Title: Precision Physics in Storage Rings

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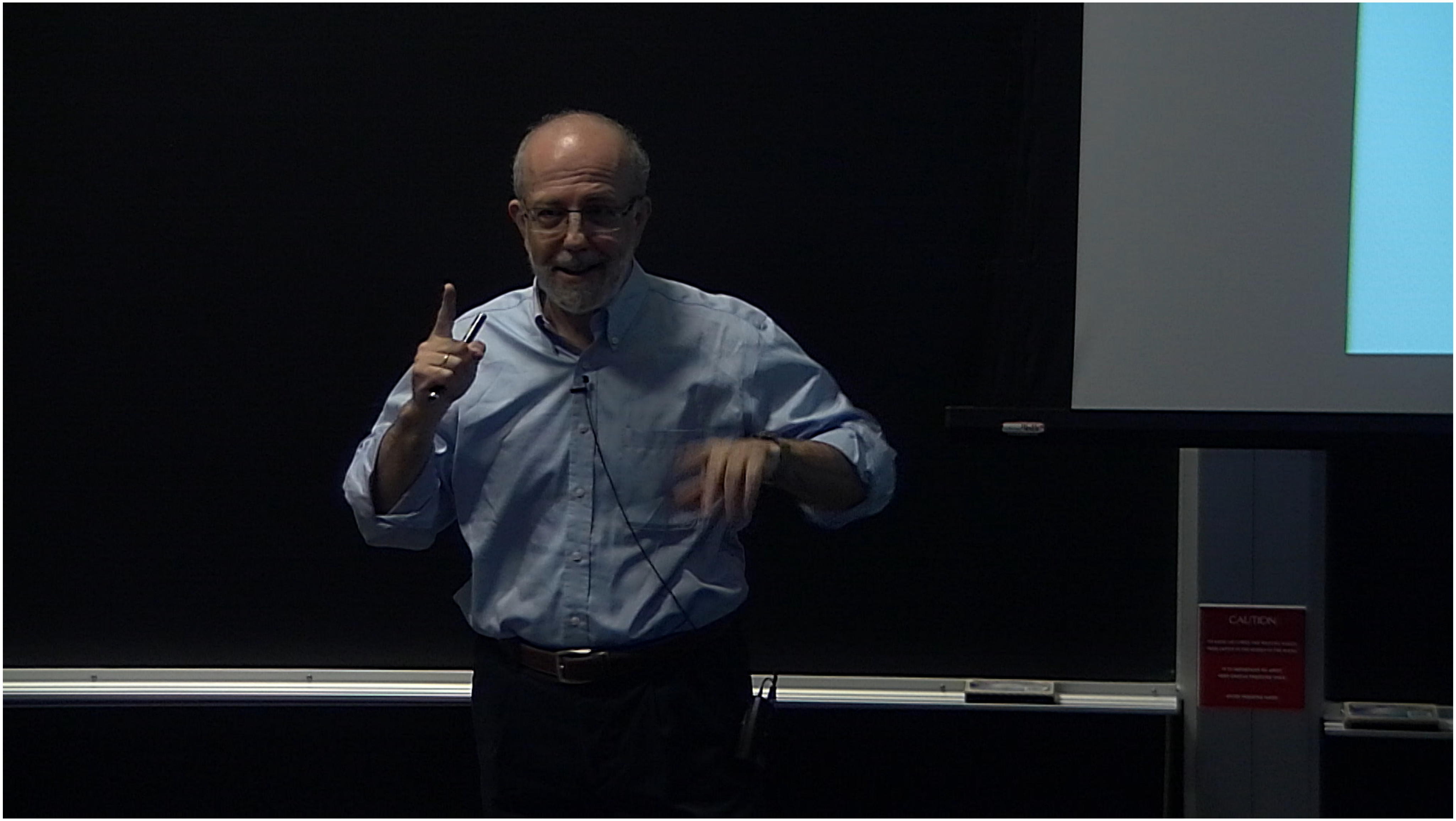
Abstract:


CAUTION

August 22, 2017
Perimeter Institute
Waterloo, Canada

KAIST

ibs Institute for Basic Science 기초과학연구원

CAPP
Center for Axion and Precision Physics Research

Precision physics in storage rings: Probing new and old physics. Axion dark matter

Yannis K. Semertzidis,
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- ✓Storage rings: muon g-2 and proton/deuteron EDM
- ✓Axion dark matter experiments

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- ✓Storage rings: muon g-2 and proton/deuteron EDM
- ✓Axion dark matter experiments
- ✓High field magnets; high volume geometries

Center for Axion and Precision Physics KAIST, Daejeon, Korea

IBS/CAPP-Physics approach

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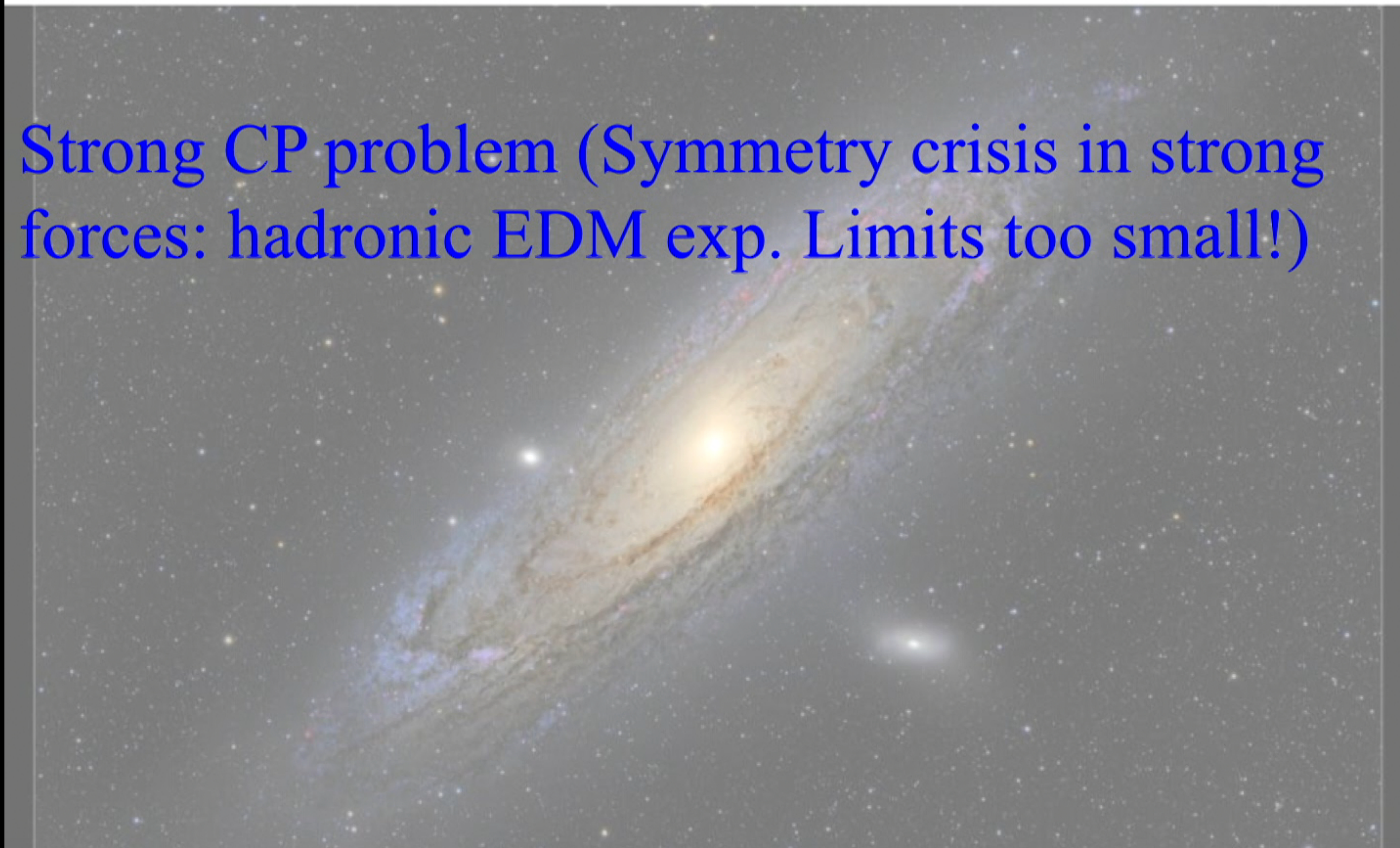
Strong CP problem (Symmetry crisis in strong forces: hadronic EDM exp. Limits too small!)



IBS/CAPP-Physics approach

Strong CP problem (Symmetry crisis in strong forces: hadronic EDM exp. Limits too small!)

- Cosmic Frontier (Dark Matter axions): Improve in all possible fronts: B-field, Volume, Resonator Quality factor, Physical and Electronic noise. Check dark matter down to 10% of axion content.

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- Storage ring proton EDM (most sensitive hadronic EDM experiment). Improve theta_QCD sensitivity by three to four orders of magnitude!
- Together with long-range monopole-dipole (axion mediated) forces probe axion Physics!

Major activities

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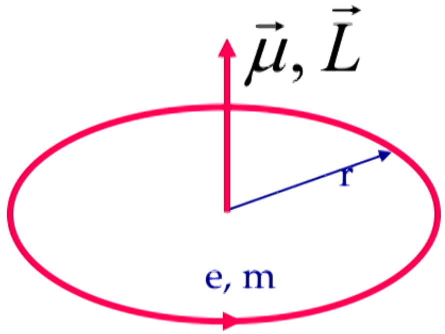
4. Proton EDM development for an exp. @ CERN

Magnetic Dipole Moments

A circulating particle with charge e and mass m:



- Angular momentum

$$L = mvr$$

- Magnetic dipole moment

$$\mu = IA$$

For particles with intrinsic angular momentum (spin S):

$$\vec{\mu} = g\frac{e}{2m}\vec{S}$$

In a magnetic field (B), there is a torque:

$$\vec{\tau} = \vec{\mu} \times \vec{B}$$

Definition of g-Factor

$$g \equiv \frac{\dfrac{\text{magnetic moment}}{e\hbar/2m}}{\dfrac{\text{angular momentum}}{\hbar}}$$

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g-2 measures the difference between the charge and mass distribution.
g-2=0 when they are the same all the time…
From Dirac equation g-2=0 for point-like, spin ½ particles, e.g leptons.

Magnetic Dipole Moments: μ

- Nuclear Magnetic Resonance: a new direct method of detecting NMR, I. Rabi *et al.*, 1938

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

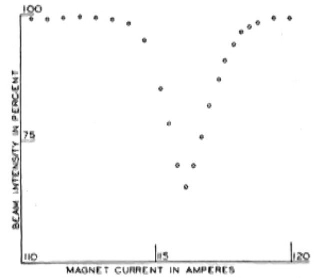
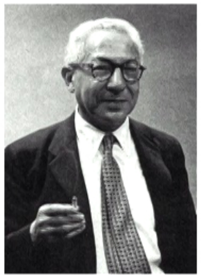
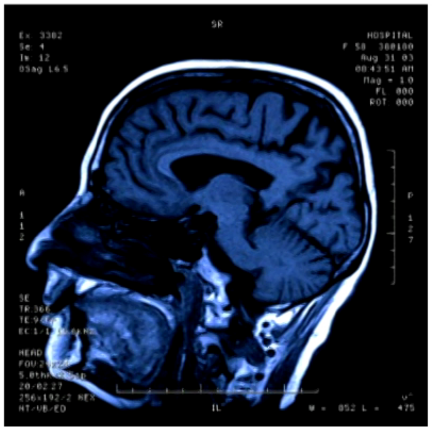


FIG. 1. Curve showing refocused beam intensity at various values of the homogeneous field. One ampere corresponds to about 18.4 gauss. The frequency of the oscillating field was held constant at 3.518×10^6 cycles per second.

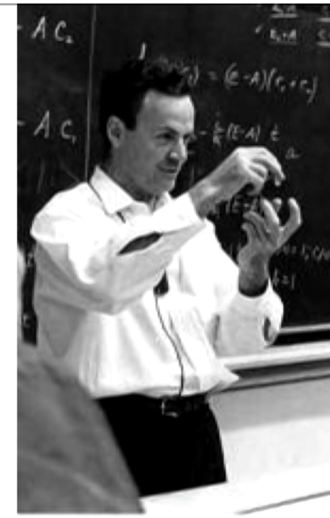


- Used in Magnetic Resonance

Imaging



MDM can also tell us about Quantum Field Fluctuations



- A "soup" of virtual particles is coming in and out of existence affecting the MDM interaction of particles with B-fields.
- The interaction is estimated using Feynman diagrams.
- It is expressed with the so-called g-2 factor: $a = (g-2)/2$, the anomaly.

g-factors:

- Proton (g_p=+5.586) and the neutron (g_n=-3.826) are composite particles.
- The ratio g_p/g_n=-1.46 close to the predicted –3/2 was the first success of the constituent quark model.

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- The anomalous magnetic moment of leptons can be estimated with high accuracy

Electron Magnetic Dipole Moment

D. Hanneke, S. Fogwell, and G. Gabrielse, PRL **100**, 120801 (2008)

$$\vec{\mu} = -g\left(\frac{e}{2m}\right)\vec{s} \qquad \frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B}$$

$$g/2 = 1.001\ 159\ 652\ 180\ 73\ (28)\ [0.28\ \text{ppt}]$$

$$\frac{g}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + C_{10}\left(\frac{\alpha}{\pi}\right)^5 + \ldots + a_{\mu\tau} + a_{\text{hadronic}} + a_{\text{weak}}, \quad (4)$$

It's a triumph of QED!

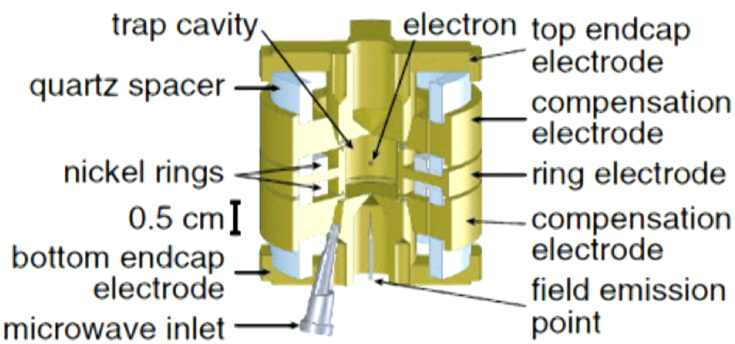

FIG. 2 (color). Cylindrical Penning trap cavity used to confine a single electron and inhibit spontaneous emission.

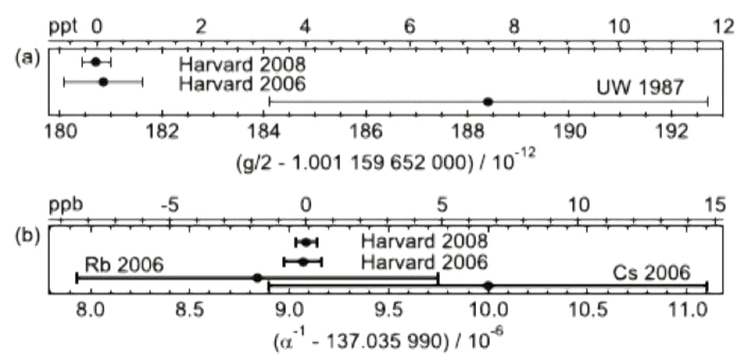

FIG. 1. Most accurate measurements of the electron $g/2$ (a), and most accurate determinations of α (b).

g-factors: Muon case

- The g_μ-2 is more sensitive to a class of particles than the g_e-2 by $(m_\mu/m_e)^2$~40,000. A thicker "soup" of virtual particles coming in and out of existence…

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- Muons are sensitive to W, Z, and new physics, e.g. SUSY: neutralino

The Standard Model

Leptons

e	μ	τ
ν_e	ν_μ	ν_τ

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Muon decay

- Decay is self analyzing

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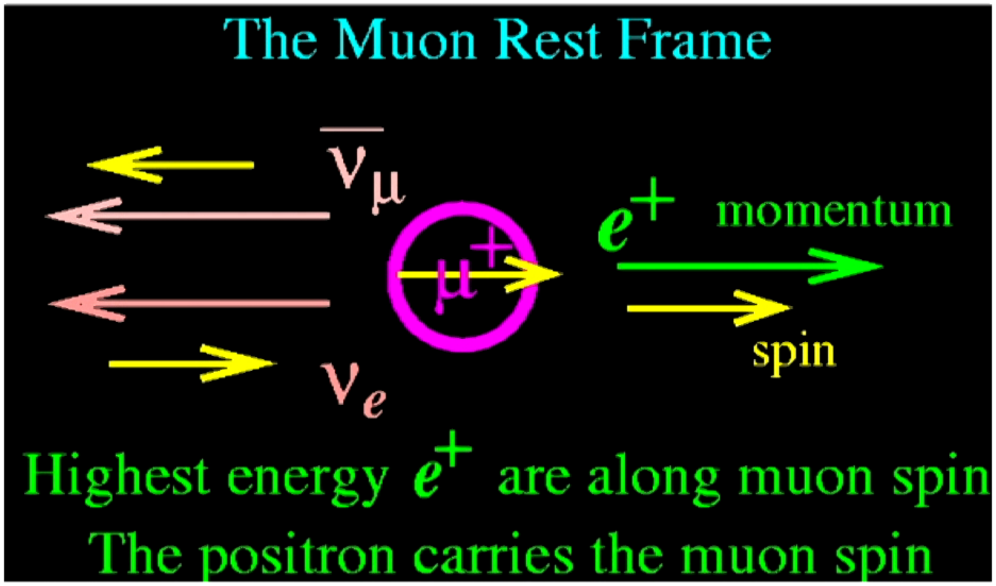
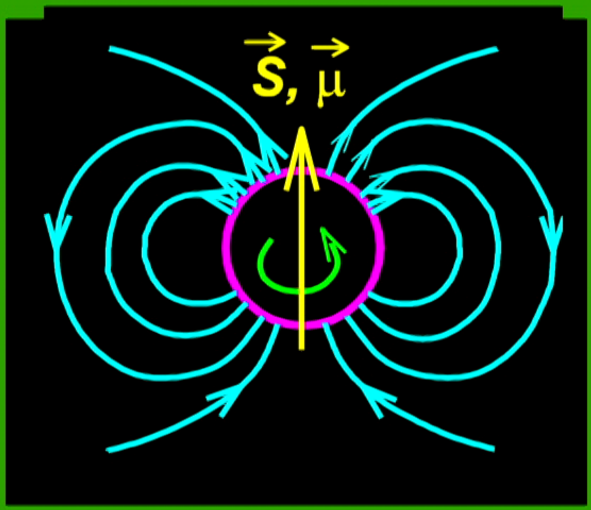


- The highest energy $e^{\pm}$ from $\mu^{\pm}$ decay carry information of the muon spin direction.

Summary of μ_S

$$\vec{\mu}_s = g_s \left(\frac{e\hbar}{2m}\right) \vec{s}$$



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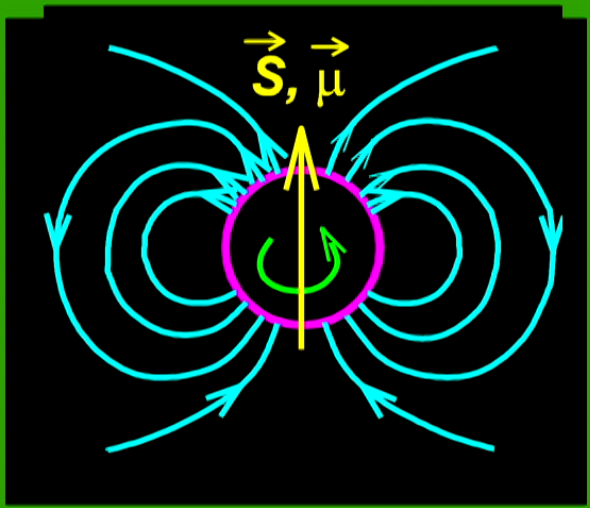
the moment consists of 2 parts

$$\mu = (1 + a)\,\frac{e\hbar}{2m}$$

Dirac + Pauli moment



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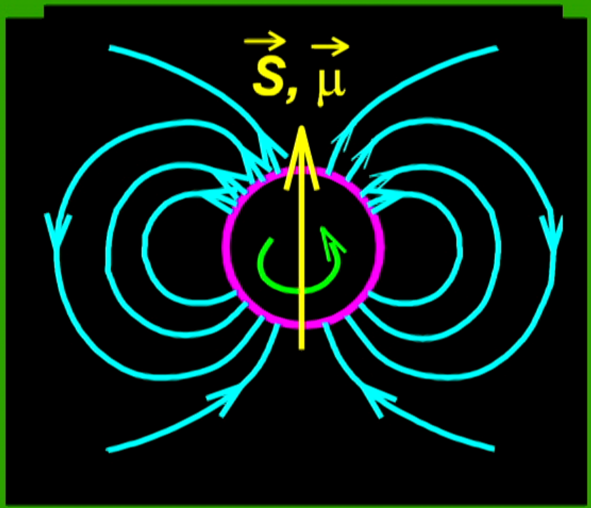


the moment consists of 2 parts

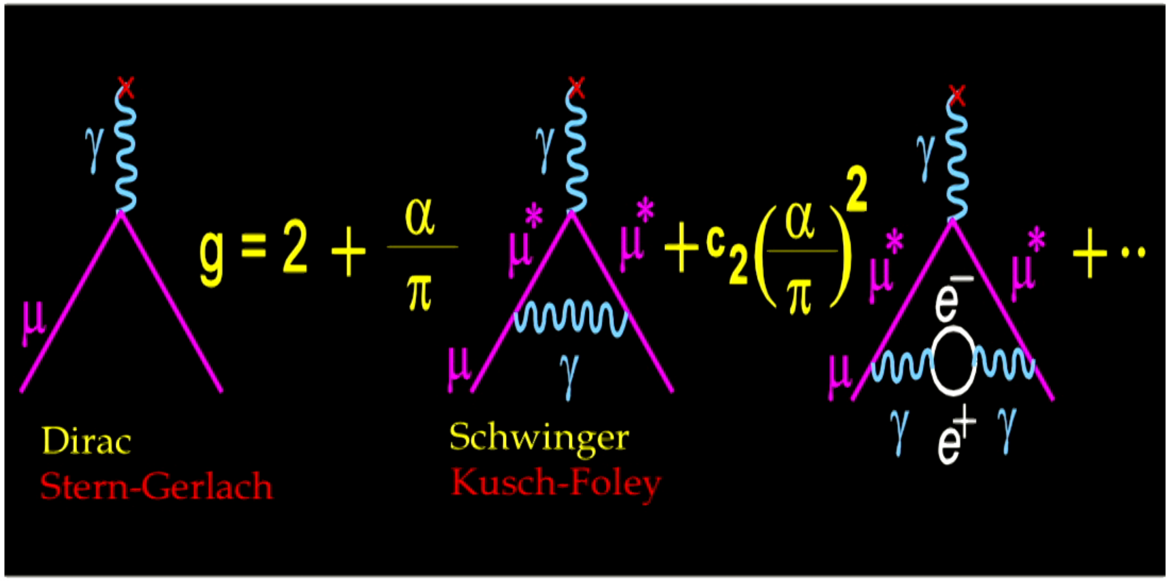
$$\mu = (1 + a)\,\frac{e\hbar}{2m}$$

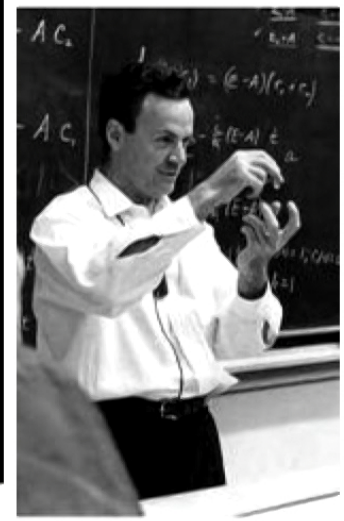
Dirac + Pauli moment

the anomaly $a = \left(\frac{g-2}{2}\right)$; or $g = 2(1+a)$

QED predicts a

Radiative corrections change g from its Dirac value of 2. We symbolically express these corrections as Feynman diagrams





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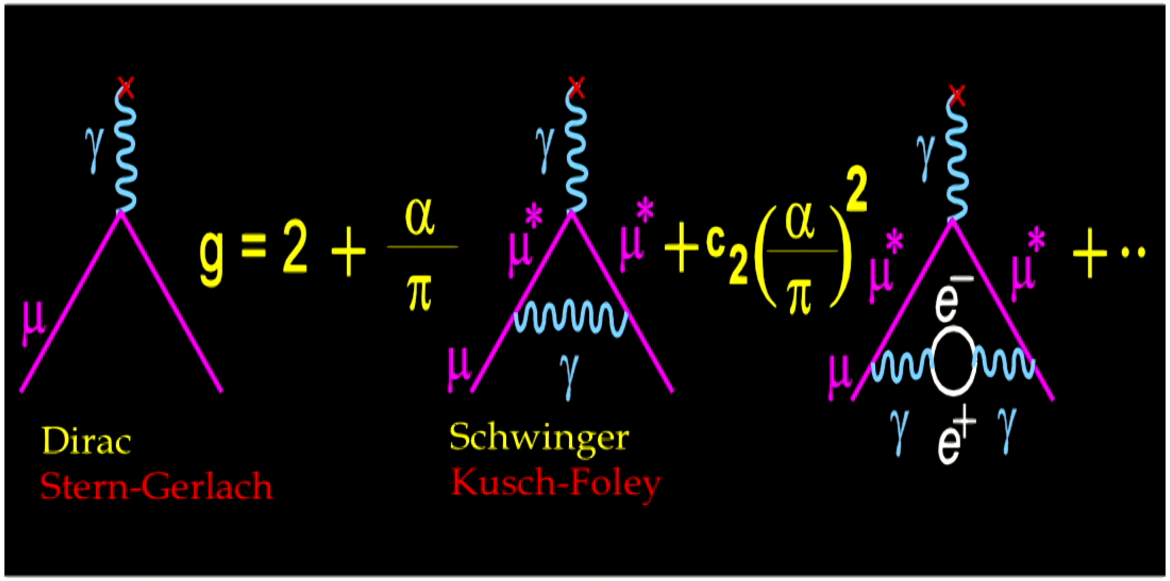
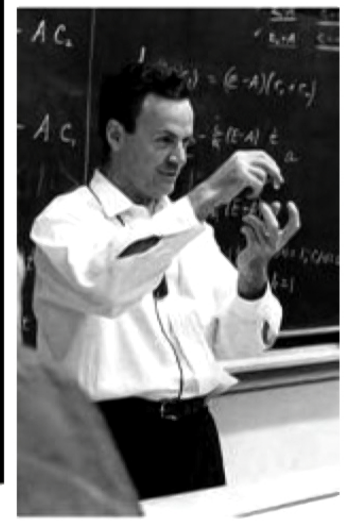


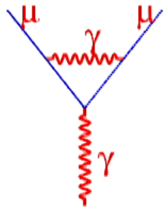


We have a pertubation expansion:

$$a(\text{QED}) = \frac{1}{2}\frac{\alpha}{\pi} + C_2\left(\frac{\alpha}{\pi}\right)^2 + C_3\left(\frac{\alpha}{\pi}\right)^3 + C_4\left(\frac{\alpha}{\pi}\right)^4 + C_5\left(\frac{\alpha}{\pi}\right)^5 + \cdots$$

g - 2 for the muon, SM contributions

Largest contribution : $a_\mu = \frac{\alpha}{2\pi} \approx \frac{1}{800}$



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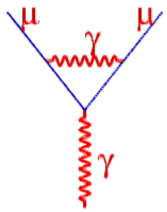
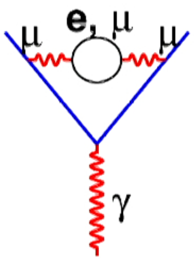


Other standard model contributions :



QED

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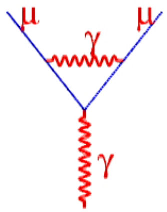

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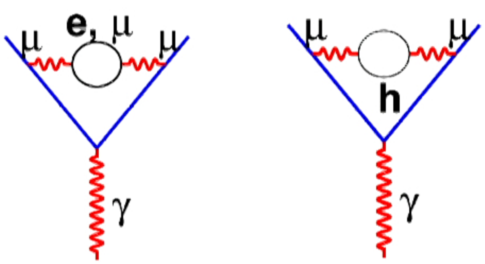

QED hadronic

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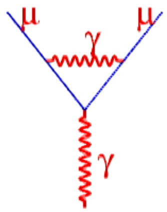

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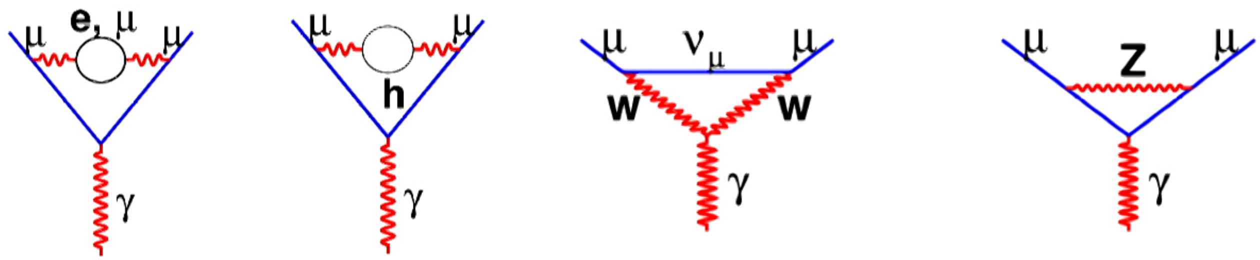
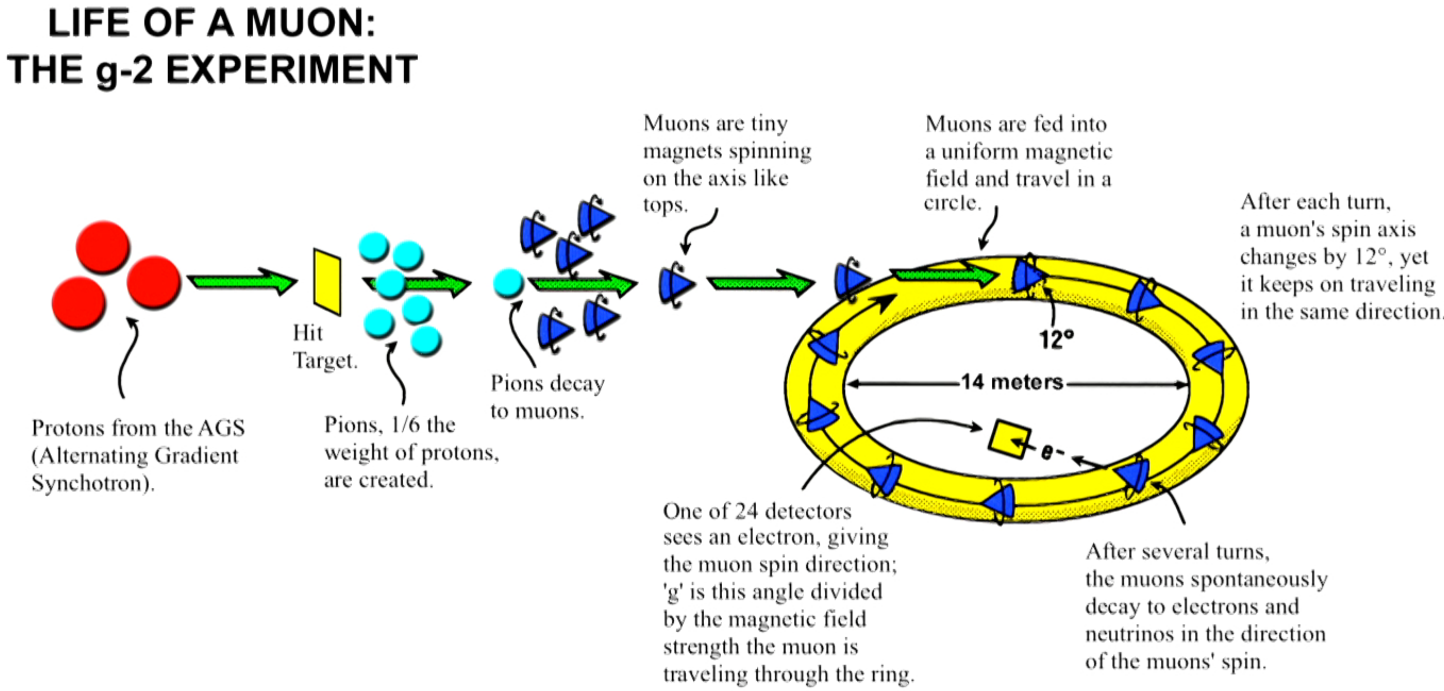


QED hadronic weak

Muon g-2 experiment: major challenge to the Standard Model

- E821 at BNL: 1997-2004
- E989 at FNAL: first data in 2017



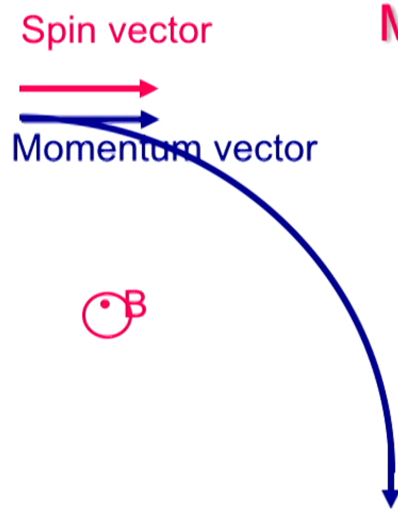
Spin Precession Rate at Rest

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

The Principle of g-2

$$\text{At rest}: \quad \frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B}$$

Moving: Thomas precession!



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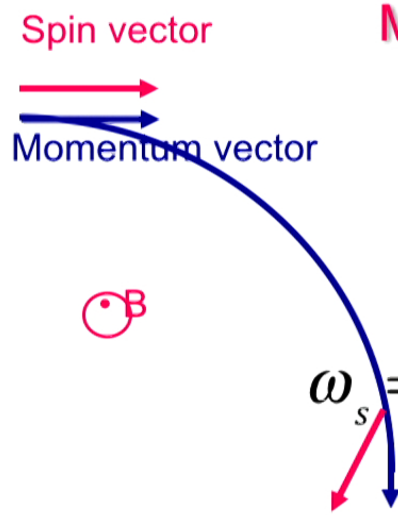

$$\omega_c = \frac{eB}{m\gamma}$$

$$\omega_s = \frac{g}{2}\frac{eB}{m} + (1-\gamma)\frac{eB}{m\gamma}$$

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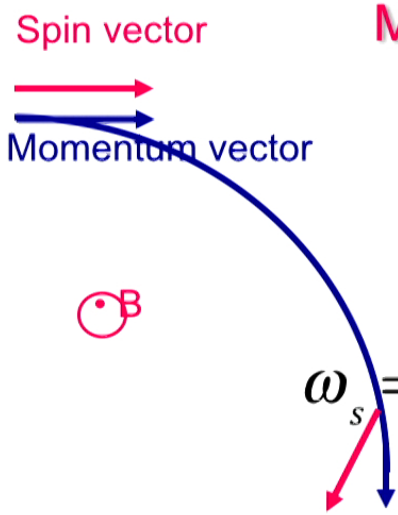

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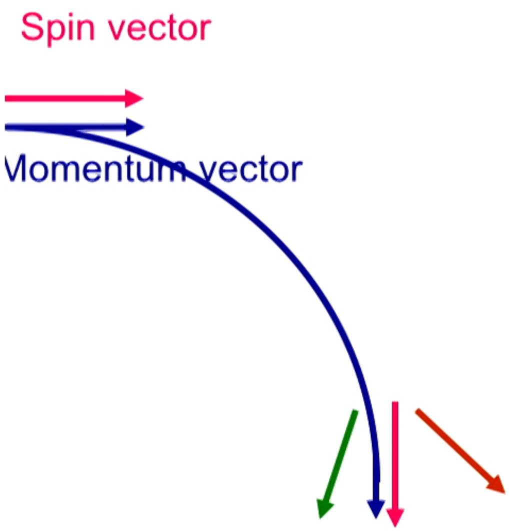
Effect of Radial Electric Field

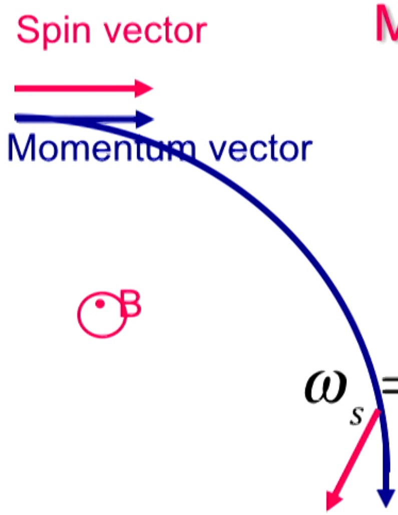


- Low energy particle
- …just right
- High energy particle

The Principle of g-2

$$\text{At rest}: \frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B}$$

Moving: Thomas precession!



