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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Consultative Committee for Mass and Related Quantities

Sevres, France


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Outline – Three mysteries

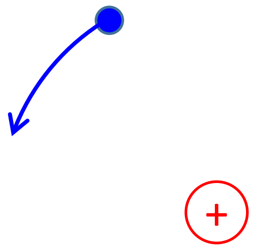
- The mystery of mass
- The mystery of explaining the unit of mass
- The mystery of what’s next

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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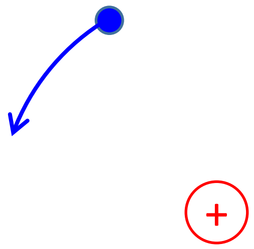

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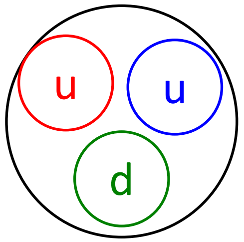
- Example: proton



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

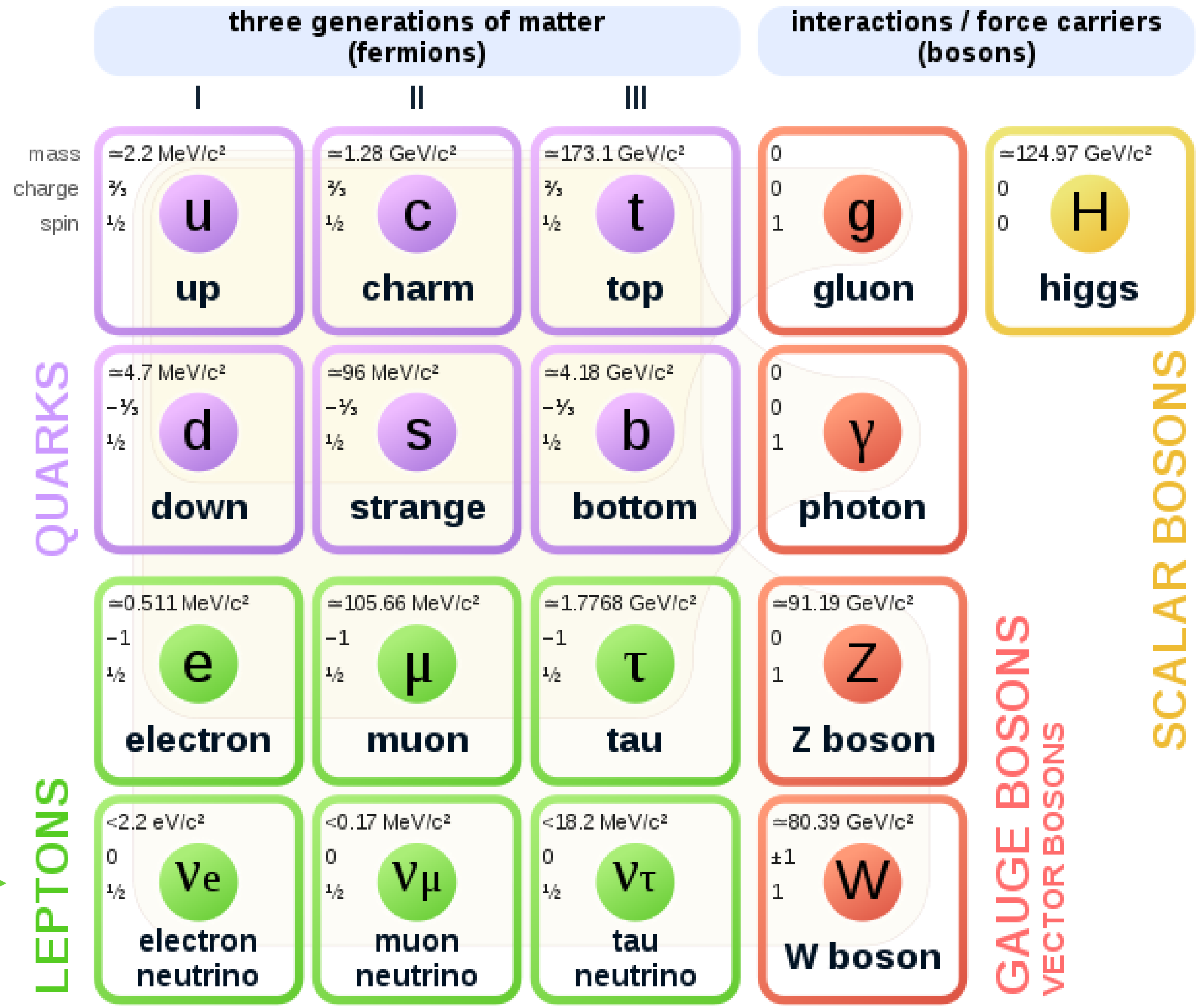
$$m_u = 2.2\ \mathrm{MeV/c^2}$$

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

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

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

Standard Model of Elementary Particles

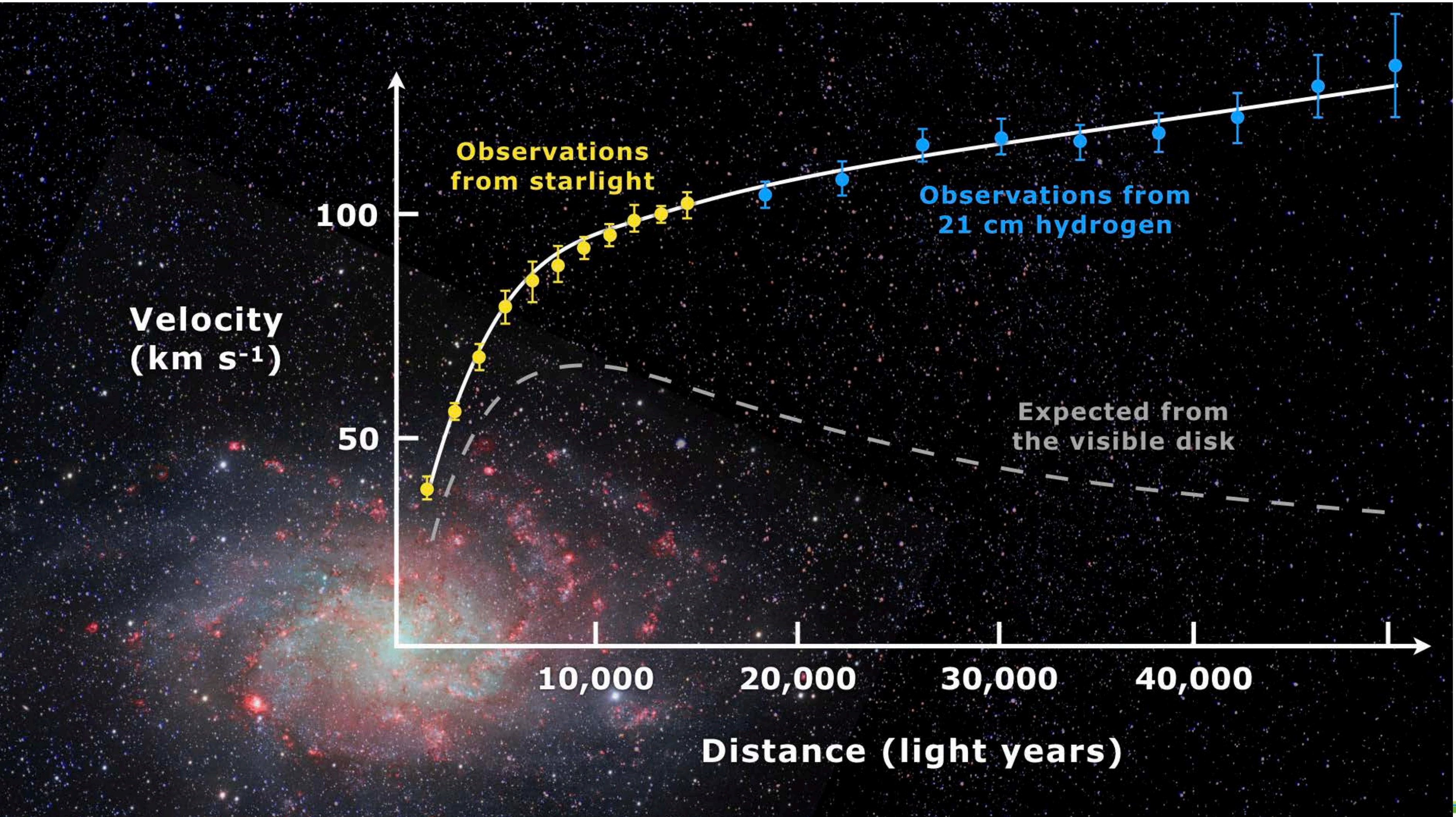


Generates masses of the leptons, the quarks,
and the weak gauge bosons.
The existences of the Higgs boson was confirmed in 2012.

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

source: wikipedia

At large scales, mass is weird



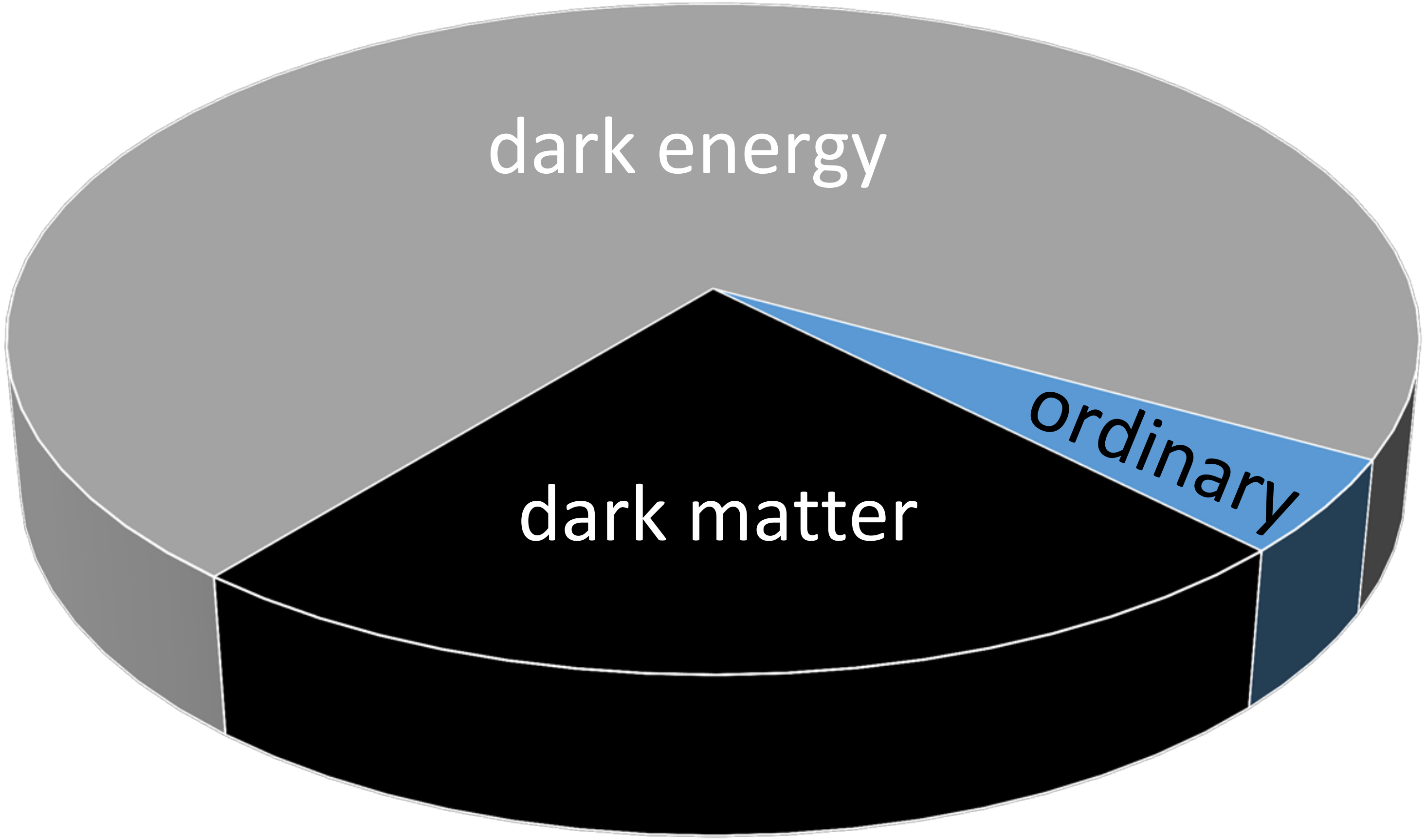
The rotation curves of galaxies (here M33) does not follow our expectation (based on the visible baryonic matter).

