Cosmology

TUM WS 2019/2020

Lecture 13

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(http://www.eso.org/~bleibund/Cosmology)

Dark Energy - Background

- Discovered only in 1998
- 'Cosmological constant' added by Einstein (1917) to his equations to allow for a static solution

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu}\mathrm{R} - \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- Alternatively one could add a (constant) vacuum energy to the energy-momentum tensor $T_{\mu\nu}$

Dark Energy - Background

The corresponding Friedmann-Lemaître equation is

$$\frac{\dot{a}^2}{a^2} = H^2(t) = \frac{8\pi G}{3}\rho(t) - \frac{k}{a^2}$$

with the density summed over all components:

$$\rho(t) = \rho_M + \rho_R + \rho_{vac}$$

The vacuum density is related to the cosmological constant through

$$\rho_{vac} = \frac{\Lambda}{8\pi G}$$

Acceleration

The dynamics of the expansion is given by (Lectures 3 and 4)

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\rho c^2 + 3p)$$

(from the time part of the Einstein equations)

Acceleration ($\ddot{a} > 0$) means $(\rho c^2 + 3p) < 0$

– Negative pressure can lead to acceleration!

Equation of state

Using the equation of state formalism for a perfect fluid we have $W := \frac{p}{\rho c^2}$ and the density then relates to the scale parameter through $\frac{\dot{\rho}}{\rho} = -3(1+W)\frac{\dot{a}}{a}$, which leads to
$\rho = const. \times a^{-3(1+W)}$

For a cosmological constant: $W = -1$ and $\rho = const.$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\rho c^2 + 3p) = +\frac{4\pi G}{3c^2}\, 2\rho c^2 > 0$$

Distances

For full generality allow for a changing equation of state parameter $W \neq const.$

The distance then becomes

$$D_L = \frac{c(1+z)}{H_0\sqrt{|\Omega_k|}} S\left(\sqrt{|\Omega_k|}\int_0^z \frac{dz'}{\sqrt{\Omega_M(1+z')^3 + \Omega_R(1+z')^4 + \Omega_k(1+z')^2 + \Omega_X f_X(z')}}\right)$$

As before $S = \begin{cases} \sin(x) & k > 1 \\ x & k = 1 \\ \sinh(x) & k < 1 \end{cases}$

and $f_X(z) = e^{3\int_0^z \frac{1+W_X(z')}{1+z'}dz'}$

Distances today

- Radiation density very low $\Omega_R < 10^{-5}$
- Curvature $\Omega_k \approx 0$ (flat space - from CMB)
- Assume cosmological constant
  - Mostly for simplicity

$$D_L = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_M (1+z')^3 + \Omega_\Lambda}}$$

Dark Energy (cosmological constant)

- Measure the expansion rate of the universe to determine its content
- Luminosity distance (Lecture 4)

$$D_L = a_0 r_1 (1+z) = \frac{c(1+z)}{H_0 \sqrt{|\Omega_k|}} S\left(\sqrt{|\Omega_k|} \int_0^z \frac{dz'}{\sqrt{\Omega_{matter}(1+z')^3 + \Omega_{rad}(1+z')^4 + \Omega_\Lambda + \Omega_k (1+z')^2}} \right)$$

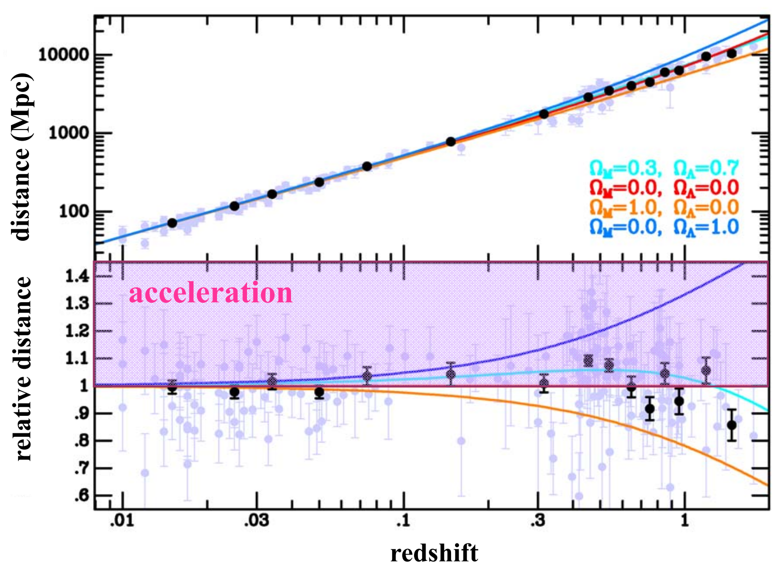
$$S = \begin{Bmatrix} \sin x & k > 0 \\ x & k = 0 \\ \sinh x & k < 0 \end{Bmatrix}$$

