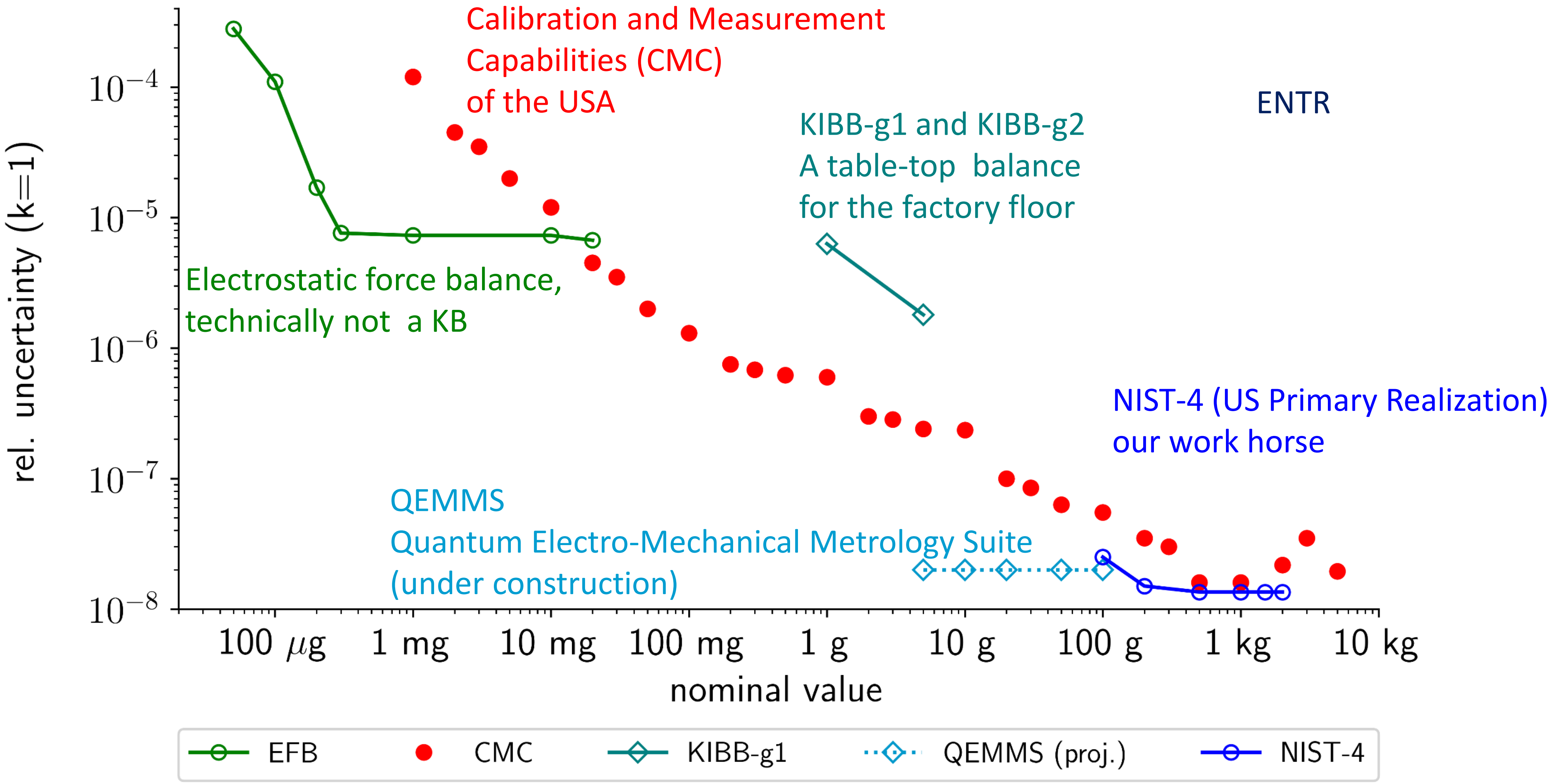
Recent developments of tabletop Kibble-based technologies at NIST: a step towards commercialization

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

CCM
May 25 2023

Dr. Darine Haddad

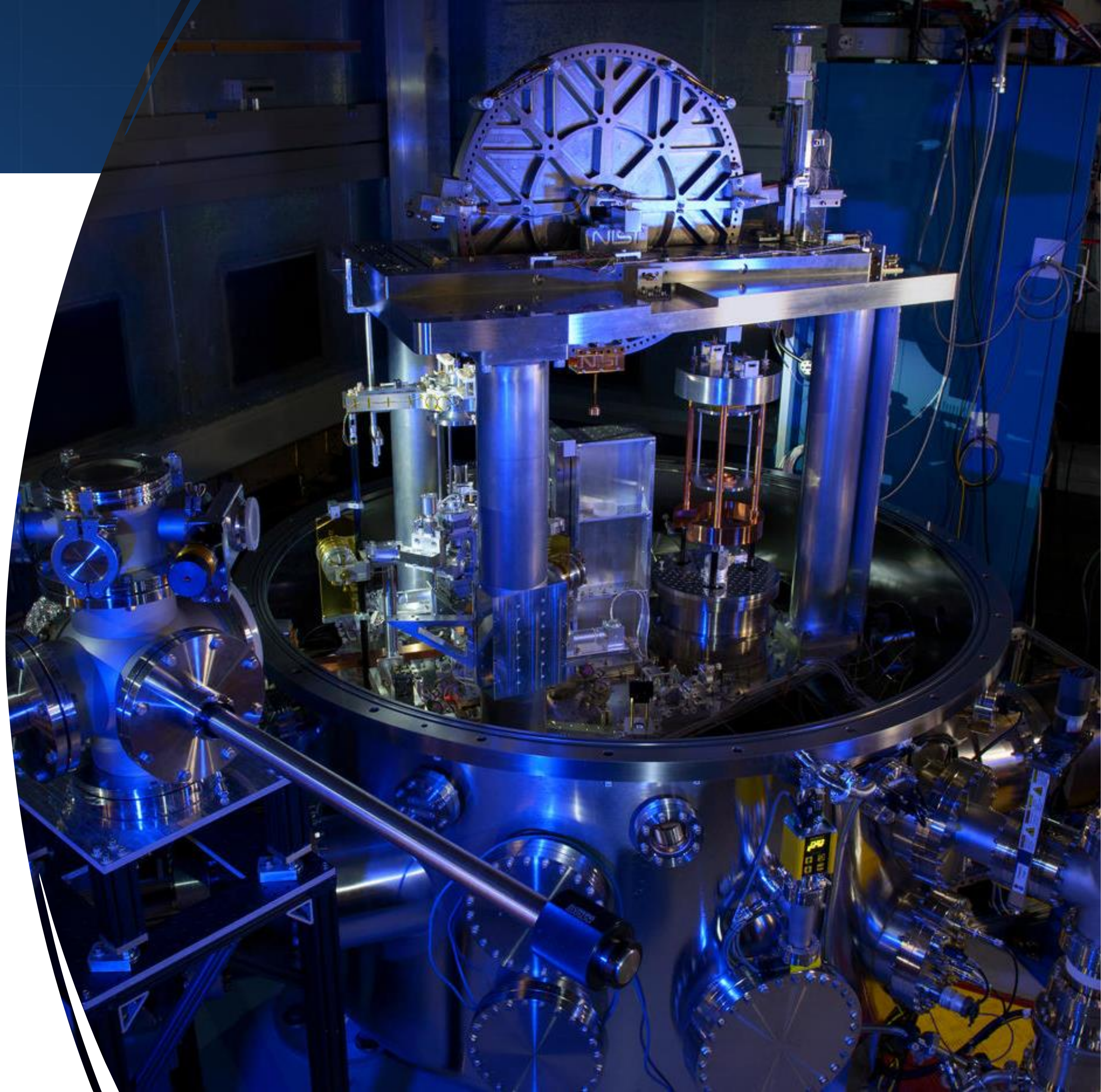
New SI mass scaling at NIST/PREME Team



NIST-4 Kibble Balance

- NIST primary realization to parts in 10^8 uncertainty
- Primary realization of masses from 50g to 2kg

- 2016 pilot study
- 2017 Planck constant publication
- 2019, 2021 Key comparison and future ones



