Universo Primitivo

2024-2025 (1º Semestre)

Mestrado em Física - Astronomia

Chapter 1

1. The observed Universe
   - Foreword: The Olbers' paradox;
   - The Universe at different scales;
   - Observational Cosmology: empirical facts and the hot Big-Bang theory
     - Cosmic Expansion: The Hubble law;
     - The abundancies of the light elements;
     - The existence of a Cosmic Background Radiation;
     - The isotropy of distant objects;
     - The existent of dark matter;
     - The accelerated expansion of the Universe
   - Formation and evolution of cosmic structure

Foreword: The Olbers' paradox and the present view of the Universe

Foreword: Why is the sky dark at night?

Heinrich Olbers

(1758–1840)

Foreword: Why is the sky dark at night?

Heinrich Olbers

(1758–1840

Olbers' paradox (1826) : argues that "the **darkness of the sky** at night **conflicts with the concept of an infinite and eternal static universe**", with stars distributed uniformly.

$$\text{light} = \int_{r_0}^{\infty} L(r)N(r)\,dr$$

Foreword: Why is the sky dark at night?

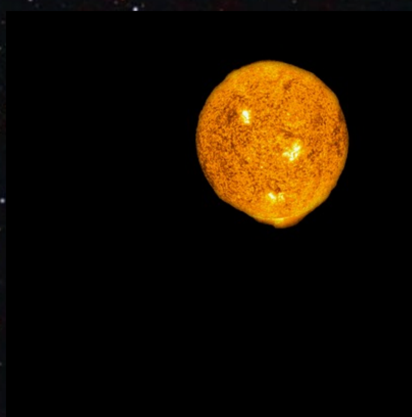
Heinrich Olbers

(1758–1840

Olbers' paradox (1826) : argues that "the **darkness of the sky** at night **conflicts with the concept of an infinite and eternal static universe**", with stars distributed uniformly.

Oblers paradox in action.

Exercise: prove why this happens



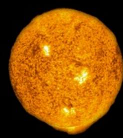
Foreword: Why is the sky dark at night?

Heinrich Olber's

(1758–1840

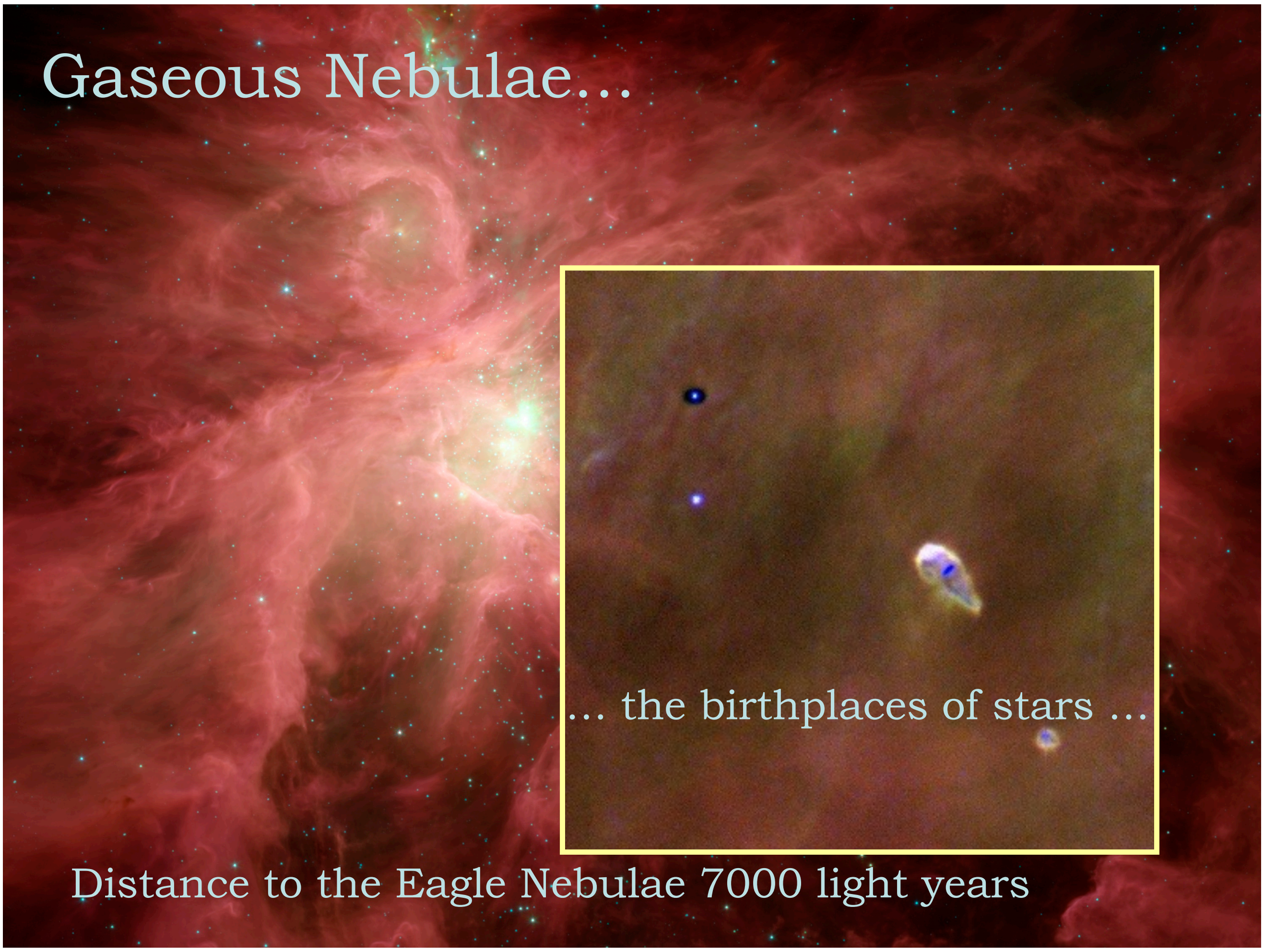
Some possible explanations:

1. Too much dust absorbs light from distant stars.
2. The number of stars in the Universe is finite.
3. The distribution of stars is not uniform.
4. The Universe is expanding. Light from distant stars are dimmed (redshifted) into obscurity.
5. The observed Universe has a finite age. Distant light hasn't even reached us yet.

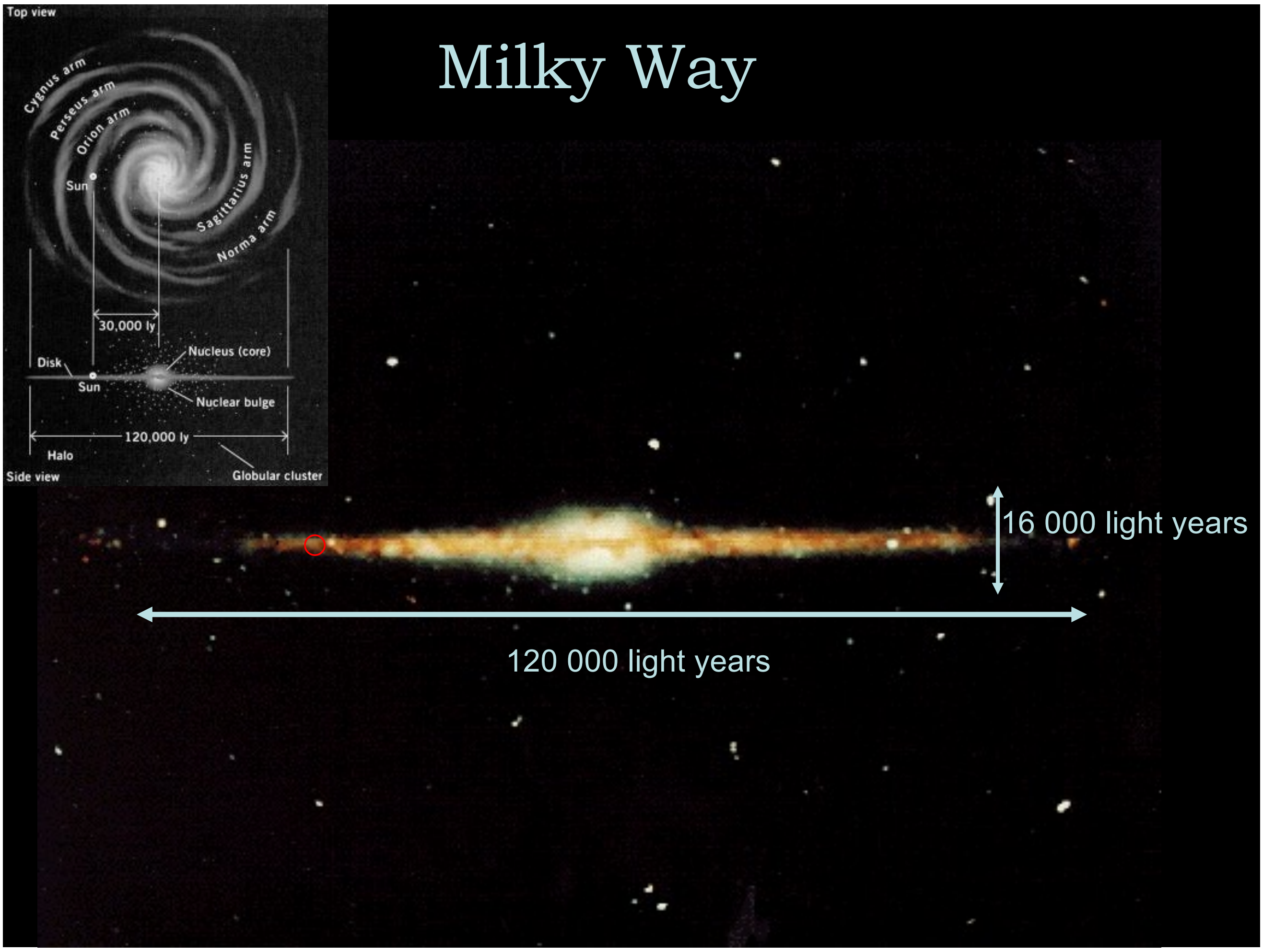


The Universe at different scales

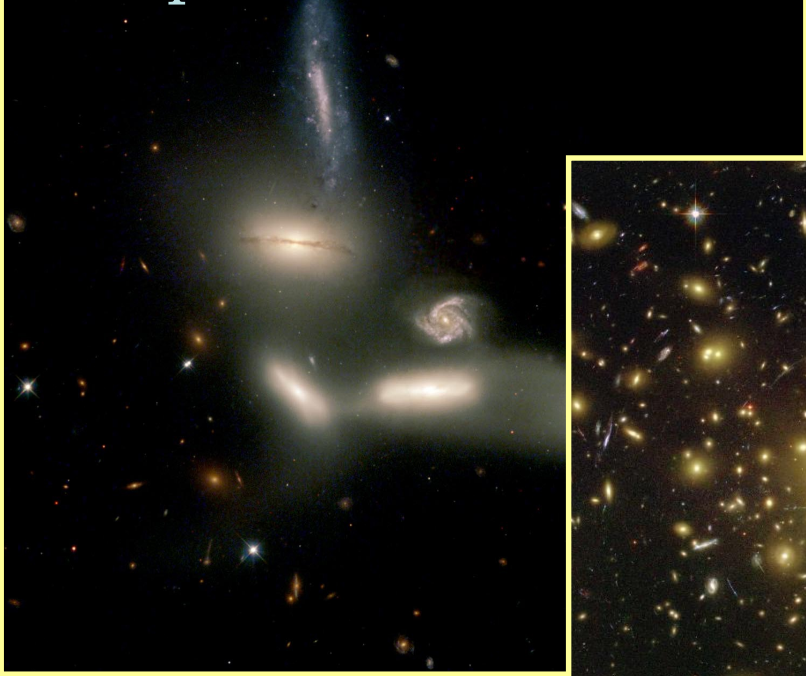

Stars…
Sun: 8 light minutes away
α-Centauro 4,25 light years

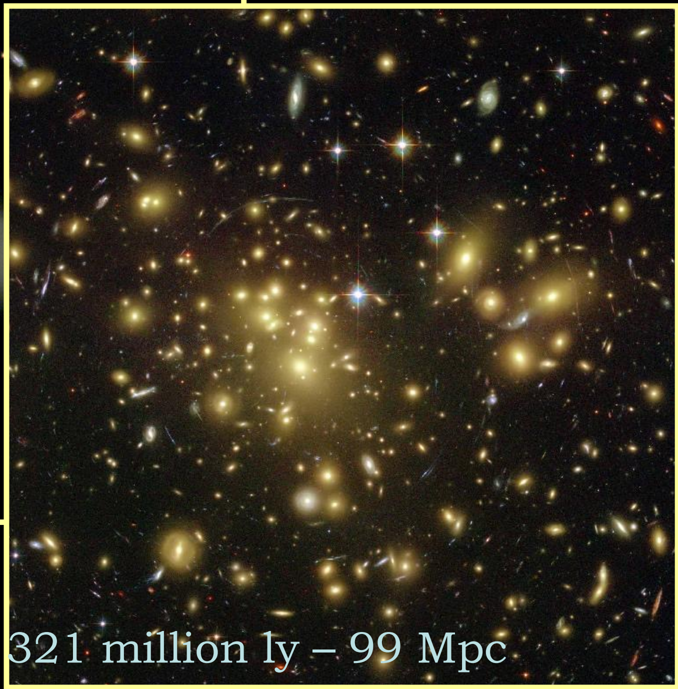

Gaseous Nebulae…
… the birthplaces of stars …
Distance to the Eagle Nebulae 7000 light years


The galaxy…
A home for billions of stars…


Milky Way
Top view
Cygnus arm
Perseus arm
Orion arm
Sun
Sagittarius arm
Norma arm
30,000 ly
Nucleus (core)
Disk
Sun
Nuclear bulge
120,000 ly
Halo
Side view
Globular cluster
16 000 light years
120 000 light years

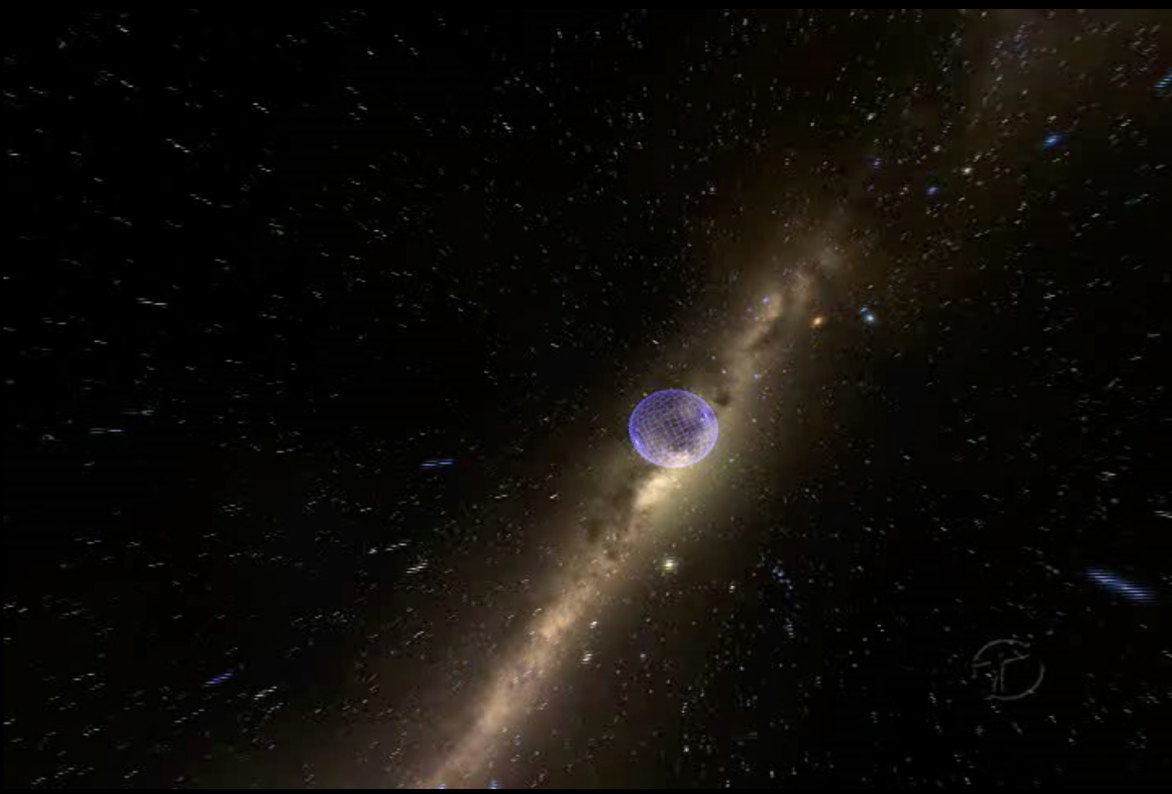
Groups and Clusters of Galaxies…





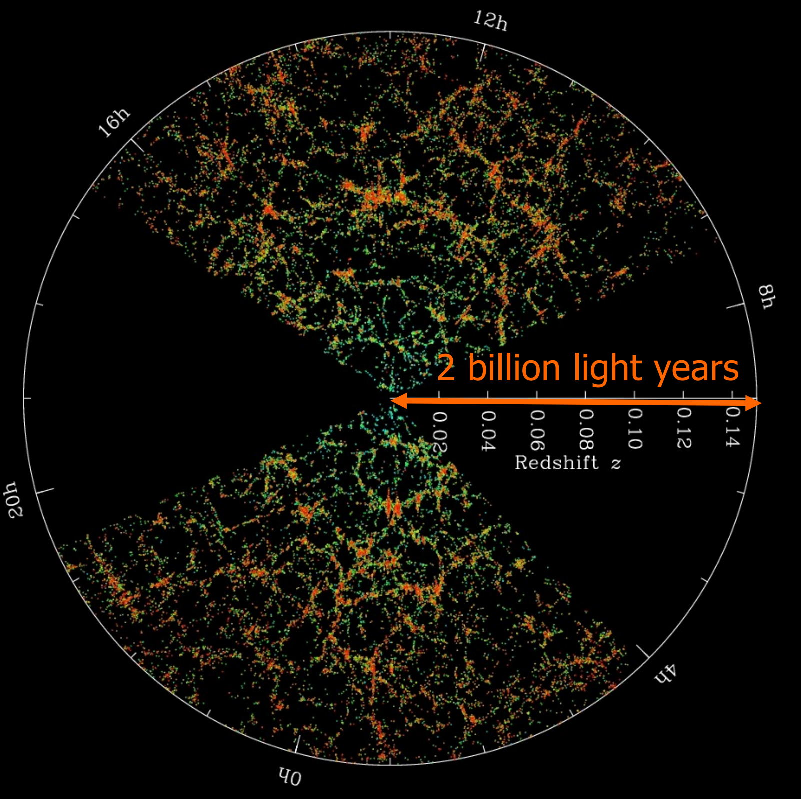
Distance to Coma cluster 321 million ly – 99 Mpc

Our place in the Universe…



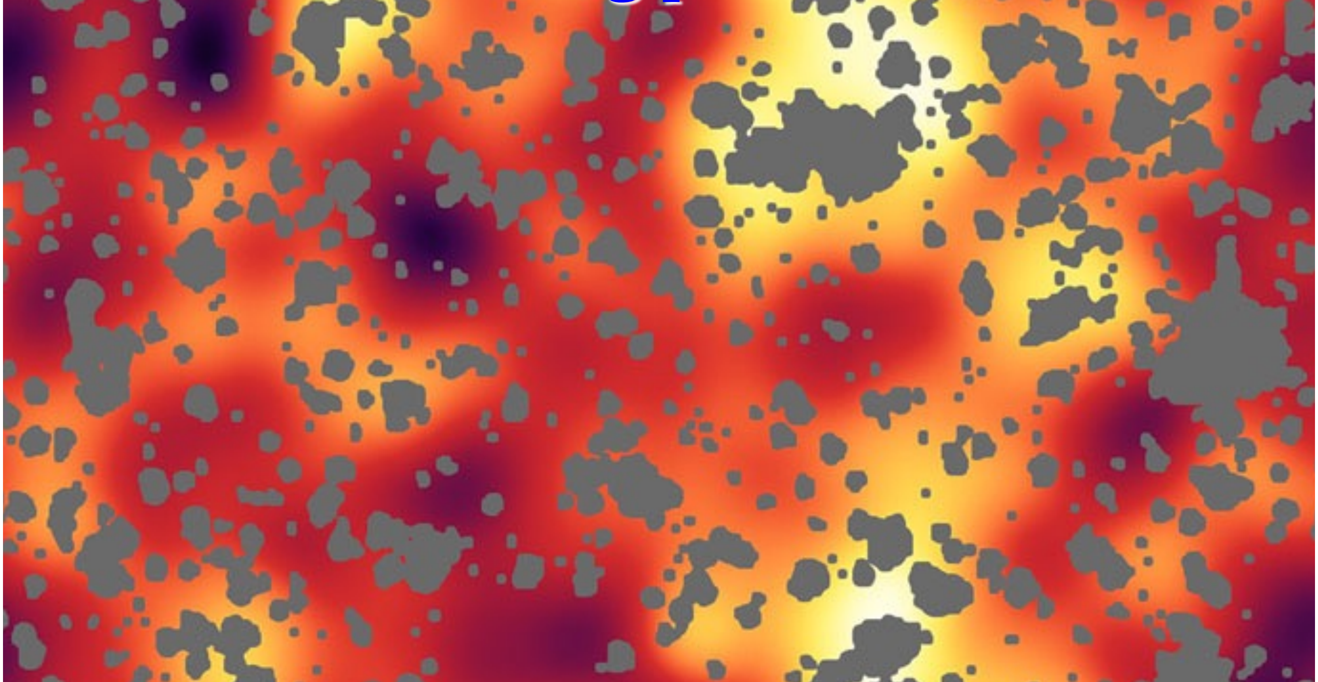
Credits: American Natural History Museum; gently provided by Miguel de Avillez U. Évora

