The Proton EDM

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The Strong CP problem

"The most underrated puzzle in all of physics."

Forbes, 2019.

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Strong CP Problem

QCD (& The SM) has a glaring hole in it…

$$\mathcal{L}_{QCD} = (\ldots) + \boxed{\frac{g^2}{32\pi^2}\,\bar{\theta}\,\tilde{G}^a_{\mu\nu}G^{\mu\nu a}}$$

P-violating

T-violating

CP-violating

Non-zero nucleon (N) Electric Dipole Moment (EDM) → $|\vec{d}_N| = \vartheta(\theta)$.

BUT, no CP violation in strong interactions…

[$\bar{\theta} = \theta + \varphi$ = QCD θ -term + quark mass phase.]

→ No CP violation implies: $\boldsymbol{\bar{\theta} = \theta + \varphi = 0}$ **(Fine tuning!)**

→ No EDM implies $|\bar{\theta}| \lesssim 10^{-10} \rightarrow |\vec{d}_N^{SM}| \lesssim 10^{-31}\ e\cdot cm$ **(Fine tuning!)**

The Strong CP problem is a whole community problem…

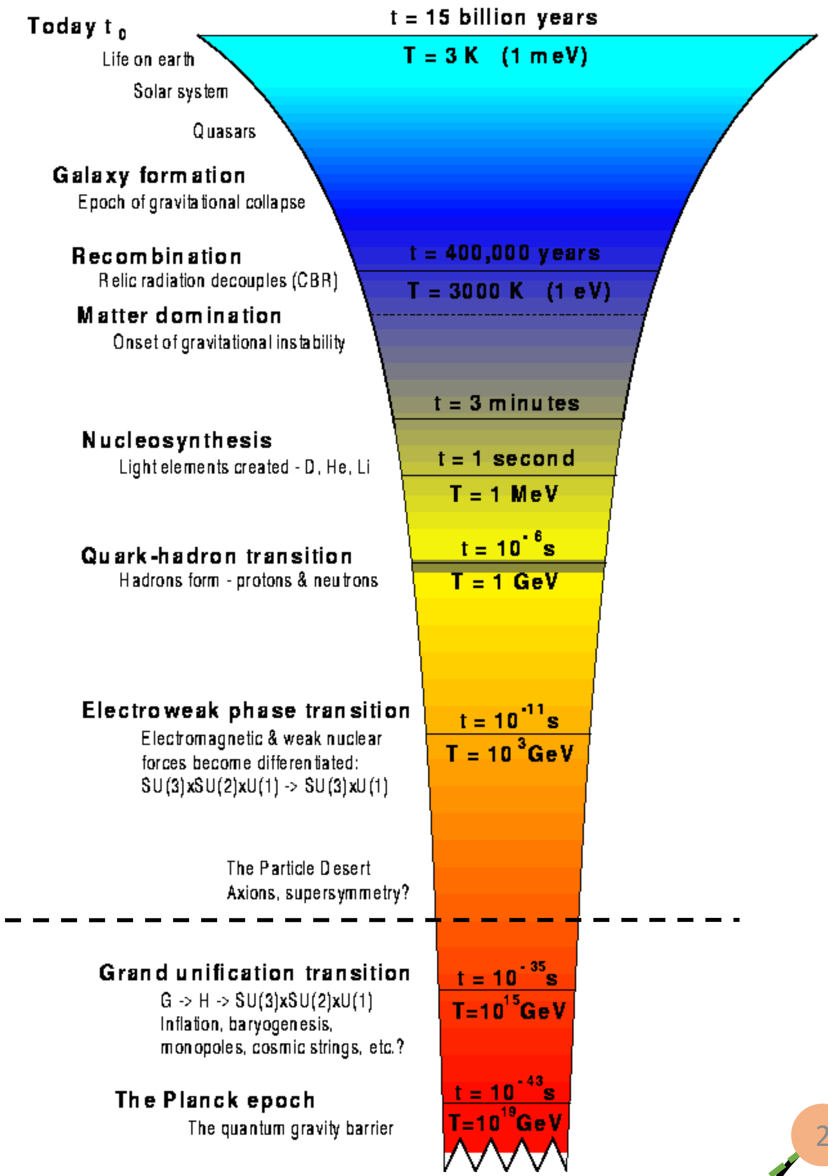
Non-zero proton EDM (pEDM), e.g. $10^{-25}\ e\cdot cm \gtrsim |\vec{d}_N| \gtrsim 10^{-30}\ e\cdot cm$:

= Solves strong CP-problem!

