SIGRAV school

2/19/25

Vietri, Italy, 2/16/2024
S. Schlamminger
National Institute of Standards and Technology

About me

NIST

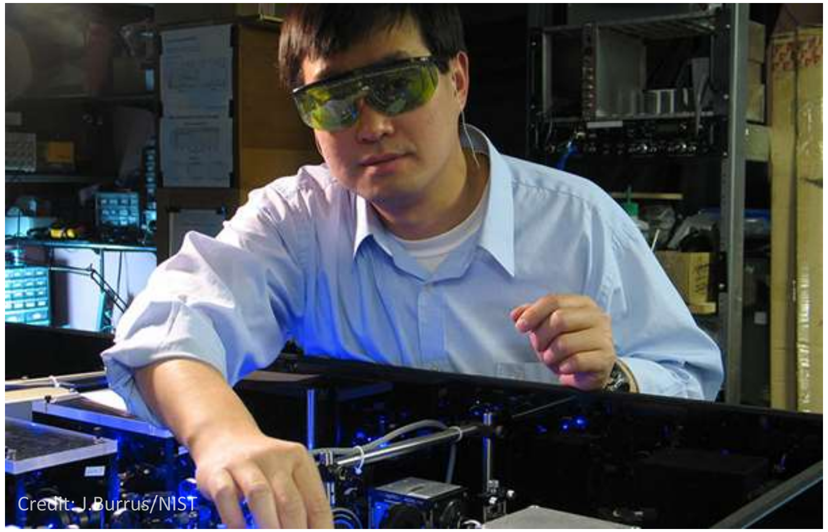
- 1998 -2002 PhD at the University of Zurich:
  - on the determination of *G*
- 2003- 2010 post-doc at the University of Washington
  - Equivalence principle
  - Noise measurements/ patch fields and such for LIGO
  - Inverse square law test
- 2011 – 2017 physicist National Institute of Standards and Technology
  - Built a Kibble balance that ultimately led to the revision of the SI
- 2018 – 2019 Prof. at the University of Applied Science in Regensburg
- 2019 – today National Institute of Standards and Technology
  - Table top Kibble balances
  - Measurement of *G*
  - Impedance metrology

About the four lectures

1. Traceability of mass and force measurements.
   - The SI,
   - how well can we measure a Newton
2. Source masses
   - What do you have to pay attention to
3. Thermal noise and inelastic effects
   - How they come about and
   - How the limit the measurement
4. Practical tips and experiences
   - big G measurements
   - EP measuremens
   - Inverse square law measurements

NIST Mission

To promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life



Measurements essential to commerce, trade, and innovation

Federal role established in the U.S. Constitution

NIST AT A GLANCE

Industry's National Laboratory

3,400+
FEDERAL EMPLOYEES

5
NOBEL PRIZES

2 CAMPUSES
GAITHERSBURG, MD [HQ]
BOULDER, CO

3,500+
ASSOCIATES

10
COLLABORATIVE INSTITUTES

400+
BUSINESSES USING NIST FACILITIES

ManufacturingUSA

16
NATL OFFICE FOR MANUFACTURING INSTITUTES

51
MANUFACTURING EXTENSION PARTNERSHIP CENTERS

U.S. BALDRIGE PERFORMANCE EXCELLENCE PROGRAM

NIST Joint Institute and Center Locations

Gaithersburg, MD
Boulder, CO

Joint Institutes and Centers

National Cybersecurity Center of Excellence

Institute for Bioscience & Biotechnology Research

Joint Institute for Quantum Computer Science

Joint Quantum Institute

JILA

Hollings Marine Laboratory

Brookhaven National Laboratory

Joint Initiative for Metrology in Biology

Atomic Clock Signal Stations

NIST Kauai HI WWVH

NIST Ft. Collins CO WWV

NIST Centers of Excellence

Forensic Science

Disaster Resilience

Advanced Materials

NIST Laboratory Programs

Material Measurement Laboratory

Physical Measurement Laboratory

Engineering Laboratory

Information Technology Laboratory

Communication Technology Laboratory

NIST Center for Neutron Research

NIST | NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

NIST

Physical Measurement Laboratory .. 6 Laboratory Programs

Quantum Measurement Division .. 10 Divisions

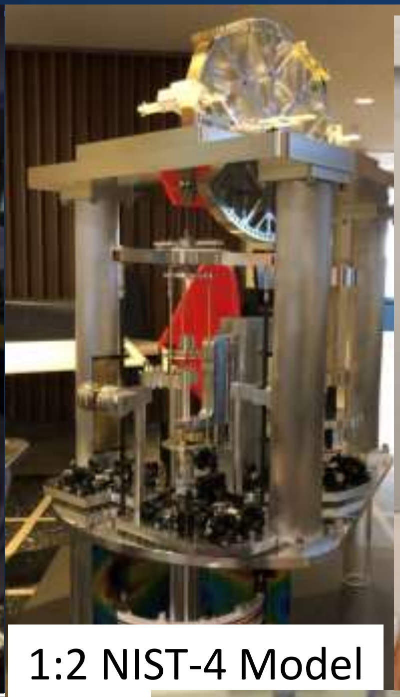
Fundamental Electrical Measurement Group .. 7 Groups

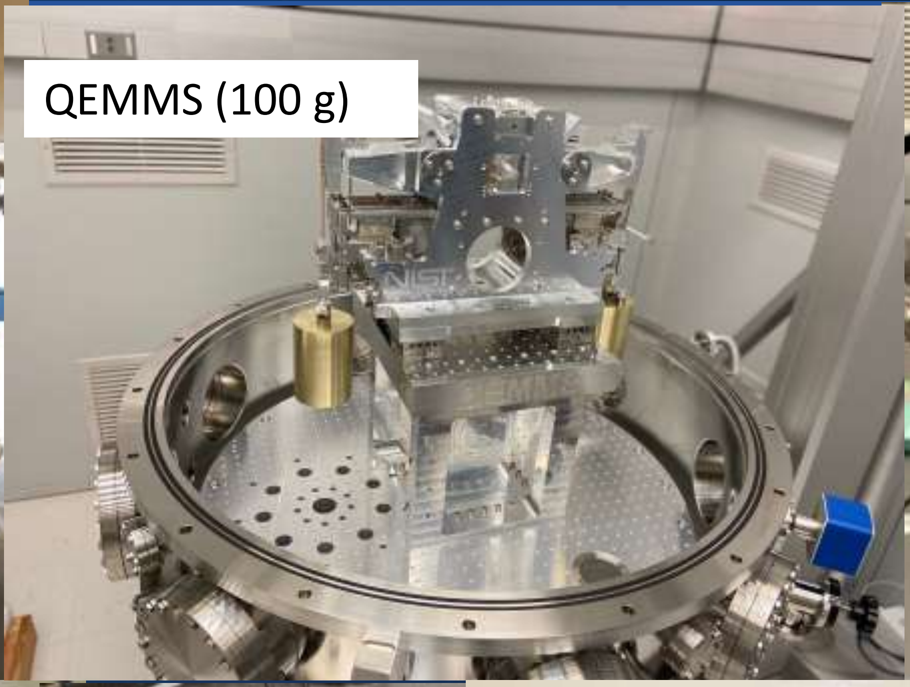
Precision Electro Mechanical Experiments .. 5 Projects

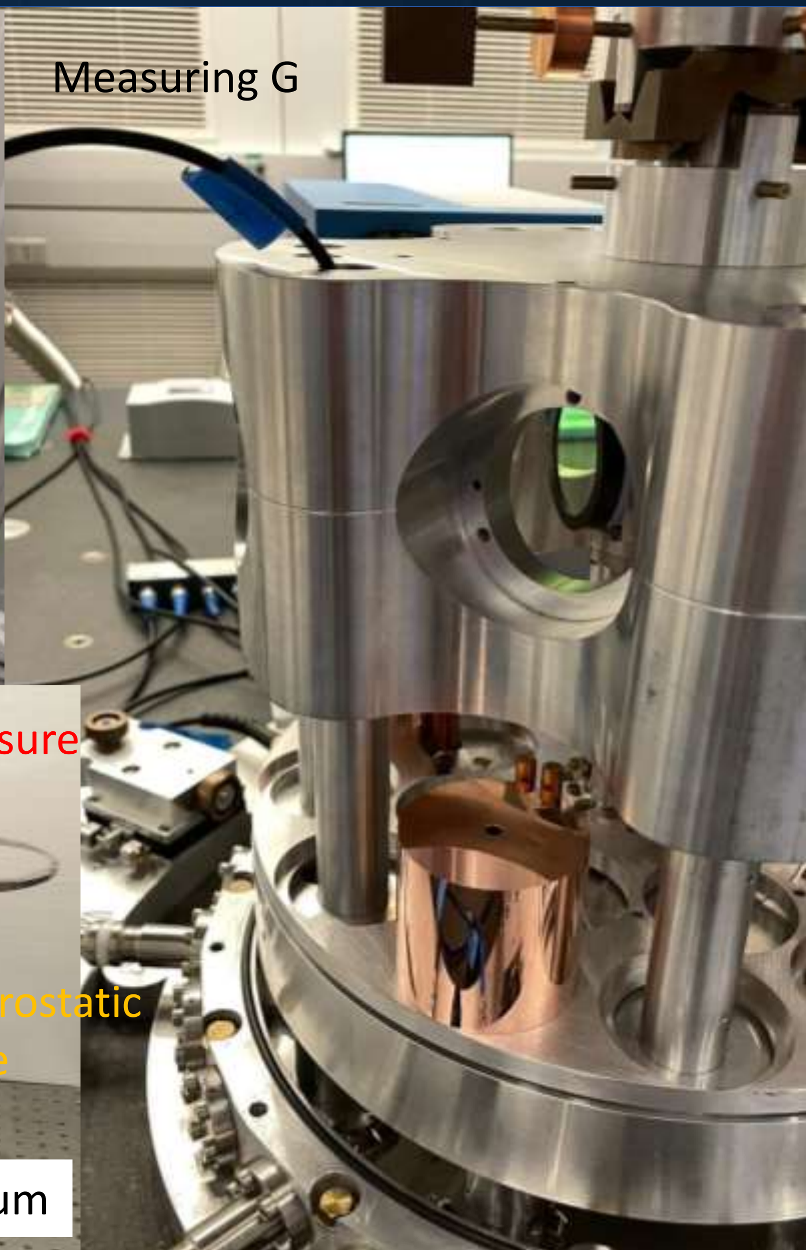
NIST's PREME* Team

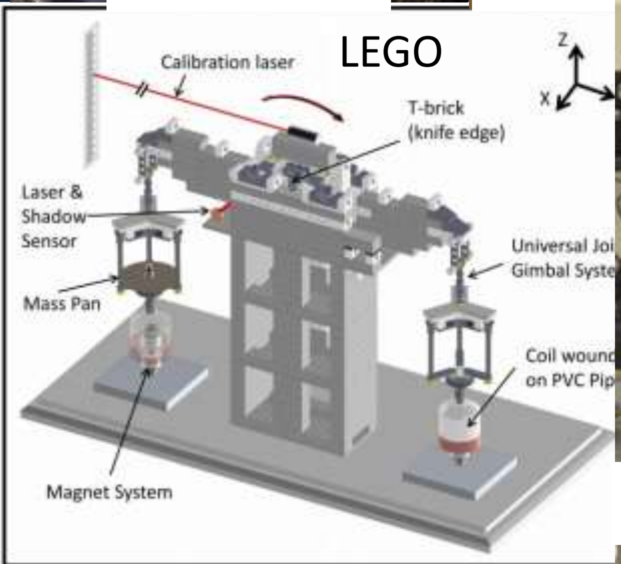
* Precision Electro-Mechanical Experiments.

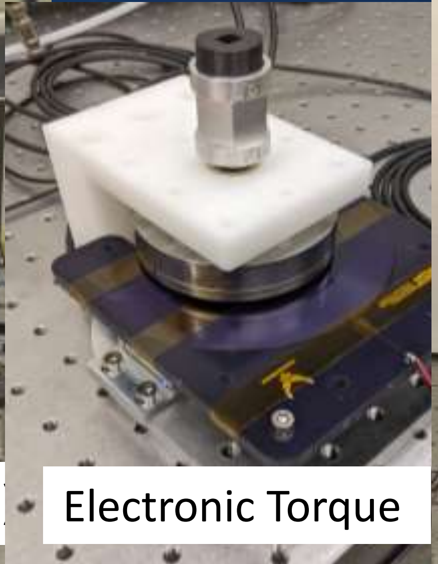
Typical Experiments

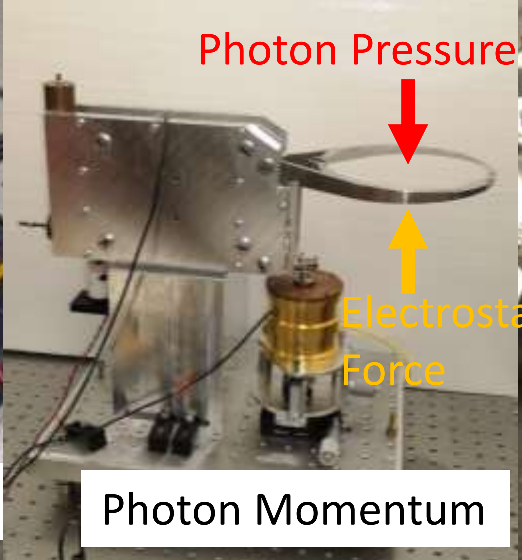












Measurement process

Quantity

Unit

$$l = 1.2\ \mathrm{m}$$

Numerical value

$$l = \{l\}_m\ [\mathrm{m}]$$

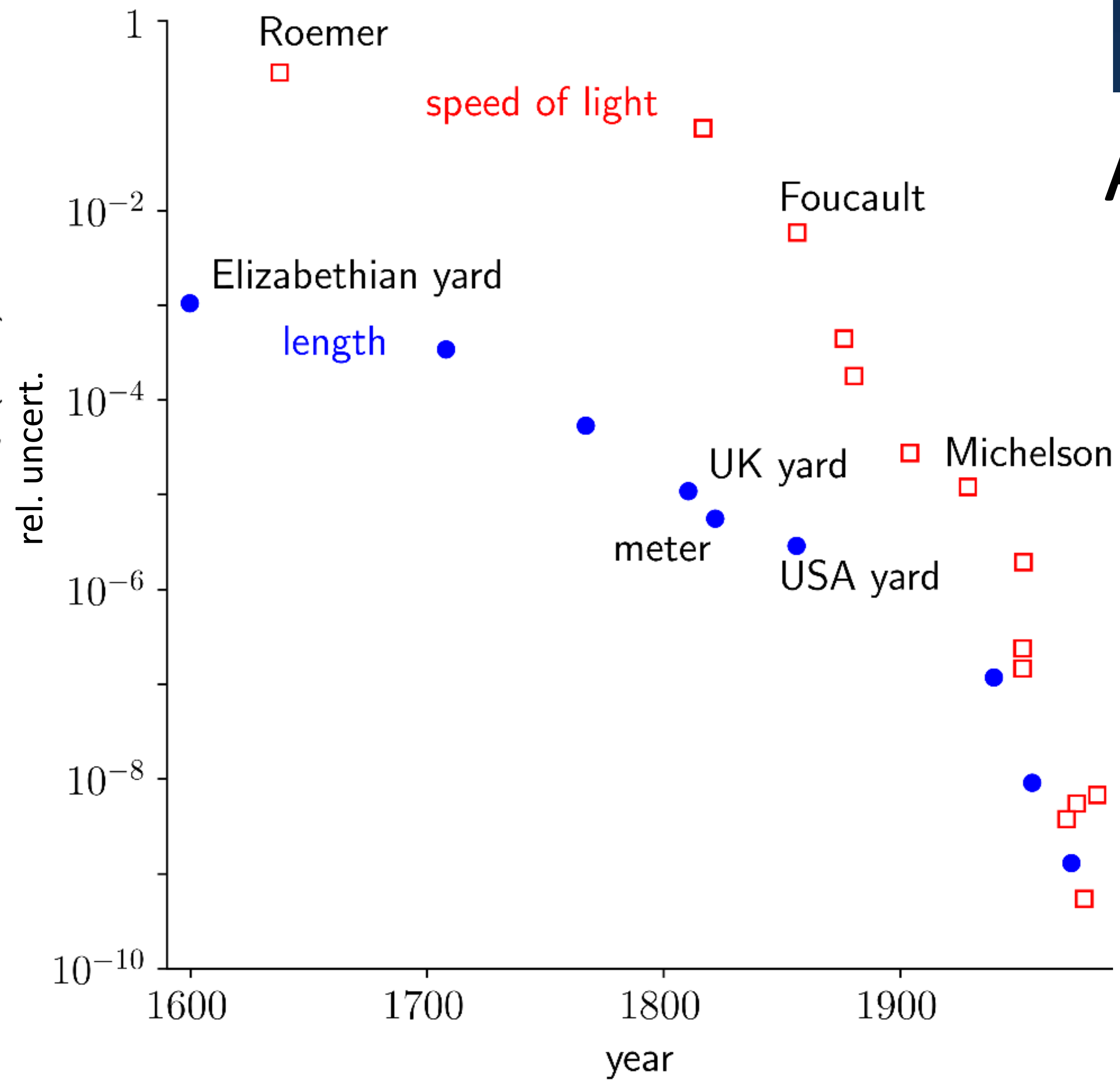
$$l = 4\ \mathrm{ft}$$

System of units (before 2019)

am·pere

That constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed one metre apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newtons per metre of length.

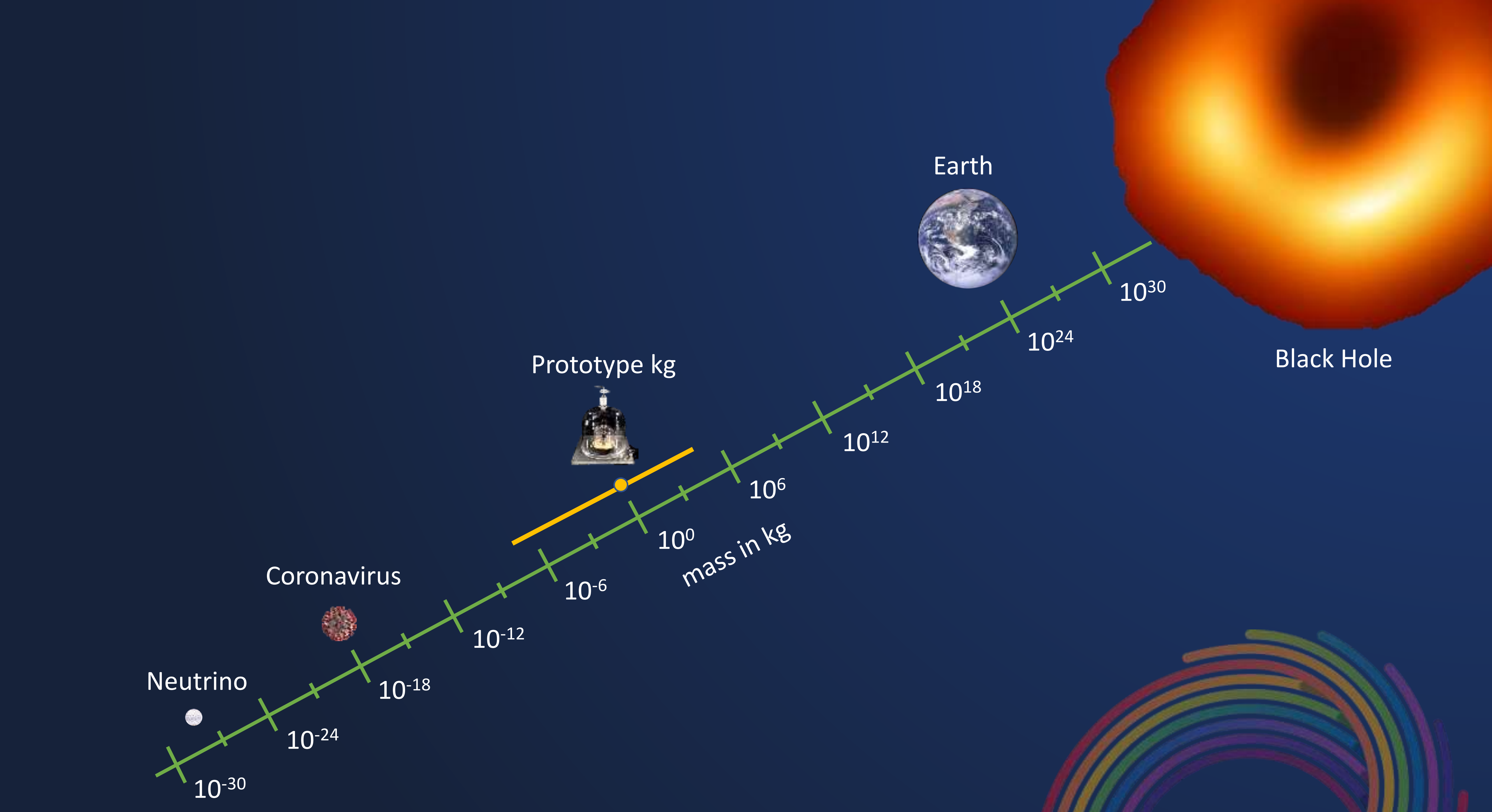
A unit system is dynamic



Fundamental constants

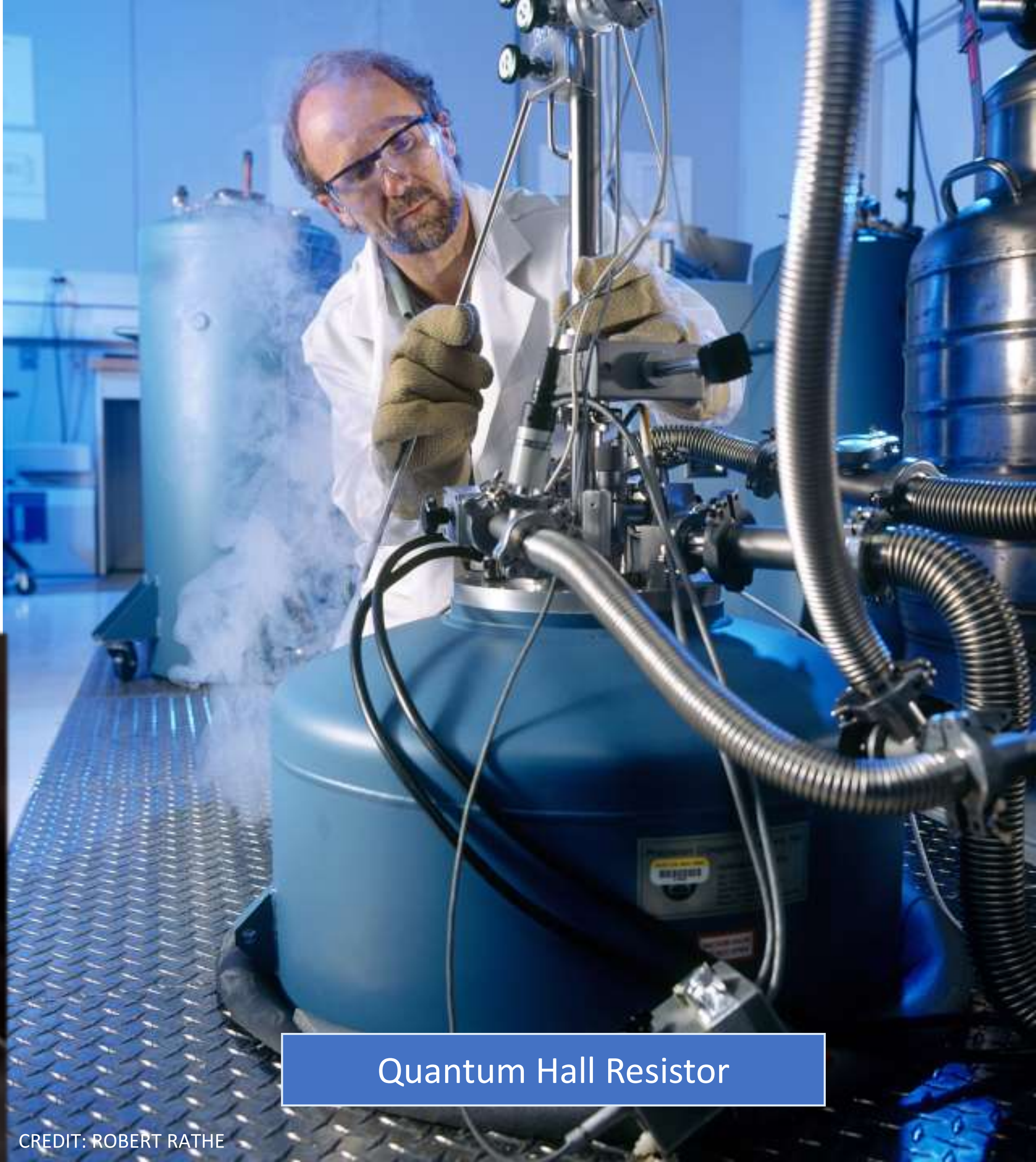
are:

- scale invariant
- independent of space & time



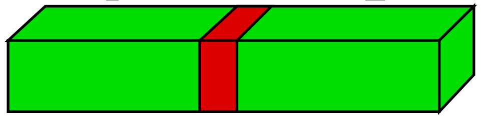
CREDITS: NASA; NEVEN KRCMAREK ON UNSPLASH

Josephson Voltage Standard


Quantum Hall Resistor

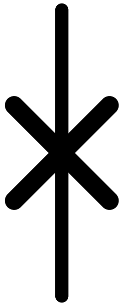
CREDIT: ROBERT RATHE

$\Psi_1 = A_1 e^{\theta_1}$ $\Psi_2 = A_2 e^{\theta_2}$

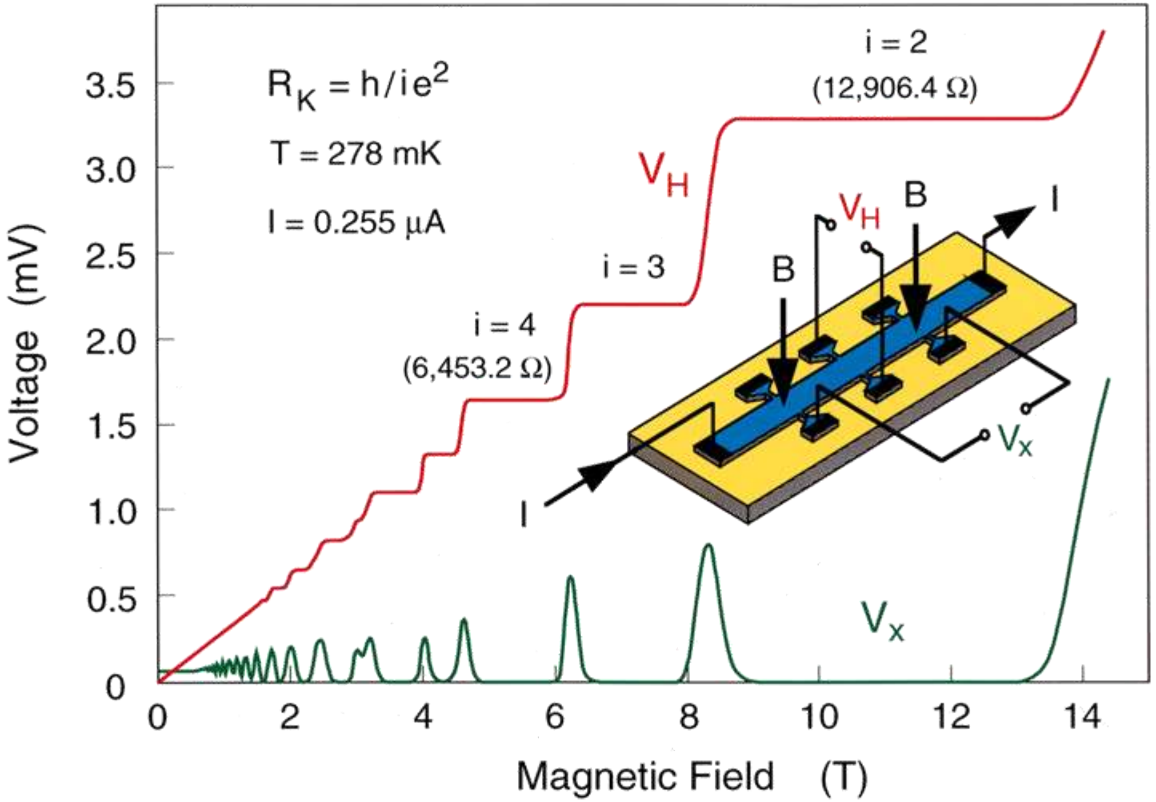


$\phi = \theta_2 - \theta_1$

$=$



$$V = \frac{h}{2e} f$$



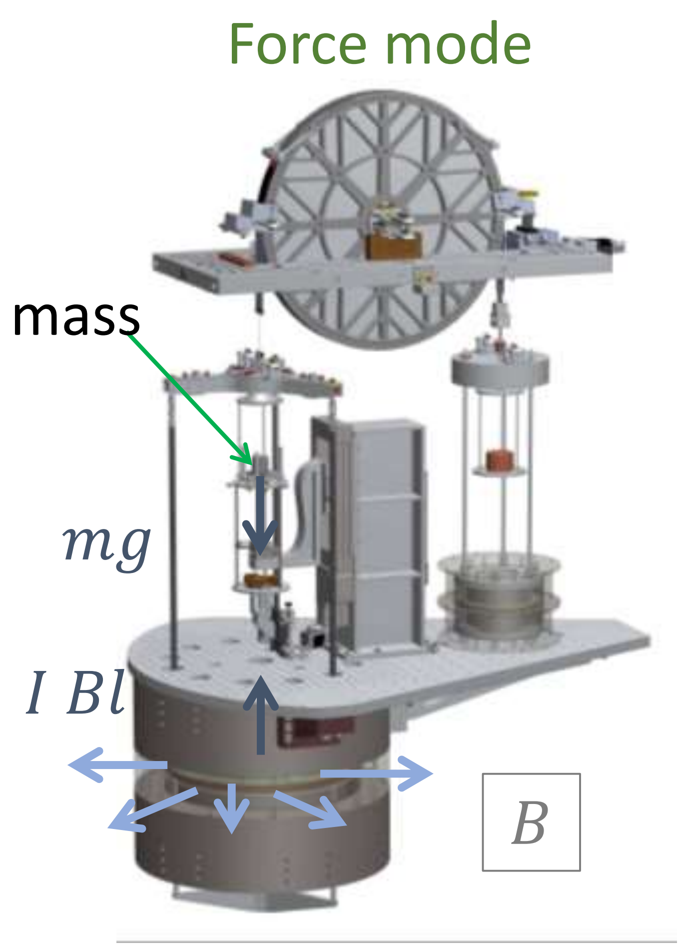
$$R_H = \frac{V_H}{I} = \frac{B}{eN_s}$$