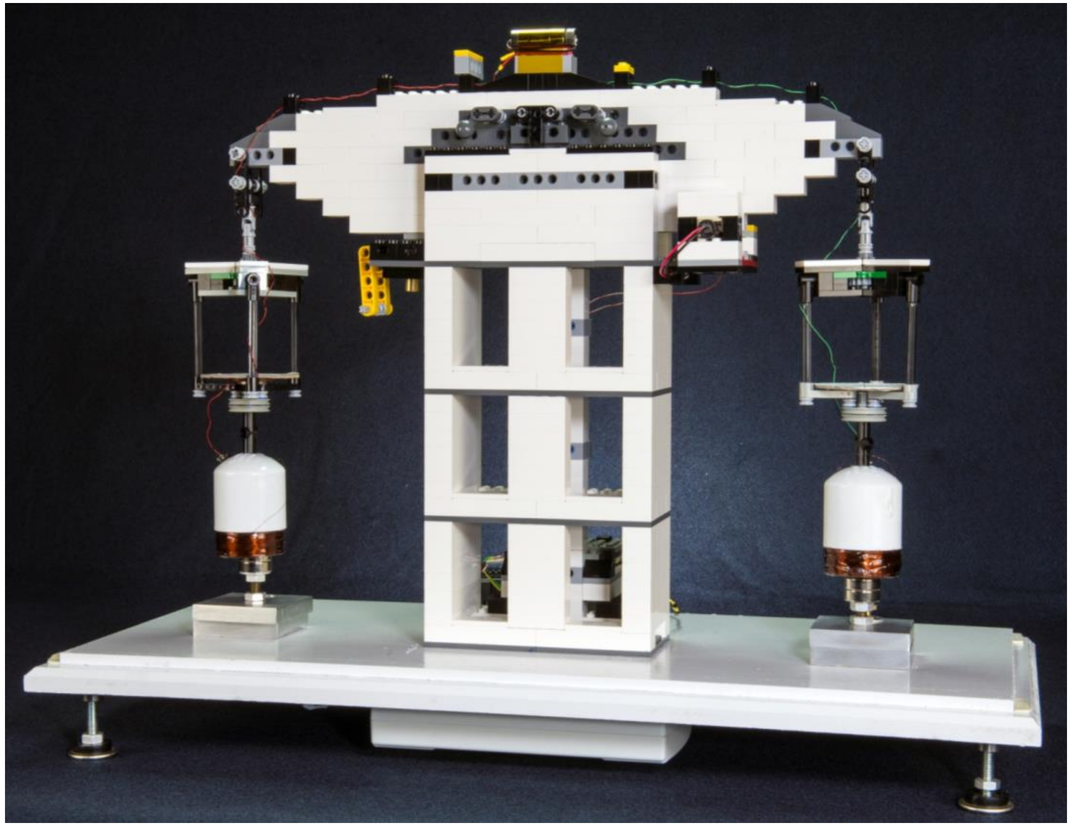
The LEGO Kibble Balance (2014)

1000g

0.000001% uncertainty

10 % fun

vs.



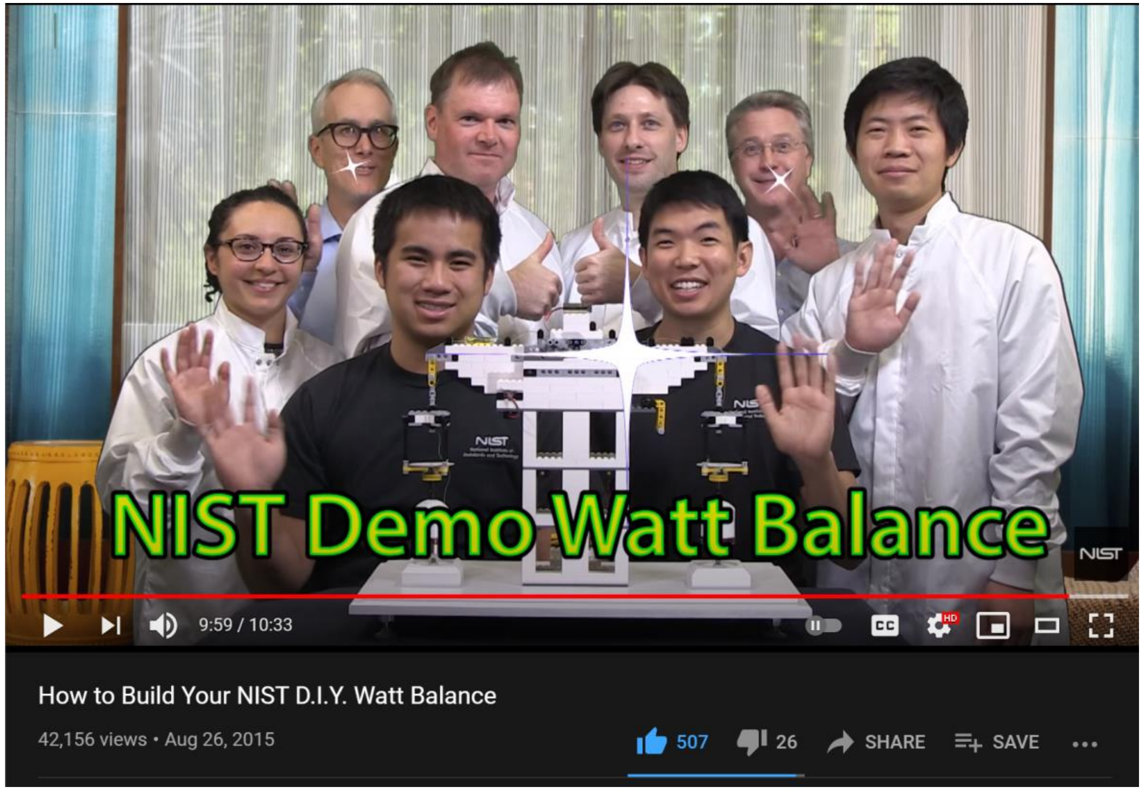
1g - 10 g

1 % uncertainty

100 % fun

*Thanks Terry Quinn, BIPM

LEGO Kibble Balance Outreach (2015)

