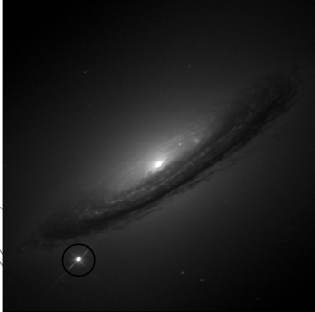


# Cosmology AS7009, 2011

## Lecture 5



### Outline

- Cosmological parameters
- Measuring distances
  - Luminosity distance
  - Angular-diameter distance
  - Standard candles
  - Magnitude system
- Supernova cosmology
- Dark energy

Covers chapter 7 in Ryden

### Cosmological parameters I

Remember these ones?

- $\Omega_M$ : Matter
- $\Omega_R$ : Radiation
- $\Omega_\Lambda$  or  $\Omega_{DE}$ : Cosmological constant or dark energy
- $\Omega_{tot}$  (or just  $\Omega$ ): Sum of the other  $\Omega$ s
- $\kappa$ : Curvature (+1,0,-1) – related to  $\Omega_{tot}$
- $R_0$ : Curvature radius of the Universe
- $w_{DE}$ : Equation of state of dark energy
- $H_0$ : Hubble parameter at current time (often expressed as  $h$ :  $H_0=100h \text{ km s}^{-1} \text{ Mpc}^{-1}$ )
- $t_0$ : Current age of the Universe

### Cosmological parameters II

An endless number of subpopulations can be introduced if necessary...

- $\Omega_{CDM}$ : Cold dark matter
- $\Omega_{bar}$ : Baryons
- $\Omega_{stars}$ : Stars
- $\Omega_{CMBR}$ : CMBR photons
- $\Omega_\nu$ : Neutrinos
- $\Omega_{BH}$ : Black holes
- $\Omega_{Robots}$ : Robots (see exercises)

### A few others...

- $q_0$ : Deceleration parameter
- $\sigma_8$ : Root-mean-square mass fluctuation amplitude in spheres of size  $8h^{-1} \text{ Mpc}$
- $\tau$ : Electron-scattering optical depth
- $\eta$ : Inhomogeneity parameter
- $n_s$ : Slope of matter power spectrum
- $z_{reion}$ : Redshift of reionization
- $N_{eff}$ : Effective number of neutrino species

Not really covered in this course...

### Deceleration parameter I

Definition:

$$q_0 = -\left(\frac{\ddot{a}a}{\dot{a}^2}\right)_{t=t_0} = -\left(\frac{\ddot{a}}{aH^2}\right)_{t=t_0}$$

$q_0 > 0 \Rightarrow$  Expansion slowing down (deceleration)

$q_0 < 0 \Rightarrow$  Expansion speeding up (acceleration)

## Deceleration parameter II

Acceleration equation  $\rightarrow$

$$q_0 = \frac{1}{2} \sum_w \Omega_{w,0} (1 + 3w)$$

Radiation, matter &  $\Lambda \rightarrow$

$$q_0 = \Omega_{R,0} + \frac{1}{2} \Omega_{M,0} - \Omega_{\Lambda,0}$$

Benchmark model:

$$\Omega_{R,0} \approx 0, \Omega_{M,0} \approx 0.3, \Omega_{\Lambda,0} \approx 0.7 \Rightarrow$$

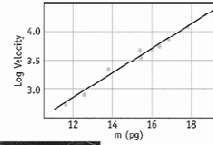
$$q_0 \approx -0.55 \quad \text{Acceleration!}$$

## Cosmological distances I

DISCOVERY OF EXPANDING UNIVERSE



EDWIN HUBBLE



Mt. Wilson  
100 Inch  
Telescope

$D(z)$  depend on cosmological parameters  $\rightarrow$   
 $H_0, \Omega_M, \Omega_\Lambda$  etc. can be extracted from measurements of  $D(z)$   
 Problem: In an expanding and/or curved Universe, there are many ways to define  $D(z)$

## Cosmological distances II

- Proper distance

Remember: Length of spatial geodesic at time  $t$  if scale factor is fixed at  $a(t)$ . This is sometimes referred to as "distance as measured by a rigid ruler"

The proper distance is important for theoretical reasons, but impossible to measure in practice, since you cannot halt the expansion of space!

