Extragalactic astronomy

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About the Exam!

- On April 12th at 9 -11.
- Duration 2 hours.
- Room TU3.
- Note: You are allowed to bring with you a collection of equations (with no additional text – this will be checked!)
- **Instructions in MyCourses under “Evaluation and grading”.**

Today's lecture (1.4.)

- 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

Practice session 5.4.

- Due to the exam on the following week,
  only the group exercises will be required from this week's lecture topics.
- Submission DL as usual on the following Friday,
  but if you are active during the session,
  you can probably submit early (and save time for studying for the exam ☺)

Extragalactic
= outside the Milky Way

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

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

The Hubble Deep Field

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.

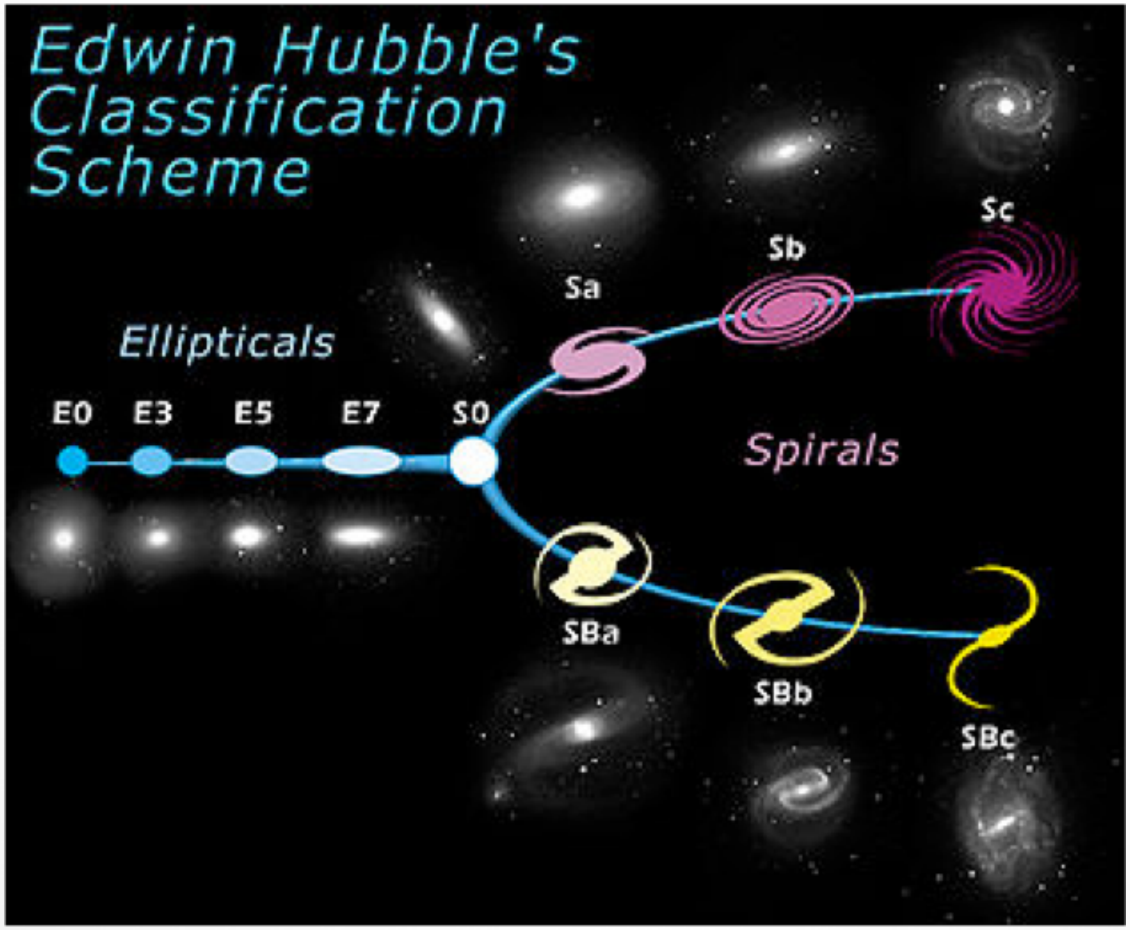


Expansion of the universe

- 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.
- Highest known redshift for a galaxy: z=11.1 (GN-z11 discovered in March 2016).

Hubble Sequence

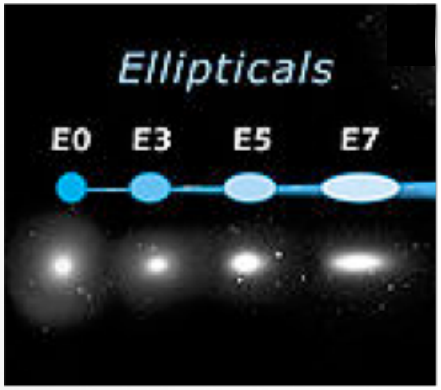
The "tuning fork diagram"



S0: lenticular galaxies

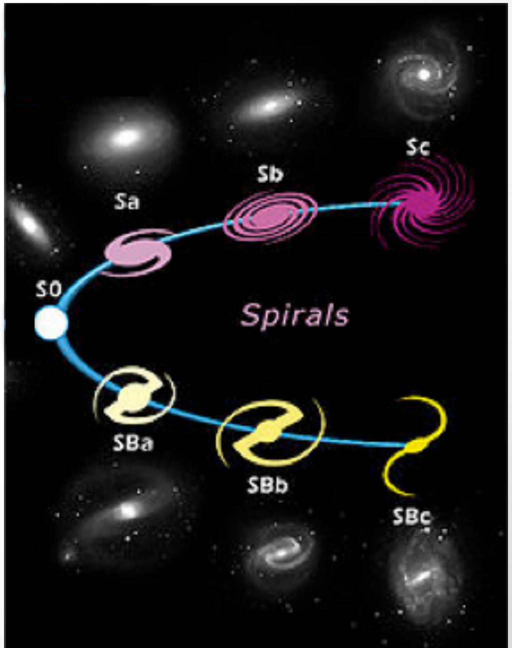
Elliptical galaxies

- Smooth, featureless, ellipse-like appearance.
- E*n*, where *n* denotes the degree of (10 x) ellipticity in the sky.
    - 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.
-



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.

Irregular galaxies

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

PGC 1843, a dwarf irregular galaxy

NGC 1427A (Irr-1)

