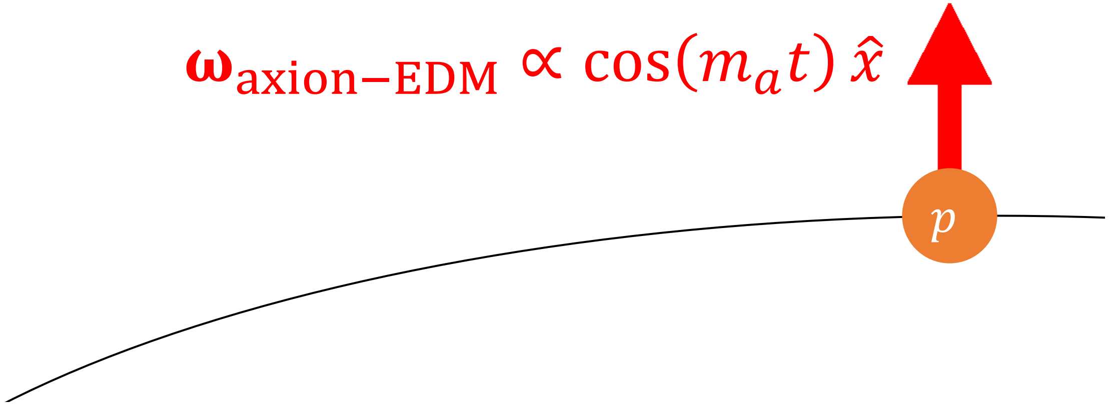


Storage ring probes of DM/DE

P. Graham and S. Rajendran, PRD **88**, 035023 (2013)
P. Graham et al., PRD **103**, 055010 (2021)

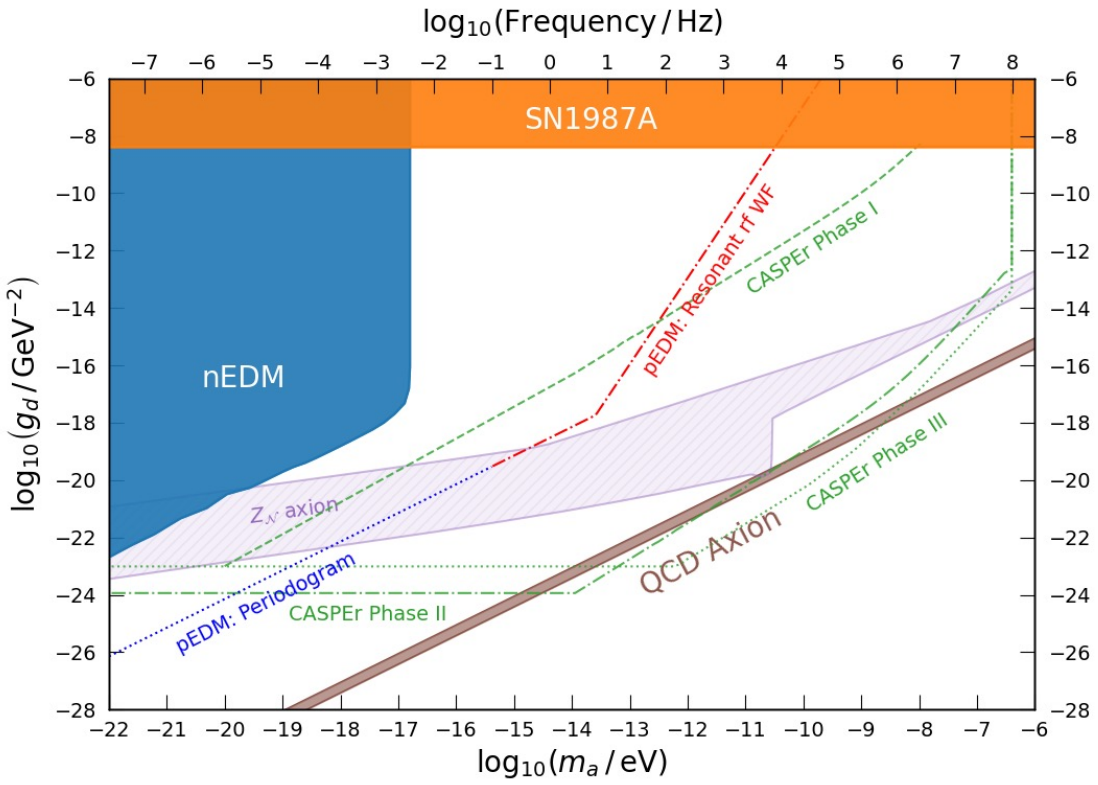
- Couplings with dark matter (DM) and dark energy (DE)
  - ALP DM-EDM ($g_{aN\gamma} a \hat{\sigma}_N \cdot \mathbf{E}$) ⇒ oscillating EDM at m_a. For the QCD axion: $d_N^{\mathrm{QCD}} \approx 10^{-34} \cos(m_a t)\ e \cdot \mathrm{cm}$.

First experimental application at COSY 2019-2022


$$\boldsymbol{\omega}_{\mathrm{axion-EDM}} \propto \cos(m_a t)\,\hat{x}$$

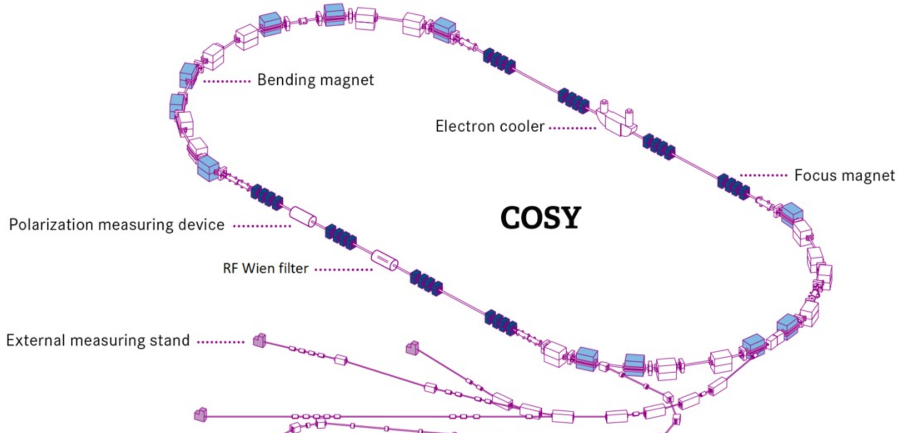
- Storage ring probes of axion-induced oscillating EDM
  S. Chang *et al.*, PRD **99**, 083002 (2019).
- Complementary method using an rf Wien filter
  On Kim and Y. Semertzidis, PRD **104**, 096006 (2021)
- Parasitic measurement with pEDM experiment
  - Low frequency: Periodogram analysis.
  - High frequency: Resonant rf Wien filter.

ALP-EDM coupling



Axion dark matter search in storage rings

- First experimental application at COSY/Juelich 2019-2022, JEDI coll., Phys. Rev. X13, 031004 (2023)



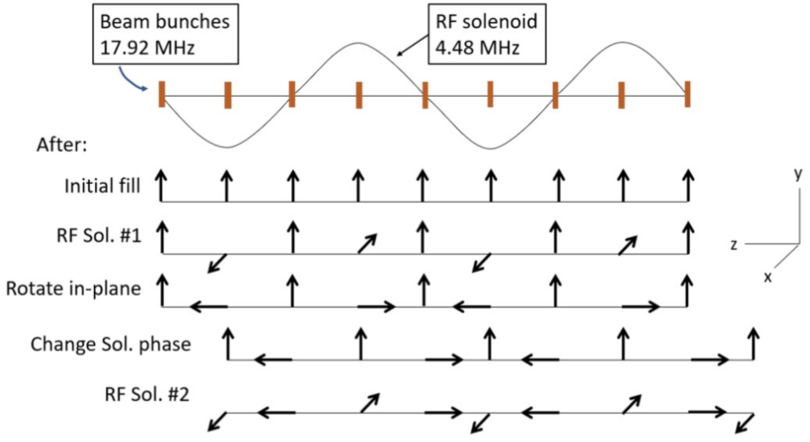
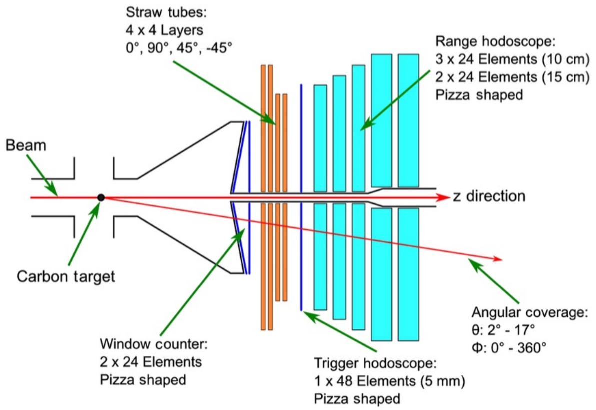
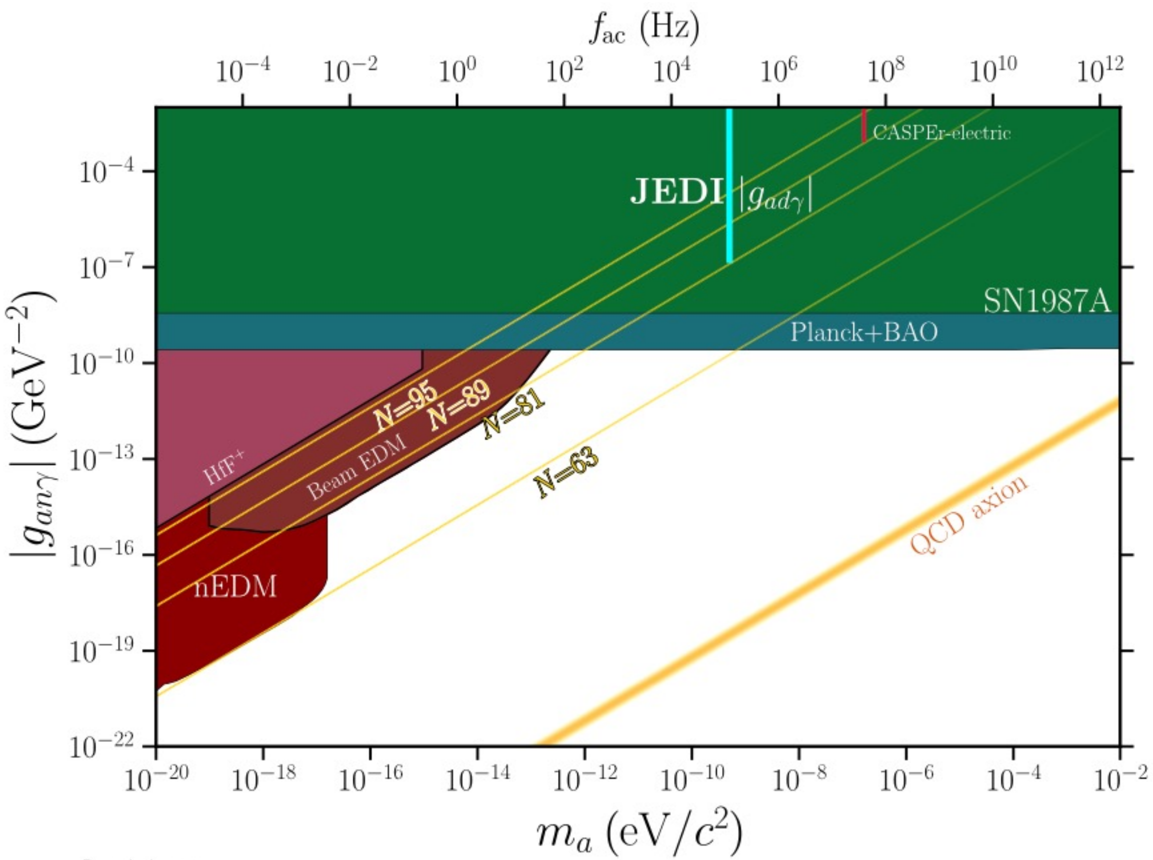


Figure 4: The figure illustrates the steps needed to produce in-plane polarization in four directions. The stored beam in, e.g., the CW direction, has all bunches polarized in the vertical direction, represented by the vertical arrows in line 1 (labeled "Initial fill"). The RF-solenoid is powered to rotate two bunches at a time, shown in line 2, and then in line 5.

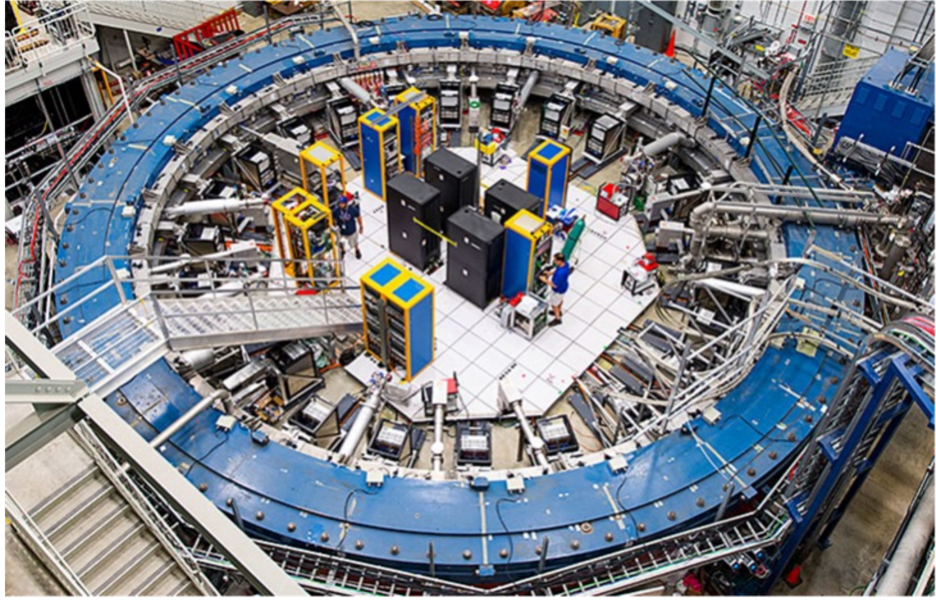




When the particle g-2 frequency is in resonance with the axion dark matter frequency, then the spin precesses in the vertical direction

Muon g-2 experiment

- Muon g-2 results at Fermilab, confirmed and improved BNL results.
- The collaboration developed several new tools for systematic error probing.
- High-precision numerical integrators for beam/spin dynamics simulations,…
- Bill Morse and Lee Roberts are the recipients of the APS 2023 Panofsky Prize.



