Our current view of the Universe

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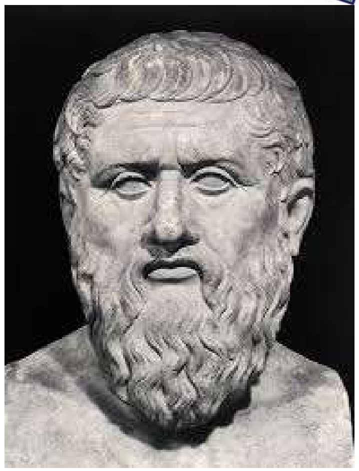
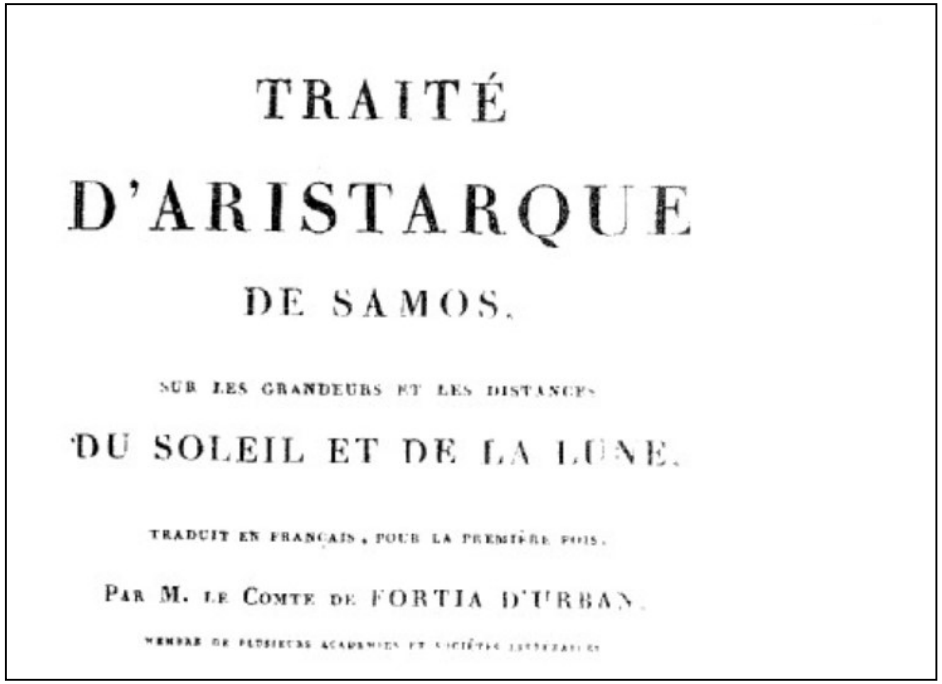
1. Universe in early times (10’)
2. Fundamental constants (20’)
3. Universe according to fundamental constants (20’)
4. Universe content as we know it today (15’)
5. Dark matter search (15’)

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

Universe in early times

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.

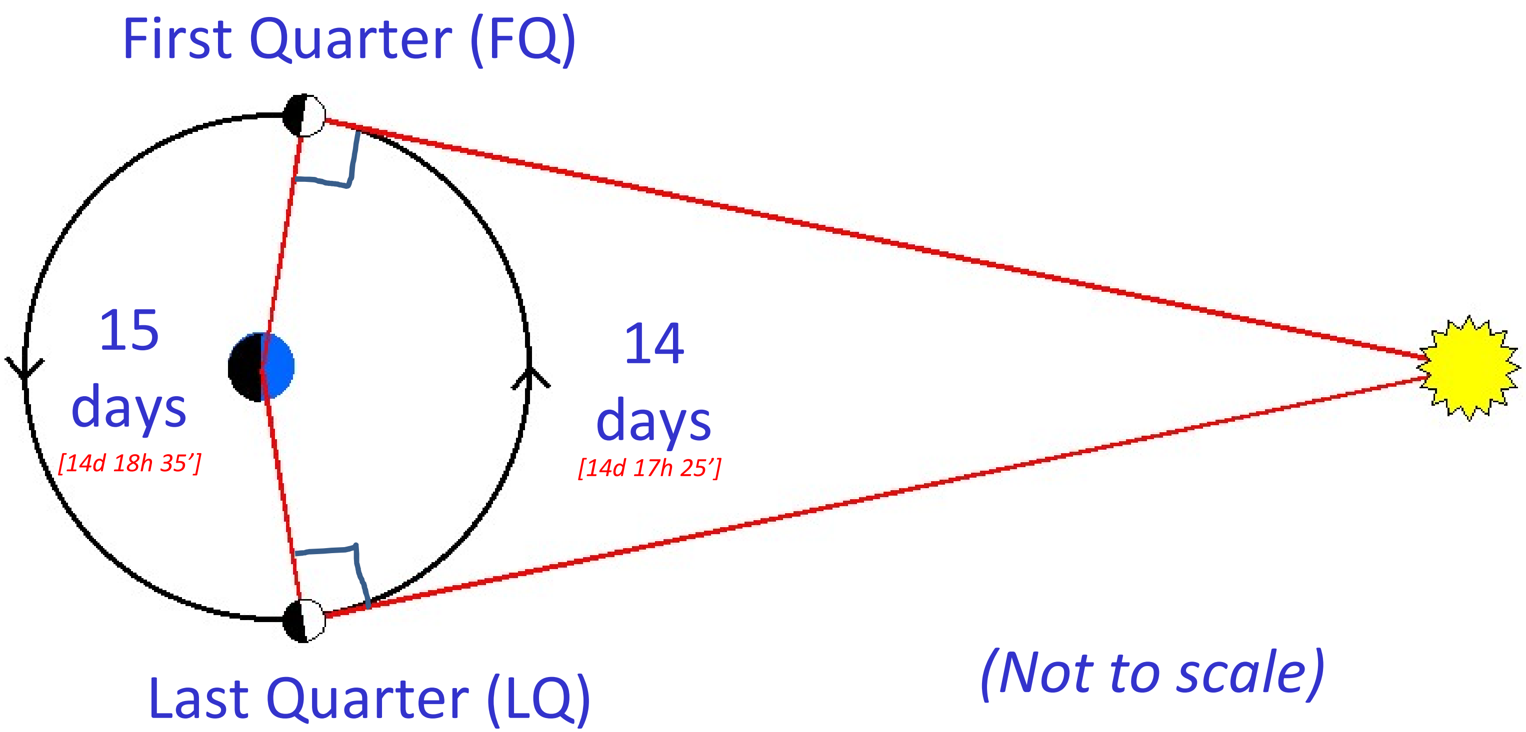
PAR M. LE COMTE DE FORTIA D'URBAN.

Translated from ancient Greek to French (1823)

Universe in early times

[Values as of today]

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

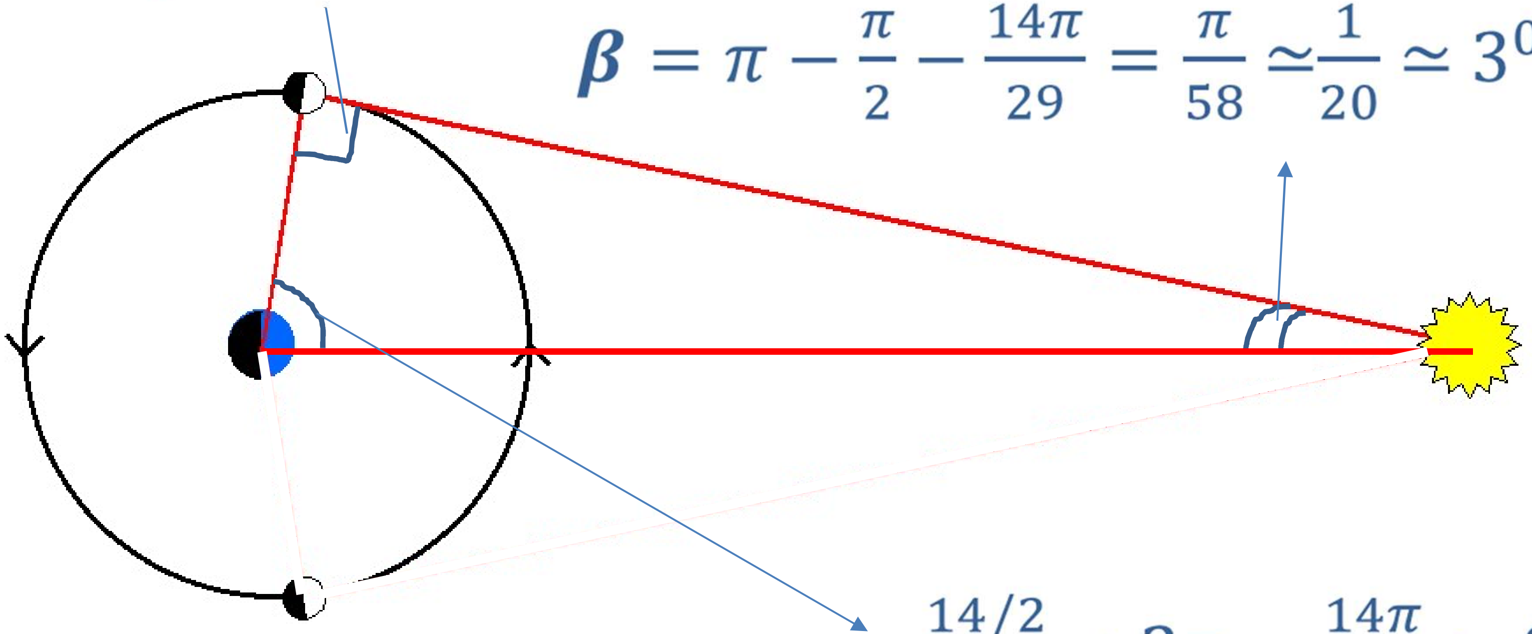


Universe in early times

[Values as of today]

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

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



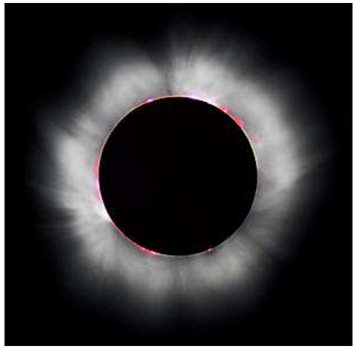
$$\frac{14/2}{14+15} * 2\pi = \frac{14\pi}{29} \simeq 87^0$$ [89.85 ^{0}]

sinβ≈β* which gives $\frac{EM}{ES} \simeq \frac{1}{20}$ [$\frac{1}{387}$]

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

Universe in early times

[Values as of today]

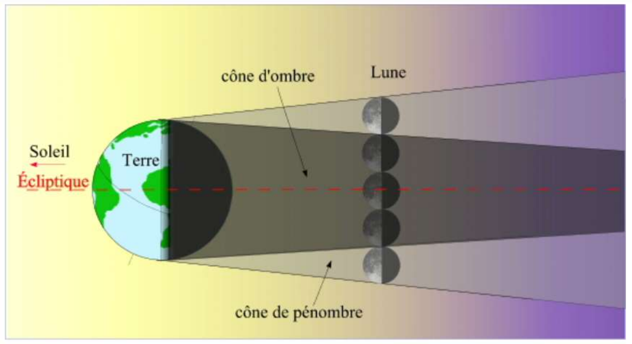


As seen from the earth a sun eclipse tells us that $D_S = D_M$

[$D_S = D_M$]

From Moon eclipse Aristarchus estimated $D_M = 0.33\ D_E$

[$D_M = 0.273\ D_E$]



Cônes d'ombre et de pénombre.

Crédit : IMCCE/Patrick Rocher

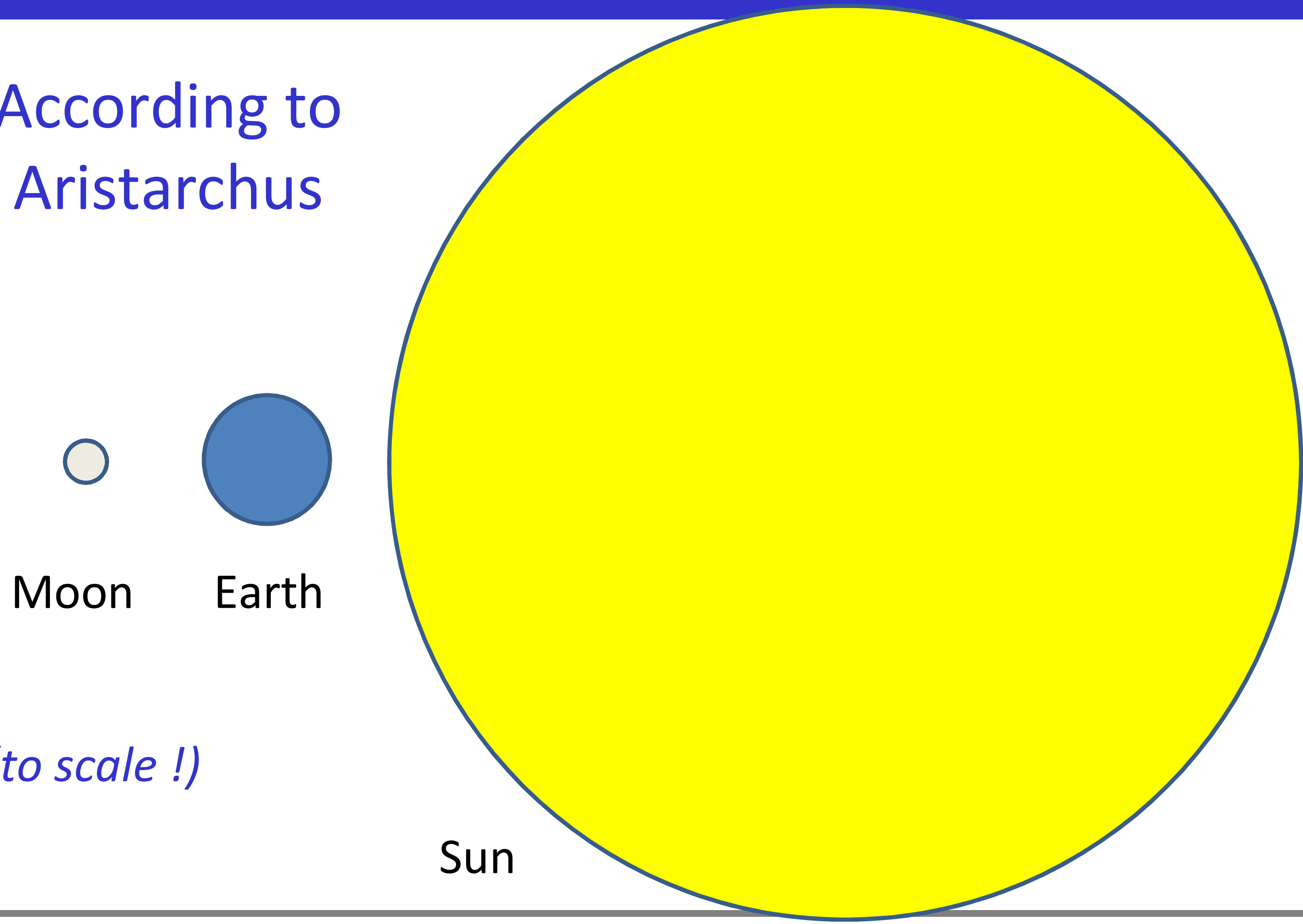
Pictures taken every 30'
(28-Aug 2007)

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

[$D_S = 110\ D_E$]

Universe in early times

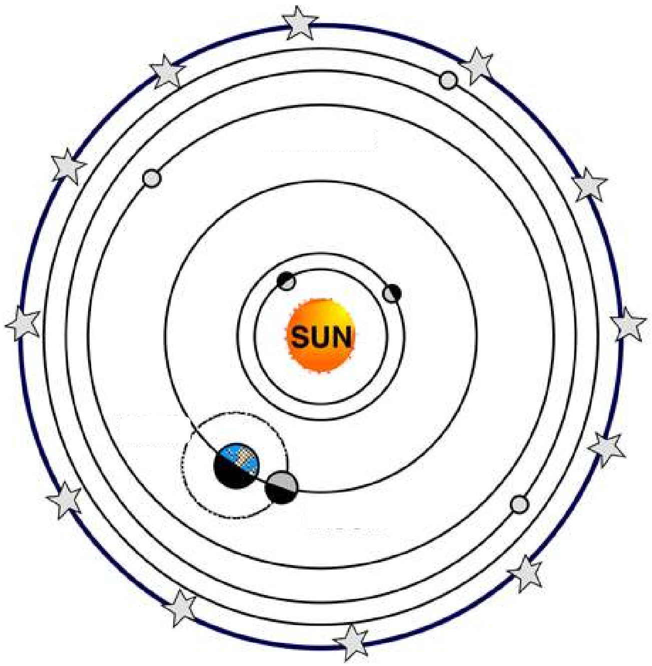
According to Aristarchus



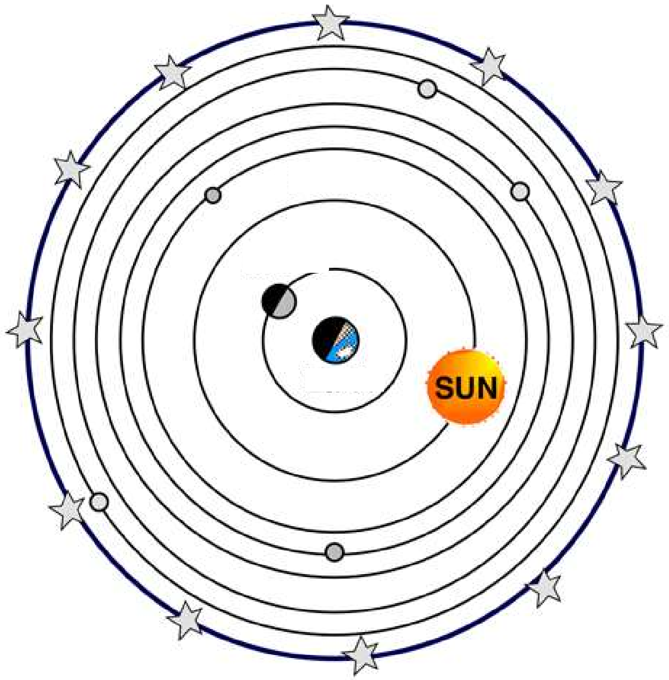
(to scale !)

Universe in early times

Aristarchus



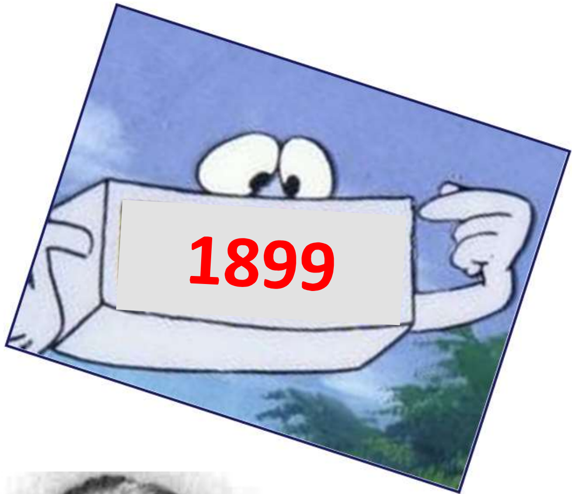
Archimedes, Aristotle



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

Fundamental constants

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:

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

als Einheit der Masse:

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

als Einheit der Zeit:

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

Unveiled p. 29 !