dark matter

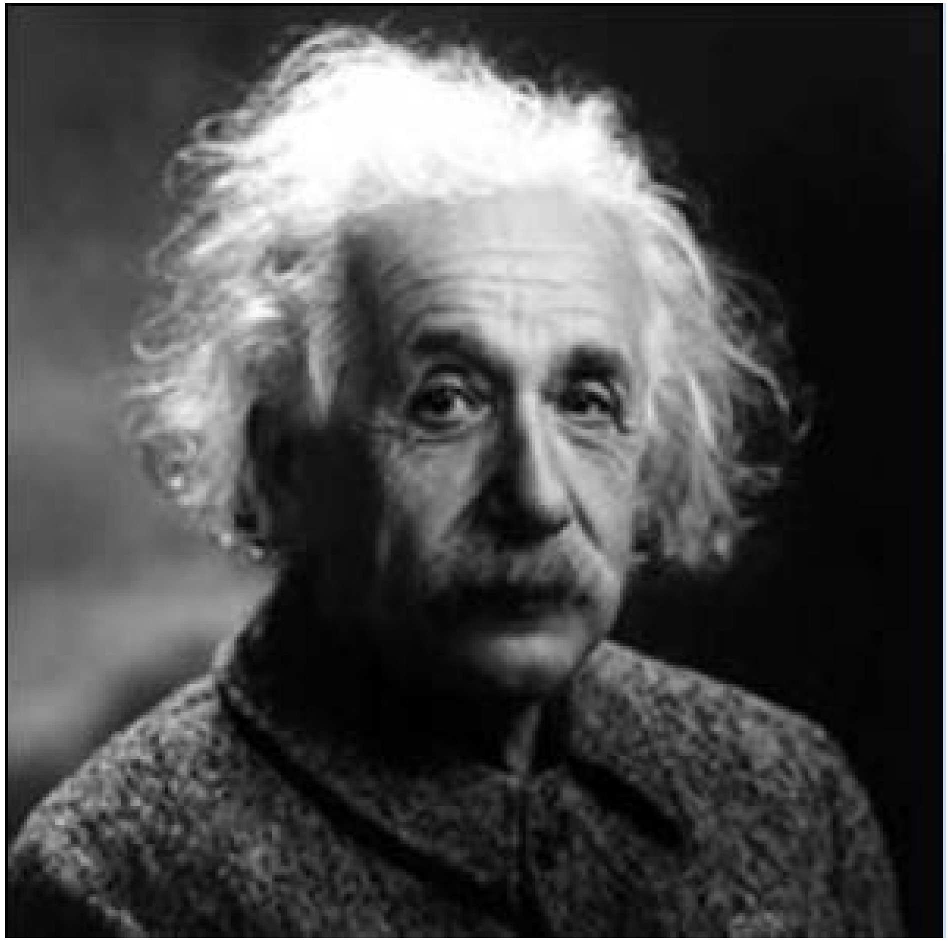
It get's worse

- 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



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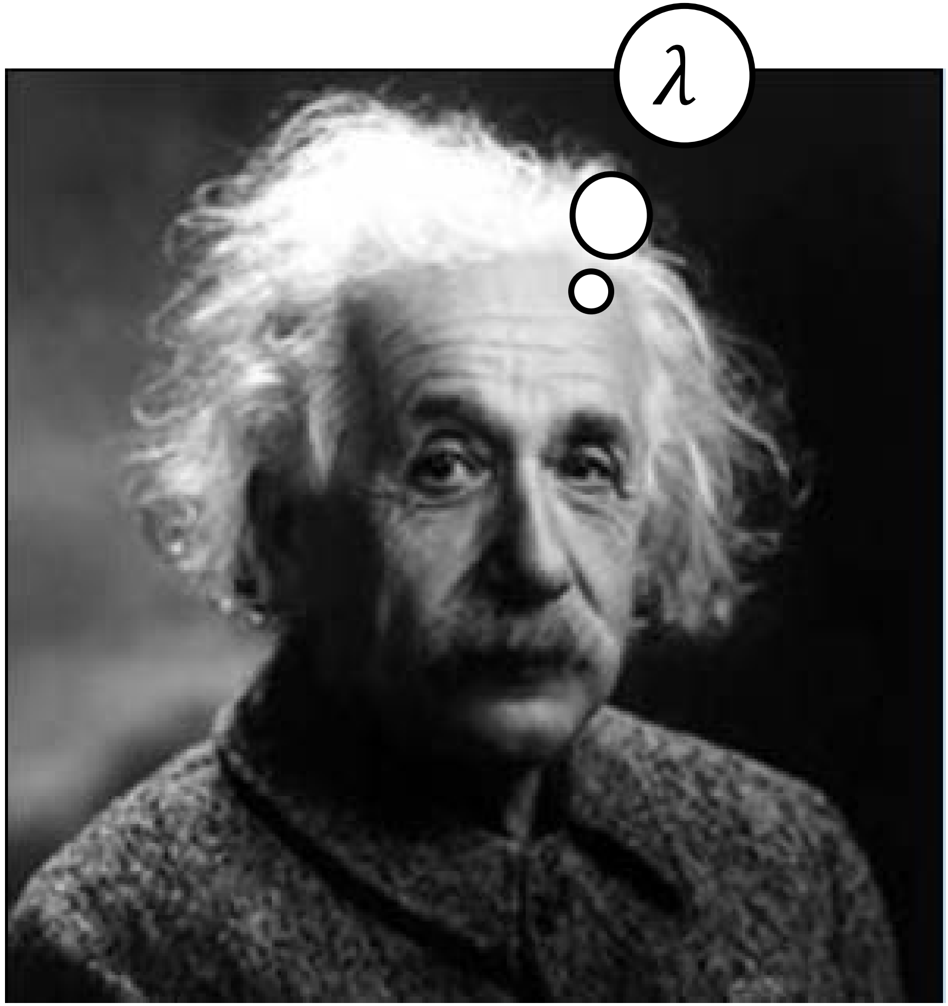
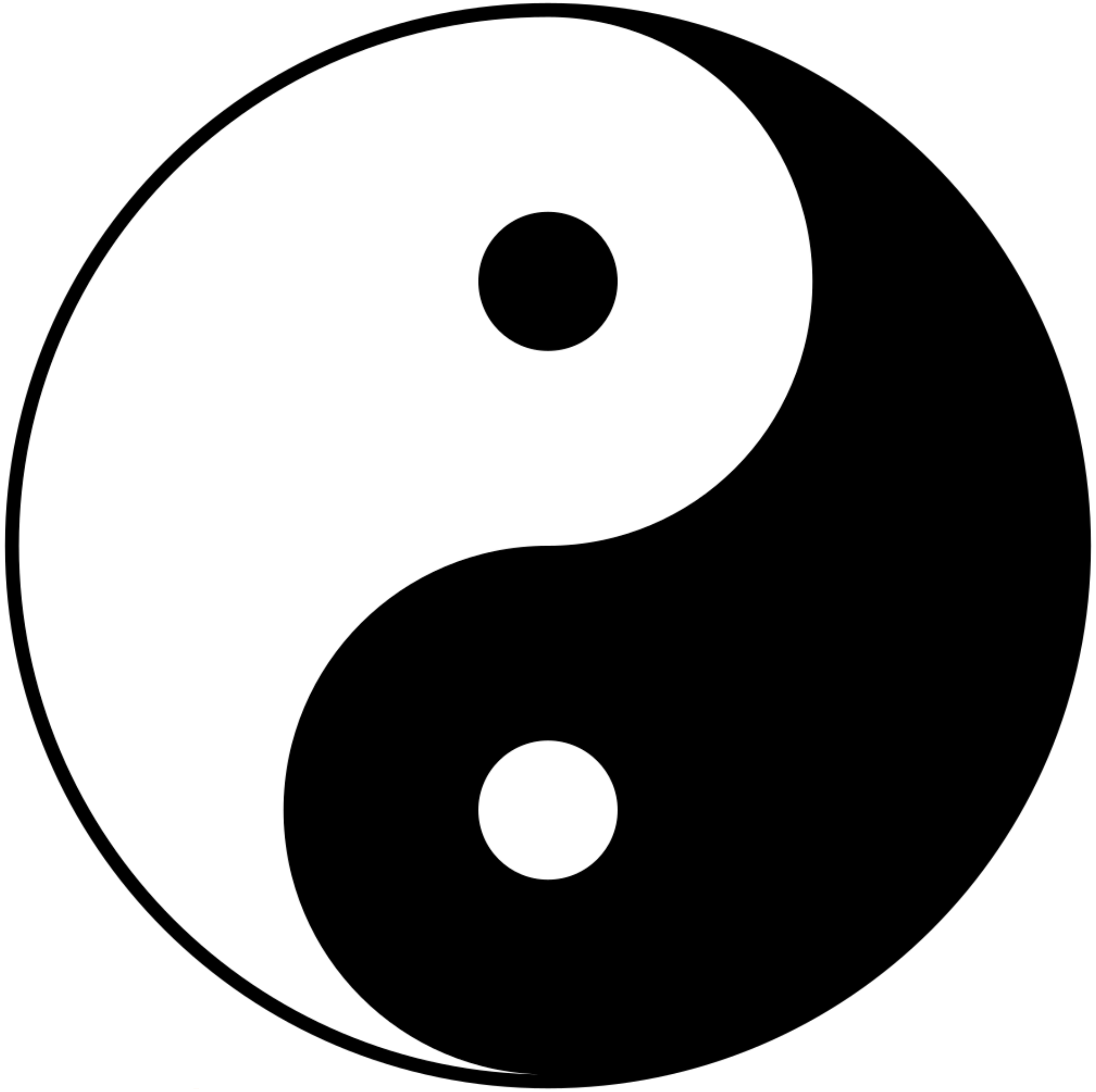


Physics Metrology



Challenges and opportunities

- We are far from understanding mass
- Mass is complicated

- Many important questions in physic 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 level
- 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	$299\,792\,458$	$\mathrm{m\ s}^{-1}$	1
3	kg	Planck constant	h	$6.626\,070\,15 \times 10^{-34}$	$\mathrm{kg\ m}^2\ \mathrm{s}^{-1}$	2
4	A	elementary charge	e	$1.602\,176\,634 \times 10^{-19}$	$\mathrm{A\ s}$	1
5	K	Boltzmann constant	k	$1.380\,649 \times 10^{-23}$	$\mathrm{kg\ m}^2\ \mathrm{s}^{-1}\mathrm{K}^{-1}$	3
6	mol	Avogadro constant	N_A	$6.022\,140\,86 \times 10^{23}$	mol^{-1}	0
7	cd	luminous efficacy	K_{cd}	683	$\mathrm{lm\ s}^3\ \mathrm{kg}^{-1}\mathrm{m}^{-2}$	3

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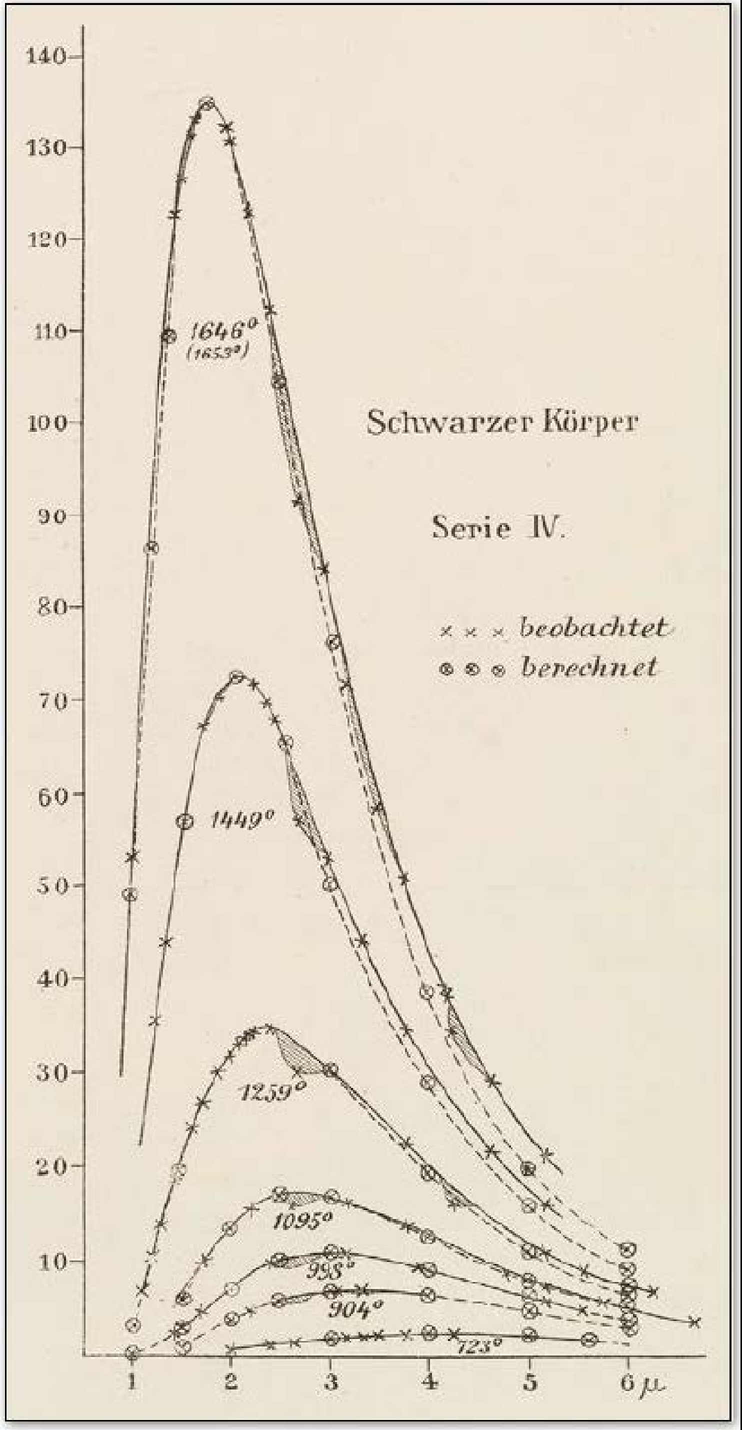
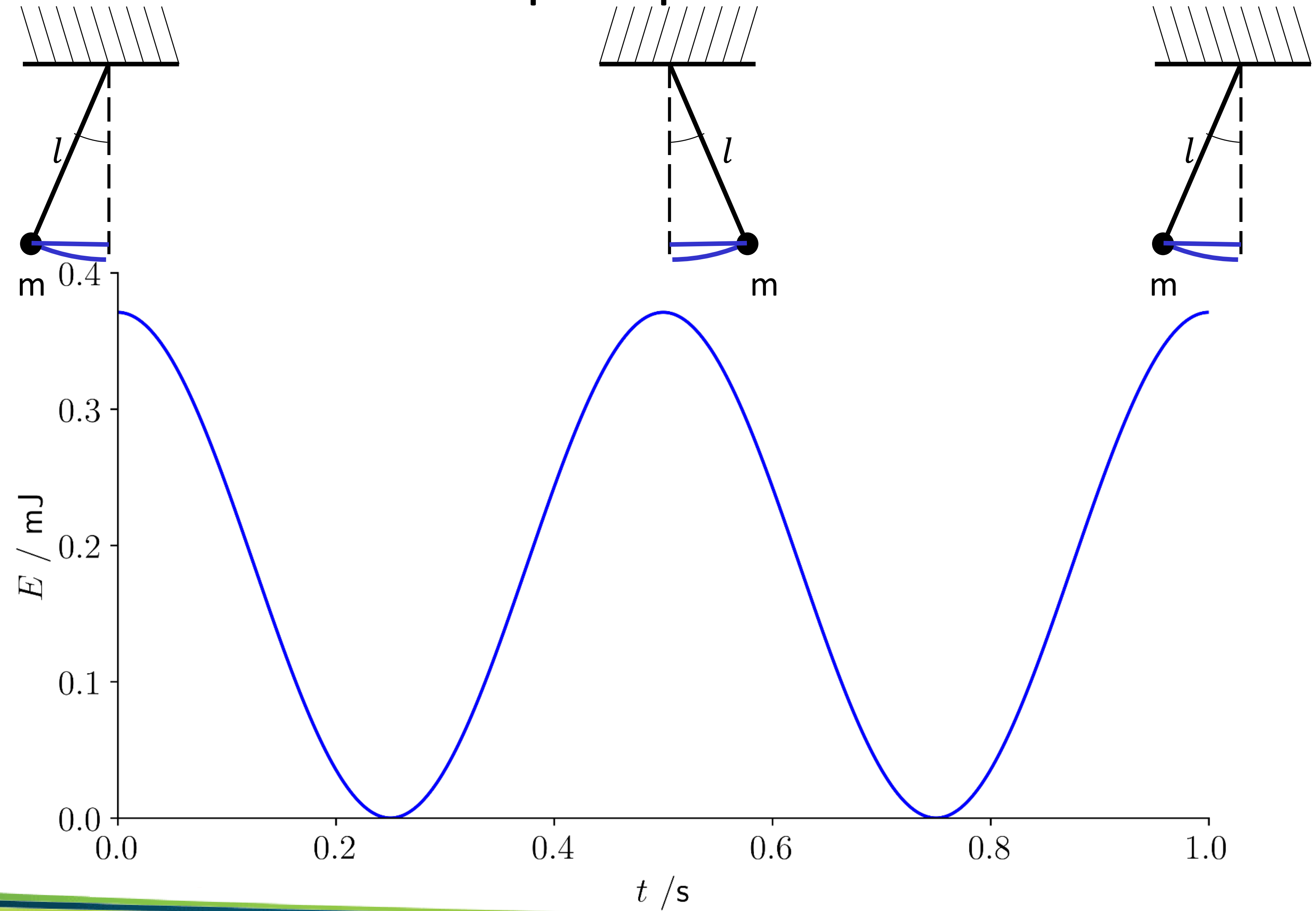


h

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

Consider the simple pendulum



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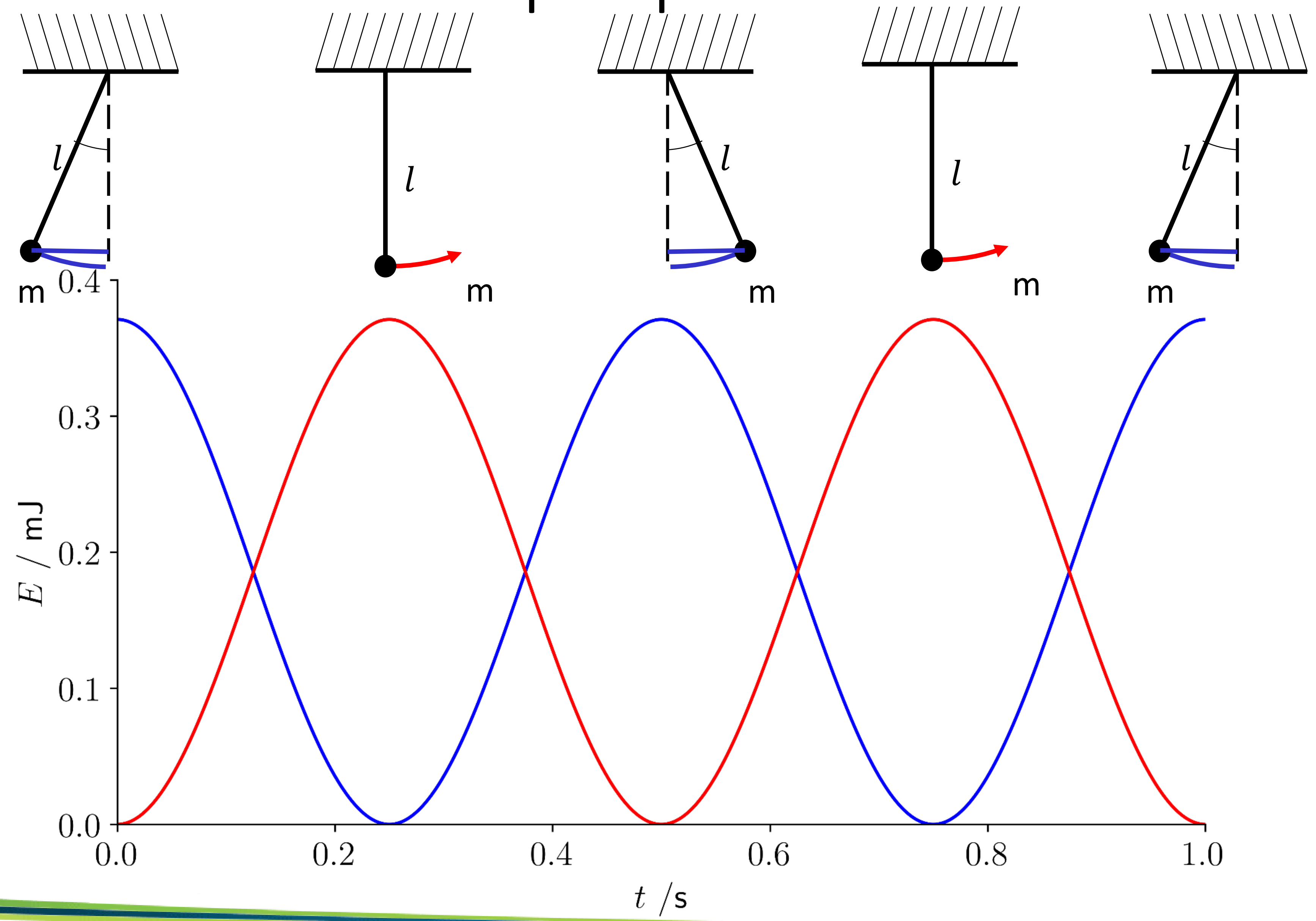