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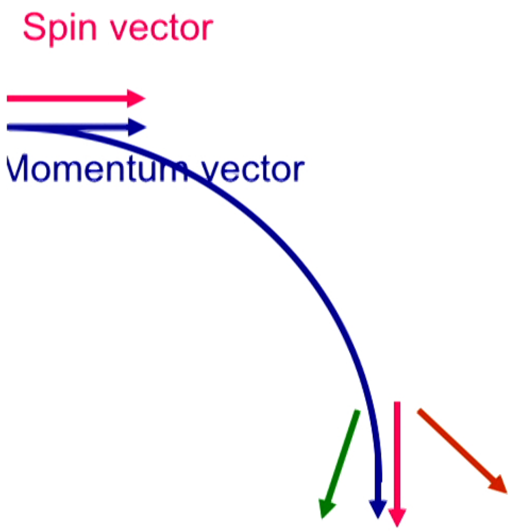
Independent of velocity!

Effect of Radial Electric Field



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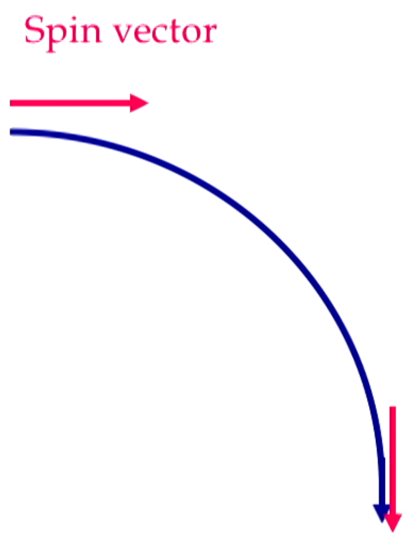

- …just right, γ~29.3 for muons, "magic" momentum (~3GeV/c)

Breakthrough concept: Freezing the horizontal spin precession due to E-field

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

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Muon g-2 focusing is electric: The spin precession due to E-field is zero at "magic" momentum (3.1GeV/c for muons, 0.7 GeV/c for protons,…)

$$p = \frac{mc}{\sqrt{a}}, \text{ with } G = a = \frac{g-2}{2}$$

We measure the difference frequency between the spin and momentum precession

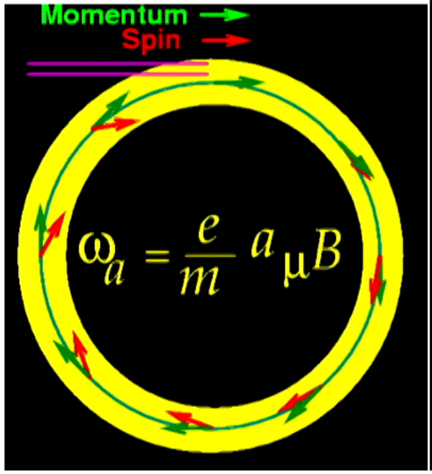
$$\omega_a = \omega_S - \omega_C = \left(\frac{g-2}{2}\right)\frac{eB}{mc} \quad B \Rightarrow \langle B \rangle_{\mu-\mathrm{dist}}$$

With an electric quadrupole field for vertical focusing

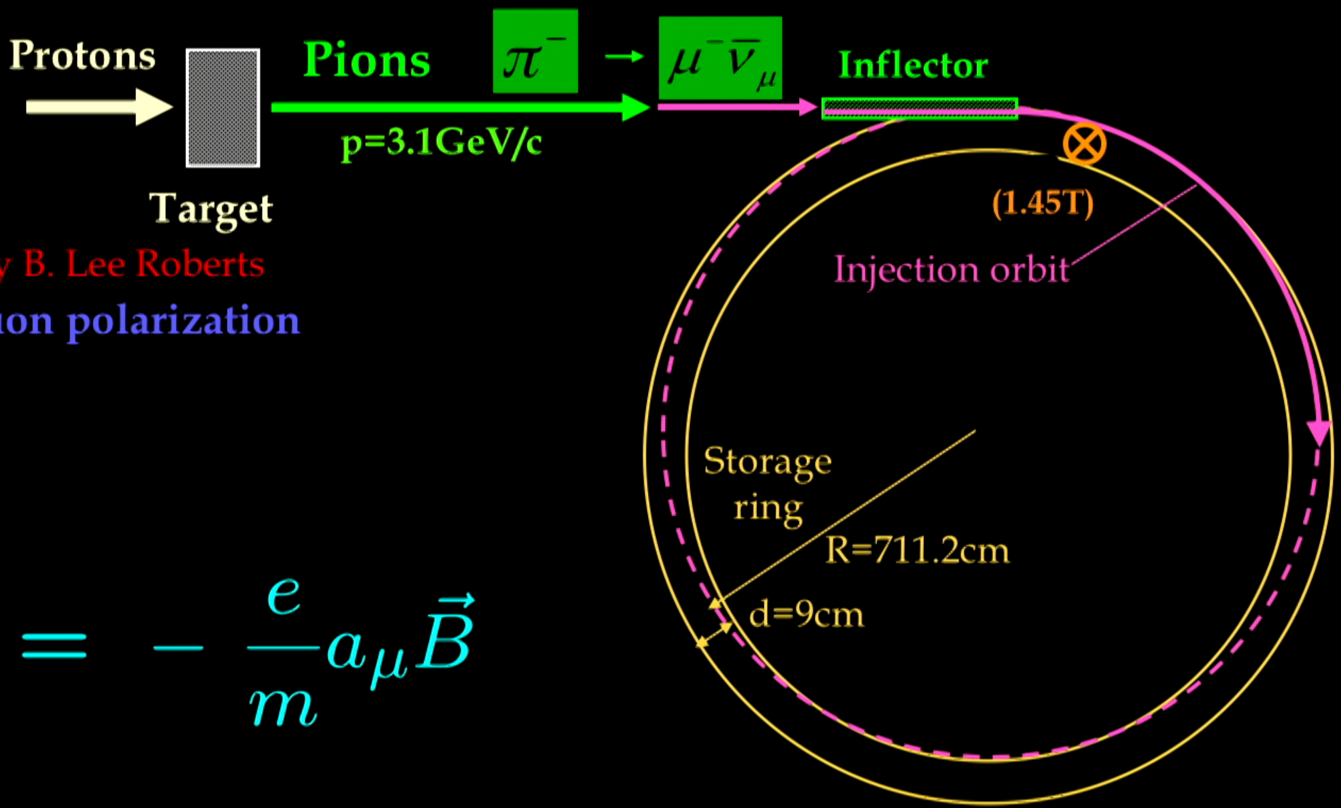
$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

$$\gamma_{\mathrm{magic}} = 29.3$$

$$p_{\mathrm{magic}} = 3.09\ \mathrm{GeV/c}$$



Experimental Technique



slide by B. Lee Roberts

Muon polarization

$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

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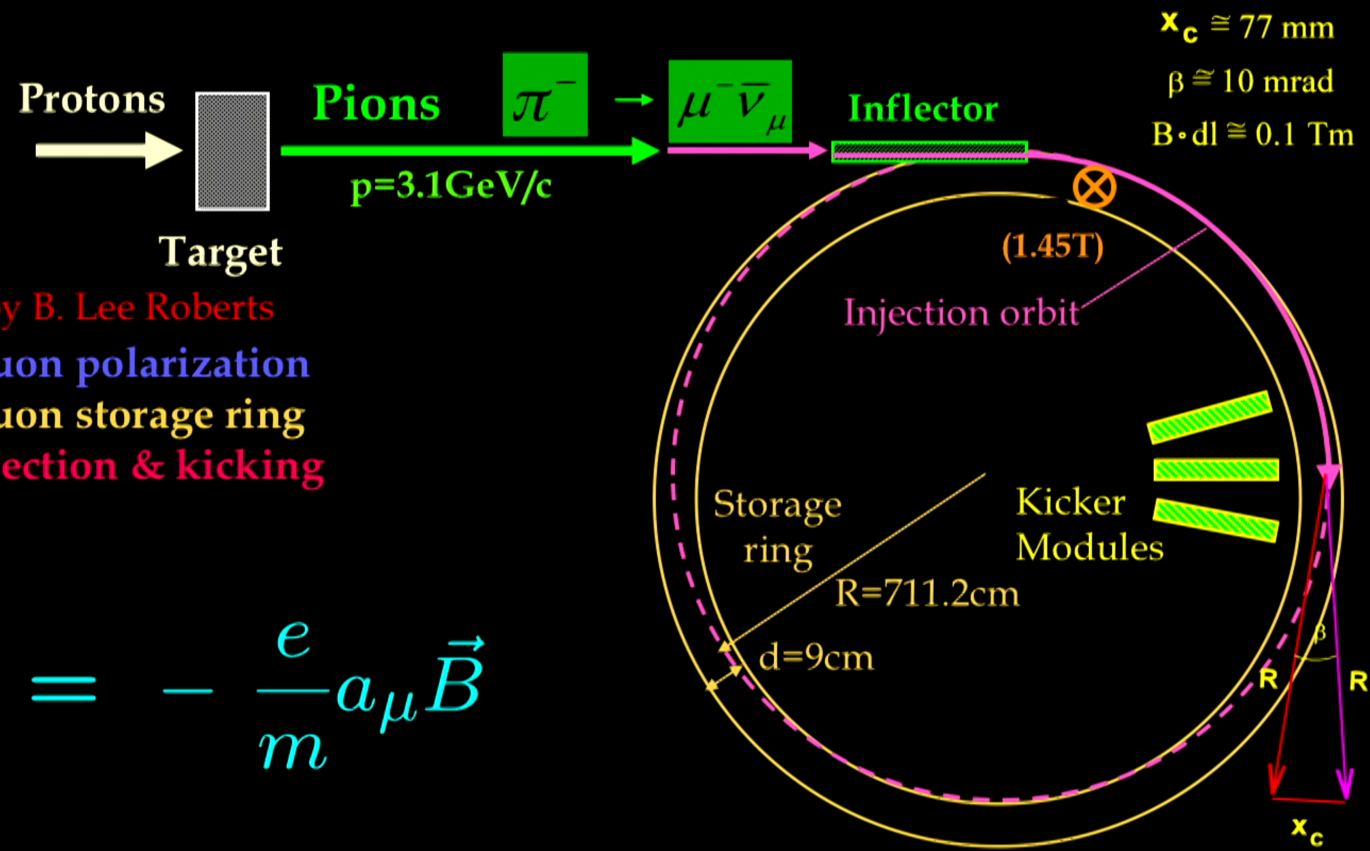

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Muon polarization
Muon storage ring
injection & kicking

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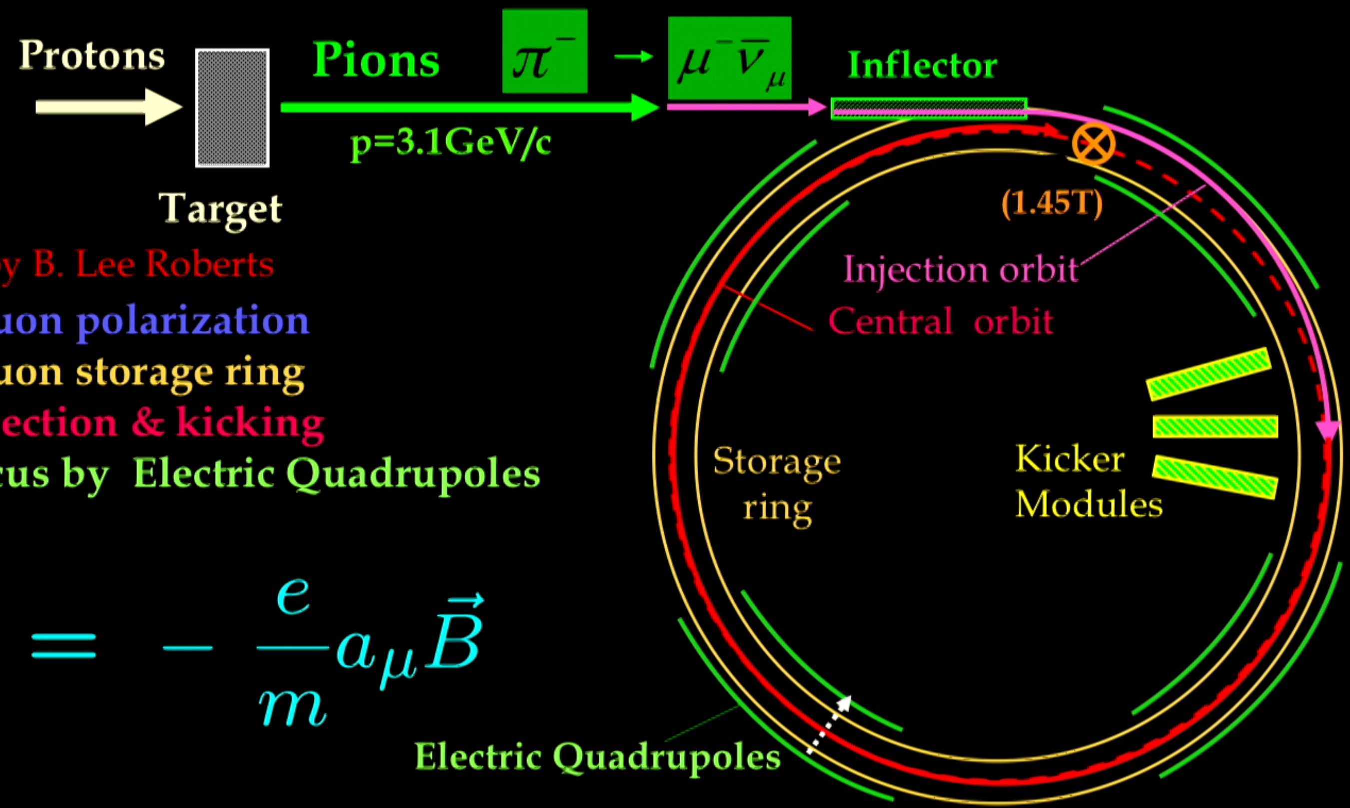
Experimental Technique

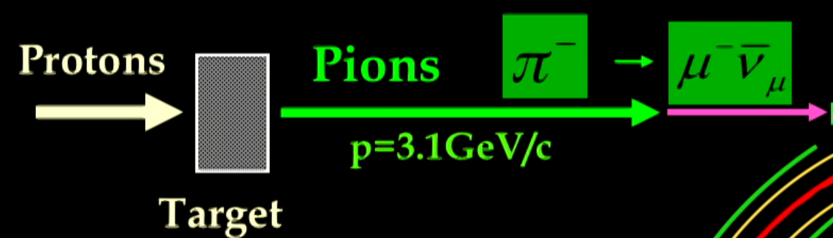


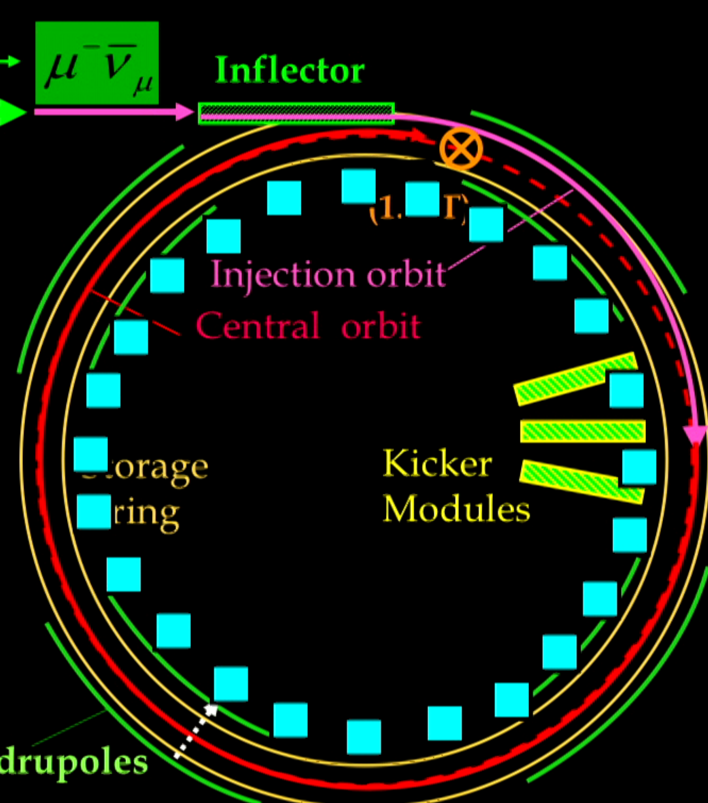
slide by B. Lee Roberts

- Muon polarization
- Muon storage ring
- injection & kicking
- focus by Electric Quadrupoles

$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

Experimental Technique



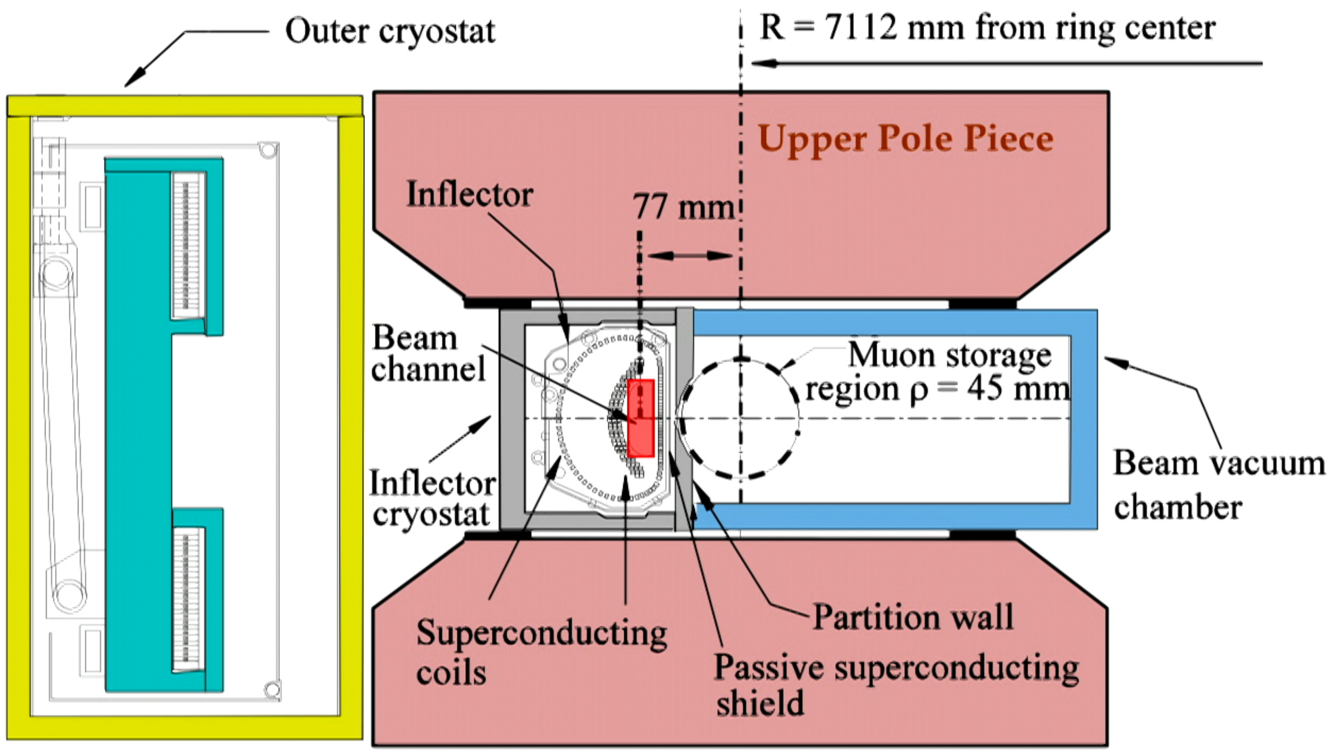


slide by B. Lee Roberts

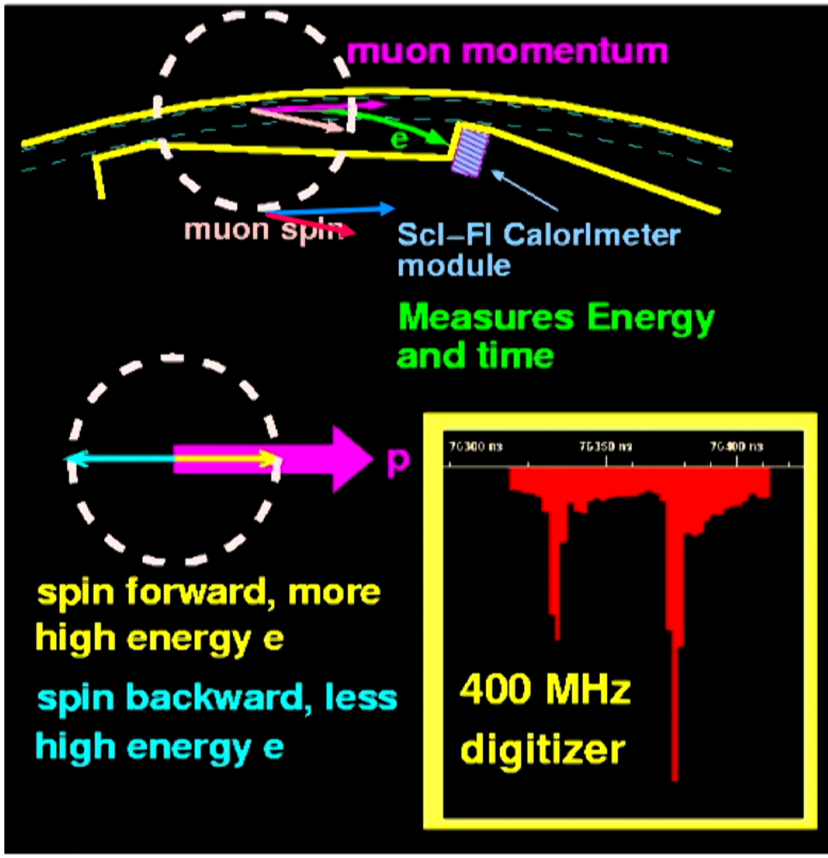
- Muon polarization
- Muon storage ring
- injection & kicking
- focus by Electric Quadrupoles
- 24 electron calorimeters

$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

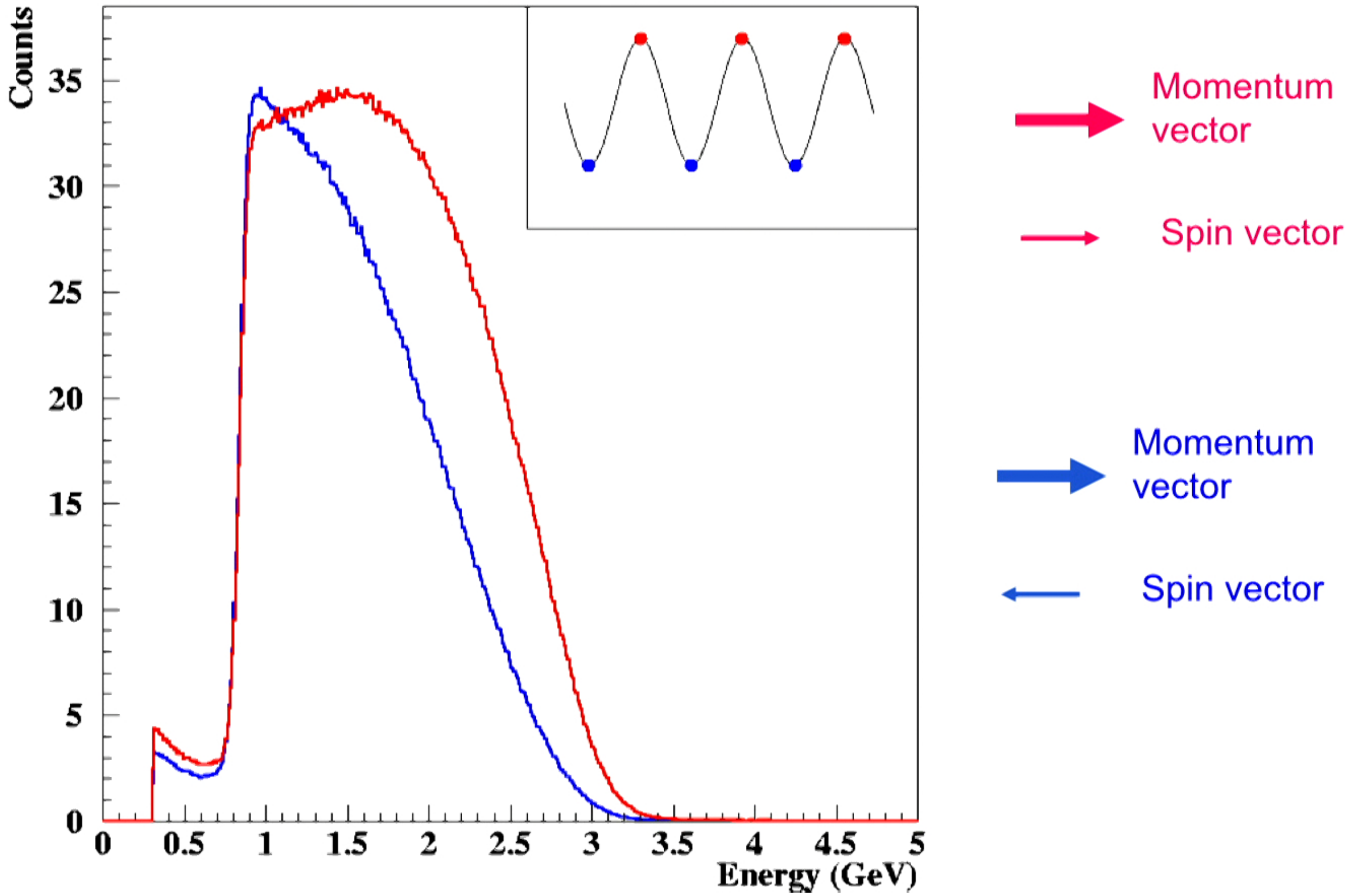
Space limitations prevent matching the inflector exit to the storage aperture



Detectors and vacuum chamber



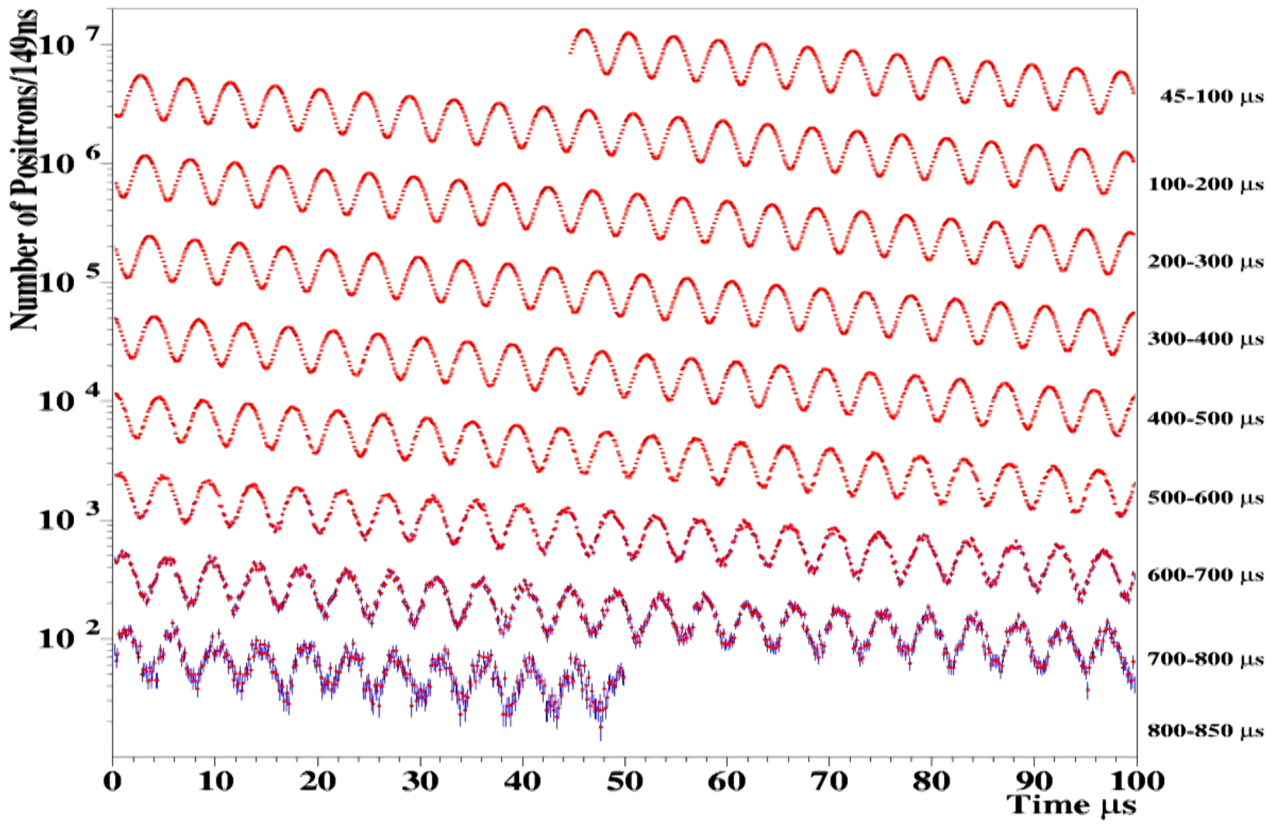
Energy Spectrum of Detected Positrons depends on spin direction



• Muon g-2: Precision physics in a Storage Ring

Muon g-2: 4 Billion e^+ with E>2GeV

$$dN/dt = N_0 e^{-\frac{t}{\tau}}\left[1 + A\cos(\omega_a t + \phi_a)\right]$$



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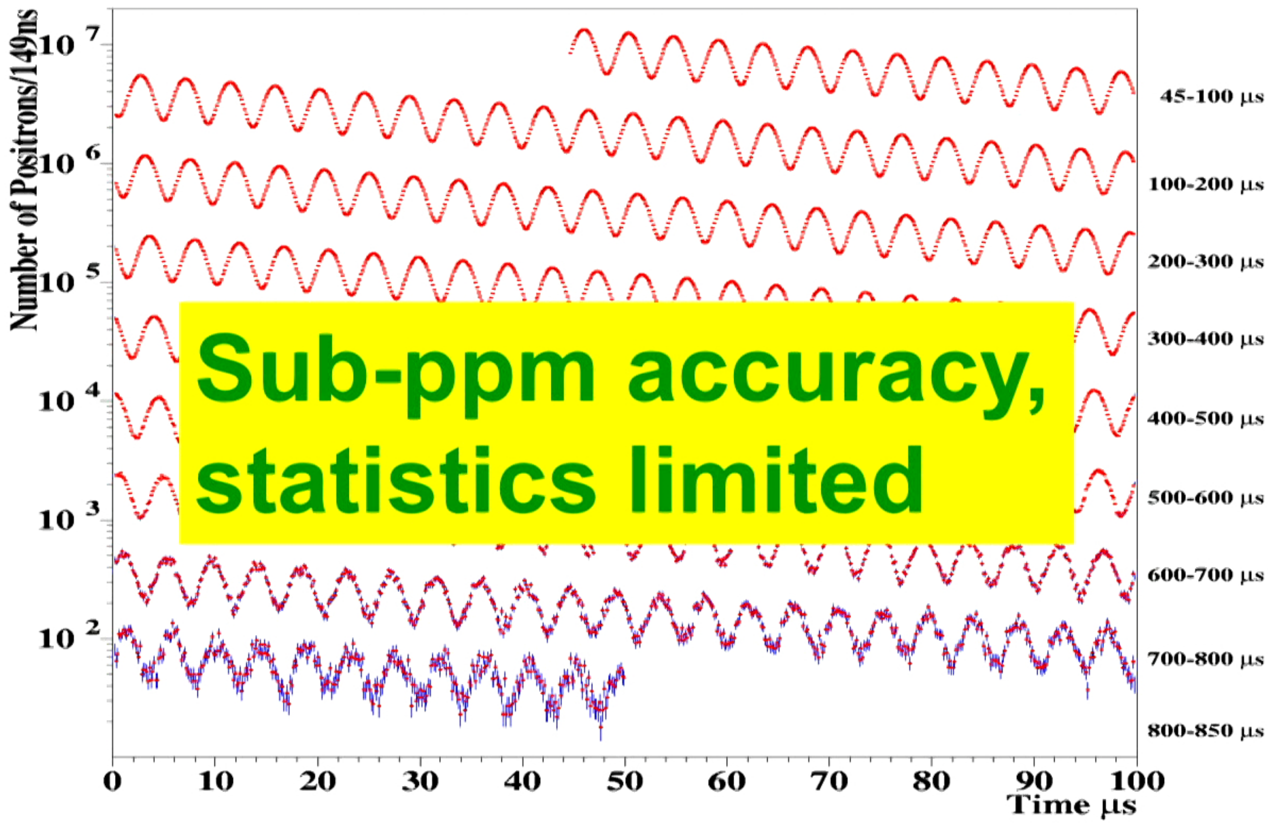
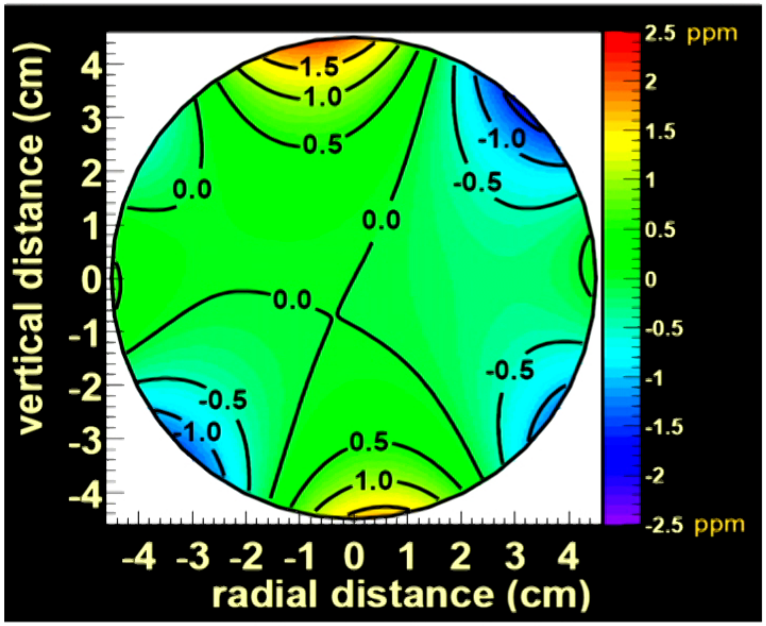


Sub-ppm accuracy, statistics limited

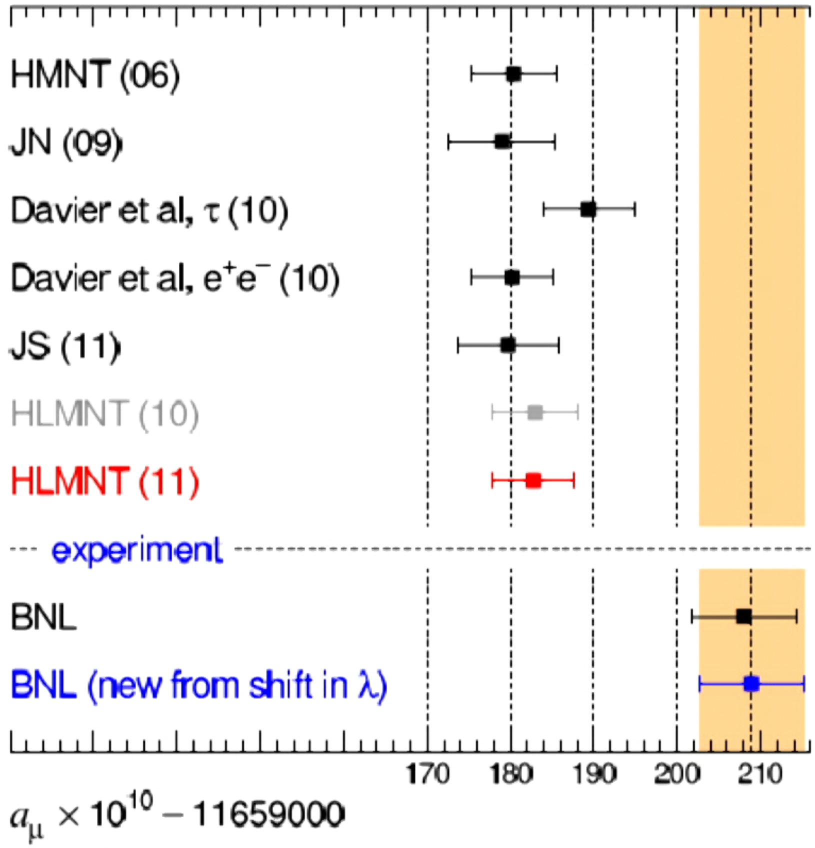
The ± 1 ppm uniformity in the average field is obtained with special shimming tools.



$\langle B \rangle_{\text{azimuth}}$

σ_{syst} on $\langle B \rangle_{\mu-\text{dist}} = \pm 0.03$ ppm

Comparison of Theory/Experiment



Yannis Semertzidis

Figure 1: Standard model predictions of a_μ by several groups compared to the measurement from BNL

Comparison of Theory/Experiment

The result is 3.5 s.d. away from theory! What is it?

