Basic Concepts of Cosmology

General introduction: main components of the Universe and their observational evidences

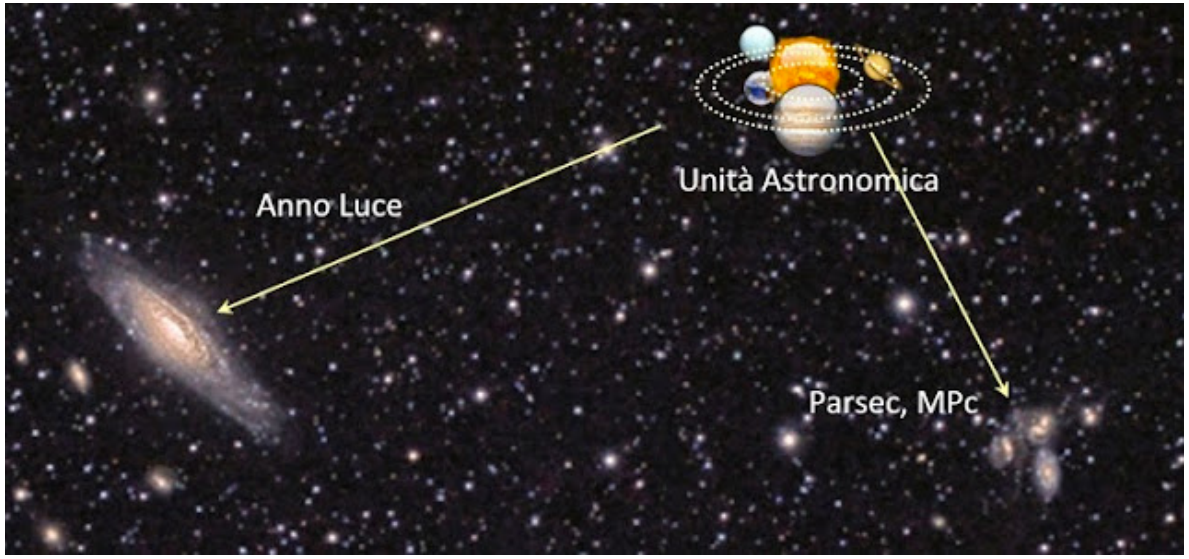
Basic concepts of Cosmology

- Cosmology is the study of the Universe (to be more precise of our observable Universe) on large scales.

- What do we mean by "large" scales? The typical separation of stars in a galaxy like the Milky way is of the order of a parsec (1 pc $\approx 3.086 \times 10^{13}$ km).
  The typical separation of bright galaxies is of the order of 1 Mpc.
  Therefore the typical scales one has in mind for cosmology are $l \geq$ 1 Mpc.

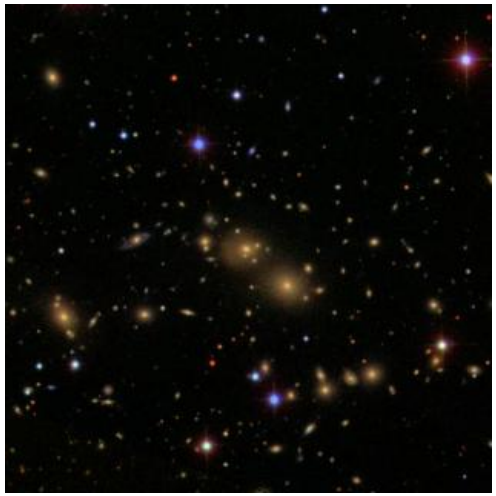
- We know that the universe is expanding (and right now the expansion is accelerated!!). Expansion is one of the pillars of what has emerged since the 1960s as the so called "standard Hot Big-Bang model": by that what we mean is an isotropic and homogeneous expanding Universe that in an early phase of its evolution is dominated by radiation, and the Universe has a temperature much larger than 1 MeV.

- On very large scales (say > 100 Mpc) we (to be more precise a comoving observer) observe, on average, a homogeneous and isotropic universe
  → Cosmologocial principle (we wll come back on this later)

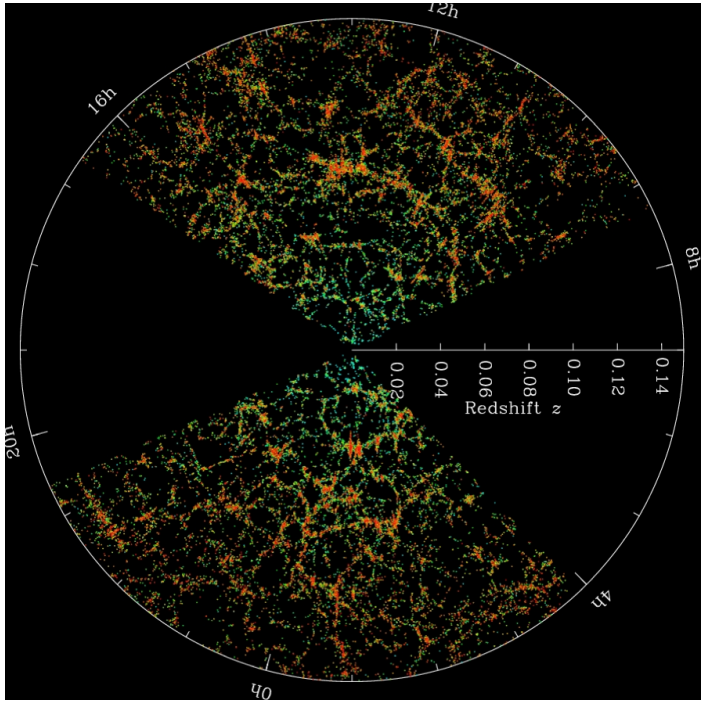


Large-Scale Structures

Rich cluster of galaxies



~10 Mpc



Nowadays can reach ~ 1000 Mpc

Basic concepts of Cosmology

- Indeed there are 3 main Observational pillars of the standard Hot Big-Bang model:
  Hubble diagram, Big-Bang nucleosynthesis, and the Cosmic Microwave Background (CMB) radiation with a *blackbody spectrum*

- *However in the last two decades of the 20th century there have been various developments – both observational and theoretical – that confirmed/pointed out to some elements that go beyond what we call "Hot Big Bang model" and that contributed to shape what nowadays is the well-established*
  Standard Model of Cosmology

- These elements are:
  - **dark matter and dark energy**
  - **large-scale structures in the Universe**: homogeneity and isotropy is just a zero-order approximation: the real physical universe we observe is characterized by **deviations from homogeneity & isotropy** (and equilibrium): these deviations are the different structures we observe
    e.g.: galaxies, clusters of galaxies, anisotropies in the temperature & polarization of the CMB
  - **inflationary models** as the generator of these perturbations

THE MAIN COMPONENTS OF THE *PRESENT* UNIVERSE: THE ΛCDM MODEL

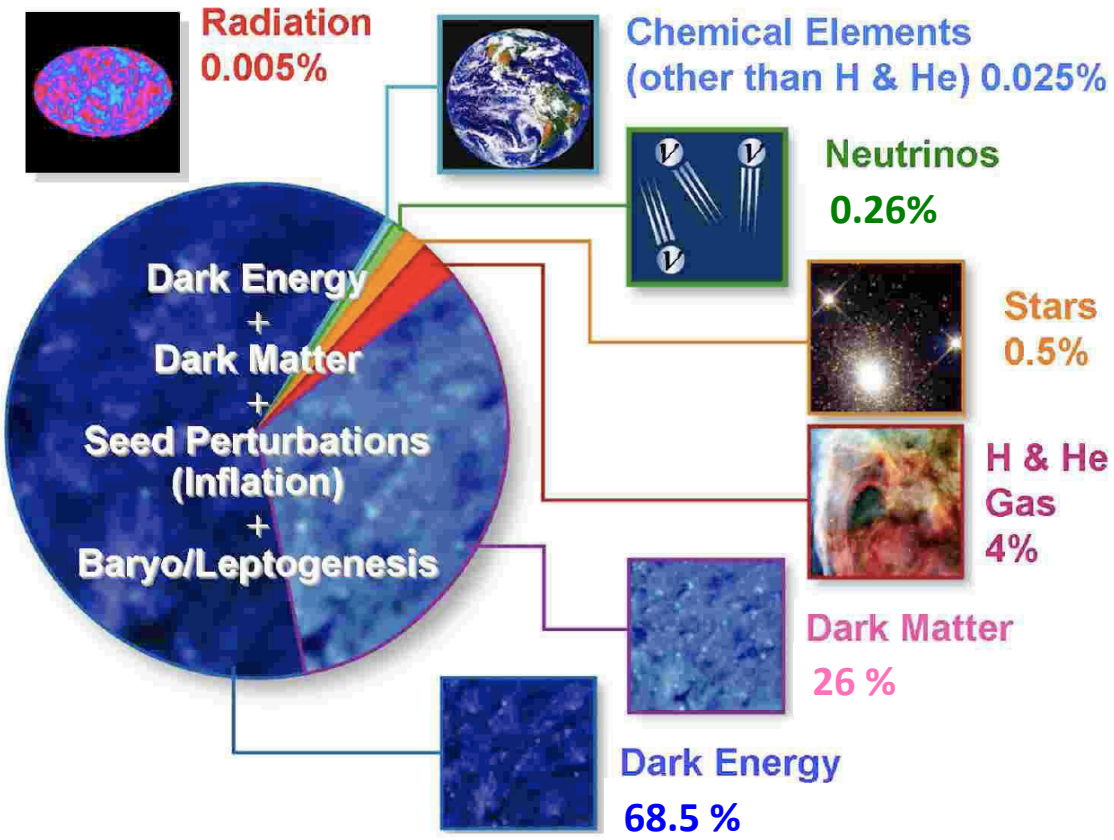
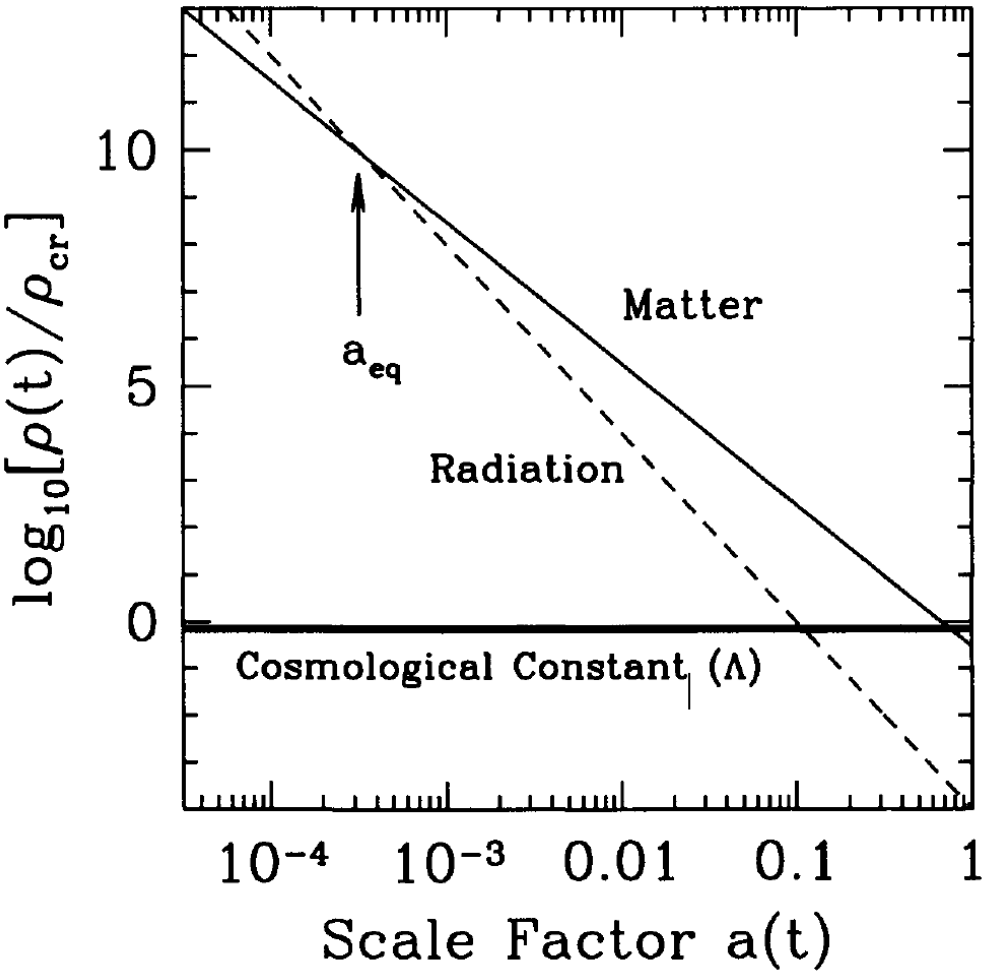


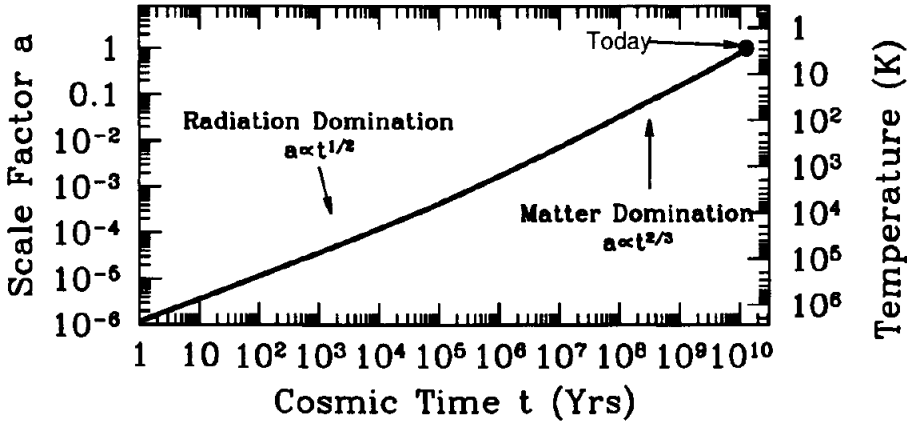
FIG. 1: Elements of the standard ΛCDM cosmological model. Illustrated by the pie is the fraction of the mass-energy of the Universe in various components. Also noted are some other necessary parts of the standard model, namely seed perturbations and baryo/leptogenesis.