= CP-violation source for Baryon Asymmetry!

= Unambiguous new physics (with no SM theory needed!).

Must understand the Strong CP Problem



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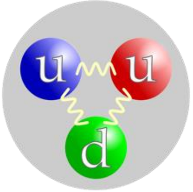
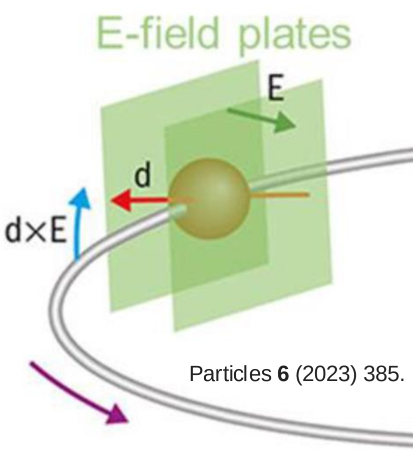
The Proton EDM

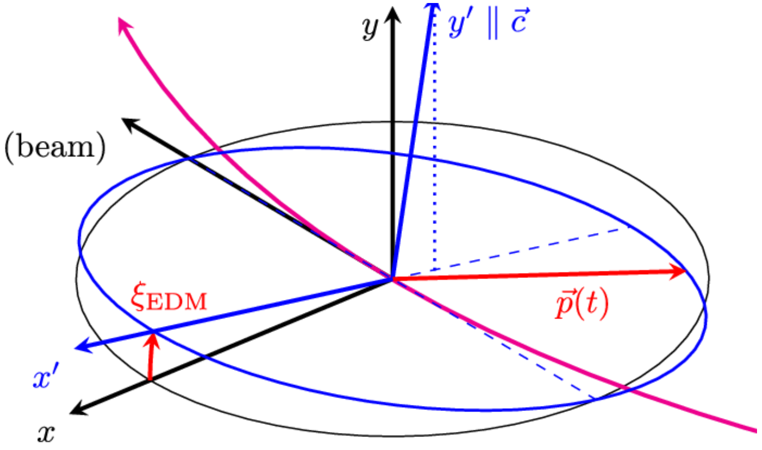
- Measure of charge separation of the system:
  - i.e. distribution of positive (u) and negative (d) charge within the proton.



- Uneven charge + electric field = EDM-induced torque.
- Results in vertical tilt the spin/polarisation:
  - We just need to measure an angle!



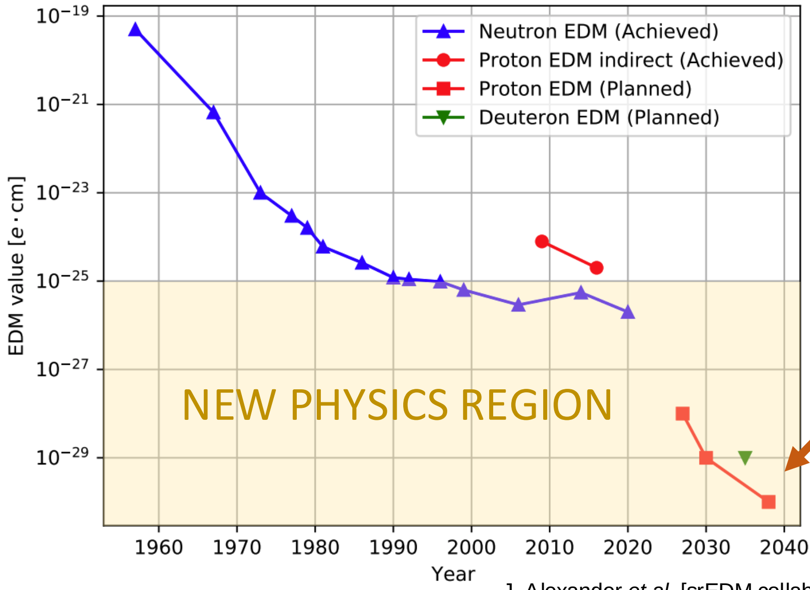
Particles **6** (2023) 385.



