Our (current) view of the Universe

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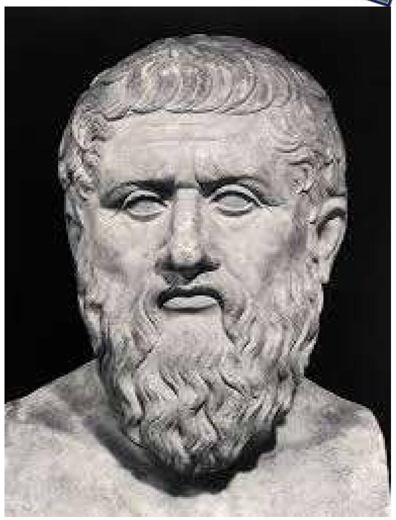
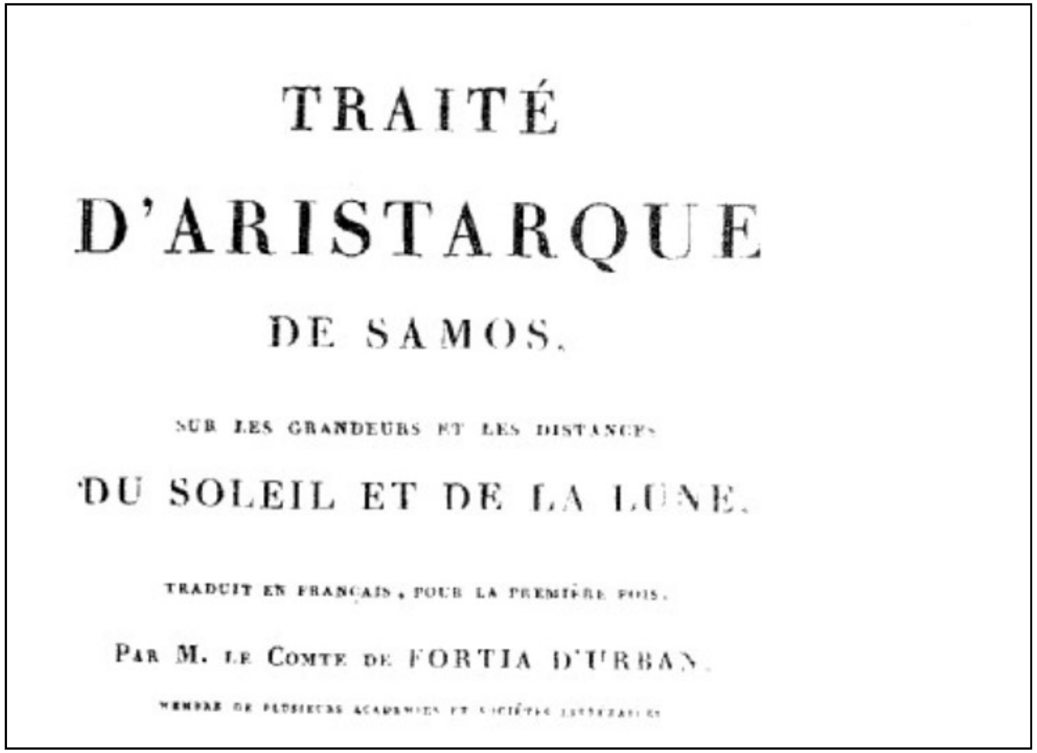
1. Introduction (10')
2. Modern science and fundamental constants (30')
3. Fundamental constants → **Planck** constants (30')
4. Interpretation (19')
5. The Universe as we know it today (1')

"When you change the way you look at things, the things you look at change" (Max Planck)

Turning point in physics (1)

Measuring Earth-Sun distance → Change our view of the Universe





TRAITÉ

D'ARISTARQUE

DE SAMOS,

SUR LES GRANDEURS ET LES DISTANCES

DU SOLEIL ET DE LA LUNE,

TRADUIT EN FRANÇAIS, POUR LA PREMIÈRE FOIS,

PAR M. LE COMTE DE FORTIA D'URBAN,

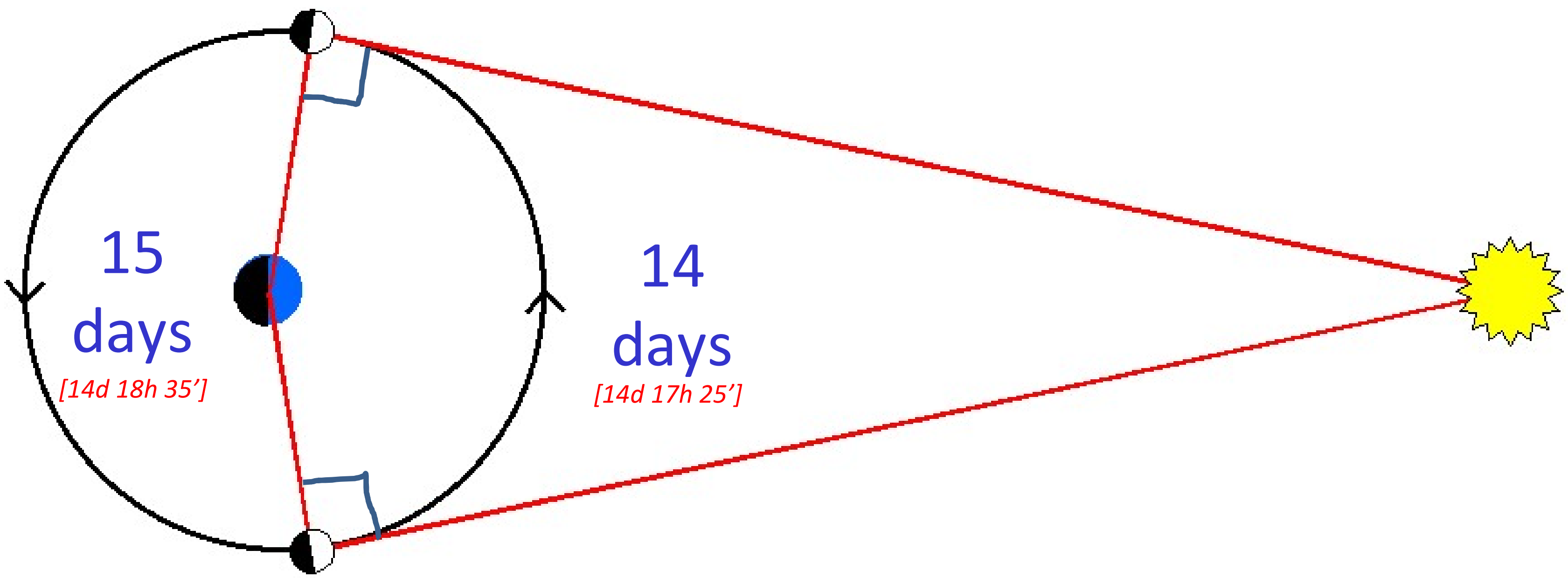
MEMBRE DE PLUSIEURS ACADÉMIES ET SOCIÉTÉS LITTÉRAIRES

Translated from ancient Greek to French (1823)

Turning point in physics (1)

[Values as of today]

Aristarchus measures a difference between LQ-FQ and FQ-LQ
→ Sun is not infinitely far from Earth



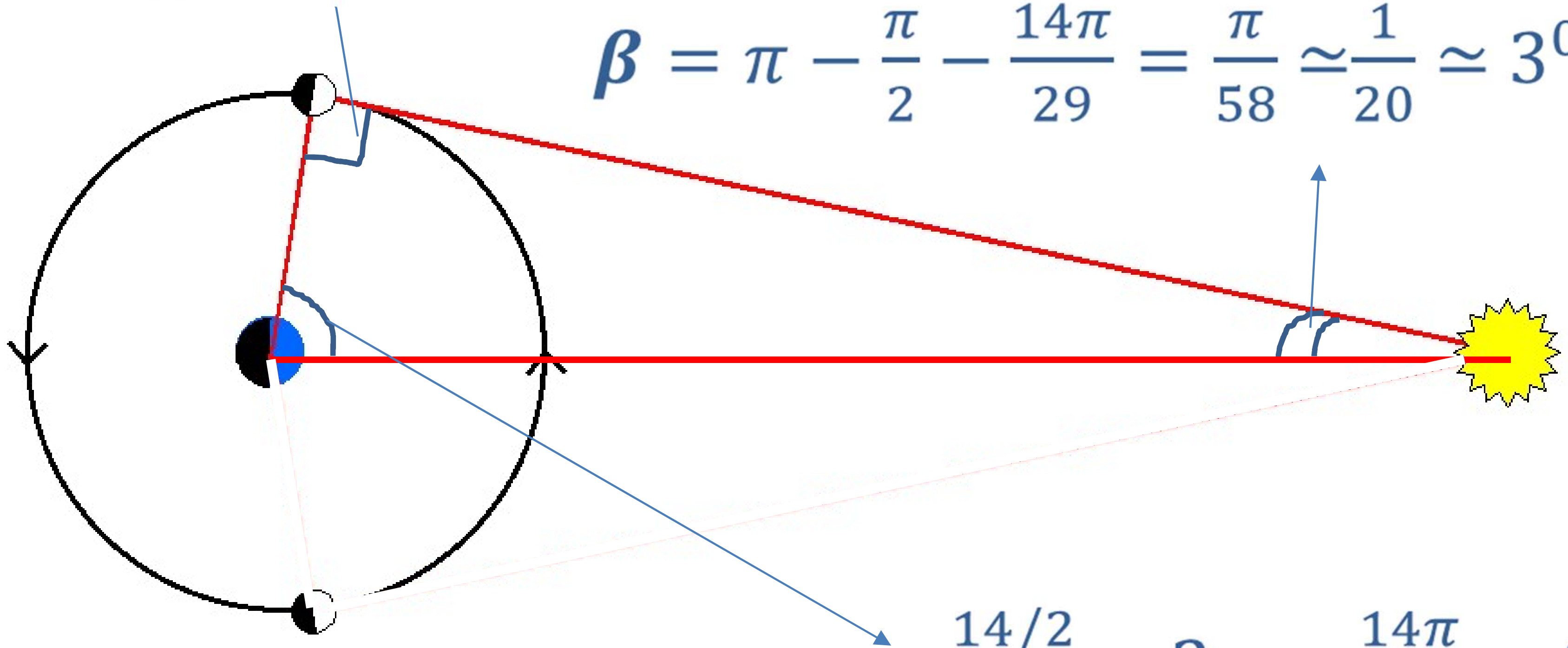
(Not to scale)

Turning point in physics (1)

[Values as of today]

$$\frac{\pi}{2} \simeq 90^0$$

$$\beta = \pi - \frac{\pi}{2} - \frac{14\pi}{29} = \frac{\pi}{58} \simeq \frac{1}{20} \simeq 3^0 \quad [0.15^0]$$



$$\frac{14/2}{14+15} * 2\pi = \frac{14\pi}{29} \simeq 87^0 \quad [89.85^0]$$

$$\sin\beta \approx \beta^* \text{ which gives } \frac{EM}{ES} \simeq \frac{1}{20} \quad [\frac{1}{387}]$$

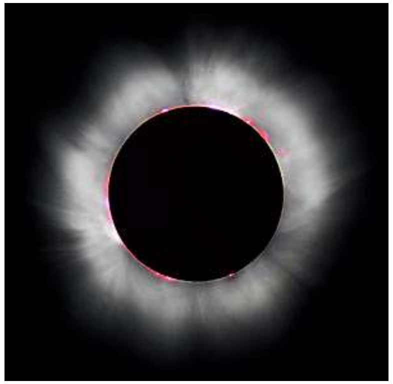
*Note that trigonometry was not yet invented so Aristarchus uses purely geometrical arguments

Turning point in physics (1)

[Values as of today]

