Comprendre l'Infiniment Grand
-
Introduction to Cosmology

Ch. Yèche, CEA-Saclay, IRFU/DPhP

July 11, 2023

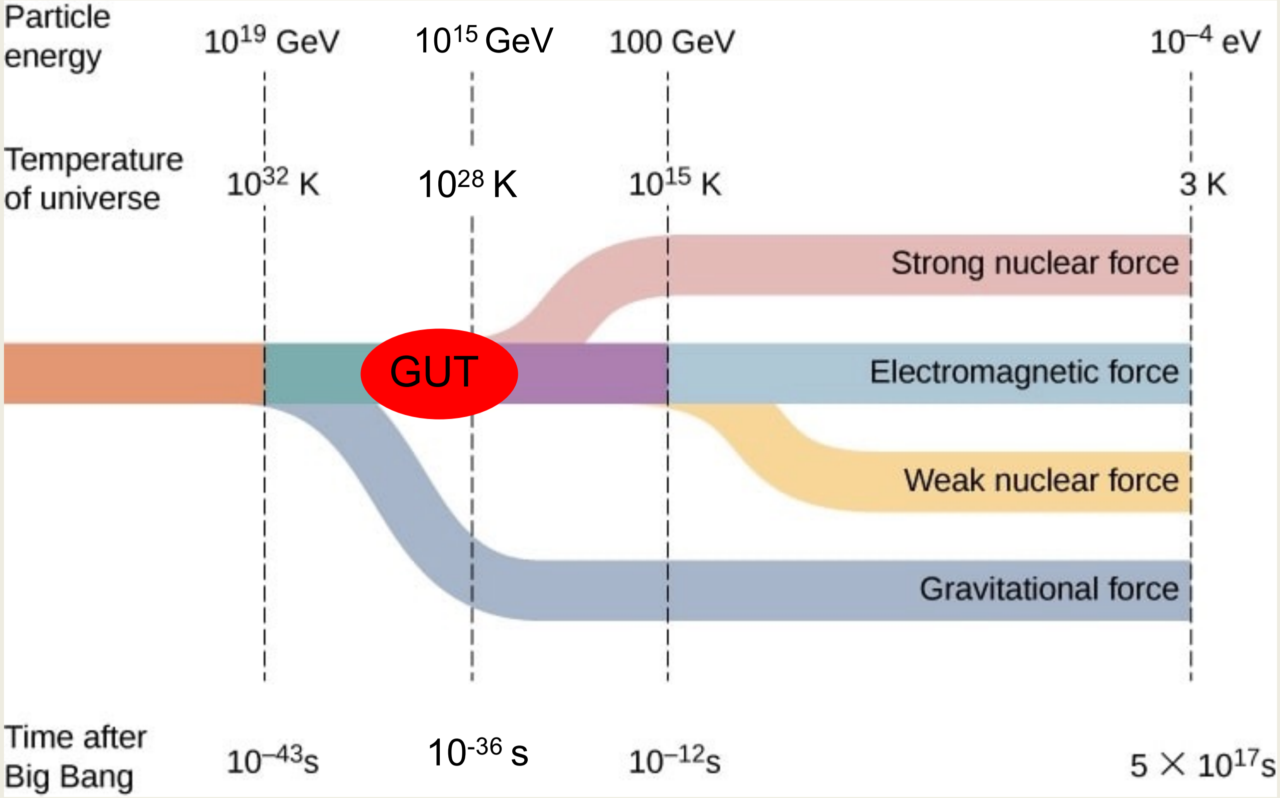
Cosmology - Part I

1. **Introduction**
    - Hubble law
    - Content of the Universe

2. **Gravitation and General Relativity**
    - Equivalence principle
    - Tests of GR

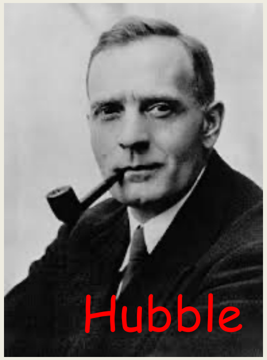
1) Introduction

Unification of forces



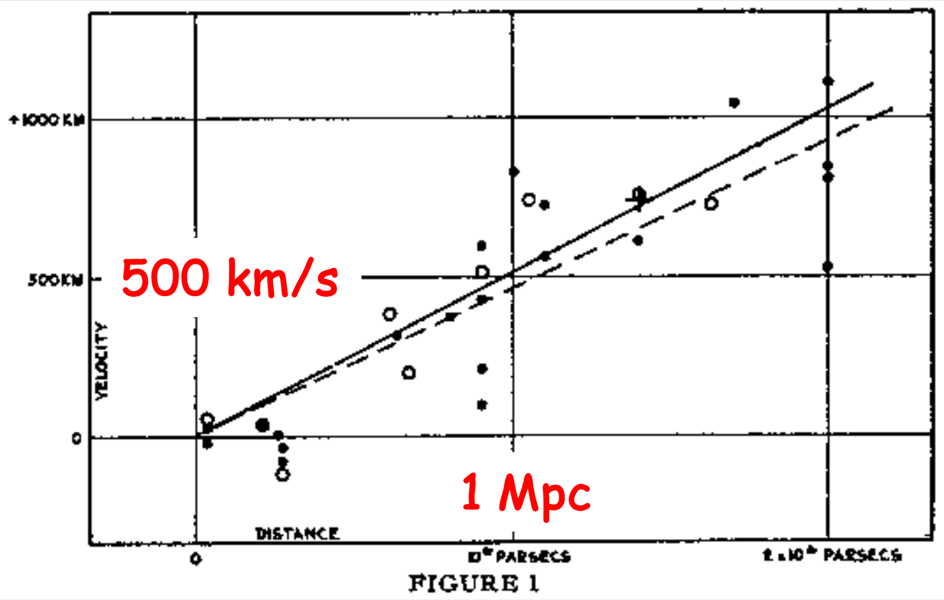
- EW force ~ 100 GeV
- Grand unification Theory (GUT) ~10^{15} GeV at 10^{-36}s after BB
- Theory of Everything ~10^{19} GeV (Planck scale)

Expanding Universe



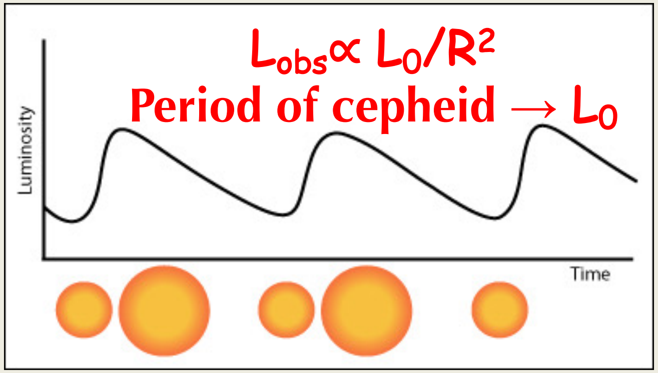
History of the discovery

- 1914, Slipher: farther the « nebula » (galaxy) is from us, the more it seems to be escaping away
- 1927, Lemaître: solutions of Einstein General Relativity for a non static universe ⇒ velocity proportional to distance.

