Cosmology 1FA209, 2016
Lecture 5: Cosmological parameters, dark energy

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

The most important ones in this course:

- Ω_M: Matter
- Ω_R: Radiation
- Ω_Λ or Ω_{DE}: Cosmological constant or dark energy
- Ω_{tot} (or just Ω): Sum of the other Ωs
- κ: Curvature (+1,0,-1) – related to Ω_{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*: $H_0=100h$ km s^{-1} Mpc^{-1})
- t_0: Current age of the Universe

Cosmological parameters II

An endless number of subpopulations can be introduced if necessary…

- Ω_{CDM}: Cold dark matter
- Ω_{bar}: Baryons
- Ω_{stars}: Stars
- Ω_{CMBR}: CMBR photons
- Ω_{ν}: Neutrinos
- Ω_{BH}: Black holes
- Ω_{Robots}: Robots (see exercises)

A few others…

- q_o: Deceleration parameter
- σ_8: Root-mean-square mass fluctuation amplitude in spheres of size $8h^{-1}$ Mpc
- τ: Electron-scattering optical depth
- η: Inhomogeneity parameter
- n_s: Slope of matter power spectrum
- z_{reion}: Redshift of reionization
- N_{eff}: Effective number of neutrino species

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 & $\Lambda \rightarrow$

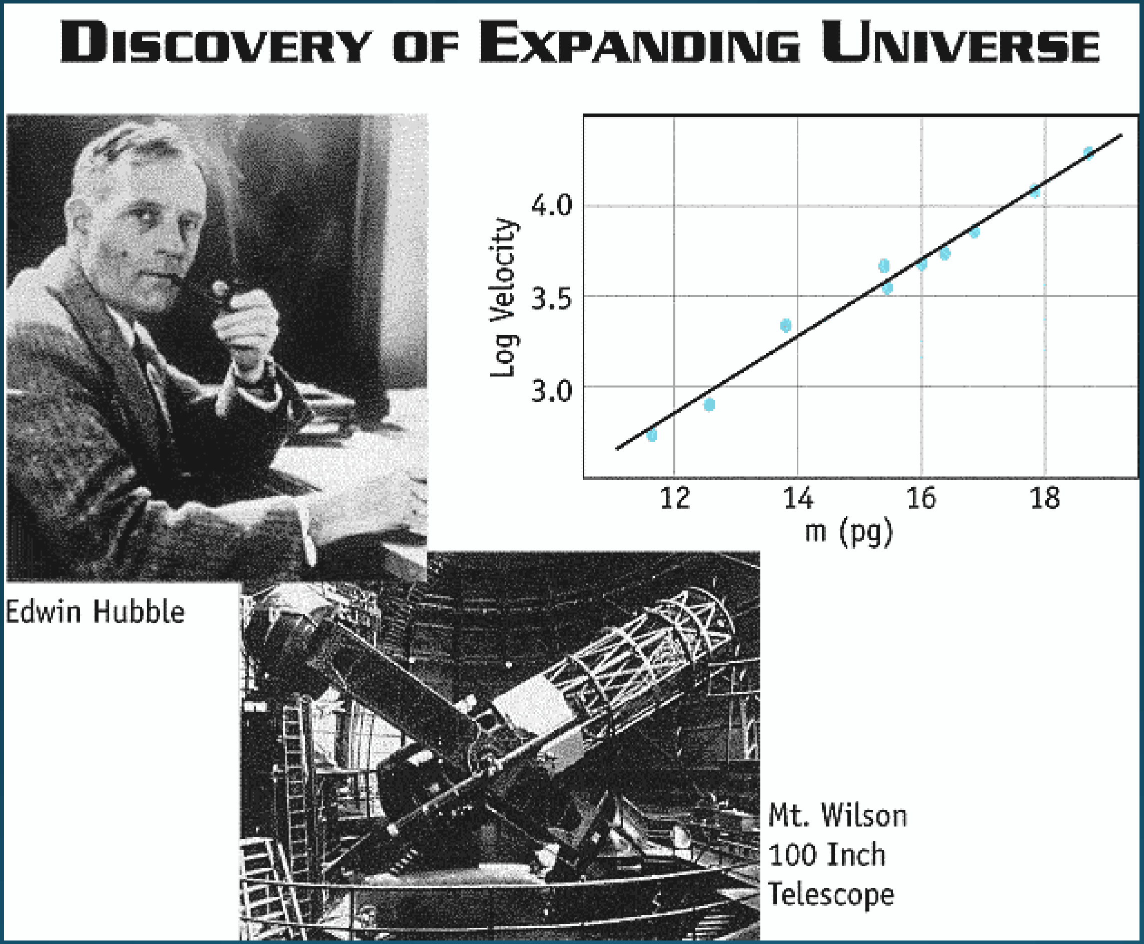
$$q_0 = \Omega_{\mathrm{R},0} + \frac{1}{2}\Omega_{\mathrm{M},0} - \Omega_{\Lambda,0}$$

Benchmark model:

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

$q_0 \approx -0.55$ Acceleration!

Cosmological distances I



D(z) depend on cosmological parameters $\rightarrow$
H_0, Ω_M, Ω_Λ 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

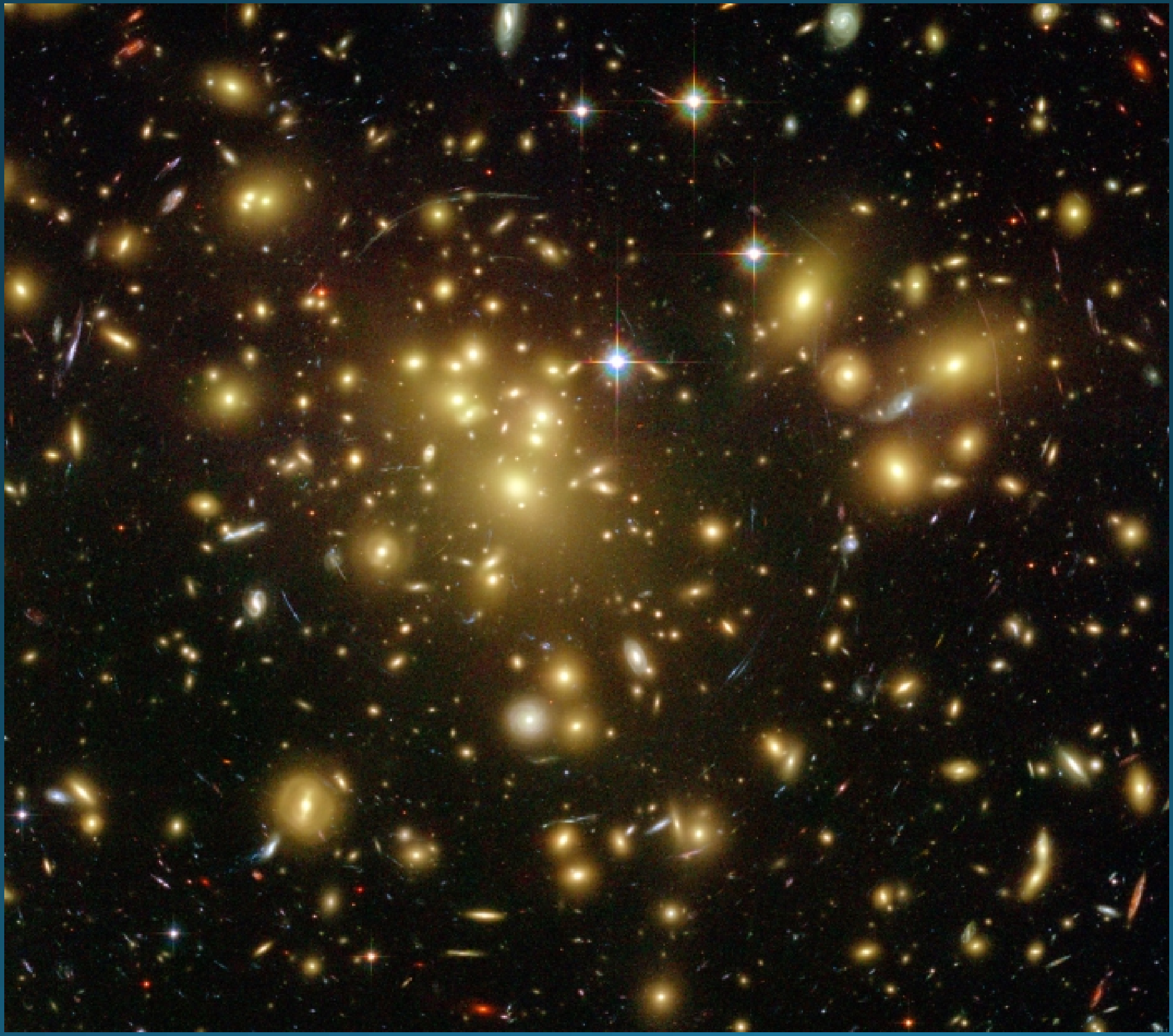
Remember: Length of spatial geodesic at time t if scale factor is fixed at $a(t)$. This is sometimes referred to as "distance as measured by a rigid ruler"

