The standard model of cosmology: the ΛCDM component

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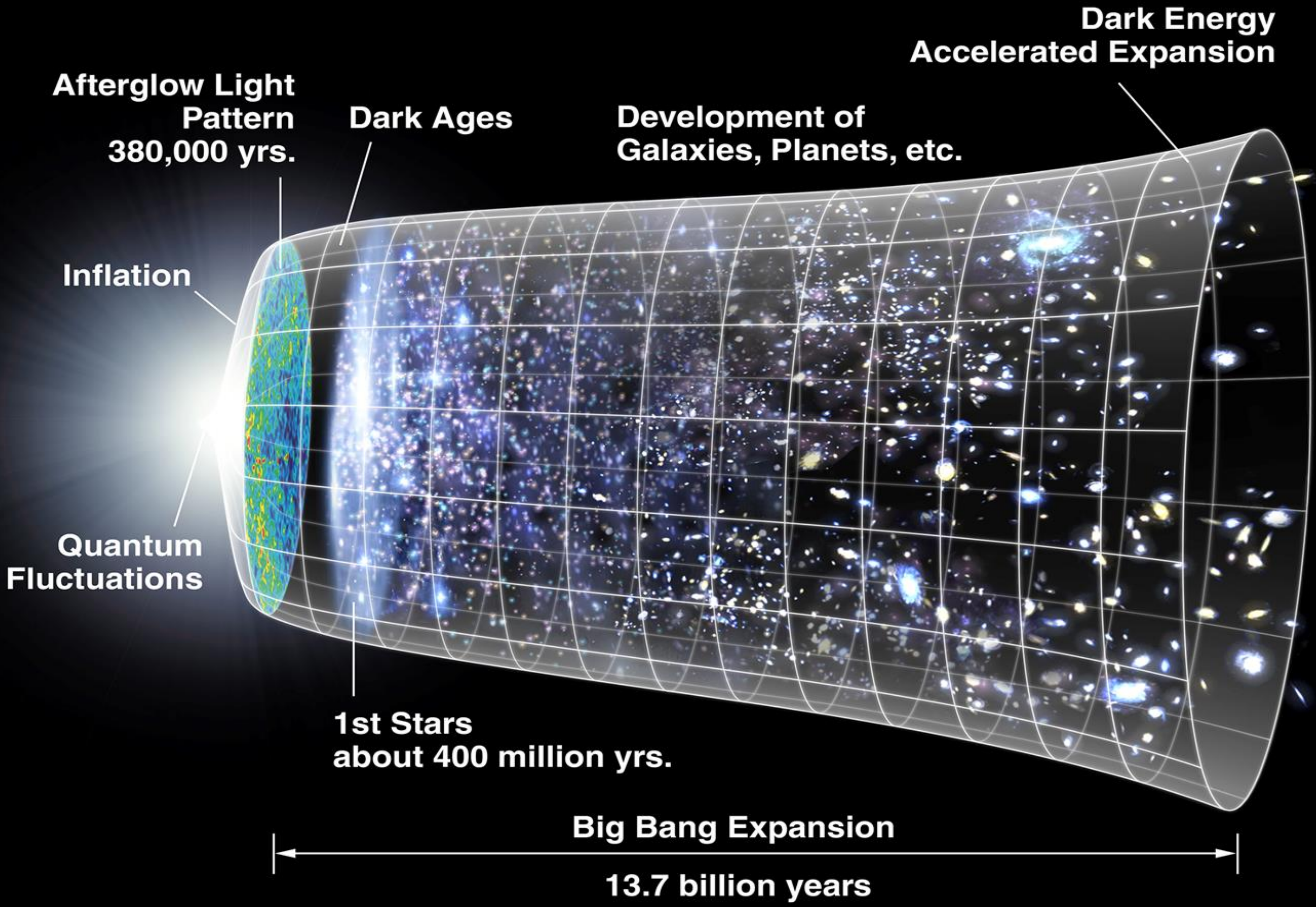
Faculty of Physical Sciences, University of Iceland

ISAPP 2021 Madrid: “Gamma rays to shed light on dark matter”, June 2021

Timeline of the Universe



Andromeda

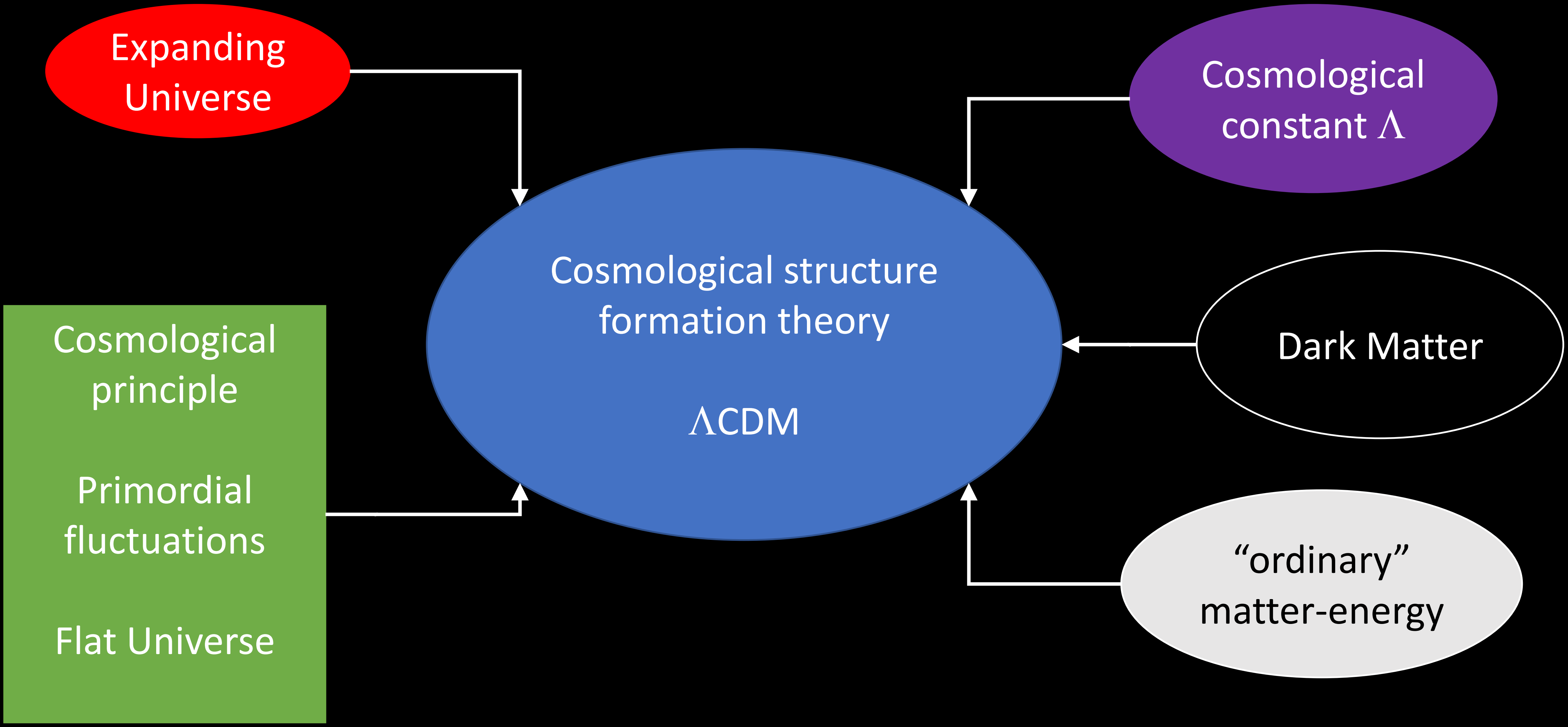
A perspective on the ΛCDM model:

- The notion of a Standard Cosmological Model can be split into two regimes with the epoch of recombination/photon-decoupling as the threshold:
  - Early-Universe Cosmology: some elements discussed in this talk
  - Late-Universe Cosmology: mostly discussed in my 2nd talk (Wed. 23rd)

- The ΛCDM model is a component of the Standard Cosmological model.
  It is a structure formation theory with an “effective parametrization” of its fundamental ingredients:
  - it is essential to explain key observables of the Early-Universe
  - it is (still) sufficient to explain (broadly) the Late-Universe (no extra parameters needed)

- In this perspective, the ΛCDM model is not a complete theory since it does not address the nature of its fundamental ingredients.

Main ingredients and principles of the ΛCDM model



Expanding Universe

Cosmological constant Λ

Cosmological structure formation theory

ΛCDM

Dark Matter

Cosmological principle

Primordial fluctuations

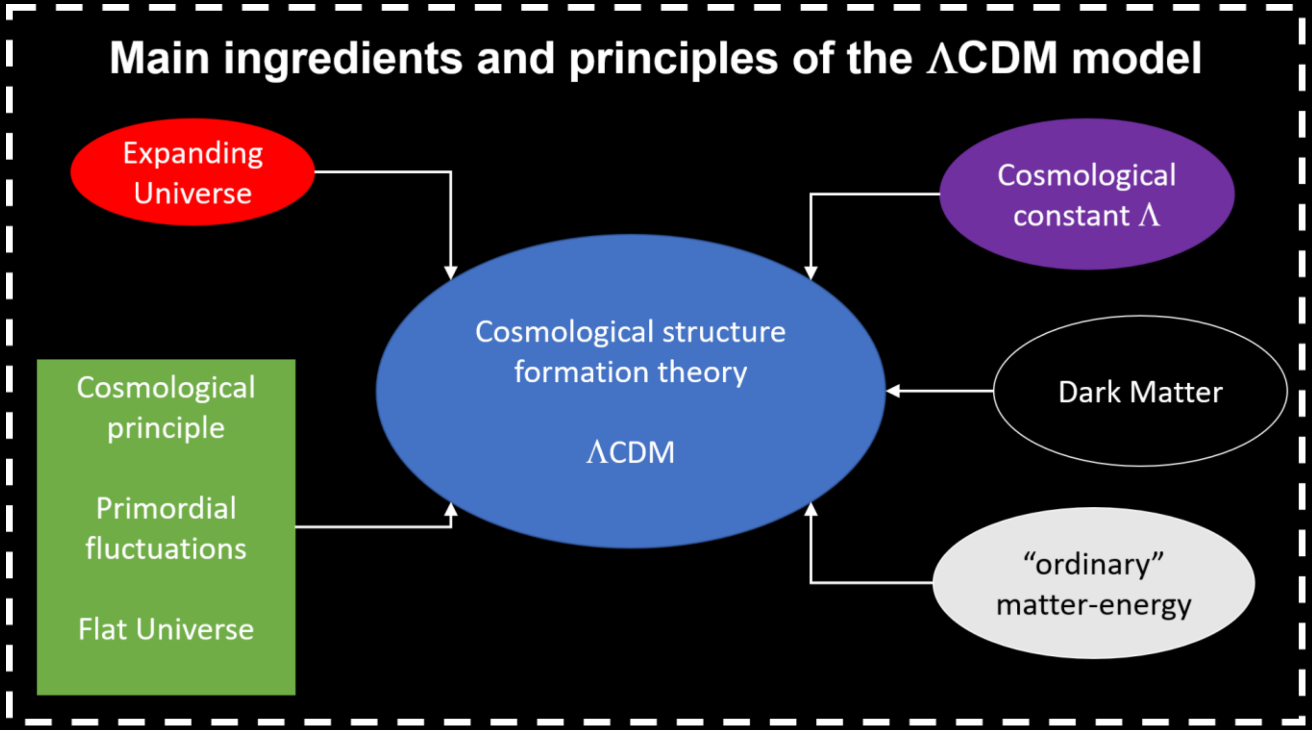
Flat Universe

“ordinary” matter-energy

(Towards) the standard model of cosmology

Big Bang

Inflation



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“ordinary” matter-energy

Vacuum energy density
??

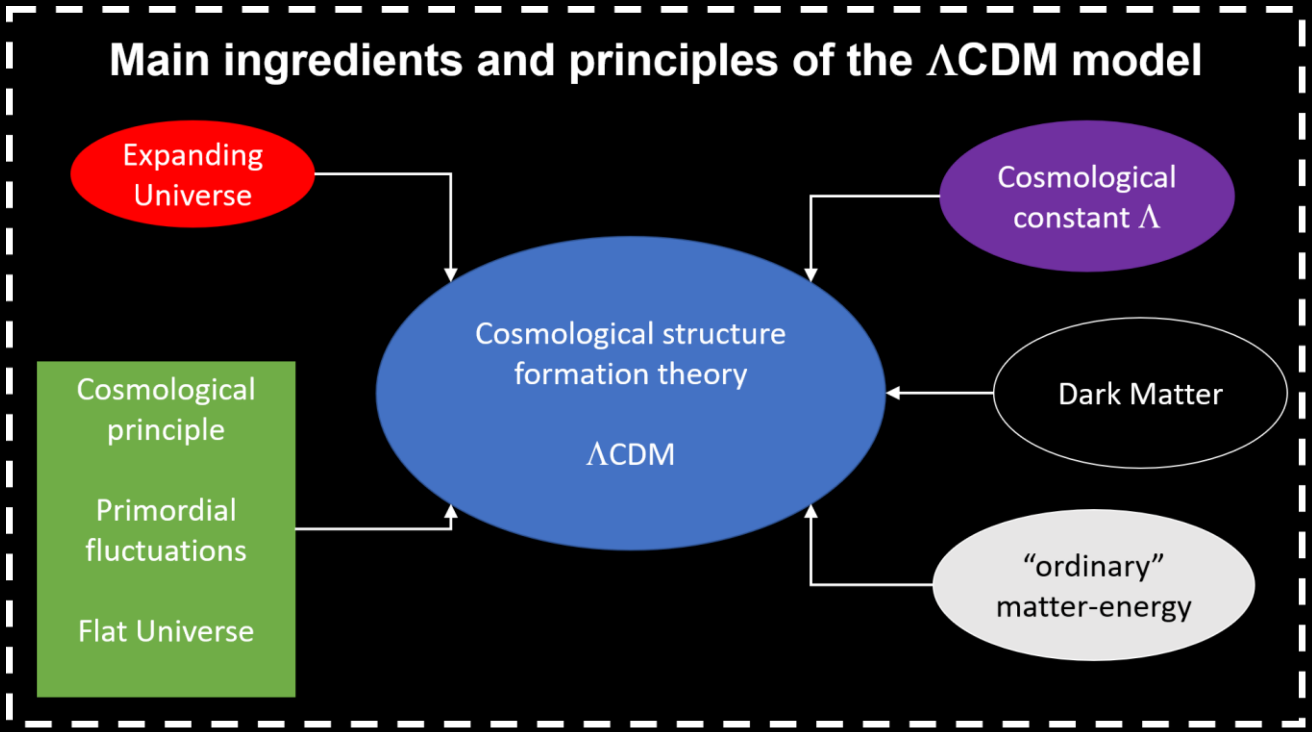
WIMPs
Sterile neutrinos
SIDM particles
Fuzzy DM
??

Notice that the fundamental theories supporting/predicting the different ingredients in LCDM are not “needed” for the model to work as a structure formation theory

(Towards) the standard model of cosmology

Big Bang

Inflation



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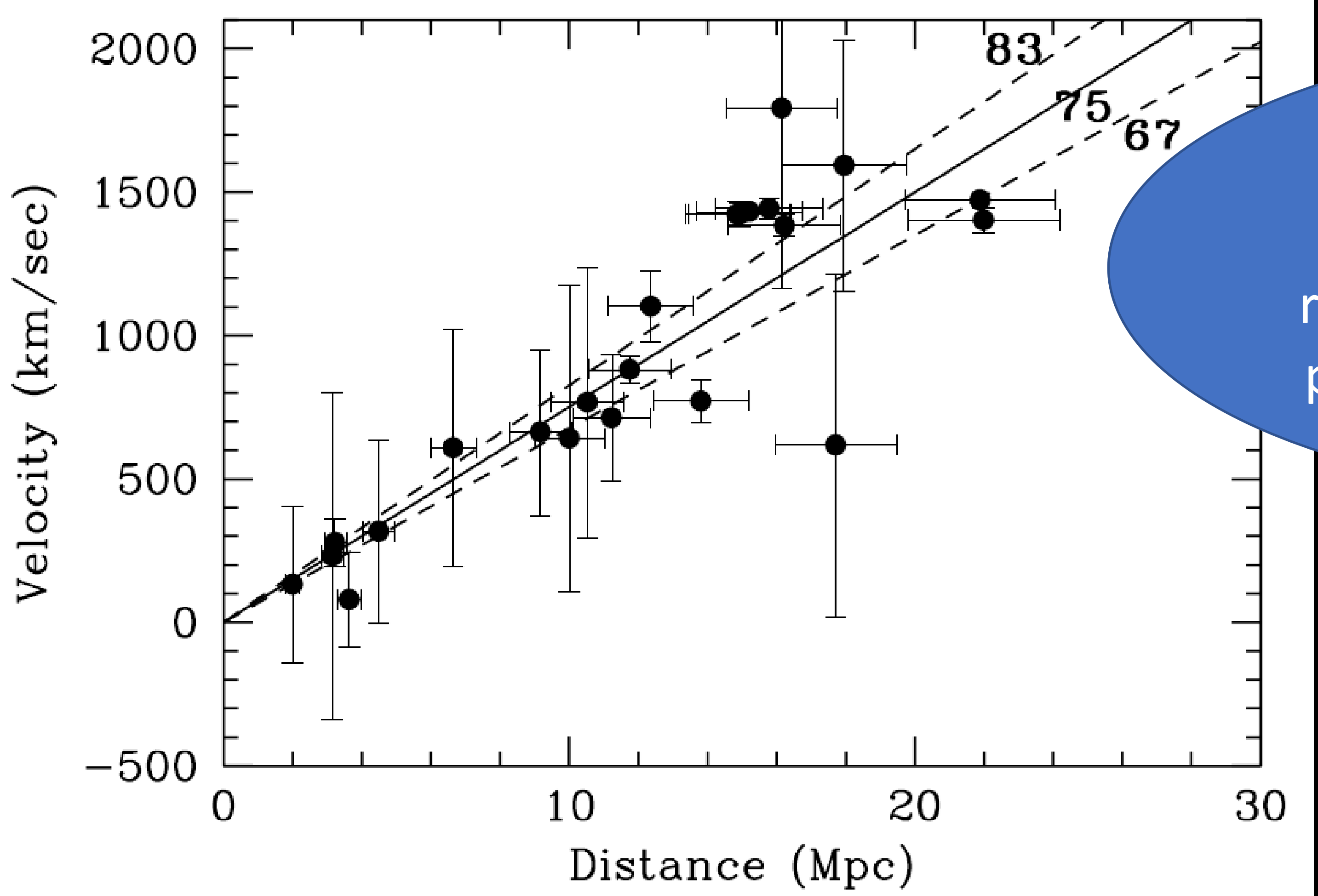
Given the topic of the School, I will focus mostly on Dark Mater

The expanding Universe and evidence for the Big Bang theory

Big Bang motivation:
The (local) expansion of the Universe
(Hubble-Lemaître law ~1920)


Lemaître


Hubble



HST key project Freedman et al. 2001

galaxies around us move away from us with a recessional velocity in direct proportion to their distance

$$v_r = H_0 d_L$$

Hubble constant

$$H_0 = 100\, h \ \mathrm{km/s\ Mpc^{-1}}$$

The (local) expansion of the Universe

Recessional velocity is measured through the (Special) relativistic Doppler effect:

$$\underset{\text{redshift}}{1+z} = \frac{\lambda_{obs}}{\underset{\text{rest frame}}{\lambda_{em}}} = \frac{\nu_{em}}{\nu_{obs}} = \left(\frac{1+\beta}{1-\beta}\right)^{1/2} \qquad \beta = \frac{V_r}{c} \rightarrow \text{recessional velocity}$$

For the low velocity regime: $\beta << 1 \Rightarrow \boxed{V_r \sim cz}$

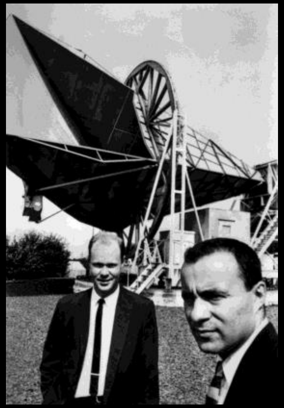
Luminosity distance: $\overset{\text{absolute}}{M} = \underset{\text{apparent}}{m} - 5(\log_{10} d_L - 1)$

$$\Rightarrow \boxed{\frac{cz}{H_0} \sim d_L} \quad (\beta << 1)$$

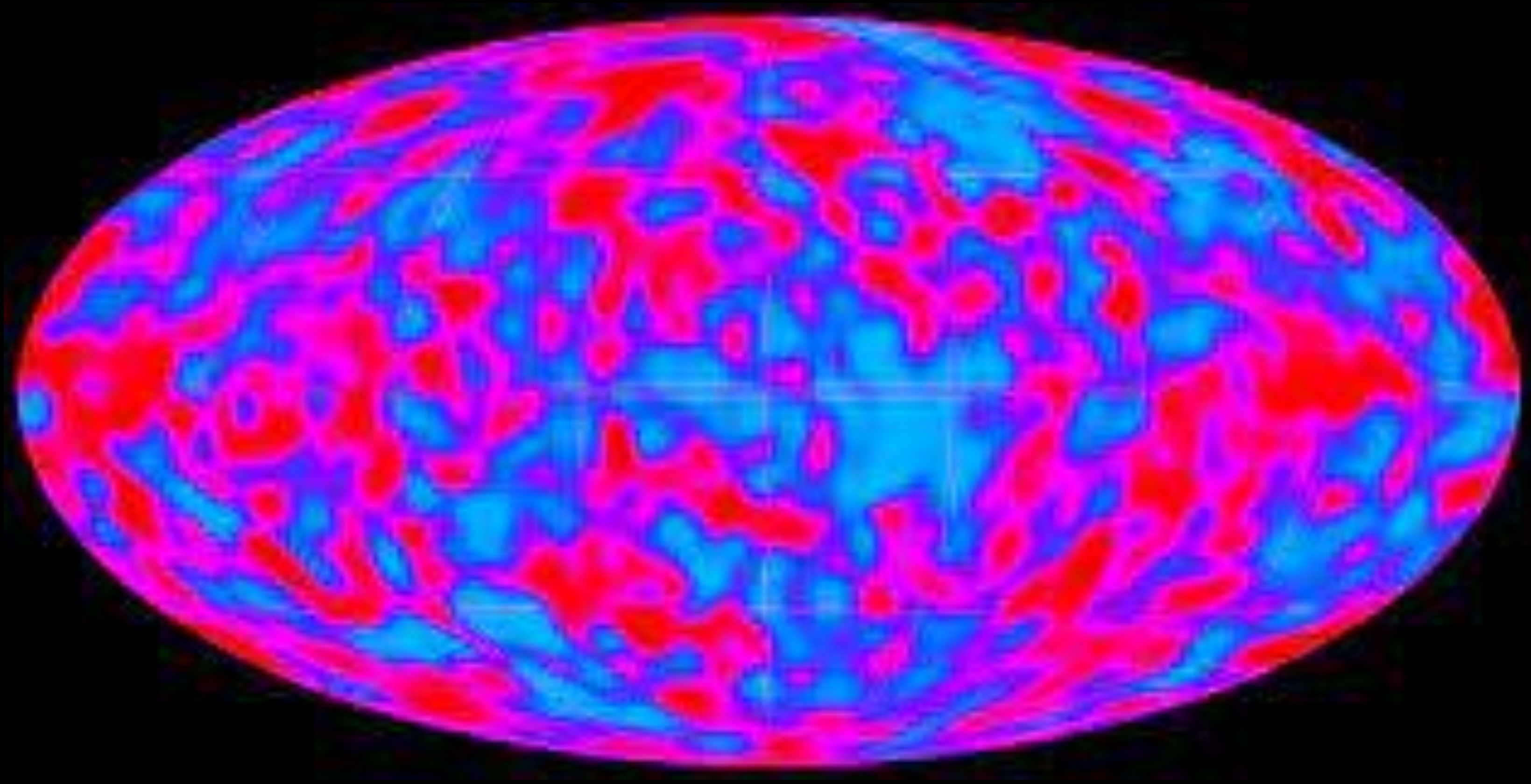
HL law

Big Bang evidence:
Cosmic Microwave Background Radiation

CMB discovery



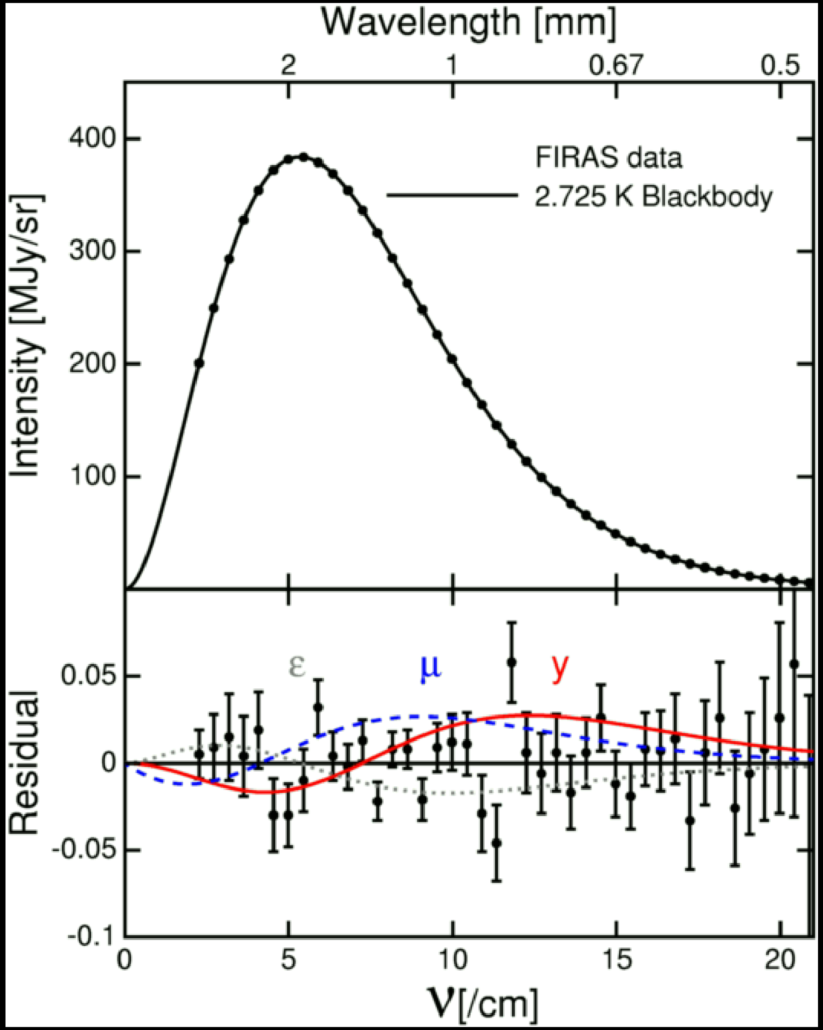
Penzias and Wilson 1964
Nobel prize 1978



