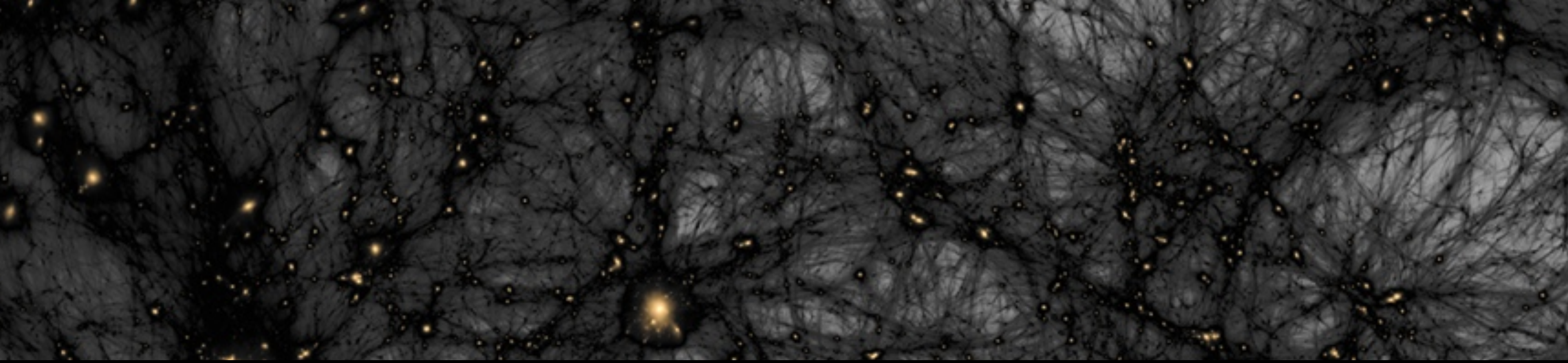


LECTURE I: THE UNIFORM UNIVERSE

Alkistis Pourtsidou

Queen Mary University of London

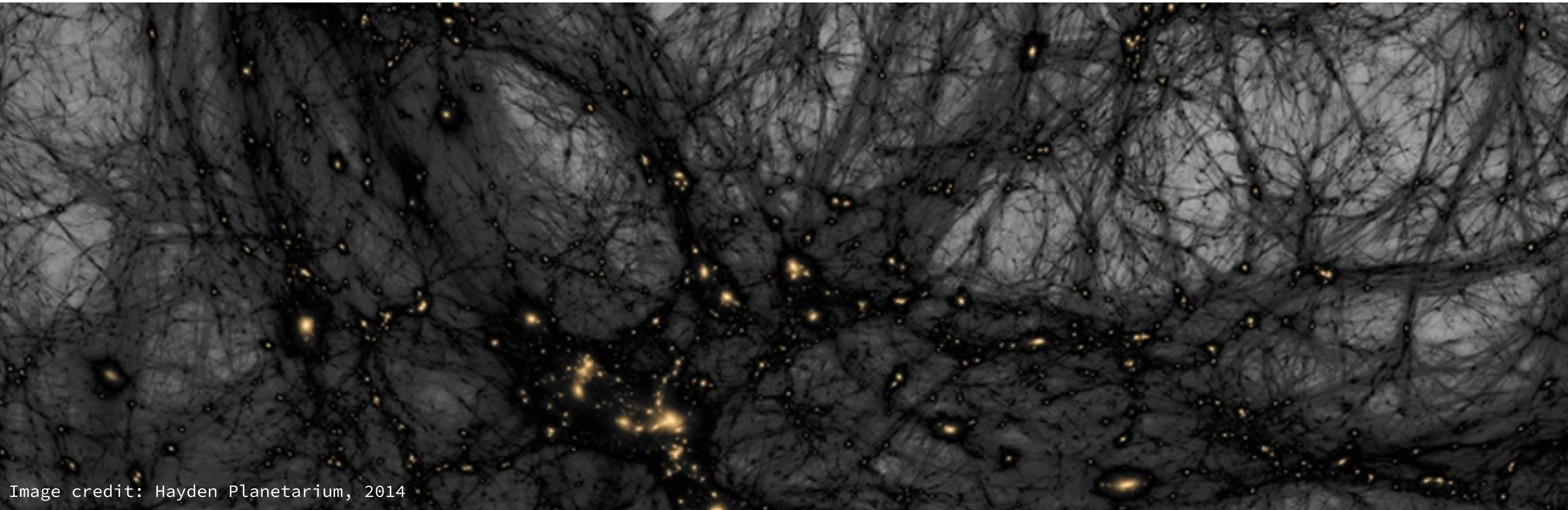
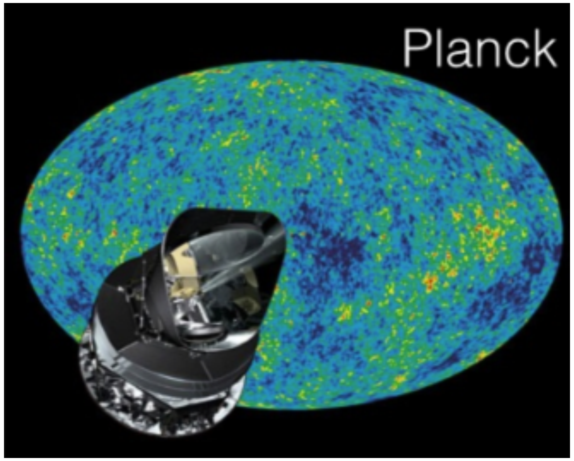
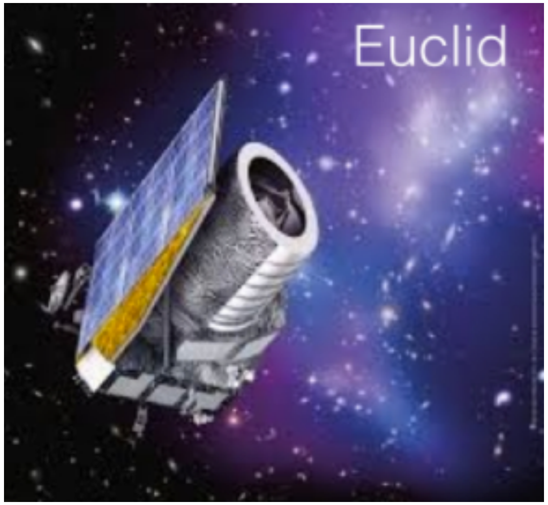


Image credit: Hayden Planetarium, 2014

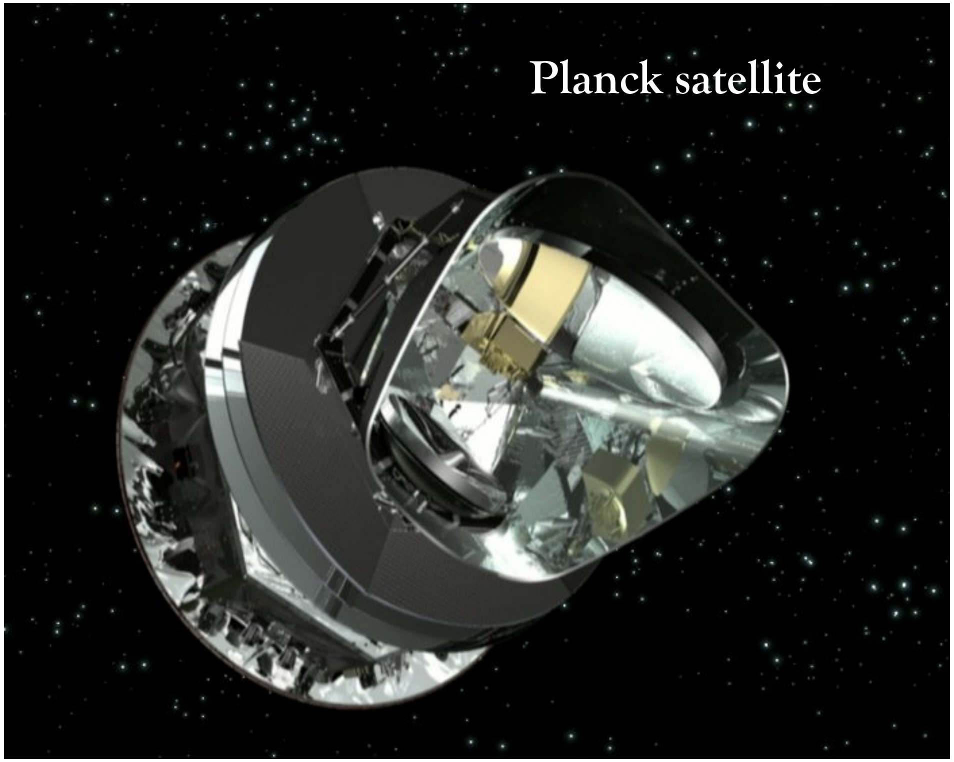
Our universe

- What does the Universe look like? How has it evolved throughout cosmic time? We need a map!
- Our Universe evolves in time, so we need a 3D map, to capture all the information: across the sky and along time
- We utilise ground based telescopes as well as satellites.





THE PLANCK SATELLITE

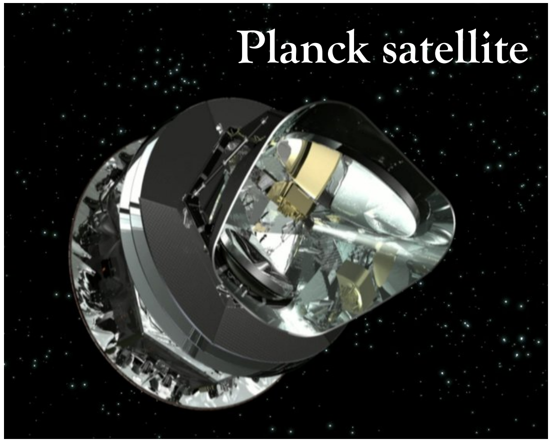


Scanned the sky for 4 years (2009-2013).

Detected the Cosmic Microwave Background with unprecedented precision.

But also stellar cradles in the Milky Way, a multitude of other galaxies, galaxy clusters.

THE COSMIC MICROWAVE BACKGROUND (CMB)



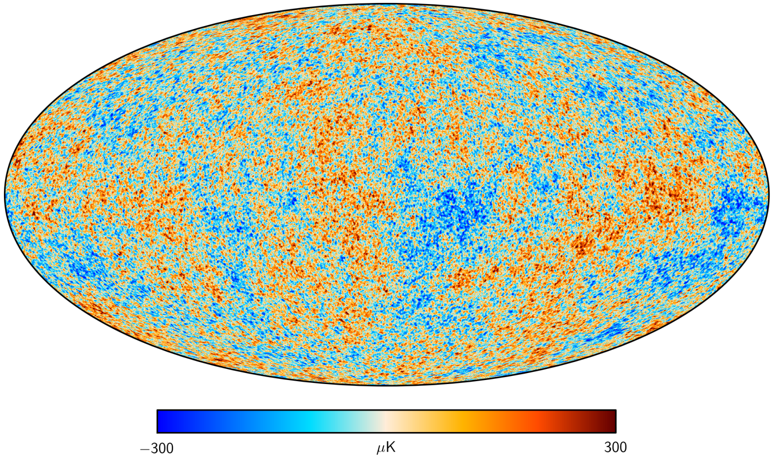


Figure 1: CMB map from the Planck satellite 2015 data.

Figure 1 is a snapshot of the Universe 400,000 years after the Big Bang! Our Universe is 14 billion years old. So the CMB is the “baby” Universe. The CMB map shows very small temperature fluctuations that correspond to (slightly) different densities in the early Universe. These are the seeds of all structure we see today (galaxies etc.).

