Extragalactic astronomy

Merja Tornikoski

Aalto University Metsähovi Radio Observatory

Structure of these slides

- I have modified my earlier lecture slides to better be suitable for self-learning during the quarantine.
- Slides still contain regular ”lecture-type” slides, with some additional notes added, but also with extra pages of information that would normally be explained orally during the lecture. Read them carefully.
- At the end of the slides I have added some ”practice these” –hints for self-learning. Go through my questions and try to answer them. Go back to read the slides if you do not know the answers.
  Note: if you plan to take our course *Radio Astronomy* later, we expect you to be well familiar with all this material and understand the bascis of it all.

Today's lecture outline

- Galaxies, general
- Expansion of the universe; redshift
- Hubble Sequence for galaxies
- Galaxy formation continued
- Galaxy clusters and superclusters
- Quasars and other Active Galactic Nuclei
    - Quasar variability
    - Quasar research in Metsähovi
- Cosmology
    - Hubble's law
    - Cosmic Microwave Background

Extragalactic
= outside the Milky Way

- Galaxies
- Galaxy groups
- Galaxy clusters
- Superclusters
- Walls, filaments, voids

- Radio galaxies
- Quasars
- Supernovae
- Intergalactic dust etc.

These all will be covered in slides to come!

The Hubble Deep Field

Notes page: Hubble Deep Field (HDF)

HDF (image on the previous slide) is an image of a small region in the constellation Ursa Major, constructed from a series of observations by the Hubble Space Telescope. It covers an area 2.5 arcminutes across, 1/30 of the size of the full Moon (compare: approximately equal to the size of the Metsähovi radio telescope's beam at 37 GHz).

The image was assembled from 342 separate exposures taken over ten consecutive days in December 1995. It is an awesome evidence of how many distant objects we can observe if we can ”look far enough”.

The field is so small that only a few foreground stars in the Milky Way lie within it; thus, almost all of the 3000 objects in the image are galaxies, some of them very distant and young. By revealing such large numbers of very young galaxies, the HDF has become a landmark image in the study of the early universe.

The field selected for the observations needed to fulfill several criteria. It had to be at a high galactic latitude, because dust and obscuring matter in the plane of the Milky Way's disc prevents observations of distant galaxies at low galactic latitudes (re: Galactic Astronomy lectures in this course). The target field had to avoid known bright sources of visible light, such as foreground stars, and infrared, ultraviolet and X-ray emissions, to facilitate later studies at many wavelengths of the objects in the deep field. It also needed to be in a region with a low background infrared 'cirrus', the diffuse, wispy infrared emission believed to be caused by warm dust grains in cool clouds of hydrogen gas, HI regions.

It was decided that the target should be in Hubble's continuous viewing zones which are not occulted by the Earth or the moon during Hubble's orbit. The working group decided to concentrate on the northern zone to able certain northern-hemisphere telescopes to conduct follow-up observations at several wavelength regions. Twenty fields satisfying these criteria were initially identified, from which three optimal candidate fields were selected, all within the constellation of Ursa Major. Radio snapshot observations ruled out one of these fields because it contained a bright radio source, and the final decision between the other two was made on the basis of the availability of guide stars near the field.

An HDF counterpart in the southern celestial hemisphere was created in 1998: the HDF-South. In 2003-2004 a yet ”deeper”, ie. longer exposure Hubble Ultra Deep Field image was produced.

Extragalactic

- Huge range of distances (< 1 Mly to > 10 Gly). (*
- Only the nearest galaxies can be studied in detail.
  - Local Group (that's where Milky Way belongs to)
  - Contents of the galaxies, their supernova remnants etc.
- Far-away galaxies: only the brighest phenomena can be studied.
- With improving instrumentation, more distant objects can be studied in some detail.

(* Note on large-number scales:

Anglo-american "short scale": billion = a thousand million, etc.
European "long scale": billion = a million million ("million to a power of 2")
When we lecture in English, we use the short scale, in Finnish the long scale.

Galaxies

- A gravitationally bound system of stars, interstellar gas, dust, and dark matter.
- 170 billion (1.7×10^{11}) to 200 billion (2.0×10^{11}) in the observable universe.
- Contain a few thousand (10^{3}) stars to one hundred trillion (10^{14}) stars.
- Classified according to their visual appearance:
  spiral, elliptical, or irregular galaxies.

Expansion of the universe

- Edwin Hubble in 1929: Redshift of distant galaxies.
    - Spectral lines of galaxies are shifted to lower frequencies, proportional to the distance ⇒ large redshift
- Redshift $z = (\lambda - \lambda_0) / \lambda_0$
    - λ_0 = wavelength at rest
    - λ = redshifted wavelength
- The Universe is expanding: galaxies were once much closer to each other.
- General relativity (Einstein): the galaxies are not moving, but the space between them is expanding Wavelength expands with the universe.
- Highest known redshift for a galaxy: z=11.1 (GN-z11 discovered in March 2016).

Notes page: Redshifts and distances

GN-z11's name is derived from its location in the GOODS-North field of galaxies and its high cosmological redshift number (GN + z11)

It has a spectroscopic redshift of z = 11.09, which corresponds to a proper distance of approximately 32 billion (short scale) light-years or 9.8 billion parsecs. In scientific use we should use units of parsecs. Light-years are illustrative in material for general audience, but since they can be easily converted (a parsec is equivalent to ca. 3.26 light years), I tend not to be too picky about its use in teaching especially in situations where distances and ages are being compared.

At first glance, the distance of 32 billion light-years might seem impossibly far away in a Universe that is only 13.8 billion years old, where a light-year is the distance that light travels in a year, and where nothing can travel faster than the speed of light. However, because of the expansion of the universe, the distance of 2.66 billion light-years between GN-z11 and the Milky Way at the time when the light was emitted increased by a factor of (z+1)=12.1 to a distance of 32.2 billion light-years during the 13.4 billion years it has taken the light to reach us.

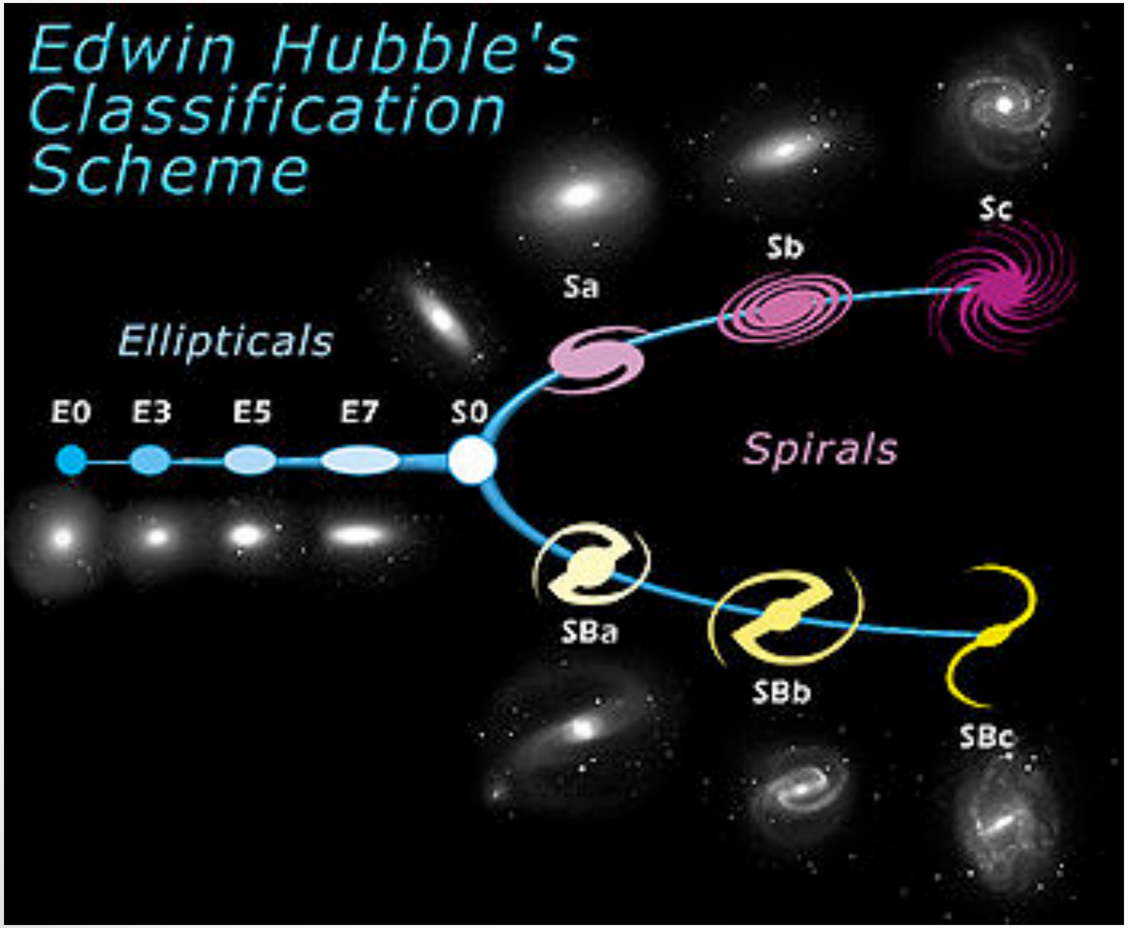
Another illustrative way of talking about the distant objects goes like this: GN-z11 is observed as it existed 13.4 billion years ago, only 400 million years after the Big Bang. As a result, GN-z11's distance is sometimes inappropriately reported as 13.4 billion light-years. But if this number is used, it should be called its *light-travel distance* measurement.

The most distant signal that we can observe, the Cosmic Microwave Background (CMB; slides to come towards the end of this lecture) has a redshift of z = 1089, corresponding to an age of approximately 379 000 years after the Big Bang and a comoving distance of more than 46 billion light years.

High-redshift events predicted by physics but not presently observable are the cosmic neutrino background from about two seconds after the Big Bang (and a redshift in excess of z > 10^10) and the cosmic gravitational wave background emitted directly from inflation at a redshift in excess of z > 10^25.

Hubble Sequence

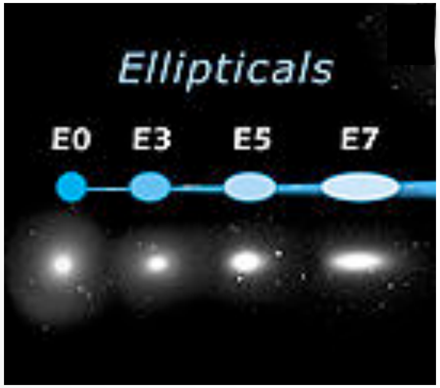
The "tuning fork diagram" presented by Hubble and still widely used



S0: lenticular galaxies

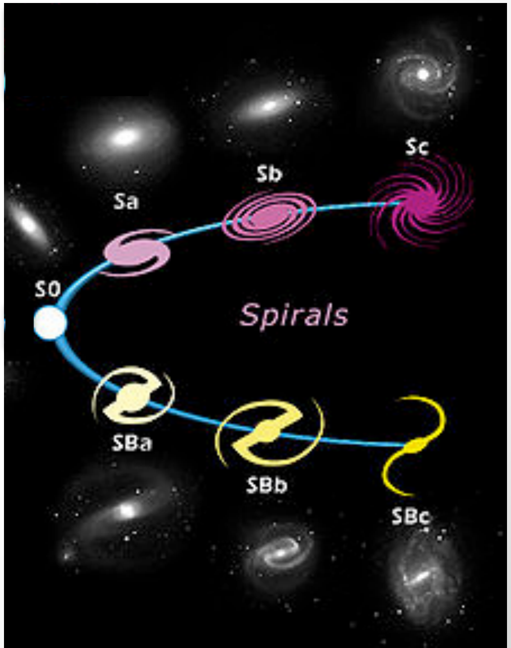
Elliptical galaxies

- Smooth, featureless, ellipse-like appearance.
- E*n*, where *n* denotes the degree of (10 ^{x}) ellipticity in the sky
  the ratio of the major (a) to the minor (b) axes, 10 x (1 – b/a)
  - Note: the true ellipticity may differ from the observational projection!