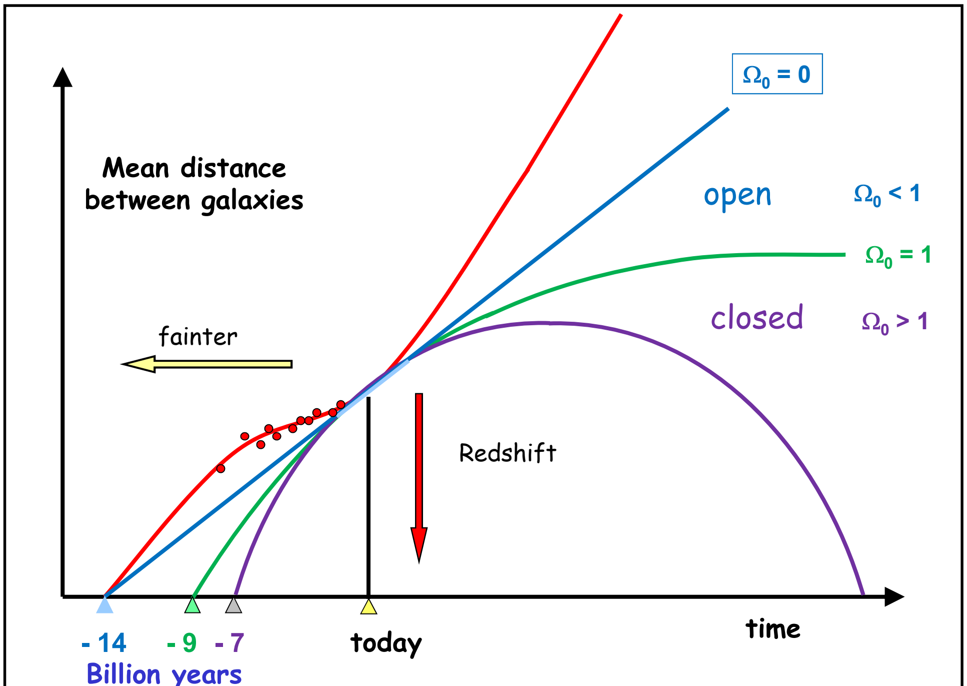
- Measure luminosity over several redshifts will give the combination of the densities

Measuring distances

- Type Ia Supernovae are the best cosmological distance indicators
- Measure them over a range of redshifts (out to z≈1) and then plot the Hubble diagrams

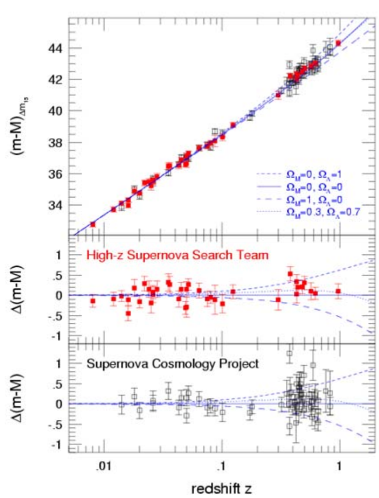
Measure acceleration





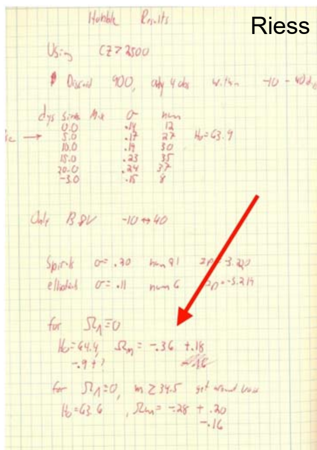
The Supernova Hubble diagram

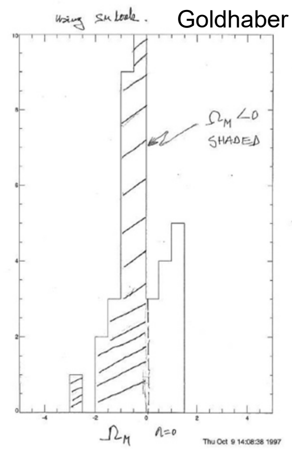
- Two teams pursued this research



Only way out is to allow an extra component

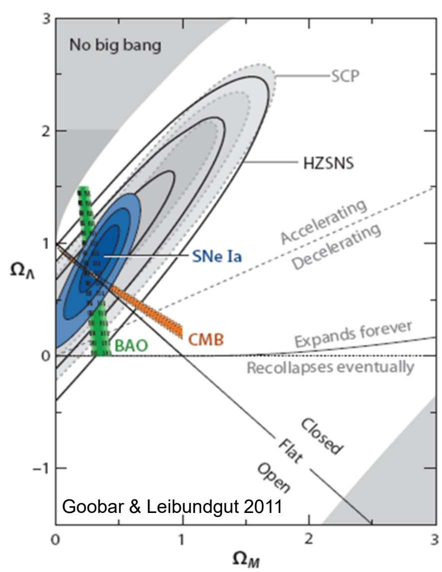
- With only matter the data lead to an absurd result





Allow a cosmological constant

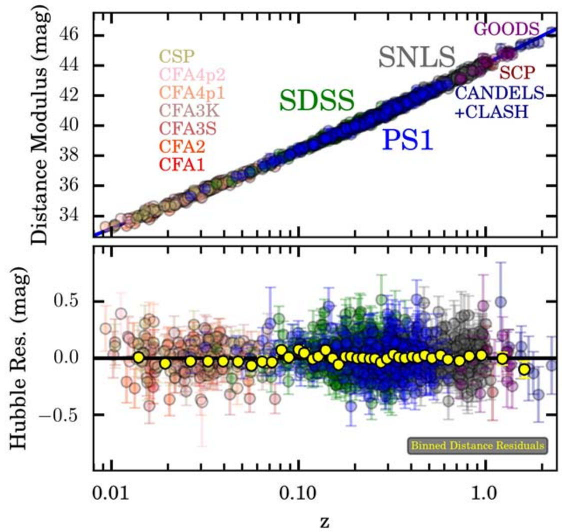
- Diagram with cosmological constant
- This is the diagram requiring Dark Energy



