Australian National University

ASTR2013 – *Foundations of Astrophysics*

Week 11: Big Bang Cosmology

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Course Overview

- Quality of Field trip reports (on a skim) excellent.
- One problem set (6.7%) and final exam (30%) the only assessments remaining.
- Final exam will have some relatively easy questions (e.g. based on concepts re-iterated at the start of each lecture), some based on tutorials, problem sets and field trip worksheet, and 1-2 challenge questions.
- Some feedback though Matthew Dotta. Please send final feedback to course representatives.

Properties of other galaxies

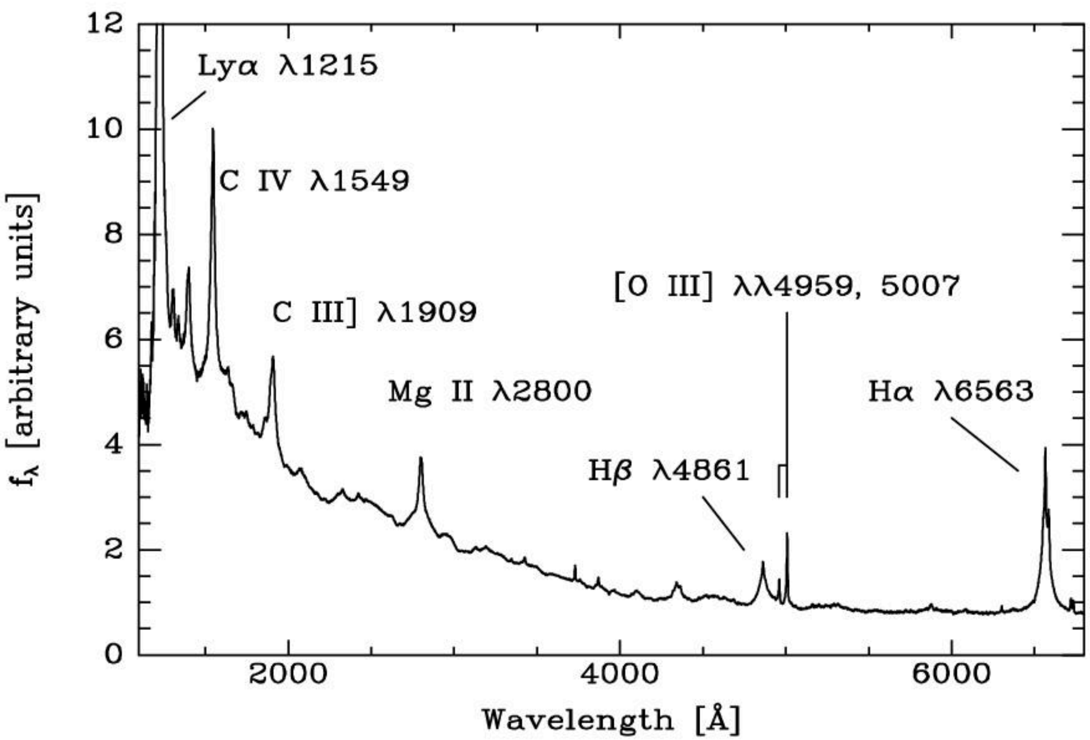
- The distribution of galaxy luminosities is approximately described by the *Schechter* function:

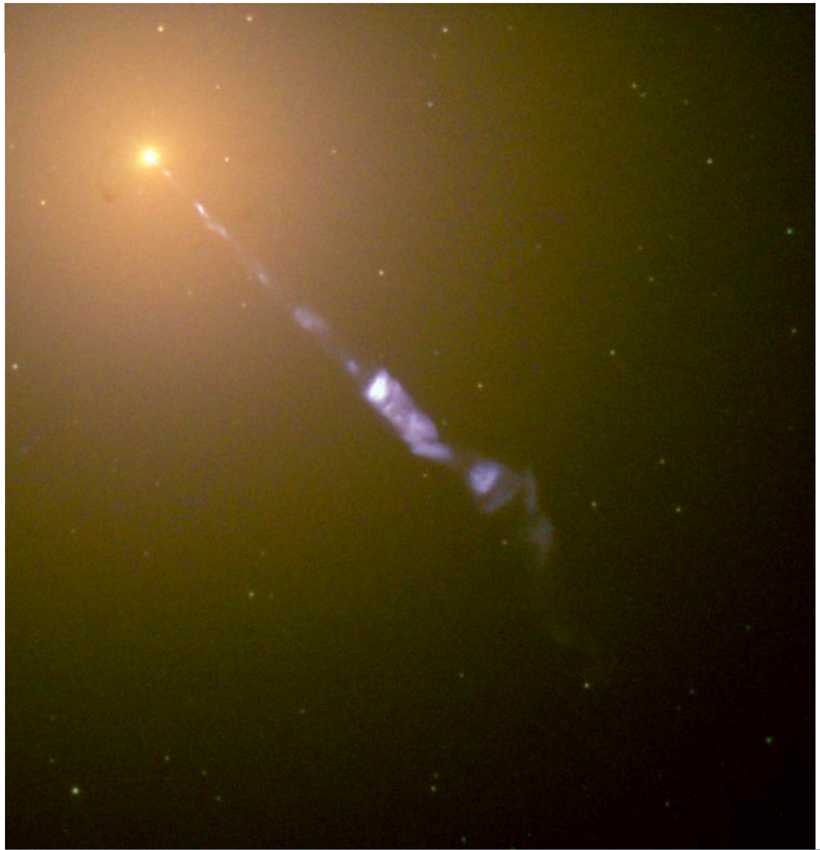
$$\phi(L)\,dL \approx \phi(L_*)\left(\frac{L}{L_*}\right)^{-1}\exp\left(-\frac{L}{L_*}\right)dL.$$

- The critical turning point in this distribution, L_*, is approximately the Milky Way.
- Galaxies can be irregular, spiral or elliptical.
- The most massive galaxies are elliptical, and may have resulted from galaxy mergers.

