Introduction to Astrophysics and Cosmology

Extragalactic astrophysics 2 - Active Galaxies, Galaxy clusters, large scale structure of the Universe

Helga Dénes 2025 S1 Yachay Tech

hdenes@yachaytech.edu.ec

Active galaxies

If the compact nucleus at the centre of galaxies is giving out copious amounts of radiation in several bands of electromagnetic spectrum from the radio to X-rays. Such a galaxy is called an ***active galaxy*** and its nucleus is called an ***active galactic nucleus*, abbreviated as *AGN***.

- Objects which we now recognize to be very similar were often not realized to have anything in common when they were first discovered. As a result, the nomenclature in this field is heavily loaded with historical baggage. The names of different types of active galaxies give no clue as to how these different types of active galaxies may be related to each other.
- Seyfert (1943) noted that some spiral galaxies had unusually bright nuclei. The spectra of these nuclei were found to be totally different from the spectra of stars and had strong emission lines. **Depending on whether the emission lines were broad or narrow, these galaxies are now put in two classes.**
    - Galaxies with nuclei emitting very **broad lines are called *Seyfert 1*** galaxies.
    - On the other hand, if the **emission lines are narrow**, then the galaxies are called ***Seyfert 2*** galaxies.

Active galaxies

It was found that some galaxies emitted radio waves. As resolutions of radio telescopes improved with the development of interferometric techniques, it became possible to study the detailed natures of these so-called ***radio galaxies***. There are 2 types of radio galaxies:

- Galaxies with an active galactic nucleus (AGN) - *the book and the slides after this one refer to this*
- Galaxies with intense star formation

Jennison and Das Gupta (1953) discovered that the radio emission of the galaxy Cygnus A comes from two lobes located on two sides of the galaxy lying quite a bit outside the optical image of the galaxy.

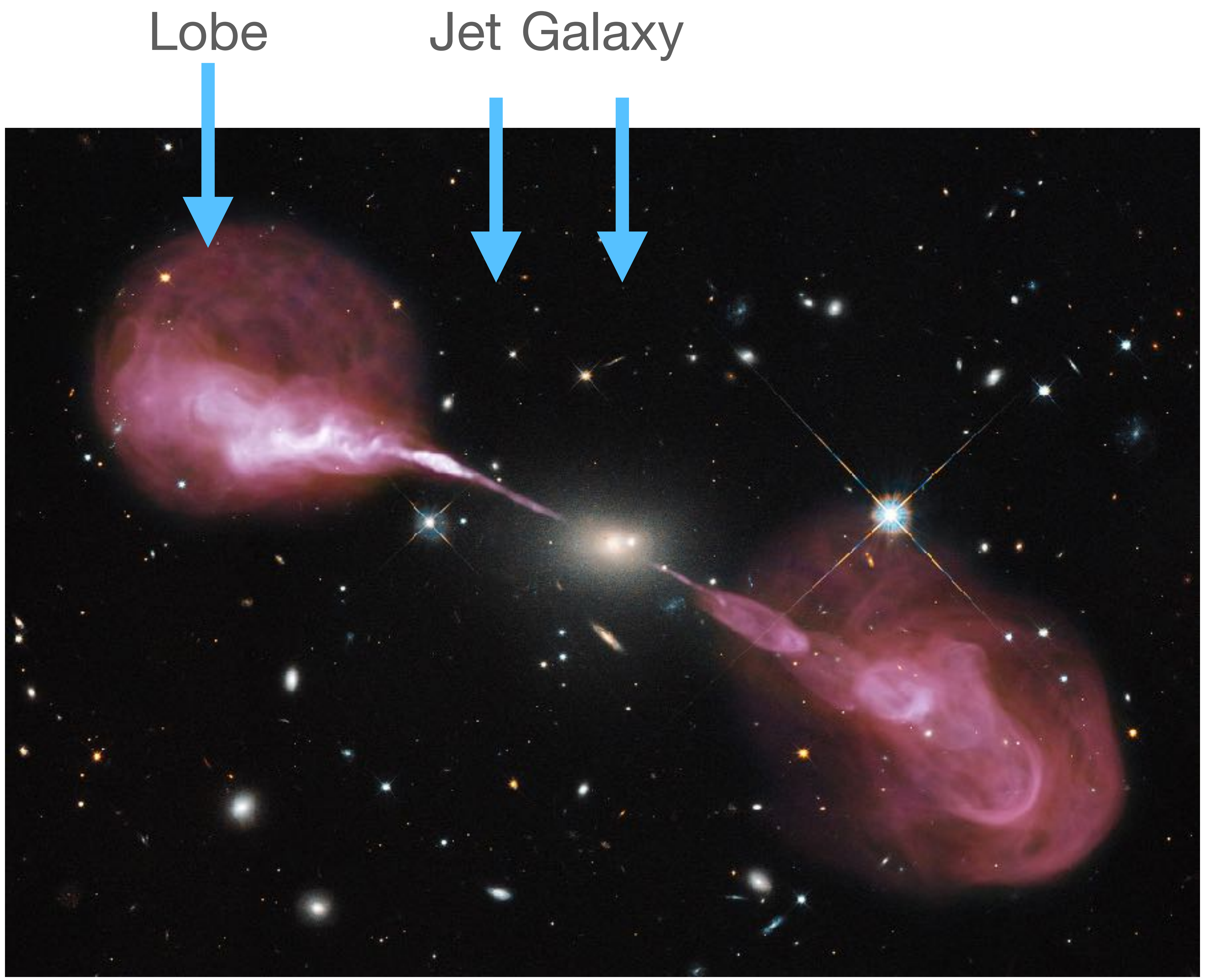
Many radio galaxies consist of radio-emitting lobes lying outside the galaxy on two sides. The obvious question which bothered astronomers was: what could be the source of energy for powering radio emission from these lobes lying so far outside the galaxies?

Active galaxies

- At first sight, radio galaxies seemed to have nothing in common with Seyfert galaxies. **Seyfert galaxies are spiral galaxies with bright nuclei.**
- On the other hand, the **radio galaxies**, which were **mostly found to be elliptical galaxies,** have the radio emissions coming from lobes lying outside the galaxies.
- The fact that they could have something in common became apparent only when astronomers started probing the source of energy in radio galaxies. With improved radio telescopes, it was found that **often oppositely directed radio-emitting jets were squirted out of the central regions of radio galaxies**.
- These jets, which are presumably made of plasma flowing out at very high speed, made their ways by pushing away the intergalactic medium surrounding the galaxies.
- The **lobes are located where the jets are finally stopped by the intergalactic medium**.

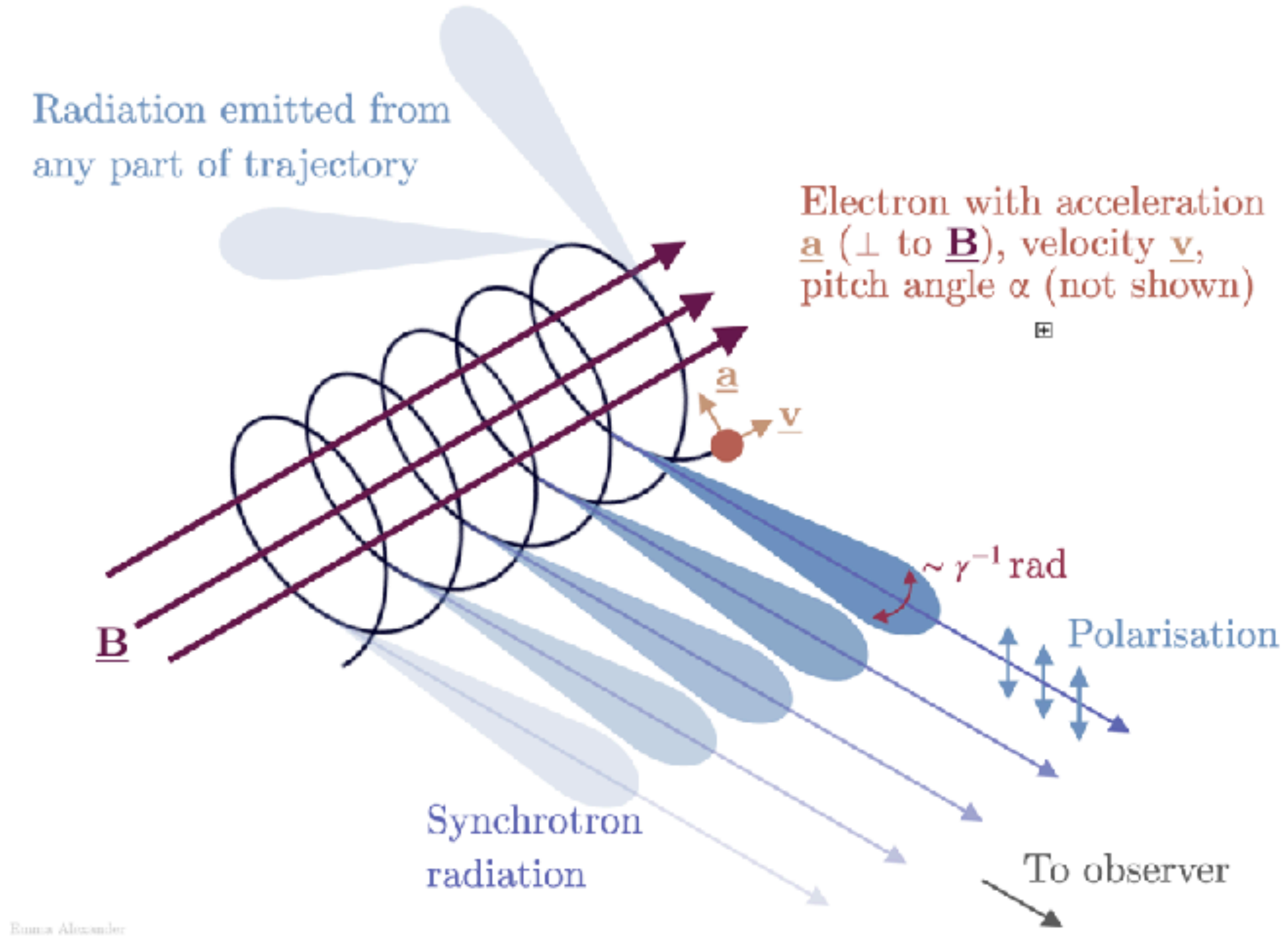
Active galaxies

- The Figure shows the radio image of Hercules A, which has almost symmetrical radio jets ending in radio-emitting lobes.
- It appears that the ultimate **source of energy of a radio galaxy lies in its nucleus that produces the jets**.
- Like Seyfert galaxies, radio galaxies are also galaxies which have active nuclei. The radio emissions from the jets and lobes of radio galaxies seem to be of the nature of **synchrotron radiation**, since they have the power-law spectra characteristic of synchrotron radiation.
- Synchrotron radiation implies that the jets and lobes must have magnetic fields around which relativistic electrons are gyrating.



Synchrotron radiation

- **Synchrotron radiation is the electromagnetic radiation emitted when relativistic charged particles are subject to an acceleration perpendicular to their velocity**. It is produced naturally by fast electrons moving through magnetic fields. The radiation produced in this way has a characteristic polarization and the frequencies generated can range over a large portion of the electromagnetic spectrum.
- Synchrotron radiation is similar to bremsstrahlung radiation, which is emitted by a charged particle when the acceleration is parallel to the direction of motion.
- The **general term for radiation emitted by particles in a magnetic field is gyromagnetic radiation**, for which synchrotron radiation is the ultra-relativistic special case. Radiation emitted by charged particles moving non-relativistically in a magnetic field is called cyclotron emission. For particles in the mildly relativistic range (≈85% of the speed of light), the emission is termed gyro-synchrotron radiation.



https://en.wikipedia.org/wiki/Synchrotron_radiation

Active galaxies - Quasars

Quasars are radio sources of very compact size, some of which could be identified with optical sources looking very much like stars. Quasar comes from: quasi stellar radio object.

However, these optical sources were found to have **broad emission lines in the spectra**, which seemed mysterious at first.

Schmidt (1963) identified the spectral lines of the quasar 3C 273 to be nothing other than the ordinary spectral lines of hydrogen redshifted by an amount $z = 0.158$, which was considered an unbelievably **large redshift** at that time.

Spectral lines of many other quasars were soon identified to be ordinary lines which had undergone even larger redshifts. If these redshifts are caused by recession velocities due to the expansion of the Universe, then these quasars must be lying at enormous distances – beyond the distances of most ordinary galaxies known at that time.

If the quasars were really at such distances and still appeared so bright, then the typical luminosity of a quasar should be of order 10^{39} W, making it more than **100 times brighter than an ordinary galaxy.**

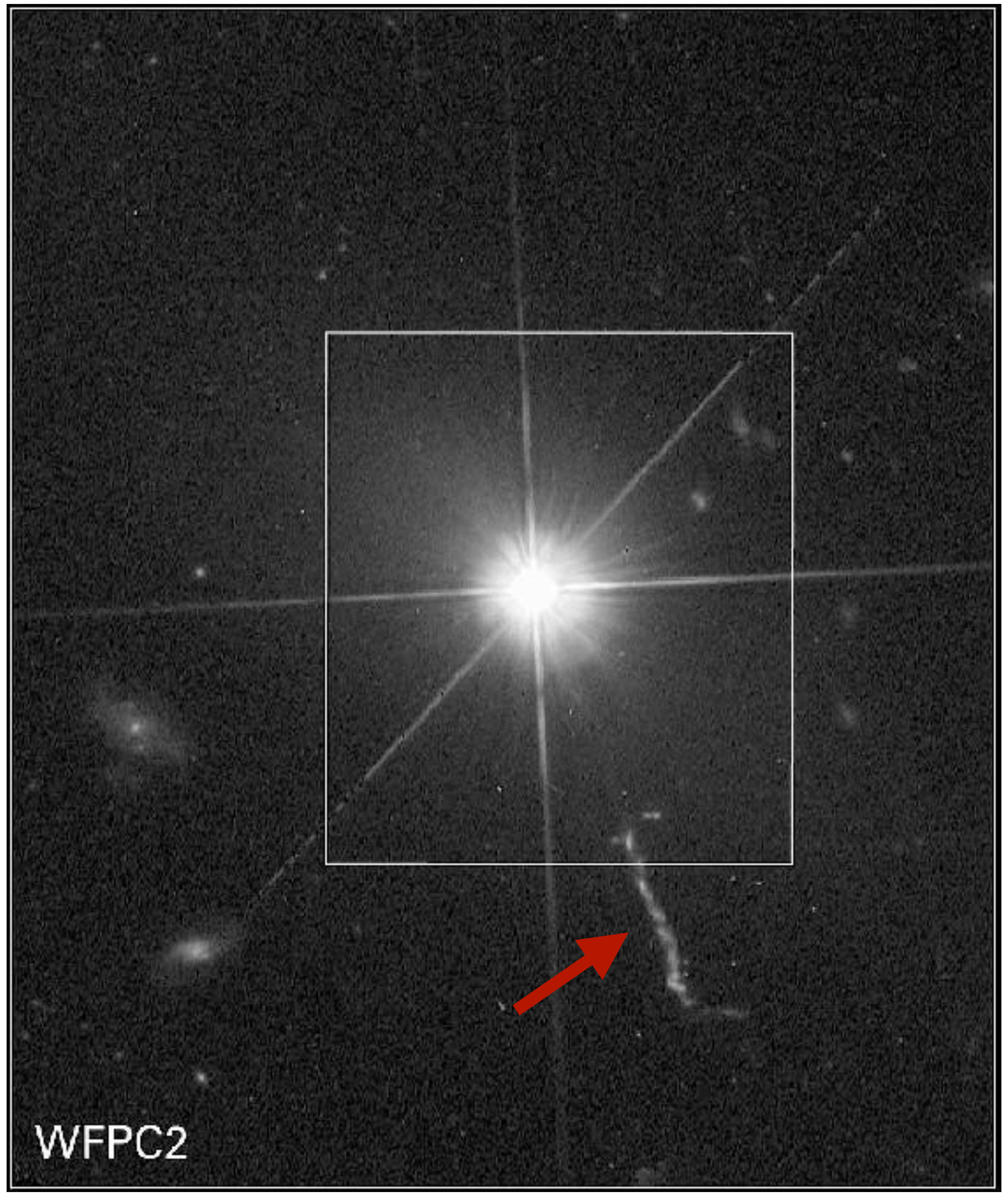
Quasars

What baffled astronomers further is that the emissions from some quasars were found to be **variable in time**, the time scale of variation being sometimes of the **order of days**.

If t is the typical time scale of variation, then the size of the emitting region cannot be larger than ct. It was inferred that **some quasars were emitting their huge energies from very small nuclear regions**, which could not be much larger than the solar system.

Quasars are really far-away objects and must be awesome energy-producing machines.

In the case of at least a few nearby quasars, it became possible to show that they **reside inside galaxies and must be nuclei of galaxies**. Such observations are not easy to do, since the nuclei are many times brighter than the host galaxies and the remaining parts of the galaxies get obscured by the glare of the nuclei.



Optical image of quasar 3C 273. The quasar's jet can be seen extending downward and to the right from the quasar.

Quasars

A typical quasars spectra is very similar to the spectra of Seyfert I galaxies (broad lines).

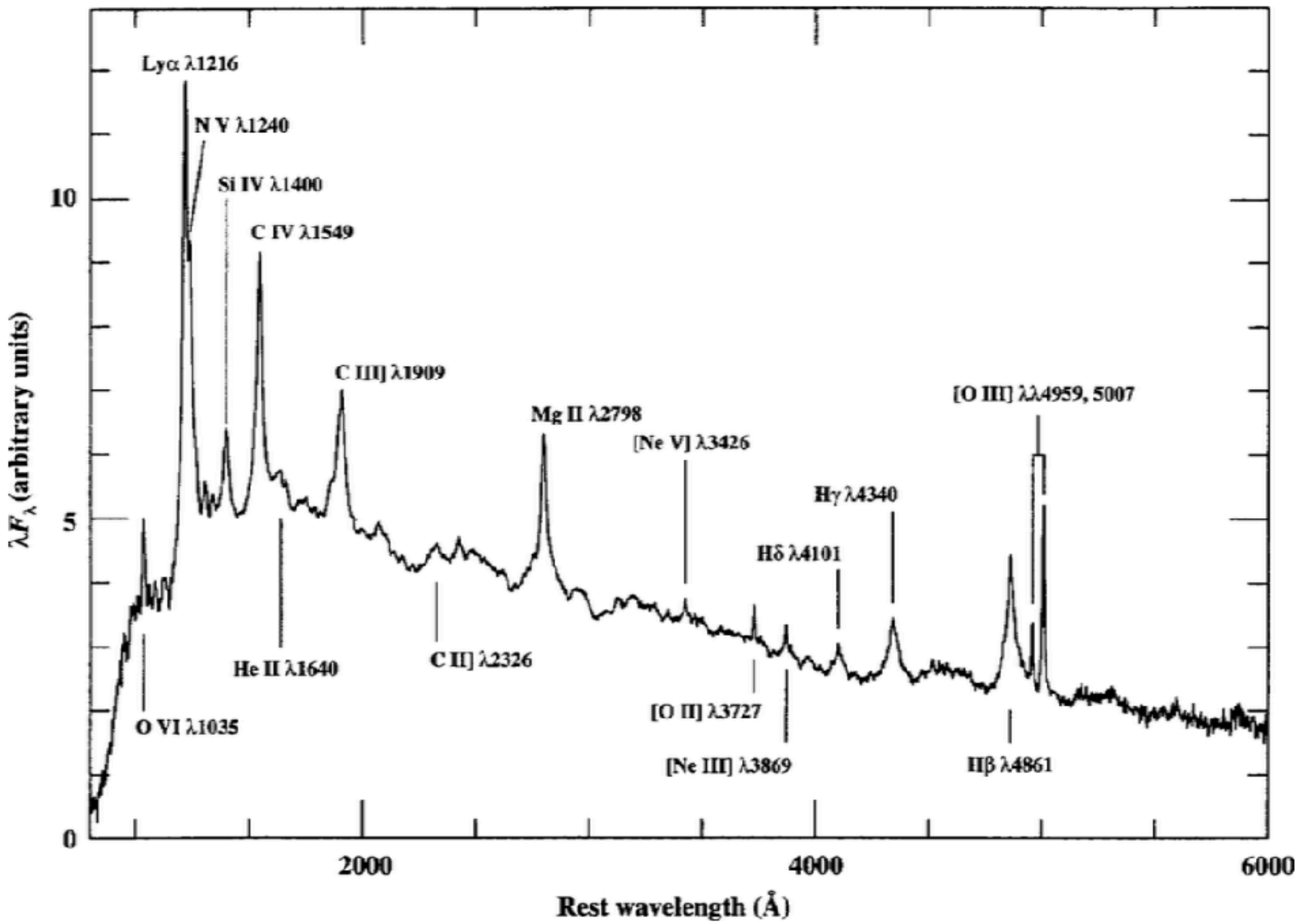


Fig. 9.11 The typical quasar spectrum in the rest wavelength. This is a composite spectrum obtained by averaging the spectra of many quasars. From Francis *et al.* (1991). (©American Astronomical Society. Reproduced with permission from *Astrophysical Journal*.)

Quasars

- The similarity in spectra suggests that Seyfert galaxies and quasars may be similar kinds of active galaxies, the Seyfert galaxies being the milder form of such active galaxies, whereas the quasars are the more extreme and
- Quasars emit very strongly in UV.
- One efficient method of searching for quasars is to look for stellar-looking objects for which the UV brightness compared to the optical brightness is much higher than what we expect in the case of a star. As a result of such searches, a large number of sources could be found having all the other properties of quasars, except that they did not emit in the radio wavelengths.
- These **radio-quiet quasars** are often called ***quasi-stellar objects***, abbreviated as **QSO**s. Since some authors use the terms 'quasar' and 'QSO' almost interchangeably, we shall use the terms radio-loud and radio-quiet quasars to denote quasars which do and do not emit in the radio. **Radio-quiet quasars seem much more numerous than radio-loud quasars. Only a few percent of all quasars seem to be radio-emitters.**

Superluminal motion

- The only things in common between a radio galaxy and a radio-loud quasar may seem that they are both emitters of radio waves. Otherwise, they may at first sight appear to be very different kinds of objects, with quasars being very compact in appearance and radio galaxies being extended sources with huge jets and lobes.
- The fact that they may actually be the same objects became clear only when **VLBI (very long baseline interferometry) was used to produce high-resolution maps of quasars** showing moving parts inside them.
- Figure 9.12 shows images of 3C 273 taken in different years. It is clear that a radio-emitting blob is moving away from the central region.

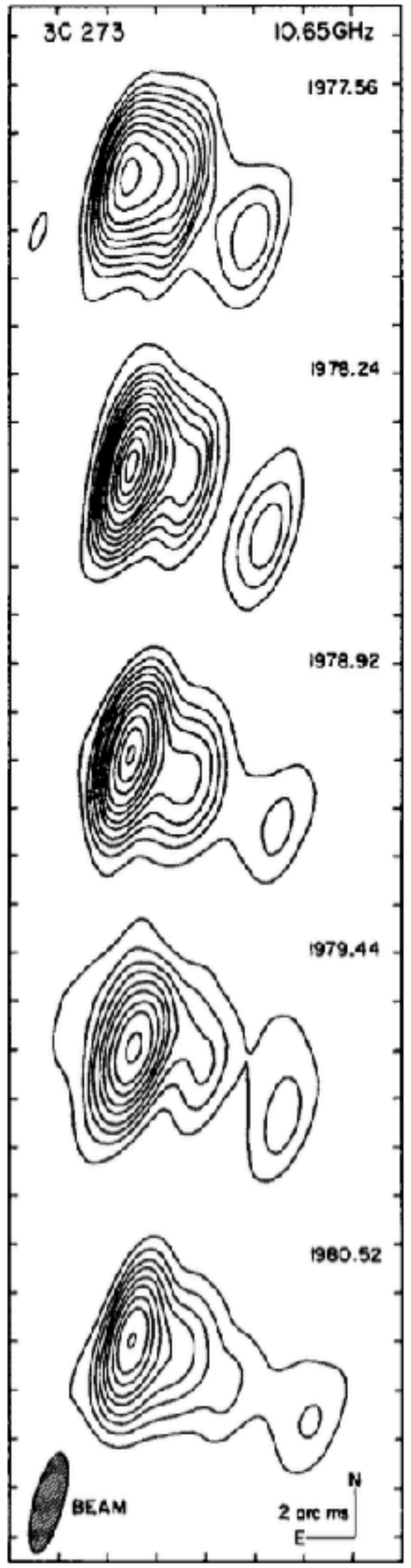


Fig. 9.12 High-resolution radio maps of the quasar 3C 273 obtained by VLBI (Very Large Baseline Interferometry) at different epochs. From Pearson *et al.* (1981). (©Nature Publishing Group. Reproduced with permission from *Nature*.)