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

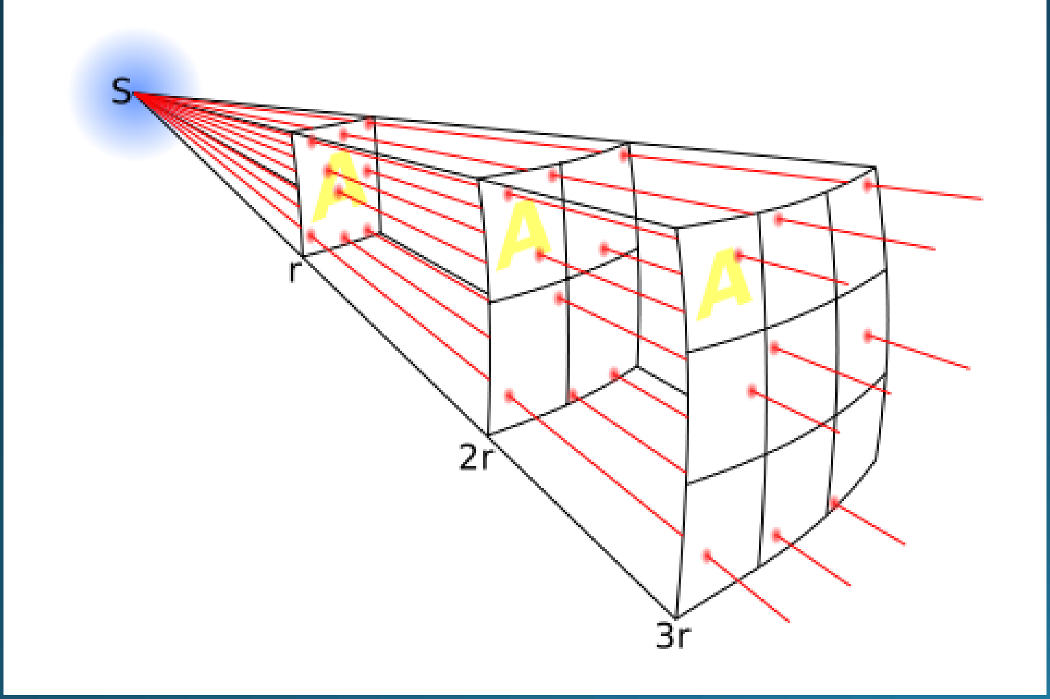
In a static Euclidian (flat) Universe, these would all be equivalent – but in our Universe, they're not!

Intermission: What is this?



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.



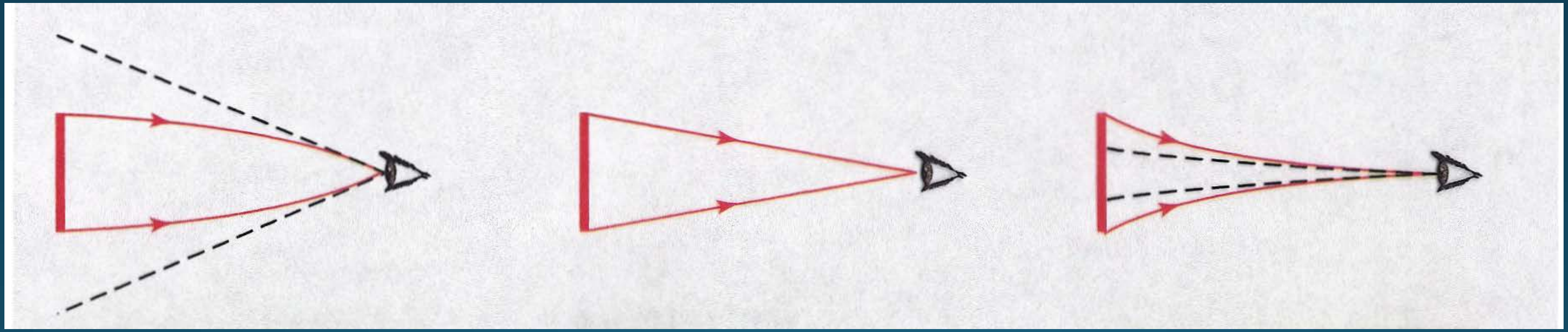
Inverse square law :

$$f_S = \frac{L_S}{4\pi r^2}$$

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 :

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

Luminosity distance IV

Radiation, matter and Λ in a flat Universe :

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

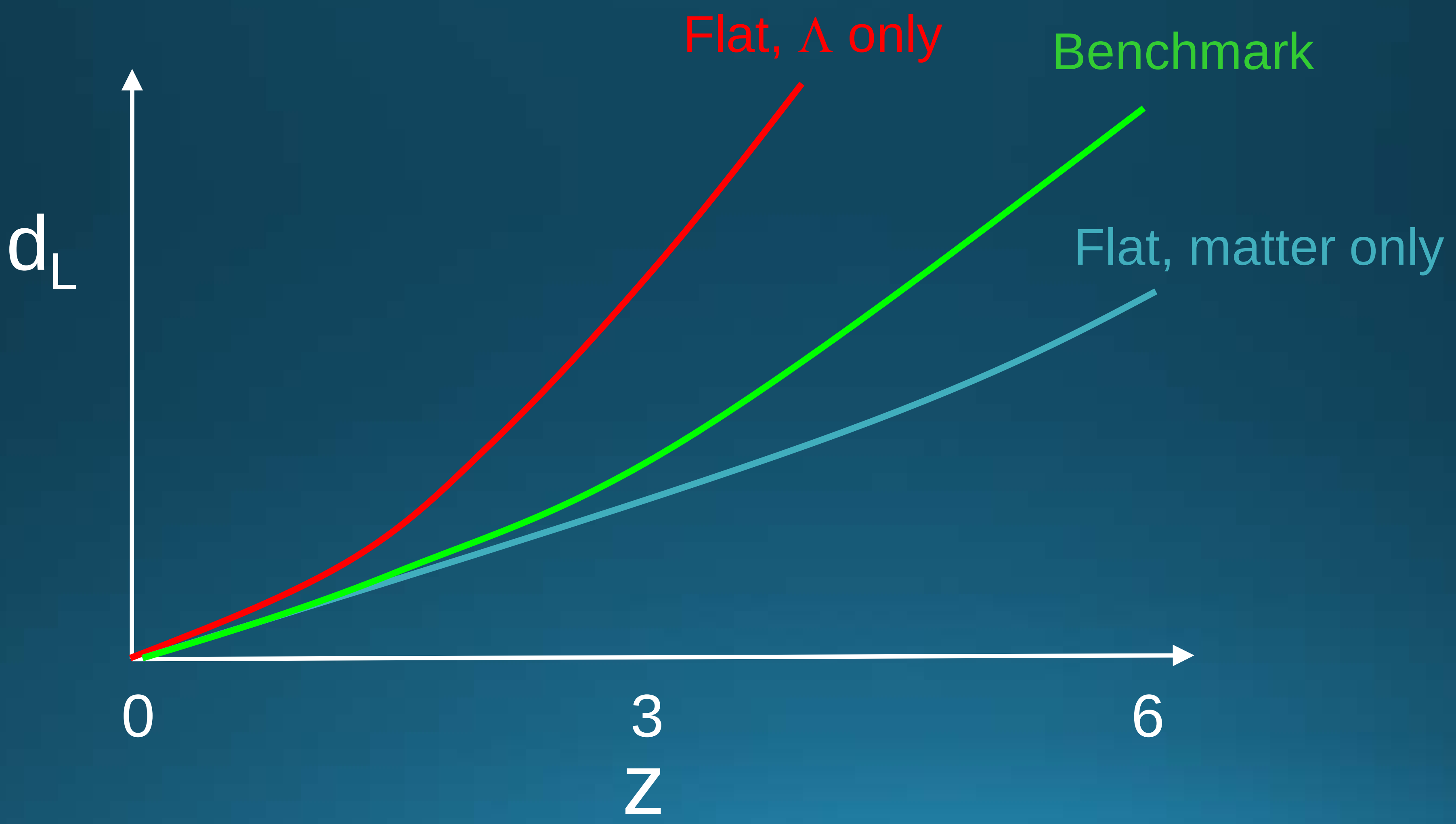
Approximation :

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

Note : $\mathrm{z} \to 0 \Rightarrow$

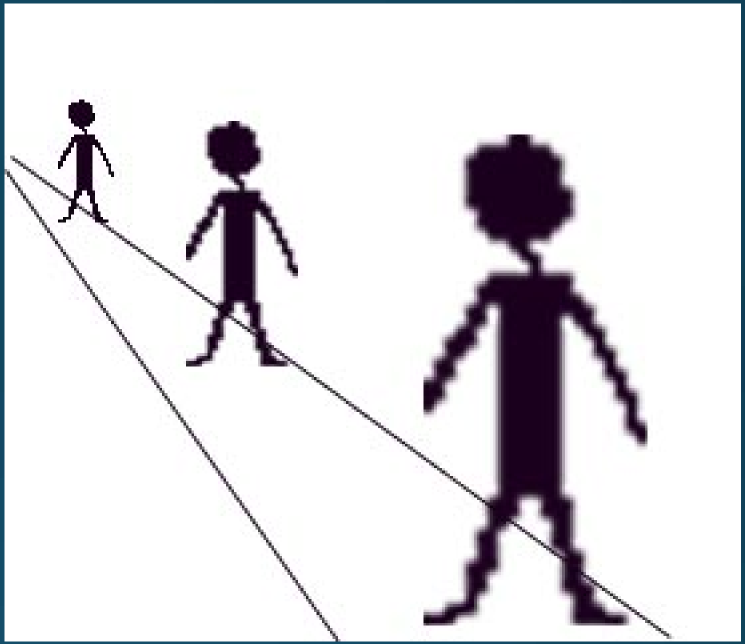
$$d_L \approx \frac{c}{H_0} z \quad \text{(Hubble's law)}$$

Luminosity distance V



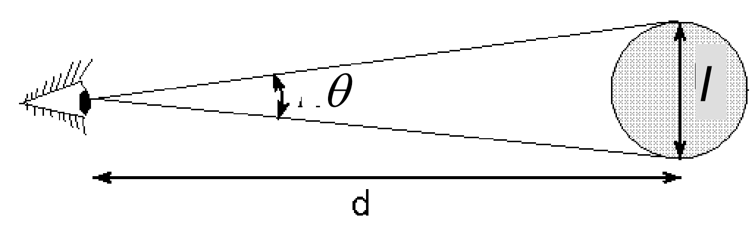
Angular-diameter distance I

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 :

