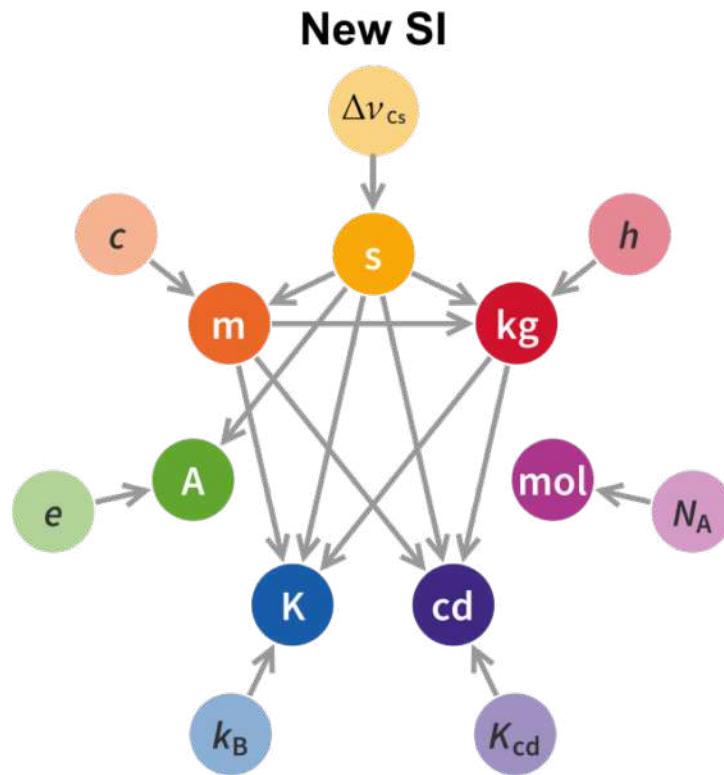


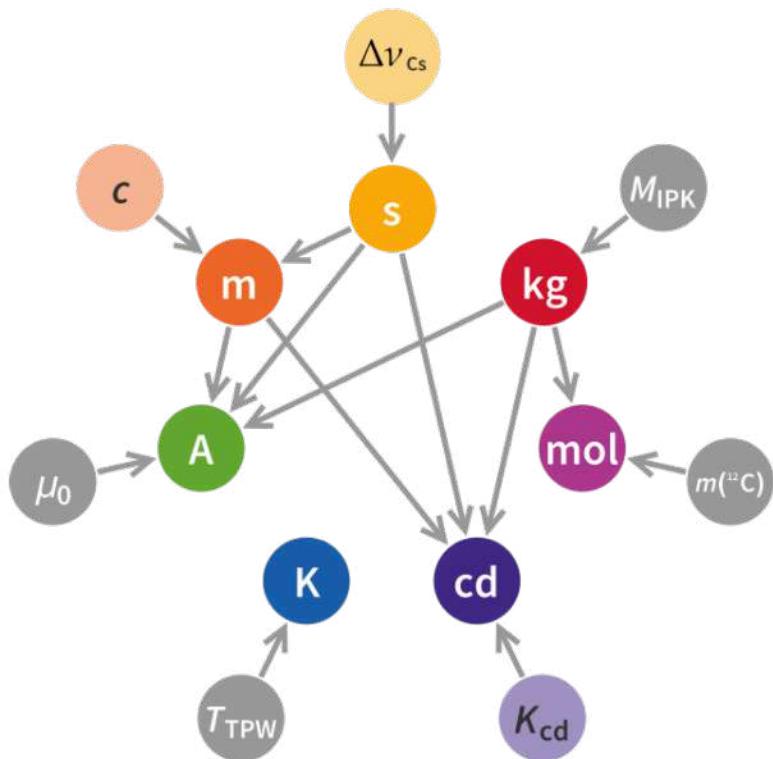
# *Het nieuwe SI: le Système International nouveau est arrivé*



*SI: Système International (d'unités)*  
*International System of Units*  
*Internationale Stelsel van Eenheden*

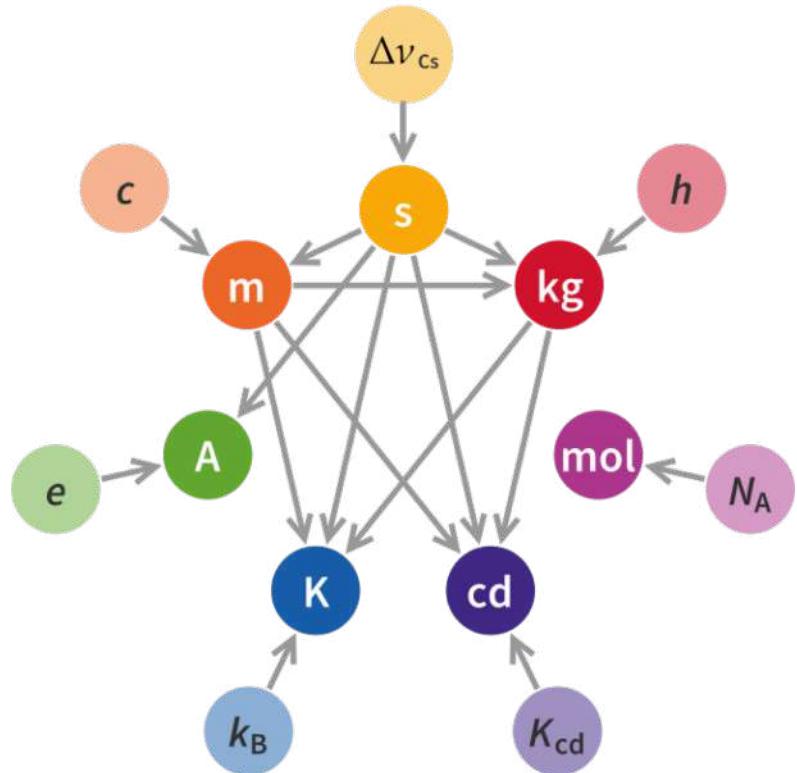
# May 20, 2019: the new SI

Old SI



1983-2019

New SI



From May 20, 2019

(Convention du Mètre: Paris May 20, 1875)

LE BEAUJOLAIS  
NOUVEAU  
EST ARRIVÉ !