- Other distance definitions:

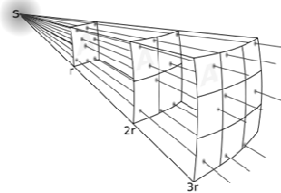
- Luminosity distance
- Angular size distance

In a static Euclidian (flat) Universe, these would all be equivalent – but in our Universe, they're not!

## Luminosity distance I

In a static, flat Universe, the brightness of a light source is determined by *the inverse-square law*.

However, in an expanding and/or curved Universe, this is not the case.



Inverse square law :

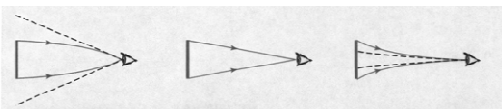
$$f_s = \frac{L_s}{4\pi r^2}$$

## Luminosity distance II

Why does the inverse square law not hold at cosmological distances?

- Geometry:

- Affects the area that photons are spread out over



- Expansion:

- Photons lose energy due to wavelength shift
- Time signals stretched by redshift

## Luminosity distance III

Definition :

$$d_L = \left( \frac{L}{4\pi f} \right)^{1/2}$$

## Luminosity distance IV

Radiation, matter and  $\Lambda$  :

$$d_L = \frac{c(1+z)}{H_0} \int_0^z \frac{dz}{\sqrt{\Omega_M(1+z)^3 - (\Omega_M + \Omega_\Lambda - 1)(1+z)^2 + \Omega_\Lambda}}$$

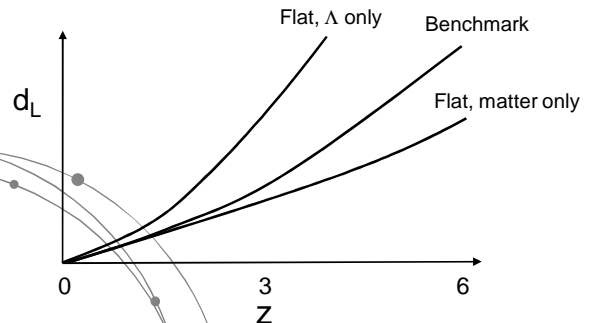
Approximation in a nearly flat Universe :

$$d_L \approx \frac{c}{H_0} z \left( 1 + \frac{1-q_0}{2} z \right)$$

Note:  $z \rightarrow 0 \Rightarrow$

$$d_L \approx \frac{c}{H_0} z \quad (\text{Hubble's law})$$

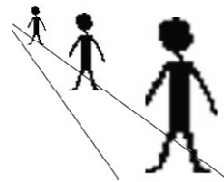
## Luminosity distance V



## Angular-diameter distance I

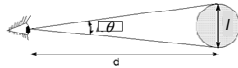
In a static, flat Universe, objects of a fixed length appear smaller if they are further away.

In an expanding and/or curved Universe, this is not the case.



Static, Euclidian space :

$$d = \frac{l}{\tan(\theta)} \approx \frac{l}{\theta} \quad \text{for small angles}$$



## Angular-diameter distance II

Definition :

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

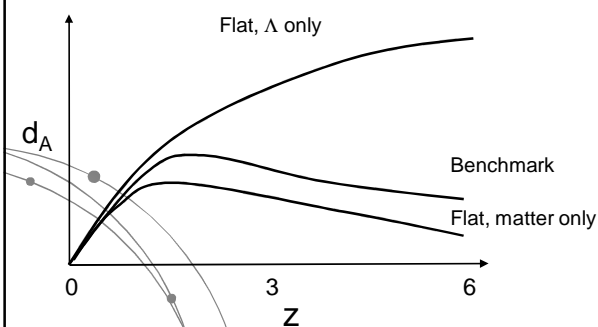
One can show that :

$$d_A = \frac{d_L}{(1+z)^2}$$

Problematic as a cosmological probe...  
No good standard rods/yardsticks have yet been discovered at cosmological distances

## Angular diameter distance III

Bizarre: After a certain redshift, distant objects start appearing larger in the sky – not smaller!