change the shorts …

High-z SN Supernova Search Team December 2011

Most recent results



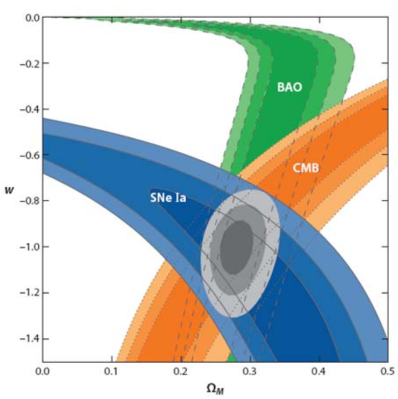
≈ 1000 spectroscop. confirmed type Ia supernovae!

Ω_m = 0.307±0.012

W = -1.026±0.041

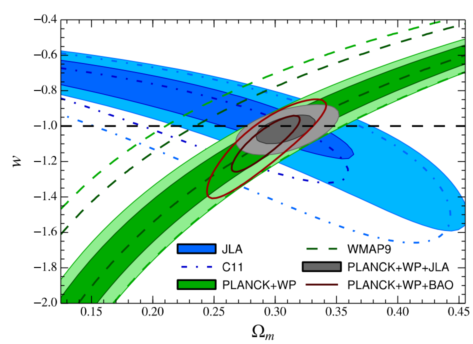
(Scolnic et al., 2018)

Equation of state parameter W (from data)