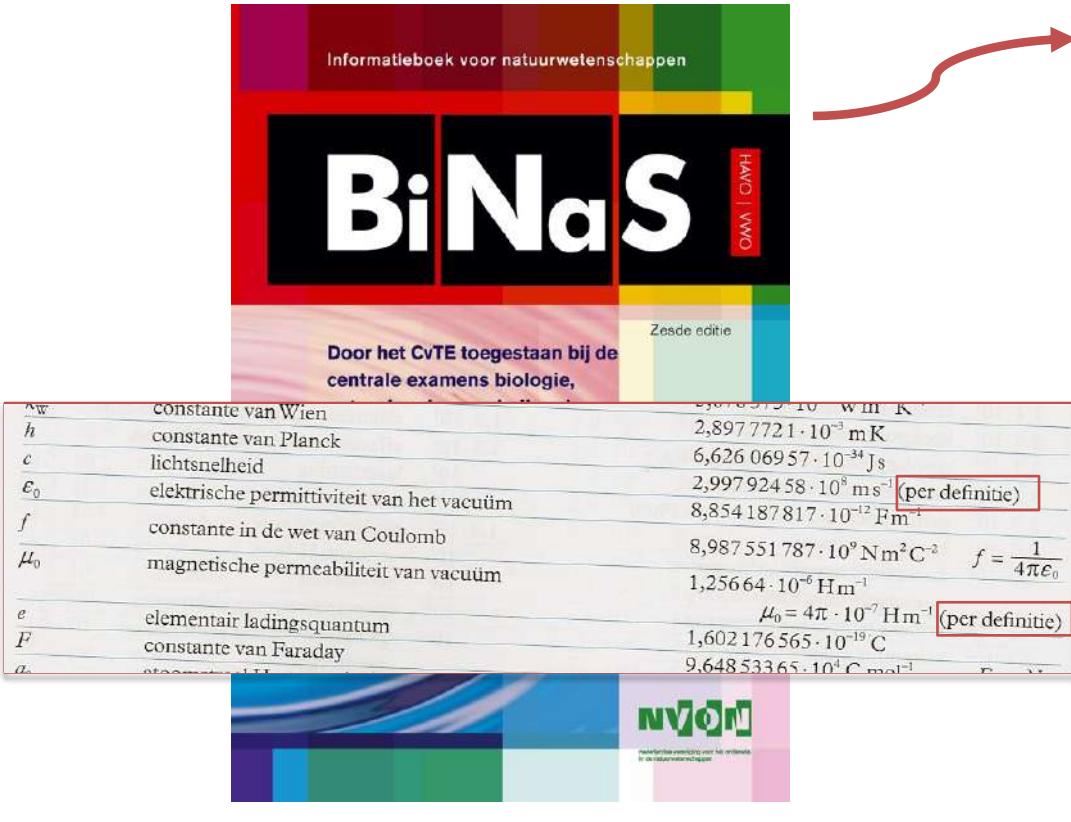
Le Beaujolais est nouveau arrivé !

#179504813



(21 novembre 2019)

# SI in BINAS



Tabel 7A (de eerste natuurkunde tabel):

X

**A Waarden van enige constanten**

symbool	naam	waarde
$G$	gravitatieconstante	$6,670\,36 \cdot 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$
$g$	strekveerconstante (gemiddeld in Nederland)	$2,45 \cdot 10^3 \text{ N m}^{-1}$
$p_0$	smeltpunt van ijs ( $p = p_0$ en $T = 0^\circ\text{C}$ )	$273,15 \text{ K}$
$V_0$	molculaire afstand	$1,32 \cdot 10^{-10} \text{ m}$
$\sigma_{\text{ideal}}$	(ideale gas) constante van $T = 15 \text{ K}$ en $p = p_0$	$2,241\,396\,8 \cdot 10^{-4} \text{ J m}^2 \text{ K}^{-1}$
$\sigma_{\text{gas}}$	(gasvormige stof) constante van $T = 0^\circ\text{C}$ en $p = p_0$	$2,45 \cdot 10^{-3} \text{ m}^2 \text{ mol}^{-1}$
$N_A$	constante van Avogadro	$6,022\,140 \cdot 10^{23} \text{ mol}^{-1}$
$R$	gasconstante	$8,314\,462 \cdot 1 \text{ J mol}^{-1} \text{ K}^{-1}$
$\sigma_B$	constante van Boltzmann	$1,380\,488 \cdot 10^{-23} \text{ J K}^{-1}$
$\sigma_S$	constante van Stefan-Boltzmann	$5,670\,373 \cdot 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$
$k$	constante van de wärmeleidbaarheid	$2,897\,723 \cdot 10^{-8} \text{ m K}^2$
$\epsilon_0$	constante van de elektrolytische capaciteit	$8,636\,069 \cdot 10^{-12} \text{ F m}^{-1}$
$\epsilon_0$	lichtsnelheid	$2,997\,924\,58 \cdot 10^8 \text{ m s}^{-1}$ (per definitie)
$f$	constante in de wet van Coulomb	$8,987\,551\,787 \cdot 10^9 \text{ N m}^2 \text{ C}^{-2}$ $f = \frac{1}{4\pi\epsilon_0}$
$\mu_0$	magnetische permeabiliteit van vacuüm	$1,256\,64 \cdot 10^{-6} \text{ H m}^{-1}$
$e$	elementair ladingsquantum	$1,602\,176\,565 \cdot 10^{-19} \text{ C}$ (per definitie)
$F$	constante van Faraday	$9,648\,533\,65 \cdot 10^{-10} \text{ C mol}^{-1}$
$a_0$	atoomstraal	$9,648\,533\,65 \cdot 10^{-10} \text{ m}$
$\rho_{\text{water}}$	rijchbergverhouding voor waterstaal	$1,096\,775\,834 \cdot 10^{-3}$

