From the *Mise-en-pratique* for Mass to the Future of Metrology for the SI

DR. CARL J. WILLIAMS
Deputy Director
Physical Measurement Laboratory (PML)
National Institute of Standards and Technology

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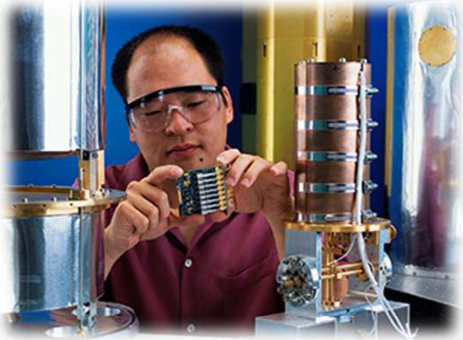
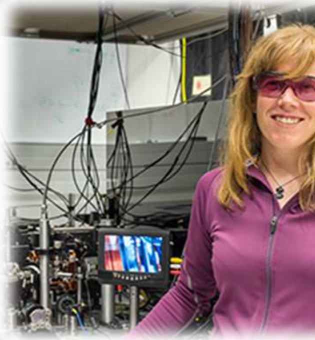
carl.williams@nist.gov



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



PML
PHYSICAL MEASUREMENT LABORAT

Outline

- Problems with the Current SI
- Brief Review of the Redefinition of the SI
- Primary Realization of the Definition of the Kilogram in the new SI
- The *Mise-en-pratique* of the Kilogram at NIST
- Small Mass Realization and Metrology at NIST
- The "Quantum SI," Quantum Information, and the Standard Model
- Future Metrology
- Ubiquitous embedded measurements

Disclaimer: This talk is very "NIST-centric"

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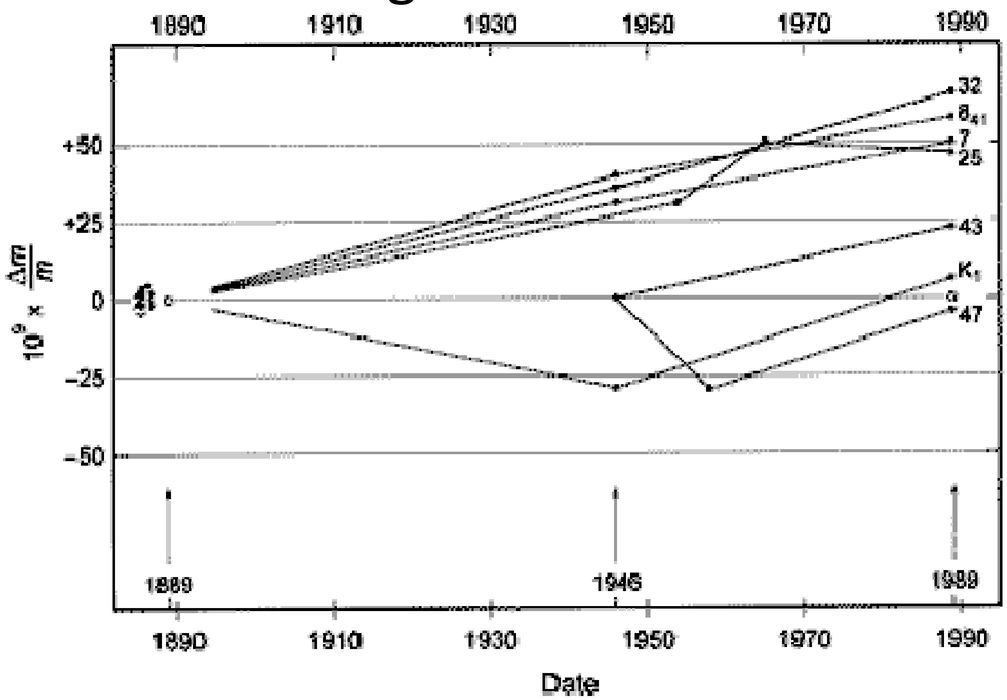
The Two Biggest Headaches in SI Today

) The artifact kilogram



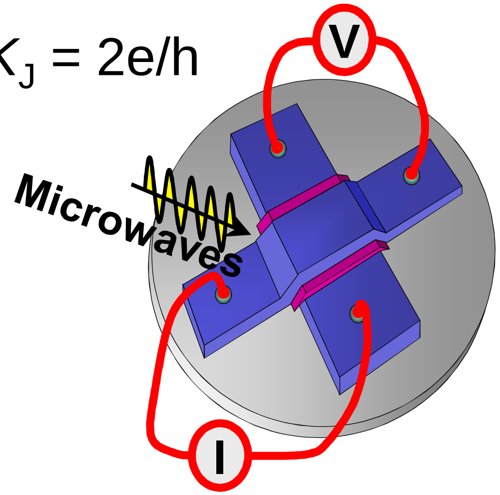
Shown: International Prototype of the Kilogram, kept at BIPM

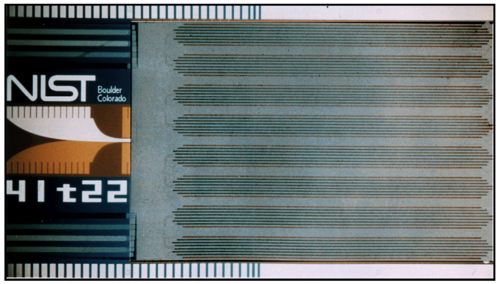
In 2013, in preparation for the redefinition, the BIPM conducted an "extraordinary comparison" of its working standards with the IPK. In the 25 years since the 3rd periodic verification the unit of mass as maintained by the BIPM through its working standards was found to be *0.035 mg too high relative to the*

) The electrical units…

Standards for Electrical Units Since 1990

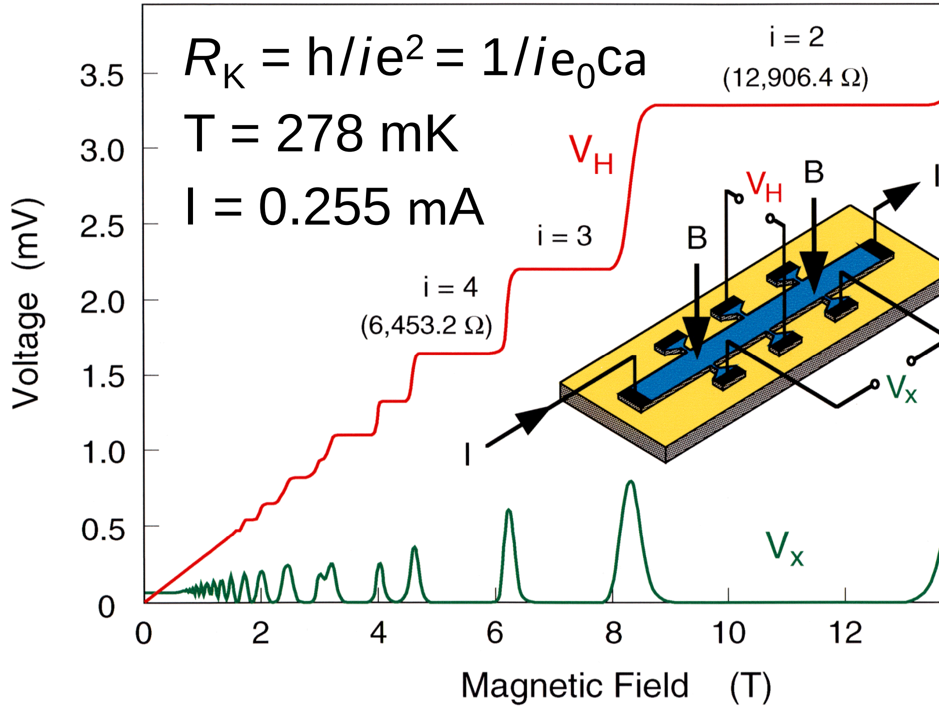
Josephson Voltage Standard





The "volt" realized by Josephson Junction devices, with K_{J-90} = 483,597.9 GHz/V

GaAs Quantum Hall Resistanc



The "ohm" realized by Quantum Hall Effect devices, with R_{K-90} = 25,812.807 Ω

e quantum standards, the Josephson effect (1962, Nobel Prize 1973) and
quantum Hall effect (von Klitzing 1980, Nobel Prize 1985) are so robust that
87 the CGPM (Resolution 6) established *conventional electrical units!*

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The Redefinition: "Quantum SI"

NIST, along with the BIPM and other NMIs (especially NRC, PTB and NMIJ), are at the center of the redefinition

The "Quantum SI"

- A proposal by Mohr, Taylor, and E. Williams (NIST) along with Terry Quinn (*here)* and Ian Mills
- CODATA/ICSU (Committee on Data for Science and Technology) recommended values will be basis for fixing the constants

Quantum Measurement Division (QMD) within PML realizes electrical, mass, and force units

- NIST Reorganization (2011) created a *unique* opportunity for the mise-en-pratique for mass!
- Quantum based measurements provides foundation for advances in all units including beyond the standard quantum limit

INSTITUTE OF PHYSICS PUBLISHING METROLOGIA
Metrologia 43 (2006) 227–246 doi:10.1088/0026-1394/43/3/006

Redefinition of the kilogram, ampere, kelvin and mole: a proposed approach to implementing CIPM recommendation 1 (CI-2005)

Ian M Mills[1], Peter J Mohr[2], Terry J Quinn[3], Barry N Taylor[2] and Edwin R Williams[2]

2014 CODATA RECOMMENDED VALUES OF THE FUNDAMENTAL CONSTANTS OF PHYSICS AND CHEMISTRY NIST SP 959 (Aug 2015)

See: P. J. Mohr, D. B. Newell, and B. N. Taylor, arxiv.org/pdf/1507.07956v1.pdf (2015). A more extensive listing of constants is available in the reference given above and on the NIST Physical Measurement Laboratory Web site: physics.nist.gov/constants.

Quantity	Symbol	Numerical value	Unit
speed of light in vacuum	c, c_0	299 792 458 (exact)	$\mathrm{m\ s^{-1}}$
magnetic constant	μ_0	$4\pi \times 10^{-7}$ (exact)	$\mathrm{N\ A^{-2}}$
electric constant $1/\mu_0 c^2$	ϵ_0	$8.854\,187\,817... \times 10^{-12}$	$\mathrm{F\ m^{-1}}$
Newtonian constant of gravitation	G	$6.674\,08(31) \times 10^{-11}$	$\mathrm{m^3\ kg^{-1}\ s^{-2}}$
Planck constant	h	$6.626\,070\,040(81) \times 10^{-34}$	J s
$h/2\pi$	$\hbar$	$1.054\,571\,800(13) \times 10^{-34}$	J s
elementary charge	e	$1.602\,176\,6208(98) \times 10^{-19}$	C
fine-structure constant $e^2/4\pi\epsilon_0\hbar c$	α	$7.297\,352\,5664(17) \times 10^{-3}$	
inverse fine-structure constant	α^{-1}	137.035 999 139(31)	
Rydberg constant $\alpha^2 m_e c/2h$	R_∞	10 973 731.568 508(65)	$\mathrm{m^{-1}}$
Bohr radius $\alpha/4\pi R_\infty$	a_0	$0.529\,177\,210\,67(12) \times 10^{-10}$	m
Bohr magneton $e\hbar/2m_e$	μ_B	$927.400\,9994(57) \times 10^{-26}$	$\mathrm{J\ T^{-1}}$

Redefinition of the SI: What's up?

We are on schedule for a possible redefinition in 2018: See Resolution 1 of the 24th (2011) and 25th (2014) CGPM

December 2013, International Prototype Kilogram (IPK) brought out for first time in 25 years: **Extraordinary Comparison (Feb 2015)**

- Result: BIPM mass scale found to be .035 mg too high relative to IPK
- This largely cancels the .045 mg shift NIST *accepted* in 2010

Le Grand K (I

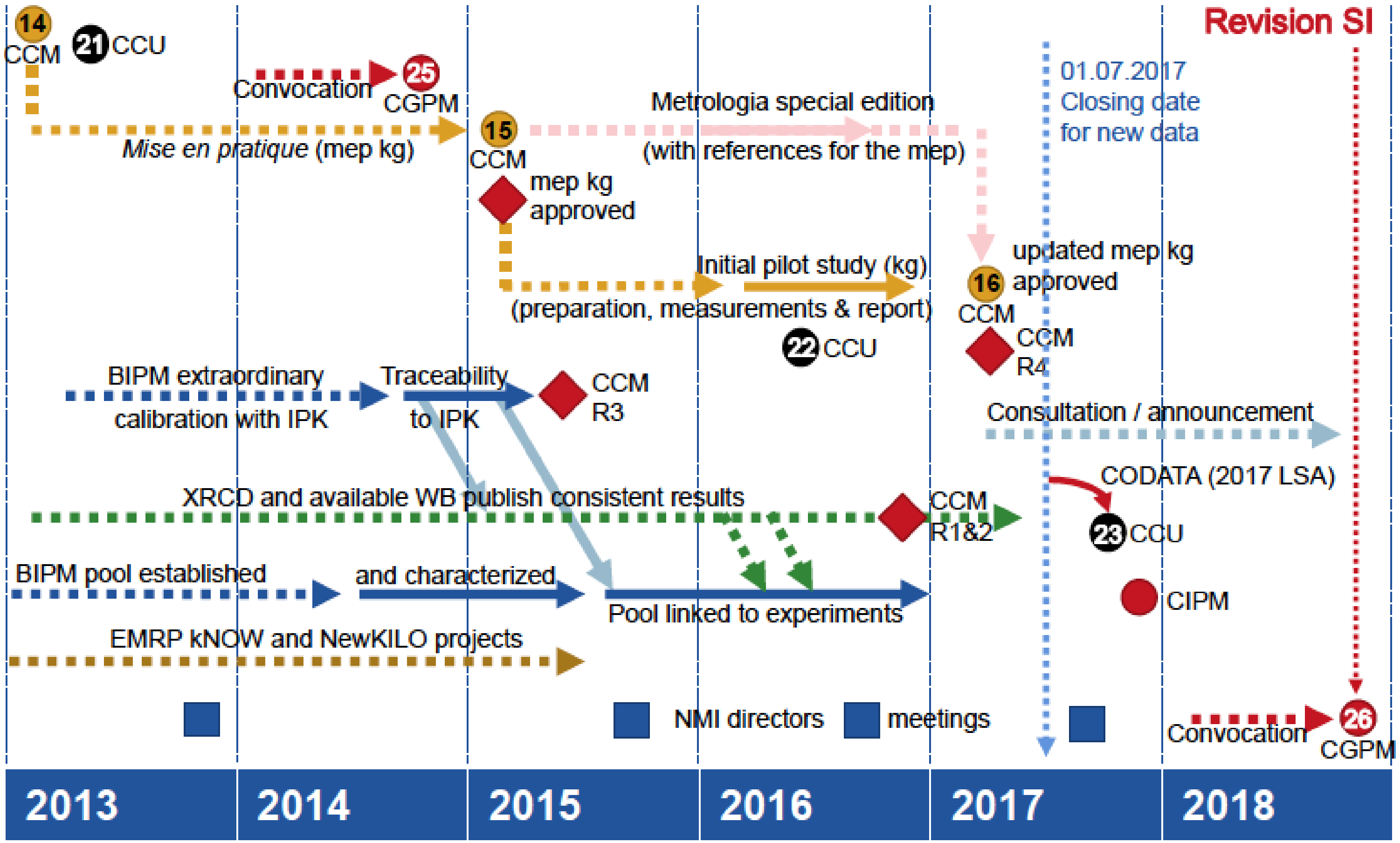
Agreement of Planck's constant determinations is sufficient to support redefinition

CODATA 2014 values are available on web, including Planck's constant

Pilot study – a dry run of the new *mise-en-pratique* for mass is underway

Redefinition of the SI is Coming

Joint CCM and CCU roadmap for the new SI



So how will we realiz
the definition of the
kilogram in the new
SI?

mise-en-pratique:
the instruction set fo
realizing the definitio
of a unit at the highe
level

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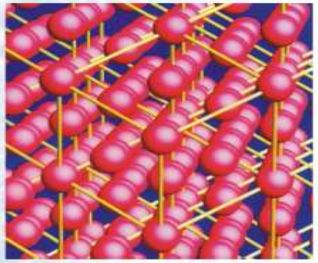
Primary Realization of the Definition of the Kilogram

Watt Balance: Equates mechanical quantity of power to the corresponding electrical quantity when the latter is measured in terms of quantum electrical effects – used to determine *h*

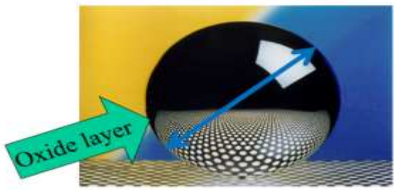
X-Ray Crystal Density (Avogadro): Compares a macroscopic mass to the mass of a single atom of a specified isotope – used to determine N_A

How to count 10^{23} atoms? PTB

With a crystal!



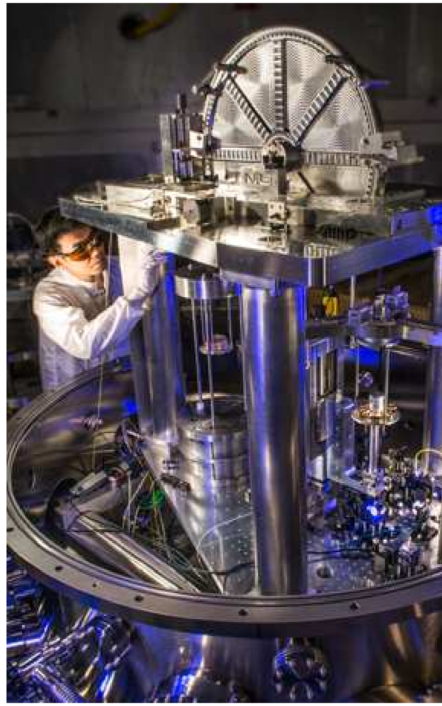
1. Volume a_0^3 of the unit cell
2. Volume of an atom: $a_0^3/8$
3. Volume *V* of a sphere
4. Number *n* of the atoms



$$N_A = \frac{8\,V}{a_0^3} \cdot \frac{M_{mol}}{m_{sphere}}$$

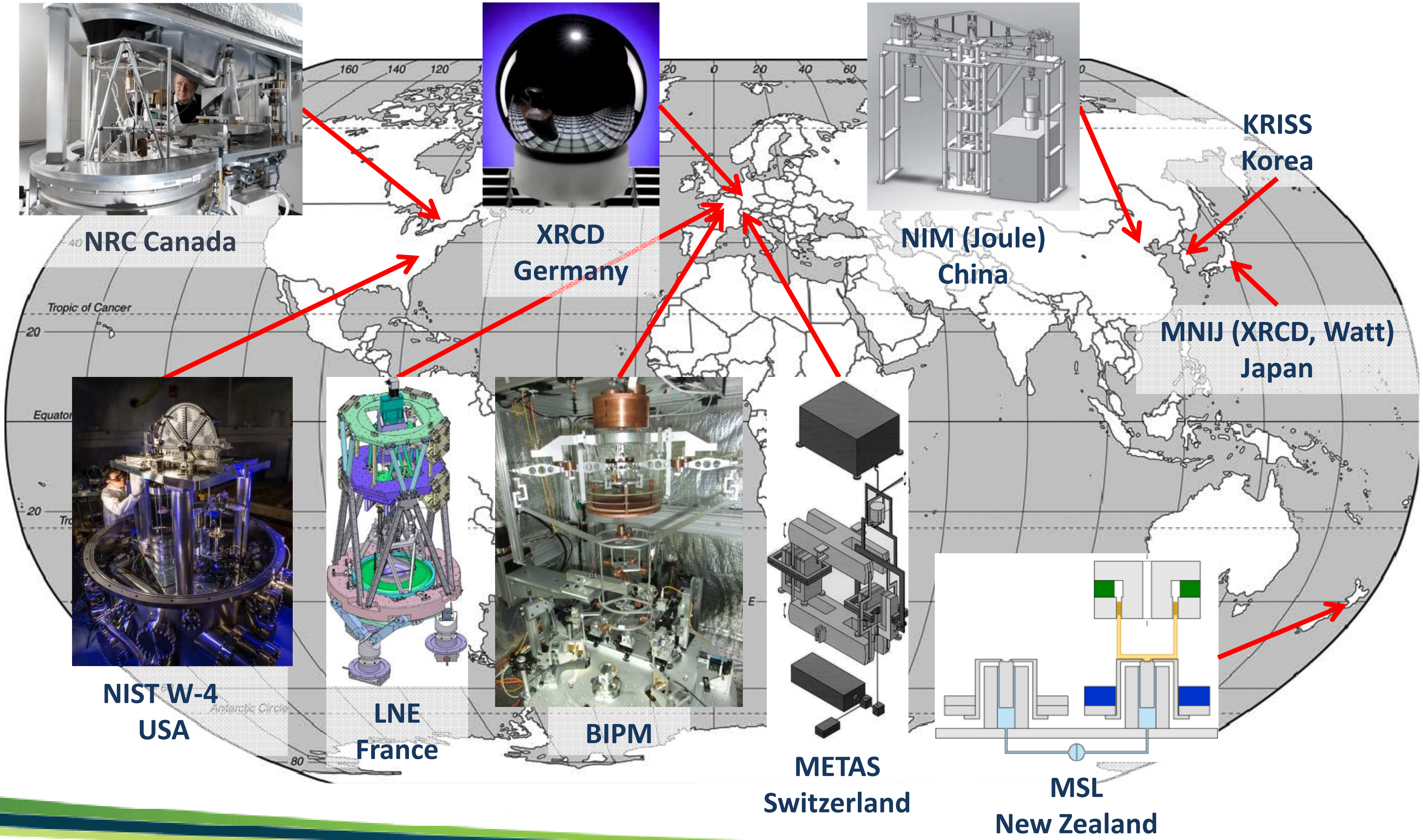
The Perfect Artifact!

$$N_A h = \frac{M(e)}{m(e)} \cdot h = \frac{M(e)\,c\,\alpha^2}{2R_\infty}$$



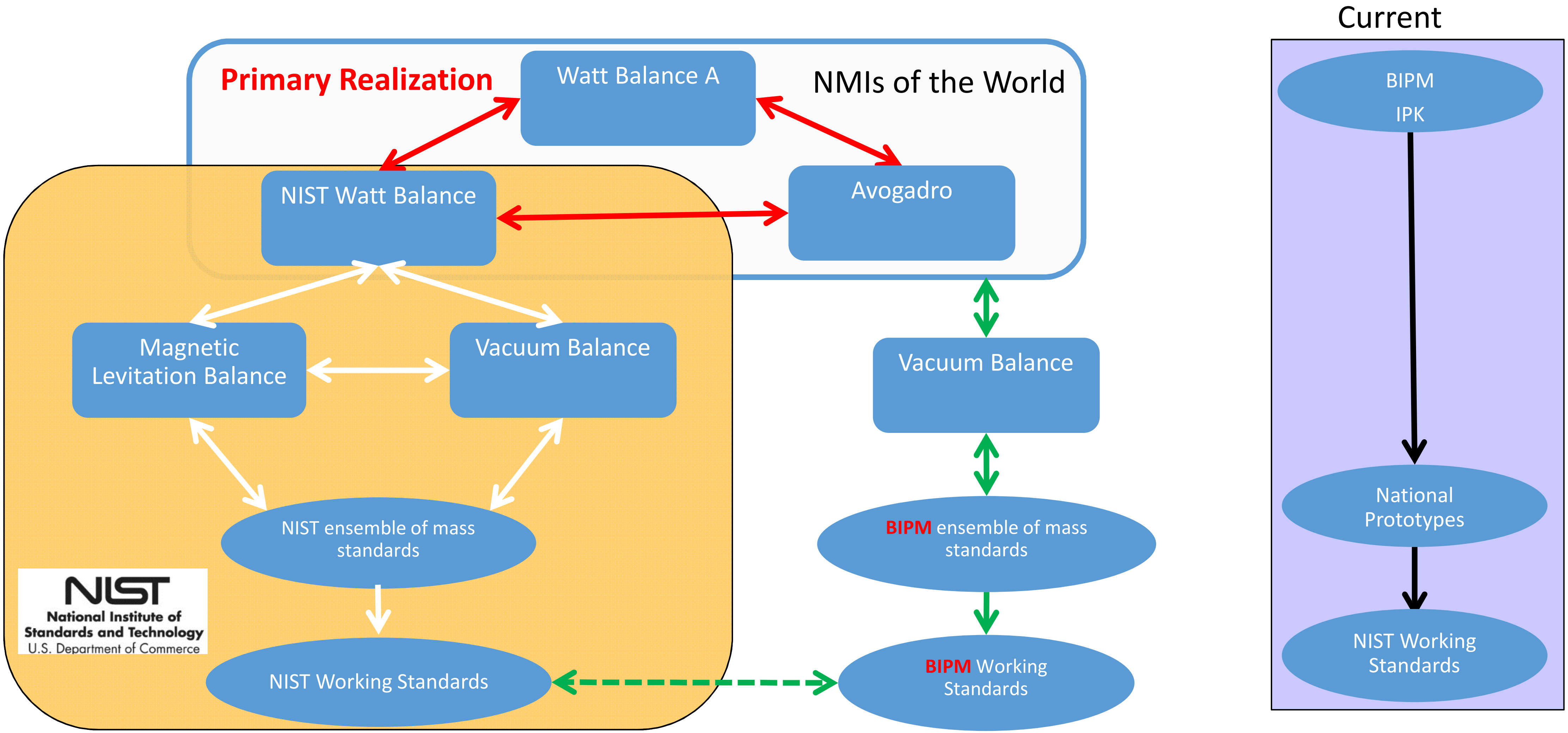
- Approaches are complementary - Either can be used to realize the definition of the kilogram.
- SI kilogram realized in vacuum.

