Something about modern cosmology and new observations

Gravitational Waves

Some theoretical background:

Einstein's special theory of relativity, 1905

- Postulates the constancy of the speed of light, $c = 3 \cdot 10^8$ m/s
- Valid for reference systems that move rectilinearly and do not accelerate with respect to one another (inertial systems).

Space and time merge into spacetime, t, $\mathbf{r} \rightarrow$ (ct, **r**) = (ct, x, y, z) = $(x^0, x^1, x^2, x^3) \equiv x^\mu$ $(\mu = 0,1,2,3)$

The spacetime distance between two nearby events is

$\Delta s^2 = (cdt)^2 - d\mathbf{r}^2 = (\Delta x^0)^2 - (\Delta x^1)^2 - (\Delta x^2)^2 - (\Delta x^3)^2$, or

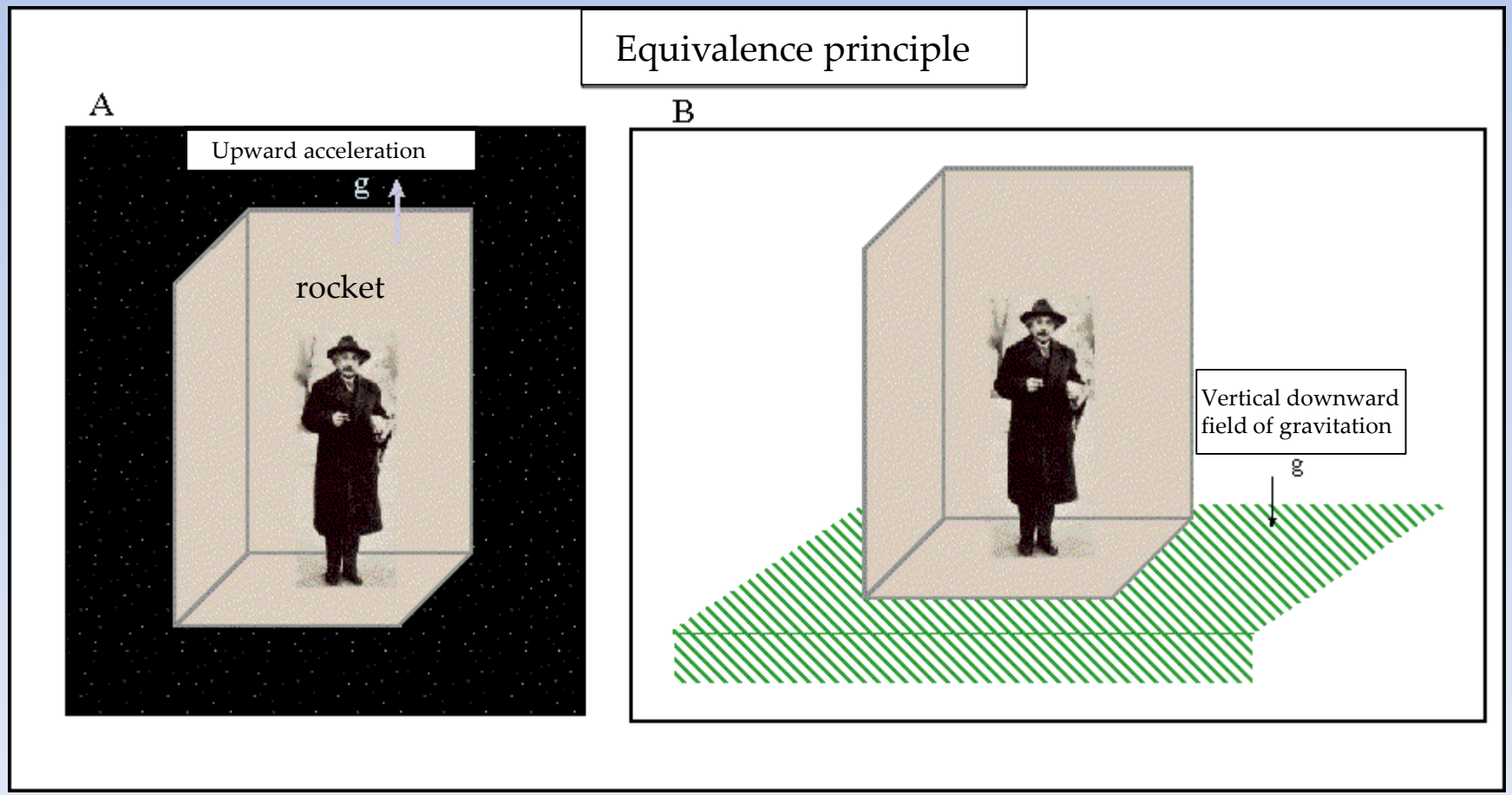
$\Delta s^2 = g_{\mu\nu} \Delta x^\mu \Delta x^\nu$ (repeated indices are summed from 0 to 3; Einstein's summation convention) In matrix form:

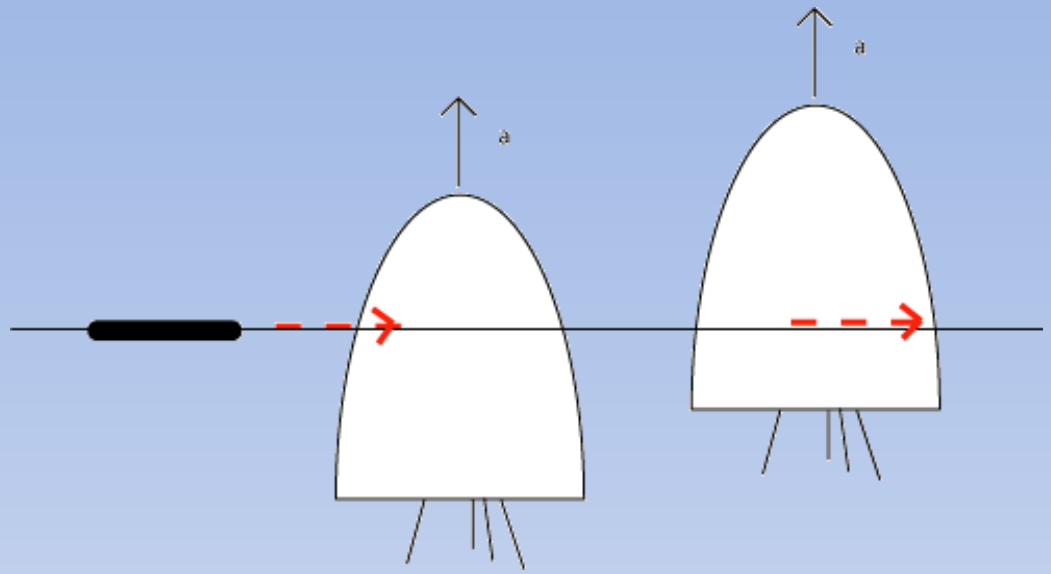
$$g_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Einstein's general theory of relativity

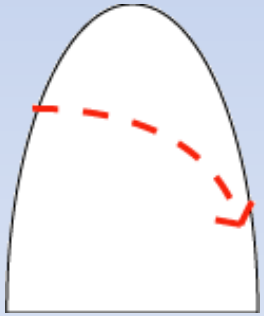
Equivalence principle:

There is nothing that distinguishes a uniform acceleration from a homogeneous gravitational field





Light that we send through an accelerating rocket, seen from an outside inertial frame. There the light beam moves in a straight line.



The motion of the light beam seen from inside the rocket – light moves in a curved path (here much exaggerated).

1. In an accelerated system (the rocket) light moves in a curved path.
2. According to the equivalence principle light should then also move in a curved path in a gravitational field
3. But light always takes the shortest path (Fermat's principle).
4. Thus, the shortest path is curved in a gravitational field.
5. But this means that space (and spacetime) is curved when there is gravitation!