EXAMPLE: THE COSMIC MICROWAVE BACKGROUND (CMB)

$$\bar{T} = 2.73\,\mathrm{K}$$

$$\frac{\delta T}{\bar{T}} \sim 10^{-5}$$

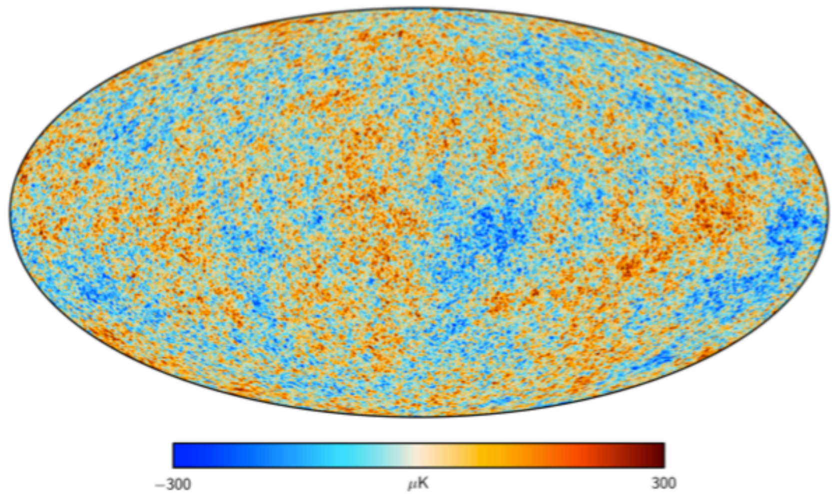


Figure: Temperature data from the Planck satellite, 2015.

- Early Universe photons scatter off electrons - the process of multiple scattering produced a thermal (blackbody) spectrum
- Eventually, the Universe cooled down enough, e and p formed neutral atoms and CMB photons could travel freely

EXAMPLE: LARGE SCALE STRUCTURE (LSS)

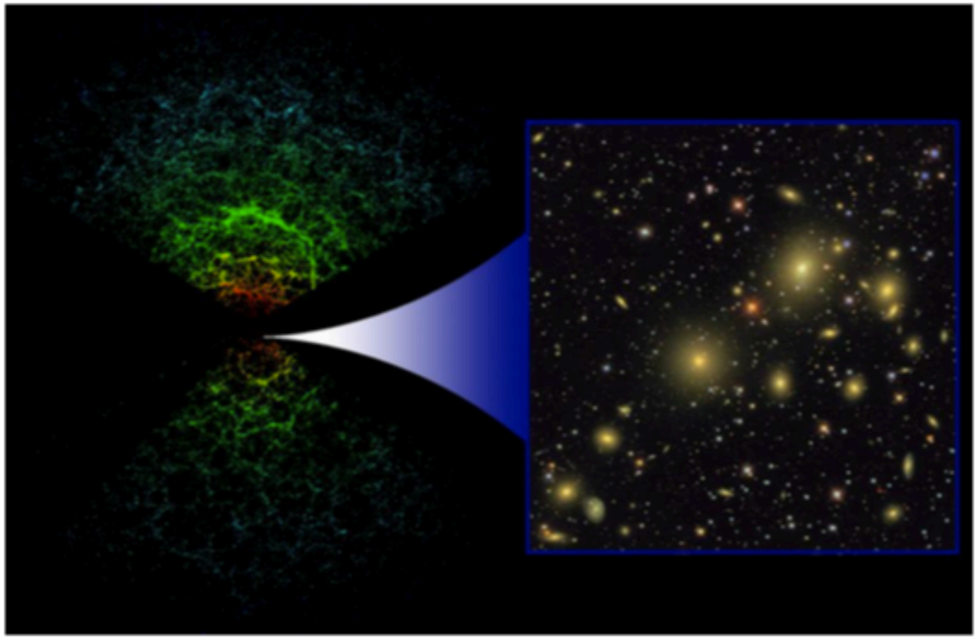
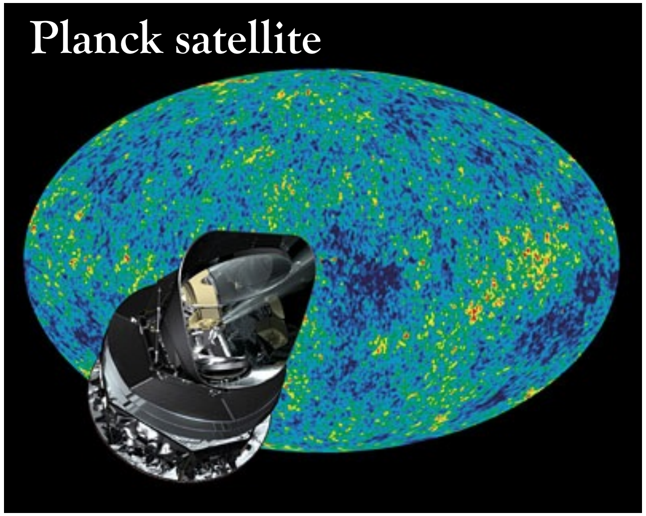
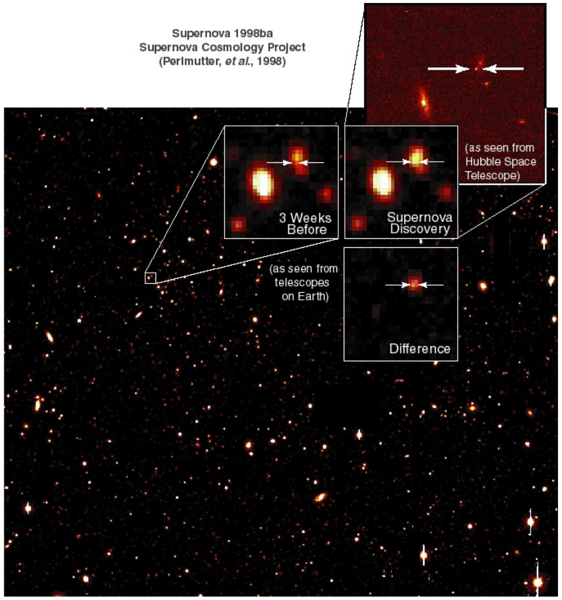


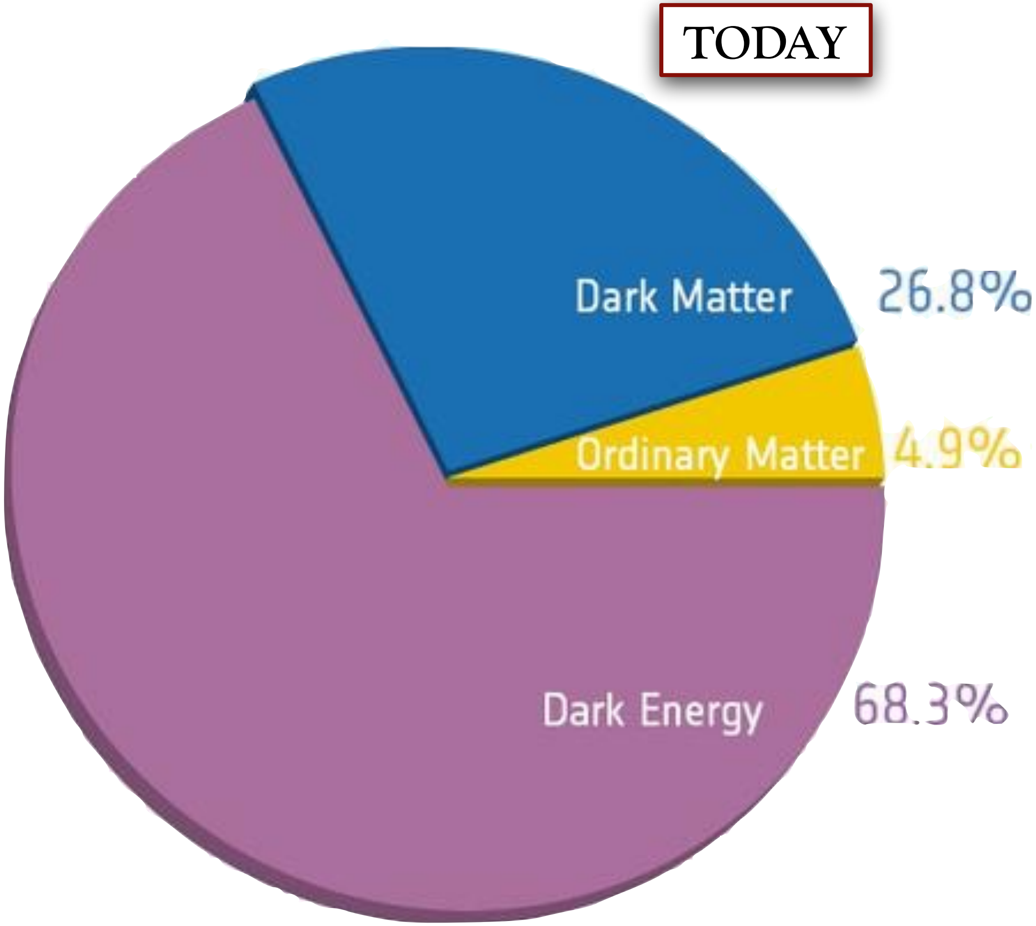
Figure: A map of the observed distribution of galaxies on large scales, from the Sloan Digital Sky Survey (SDSS).

This is the Universe “today! On large scales, we see galaxies and clusters of galaxies, and voids (empty space between clusters of galaxies).

WHAT IS OUR UNIVERSE MADE OFF?







NORMAL MATTER IS JUST 5%!

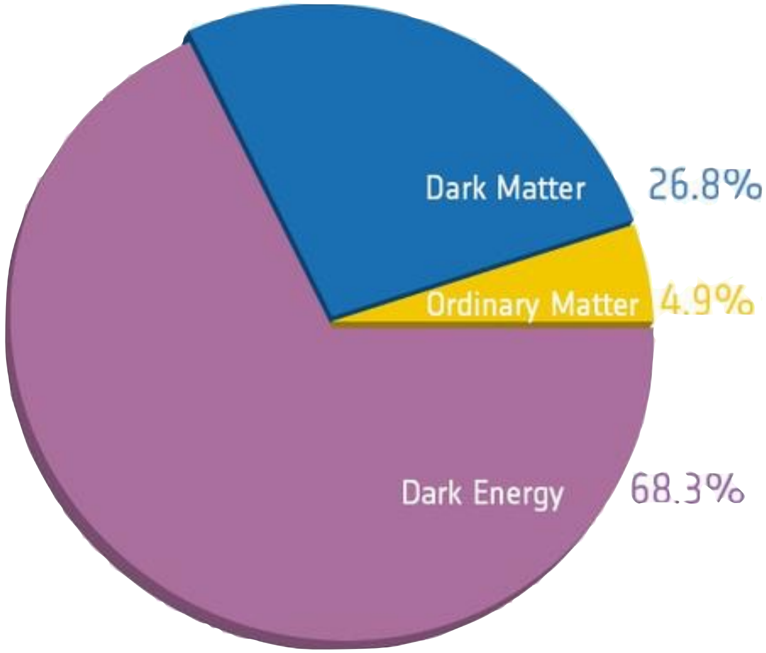
THE PERIODIC TABLE OF THE ELEMENTS

1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.972	35 Br Bromine 79.904	36 Kr Krypton 84.80
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

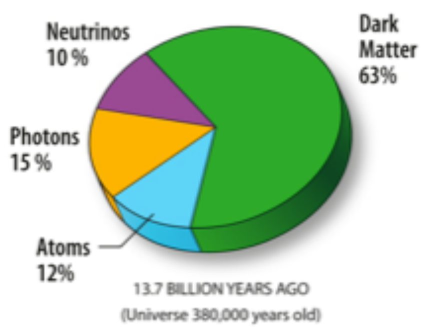
Lanthanide Series	57 La Lanthanum 138.906	58 Ce Cerium 140.115	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.966	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

Alkali Metal | Alkaline Earth | Transition Metal | Basic Metal | Semimetal | Nonmetal | Halogen | Noble Gas | Lanthanide | Actinide