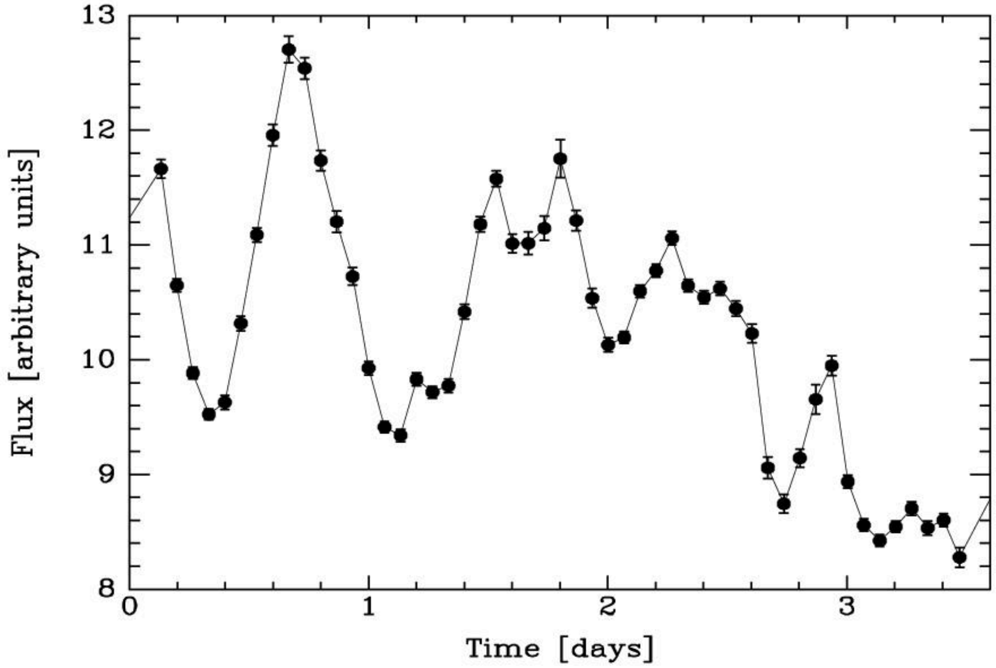
Quasars

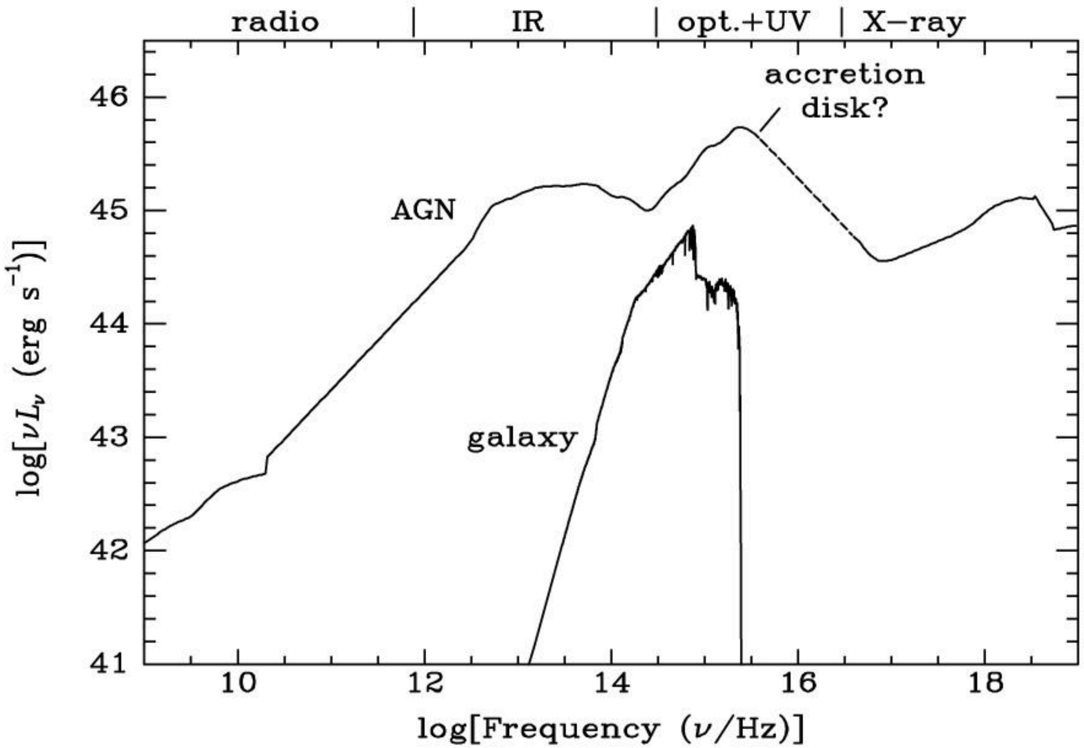
Quasars have a characteristic spectrum, with emission at all wavelengths as occurs in an accretion disk, and emission lines of highly ionized elements.





Quasar variability (top) and spectrum (bottom) are very different to a galaxy.





discuss

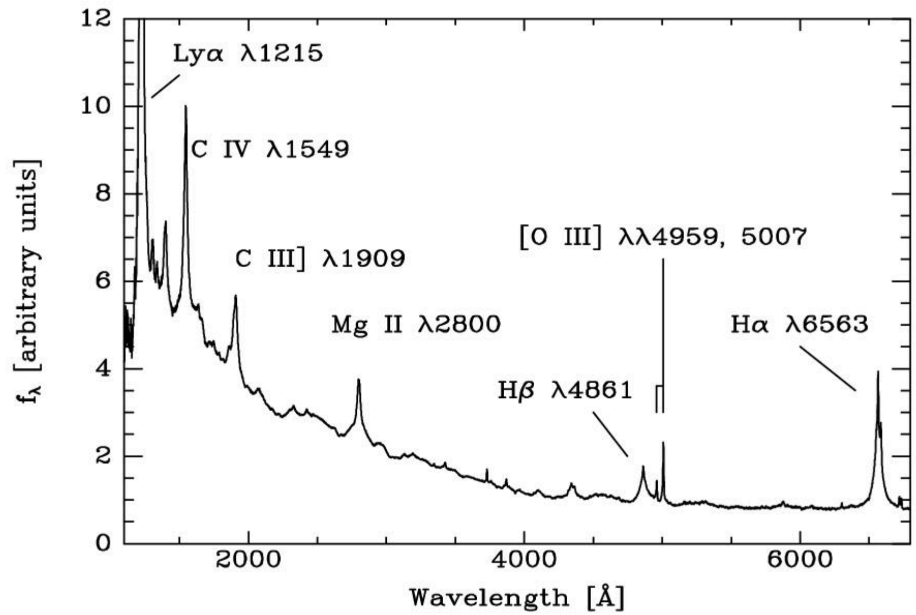
Quasars and Eddington Luminosity

- Quasars have luminosities limited only by the absorbed photon momentum (e.g. from Thompson scattering) equaling gravitational attraction – called Eddington-limited accretion.
- Key equations:

$$L = L_E = 1.3 \times 10^{38} \text{ erg s}^{-1} \frac{M}{M_\odot}$$

$$L = 0.057 \dot{M} c^2$$

- They have a characteristic spectrum when not obscured:



Week 11 Summary

Textbook: Sections 8.1, 8.3, 8.4, 8.5, equation 9.28, 9.55 and 9.96 (briefly only!), 10.1, 10.2 and 10.3. This is half of a 3rd year course – a super-brief intro only this week.

- Olbers Paradox – the Universe is not infinite.
- Hubble's law, age and isotropy of the Universe.
- Solution to the Friedman equations: what the scale parameter R means, and what the *critical density* is.
- Cosmological redshift from an observational perspective.
- The Cosmic Microwave Background.

Olbers Paradox

- The simplest cosmological observation is that the night sky (i.e. the space between the stars) is dark.
- In an (simplistic) infinite universe made up of space and stars, all sight lines would eventually hit a stellar surface.
- This means that either:
  1. The Universe is finite.
  2. The Universe has finite age.
  3. Something about physics removes photon energies when they travel large distances.
  4. More than 1 of the above.

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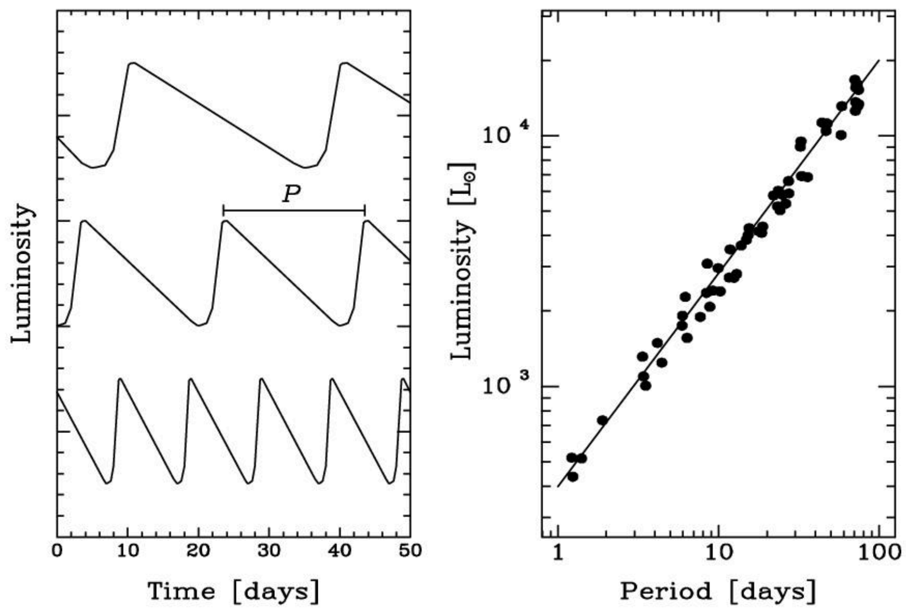
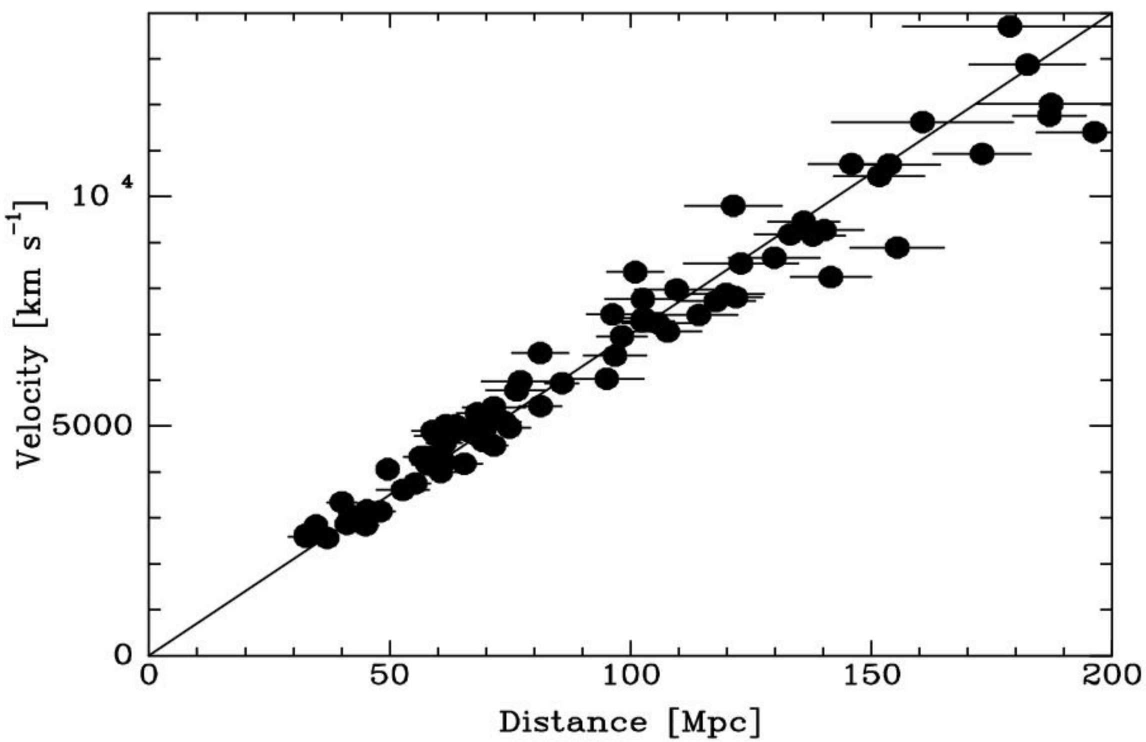
Extragalactic Distances