Phys. Rev. Accel. Beams **23** (2020) 024601.

- Requires:
  - Longitudinally polarised protons.
  - Electric storage ring (electric field bending).
  - Polarimeters to measure polarisation.

- Direct nEDM limit: $|\vec{d}_n| < \mathbf{1.8 \times 10^{-26}}\ \boldsymbol{e \cdot cm}$.
- No direct limit on pEDM!
- Best indirect limit: $\left|d_p^{\downarrow 199\mathrm{Hg}}\right| < \mathbf{2.0 \times 10^{-25}}\ \boldsymbol{e \cdot cm}$.



J. Alexander *et al*. [srEDM collaboration], arXiv:2205.00830.

New paradigm of sensitivity

[Statistics > nEDM.]

Proton EDM experiment sensitivity ~ $\mathbf{10^{-30}}\ \boldsymbol{e \cdot cm}$!

[That's 0.000000000000000000000000000001 $\boldsymbol{e \cdot cm}$]

→ **pEDM improved > $\mathcal{O}(10^4)$.**

→ **$\theta_{\rm QCD}$ (strong CP problem) improved > $\mathcal{O}(10^3)$.**

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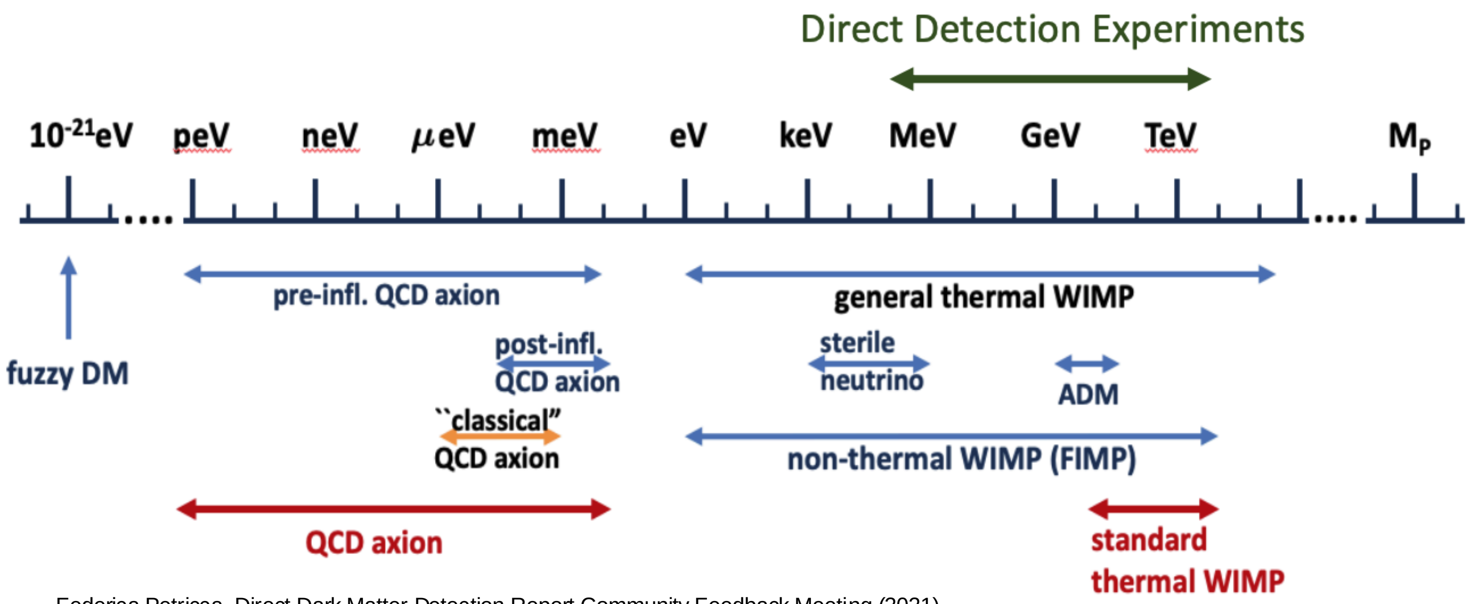
pEDM Experiment: New Physics Reach