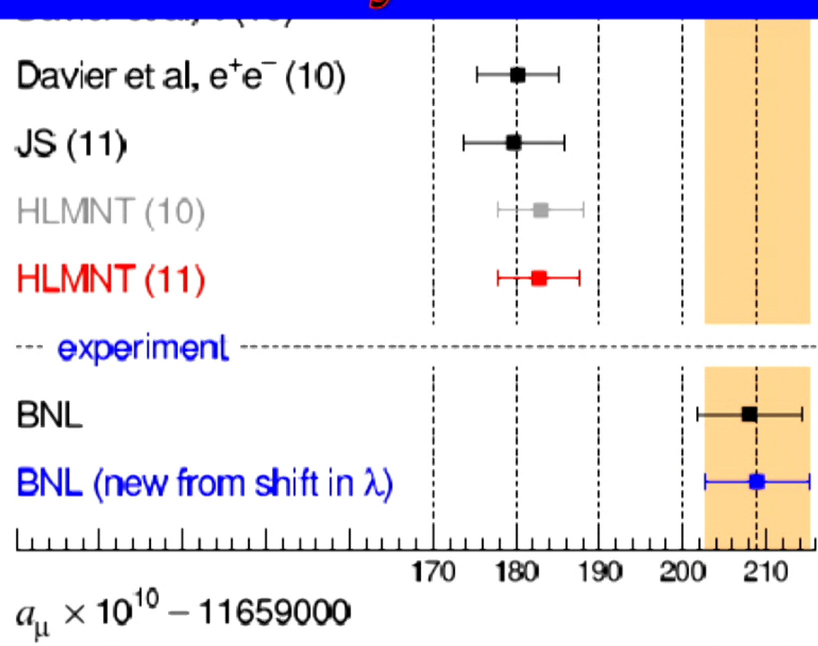


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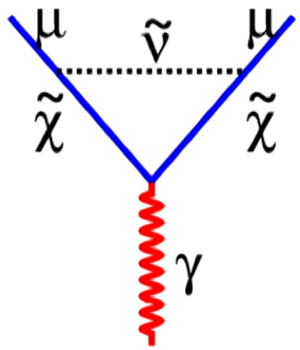
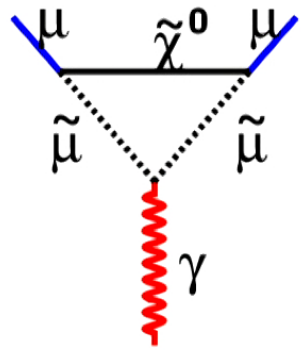
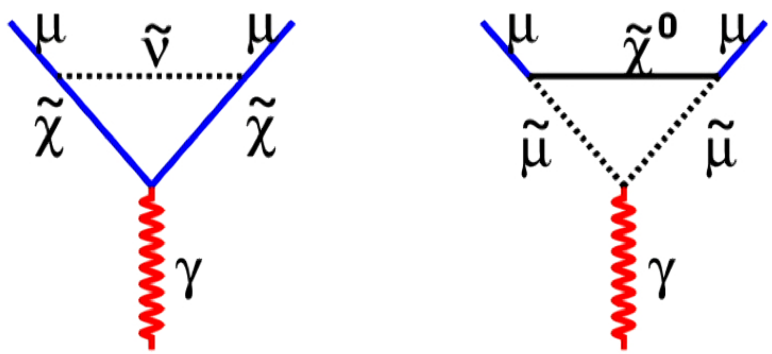
Figure 1: Standard model predictions of a_μ by several groups compared to the measurement from BNL

Beyond standard model, e.g. SUSY





Beyond standard model, e.g. SUSY



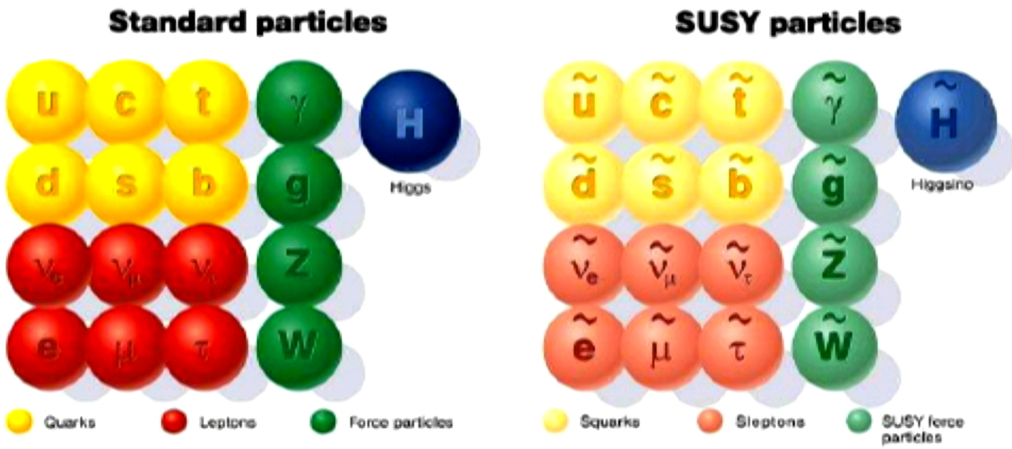
$$a_\mu^{\text{susy}} \cong \text{sgn}(\mu) \times 13 \times 10^{-10} \left(\frac{100\text{GeV}}{m_{\text{susy}}} \right)^2 \tan\beta$$

W. Marciano, J. Phys. G29 (2003) 225

Muon g-2 sensitivity to the "image world" of SUSY

$$a_\mu^{\rm SUSY} \approx 13\times10^{-10}\tan\beta\ {\rm sign}(\mu)\left(\frac{100{\rm GeV}}{M_{\rm SUSY}}\right)^2$$

Mass of Neutralino!



The muon ring moved to Fermilab (22 June – 25 July 2013)

37

The muon ring arrived at Fermilab

38

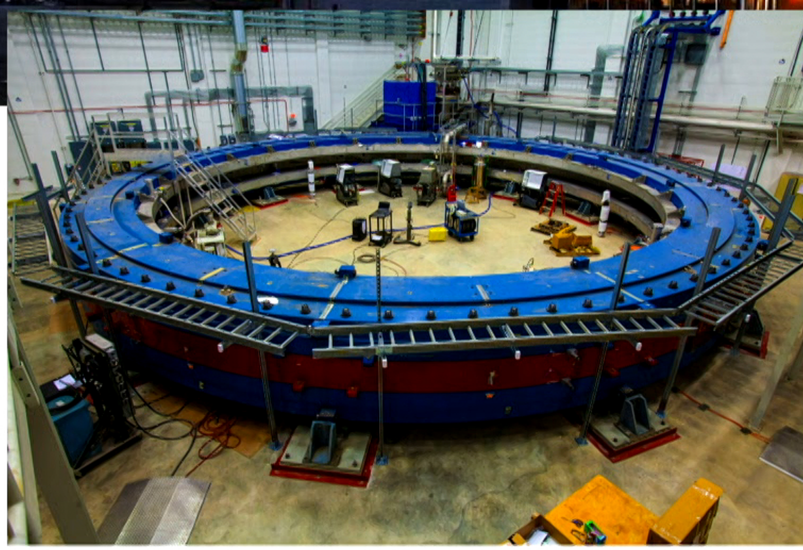
39

The muon ring is at Fermilab

- Goal: 0.14ppm (20 times the statistics)

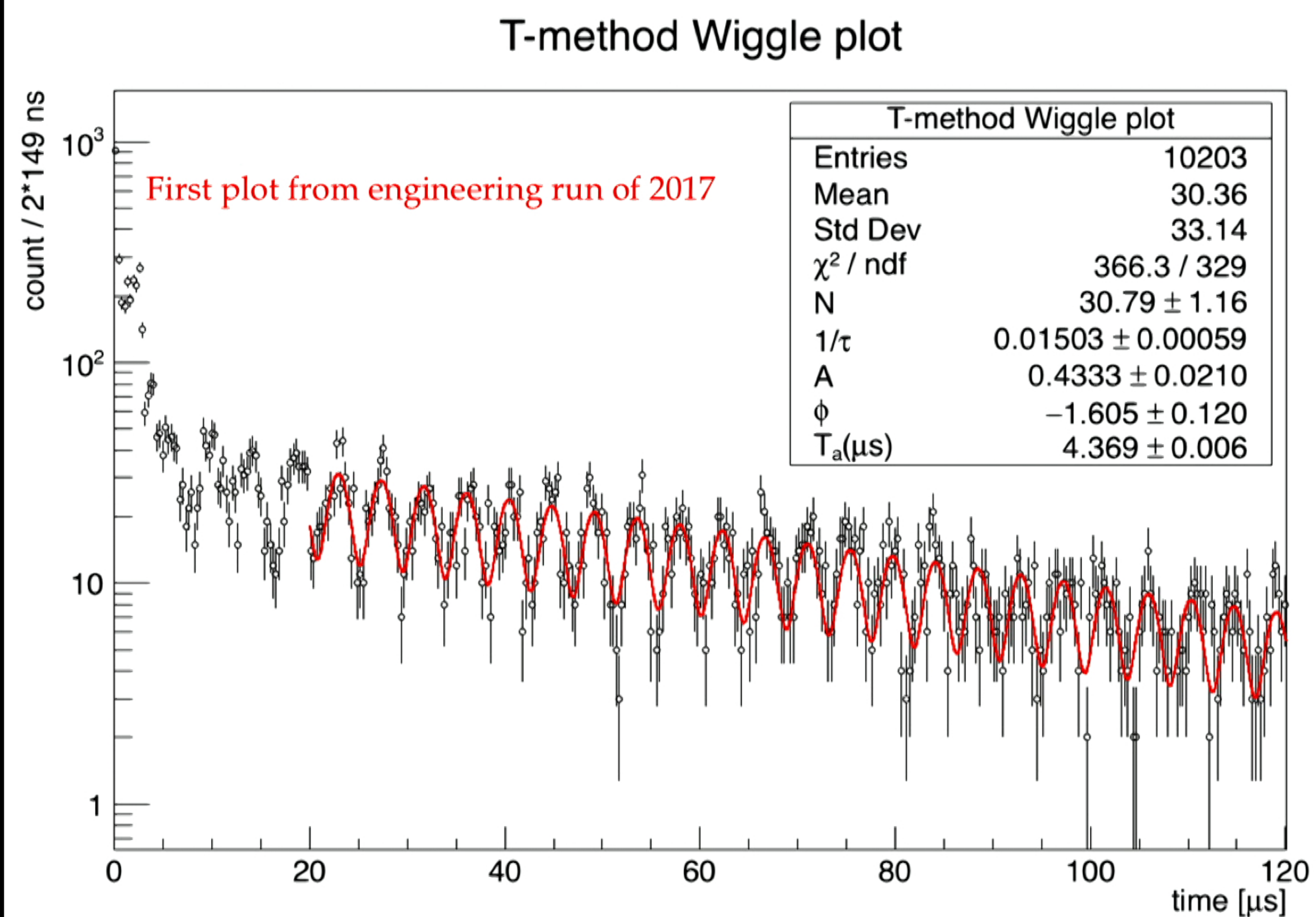
- Reduce cycle time from 3s to 1s, more muons/proton (Li lens), run longer.
- Longer beam-line to double the number of muons/proton. No pion or proton contamination, no need to gate-off electronics (gain stability). Better matching of beam-line with ring phase-space, reduce CBO.

Muon g-2 Project Overview



Muon g-2

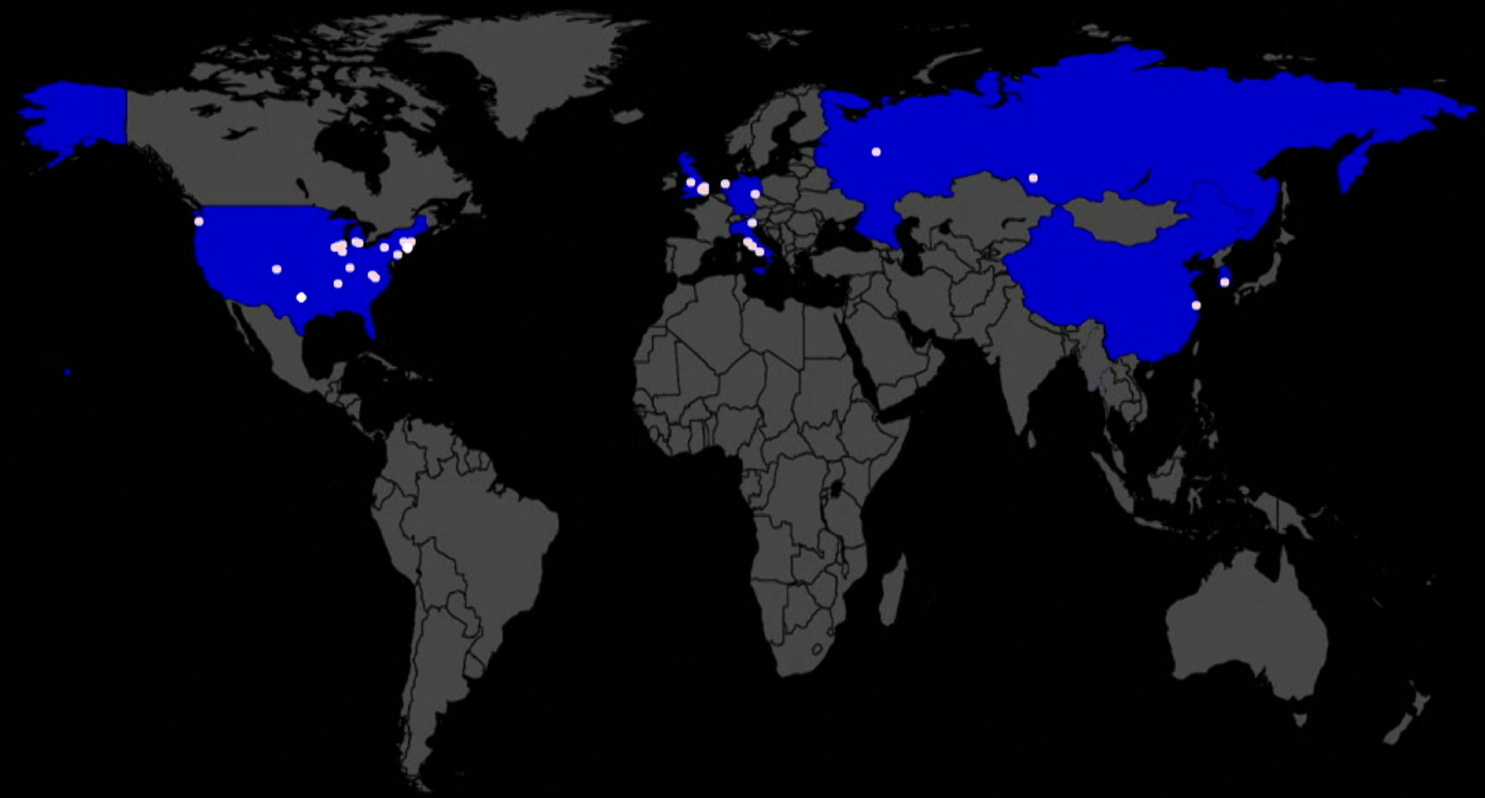
The ring has been reassembled and fully powered to 1.45T! First data: 2017



T-method Wiggle plot
First plot from engineering run of 2017
count / 2*149 ns
time [µs]
T-method Wiggle plot
Entries 10203
Mean 30.36
Std Dev 33.14
χ² / ndf 366.3 / 329
N 30.79 ± 1.16
1/τ 0.01503 ± 0.00059
A 0.4333 ± 0.0210
φ −1.605 ± 0.120
Tₐ(µs) 4.369 ± 0.006

E989 Muon g-2 Collaboration

8 Countries, 33 Institutions



Systematic errors for the muon g-2 exp. at BNL and at FNAL (projections)

Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to ring	< 30
E and pitch	50	Improved tracker	
		Precise storage ring simulations	30
Total	180	Quadrature sum	70

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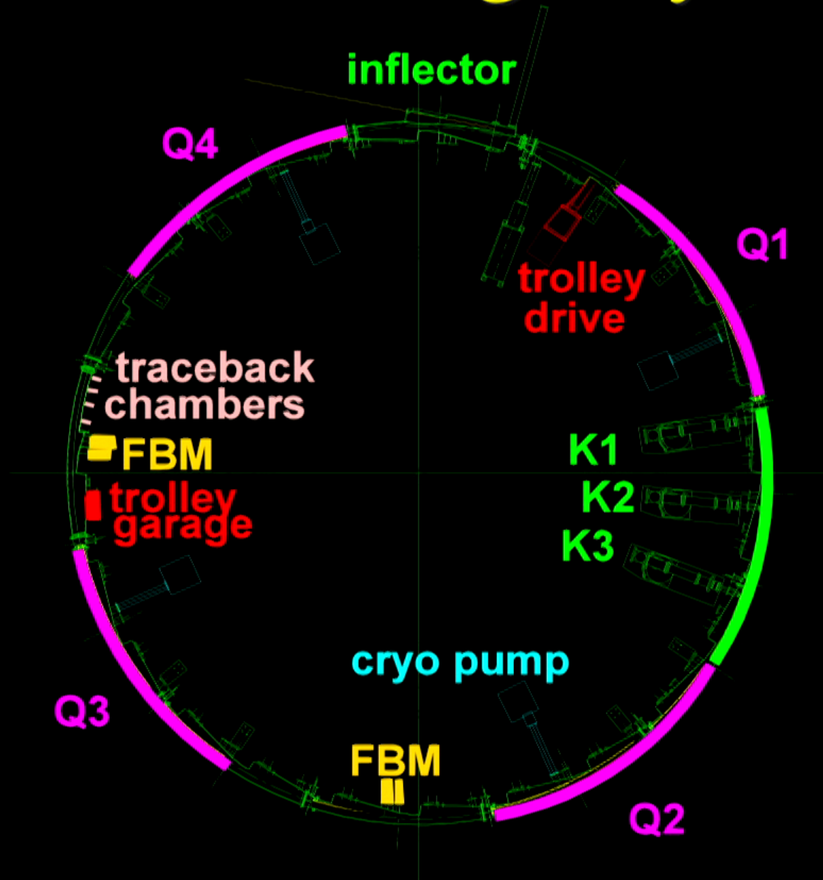
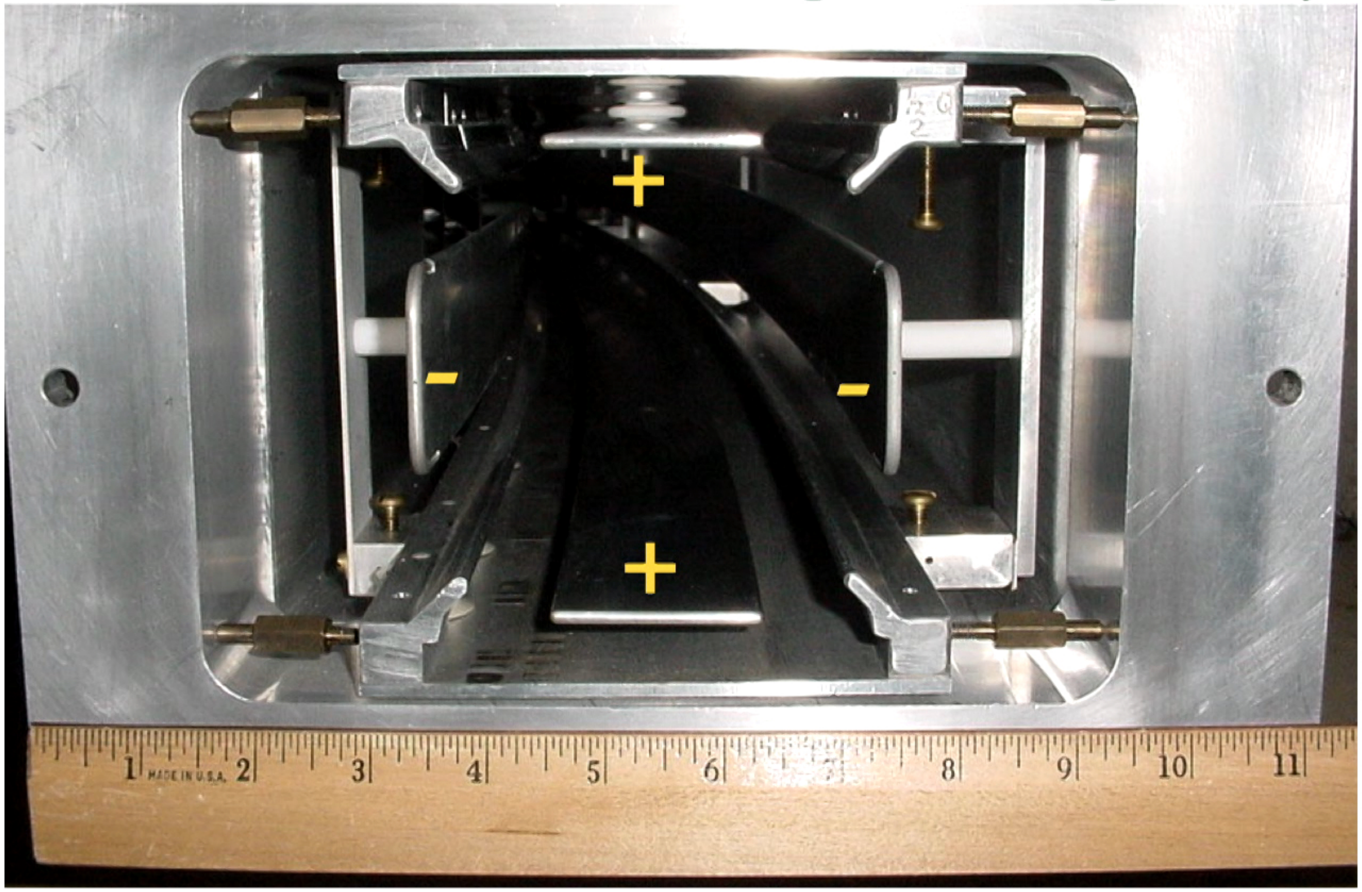
The Ring Layout