$$N_s = \left(\frac{eB}{h}\right) i$$

$$R_H = \left(\frac{h}{ie^2}\right)$$

$$P_{el} = V^2 \; R^{-1}$$

Watt balance – Kibble balance

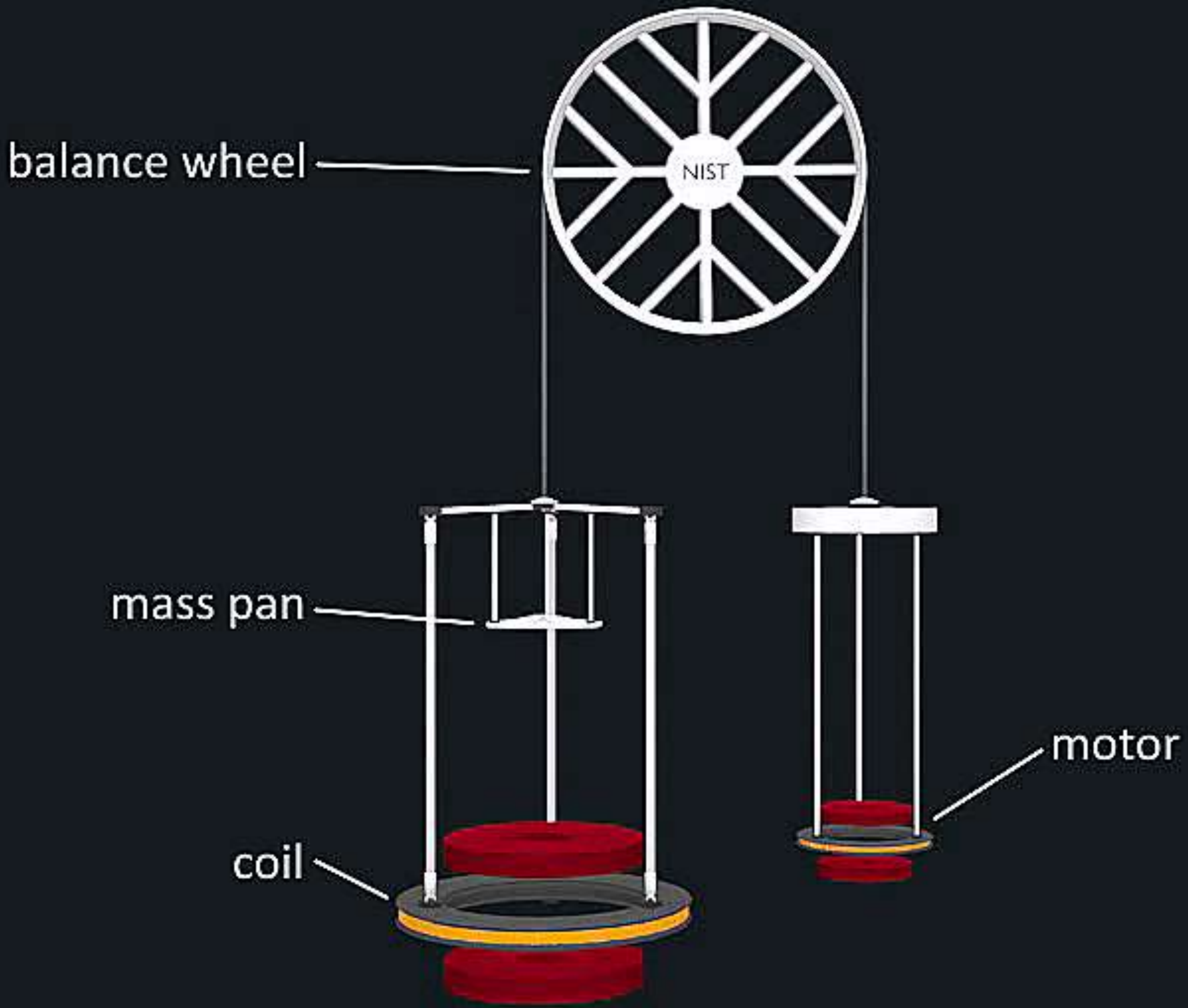


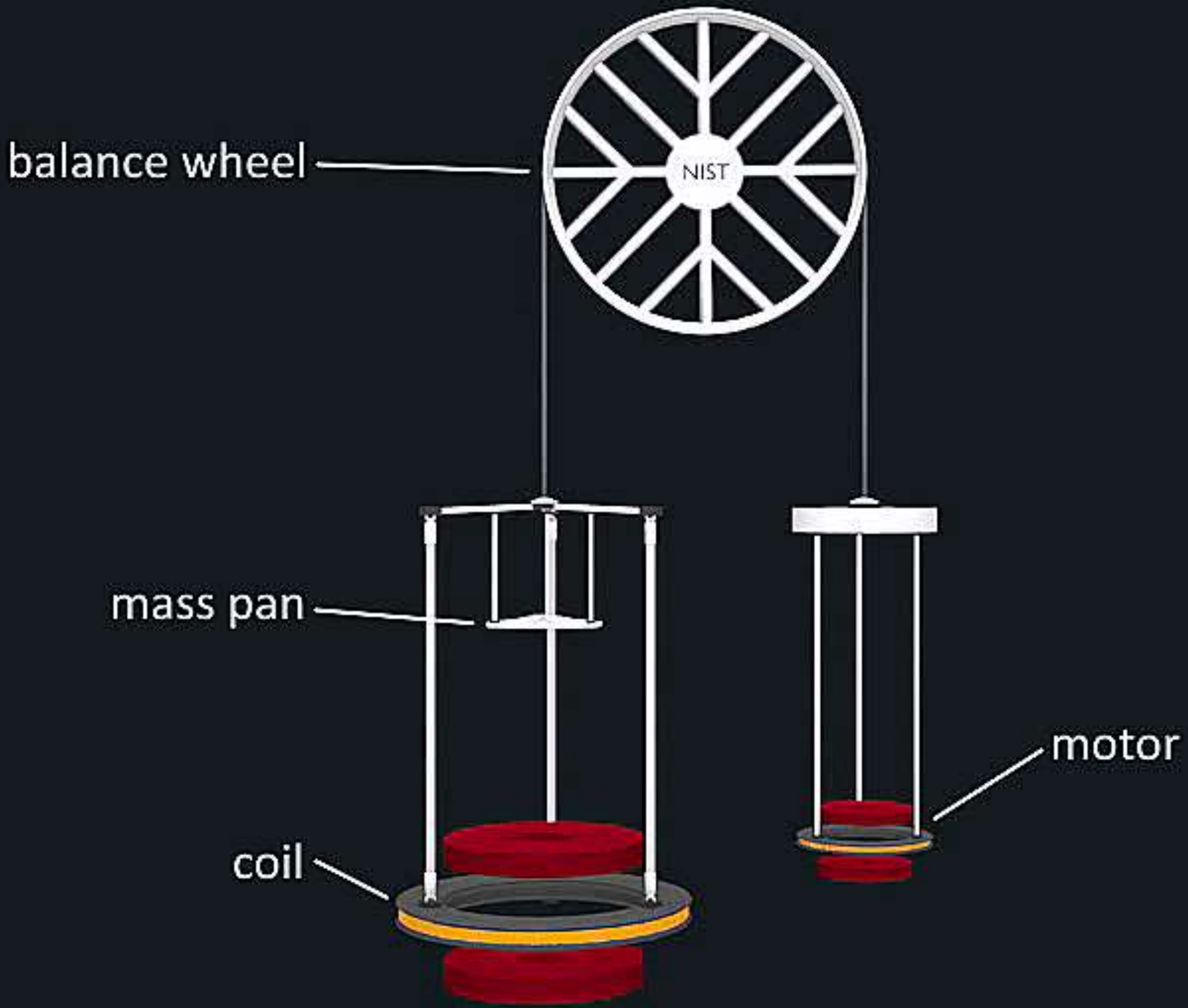
$$mg = I\,Bl \qquad U = v\,Bl$$

$$\frac{mg}{U} = \frac{I}{v}$$

$$mgv = UI$$

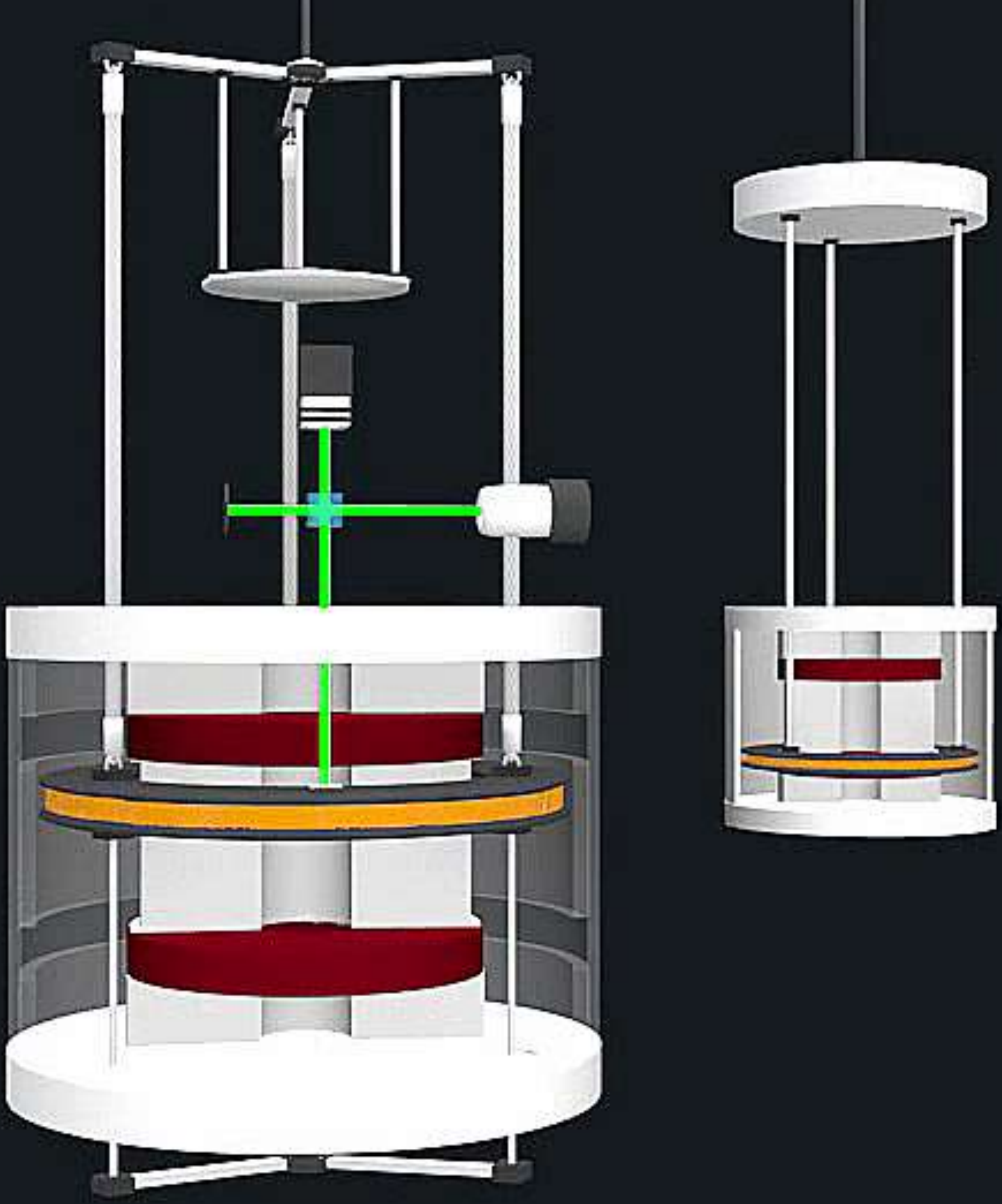
$$mgv = \frac{n\,ni}{4} f_1 f_2 h$$

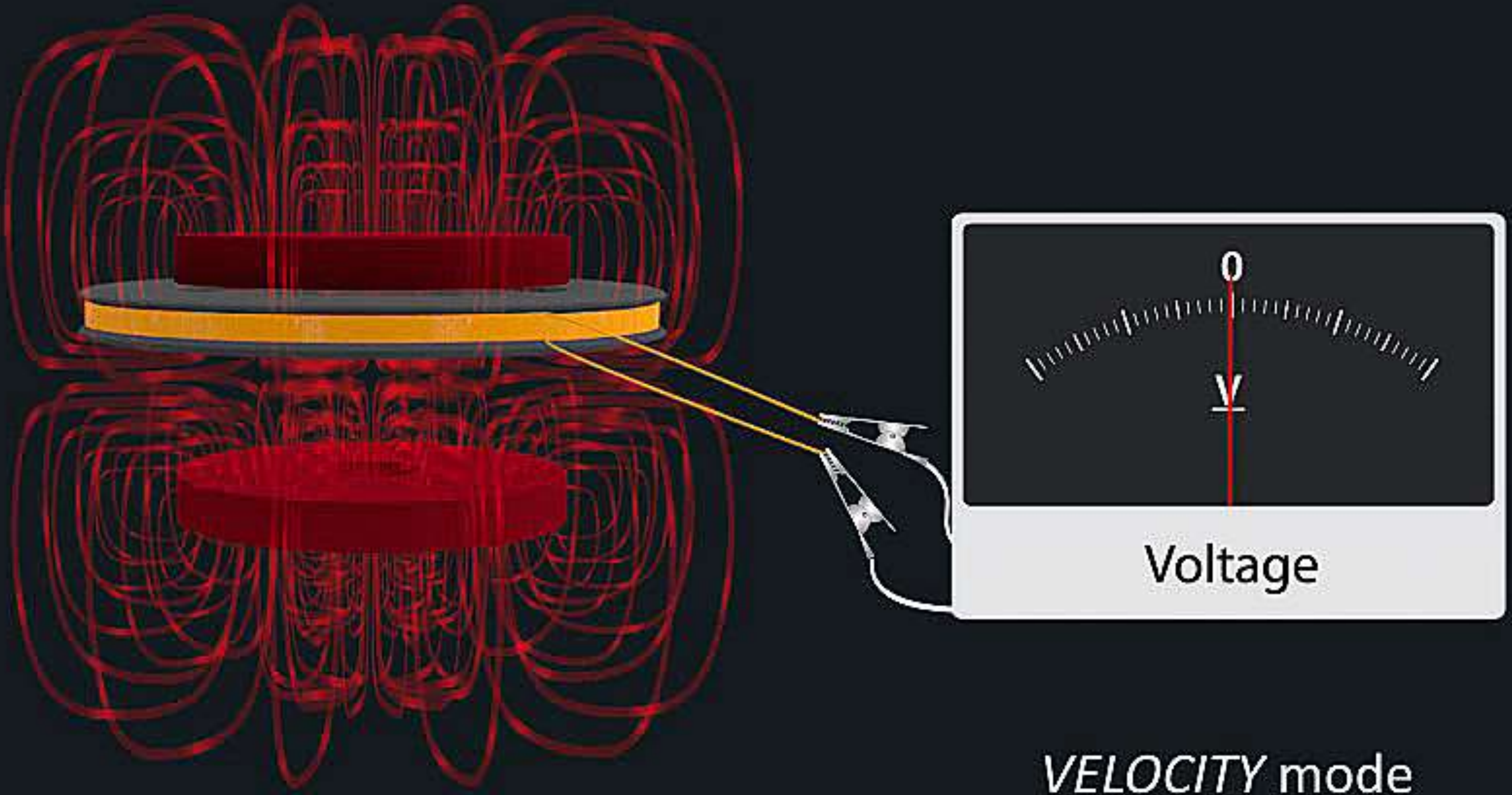

balance wheel
NIST
mass pan
motor
coil


balance wheel
NIST
mass pan
motor
coil

VELOCITY mode

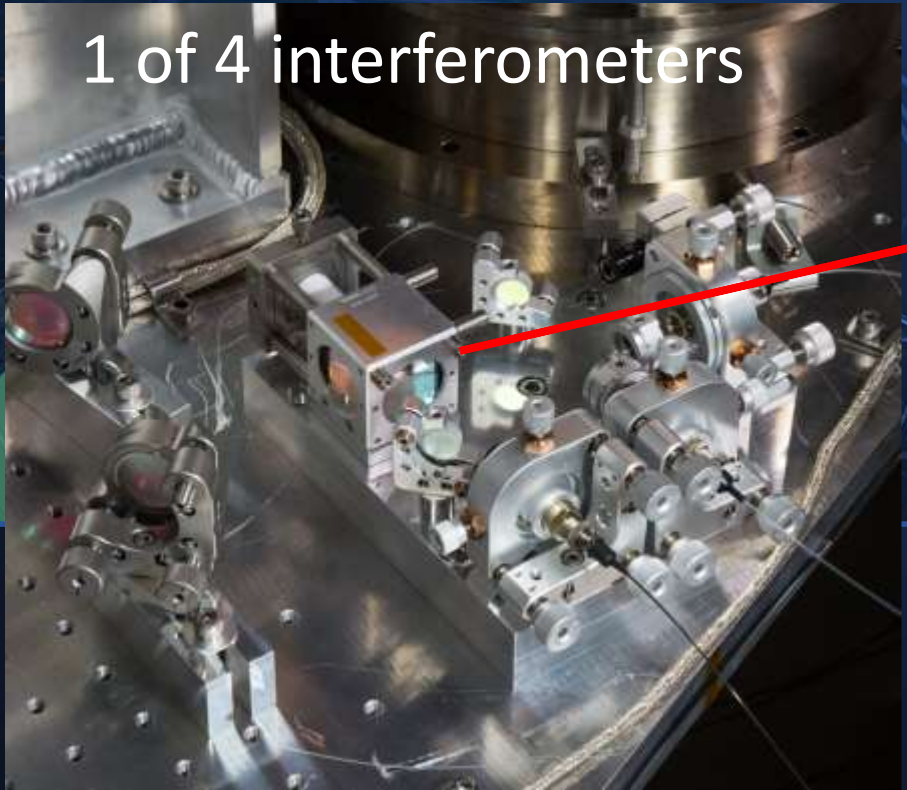
flux

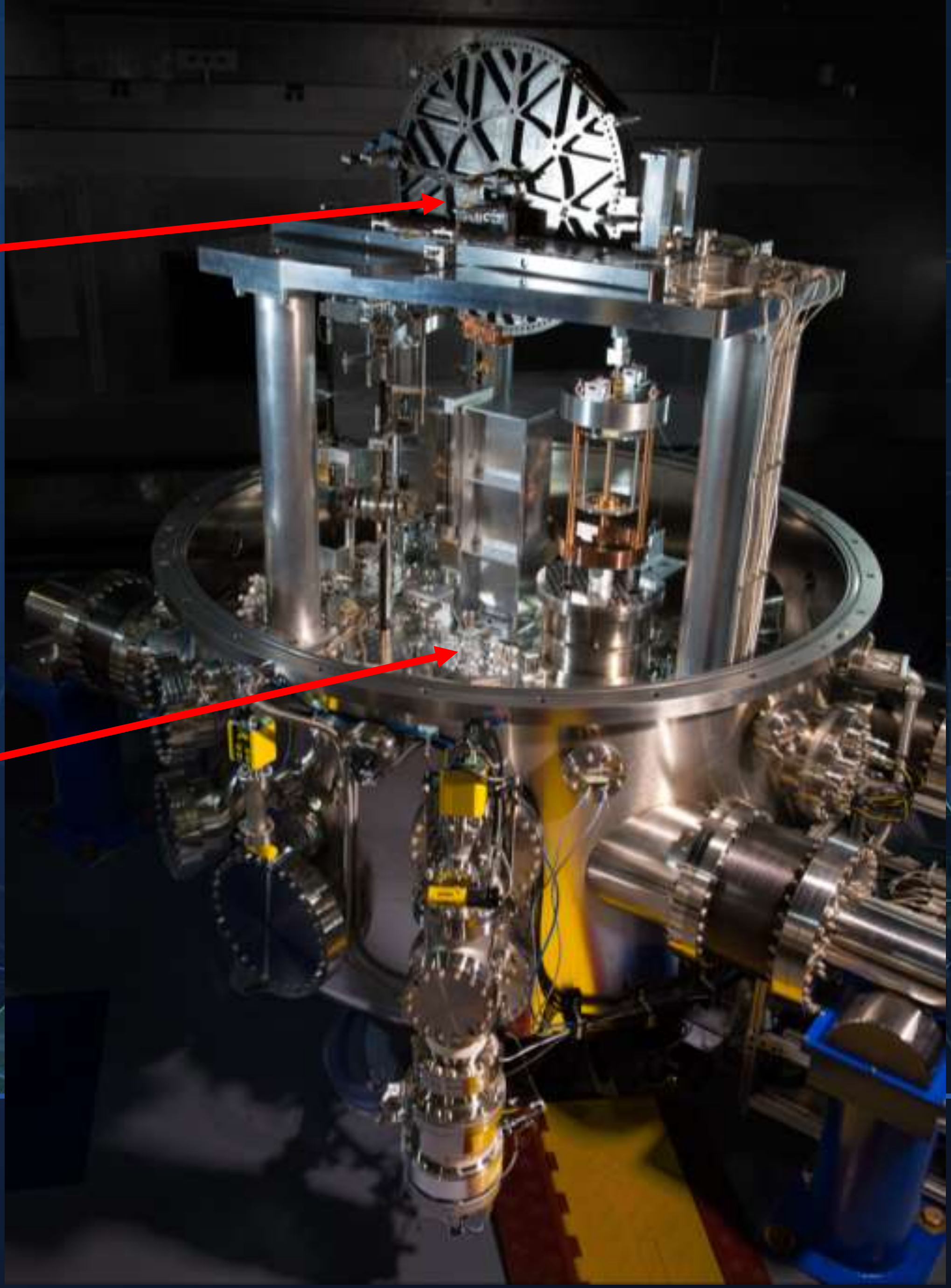


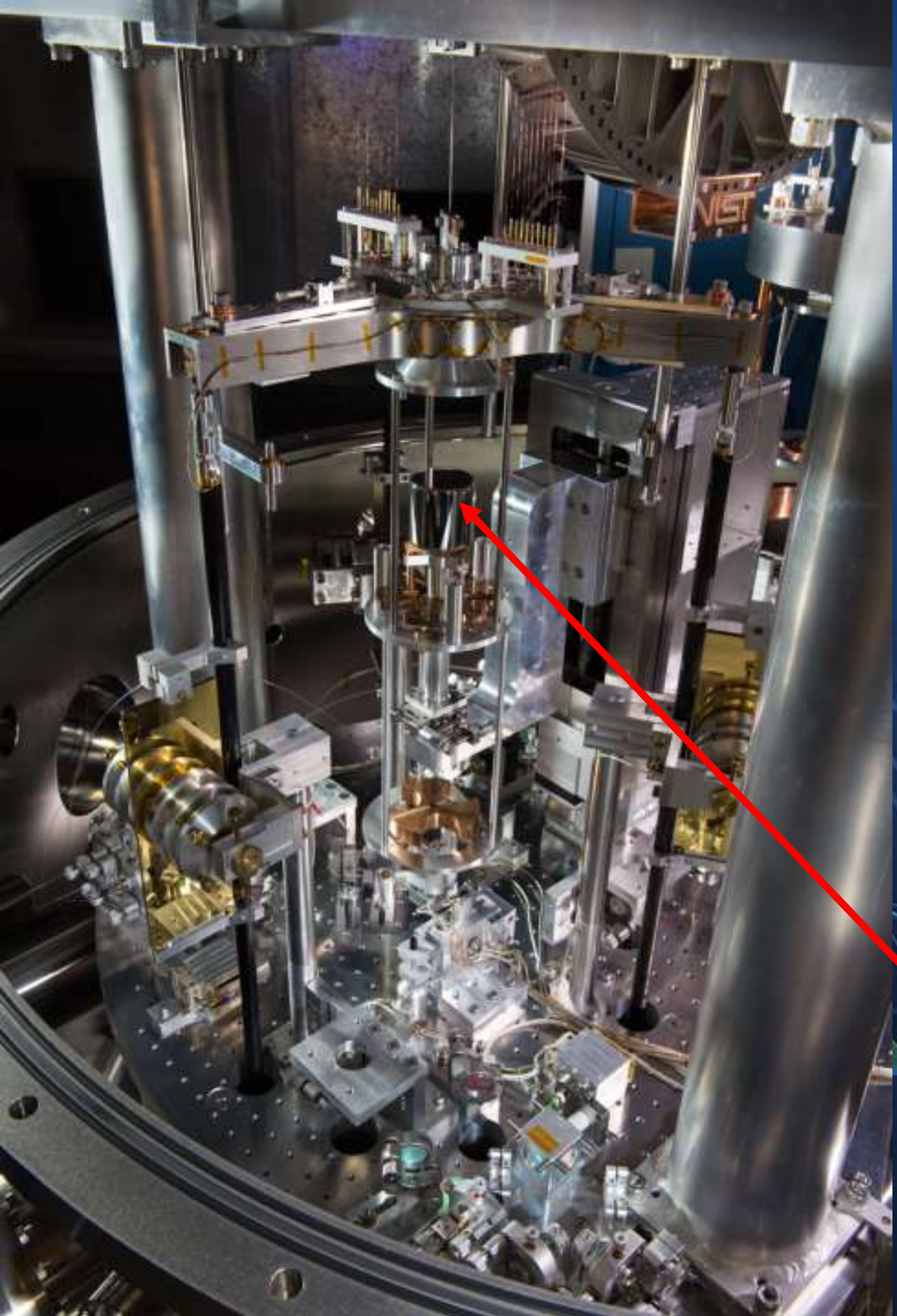


VELOCITY mode

knife edge as a pivot



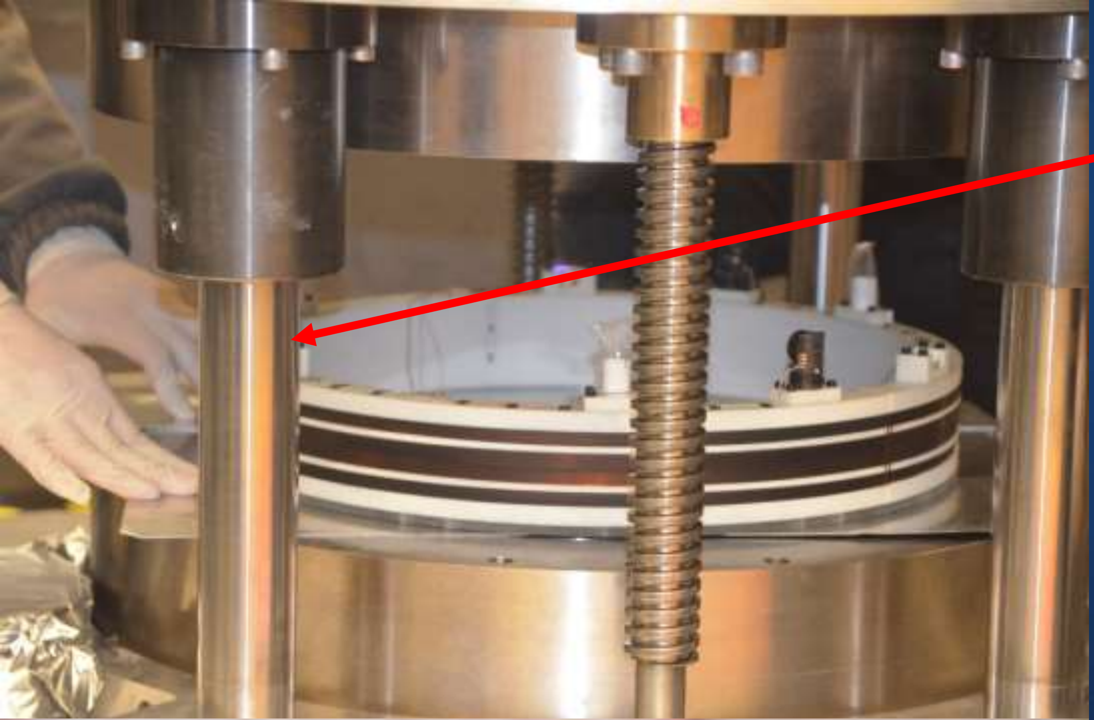




Busy main mass side

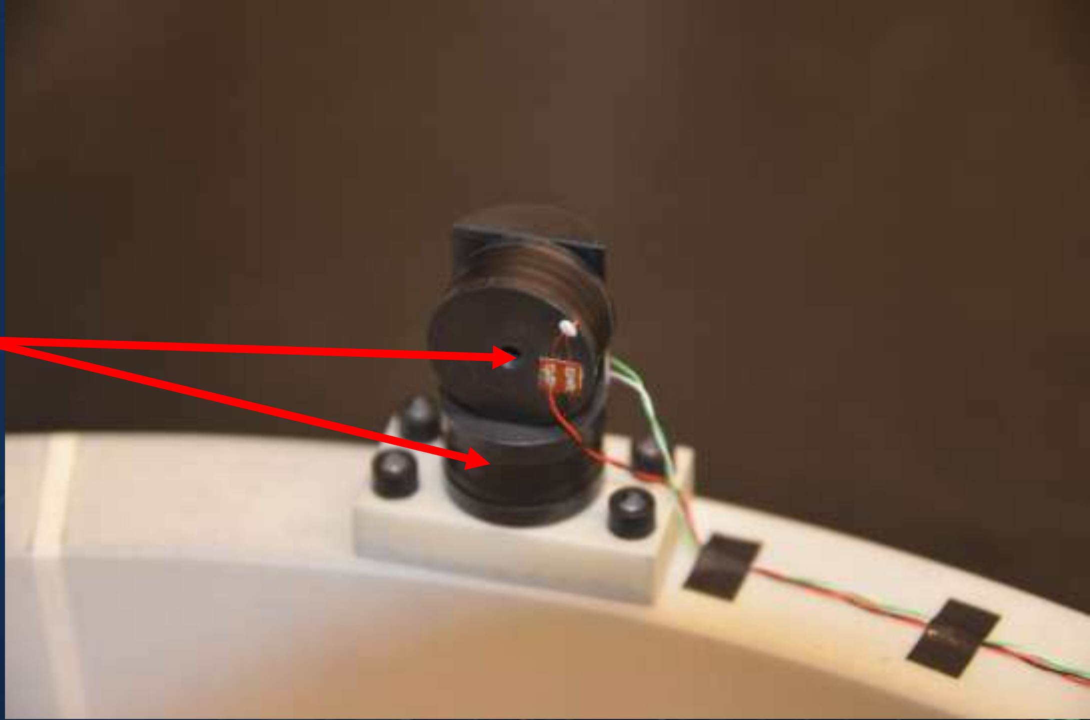
Counter mass side with dead weight and motor to move coil

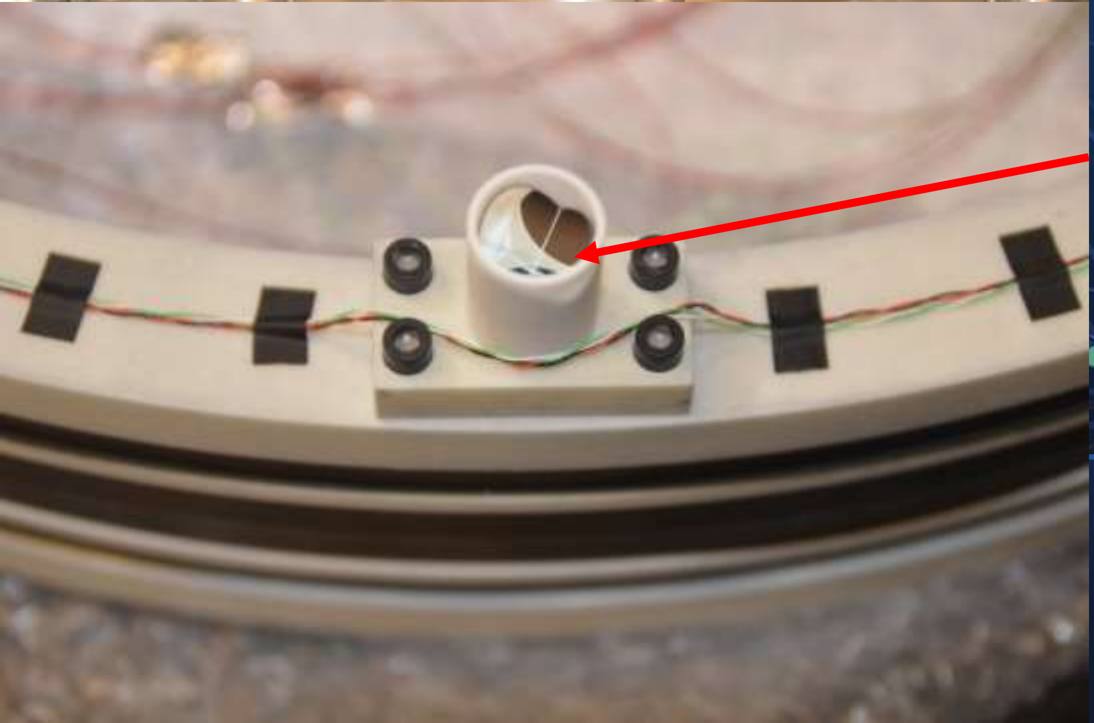
PtIr mass



Installation of the coil

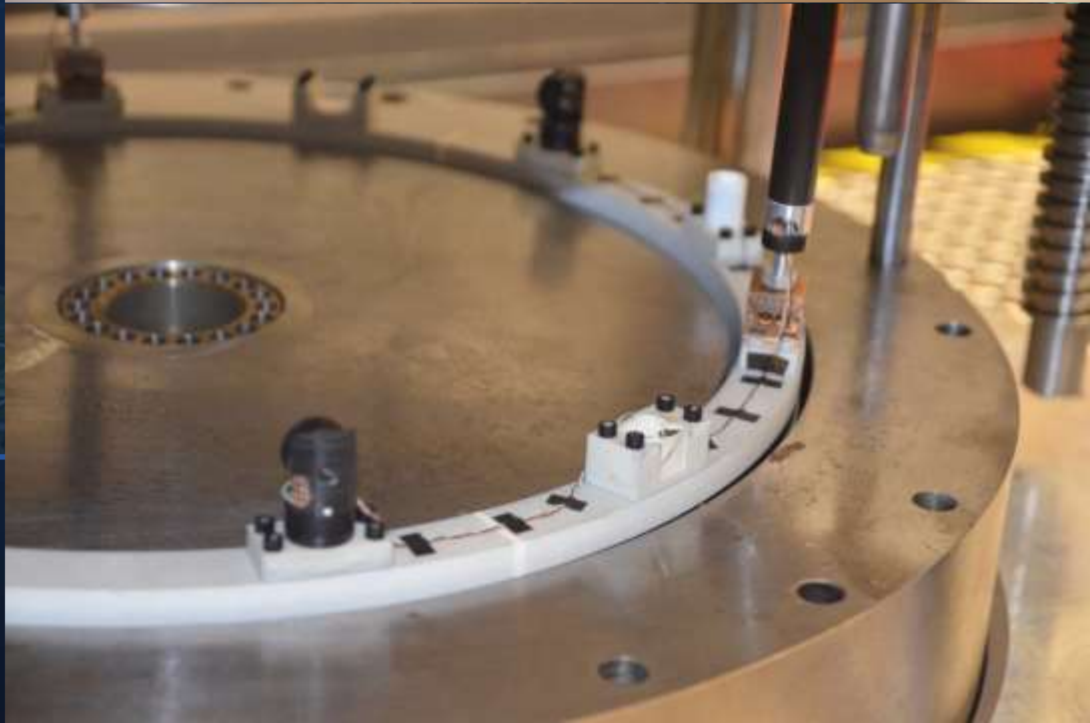
2 of 6 coils for x/y and Θ_x/Θ_y damping

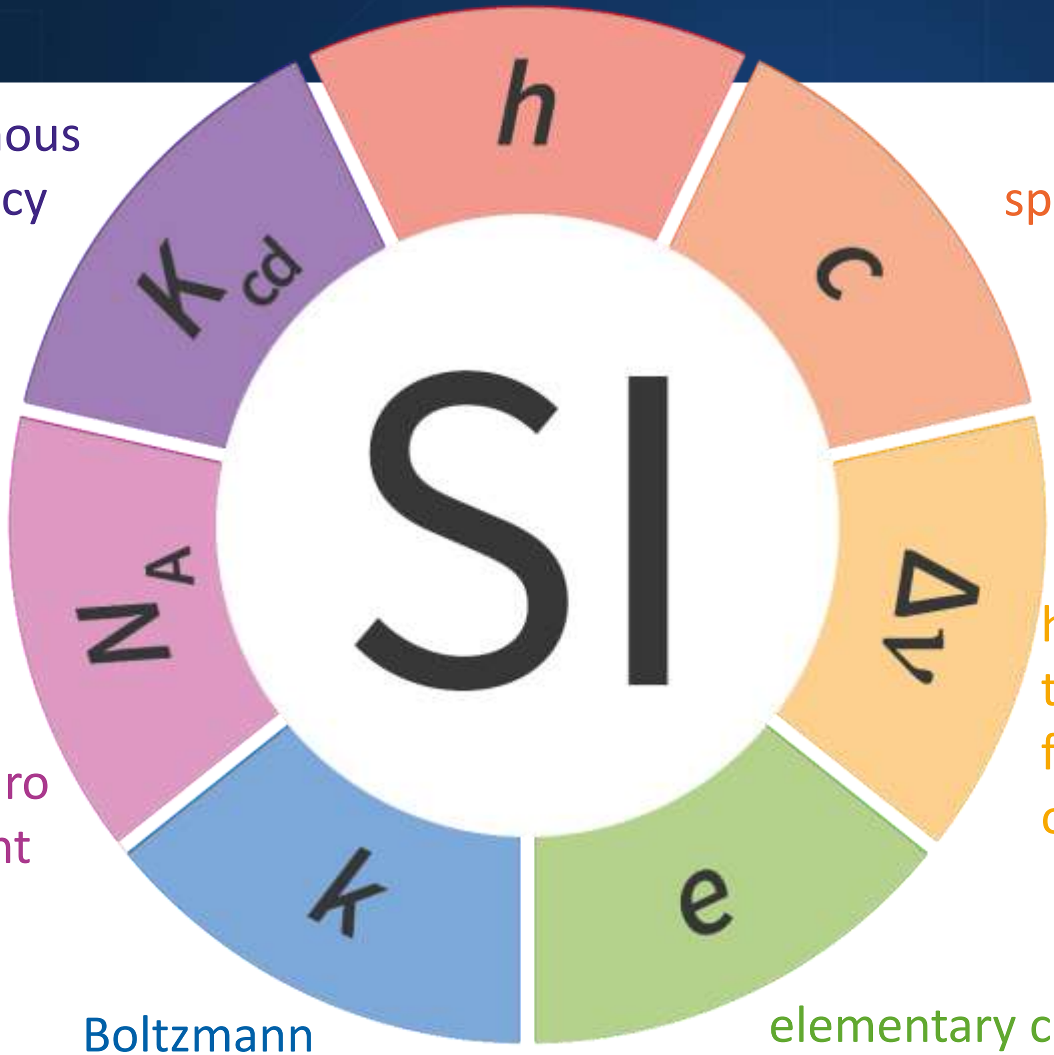




1 of 3 corner cubes for inter-ferometer

Coil inside air gap





System of units since 5/20/2019

A Tale of g and his brother

$$g = 9.797\,724\,52(4)\ \frac{\mathrm{m}}{\mathrm{s}^2}$$

$$G = 6.674\,30(15) \times 10^{-11}\,\frac{\mathrm{m}^3}{\mathrm{kg\ s}^2}$$

Why?

measure an acceleration

measure a force

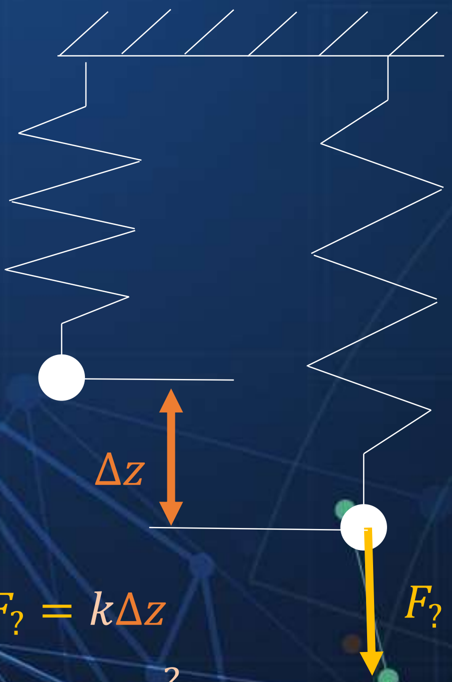
How to measure an unknown force

Measure the effect of the force

m $F_?$

$F_? = m\,a$

measure a and infer $F_?$



$F_? = k\Delta z$

$k = m\,\omega^2$

Compensate the force with a known force F_c

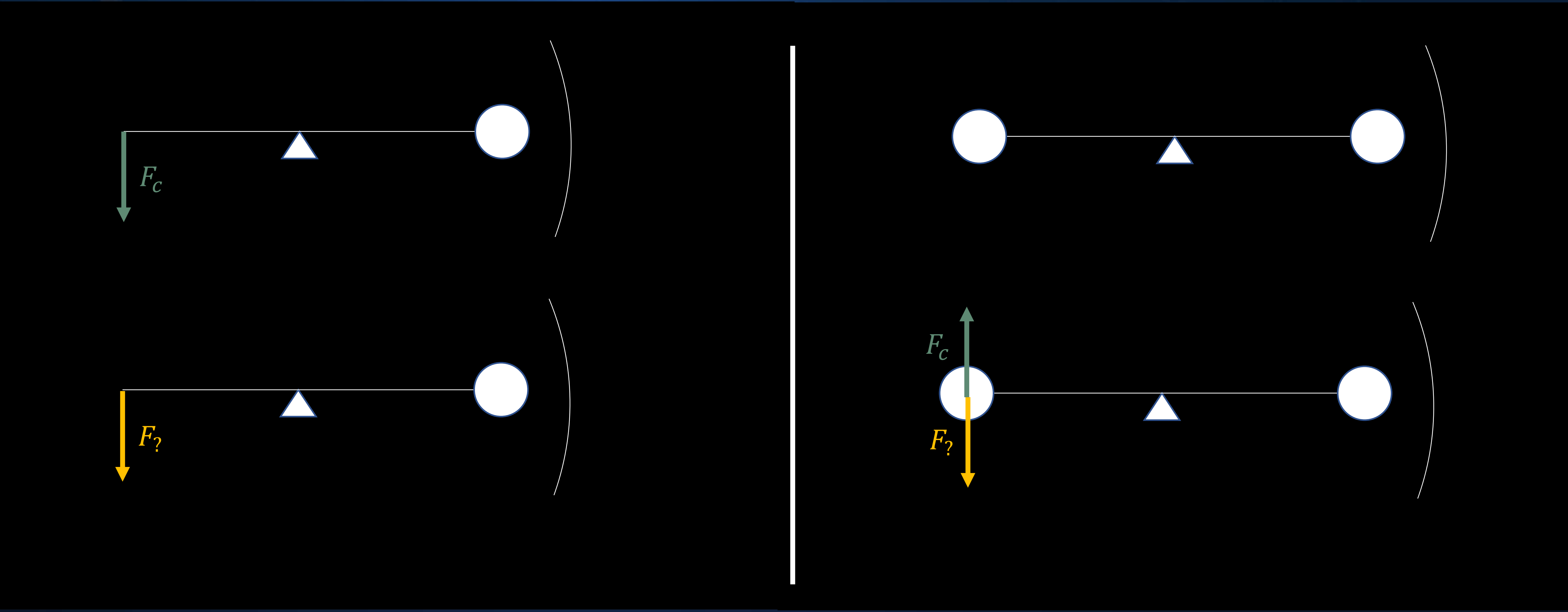
$\sum F = 0 \rightarrow a = 0$

F_c $F_?$

$a = 0 \rightarrow F_? = F_c$

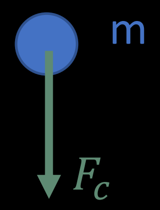
National Institute of Standards and Technology
U.S. Department of Commerce