This paper allows to:
- summarize physics of the past (<1900)
- lay the foundations of modern physics (>1900)

→ All based on three fundamental constants

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

Units of Space, Time and matter

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 before XVIIIth century

Units of Space, Time and matter

Space Time Matter

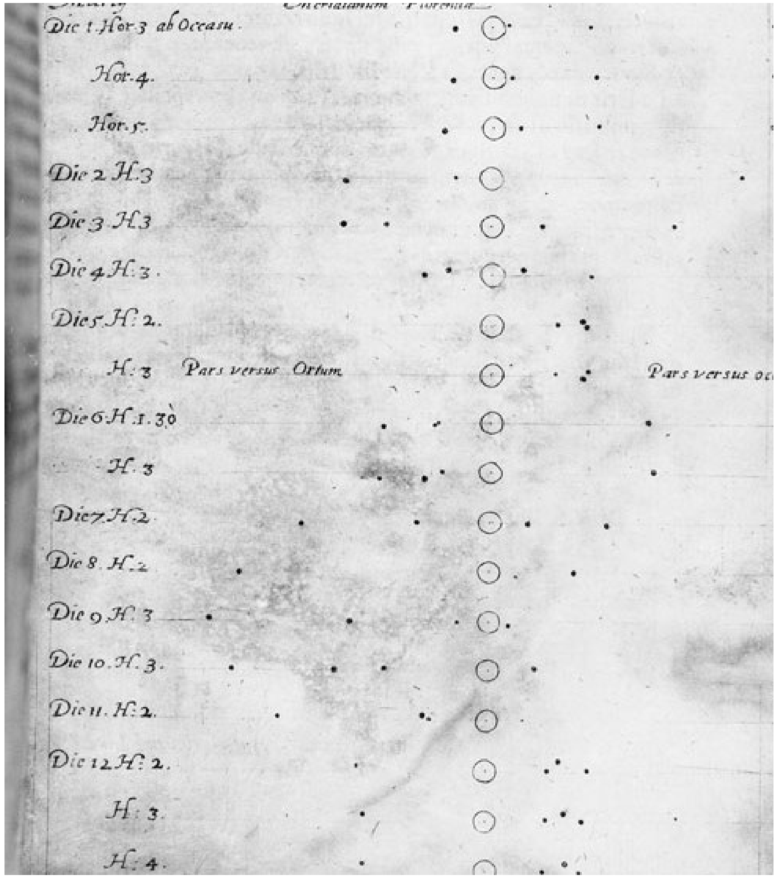
Length (L)	Time (T)	Mass (M)
→ Decimal 1/10^7 of the North part of the meridian: 40 000 km / 4 / 10^7 = 10^{-3} km → **Meter**	→ Sexagesimal 1/86400 part of the solar day → **Second**	→ Decimal Mass of water in a cube of 1 cm. Water density= 1 g.cm^{-3} → **Gram**

+ : practical, precise
- : not universal (geocentric)

Earth related measurement from XIXth century on

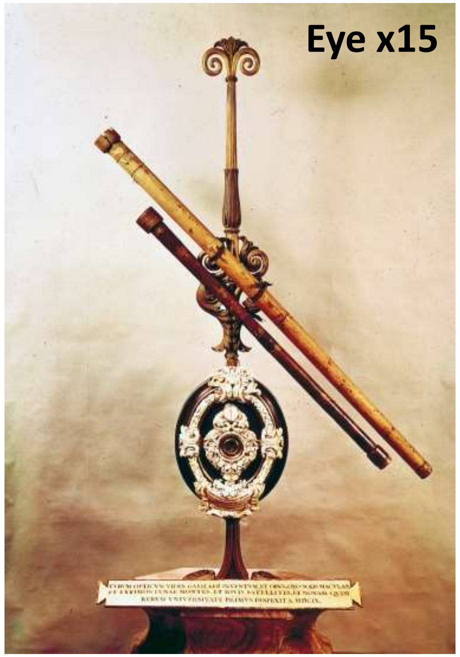
Fundamental Constant (1)

Speed of light (c)



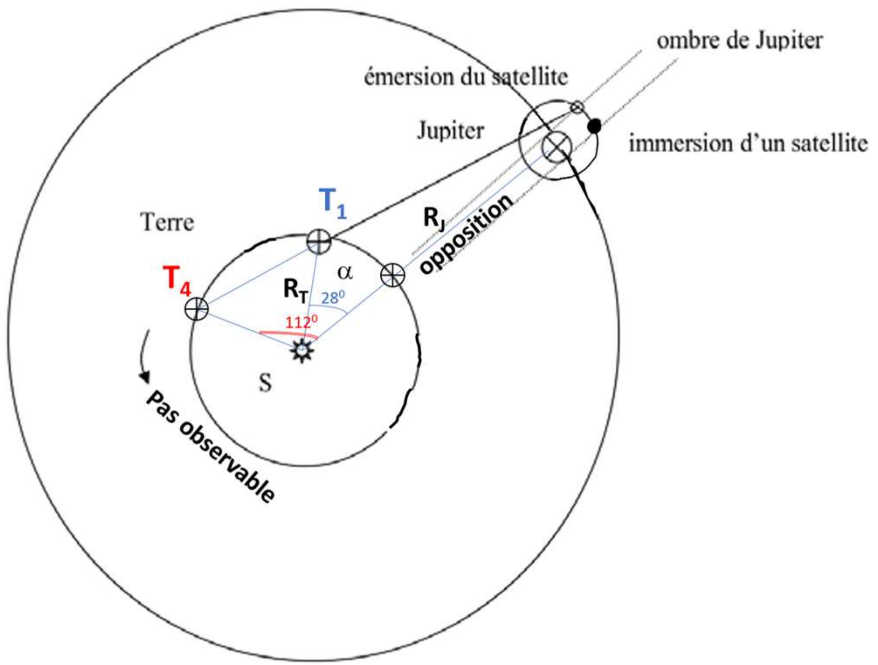
Sidereus Nuncius (Mar 1610)

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

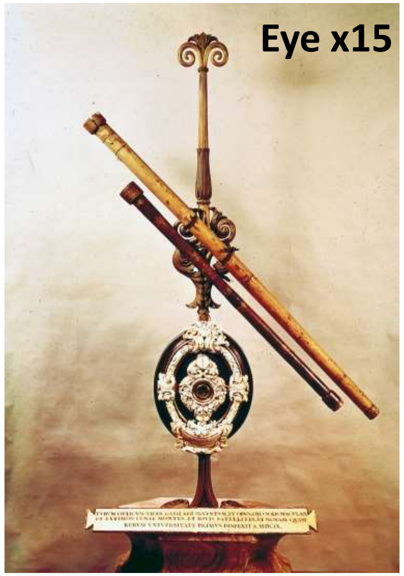


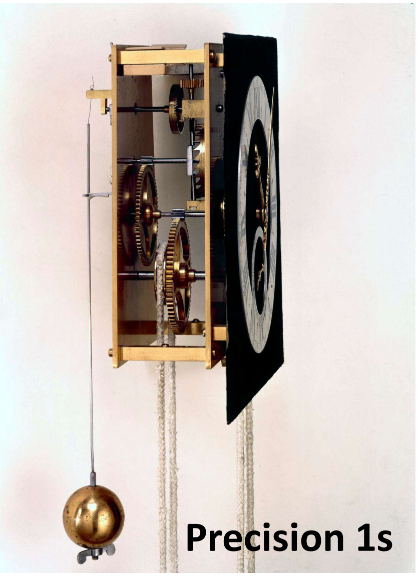
Fundamental Constant (1)

Speed 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

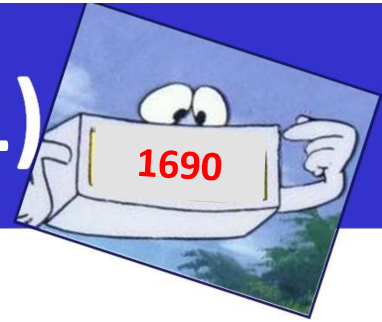




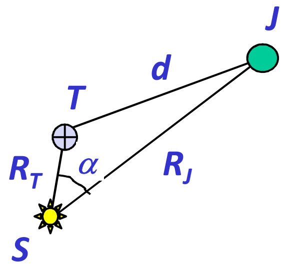
Romer predicts that Io emersion will arrive 10' (600 s) later when Earth is in T4 than when he measured it in T1

Published 7 Dec 1676 in «Journal des sçavans»

Fundamental Constant (1)



Speed of light (c)

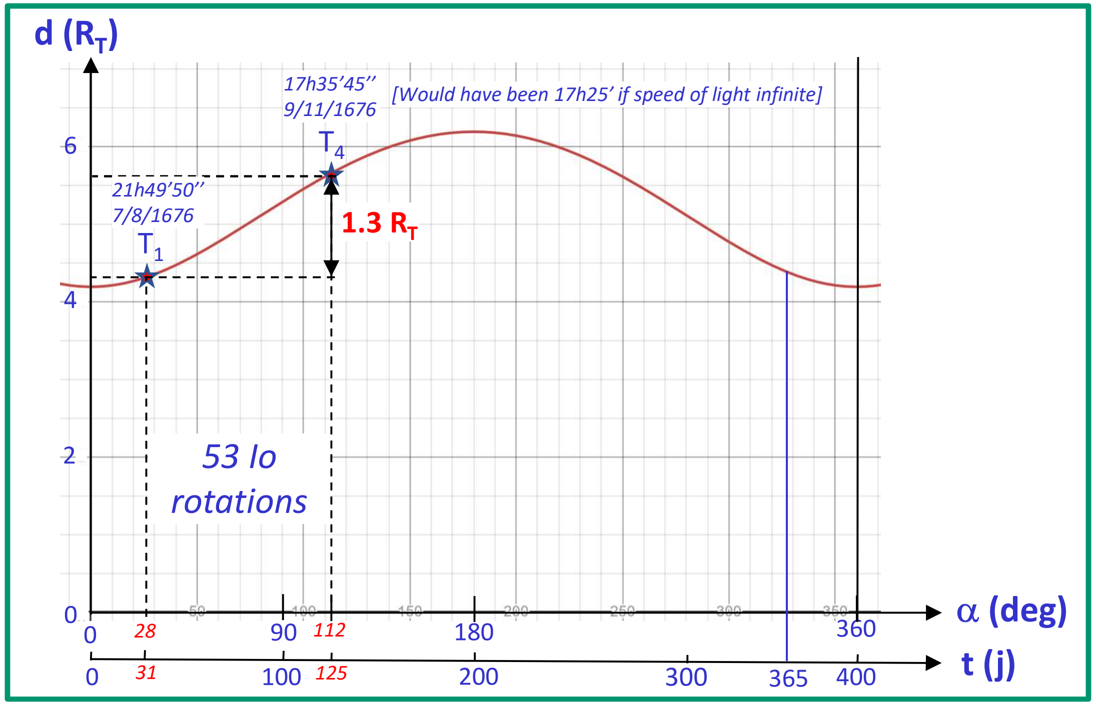


$TJ^2 = d^2 = R_T^2 + R_J^2 - 2R_JR_T\cos(\alpha)$

$R_J = (P_J/P_T)^{2/3} R_T = 5.2\ R_T$ (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}**

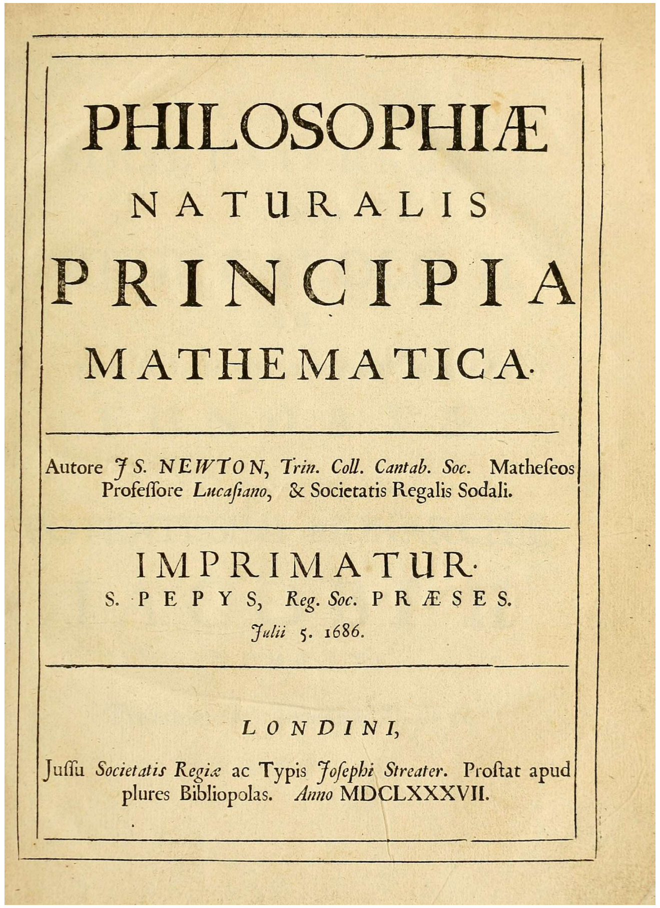
150 000 000 km

1690

Huyghens

Fundamental Constant (2)

Gravitational constant (G)



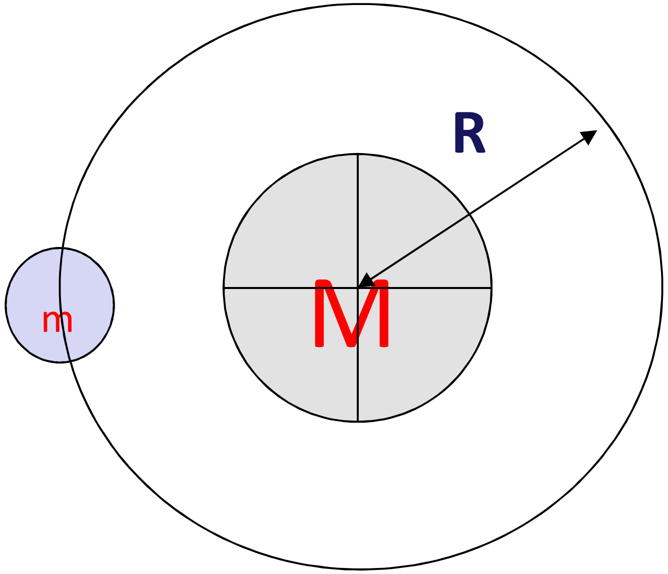
PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

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)

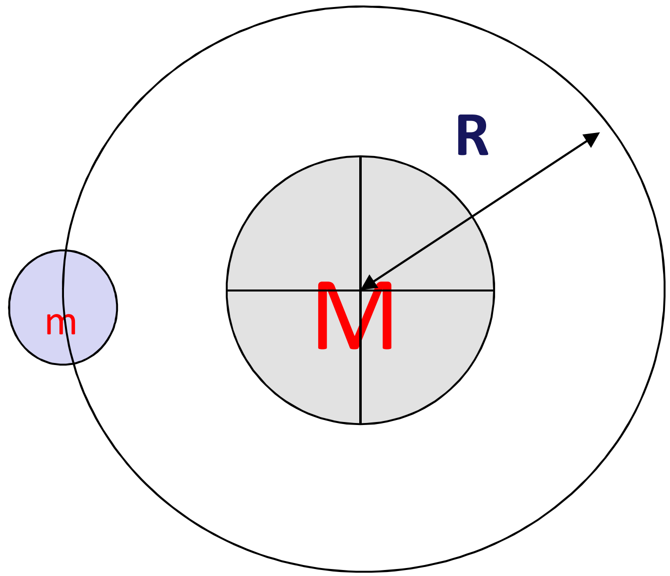
Newton 2nd law : F = m a → kg m s^{-2}

Newton universal gravitation :

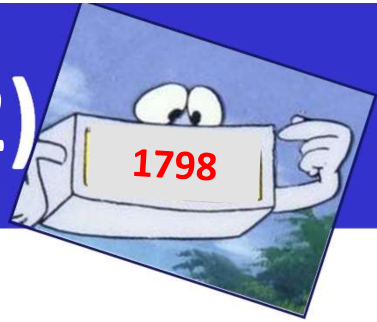
$$F \propto \frac{m\,M}{R^2} \rightarrow kg^2\,m^{-2}$$

Need a constant G to restore the units

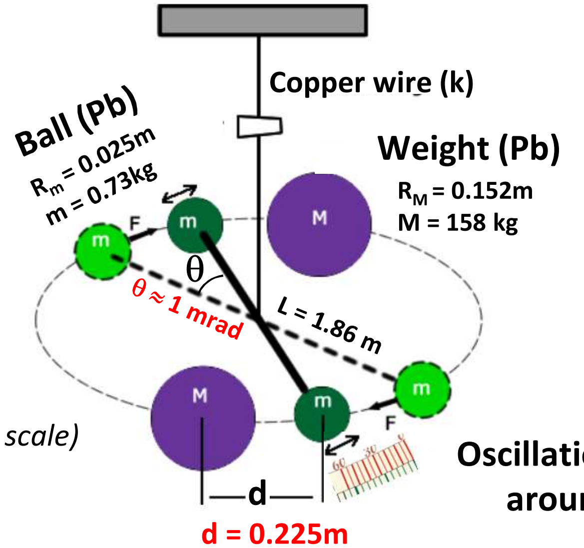
$$[G] = kg\;m\;s^{-2} / (kg^2\;m^{-2}) = kg^{-1}\;m^3\;s^{-2}$$



Fundamental Constant (2)



Gravitational constant (G)



(Not to scale)

Oscillation period T=420 s around equilibrium

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

At equilibrium of the 2 forces :

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

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

$G = 6.67\times10^{-11} kg^{-1}.m^3.s^{-2}$

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)

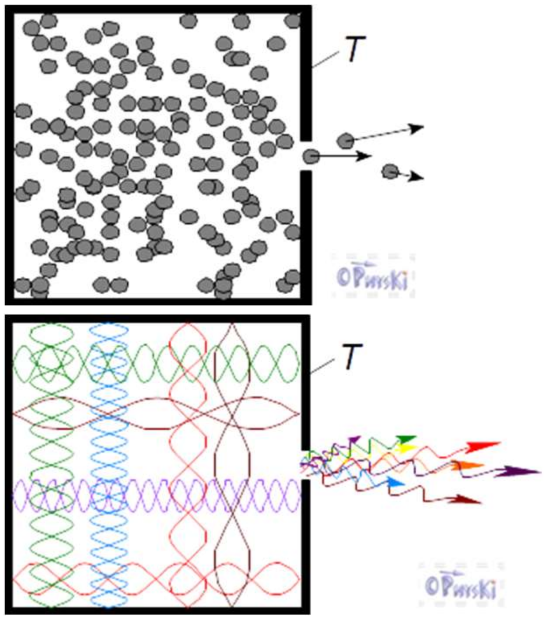
Long standing question: how can the steel or the coal change color when it is heated ?