## How to use the luminosity distance as a probe of cosmology

Remember :

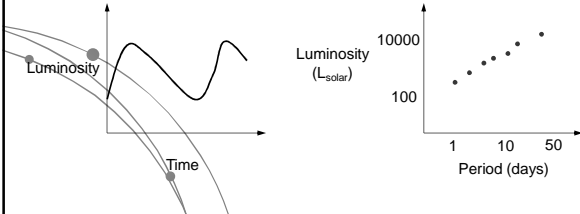
$$d_L = \left( \frac{L}{4\pi f} \right)^{1/2}$$

$$d_L = \frac{c(1+z)}{H_0} \int_0^z \frac{dz}{\sqrt{\Omega_M(1+z)^3 - (\Omega_M + \Omega_\Lambda - 1)(1+z)^2 + \Omega_\Lambda}}$$

- **Observables:**  $z$  and  $f$
- If you know the intrinsic luminosity  $L$  of a light source, you can get information on  $H_0$ ,  $\Omega_M$ ,  $\Omega_\Lambda$ ...
- **Standard candles:** Light sources for which  $L$  can be derived through some independent means

## Standard candles I: Cepheid Variables

- Radially pulsating stars
- Period → Luminosity (Absolute Magnitude) → Distance
- Applicable out to ~ 30 Mpc (slightly beyond the Virgo galaxy cluster)

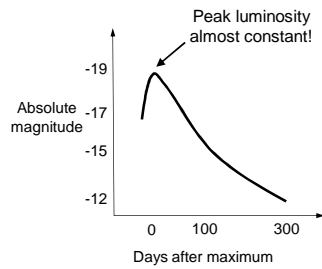


Standard candles must be observable at high redshifts to be useful

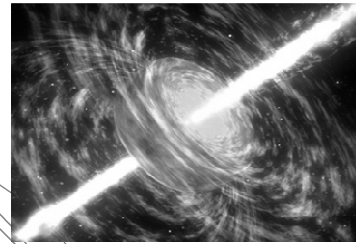


## Standard candles II: Supernovae Type Ia

- Useful at least out to  $z \sim 2$  (~3000 Mpc)
- Probably formed in binary system in which matter from a red giant falls onto a white dwarf



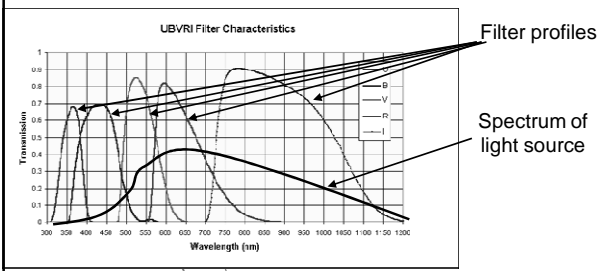
Suggestion for Literature Exercise: Gamma-ray bursts as probes of cosmology



- May be detectable up to  $z \sim 10$
- But: Are they good standard candles?

## The magnitude system I

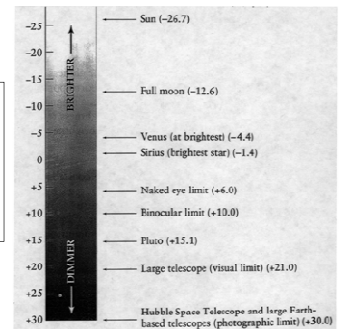
In astronomy, one often measures the flux of light sources using photometry – i.e. the flux received within a well-defined filter



## The magnitude system II

Apparent magnitude :

$$m = -2.5 \log \left( \frac{f}{f_{\text{reference}}} \right)$$



### The magnitude system III

Luminosities are often given as absolute magnitudes, i.e. the apparent magnitude a light source of intrinsic luminosity  $L$  would have at a fixed distance of 10 pc

Absolute magnitude :

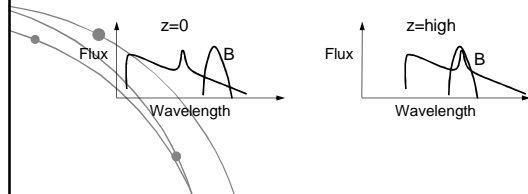
$$M = -2.5 \log \left( \frac{L}{L_{\text{reference}}} \right)$$

$$m = M + 5 \log \left( \frac{d_L}{10 \text{ pc}} \right)$$

$$m = M + 5 \log \left( \frac{d_L}{1 \text{ Mpc}} \right) + 25$$

### Complications I: K-correction

For two identical objects at different  $z$ , a given filter probes different parts of the spectrum (and different physical processes)  $\rightarrow$  Low- $z$  magnitudes cannot be directly compared to high- $z$  magnitudes



