Introduction & Basic Concepts

Karina Caputi

Formation and Evolution of Galaxies 2023/24 Q1
Rijksuniversiteit Groningen

Course Information

Teachers: **Prof. Karina Caputi (lectures)**
Fernanda Roman de Oliveira (tutorials)

Timetable: **Lectures on Thursdays (13-15 h) and Fridays (11-13 h)**
Tutorials Wednesdays (13-15 / 15 -17 h) : paper reading & comp. assignm.
***Check schedule* ***

Course Assessment:

Special Assignments (40%)	**Deadlines: 10.Oct & 24.Oct**
Final Exam (60%)	**31 October 2023 (resit 1 Feb 2024)**

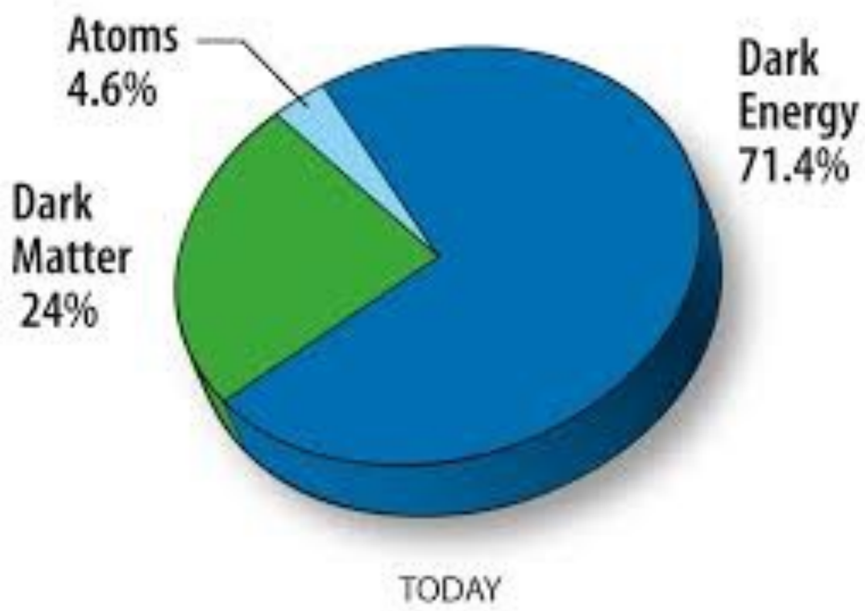
minimum grade 5 is needed in each assignment and final exam/resit

All necessary info available at:

* https://www.astro.rug.nl/~karina/feg_schedule.html

This Course in Context

The Universe we live in

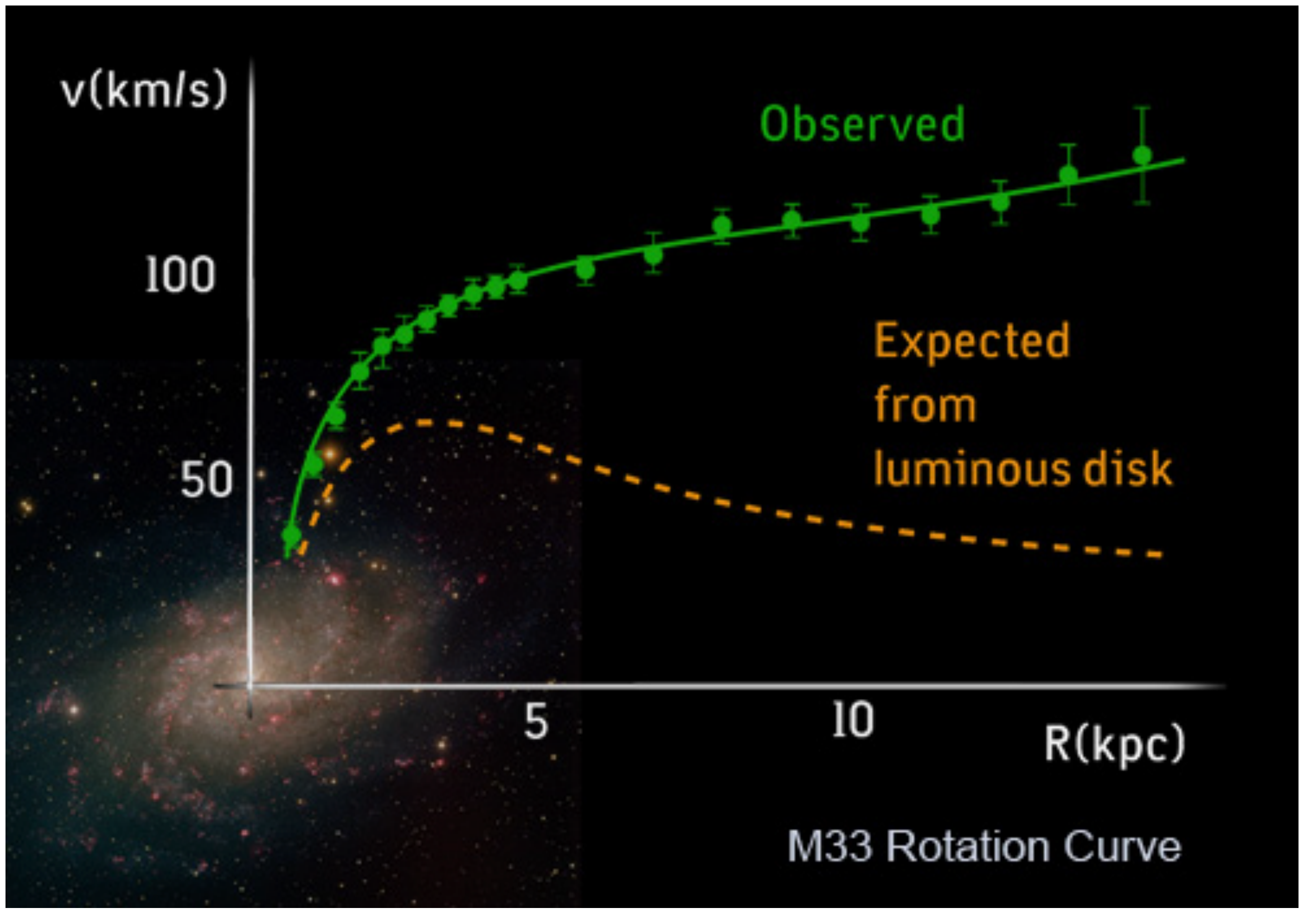


In this course we will mostly deal with baryonic matter

Gravitational collapse makes that most baryons are aggregated in stars and galaxies

Galaxies are gravitational bound units composed of stars, gas and dust, which live in dark matter haloes

Evidence for the existence of dark matter (DM)