Credit: NASA/COBE Science Team

COBE CMB observations 1993

Big Bang evidence:
Cosmic Microwave Background Radiation

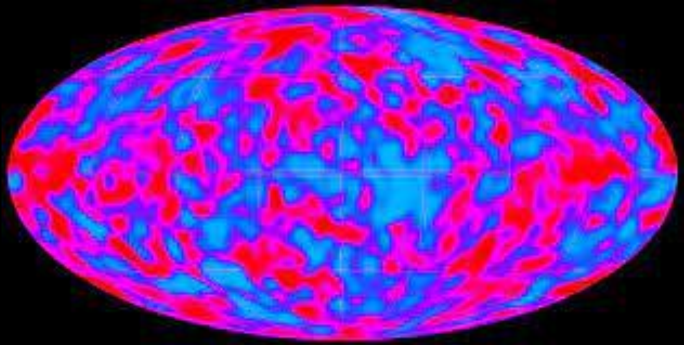


Credit: NASA/COBE Science Team

→ The CMB energy spectrum is a perfect (up to measurement) black body spectrum

thermal radiation by system in therm. equilibrium

Planck's law → depends only on temperature



Big Bang evidence:
Cosmic Microwave Background Radiation

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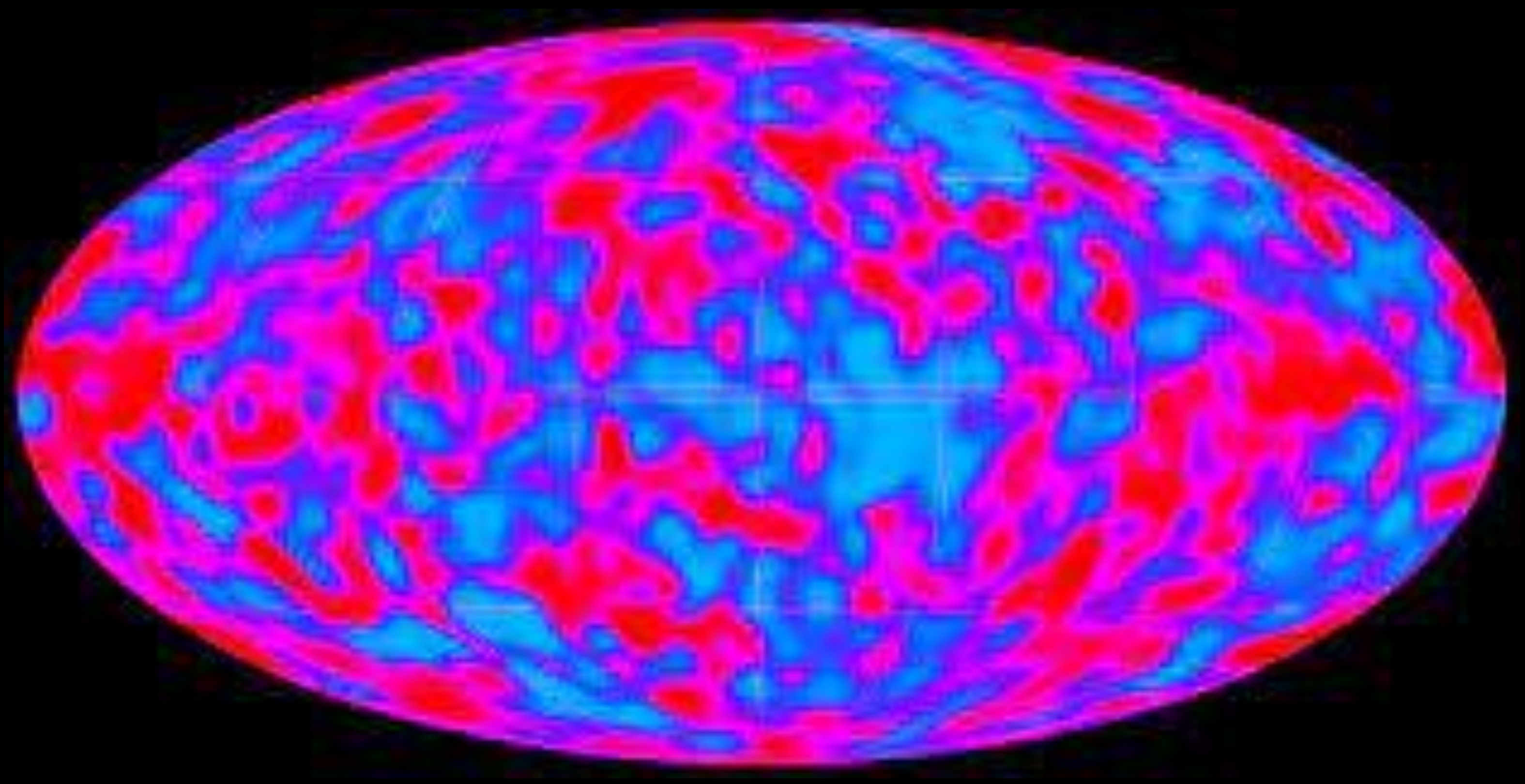


Credit: NASA/COBE Science Team

mean temperature
$\langle T \rangle = 2.73$

temperature anisotropies
$1/10^5$

Mather

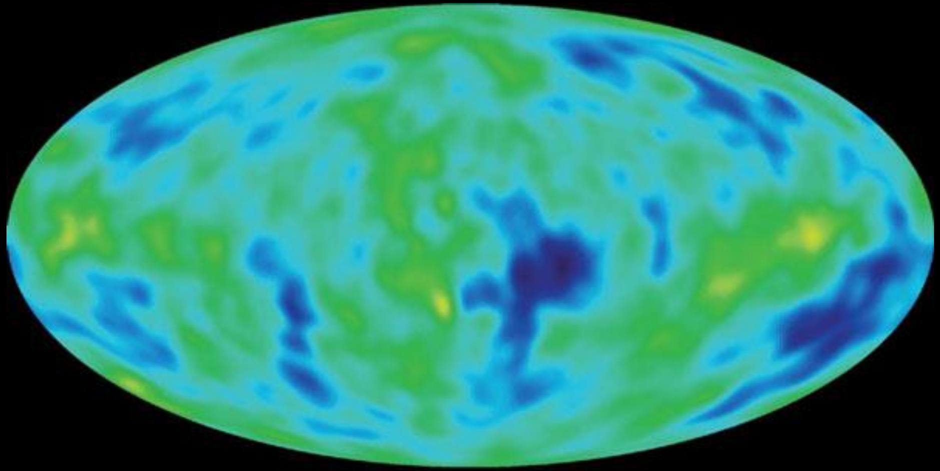
Smoot

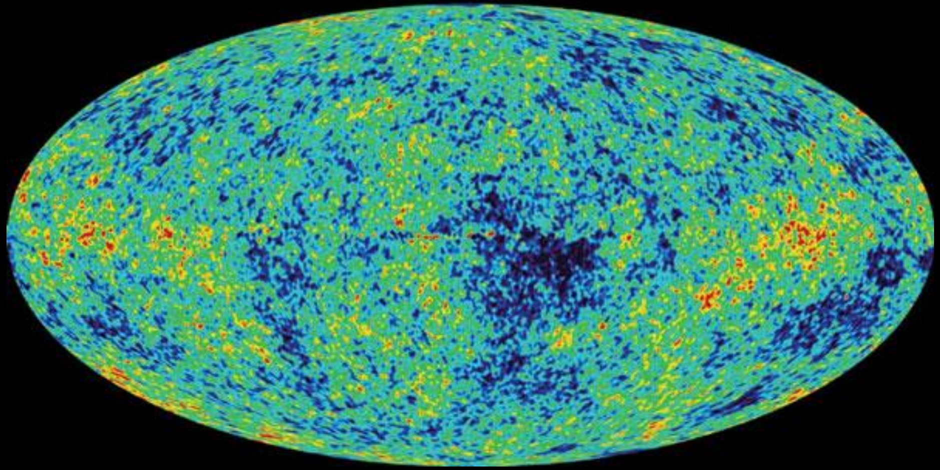
Nobel prize 2006

The seeds for structure formation:
the cosmic microwave background radiation

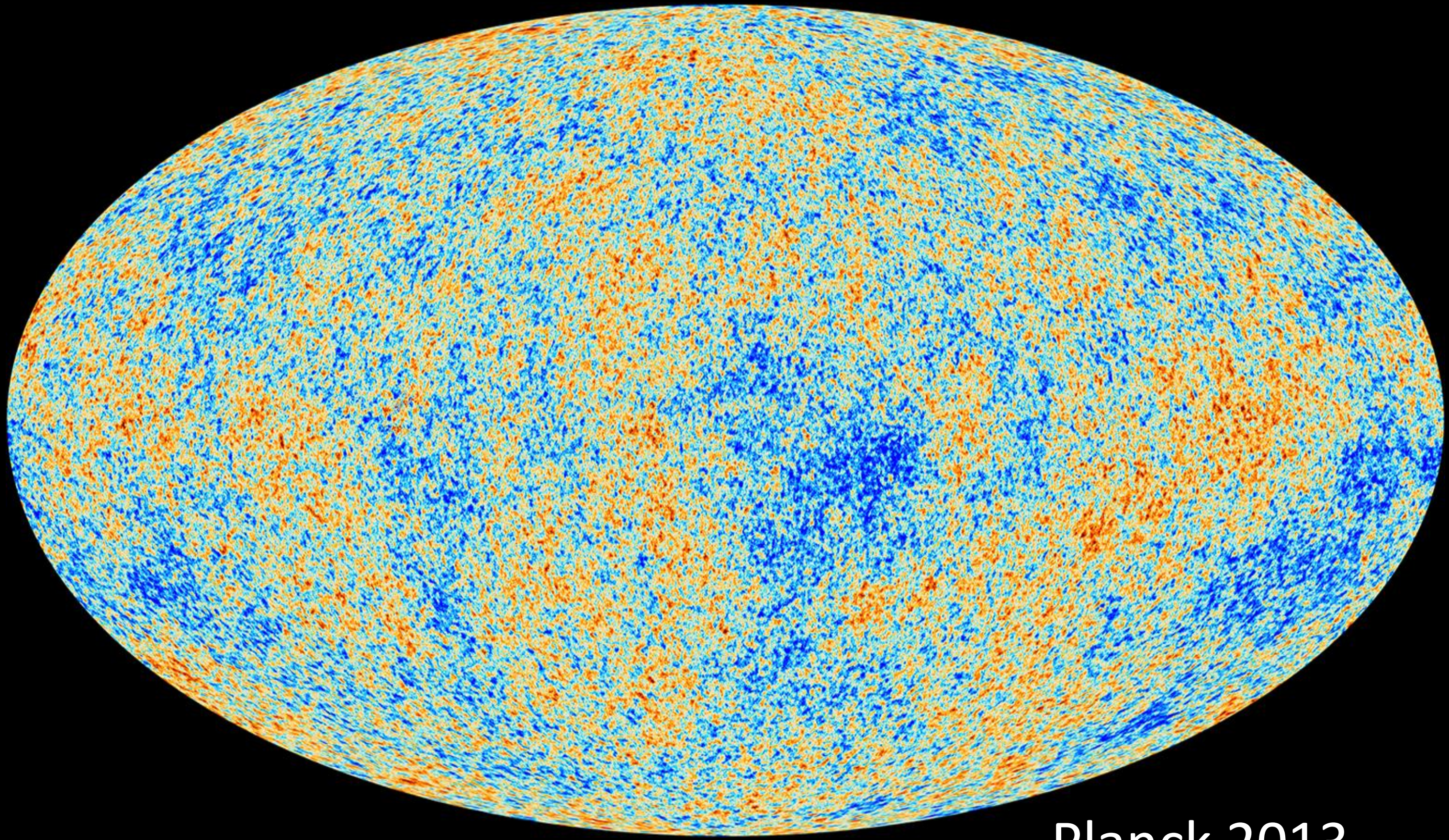
Big Bang evidence:
Cosmic Microwave Background Radiation