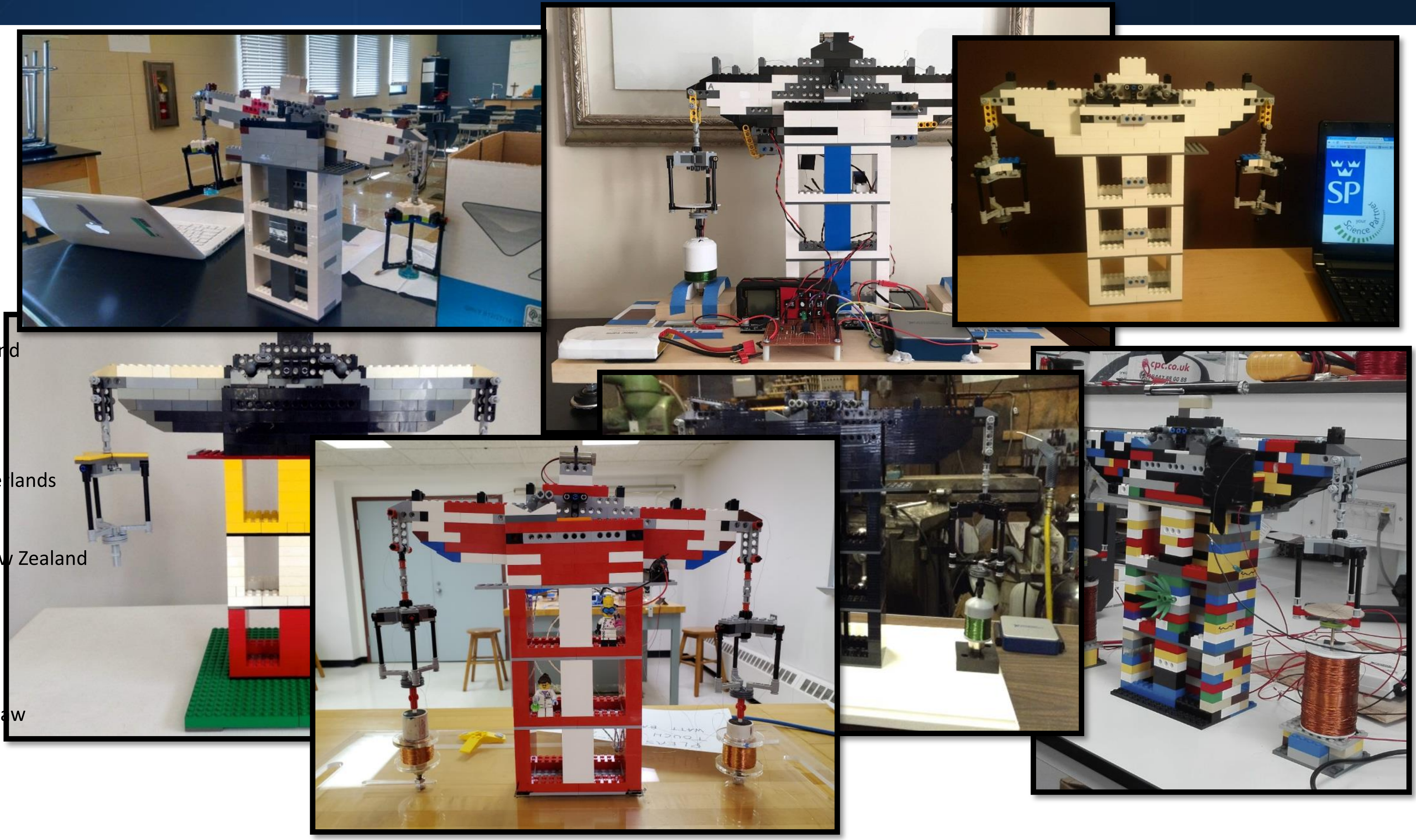


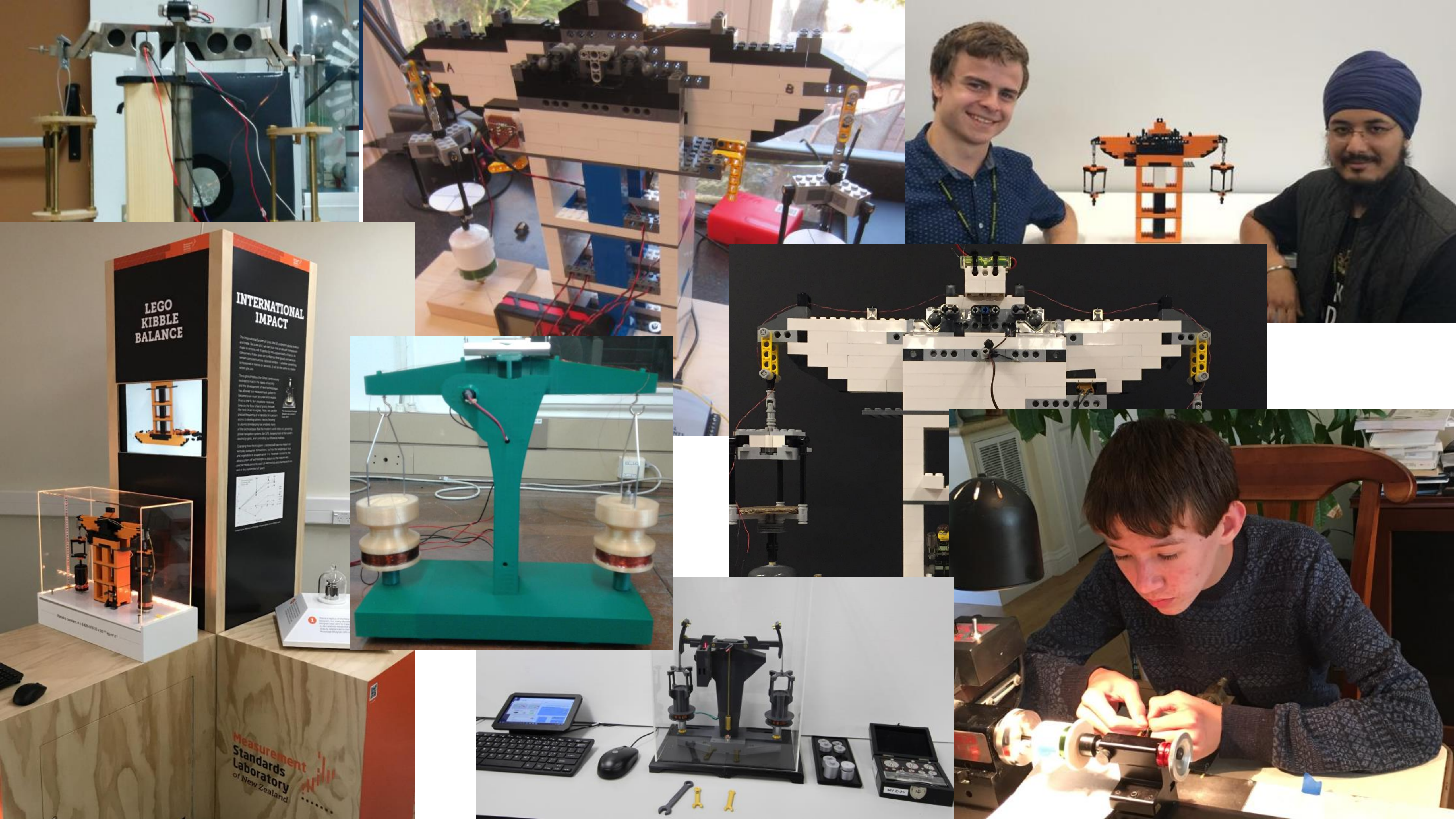
Produced by Jenny Lee, PML, NIST

Part Name	Part No.	Quantity	Total Price ($)
Custom LEGO Watt Balance Software	Contact leon.chao@nist.gov	1	Free
Order from http://shop.lego.com/en-US/Pick-A-Brick-ByTheme			
Brick 2x4	300101	65	19.50
Brick 2x8	6033776	73	36.50
Brick 1x2 with cross hole	4233487	12	4.20
T-Beam 3x3 w/hole O4.8	4552347	2	0.60
Technic Brick 1x2 O4.9	370026	16	2.40
Technic Brick 1x4 O4.9	4211441	48	12.00
Technic Brick 1x6 O4.9	389426	2	0.80
Technic Brick 1x8 O4.9	4211442	2	1.00
Technic Ang. Beam 3x5 90 Deg.	4211713	2	0.60
Plate 8x8	4210802	9	9.90
Plate 1x2	4211398	15	1.50
Plate 1x4	4211445	10	1.50
Plate 2x3	4211396	6	1.20
Cross Axle 2M W. Groove	4109810	8	0.80
Cross Axle 3M	4211815	6	0.14
Cross Axle 5M	4211639	6	1.20
Cross Axle 8M	370726	8	1.60
Bush for Cross Axle	4211622	14	2.10
1/2 Bush for Cross Axle	4211573	28	2.80
Double Bush 3M O4.9	4560175	6	1.20
Roof Tile 2x2/45 deg	303926	4	0.80
Roof Tile 2x2/45 deg Inv.	366026	2	0.40
Roof Tile 2x3/25 deg	4211106	2	0.40
Roof Tile 2X3/25 deg Inv.	374726	4	0.80
Connector Peg W. Friction 3M	4514553	8	2.00
Connector Peg/Cross Axle	4666579	6	0.60
Catch w. Cross Hole	4107081	8	1.60
Flat Tile 2x4	4560178	4	1.20
Hinge 1x2 Lower Part	383101	6	1.50
Hinge 1x2 Upper Part	6011456	6	1.50
Double Conical Wheel Z12 1M	4177431	2	0.60
Angle Element, 180 Degrees [2]	4107783	2	0.40
Order from http://atrbricks.brickowl.com/			
Technic Beam 1 x 4 x 0.5 with Boss	2825 / 32006	6	0.30
Technic Beam 2 Beam w. Angled Ball Joint	50923 / 59141	2	0.13
Beam 5 x 0.5	32017	4	0.76
Wedge Belt Wheel	2786 / 4185	4	1.00
Gear with 8 Teeth (Narrow)	3647	2	0.20
Order from http://thatspecialbrick.brickowl.com/			
Universal Joint	61903	2	0.94
Gear with 16 teeth	94925	2	0.34
Bevel Gear with 12 teeth	6589	2	0.26
Order from http://www.labjack.com/u6			
Multifunction DAQ with USB - 16 Bit	U6	1	299.00
Order from http://www.phidgets.com			
PhidgetAnalog 4 Output	1002_0	1	90.00
Order from http://www.apinex.com			
Focus. Line Red Laser Module <1mW	YCHG-650	1	15.00
Line Laser Module (650nm) - <1mW	LN60-650	1	15.00
Order from http://www.mouser.com			
Photodiode 7.98mm Dia Area	718-PC50-7-TO8	1	61.63
USB Cables USB A - MINI-B	538-88732-8702	1	1.65
USB A-TO-B Shielded 2.09m	538-88732-9200	1	3.58
Low signal Relay	769-TXS2-4.5V	1	4.58
Resistors 240ohms	291-240-RC	1	0.10
Resistors 330ohms	291-330-RC	4	0.40
Resistors 1500ohms	291-1.5k-RC	1	0.10
Linear Voltage Regulators	511-LM317T	1	0.72
Order from http://www.magnet4less.com			
N48 grade - 3/4 (OD) x 1/4 (ID) x 3/4 in. ring magnet	NR011-1	4	15.96
Order from http://www.mcmaster.com			
Brass Threaded Rod - 1/4”-20 Thread, 1’ length	98812A039	1	2.65
White PVC Pipe Fitting	4880K53	2	1.00
White PVC Unthreaded Pipe	48925K93	1	5.27
Total			633.77

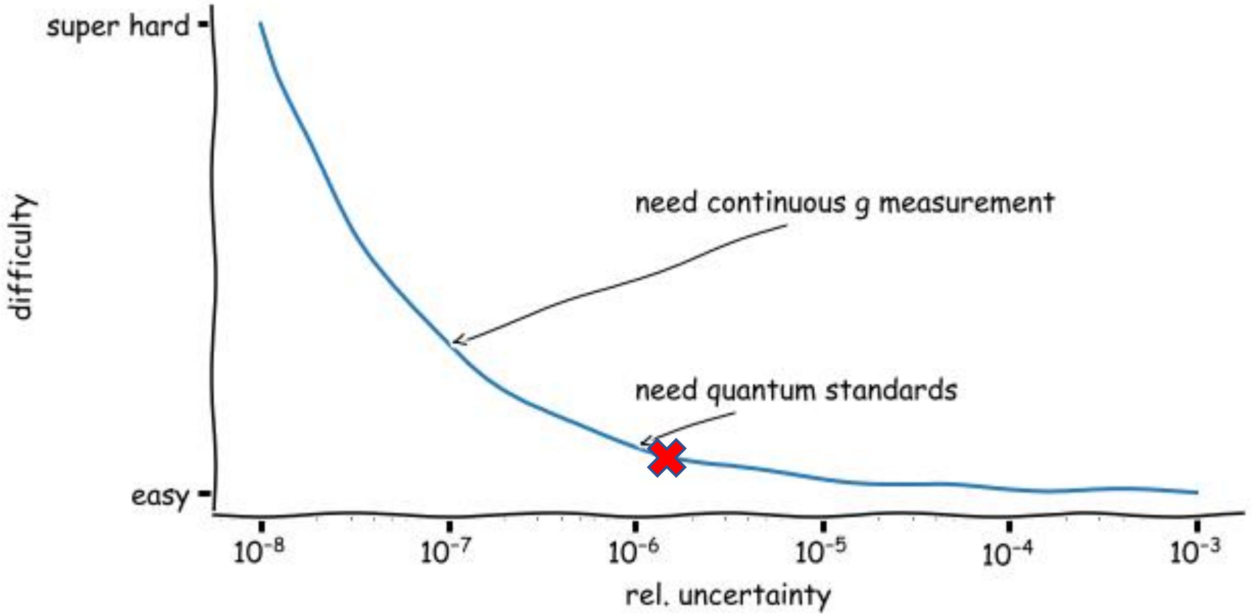
LEGO Kibble Balance Builders of the World