Spiral galaxies

- A flatttened disk with stars forming a spiral structure.
- A central concentration of stars known as the “bulge”.
- Ca. half also have a bar-like structure from the bulge to the beginning of the spiral arms.
- Sa/SBa to Sd/SBd (orig. Sc/SBc): tightly wound with a bright bulge to loosely wound with brighter arms.



Notes page: Spiral galaxies (previous slide)

Images on the right:

Top: The Pinwheel Galaxy (Messier 101/NGC 5457): a spiral galaxy classified as type Scd on the Hubble sequence.

Second from top: The barred spiral galaxy NGC 1300: a type SBbc

A spiral galaxy is observed as a flattened disk with stars forming a (usually two-armed) spiral structure, and a central concentration of stars known as the bulge. Roughly half (or 2/3) of all spirals are also observed to have a bar-like structure, extending from the central bulge, at the ends of which the spiral arms begin.

The proportion of barred spirals relative to their barless cousins has changed over the history of the Universe, with only about 10% containing bars about 8 billion years ago.

Our own Milky Way has in the 1990s and after that been suggested to be a barred spiral. The morphology is difficult to determine because we cannot observe the Milky Way ”from the outside”, and the bar itself is difficult to observe from the Earth's current position within the galactic disc. It has been suggested to be one of the following classes: Sb, Sbc, SBb, SBc, or SBbc.

The mass distribution within the Milky Way closely resembles the type Sbc in the Hubble classification, which represents spiral galaxies with relatively loosely wound arms. Astronomers first began to suspect that the Milky Way is a barred spiral galaxy, rather than an ordinary spiral galaxy, in the 1960s, and this has been later confirmed by the Spitzer Space Telescope observations in 2005 that showed the Milky Way's central bar to be larger than previously thought.

Lenticular galaxies, S0

- A bright central bulge, surrounded by a disk, but no visible spiral structure.
- Face-on they are difficult to distinguish from E0.

Unlike spiral galaxies, the disks of lenticular galaxies have no visible spiral structure and are not actively forming stars in any significant quantity. The bulge component is often the dominant source of light in a lenticular galaxy. Lenticular galaxies may be evolved spiral galaxies, whose gas has been stripped away leaving no fuel for continued star formation.

Irregular galaxies

- Neither disk-like nor ellipsoidal.
- Some borderline cases:
  eg., the Magellanic Clouds

PGC 1843, a dwarf irregular galaxy

NGC 1427A (Irr-1)

Notes page: Hubble sequence

Classification is observational/empirical, not direct reflection of physical properties.

However, it is still important in observational astronomy. Many properties correlate with the Hubble type, such as luminosities, star forming rates, masses …

Elliptical and lenticular galaxies are commonly referred to together as “early-type” galaxies, while spirals and irregular galaxies are referred to as “late types”. This nomenclature is the source of the common, but erroneous, belief that the Hubble sequence was intended to reflect a supposed evolutionary sequence, from elliptical galaxies through lenticulars to either barred or regular spirals. In fact, Hubble was clear from the beginning that such interpretation was **not** implied.

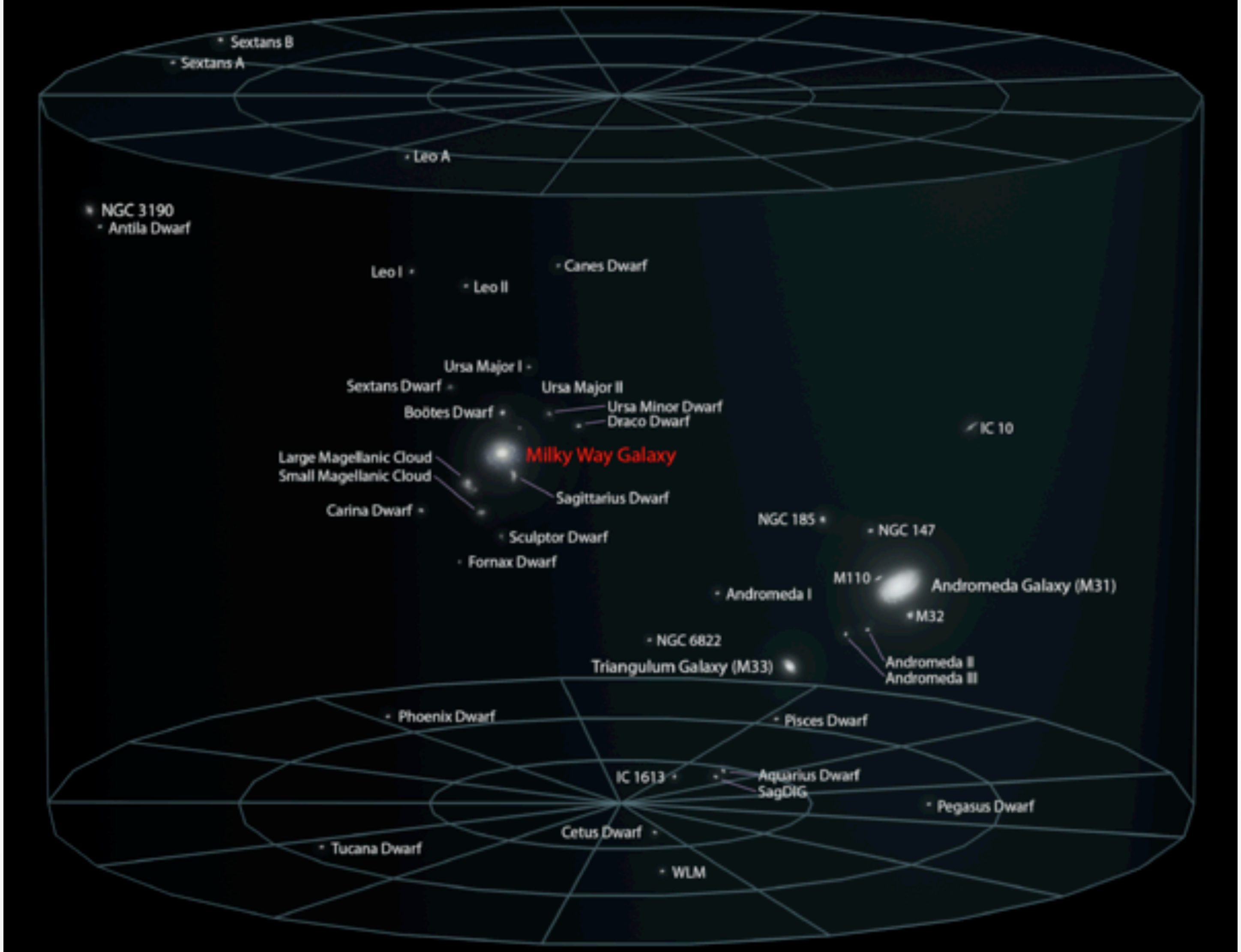
But this nomenclature is still being used -- “Early-type galaxies” include all classes of elliptical and S0 galaxies.
But I repeat: *this is not an evolutionary sequence*!

In fact, current evidence suggests the opposite: the early Universe appears to be dominated by spiral and irregular galaxies. In the currently favored picture of galaxy formation, present-day ellipticals formed as a result of mergers between these earlier building blocks. Lenticular galaxies may also be evolved spiral galaxies, whose gas has been stripped away leaving no fuel for continued star formation.

Galaxy formation

- Was already partly covered on the lecture "Galactic astronomy I" – spiral galaxies, Milky Way.
- Elliptical galaxies are mostly the product of smaller galaxies merging
    - Merging is a very common, violent process, producing a galaxy that can be very different from the original galaxies that collided.
    - Stars in ellipticals are on randomly oriented orbits (not rotating like in disk galaxies).
    - Supermassive black holes in the center, mass correlates with the mass of the galaxy.
    - Typically found in crowded regions (galaxy clusters).

Local Galactic Group



Notes page: Collision of the Milky Way

The Milky Way is in the Local Group galaxy cluster (3.1 Mpc, ~ 54 galaxies). Andromeda Galaxy: ca. 780 kpc. Large Magellanic Cloud: 50 kpc.

The Andromeda–Milky Way collision is a galactic collision predicted to occur in about 4 billion years between the two largest galaxies in the Local Group, the Milky Way and the Andromeda Galaxy.

It is important to understand that chances of two stars colliding are neglible because of the huge distances between them compared to their sizes, but collisions of galaxies are common. Andromeda, for example, is believed to have collided with at least one other galaxy in the past, and several dwarf galaxies are currently colliding with the Milky Way and being merged into it.

According to some simulations, this object after Milky Way – Andromeda –collision will look like a giant elliptical galaxy, but with a center showing less stellar density than current elliptical galaxies. It is however possible the resulting object will be a large disk galaxy, depending on the amount of remaining gas in the Milky Way and Andromeda.

Studies also suggest that M33, the Triangulum Galaxy — the third largest and brightest galaxy of the Local Group — will participate in this event too. Its most likely fate is to end up orbiting the merger remnant of the Milky Way and Andromeda galaxies to finally merge with it in an even farther future, but a collision with the Milky Way before it collides with the Andromeda Galaxy or being ejected from the Local Group cannot be ruled out.

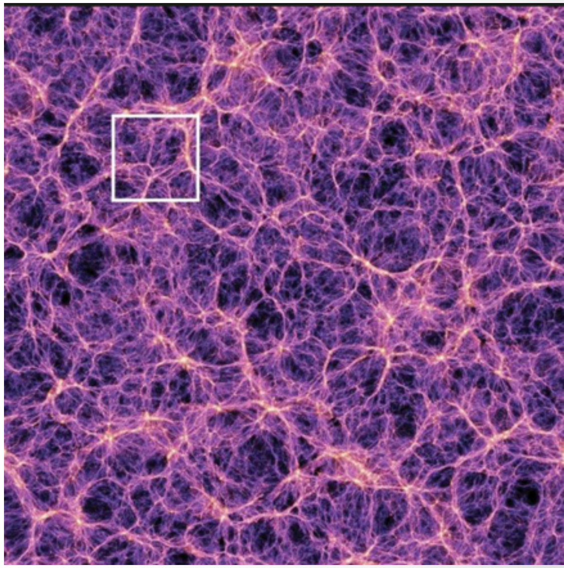
Just recently it has been found that the mass of Andormeda Galaxy has probably been overestimated earlier, to be about three times the mass of the Milky Way. Now it is proposed that the masses of the two galaxies are almost identical, which requires refinements to the models and simulations. Also the timeline of the predicted collision may need to be revised.