- Measuring the luminosity of Galaxies (last lecture) or inferring the structure of the universe needs *standard candles*.
- Measure luminosity and flux to derive distance.
- A huge literature exists on this topic – one example is the Cepheid period-luminosity relationship. Physics: period measures dynamical timescale and radius.



Hubble's Law

- As soon as the first (rather inaccurate) distances were available, Hubble (1929) measured galaxy velocities and published a trend – more distant galaxies were receding.



$$v = H_0 D.$$

$$H_0 = 70 \pm 5\,\mathrm{km\,s^{-1}Mpc^{-1}}$$

Hubble "constant"

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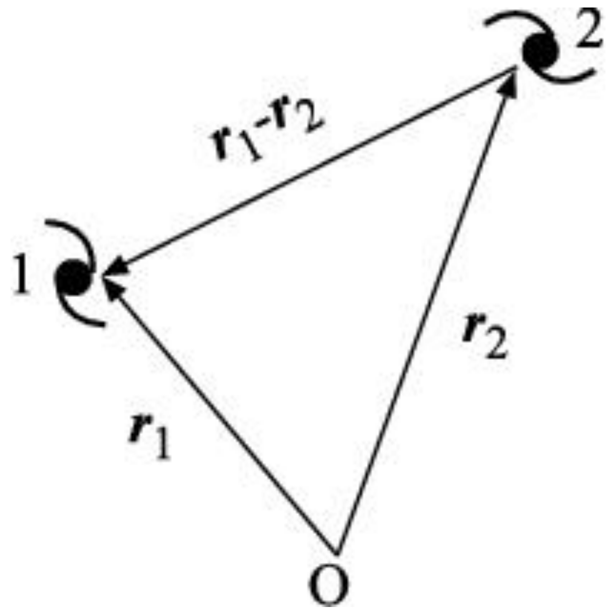
Consequences of Hubble's Law

- If H_0 was a constant, then all observers everywhere see the same Hubble flow (i.e. expansion of the local Universe)
- Tracing this uniform expansion backwards in time means the Universe has an age equal to the Hubble time (14 Gyr).

$$t_0 = \frac{1}{H_0} = \frac{1}{70\ \mathrm{km\ s^{-1} Mpc^{-1}}}$$



Universe Age and Isotropy

- The age of objects in the Universe provide a lower limit on its age.
- E.g. the solar system is 4.6 Gyr old. Based on nucleosynthesis calculations, the Uranium itself is 6.2 Gyr old.
- The oldest stars are ~13 Gyr old, and the oldest white dwarfs around 10 Gyr.