Worldwide Realizations of the New Kilogram

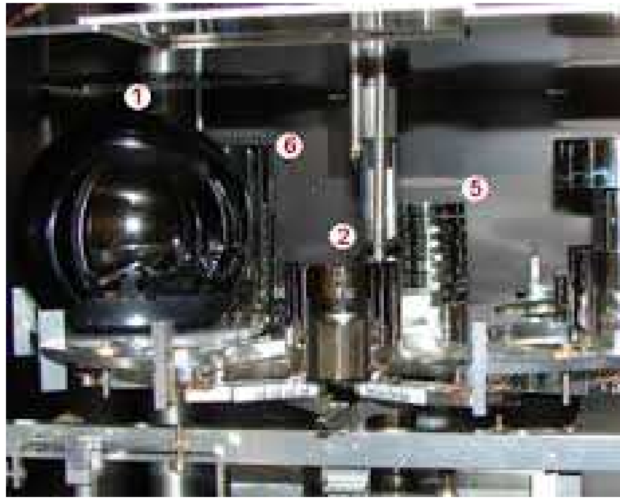


Plans for
table top w
balances in
Mexico and
South Afric

Dissemination From a Primary Realization



Realization of Kilogram: XRCD



View into weighing chamber showi
(1) ^{28}Si sphere (AVO28-S8), (2) Prot
kilogram No. 70, and (3-6) absorp
and air buoyancy artifacts. (from

- Carefully maintain the Si sphere
- Monitor surface layers (oxidation)
  - Spectral ellipsometry, X-ray refractometry, photoelectron spectrometry, X-ray fluorescence, and infrared absorption
- Monitor volume of sphere
- Assumes that the crystal spacing is constant with time and the molar mass will not change
- Si sphere mass can be measured in vacuum or in air (buoyancy correction required – but the density and volume are known very well)
- Determining N_A was much harder then realizing mass with the sphere

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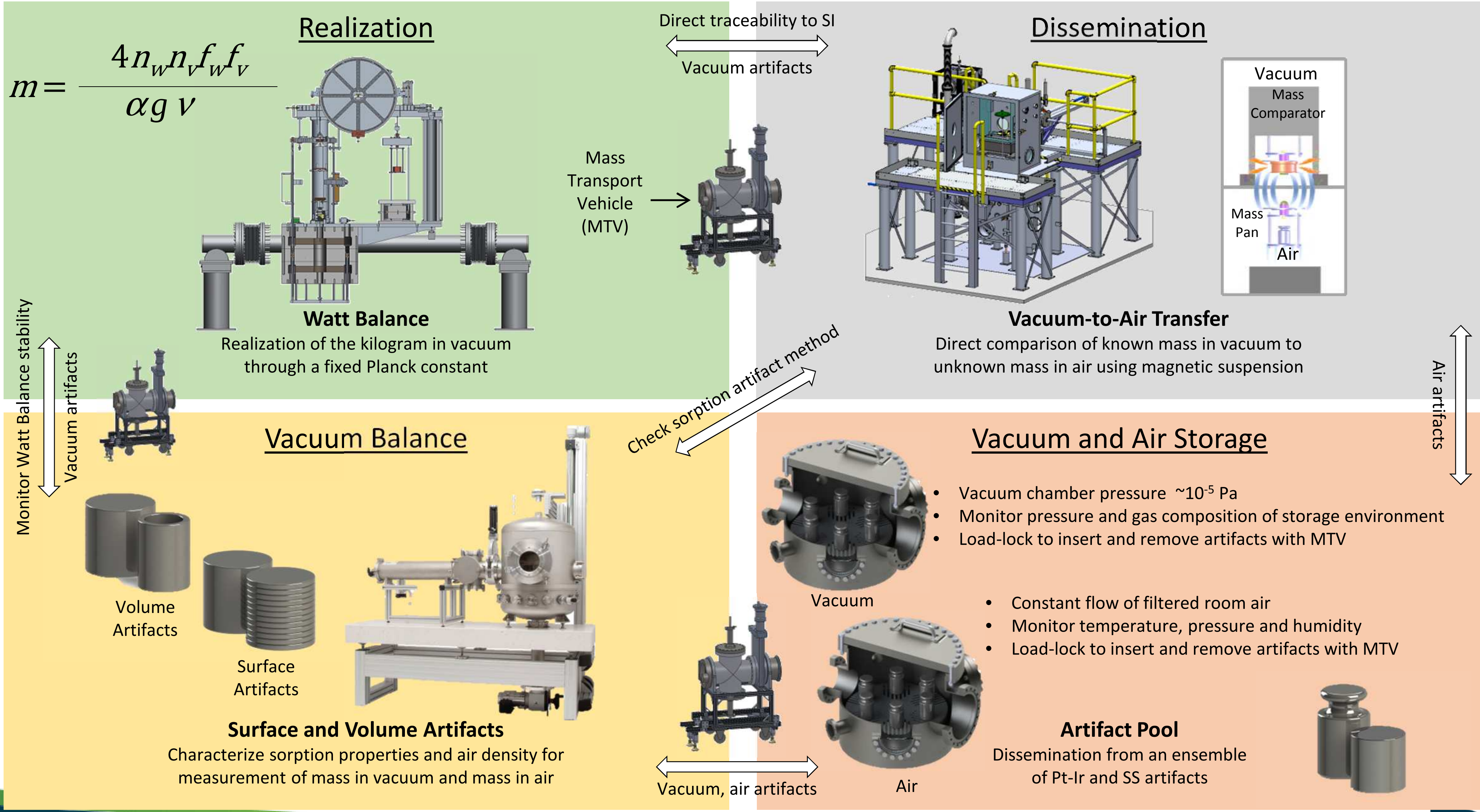
Mise-en-pratique for Kilogram at NIST



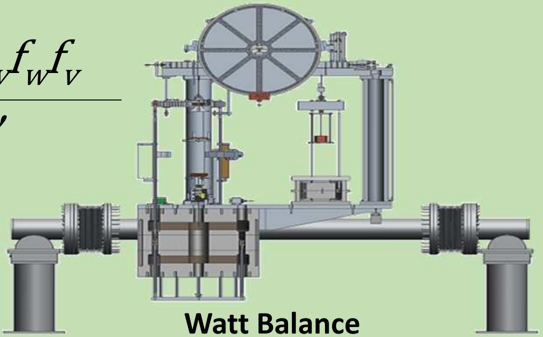
MISE EN PRATIQUE

For the Realization and Dissemination of the Redefined Kilogram

Patrick J. Abbott, Edward Mulhern, Eric Benck, Corey Stambaugh, Zeina Kubarych

Realization

$$m = \frac{4 n_w n_v f_w f_v}{\alpha g v}$$



Watt Balance

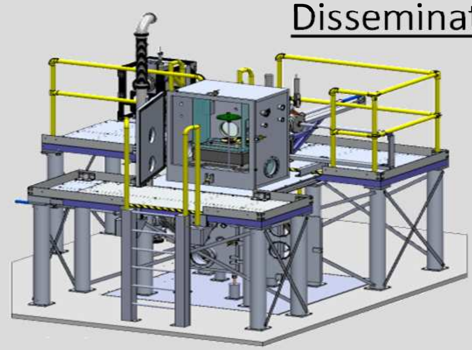
Realization of the kilogram in vacuum through a fixed Planck constant

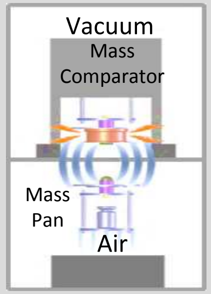
Direct traceability to SI

Vacuum artifacts

Mass Transport Vehicle (MTV)

Dissemination





Vacuum-to-Air Transfer

Direct comparison of known mass in vacuum to unknown mass in air using magnetic suspension

Air artifacts

Vacuum artifacts

Check sorption artifact method

Vacuum Balance

Volume Artifacts

Surface Artifacts

Surface and Volume Artifacts

Characterize sorption properties and air density for measurement of mass in vacuum and mass in air

Vacuum, air artifacts

Vacuum and Air Storage

Vacuum

- Vacuum chamber pressure ~10^{-5} Pa
- Monitor pressure and gas composition of storage environment
- Load-lock to insert and remove artifacts with MTV

Air

- Constant flow of filtered room air
- Monitor temperature, pressure and humidity
- Load-lock to insert and remove artifacts with MTV

Artifact Pool

Dissemination from an ensemble of Pt-Ir and SS artifacts

Traceability and Dissemination

New SI kg Watt Balance (Vacuum)	Primary 1kg Mass (Vacuum)	Secondary 1kg Mass (Vacuum)

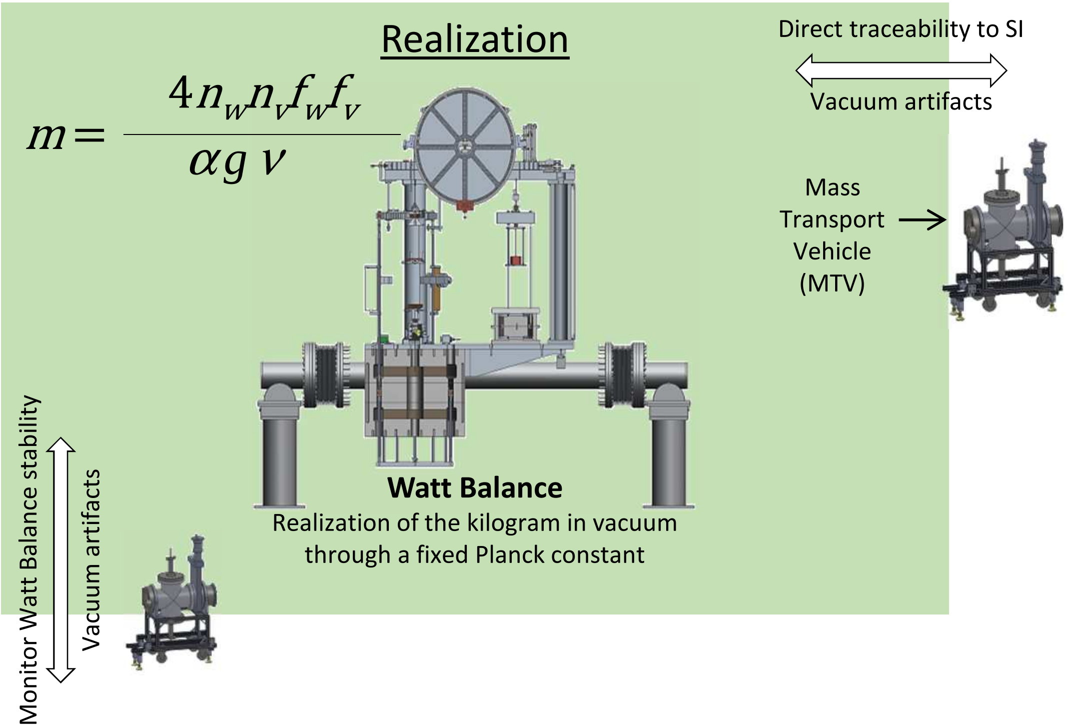
Magnetic Levitation Transfer

BIPM IPK (Air)	US National Standard (Air)	Secondary 1kg Mass (Air)	Disseminate New SI kg

Current System

Magnetic Levitation Transfer

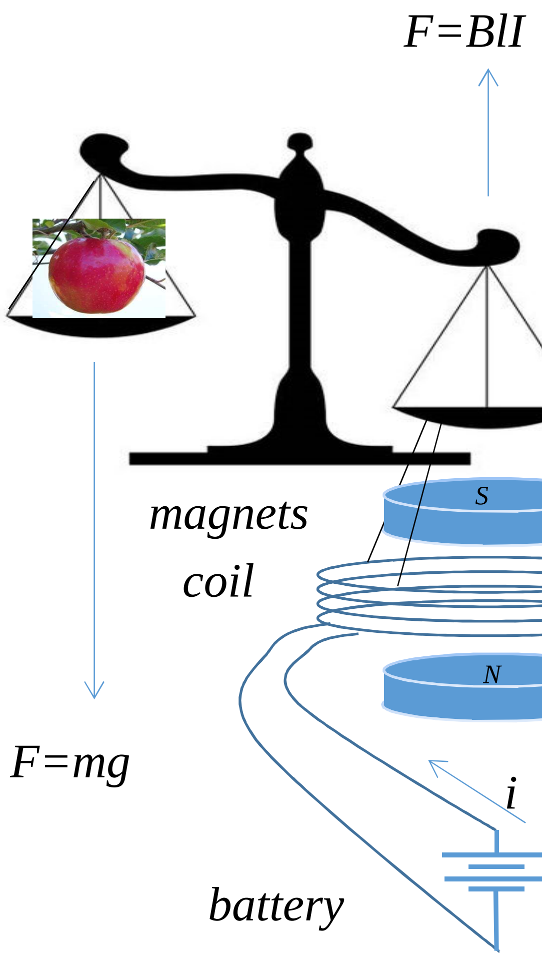
Mise-en-pratique at NIST: Part 1 Realization



You can Weigh an Apple with a Scale

One usually weighs apples using a cale to compare their gravitational rce to that of a known artifact (see painting on the right)

With a watt balance electromagnetic scale (see magazine cover at the left) one **compares the apple's gravitational force to that of a *calculable* force that is known in terms of physical invariants, like the figure on the right**



Watt Balance Basics

Weighing or Force mode: An unknown weight *mg* is balanced by an electromagnetic force on a horizontal coil of wire-length *L* in a radial magnetic field of flux density *B* when a current *I* flows through the coil

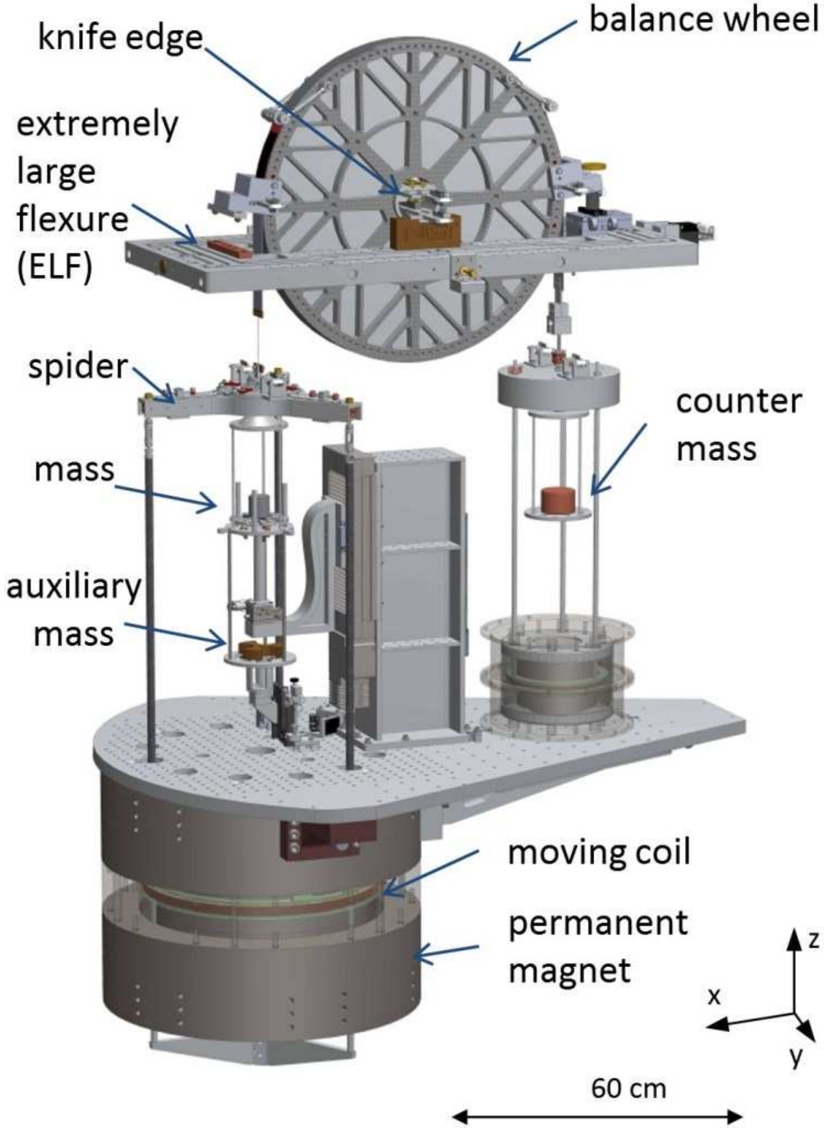
$$mg = BLI$$

Calibration or Velocity mode: The magnet's strength *BL* is measured by moving the coil at a velocity *v* while recording the voltage *V* across the coil terminals

$$BL = \frac{V}{v}$$

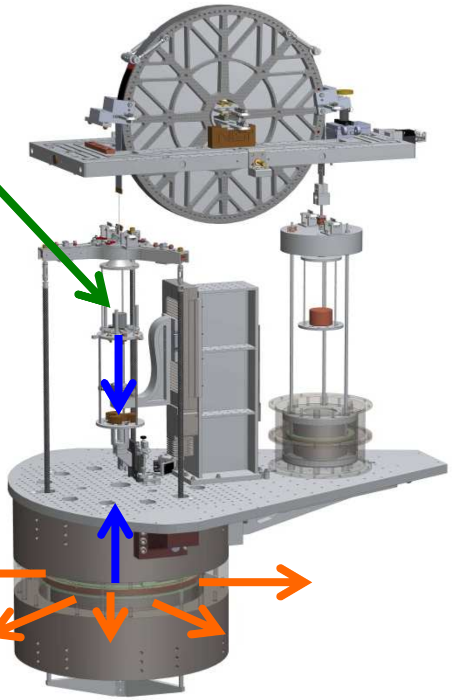
The two modes can compare mechanical and electrical power, hence the name, watt balance

$$mgv = VI$$



Watt Balance Principles in one-Slide

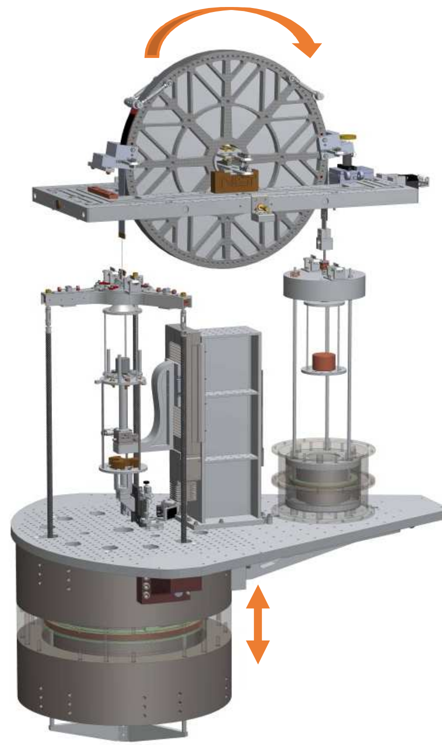
Force mode



$$mg = BLI$$

$$BL = \frac{mg}{I}$$

Velocity mode



$$V = \nu BL$$

$$BL = \frac{V}{v}$$

$$\frac{mg}{I} = \frac{V}{\nu}$$

$$mg\nu = VI$$

$$mg\nu = \frac{V_1 V_2}{R}$$

$$mg\nu = \frac{n_1 f_1 \frac{h}{2e} n_2 f_2 \frac{h}{2e}}{\alpha \frac{h}{e^2}} = \frac{n_1 n_2}{4\alpha} f_1 f_2 h$$

