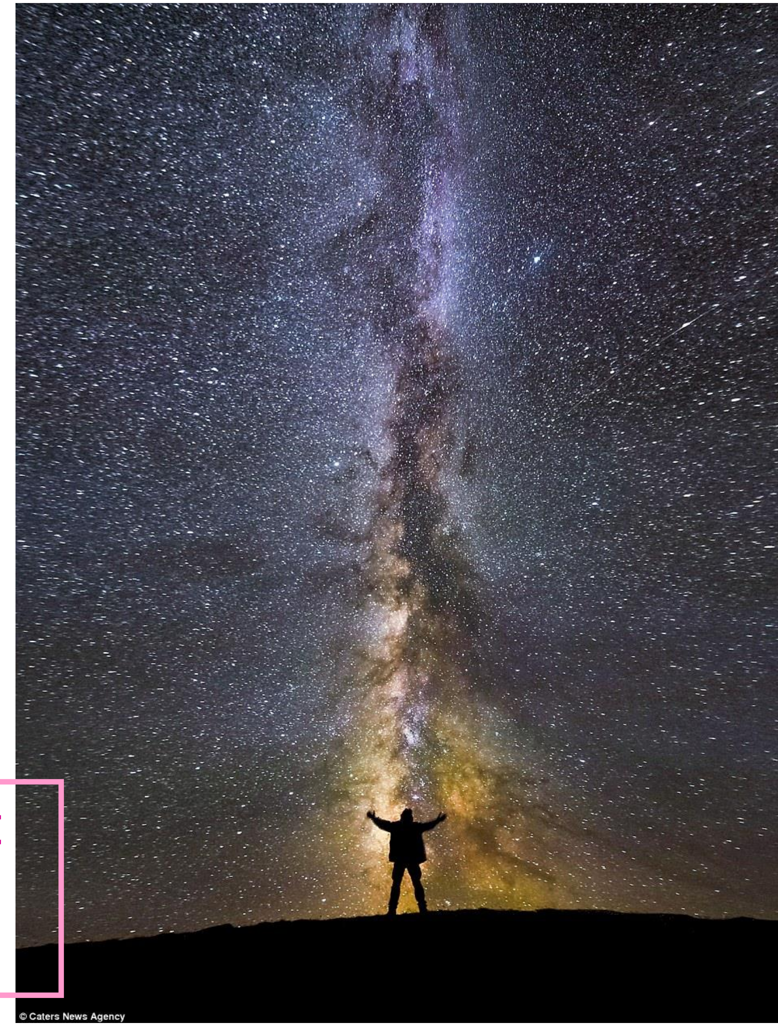
INTRODUCTION TO SPACE 16.11.2020

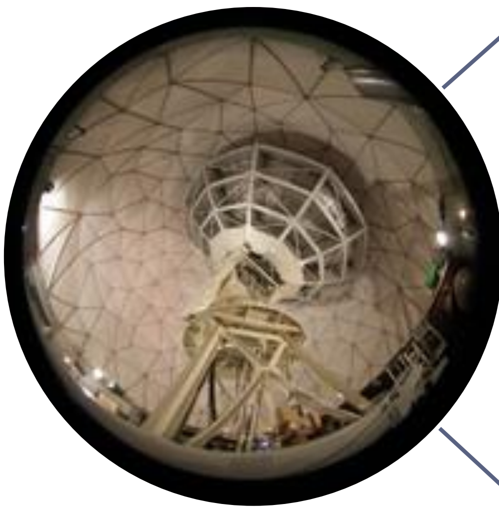
- The Galaxy I:
  - Magnitude systems
  - Structure, rotation, spiral arms
  - Evolution
  - Galactic continuum
  - Galactic centre



Boris Dmitriev

23.11. The Galaxy II: stars, gas, dust
30.11. Extragalactic & cosmology
8.12. Exam

BASICS OF ASTRONOMY?



ELEC-E4530 Radio Astronomy
ELEC-E4220 Space Instrumentation

Coordinate systems

- Observational techniques
- Feasibility

Emission mechanisms

- Source spectrum
- Source properties

Astronomy (galactic & extragalactic)

- What kind of sources?
- What kind of science?

Why do we study astronomy on this course

- Needed on other space courses, and by anyone who wishes to continue in astronomical research.
- The astronomy part on this course consists of coordinate systems, emission mechanisms, and the basics of celestial objects, such as galactic and extragalactic sources.

REMINDER: LUMINOSITY

- The luminosity emitted by a source (= the total radiated energy)

$$L = 4\pi r^2 \sigma T^4$$

can be divided into two parts:

$$L = 4\pi r^2 F$$

$$F = \sigma T^4 \quad \text{(Stefan-Boltzmann law)}$$

- Luminosity is proportional to the **size** and the fourth power of the **temperature**
- High luminosity $\rightarrow$ the source is hot or large in size, or both

Effective temperature = the temperature of a black body that would emit the same total amount of electromagnetic radiation

BRIGHTNESS OF STARS?

MAGNITUDE SYSTEMS

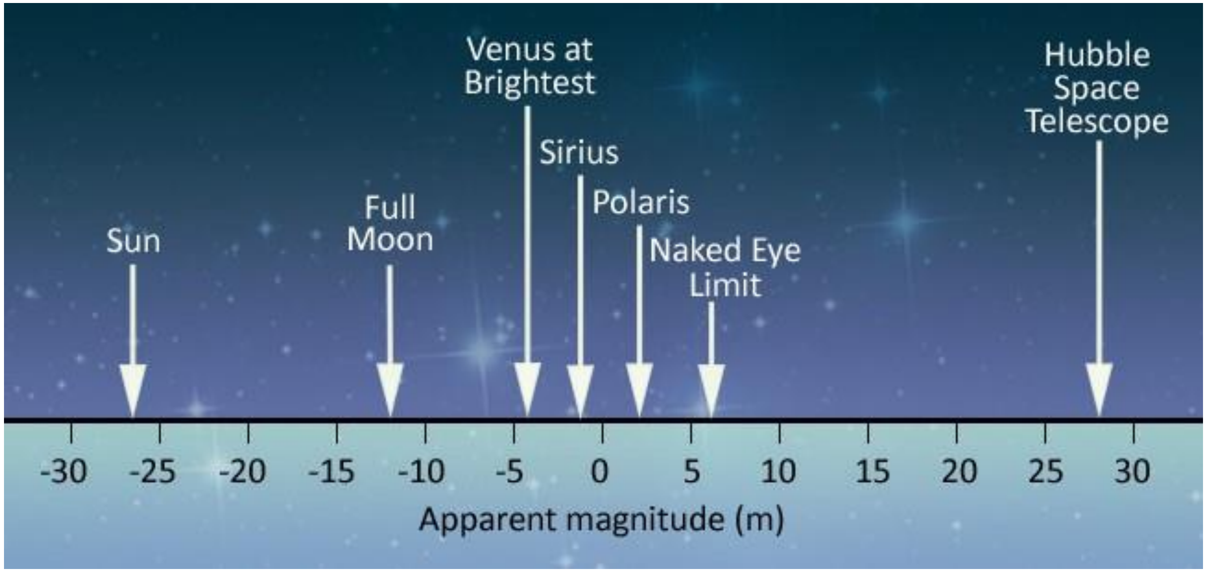
- Describe the optical brightness of celestial objects
  - Logarithmic
- **Apparent magnitude**: $m = -2.5 \lg F/F_0$ $[F]=W/m^2$
  - $m_1 - m_2 = -2.5 \lg F_1/F_2$
- **Bolometric magnitude** at all wavelengths: $m_{bol}=m_v - BC$
  - **Visual magnitude** m_v corresponds to the sensitivity of the eye
- **Absolute magnitude M** (= the apparent m at a distance of 10pc): $m - M = 5 \lg (r/10pc)$
- **Absolute bolometric magnitude**: $M_{bol} - M_{bol,\odot} = -2.5 \lg L/L_\odot$

BC = Bolometric correction, zero for sun-like emission.

- With magnitude systems we can set a scale for the brightness of celestial objects. The smaller the value, the brighter the object.
- The best reference for this is Chapter 4 of Fundamental Astronomy, written by Karttunen et al., Springer, ISBN: 978-3-540-34143-7 (in Finnish: "***Tähtitieteen perusteet***", Tähtitieteellinen yhdistys Ursa). Ebook is available for a fee.
- For free material look at, for example, Wikipedia:
  - https://en.wikipedia.org/wiki/Apparent_magnitude
  - https://en.wikipedia.org/wiki/Absolute_magnitude
  - https://en.wikipedia.org/wiki/Bolometric_correction

MAGNITUDES: EXAMPLES

- Apparent magnitudes of celestial objects
  - The Sun –26.8m
  - Full Moon –12.5m
  - Venus –4.4m
  - Sirius –1.5m
  - Polaris +2m



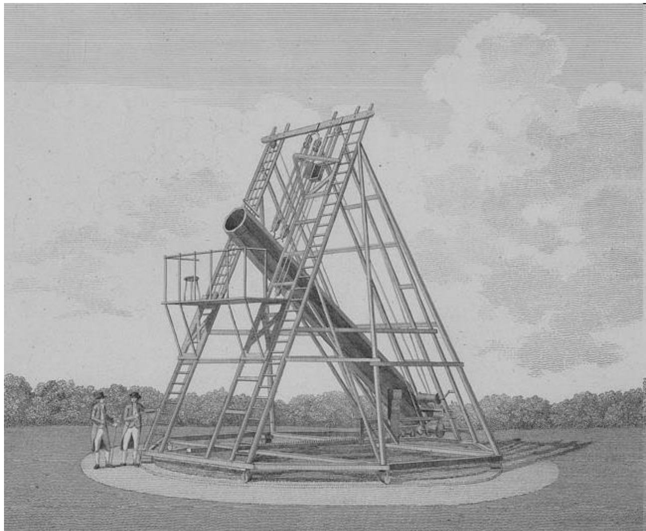
Tim Trott

Capital G for our own Milky Way

The Galaxy, Milky Way

- A galaxy among other galaxies
  - a flat, disc shaped system that primarily contains stars.

- History:
  - **G. Galilei** observed, using his first telescope, innumerable individual stars (early **1600's**).
  - **W. Herschel** attempted to define the shape and the size of the Galaxy by means of star counts.
  - $\Rightarrow$ It is a flat system, the Sun is in the centre (late **1700's**).



The Galaxy: History

- **J. Herschel** understood that G is a huge disc of irregular shape and size, and the Sun is located asymmetrically more to the south rather than the north (**1800's**).
- **J. Kapteyn** estimated the size of the G by counting stars, the Sun is in the centre, proof for galactic rotation (Kapteyn's universe, early **1900's**.)

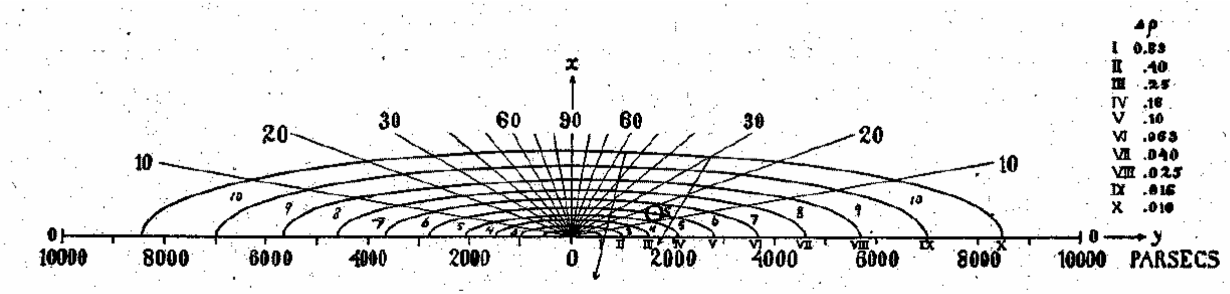
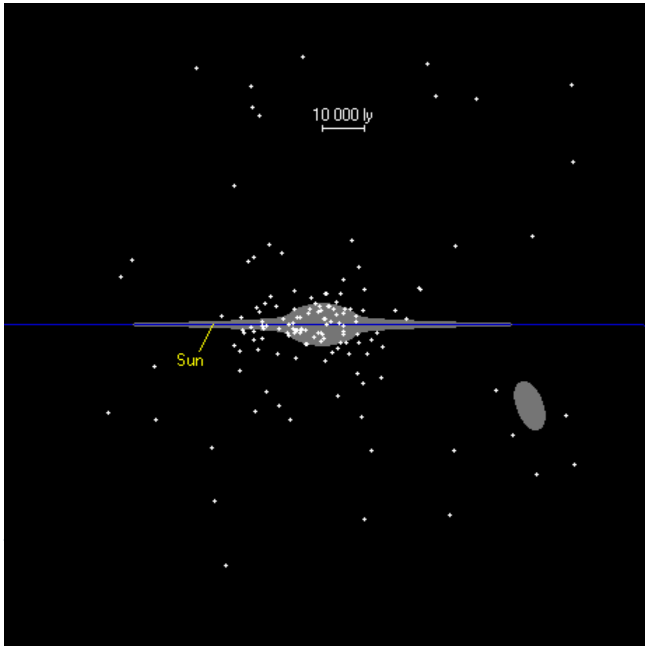


FIG. I

- **H. Shapley** found out the size of the G and the location of the Sun from studies of globular star clusters (**1920's**).

