

The revised SI

Challenges and opportunities for mass and related quantities

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National Institute of Standards and Technology

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at the 17th meeting of the

Consultative Committee for Mass and Related Quantities

Sevres, France



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Outline – Three mysteries

- The mystery of mass
- The mystery of explaining the unit of mass
- The mystery of what's next

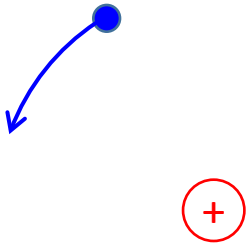
The mystery of mass

- Mass is among the first quantities measured by humans
- The origin of mass is complicated
- Mass is active and passive
- active = gravitational mass
- passive = inertial mass



At small scales, mass is weird

- Example: Hydrogen Atom



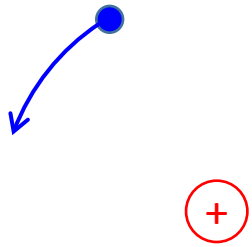
in the ground state:

$$m_H = m_e + m_p - 13.6 \frac{\text{eV}}{c^2}$$

$$\frac{13.6 \text{ eV}}{m_H c^2} = 1.4 \times 10^{-8}$$

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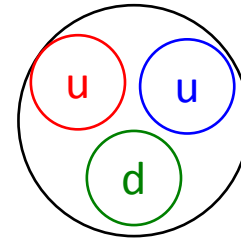


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- Example: proton



$$m_p = 938.3 \text{ MeV}/c^2$$

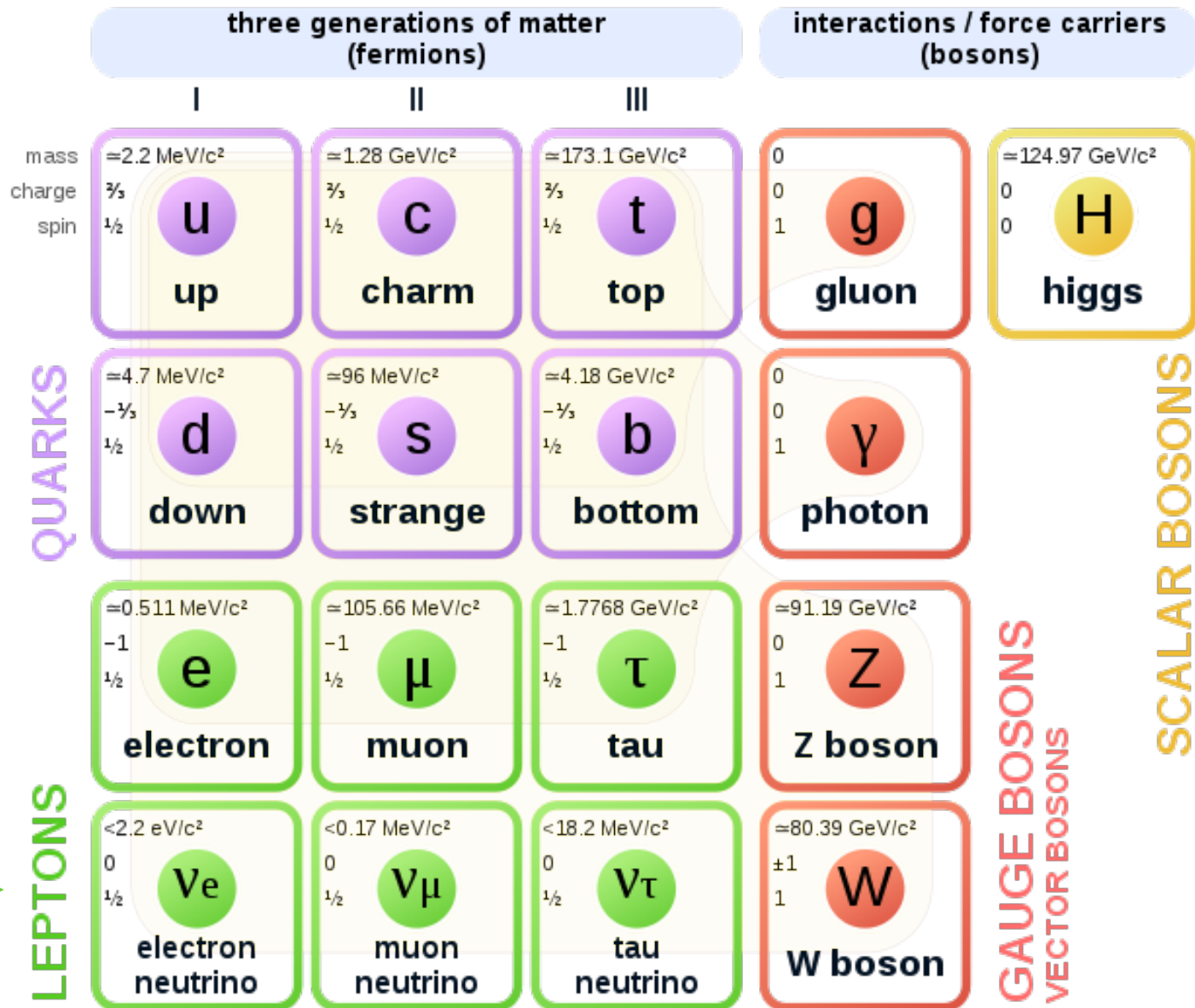
$$m_u = 2.2 \text{ MeV}/c^2$$

$$m_d = 4.7 \text{ MeV}/c^2$$

$$m_p = 2 m_u + m_d + 929.2 \frac{\text{MeV}}{c^2}$$

$$\frac{929.2 \text{ MeV}}{m_p c^2} = 99 \%$$

Standard Model of Elementary Particles

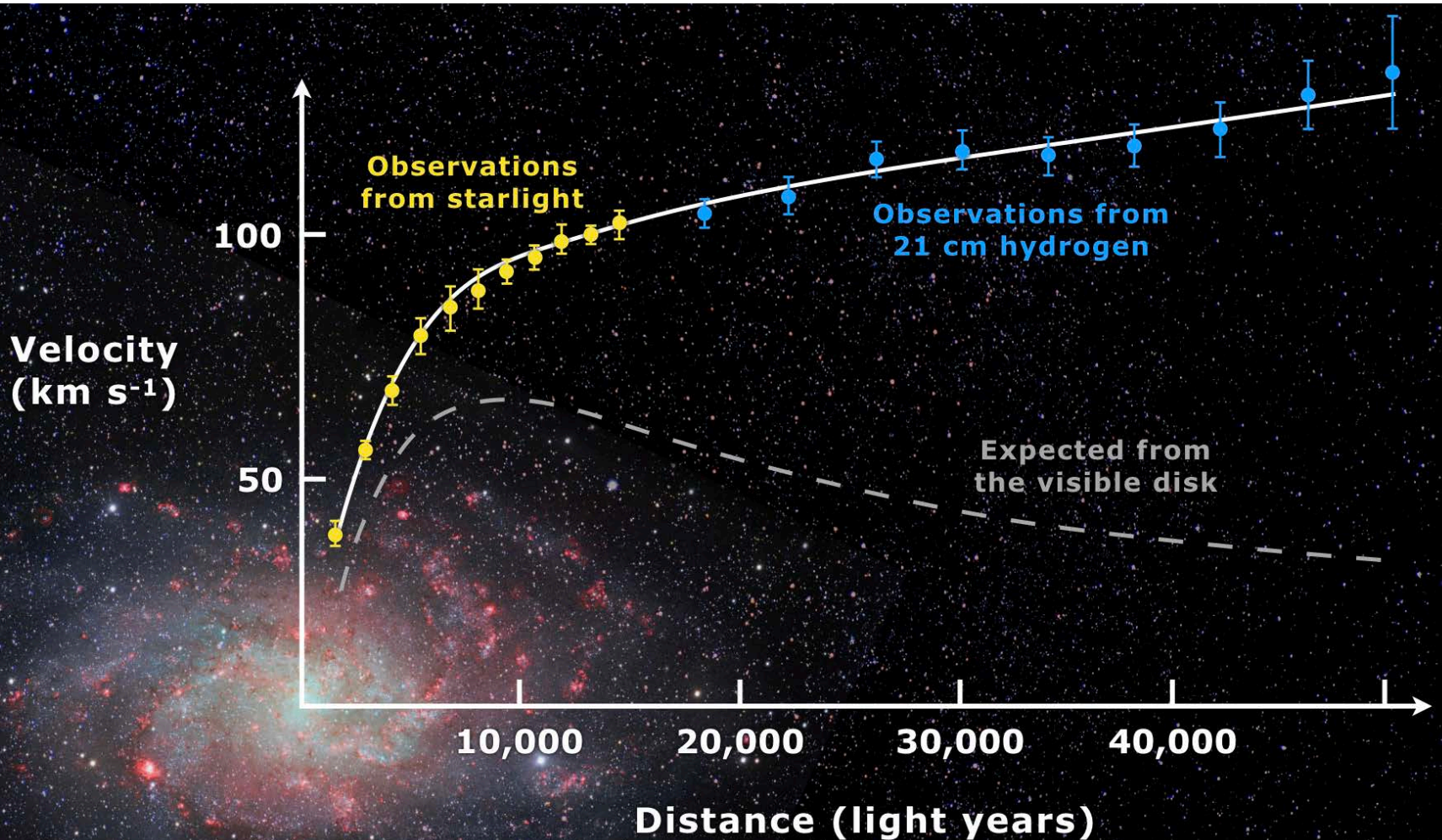


Generates masses of the leptons, the quarks, and the weak gauge bosons. The existence of the Higgs boson was confirmed in 2012.

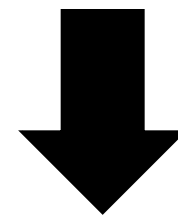
Absolute mass is unclear. We have information on the mass differences.

source: wikipedia

At large scales, mass is weird



The rotation curves of galaxies (here M33) does not follow our expectation (based on the visible baryonic matter).

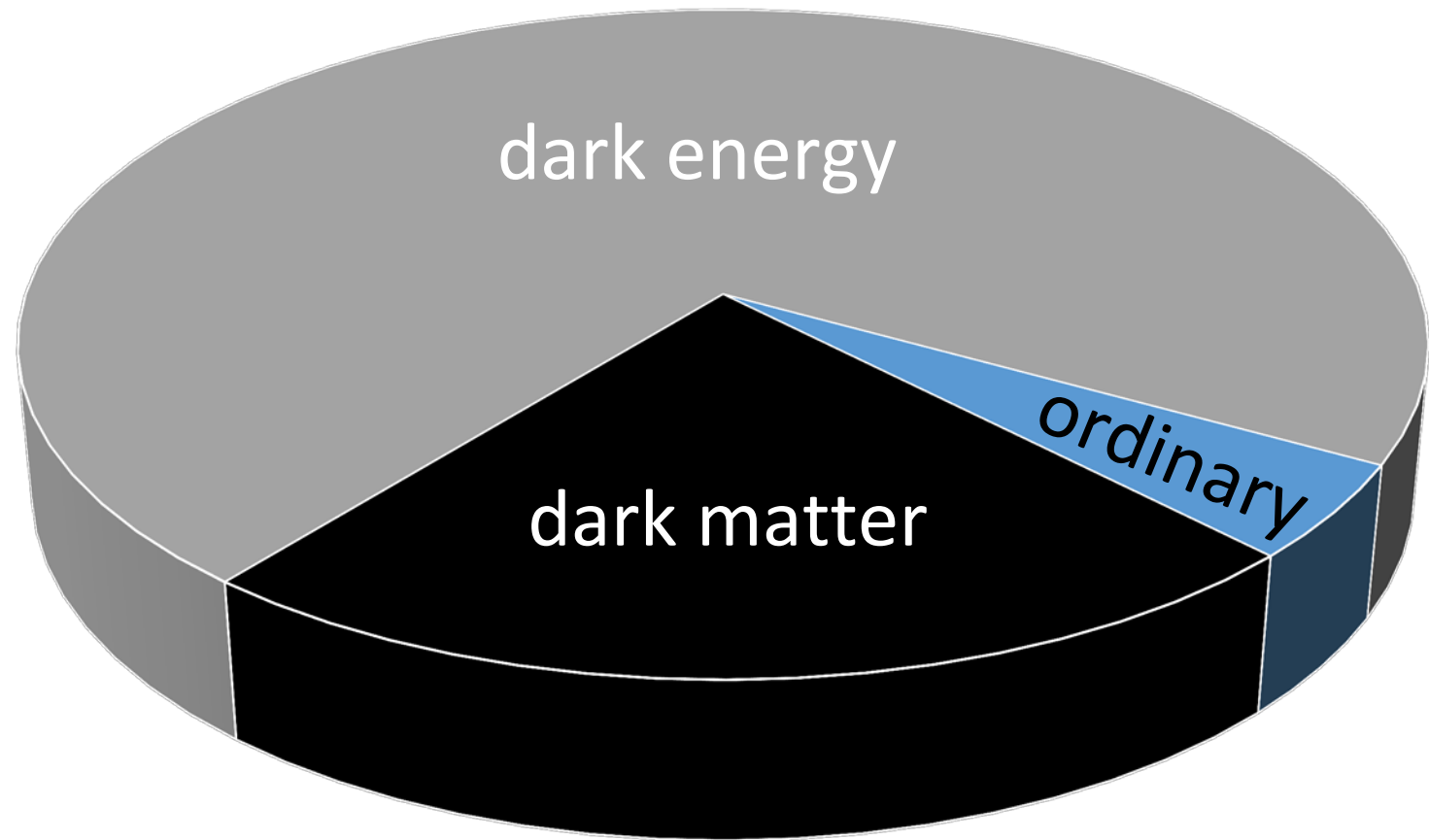


dark matter

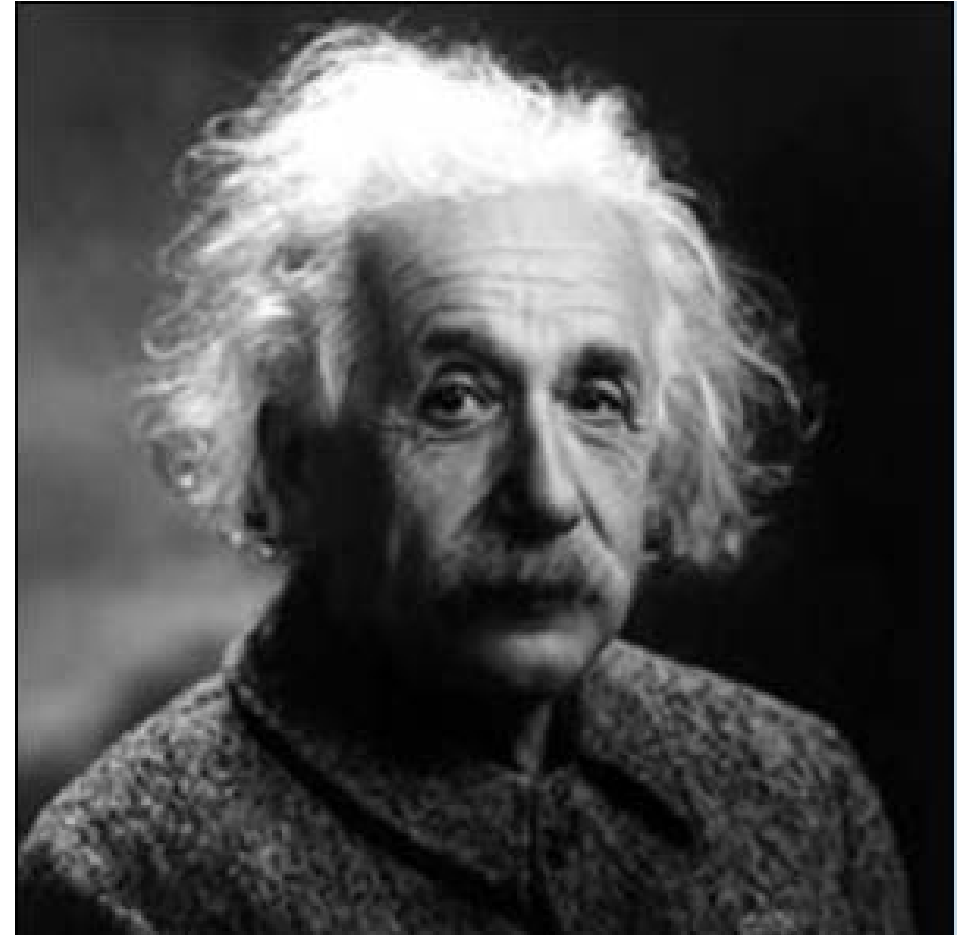
It get's worse

- Einstein's "biggest blunder of his life": the introduction of the **cosmological constant** – what we call today dark energy.