LSS: "The fingers of God"…

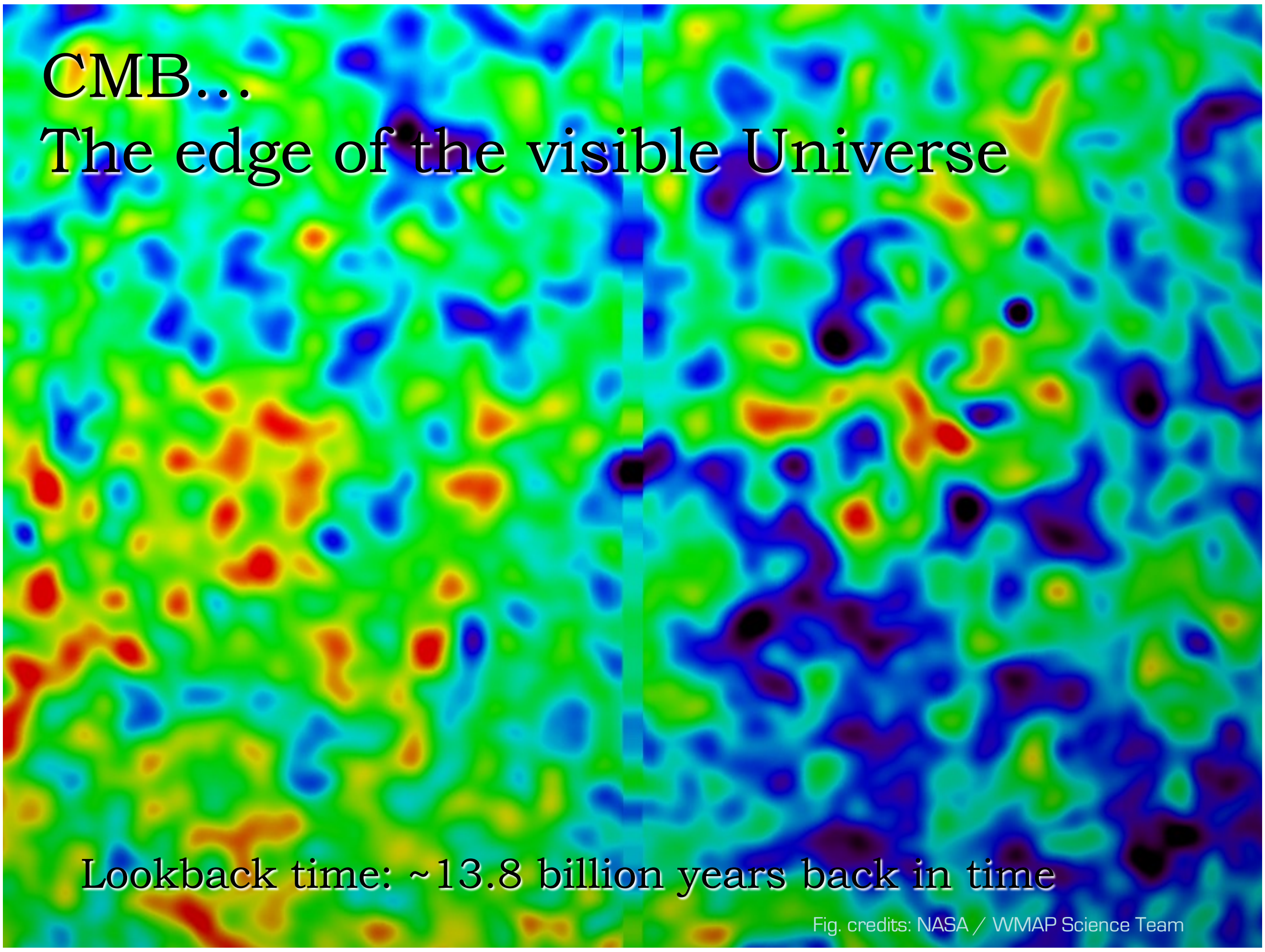


Credit: M. Blanton and the Sloan Digital Sky Survey

Further away and back in time… First stars forming period



Lookback time: 12.8 – 13.4 billion years back in time



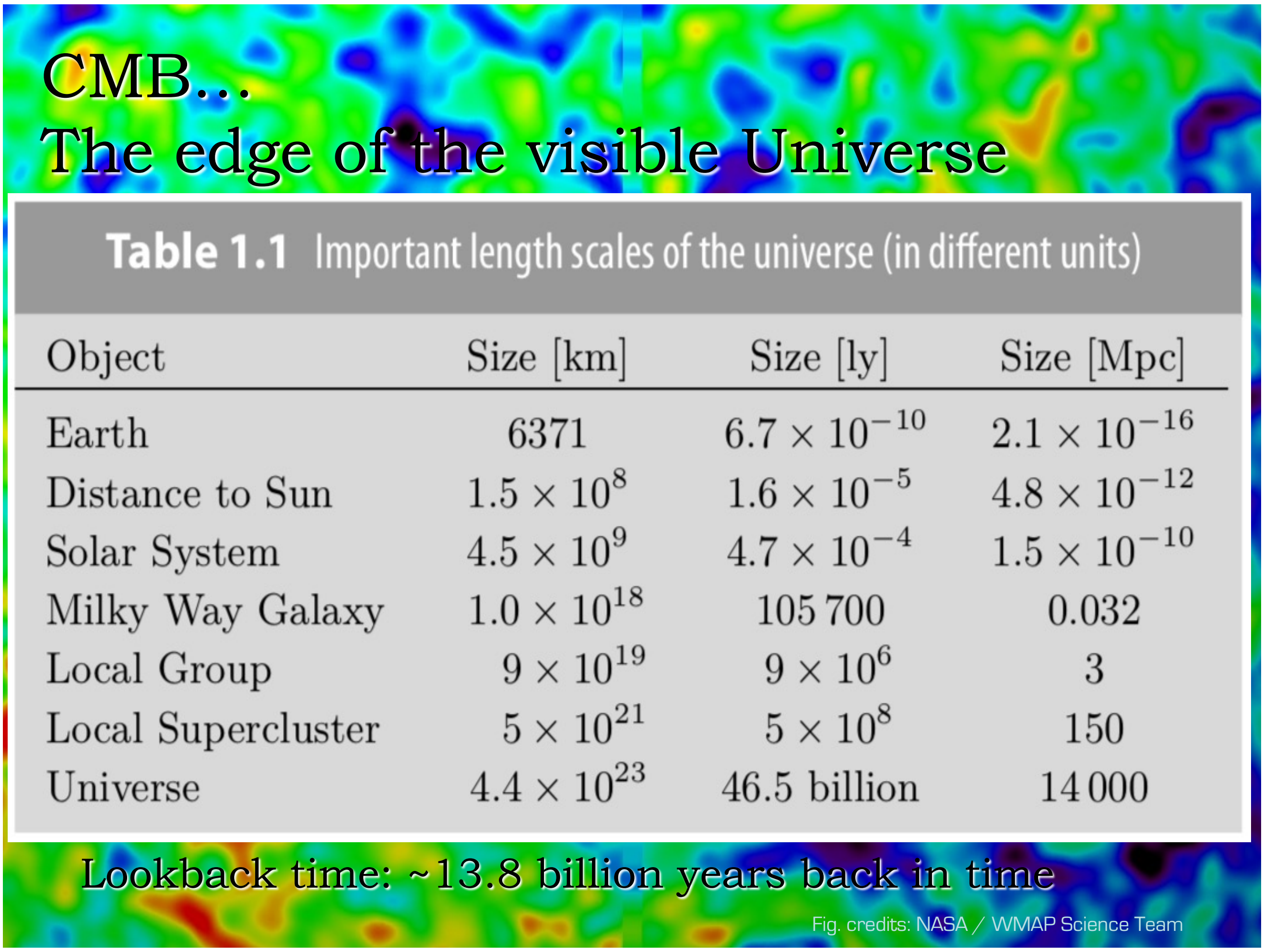
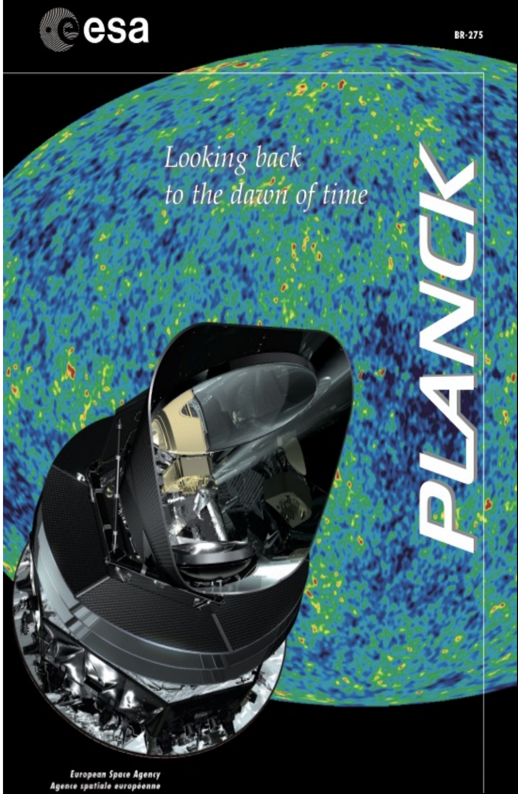


Table 1.1 Important length scales of the universe (in different units)

Object	Size [km]	Size [ly]	Size [Mpc]
Earth	6371	6.7×10^{-10}	2.1×10^{-16}
Distance to Sun	1.5×10^{8}	1.6×10^{-5}	4.8×10^{-12}
Solar System	4.5×10^{9}	4.7×10^{-4}	1.5×10^{-10}
Milky Way Galaxy	1.0×10^{18}	105 700	0.032
Local Group	9×10^{19}	9×10^{6}	3
Local Supercluster	5×10^{21}	5×10^{8}	150
Universe	4.4×10^{23}	46.5 billion	14 000

Planck Surveyor: looking back to the dawn of time



Project: ESA lead mission to observe the temperature and polarization anisotropies of the Cosmic Microwave Background (CMB) radiation with unprecedented precision.

Total Cost: about €700 million (€1 / person in EU)

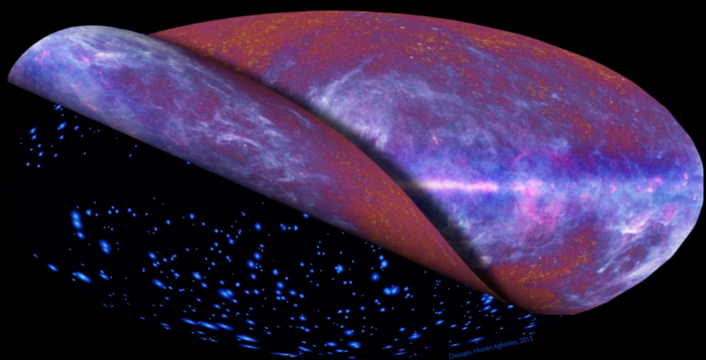
Mission timeline:
- Launch: 14 May 2009
- Operational orbit at L2: July 2009
- Nominal science phase: end of January 2011
- Extended mission: Shut down date: 19 Oct. 2013

Payload:
- Telescope: 1.5 m projected apertures
- Low Frequency Instrument (LFI): array of 22 tuned radio receivers operating at 30, 44 and 70 GHz.
- High Frequency Instrument (HFI): array of 52 bolometers operating at 100, 143, 217, 353, 545, and 857 GHz.

Fig. credits: ESA

Planck CMB observations

2009-2013: Planck satellite observes the CMB sky with unprecedented angular resolution and sensitivity.



Animation credits: ESA and the Planck collaboration; Cluster map by Douspis, Hurier, Aghanim 2013

Planck CMB observations

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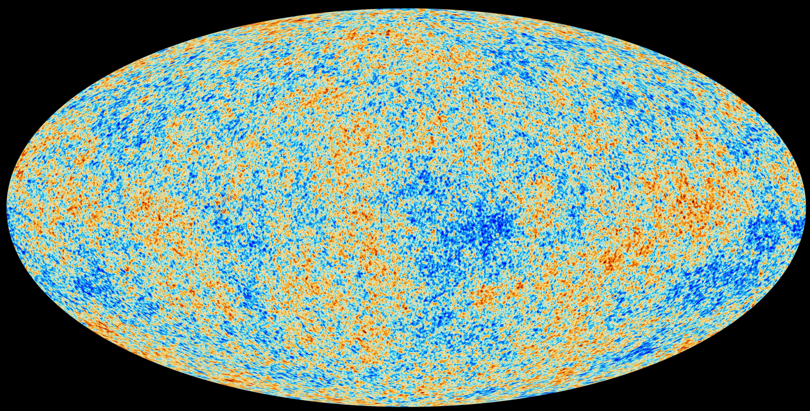
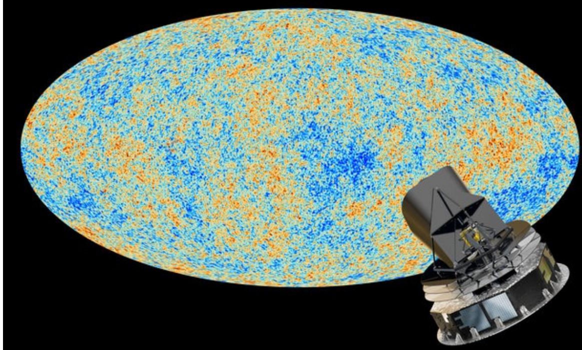


Animation & Fig. credits: ESA and the Planck collaboration

Galaxy surveys: 3D mapping of the Universe…

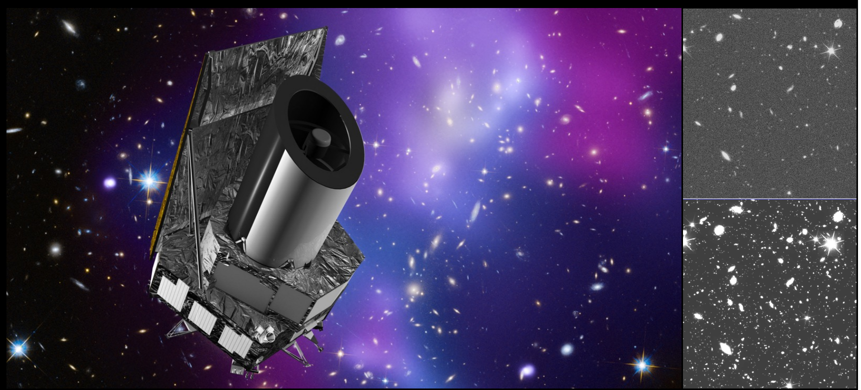
SDSS: aims at ~25% of the sky; ~100 million objects

ESA Cosmology missions



ESA/NASA Planck Surveyor:
2009 - 2013

ESA Euclid:
2023 - 2029



Euclid mission (ESA): Galaxy Surveys from space (launch 2023)

Primary Objective: To map the distribution and evolution of (dark) matter in the Universe to:

- Measure the accelerated expansion
- Unveil the nature of dark energy
- Test models of gravity, dark matter, and of the primordial universe

Present observations suggest that dark energy (DE) and dark matter (DM) are 96% of the total energy density budget of the universe.

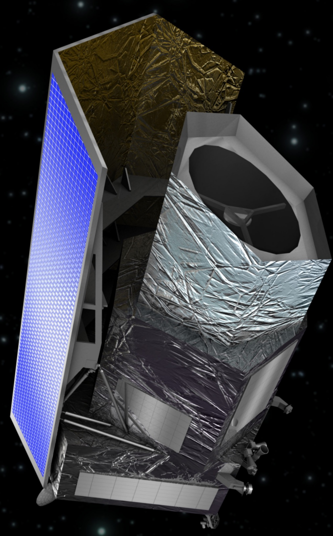
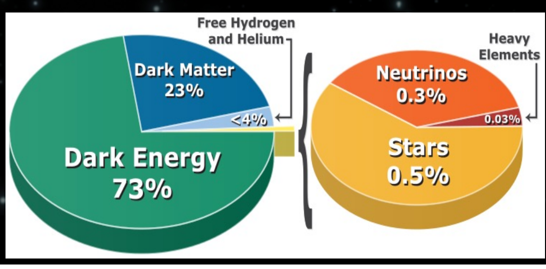


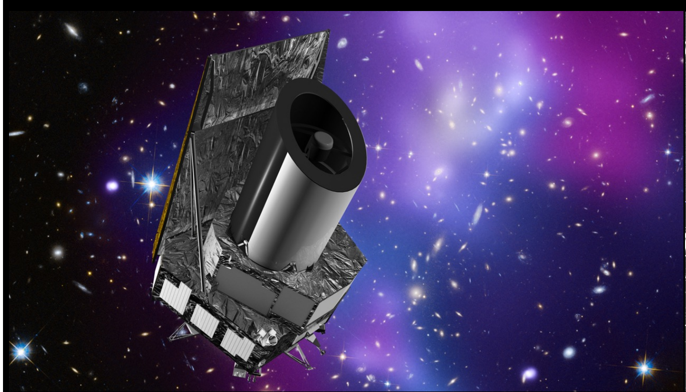
Fig. credits: ESA - C. Carreau.