Successive or simultaneous F_c



Three options for F_c

gravitational



$$F_c = mg$$

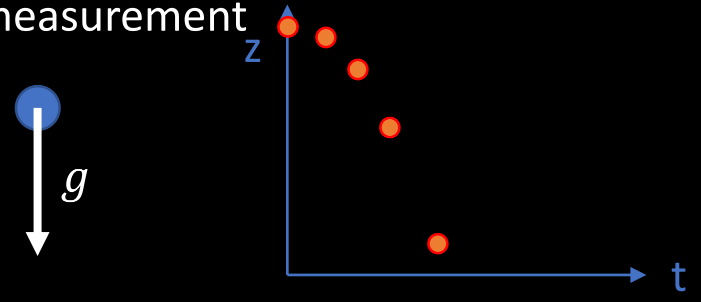
calibration phase

determine m

g can be looked up for $\frac{\sigma_g}{g} > 2 \times 10^{-6}$

For smaller uncertainty =>

measurement



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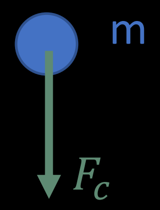

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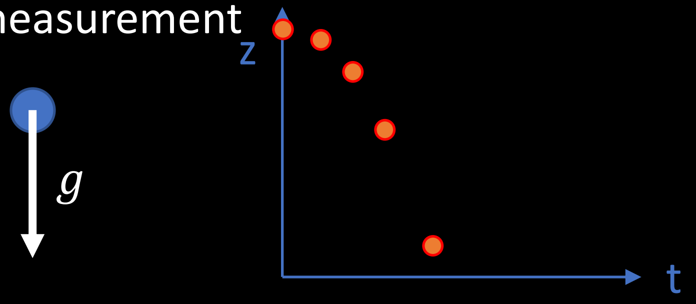
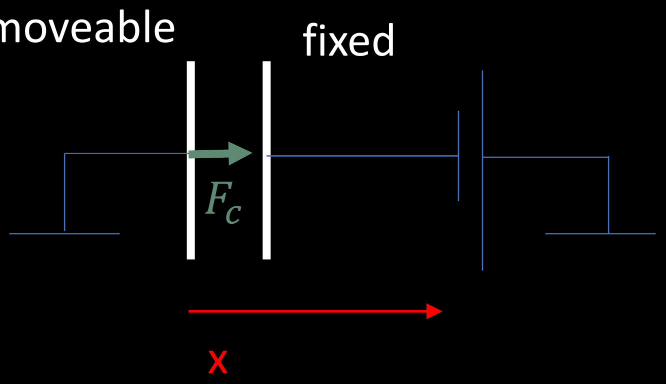


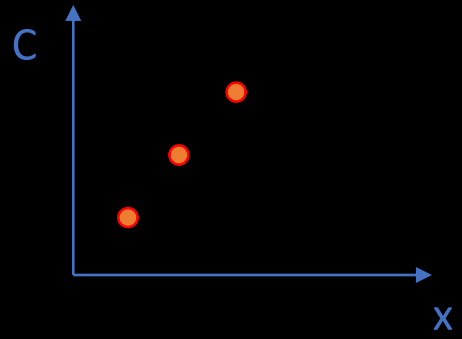
electrostatic



$$F_c = \frac{1}{2} V^2 \frac{dC}{dx}$$

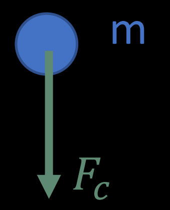
calibration phase

measure C(x) -> dC/dx



Three options for F_c

gravitational



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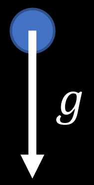
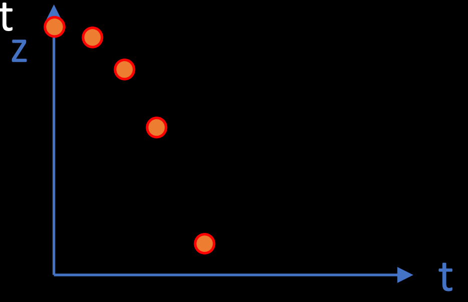
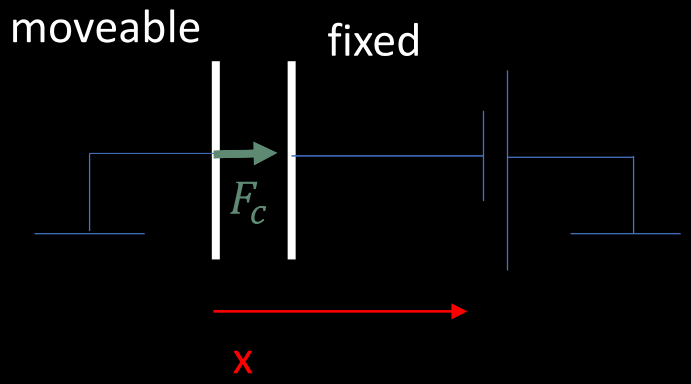
For smaller uncertainty => measurement





electrostatic



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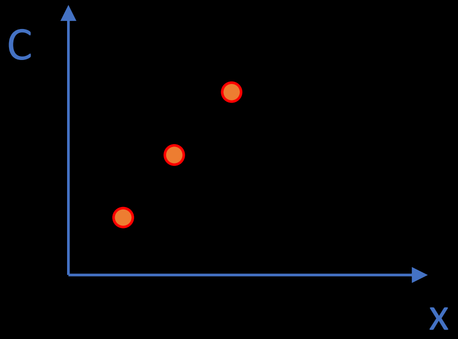
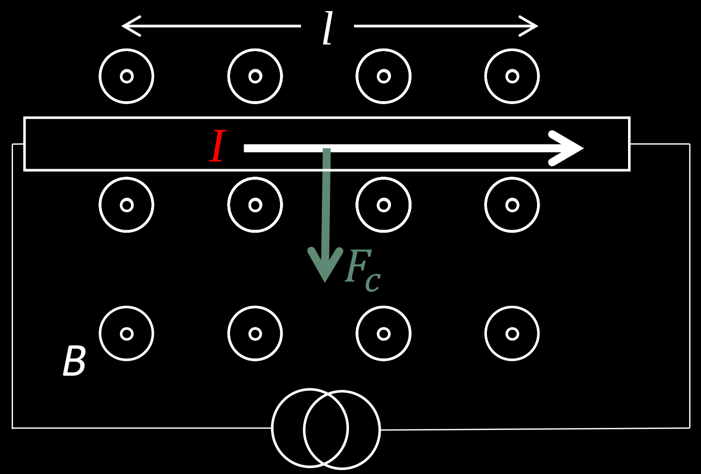
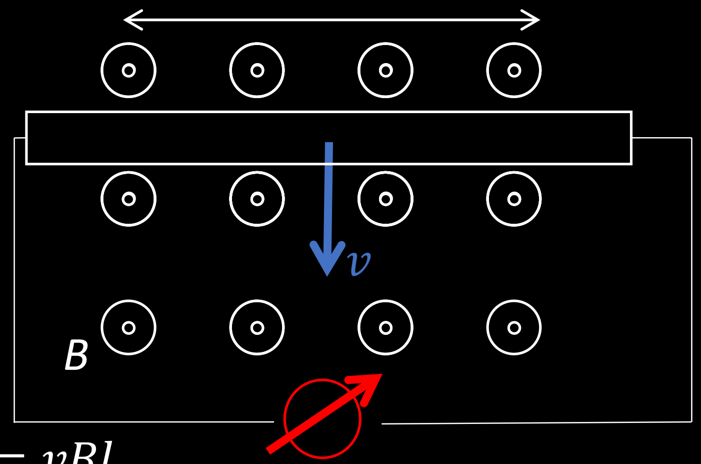


electromagnetic



$$F_c = IBl$$

calibration phase



$$U = vBl$$

Traceability

gravitational

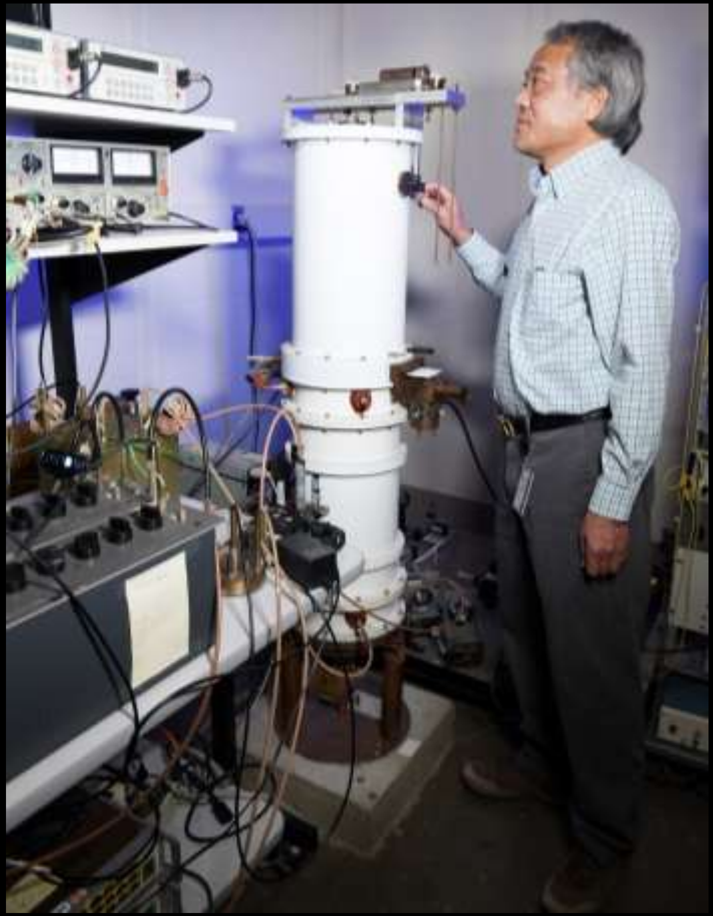
works for forces

$$10^{-5}N \leq F_c \leq 4.5 \times 10^{6}N$$

Photo: J. Lee/NIST

electrostatic

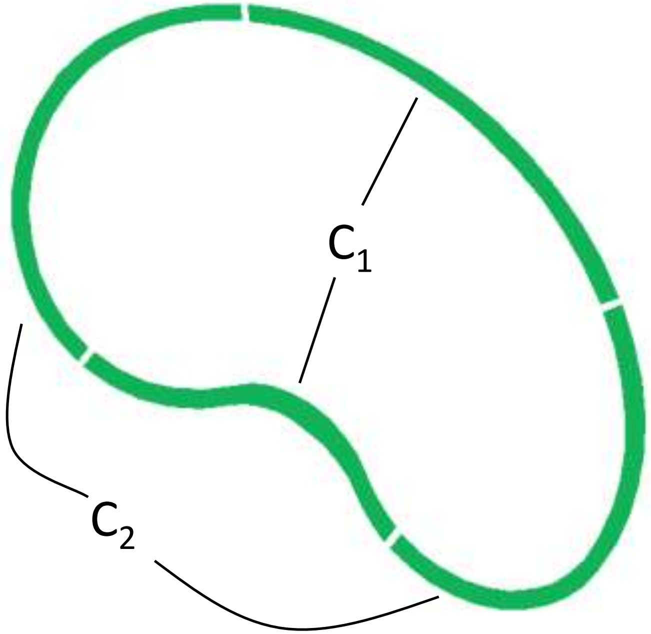
Is traceable to fundamental constants via calculable capacitor or AC QHR



electromagnetic

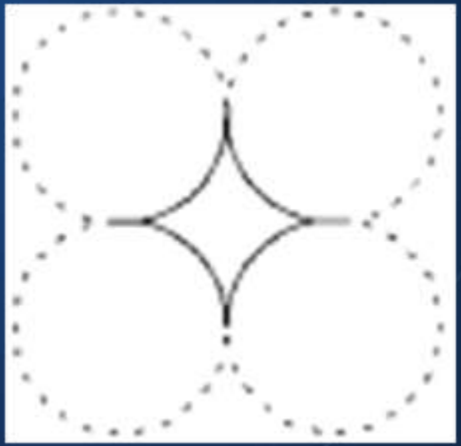
Is traceable to fundamental constants via Quantum Hall Effect and Josephson effect.

Calculable Capacitor?

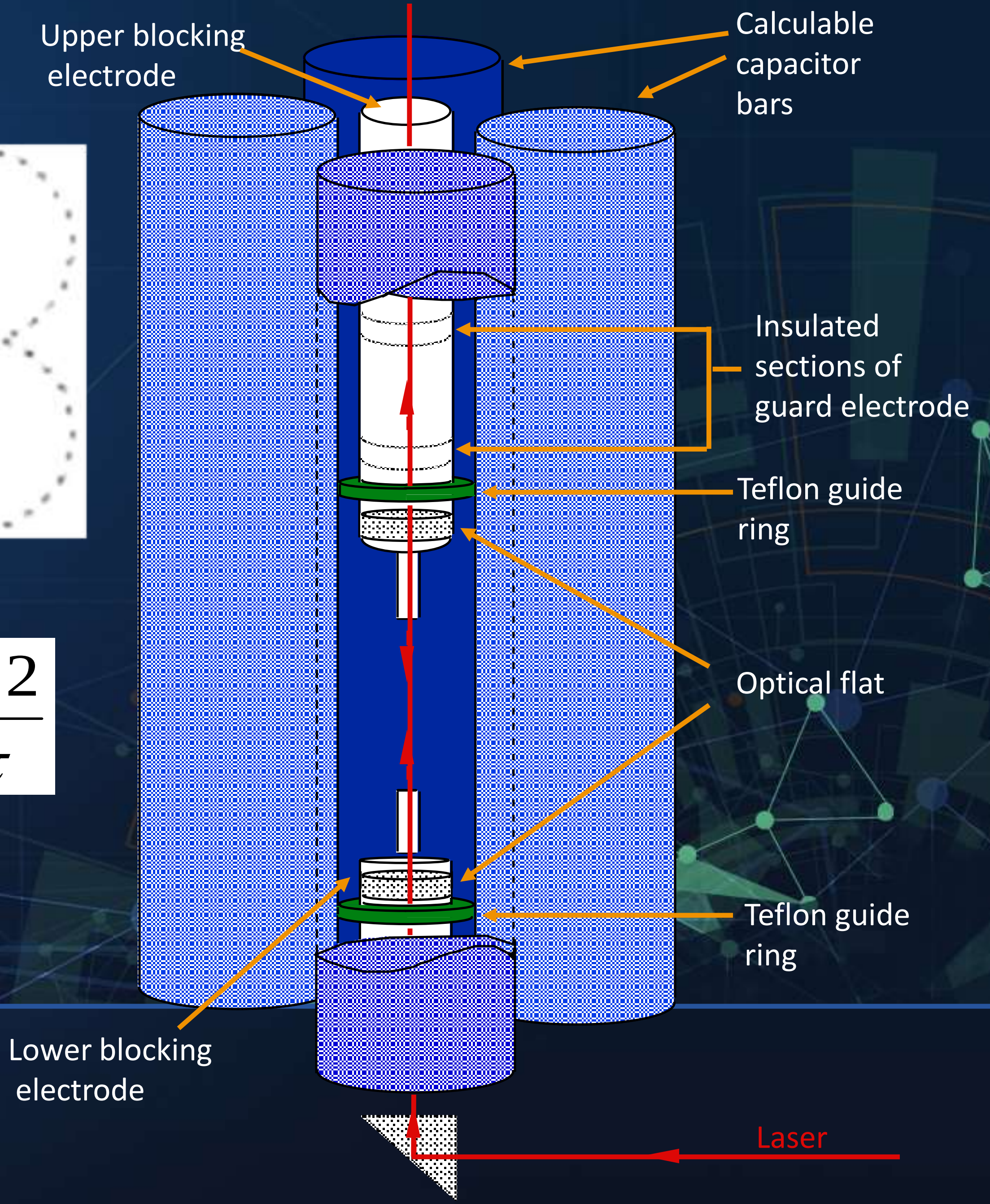


$$\exp\left(\frac{-\pi C_1}{\varepsilon_o L}\right) + \exp\left(\frac{-\pi C_2}{\varepsilon_o L}\right) = 1$$

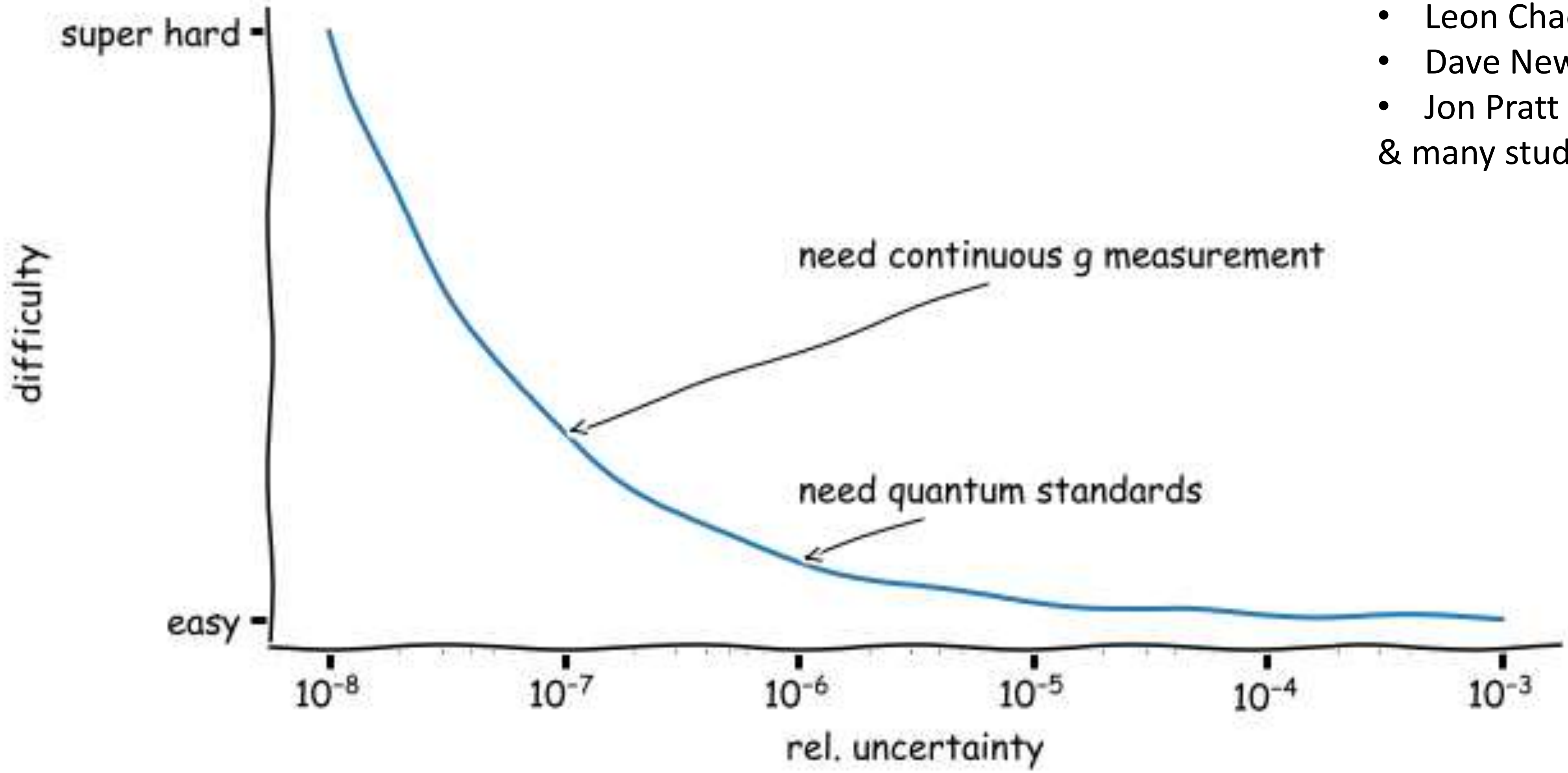
A. Thomson, D. Lampard, Nature 177, 88 (1956).



$$\frac{C_o}{L} = \varepsilon_\circ \frac{\ln 2}{\pi}$$

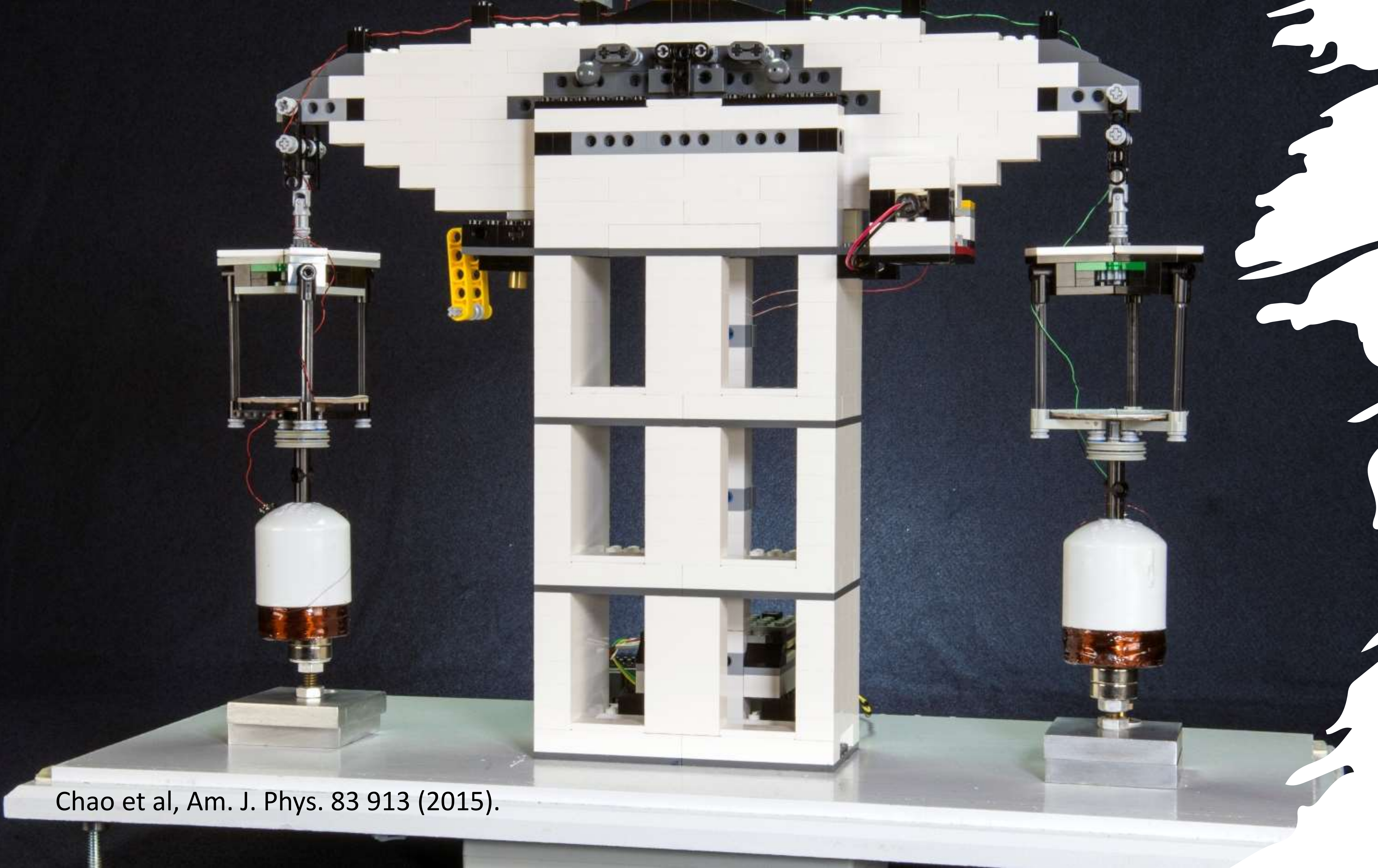


Level of difficulty building a KB

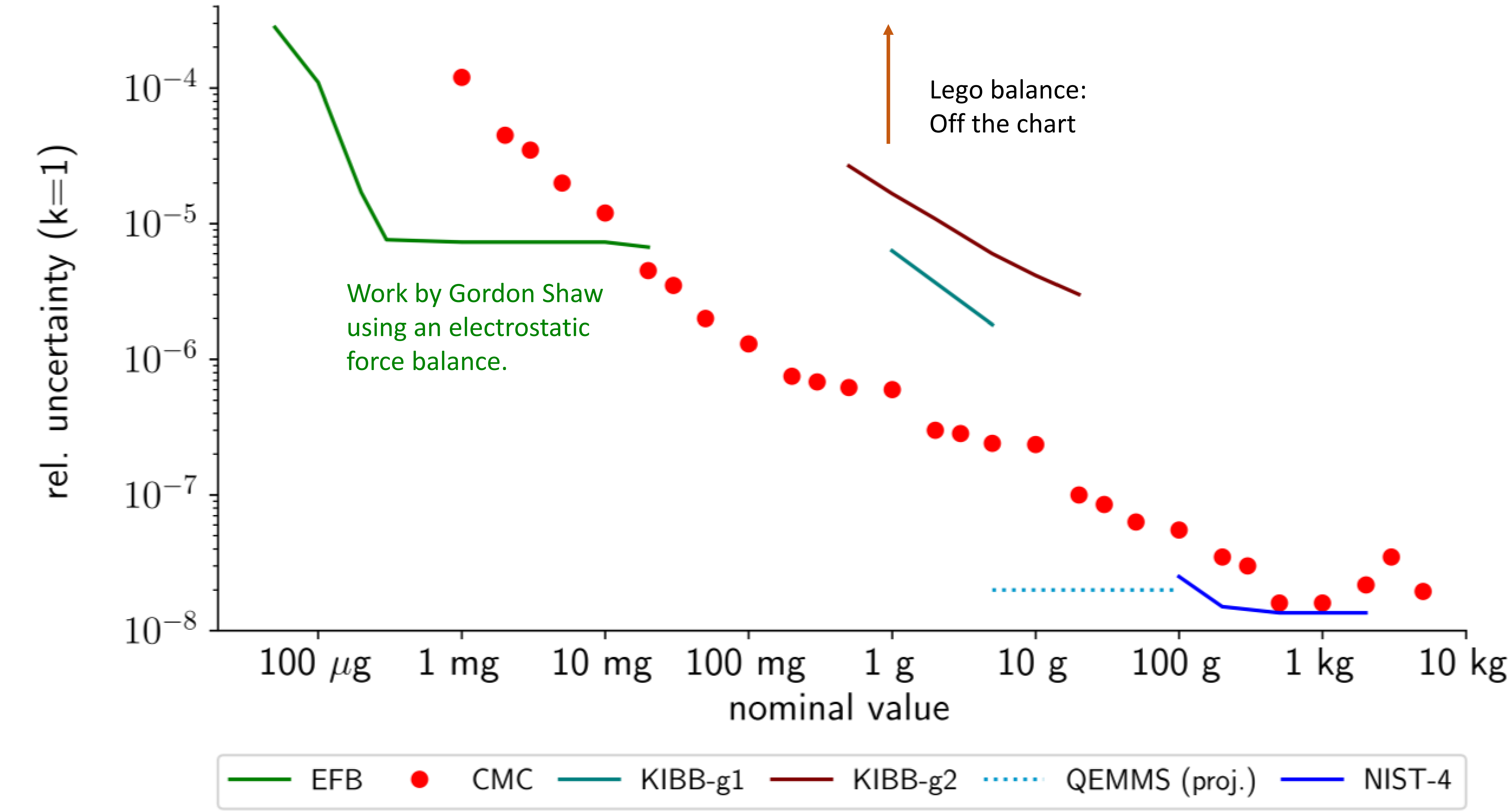


Kibble balance work with
- Darine Haddad
- Frank Seifert
- Leon Chao
- Dave Newell
- Jon Pratt

& many students

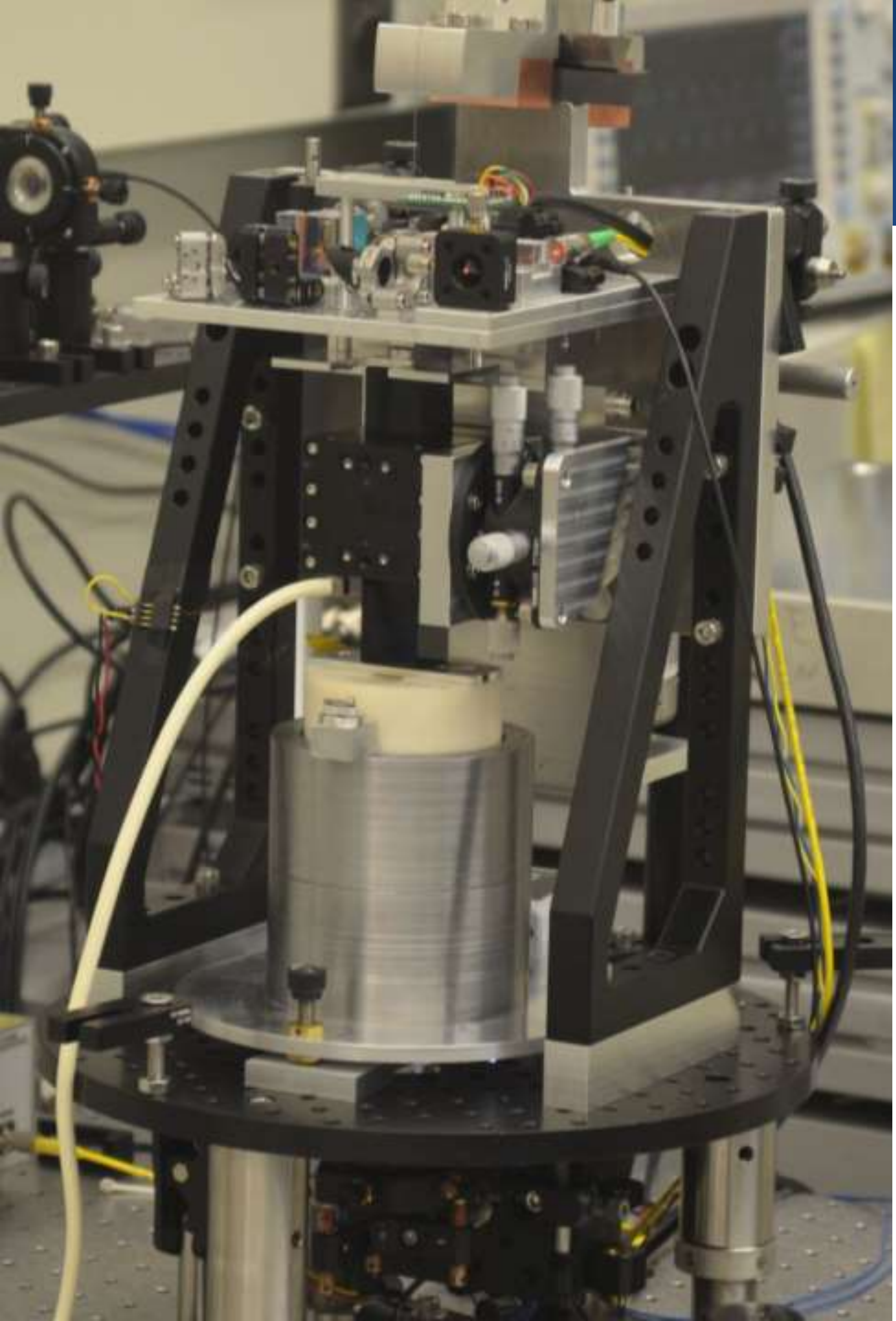


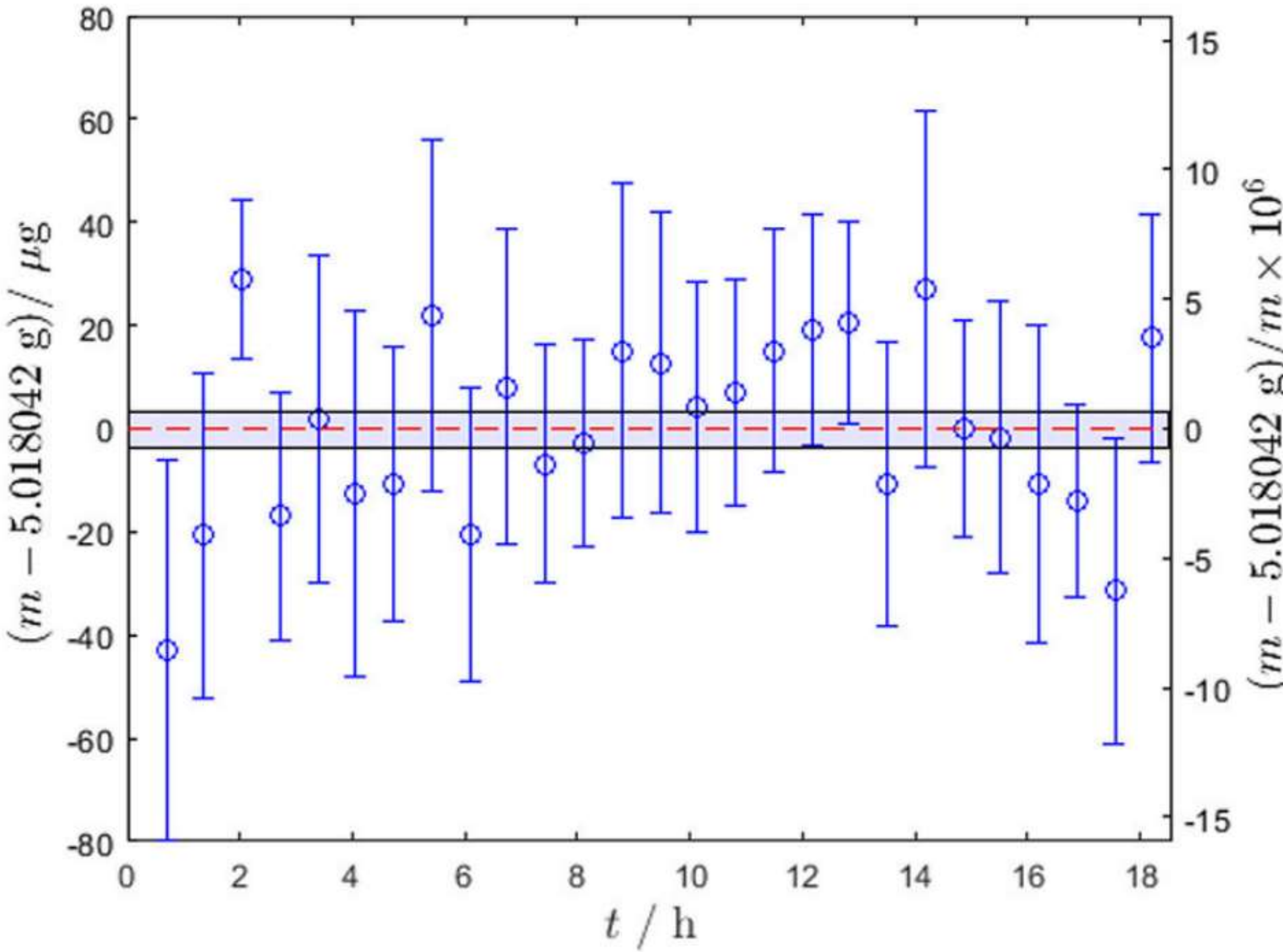
Chao et al, Am. J. Phys. 83 913 (2015).