As seen from the earth a sun eclipse tells us that $D_S = D_M$

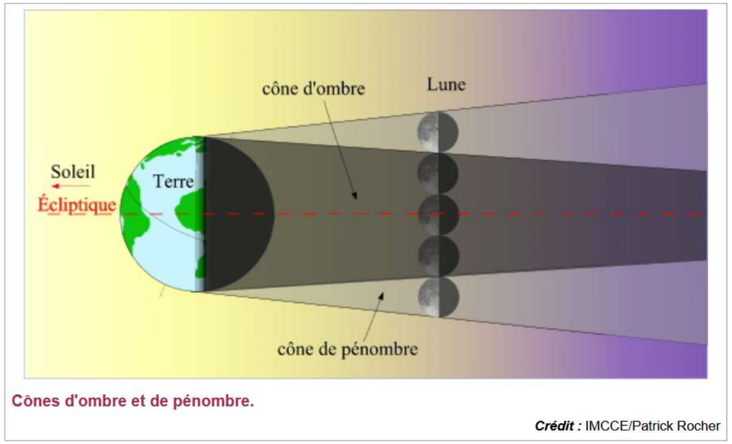
[$D_S = D_M$]



From Moon eclipse Aristarchus estimated

$D_M = 0.33\ D_E$

[$D_M = 0.273\ D_E$]



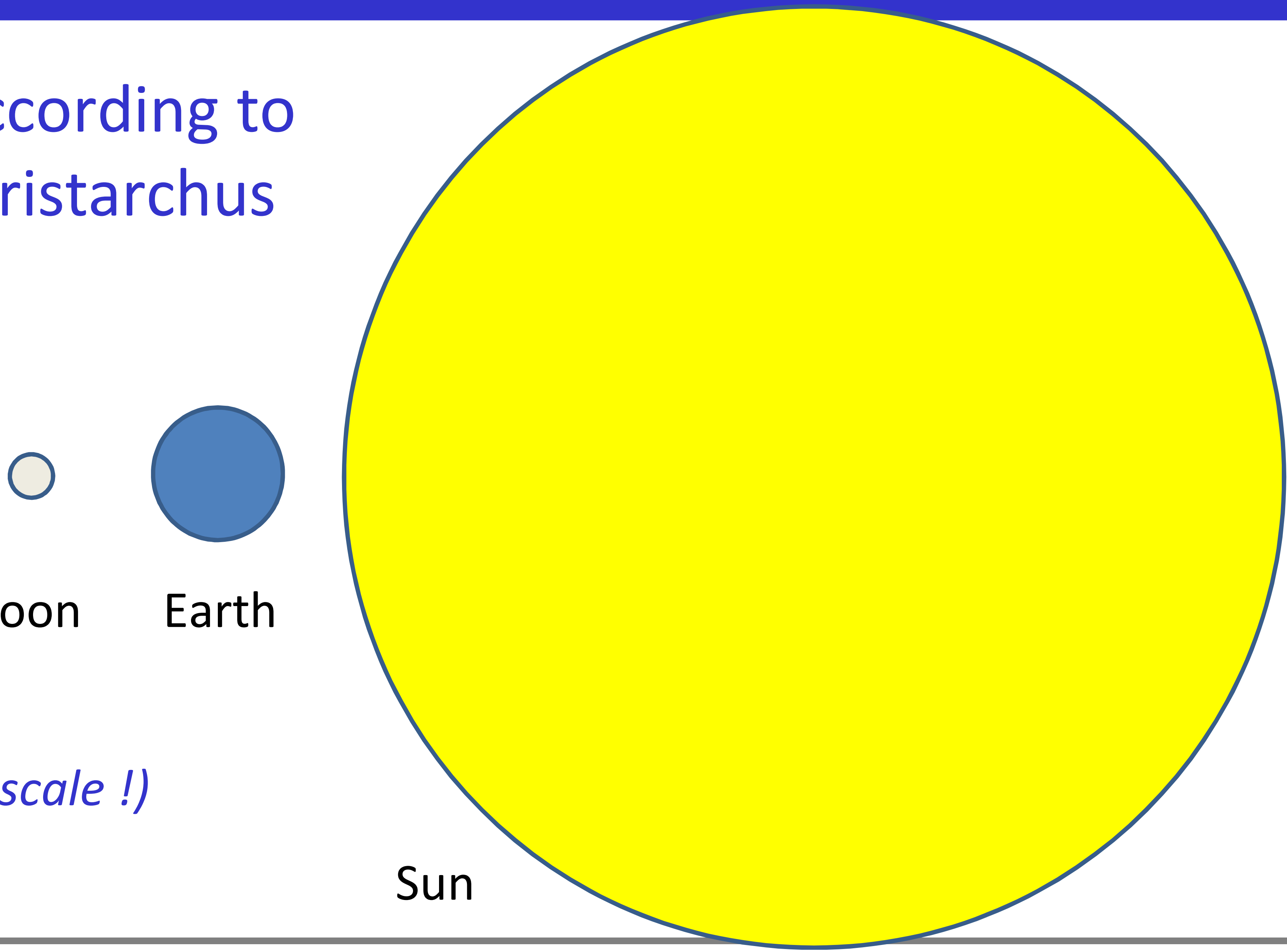
Pictures taken every 30'
(28-Aug 2007)

Sun diameter is therefore $D_S = 20 \times 0.33 \times D_E = 7\ D_E$

[$D_S = 110\ D_E$]

Turning point in physics (1)

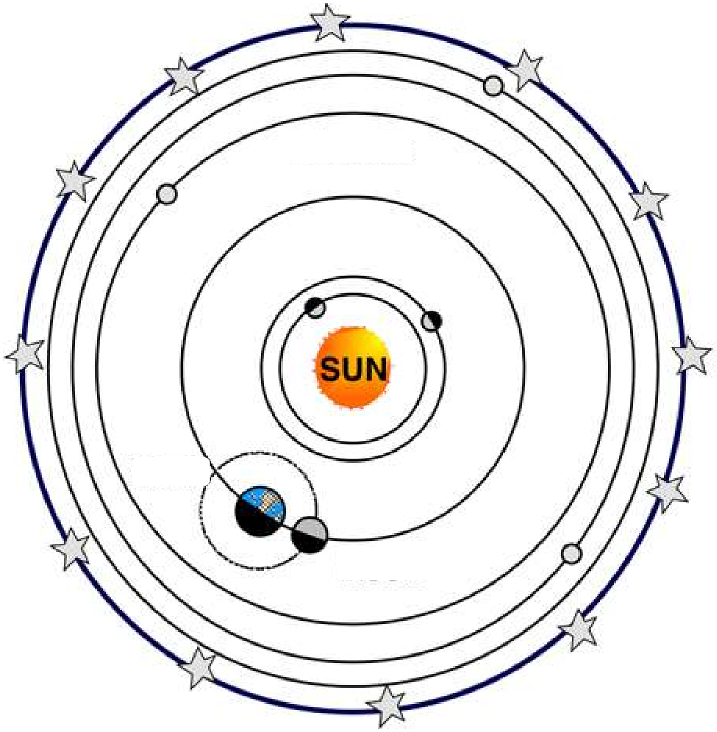
According to Aristarchus



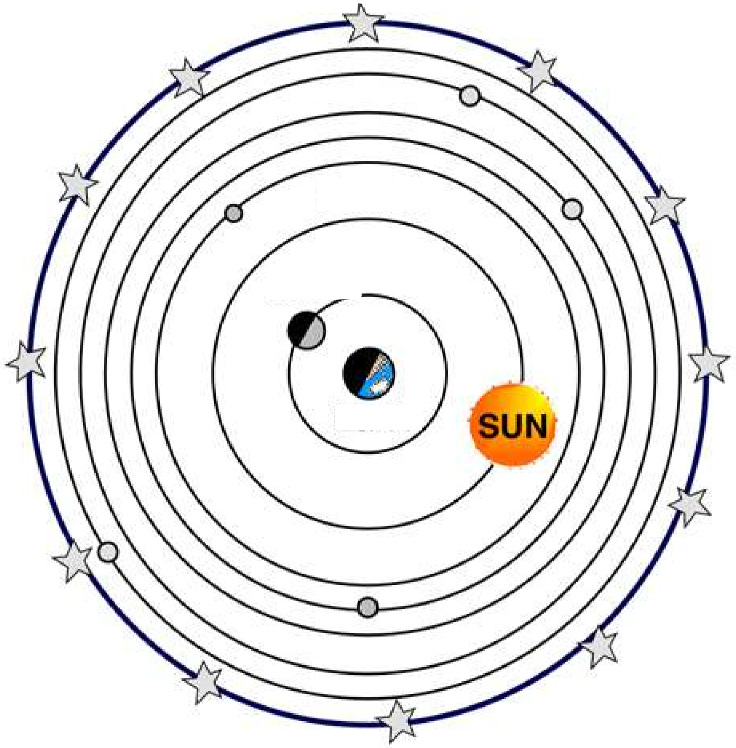
(to scale !)

Turning point in physics (1)

Aristarchus



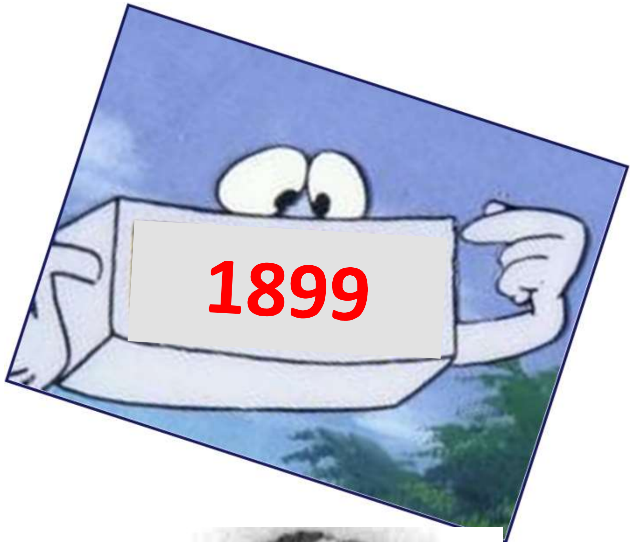
Archimedes, Aristotle



Aristarchus was correct, but geocentric model was retained … for ~2000 years (!)

Turning point in physics (2)

Why coal turn red when heated? → Change our view of the Universe



4. *Ueber irreversible Strahlungsvorgänge;*
von Max Planck.

(Nach den Sitzungsber. d. k. Akad. d. Wissensch. zu Berlin vom 4. Februar 1897, 8. Juli 1897, 16. December 1897, 7. Juli 1898, 18. Mai 1899 und nach einem auf der 71. Naturf.-Vers. in München gehaltenen Vortrage für die Annalen bearbeitet vom Verfasser.)

(Eingegangen 7. November 1899.)

Conclusion of the article (p.54)

Wählt man nun die „natürlichen Einheiten" so, dass in dem neuen Maasssystem jede der vorstehenden vier Constanten den Wert 1 annimmt, so erhält man als Einheit der Länge die Grösse:

$$\sqrt{\frac{bf}{c^3}} = \text{[redacted] cm},$$

als Einheit der Masse:

$$\sqrt{\frac{bc}{f}} = \text{[redacted] g},$$

als Einheit der Zeit:

$$\sqrt{\frac{bf}{c^5}} = \text{[redacted] sec},$$

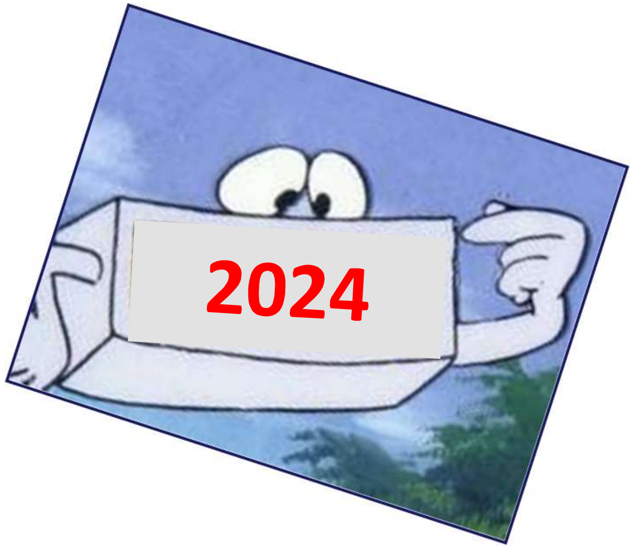
Unveiled p. 29 !