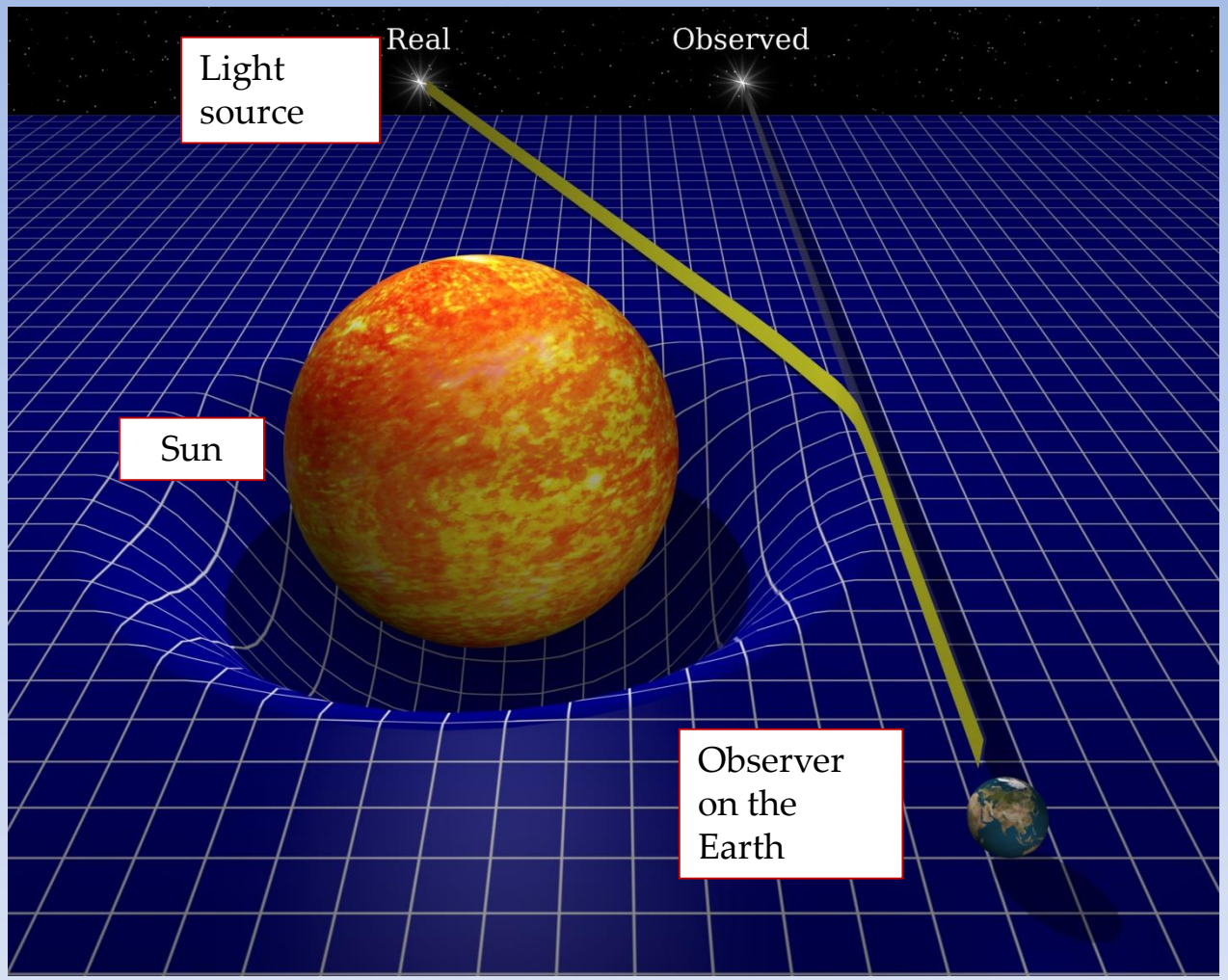
This leads to a new interpretation of gravity in Einstein's theory. Particles move in trajectories that are curved by the presence of the gravitational field.

This explains Galileo's discovery that all masses fall equally fast in a gravitational field – they all move along the same curved trajectories. One can see gravity as geometry – spacetime has curvature!

Two-dimensional example when the shortest path is not a straight line – airplane flight along part of a great circle on the Earth:

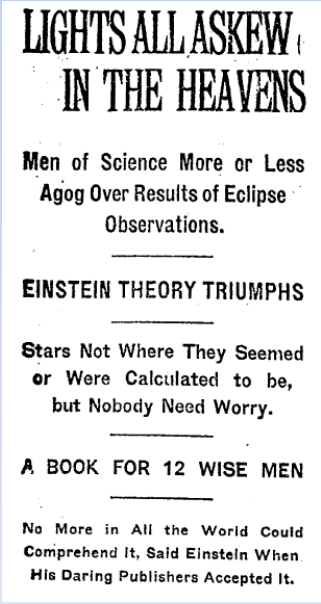
To describe curvature, one needs non-trivial mathematics

Two-dimensional illustration (exaggerated) of the curvature of space caused by the mass of the Sun.



This bending of light was measured by Eddington in 1919 – it has **twice the value** predicted **compared to Newton's theory**.

From that moment, Einstein was a media star!...



LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

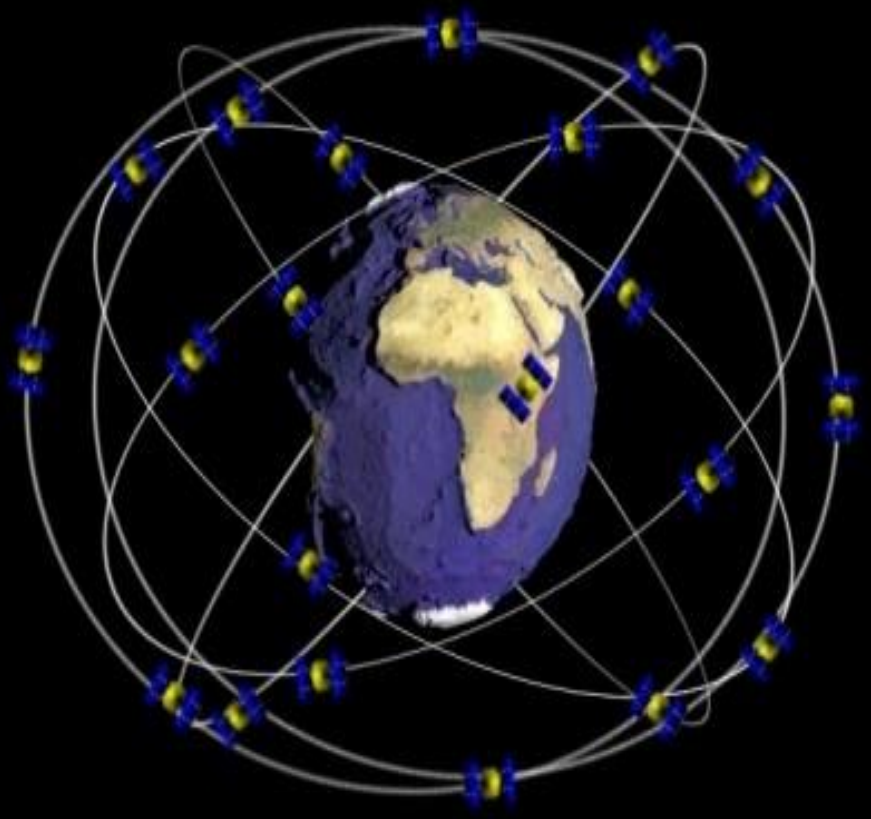
A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

New York Times, 1919

The most important lesson is that space and time are dynamical quantities, and that gravity causes spacetime to curve!

General relativity at work: GPS (Global Positioning System)

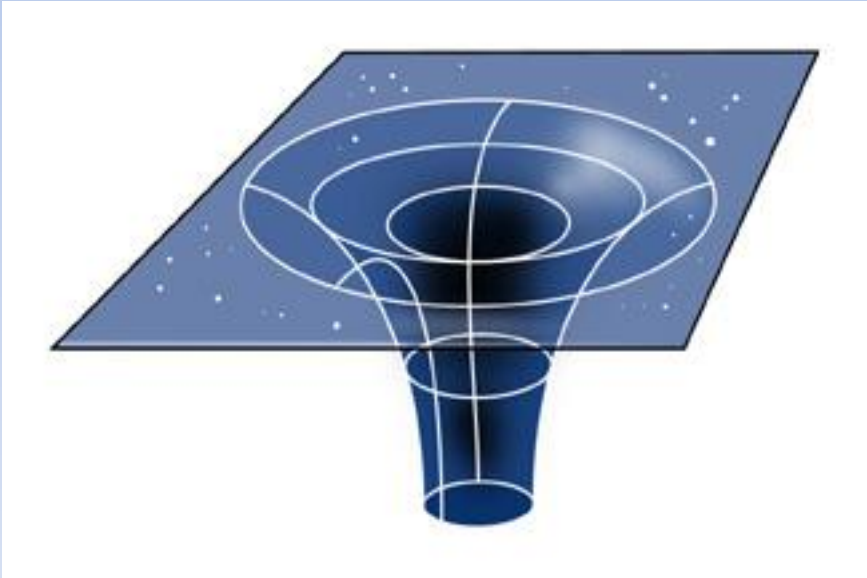


30 satellites, velocity 14 000 km/h, altitude 20 000 km

Correction due to relativity, including spacetime curvature:

7 microseconds/24 hrs – time goes faster at high altitude!