All this is consistent with a Big Bang cosmology, as long as the Universe hasn't been expanding nearly constantly.

- The Universe is also isotropic on large scales (e.g. 2dF from last lecture), meaning that it is worthwhile to consider the action of gravity on the Universe as a whole.

General Relativity and the Universe

- Several theorists attempted to apply Einstein's general relativity theory to the Universe as a whole.
- An isotropic universe is described by a *scale factor R*. This could be the Universe radius (e.g. a 3D universe that is like the surface of a 4D sphere)… but curved spacetime is no longer as relevant.
- For flat spacetime, for some co-moving (i.e. constant for an isotropic universe) coordinate *r*, we have lengths:

$$l = R(t)r$$

Draw picture on board

- The scale parameter *R* follows the Friedman equation:

$$\dot{H} = \frac{\ddot{R}}{R} = -\frac{4\pi G}{3c^2}(\rho c^2 + 3P).$$

- If we ignore pressure (e.g. current Universe) there is a critical density where the Hubble parameter is always (just) constant:

$$\rho_{c,0} = \frac{3H_0^2}{8\pi G}$$

- In the late 1900s, a lot of effort went in to determining the Hubble parameter derivative, and if the Universe was above or below this density. However, this didn't work, and a constant had to be added to the equation (dating back to Einstein):

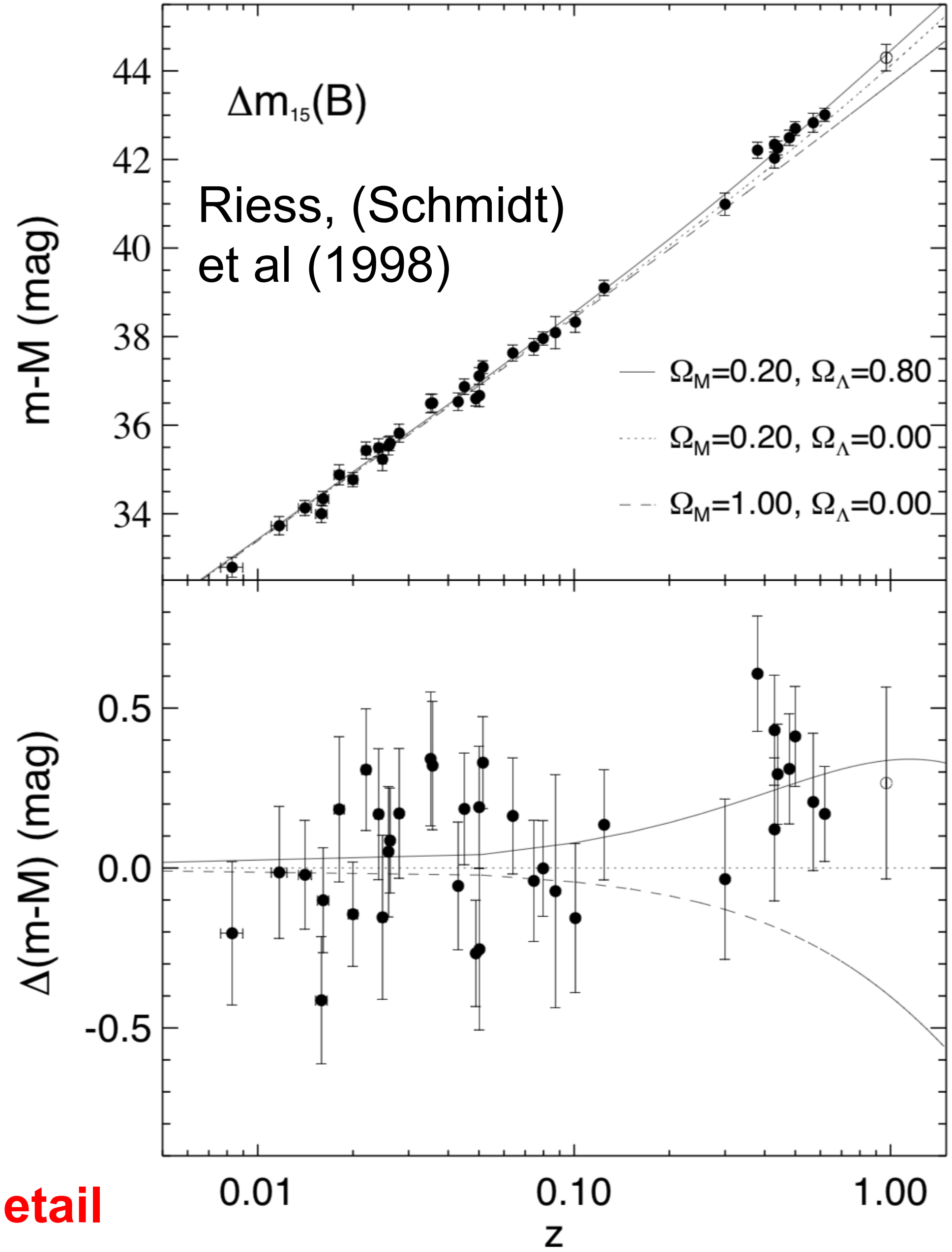
$$\dot{H} = \quad \frac{\ddot{R}}{R} = -\frac{4\pi G}{3c^2}(\rho c^2 + 3P) + \frac{\Lambda}{3}.$$