Superluminal motion

- Multiplying the angular velocity of separation by the distance of the quasar, one finds a linear **velocity larger than c**. This phenomenon is referred to as **superluminal motion.**
- **How is this possible?**

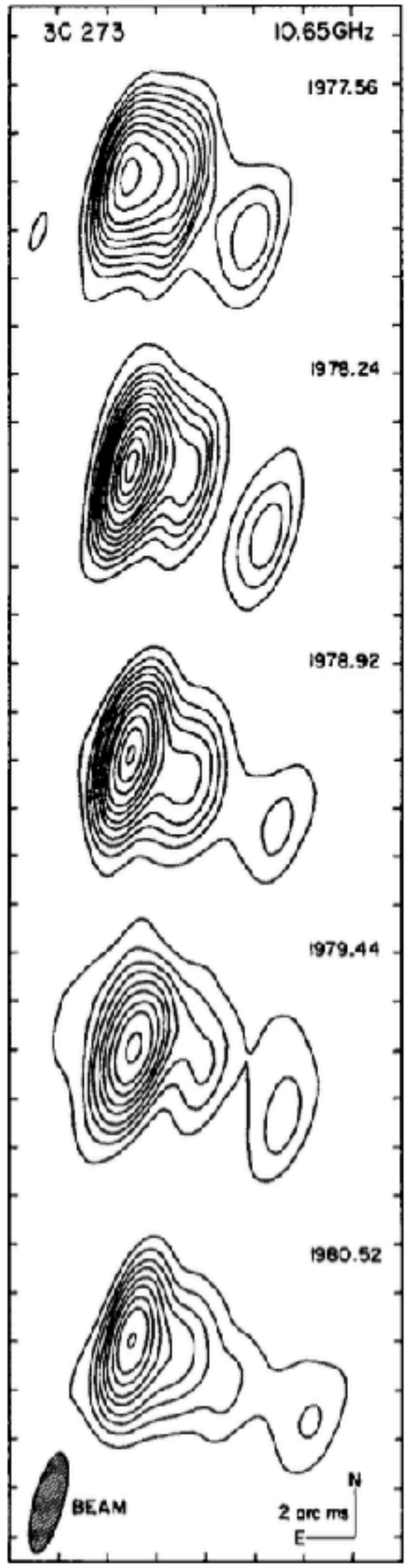


Fig. 9.12 High-resolution radio maps of the quasar 3C 273 obtained by VLBI (Very Large Baseline Interferometry) at different epochs. From Pearson *et al.* (1981). (©Nature Publishing Group. Reproduced with permission from *Nature*.)

Superluminal motion

- The possibility of **apparent superluminal motions if something is moving towards the observer at a speed v comparable to *c* making a very small angle θ with respect to the line of sight.**
- This is illustrated in Figure 9.13, where a source of radiation has moved from *A* to *B* in time δt such that $AB = v\,\delta t$. If the source emitted a signal when it was at *A* (setting $t = 0$ when the source was at *A*), then that signal would reach the observer *O* at a distance *D* away at time:

$$t_{AO} = \frac{D}{c}.$$

If another signal is emitted after time δt when the source is at *B*, this signal will reach the observer at time:

$$t_{BO} = \delta t + \frac{D - v\,\delta t\cos\theta}{c}$$

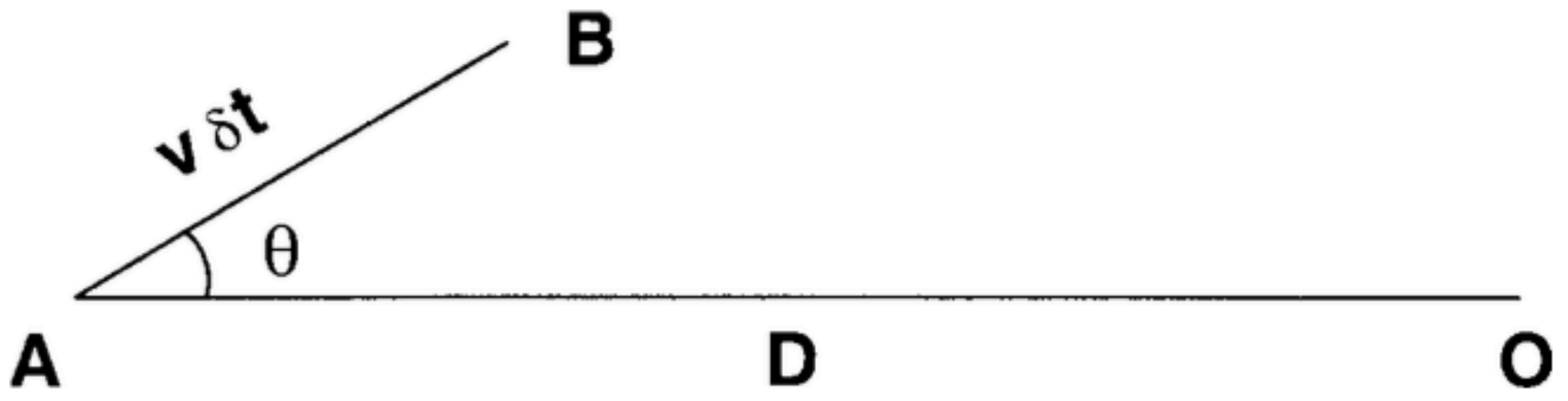


Fig. 9.13 A sketch illustrating how superluminal motion arises.

Superluminal motion

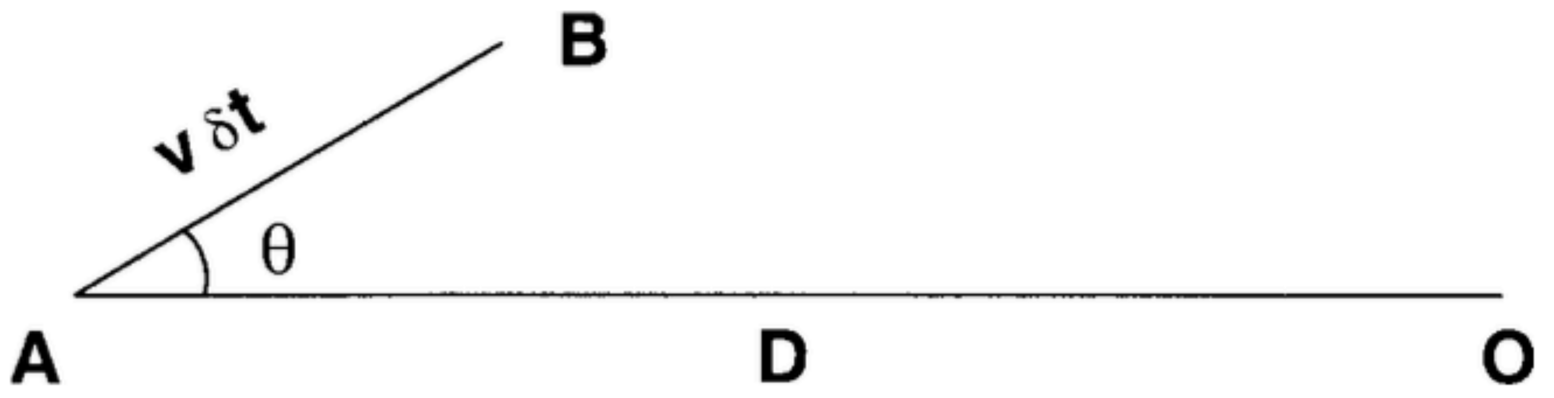


Fig. 9.13 A sketch illustrating how superluminal motion arises.

So the observer will receive the two signals at times differing by

$$t_{BO} - t_{AO} = \delta t \left(1 - \frac{v}{c}\cos\theta\right)$$

Since the observer will find that the source has moved by an amount v sin θ δ*t* in the sky, it will appear to the observer that the transverse speed of the source perpendicular to the line of sight is:

$$v_{\perp} = \frac{v \sin\theta\, \delta t}{t_{BO} - t_{AO}} = \frac{v \sin\theta}{1 - (v/c)\cos\theta}$$

$v_{\perp}$ can be larger than *c* if v is close to *c* and θ is small

Superluminal motion

The existence of superluminal motion makes it clear that quasars often have parts moving towards the observer with relativistic speeds. -> The moving part is a **jet ejected from the nucleus**.

This means that a **radio galaxy and a radio-loud quasar are the same kind of object viewed from different angles**.

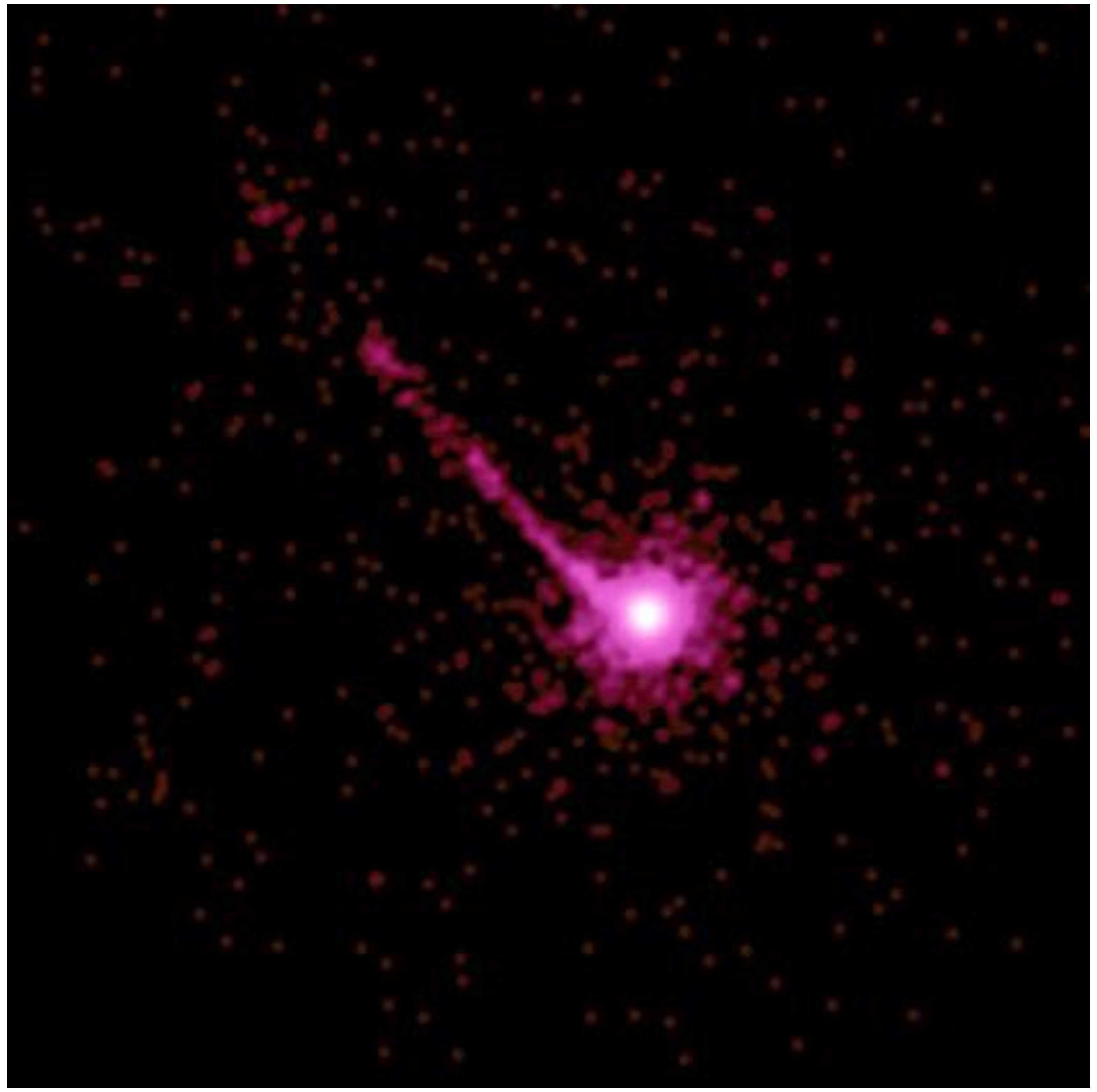
- The **radio galaxy has jets at large inclinations** to the line of sight so that the jets are seen as extended objects in the sky.
- On the other hand, if the **jet is directed towards the observer at a small angle** to the line of sight, then the source is seen as a **quasar**.

Radiation from a relativistically moving source appears to an observer to be beamed in the forward direction. The radio emission from the jet of a quasar (presumably by the synchrotron process) would be beamed in the direction of the jet and an observer lying in that direction would receive the beamed radiation, whereas an observer lying at a large angle with respect to the direction of the jet would get much less radiation. It is because of this **relativistic beaming that the radio emission from a quasar appears amplified** and quasars **can be observed at very large distances** where radio galaxies would be too faint to be detected.

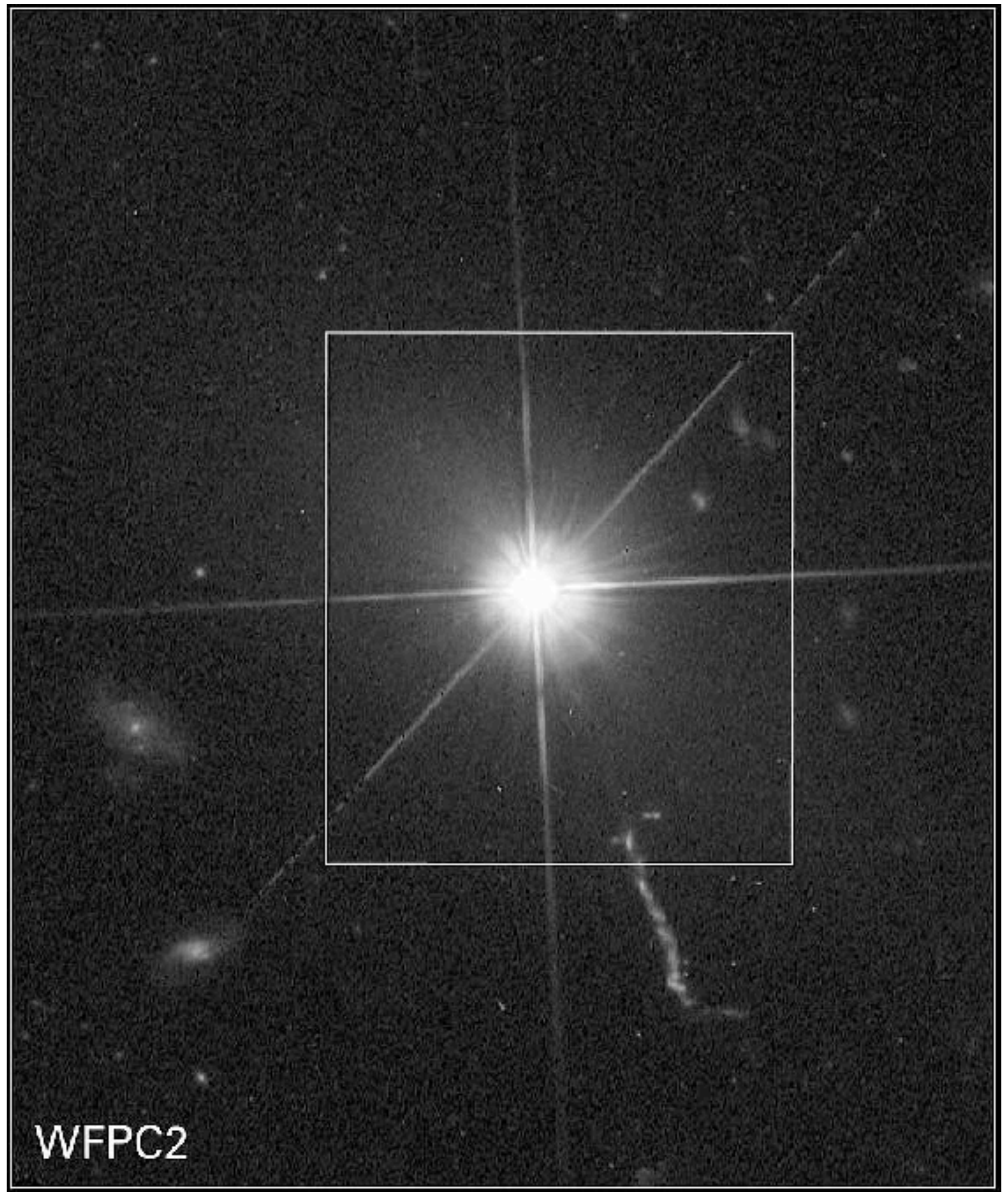
Superluminal motion

Note: many radio galaxies have **jets only on one direction**.

What is the reason?



X-ray image of quasar PKS 1127-145.