Extreme curvature – a black hole (illustrated in 2 dimensions)



"The most beautiful equation in the world", Einstein's equation in general relativity

$$G_{\mu\nu} = \frac{8\pi G_N}{c^4} T_{\mu\nu}$$

The factor $8\pi G_N/c^4$ gives Newtonian mechanics as a special solution

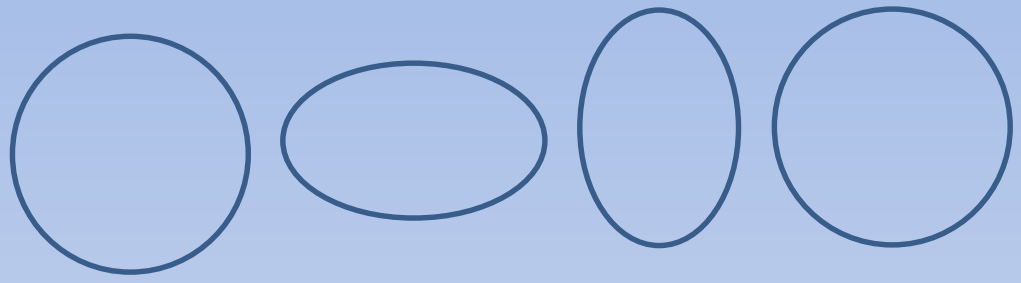
Spacetime curvature tensor

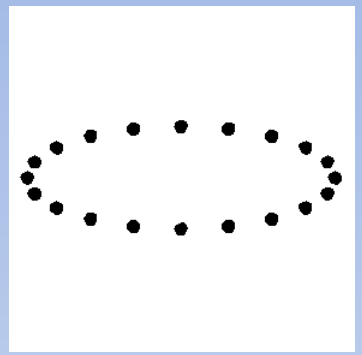
Energy and momentum tensor or "stress-energy tensor"

$G_{\mu\nu}$ consists of the metric tensor $g_{\mu\nu}$ and its second derivatives.

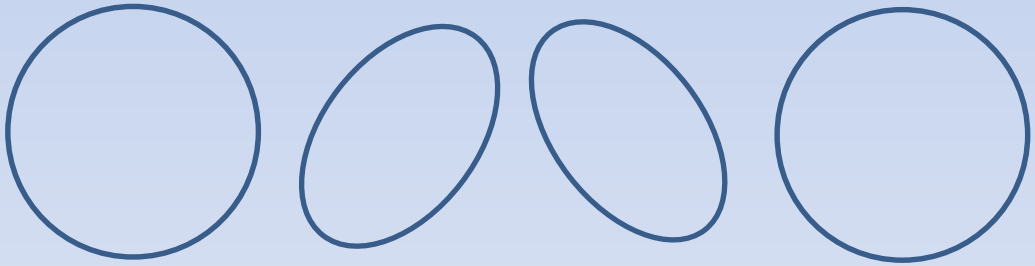
Einstein 1916: If masses are in motion, i.e. if $T_{\mu\nu}$ depends on time, then gravitational waves may form and propagate. (Compare electrodynamics: If charged particles move, then electromagnetic waves can form and propagate.)

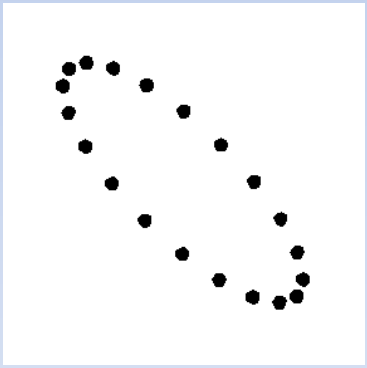
One can show that the unit circle will be successively ”compressed” or ”squeezed” when a gravitational wave passes





and





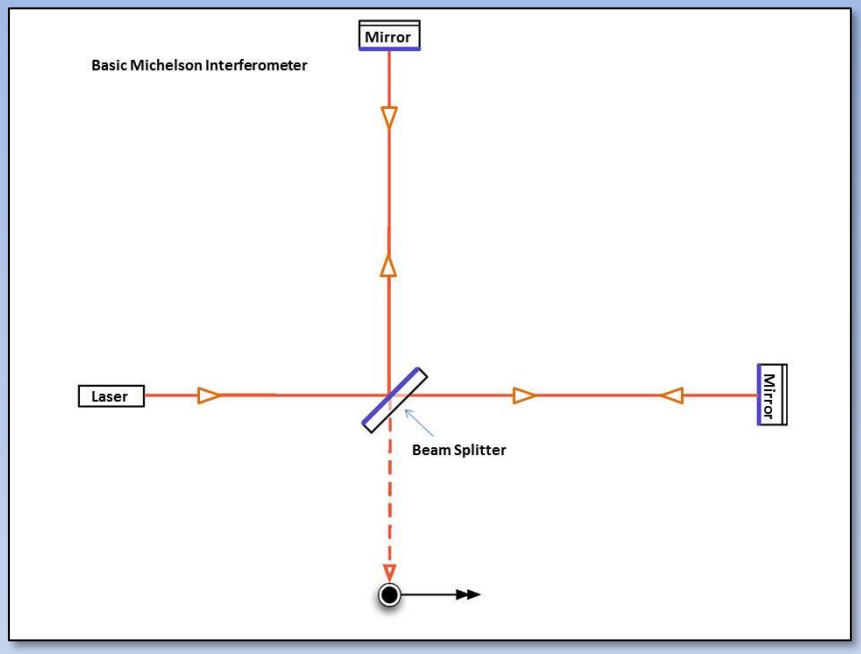
LIGO: Laser Interferometer Gravitational-Wave Observatory – one of the most accurate measuring devices on earth – has been developed during some 40 years:

LIGO-West, Hanford, Washington

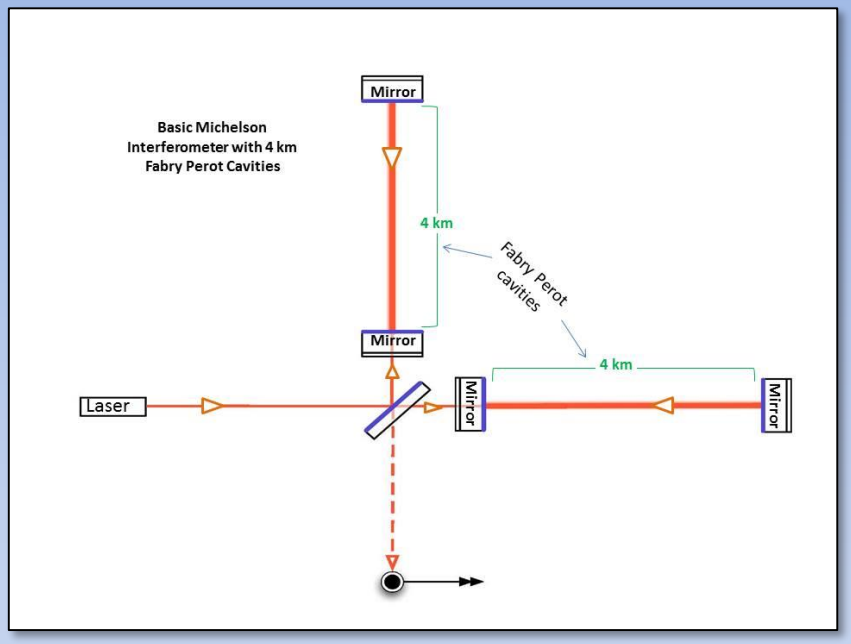
LIGO-East, Livingston, Louisiana

(Now also VIRGO near Pisa, Italy)