DARK MATTER AND DARK ENERGY



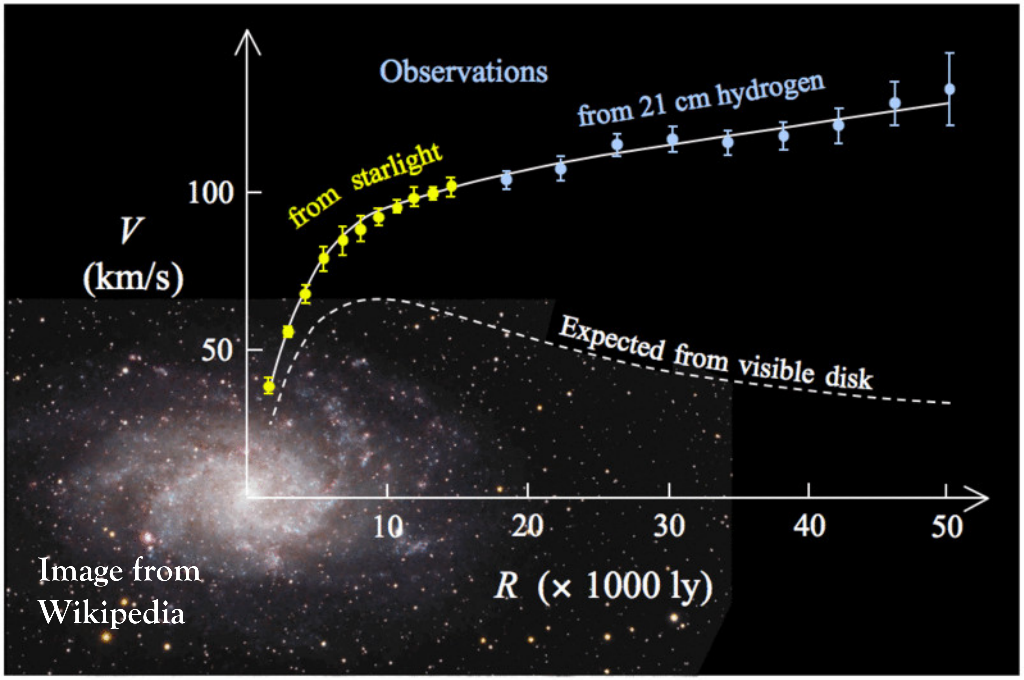
- Note things were very different in the past…



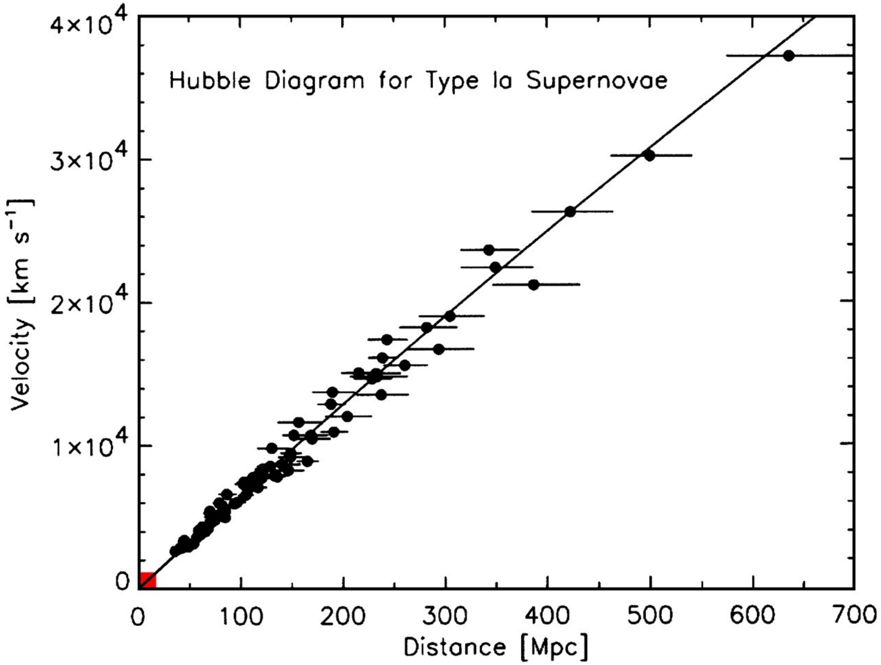
- Most of our Universe is made of dark matter and dark energy.
- Dark matter accounts for the missing mass in the Universe. It doesn't interact with light.
- Effects of DM can be seen gravitationally.
- Popular DM candidate: **WIMP** (Weakly Interacting Massive Particle)
- Back in fashion: **Primordial Black Holes**
- My personal favourite: **Neutrinos** (but it's hard…)

Evidence for dark matter: Galaxy rotation curves

- Newtonian expectation for the orbital velocity: $$v = 1/\sqrt{R}$$
- The discrepancy between the two curves can be accounted for by adding a dark matter halo surrounding the galaxy



THE UNIVERSE IS EXPANDING

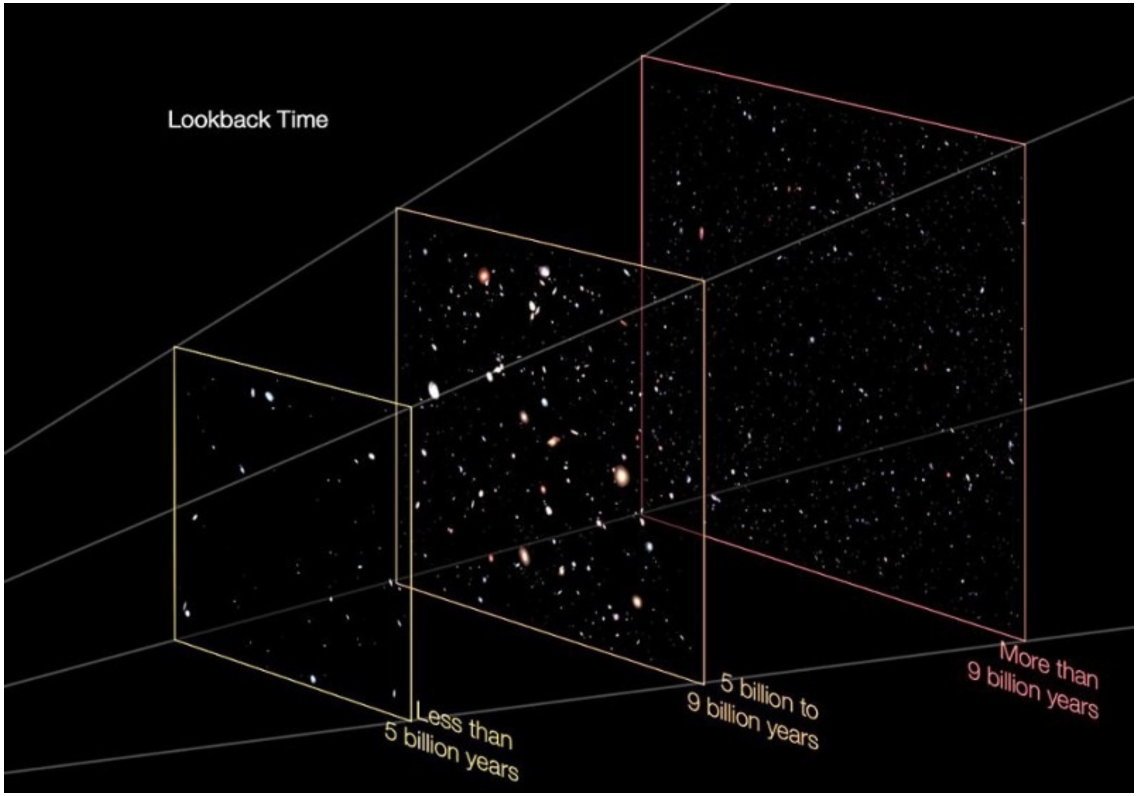


- In the 1920's, Hubble discovered that the Universe is expanding.
- Galaxies move away from us, their velocities are proportional to their distance from us.

$$v = H_0 d$$

$$H_0 = 100h \,\mathrm{km/sec/Mpc}$$

THE UNIVERSE IS EXPANDING



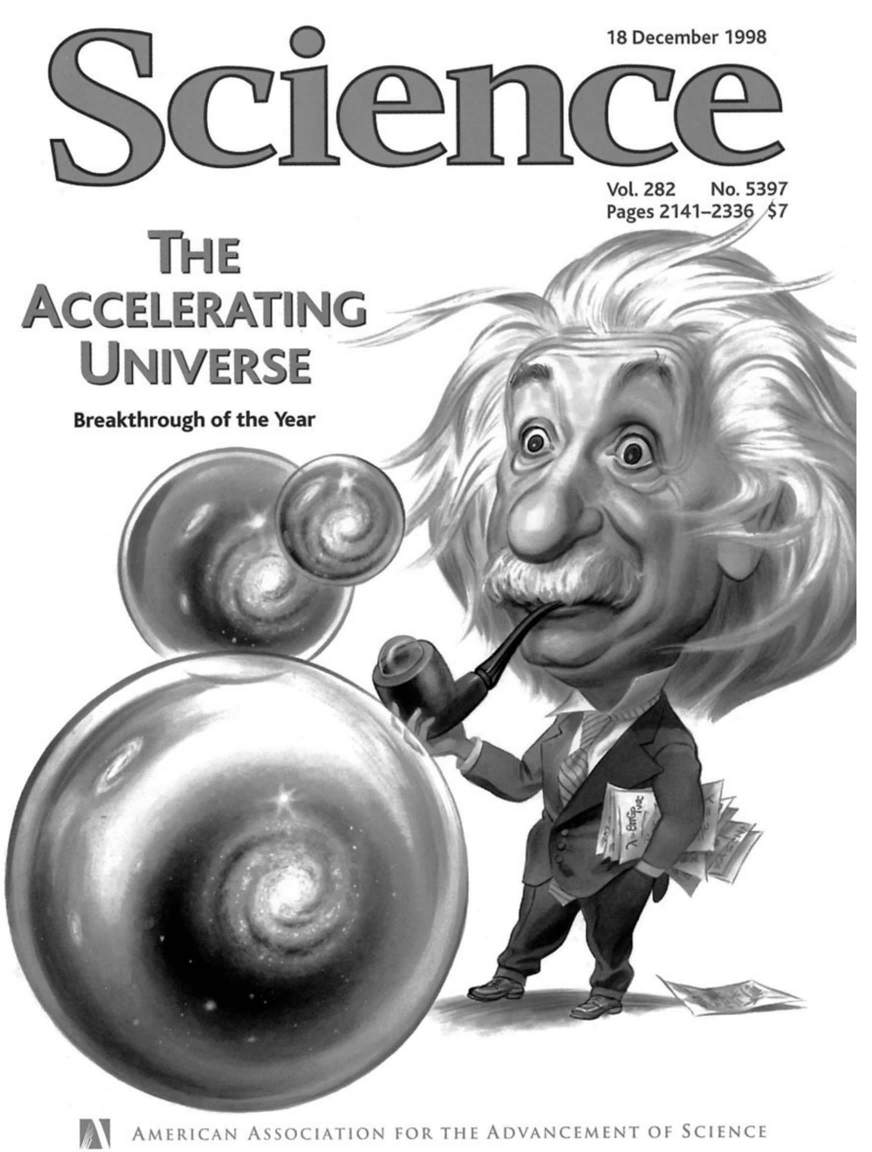
- The Universe is expanding, but matter will slow the expansion down.
- The more matter, the more rapidly the expansion slows down

THE DARK ENERGY BREAKTHROUGH

- **1998:** Two teams measured the expansion of the Universe and discovered that the Universe's expansion is currently speeding up!

- Galaxies are accelerating away from us! This means something other than matter is present in the Universe…

    - **Dark energy!**



DARK ENERGY IS STRANGE

- Dark Energy is repulsive, not attractive: pulls things apart
- Smoothly filling space
- Constant energy per unit volume
- **More energy as space expands!**

WHAT COULD DARK ENERGY BE?

- **Cosmological constant (Λ)**
- Energy of the vacuum. Quantum fluctuations in the vacuum have energy.
- In terms of a mass scale: $\rho_V = M_V^4$
- This leads to a discrepancy of 30 orders of magnitude between theory (Quantum Field Theory) and observations for M_V
- We need **extreme fine tuning** to get the final, observed, **tiny value**
- Alternatives: evolving scalar field (e.g. quintessence - has the same problem), modified gravity - often has the same problem or doesn't manage to do the job!