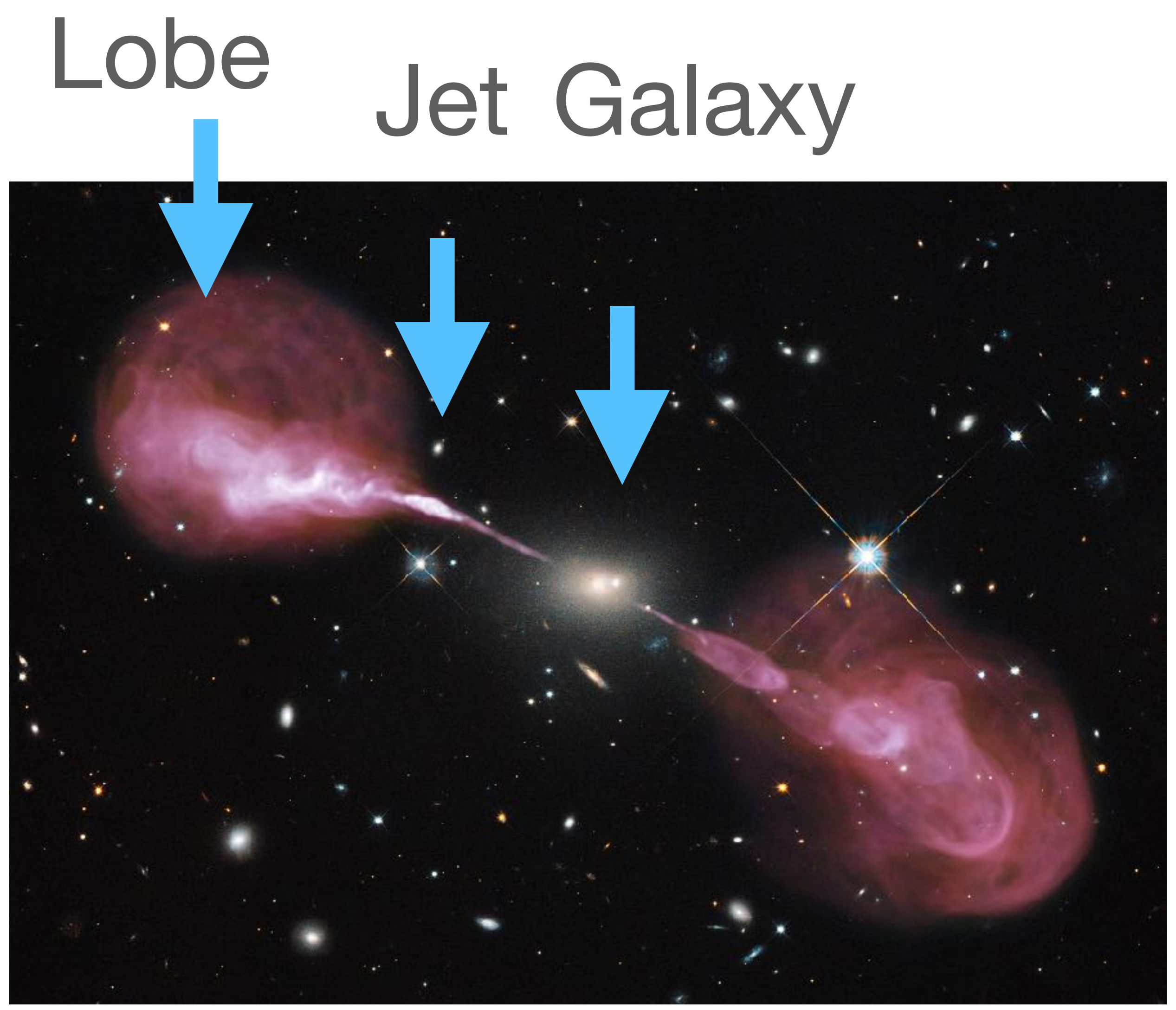
Optical image of quasar 3C 273

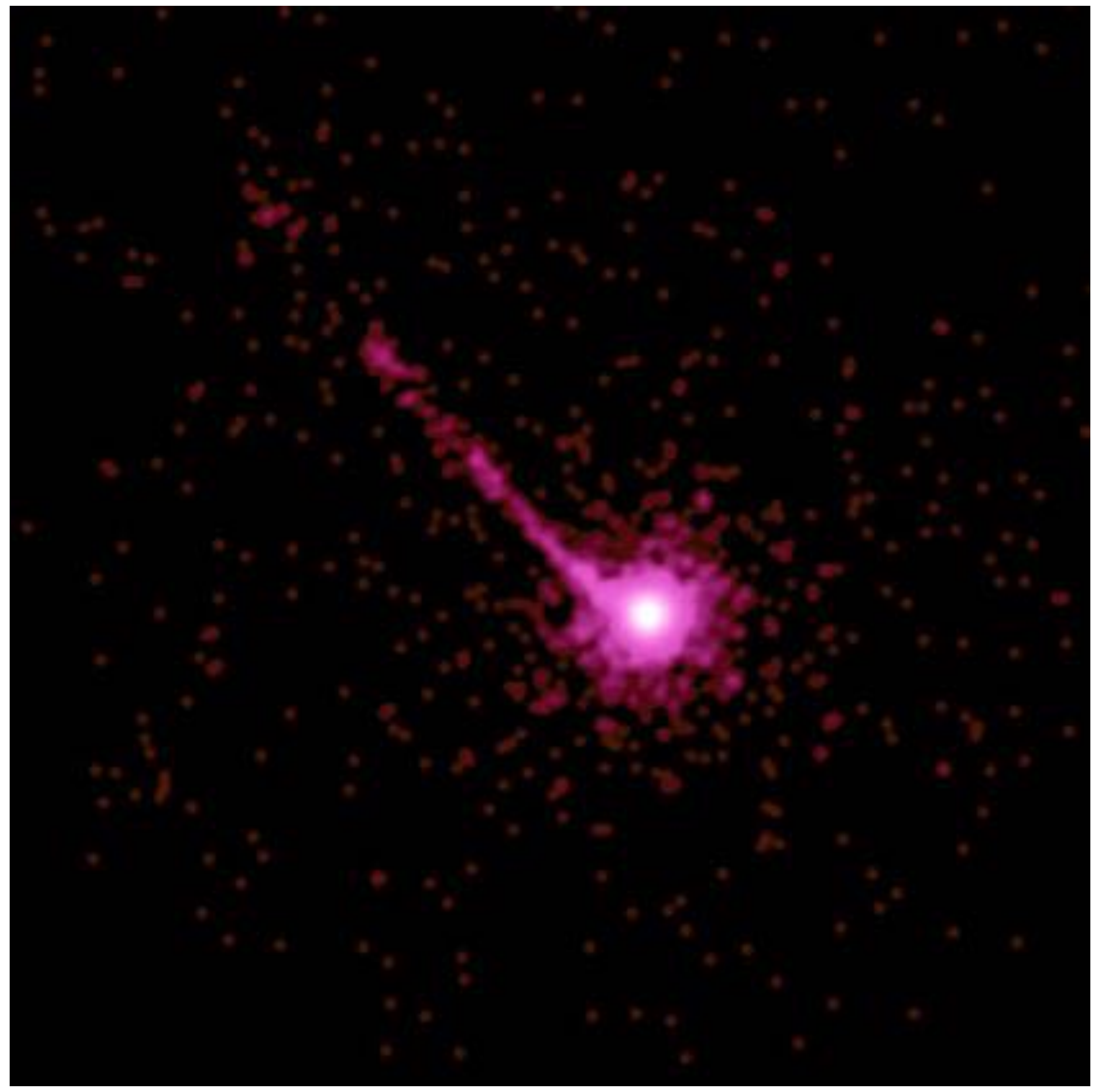
Superluminal motion

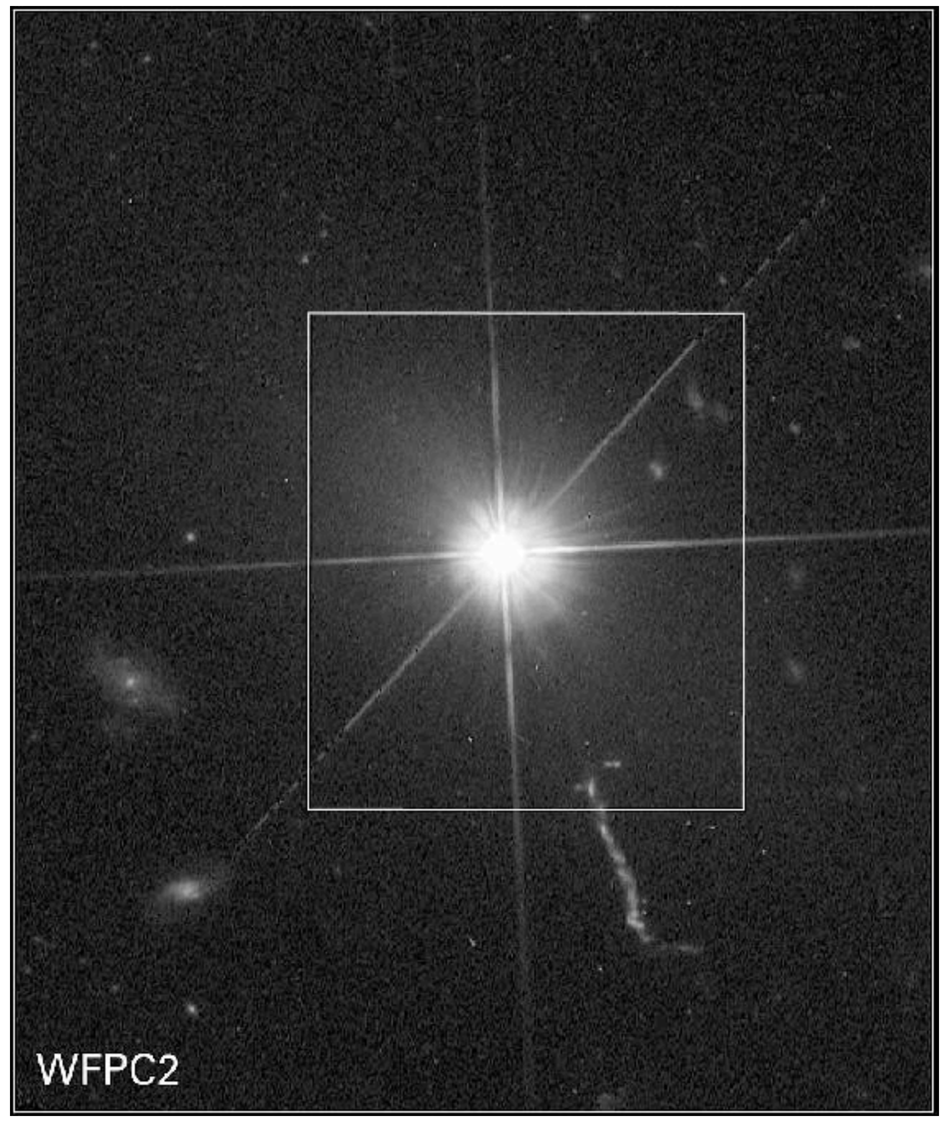
Note: many radio galaxies have **jets only on one direction**.

Since jets seem to be made up of relativistically moving plasma, relativistic beaming provides a natural explanation for this one-sidedness. **If a jet has a component of velocity towards the observer, relativistic beaming makes it brighter than the jet in the opposite direction.**

Radio galaxies also have radio-emitting lobes where the radio jets end. Presumably the lobes are not moving relativistically and radiation from the lobes is not relativistically beamed. That is why lobes of very distant quasars are not detectable and we receive relativistically beamed radiation coming primarily from the jet moving towards the observer.







The source of activity

What powers an active galactic nucleus, making it able to produce huge amounts of energy in a very small volume?

The source of activity

What powers an active galactic nucleus, making it able to produce huge amounts of energy in a very small volume?

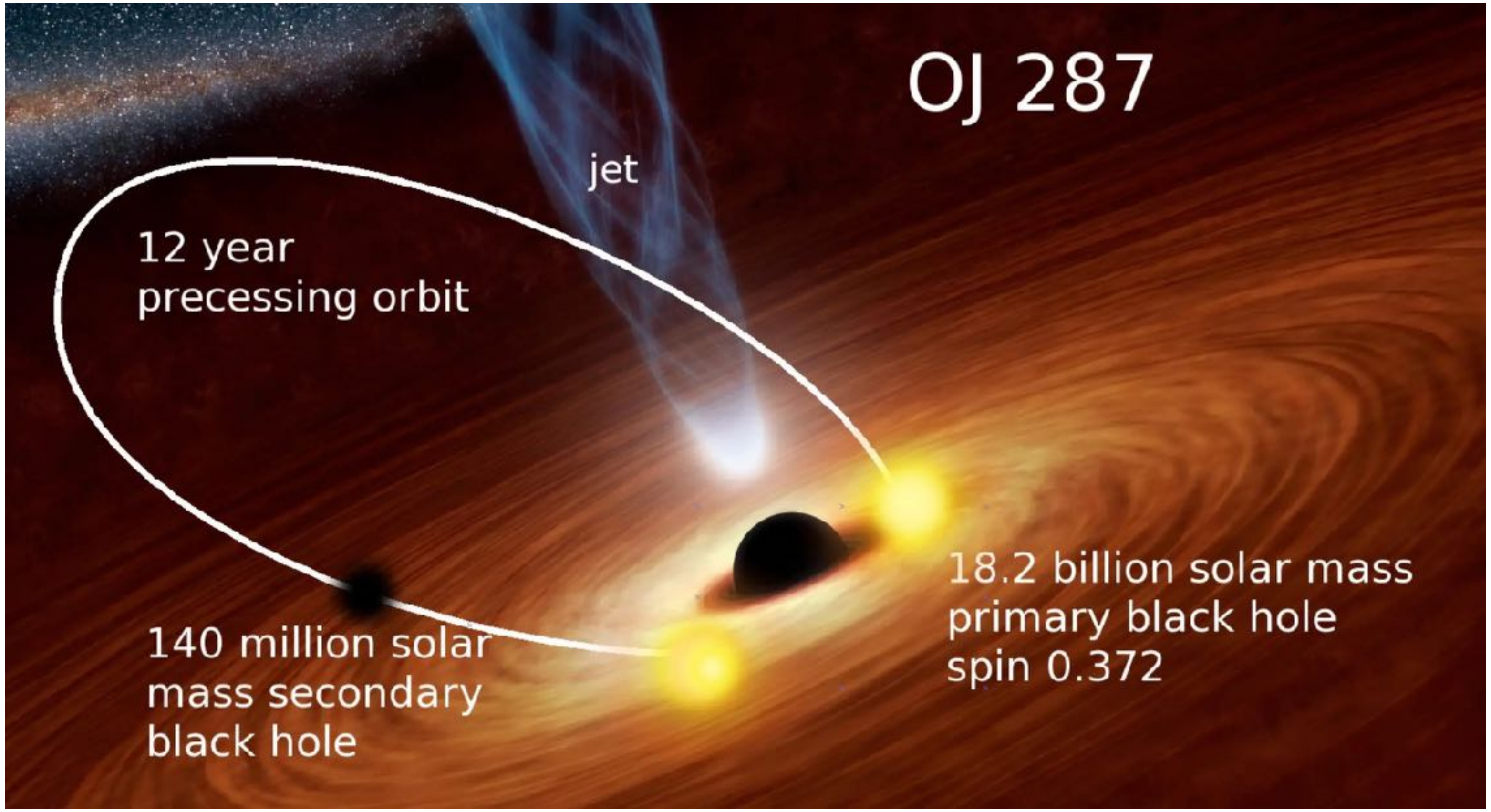
- We saw that binary X-ray sources are powered by material falling in the deep potential wells of neutron stars or black holes through accretion disks and by the conversion of a part of the lost gravitational potential energy to other forms.
- **Active galaxies must have black holes at their centres** and **matter losing gravitational potential energy in accretion disks** around them should be **providing the energy**.
- We can **estimate the mass of the central black hole** from if we assume that the energy output from the active nucleus is close to the Eddington luminosity. In order to produce a luminosity of 10^{39} W, we need a black hole of mass ≈ $\mathbf{10^8\ M_\odot}$**.**
- Once matter falls within the **Schwarzschild radius (boundary of the black hole)**, it cannot send a signal to the outside world any more.
- So most of the **radiation produced in an accretion disk around a black hole** should be coming from regions a little bit beyond the Schwarzschild radius.

Supermassive black holes

Two supermassive black holes orbiting each other at the core of the distant galaxy OJ 287.

The orbital motion is revealed by a **series of flares** that arise when the **secondary black hole plunges regularly through the accretion disk of the primary black hole** at speeds that are a fraction slower than the speed of light.

This **heats the disk material** and the hot gas is **released as expanding bubbles.** These hot bubbles take months to cool while they radiate and cause a flash of light – a flare – that lasts roughly a fortnight and is brighter than a trillion stars.

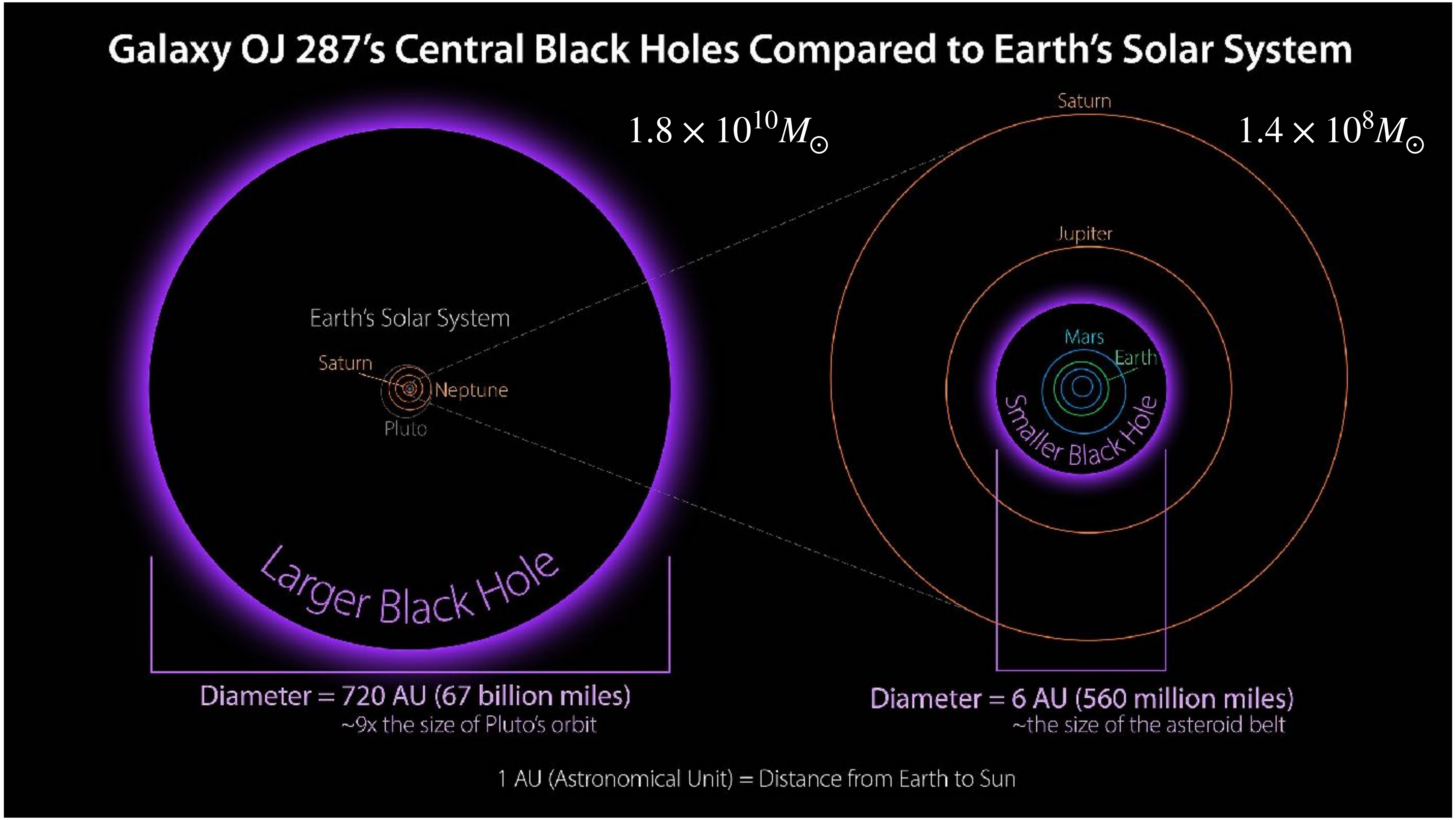


https://scitechdaily.com/flash-of-light-brighter-than-a-trillion-stars-leads-to-supermassive-black-hole-breakthrough/

Supermassive black holes

Two supermassive black holes orbiting each other at the core of the distant galaxy OJ 287.

The larger one, with about 18 billion times the mass of our sun (left), the smaller one is about 150 million times the mass of our sun (right).



https://en.wikipedia.org/wiki/Supermassive_black_hole

The black hole in the centre of AGN

The **Schwarzschild radius** is given by

$$r_S = \frac{2GM}{c^2} = 3.0 \times 10^{11} M_8 \text{ m}$$

where M_8 is the mass of the black hole in units of $10^8\ M_\odot$. This is **of the order of the Sun–Earth distance if $M_8 \approx 1$.**

We can estimate the temperature of the energy-producing region by equating the Eddington luminosity to $4\pi r_S^2 \sigma T^4$.

$$L_{\text{Edd}} = \frac{4\pi c\, GMm_{\text{H}}}{\sigma_{\text{T}}} \longrightarrow \frac{c\, GMm_{\text{H}}}{\sigma_{\text{T}}} = \left(\frac{2GM}{c^2}\right)^2 \sigma T^4, \longrightarrow T \approx 3.7 \times 10^5 M_8^{-1/4}.$$

It thus follows that **more massive black holes are associated with smaller temperatures**, which may seem counter-intuitive at first sight.

The black hole in the centre of AGN

In the case of larger black holes, however, the gravitational potential energy is lost over a larger radial distance, leading to a reduction in temperature. For a black hole of mass $10^8\ M_\odot$ the temperature would be appropriate for producing radiation in the extreme UV.

We now estimate the mass **infall rate required to produce the typical luminosity 10^{39} W of an AGN**.

Accretion is an efficient energy conversion mechanism in which a large fraction η of the rest mass energy can be converted into heat and radiation. Under favourable circumstances η can be as large as 0.1. If $\dot{M}$ is the mass accretion rate, then we must have

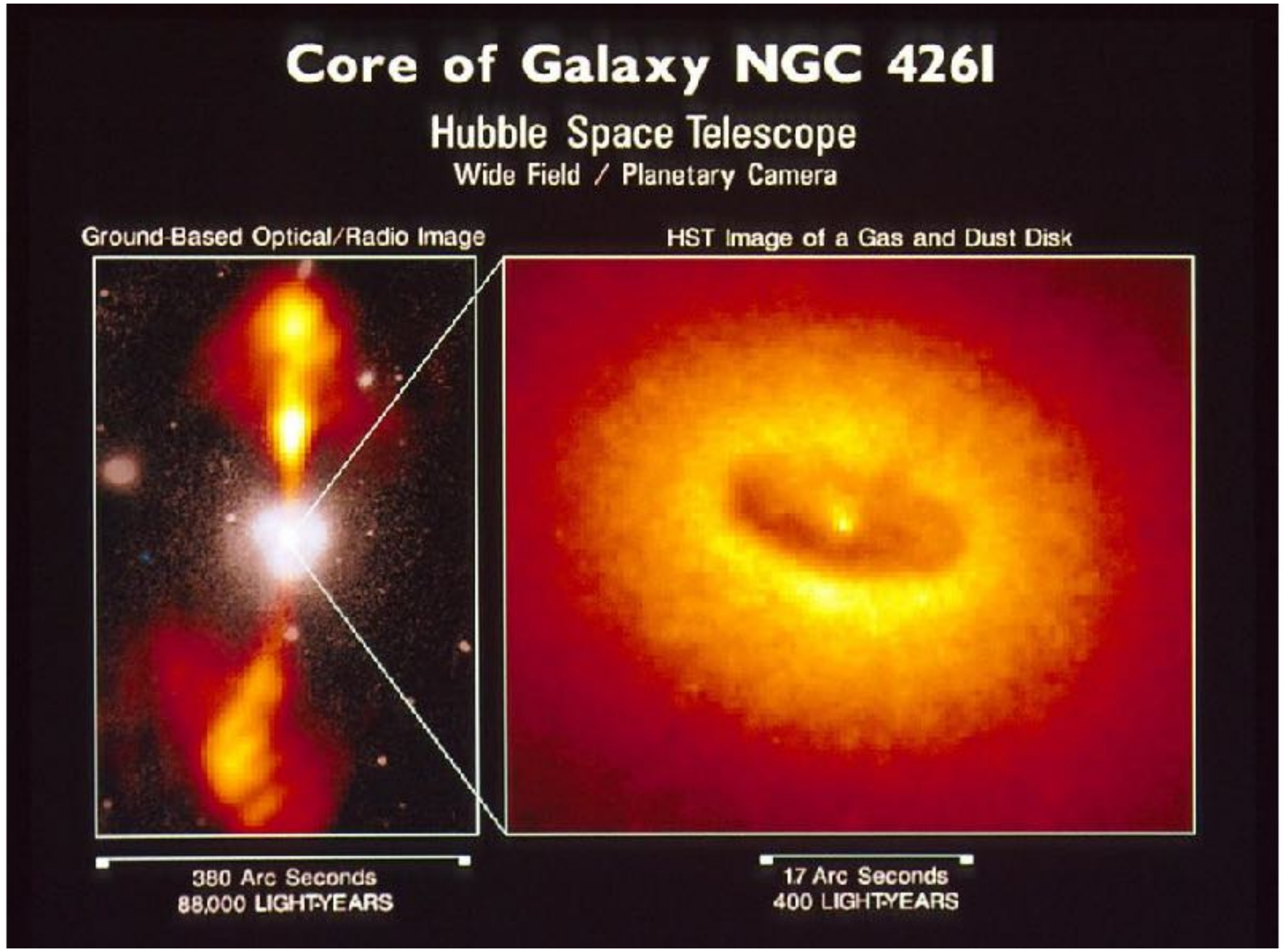
$$\eta \dot{M} c^2 \approx 10^{39}\ \mathrm{W} \longrightarrow \dot{M} \approx 1.5 M_\odot\ \mathrm{yr}^{-1}$$

on taking $\eta = 0.1$. We see that many of the observed characteristics of active galaxies are explained by assuming that there is a black hole of mass $10^8\ M_\odot$ in the galactic nucleus and that matter is falling into it through an accretion disk.

The black hole in the centre of AGN

More direct evidence that black holes may power active galaxies came when the Hubble Space Telescope photographed a disk of gas and dust at the centre of the active galaxy NGC 4261.

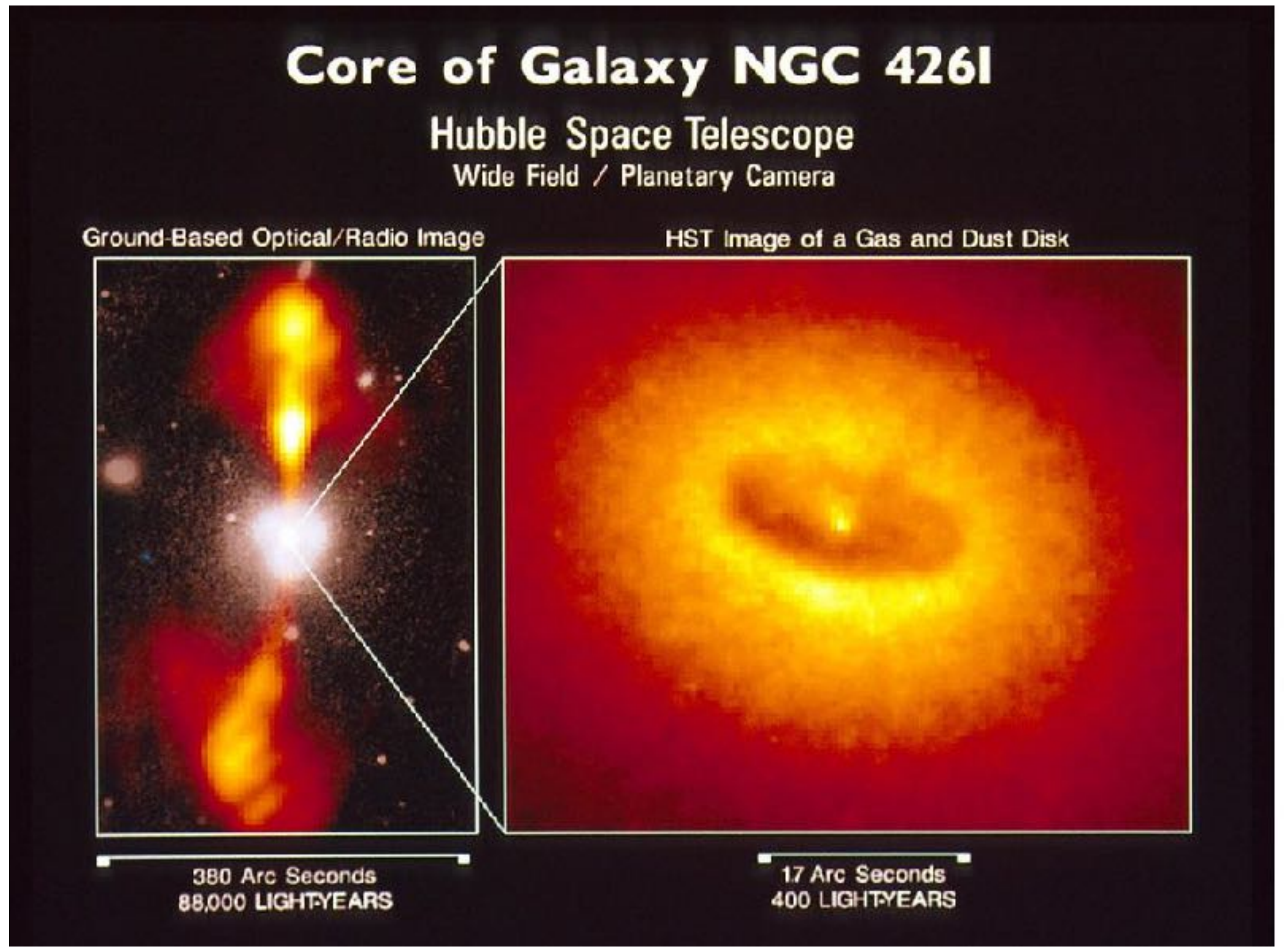
This disk, shown in the Figure, is the colder outer region of the accretion disk which is feeding the black hole located inside.