Principle of LIGO

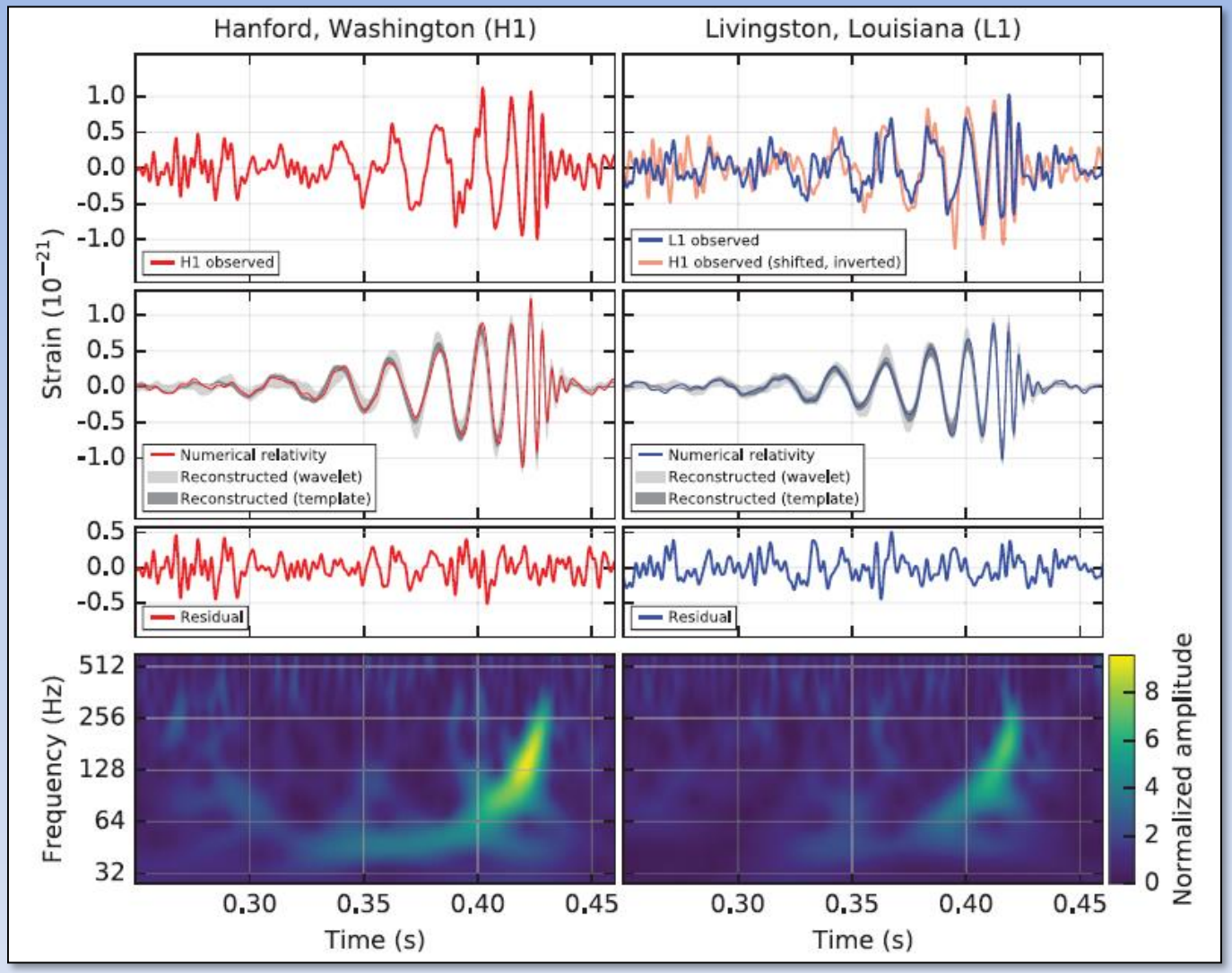


Michelson interferometer: Light is split in two paths and is then made to interfere. If the distance travelled is changing, the interference fringes will move.



LIGOs Michelson interferometer has two mirrors added (Fabry-Perot-interferometer). Light will bounce back and forth a large number of times (around 300) between the mirrors, and the distance travelled will 1200 km instead of 4 km!

The discovery! September 14th, 2015 (”GW 150914”), announced on February 12th 2016



Note order of magnitude of strain, 10^{-21}, corresponding to the diameter of a human hair at the distance of the nearest star (Proxima Centauri, 4.2 light years)!

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The Nobel Prize in Physics 2017

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Rainer Weiss
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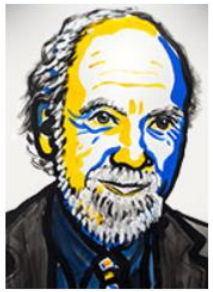

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Barry C. Barish
Prize share: 1/4

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Kip S. Thorne
Prize share: 1/4

The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne *"for decisive contributions to the LIGO detector and the observation of gravitational waves"*.

2017 PHYSICS PRIZE QUESTION

Did you know that gravitational waves were predicted by Albert Einstein a hundred years ago?

Yes No

Dark Matter

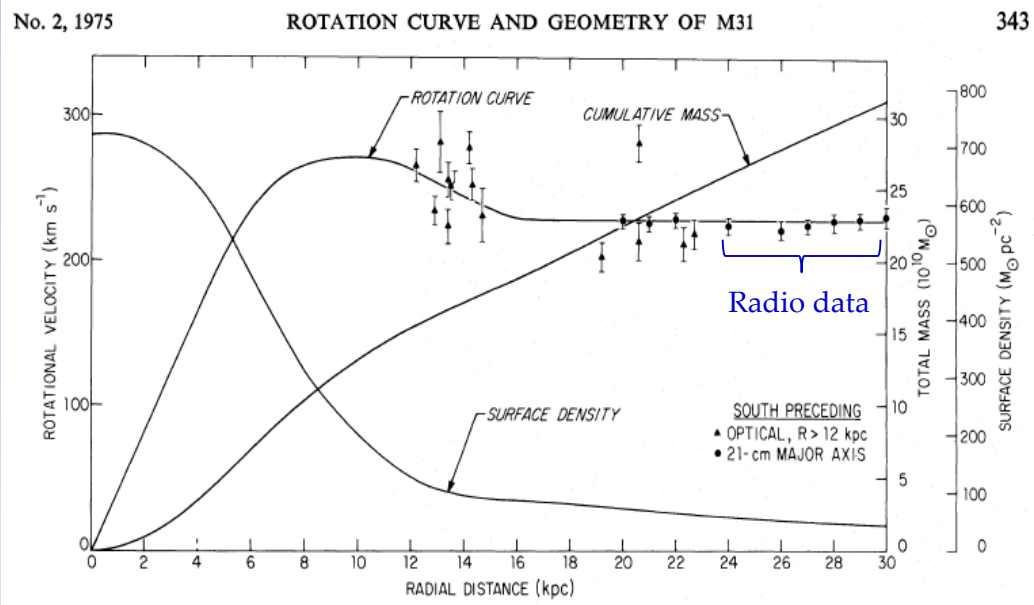
Fritz Zwicky, 1933: Velocity dispersion σ of galaxies in Coma cluster indicates presence of Dark Matter , σ ~ 1000 km/s ⇒

(Dark mass)/(luminous mass) ~ 50

”If this over-density is confirmed we would arrive at the astonishing conclusion that dark matter is present [in Coma] with a much greater density than luminous matter.”

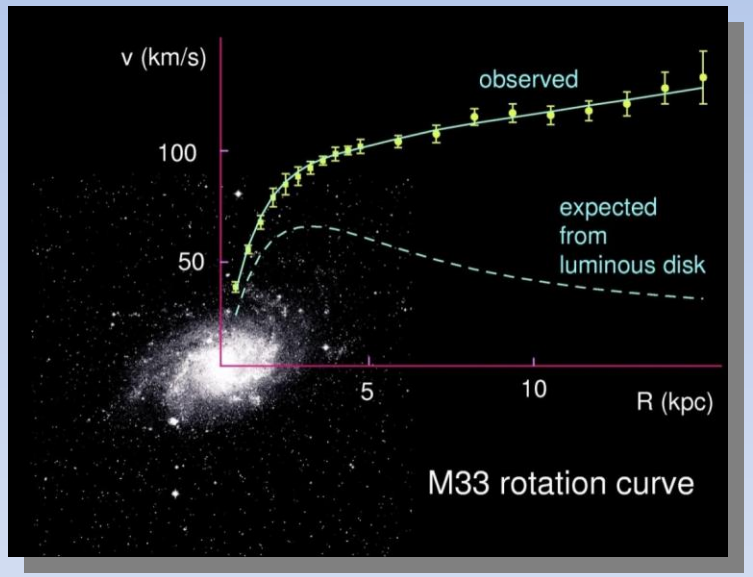
Then essentially nothing happened for 30 years,
until the "next generation" of astronomers came:

Vera Rubin & Kent Ford (1970) measured optically a flat rotation curve of the Andromeda galaxy, and Morton Roberts & Robert Whitehurst (1975) measured (in radio emission) a flat curve far outside the optical radius.

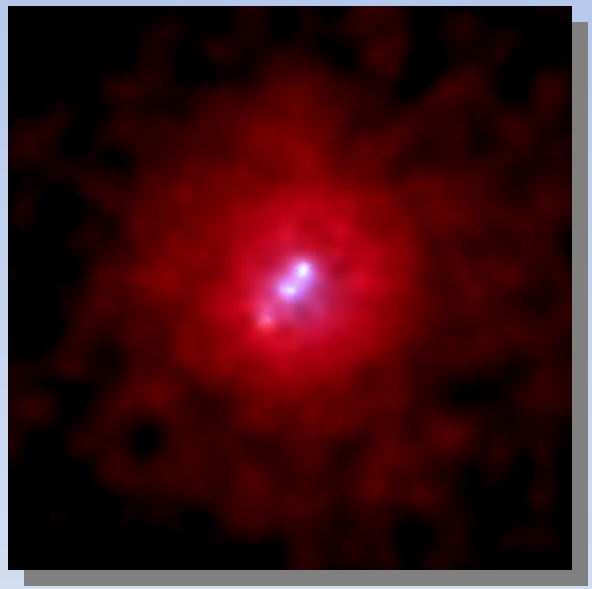


Dark matter needed on all scales!
⇒ Attemps to modify Einstein or Newton gravity seem unnatural & unlikely