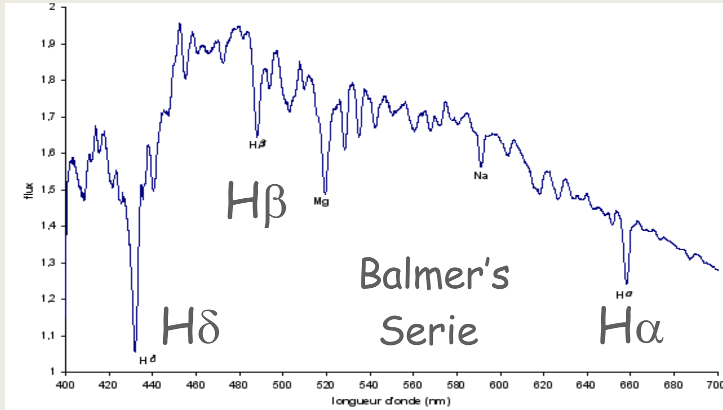


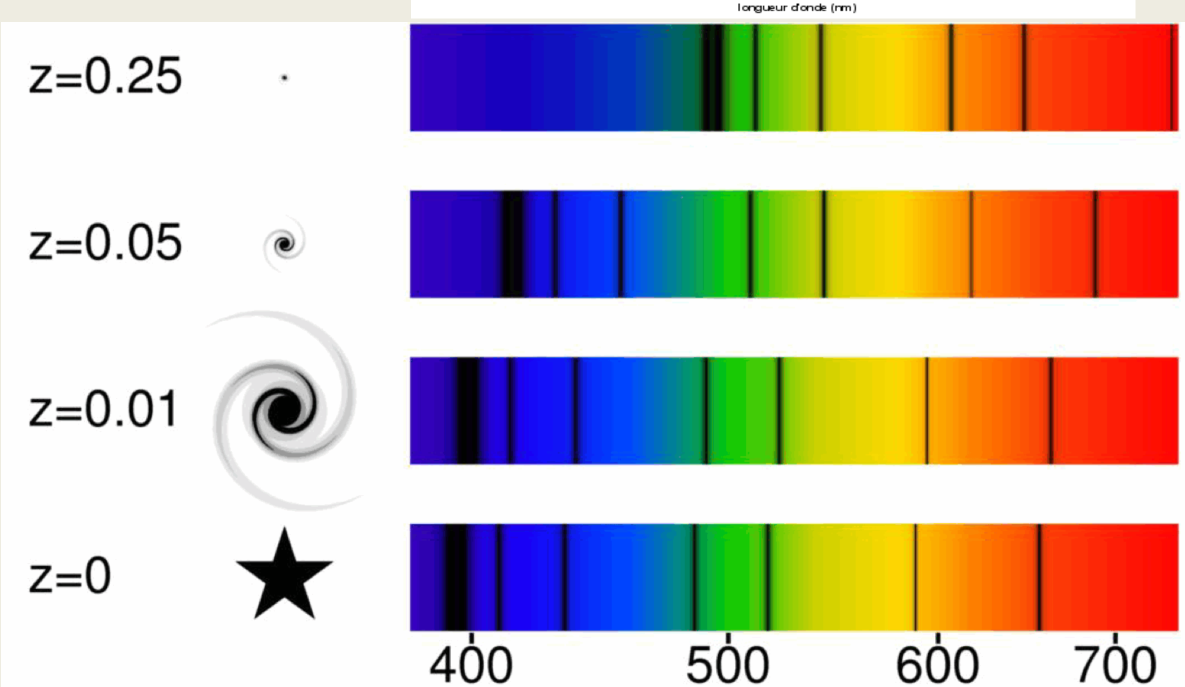
1 parsec= 3 light years

- 1929, Hubble: Relation distance – velocity thanks to cepheid in extragalactic "nebula "



How do we measure velocity?





Stars spectra

Absorption lines

Galaxies

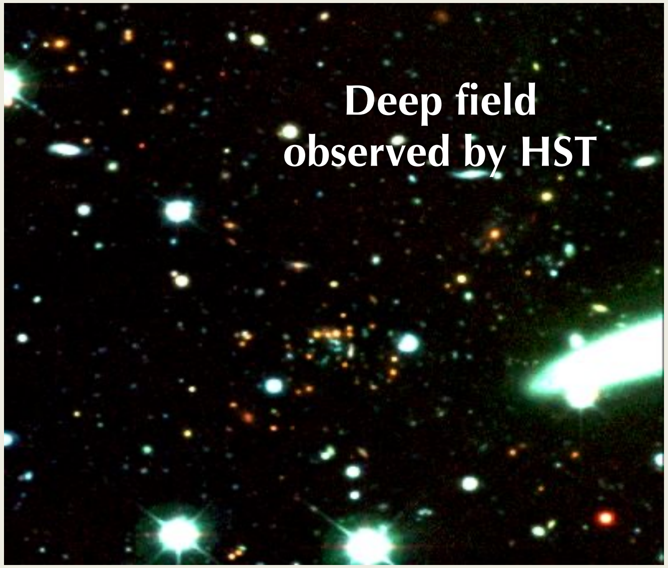
- Emission lines
- Balmer/Lyman breaks

Redshift

Doppler effect

$V/c=(\lambda-\lambda_0)/\lambda_0=z$

Expanding Universe



Hubble's law

$V = H_0 D$

- Measurement of the velocity of galaxies with **their redshift (z)**
Doppler effect : $v/c = (\lambda - \lambda_0)/\lambda_0 = z$
- Increasing z $\Rightarrow$ Back in time

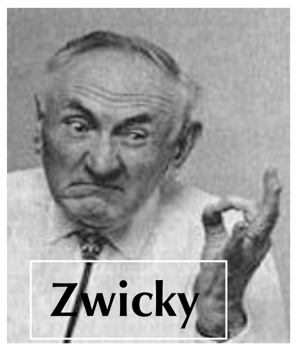
What value of H_0?

- Controversial and controverted measurement.