Since the a few years ago we also have now images of the central part of the accretion disk with the Event Horizon Telescope. Image of M87.

The black hole in the centre of AGN

- One of the important characteristics of many active galaxies is the **radio-emitting jets.** A tiny fraction of the material falling into the black hole has to be ejected in the form of jets, which come out **perpendicular to the accretion disk**.
- Understanding this mechanism is part of active research.
- The active galaxy NGC 4261 has radio-emitting jets and the disk shown in the Figure is approximately perpendicular to the axis of the jets.
- Many of the jets appear highly collimated. **Magnetic fields play an important role in the collimation of the jets.**
- The emission of synchrotron radiation from the jets shows that these relativistic plasma jets must have magnetic fields and accelerated electrons. If the electrons were accelerated in the galactic nucleus and then carried with the magnetized plasma flowing into the jets, simple estimates show that the electrons may cool by the time they reach the extremities of the jets. Hence ***in situ* particle acceleration has to take place inside jets.**



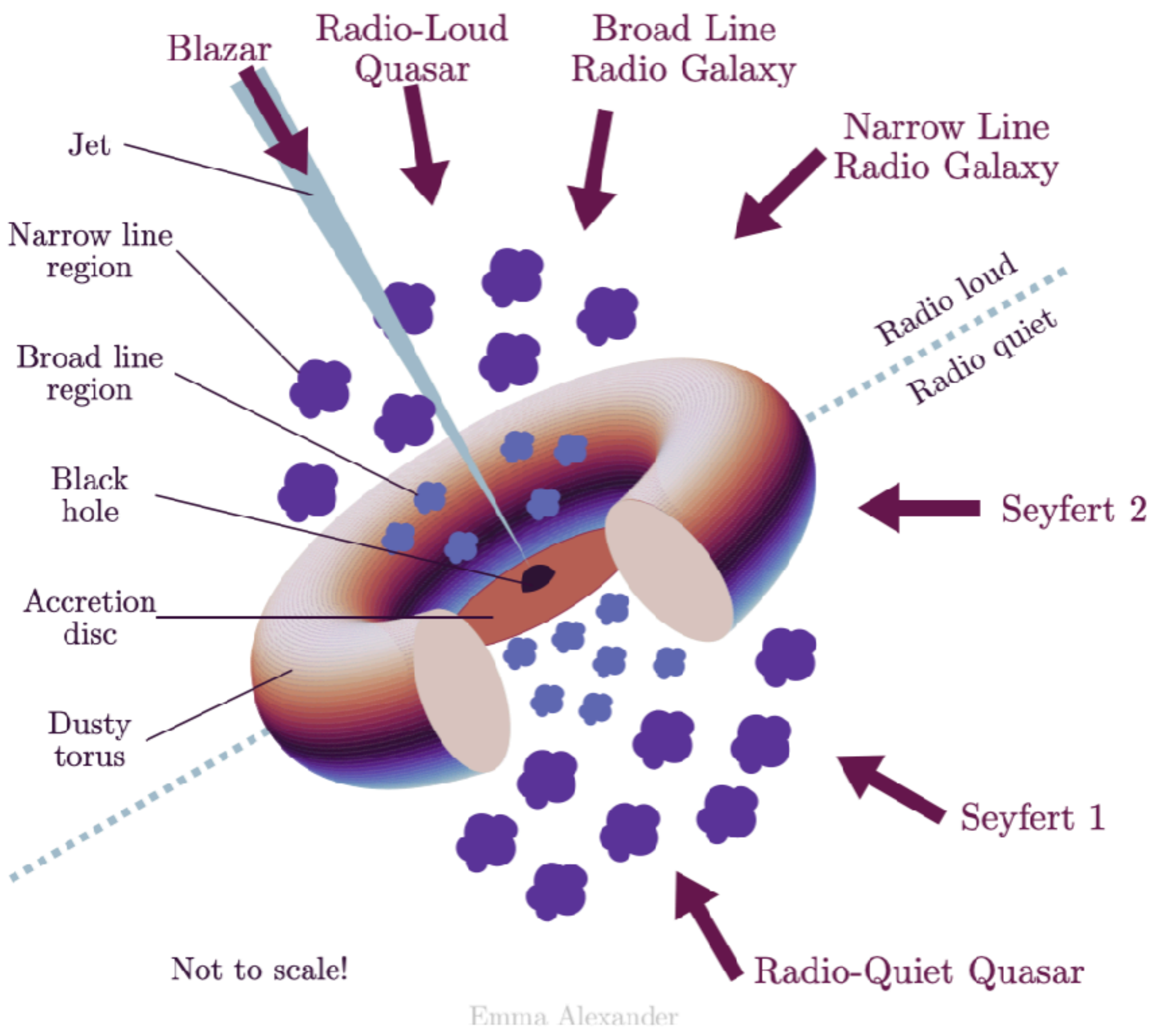
The unified model of AGN

- Seyfert galaxies and quasars appear to be similar kinds of objects, the only difference being that quasars have much more powerful central engines. Presumably Seyfert galaxies have less massive black holes in their central nuclei.
- **Radio galaxies and radio-loud quasars also seem to be the same objects viewed from different viewing angles**. Is it possible that all active galaxies simply form a simple sequence according to the strength of their central engines, but appear as different kinds of objects to observers due to the different viewing angles?
- It was proposed that there are **fast-moving gas blobs called *broad-line regions*** (abbreviated as *BLR*s) near the central engine. Only in the case of **Seyfert 1**, radiation emitted by these reaches the observer and the emission lines appear broadened due to the Doppler-broadening of these fast-moving gas blobs.
- In the case of **Seyfert 2,** we receive radiation only from **gas blobs much further away from the central engine** which are moving **more slowly** and are known as ***narrow-line regions*** (abbreviated as *NLR*s), giving rise to narrower emission lines.

The unified model of AGN

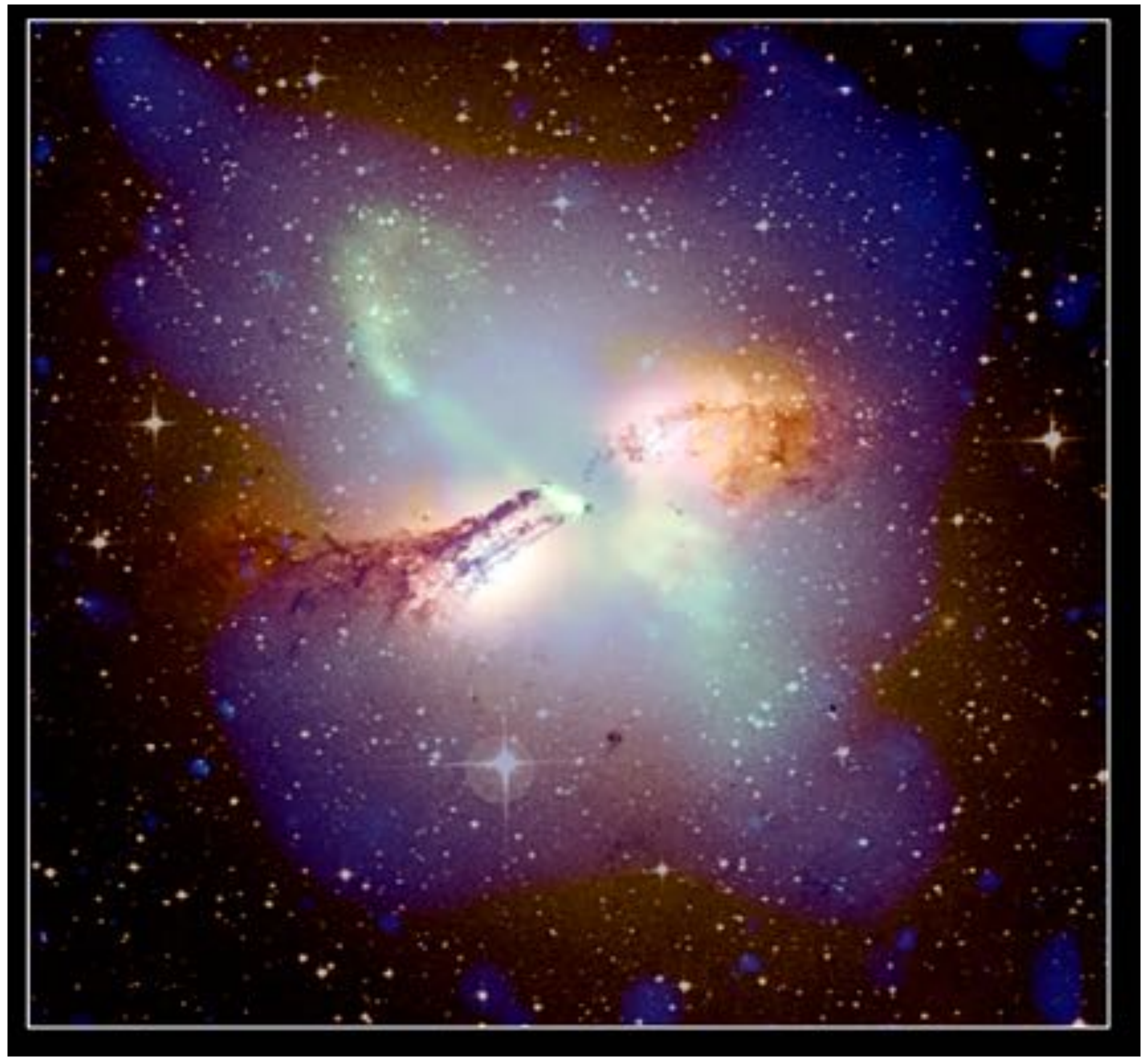
Summary: Unified model of AGN adapted from Urry & Padovani (1995). T

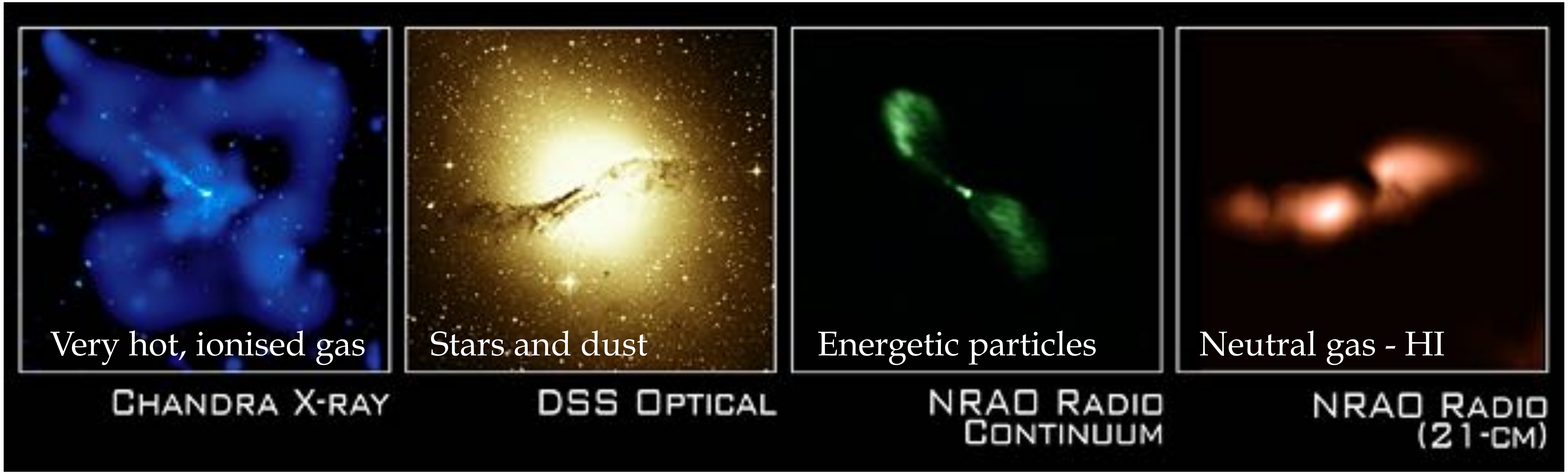
he thick arrows represent different viewing angles, and the observed object which results from them. Note the asymmetry of the diagram; this is to demonstrate the two different possibilities of radio loud/quiet and is not representative of a single object.



Active galaxies

The AGN **Centaurus A,** also known as **NGC 5128**
Observed at different wavelengths





Active galaxies

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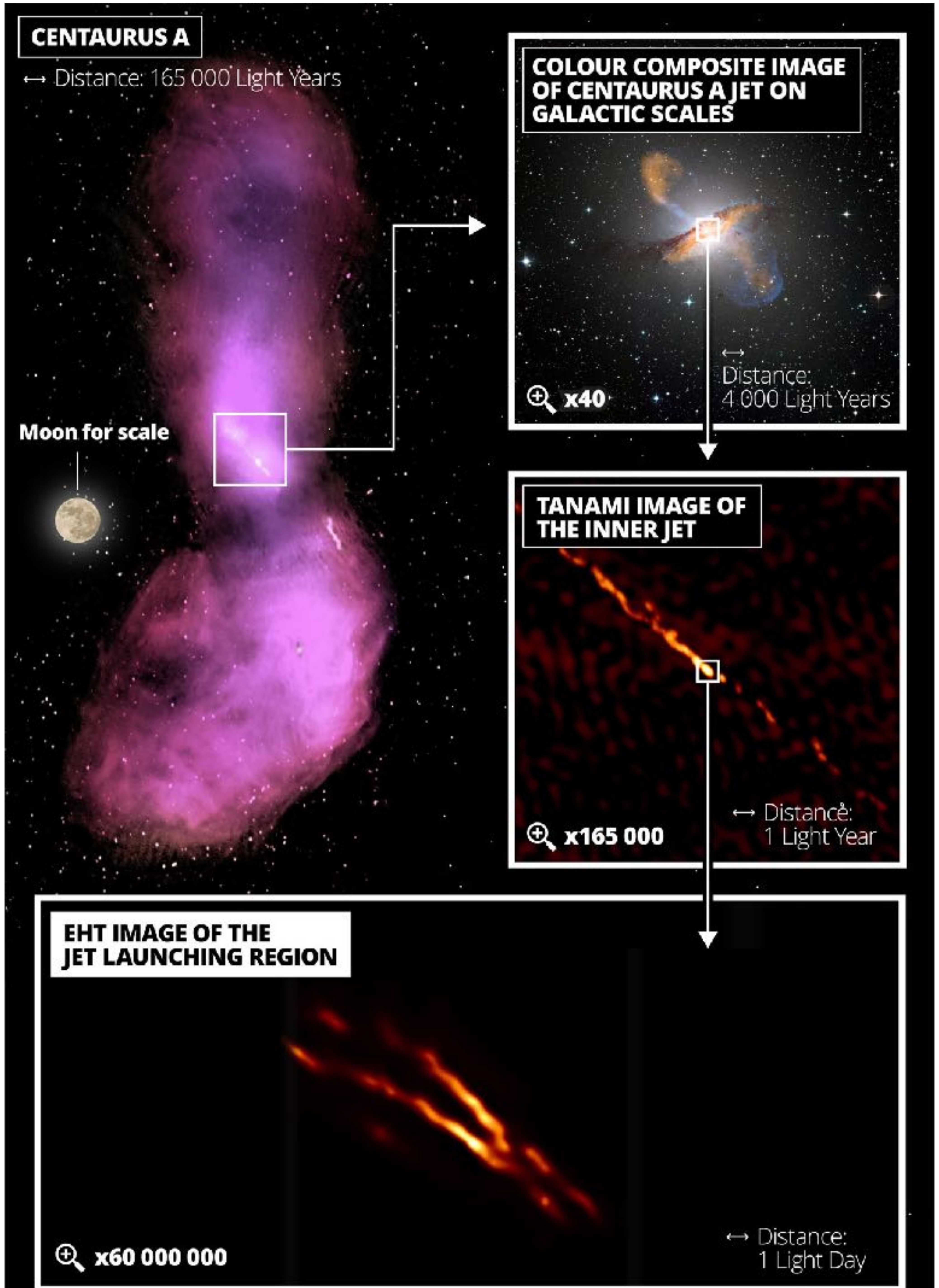
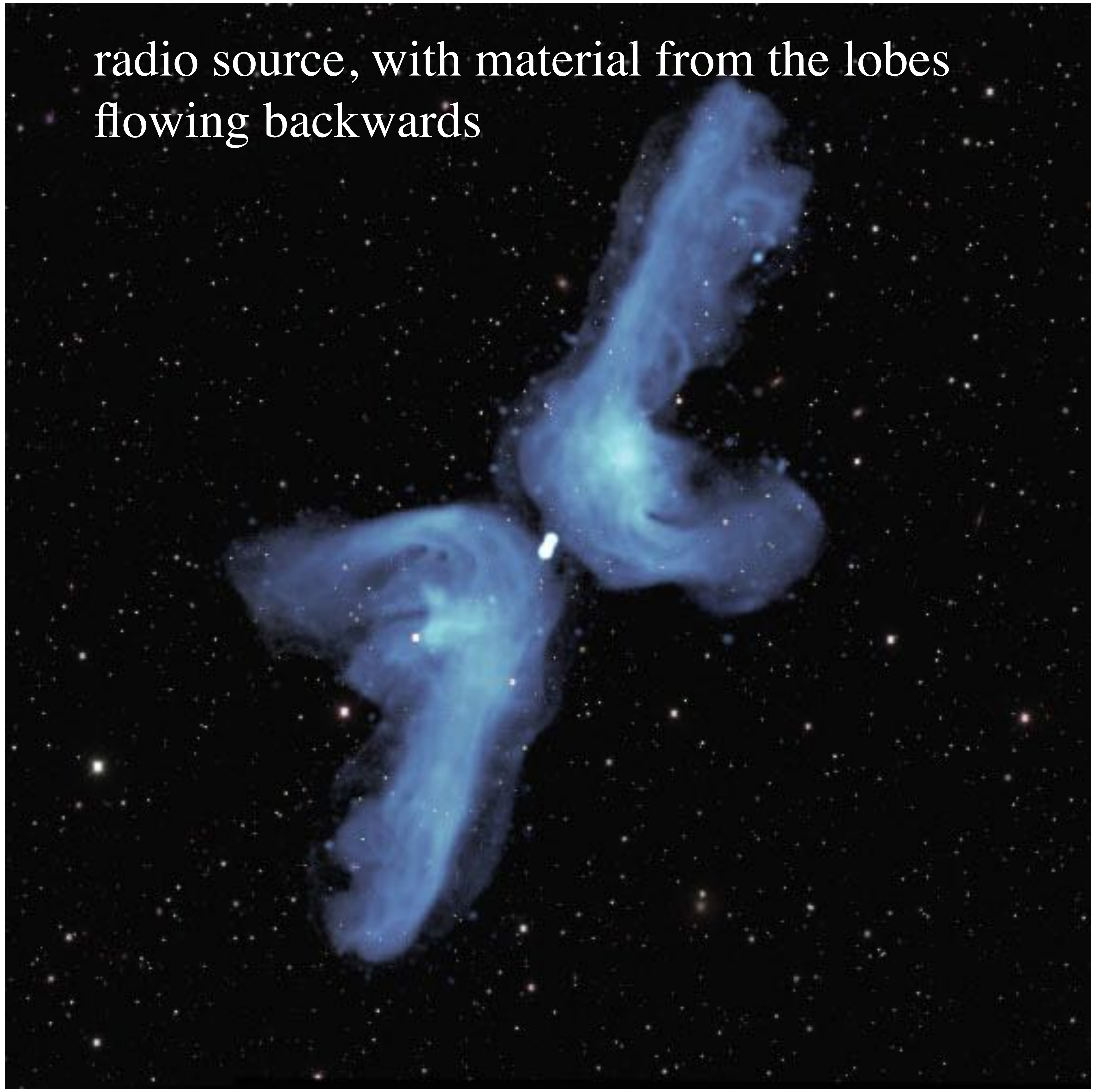
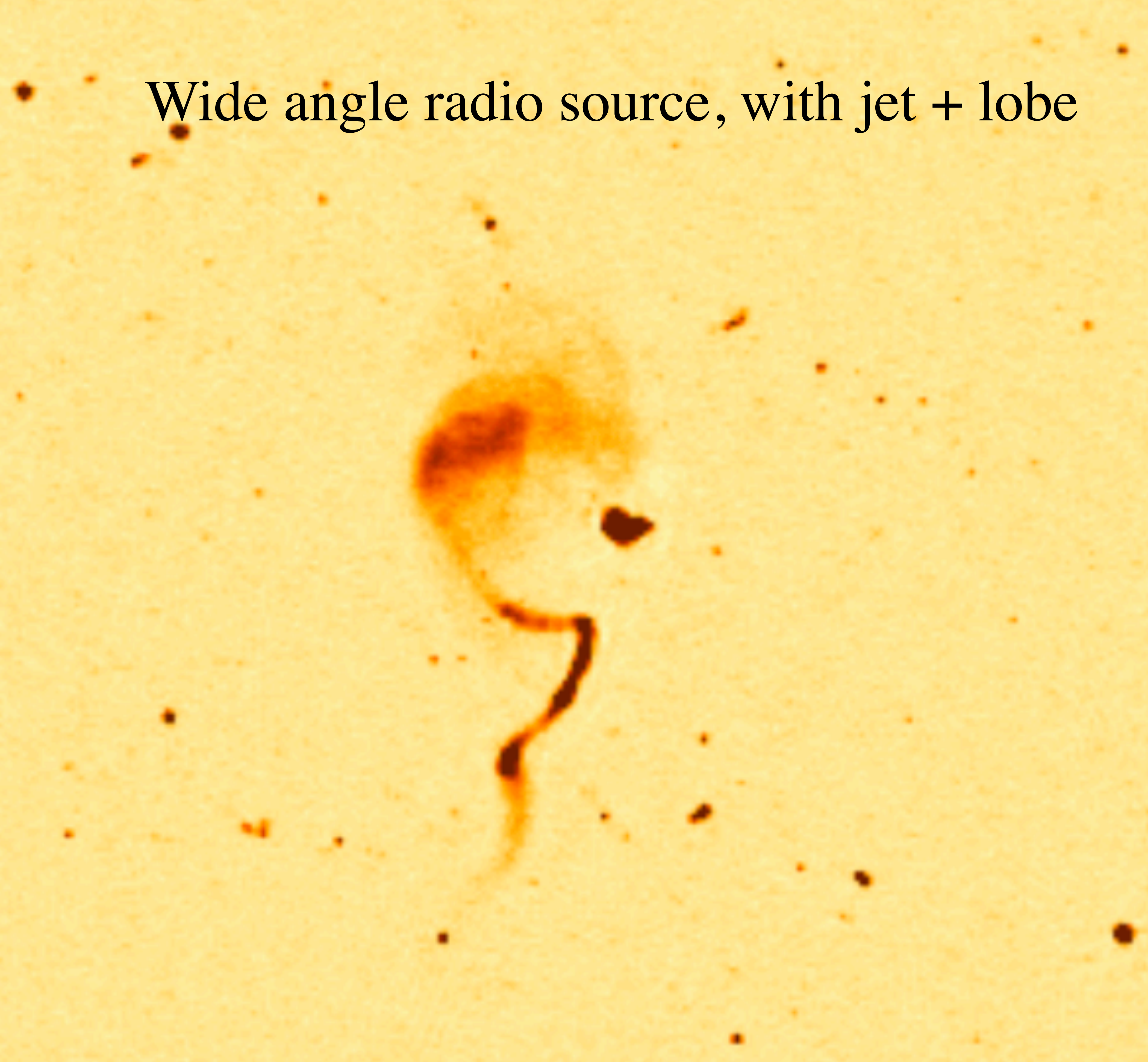