Superclusters

- Galaxies are not uniformly distributed, but form clusters and superclusters.
    - Poor clusters: maybe just a few dozen galaxies.
    - Rich clusters: may contain hundreds to thousand galaxies.
    - Typically superclusters contain dozens of individual clusters.
- Clusters are bound together due to gravity, superclusters are not, they shift away from each other.
- The Milky Way is in the Local Group galaxy cluster (3.1 Mpc, ~ 54 galaxies), which is in the Laniakea Supercluster (160 Mpc, 10^{17} M_{Sun}, 100 000 M_{MW}).
    - Until 2014 the Milky Way was considered to be in the Virgo Supercluster, but now the former Virgo Supercluster is confirmed to be only a lobe of the Laniakea supercluster.
    - Laniaeka Supercluster is also called Local Supercluster. Easier to remeber ☺
    - Nice-to-know: Laniakea is a Hawaiian word which means ‘immeasurable heaven”.
- Ca. 10 million superclusters in the observable universe.

Filaments and voids

- Superclusters seem to lie along filaments, between them are huge voids with very few galaxies.
- Some dim galaxies or hydrogen clouds can be found in some voids, but most galaxies are found in sheets between the voids.
- “The Cosmic Web”.
- The pattern of sheets and voids contains information about how galaxy clusters formed in the early universe, and about initial conditions.
- At some point challenges the cosmological principle?



Notes page: The cosmological principle

The cosmological principle = distribution of matter in the universe should be homogeneous and isotropic when viewed on a large enough scale. ”Different places of the universe should appear similar to one another.”

This is because forces are expected to act uniformly throughout the universe, and should, therefore, produce no observable irregularities in the large scale structuring over the course of evolution of the matter that was initially produced after the Big Bang.

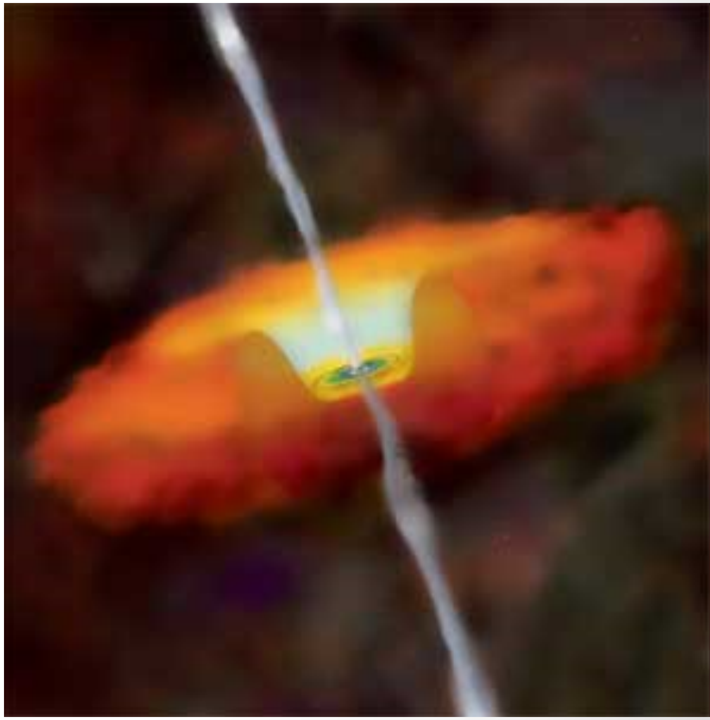
The key point here, however, is the ”large scale”. It is obvious that there are lots of inhomogenities in smaller scales, as we know (think about stars, galaxies, clusters, etc. and the space between them).

Cosmologists still argue what would be the maximum size of a structure that would still be consistent with the cosmological principle. It has been suggested that this should be about 370 Mpc. But this is by no means an exact value.

The Sloan Great Wall, discovered in 2003, has a length of 423 Mpc, which is only just consistent with the cosmological principle.

The ”Huge Large Quasar Group” (that’s what it is called, indeed!), discovered in 2012, is three times longer than, and twice as wide as is predicted possible according to these current models. It has been widely discussed whether this now challenges our understanding of the universe on large scales, or whether the algorithm used for identifying the structures is biased to ”identify” structures that do not actually belong together. Thus, it is possible that this group is not a real structure at all. The investigations are ongoing.

Quasars and other Active Galactic Nuclei



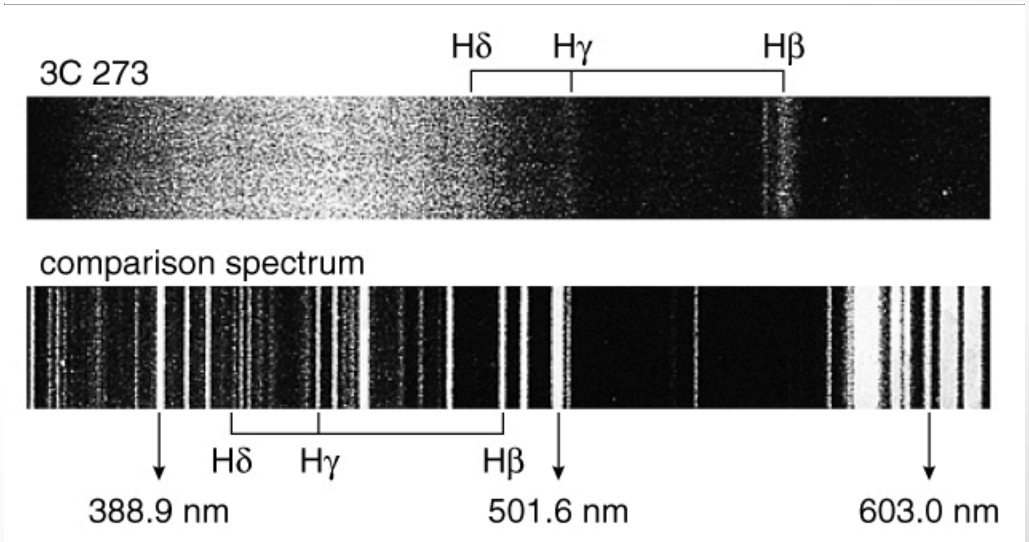
- Quasar
  (In Finnish: “Kvasaari”)

  name comes from
  “quasi-stellar radio source”
  (“almost like a star but not quite”)

  qsr → quasar
- Also: “quasi-stellar object”, qso

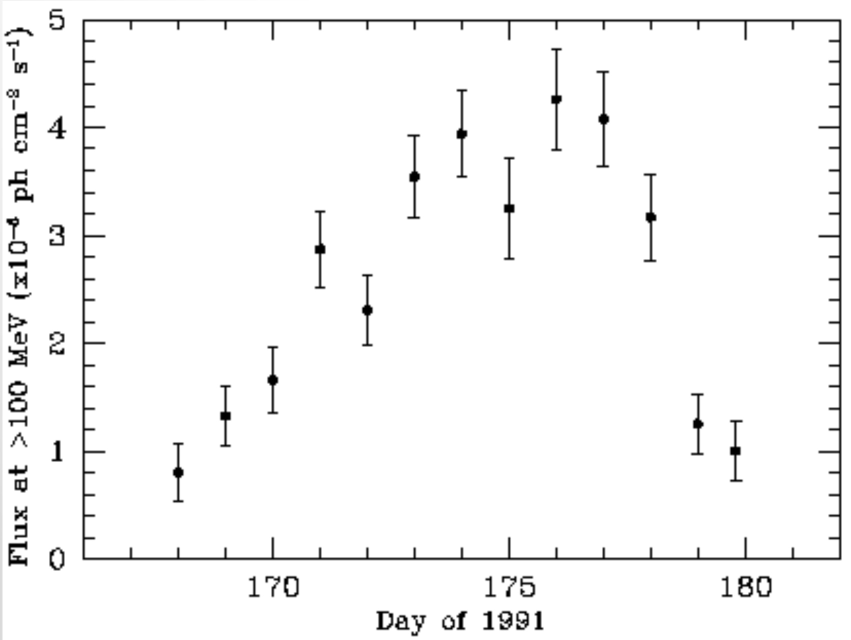
Approximately half a century ago…

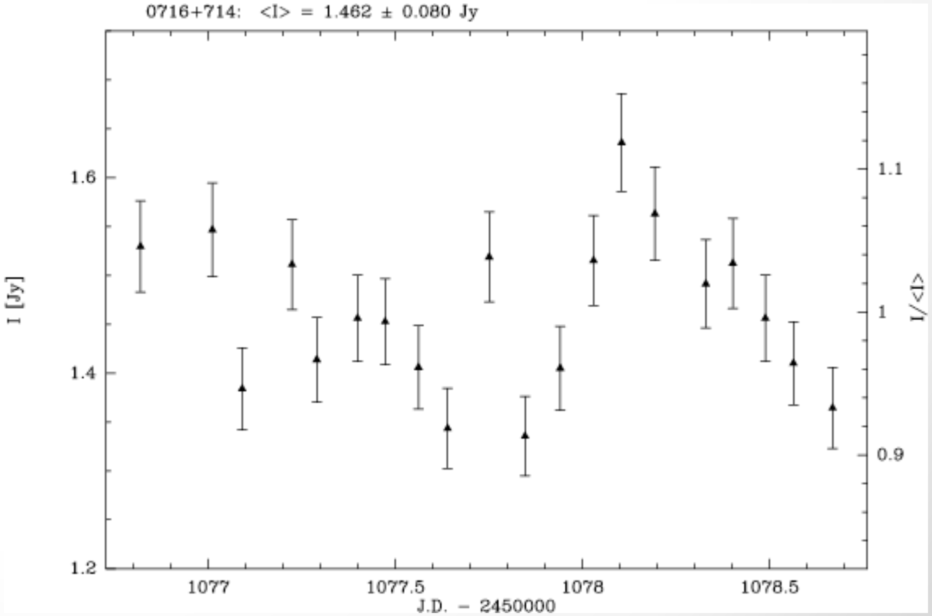
- "Why do some stars emit in radio wavebands?"
  - In 1963 Maarten Schmidt used the optical telescope on Mt. Palomar. Object named 3C273 (=object nr. 273 in the third Cambridge radio catalogue) was star-like in optical observations and initially assumed to be located in our own Galaxy.
  - Schmidt realized that its optical spectrum, which revealed strange-looking emission lines, actually contained spectral lines of hydrogen which were redshifted at the rate of 15.8%.
    This means that it had to be far away and very bright.