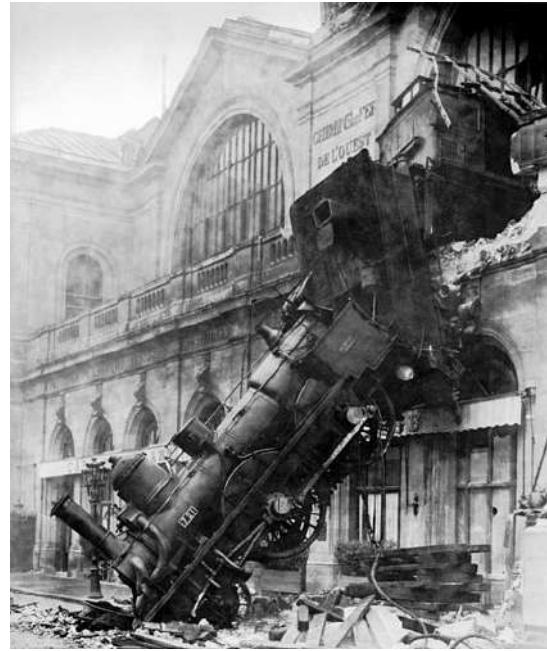
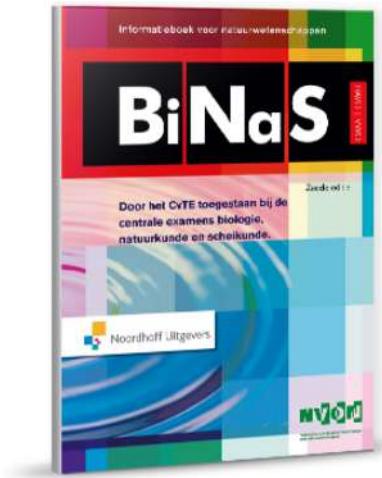
**B Massa en energie**

symbool	naam	u	kg	MeV	J
$m_u$	atomaire massa-eenhed	1			
$m_p$	rustmassa proton	$1,699\,538\,921 \cdot 10^{-29}$	$931\,494\,061$	$1,492\,417\,984 \cdot 10^{-10}$	
$m_n$	rustmassa neutron	$1,007\,276\,466\,812$	$1,672\,821\,777 \cdot 10^{-29}$	$938,272\,046$	$1,503\,277\,484 \cdot 10^{-10}$
$m_e$	rustmassa elektron	$5,485\,799\,0946 \cdot 10^{-31}$	$9,109\,381\,911 \cdot 10^{-31}$	$0,510\,998\,928$	$8,187\,105\,072 \cdot 10^{-10}$

**C Planck-eenheden**

voertuig	herhaling	voertuig	voertuig
plancklengte	$\sqrt{(2\pi)^3 \hbar G c}$	$l_p$	$1,616\,252 \cdot 10^{-35} \text{ m}$
planckmassa	$\sqrt{(2\pi)^3 \hbar G c^5}$	$m_p$	$2,176\,44 \cdot 10^{-8} \text{ kg}$
plancktijd	$\sqrt{(2\pi)^3 \hbar G c^5}$	$t_p$	$5,391\,24 \cdot 10^{-43} \text{ s}$
plancktemperatuur	$\sqrt{(2\pi)^3 \hbar G c^5 k_B}$	$T_p$	$1,418\,785 \cdot 10^{32} \text{ K}$
magnetisch fluxquantum	$2 \cdot h e$	$Q_p$	$2,068\,833\,667 \cdot 10^{-11} \text{ Wh}$
van Klitzingconstante	$h e^2$	$R_p$	$2,581\,280\,755 \cdot 10^6 \text{ Q}$
geleidingsquantum	$2 \hbar e^2$	$G_p$	$7,748\,011\,700 \cdot 10^{-8} \text{ S}$

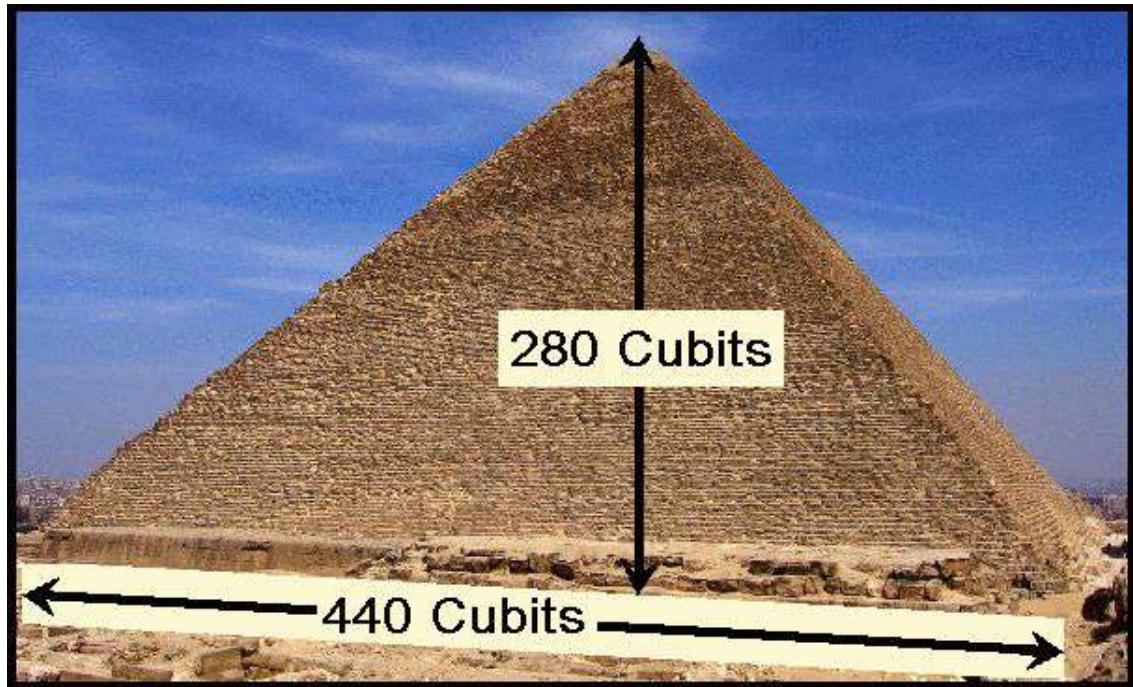
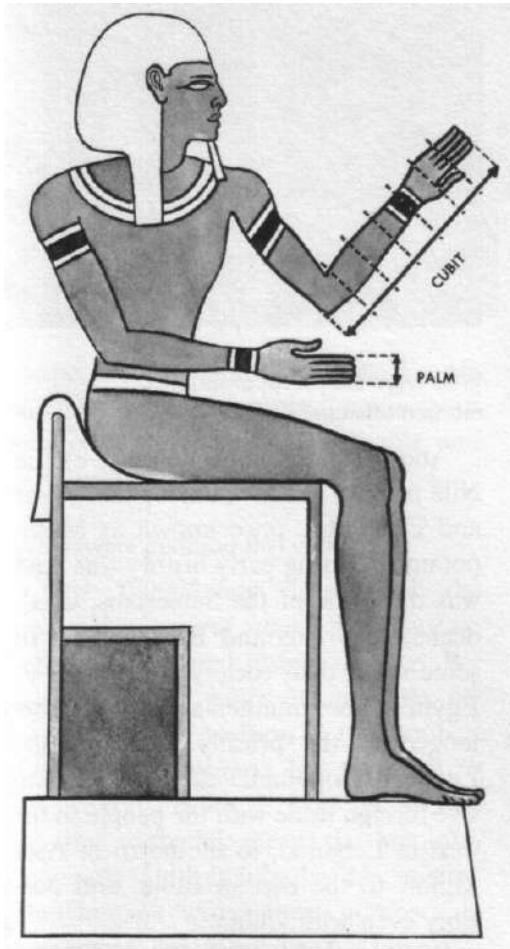
# Meten, maten en eenheden