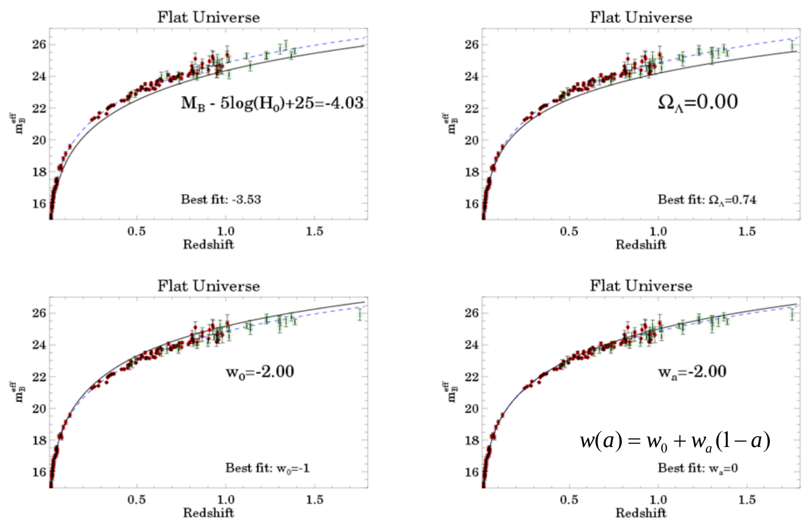


Goobar & Leibundgut 2011

Betoule et al. 2014



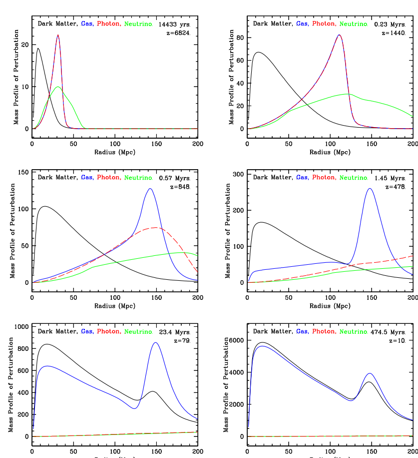
Multi-parameter problem



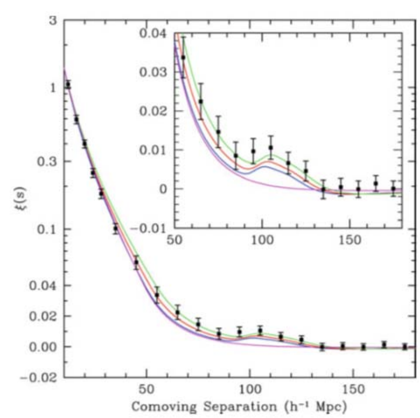
Ariel Goobar

Confirmed by other methods

- Baryonic acoustic oscillations

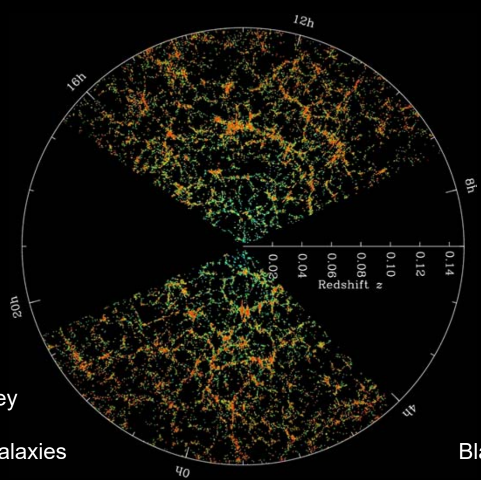


Eisenstein et al. 2007



Eisenstein et al. 2005 - SDSS

Based on redshift surveys

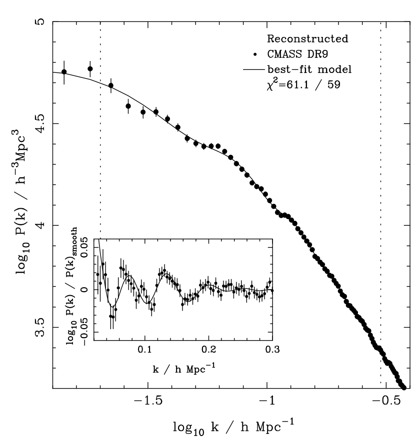


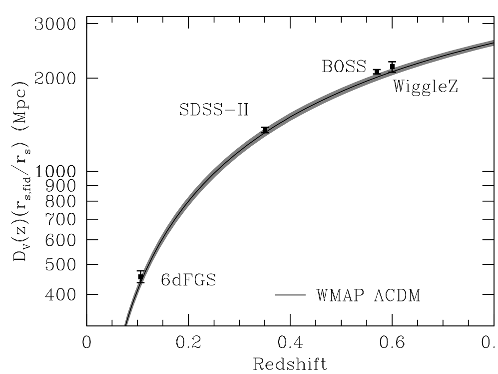
Baryon Oscillations
Spectroscopic Survey
(BOSS, SDSS-III)
More than 1.8 10^6 galaxies

Blanton and SDSS

Baryonic Acoustic Oscillations

- Provides a standard ruler
  - Angular size distance

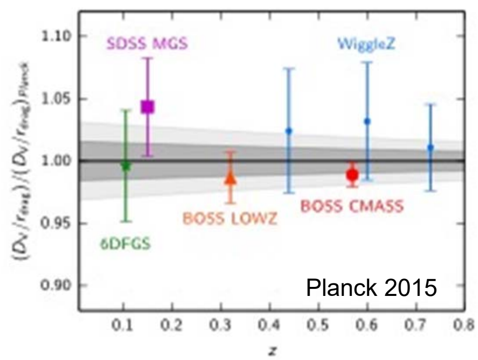


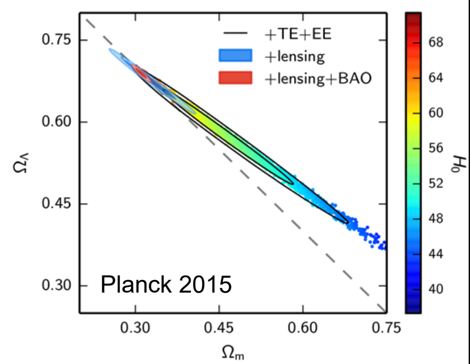


Anderson et al. 2012

Consistent picture

- Planck 2015 results





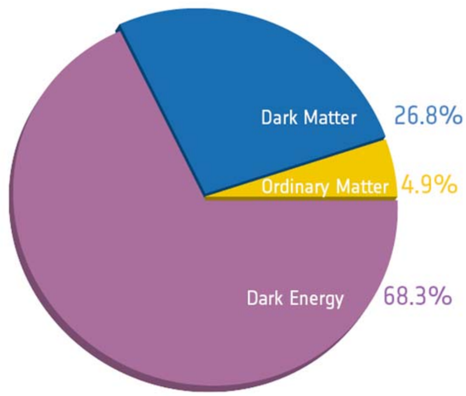
Concordance

Currently all available determinations of cosmological parameters converge to single values

- Matter density $\Omega_M \approx 0.3$
  - CMB, Galaxy clusters
- Cosmological constant $\Omega_\Lambda \approx 0.7$
  - Supernovae, CMB, baryonic acoustic oscillations
- No curvature $\Omega_k = 0.0$
- Radiation negligible $\Omega_R \approx 10^{-5}$
- No deviations from cosmological constant $w \approx -1$

Total energy content of the universe

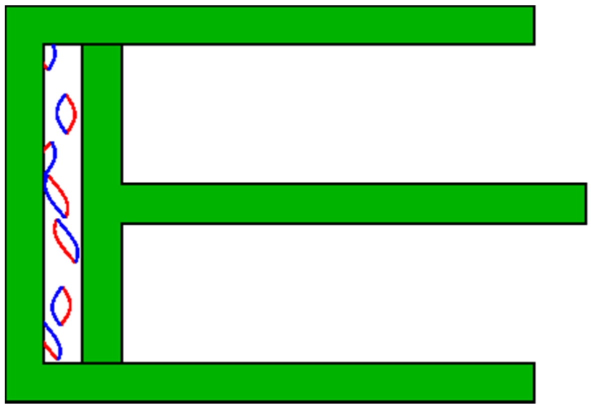
- Adding all densities relevant today together



Planck

What is the Dark Energy?

- Cosmological constant/vacuum energy?
  Consistent with data. But: Why is it so small?
- Some scalar field?
  Use it for inflation. Why not for the DE also?
- Can we determine its nature?
  In principle, yes, by mapping H(z) with very high accuracy.



The quantum vacuum acts like a gas of negative pressure!