This paper allows to:

- summarize physics of the past (<1900)
- lay the foundations of modern physics (>1900)

Bonus: It took all XXth century to interpret the results !

Turning point in physics (2)



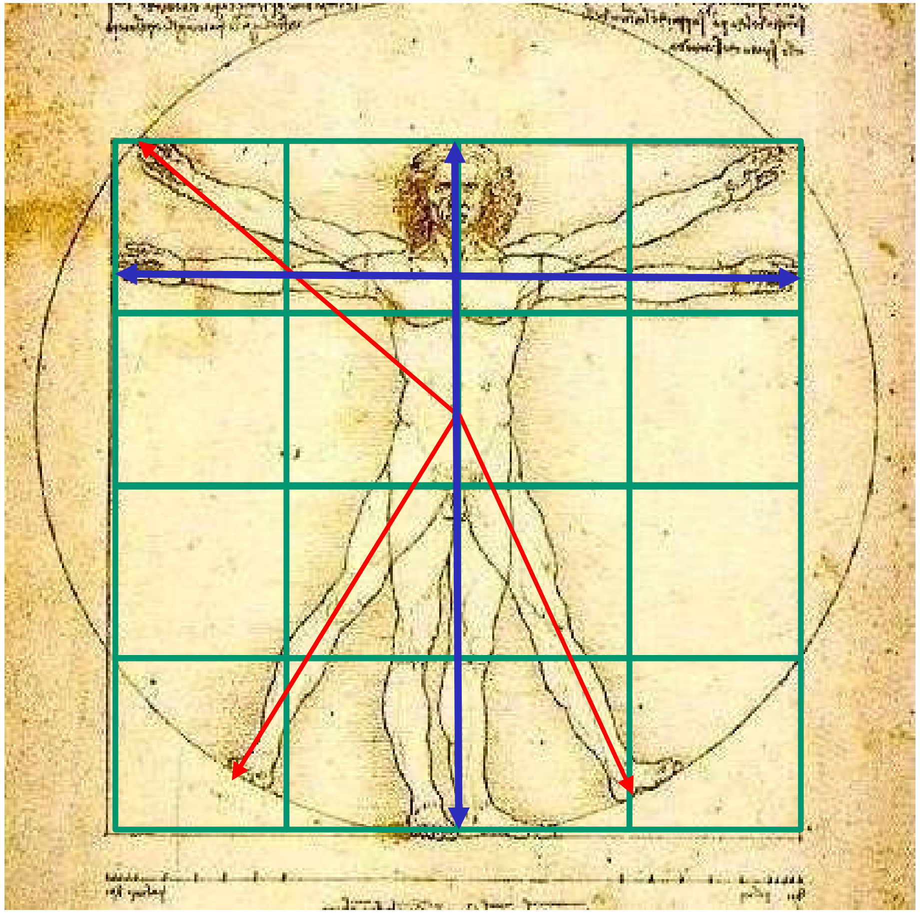
Today

- **I** will summarize physics of the past (<1900) 30’
- **You** will lay the foundations of modern physics (>1900) 30’
- **We** will make the interpretation 20’

Human

Which constant define us ?

Human



Vitruvian Man – Leonardo da Vinci (≈1490)

WingSpan
--------------- = **1**
Height

Note : Navel center of a circle with radius = Height/2

Guitar

Which constant(s) define a guitar ?

Guitar

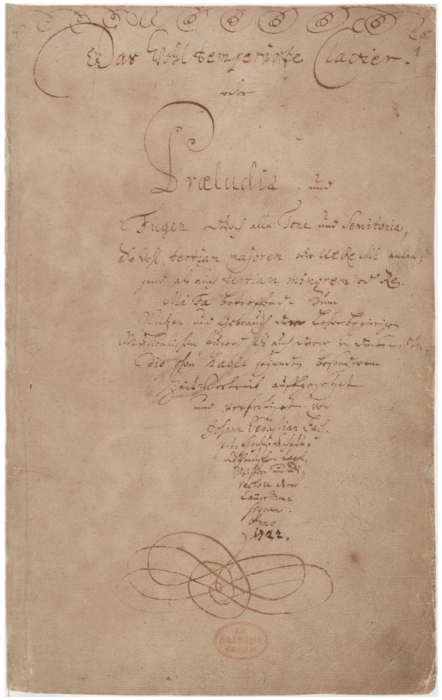
$$\left(\frac{3}{2}\right)^n = 2^p$$

1) How many of perfect fifths can fit p octave ?

Answer: no (n,p) solution exists to $3^n = 2^{n+p}$

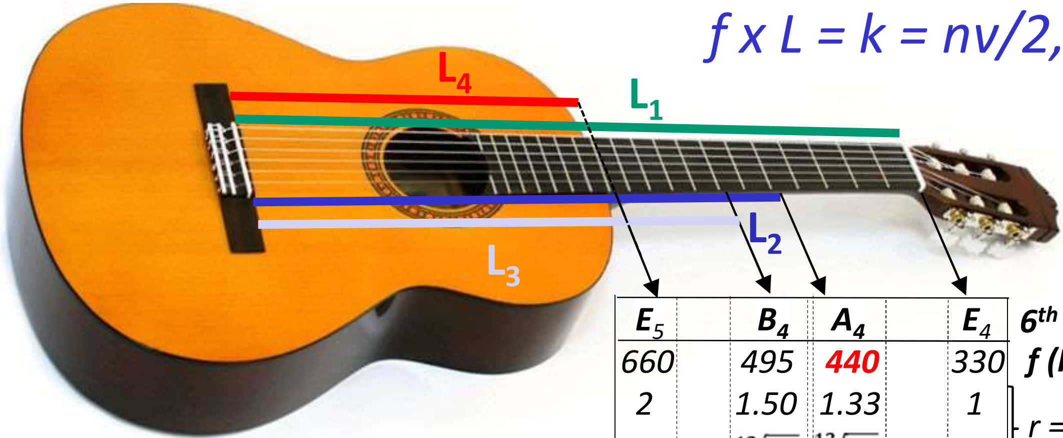
Best affordable approximation *:

- n=12, p=7 *[129.7 = 128 @ 1%]* → 12 notes in one octave
- Using r = *f*(Note n+1) / *f*(Note n) = cte, *f =frequency*
- $r^{12} = 2$ → r = $\sqrt[12]{2} \approx 1.059$



Well-Tempered Clavier
(1rst book 1722)

$f \times L = k = nv/2$, $n \in N^*$



	E_5	B_4	A_4	E_4	*6^{th} string*
	660	*495*	***440***	*330*	***f (Hz)***
	2	*1.50*	*1.33*	*1*	*r = f / f(E_4)*
		$\sqrt[12]{2^7}$	$\sqrt[12]{2^5}$		
	325	*434*	*486*	*650*	***L (mm)***
	0.5	*0.66*	*0.75*	*1*	*$L_n / L_1 = 1/r$*

2) Arbitrary **L = 650 mm**

** (n=3, p=5) @5% and (n=31,p=53)@0.2% also possible*

Fundamental constants

What about the Universe ?????

How to measure L, T, M ?

Space | Time | Matter

Length (L)	Time (T)	Mass (M)
• Finger • Hand • Feet • Forearm • Farm units → **inch, foot, yard** → **mile**	• Heart beat (≈1s) • day / night • Moon cycle • Season cycle (360 days) • Tropical year (365.25 days) → **Water clock** → **Day, year**	• Grain • Food container → **grain, ounce, pound…**

+ : practical

- : not precise and not universal (depends on the region)

Human related measurement

How to measure L, T, M ?

Metric units introduced to harmonize the units among French regions

Length and Mass from French revolution (1792-99)

- Under Lavoisier guidance, put in place a decimal system (dm, cm, mm, dg, hg, kg) 18 germinal an III (7 april 1795)

Time

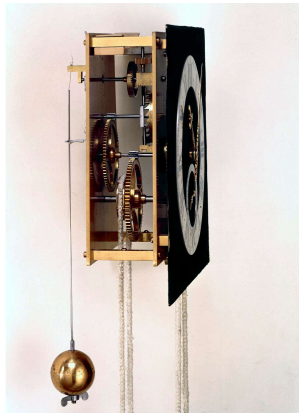
- benefits from the clock's development in XVIIth century

(36 Rue de Vaugirard Paris)

Defined as the ten millionth part of ½ of the earth's meridian, first precisely measured by Picard in 1669

[1 kg platinum standard]

One gram is defined as the absolute weight of a volume of pure water equal to the cube of the hundredth part of a meter, and at the temperature of melting ice. **Water density= 10^3 kg.m^{-3}**



[pendulum clock]

… and the division of time on the basis of the solar year (360+5 days for the Egyptians) and the base 60 of the Sumerian system (24 hours, 60 minutes, 60 seconds).

How to measure L, T, M ?

Length (L)	Time (T)	Mass (M)
→ Decimal 1/10^7 of the North part of the meridian: 40 000 km / 4 / 10^7 = 10^{-3} km → **Meter**	→ Sexagesimal 1/86400 part of the solar day → **Second**	→ Decimal Mass of water in a cube of 1 cm. Water density= 1 g.cm^{-3} → **Gram**

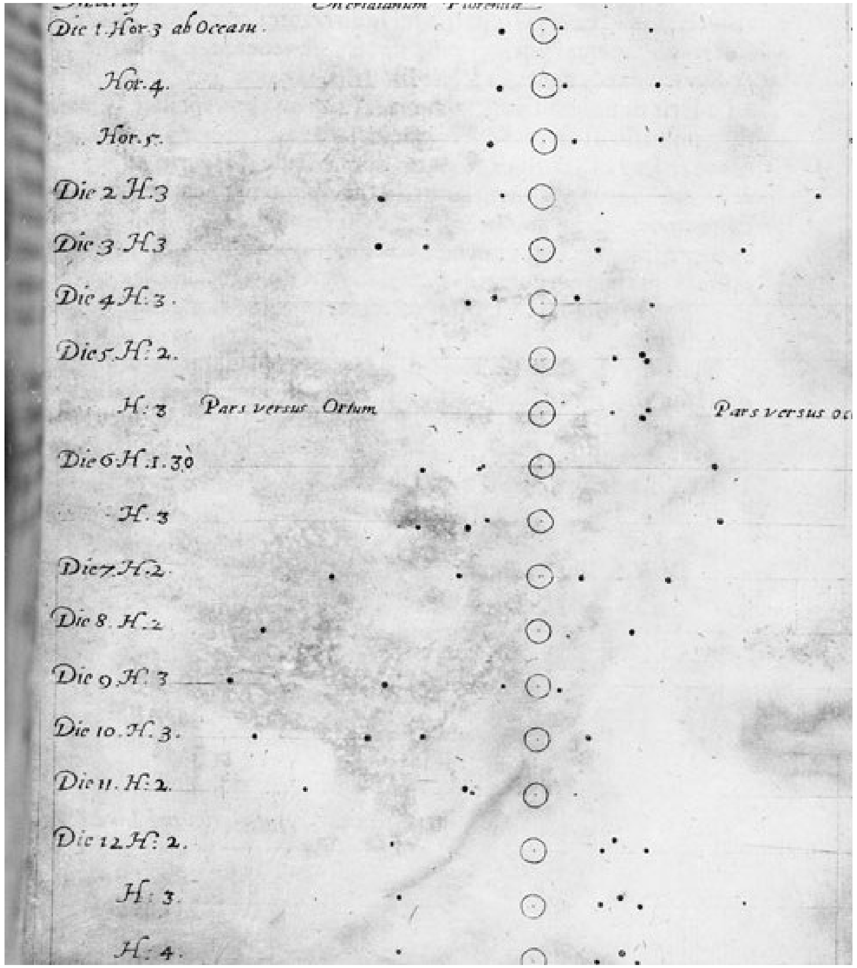
+ : practical, precise

- : not universal (geocentric)