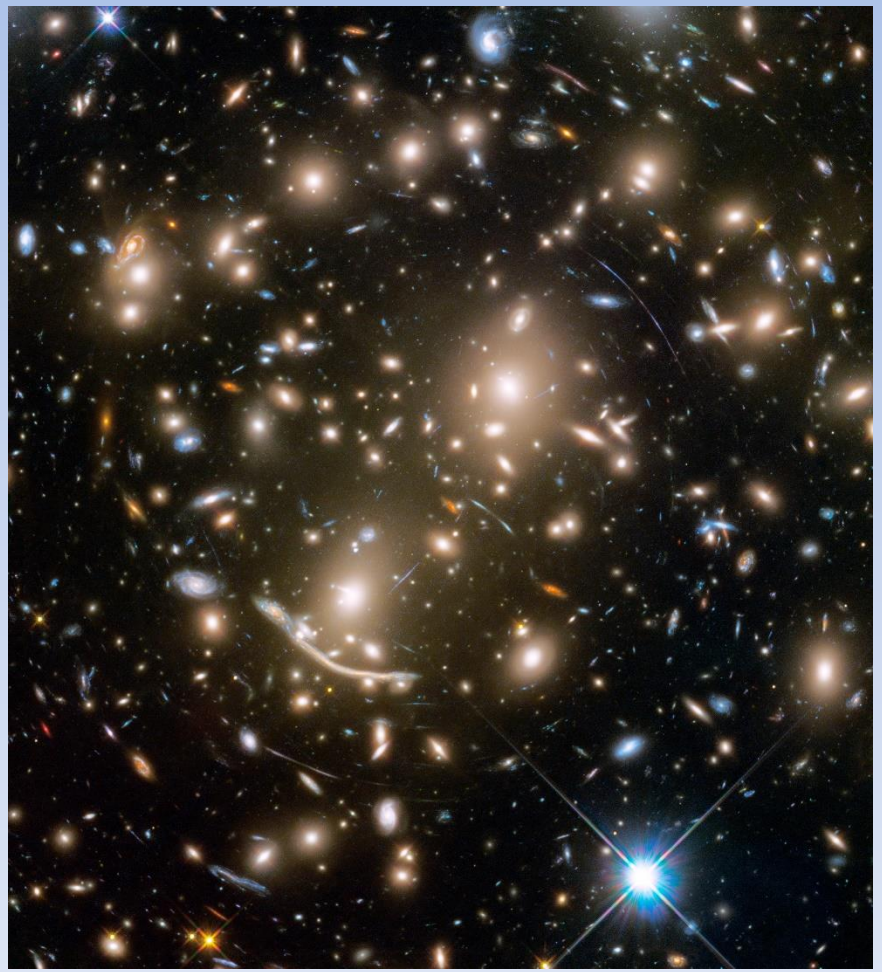
Galaxy rotation curves



X-ray emitting galaxy clusters



Bending of light (”gravitational lensing”) from galaxy clusters shows that around 80 % of the matter is invisible (”dark”)



The cosmic microwave background (CMB) and the accelerating universe

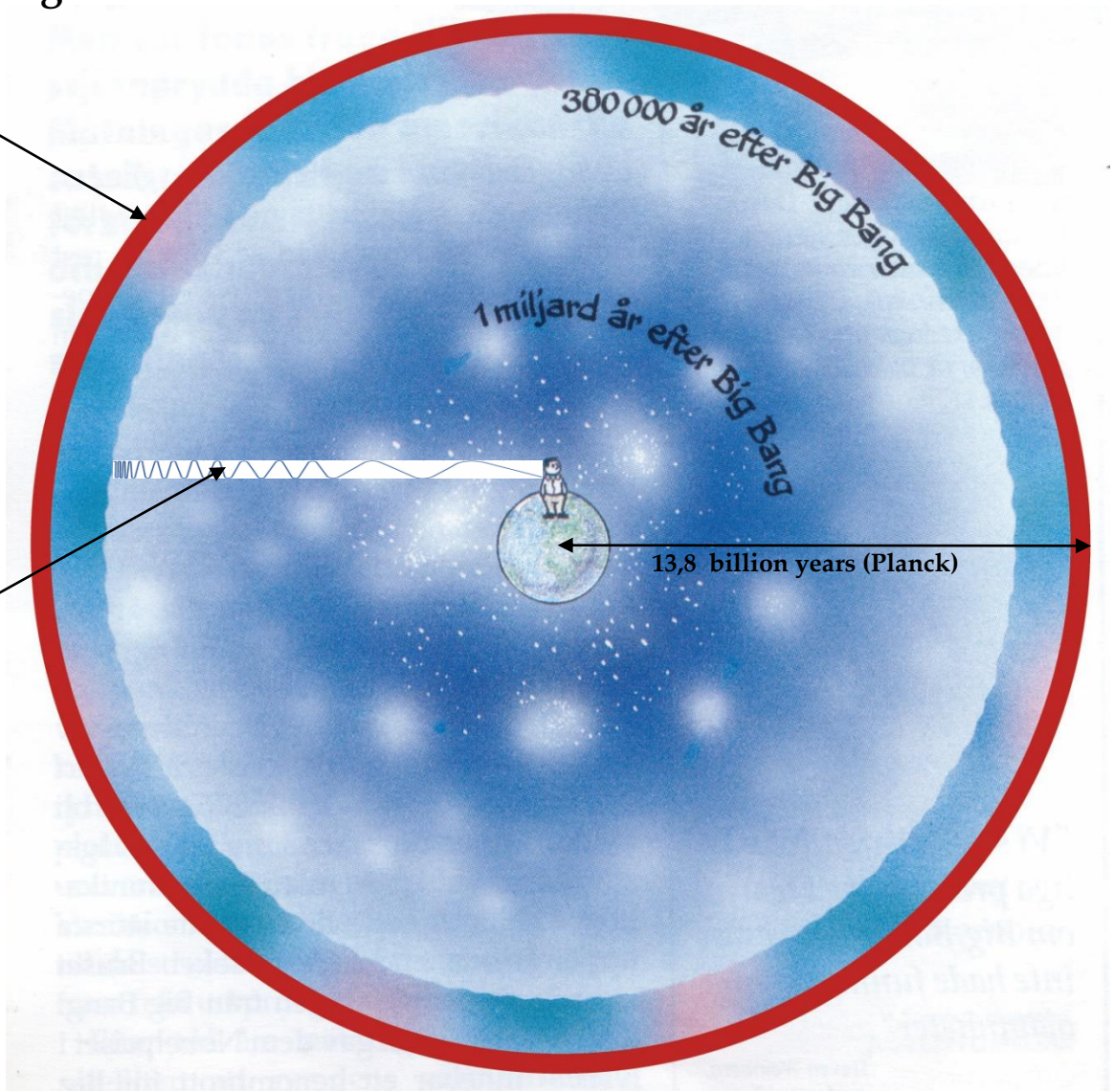
Observations in an expanding Universe:

Time = 0, **Big Bang**.

This moment cannot yet be treated scientifically (need quantum gravity).

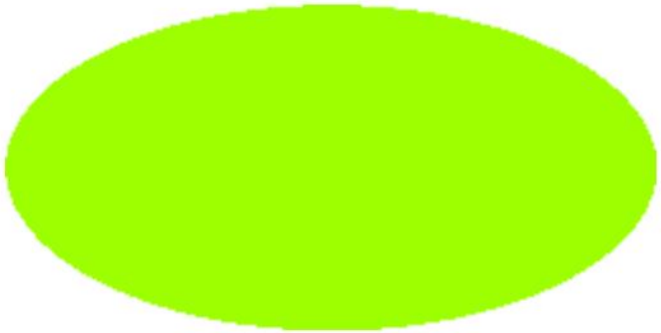
Universe may be bigger, but we cannot see further (our cosmic horizon)

Lightwaves are being stretched as they travel to us – the radiation which was 3000 K at emissions become microwaves – a Planck distribution of only 2.73 K

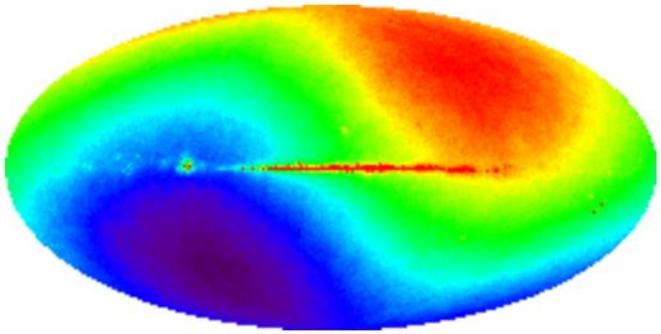


Ill: Hans Nilsson/Lars Bergström

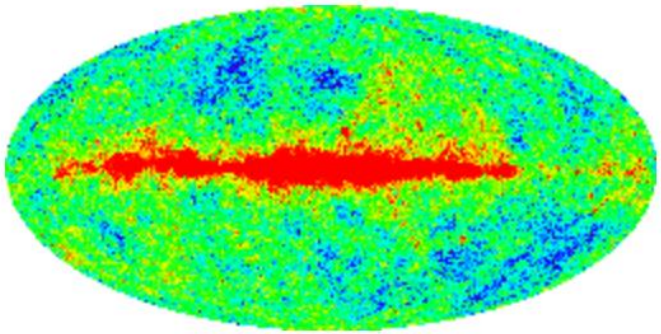
The Universe as a ”baby” (380 000 years after the Big Bang)