U of Halmstad, Sweden
San Carlos school, CA
NIM, Thailand
Cal State San Bernardino, CA
Wofford College, SC
École Polytechnique, France
Masy, MA
Infiltec, MD
Youtube "Practical Engineering"
Pohang Unviersity, Korea
Nevada Dept. Agriculture
University College London, England
NMISA, South Africa
U of Pittsburg, PA
Johannesburg, South Africa
Johns Hopkins U, MD
Dutch Metrology Institute, Netherlands
St. Lawrence U, NY
Public high school, Italy
Measurement Standards Lab, New Zealand
U of Waterloo, Canada
Avery County Public Schools, NC
Canisius College, NY
Albuquerque High School, NM
U of Helsinki, Finland
Central Office of Measures, Warsaw
Cal State East Bay, CA
Sydney, AU
NIST, MD
Greenwich High School, CT




LEGO KIBBLE BALANCE
INTERNATIONAL IMPACT
Measurement Standards Laboratory of New Zealand

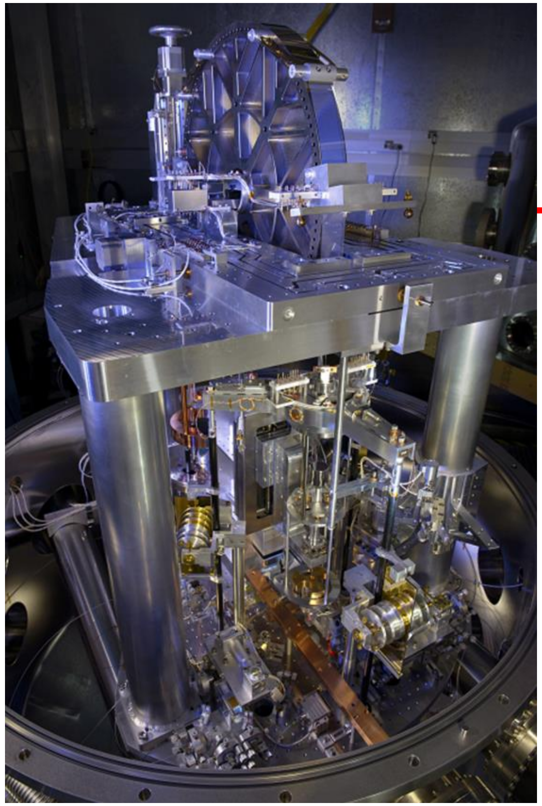
NIST's path forward in modernizing commercial mass metrology.



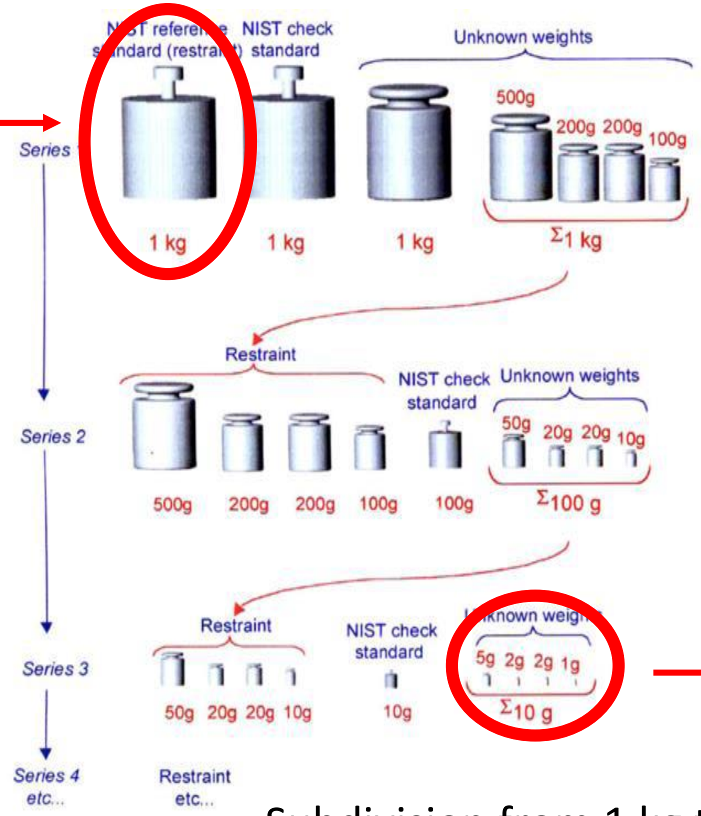
✖ = optimal point to begin endeavor

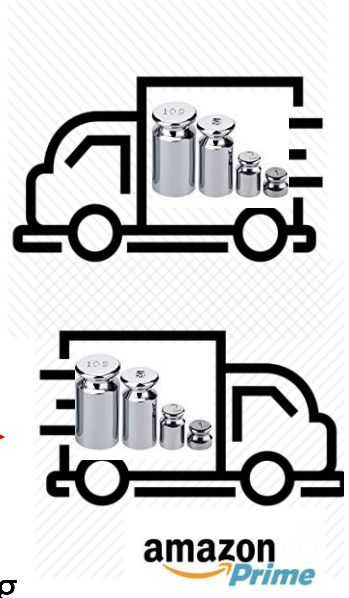
- No vacuum required
- No need for quantum standards
- Tabletop-sized instrument & low complexity
- Compete with commercial OIML class E2 gram-level mass standards
- Uncertainty on the order of parts in 10^6
- New area of research

Present state of Mass Dissemination

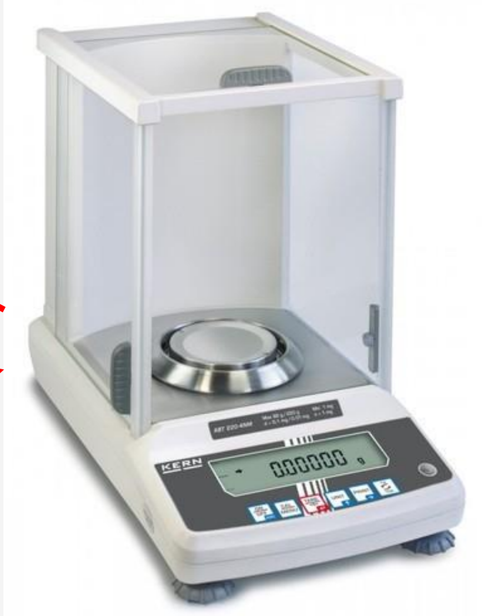


NIST





Mass Metrology Lab



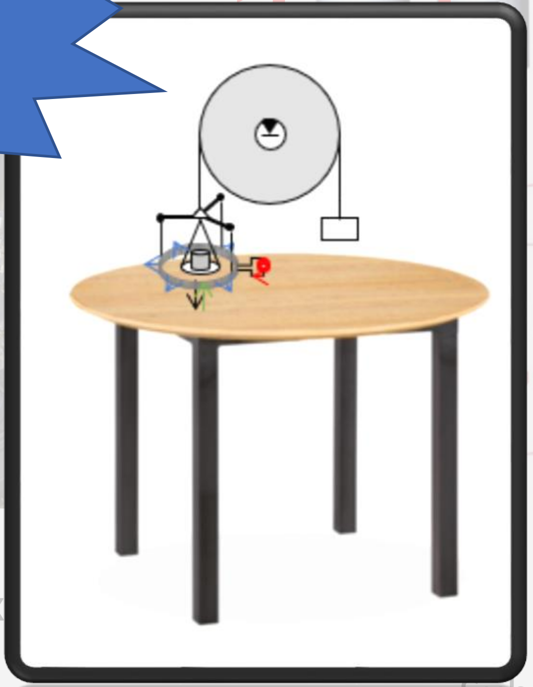
Subdivision from 1 kg to 1 g

- ~1 week to complete
- 44 weighings
- 1200 individual measurements
- Uncertainties now on the order of 10^{-6}

Truncate the traceability chain

NIST

Freedom from NMIs



Tabletop Kibble Balance
Best Features:

- ~~Too~~ Less complicated
- ~~Too~~ Less expensive
- ~~Too~~ Less big
- ~~Too~~ Less difficult to operate
- ~~Too~~ Less accurate

Given the Planck constant is now fix[ed] 1-kg mass can be realized with uncertainties on the order of 1×10^{-8} with a Kibble balance

Subdivision from 1 kg to 1 g
- ~1 week to complete
- 44 weighings
- 1200 individual measurements
- Uncertainties now on the order of 10^{-6}