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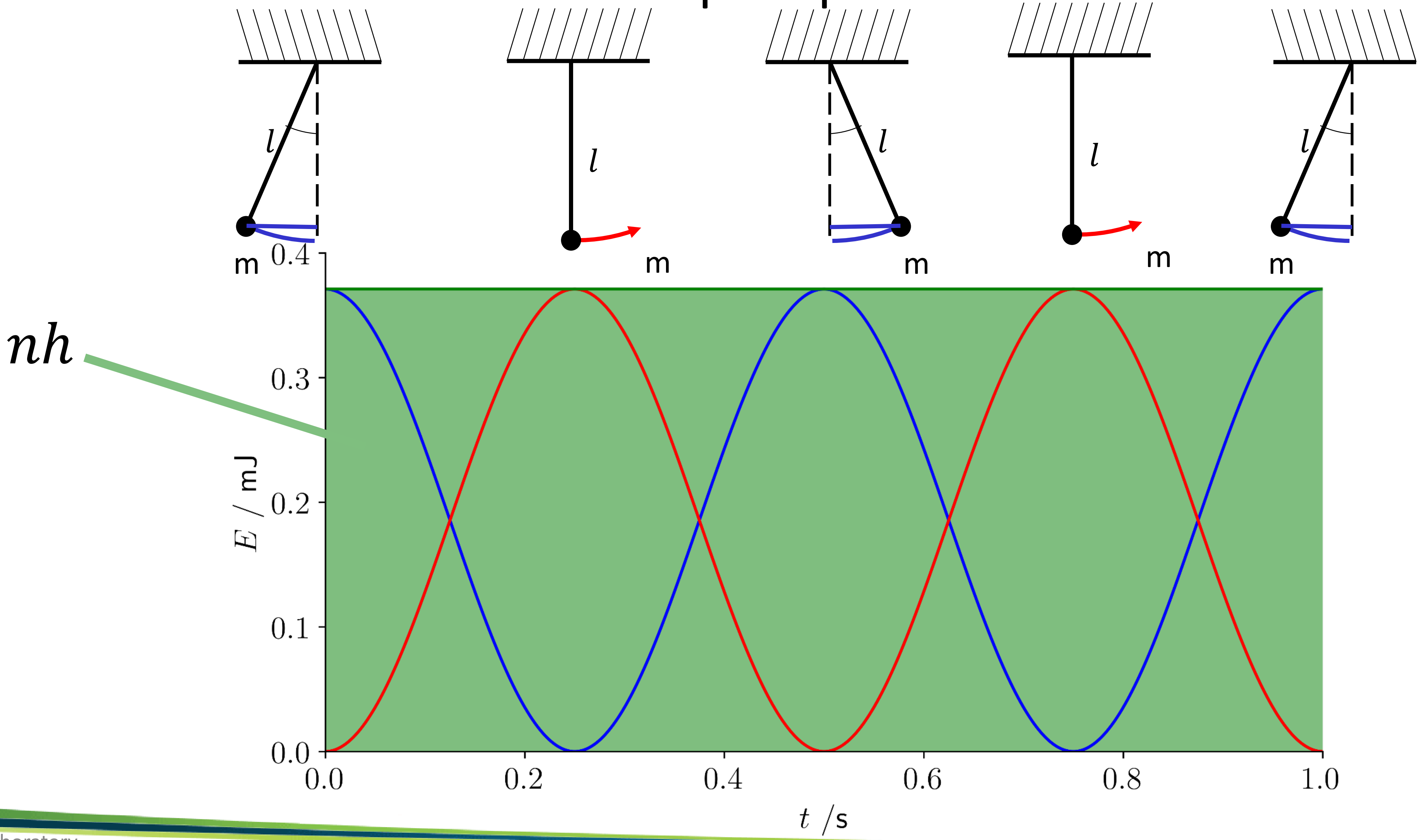

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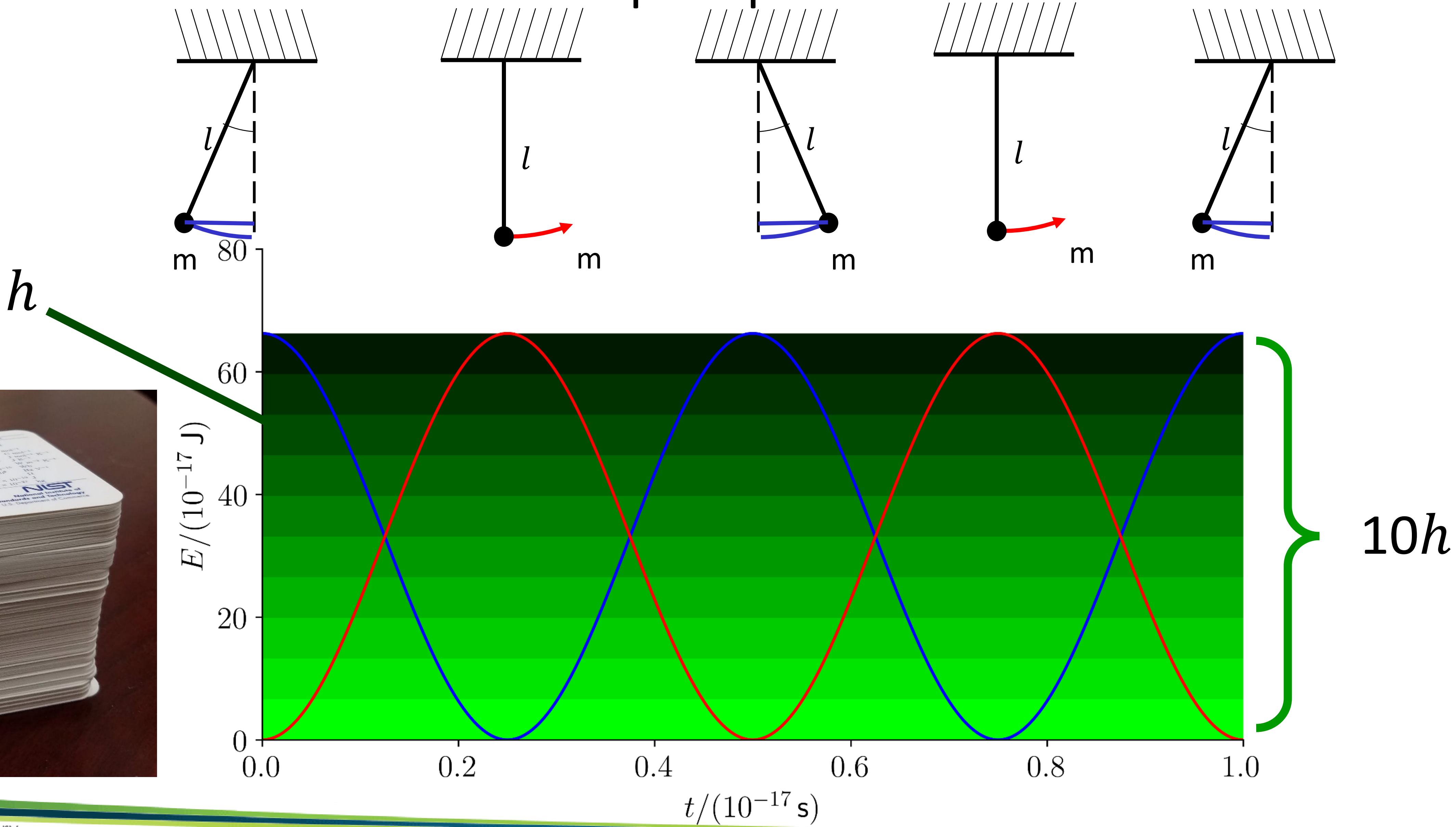

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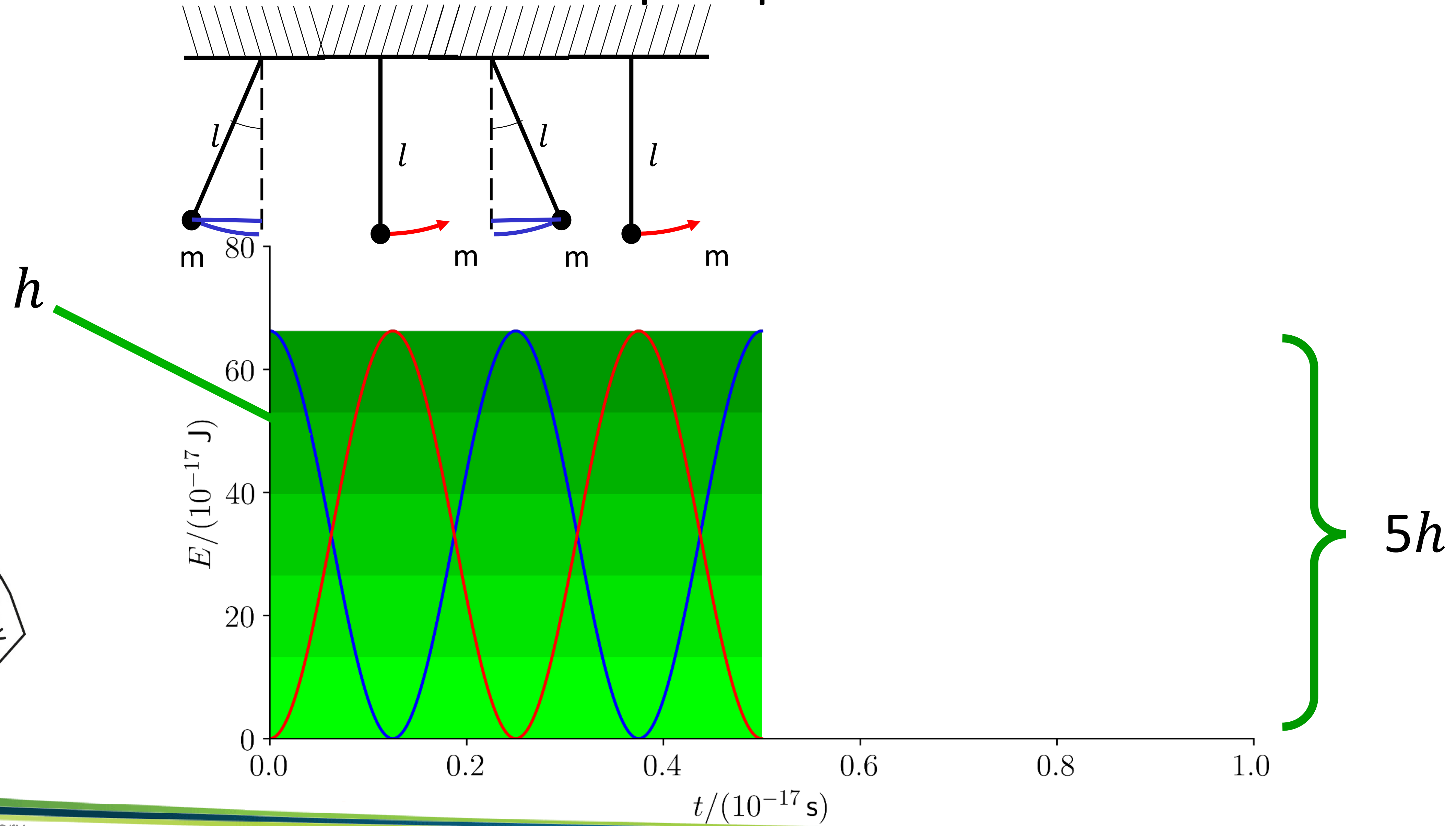

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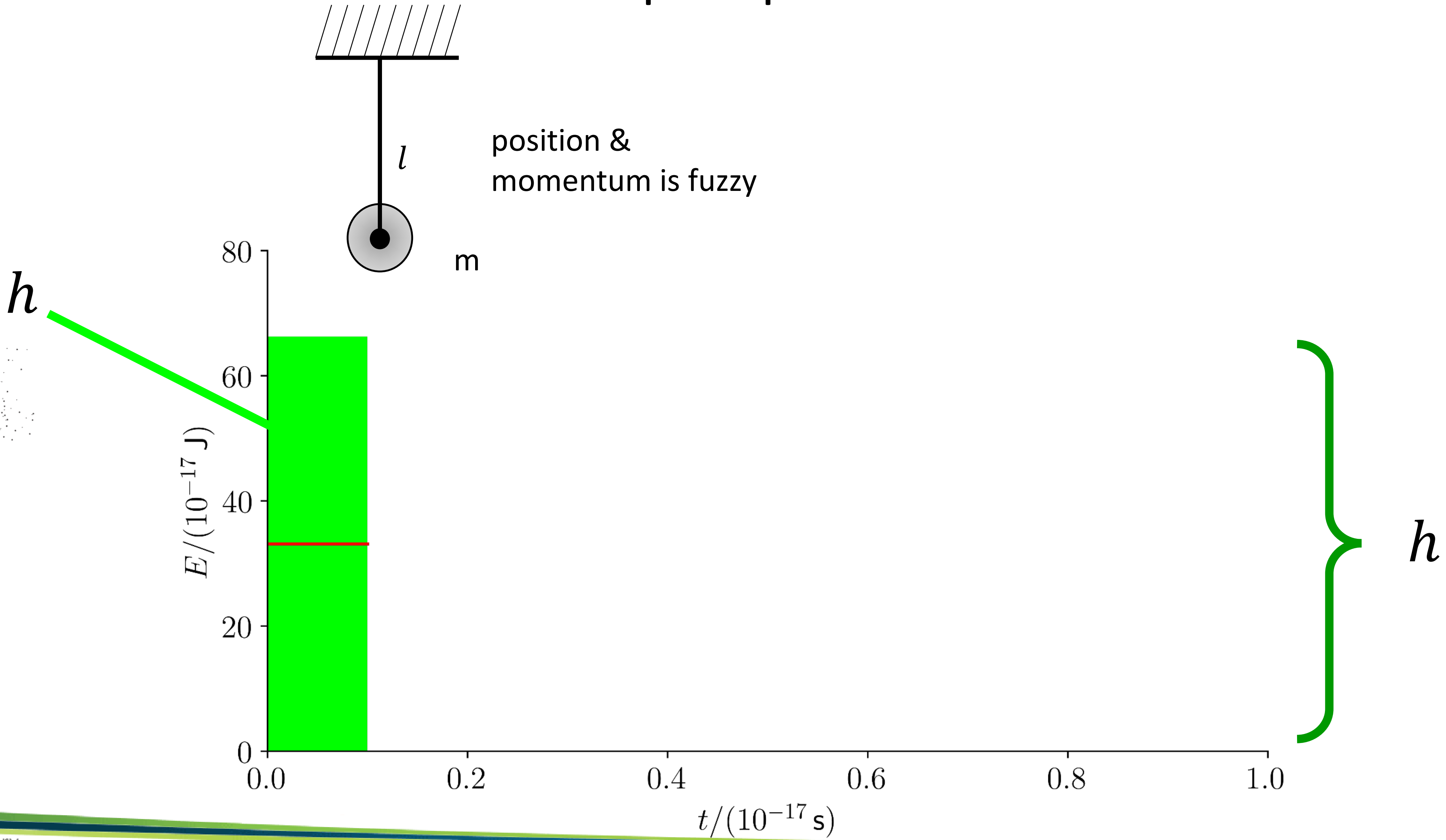