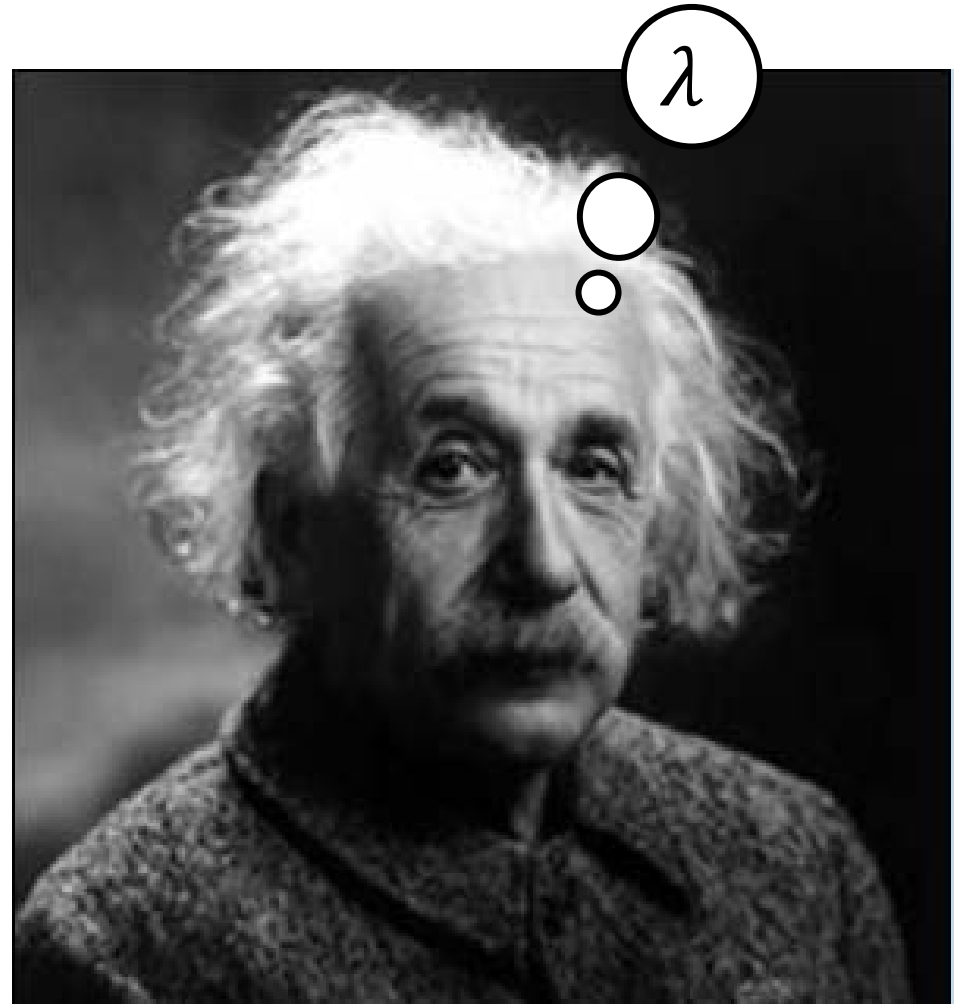
The total mass of the universe



Mass has an incredible intellectual bandwidth

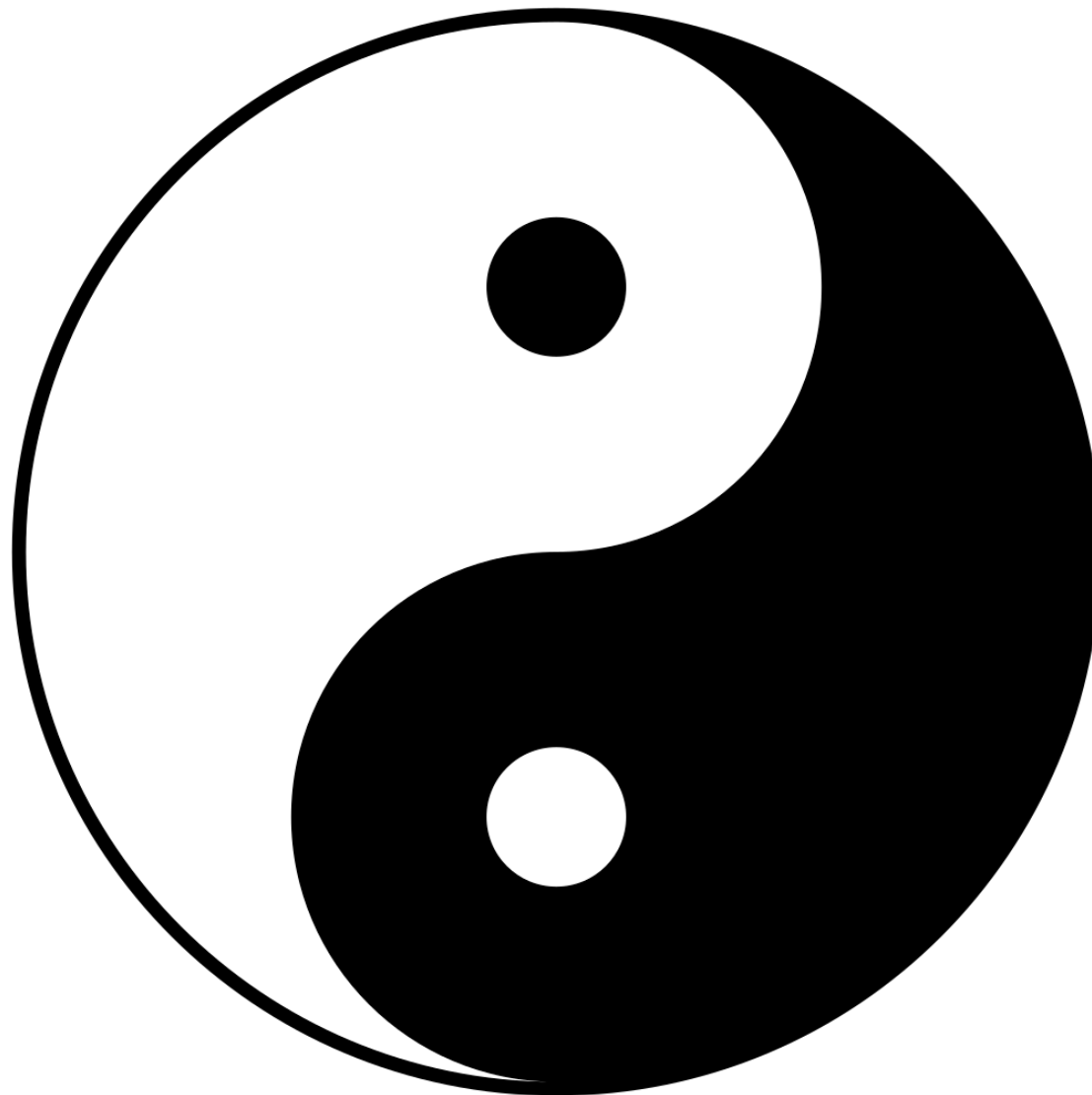


Mass has an incredible intellectual bandwidth



Physics

Metrology



Challenges and opportunities

- We are far from understanding mass
- Mass is complicated
- Many important questions in physics have to do with mass
- Mass, especially dark energy and dark matter, will be an exciting topic in science for years to come
- Conversations about mass could be held at all levels
- We should have these conversations
- We should stay engaged

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Thesis

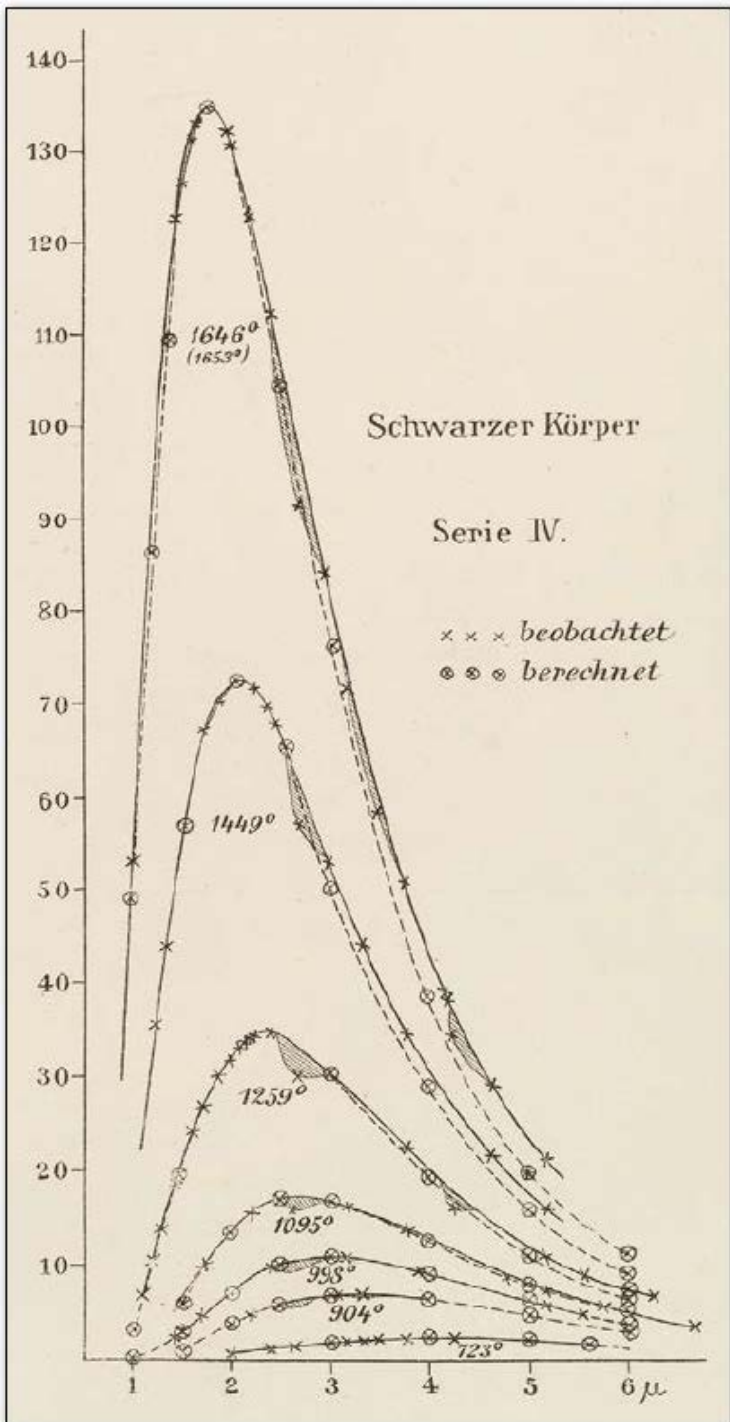
The definition of the kilogram in the SI is the third most difficult (base) unit to explain.

Proof

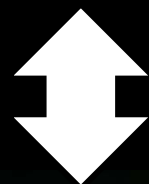
	unit	constant name	Symbol	Num. value	base unit	dep.
1	s	hyperf. trans. freq.	$\Delta\nu$	9 192 631 770	s^{-1}	0
2	m	speed of light	c	299 792 458	$m s^{-1}$	1
3	kg	Planck constant	h	$6.626\ 070\ 15 \times 10^{-34}$	$kg\ m^2\ s^{-1}$	2
4	A	elementary charge	e	$1.602\ 176\ 634 \times 10^{-19}$	A s	1
5	K	Boltzmann constant	k	$1.380\ 649 \times 10^{-23}$	$kg\ m^2\ s^{-1}K^{-1}$	3
6	mol	Avogadro constant	N_A	$6.022\ 140\ 86 \times 10^{23}$	mol^{-1}	0
7	cd	luminous efficacy	K_{cd}	683	$lm\ s^3\ kg^{-1}m^{-2}$	3

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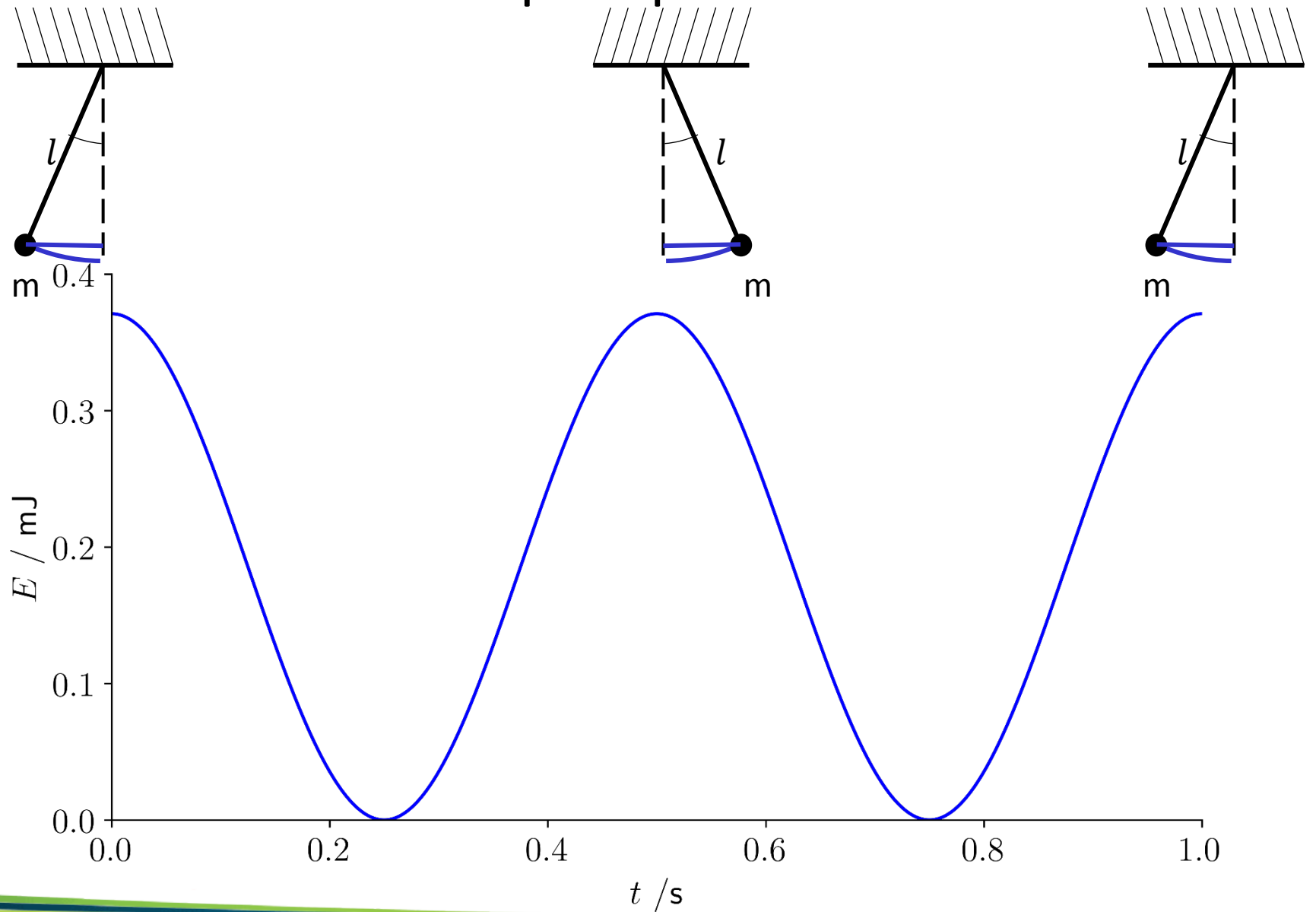
h



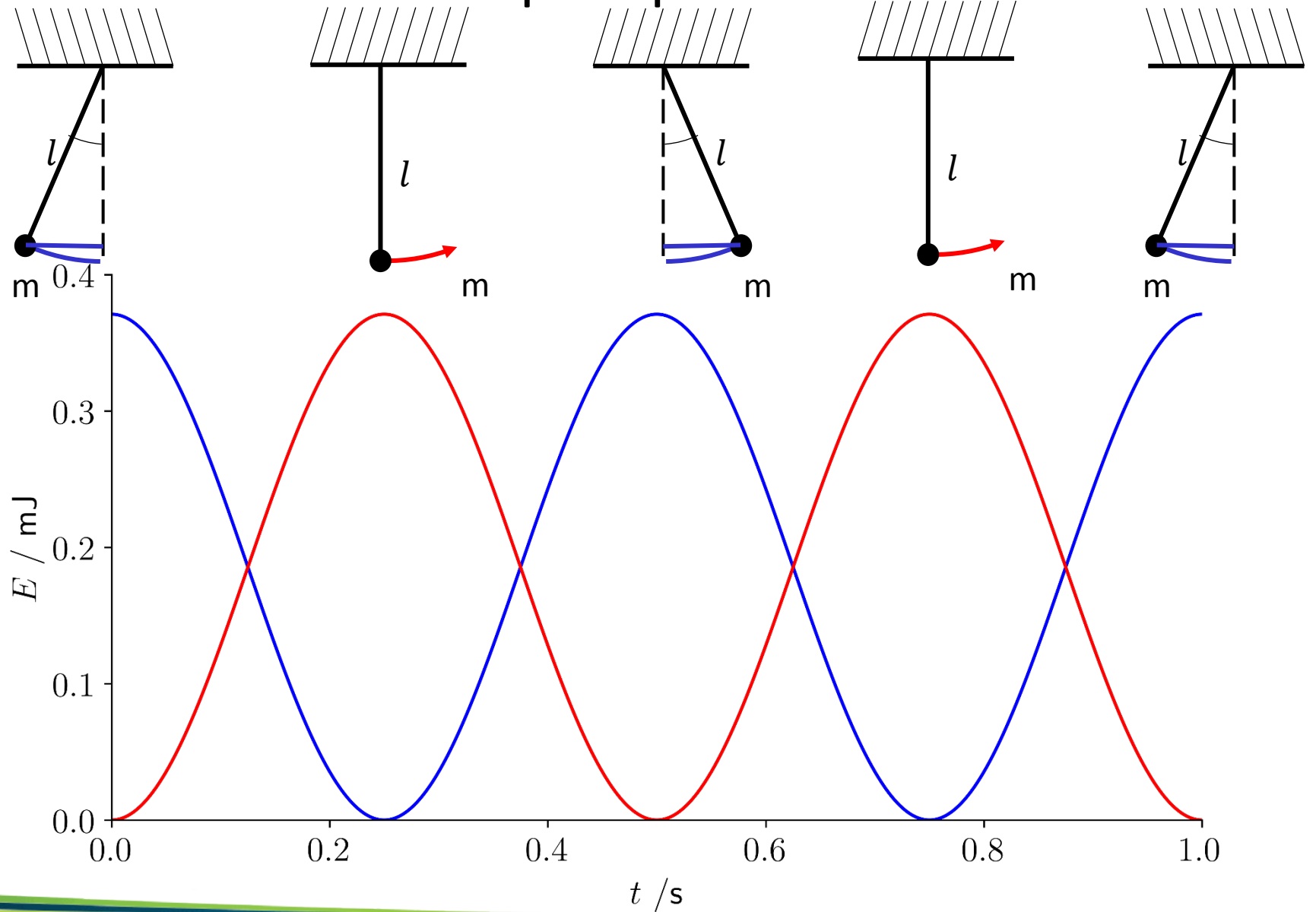
H. Kubbinga, A tribute to Max Planck,
Europhysics News 49, 27 (2018)