Cosmological Redshift

- As light travels through an expanding universe, the wavelength must increase as space expands… just like *any* comoving distance. This is fully consistent with time dilation, as would be expected in a relativistic theory: $$\frac{\Delta t_0}{\Delta t_e} = \frac{\lambda_0}{\lambda_e} = \frac{\nu_e}{\nu_0} = \frac{R(t_0)}{R(t_e)} \equiv 1 + z,$$
- Redshift *z* is defined so that the change in scale parameter *R* is (1+*z*).

"Dark Energy"

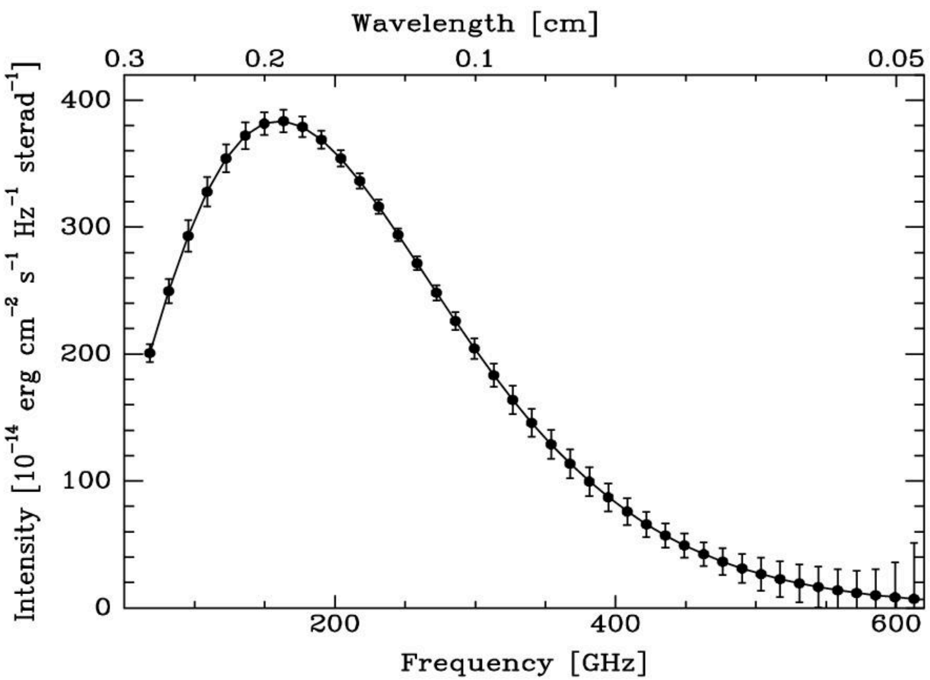
- Since 1998, it has been clear that a Universe decelerating by matter only doesn't make sense.
- The equation with the cosmological constant Λ is needed.
- It is called "dark energy", but is observationally just a functional form of redshift versus distance.