Universe was an (almost) homogeneous, hot ”primordial soup” – a plasma. The radiation was enormous (T = 3000 K, now redshifted to T = 2.73 K)

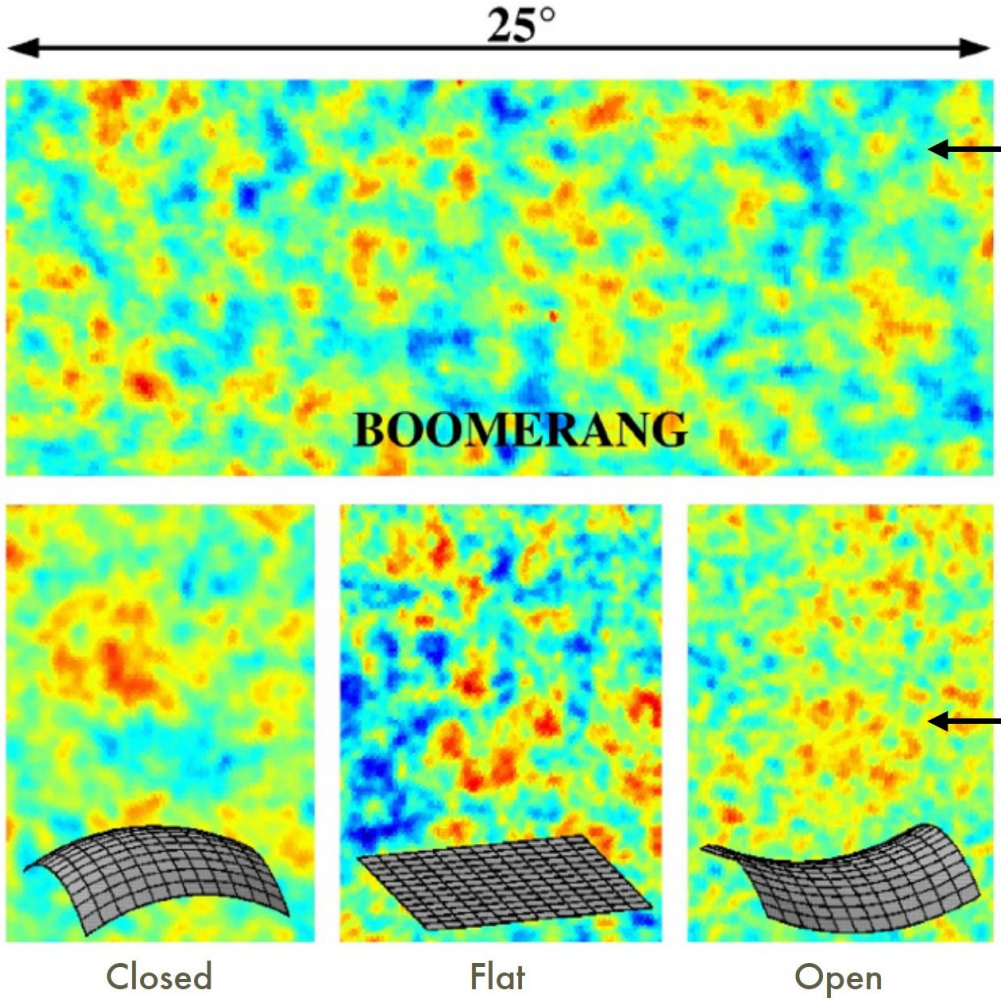


A dipole pattern is caused by our movement through space! (Contrast has been increased – it is only a permille of the map above)



Some inhomogeneities (a few parts per 100 000) can be the seeds of our galaxies! WMAP satellite, 2008

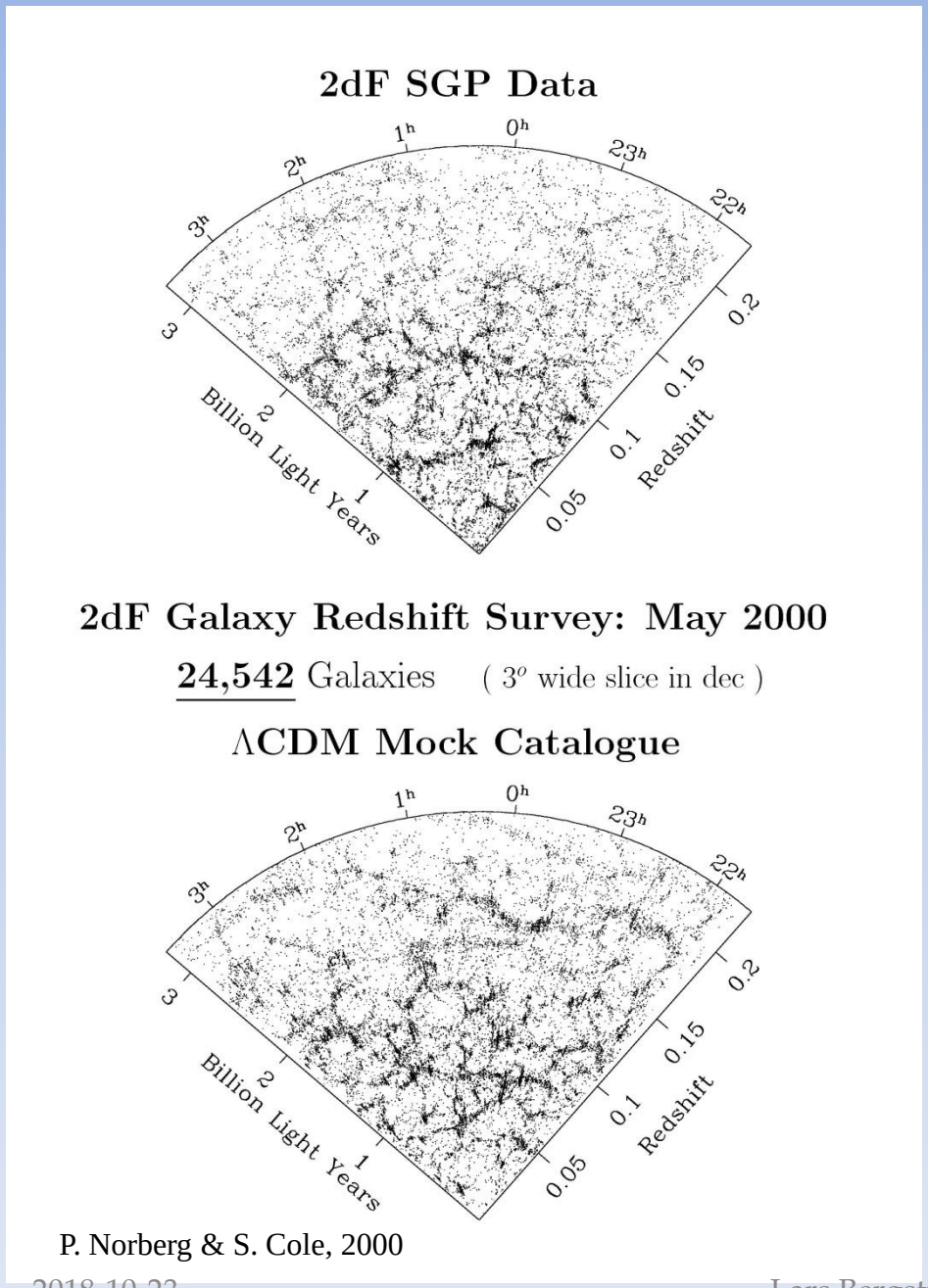
CMB data and simulations



Data from Boomerang (1997, 1998, 2003)