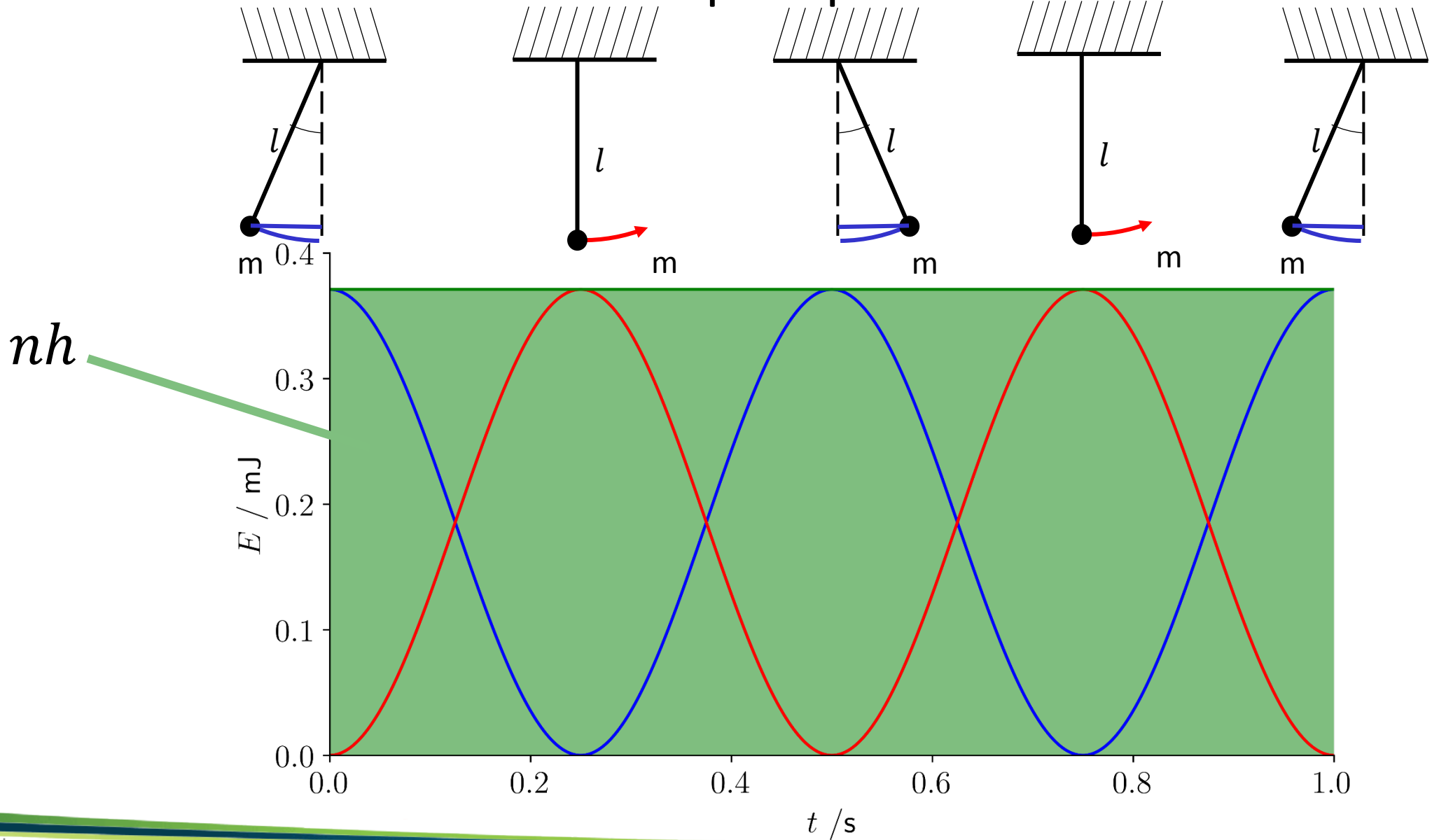
Consider the simple pendulum



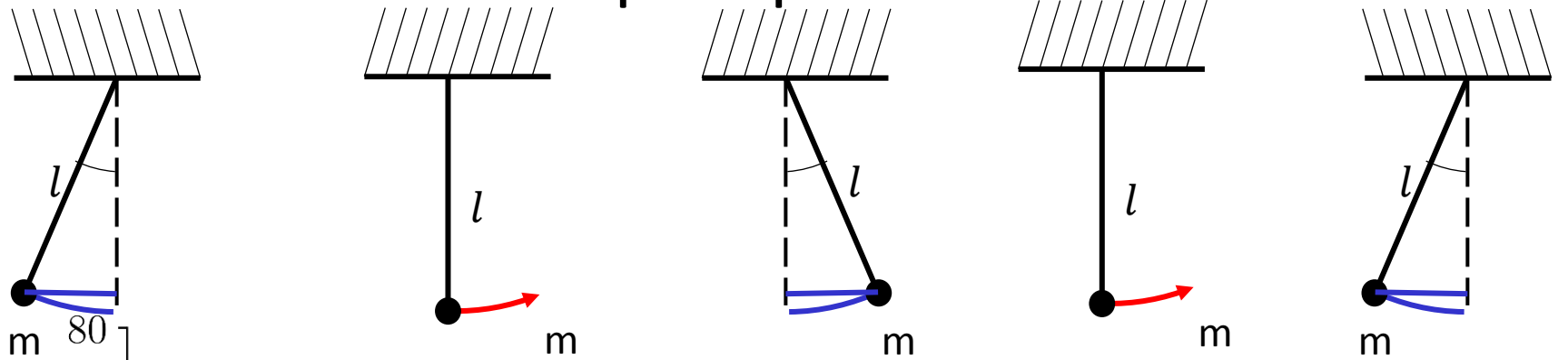
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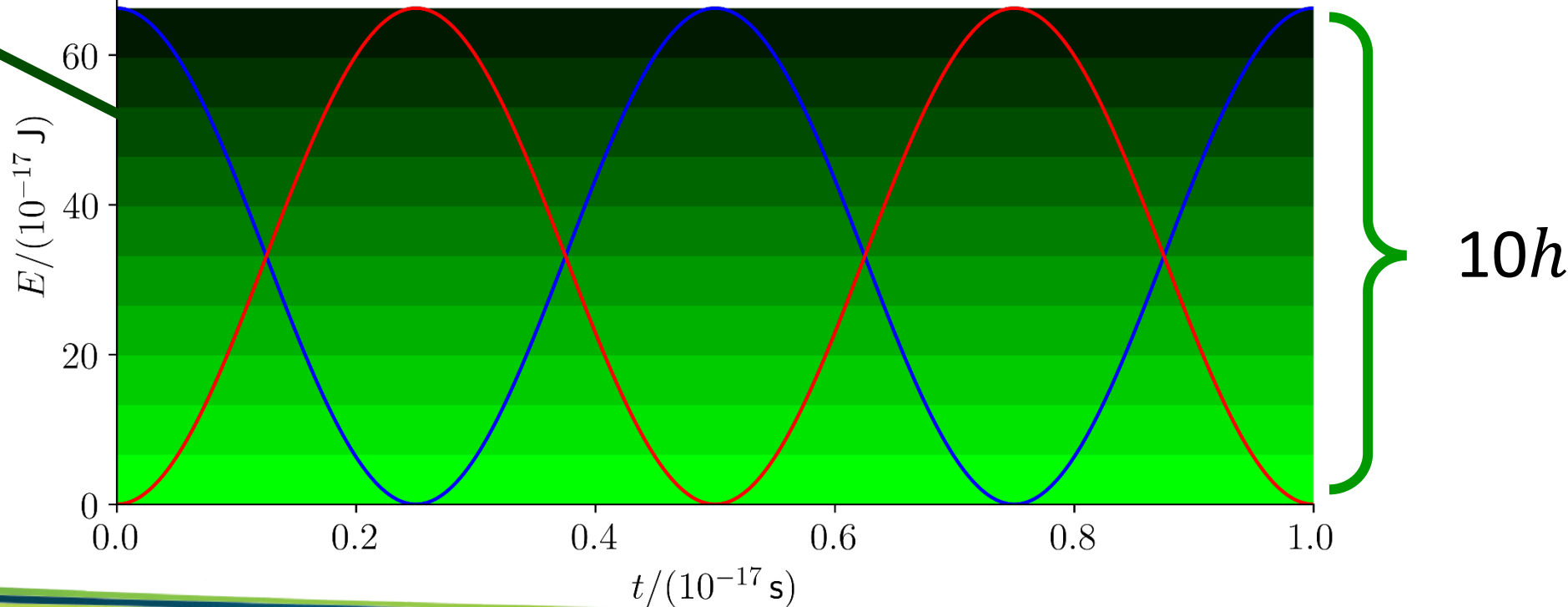
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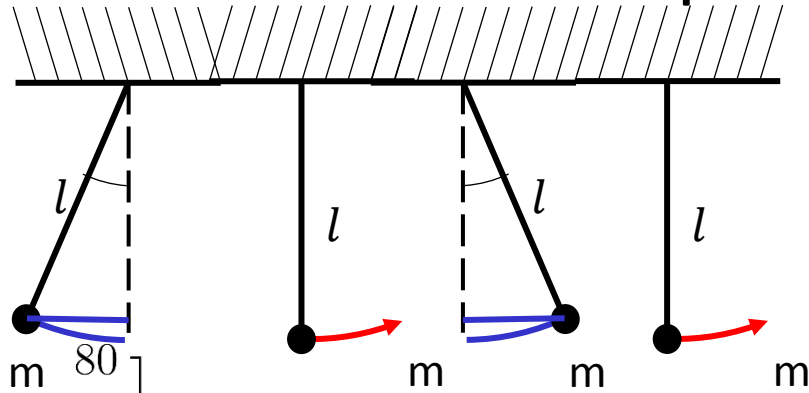
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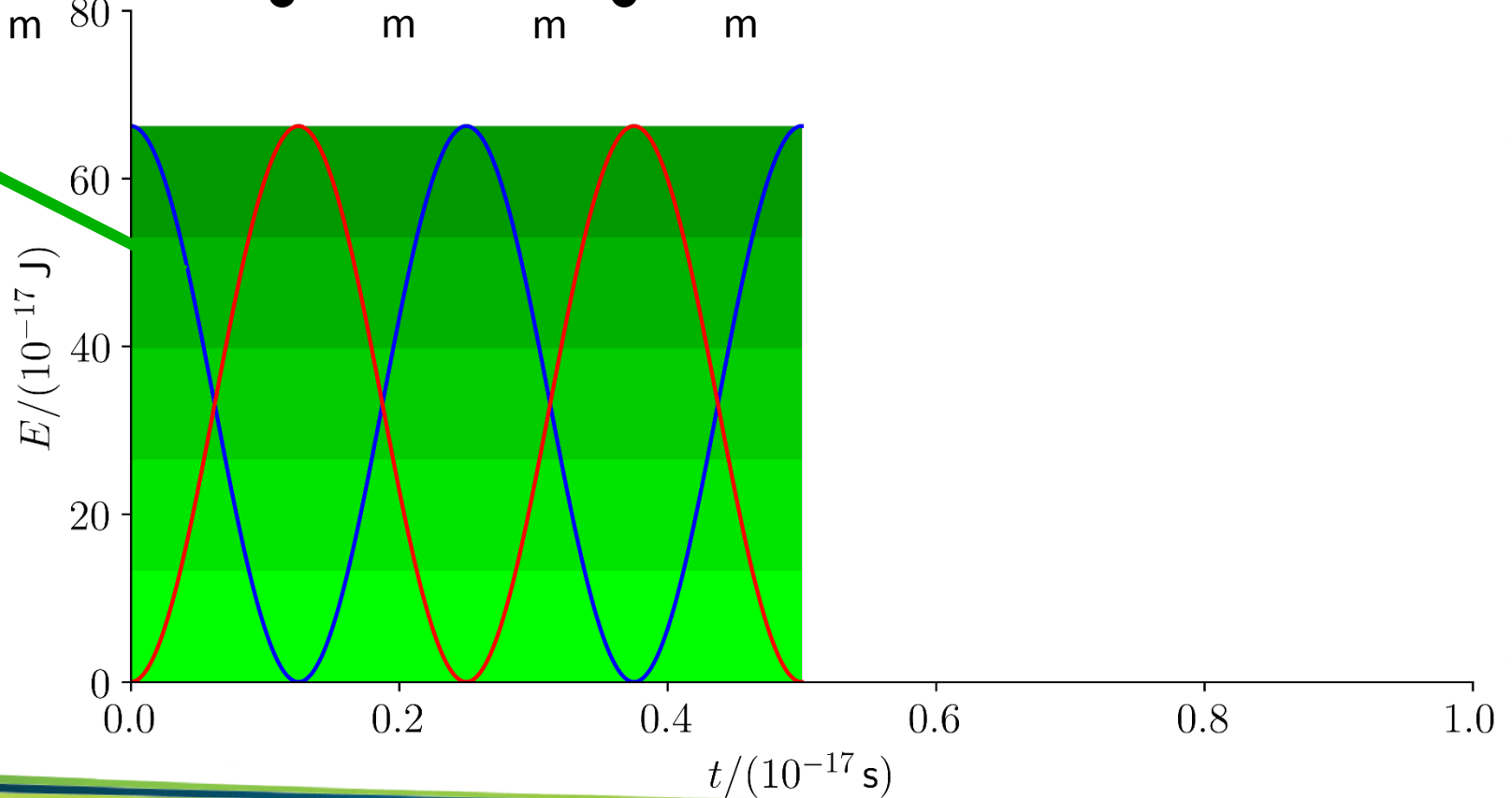
h



Consider the simple pendulum

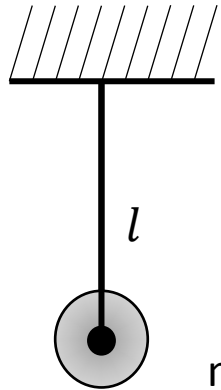


h

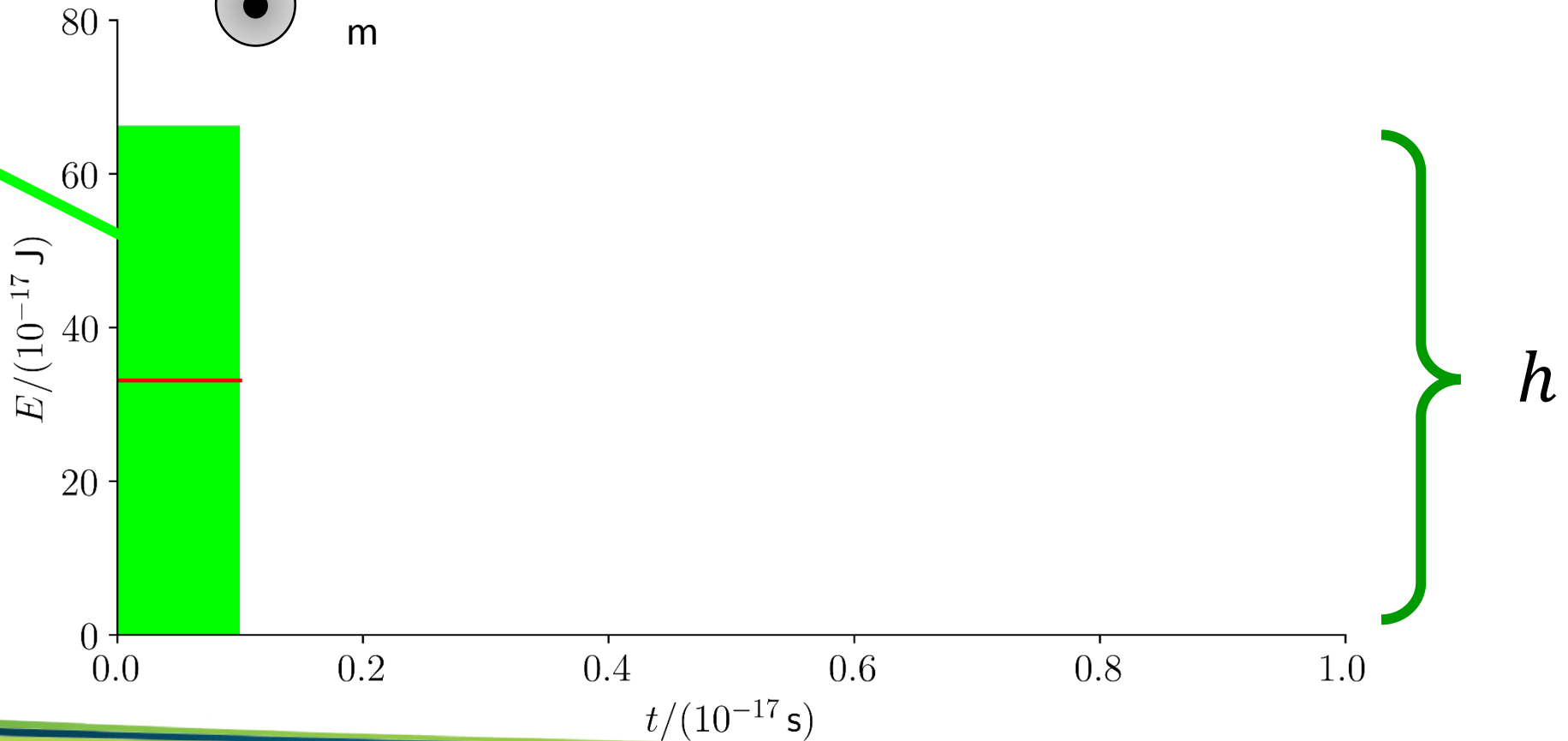


$5h$

Consider the simple pendulum



position & momentum is fuzzy



quantum mechanics

$$i\hbar \frac{\partial}{\partial t} \Psi = \left(-\frac{\hbar^2}{2m} \nabla^2 + V \right) \Psi$$