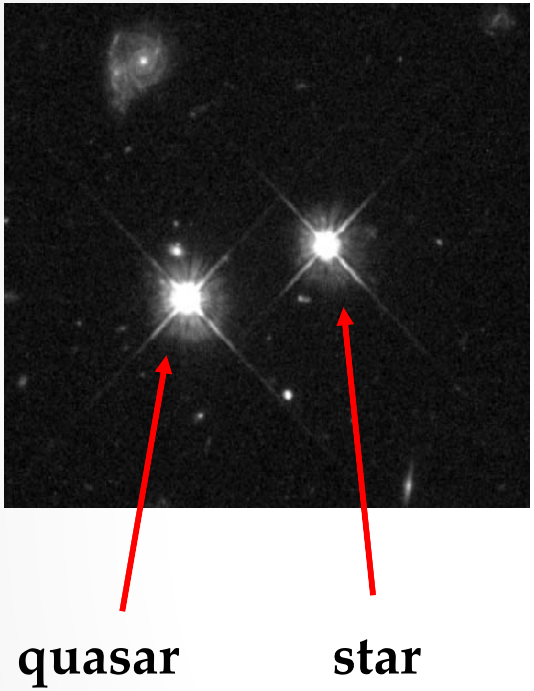


Quasar variability

- Emission from quasars varies (across the electromagnetic spectrum),
  and the variations can be very rapid.
- This means that their radiation must come from a very small volume within their nucleus.







Quasars are a subclass of
Active Galactic Nuclei (AGN)

When observed from a large distance, they appear star-like. (That is why they were initially assumed to be stars.)

There are numerous subclasses of AGNs.
Quasars are the most extreme of them,
with very bright nuclei and very rapid variability.

Even for an astronomer, these two objects in the Hubble image appear similar, so it is no wonder that quasars were thought to be "star-like" at first.
In reality, the star in the right is in our own Milky Way, and the quasar in the left is 9 billion light years away from us!

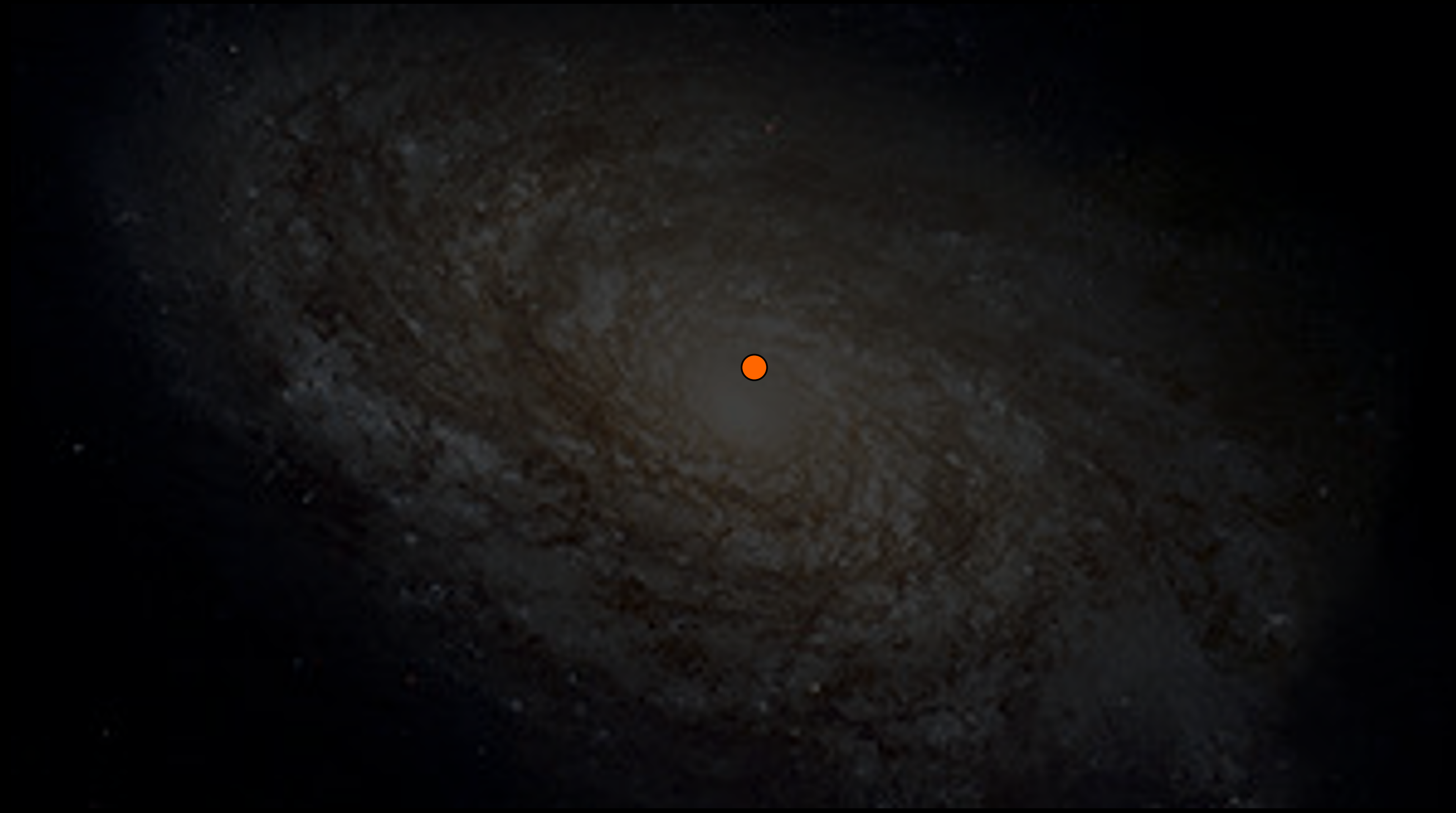
“Normal” galaxies

- The total energy that normal galaxies (= not active galaxies) radiate approximately equals the sum of the radiation from all the stars in that galaxy.
- Only very little radio emission.

Galaxies vs. active galaxies

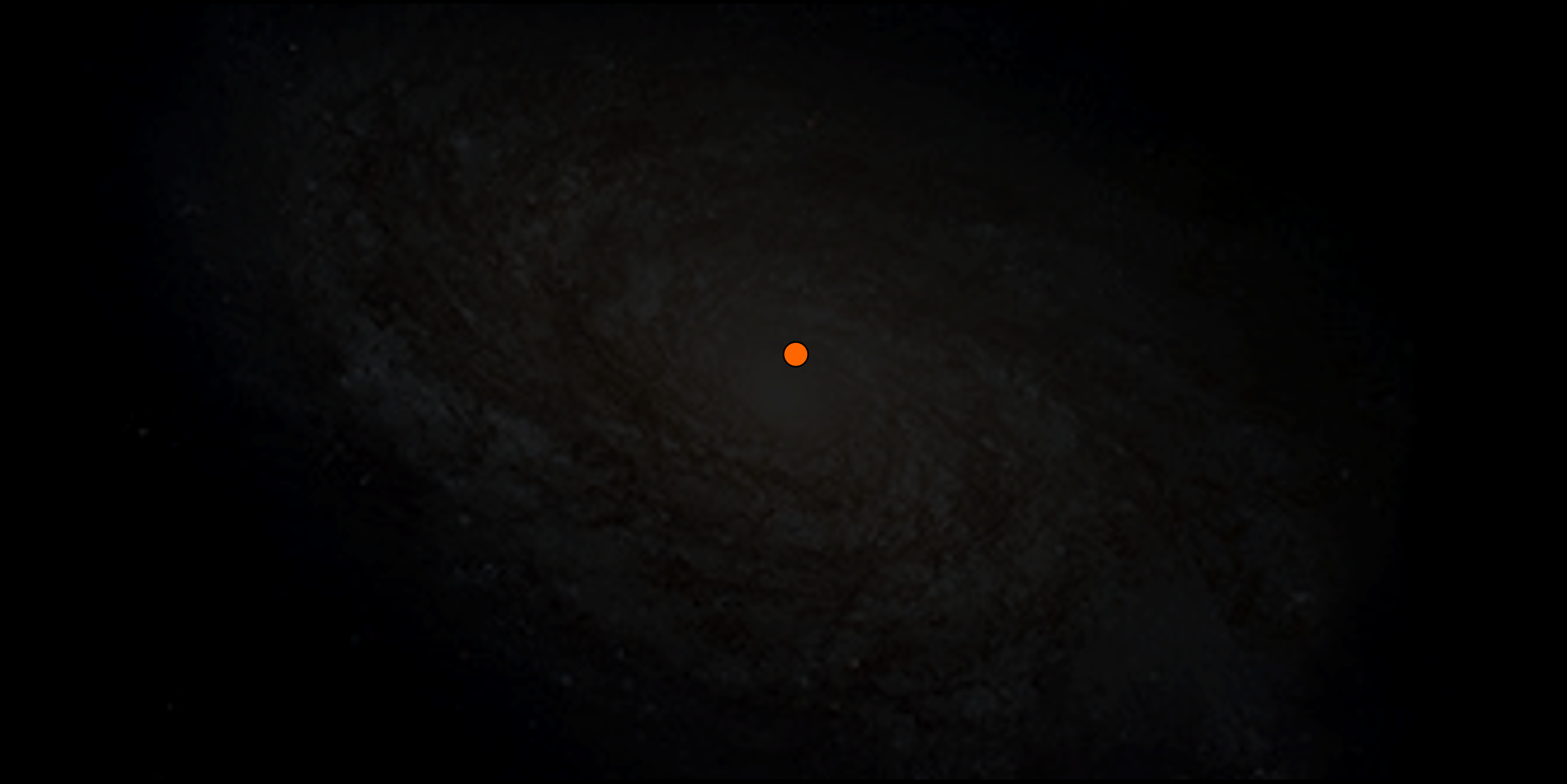
Normally the brightness of a galaxy comes from the starlight of the stars in the galaxy

Active galaxies have a compact nucleus that is very bright compared to the starlight of that galaxy. If this galaxy is observed from further away, the starlight gets fairly dim to the observer, but the nucleus can still be seen.

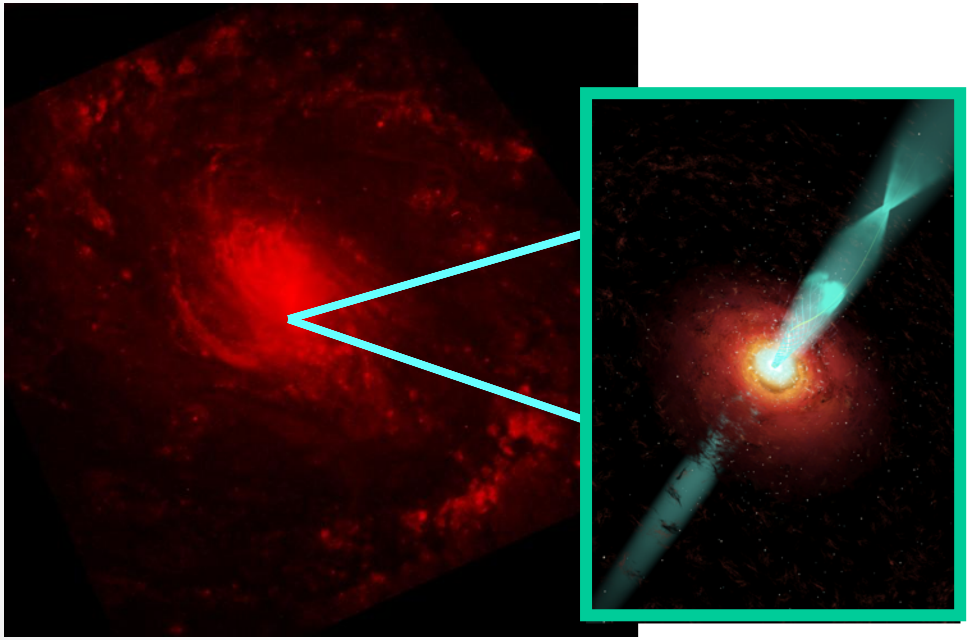


When observations are made from further away, the starlight is not seen at all, but the nucleus can still be observed (sometimes in the optical, sometimes in radio, sometimes across the electromagnetic spectrum).