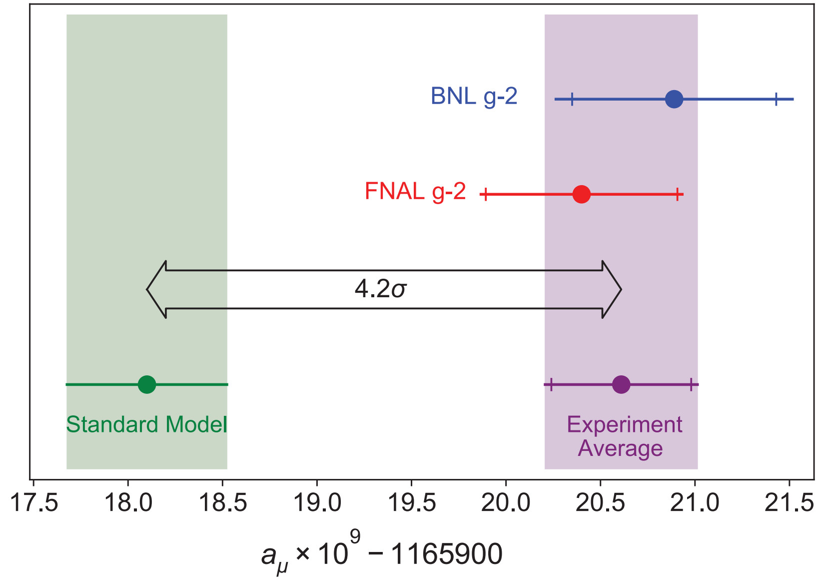
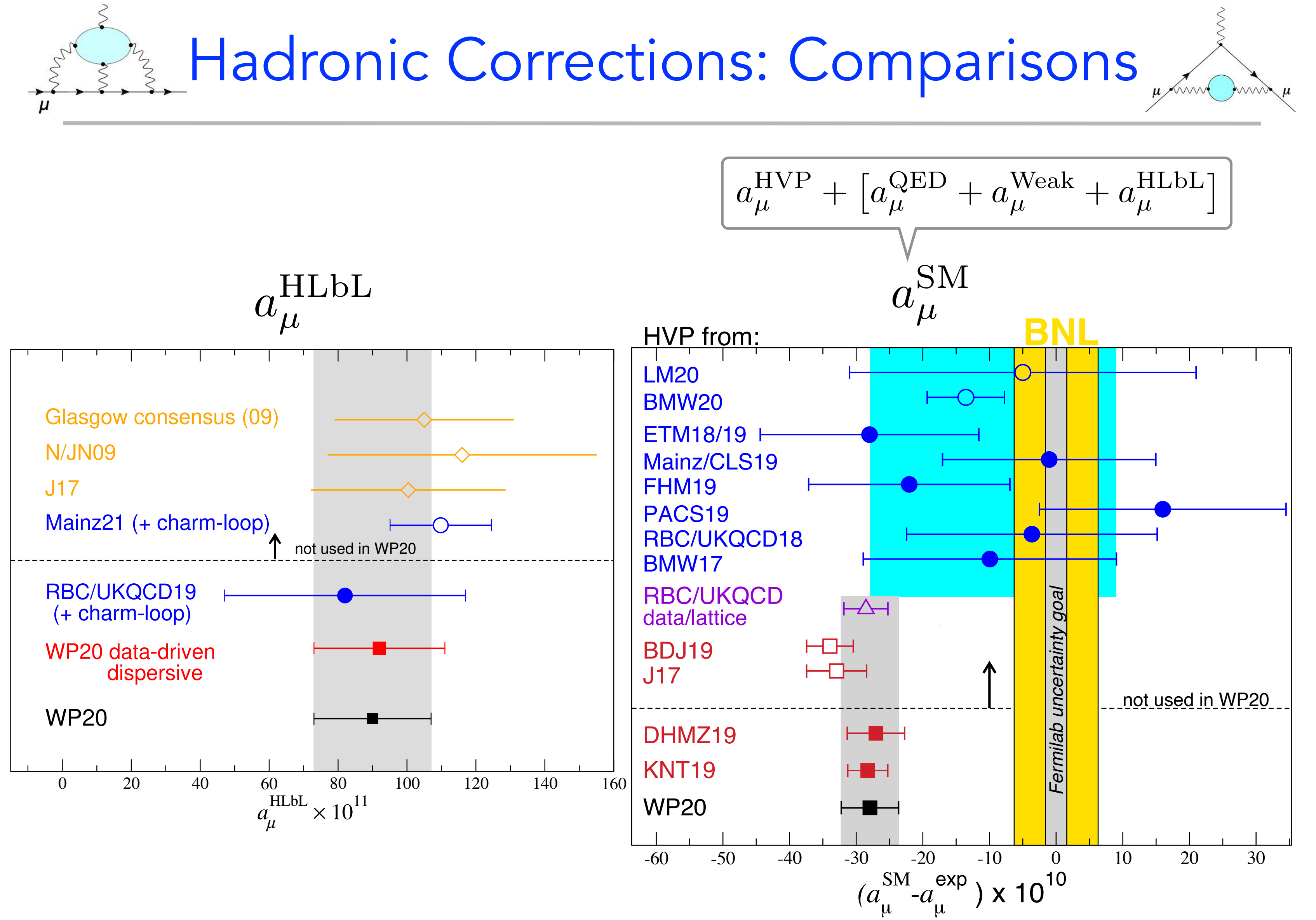


FIG. 4. From top to bottom: experimental values of a_μ from BNL E821, this measurement, and the combined average. The inner tick marks indicate the statistical contribution to the total uncertainties. The Muon $g-2$ Theory Initiative recommended value [13] for the standard model is also shown.

Muon g-2 announcement, theory vs. theory

- Theory :



Hadronic Corrections: Comparisons

$$a_\mu^{\rm HVP} + [a_\mu^{\rm QED} + a_\mu^{\rm Weak} + a_\mu^{\rm HLbL}]$$

A. El-Khadra JETP 07 April 2021 14

Bill Morse, Lee Roberts 2023 Panofsky Prize

- We built the largest single diameter (15m) superconducting magnet coil at the time. Moved it across the country to repeat the experiment.
- Uniformity of B-field (1.5T) in cross-section to better than 10^{-6} measured it (absolute) to better than 10^{-7} calibrated with two independent methods
- Developed a trolley system measuring the B-field in situ (>5000 points)
- Introduced a new DC inflector with innovative B-field shield at 3T without being detectable at storage region <10 cm away
- Built a fast (200ns, 300G) magnet (kicker) without ferrite, measured the pulsed B-field eddy currents to 10^{-8} requiring enormous dynamic range
- Developed electrostatic quads with twice the CERN gradient; measured the Electric field gradient.
- Our calorimeter detectors had to have time stability, early to late in storage, of <20ps, measured it <2ps; gain stability to 10^{-4}
- Used combinatorics to remove pileup pulses; segmented calo detectors
- Traceback system monitoring motion in real time, without affecting muons
- Used RF, riding on the quads, for 30 us to adjust coherent beam motion and reduce muon losses, both by an order of magnitude
- …
- Project manager (Chris Polly, Fermilab) received DOE management Prize

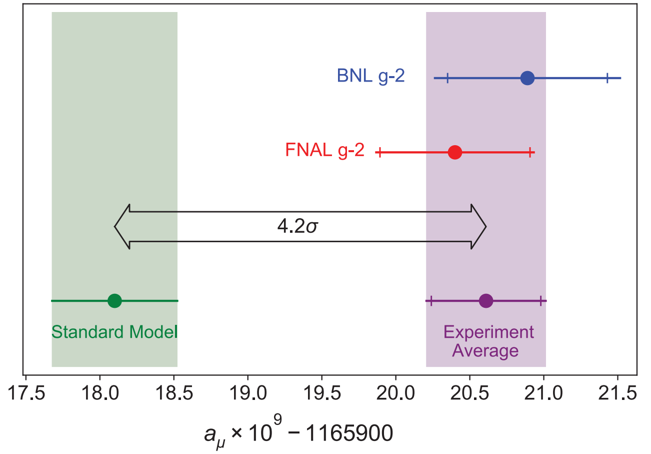
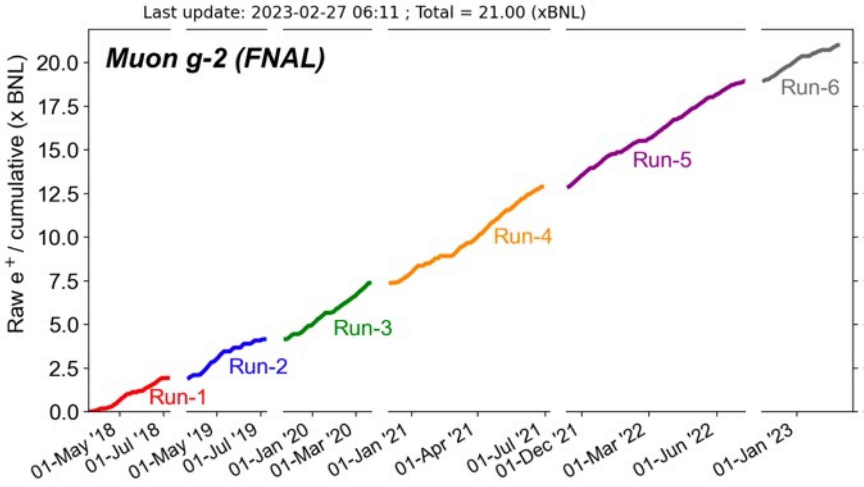


FIG. 4. From top to bottom: experimental values of a_μ from BNL E821, this measurement, and the combined average. The inner tick marks indicate the statistical contribution to the total uncertainties. The Muon $g-2$ Theory Initiative recommended value [13] for the standard model is also shown.

On time, on budget

Bill Morse, Lee Roberts 2023 Panofsky Prize



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- …
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On time, on budget, delivered!

How the srEDM exp. at 10^{-29} *e*-cm works

✓Required radial E-field <5 MV/m, for 40mm plate separation

✓Beam and spin dynamics stable for required beam intensity

✓Spin coherence time estimated $>10^3$s using sextupoles (no stochastic cooling)

✓Alternate magnetic focusing all but eliminating external B-field sensitivity

✓Symmetric lattice significantly reducing systematic error sources

✓Required ring planarity <0.1mm; CW & CCW beam separation <0.01mm

Classification of systematic errors at 10^{-29} *e*-cm

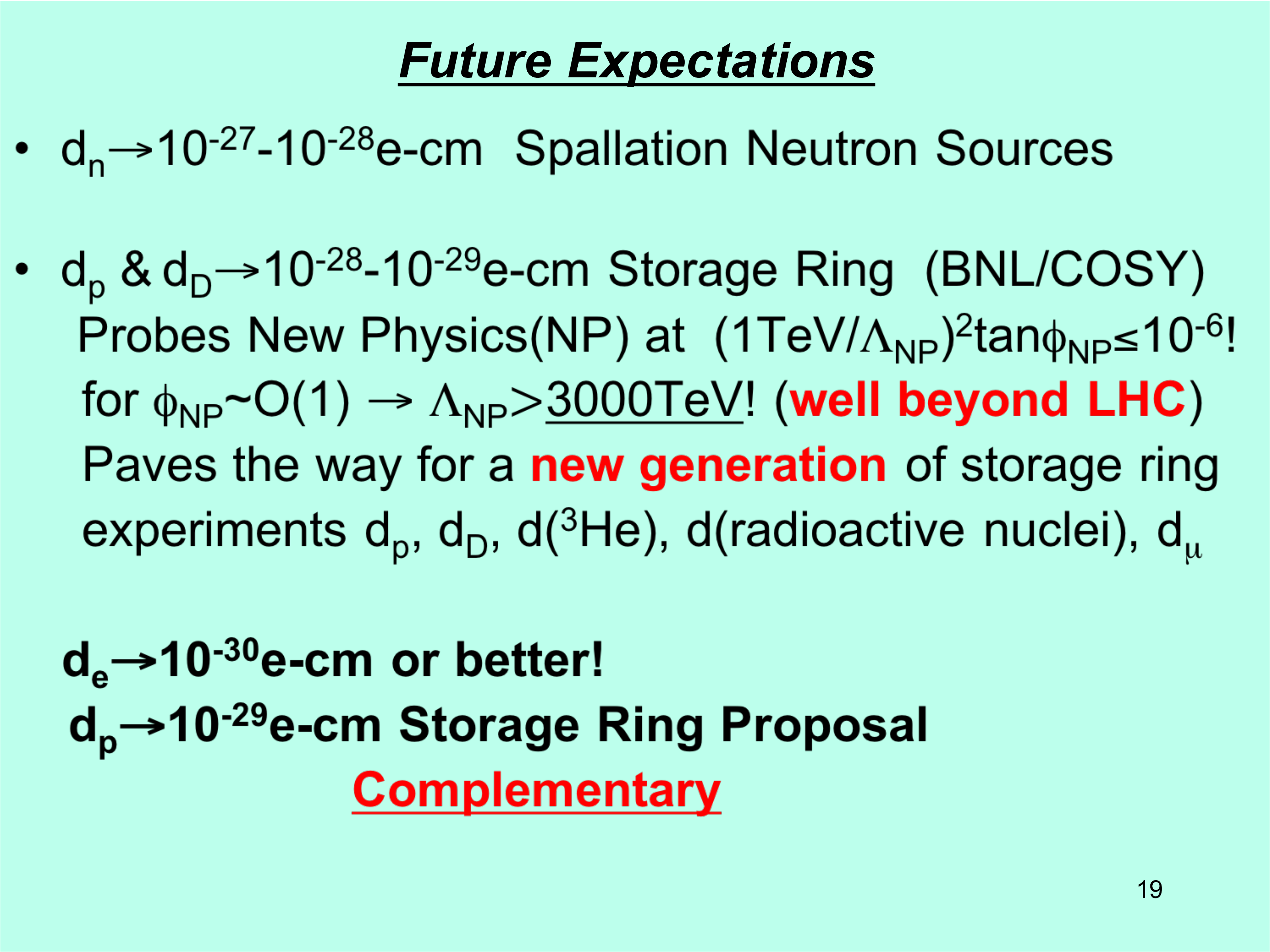
- ✓Alternate magnetic focusing allows simultaneous CW & CCW storage and shields against external B-fields. Vertical dipole E-fields eliminated (its own "co-magnetometer"), unique feature of this lattice.

- ✓Symmetric lattice significantly reduces systematic errors associated with vertical velocity (major source). Using longitudinal, radial and vertical polarization directions, since they are sensitive to different physics/systematic errors.

- ✓Required ring planarity <0.1mm; CW & CCW beam separation <0.01mm, resolves issues with geometrical phases

System	Risk factor, comments
Ring construction, beam storage, stability, IBS	Low. Strong (alternate) focusing, a ring prototype has been built (AGS analog at BNL) in 60’s. Lattice elements placement specs are ordinary. IBS OK below transition.
E-field strength	Low. Plate-units are similar to those ran at Tevatron with higher specs.
E-field plates shape	Low. Make as flat as conventionally possible. Shim out high order fields by intentionally splitting the CR-beams
Spin coherence time	Low. Ordinary sextupoles will provide ~10^3s, with stochastic cooling we expect much longer, under study.
Beam position monitors (BPM), SQUID-based BPMs.	Low, medium. Ordinary BPMs and HLS (similar to FNAL’s) to level the ring to better than 0.1mm, Regular split-geometry and/or SQUID-based BPMs to check CR-beams split to 0.01mm.
High-precision, efficient software	Low. We have several of them already, cross-checking our results routinely. Need to scale it up (thousands of particles)
Polarimeter	Low. Mature technology available

Bill Marciano
Snowmass Workshop,
September 15, 2020



Future Expectations

- $d_n \rightarrow 10^{-27}$-10^{-28}e-cm Spallation Neutron Sources
- d_p & $d_D \rightarrow 10^{-28}$-10^{-29}e-cm Storage Ring (BNL/COSY)
  Probes New Physics(NP) at $(1\text{TeV}/\Lambda_{NP})^2 \tan\phi_{NP} \leq 10^{-6}$!
  for $\phi_{NP} \sim O(1) \rightarrow \Lambda_{NP} > \underline{3000\text{TeV}}$! (**well beyond LHC**)
  Paves the way for a **new generation** of storage ring
  experiments d_p, d_D, $d(^3\text{He})$, d(radioactive nuclei), d_μ

$d_e \rightarrow 10^{-30}$e-cm or better!
$d_p \rightarrow 10^{-29}$e-cm Storage Ring Proposal

Complementary

Bill Marciano
Snowmass Workshop,
September 15, 2020

Outlook

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)

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

The Higgs Mechanism critical for our existence!