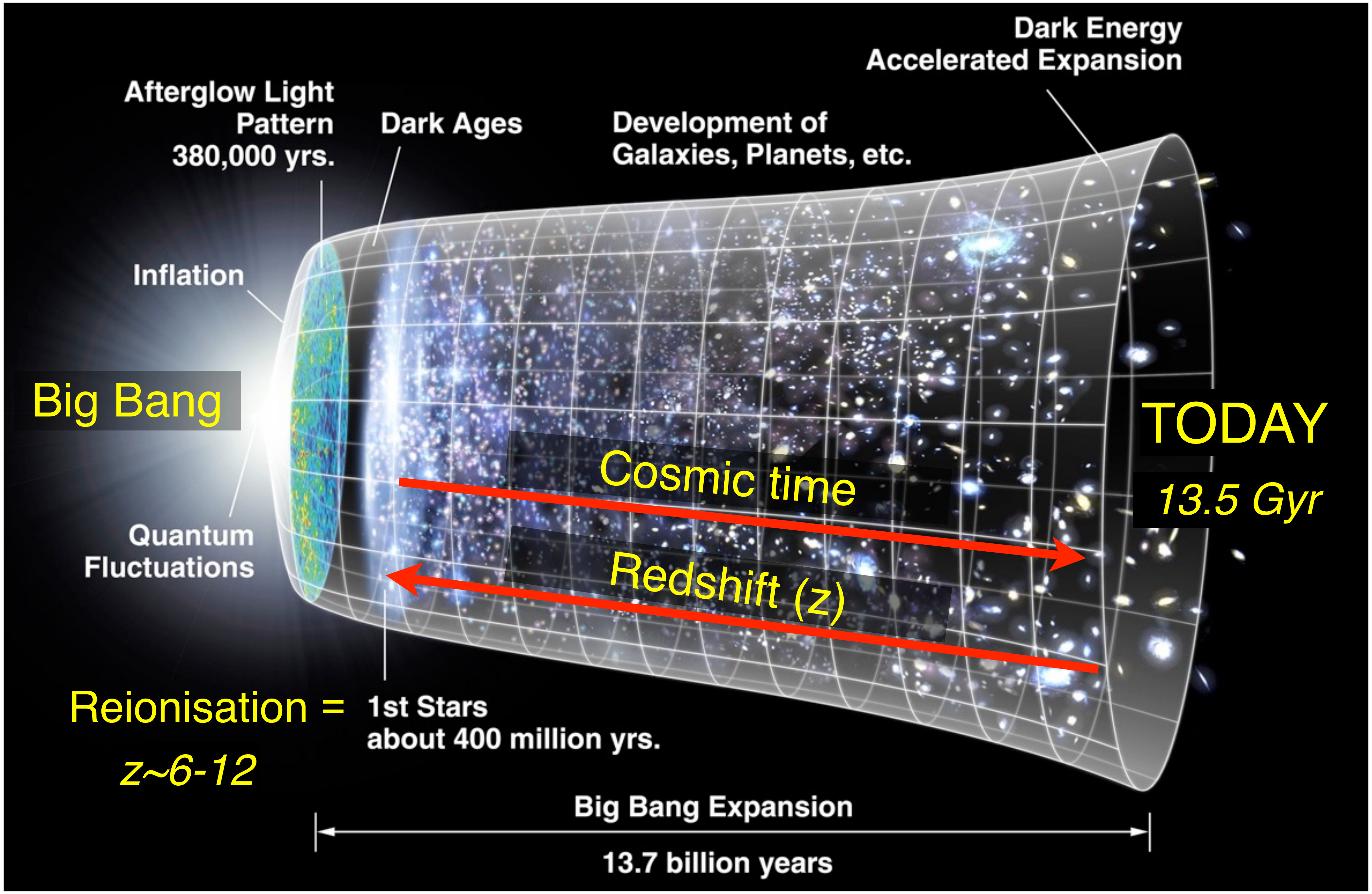


1930s - Zwicky suggests that most mass in the Coma galaxy cluster must be in form of DM

1970s - Ostriker & Peebles found that massive spherical haloes of DM are necessary to stabilise galactic discs against bar instability

1970s - Extended DM haloes are also necessary to explain HI rotation curves, mainly in the outskirts

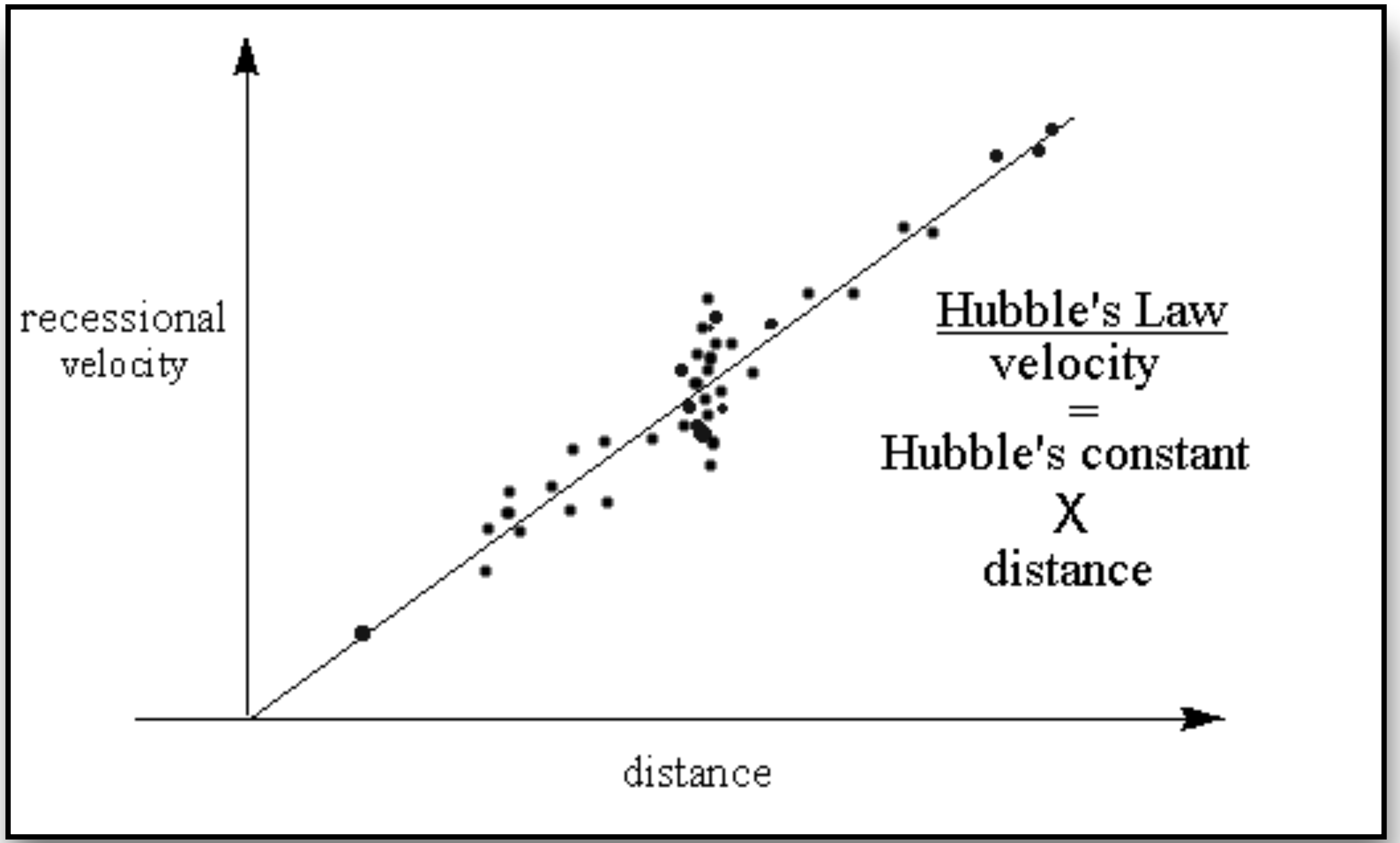
The Universe timeline



A bit of history…

The cosmology revolution

Edwin Hubble



Hubble's Law:

v = H0 x d

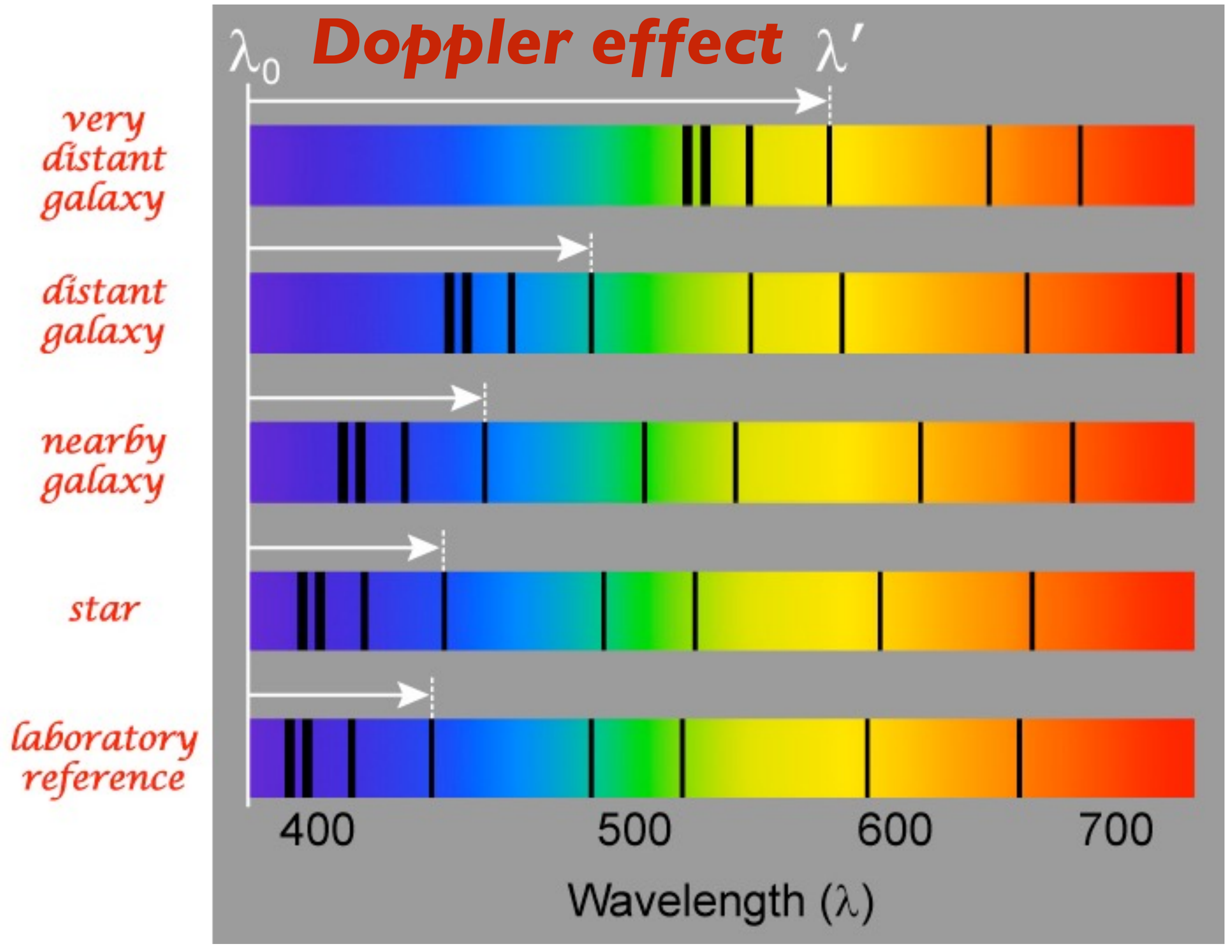
The Universe is expanding!

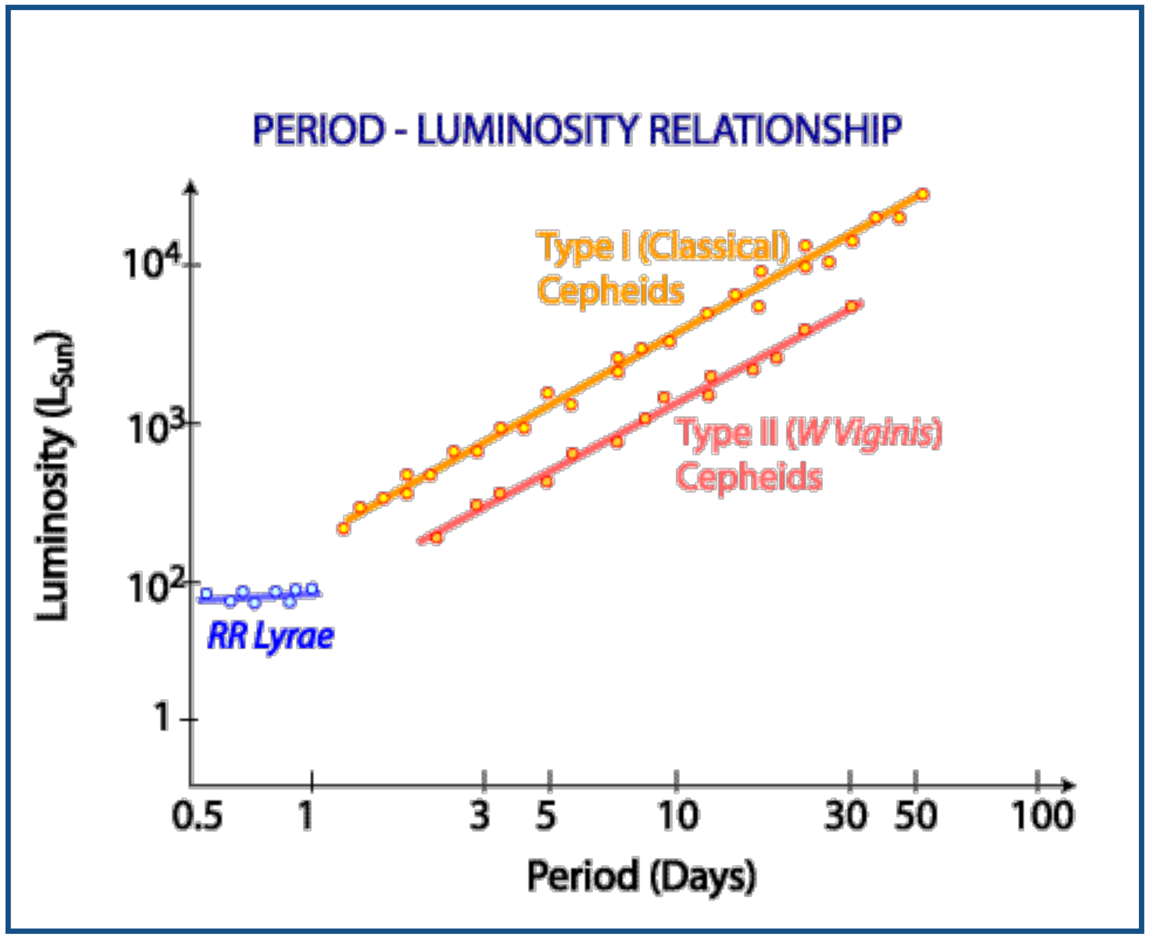
Karina Caputi 15 Feb 2017, 22:09
Typical distances on x axis up to 100 Mpc ~ 10^21 km. This is the typical maximum scale in which distances can be measured through Cepheids. Supernovae type I can be used up to at least 1000 Mpc.