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

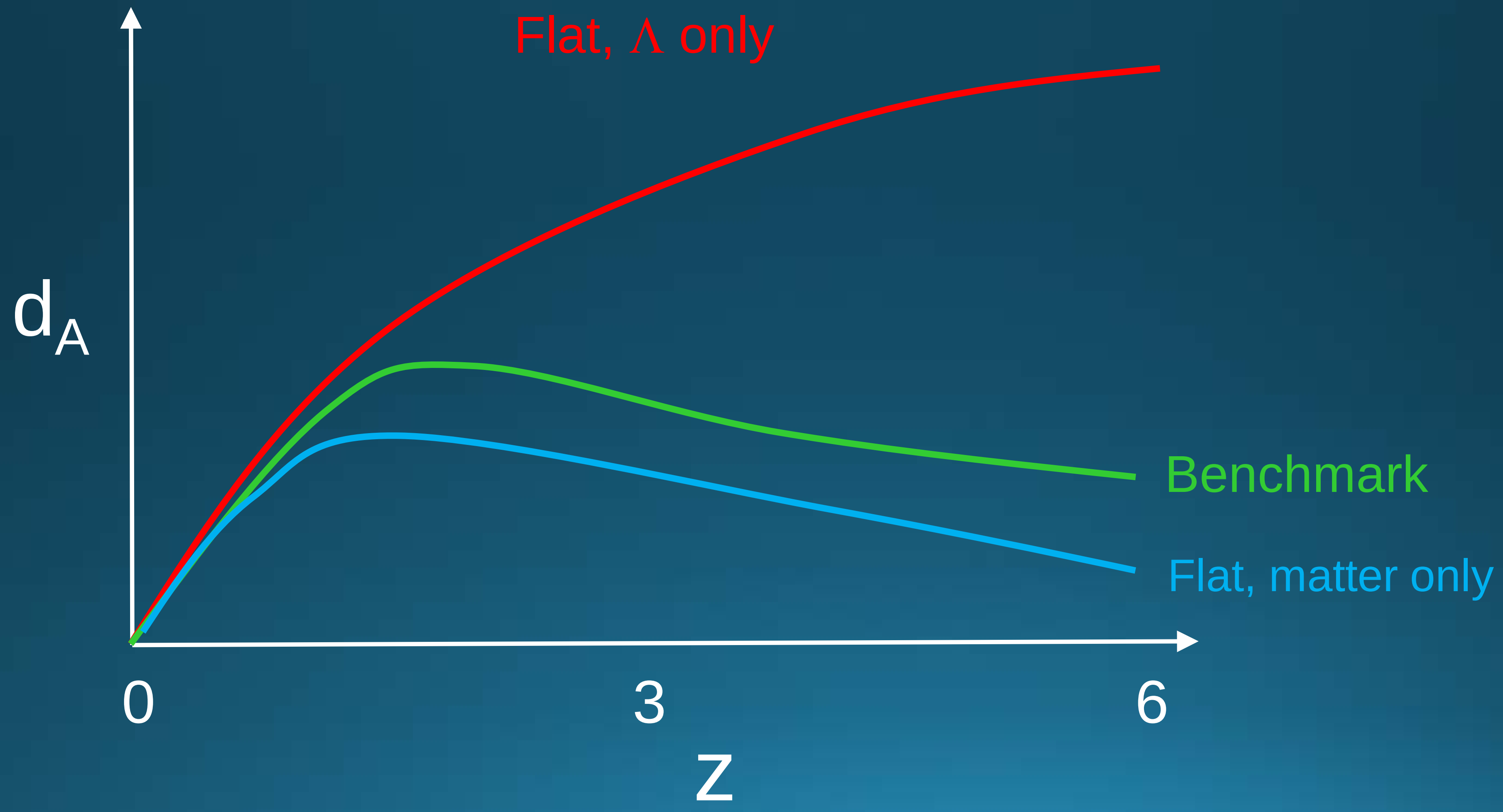
One can show that :

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

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:

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

For a flat Universe:

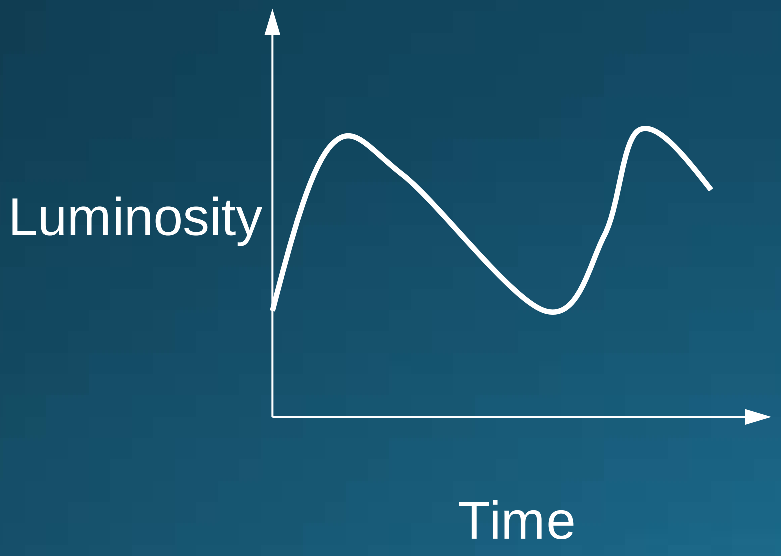
$$d_L = \frac{c(1+z)}{H_0}\int_0^z \frac{\mathrm{d}z}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}$$

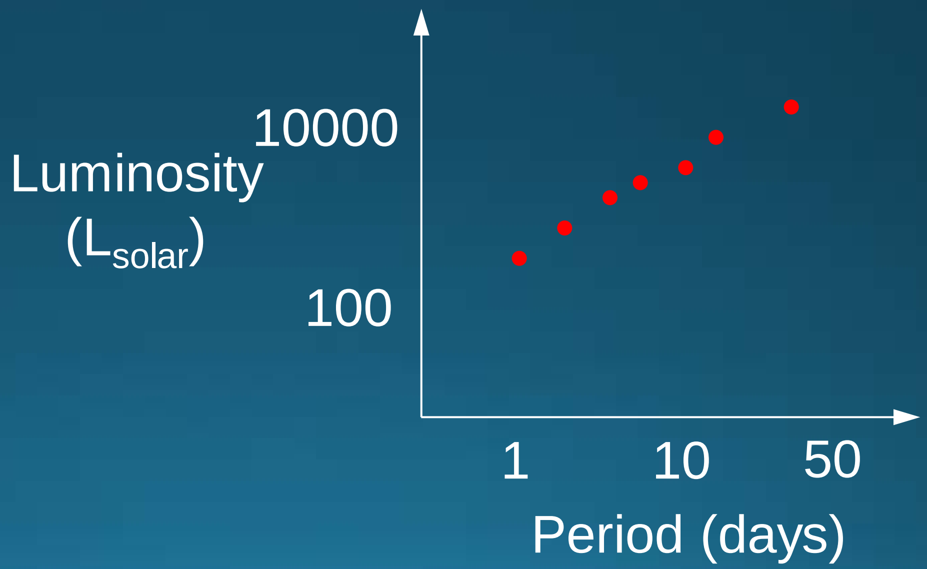
- Observables: z and f
- If you know the intrinsic luminosity L of a light source, you can get information on H_o, Ω_M, Ω_Λ…
- Standard candles: Light sources for which L can be derived through some independent means

Intermission: What’ s going on here?