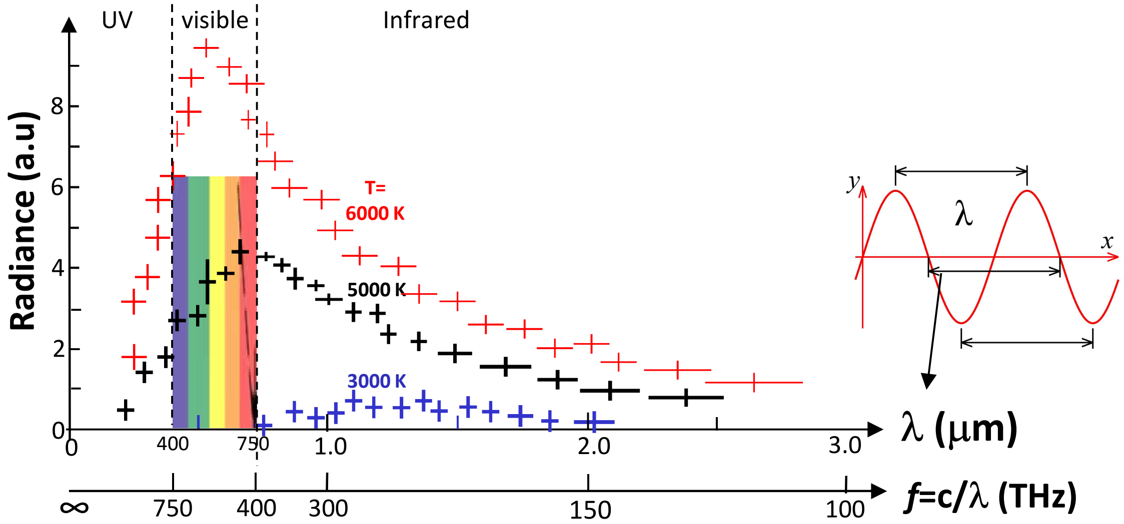
Fundamental Constant (3)

Planck constant (h)

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

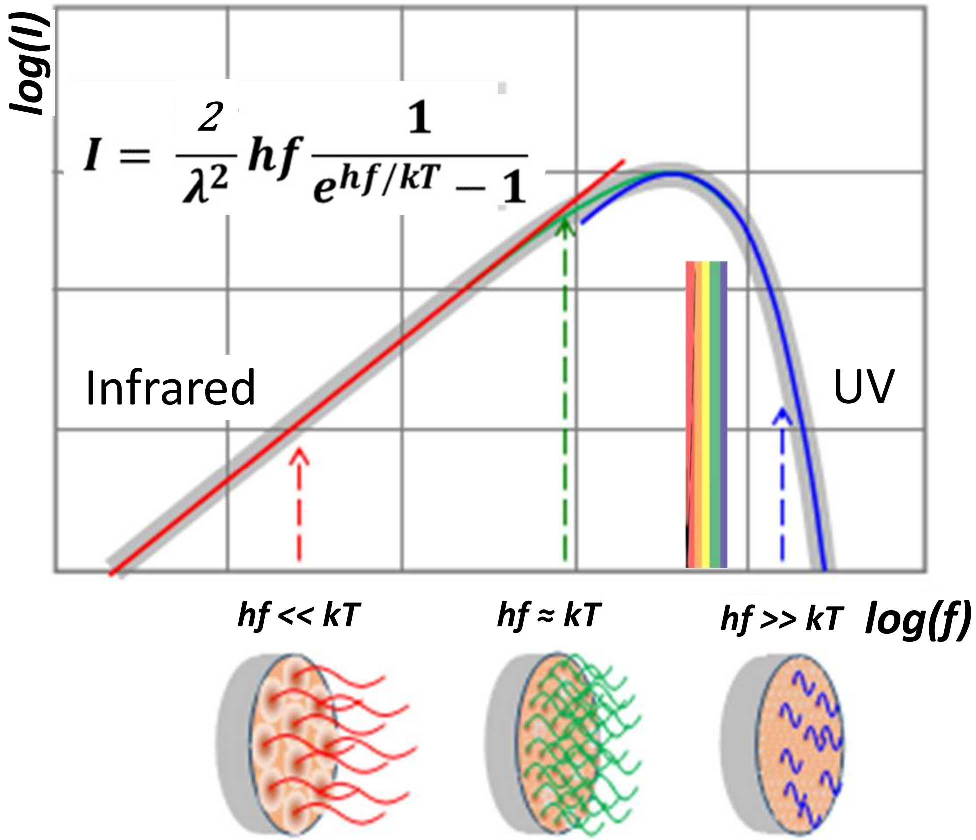
→ **Measurements described by an Universal law** *(Kirchhoff, 1867)* → **function?**





Fundamental Constant (3)

Planck constant (h)

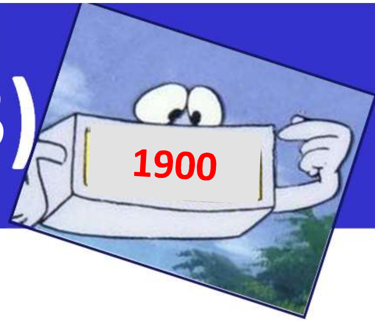


$$I \approx \frac{2}{\lambda^2} kT = \frac{2\,kT}{c^2} f^2 \qquad I \approx \frac{2\,h}{1.7c^2} f^3 \qquad I \approx \frac{2}{\lambda^2} hf\, e^{-\frac{hf}{kT}} = \frac{2\,h}{c^2} f^3\ e^{-\frac{hf}{kT}}$$

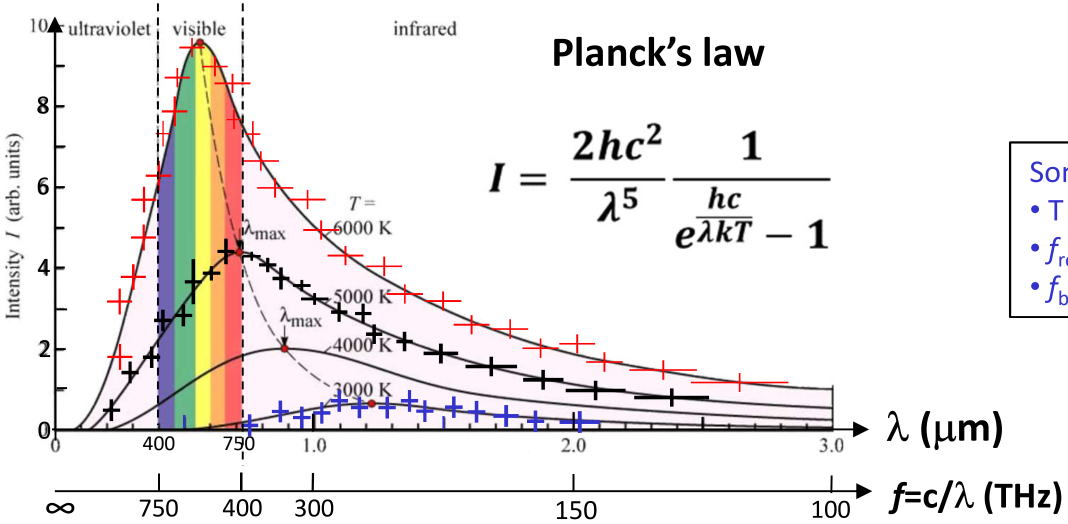
Planck discovered the law in **1900** saying that **atoms** are **harmonic oscillators** with **E = h*f***. Probability of light emission at frequency *f* depends on temperature which corresponds to **E = kT**:

- **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)



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 ($M_P = [M]$)

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** $= [L]^2 \times [T]^{-1} \times [M]^{1} = 6.6\ 10^{-34}$ $m^2.s^{-1}.kg$

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

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

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

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

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

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

Interpretation

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

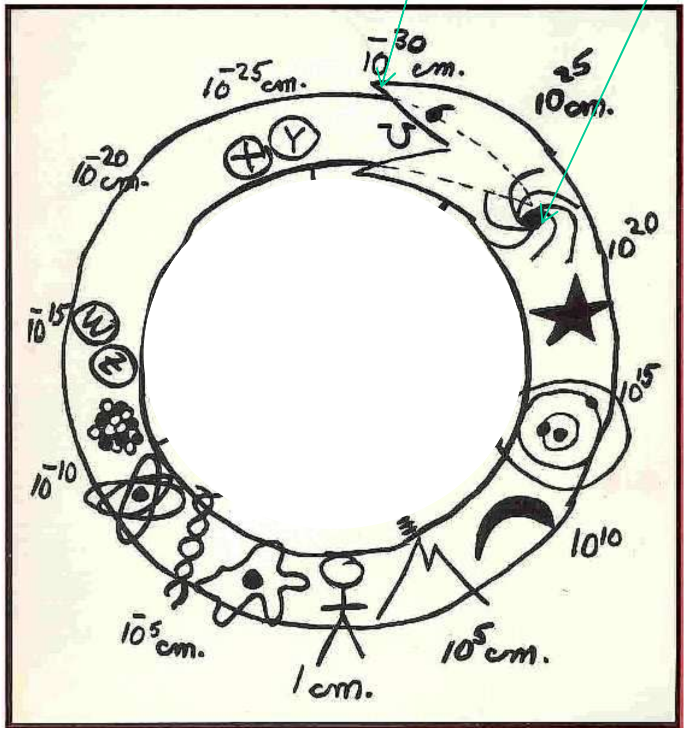
$c \times T_U =$

$3.10^8 \times (1.5\ 10^{10} \times 3.10^7)$

$= 10^{26}$ m

Observable Universe: 10^{28}cm

$\approx 10^{-33}$cm



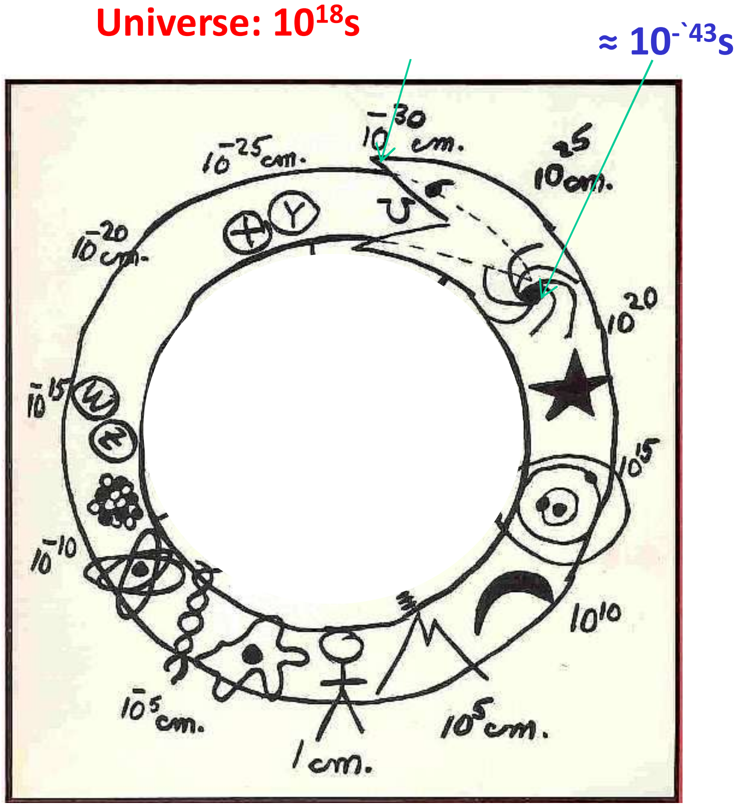
S. Glashow serpent swallowing its tail

New York Times Magazine, Sept. 26, 1982, p. 40

Interpretation

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

$T_U = 1.5\ 10^{10} \times 3.10^{7}$
$= 5\ 10^{17}\ s$



Interpretation

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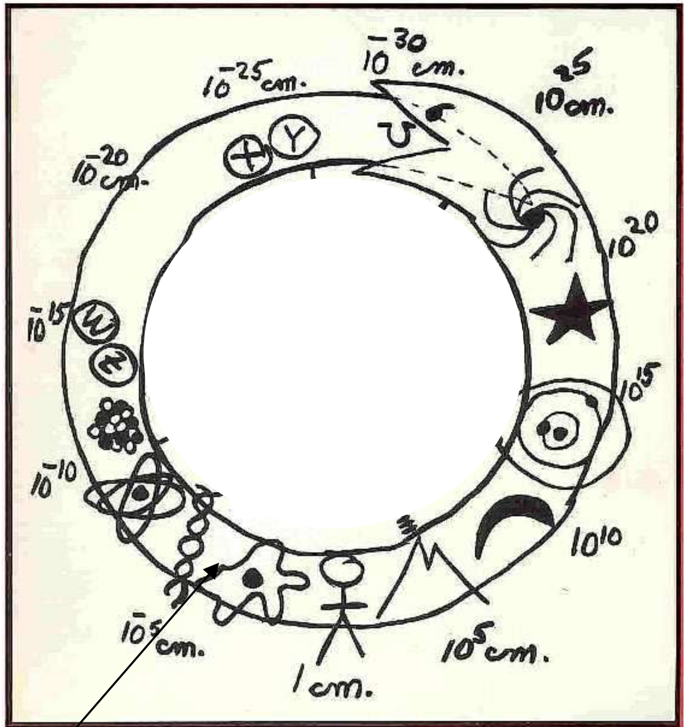
M_P = 0.05 mg ≈ cell weight ??



≈ 10^{-8}kg

Interpretation

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

$d_P = M_P / V_P$

$\approx M_P / L_P^3$

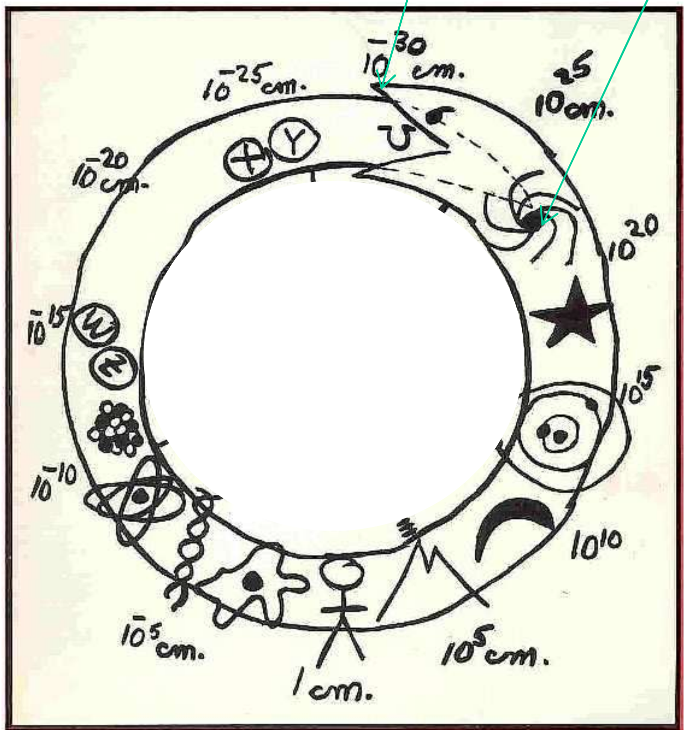
$\approx 10^{97}\ kg.m^{-3}$

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

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

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

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

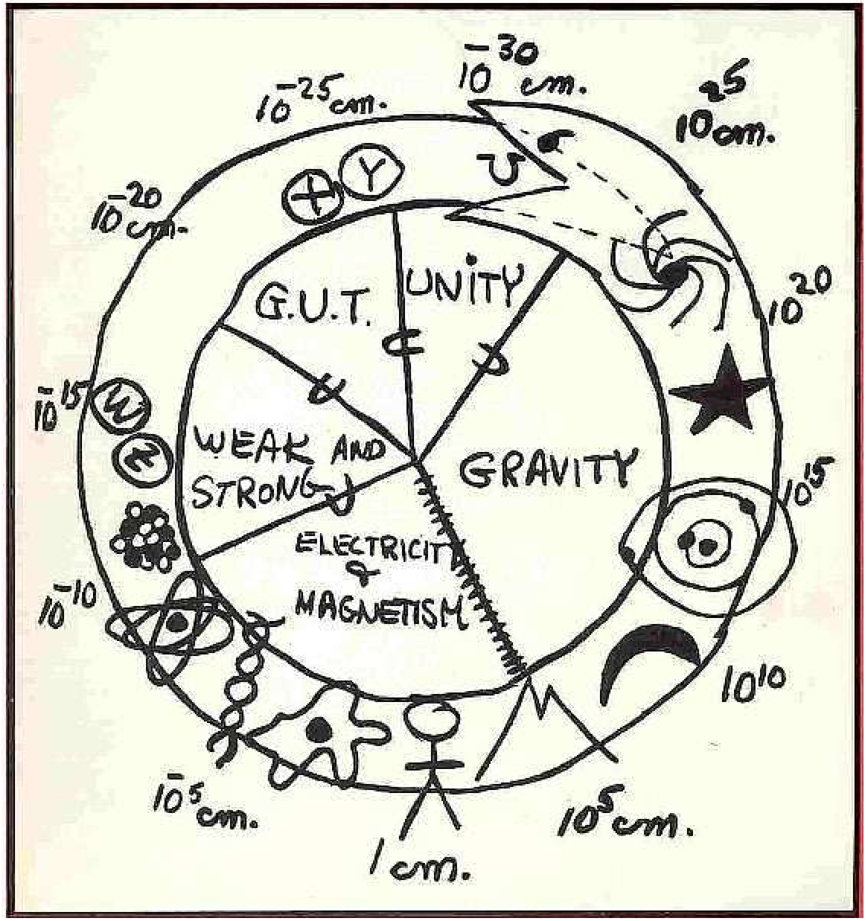


Interpretation

- ✓ 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

Content of the Universe

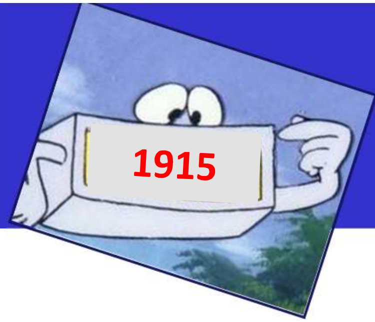
2- Particle physics
status and open questions.
New hypothetic particles ?



1- Observations in cosmology

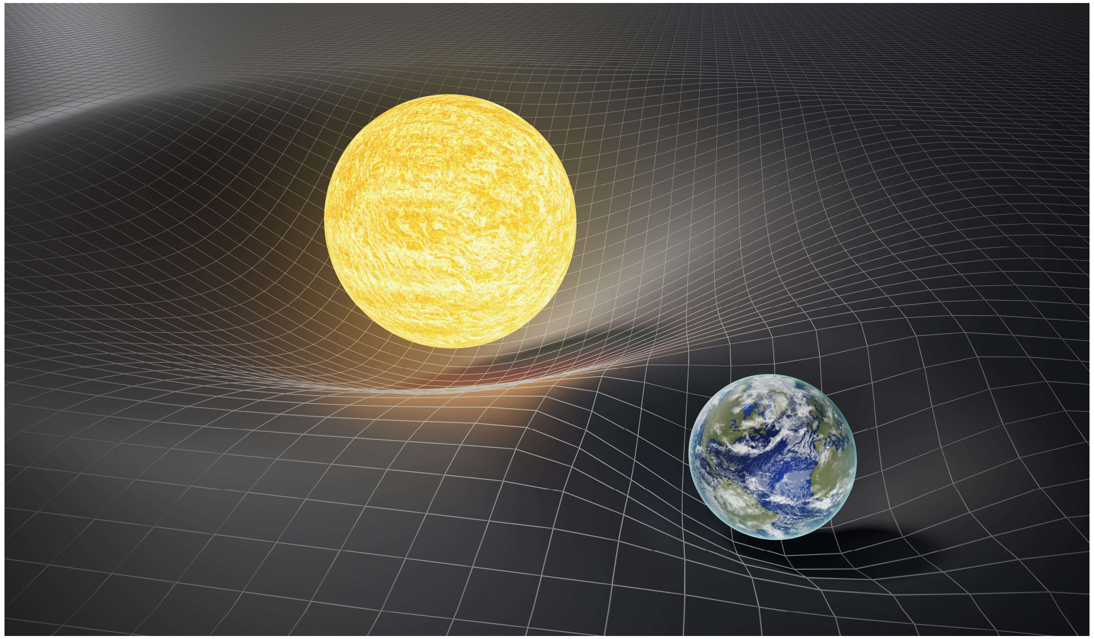
3- What is Universe made of ?