This is why they are called active galaxies. They still have all the stars, too, just like all galaxies do, but we can’t distiguish them from such distance.



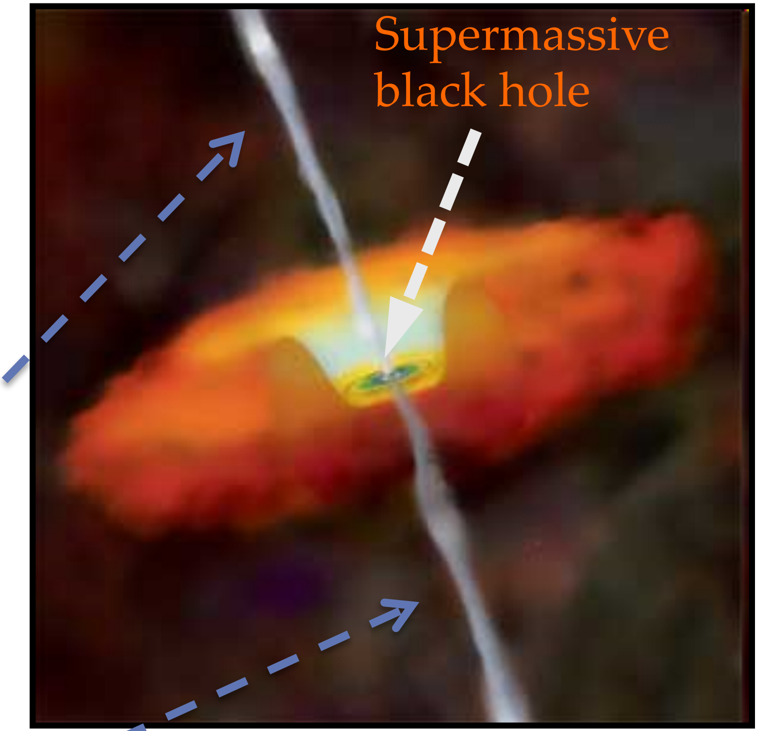
- Quasars are distant, active galaxies.
- Their excess emission is concentrated in the nucleus.
- In their nucleus they harbour a supermassive black hole
  = mass of the order 10^6-10^9 Solar masses,
  in a volume ca. that of our solar system.



What is shown in the right can not be directly observed or "seen",
because it is in such a small volume in the nucleus.
This is an "artistic concept" based on the models that we have produced from decades of multifrequency observations and careful physical models and simulations.

The inferred structure of a quasar

(= not directy observable due to the small volume!)



Plasma jets where particles are accelerated to near light speed. Plasma "shocks" propagate down the jets and produce the observable (radio) variability.

Observational results depend on the observer's viewing angle!

Note (yet) observable like this:

Credit: NRAO/AUI/NSF

Quasar observations in reality

Due to their distance and compactness, individual instruments observe quasars as point-like sources with no information about their actual structure or other details.

We can only observe what the brightness is at a given frequency band (sometimes not detected at all!), and how it varies over time.

So, one-epoch observations would be something like this:

● Radio...

● Infrared...

● Optical...

● UV...

● X-ray...

● Gamma-ray...

Variability studies allow us to infer, calculate and model the emission location and mechanisms at various wavebands.

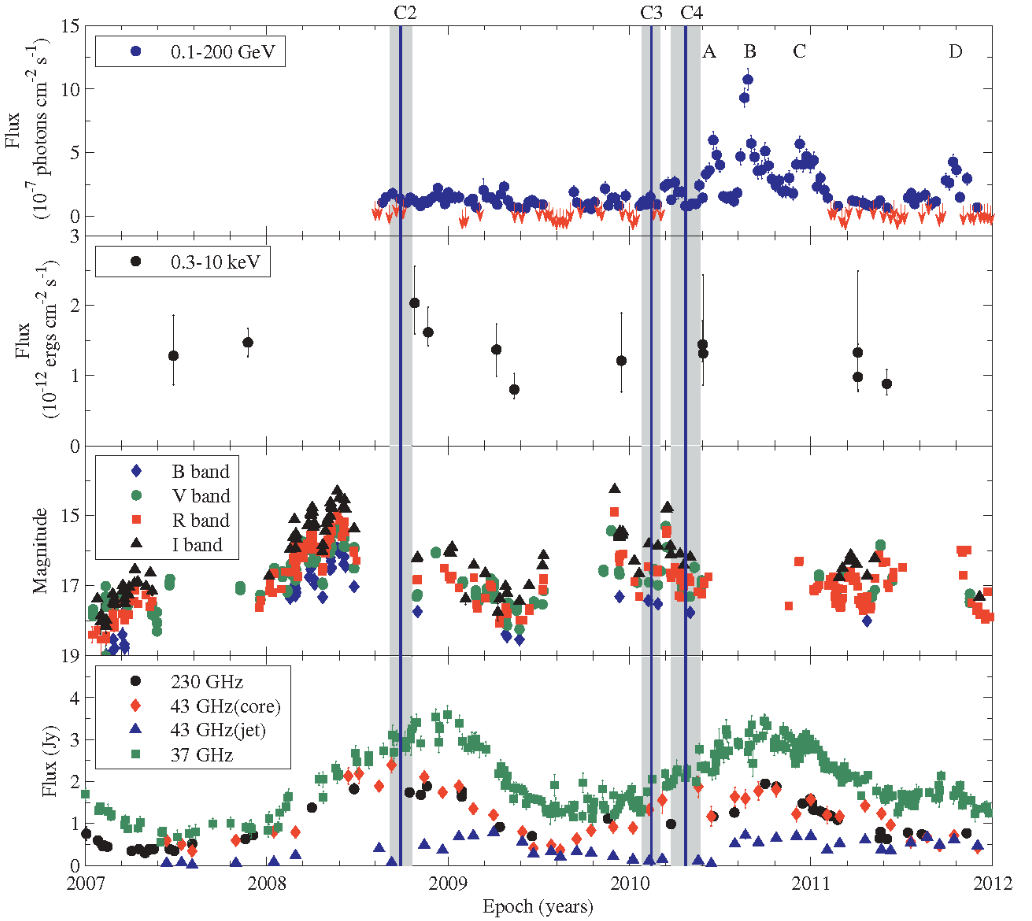
But it is not easy!

We need huge amounts of data,

preferably simultaneously taken with various instruments,

for long periods of time, for a large set of sources...

Even then, there are always bound to be gaps in the data, or otherwise incomplete data sets.



Ramakrishnan et al. 2014

Terminology

Note: these definitions are not unambiguous!

- Active galaxies, Active Galactic Nuclei (AGN)
  - Galaxies with excess emission from the nucleus
- Quasar
  - Usually also rapid variability
- Blazar ("blazing quasar")
  - Bright and variable, often with high (optical) polarization
  - With prominent plasma jets pointed at our direction
  - Nowadays often refers to gamma-ray bright quasars

Many blazar researchers (eg. the Metsähovi team) often talk about "quasars" or even "AGN" when they refer to bright, variable, radio-detected sources with radio jets. Many others in the extragalactic community talk about "AGN" when they refer to galaxies with higher luminosities than regular galaxies, but which often are radio-quiet.
→ If uncertain, ask!

Quasar structure and scales

- Supermassive black hole (SMBH).
- Accretion disk.
- Broad-line region (BLR).
- Molecular torus.
- Narrow-line region.
- Host galaxy.
- Extended radio lobes, hotspots, ...

~ AU

1 mpc

1 pc

100 pc

1 Mpc

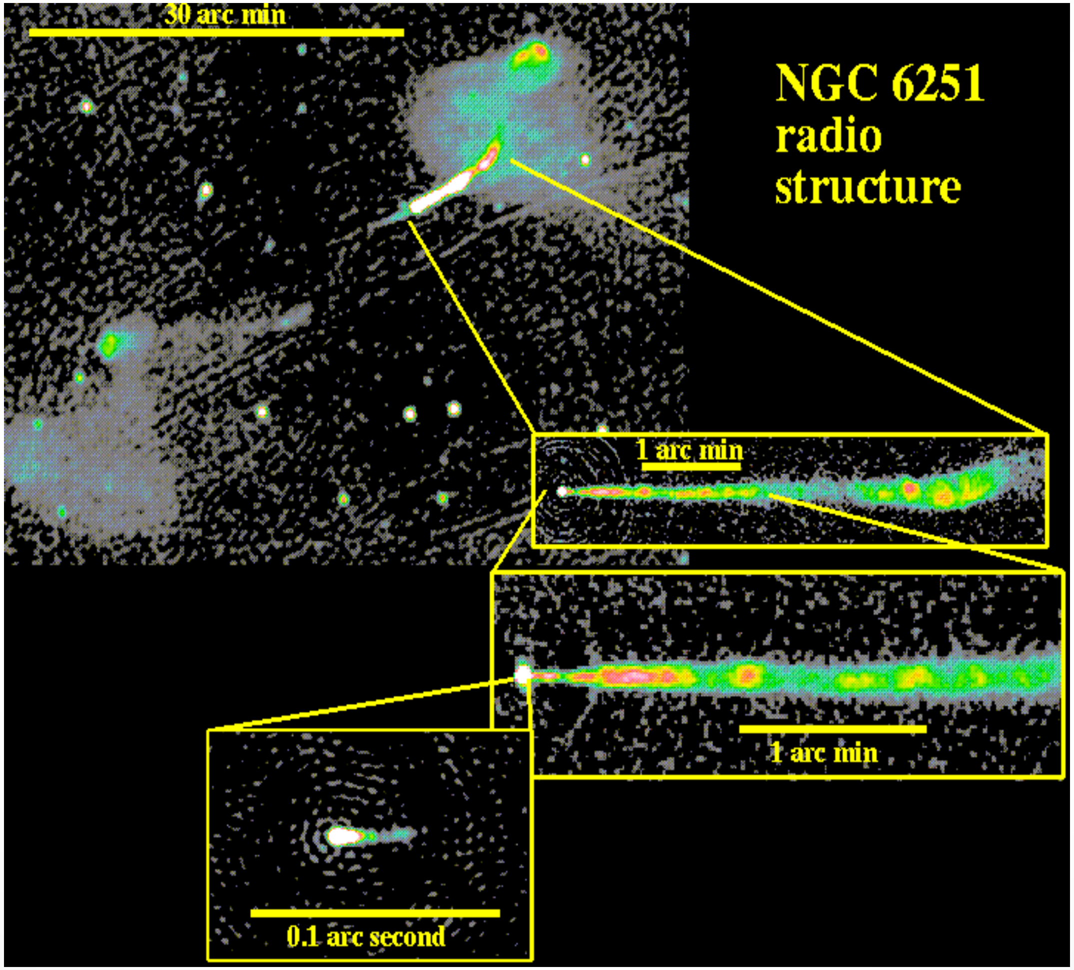
Why a supermassive black hole (SMBH)?