Standard candles I: Cepheid Variables

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

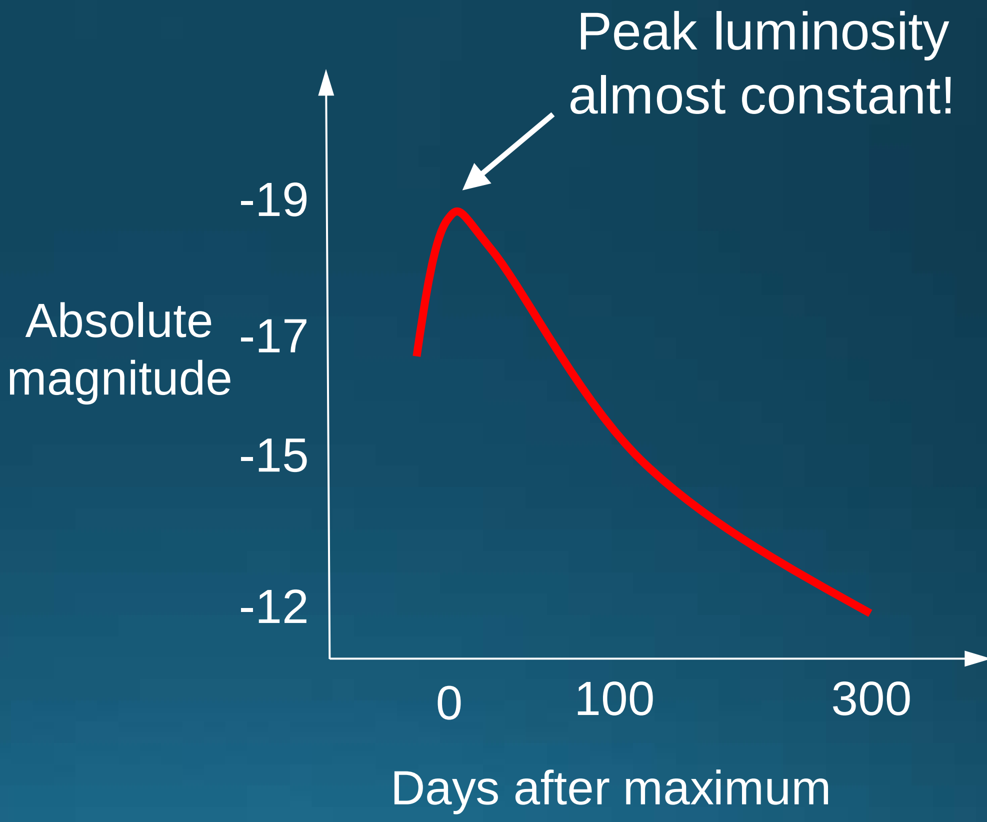




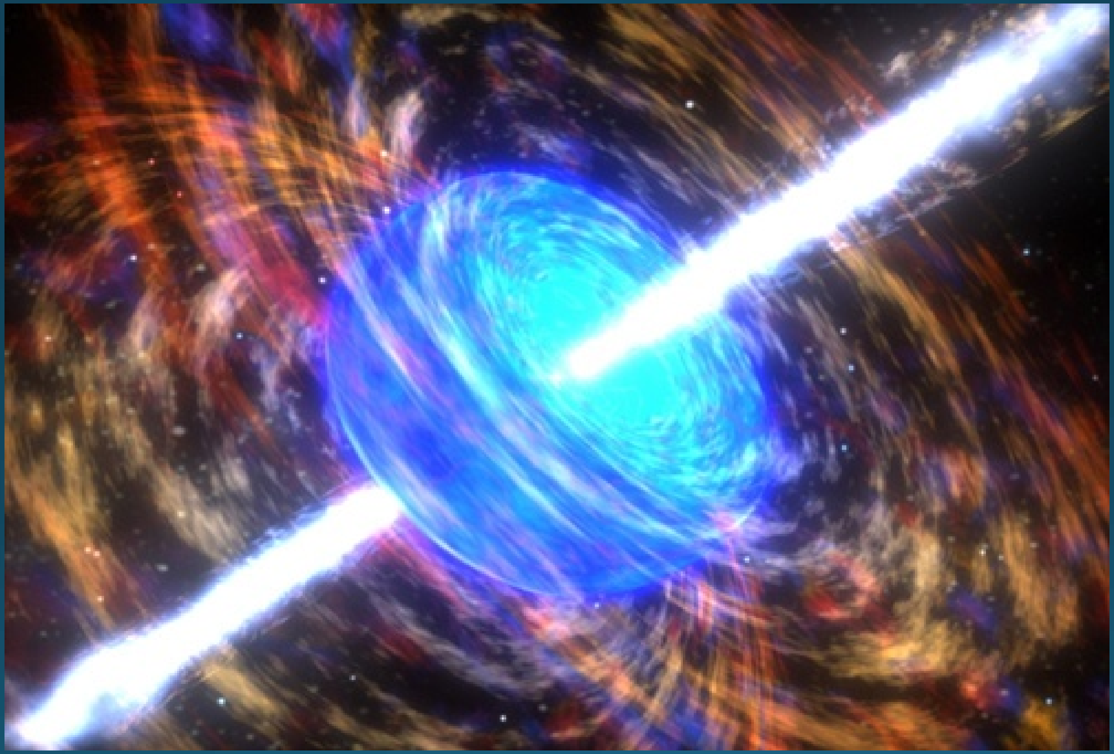
Standard candles must be observable at substantial redshifts to be useful

Standard candles II: Supernovae Type Ia

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



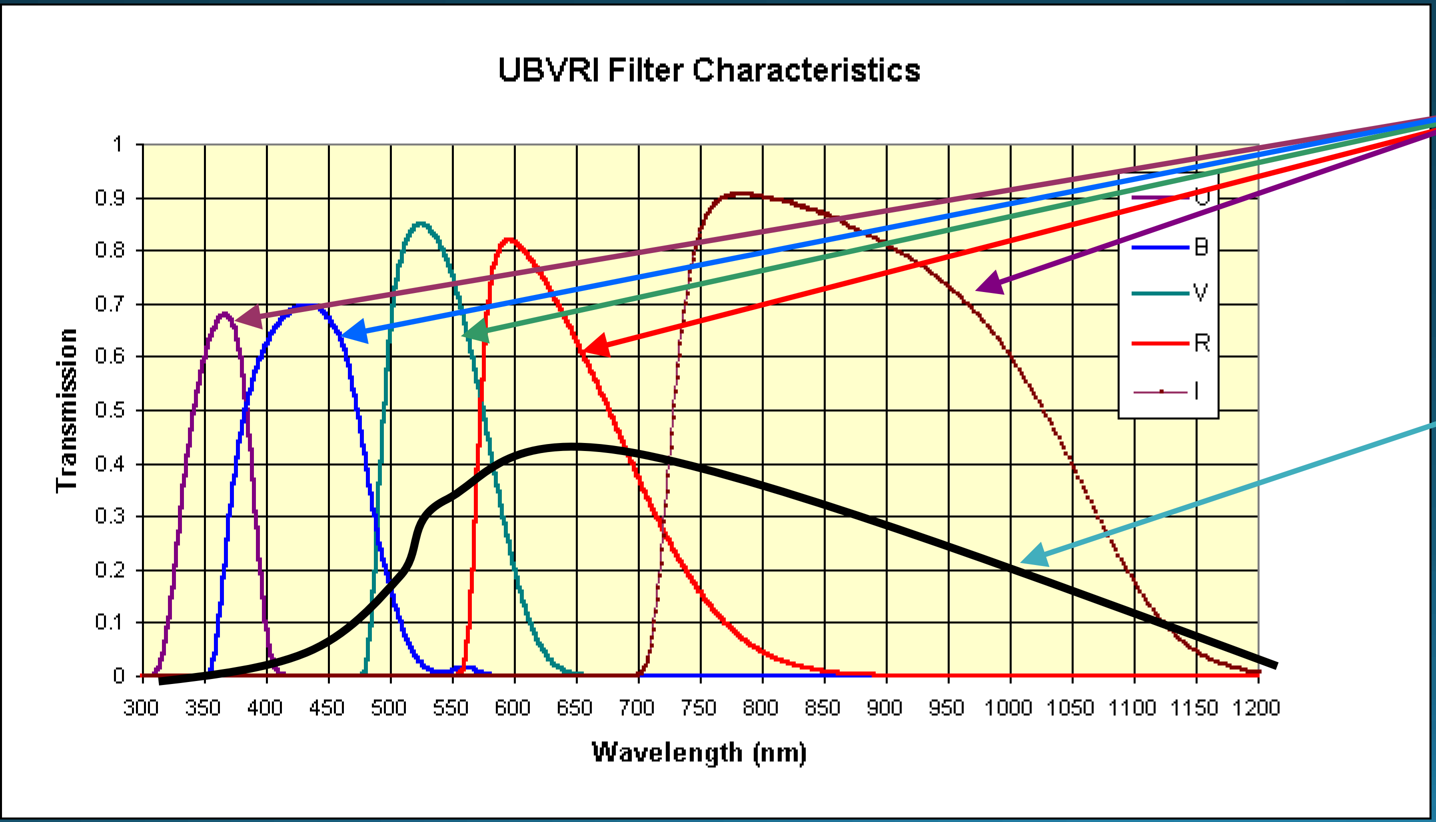
Suggestion for Literature Exercise: Gamma-ray bursts as probes of cosmology



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

The magnitude system I

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



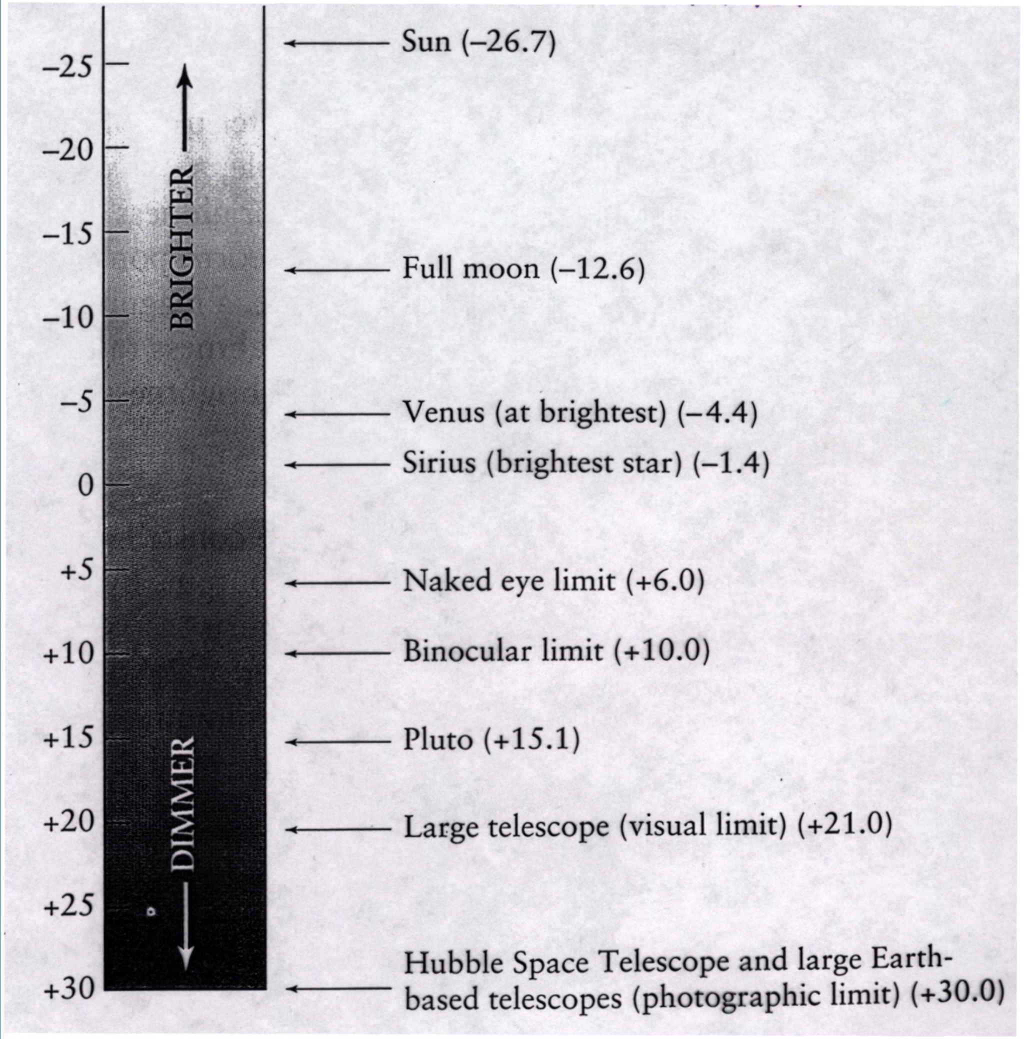
Filter profiles

Spectrum of light source

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

Absolure magnitude:

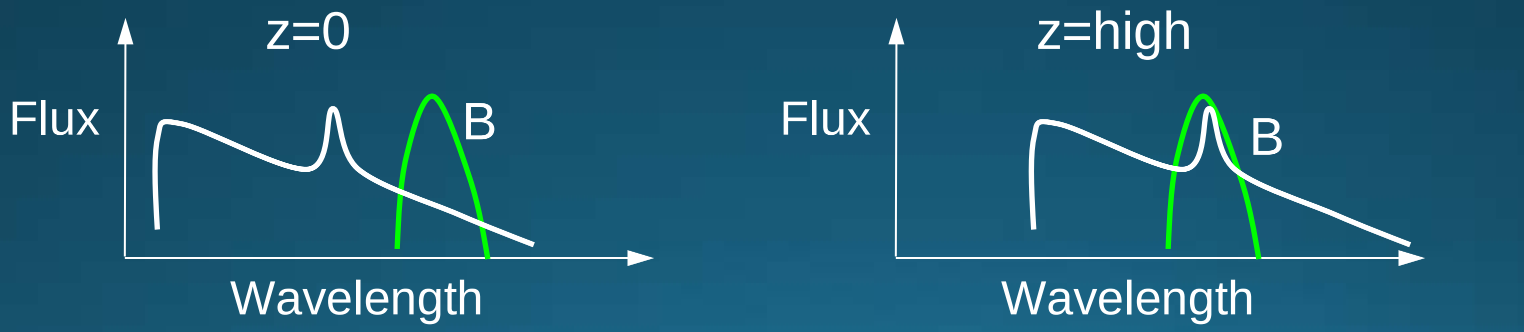
$$M = -2.5 \log\left(\frac{L}{L_{\mathrm{reference}}}\right)$$

$$m = M + 5 \log\left(\frac{d_{\mathrm{L}}}{10\ \mathrm{pc}}\right)$$

$$m = M + 5 \log\left(\frac{d_{\mathrm{L}}}{1\ \mathrm{Mpc}}\right) + 25$$

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



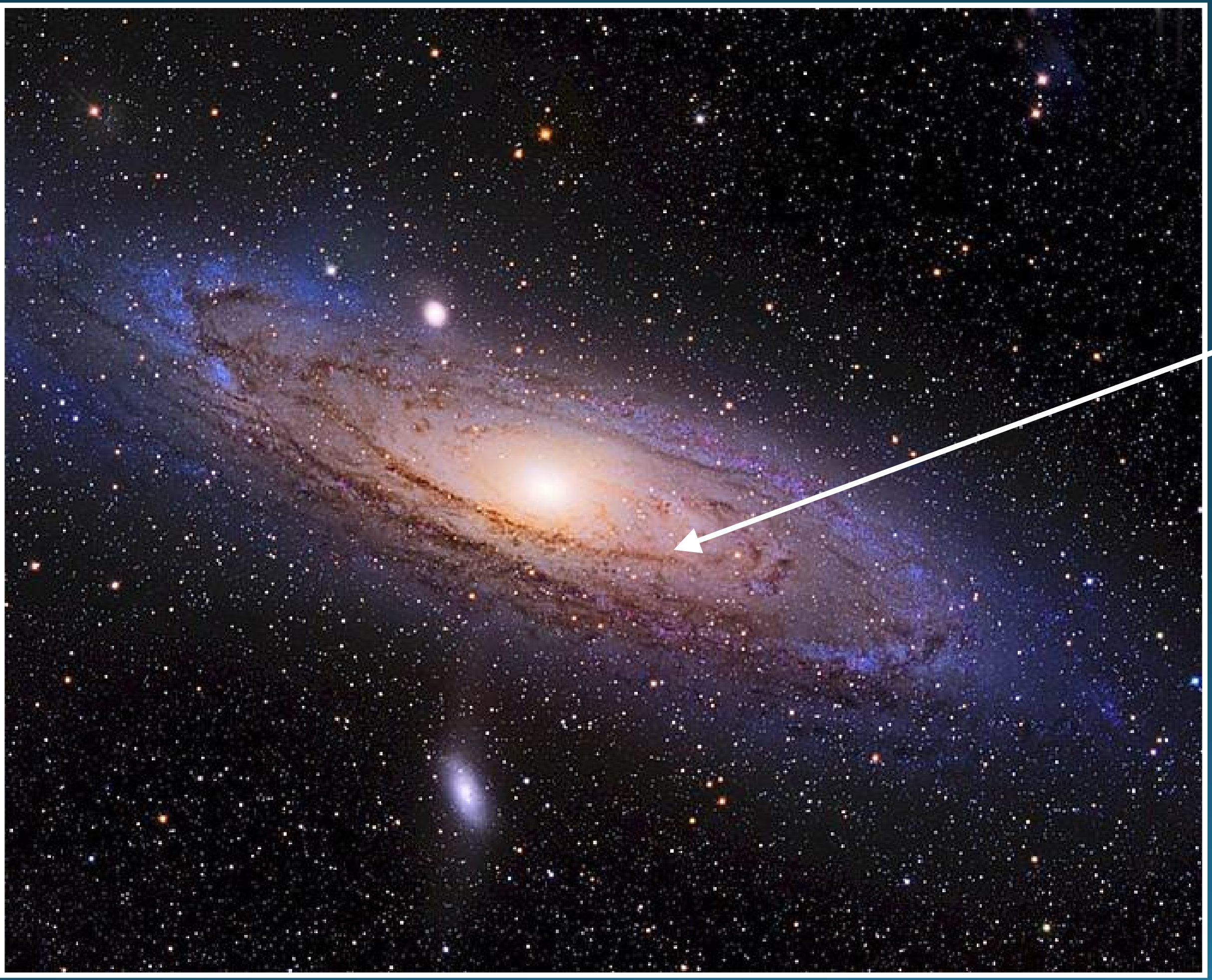
Complications I: K-correction

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

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

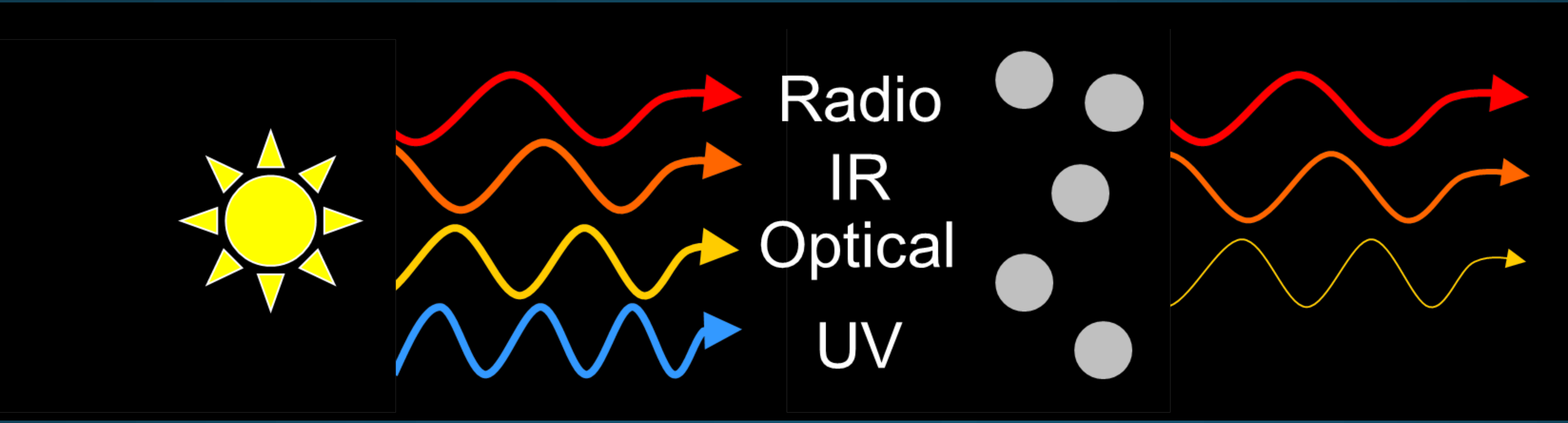
Often a complicated function, based on assumptions about the shape of the source spectrum…