Early Universe and Beyond

Must Be Fully Explored

pEDM: Complementary physics with Colliders

The Higgs requires more precision.

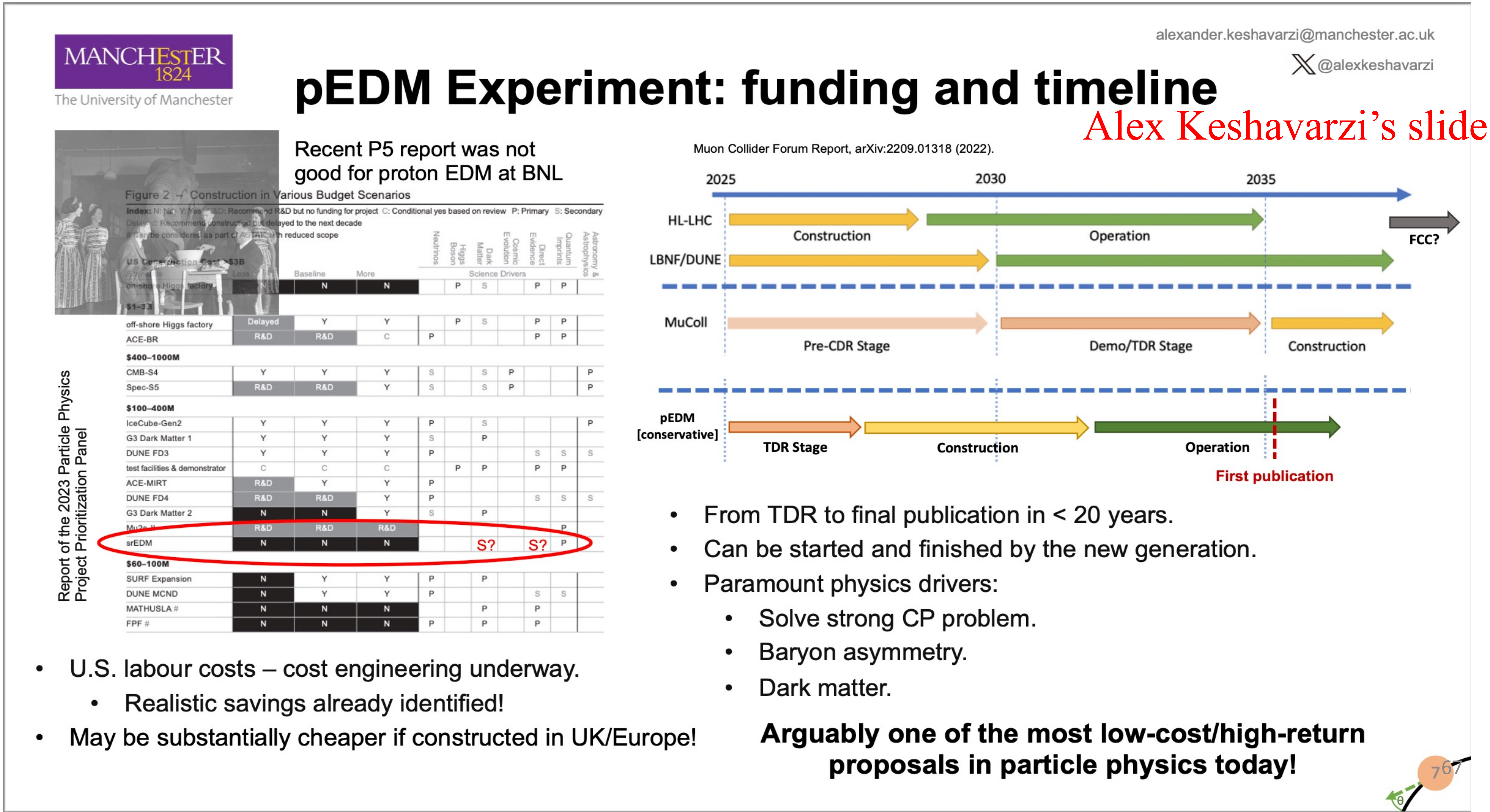
"The Higgs isn't everything; it's the only thing!"*
The scalar discovery in 2012 has been an important milestone for HEP.
Many of us are still excited about it. Others should be too.

Higgs = **new forces** of different nature than the interactions known so far
- No underlying local symmetry.
- No quantised charges.
- Deeply connected to the space-time vacuum structure.

The knowledge of the values of the **Higgs couplings** is essential
to understand the deep structure of matter/Universe:

Christoph Grojean, Corfu on FCC-ee

P5 didn't rank it well despite the excellent Snowmass endorsement!



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pEDM Experiment: funding and timeline

Alex Keshavarzi's slide

Recent P5 report was not good for proton EDM at BNL

Figure 2 – Construction in Various Budget Scenarios

Index: N: No Y: Yes R&D: Recommend R&D but no funding for project C: Conditional yes based on review P: Primary S: Secondary
Delayed: Recommend construction but delayed to the next decade
Can be considered as part of ASTAE with reduced scope

Scenarios	Less	Baseline	More	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
US Construction Cost >$3B										
on-shore Higgs factory	N	N	N		P	S		P	P	
$1–3B										
off-shore Higgs factory	Delayed	Y	Y		P	S		P	P	
ACE-BR	R&D	R&D	C	P				P	P	
$400–1000M										
CMB-S4	Y	Y	Y	S		S	P			P
Spec-S5	R&D	R&D	Y	S		S	P			P
$100–400M										
IceCube-Gen2	Y	Y	Y	P		S				P
G3 Dark Matter 1	Y	Y	Y	S		P				
DUNE FD3	Y	Y	Y	P				S	S	S
test facilities & demonstrator	C	C	C		P	P		P	P	
ACE-MIRT	R&D	Y	Y	P						
DUNE FD4	R&D	R&D	Y	P				S	S	S
G3 Dark Matter 2	N	N	Y	S		P				
Mu2e-II	R&D	R&D	R&D						P	
srEDM	N	N	N			S?		S?	P	
$60–100M										
SURF Expansion	N	Y	Y	P		P				
DUNE MCND	N	Y	Y	P				S	S	
MATHUSLA #	N	N	N			P		P		
FPF #	N	N	N	P		P		P		

Report of the 2023 Particle Physics Project Prioritization Panel

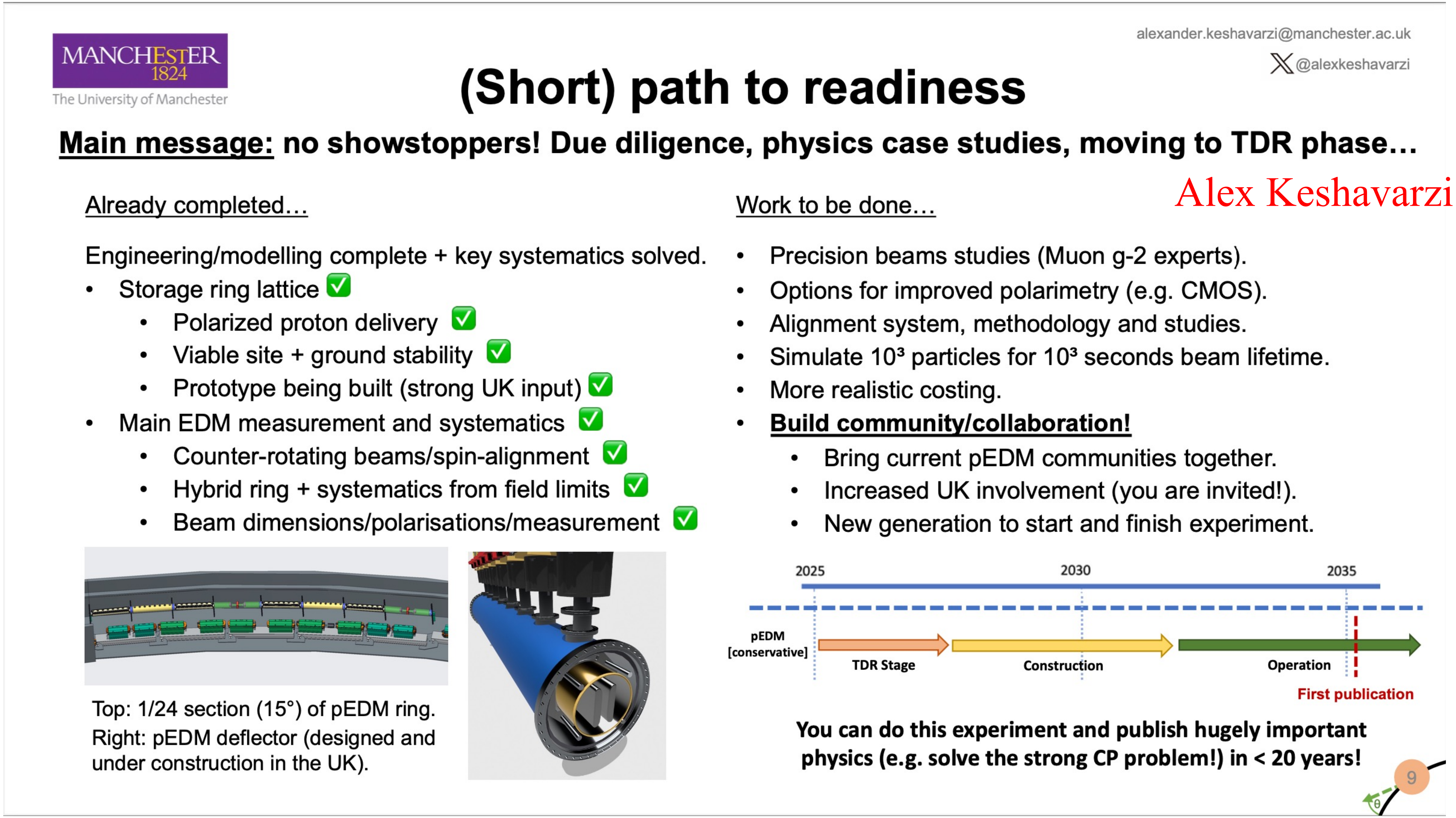
Muon Collider Forum Report, arXiv:2209.01318 (2022).

- U.S. labour costs – cost engineering underway.
    - Realistic savings already identified!
- May be substantially cheaper if constructed in UK/Europe!

- From TDR to final publication in < 20 years.
- Can be started and finished by the new generation.
- Paramount physics drivers:
    - Solve strong CP problem.
    - Baryon asymmetry.
    - Dark matter.

Arguably one of the most low-cost/high-return proposals in particle physics today!

Status: what we already have done, what's missing



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(Short) path to readiness

<u>Main message:</u> no showstoppers! Due diligence, physics case studies, moving to TDR phase…

Alex Keshavarzi's slide

Already completed…

Engineering/modelling complete + key systematics solved.

- Storage ring lattice ☑
    - Polarized proton delivery ☑
    - Viable site + ground stability ☑
    - Prototype being built (strong UK input) ☑
- Main EDM measurement and systematics ☑
    - Counter-rotating beams/spin-alignment ☑
    - Hybrid ring + systematics from field limits ☑
    - Beam dimensions/polarisations/measurement ☑

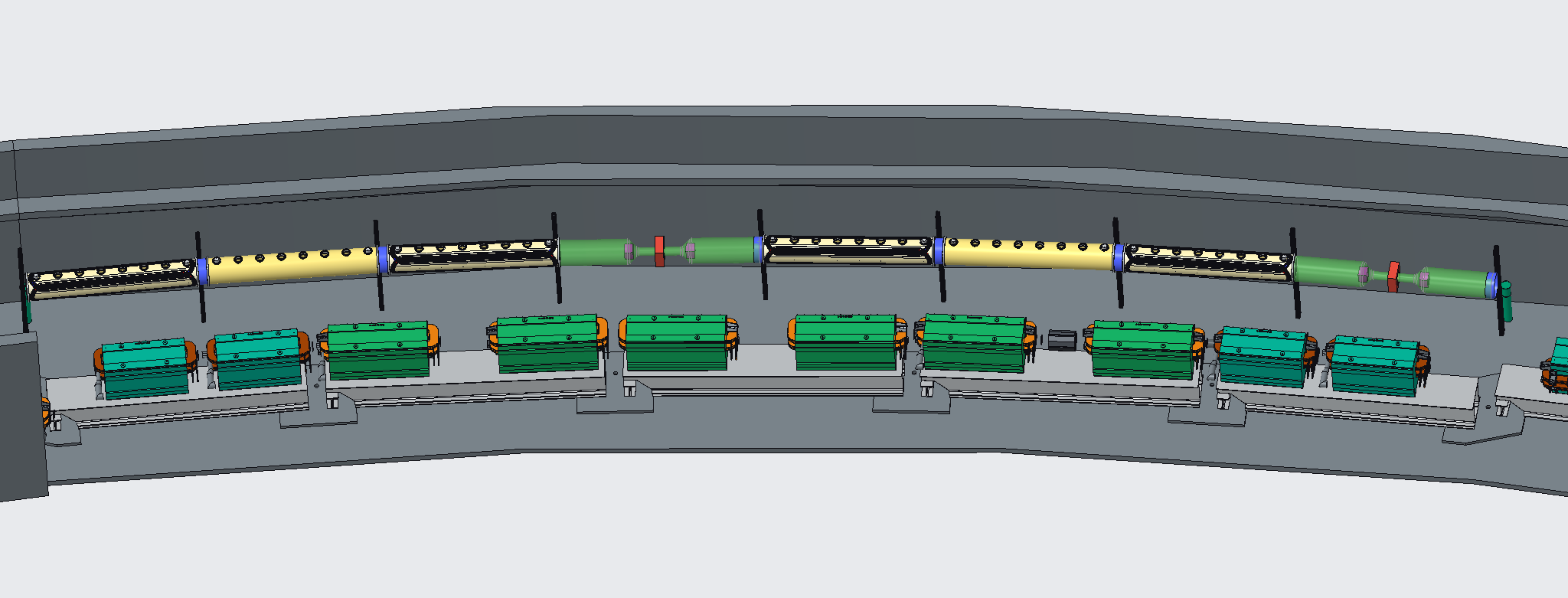
Top: 1/24 section (15°) of pEDM ring.
Right: pEDM deflector (designed and under construction in the UK).