- Rapid variability: timescales of hours-days correspond to the size of the emitting region.
- Emission line widths: fast-moving gas closer to the nucleus is a sign of a massive object in the center.
- Radio observations: small + large scale jets maintain the same direction (for millions of years!); relativistic bulk motion.
- Power+ efficiency: at least in theory, SMBH is the most efficient way to produce energy.
- Stellar dynamics: velocity dispersion of stars towards the center of the galaxy is a sign of a massive object in the center.
- Evolution of galactic cores: dense cluster is unstable. Also in simulations this ends up as an SMBH.

Jets

- A highly collimated outflow of relativistic plasma.
- Jet formation+propagation details not well known.
- Lobes: the termination of the jet,
  occur on a dumbbell structure.
- “Jet memory”: the pc-scale jets in the core regions are collimated with the extended radio structure at Mpc scales.
- Pay attention to the scales!
  VLBI-jet at 0.1 pc, lobes at 1 Mpc!
  - Very Long Baseline Ineterferometry,
    method to combine many radio telescopes to make a huge “virtual telescope” with superior angular resolution; the only way to produce images of quasars in some detail.

… Jets


30 arc min
NGC 6251
radio
structure
1 arc min
1 arc min
0.1 arc second

Shocks in jets: radio variability!

Plasma shocks propagate down the jets and produce synchrotron emission that we observe as radio variability. See the notes page! (Next slide)

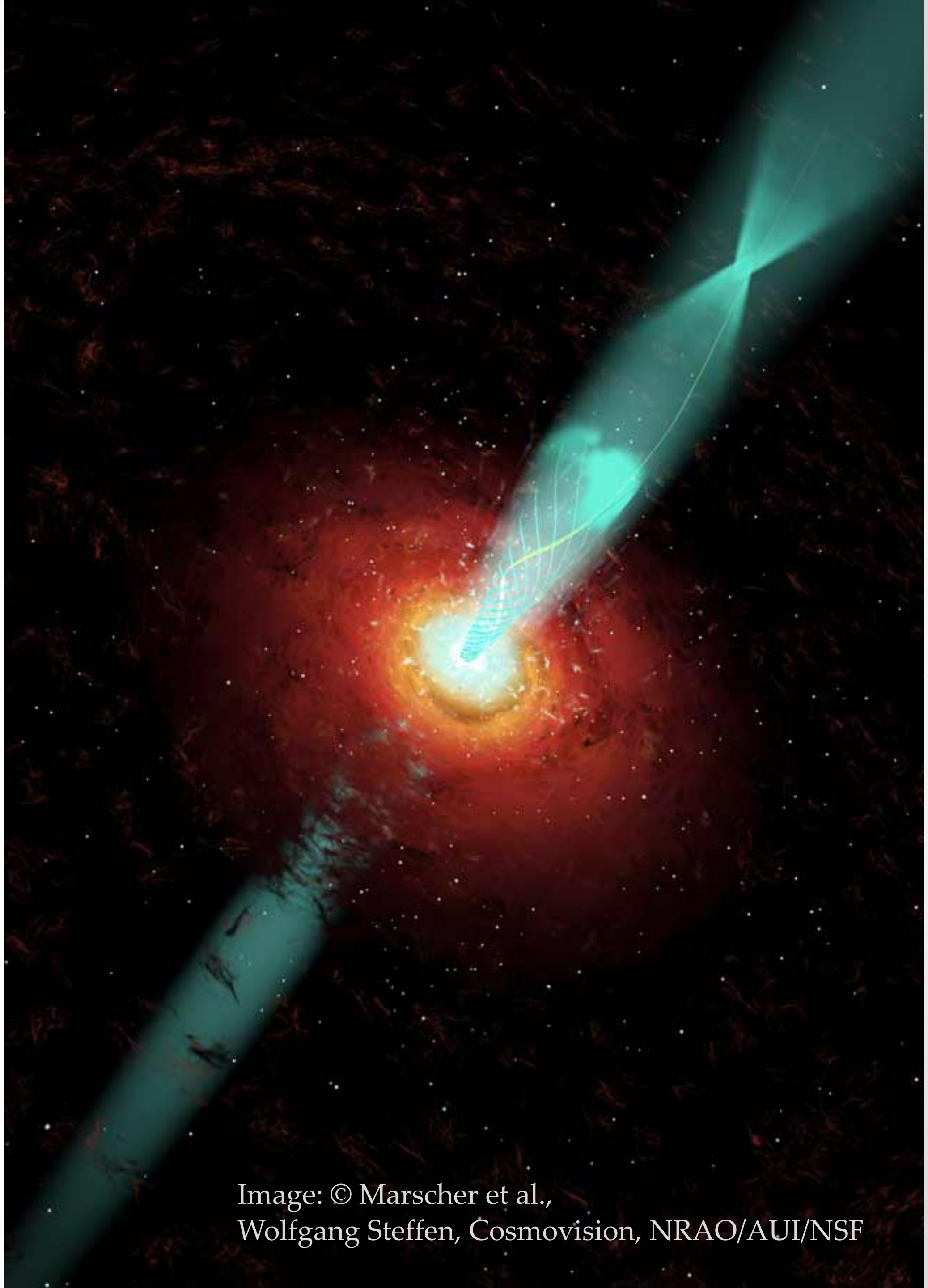


Image: © Marscher et al.,
Wolfgang Steffen, Cosmovision, NRAO/AUI/NSF

Notes page: Quasar jets

In the quasar case, the relativistic jet points almost toward us and everything that we see is relativistically ”boosted” to be more extreme. In some other clases of Active Galactic Nuclei we probably observe the jets from the side view, and the phenomena that are observed are not as extreme. This is called the ”orientation-dependent” scenario of AGN unification.

It is not yet clear how jets form and propagate, by what physical process is matter accelerated to Lorentz factors of >= 5, etc.

According to the currently favoured picture, relativistic jets in AGN are launched in the vicinity of the supermassive black hole by magnetic fields extracting energy from the spinning black hole via the Blandford-Znajek mechanism (Blandford & Znajek 1977), while rotating inner regions of the accretion disk form an outflowing wind that helps to collimate the jet (Blandford & Payne, 1982). In this picture, the jet is launched as a magnetically dominated outflow with strong magnetic fields accelerating the flow to relativistic velocities.

One of the fundamental unknowns is the composition of the jet plasma, which determines whether the jets are predominantly magnetically or kinetically dominated. It is not known whether the jets consist of pair plasma with electrons and positrons, or if heavy particles (protons) are also involved..

Jet formation and motion is probably affected by local gas environment, and the jet motion is probably also affected by competition between gravitational force and radiation pressure, which moderates the accretion rate.

The tiny parsec-scale jets in the core regions point to the same direction as the extended radio structure which may stretch to Mpc scales (i.e,, even out of the host galaxy). Thus the central engine must continue to eject material in nearly the same direction for several million years!

The variability observed in radio to optical bands has been successfully modeled by plasma shocks moving down the jets and producing synchrotron emission. In the flux curves we can see the growing and decaying shocks, and often also several superposed components of shocks in various stages of their propagation and development.

The highest-frequency synchrotron emission requires the highest energy electrons, which are found only very close to the location where they were energized, since they lose energy rapidly by emitting radiation.

AGN: Questions

- Cause for the activity?
- Relationship to normal galaxies?
- Why are there different kinds of AGNs?
- The primary energy production mechanism?
- The reprosessing mechanism(s)?
- The structure of the nuclear region?
- Collimated energy outflow?
- Variability mechanisms?

AGN Observations

- Point source! = we can not observe structure details.
- Flux density variability
  - Multifrequency light curves.
  - Amplitudes. Time scales. Different types of flares.
  - Correlations between frequency domains / frequencies.
  - Time delays between frequency domains / frequencies.
  - Multifrequency observations also:
    spectral shape, spectral energy distribution.
- Very Long Baseline Interferometry (VLBI) images
  -- not of the central region!
- Polarization observations.
- CCD images of the host galaxy / surrounding regions.
- Spectral line observations.

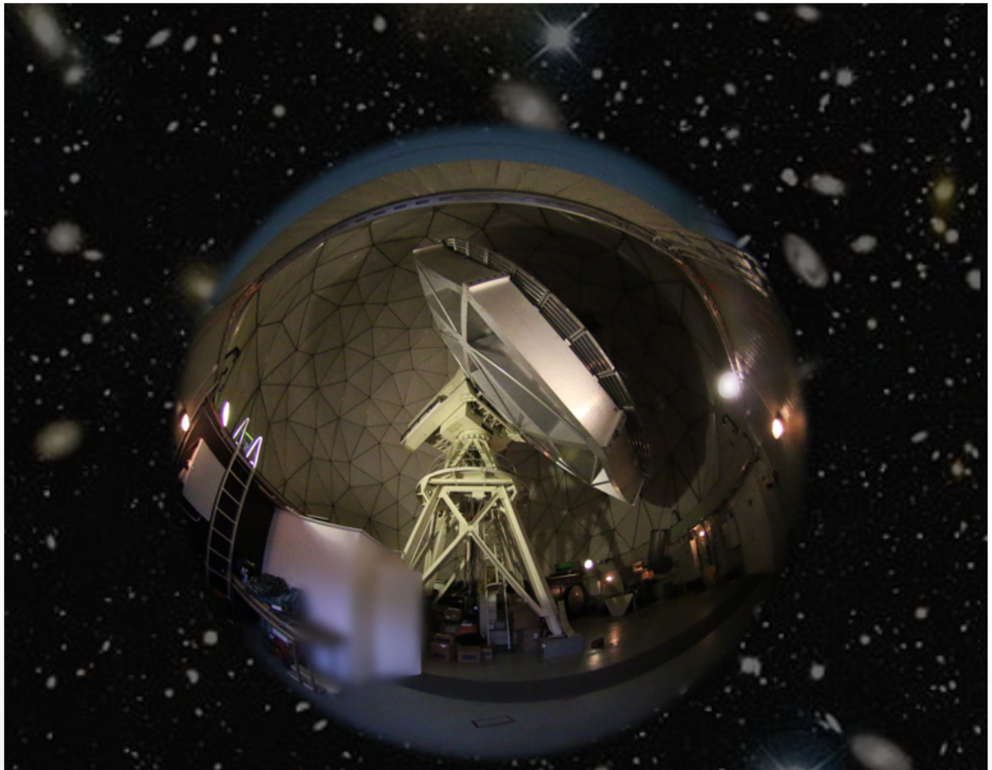
Emission mechanisms

- At least:
  - Thermal radiation.
  - Synchrotron radiation.
  - Inverse Compton-scattered radiation.

- Radio emission in AGNs is always of synchrotron origin!
  - Studying correlations of radio and other frequency bands helps us constrain the emission models (location, mechanism) also in the other frequency domains.