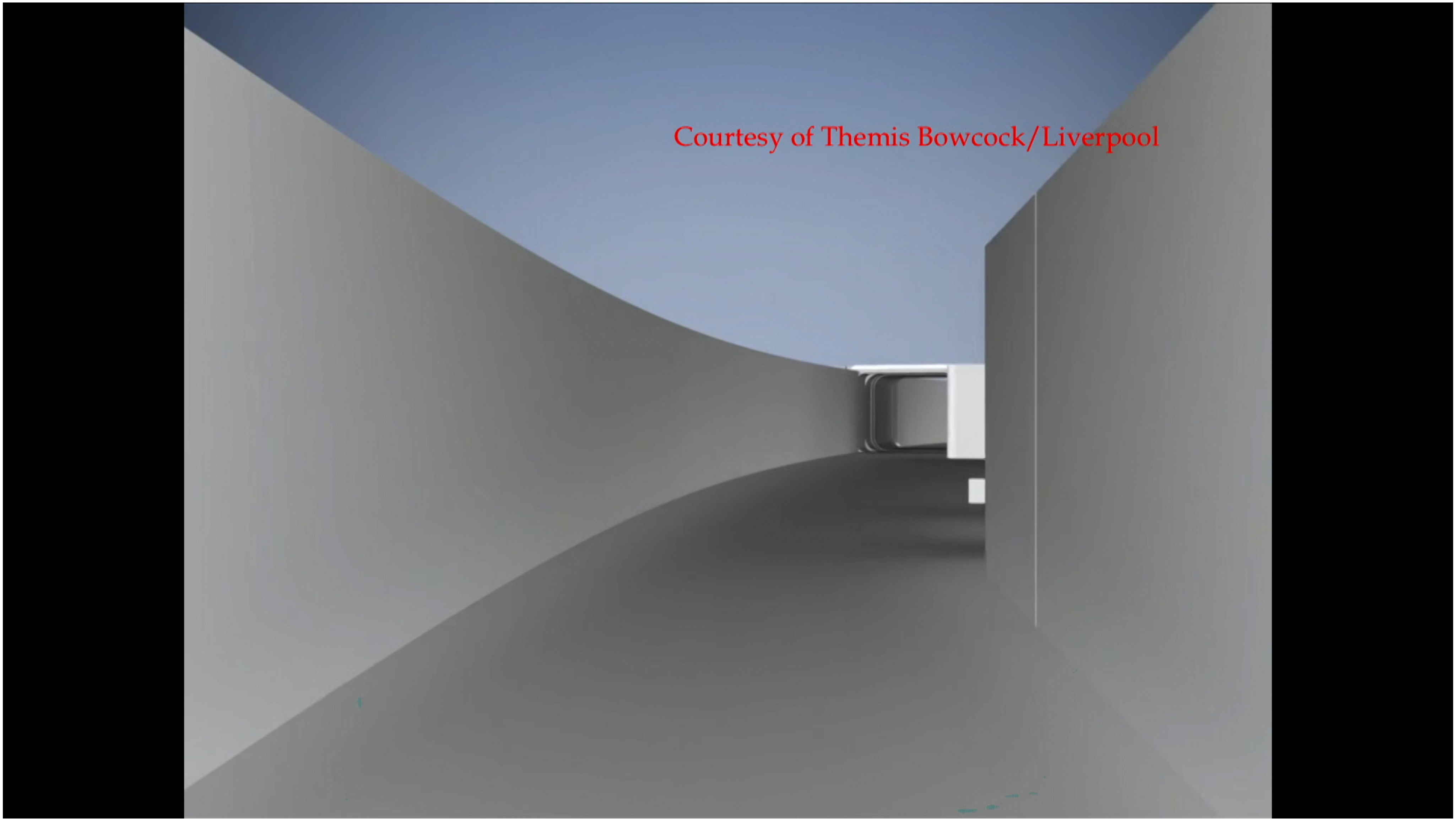


quads cover 43% of the ring

The Electrostatic Quadrupoles: μ^+ polarity



~ ± 24 kV at full power,   17 kV for beam scraping after injection


Courtesy of Themis Bowcock/Liverpool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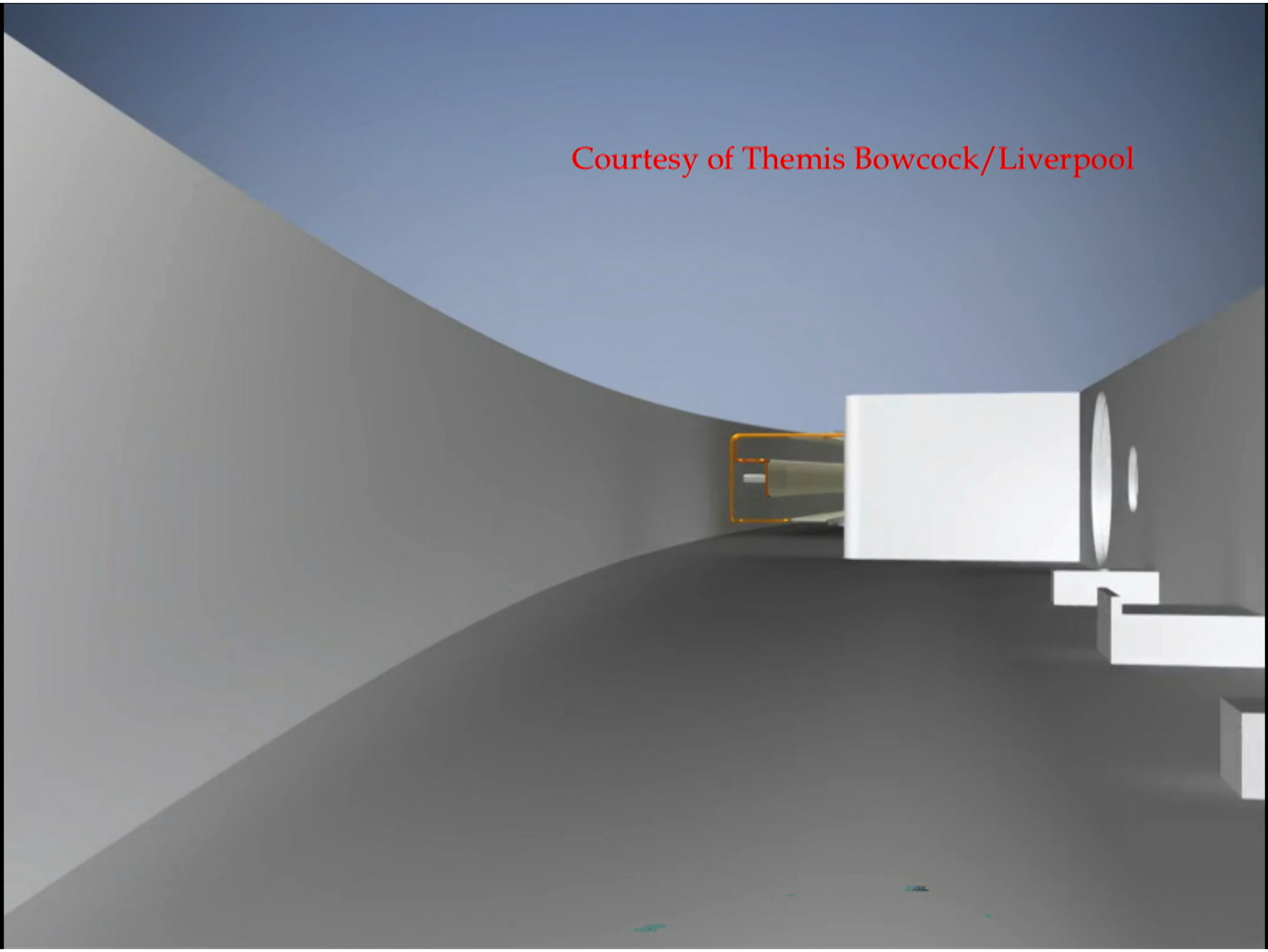
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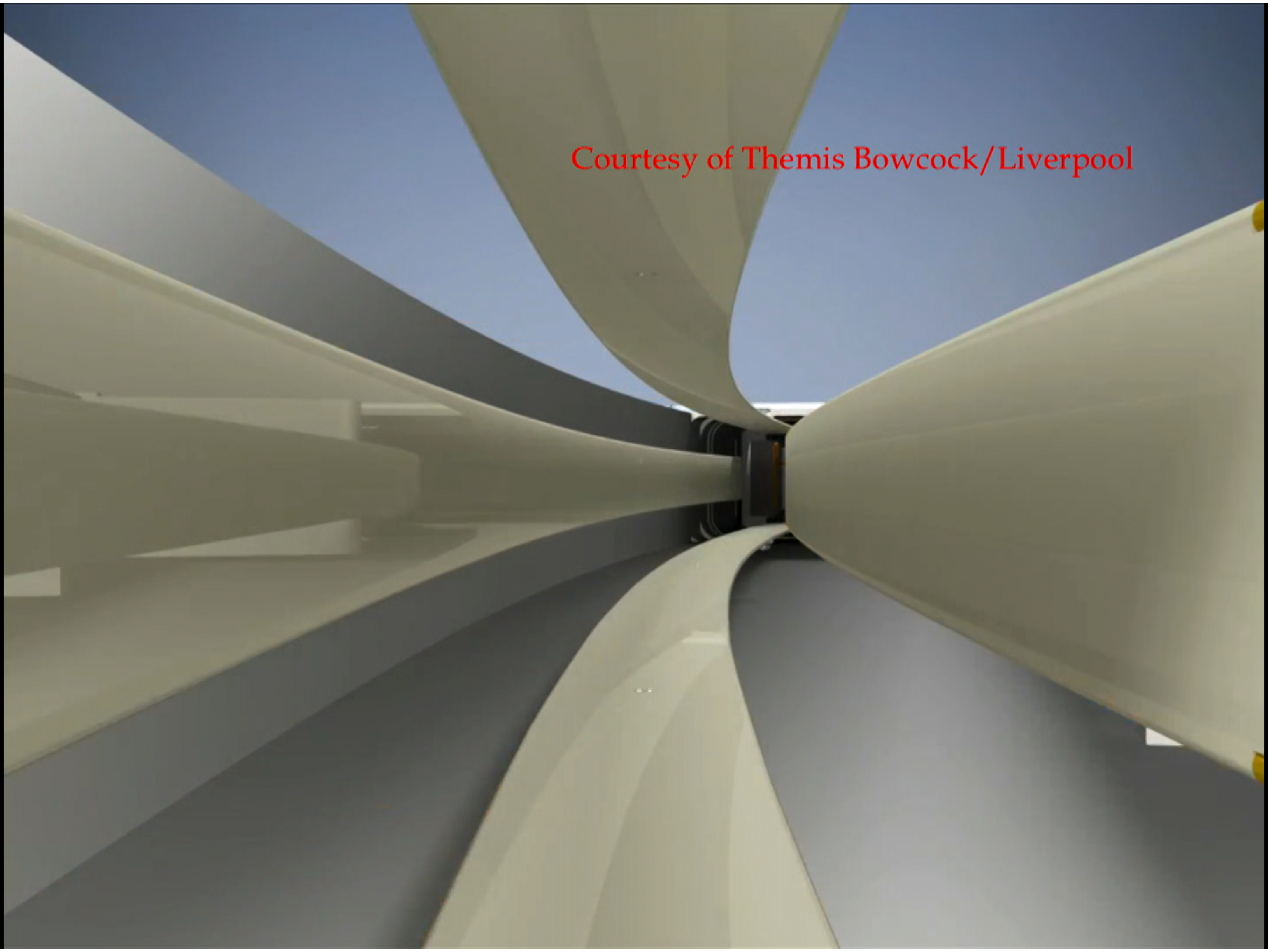
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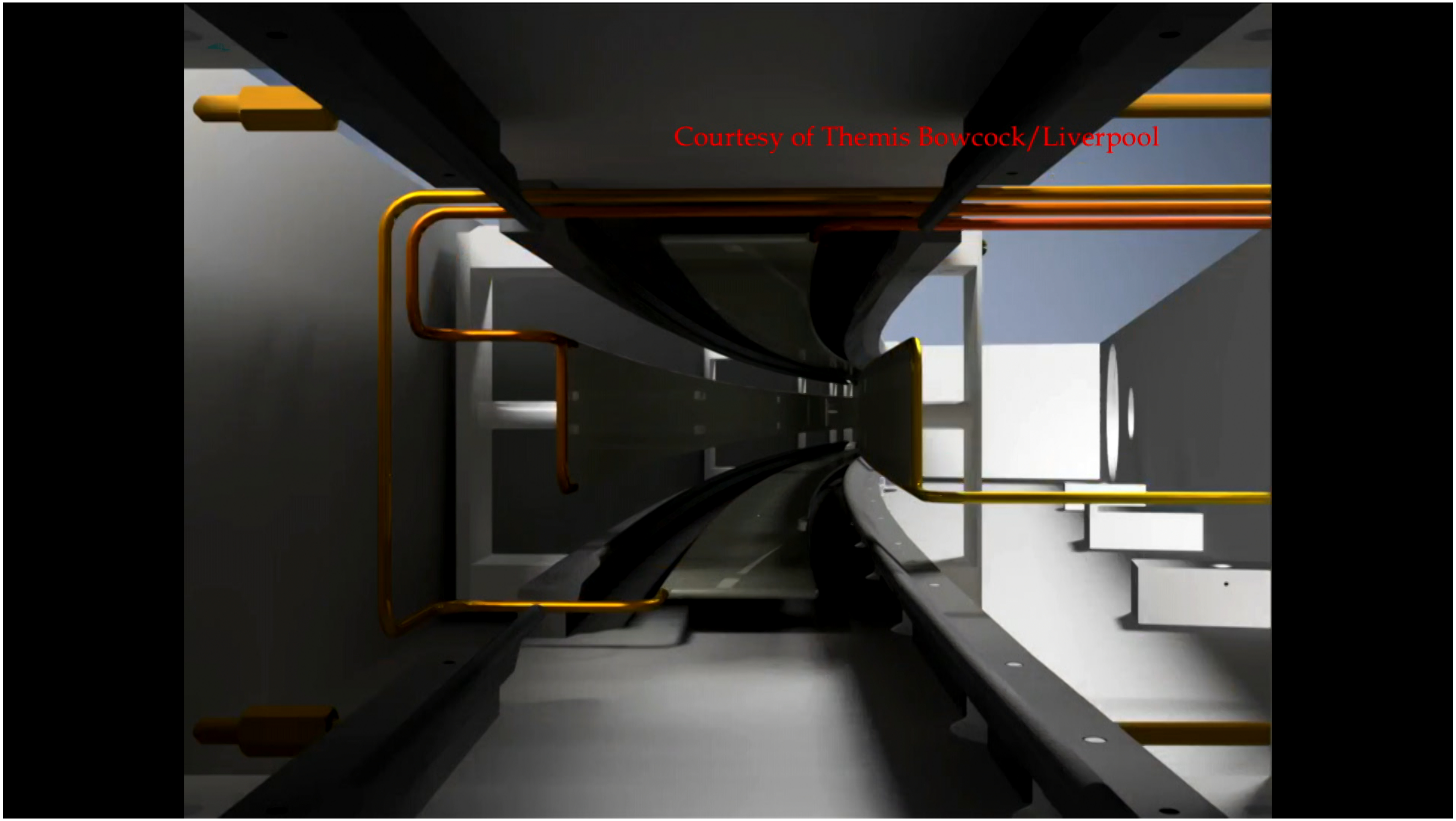
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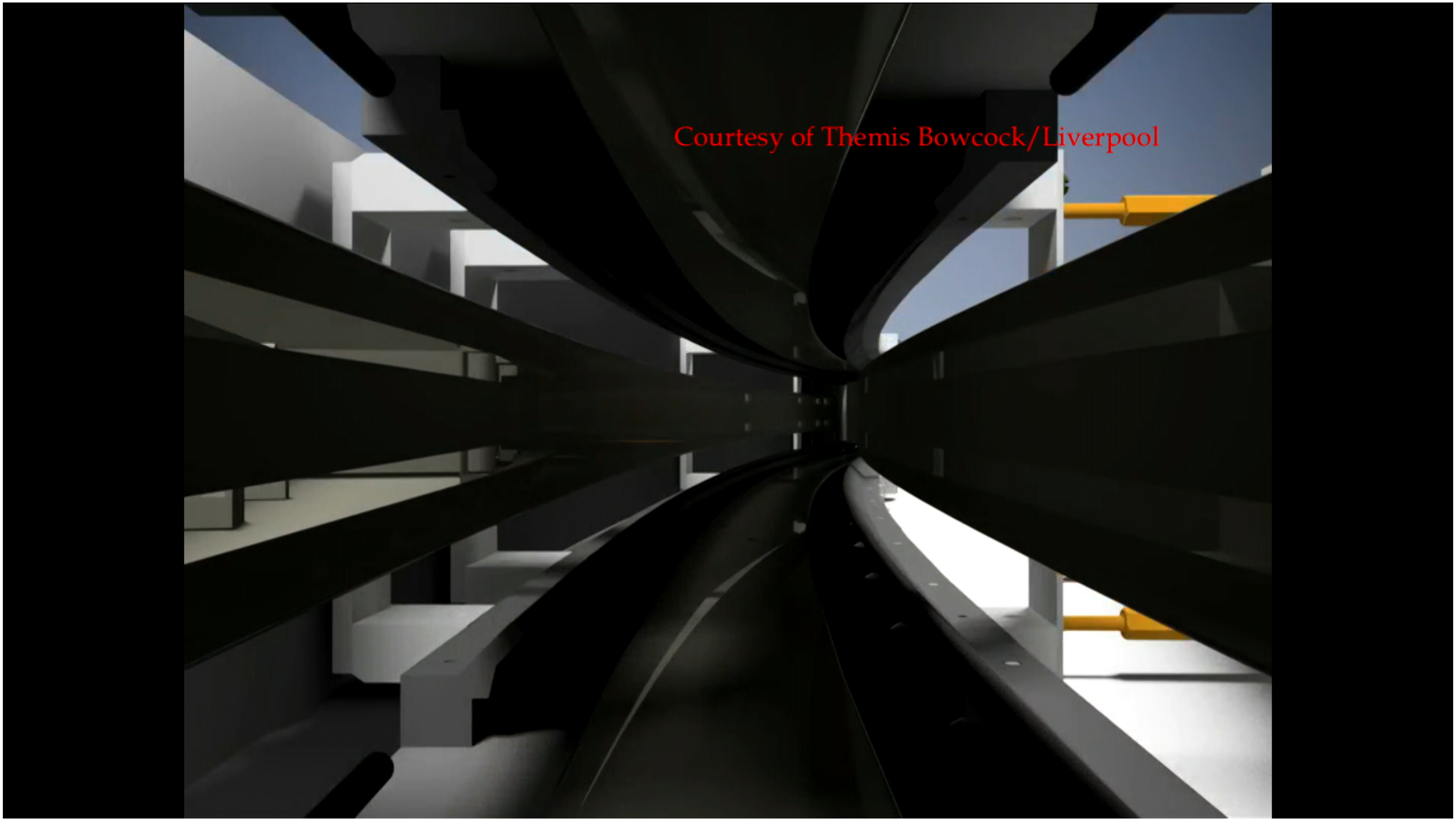
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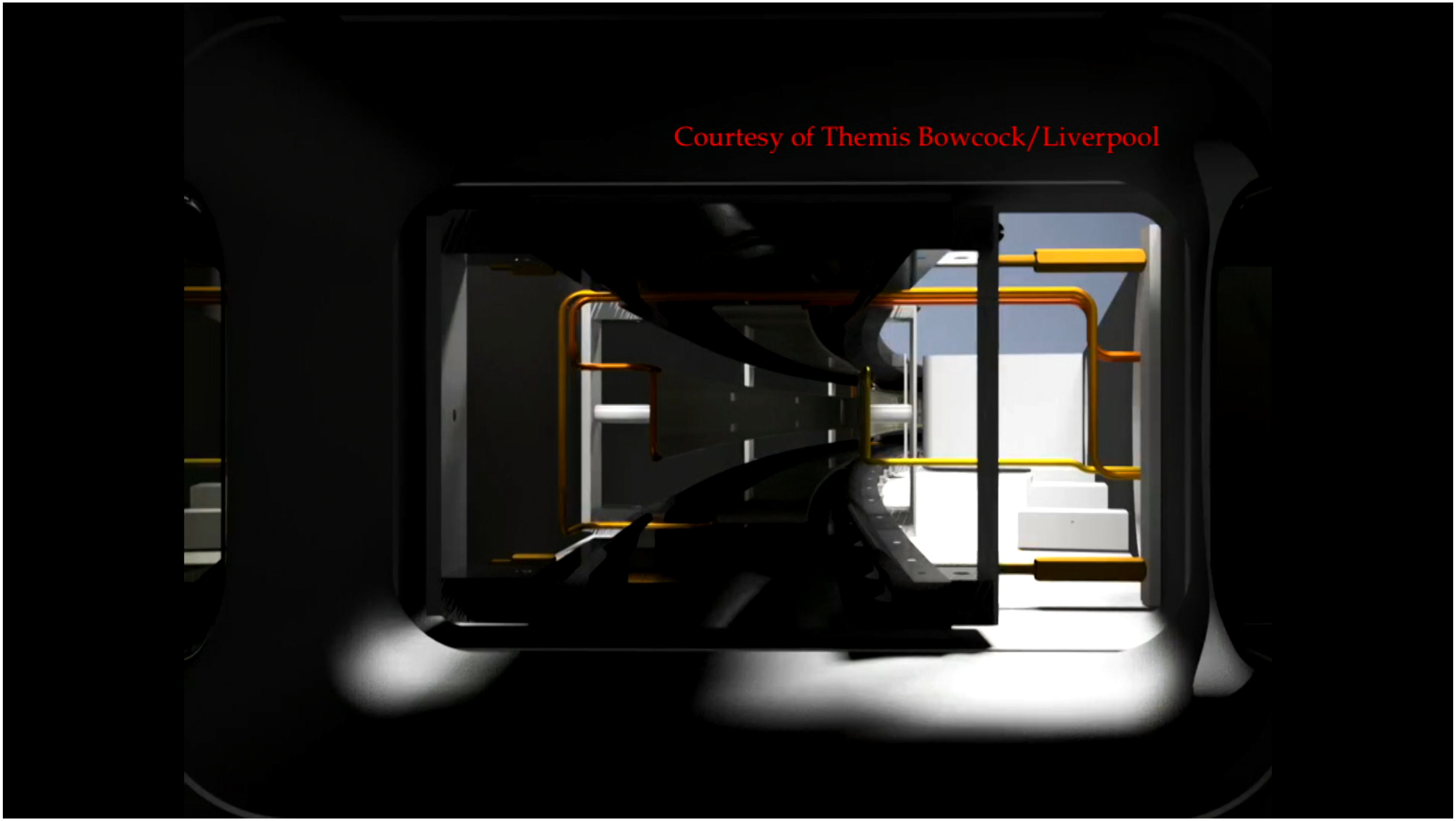
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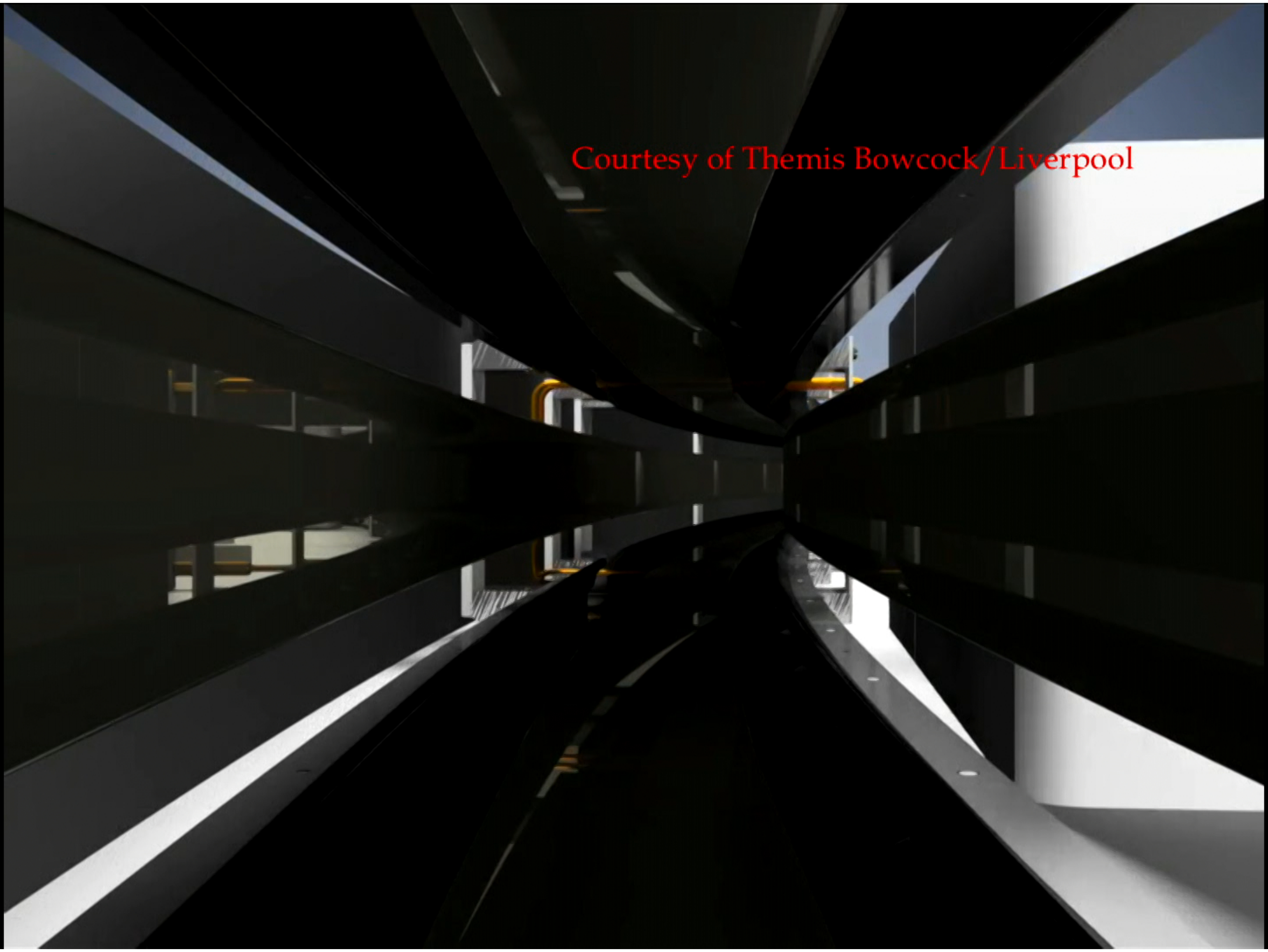
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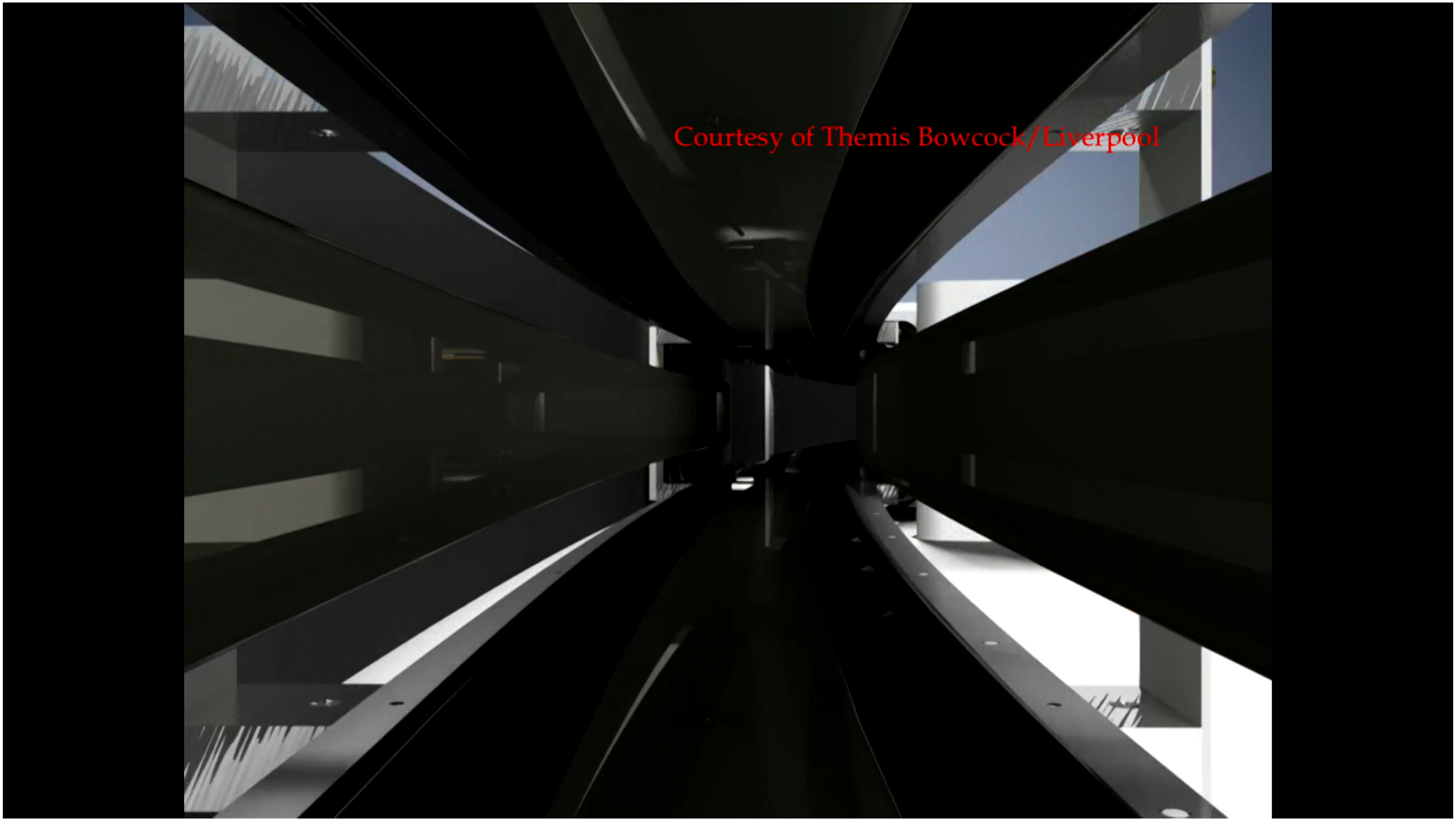
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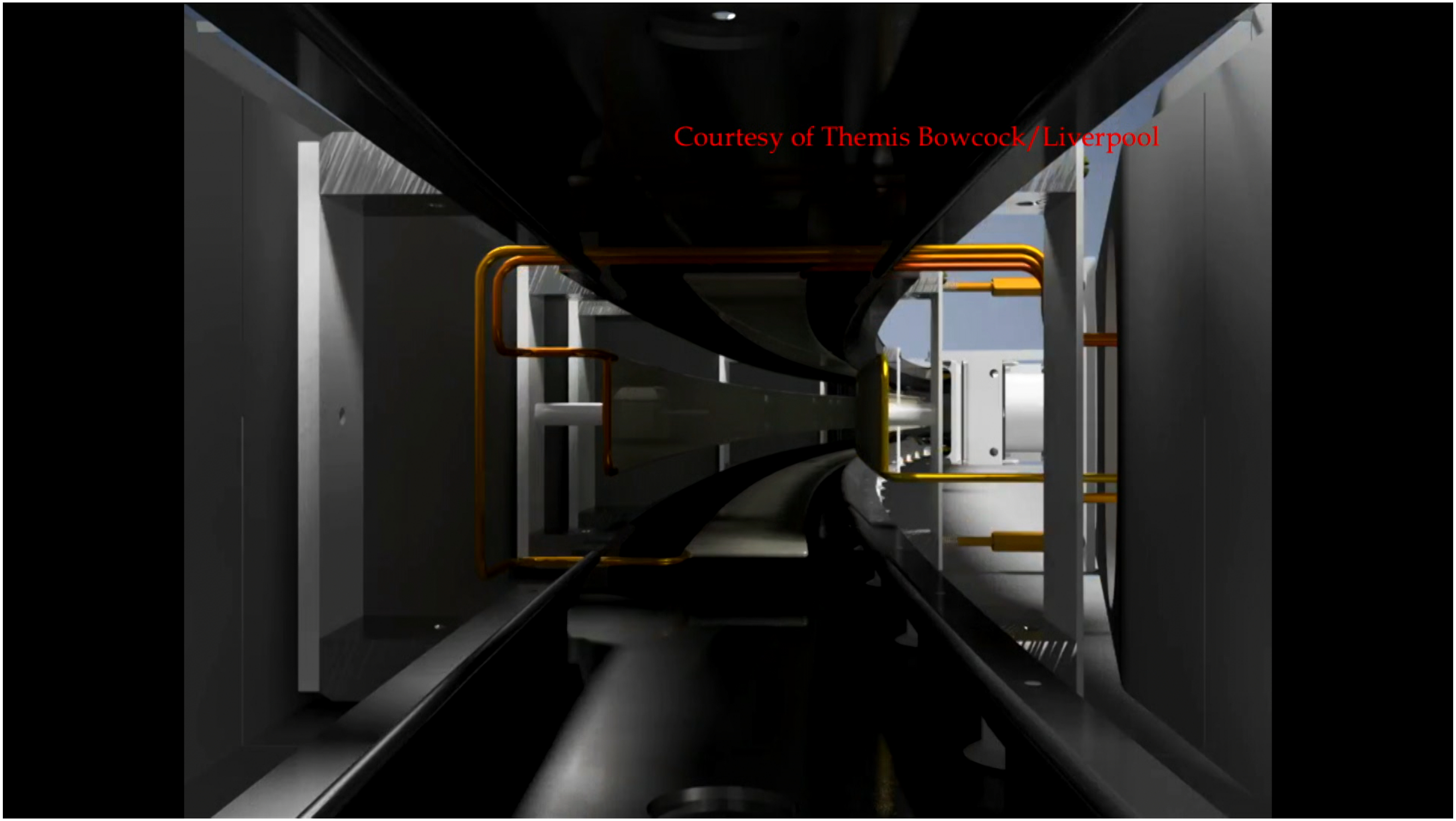
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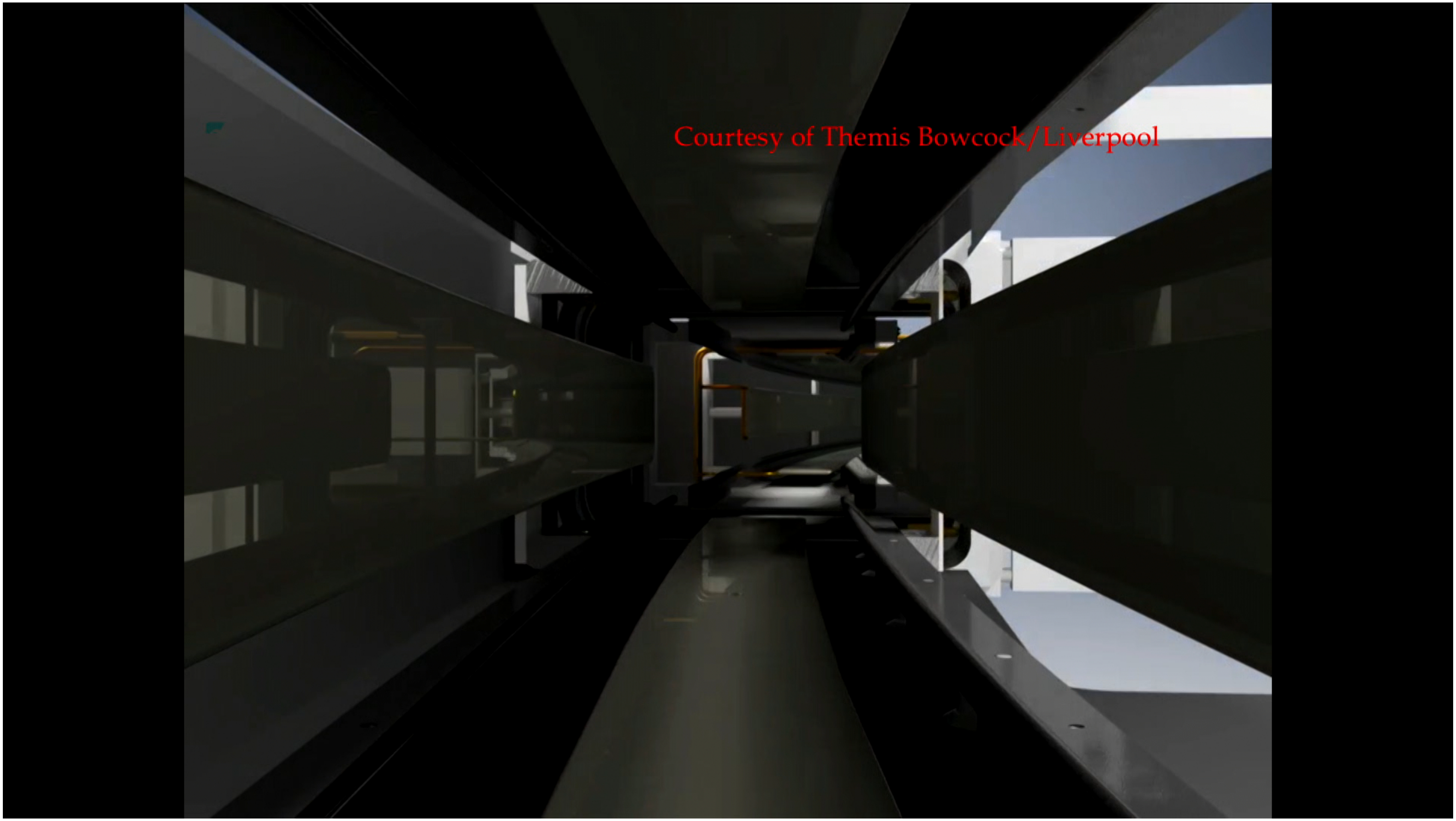
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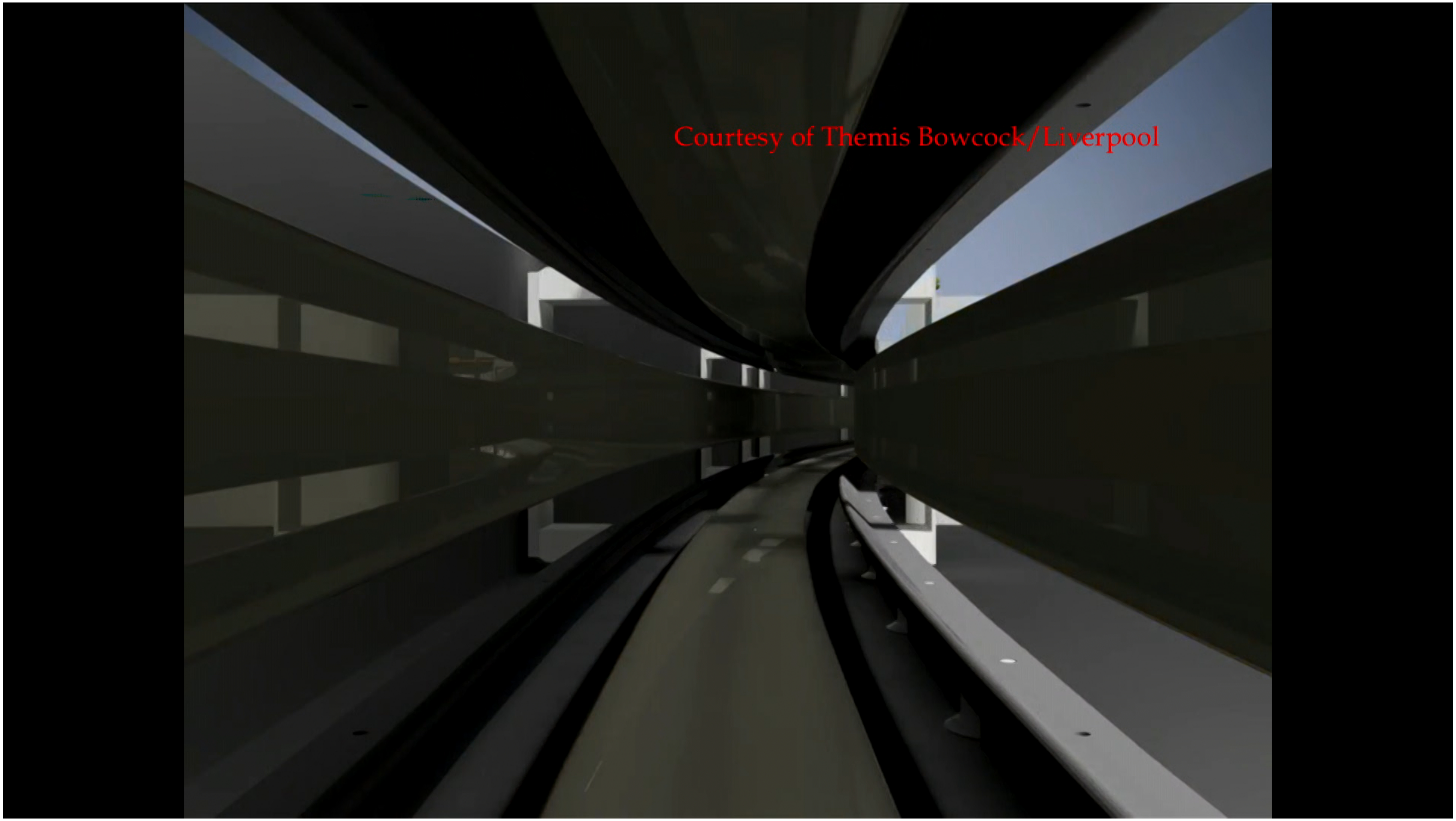
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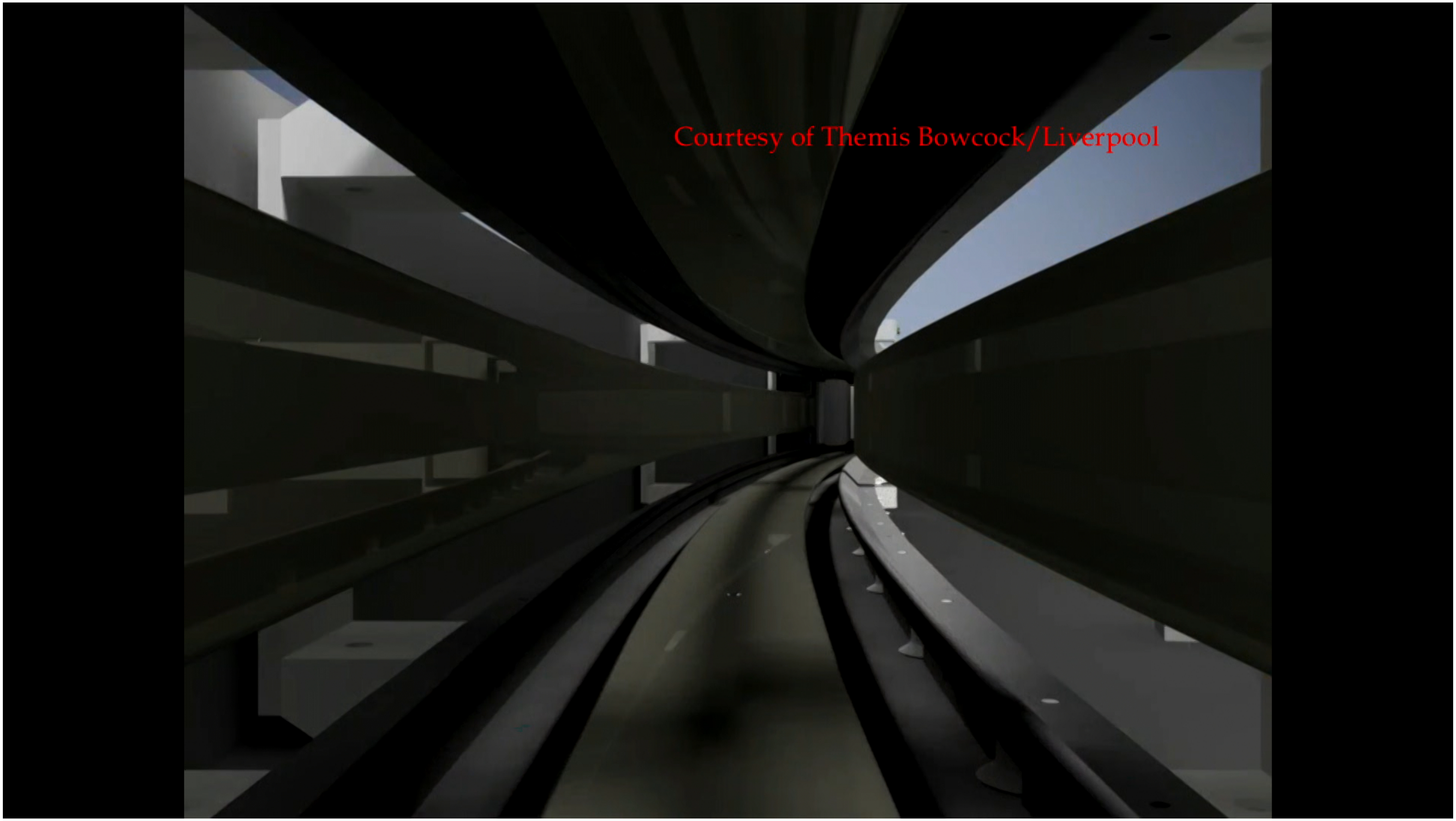
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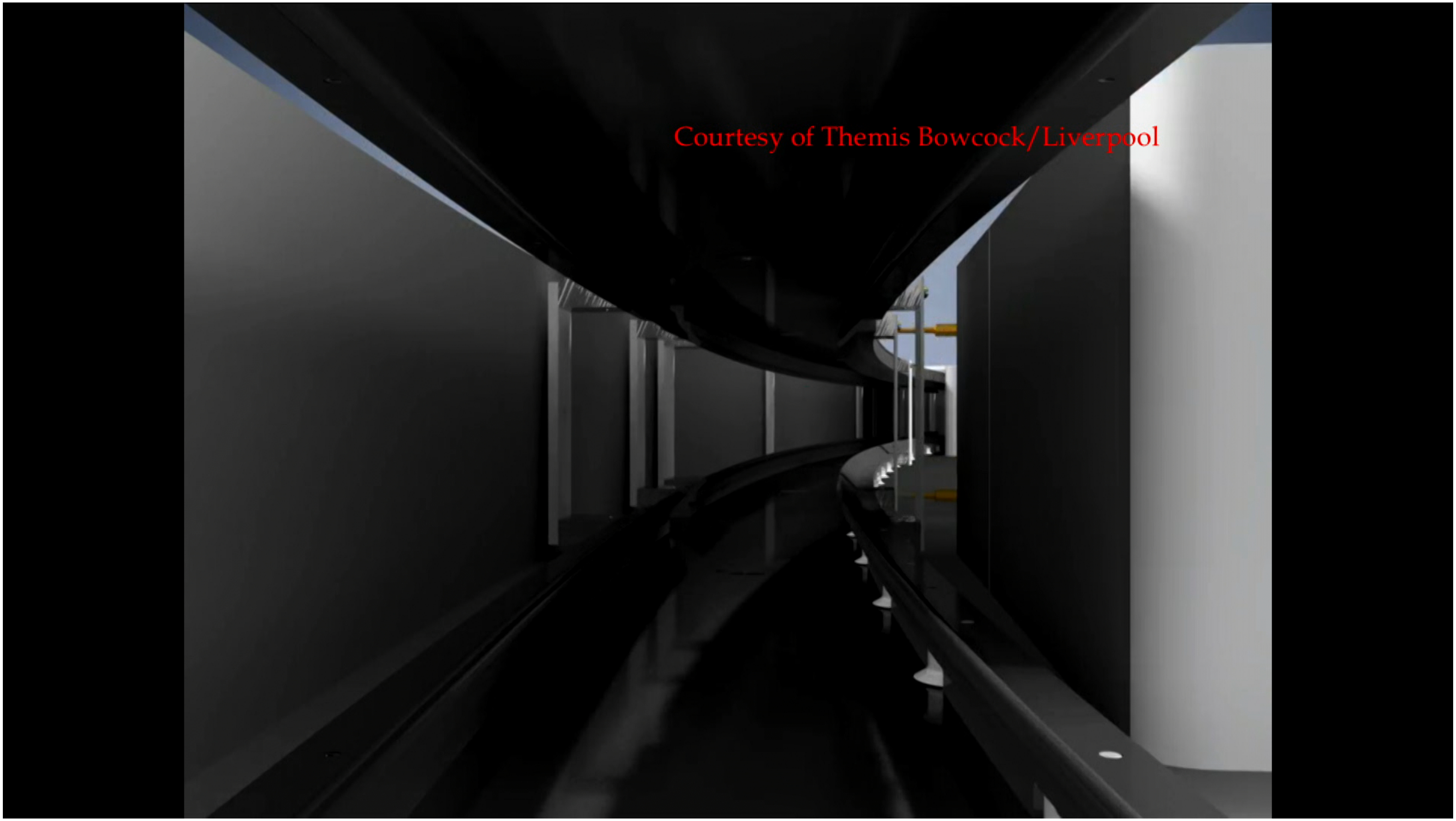
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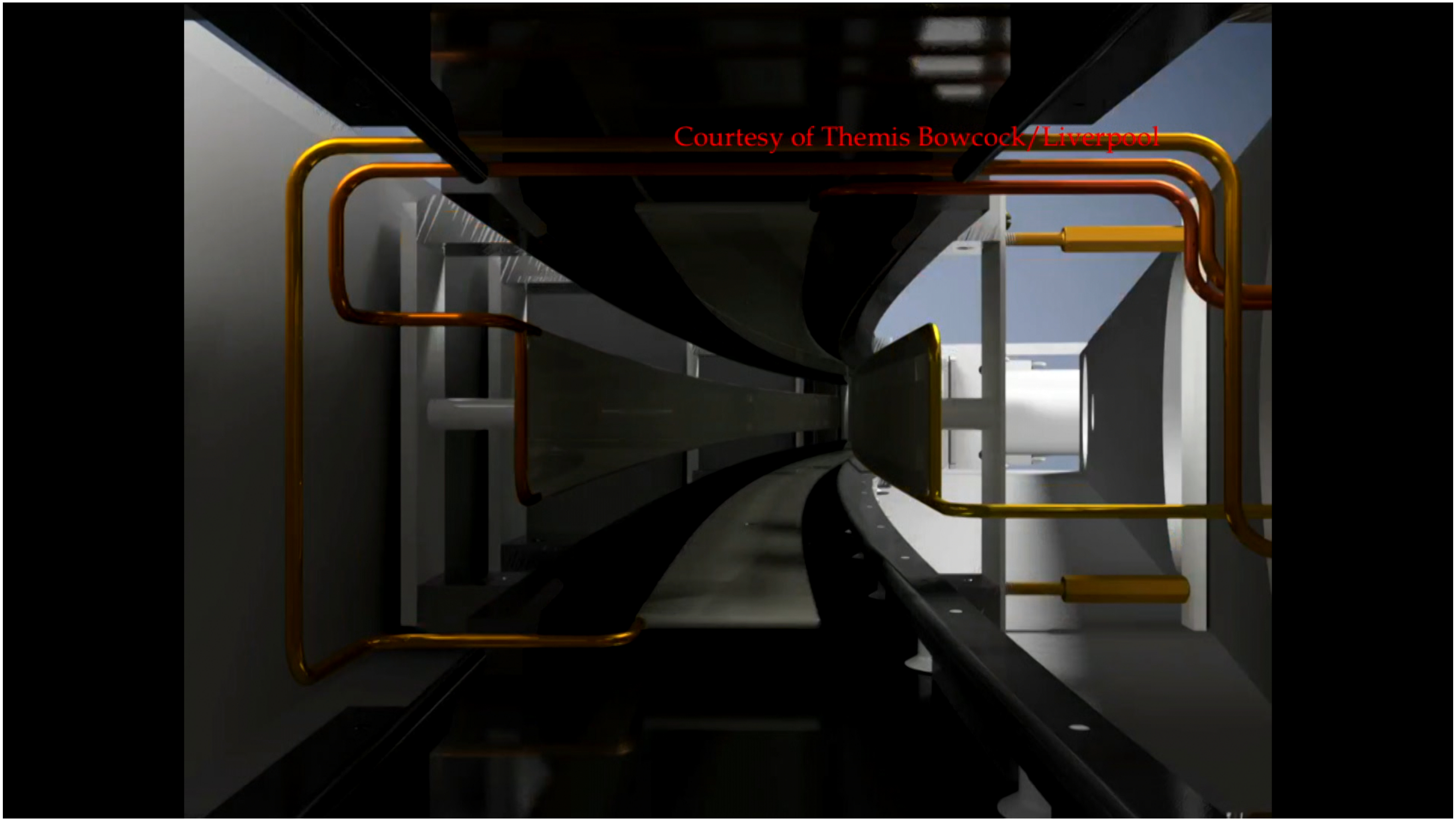