Work to be done…

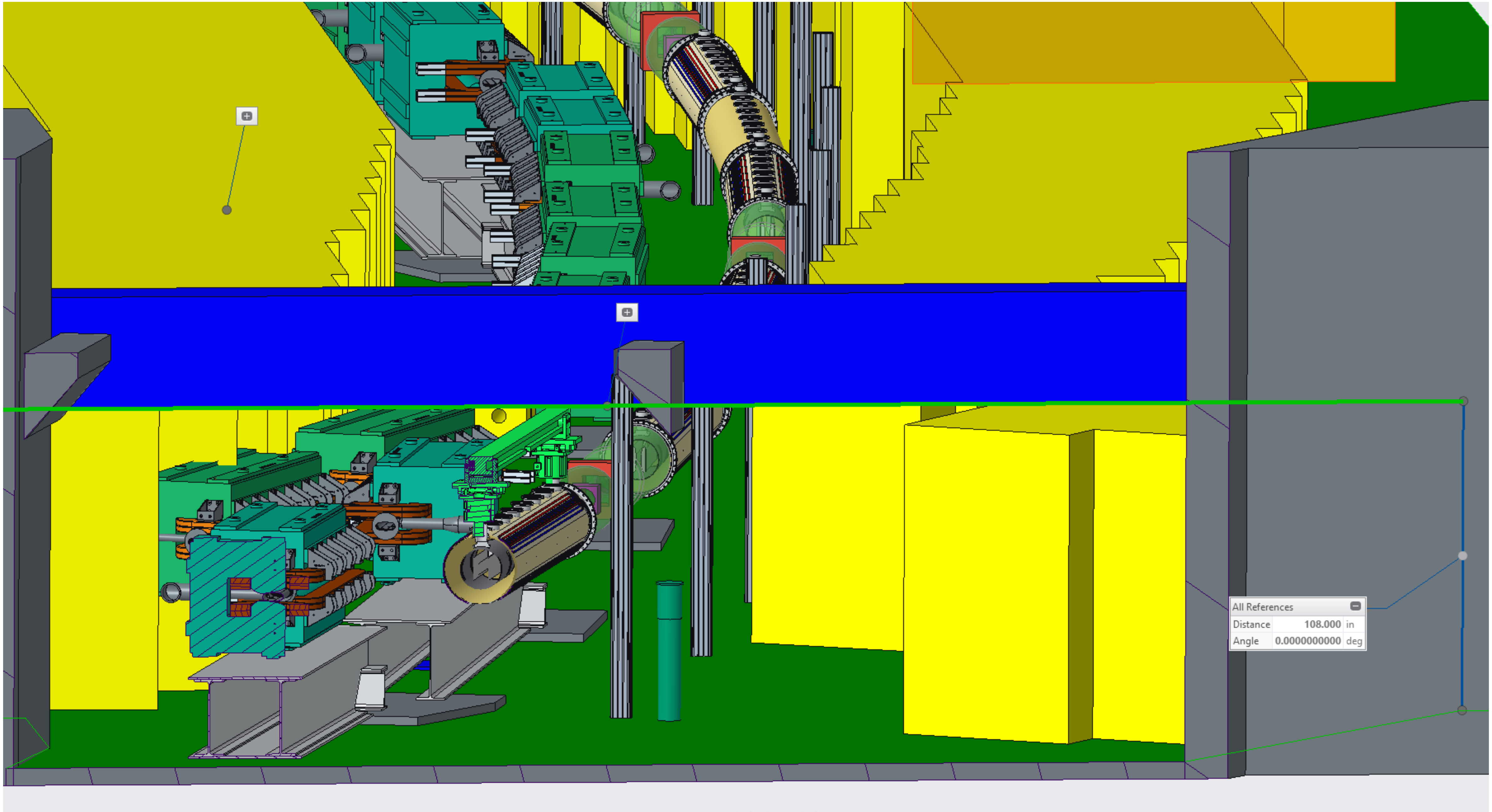
- Precision beams studies (Muon g-2 experts).
- Options for improved polarimetry (e.g. CMOS).
- Alignment system, methodology and studies.
- Simulate 10^3 particles for 10^3 seconds beam lifetime.
- More realistic costing.
- **Build community/collaboration!**
    - Bring current pEDM communities together.
    - Increased UK involvement (you are invited!).
    - New generation to start and finish experiment.

You can do this experiment and publish hugely important physics (e.g. solve the strong CP problem!) in < 20 years!

John Benante, Bill Morse in AGS tunnel of BNL, plenty of room for the EDM ring.

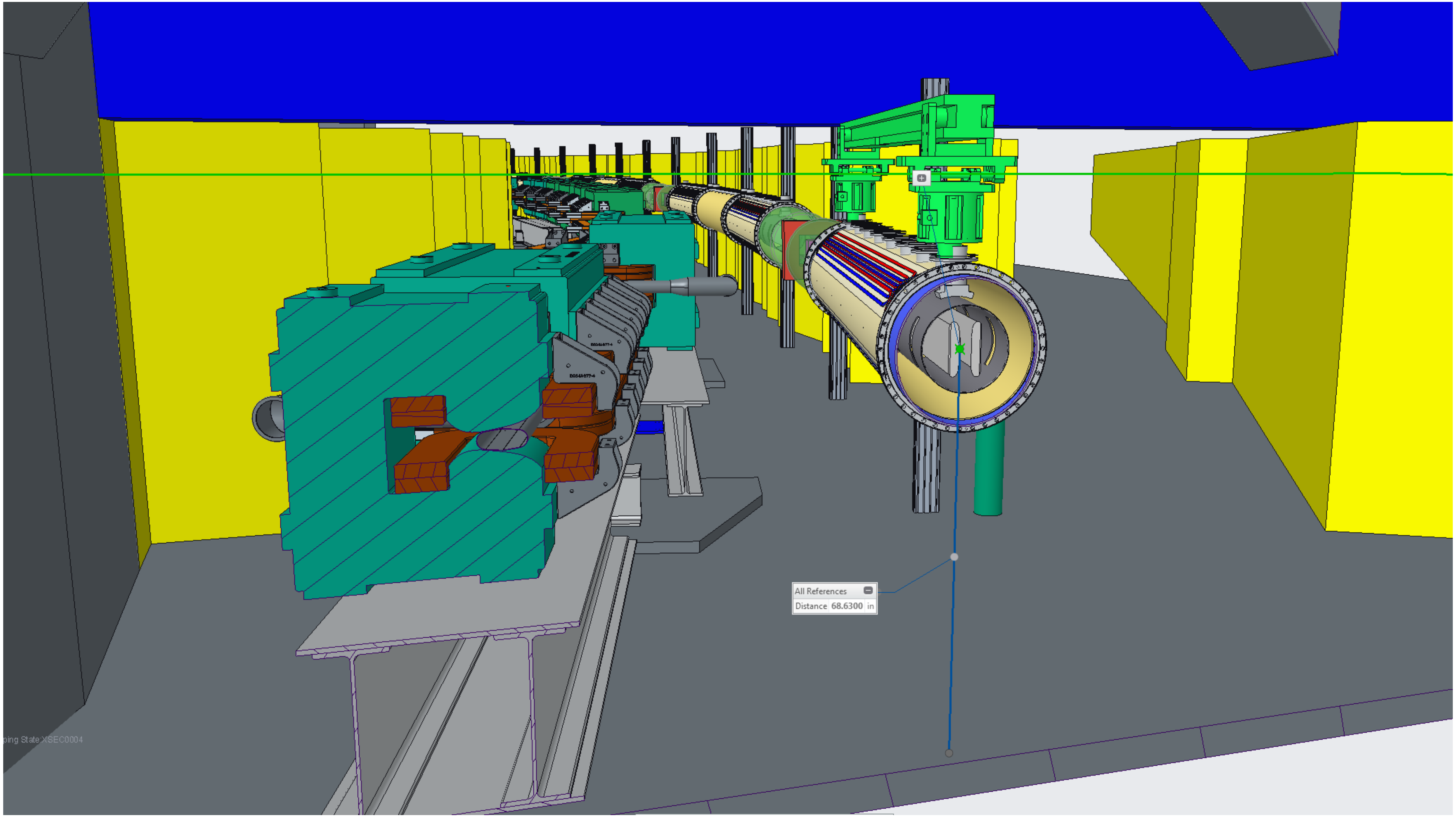


1/24 section (15°) of pEDM ring



All References
Distance 108.000 in
Angle 0.0000000000 deg

Section at F20 experimental blockhouse
Note: ceiling elevation = 108” (9’-0”)

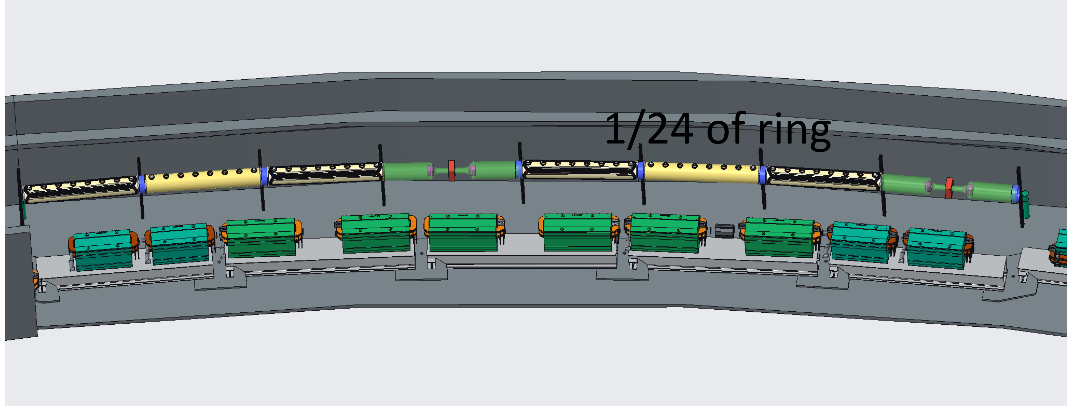


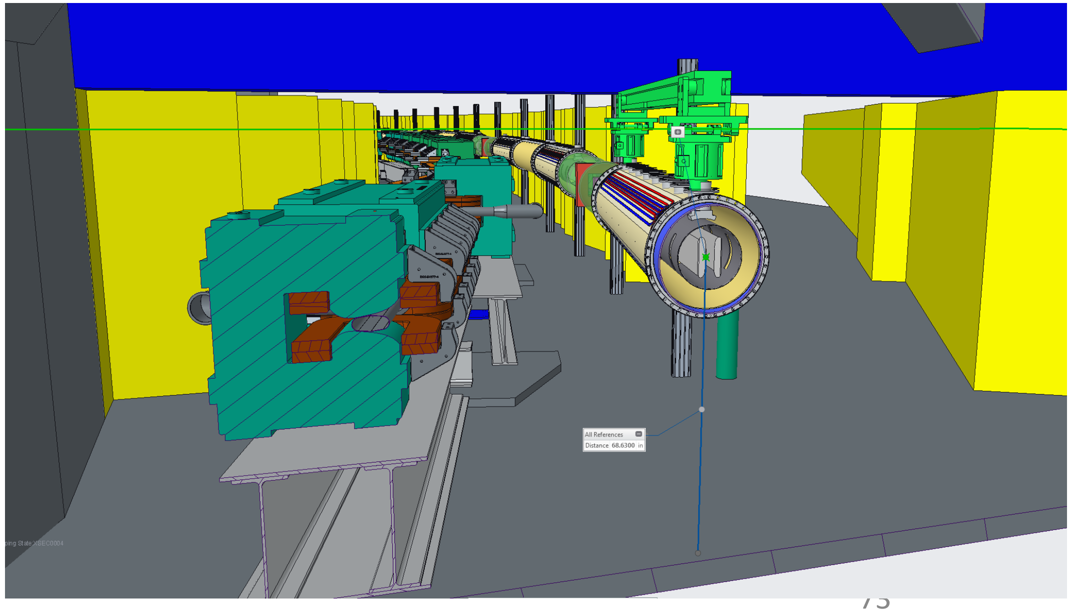
Section at F20 experimental blockhouse

Note: preliminary ring elevation (centerline) = 68.63”

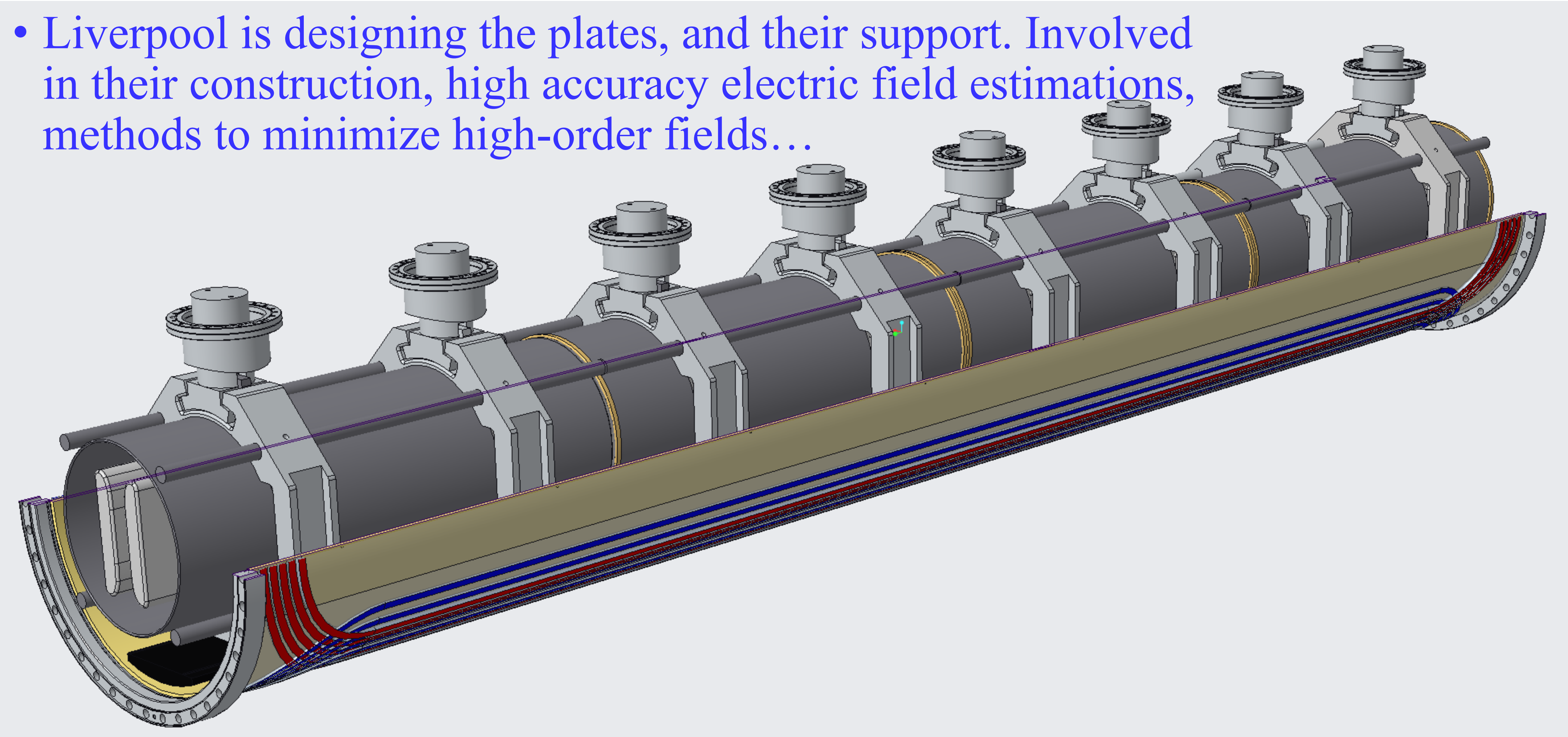
What next?

- BNL is funding an ongoing R&D, building one unit of the symmetric lattice for a ring in the AGS tunnel.
- Develop electric field plates with advanced coating (TiN) for high-voltage (HV). Need DC HV 4.5MV/m and low (pA) or <pA current.
- Study stochastic cooling for even better statistics experiment.