quantum mechanics

classical mechanics

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

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

$$\lambda_{DB} > d$$

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

$$\lambda_{DB} < d$$

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

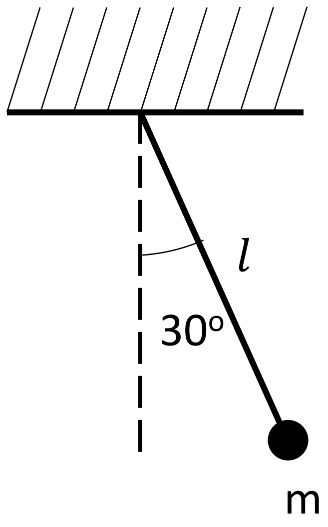
h is here

kg is here

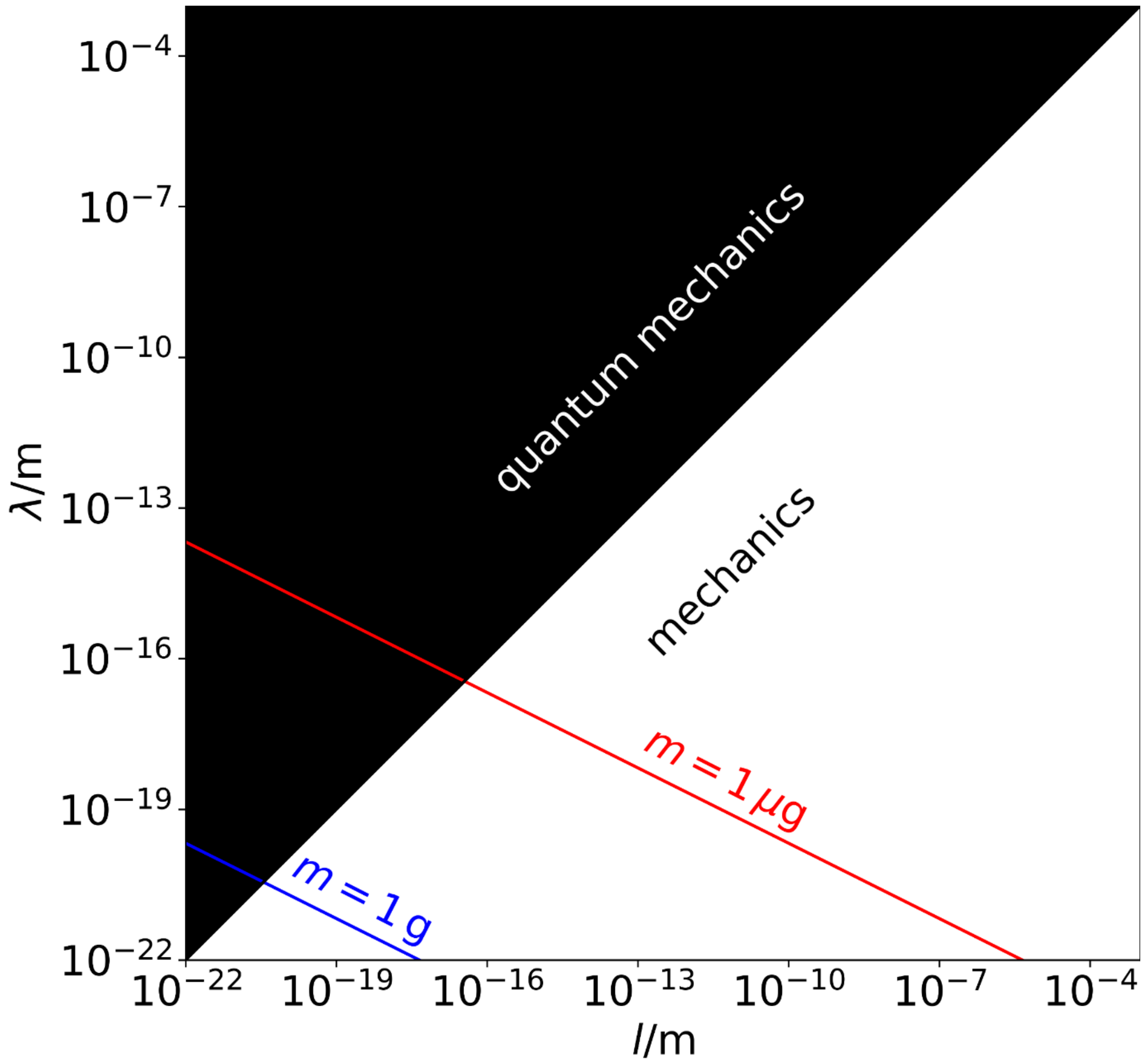
DeBroglie wavelength

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

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
- $m_\mathrm{e} \propto h$
- $M = n \cdot N_A \cdot r \cdot m_\mathrm{e}$

X-**R**ay **C**rystal **D**ensity Method (XRCD)

- Quantum electrical standards
- $R_K = \frac{h}{e^2}$ & $K_J = \frac{h}{2e}$
- $\frac{K_J^2}{R_K} = \frac{h}{4}$
- $P_{el} = P_{mech}$

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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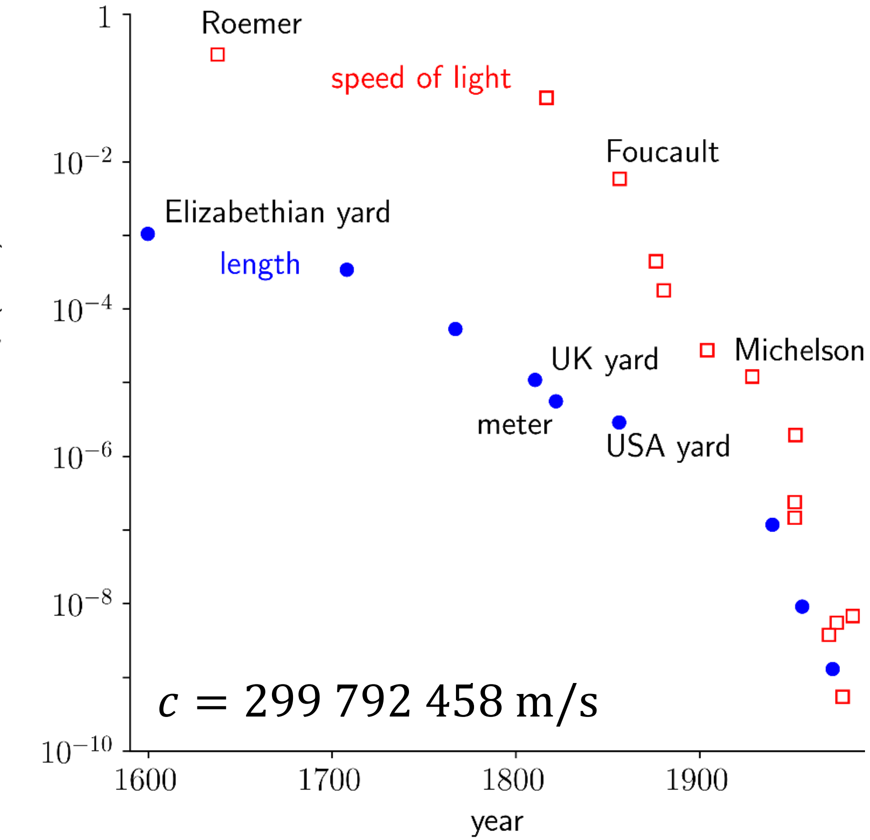
From a fixed point to a scale-invariant constant

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



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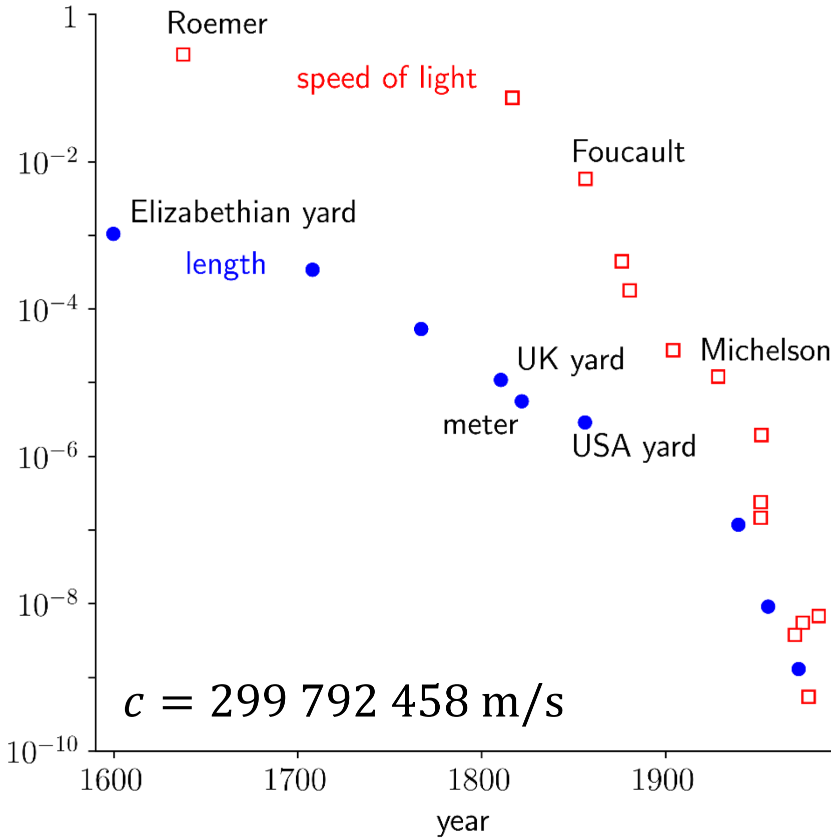

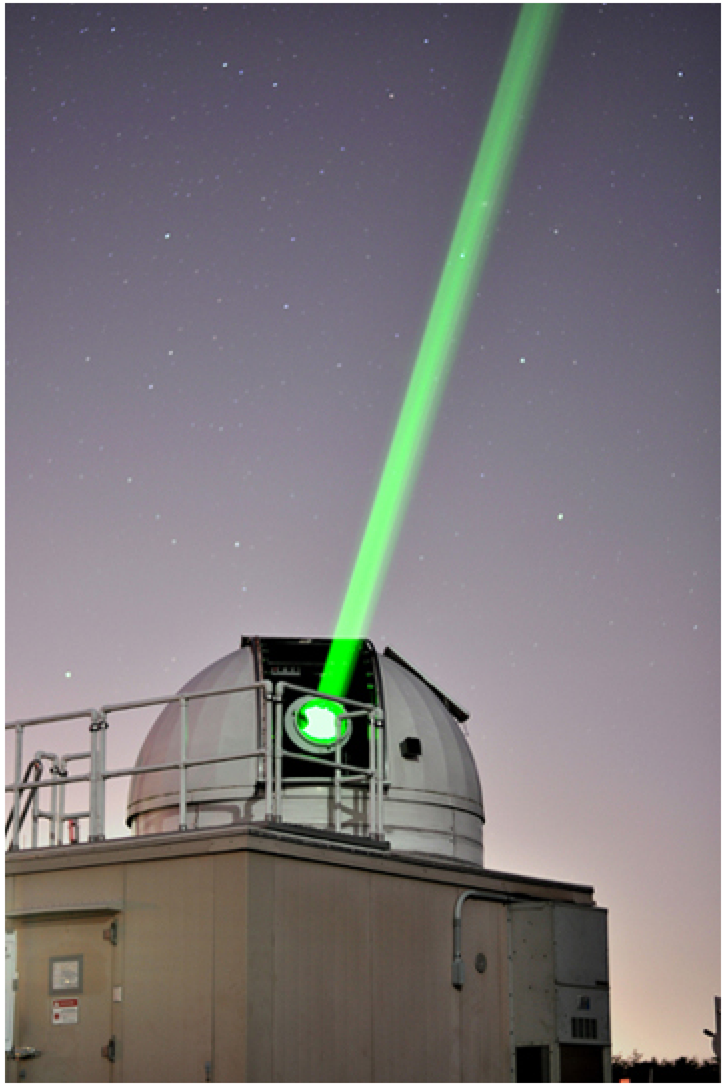

https://space-geodesy.nasa.gov/NSGN/sites/GGAO/GGAO_photos.html

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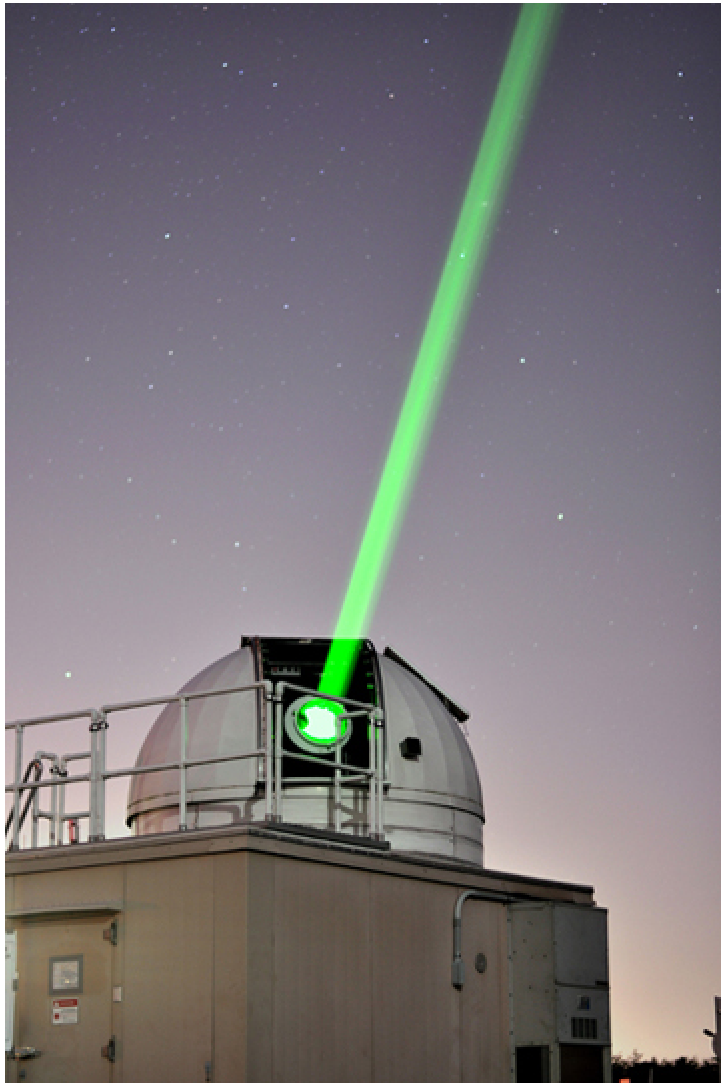

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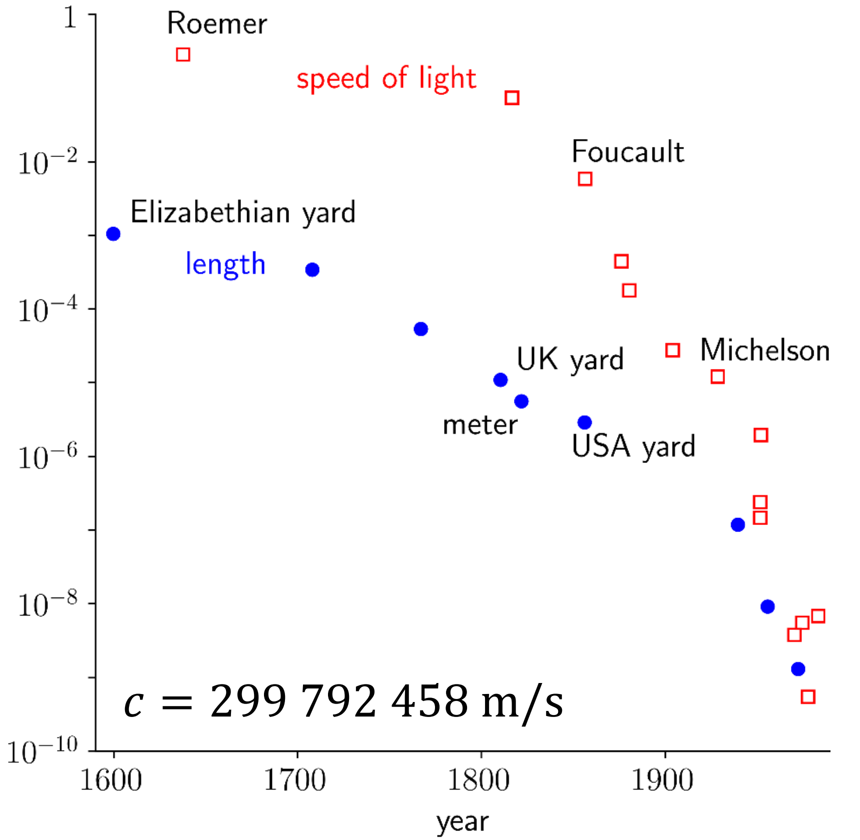

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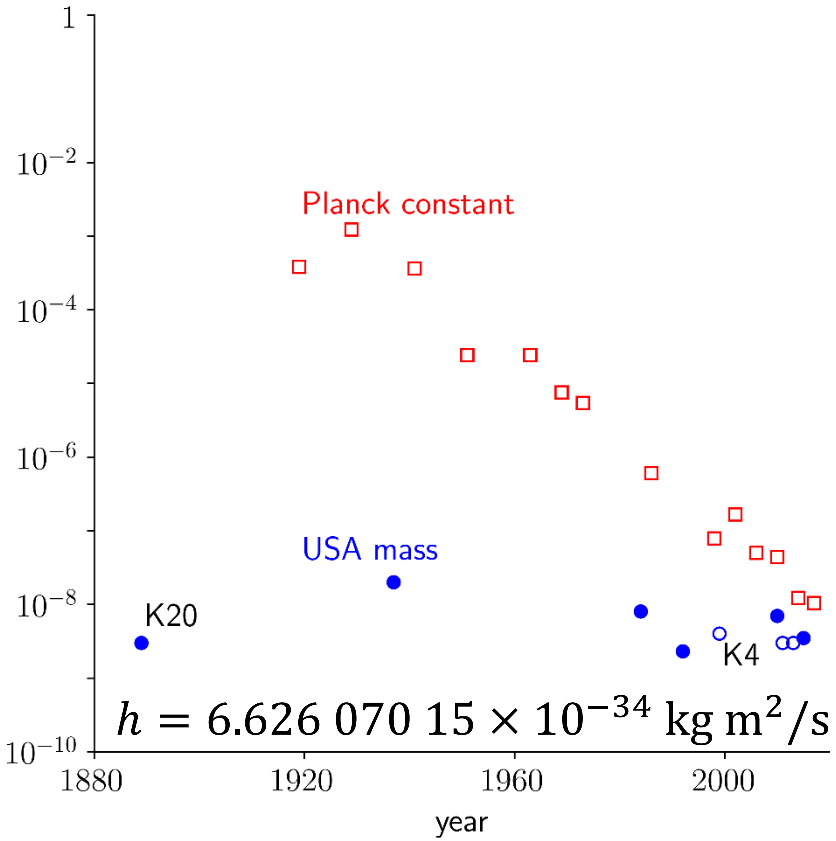