Earth related measurement

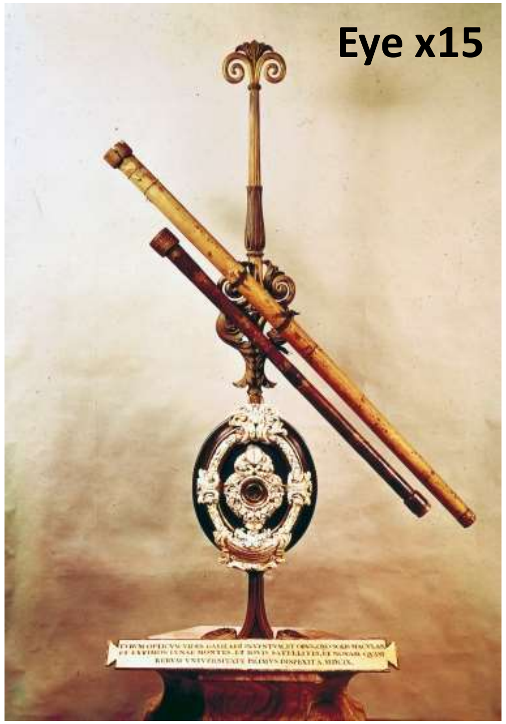
Fundamental Constant (1)

Speed of light (c)



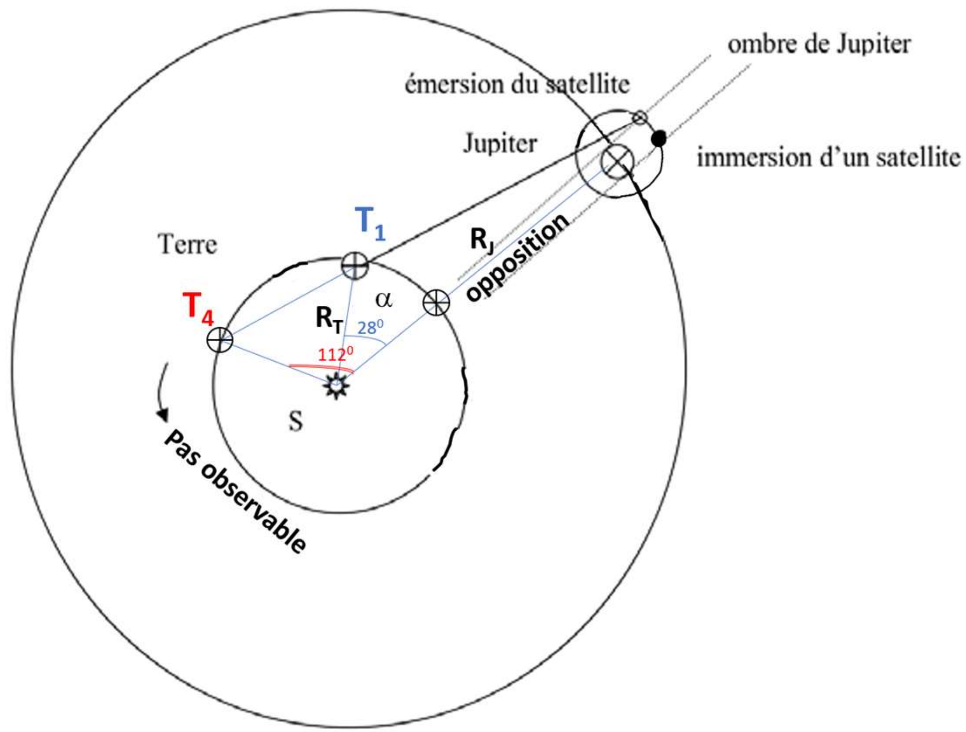
Sidereus Nuncius (Mar 1610)

Galileo uses **telescope** to discover Jupiter Moons (Jan-Mar 1610)

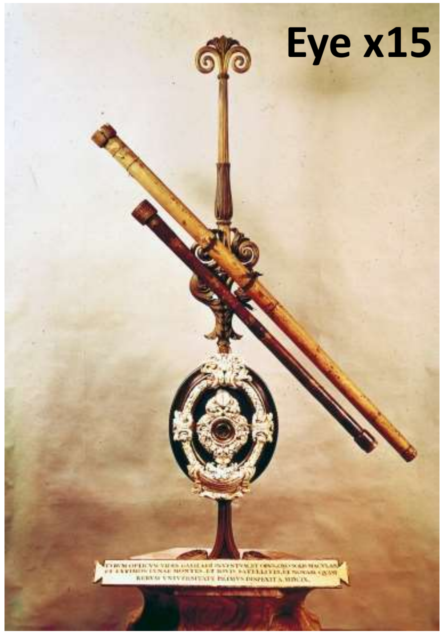


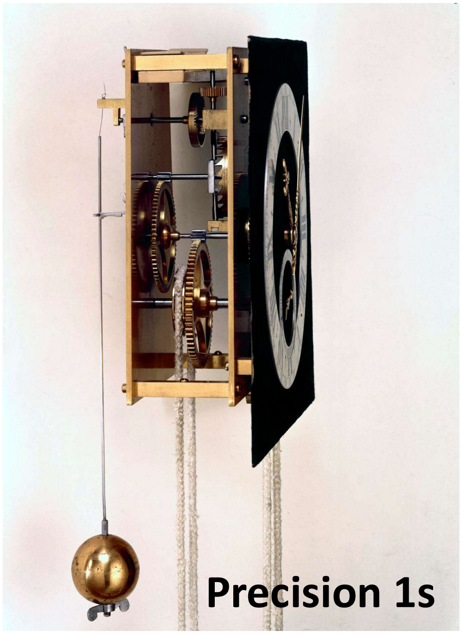
Fundamental Constant (1)

Speech of light (c)



Ole Romer uses a **telescope** and a **pendulum clock** to measure time of Jupiter Moon Io emersion (1670-76)
→ **42.5** hours for one rotation

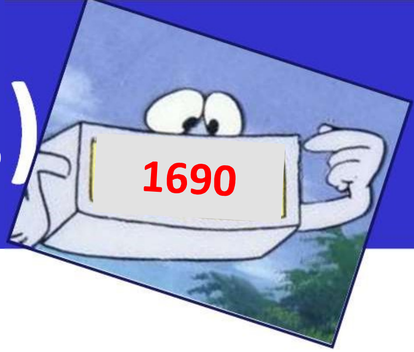




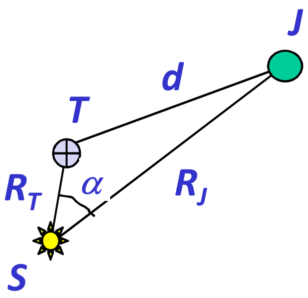
Romer predicts that Io emersion will arrive 10' (600 s) later when Earth is in T4 than when he measured it in T1

Published 7 Dec 1676 in «Journal des sçavans»

Fundamental Constant (1)



Speed of light (c)

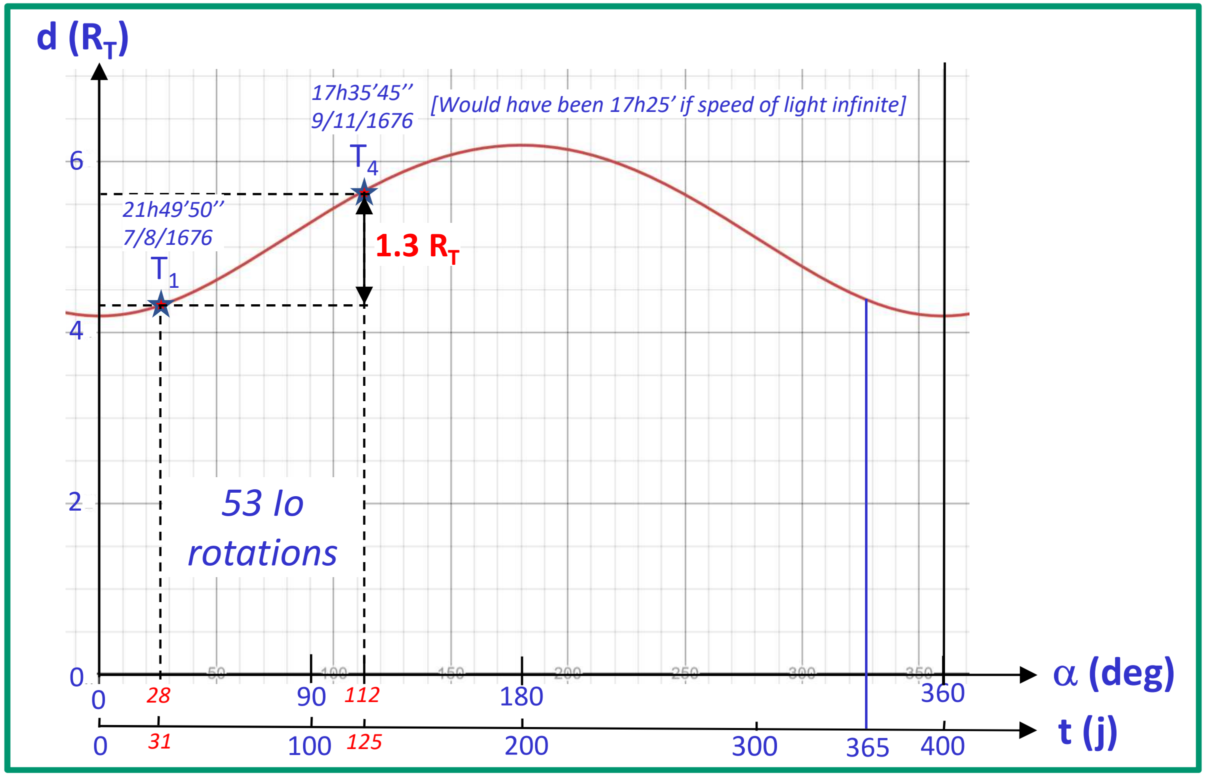


$TJ^2 = d^2 = R_T^2 + R_J^2 - 2R_JR_T\cos(\alpha)$

$R_J = (P_J/P_T)^{2/3} R_T = 5.2 R_T$ (P_J=11.8 yr)

$\rightarrow d = R_T\sqrt{28-10.4\cos(\alpha)}$

Evolution of Earth – Jupiter distance between two oppositions



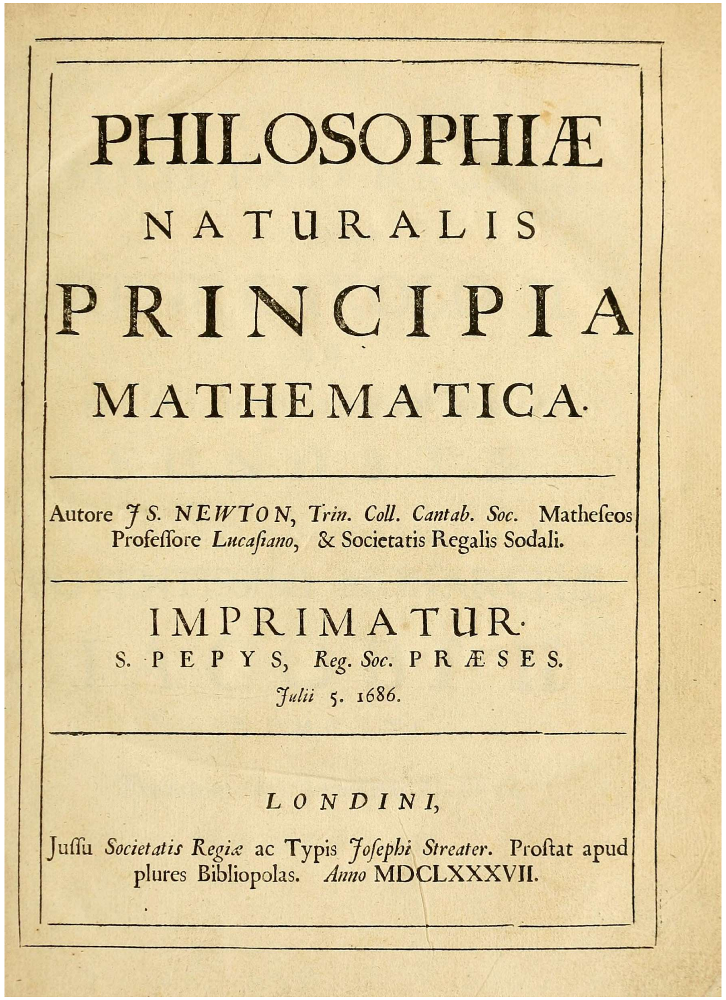
$c = 1.3\ R_T/600 \approx$ **300 000 km/s = 3 10^8 m.s^{-1}**