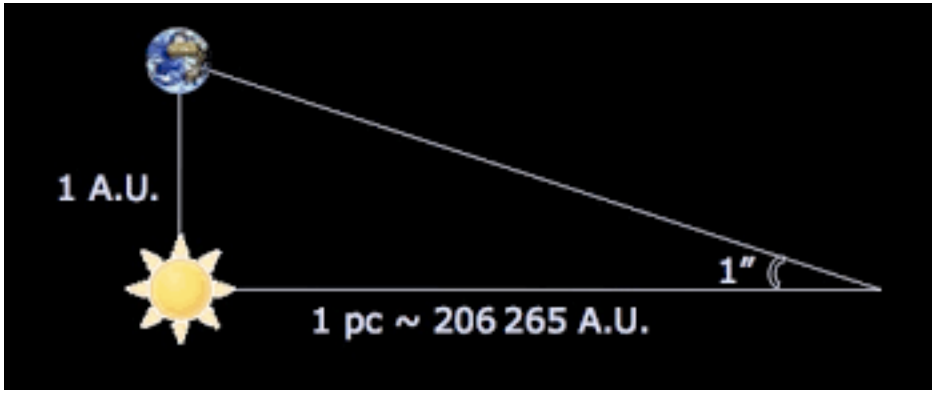
COSMIC LENGTH SCALES

Cosmological length units reminder:

- **The astronomical unit (AU):** The mean distance form the Sun to the Earth. **1 AU=149.6 × 10^6 km**

- **The parsec (pc):** the distance at which 1 AU subtends 1 arc sec (1 arcsec = 1/3600 degrees). In cosmology we usually encounter **Mpc**.

- **Lightyear (LY):** the distance light travels in a year in vacuum. This is equal to 9.46 x 10^{15} m.

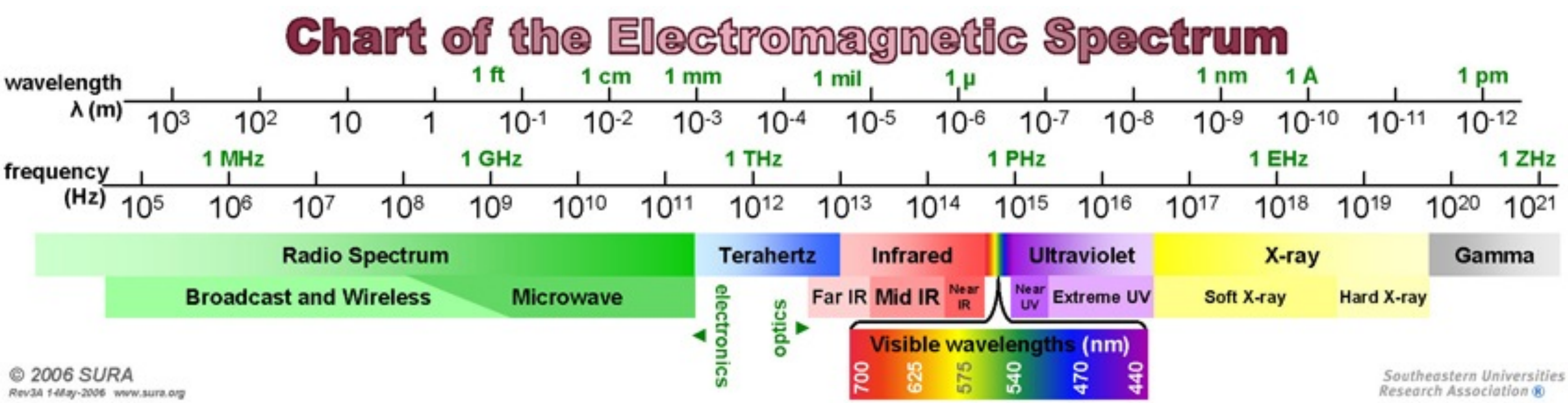


http://wwwhip.obspm.fr

BUT WHAT DO WE MEAN BY "LIGHT"?

We observe in many different wavelengths (frequencies):

- ✦ Radio waves
- ✦ Infrared light
- ✦ Visible light
- ✦ Ultraviolet light
- ✦ X-rays
- ✦ Gamma rays

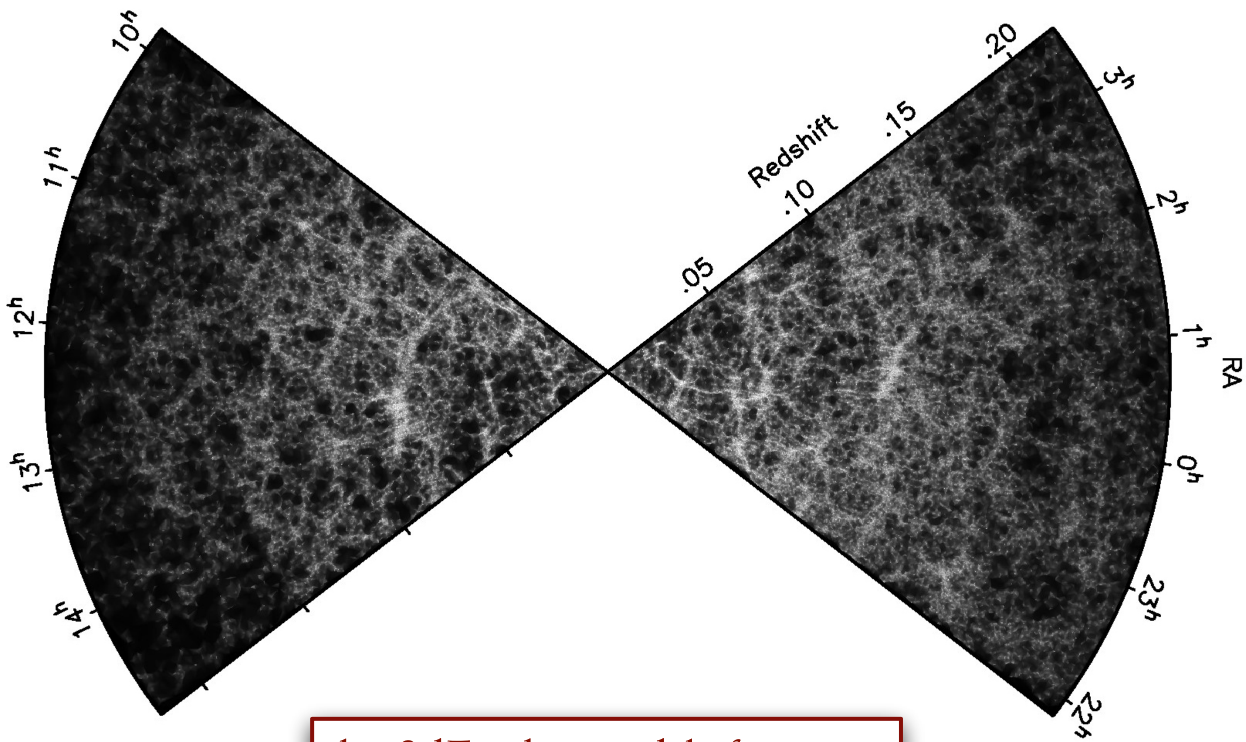


VISIBLE LIGHT: STARS AND GALAXIES

- Visible light from nuclear fusion within stars.
- The Sun is an average star (2 x 10^{30} kilograms = 1 solar mass). The nearest stars to us are a few lightyears away.
- In cosmology, we rarely talk about individual stars. We work with the collection of stars called **galaxies**.
- Galaxies are beautiful and complicated objects, but in cosmology we just treat them as point-like objects emitting light.

CLUSTERS OF GALAXIES, SUPERCLUSTERS, AND VOIDS

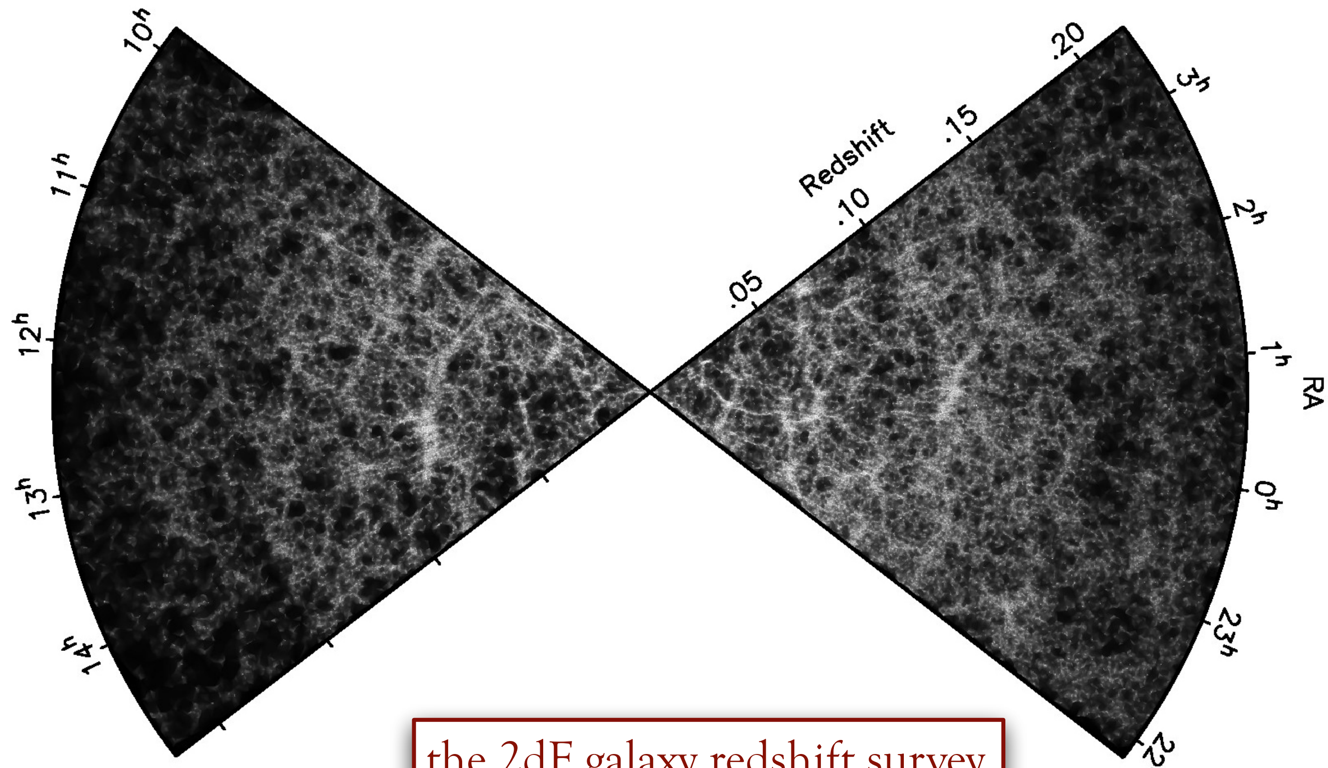
✦ Surveying larger regions of the Universe, say on a scale of hundreds of Mpc, one sees a variety of large-scale structures.



the 2dF galaxy redshift survey

CLUSTERS OF GALAXIES, SUPERCLUSTERS, AND VOIDS

- The Figure is a carefully reconstructed map of the nearby region of our Universe (scale 1:10^{27})
- In some places galaxies are **clearly grouped into clusters of galaxies.**