Mass Metrology Lab

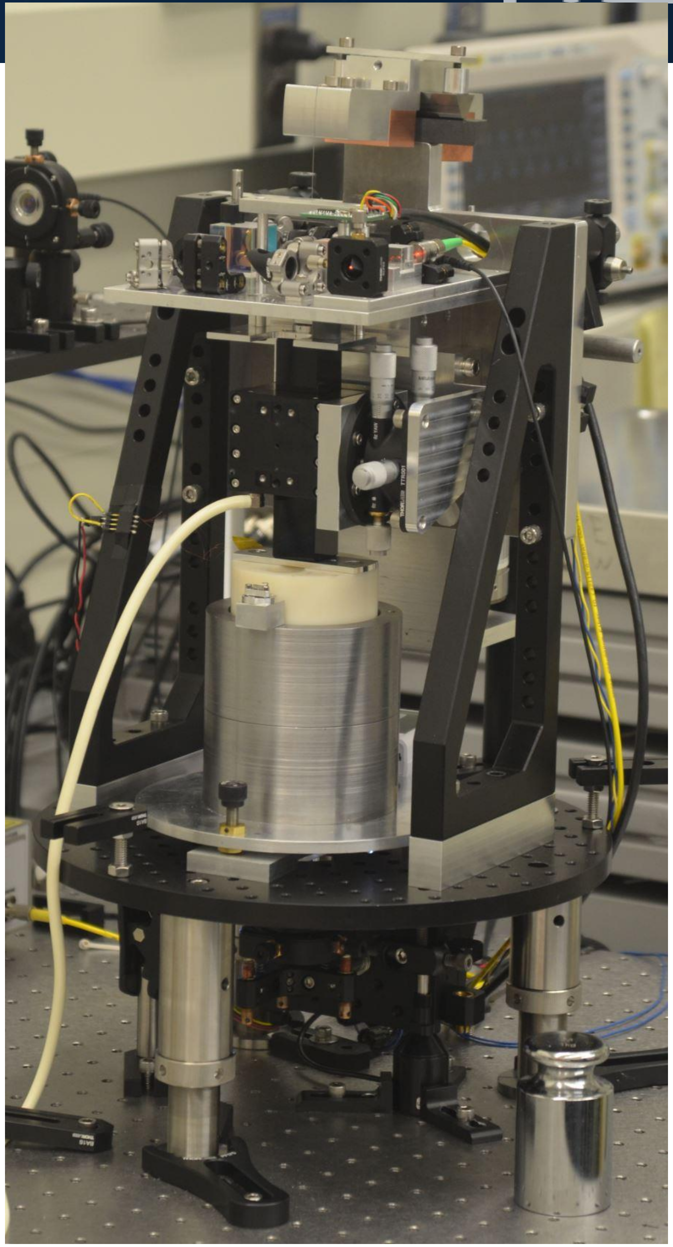
Realize and Disseminate gram-level masses In the comfort of your own laboratory!

KIBB-g1 (2017-2019)

NIST first generation tabletop Kibble balance

Target:

(1) Nominal values: between 1 g–10 g
(2) Relative uncertainties: single digit ppm
(3) Form factor: 'tabletop' sized instrument
(4) Convenience: operates in air (no vacuum required)
(5) Cost: <50 000 USD.



Uncertainty Budget

OPEN ACCESS
IOP Publishing

Metrologia

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The performance of the KIBB-g1 tabletop Kibble balance at NIST

Leon Chao, Frank Seifert, Darine Haddad, Jon Pratt, David Newell and Stephan Schlamminger

National Institute of Standards and Technology, 100 Bureau Dr., Gaithersburg, MD 20899, United States of America

E-mail: leon.chao@nist.gov

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CrossMark

COMPARISON OF E_2 MASS VS. KIBB-G1 MASS REALIZATION RELATIVE UNCERTAINTIES

	5 g mass	1 g mass
$\Delta m_{E2}/m_{E2} \times 10^6$	2	5
$\Delta m/m \times 10^6$	1.8	6.3

TABLE I
KIBB-G1 UNCERTAINTY BUDGET. ALL UNCERTAINTIES ARE $\times 10^{-6}$

Source	5 g measurement		1 g measurement	
	Item	Subtotal	Item	Subtotal
Laser Stability/Accuracy	0.0		0.0	
Deadpath Error	0.0		0.0	
Optics Thermal Drift	0.0		0.0	
Electronics Error	0.1		0.1	
Interferometer Readout		**0.1**		**0.1**
Abbe Error	0.0		0.0	
Off Axis Motions	0.0		0.0	
Cosine Error	0.1		0.1	
Alignment		**0.1**		**0.1**
Timing Jitter	0.0		0.0	
Wavelength Compensation	0.2		0.2	
Velocity		**0.2**		**0.2**
Field Gradient	0.0		0.0	
Material Thermal Expansion	0.4		0.4	
Coil Z Position		**0.4**		**0.4**
Statistical		**0.7**		**2.8**
BL Interpolation	0.2		0.2	
Individual BL Profile	0.7		0.7	
Profile Fitting		**0.7**		**0.7**
Resistor	0.1		0.1	
DVM (Force Mode)	0.4		0.4	
DVM (Velocity Mode)	0.4		0.4	
Electrical		**0.8**		**0.8**
Magnetic Susc. of Mass	0.0		0.0	
Balance Sensitivity	0.0		0.0	
Buoyancy	0.1		0.1	
Balance Mechanics	0.2		1.0	
Gravity	0.3		0.3	
Magnet Nonlinearity	0.4		0.4	
Air Bearing Pressure	1.1		5.4	
Forces on mass		**1.2**		**5.5**
Total		**1.8**		**6.3**

KIBB-g1 inducted into the NOAC program (2020)

NIST

Introduction

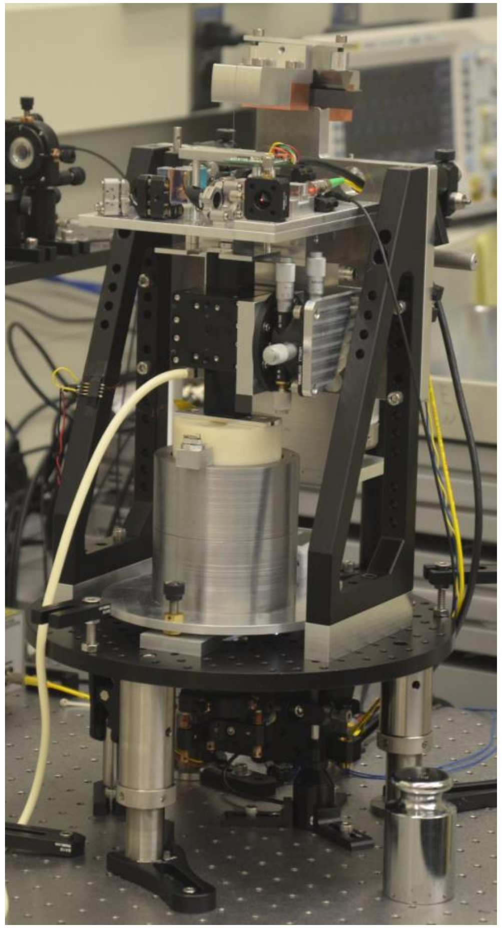
The Technology

- Time and Frequency
- Magnetic and Electric Fields
- Thermodynamics
- Dimensional Metrology
- Fluid Measurements
- Mass, Force and Acceleration
- Current and Voltage
- Quantum Optics and Radiometry
- Radiation

NIST On A Chip

Barbara Goldstein, Program Manager
barbara.goldstein@nist.gov

Jay Hendricks, Deputy Program Manager
jay.hendricks@nist.gov



* Not quite on a chip, but at least on a table

US Dept. of Defense Interest (summer 2020)

- Army USATA (Test, Measurement, Diagnostic Equipment Activity) SOW on KIBB-g2: 3 year funding for a the development of the next generation tabletop Kibble balance with a focus on design for commercialization at OIML Class F2 uncertainties

- AFMETCAL (Air Force Metrology and Calibration) SOW on torque realization: 3 year funding for the development of an absolute standard having a dynamic range of 0.1 – 142 in-ozf with 0.1% uncertainty