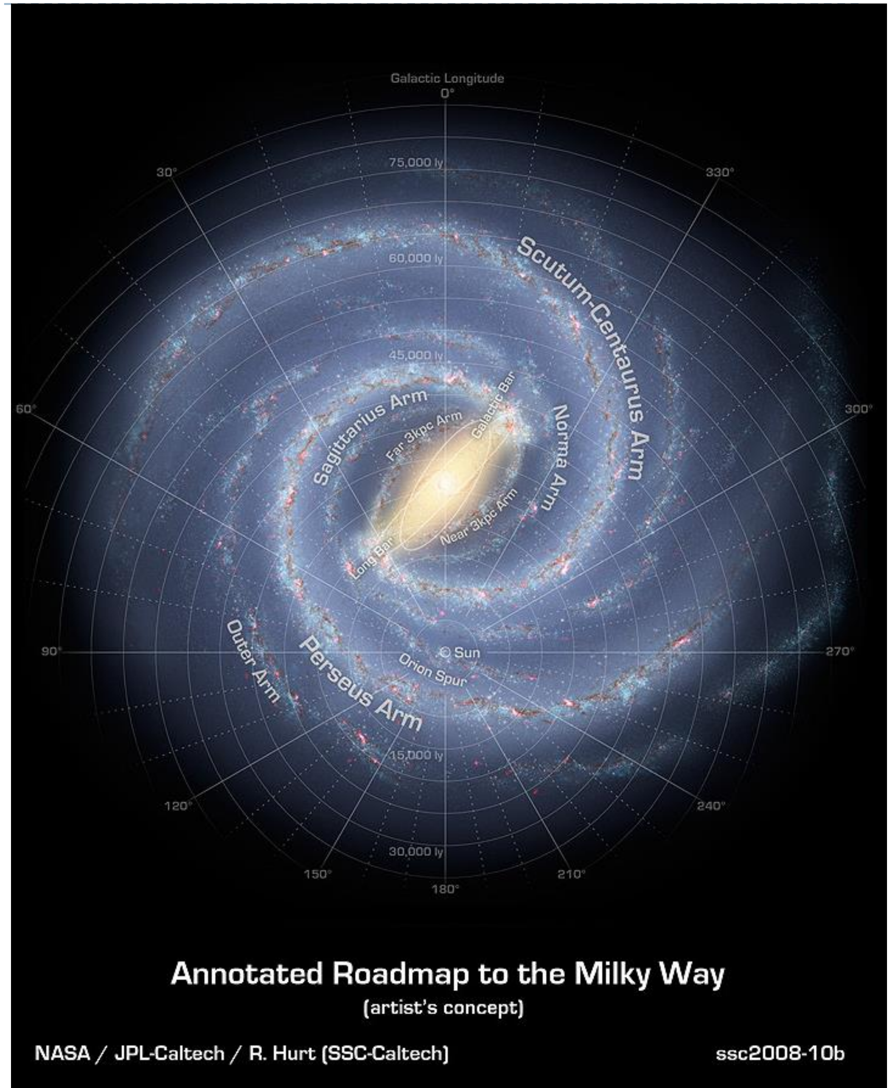


BUILDING BLOCKS OF THE GALAXY

- stars & star formation regions
- dying stars
- supernova remnants
- molecular clouds
- neutral hydrogen, HI, and ionized hydrogen, HII
- masers
- dust
- cosmic rays
- magnetic field
- black hole ?
- dark matter ?

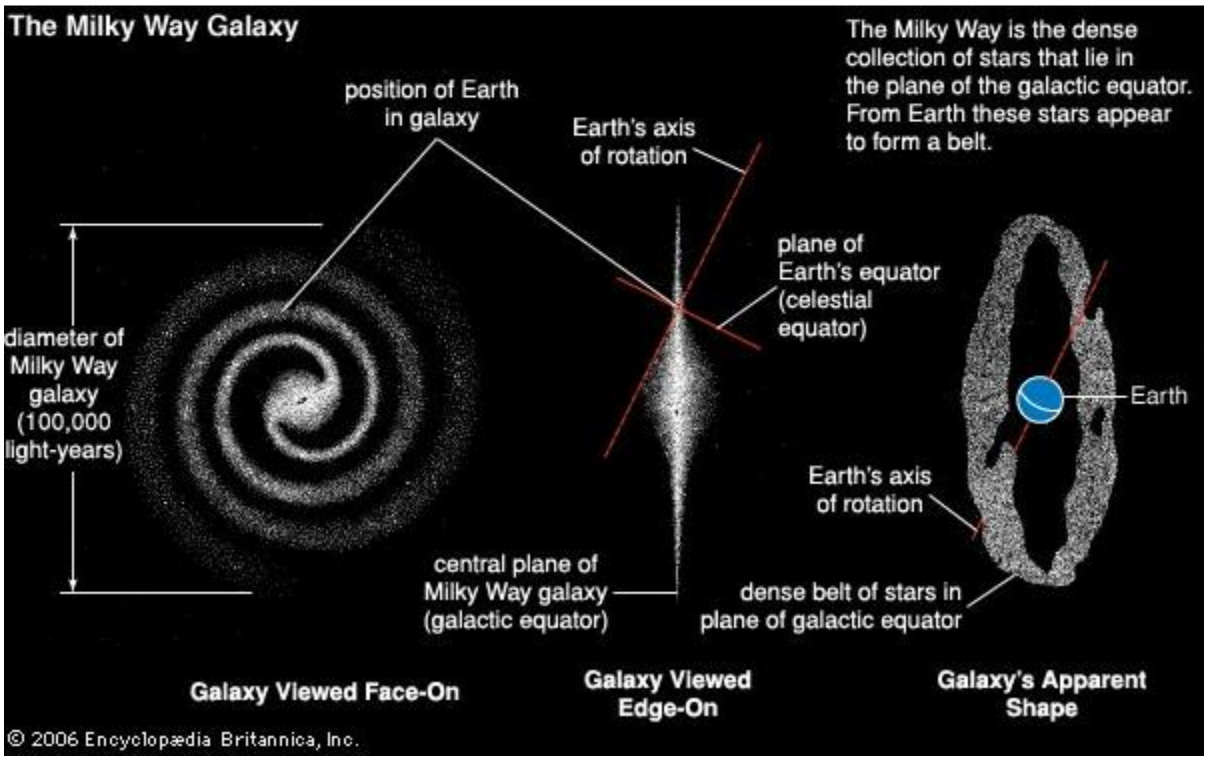
STRUCTURE OF THE GALAXY

- (Barred) spiral galaxy
- As we are inside it, it's very hard to actually see how it looks like! The image on the right is an artist's concept, we cannot see our own Galaxy from the outside.
- Note the various spiral arms and the location of the Sun.



STRUCTURE OF THE GALAXY

- Note the position of our solar system in the Galaxy

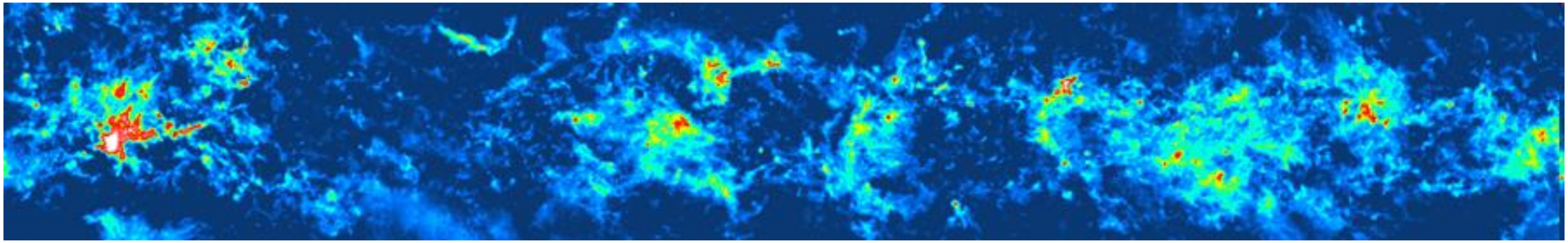


STRUCTURE OF THE GALAXY

- **Central area:**
  - Dense, contains both new and old stars
  - 5 - 10 % of the total mass of the Galaxy
  - The other side of the central area has an asymmetrical bulge: a bar the longitudinal axis of which is close to the viewing angle
    - more evidence for a bar: carbon stars (old red giants) aligned along the axis
  - The bar at a 30° angle, 15 000 x 5 000 ly (best guess)
  - The bar may have been caused by several close-by galaxies passing by (tidal forces), and it could be part of galaxy evolution.
    - https://www.newscientist.com/article/dn14431-barred-spiral-galaxies-becoming-more-common/

STRUCTURE OF THE GALAXY

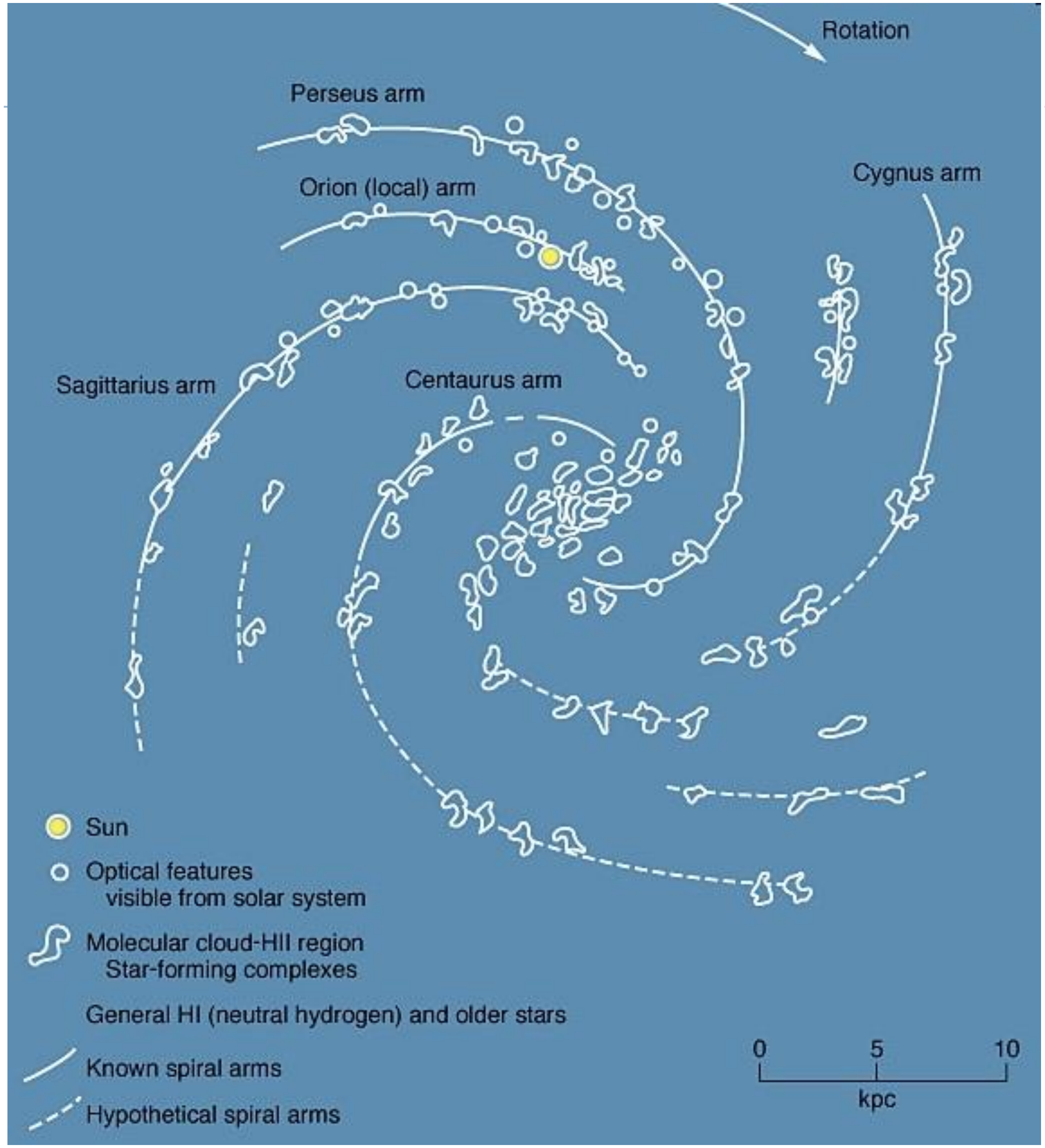
- A ring composed of molecular clouds surrounds the central area at a distance of 10 000 – 16 000 ly (gas and dust); lots of star formation! The picture below is a 110 GHz radio image of the ring.
- http://www.bu.edu/galacticring/outgoing/PressRelease/



- This is how the molecular ring around our Galaxy, could look like. Looking from Andromeda, our neighbour galaxy, the ring would be the brightest feature of the Galaxy.
- This is another galaxy though, called NGC 7742.