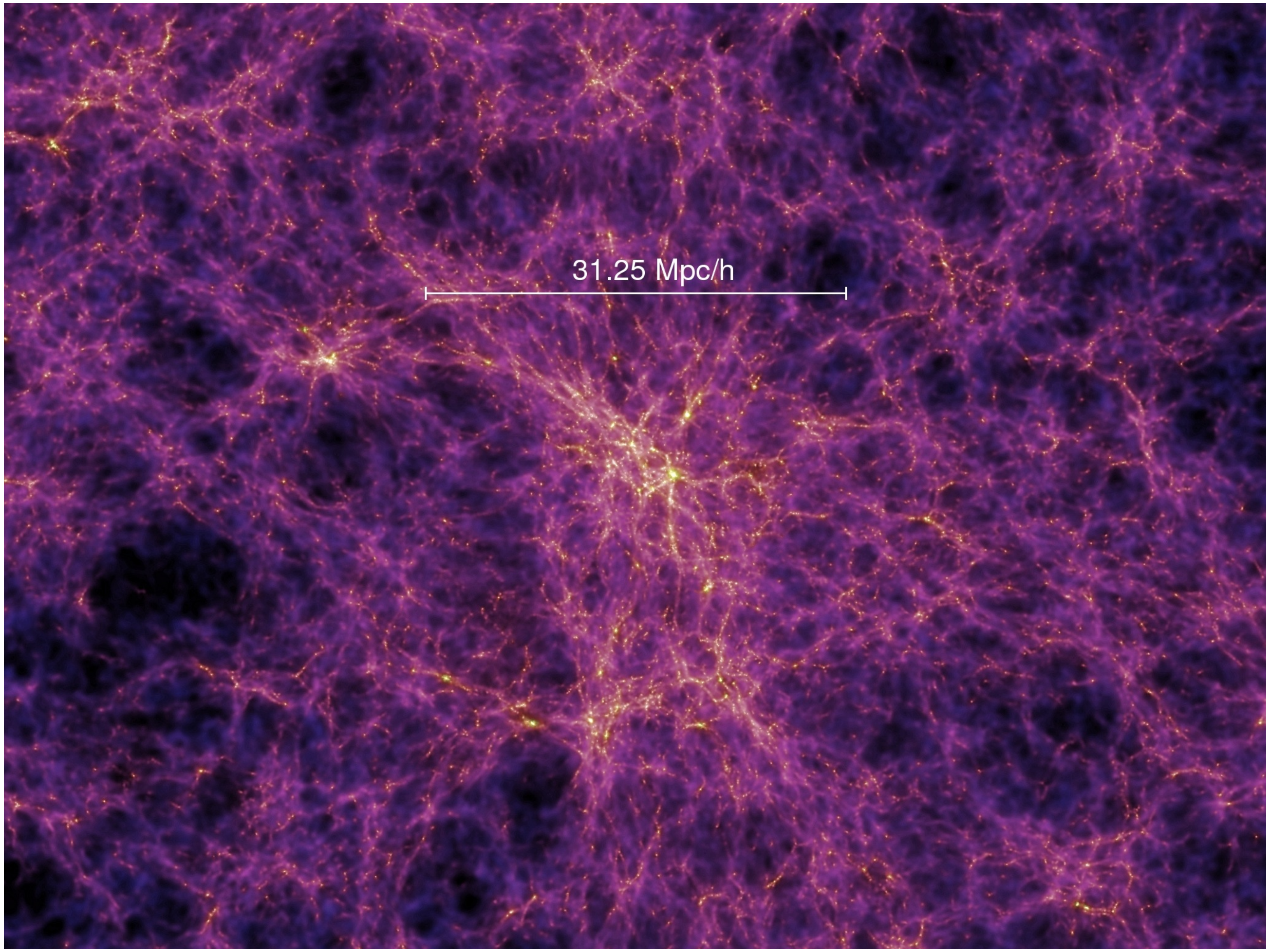
the 2dF galaxy redshift survey

CLUSTERS OF GALAXIES, SUPERCLUSTERS, AND VOIDS

- Galaxy clusters are themselves grouped into superclusters, joined by “filaments"and “walls” of galaxies.
- In between this “foamlike” structure lie large voids, some as large as 50 Mpc across.
- **Large-scale smoothness: Only once we get to scales of 100 Mpc or more does the Universe begin to appear smooth. This means that we cannot find any large structures on scales greater than about 100 Mpc.**
- The galaxy superclusters and voids are believed to be the biggest structures in the Universe.

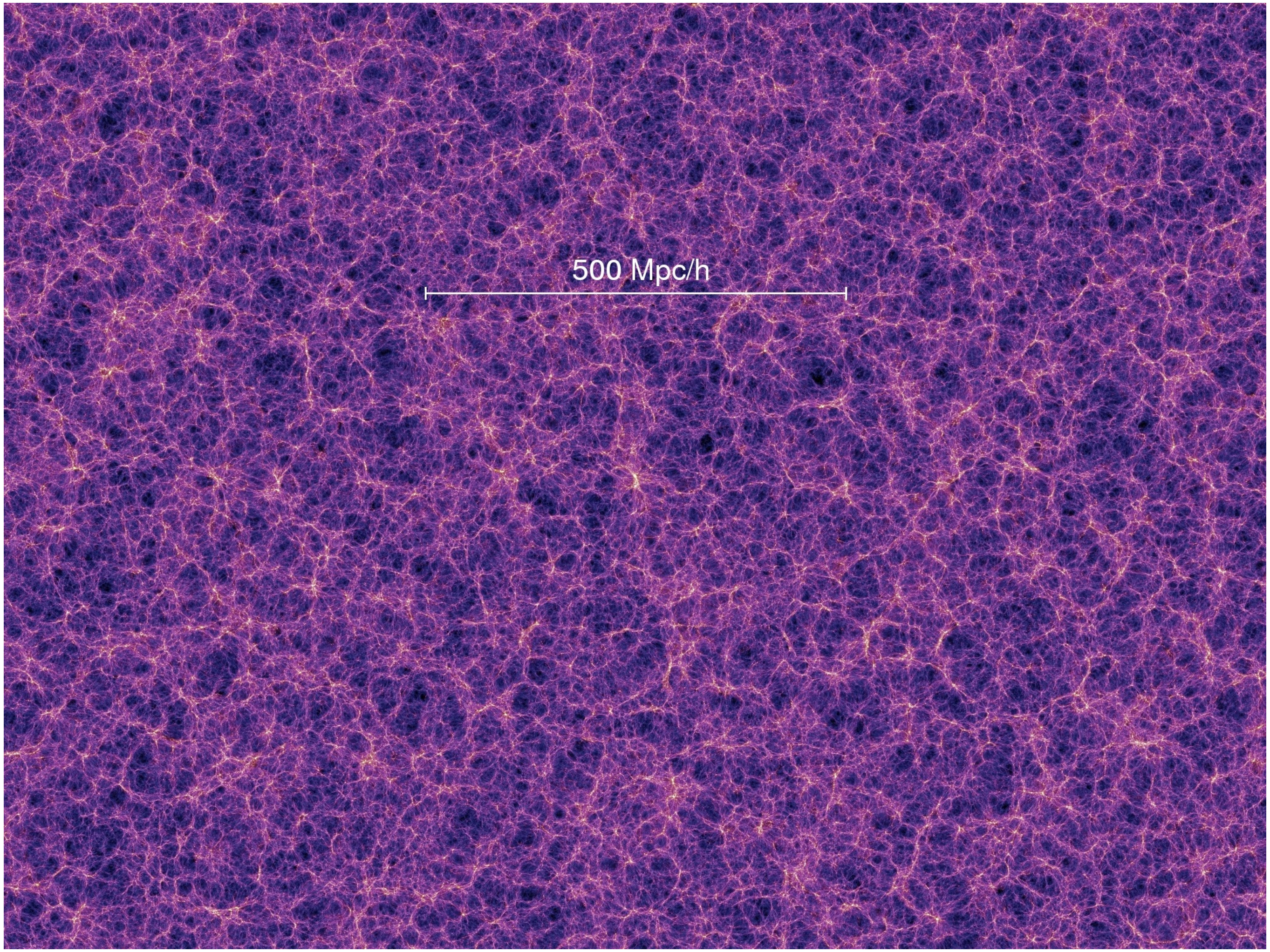
MATTER DISTRIBUTION ON LARGE SCALES

[Image from the Millennium Simulation]



MATTER DISTRIBUTION ON LARGE SCALES

[Image from the Millennium Simulation]

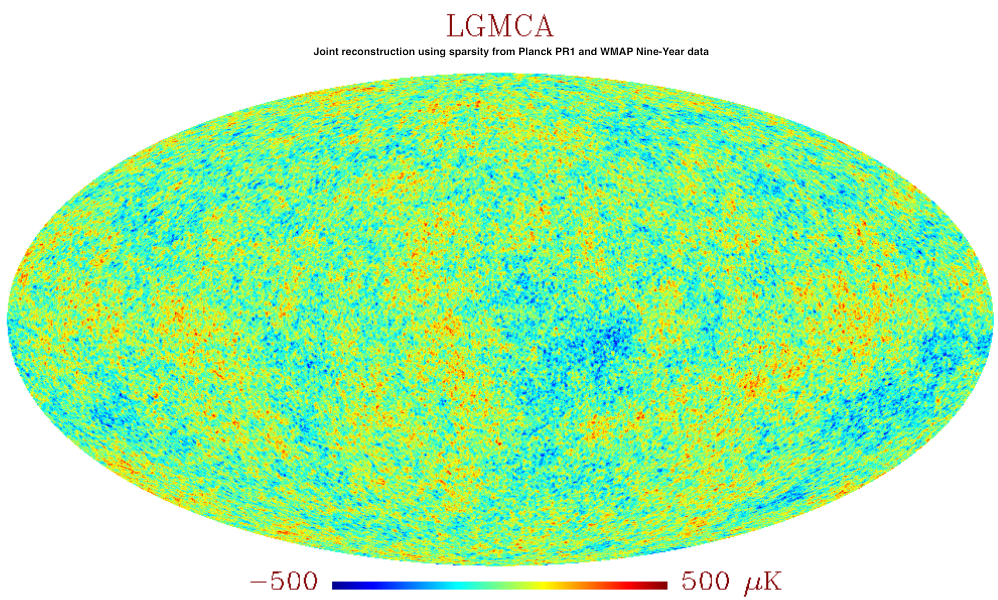


HOMOGENEITY AND ISOTROPY

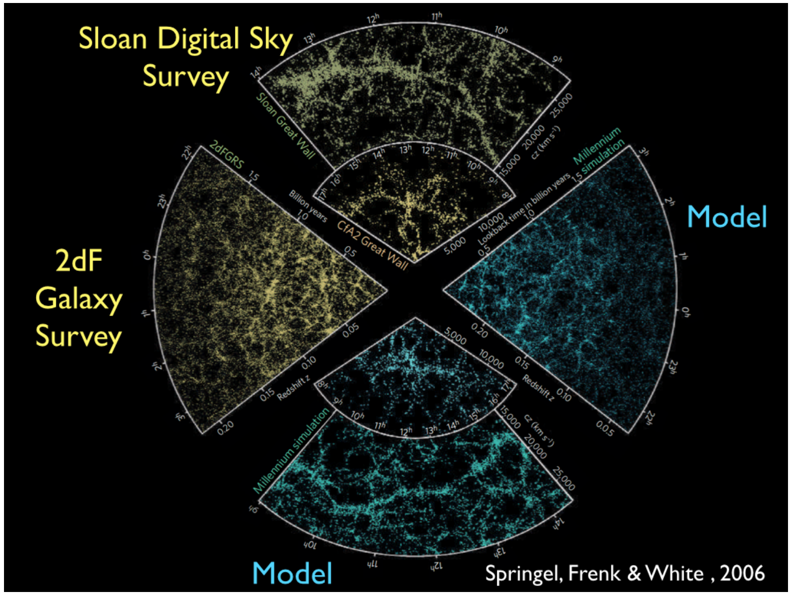
- **The largest structures have a size of the order of 100 Mpc**
  - Beyond this the Universe appears to be smooth, i.e. no larger structures on larger scales
  - We therefore say that the Universe on the largest scales is homogeneous (uniform) and isotropic (no preferred direction)
  - This is called **the cosmological principle**, and it is the underpinning of modern cosmology.

OBSERVATIONS THAT SUPPORT THE COSMOLOGICAL PRINCIPLE

- The cosmic microwave background is smooth (fluctuations are only *1/100,000* at large scales).
- Large scale structure observations from galaxy surveys.
- Simulations of the Universe only in agreement with observations if the cosmological principle is assumed!