Literature

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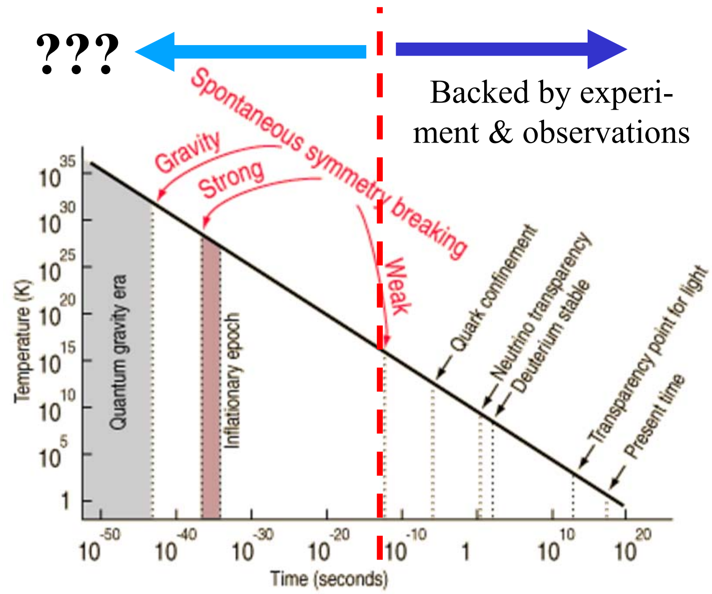
- Scott Dodelson, Modern Cosmology, Boston, Academic Press 2013 ISBN: 0122191412
- Malcolm S. Longair, Galaxy Formation, Astronomy and Astrophysics Library, Springer Verlag: ISBN 978-3-540-73477-2
- Joshua Friedman, Michael Turner, Dragan Huterer, Annual Reviews of Astronomy & Astrophysics, 46, 385 (2008)
- Bruno Leibundgut, Annual Reviews of Astronomy & Astrophysics, 39, 67 (2001)
- Bruno Leibundgut, General Relativity and Gravitation, 40, 221 (2008)
- Ariel Goobar and Bruno Leibundgut, Annual Reviews of Nuclear and Particle Physics, 61, 251 (2011)

Cosmology Recap: Timeline of the Universe



Cosmology Recap

- Define the involved forces
  - Gravity: General Relativity
    Einstein's Field equations

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

  - requires metric $g_{\mu\nu}$ (RW) and sources $T_{\mu\nu}$(IF)

  <u>Possible problems:</u>
  - is General Relativity the correct theory for gravity? Other forces than gravity relevant?

Cosmology Recap

- Translate into observables
  - connect to parameters that can be measured today
  - distances

$$D_L = a_0 r_1 (1+z) = \frac{c(1+z)}{H_0\sqrt{|\Omega_K|}} S\left(\sqrt{|\Omega_K|}\int_0^z \frac{dz}{\sqrt{\Omega_M(1+z)^3+\Omega_R(1+z)^4+\Omega_\Lambda+\Omega_K(1+z)^2}}\right)$$

with
$$S(x) = \begin{cases} \sin(x) & k=1 \\ x & k=0 \\ \sinh(x) & k=-1 \end{cases}$$

  - Hubble constant, curvature, densities, redshift

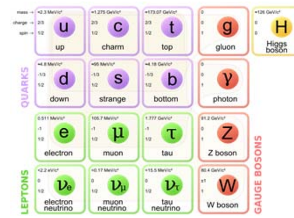
Cosmology Recap

- Use homogeneity and isotropy (metric) and a "perfect fluid" for the contents
  - leads to the Friedmann equation

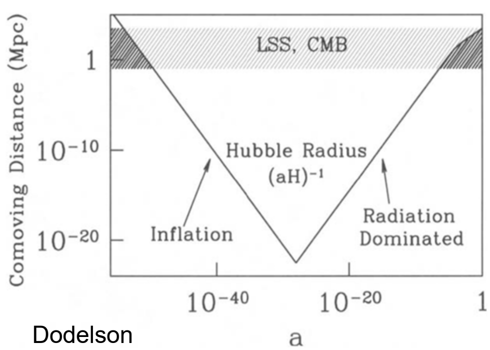
$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{kc^2}{a^2} = \frac{8\pi G}{3}\rho$$

  - encodes the scale parameter (*a*), expansion (*H*), the curvature (*k*) and the total energy density (*ρ*)
- Problem:
  - do we know all ingredients?

Cosmology Recap

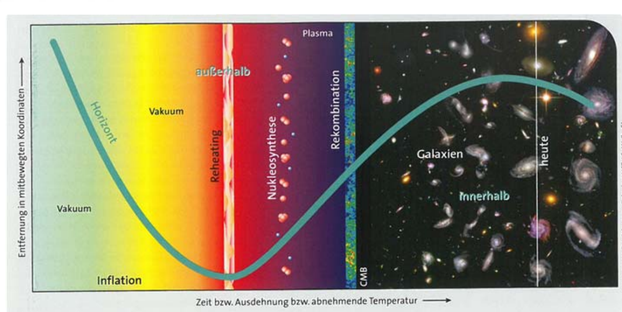


- Contents of the universe
  - standard model of particle physics
    - baryons (quarks, gluons), electrons, neutrinos (and their anti-particles)
- Problem:
  - Is the standard model complete?
    - Other particles? Dark matter particles? Neutrino masses?
    - Extensions to the standard model?
      - supersymmetry and others