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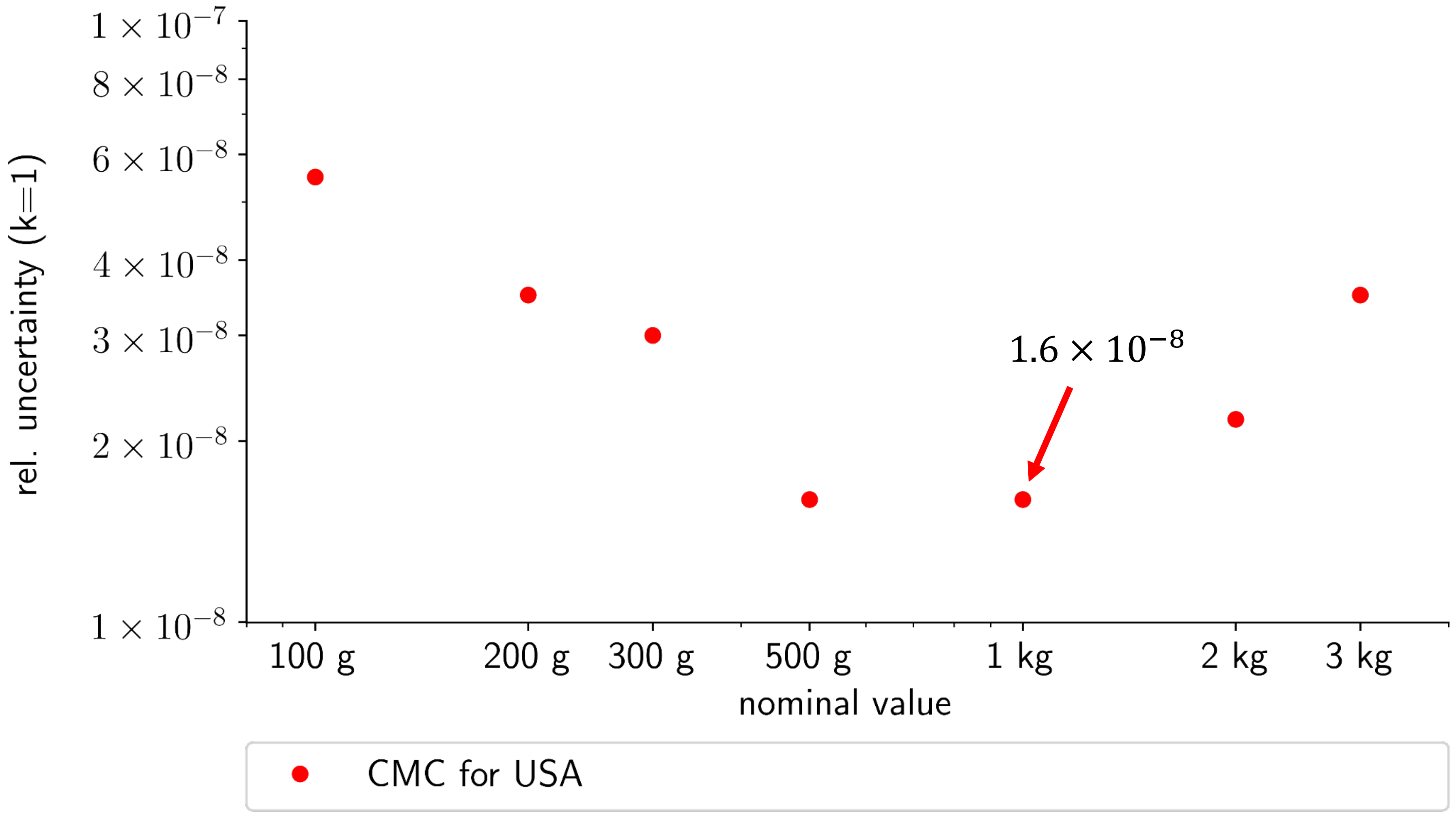

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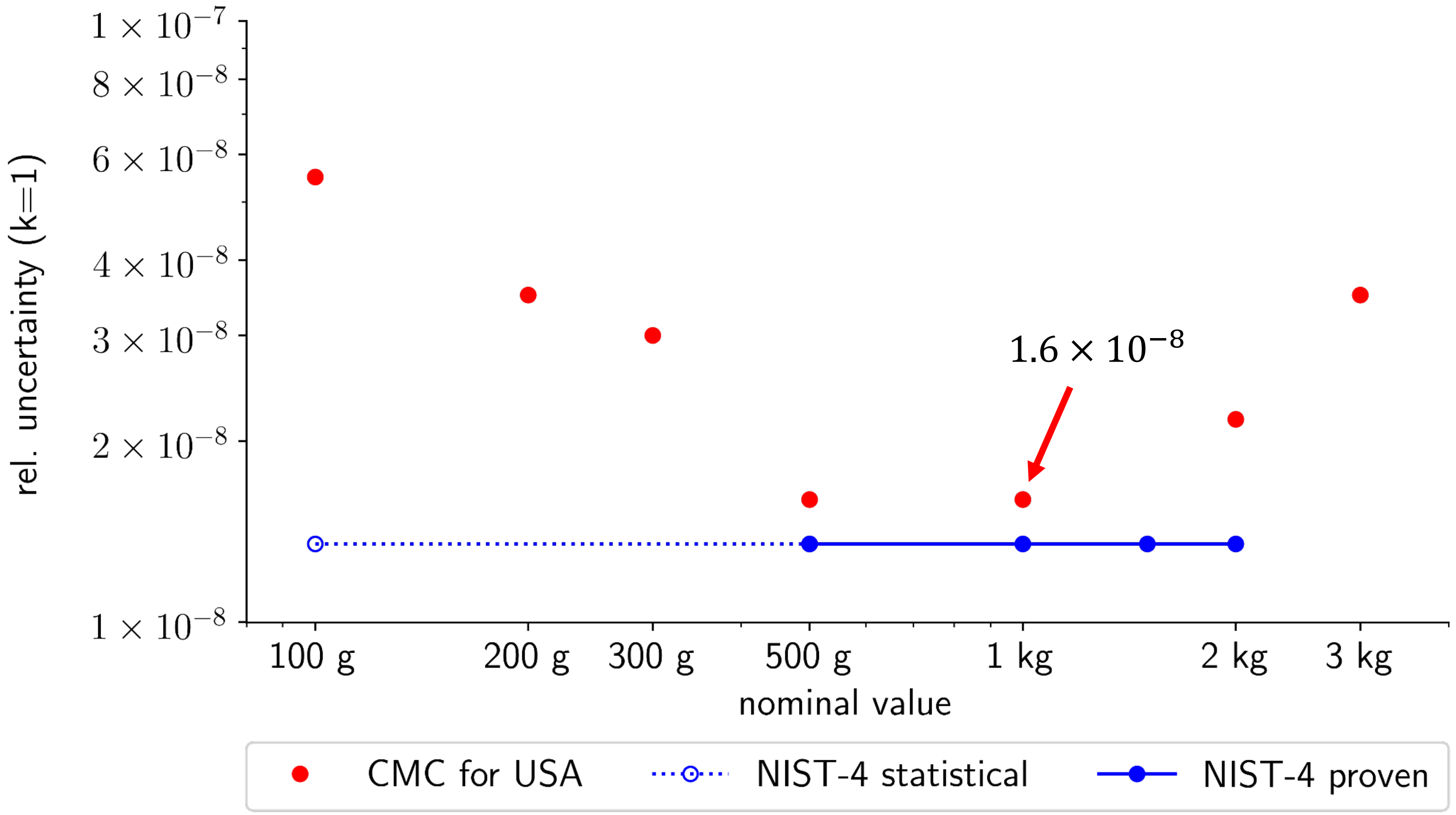

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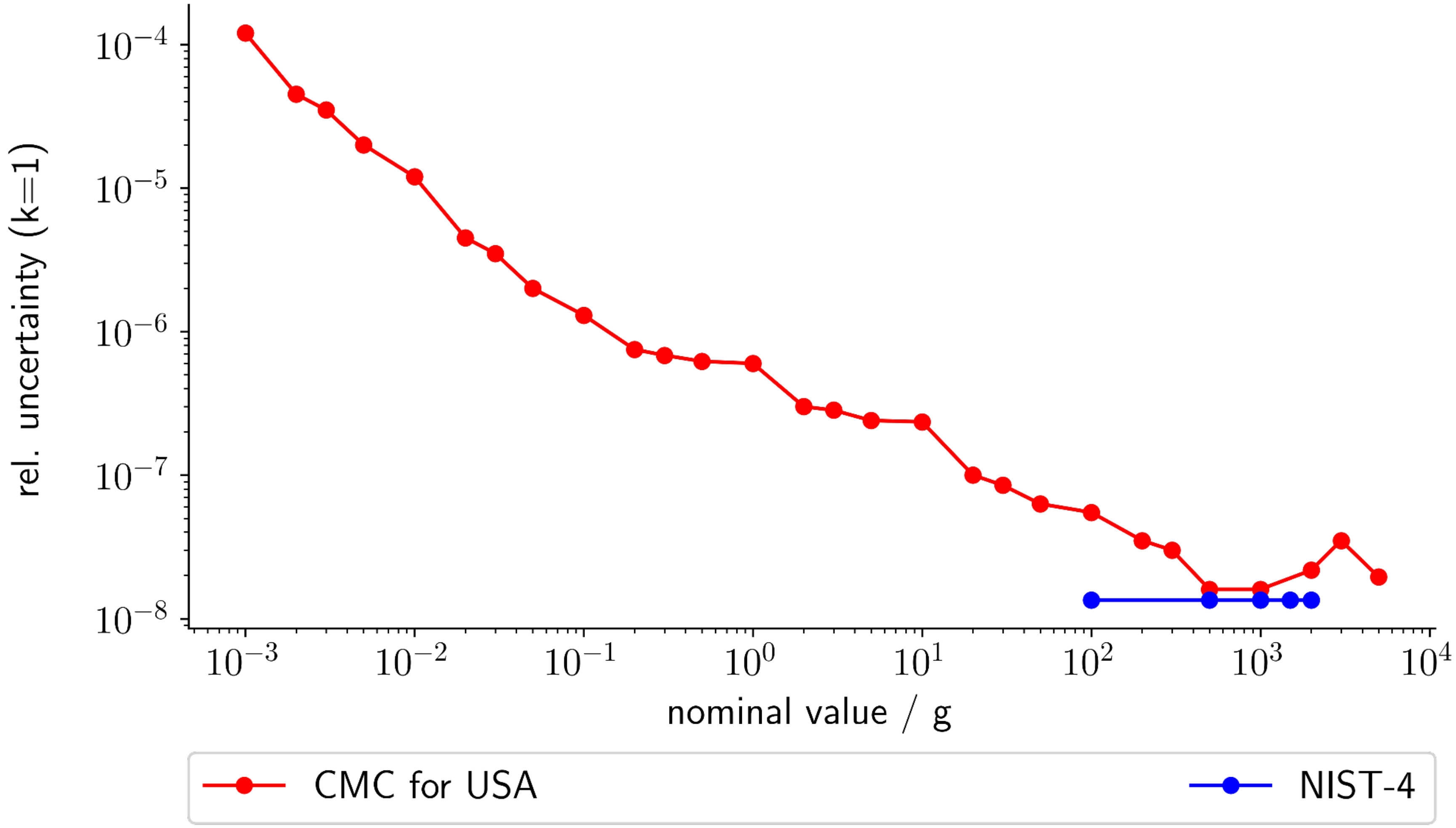

Why lower the uncertainties for lower values?

- Commerce:
- Science

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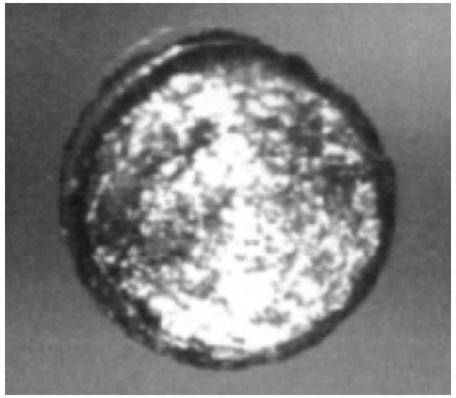
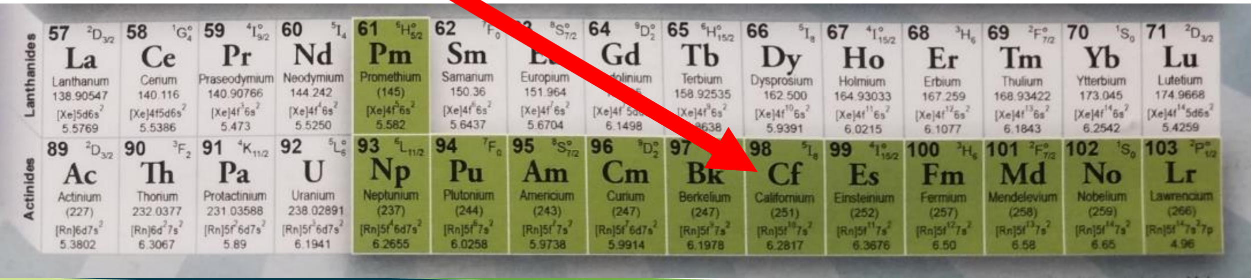
- Commerce:

Californium $_{98}$Cf



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

Here it is



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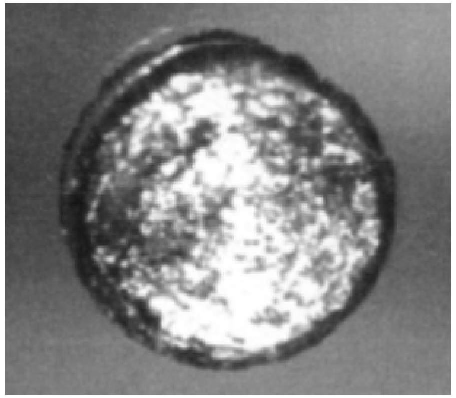

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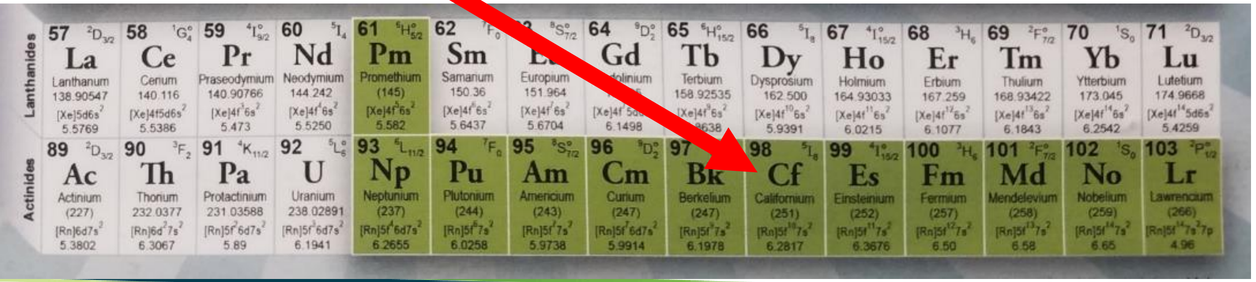