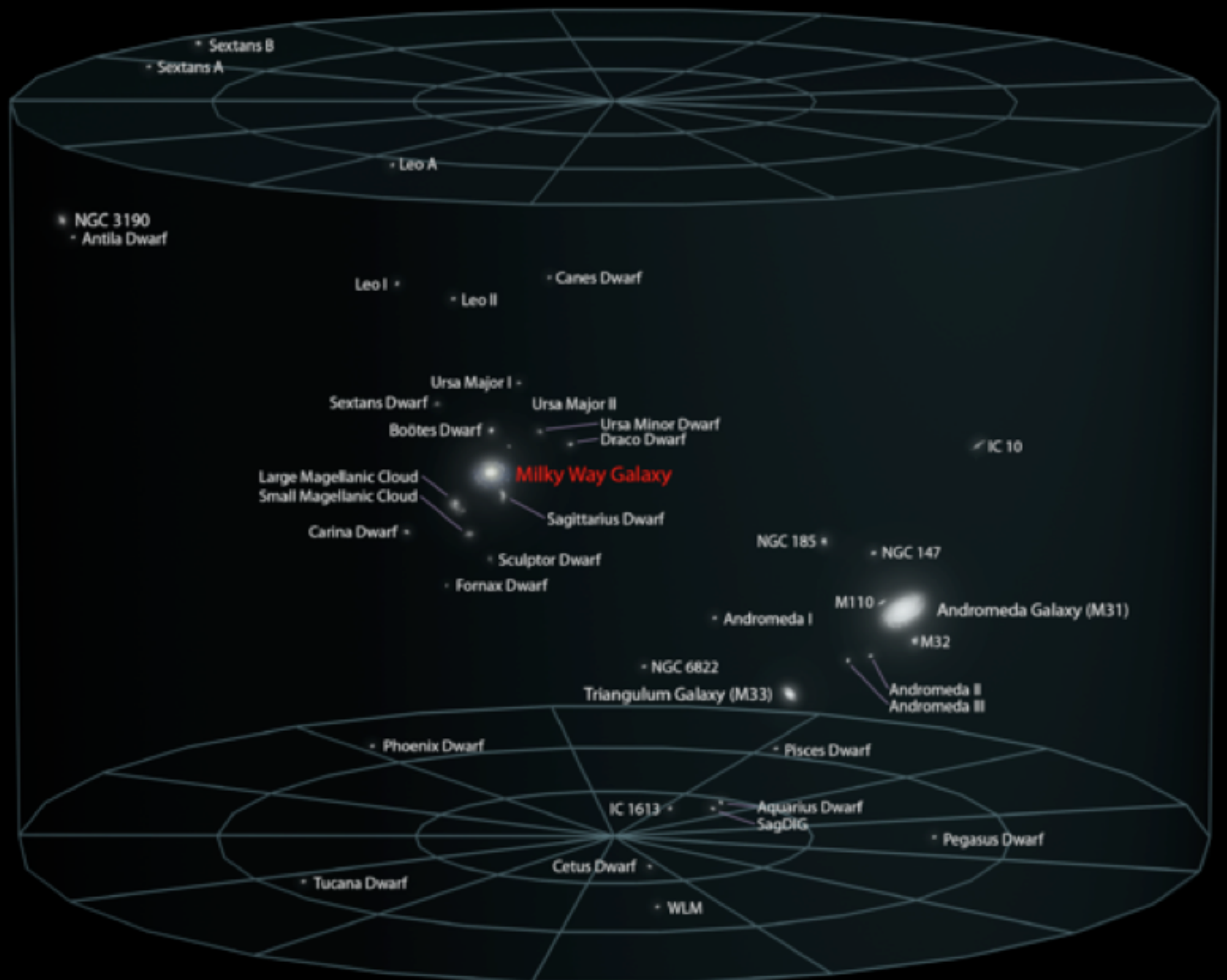
Hubble Sequence: notes

- Classification is observational/empirical, not direct reflection of physical properties.
- Not an evolutionary sequence!
    - "Early type galaxy" still refers to E - S0!
- Still important in observational astronomy: many properties correlate with the Hubble type
    - Luminosities, star forming rates, masses …

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

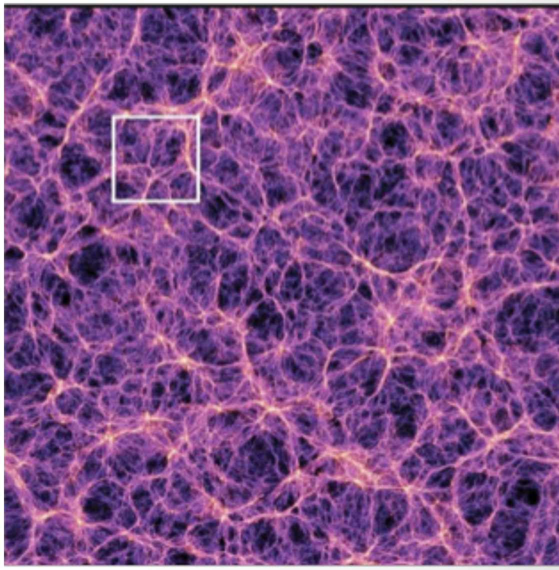


Superclusters

- Galaxies are not uniformly distributed, but form clusters and superclusters.
  - Poor clusters, rich clusters.
- Clusters are bound together due to gravity, superclusters are not.
- 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}).
  - 2014: Virgo Supercluster is only a lobe of the Laniakea SC.
- 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.
- "The Cosmic Web".
- The pattern of sheets and voids contains information about how galaxy clusters formed in the early universe, and initial conditions.
- At some point challenges the cosmological principle?
    - = distribution of matter in the universe is homogeneous and isotropic when viewed on a large enough scale.
    - The maximum size of a structure should be about 370 Mpc.



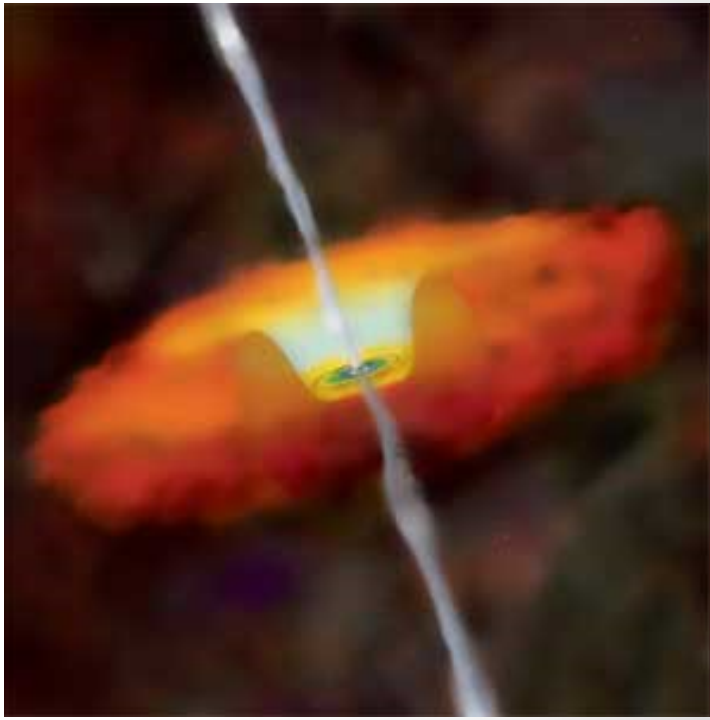
Quasars and other Active Galactic Nuclei

- Quasar
  (In Finnish: "Kvasaari")

  "quasi-stellar radio source"
  ("almost like a star but not quite")