Adapted from E.W. Kolb, arXiv:0709.3102 ``Cosmology and the unexpected''.

Evolution in an expanding Universe

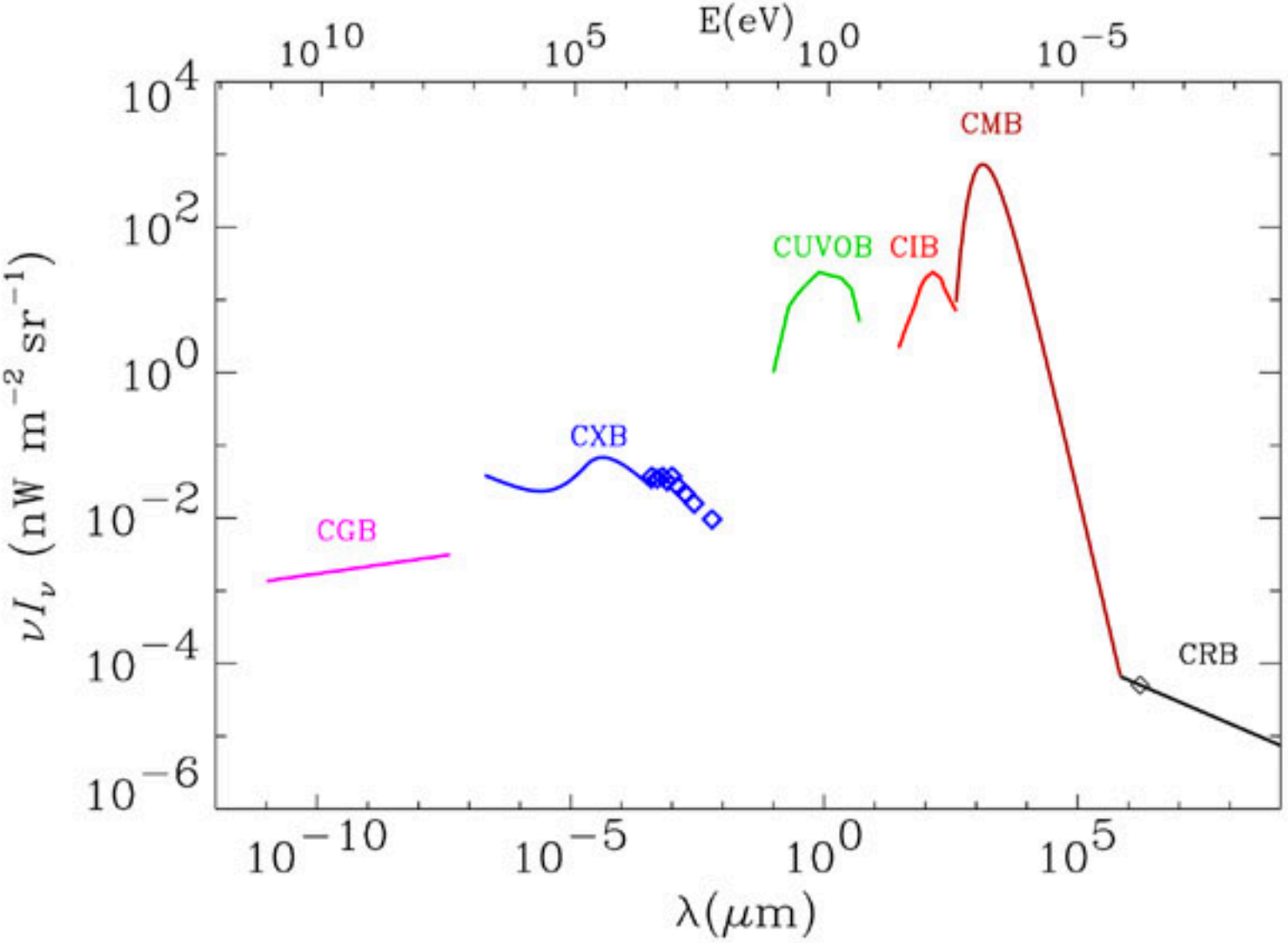


N.B.: here eq. stands for the epoch of equivalence between radiation and matter, i.. when the energy density of radiation is equal to that of non-relativistic matter



Adapted from S. Dodelson ''Modern Cosmology", Academic Press 2003.

COSMIC INVENTORY: PHOTONS



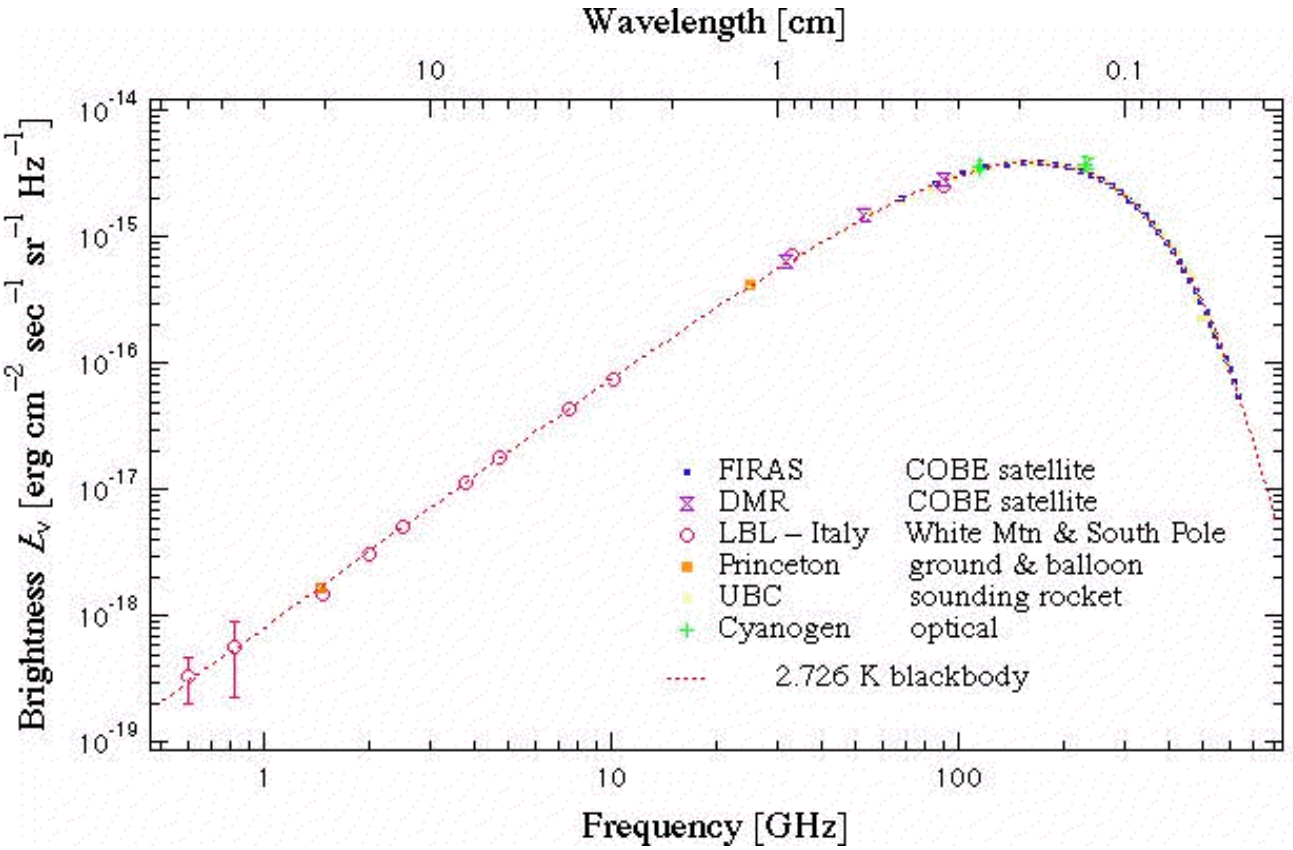
COSMIC INVENTORY: CMB PHOTONS

THE CMB INTENSITY SPECTRUM

Best fit T_0=2.725 ± 0.002K (95% CL)
No spectral distortions detected
(apart y-distortions from Sunyaev-Zel'dovich effect)

A ``perfect'' blackbody spectrum

$$I_\nu = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}}-1}$$



COSMIC INVENTORY: PHOTONS

A ``perfect'' blackbody spectrum $$I_\nu = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}}-1}$$

$$\rho_\gamma = \frac{4\pi}{c}\int d\nu I_\nu = \frac{8\pi h}{c^3}\int d\nu \frac{\nu^3}{e^{\frac{h\nu}{kT}}-1} \longrightarrow \rho_\gamma = \frac{\pi^2}{15}T^4$$

(I use c=k=ħ=1)

$$n_\gamma = \frac{4\pi}{c}\int d\nu \frac{I_\nu}{h\nu} = \frac{8\pi}{c^3}\int d\nu \frac{\nu^2}{e^{\frac{h\nu}{kT}}-1} \longrightarrow n_\gamma = \frac{2\zeta(3)}{\pi^2}T^3 \simeq 422\,\mathrm{cm}^{-3}$$

(If $T=T_0=2.725$ K)

N.B.:

$$\rho_{0crit} = \frac{3H_0^2}{8\pi G} = 1.88\,h^2\,10^{-29}\mathrm{g\,cm}^{-3} \simeq 8.1\times10^{-11}h^2(\mathrm{eV})^4$$

$$H_0 = 100\,h\,\mathrm{km\,sec}^{-1}\,\mathrm{Mpc}^{-1} = 2.133\times10^{-33}\,h\,\mathrm{eV}$$

$$H_0 = 67.4\pm0.5\ \ \mathrm{km\,s}^{-1}\,\mathrm{Mpc}^{-1}$$ ***(from the Planck satellite 2018 measurements)***

$$\Omega_{0\gamma} = \frac{\rho_{0\gamma}}{\rho_{0crit}} = \frac{\pi^2}{15}(2.725\,K)^4\frac{1}{8.1\times10^{-11}h^2\mathrm{eV}^4} \simeq 2.47\times10^{-5}h^{-2}$$

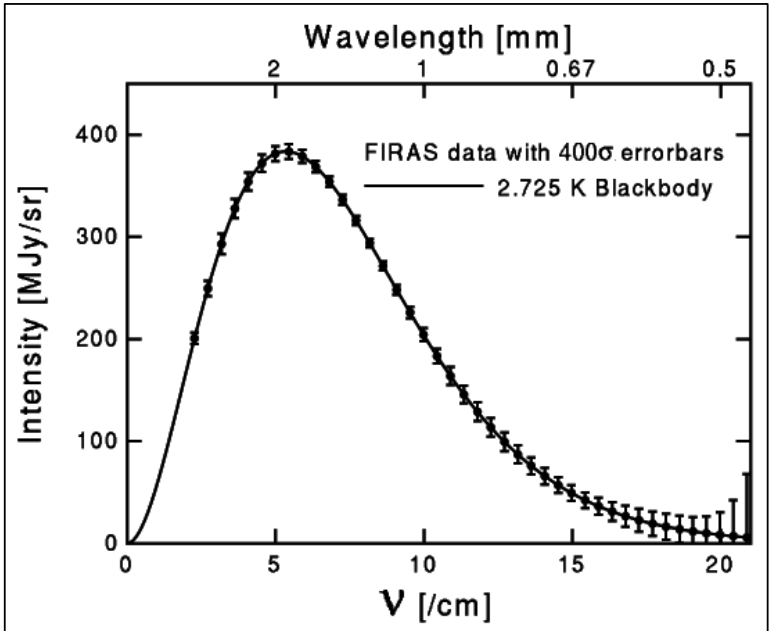
CMB spectral distortions

- However notice that…….we know there must be tiny deviations from a perfect black body of the CMB spectrum in the frequency domain