- *Meten is weten*
- *Precisie is van belang, ook in de praktijk*

*Hoe meet je eigenlijk? ....*

# Early length standard



© somewhere on the internet

# Length standard 1893-1960: Pt:Ir bar

## International prototype metre

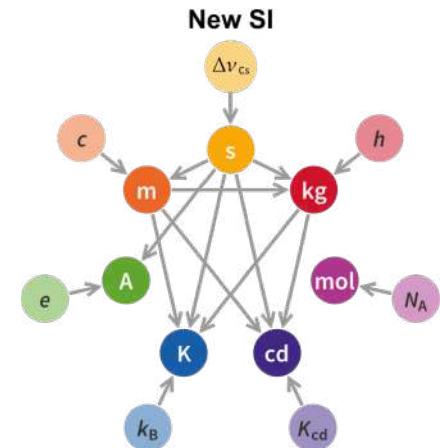


Closeup of National Prototype Metre Bar No. 27, made in 1889 by the International Bureau of Weights and Measures (BIPM) and given to the United States, which served as the standard for defining all units of length in the US from 1893 to 1960

© wikipedia

With i  
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# SI: Système Internationale



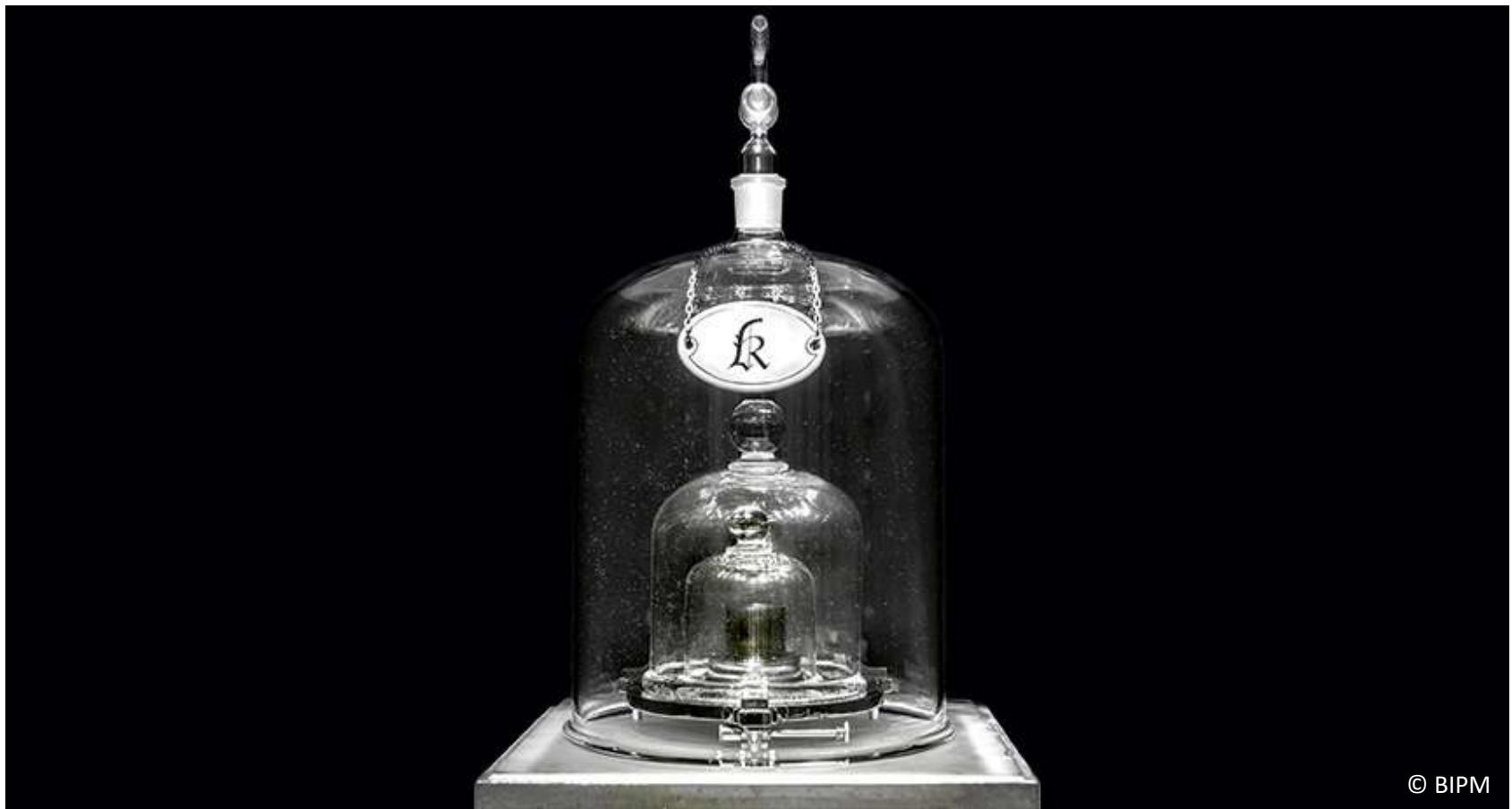
Time (since 1967):  $\Delta\nu_{\text{Cs}} \equiv 9\,192\,631\,770 \text{ Hz}$