Strong CP Problem	Matter-Antimatter Asymmetry	Dark Matter	EDM loop induced = wide range of interactions/energy scales $d_p \sim (g^2/16\pi^2)\,(e\,m_q)/\Lambda_{\rm NP}^2\ \sin\phi^{\rm NP}\ \ e\cdot cm$ m_q = mass of 1-loop quark, $\phi^{\rm NP}$ = complex CP violation phase of NP	
Solved!	Model-independent CP-violation.	Oscillating pEDM signature = **axion** [$\mathcal{O}(10^2)$ larger than nEDM!]. ERJC **84** (2024) 12, arXiv:2308.16135, PRD **99** (2019) 083002, PRD **104** (2021) 096006	Light, weak new physics: $\Lambda_{\rm NP}\sim 1$ GeV, $g \lesssim 10^{-5}$, $\phi^{\rm NP}\sim 10^{-10}$. [e.g. LZ, LDMX, FASER, SHiP.]	$\mathcal{O}$(PeV) mass scale: $\phi^{\rm NP}\sim 1$, $\Lambda_{\rm NP}\sim 3\times 10^3$ TeV. [e.g. LHC/FCC.]



Federica Petricca, Direct Dark Matter Detection Report Community Feedback Meeting (2021).

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pEDM Experiment: a Muon g-2 spin-off

Consider Muon g-2 experiment: charged particle in magnetic ($\vec{B}$) and electric ($\vec{E}$) fields:

$$\vec{\omega}_{spin} = \vec{\omega}_{MDM} \approx \frac{e}{m}\left[a\vec{B} + \left(a - \frac{1}{\gamma^2-1}\right)(\vec{\beta} \times \vec{E})\right].$$

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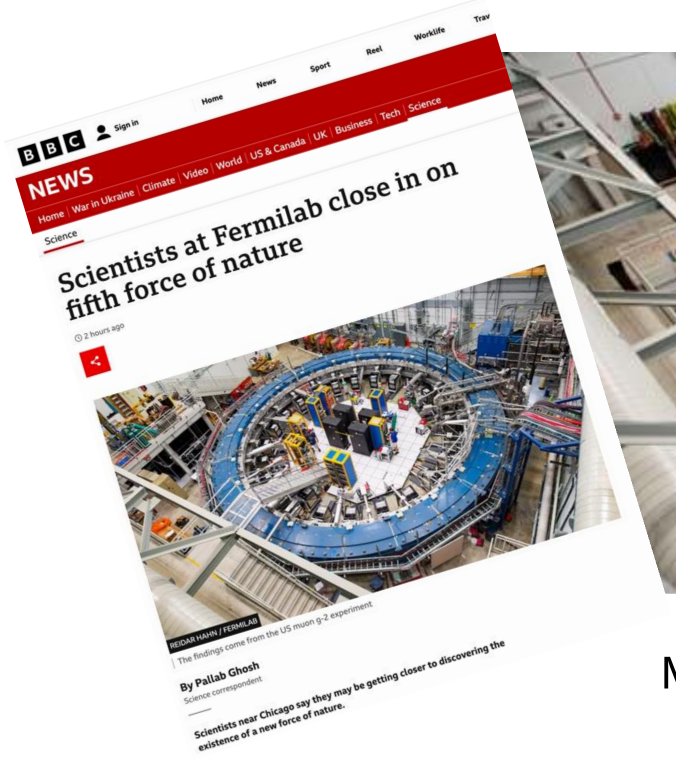
Muon → storage ring magnet $R_0 = 7.112\ \mathrm{m}$ and $B = 1.45\ \mathrm{T}$ ...