Complications II: Dust extinction



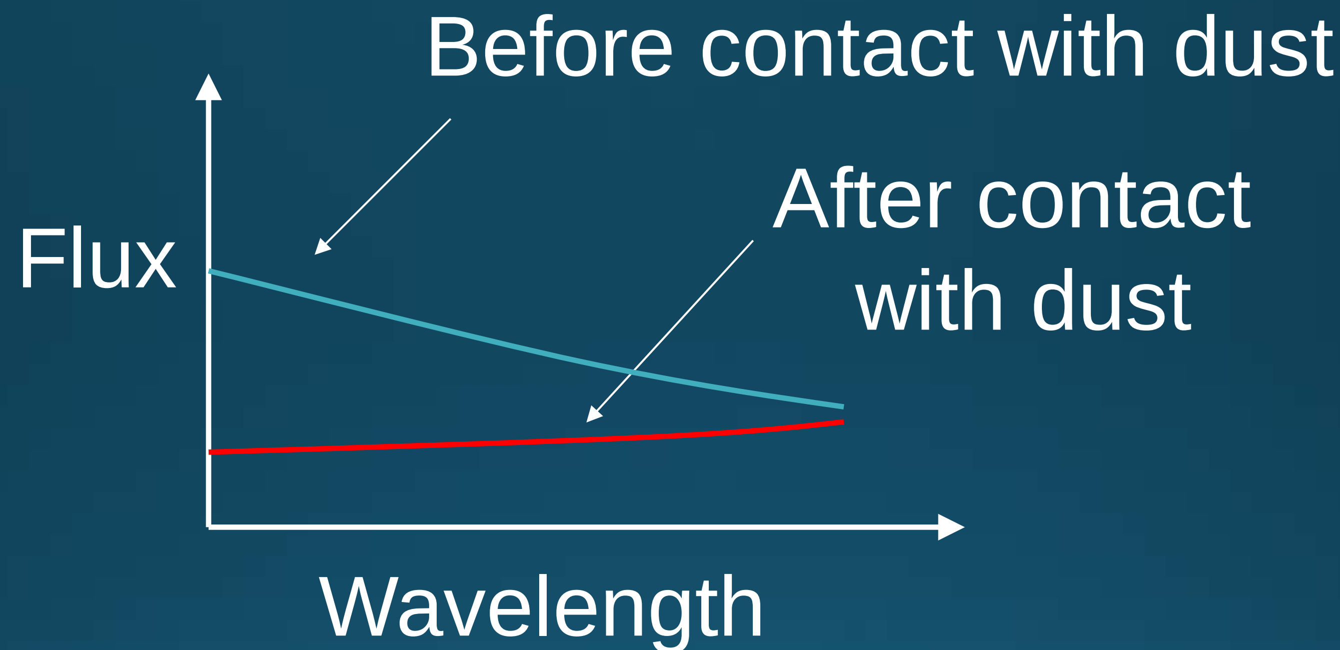
What are these black stripes?

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



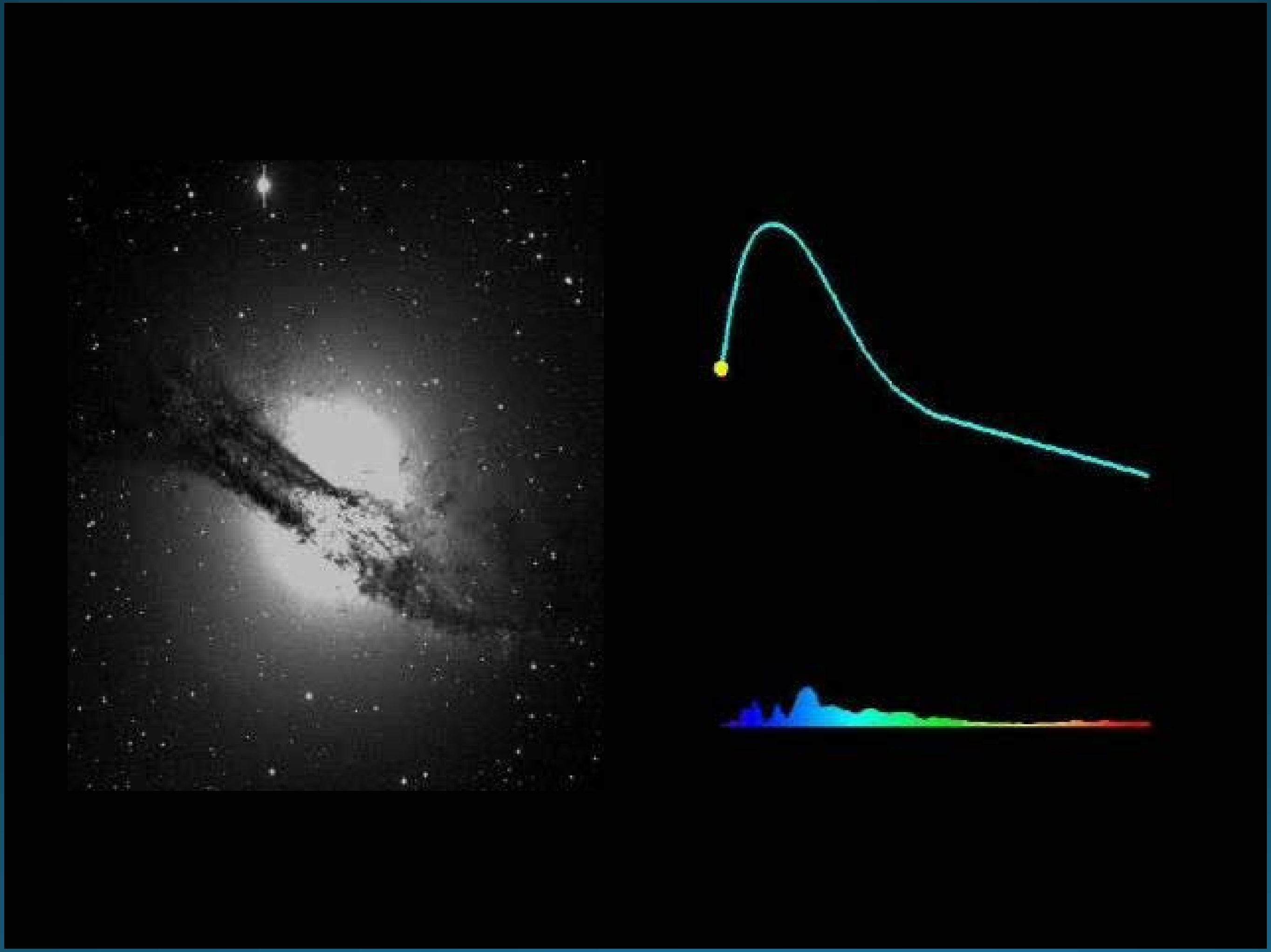
$$m_{\mathrm{intrinsic}} = m_{\mathrm{obs}} - A(\lambda)$$

Extinction correction

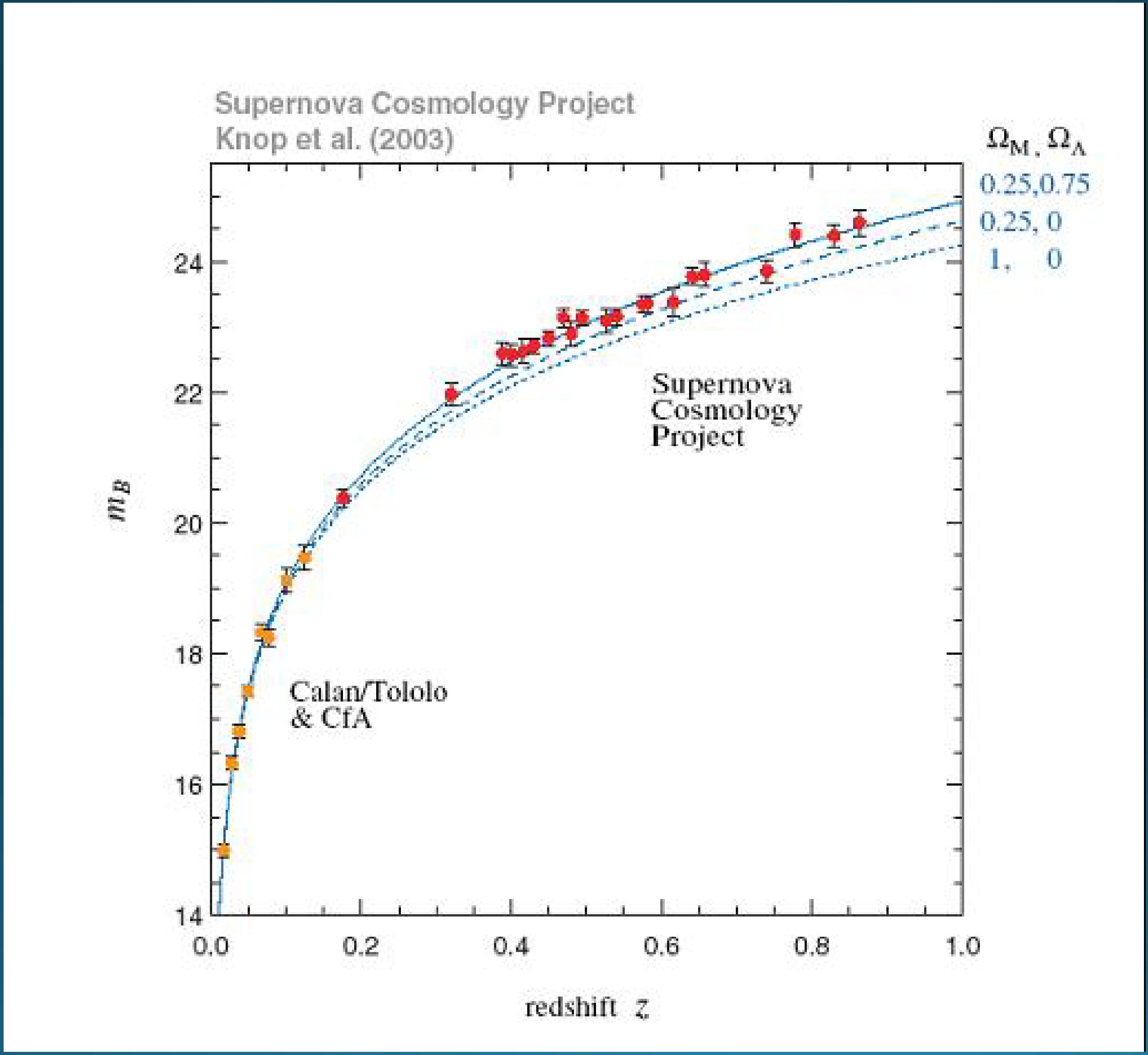
Intermission: What's this?