Courtesy of Themis Bowcock/Liverpool

Weak Focusing Betatron

Field index: $n = \frac{\kappa R_0}{\beta B_0} \simeq 0.135$

$$f_y = f_C\sqrt{n} \simeq 0.37 f_C;$$

$$f_x = f_C\sqrt{1-n} \simeq 0.929 f_C$$

- Detector acceptance depends on the radial coordinate x. The beam moves coherently radially relative to a detector with the "Coherent Betatron Oscillation" (CBO)

$$f_{\text{CBO}} = f_C - f_x = (1 - \sqrt{1-n}) f_C$$

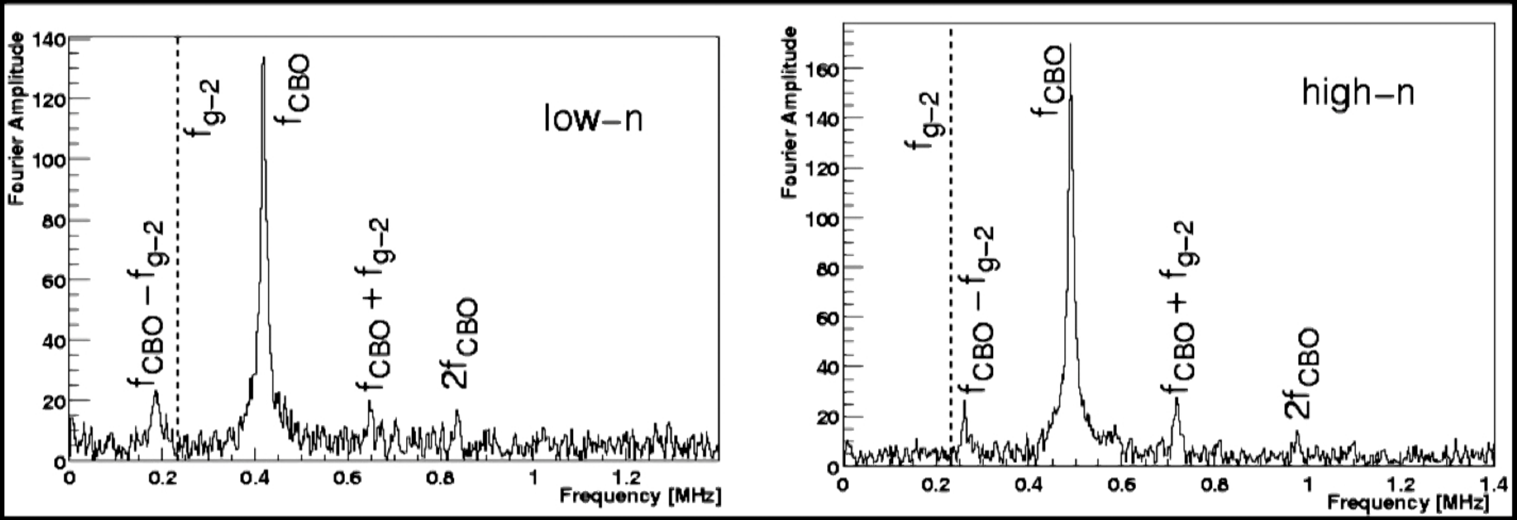
Frequencies in the (g-2) Ring

Quantity	Expression	Frequency	Period
f_a	$\frac{e}{2\pi mc} a_\mu B$	0.23 MHz	4.37 μs
f_c	$\frac{v}{2\pi R_0}$	6.7 MHz	149 ns
f_x	$\sqrt{1-n} f_c$	6.23 MHz	160 ns
f_y	$\sqrt{n} f_c$	2.48 MHz	402 ns
f_{CBO}	$f_c - f_x$	0.477 MHz	2.10 μs
f_{VW}	$f_c - 2f_y$	1.74 MHz	0.574 μs

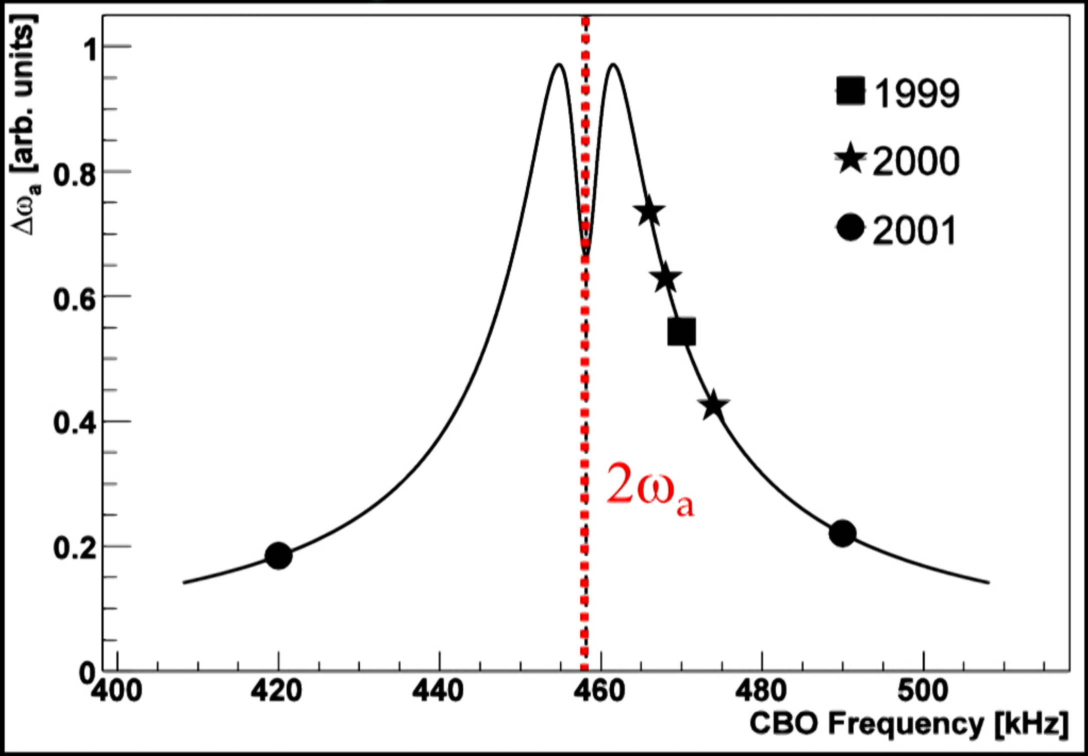
CBO in the 2001 Data Set

$$f(t) = N_0 e^{-\lambda t}[1 + A\cos(\omega_a t + \phi)]$$

Residuals from fitting the 5-parameter function



Relative Amplitude of the CBO effect



$\sigma_{systematic}$	1999	2000	2001	E989
CBO	0.05	0.21	0.07	0.04
total	0.3	0.31	0.21	0.11

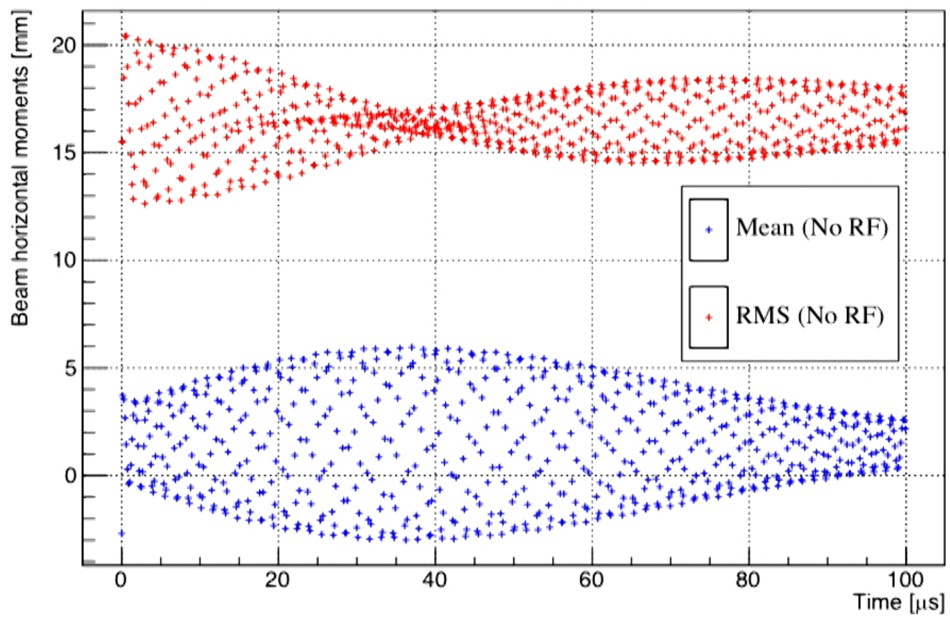
Concepts

By PhD student: On Kim, KAIST

- RF scraping[1]
  - Dipole RF field with the CBO frequency.
- RF matching
  - Quadrupole RF field with twice the CBO frequency.
- RF CBO reduction (New)
  - Quadrupole RF field with the CBO frequency.

[1] Y. Orlov and Y. Semertzidis, *To Get Rid of CBO (and to get scraping without resonance crossings)*, E821 Note No.431 (2003)

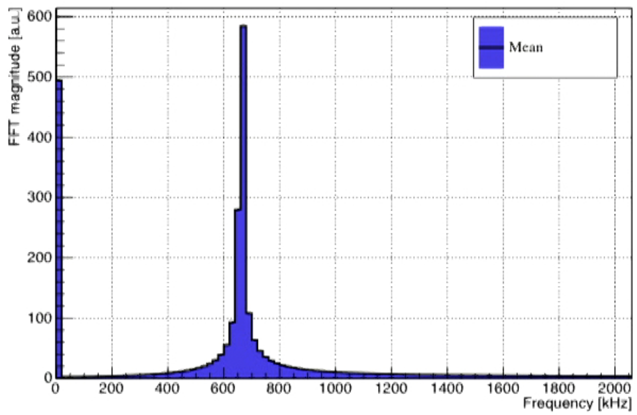
CBO amplitude in simulation



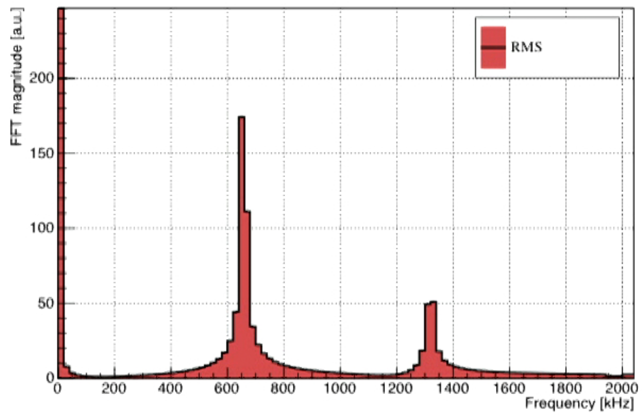
9,015 muons in the magnetic ring with continuous and ideal quadrupole E-field.

The bin width is 149 ns (the revolution period).

CBO amplitude in simulation



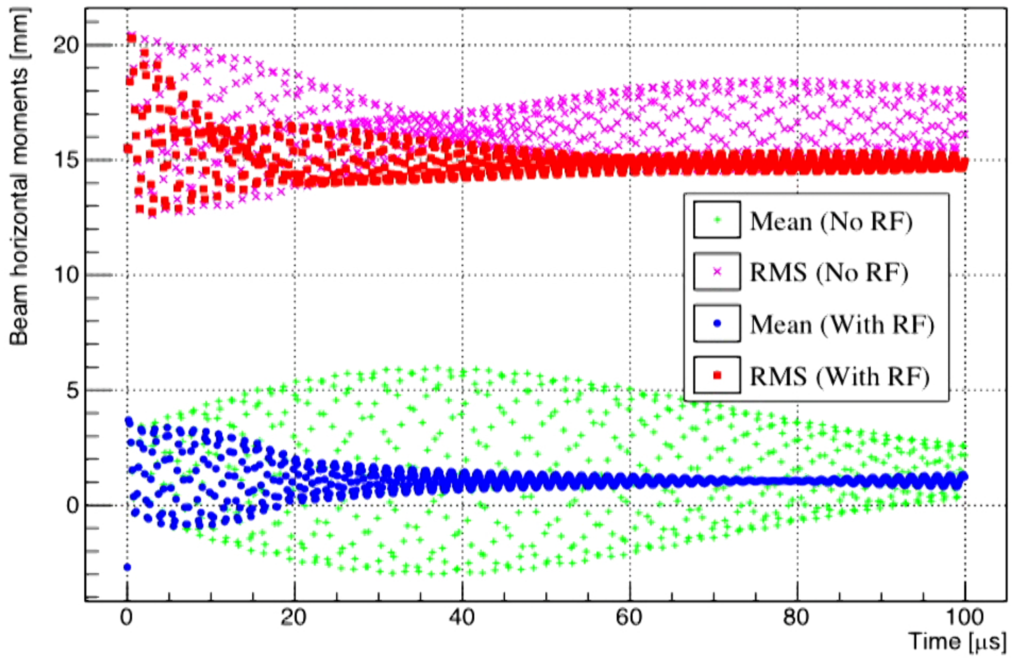
(a) FFT of horizontal mean



(b) FFT of horizontal RMS

Oscillates with the CBO frequency = 650 kHz.

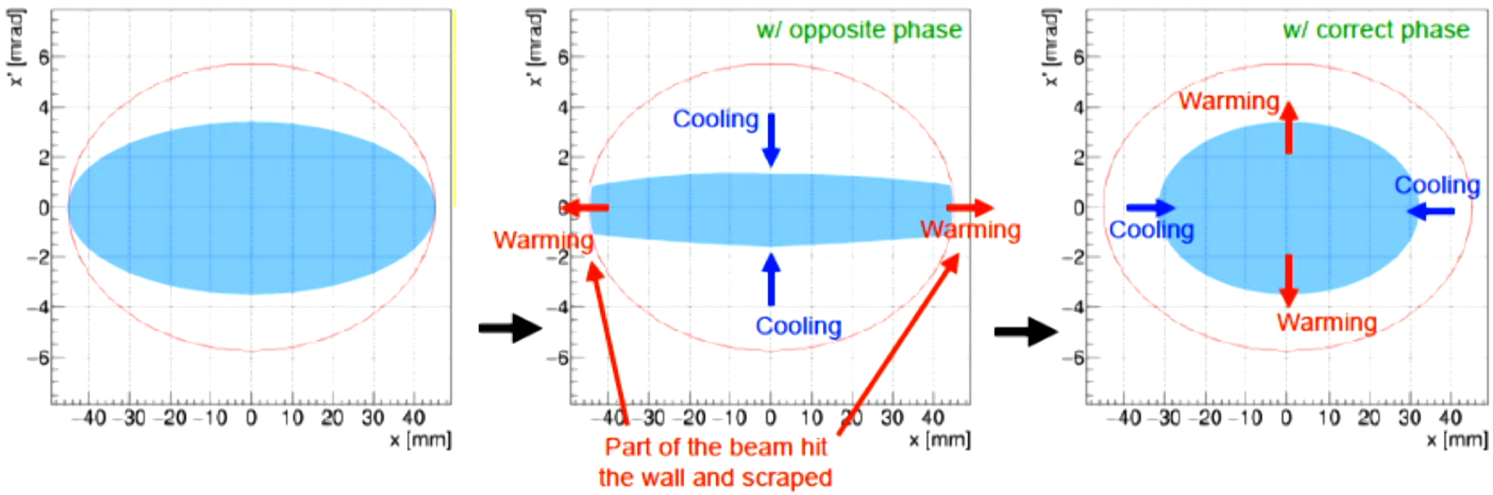
Simulation result with RF



CBO amplitude : 7.0 mm → 0.7 mm (a factor of 10 improvement),
RMS amplitude : 2.1 mm → 1.0 mm (a factor of 2 improvement).

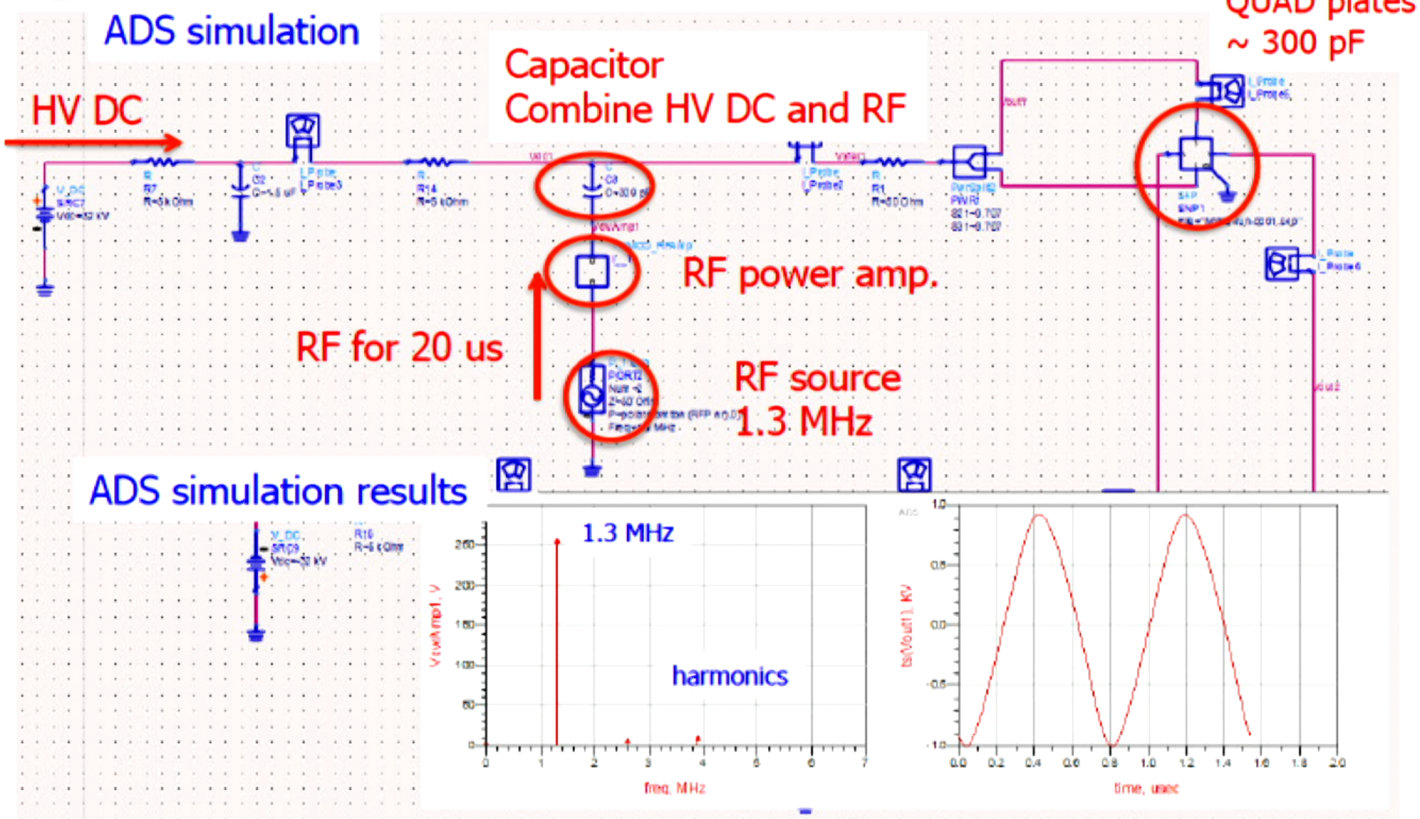
Yet another idea with RF matching

- RF matching can be another solution for the scraping
- Stretching the beam with opposite phase, and bring it back with correct phase



Simulation: Dr. Soohyung Lee

Circuit simulation



Slide: Dr. YoungIm Kim

CAPP's work on the RF promises to

- Reduce the CBO amplitude due to the phase-space mismatch between the beamline and the storage ring:
  - Insufficient amplitude of the fast kicker pulse
  - Momentum dispersion in the stored muons

- Reduce significantly muon losses with minimal statistics loss

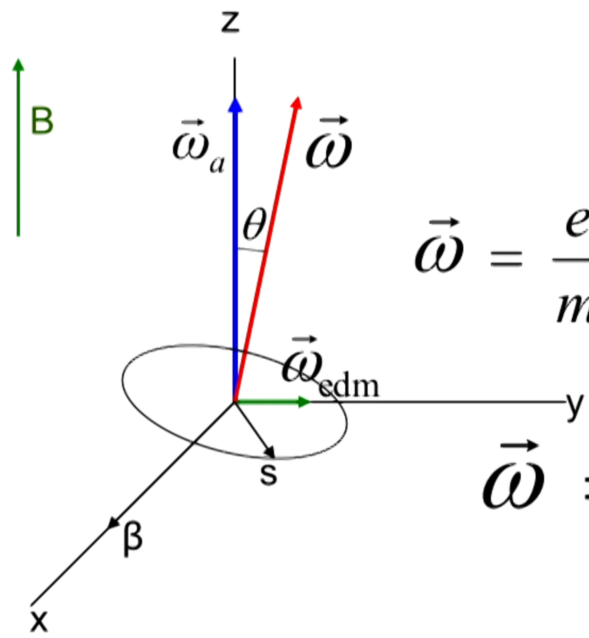
Electric Dipole Moments in Magnetic Storage Rings

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

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

Yannis Semertzidis

Indirect Muon EDM limit from the g-2 Experiment



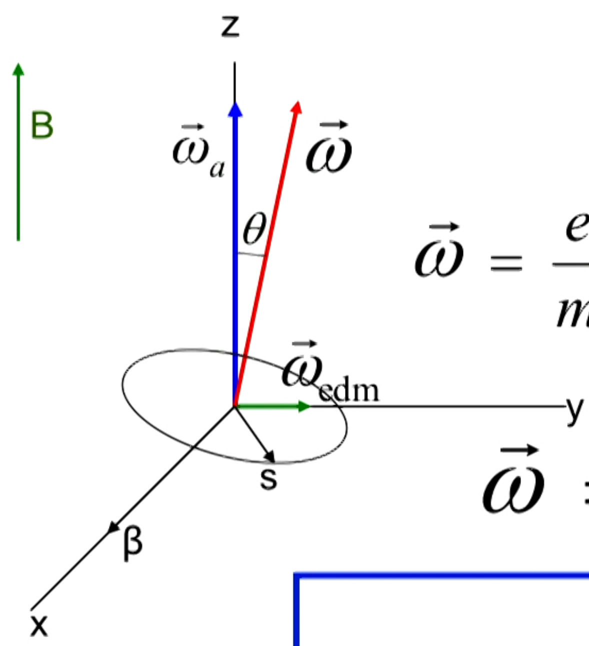
$$\vec{\omega} = \frac{e}{m}\left\{a\vec{B} + \frac{\eta}{2c}\left(\vec{v}\times\vec{B}\right)\right\}$$

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

Yannis Semertzidis

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

Indirect Muon EDM limit from the g-2 Experiment



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

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

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

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

Yannis Semertzidis

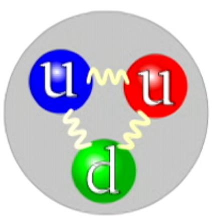

Fundamental particle EDM:
study of CP-violation beyond
the Standard Model

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

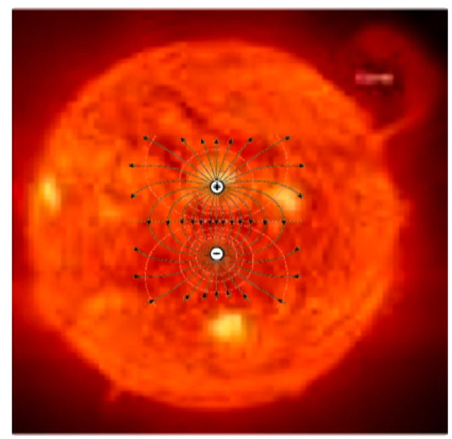
Proton EDM proposal: d=$10^{-29}$$e$.cm

- 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

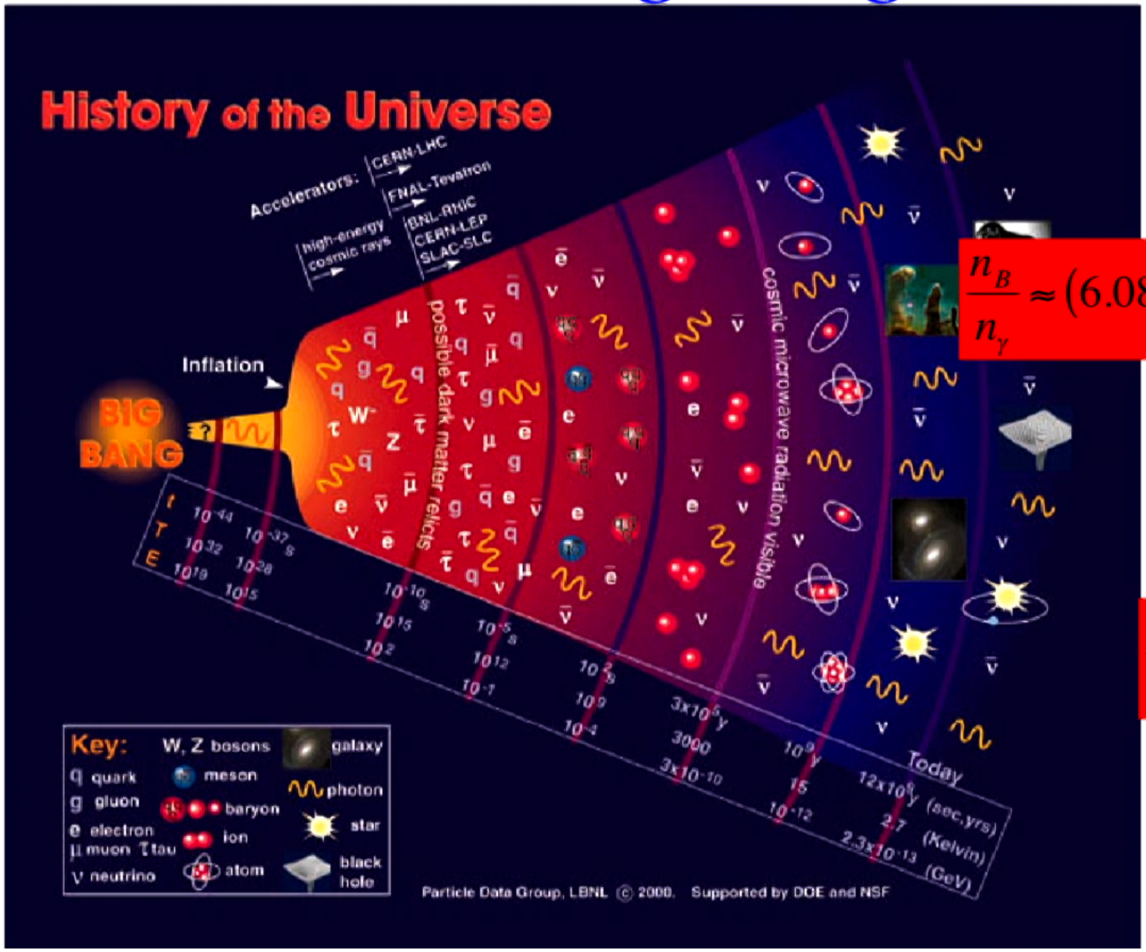


Sun



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

Why is there so much matter after the Big Bang:

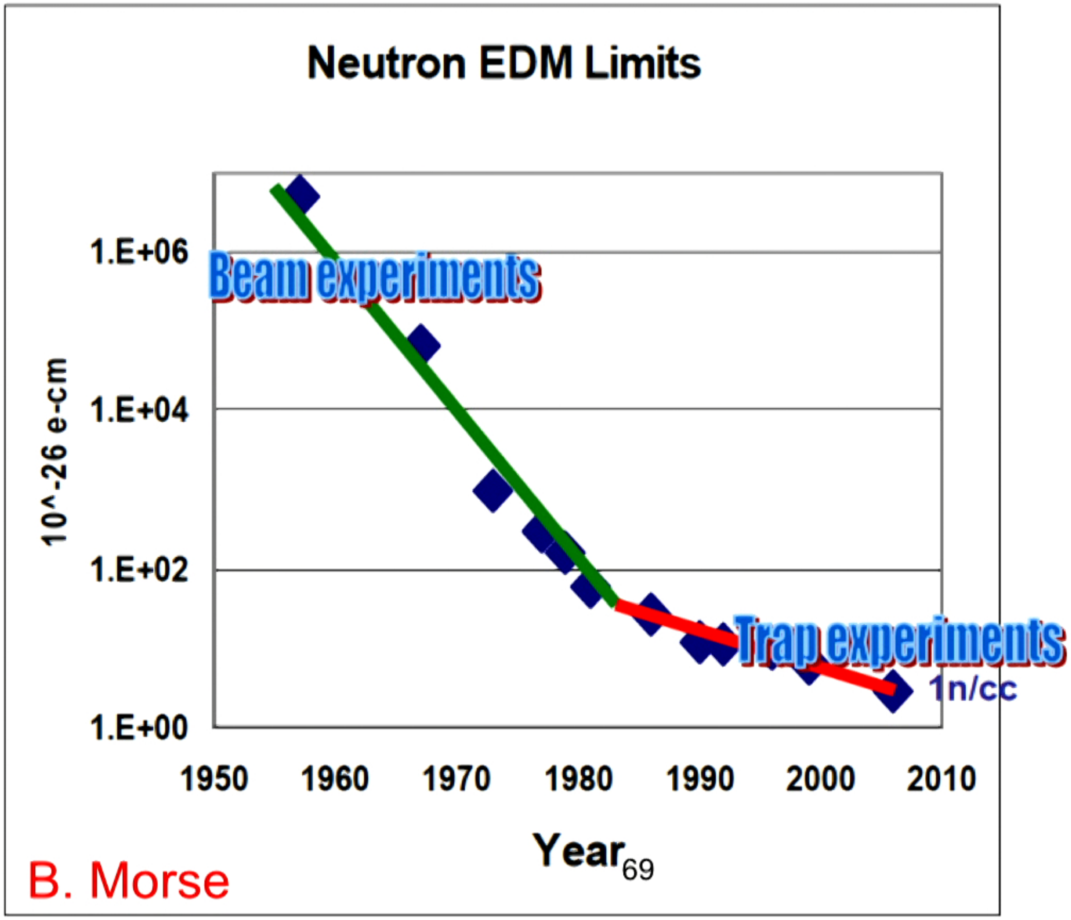


We see:

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

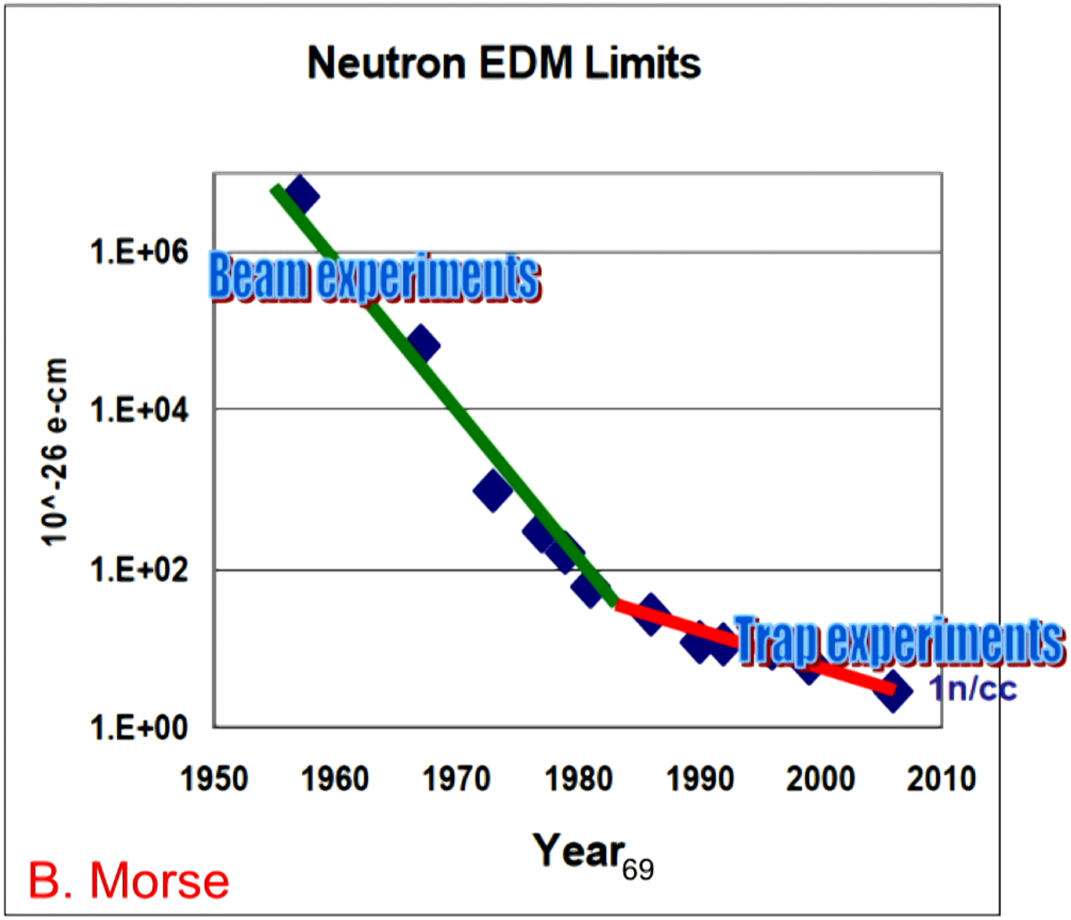
From the SM:

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



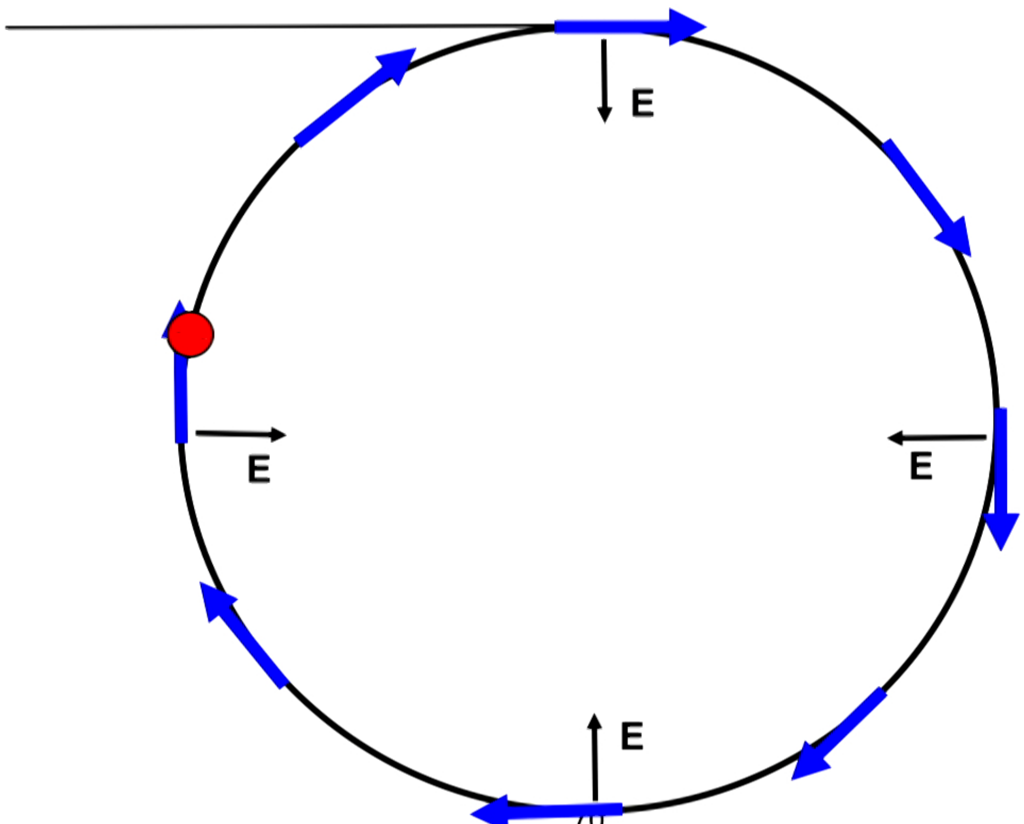
Neutron EDM Limits
1.E+06
1.E+04
1.E+02
1.E+00
10^-26 e-cm
Beam experiments
Trap experiments
1n/cc
1950
1960
1970
1980
1990
2000
2010
Year
69
B. Morse

Proton storage ring EDM experiment is combination of beam + a trap



69

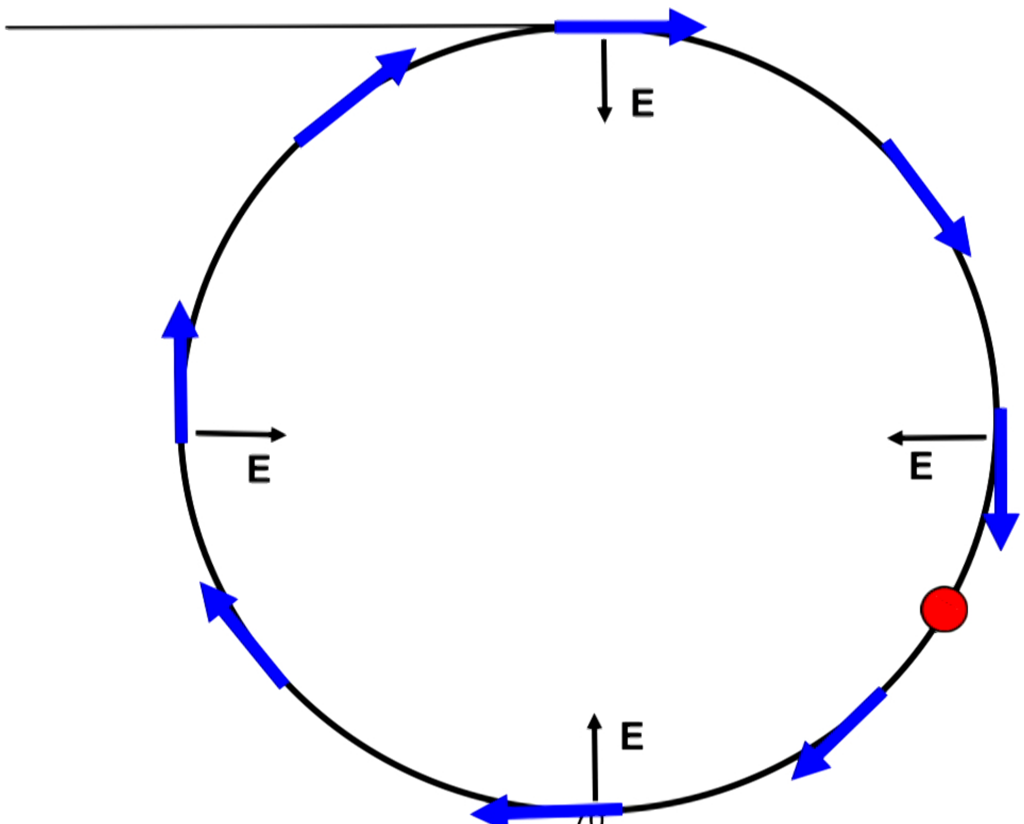
Stored beam: The radial E-field force is balanced by the centrifugal force.