150 000 000 km

1690

Huyghens

Gravitational constant (G)



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

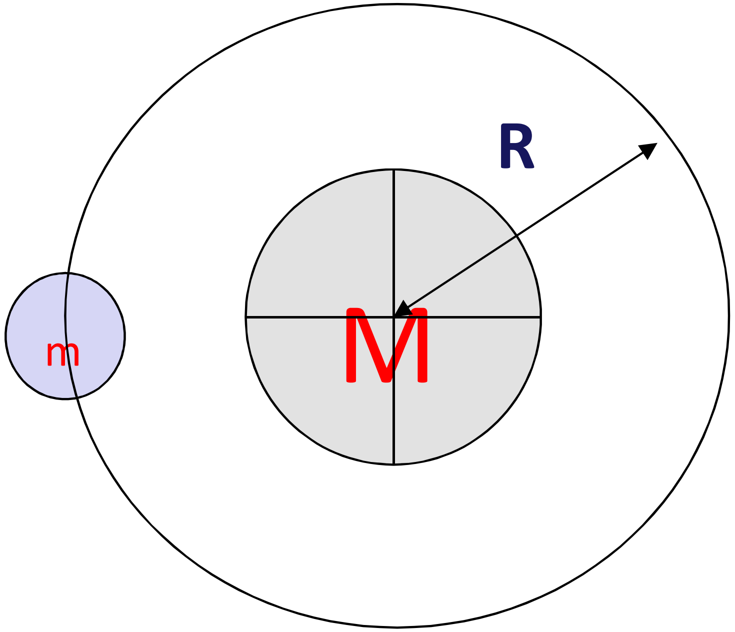
Autore J S. NEWTON, *Trin. Coll. Cantab. Soc.* Matheſeos Profeſſore *Lucaſiano*, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,

Juſſu *Societatis Regiæ* ac Typis *Joſephi Streater*. Proſtat apud plures Bibliopolas. *Anno* MDCLXXXVII.

Isaac Newton developed a mathematical theory of the attraction between two objects using infinitesimal calculus (1687)



Fundamental Constant (2)

Gravitational constant (G)

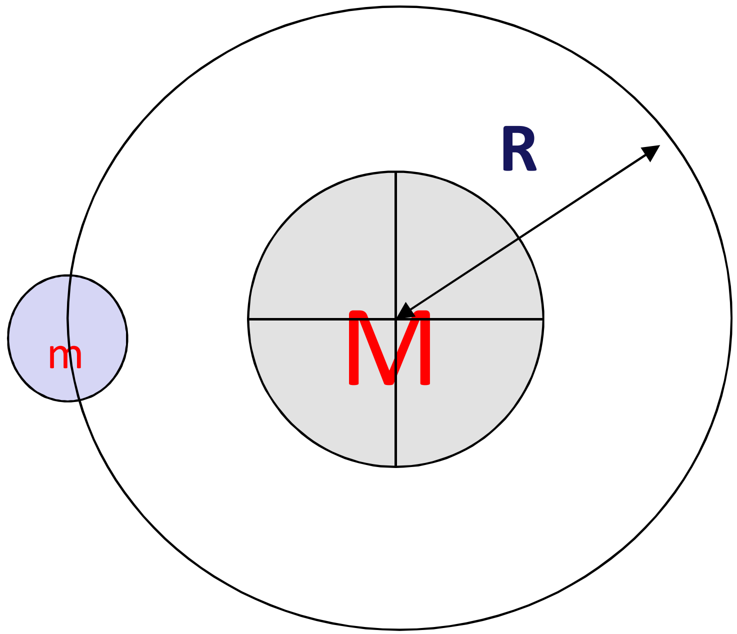
Newton 2nd law : F = m a → kg m s^{-2}

Newton universal gravitation :

$$F \propto \frac{m\,M}{R^2} \rightarrow \text{kg}^2\ \text{m}^{-2}$$

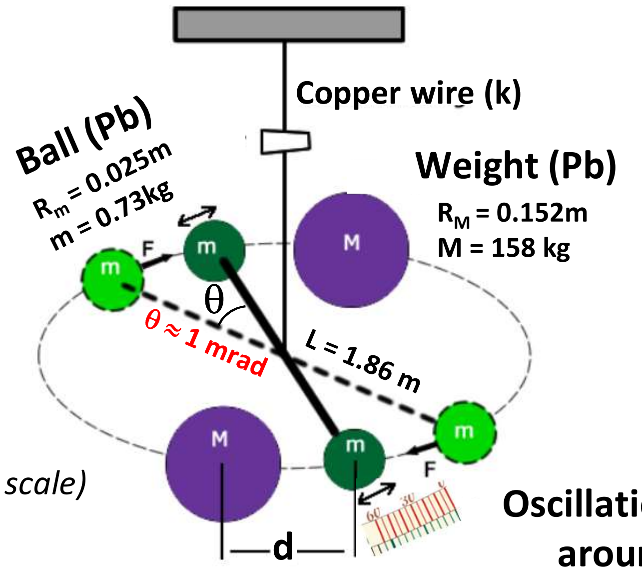
Need a constant G to restore the units

[G] = **kg m s^{-2} / (kg^2 m^{-2}) = kg^{-1} m^3 s^{-2}**



Fundamental Constant (2)

Gravitational constant (G)



Henry Cavendish makes the first measurement of G (**1798**), writing first modern experimental paper (60 pages), including systematics

At equilibrium of the 2 forces :

$$F_{grav} = G\frac{mM}{d^2} = \frac{2\pi^2 mL\theta}{T^2}$$

$$G = 2\pi^2 \frac{L}{M}\frac{\theta d^2}{T^2}$$

$G = 6.67\text{x}10^{-11}\text{kg}^{-1}.\text{m}^3.\text{s}^{-2}$

Torque: F L= $k\,\theta$ *(like a spring with a constant k)*

Moment of Inertia of the 2 balls: $J = 2m(L/2)^2 = mL^2/2$

Angular speed: $\omega = \frac{2\pi}{T} = \sqrt{\frac{k}{J}}$ *(like a pendulum* $\sqrt{\frac{g\,(m.s^{-2})}{l\,(m)}} = \sqrt{\frac{10}{l}}$*)*

→ $k = 2\pi^2 mL^2/T^2$ → $F = 2\pi^2 mL\theta/T^2 \approx 10^{-7}$ N

To be exact, Cavendish did not compute G, it was done a century later – but he could have !

Fundamental Constant (3)

Planck constant (h)

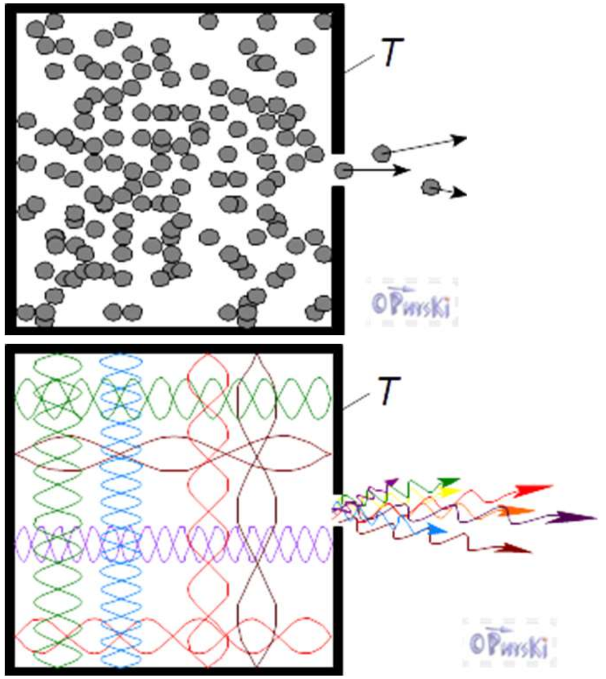
Long standing question: how can the steel or the coal change color when it is heated ?

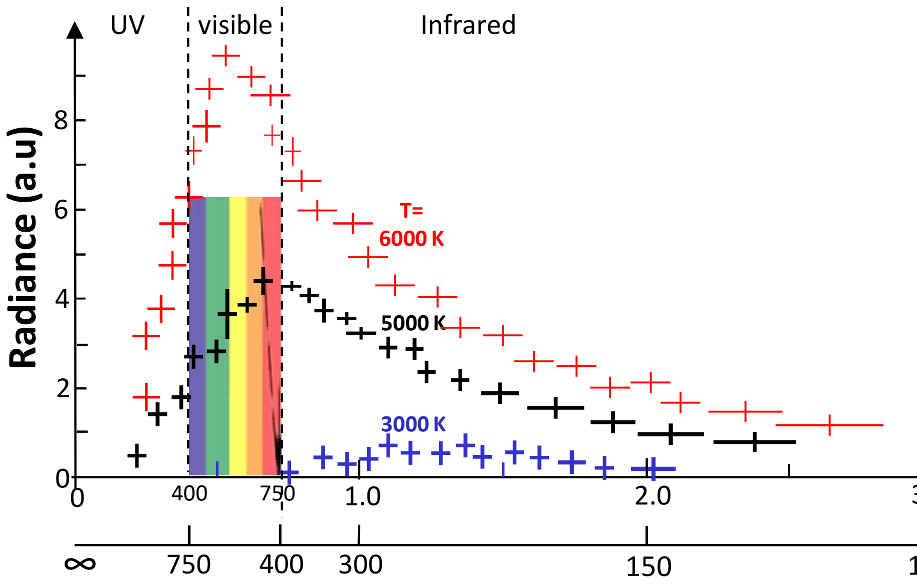
Fundamental Constant (3)

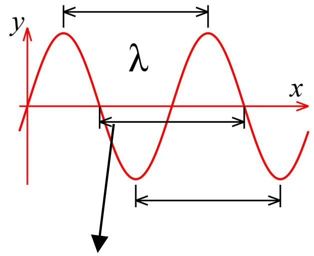
Planck constant (h)

XIXth century: atomic theory of heat (statistical thermodynamic) + development of electromagnetism (mediated by light) + measurements of (ideal) black body radiations

→ **Measurements described by an Universal law** *(Kirchhoff, 1867)* → **function?**