BILD 8.15

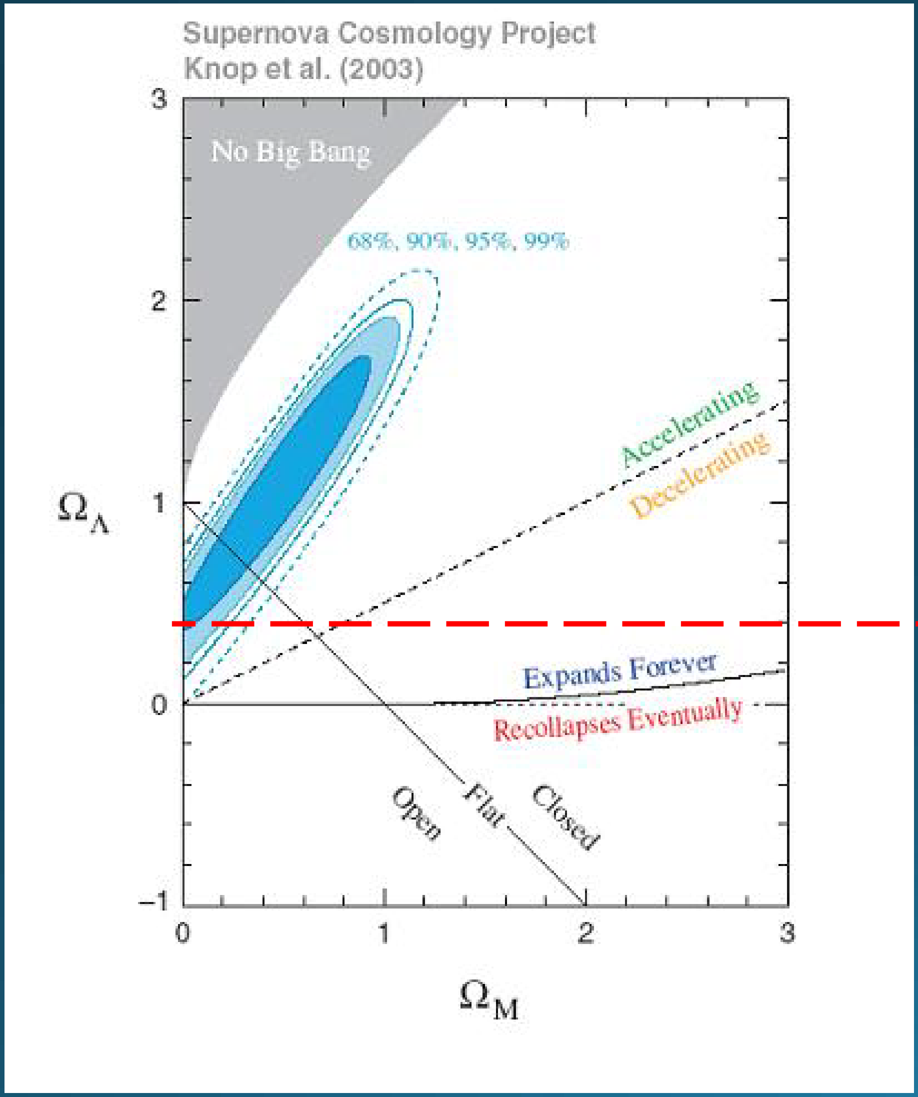
Supernova cosmology I



Supernova cosmology II



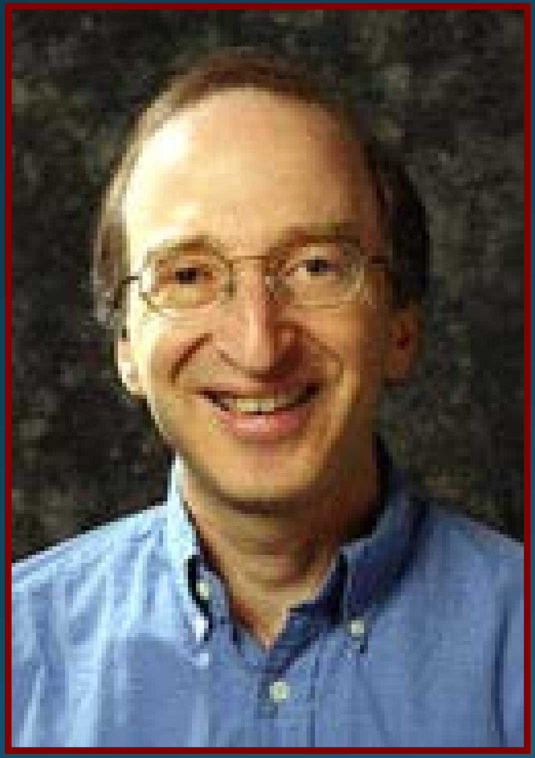
Supernova cosmology III



$\Omega_\Lambda > 0$!

Major breakthrough!