COBE 1993





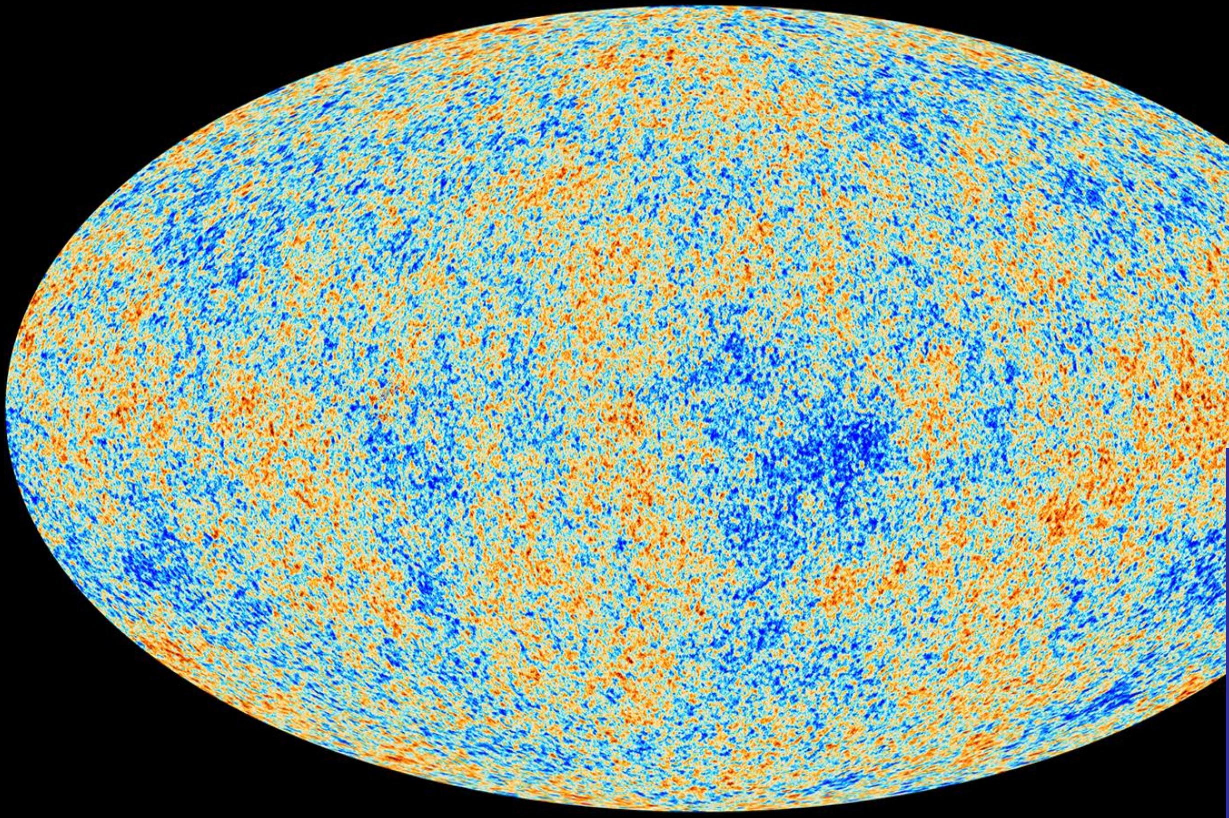
WMAP 2003

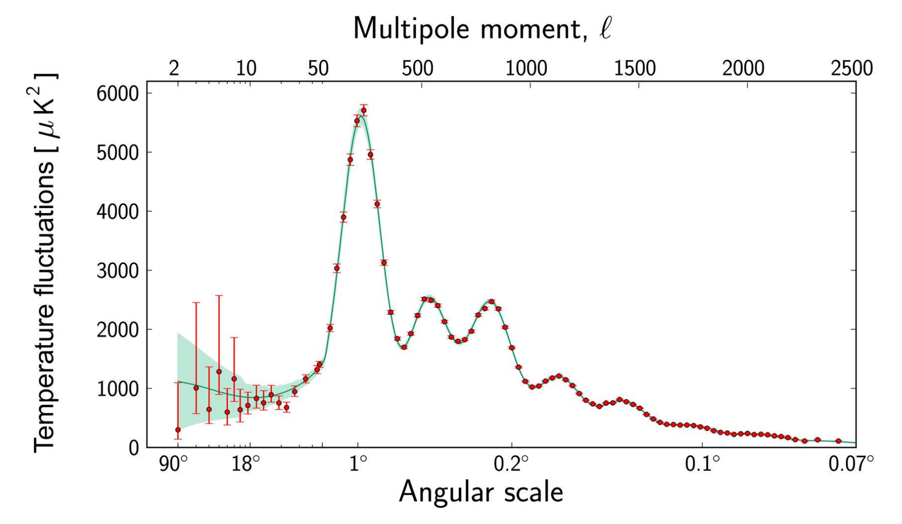


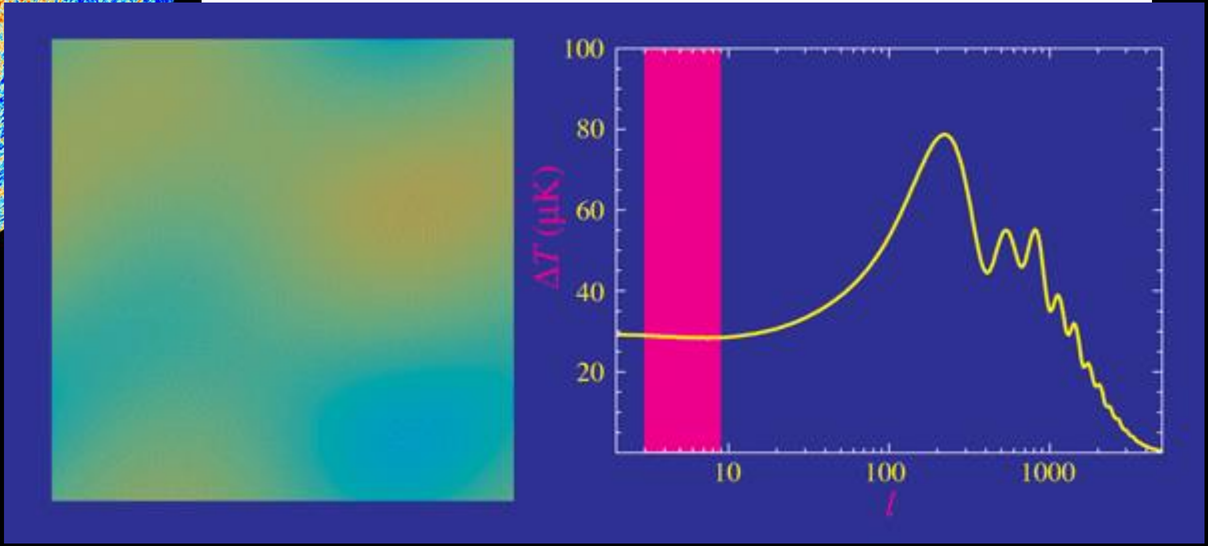
Planck 2013

Temperature/density fluctuations:
Cosmic Microwave Background Radiation

Planck 2013



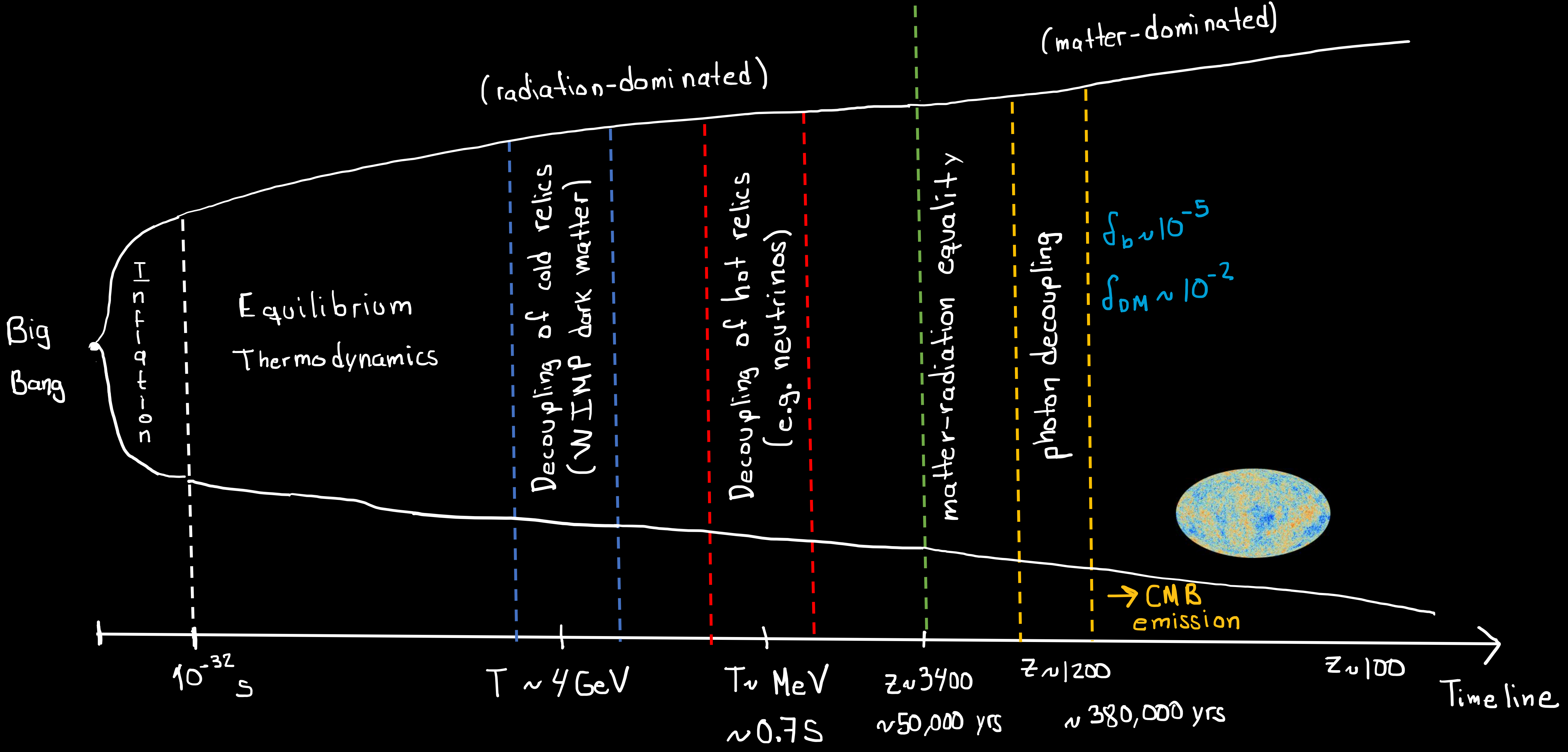




Credit: W. Hu

Inflation provides an explanation to the origin of these fluctuations

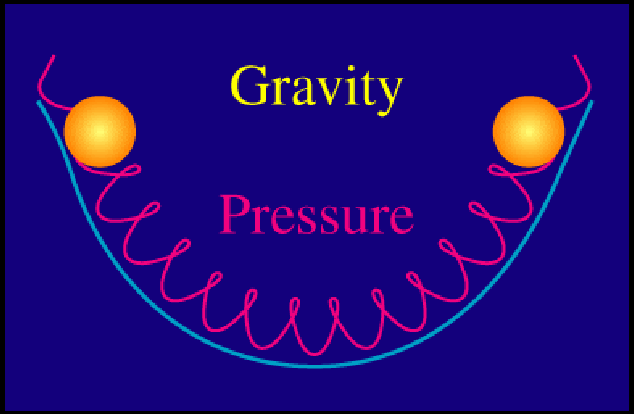
Early-Universe Cosmology in a nutshell

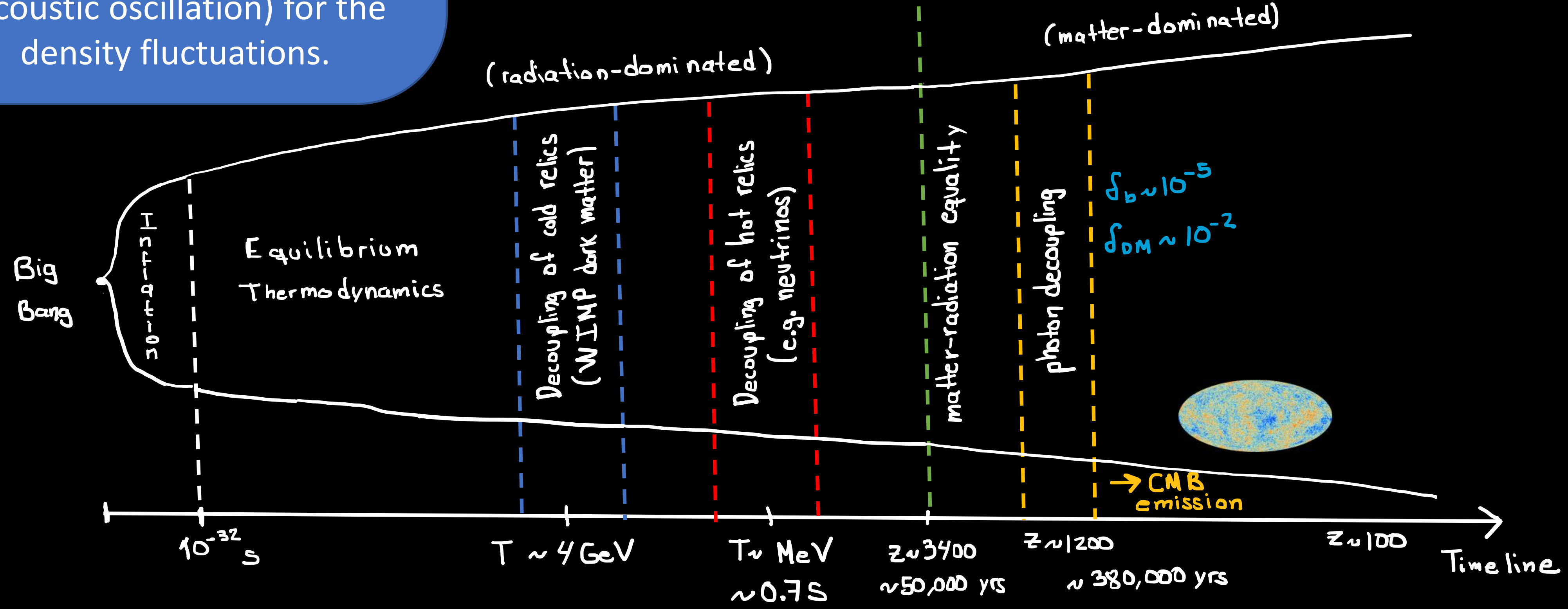


Early-Universe Cosmology: main features of the CMB

Early on, the photon-baryon was tightly coupled (through Compton scattering).
The plasma acted as a single fluid: gravity tries to compress the fluid while radiation pressure expands it.
This creates a stable oscillatory behaviour (acoustic oscillation) for the density fluctuations.

Credit: W. Hu





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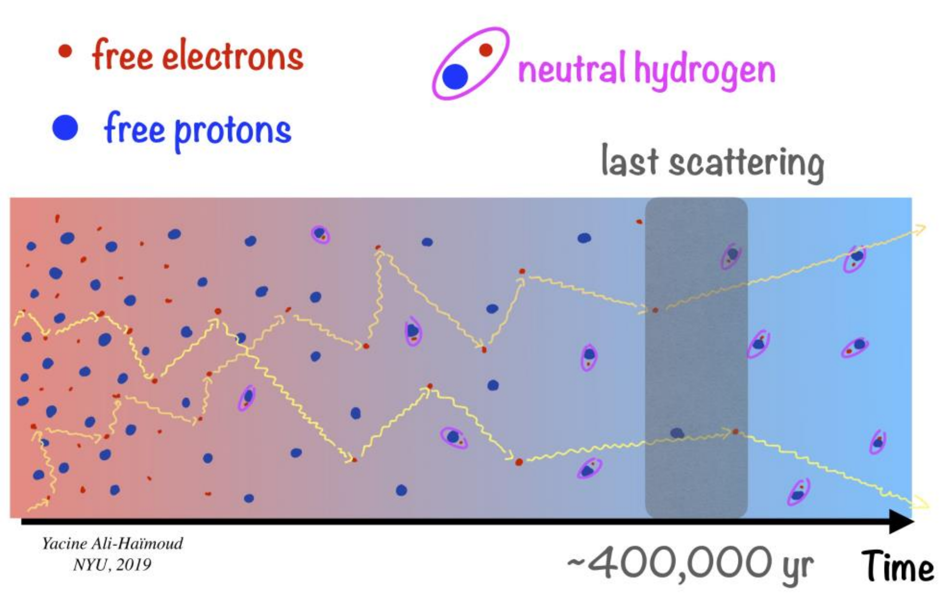
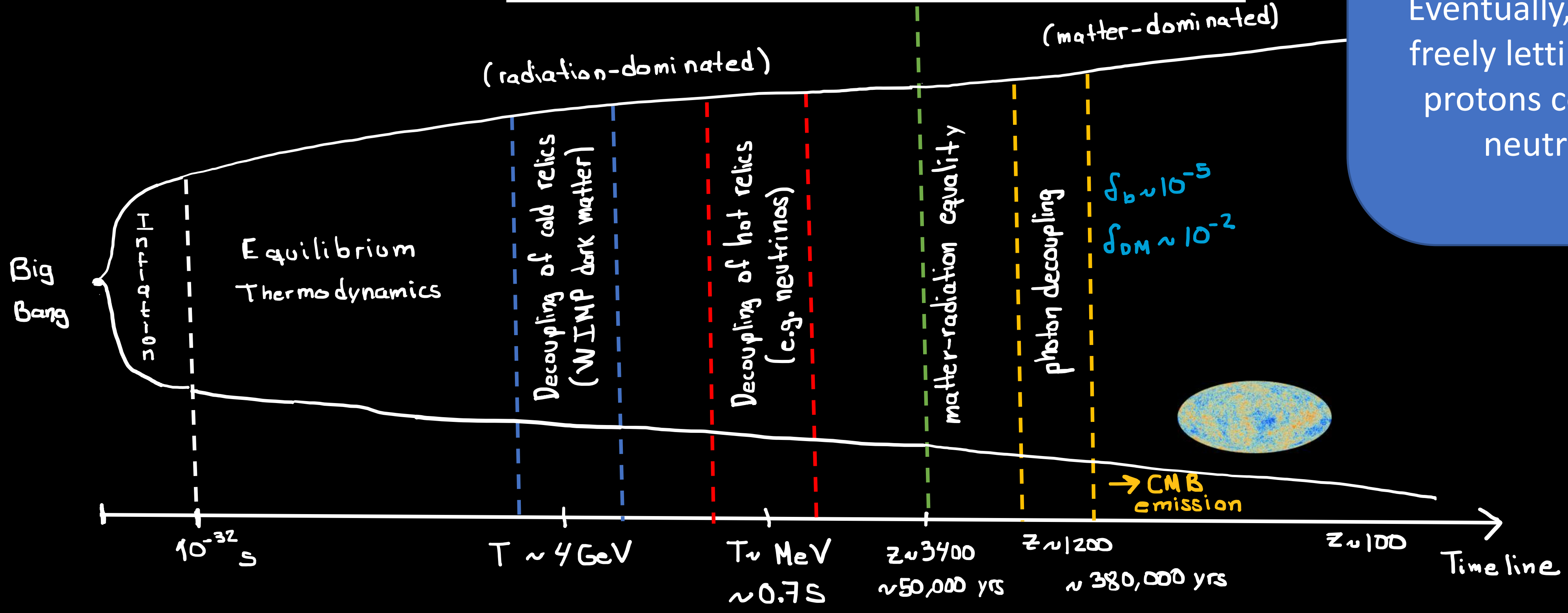


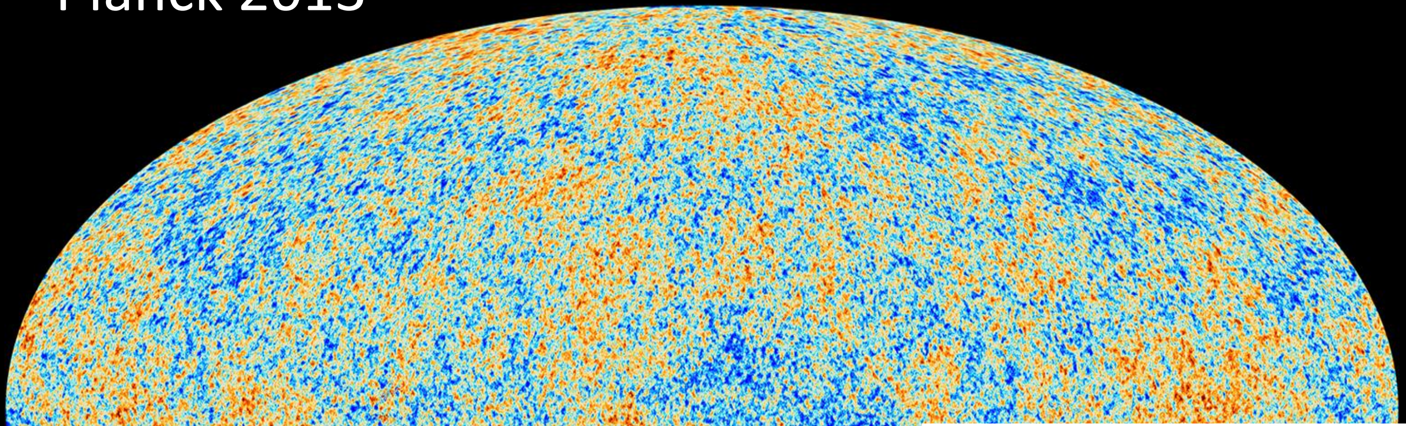


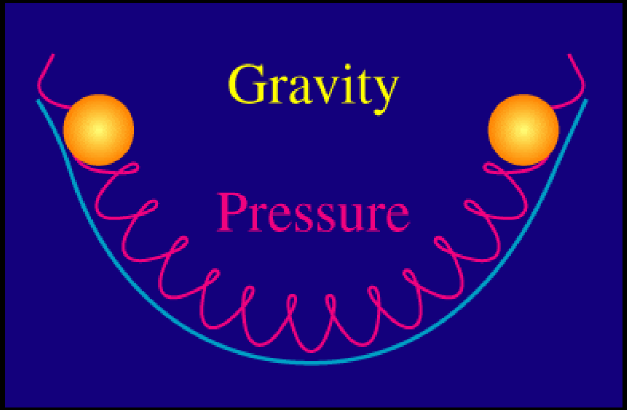
As the Universe expands and cools down, the photon mean free path increases reducing the interaction (Compton scattering) rate.

Eventually, photons stream freely letting electrons and protons combine to form neutral hydrogen

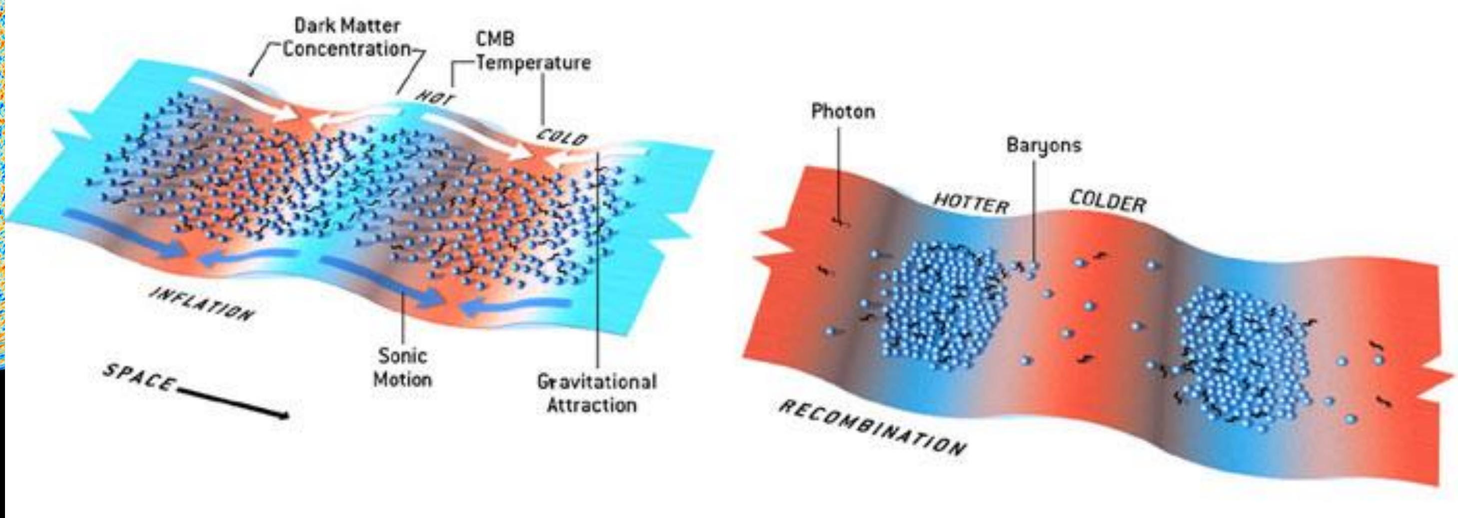
Temperature/density fluctuations:
Cosmic Microwave Background Radiation

Planck 2013





Credit: W. Hu



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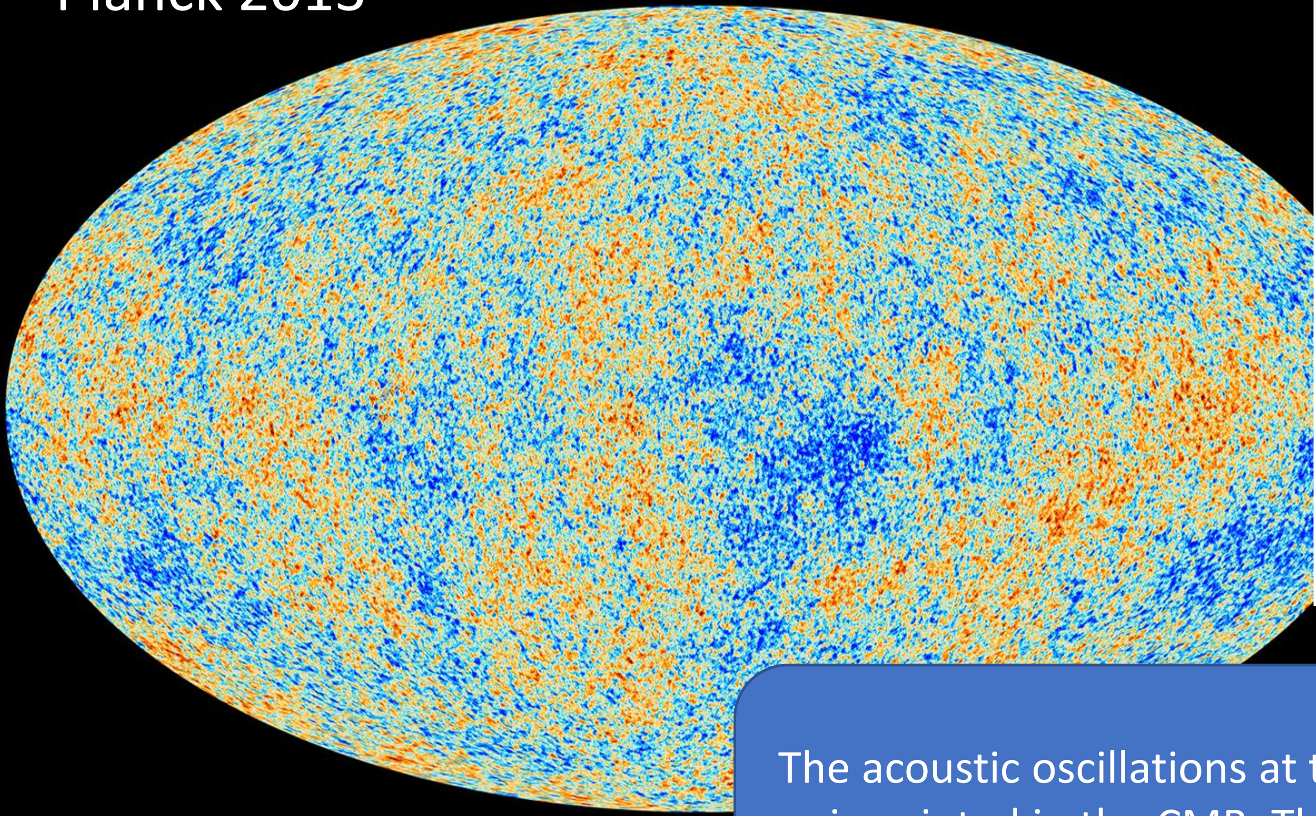
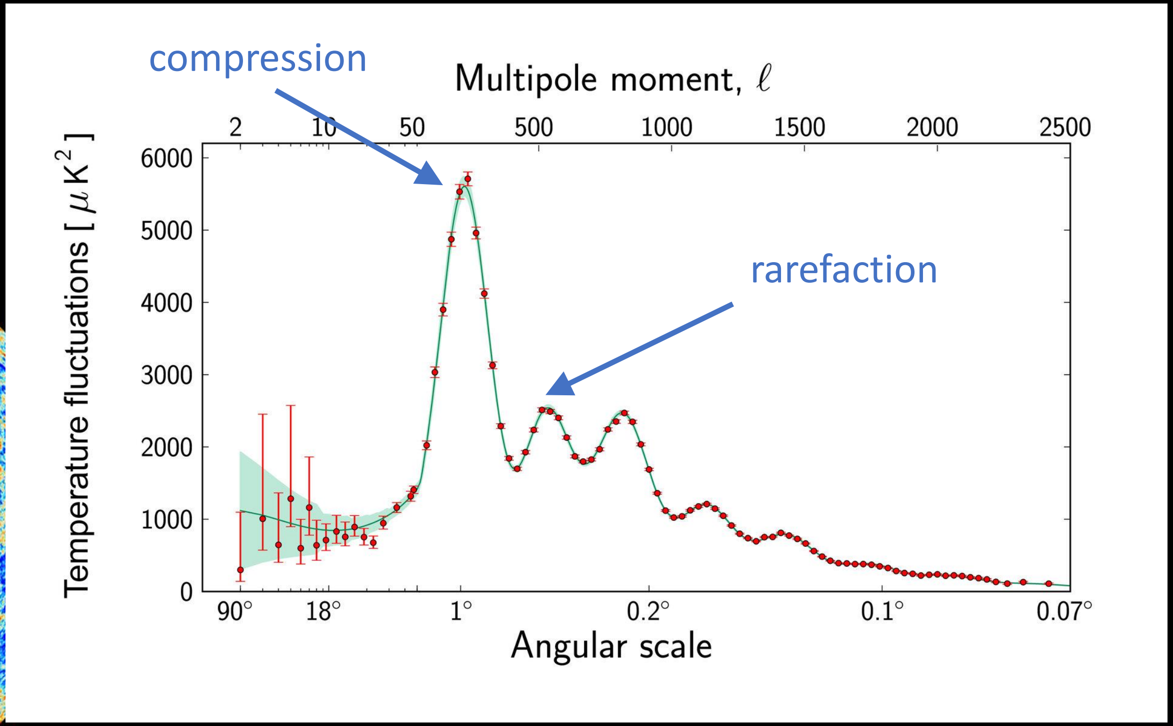
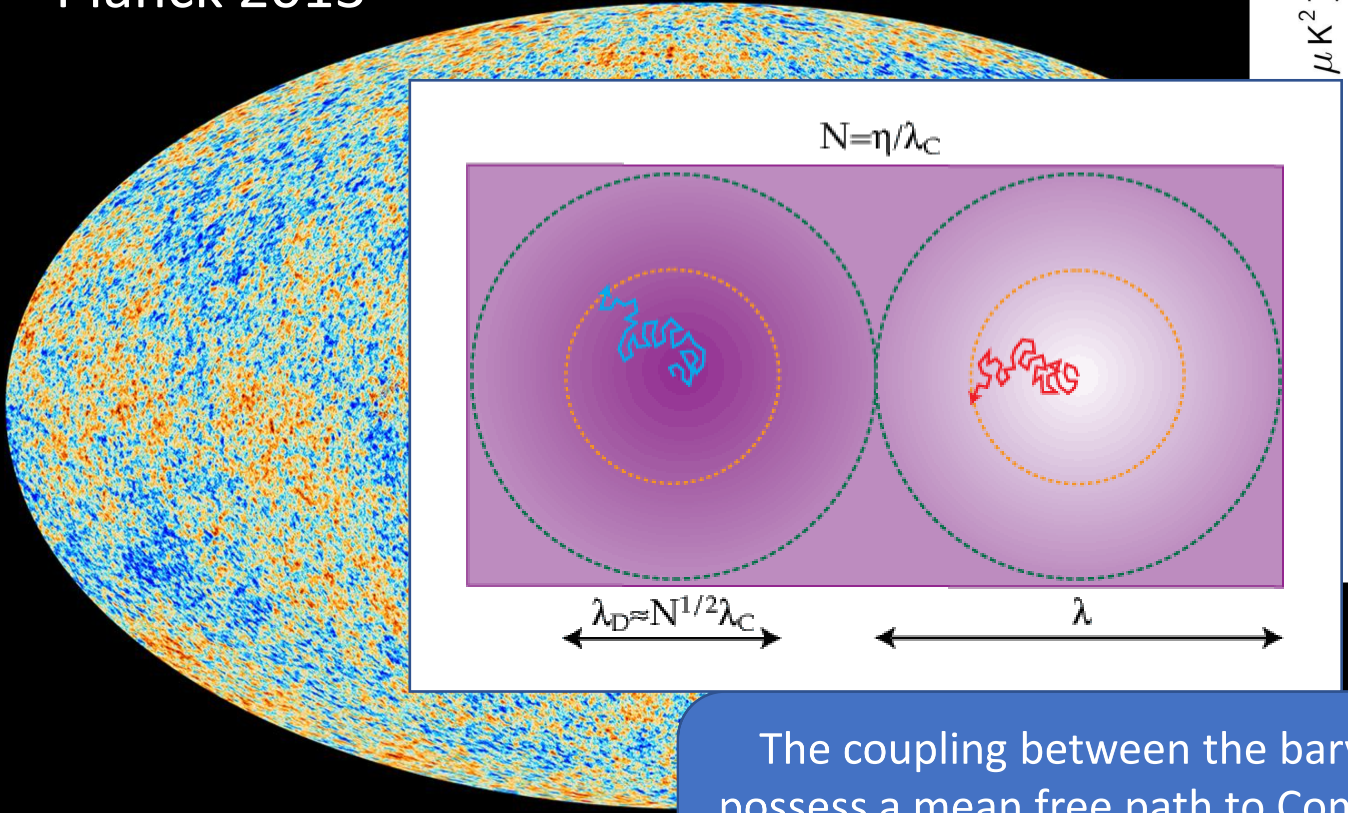