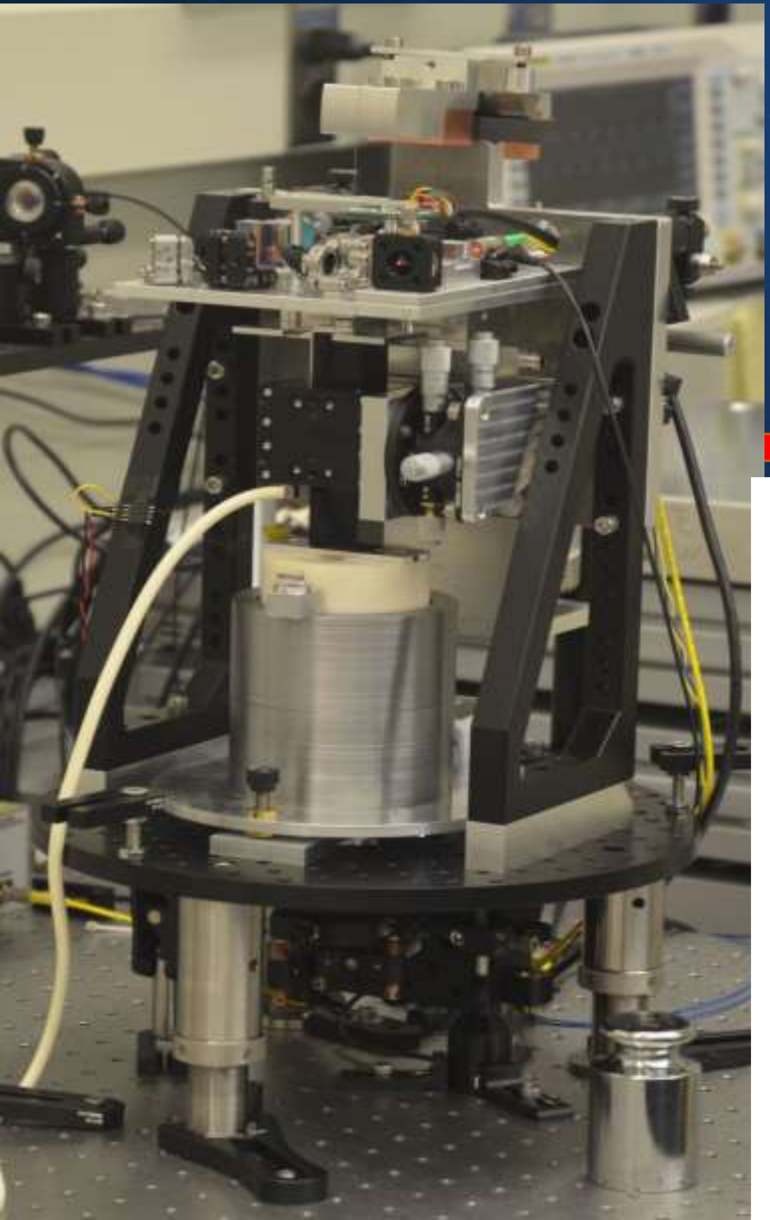
Lego balance:
Off the chart
Work by Gordon Shaw
using an electrostatic
force balance.
rel. uncertainty (k=1)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
100 μg
1 mg
10 mg
100 mg
1 g
10 g
100 g
1 kg
10 kg
nominal value
EFB
CMC
KIBB-g1
KIBB-g2
QEMMS (proj.)
NIST-4

for 1g $\frac{\sigma_m}{m} = 1.8 \times 10^{-6}$ for 5g $\frac{\sigma_m}{m} = 6.3 \times 10^{-6}$

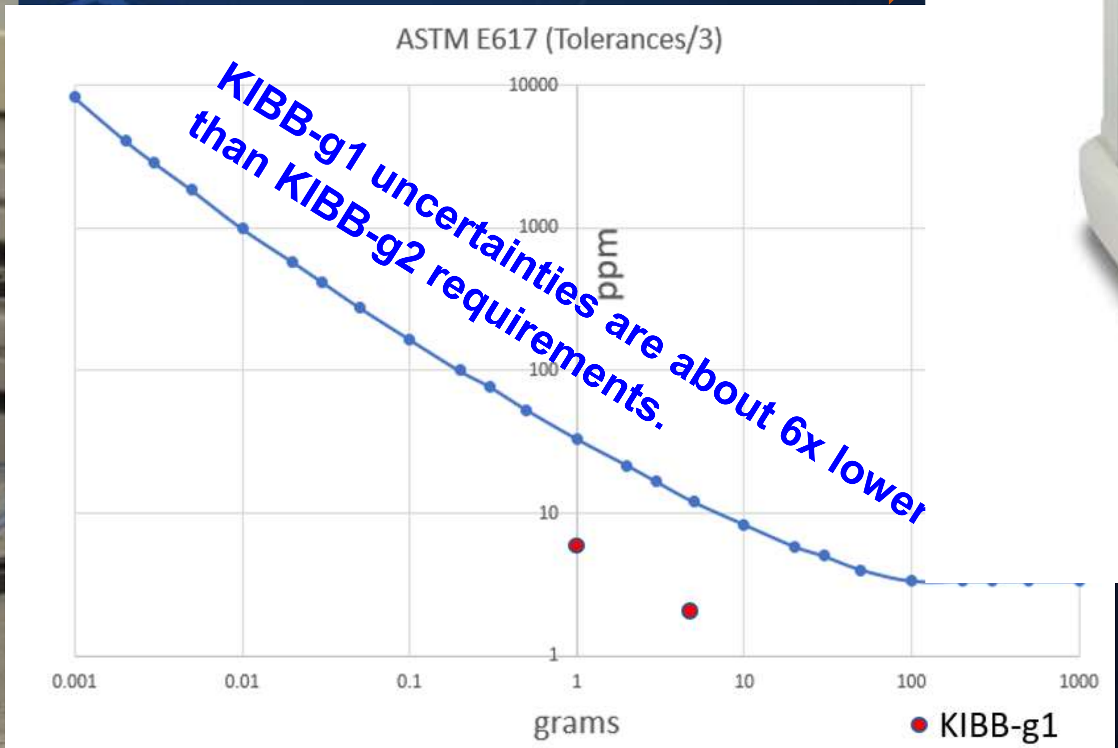


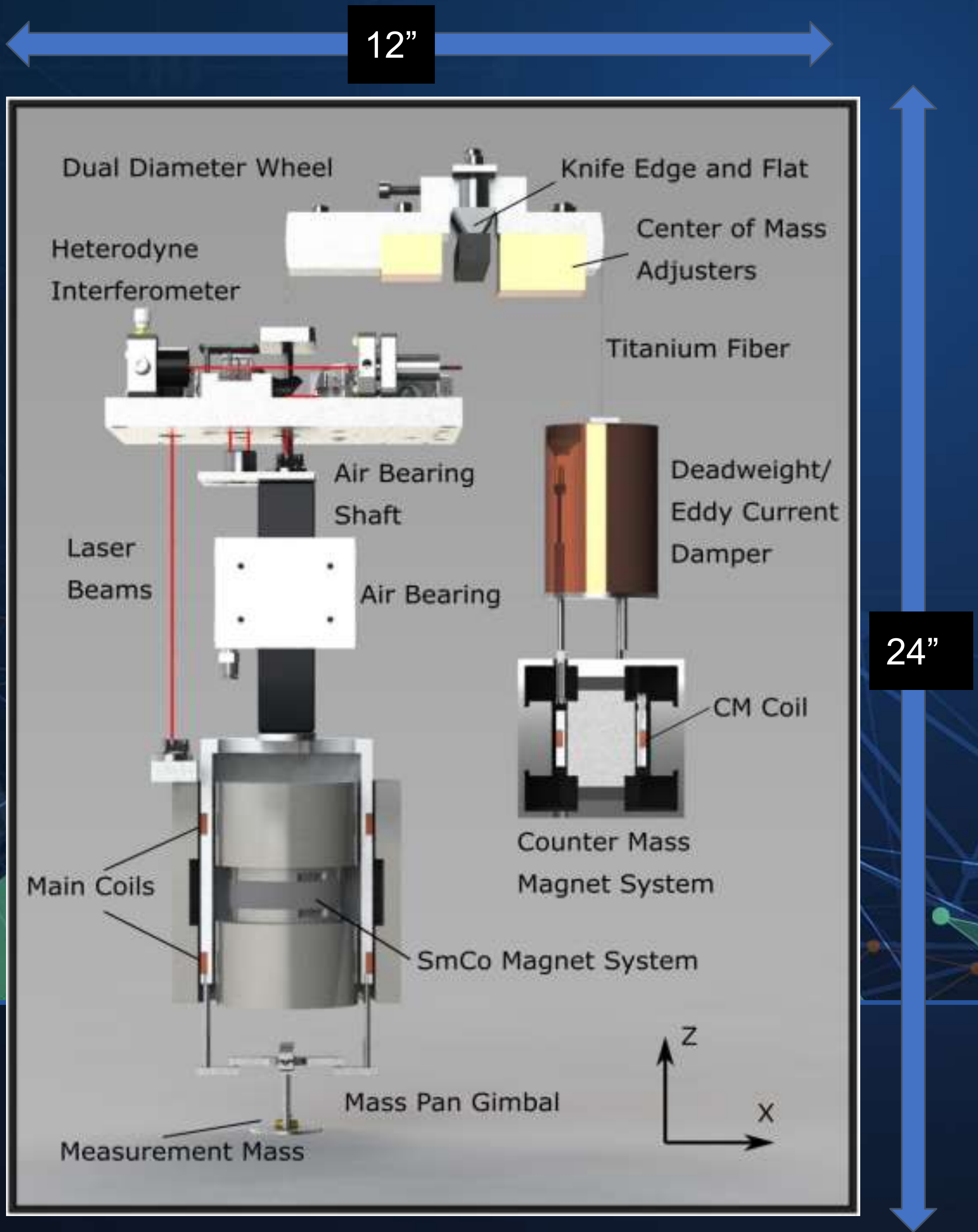


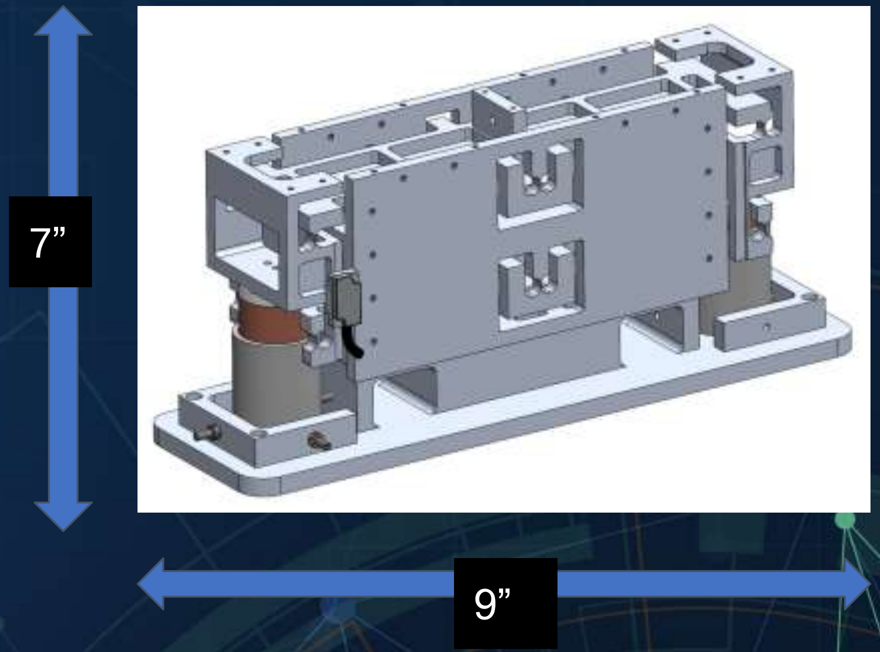
Next Generation Tabletop Balance



KIBB-g2 SOW: To design and construct two identical pushbutton tabletop Kibble balance systems capable of directly realizing **[500 mg – 20 g]** mass artifacts with uncertainties **less than 1/3 the Class 3 Tolerance as defined in ASTM E617** within three calendar years.

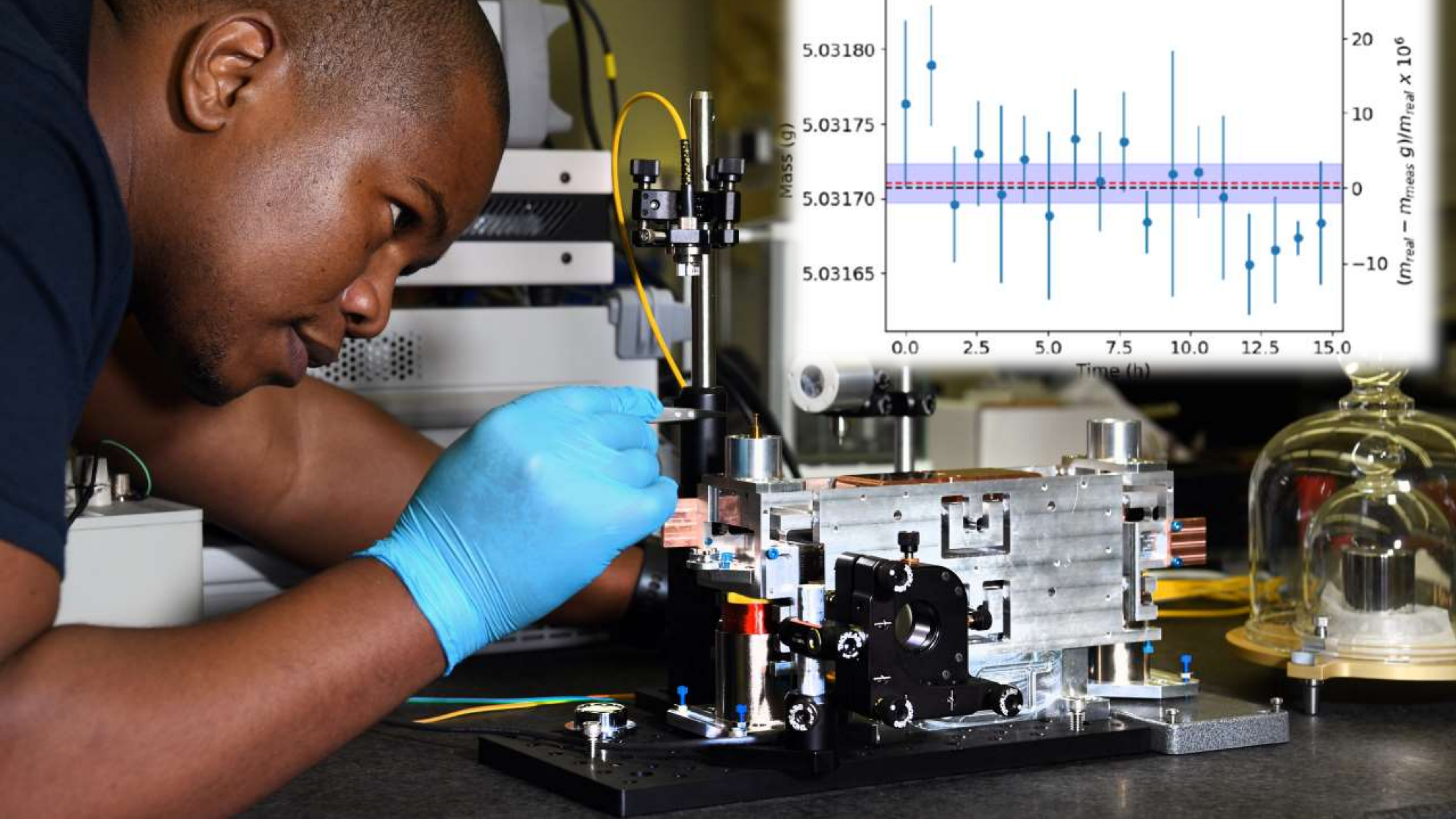




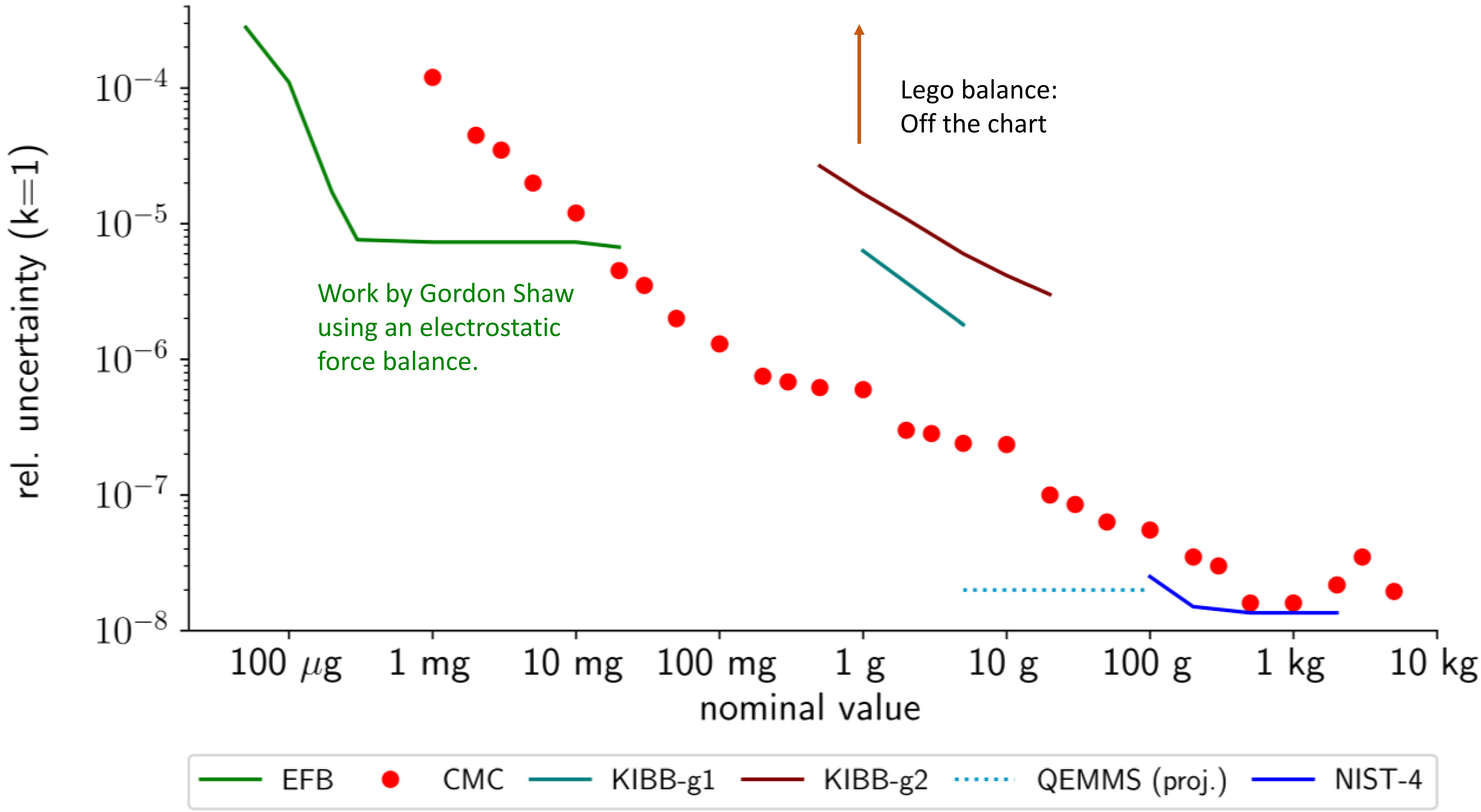


Flexure based design.

Work with John Dragonov, Leon Chao, Darine Haddad



5.03180
5.03175
5.03170
5.03165
Mass (g)
20
10
0
−10
$(m_{real} - m_{meas}\ g)/m_{real} \times 10^6$
0.0
2.5
5.0
7.5
10.0
12.5
15.0
Time (h)



rel. uncertainty (k=1)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
100 μg
1 mg
10 mg
100 mg
1 g
10 g
100 g
1 kg
10 kg
nominal value
Lego balance:
Off the chart
Work by Gordon Shaw
using an electrostatic
force balance.
EFB
CMC
KIBB-g1
KIBB-g2
QEMMS (proj.)
NIST-4

QEMMS

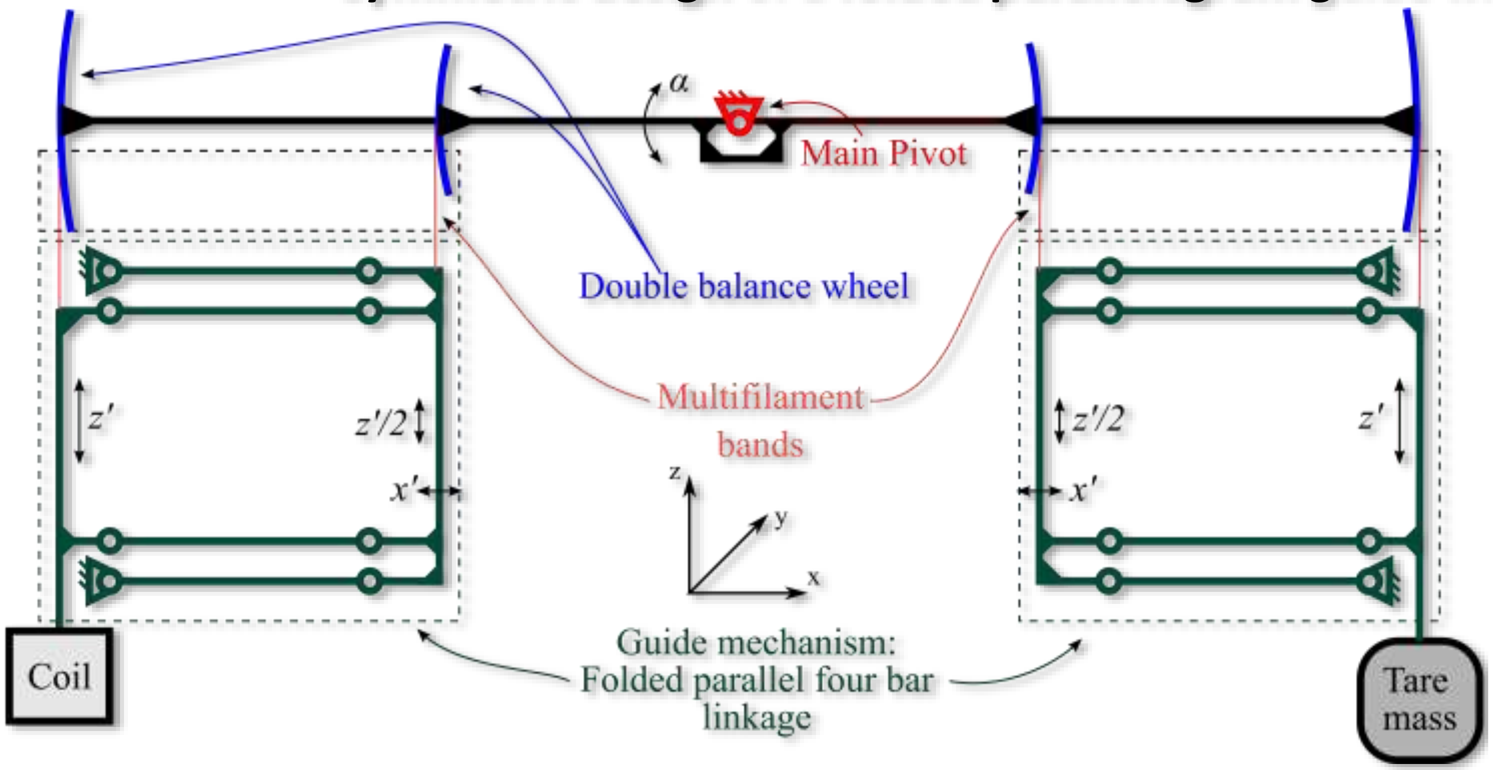
- Quantum Electro-Mechanical Metrology Suite (QEMMS): a NMI in a room featuring a Kibble balance
- Measurement uncertainty < 2 µg for masses < 100 g
- Design and construction in 5 years (2019-2024)

Graphene Quantum Hall Resistor

Cryo-cooled PJVS

Kinematic Chain

Symmetric design of a **folded parallelogram** guide with **external linkage**



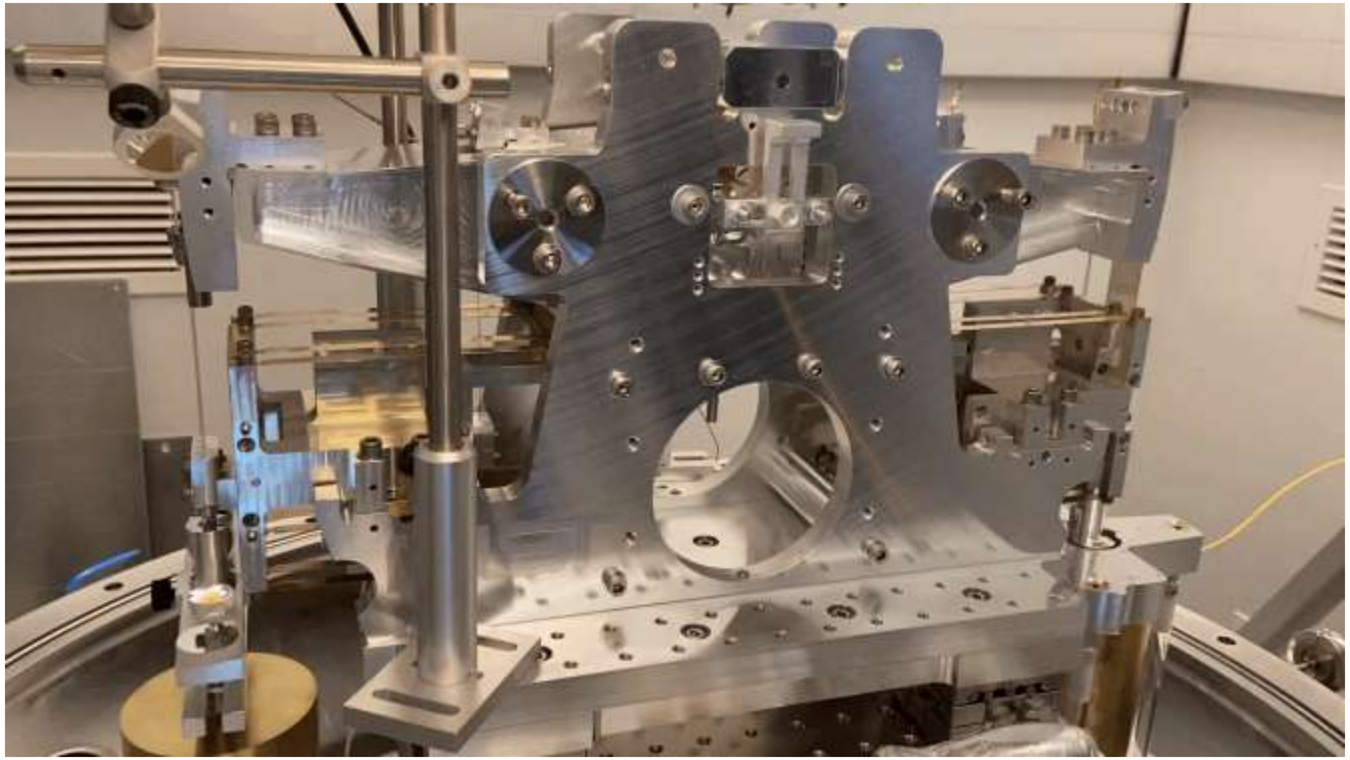
Total suspended mass: $\mathbf{15\ kg}$

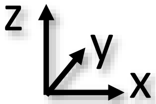
$z' = \pm\mathbf{30\ mm}$

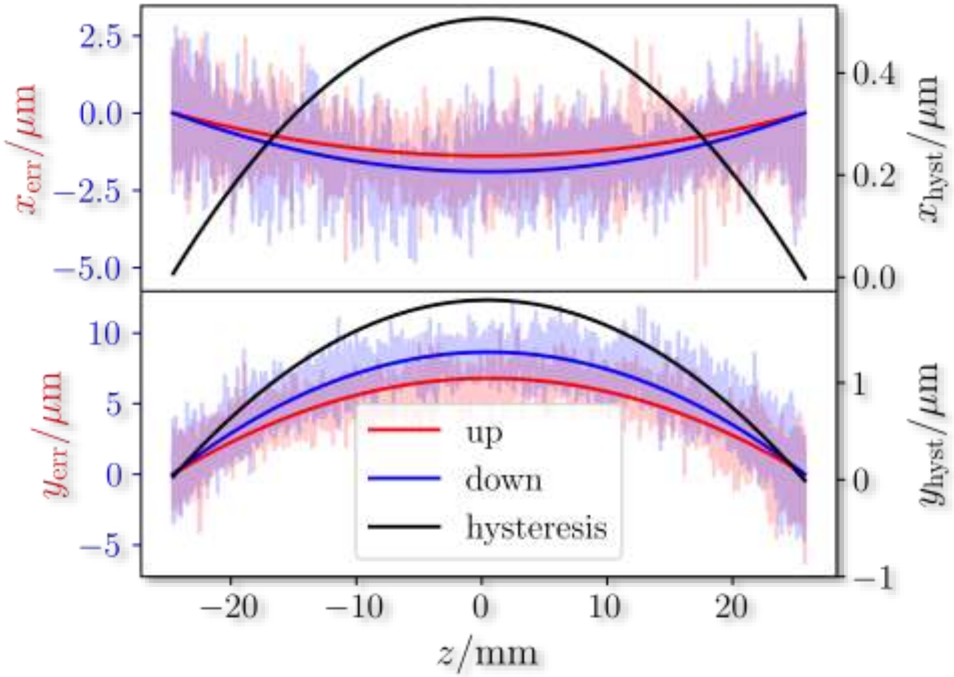
$\alpha \approx \pm\mathbf{7}\,^{\circ}$

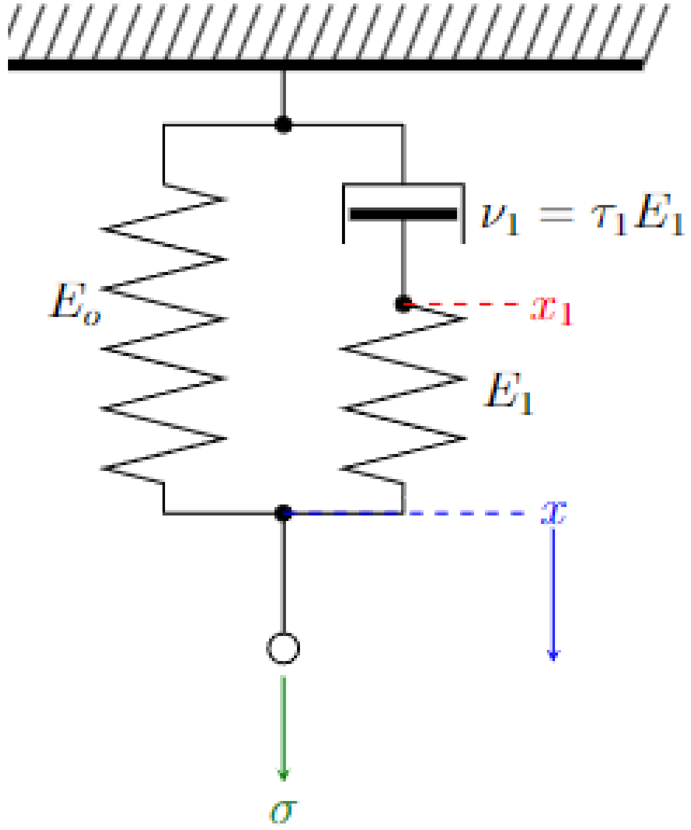
Work with Lorenz Keck, Frank Seifert, Darine Haddad