70

Yannis Semertzidis, IBS/CAPP & KAIST

Stored beam: The radial E-field force is balanced by the centrifugal force.



70

Yannis Semertzidis, IBS/CAPP & KAIST

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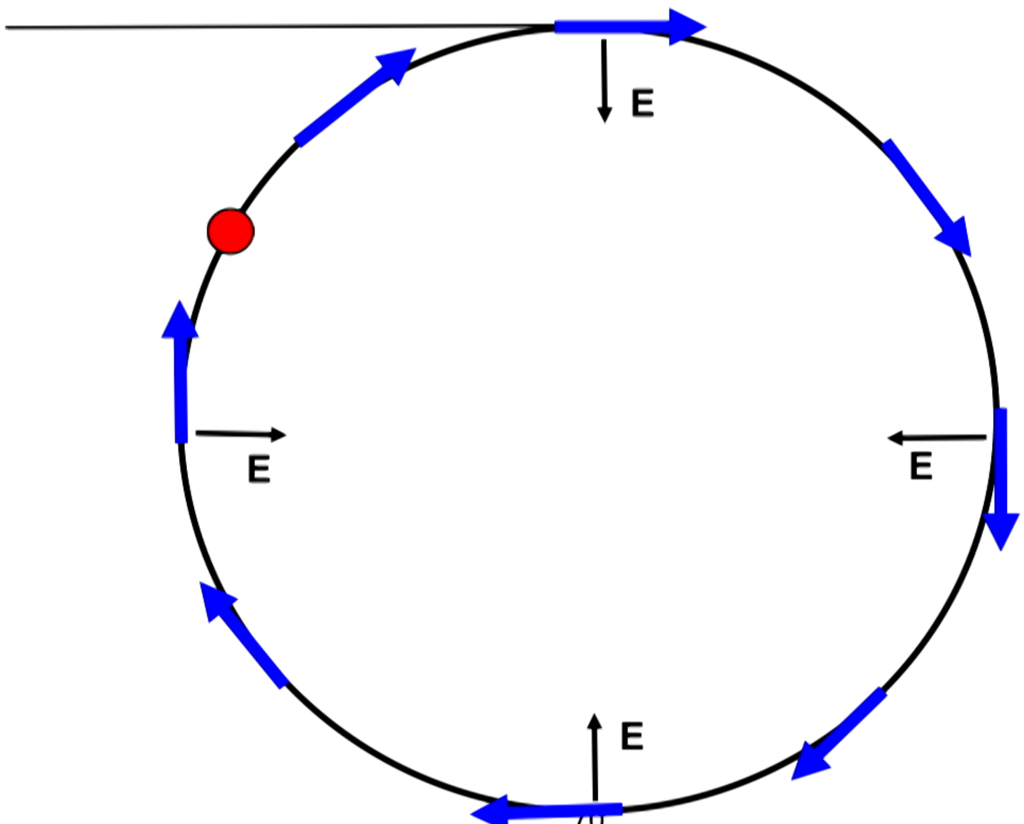

70

Yannis Semertzidis, IBS/CAPP & KAIST

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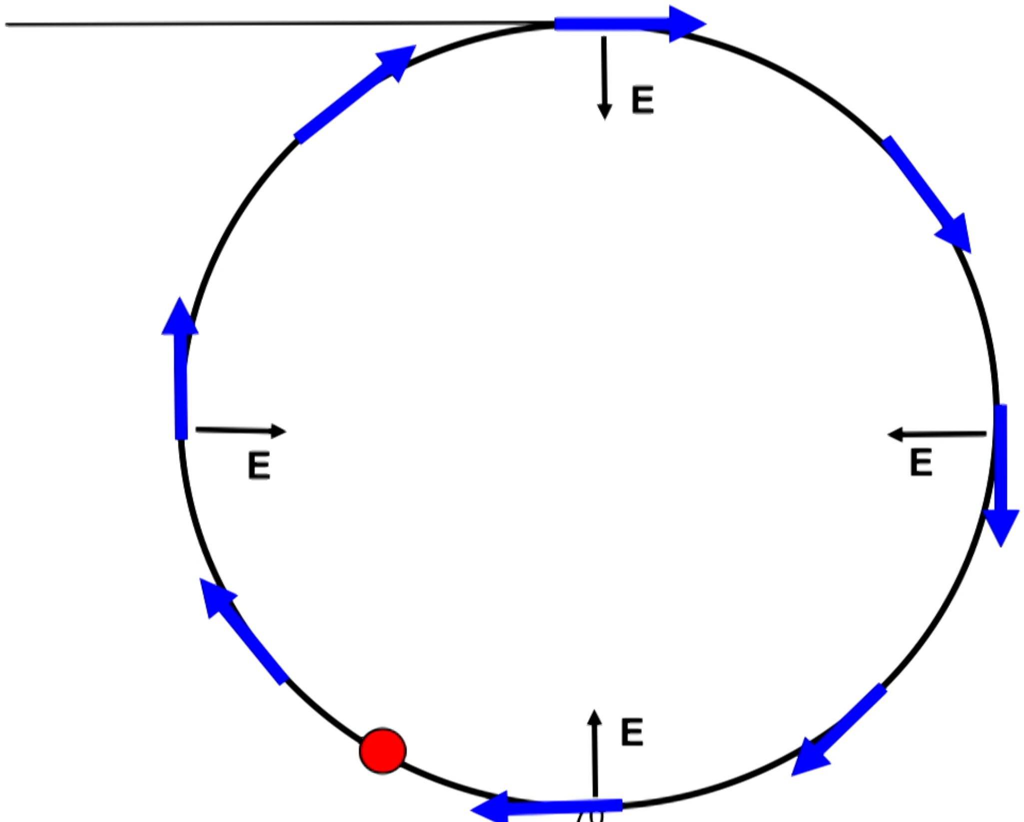
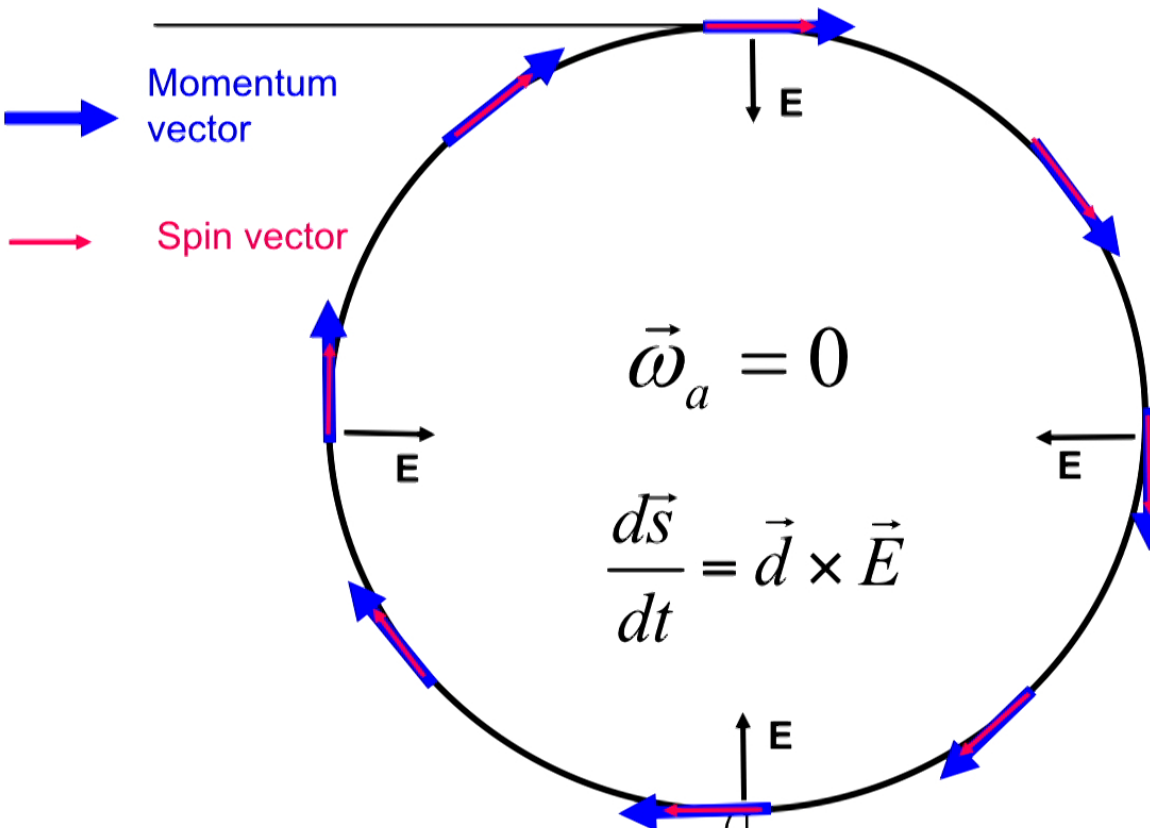


70

Yannis Semertzidis, IBS/CAPP & KAIST

The proton EDM uses an ALL-ELECTRIC ring: spin is aligned with the momentum vector



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

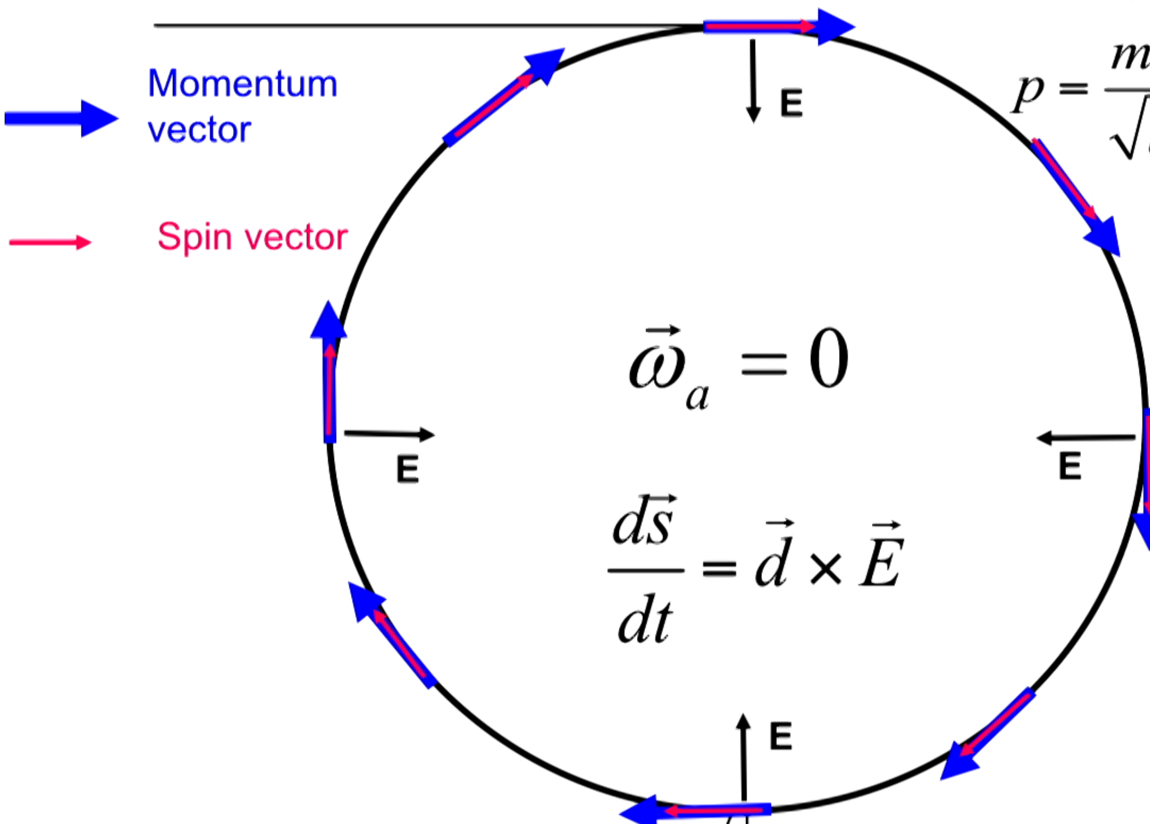
$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

Yannis Semertzidis, IBS/CAPP & KAIST

The proton EDM uses an ALL-ELECTRIC ring: spin is aligned with the momentum vector

at the magic momentum

$$p = \frac{mc}{\sqrt{a}} = 0.7 \text{ GeV/c}$$



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

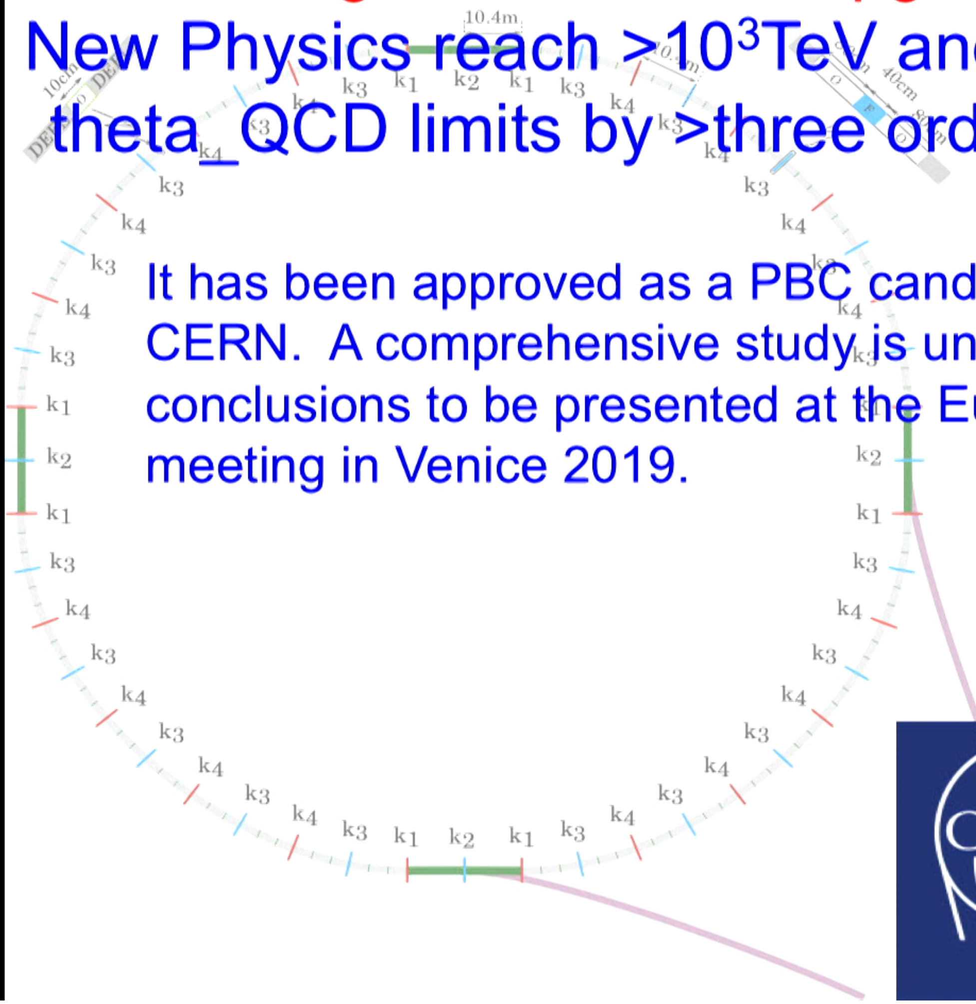
$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

Yannis Semertzidis, IBS/CAPP & KAIST

The proton EDM electric ring, 500m circ.

Current goal 10^{-29} *e*-cm; upgraded: 10^{-30} *e*-cm.

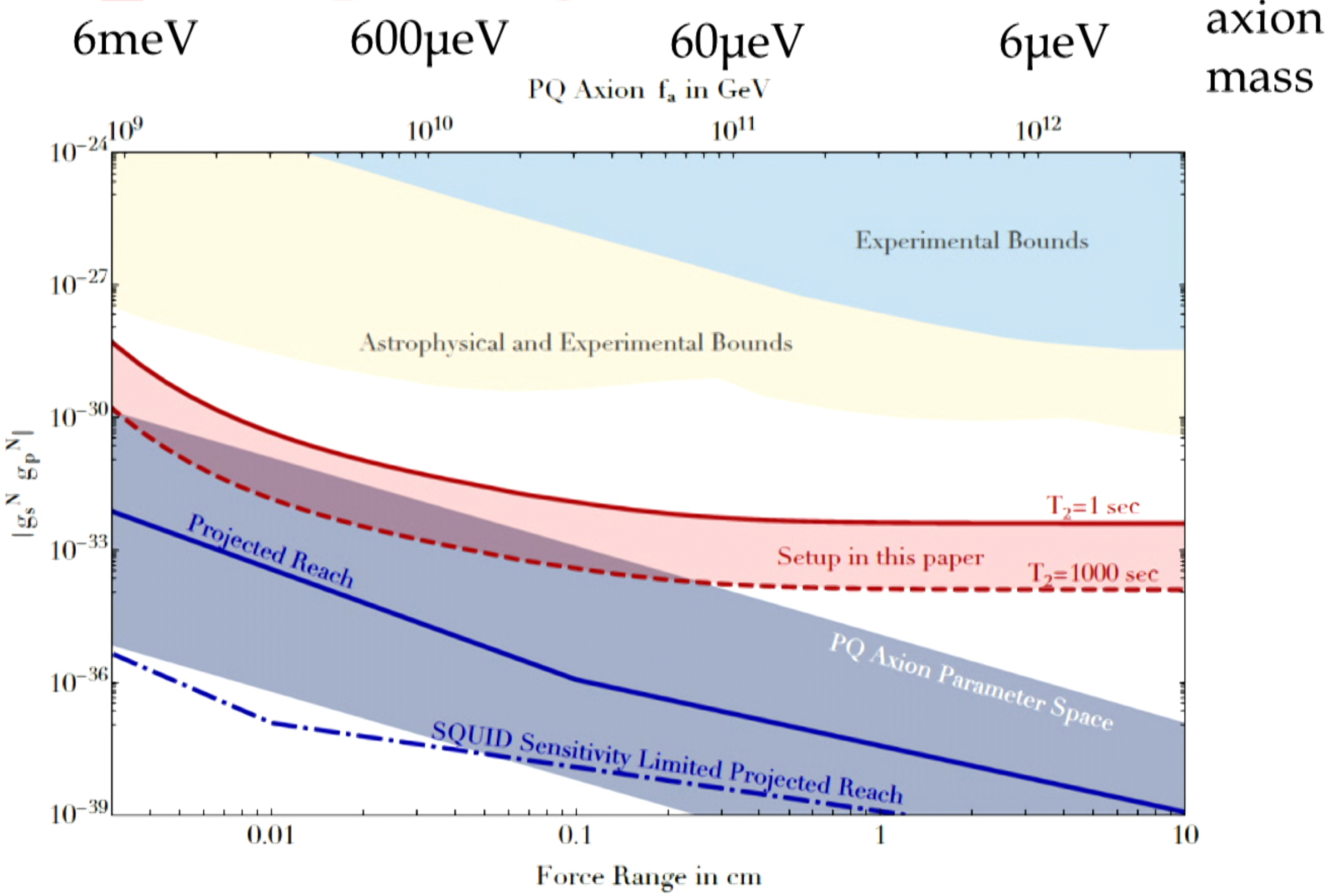
New Physics reach >10^3TeV and improve present theta_QCD limits by >three orders of magnitude



It has been approved as a PBC candidate project at CERN. A comprehensive study is underway with the conclusions to be presented at the European Strategy meeting in Venice 2019.

CERN Physics Beyond Colliders

SUSY-like physics induces a non-zero theta_QCD probing the axion mechanism!



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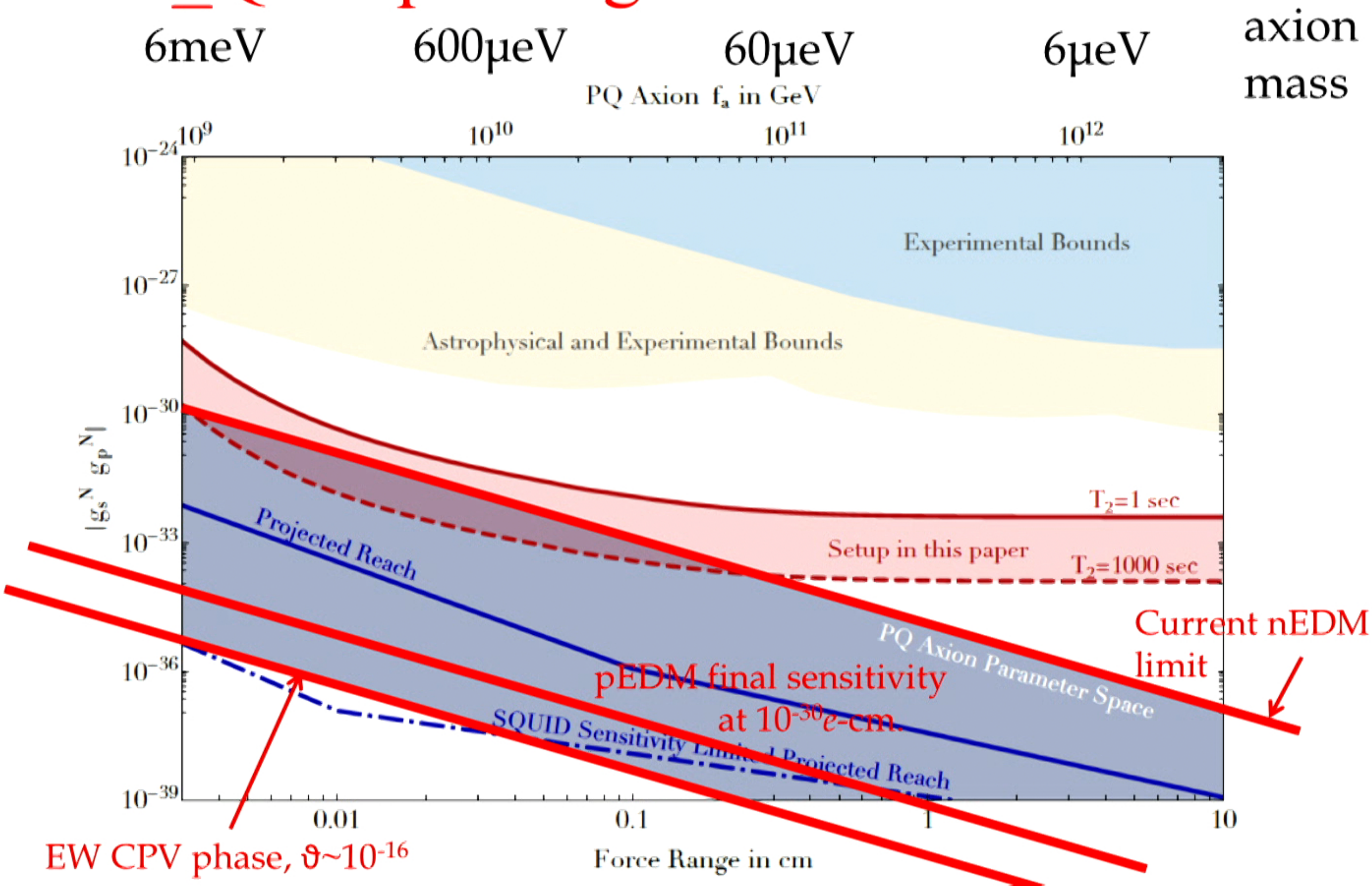
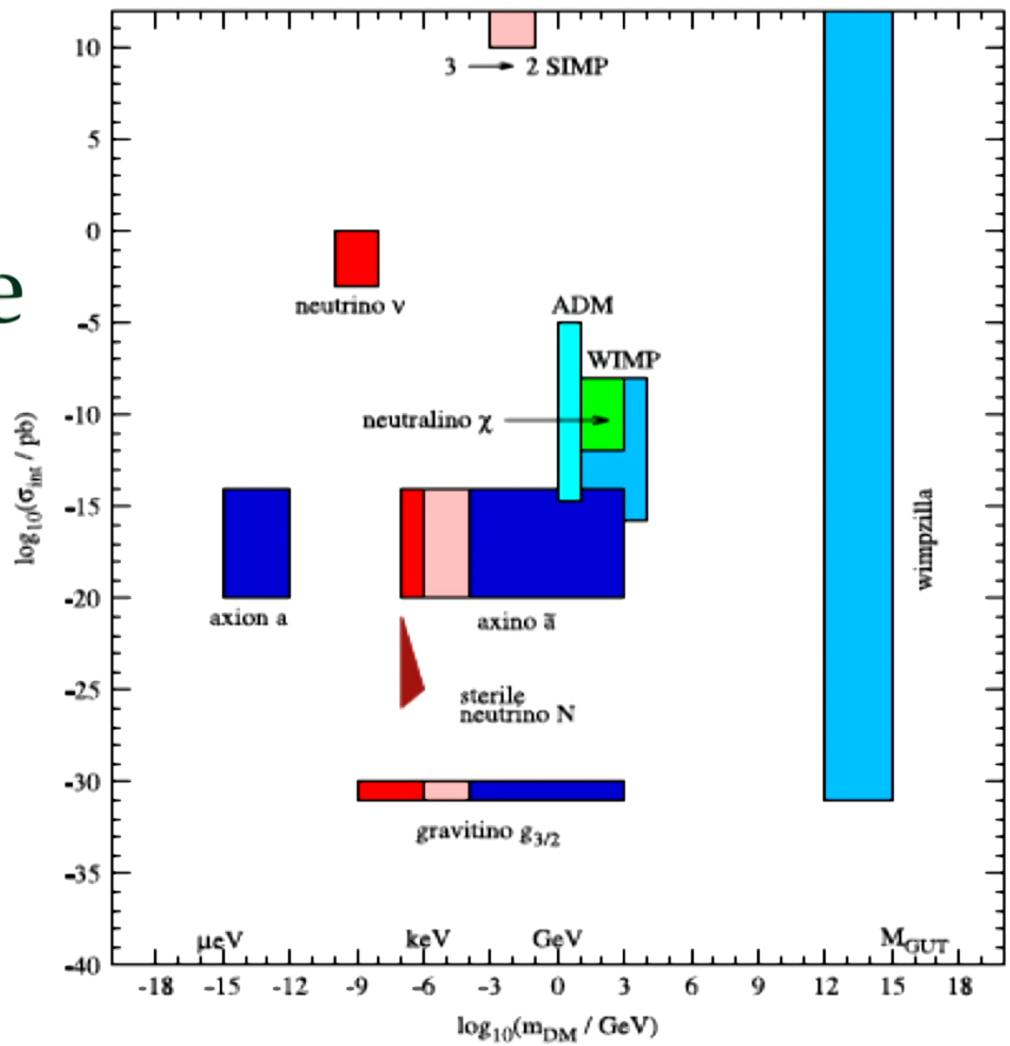


Axion Dark Matter

Dark matter candidates

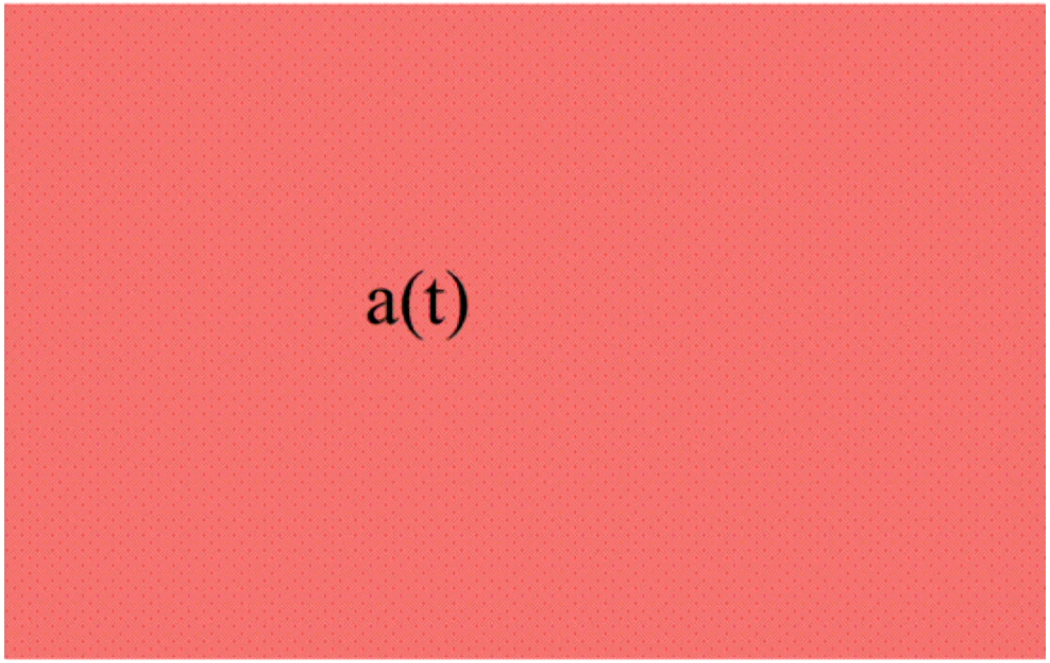
H. Baer et al. / Physics Reports 555 (2015) 1–60



Axion Dark matter

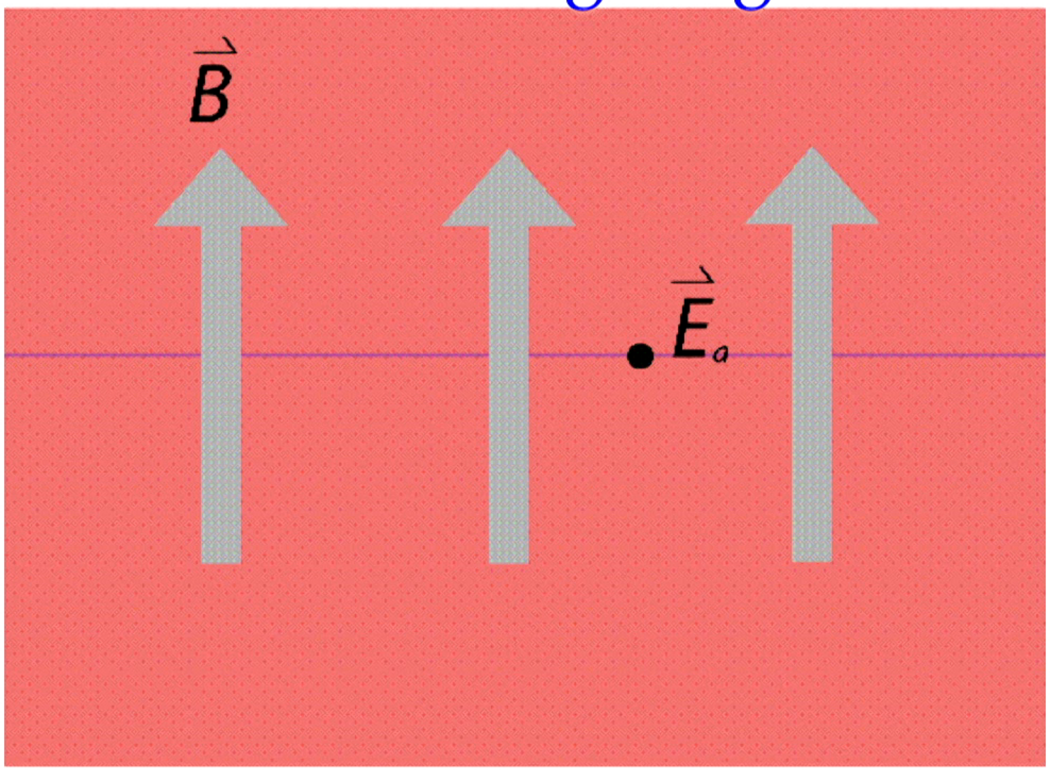
- Dark matter: 0.3-0.5 GeV/cm^3
- Axions in the 1-300μeV range: 10^{12}-10^{14}/cm^3, classical system.
- Lifetime ~7×10^{44}s (100μeV / m_a)^5
- Kinetic energy ~$10^{-6}m_a$, very narrow line in spectrum.

Axion (Higgslet) dark matter: Imprint on the vacuum since soon after the Big-Bang!



Animation by Kristian Themann

Axion dark matter is partially converted to a very weak flickering Electric (E) field in the presence of a strong magnetic field (B).