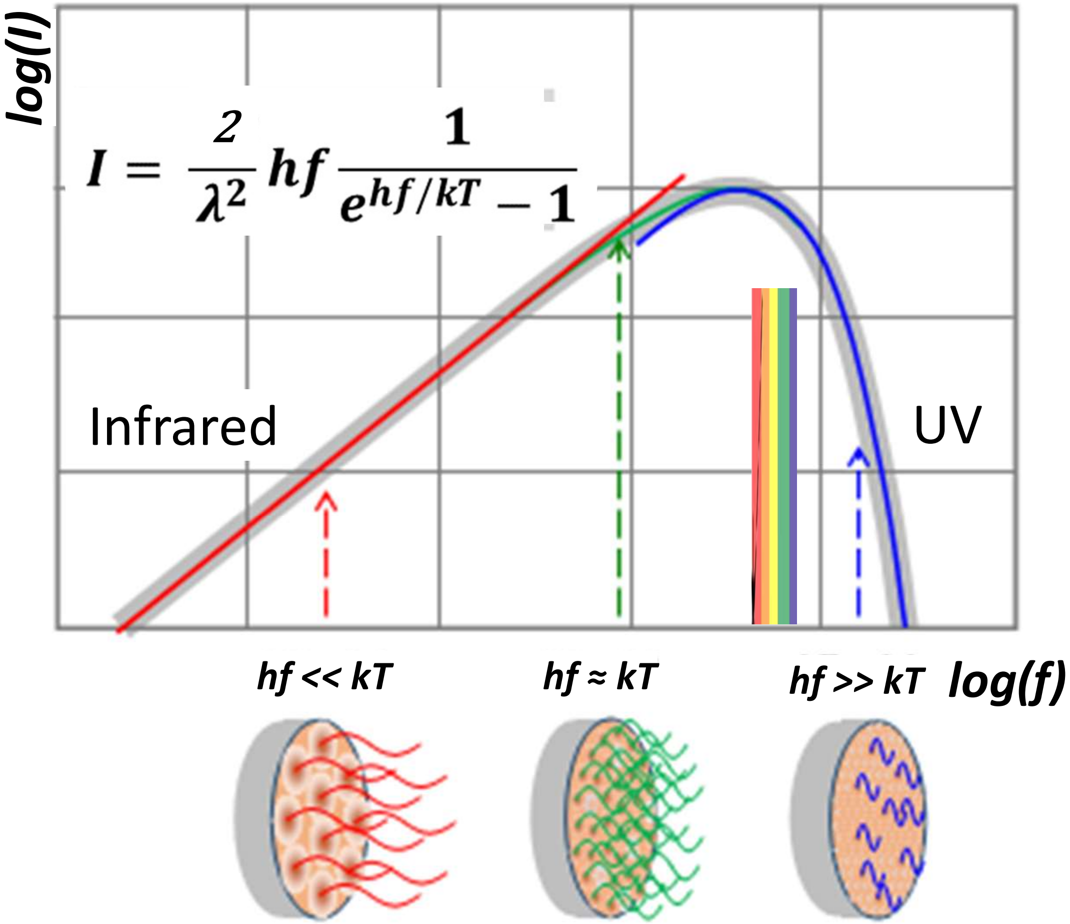






Fundamental Constant (3)

Planck constant (h)

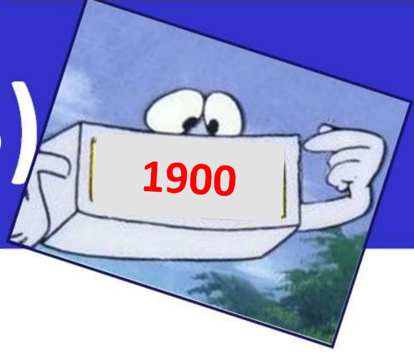


$$I \approx \frac{2}{\lambda^2} kT = \frac{2\,kT}{c^2} f^2 \qquad I \approx \frac{2\,h}{1.7c^2} f^3 \qquad I \approx \frac{2}{\lambda^2} hf\, e^{-\frac{hf}{kT}} = \frac{2\,h}{c^2} f^3\; e^{-\frac{hf}{kT}}$$

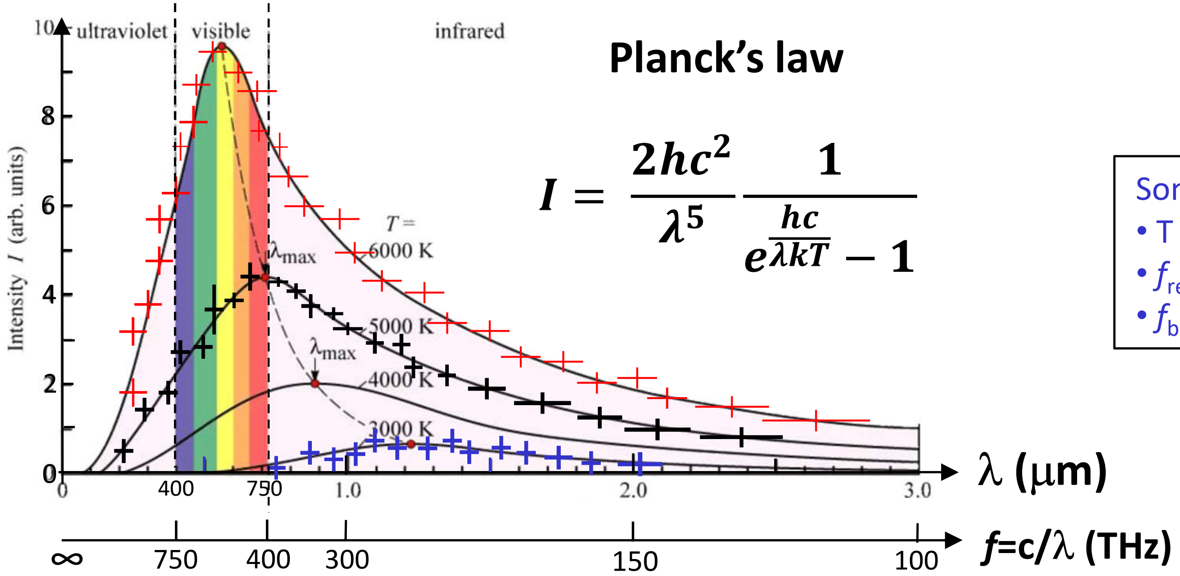
Planck discovered the law in **1900** saying that **atoms** are **harmonic oscillators** with **E = h*f***. Probability of light emission at frequency *f* depends on temperature which corresponds to **E = kT**:

- **h*f* << kT** : growing probability to emit light of frequency *f*
- **h*f* >> kT** : low probability to emit light of frequency *f*

Fundamental Constant (3)



Planck constant (h)



Planck's law

$$I = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda kT}} - 1}$$

Some numbers for the Sun (more in back-up):
- T = 5800 K → E = kT ≈ 1 10^{-19} kg.m^2.s^{-2}
- f_{red} = 430x10^{12} Hz → E = hf ≈ 3 10^{-19} kg.m^2.s^{-2}
- f_{blue} = 750x10^{12} Hz → E = hf ≈ 5 10^{-19} kg.m^2.s^{-2}

The measurements (1900) allow to determine the value of h (and k)

- **h = 6.6 10^{-34} kg.m^2.s^{-1}**
- k = 1.4 10^{-23} kg.m^2.s^{-2}.K^{-1}

Fundamental constants → Universe ?

***3* fundamental constants (« universal ») known**

- Speed of light : **c** $= [L]^1 \times [T]^{-1} = 3.0\ 10^{8}\ m.s^{-1}$
- Gravitational constant : **G** $= [L]^3 \times [T]^{-2} \times [M]^{-1} = 6.7\ 10^{-11}\ m^3.s^{-2}.kg^{-1}$
- Quanta dynamics : **h** $= [L]^2 \times [T]^{-1} \times [M]^{1} = 6.6\ 10^{-34}\ m^2.s^{-1}.kg$

+ : practical, precise, universal (!)

Use these constants to deduce a characteristic length ($L_P = [L]$), a time ($T_P = [T]$) and a mass ($M_P = [M]$)

Universal constants → Universe ?

***3* fundamental constants (« universal ») known**

- Speed of light : **c** = $[L]^1 \times [T]^{-1}$ = $3.0\ 10^{8}$ $m.s^{-1}$
- Gravitational constant : **G** = $[L]^3 \times [T]^{-2} \times [M]^{-1}$ = $6.7\ 10^{-11}$ $m^3.s^{-2}.kg^{-1}$
- Quanta dynamics : **h** = $[L]^2 \times [T]^{-1} \times [M]^{1}$ = $6.6\ 10^{-34}$ $m^2.s^{-1}.kg$

$$L_P = \sqrt{\frac{Gh}{c^3}} = \sqrt{\frac{40\times10^{-45}}{27\times10^{24}}} = \sqrt{1.5\times10^{-69}} = \sqrt{15\times10^{-70}} = \mathbf{4\times10^{-35}\ m}$$

$$\sqrt{\frac{b\,f}{c^3}} = 4{,}13\,.\,10^{-33}\ \text{cm},$$

$$t_P = \sqrt{\frac{Gh}{c^5}} = \sqrt{\frac{40\times10^{-45}}{243\times10^{40}}} = \sqrt{0.15\times10^{-85}} = \sqrt{1.5\times10^{-86}} = \mathbf{1.2\times10^{-43}\ s}$$

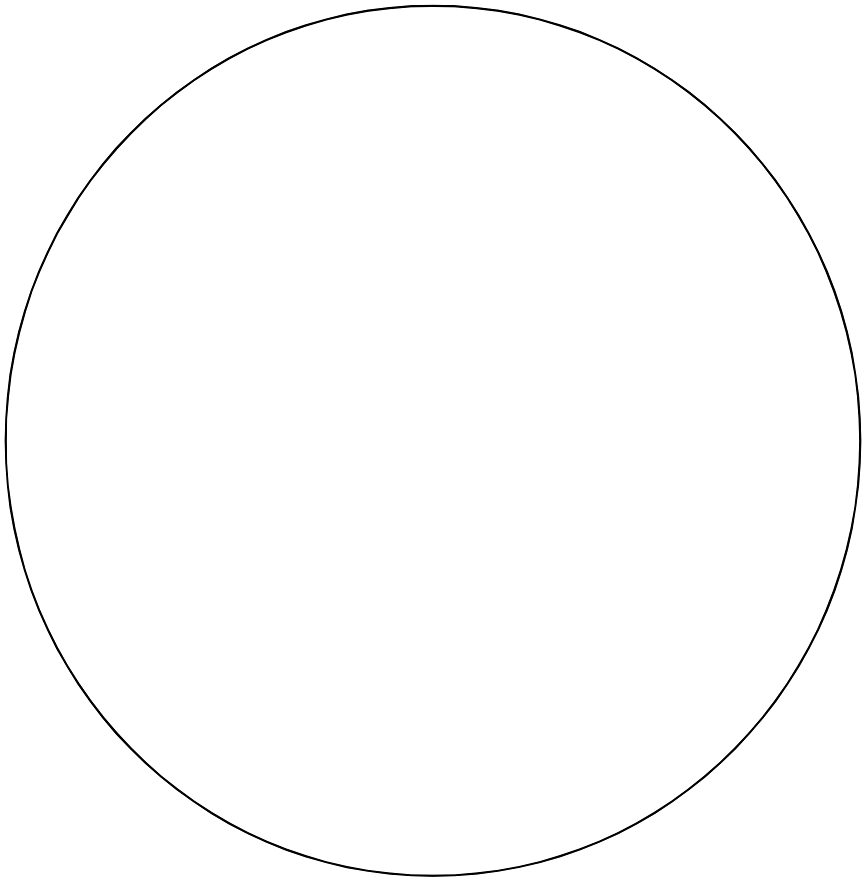
$$\sqrt{\frac{b\,f}{c^5}} = 1{,}38\,.\,10^{-43}\ \text{sec},$$