Kinematic Analysis

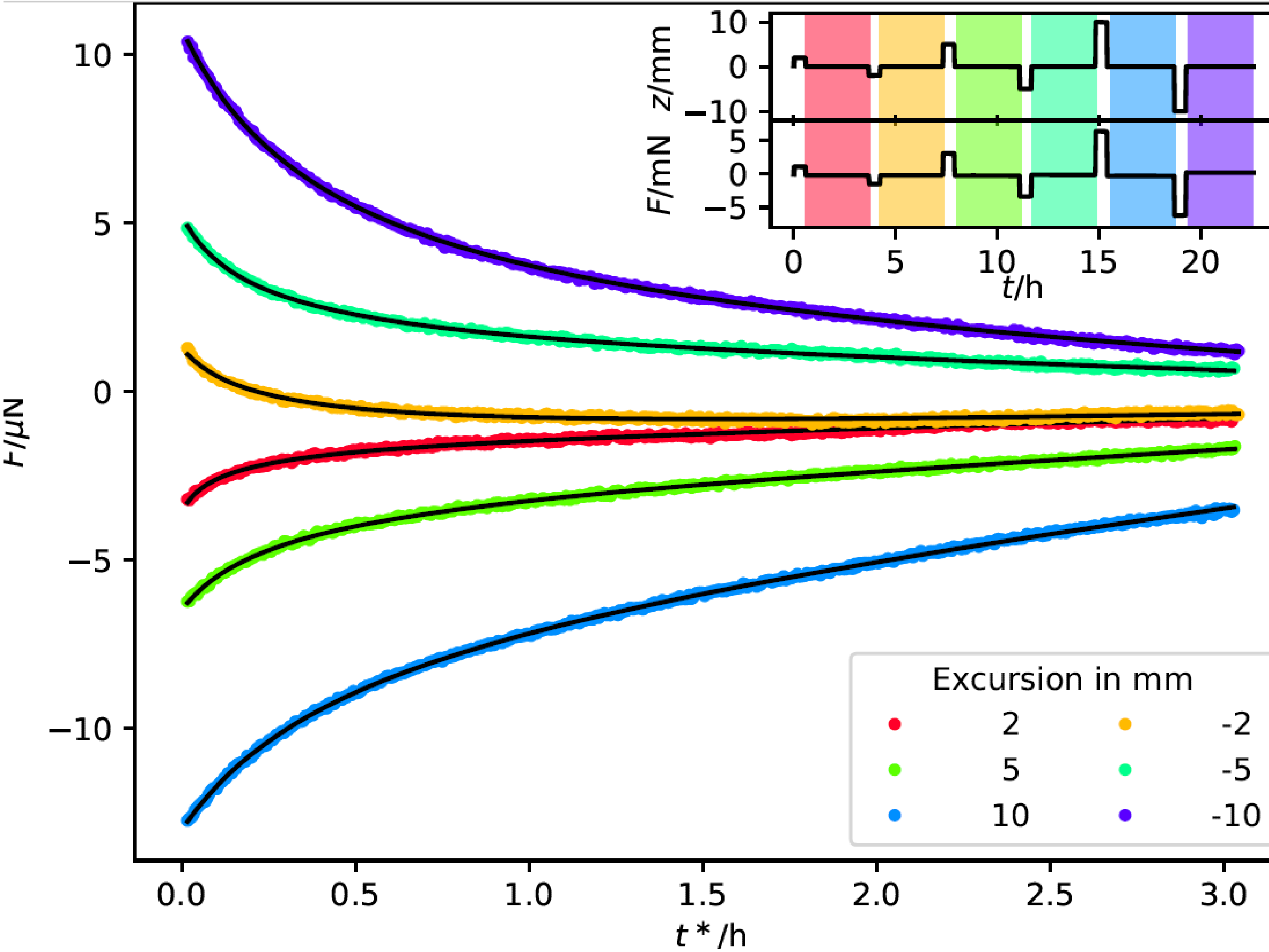








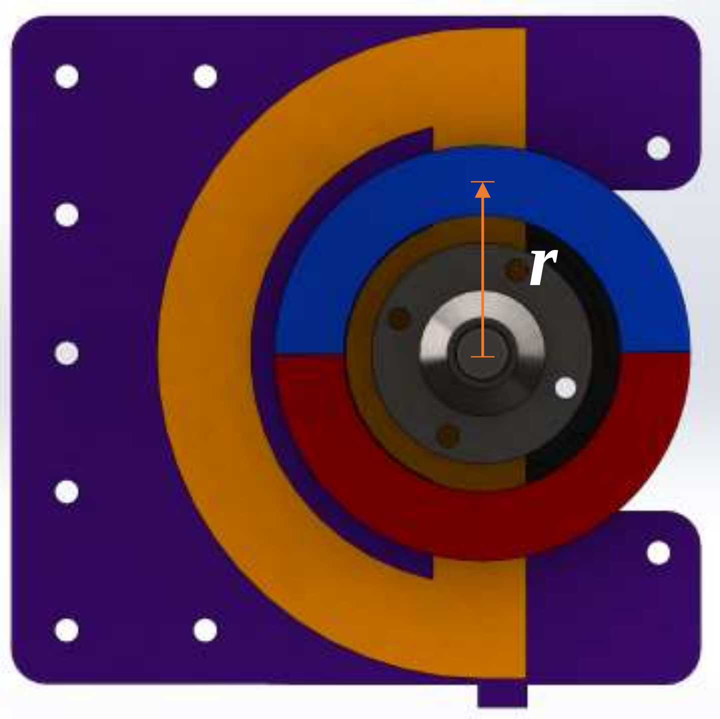
$\nu_1 = \tau_1 E_1$
E_o
x_1
E_1
x
σ



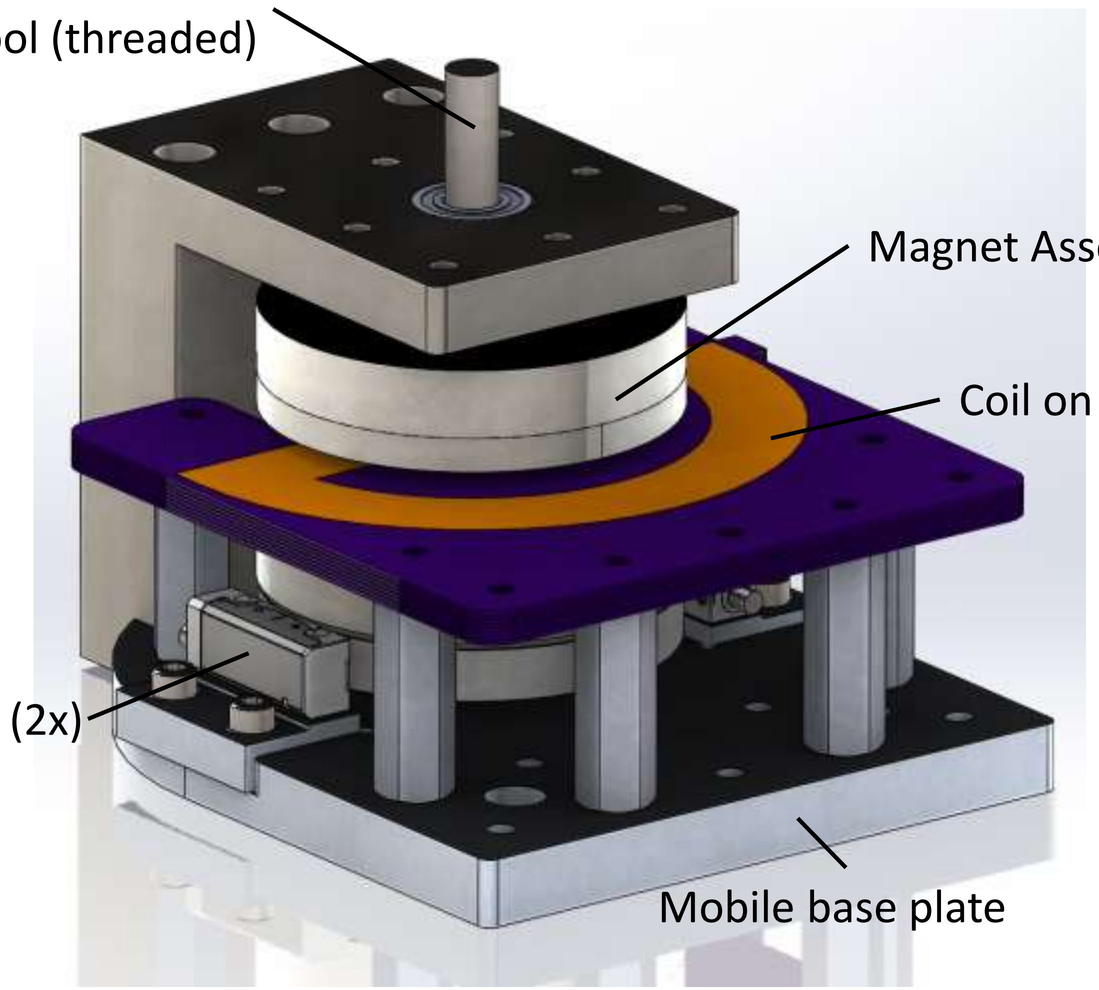
F/µN
t * /h
10
5
0
−5
−10
0.0
0.5
1.0
1.5
2.0
2.5
3.0
z/mm
F/mN
t/h
Excursion in mm
2
-2
5
-5
10
-10

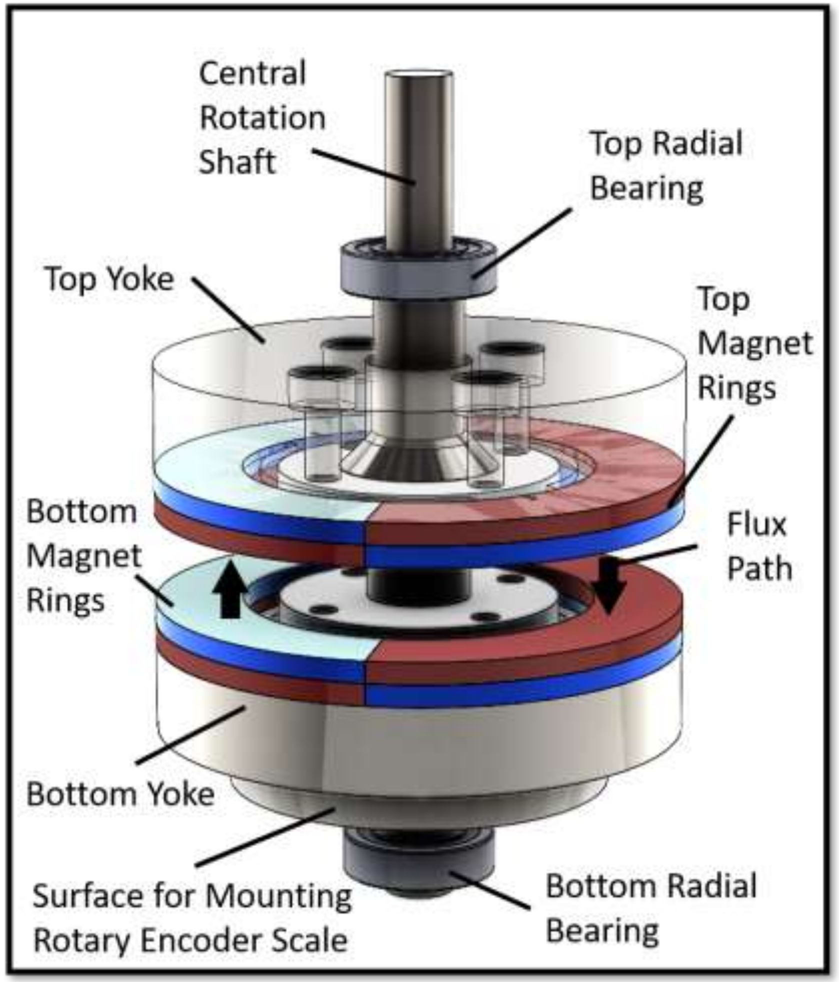
Kibble Principle in Rotational Frames

	Linear	Rotational
Self-Calibration Mode	$V = BLv$ *Velocity Mode*	$V = B(\varphi)Lr\dot{\varphi}$ *Spin Mode*
Measurement Mode	$mg = BLI$ *Force Mode*	$\tau = B(\varphi)LrI$ *Torque Mode*
	BL is common in both equations	$B(\varphi)Lr$ is common in both equations
	$mg = I\,(V / v)$	$\tau = I\,\dfrac{V}{\dot{\varphi}}$



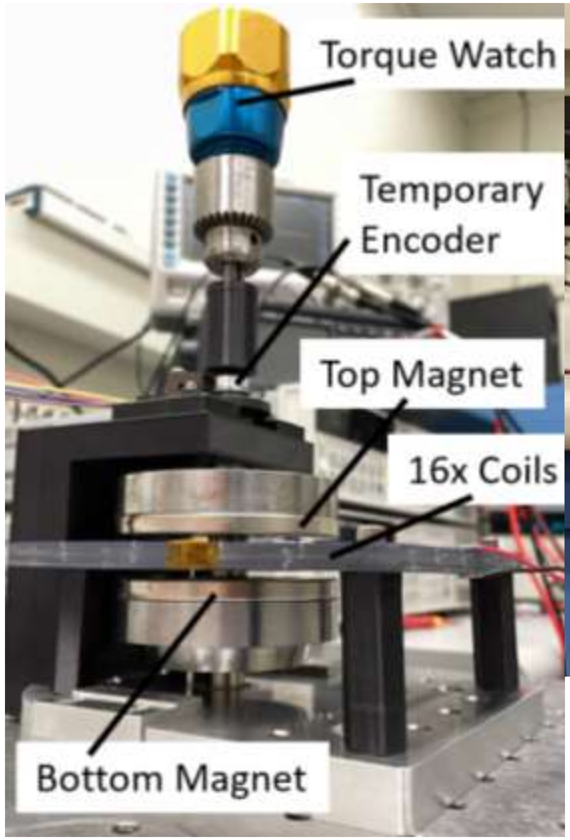
Electronic NIST Torque Realizer (ENTR)



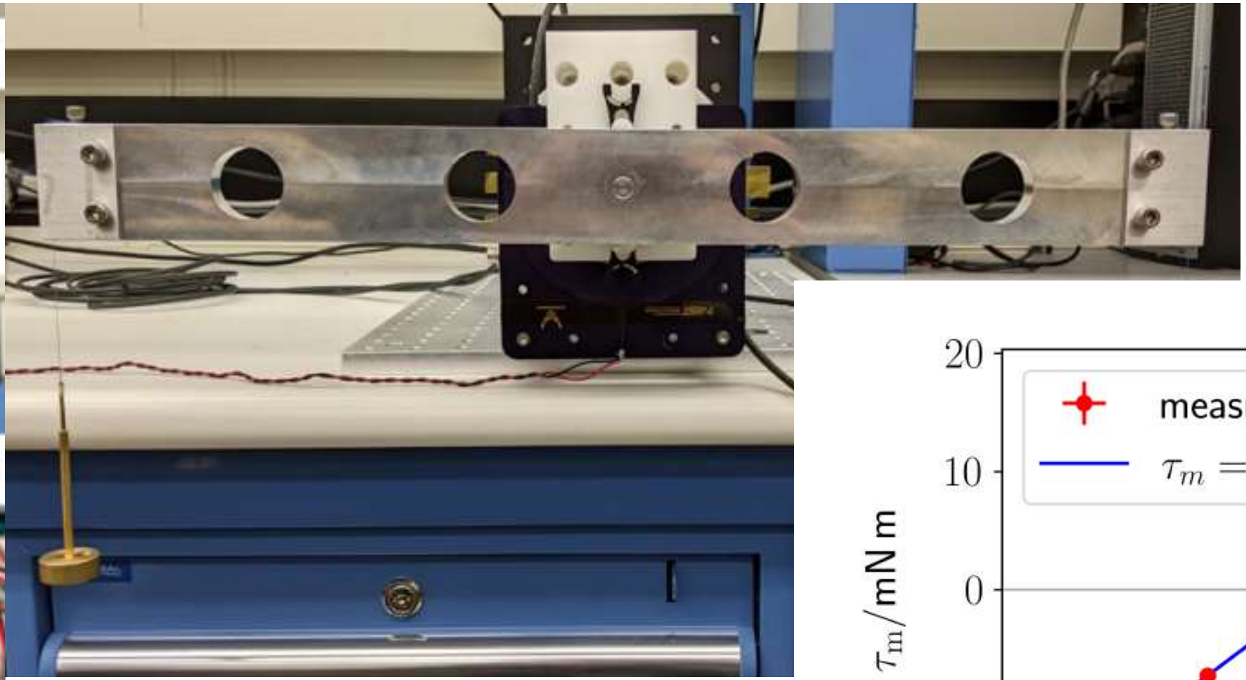


Magnet Assembly Detail

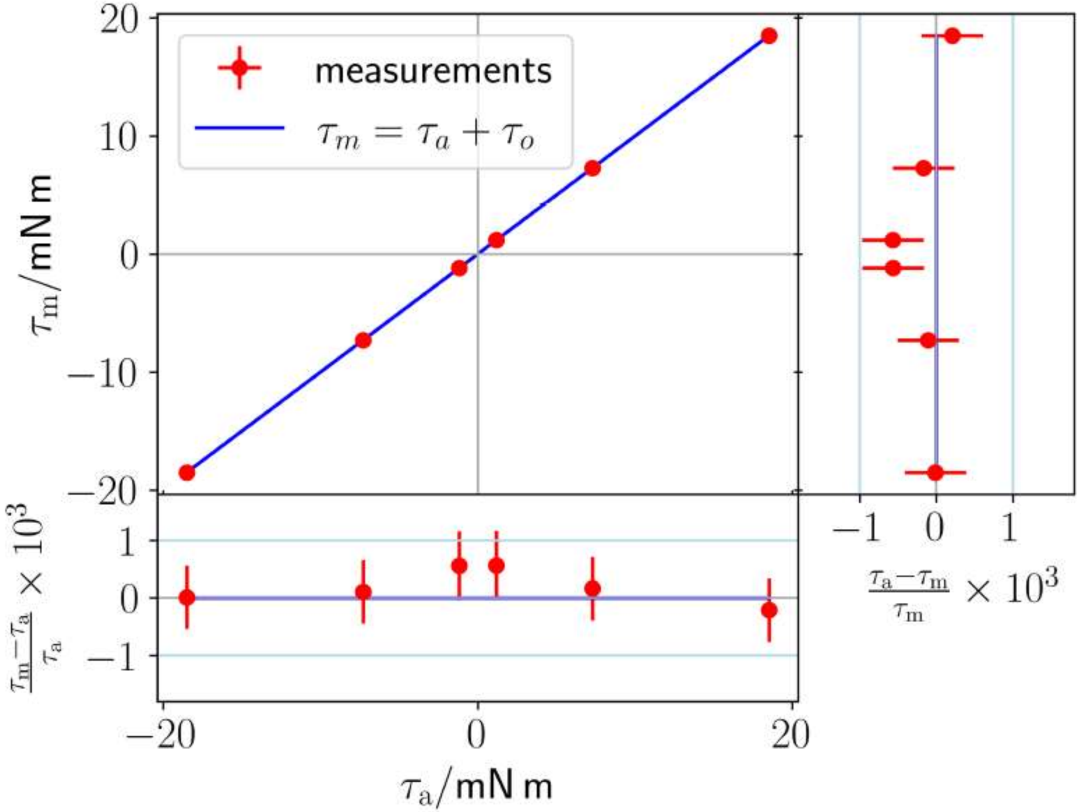
ENTR Prototype



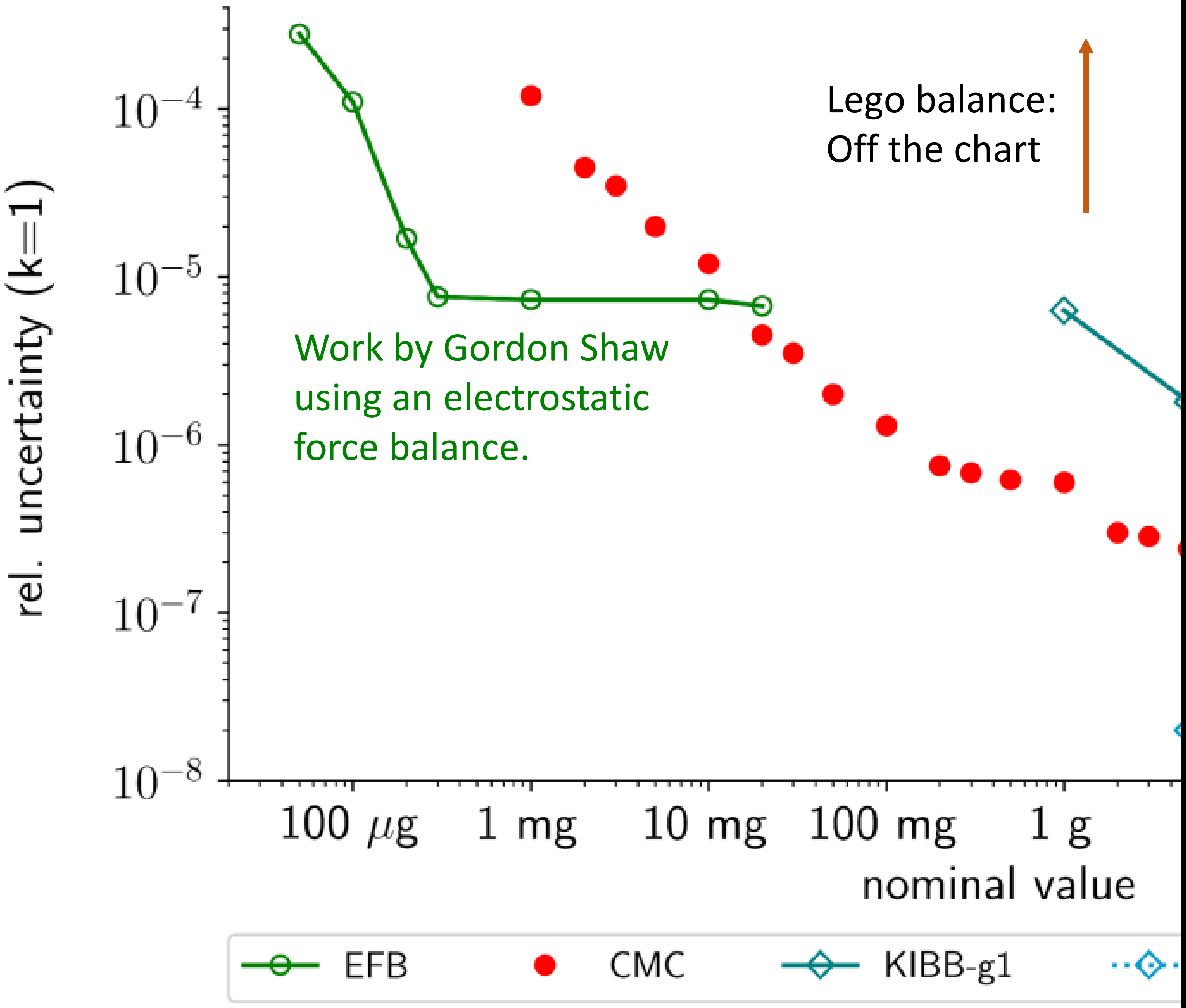
Vertical Orientation



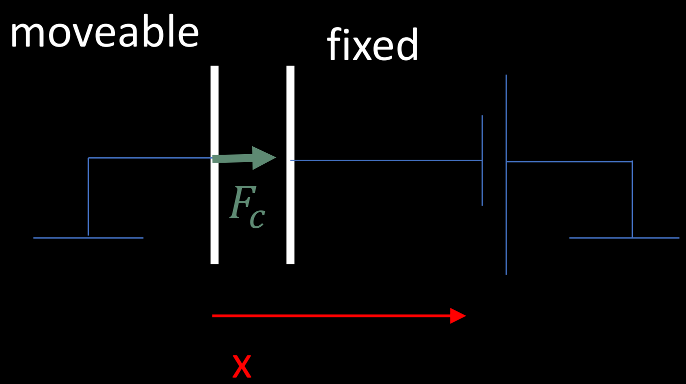
Horizontal Orientation



work with Z. Comden, L. Chao,. C. Waduwarage Perera, F. Seifert



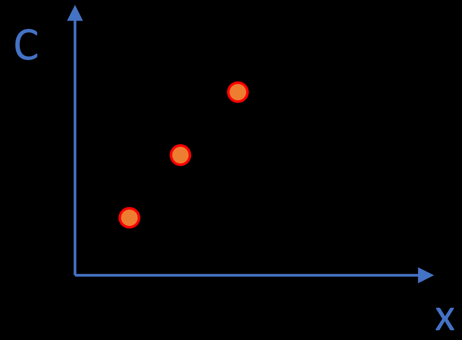
electrostatic



$$F_c = \frac{1}{2} V^2 \frac{dC}{dx}$$

calibration phase

measure C(x) -> dC/dx

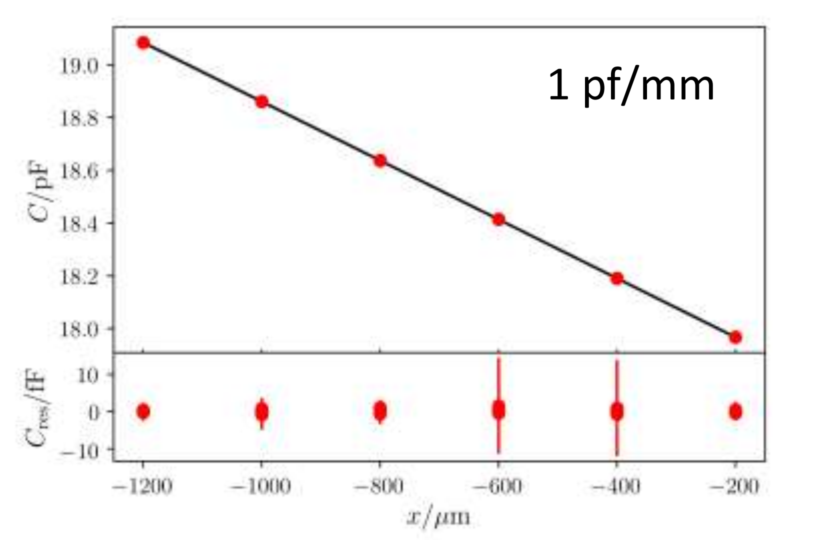


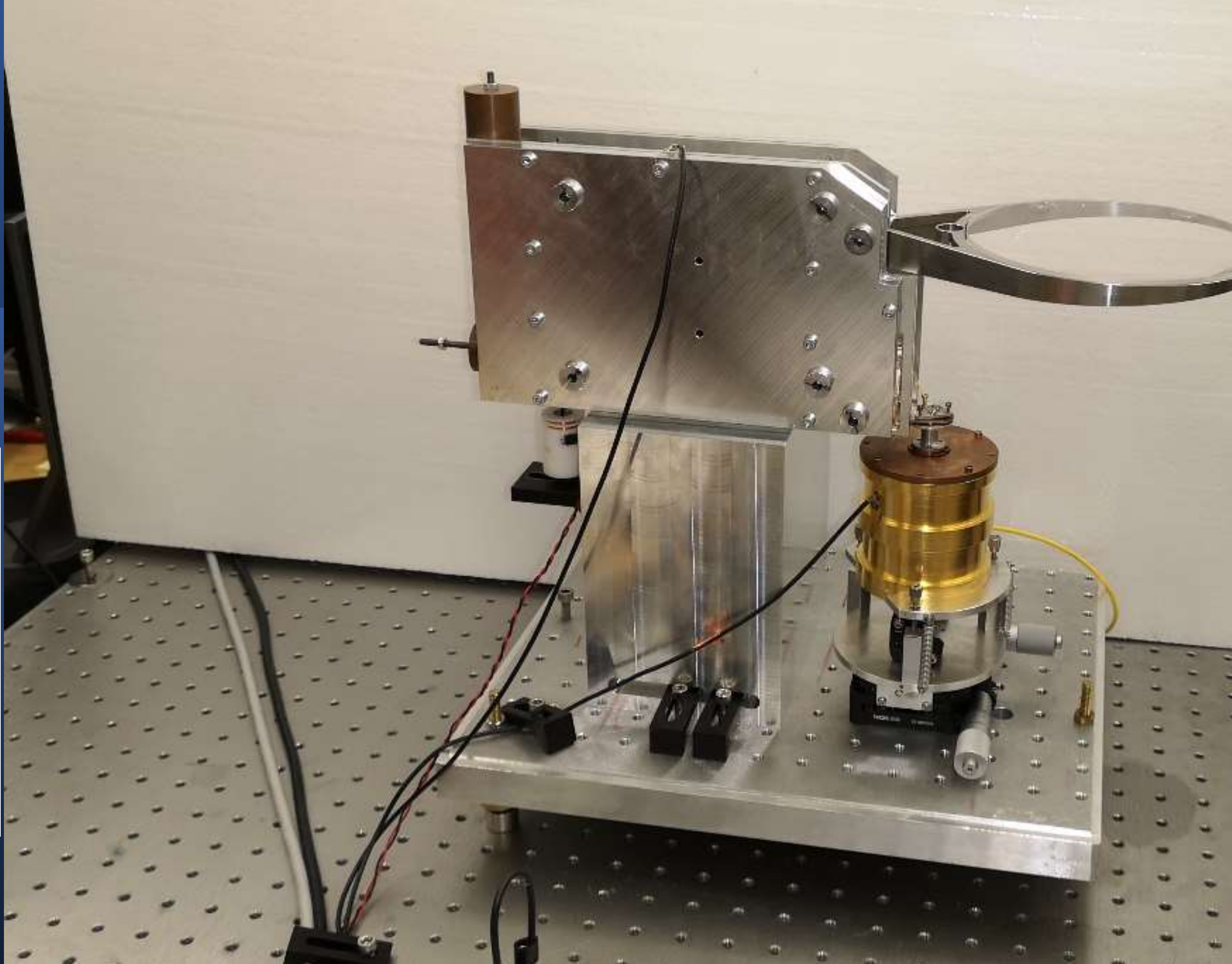
Standards and Technology
U.S. Department of Commerce

Work with L. Keck, G. Shaw, S. Schulze, F. Seifert K. Arumugam

Photonic pressure balance

100 kW Laser produces in reflection 667 μN.





Keck, et al., IEEE Trans. Instr. Meas. (2021)
DOI: 10.1109/TIM.2021.3060575

Torque measurements to determine G

$$F = G\frac{m_1 m_2}{r^2}$$

$$G \approx 6.67 \times 10^{-11}\mathrm{m^3kg^{-1}s^{-2}}$$

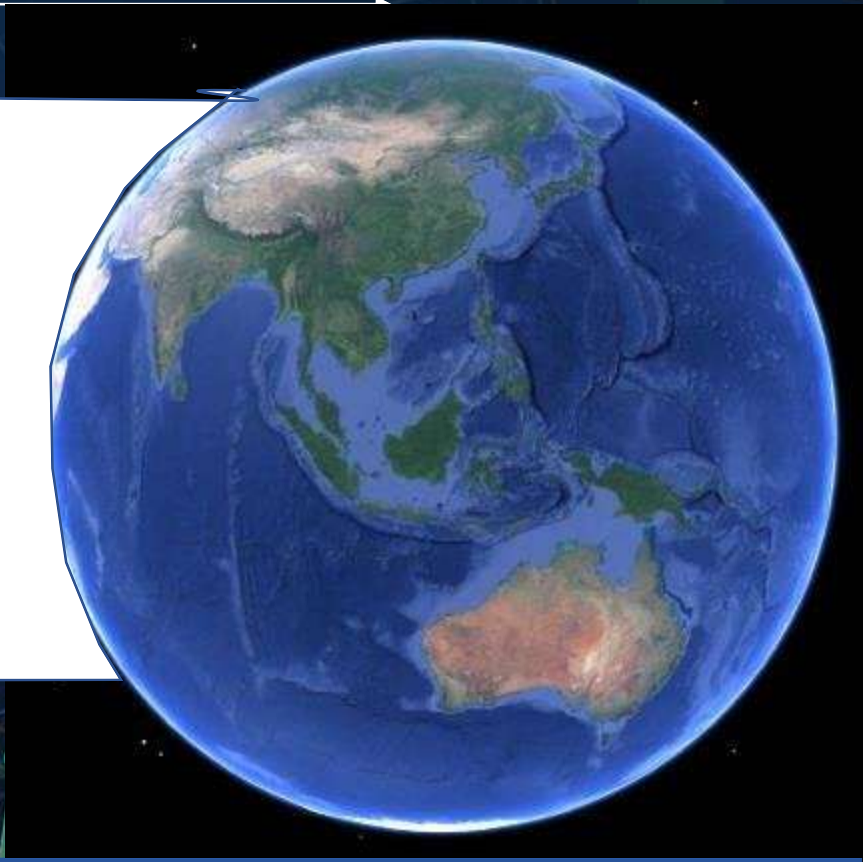
How big would a steel cable have to be to keep Earth going around the sun to replace gravity?

1.5×10^{11} m

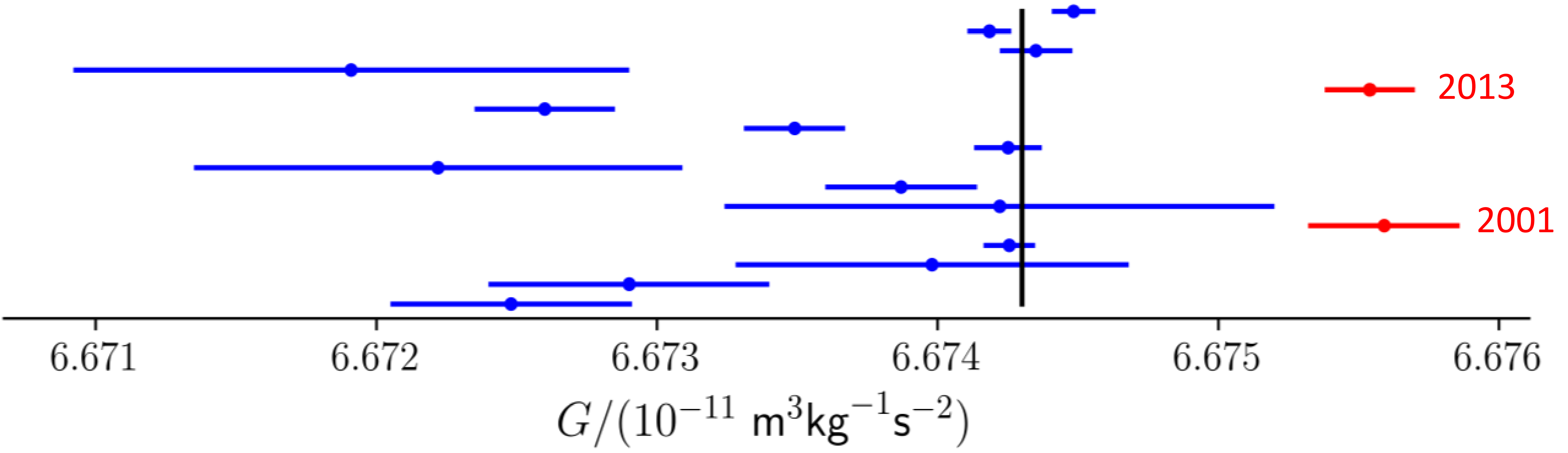
How big would a steel cable have to be to keep Earth going around the sun to replace gravity?

1.5×10^{11} m

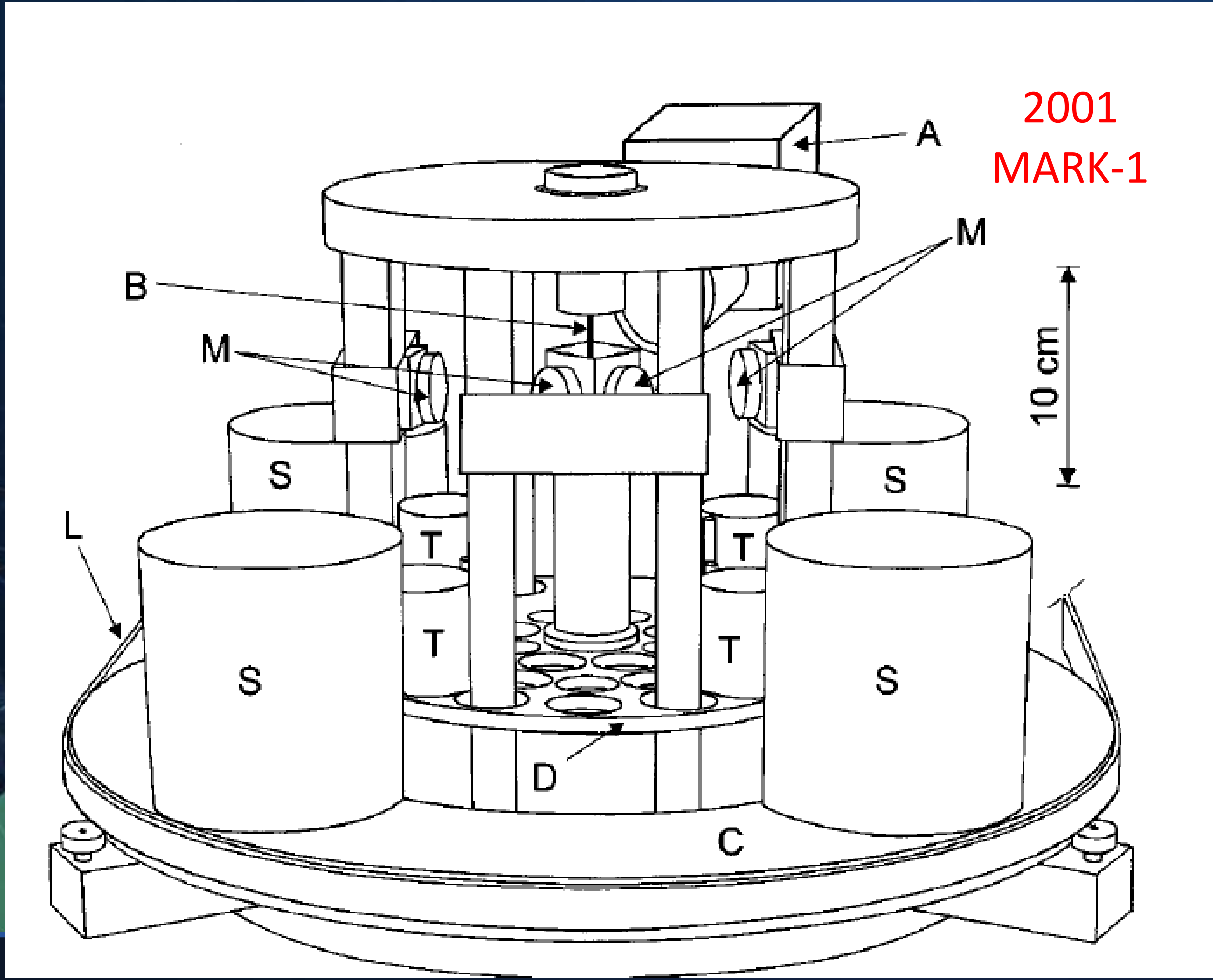
Steel cable 2/3 D_{Earth}

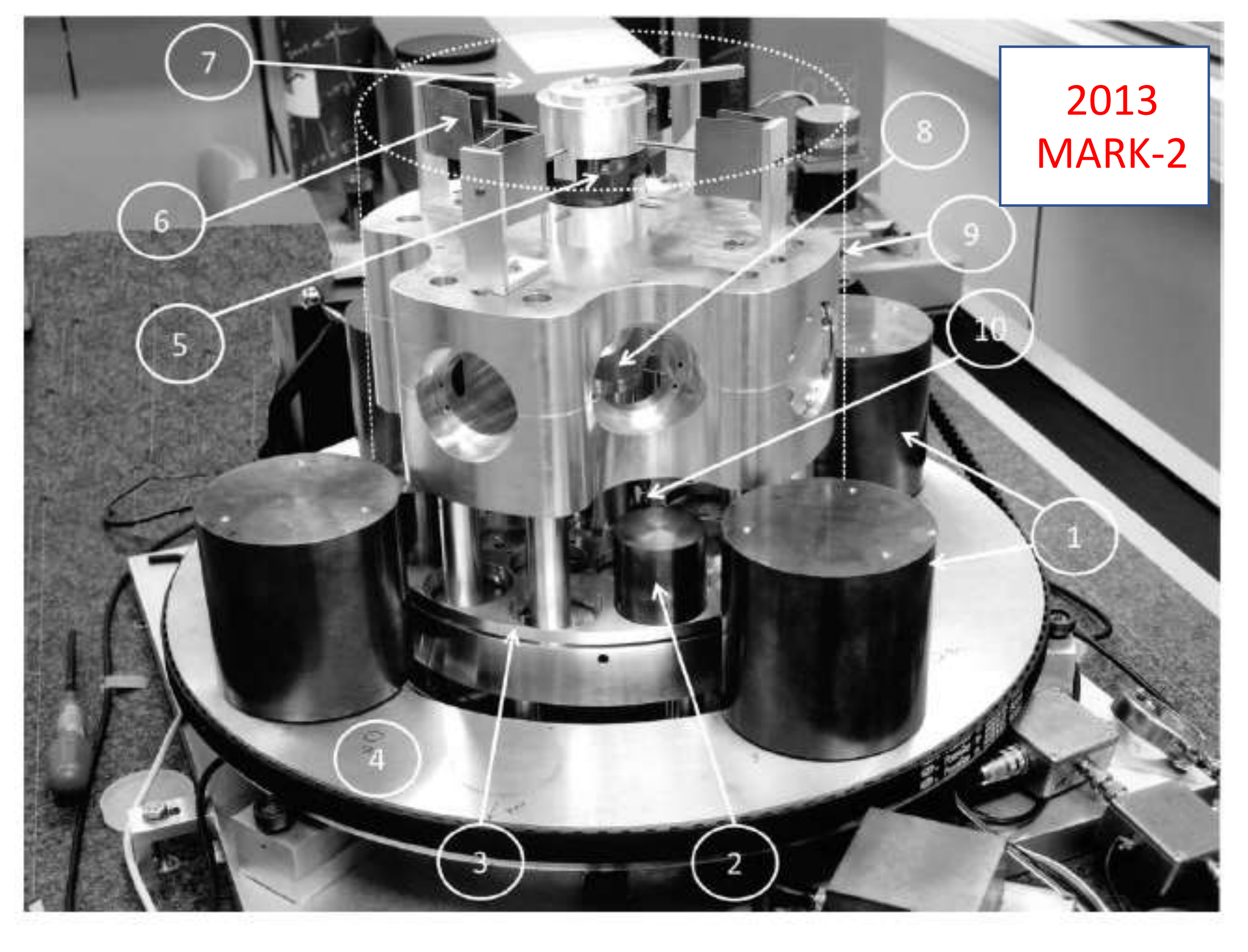


The story


2013
2001
6.671
6.672
6.673
6.674
6.675
6.676
$G/(10^{-11}\ \mathrm{m^3 kg^{-1} s^{-2}})$