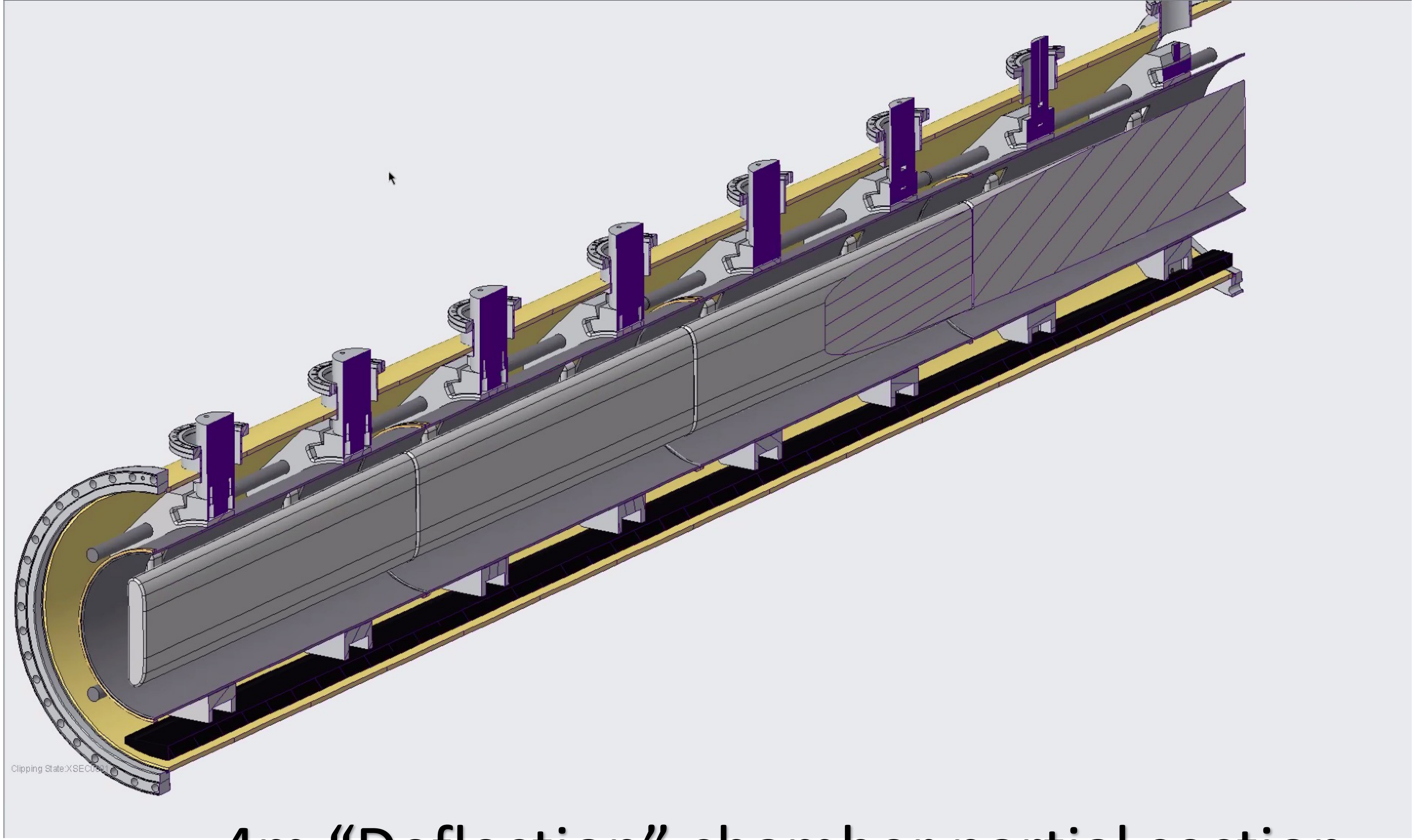




- Liverpool is designing the plates, and their support. Involved in their construction, high accuracy electric field estimations, methods to minimize high-order fields…



4m “Deflection” chamber partial section



4m “Deflection” chamber partial section

Summary

✓EDM physics is must do, exciting and timely, CP-violation, axion physics.

✓Hybrid, symmetric ring lattice works well. Minimized systematic error sources. Statistics and systematics to 10^{-29}*e*-cm. Technically, ready to go.

✓pEDM lattice with long SCT and large enough acceptance provides the statistics

✓Ring planarity <0.1mm, CW & CCW beam separation <0.01mm

✓Great complementarity between collider and high-precision physics!

✓Support it, it’s great physics!

References

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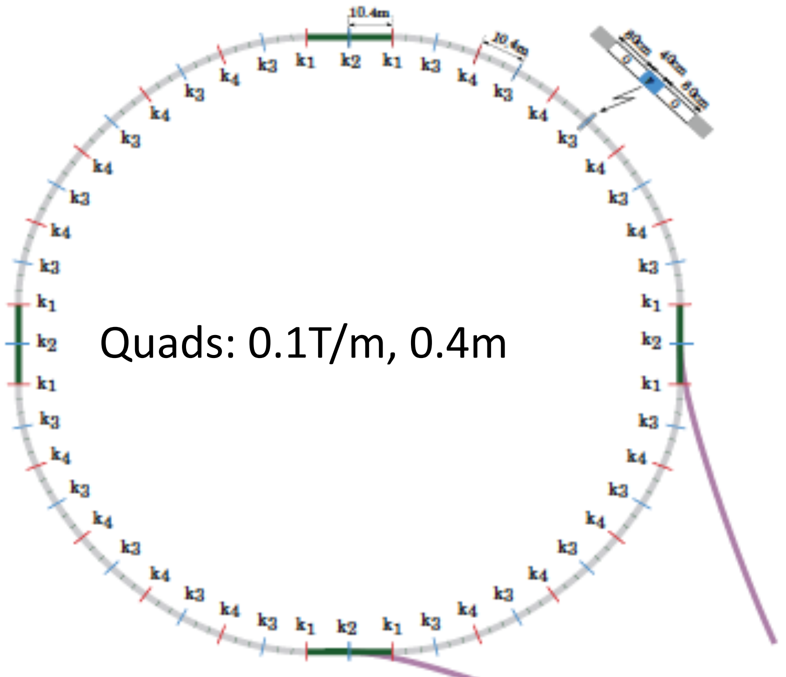
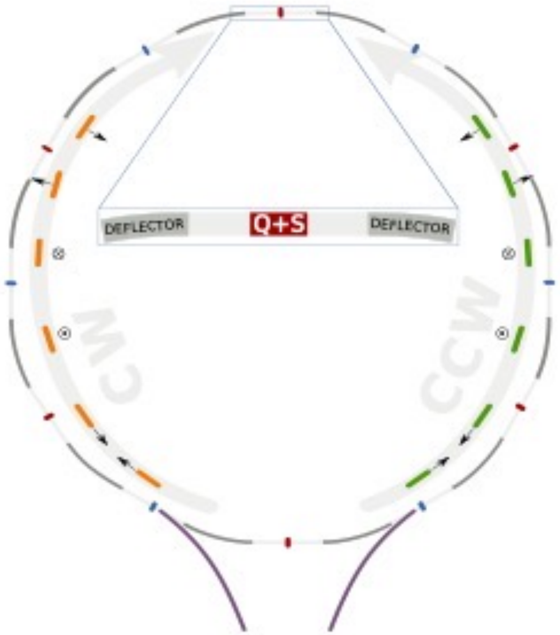
12. W.M. Morse *et al.*, rf Wien filter in an electric dipole moment storage ring: The “partially frozen spin” effect, Phys. Rev. Accel. Beams 16 (11), 114001 (2013)
13. N.P.M. Brantjes *et al.,* Correction systematic errors in high-sensitivity deuteron polarization measurements, Nucl. Instrum. Meth. A664, 49 (2012)
14. G.W. Bennett *et al.,* An improved limit on the muon electric dipole moment, Phys. Rev. D 80, 052008 (2009)
15. F.J.M. Farley *et al.,* A new method of measuring electric dipole moments in storage rings, Phys. Rev. Lett. 93, 052001 (2004)
16. …

Extra slides

Relevant parameter:
The average vertical speed in deflectors needs to be close to zero!



Quads: 0.1T/m, 0.4m



Keep the lattice symmetric!

so that a vertical quad offset still keeps the average vertical velocity in E-field regions $<V_v>$ near zero.

Spin Coherence Time

- Not all particles have same deviation from magic momentum, or same horizontal and vertical divergence (second order effects)

- They Cause a spread in the g-2 frequencies:

$$d\omega_a = a\vartheta_x^2 + b\vartheta_y^2 + c\left(\frac{dP}{P}\right)^2$$

- Correct by tuning plate shape/straight section length plus fine tuning with sextupoles (current plan) or cooling (mixing) during storage (under evaluation).

Is the polarimeter analyzing power good at P_{magic}? YES!

Analyzing power can be further optimized

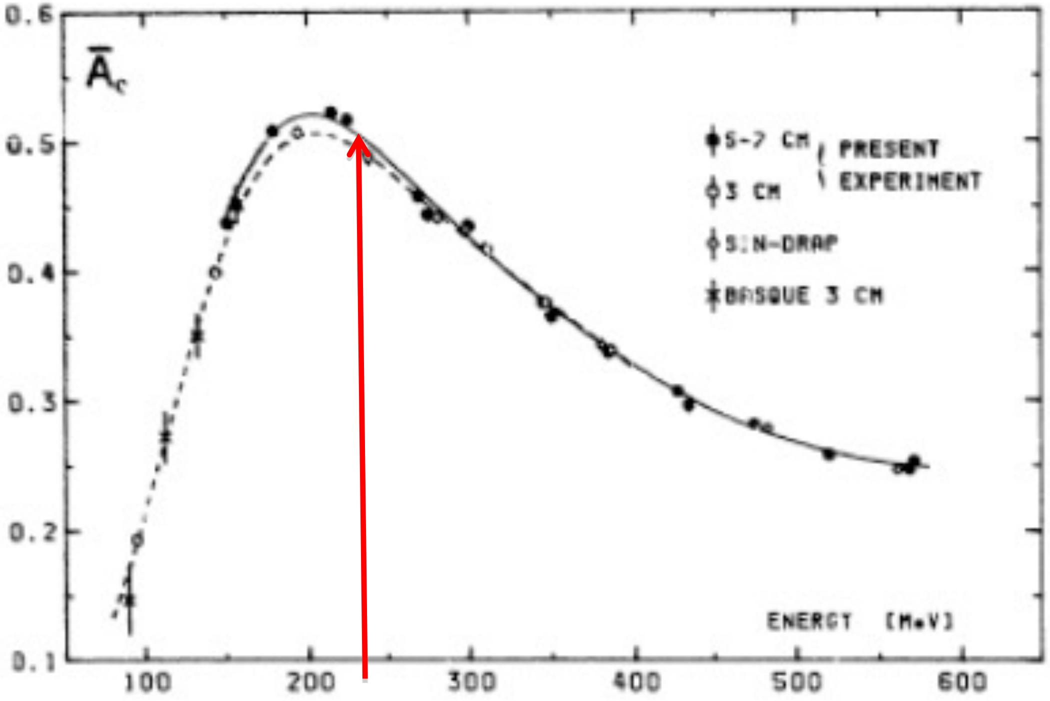


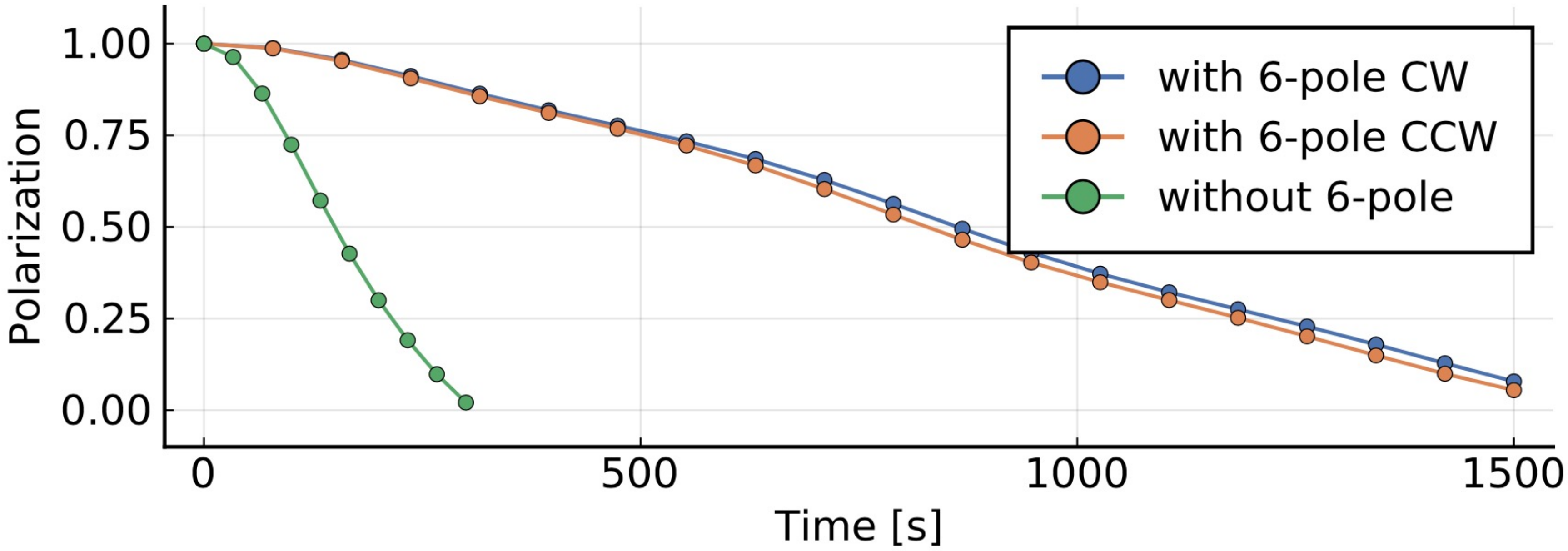
Fig. 4. Angle-averaged effective analyzing power. Curves show our fits. Points are the data included in the fits. Errors are statistical only

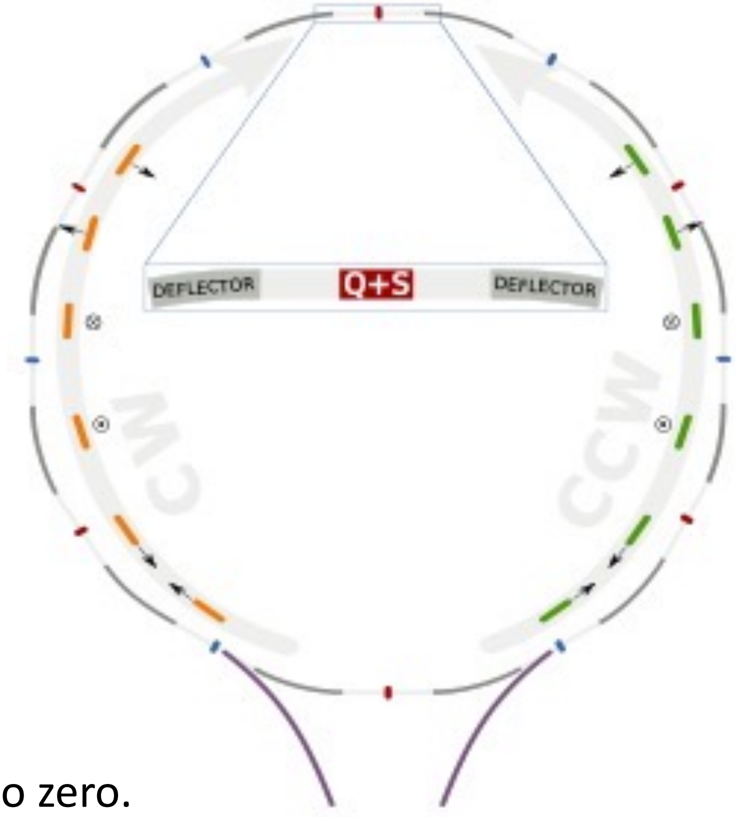
Fig.4. The angle averaged effective analyzing power as a function of the proton kinetic energy. The magic momentum of 0.7GeV/c corresponds to 232MeV.

