AGN Surveys and AGN Environment

Introduction

Result of previous lectures:

AGN produce large amounts of energy over timescales of $\gtrsim 10^8$ years and they strongly interact with their environment.

Questions:

- What galaxies harbor AGN?
- Are these galaxies different from others?
- How do galaxies with AGN evolve?
- How do AGN form?

To answer these questions, we need to study statistical properties of AGN and their hosts, both among morphological type and with time: AGN surveys

But first, we need to talk about the basics of doing science in an expanding universe.

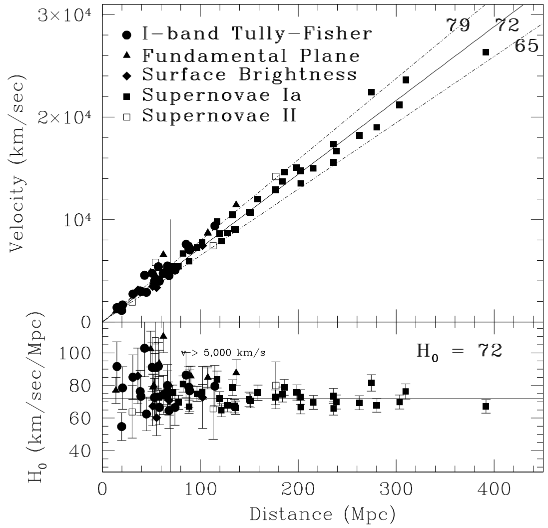
Basic Facts

Observations show that there are *four major facts* about the universe as a whole:

The universe is:	• expanding, • isotropic, • and homogeneous.

That the universe is isotropic and homogeneous is called the *cosmological principle*.

Expansion, I



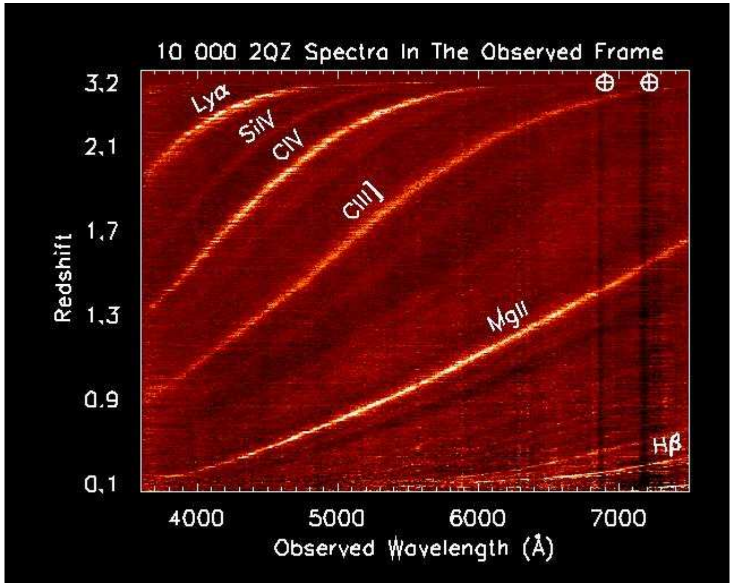
Hubble (1929): The "velocity", v, of a galaxy depends linearly from its distance, d: $v(r) = H_0 d$

where $v/c = \Delta\lambda/\lambda$ and where H_0: Hubble constant or Hubble parameter.

Currently accepted value:

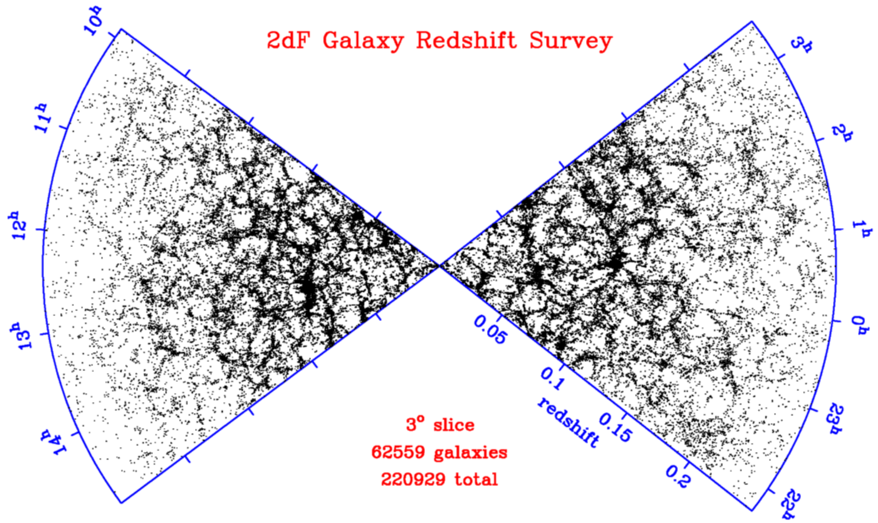
$$H_0 = 72 \pm 8\,\mathrm{km\,s^{-1}\,Mpc^{-1}} \tag{11.1}$$

Freedman et al. (2001, Fig. 4)



courtesy 2dF QSO Redshift survey

As a consequence of the cosmological redshift, for different z different parts of the spectrum of a distant source are visible.



2dF Survey, ~220000 galaxies total

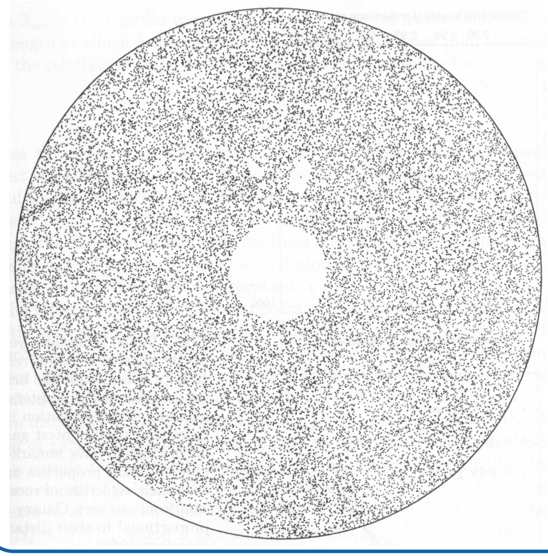
The universe is homogeneous $\Longleftrightarrow$ The universe looks the same everywhere in space

Testable by observing spatial distribution of galaxies.

On scales $\gg$ 100 Mpc the universe looks indeed the same. Below that: structure.

Structures seen are galaxy clusters (gravitationally bound) and superclusters (larger structures, not [yet] gravitationally bound).

Isotropy



The universe is isotropic $\Longleftrightarrow$ The universe looks the same in all directions

Radio galaxies are mainly quasars $\Longrightarrow$ Sample large space volume ($z \gtrsim 1$) $\Longrightarrow$ Clear isotropy.

Anisotropy in the image: galactic plane, exclusion region around Cyg A, Cas A, and the north celestial pole.

Peebles (1993): Distribution of 31000 objects at λ =6 cm from the Greenbank Catalogue.

World Models, I

World Model: theoretical framework describing a world governed by the cosmological principle.

Use combination of

- General Relativity
- Thermodynamics
- Quantum Mechanics

$\Longrightarrow$ Complicated!

For 99% of the work, the above points can be dealt with separately:

1. Define metric obeying cosmological principle.
2. Obtain equation for evolution of universe using Einstein field equations.
3. Use thermo/QM to obtain equation of state.
4. Solve equations.

World Models, II

Before we can start to think about universe: **Brief introduction to assumptions of general relativity.**

$\Longrightarrow$ See theory lectures for the gory details, or check with the literature (Weinberg or MTW).

Assumptions of GRT:

- **Space is 4-dimensional**, might be curved
- **Matter (=Energy) modifies space** (Einstein field equation).
- **Covariance: physical laws** must be formulated in a **coordinate-system independent** way.
- **Strong equivalence principle**: There is no experiment by which one can distinguish between free falling coordinate systems and inertial systems.
- At each point, space is **locally Minkowski** (i.e., locally, SRT holds).