Choose muon g-2 magic-momentum, $\gamma_{\mathrm{magic}} = \sqrt{1 + 1/a} \rightarrow p = 3.094\ \mathrm{GeV/c}$.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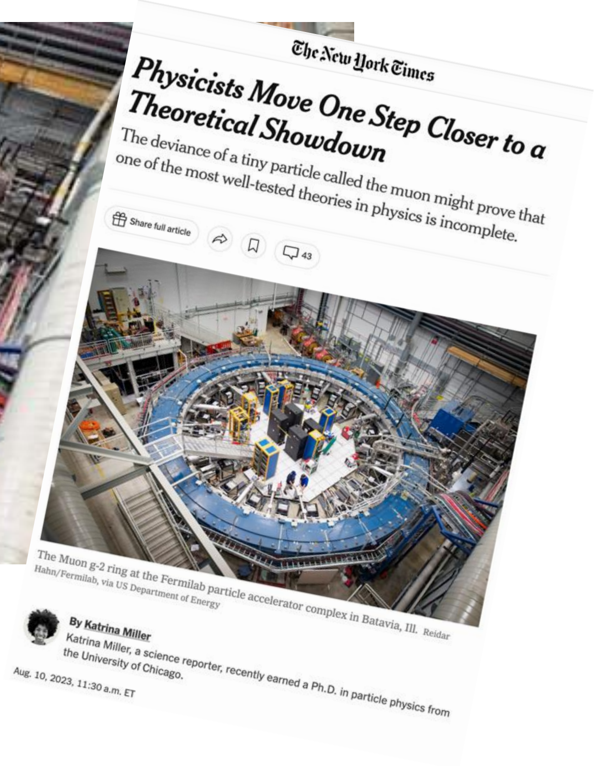
Science
Scientists at Fermilab close in on fifth force of nature
2 hours ago
REIDAR HAHN / FERMILAB
The findings come from the US muon g-2 experiment
By Pallab Ghosh
Science correspondent
Scientists near Chicago say they may be getting closer to discovering the existence of a new force of nature.


The New York Times
Physicists Move One Step Closer to a Theoretical Showdown
The deviance of a tiny particle called the muon might prove that one of the most well-tested theories in physics is incomplete.
Share full article
The Muon g-2 ring at the Fermilab particle accelerator complex in Batavia, Ill. Reidar Hahn/Fermilab, via US Department of Energy
By Katrina Miller
Katrina Miller, a science reporter, recently earned a Ph.D. in particle physics from the University of Chicago.
Aug. 10, 2023, 11:30 a.m. ET

Major experimental and particle physics success!
Currently 200ppb precision!

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Use Muon g-2 principles: charged particle with EDM in magnetic ($\vec{B}$) and electric ($\vec{E}$) fields:

$$\vec{\omega}_{spin} = \vec{\omega}_{MDM} + \vec{\omega}_{EDM} \approx \frac{e}{m}\left[a\vec{B} + \left(a - \frac{1}{\gamma^2-1}\right)(\vec{\beta} \times \vec{E}) + \frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B}\right)\right], \quad \vec{d} = \eta\frac{q\hbar}{2mc}\vec{S}.$$

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Frozen-spin technique!

Proton → electric storage ring $R_0 = 800\ \mathrm{m}$ and $E = 4.4\ \mathrm{M/m}$ ...

Choose pEDM <u>magic-momentum</u>: $a\vec{B} + \left(a - \frac{1}{\gamma^2-1}\right)\left(\vec{\beta}\times\vec{E}\right) = 0 \rightarrow p = 0.7\ \mathrm{GeV/c}$.