Hybrid, symmetric lattice storage ring. Spin coherence time with sextupoles

arXiv:2007.10332v2 [physics.acc-ph] 29 Dec 2020

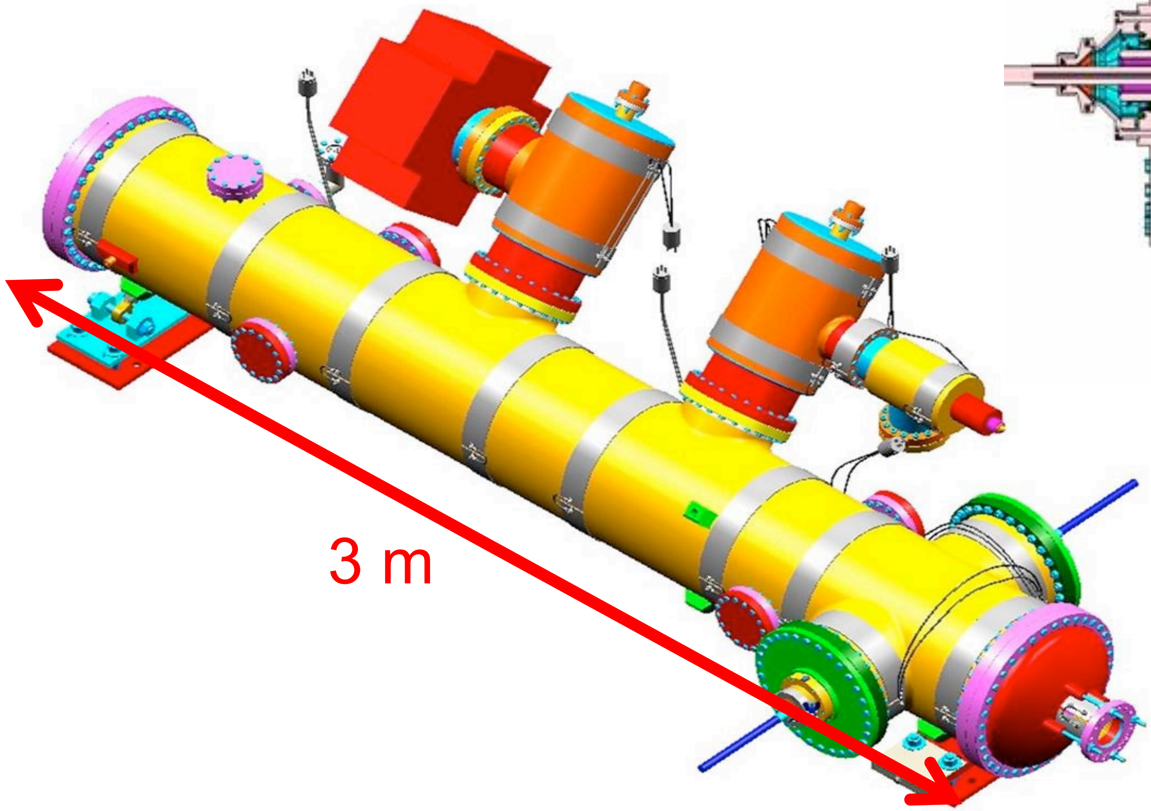
Z. Omarov et al.

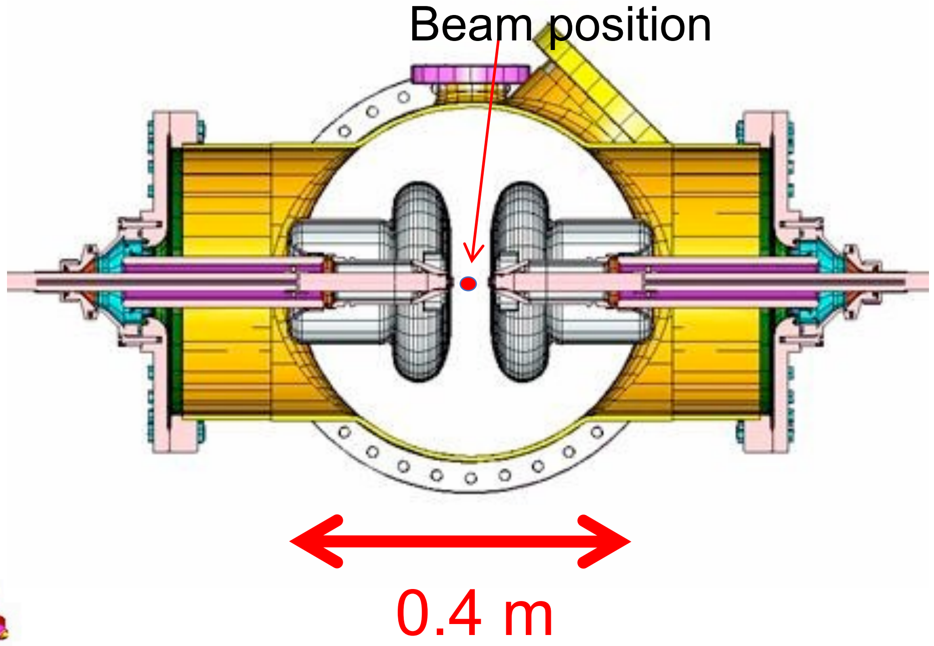




In electric field dominated rings, there are two independent parameters to be tuned to zero.
In magnetic field dominated rings, there are three independent parameters (much harder to achieve).

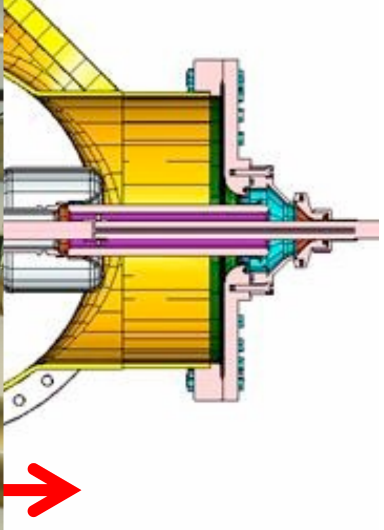
E-field plate modules: The (24) FNAL Tevatron ES-separators ran for years with harder specs





E-field plate modules: The (24) FNAL Tevatron ES-separators ran for years with harder specs

position



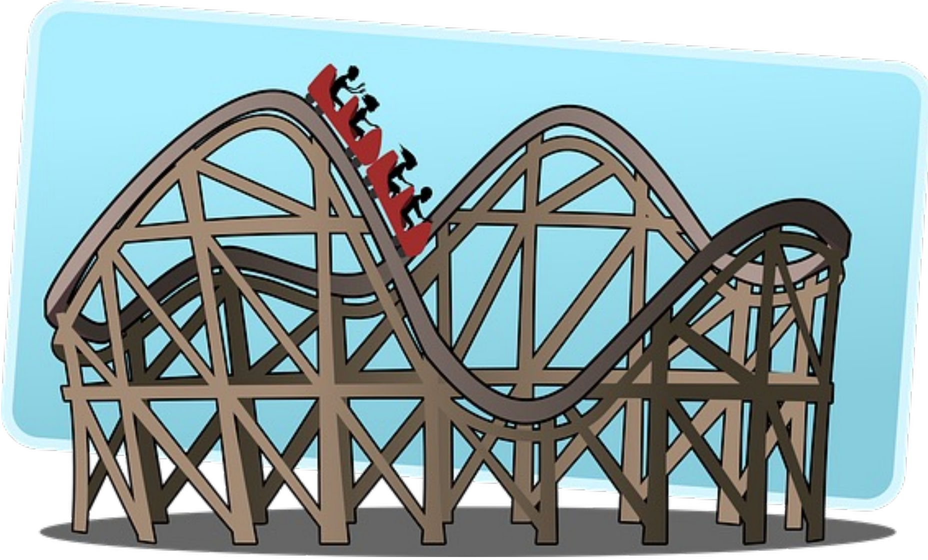
Their specs were
<1spark/year at 6MV/m
& 5cm plate separation

Large Scale Electrodes

Parameter	Tevatron pbar-p Separators	BNL K-pi Separators	pEDM (low risk)
Length	2.6m	4.5m	12.5m
Gap	5cm	10cm	4cm
Height	0.2m	0.4m	0.2m
Number	24	2	48
Max. HV	±(150-180)KV	±200KV	±90KV

Ring planarity critical to control geometrical phase errors

- The beam planarity requirement: <0.1mm, within existing technology
- Clock-wise (CW) and counter-clock-wise (CCW) beam storage split to <0.01mm. SQUID-based BPMs (S-BPM) resolution: 10nm/sqrt(Hz)!



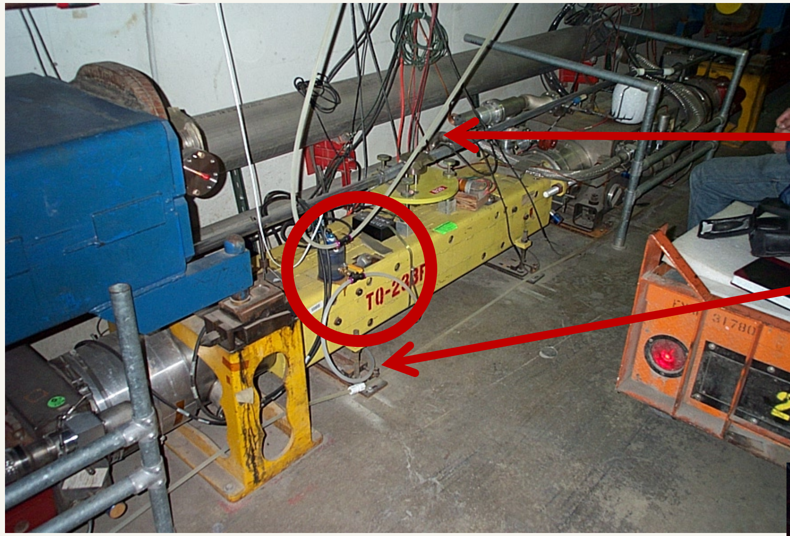
Ring planarity critical to control geometrical phase errors

- Numerous studies on slow ground motion in accelerators, Hydrostatic Level System for slow ground motion studies at Fermilab.

- Thorough review by Vladimir Shiltsev (FNAL):

https://arxiv.org/pdf/0905.4194.pdf

Tevatron Sensors on Quad



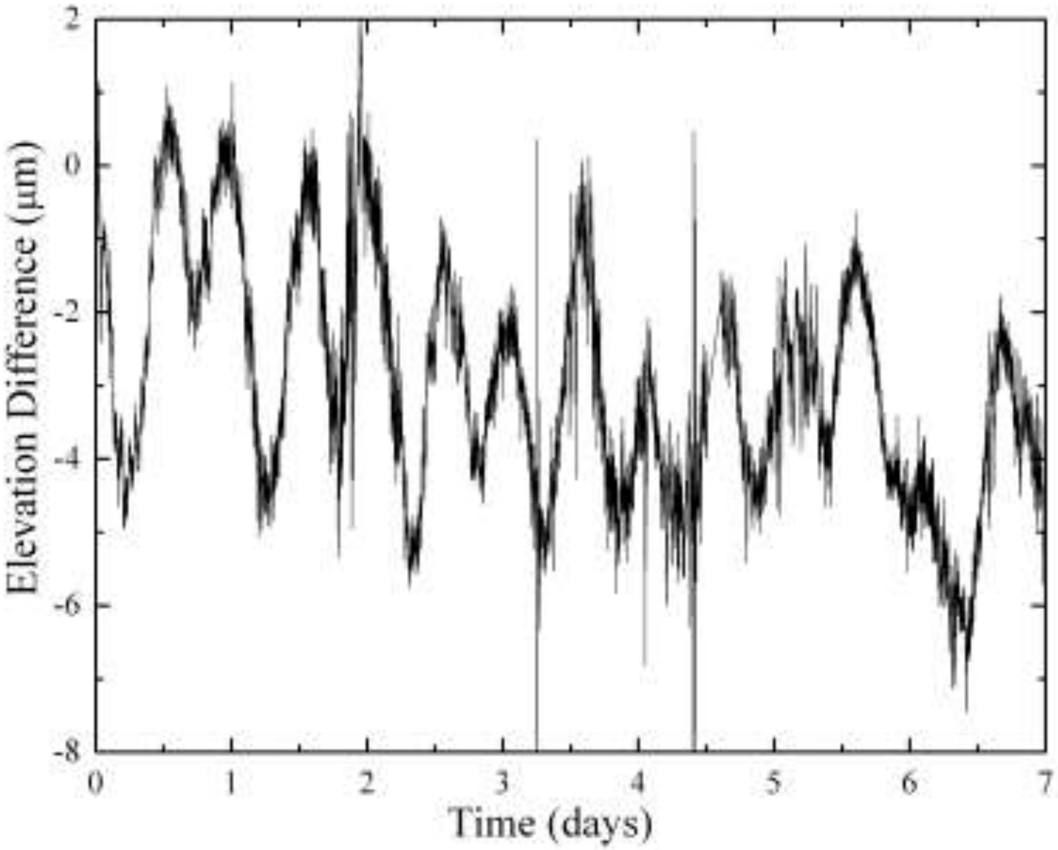
Air Line

Water line

In the circle is a water level pot on a Tevatron quadrupole

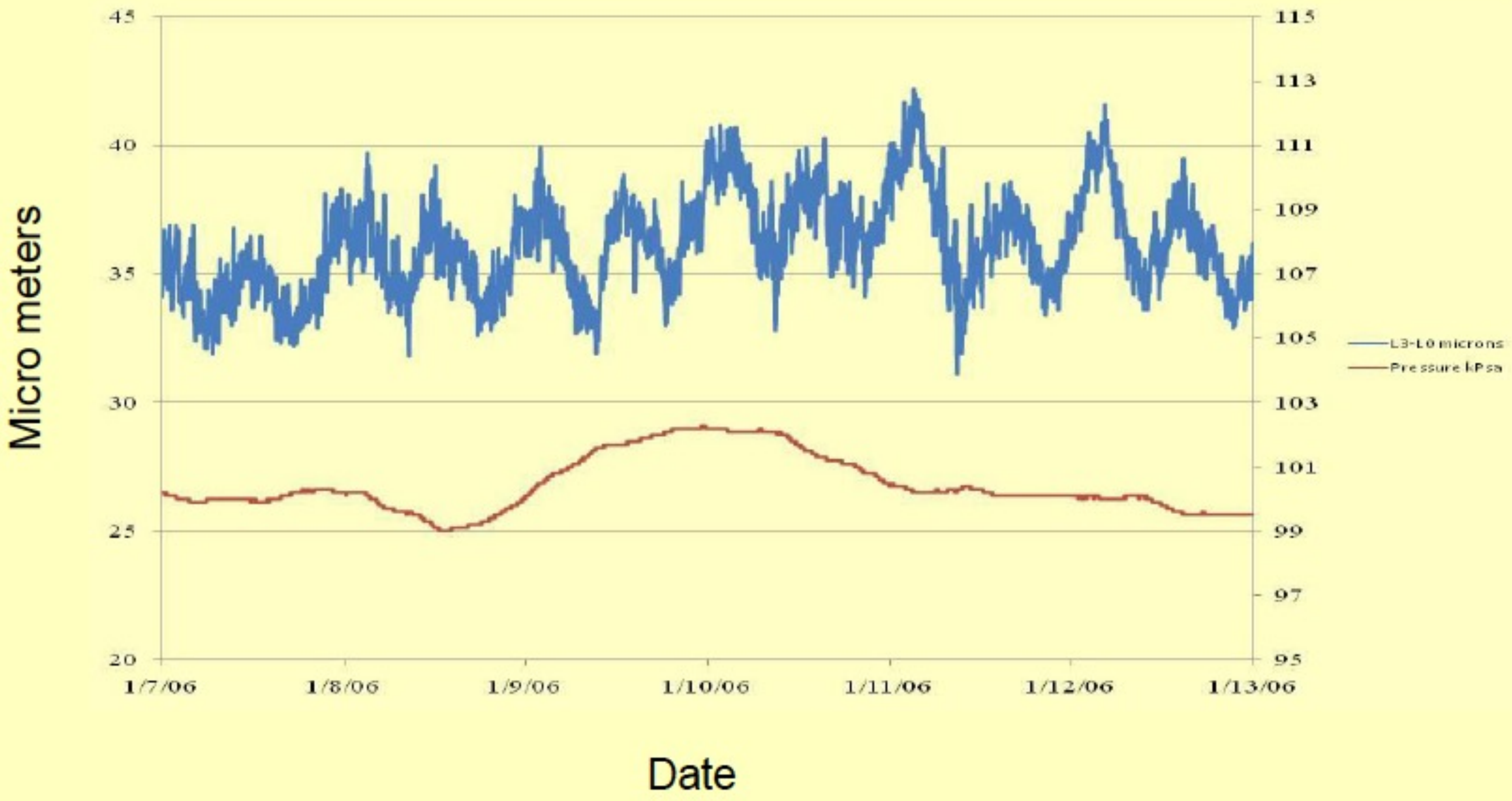
HLS measurements at Fermilab

Fig.35. HLS probe on Tevatron accelerator focusing magnet.