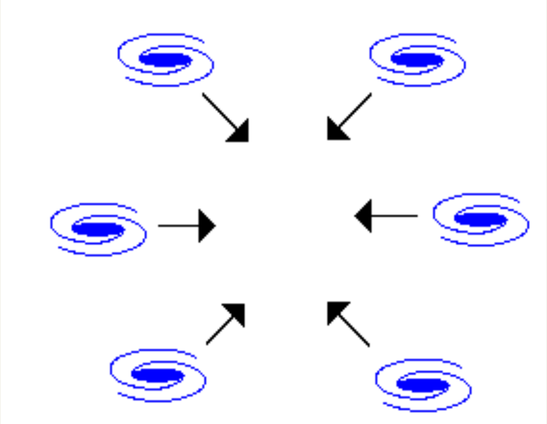
What about gravitation?

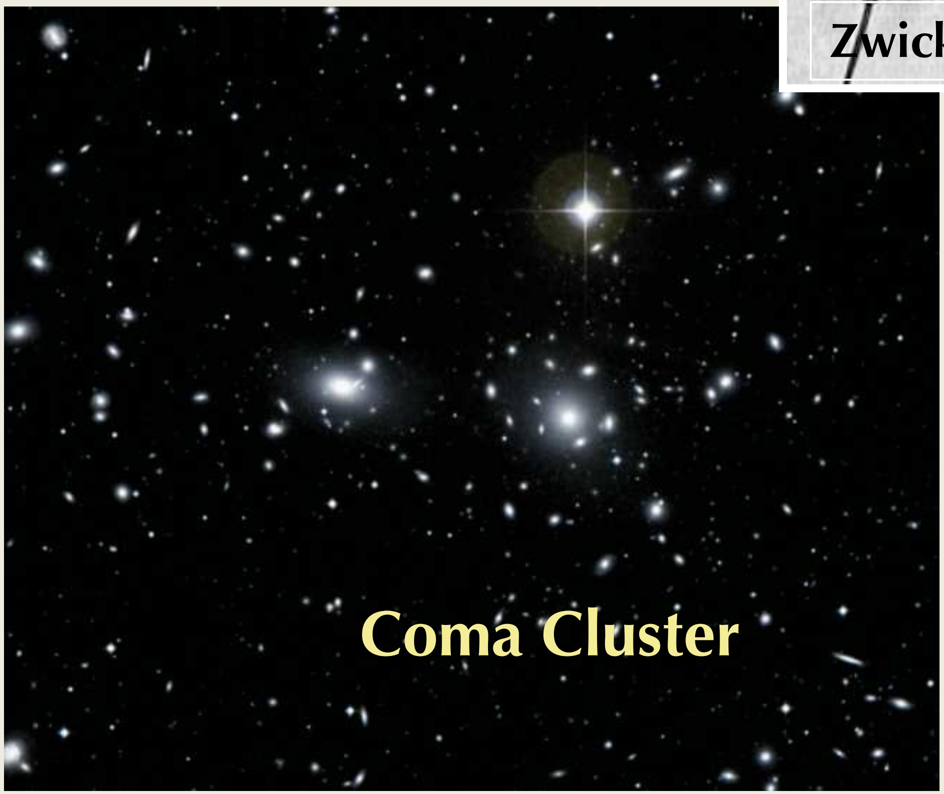
- It will slow the expansion of the universe for dark matter - Deceleration.
- It will accelerate the expansion of the universe for "repulsive" matter - Acceleration.

Discovery of Dark Matter



Zwicky, 1933





“Invisible” matter

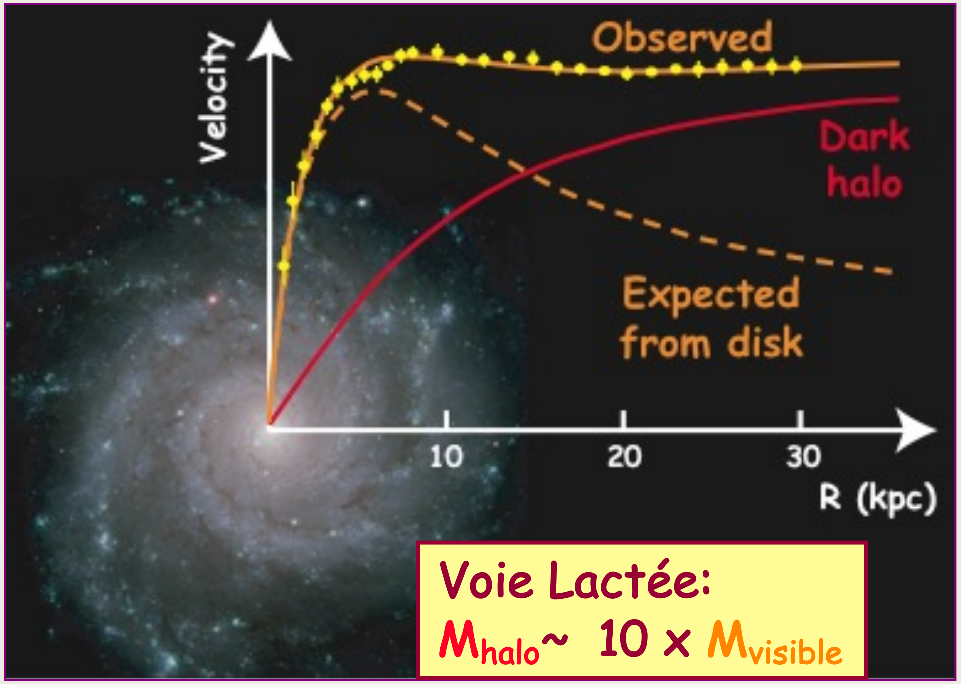
- Galaxy cluster.
- Peculiar velocity of galaxies too high.
- Virial theorem.
- Visible galaxies are about 1-10% of the total mass.

$$E_p + 2\,E_c = 0$$

E_c =1/2 M v^2 and E_p = -½ GM^2/R

$M = 2Rv^2/G$

1970: how to weigh galaxies?