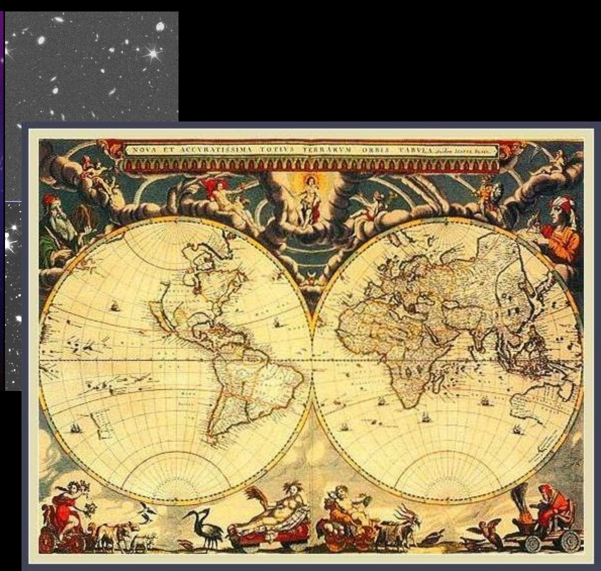


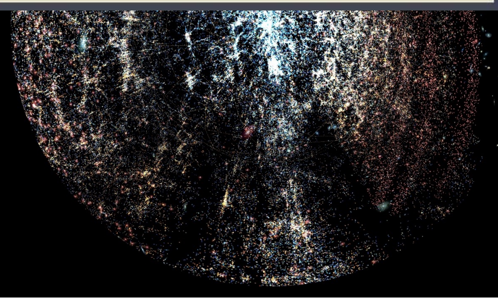
3D galaxy surveys

Subbarao, Surendran, e Landsberg. (SDSS)

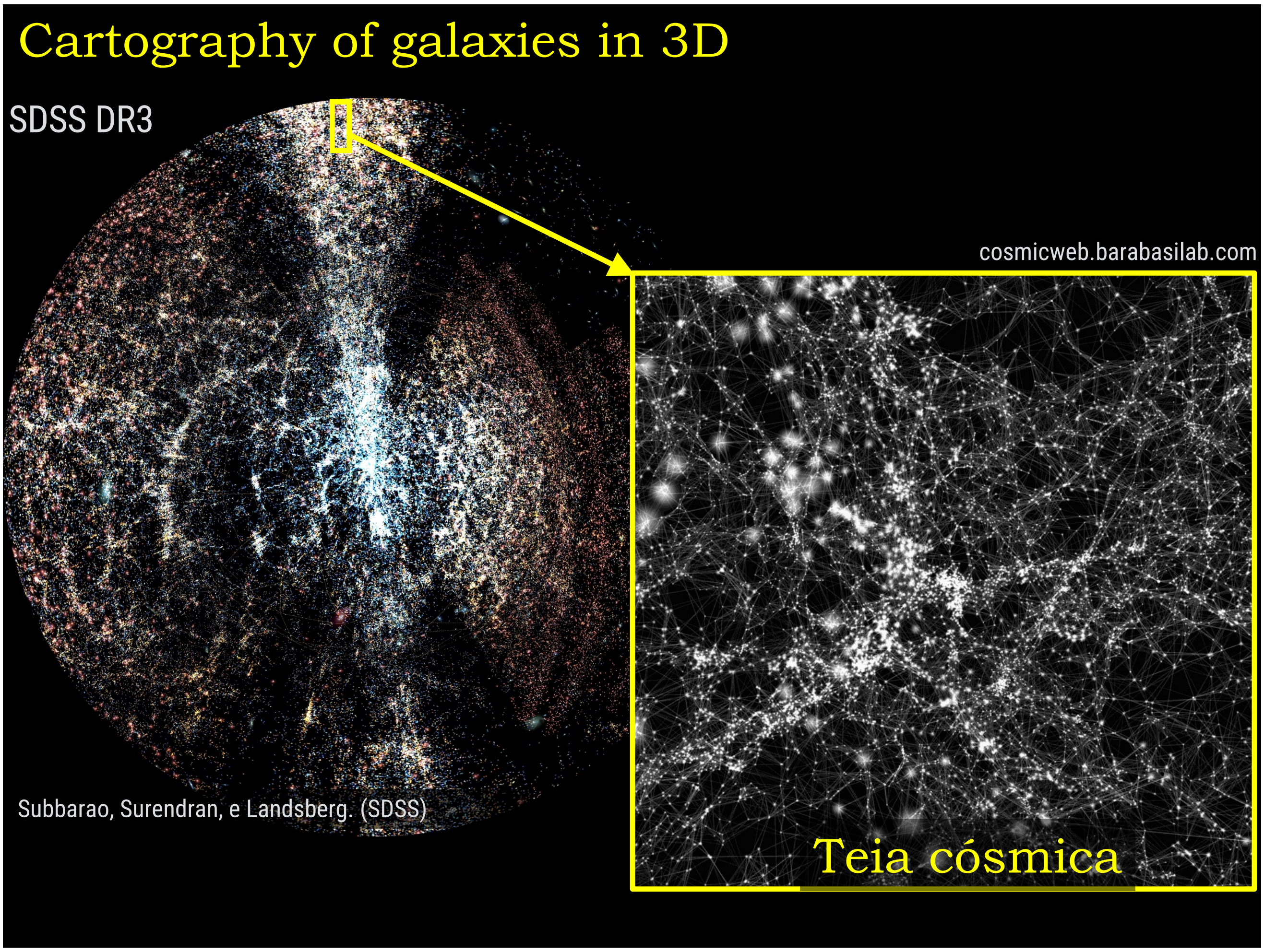
Cartography of galaxies in 3D with Euclid

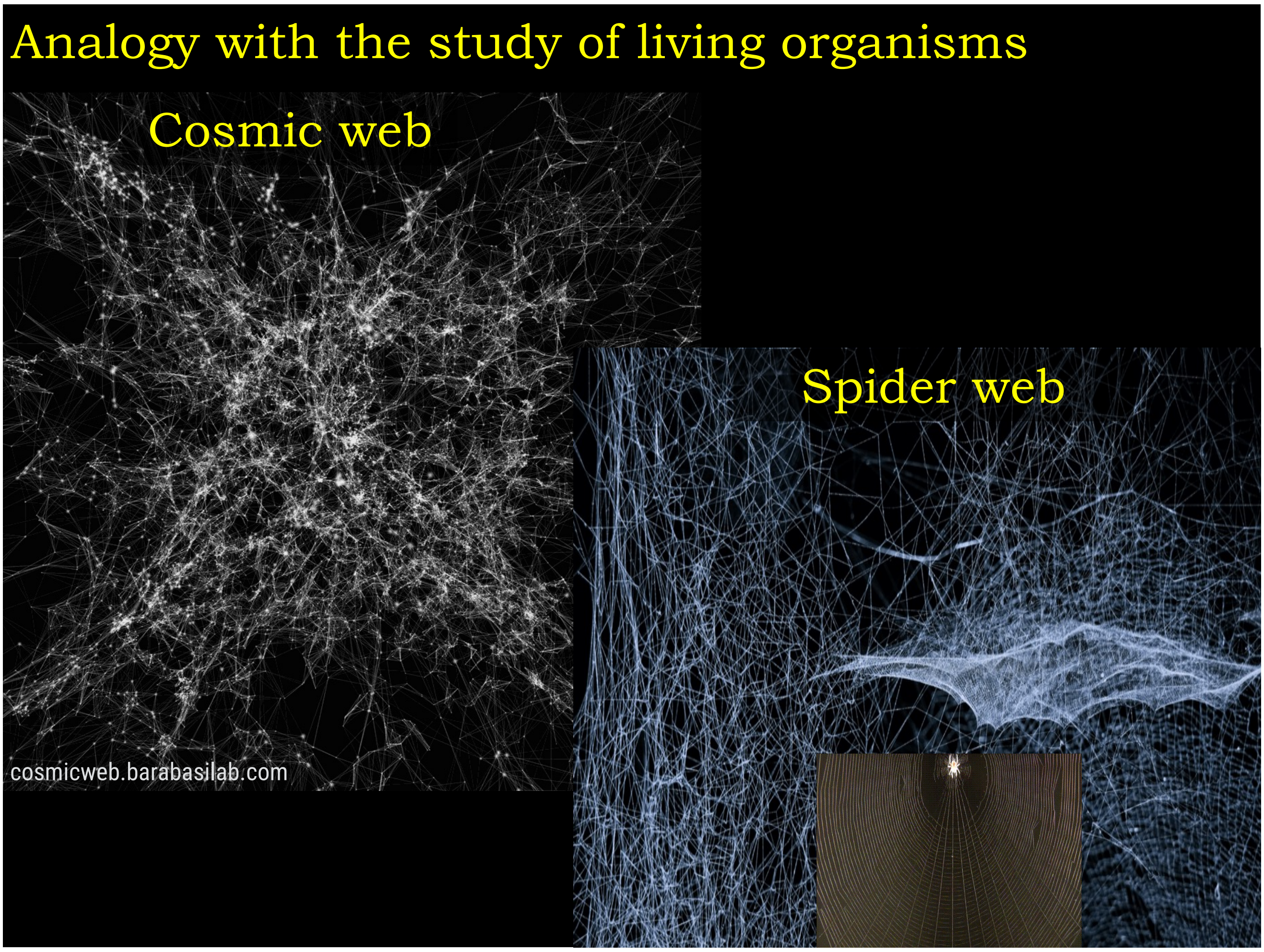






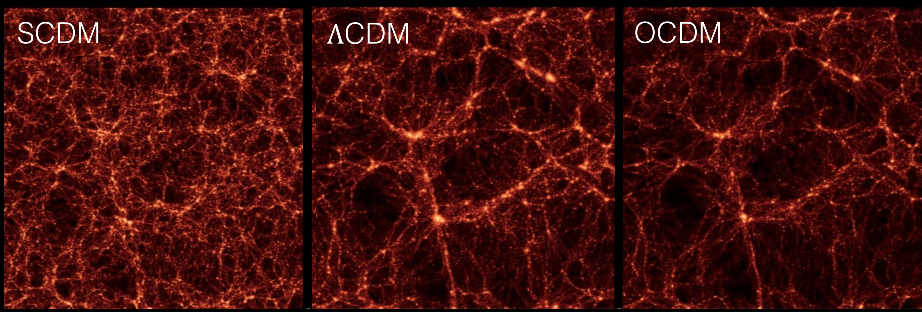
O Euclid fará a maior e mais precisa cartografia, de galáxias no Universo, observando imagens e obtendo espectros a partir do espaço.

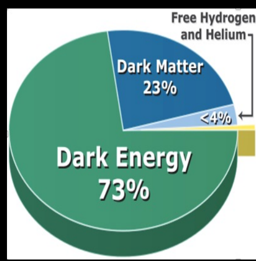

Cartography of galaxies in 3D
SDSS DR3
cosmicweb.barabasilab.com
Teia cósmica
Subbarao, Surendran, e Landsberg. (SDSS)


Analogy with the study of living organisms
Cosmic web
Spider web
cosmicweb.barabasilab.com

Spider webs (effect of caffeine concentration)

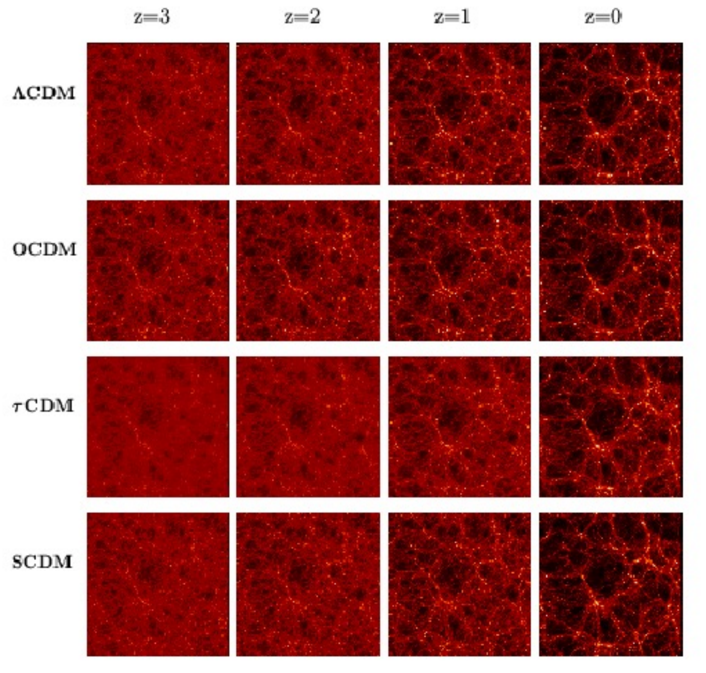
Cosmic webs (with different amounts of DM & DE)

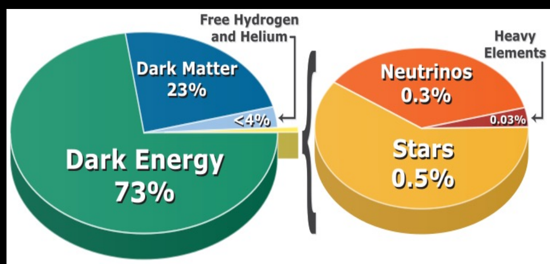




Cosmic web probes cosmology & particle physics parameters

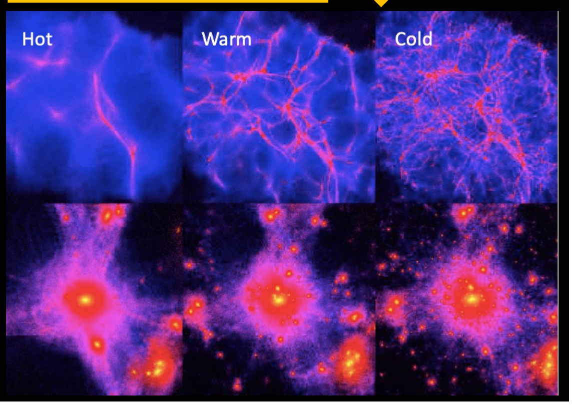
Model	Omega0	lambda	h	Gamma	Sigma8	Npar	L (Mpc/h)	m_p (M_sun/h)	l_soft (Kpc/h)
SCDM	1.0	0.0	0.5	0.50	0.6	256^3	84.5	1.0×10^{10}	36
tCDM	1.0	0.0	0.5	0.21	0.6	256^3	84.5	1.0×10^{10}	36
LCDM	0.3	0.7	0.7	0.21	0.90	256^3	141.3	1.4×10^{10}	20
OCDM	0.3	0.0	0.7	0.21	0.85	256^3	141.3	1.4×10^{10}	30





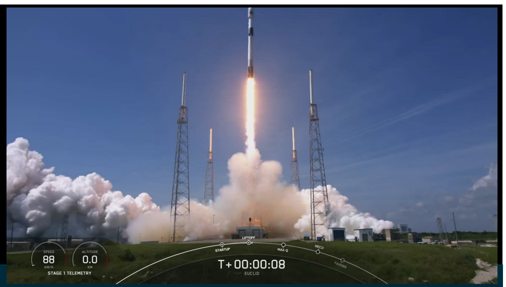
Impact of Dark Matter & Dark Energy; Hubble constant; Primordial power spectrum

Impact of the nature of the Dark Matter (Part. Physics model)

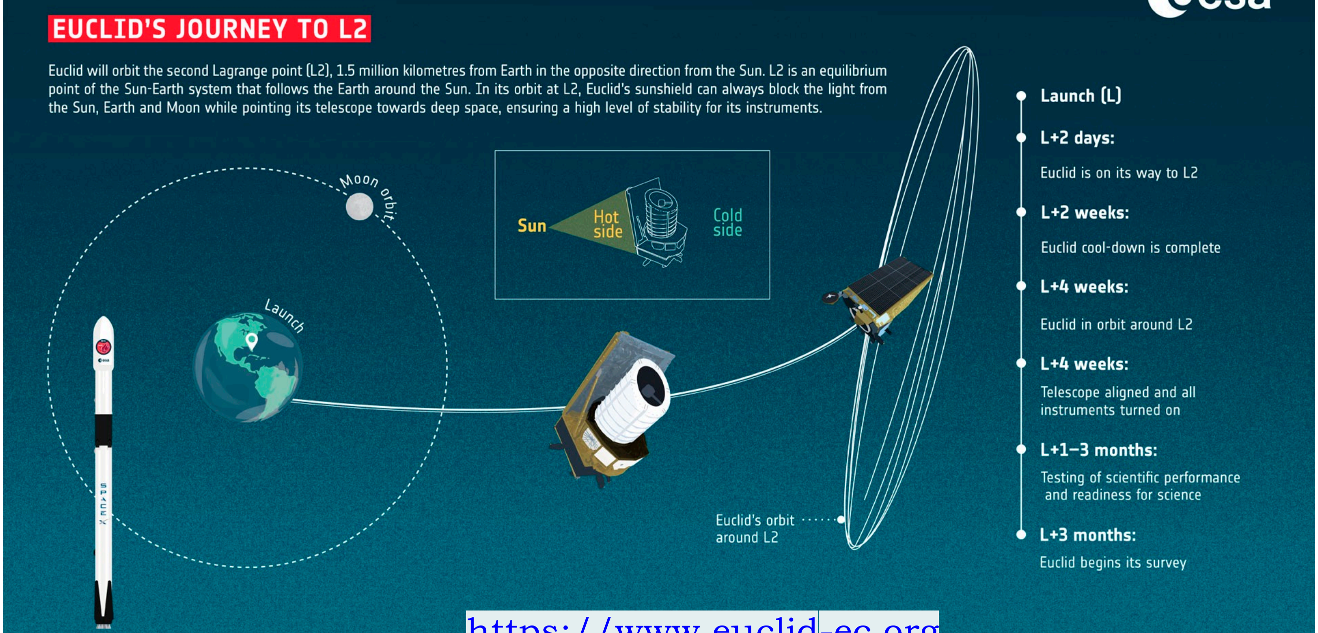


Euclid launch:

1 July, 2023, launched by a
Space X Falcon 9 rocket



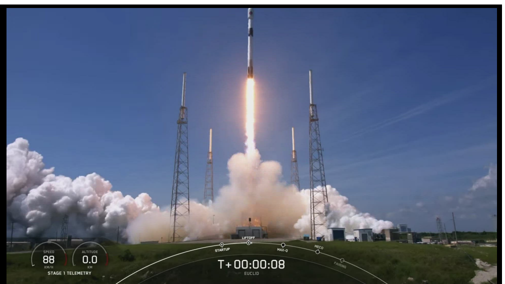
https://www.youtube.com/watch?v=CAbS8G9EBng



https://www.euclid-ec.org

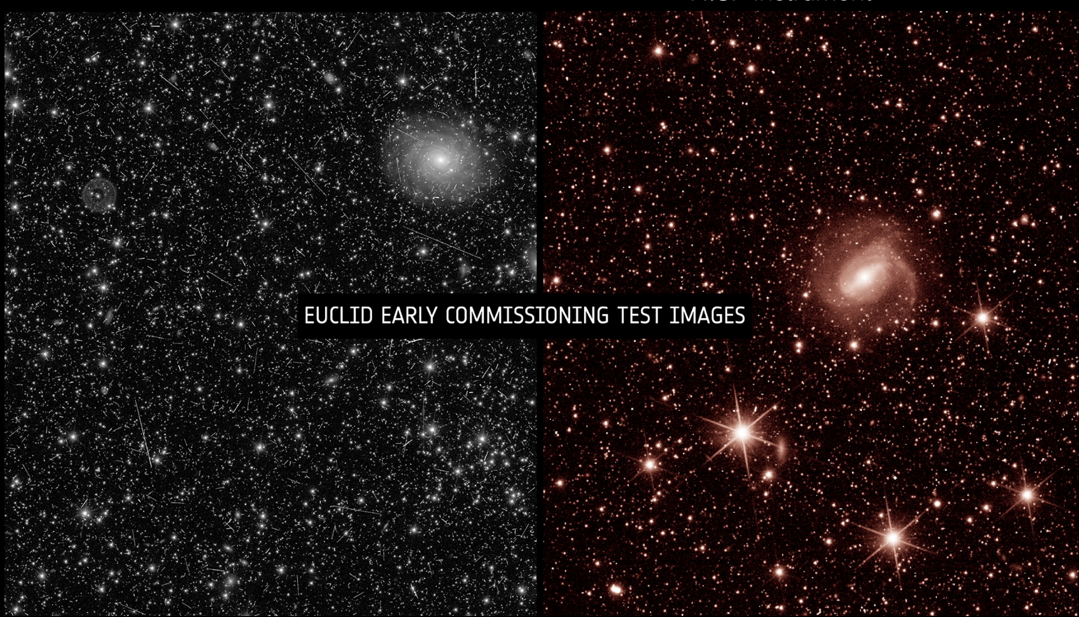
Euclid first light (raw images)

Early Commissioning Test Images



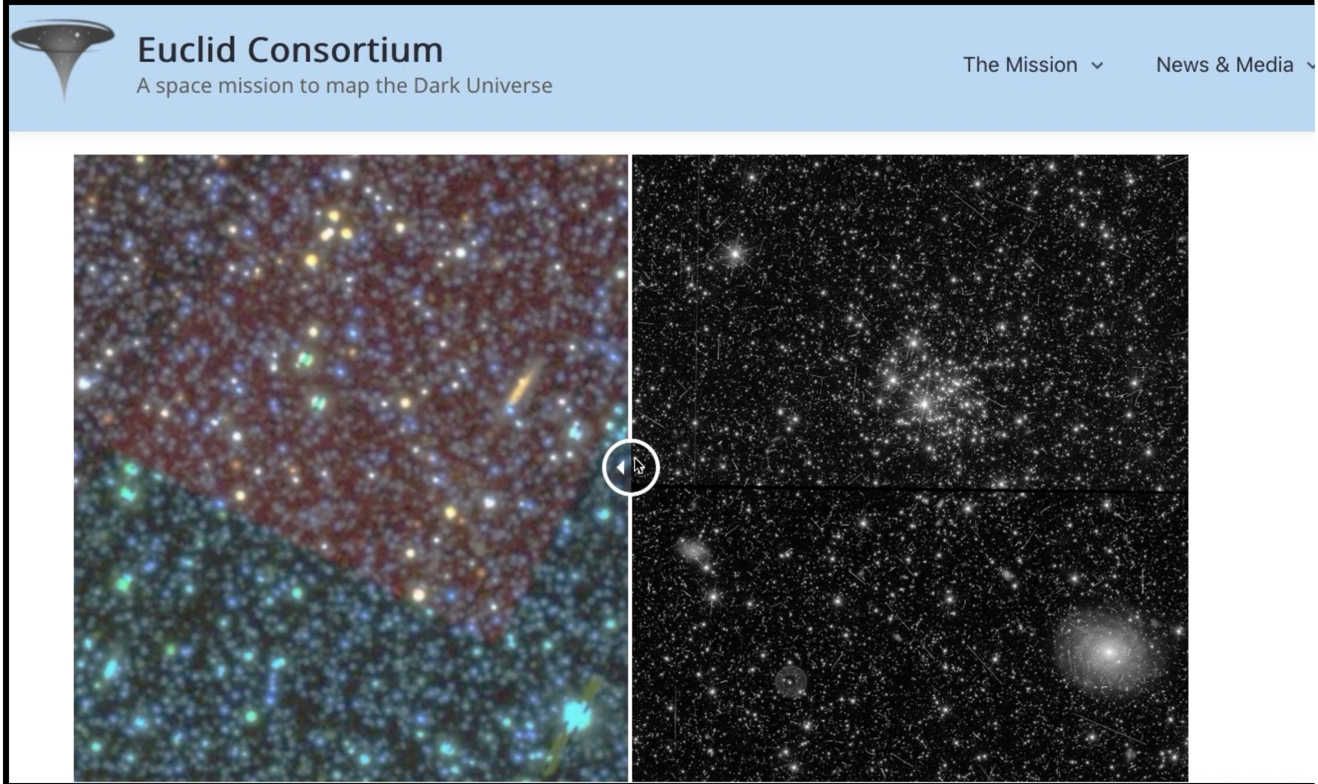
VIS instrument

NISP instrument



Euclid versus ground telescopes (DESI)