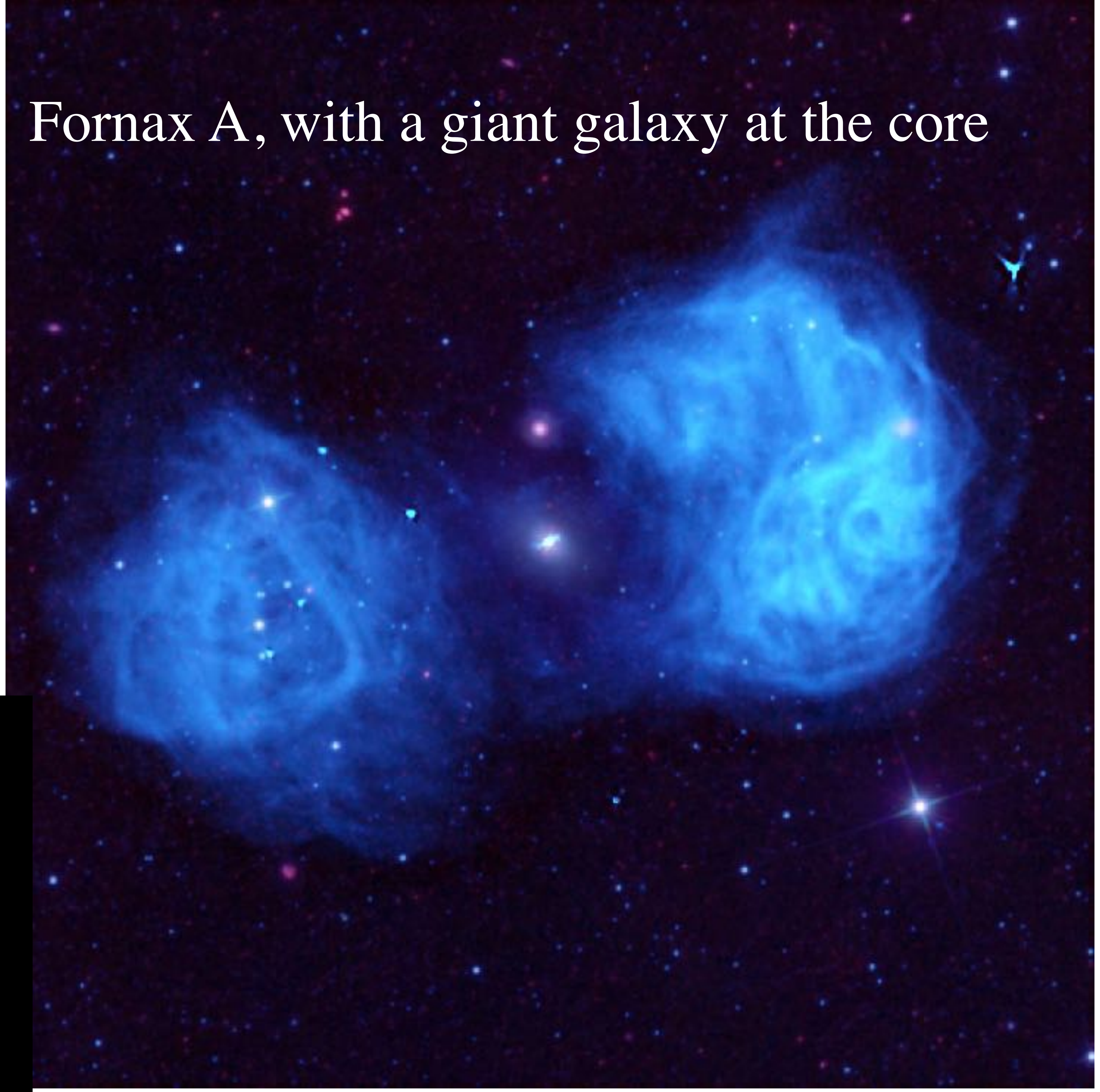
Active galaxies



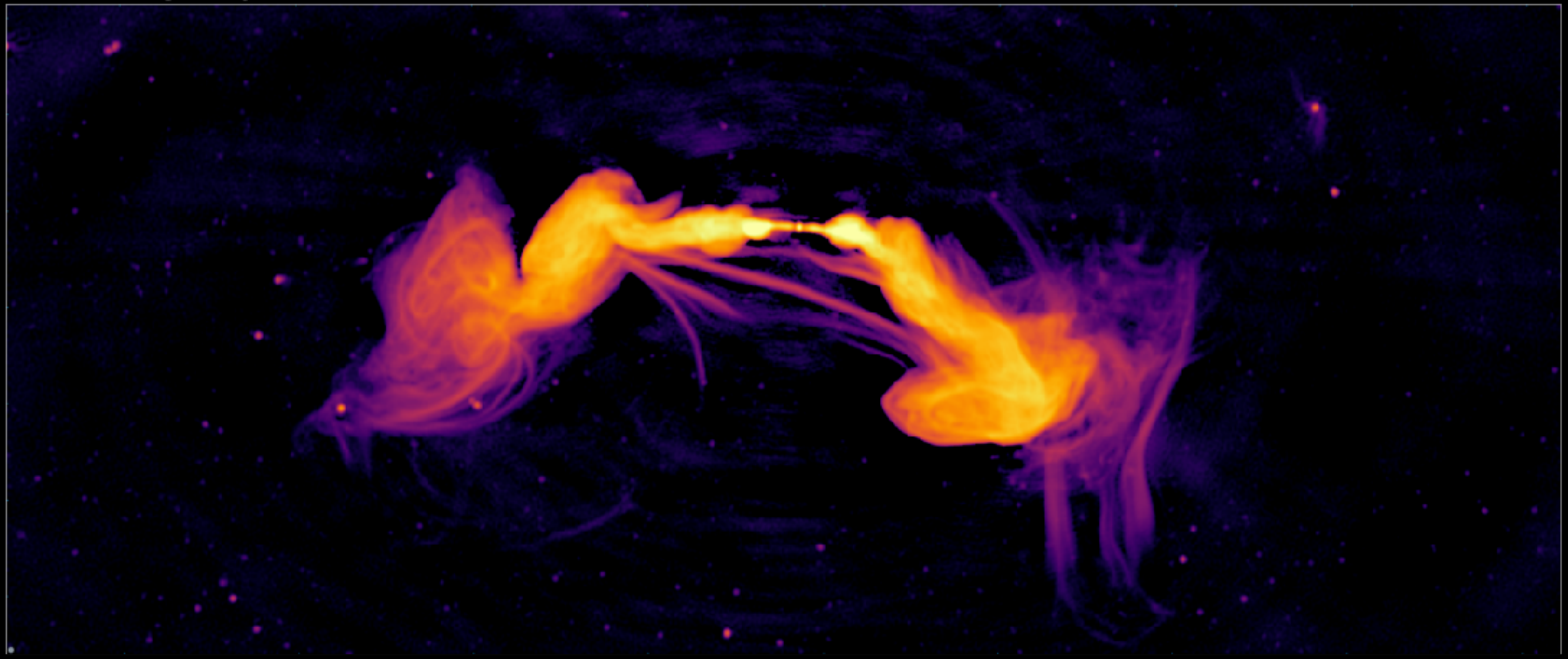


Active galaxies

New interferometers with amazing spatial resolution make it possible to detect these features in nearby bright radio galaxies



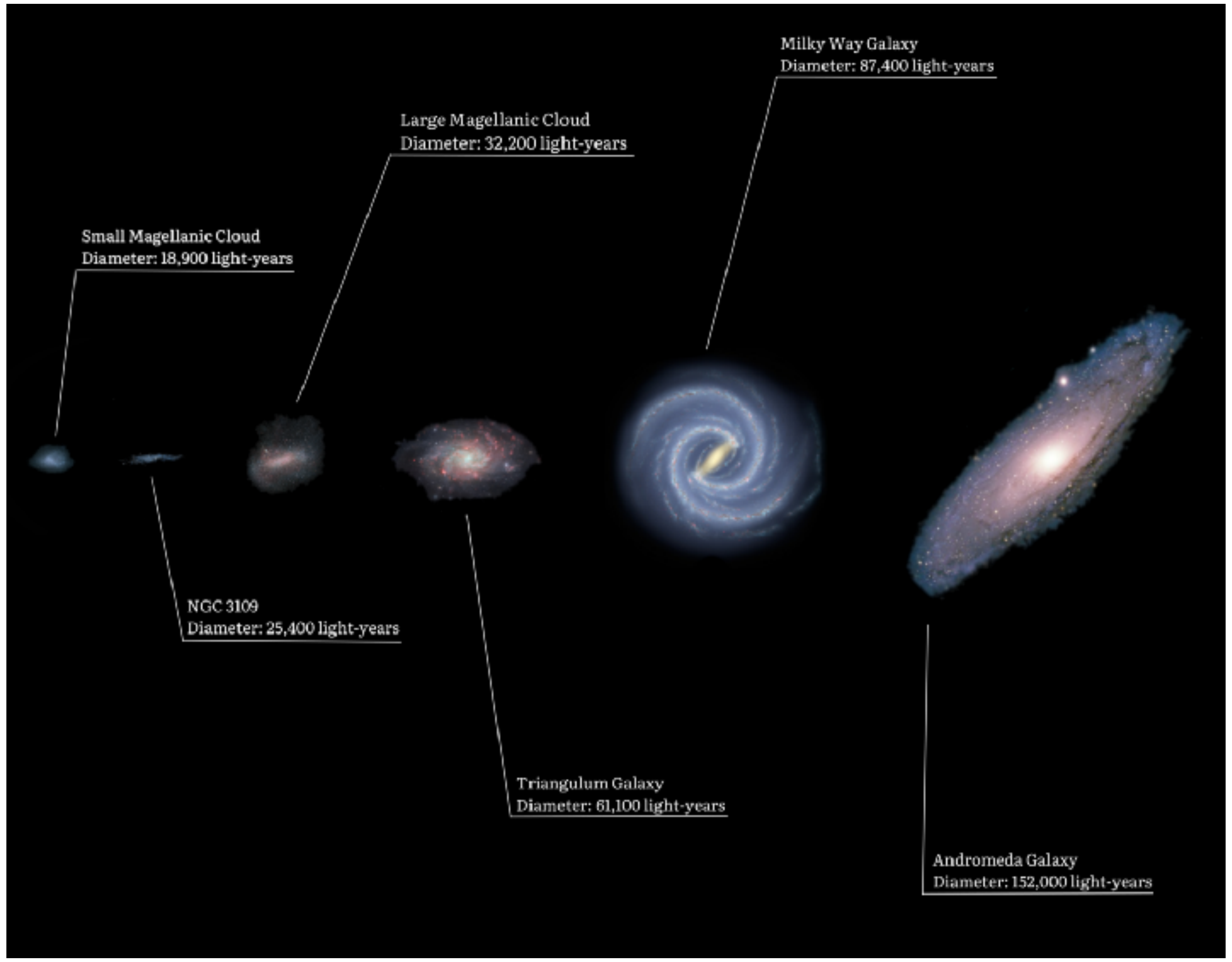
The radio galaxy ESO 137-006



"Collimated synchrotron threads linking the radio lobes of ESO 137-006", M. Ramatsoku et al. 2020, A&A
MeerKAT Radio Telescope image at 1000 MHz
Image credits: Rhodes University / INAF / SARAO

Galaxy clusters

- Galaxies are often grouped together in galaxy groups or clusters.
- Our Galaxy is a member of a cluster of about 80 galaxies called the ***Local Group*.**
- The **Andromeda Galaxy (M31) is the most prominent member of the Local Group** and our Galaxy is the second most prominent member.
- The members of the Local Group are spatially distributed in an irregular fashion without any symmetry.



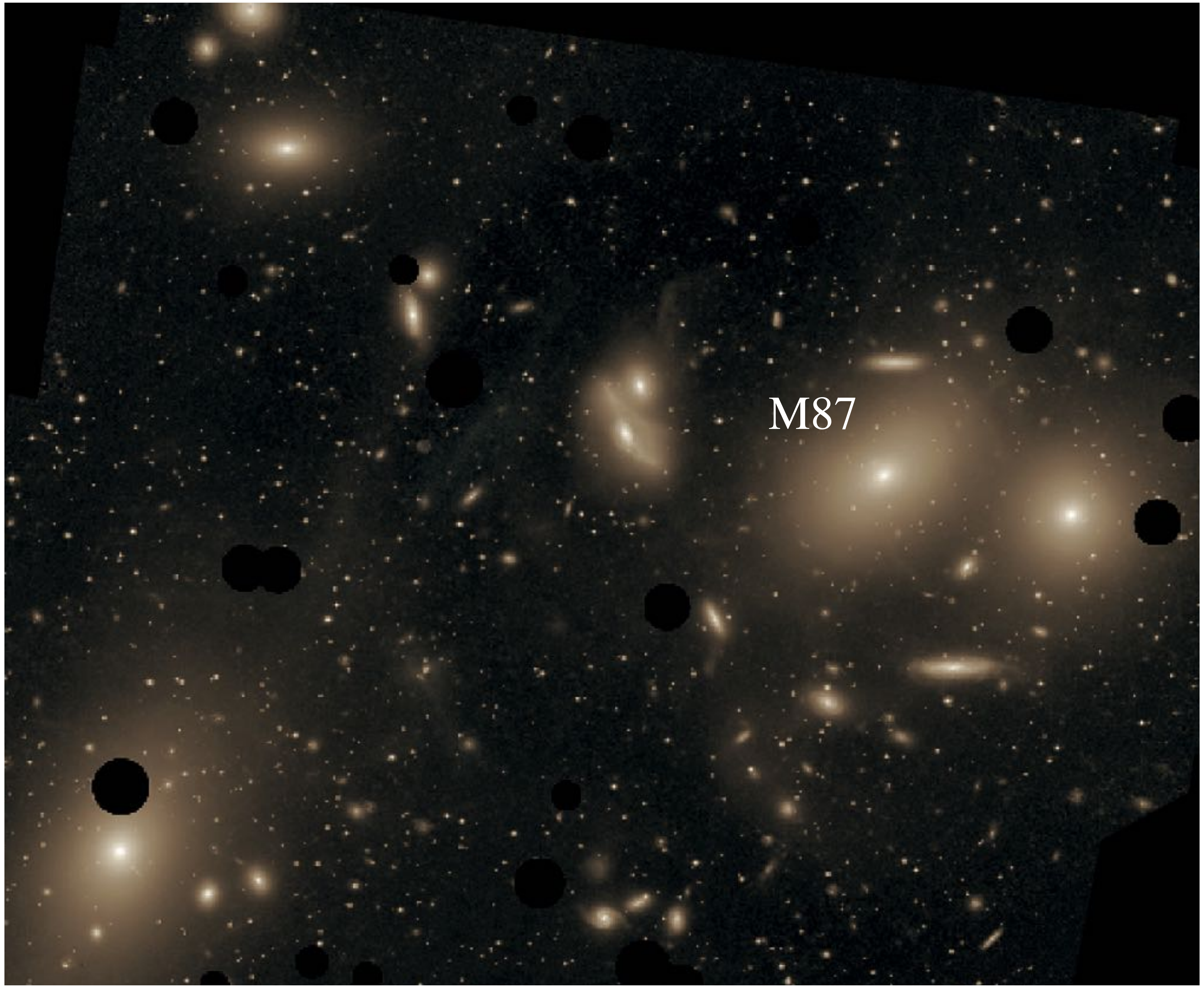
Galaxy clusters

- Rich clusters (clusters with many galaxies), however, tend to have more symmetric and regular appearance. A typical rich cluster can have more than 100 galaxies distributed within a range of order 1 Mpc.
- Abell (1958) catalogued a few thousand clusters of galaxies, all lying within several hundred Mpc from us.
- **A cluster of galaxies is usually a gravitationally bound system and does not expand with the expansion of the Universe.** So it is the clusters of galaxies rather than galaxies themselves which are moving away from each other with the expansion of the Universe.
- In fact, there are indications that **the Local Group has an infall velocity of a few hundred km/s towards the Virgo cluster,** the nearest large cluster, superposed on the Hubble expansion.

Galaxy clusters

- The large elliptical galaxy M87 is at the centre of the Virgo cluster.
- It is quite **common to find a large elliptical galaxy at the centre of a large cluster of galaxies**.
- Such galaxies form due to the **merger of several galaxies.**
- Stars occupy only a tiny fraction of volume inside a galaxy, physical collisions between stars inside a galaxy is an extremely unlikely event.

The Virgo galaxy cluster



Galaxy clusters

- The Figure shows a pair of **colliding galaxies**, which interestingly have produced long tail-like structures. Such colliding galaxies merge together.
- **Galaxies at the centre of a cluster** are the result of the **merger of a few large galaxies.**
- A galaxy moving in a galaxy cluster also can be slowed down by dynamical friction.
- Once a central galaxy forms, other galaxies moving through nearby regions may lose their energy due to dynamical friction and then fall into the central galaxy.

Major merger of galaxies

Galaxy clusters

- The Galaxies inside a cluster typically have velocity dispersions of order 1000 km/s.
- The **virial theorem** **can be applied to estimate the mass of a star cluster**. If a galaxy cluster is relaxed, then one can apply

$$\langle v^2 \rangle \approx \frac{GM}{\langle R \rangle}$$

- to estimate the mass of the galaxy cluster.
- On substituting v ≈ 1000 km/s and $R \approx 1$ Mpc, the mass of a galaxy cluster **typically turns out to be of order $M_{gc} \approx 10^{15} M_{\odot}$.**

Major merger of galaxies

Galaxy clusters

- On the other hand, the total luminosity of a galaxy cluster typically is of order $L_{gc} \approx 10^{13} L_\odot$. For a typical galaxy cluster, we then have

$$\frac{M_{\mathrm{gc}}}{L_{\mathrm{gc}}} \approx 100 \frac{M_\odot}{L_\odot}$$

- If the galaxies in a cluster were made up of stars like the Sun and there was no other matter inside the cluster, then one would have M_{gc}/L_{gc} equal to $M_\odot/L_\odot$ ***(mass to light ratio).***
- If a galaxy has lots of stars less massive than the Sun and much less efficient in producing energy (due to the mass–luminosity relation), then it is possible that M/L of the stellar component can be of order $10 M_\odot/L_\odot$.
- A **factor of 100 implies** that it is not possible for the stars inside the galaxies to account for more than 10% of the mass of a typical galaxy cluster. **Most of the matter in a galaxy cluster has to be dark matter,** leading to the high random velocities of the galaxies in the cluster.
- Careful analyses indicate that at most 30% of the dark matter in a galaxy cluster may be attached to galaxies. The rest of the **dark matter is somehow distributed within the cluster.** Nobody at present has a good clue about how this dark matter is distributed in a galaxy cluster or what it is made of.

Galaxy clusters

- X-ray emission (pink) superposed on the optical image of the Coma cluster.

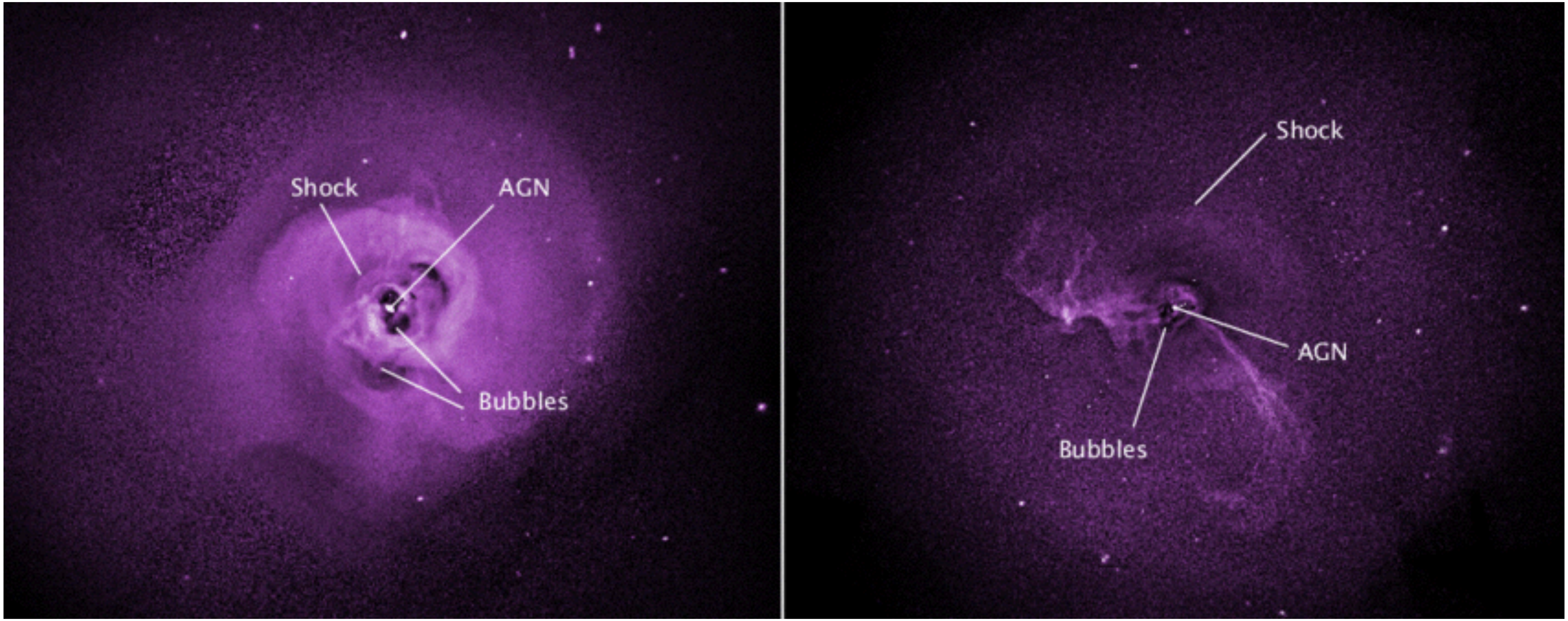
- Some of the material in galaxy cluster is outside galaxies, and a small fraction of it exists in the form of hot thin gas → this gas emits X-rays.
- The first extragalactic X-ray source to be detected was M87 in the Virgo cluster.
- **Many galaxy clusters are X-ray sources.**
- The approximately spherical X-ray image suggests that the hot gas emitting X-rays is distributed fairly uniformly and symmetrically throughout the galaxy cluster.
- The **primary emission mechanism is believed to be bremsstrahlung.**

Galaxy clusters

- Various aspects of the X-ray emission of galaxy clusters can be explained by assuming that it is bremsstrahlung emitted by a hot plasma of **temperature 10^8 K** with particle number density $n_e \approx 10^3\ \mathrm{m}^{-3}$.
- Assuming that the total volume of the gas is of order 1 Mpc^3, it is easy to show that the total X-ray luminosity from the cluster would be 10^{37} W. This is a typical X-ray luminosity of galaxy clusters.
- The total mass of the hot gas is of order $10^{13}\ M_\odot$, indicating that the **hot gas contributes only a small fraction of the mass of the galaxy cluster.**

Galaxy clusters

- We can also study the **structure of the gas distribution**, thanks to new generations of X-ray satellite observatories.
- These examples of the Perseus and the Virgo cluster were taken by the Chandra X-ray observatory



Galaxy clusters

- **From where did the gas in the galaxy cluster cam from and why it is so hot?**

Galaxy clusters

- **From where did the gas in the galaxy cluster cam from and why it is so hot?**
- Presumably, when the galaxy clusters formed, some of the primordial gas got trapped within the cluster. The trapped gas can become heated simply by falling in the gravitational potential well of the cluster.
- The overall X-ray spectra from galaxy clusters can be explained quite well by assuming the emission to be due to bremsstrahlung.
- The spectra of some clusters show an emission line at 7 keV, which is identified as a line due to **highly ionized iron.** From the intensity of this line, one concludes that the ratio of the number of iron atoms to the number of hydrogen atoms in a typical galaxy cluster is of order

$$\frac{\mathrm{Fe}}{\mathrm{H}} \approx 2 \times 10^{-5},$$

- which is about half the solar value.
- As far as we know, heavy elements like **iron can be synthesised only in the interiors of massive stars.**
- The ISM of a galaxy gets contaminated with such heavy elements when supernovae spew out materials from the interiors of massive stars into the ISM.