$$\lambda_{DB} > d$$

h is here

$$\lambda_{DB} \approx d$$

$$\lambda_{DB} = \frac{h}{p}$$

DeBroglie
wavelength

classical mechanics

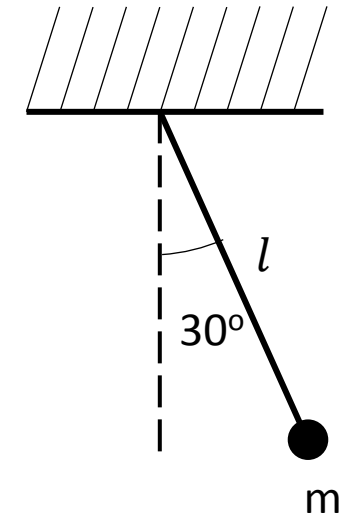
$$\vec{F} = m \frac{d^2 \vec{r}}{dt^2}$$

$$\lambda_{DB} < d$$

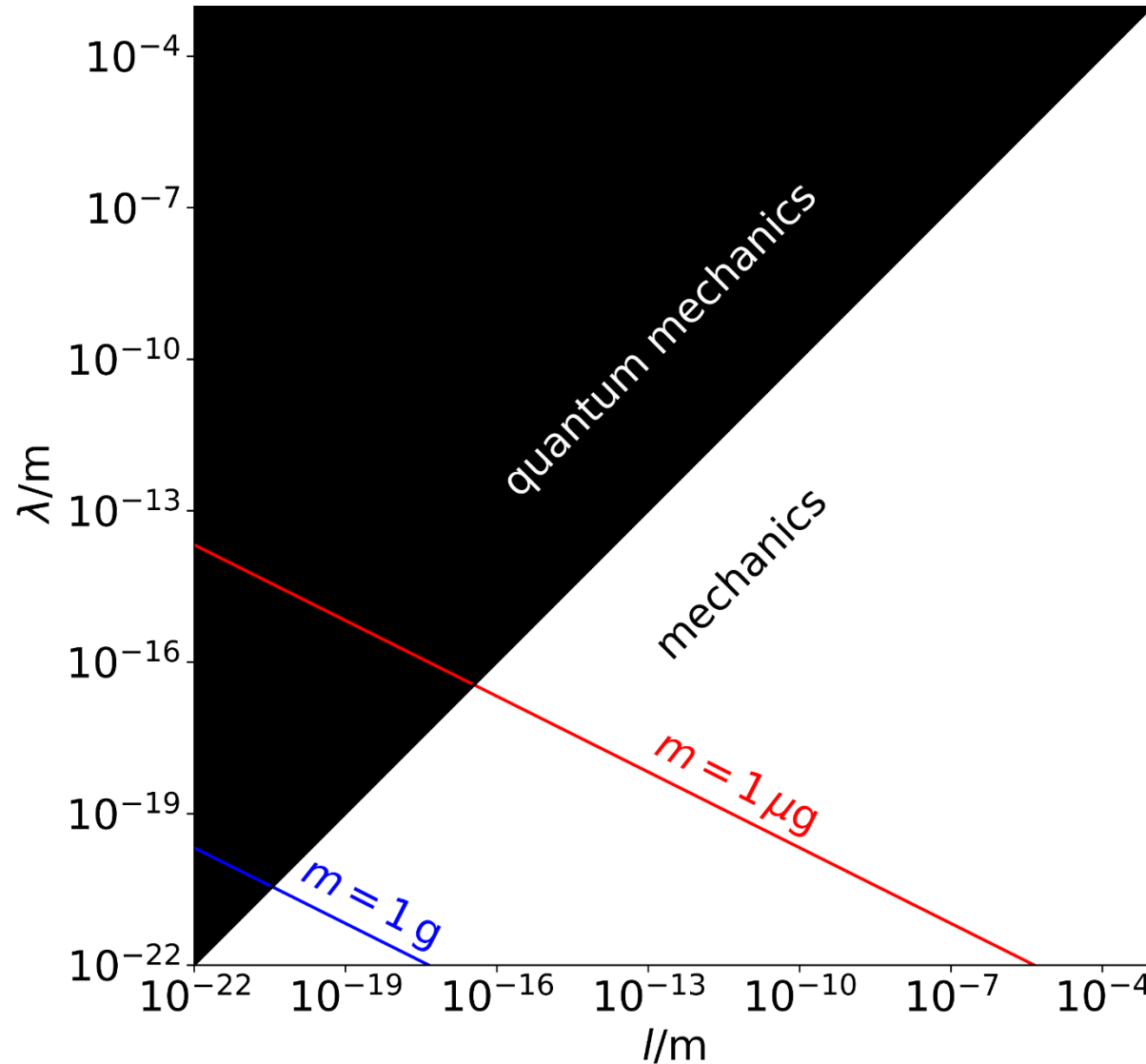
kg is here

$$\omega = \sqrt{g/l}$$

Consider the simple pendulum



$$\lambda = \frac{h}{m\sqrt{gl}}$$



kilogram-sized masses
are very far
(read: 30 orders)
away from the
quantum mechanical
regime

Two ways to connect h to the kilogram at 1kg level

- Use a small mass
- Scale
- $m_e \propto h$
- $M = n \cdot N_A \cdot r \cdot m_e$
- Quantum electrical standards
- $R_K = \frac{h}{e^2}$ & $K_J = \frac{h}{2e}$
- $\frac{K_J^2}{R_K} = \frac{h}{4}$
- $P_{el} = P_{mech}$

X-Ray Crystal Density Method (XRCD)

Kibble balance

Challenges and opportunities

- Explaining the realization of the kg from h is hard.
- Explaining the Planck constant is hard.
- Explaining the two realization experiments is hard.
- We have the opportunity to talk about quantum mechanics when asked a simple question, “What is a kilogram?”
- The realization experiments are fun!

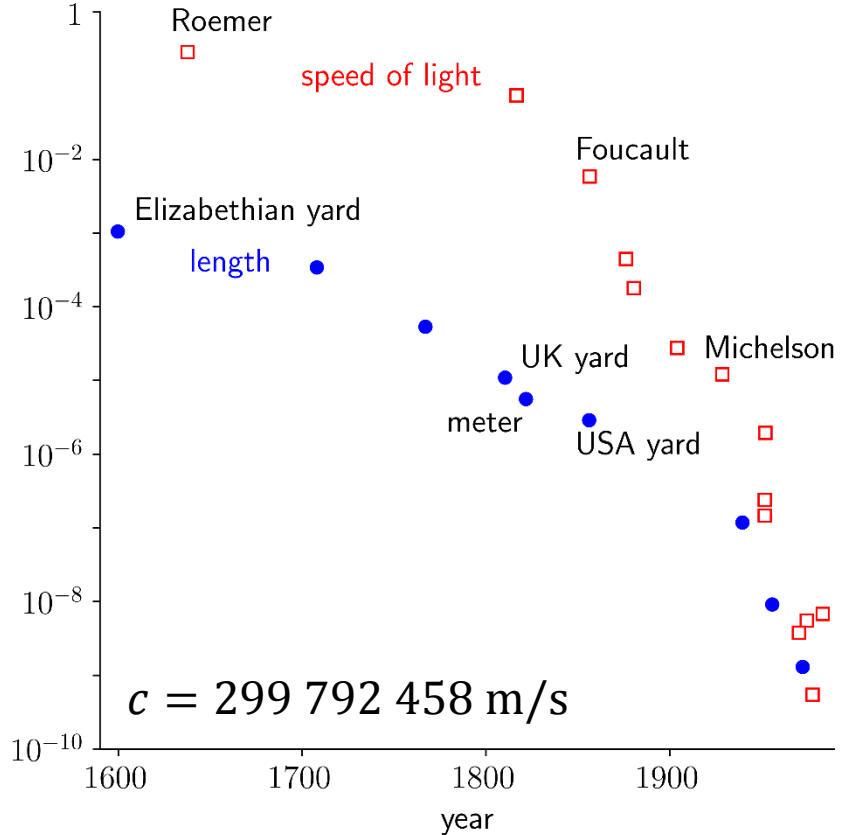
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From a fixed point to a scale-invariant constant



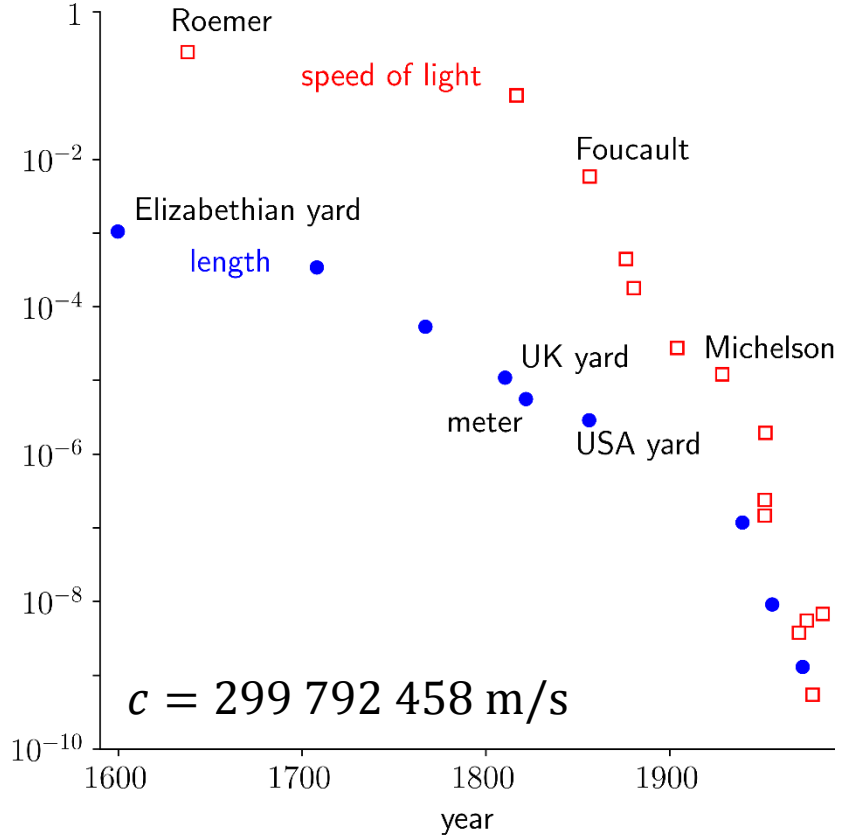
Graph adapted from: B.W. Petley,
Physical constants and the SI, NPL News Jan.1987.



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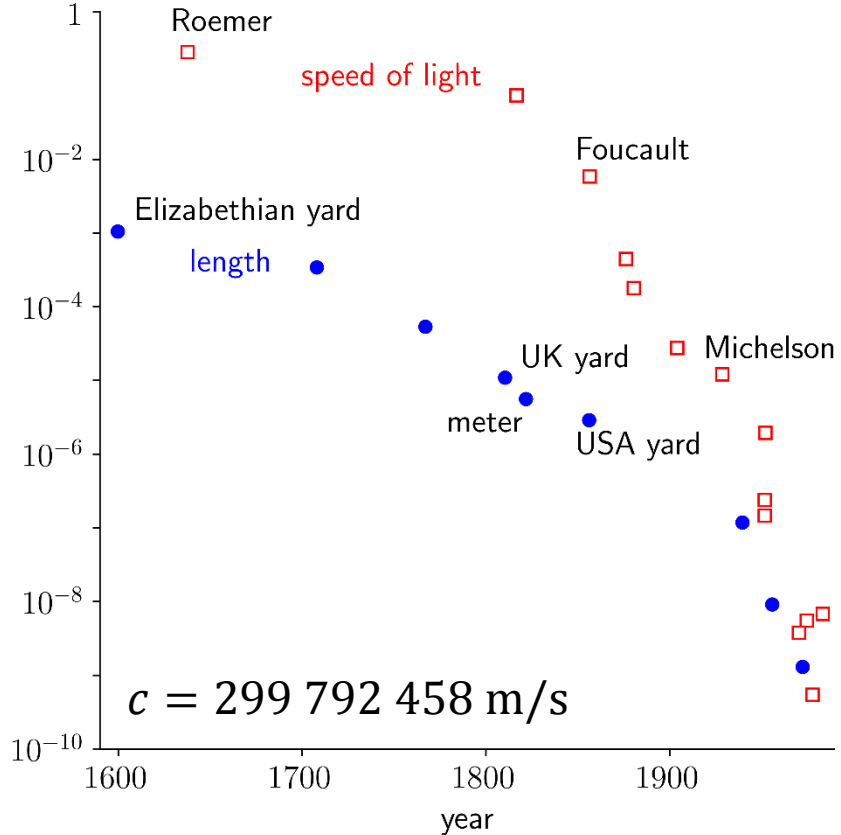