- **Disc and spiral arms:**
  - The spiral arms have been mapped at radio frequencies, with the help of star clusters and hydrogen clouds + pulsars. (This will be discussed on the Radio Astronomy course.)

$\Rightarrow$ 4 (5?) spiral arms, originating in the molecular ring, open up at a 20° angle

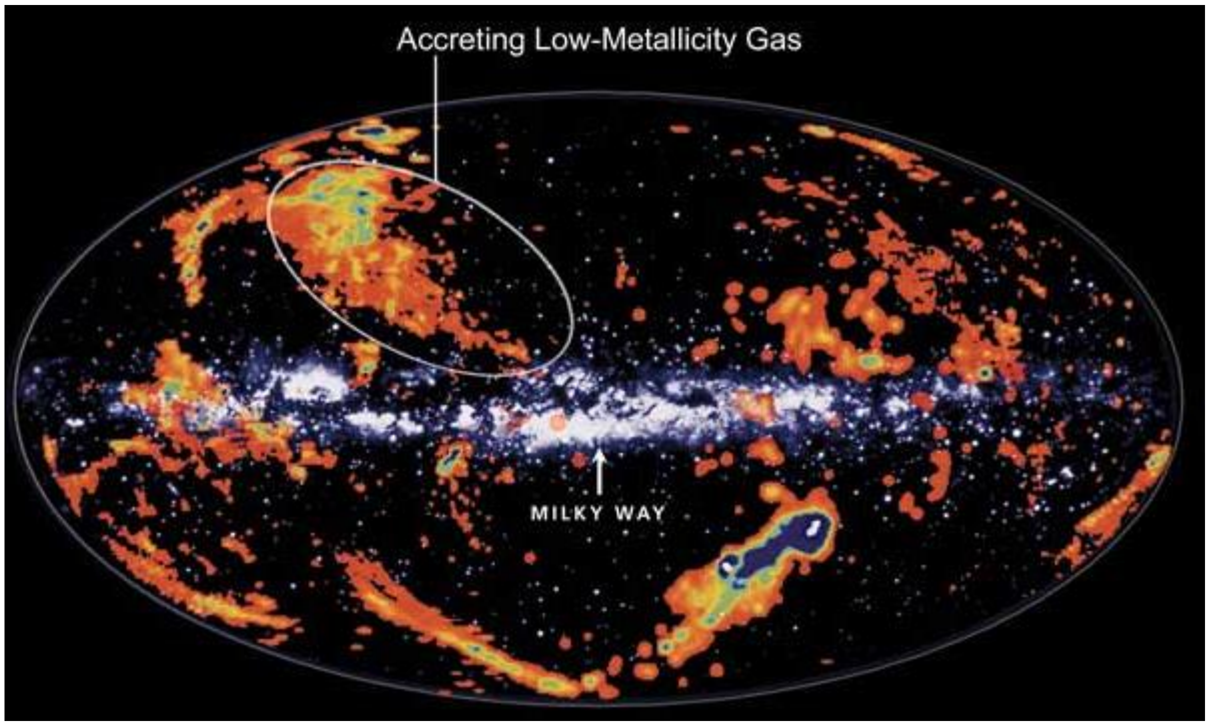

Rotation
Perseus arm
Orion (local) arm
Cygnus arm
Sagittarius arm
Centaurus arm
Sun
Optical features
visible from solar system
Molecular cloud-HII region
Star-forming complexes
General HI (neutral hydrogen) and older stars
Known spiral arms
Hypothetical spiral arms
0
5
10
kpc

STRUCTURE OF THE GALAXY

- Newly formed and young stars located in the galactic plane in circular orbits (in one year ~1 $M_\odot$ new stars are born).
- The metallicity of young stars increases.

- Open star clusters, interstellar matter.
- Also an "outer" disc of hydrogen (15 000 ly away) and a large disc of warm gas (~10 000K).
- High-velocity clouds (HVC), intermediate-velocity clouds (IVC).
- "Star ribbons", caused by dwarf galaxies and globular star clusters interacting with the Galaxy.

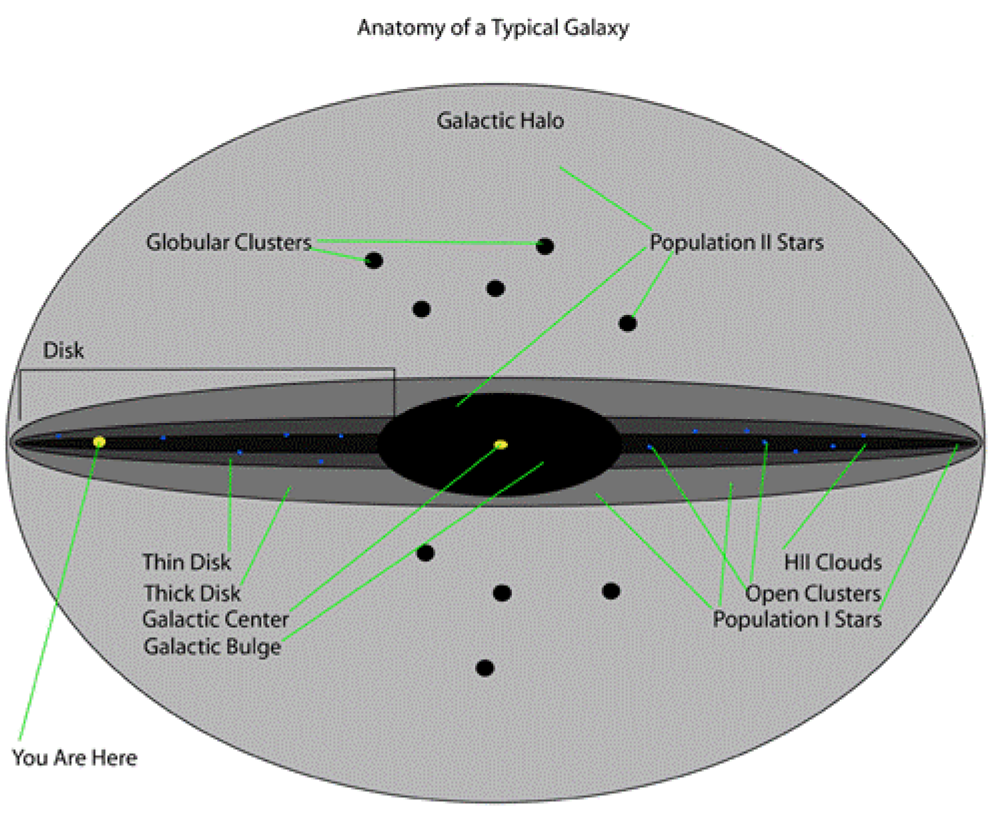
- Example of HVC clouds



STRUCTURE OF THE GALAXY

- **Halo:**
  - old stars (up to ~13.5 billion years) in eccentric orbits, no preference for the galactic plane
  - very little gas, metal-poor
  - globular star clusters
  - no star formation
- **Corona:**
  - very little interstellar matter, at least what can be observed ⇒ dark matter could be located here?
  - size (possibly) up to hundreds of kiloparsecs (>100 000 ly)

- What's in the galactic plane vs. the halo



STAR CLUSTERS

- A group of stars of roughly the same age, evolved from the same interstellar cloud and still located close to each other.

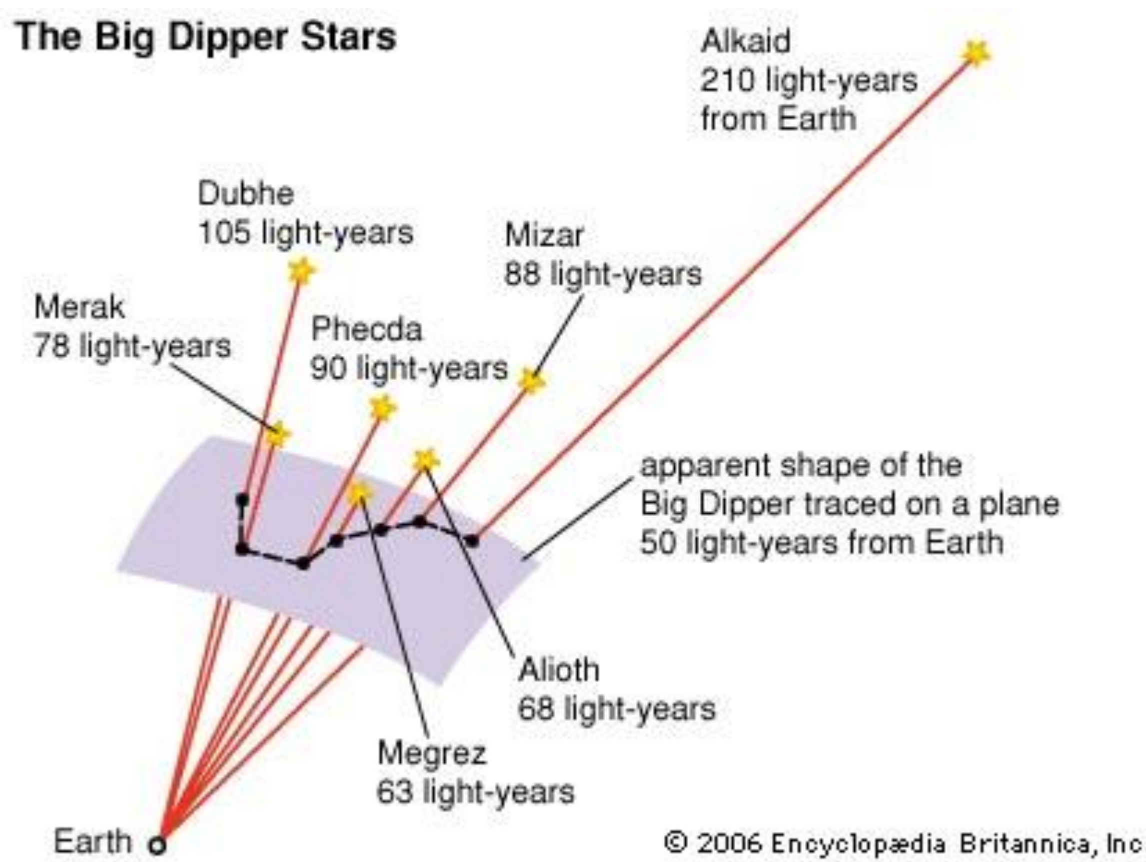
Globular cluster

Open cluster

CONSTELLATIONS

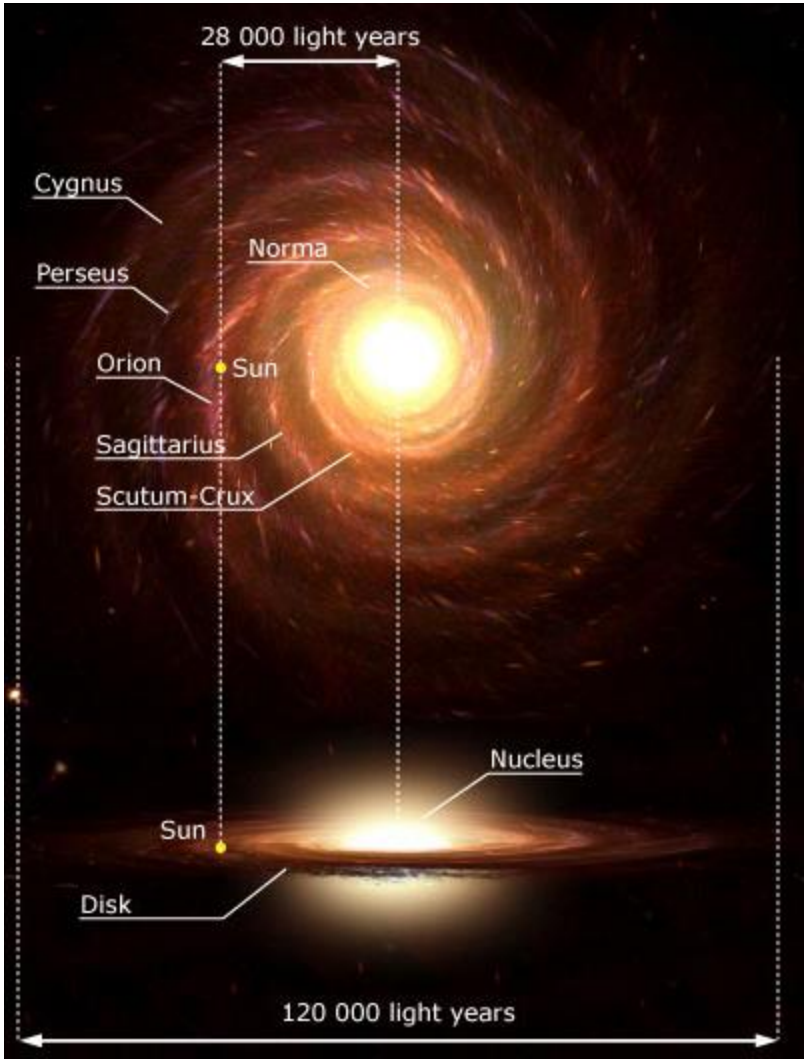
- Patterns of stars.
- Stars in them could be located at different distances (not clusters!)