MINOS Tidal Data

Difference in two sensors 90 meters apart



J T Volk Fermilab Dec 2008

Storage ring EDM Collaboration

Snowmass LOI, 2020

Storage Ring EDM Collaboration members (*) and LOI endorsers:

Jim Alexander,[7] Vassilis Anastassopoulos,[34*] Rick Baartman,[26*] Stefan Baessler,[37*] Franco Bedeschi,[19] Martin Berz,[17*] Michael Blaskiewicz,[4*] Themis Bowcock,[31*] Kevin Brown,[4*] Dmitry Budker,[9,29*] Sergey Burdin,[31] Gianluigi Casse,[31*] Giovanni Cantatore,[36*] Timothy Chupp,[32*] Hooman Davoudiasl,[4*] Milind V. Diwan,[4*] George Fanourakis,[20*] Antonios Gardikiotis,[28,34*] Claudio Gatti,[18*] James Gooding,[31*] Renee Fatemi,[30] Wolfram Fischer,[4*] Peter Graham,[25*] Frederick Gray,[22*] Selcuk Haciomeroglu,[6*] Georg H. Hoffstaetter,[7*] Haixin Huang,[4*] Marco Incagli,[19*] Hoyong Jeong,[16*] David Kaplan,[13*] On Kim,[6,15*] Ivan Koop,[5*] Marin Karuza,[35*] David Kawall,[27*] Valeri Lebedev,[8*] MyeongJae Lee,[6*] Soohyung Lee,[6*] Alberto Lusiani,[24,19*] William J. Marciano,[4*] Marios Maroudas,[34*] Andrei Matlashov,[6*] Francois Meot,[4*] James P. Miller,[3*] William M. Morse,[4*] James Mott,[3,8] Zhanibek Omarov,[6,15*] Yuri F. Orlov,[7*] Cenap Ozben,[11*] SeongTae Park,[6*] Giovanni Maria Piacentino,[33*] Boris Podobedov,[4*] Matthew Poelker,[12] Dinko Pocanic,[37*] Joe Price,[31*] Deepak Raparia,[4*] Surjeet Rajendran,[13*] Sergio Rescia,[4*] B. Lee Roberts,[3*] Yannis K. Semertzidis,[6,15*] Alexander Silenko,[14*] Edward Stephenson,[10*] Riad Suleiman,[12*] Michael Syphers,[21*] Pia Thoerngren,[23*] Volodya Tishchenko,[4*] Nikolaos Tsoupas,[4*] Spyros Tzamarias,[1*] Alessandro Variola,[18*] Graziano Venanzoni,[19*] Eva Vilella,[31*] Joost Vossebeld,[31*] Peter Winter,[2] Eunil Won,[16*] Konstantin Zioutas.[34*]

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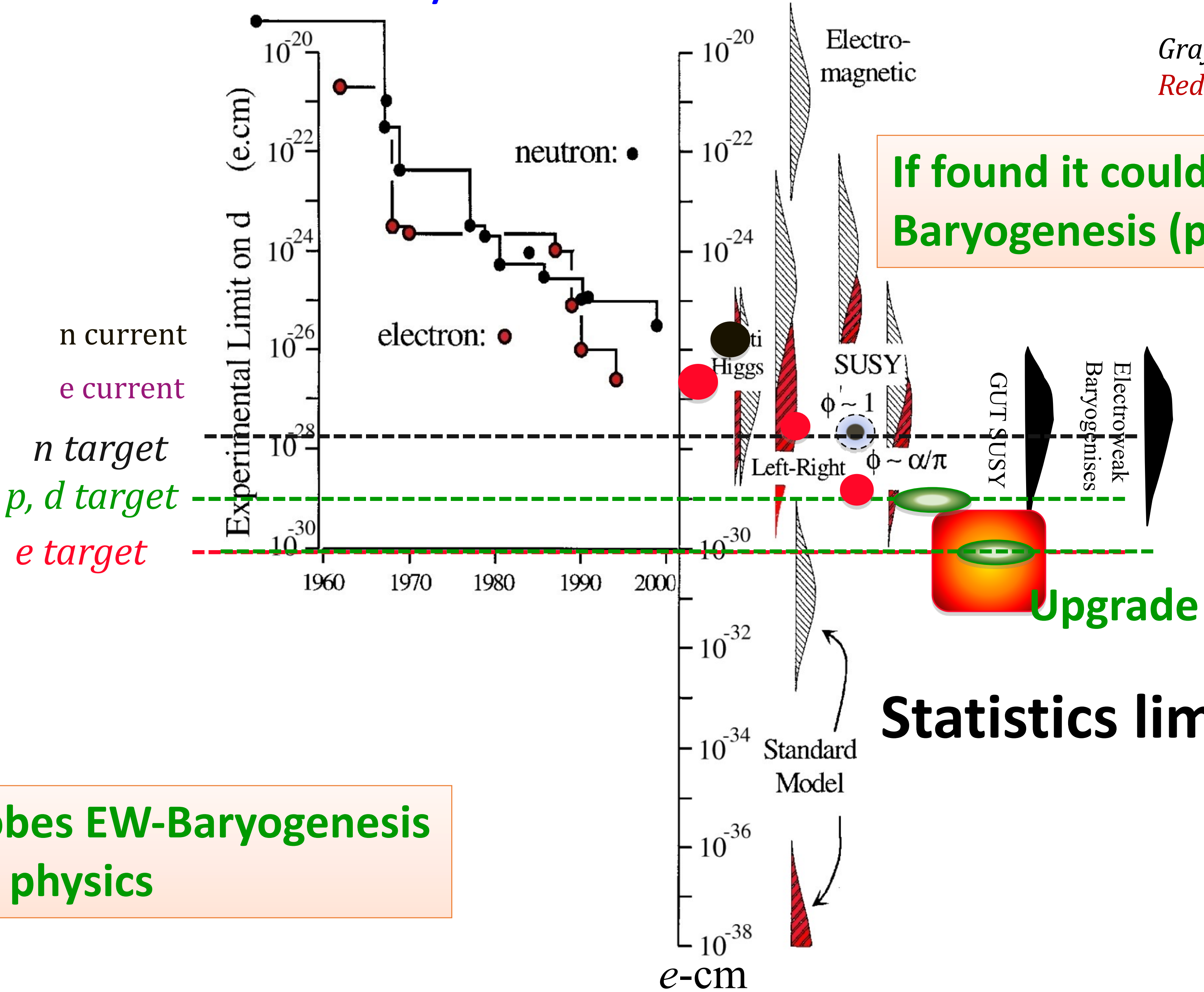
Sensitivity to Rule on Several New Models



Gray: Neutron
Red: Electron

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

Statistics limited

pEDM probes EW-Baryogenesis and axion physics

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

Physics strength comparison (Marciano)

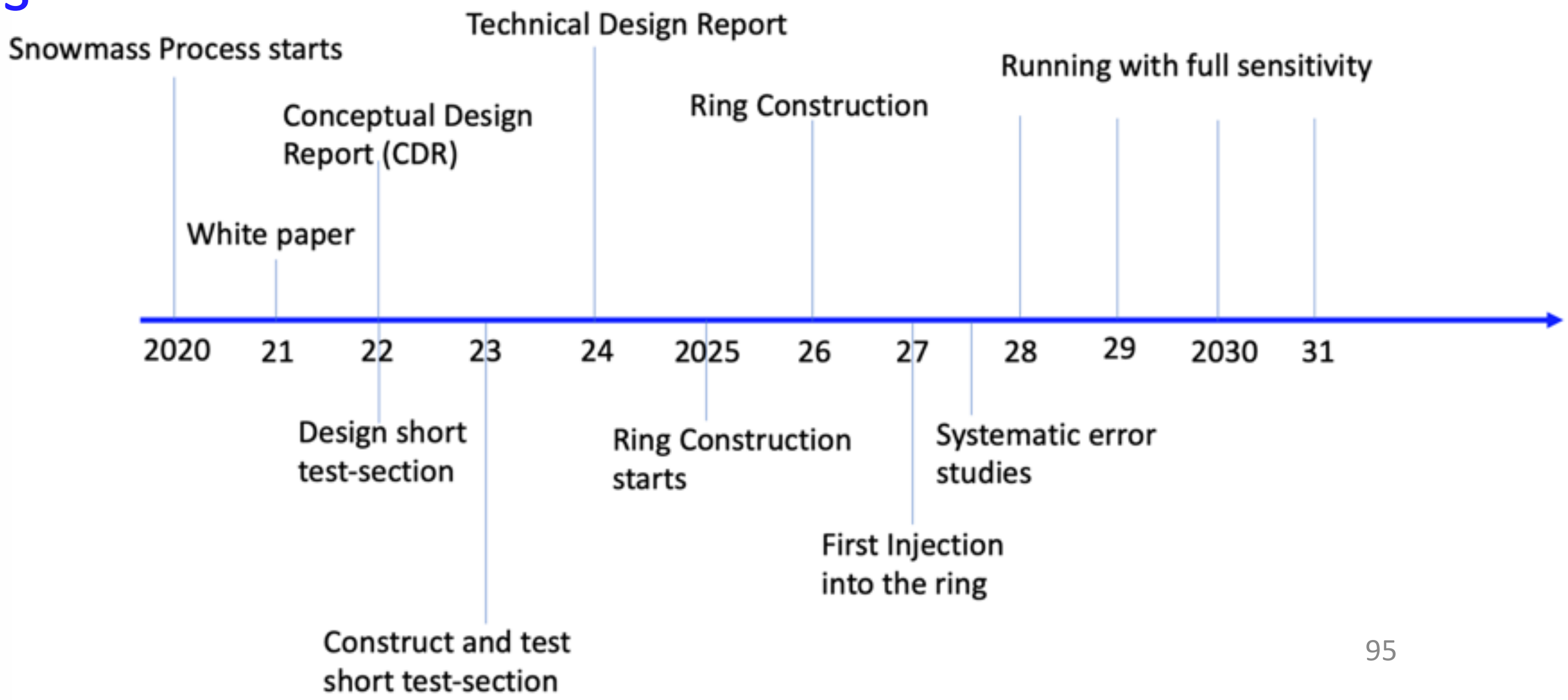
System	Current limit [e·cm]	Future goal	Neutron equivalent
Neutron	$<1.6 \times 10^{-26}$	$\sim 10^{-28}$	10^{-28}
^{199}Hg atom	$<7 \times 10^{-30}$	$<10^{-30}$	10^{-26}
^{129}Xe atom	$<6 \times 10^{-27}$	$\sim 10^{-29}$-10^{-31}	10^{-25}-10^{-27}
Deuteron nucleus		$\sim 10^{-29}$	3×10^{-29}- 5×10^{-31}
Proton nucleus	$<2 \times 10^{-25}$	$\sim 10^{-29}$	10^{-29}

From theta-QCD

From SUSY-like CPV

Technically driven timeline

- We have submitted our LOI to the Snowmass Process in the US and writing a White Paper for it.
- Preparing a CDR document, critical studies are finished
- Most of the collaborators are either Muon g-2 collaborators and/or original Storage ring EDM proponents



Snowmass Process starts

White paper

Conceptual Design Report (CDR)

Technical Design Report

Ring Construction

Running with full sensitivity

2020 21 22 23 24 2025 26 27 28 29 2030 31

Design short test-section

Construct and test short test-section

Ring Construction starts

First Injection into the ring

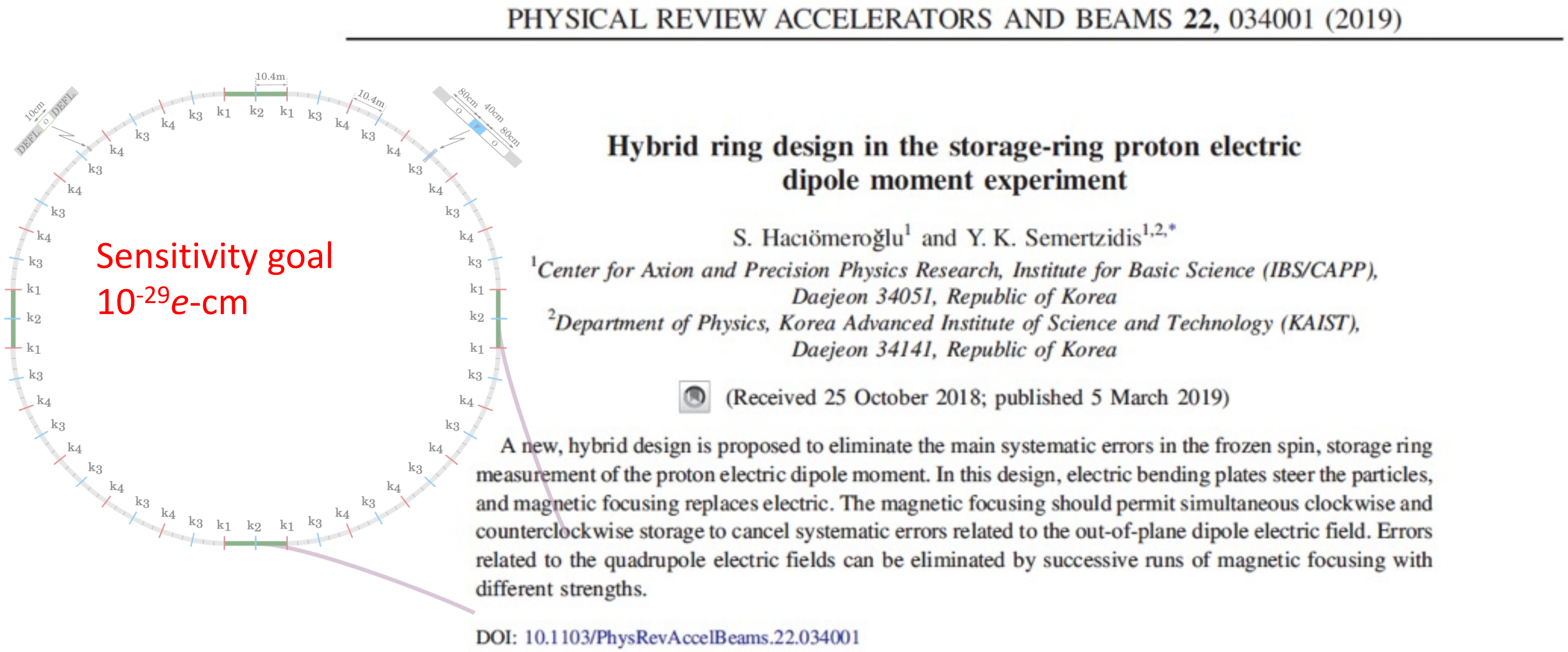
Systematic error studies

Storage Ring Electric Dipole Moments exp. options

Fields	Example	EDM signal term	Comments
Dipole magnetic field **(B)** **(Parasitic)**	Muon g-2	Tilt of the spin precession plane. **(Limited statistical sensitivity due to spin precession)**	Eventually limited by geometrical alignment. **Requires consecutive CW and CCW injection to eliminate systematic errors**
Combination of electric & and magnetic fields **(E, B)** **(Combined lattice)**	Deuteron, ^{3}He, proton, etc.	Mainly: $\boxed{\frac{d\vec{s}}{dt} = \vec{d} \times \left(\vec{v} \times \vec{B}\right)}$	High statistical sensitivity. **Requires consecutive CW and CCW injection with main fields flipping sign to eliminate systematic errors**
Radial Electric field **(E)** & Electric focusing **(E)** **(All electric lattice)**	Proton, etc.	$\boxed{\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}}$	Large ring, CW & CCW storage. **Requires demonstration of adequate sensitivity to radial B-field syst. error**
Radial Electric field **(E)** & Magnetic focusing **(B)** **(Hybrid, symmetric lattice)**	Proton, etc.	$\boxed{\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}}$	Large ring, CW & CCW storage. **Only lattice to achieve direct cancellation of main systematic error sources (its own “co-magnetometer”).**

Hybrid lattice storage ring: E-bending, B-focusing

- It eliminates the main syst. error sources: vertical E-fields, external B-fields



Sensitivity goal
$10^{-29}e$-cm

PHYSICAL REVIEW ACCELERATORS AND BEAMS **22,** 034001 (2019)

Hybrid ring design in the storage-ring proton electric dipole moment experiment

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(Received 25 October 2018; published 5 March 2019)

A new, hybrid design is proposed to eliminate the main systematic errors in the frozen spin, storage ring measurement of the proton electric dipole moment. In this design, electric bending plates steer the particles, and magnetic focusing replaces electric. The magnetic focusing should permit simultaneous clockwise and counterclockwise storage to cancel systematic errors related to the out-of-plane dipole electric field. Errors related to the quadrupole electric fields can be eliminated by successive runs of magnetic focusing with different strengths.