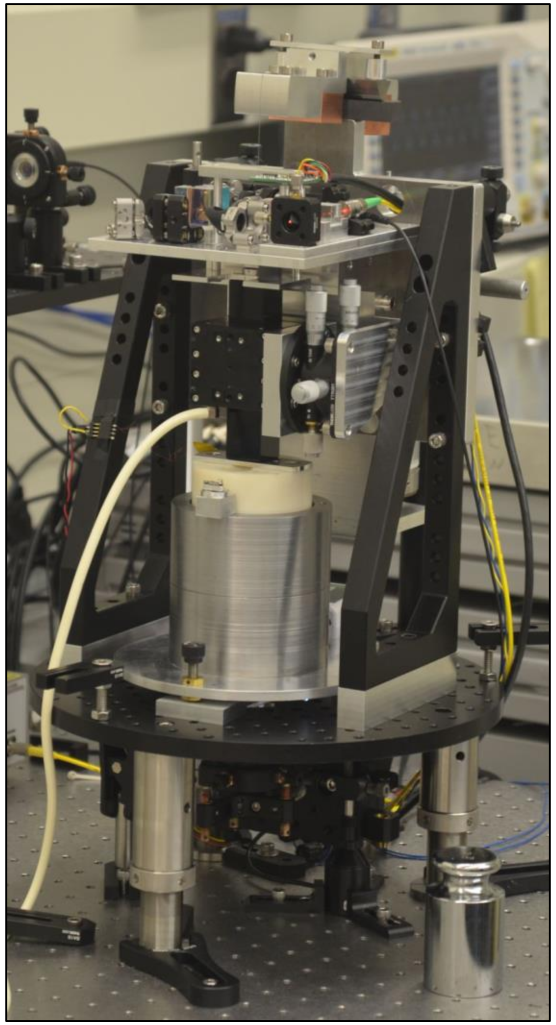
NIST PREME

Second Generation Tabletop KB, KIBB-g2

NIST

KIBB-g1

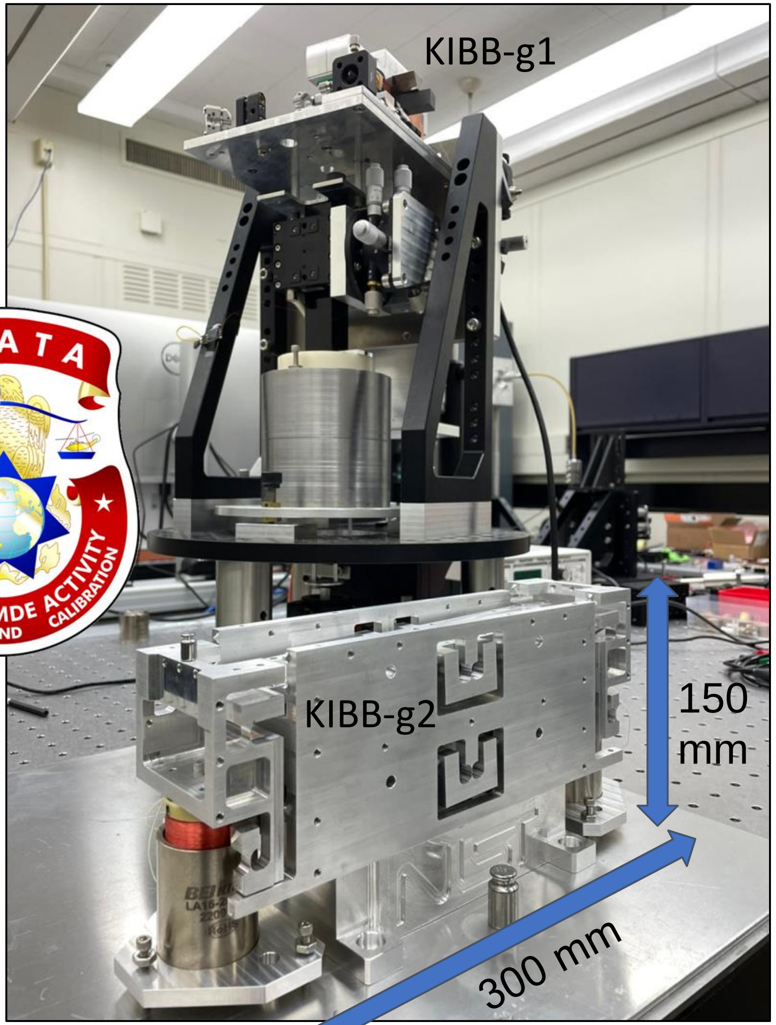
600 mm



300 mm

Goal: Construct a second generation tabletop Kibble balance for directly realizing [500 mg – 20 g] masses with ASTM Class 3 accuracies (OIML Class F2)

- US Army Funded
- Flexure-based mechanics
- Commercial voice coils
- Commercial optical encoder



Kibble Principle for Torque

Self-Calibration Mode

$$V = B(\varphi)Lr\dot{\varphi}$$

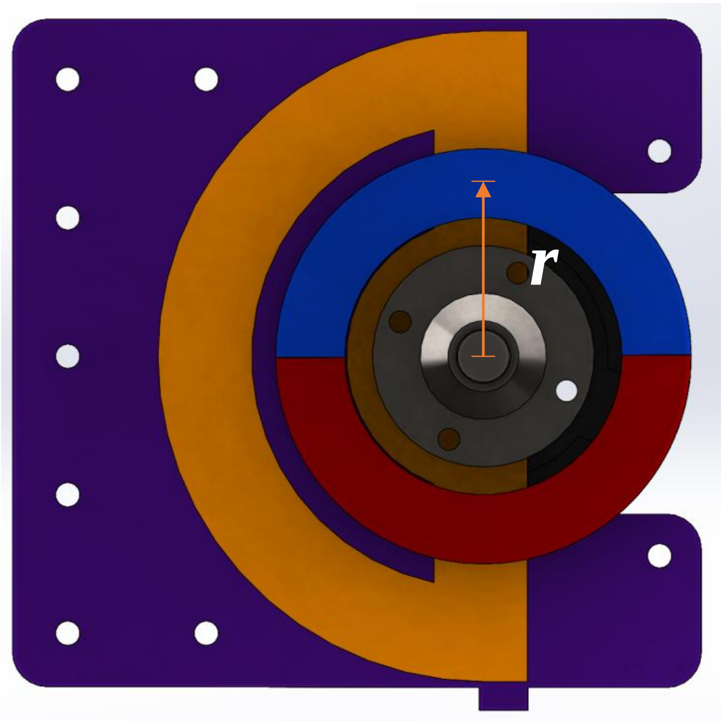
Spin Mode

Measurement Mode

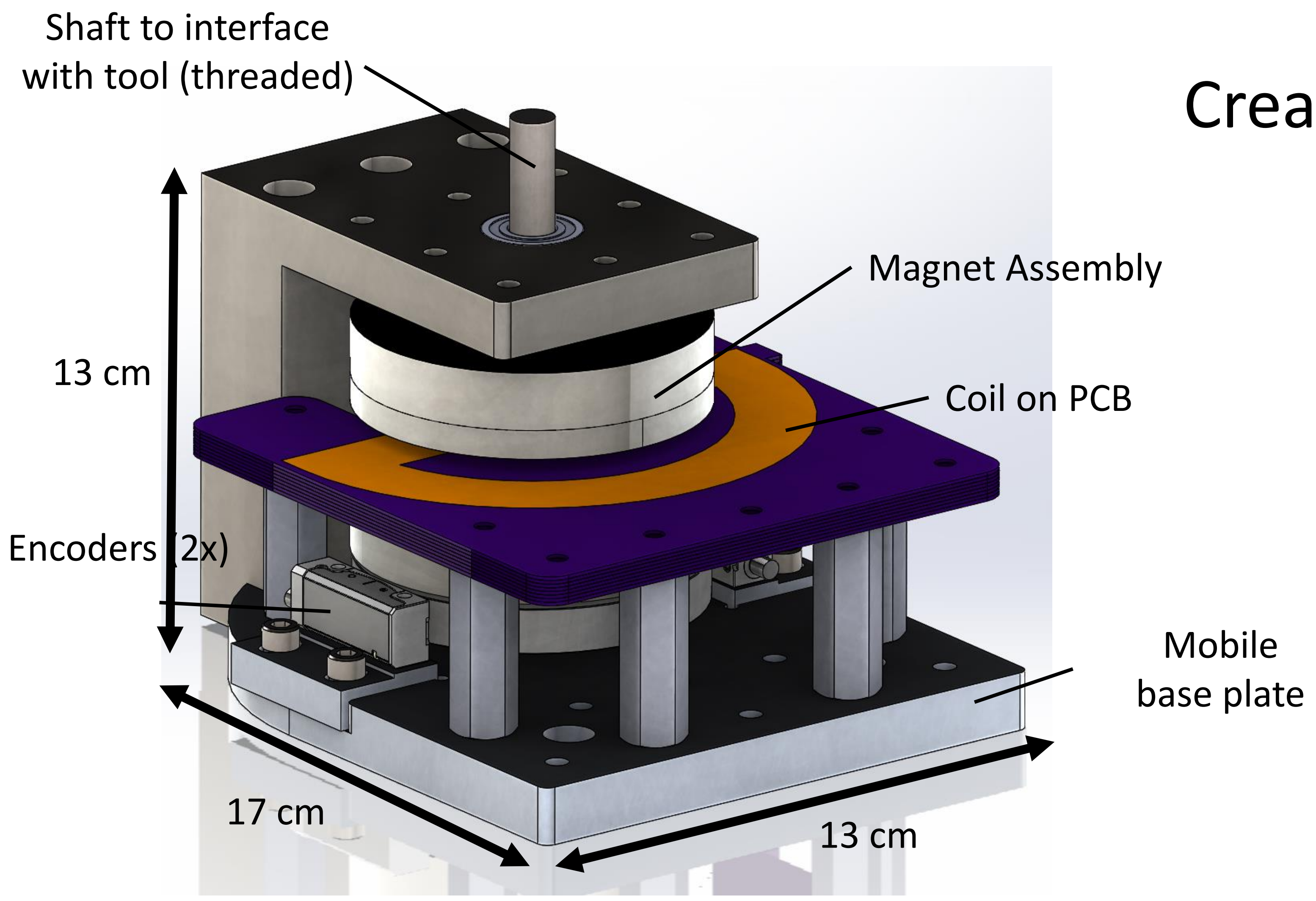
$$\tau = B(\varphi)LrI$$

Torque Mode

$$\tau = I\,\frac{V}{\dot{\varphi}}$$



Electronic NIST Torque Realizer (ENTR)



Create an absolute small torque standard with range:

0.1 in ozf – 142 in ozf

(7×10^{-4} N m – 1 N m)

and uncertainty of:

0.1%

(7×10^{-7} N m)