Cosmology



❑ General relativity in one slide !

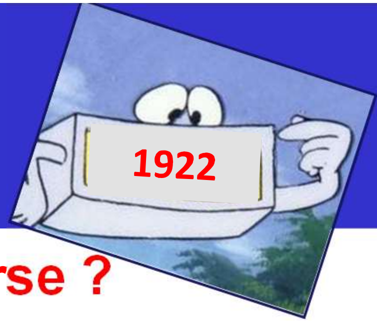
- Shape of space time is directly related to the energy of matter or radiation present



$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$R_{\mu\nu}$= curvature, $g_{\mu\nu}$= space metric, G=Gravity constant,
c=speed of light, $T_{\mu\nu}$= energy-momentum

Cosmology



❑ Possible to solve Einstein equation for the whole Universe ?

- The Universe is homogeneous and isotropic
  - ✓ Space-time metric: scale factor* *(a)* and curvature *(k)*
- Energy and matter: perfect fluid *(ρ = energy density)*

➔ Friedman equation

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2}.$$

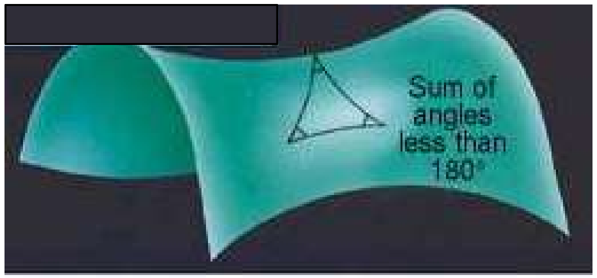
H = Hubble parameter (expansion)

$\Omega = 8\pi G\rho/(3H^2)$ = abundance

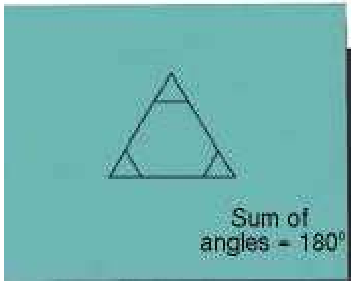
- Knowing Universe **total** (energy+matter) **abundance** Ω → Universe **curvature**

$$\Omega = 1 + \kappa/\dot{a}^2, \quad \text{so} \quad \begin{matrix} \Omega < 1 \\ \Omega = 1 \\ \Omega > 1 \end{matrix} \quad \text{implies} \quad \begin{matrix} \kappa < 0. \\ \kappa = 0. \\ \kappa > 0. \end{matrix}$$

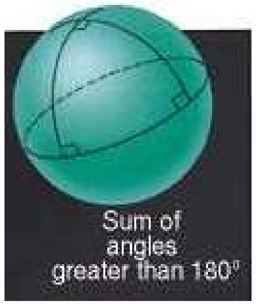
K<0 e.g.Torus



Euclidean (flat)



K>0, e.g. Sphere



* Relative size of the Universe

Cosmology

❑ Possible to solve Einstein equation for the whole Universe ?

- The Universe is homogeneous and isotropic
  - ✓ Space-time metric: scale factor* *(a)* and curvature *(k)*
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H = Hubble parameter (expansion)

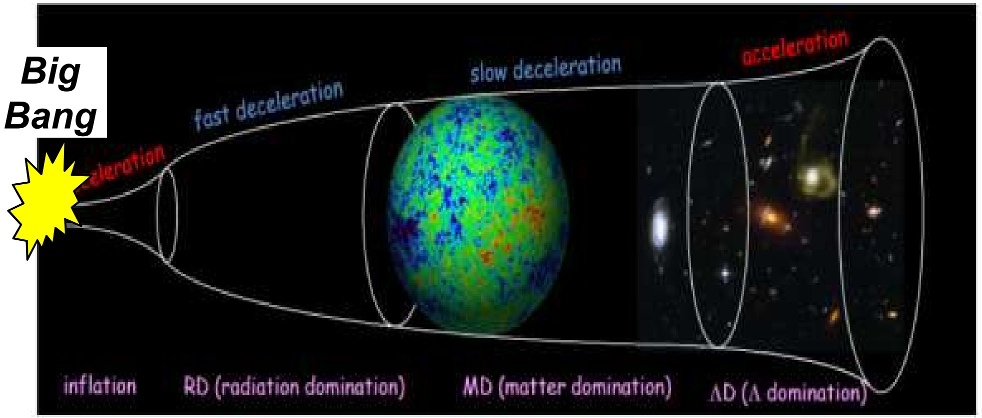
$\Omega = 8\pi G\rho/(3H^2)$ = abundance

- Knowing Universe **composition** → Universe **evolution** *(in Euclidean/flat space)*
  - ✓ Matter particles (p, n, e-)
  - ✓ Cold Dark Matter (CDM)
  - ✓ Radiation (γ, ν)
  - ✓ Dark Energy (Λ)

ΛCDM Model

if κ=0 $\quad \frac{8\pi G}{3}\rho = \left(\frac{\dot{a}}{a}\right)^2$

matter:	p, n, e$^-$	$\rho = \rho_M \propto a^{-3} \rightarrow a \propto t^{2/3}$
radiation:	γ, ν	$\rho = \rho_R \propto a^{-4} \rightarrow a \propto t^{1/2}$
vacuum:	Λ	$\rho = \rho_{vac} \propto a^{0} \rightarrow a \propto e^{H_0 t}$

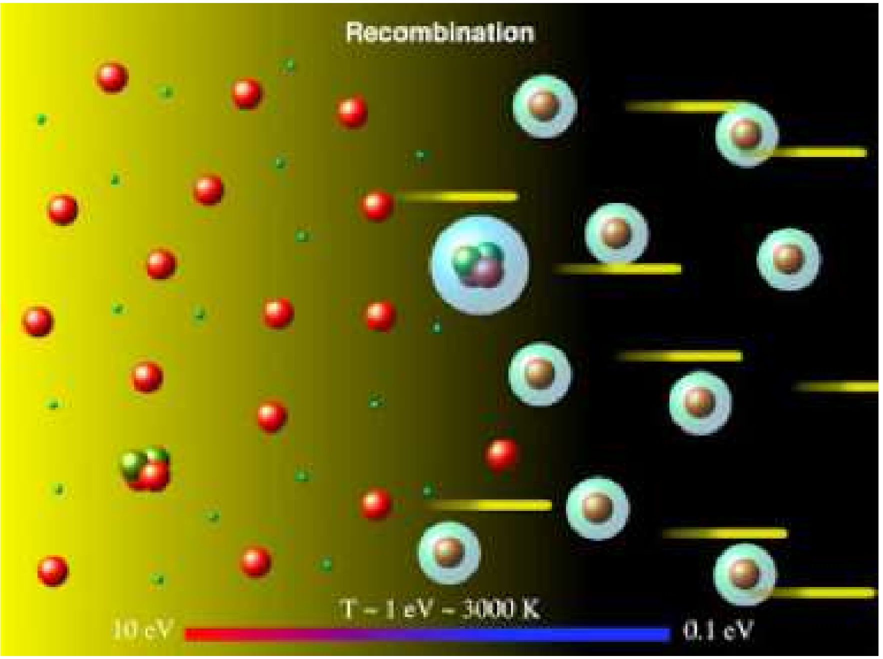


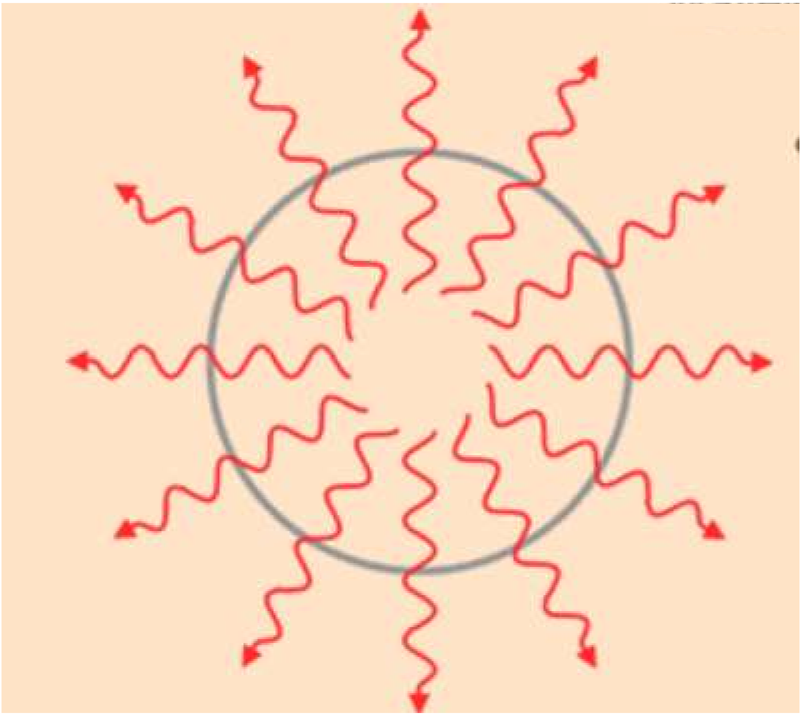
Need to measure adundances !

* Relative size of the Universe

Cosmic microwave background

- **Early Universe: dense plasma of charged particles and photons**
  - Rapidly expanding and cooling during 380 000 years …
  - … until neutral atoms formed (T=3000 K) → Universe transparent to photons …
  - … which create an isotropic relic radiation *(cosmic microwave background)*





Cosmic microwave background

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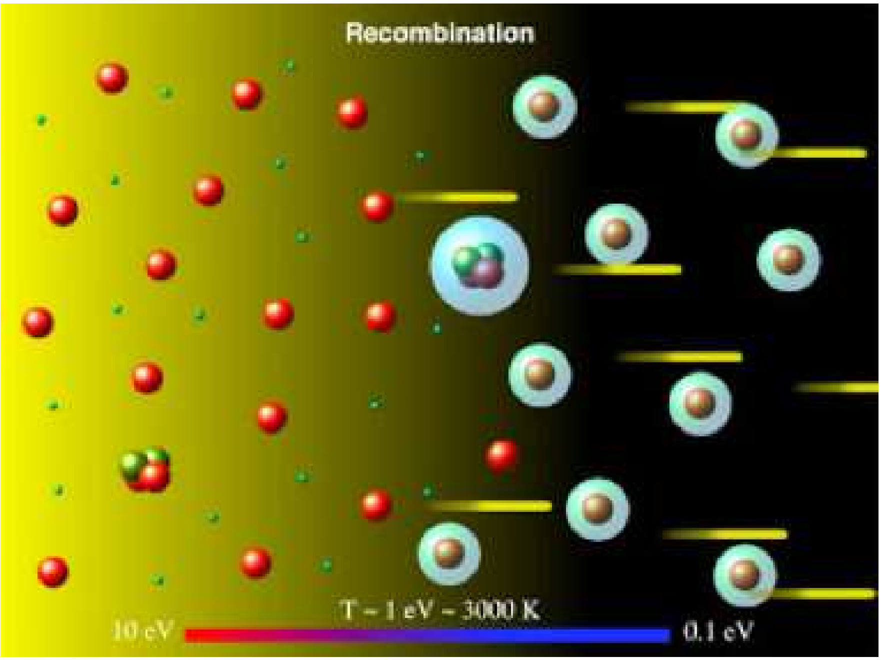
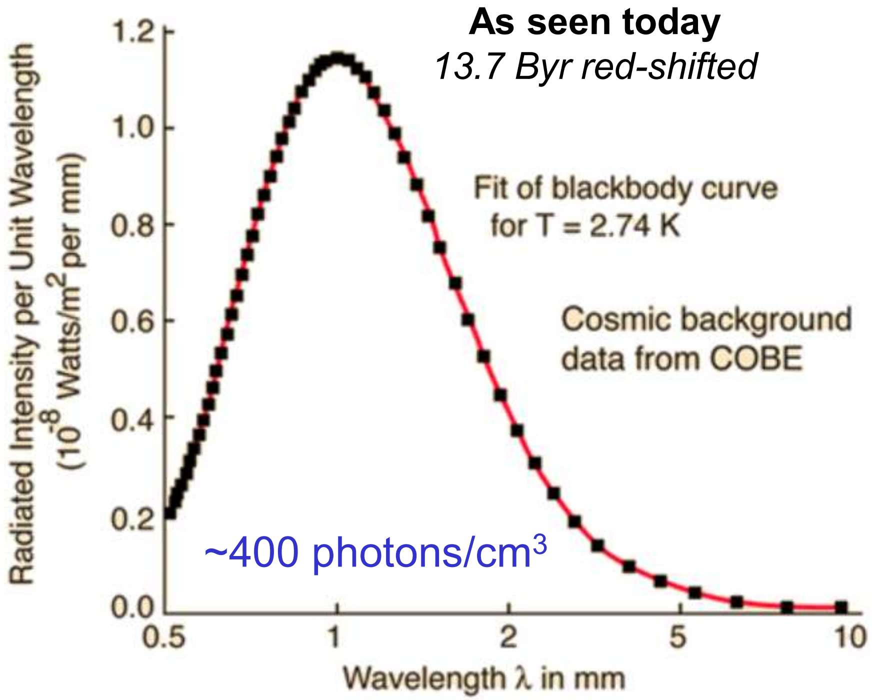




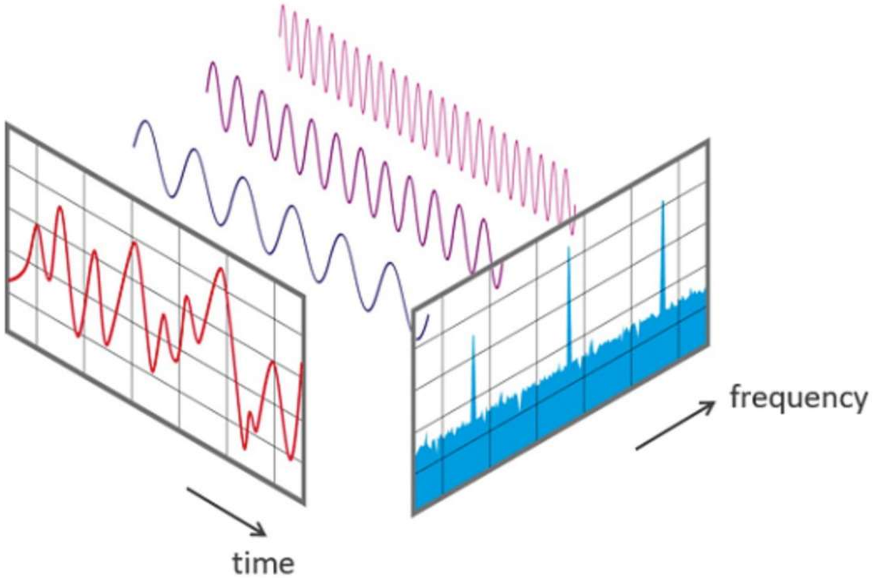
Intermezzo

- **When you listen to a note played by a musical instrument …**
  - … you can directly infer what is the instrument. How it is possible ?

Uniform blow
in a music instrument

Ear
+ brain

➔ **Spectral analysis (Fourier transform):**
Which material produce this sound



Cosmic microwave background

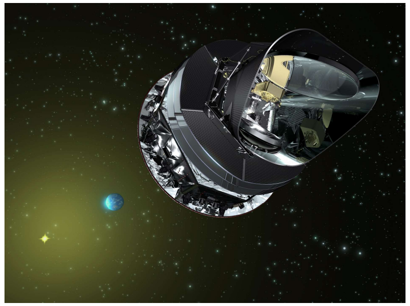
❑ **Use this photon flux to know the composition of the Universe**

Uniform blow
in a music instrument

Ear
+ brain

→ **Spectral analysis (Fourier transform):**
Which material produce this sound

Uniform light
in the whole Universe

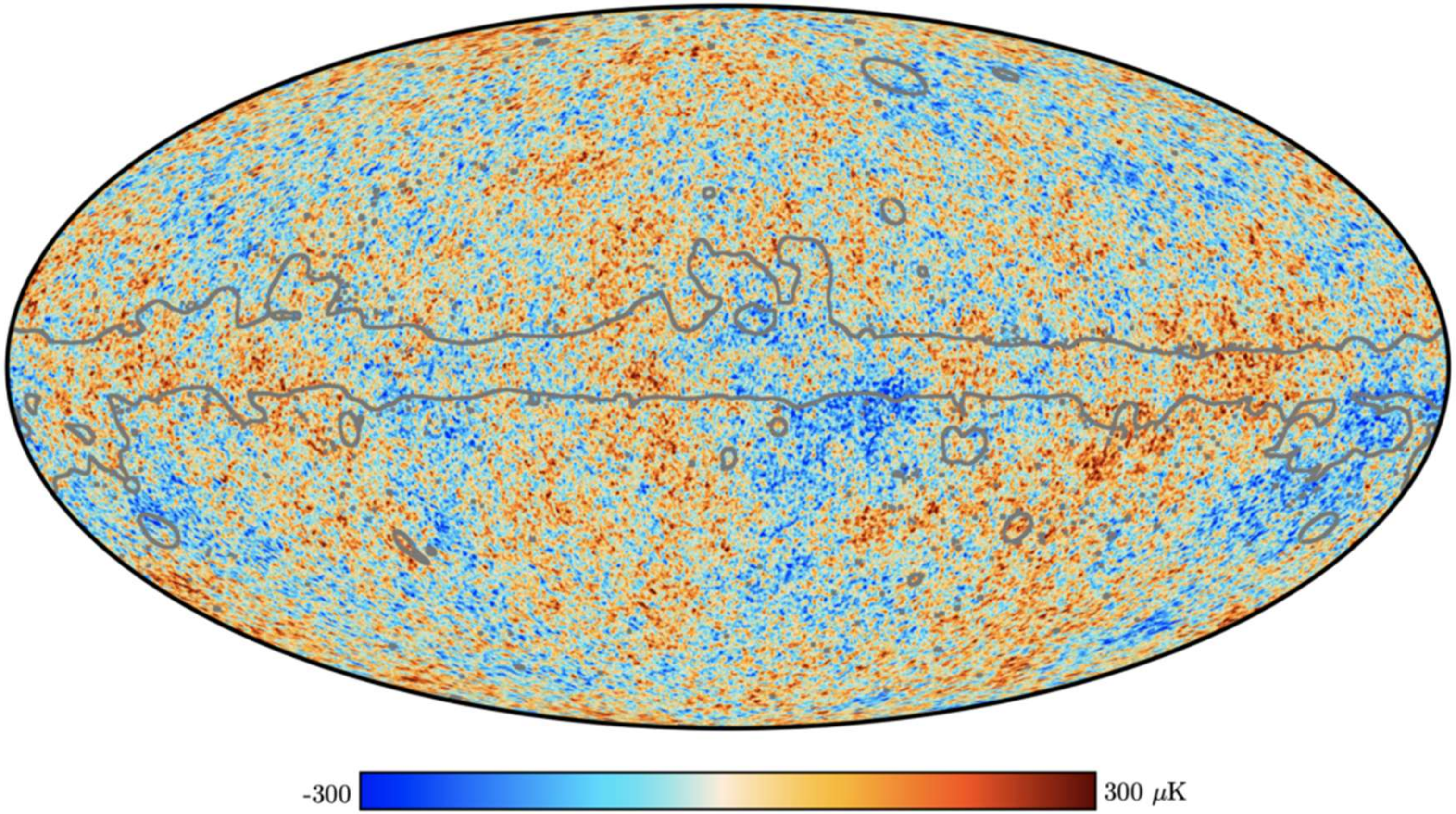


Spatial telescope
+ computer

→ **Angular analysis of thermal fluctuation around 2.74 K:**
What is the Universe composition ?