- Ursa Major is a ***constellation*** which includes the ***asterism*** called the Bip Dipper.

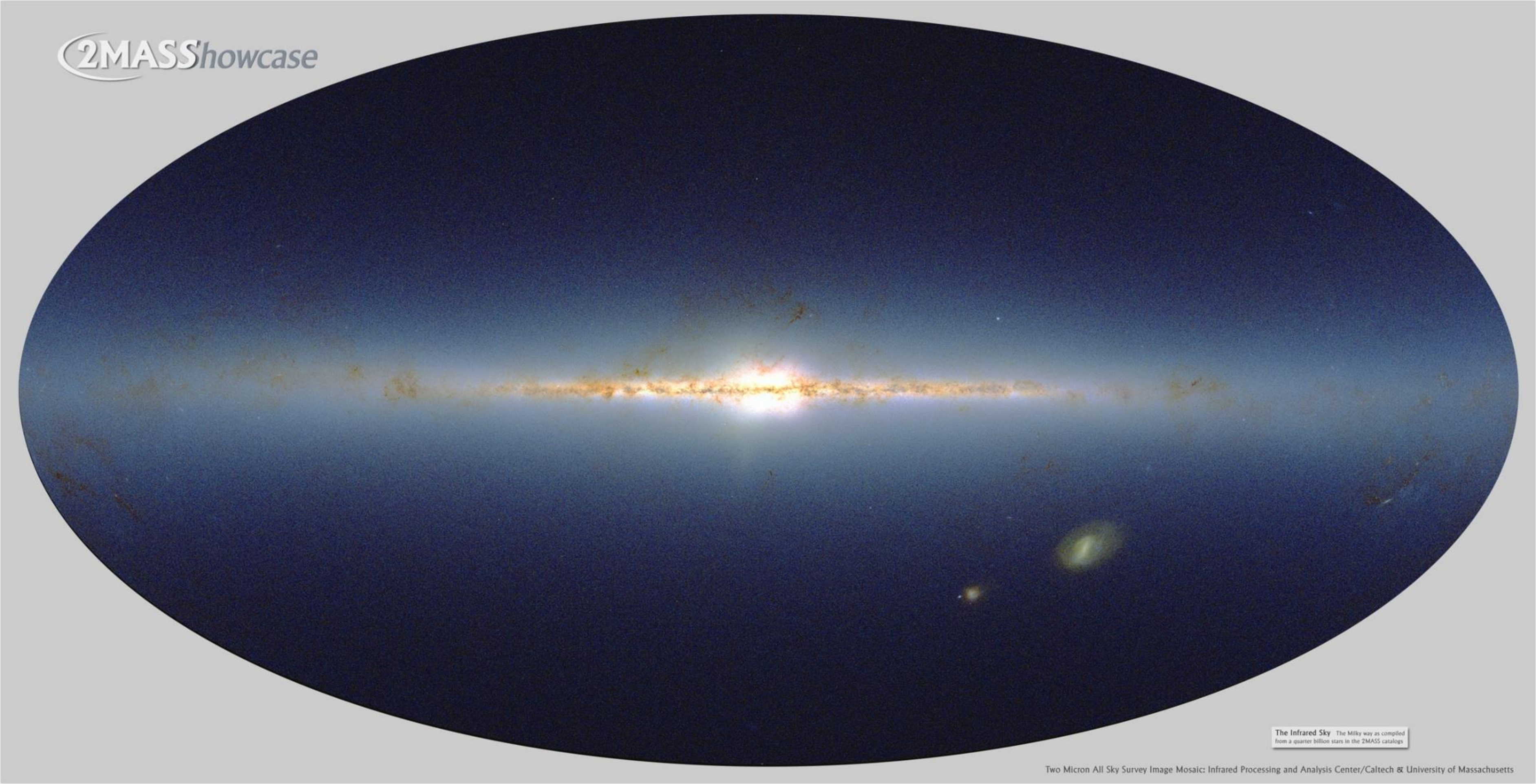


Summary: STRUCTURE OF THE GALAXY

- **Size**
  - diameter 30 kpc (100 000 ly)
  - Thickness 1 kpc
  - Mass 600 x 10^9 $M_\odot$
  - Orbital period of the Sun 225 x 10^6 years
- **Earth:**
  - in a spiral arm, 8.5 kpc (28 000 ly) from the Galactic Centre



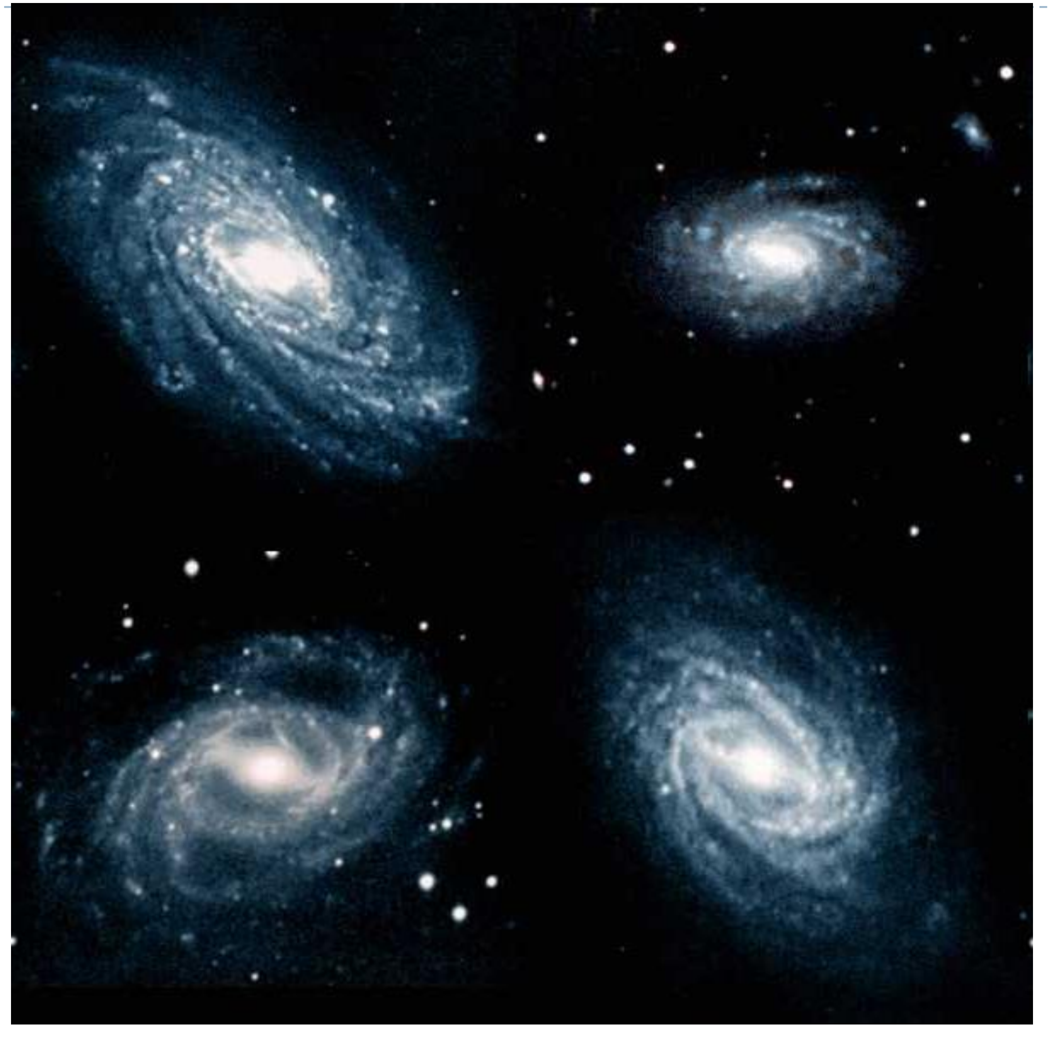
The Galaxy @ 2μm



For more information about what is in the image above, go to https://old.ipac.caltech.edu/2mass/gallery/images_misc.html

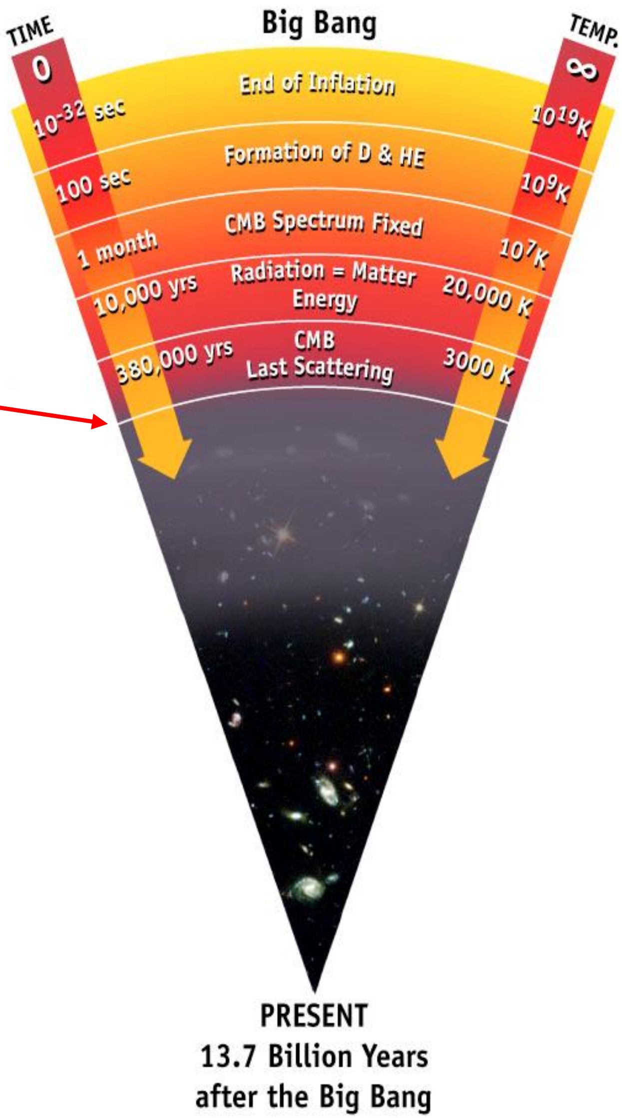
Examples of BARRED SPIRAL GALAXIES that resemble the Galaxy

- NGC 3953
- NGC 5970
- NGC 7329
- NGC 7723



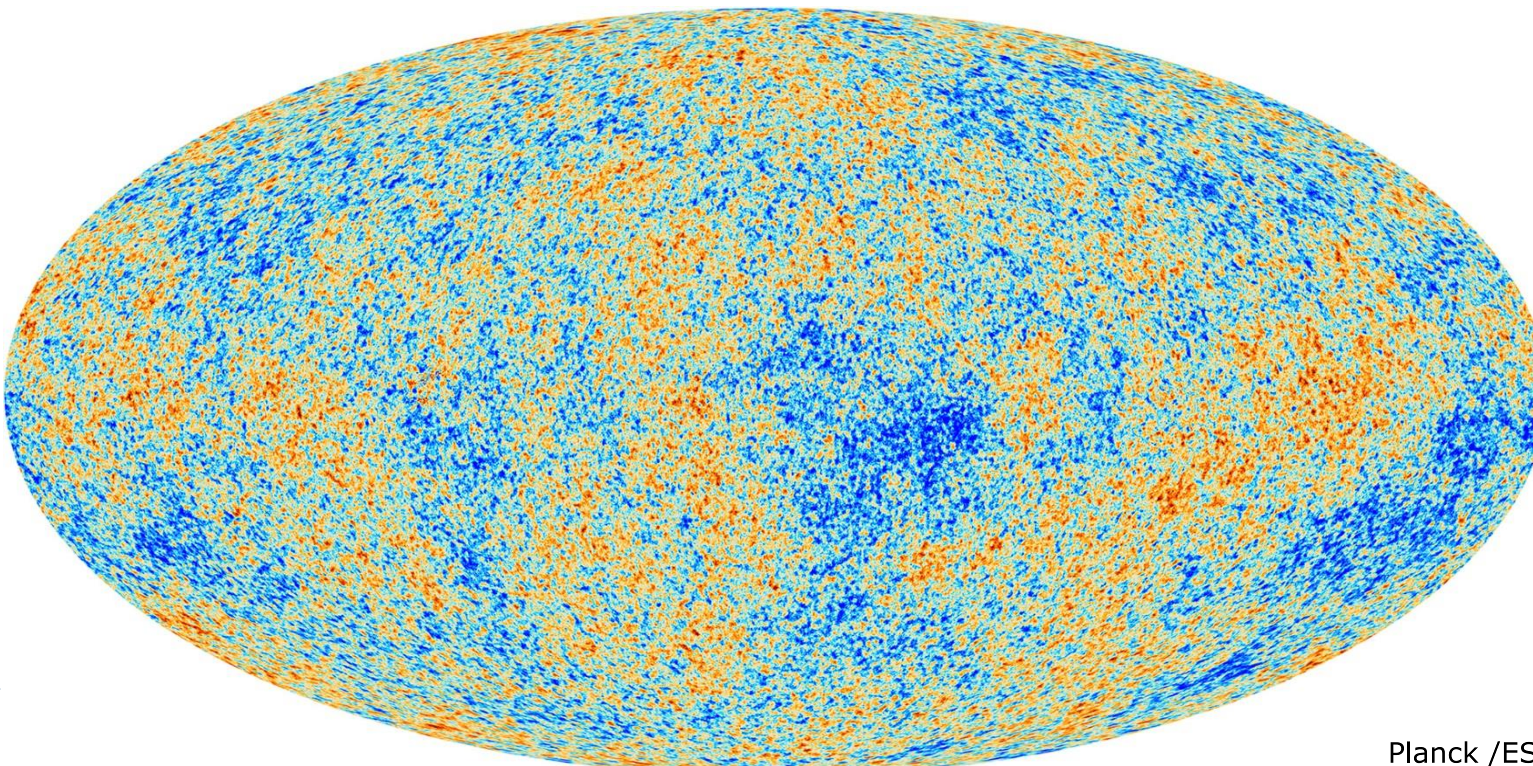
IT ALL STARTED WITH A BANG

- In the beginning opaque photon-baryon plasma until…
- Photons scattered from matter for the last time.
- This is the cosmic microwave background (CMB).
- Radiation propagates freely in the current universe.