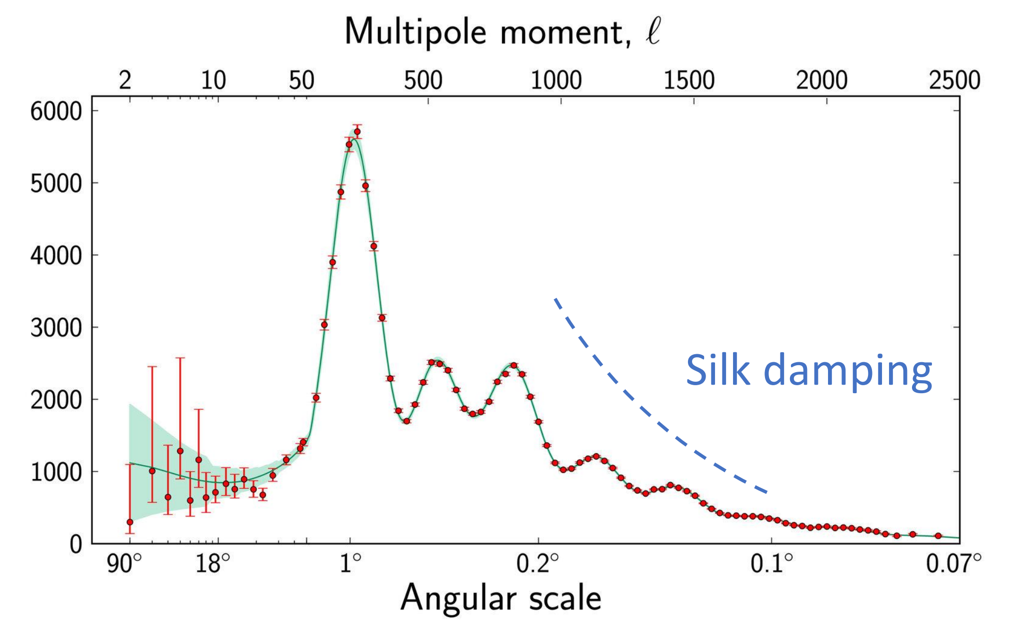


The acoustic oscillations at the time of recombination (approx. photon decoupling) are imprinted in the CMB. The position of the first peak is roughly given by the sound horizon scale at recombination (distance sound waves can travel by recombination)

Temperature/density fluctuations:
Cosmic Microwave Background Radiation

Planck 2013

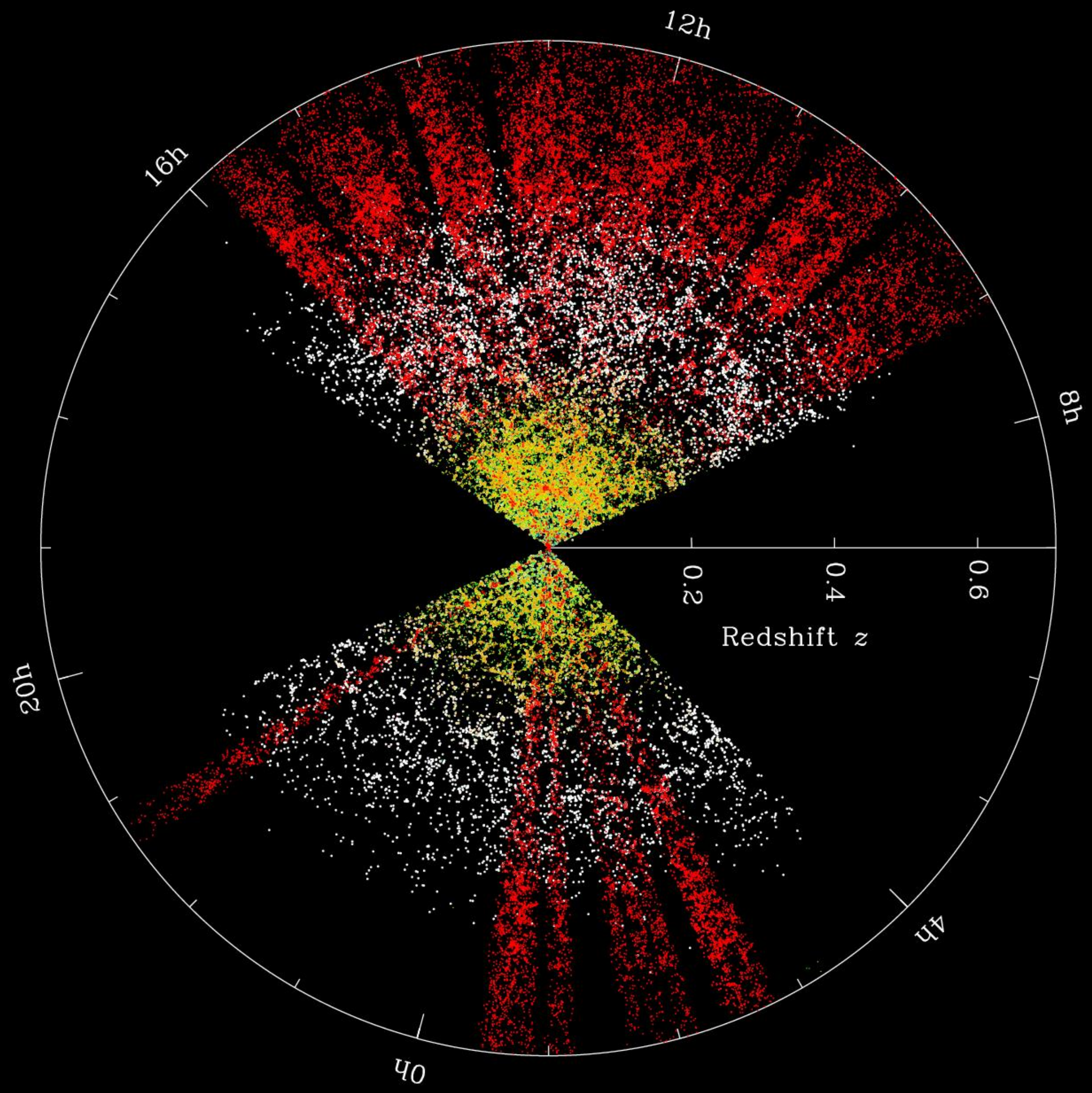


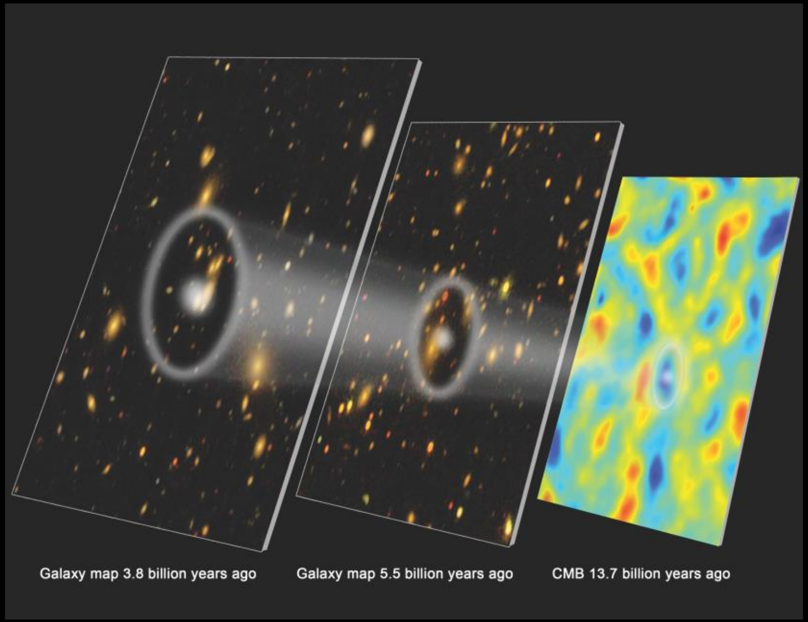


The coupling between the baryons and the photons is imperfect since the photons possess a mean free path to Compton scattering. As the photons random walk through the baryons, hot and cold regions are mixed, damping fluctuations smaller than the diffusion length. The diffusion length is mainly given by the decoupling epoch.

Baryon acoustic oscillations in galaxy surveys

SDSS and BOSS surveys

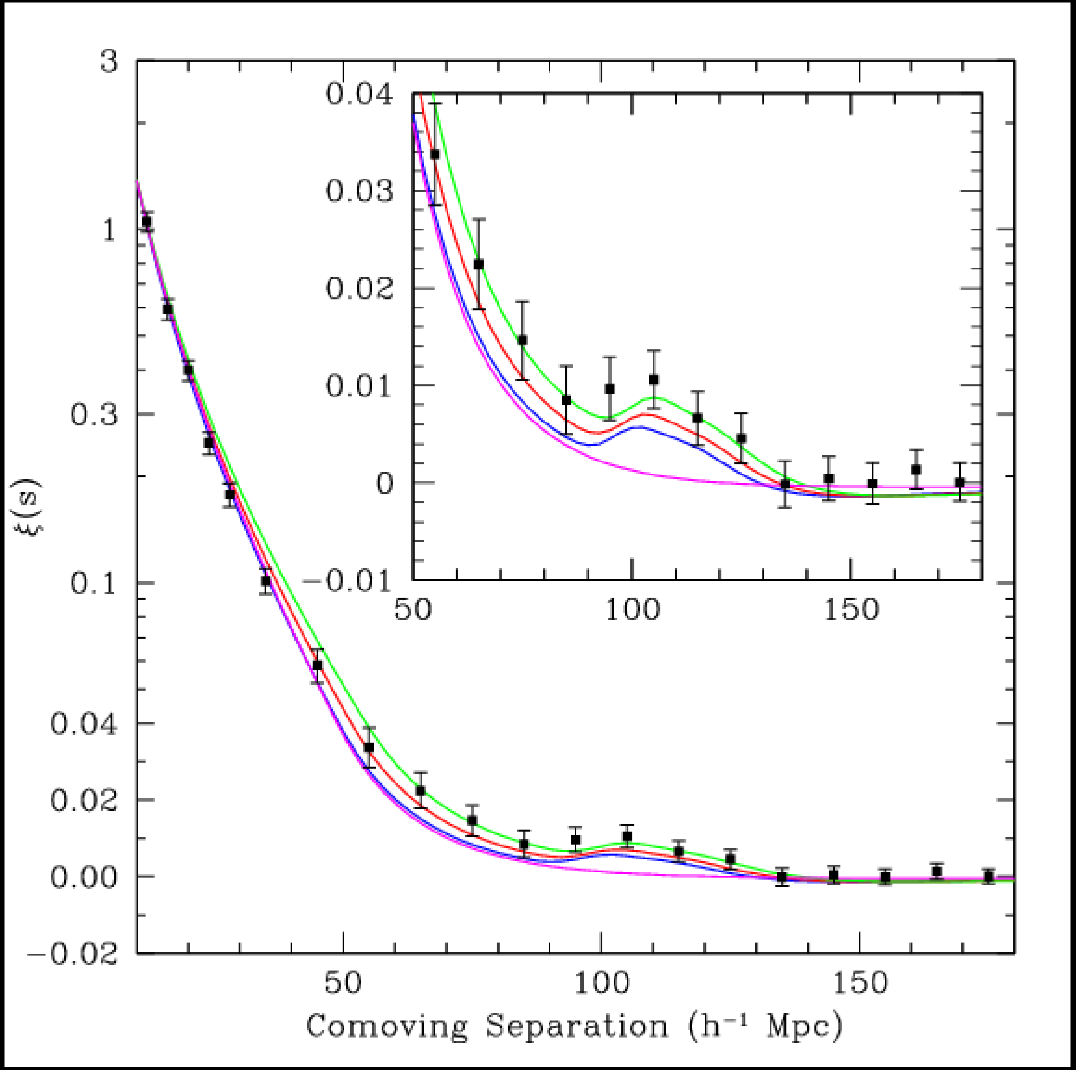


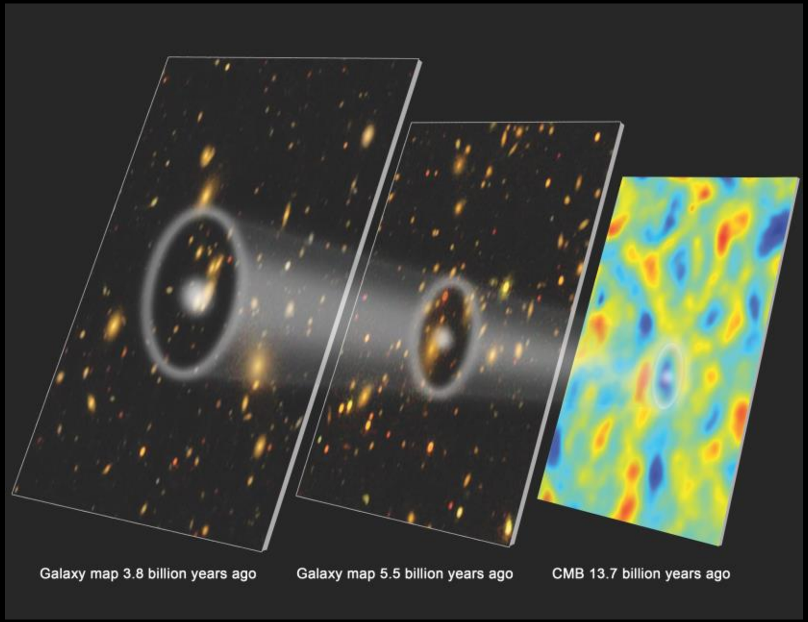


The acoustic oscillations imprinted in the density fluctuations at the time of the CMB leave an imprint in the large-scale distribution of galaxies in the late Universe

Baryon acoustic oscillations in galaxy surveys

SDSS and BOSS surveys





The acoustic oscillations imprinted in the density fluctuations at the time of the CMB leave an imprint in the large-scale distribution of galaxies in the late Universe

The homogeneous and isotropic background Universe

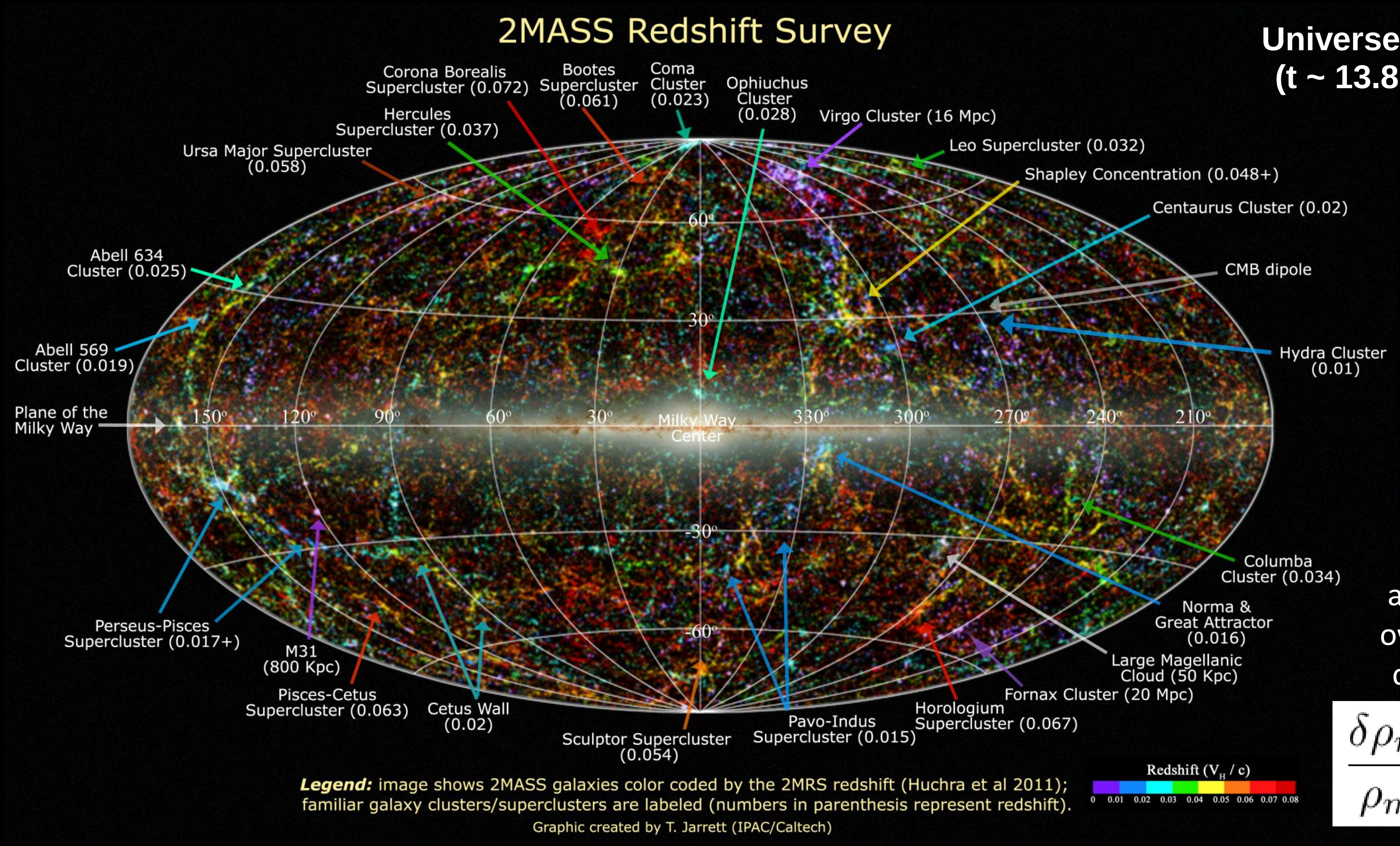
The Cosmological principle

The Universe is <u>homogeneous</u> and <u>isotropic</u> on “large” scales

- ➢ Notion of a Copernican principle: there is no preferred location or direction. The Universe looks “the same” for all observers in terms of the physical laws we derive (translational and rotational invariance)
- ➢ What do we mean by large scales?

The Cosmological principle: evidence

2MRS galaxy “map”, large-scale structure (~300 Mpc)



Legend: image shows 2MASS galaxies color coded by the 2MRS redshift (Huchra et al 2011); familiar galaxy clusters/superclusters are labeled (numbers in parenthesis represent redshift).

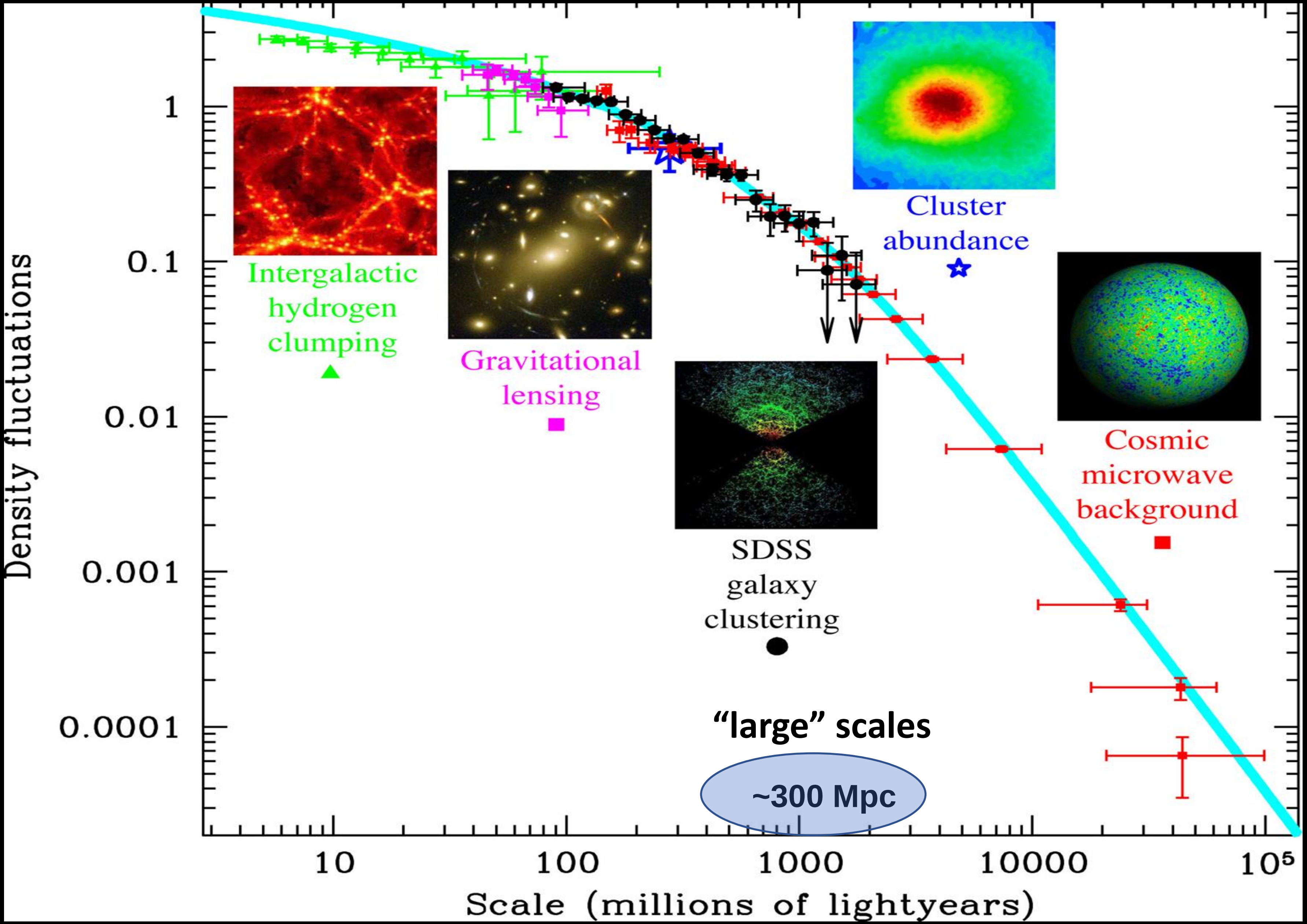
Graphic created by T. Jarrett (IPAC/Caltech)

Universe today
(t ~ 13.8 Gyrs)

anisotropies over random distribution

$$\frac{\delta \rho_m}{\rho_m} \sim 10^{-1}$$

The cosmological principle: inhomogeneity as a function of scale



“large” scales

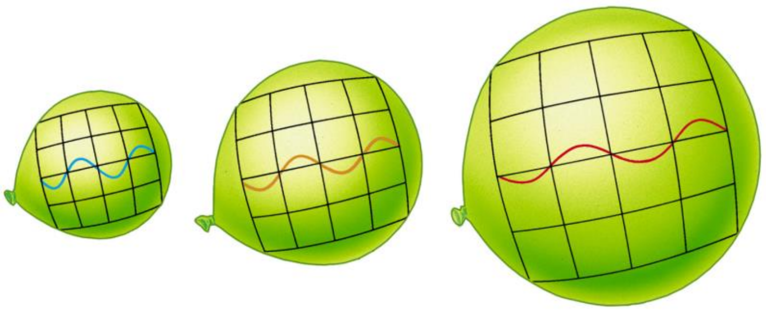
~300 Mpc

Credit: Max Tegmark and SDSS collaboration

The (global) expansion of the Universe

- The HL law and the cosmological principle can be reconciled only if the Universe as a whole is expanding

expansion of a 2D Universe (balloon surface)



redshift

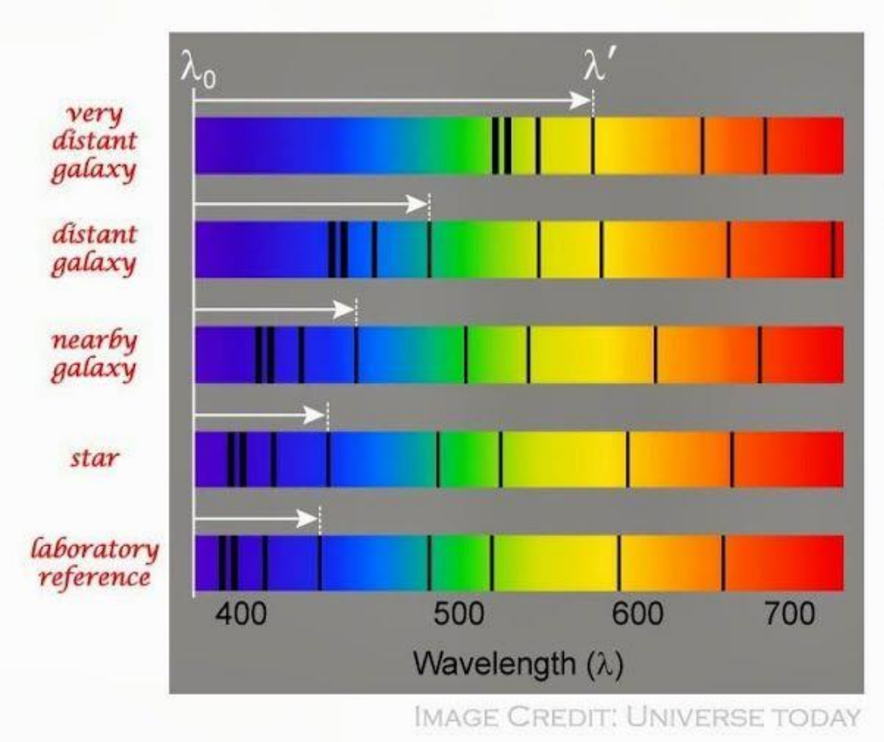


IMAGE CREDIT: UNIVERSE TODAY

light waves coming from galaxies at various distances away from Earth are stretched (redshifted) by the time they reach us because space itself in **the Universe Is expanding!**

Comoving coordinates

scale factor → absorbs the expansion

$$\vec{X}_{phys} = a(t)\,\vec{r}$$

physical coord.

comoving coord. → comoving with the expansion

If $\dot{\vec{r}} = 0$ $\Rightarrow$ $\vec{V}_{phys} = \frac{\dot{a}(t)}{a(t)}\,\vec{X}_{phys}$

For a galaxy receding, $V_r = |\vec{V}_{phys}|$ and $d_L = |\vec{X}_{phys}|$

$\Rightarrow$ we identify $\boxed{H(t) = \frac{\dot{a}(t)}{a(t)}}$

Note: $t_0 \sim \frac{X_{phys}}{V_{phys}} \sim \frac{1}{H_0} \sim 15\,Gyr$

Hubble time ∼ Age of the Universe

The Friedmann-Robertson-Walker (FRW) metric

- A metric in GR is a mathematical object that captures the geometry of spacetime: it allows us to define distances in spacetime.