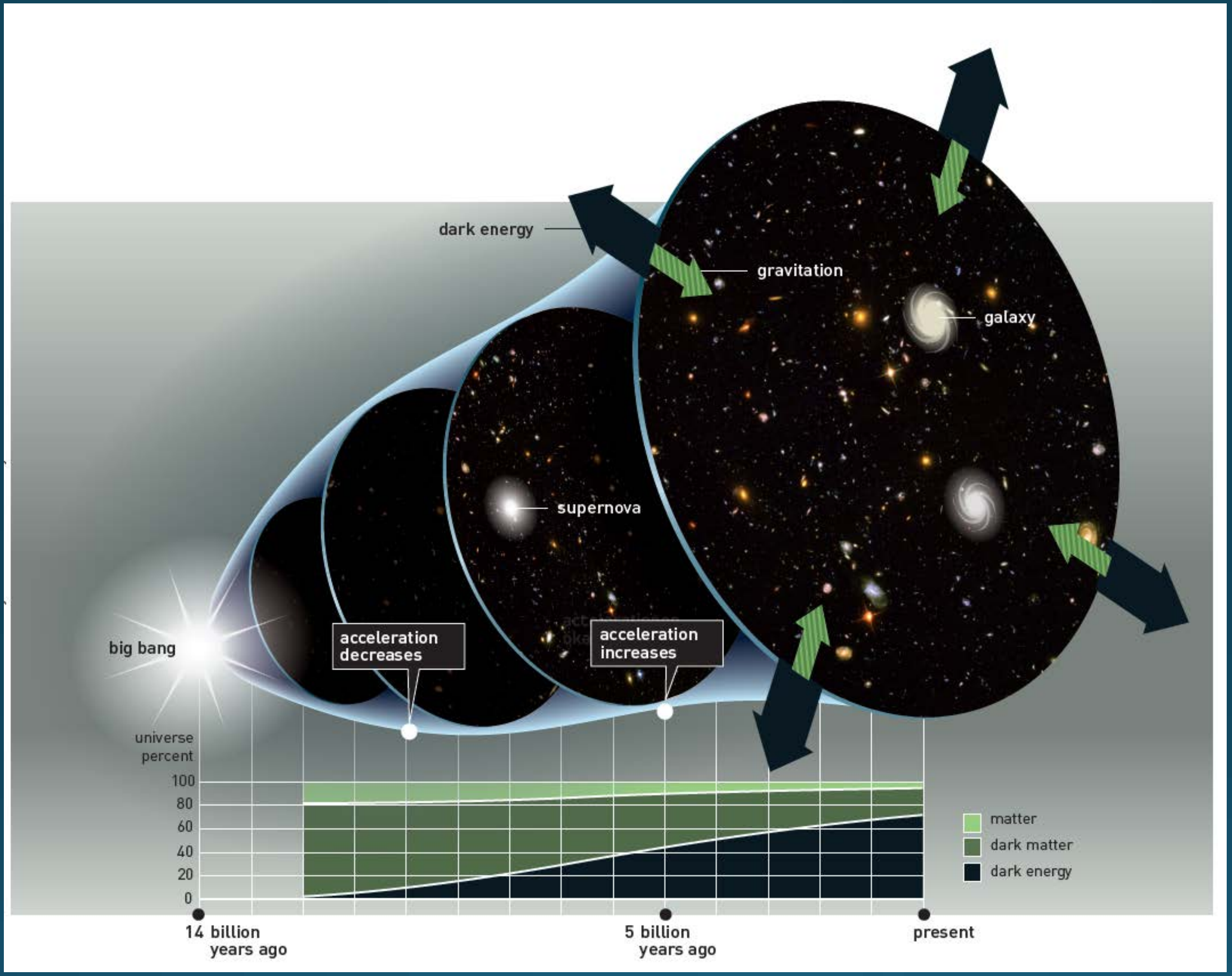
2011 Nobel prize in Physics



Saul Perlmutter

Brian P. Schmidt

Adam G. Riess



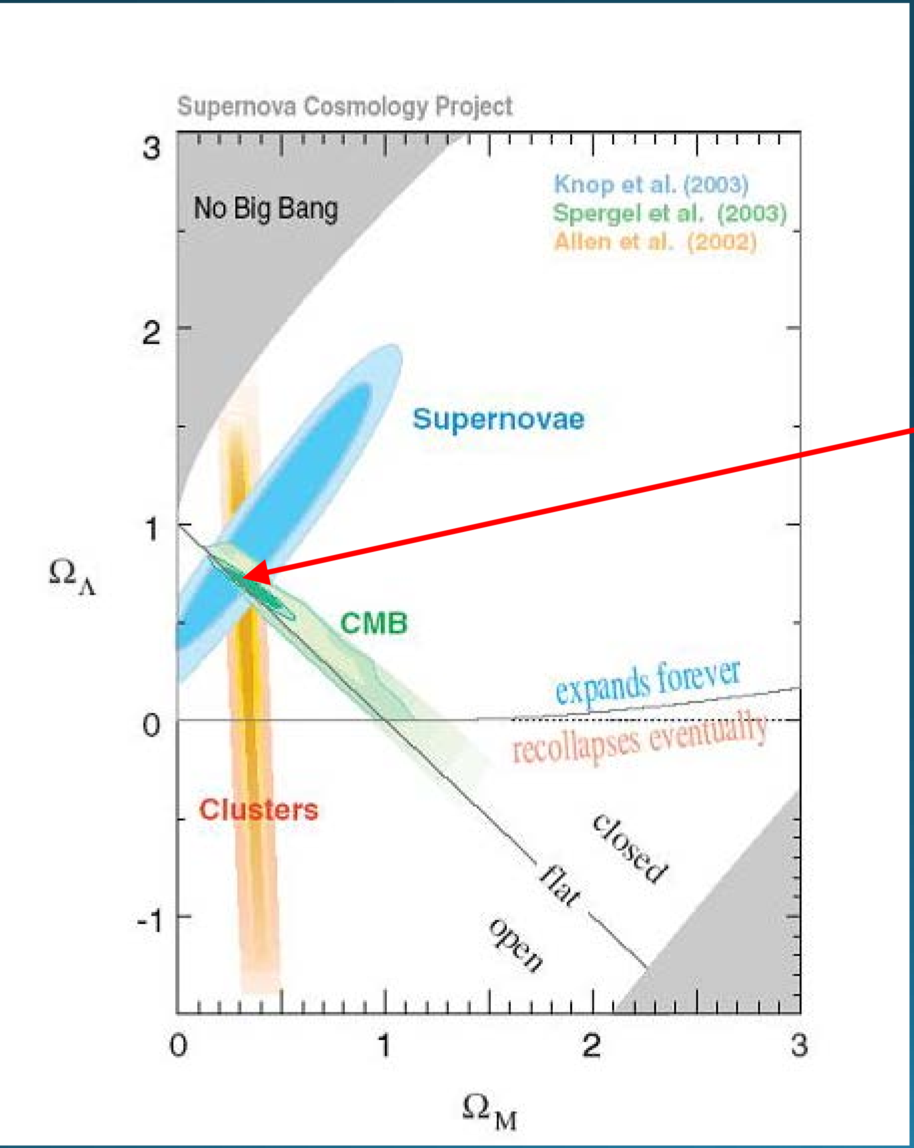
”for the discovery of the accelerating expansion of the Universe through observations of distant supernovae“

A few other probes of cosmological parameters

- CMBR ← Lecture 7
- Large scale structure ← Lecture 9
- Galaxy clusters
- Weak gravitational lensing
- Redshift shifts over time

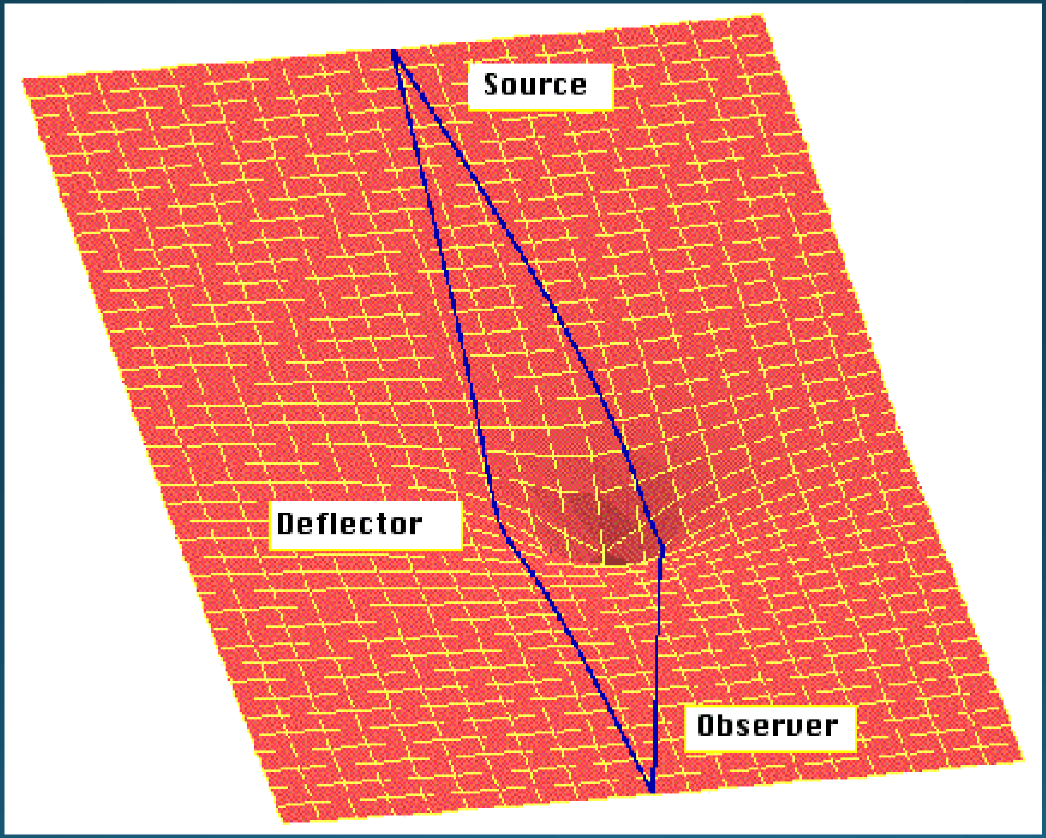
Suitable for literature exercises

Combined constraints



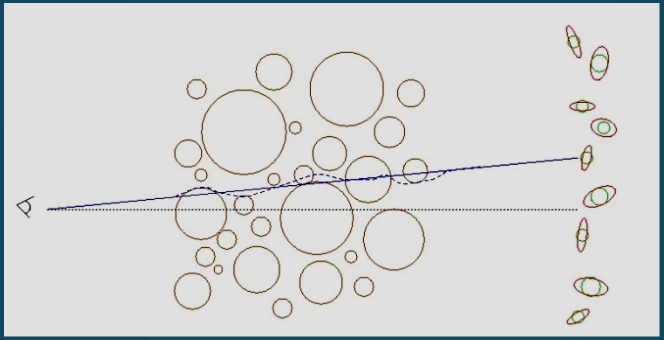
Benchmark model
Ω_M=0.3, Ω_Λ=0.7
H_0=72 km s^{-1} Mpc^{-1}

Gravitational lensing

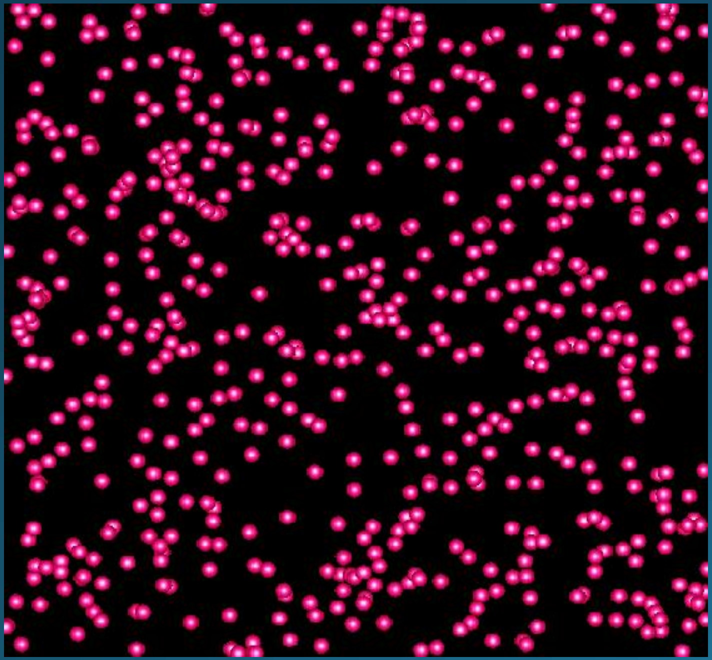


More on this also in the dark matter lecture…

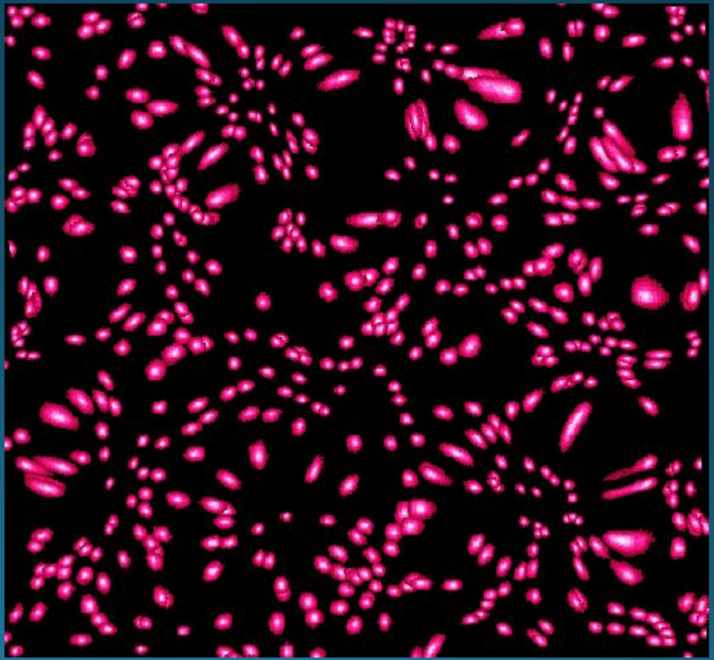
Suggestion for Literature Exercise: Weak gravitational lensing



Distortion of background images by foreground matter



Unlensed



Lensed

Dark energy and other alternatives

Alternatives to a cosmological constant:

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

$\left.\right\}$ 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
~ 1 Gyr	First Galaxies Formed
~ 15 Gyr	*Today*
$t_{rip} - 1$ Gyr	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)