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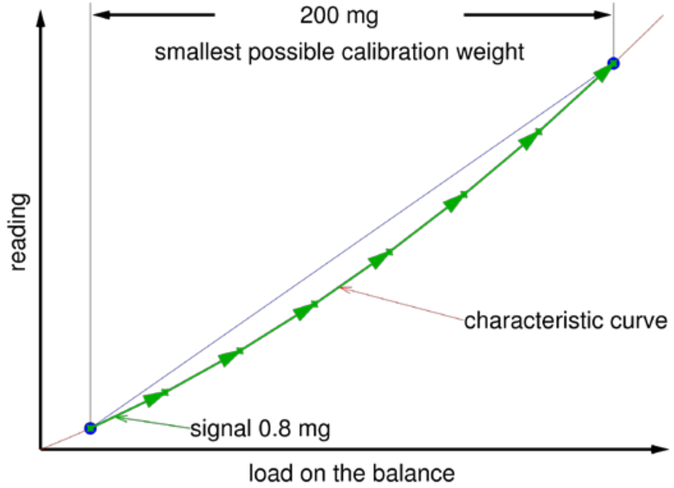
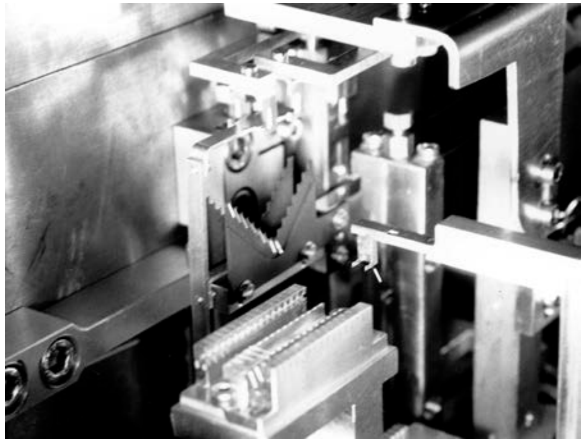
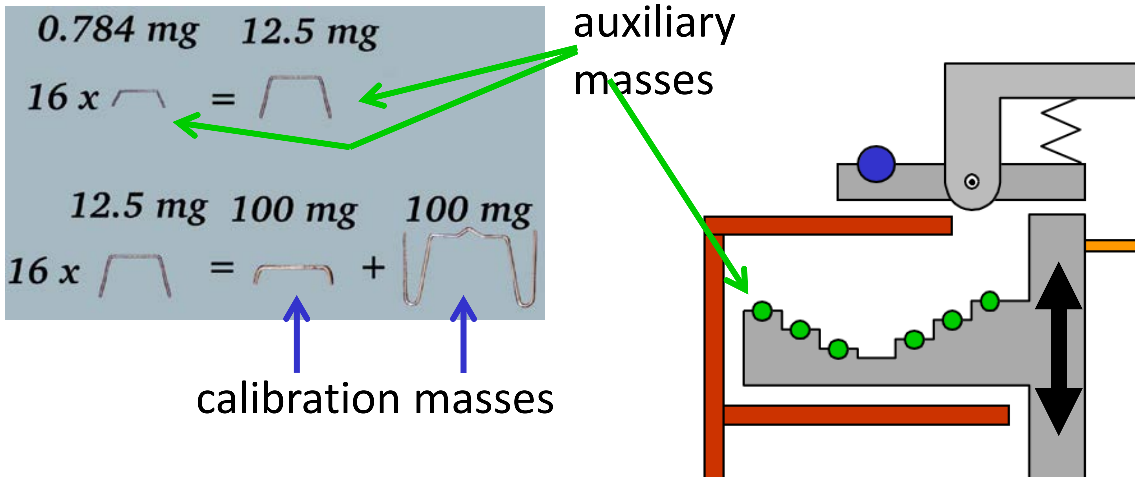
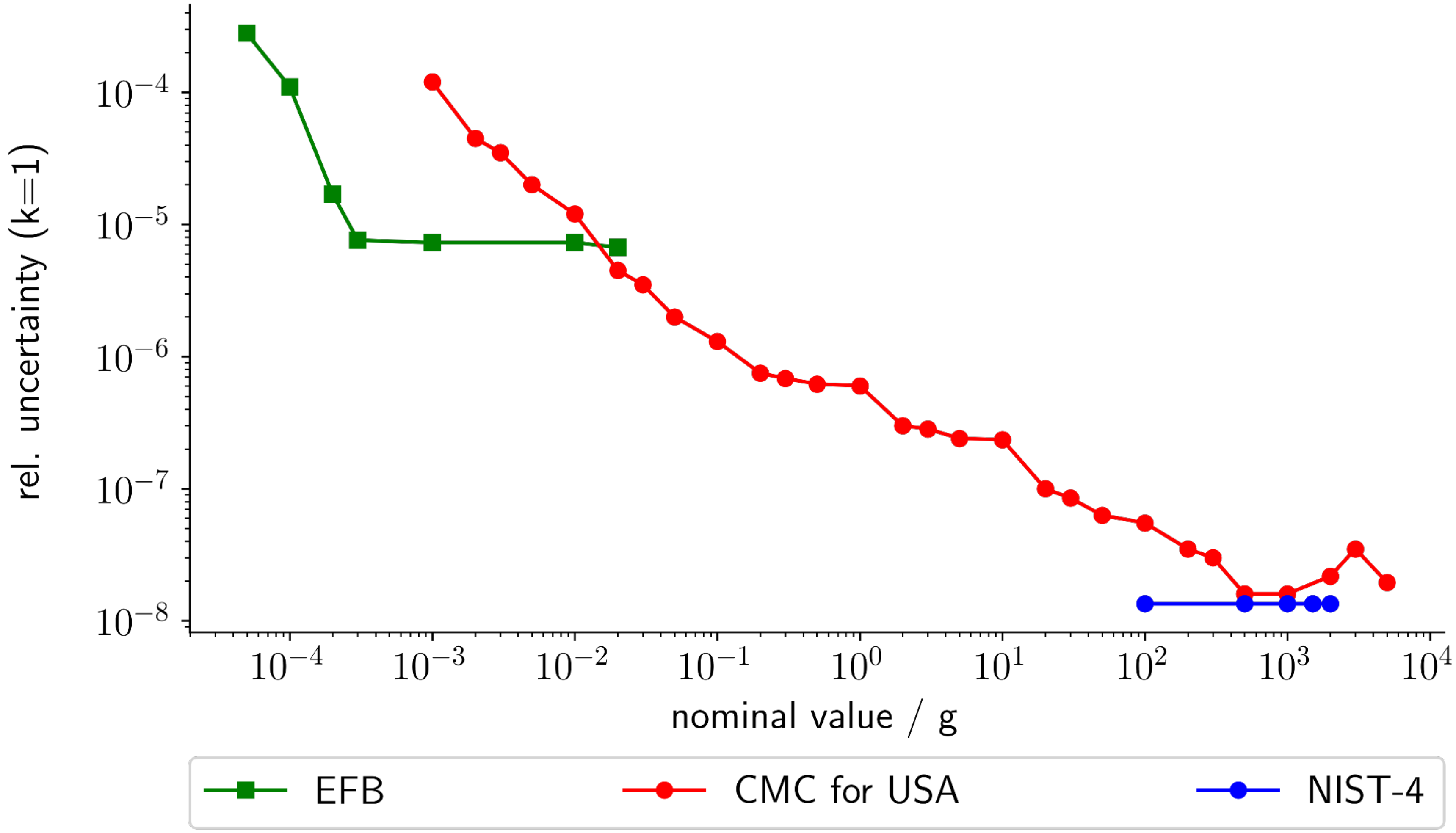






From a point to a scale invariant constant



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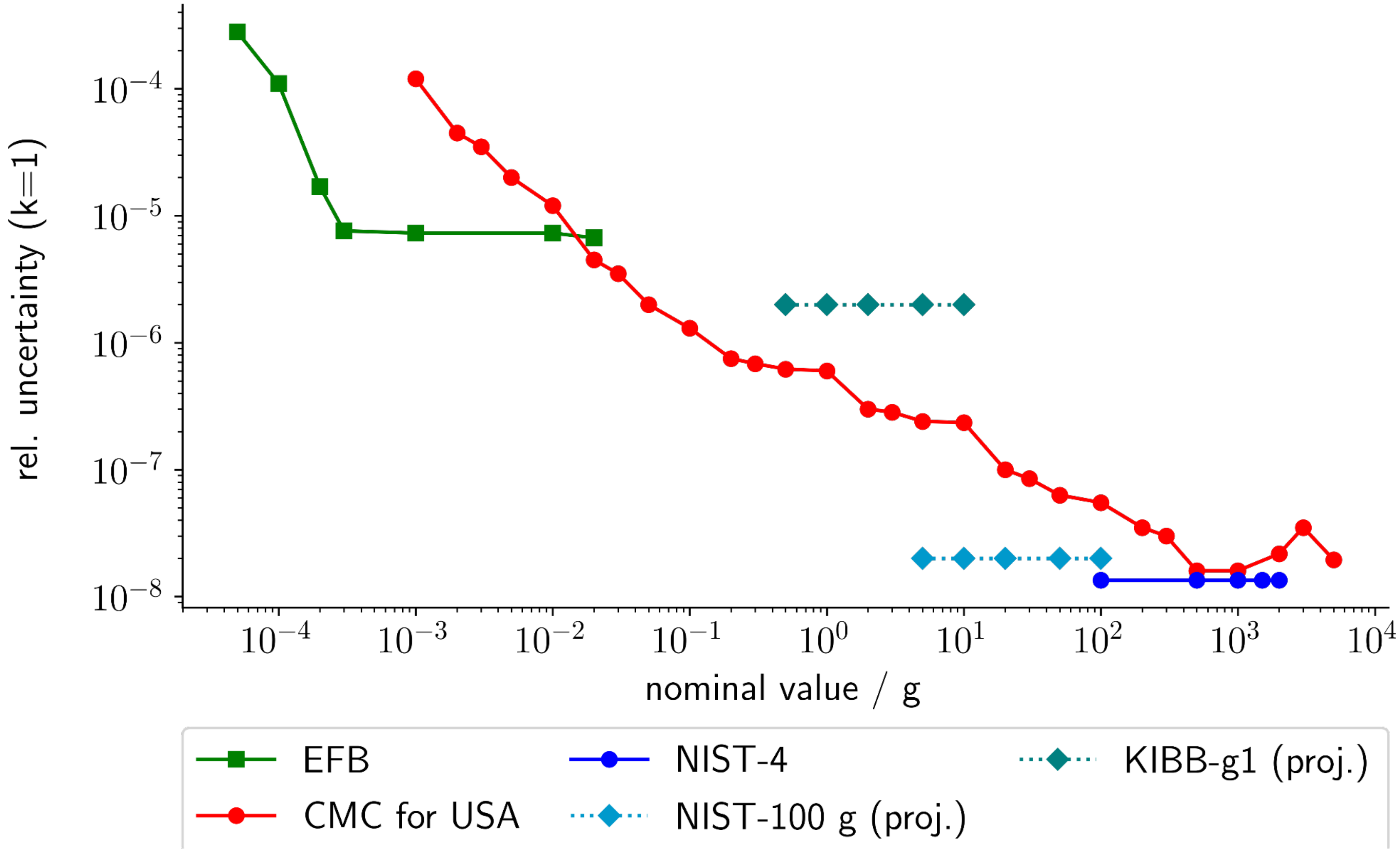

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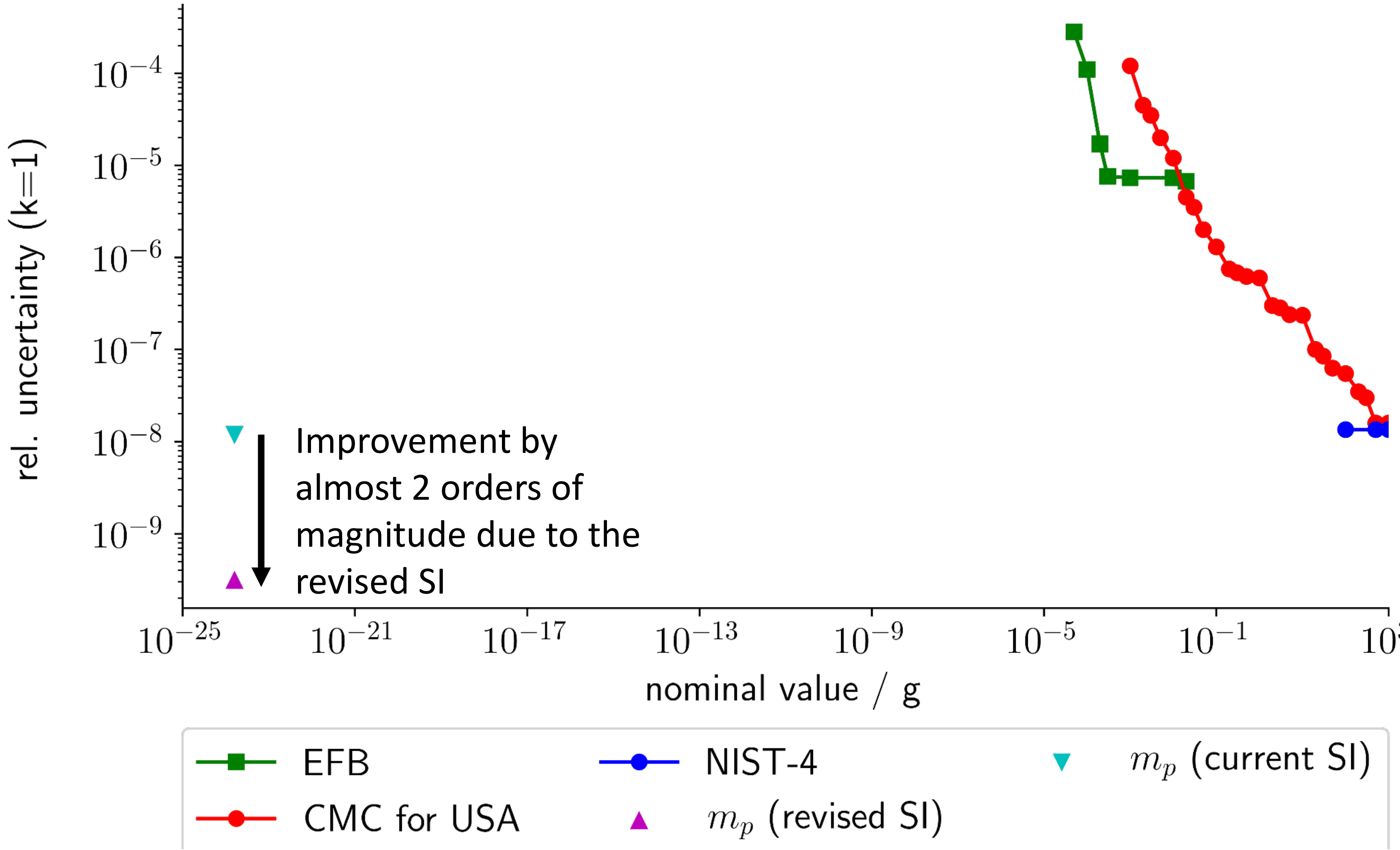
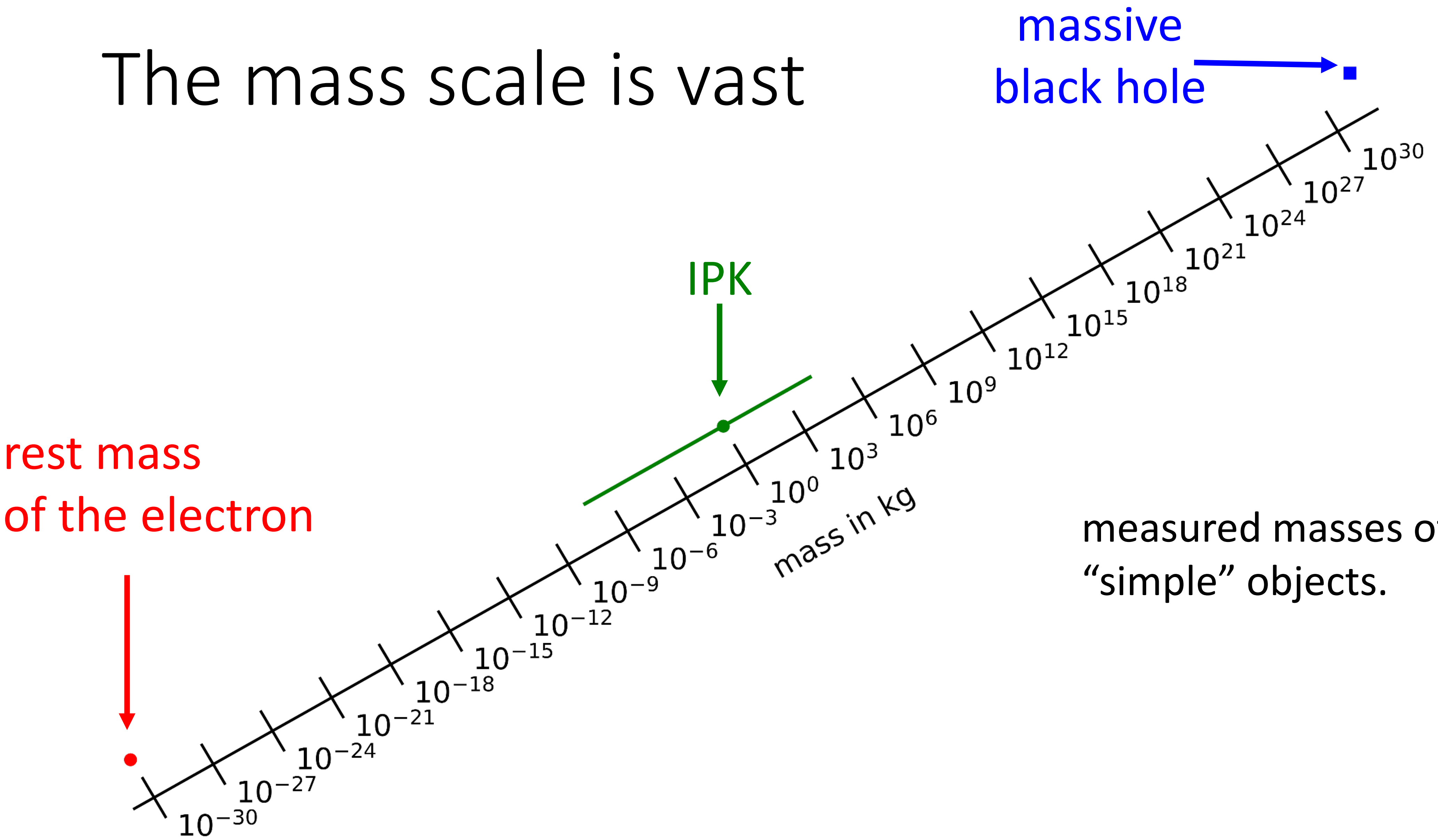