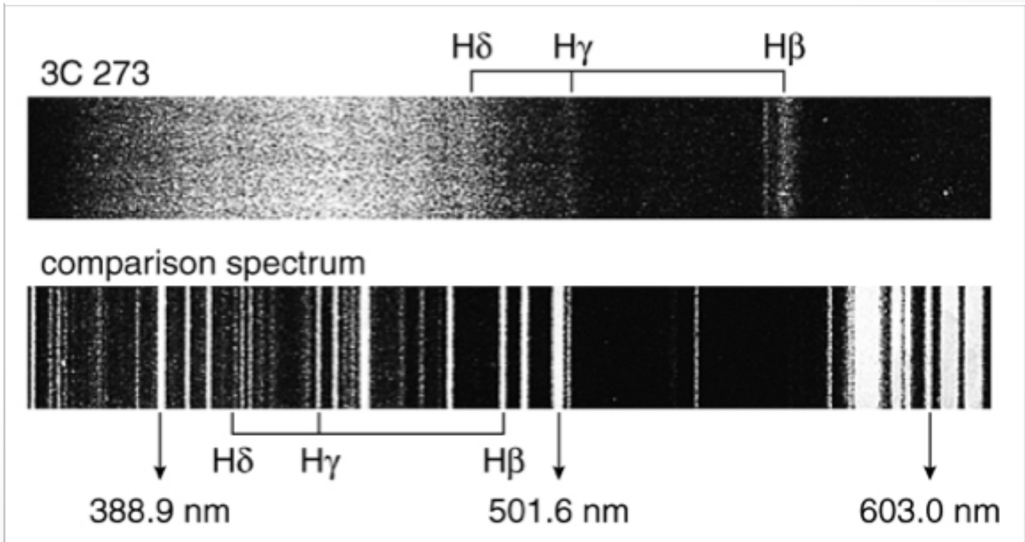
  qsr → quasar

- Also: "quasi-stellar object", qso



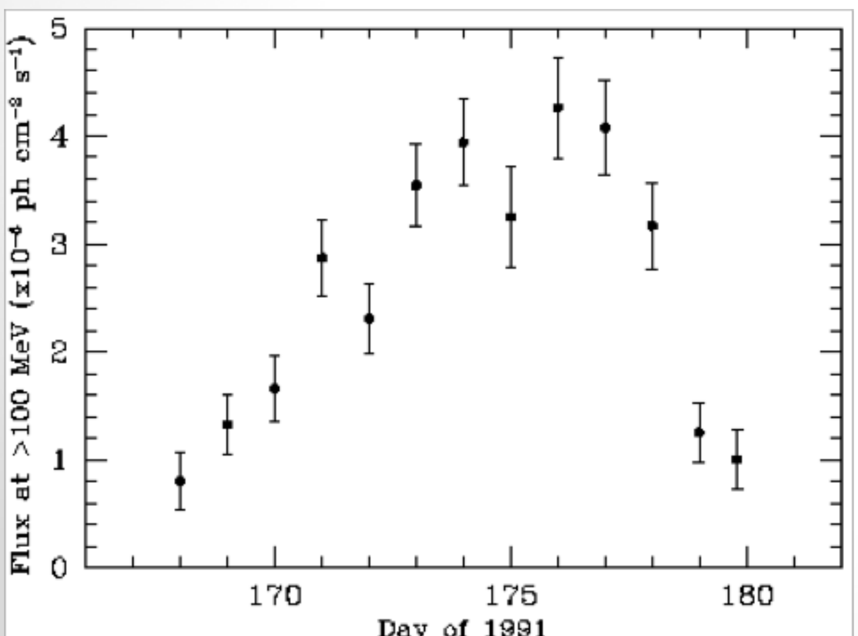
Approximately half a century ago…

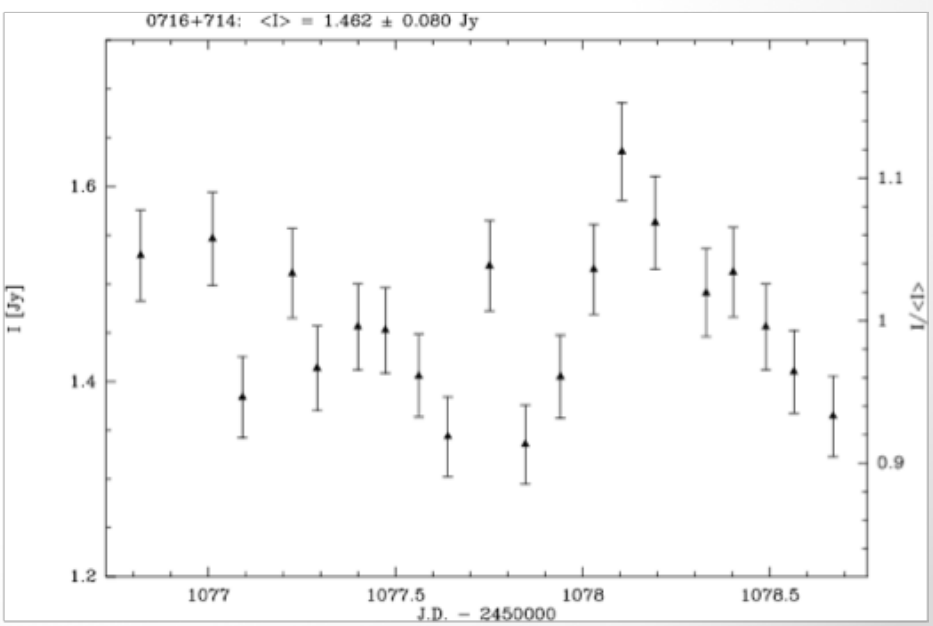
- "Why do some stars emit in radio wavebands?"
  - In 1963 Maarten Schmidt used the optical telescope on Mt. Palomar. Object named 3C273 (=object nr. 273 in the third Cambridge radio catalogue) was star-like in optical observations and initially assumed to be located in our own Galaxy.
  - Schmidt realized 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.

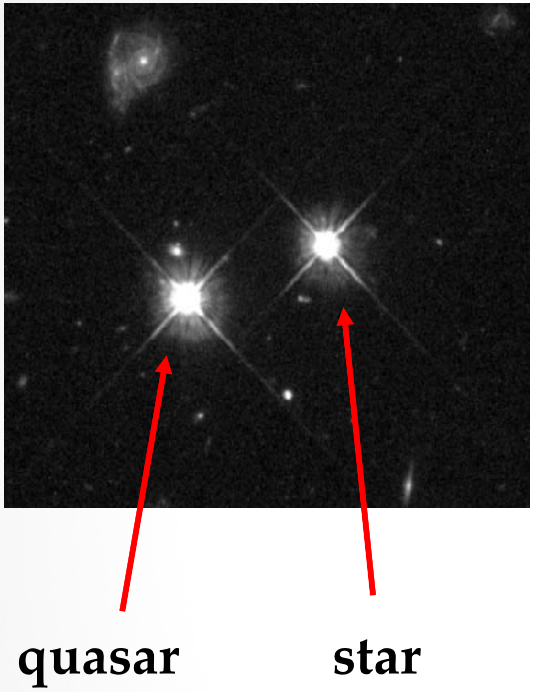


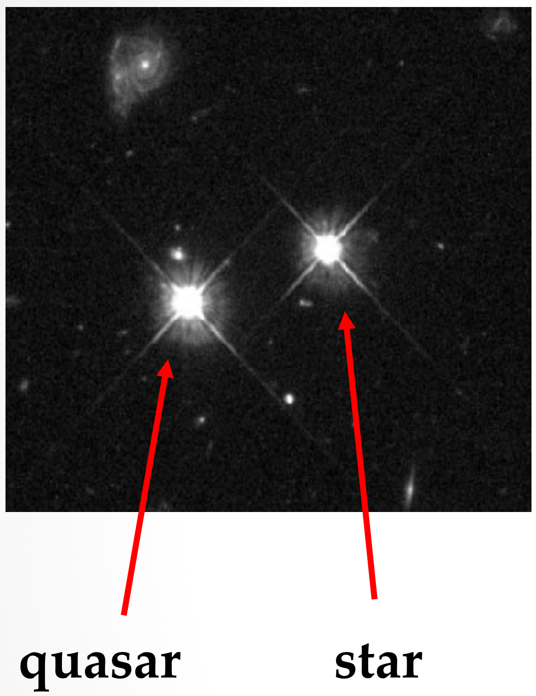
Quasar variability

- 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.






quasar
star



Quasars are a subclass of
Active Galactic Nuclei (AGN)