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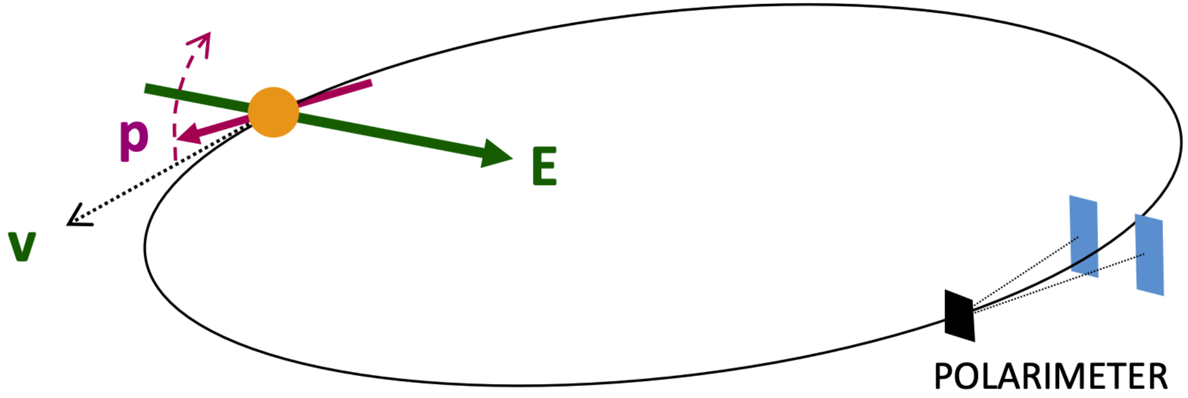

- Inject $\mathcal{O}(10^{10})$ polarized protons every twenty minutes.
- $\vec{E}$-field bending and $\vec{B}$-field focusing.
- Vertical polarization in polarimeter = static EDM.

And no SM calculation to compare to!

What about large, T-conserving systematics that mimic vertical, T-violating EDM, e.g. radial $\vec{B}$ field?

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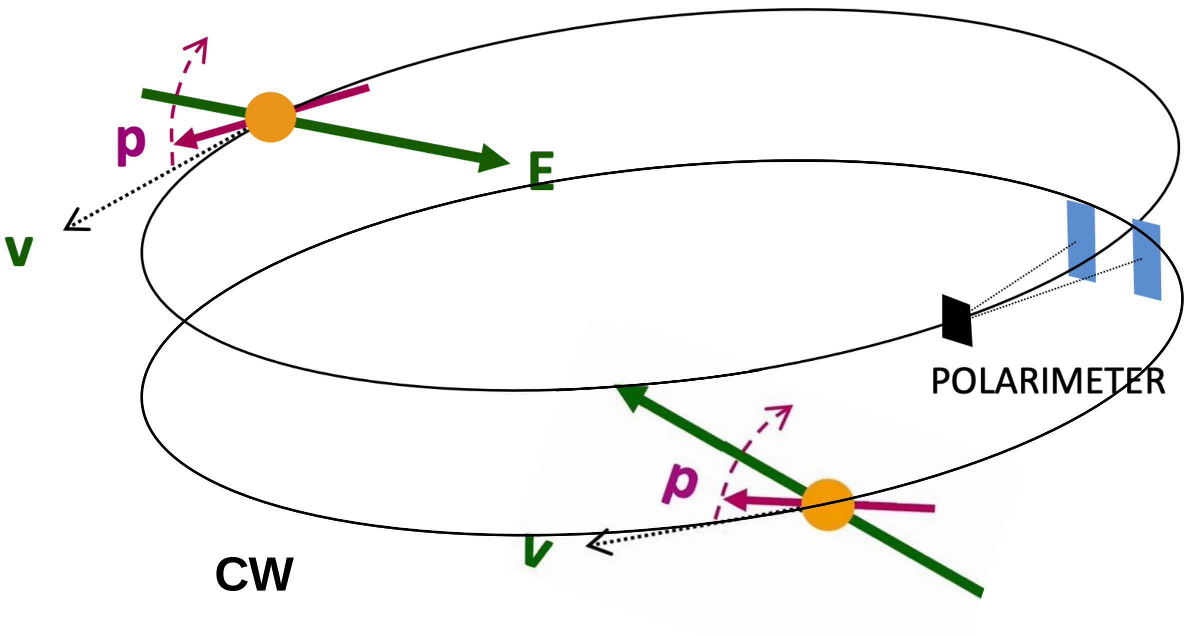

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→ Store CW and CCW beams (time reverse of each other) to cancel these effects!

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pEDM potential locations

BNL

- R&D and planning done for 800m ring at AGS:
  - Well-understood polarised proton delivery.
  - Viable site with thought-out ring.
  - Ground stability already understood.
- Genesis of current g-2 team and expertise.
- Construction/engineering can be done in UK/EU.
- Least work to realisation.