How we measure distances

From this formula, we get that v_r = c at z=2. However, at these redshifts the approximation is not valid any more. In reality, solving Friedmann's equation gives that v_r = c at z~1.5.

In the nearby Universe, we calibrate Hubble's Law **$v = H0 \times d$**





In the distant Universe, we only measure spectral line shifts (*redshifts*) and infer distances

$\boxed{z = (\lambda o - \lambda e) / \lambda e}$ $\boxed{v_r = c\ (\lambda o - \lambda e) / \lambda e}$ (if $v_r << c$)

A framework for galaxy evolution

Framework: The hot Big Bang model

- Four independent pieces of evidence
  - Expansion of the distribution of galaxies in the universe (Hubble 1929) *Redshift*
  - Cosmic microwave background radiation: black body and very isotropic (Penzias & Wilson 1965, prediction by Gamow 1940)
  - formation of light elements by primordial nucleosynthesis (Alpher, Herman, Gamow 1948) *Abundance as predicted by BB model*
  - comparable ages of oldest stars and expansion age of the Universe

- More is needed
  - Flatness and homogeneity/isotropy of the Universe

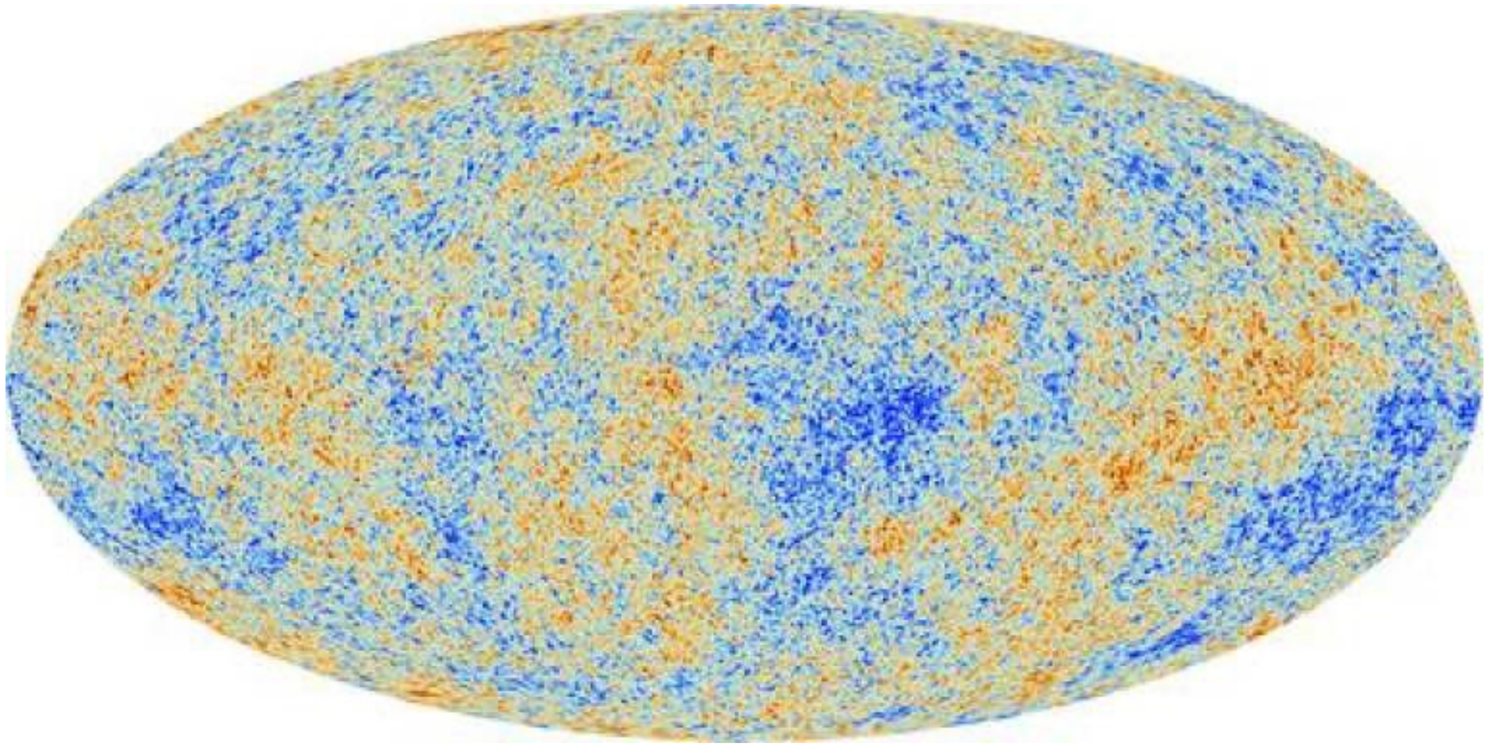
→ Inflation

Gravitational Instabilities in the Early Universe

Gravitational instabilities are the basis for the formation of large-scale structure (in matter-dominance era)

Universe starts being homogeneous, except for tiny density/ velocity perturbations

These inhomogeneities generate from quantum fluctuations during inflation



Full sky by Planck. Credit: ESA/Planck

Equations of Motion for the Early Universe

On large scales, matter and radiation behave like a continuous fluid

$$\boxed{\begin{aligned} \frac{d\rho}{dt} &= -\rho(\vec{\nabla}\cdot\vec{v}) \\ \frac{d\vec{v}}{dt} &= -\frac{1}{\rho}\vec{\nabla}p - \vec{\nabla}\Phi \\ \nabla^2\Phi &= 4\pi G\rho \end{aligned}}$$

Conservation of mass (continuity eq.)

Equation of motion (Euler eq.)