Cesium atomic clock (ground-state hyperfine transition frequency) as primary time standard

Length (since 1983):  $c \equiv 299\,792\,458 \text{ m/s}$

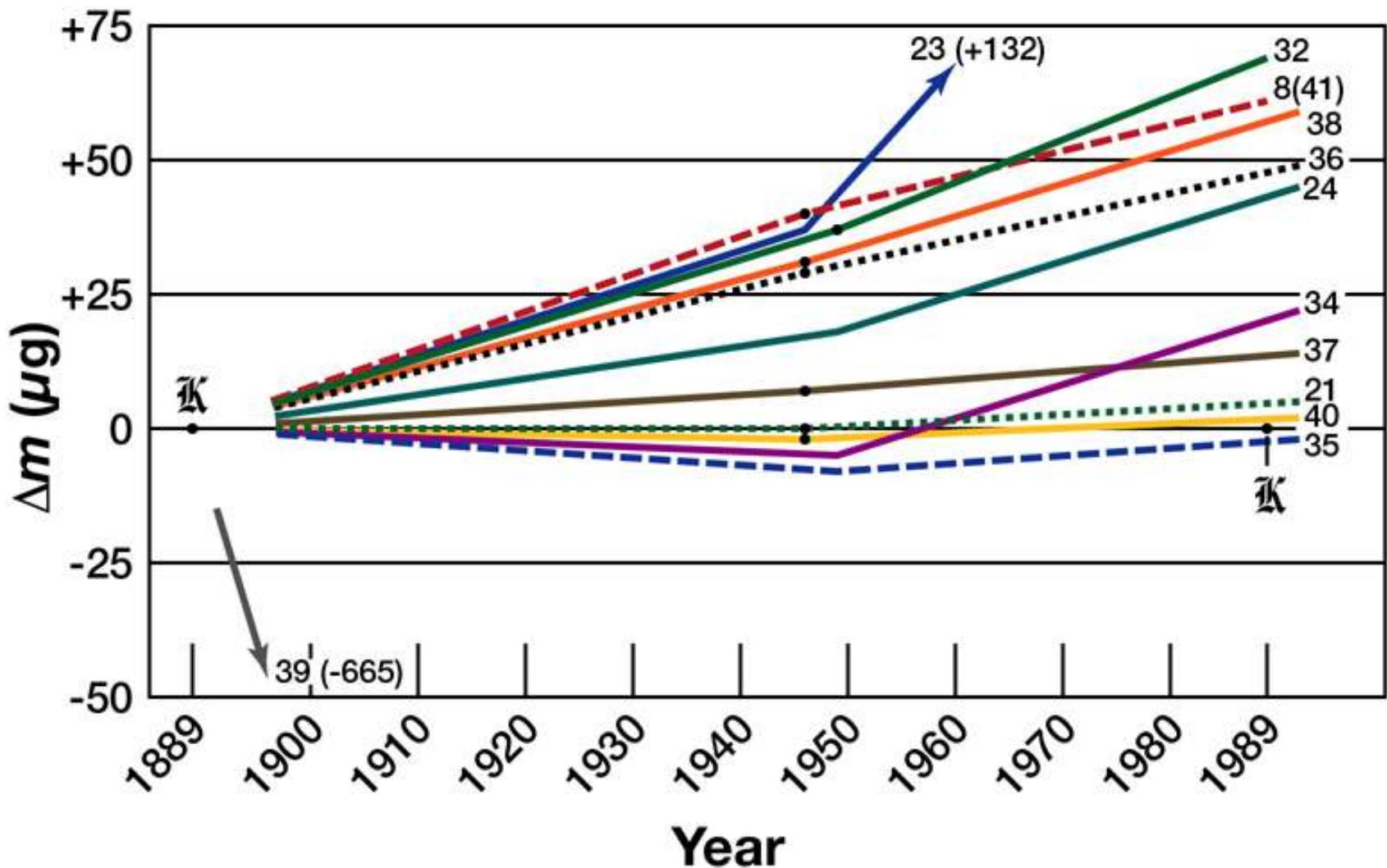
Mass: since 1889:

# Le Grand K (1889-2019)



© BIPM

# Relative drift of mass standards



# The defining constants of the new SI

$$\Delta\nu_{\text{Cs}} \equiv 9\,192\,631\,770 \text{ Hz}$$

$$c \equiv 299\,792\,458 \text{ m/s}$$

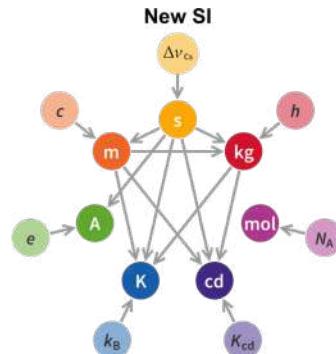
$$h \equiv 6.626\,070\,15 \times 10^{-34} \text{ Js}$$

$$e \equiv 1.602\,176\,634 \times 10^{-19} \text{ C}$$

$$k \equiv 1.380\,649 \times 10^{-23} \text{ J/K}$$

$$N_A \equiv 6.022\,140\,76 \times 10^{23} \text{ mol}^{-1}$$

$$K_{\text{cd}} \equiv 683 \text{ lm/W}$$



# Josephson voltage standard



© wikipedia

- AC Josephson effect:  
(voltage across a tunneling junction,  
an insulator between two superconductors)  
$$V = \frac{h\nu}{2e}$$
- Josephson constant:  
$$K_J = \frac{2e}{h}$$
- Since 1990:  $K_{J-90} \equiv 483\,597.9 \text{ GHz/V}$
- New SI:  $K_J \equiv 483\,597.848\,4\dots \text{ GHz/V}$