Dodelson

Horizon



Niemeyer & Schwarz 2015

Cosmology Recap

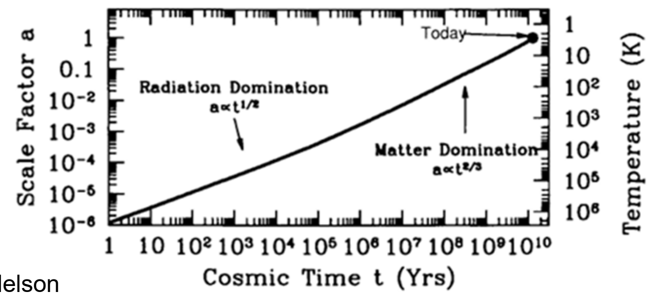
- Expansion history
  - free expansion in a matter-dominated universe
  - no other physical interactions influencing the metric on a global scale
- Additional contents of unknown origin
  - Dark Matter
  - Dark Energy

Cosmic Inventory

name	density	EOS w
baryons	0.04	≈ 0
CDM	0.26	≈ 0
radiation	0.0001	1/3
Massive neutrinos	<0.05	≈ 0
Cosm. const.	0.70	-1
curvature	<0.03	-1/3
Other ?	?	?

Time and scale parameter

- Depending on the dominant density the scale parameter evolves differently

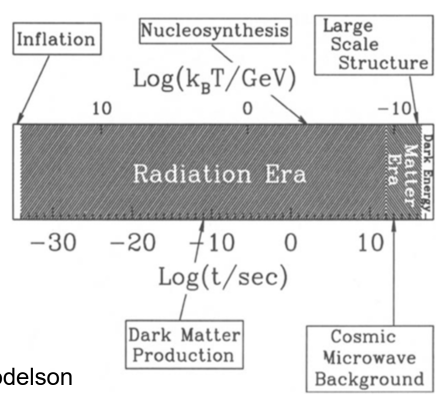


Dodelson

Figure 1.2. Evolution of the scale factor of the universe with cosmic time. When the universe was very young, radiation was the dominant component, and the scale factor increased as $t^{1/2}$. At later times, when matter came to dominate, this dependence switched to $t^{2/3}$. The right axis shows the corresponding temperature, today equal to 3K.

Thermal history of the universe

- A theorist plot!
  - left 2/3 is the first second of the universe



Dodelson

Figure 1.15. A history of the universe. Any epoch can be associated with either temperature (top scale) or time (bottom scale).

Cosmology Recap

- Thermal history of the universe
  - interplay between expansion and reaction rates
    - Boltzmann equations
    - involves terms with $\frac{mc^2}{k_B T}$
  - thermal equilibrium $\frac{mc^2}{k_B T} << 1$
  - "freeze-out" $\frac{mc^2}{k_B T} > 1$

Cosmology Recap

- Relevant physics
  - weak interaction for neutrino decoupling
  - e^+e^- annihilation, photon reheating
  - nucleosynthesis
    - neutron decay (weak interaction)
    - nucleon binding energies (strong interaction)
    - H, D, He, Li
  - radiation-matter equality
    - influences metric (a^{-4} vs. a^{-3})
  - recombination
    - atomic physics (Saha equation)

Overview

- Metric/expansion define the cooling
- Interactions modulate the different transitions
  - weak interaction for the neutrino decoupling
  - scattering between baryons and photons

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
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

Daniel Baumann, Cambridge

Table 3.1: *Key events in the thermal history of the universe.*

Cosmological Recap

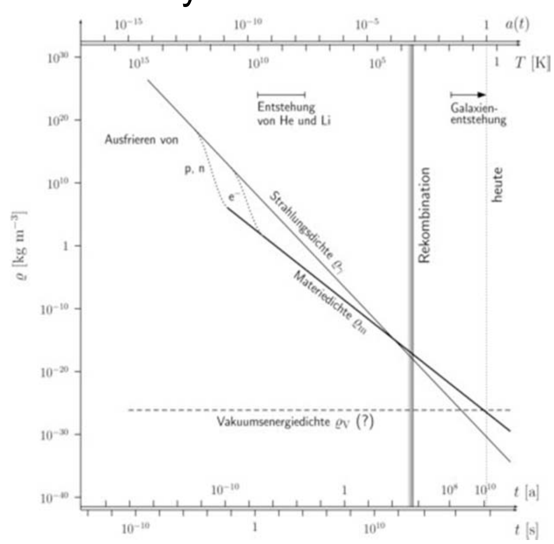
- Metric perturbations
  - creation?
    - inflation is a good candidate
    - spectral index n_S possible signature
  - Perturbations are required for
    - temperature variations in the CMB
    - density fluctuations setting the growth of large scale structure

Cosmology Recap

- Some problems of the standard model of cosmology
  - Why is there more matter than anti-matter in the universe?
    - baryogenesis/leptogenesis
  - flatness
  - horizon
  - topological defects (“monopoles”)
  - Why is there a hot start to the universe?

Density evolution

- Evolution of the density with time



Weigert, Wendker & Wisotzki

Time evolution

- The same in English
- "Coincidence problem" is shown here
  - do we live in a special era?

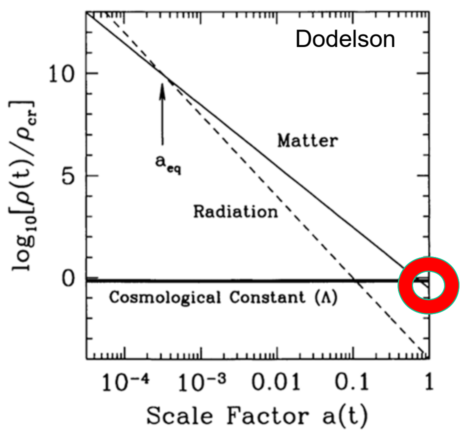


Figure 1.3. Energy density vs scale factor for different constituents of a flat universe. Shown are nonrelativistic matter, radiation, and a cosmological constant. All are in units of the critical density today. Even though matter and cosmological constant dominate today, at early times, the radiation density was largest. The epoch at which matter and radiation are equal is a_{eq}.