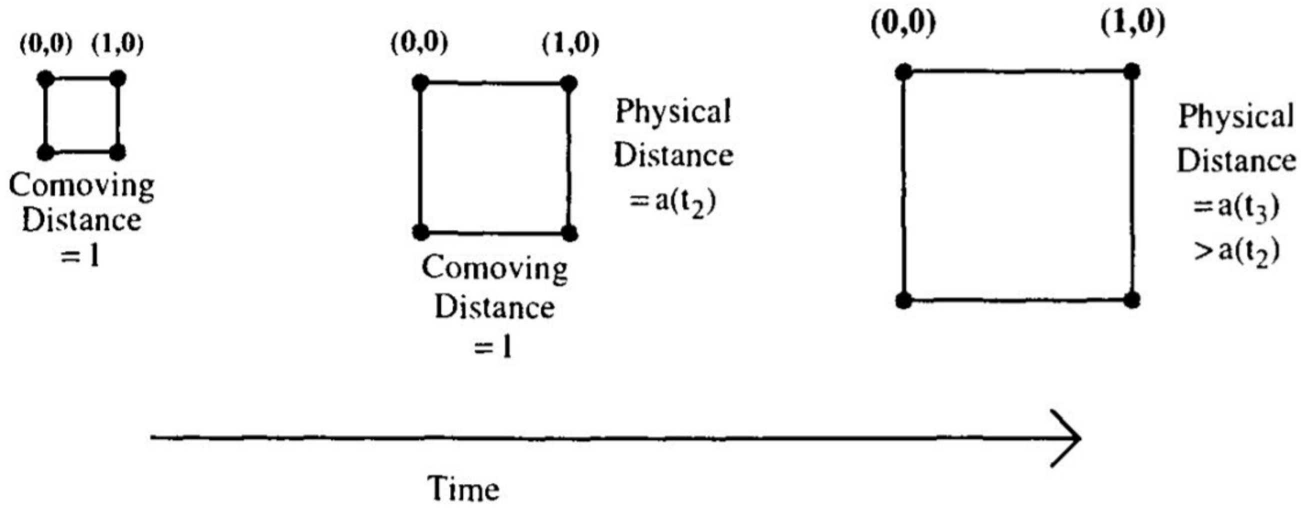
CEA-Irfu, http://www.cosmostat.org/planck_wpr1.html



EXPANSION OF THE UNIVERSE

- What does expansion mean?
- It **does not** mean that the Earth's orbit is going to get further from the Sun (gravity wins!).
- It **does not** mean that the stars within our galaxy are going to be more widely separated with time (gravity wins!).
- But it **does mean** that distant galaxies are getting further apart. There we do not have excess density (pretty much homogeneous/isotropic), and galaxies are flying apart from one another.
- **Hence:** the expansion of the Universe is felt on large scales, on which the cosmological principle applies.

THE EXPANDING UNIVERSE: COMOVING COORDINATES



Expansion of the universe. The comoving distance between points on a hypothetical grid remains constant as the universe expands. The physical distance is proportional to the comoving distance times the scale factor, so it gets larger as time evolves.

$$d_{\mathrm{phys}} = a d_{\mathrm{com}}$$

Figure from S. Dodelson

REDSHIFT

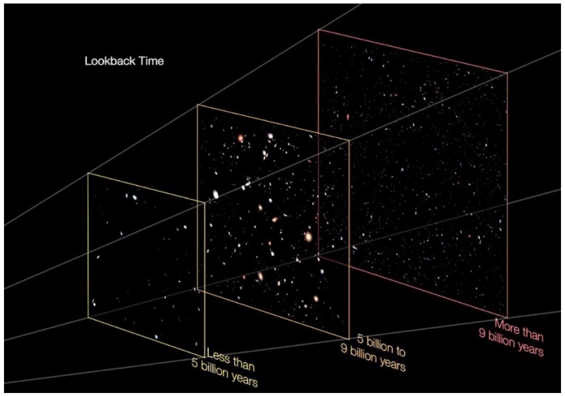
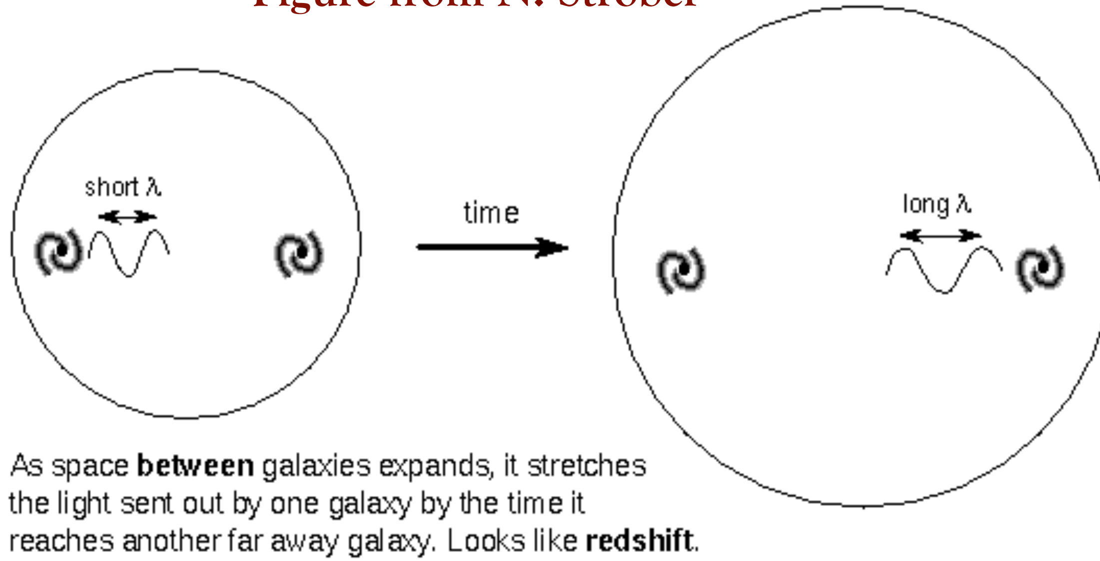


Figure from N. Strobel



- Redshift (z) is related to the expansion (the scale factor, a)

$$1 + z = \frac{1}{a}$$

Calculation of redshift, z

Based on wavelength	Based on frequency
$z = \frac{\lambda_{\mathrm{obsv}} - \lambda_{\mathrm{emit}}}{\lambda_{\mathrm{emit}}}$	$z = \frac{f_{\mathrm{emit}} - f_{\mathrm{obsv}}}{f_{\mathrm{obsv}}}$
$1 + z = \frac{\lambda_{\mathrm{obsv}}}{\lambda_{\mathrm{emit}}}$	$1 + z = \frac{f_{\mathrm{emit}}}{f_{\mathrm{obsv}}}$

THEORY

What underlying theory or theories govern the evolution of the Universe?

- on small scales *Quantum Field Theory* (sets the initial conditions)
- on large scales *Einstein's General Relativity*
- to understand the "details" – what drives inflation, what is the nature of dark matter and dark energy – need to confront theory with observations, make sense of observations
- However, "details" – what is the dark stuff (dark energy, dark matter), what are the initial conditions, etc. – still unclear: cosmology is a very active area of research!

Simulations

- Put initial conditions in a numerical simulation and solve the evolution equations
- It works! We get the structure we observe (clusters, voids, ...)

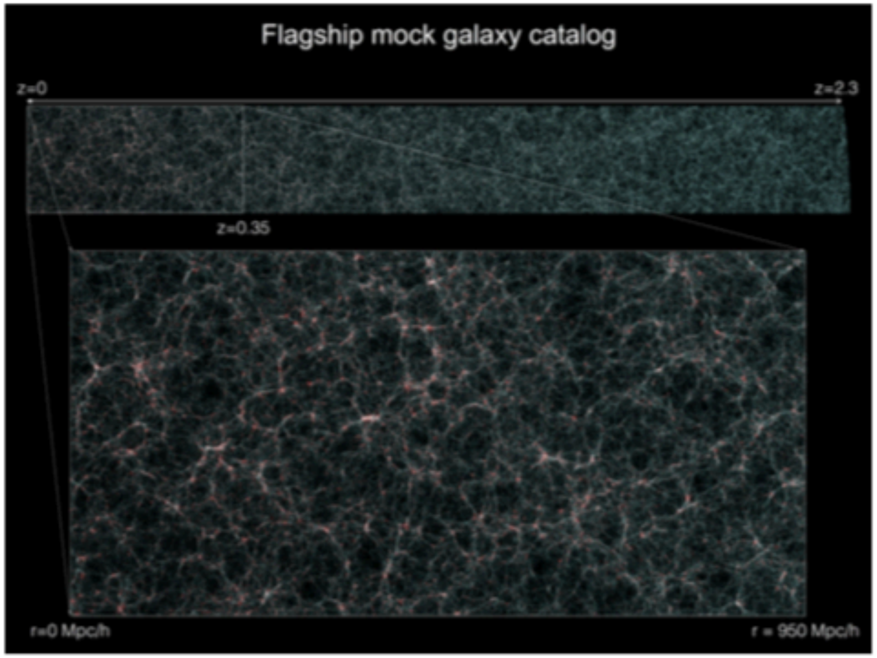
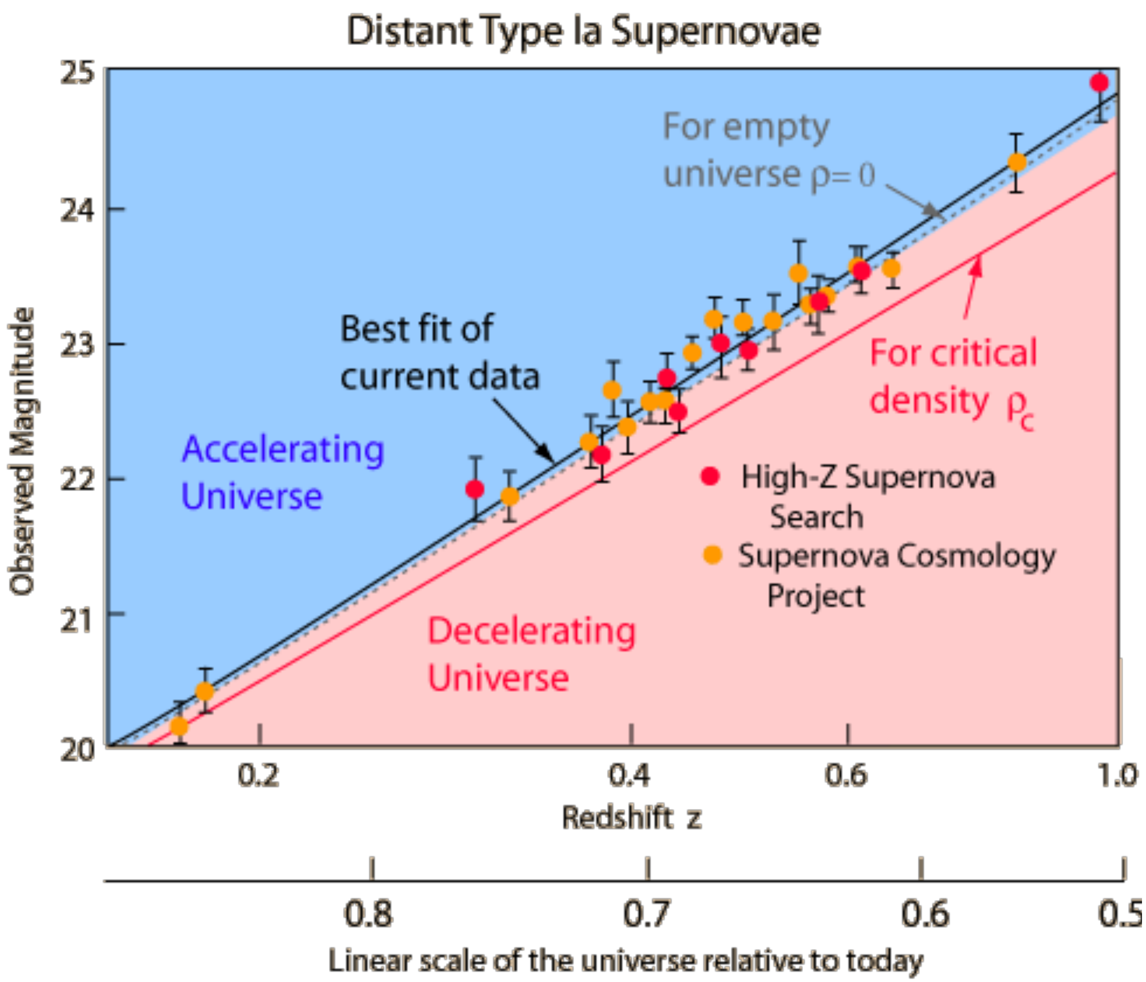


Figure: Euclid Consortium Cosmological Simulations Science Working Group.

OBSERVATIONS / DATA ANALYSIS

Get the data, analyse them, and compare them with the predictions of your favourite model (informed by simulations). Statistics crucial for cosmology!