Galactic rotation curves

➢ Final proof by measuring the velocity of stars within galaxies

➢Work of Vera Rubin and Kent Ford in the 70'

Newton Law

$$\boxed{\begin{array}{l} E_c + E_p = 0 \\ V_{rot} = \sqrt{\dfrac{2GM}{R}} \end{array}}$$

Constant rotation curve

$\Downarrow$

Halo of Dark Matter

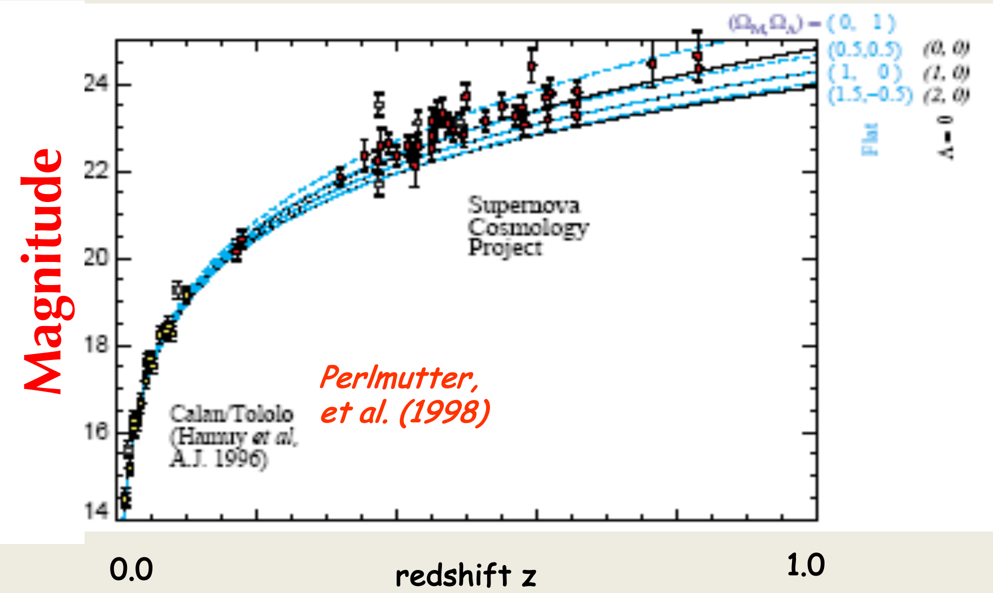
Dark energy

Discovery with supernovae

- **In 1998,** Hubble diagram (magnitude ↔ z) with standard candles (SN Ia)

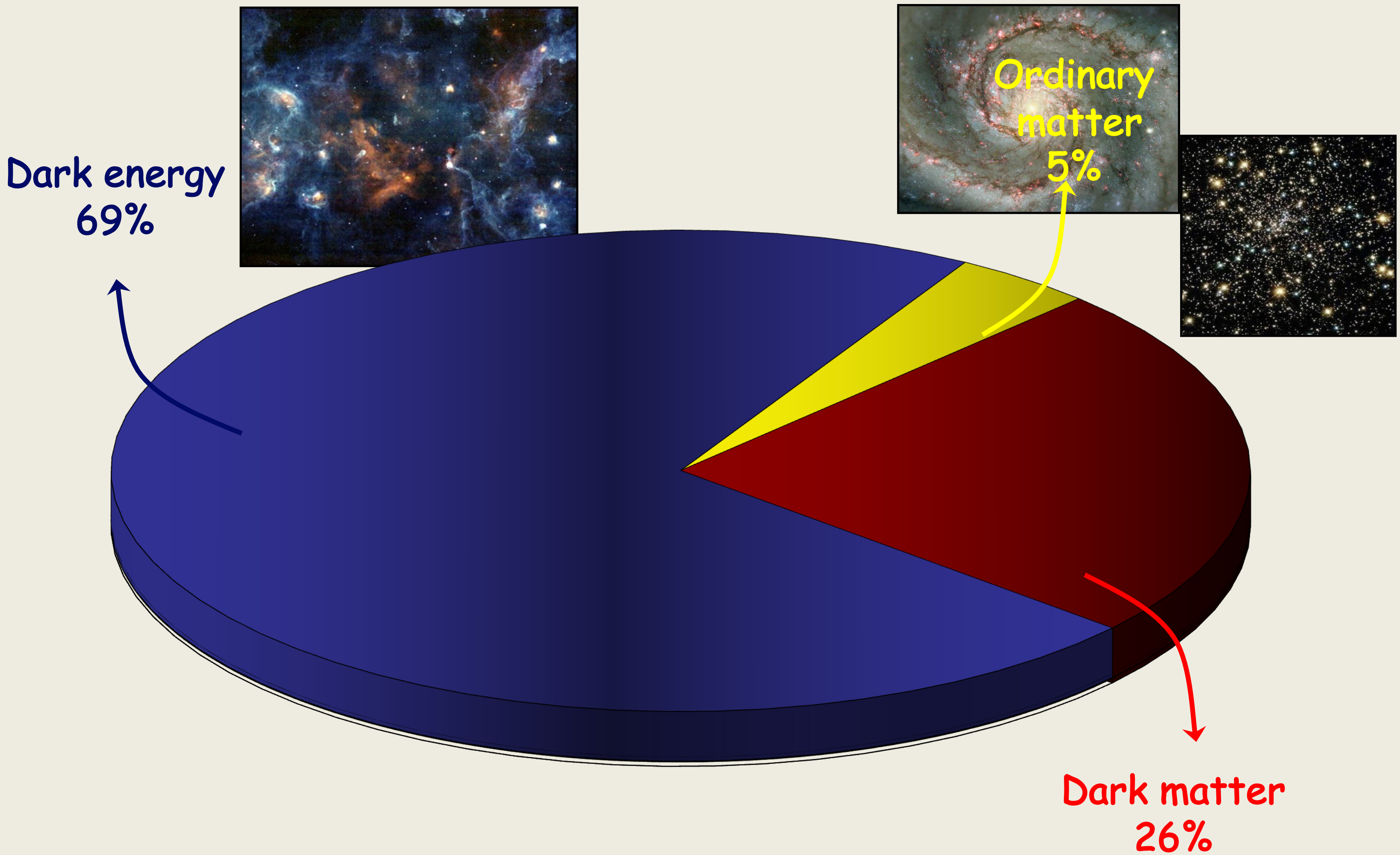
$$L_{obs} \propto L_0/R^2$$

- Acceleration of expanding Universe



- **~2/3 of Dark Energy** repulsive for gravitation
- **~1/3** "classical" matter

Content of the Universe



Summary - Content of the Universe

- Radiation 5 10^{-5}
  Cosmic microwave background (CMB) + neutrinos
- Ordinary matter (baryonic) ~5% ~ 1 proton / 4 m^3
  - galaxies (stars, interstellar gas, dust)
  - typical galaxy: 10^{12} $M_\odot$
  - $\langle\rho_{visible}\rangle = 10^{-31}$ g / cm^3 0.2%
  - intergalactic gas
- Dark matter ~26%, many evidences:
  - star rotation curves in galaxies
  - galaxy rotation curves in clusters
  - structure development, …
- Dark energy ~69%
  - Acceleration of the Universe expansion (SNIa)

2) Gravitation and General Relativity

Gravitation and relativity

- 1905 : Special Relativity

- Incompatible with Newton $$F = \frac{G m_1 m_2}{\left| r_1(t) - r_2(t) \right|^2}$$
- Instantaneous force, $r_1(t)$ et $r_2(t)$ at the *same t*
- Newton = approximation of a more fundamental theory

$$F = \frac{1}{4\pi\varepsilon_0} \frac{q_1 q_2}{r_{12}^2}$$ Coulomb law approximation of Maxwell eq.