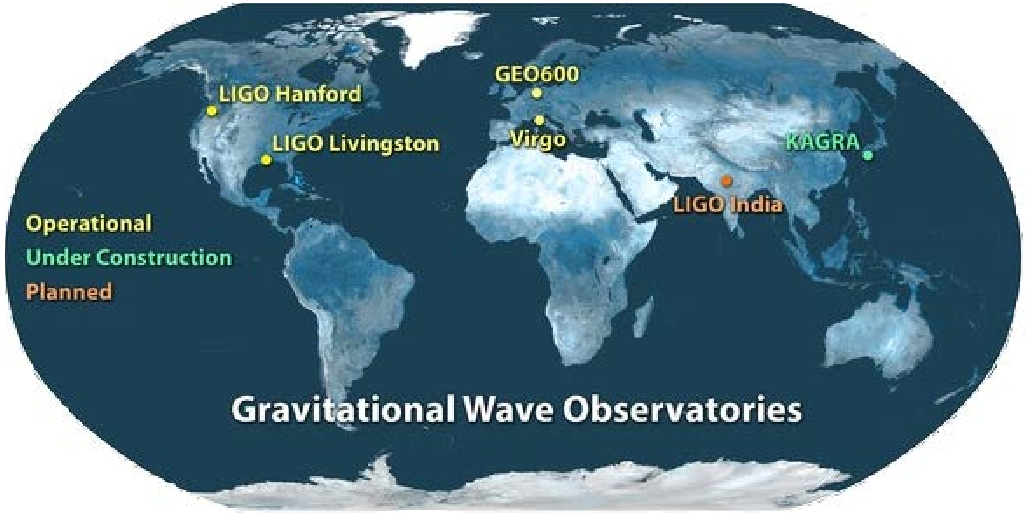
The mass scale is vast

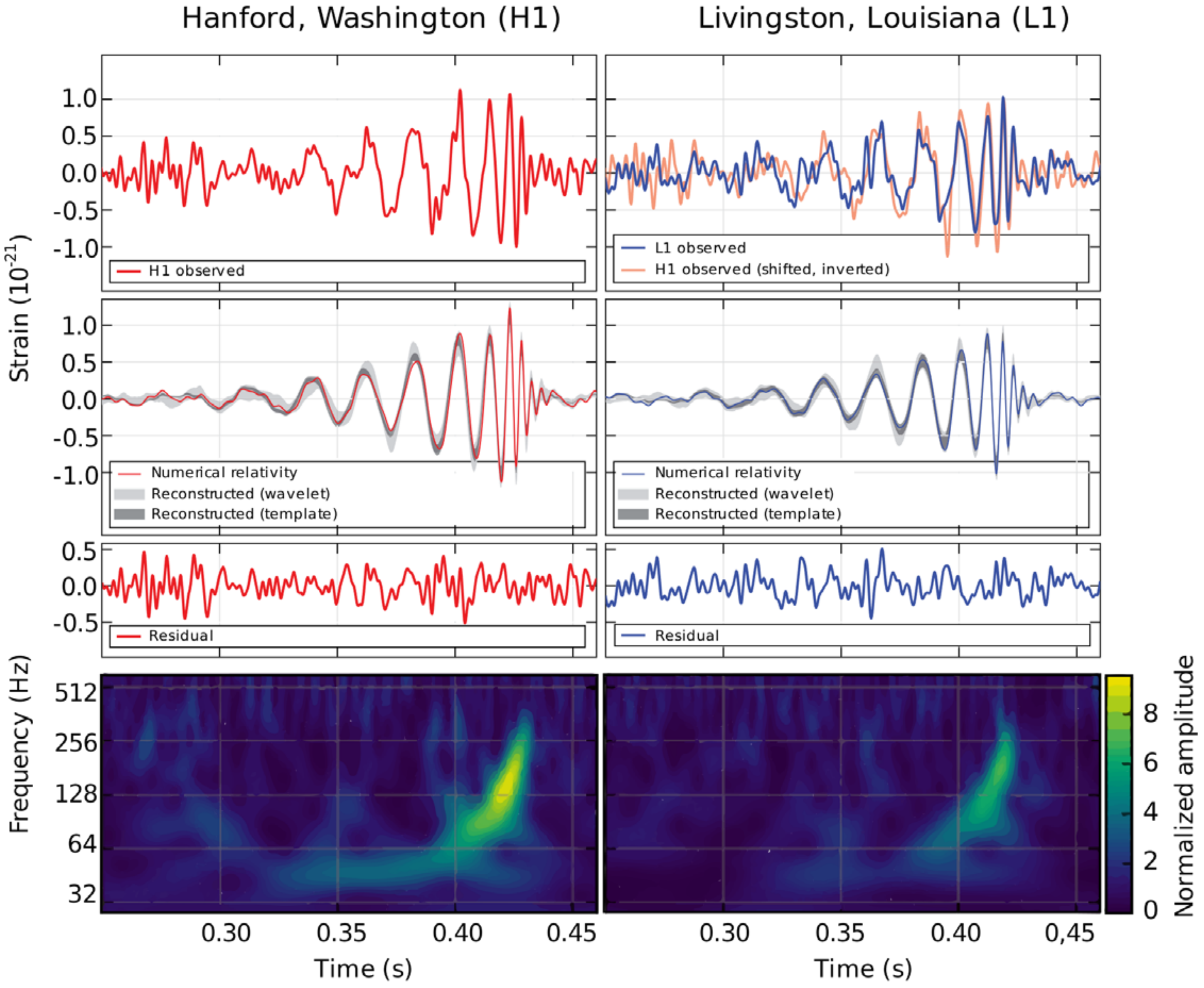


measured masses of “simple” objects.

Weighing 29(4) solar masses

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

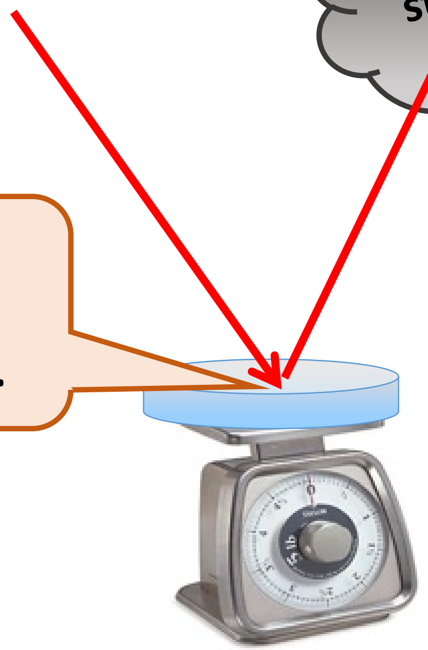




- Multiple gravitational wave detectors require consistent calibration.
- Calibration cam be performed by photon pressure on the end mirror.
- Needs precise (10^{-4}) calibration of laser power.

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

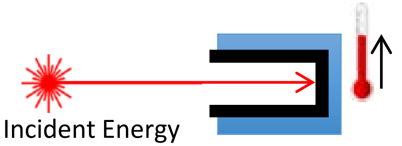
Laser light still available for use



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

Traditional approach:

Energy meter
Absorption-based
Energy $\propto \Delta T$



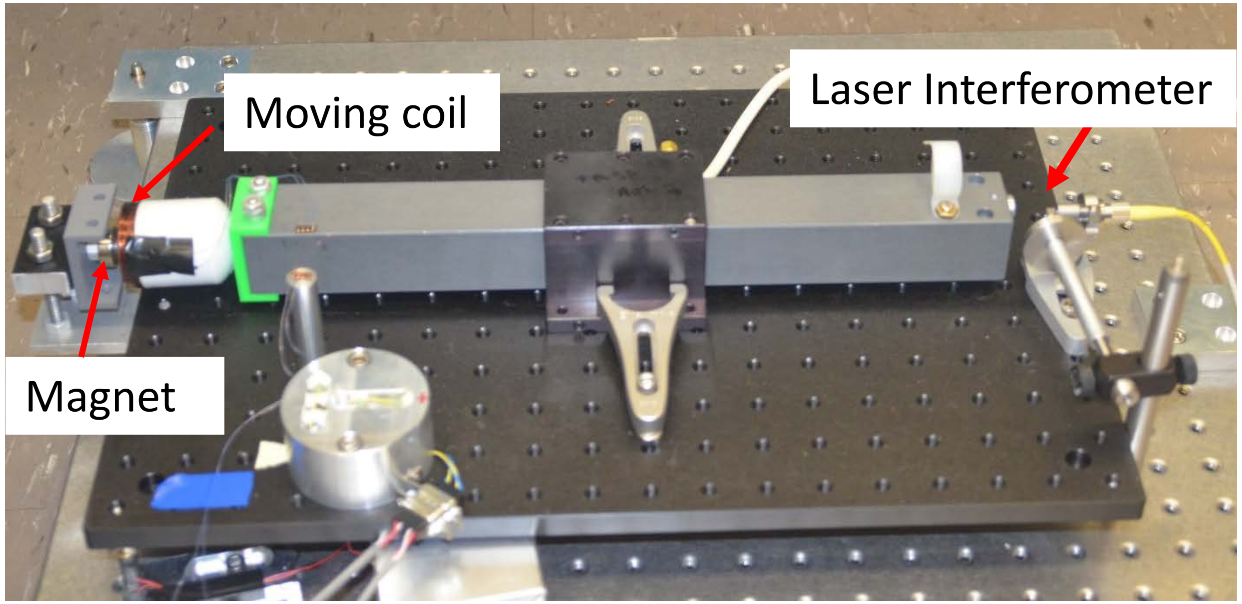
Calorimeter:

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

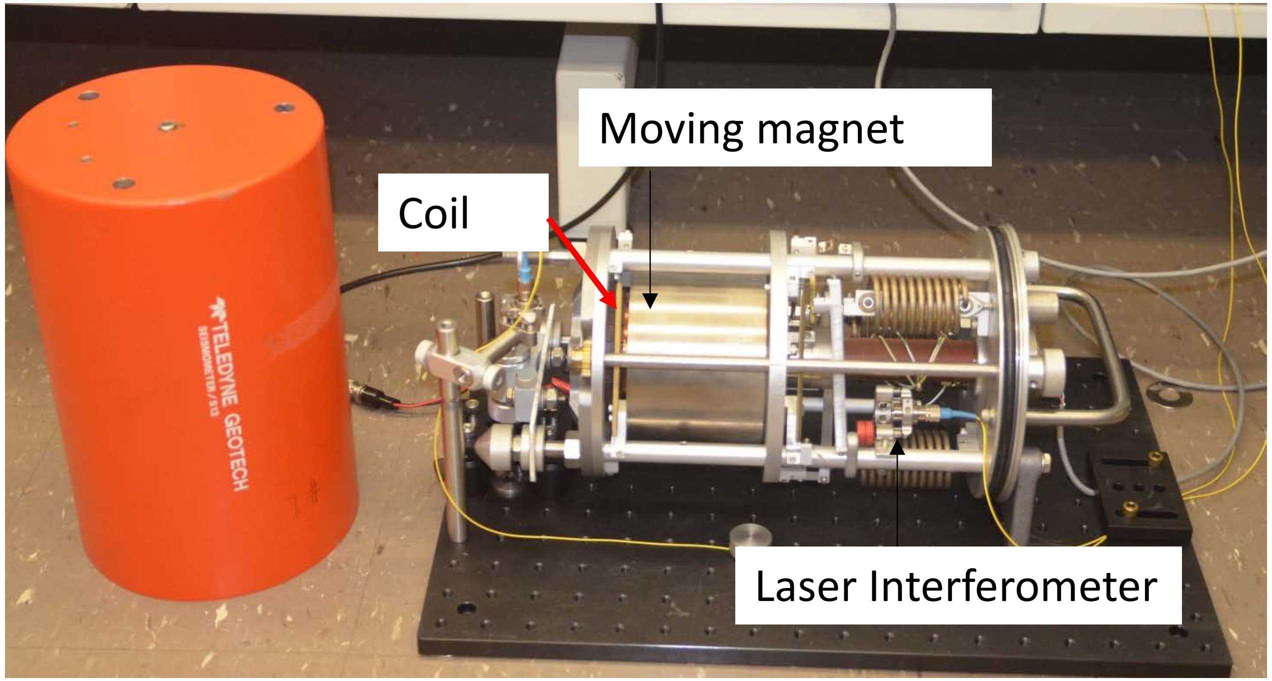
Laser power	Application	Equivalent mass	Object
10 W	Marking	6.7 microgram	eyelash
1 kW	Welding/Cutting	670 microgram	grain of sand
100 kW	Research / Defense	67 milligrams	two staples

The horizontal Kibble/electrostatic force balance

Air bearing setup



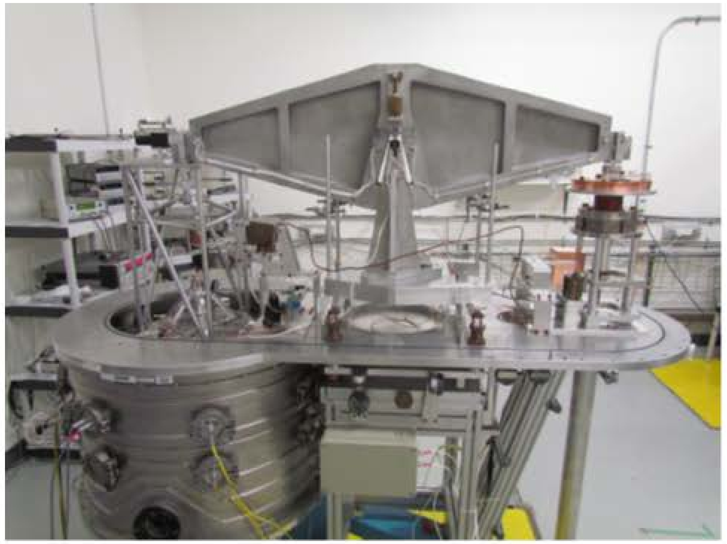
Seismometer suspension in horizontal plane