- Not detected yet (apart y-distortions from Sunyaev-Zel'dovich effect)

$$\frac{\Delta I_\nu}{I_\nu} < 10^{-4} \qquad y < 1.5\times10^{-5} \qquad \mu/T < 9\times10^{-5} \qquad (95\%\ \mathrm{C.L})$$

FROM COBE/FIRAS

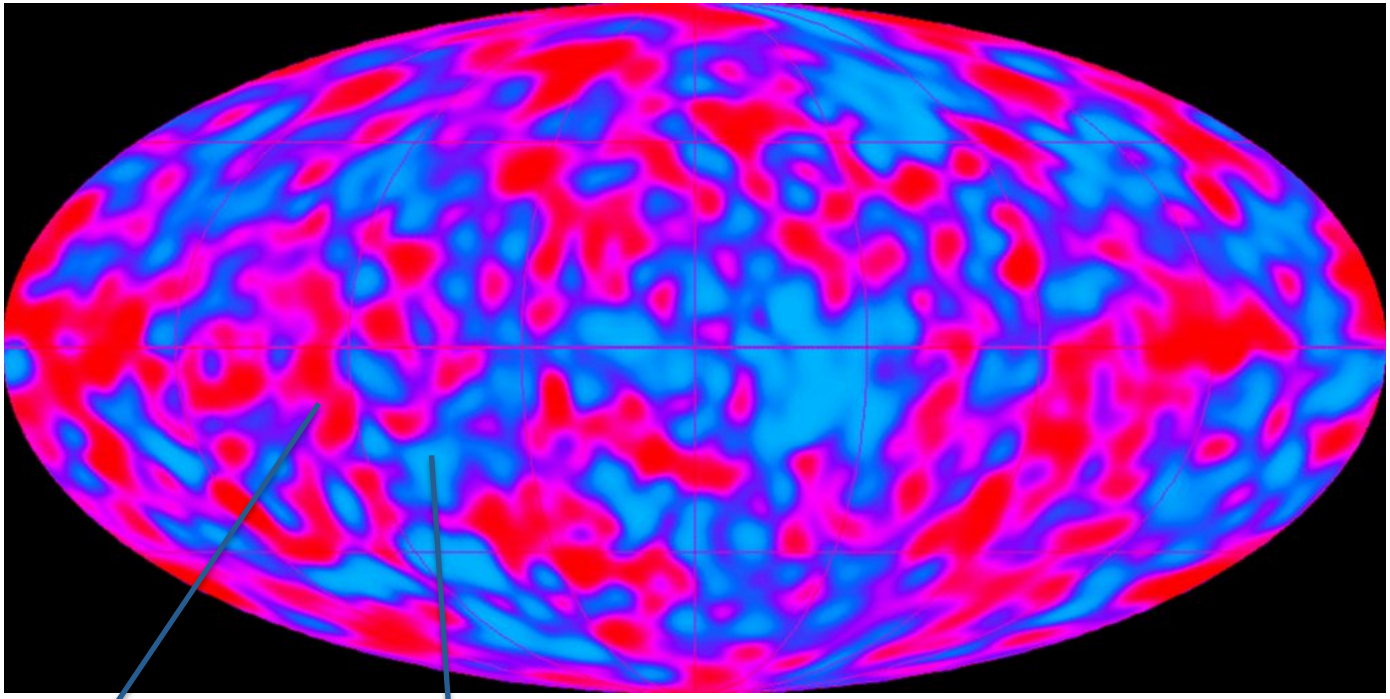


$$f = \frac{1}{e^{(h\nu-\mu)/k_BT} - 1}$$

e.g. standard cosmological model predicts μ-distortions ~μ/T~ 1.9×10^{-8}

The ALMOST ``smooth'' isotropic universe

Full-sky map of CMB temperature anisotropies from COBE-DMR satellite (1994)



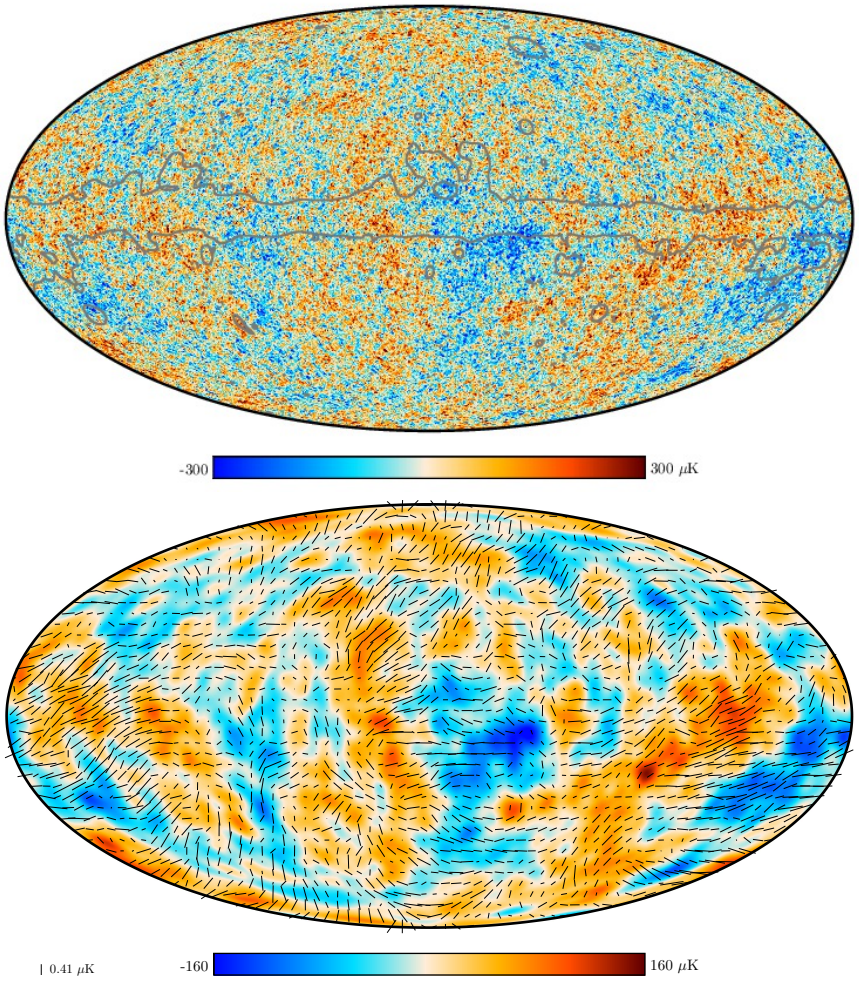
T=2.7251 K

T=2.7252 K

$$\frac{\Delta T}{\overline{T}}(t_0, \mathbf{n}) \equiv \frac{T(t_0, \mathbf{n}) - \overline{T}}{\overline{T}} \simeq \frac{35\,\mu K}{2.725 K} \simeq 10^{-5}$$

The ALMOST ``smooth'' isotropic universe

Full-sky map of CMB temperature anisotropies and polarization from *Planck* satellite (2018)



Angular resolution ~ 5 arcminutes

Planck 2018 Results. I. Overview and the cosmological legacy of Planck.

COSMIC INVENTORY: BARYONS

BARYONS

4 main methods to measure the baryon density

1. Observe baryons in stars and galaxies, via optical and X-ray radiation
2. Looking at spectra from distant quasars: light absorbed by intervening hydrogen (related to baryon density)
3. Primordial nucleosynthesis: we will se in details that the abundances of the first light nuclei strongly depends on the amount of baryons
4. Anisotropies in the temperature of the CMB photons strongly depends on the amount of baryons

Observations 3 and 4 are in excellent agreement. Typically Observations 1 provide an abundance of baryons that is smaller: indeed up to recently there has been a **"missing baryon problem"**. A common view, supported by various investigations is that most of the baryons are inside a diffuse gas in groups of galaxies (filaments connecting galaxies) at a temperature too low so that they can emit X-rays.

$$\Omega_b \, h^2 = 0.0224 \pm 0.0001$$ ***(from the satellite Planck 2018 measurements)***

COSMIC INVENTORY: MATTER…….DARK MATTER!

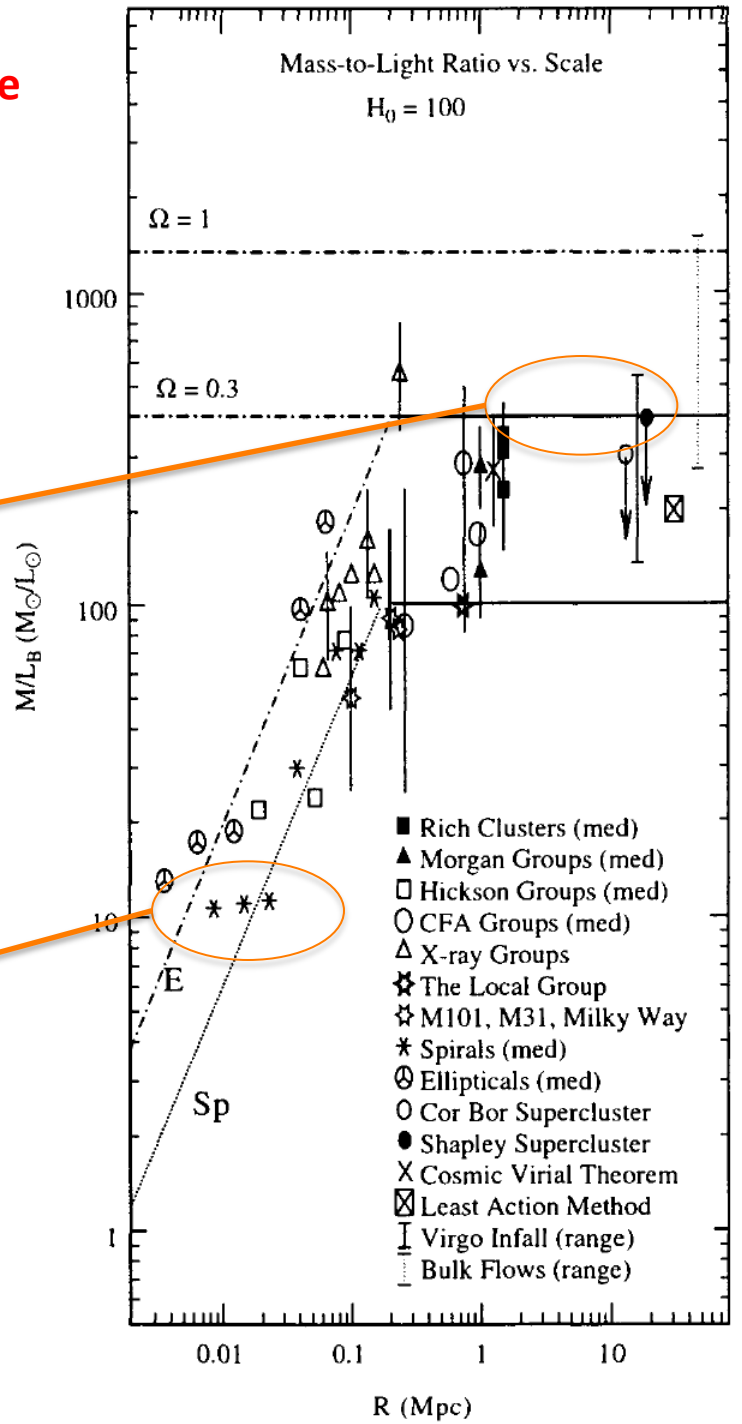
MATTER

The methods above to measure the baryon density all rely at some level on the interaction of matter and radiation, leading to "weighting" the visible part of the Universe.

However there are various methods that do not rely on how matter and light (more in general radiation) interact. In this case **typically one exploits the gravitational effects that matter determine, e.g. the gravitational field produced by a given system from which one infers the mass of the system.**

- These kind of measurements have paved the way to what we call "dark matter", i.e. matter (non relativistic-today) that does not interact (at least on cosmological scales), apart from just gravitationally, and therefore it is effectively pressurless and it is "dark" because it does not emit radiation.