Animation by Kristian Themann

Axion dark matter

Axion dark matter

1. Addresses one of the most important Physics questions today Dark Matter, Strong CP-problem

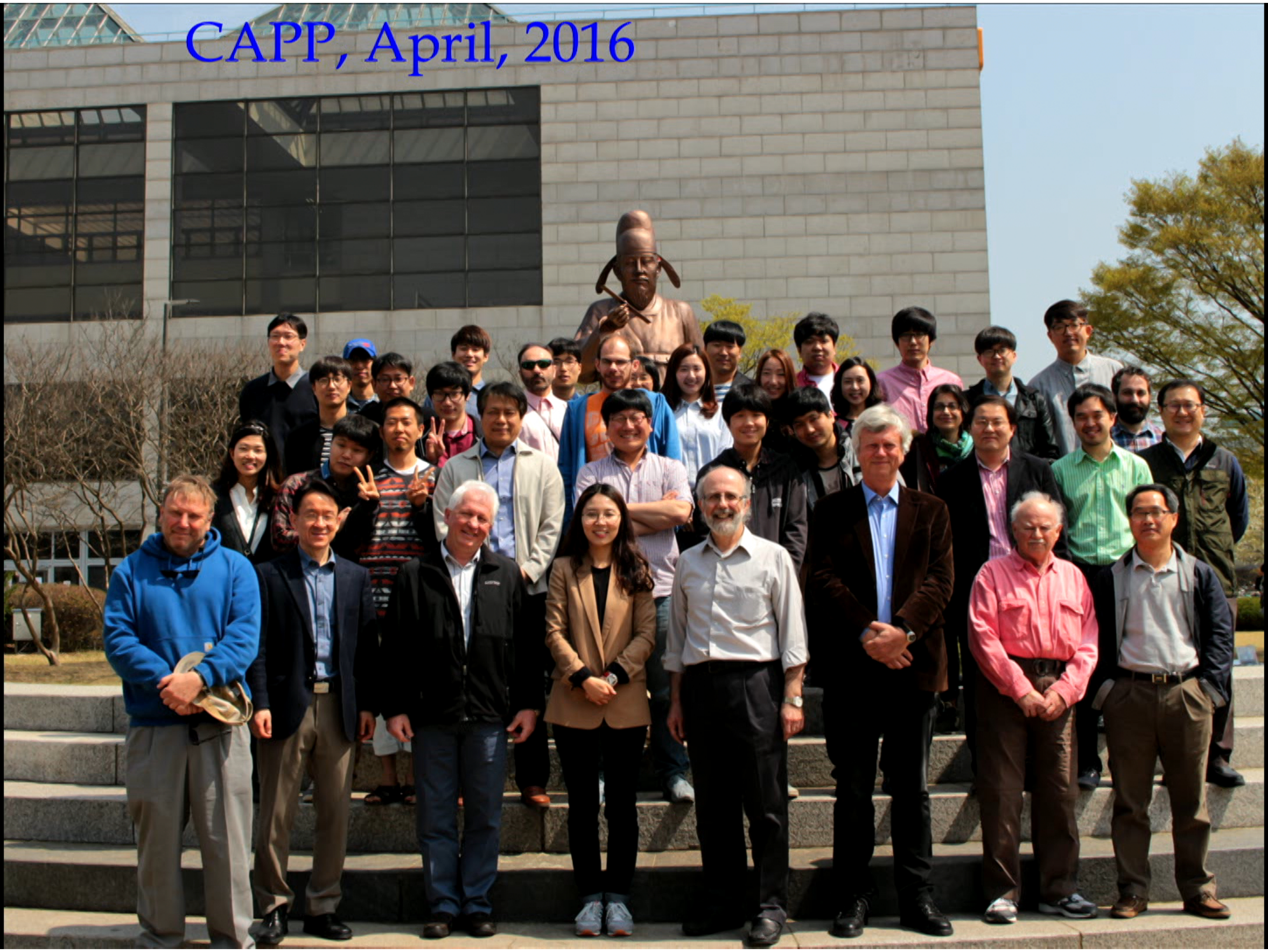
2. Microwave cavity technology: It is possible to probe axions with existing technology in the 1-10GHz today and develop new techniques to expand sensitivity range to higher frequencies

Axion dark matter

1. Addresses one of the most important Physics questions today Dark Matter, Strong CP-problem

2. Microwave cavity technology: It is possible to probe axions with existing technology in the 1-10GHz today and develop new techniques to expand sensitivity range to higher frequencies

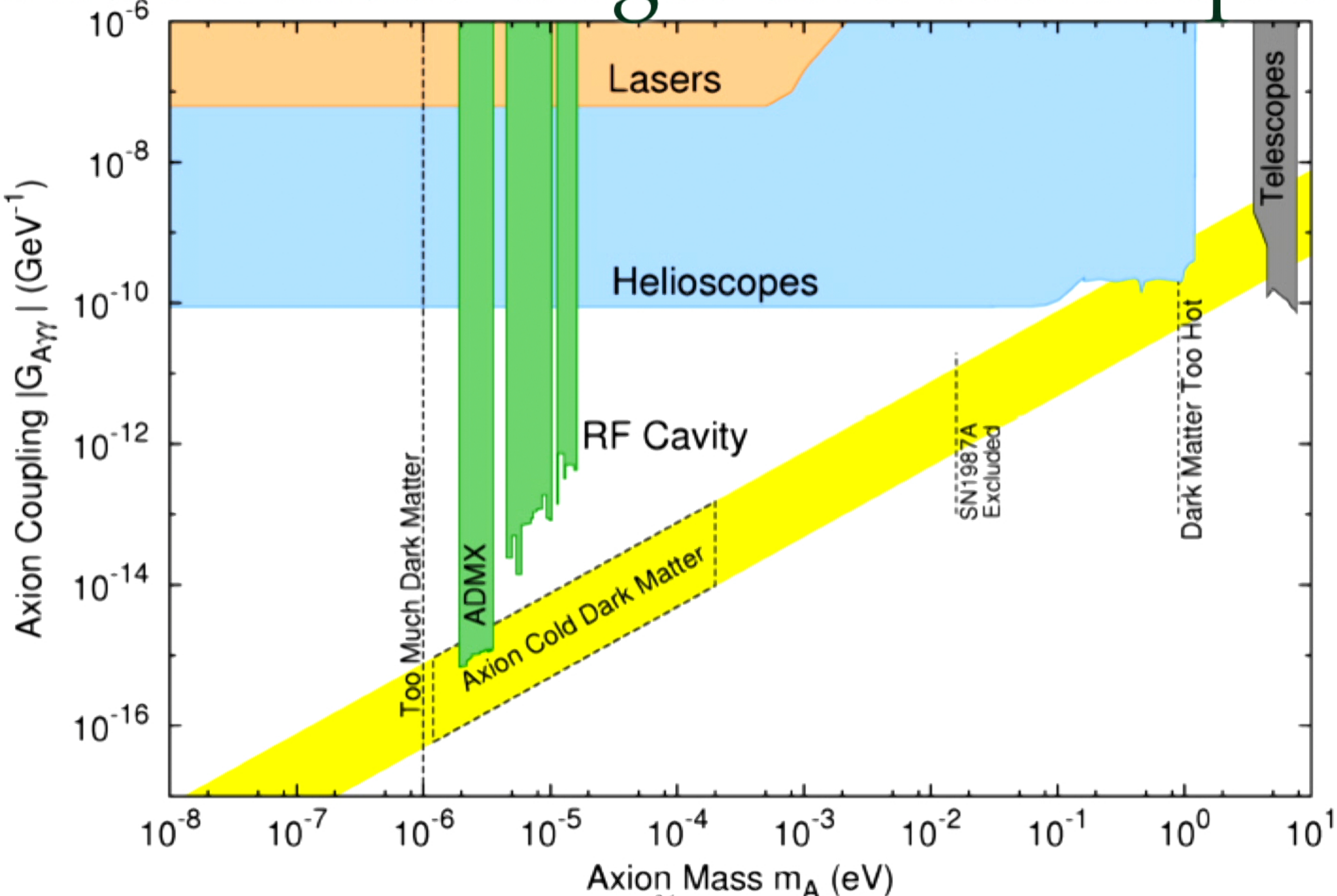
3. Cavity exps: CULTASK, ADMX, HAYSTAC,…
4. High/low freq.: CASPEr, MIT (ABRA…), MADMAX


CAPP, April, 2016

>>100 participants, 12th Patras Workshop on AXIONs, WIMPs, and WISPs, Jeju Island/South Korea, 20-24 June, 2016.

>>100 participants, 13th Patras Workshop on AXIONs, WIMPs, and WISPs, Thessaloniki/Greece, 15-19 May, 2017.

Axion mass target and technique



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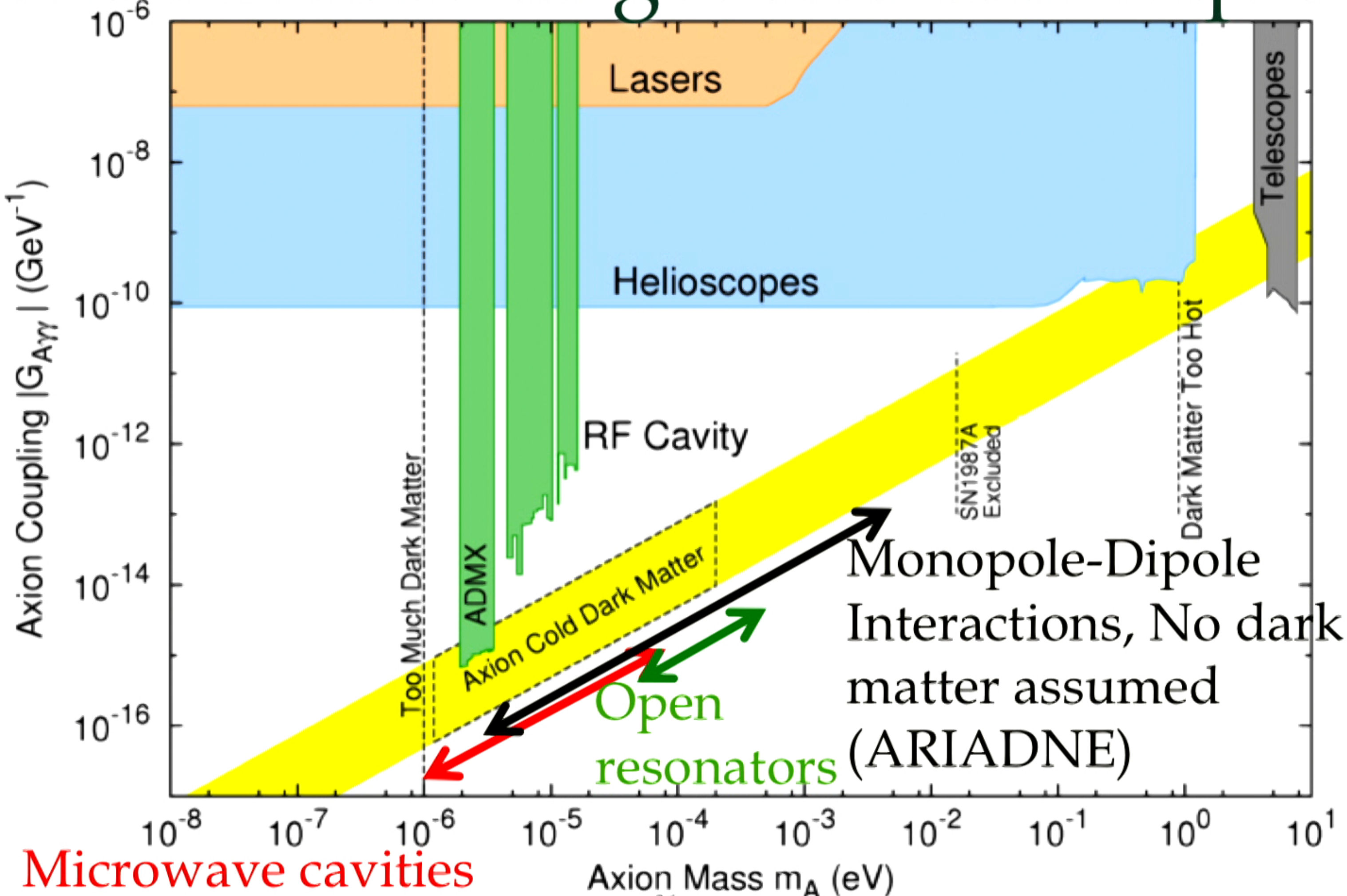
Axion mass target and technique



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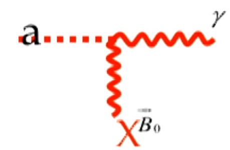
Axion Detection Scheme



P. Sikivie's Haloscope:

Axion Conversion Power (~10^{-24}W): $P_{a\to\gamma\gamma} = g_{a\gamma\gamma}^2 \dfrac{\rho_a}{m_a} B^2 V C_{mnp} \min(Q_L, Q_a)$

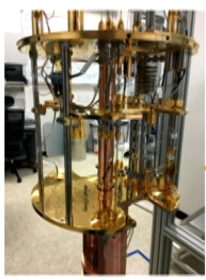
Signal to Noise Ratio: $SNR \equiv \dfrac{P_{signal}}{P_{noise}} = \dfrac{P_{a\to\gamma\gamma}}{k_B T_{syst}} \sqrt{\dfrac{t_{\text{int}}}{\Delta f_a}}$

Scan rate:

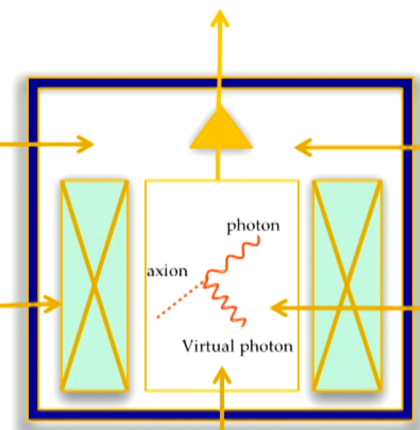
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

Cryogenics

<50mK

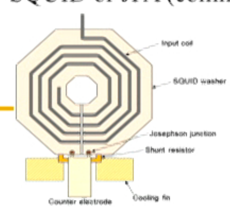


To RF Receiver



SQUID Amplifier

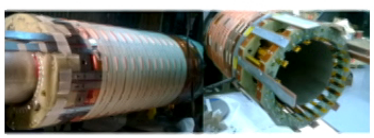
SQUID or JPA (commercial?)



High Field SC Magnet

25T and then 35T

BNL (HTS Technology) Design

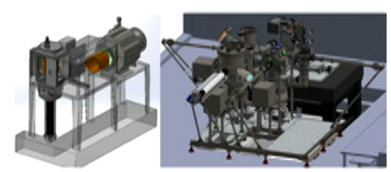


(Reverse) Primakoff Effect

High Q Tunable Cavity

Superconducting Coating

Prof. Jhinhwan Lee of KAIST



Woohyun Chang

$$a \to \gamma$$

The conversion power on resonance

$$P = \left(\frac{\alpha g_\gamma}{\pi f_a}\right)^2 V B_0^2 \rho_a C m_a^{-1} Q_L$$

$$= 2\cdot 10^{-22}\ \text{Watt} \left(\frac{V}{500\ \text{liter}}\right)\left(\frac{B_0}{7\ \text{Tesla}}\right)^2\left(\frac{C}{0.4}\right)$$

$$\left(\frac{g_\gamma}{0.36}\right)^2\left(\frac{\rho_a}{5\cdot 10^{-25}\ \text{gr/cm}^3}\right)\left(\frac{m_a c^2}{h\,\text{GHz}}\right)\left(\frac{Q_L}{10^5}\right)$$

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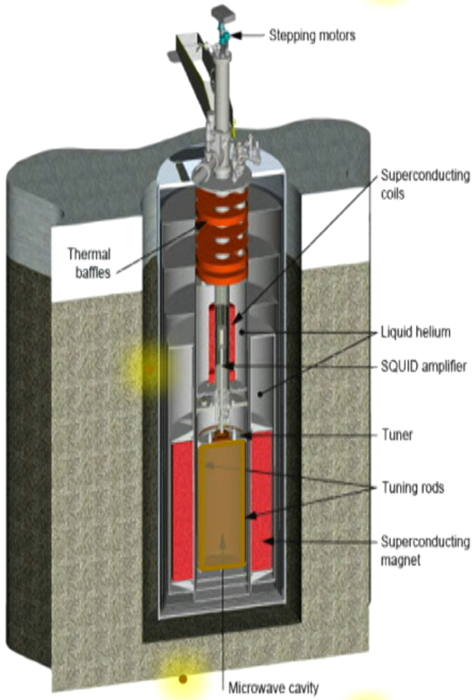
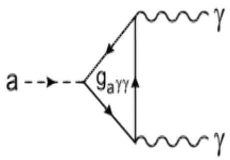


Conversion of Axion
into microwave photons:



$$P = \left(\frac{\alpha g_\gamma}{\pi f_a}\right)^2 V\, B_0^{\,2}\, \rho_a\, C\, m_a^{-1}\, Q_L$$

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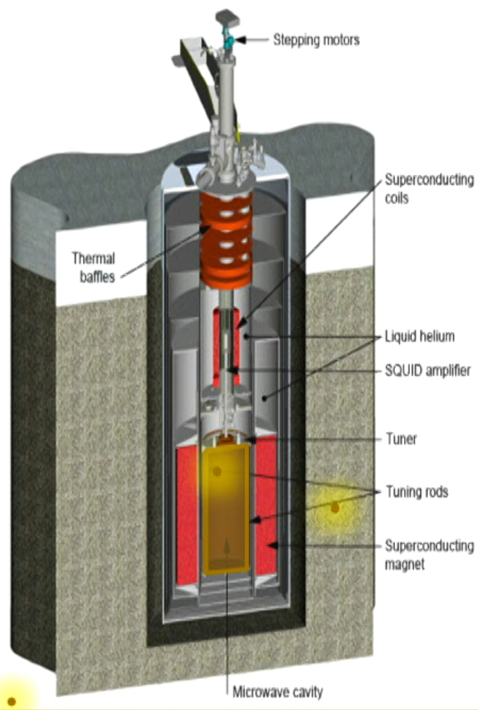

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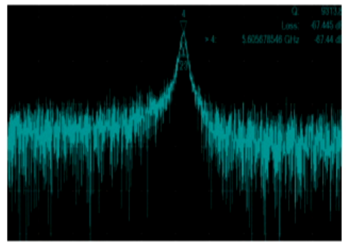

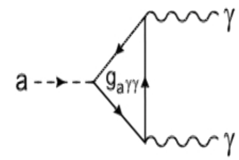

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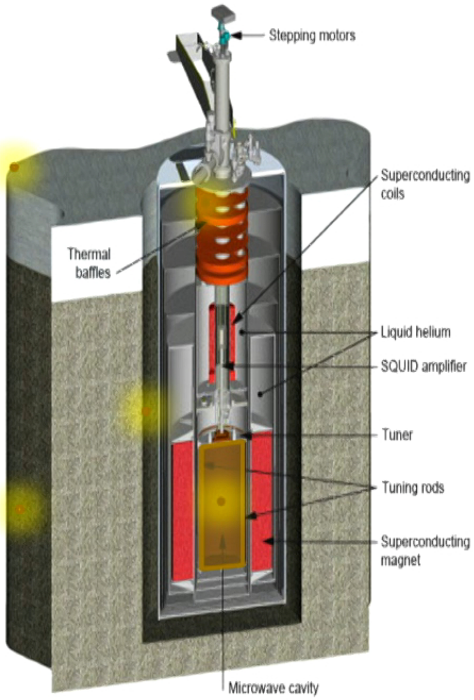

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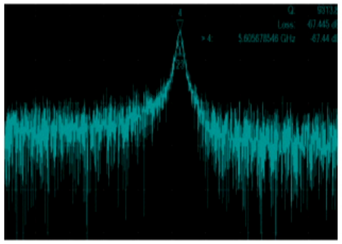

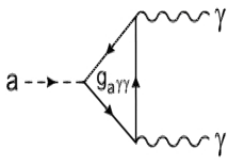

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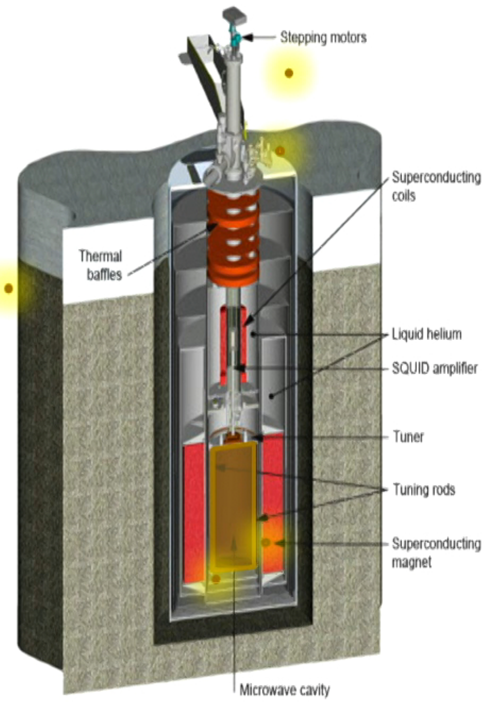

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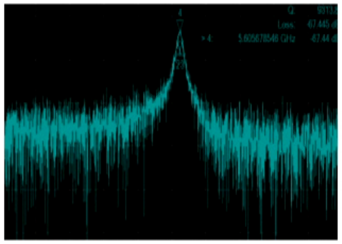

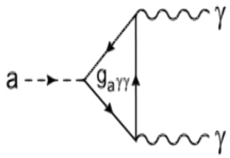

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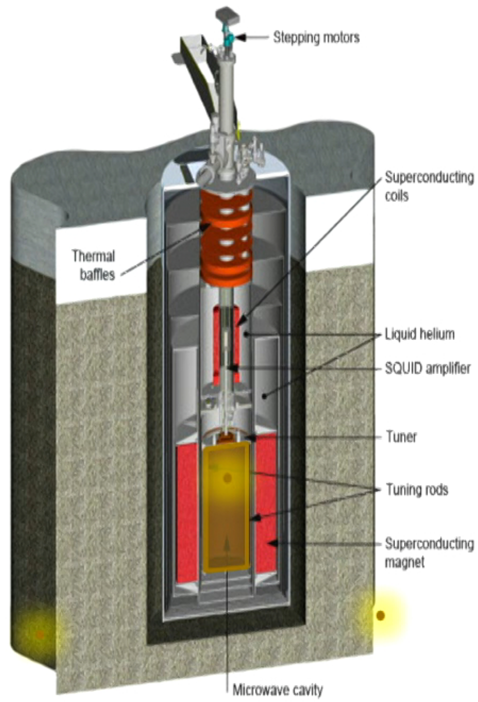

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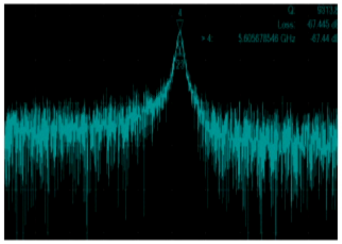

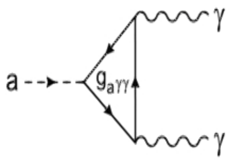

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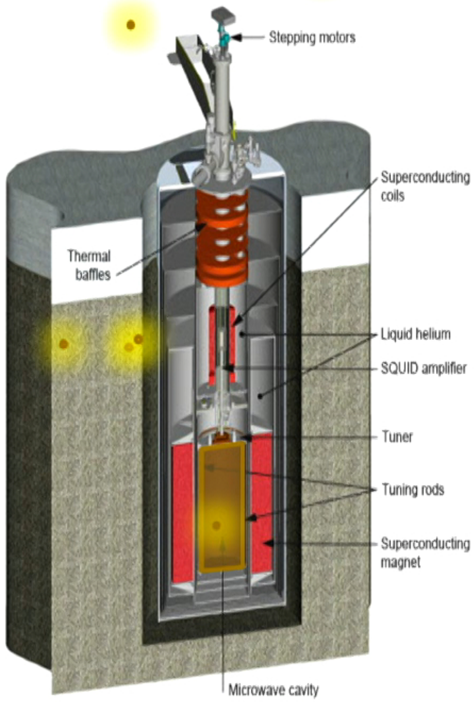

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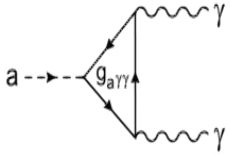

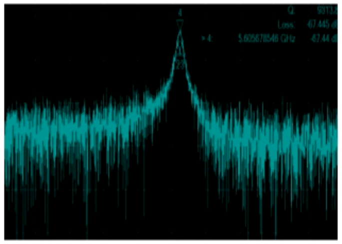

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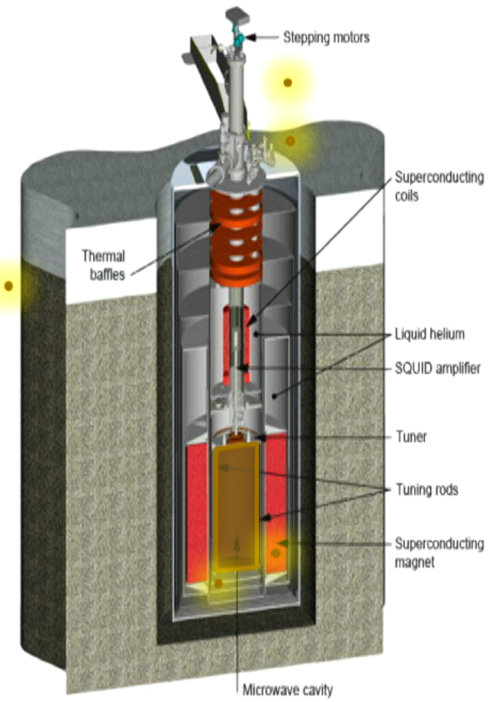

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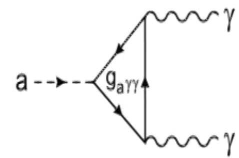

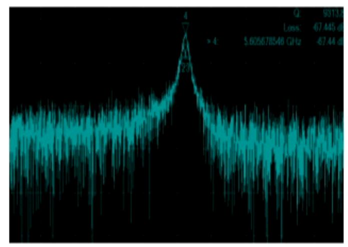

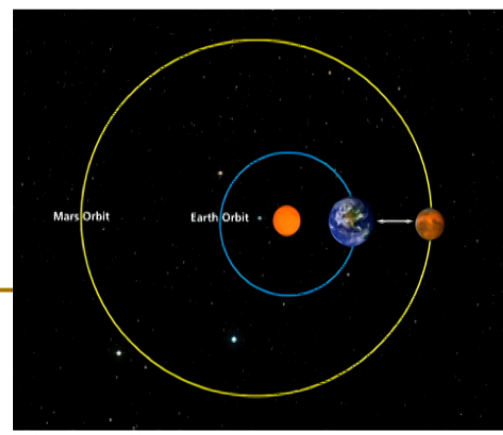

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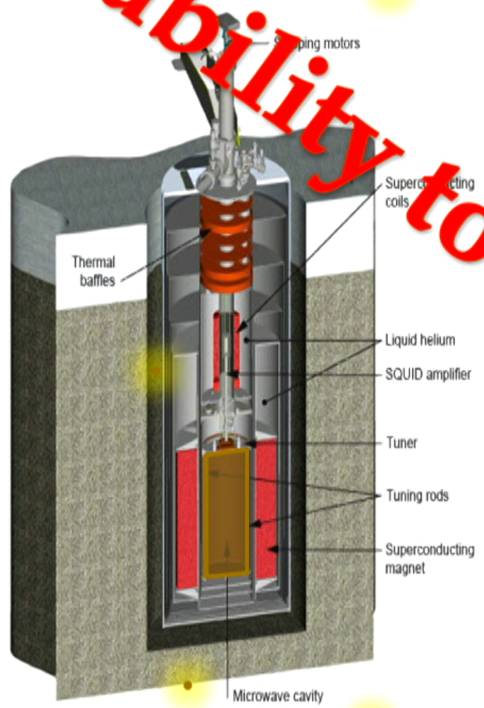

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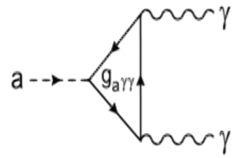

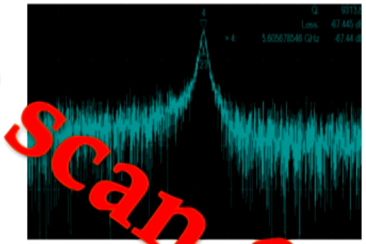

The ability to scan fast is critical!

IBS/CAPP axion plan

Scanning rate:

$$\frac{df}{dt} = \frac{f}{Q}\frac{1}{t} \approx \frac{1\ \text{GHz}}{year}\left(g_{a\gamma\gamma}10^{15}\text{GeV}\right)^4\left(\frac{5\ \text{GHz}}{f}\right)^2\left(\frac{4}{SNR}\right)^2\left(\frac{0.25\ \text{K}}{T}\right)^2$$

$$\times\left(\frac{B}{25T}\right)^4\left(\frac{c}{0.6}\right)^2\left(\frac{V}{5l}\right)^2\left(\frac{Q}{10^5}\right)$$

IBS/CAPP axion plan

Scanning rate:

$$\frac{df}{dt} = \frac{f}{Q}\frac{1}{t} \approx \frac{1\ \text{GHz}}{year}\left(g_{a\gamma\gamma}10^{15}\text{GeV}\right)^4\left(\frac{5\ \text{GHz}}{f}\right)^2\left(\frac{4}{SNR}\right)^2\left(\frac{0.25\ \text{K}}{T}\right)^2$$

$$\times\left(\frac{B}{25T}\right)^4\left(\frac{c}{0.6}\right)^2\left(\frac{V}{5l}\right)^2\left(\frac{Q}{10^5}\right)$$

- Major improvement elements:
  - High field solenoid magnets: B
  - High volume magnets/cavities: V
  - High quality factor of cavity: Q
  - Low noise amplifiers: T_N
  - Low physical temperature: T_{ph}

IBS/CAPP axion plan

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Overall Plan

- Main effort: Comprehensive Axion Dark Matter experiments.
- Use different type of resonators depending on the resonant frequency.
- High volume, high quality factors.
- Use new powerful magnets,…

IBS/CAPP axion plan

- Major improvement elements:

High field solenoid magnets, B: 9T→25T→40T

High volume magnets/cavities, V: 5l→50l

High quality factor of cavity, Q: 10^5→10^6

Low noise amplifiers, T_N: 2K→0.25K

Low physical temperature, T_{ph}: 1K→0.1K

Scanning rate improvement: 25×10^6

Improvement in coupling constant: 70

Overall Plan

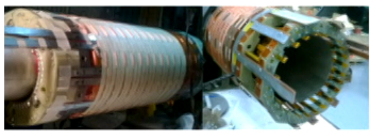
- Main effort: Comprehensive Axion Dark Matter experiments.
- Use different type of resonators depending on the resonant frequency.
- High volume, high quality factors.
- Use new powerful magnets,…

CAPP's R & D

R&D for Axion Research

HF SC Magnets

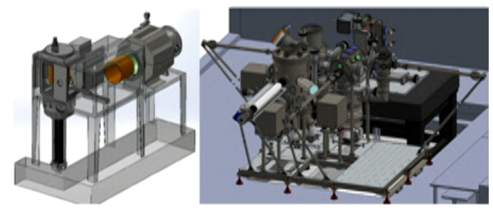
HTS 25T-10cm (->35T) by BNL
HTS 18T-7cm (SuNAM)
HTS 26T-3.5cm (SuNAM:WR)
LTS 12T-32 cm (Oxford)



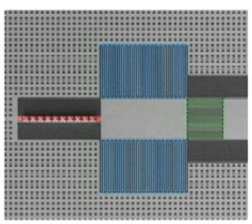
Small Toroid 12T, V=80 L
Giant Toroid 5T, V=9900 L

SC High Q Cavity

Jhinhwan Lee
Equipment setup complete
First Sputtering Sc coating

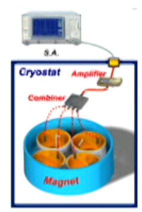


SQUID Amp

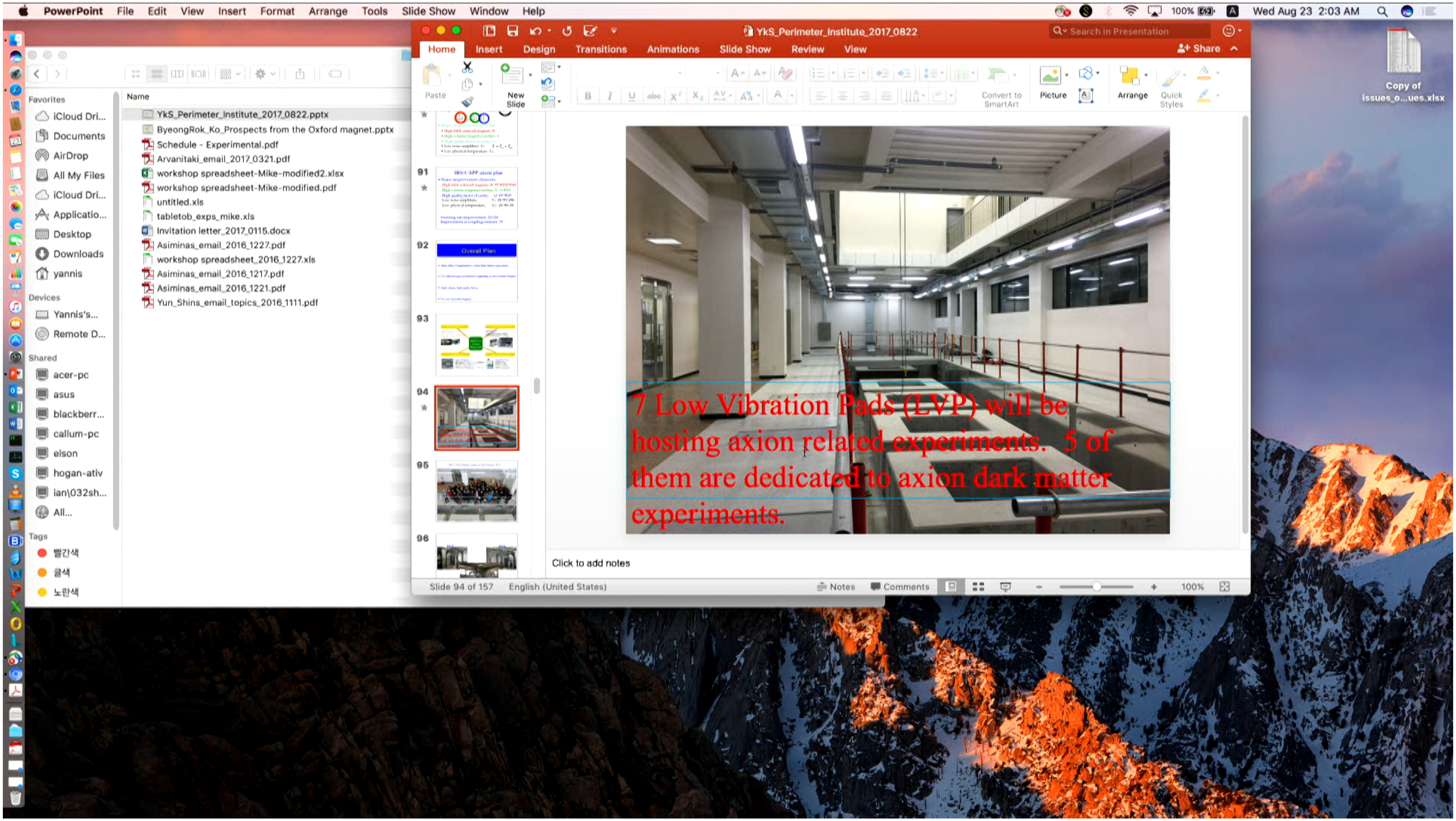


Andrei Matlashov
MSA from Young-Ho Lee (KRISS)
JBA/JPC from Yale (QCI)
MSA from M. Mueck (ez-SQUID)

Multiple Cavities



SungWoo Youn
Higher Freq.
Phase locking
R&D in progress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Overall Plan
7 Low Vibration Pads (LVP) will be hosting axion related experiments. 5 of them are dedicated to axion dark matter experiments.
Click to add notes
Slide 94 of 157 English (United States)
Notes Comments 100%
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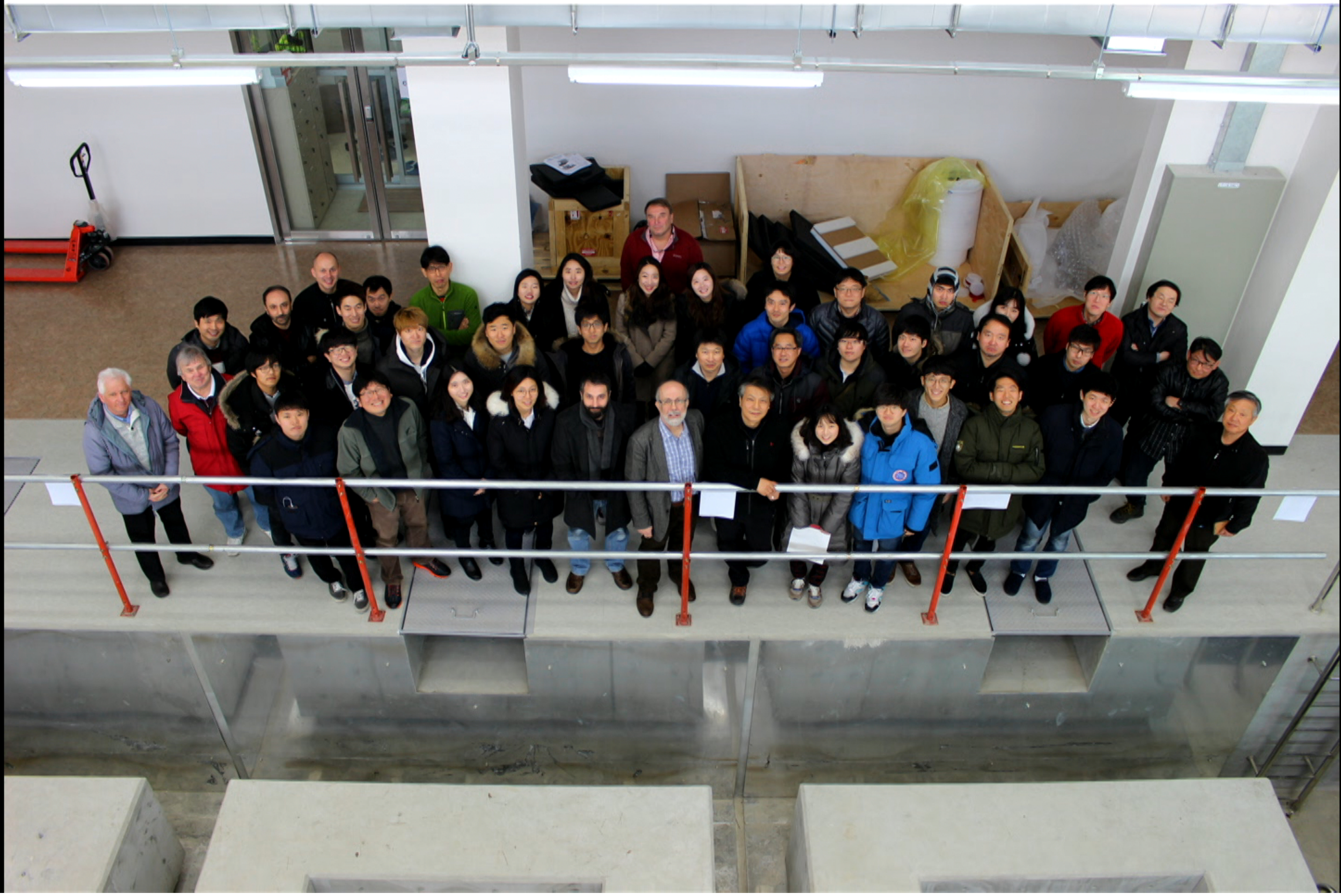
7 Low Vibration Pads (LVP) will be hosting axion related experiments. 5 of them are dedicated to axion dark matter experiments.