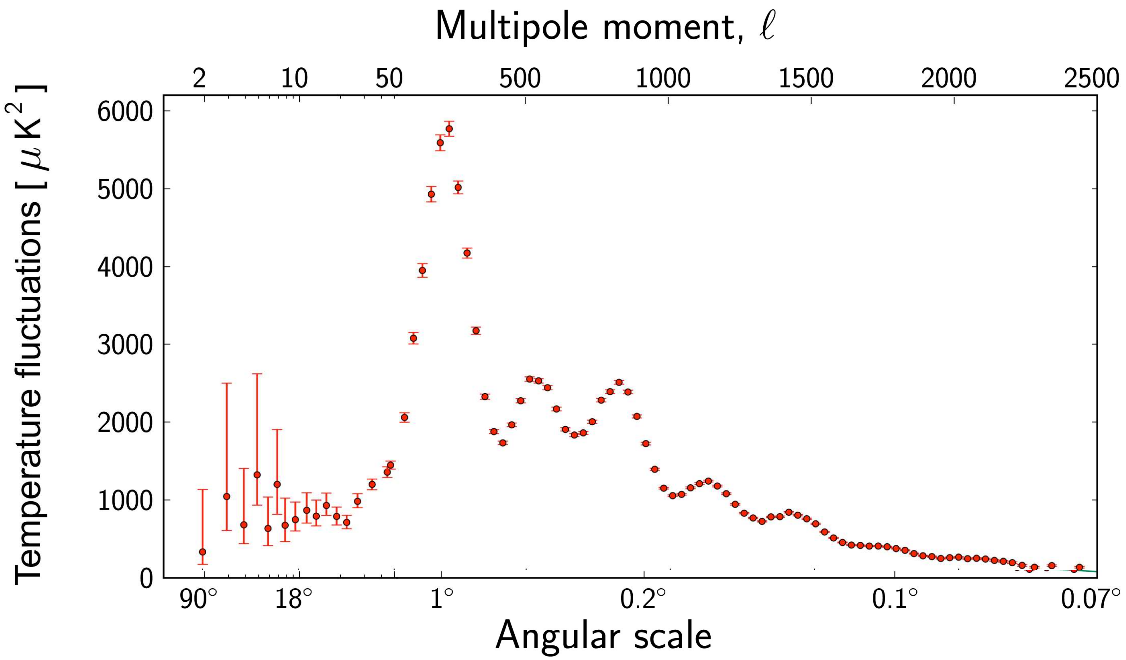
Cosmic microwave background

- **Use this photon flux to know the composition of the Universe**
  - Very small anisotropy (μK) observed – once background subtracted



Cosmic microwave background

- **Use this photon flux to know the composition of the Universe**
  - Decompose data in spherical harmonics
  - Amplitude and position of "acoustic" peaks gives the composition of the Universe



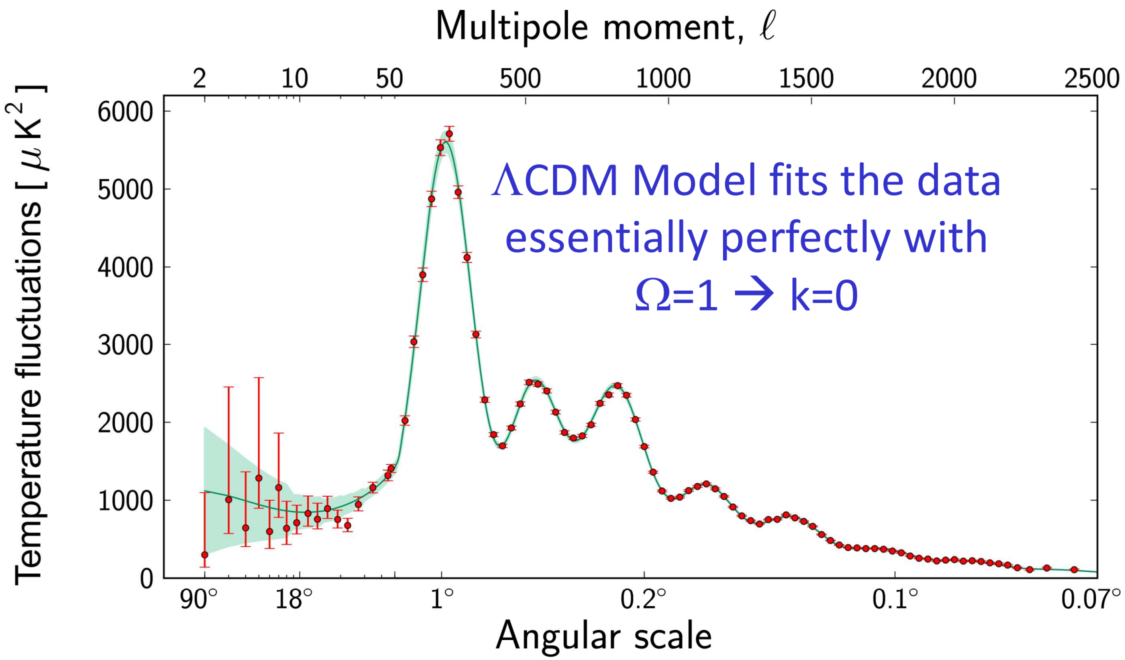
ΛCDM Model

- ✓ Matter particles (p, n, e-)
- ✓ Cold Dark Matter (CDM)
- ✓ Radiation (γ, ν)
- ✓ Dark Energy (Λ)

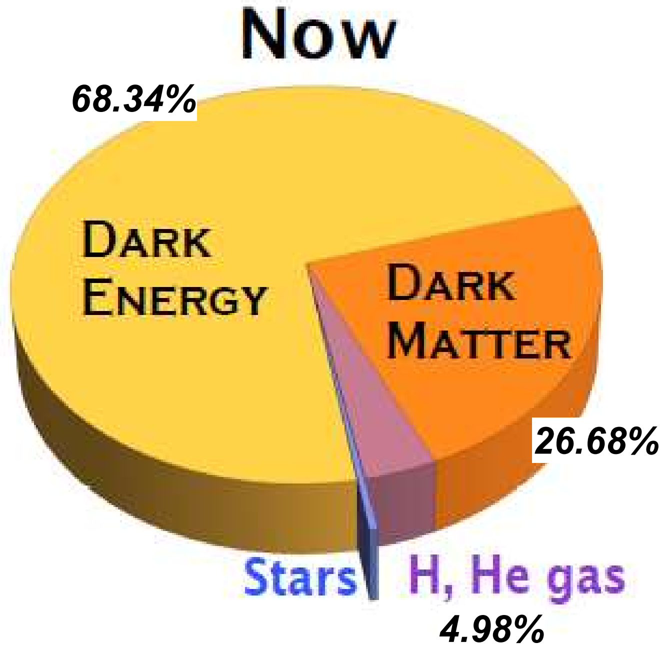
Ready to extract the abundances Ω of the ΛCDM Model ?

Cosmic microwave backgro

- **Use this photon flux to know the composition of the Universe**
  - Decompose data in spherical harmonics
  - Amplitude and position of "acoustic" peaks gives the composition of the Universe



ΛCDM Model fits the data essentially perfectly with Ω=1 → k=0



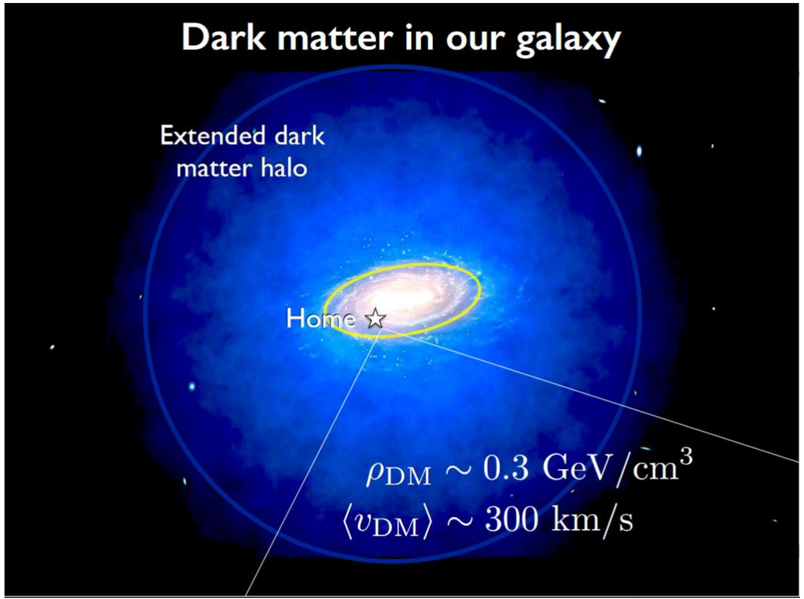
Cosmology is making precision measurements … **and**
we don't know 95% of the Universe and 85% of the matter !

Characteristics of Dark Matter

- **Many other proofs of dark matter**

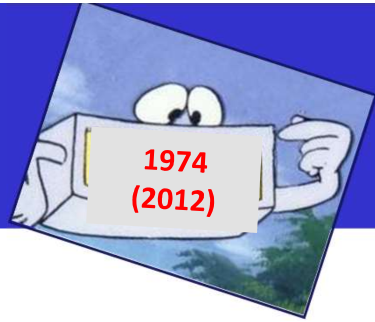
- **Dark matter exists (!)**
  - ✓ **Massive**: Interact with gravitational forces
  - ✓ **Form a halo** in our galaxy → favorable for direct exploration → **part II**

- **If it is a new particle it should be**
  - ✓ **Neutral** (dark)
  - ✓ **Stable** or very long-lived (Big Bang)
  - ✓ **Very weakly interacting with known particles**
  - ✓ **Non relativistic** to form galaxies

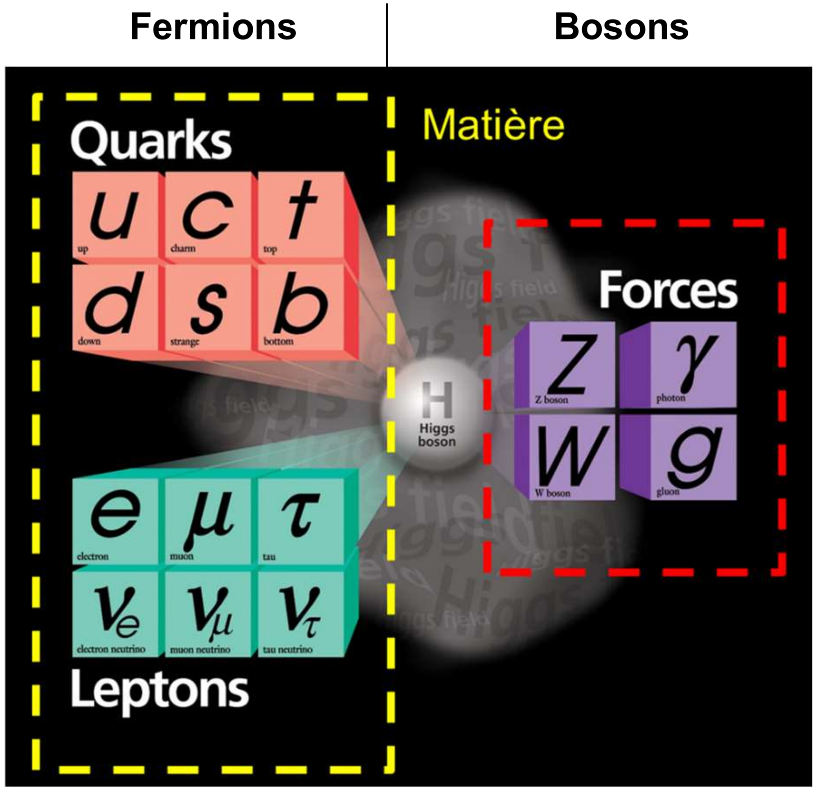


What is the nature of Dark matter ?

Particle physics



❑ Elementary particles in a Standard Model



- ✓ Massive
- ✓ Neutral
- ✓ Stable
- ✓ Weakly interacting
- ✓ Non relativistic

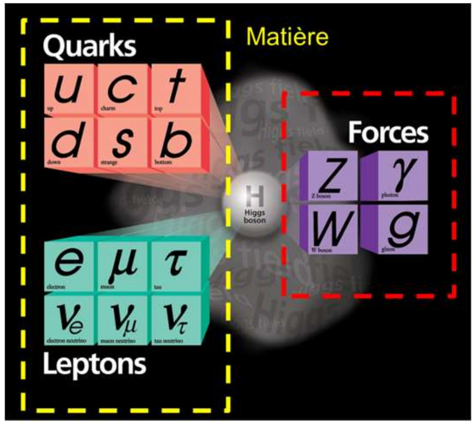
None of them has the required characteristics to be a dark matter particle

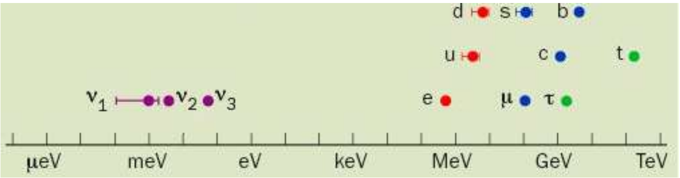
→ Dark Matter calls for New physics

Particle physics

❑ Standard Model status

- **26** free parameters* (21 **measured**) → *5 not measured*
  - ✓ **12 fermion masses (9)** → *ν masses*
  - ✓ **8 weak angles (7)**: 6 mixing (**6**), 2 CP phases δ (**1**) → *ν CP phase*
  - ✓ **1 strong angle (0)**: 1 CP phase θ → Θ_{strong}
  - ✓ **3 coupling constants (3)**: α_{EM}, G_F, α_S
  - ✓ **2 Higgs parameters (2)**: m_H, f_{EWSB}





- Some parameters look strange
  - ✓ **m_ν < eV** while m(charged fermion) > 0.5 MeV: why ? → **ν mass origin problem**
  - ✓ **$|\Theta_{strong}| < 10^{-10}$**: why ? → **strong CP problem**
  - ✓ **Higgs Mass**: very high radiative corrections → **gauge hierarchy problem**

We need new particles to solve these problems

* Assuming ν Dirac particles (if Majorana, add 2 other phases)

Particle physics

❑ Standard Model status

- **26** free parameters* (21 **measured**) → *5 not measured*
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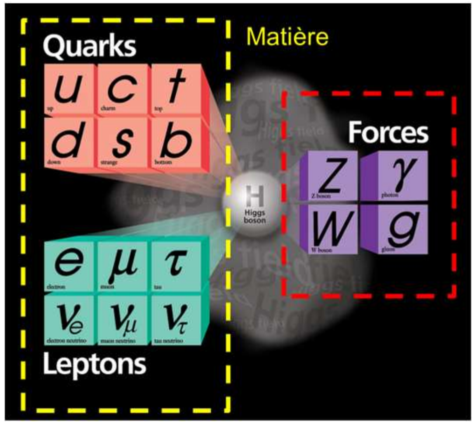
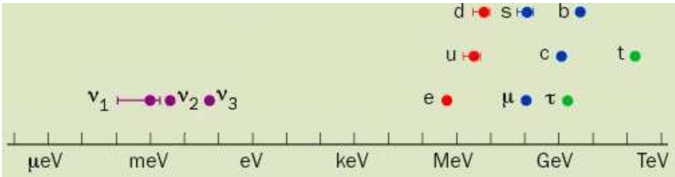




- Some parameters look strange
  - ✓ **m_ν < eV** while m(charged fermion) > 0.5 MeV: why ? → **Sterile Neutrino**
  - ✓ **$|\Theta_{strong}|$ < 10^{-10}**: why ? → **Axion**
  - ✓ **Higgs Mass**: very high radiative corrections → **Weakly Interacting Massive Particle (WIMP)**

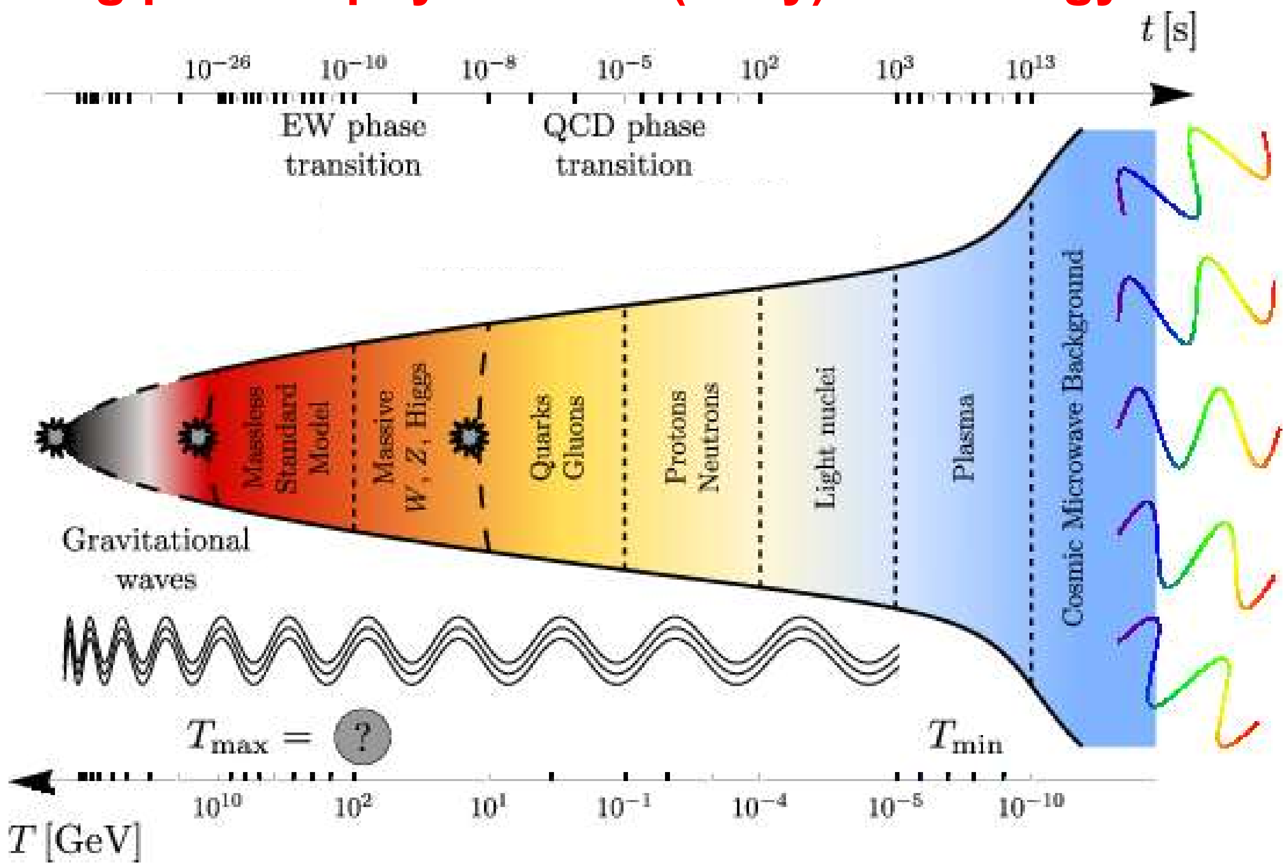
3 candidates fulfilling the dark matter criteria !