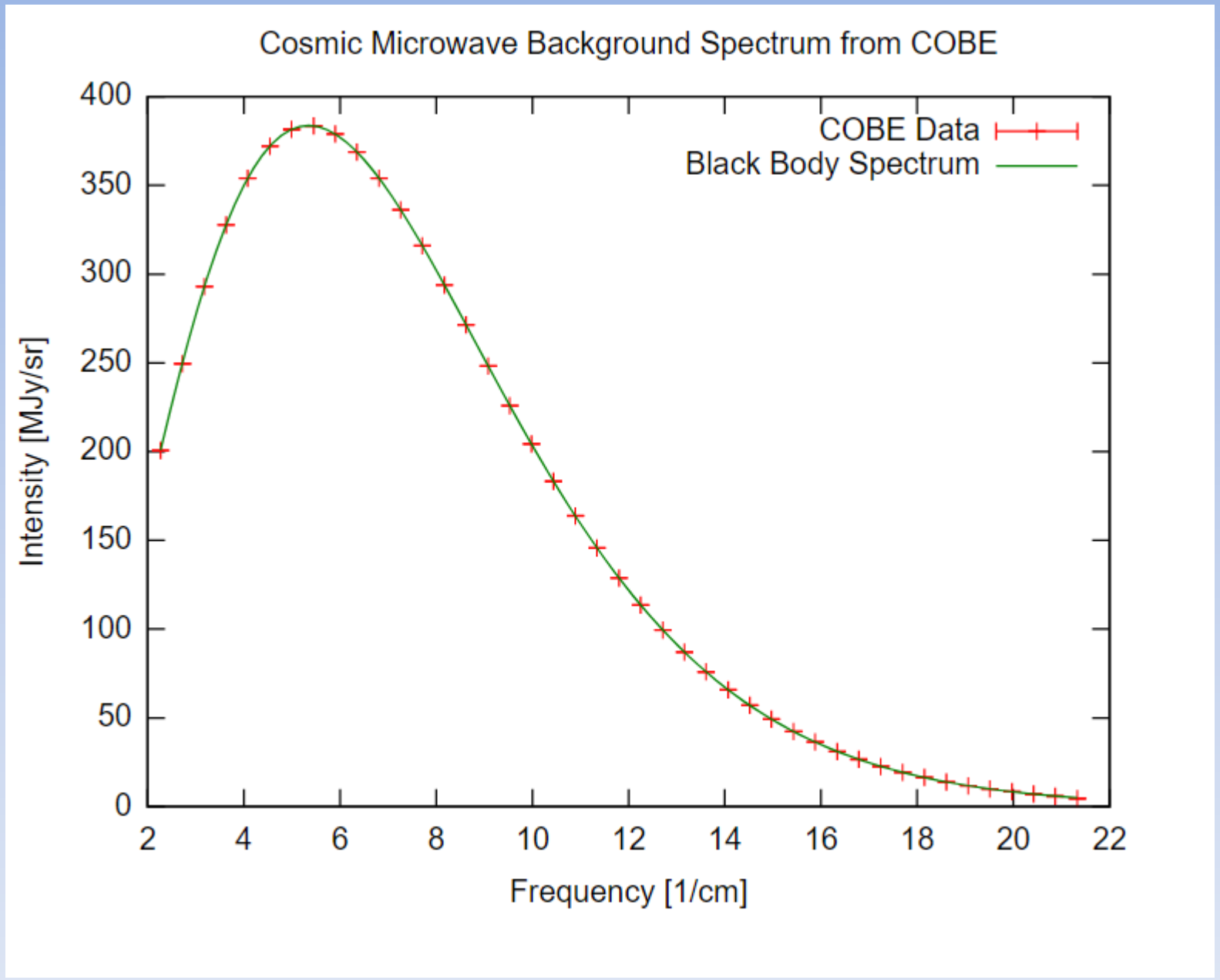
Simulations

What is the geometry of the universe?

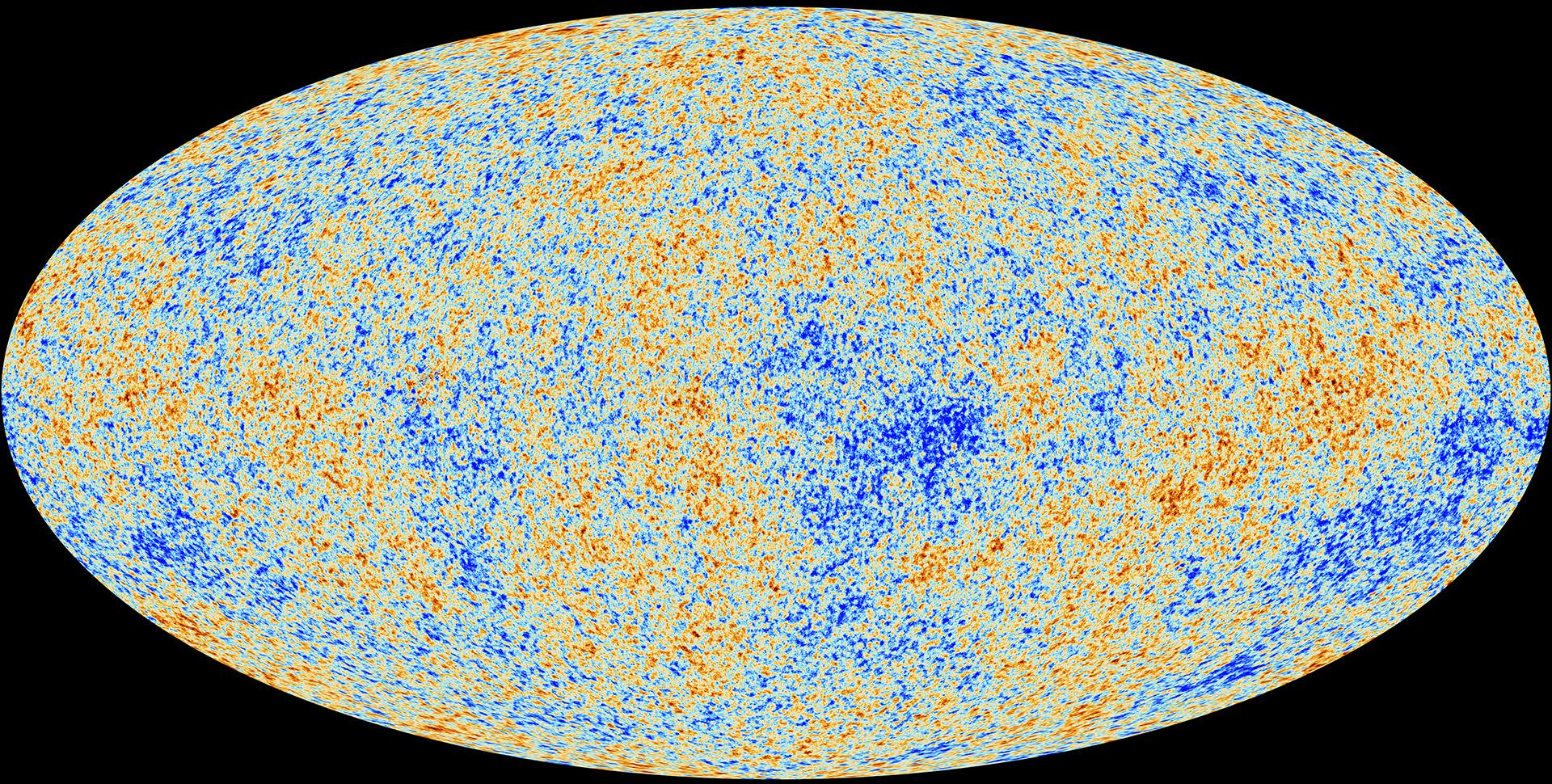


P. Norberg & S. Cole, 2000

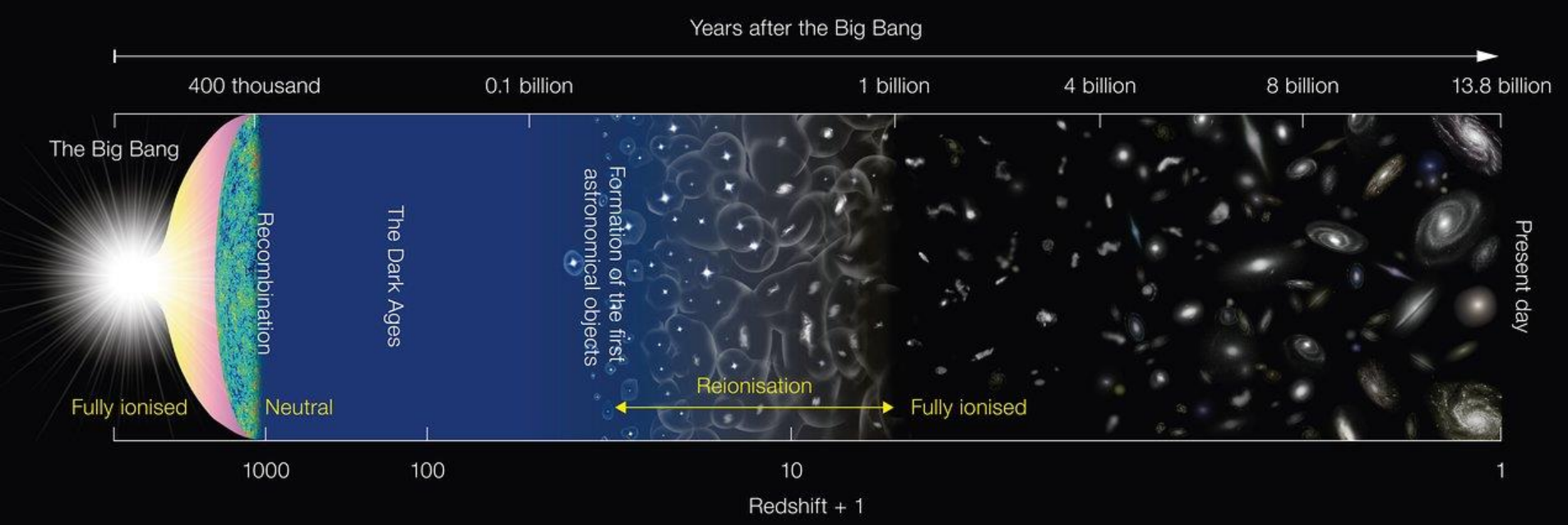
Supercomputer simulations in the ΛCDM ("Lambda Cold Dark Matter") model agree with large galaxy surveys