The BIPM instruments





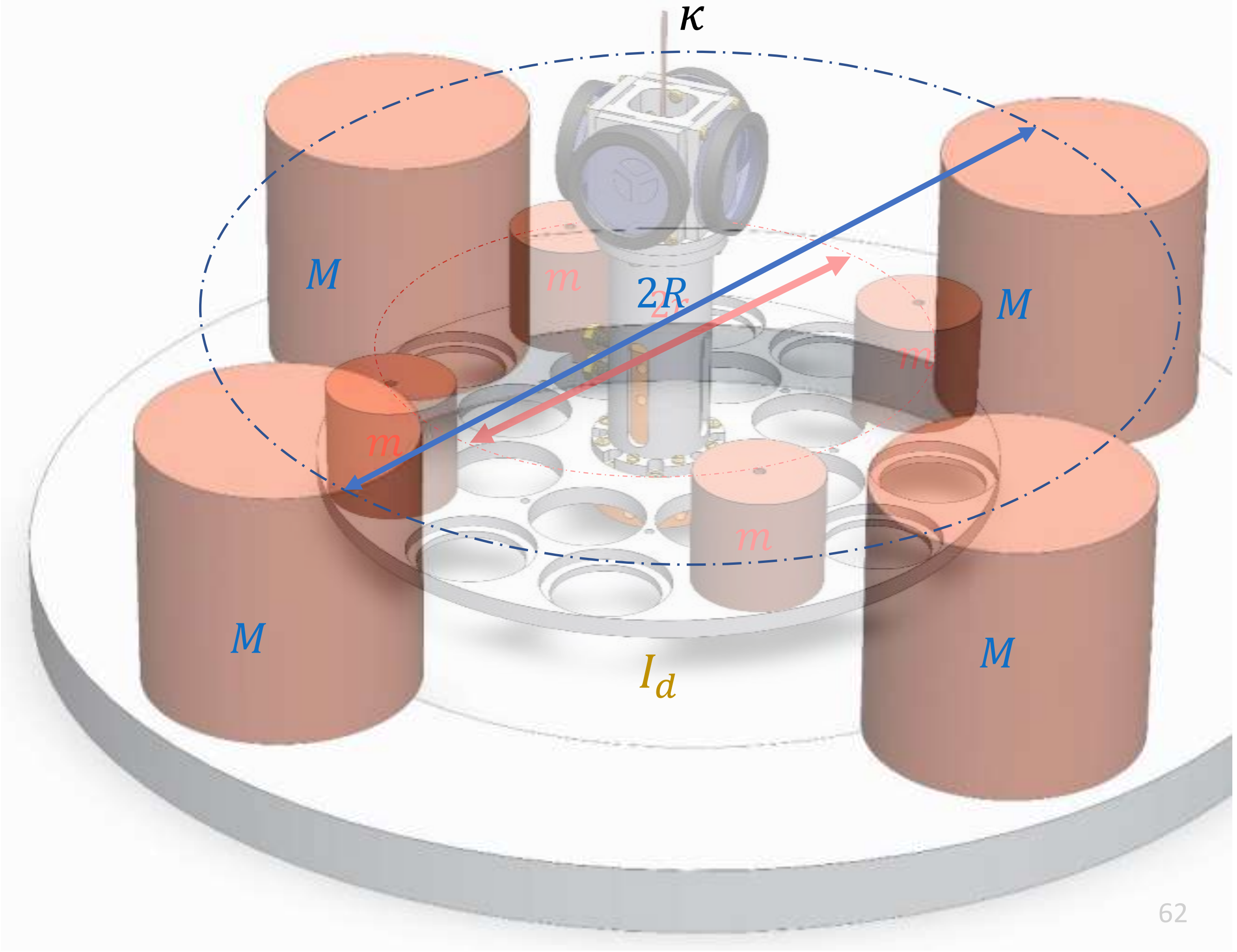
National Institute of Standards and Technology
U.S. Department of Commerce

Work with V. Lee, C.C. Speake, L. Chao

Technical Data

m	1.2	kg
r	120	mm
κ	204	μN m
I_d	745	g dm²
$^{I_d}/_{(4m\,r^2)}$	0.11	
T_o	121	s

Vacuum can not shown!



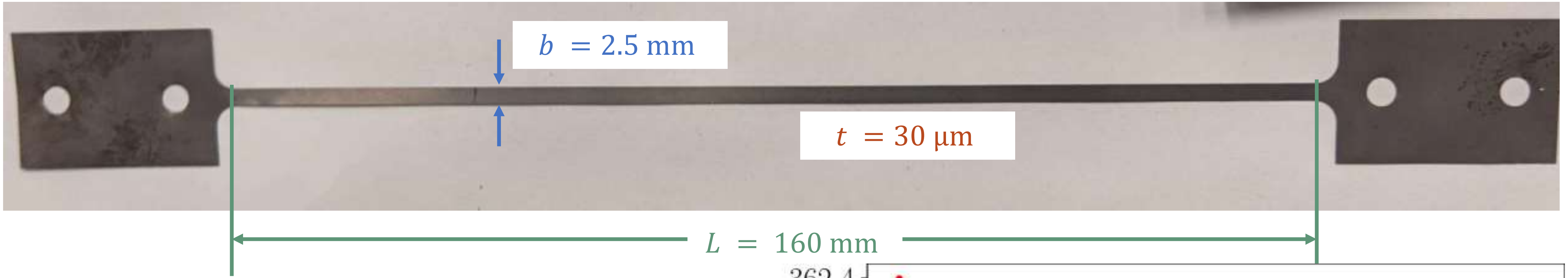
Remarkable Experiment

1. One instrument, two measurements: Cavendish and electrostatic servo

- Different sensitivities to different parameters:

$$G_{Cav} \propto \phi \qquad G_{servo} \propto \phi^{-1}$$
$$G_{Cav} \propto m^{0.1} \qquad G_{servo} \propto m$$
$$G_{Cav} \propto r^{2.2} \qquad G_{servo} \propto r^{4}$$

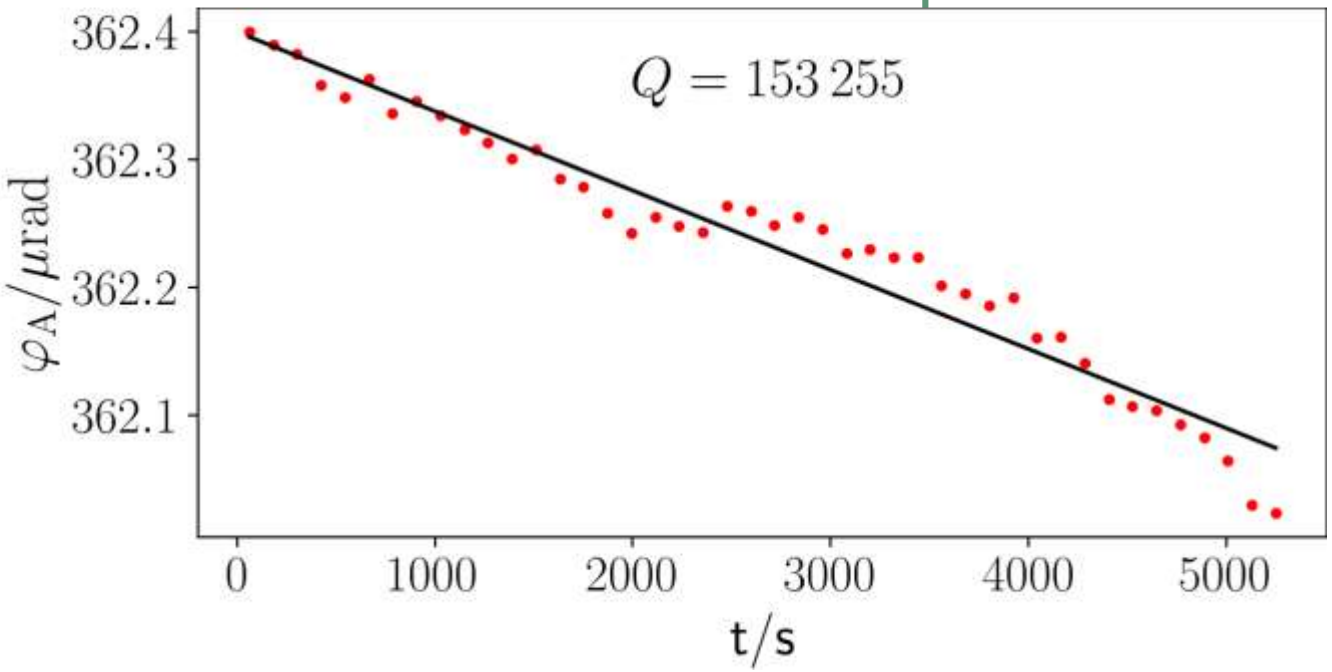
The torsion strip



$$\kappa = \underbrace{\frac{b t^3 F}{3\,L}}_{\text{elastic}} + \underbrace{\frac{(4m + m_{disk}) g\, b^2}{12\,L}}_{\text{conservative}}$$

elastic 4%

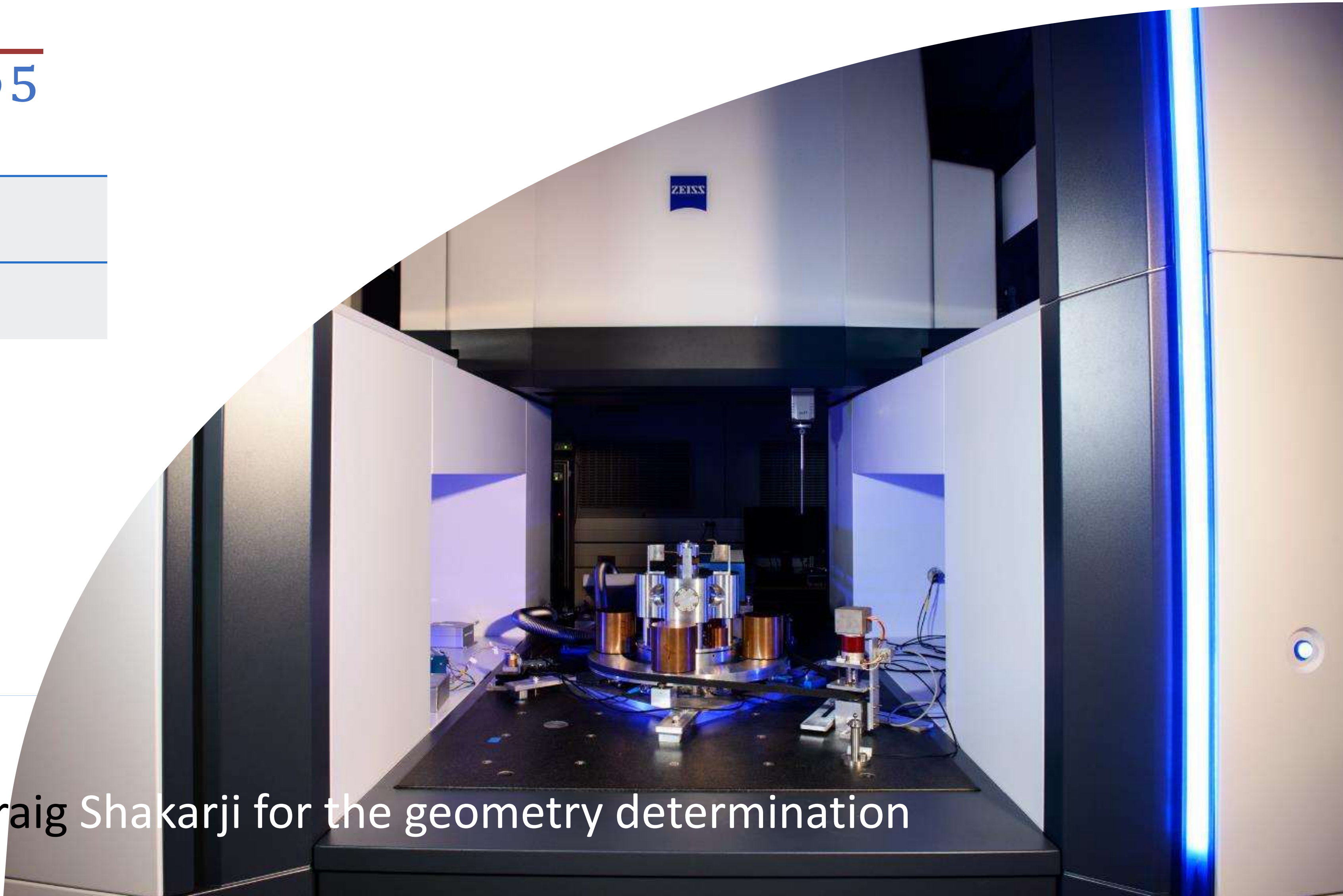
conservative 96%



Hexadecapole gravitational attraction

$$\Delta N \approx G\, 70\, Mm \frac{r^4}{R^5}$$

r	120	mm
R	240	mm



Thank you, Vincent Lee and Craig Shakarji for the geometry determination

Blind measurement

$$M_{adj} = (1 + R)M$$

$$-10^{-3} \leq R \leq 10^{-3}$$

Test	σ_m/m	5	$\times 10^{-8}$
Copper	σ_M/M	2	$\times 10^{-7}$
Sapphire	σ_M/M	4	$\times 10^{-7}$

Thank you, Patrick Abbott for the mass determination.

Cavendish mode

$$G_{Cav} = \Delta\varphi \frac{16\pi^2}{T_o^2} \frac{R^5}{70Mr^2} \left(1 + \frac{I_\mathrm{d}}{4mr^2}\right)$$

To be measured:

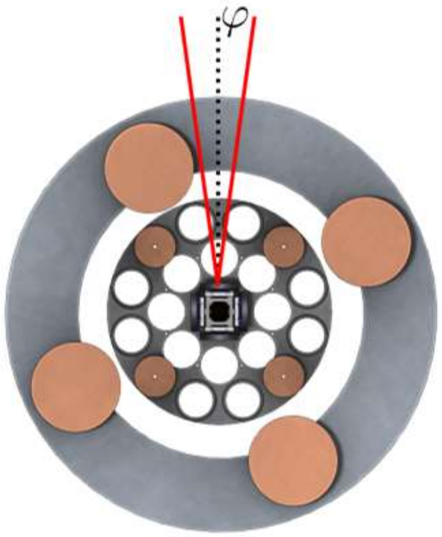
T_o,$\Delta\varphi$

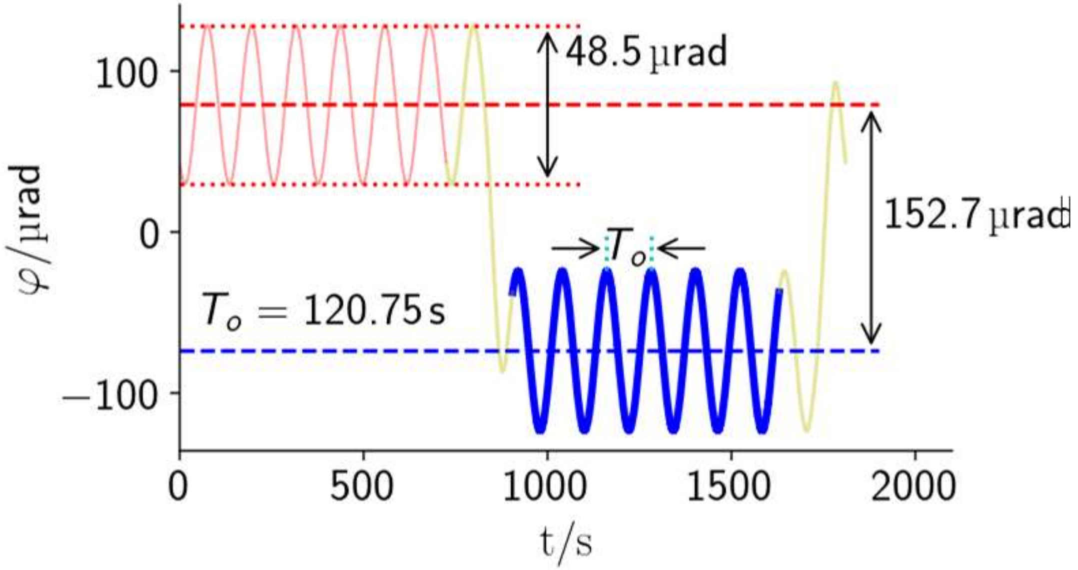
Geometry and masses:

m, M, r, R

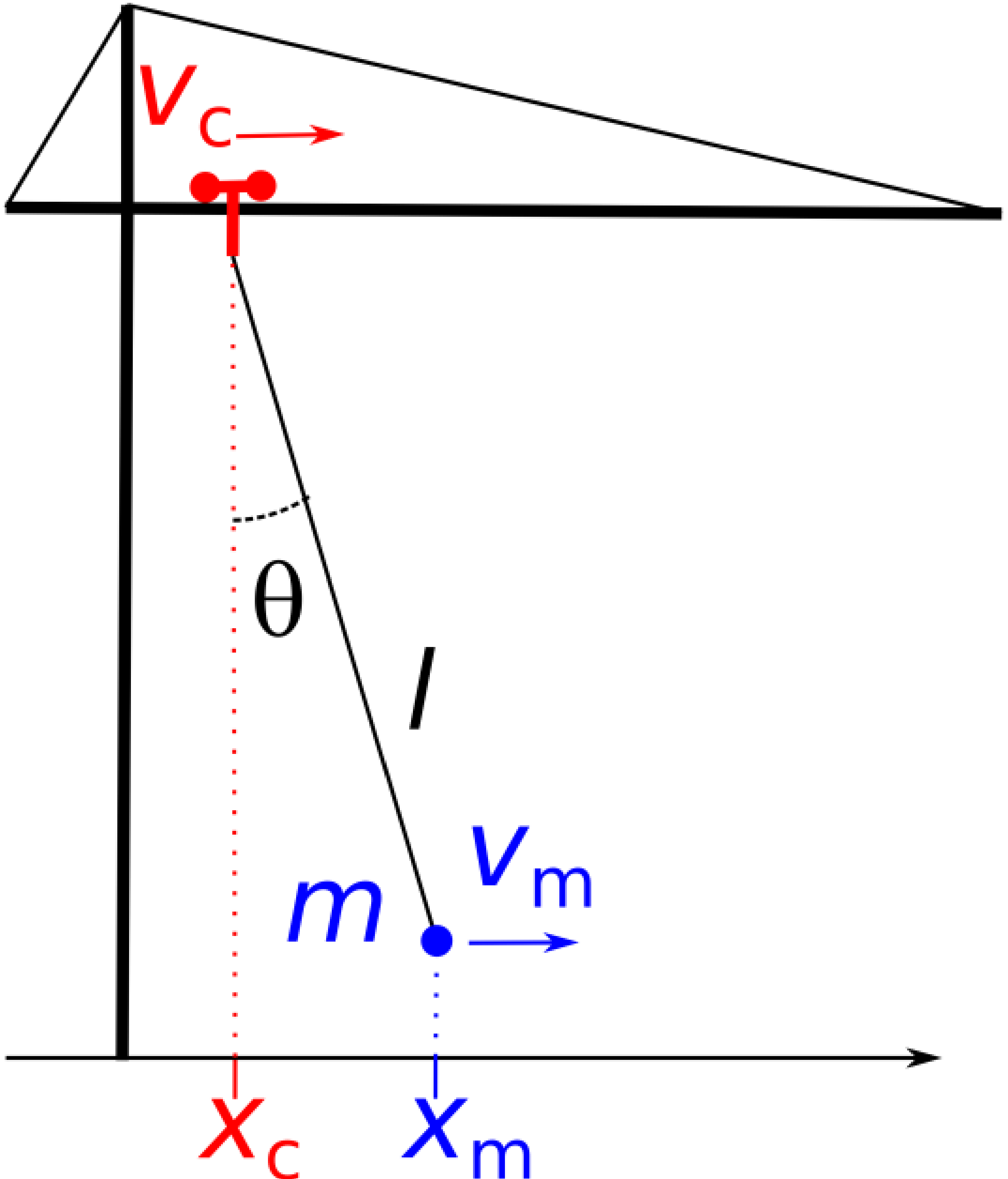
To be calculated:

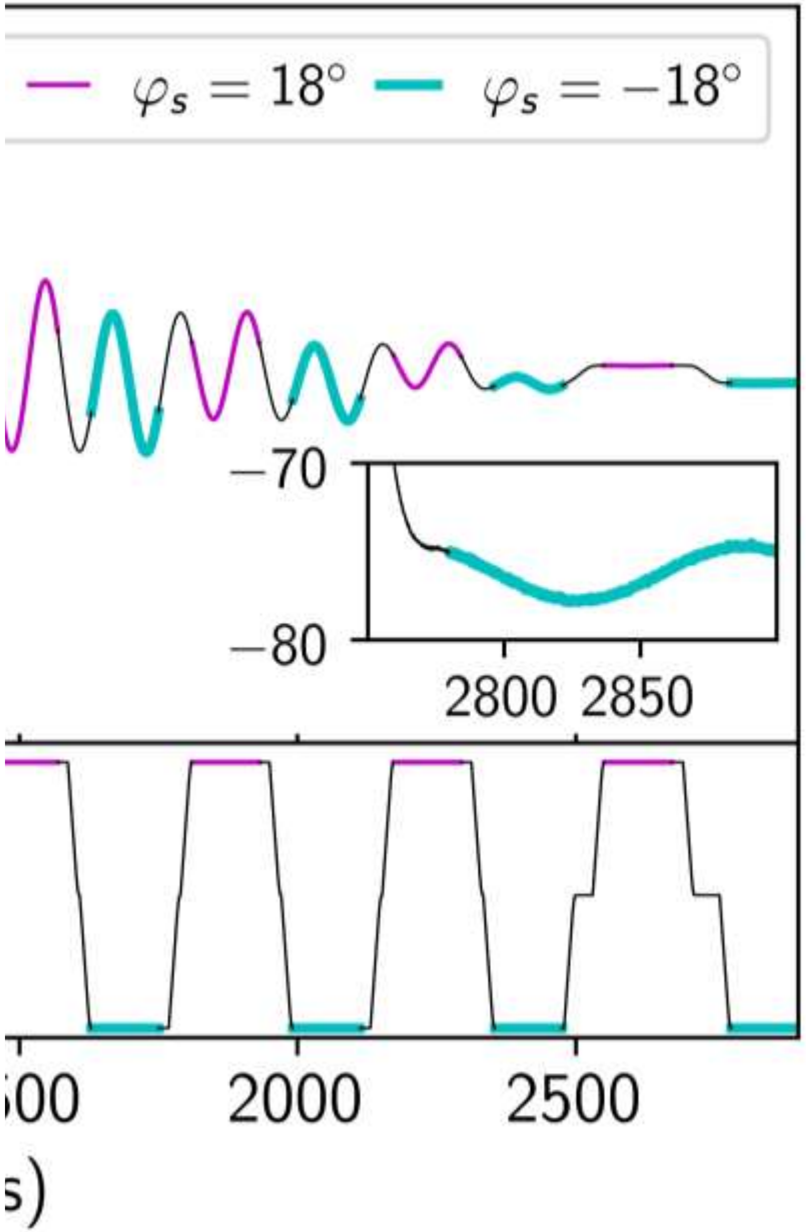
I_d

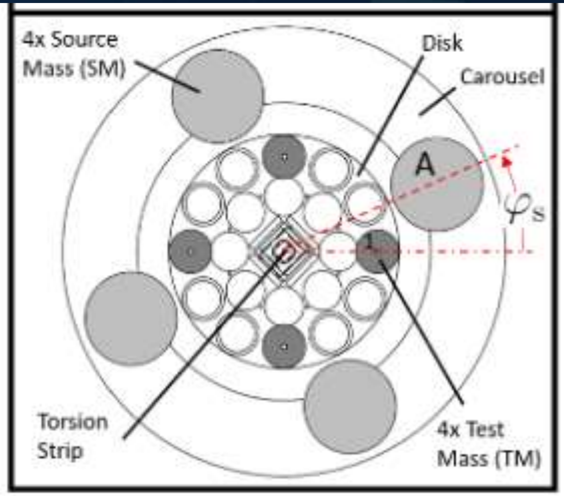




Our contribution to crane safety

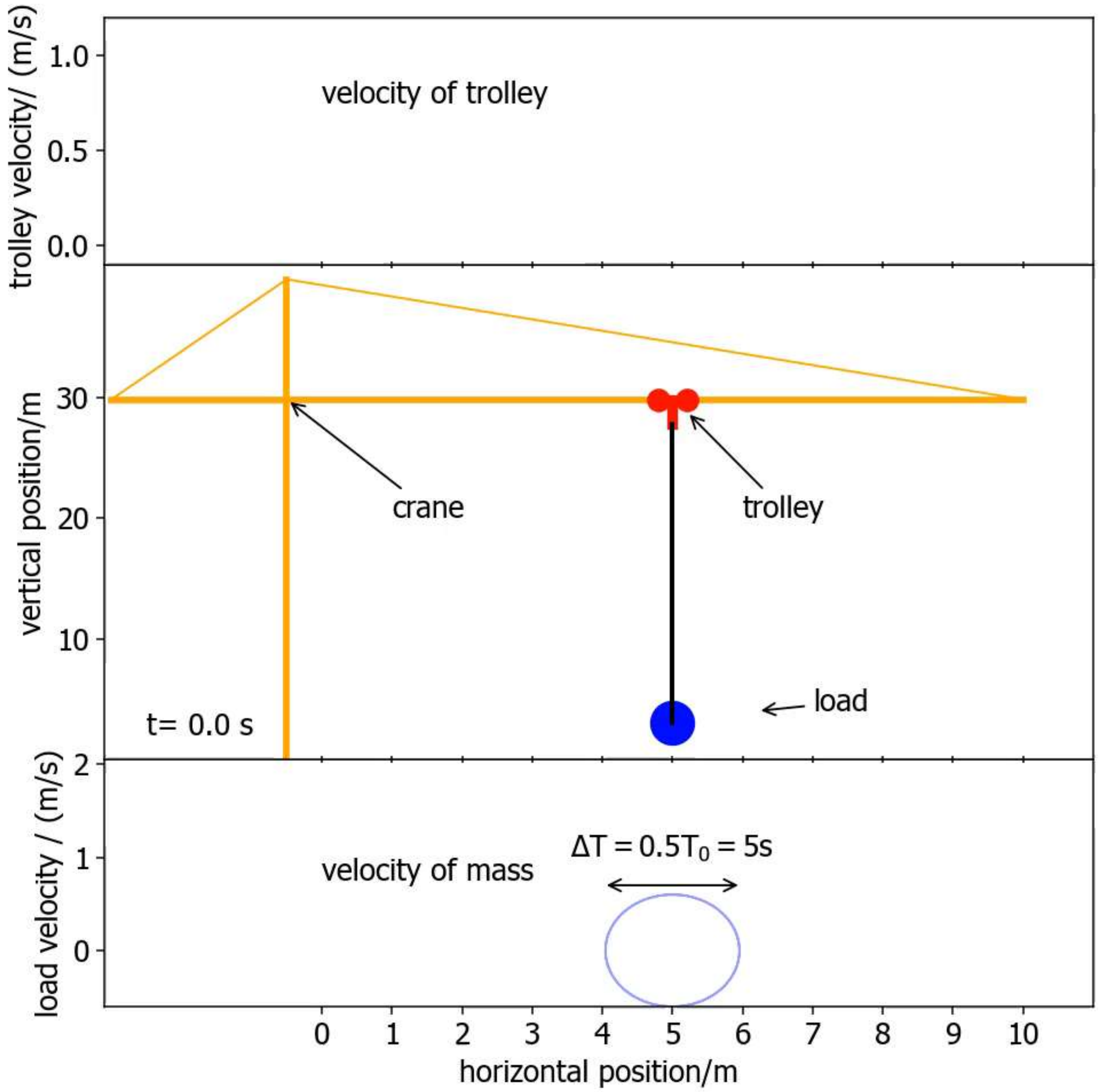




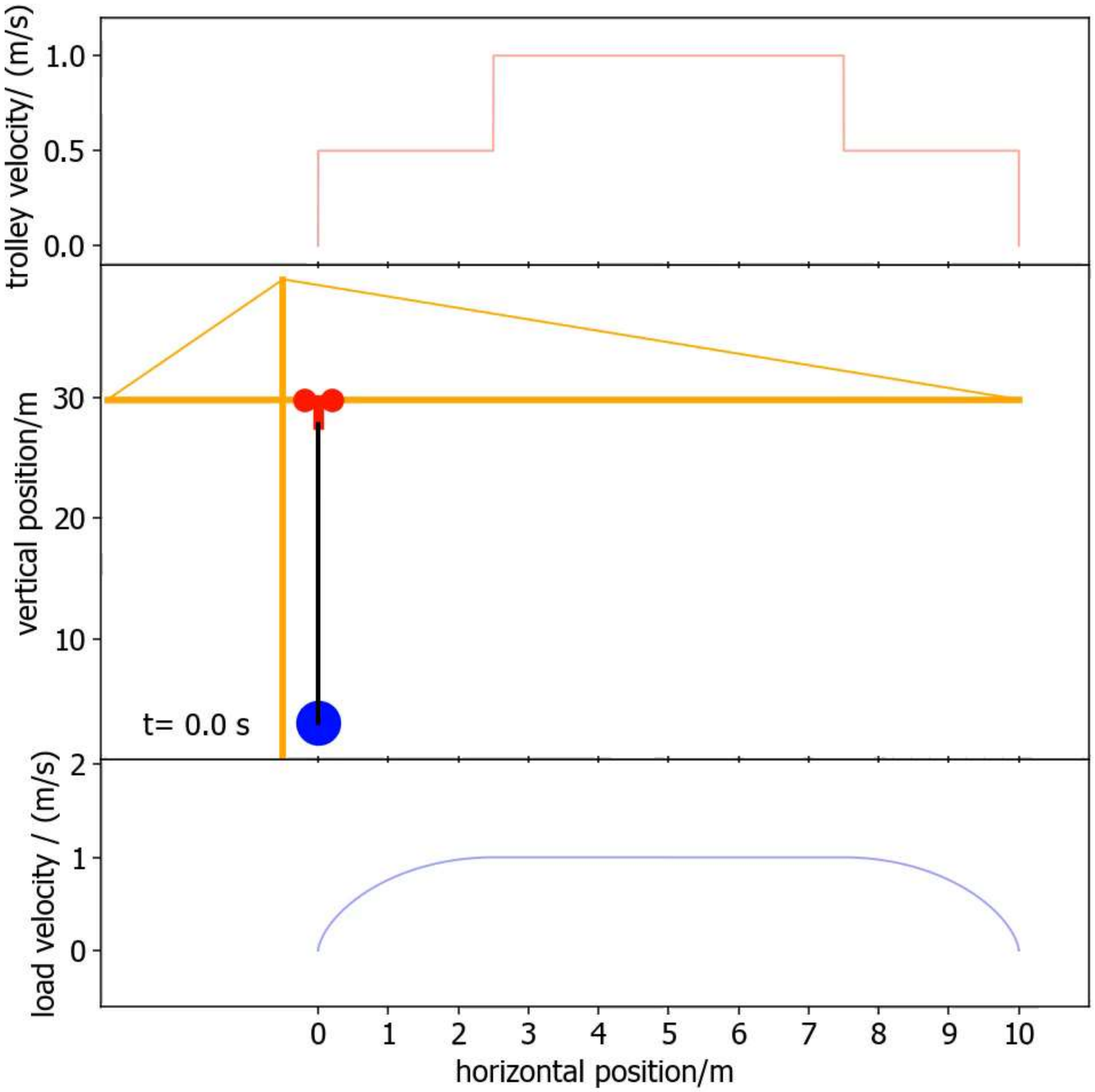


"The Crane Operator's Trick and other Shenanigans with a Pendulum",
Am. J. Physics.