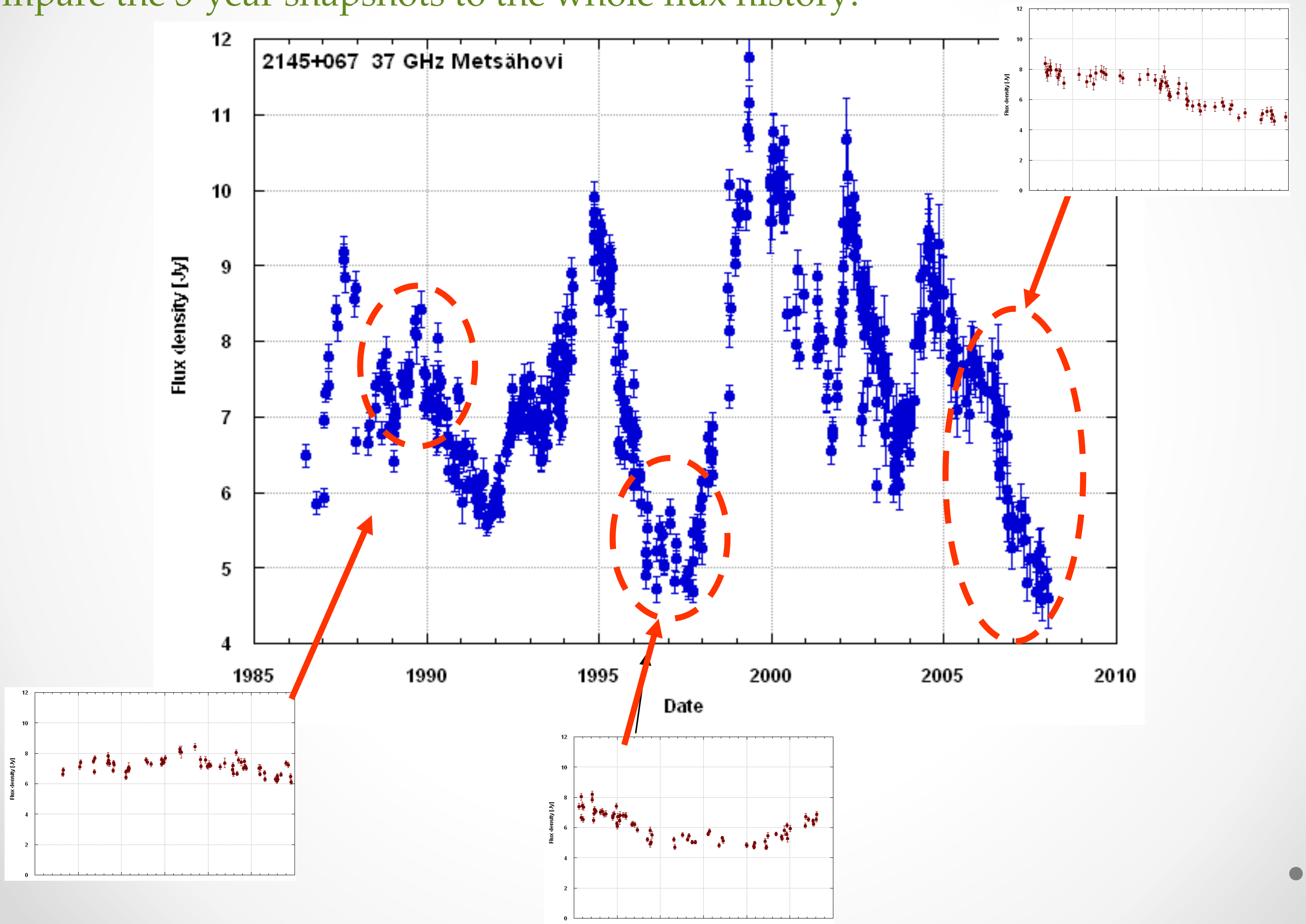
Quasar research in Metsähovi

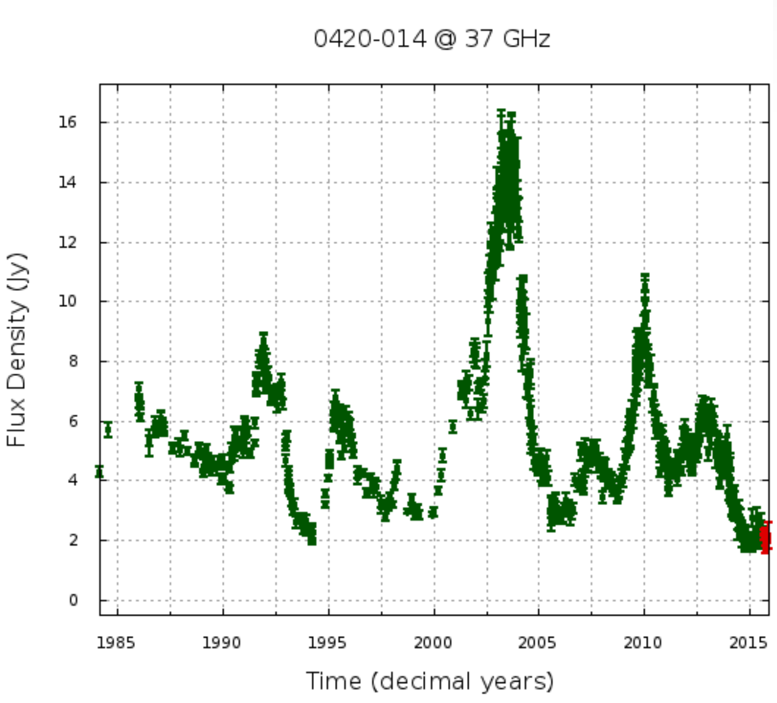
- Radio observations practically 24/7.
- Observations also with other instruments, satellites, etc. also through active international collaboration.
- Theory and modelling.

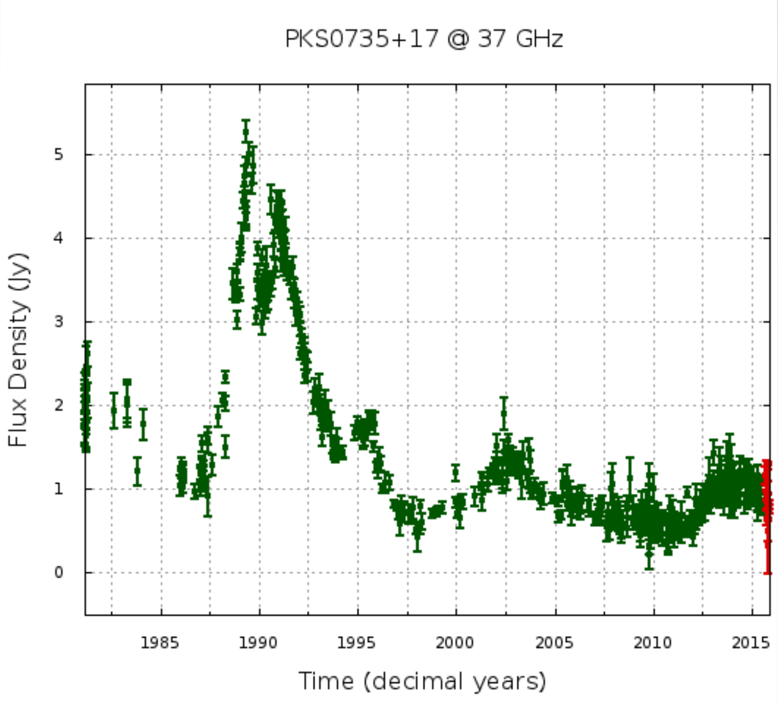


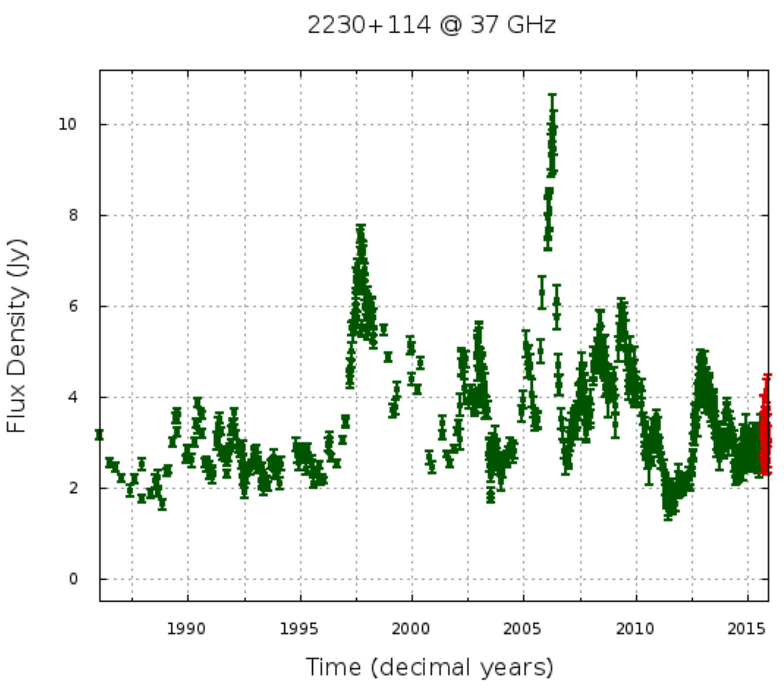
Radio flux density curves: time variability

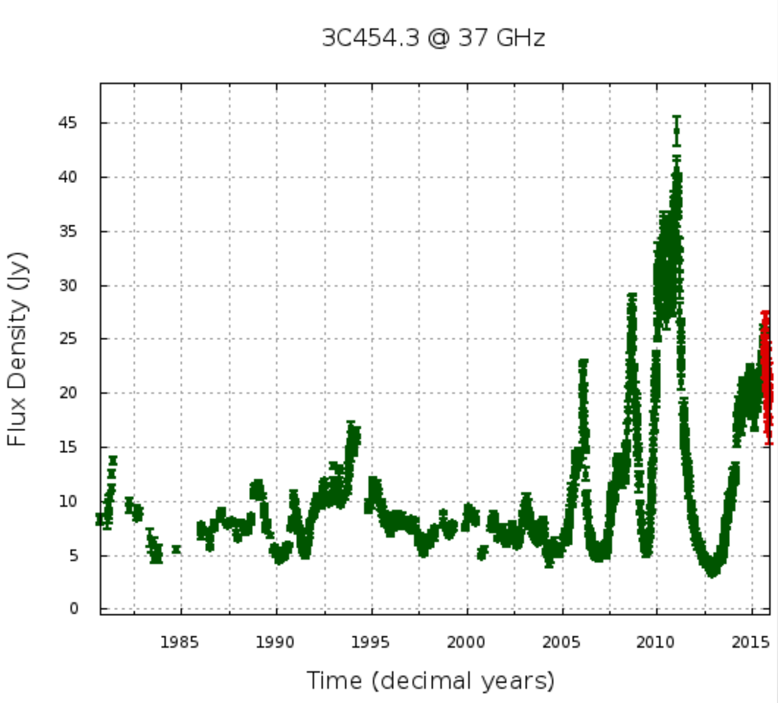
An example to show why dense, long-term monitoring is essential.
Compare the 3-year snapshots to the whole flux history!




0420-014 @ 37 GHz


PKS0735+17 @ 37 GHz


2230+114 @ 37 GHz


3C454.3 @ 37 GHz

Radio observations in Metsähovi

- Total flux density variability of quasars: information about their structure, emission mechanisms and radio behaviour of the various quasar subpopulations.
- Practically 24/7/365
  → uninterrupted flux curves for a large sample of quasars.
- Radio vs. other wavebands
  → multifrequency studies.
- With Very Long Baseline Interferometry (VLBI) also some structural details can be studied.