- For instance in SR, which deals with inertial frames (no acceleration/gravity):

$$\underset{\swarrow}{ds^2} = \underbrace{c^2dt^2 - [dx^2 + dy^2 + dz^2]}_{\text{space and time unified}}$$

Minkowski metric

spacetime interval

Now, imagine we replace the spatial coordinates by comoving coordinates in an expanding Universe, which is homogeneous and isotropic, then we can "guess":

$$ds^2 = c^2dt^2 - a^2(t)\left[dx_{com}^2 + dy_{com}^2 + dz_{com}^2\right]$$

The Friedmann-Robertson-Walker (FRW) metric

Now, imagine we replace the spatial coordinates by comoving coordinates in an expanding Universe, which is homogeneous and isotropic, then we can “guess”:

$$ds^2 = c^2dt^2 - a^2(t)\left[dx_{com}^2 + dy_{com}^2 + dz_{com}^2\right]$$

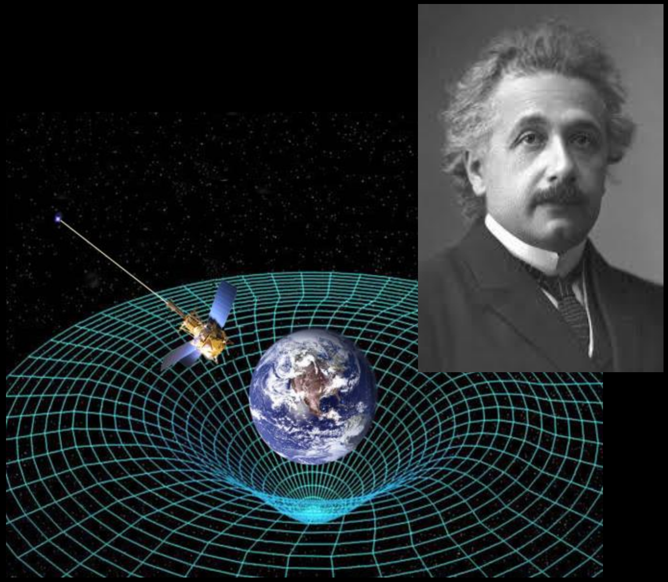
Formally, this is not the only possibility, in general we have:

$$ds^2 = c^2dt^2 - a^2(t)\left[\frac{dr^2}{1-Kr^2} + r^2(d\theta^2 + \sin^2\theta d\varphi^2\right]$$ FRW metric

r, θ, φ are comoving spherical coordinates

$K \rightarrow$ spatial curvature of the Universe

Friedmann equation



- Modern cosmology is founded upon Einstein's theory of General Relativity in which space and time are unified and connected to the matter-energy content of the Universe

eqs. of motion (background Universe) Friedmann equation

Originally introduced by Einstein 1917

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{Kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

$$\rho = \rho_m + \rho_r + \rho_\Lambda$$

$\Lambda \equiv$ cosmological constant

$$\rho_\Lambda = \frac{\Lambda c^2}{8\pi G} \qquad P_\Lambda = -\rho_\Lambda c^2$$

Friedmann equation

eqs. of motion (background Universe) Friedmann equation

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{Kc^2}{a^2} + \frac{\Lambda c^2}{3} \qquad \rho = \rho_m + \rho_r + \rho_\Lambda$$

→ It is useful/customary to write densities in terms of the so-called critical density today

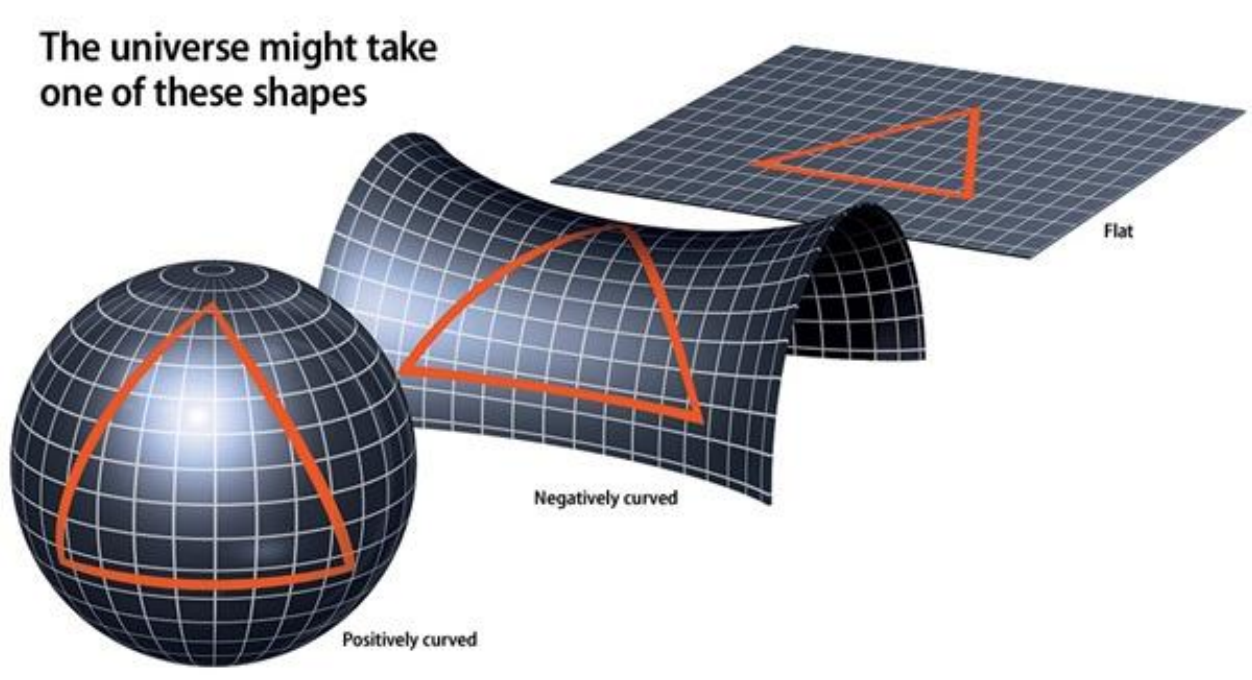
$$\rho_{crit,0} = \frac{3H_0^2}{8\pi G} \sim 1.88 \times 10^{-29}\, h^2\, g/cm^3$$

$$\boxed{\Omega_{i,0} = \frac{\rho_{i,0}}{\rho_{crit,0}}}$$

overdensity parameter

$$H^2(z) = H_0^2 \left\{ \Omega_{m,0}(1+z)^3 + \Omega_{r,0}(1+z)^4 + \Omega_{\Lambda,0} \right\}$$

Spatial curvature of the Universe

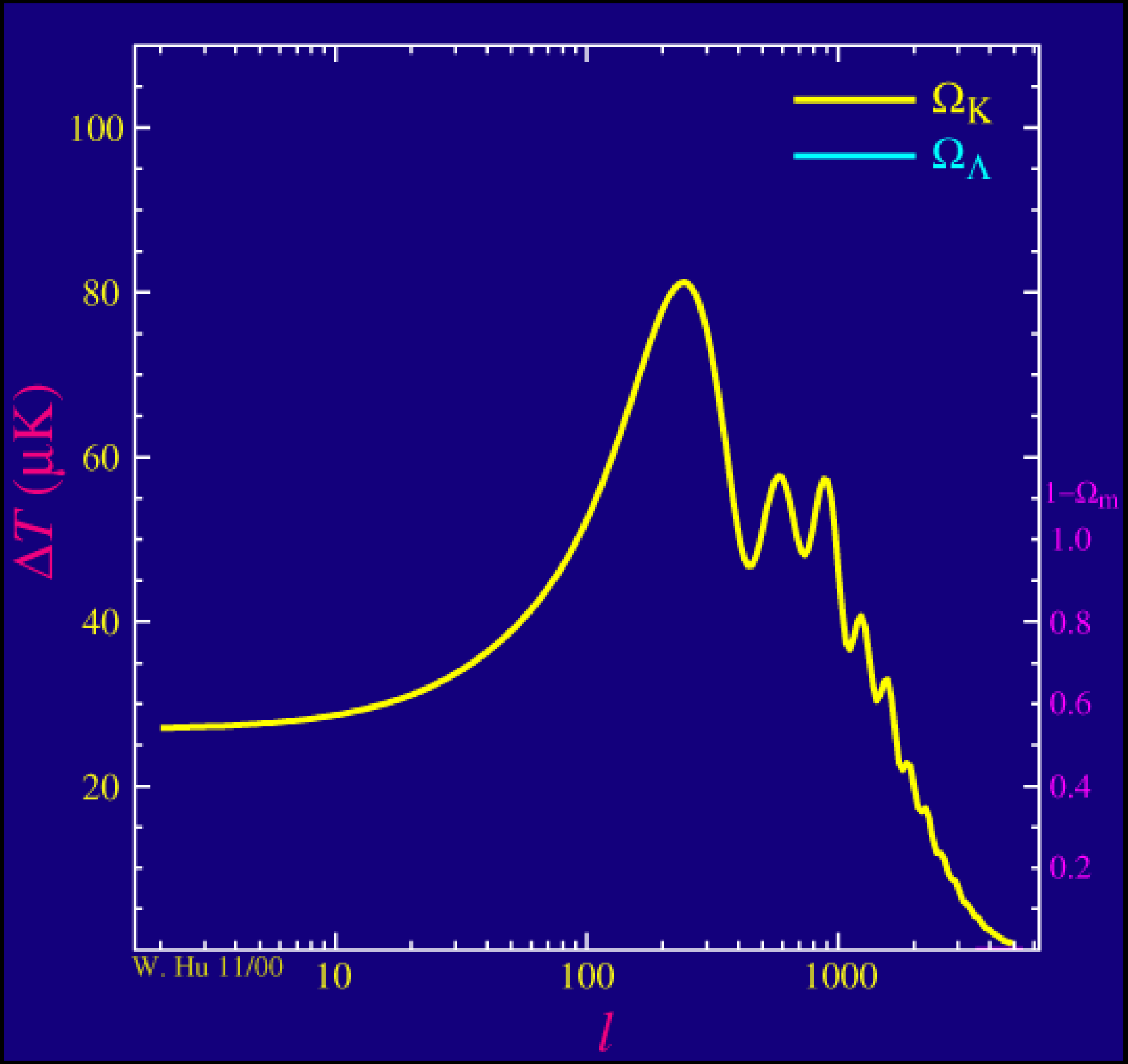


’*k*’ is related to the type of geometry that applies to measure (spatial) distances:

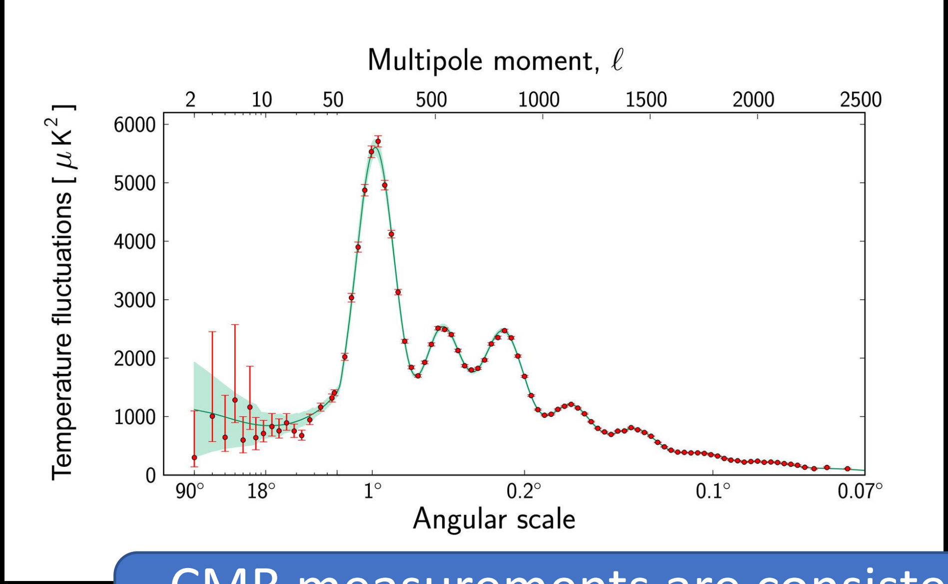
- *k*=0 (Flat or Euclidean geometry)
- *k*=-1 (negative curvature/open geometry)
- *k*=+1 (positive curvature/closed geometry)

The flatness of the Universe: evidence

Credit: W. Hu



The spatial curvature of the Universe affects the position of the peaks in the CMB



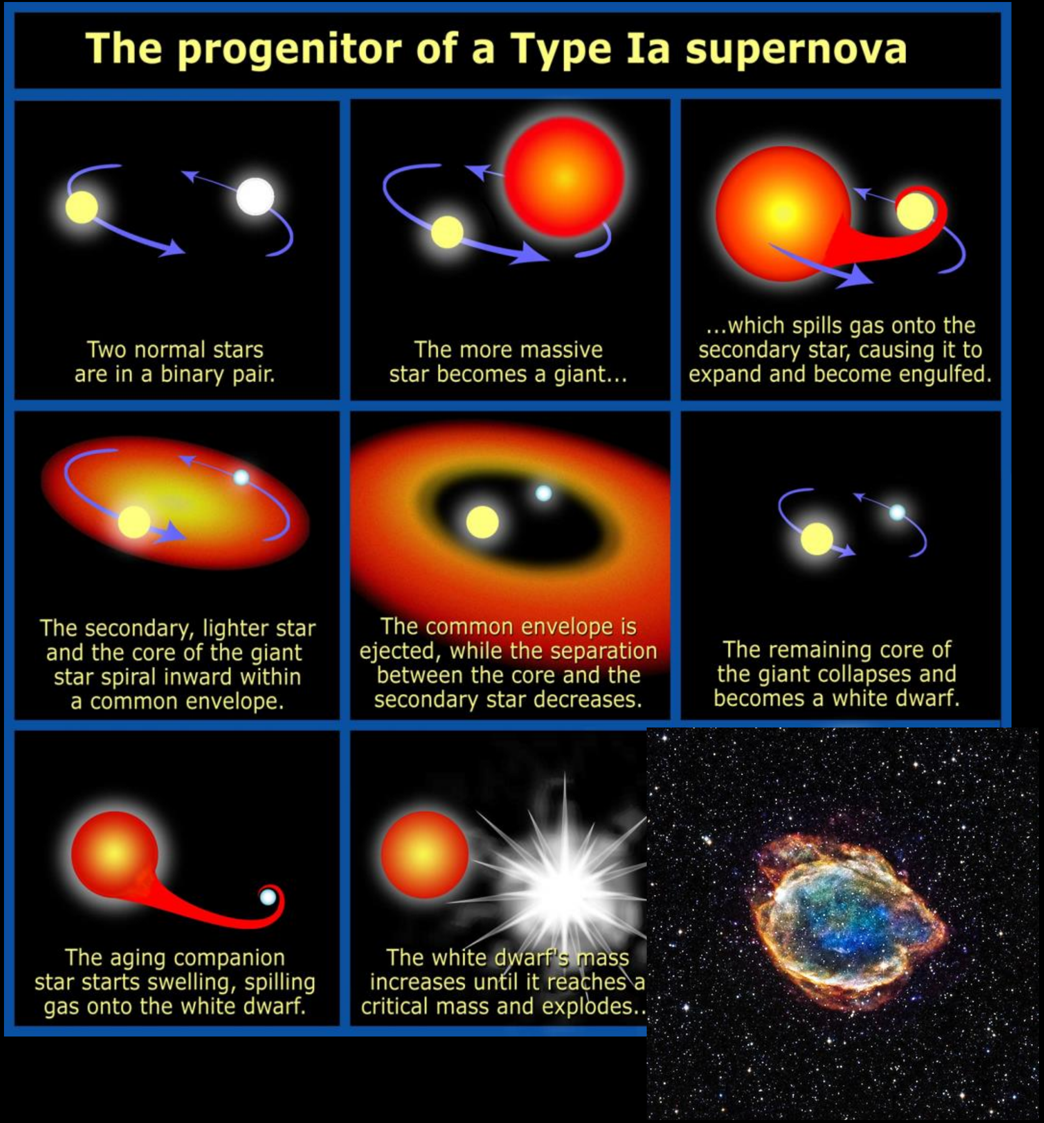
CMB measurements are consistent with a flat Universe

$$\Omega_{K,0} = -0.0096 \pm 0.0061$$ → consistent with zero!

The accelerated expansion of the Universe and the cosmological constant

The accelerated expansion of the Universe: Cosmological distances with supernovae

having the same physical mechanism of formation, type Ia SN have essentially the same intrinsic brightness, then their apparent brightness only depends on distance (“standard candles”)



The progenitor of a Type Ia supernova

Two normal stars are in a binary pair.

The more massive star becomes a giant...

...which spills gas onto the secondary star, causing it to expand and become engulfed.

The secondary, lighter star and the core of the giant star spiral inward within a common envelope.

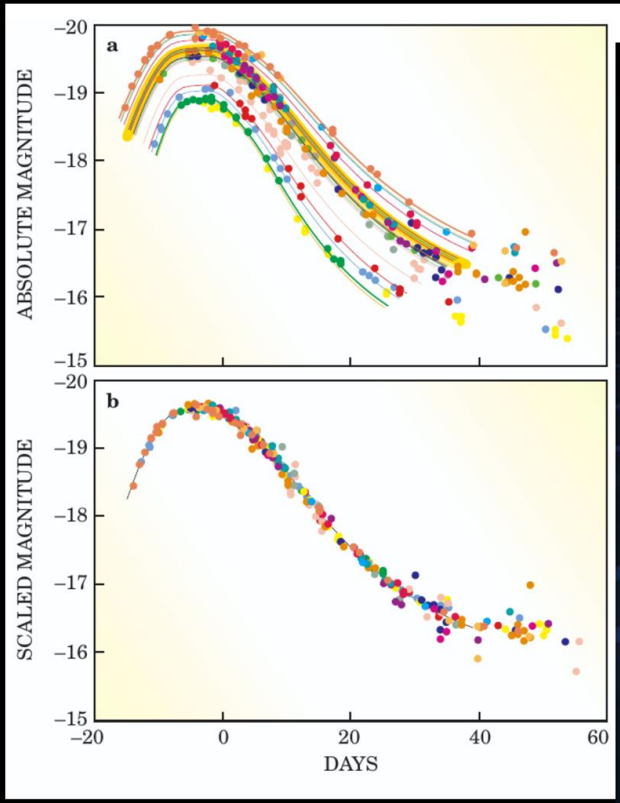
The common envelope is ejected, while the separation between the core and the secondary star decreases.

The remaining core of the giant collapses and becomes a white dwarf.

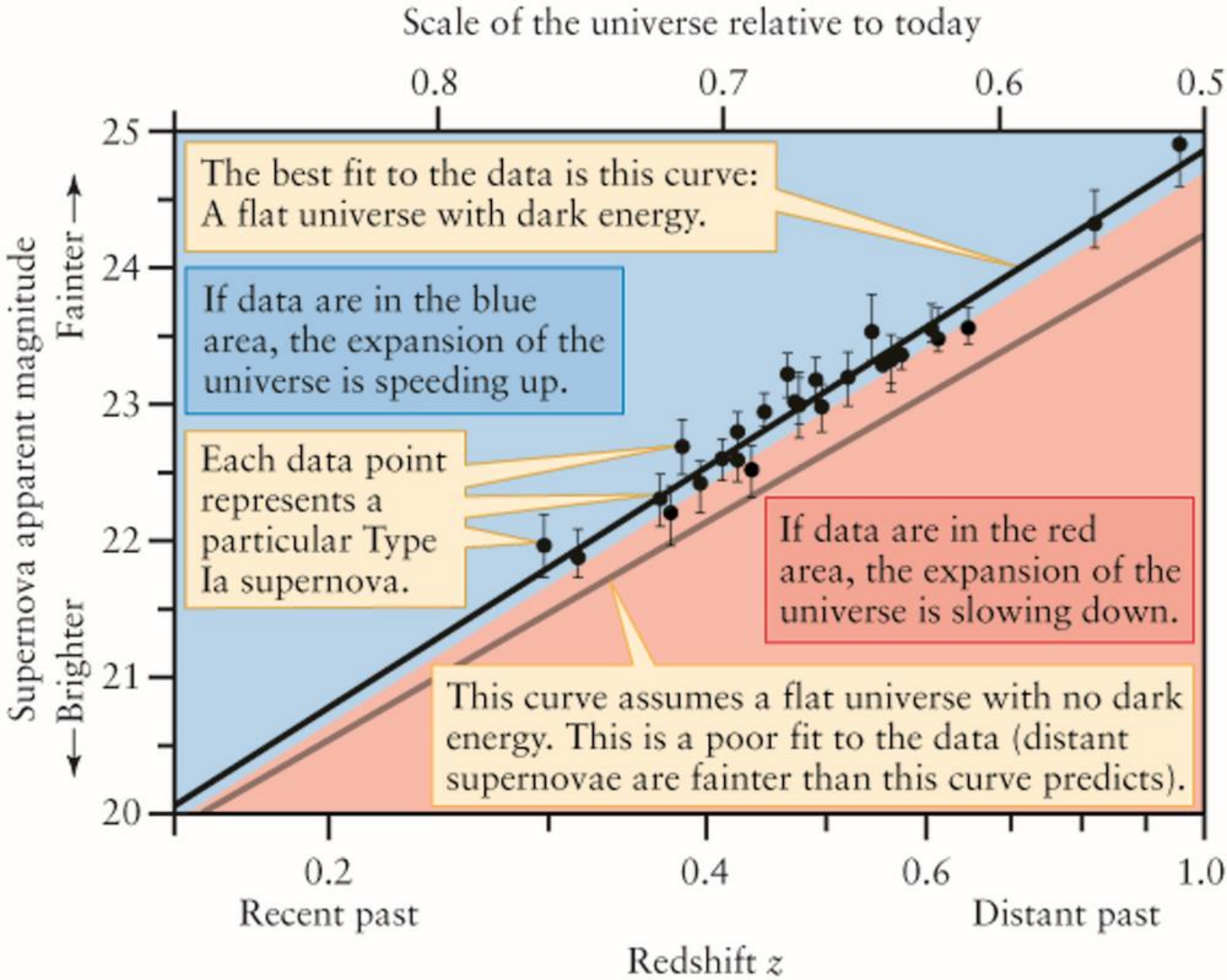
The aging companion star starts swelling, spilling gas onto the white dwarf.