Utilizing commercial components

NIST

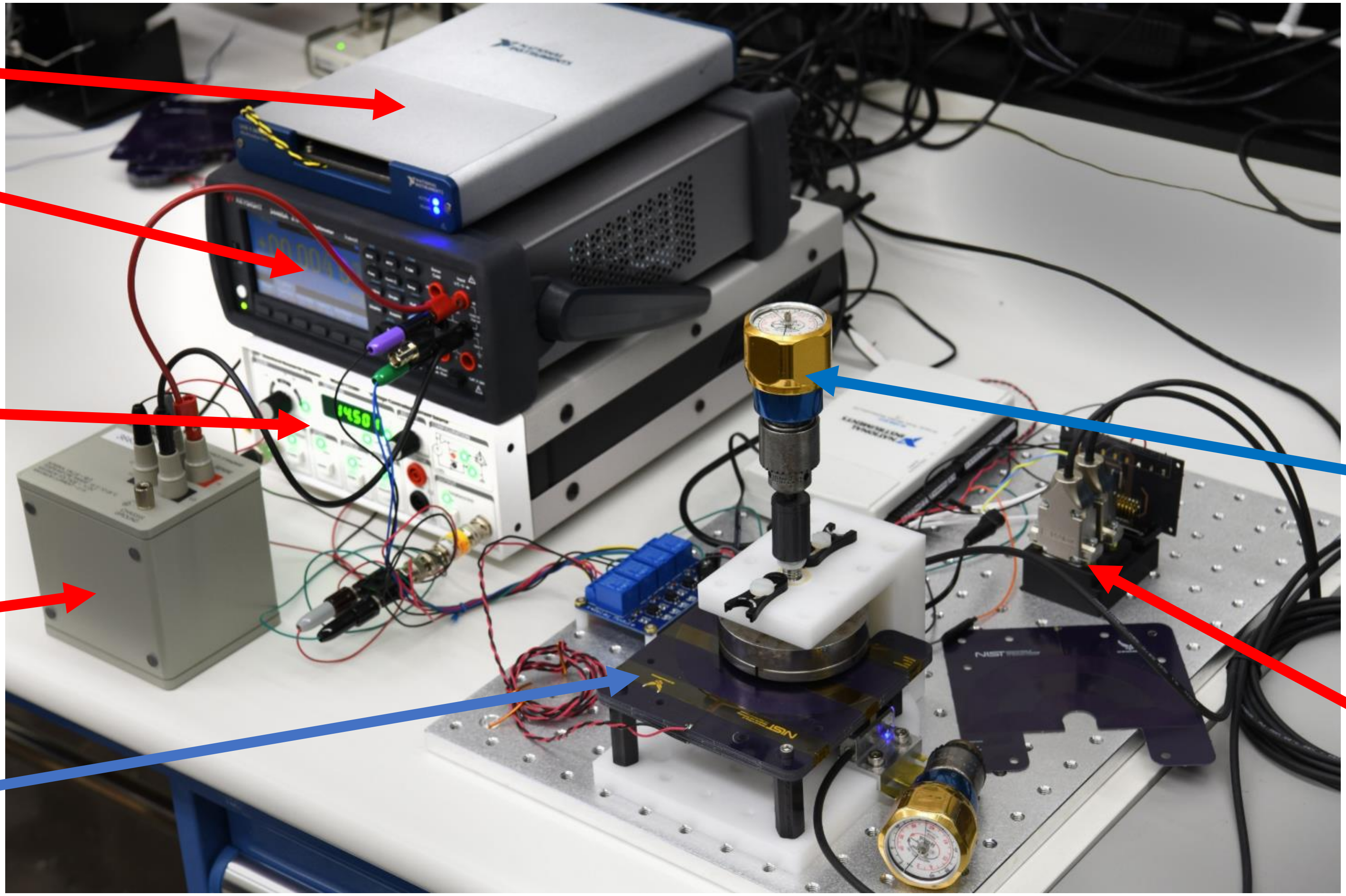
USB DAQ I/O

6.5 Digit Voltmeter

Programmable
Current Source

Calibrated Resistor

ENTR



Can produce holding torque up to:

2×10^{-2} N m
(3 in-ozf)

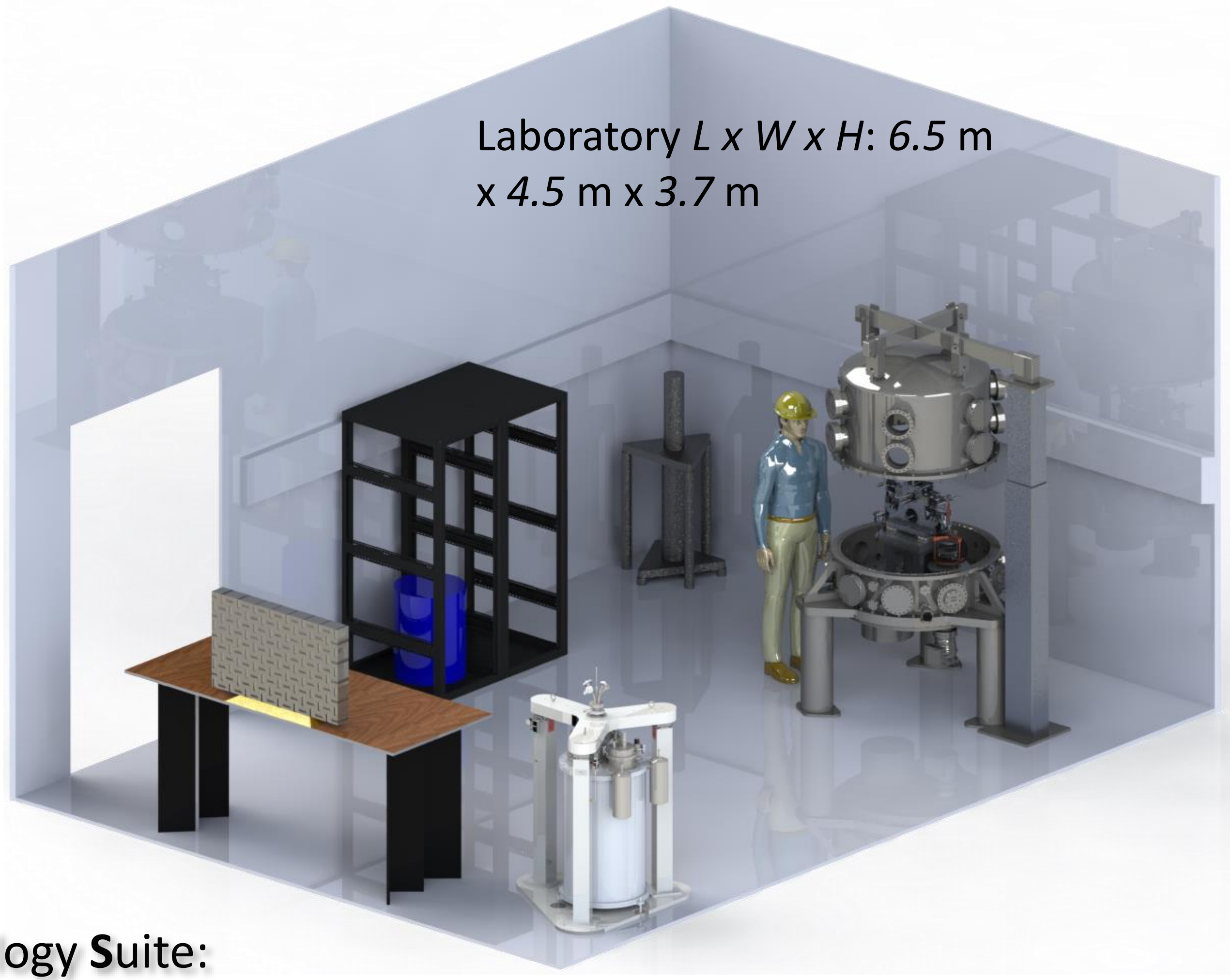
Torque tool
under test

Dual read head
encoder system

Disclaimer: Certain commercial equipment, instruments, and materials are identified in this presentation in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

QEMMS as an NMI in one lab

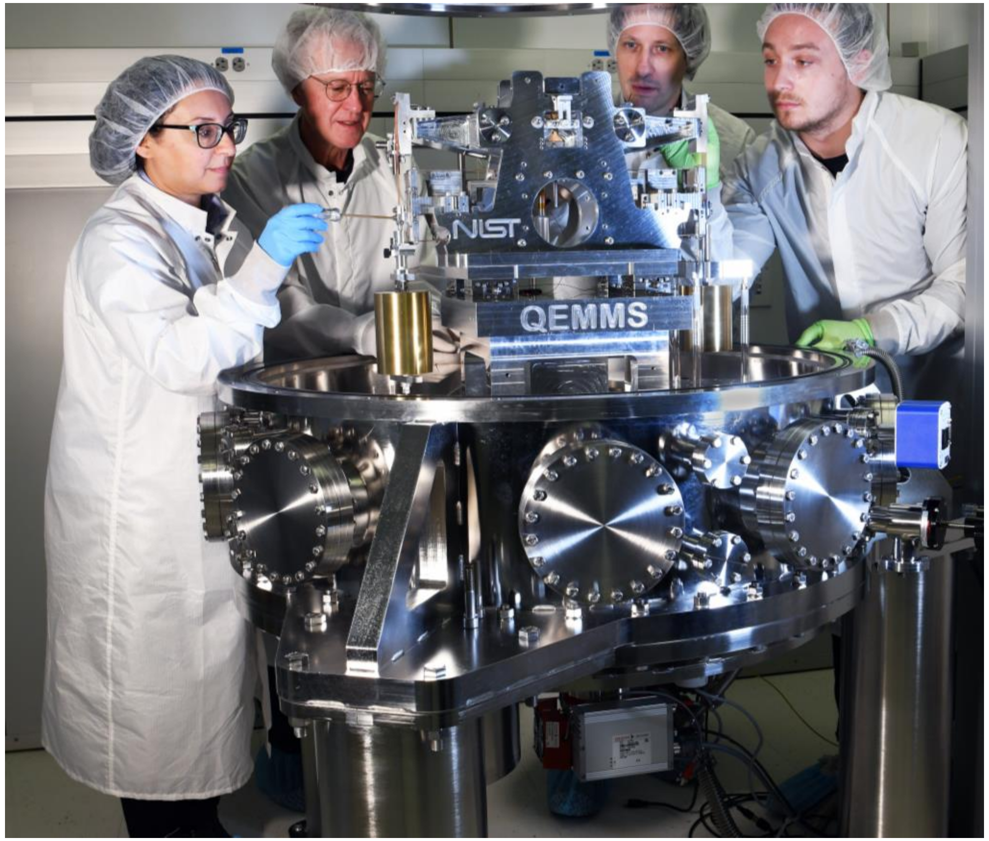
1. Kibble balance
2. Graphene quantum Hall array resistance standard
3. Programmable Josephson voltage system (PJVS)
4. Absolute gravimetre
5. Caesium clock time standard
6. Iodine stabilized HeNe-laser length standard