COSMIC MICROWAVE BACKGROUND

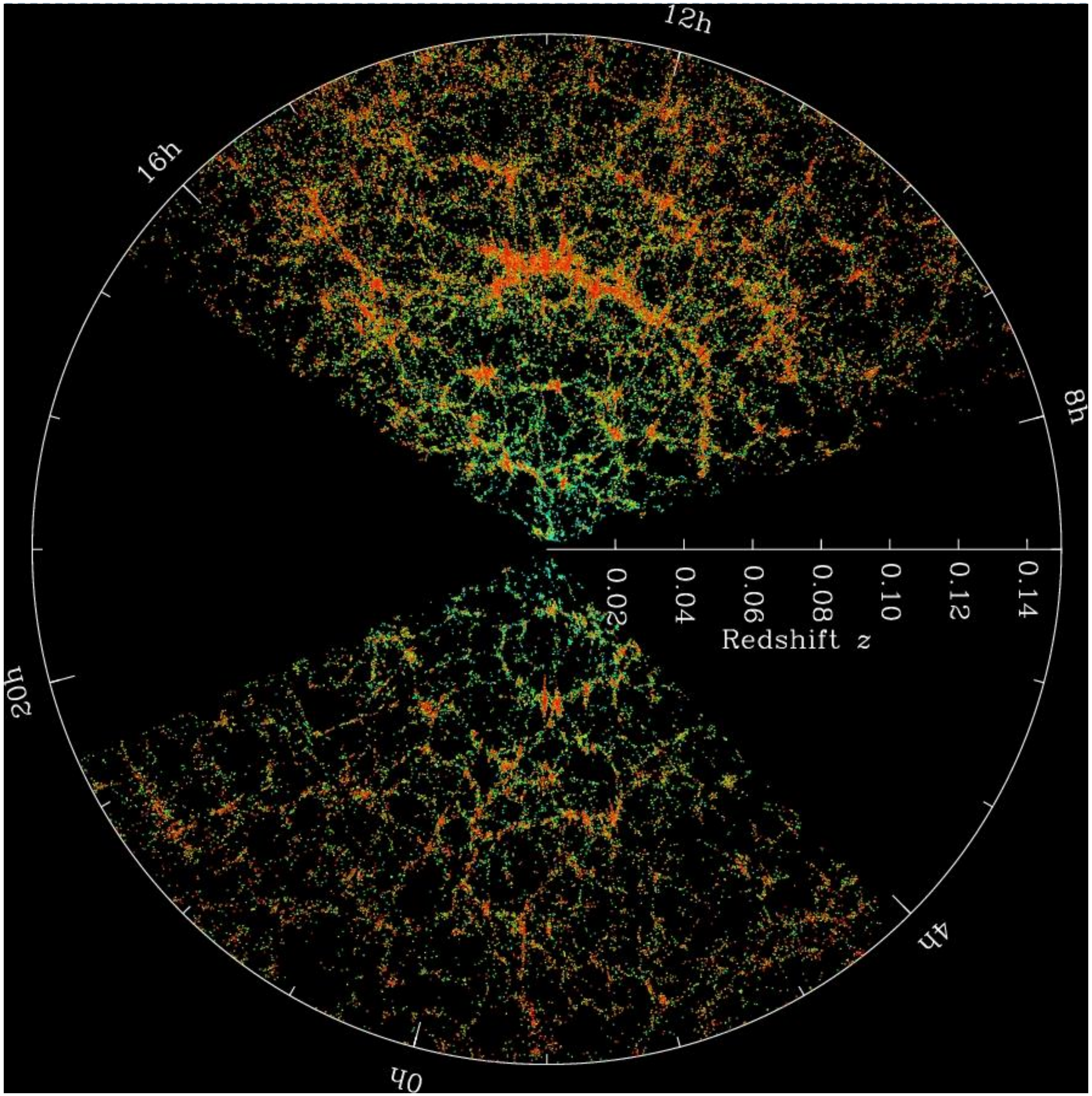
- Cosmic microwave background emission (CMB), 3K, is like a photograph of the young universe.
- The tiny temperature anisotropies of the CMB reveal how the structure of the universe started to form.



Planck /ESA

- Red denotes warmer areas with more mass, blue denotes cooler areas with less mass. This anisotropy enabled gravity to start pulling matter together, and therefore the formation of structure, such as first stars and galaxies. Without these anisotropies we would not be here!

STRUCTURE OF THE UNIVERSE



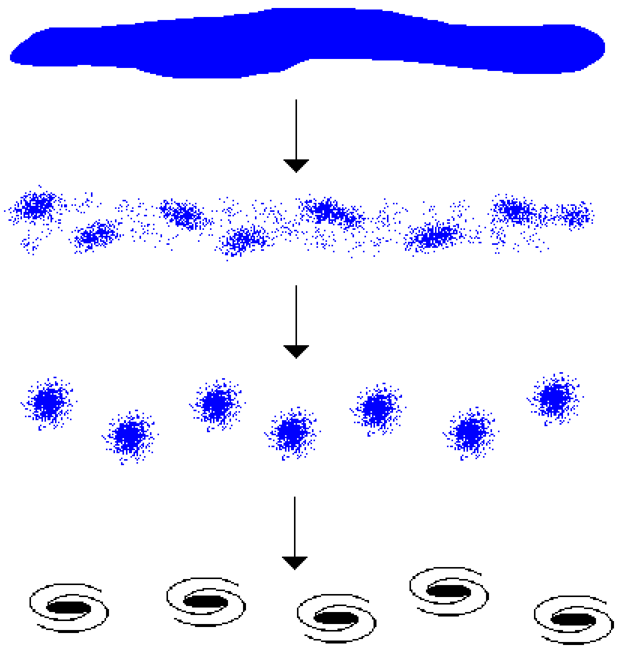
Sloan Digital Sky Survey

- Map of the universe: each dot is a galaxy.
- Distances are expressed in redshift.
- The mapping was possible only in directions outside the Galactic plane.

FORMATION OF STRUCTURE

Top–Down Structure Formation

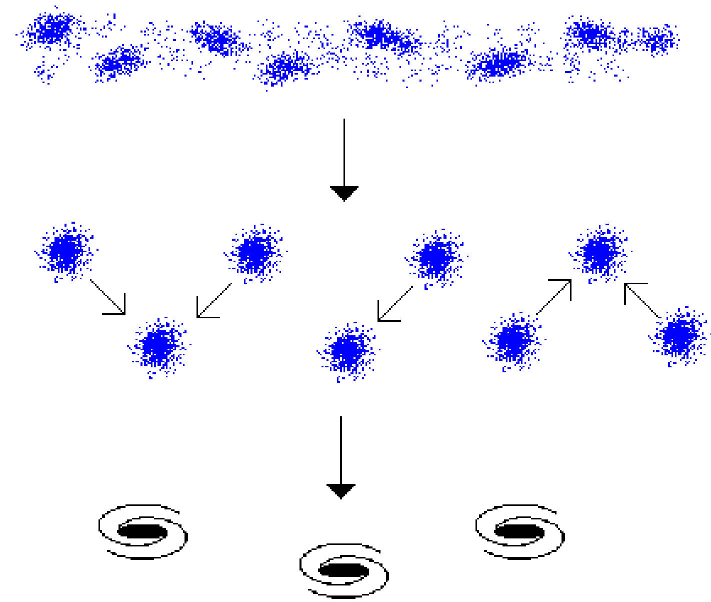
in a top–down scenario, large pancakes of matter form first, than fragment into galaxy–sized lumps



Requires hot dark matter (HDM) that moves at ultrarelativistic velocities, such as neutrinos.

Bottom–Up Structure Formation

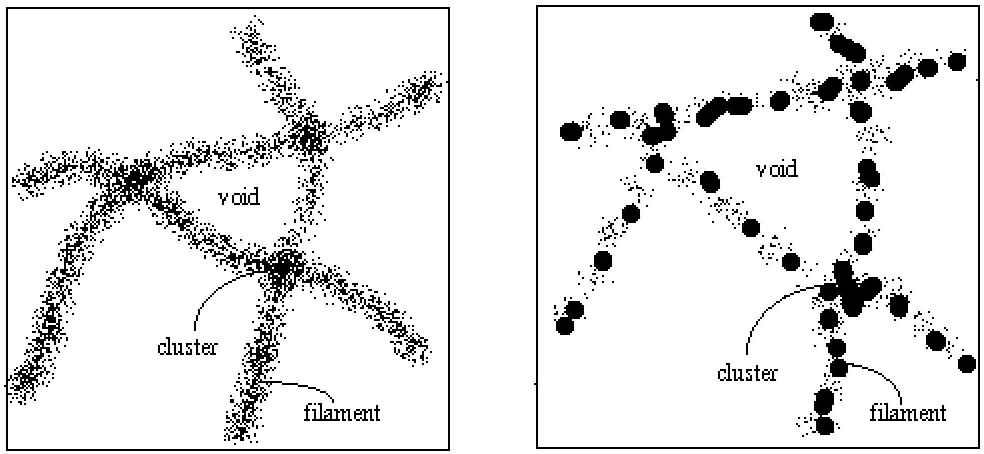
in a bottom–up scenario, small, dwarf galaxy–sized lumps form first, then merger to make galaxies and clusters of galaxies



Requires cold dark matter (CDM) that moves slowly compared to light speed, such as massive compact halo objects (MACHOs), weakly interacting massive particles (WIMPs) etc…