Mass vs. light ratio as a function of scale



Scales of superclusters of galaxies

Scales of galaxies

(Bachall et al 2000)

DARK MATTER ON GALACTIC SCALES

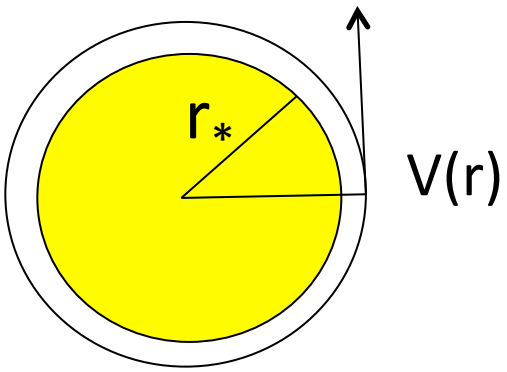
A reminder: Keplerian fall-off

Take rotational velocity in a spiral galaxy:

$$V^2(r) \propto \frac{M(r)}{r}$$

If only luminous matter: M(r) costant for $r > r_*$:

$$V(r) \propto \frac{1}{r^{1/2}}$$



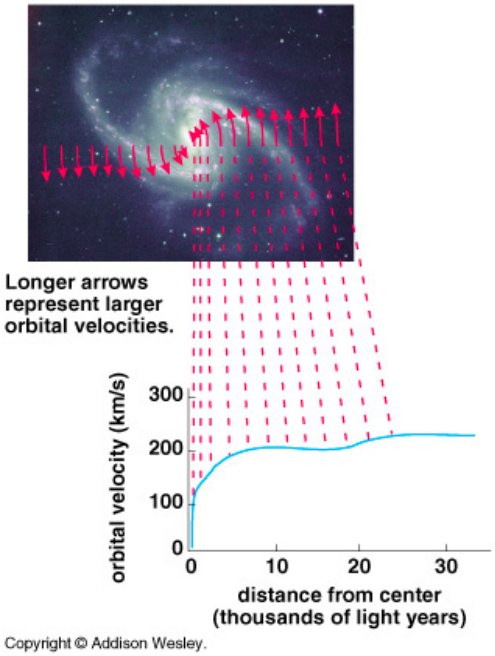
ROTATION CURVES (RC)

Symmetric circular rotation of a disk characterized by

- Sky coordinates of the galaxy centre
- Systemic velocity V_{sys}
- Circular velocity $V(R)$
- Inclination angle

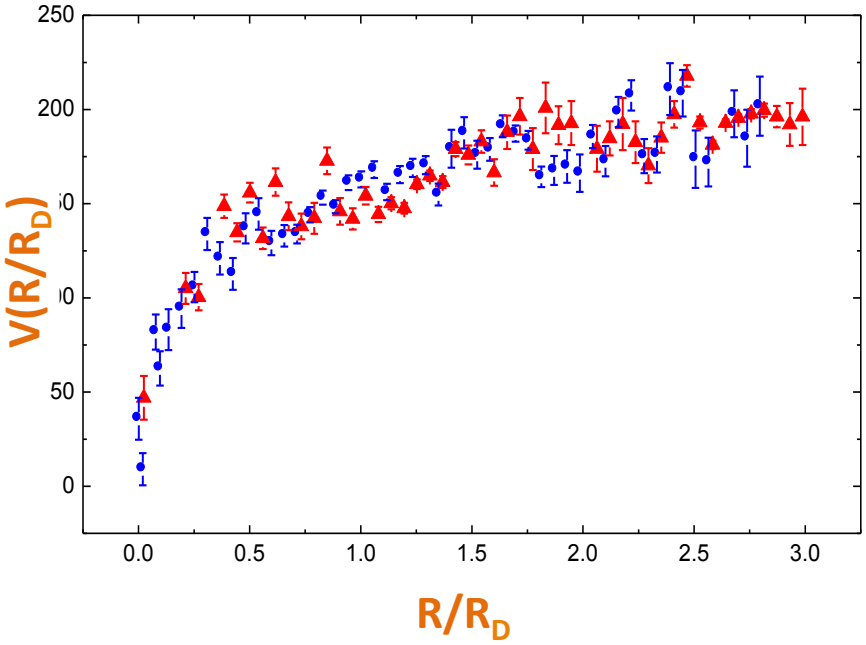
θ = azimuthal angle

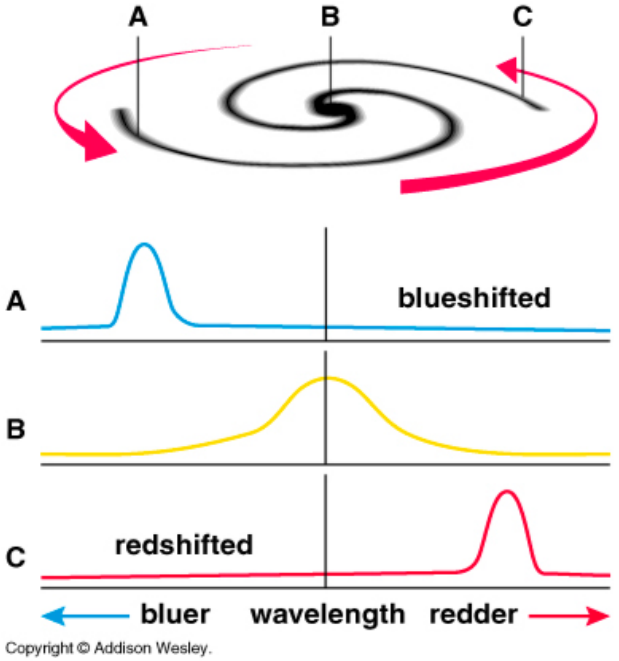
$$V_{obs}(\xi,\eta) = V_{sys} + V(R)\cos\theta\,\sin i$$



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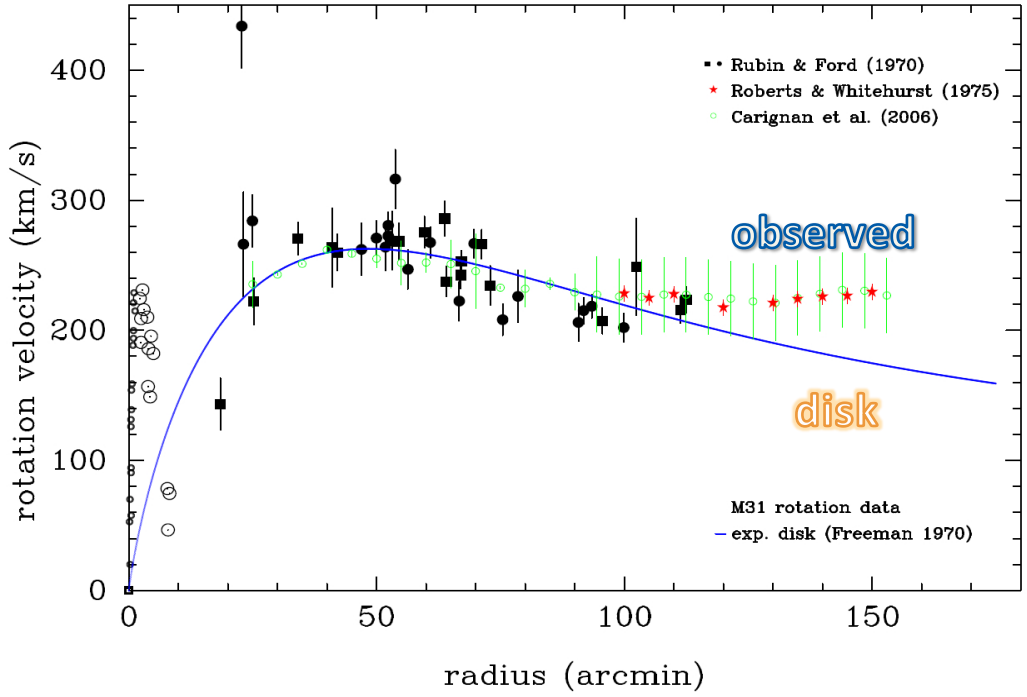
UGC2405 EXEMPLE OF HIGH QUALITY RC



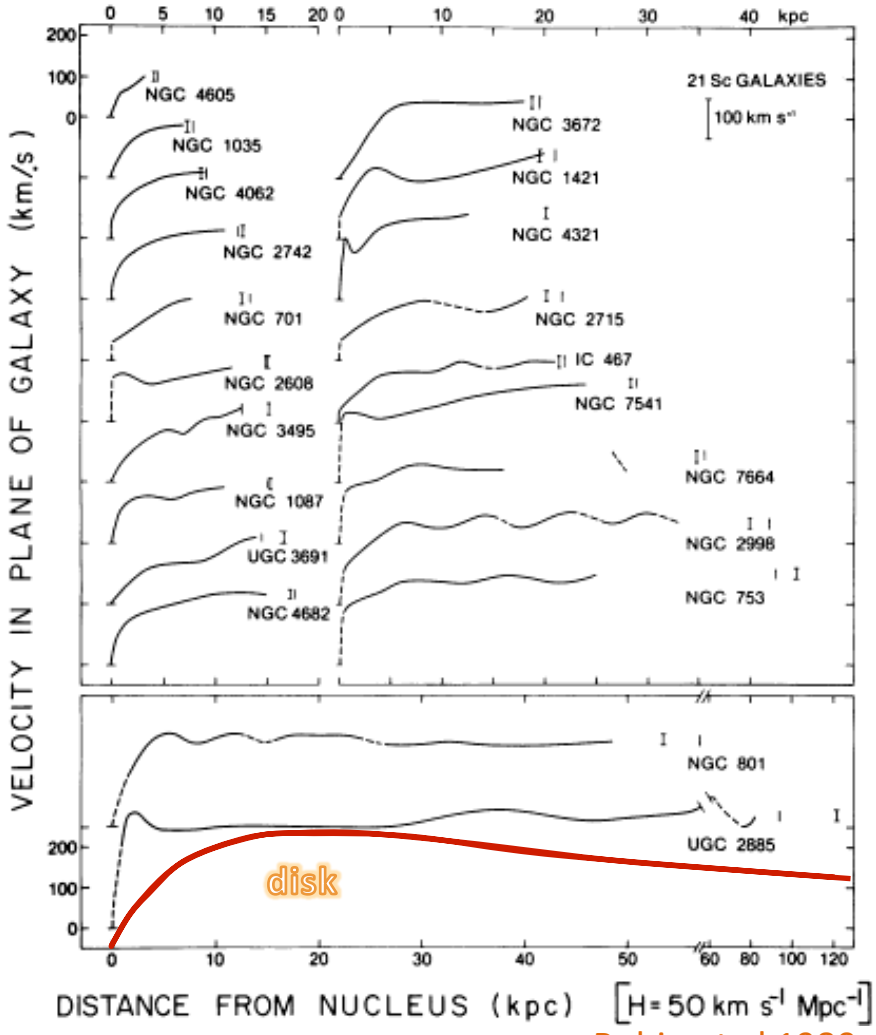


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Early discovery from optical and HI RCs



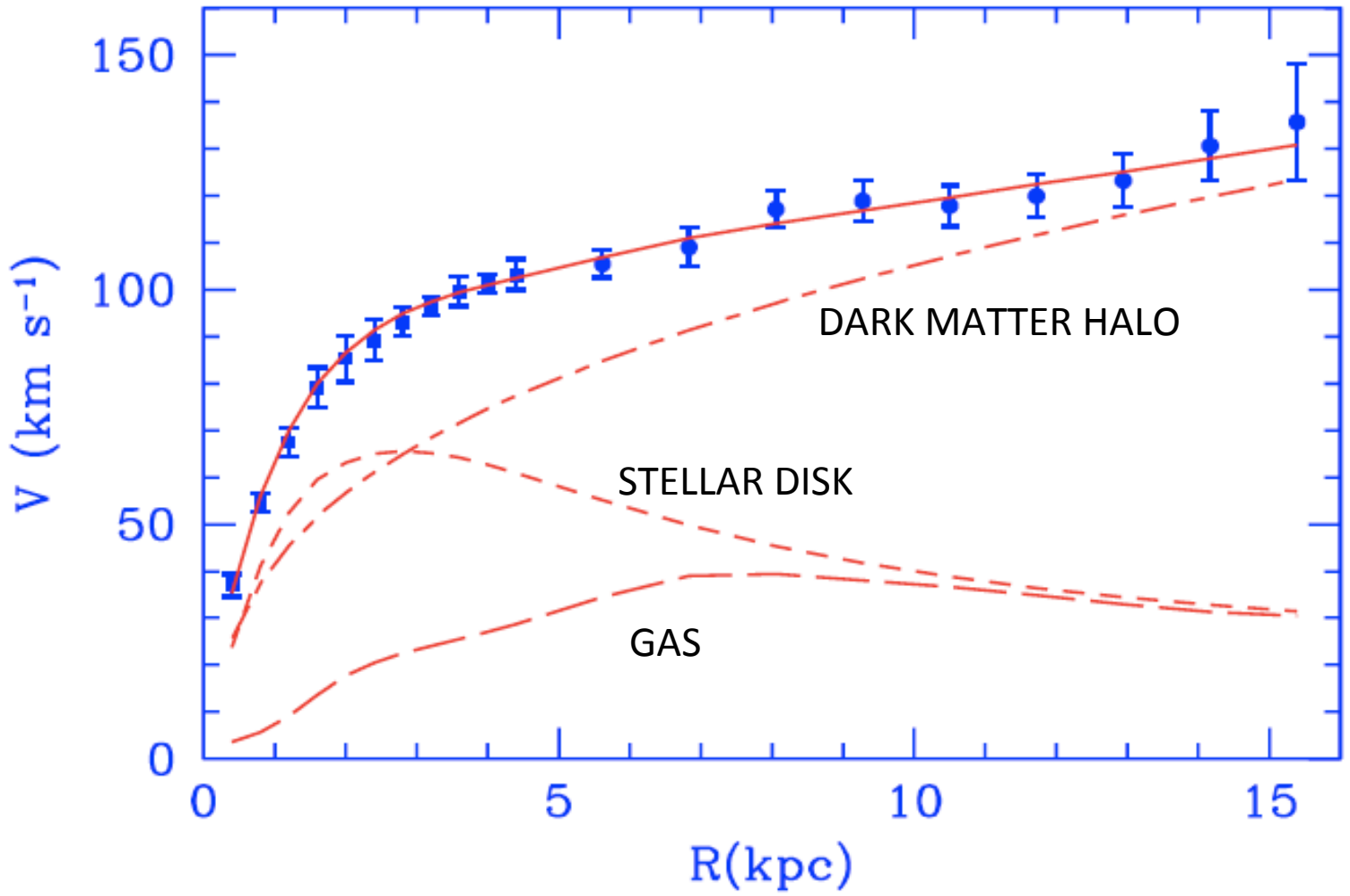
NO RC FOLLOWS THE STELLAR DISK VELOCITY PROFILE



Rubin et al 1980

MASS DISCREPANCY AT OUTER RADII

EVIDENCE OF DARK MATTER from RC



From Corbelli & Salucci, MNRAS 311, 441 (2000)

COSMIC INVENTORY: MATTER…….DARK MATTER!