$\Longrightarrow$ Understanding of geometry of space necessary to understand physics.

RW Metric, I

- **Cosmological principle** $+$ **expansion** $\Longrightarrow$ $\exists$ **freely expanding cosmical coordinate system.**
  - Observers $=:$ **fundamental observers**
  - Time $=:$ cosmic time

  This is the coordinate system in which the 3K radiation is isotropic, clocks can be synchronized, e.g., by adjusting time to the local density of the universe.

  $\Longrightarrow$ Metric has temporal and spatial part.

  This also follows directly from the equivalence principle.
- *Homogeneity and isotropy* $\Longrightarrow$ spatial part is **spherically symmetric**:

$$d\psi^2 := d\theta^2 + \sin^2\theta \, d\phi^2 \tag{11.2}$$

- *Expansion:* $\exists$ scale factor, $R(t)$ $\Longrightarrow$ measure distances using **comoving coordinates.**

RW Metric, II

A metric based on these points looks like

$$ds^2 = c^2\,dt^2 - R^2(t)\left[f^2(r)\,dr^2 + g^2(r)\,d\psi^2\right] \tag{11.3}$$

where $f(r)$ and $g(r)$ are arbitrary.

Metrics of the form of eq. (11.3) are called **Robertson-Walker** (RW) **metrics** (1935), but have been previously also studied by Friedmann and Lemaître.

One common choice is

$$ds^2 = c^2\,dt^2 - R^2(t)\left[dr^2 + S_k^2(r)\,d\psi^2\right] \tag{11.4}$$

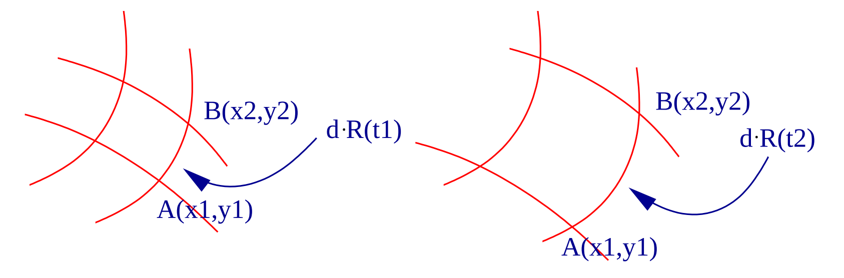
where $R(t)$: scale factor, containing the physics, t: cosmic time, r, θ, ϕ: comoving coordinates, and where

$$S_k(\theta) = \begin{cases} \sin\theta & \text{for } k = +1 \\ \theta & \text{for } k = 0 \\ \sinh\theta & \text{for } k = -1 \end{cases} \tag{11.5}$$

Remark: θ and ϕ describe **directions** on sky, as seen from the arbitrary center of the coordinate system (=us), r can be interpreted as a radial coordinate.

RW Metric, III

RW metric: defines universal coordinate system tied to the expansion of space:



Scale factor $R(t)$ describes evolution of universe.

- d is called the **comoving distance.**
- $D(t) := d \cdot R(t)$ is called the **proper distance.**

(note that R is unitless, i.e., d and $d \cdot R(t)$ are measured in Mpc)

Hubble's Law, I

Hubble's Law follows from the variation of $R(t)$:

Small scales $\Longrightarrow$ Euclidean geometry. Proper distance between two observers:

$$D(t) = d \cdot R(t) \tag{11.6}$$

Expansion $\Longrightarrow$ proper separation changes:

$$\frac{\Delta D}{\Delta t} = \frac{R(t+\Delta t)d - R(t)d}{\Delta t} \quad \text{with } \lim_{\Delta t \to 0}: \quad v = \frac{\mathrm{d}D}{\mathrm{d}t} = \dot{R}\, d = \frac{\dot{R}}{R} D =: H\, D \tag{11.7}$$

$\Longrightarrow$ Identify local Hubble "constant" with

$$H = \dot{R}/R = \dot{a}(t) \quad \text{where} \quad a(t) = R(t)/R(\text{today}) \tag{11.8}$$

Note that $R = R(t) \Longrightarrow H$ is time-dependent!