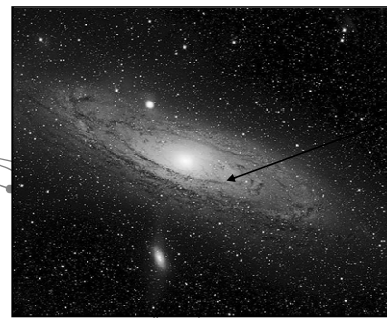
### Complications I: K-correction

K-correction: An attempt to correct from observed (redshifted) to intrinsic (non-redshifted) spectrum

$$m_{\text{intrinsic}} = m_{\text{obs}} - k(z)$$

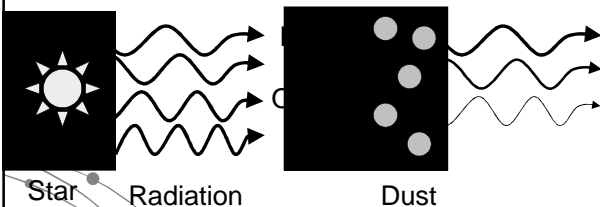
Often a complicated function, based on assumptions about the shape of the source spectrum...

### Complications II: Dust extinction



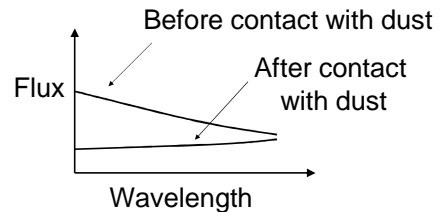
What are these black stripes?

### Wavelength dependence of dust extinction



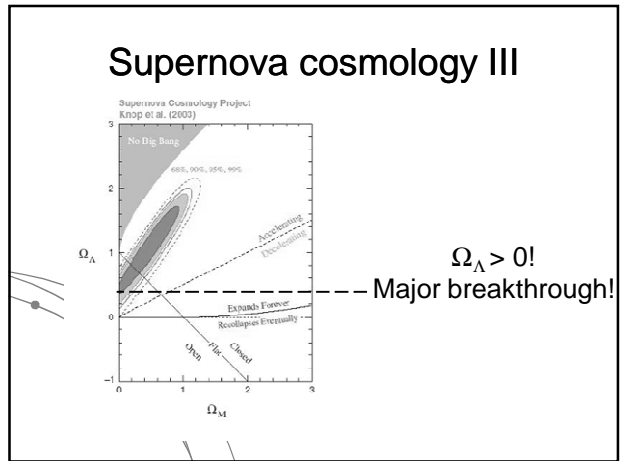
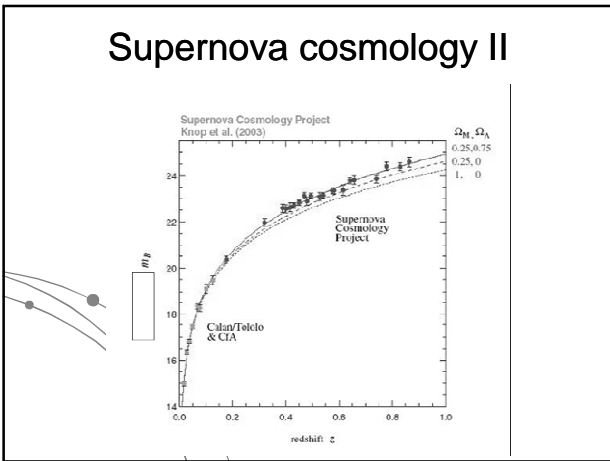
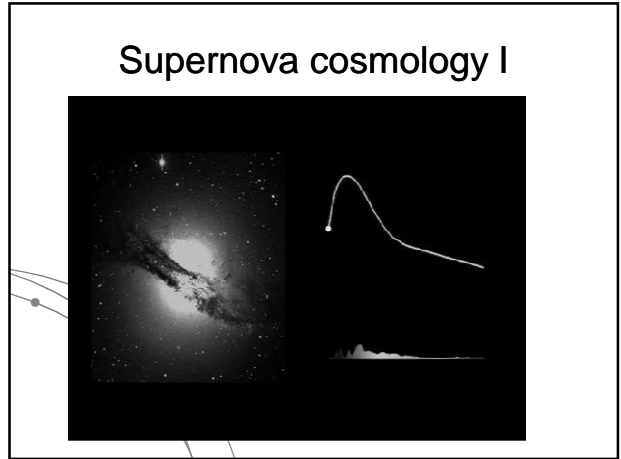
Photons at infrared and radio wavelengths are less affected by dust than optical or ultraviolet photons are