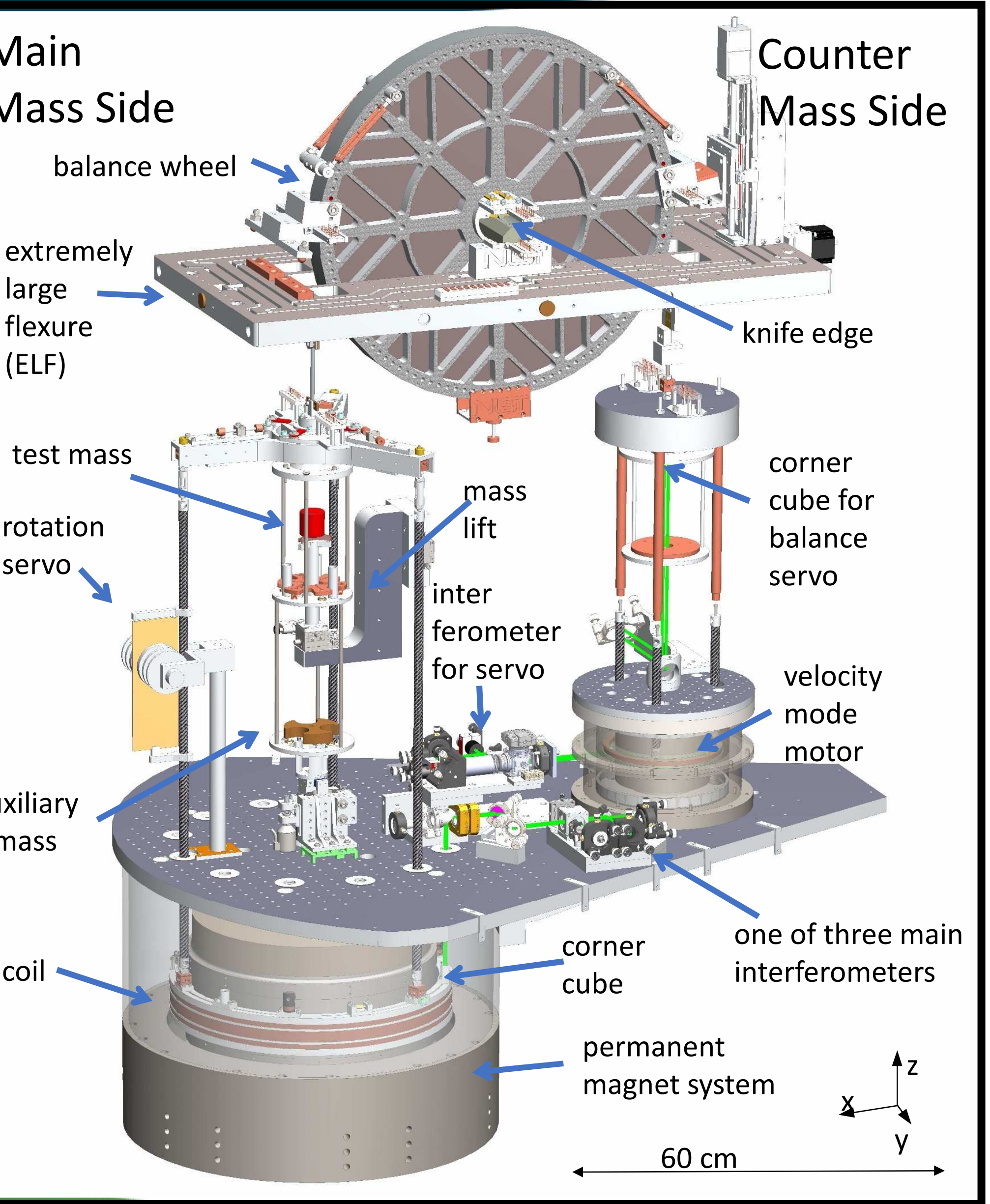
$$h = \frac{4\alpha}{n_1 n_2} \frac{g\nu}{f_1 f_2} m$$

before redefinition

after redefinition

$$m = \frac{n_1 n_2}{4\alpha} \frac{f_1 f_2}{g\nu} h$$

NIST-4 Watt Balance

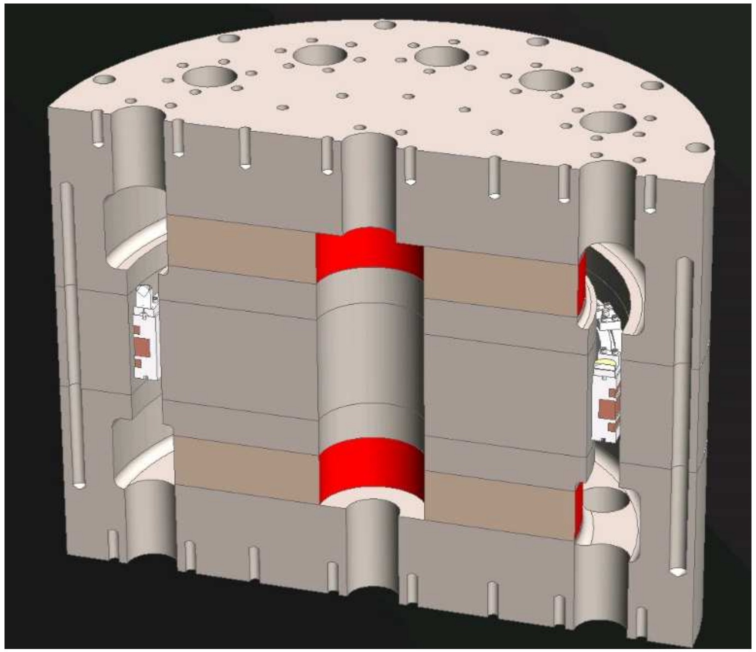


Magnet system constructed from soft iron and Sm_2Co_{17}.

- total 91 kg of Sm_2Co_{17}
- flux density: 0.55 T
- 3 cm gap
- 10 cm tall
- magnet can be split

Coil

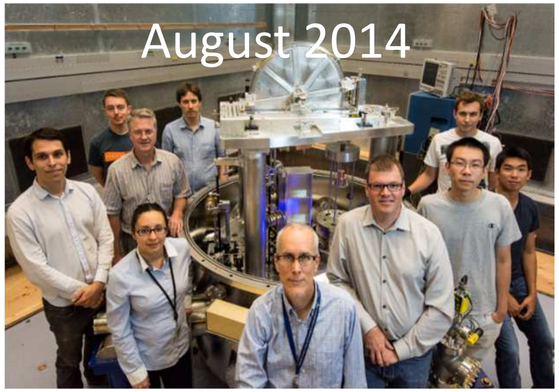
- alumina former
- three groves
- main coil (945 turns)
- wire length: 1271 m
- U = 0.69 V (1 mm/s)
- two gradient coils (135 turns)

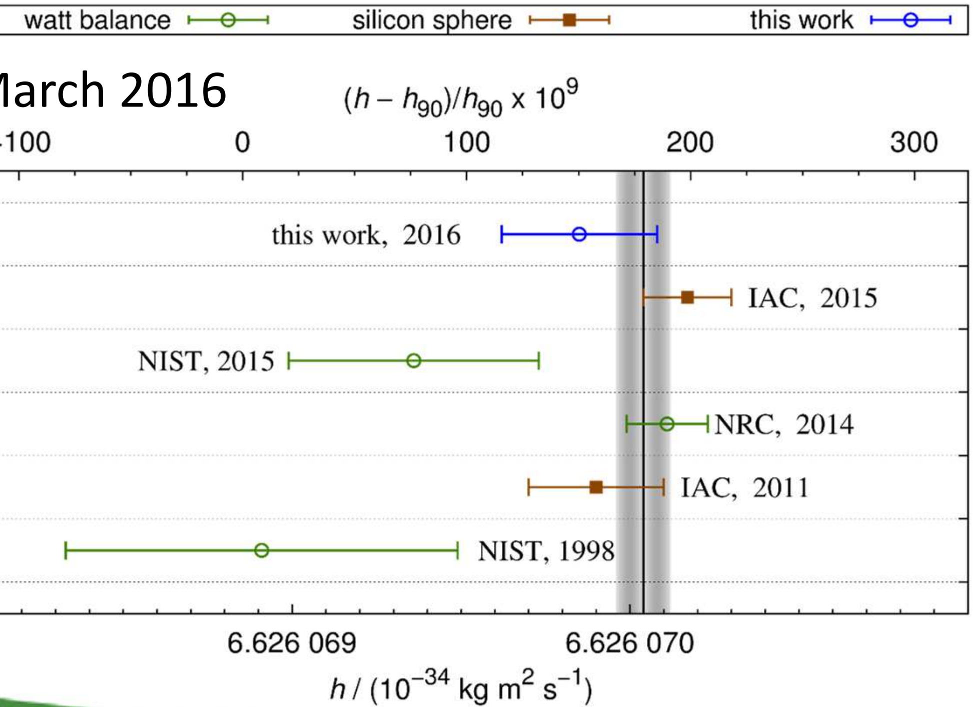


Watt Balance require
precision measureme

- Current
- Voltage
- Resistance
- Gravity
- Length
- Time

The NIST-4 Watt Balance

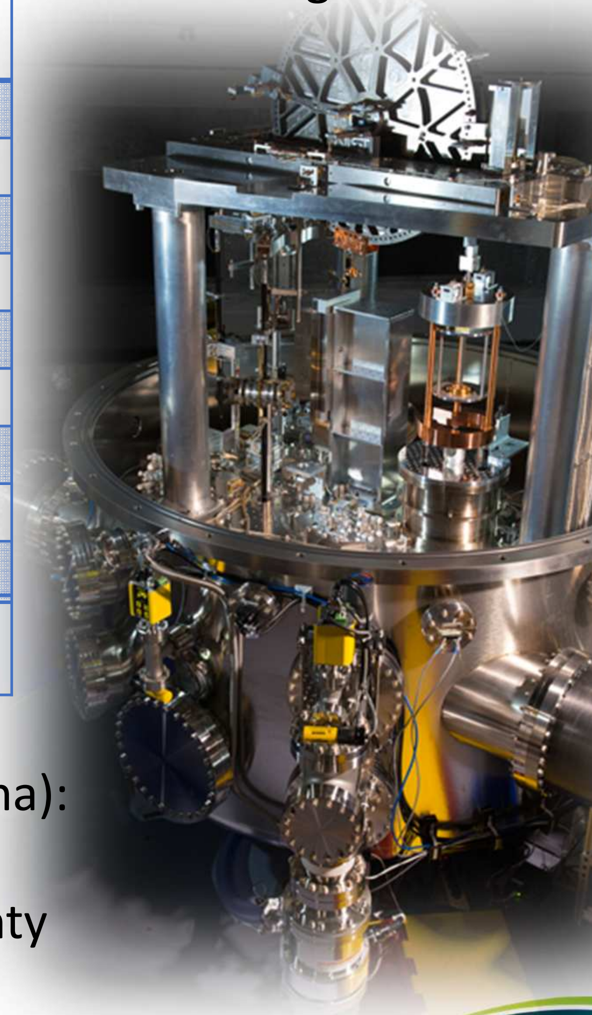




Source	Uncertainty (10^{-9})
Statistical	25.3
Magnetic field	15.4
Electrical	10.9
Alignment	7.0
Mass metrology	6.3
Mathematical	5.0
Balance mechanics	5.0
Local acceleration, g	4.4
Velocity	1.7
Total relative uncertainty	**33.7**

- relative uncertainty (1-sigma): 34×10^{-9}
- projected relative uncertainty *by June 2017*: 20×10^{-9}

August 2015



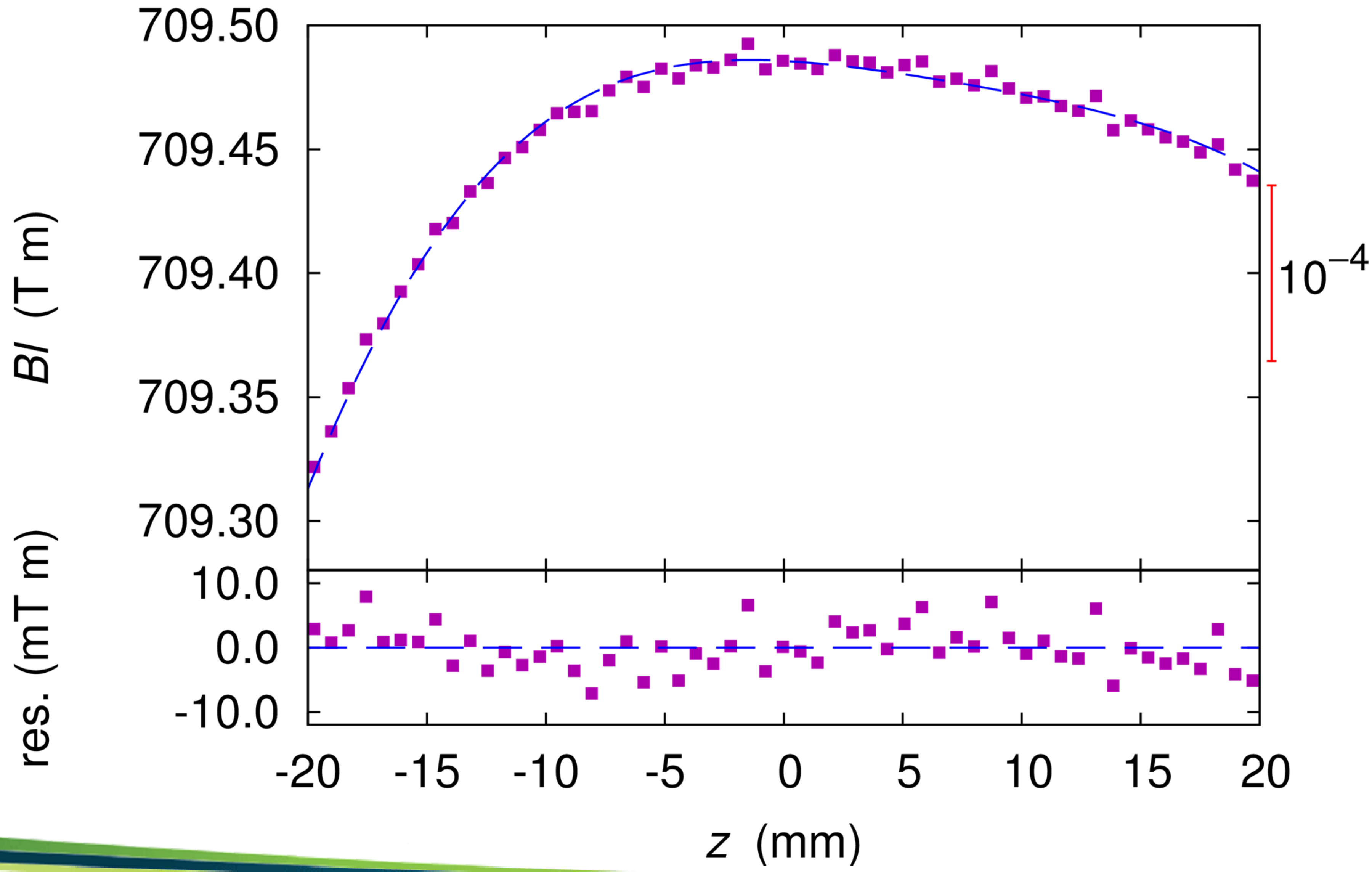
NIST and the Redefinition

- NIST-4 Watt Balance
  - Fully operational and has a *great* noise floor
  - First value of Planck published (RSI **87**, 061301 (2016))
  - Final value of Planck expected early 2017
- Vacuum Levitation Balance concept validated
- Pilot study of the *new mise-en-pratique* for mass is underway and should be completed by fall 2016
- CODATA will provide final constants for redefinition in 2017
- CODATA will determine the constants for the "*new SI*" in 2018

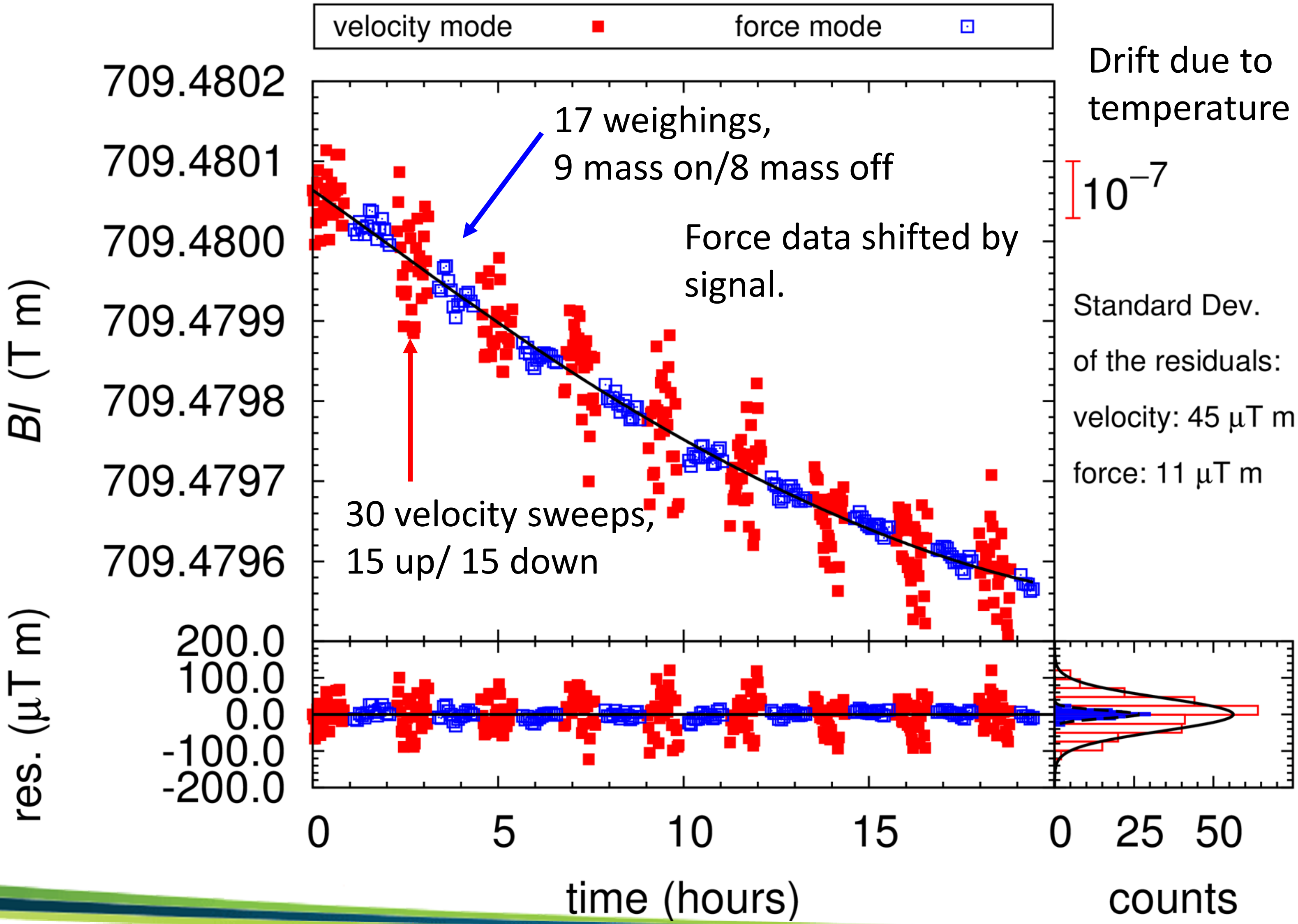
Am. J. Phys. 83, 913 (2

NIST Do It Yourself Watt Balance made of Lego®: *Educational Outreach*

Coil Sweep in Velocity Mode



Typical Measurement Sequence



Drift due to temperature change.

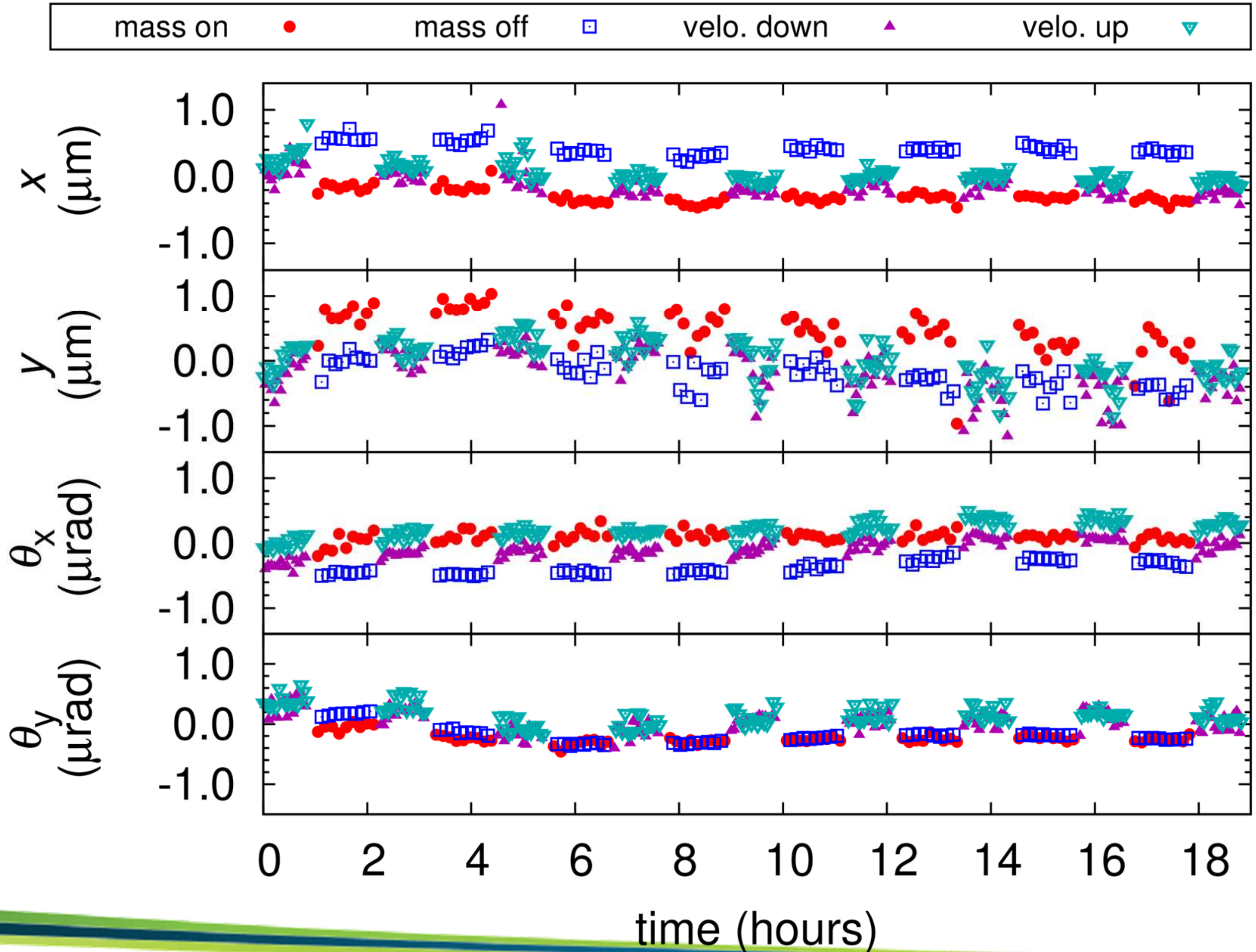
Standard Dev.

of the residuals:

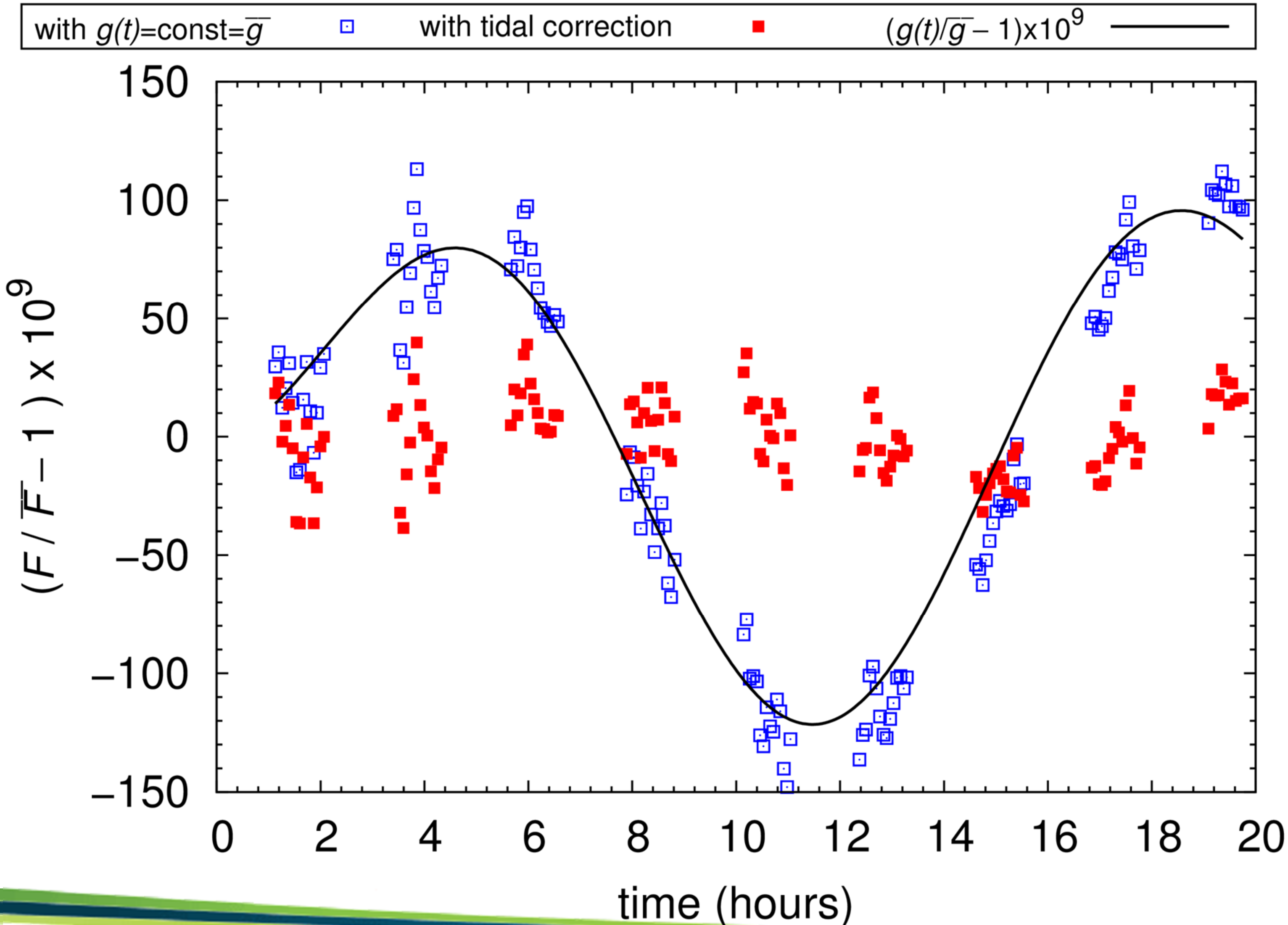
velocity: 45 µT m

force: 11 µT m

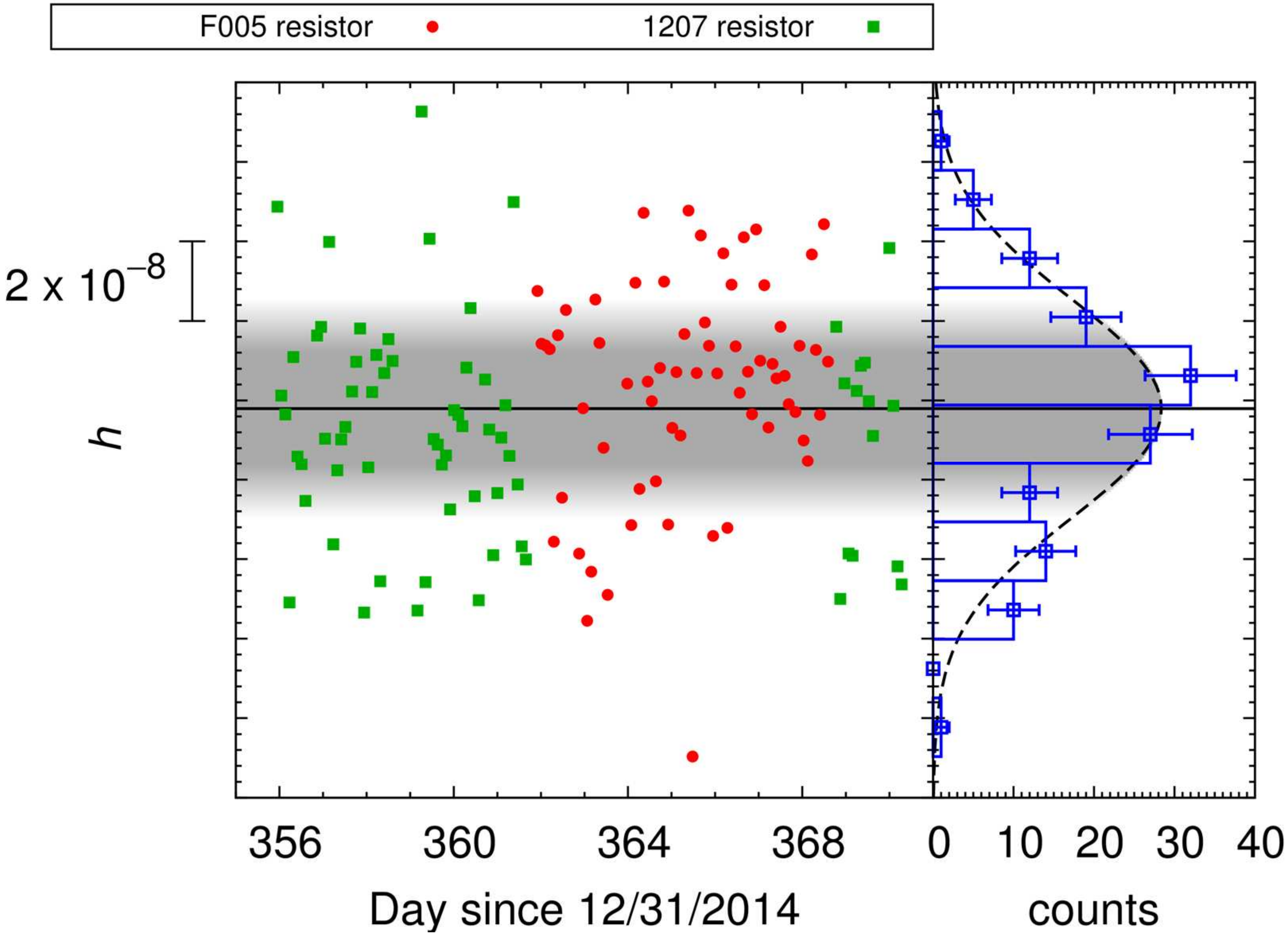
Parasitic Forces and Torques on the Coil



Clear Tidal Signature



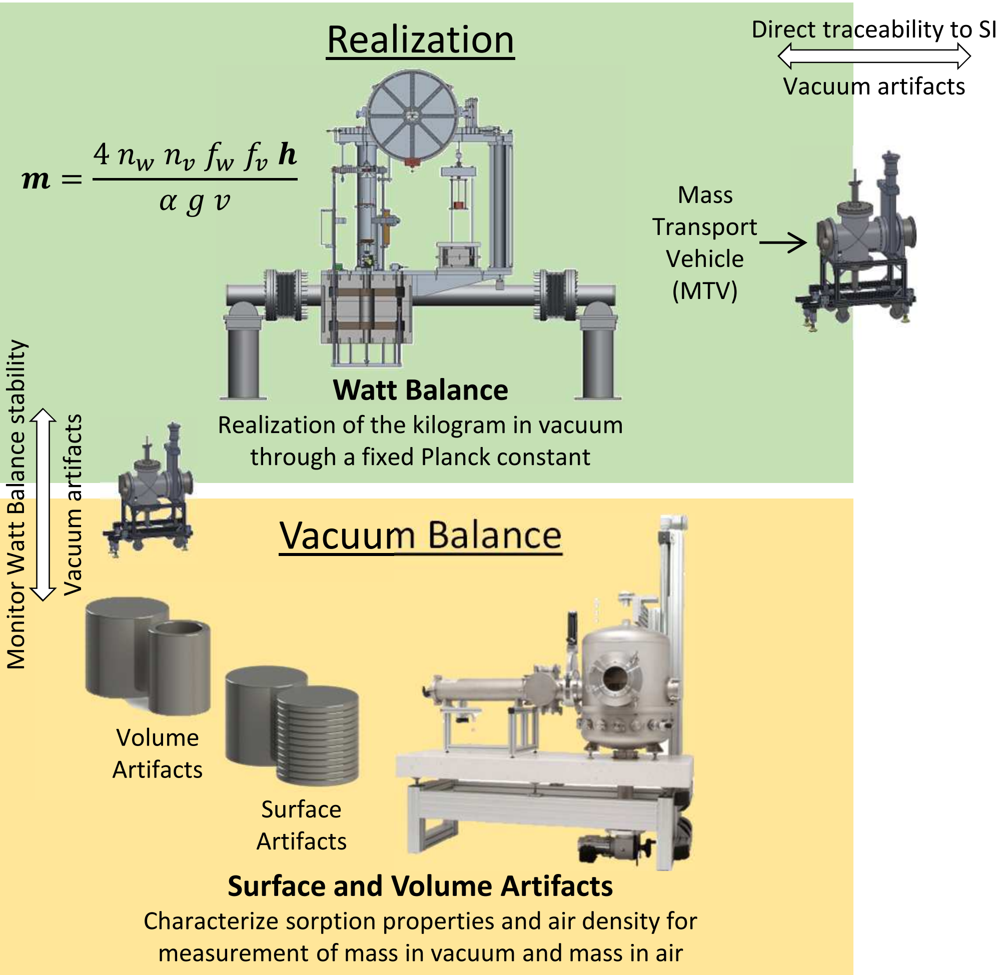
Data Taken with Prototype K85



133 points
Rel. standard deviation: 25.3×10^{-9}

Estimated total relative uncertainty: $< 40 \times 10^{-9}$.

Mise-en-pratique at NIST: Part 2 Air-Vacuum



Mass Transport Vehicle (MTV) Details

Vacuum-Air Weighing with Sorption Artifacts

Plasma Cleaning

uum
ance

Mass of stack – Mass of cylinder 89

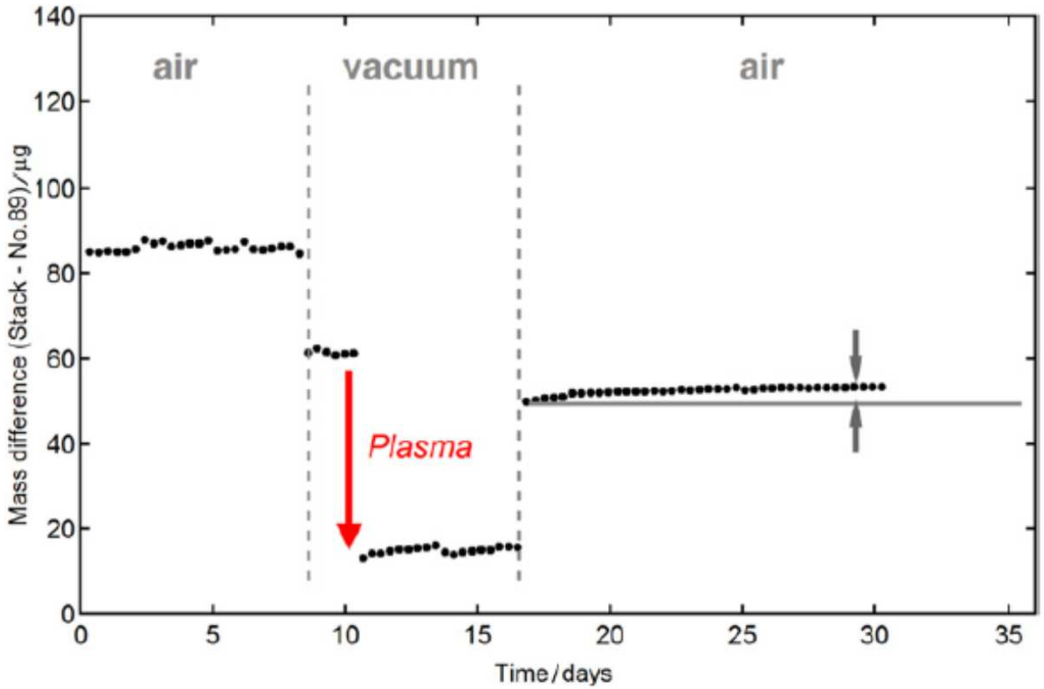
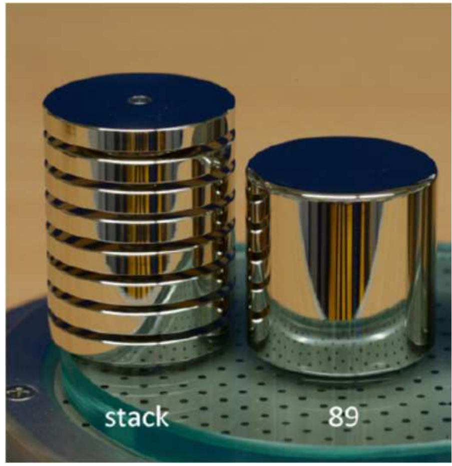


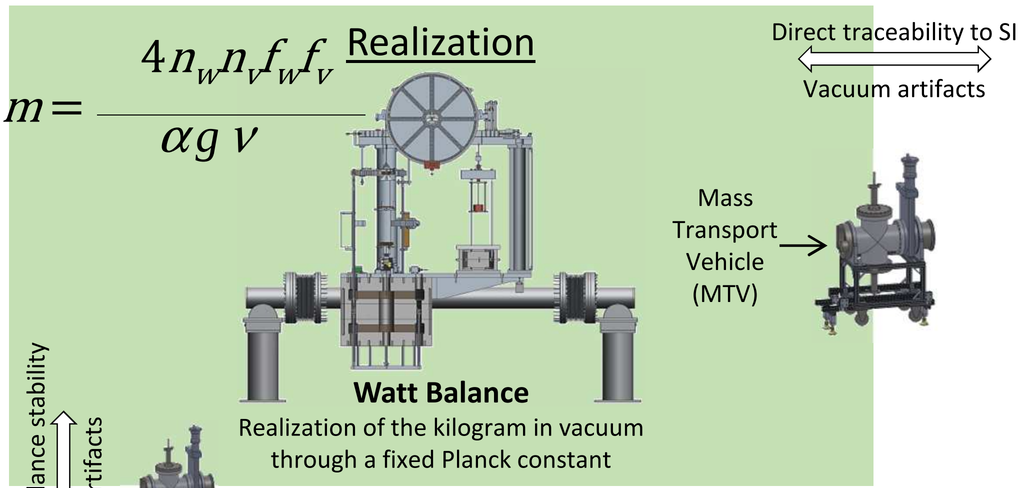
Figure 4. Evolution of the mass difference between the stack of discs and the surface artefact No 89 with time. The mass difference significantly decreases after air-to-vacuum transfer and decreases further by H-plasma treatment. The mass difference increases significantly after vacuum-to-air transfer. The gain in mass at ambient after cleaning is indicated by the horizontal line and arrows.



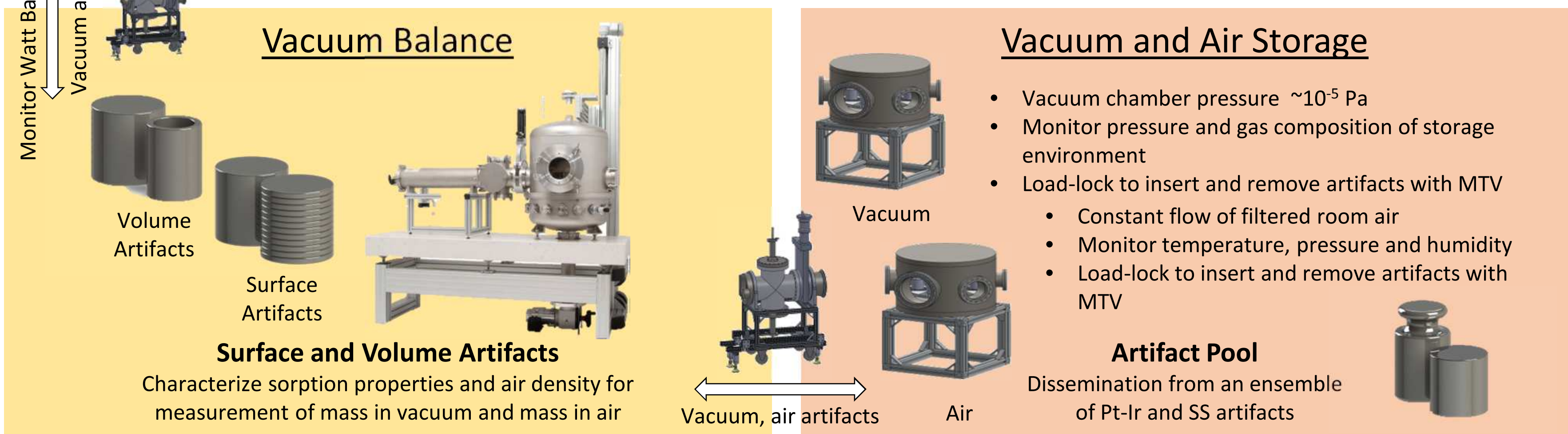
Reference: Fuchs, Marti & Ru
Metrologia, **49** (2012) 607–6

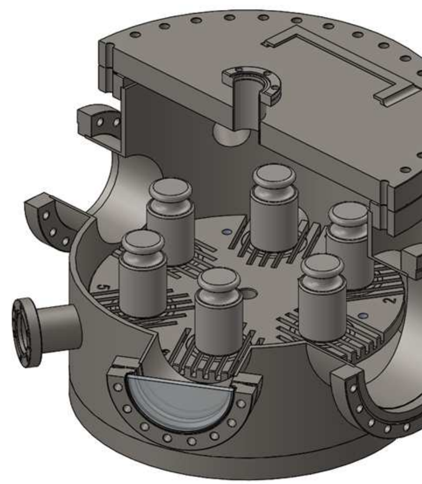
NIST will do this at least initially

Mise-en-pratique at NIST: Part 3 Store Artifacts



- "Pool of Artifacts" traceable to NIST WB stored in filtered lab air or vacuum
- Artifacts enter and leave chambers via Mass Transp Vehicle
- **The unit of mass disseminated by NIST will be an "ensemble average" of the mass values of these artifacts – both Pt-Ir and Stainless**
- NIST owns K4, K20, K79, K85, K92, K102, K104, K10

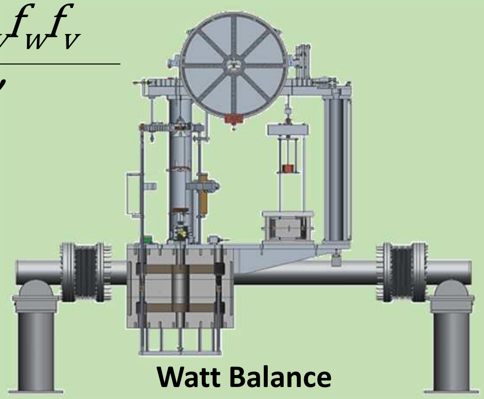




Mise-en-pratique at NIST: Part 4 Dissemination

Realization

$$m = \frac{4 n_w n_v f_w f_v}{\alpha g\, v}$$

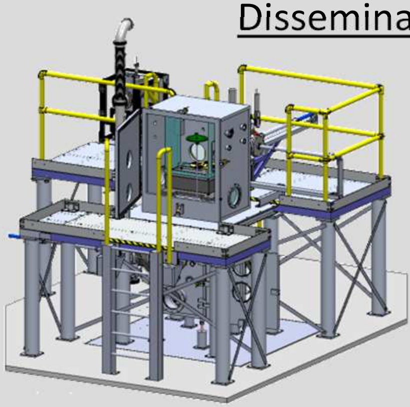


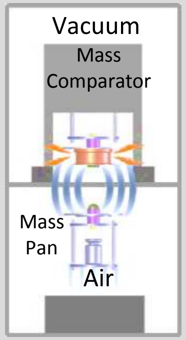
Watt Balance
Realization of the kilogram in vacuum through a fixed Planck constant

Direct traceability to SI
Vacuum artifacts

Mass Transport Vehicle (MTV) →

Dissemination





Vacuum-to-Air Transfer
Direct comparison of known mass in vacuum to unknown mass in air using magnetic suspension

Monitor Watt Balance stability

Vacuum artifacts

Check sorption artifact method

Air artifacts

Vacuum Balance

Volume Artifacts

Surface Artifacts

Surface and Volume Artifacts
Characterize sorption properties and air density for measurement of mass in vacuum and mass in air

Vacuum and Air Storage

Vacuum

- Vacuum chamber pressure ~10^{-5} Pa
- Monitor pressure and gas composition of storage environment
- Load-lock to insert and remove artifacts with MTV

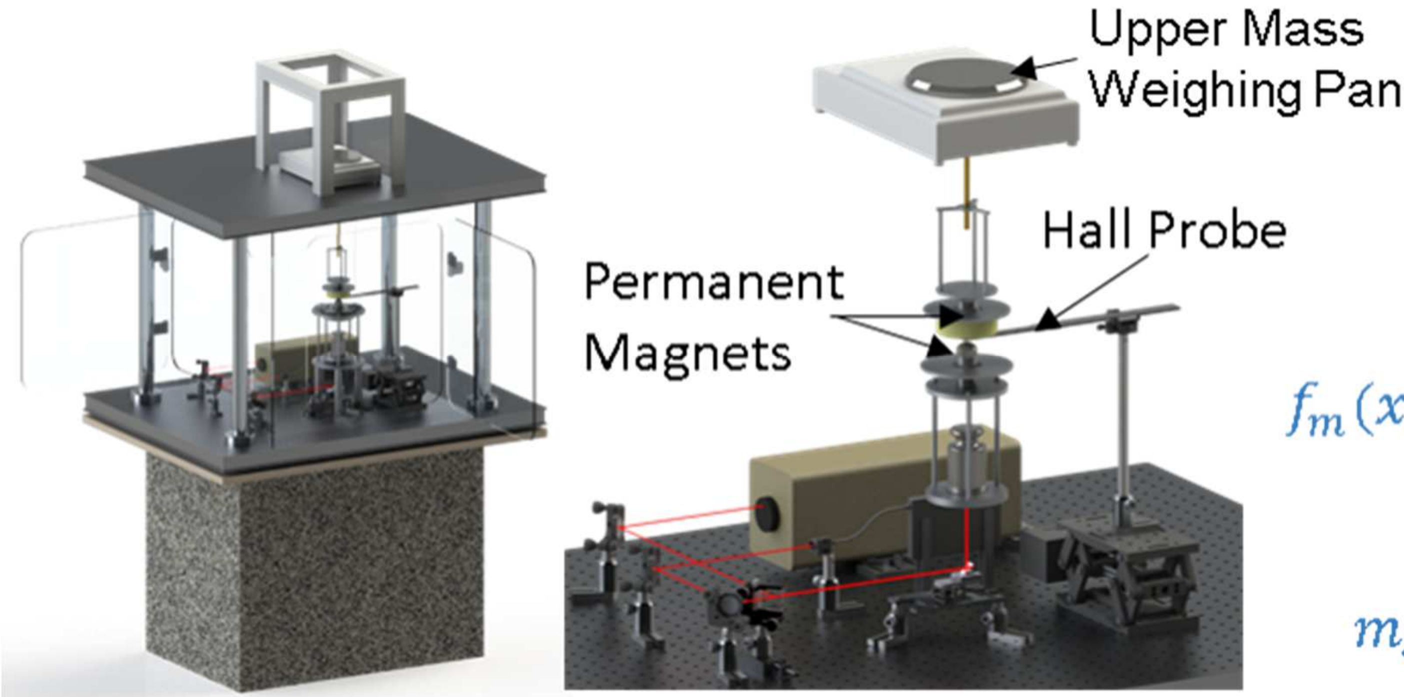
Air

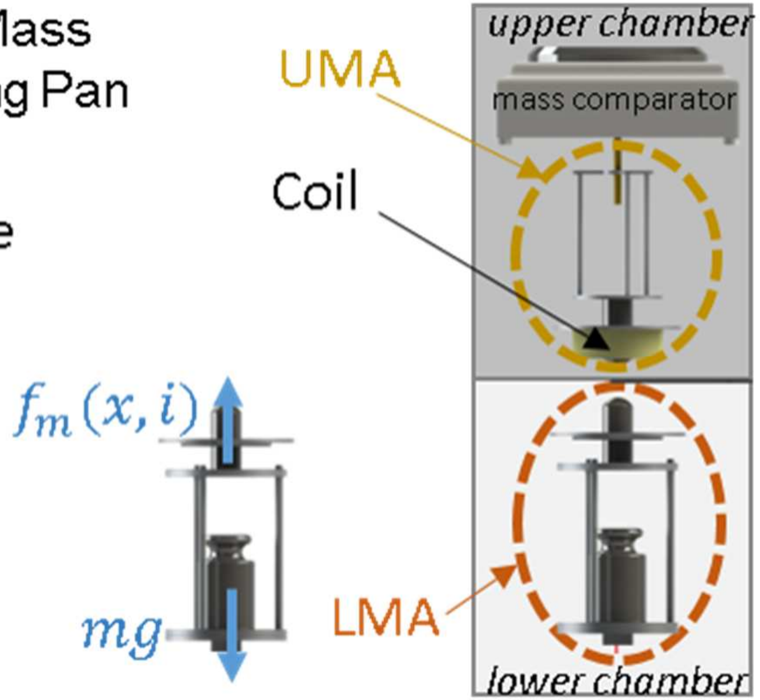
- Constant flow of filtered room air
- Monitor temperature, pressure and humidity
- Load-lock to insert and remove artifacts with MTV