Hubble's Law, II

The cosmological redshift is a consequence of the expansion of the universe:

Since the comoving distance is constant:

$$d = \frac{D(t=\text{today})}{R(t=\text{today})} = \frac{D(t)}{R(t)} = \text{const.} \tag{11.9}$$

Set $a(t) = R(t)/R(t=\text{today})$, then Eq. (11.9) implies

$$\lambda_{\text{obs}} = \frac{\lambda_{\text{emit}}}{a_{\text{emit}}} \quad \Longleftrightarrow \quad z = \frac{\lambda_{\text{obs}} - \lambda_{\text{emit}}}{\lambda_{\text{emit}}} = \frac{\lambda_{\text{obs}}}{\lambda_{\text{emit}}} - 1 \tag{11.10}$$

(z: observed redshift, λ_{obs}: observed wavelength, λ_{emit}: emitted wavelength)

$$1 + z = \frac{1}{a_{\text{emit}}} = \frac{R(t=\text{today})}{R(t)} \tag{11.11}$$

Light emitted at $z = 1$ was emitted when the universe was half as big as today!

z: measure for *relative size* of universe at time the observed light was emitted.

Hubble's Law, III

For light, $d = c\Delta t$. Therefore

$$\frac{c\,\Delta t_{\text{e}}}{R(t_{\text{emit}})} = \frac{c\,\Delta t_{\text{obs}}}{R(t_{\text{obs}})} \quad \text{such that} \quad \frac{\mathrm{d}t}{R(t)} = \text{const.} \tag{11.12}$$

This means that

$$\frac{\mathrm{d}t_{\text{obs}}}{\mathrm{d}t_{\text{emit}}} = \frac{R(t_{\text{obs}})}{R(t_{\text{emit}})} = 1 + z \tag{11.13}$$

$\Longrightarrow$ Time dilatation of events at large z.

This cosmological time dilatation has been observed in the light curves of supernova outbursts.

Expansion and Spectra

The total number of photons in a box $\mathrm{d}A \cdot c\mathrm{d}t$ and in a frequency range ν to $\nu + \mathrm{d}\nu$ is

$$N = n_\nu(\nu)\,\mathrm{d}A\,\mathrm{d}\nu\,c\,\mathrm{d}t \tag{11.14}$$

This number is conserved during the expansion of the universe:

$$n_\nu(\nu_{\text{emit}})\,\mathrm{d}A\,\mathrm{d}\nu_{\text{emit}}\,c\,\mathrm{d}t_{\text{emit}} = n_\nu(\nu_{\text{obs}})\frac{d\nu_{\text{emit}}}{1+z}\mathrm{d}A\,c\,\mathrm{d}t_{\text{emit}}(1+z) \tag{11.15}$$

$$n_\nu(\nu_{\text{obs}})\,\mathrm{d}A\,\mathrm{d}\nu_{\text{obs}}\,c\,\mathrm{d}t_{\text{obs}} \tag{11.16}$$

but: arrival time differs $\Longrightarrow$ energy flux density changes:

$$F_\nu(\nu_{\text{obs}}) = h\nu_{\text{obs}} n_\nu(\nu_{\text{obs}}) = h\frac{\nu_{\text{emit}}}{1+z}\nu_n(\nu_{\text{emit}}) = \frac{F_\nu(\nu_{\text{emit}})}{1+z} \tag{11.17}$$

and consequently the total flux in a certain energy band changes as well:

$$F_{\text{obs}} = \int F_\nu(\nu_{\text{obs}})\,\mathrm{d}\nu_{\text{obs}} = \int \frac{F_\nu(\nu_{\text{emit}})}{1+z} \cdot \frac{\mathrm{d}\nu_{\text{emit}}}{1+z} = \frac{F_{\text{emit}}}{(1+z)^2} \tag{11.18}$$

One power of $1 + z$ from decreased photon energy, one from decreased arrival rate.

For wavelength based flux densities, since $F_\lambda = F_\nu c/\lambda^2$ one finds $F_\lambda(\lambda_{\text{obs}}) = F_\lambda(\lambda_{\text{emit}})/(1+z)^3$.