- 1915 : General relativity

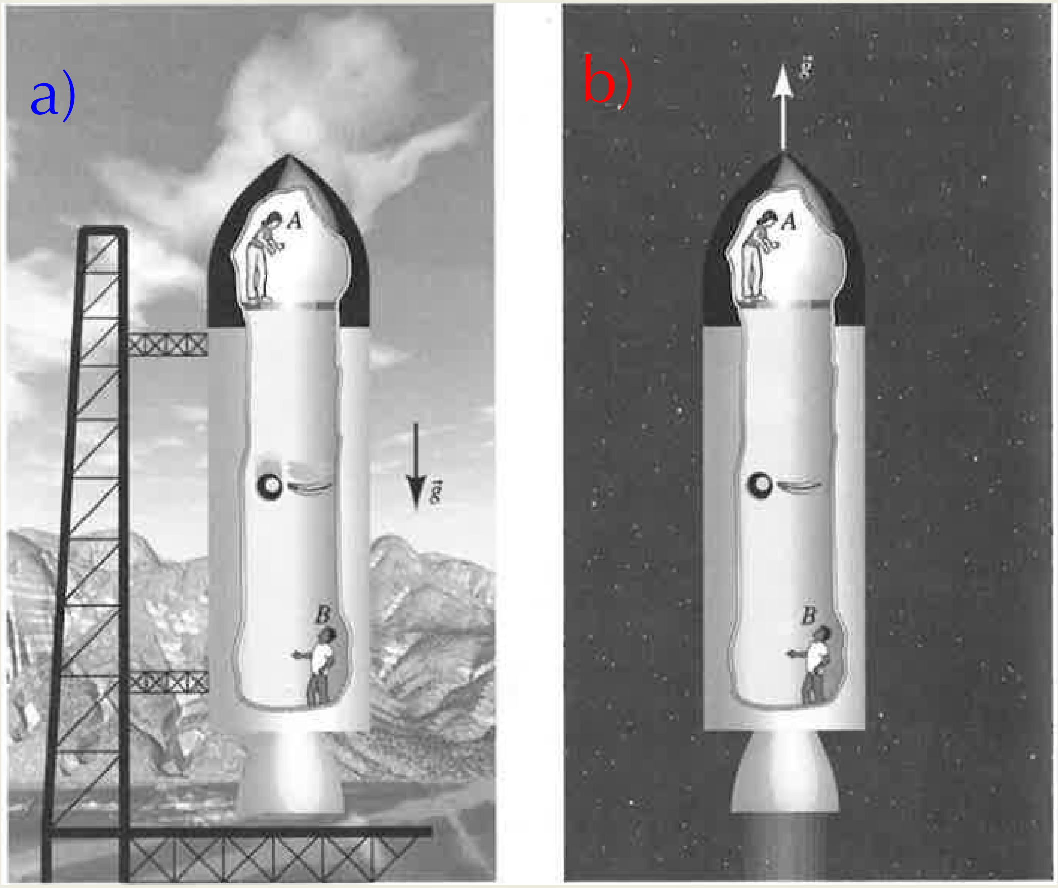
- Not just a new theory of gravitation
- But a revolution in our conception of space and time
- Gravitation = curvature of spacetime → Pure geometry

Equivalence principle

a) $m_i a = m_g\, g \Rightarrow$
the lead ball and the feather experience the same Acceleration
$\Rightarrow m_i = m_g$ and $a = g$

b) they have the same constant speed but appear with the same acceleration

- uniform gravitational field
  = uniform acceleration



James B. Hartle

study effect of acceleration $\Rightarrow$ study gravitation

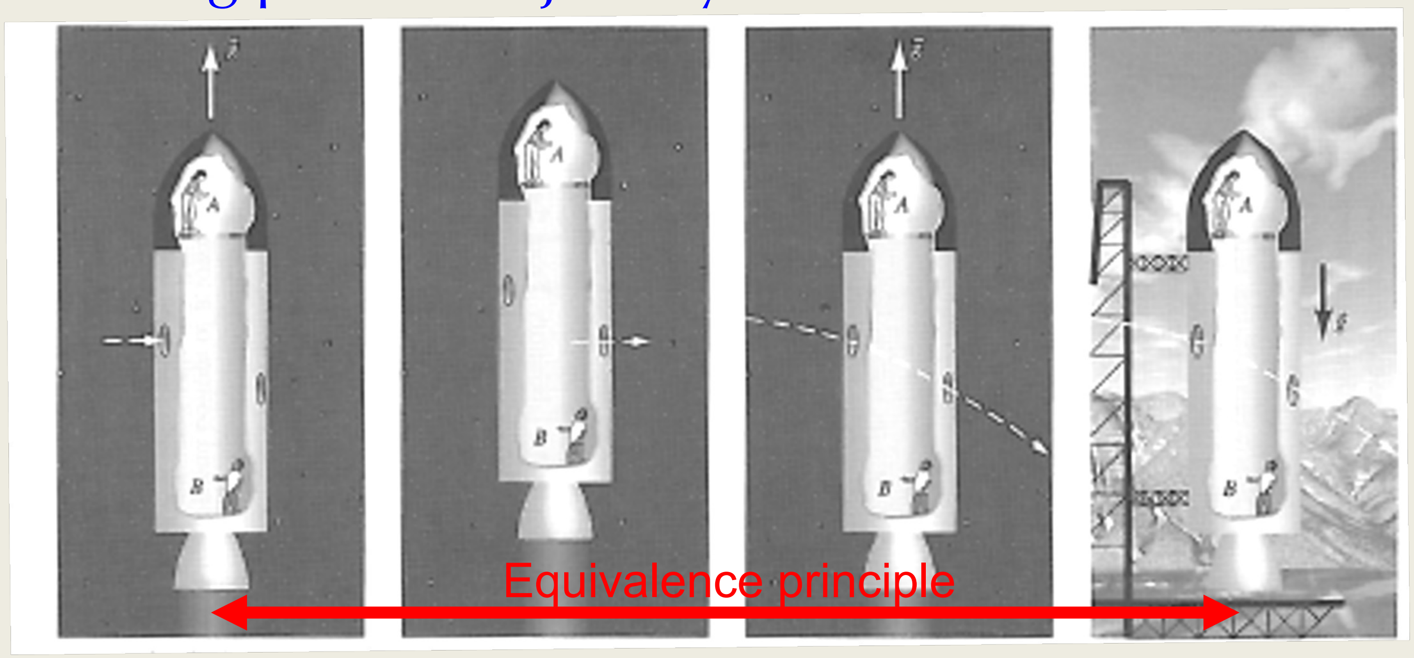
Equivalence principle

Equivalence Principle: An experiment in a freely falling laboratory, small enough and over a sufficiently small duration, is indistinguishable from the same experiment in an inertial frame away from all sources of gravitation