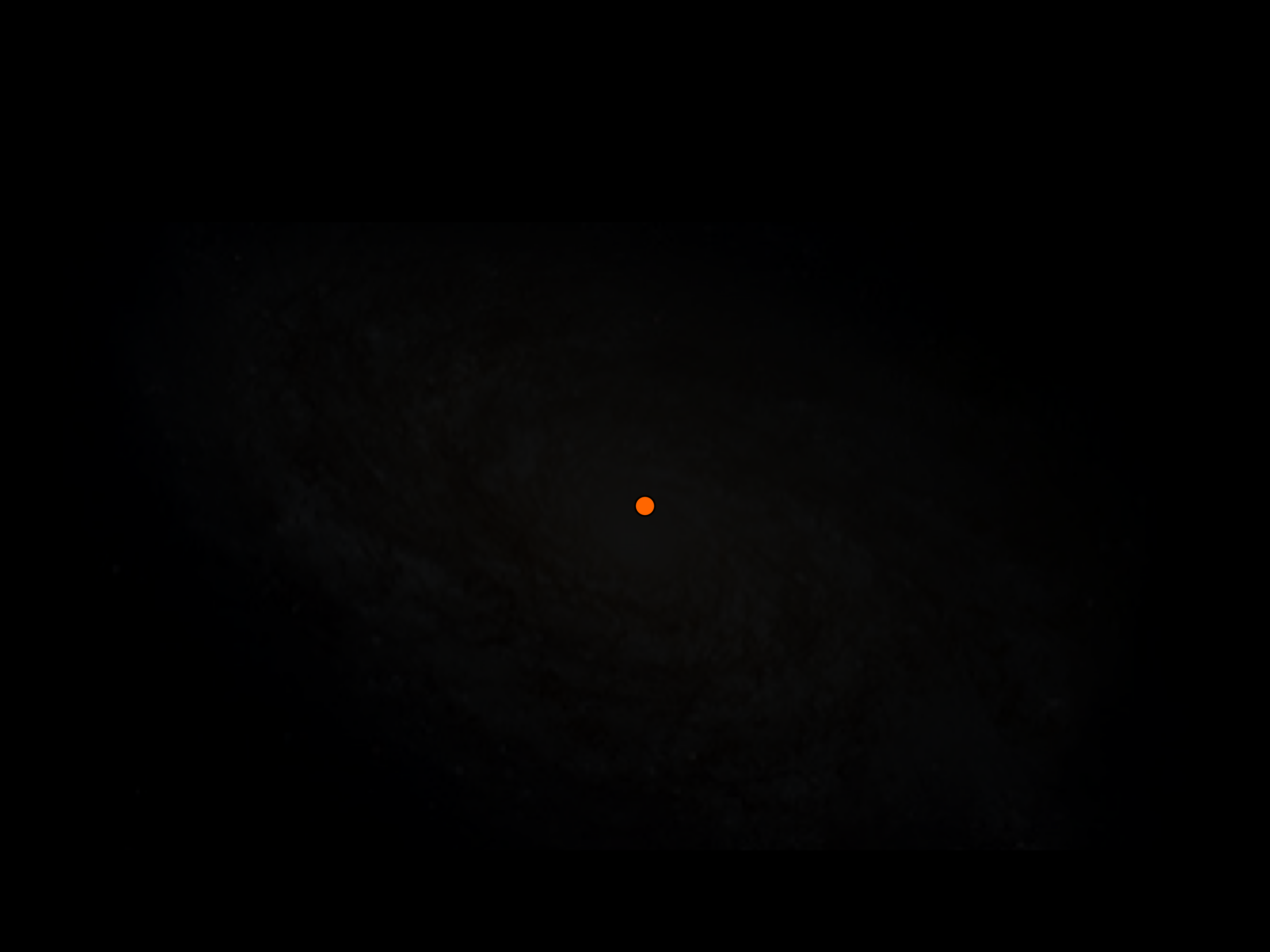
When observed from a large distance, they appear star-like. (That is why they were initially assumed to be stars.)

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

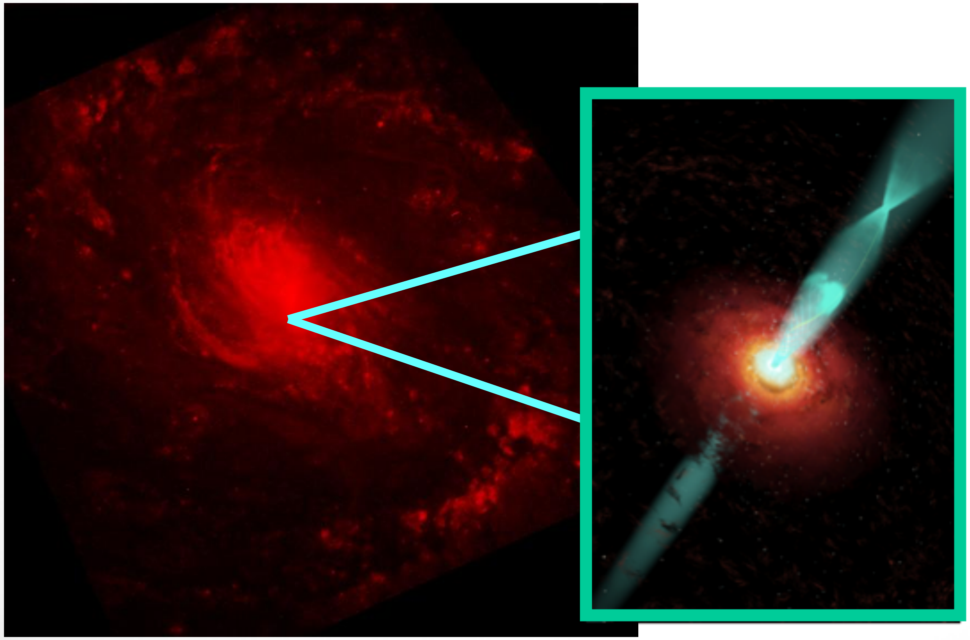
“Normal” galaxies

- 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

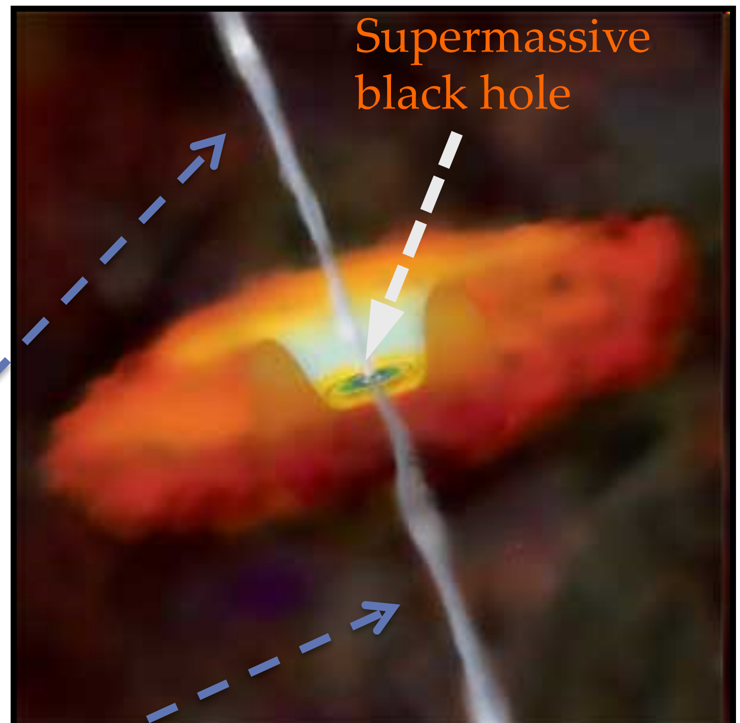


- Quasars are distant, active galaxies.
- Their excess emission is concetrated in the nucleus.
- In their nucleus they harbour a supermassive black hole = mass of the order 10^6-10^9 Solar masses, in a volume ca. that of our solar system.