# Quantum Hall effect as a reference



© Nobel Foundation

- Integer quantum Hall effect:  
(Hall conductance of 2DEG in strong magnetic field)

$$\sigma = \frac{I_{\text{channel}}}{V_{\text{Hall}}} = n \frac{e^2}{h}$$

- Von Klitzing constant:  $R_K = \frac{h}{e^2}$
- Since 1990:  $R_{K-90} \equiv 25\,812.807\,\Omega$
- New SI:  $R_K \equiv 25\,812.807\,45\dots\Omega$

# The electromagnetic constants



Maxwell:  $c = \frac{1}{\sqrt{\epsilon_0 \mu_0}}$

Old SI:  $c \equiv 299\,792\,458 \text{ m/s}$

$$\mu_0 \equiv 4\pi \times 10^{-7} \text{ N/A}^2$$

$$\Rightarrow \epsilon_0 \equiv 8.854 \dots \times 10^{-12} \text{ F/m}$$

# The electromagnetic constants

Maxwell:  $c = \frac{1}{\sqrt{\epsilon_0 \mu_0}}$



New SI:  $e, h, c$  **defined**

$$\epsilon_0 \equiv \frac{e^2}{2\alpha} \frac{1}{hc} = 8.854\,187\,8128(13) \times 10^{-12} \text{ F/m}$$

$$\Rightarrow \mu_0 = 1.256\,637\,062\,12(19) \times 10^{-6} \text{ N/A}^2$$

$$4\pi \times 10^{-7} = 1.256\,637\,061\,435\dots \times 10^{-6}$$

# The defining constants of the new SI

$$\Delta\nu_{\text{Cs}} \equiv 9\,192\,631\,770 \text{ Hz}$$

$$c \equiv 299\,792\,458 \text{ m/s}$$

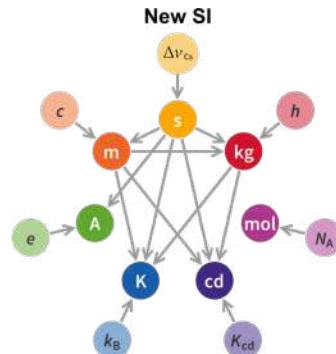
$$h \equiv 6.626\,070\,15 \times 10^{-34} \text{ Js}$$

$$e \equiv 1.602\,176\,634 \times 10^{-19} \text{ C}$$

$$k \equiv 1.380\,649 \times 10^{-23} \text{ J/K}$$

$$N_A \equiv 6.022\,140\,76 \times 10^{23} \text{ mol}^{-1}$$

$$K_{\text{cd}} \equiv 683 \text{ lm/W}$$

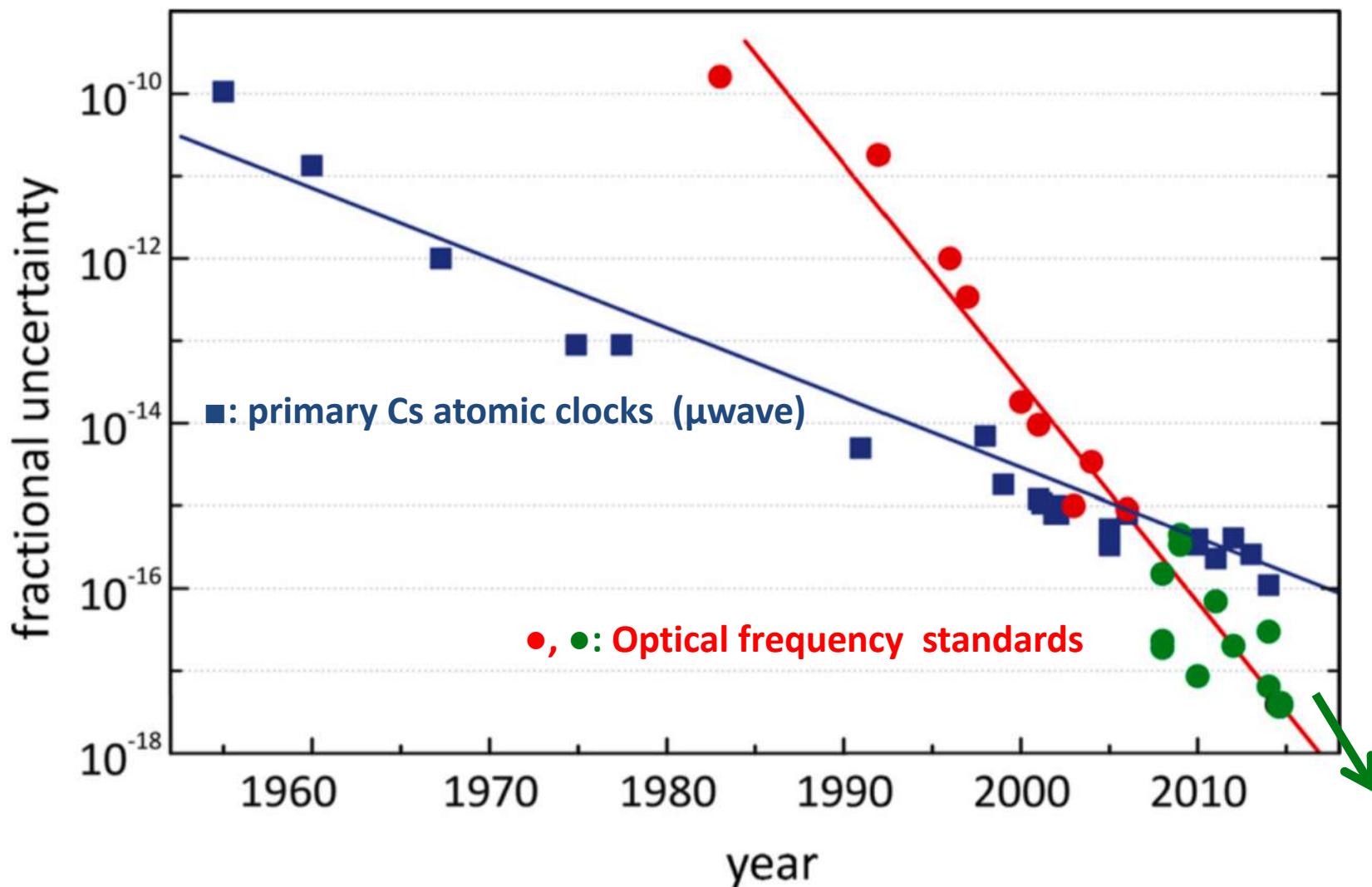


# A tous les temps, à tous les peuples



© JASON STOUGHTON/NIST

# Progress in atomic clocks



Science

# Optical atomic clocks

With Uncertainty of  $2.0 \times 10^{-18}$

Editors' Suggestion

Featured in Physics

PHYSICAL REVIEW LETTERS 123, 033201 (2019)  
doi:10.1103/PhysRevLett.123.033201  
Published 15 July 2019