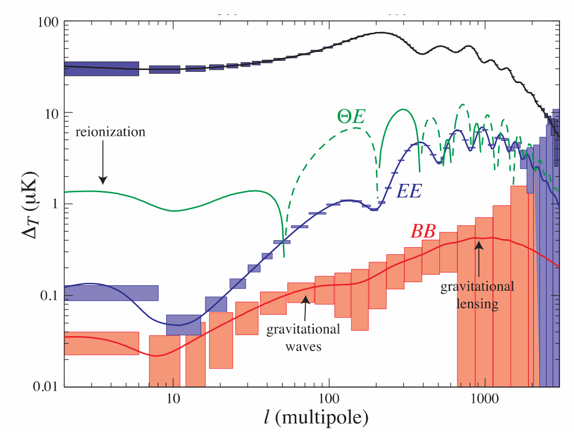
Coincidence Problem

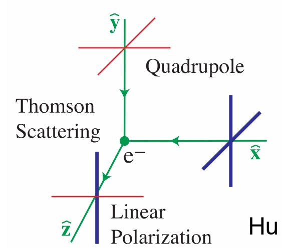
- Theorists claim that we have a problem
- Today: $\frac{\Omega_M}{\Omega_\Lambda} \approx \frac{0.3}{0.7} \approx \frac{1}{2}$
- There is no good reason why it should be so close to 1
  - see curves in the previous figures
- However

$$\frac{\Omega_M}{\Omega_\Lambda} = \left(\frac{\Omega_M}{\Omega_\Lambda}\right)_{z=0} \left(\frac{(1+z)^3}{1}\right) \quad \text{e.g.} \quad \left(\frac{\Omega_M}{\Omega_\Lambda}\right)_{z=1} = 8 * \left(\frac{\Omega_M}{\Omega_\Lambda}\right)_{z=0} \approx 4$$

Topics not covered

- Polarisation in the CMB
  - Planck results





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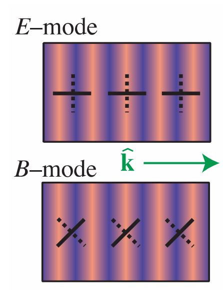
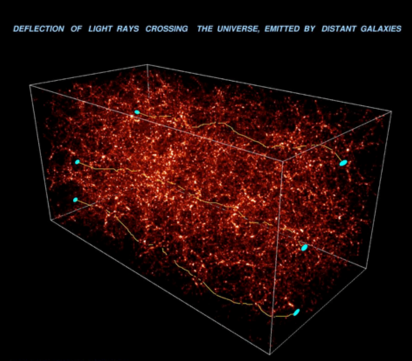
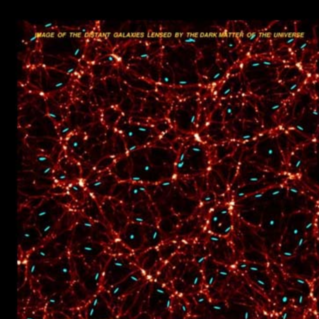


Topics not covered

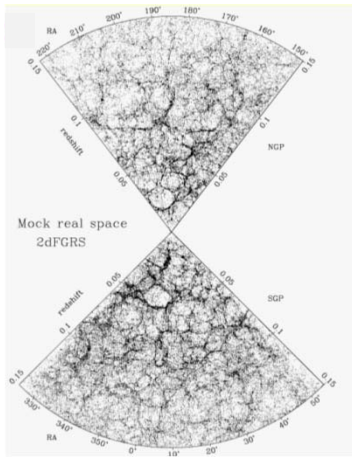
- Weak shear/weak gravitational lensing
  - distortion of background images by foreground structure
  - used to get distances to billions of galaxies

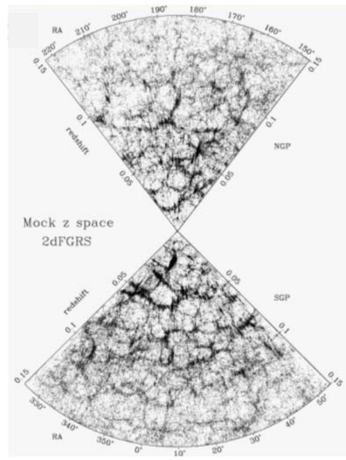




Topics not covered

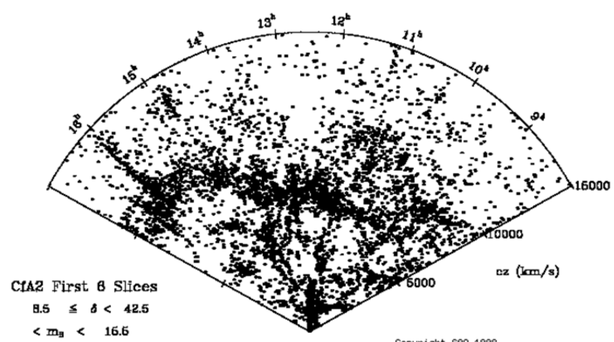
- Redshift distortions
  - redshift do not fully reflect the spatial distribution