Poisson's eq. for gravitational potential

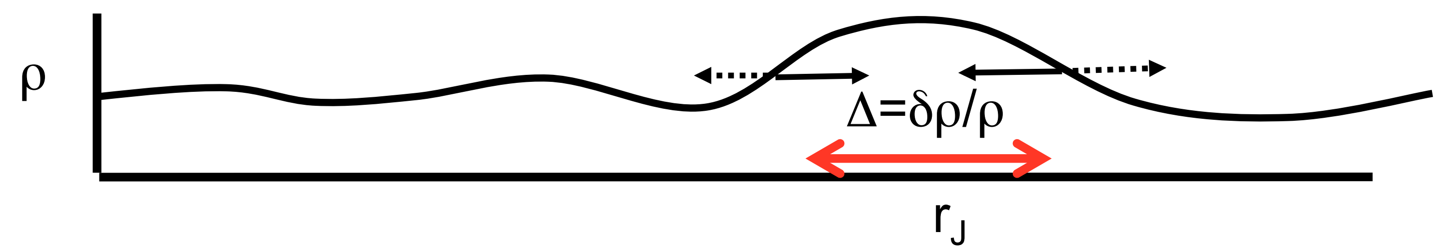
$$\vec{v} = \frac{\delta\vec{x}}{\delta t} = \frac{da}{dt}\vec{r} + a(t)\frac{d\vec{r}}{dt}$$

with **x** = a(t) **r** (comoving coordinates)

Introducing small perturbations to these equations, we can explain formation of structures

Small Perturbations in the Early Universe

$$\Delta = \delta\rho/\rho$$



Considering $\delta p = c_s^2 \delta\rho$ **Adiabatic perturbations**

$$\frac{d^2\Delta}{dt^2} + 2\left(\frac{\dot{a}}{a}\right)\frac{d\Delta}{dt} = \frac{c_s^2}{\rho_e a^2}\nabla_c^2 \delta\rho + 4\pi G \delta\rho$$

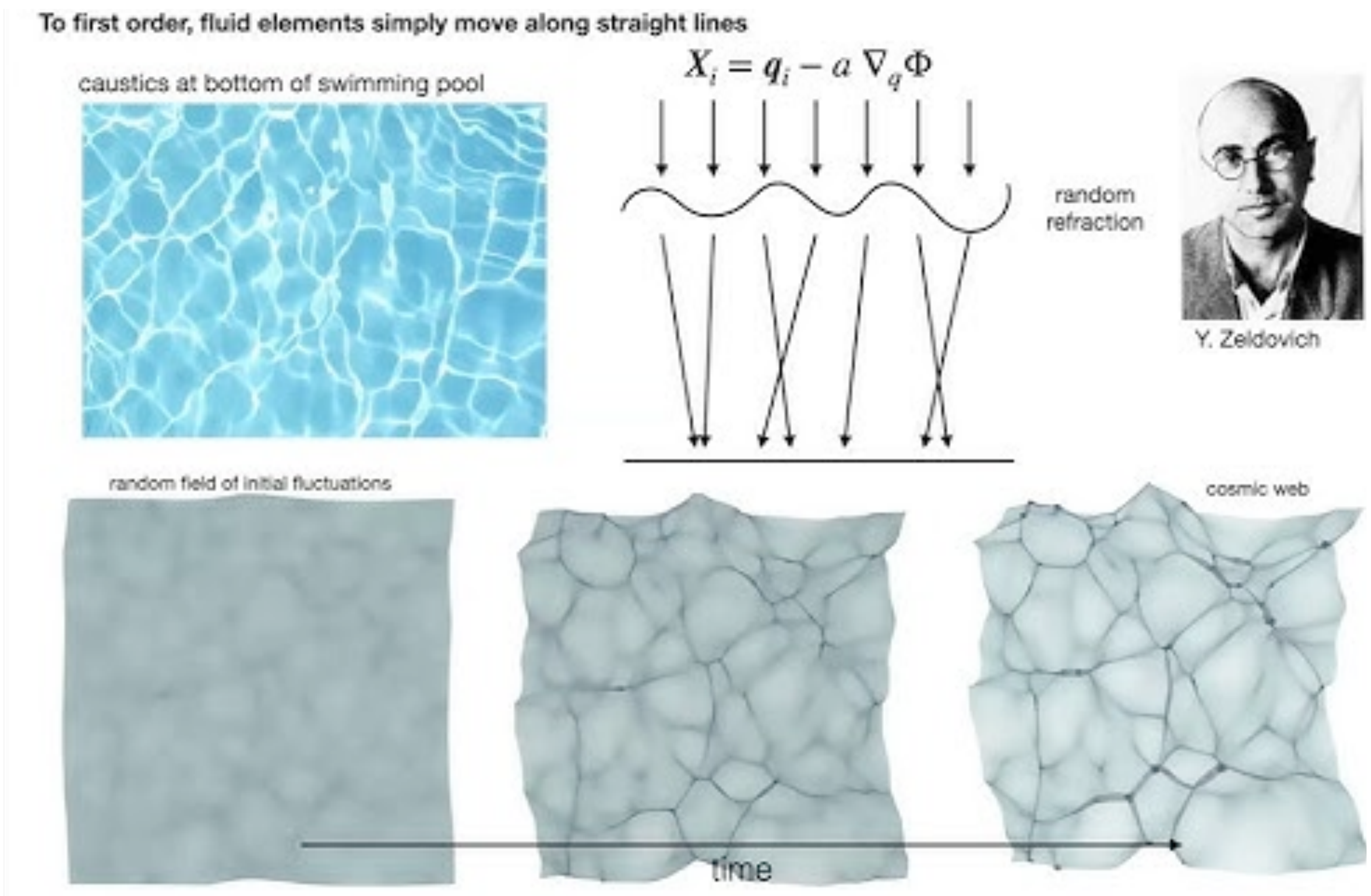
$$\boxed{\frac{d^2\Delta}{dt^2} + 2\left(\frac{\dot{a}}{a}\right)\frac{d\Delta}{dt} = \Delta(4\pi G\rho_e - k^2 c_s^2)}$$

Wave equation for Δ

(all in comoving coordinates)

The Zel’dovich approximation

Perturbations lead to particles deviating from parallel trajectories



Credit: Oliver Hahn (U. of Vienna)

Fluctuations spectrum

- Novikov (1964) showed that to have galaxies and clusters by today $\rightarrow$ initial fluctuations must have been $\delta\rho/\rho \approx 10^{-4}$
- Harrison (1970) and Zeldovich (1972) showed that observed structures in Universe could be accounted for if mass fluctuation spectrum had form

$$\boxed{\Delta = \delta\rho/\rho \propto M^{-2/3}}$$

in very early Universe, corresponding to a power spectrum of initial fluctuations P(k) of the form

$$\boxed{|\Delta_k|^2 \propto k^n \qquad \text{with } n = 1}$$

This is the Harrison-Zeldovich spectrum

Problems

- Searches in 1980s for fluctuations of 10^{-4} in amplitude in CMB failed
  - These were required in models in which baryons are only form of matter, so that fluctuations could grow enough by the present day

- Low density baryonic Universe needed for primordial nucleosynthesis

- All pointing in direction of more matter… non-baryonic dark matter
  - **hot dark matter**: relativistic at the time of decoupling (such as neutrinos); so weakly interacting that free-streaming scale is very large; large objects form first, galaxies form late. Found support in a claim of a measurement of the mass of the neutrino of 30 eV, enough to make $\Omega = 1$ (Lyubimov et al. 1980)
  - **cold dark matter**: many candidates from particle physics and supersymmetry (neutralinos, gravitinos…); non-relativistic at decoupling, which occurs before recombination, and so perturbations grow early on and are not necessarily very large on CMB