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:

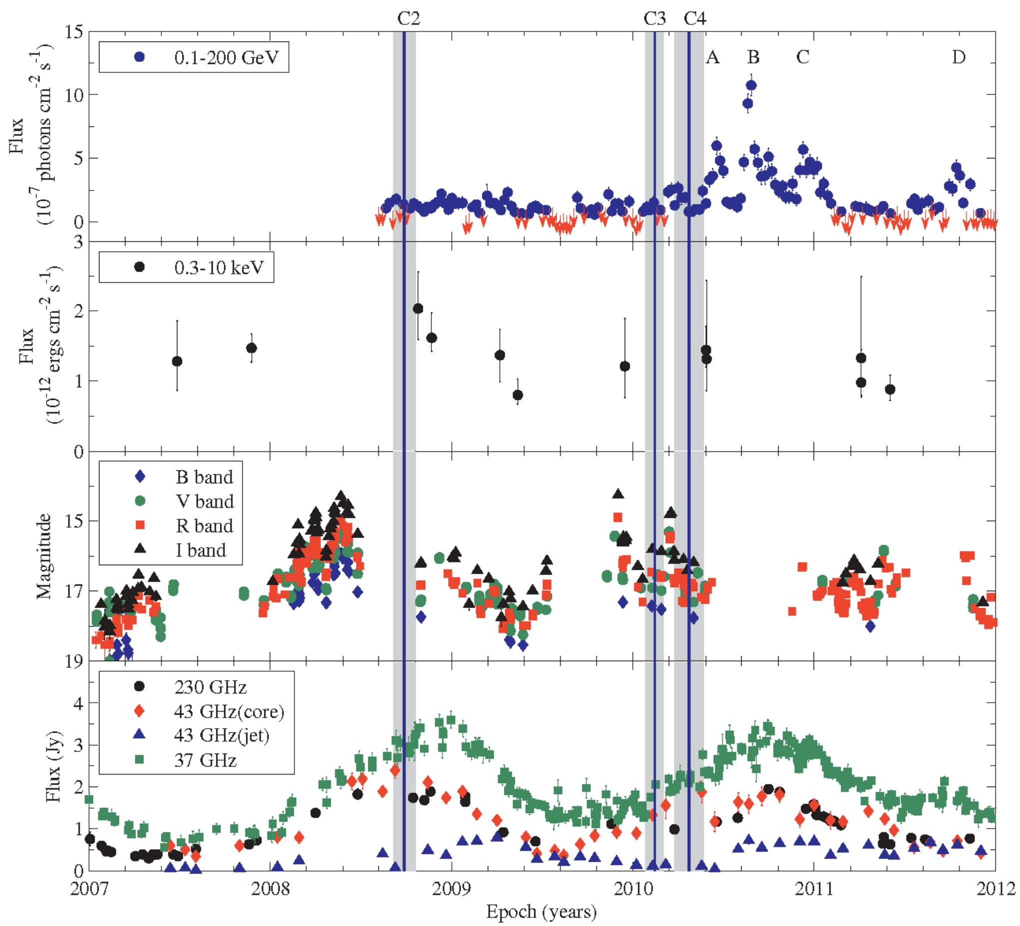
Credit: NRAO/AUI/NSF

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.

- 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...



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

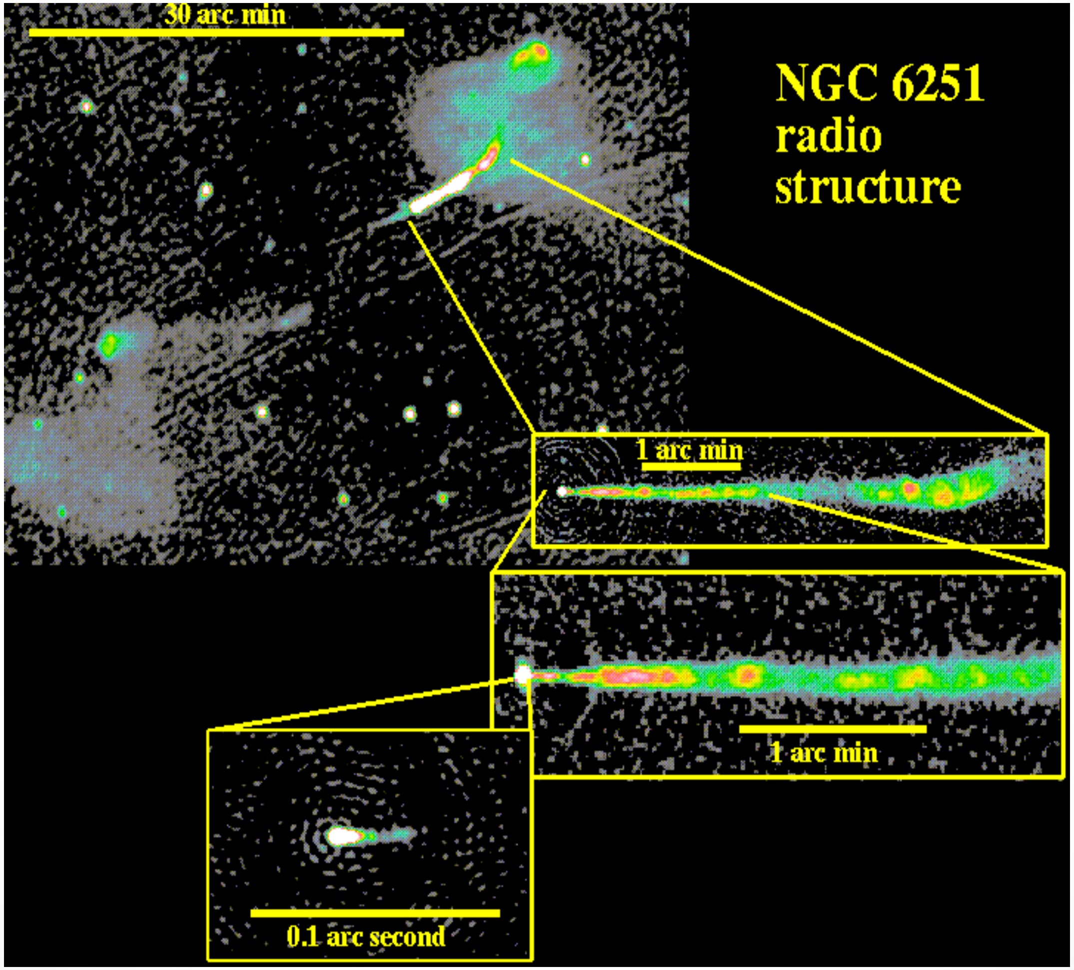
100 pc

1 Mpc

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!