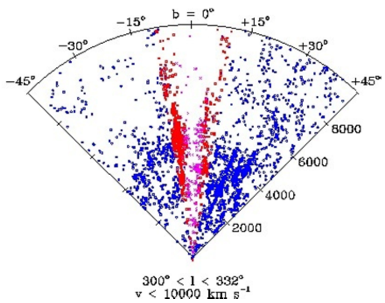
Topics not covered

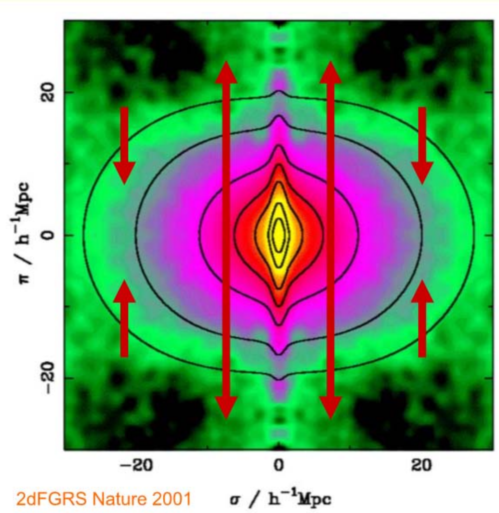
- Redshift distortion
  - Finger of God effect



Topics not covered

- Redshift distortion
  - Finger of God effect
  - compression on the outside





2dFGRS Nature 2001

Topics not covered

- Unification of quantum theories with GR
  - fundamental difference between the quantized description of the world and the field theory as represented by GR
  - requires higher dimensional theories
    - supersymmetry
      - every fermion has a corresponding boson
        - » e.g. squarks, selectron, sneutrino
      - every boson has a corresponding fermion
        - » photino, Zino, Wino, gravitino
    - LHC is searching for these

Multiverses

- Attempt to avoid the Anthropic Principle
  - "The universe has the right attributes to allow (human) life"
    - this applies e.g. to physical constants
  - If there is a single universe, why would it be made to sustain life?
- Invoke a statistical principle
  - If our universe is just one out a large number then it is not surprising that we are living in one that allows life

Multiverses

- Difficult (impossible?) to prove wrong?
  - how would we observe another universe?
    - our horizon much smaller than the universe (inflation!)
    - imprints of other universes in our?
      - causality issues
- Philosophical argument

Future cosmology

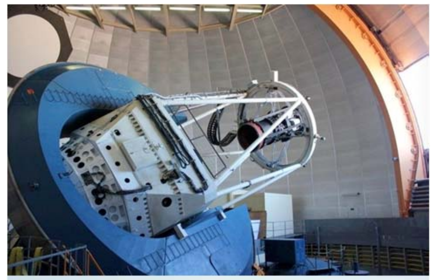
- Main problems
  - Dark Energy
    - cosmological constant or decaying particle field?
      - equation of state parameter, deviations from $w = -1$?
  - Dark Matter
    - direct detection of the dark matter particle
      - LHC, underground experiments, annihilation signals
  - Testing inflation
    - gravitational waves
    - signature in CMB polarisation
      - tensor to scalar ratio
      - awaiting future Planck analysis

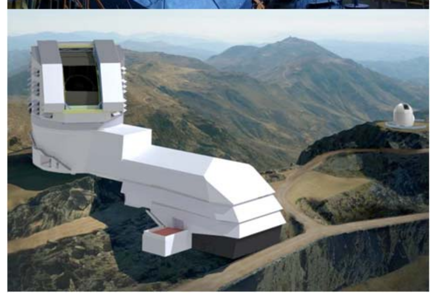
Future cosmology

- Constrain Dark Energy
  - search for $w \neq -1$
  - large surveys
    - Type Ia Supernovae
      - sample size > 10^3
    - weak lensing
      - >10^9 galaxies
    - baryonic acoustic oscillation
      - a few 10^5 redshifts
    - redshift distortions
      - a few 10^5 redshifts

Future cosmology

- Dark Energy
  - large surveys
    - Dark Energy Survey





    - Large Synoptic Survey Telescope (LSST)

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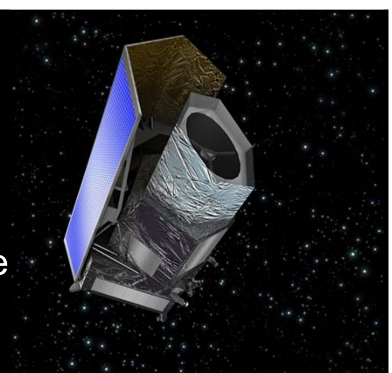

- ESA satellite
  - Investigate 15000 square degree
    - ~half the sky
  - Use weak lensing and acoustic baryonic oscillations to determine w (and a possible time dependent w(t)
  - Determine growth of structure
  - Test General Relativity

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Future cosmology

- Astroparticle physics
- Fundamental constants
  - changing with time?
    - fine-structure constant $\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c}$
    - e.g. variable speed of light c
    - changes in Newton's constant G

There is a theory which states that if ever anyone discovers exactly what the Universe is for, and why it is here, it will instantly disappear and be replaced by something even more bizarrely inexplicable.

There is another theory which states that this has already happened.

Douglas Adams