Some main messages:

- The fact that in the Universe there is more matter than baryonic matter points to some form of new, non-baryonic (i.e. non-"standard") matter: dark matter!

- Be careful: the evidence just discussed for rotation curves of spiral galaxies is true to explain galactic curves…..and so holds only on galactic scales
  actually the clearest and most robust evidences of dark matter come
  from the necessity to explain a variety of observations ***on cosmological scales***
  (see next slides)

COSMIC INVENTORY: MATTER…….DARK MATTER!

MATTER

Other (although very similar in main principles) techniques that have been developed and exploited through the years are:

1. **Distribution of galaxies on large scales** strongly dependent on $\Omega_m h$
2. **Cosmic velocity fields**
3. **Measurements that depend on Ω_b/Ω_m**, so that, using the value of the baryon content, one can then infer the value of the total matter density Ω_m.
   - E.g. most of the baryons are in cluster of galaxies in the form of hot gas. The ratio of the mass of gas in clusters of galaxies to the total mass can be measured from X-rays emitted by baryons, or by the so called Sunyaev-Zel'dovich effect (scattering of CMB photons off hot electrons in cluster fo galaxies).

   If this ratio is representative of its mean value in the Universe, i.e., of Ω_b/Ω_m (a fair hypothesis given that cluster of galaxies are very large objects) then one can obtain an estimate of Ω_m.
   - other way to measure the ratio Ω_b/Ω_m : if Ω_b is just a small fraction, then there should be some specific features (wiggles) in the large-scale distribution of galaxies (these are called **Baryon Acoustic Oscillations)**. Nowadays these features have been robustly measured and allow to pin down a ratio Ω_b/Ω_m that is consistent with all other methods.
4. Finally, and very important, **CMB temperature anisotropies (and CMB polarization)**

$$\Omega_m = 0.315 \pm 0.007$$

COSMIC INVENTORY: BARYONS, DARK MATTER

- We therefore have an enormous amount of evidence telling us that the baryon density is of order 5% the critical density, while the total matter density is some five times larger. Most of the matter in the universe must not be baryons. ***It must be some new form of matter: dark matter***

- Indeed, as we said, all these kind of measurements have paved the way to what we call "dark matter"

$$\Omega_{\rm m} = 0.315 \pm 0.007$$

$$\Omega_b\, h^2 = 0.0224 \pm 0.0001$$ ***(from the satellite Planck 2018 measurements)***

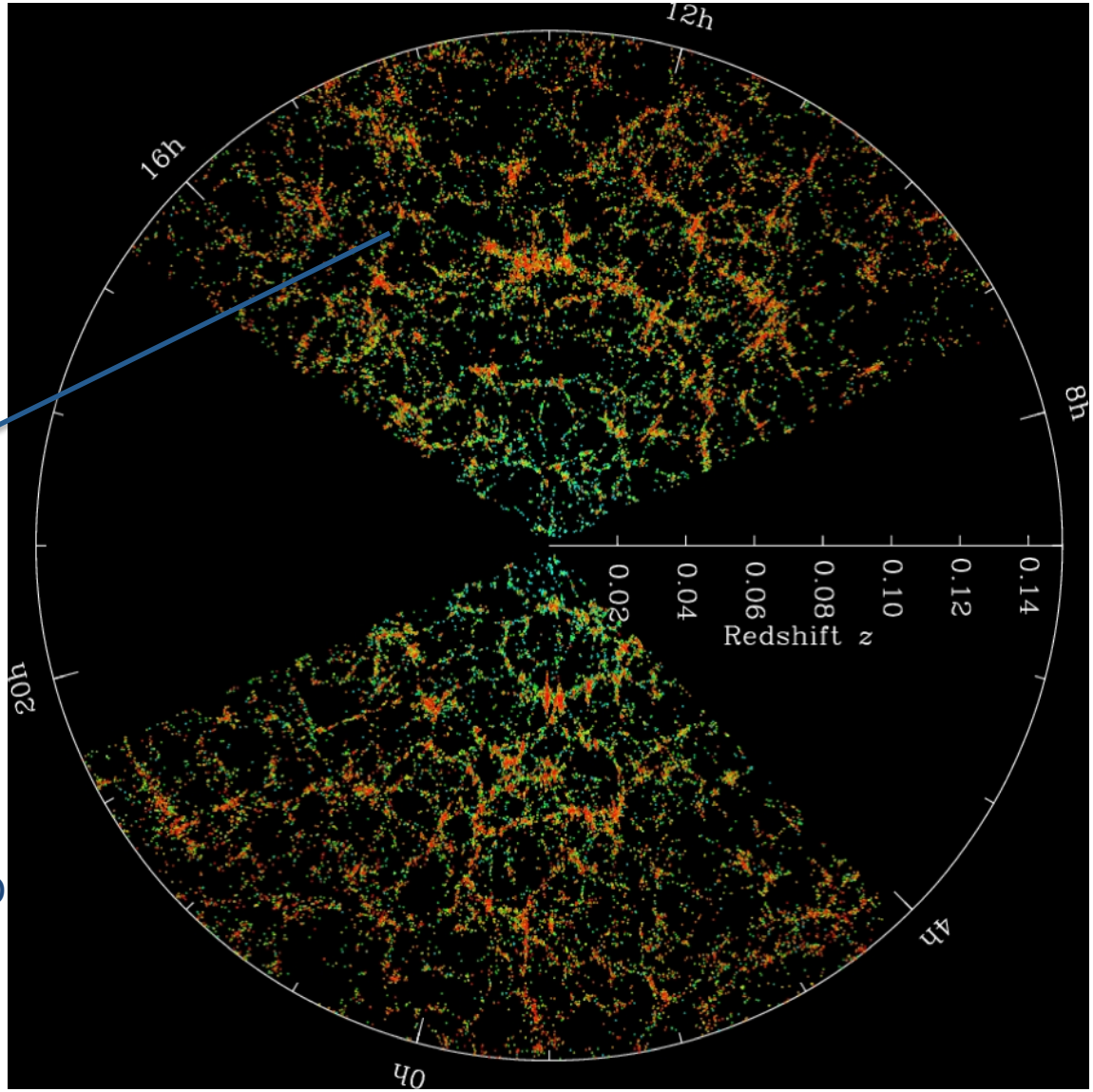
DARK MATTER ABUNDANCE:

$$\Omega_{dm}\, h^2 = 0.120 \pm 0.001$$ ***(from the satellite Planck 2018 measurements)***

- What is dark matter made of? What is its origin?
  We will see the basics of some mechanisms to explain its origin if we think of dark matter in the form of some yet unknown particle species.

The ALMOST ``smooth'' isotropic universe

Sloan-Digital-Sky-Survey (SDSS)
more than 930,000 galaxies
and more than 120,000 quasars
on ~ one third of the sky



THE SPATIAL DISTRIBUTION OF THE GALAXIES IS NOT RANDOM IT FOLLOWS A STATISTICAL PATTERN: WHY? THIS IS RELATED TO THE ORIGIN AND EVOLUTION OF THESE OBJECTS THAT FORMED FROM INITIAL VERY SMALL INHOMOGENEITIES

The NOT SO ``smooth'' homogeneous universe

https://www.youtube.com/watch?v=FBkYIqtYb0I

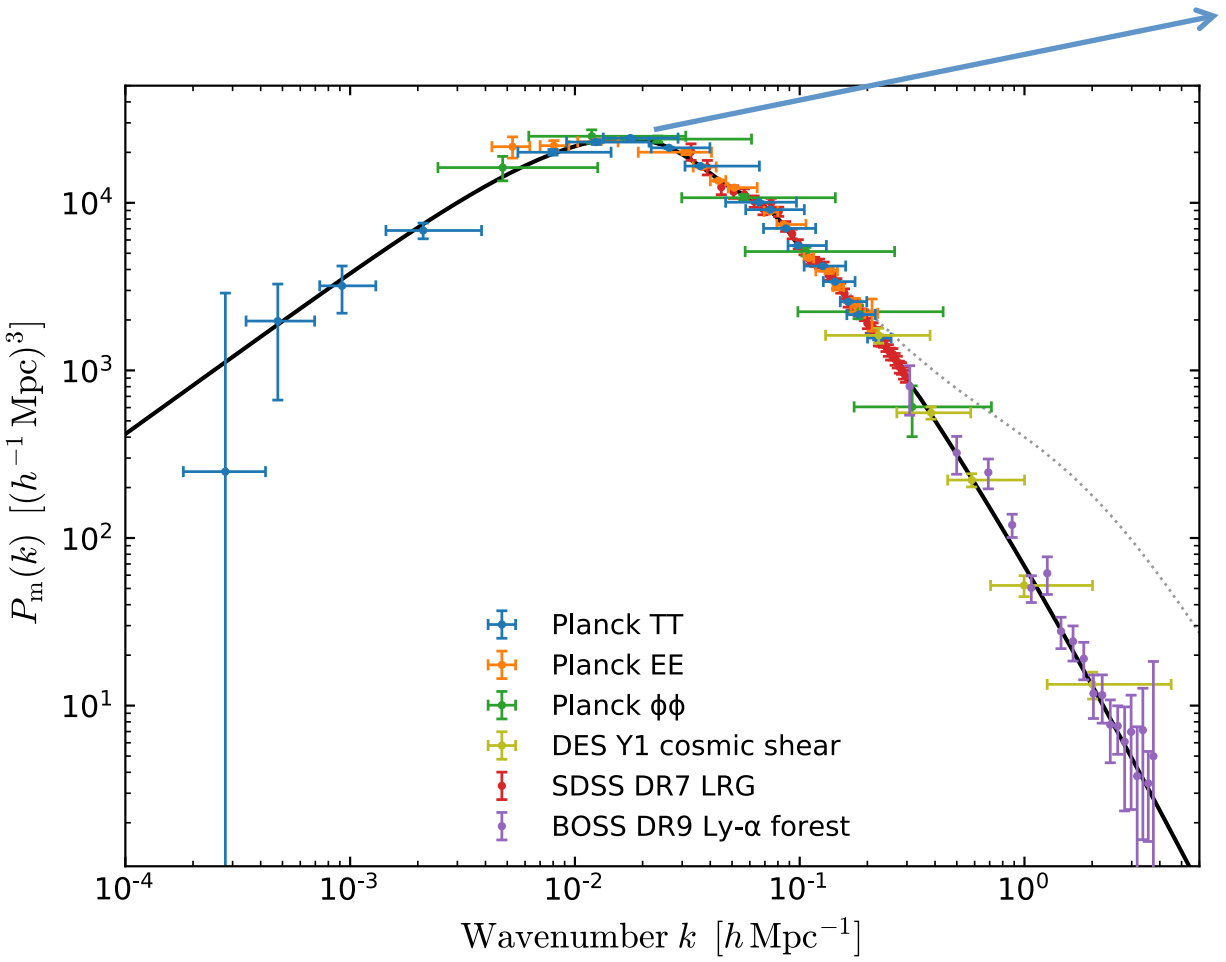
Credit to Volker Springel and to Max-Planck-Institute for Astrophysics.

Follow the link http://www.mpa-garching.mpg.de/galform/data_vis/lcdm_color1_lowres_divx.avi
(write the address by hand otherwise it does not work).