- ✓ Massive
- ✓ Neutral
- ✓ Stable
- ✓ Weakly interacting
- ✓ Non relativistic

* Assuming ν Dirac particles (if Majorana, add 2 other phases)

History of the Universe

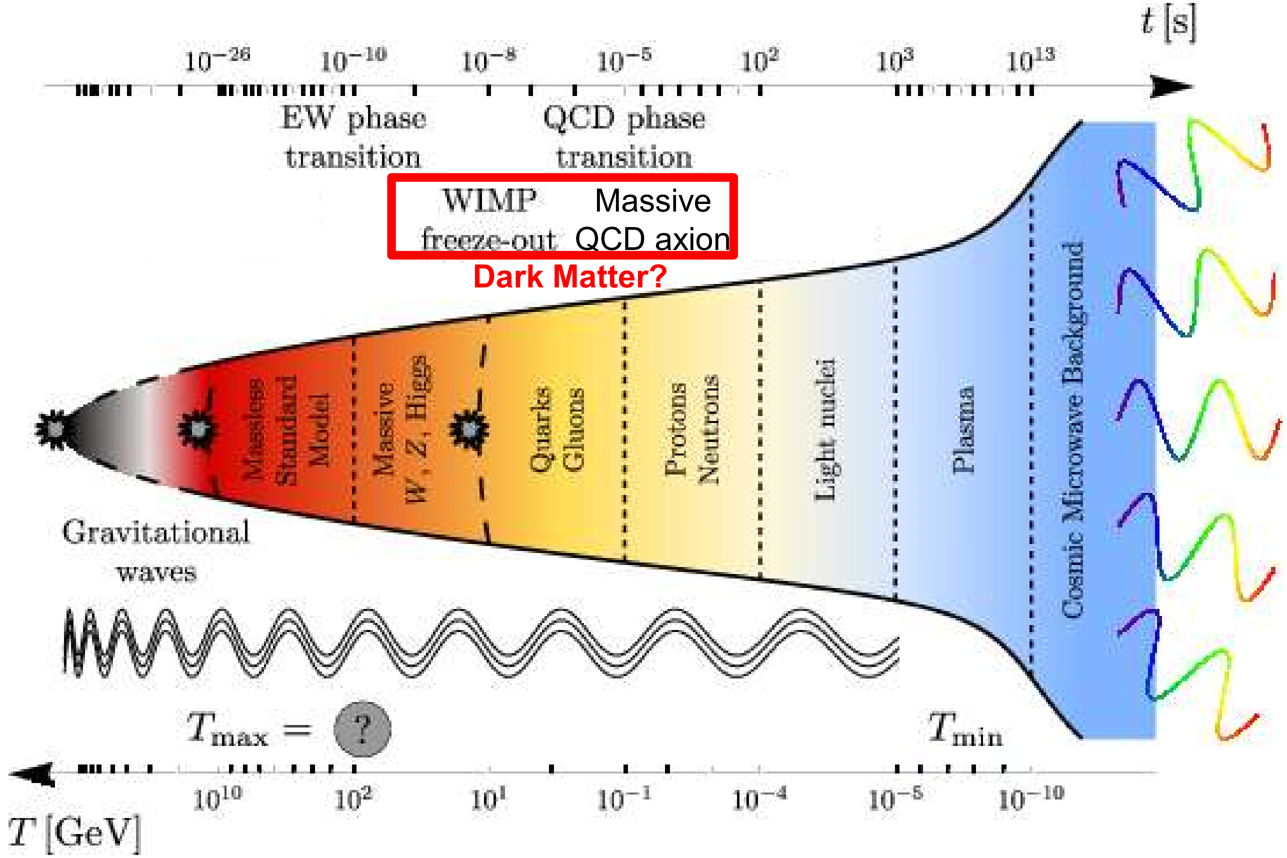
- Reconciling particle physics and (early) cosmology ?



History of the Universe

- ✓ Massive
- ✓ Neutral
- ✓ Stable
- ✓ Weakly interacting
- ✓ Non relativistic

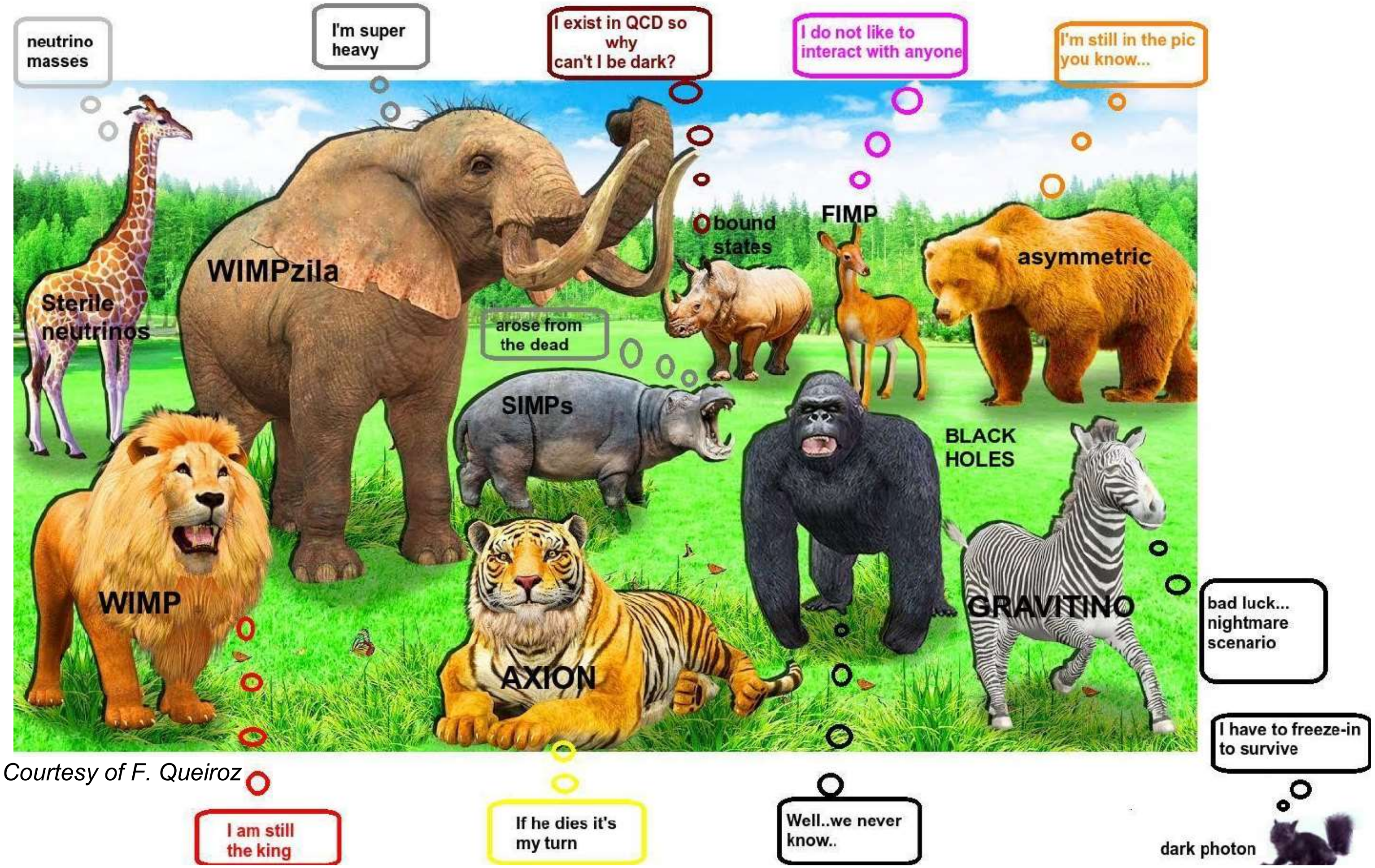
❑ Reconciling particle physics and (early) cosmology ?



Dark Matter appears at the very early instant of the Universe ?

WIMP or axion t <1 s

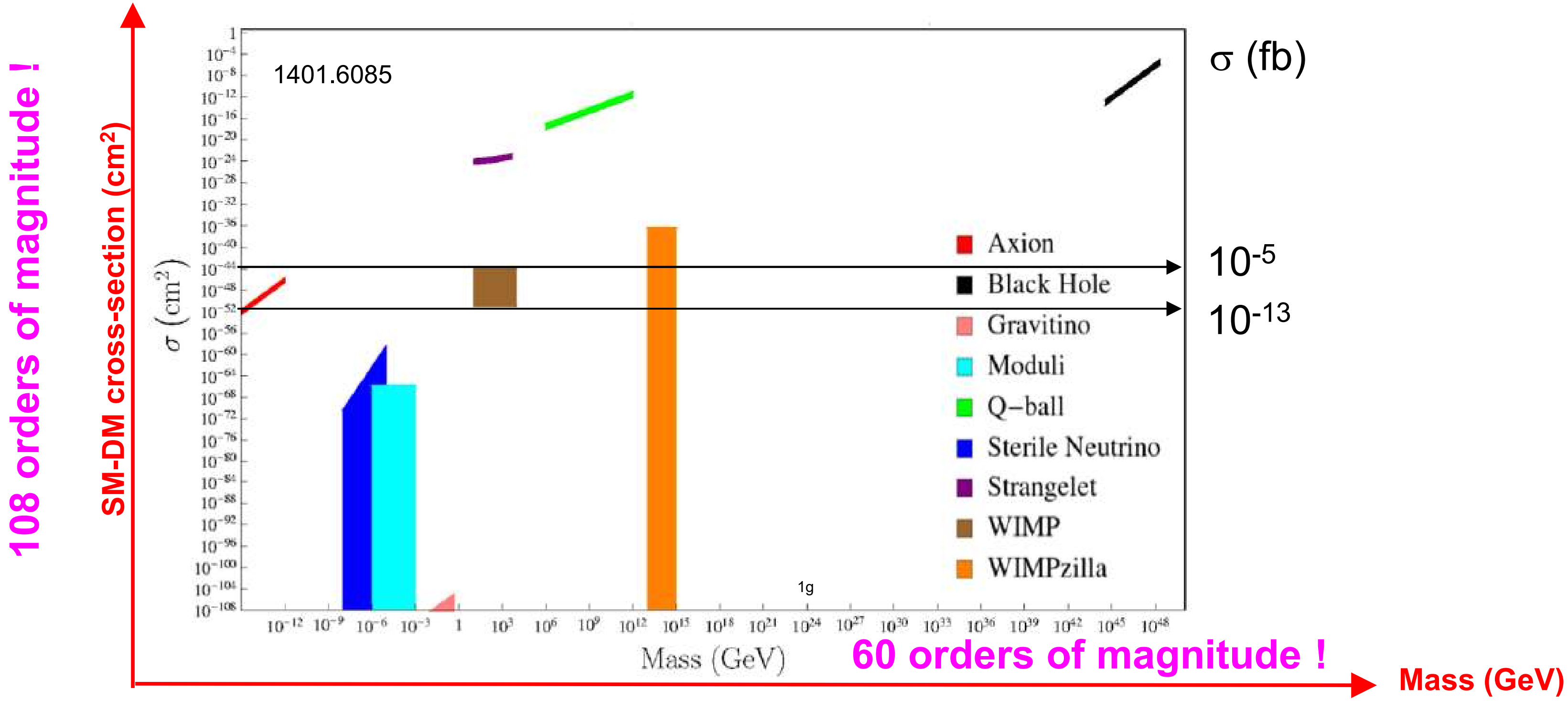
Nature of Dark Matter



Courtesy of F. Queiroz

Nature of Dark Matter

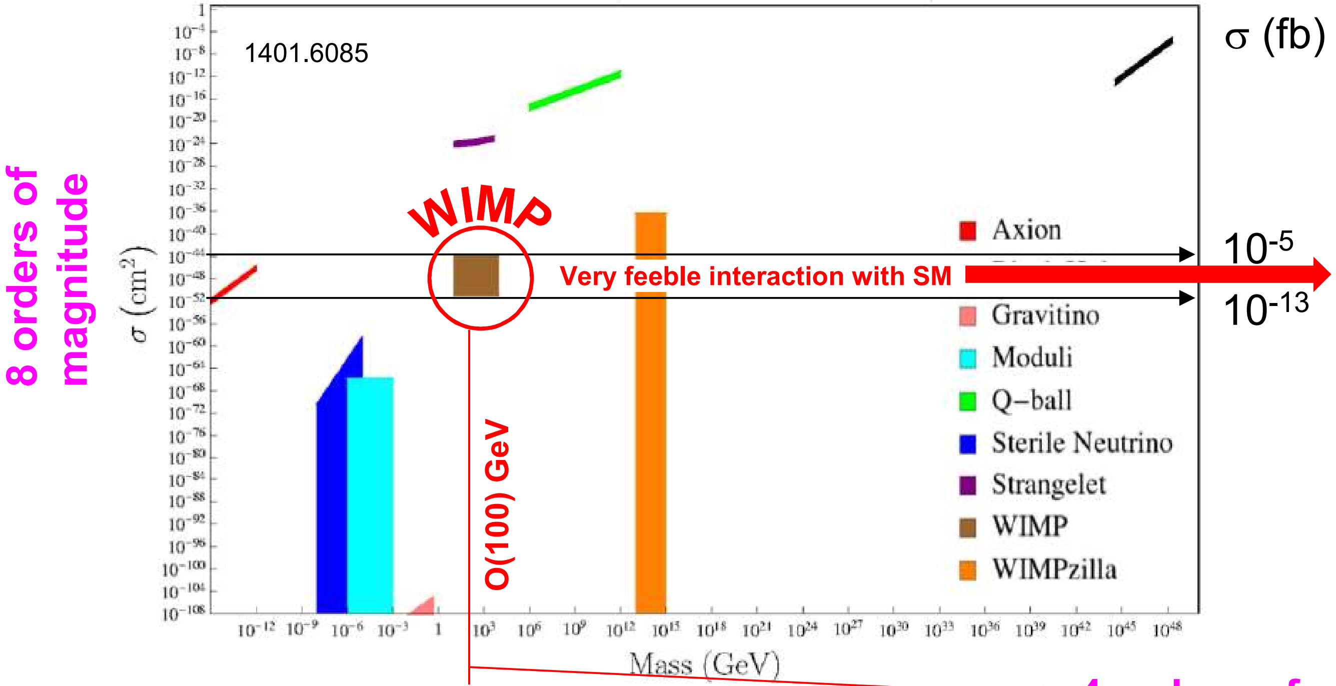
- Many dark matter candidates in a gigantic phase space

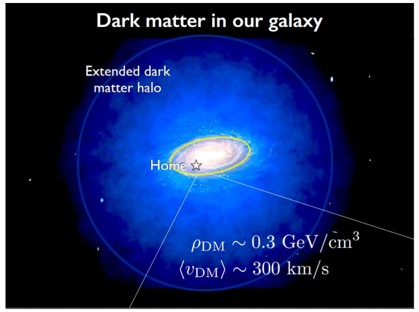


Direct searches are restricted to 2 well-motivated spots: WIMPs, axions

Nature of Dark Matter

❑ Experimental challenges of direct searches





… balanced the abundance of DM particles* in the galaxy halo → 0.3 GeV/cm^3 moving at $v=10^{-3}c$ wrt earth

*produced in very early Universe

4 orders of magnitude

- High mass → visible signal
- $O(10^{-3})/cm^3$ → **low occupancy** (1 / coffee mug)
- Large detector → **background under control**

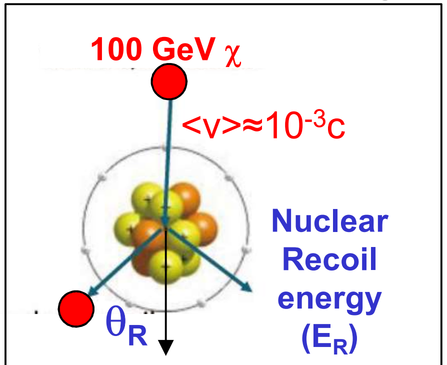
➔ Large volume, very low background

WIMP Detection

❑ Event rate expected in the detector

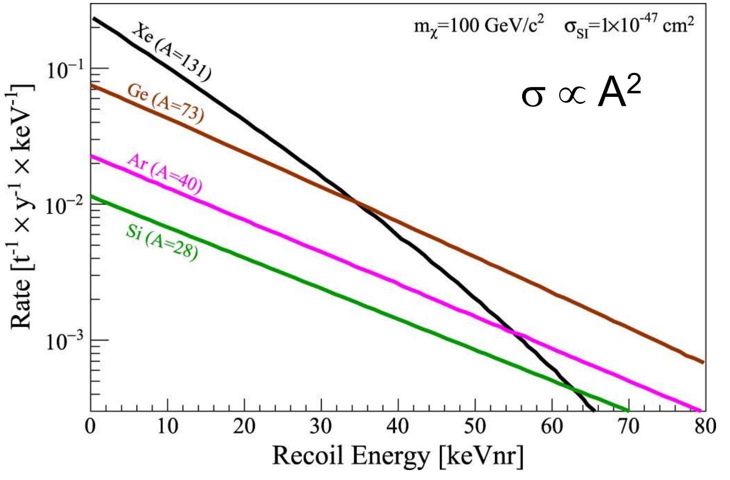
- Galactic halo WIMP elastically scatters on a target nucleus (Xe, Ar, Ge, Na)

Elastic scattering



$$E_R = \left(\frac{m_\chi m_A}{m_\chi + m_A}\right)^2 \frac{v^2}{m_A}(1 - \cos\theta_R)$$

$\langle E_R \rangle \approx 40$ keV



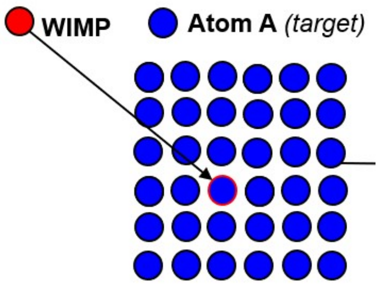
40 keV is very very low : 6.4 10^{-15} J !

- For a detector filled with 1 ton of Ar, taking data during one year and $\sigma_{\chi N}=10^{-47}\text{cm}^2$, we get **R ≈ 1 evt / (ton.year)**

Very low number of event expected per year !