Advertisement ☺

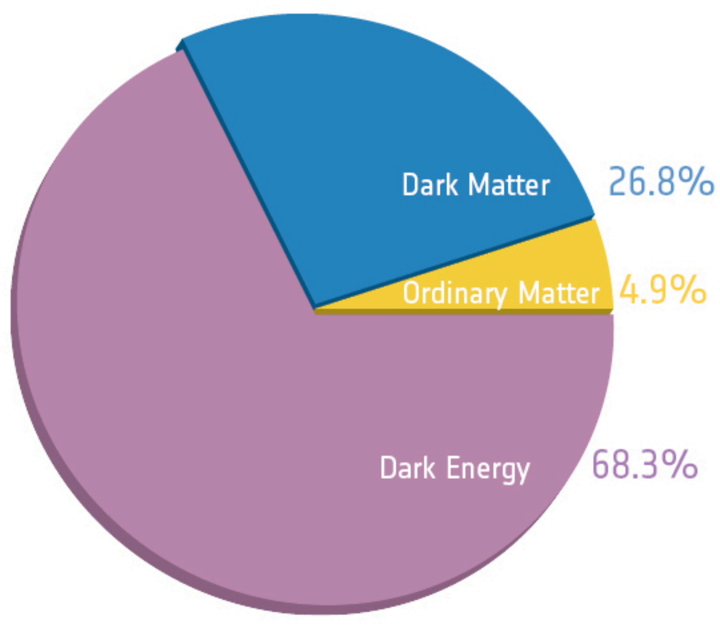
ELEC-E4530 - Radio Astronomy

Cosmology

- The present universe is a result of evolution.
- Cosmology studies the origin, evolution and future of our universe.
- Observations:
  - Redshifts of distant galaxies.
  - Primordial abundances of light elements.
  - Cosmic microwawe background (CMB) – recent satellite missions!
- The universe is 13.8 billion years old and is composed of 4.9% atomic matter, 26.6% dark matter and 68.5% dark energy.

(Planck consortium 2014)

Composition of the universe



Ordinary matter:
atoms, ions, elementary particles and everything that they form.

Dark matter:
invisible to the entire electromagnetic spectrum, but it has gravitational effects on visible matter and radiation.
Possible explanations: compact massive objects, some "exotic" particles, etc. Also: neutrinos.

Dark energy:
explanation for why the expansion of the Universe is accelerating.

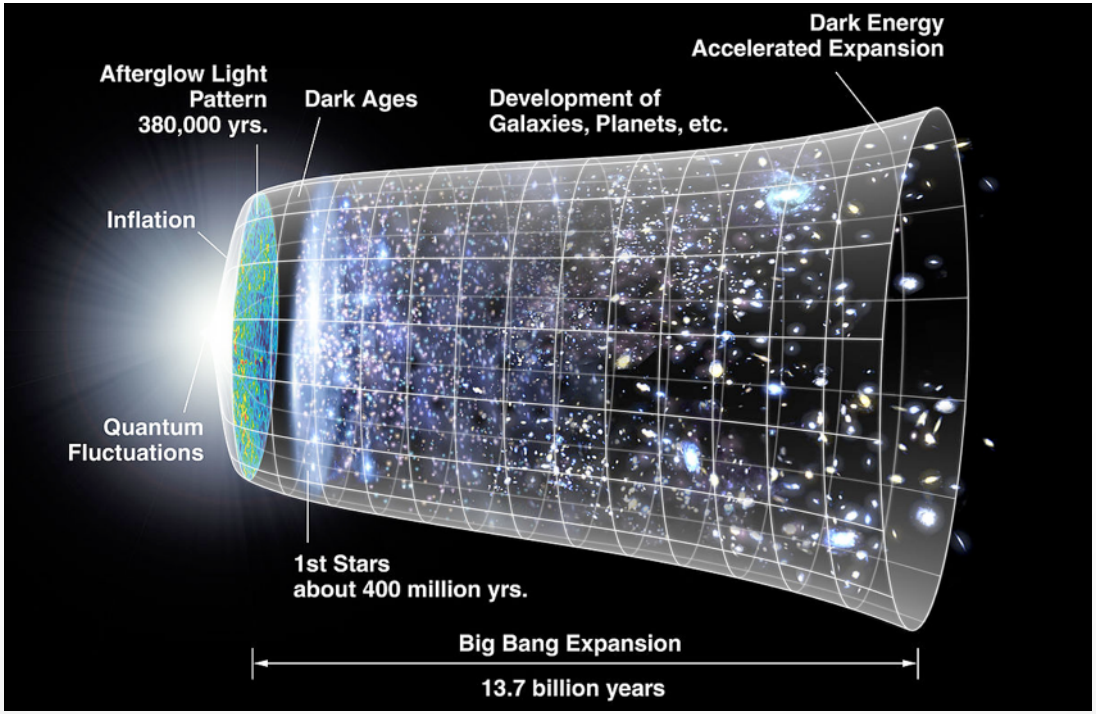
~~Hubble's law~~

Hubble–Lemaître law

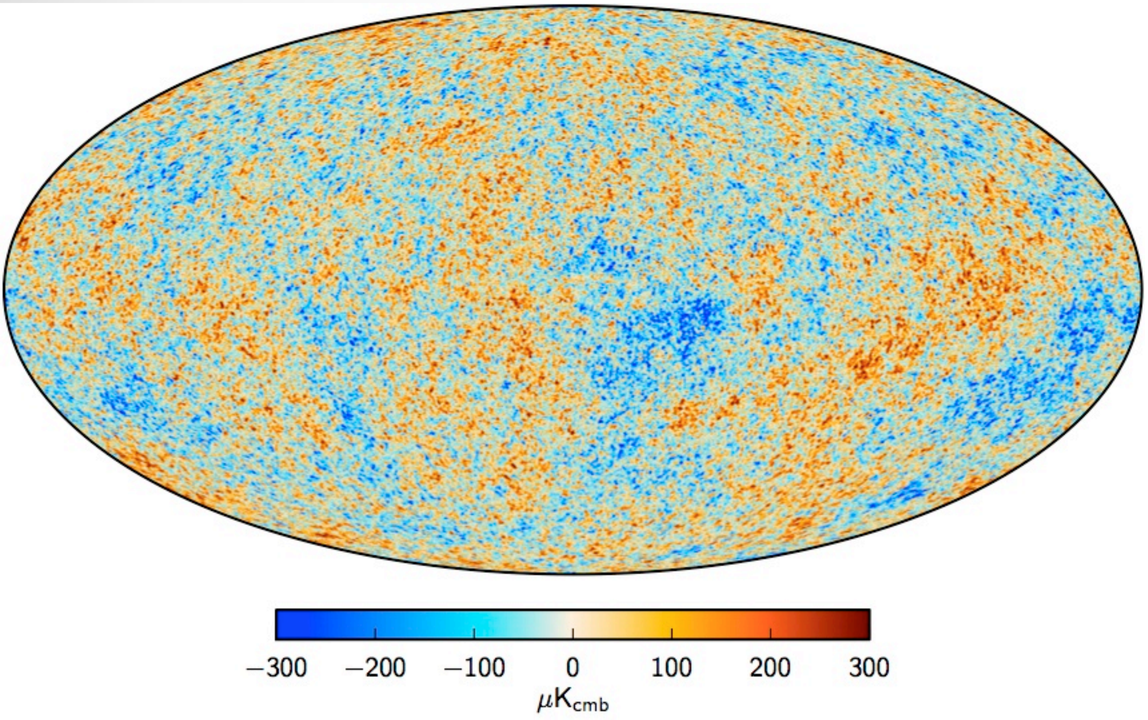
- The first observational basis for the expansion of the universe.
- $v = H_0 D$
  - v is the recessional velocity of the galaxy
  - D is the distance to the object
  - H_0 is Hubble's constant, 68 (km/s)/Mpc [Planck consortium 2014]
  - The SI unit of H_0 is s^{-1} but it is most frequently quoted in (km/s)/Mpc, thus giving the speed in km/s of a galaxy 1 megaparsec (3.09×10^{19} km) away.
- The reciprocal of H_0, H_0^{-1}, gives the age of the universe if the expansion had been linear.

Cosmic Microwave Background (CMB)

- A "snapshot" of the oldest light in our Universe, imprinted on the sky when the Universe was just 380,000 years old.



CMB



A CMB map like this is produced by a satellite that has observed in all directions in the sky, then the observations are combined, the foreground effect of the Milky Way is removed, and the initially spherical map is unfolded so that it can be represented as an image plotted on a plane.

The temperature fluctuations trace fluctuations in the density of matter in the early universe and thus reveal details about the origin of galaxies and large scale structure in the universe.
The tiny anisotropies are very important: if no anisotropies existed, matter would be quite evenly distributed and no structures could have formed!

Notes page:
The Cosmic Microwave Background (CMB)

CMB is the oldest electromagnetic radiation in the universe, dating to the ”epoch of recombination”. It is the famous 3 K radiation (more precisely, 2.73 K), the peak of which is in the millimetre-domain radio band (160 GHz). The recombination happened when the universe was ca. 380 000 years old, and the temperature then was ca. 3000 K.

It was accidentally discovered in 1964 by American radio astronomers Arno Penzias and Robert Wilson, ant they earned the 1978 Nobel Prize in Physics. The discovery might have gone unnoticed without the consultation of Robert Dicke, James Peebles, P. G. Roll, and D. T. Wilkinson, who interpreted this radiation as a signature of the Big Bang.

When the universe was young, before the formation of stars and planets, it was denser, much hotter, and filled with a uniform glow from hydrogen plasma. As the universe expanded, both the plasma and the radiation filling it grew cooler. When the universe cooled enough, protons and electrons combined to form neutral hydrogen atoms. Unlike the uncombined protons and electrons, they could not absorb the thermal radiation, and so the universe became transparent instead of being opaque. And soon after that, photons started to travel freely through space rather than constantly being scattered by electrons and protons in plasma, and they have been traveling ever since. Please note: this is called the ”epoch of recombination” for historical reasons, even though the word **RE**combination may be misleading, because this was the very first time that protons and electrons combined!

The CMB signal, especially the all-sky CMB anisotropy maps, is extremely useful to cosmologists and astronomers because it helps us learn how the early universe was formed. It is at an near-uniform temperature (almost perfect black body temperature of 2.73 K) with only small fluctuations visible with precise instruments, most recently the cosmology satellites COBE, WMAP and Planck. By studying these fluctuations, we can learn about the origin of galaxies and large-scale structures of galaxies and we can determine the basic parameters of the Big Bang theory, such as the age and geometry of the universe.

Test questions: can you answer these? If not, read again ☺

- What are the main types of galaxies and why do (we currently think) the various types exist?
- In the Galactic astronomy lectures you learned about microquasars, and now about quasars.
  1) What do these two types of objects have in common?
  2) What are the main differences?
- What kind of obervations are needed to model the structure and physics of quasars, and why?
- What are the main advantages of radio observations of quasars compared to e.g., optical observations?
- Cosmic Microwave Background: Try to explain it in your own words as you would explain it to another fellow student that has not yet taken this course.
  In particular, what is it, how can it be studied, why do we want to study it?