### Wavelength dependence of dust extinction II



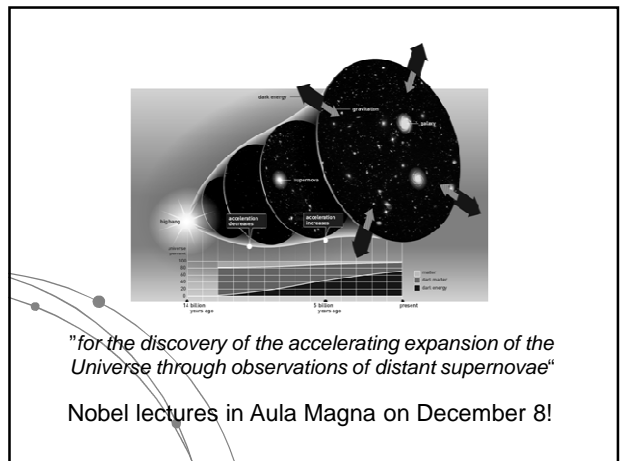
$$m_{\text{intrinsic}} = m_{\text{obs}} - A(\lambda)$$

Extinction correction



### 2011 Nobel prize in Physics

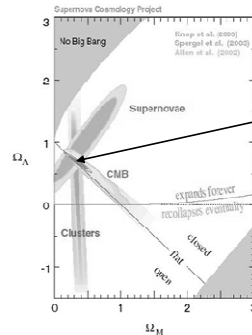
Saul Perlmutter    Brian P. Schmidt    Adam G. Riess



## A few other probes of cosmological parameters

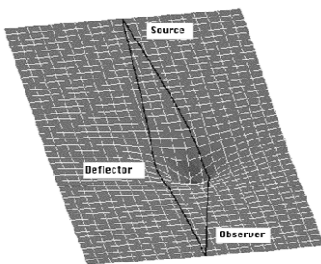
- CMB ← Lecture 7
  - Large scale structure ← Lecture 10
  - Galaxy clusters
  - Weak gravitational lensing
  - Redshift shifts over time
- } Suitable for literature exercises

## Combined constraints



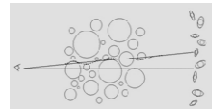
Benchmark model  
 $\Omega_M=0.3, \Omega_\Lambda=0.7$   
 $H_0=72 \text{ km s}^{-1} \text{ Mpc}^{-1}$

## Gravitational lensing

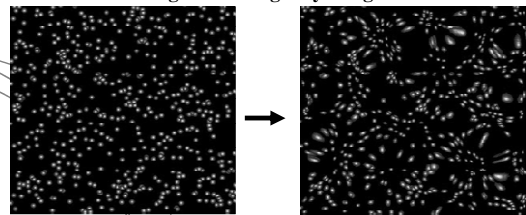


More on this also in the dark matter lecture...

## Suggestion for Literature Exercise: Weak gravitational lensing



Distortion of background images by foreground matter



## Dark energy and other alternatives

Alternatives to a cosmological constant:

- Dark energy with constant  $w \neq -1$
  - Dark energy with  $w(z)$
  - Modification of Friedmann equation, for instance due to:
    - Alternative theories of gravity
    - Additional spatial dimensions
    - Breakdown of cosmological principle
    - Non-standard models of dark matter
- } Suitable for literature exercises

## The Big Rip I

Phantom energy with equation of state  $w < -1$  →  
 Dark energy grows over time →  
 Alternative fate of the Universe in which  
 currently bound structures will get  
 disassembled in the future



## The Big Rip II

TABLE I: The history and future of the Universe with  $w = -3/2$  phantom energy.

Time	Event
$\sim 10^{-43}$ s	Planck era
$\sim 10^{-36}$ s	Inflation
First Three Minutes	Light Elements Formed
$\sim 10^5$ yr	Atoms Formed
$\sim 1$ Gyr	First Galaxies Formed
$\sim 15$ Gyr	<i>Today</i>
$t_{rip} = 1$ Cyr	Erase Galaxy Clusters
$t_{rip} = 60$ Myr	Destroy Milky Way
$t_{rip} = 3$ months	Unbind Solar System
$t_{rip} = 30$ minutes	Earth Explodes
$t_{rip} = 10^{-19}$ s	Dissociate Atoms
$t_{rip} = 35$ Gyrs	Big Rip

Caldwell et al. (2003)