The white dwarf's mass increases until it reaches a critical mass and explodes...

light curves of nearby type Ia SNe

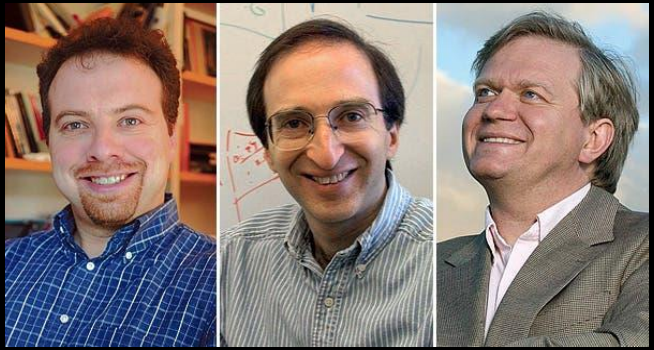


The accelerated expansion of the Universe

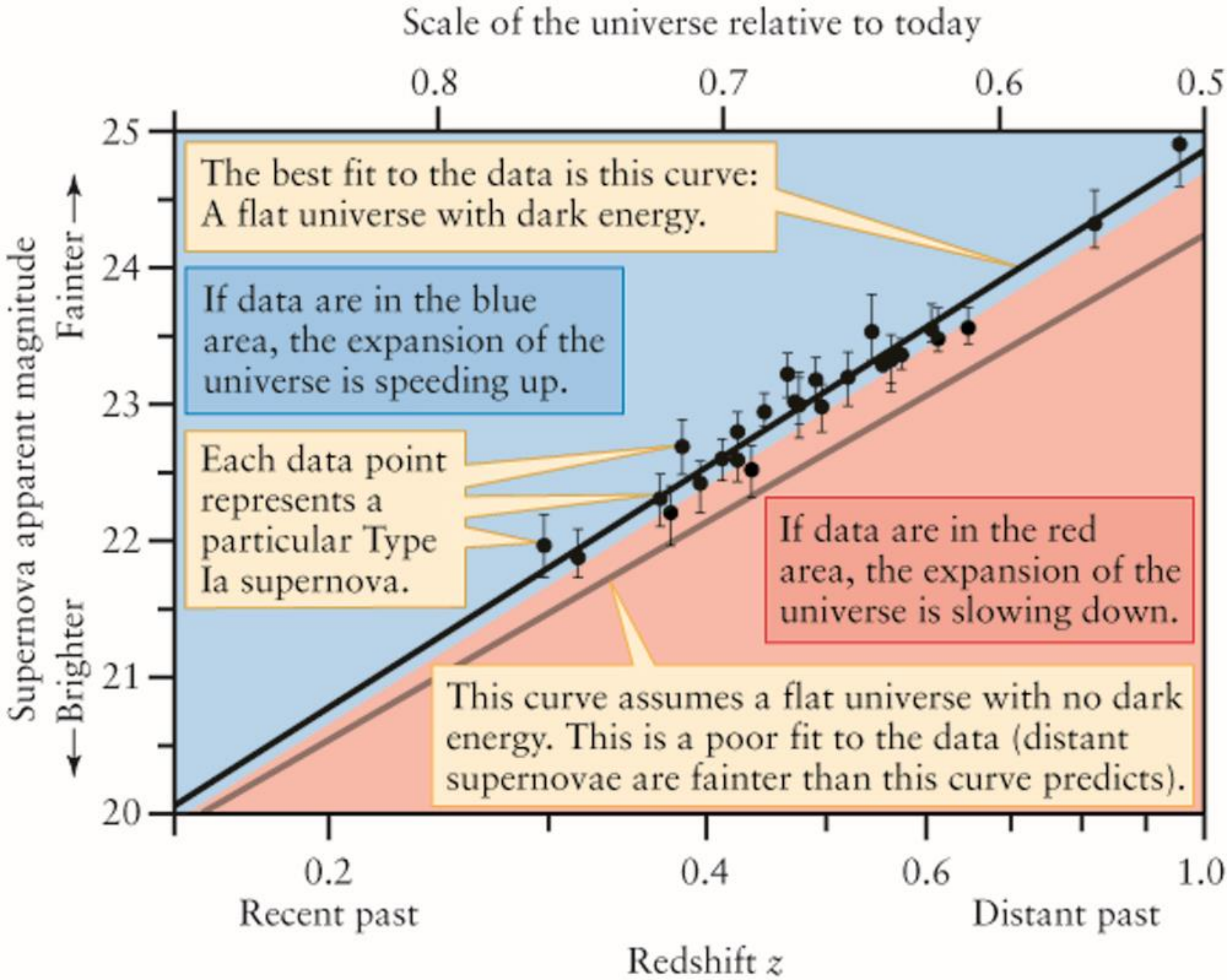


Perlmutter 2003

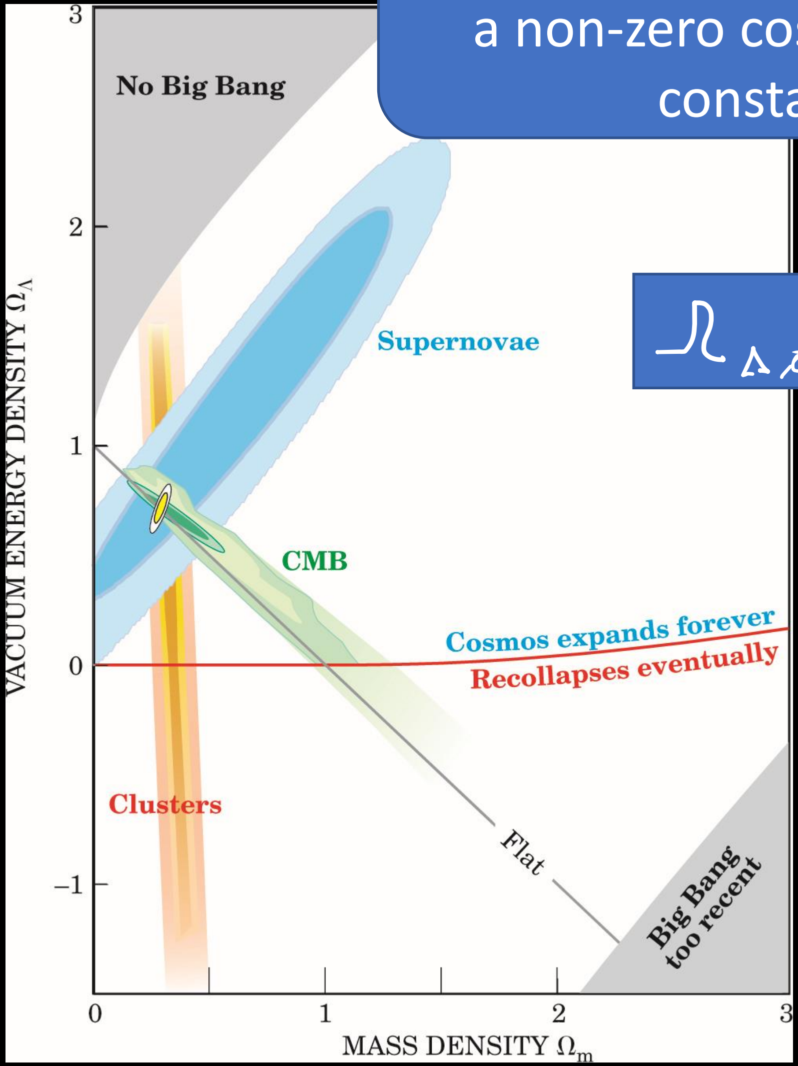
Nobel Prize in Physics 2011:
Riess, Perlmutter and Schmidt



The accelerated expansion of the Universe and the cosmological constant



Perlmutter 2003



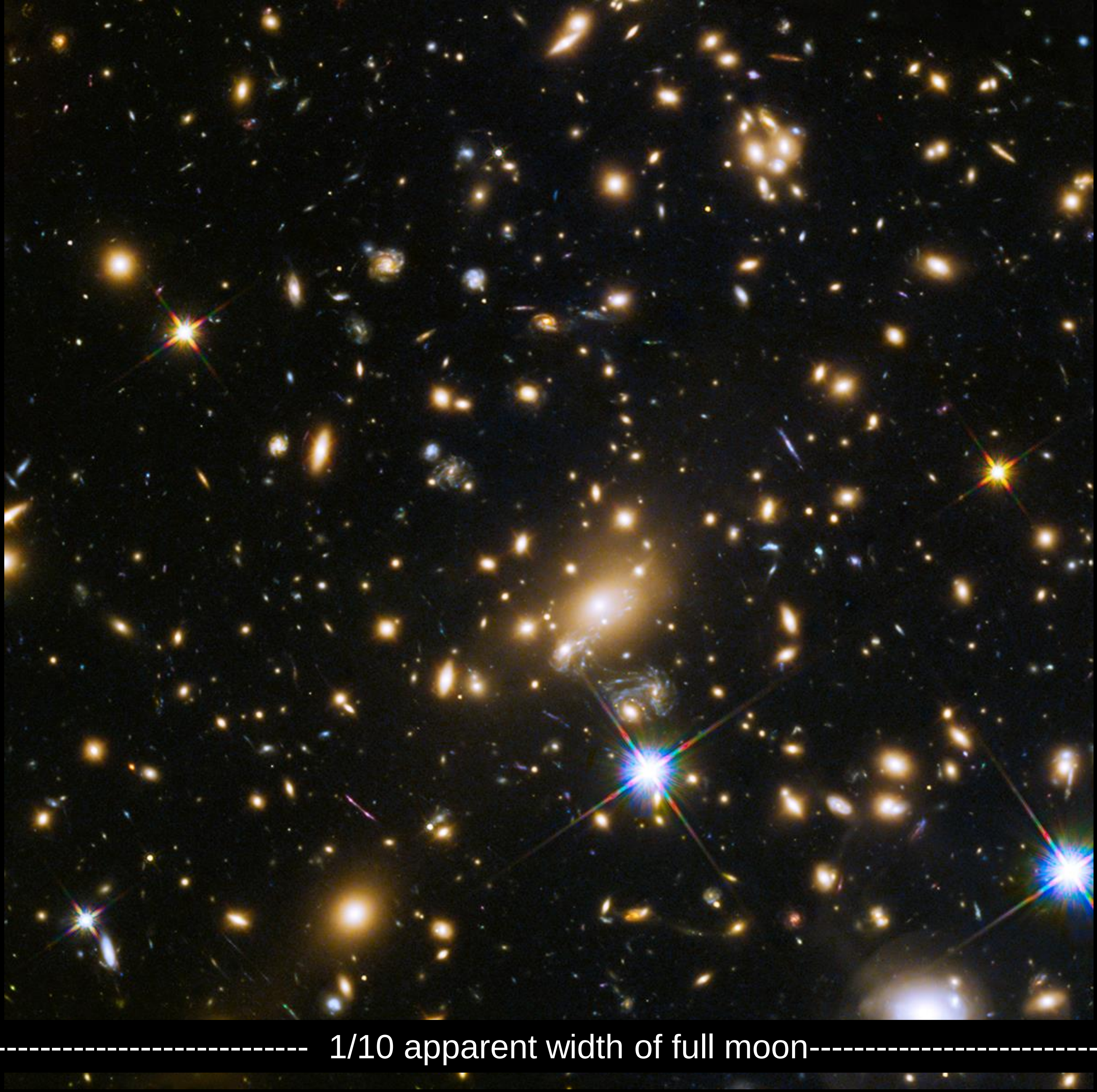
The accelerated expansion of the Universe implies a non-zero cosmological constant

$\Omega_{\Lambda 0} \sim 0.68$

Dark matter: evidence

modern cosmology in a single image

Galaxy Cluster MACS J1149.6+2223 z=0.54

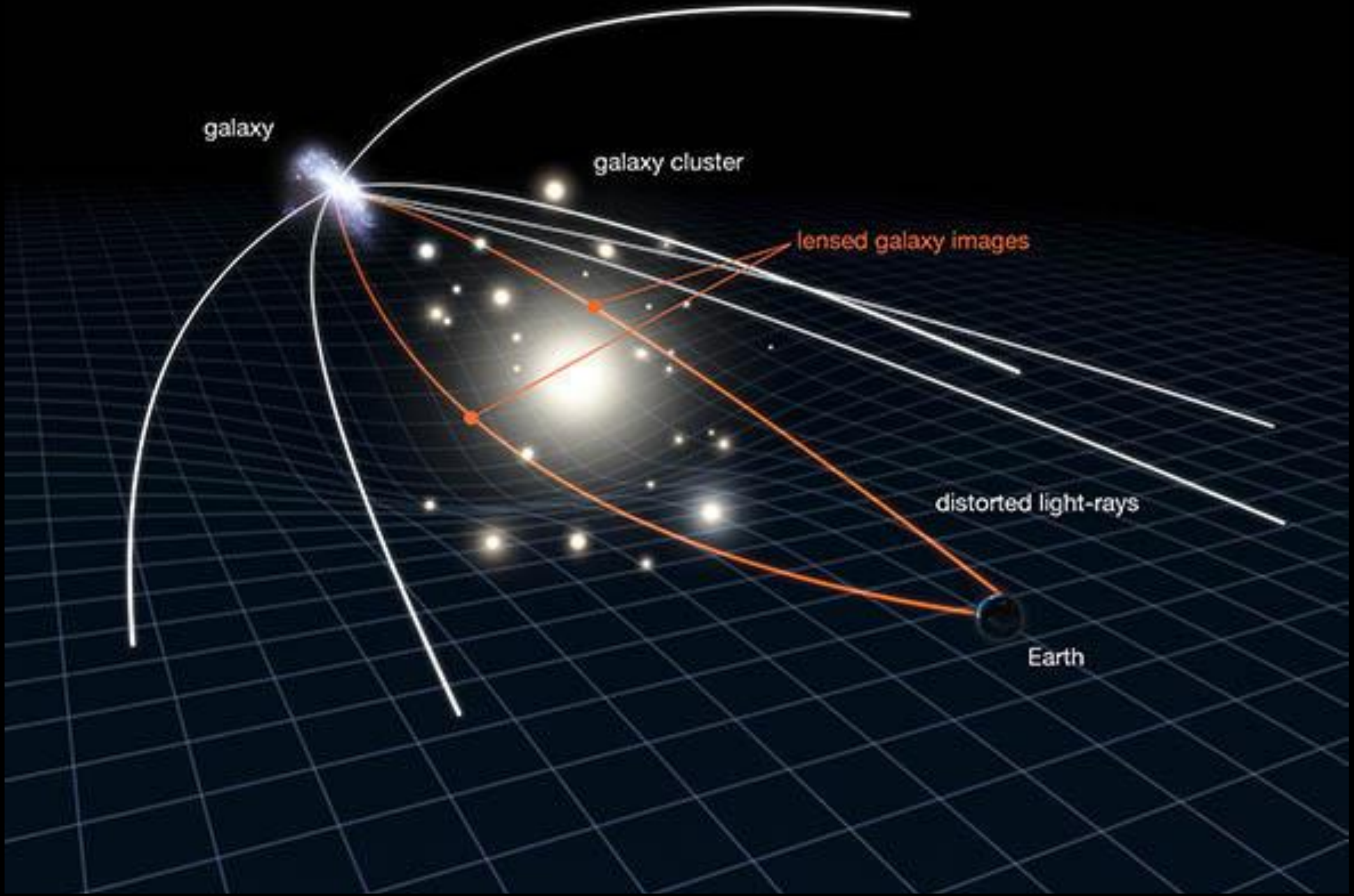


|--------------------------- 1/10 apparent width of full moon---------------------------|

Hubble
Space Telescope

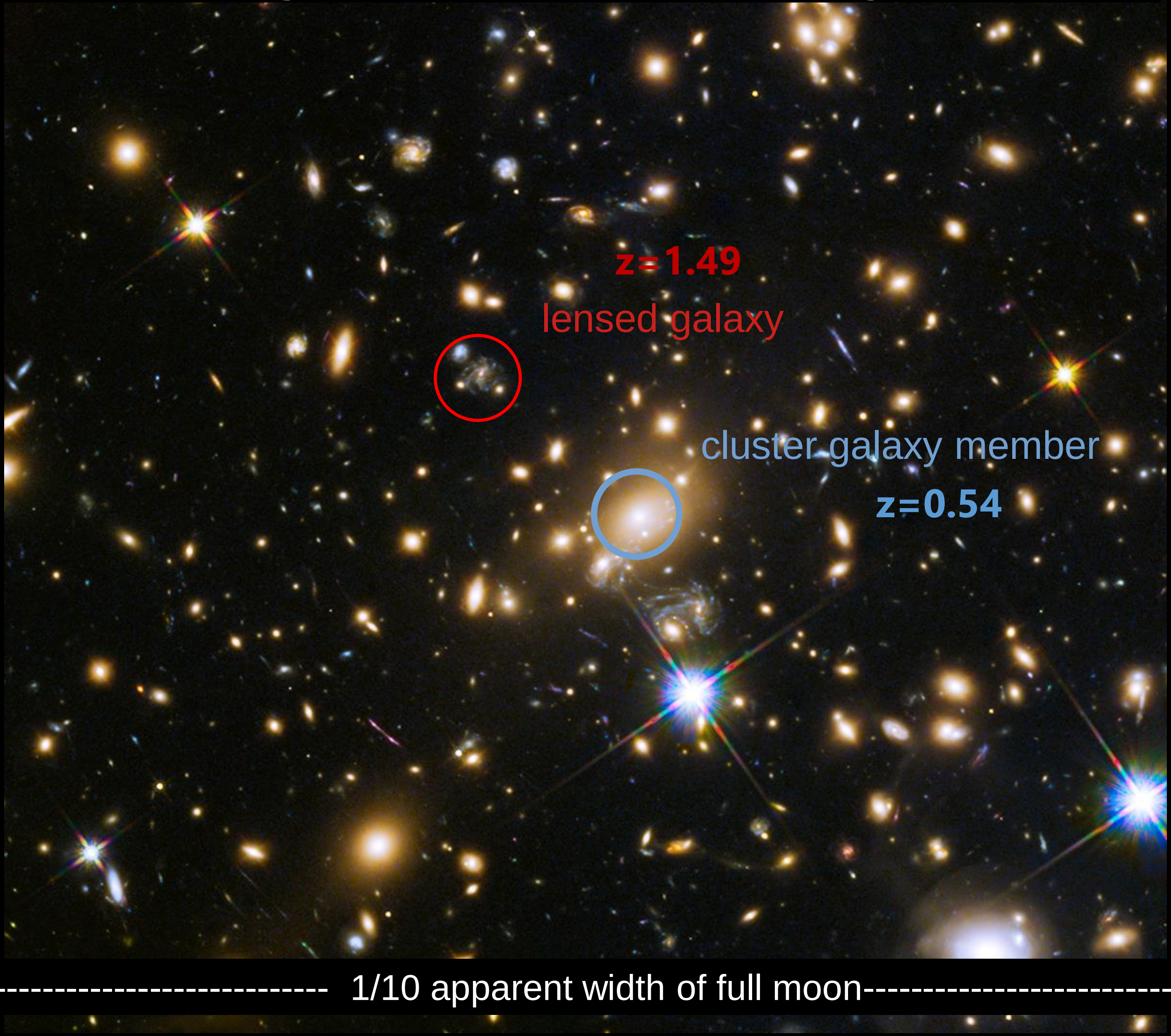
Gravitational Lensing

prediction from Einstein's General Relativity (1915)



the distorted image seen on Earth can be used to “weight” the intervening matter

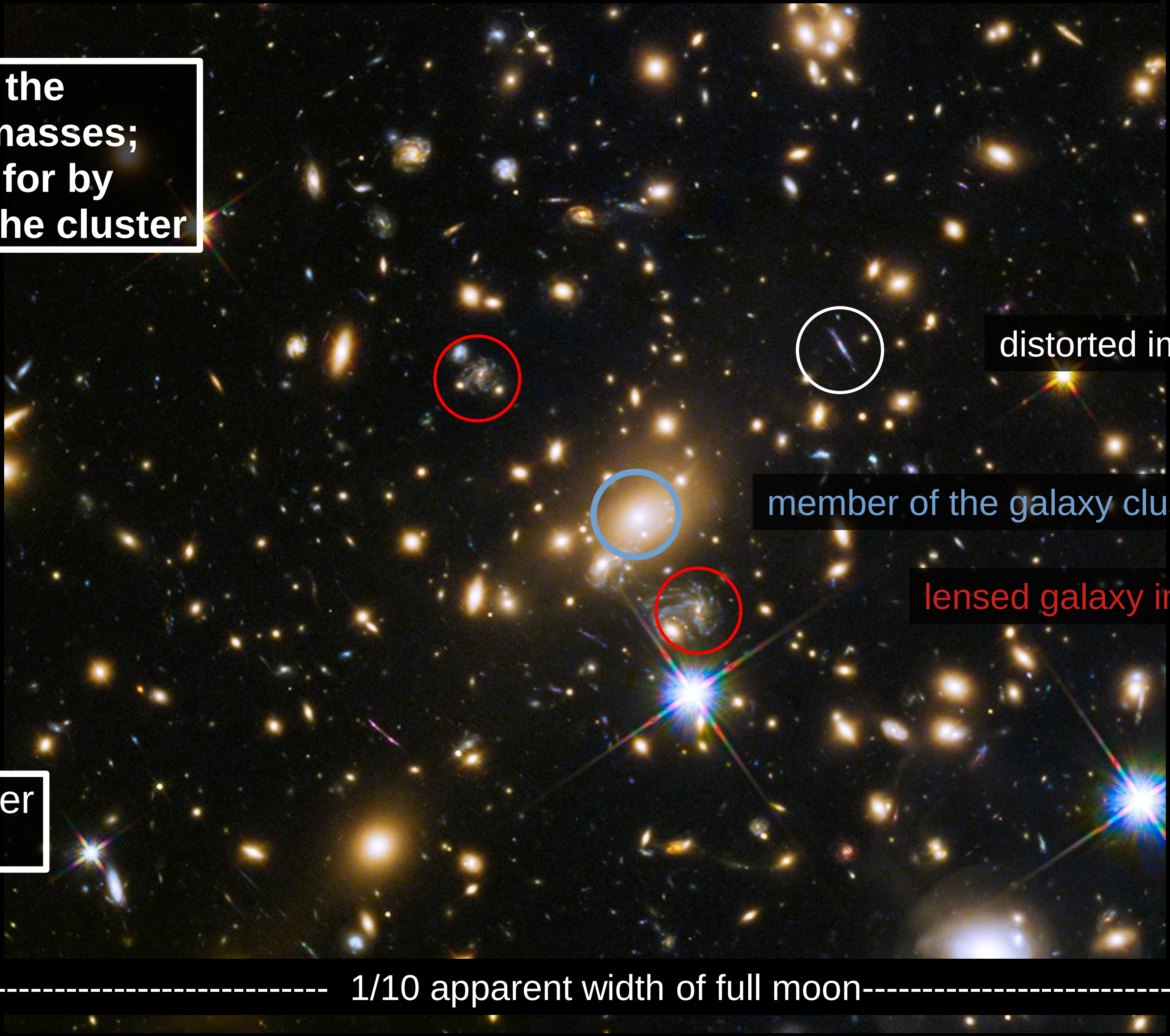
modern cosmology in a single image: gravitational lensing