State of the art for the matter-power spectrum $P_m(k)$ today

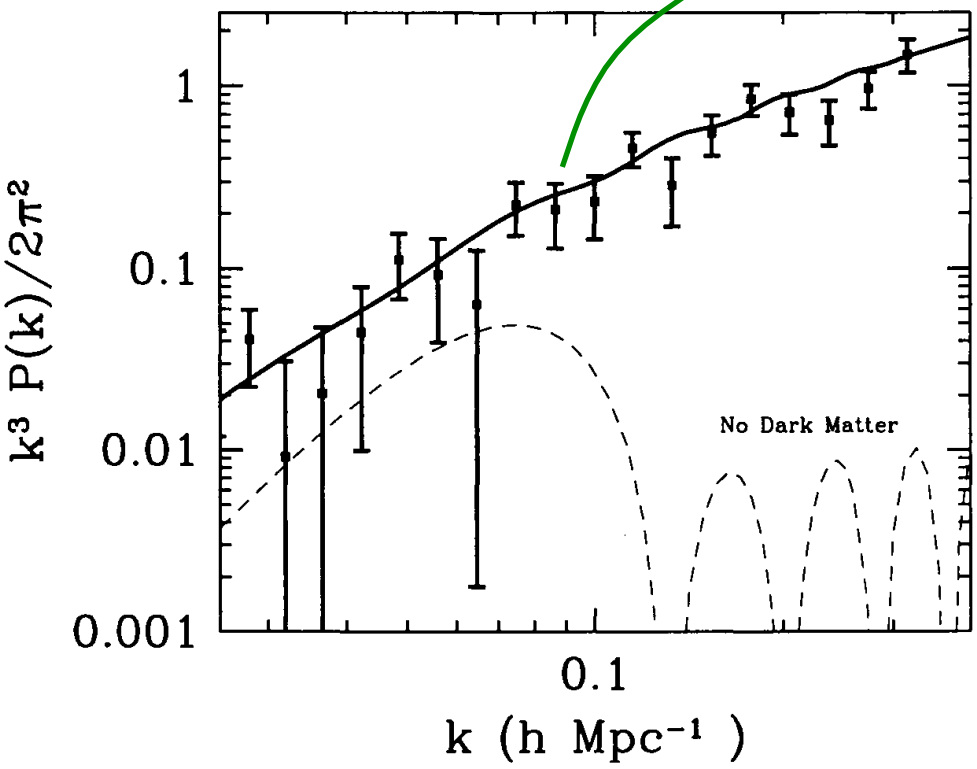
Here $P_m(k)$ is a (statistical measurement) of the amplitude of matter perturbations on a given cosmological scale λ~1/k; roughly sepaking:

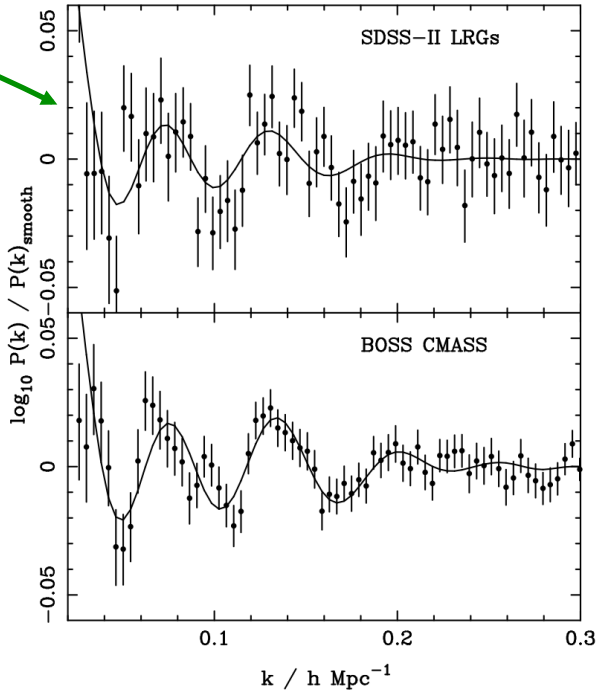
$$P_m(k) \sim \frac{\rho_m - \bar{\rho}_m}{\bar{\rho}_m} = \frac{\delta\rho_m}{\bar{\rho}_m}$$



this turn-around of the amplitude depends on the so called epoch of equality of radiation with matter, i.e. when the contribution of non-relativistic matter is equal to that of radiation, thetefore it is sensitive to the amount of matter.

DARK MATTER vs baryons only: BARYON ACOUSTIC OSCILLATIONS



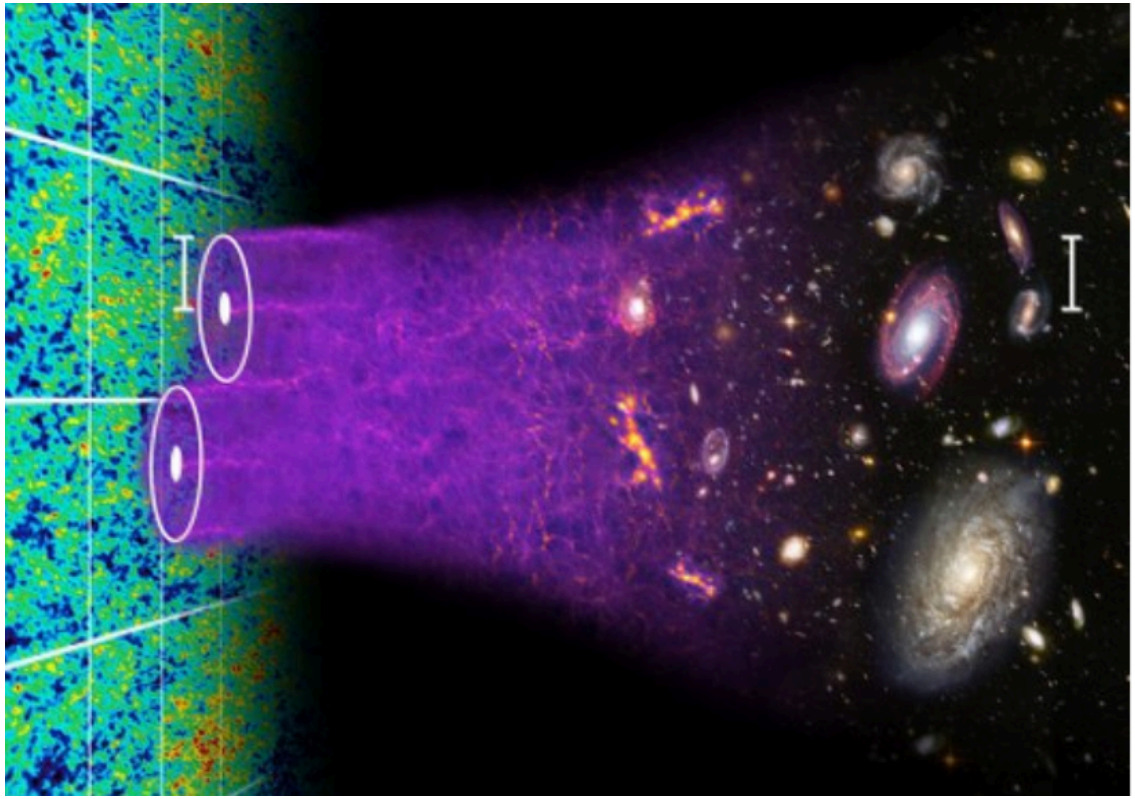


Baryon acoustic oscillations (BAO) from (BOSS) SDSS data

Figure 1.13. The variance $\Delta^2 \equiv k^3 P(k)/2\pi^2$ of the Fourier transform of the galaxy distribution as a function of scale. On large scales, the variance is smaller than unity, so the distribution is smooth. The solid line is the theoretical prediction from a model in which the universe contains dark matter, a cosmological constant, with perturbations generated by inflation. The dashed line is a theory with only baryons and no dark matter. Data come from the PSCz survey (Saunders *et al.*, 2000) as analyzed by Hamilton and Tegmark (2001).

From Scott Dodelson, ``Modern Cosmology'' Academic press 2003.

DARK MATTER vs baryons only: BARYON ACOUSTIC OSCILLATIONS



An illustration of the concept of baryon acoustic oscillations, which are imprinted in the early Universe and can still be seen today in galaxy surveys like BOSS.
(Illustration courtesy of Chris Blake and Sam Moorfield.)

The SDSS's Baryon Oscillation Spectroscopic Survey (BOSS) mapped the spatial distribution of luminous red galaxies (LRGs) and quasars to detect the characteristic scale imprinted by baryon acoustic oscillations in the early Universe. Sound waves that propagate in the early Universe, like spreading ripples in a pond, imprint a characteristic scale on cosmic microwave background fluctuations. These fluctuations have evolved into today's walls and voids of galaxies, meaning this baryon acoustic oscillation (BAO) scale (about 150 Mpc) is visible among galaxies today.

COSMIC INVENTORY: NEUTRINOS

- Cosmic neutrinos, i.e. a background of neutrinos with a given T (as for photons) have not been observed yet.

- Solar, atmospheric neutrinos have been observed and these obervations revealed that neutrinos have masses (these are however light neutrinos), with at least two species (out of 3) non-relativistic today.

- Neutrinos are fermions, and *weakly interacting. Therefore, as we will see in some details, at early times they were in equilibrium with the thermal plasma, but at some point (T~1MeV) they lost thermal contact and decoupled. Today their T sould be* (4/11)^(1/3) lower than that of CMB photons.

- Even though cosmic neutrinos have not been directly observed, still they leav a series of specific imprints both on CMB temperature anisotopies and especially on how structres form in the Universe on relatively small scales.

- NEUTRINOS: 3 light-mass neutrinos species

$$\sum m_\nu < 0.12\,\mathrm{eV} \quad (95\%\,\mathrm{CL}) \qquad \Omega_\nu h^2 < 0.0012 \quad (95\%\,\mathrm{CL})$$

(from *Planck 2018 temperature anisotropies and polarization* +lensing of CMB + BAO)

COSMIC INVENTORY: DARK ENERGY

- The Hubble diagram is still the most direct evidence we have that the Universe is expanding.
- At low redshift it allows to determine the Hubble parameter (it's not the only way, one can use a variety of other methods, and in particular CMB data on temperature CMB anisotropies)

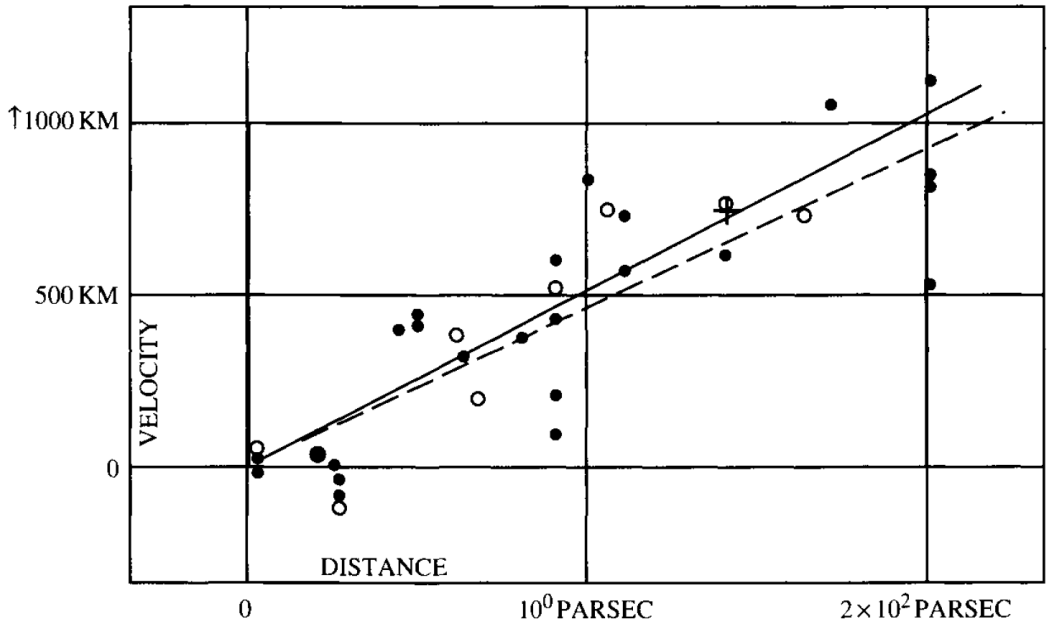


Figure 1.5. The original Hubble diagram (Hubble, 1929). Velocities of distant galaxies (units should be km $\sec^{-1}$) are plotted vs distance (units should be Mpc). Solid (dashed) line is the best fit to the filled (open) points which are corrected (uncorrected) for the sun's motion.

Hubble Law (for low redshifts)

$$V = H_0 d \quad z \cong V / c$$

$H_0 = 73.04 \pm 1.04$

From local, low redshift direct measurements using SNIa (Riess et al. 2022).

$H_0 = 67.4 \pm 0.5 \ \ \mathrm{km\,s^{-1}\,Mpc^{-1}}$

(from CMB data)

COSMIC INVENTORY: DARK ENERGY

- The Hubble diagram is still the most direct evidence we have that the Universe is expanding.

- At low redshift it allows to determine the Hubble parameter (it's not the only way, one can use a variety of other methods, and in particular CMB data on temperature CMB anisotropies)

- The Hubble law at high redshift is sensitive to the components of the Universe, and it is one of the main observational evidences (actually the more direct) for the presence of an additional component, either in form of ***a cosmological costant*** Λ or more generally speaking a ***"dark energy"*** **component that should dominate today the total energy budget of the Universe, being responsible for its present accelerated expansion.**

- This is possible by exploiting the same original principle of the Hubble diagram: determine the distance and redshift of distant objects. Now measuring redshifts is the easier part, what is difficult is measuring distances of objects which have an unknown intrinsic brightness.