## $^{27}\text{Al}^+$ Quantum-Logic Clock with a Systematic Uncertainty below $10^{-18}$

S. M. Brewer,<sup>1,2,\*</sup> J.-S. Chen,<sup>1,2,†</sup> A. M. Hankin,<sup>1,2,‡</sup> E. R. Clements,<sup>1,2</sup> C. W. Chou,<sup>1</sup> D. J. Wineland,<sup>1,2,3</sup>  
<sup>1</sup>Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80305, USA  
<sup>2</sup>Department of Physics, University of Colorado, Boulder, Colorado 80309, USA  
<sup>3</sup>Department of Physics, University of Oregon, Eugene, Oregon 97403, USA

(Received 21 March 2019; revised manuscript received 17 May 2019; published 15 July 2019)



JILA, Nation  
2Nati

Information science.

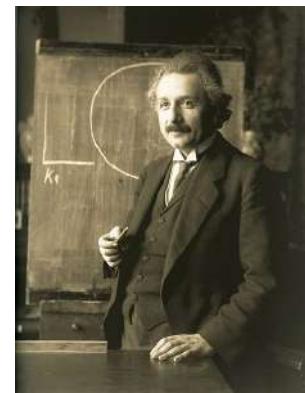
arXiv:1906

In fact already suggested by Maxwell (according to Lord Kelvin)

# Gravitational redshift

- Equivalence principle:

locally, gravitational field equivalent to acceleration



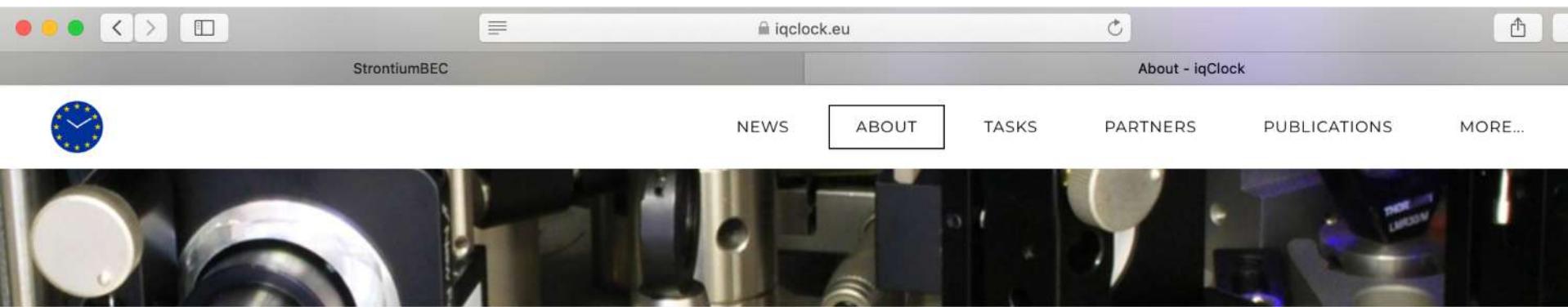
- Gravitational redshift:

$$\frac{\Delta\nu}{\nu} = \frac{g\Delta h}{c^2}$$

Numerical value:

$$\frac{g}{c^2} \approx 1.1 \times 10^{-16} \text{ m}^{-1}$$

# iqClock EU quantum flagship consortium

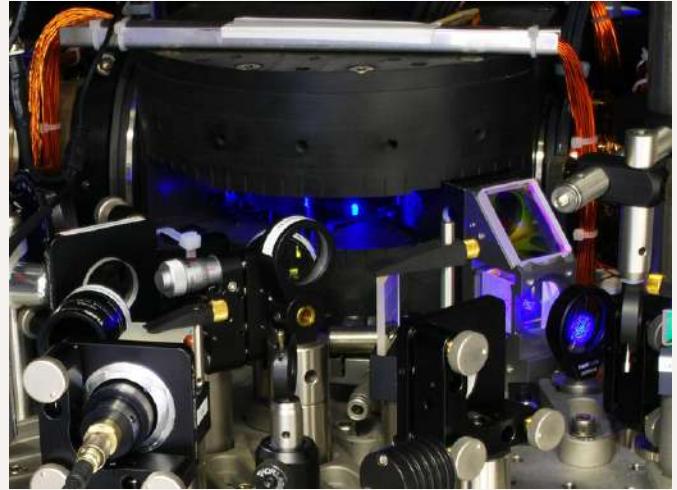


The screenshot shows a web browser window with the URL [iqclock.eu](http://iqclock.eu) in the address bar. The page title is "StrontiumBEC". On the right, there's a navigation menu with "ABOUT" highlighted in a box, along with links for "NEWS", "TASKS", "PARTNERS", "PUBLICATIONS", and "MORE...". A small European Union flag icon is in the top left corner.

## The goal of iqClock



A video player interface is shown. The video is from "FOLIA" and has the subtitle "Deze UvA-natuurkundige bouwt de allern...". Below the video, text reads: "De atomen schieten hier met honderden meters per seconde voorbij". The video controls include a play button, a timestamp (0:00), and buttons for "Watch later" and "Share".