https://space-geodesy.nasa.gov/NSGN/sites/GGAAO/GGAAO_photos.html

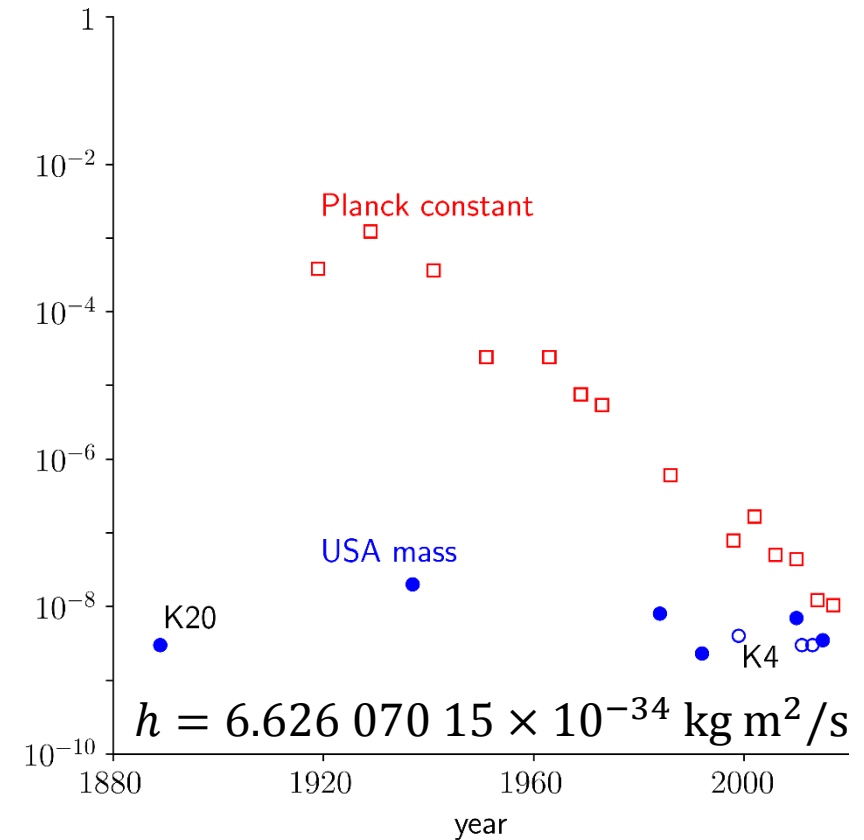
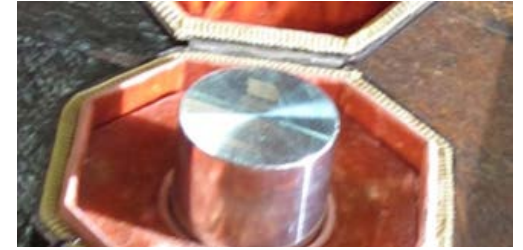
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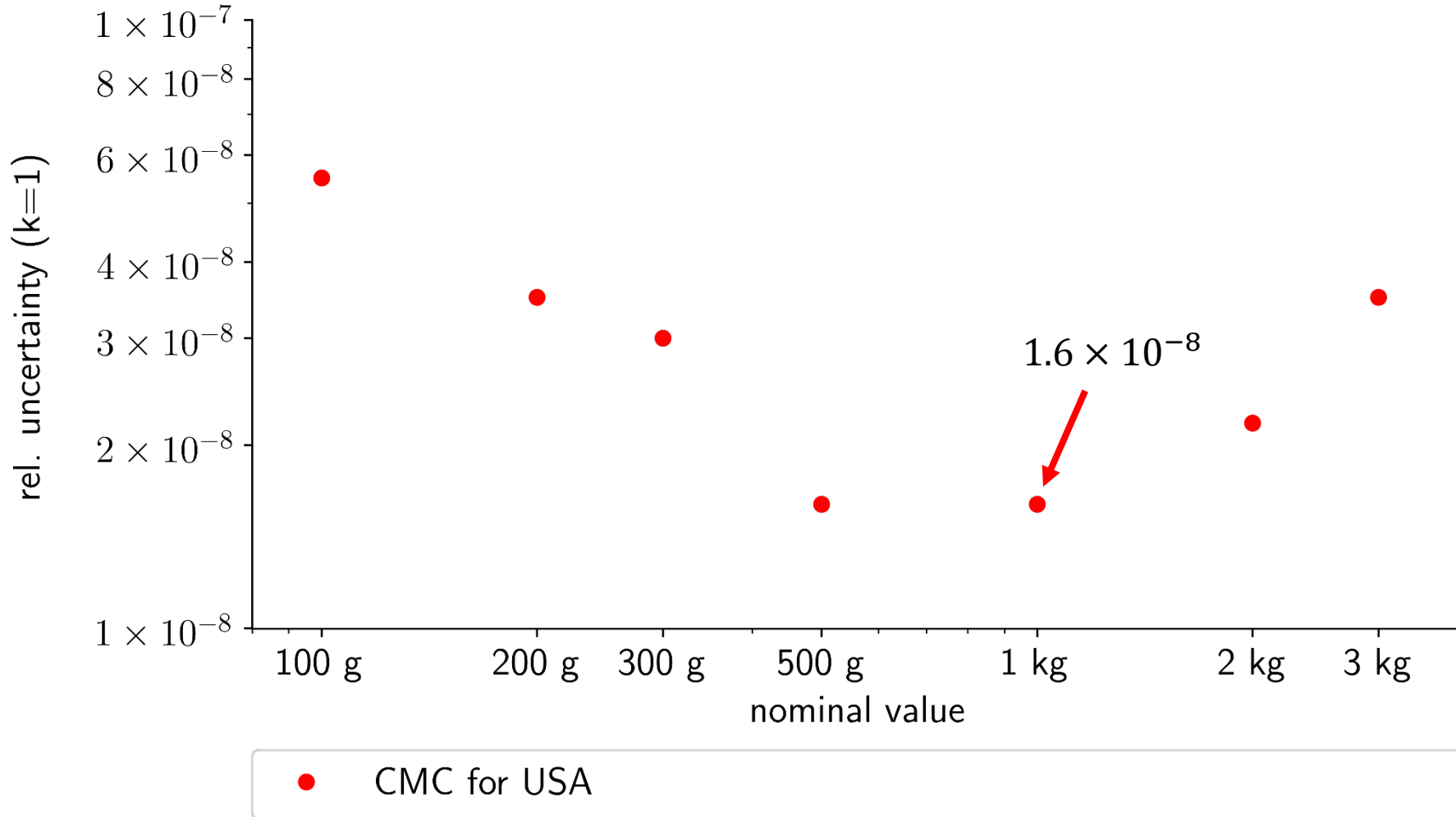
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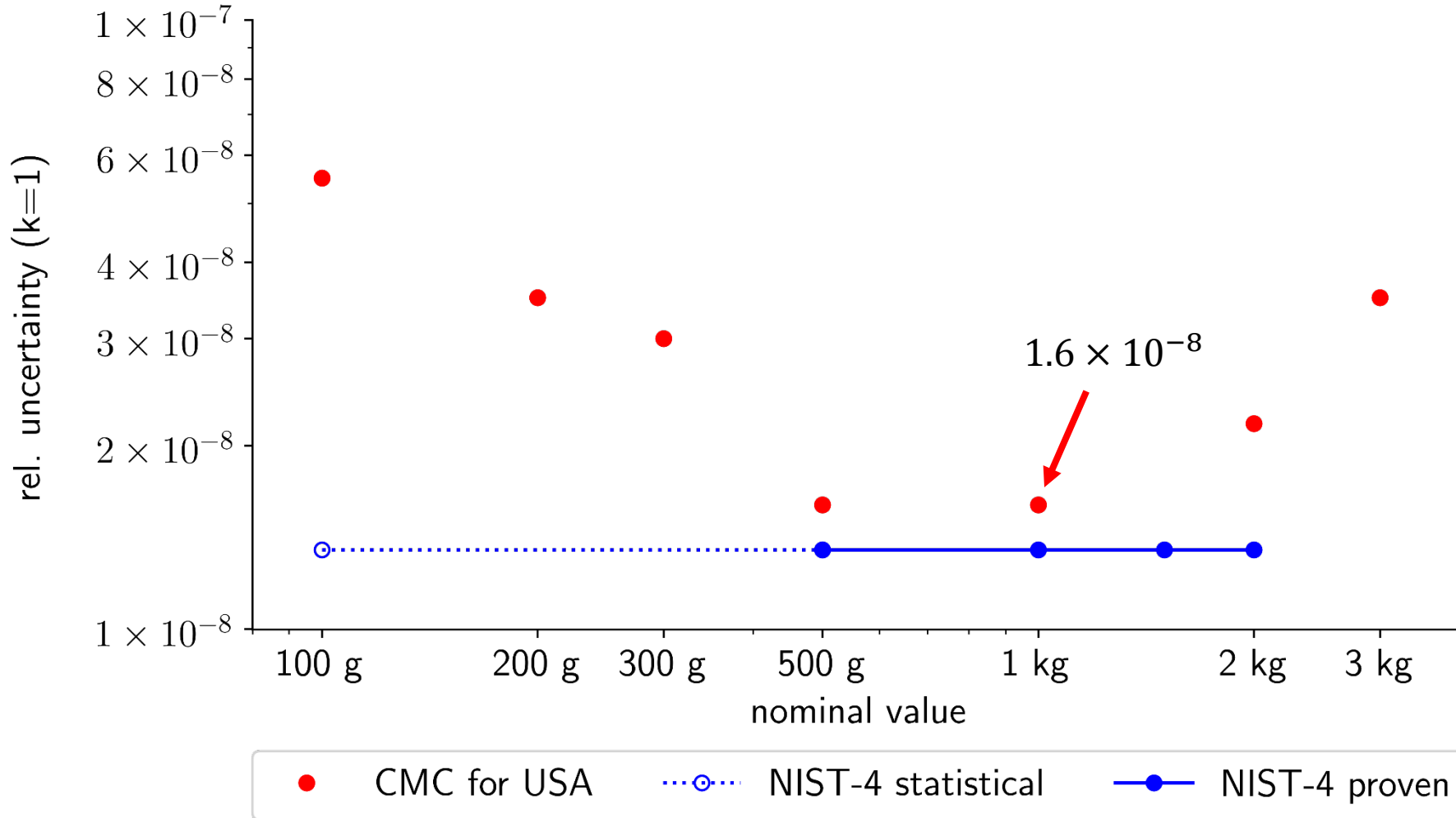
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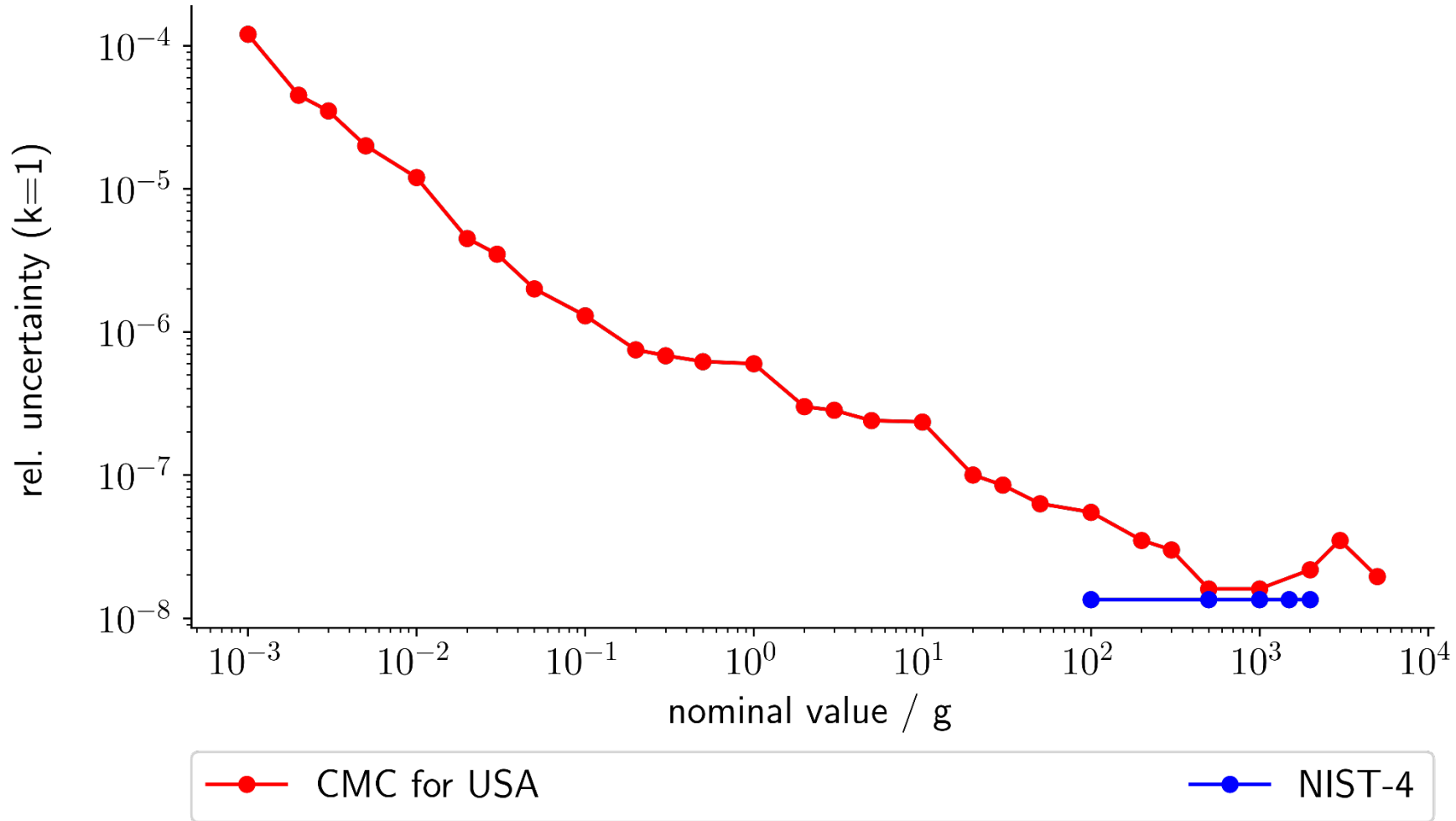
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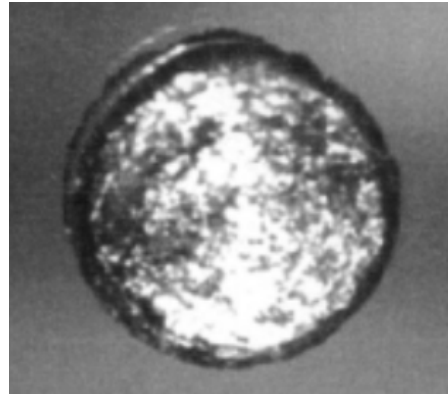
Why lower the uncertainties for lower values?

- Commerce:
- Science

Why lower the uncertainties for lower values?

- Commerce:

Californium ${}_{98}\text{Cf}$



- Science

1 kg is valued at 27,000,000,000 USD = 2.7×10^{10} USD

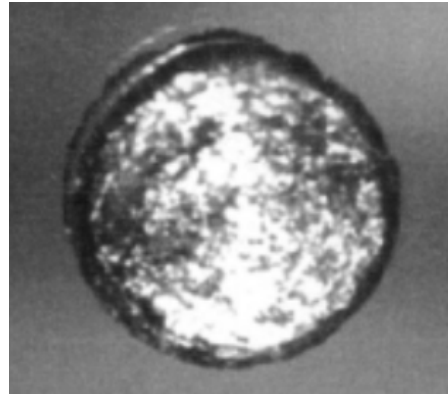


Here it is

	57 ${}^2D_{3/2}$ La Lanthanum 138.90547 [Xe]5d6s ² 5.5769	58 1G_4 Ce Cerium 140.116 [Xe]4f5d6s ² 5.5386	59 ${}^4I_{9/2}$ Pr Praseodymium 140.90766 [Xe]4f6s ² 5.473	60 3I_4 Nd Neodymium 144.242 [Xe]4f6s ² 5.5250	61 ${}^4I_{5/2}$ Pm Promethium (145) [Xe]4f6s ² 5.582	62 3F_4 Sm Samarium 150.36 [Xe]4f6s ² 5.6437	63 ${}^8S_{7/2}$ Eu Europium 151.964 [Xe]4f6s ² 5.6704	64 ${}^6D_7/2$ Gd Gadolinium 157.25 [Xe]4f7s ² 6.1498	65 ${}^6H_{15/2}$ Tb Terbium 158.92535 [Xe]4f7s ² 5.938	66 3I_4 Dy Dysprosium 162.500 [Xe]4f9s ² 5.9391	67 ${}^4I_{15/2}$ Ho Holmium 164.93033 [Xe]4f11s ² 6.0215	68 3H_6 Er Erbium 167.259 [Xe]4f12s ² 6.1077	69 ${}^2F_{7/2}$ Tm Thulium 168.93422 [Xe]4f13s ² 6.1843	70 1S_0 Yb Ytterbium 173.045 [Xe]4f14s ² 6.2542	71 ${}^2D_{3/2}$ Lu Lutetium 174.9668 [Xe]4f145d6s ² 5.4259
	89 ${}^2D_{3/2}$ Ac Actinium (227) [Rn]6d7s ² 5.3802	90 3F_2 Th Thorium 232.0377 [Rn]6d7s ² 6.3067	91 ${}^4K_{11/2}$ Pa Protactinium 231.03588 [Rn]5f6d7s ² 5.89	92 3L_4 U Uranium 238.02891 [Rn]5f6d7s ² 6.1941	93 ${}^4L_{11/2}$ Np Neptunium (237) [Rn]5f6d7s ² 6.2655	94 3F_4 Pu Plutonium (244) [Rn]5f7s ² 6.0258	95 ${}^8S_{7/2}$ Am Americium (243) [Rn]5f7s ² 5.9738	96 3D_3 Cm Curium (247) [Rn]5f6d7s ² 5.9914	97 ${}^8S_{7/2}$ Bk Berkelium (247) [Rn]5f7s ² 6.1978	98 3I_4 Cf Californium (251) [Rn]5f7s ² 6.2817	99 ${}^4I_{15/2}$ Es Einsteinium (252) [Rn]5f7s ² 6.3676	100 3H_4 Fm Fermium (257) [Rn]5f7s ² 6.50	101 ${}^2F_{7/2}$ Md Mendelevium (258) [Rn]5f7s ² 6.58	102 1S_0 No Nobelium (259) [Rn]5f7s ² 6.65	103 ${}^2P_{1/2}$ Lr Lawrencium (266) [Rn]5f7s7p 4.96

Why lower the uncertainties for lower values?

- Commerce:
Californium $_{98}\text{Cf}$



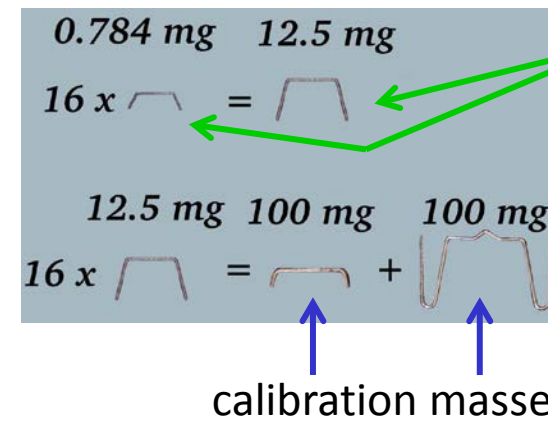
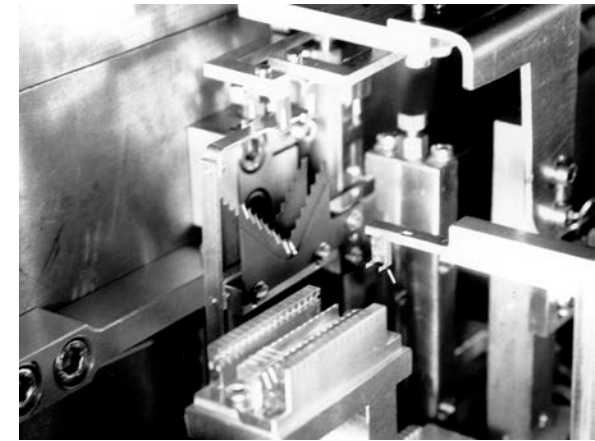
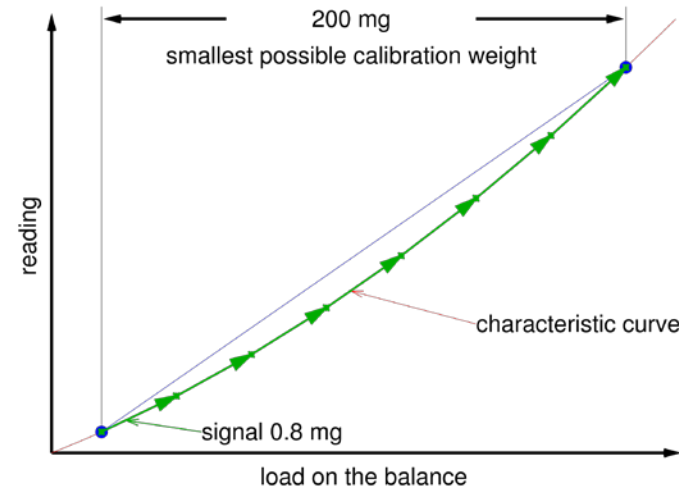
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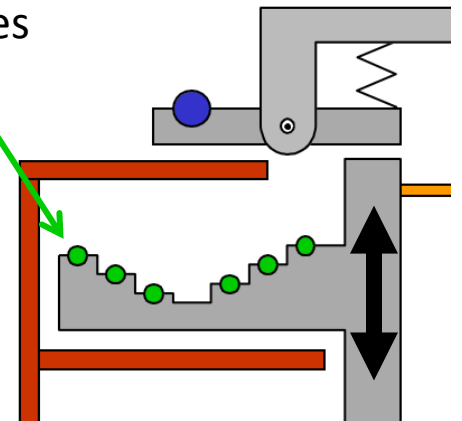
	57 $^{2}_{32}\text{D}$	58 $^{1}_{52}\text{Ce}$	59 $^{1}_{92}\text{Pr}$	60 $^{1}_{142}\text{Nd}$	61 $^{1}_{152}\text{Pm}$	62 $^{1}_{142}\text{Sm}$	63 $^{1}_{152}\text{Eu}$	64 $^{1}_{152}\text{Gd}$	65 $^{1}_{152}\text{Tb}$	66 $^{1}_{152}\text{Dy}$	67 $^{1}_{152}\text{Ho}$	68 $^{1}_{152}\text{Er}$	69 $^{1}_{152}\text{Tm}$	70 $^{1}_{152}\text{Yb}$	71 $^{1}_{152}\text{Lu}$
Lanthanides	La Lanthanum 138.90547 [Xe]5d ¹ 6s ² 5.5769	Ce Cerium 140.116 [Xe]4f ¹ 5d ¹ 6s ² 5.5386	Pr Praseodymium 140.90766 [Xe]4f ³ 6s ² 5.473	Nd Neodymium 144.242 [Xe]4f ⁴ 6s ² 5.5250	Pm Promethium (145) [Xe]4f ⁵ 6s ² 5.582	Sm Samarium 150.36 [Xe]4f ⁶ 6s ² 5.6437	Eu Europium 151.964 [Xe]4f ⁷ 6s ² 5.6704	Gd Gadolinium 157.25 [Xe]4f ⁷ 5d ¹ 6s ² 6.1498	Tb Terbium 158.92535 [Xe]4f ⁹ 6s ² 6.1638	Dy Dysprosium 162.500 [Xe]4f ¹⁰ 6s ² 5.9391	Ho Holmium 164.93033 [Xe]4f ¹¹ 6s ² 6.0215	Er Erbium 167.259 [Xe]4f ¹² 6s ² 6.1077	Tm Thulium 168.93422 [Xe]4f ¹³ 6s ² 6.1843	Yb Ytterbium 173.045 [Xe]4f ¹⁴ 6s ² 5.4259	Lu Lutetium 174.9668 [Xe]4f ¹⁴ 5d ¹ 6s ² 5.4259
	89 $^{2}_{32}\text{Ac}$	90 $^{2}_{32}\text{Th}$	91 $^{2}_{32}\text{Pa}$	92 $^{2}_{88}\text{U}$	93 $^{2}_{88}\text{Np}$	94 $^{2}_{88}\text{Pu}$	95 $^{2}_{88}\text{Am}$	96 $^{2}_{88}\text{Cm}$	97 $^{2}_{88}\text{Bk}$	98 $^{2}_{98}\text{Cf}$	99 $^{2}_{98}\text{Es}$	100 $^{2}_{98}\text{Fm}$	101 $^{2}_{98}\text{Md}$	102 $^{2}_{98}\text{No}$	103 $^{2}_{98}\text{Lr}$
Actinides	Ac Actinium (227) [Rn]6d ¹ 7s ² 5.3802	Th Thorium 232.0377 [Rn]6d ² 7s ² 6.3067	Pa Protactinium 231.03688 [Rn]5f ² 6d ¹ 7s ² 5.89	U Uranium 238.02891 [Rn]5f ³ 6d ¹ 7s ² 6.1941	Np Neptunium (237) [Rn]5f ⁴ 6d ¹ 7s ² 6.2655	Pu Plutonium (244) [Rn]5f ⁶ 7s ² 6.0258	Am Americium (243) [Rn]5f ⁷ 7s ² 5.9738	Cm Curium (247) [Rn]5f ⁸ 6d ¹ 7s ² 5.9914	Bk Berkelium (247) [Rn]5f ⁹ 7s ² 6.1978	Cf Californium (251) [Rn]5f ¹⁰ 7s ² 6.2817	Es Einsteinium (252) [Rn]5f ¹¹ 7s ² 6.3676	Fm Fermium (257) [Rn]5f ¹² 7s ² 6.50	Md Mendelevium (258) [Rn]5f ¹³ 7s ² 6.58	No Nobelium (259) [Rn]5f ¹⁴ 7s ² 6.65	Lr Lawrencium (266) [Rn]5f ¹⁴ 7p ¹ 4.96