  One important way to do it is to make use of what we call ***"standard candles"***, i.e. a *class* of objects which have the same intrisinc brightness. Because in this case, any difference between the apparent brightness among two such objects must be due to their different distances from us.

COSMIC INVENTORY: DARK ENERGY

- Such a method can be extended by finding a correlation between an observable and the intrinsic brightness. For example Cepheid variables are stars whose period is strongly related to their intrinsic brightness.

For example the Hubble space telescope have measured the periods of thousands of Cepheids far away as 20Mpc from us. In this wav we have an anchor in distance to use to calibrate other standard candles and therefore then going further in distance measurements if possible.

One therefore is building what is called the *"cosmic ladder".*

As shown in the figure Supernovae Ia (SNIa) are the best standard candles, both in terms of small dispersion errors when calibrating the relation between peak of luminosity and intrisic brightness and in terms of the standard candels that can be seen at the highest redshifts.

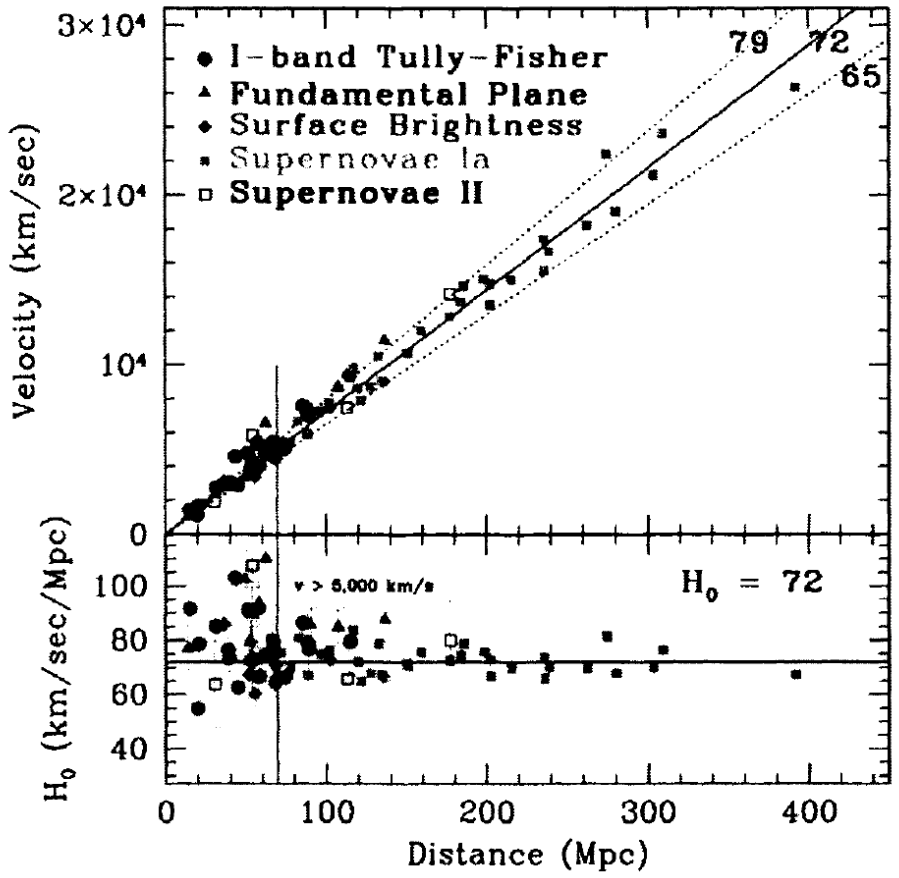
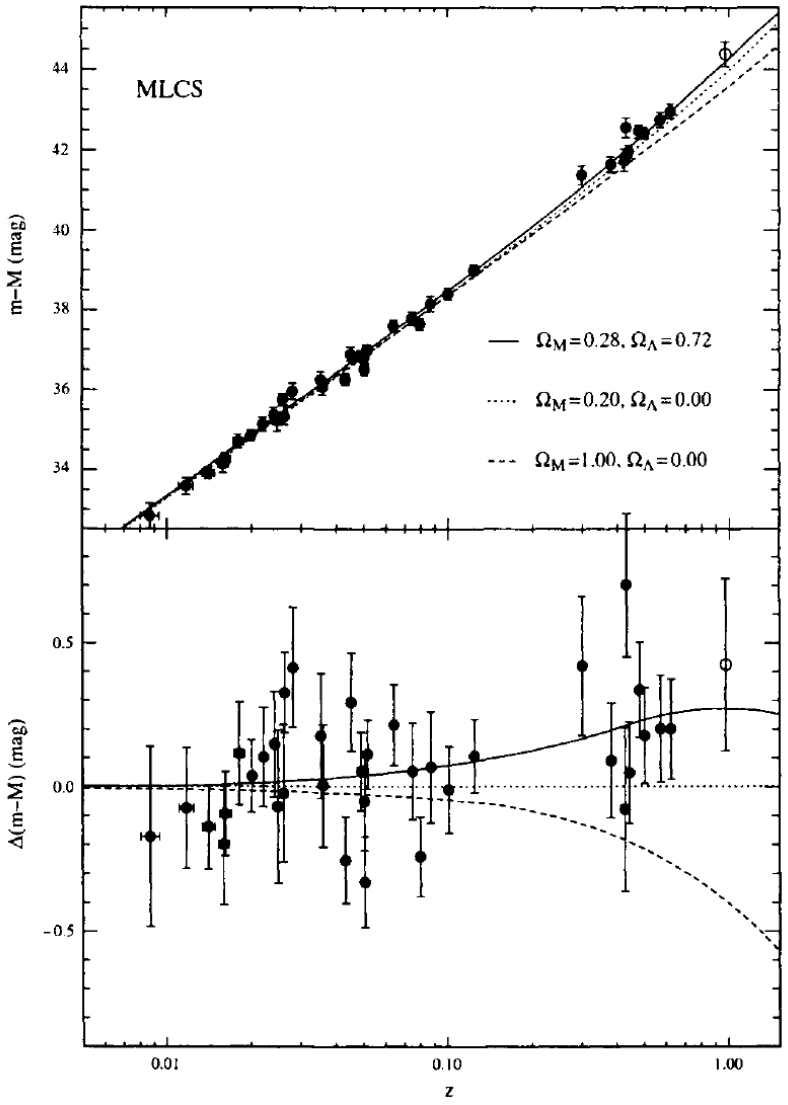


Fig. from Freedmann et al. 2011, HST Key Project

COSMIC INVENTORY: DARK ENERGY

- Notice that, as we will see, at high redshifts the "usual" Doppler expression is not valid anymore and the Hubble law assumes a different form (which actually is the most general one, in terms of the so-called *luminosity distance*).

- **Now, the crucial point is that at high redshift the expression of the (luminosity) distance *depends on the content of the Universe*.**



From S. Dodelson, "Modern Cosmology"

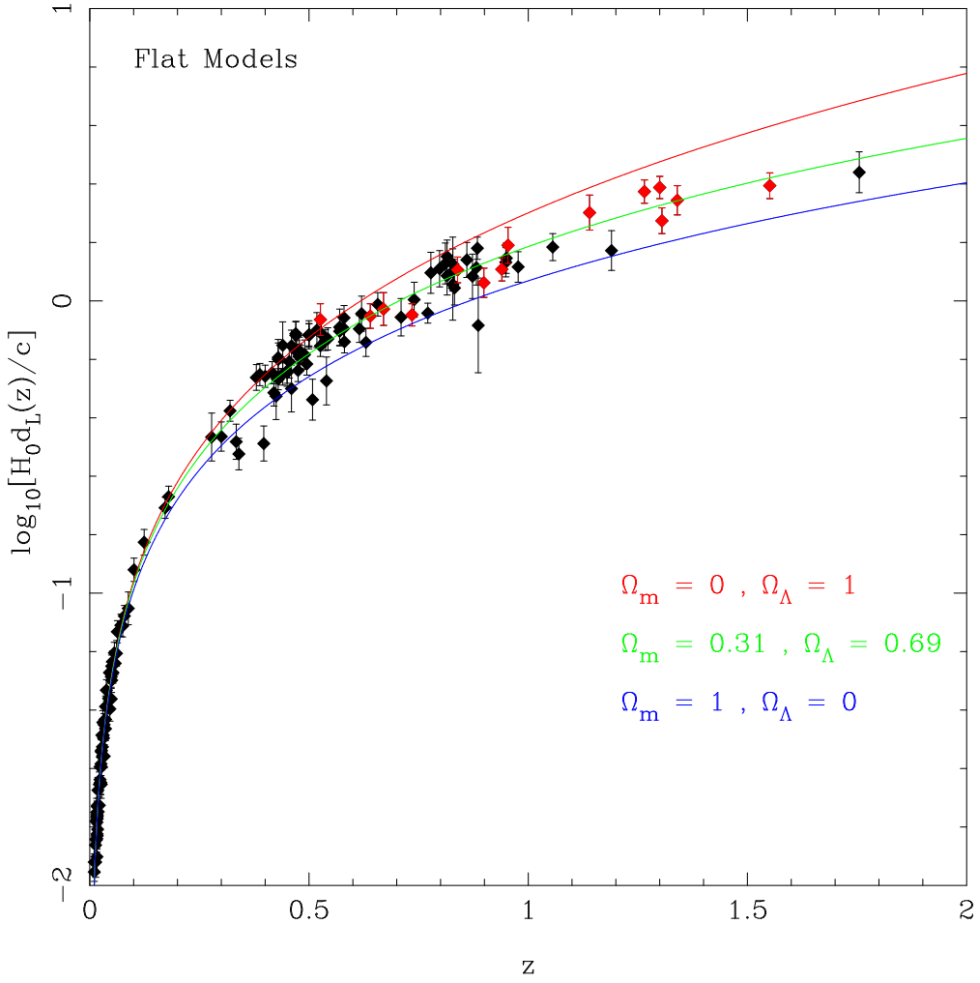
DARK ENERGY

The dominant component in the universe (almost 68.5%) that is accelerating the universe today:
A cosmological constant Λ (with negative pressure)??

$$d_{\mathrm{L}} = \frac{c}{H_0}[z + \tfrac{1}{2}(1 - q_0)z^2 + \cdots]$$

$$q_0 = -\frac{\ddot{a}(t_0)a_0}{\dot{a}(t_0)^2}$$

$$\Omega_\Lambda = 0.6847 \pm 0.0073$$



From Choudhury & Padmanabhan A&A 429, 807 (2005)

COSMIC INVENTORY: DARK ENERGY

- There are other observational evidences for the presence of Dark energy in the Universe. We will mention a few, the main important ones.

- One is about a deficitary budget: from CMB temperature anisotropies we know that the ***total*** parameter density (properly normalized by the critical density) is very close to unity:

$$\Omega_K = 1 - \Omega_0 = 0.001 \pm 0.002 \qquad (68\%\,\mathrm{CL})$$

(*Planck 2018 CMB temperature anisotropies and polarization* +lensing of CMB + BAO)

Notice that from a theoretical point of view, this is what we would expect in general from the so called models of Inflation for the Early Universe (see later lectures)

On the other hand the sum of the energy density contribution from all the other components seen in the previous slides (I am referring to: baryons, dark matter, radiation and neutrinos) amount to approximately (1/3) the total energy budget of the Universe *(today)*: so necessarily there is the need to introduce an additional component.
This component (that we call Dark energy) needs to have some peculiar features: very weakly interacting and very weakly clustering, so very smooth, otherwise we should have already "detected" either directly or indirectly. **This component needs also to have *a negative pressure in order to drive the accelerated expansion today.***

COSMIC INVENTORY: DARK ENERGY

N.B.: A cosmological constant is, as the name itself says, a component whose energy density is constant (in time and space), and so in particular it does not get diluited with the expansion of the Universe
(we will see that this can happen if p=-ρ exactly).
Dark energy refers to a component with a negative pressure (and in particular p<-(1/3) ρ), which *can evolve in time (and whose energy density can also weakly vary in space).*
At present a cosmological constant term is the form of dark energy that best fits a variety of data.