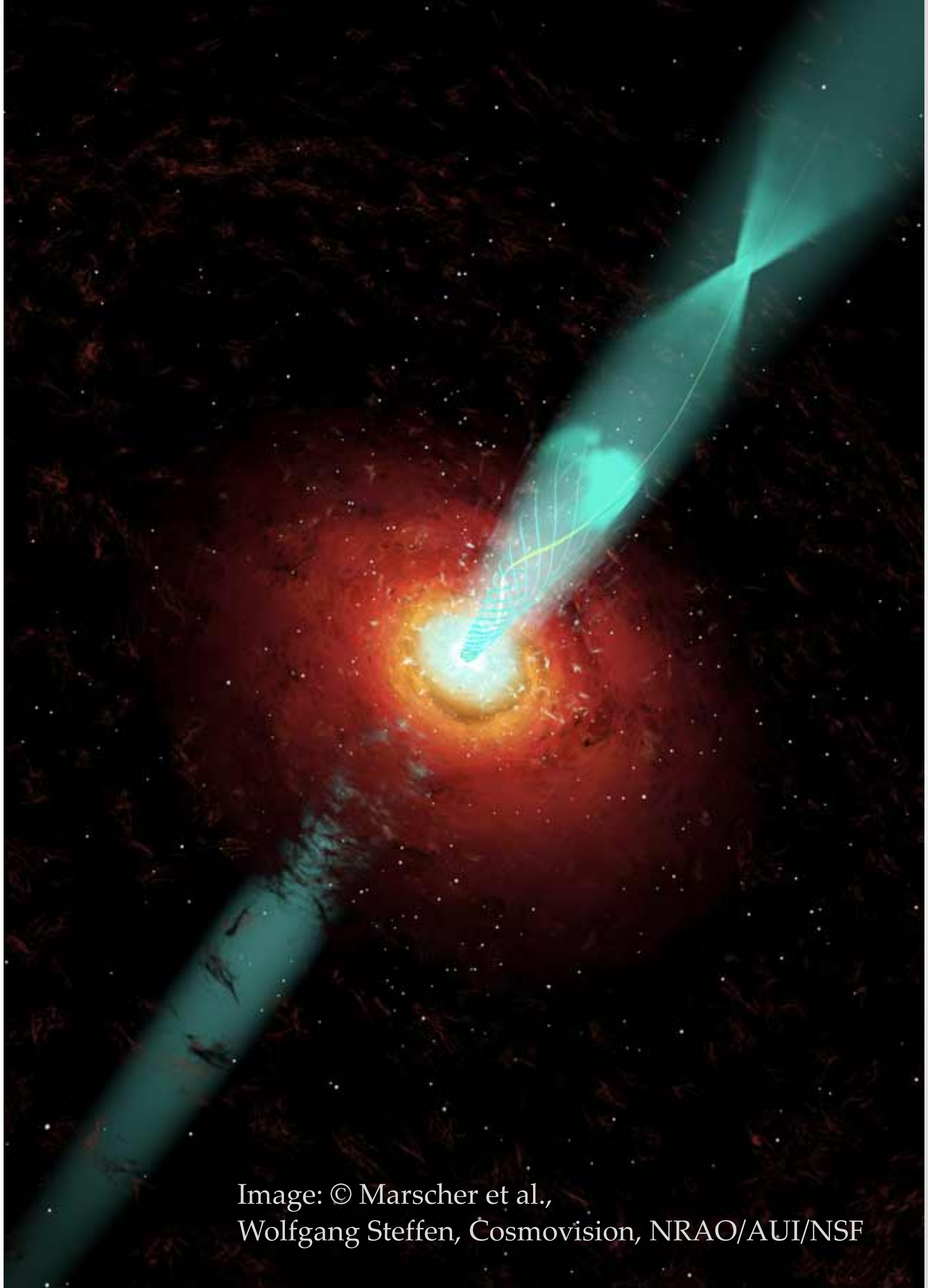


Image: © Marscher et al.,
Wolfgang Steffen, Cosmovision, NRAO/AUI/NSF

Image:
Marc Türler, ISDC

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!
- 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.
- VLBI maps (not of the central region!)
- Polarization observations.
- CCD images of the host galaxy / surrounding regions.
- Spectral line observations.

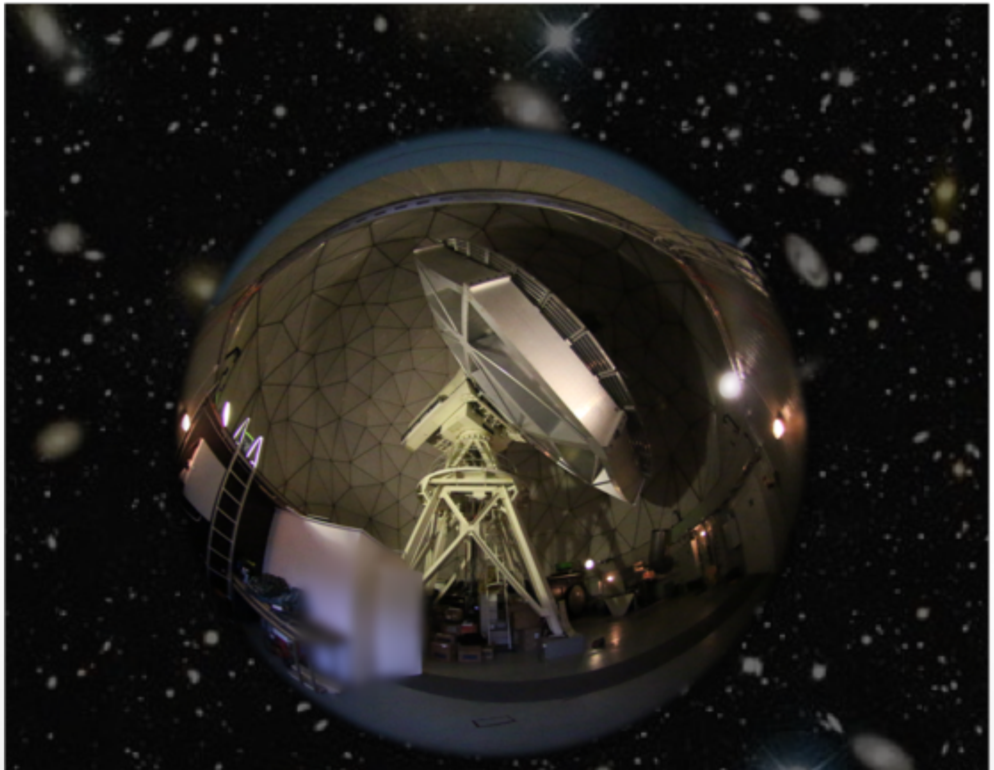
Emission mechanisms

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

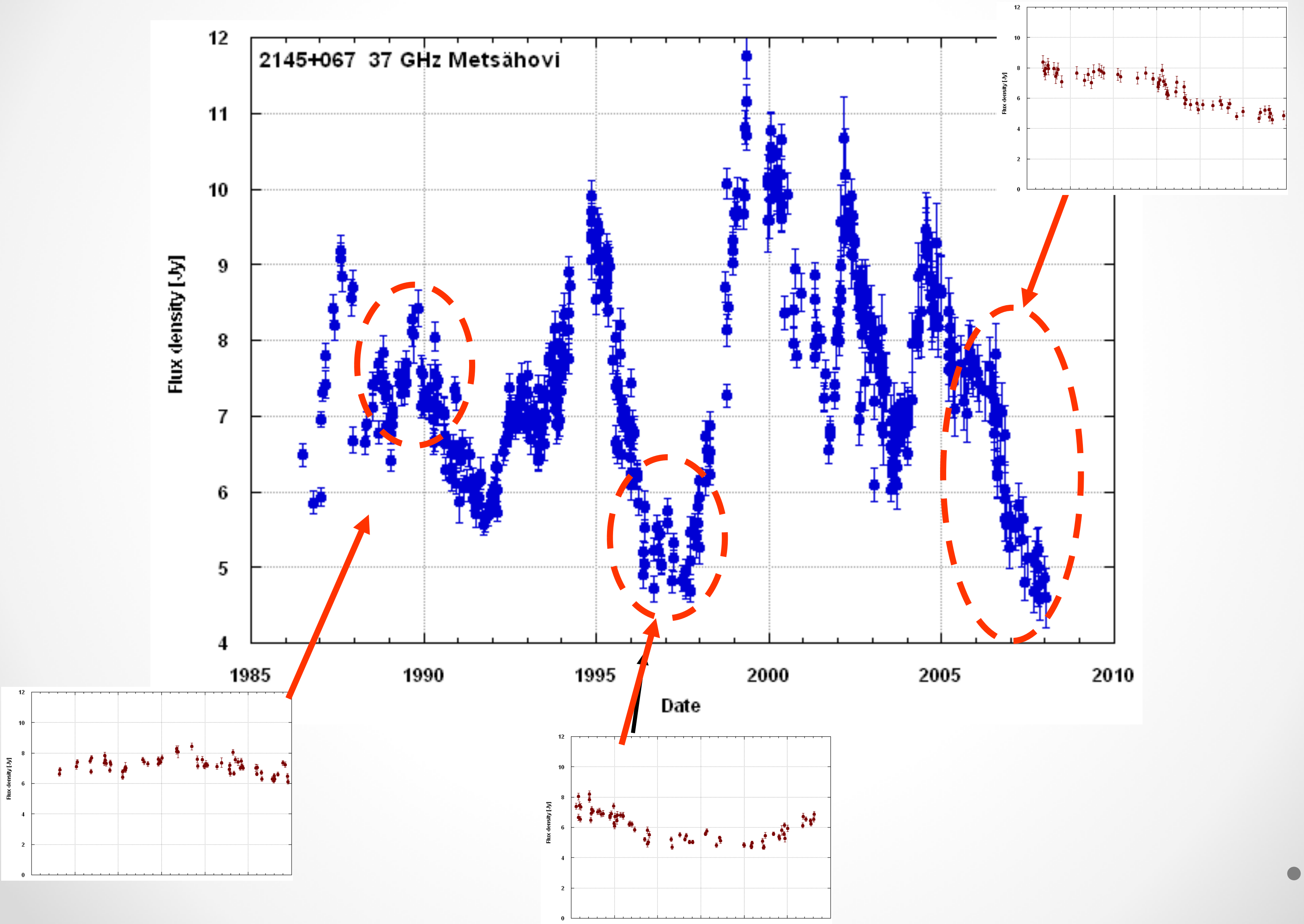
- Radio emission in AGNs is always of synchrotron origin!