Vacuum, air artifacts

Artifact Pool
Dissemination from an ensemble of Pt-Ir and SS artifacts

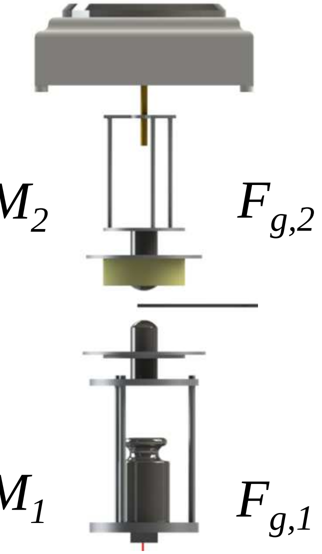
Magnetic Levitation Concept





*Images by E. C. Mulhern

Magnetic Suspension: Proof of Concept



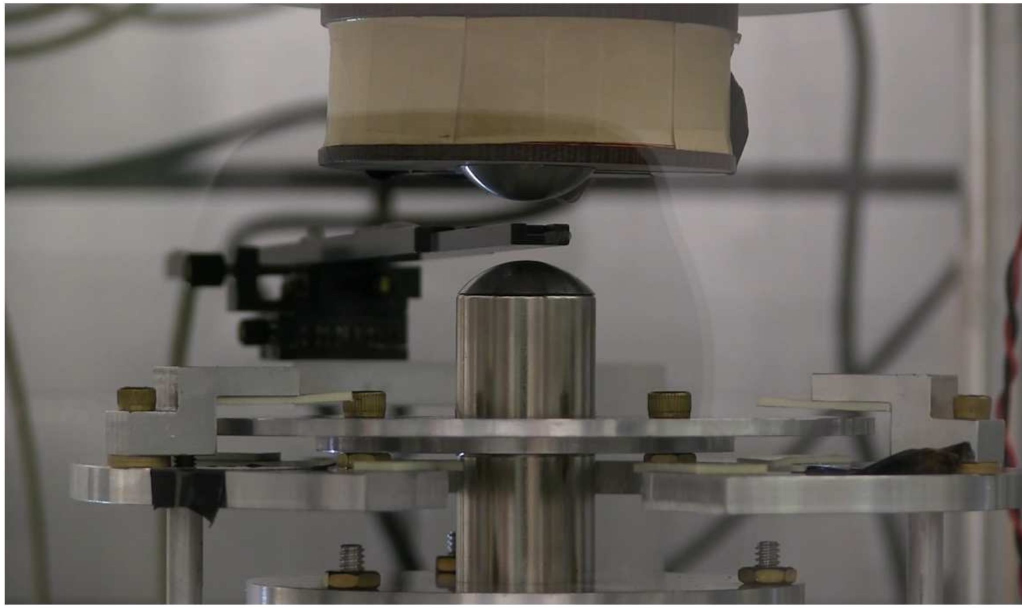
$$F_{scale} = F_{g,2} + F_{g,1}$$

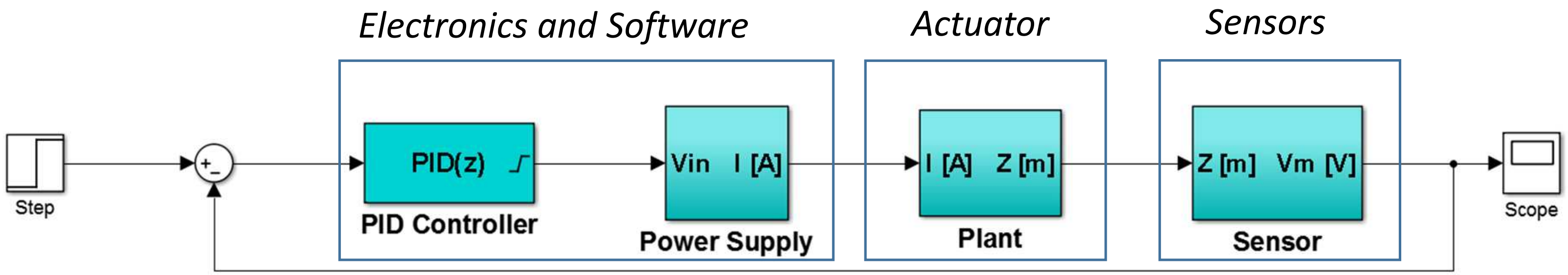
Not quite!
Earnshaw's theorem – Basically you can't achieve stable suspension using fixed (permanent) magnets and static charges.

Need Feedback - Closed-Loop

$$\text{Instead } \ddot{x} \neq 0$$

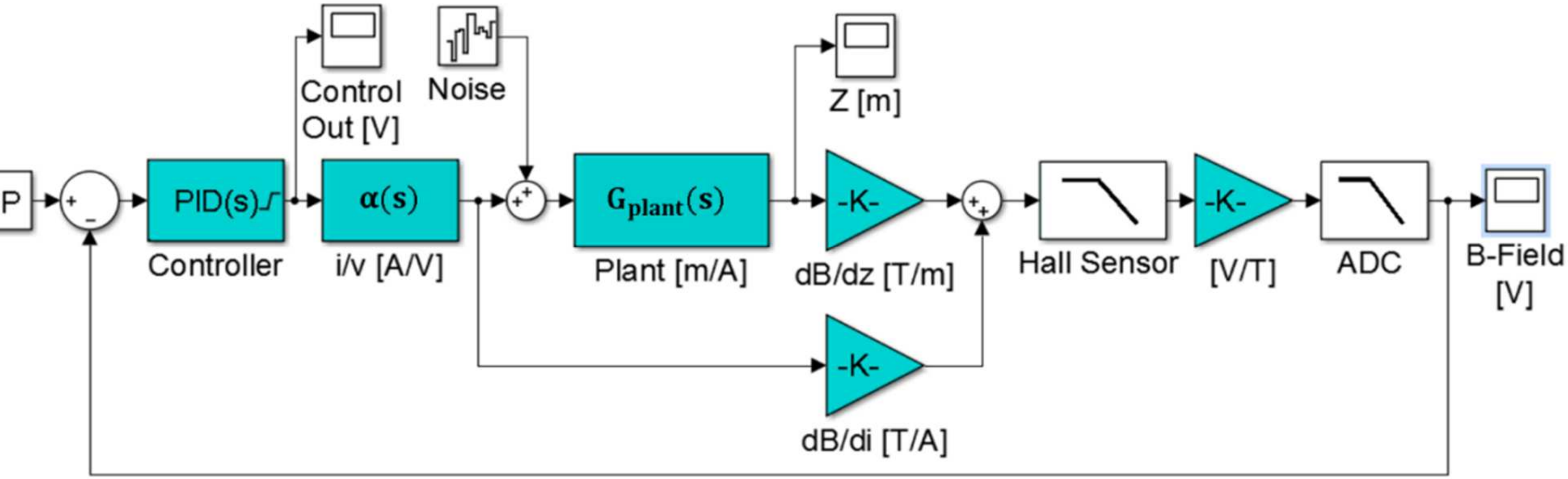
$$F_{scale} = F_{g,2} + F_{g,1} + M_1 \ddot{x}_1$$



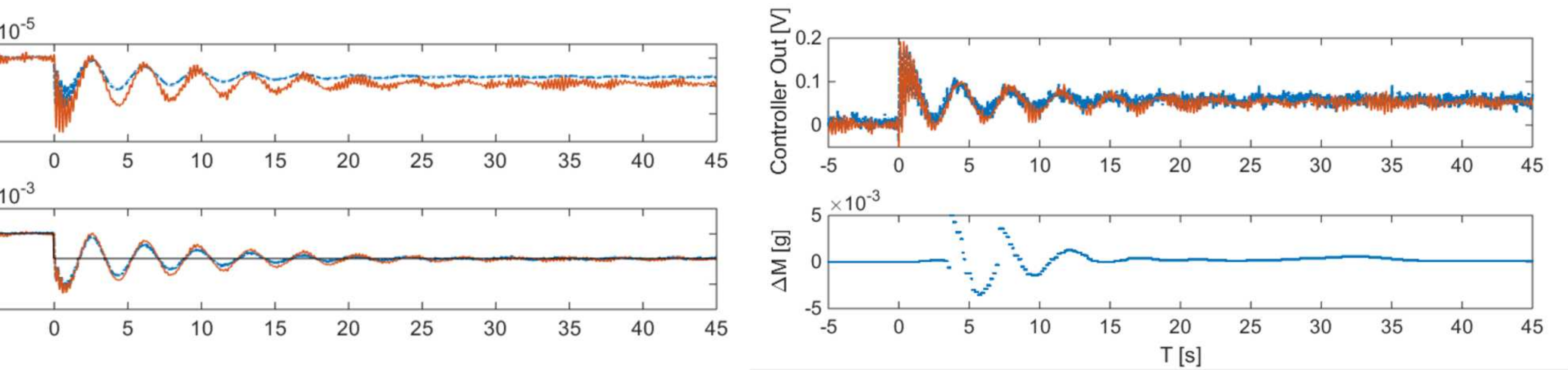


W. Earnshaw, "On the nature of the molecular forces that regulate the constitution of the luminferous ether", Trans. Camb. Phil. Soc., **7**, 97—112 (1842)

Proof of Concept



Verification of Feedback Loop



Status:

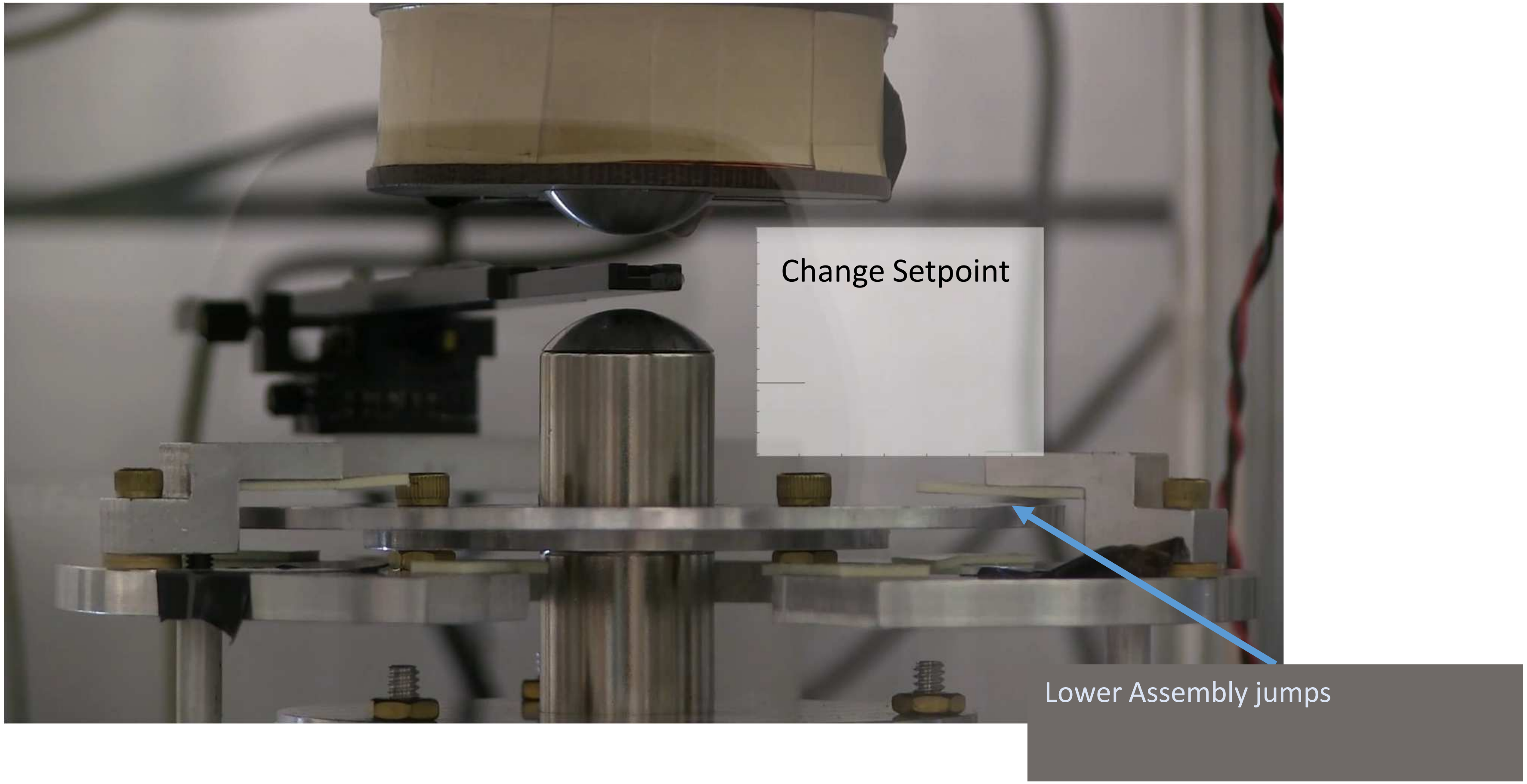
- Tested system using a comparator with a 10 μg readability
- A comparator with a 10 μg readability has been installed
- Final testing underwa

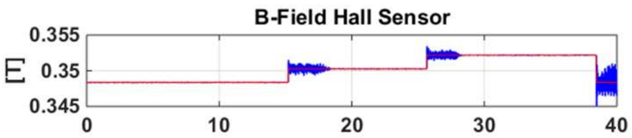
Validation of Conce

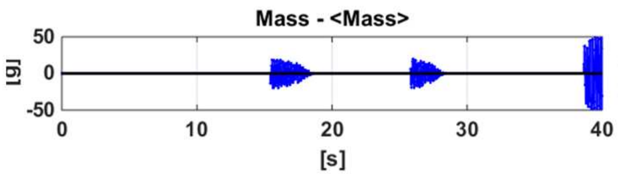
Two masses compared

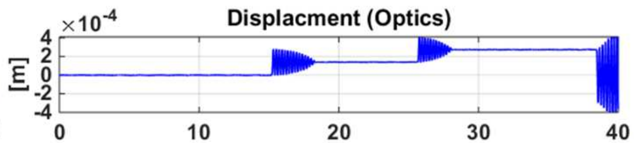
- From mass calibratio $m_1 - m_2 = 1.01 \pm 0.01$
- From magnetic mass suspension compara $m_1 - m_2 = 0.95 \pm 0.13$

Step Response of Suspend Mass

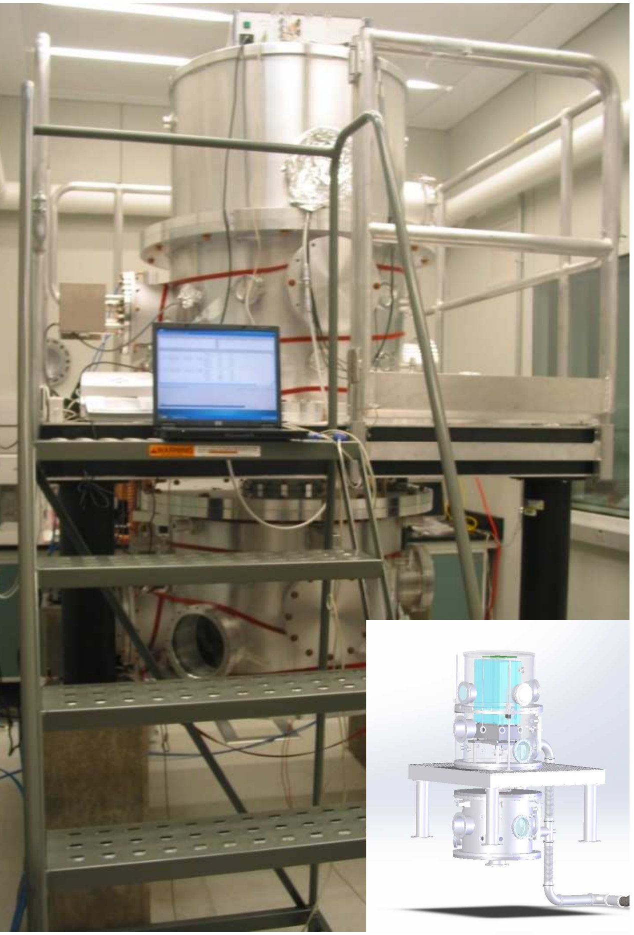


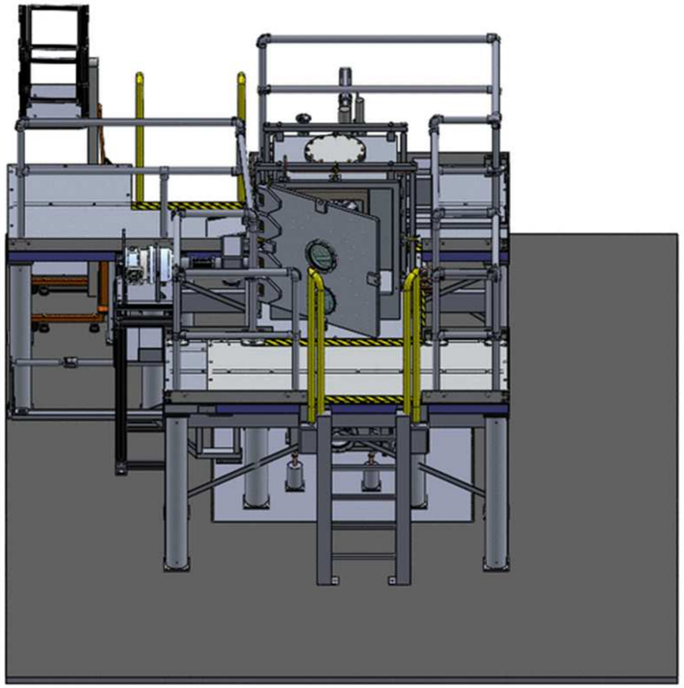


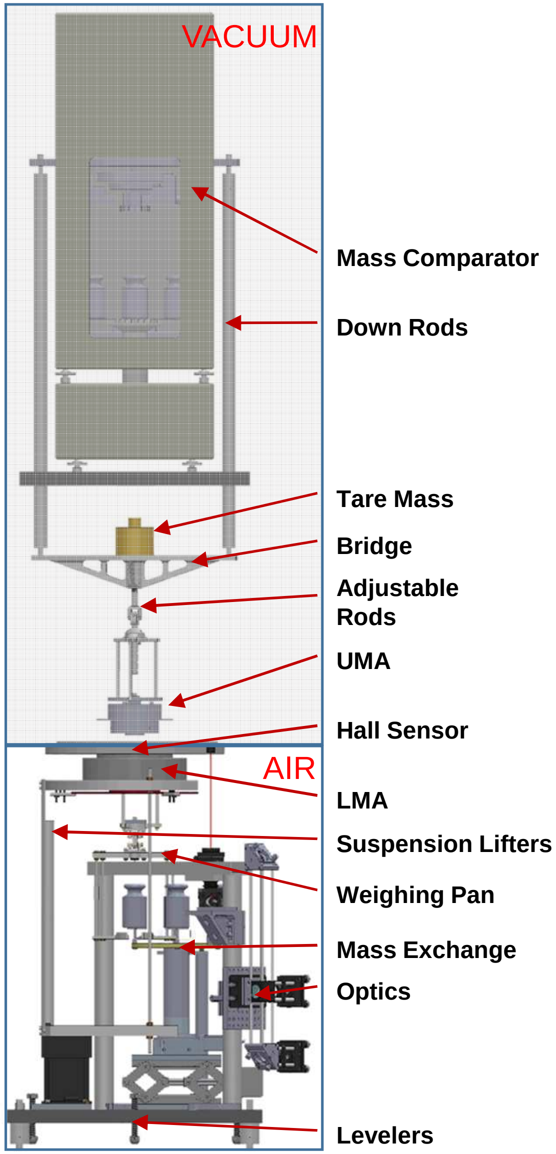




Magnetic Suspension Mass Comparator







Two Aluminum 6061 Chambers
20+ ports (KF-40,KF-50,ISO-100,…) on each chamber

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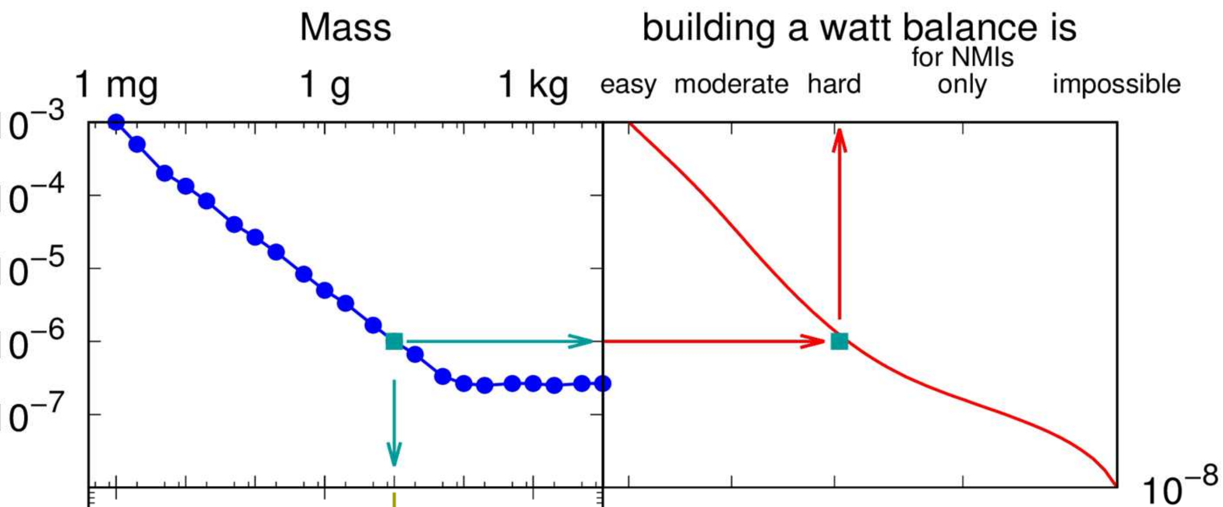
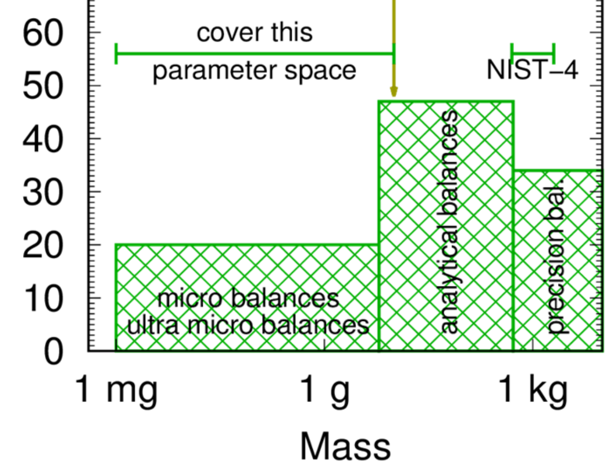
- Ubiquitous embedded measurements