|---------------------------- 1/10 apparent width of full moon----------------------------|

modern cosmology in a single image: dark matter evidence

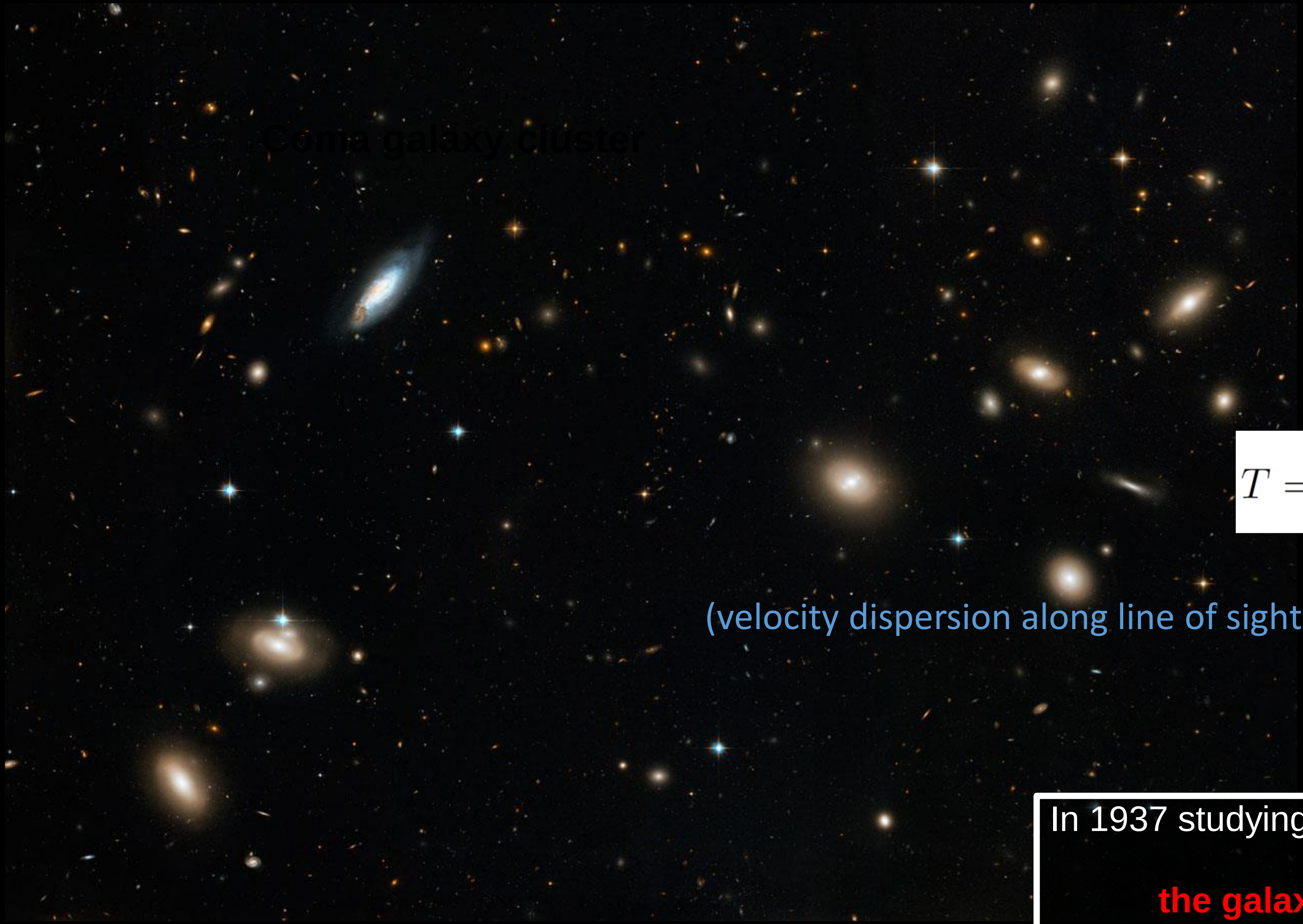
The intervening matter in the galaxy cluster is ~10^{15} solar masses; only ~1% can be accounted for by the stars in the galaxies within the cluster



~300 galaxies belong to the cluster
~600 lensed galaxies

|---------------------------- 1/10 apparent width of full moon---------------------------|

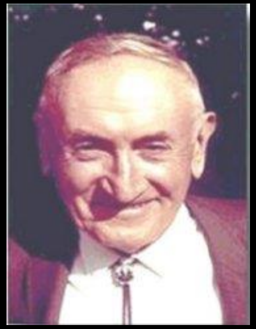
Dark Matter evidence: inner dynamics of galaxy clusters



Coma galaxy cluster

Virial equilibrium

2T+U = 0



Zwicky

$$T = \frac{3}{2} M \langle v_{\|}^2 \rangle$$

$$U \sim -G\frac{M^2}{R}$$

(velocity dispersion along line of sight)^2

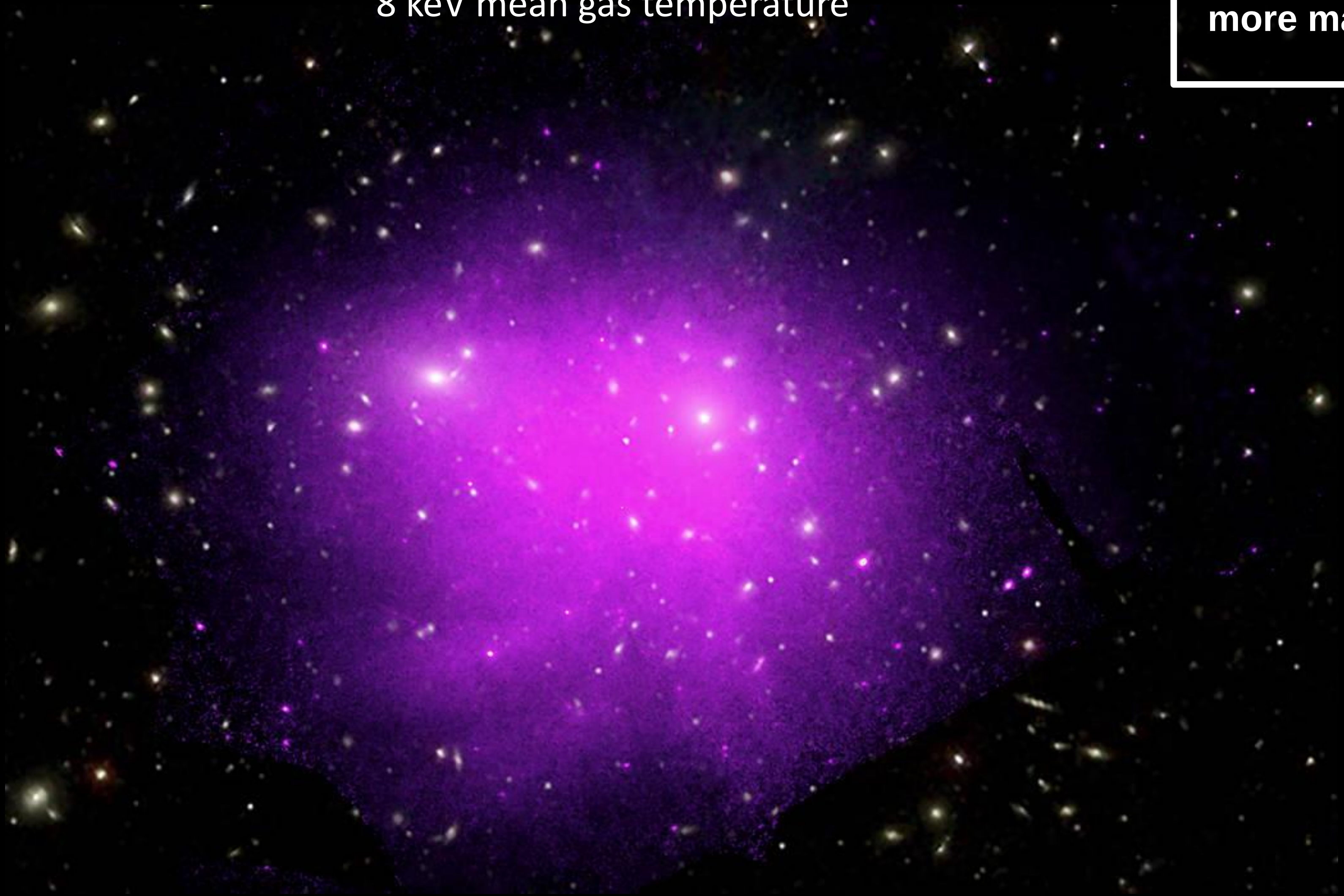
M = *total* mass

R = cluster radius

In 1937 studying the motions of the galaxies within Coma:

the galaxies move too fast for the cluster to be bound together by the visible matter; over 99% of the needed matter is invisible

Dark Matter evidence: hot gas in galaxy clusters



Hot gas in the Coma cluster as seen in X-ray emission
8 keV mean gas temperature

The hot gas in Coma contains about 6 times more mass than all galaxies in the cluster

Credit: X-ray: NASA/CXC/Univ. of Chicago, I. Zhuravleva et al, Optical: SDSS

Dark Matter evidence: hot gas in galaxy clusters

Hot gas in the Coma cluster as seen in X-ray emission
8 keV mean gas temperature

Credit: X-ray: NASA/CXC/Univ. of Chicago, I. Zhuravleva et al, Optical: SDSS

Hydrostatic equilibrium

→ Steady-state case of the Euler equation

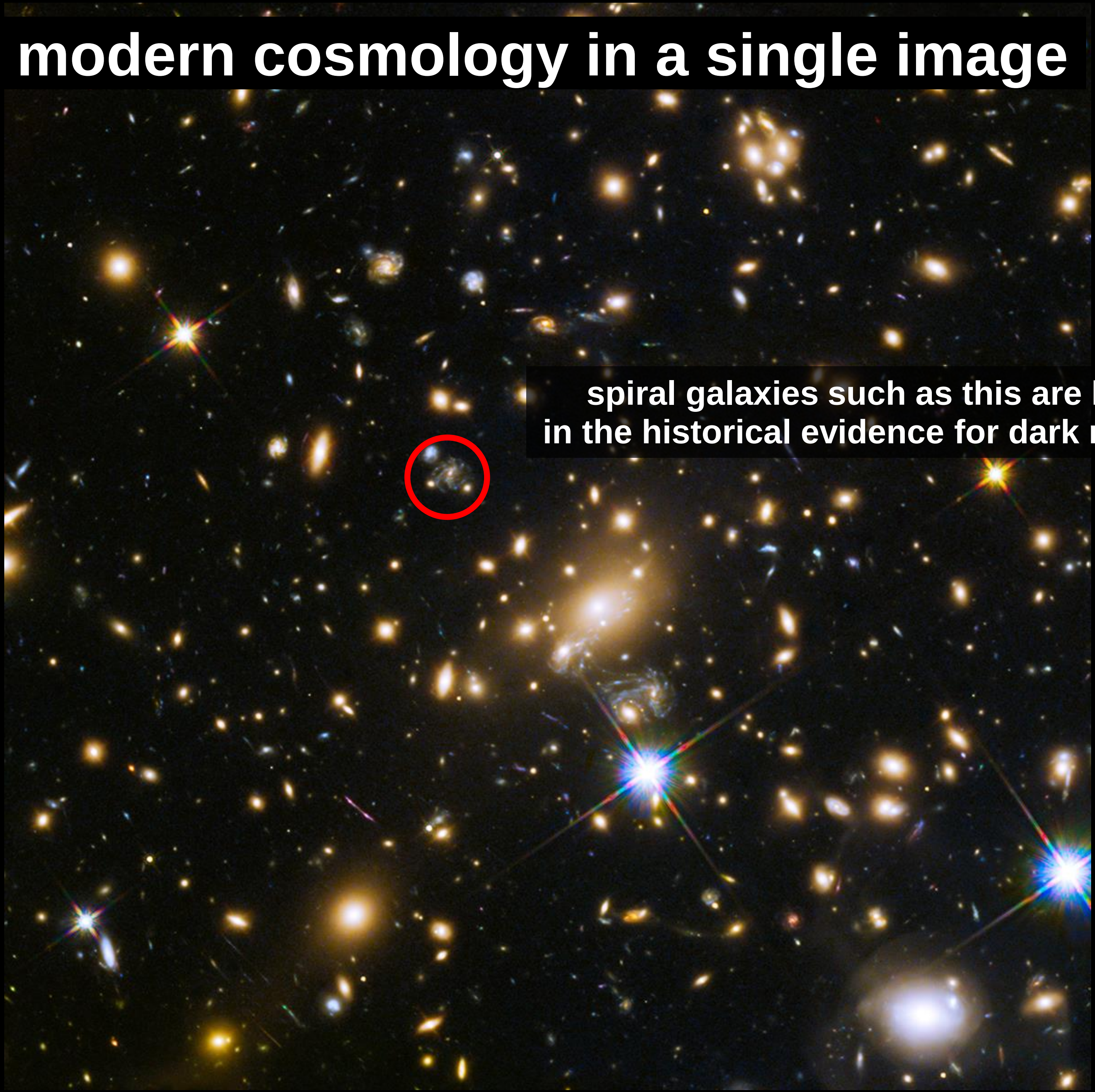
$$\underbrace{\nabla P_{gas}}_{\text{pressure gradient}} = \underbrace{-\rho_{gas} \nabla \Phi_{Total}}_{\text{gravitational force}} \quad \rightarrow \text{Total (DM + gas)}$$

→ Under spherical symmetry for an ideal gas:

$$M_T(<r) = -\left(\frac{k_B}{\mu m_p G}\right) T_{gas}(r)\, r \left\{ \frac{d\ln T_{gas}}{d\ln r} + \frac{d\ln \rho_{gas}}{d\ln r} \right\}$$

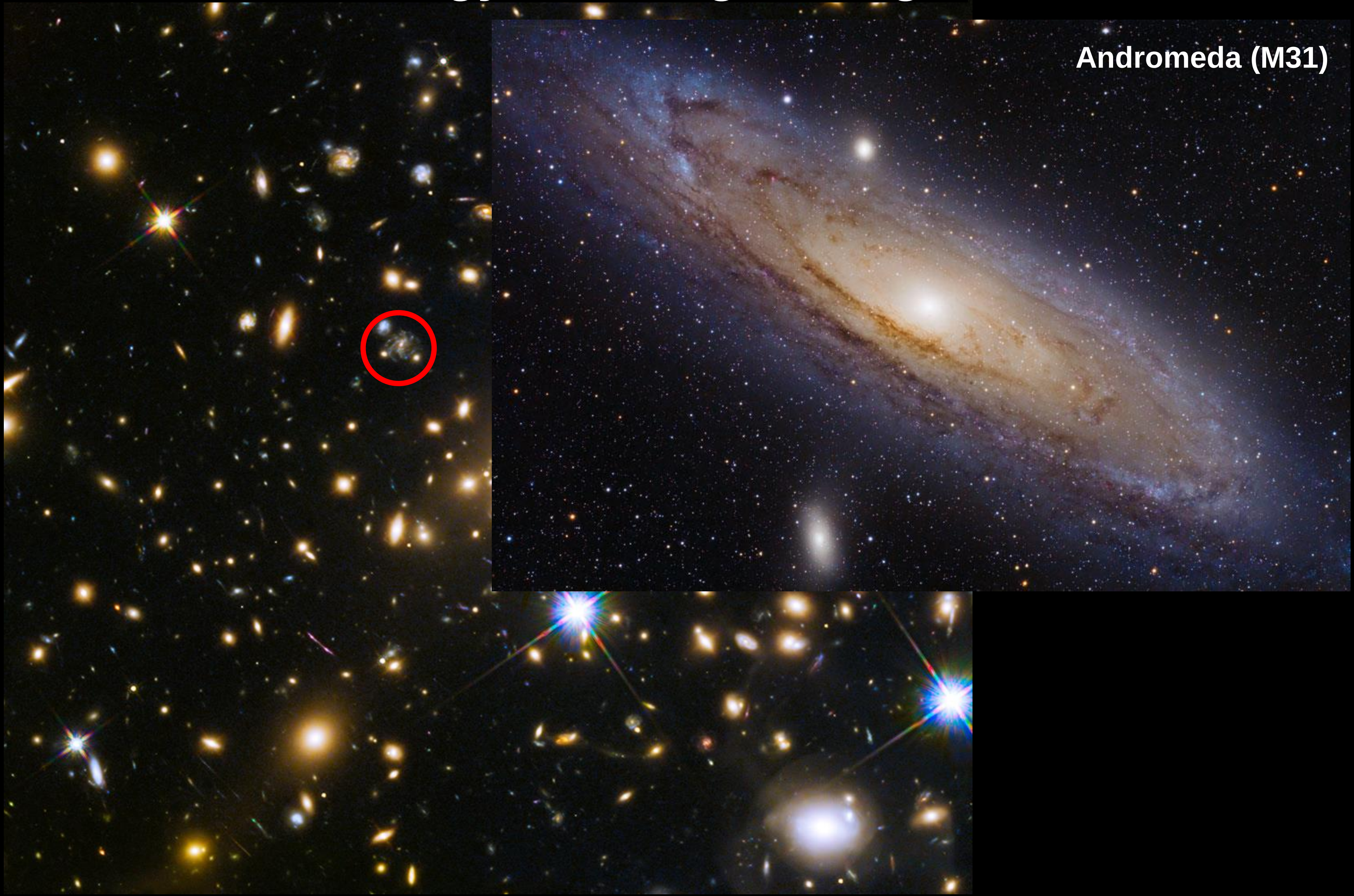
The total amount of mass in visible components (baryonic mass) is around 15%

modern cosmology in a single image



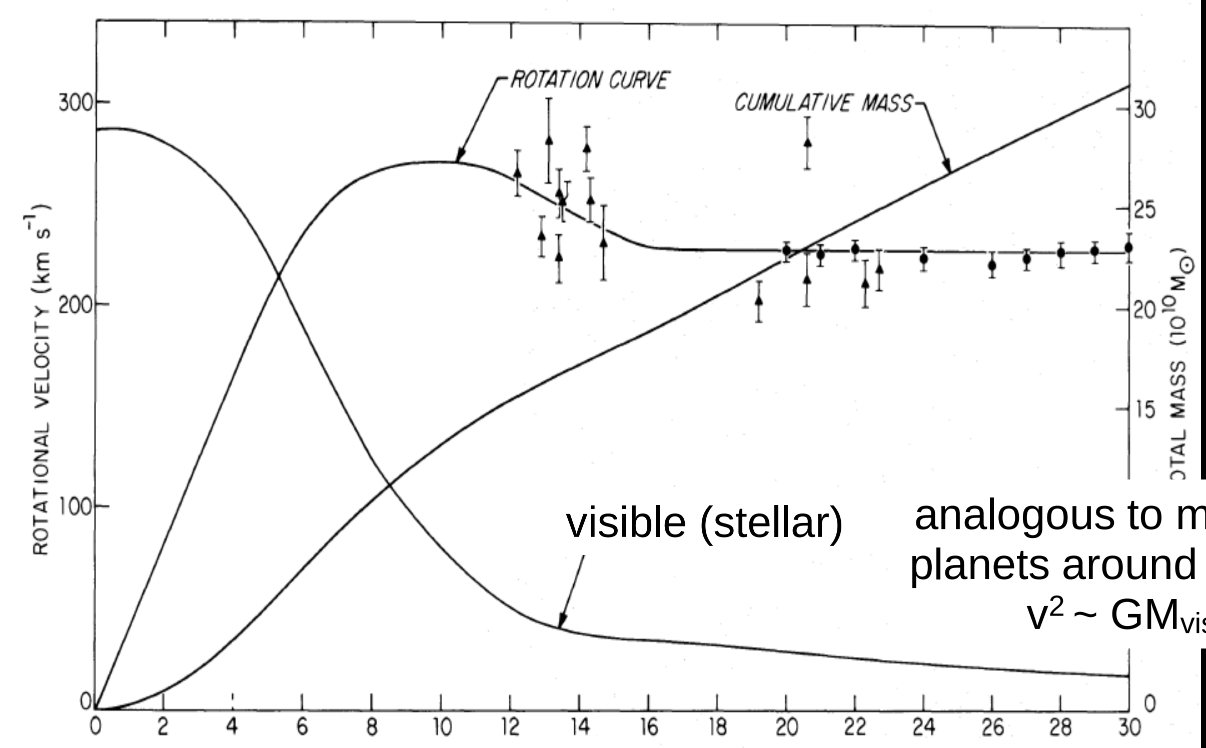
spiral galaxies such as this are key
in the historical evidence for dark matter

modern cosmology in a single image



Dark matter evidence: rotation curves in spiral galaxies

evidence from the rotation of galaxies since the 1970’s



visible (stellar)

analogous to motion of
planets around the Sun
$v^2 \sim GM_{vis}/r$

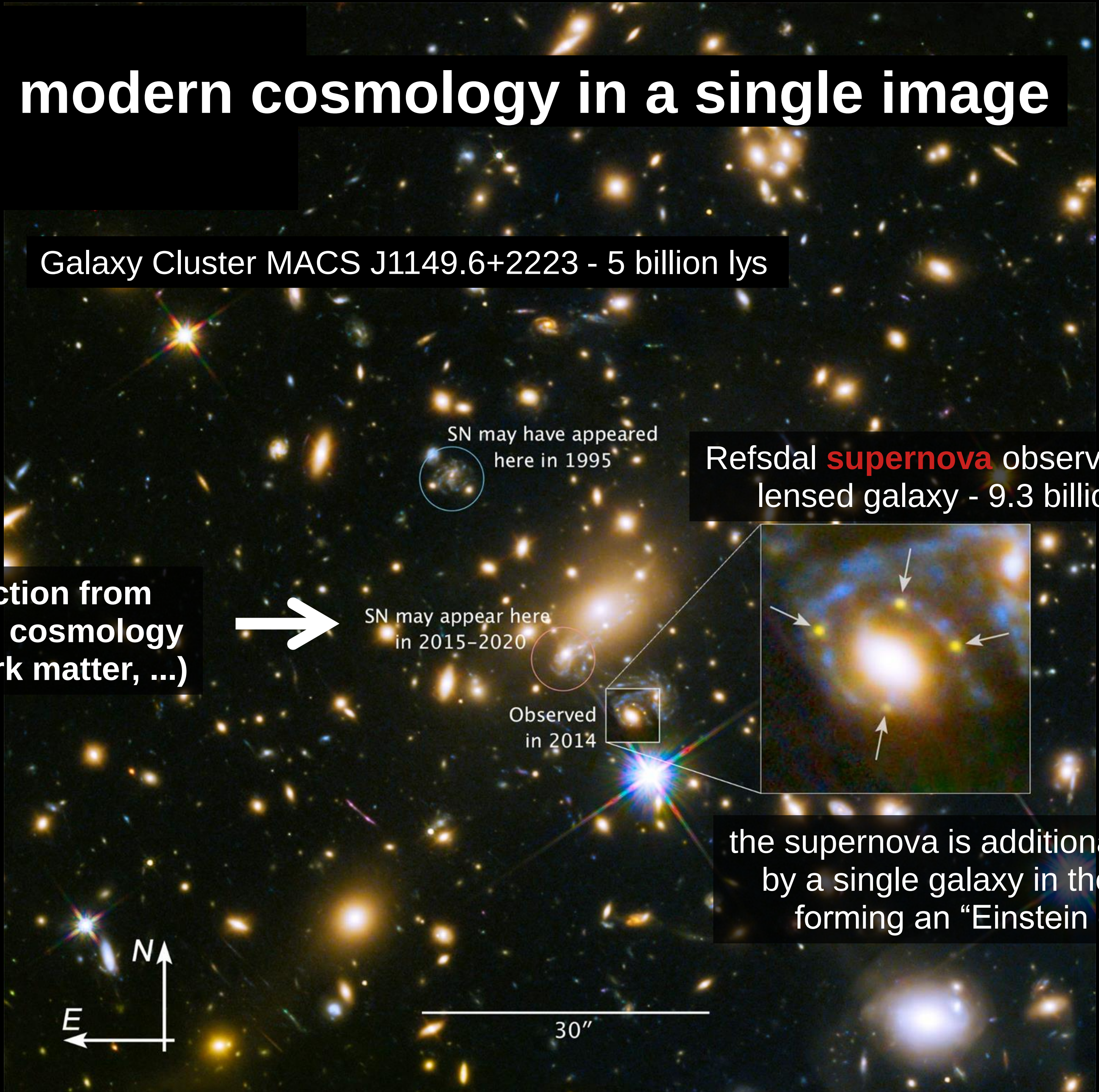
Rubin

In the 1970s studying the rotation of spiral galaxies:

the stars/gas in the galaxies rotates too fast
in the outskirts to be bound together by the visible matter
over 90% of the needed matter is invisible

modern cosmology in a single image

Galaxy Cluster MACS J1149.6+2223 - 5 billion lys



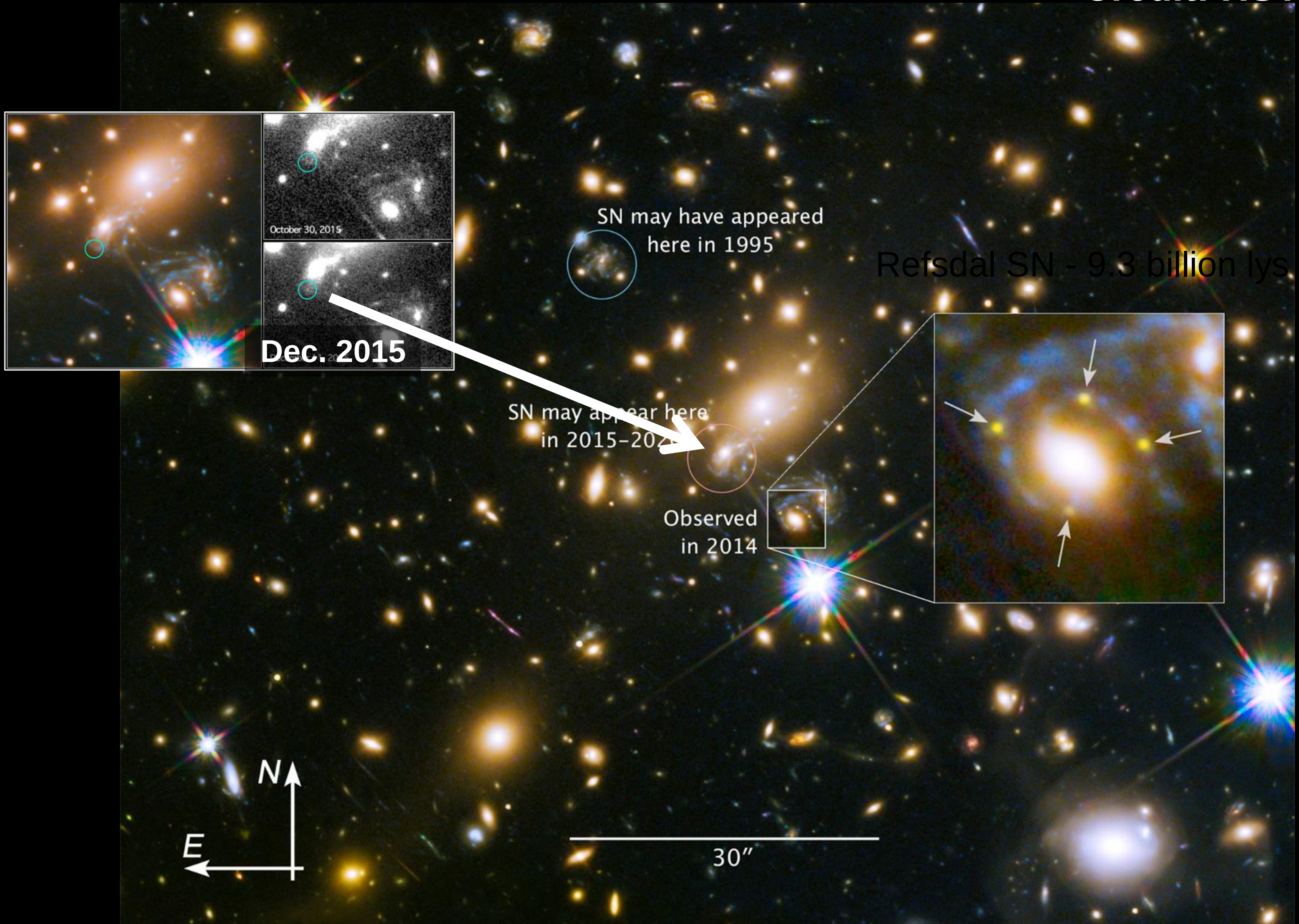
Refsdal **supernova** observed in the lensed galaxy - 9.3 billion lys

prediction from modern cosmology (GR, dark matter, ...) →

the supernova is additionally lensed by a single galaxy in the cluster forming an “Einstein cross”

A spectacular example of a GR effect and a strong indication of the existence of DM

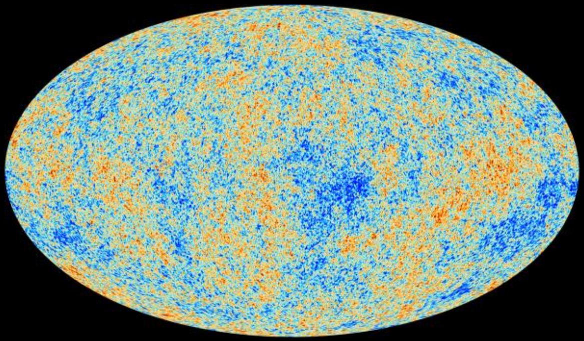
Credit: HST

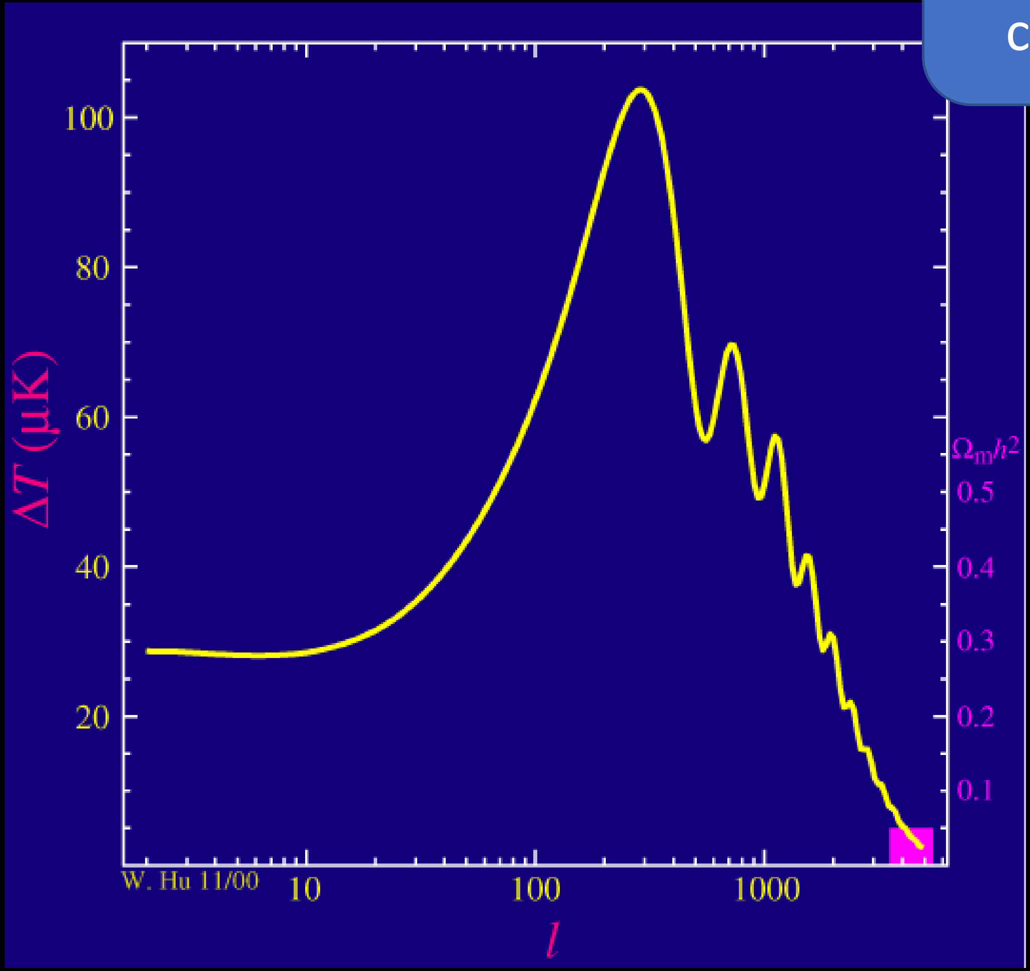


Dec. 2015

Refsdal SN - 9.3 billion lys

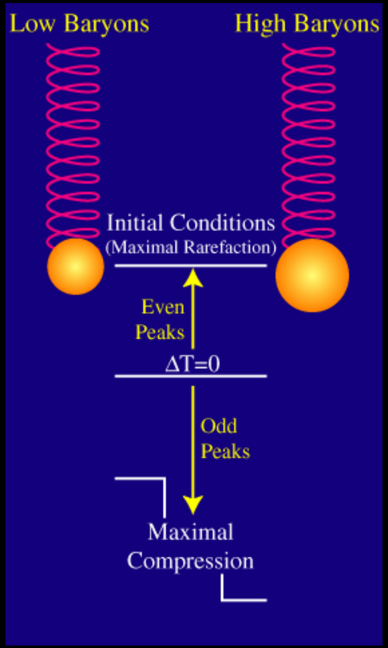
Dark Matter evidence: CMB



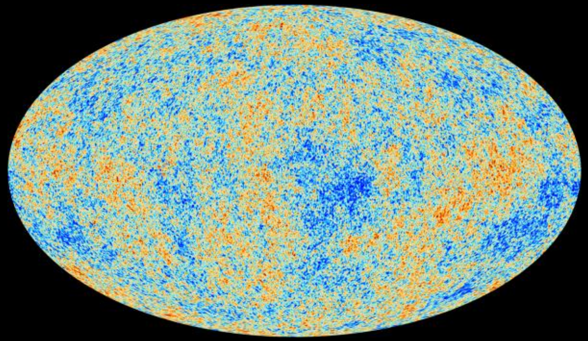


Credit: W. Hu

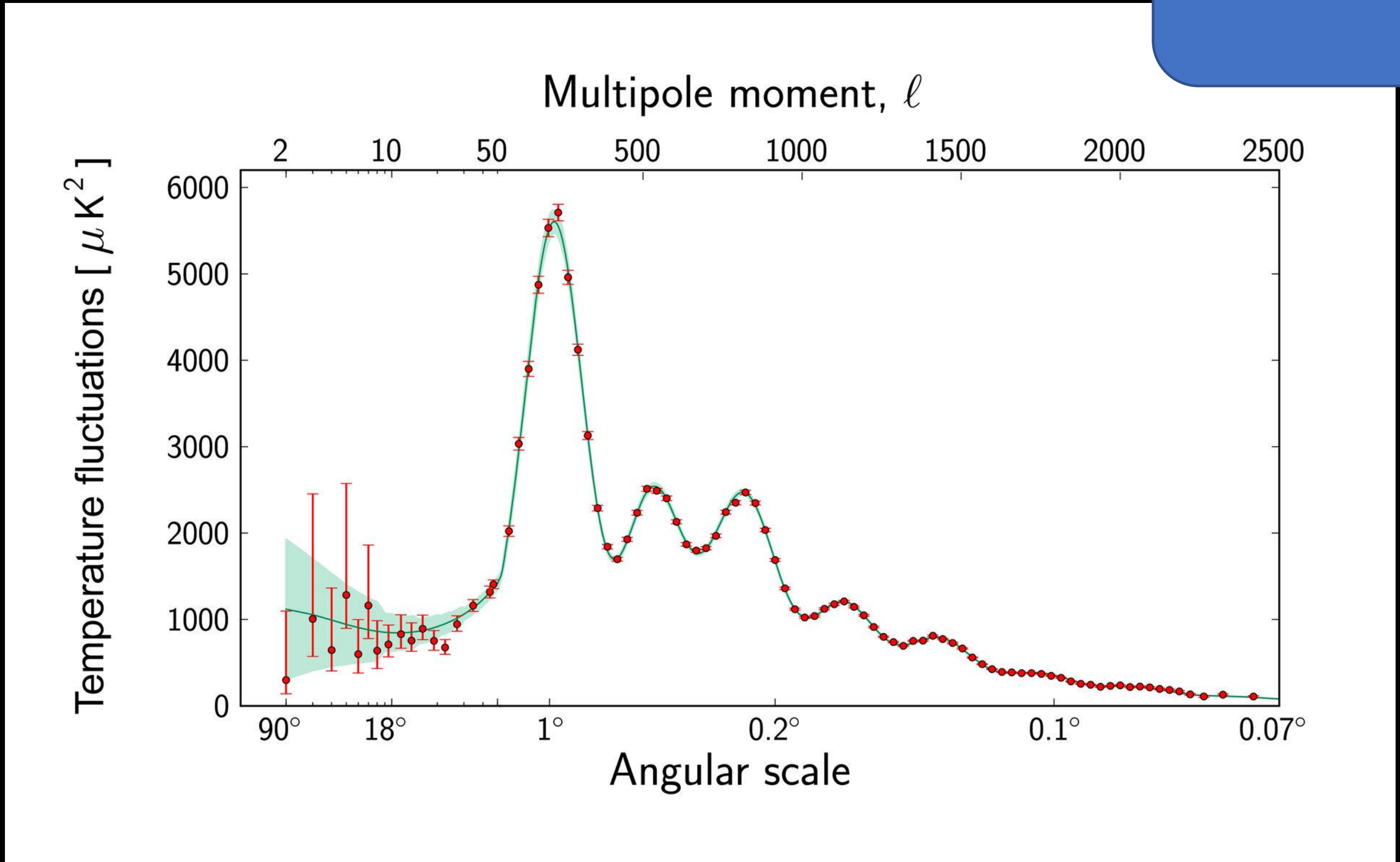
Increasing the amount of baryons reduces the ratio between compression and rarefaction peaks



As DM content increases, the expansion rate increases, reducing the epoch of photon decoupling and thus reducing the diffusion length: the damping of the peaks increases



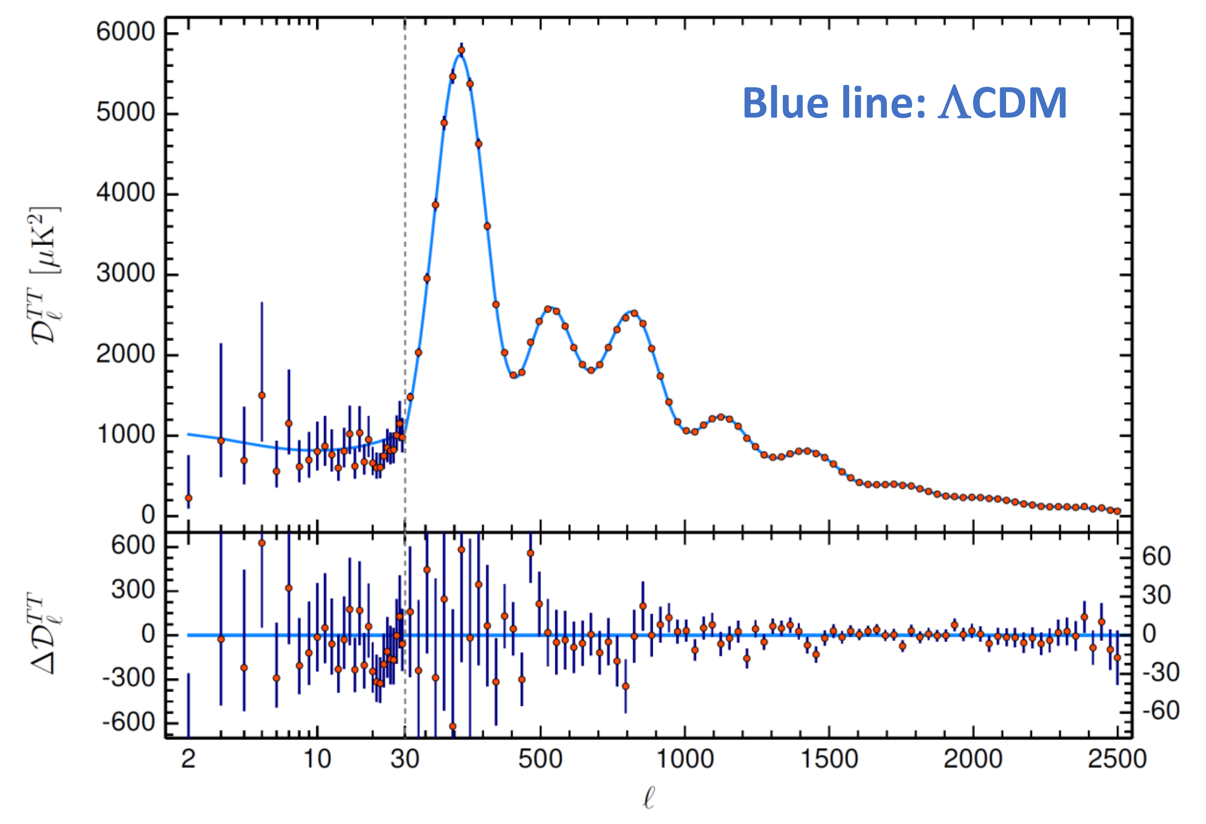
Dark Matter evidence: CMB



The relative amplitude between compression and rarefaction peaks (3^{rd} and 2^{nd}) is sensitive to the DM content

the ratio of baryonic to dark matter from CMB data is around 0.16

The ΛCDM model: evidence from the CMB



i) matter: $\Omega_{m,0}h^2 \sim 0.14$

ii) Hubble constant : $h \sim 0.67$

iii) curvature : $\Omega_{K,0} \sim 0$

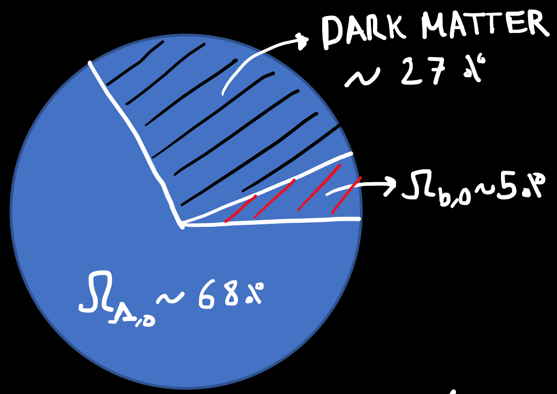
iv) radiation : $\Omega_{r,0}h^2 \sim 4.2\times10^{-5}$

v) baryonic matter : $\Omega_{b,0}h^2 \sim 0.022$

vi) dark matter : $\Omega_{c,0}h^2 \sim 0.12$

vii) cosmological constant : $\Omega_{\Lambda,0} \sim 0.68$

parameter fit to the data
or measurements of he
fundamental parameters?

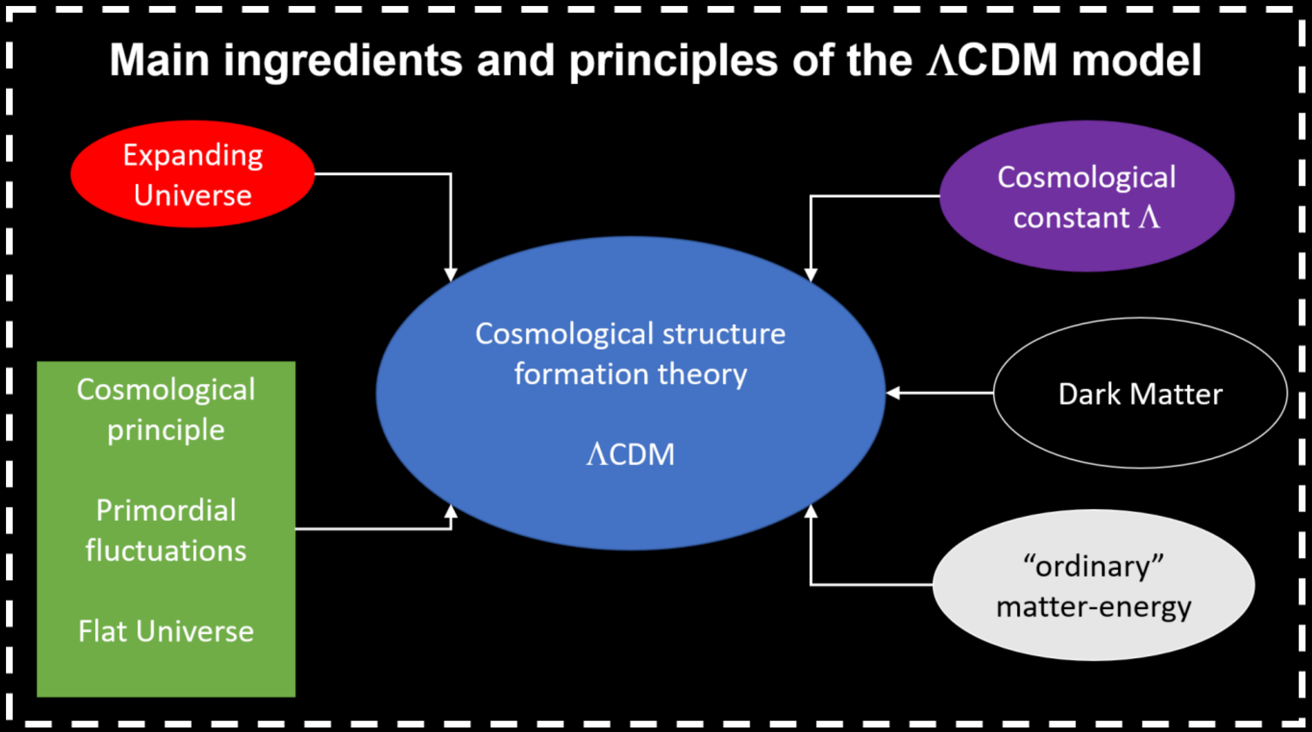


$\Omega_0 = \Omega_{m,0} + \Omega_{r,0} + \Omega_{\Lambda,0} = 1$

(Towards) the standard model of cosmology

Big Bang

Inflation



Main ingredients and principles of the ΛCDM model

Expanding Universe

Cosmological principle

Primordial fluctuations

Flat Universe

Cosmological structure formation theory

ΛCDM

Cosmological constant Λ

Dark Matter

“ordinary” matter-energy

Vacuum energy density
??

WIMPs
Sterile neutrinos
SIDM particles
Fuzzy DM
??

Closing thoughts on the ΛCDM model:

- The ΛCDM model is well established empirically by precision measurements from the CMB and other large scale structure observables
- Any competing models must behave like ΛCDM at large scales (more on this on my next lecture on Wednesday)
- Key principles adopted by the model require other theories for explanation: cosmological principle, flatness of the Universe, origin of fluctuations, expansion of the Universe,… require Big Bang and inflation
- Key parameters of the model remain unexplained, or there are too many explanations, perhaps all equally “exotic” (new physics)

Closing thoughts on the ΛCDM model:

- The ΛCDM model is a structure formation theory with an “effective parametrization” of its fundamental ingredients:

  - the ‘Λ’ in ΛCDM does not have to be a cosmological constant (e.g. quintessence), but it has to behave quite close to it.

  - the ‘C’ in ΛCDM stands for “cold” and “collisionless” dark matter, which is misleading since what the model actually requires is that DM interacts only gravitationally (down to galactic scales). This is a hypothesis that remains to be proven (more on this on the next lecture). Observations in the early Universe do not constrain this hypothesis strongly.