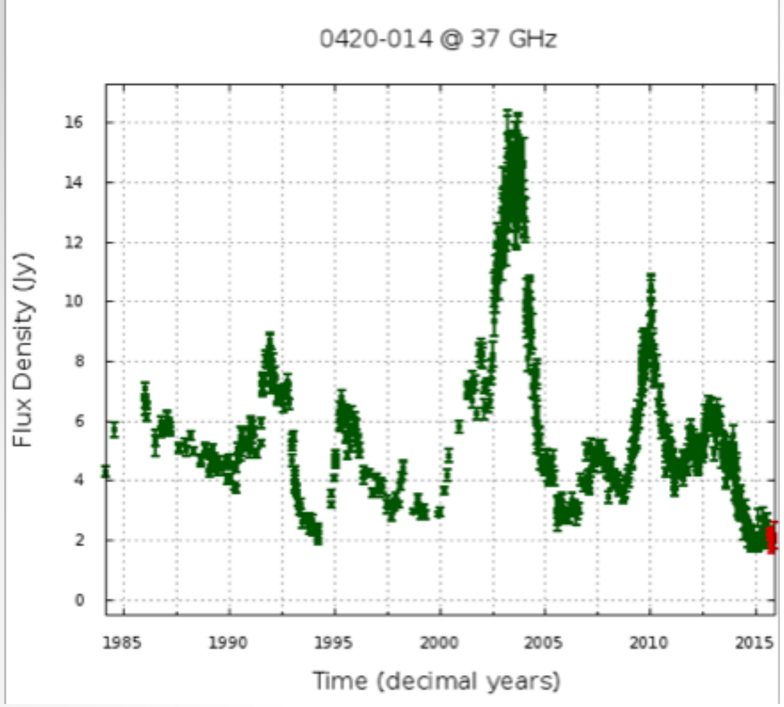
Quasar research in Metsähovi

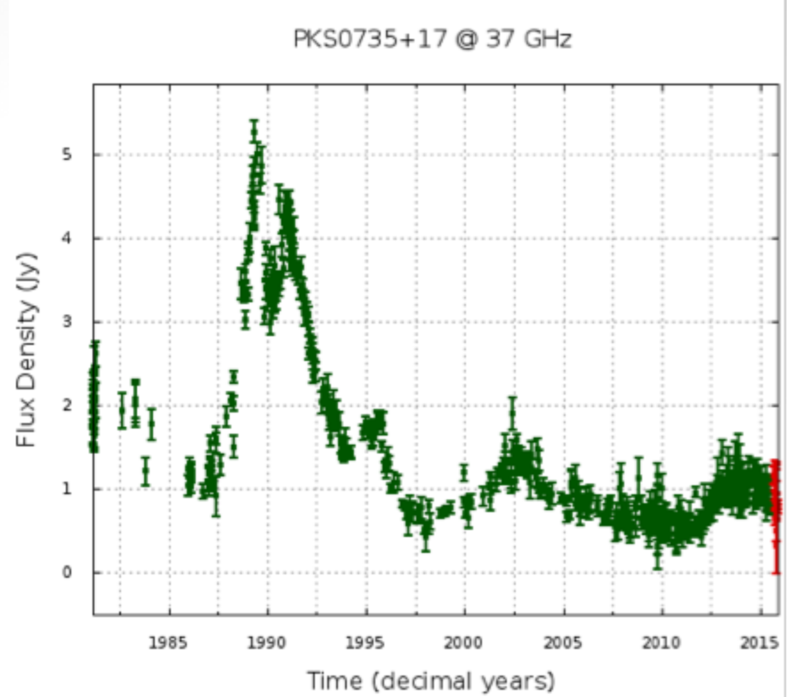
- Radio observations practically 24/7.
- Observations also with other instruments, satellites, etc. also through active international collaboration.
- Theory and modelling.

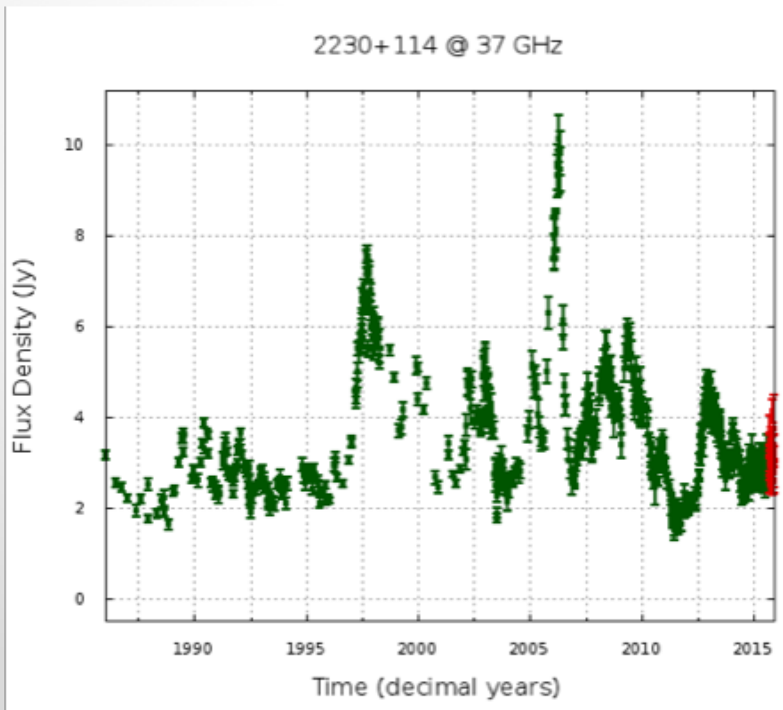


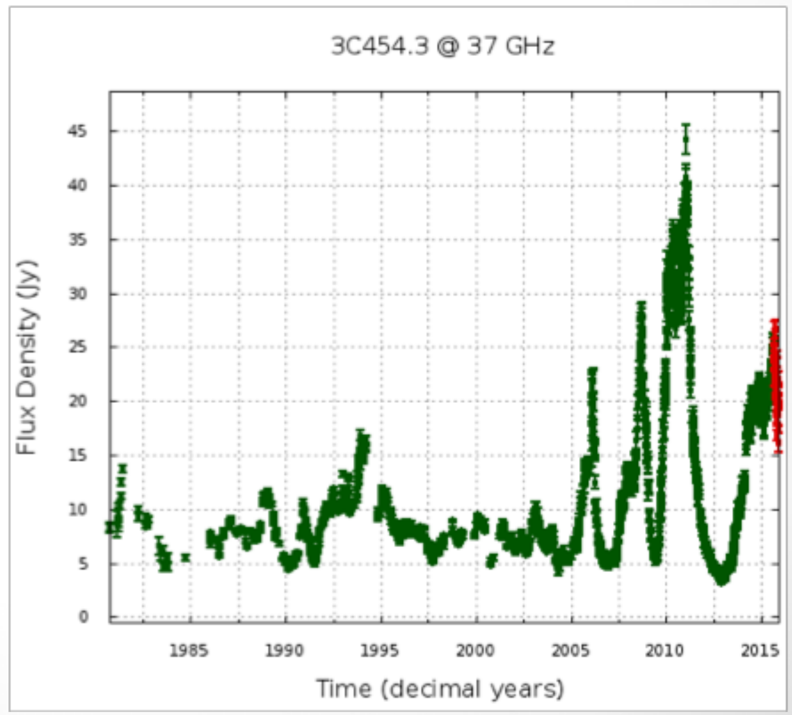
Radio flux density curves: time variability