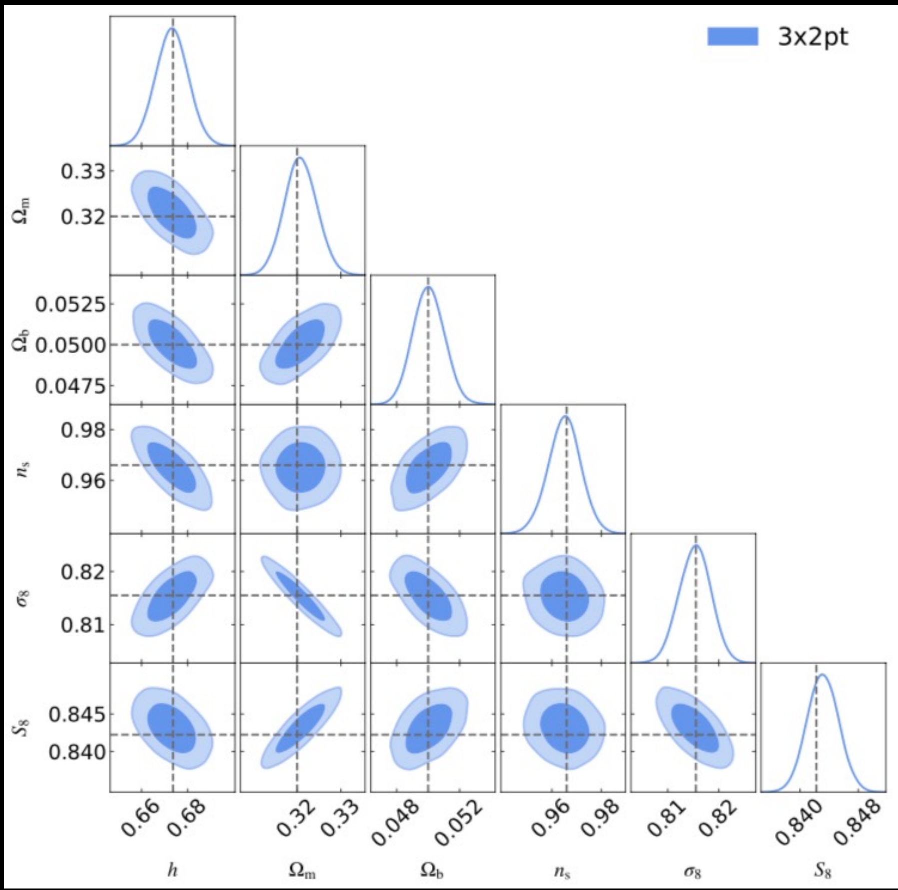
https://www.euclid-ec.org/why-is-going-to-space-crucial-to-map-dark-matter



Euclid Early Release observations

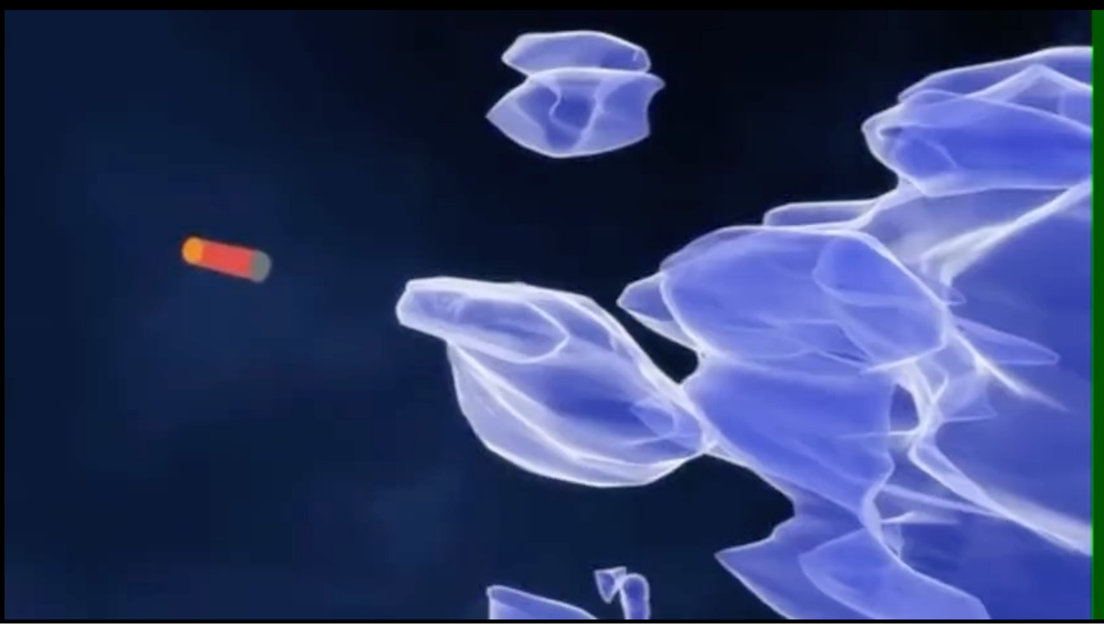
Fig. B.2. Released on 7 November 2023, the first set of five colour images unveiled *Euclid*'s capabilities to the global community. The images (cropped FoV= $0.5\,\mathrm{deg}^2$), starting from the top left, feature the Perseus cluster, IC 342, NGC 6822, NGC 6397, and the Horsehead nebula, along with a cutout on the lower right ($10' \times 10'$) that highlights the image resolution and depth achieved by *Euclid*. The pipeline detailed in this paper produced each of the three channels that contributed to the initial RGB images. These images were subsequently refined using external tools. The chosen colour palette assigns assigns the I_E-, Y_E-, and H_E-bands to the blue, green, and red channels respectively, displaying the full sensitivity range of the observatory and offering a new perspective on these astronomical subjects. Credit: ESA/Euclid/Euclid Consortium/NASA, image processing by J.-C. Cuillandre (CEA Paris-Saclay), G. Anselmi.

Euclid Forecasts:



Euclid: Lensing probes

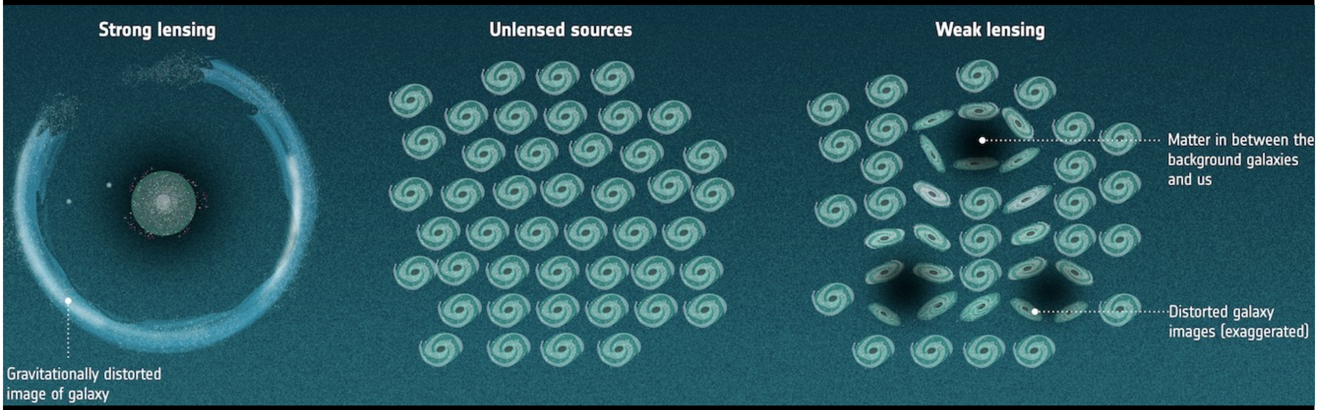
Euclid will observe more than a billion of galaxies during 6 years of operations. The light emitted by galaxies is lensed (deflected) by invisible structures of Dark Matter and are observed with distortion.



Euclid: Lensing probes

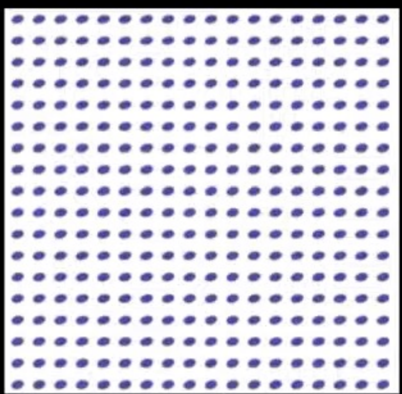
Lensing effects are said **strong** or **weak** depending if distortions are very apparent or very difficult to see without a statistical analysis in images with a large collection of background galaxies.

Strong lensing generally arises from lensing generated by individual (massive) lenses, whereas weak lensing provides a way to infer about the distribution of the lensing sources (mostly the dark matter distribution) across the images.



Euclid: an M-class mission of ESA's scientific program

The distortions are very small. But with the observation of a billion galaxies, there is enough statistics to map the dark matter and study the nature of dark energy.



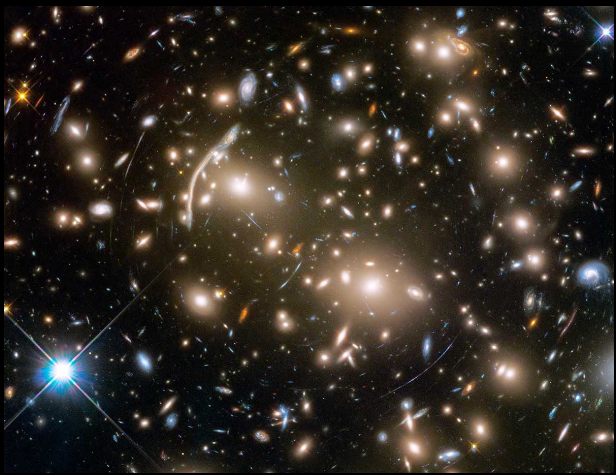
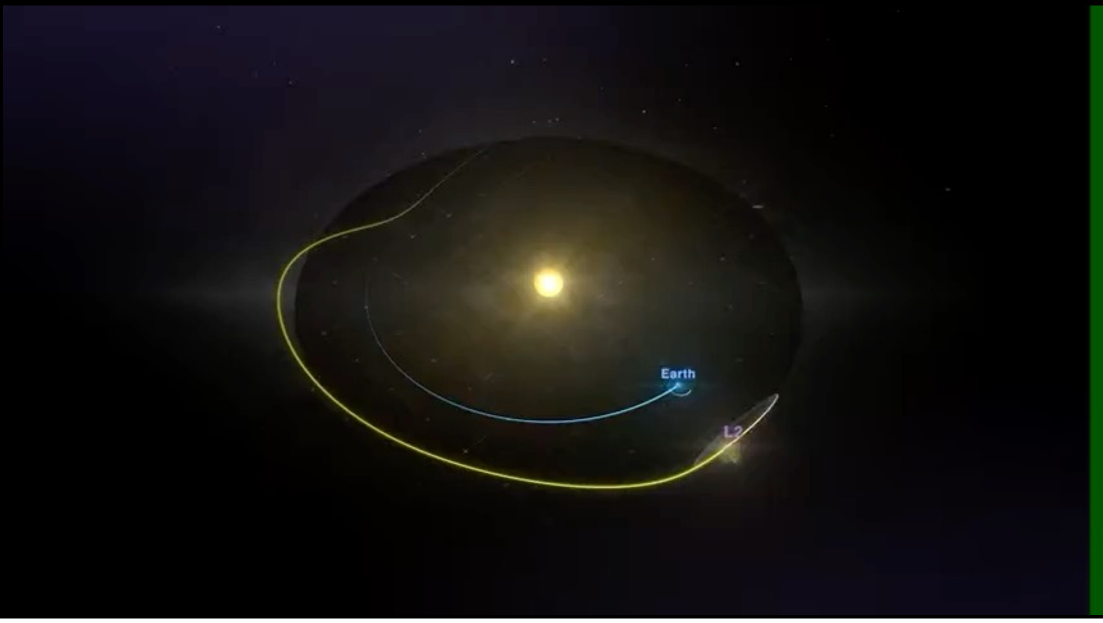


Imagem do Hubble do enxame de galáxias Abell 370
(a 4 biliões de anos luz da terra)

Euclid: an M-class mission of ESA's scientific program

To obtain good images, the satellite is in an orbit at the Lagrange point L2, with its "back turned" to the sun, pointing successively to different directions of the darkest regions of the sky. Each field will have to be observed for 1h15. The total area of observation will be 15000 square degrees.

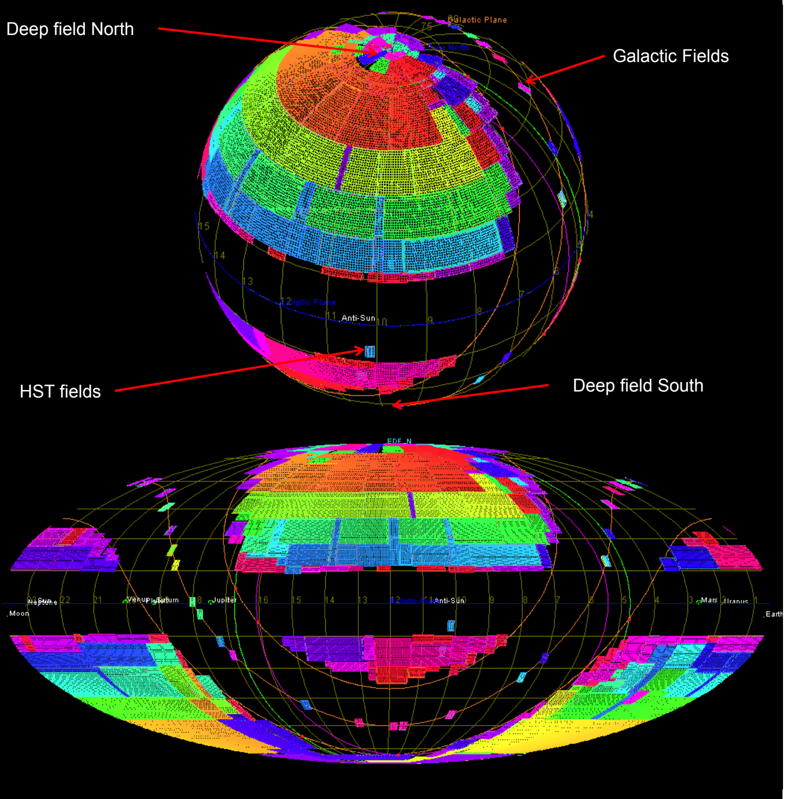


Euclid: Portugal responsablities coordinated at IA/FCUL

Euclid Survey planning

In-kind contribution is being delivered by the ECSURV-PT /SOST team at IA:

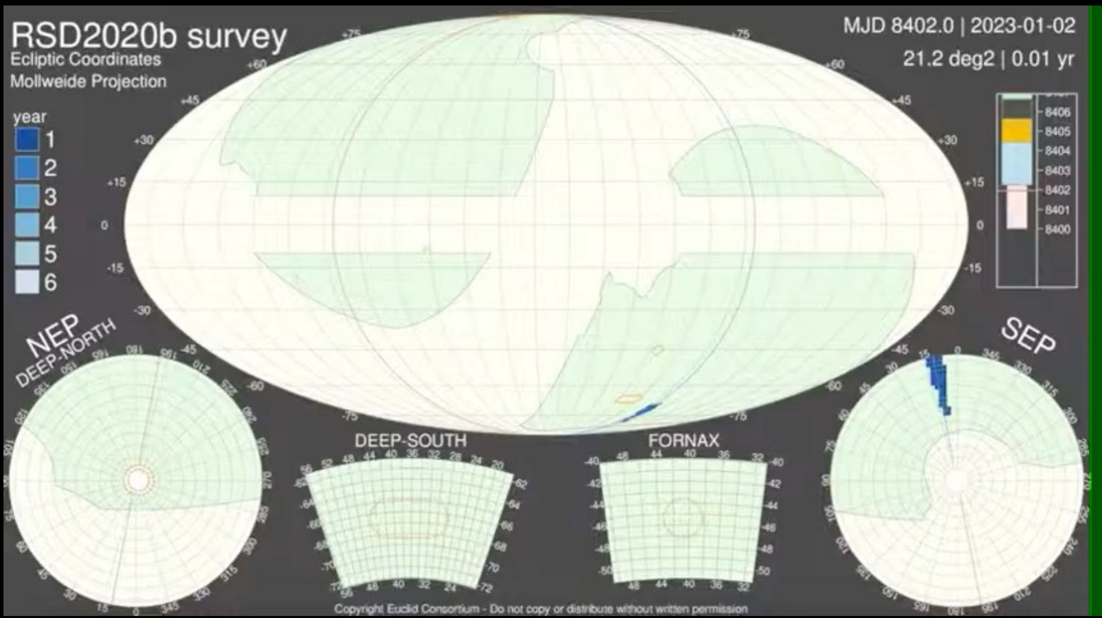
- Ismael Tereno
- João Dinis
- António da Silva
- Carla S. Carvalho (former)
- David Oliveira (former)



From: Euclid Preparation I. The Euclid Wide Survey, 2021 DOI: 10.1051/0004-6361/202141938

Euclid Sky Survey implementation and optimization is a PT, national, responsibility

https://www.youtube.com/watch?v=y89SXN-Xd9A

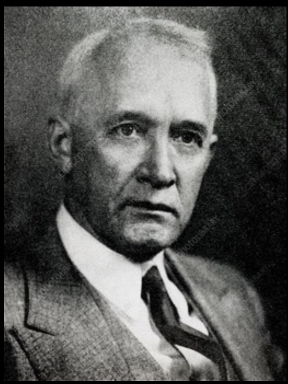


Animação criada por J. Dinis (FCUL / IA)

Another documentary by IA/FCUL: "O que se esconde na luz? – O telescópio Euclid e o Universo invisível", Sergio Pereira, IA", https://www.youtube.com/watch?v=KX-aAk_H308

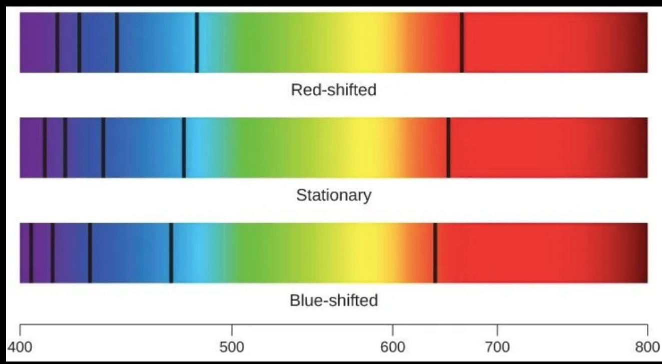
Observational cosmology: empirical facts about the Universe

1. The Universe is expanding



Vesto Slipher
(1875-1969)

1912: Vesto Slipher is the first to observe spectral line (red)shifts towards nebulae and to relate these **redshifts** to their recessional velocities.