- Science

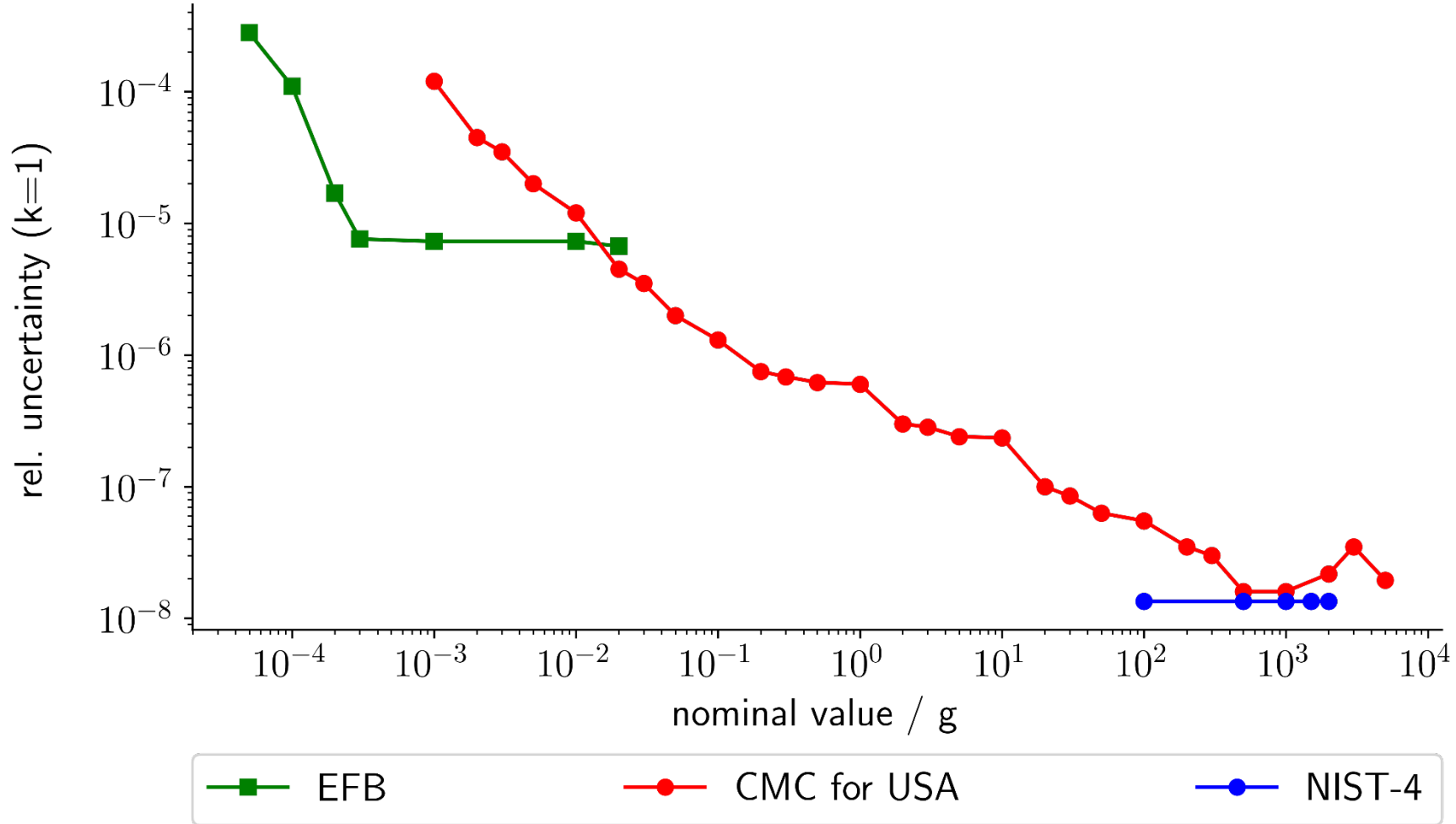


auxiliary masses

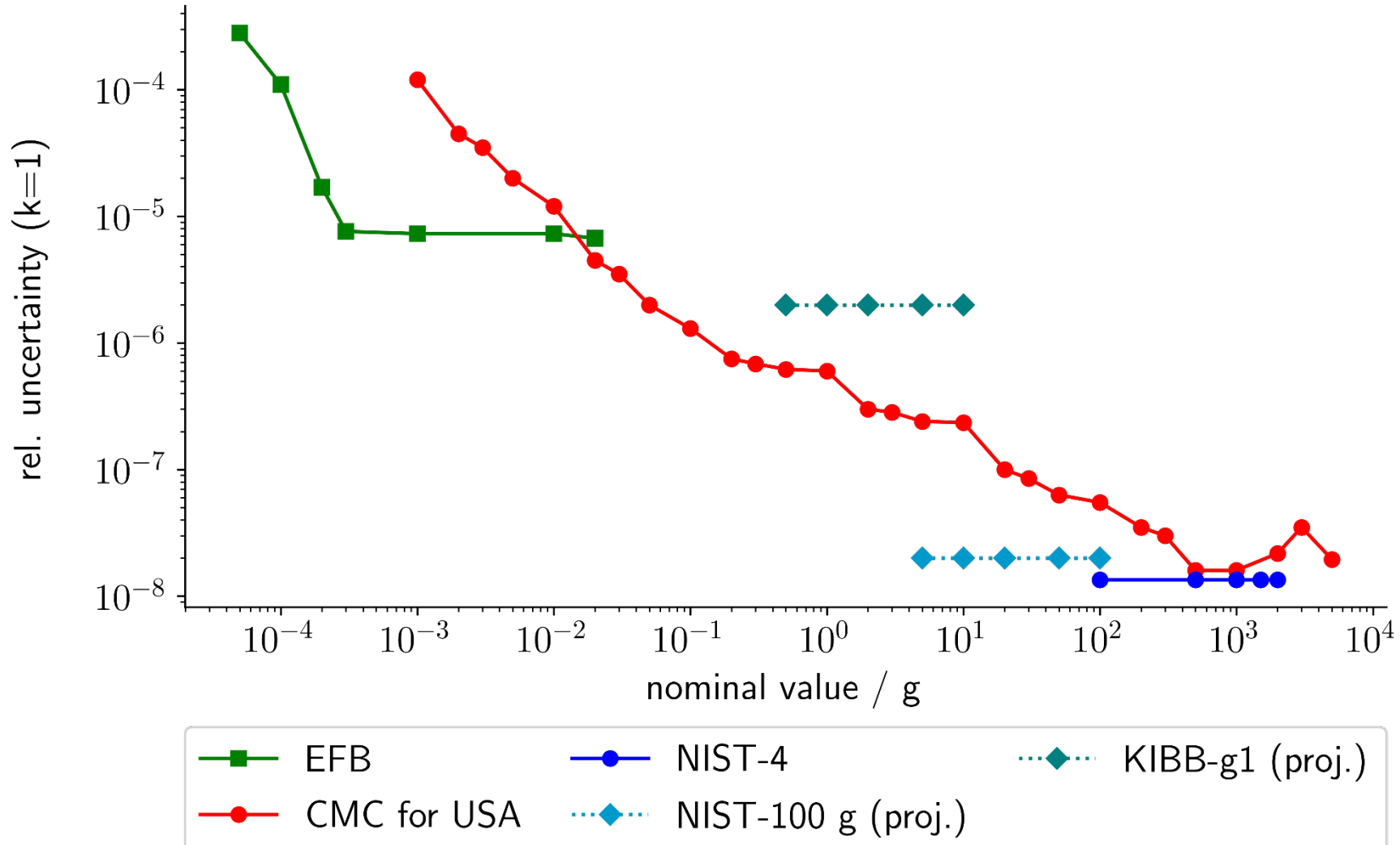
calibration masses



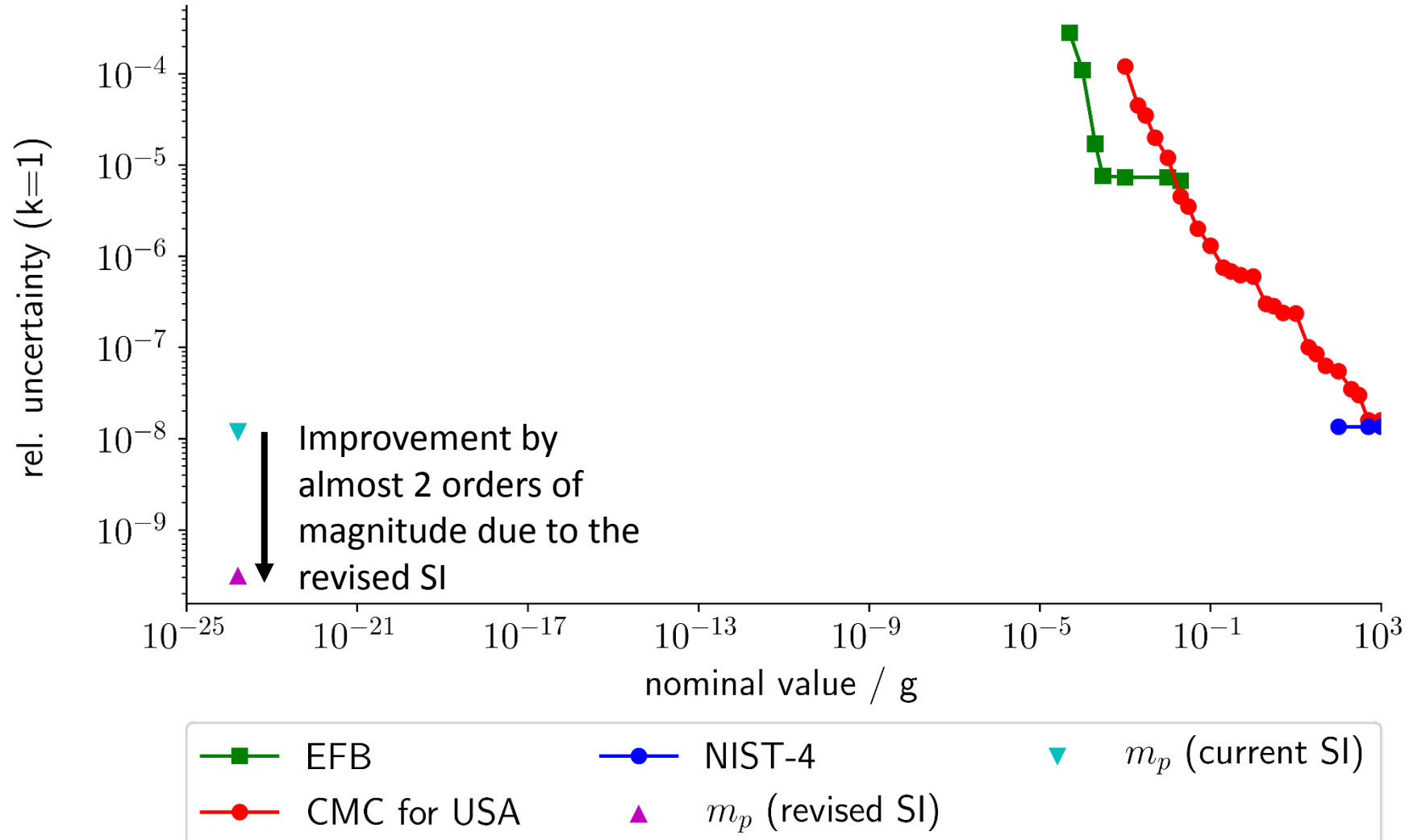
From a point to a scale invariant constant



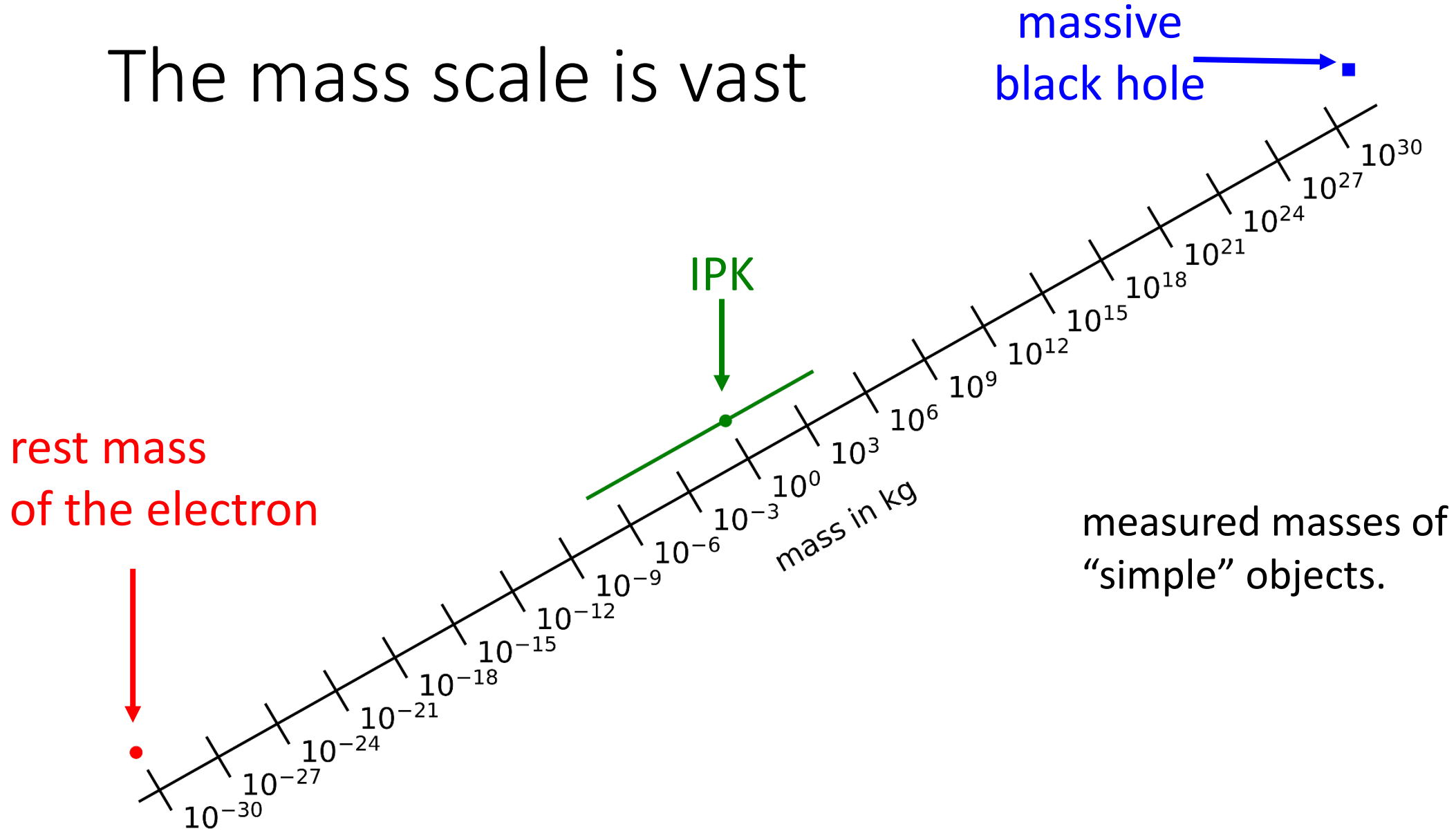
From a point to a scale invariant constant