0420-014 @ 37 GHz
Flux Density (Jy)
Time (decimal years)


PKS0735+17 @ 37 GHz
Flux Density (Jy)
Time (decimal years)


2230+114 @ 37 GHz
Flux Density (Jy)
Time (decimal years)


3C454.3 @ 37 GHz
Flux Density (Jy)
Time (decimal years)

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 ☺

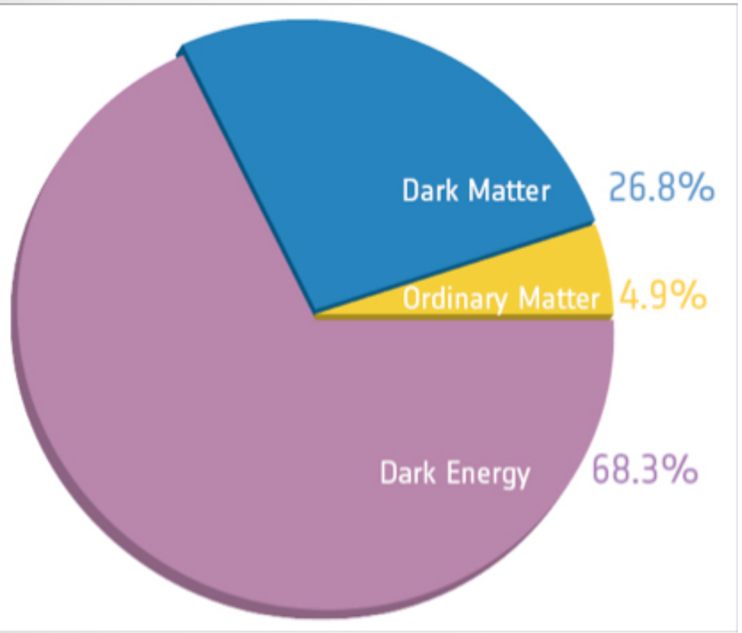
ELEC-E4530 - Radio Astronomy in the fall!

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.

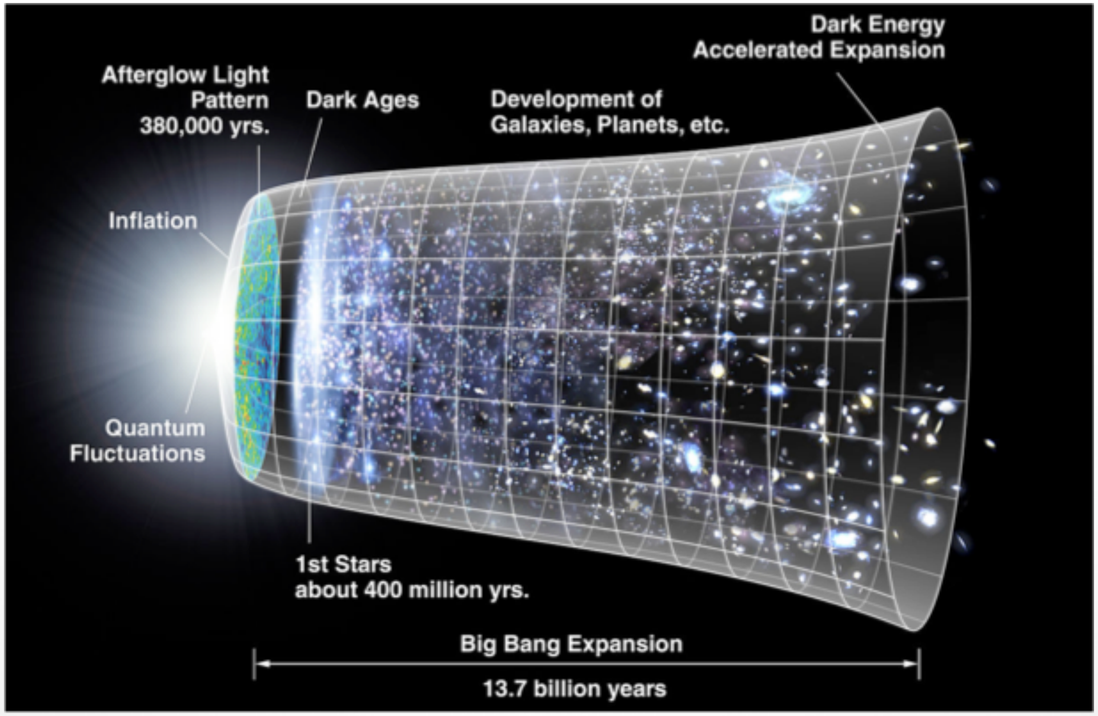
~~Hubble's law~~

Hubble–Lemaître law

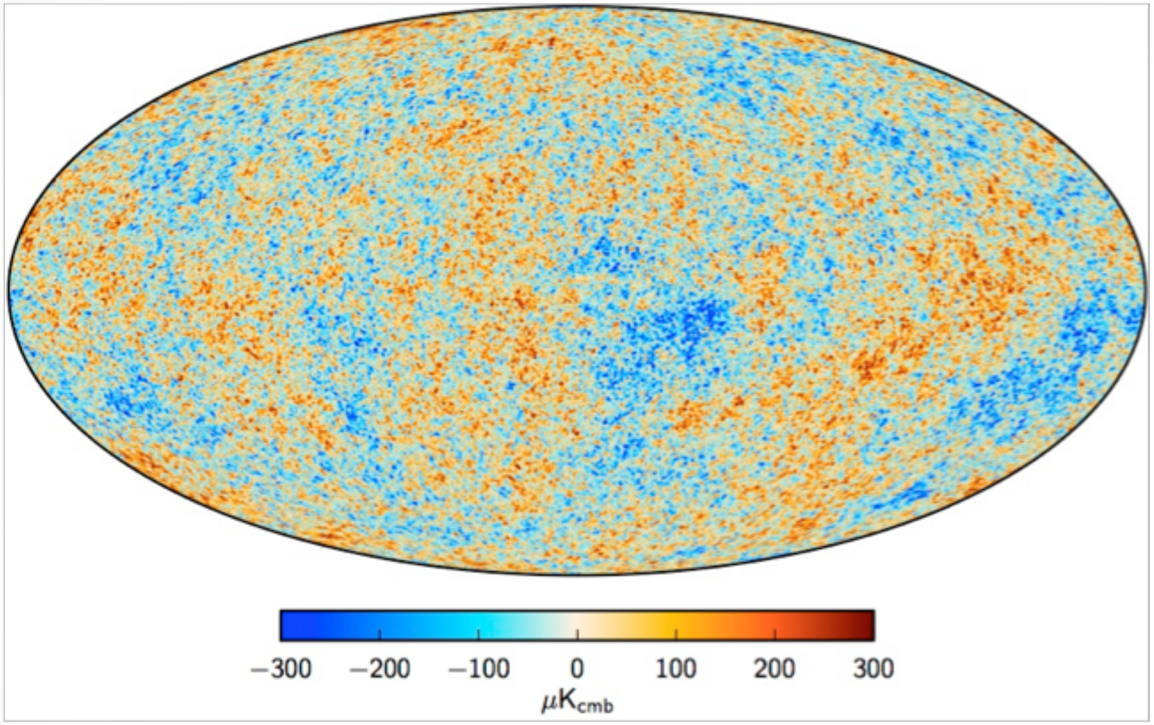
- The first observational basis for the expansion of the universe.
- $v = H_0 D$
  - v is the recessional velocity of the galaxy
  - D is the distance to the object
  - H_0 is Hubble's constant, 68 (km/s)/Mpc [Planck consortium 2014]
  - The SI unit of H_0 is s^{-1} but it is most frequently quoted in (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



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.