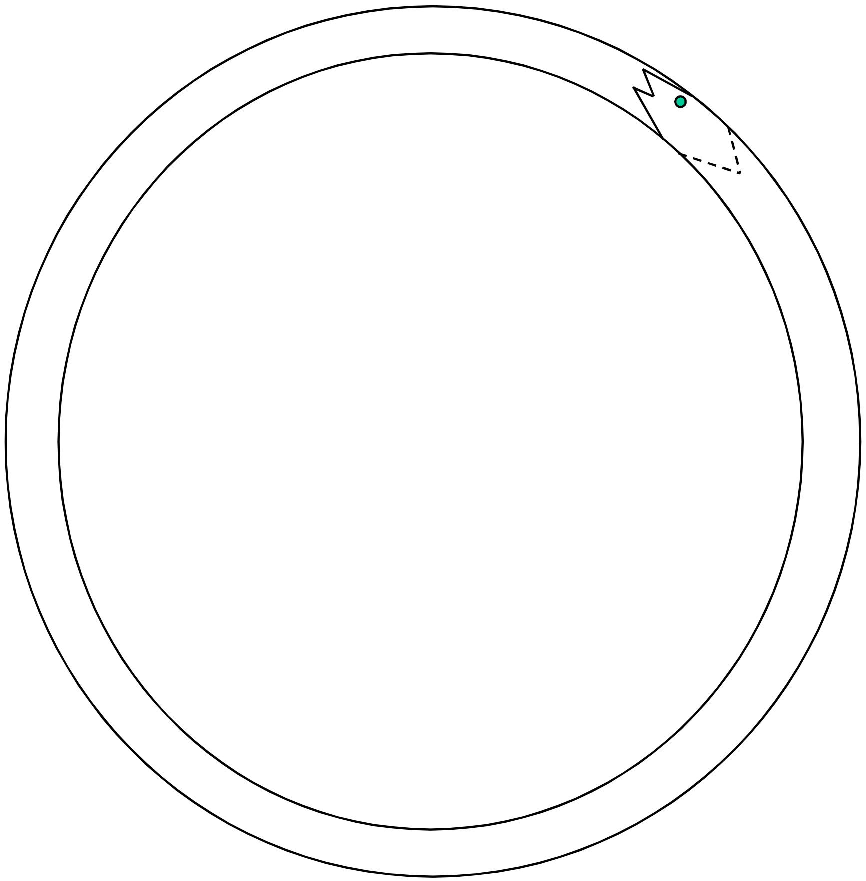
$$M_P = \sqrt{\frac{hc}{G}} = \sqrt{\frac{20\times10^{-26}}{6.7\times10^{-11}}} = \sqrt{3\times10^{-15}} = \sqrt{30\times10^{-16}} = \mathbf{5.5\times10^{-8}\ kg}$$

$$\sqrt{\frac{b\,c}{f}} = 5{,}56\,.\,10^{-5}\ \text{g},$$

Interpretation

$$L_P = \sqrt{\frac{Gh}{c^3}} = \sqrt{\frac{40\times10^{-45}}{27\times10^{24}}} = \sqrt{1.5\times10^{-69}} = \sqrt{15\times10^{-70}} = \mathbf{4\times10^{-35}\ m}$$





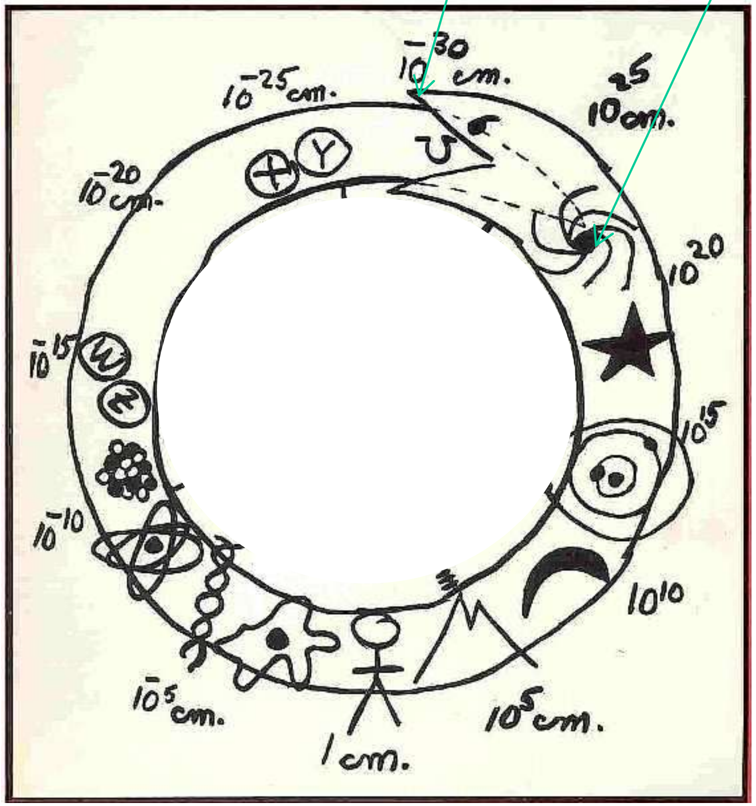
Interpretation

$$L_P = \sqrt{\frac{Gh}{c^3}} = \sqrt{\frac{40\times10^{-45}}{27\times10^{24}}} = \sqrt{1.5 \times 10^{-69}} = \sqrt{15 \times 10^{-70}} = \mathbf{4 \times 10^{-35}\ m}$$

$c \times T_U =$
$3.10^8 \times (1.5\ 10^{10} \times 3.10^7)$
$= 10^{26}$ m

Observable Universe: 10^{28}cm

≈ 10^{-33}cm



S. Glashow serpent swallowing its tail
New York Times Magazine, Sept. 26, 1982, p. 40

Interpretation

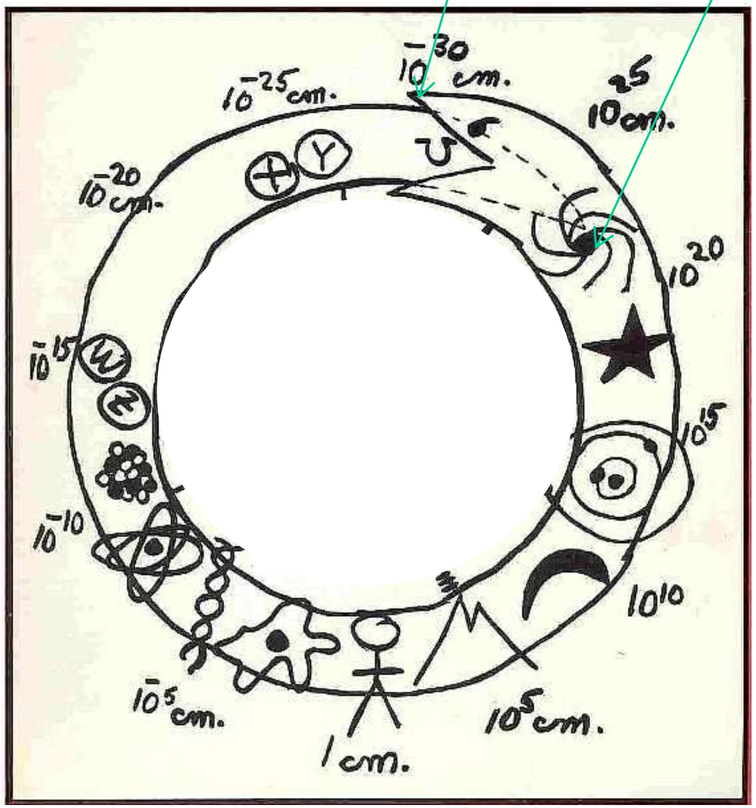
$$t_P = \sqrt{\frac{Gh}{c^5}} = \sqrt{\frac{40\times10^{-45}}{243\times10^{40}}} = \sqrt{0.15\times10^{-85}} = \sqrt{1.5\times10^{-86}} = \mathbf{1.2\times10^{-43}\ s}$$

Universe: 10^{18}s

≈ 10^{-43}s

$T_U = 1.5\ 10^{10} \times 3.10^{7}$

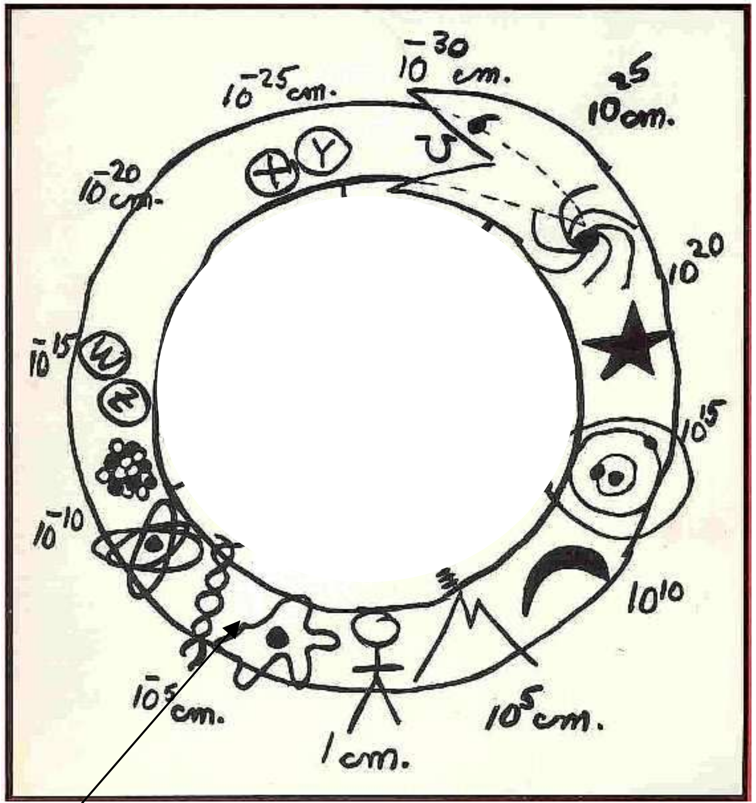
$= 5\ 10^{17}$ s



Interpretation

$$M_P = \sqrt{\frac{hc}{G}} = \sqrt{\frac{20\times10^{-26}}{6.7\times10^{-11}}} = \sqrt{3\times10^{-15}} = \sqrt{30\times10^{-16}} = \mathbf{5.5\times10^{-8}\ kg}$$

M_P = 0.05 mg ≈ cell weight ??



≈ 10^{-8}kg

Interpretation

$$M_P = \sqrt{\frac{hc}{G}} = \sqrt{\frac{20\times10^{-26}}{6.7\times10^{-11}}} = \sqrt{3\times10^{-15}} = \sqrt{30\times10^{-16}} = \mathbf{5.5\times10^{-8}\ kg}$$

$d_P = M_P / V_P$

$\approx M_P / L_P^3$

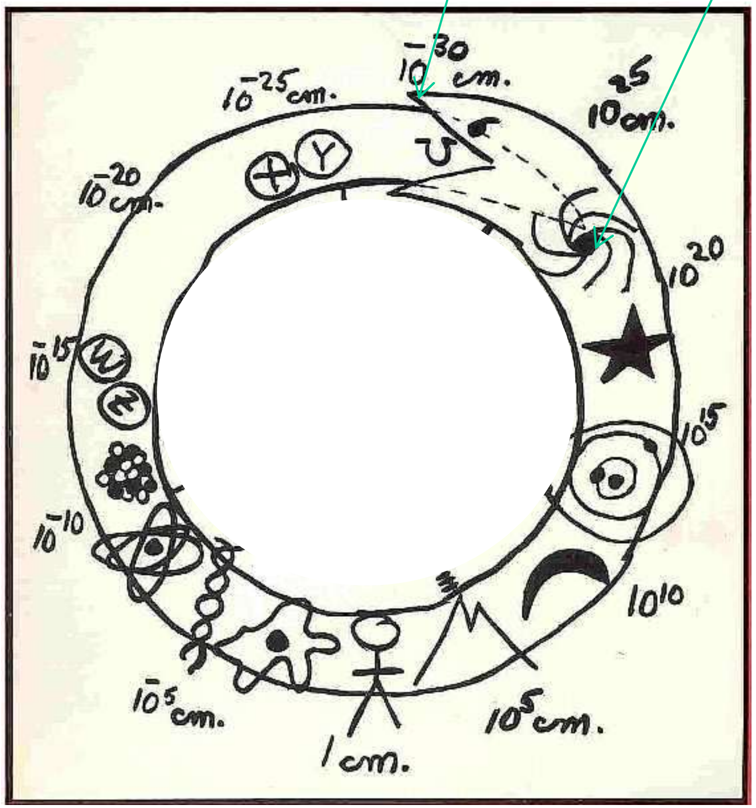
$\approx 10^{97}\ kg.m^{-3}$

$d_U \approx 10^{-28}\ kg.m^{-3}$

Note $d_{Water} \approx 10^3\ kg.m^{-3}$

Universe: 10^{-28} kg.m^{-3}

$\approx 10^{97}$ kg.m^{-3}



Conclusion (as of today)

- ✓ Originally, the Universe was contained in a 3D volume with a characteristic Planck length of $L_P \approx 10^{-35}$m

- ✓ At time $t=t_P$, the density of the Universe was $d_P = M_P/V_P \approx 10^{97}$ kg.m^{-3}, that of a black hole?