From a point to a scale invariant constant

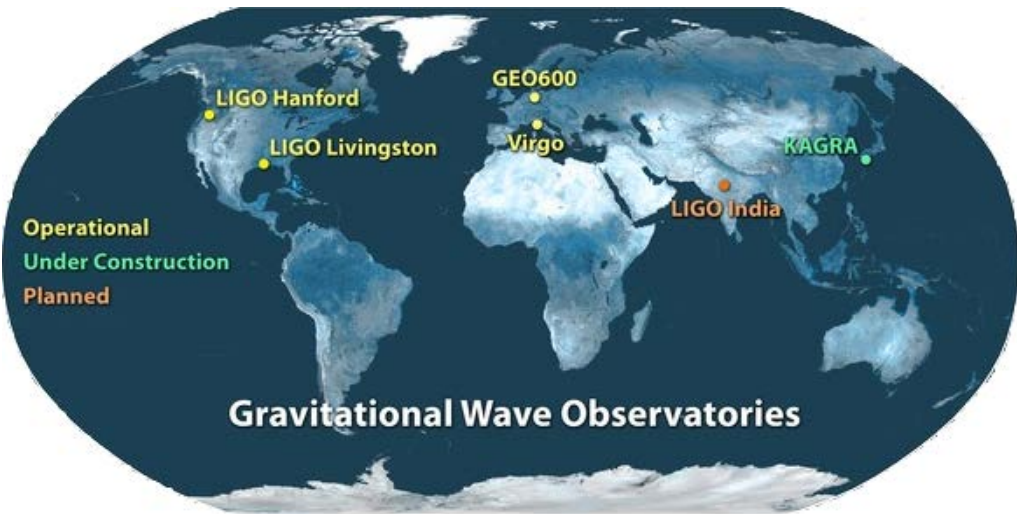


The mass scale is vast

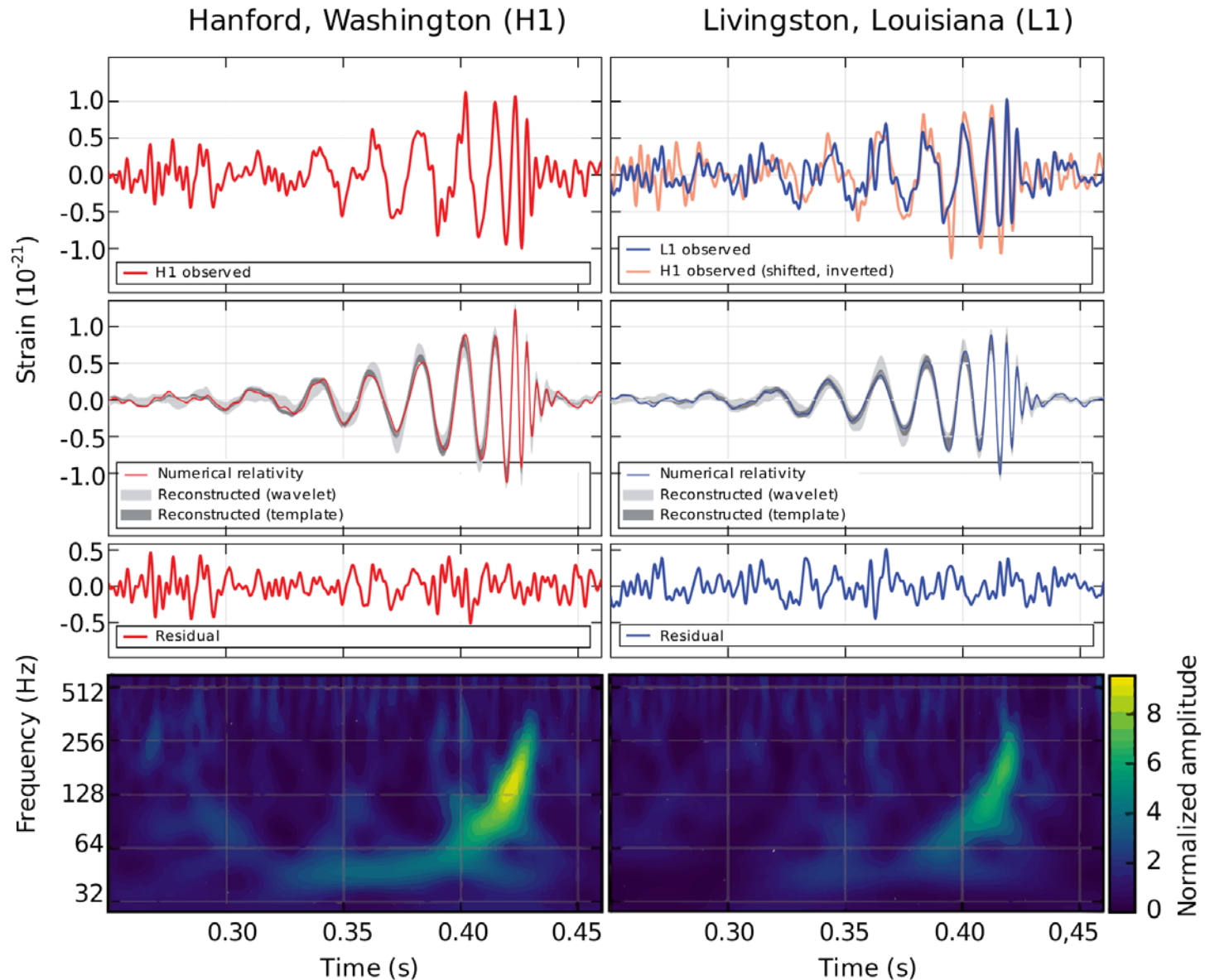


Weighing 29(4) solar masses

- $\approx 5.76(80) \times 10^{31}$ kg

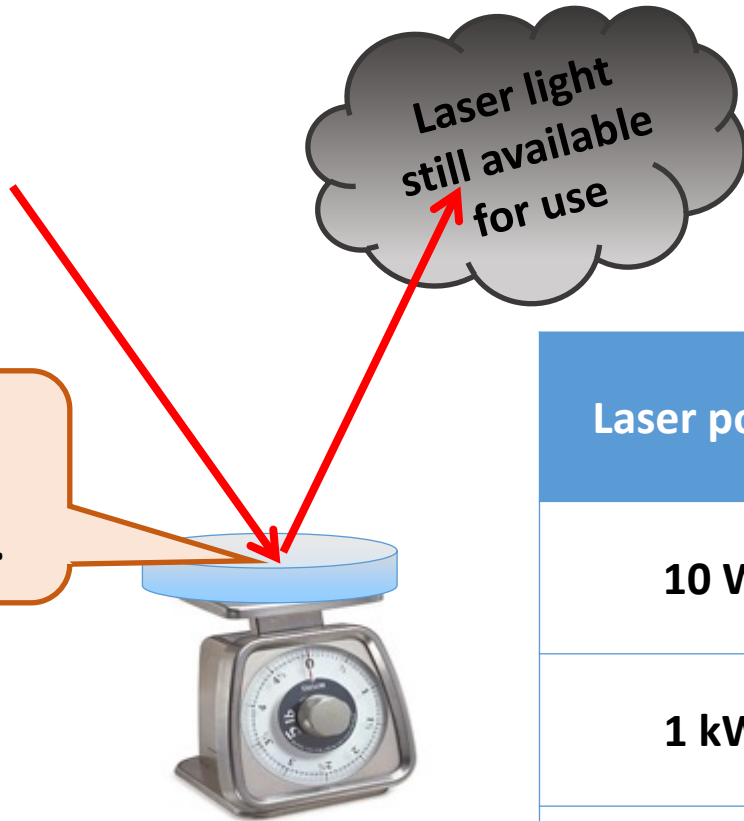


- Multiple gravitational wave detectors require consistent calibration.
- Calibration can be performed by photon pressure on the end mirror.
- Needs precise (10^{-4}) calibration of laser power.

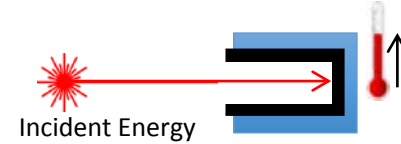


Concept: A precision scale with a mirror attached can measure the radiation force of light.

Minimal absorption, power-scalable, no thermal recovery time.



Traditional approach:
 Energy meter
 Absorption-based
 Energy $\propto \Delta T$

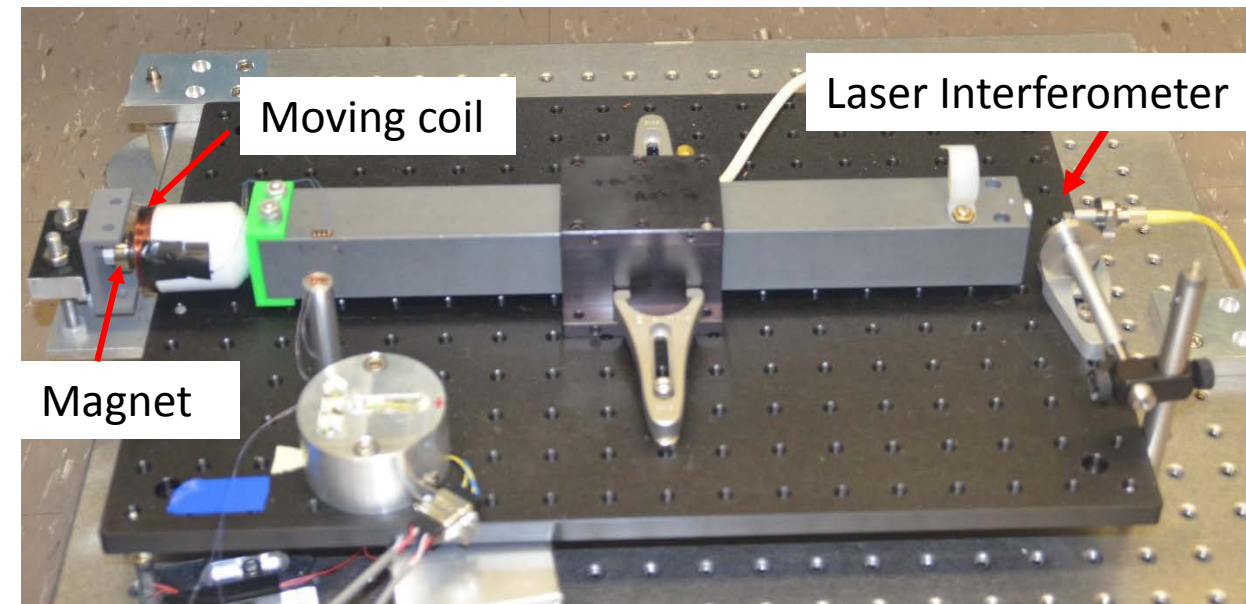


Calorimeter:
 Energy range: > 300 kJ
 Response time: *minutes*
 Size: *cubic meters*
 Weight: *hundreds of pounds*
 ~1% uncertainty

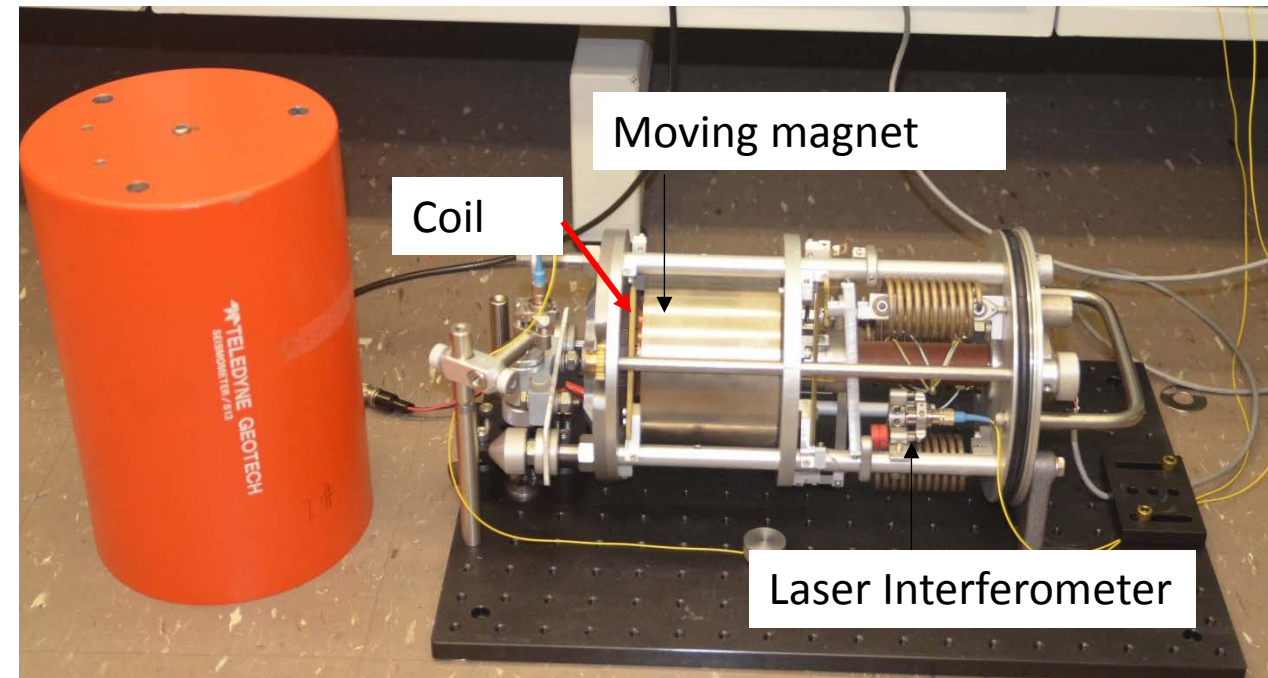
Laser power	Application	Equivalent mass	Object
10 W	Marking	6.7 microgram	eyelash
1 kW	Welding/Cutting	670 microgram	grain of sand
100 kW	Research / Defense	67 milligrams	two staples

The horizontal Kibble/electrostatic force balance

Air bearing setup



Seismometer suspension in horizontal plane



Ian Robinson:

The Kibble balance: measuring mass and related quantities in the revised SI

The future



- In three days time the Kibble balance will become a method for realising mass in the revised SI
- The method allows an NMI to make a contribution to a worldwide mass scale which is statistically independent of any other laboratory.
- All of the existing contributions to the determination of the Planck constant use balances which are physically large and have taken considerable times to develop and are not simple to operate.
- In general laboratory budgets are not increasing significantly.
- To generate further independent contributions to a robust, worldwide, mass scale smaller, simpler and cheaper Kibble balances are needed.

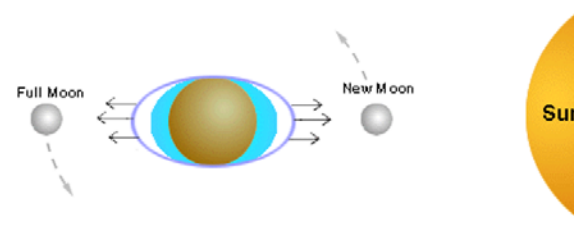


Vojtech Palinkas: Gravity measurements supporting Kibble balances

Gravity measurements supporting Kibble balances



Relations between „gravitational“, „gravity“ and „free-fall“ acceleration



Methods and technologies for „g“ determination in a Kibble balance

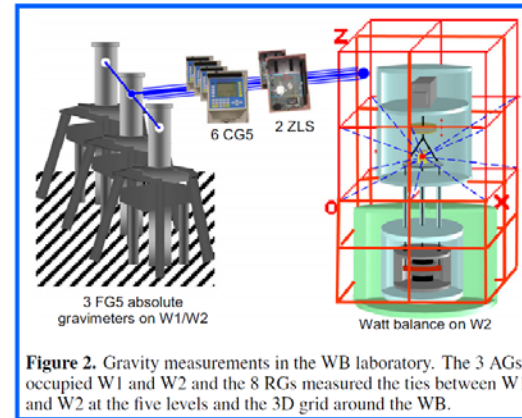
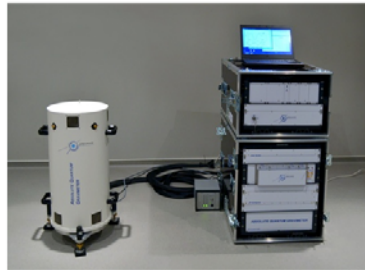
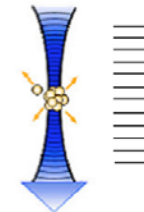
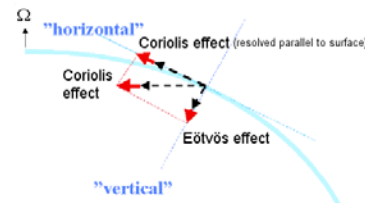
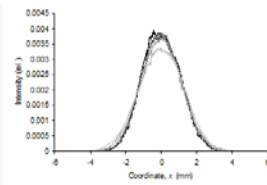
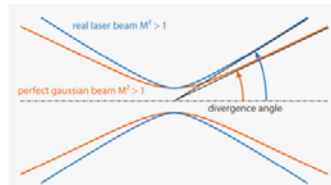


Figure 2. Gravity measurements in the WB laboratory. The 3 AGs occupied W1 and W2 and the 8 RGs measured the ties between W1 and W2 at the five levels and the 3D grid around the WB.