Large Scale Structure

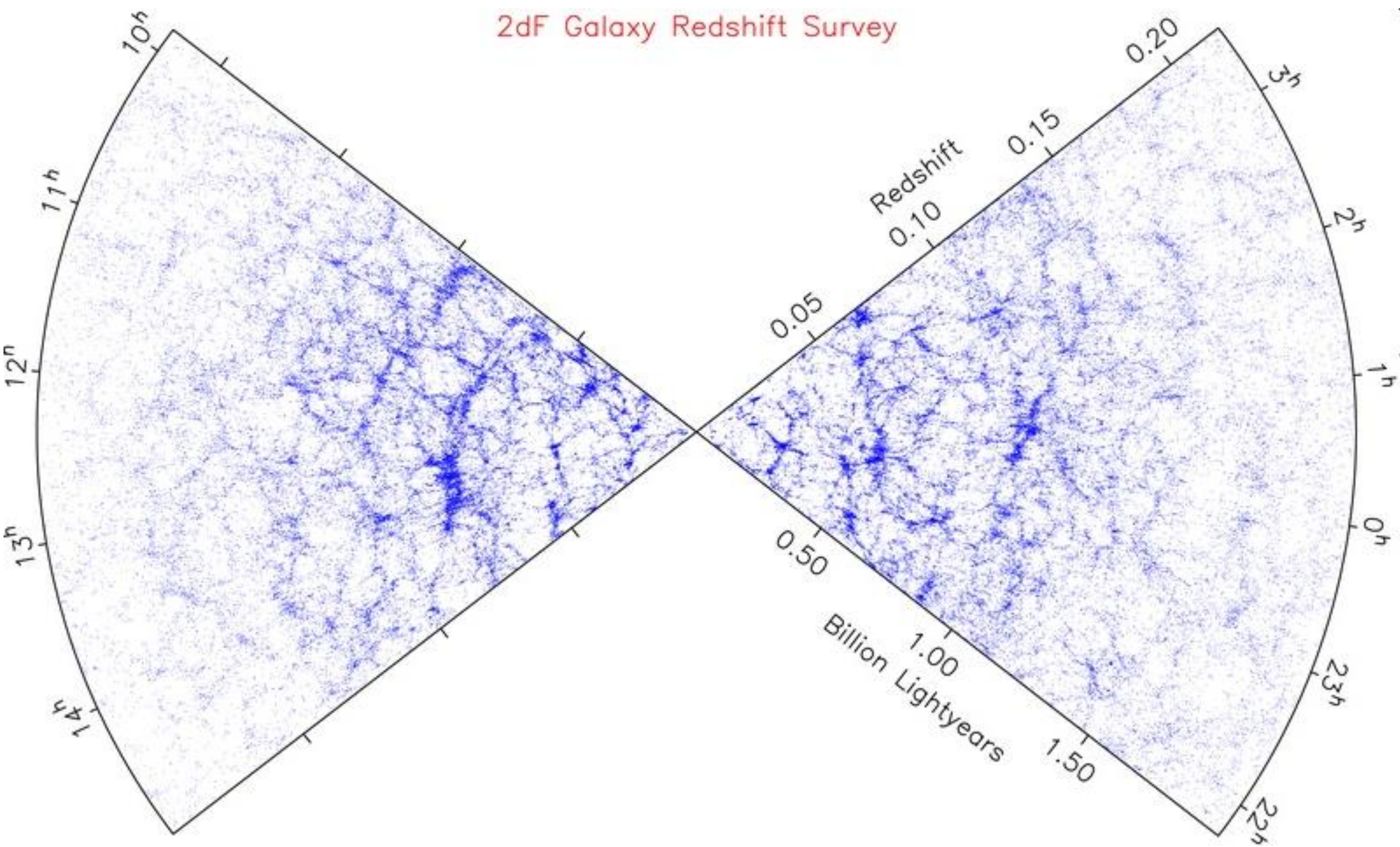
HDM and the top–down scenario predict smooth, weak features in the large scale distribution of galaxies



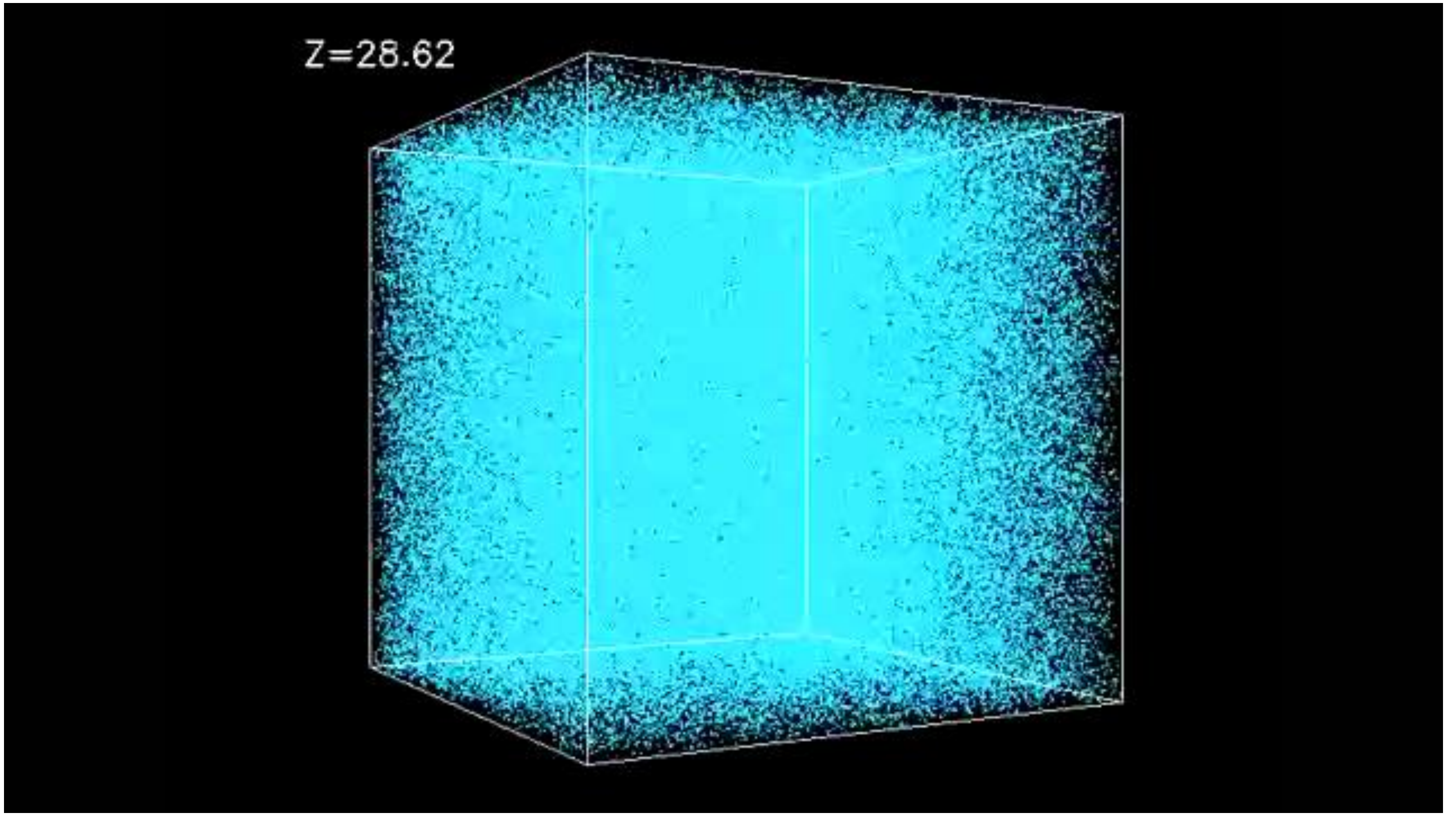
HDM CDM

CDM and the bottom–up scenario predict sharp features with weak connecting filaments

- The problem is that the observations show a universe _between_ these two options…



FORMATION OF LARGE SCALE STRUCTURE



See the simulation at
http://cosmicweb.uchicago.edu/sims.html

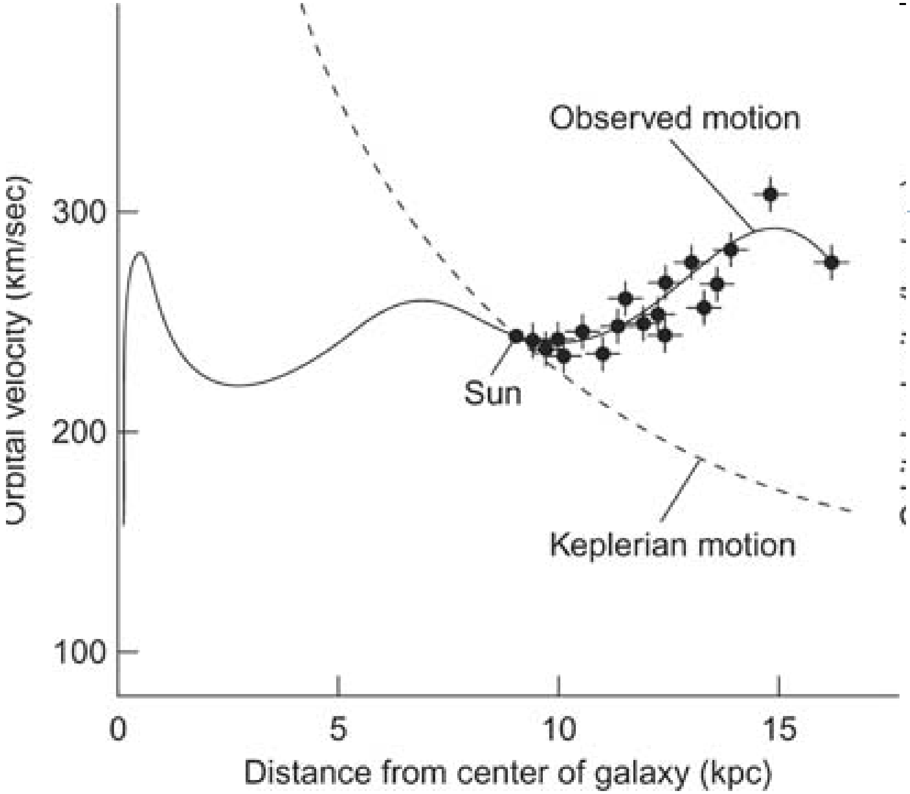
HOW THE GALAXY FORMED

- Approx. 13.5 billion years ago the Galaxy was a large turbulent cloud made of hydrogen and helium.
  - The first very massive stars formed (fast evolution, heavier elements, supernova explosions).
  - Shock waves accelerated the formation of further generations of stars.

- The Galaxy contracted under its internal gravity, the originally slow rotation accelerated.
- After a couple of billion years the cloud collapsed along its rotational axis and a disc was formed.

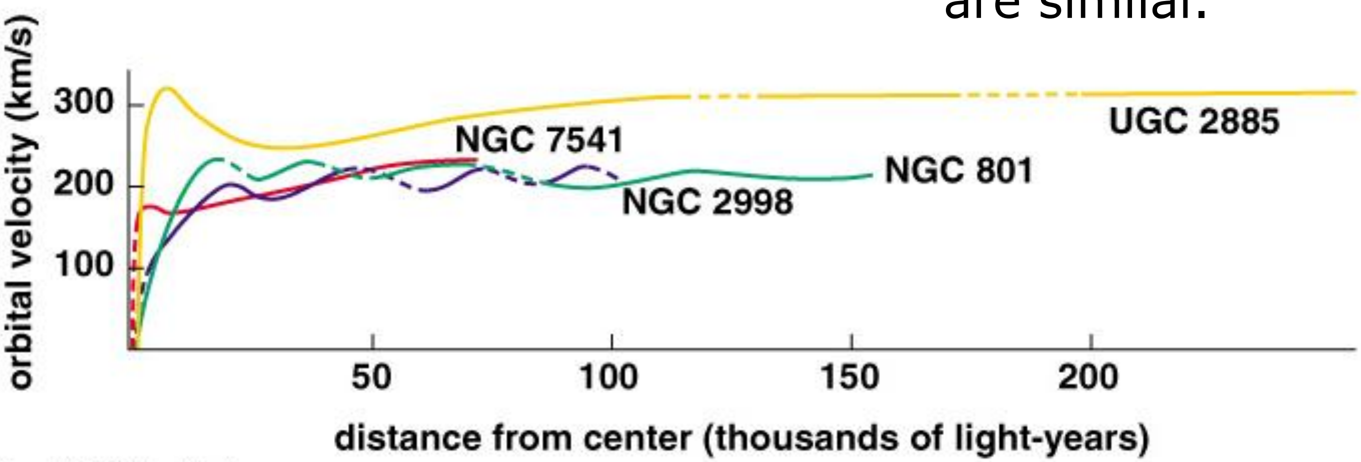
DIFFERENTIAL ROTATION

- The angular velocity of the rotation depends on the distance to the galactic centre (the velocity decreases as the distance increases). The Galaxy does not rotate as a rigid body: differential rotation.
- Studies of stars and interstellar matter to measure the rotation curve: how fast does the matter in the Galaxy rotate at various distances. The curve is surprisingly flat, which means that there is probably dark matter that keeps the rotation speed high even at large distances from the centre.



The rotation curve of the Galaxy does not follow Keplerian motion that is based on the amount of matter that we can SEE in the Galaxy. Something unseen keeps the speed high even at large distances.

Rotation curves of other galaxies are similar.



- The Sun is orbiting the Galactic centre at a speed of 220 km/s
- Mass of the Galaxy inside the solar orbit 100 x $10^9 M_\odot$
- Total mass of the Galaxy is 600 x $10^9 M_\odot$

FORMATION OF SPIRAL STRUCTURE

- There are two main theories how the spiral structure in galaxies is formed: density waves and stochastic self-propagative star formation. The first one is currently preferred.