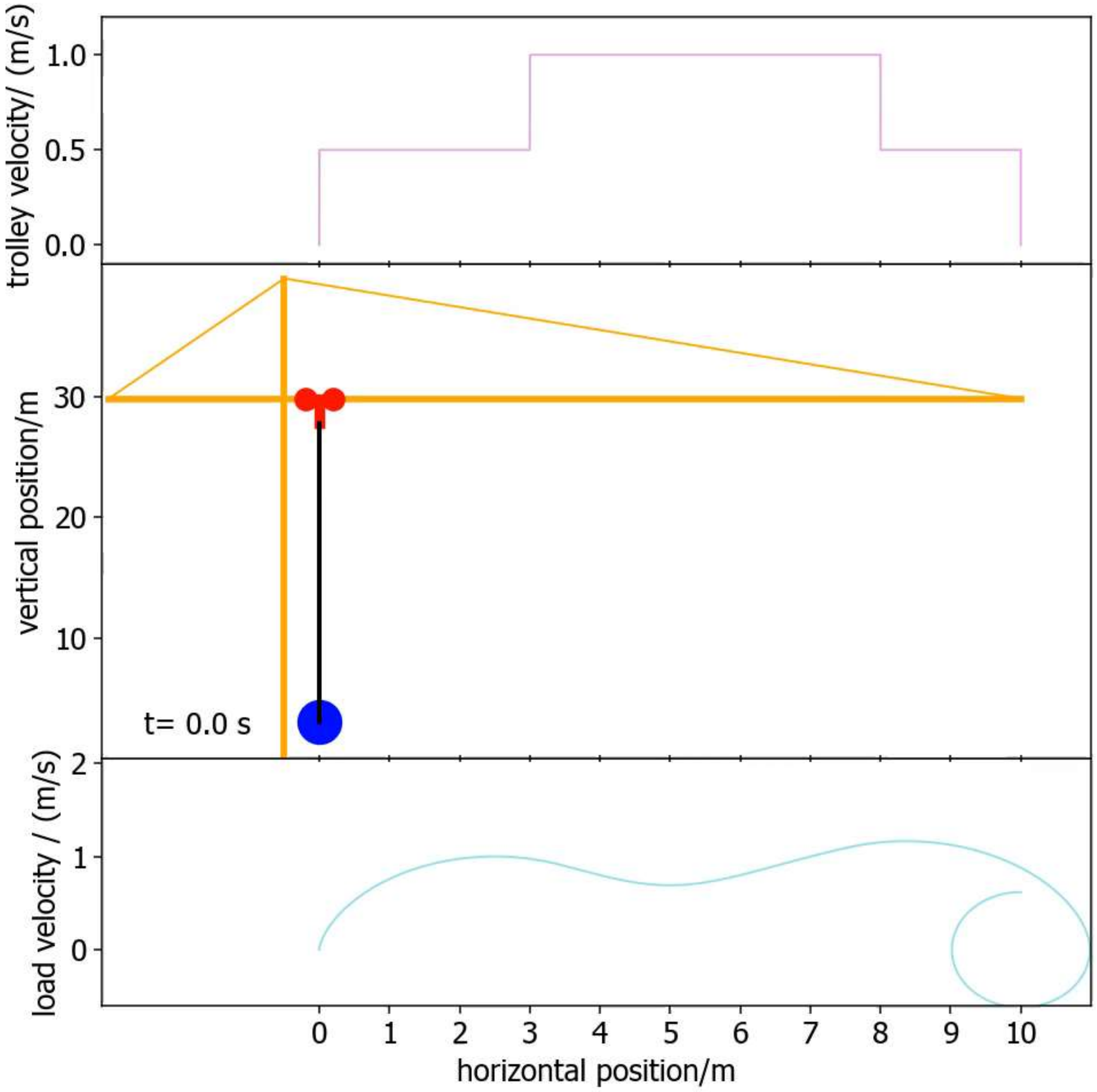
Crane analysis 1



Crane analysis 2

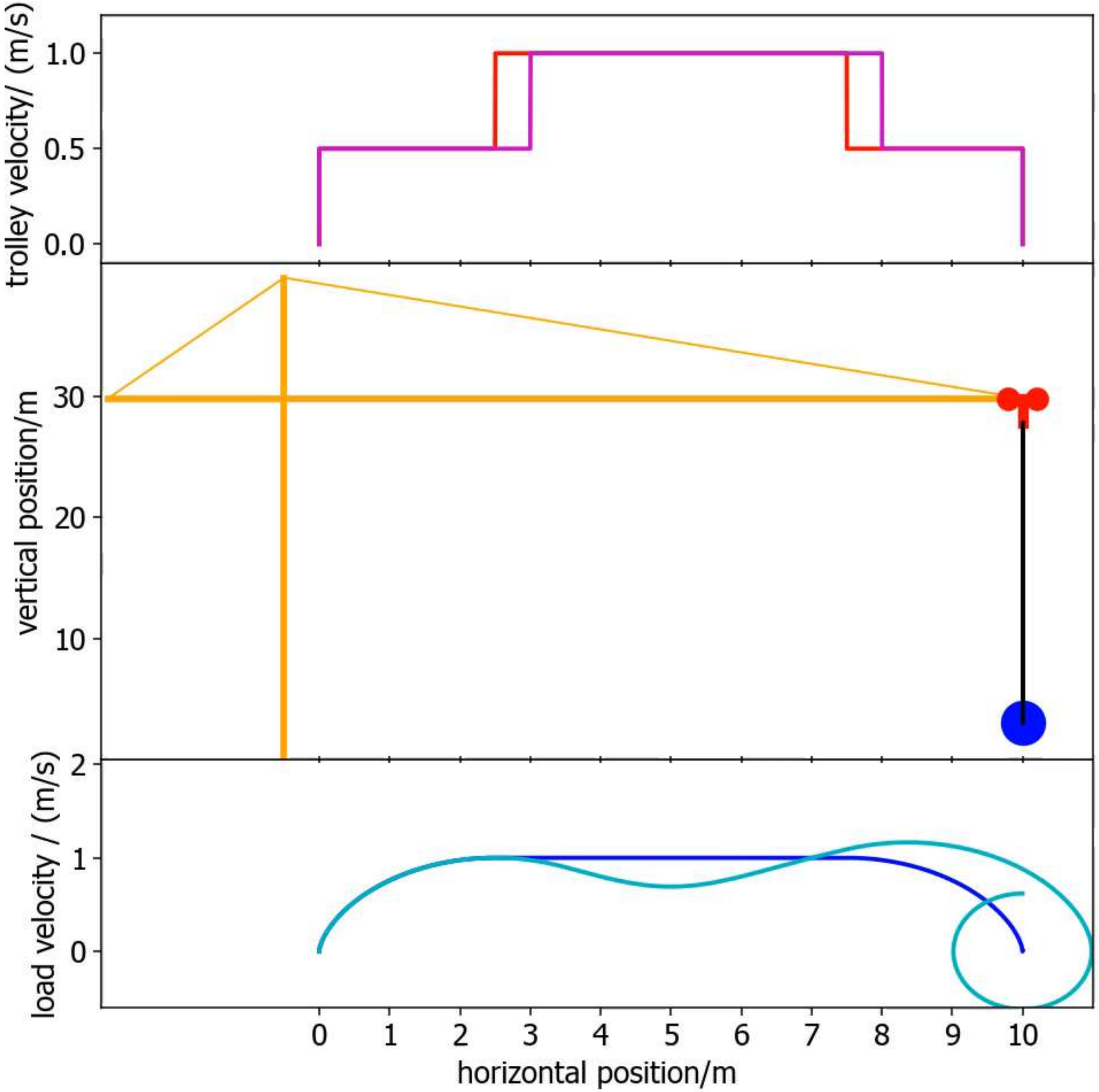


Crane analysis 3



Crane analysis 4

vs.



Electrostatic servo

$$N_{el} = -\frac{k_{12}}{2}\langle V_{12}^2\rangle - \frac{k_{13}}{2}\langle V_{13}^2\rangle - \frac{k_{23}}{2}\langle V_{23}^2\rangle$$

$$G_{servo} = \frac{R^5}{70Mmr^4}(\Delta N_{el})$$

To be measured:

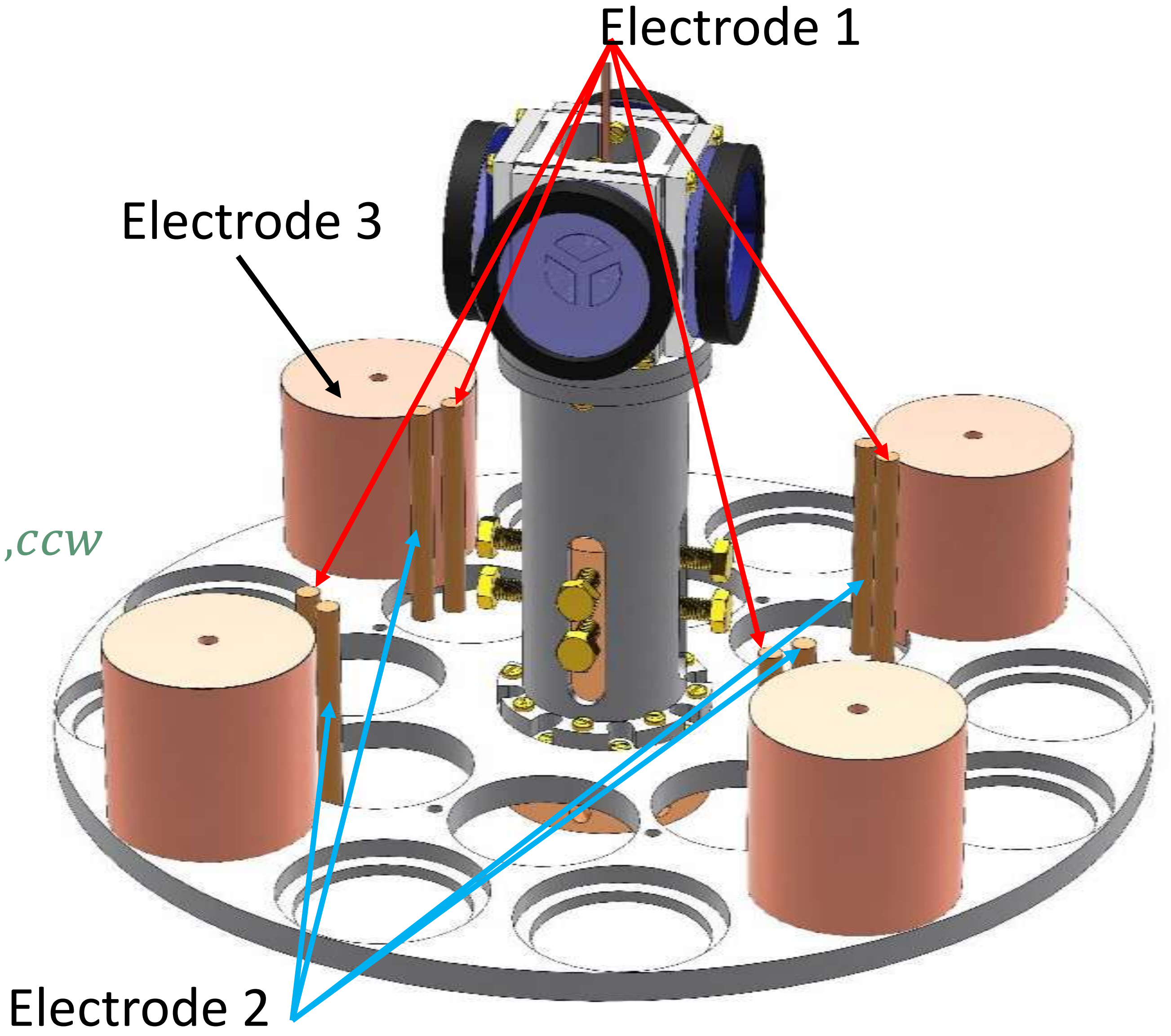
$k_{12}, k_{13}, k_{23}, V_{13,cw}, V_{23,cw}, V_{13,ccw}, V_{23,ccw}$

Geometry and masses:

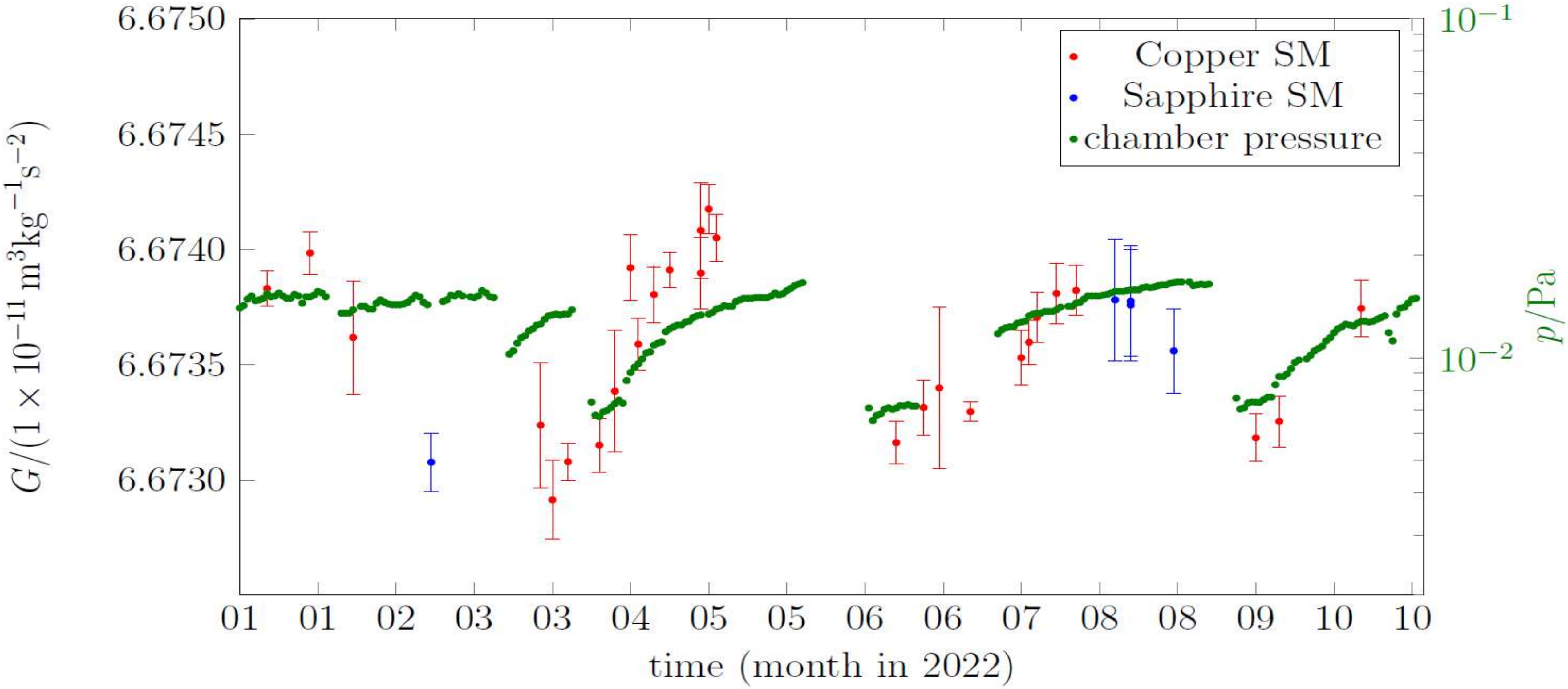
m, M, r, R

Note:

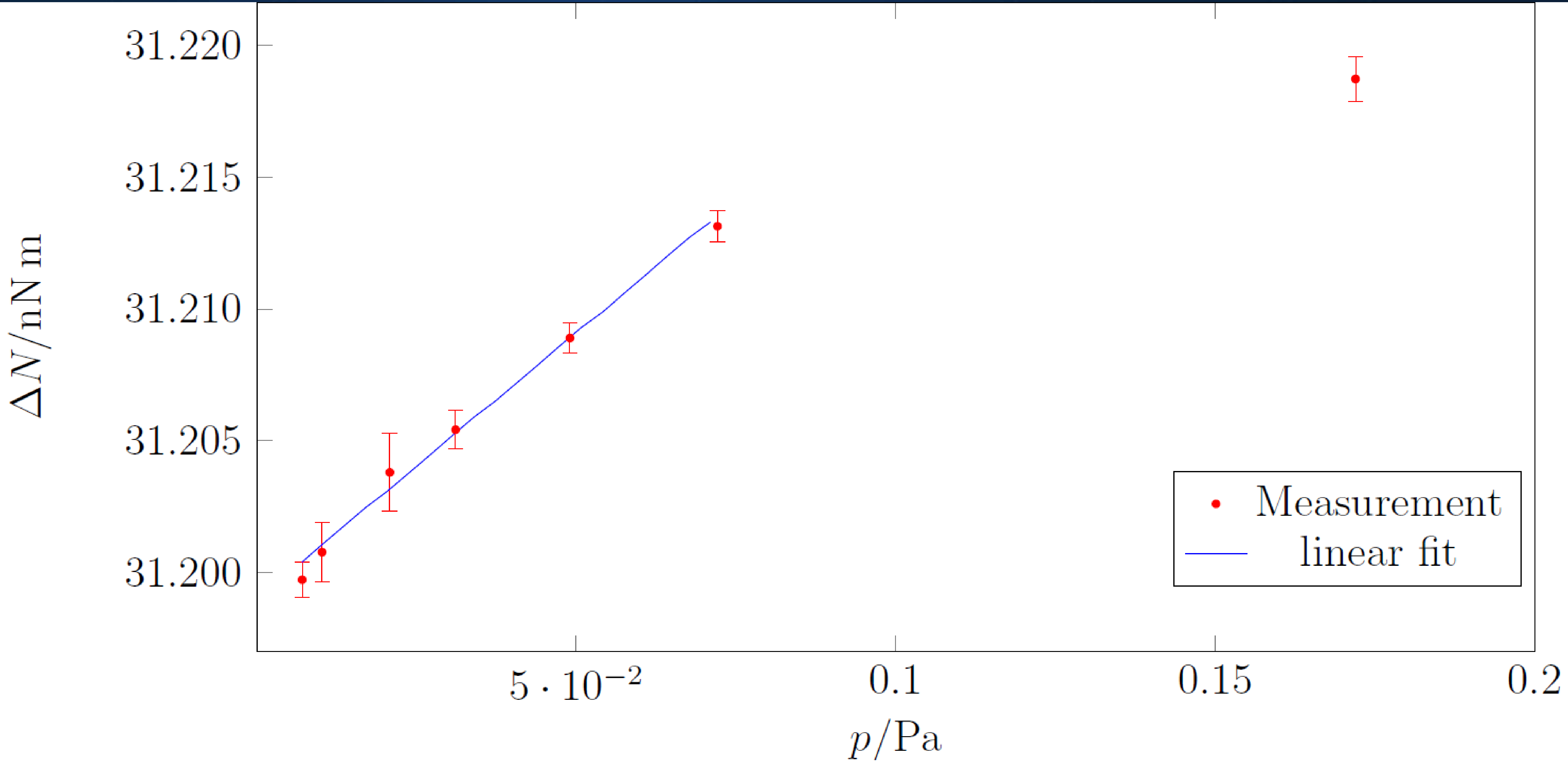
$k_{ij} = \frac{\partial C_{ij}}{\partial \varphi}$, $V_{12} = \mathrm{V}_{13} - \mathrm{V}_{23}$



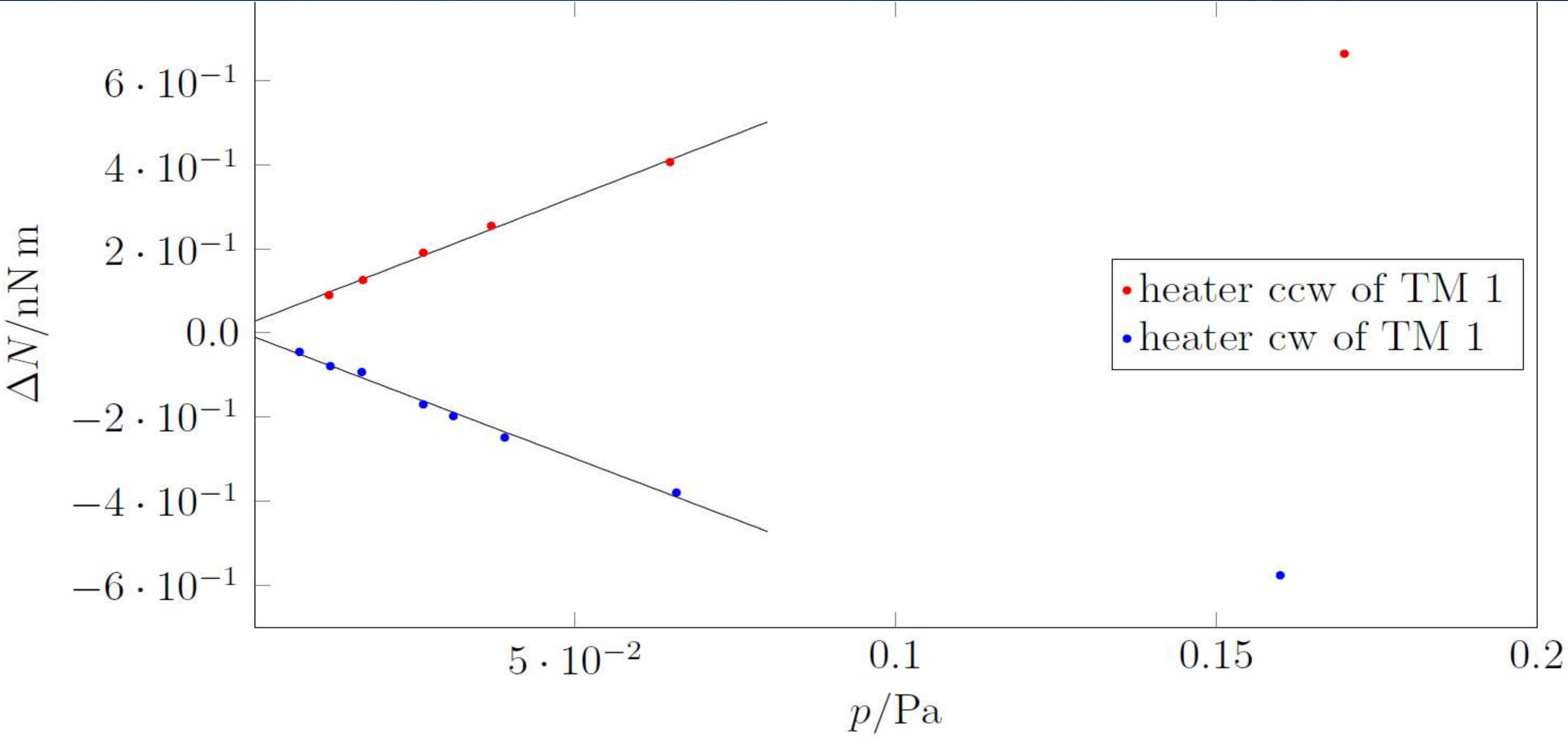
I wish, I could give you a new value for *G*



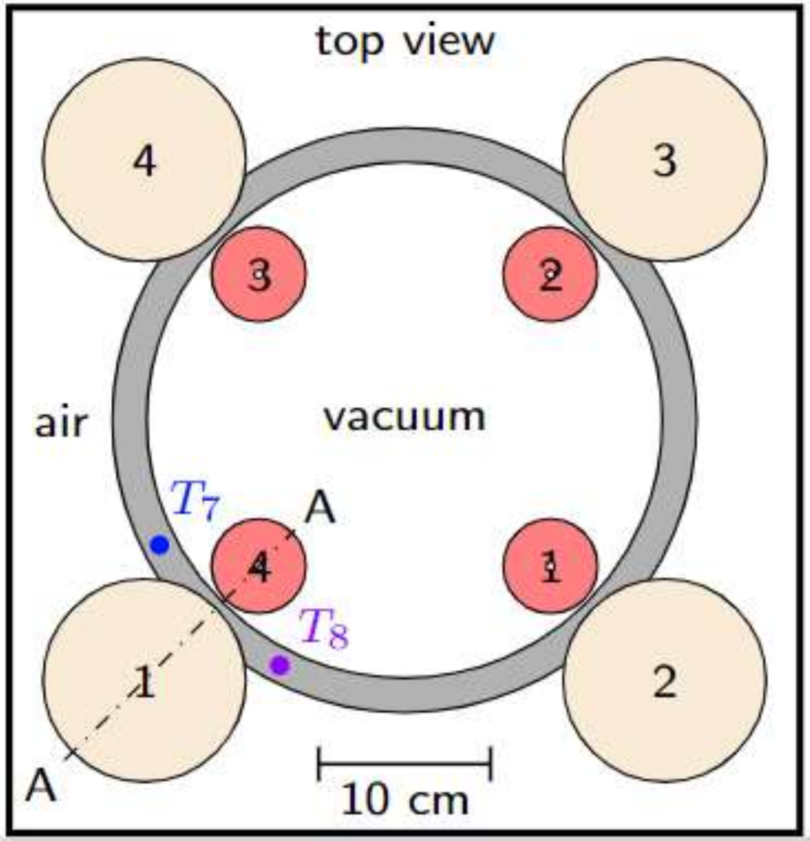
A more systematic investigation

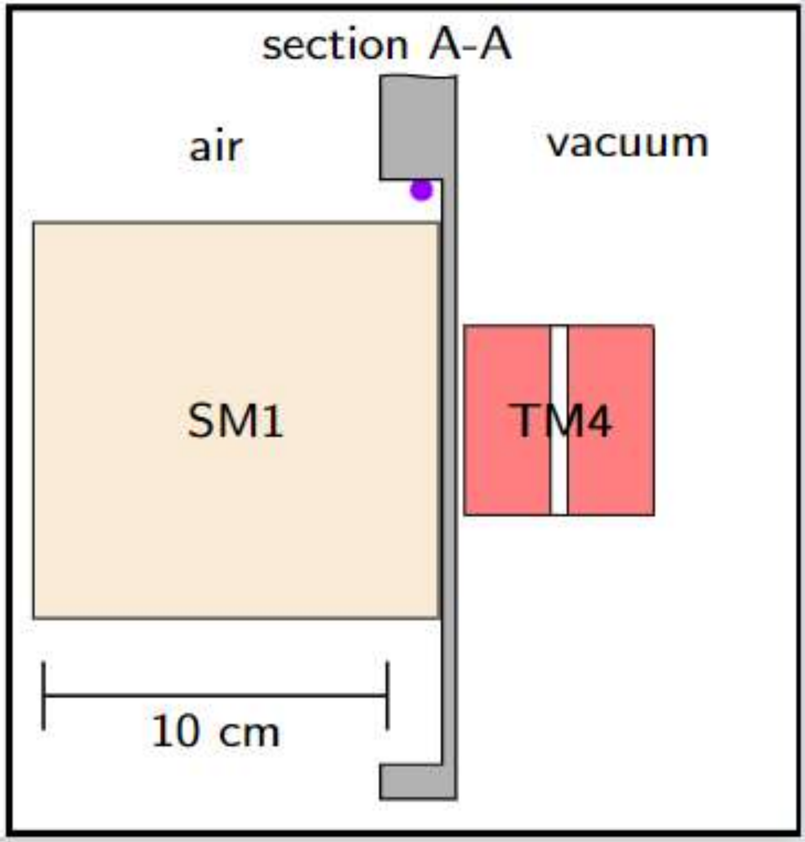


Torque generated by heat



Crooke's radiometer





$$\Delta N_{spur} = p\,\Delta T$$

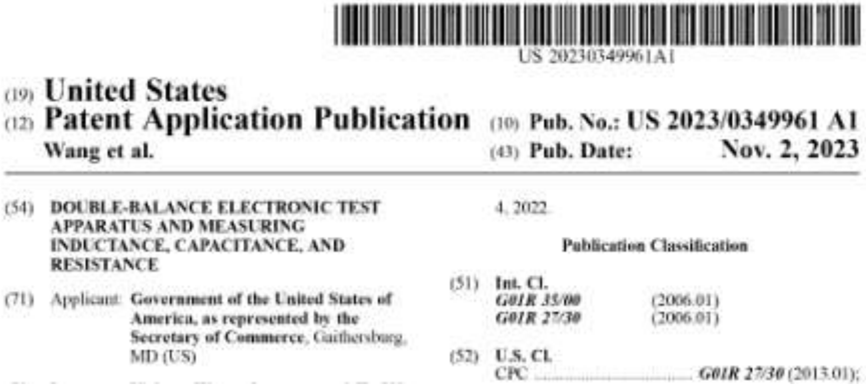
Take away points

- How it all hangs together, new SI.
- How to measure forces.
- Persist!

Postdoc opportunity for an Electrical Engineer/Physicist at the National Institute of Standards and Technology

- You’re passionate about mixed-signal design, digital techniques, data acquisition, and analysis.
- You’re curious about fundamental metrology, units, and measurements.
- Opportunity to work with a world-class team on digital techniques to compare unlike impedances (C to R) with very small relative uncertainties (10^{-7} or better).
- Work will be conducted at NIST’s Gaithersburg campus in Maryland – with at most one remote day per week.
- Overview: https://www.nist.gov/programs-projects/farad-and-impedance-metrology

- Patent pending technology:


US 20230349961A1

(19) United States
(12) Patent Application Publication
Wang et al.

(10) Pub. No.: US 2023/0349961 A1
(43) Pub. Date: Nov. 2, 2023

(54) DOUBLE-BALANCE ELECTRONIC TEST APPARATUS AND MEASURING INDUCTANCE, CAPACITANCE, AND RESISTANCE

(71) Applicant: Government of the United States of America, as represented by the Secretary of Commerce, Gaithersburg, MD (US)

4, 2022

Publication Classification

(51) Int. Cl.
G01R 35/00 (2006.01)
G01R 27/30 (2006.01)

(52) U.S. Cl.
CPC G01R 27/30 (2013.01);

Reach out to one or both us:

Yicheng Wang
yicheng.wang@nist.gov

Stephan Schlamminger
Stephan.Schlamminger@nist.gov

Thank you for your attention.

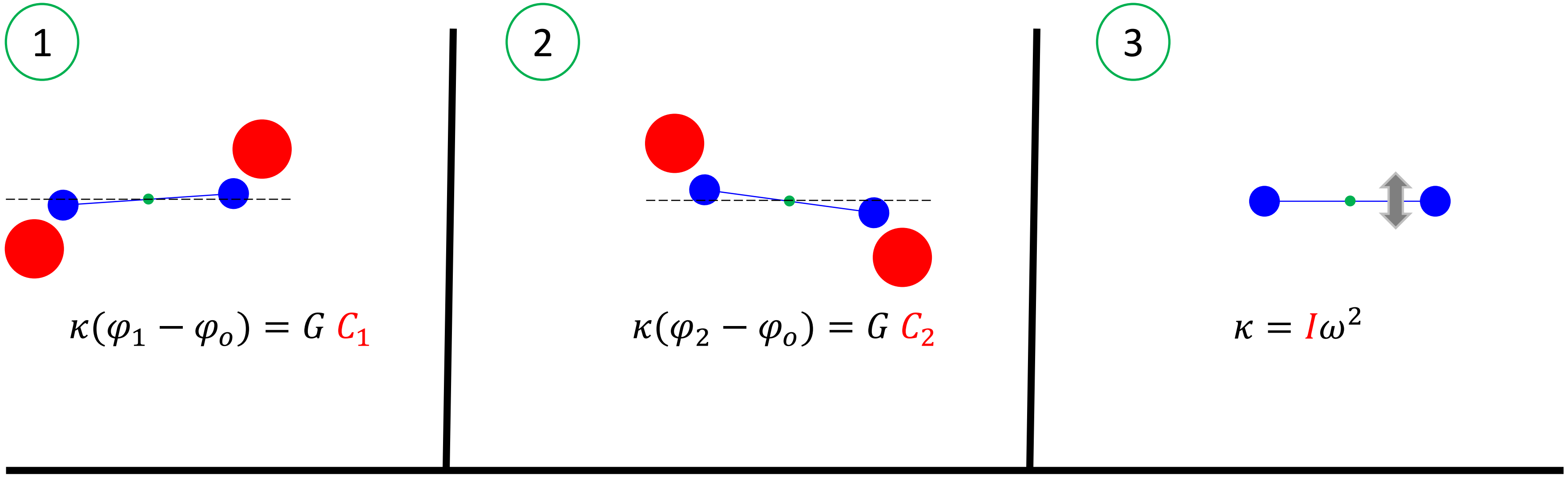
National Institute of Standards and Technology
U.S. Department of Commerce

NIST

Remarkable features

- Two methods, one instrument: Cavendish and electrostatic servo.
- Torsion strip, not a round fiber.
- Hexadecapole mass configuration.

Cavendish method



$\kappa(\varphi_1 - \varphi_o) = G\,C_1$

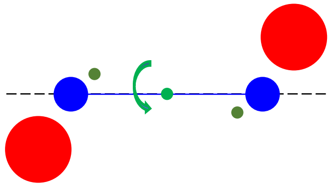
$\kappa(\varphi_2 - \varphi_o) = G\,C_2$

$\kappa = I\omega^2$

$$G = \frac{(\varphi_1 - \varphi_2)\omega^2}{C_1 - C_2} I$$

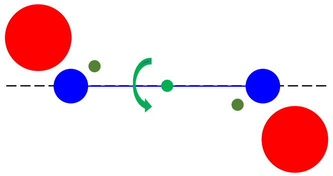
Servo method

1



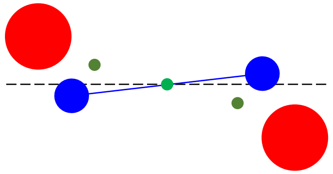
$$\kappa\varphi + \frac{1}{2}\frac{\mathrm{d}C}{\mathrm{d}\varphi}V_1^2 = G\,C_1$$

2



$$\kappa\varphi + \frac{1}{2}\frac{\mathrm{d}C}{\mathrm{d}\varphi}V_2^2 = G\,C_2$$

3

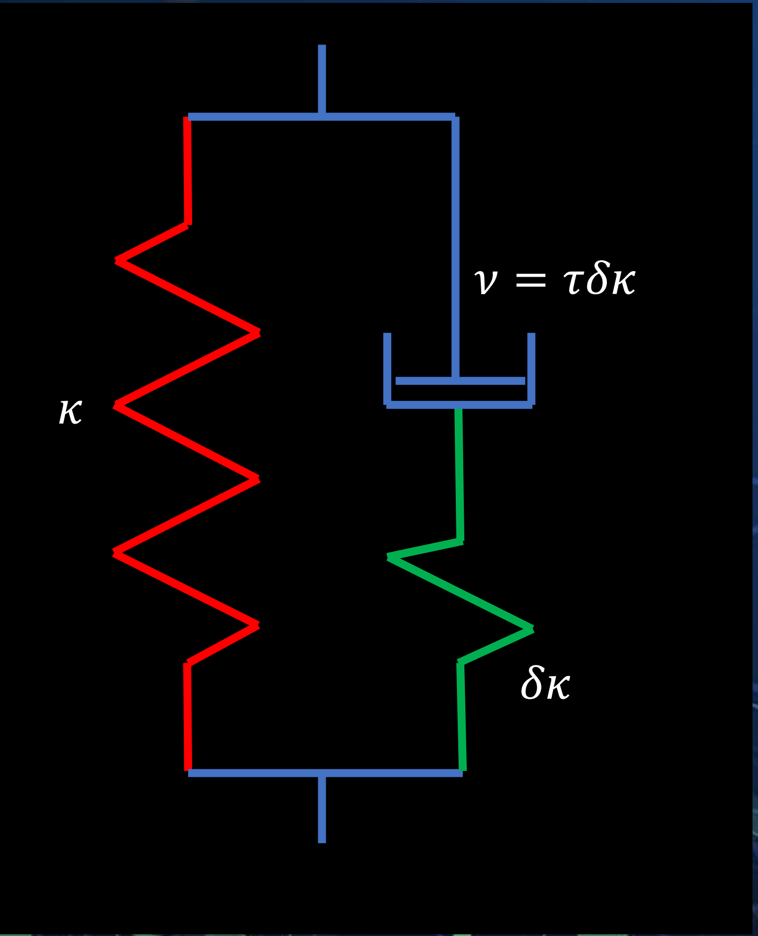


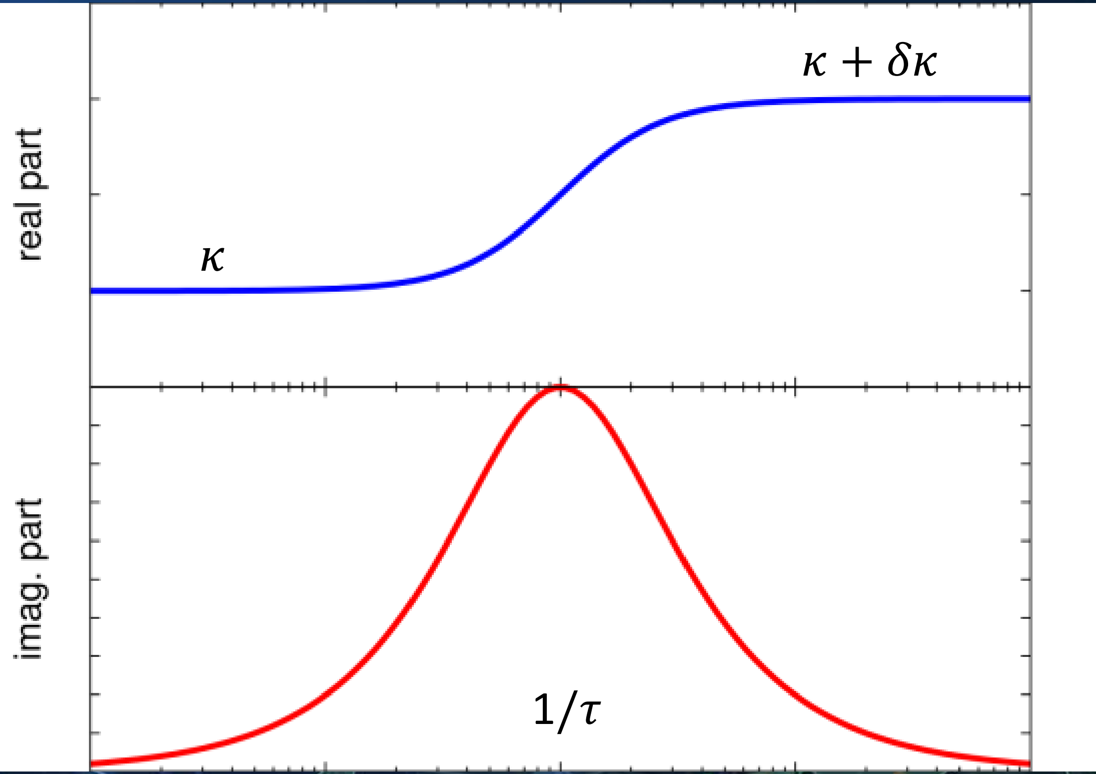
$$C(\varphi) \Rightarrow \frac{\mathrm{d}C}{\mathrm{d}\varphi}$$

$$G = \frac{1}{2}\frac{\mathrm{d}C}{\mathrm{d}\varphi}\frac{(V_1^2 - V_2^2)}{C_1 - C_2}$$