Redshif: $z = \dfrac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}}$

1. The Universe is expanding

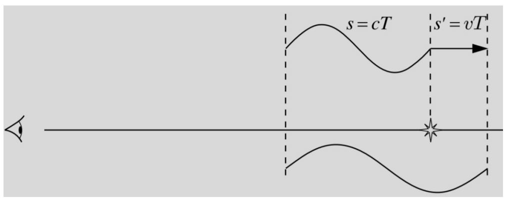
Redshift formulae

Efeito de Doppler clássico: Válido sempre que a velocidade relativa é muito inferior à da luz ($v \ll c$), e em espaços-tempo de Minkowski.

$$\lambda_{em} = c\,T$$

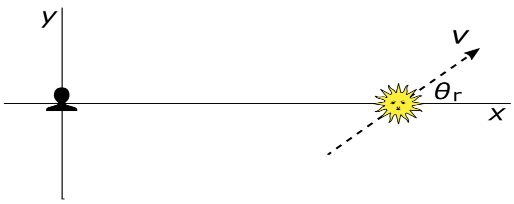
$$\lambda_{obs} = \lambda_{em} + v\,T \Leftrightarrow \lambda_{obs} - \lambda_{em} = v\,T$$

$$z = \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}} = \frac{v\,T}{c\,T} \Leftrightarrow \boxed{z = \frac{v}{c}}$$



Efeito de Doppler relativista: Válido para qualquer v, e em espaços-tempo de Minkowski.

$$\boxed{z + 1 = \frac{1 + (v\cos\theta_r)/c}{\sqrt{1 - v^2/c^2}}}$$



Movimento radial $\theta_r = 0$:

$$z + 1 = \frac{1 + v/c}{\sqrt{1 - v^2/c^2}} = \frac{1 + v/c}{\sqrt{(1 - v/c)(1 + v/c)}} \Leftrightarrow \boxed{z + 1 = \frac{\sqrt{(1 + v/c)}}{\sqrt{(1 - v/c)}}}$$

1. The Universe is expanding

Redshift formulae

Redshift gravitacional: Válido para qualquer espaço estacionário (espaço tempo de Schwarzschild).

$$z + 1 = \frac{\sqrt{g_{tt}(recepção)}}{\sqrt{g_{tt}(emissão)}}$$

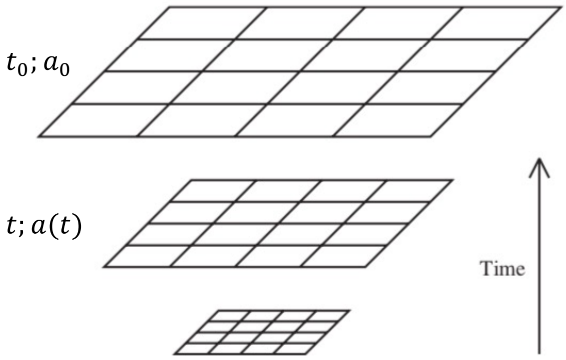
Redshift Cosmológico: Válido para espaços-tempo em expansão, $\vec{r} = a(t)\,\vec{x}$ (espaços-tempo FLRW).

$$z + 1 = \frac{a_{atual}}{a_{emisão}} = \frac{a_0}{a(t)}$$

$$\lambda_{em} = a(t)\,\lambda_c$$

$$\lambda_{obs} = a_0\,\lambda_c$$

$$z = \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}} = \frac{a_0\,\lambda_c - a(t)\,\lambda_c}{a(t)\,\lambda_c} = \frac{a_0}{a(t)} - 1$$



1. The Universe is expanding

Edwin Hubble
(1889-1953)

1924: Edwin Hubble ends debate on the nature of nebulae being galactic objects

1929: reports a linear relation between relative radial velocity and distance

$$v = H\,r$$

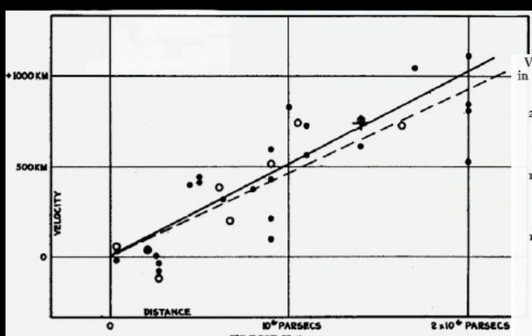
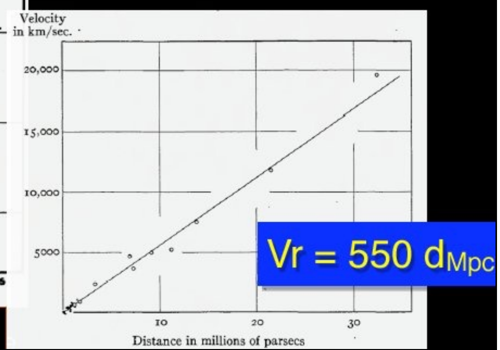


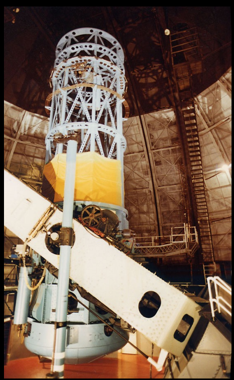
FIGURE 1



From:

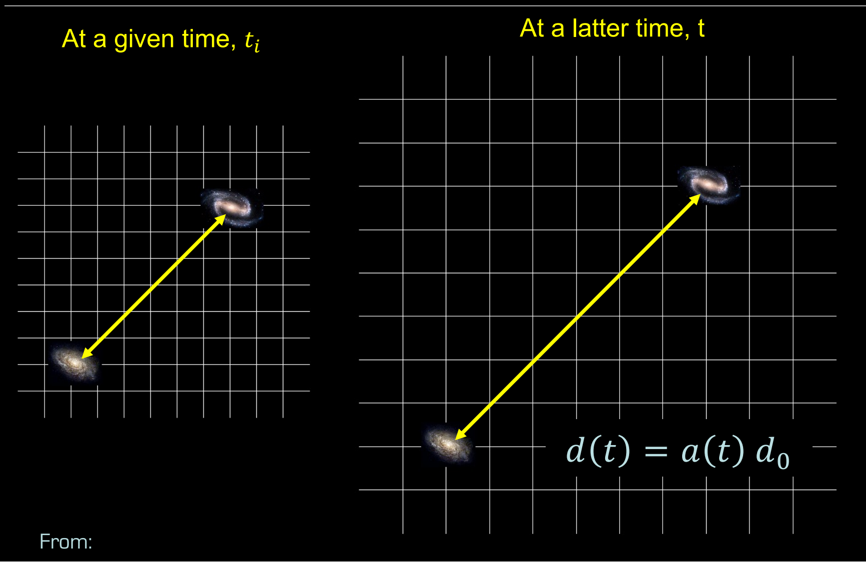
1. The Universe is expanding

Edwin Hubble



1924: Edwin Hubble ends debate on the nature of nebulae being galactic objects

1929: reports a linear relation between relative radial velocity and distance: $v = Hd$



From:

1. The Universe is expanding

Edwin Hubble

1924: Edwin Hubble ends debate on the nature of nebulae being galactic objects

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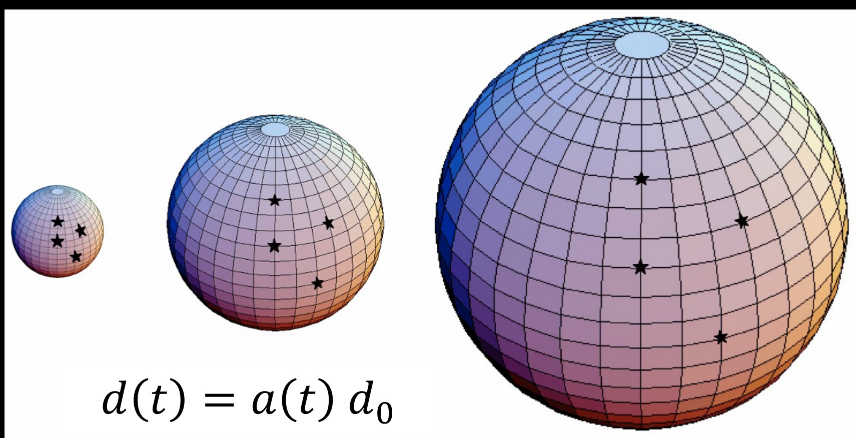
Time evolution of an expanding spherical surface



From:

The basic idea behind the Big-Bang theory

- If the universe is expanding and matter-energy is conserved during the expansion then the universe had to be smaller, denser and hotter in the past!

- If so, the Universe must have evolved from a state where matter and radiation form a ultra dense and hot ionized plasma of fundamental particles

- As the universe expands and cools down:
  - o interactions between the plasma components become less frequent;
  - o different particle species should decouple from the plasma;
  - o eventually the universe becomes neutral and transparent to radiation

According to the Big-Bang theory, in the early instants…

" the Universe was a extremely hot and dense plasma, like a 'torrid bright fog'…

… radiation was trapped in this plasma through collisions with other plasma particles

… as the universe expands, the plasma temperature drops, atomic nuclei form and capture the free electrons in the plasma. When the number of free electrons is too small, radiation no longer interacts with the plasma and propagates freely, giving rise to the Cosmic Microwave Background and neutral matter"

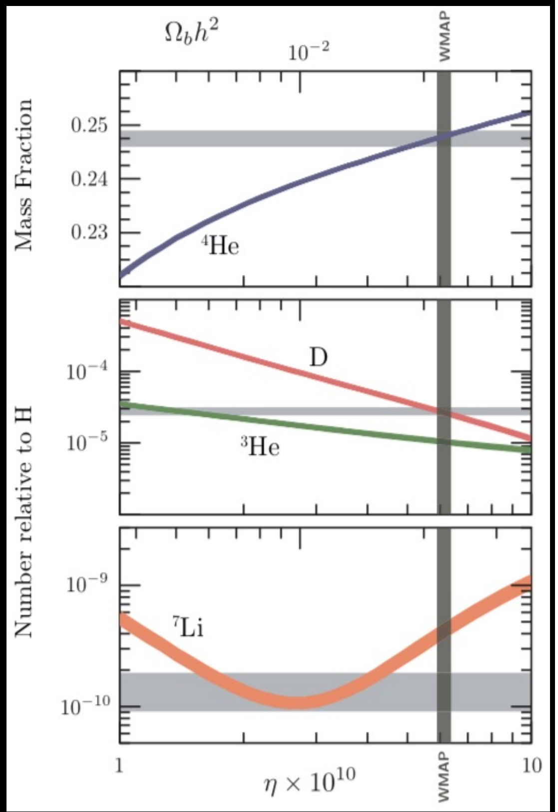
2. The abundance of light nuclei

Herman, Gamow, Alpher

The relative abundance of light elements can not be explained by stellar nucleosynthesis

1948: Alpher & Gamow computed the abundance of light elements in the context of the Big Bang theory

Light elements were produced at low temperatures (<1e9K and high densities) during several tens of minutes



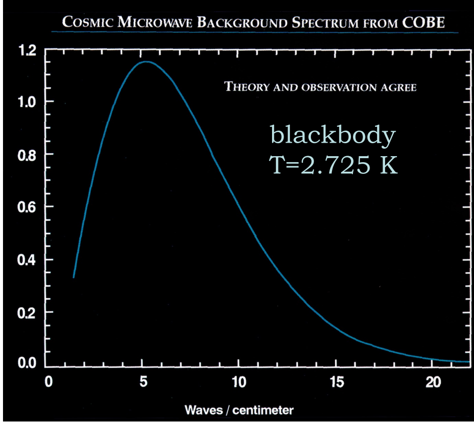
From:

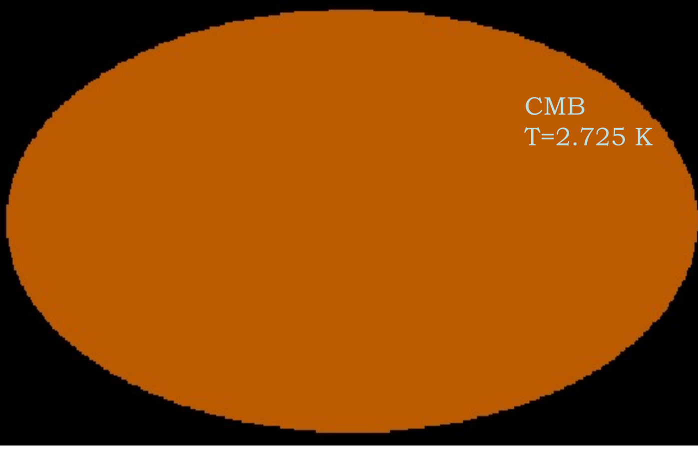
3. Cosmic Microwave Background

Penzias & Wilson

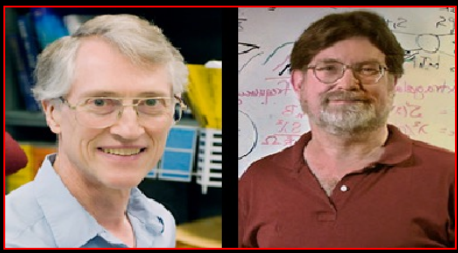
1965: Penzias & Wilson serendipitously discovered a uniform radiation (“excess”) across the sky.

This was the cosmic microwave background radiation predicted by Gamow and Alpher in 1948





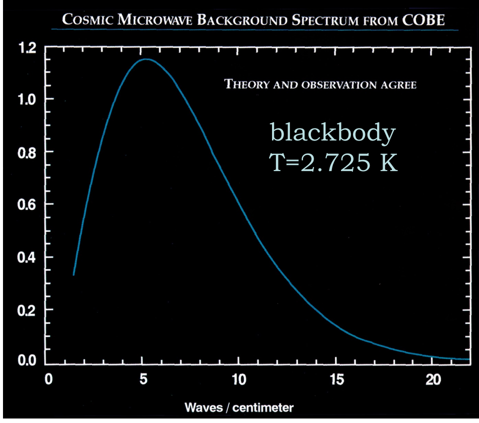
3. Cosmic Microwave Background



John Matter & George Smooth

1991: High precision measurement of CMB temperature by COBE and 1st detection of temperature fluctuations (Mather & Smoot)

2001: State of the art measurements of dT/T~1e-5 temperature fluctuations by WMAP



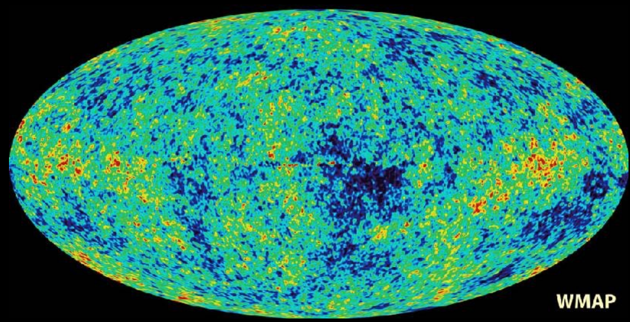
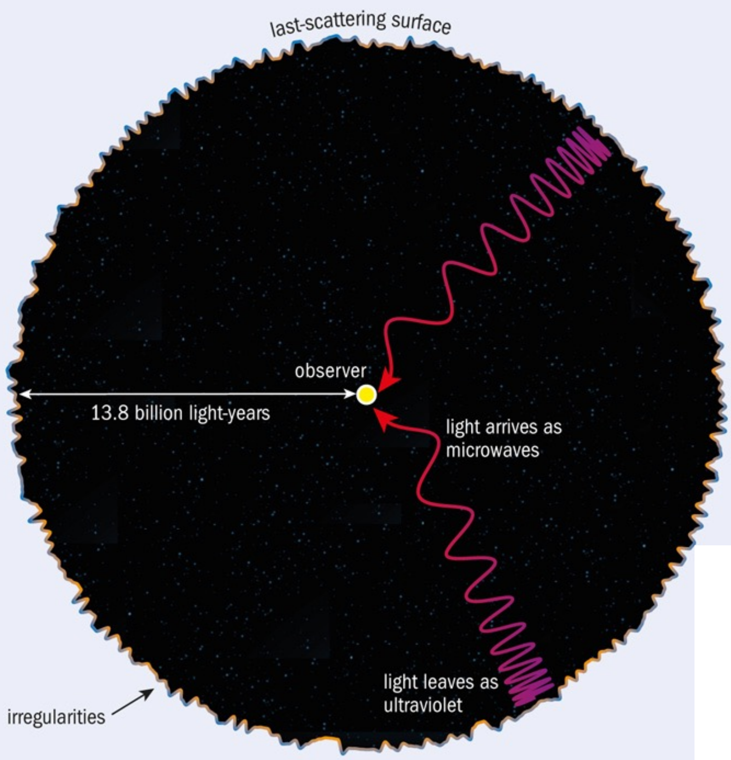
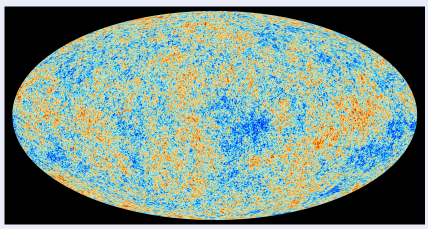


Fig. credits: NASA / WMAP Science Team

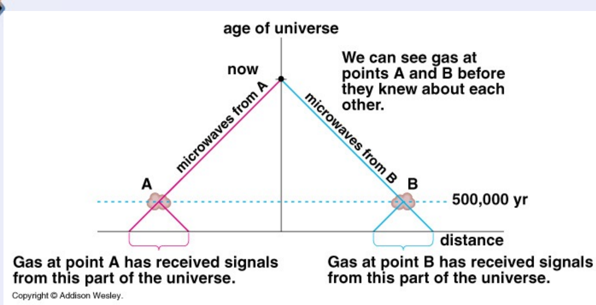
CMB: the last scattering surface

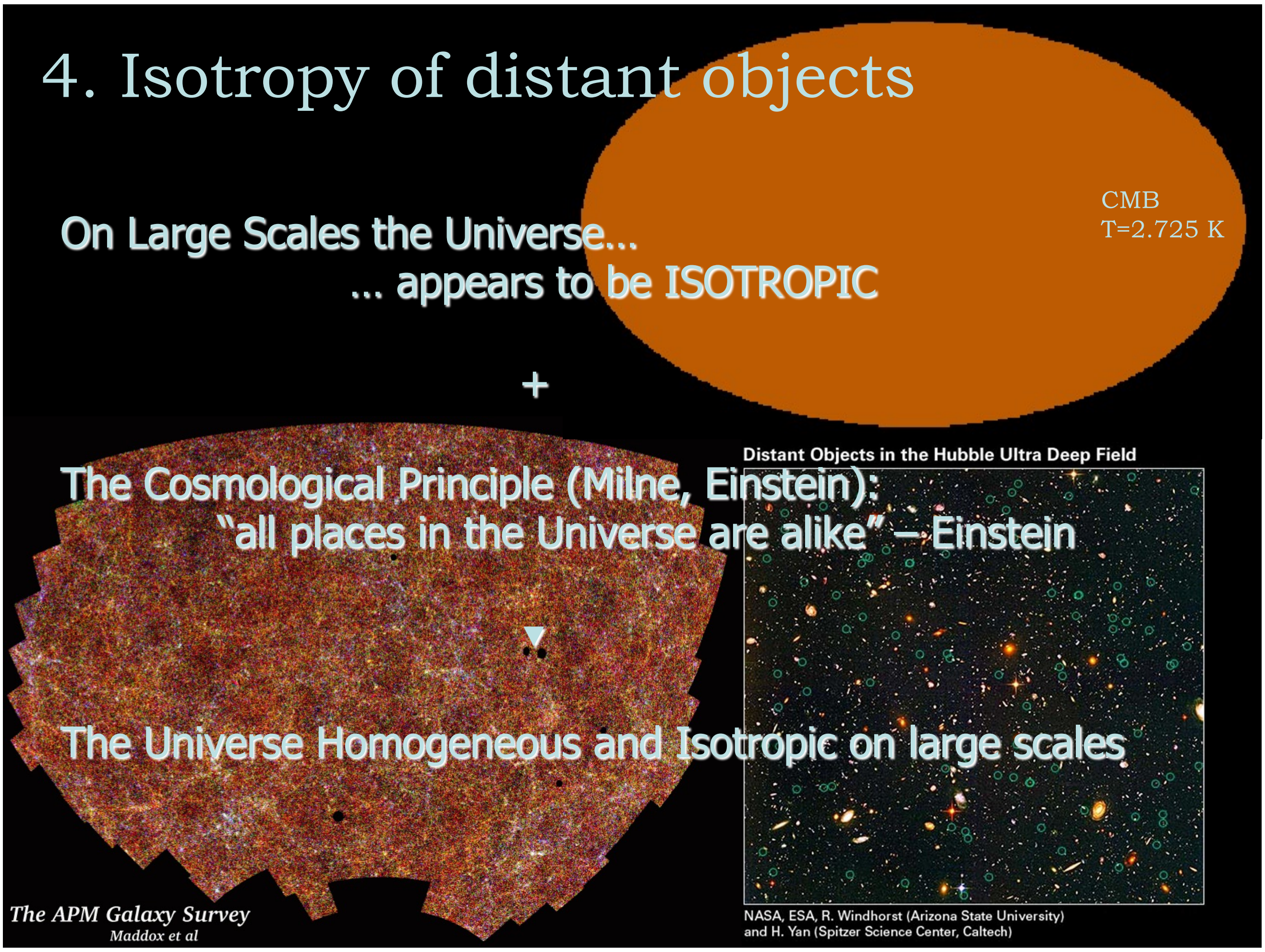
Reprinted from:
http://physicsworld.com/cws/article/indepth/2014/jan/09/planck-perspectives