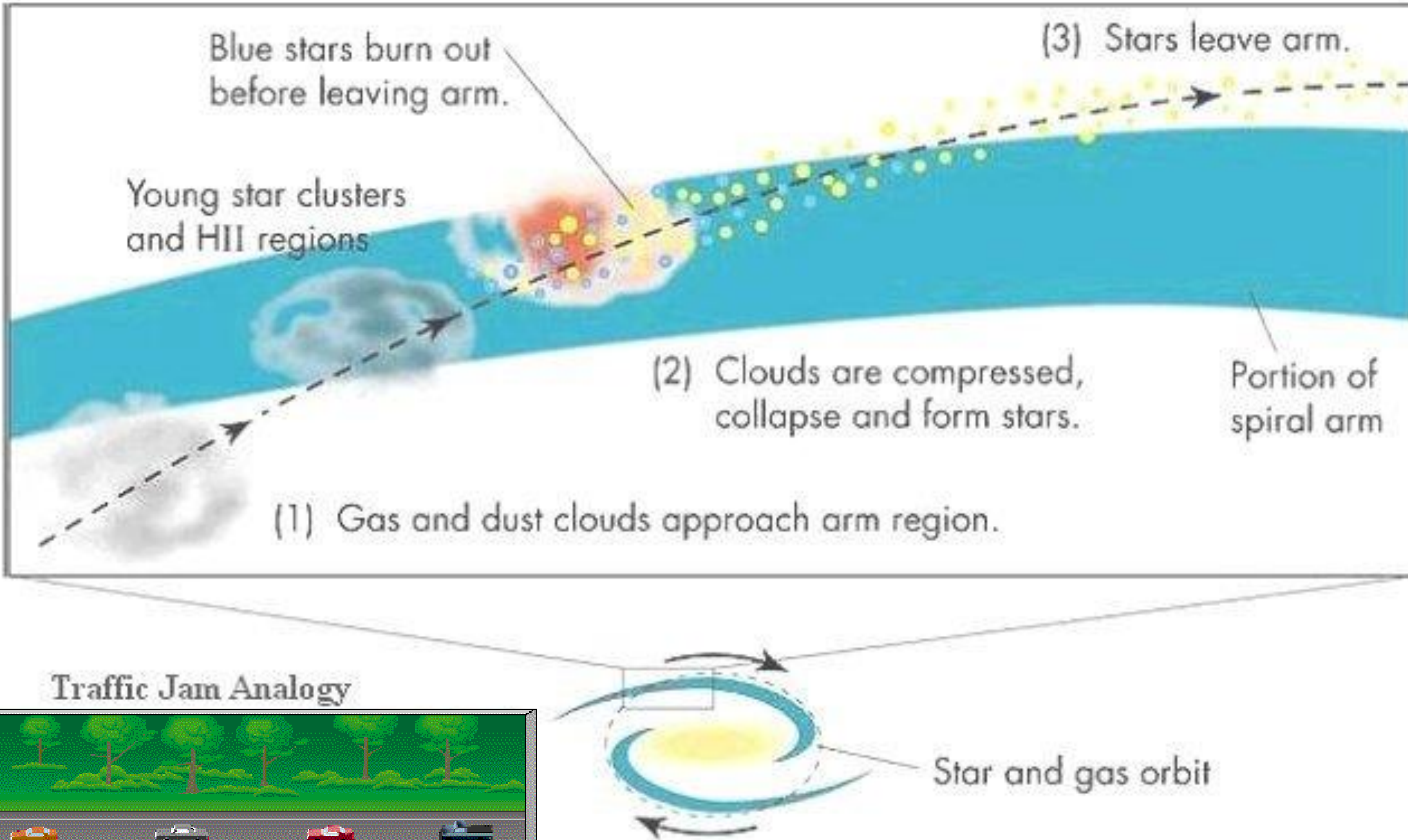
FORMATION OF SPIRAL STRUCTURE

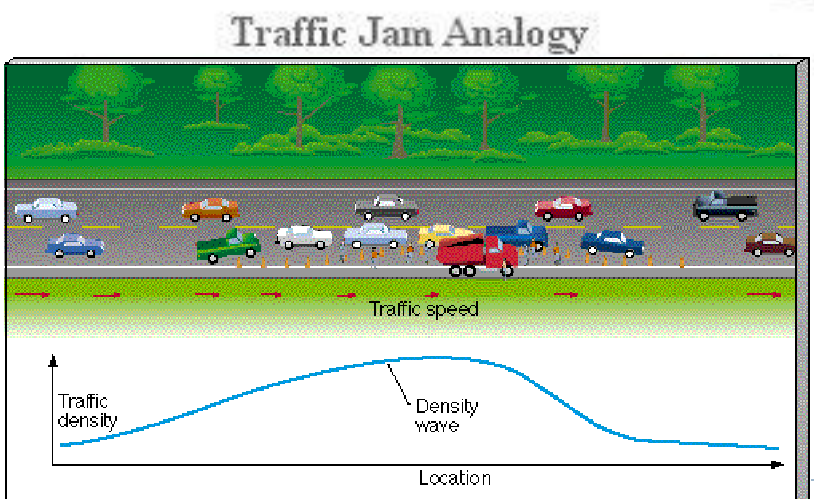
1. Density wave theory

- Applies particularly for "Grand Design" spiral galaxies with clearly defined spiral structure.
- Note that spiral arms are not solid.
- A spiral-shaped gravitational disturbance, that is, a density wave is formed. It rotates around the centre with constant radial velocity. At the distance of the Sun that is half of the radial velocity of matter.
- At the moment it is not clear how the density wave is generated (or maintained) in the first place.

FORMATION OF SPIRAL STRUCTURE

- Gas (or a star) hits the density wave, is slowed by the local gravitational field, and compresses, then expands after having moved through the wave.
  - condensation of gas and stars in the density wave produces a spiral arm
- However, stars move faster (or slower) than the density wave, and move in and out of the spiral arm area and don't stay there forever.
- Young objects in the spiral arms, for example, star formation at the inner edge of the spiral arms.
- Problematic details: how is the wave formed and maintained, why do not all galaxies have spiral arms ?





Density waves in real life: a traffic jam. A density wave moves with the slow truck, traffic is slowed down around it, but returns to normal speed after passing the truck (and the density wave).

FORMATION OF SPIRAL STRUCTURE

2. Stochastic Self-Propagative Star Formation

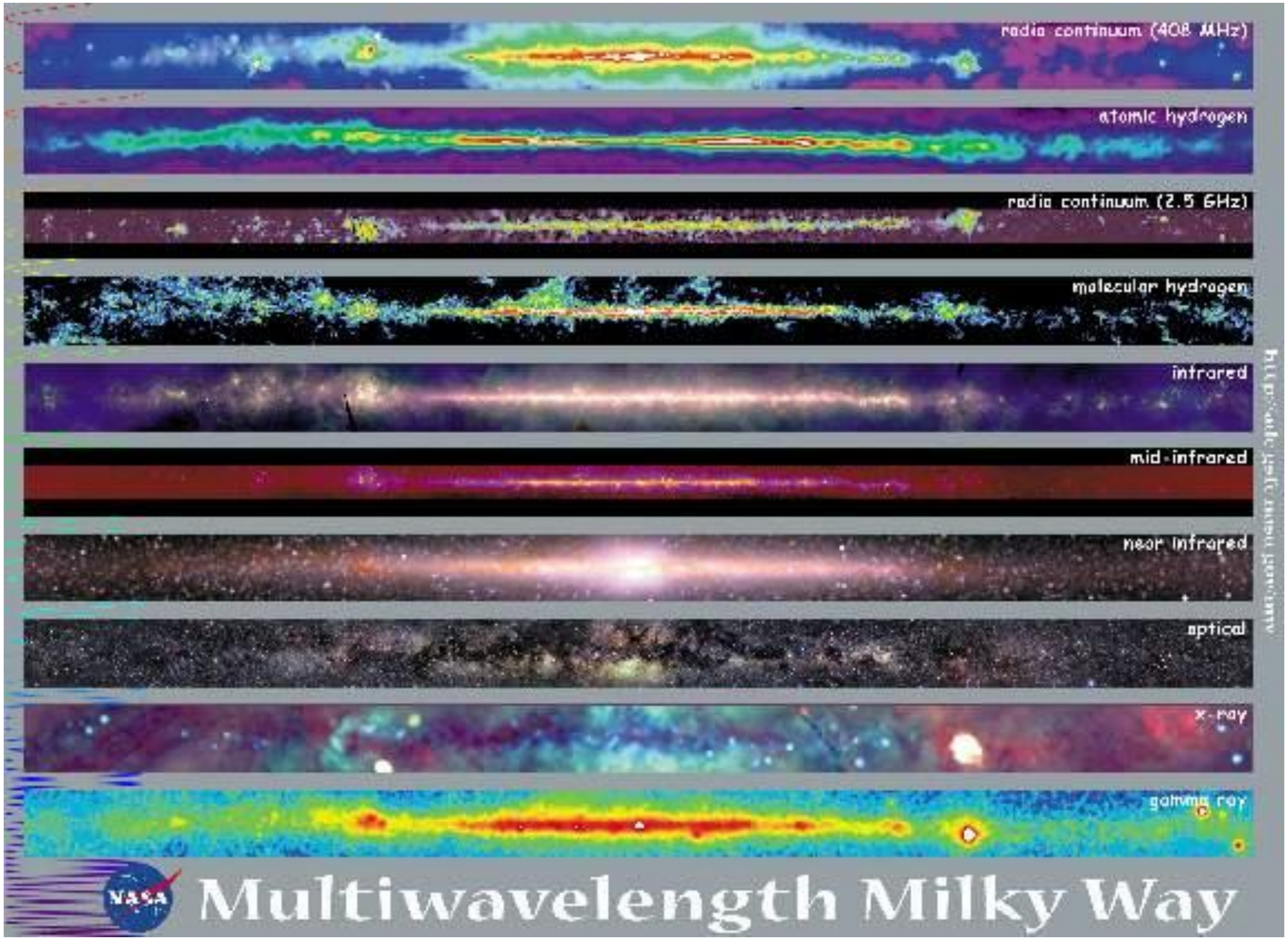
- Flocculent spiral galaxies, with spiral arm structure that is not so well defined but rather "fluffier".

- Stochastic = constant but random star formation here and there in the galaxy.
- Star formation triggers more star formation in neighbouring areas: "chain reaction of supernovae"
- Spiral arms are formed because the galaxy is rotating
    - …but not all galaxies are rotating much…?

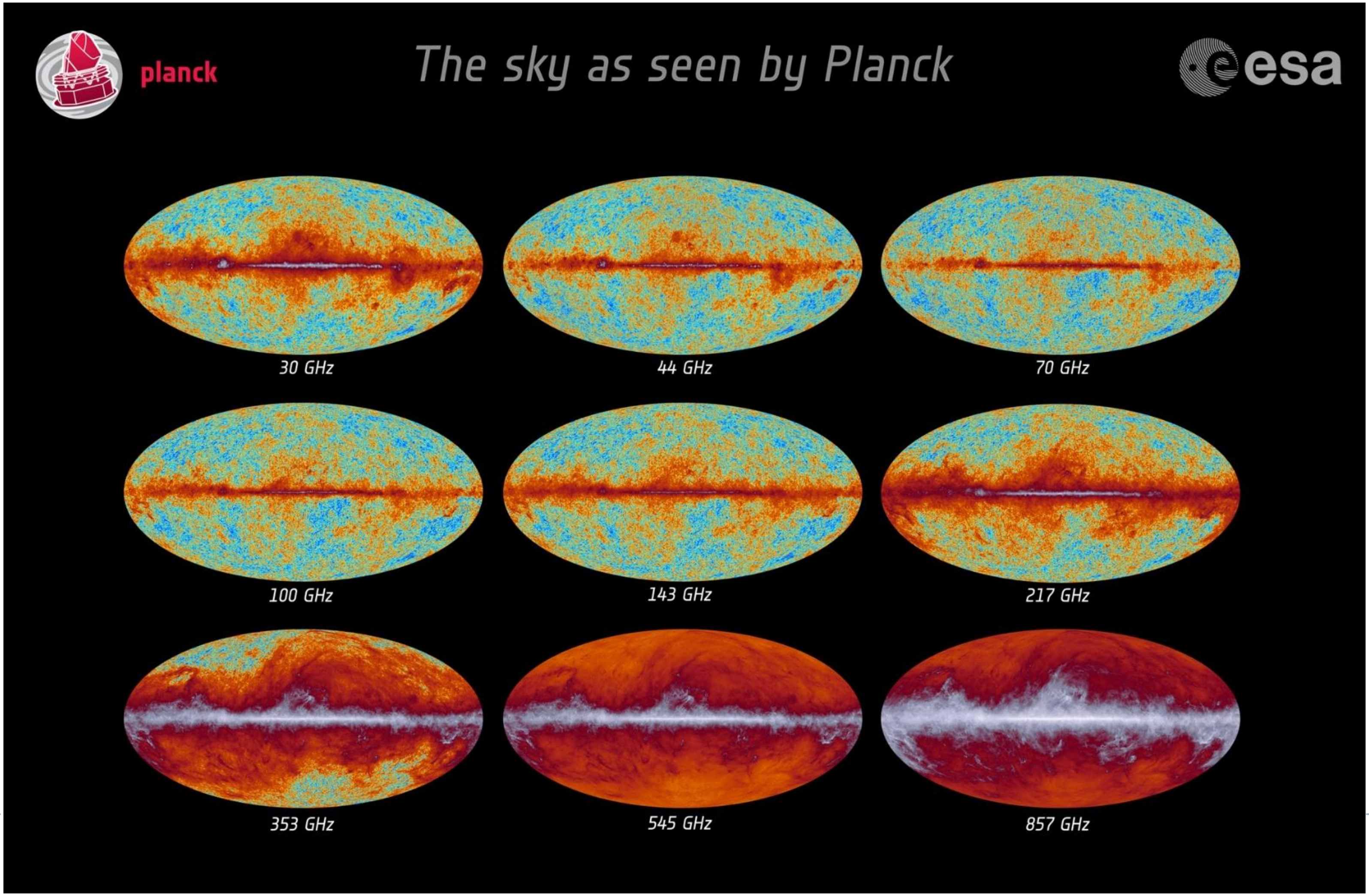
THE GALACTIC CONTINUUM

- The Galaxy looks different depending on which wavelength we use for observing it; it therefore emits at most if not all wavelengths creating a continuum of emission.
- Look at the image on the next page and how different the Galaxy looks, for example, at radio and optical wavelenthgs. At radio we can see through the obscuring dust, which at optical covers most of the Galactic plane (and the Galactic centre!) very effectively.
- The various emission mechanisms (as your have learned on the previous lectures) in celestial objects and matter are responsible for this.