Gravity can be removed by free fall or conversely created by an acceleration

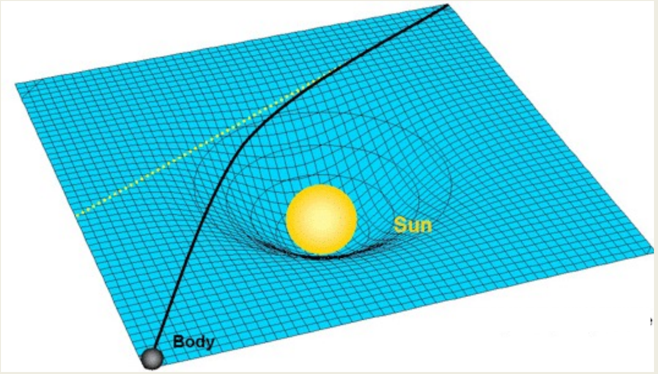
Light is falling !

- Equivalence principle applies for all physical laws
  including photon trajectory

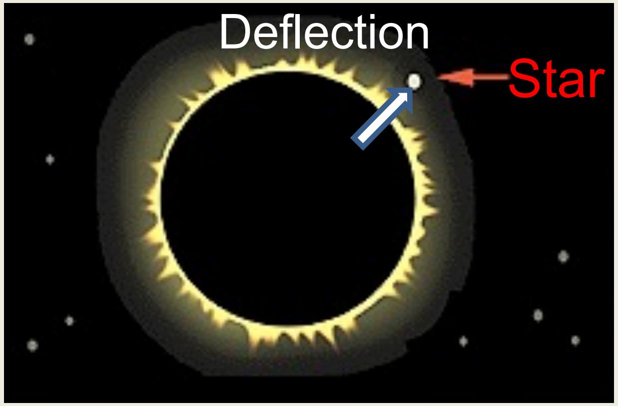


- $\Delta v = g\,\Delta t = g\,d/c \ll c \;\Rightarrow\;$ tiny effect on earth
  $\theta \sim \Delta v/c \sim gd / c^2$ $\quad d=10\text{m} \;\Rightarrow\; \theta \sim 9.81\text{x}10 / (3\ 10^8)^2 = 10^{-15}$!
  $\theta \sim 2GM/Rc^2 \sim 4$ µrad around sun!

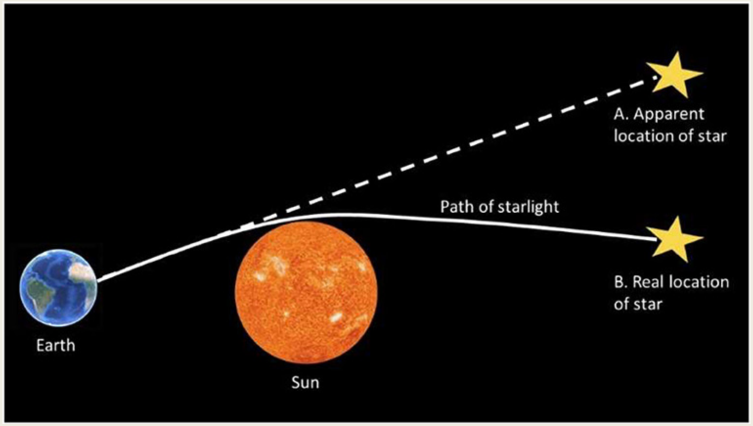
Curved spacetime - Light rays are bent



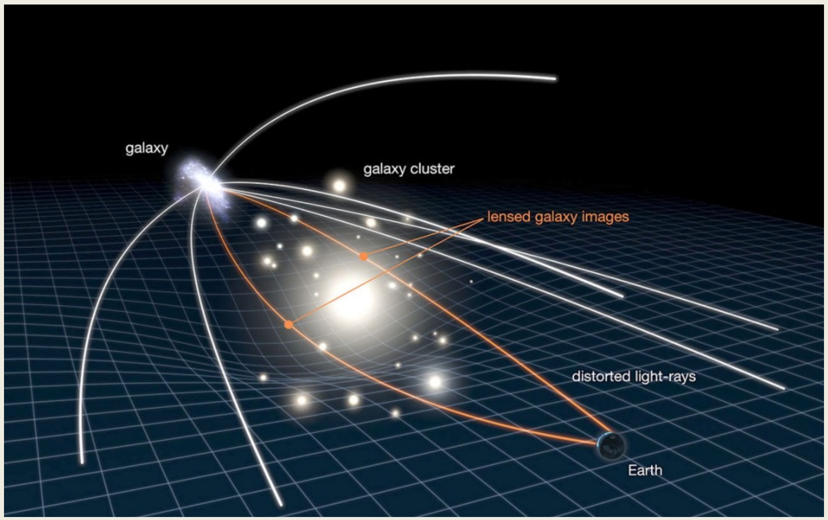
- 1915 : Einstein, General Relativity
  mass curves spacetime
  and bends light



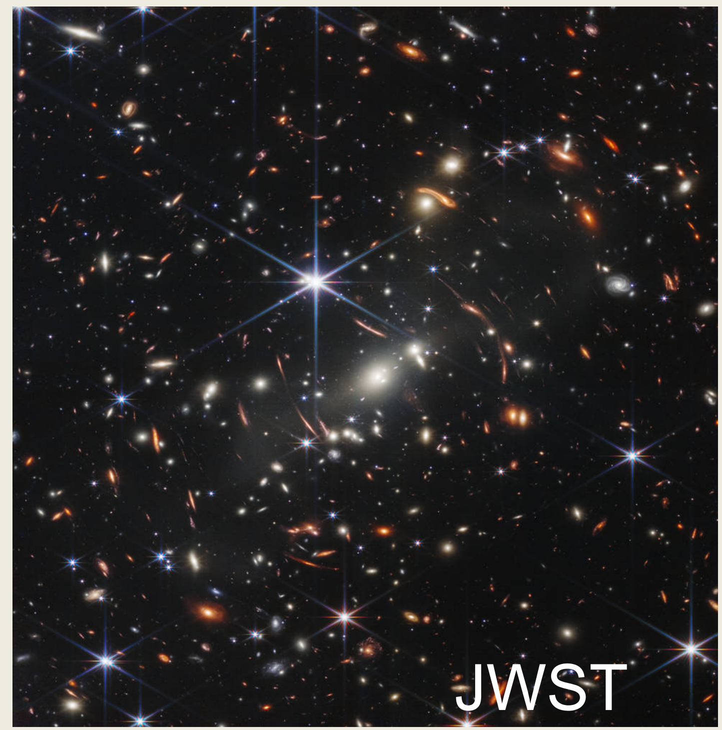
- 1919 : Arthur Eddington observes light deviation by the sun during a solar eclipse:
  - 1.75 arc second = 8.5 µrad as predicted by Einstein
  - Twice the deflection predicted by first computation (based on Eq. principle alone)