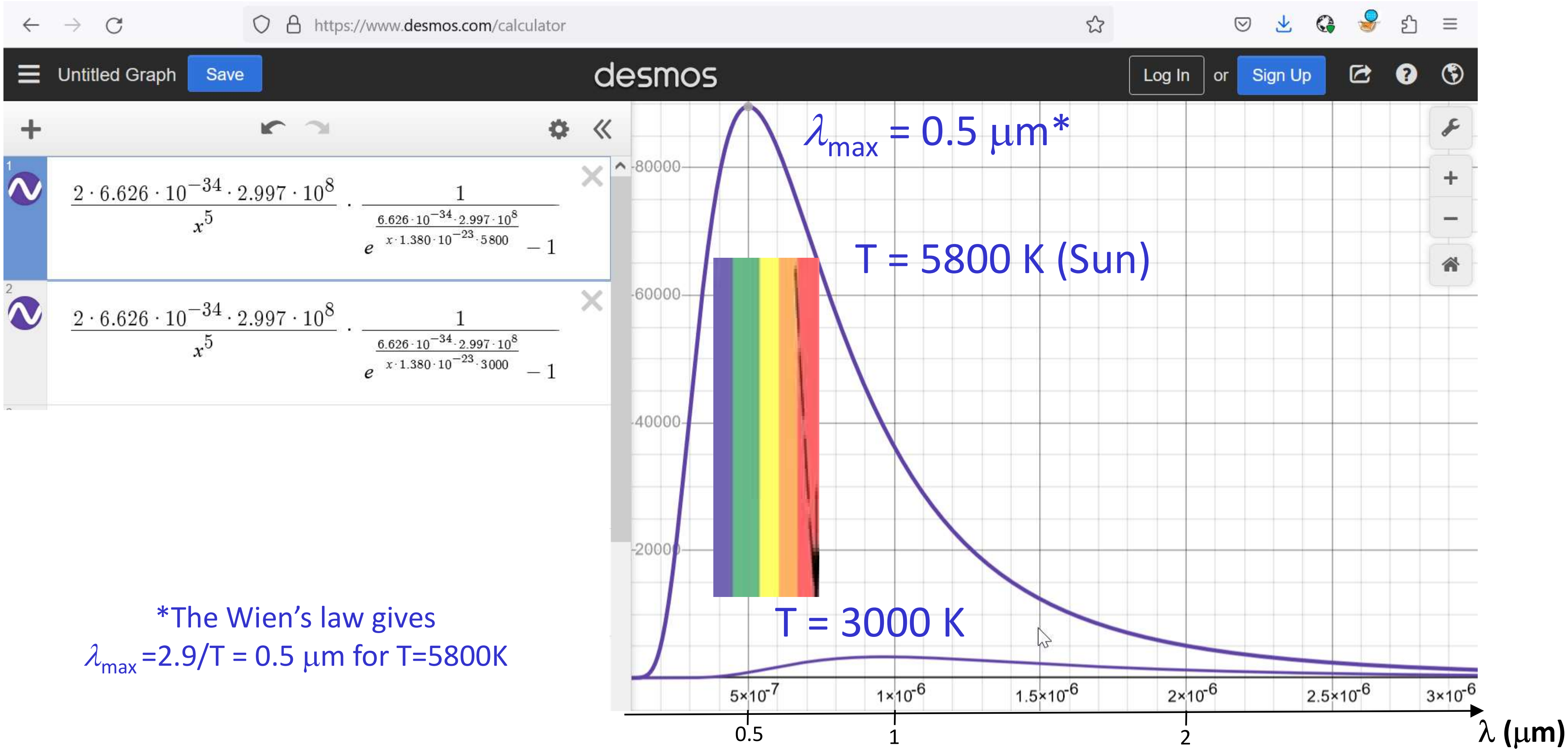
- ✓ Since then, the time increments in steps of $t = t_P \approx 10^{-43}$ s

Back-up

Planck's Law vs wavelength

Spectral Radiance *I*
[10^{-3} kg. s^{-2}.sr^{-1}]

$$I = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda kT}}-1}$$



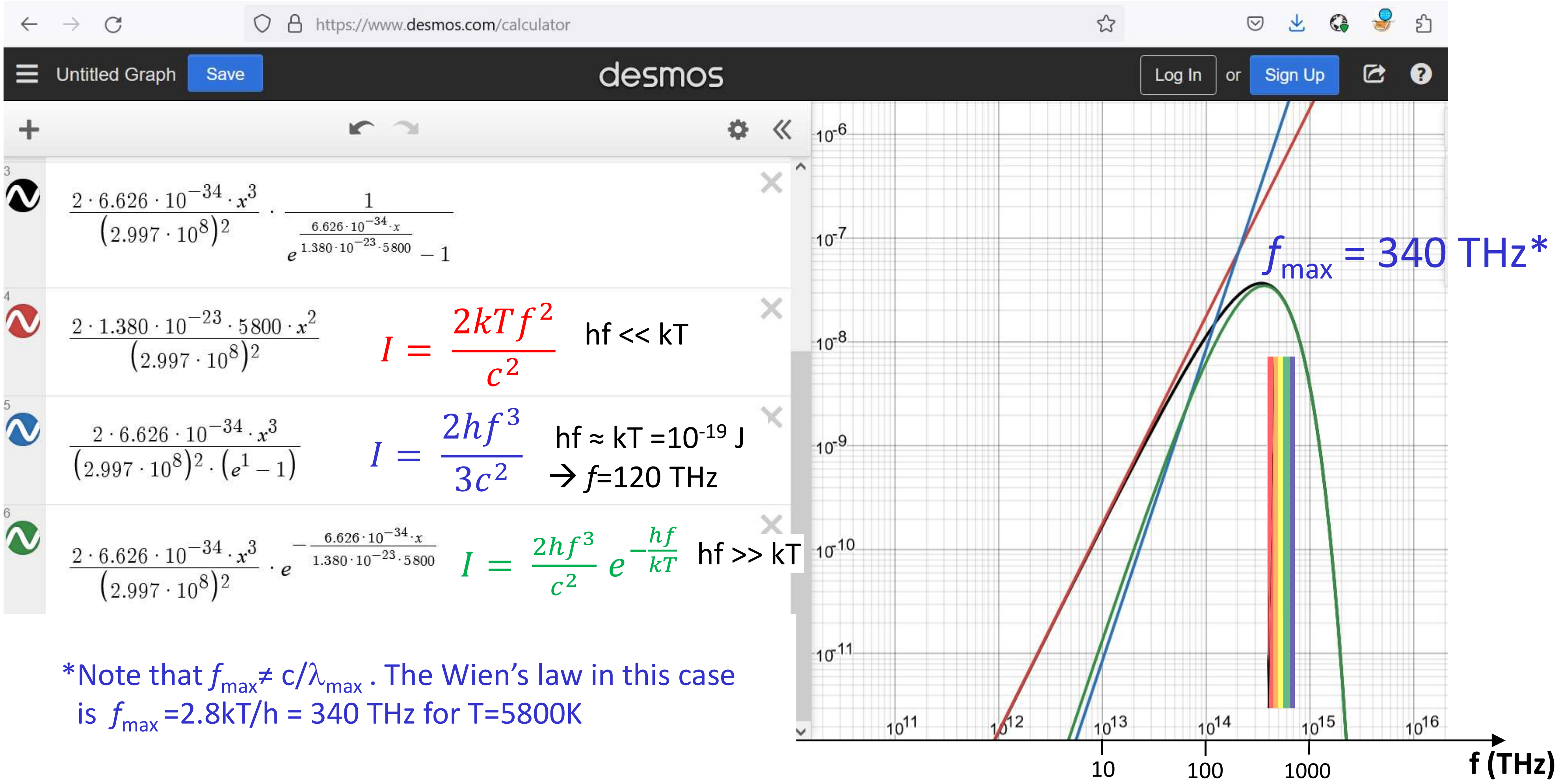
*The Wien's law gives
λ_{max} =2.9/T = 0.5 µm for T=5800K

Planck's Law vs frequency

Spectral Radiance *I*
[kg.s⁻² .sr⁻¹]

$$I = \frac{2hf^3}{c^2}\frac{1}{e^{\frac{hf}{kT}}-1} = \frac{2hf}{\lambda^2}\frac{1}{e^{\frac{hf}{kT}}-1}$$

T = 5800 K (Sun)



*Note that $f_{max} \neq c/\lambda_{max}$. The Wien's law in this case is f_{max} =2.8kT/h = 340 THz for T=5800K

Planck's Law vs data

One measurement at low *f*=cte showing I vs T

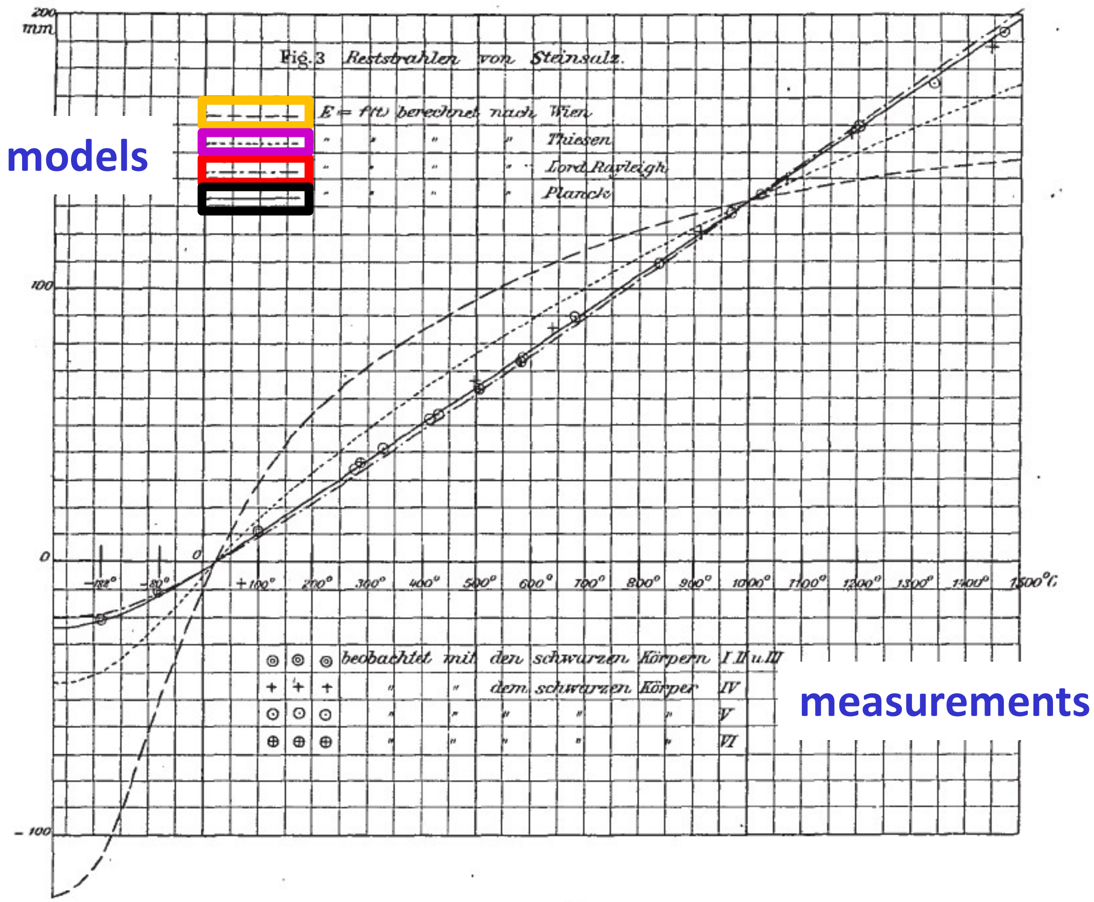


Fig. 3.

Rubens and Kurlbaum, Annalen der Physik, 4, 649, 1901