Uncertainty of „g“ measurements, key systematic effects



Horst Bettin:
Silicon spheres for the realization of the new kilogram definition

Silicon spheres for the realization
of the new kilogram definition



Horst Bettin, PTB Germany

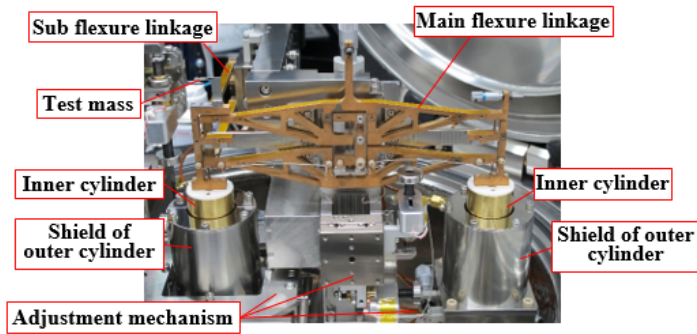


Kenichi Fujii:

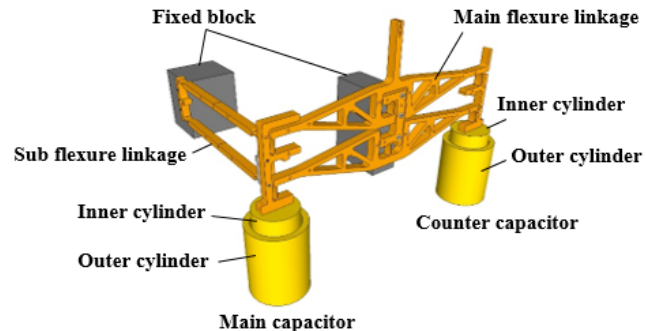
Realization of small mass, force and torque measurements based on the new definition of the kilogram

Voltage balance with MEMS technologies

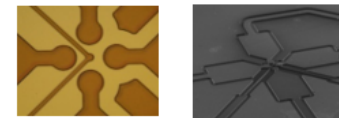
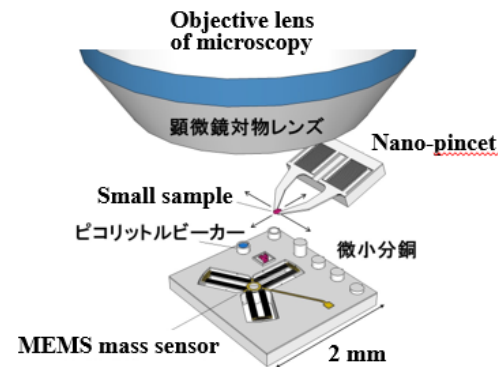
Nanogram region



Monolithic Roberval mechanism realized by flexure hinges



Picogram region

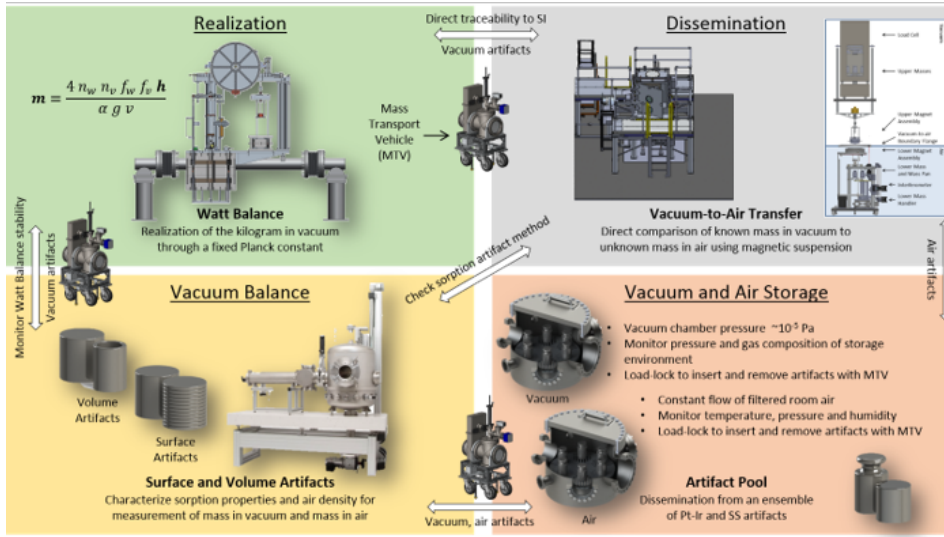


Photoregister SEM image
MEMS sensor

Small mass measurement under microscope using MEMS technologies

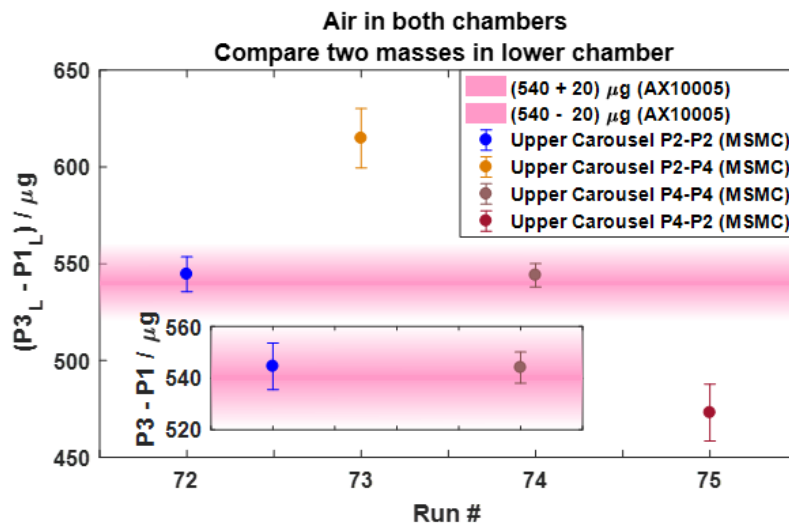
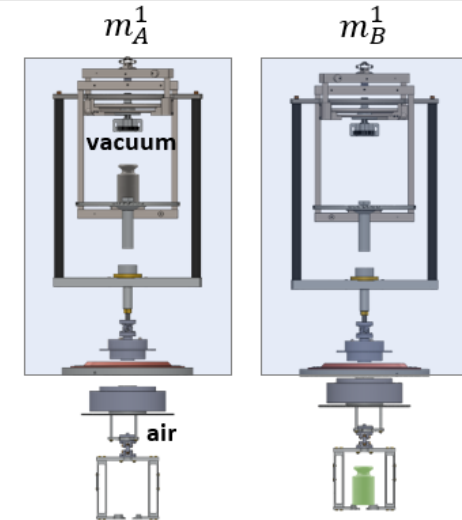
Y. Yamamoto, K. Fujita and K. Fujii: SI Traceable Small Mass Measurement Using the Voltage Balance Apparatus at NMIJ, CPEM 2018, July 8-13, 2018, Paris

Corey Stambaugh: The NIST Magnetic Suspension Mass Comparator for Vacuum-to-Air Transfer of the Unit of Mass: Current Status



Magnetic Suspension Mass Comparator

Goal: Direct comparison of a known mass in vacuum (top) to unknown mass in air (bottom) with a standard ($k=1$) uncertainty that allows dissemination at the OIML E1 class weight level for 1 kg mass.



Main themes to be discussed in Friday's Talk:

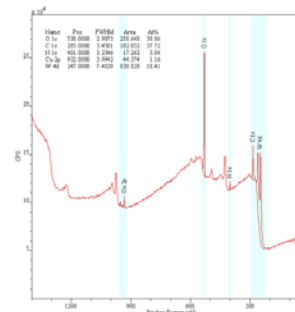
- Magnetic Suspension does NOT affect the stability of a mass reading. Mass readings stable to below balance resolution.
- Magnetic interactions or force transduction errors have proven to be more challenging than desired. However, these interactions can be taken into account.

Corey Stambaugh (Project Lead), Z. Kubarych (Group Leader), P. Abbott, E. Mulhern, N. Vljic, M. Berilla, M. Davis, E. Benck

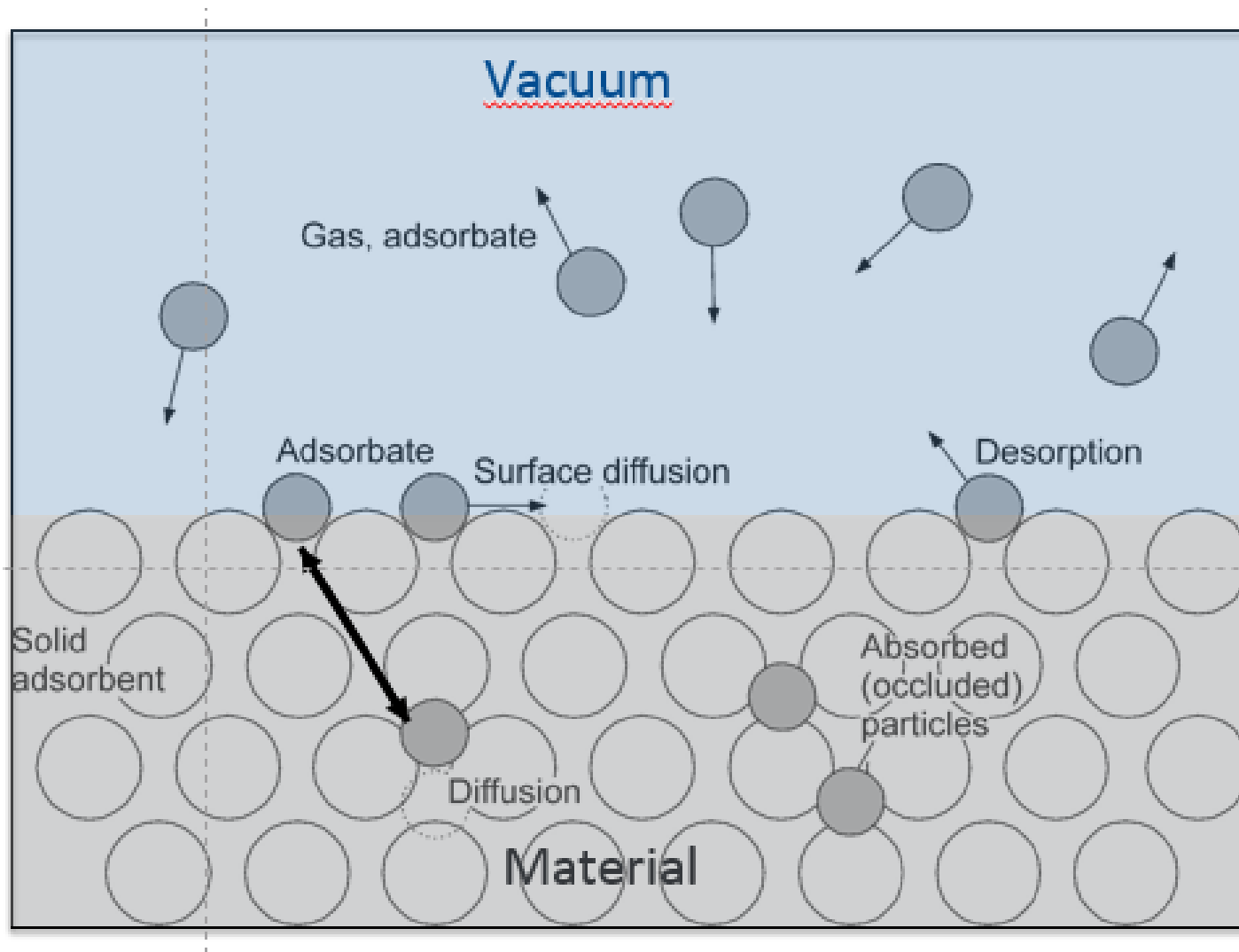
Stuart Davidson: Real-time contamination monitoring on mass standards stored in inert gas

Summary

- Careful storage of mass standards is critical for;
 - Stability of national standards at NMIs
 - Maintenance of the mass scale between key comparisons of realization experiments
 - Continuity of access to the mass scale disseminated from (individual) realizations
- Storage in inert gas has been shown to improve the medium to long-term stability
- A relatively simple apparatus for storage of mass standards in inert gas has been developed
- Real time monitoring of surface contamination by QCM (Sauerbrey equation applied)
- XPS can be used pre- and post-storage to validate QCM measurements and characterise surface accretion



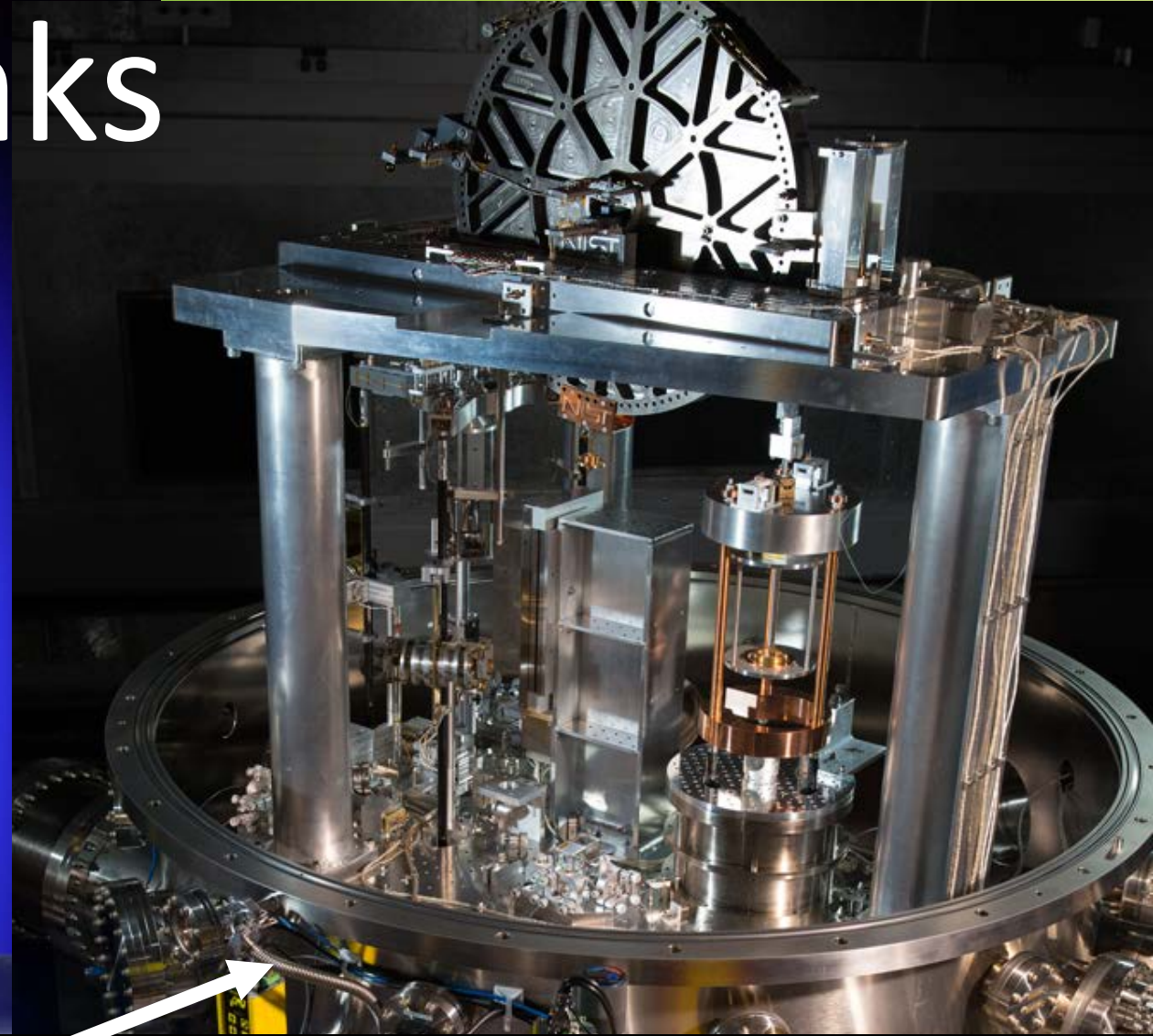
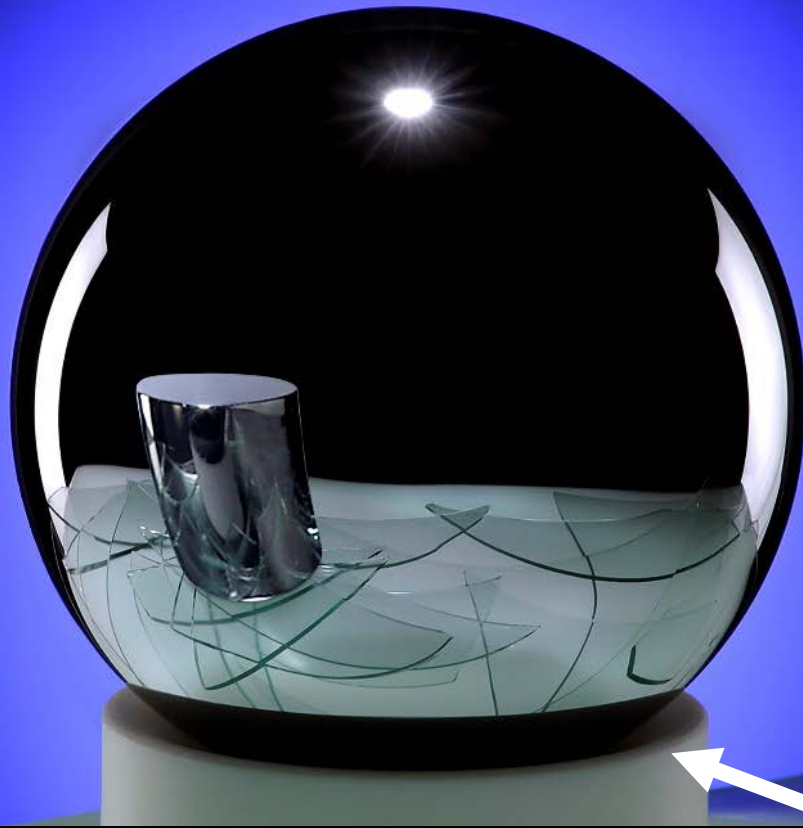
Karl Jousten:
Traceable desorption and outgassing rate measurements



Challenges and opportunities

- It will a while until the scale will be freed from the cardinal point at 1 kg
- laser power outside scope of CCM
- Let's shoot for the stars!
- Kibble/electrostatic balances for quantities other than mass: force, torque, laser power
- Let's expand the range of KBs/EFBs to small masses
- Collaborations between CCs

Thanks



Time machines

you work on these and 10 years feel like 1 year!