Curved spacetime - Gravitational lensing



- Strong gravitational lensing: modern proof of RG



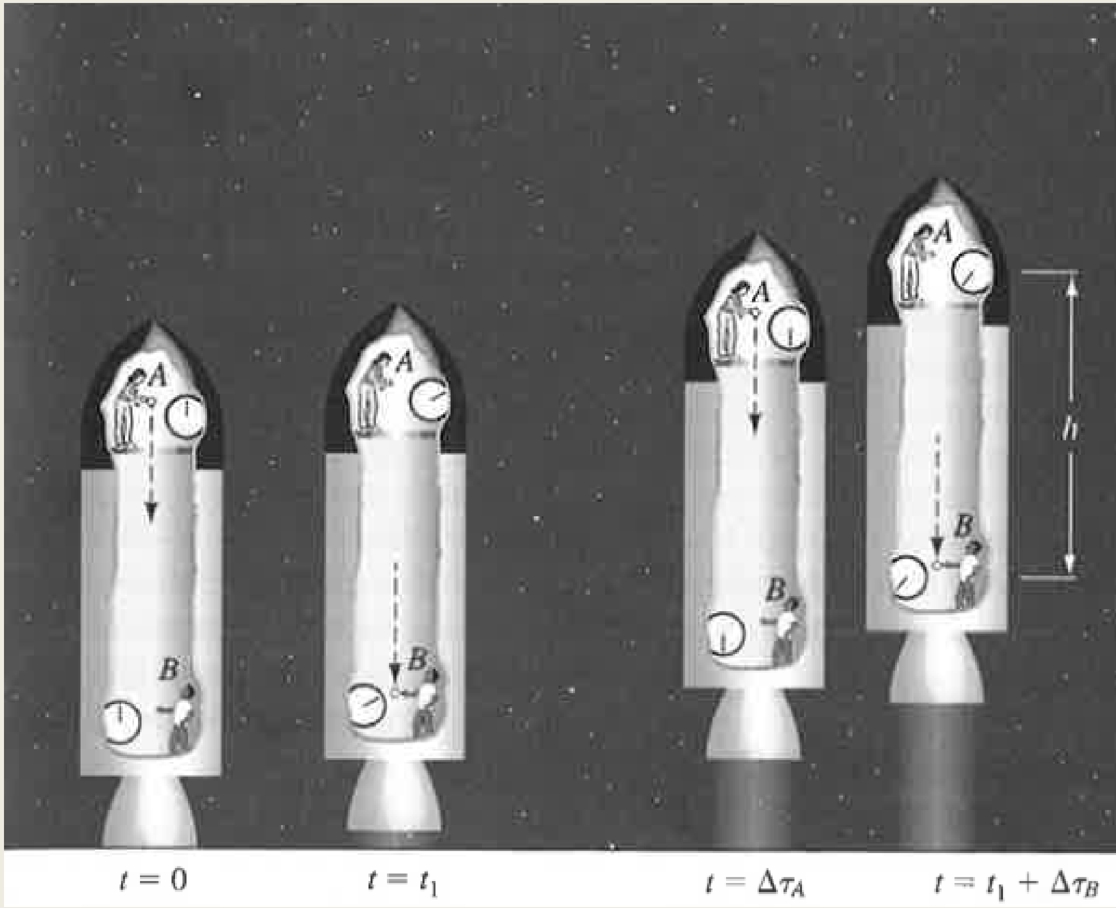
2.25 arcmin, 0.7Mpc at z=0.39

- On July 11 2022 James Webb Space Telescope released this deep field

- Galaxies behind galaxy cluster SMACS 0723 ($z=0.39$, $R_{vir}=2.4$Mpc) are curved and warped

Clocks and gravitation

- a rocket in deep space with acceleration +g
- A emits at t=0 and $\Delta\tau_A$
- B receives at $t=t_1$ and $t_1 + \Delta\tau_B$



- Propagation time : $(t_1 – 0)$
  acceleration $\Rightarrow$ faster
  $(t_1+\Delta\tau_B) – \Delta\tau_A < t_1 – 0$
  $\Rightarrow$ $\mathbf{\Delta\tau_B < \Delta\tau_A}$

- Calculation gives (totally classic):

$$\boxed{\Delta t_B = \left(1 - \frac{gh}{c^2}\right)\Delta t_A}$$

Clocks and gravitation

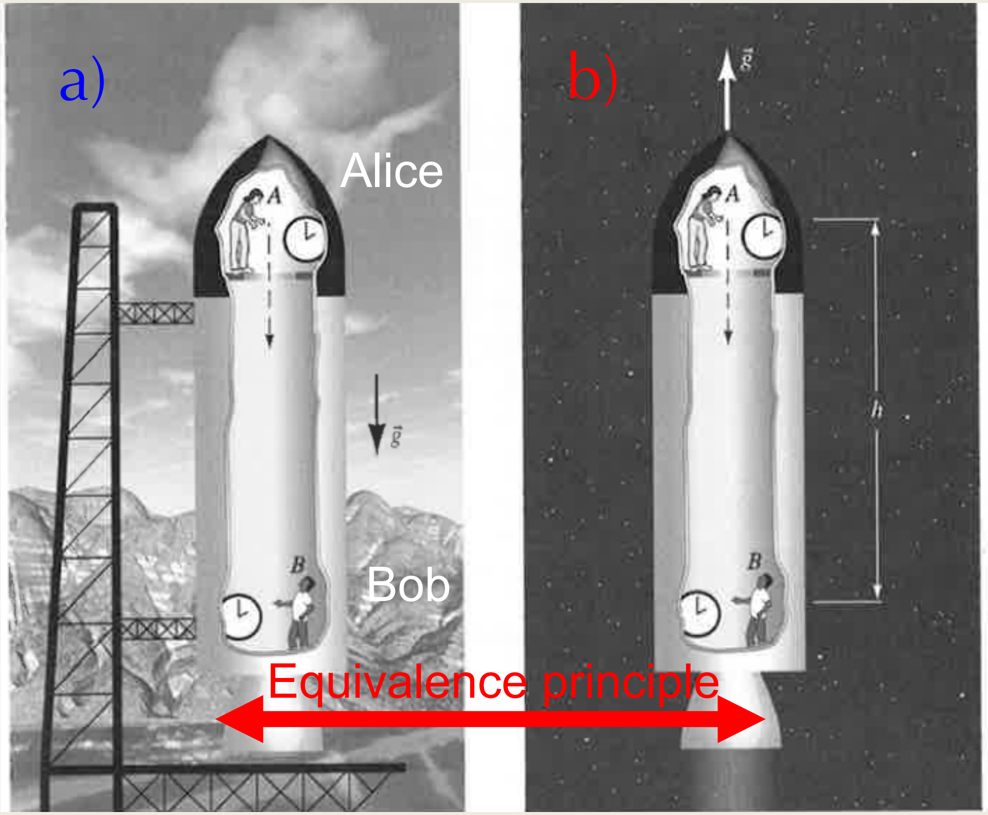
Equivalence Principle
(a) equivalent to (b)