IBS/CAPP at Munji Campus, KAIST, January 2017.



CULTASK 2017 w/ Four DRs

BF3

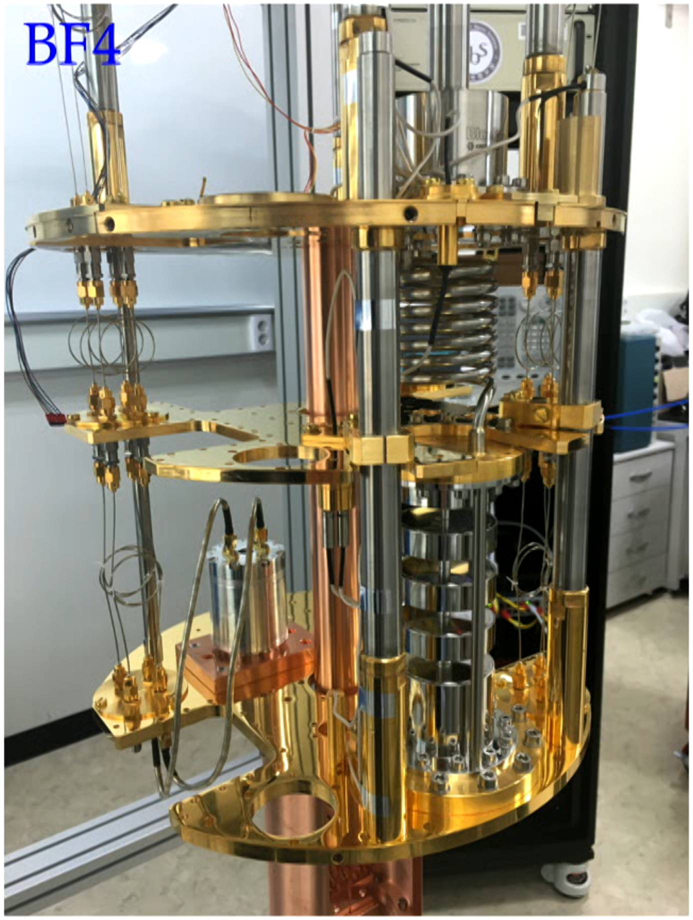
BF4

BF5

BF6

Woohyun Chang

CULTASK 2017 w/ Four DRs

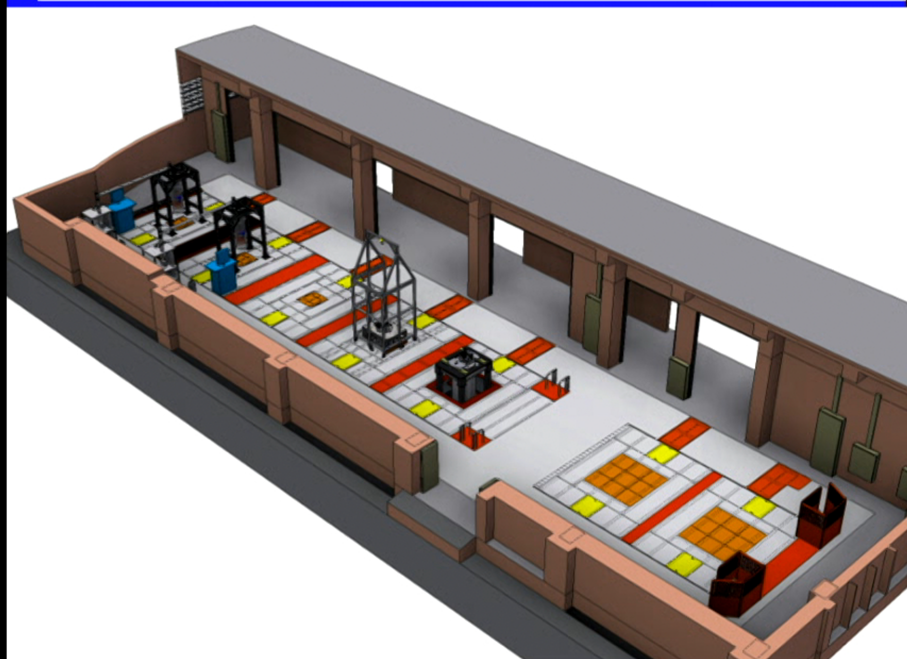


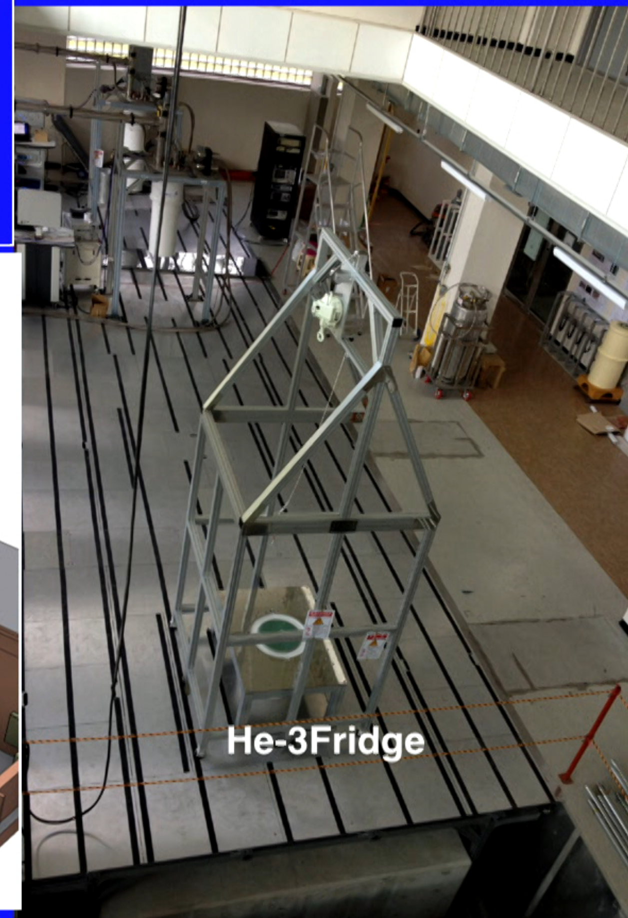
Woohyun Chang

Low vibration facility

For axion search

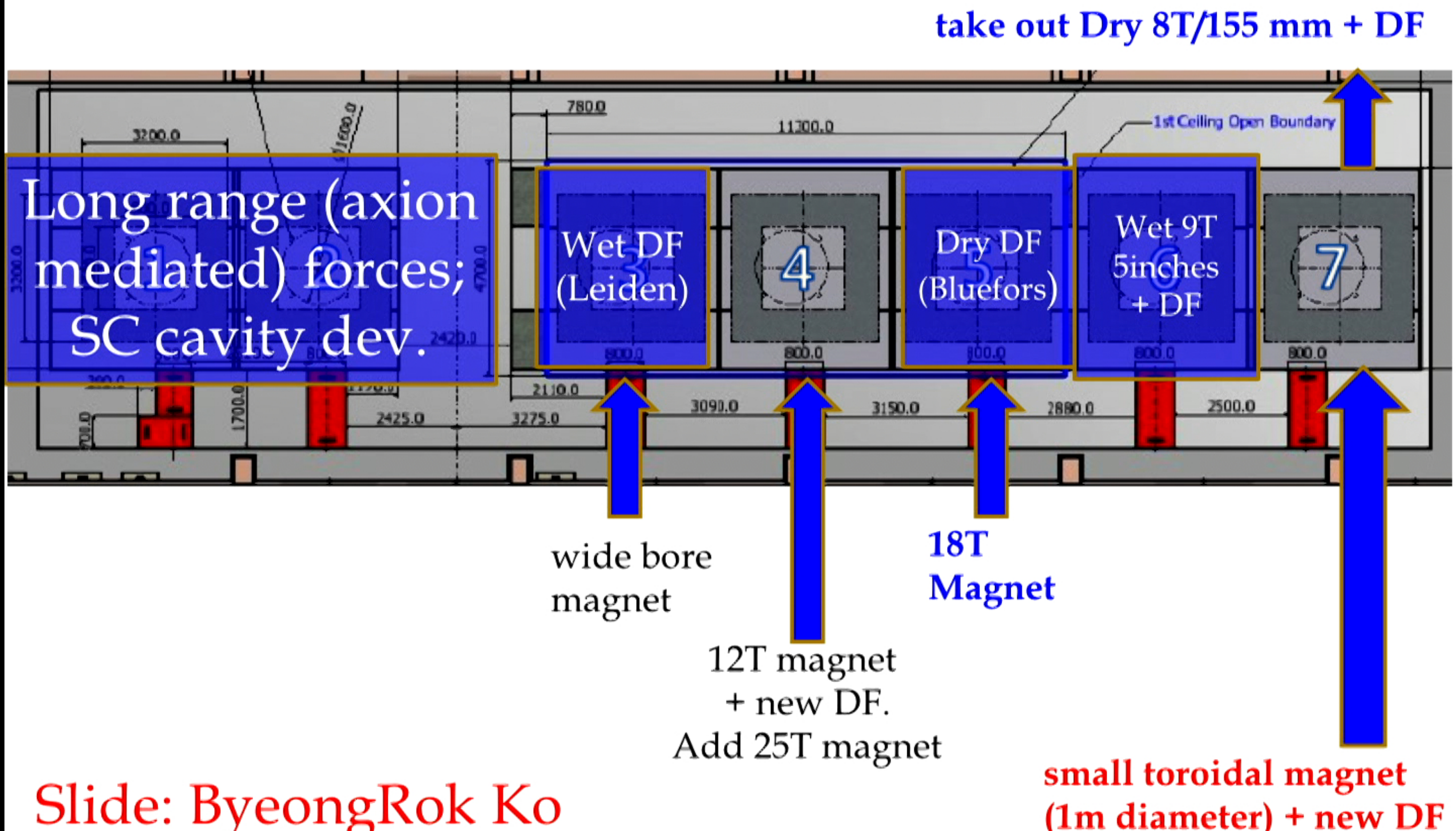
More than five large scale axion search
Search system to be installed and operated





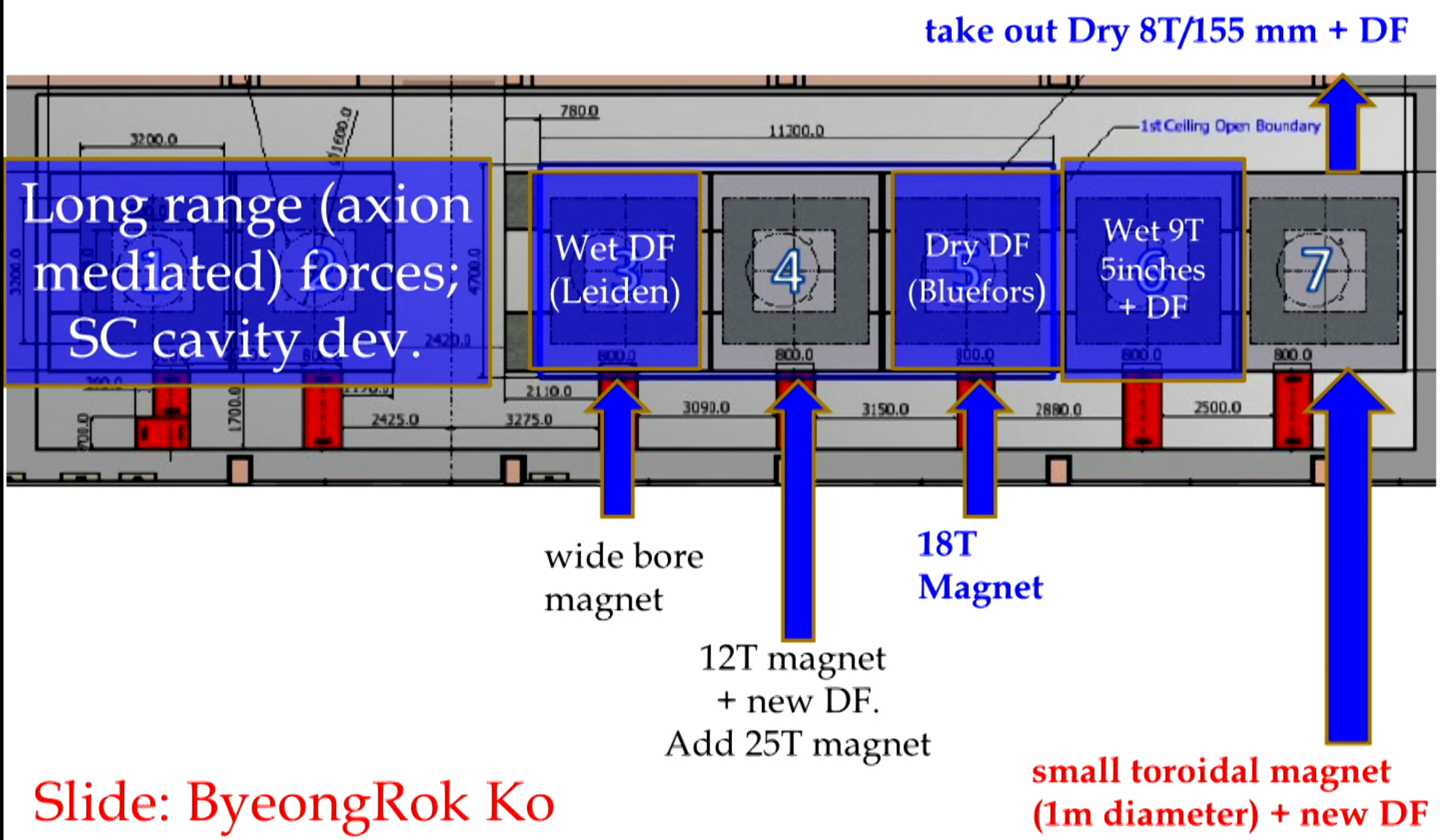
DonLak Kim's slide

Low Vibration Pad Assignment



Slide: ByeongRok Ko

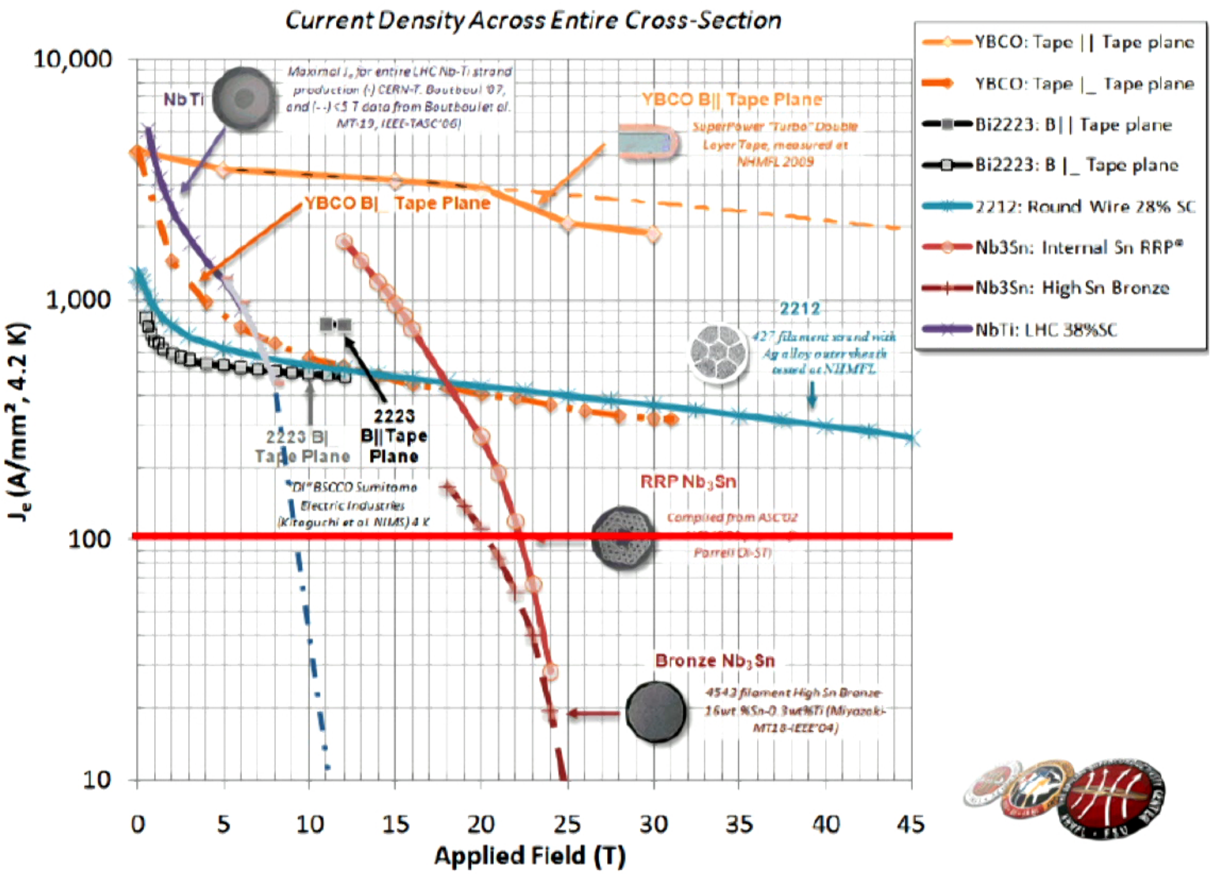
Low Vibration Pad Assignment



Slide: ByeongRok Ko

Future Solenoids:

High- Temperature Superconductors



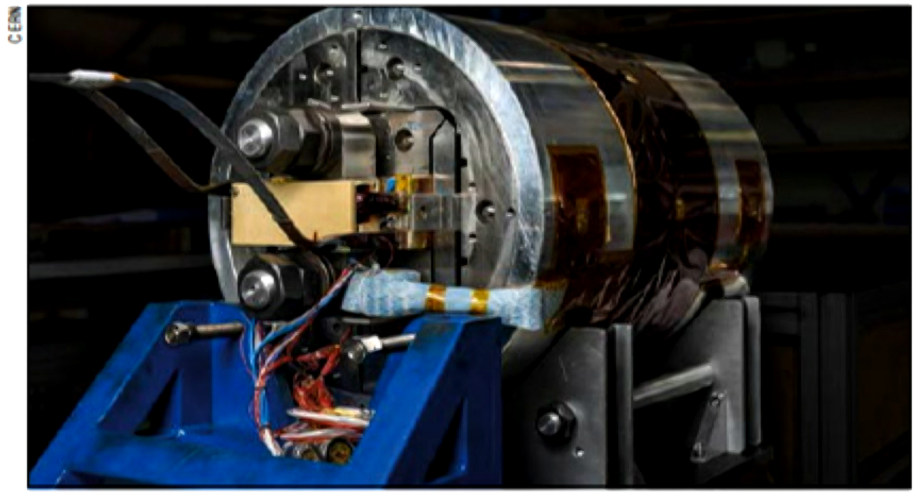
Plot maintained by Peter Lee at: http://magnet.fsu.edu/~lee/plot/plot.htm

102

Traditional magnets: LHC magnets made with NbTi conductors

9T max

Next magnets are made with Nb_3Sn conductors



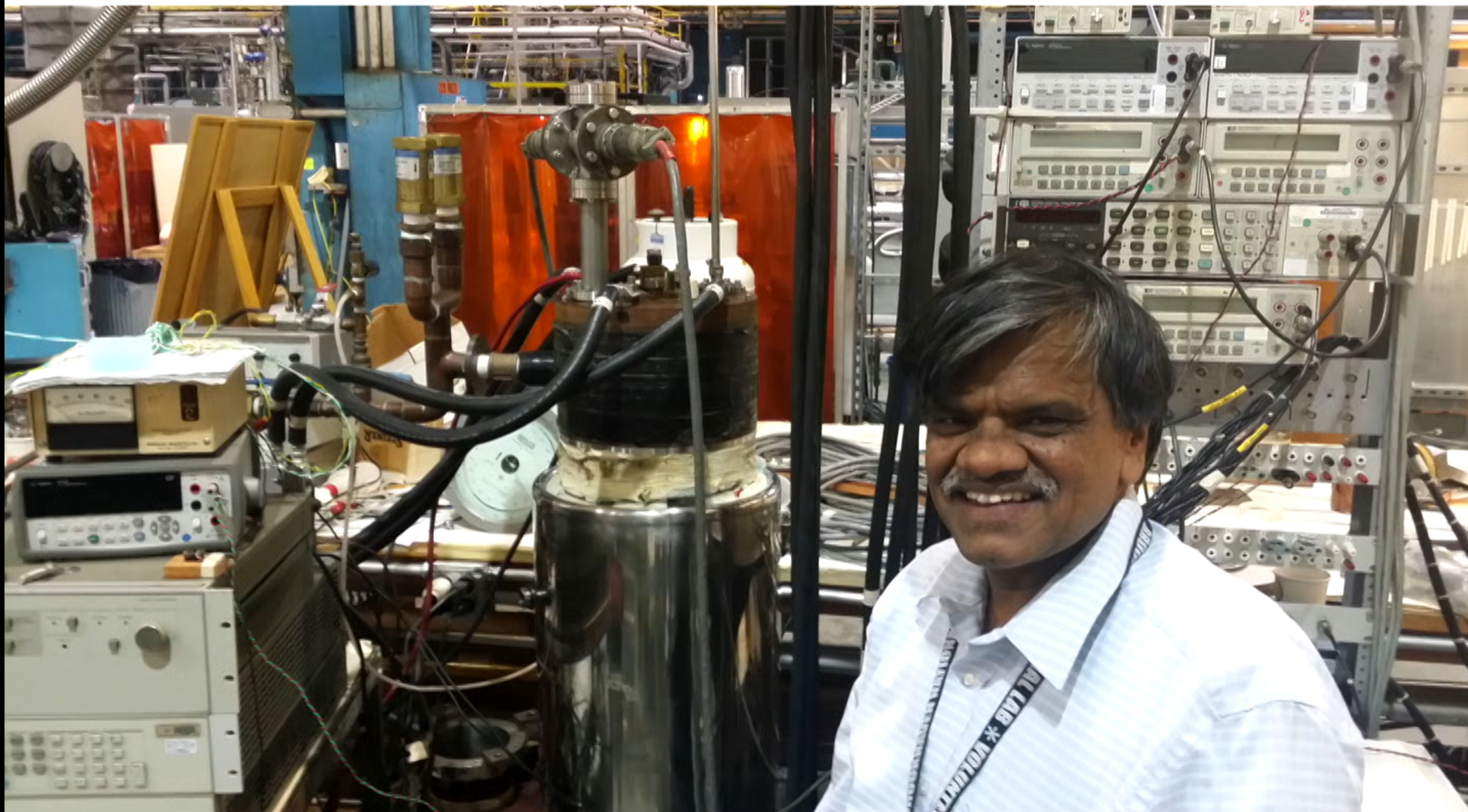
16T max B-field.

This model magnet recently achieved a field of 16.2 T at CERN, twice the nominal field of the LHC dipoles, offering promise for a long-term accelerator-based future for the laboratory.

By Fabiola Gianotti

Over the next five years, key events shaping the future of particle physics will unfold. We will have results from the second run of the LHC, and from other particle and astroparticle physics projects around the world. These will help us to chart the future scientific road map for our field. The international collaboration

Prototype high T_c magnet development with Brookhaven National Laboratory (Dr. R. Gupta, Magnet Division)



Contract approved for 25 T, 10 cm diameter High Tc magnet.

Multi-cavity phase matching demonstrated. Will be applied soon…

Column

자율·독립적인 연구 환경이 끊임없이 동기부여

윤성우 IBS-Young Scientist

78

Multi-cavity phase matching demonstrated.

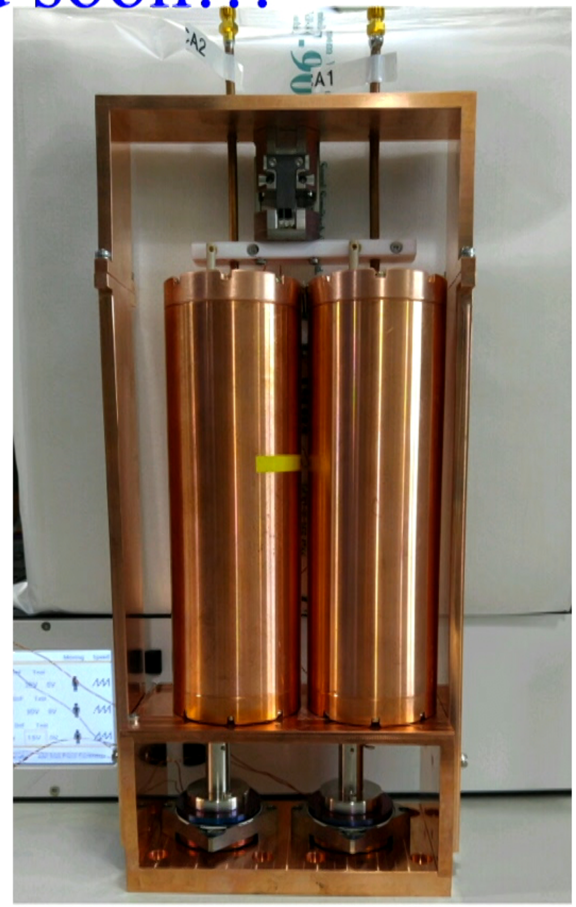
Will be applied soon…

Column

자율·독립적인 연구 환경이
끊임없이 동기부여

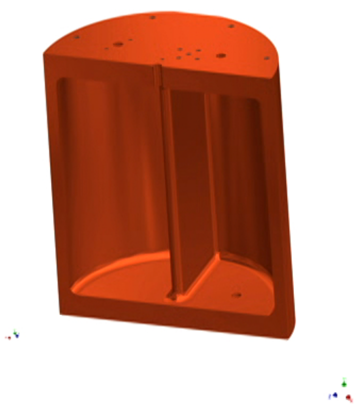
윤성우 IBS-Young Scientist

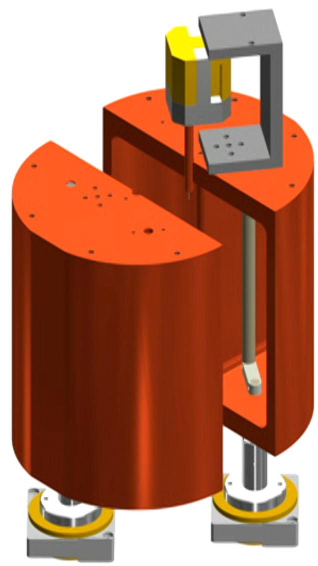
78



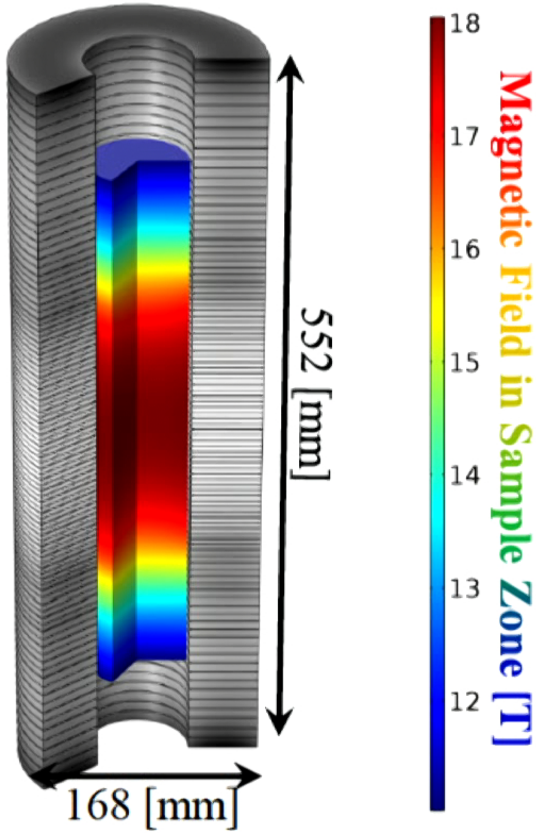
Multi-cavity phase matching demonstrated. Applied to double and four-cell cavities…

SungWoo Youn





18T HTS Magnet (7cm Bore)



A strong B-field and large bore HTS magnet can be commercially produced by SuNAM Co. Ltd.

2G HTS Superconducting Magnet
Magnetic field : 18 Tesla
Dimension: 70 mm ID / 168mm OD
200 mm uniform field (>90%)
552 mm length
Quench free design (No-Insulation winding)
Compact and easy to operate

The magnet delivery by summer 2017

Initial DM axion mass range to probe:
14 μeV to 20 μeV

→ Then apply multiple cavity method to probe higher mass range search

CAPP18T Schedule

Janis He-3 fridge - 18 T HTS magnet integration plan

2017

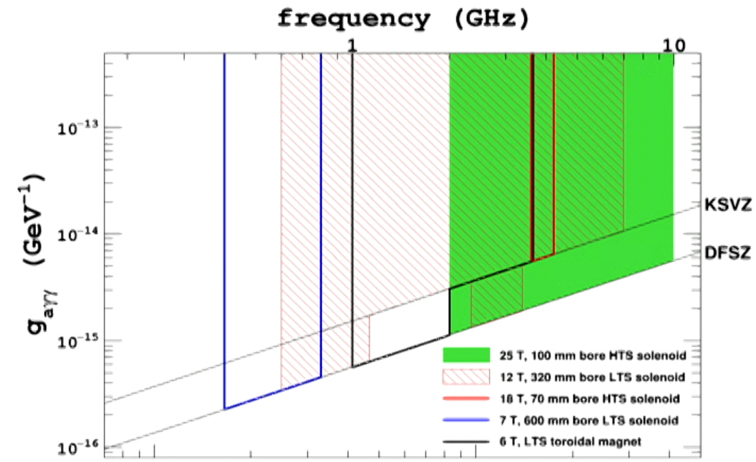
	contents	4	5	6	7	8	9	10	11	12
1	Janis system dimension confirm									
2	Janis modification item & drawing									
3	prepare modification parts									
4	SuNAM 18 T magnet delivery & inspection test									
5	SuNAM 18 T magnet lift out & confirm structure dimension									
6	SuNAM 18 T magnet separate with mag. support									
7	Janis insert lift out from cryostat & re-check dimension									
8	Janis 9 T mamgnet detach from top-plate									
9	250 A Current Lead install on Janis top-plate for 18 T magnet									
10	18 T magnet install on Janis top-plate									
11	Janis cryostat-18 T system cool-down & current charge test									
12	Janis cryostat-18 T system magnetic field mapping									
13	Janis He-3 fridge IVC replace for 18 T magnet									
14	Janis He-3 fridg-18 T system integration									
15	Janis He-3 fridg-18 T system cooling & performance test									
16	Install field cancellation coil on Janis He-3 fridg									
17										
18	Janis He-3 system performance test									
19	Janis He-3 system + cavity test operation									

Initial test and commissioning

Assembly

Magnet schedule

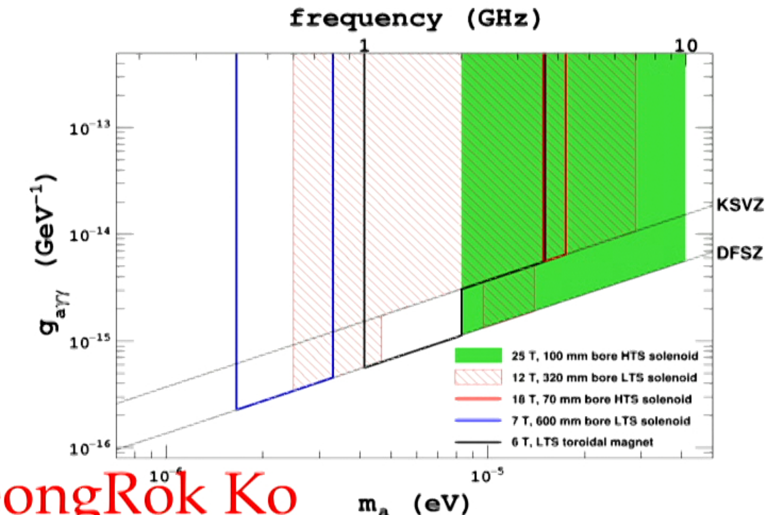
The small toroidal magnet schedule depends on available funding



Slide: ByeongRok Ko

Magnet schedule

The small toroidal magnet schedule depends on available funding



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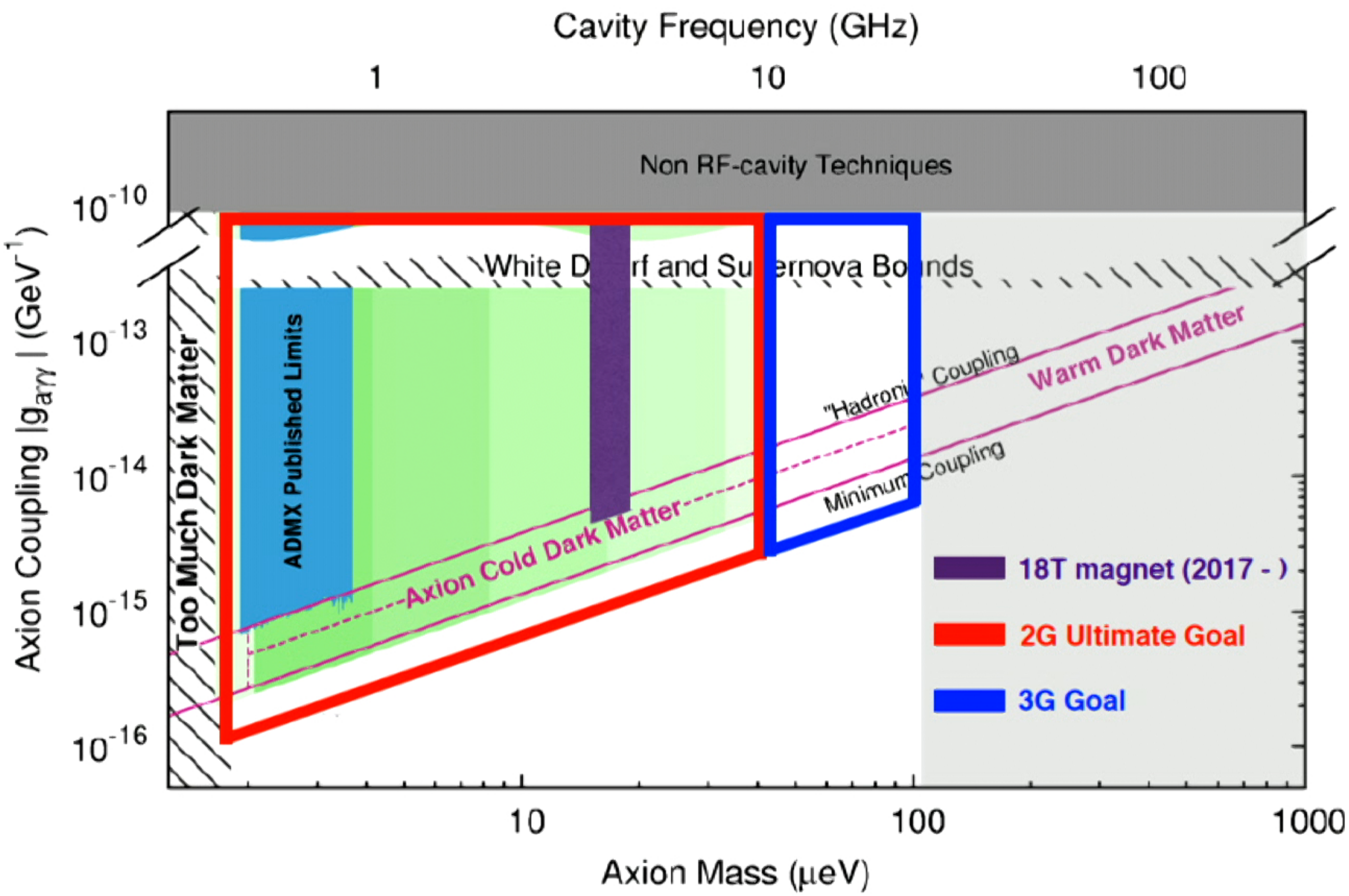
Sensitivity



Summary

- Muon g-2 is online! Major challenge to SM. Significant improvements in statistical and systematic errors.
- Dark matter is a great mystery and challenge. IBS/CAPP is established to answer whether axions are the dark matter of our universe and develop the best hadronic (proton and deuteron) EDM experiments.
- New powerful magnets/new techniques in the axion dark matter search
- Within the next five years we will be reaching (publishing?) the theoretical axion parameters in the mass range possible by microwave cavities. Within next ten years major progress!
- Proton EDM exp. and ARIADNE probing axion Physics in unique ways!