Galaxy clusters

- The presence of iron in the gas in galaxy clusters indicates that this gas could not be pure primordial gas, but material from the ISMs of the galaxies in the cluster also must have been mixed with the gas.
- This issue is connected with the issue that the fraction of spiral galaxies in the central regions of rich clusters is much less than that fraction in the low-density regions of the Universe.
- The most plausible explanation would be that **some of the spiral galaxies in the cluster have been converted into elliptical galaxies by losing their ISMs and this gas lost from the spiral galaxies has been mixed with the gas in the cluster,** thereby causing the observed iron abundance in that gas.
- How do spiral galaxies in a cluster lose their ISM?
- **When a spiral galaxy moves fast through the cluster, the gas in the cluster would seem to blow against it like a strong wind.** This wind blowing against the galaxy would exert a pressure on the surface of the galaxy where the wind is braked. This is called the ***ram pressure***. This ram pressure can force the ISM out of the galaxy, provided it is strong enough to overcome the gravitational force with which the ISM is bound in the galaxy.

Large scale structure

Are the galaxy clusters the largest structures in the Universe or are there even bigger structures?

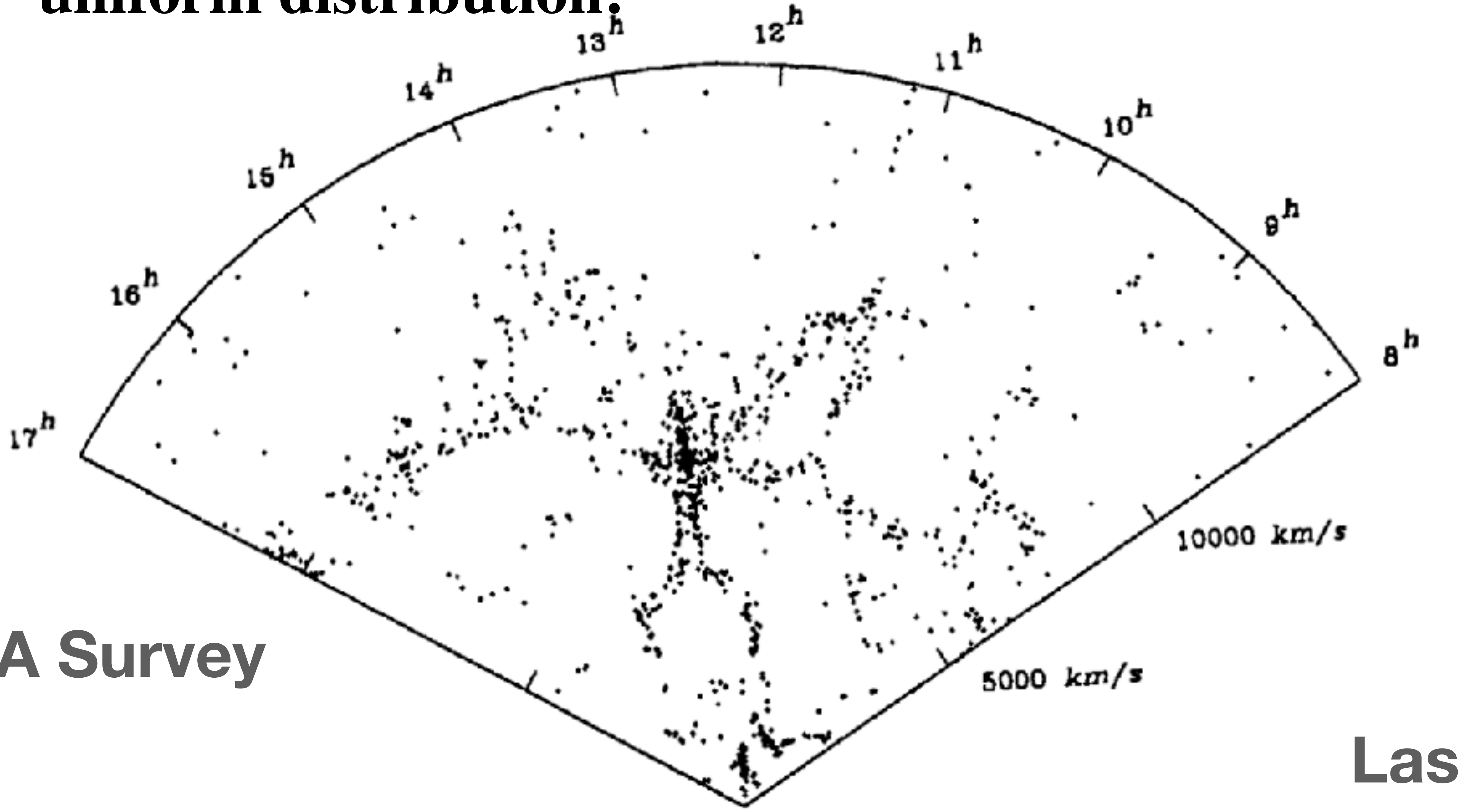
Large scale structure

Are the galaxy clusters the largest structures in the Universe or are there even bigger structures?

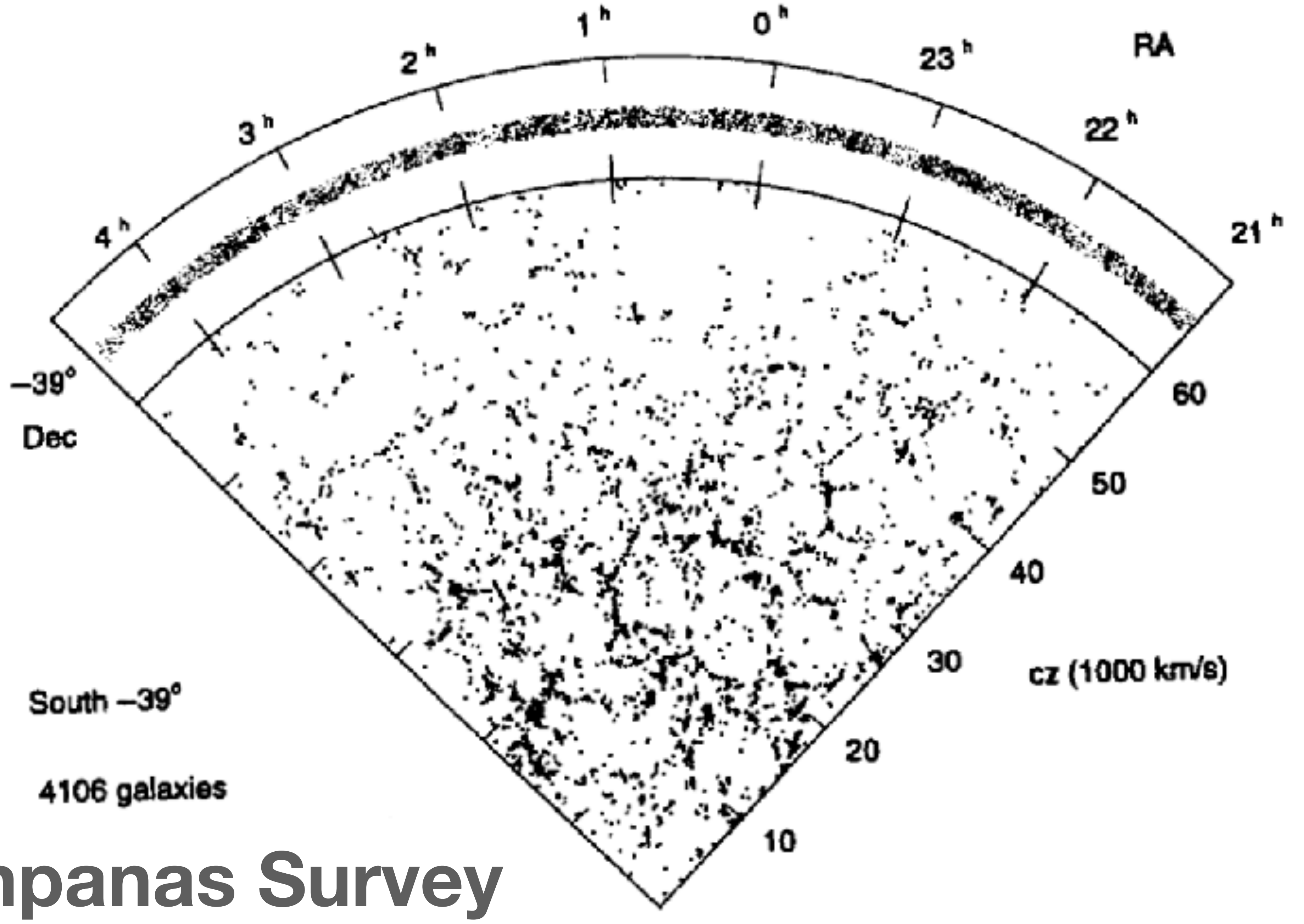
- To answer this question, it is necessary to map the **three-dimensional distribution of many galaxies**.
- Once we find the **redshift** of a galaxy, we can find its distance and thereby obtain its position in three dimensions.
- We therefore need to measure redshifts of many galaxies to construct a three-dimensional map of galaxy distribution. This is a rather **telescope-intensive project**, since it takes a few minutes to obtain the spectrum of a faint galaxy to measure its redshift and redshifts of only a limited number of galaxies can be determined in one night.
- The first pioneering project of this type was the CfA Survey, which was later followed by much bigger projects like the Las Campanas Survey, the Sloan Digital Sky Survey and the 2dF Survey.

Large scale structure

- The Figures show a famous slice of the sky from the CfA Survey along with a similar slice from the Las Campanas Survey exactly a decade later.
- The radial coordinate is the redshift distance cz. Remember that cz = 10,000 km/s corresponds to a distance of $100h^{-1}$ Mpc and a redshift of z = 0.033.
- The Las Campanas Survey covers galaxies at much larger distances than the CfA Survey. Even in the CfA Survey, the distances over the slice are much larger than the sizes of galaxy clusters. Still **we do not find a uniform distribution.**



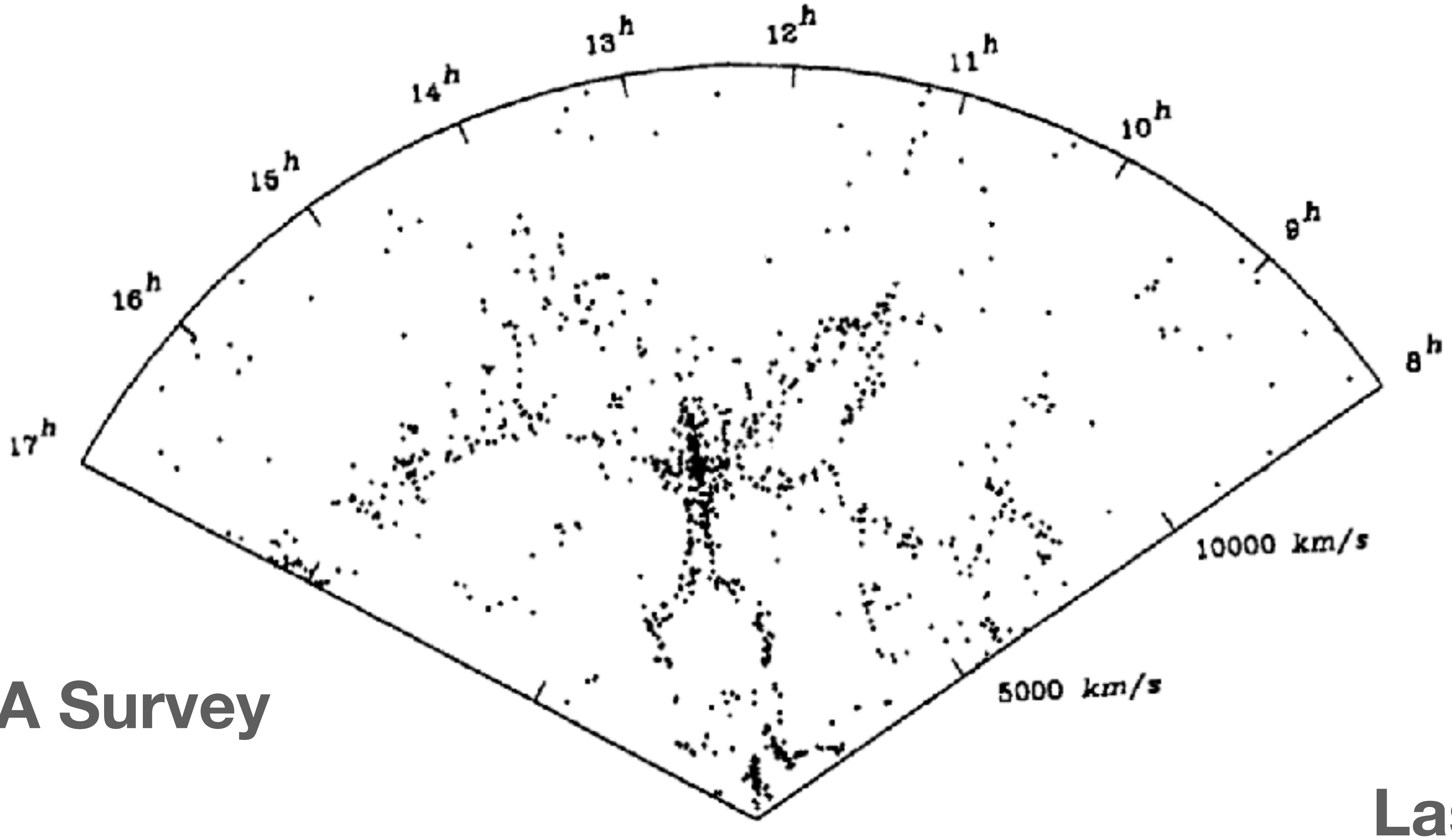
CfA Survey



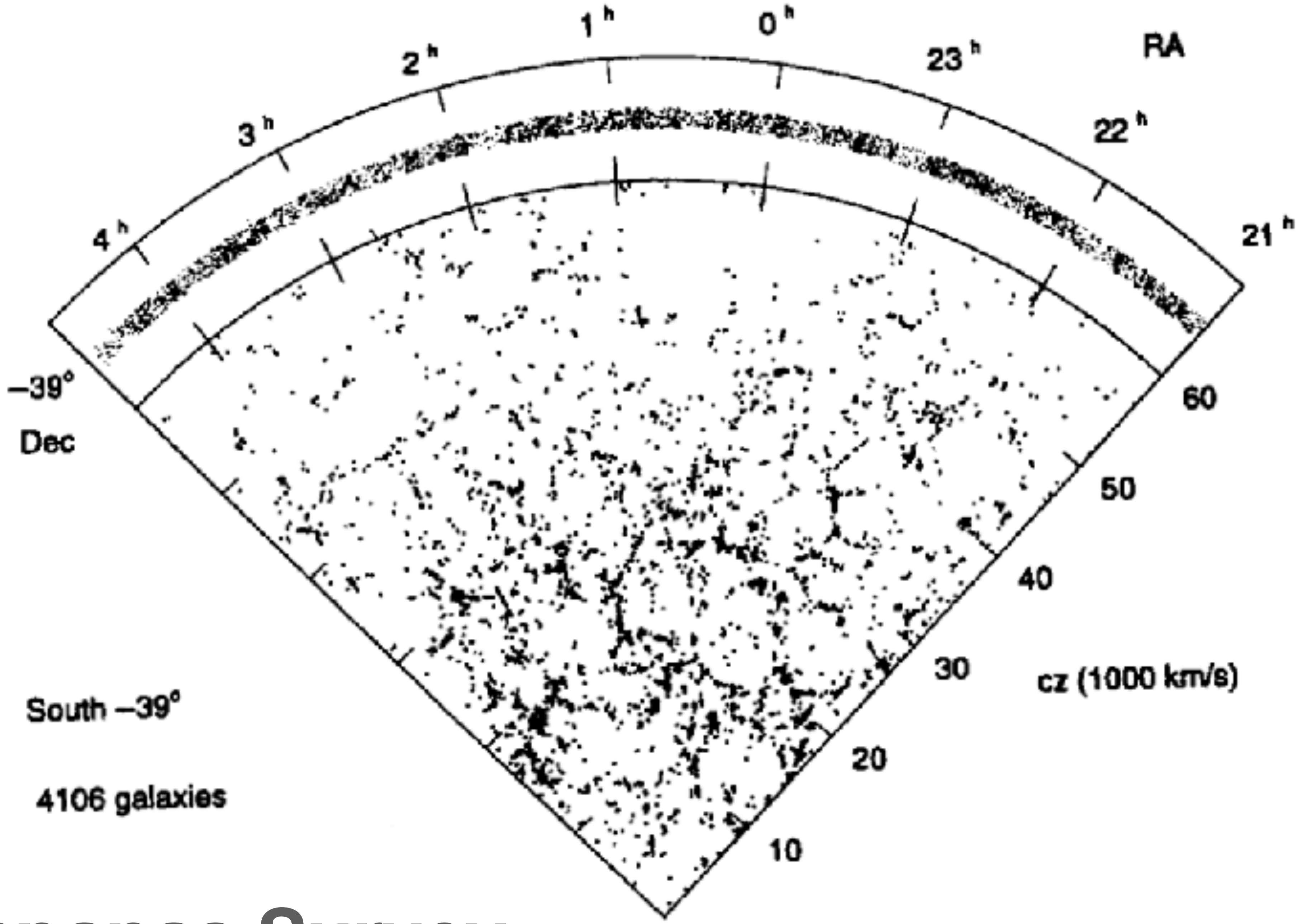
Las Campanas Survey

Large scale structure

- It seems that the **galaxy clusters make up larger wall-like structures** which are called **superclusters** of galaxies.
- **Between the superclusters, we see voids** typically of size $30h^{-1}$ Mpc which are **regions free from galaxies.** The distribution of matter looks like bubbles of empty space surrounded by matter.



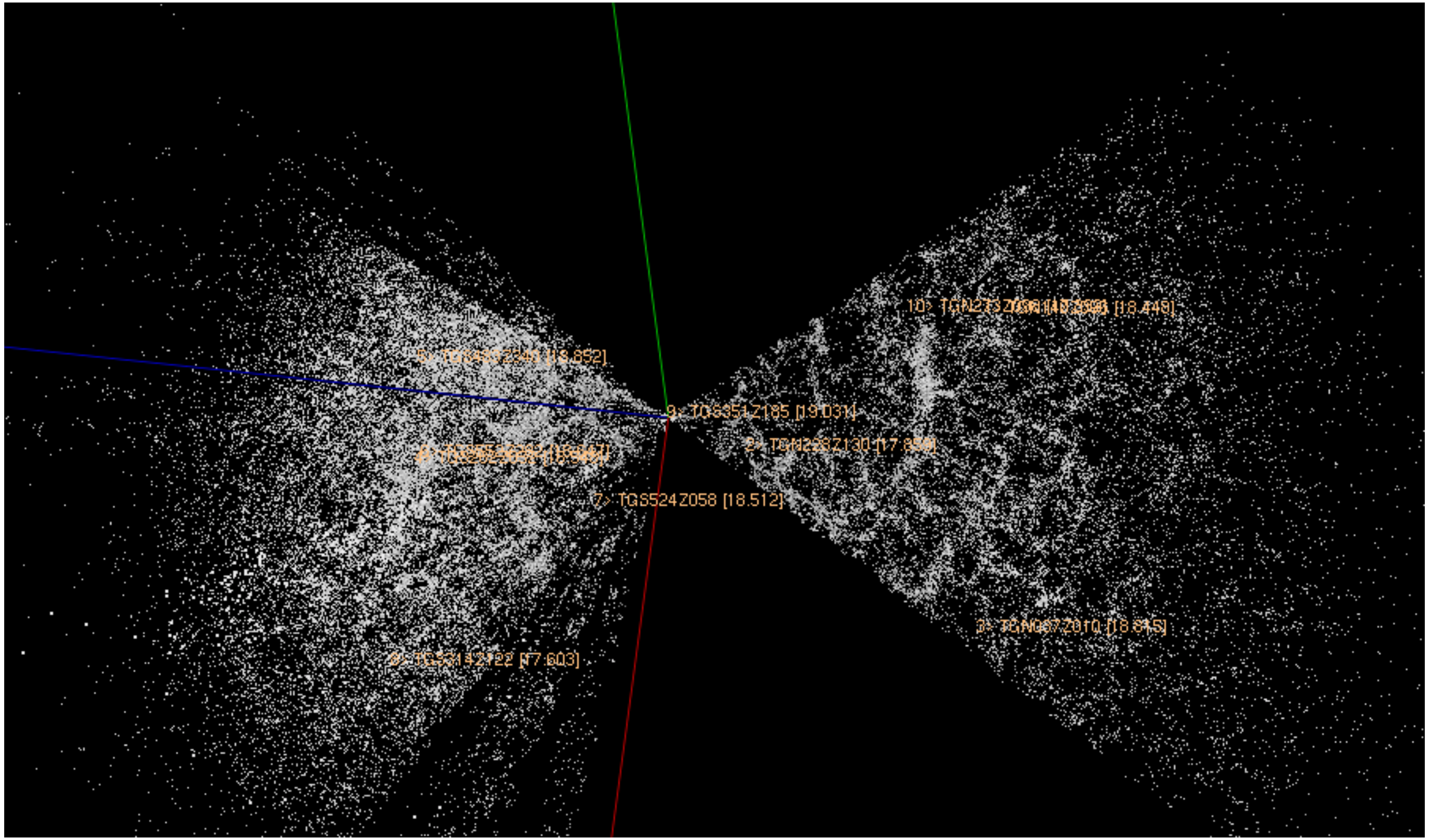
CfA Survey



Las Campanas Survey

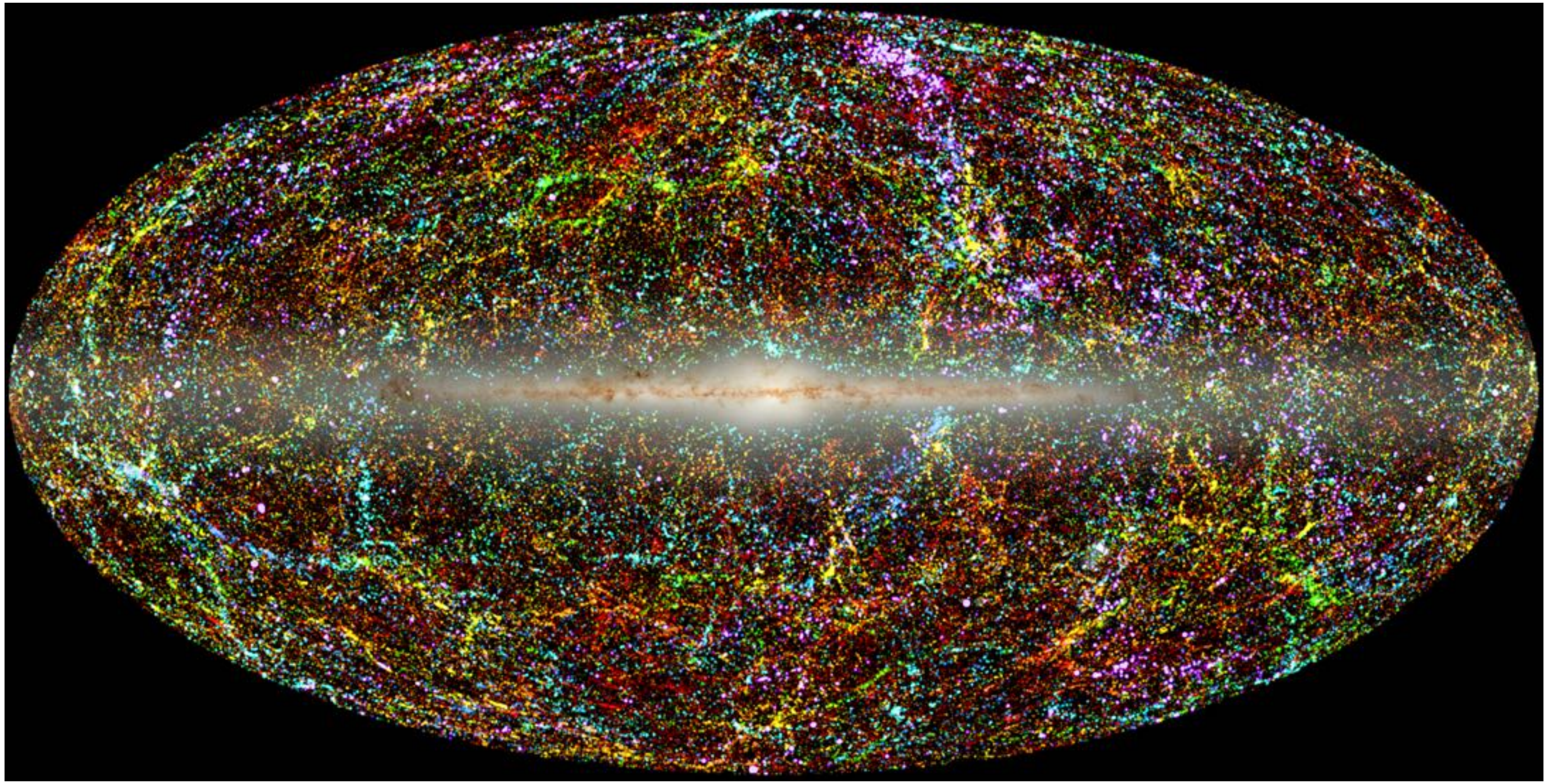
Large scale structure

- Large scale map from the 2dF survey - each point is a galaxy - this structure is also called the **cosmic web**



Large scale structure

Panoramic view of the entire near-infrared sky reveals the distribution of galaxies beyond the Milky Way. The image is derived from the 2MASS Extended Source Catalog (XSC)--more than 1.5 million galaxies. The galaxies are color coded by "redshift". Blue are the nearest sources ($z < 0.01$); green are at moderate distances ($0.01 < z < 0.04$) and red are the most distant sources that 2MASS resolves ($0.04 < z < 0.1$). Image from Jarrett (2004).