$$\Delta t_B = \left(1 - \frac{gh}{c^2}\right)\Delta t_A$$

Times run slower in a gravitational field !

$h=z_A-z_B \Rightarrow gh \sim \Phi_A - \Phi_B$

$$\boxed{\Delta t_B = \left(1 - \frac{\Phi_A - \Phi_B}{c^2}\right)\Delta t_A}$$



Bob is younger than Alice….

Gravitational "redshift"

$$\Delta t_B = \left(1 - \frac{\Phi_A - \Phi_B}{c^2}\right)\Delta t_A$$

- at the surface of a star: $\phi_A = -GM/R$

  far away: $\phi_B = 0$

$$\Delta t_\infty = \left(1 + \frac{GM}{Rc^2}\right)\Delta t_*$$

$$\nu_\infty = \left(1 - \frac{GM}{Rc^2}\right)\nu_* < \nu_*$$

$\Rightarrow$ gravitational redshift

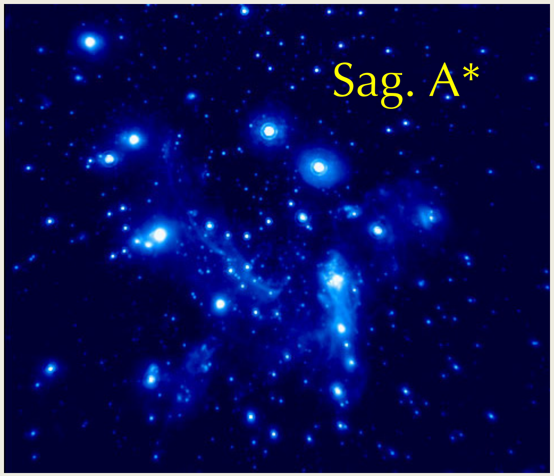
the photon looses energy going out of the potential well

Positive shift in wavelength $\Delta\lambda/\lambda > 0$

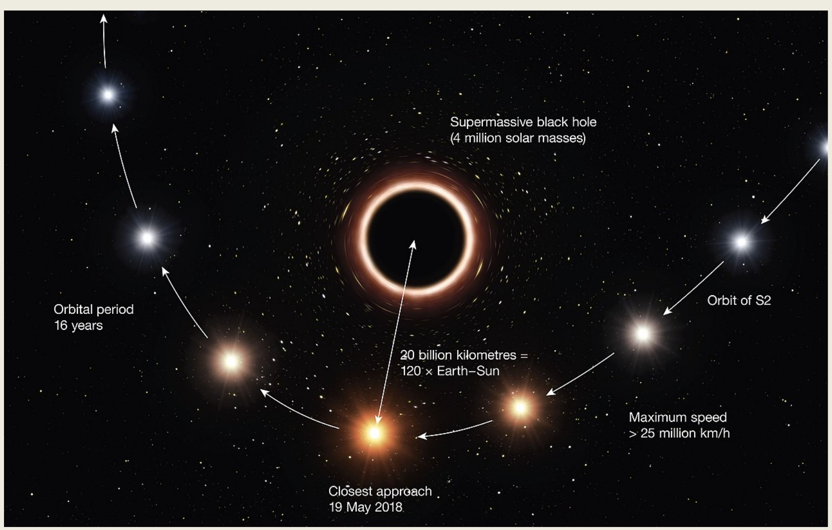
- very important for GPS : $\Delta\nu/\nu \sim 4.10^{-10}$

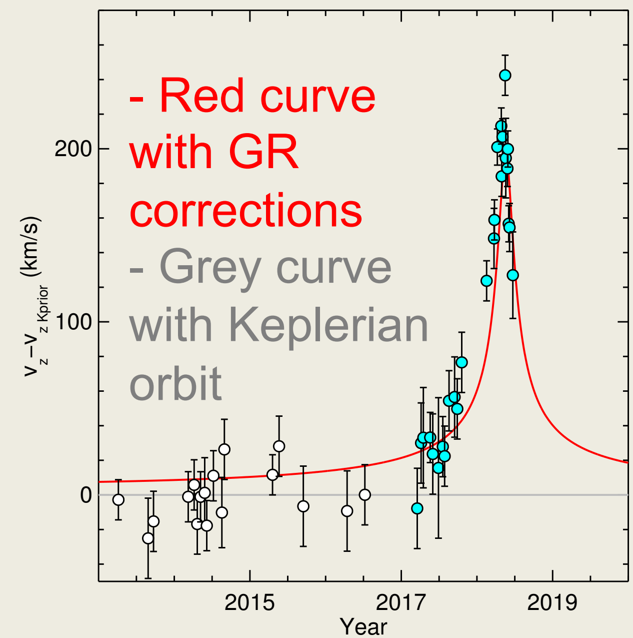
  after 1h : 10^{-10} x 3600 s error $\Rightarrow$ ~400 m error

S2 star close to MW black Hole



- Close to source Sagittarius A*, BH in the Milky way (~4.10^6 solar mass)
- S2 star very close to the BH on May 19 2018
- Verification of Einstein shift (plot below)
- Redshift ($c.\Delta\lambda/\lambda \rightarrow$ speed km/s), note sign!





Science in movies

Planet of the Apes

- Twin paradox in Special Relativity (SR)
- Lorentz boost

  $ct=\gamma(ct' + \beta x)$

  $\gamma = 1/(1 - \beta^2)^{1/2} > 1$
- Time dilatation **$T=\gamma T'$**

Interstellar

- Strong gravitational field (GR)
- Proximity to a black hole (BH)
- **$T=(1+GM/(Rc^2)).T'$**