Disclaimer: This talk is very "NIST-centric"

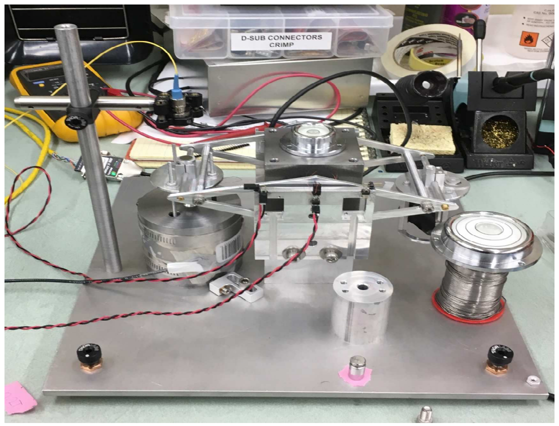
Redefinition Frees the Mass Scale: Tabletop Watt



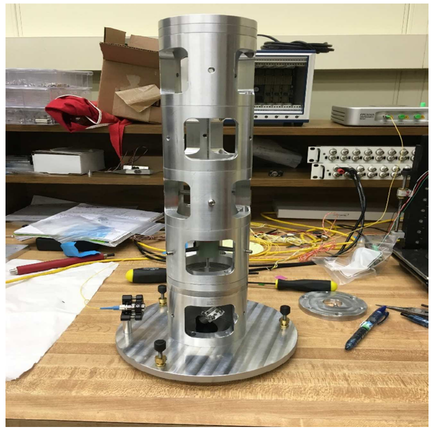


- Building a 1 kg watt balance is involved & expens
- At 1 g a rel. uncertainty of 10^{-6} can compete with current system
- A tabletop watt balance can be used for calibrati at the factory floor or a calibration lab
- Or for realization of the unit of mass at smaller N

Objective: Build a tabletop watt balance for 1 g, 1 p <$50k – two prototypes built at NIST in spring 2016



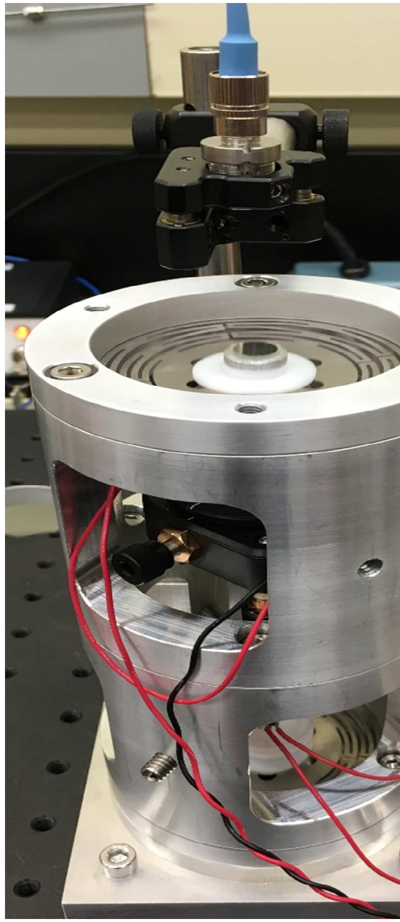
Prototype Classical beam balance



Prototype Seismometer balance

In collaboratio with Luis Pena Perez from CEN

Status: Tabletop Watt Balance



allenges and questions (nothing is easy when it costs you!):

C versus DC metrology

Prototypes explore low-frequency sinusoidal motion measured using conventional multimeters.

Could high frequency designs be coupled directly to low cost thermal converter chips?

raceable velocity measurement

Built a universal interferometer from catalog components.

Could entire system be replaced with NIST fiber frequency comb technologies?

obust data acquisition and control

Began with NI/Labview, migrated to NI/Labview FPGA based data acquisition with trigger pulse.

Could dedicated FPGA be the solution for truly low-cost implementation?

lectromagnetic design

Moving coil or moving magnet? Built two optimized coil/magnet systems to explore tradeoffs.

-D Constrained motion to 1 ppm

Spring or balance suspension? Mechanics is unexpectedly difficult and currently undergoing a revision. Need to minimize off-axis motion. Extent depends on magnet design, but since we hope to relax the constraints on the magnet, anticipate needing vertical motions of millimeters with horizontal motions of nanometers!

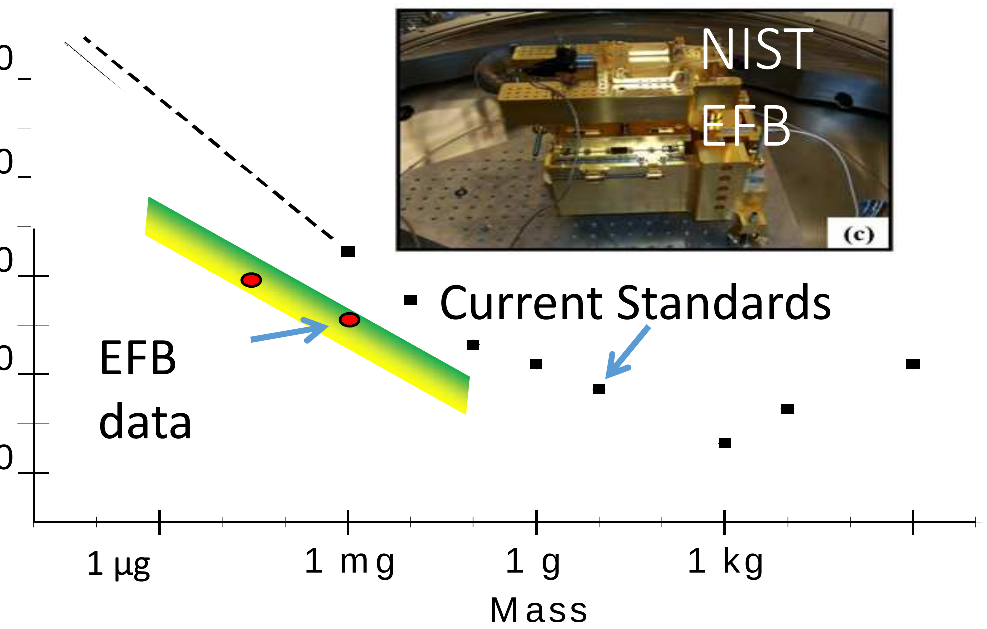
rk this summer on a detailed uncertainty budget for the table top watt balance. Prototypes
ow promising precision: balance design has executed ppm weighing; seismometer design
has shown ppm moving mode measurements

Small Mass and Force Metrology

l Mass Calibrations – towards an electronic milligram

Electrostatic Force Balance

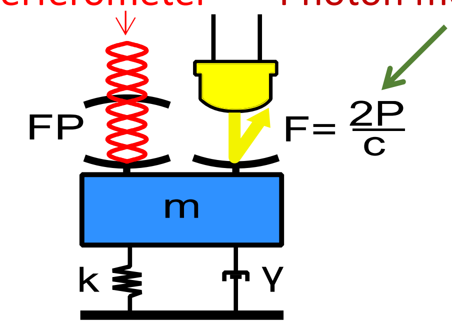
F = mg = 1/2(dC/dz)V²

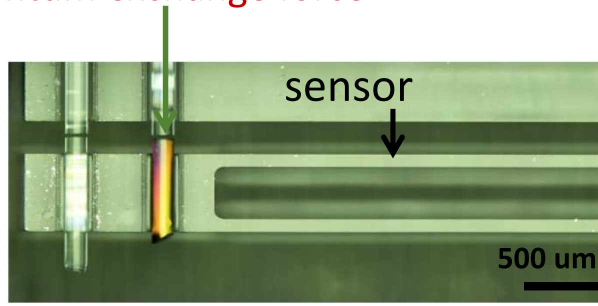


orders of magnitude less uncertainty

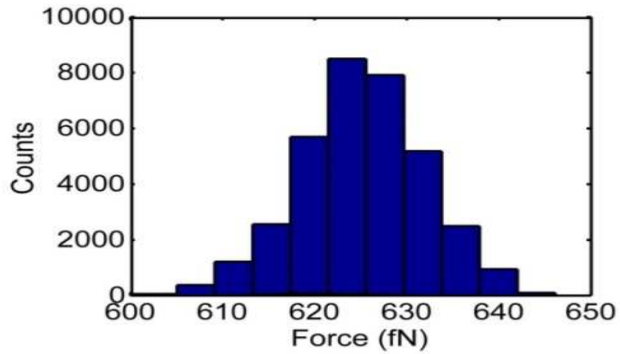
orators: J. Pratt, J. Kramar, A. Koffman, R. Steiner, P. Abbott, Z.
ch

Uniting Mass, Force, & Laser Power on Chip





fN resolution



A self-calibrating optomechanical syste
links SI mass, force ar
laser power using
frequency.

New cryogenic UHV compatible AFM sensor

Collaborators: J. Taylor, A. Chijoke, F. Guzman, R. Mirin, S. Nam, T. G
P. Williams, J. Lehman

Mass from Electrostatic Force Balance

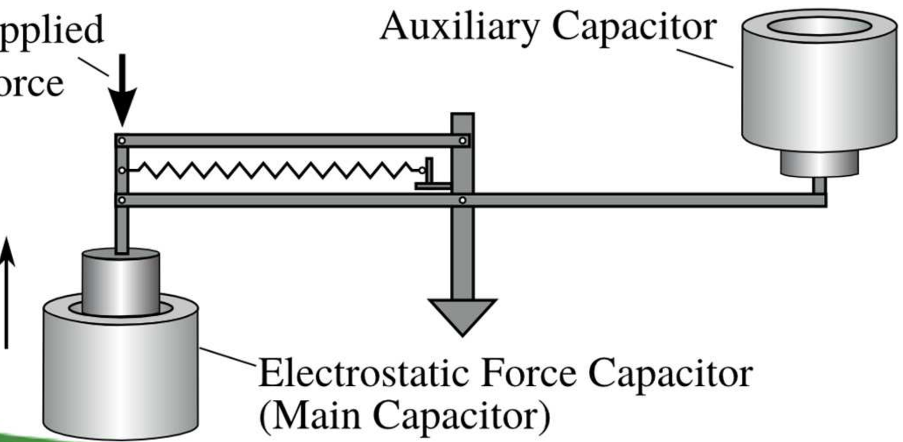
Control balance position with potential across either capacitor

Controlling on Aux. measure capacitance of main vs *z*

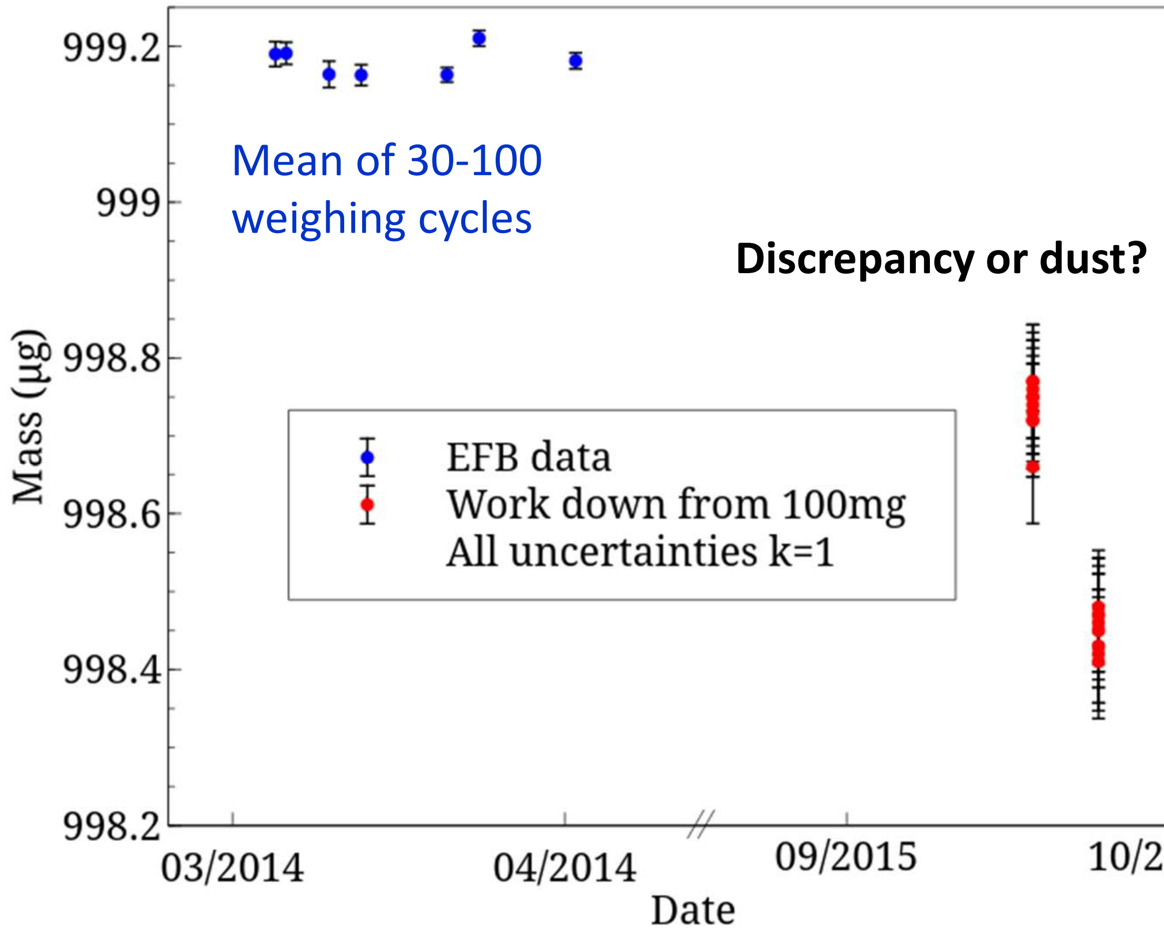
Electrostatic force when controlling on main is

$$F_z = \frac{1}{2}V^2\frac{\partial C}{\partial z}$$

Perform differential measurement with and without applied force

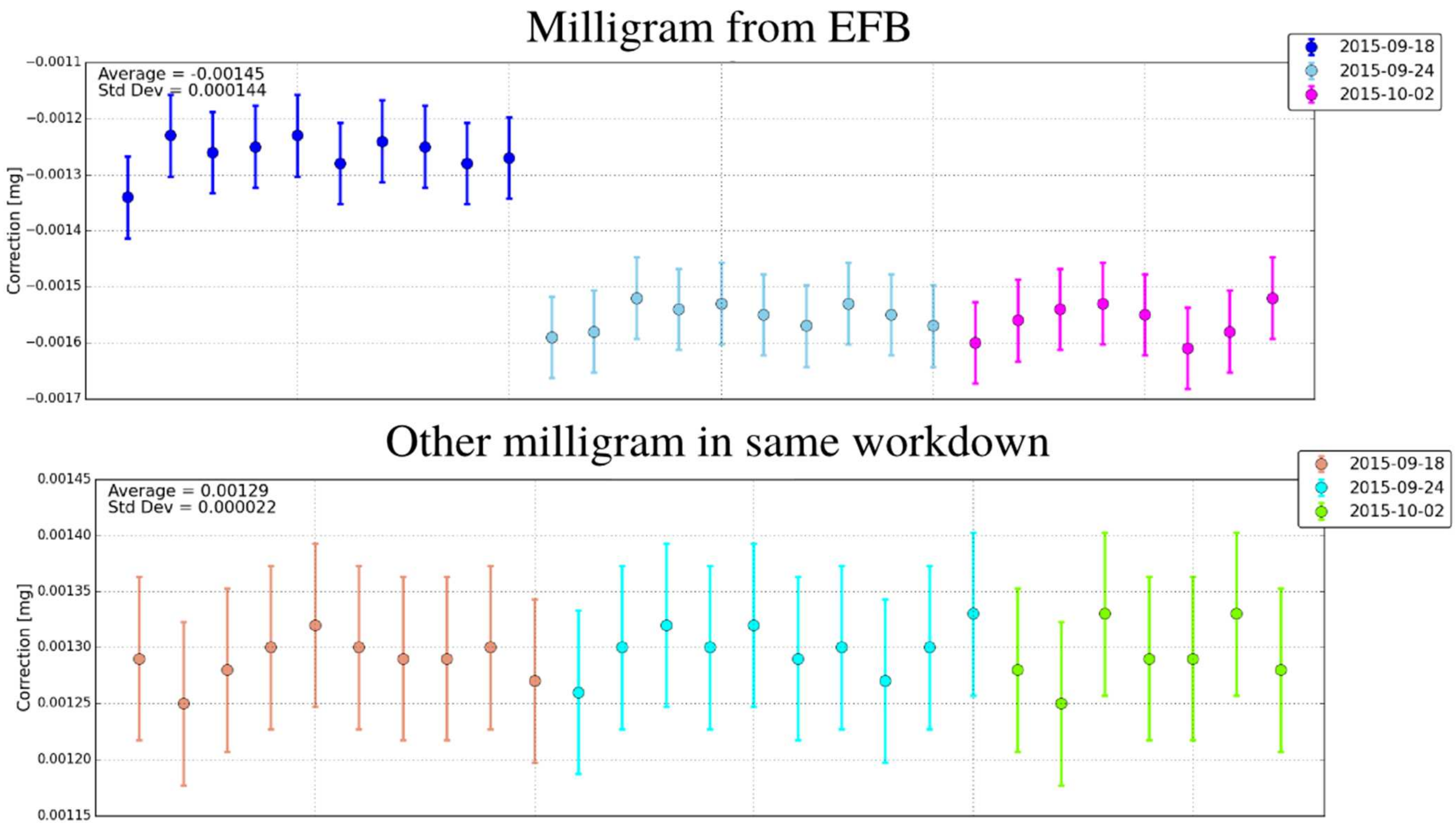


Comparison of 1 mg mass measured by electrostatics and work down from 100 mg

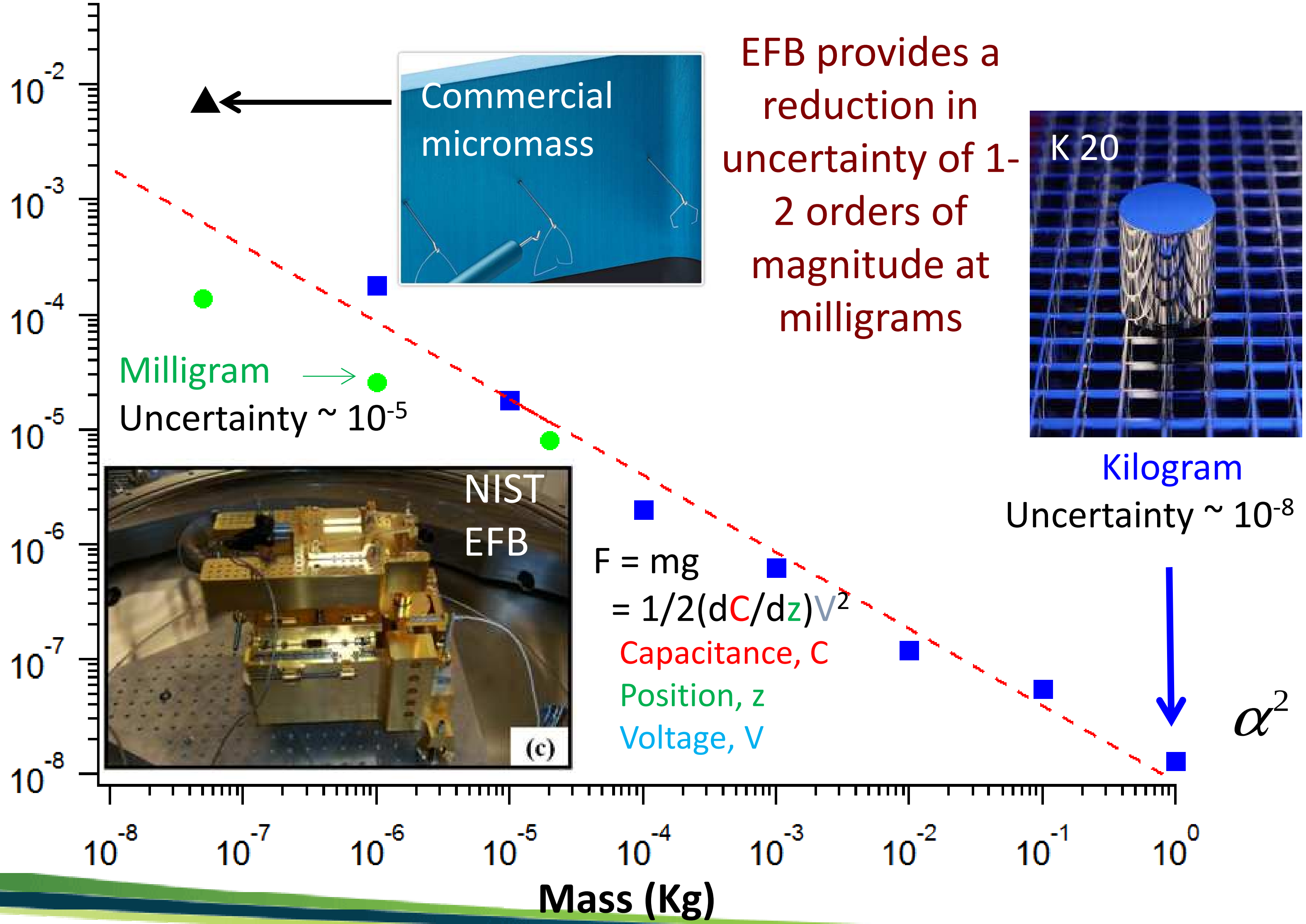


G. Shaw, J. Stirling, A. Moses

Something Clearly Happened



Improving Mass from the Bottom Up



EFB provides a reduction in uncertainty of 1-2 orders of magnitude at milligrams

Kilogram
Uncertainty ~ 10^{-8}

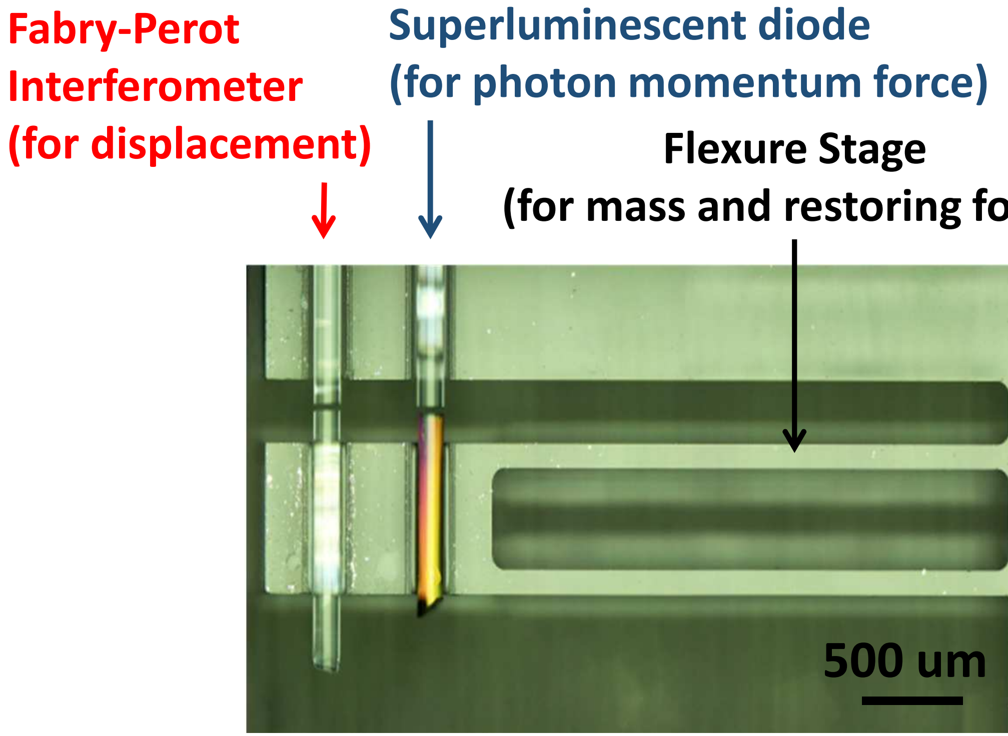
Mass of an atom: Currentl atom recoil experiments a used to determine the fin structure constant. These could be inverted to determine mass at the accuracy of the fine structure constant

$$R_\infty = \frac{\alpha^2 m_e c}{2h}$$

$$\alpha^2 = \frac{2R_\infty}{c}\frac{h}{m_e} = \frac{2R_\infty}{c}\frac{A_r(x}{A_r(e}$$

Techniques for Small Masses and Forces

- Optomechanical system can balance mechanical force with photon pressure force
- Integrated interferometer and calibrated light source
- Optical power standards provide low uncertainty for small force measurements
  - Scales down to the single photon level
  - Femtonewton resolution
- Calibration of atomic force microscopy



See: J. Melcher, et al., "*A self-calibrating optomechanical force sensor with femtonewton resolution*," Appl. Phys. Lett. **105**, 233109 (2014); http://dx.doi.org/10.1063/1.4903801

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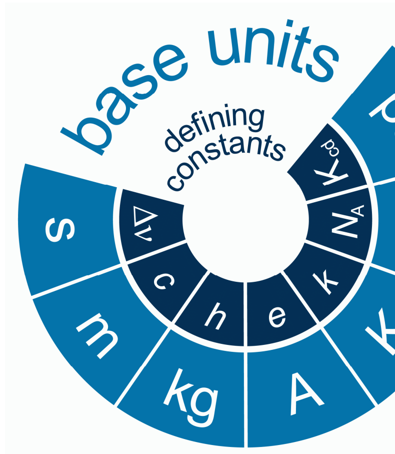
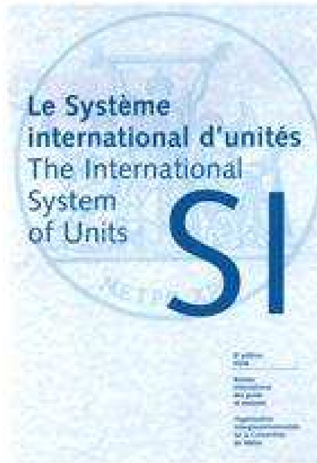
Comparing the Current and New SI

Current SI		New "Quantum" SI	
Base quantity	**Base unit**	**Base quantity**	**Defining Constant**
Time	second (s)	Frequency	$\Delta\nu(^{133}Cs)_{hfs}$
Length	meter (m)	Velocity	c
Mass	kilogram (kg)	Action	h
Electrical Current	ampere (A)	Electric Charge	e
Therm. Temperature	kelvin (K)	Heat Capacity	k
Amount of Substance	mole (mol)	Amt of Substance	N_A
Luminous intensity	candela (cd)	Luminous intensity	K_{cd}



From: D. Newell, *"A more fundamental International System of Units," Physics Today* **67(7),** July 2014.