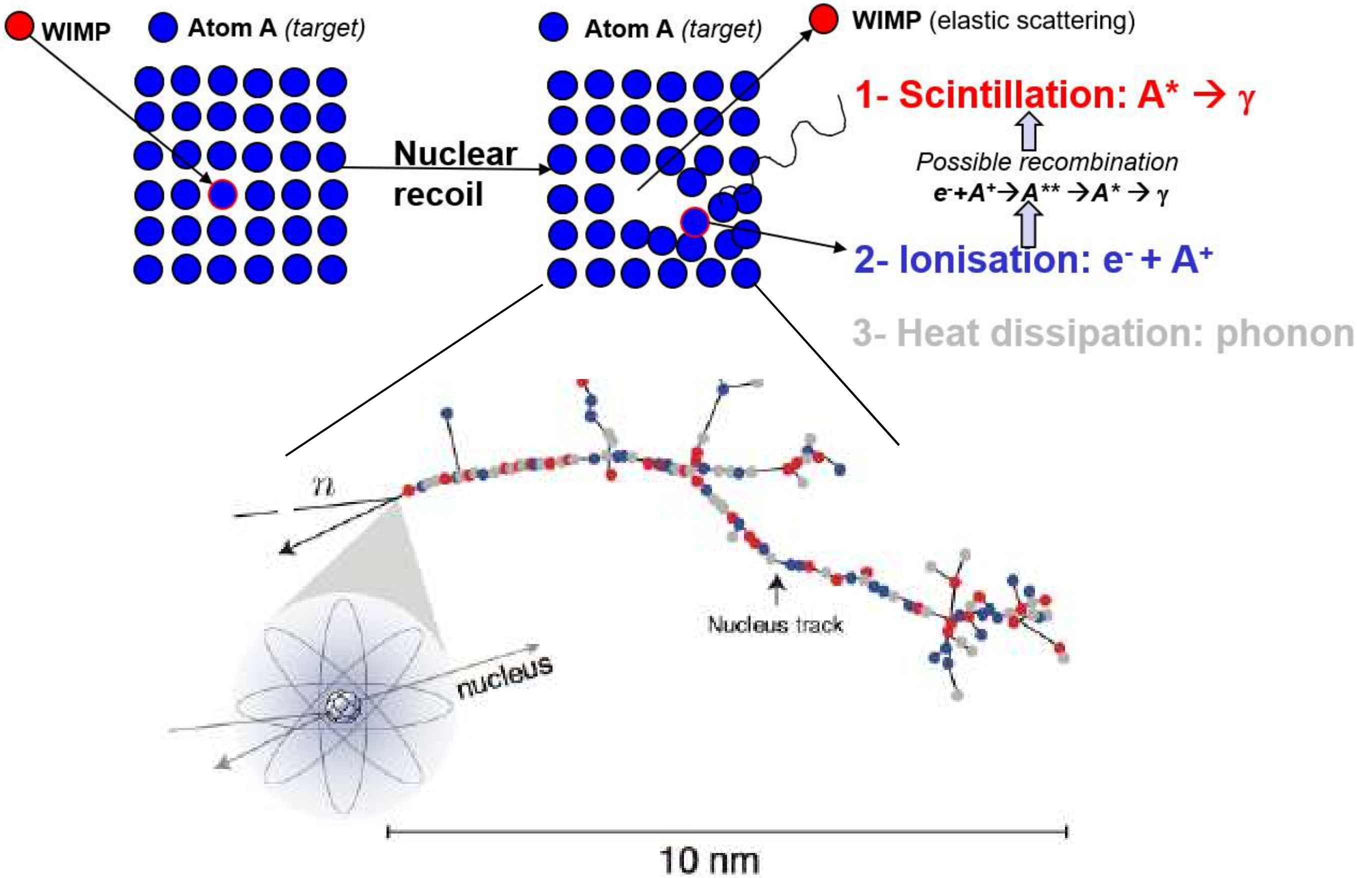
WIMP Detection

- How to measure the nuclear recoil energy ?



WIMP Detection

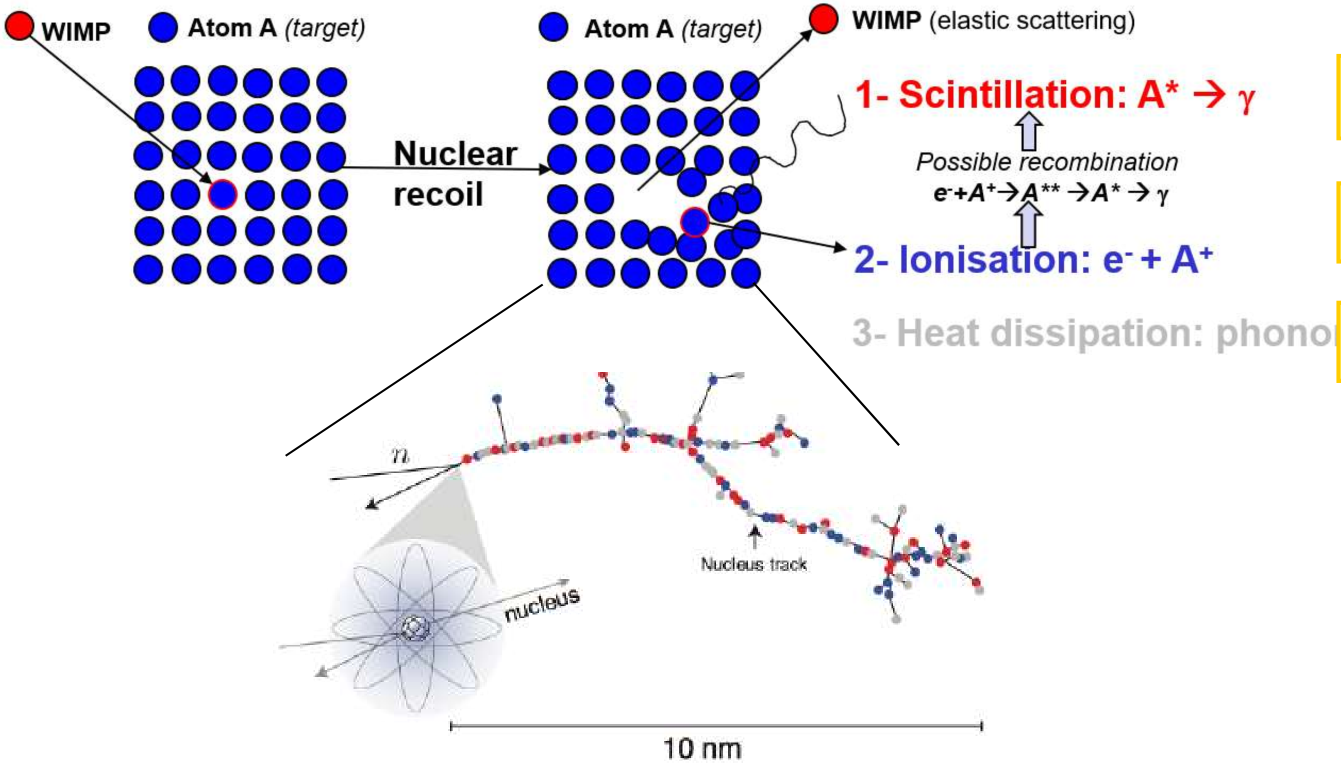
❑ **How to measure the nuclear recoil energy ?**



WIMP Detection

❑ **How to measure the nuclear recoil energy ?**

Exp. constraints



PhotoMultipliers *(single γ)*

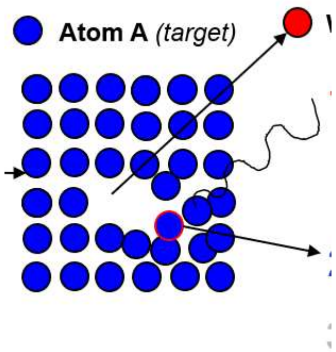
High Electric Field *(kV/cm)*

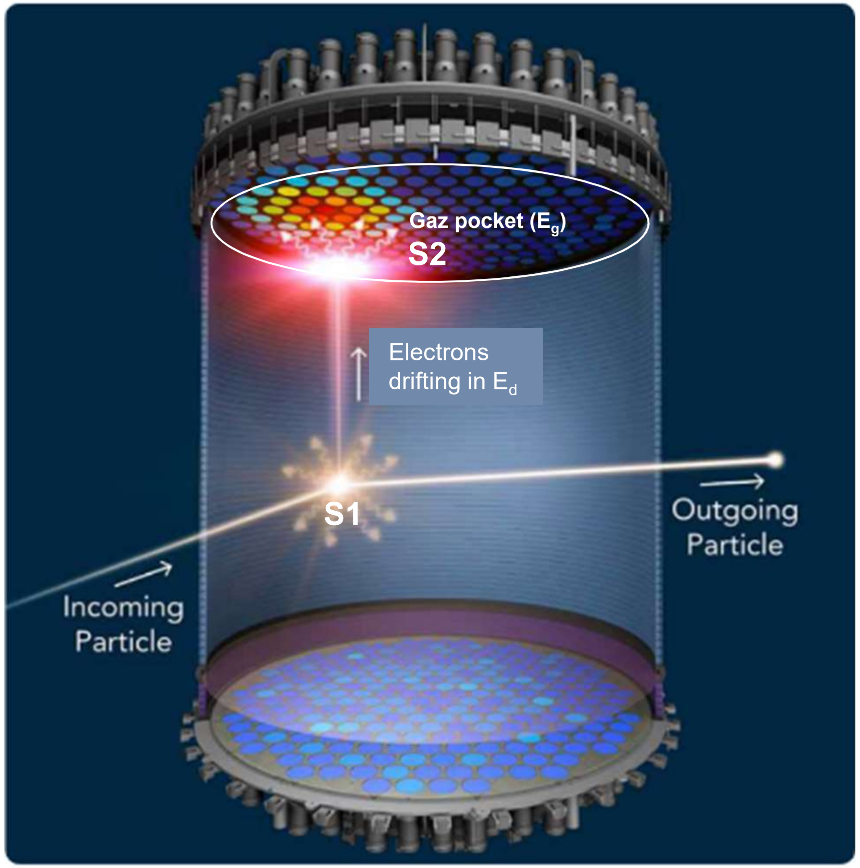
Very low temperature *(mK)*

WIMP search rich in experimental challenges

WIMP Detection

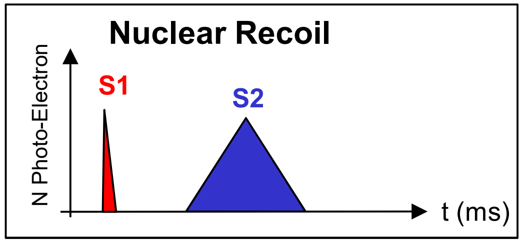
- **Most sensitive detector is Time Projection chamber (TPC)**
  - Combining two signals: prompt **scintillation** (S1) and delayed **ionization** (S2)





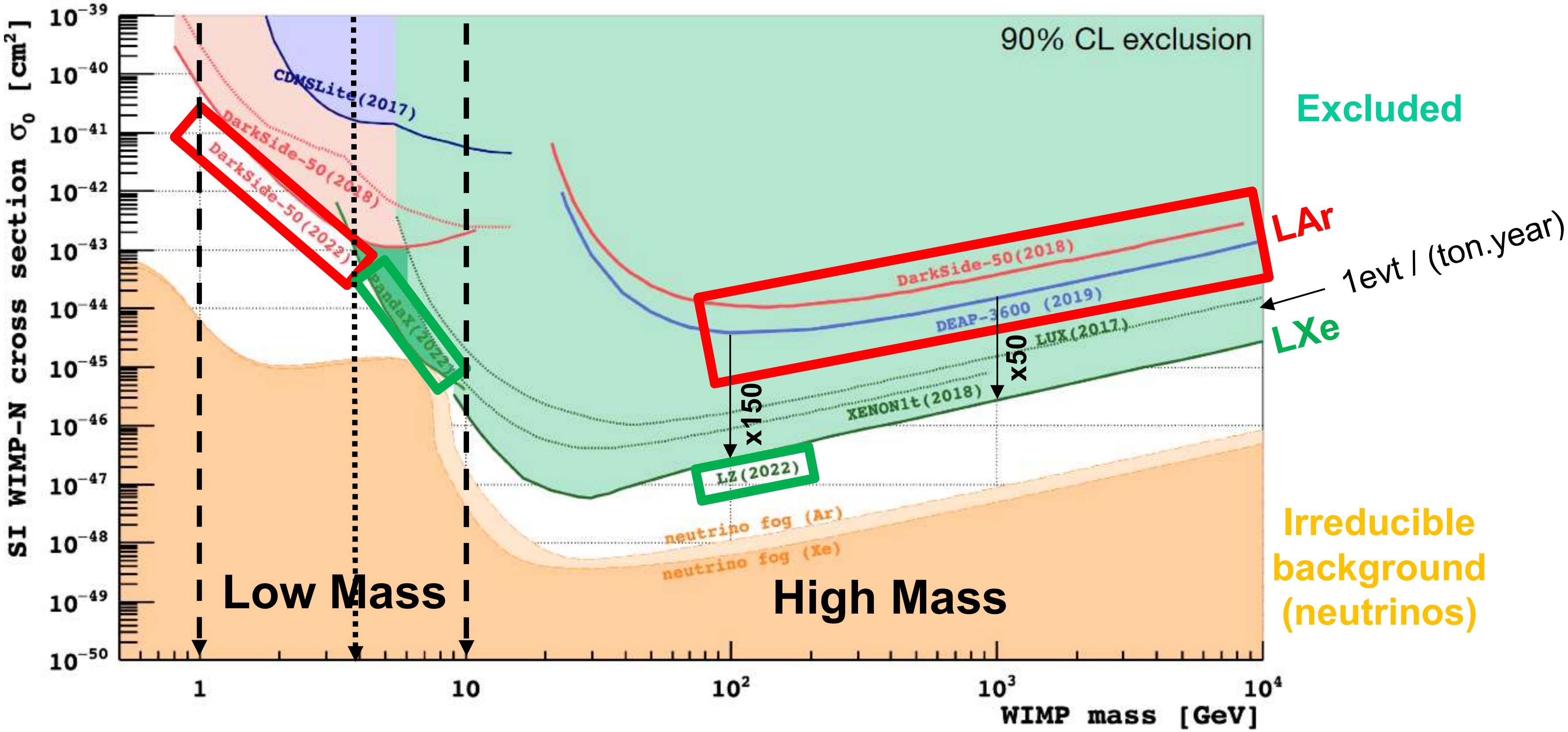
E_g~3kV/cm

E_d=200 V/cm



Status of WIMP search

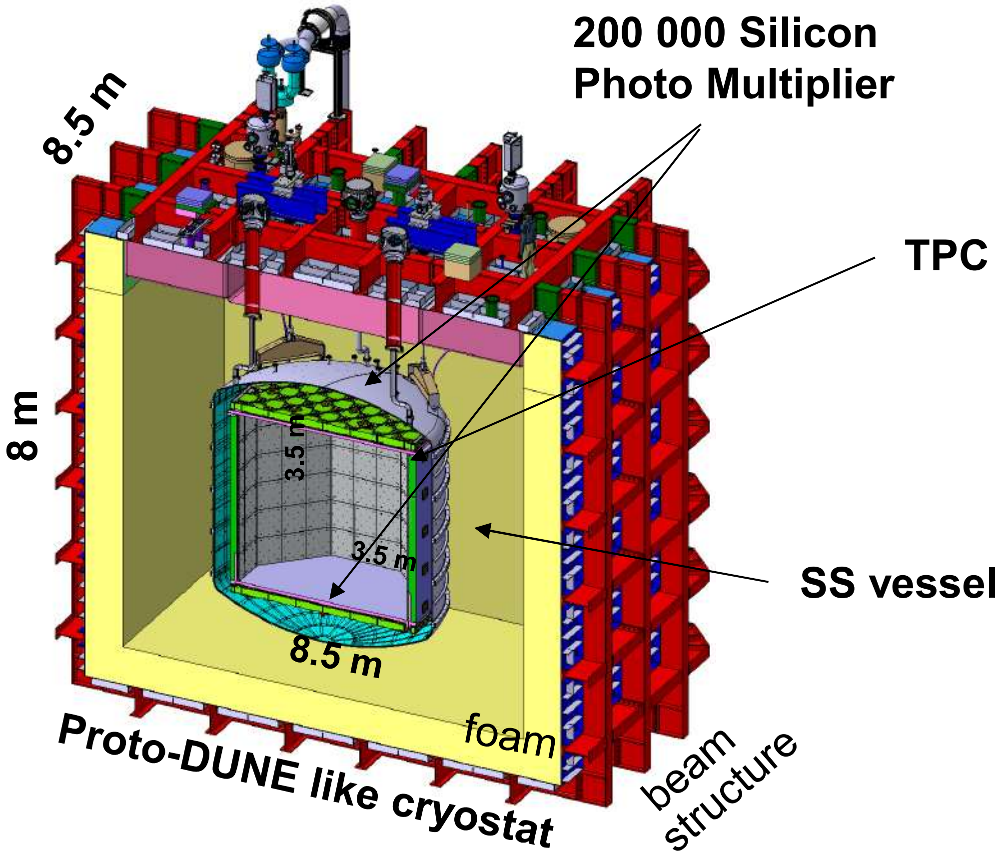
❑ Direct detection of Dark Matter WIMPs



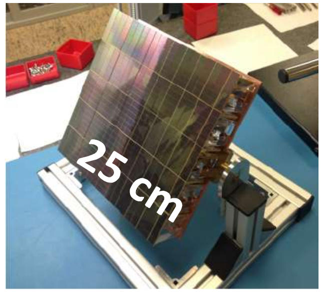
All the white space is well motivated by theory and still to explore !