- Other observational evidences for Dark Energy: a cosmological constant term Λ (or a dark energy component) has some sepcifics effect on the CMB temperature anisotropies

COSMIC INVENTORY: DARK ENERGY

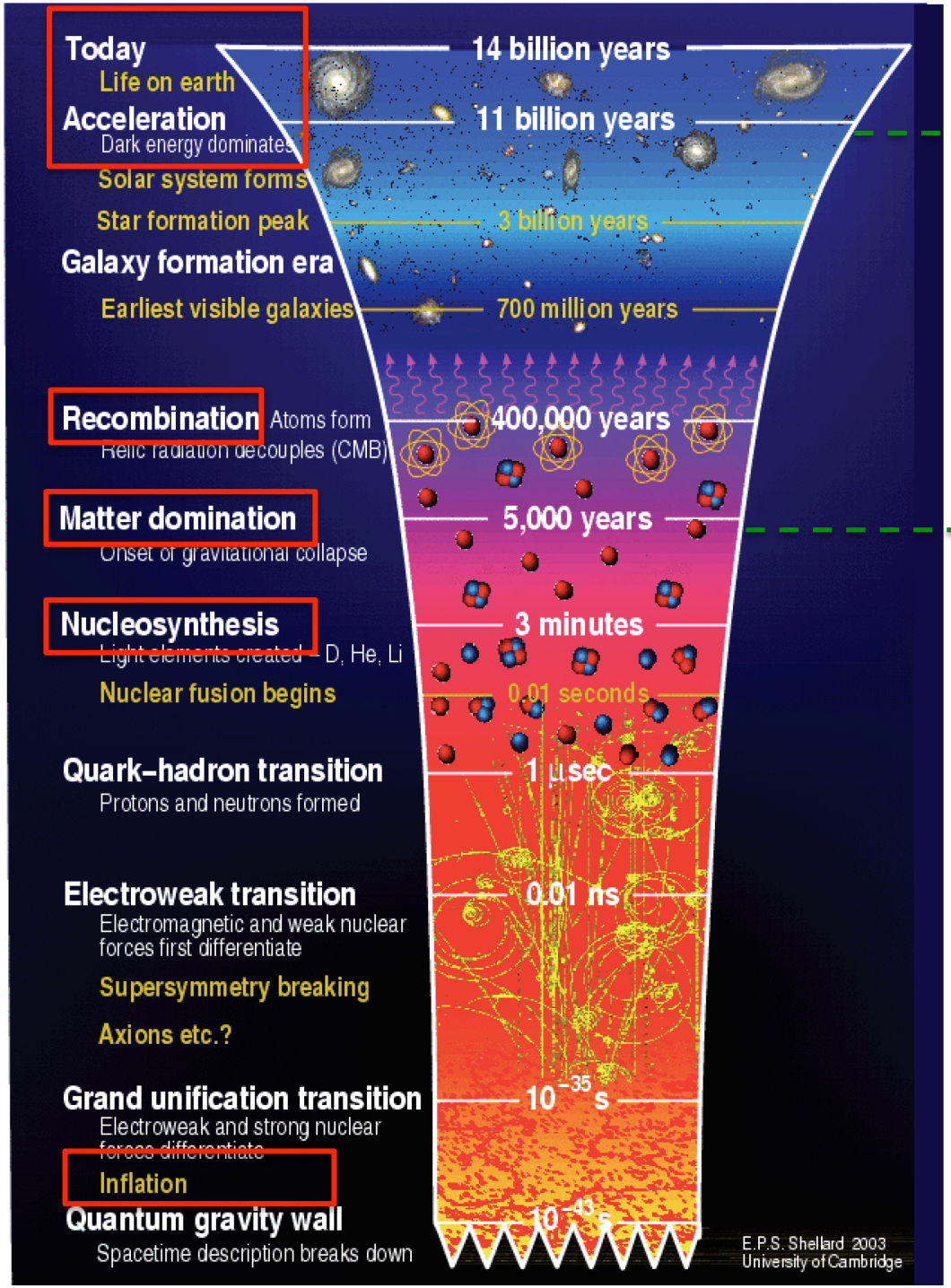
- Finally let me mention another piece of evidence, that was also crucial, also historically, for the discovery of the accelerated expansion of the Universe and hence for the presence of dark energy: the age of the Universe (that we will compute explicitely later on)

If a Universe is matter-dominated the age of the Universe would be (a suffix "0" indicates quantities evaluated today)

$$t_0 = \frac{2}{3H_0}$$

Now: given the value measured today of H_0=(67.4 ± 0.5) km s^{-1} Mpc^{-1} (from CMB data) this can be converted in time via H_0^{-1} = 9.7776 h^{-1} X 10^9 years, defining h as a paremetrization for th Hublle parameter today: H_0=100 h km s^{-1} Mpc^{-1}

Therefeore we would get an age of 9.6 X 10^9 years, which is clearly at odd with present (and independent) meaurements of the age of our Universe which is 13.8 X 10^9 years. A cosmological constant is able to solve this problem.



We are here

Z~0 (REDSHIFT $1+z=a_0/a(t)$)

Dark Energy

Z_{rec}~1100 (T~0.25 eV): CMB

Z_{eq}~3300

Matter domination

Radiation domination

T~1 MeV

T~1 GeV

T~100 GeV (Dark Matter production??

$T\sim10^{16}$ GeV Baryogenesis?

N.B.: At slide 13 I mentioned the “missing baryon problem”: indeed observations mentioned in point 1 in the list provide something like ~2% of the total budget of the Universe, roughly half of the total baryon density contribution obtained, e.g., by methods 3 (BBN) and 4 (CMB).
We talk here therefore of “missing baryons” or “dark baryons”.

Find out here the recent discovery of the so called “dark baryons”, residing in diffuse gas in filaments (connecting galaxies) too cold to be detected directly via X-ray emission,
in this interesting reading at

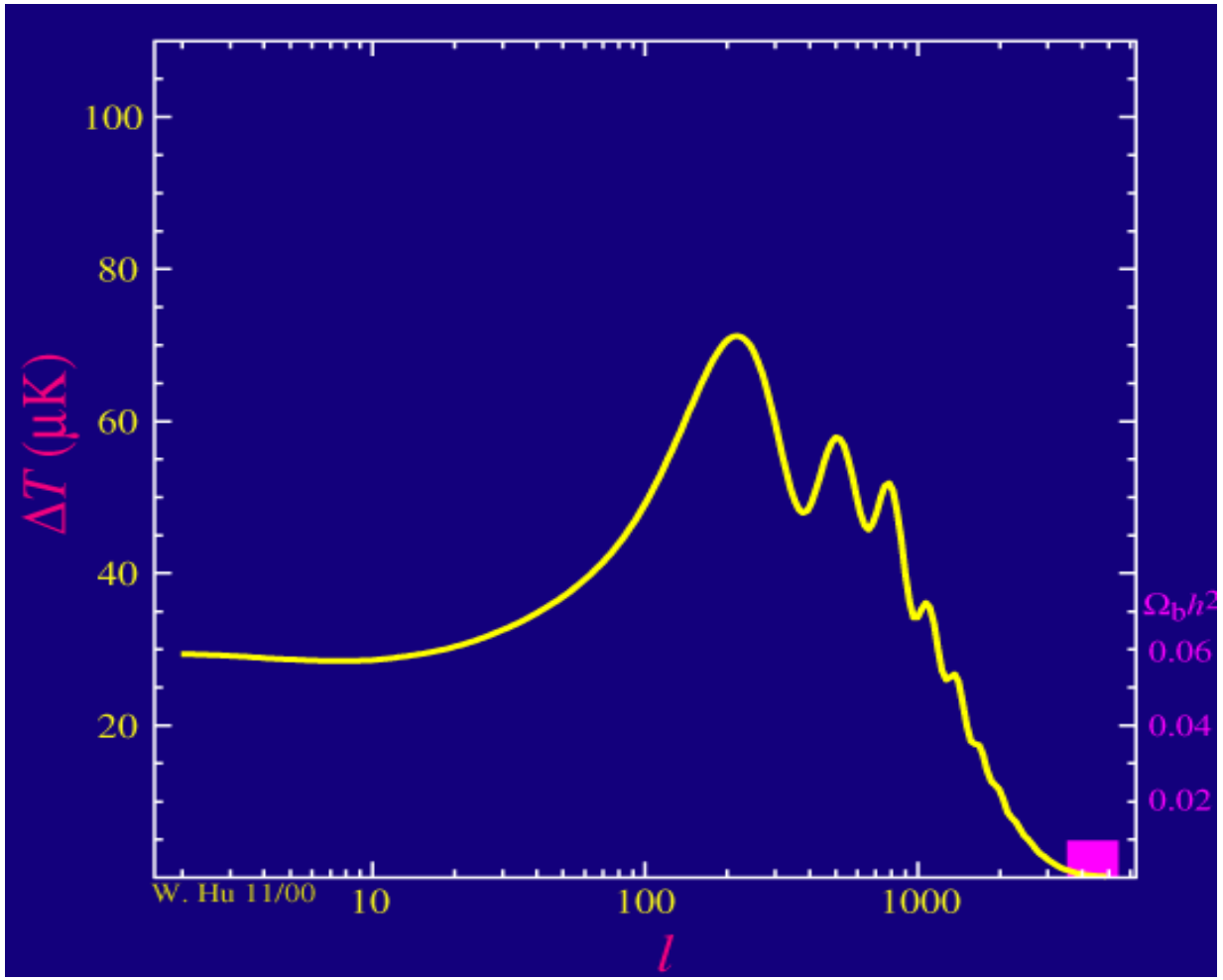
https://www.newscientist.com/article/2149742-half-the-universes-missing-matter-has-just-been-finally-found/

Back-up slides

Effect of amount of baryons on CMB temperature fluctuations

See https://background.uchicago.edu/~whu/animbut/anim1.html

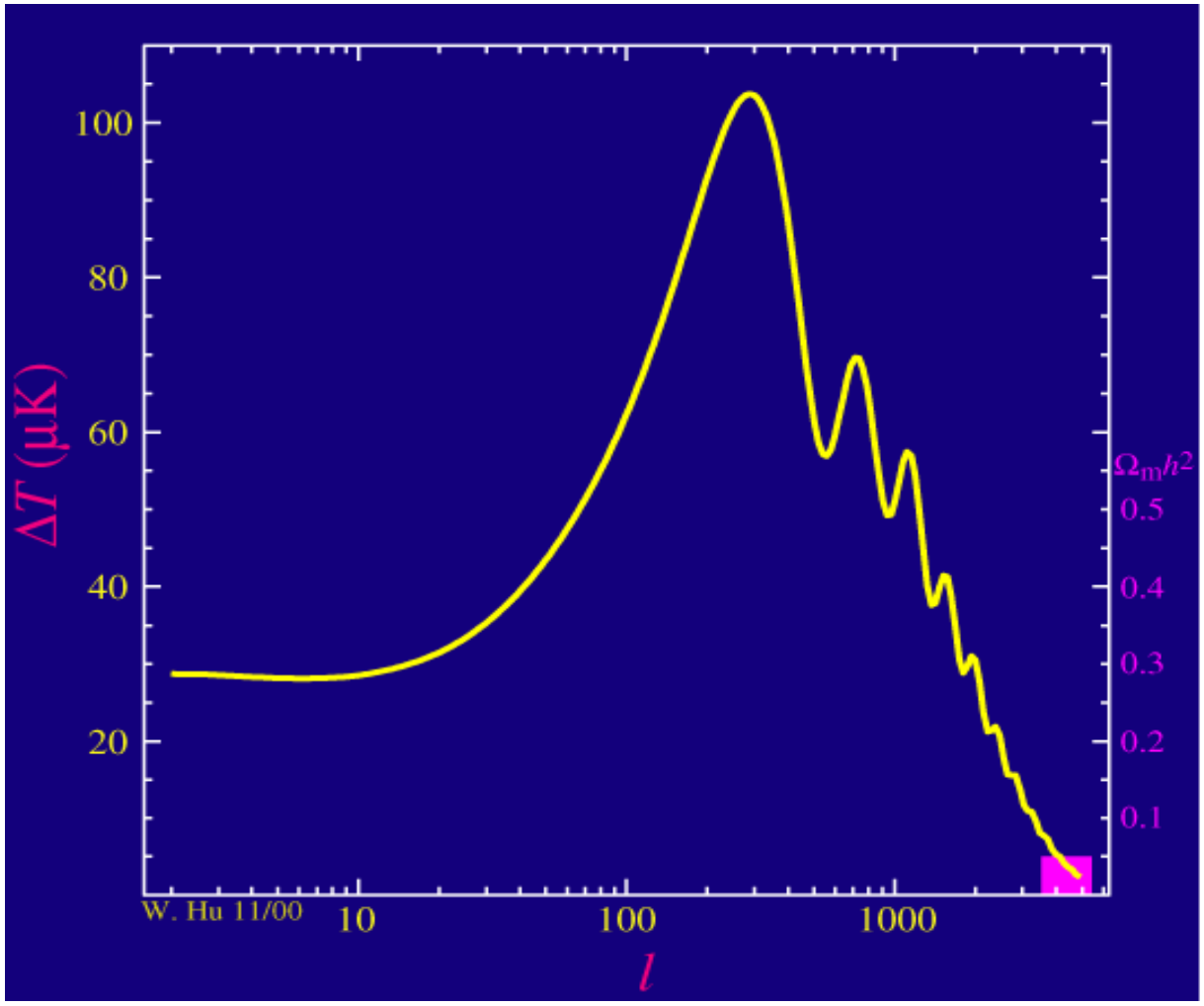
Angular scale 180° 18° 1° 0.2° 0.1° 0.07°



Effect of total amount of matter on CMB temperature fluctuations

See :https://background.uchicago.edu/~whu/animbut/anim2.html

Angular scale 180° 18° 1° 0.2° 0.1° 0.07°



Effect of changing parameters on C_l