Large scale structure

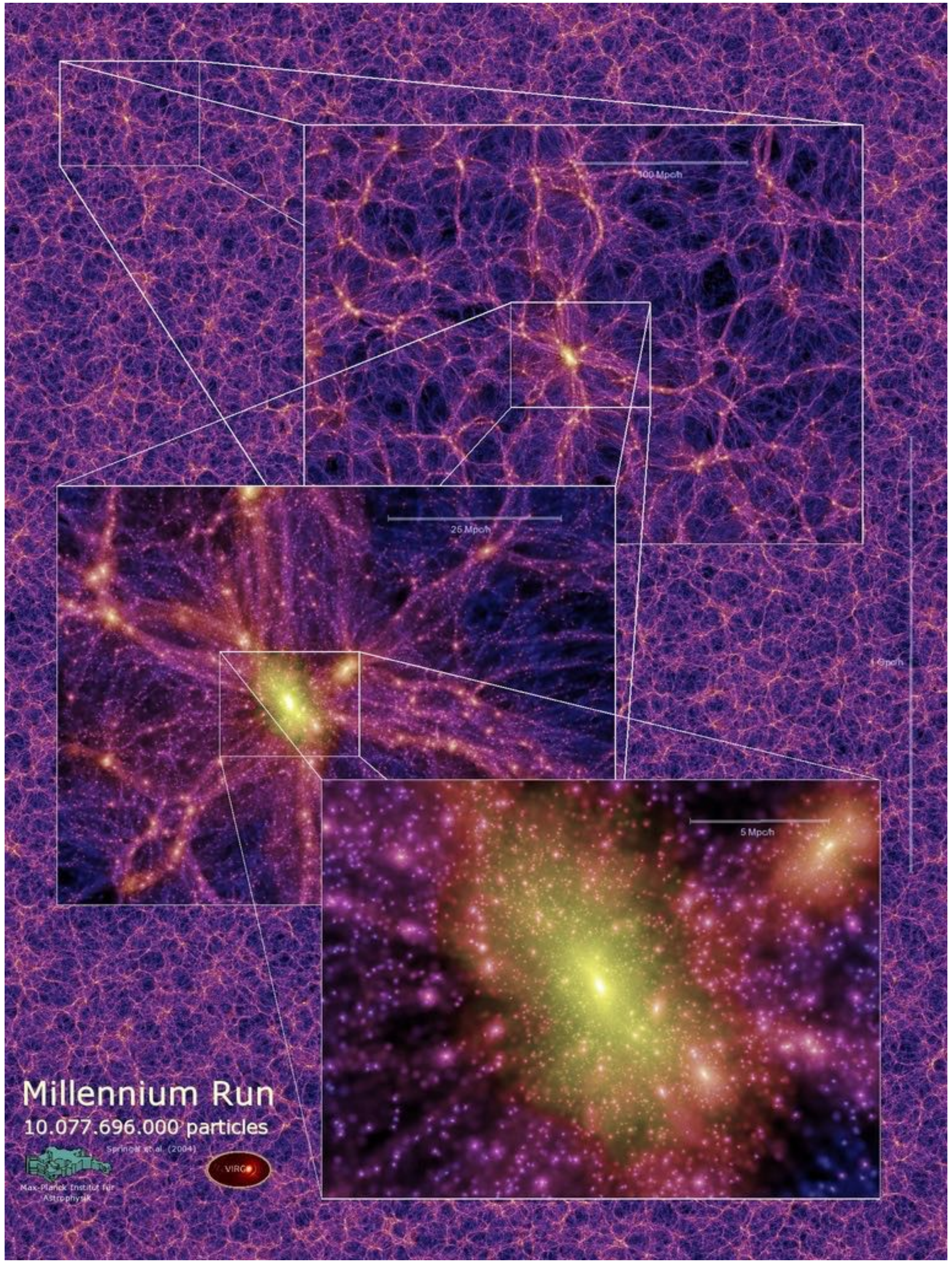
A slice through the Millennium **simulation** showing the cosmic web of structures. The bright yellow regions are the high density clusters that form at the intersection of filaments.

The Millennium simulation is a **dark matter only** simulation where particles represent mass and interact with other particles only trough gravity.

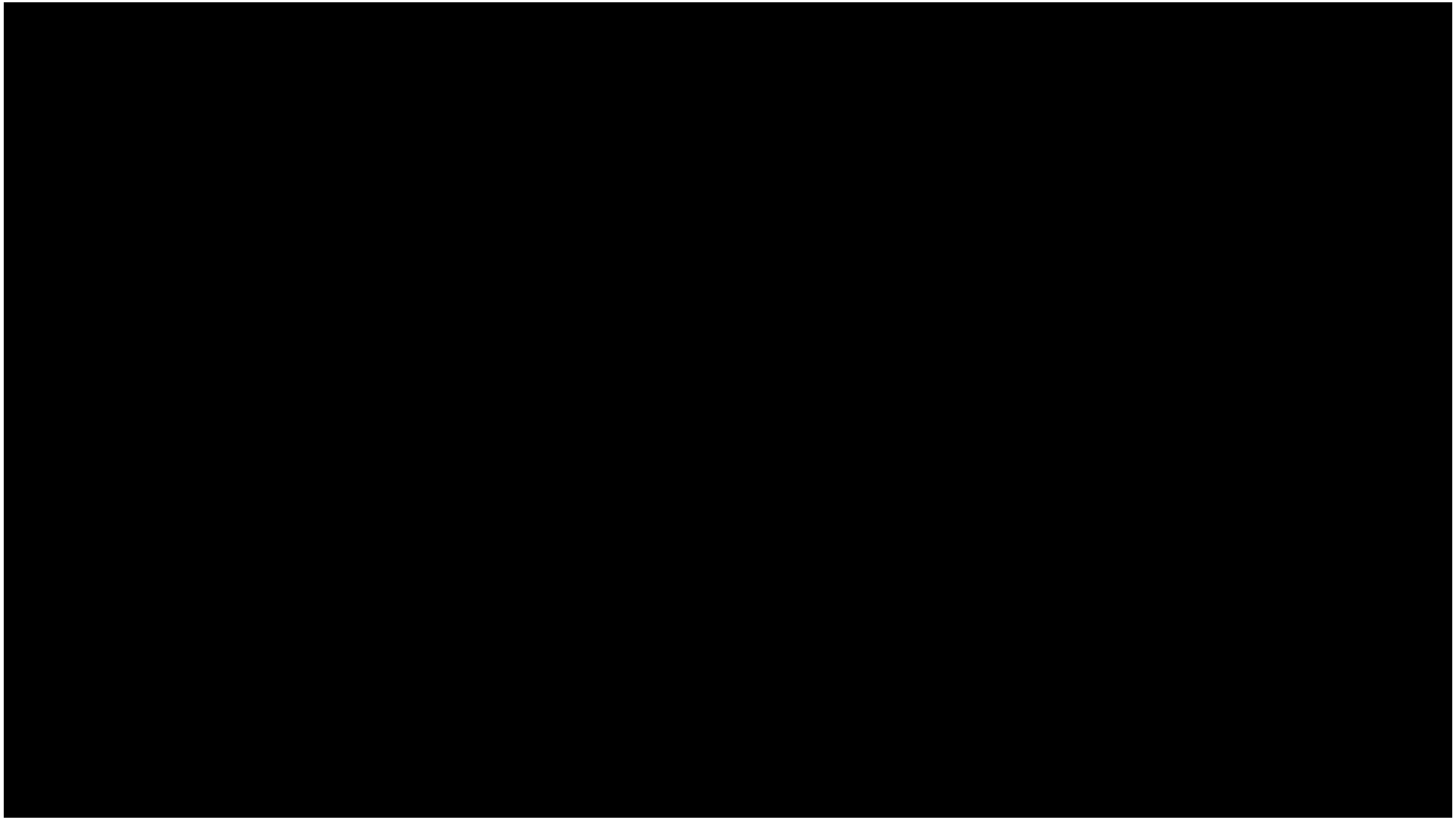
The input is a **matter distribution based on the Cosmic Microwave Background radiation.**

As time passes the dark matter forms the filamentary structure of the Universe that we can observe as the distribution of galaxies.

https://wwwmpa.mpa-garching.mpg.de/galform/virgo/millennium/



Large scale structure

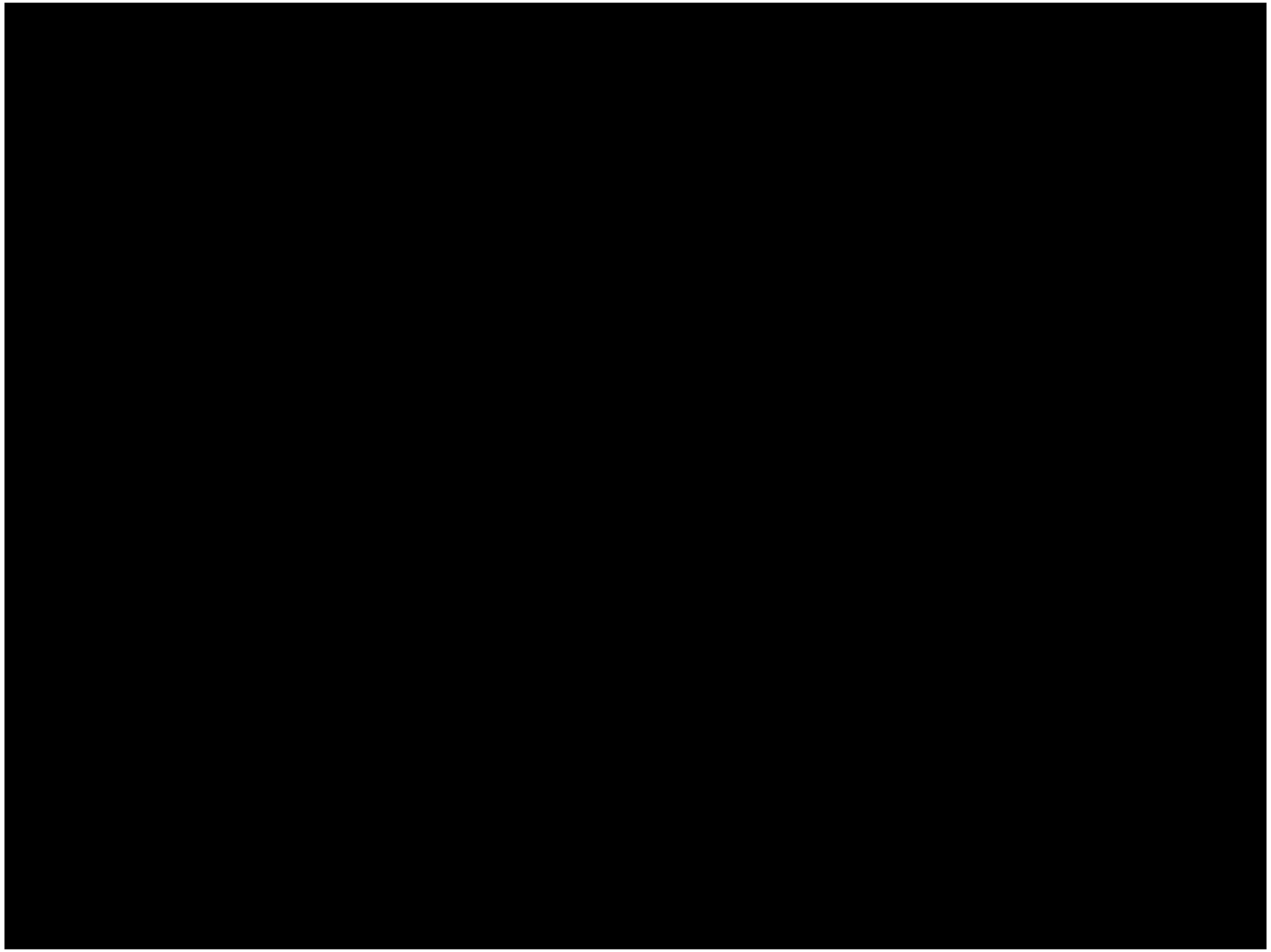


Simulation TNG50: A Galaxy Cluster Forms

Credit: IllustrisTNG Project
Visualization: Dylan Nelson et al.

https://www.youtube.com/watch?v=cNT5yAqpBmI&ab_channel=APODVideos

Large scale structure



Cosmological N-body simulation of the formation and evolution of large scale structures in the Universe.

The number of simulated particles is 512^3.
The size of the simulation box is ~100Mpc (about 300 millon light years).
This simulation was carried on Cray XT4 at Center for Computational Astrophysics, CfCA, of National Astronomical Observatory of Japan.
Simulation and Visualization: Tomoaki Ishiyama (University of Tsukuba)

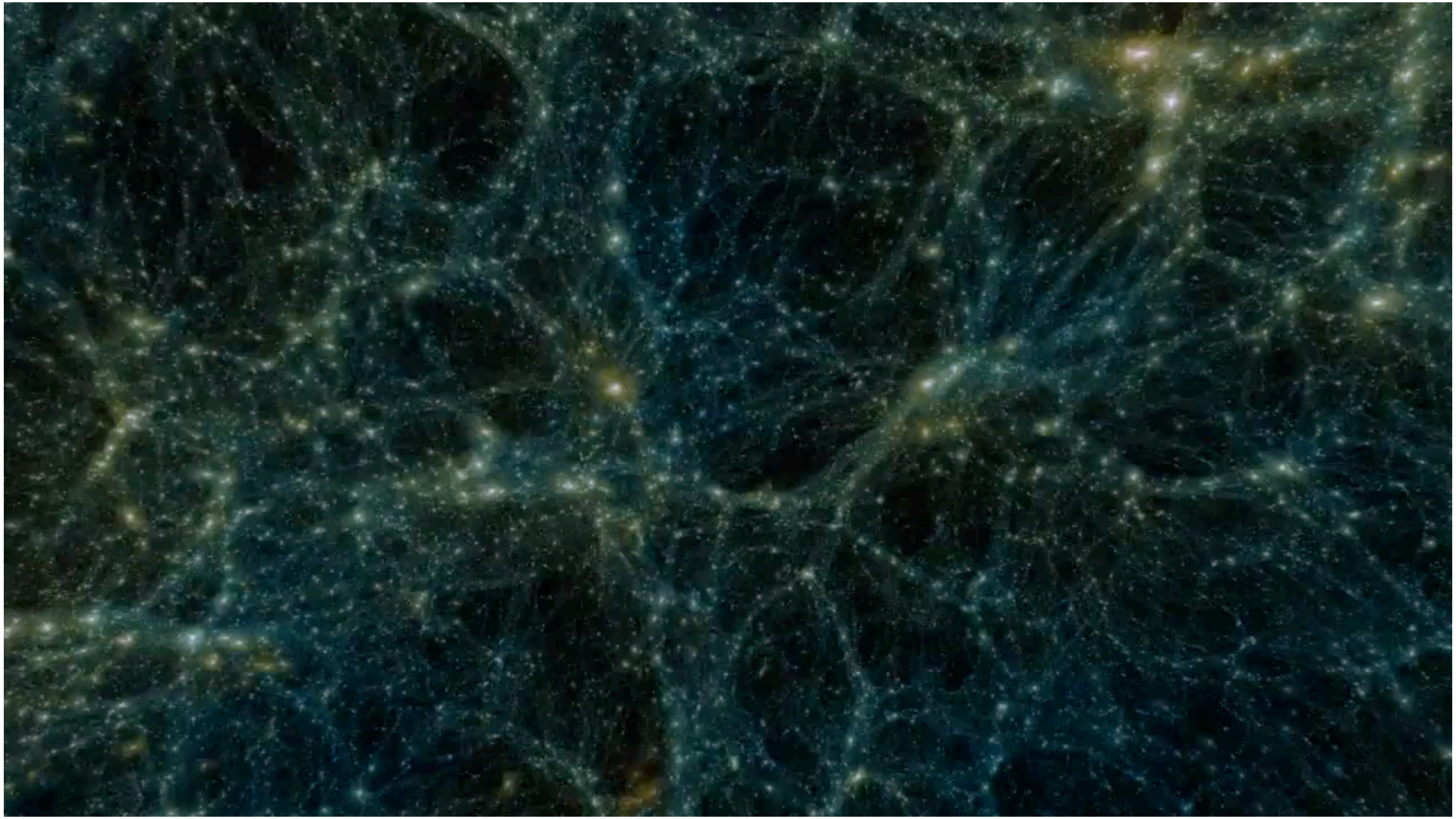
https://www.youtube.com/watch?v=nHvcqV92oqY&ab_channel=TomoakiIshiyama

Large scale structure

Cosmological N-body simulation of the formation and evolution of large scale structures in the Universe.
The size of the simulation box is ~1650Mpc (about 5.4 billon light years). This simulation was carried on the K computer at the RIKEN Advanced Institute of for Computational Science in Japan.

This simulation offers the highest mass resolution among simulations utilizing boxes larger than 1Gpc/h.

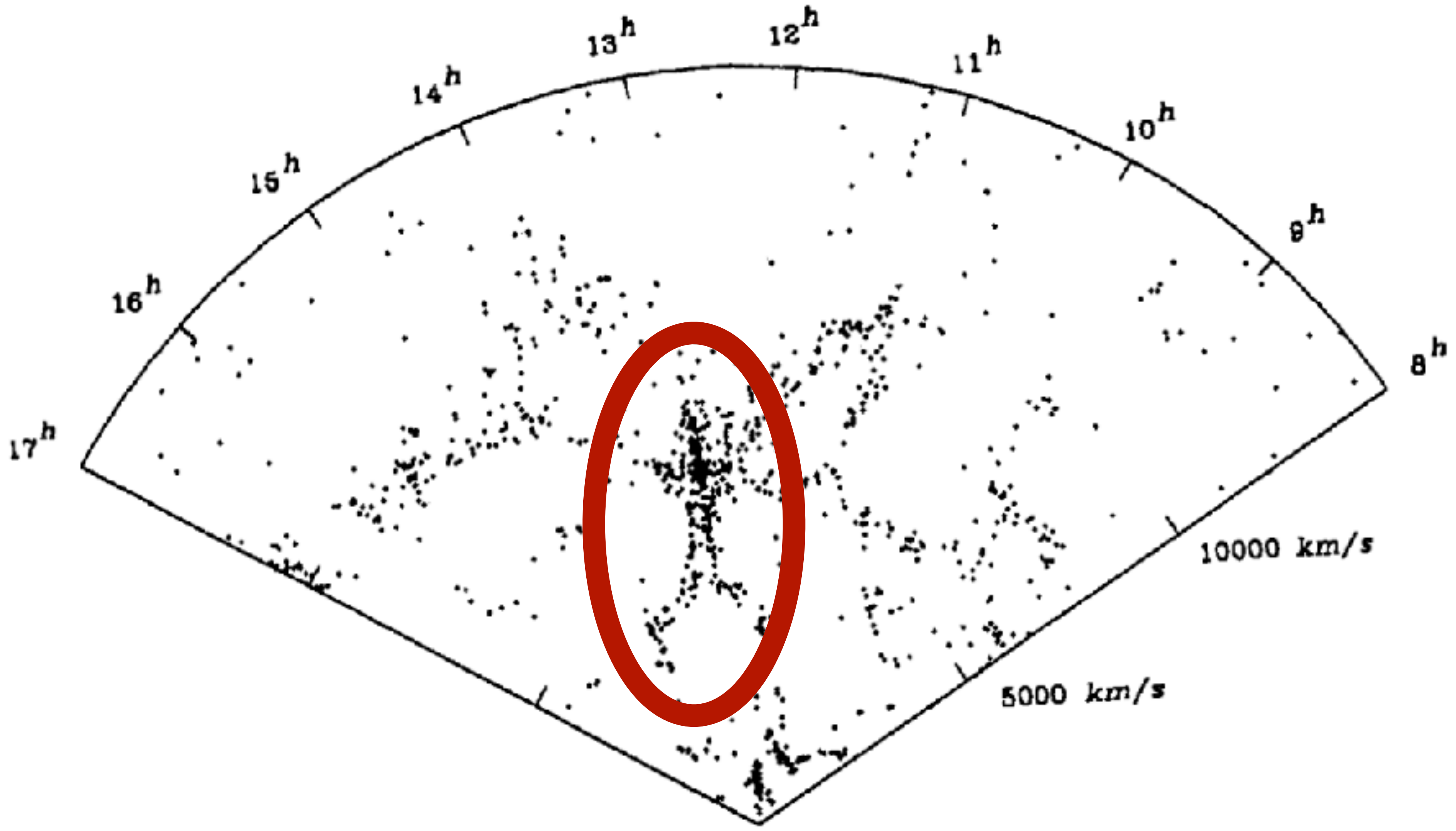
Simulations and Visualization: Tomoaki Ishiyama



https://www.youtube.com/watch?v=kndzioHG8Uc&ab_channel=TomoakiIshiyama

Large scale structure

- It may be noted that there are several **radially elongated structures** in the images of the large scale distribution of galaxies, which are particularly prominent in the upper CfA Survey panel. These are **artifacts** in the redshift distance space which may not correspond to real structures in actual space.
- To understand how they arise, let us consider a cluster of galaxies which have large random velocities caused by the gravitational field of the cluster. Some galaxies would have random velocities away from us (superposed on the mean recession velocity of the cluster) and would appear in the redshift distance space to be radially further away than the mean position of the cluster. On the other hand, galaxies with random velocities towards us would appear nearer.
- Thus **a cluster of galaxies having large random velocities appears stretched in the radial direction in the redshift distance space**.