Next generation of LAr detector

- Assembly in Gran Sasso laboratory (Italy)



400 SiPM grouped in one PDU



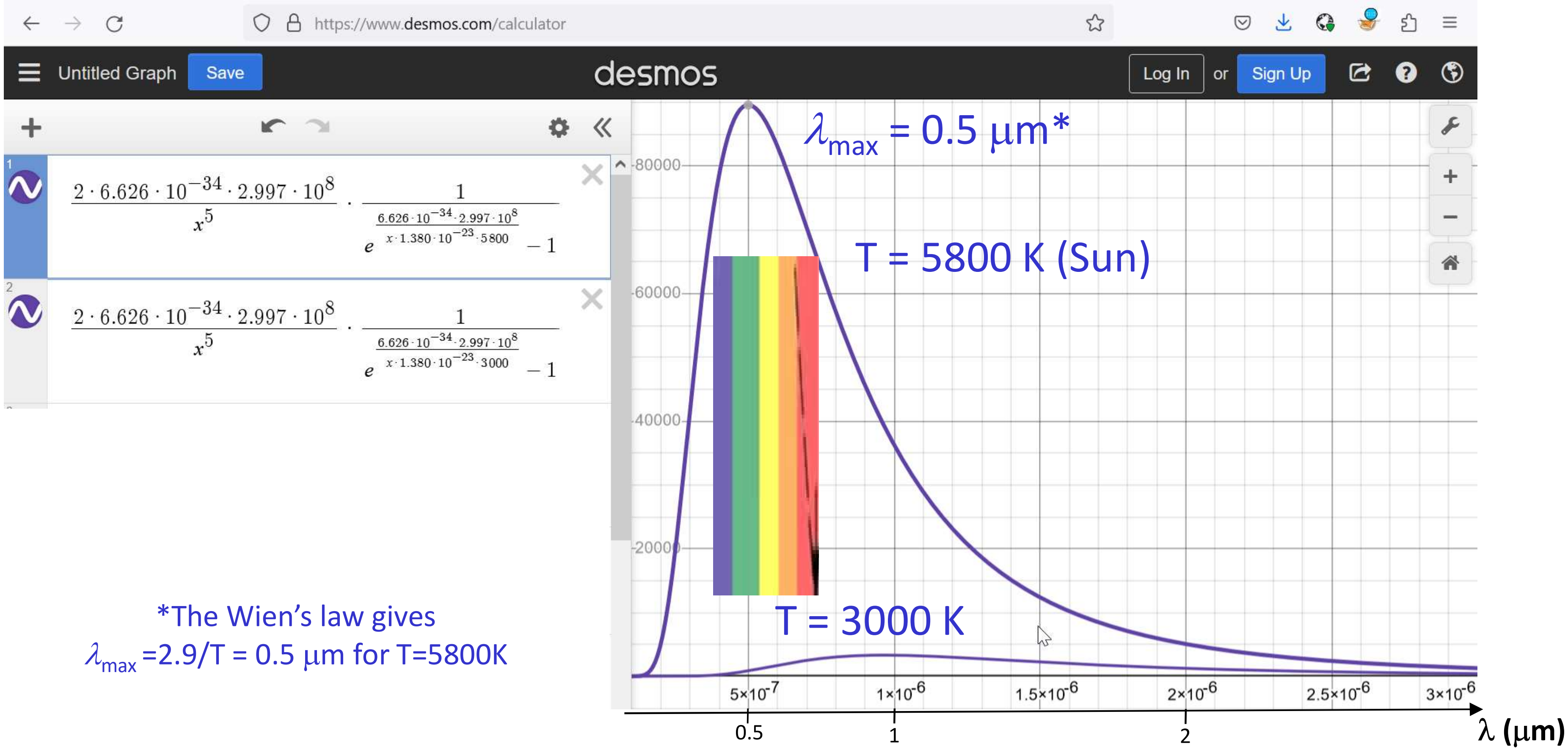
3 years of construction ahead before data daking (2027)

Back-up

Planck's Law vs wavelength

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

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



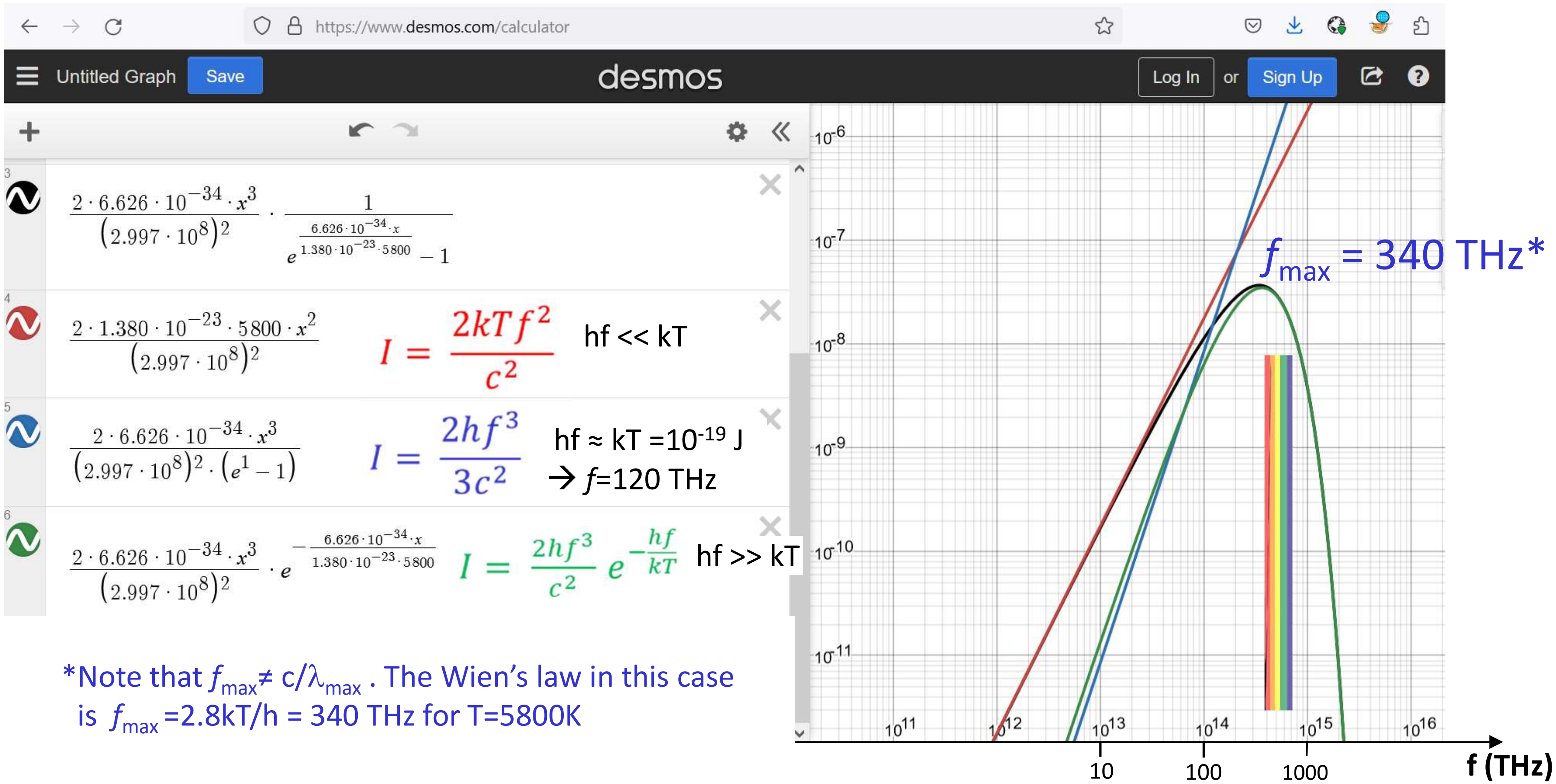
*The Wien's law gives
λ_{max} =2.9/T = 0.5 µm for T=5800K

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

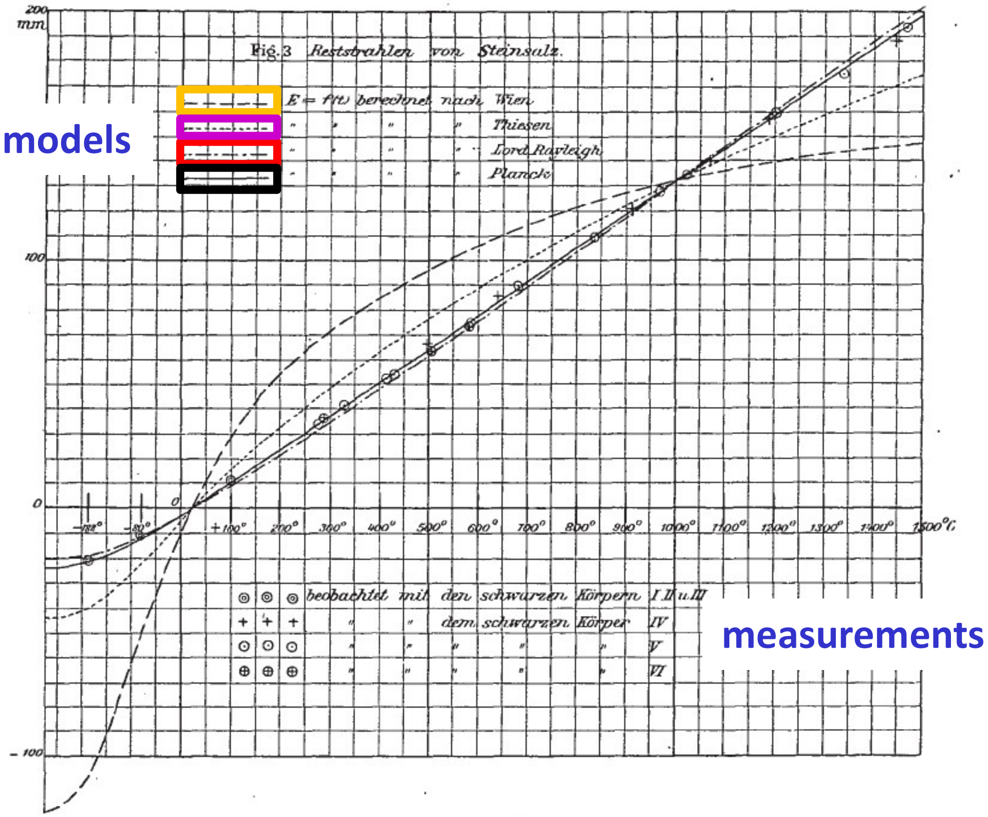


Fig. 3.

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

Units of Space, Time and matter

Metric units introduced to harmonize the units among French regions

Length and Mass from French revolution (1792-99)

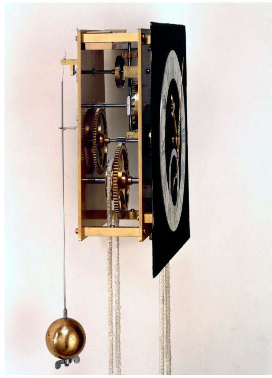
- Under Lavoisier guidance, put in place a decimal system (dm, cm, mm, dg, hg, kg) 18 germinal an III (7 april 1795)

Time

- benefits from the clock's development in XVIIth century

(36 Rue de Vaugirard Paris)

[1 kg platinum standard]



[pendulum clock]

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

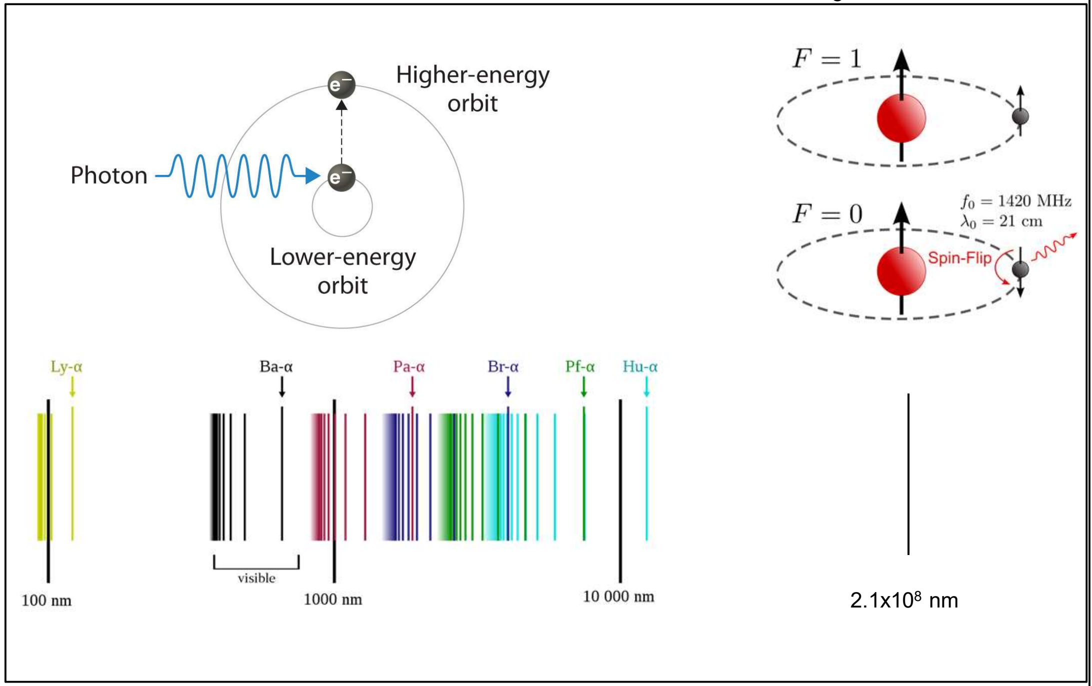
One gram is defined as the absolute weight of a volume of pure water equal to the cube of the hundredth part of a meter, and at the temperature of melting ice. **Water density= 10^3 kg.m^{-3}**

… 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).

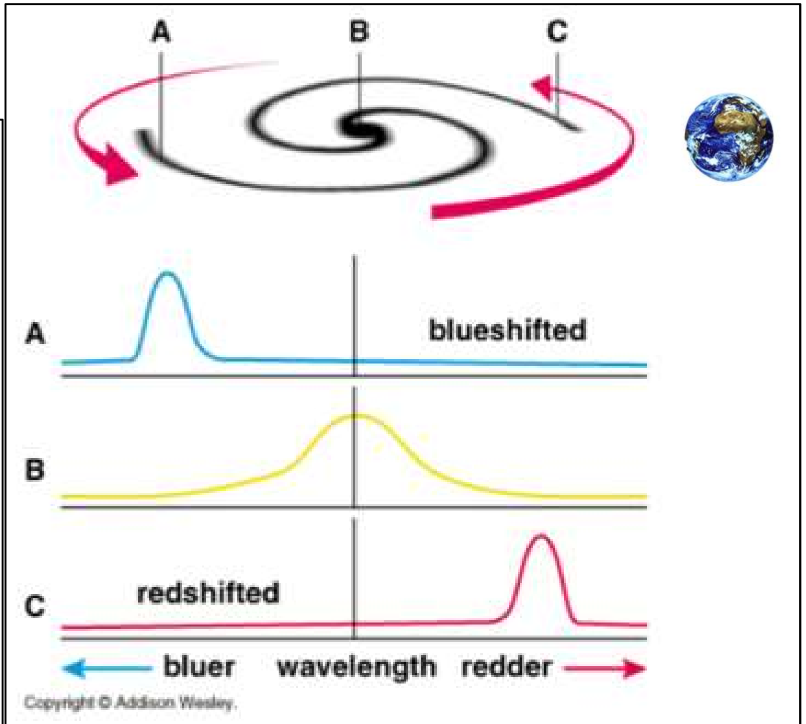
Galaxy rotation curve

❑ **Well-known spectral lines → Doppler shift → velocity curve of stars**

Hydrogen spectral lines (f_0)



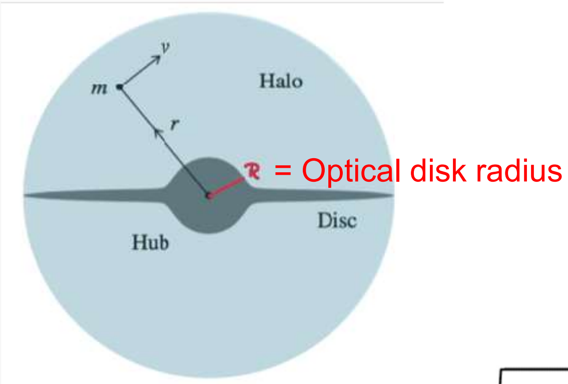
Galaxy rich in Hydrogen gaz



$$\Delta f = \frac{\Delta v}{c} f_0$$

Galaxy rotation curve

- **Well-known spectral lines → Doppler shift → velocity curve of stars**

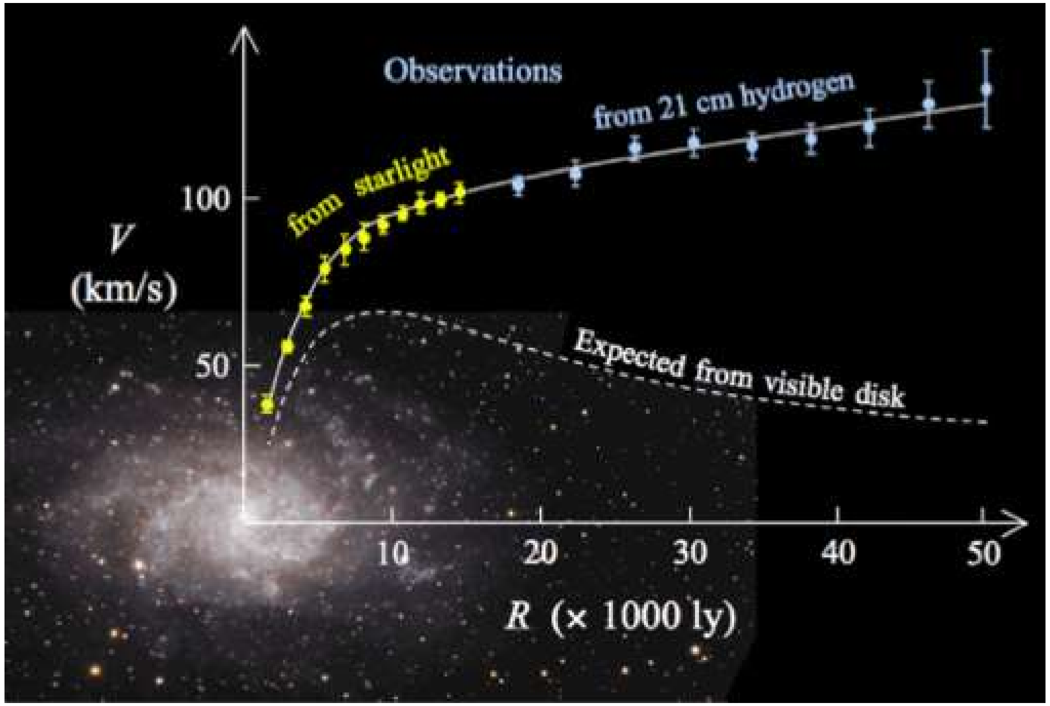


Prediction: $\frac{mv^2}{r} = \frac{mM(r)G}{r^2} \rightarrow v = \sqrt{\frac{GM(r)}{r}}$

Bulk: $r < R$: $M(r) \propto r^3 \Rightarrow v \propto r$ ✔

Disk: $r > R$: $M(r) = const \Rightarrow v \propto \frac{1}{\sqrt{r}}$ X

Observed: $r > R: v \sim const \Rightarrow M(r) \propto r$

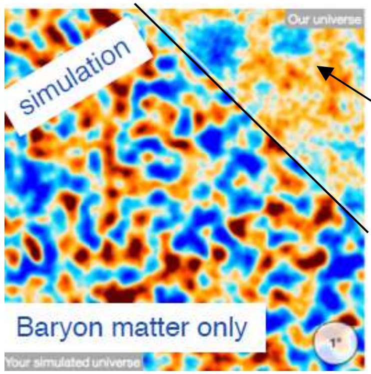


"*Mass, unlike luminosity, is not concentrated near the center of spiral galaxies*" (Vera Rubin)

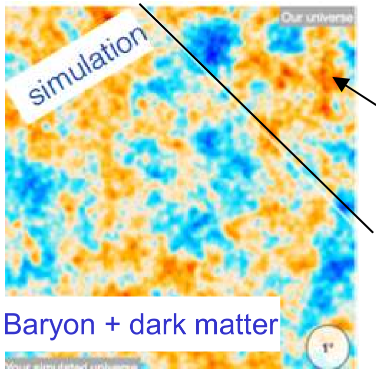
Dark matter halo in the galaxy ?

Other proofs

- Galaxy formation, evolution, collision

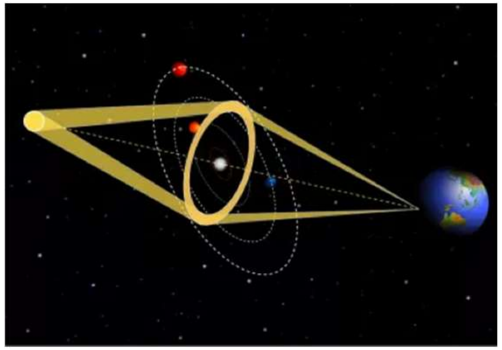


Cosmic Microwave background data



Cosmic Microwave background data

- Gravitational lensing



- Absence of massive objects made of baryonic matter

All proofs point towards dark matter