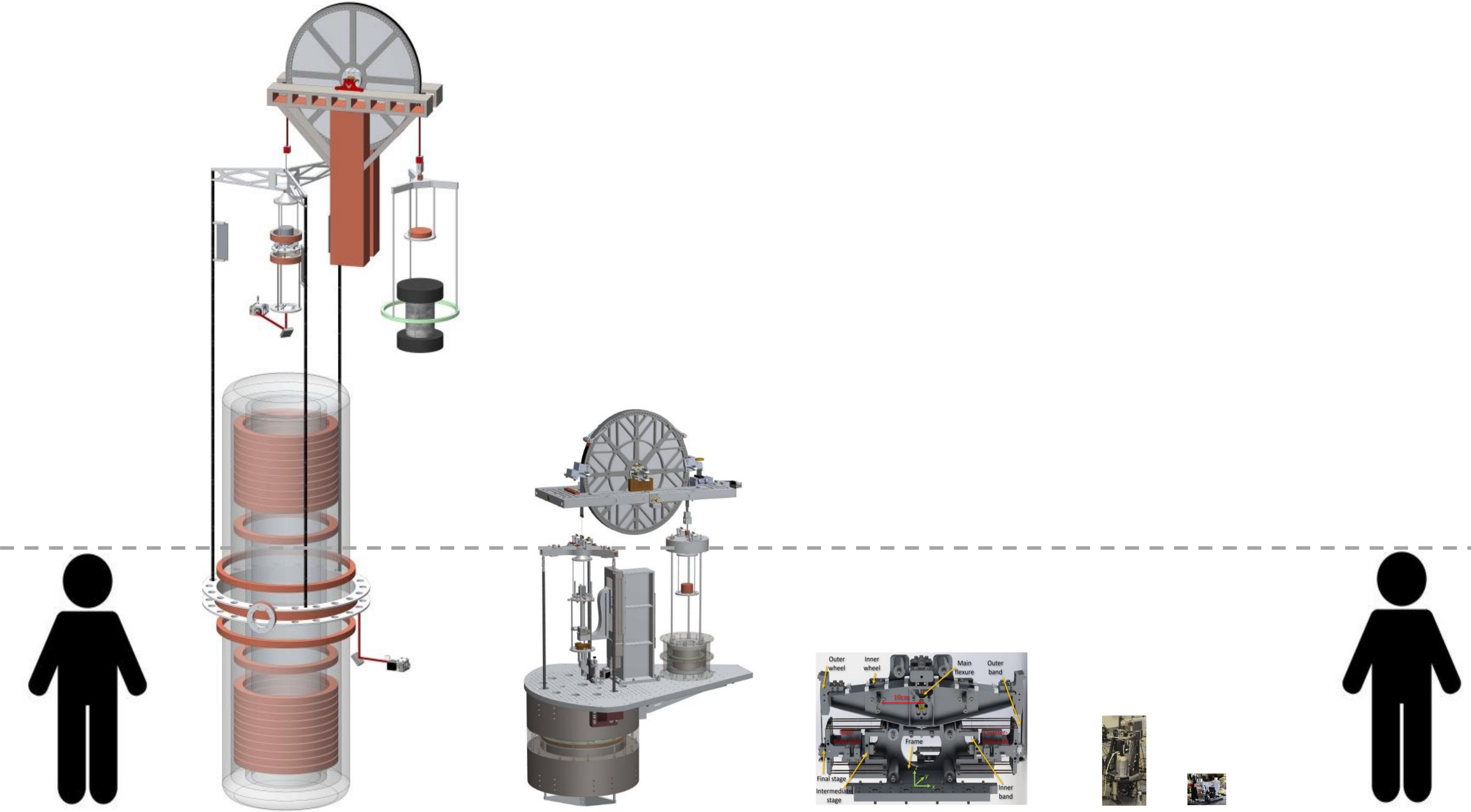


→ **Q**uantum **E**lectro-**M**echanical **M**etrology **S**uite: time, length, mass, electric current, voltage, electric resistance

Vision for the QEMMS Kibble balance

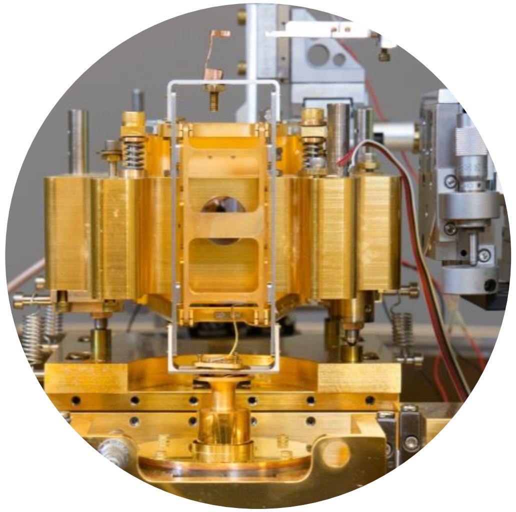
- **Balance smaller and more compact than NIST-4: makes parts structurally stiffer and allows for reduction of components/complexity**
- Measuring mass between $\mathbf{10\ g - 200\ g}$ with absolute uncertainty of $\mathbf{2\ \mu g}$ at $\mathbf{100\ g}$
- Open-source hardware and software to replicate the balance
- Comparable in size to a commercial high precision vacuum 1 kg mass comparator
- Ability to measure multiple masses withouth breaking vacuum → in vacuum mass exchange and storage
- QEMMS will be ready end of 2025, and will be also another US primary realisation

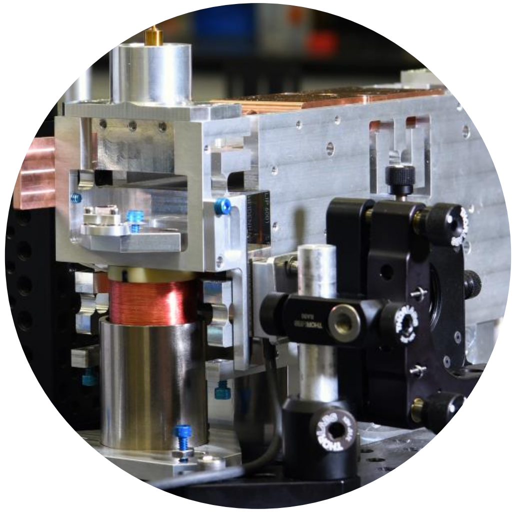


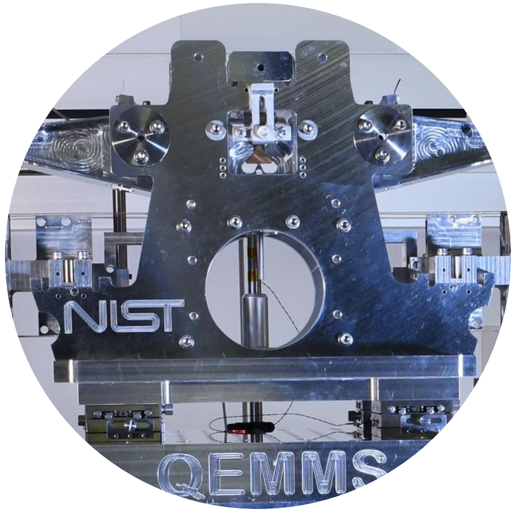

Outer wheel
Inner wheel
Main flexure
Outer band
10cm
Frame
Final stage
Intermediate stage
Inner band

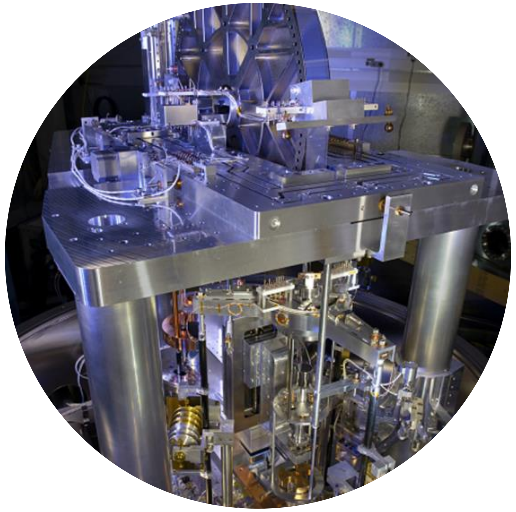
Direct Mass Realization Capabilities at NIST from 50 µg to 2 kg

NIST









Measurement Range			
50 µg – 20 mg	500 mg – 20 g	10 g – 200 g	50 g – 2 kg
Relative Uncertainty			
1×10^{-4} – 7×10^{-6}	5×10^{-5} – 5×10^{-6}	5×10^{-8} – 2×10^{-8}	3×10^{-8} – 1×10^{-8}
Relative Cost			
$$$	$	$$$	$$$$
Target Users			
National Lab	Calibrations Lab	Calibrations/National Lab	National Lab