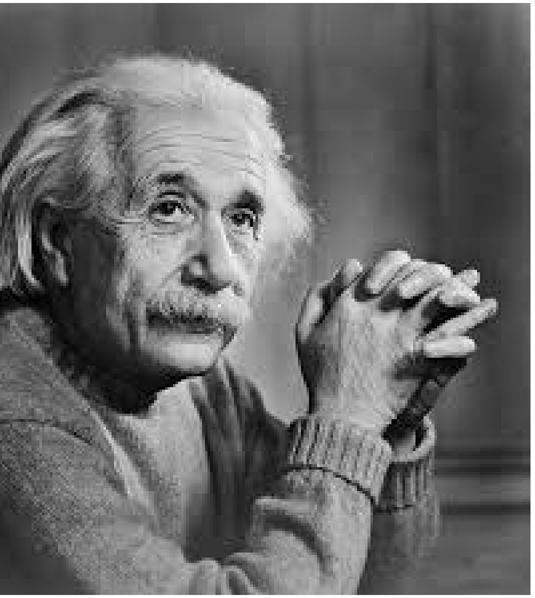
What is the future of the "Quantum SI"

- Time will get redefined but even if redefined in terms of the Rydberg constant – the structure of the "Quantum SI" remains the same
- Candela (maybe lumen) will eventually get redefined but won't change the structure of the "Quantum SI"
- So what is the limit of the "Quantum SI"?
  - It is based on the Standard Model which fails in several know ways – dark matter, dark energy, neutrino mass, …
  - Thus at some level of accuracy the Quantum SI will fail or change with time

→Need to explore the limits of the standard model

→Also, as clock approach an accuracy of 10^{-19}, the become environmental sensors! Is the end of metrology visible?

Einstein was not always right



MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

W. Pauli – "Einstein has once again expressed himself publicly on quantum mechanics, indeed in the 15 May issue of *Physical Review.* As is well known, every time this happens it is a catastrophe."

First Hints of Quantum Information

"When we get to the very, very small world---say circuits of seven atoms---we have a lot of new things that would happen that represent *completely new opportunities* for design. Atoms on a small scale behave like nothing on a large scale, for they satisfy the laws of quantum mechanics. So, as we go down and fiddle around with the atoms down there, we are working with different laws, and *we can expect to do different things*. We can manufacture in different ways. We can use, not just circuits, but some system involving the quantized energy levels, or the interactions of quantized spins, etc." **– Richard P. Feynman, "*Plenty of Room at the Bottom*", December 1959**

What is Quantum Information?

Quantum computation and quantum information is the study of the nformation processing tasks that can be accomplished using quantum nechanical systems." – M. Nielsen & I. Chuang, "*Quantum Computation nd Quantum Information*"

uantum information science (QIS) is the fundamental research, applied esearch, and technology development that are associated with the hysical and computational limits that quantum mechanics places on mple quantum information systems and the emergent behavior temming from attempts to control or manipulate complex quantum nformation systems.

Why Care about QIS

- It tells me how nature computes
- It tells me what is possible
- It is helping to provide insight into quantum many-body problems
- All of these provide insight into what is possible for metrology!

"Entanglement is a uniquely quantum mechanical resource that plays a key role in many of the interesting applications of quantum computation and quantum information; entanglement is to iron to the classical world's bronze age. In recent year there has been a tremendous effort to better understand the properties of entanglement considered a fundamental resource of Nature, of comparable importance to energy, information, entropy, or any other fundamental resource."
– M. Nielsen and I. Chuang; *Quantum Computation and Quantum Information*

The Power of Quantum Computation

Peter Shor (AT&T, 1994):

In principle, with a quantum computer (assuming one can b
built), one can factor an N-digit number in ~ N^3 steps …

First quantum algorithm to tackle an important problem tha
is classically computationally hard* – i.e. grows
exponentially in the length of an input string

Our understanding of QC and QI is providing constraints on
theories beyond the standard model and informing us on
what the quantum world allows

***This is a problem that belongs in NP (hard to factor but solution verifiable in polynomial time)! Not in NP-Complete**

Shor's Factoring Algorithm and Shor's Dilemma

her:

1. The Extended Church-Turing Thesis is false,
2. Textbook quantum mechanics is false, or
3. There's an efficient classical factoring algorithm.

All three seem like crackpot speculations.

At least one of them is true!

"In my view, this is why everyone should care about quantum computing, whether or not quantum factoring machines are ever built" -- Scott Aaronson

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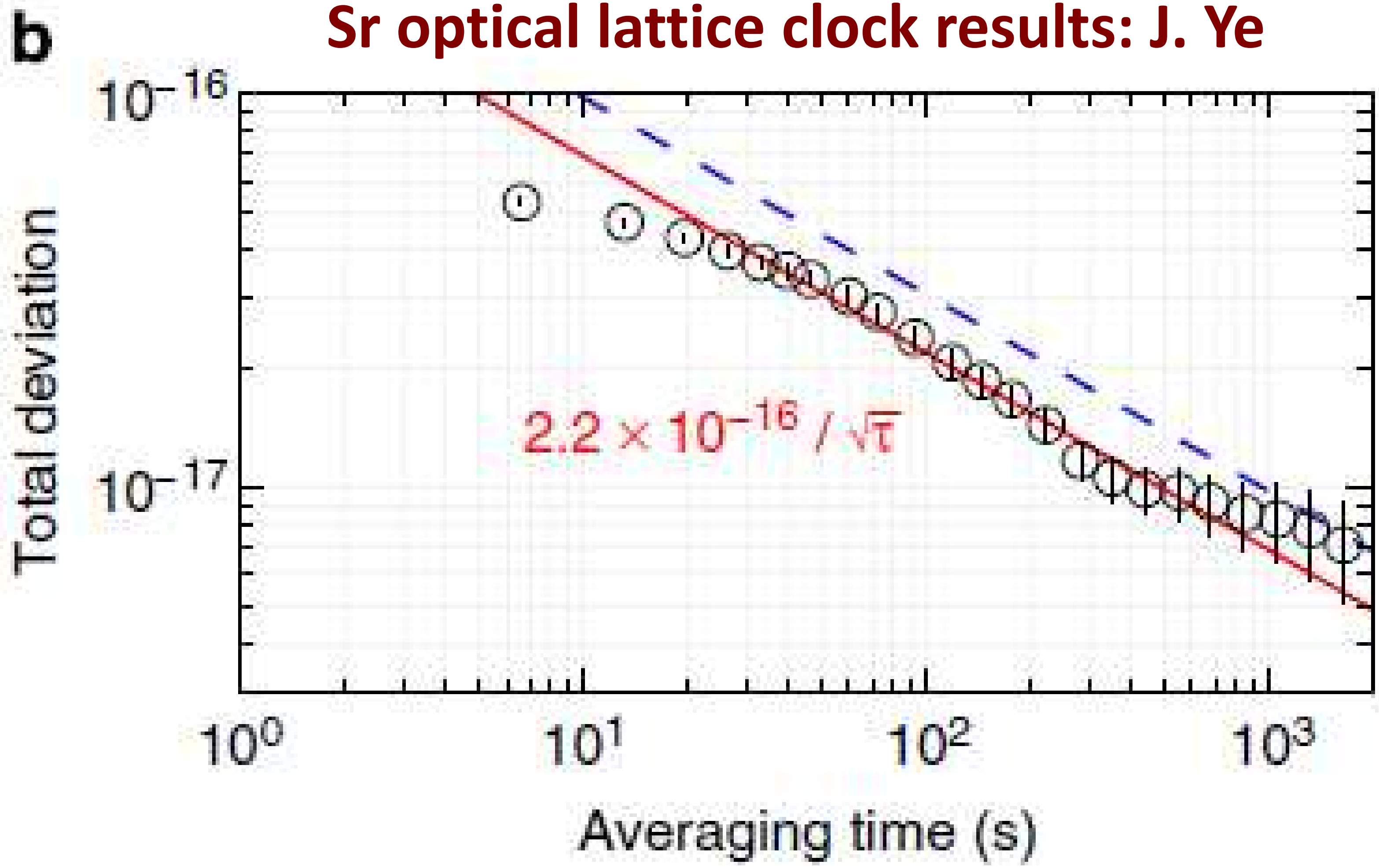
Future Metrology

- We will test the standard model
- Clocks will become increasingly environmental sensors – geodesy, time variation of the fine structure, gravity gradiometry, gravitational wave detectors
- Good metrology – near NMI quality – will become more ubiquitous
- Dynamic metrology will become more relevant

Optical Clock Frequency Stability

Sr optical lattice clock results: J. Ye

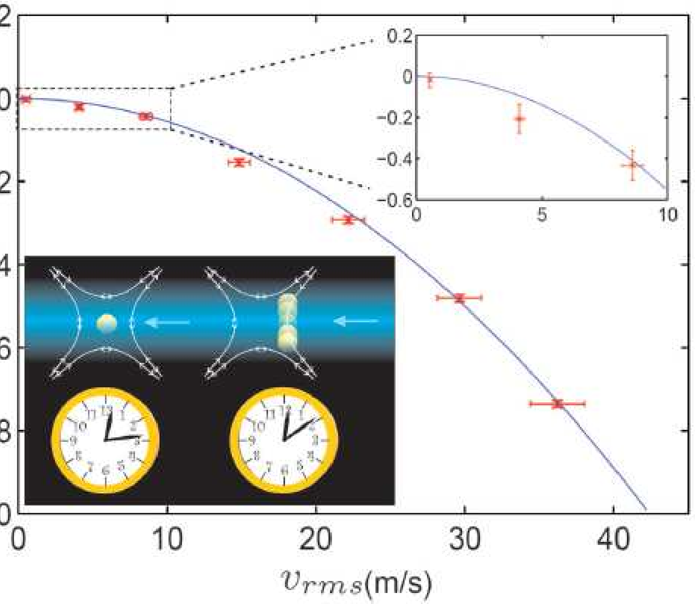


~1 x 10^{-16} at 5 second
for Sr lattice clock
vs.
~1 x 10^{-16} at 10^6
seconds for NIST-F2

Clocks and Relativity

Time dilation (special relativity)

Science 329, 11630, 2010



tivistic time dilation at familiar speeds (10 m/s = 36 km/hour ≈ 22.4 miles/hour). (Lower left Al⁺ ion in one of the twin clocks is displaced from the null of the confining RF quadrupole ield lines), it undergoes harmonic motion and experiences relativistic time dilation. In the the motion is approximately perpendicular to the probe laser beam (indicated by the blue e Al⁺ ion clock in motion advances at a rate that is slower than its rate at rest. In the figure, l frequency difference between the moving clock and the stationary clock is plotted versus the = $\sqrt{\langle v^2 \rangle}$ (rms, root mean square) of the moving clock. The solid curve represents the theoretical Upper right inset) A close-up of the results for v_{rms} < 10 m/s in the dashed box. The vertical epresent statistical uncertainties, and the horizontal ones cover the spread of measured the applied electric fields.

$$T = \frac{T_0}{\sqrt{1-\frac{v^2}{c^2}}} \approx T_0\left(1+\frac{v^2}{2c^2}\right)$$

$$v << c$$

$$T = \frac{T_0}{\sqrt{1-\frac{2GM}{Rc^2}}} \approx T_0\left(1+\frac{GM}{Rc^2}\right)$$

$$\frac{2GM}{R} << c^2$$

Gravitational time dilation (general relativity)

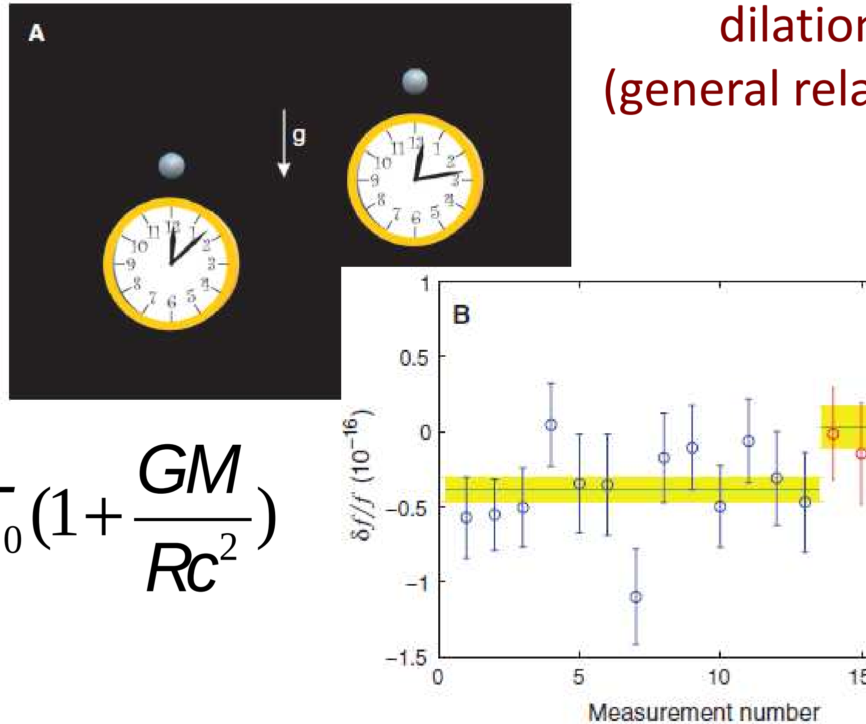


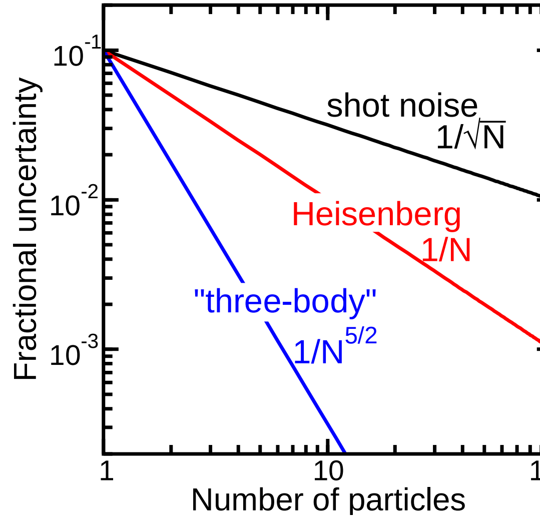
Fig. 3. Gravitational time dilation at the scale of daily life. (**A**) As one of the clocks is raised, its rate increases when compared to the clock rate at deeper gravitational potential. (**B**) The fractional difference in frequency between two Al⁺ optical clocks at different heights. The Al-Mg clock was initially 17 cm lower in height than the Al-Be clock, and subsequently, starting at data point 14, elevated by 33 cm. The net relative shift due to the increase in height is measured to be (4.1 ± 1.6) × 10^{-17}. The vertical error bars represent statistical uncertainties (reduced χ^2 = 0.87). Green lines and yellow shaded bands indicate, respectively, the averages and statistical uncertainties for the first 13 data points (blue symbols) and the remaining 5 data points (red symbols). Each data point represents about 8000 s of clock-comparison data.

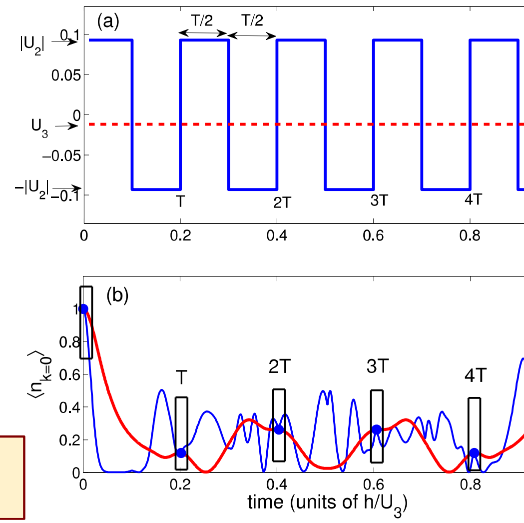
Entanglement Enhanced Measurements

How does measurement uncertainty scale with atom number ?

- For an atomic clock with N atoms
  - Independent atoms gives shot-noise limit
  - Entanglement leads to Heisenberg limit
- Applying a *stroboscopic* protocol for three-body interactions with scaling of $1/N^{5/2}$
  - Alternate between attractive/repulsive pairwise interactions, thereby undoing two-body effects, and leaving the weak three-body interactions.

This is similar to dynamical decoupling in NMR experiments!





Mahmud *et al.*, New J. Phys. 16, 103009 (2014) and Phys. Rev. A 90, 041602(R) (2014)

Quantum Many-body Optical Lattice Clock

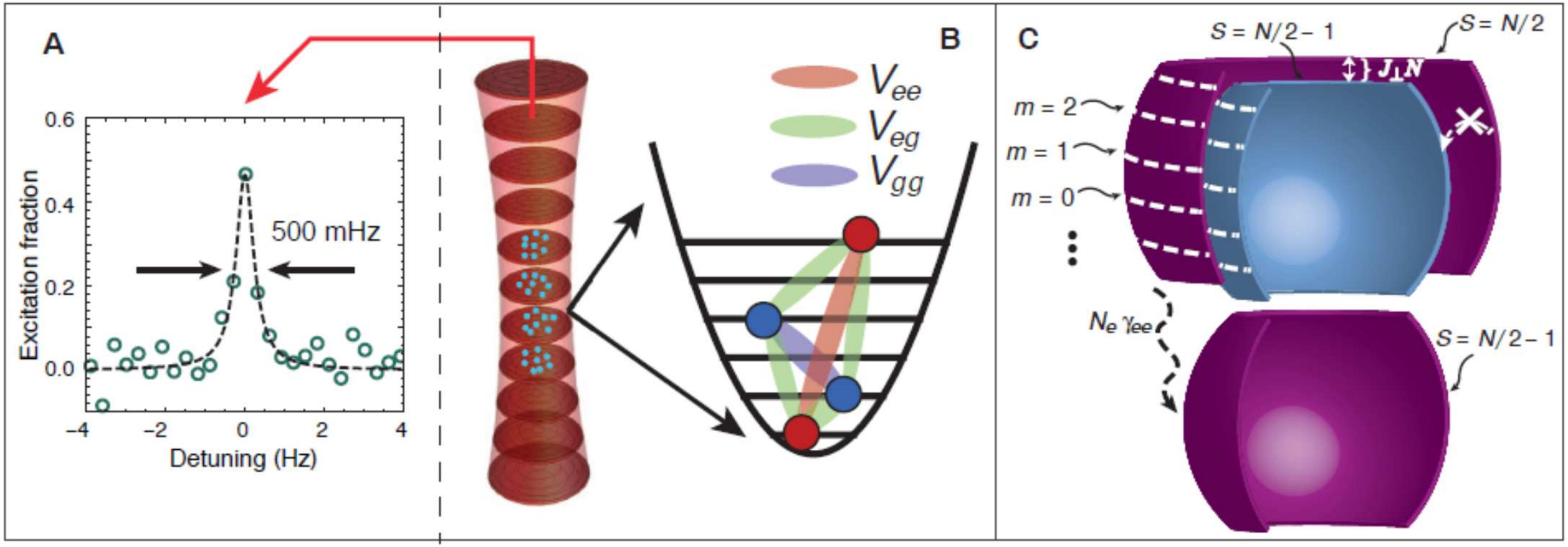
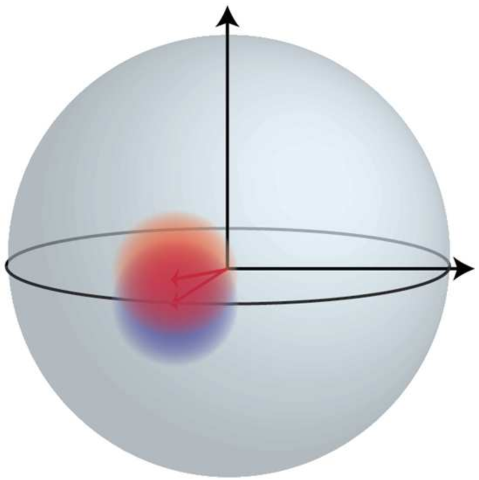


Fig. 1. Diagram of the interacting many-body system. **(A)** Spectroscopy of the ^{87}Sr clock transition in a 1D optical lattice, showing 500-mHz spectral resolution. The density is more than an order of magnitude lower than the typical operating condition. **(B)** Several hundred sites of the 1D vertical optical lattice are substantially occupied during the experiment. The average lattice occupancy is 20 atoms for the peak total atom number. Interactions between atoms are parametrized by the spin-dependent interaction parameters, $V_{gg} \propto b^3_{gg}$ (blue), $V_{eg} \propto b^3_{eg}$ (green), and $V_{ee} \propto b^3_{ee}$ (pink), with b^3 being the *p*-wave scattering volumes (*22*). **(C)** The many-body Hamiltonian has eigenstates comprising maximally symmetric superpositions (Dicke states, for which $S = N/2$) of electronic ground and excited states (purple shells). Slight inhomogeneities in the coupling strengths allow the maximally symmetric manifold to be coupled to the next lowest manifold with $S = N/2 - 1$ (nested blue shell), but this coupling is prevented by an energy gap resulting from the $J^{\perp}\vec{S} \cdot \vec{S}$ term in the Hamiltonian. Two-body inelastic losses connect maximally symmetric manifolds of $S \rightarrow S - 1$ and thus are not a strong decoherence mechanism.