Planck





4. Isotropy of distant objects

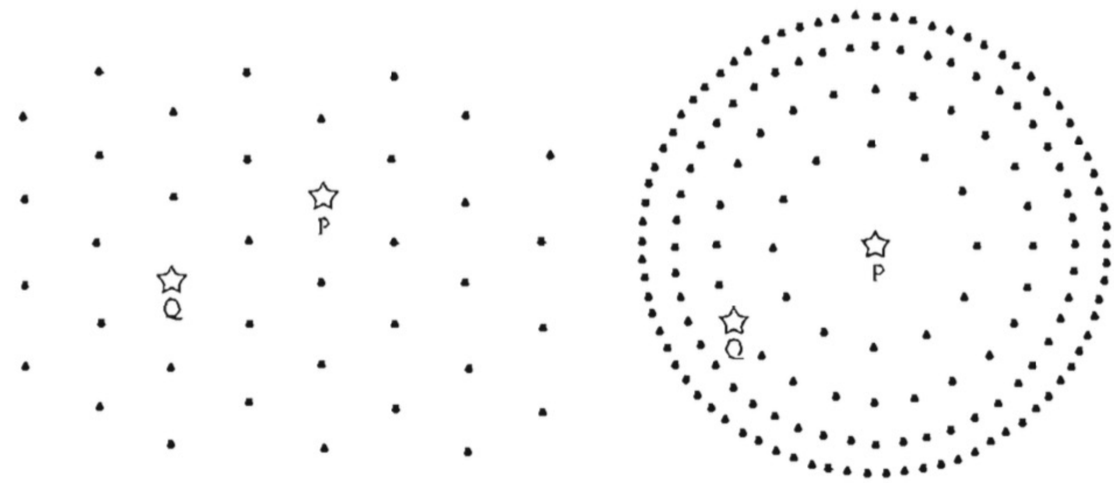
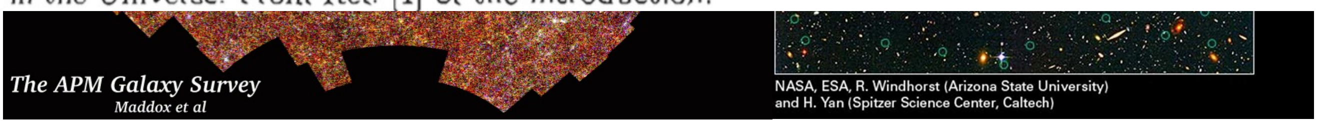


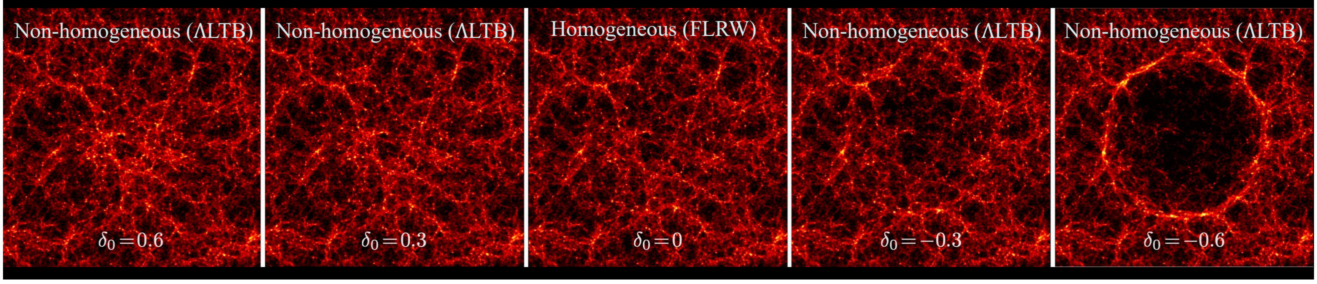
Fig. 3.1 A point distribution, statistically isotropic around every point (left) and around a unique point (P) (right). In the second version, P and Q are not equivalent. The cosmological principle excludes such kinds of solutions, which would assume that we lie in a special place in the Universe. From Ref. [1] of the introduction.

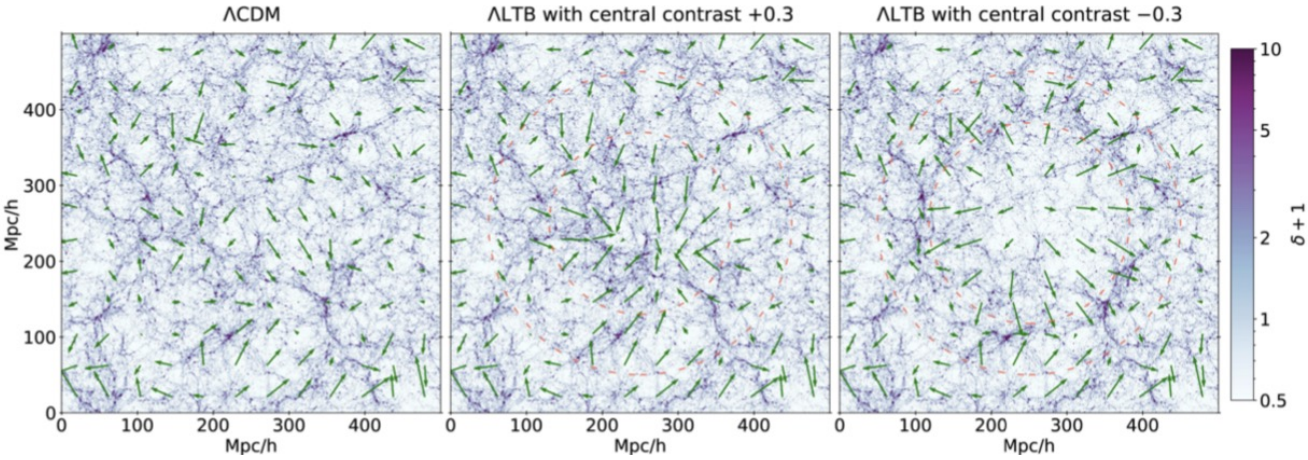


4. Isotropy of distant objects

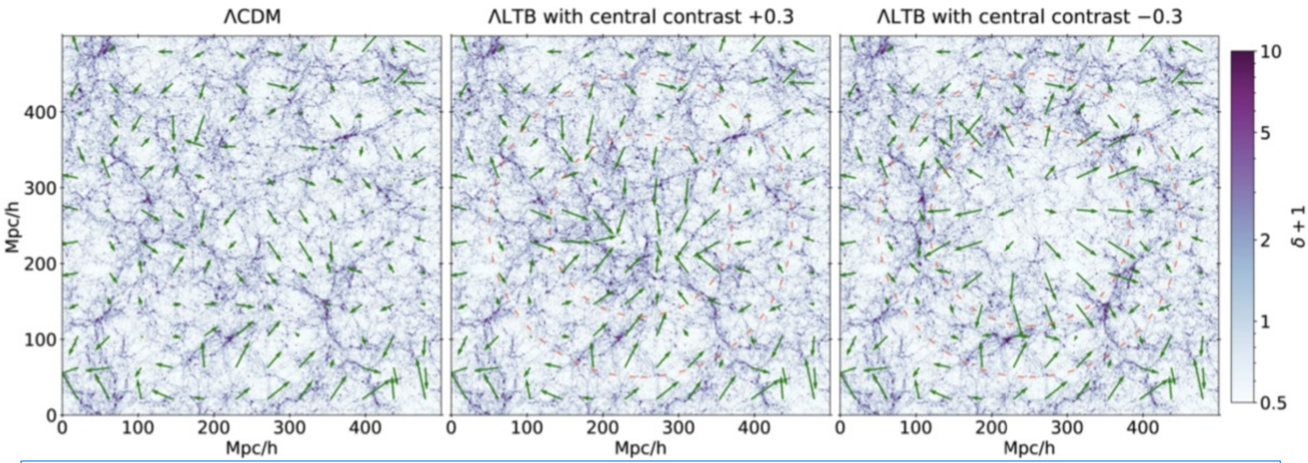
Testing the Cosmological Principle: Behomo simulations, V. Marra

https://valerio-marra.github.io/BEHOMO-project/





4. Isotropy of distant objects



Homogeneous (FLRW / ΛCDM):

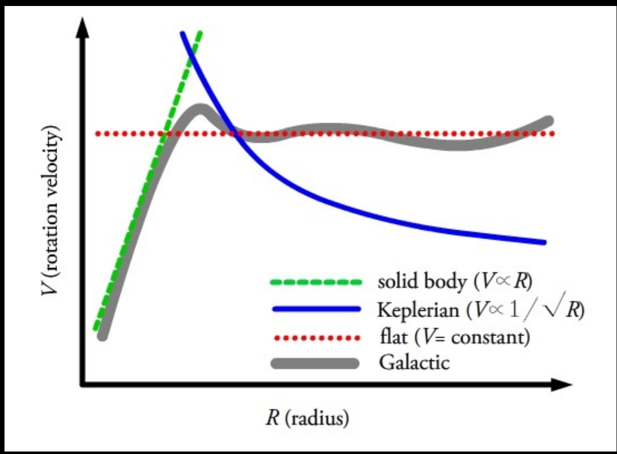
$$ds^2 = c^2dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2\left(d\theta^2 + \sin^2\theta d\phi^2\right)\right] \qquad a(t) \qquad H = \frac{\dot{a}}{a}$$

Non-homogeneous (ΛLTB):

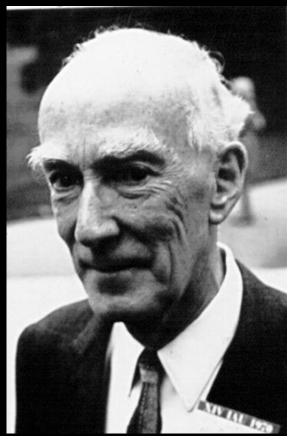
$$ds^2 = -c^2dt^2 + \frac{R'^2(t,r)}{1-K(r)r^2}dr^2 + R^2(t,r)\left(d\theta^2 + \sin^2\theta\, d\phi^2\right) \qquad a_\perp = R(r,t)/r, \qquad a_\| = R'(r,t)$$

$$H_\perp \equiv \frac{\dot{a_\perp}}{a_\perp}, \qquad H_\| \equiv \frac{\dot{a_\|}}{a_\|}$$

5. The existence of Dark Matter



From:



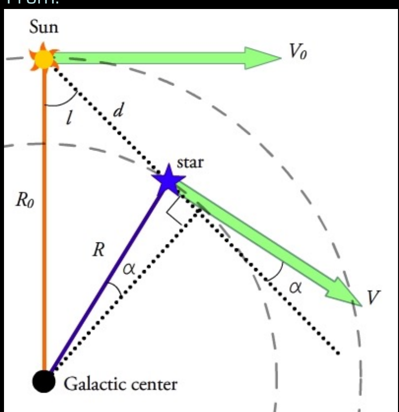
Jan Oort

1927: Jan Oort studies the rotation of stars in our galaxy and infers that their rotation is not consistent with Keplerian motion.

$$v_{circ} = \sqrt{\frac{GM(R)}{r}}$$

5. The existence of Dark Matter

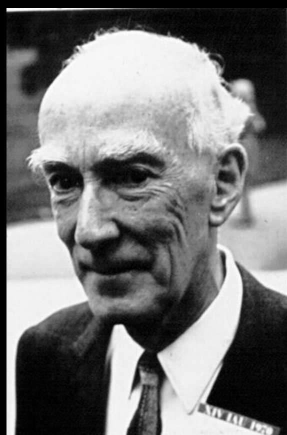
From:



Oorts constants:

$$A \equiv -\frac{1}{2}\left[\frac{dV_c}{dR}\Big|_{R_0} - \frac{V_{c,0}}{R_0}\right]$$

$$B \equiv -\frac{1}{2}\left[\frac{dV_c}{dR}\Big|_{R_0} + \frac{V_{c,0}}{R_0}\right]$$



Circular motion:

$$v_{circ} = \sqrt{\frac{GM(R)}{r}}$$

If the whole mass is mostly at the centre: *vcir ^ 2 ~ 1/r*

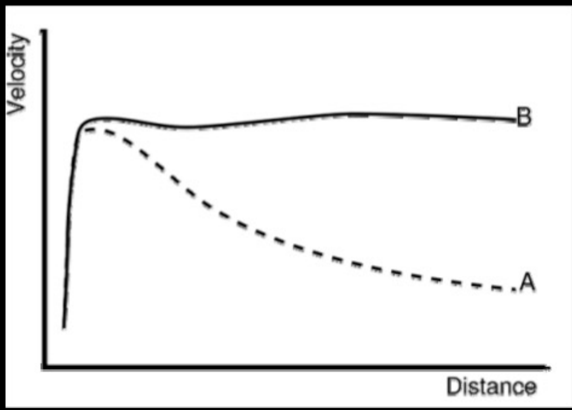
Observations vs Keplerian motion:

- Kepler. motion: (A-B)/(A+B) = 2
- Observations : (A-B)/(A+B) = 5

-Mass is not concentrated at the centre
-Non-luminous mass is required

http://icc.dur.ac.uk/~tt/Lectures/Galaxies/TeX/lec/node42.html

5. The existence of Dark Matter



B: Observations

A: theoretical expectations

1980: Vera Rubin and others also find that stars rotate too fast in the outskirts of spiral galaxies to remain bound assuming that gravity is produced only by visible matter.

5. The existence of Dark Matter

Fritz Zwicky

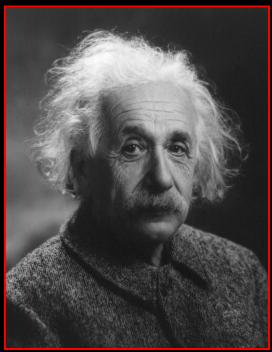
1936: Fritz Zwicky applied the Virial theorem to the velocities of galaxies in the Coma cluster and finds very high mass-to-light ratios, $\Upsilon = M/L$, for them to remain bound: $\Upsilon_{coma}/\Upsilon_{sun} = 500 \gg$ 2-10 for galaxies.

- Virial theorem (for gravitationally relaxed systems): $2\bar{E}_k + \bar{E}_p = 0$
- Mass from the virial theorem: $M_V = < v^2 >< R >/G$
- Visible luminous Mass: $M_L = N_g \, \Upsilon_g \, L_g$

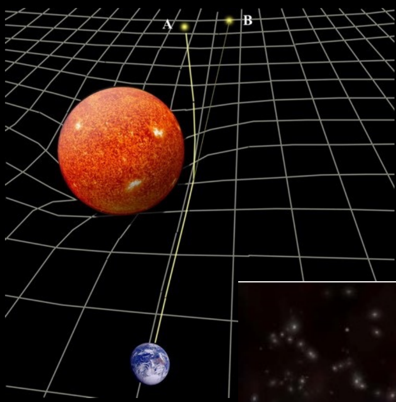
(N_g - number of galaxies; Υ_g - galaxy mass-to-light ratio; L_g galaxy luminosity)

5. The existence of Dark Matter

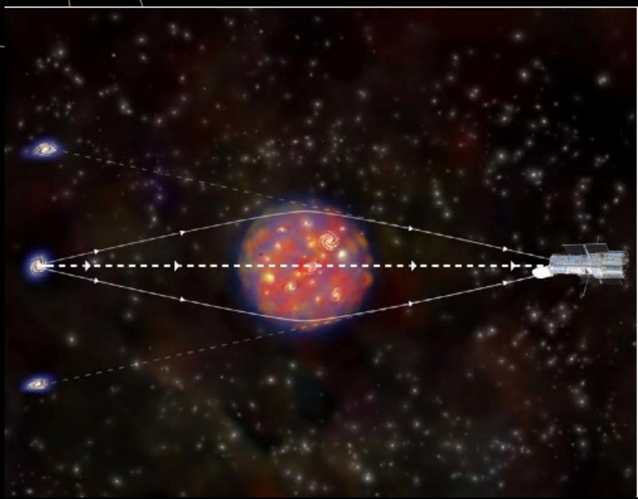
lensing effects:



Albert Einstein



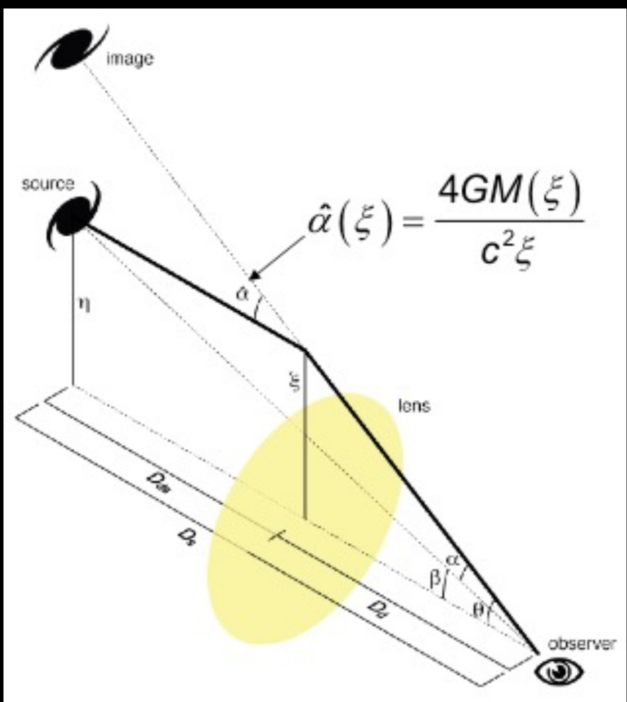
$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$



From:

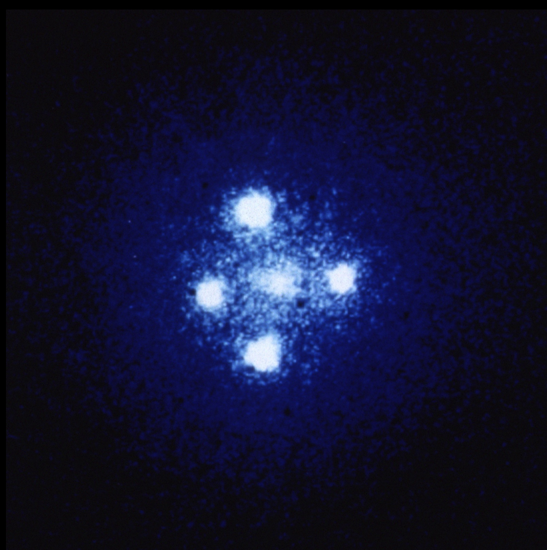
5. The existence of Dark Matter

lensing effects:



From:

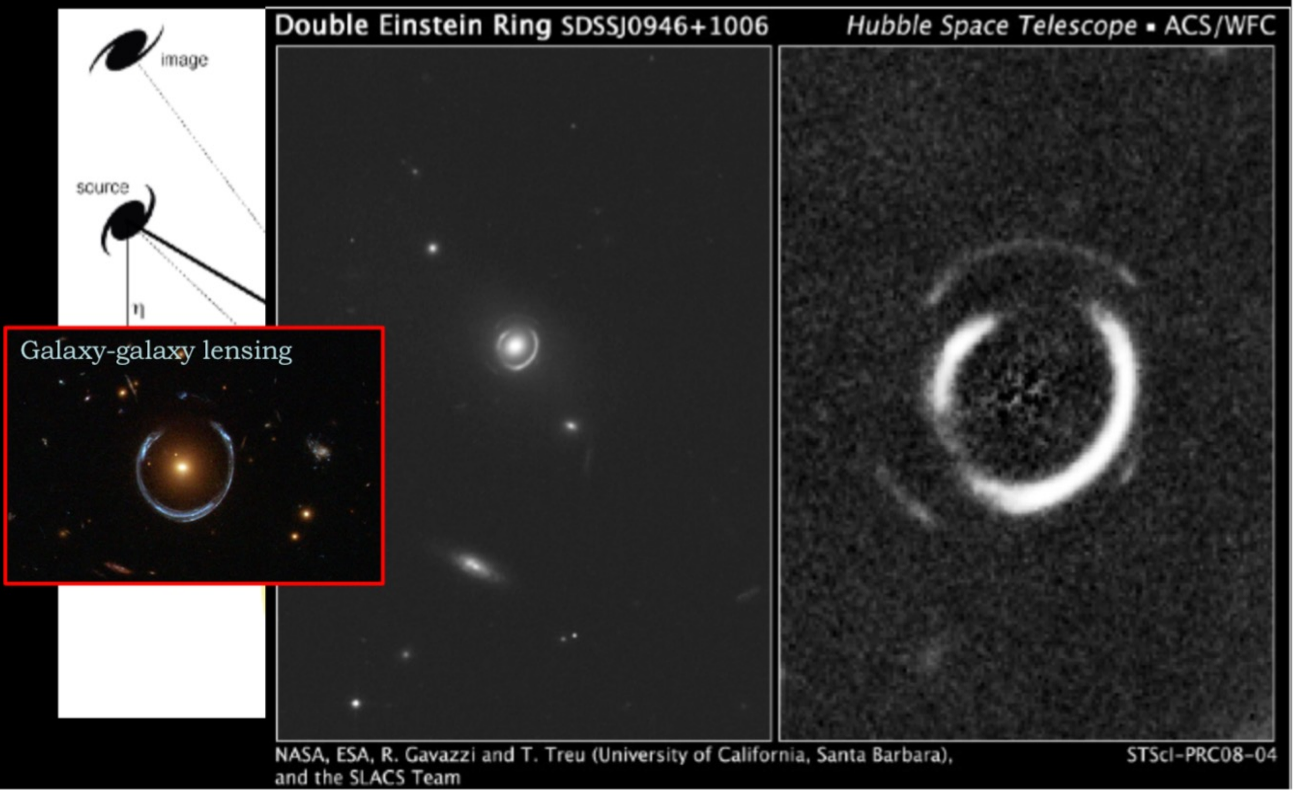
Strong lensing



5. The existence of Dark Matter

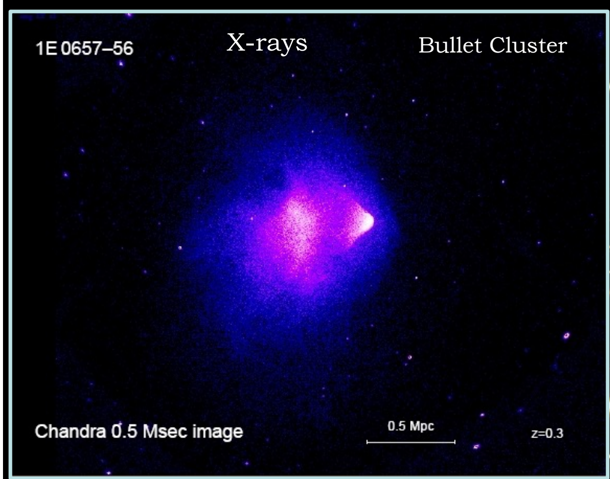
lensing effects: strong lensing

Einstein Rings

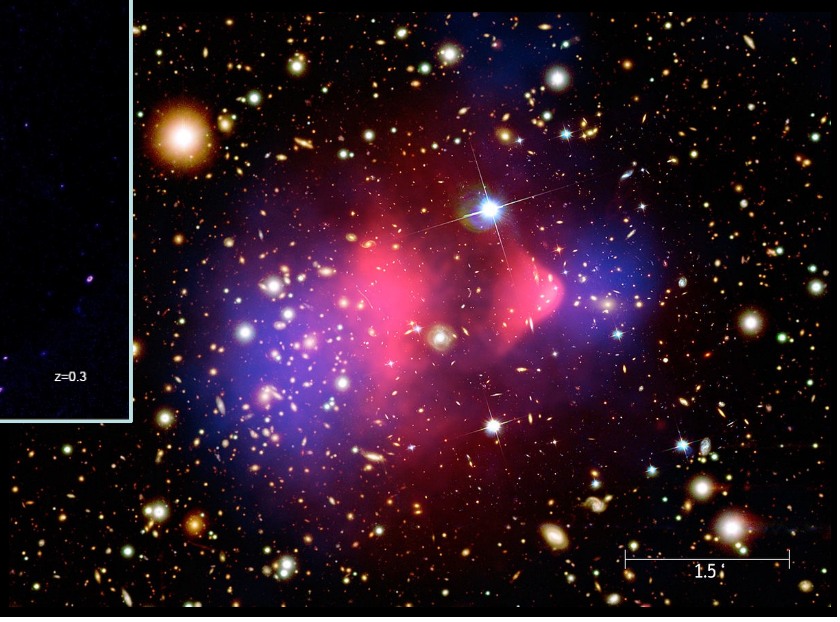


5. The existence of Dark Mater

2003: X-ray (produced by extremely hot gas – in red) vs weak lensing observations (probing the total mass distribution in blue) of the Bullet Cluster put in evidence that galaxy clusters must contain "dark matter"



X-rays + lensing + visible



Refs:
astro-ph/0309303
astro-ph/0312273

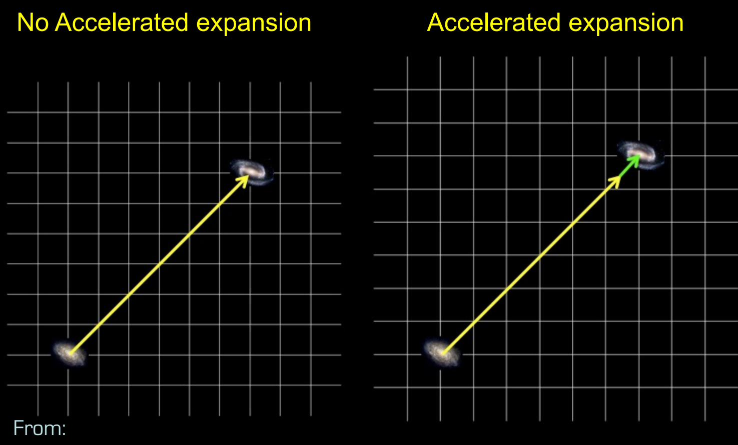
6. Cosmic expansion is accelerating

1998: S. Perlmutter and the supernova Cosmology project found first evidence for the accelerated expansion of the Universe.

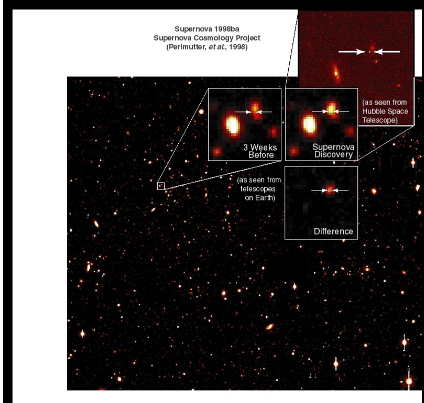
assuming supernovae are standard candles, they appear further away (green arrow) then predicted by non-accelerating expansion models (yellow arrow).

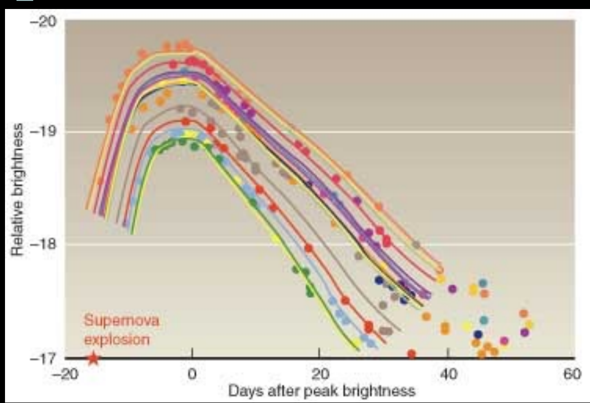
$$d(t) = a(t)\, d_0$$

with $\ddot{a}(t) > 0$



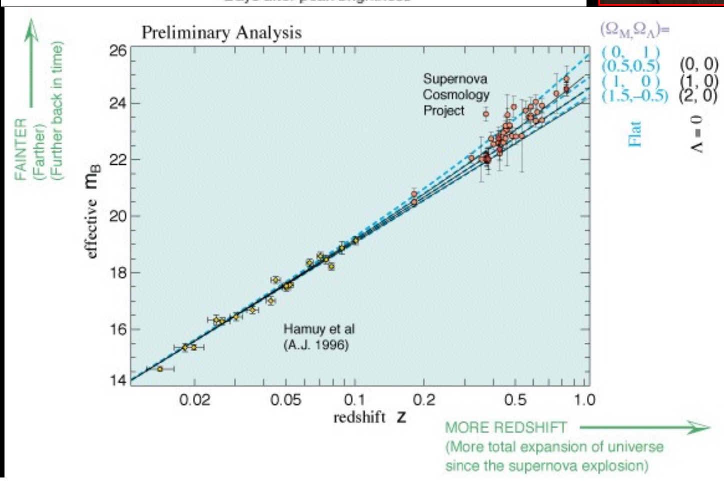
6. Cosmic expansion is accelerating



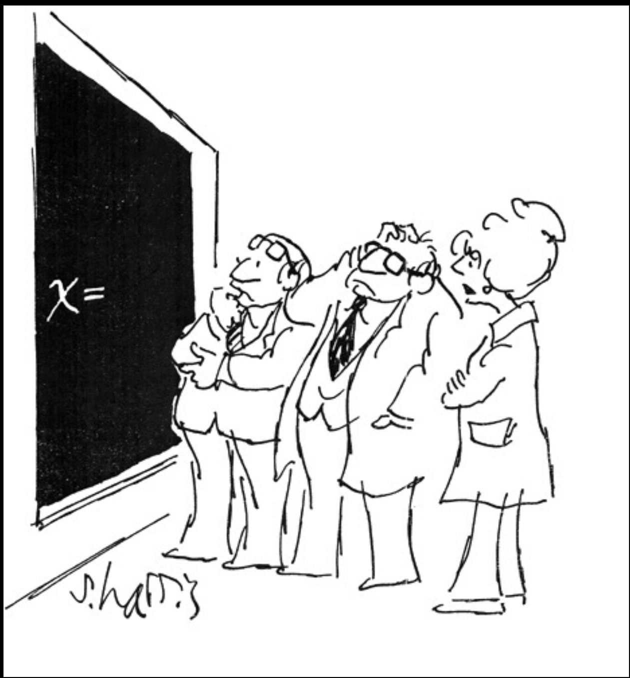


Cosmological redshift:

$$z = \frac{E - E_0}{E_0} = \\ = \frac{\nu}{\nu_0} - 1 = \\ = \frac{\lambda_0}{\lambda} - 1 = \\ = \frac{a_0}{a} - 1$$



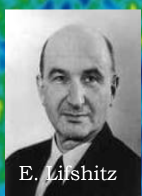
How Cosmological structure forms and evolves?

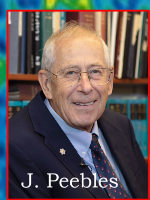


- Observations indicate that
  - on small scales the universe is NOT homogeneous and isotropic
  - On large cosmological scales the Universe does not show indications of strong anisotropies. Together with the cosmological principle this implies the universe is highly homogeneous and isotropic
  - However it shows small anisotropies in the CMB.

How structure forms and evolves?

Structures should grow due to
Gravitational Instability (Jeans, Lifshitz,…)



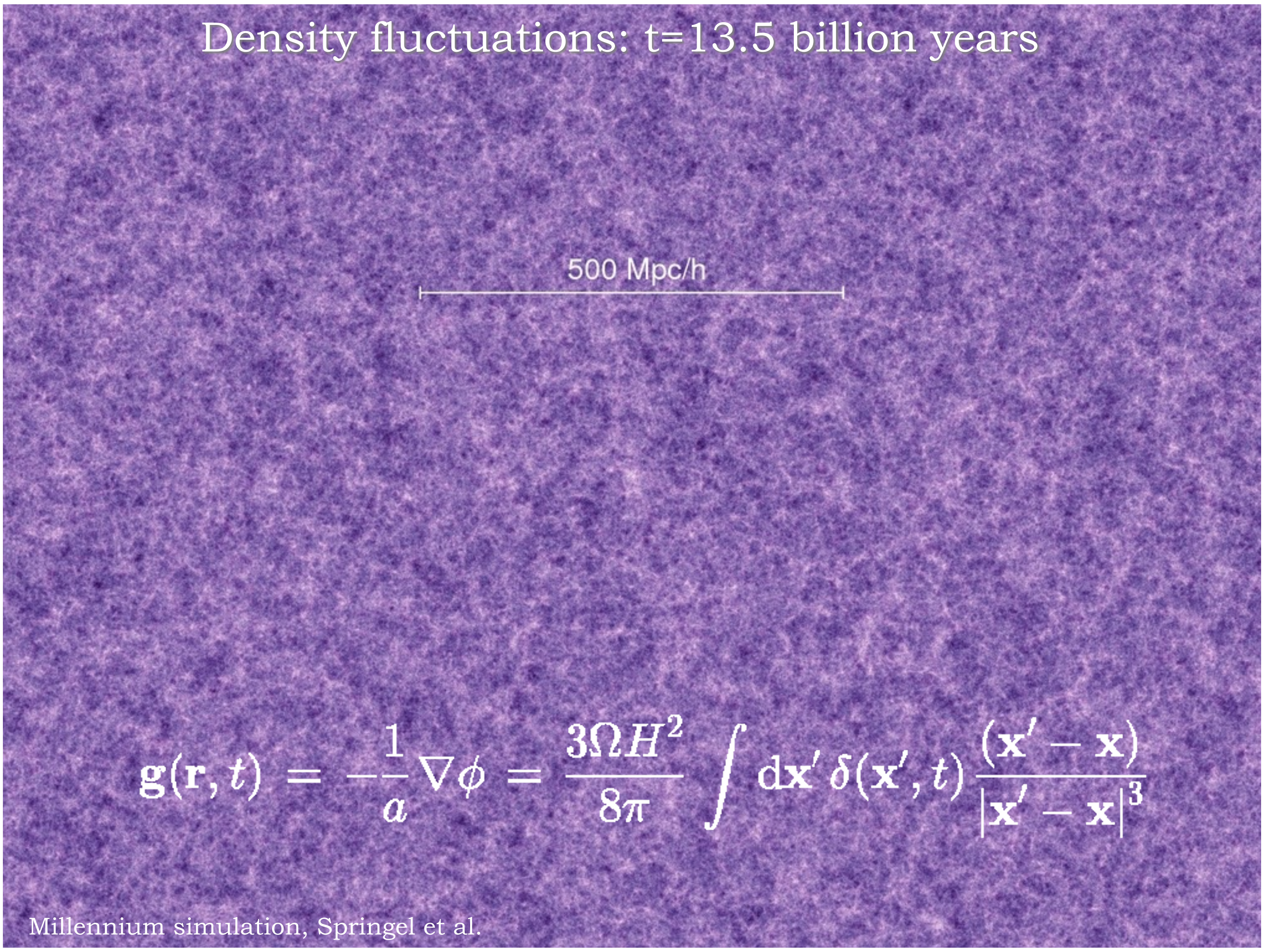


$$\mathbf{g}(\mathbf{r},t) = -\frac{1}{a}\nabla\phi = \frac{3\Omega H^2}{8\pi}\int \mathrm{d}\mathbf{x}'\,\delta(\mathbf{x}',t)\,\frac{(\mathbf{x}'-\mathbf{x})}{|\mathbf{x}'-\mathbf{x}|^3}$$

Density fluctuations: t=13.7 billion years

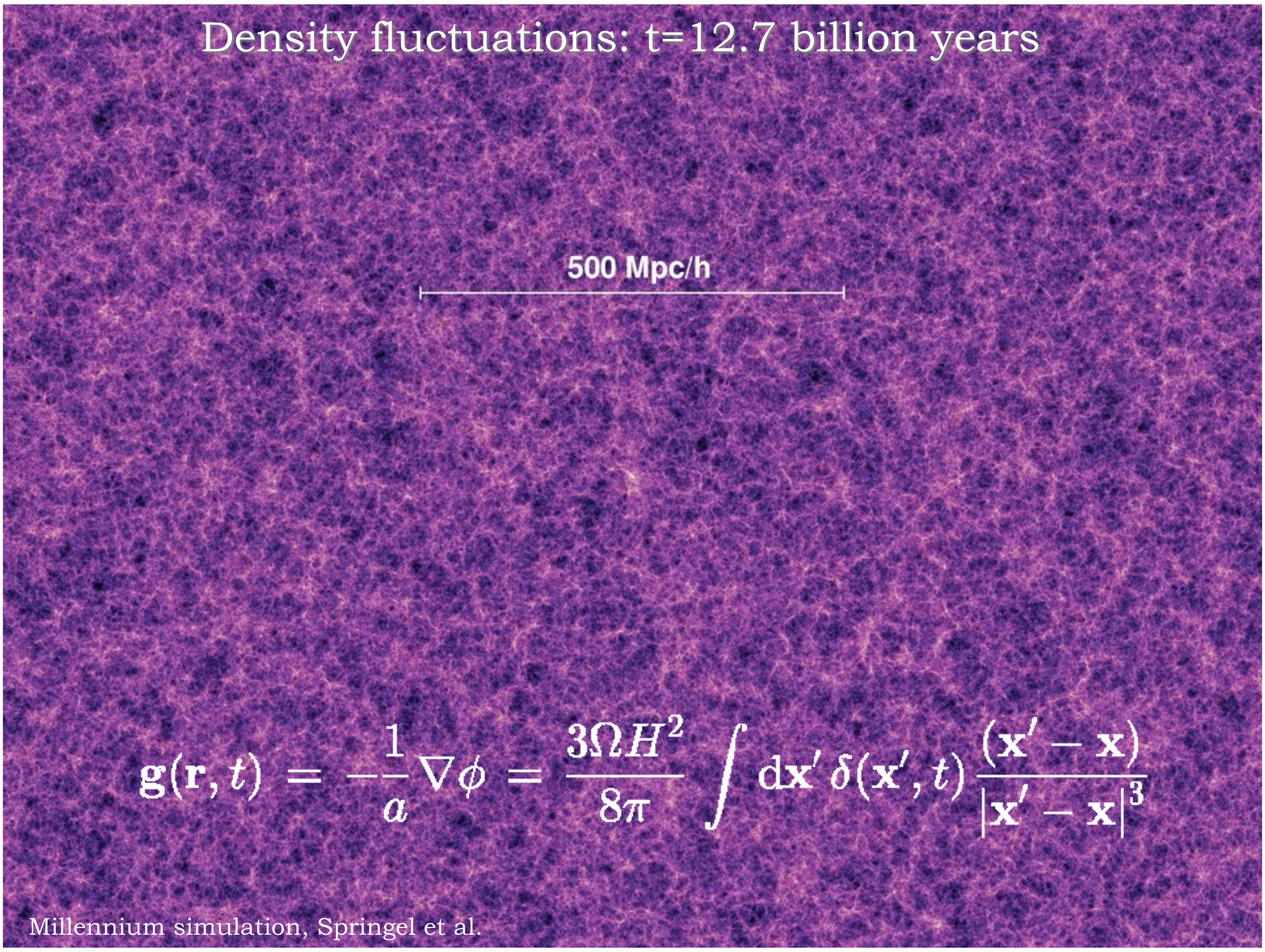
$$\mathbf{g}(\mathbf{r},t) = -\frac{1}{a}\nabla\phi = \frac{3\Omega H^2}{8\pi}\int \mathrm{d}\mathbf{x}'\,\delta(\mathbf{x}',t)\,\frac{(\mathbf{x}'-\mathbf{x})}{|\mathbf{x}'-\mathbf{x}|^3}$$

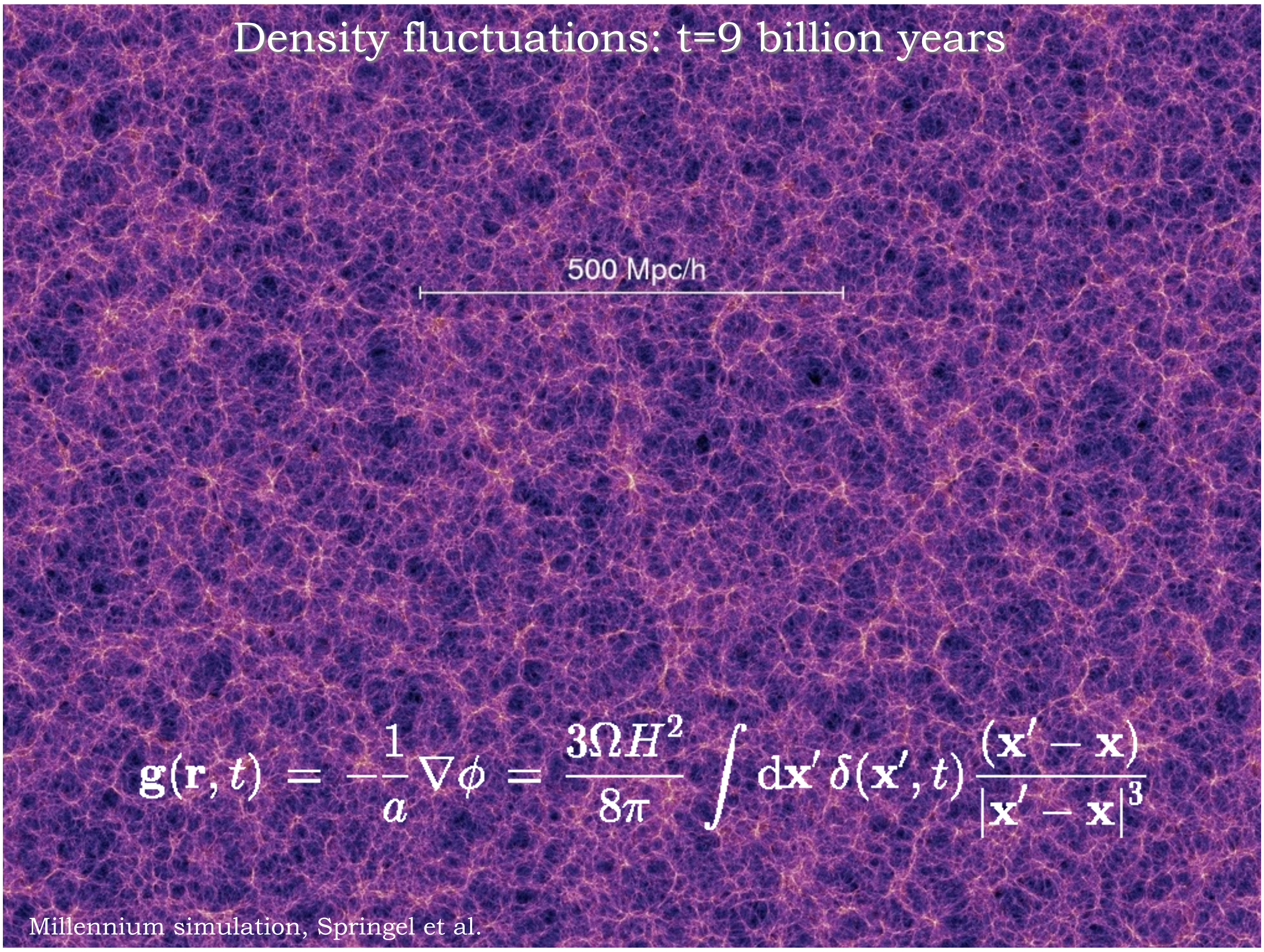
Density fluctuations: t=13.5 billion years