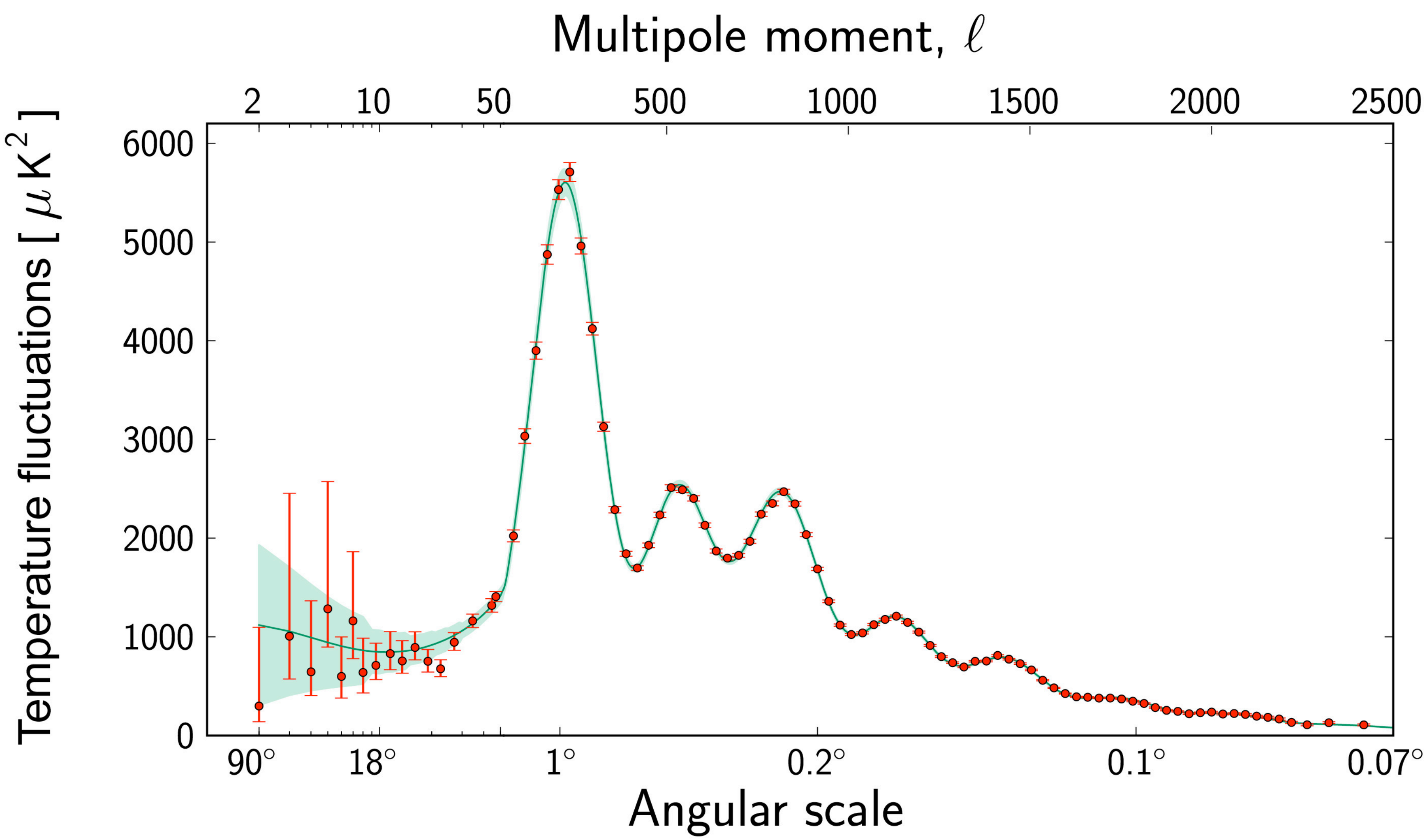
The emergence of the standard model

- Later experiments did not confirm massive neutrino and numerical simulations (Tremaine & Gunn 1979) showed degree of clustering is too large in HDM models

- CDM gained increasing popularity (with different flavors, as more data came in: SCDM, oCDM, MDM, τ CDM). Numerical simulations showed different degrees of success in reproducing LSS
  - MDM, τ CDM: structures grow too late
  - oCDM: amplitude of power is too low compared to COBE
  - LCDM: seemed to fit data, but only accepted when SN experiments measured accelerated expansion of Universe (Garnavich et al.1998; Perlmutter et al. 1999)

- COBE had detected fluctuations on scales of 10^{-5}, and the spectrum was consistent with Harrison-Zeldovich. Later confirmed with WMAP and LCDM fits the CMB seamlessly.

Power spectrum measurement by Planck and LCDM "fit"



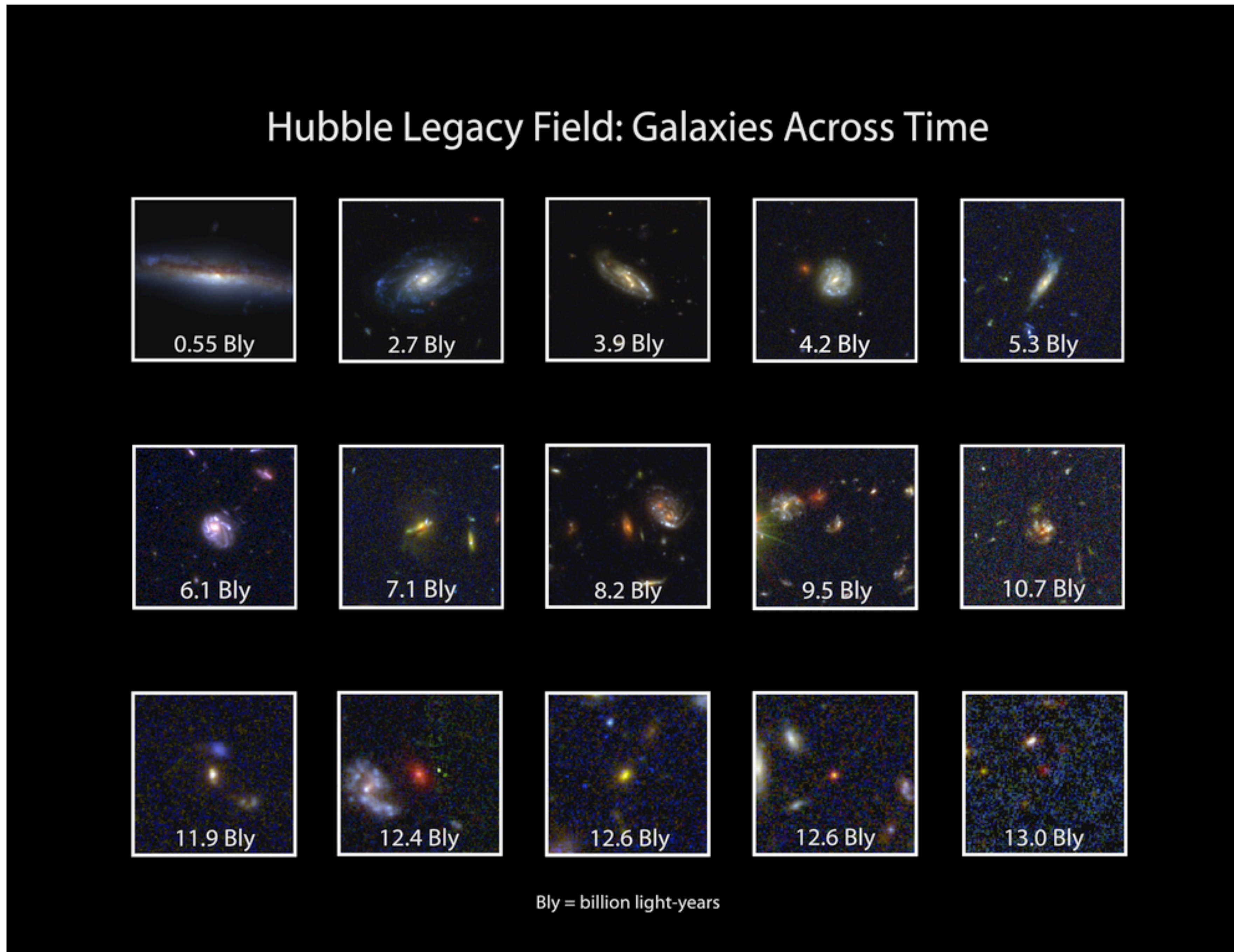
see http://background.uchicago.edu/~whu/Presentations/warnerprint.pdf