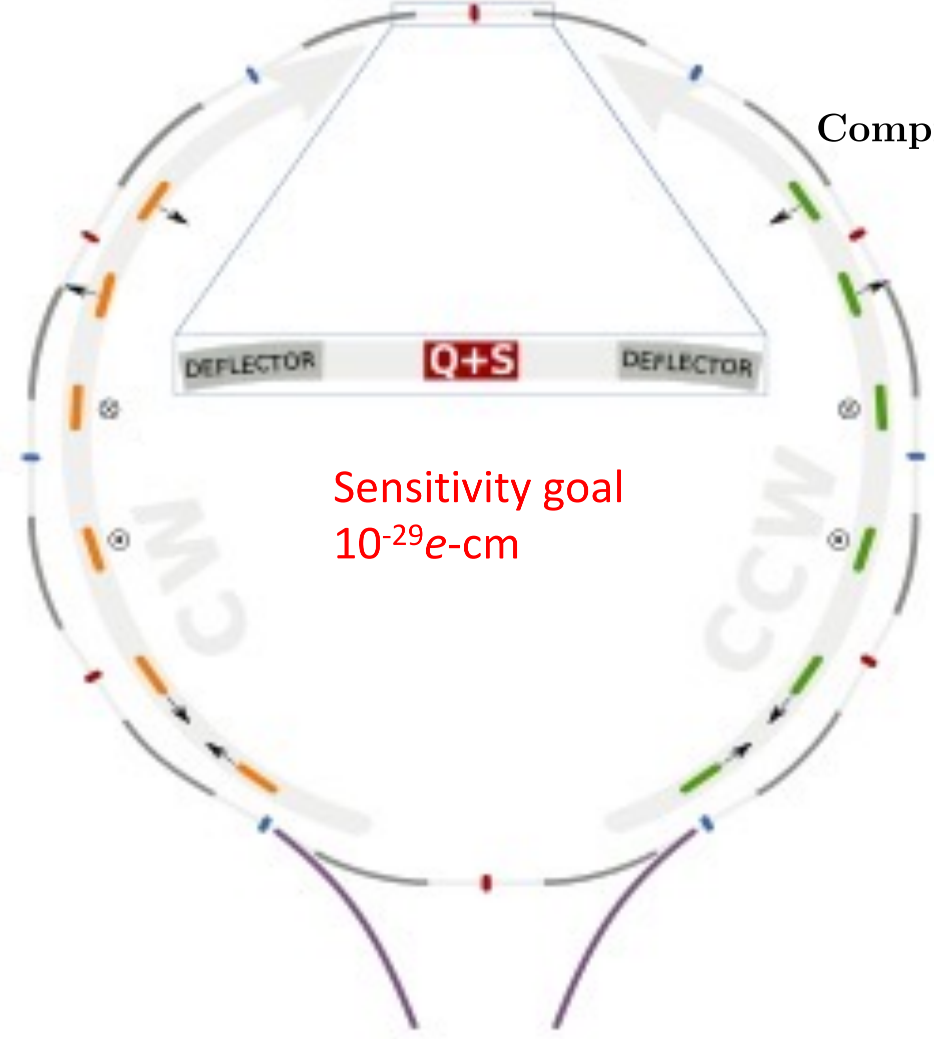
DOI: 10.1103/PhysRevAccelBeams.22.034001

All-electric vs. hybrid options

Lattice	**Comments**
All-electric lattice: Radial Electric field bending & Alternate electric focusing, below transition	CW & CCW storage. Requires: 1. Very weak vertical focusing 2. Magnetic shielding 3. Demonstration of adequate sensitivity to radial B-field syst. error, with <<nm beam separation
Hybrid lattice: Radial Electric field bending & Alternate magnetic focusing, below transition	CW & CCW storage. It has: 1. Strong vertical/horizontal focusing 2. No magnetic shielding needed 3. Beam planarity to 0.1mm and CW vs. CCW beam separation to 0.01mm Only lattice to achieve direct cancellation of main systematic error sources (its own "co-magnetometer").

Hybrid, symmetric lattice storage ring

- It eliminates the main syst. error sources: Vertical E-fields, external B-fields
- Reduces major systematic error sources by several orders of magnitude



Sensitivity goal
10^{-29}*e*-cm

arXiv:2007.10332v2 [physics.acc-ph] 29 Dec 2020

Comprehensive Symmetric-Hybrid ring design for pEDM experiment at below $10^{-29} e\cdot\mathrm{cm}$

Zhanibek Omarov,[1,2] Selcuk Hacıömeroğlu,[2,*] Valeri Lebedev,[3] William Morse,[4]
Yannis K. Semertzidis,[1,2,*] A.J. Silenko,[5] E.J. Stephenson,[6] and more...

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[5] *Research Institute for Nuclear Problems Belarusian State University Minsk 220030 Belarus*
[6] *IUCF Indiana University Bloomingto*

(Dated: September 2

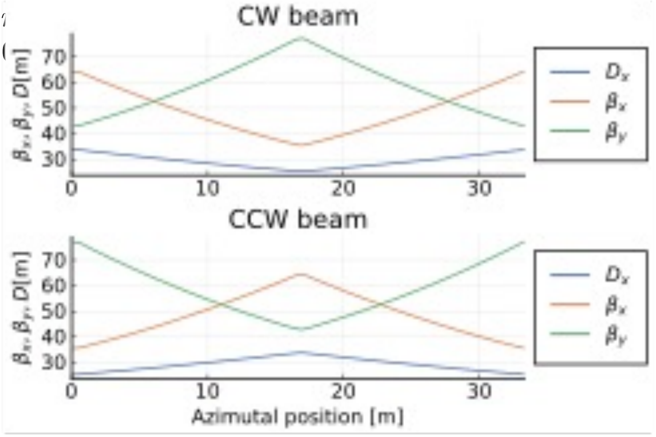


FIG. 4. Superperiod structure, beta functions and dispersion (β letter within text of the paper always refers to velocity).

EDMs of different systems

Theta_QCD:

$$d_n \simeq -d_p \simeq 3\times 10^{-16}\,\overline{\theta}\ \mathrm{e\cdot cm}$$

$$d_D\left(\overline{\theta}\right)/d_N\left(\overline{\theta}\right) \approx 1/3$$

Super-Symmetry (SUSY) model predictions:

$$d_n \simeq 1.4\left(d_d - 0.25 d_u\right) + 0.83e\left(d_u^c + d_d^c\right) - 0.27e\left(d_u^c - d_d^c\right)$$

$$d_p \simeq 1.4\left(d_d - 0.25 d_u\right) + 0.83e\left(d_u^c + d_d^c\right) + 0.27e\left(d_u^c - d_d^c\right)$$

$$d_D \simeq \left(d_u + d_d\right) - 0.2e\left(d_u^c + d_d^c\right) - 6e\left(d_u^c - d_d^c\right)$$

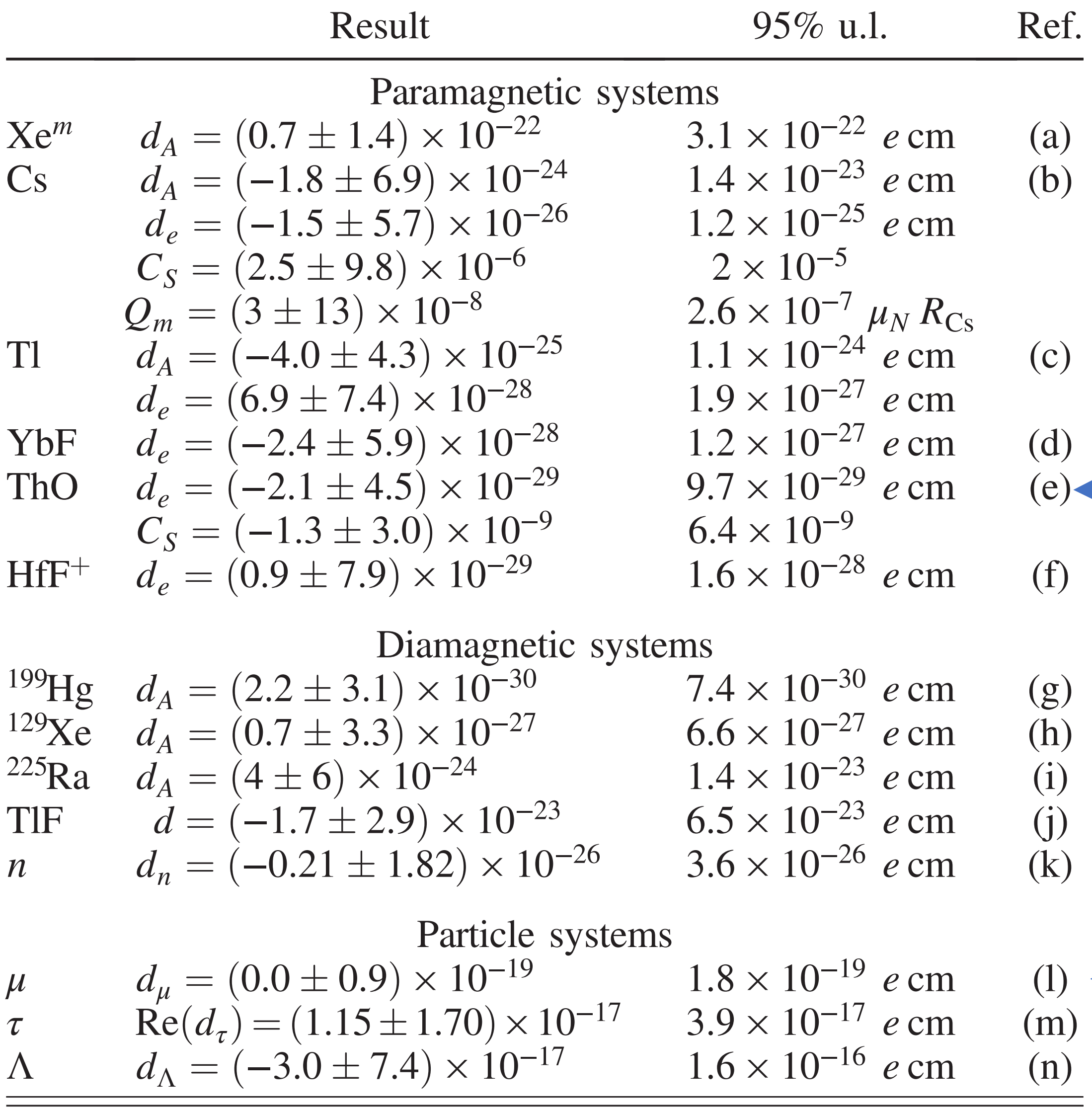
$$d_N^{I-1} \simeq 0.87\left(d_u - d_d\right) + 0.27e\left(d_u^c - d_d^c\right)$$

$$d_N^{I-0} \simeq 0.5\left(d_u + d_d\right) + 0.83e\left(d_u^c + d_d^c\right)$$

$$d_N^{I-1} = \left(d_p - d_n\right)/2$$

$$d_N^{I-0} = \left(d_p + d_n\right)/2$$

Current EDM limits



	Result	95% u.l.	Ref.
	Paramagnetic systems		
Xe^m	$d_A = (0.7 \pm 1.4) \times 10^{-22}$	3.1×10^{-22} e cm	(a)
Cs	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$	1.4×10^{-23} e cm	(b)
	$d_e = (-1.5 \pm 5.7) \times 10^{-26}$	1.2×10^{-25} e cm	
	$C_S = (2.5 \pm 9.8) \times 10^{-6}$	2×10^{-5}	
	$Q_m = (3 \pm 13) \times 10^{-8}$	2.6×10^{-7} $\mu_N R_{\mathrm{Cs}}$	
Tl	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$	1.1×10^{-24} e cm	(c)
	$d_e = (6.9 \pm 7.4) \times 10^{-28}$	1.9×10^{-27} e cm	
YbF	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$	1.2×10^{-27} e cm	(d)
ThO	$d_e = (-2.1 \pm 4.5) \times 10^{-29}$	9.7×10^{-29} e cm	(e)
	$C_S = (-1.3 \pm 3.0) \times 10^{-9}$	6.4×10^{-9}	
HfF$^+$	$d_e = (0.9 \pm 7.9) \times 10^{-29}$	1.6×10^{-28} e cm	(f)
	Diamagnetic systems		
^{199}Hg	$d_A = (2.2 \pm 3.1) \times 10^{-30}$	7.4×10^{-30} e cm	(g)
^{129}Xe	$d_A = (0.7 \pm 3.3) \times 10^{-27}$	6.6×10^{-27} e cm	(h)
^{225}Ra	$d_A = (4 \pm 6) \times 10^{-24}$	1.4×10^{-23} e cm	(i)
TlF	$d = (-1.7 \pm 2.9) \times 10^{-23}$	6.5×10^{-23} e cm	(j)
n	$d_n = (-0.21 \pm 1.82) \times 10^{-26}$	3.6×10^{-26} e cm	(k)
	Particle systems		
μ	$d_\mu = (0.0 \pm 0.9) \times 10^{-19}$	1.8×10^{-19} e cm	(l)
τ	$\mathrm{Re}(d_\tau) = (1.15 \pm 1.70) \times 10^{-17}$	3.9×10^{-17} e cm	(m)
Λ	$d_\Lambda = (-3.0 \pm 7.4) \times 10^{-17}$	1.6×10^{-16} e cm	(n)

Its own co-magnetometer

Statistics limited,
Aim for 10^{-21} *e*-cm

Rev.Mod.Phys.91.015001