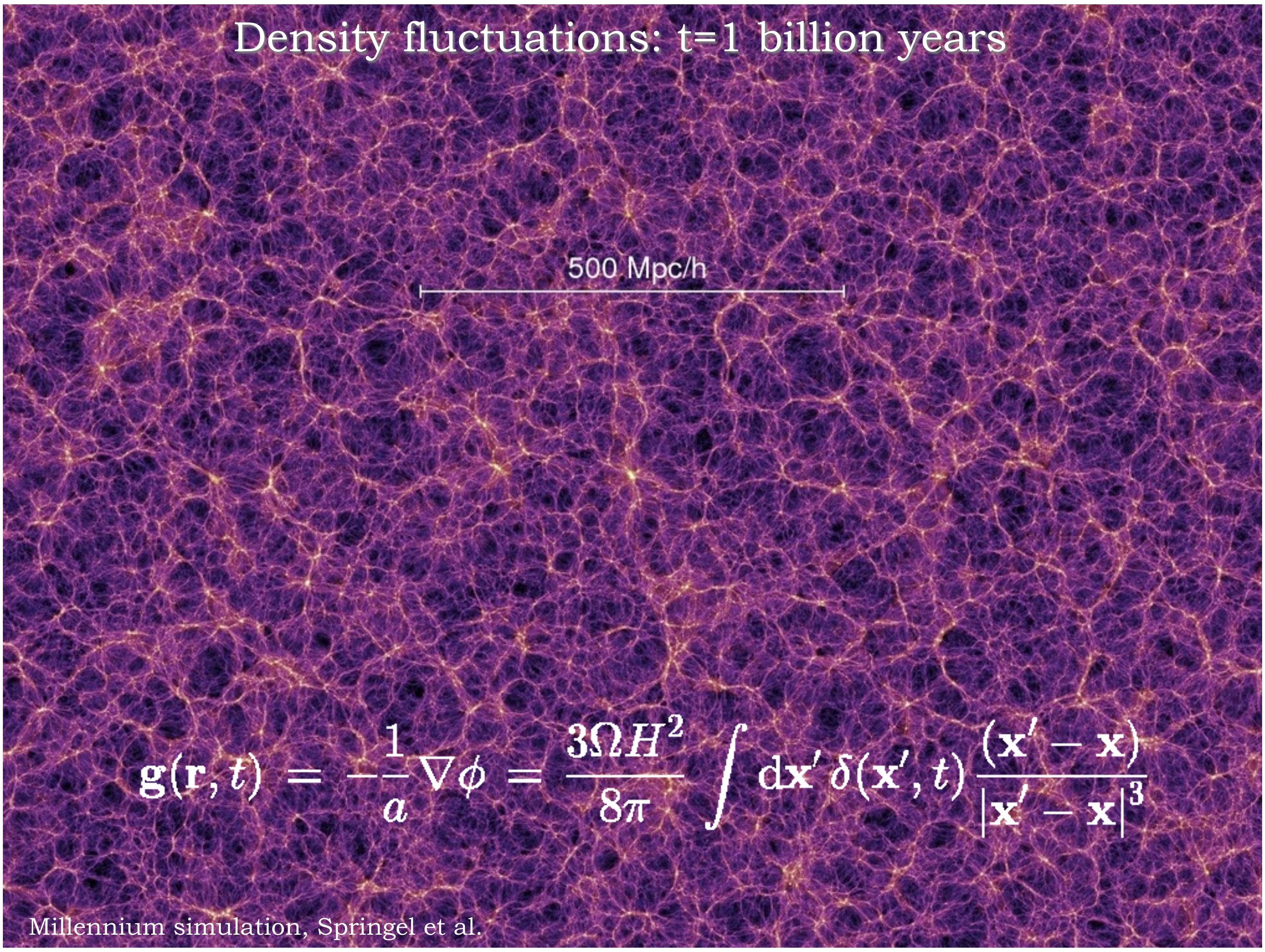


$$\mathbf{g}(\mathbf{r},t) = -\frac{1}{a}\nabla\phi = \frac{3\Omega H^2}{8\pi}\int \mathrm{d}\mathbf{x}'\,\delta(\mathbf{x}',t)\,\frac{(\mathbf{x}'-\mathbf{x})}{|\mathbf{x}'-\mathbf{x}|^3}$$

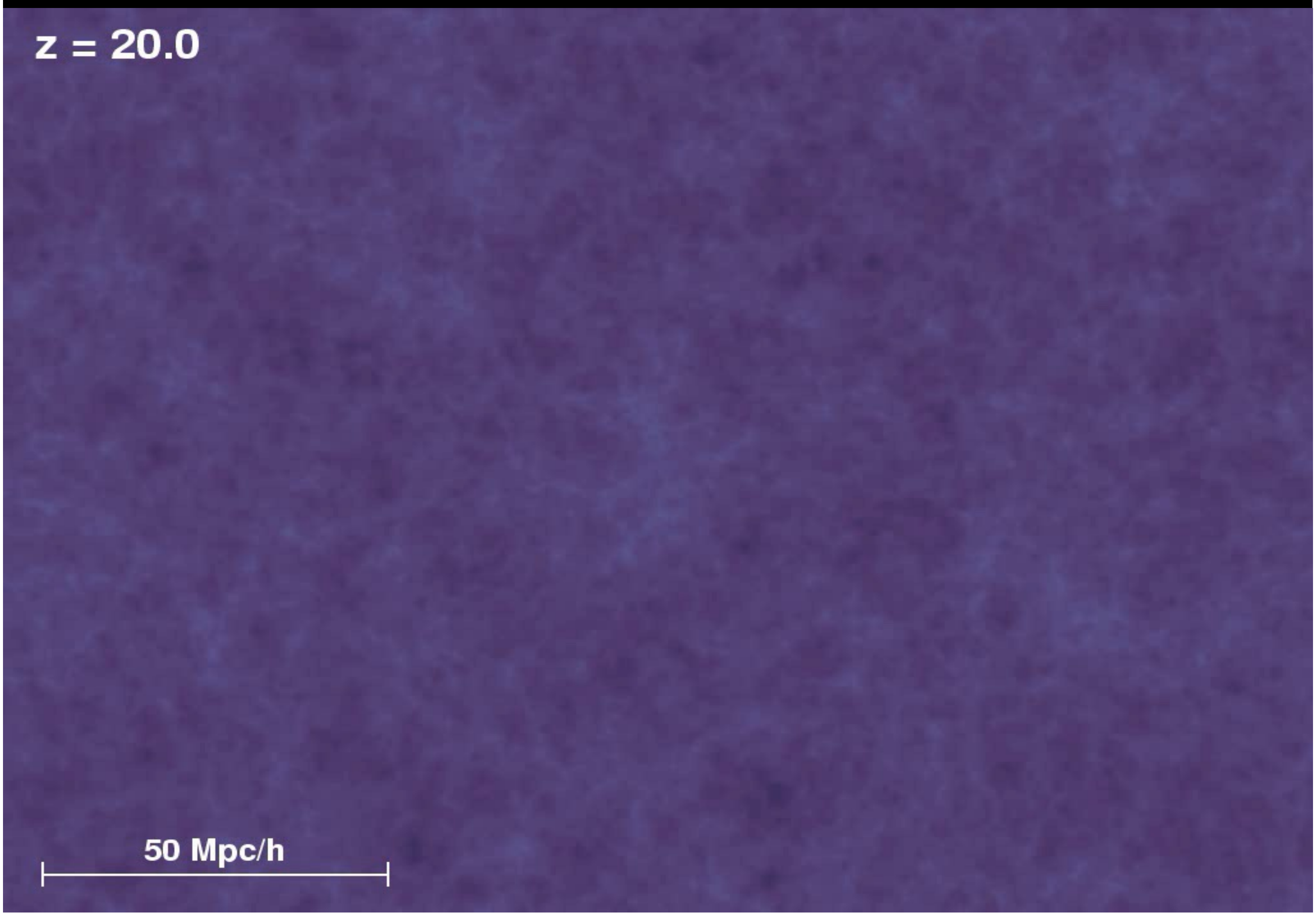
Millennium simulation, Springel et al.


Density fluctuations: t=12.7 billion years
500 Mpc/h
$\mathbf{g}(\mathbf{r},t) = -\frac{1}{a}\nabla\phi = \frac{3\Omega H^2}{8\pi}\int \mathrm{d}\mathbf{x}'\,\delta(\mathbf{x}',t)\,\frac{(\mathbf{x}'-\mathbf{x})}{|\mathbf{x}'-\mathbf{x}|^3}$
Millennium simulation, Springel et al.

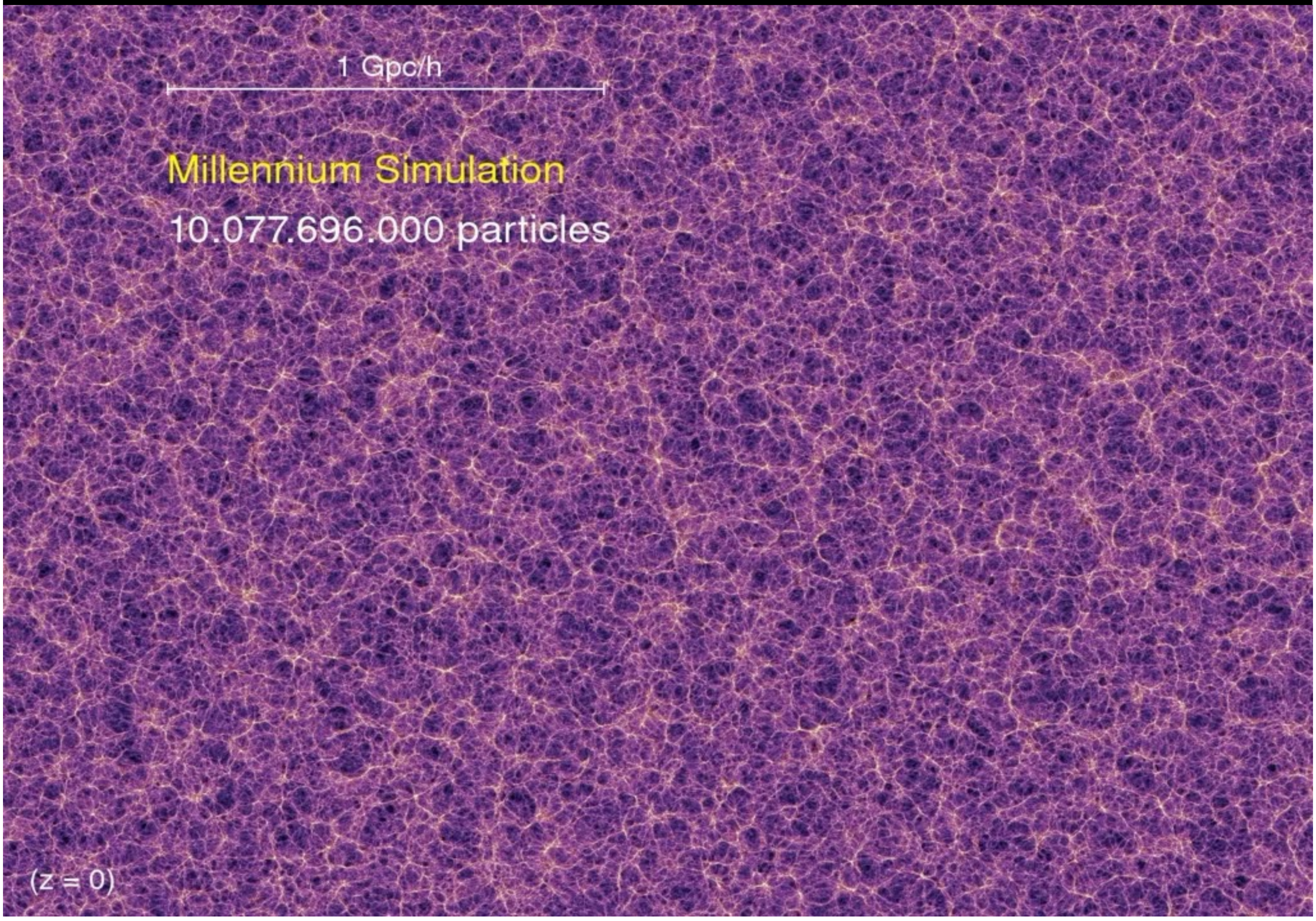

Density fluctuations: t=9 billion years
500 Mpc/h
$\mathbf{g}(\mathbf{r},t) = -\frac{1}{a}\nabla\phi = \frac{3\Omega H^2}{8\pi}\int \mathrm{d}\mathbf{x}'\,\delta(\mathbf{x}',t)\,\frac{(\mathbf{x}'-\mathbf{x})}{|\mathbf{x}'-\mathbf{x}|^3}$
Millennium simulation, Springel et al.



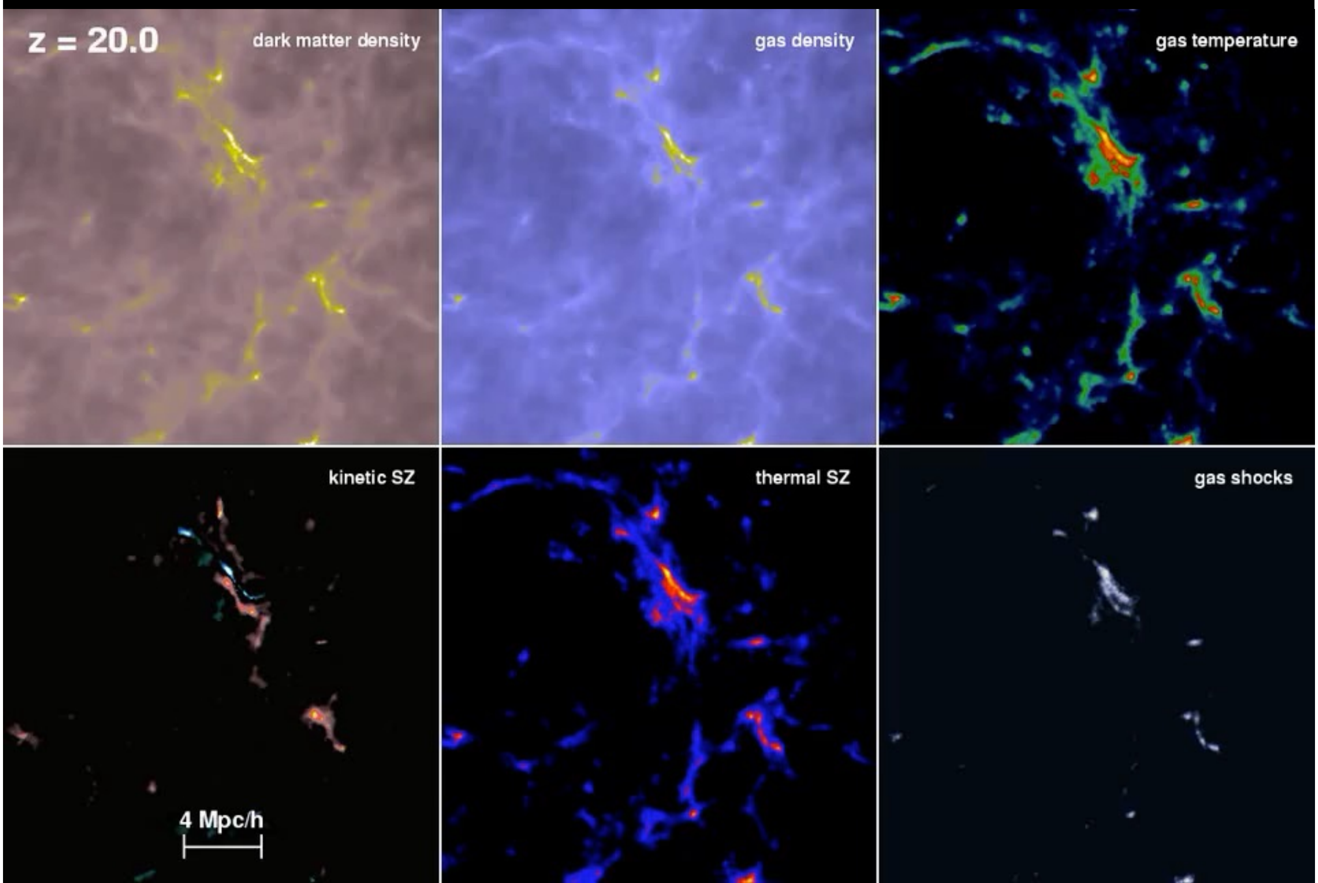
Cosmological structure formation



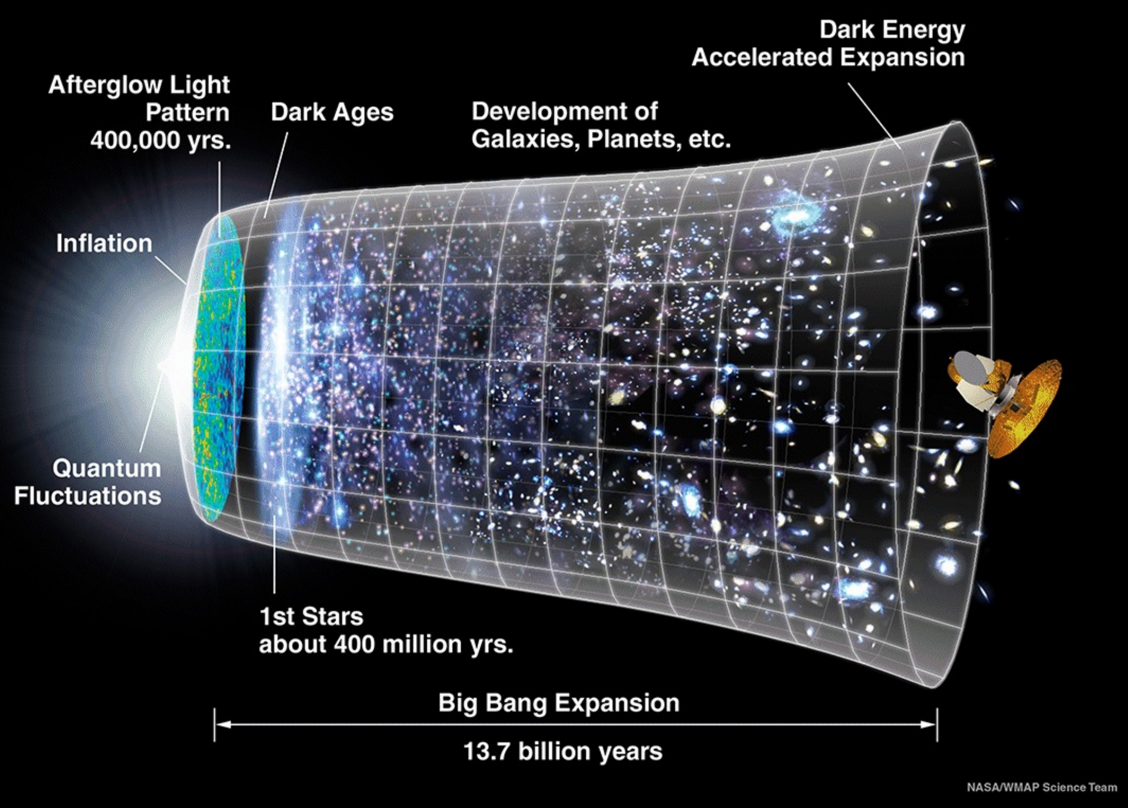
Large Scale Structure (LSS)



Large Scale Structure (LSS)



The history of the Universe:



The history of the Universe:

Fig. credits: Baumann, Cosmology , C.U.P. 2022.