COSY

- Home of pEDM precursor experiment.
- R&D/ testing ongoing at COSY (e.g. polarimeters).
- But $\mathcal{O}(10^2)$ less polarised proton intensity c.f. BNL.
- End of COSY operations after 2024 (??).

CERN

- Could make use of old ISR (CW/CCW beams).
- Could do polarised protons (or BNL polarisers).
- Cheaper than U.S. (but 950m ring = more expensive).
- More work to be done compared to BNL.
- Approved/balanced against CERN/LHC/FCC programme.

Fermilab

- Ambition to continue storage ring programme.
- High-intensity proton facility ready-to-go.
- Could borrow/use BNL polarised proton technology.
- Use substantial g-2/EDM expertise.
- Interplay with DUNE/neutrino programme.
- Continue Fermilab's wide-ranging particle physics output beyond just neutrinos in long-term.

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(Short) path to readiness

Main message: **no showstoppers! Due diligence, physics case studies, moving to TDR phase…**

Already completed…

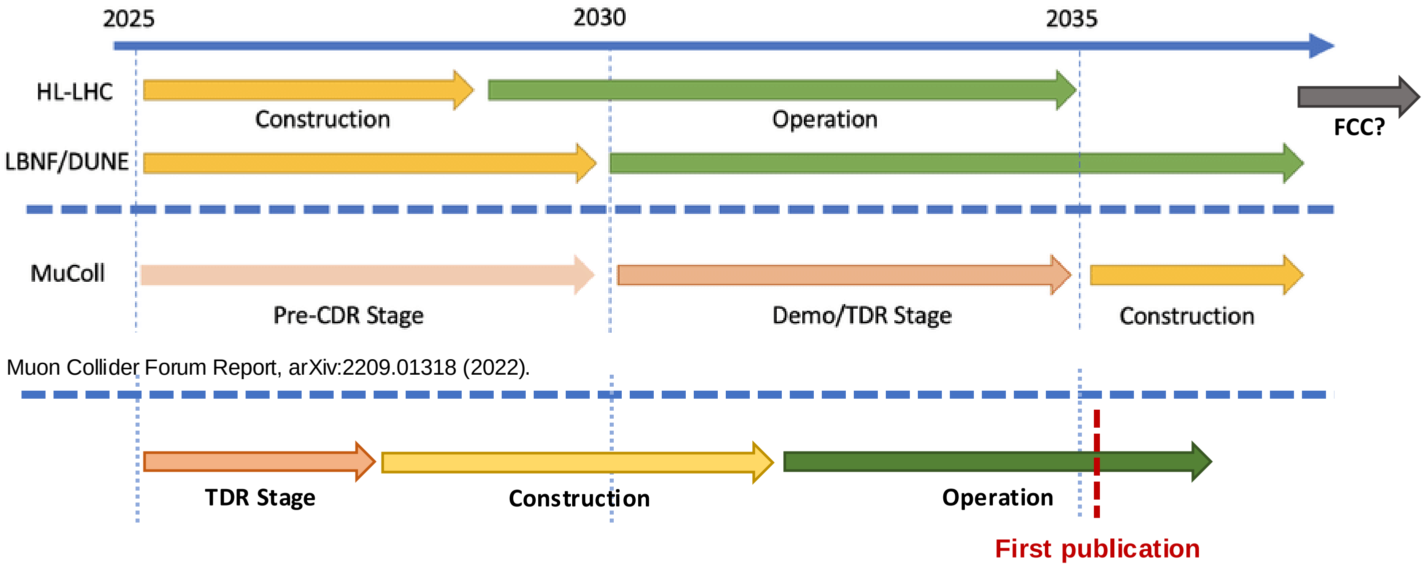
- Experiment design, engineering and modelling complete. ✅
- Prototype components under construction. ✅
- Measurement techniques understood. ✅
- Key systematics understood. ✅

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 (estimated $\mathcal{O}$($100M)).

Build community/collaboration!

- Increased involvement (you are invited!).
- New generation to start and finish experiment.



- 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!