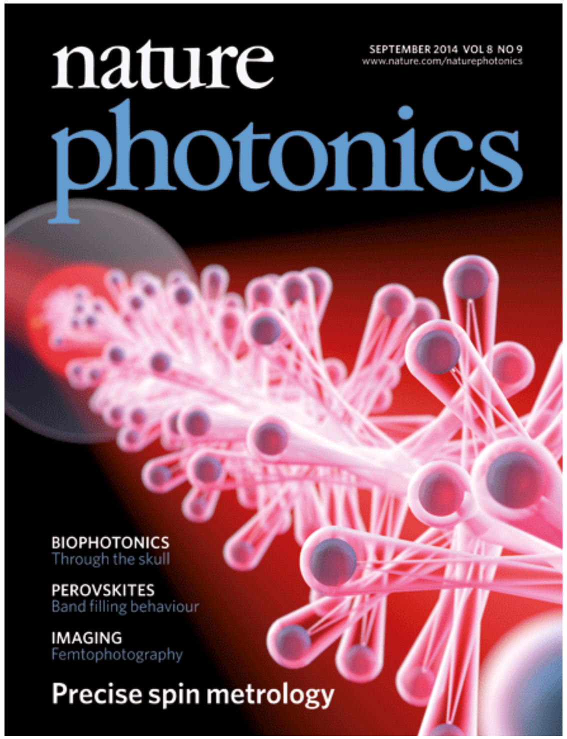
Science **341**, 632 (2013); *Nature* **506**, 71, 2014

Entanglement-Enhanced Quantum Measurements

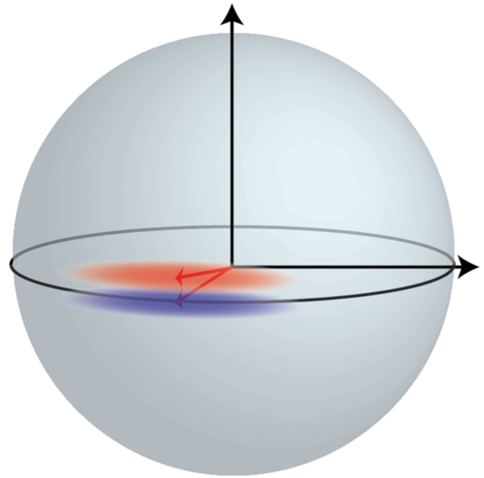
antum noise smears out the
entation of quantum sensors,
**iting the precision of the
ormation that can be extracted.**



Cavity-based **measurements forge
entanglement or quantum links
between a million atoms.**



**The entanglement squeezes
quantum noise, enhancing t
precision** of the information
can be extracted **by a factor**

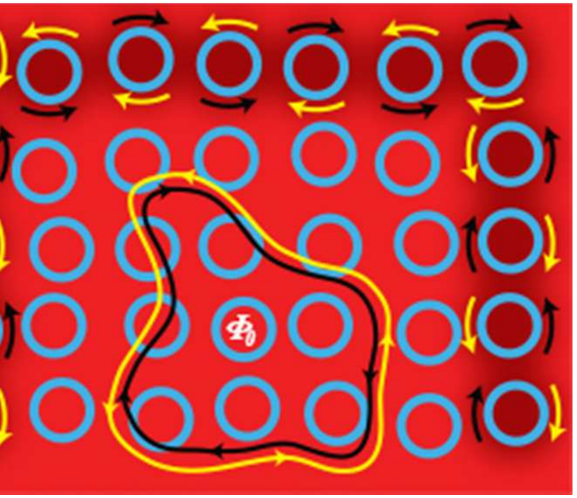


chnique directly applicable to improving state-of-the art optical lattice clocks and inertial sensors.

Bohnet; et al., *Nature Photonics* **8**, 731-736 (2014)

Photonic QHR and Edge State

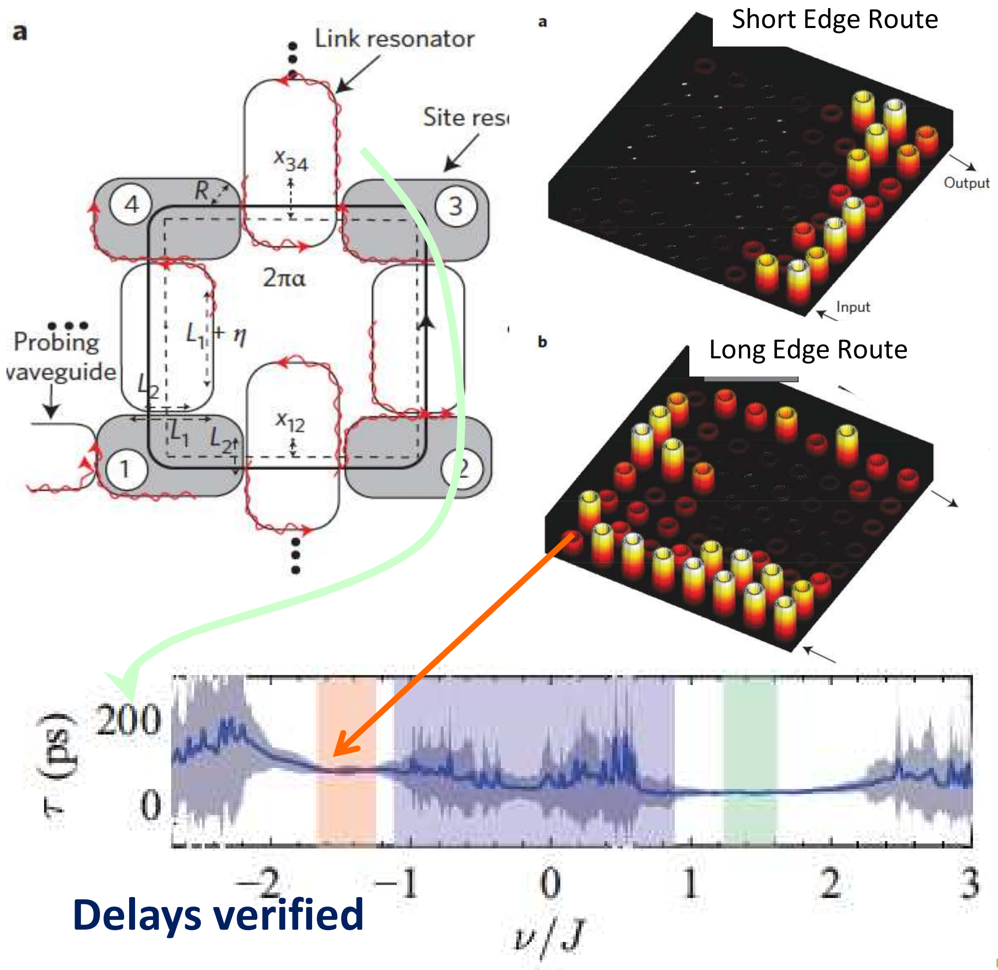
- tonic chip with ring resonators
- brication defects
- sonator frequency shifts
- ults: high loss, high scatter, & low transmittance



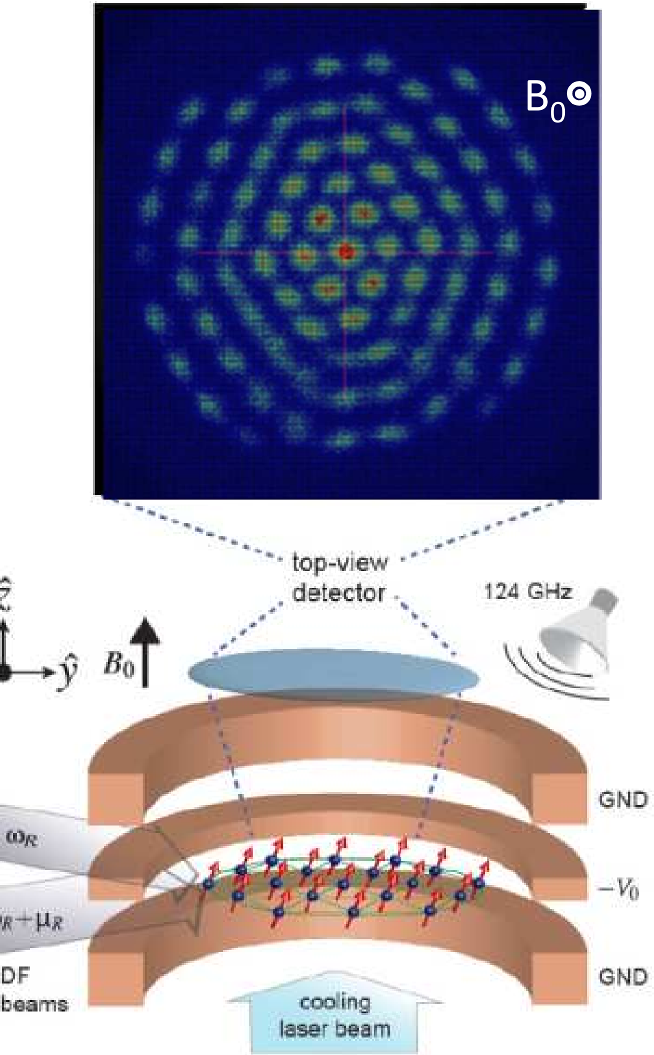
Topology to the rescue:

- Resonator pattern yields "synthetic magnetic field"
- Scattering is suppressed
- Light travels along the edge
- Transport is robust to defects

S. Mittal, *et al.*; Phys. Rev. Lett. 113, 087403 (2014)



Simulating spin-spin interactions



$$H = \frac{1}{N}\sum_{i<j} J_{i,j}\sigma_i^z\sigma_j^z + B_x\sum_i \sigma_i^x$$

2-d arrays of hundreds of ions formed and controlled in a Penning trap; provides platform for simulation of quantum magnetism with a number of spins that is intractable on a conventional computer

Synthesized transverse Ising model; benchmark with mean field theory -J. Britton et al., Nature 484, 2012

New trap, which increases spin-spin coupling by 50, is fabricated and operational.

Larger couplings (>1 kHz) should enable simulation of non-equilibrium processes that can not be simulated on a conventional computer

Time Variation of Fine Structure Constant

Possible temporal variation in fundamental constants

Fine structure constant

$$\alpha = e^2 / 4\pi\varepsilon_0 \hbar c$$

over ~ 10^{10} years from quasar observations

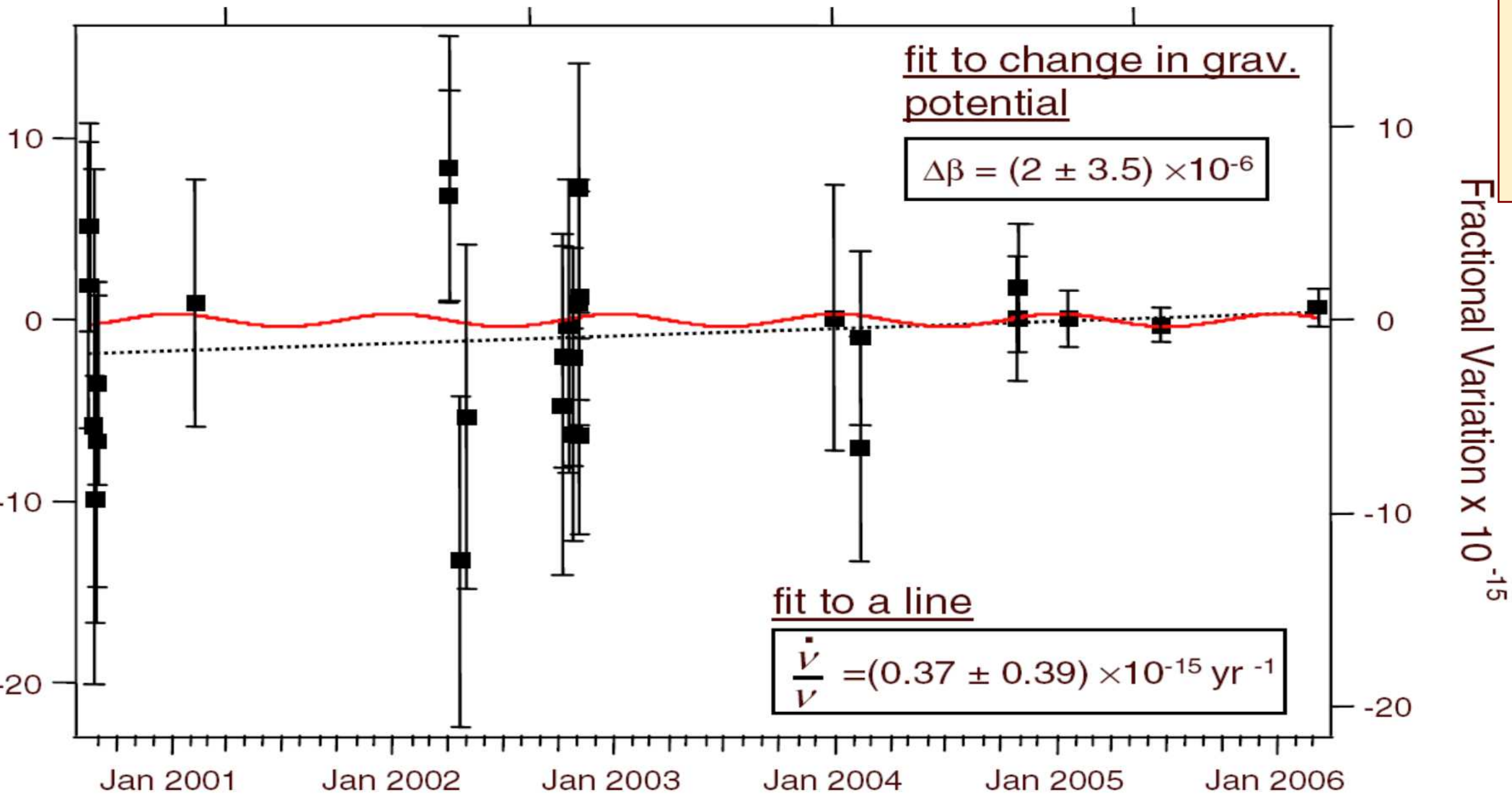
$$\frac{\Delta\alpha}{\alpha} = -0.72 \pm 0.18 \times 10^{-5}$$

Possible $\Delta\alpha/\alpha \sim 10^{-15}$/year

J. K. Webb *et al., Phys. Rev. Lett.* **87**, 091301 (2001)

Time Variation of Fine Structure Constant

$$\nu_{Cs}/\nu_{Hg} \sim g_{Cs}(m_e/m_p)\alpha^{6.0}$$



Comparing cesium, mercu
ion, aluminum ion atomi
clocks over several years

$$\left|\frac{\Delta\alpha}{\alpha}\right| < 1.6 \text{ x } 10^{-17}$$

Outline

- Problems with the Current SI
- Brief Review of the Redefinition of the SI
- Primary Realization of the Definition of the Kilogram in the new SI
- The *Mise-en-pratique* of the Kilogram at NIST
- Small Mass Realization and Metrology at NIST
- The "Quantum SI," Quantum Information, and the Standard Model
- Future Metrology
- Ubiquitous embedded measurements

Disclaimer: This talk is very "NIST-centric"

Embedded Standards

Develop SI-traceable measurements and physical standards that are:

Deployable in a factory, lab, device, system, home, anywhere...

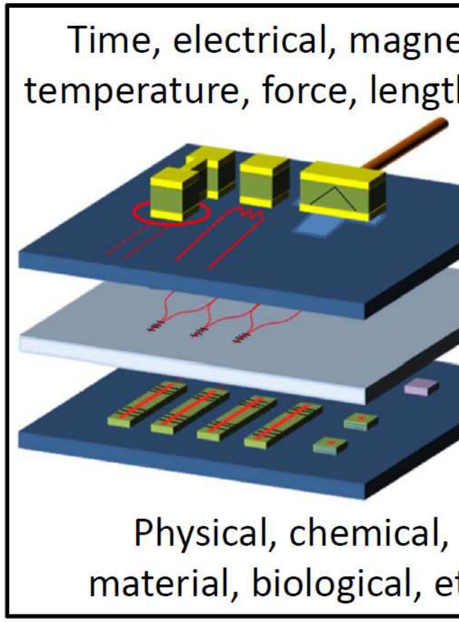
Usable:. Small size (usually), low power consumption, rugged, easily integrated and operated

Flexible: Provide a range of SI-traceable measurements and standards (often quantum-based) relevant to the customer's needs / applications

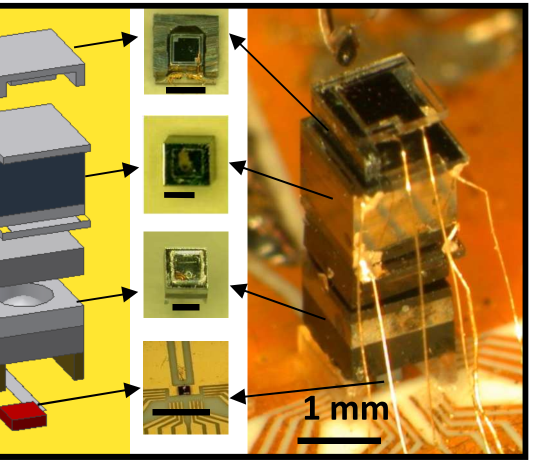
- One, few, or many measurements from a single small form package

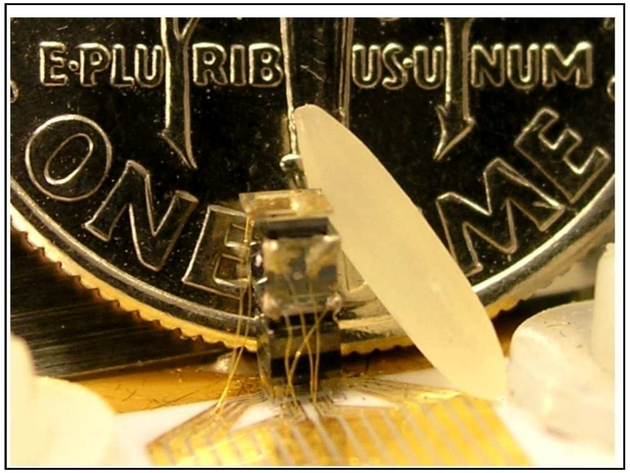
Manufacturable:

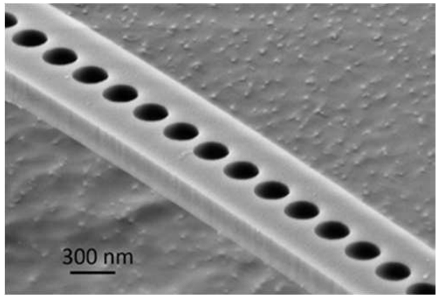
- Potential for production costs commensurate with the applications
- Low cost for broad deployment; or
- Acceptable cost for high-value applications
- Enabled by multiple technologies: micro-combs, stable lasers, ...

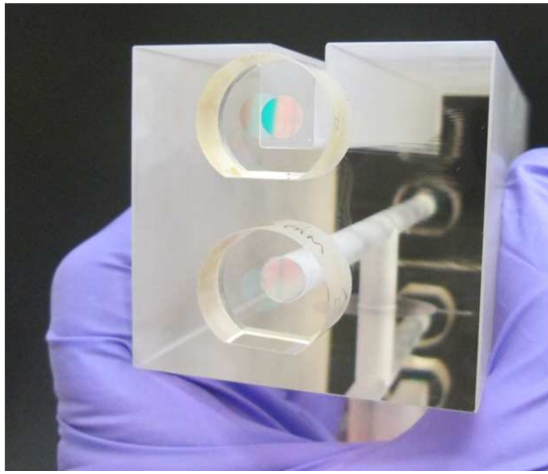


Embedded Standards and Sensors



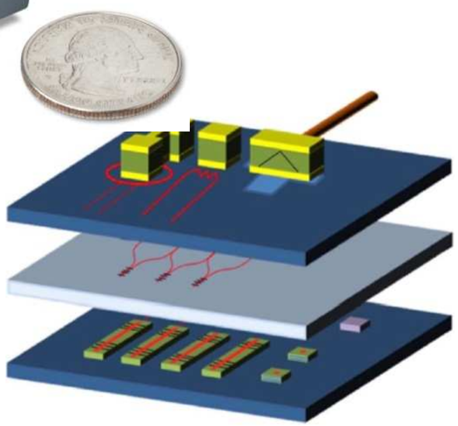




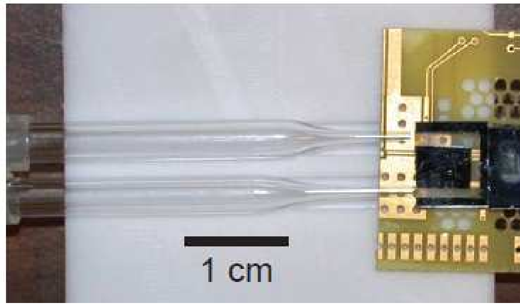


Fixed Length Optical Cavity (

Symmetricom (now Microsemi):
First commercial CSAC – $\Delta f/f \sim 10^{-11}$



Chip-scale atomic clock
Chip-scale atomic magnetometer
Ultraminiature gyroscope
Future atom-based sensors
Temperature and pressure sensors

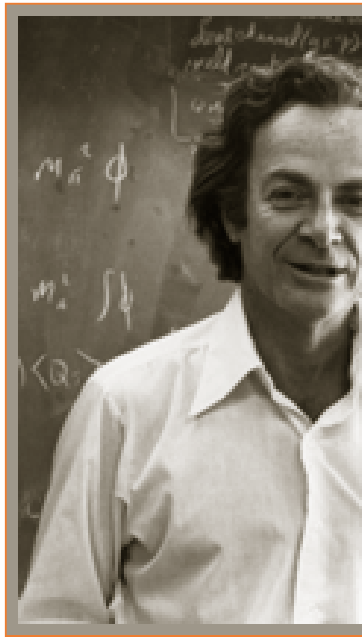


Zero-field NMR for “remote” chemical analysis and zero-field MRI.

The 2nd Quantum Revolution

We are witnessing the second quantum revolution where technology
- Will use the weird properties of quantum mechanics
- Will exploit how nature works at the quantum level

". .. and if you want to make a simulation of Nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy." -- Richard P. Feynman, "*Simulating Physics with Computers*", May 1981



- In the 20th Century only atomic clocks used the strange aspects of QM (GPS)
- Now chip scale atomic clocks are available
- Related technologies include exquisitely sensitive magnetometers, accelerometers, gravimeters are coming
- NV centers may be lead to unimaginable magnetic imaging systems

Thank you!

Any questions?

carl.williams@nist.gov

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