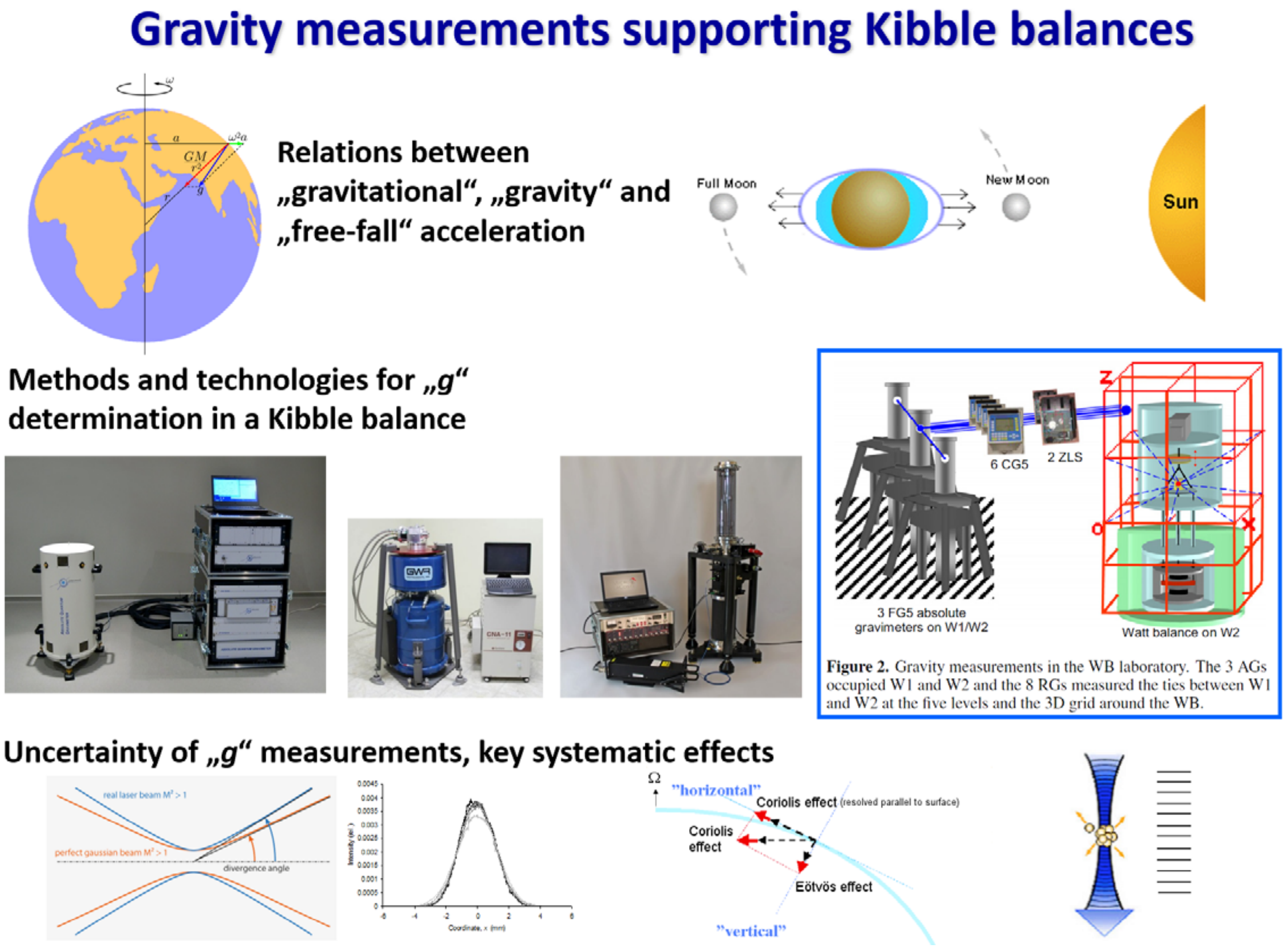
The future

NPL National Physical Laboratory

- 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



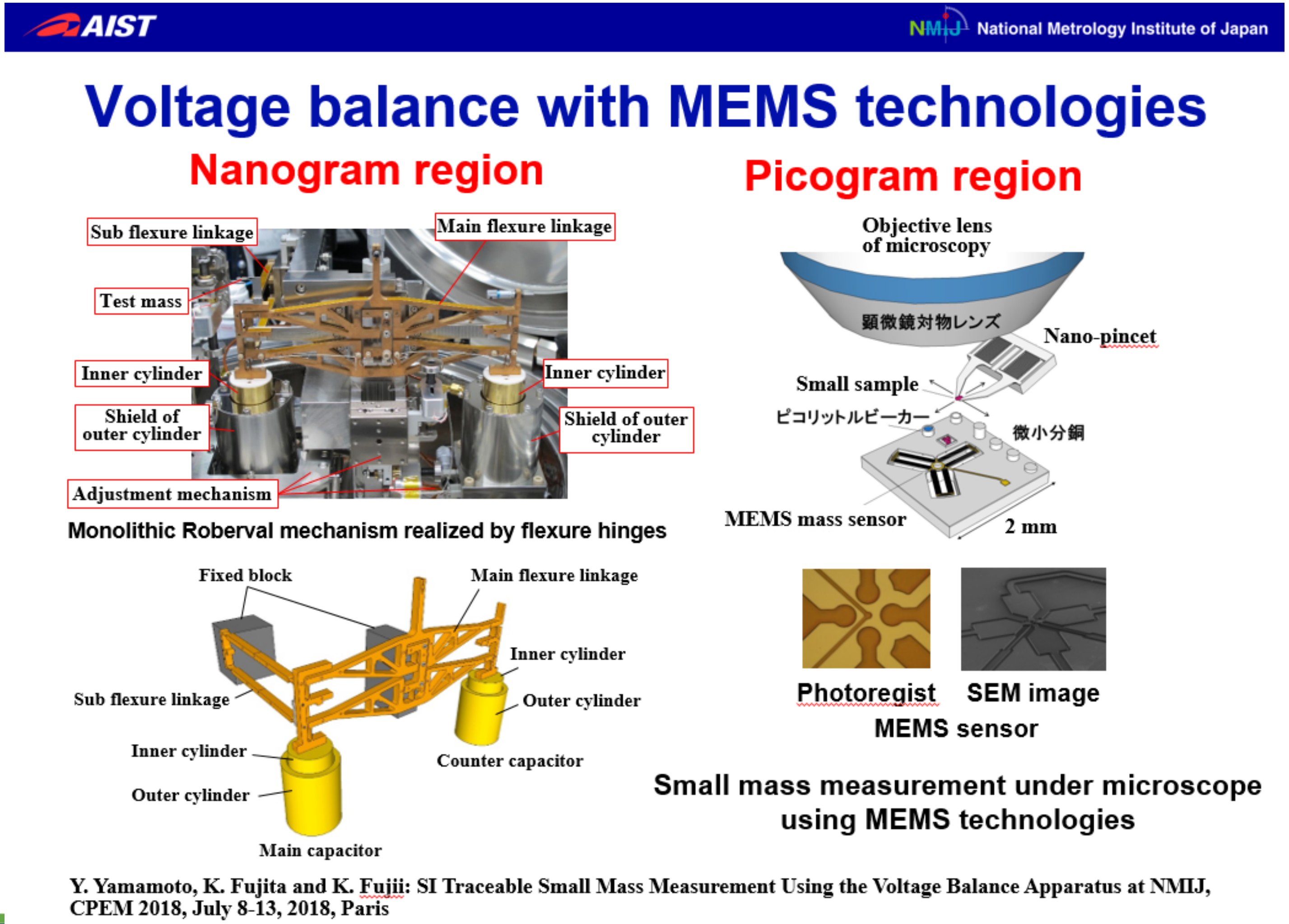
Horst Bettin:
Silicon spheres for the realization of the new kilogram definition

Silicon spheres for the realization of the new kilogram definition

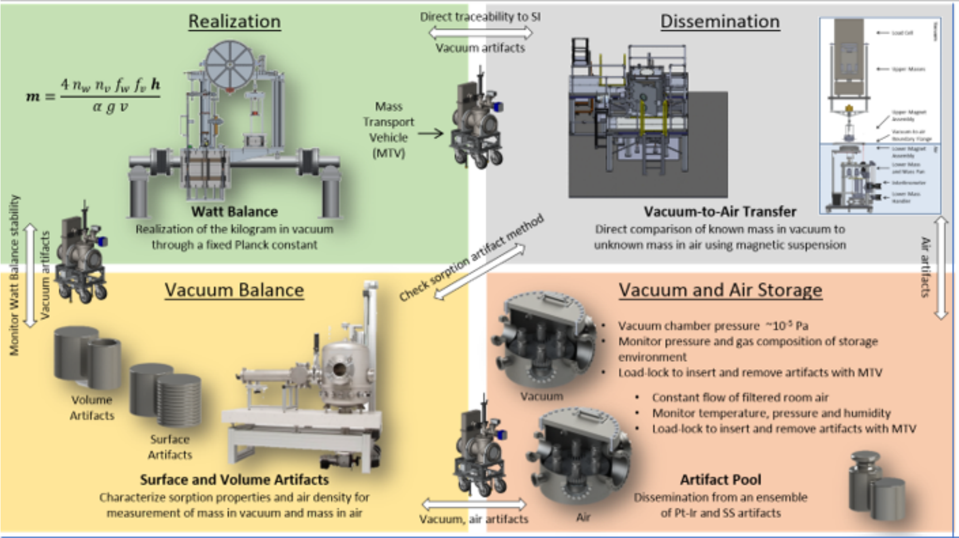
Horst Bettin, PTB Germany

Si-kg

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

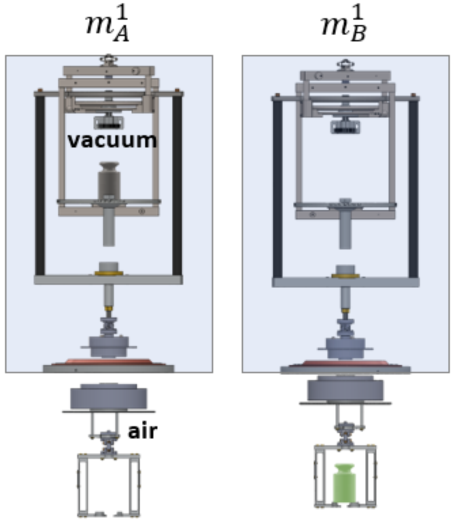


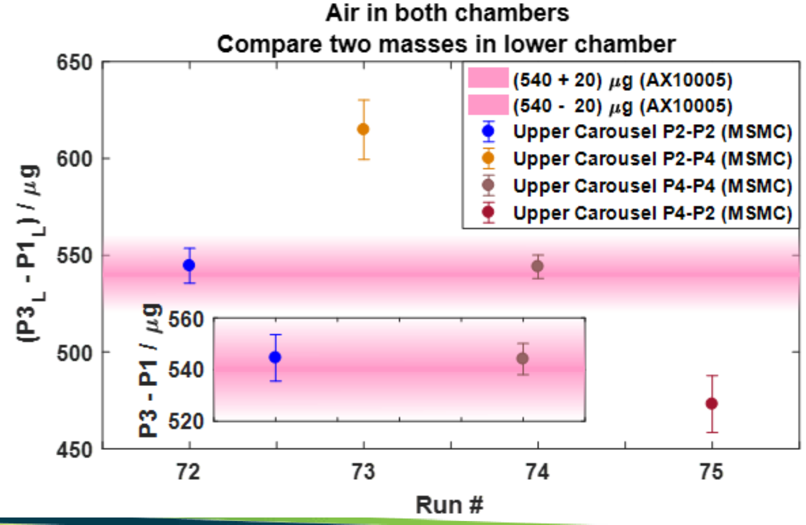
Corey Stambaugh:
The NIST Magnetic Suspension Mass Comparator for Vacuum-to-Air Transfer of the Unit of Mass: Current Status



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 move challenging than desired. However, these interactions can be taken into account.

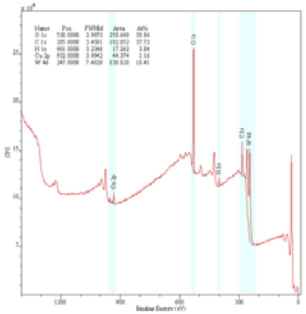
Corey Stambaugh (Project Lead), Z. Kubarych (Group Leader), P. Abbott, E. Mulhern, N. Vlajic, M. Berilla, M. Davis, E. Benck

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

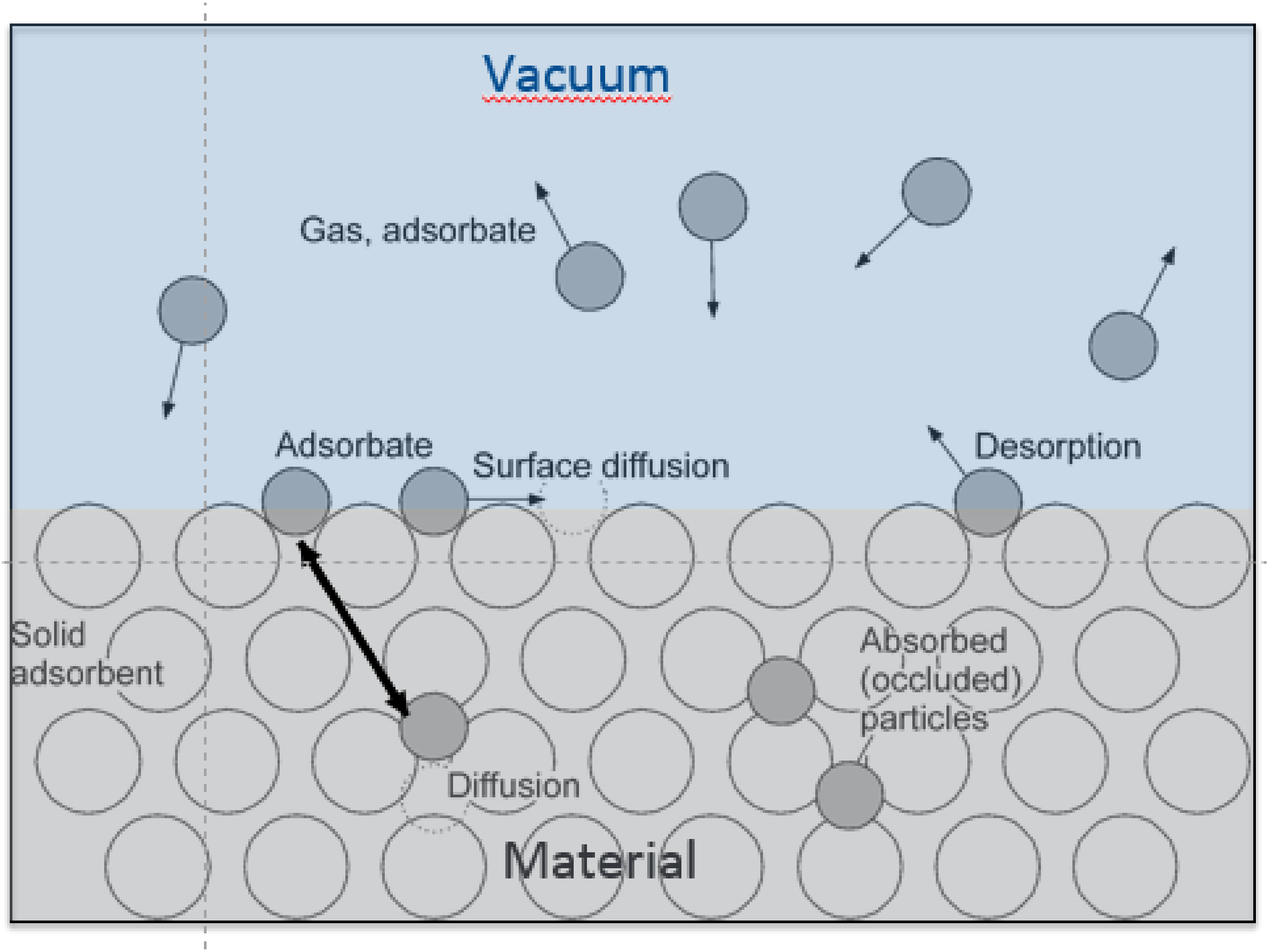
NPL National Physical Laboratory

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 inter 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

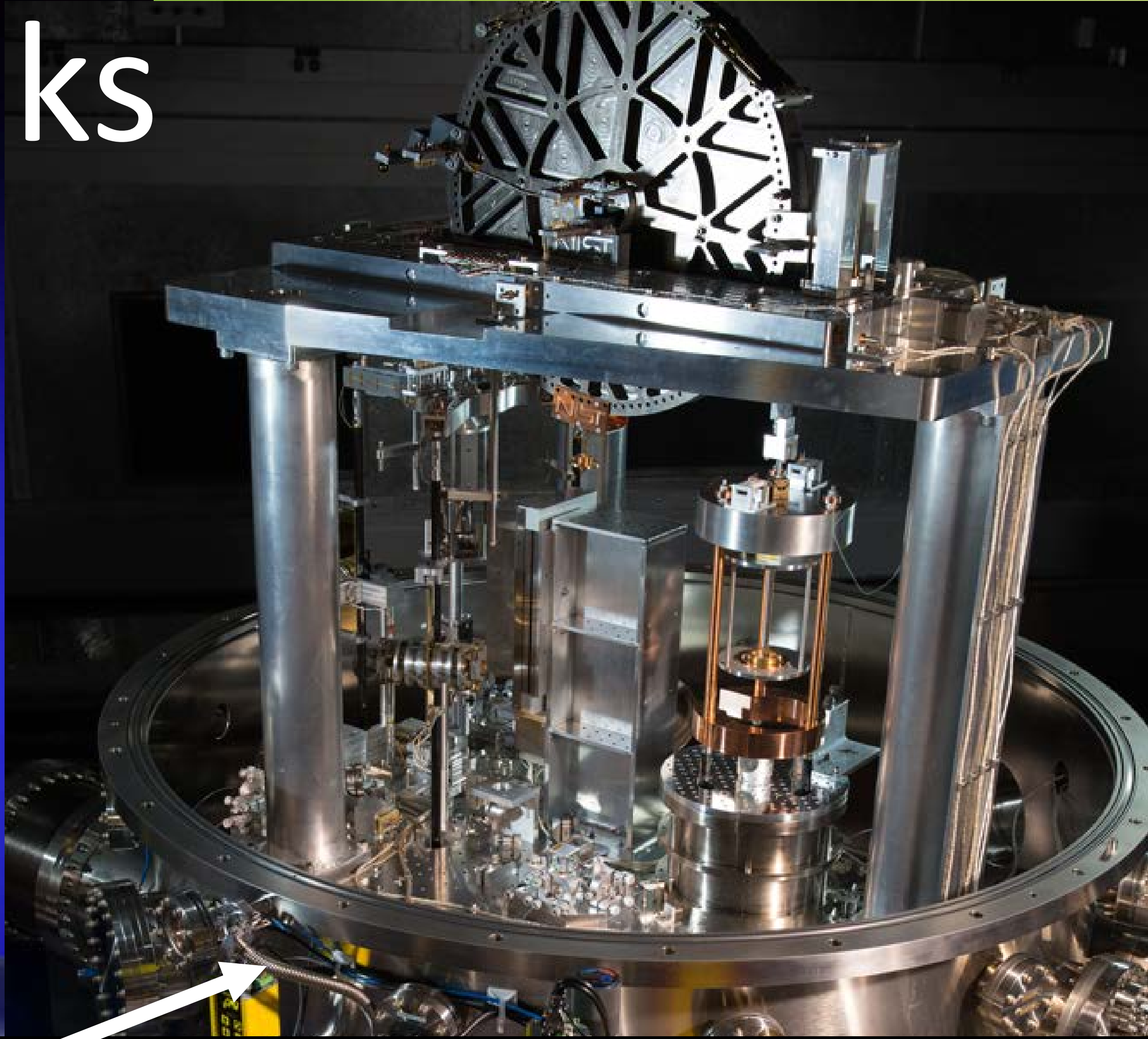


Challenges and opportunities

- 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!