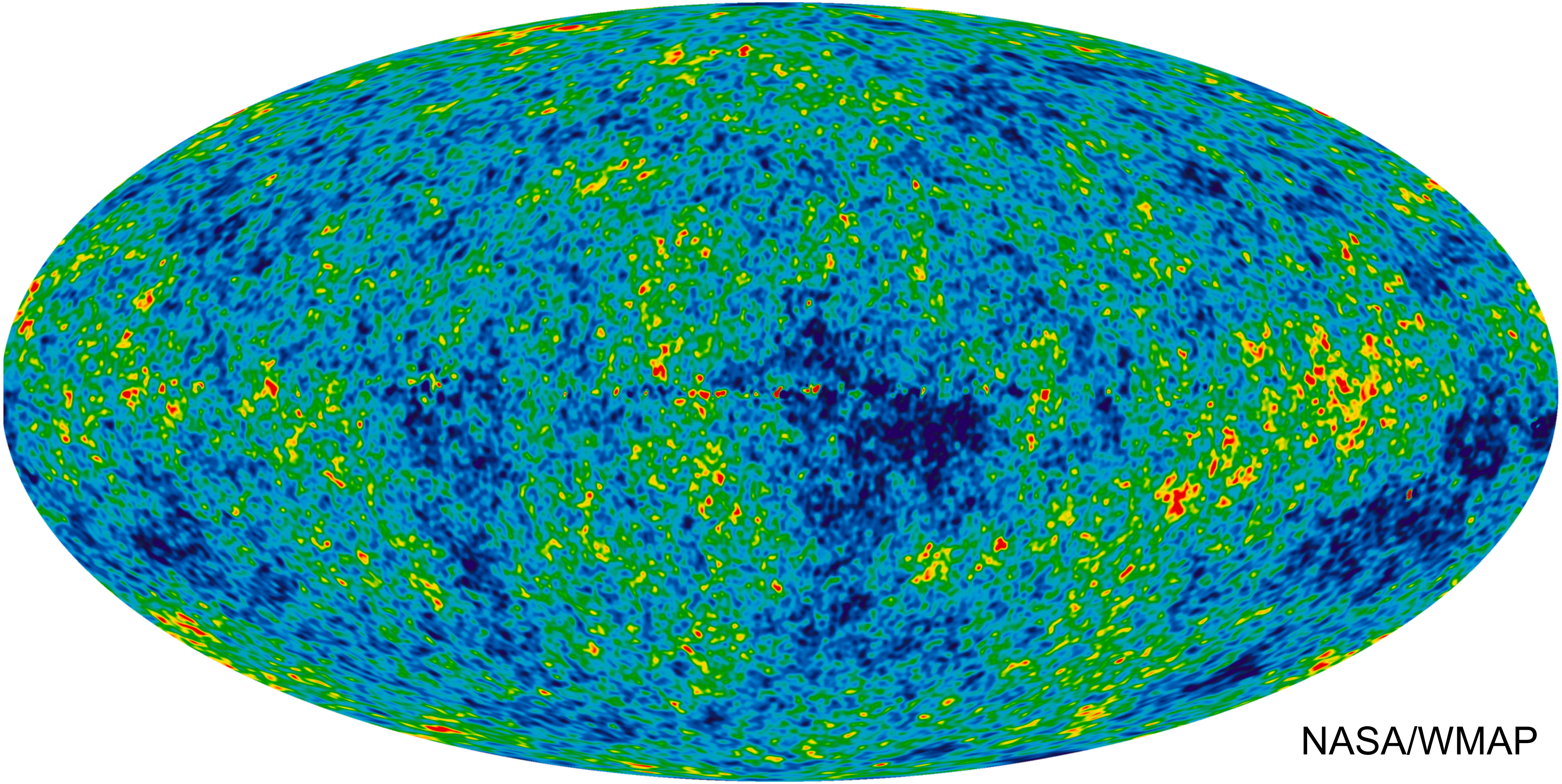
Discuss in detail

Cosmic Microwave Background

- Going back in time towards the ”Big Bang”, eventually the temperature of the Universe is high enough to ionize Hydrogen.
- Thompson scattering then prevents us from seeing any further back.
- This radiation, redshifted to ~3mm wavelengths, looks like a near-perfect Planck function:



Fluctuations in the CMB at the level of 1:100,000 were the seeds of galaxies and all structure in the Universe.



NASA/WMAP

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