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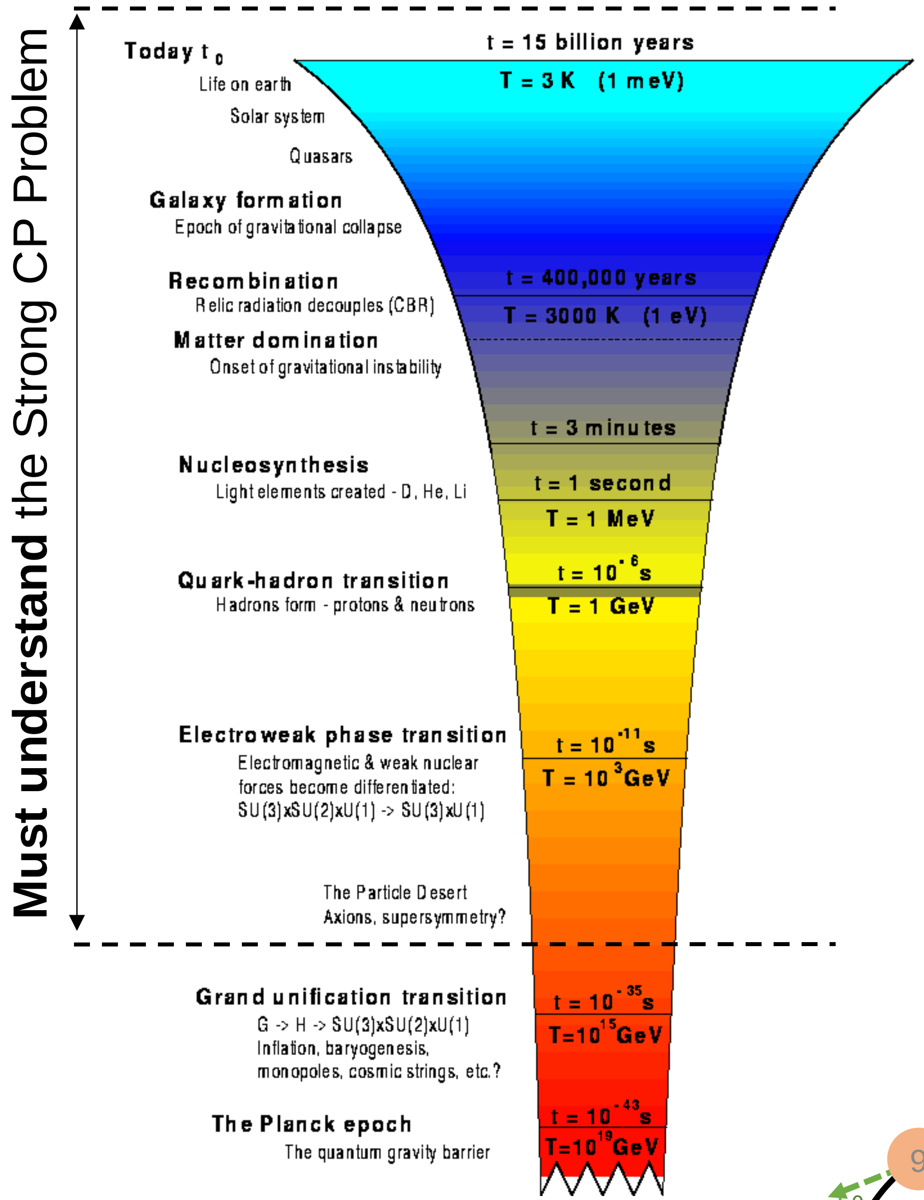
Conclusions

- pEDM experiment is the first direct search for the proton EDM.
- Improves on current (indirect) limit by $> \mathcal{O}(10^4)$.
- Directly address/solves the strong CP problem.
  - Strong CP/pEDM ↔ Astro + Particle + Nuclear.
- Significant new physics drivers:
  - CP-violation source for Baryon Asymmetry.
  - Sensitive probe for axionic dark-matter.
  - Probe light-weak new particles → PeV-scale new physics.
  - No EDM would also be dramatic → at SM limit.
- Major R&D completed / systematics understood.
- From TDR to final publication in < 20 years.
- One of the most low-cost/high-return proposals in particle physics today.



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Conclusions

This is a beautiful experiment to precisely measure an angle…

You can be a part of it.