Galaxies in the Universe

Study of nearby and far-away galaxies

The possibilities and techniques to study nearby and far-away galaxies are different, as the level of resolution is different

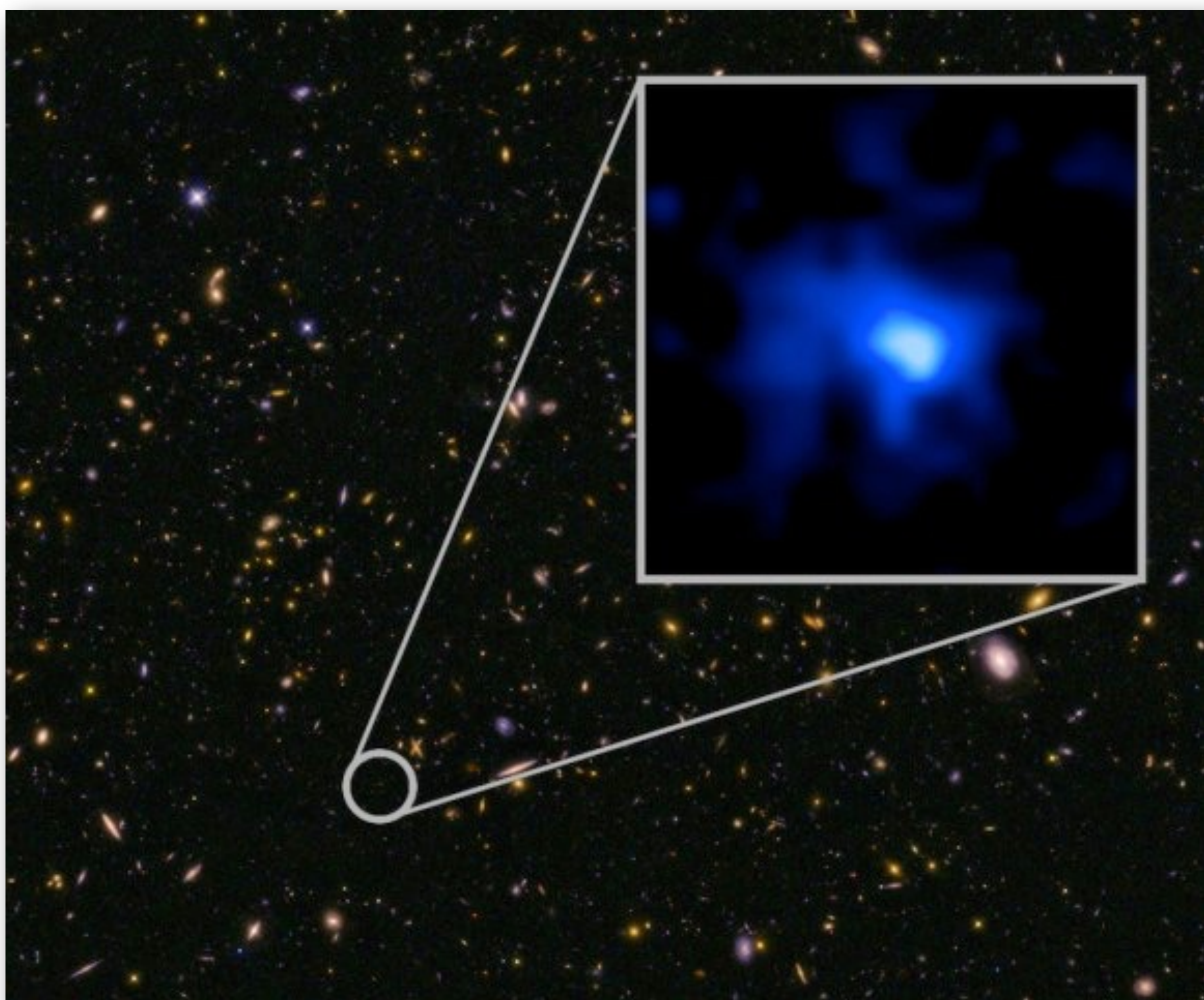
Galaxy at z~0



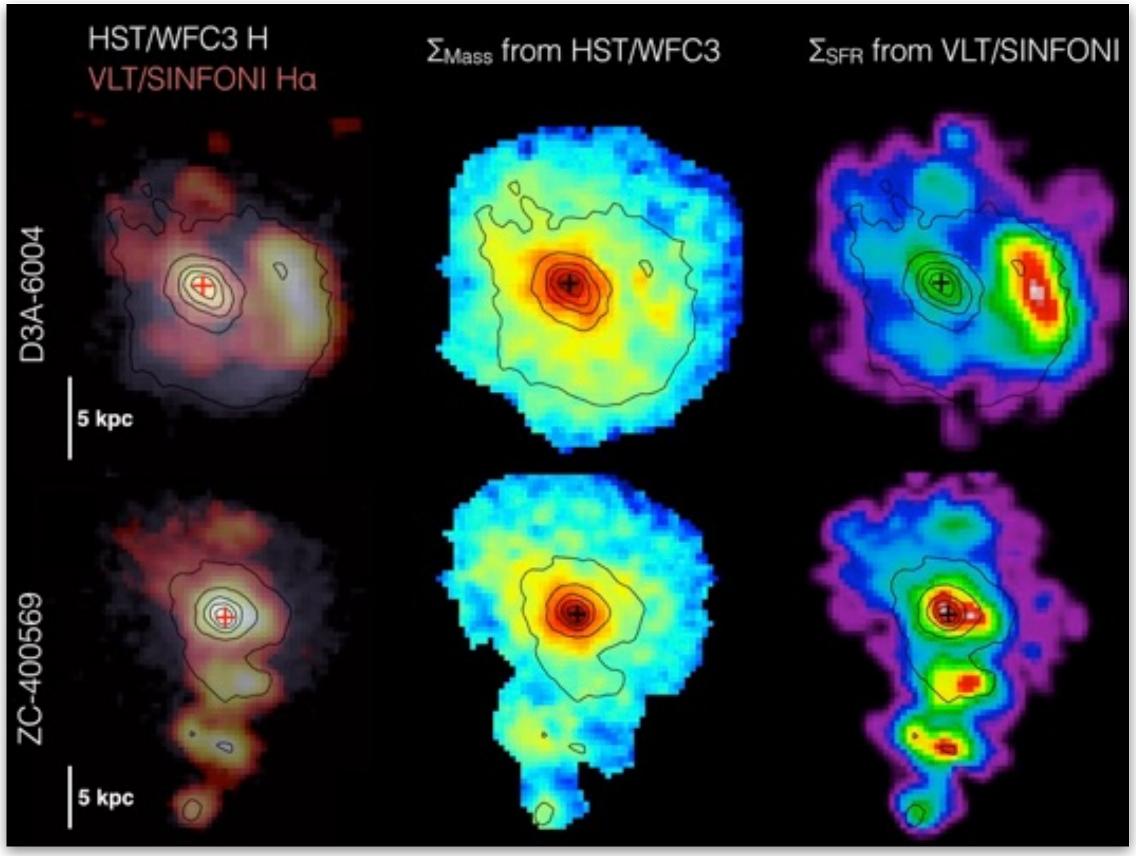
Picture credit: *NASA, ESA, Illingworth et al. (Hubble Legacy Field Team)*

Two types of studies of distant galaxies

Statistical studies
general properties of hundreds of thousands of galaxies



Individual galaxy studies
investigate detailed physical processes



Basic Concepts for Physics of Galaxies

Contents of 2nd-year Astro BSc course 'Physics of Galaxies' <u>will be assumed</u>

https://www.astro.rug.nl/~karina/pog_schedule.html

Measuring the light of a point-like source

$$L = 4\pi d_L^2 f$$

$$f \equiv \int f_\nu(\nu) d\nu = \int f_\lambda(\lambda) d\lambda$$

Angular separation of two sources at the radial distance from us:

$\alpha = D/d$ with α in radians.

Telescope diffraction limit:

$\theta = 1.22 \times \lambda/D$ with θ in radians.

Stefan-Boltzmann:

$$L = 4\pi R^2 \sigma_{SB} T^4$$

The magnitude system

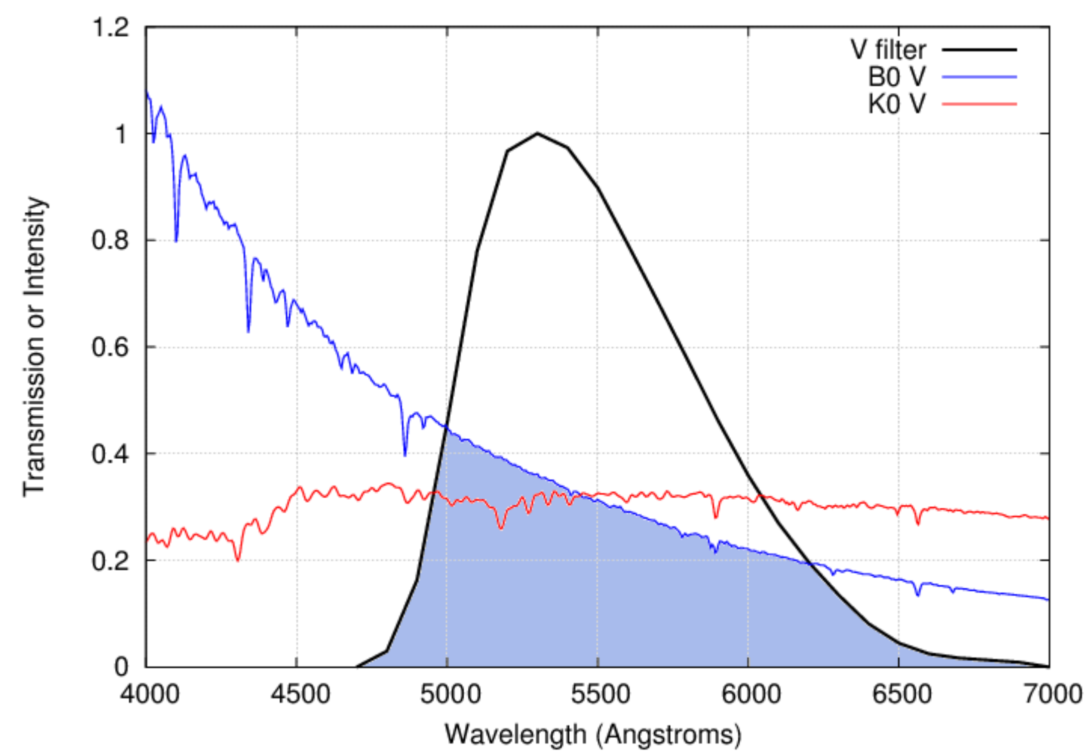
$$m = -2.5\,log_{10}(f_\nu/f_0) = -2.5\,log_{10}(f_\nu) + ZP$$