Cosmic Microwave Background Spectrum from COBE
COBE Data
Black Body Spectrum
Intensity [MJy/sr]
Frequency [1/cm]
400
350
300
250
200
150
100
50
0
2
4
6
8
10
12
14
16
18
20
22

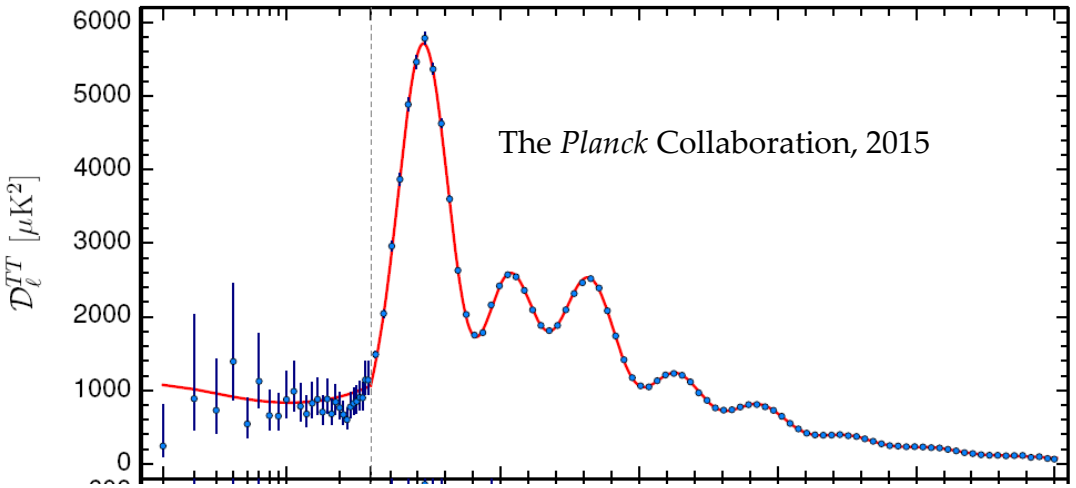
Planck satellite, 2016

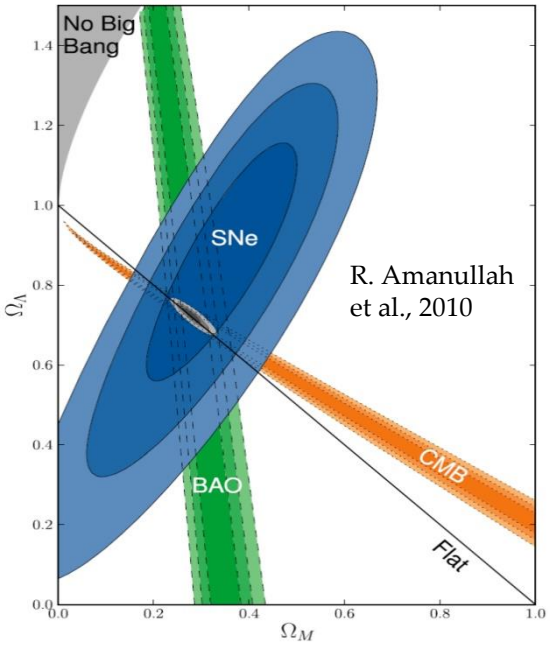


Brief history of the Universe (European Southern Observatory)



Cosmic Microwave Background (CMB) + Supernovae Ia + Baryons:
Dark Matter does exist! As does the cosmological constant!
ΛCDM has become the "Standard Model" of cosmology





$$\Omega_{tot} \equiv \frac{\rho_{tot}}{\rho_{crit}} = 1.000 \pm 0.005$$

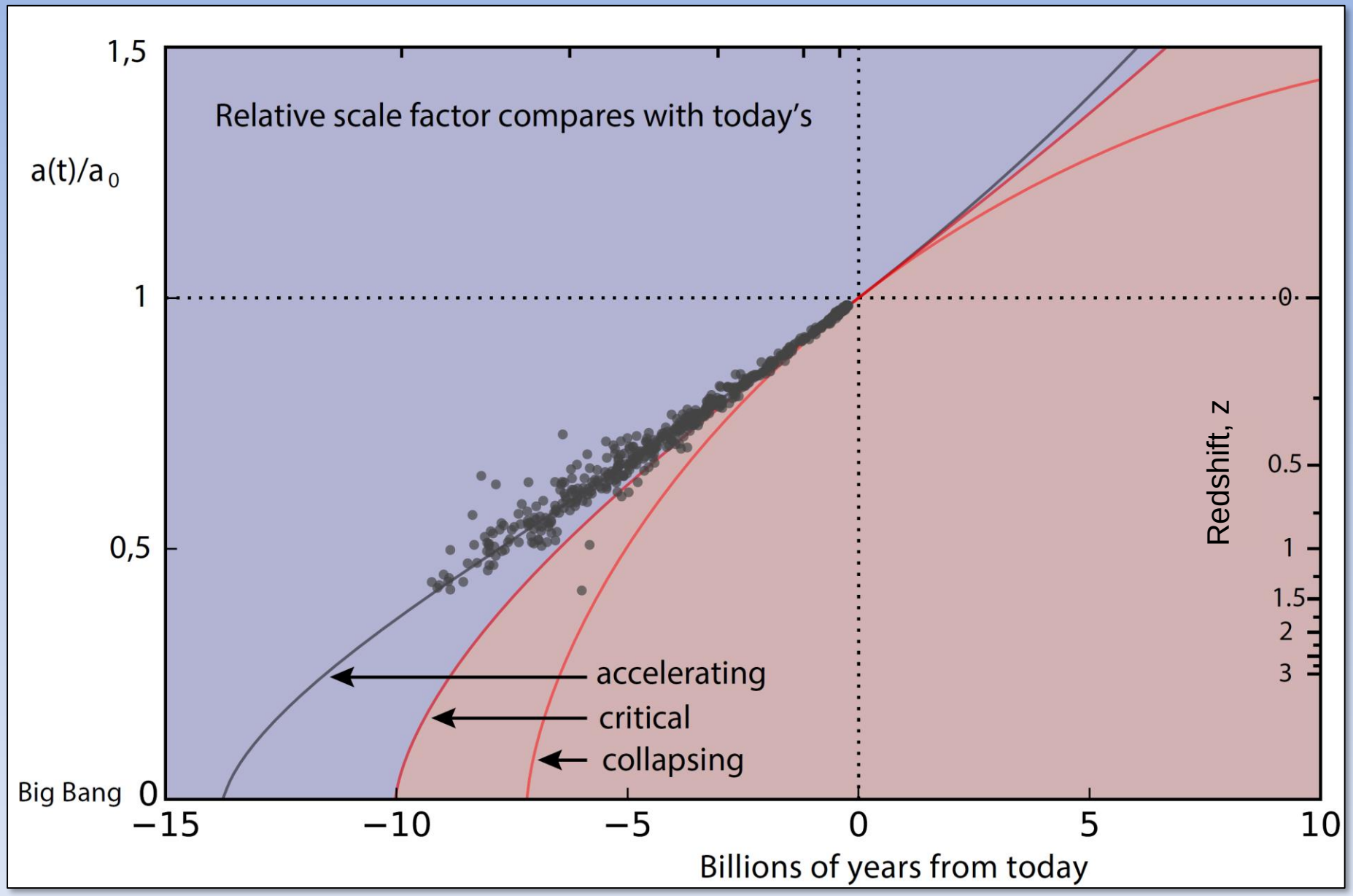
50 s.d.

$$\Omega_\Lambda = 0.691 \pm 0.006 \quad \Omega_{CDM} h^2 = 0.1199 \pm 0.0022$$

$$\Omega_B = 0.04911 \pm 0.0015 \quad h = 0.6726 \pm 0.0098$$

$$\Omega_{CDM} = 0.26, \quad \Omega_M = \Omega_{CDM} + \Omega_B = 0.31$$

Also, gravitational lensing of CMB by intervening structure gives a ~ 30 standard dev. confirmation of DM


Relative scale factor compares with today's
a(t)/a 0
1,5
1
0,5
0
Big Bang
−15
−10
−5
0
5
10
Billions of years from today
accelerating
critical
collapsing
Redshift, z
0
0.5
1
1.5
2
3

The End