OBSERVATIONS / DATA ANALYSIS

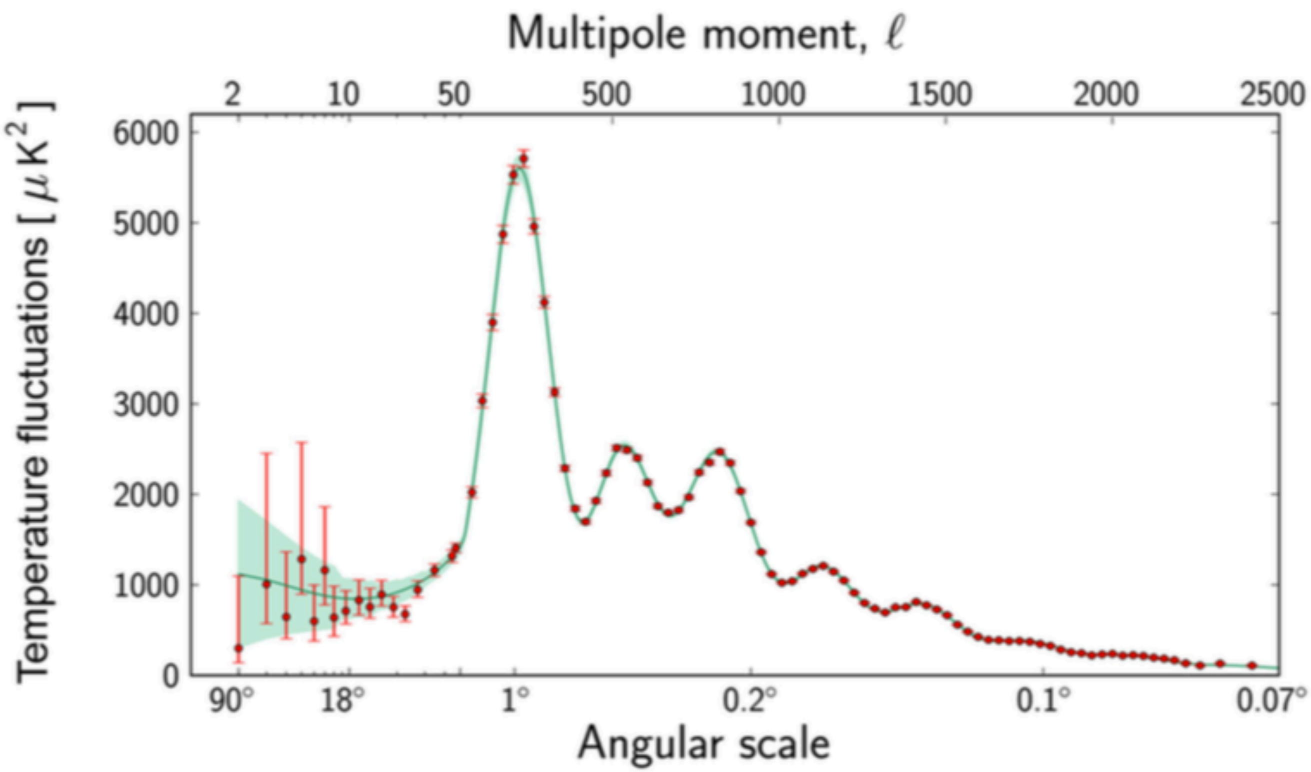
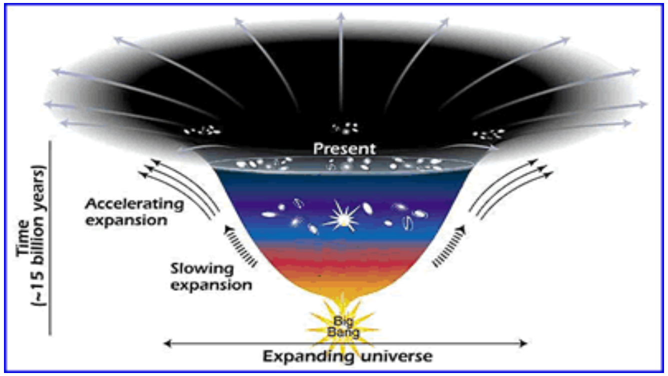


Figure: Planck 2015 data and best fit model. The agreement is near-perfect!

THE SCALE FACTOR

- We already saw that the scale factor quantifies the expansion



- We set $a=1$ today and it gets smaller as $1/(1+z)$
- *E.g.* $a=0.001$ *for* $z=999$

For low redshifts, $z \approx v/c$, so redshift directly measures recession velocity

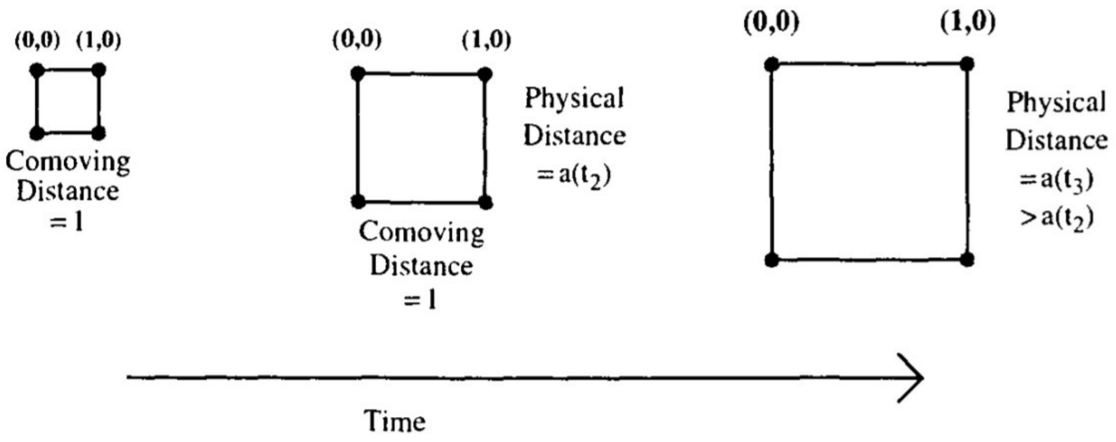
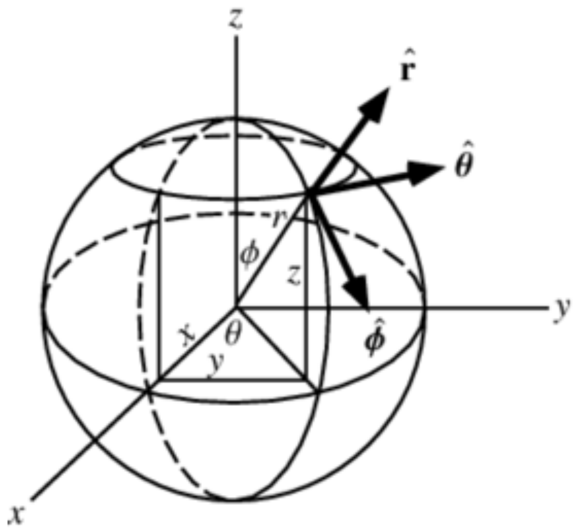


Figure 1.1. Expansion of the universe. The comoving distance between points on a hypothetical grid remains constant as the universe expands. The physical distance is proportional to the comoving distance times the scale factor, so it gets larger as time evolves.

THE METRIC

- We saw that coordinate differences on expanding grid are comoving distances
- To get a physical distance *dl*, from a set of coordinate differences, we need to use a metric.
- The metric for distances on the surface of a sphere is:



$$dl^2 = g_{ij}dx^i dx^j$$

$$dl^2 = R^2(d\theta^2 + \sin^2\theta d\phi^2)$$

$$g_{\theta\theta} = R^2$$

$$g_{\phi\phi} = R^2\sin^2\theta$$

Adapted slide from Will Percival

THE FRIEDMANN-ROBERTSON-WALKER METRIC

- A homogeneous, isotropic, expanding Universe is described by the FRW metric
- It contains the scale factor, which is a function of time

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

- The geometry of the Universe is parametrised by *k*
- Spatially flat Universe: k=0

$$ds^2 = -dt^2 + g_{ij}dx^i dx^j$$

$$g_{00} = -1 \quad g_{ij} = \delta_{ij}a(t)^2$$

GENERAL RELATIVITY

- Einstein's Equations

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Christoffel Symbol $\Gamma^{\alpha}{}_{\mu\nu} = \frac{1}{2}g^{\alpha\beta}\left[\frac{\partial g_{\beta\mu}}{\partial x^{\nu}} + \frac{\partial g_{\beta\nu}}{\partial x^{\mu}} - \frac{\partial g_{\mu\nu}}{\partial x^{\beta}}\right]$

Ricci (Curvature) Tensor

$$R_{\mu\nu} = \partial_\alpha \Gamma^{\alpha}{}_{\mu\nu} - \partial_\nu \Gamma^{\alpha}{}_{\mu\alpha} + \Gamma^{\alpha}{}_{\beta\alpha}\Gamma^{\beta}{}_{\mu\nu} - \Gamma^{\alpha}{}_{\beta\nu}\Gamma^{\beta}{}_{\mu\alpha}$$

Ricci Scalar $R = g^{\mu\nu}R_{\mu\nu}$

Energy Momentum Tensor $T_{\mu\nu}$

"Matter tells space how to curve, and space tells matter how to move"

APPLICATION TO THE FRW METRIC

FRW metric for flat space has:

$$g_{00} = -1 \quad g_{ij} = \delta_{ij} a(t)^2$$

So (for example) the Christoffel symbol reduces to:

$$\begin{aligned}
\Gamma^0{}_{ij} &= \frac{1}{2} g^{0\alpha} \left[\frac{\partial g_{\alpha i}}{\partial x^j} + \frac{\partial g_{\alpha j}}{\partial x^i} - \frac{\partial g_{ij}}{\partial x^\alpha} \right] \\
&= \frac{1}{2} g^{00} \left[\frac{\partial g_{0i}}{\partial x^j} + \frac{\partial g_{0j}}{\partial x^i} - \frac{\partial g_{ij}}{\partial x^0} \right] \\
&= \delta_{ij} \frac{1}{2} \frac{d}{dt} a^2 = \delta_{ij} \dot{a} a
\end{aligned}$$

The time-time component of Einstein's equations

$$R_{00} = -3\frac{\ddot{a}}{a} \qquad R = 6\left[\frac{\ddot{a}}{a} + \left(\frac{\dot{a}}{a}\right)^2\right]$$

$$R_{00} + \frac{1}{2}R = 8\pi G \underline{T_{00}} = 8\pi G \underline{\rho}$$

THE FRIEDMANN EQUATION FOR COSMOLOGICAL EVOLUTION

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = \frac{8\pi G}{3}\rho$$

The space-space component of Einstein's equations

$$\frac{\ddot{a}}{a} + \frac{1}{2}\left(\frac{\dot{a}}{a}\right)^2 = -4\pi G P$$

P is the diagonal space-space component of the energy momentum tensor

Combine with Friedmann to get the acceleration equation:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P)$$

Deceleration, unless $\rho + 3P < 0$

Energy conservation equation:

$$\dot{\rho} + 3\left(\frac{\dot{a}}{a}\right)(\rho + P) = 0$$

Friedman equation

- Einstein equations

if not flat

$$H(t)^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho \boxed{- \frac{K}{a^2}}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P)$$