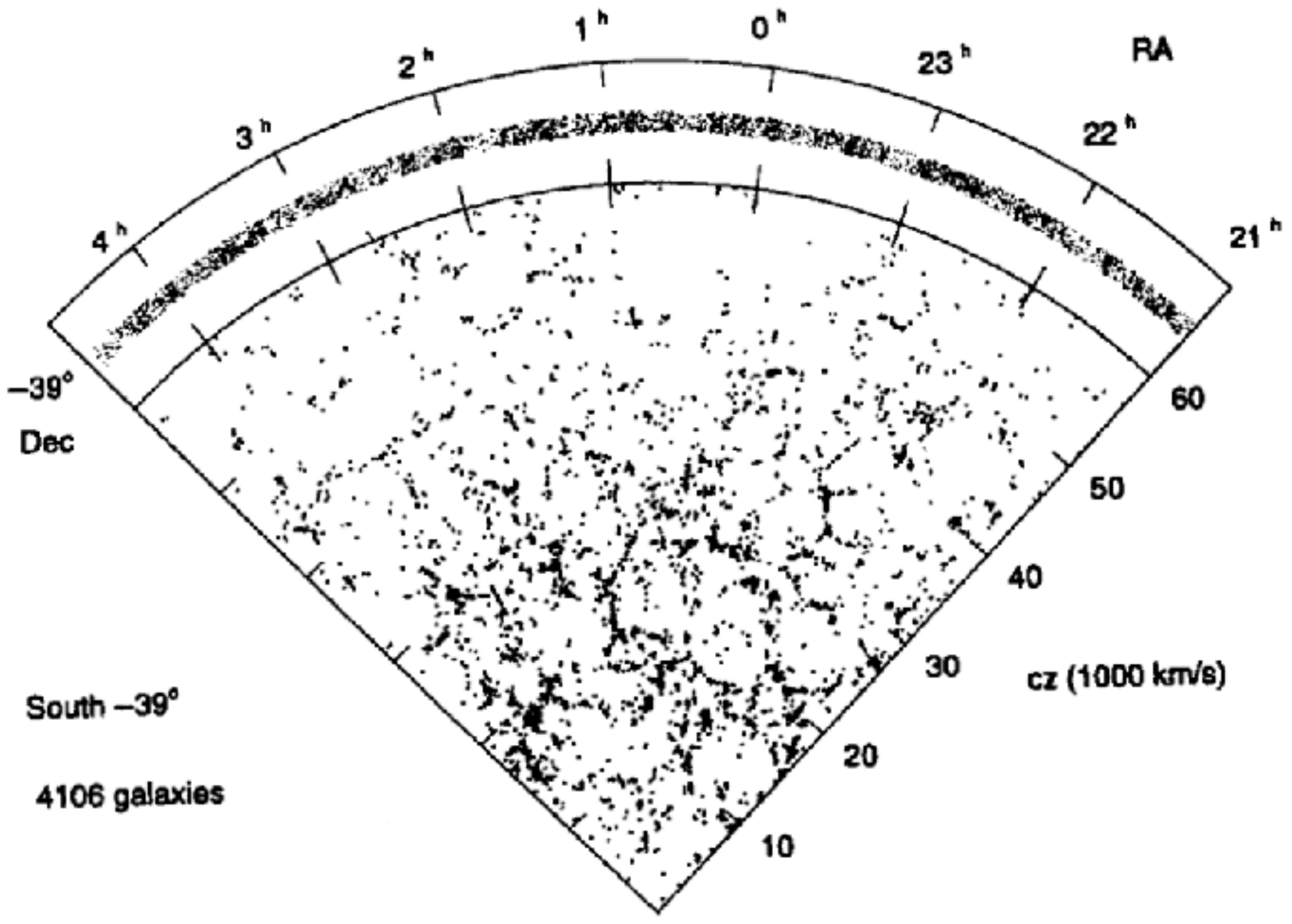


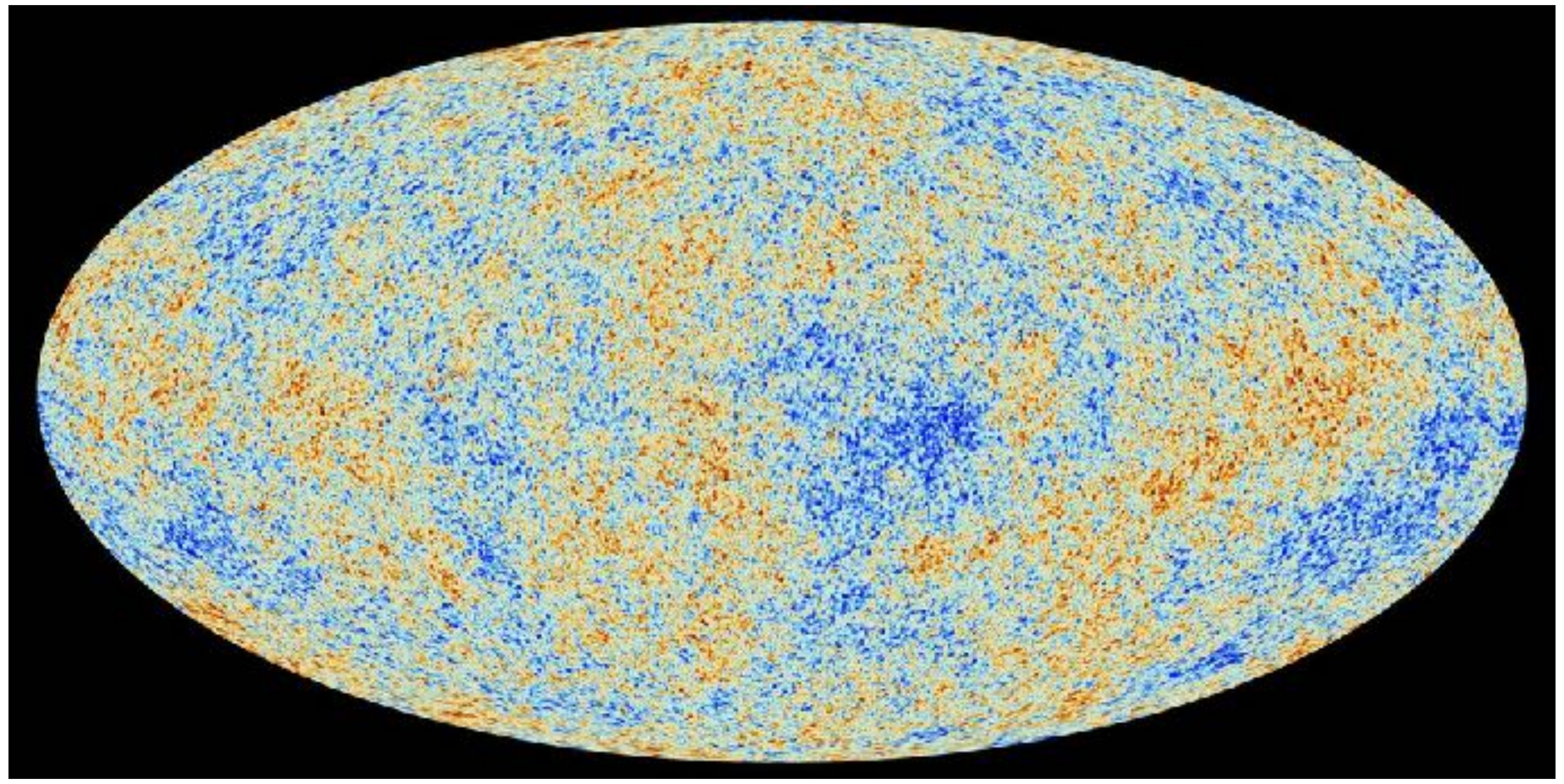
Large scale structure

- Is the matter distribution uniform in the cosmos on sufficiently large scales?

Large scale structure

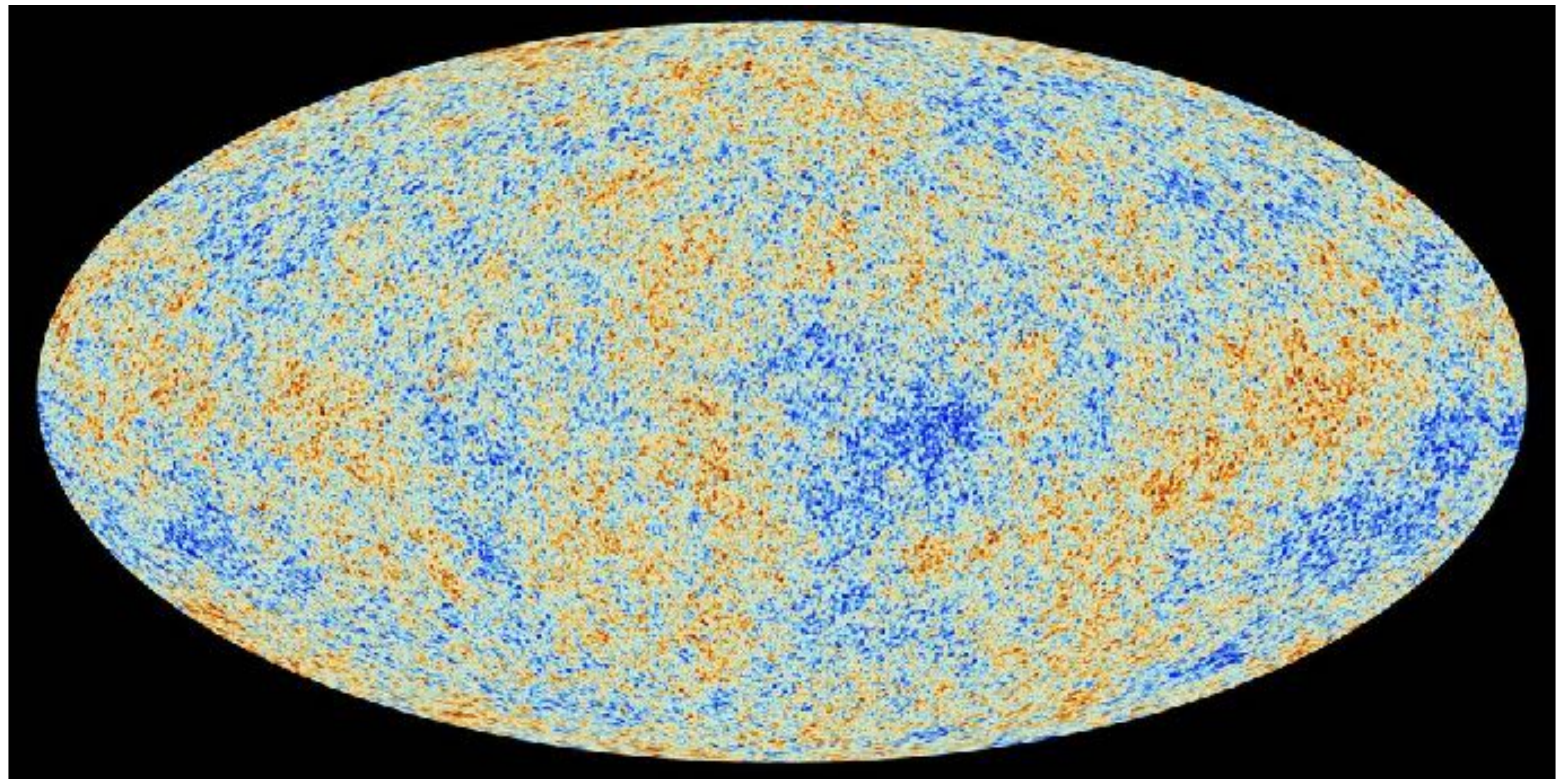
- **Is the matter distribution uniform in the cosmos on sufficiently large scales?**
- the Las Campanas survey involving many more galaxies and going to much higher redshifts shows that the superclusters may be the largest structures in the Universe and **different patches of the Universe look very similar when we go to scales larger than $100h^{-1}$ Mpc.**
- Other big observational support for the uniform matter distribution comes from the amazing uniformity of the **cosmic microwave background (CMB)** radiation.





CMB measurement from the Planck satellite

Large scale structure



- The cosmic microwave background (CMB, CMBR) is microwave radiation that fills all space.
- **CMB is evidence of the Big Bang theory** for the origin of the universe.
- In the Big Bang cosmological models, during the **earliest periods the universe** was filled with a opaque fog of dense, **hot plasma of sub-atomic particles**. As the universe expanded, this plasma cooled to the point where **protons and electrons combined to form neutral atoms** of mostly hydrogen.
- Unlike the plasma, these atoms could not scatter thermal radiation by Thomson scattering, and so the **universe became transparent**. Known as the **epoch of recombination**, this decoupling event released photons to travel freely through space – sometimes referred to as relic radiation.
- However, the photons have grown less energetic since the expansion of space causes their wavelength to increase into the microwave regime.
- The CMB is **not completely smooth -> matter distribution in the early Universe**

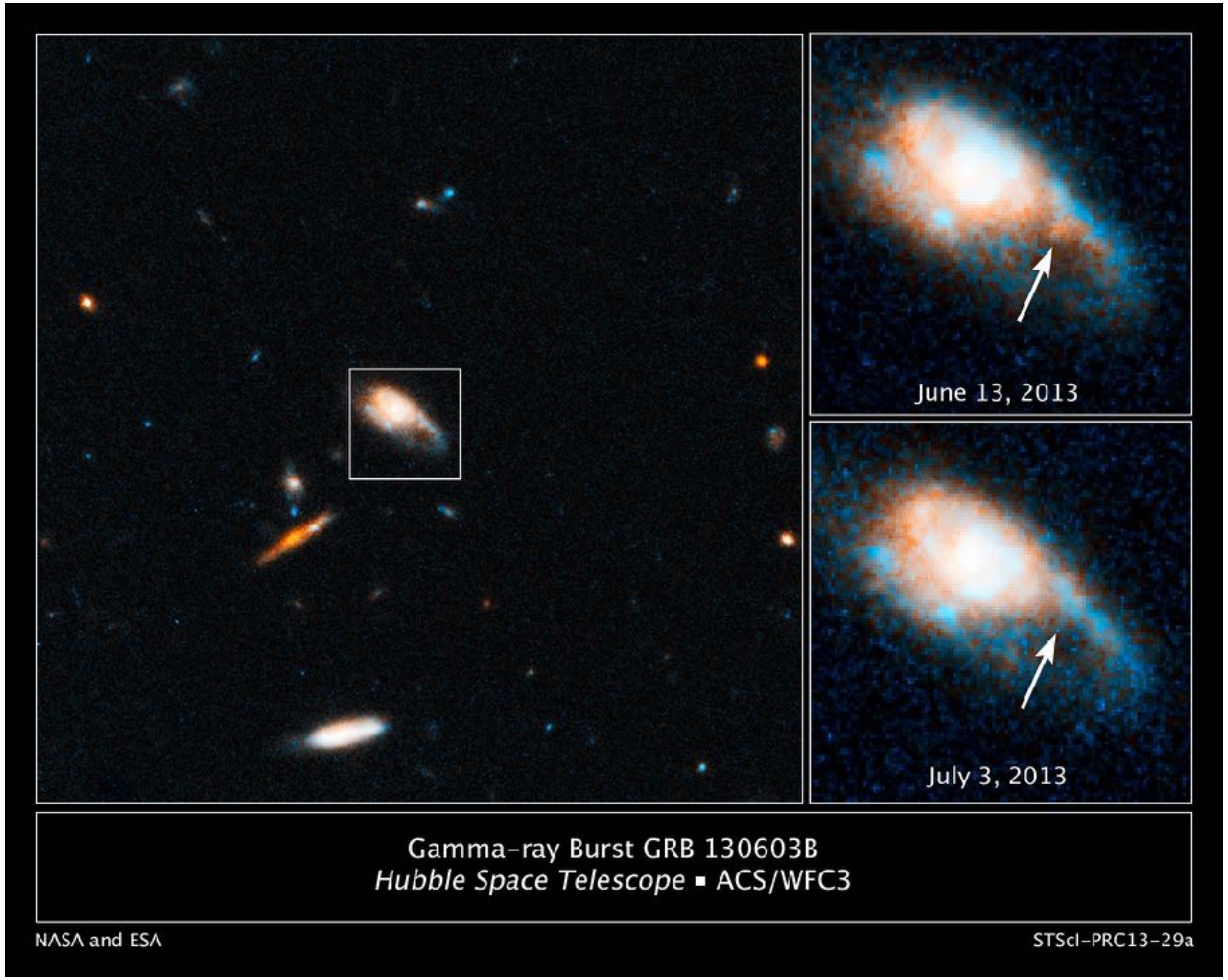
Gamma ray bursts (GRBs)

***gamma ray bursts*, abbreviated as GRBs**

- *We do know quite a bit about gamma ray bursts since the book was published, the new mystery is the Fast Radio Bursts (FRBs)*
- These are bursts of γ -rays which **can last from a few seconds to a few hours.**
- They were first detected by satellites designed to detect γ -rays from any secret nuclear tests. But it quickly became clear that some of the signals detected were of extraterrestrial origin.
- Initially it was thought that GRBs are produced within our Galaxy. But many GRBs were detected, and it became apparent that their **distribution was isotropic** and not confined to the galactic plane, suggesting an **extragalactic origin.**
- It was eventually possible to detect a **fading optical source immediately after the occurrence of a GRB** at exactly the same point in the sky. Afterwards such **optical 'afterglows'** have been found to follow many GRBs. The optical counterparts appear to be faint galaxies for many of which redshifts have been measured, leading to estimates of the distance.

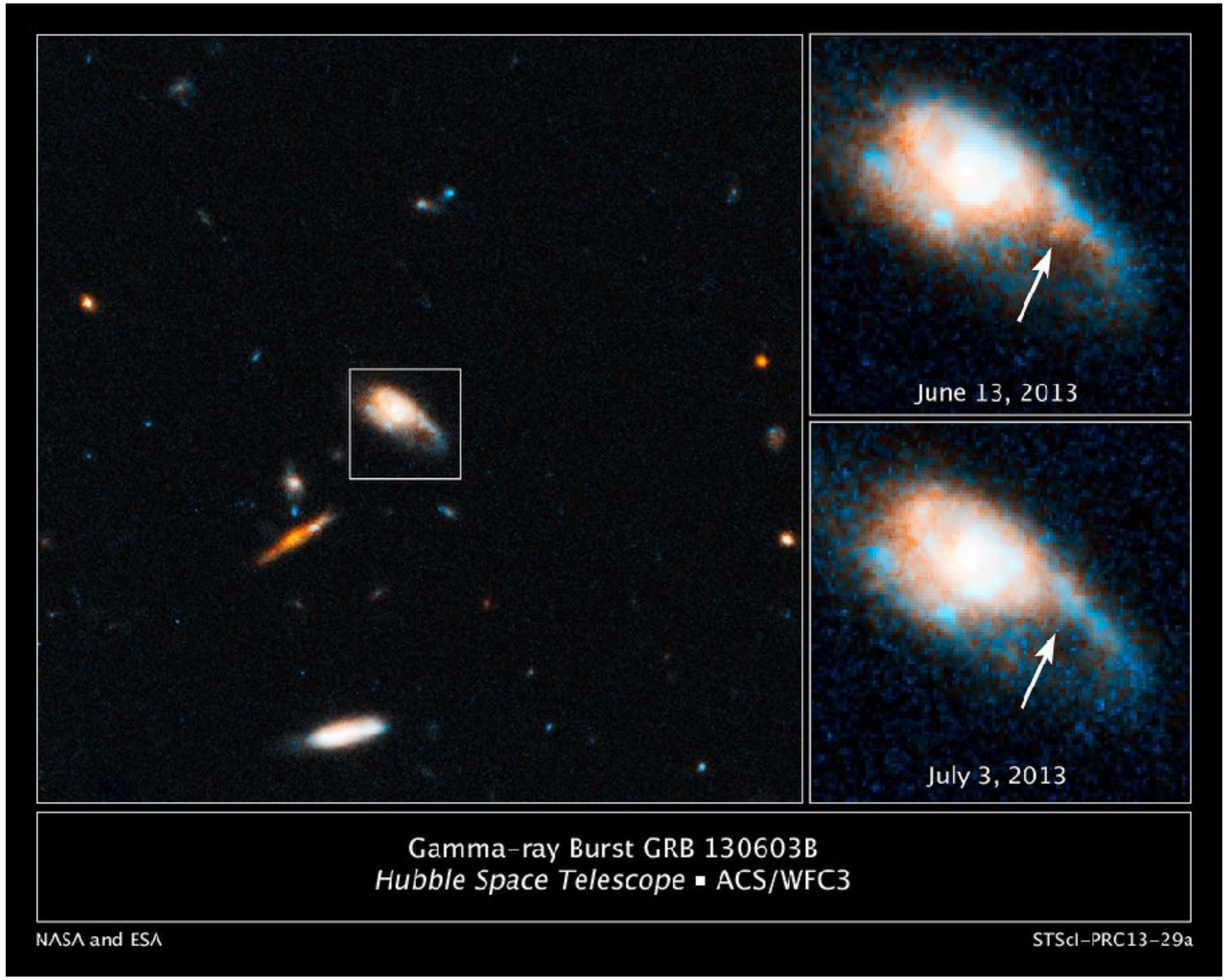
Gamma ray bursts (GRBs)

- In addition to the optical afterglow, there are also **X-ray and high energy gamma ray afterglows**
- One can try to calculate the energy emitted in a GRB from a knowledge of its distance, although such calculations become uncertain if the emitting material is moving relativistically towards the observer and the relativistic beaming effect is involved. Still it appears that **GRBs are some of the most energetic explosions in the Universe.**
- **What is the origin of GRBs?**



Gamma ray bursts (GRBs)

- There are different types based on the duration of the burst:
  - Short: **less than 2 seconds** - 30% of GRBs - origin: **mergers of binary neutron stars or a neutron star with a black hole** (it takes about 2 seconds for a black hole to destroy a neutron star). One of the detected gravitational waves GW170817, had a short GRB associated which was a signal from the merger of two neutron stars (kilonova).
  - Long: **longer than 2 seconds** - 70% of GRBs - Almost every well-studied long gamma-ray burst has been linked to a galaxy with rapid star formation, and in many cases to a **core-collapse supernova** as well, unambiguously associating long GRBs with the deaths of massive stars.
  - Ultra-long: **longer than 10000 seconds** - very few observed - origin may be the collapse of a blue supergiant star, a tidal disruption event or a new-born magnetar.



Fast Radio Bursts (FRBs)

- A fast radio burst (FRB) is a **transient radio pulse of length ranging from a fraction of a millisecond to 3 seconds**, caused by some high-energy astrophysical process not yet understood. Astronomers estimate the average FRB releases as much energy in a millisecond as the Sun puts out in three days.
- Most FRBs are extragalactic, but the first Milky Way FRB was detected.
- The exact origin and cause of the FRBs is still the subject of investigation;
- Proposals for their origin range from a rapidly rotating neutron star and a black hole, to extraterrestrial intelligence, compact-object mergers and magnetars arising from normal core collapse supernovae.

Detection of an FRB with the LOFAR telescope