Mark I: DC servo
Mark 2: AC servo

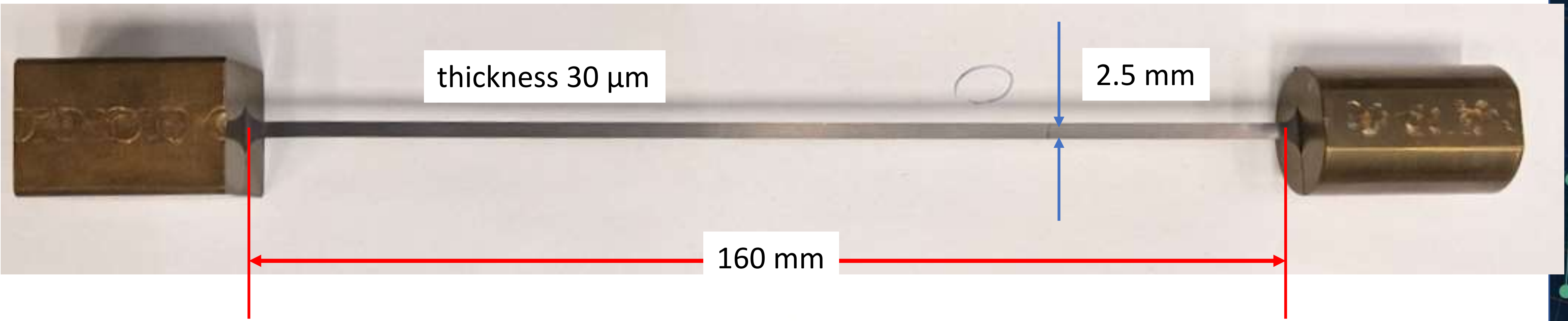
Why is the Cavendish method trouble?





$$\frac{\sigma_G}{G} = \frac{1}{2Q}$$

Torsion strip



$$k = \frac{bt^3 F}{3L} + \frac{M_p g b^2}{12L} = 0.204 \text{ mNm}$$

elastic 4%

conservative 96 %

can carry 9.9 kg

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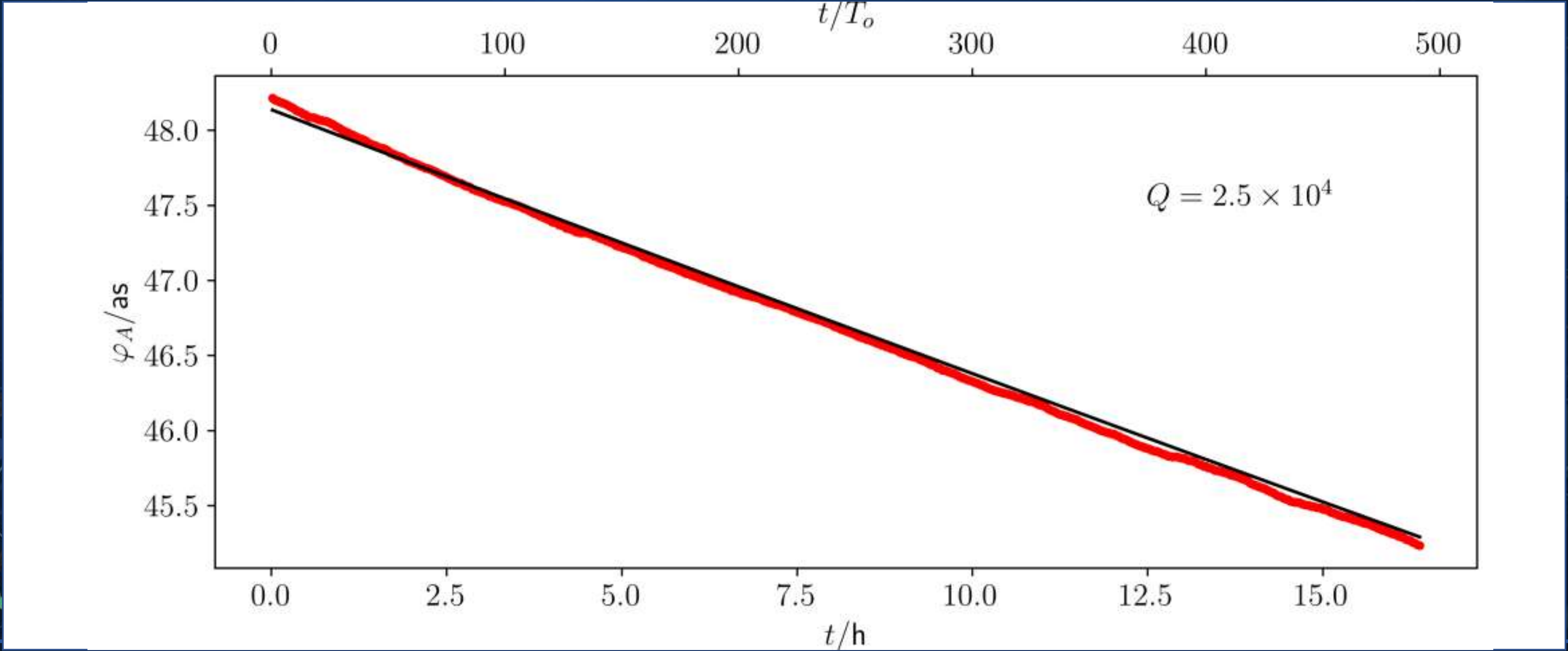
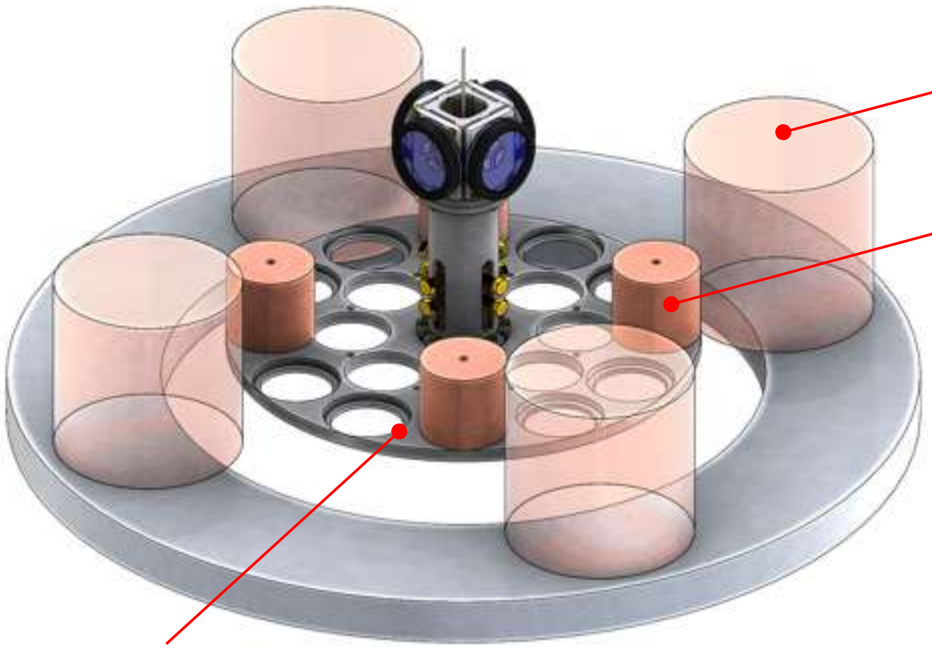
U.S. Department of Commerce

High Q



t/T_o
0
100
200
300
400
500
$Q = 2.5 \times 10^4$
48.0
47.5
47.0
46.5
46.0
45.5
φ_A/as
0.0
2.5
5.0
7.5
10.0
12.5
15.0
t/h

hexadecapole mass arrangement



source mass $M = 11.2$ kg, located at $R = 214$ mm

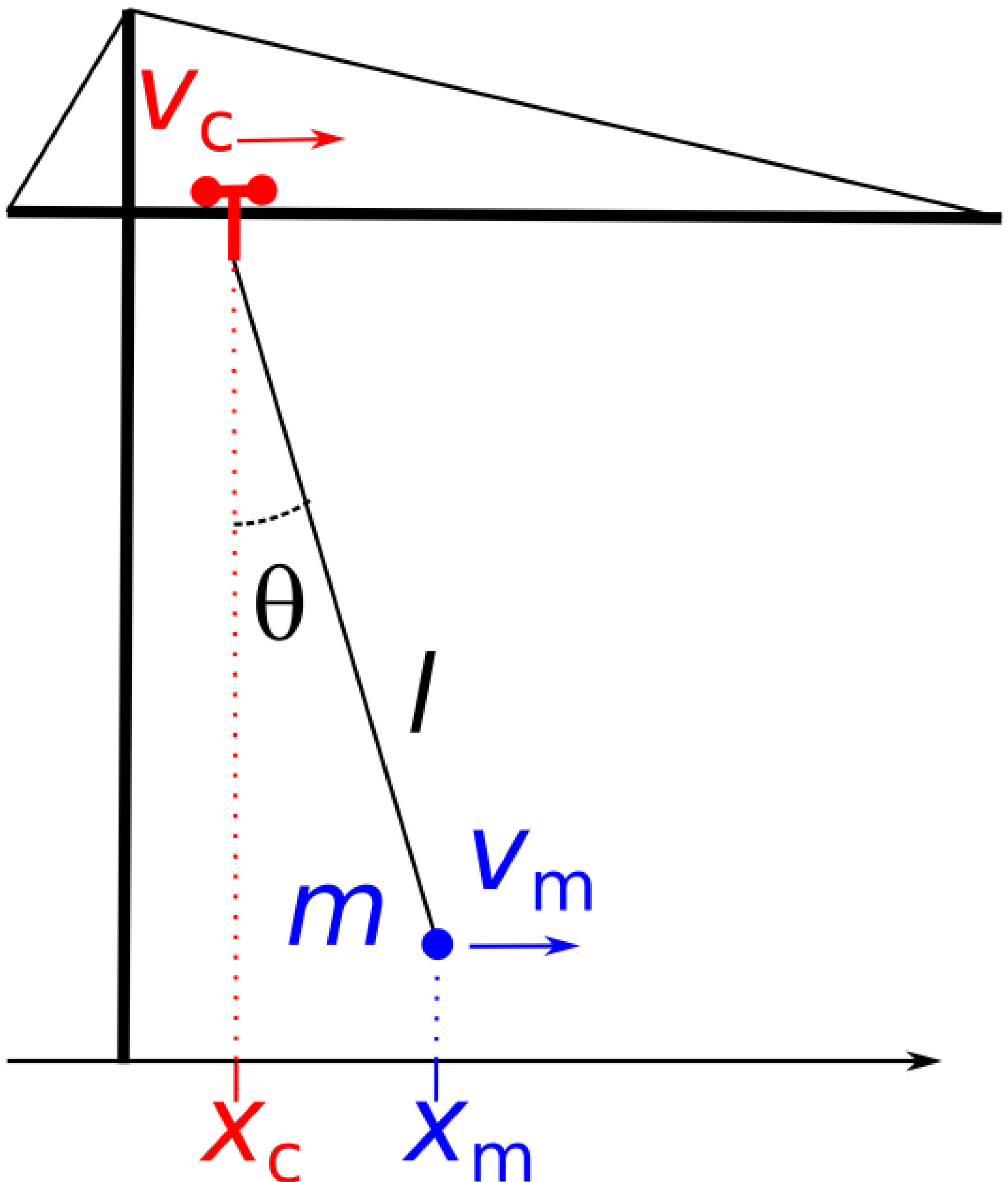
test mass $m = 1.15$ kg, located at $r = 120$ mm

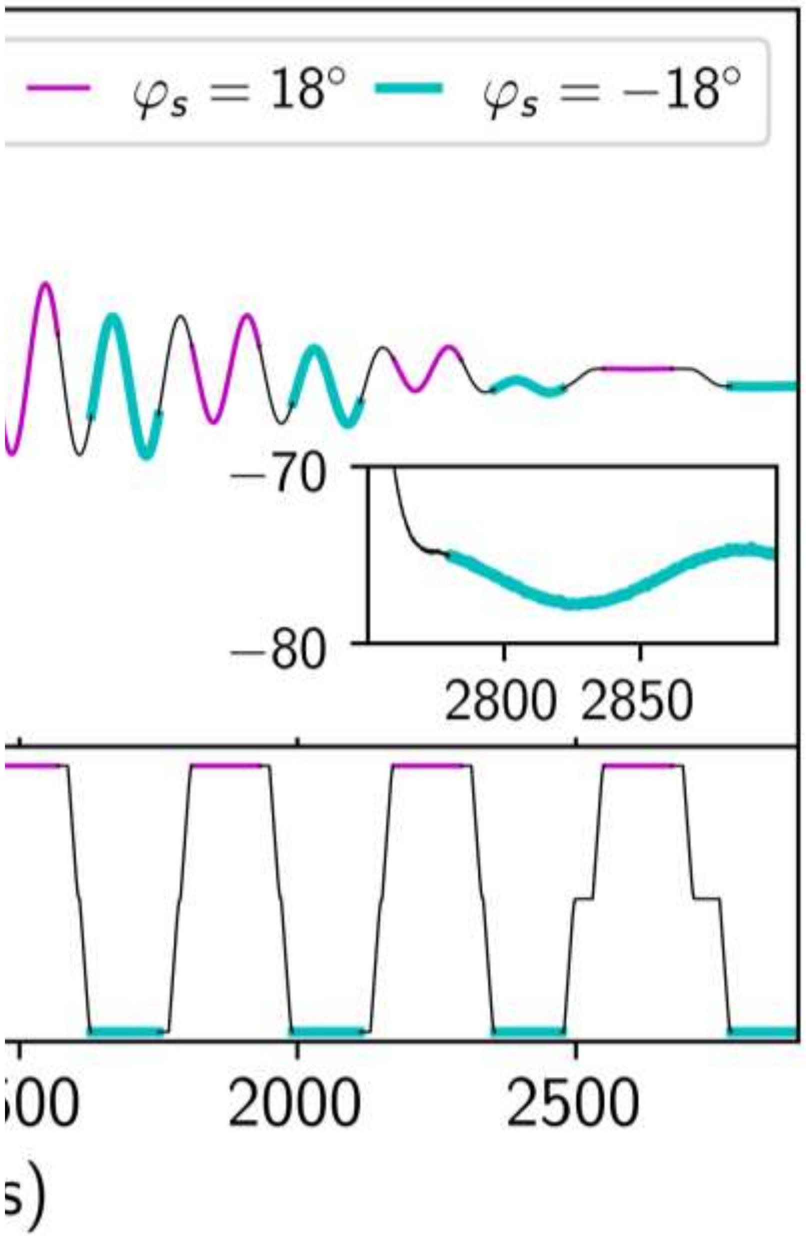
$$N_{grav} = G\,35\,M\,m\frac{r^4}{R^5}\sin 4\theta = N_0 \sin 4\theta$$

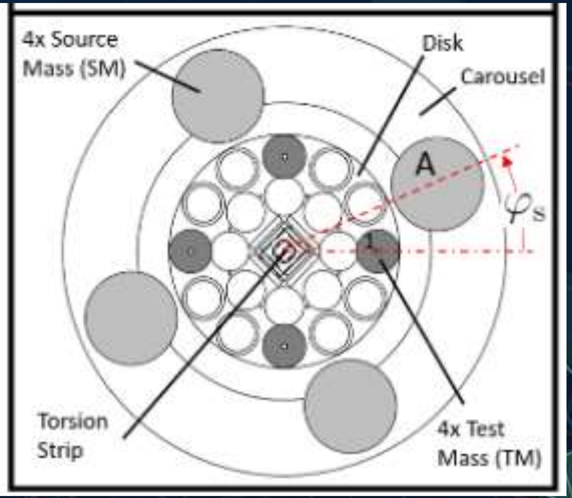
$$N_0 \approx 13.9 \text{ nNm}$$

$$\frac{\sigma_N}{N} = \sqrt{2}\;10^{-5} \Rightarrow \quad \sigma_R = 0.43\ \mu\text{m} \ \text{ and } \ \sigma_r = 0.3\ \mu\text{m}$$

Our contribution to crane safety



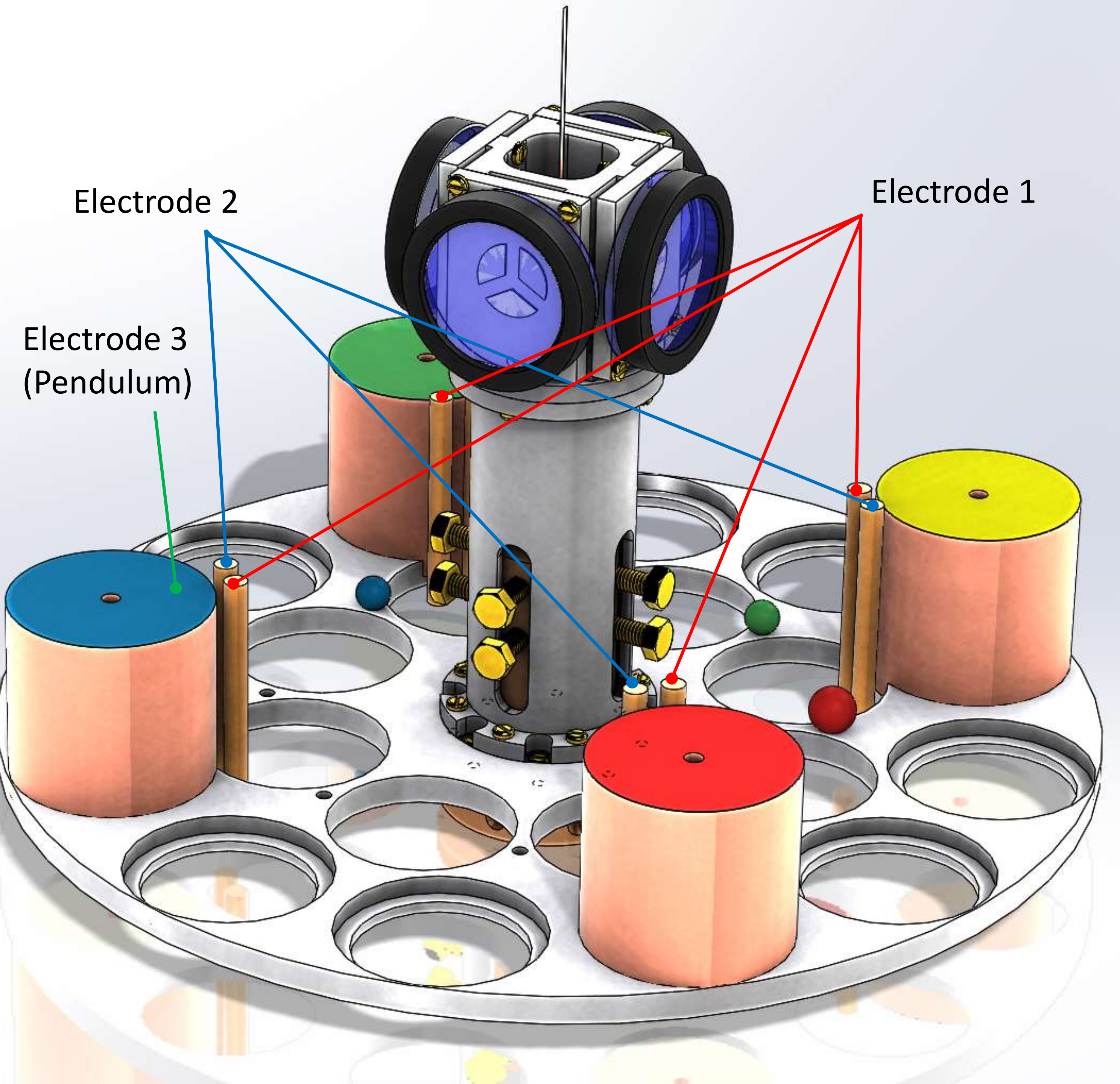




"The Crane Operator's Trick and other Shenanigans with a Pendulum",
Am. J. Physics.

Current status of the experiment

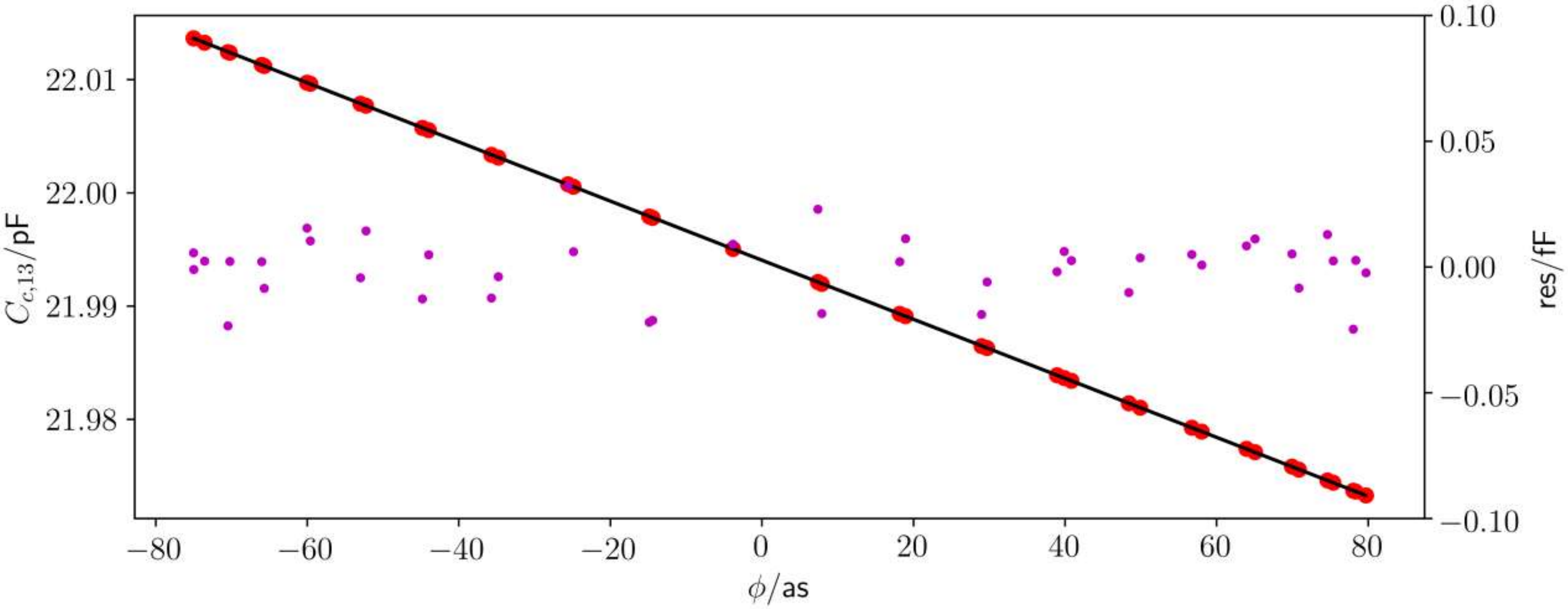
- We found a spurious torque that is proportional to .
- Electrostatic data since September 2021, work in progress.
- Uncertainty analysis in progress.
- Mass integration in progress.



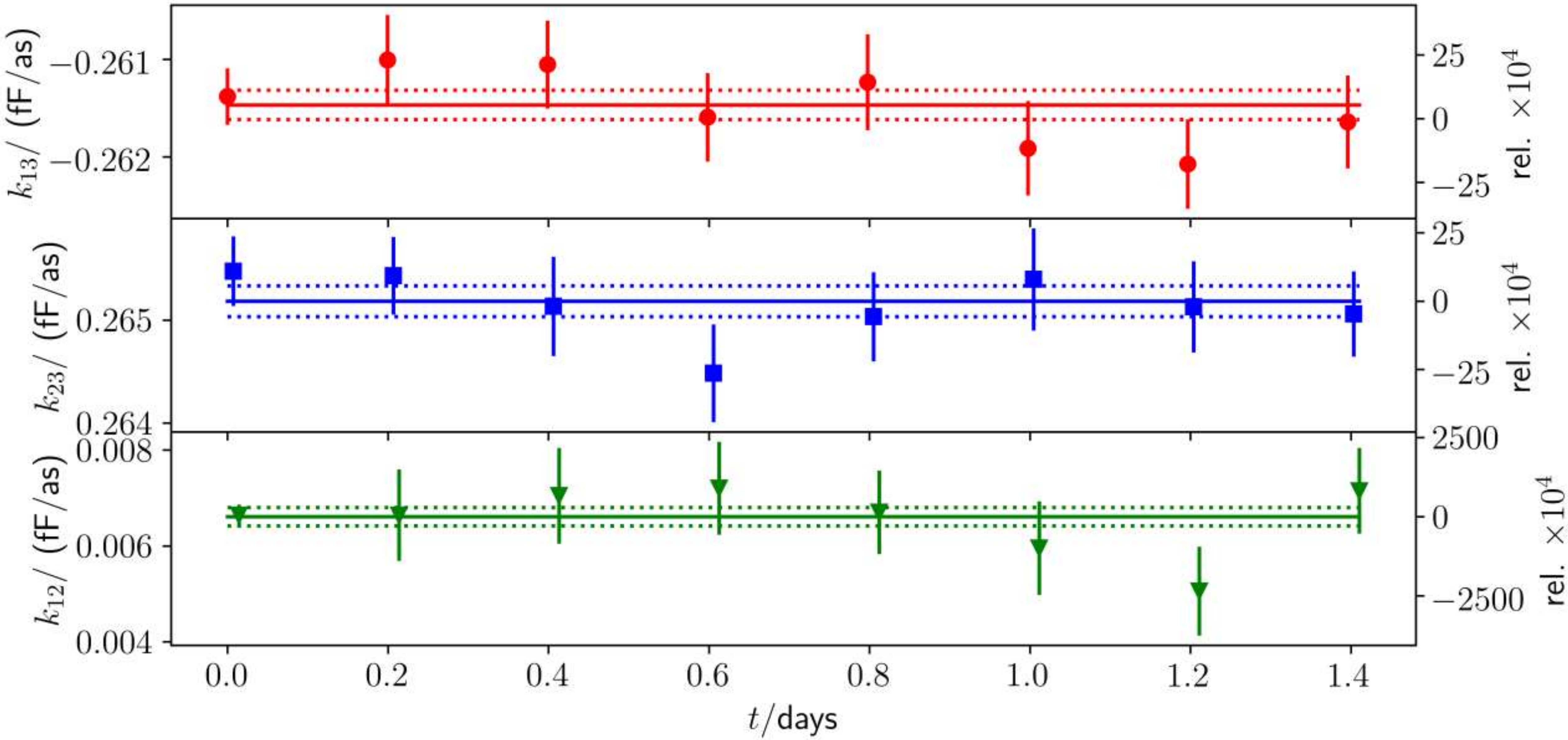
$$W = \frac{1}{2}\left(C_{\mathrm{c},12}\left(V_1 - V_2\right)^2 + C_{\mathrm{c},13}\left(V_1 - V_3\right)^2 + C_{\mathrm{c},23}\left(V_2 - V_3\right)^2\right)$$

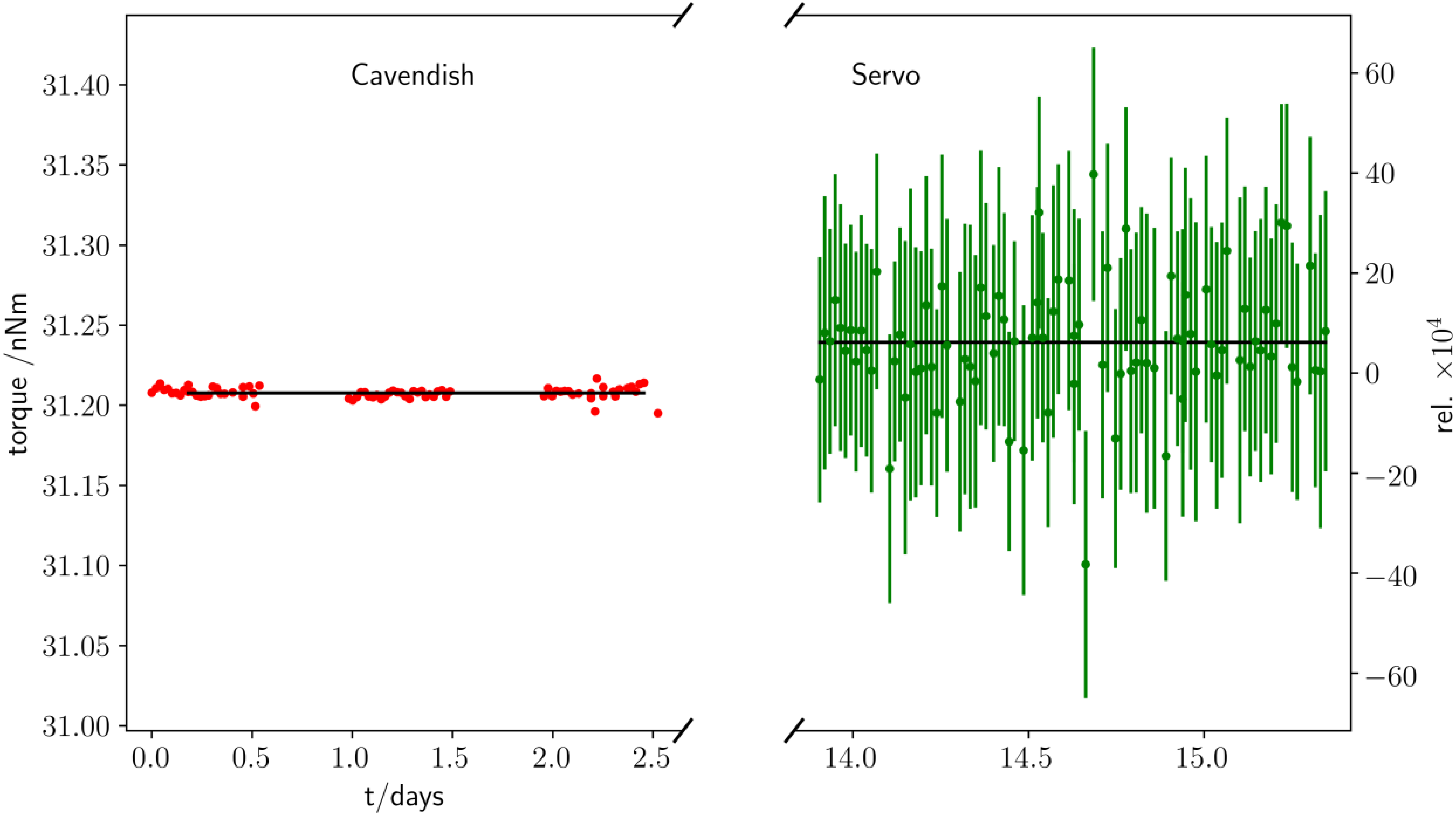
$$N = -\frac{\mathrm{d}W}{\mathrm{d}\theta} = -\frac{1}{2}\left(\frac{\mathrm{d}C_{\mathrm{c},12}}{\mathrm{d}\theta}\left(V_1 - V_2\right)^2 + \frac{\mathrm{d}C_{\mathrm{c},13}}{\mathrm{d}\theta}\left(V_1 - V_3\right)^2 + \frac{\mathrm{d}C_{\mathrm{c},23}}{\mathrm{d}\theta}\left(V_2 - V_3\right)^2\right)$$

$$k_{ij} = \frac{\mathrm{d}C_{\mathrm{c},ij}}{\mathrm{d}\theta}$$

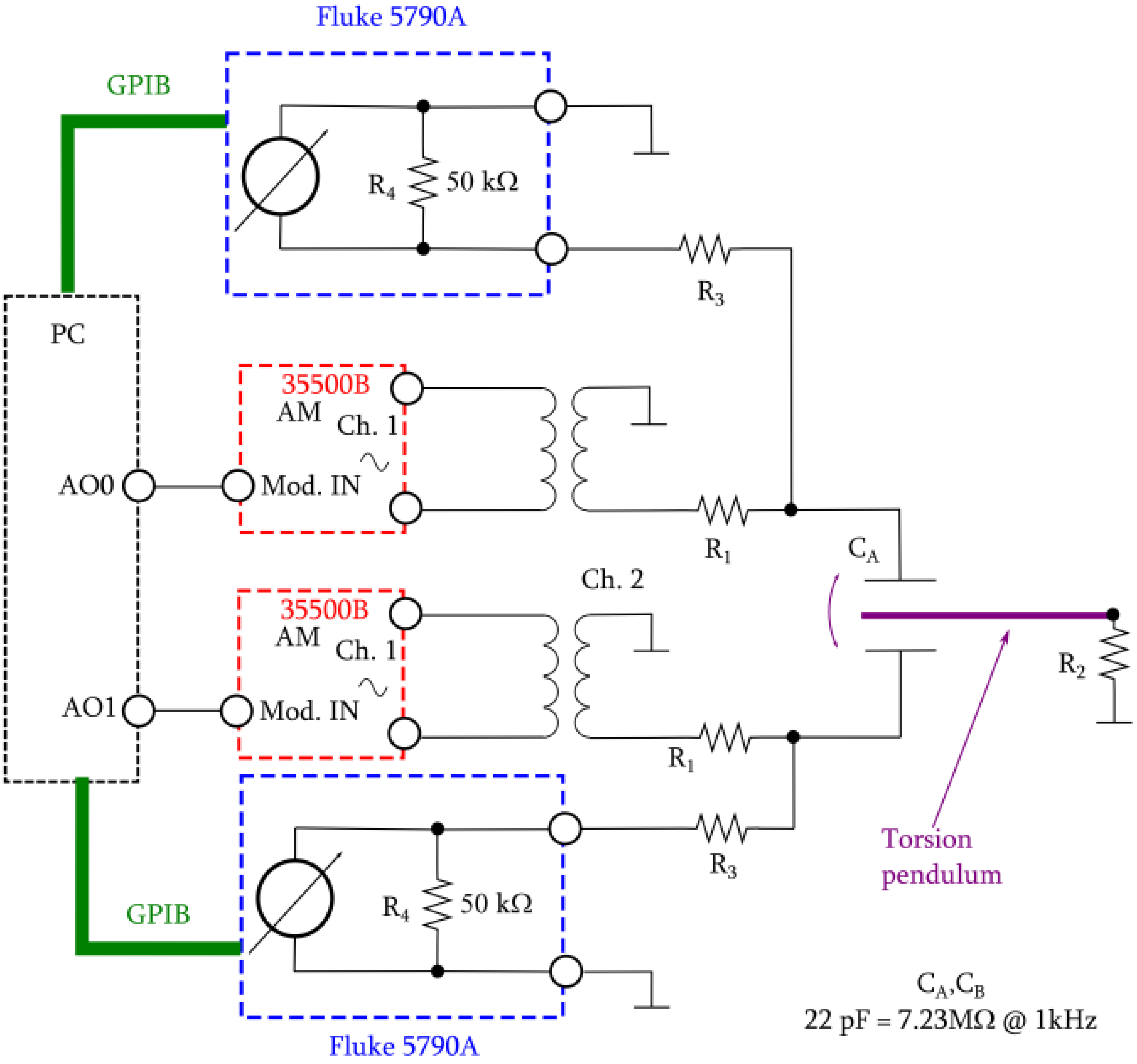


22.01
22.00
21.99
21.98
$C_{c,13}$/pF
0.10
0.05
0.00
−0.05
−0.10
res/fF
−80
−60
−40
−20
0
20
40
60
80
ϕ/as


k_{13}/ (fF/as)
−0.261
−0.262
rel. ×10^4
25
0
−25
k_{23}/ (fF/as)
0.265
0.264
rel. ×10^4
25
0
−25
k_{12}/ (fF/as)
0.008
0.006
0.004
rel. ×10^4
2500
0
−2500
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
t/days



Cavendish
Servo
torque /nNm
t/days
rel. ×10^4
31.40
31.35
31.30
31.25
31.20
31.15
31.10
31.05
31.00
0.0
0.5
1.0
1.5
2.0
2.5
14.0
14.5
15.0
60
40
20
0
−20
−40
−60



- as of now Cavendish and Servo method do not agree.
- Electrostatic method produces data that is noisier.
- stay tuned.
- Blind measurement.

public unblinding in 2022.

big G status

- We are making good progress with data taking.
- The noise in the servo mode is still high.
- A bias exists in the Servo mode. It has to be understood.
- We hope to have all data by the end of the year.
- The experiment is blind. We will unblind publicly in 2022, possibly @ APS April.

Summary

- Small forces an torques can be measured precisely using electromagnetic or electrostatic compensation.
- Relative uncertainties of 10^{-8} are possible.
- Applications include mass and torque calibration.
- The measurement of G and g depends on these techniques.

Thank you for your attention.

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