- Energy-momentum conservation

$$\dot{\rho} + 3H(\rho + P) = 0, \quad \rho = \sum_i \rho_i$$

- Two of these equations are independent

Three unknown quantities a, ρ, P

➡ we need to specify the equation of state $w = P/\rho$

Slide from Kazuya Koyama

EQUATION OF STATE PARAMETER

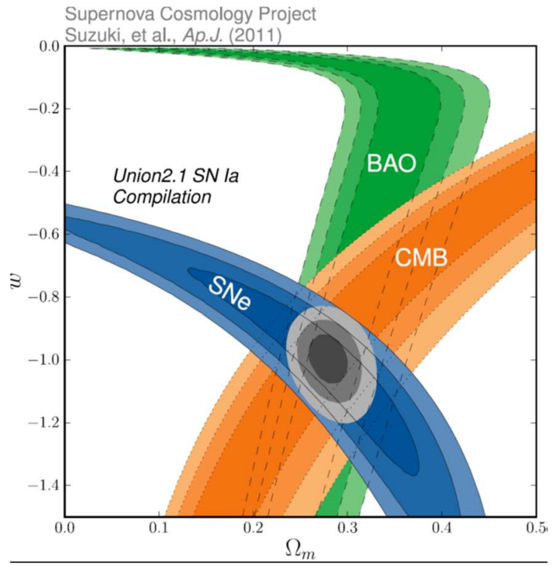
$$\boxed{w = \frac{P}{\rho}}$$

Non-Relativistic matter is pressureless $w = 0$

Radiation is relativistic $w = 1/3$

Dark energy? Cosmological constant has $w = -1$

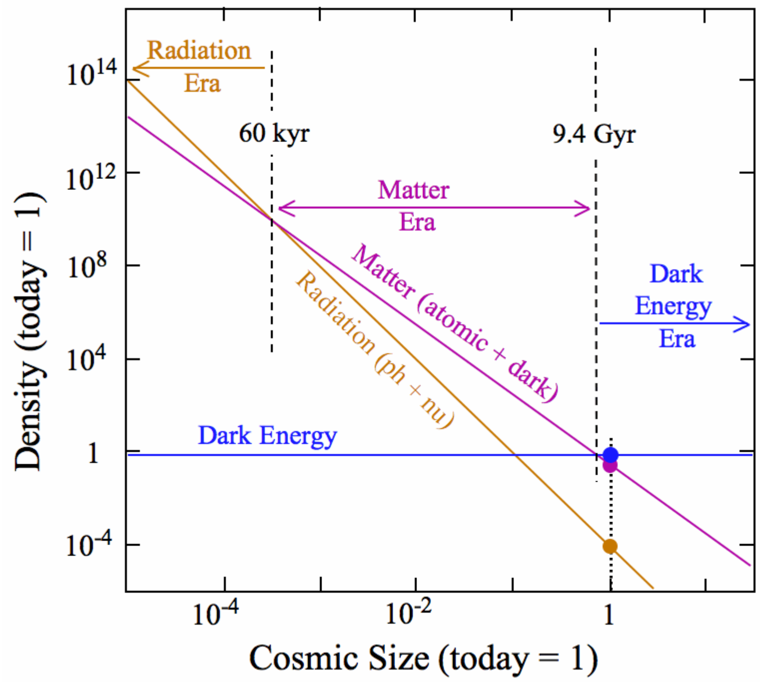
Quintessence has $w = w(a)$



EVOLUTION OF MATTER, RADIATION, DARK ENERGY

Pressureless matter: w=0

$$\rho_m(a) = \rho_{m,0}a^{-3}$$



Radiation (relativistic): w=1/3

$$\rho_\gamma(a) = \rho_{\gamma,0}a^{-4}$$

Dark energy with w=w(a):

$$\rho(a) = \rho_0 \exp\left\{3\int_a^1 \frac{da'}{a'}[1+w(a')]\right\}$$

Cosmological constant: w=-1 $\quad \rho_{\rm de} = \rho_{\rm de,0}$

DENSITY COMPONENTS

Radiation, matter (CDM and baryonic), dark energy + flat geometry

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = \frac{8\pi G}{3}\rho$$

For the Hubble rate H, we can write:

$$H^2 = \frac{8\pi G\rho}{3} = H_0^2\left\{\Omega_{\rm de}(a) + [\Omega_{\rm b}(a) + \Omega_{\rm cdm}(a)] + \Omega_\gamma(a)\right\}$$

Where $\Omega_i = \rho_i/\rho_{\rm crit}$ $\quad H_0 = 100h\,\mathrm{km\,sec}^{-1}\mathrm{Mpc}^{-1}$

$$\rho_{\rm crit} = 1.88h^2 \times 10^{-29}\,\mathrm{gcm}^{-3}$$

THE SCALES OF OUR UNIVERSE

Hubble time: $$t_H = \frac{1}{H_0} = 9.78 \times 10^9/h\,\mathrm{yr}$$

Hubble distance: $$D_H = \frac{c}{H_0} = 3000/h\,\mathrm{Mpc}$$

THE E(Z) FUNCTION

We often express the Hubble rate via: $H(z) = H_0 E(z) = 100 h E(z)$

$$E(z) = \sqrt{\Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_k(1+z)^2 + \Omega_\Lambda}$$

COMOVING DISTANCE AND CONFORMAL TIME

Light travelling on a comoving grid: $dx = cdt/a$

Total line of sight comoving distance (i.e. comoving distance from us to a distant galaxy):

$$d_{\rm comov}(a) = \int_{t(a)}^{t_0} \frac{c\,dt'}{a(t')} = \int_a^1 \frac{c\,da'}{a'^2 H(a')}$$

Example if matter dominates: $d_{\rm comov}(a) = \frac{2c}{H_0}\left[1 - a^{1/2}\right]$

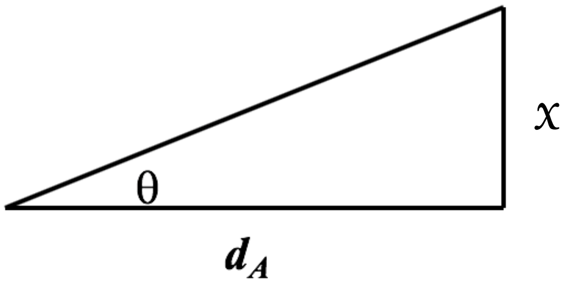
Conformal time: the comoving distance light has travelled since the big bang:

$$\eta \equiv \int_0^t \frac{cdt'}{a(t')}$$

ANGULAR DIAMETER DISTANCE

Given an object perpendicular to the line of sight with physical size x and angular size *θ<<1* as viewed from Earth, what is its distance? (assuming flat space k=0)

$$d_A = \frac{x}{\theta}$$



$$x = a d_{\rm com} \theta$$

$$d_A = a d_{\rm com} = d_{\rm com}/(1+z)$$

Generalisation for non-flat cosmologies:

$$d_A(a) = \frac{a}{H_0\sqrt{|\Omega_k|}} \begin{cases} \sinh[\sqrt{\Omega_k} H_0 d_{\rm comov}] & \Omega_k > 0 \\ \sin[\sqrt{-\Omega_k} H_0 d_{\rm comov}] & \Omega_k < 0 \end{cases}$$

THERMAL HISTORY OF THE UNIVERSE: THE HIGHLIGHTS

Event	time t	redshift z	temperature T
Inflation	10^{-34} s (?)	–	–
Baryogenesis	?	?	?
EW phase transition	20 ps	10^{15}	100 GeV
QCD phase transition	20 μs	10^{12}	150 MeV
Dark matter freeze-out	?	?	?
Neutrino decoupling	1 s	6×10^9	1 MeV
Electron-positron annihilation	6 s	2×10^9	500 keV
Big Bang nucleosynthesis	3 min	4×10^8	100 keV

D. Baumann Cosmology lectures

THERMAL history of the universe: The highlights

Event	time t	redshift z	temperature T
Matter-radiation equality	60 kyr	3400	0.75 eV
Recombination	260–380 kyr	1100–1400	0.26–0.33 eV
Photon decoupling	380 kyr	1000–1200	0.23–0.28 eV
Reionization	100–400 Myr	11–30	2.6–7.0 meV
Dark energy-matter equality	9 Gyr	0.4	0.33 meV
Present	13.8 Gyr	0	0.24 meV

D. Baumann Cosmology lectures

THERMAL HISTORY OF THE UNIVERSE: THE HIGHLIGHTS

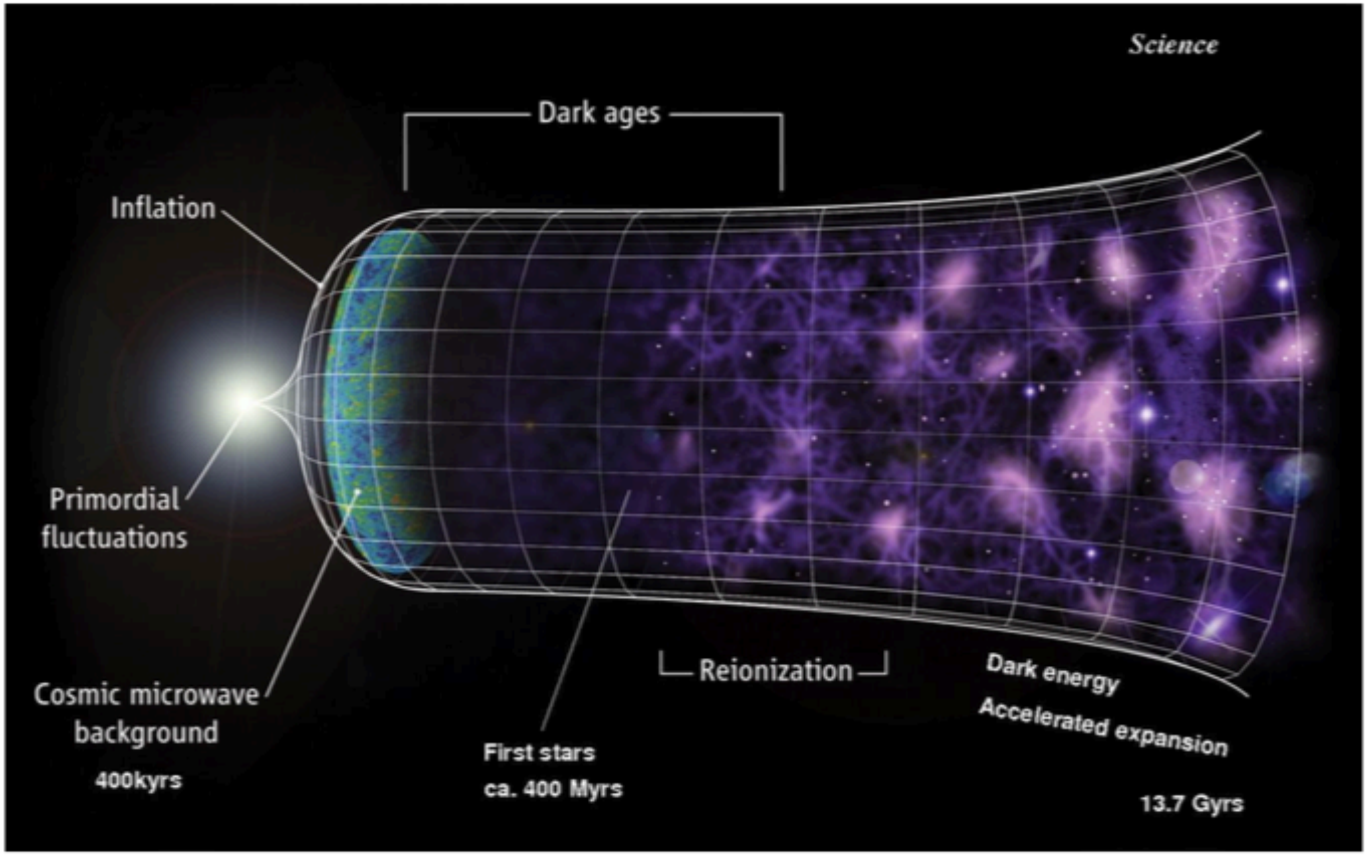
- The beginning - **Hot Big Bang**: note that **temperature evolves as 1/a**
- **Inflation** and end of inflation
- **Baryogenesis:** QFT requires the existence of antiparticles. We do observe an overabudance of matter (baryons) over anti-matter.
- **Electroweak phase transition:** At 100 GeV particles get masses via Higgs mechanism. This leads to a change in the strength of the weak interaction.
- **QCD phase transition:** Below 100 MeV strong interactions between quarks and gluons dominate. Baryons (such as n and p) are formed.
- **Nucleosynthesis:** the lightest nuclei are formed 3 mins after the Big Bang / Radiation domination

THERMAL HISTORY OF THE UNIVERSE: THE HIGHLIGHTS

- **Matter-Radiation equality**
- **Recombination:** Electrons and protons form neutral hydrogen atoms. $e^- + p^+ \rightarrow H + \gamma$
- **Photon decoupling:** Before recombination the strongest coupling between the photons and the rest of the plasma is through Thomson scattering. But recombination results in sharp drop in electron density. Photons decouple. They have since streemed freely through the Universe —> CMB
- **Reionization:** First stars start ionising the neutral hydrogen around them "Cosmic Dawn". By the end of this process, Universe completely ionised (but HI still found within galaxies).
- **Galaxy formation - dark energy domination - now and the future!**

A brief overview of the universe

The cosmological standard model: the evolution of the Universe.



REFERENCES / FURTHER READING