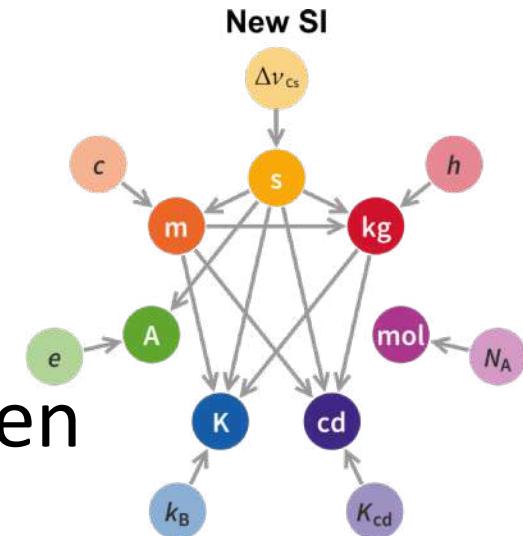
## Lab tours!

Optical clocks are amazingly stable frequency standards, which would be off by only one second over the age of the universe. Bringing those clocks from the laboratory into a robust and compact form will have a large impact on telecommunication (e.g. network synchronization, traffic bandwidth, GPS free

# Samenvattend

## Nieuwe SI (sinds 20 mei 2019)

- Gebaseerd op natuurconstanten
- Nieuwe methoden en verschijnselen
- Praktischer en preciezer
- BINAS moet herzien worden

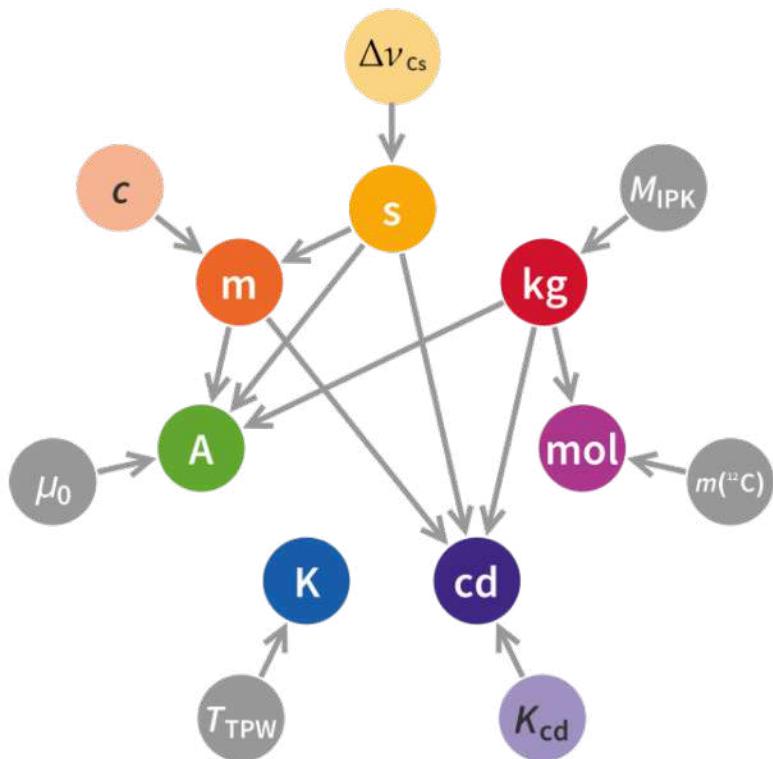


## De toekomst van ‘tijd’:

- Verschillende (optische) atoomklokken in de race
- De tijd zal het leren....

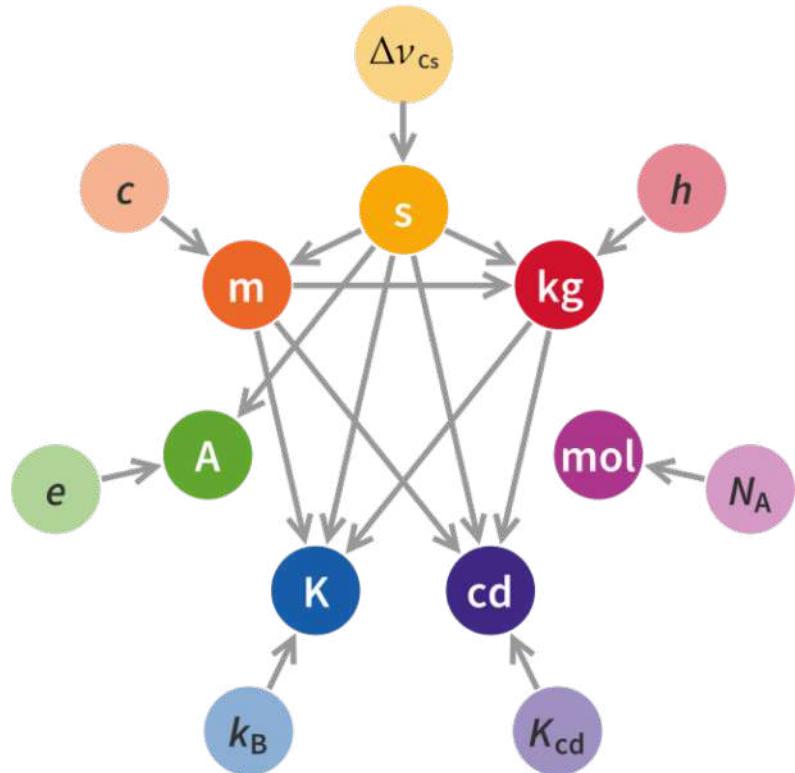
# Vragen?

Old SI



1983-2019

New SI



May 20, 2019

# Links

- Nieuwe SI:
  - [https://en.wikipedia.org/wiki/2019\\_redefinition\\_of\\_the\\_SI\\_base\\_units](https://en.wikipedia.org/wiki/2019_redefinition_of_the_SI_base_units)
  - IUPAP Public Session (ICAP 2018)  
<https://youtu.be/JsAPW27CeVY>
- Nieuwste waarden van natuurconstantes:
  - <http://physics.nist.gov/constants>
- Sr bij UvA:
  - [www.strontiumbec.com](http://www.strontiumbec.com)
  - <http://iop.uva.nl/qgqi> (en lab tours!)
- Precieze metingen bij VU:
  - [http://www.nat.vu.nl/en/research/atoms\\_molecules\\_lasers/index.aspx](http://www.nat.vu.nl/en/research/atoms_molecules_lasers/index.aspx)
- iqClock (EU project geleid door UvA):
  - [www.iqClock.eu](http://www.iqClock.eu)
  - Folia: <https://youtu.be/ryV922Jfqbg>