f_ν -> flux density, per unit of frequency
(c.g.s. units: erg s-1 cm-2 Hz-1)

Flux density measured with a filter in a passband:

$$f_\nu(\lambda_{eff}) \equiv \frac{\int_0^\infty f_\nu(\lambda)\,T(\lambda)d\lambda}{\int_0^\infty T(\lambda)d\lambda}$$

$$\lambda_{eff} \equiv \frac{\int_0^\infty \lambda\,T(\lambda)d\lambda}{\int_0^\infty T(\lambda)d\lambda}$$



Picture credit: spiff.rit.edu

More about photometry

Source (A-B) colour:

$$m_A - m_B = -2.5\, log_{10}(f_\nu^A / f_\nu^B)$$

If λ_A < λ_B then:
negative colour -> “blue” source
positive colour -> “red” source

Effect of dust extinction (uniform distribution):

$$f_{obs} = f_{em}\, e^{-\tau_\lambda}$$

optical depth

Absolute magnitudes:

$$m - M = -2.5\, log_{10}(f/F) = 5\, log_{10}(d/D)$$

distance modulus

10 pc

The contents of this course

- ☑ **Galaxy formation models**
- ☑ **Main ingredients for galaxy formation:** ***star formation and chemical enrichment***
- ☑ **Statistical studies**
- ☑ **Evolution of galaxy properties**
- ☑ **LSS and environment**
- ☑ **Formation of typical local galaxies** ***(spirals/ellipticals)***
- ☑ **High-z galaxy studies**
- ☑ **Multiwavelength observations**
- ☑ **AGN in the context of galaxy evolution**
- ☑ **The IGM**