THE GALACTIC CONTINUUM



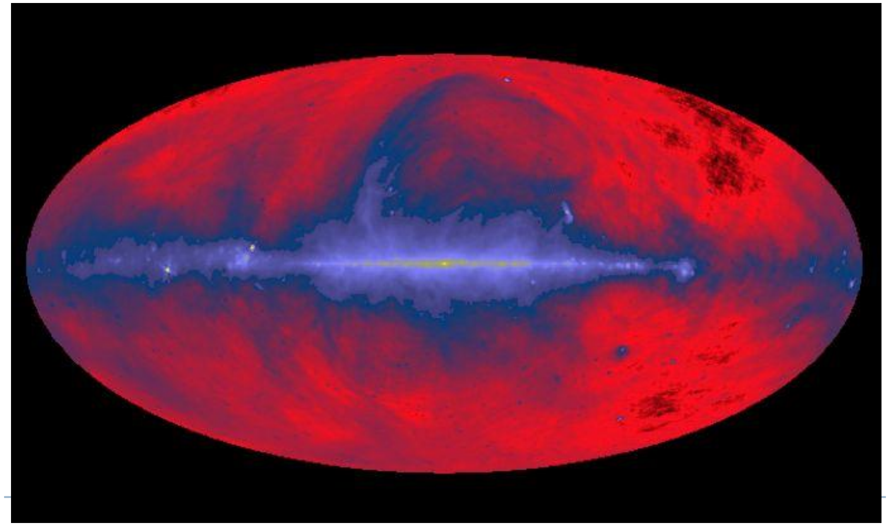
- The Galaxy looks very different also within just one wavelength range: an example at radio. This is due to the shift in emission mechanism from synchrotron to thermal, reflecting the nature of celestial sources dominating at those wavelengths.



THE GALACTIC CONTINUUM

- Interstellar space is not empty, optical and shorter wavelength radiation is absorbed (and re-emitted, scattered…).
- Radiation decreases as the distance increases.
- Dust (and gas) block observations at the short wavelengths $\Rightarrow$ we can use radio astronomy to see through them!

408 MHz

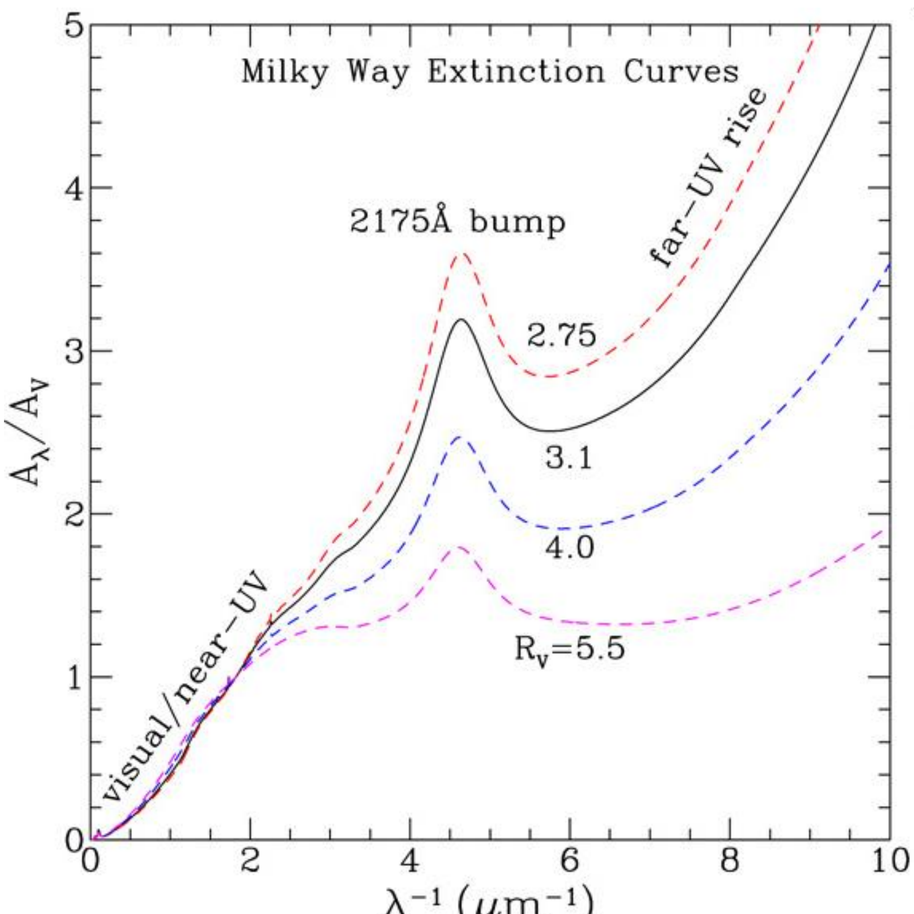


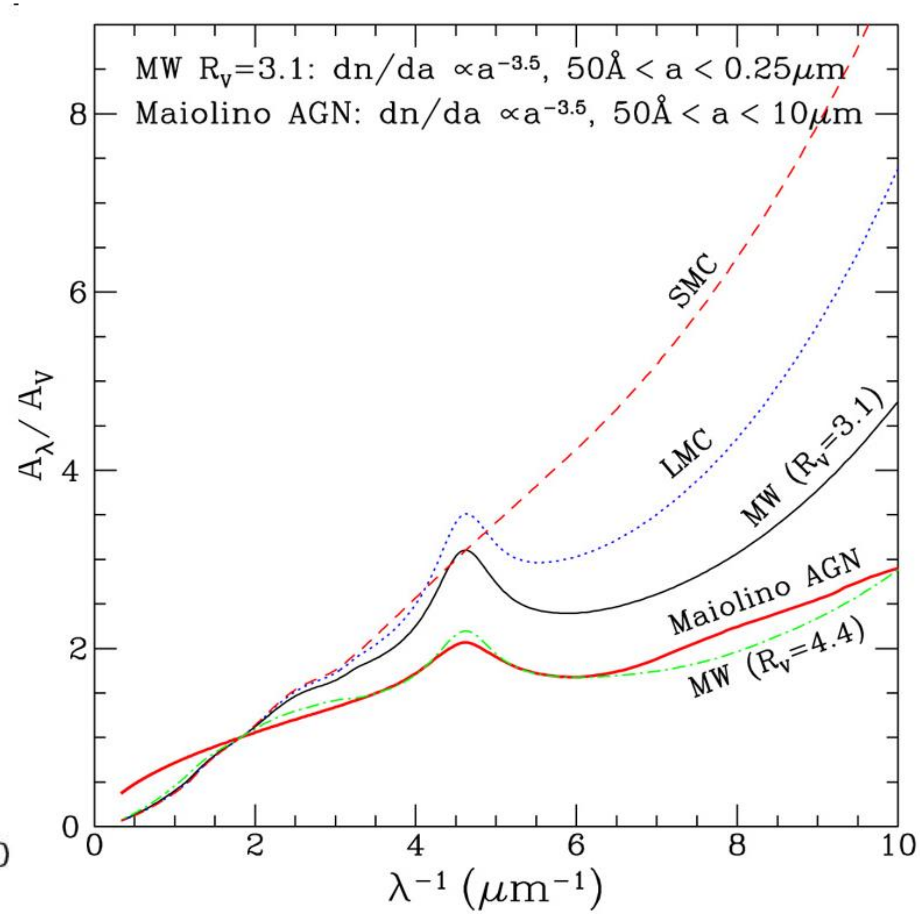
THE GALACTIC CONTINUUM

- Certain effects cause attenuation or other changes in the galactic emission. These are mostly caused by dust.

- **Extinction**
  - attenuation of radiation as it passes through a medium (**dust**, gas), radiation losses
    - radiation decreases as the distance increases
  - absorption or scattering
  - varies strongly with direction
  - in the galactic plane 1 - 2 mag / kpc
  - extinction curve based on observations, that is, how much emission is attenuated at certain wavelengths. This correlates with the dust grain size.

- Below are the extinction curves of the Galaxy (left) and some other galaxies (right). They are mostly rather similar, however, differences (such as in SMC and the AGN) are caused by a smaller dust grain size (and this is one way of studying the composition of galaxies.)





THE GALACTIC CONTINUUM

- **Reddening**
  - Blue light is scattered and absorbed (by dust) more than red (theamount of extinction is larger for shorter wavelengths).
  - The light of distant stars is redder (and dimmer) than would be expected on the basis of their spetral class.

- **Polarization**
  - Nonspherical dust particles are aligned by the interstellar magnetic field. With polarization we can:
    - study the properties of the dust particles.
    - map the structure of the galactic magnetic field.

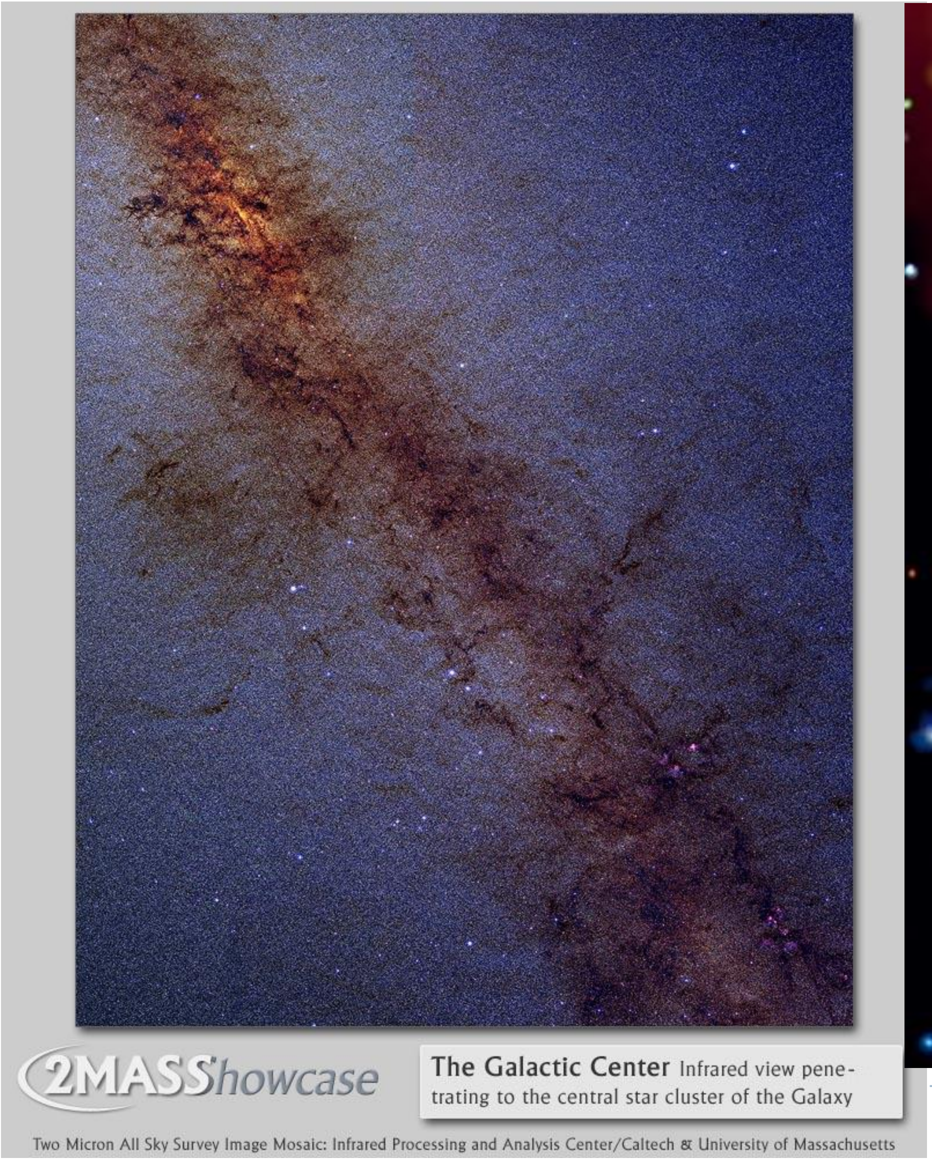
THE GALACTIC CENTRE?

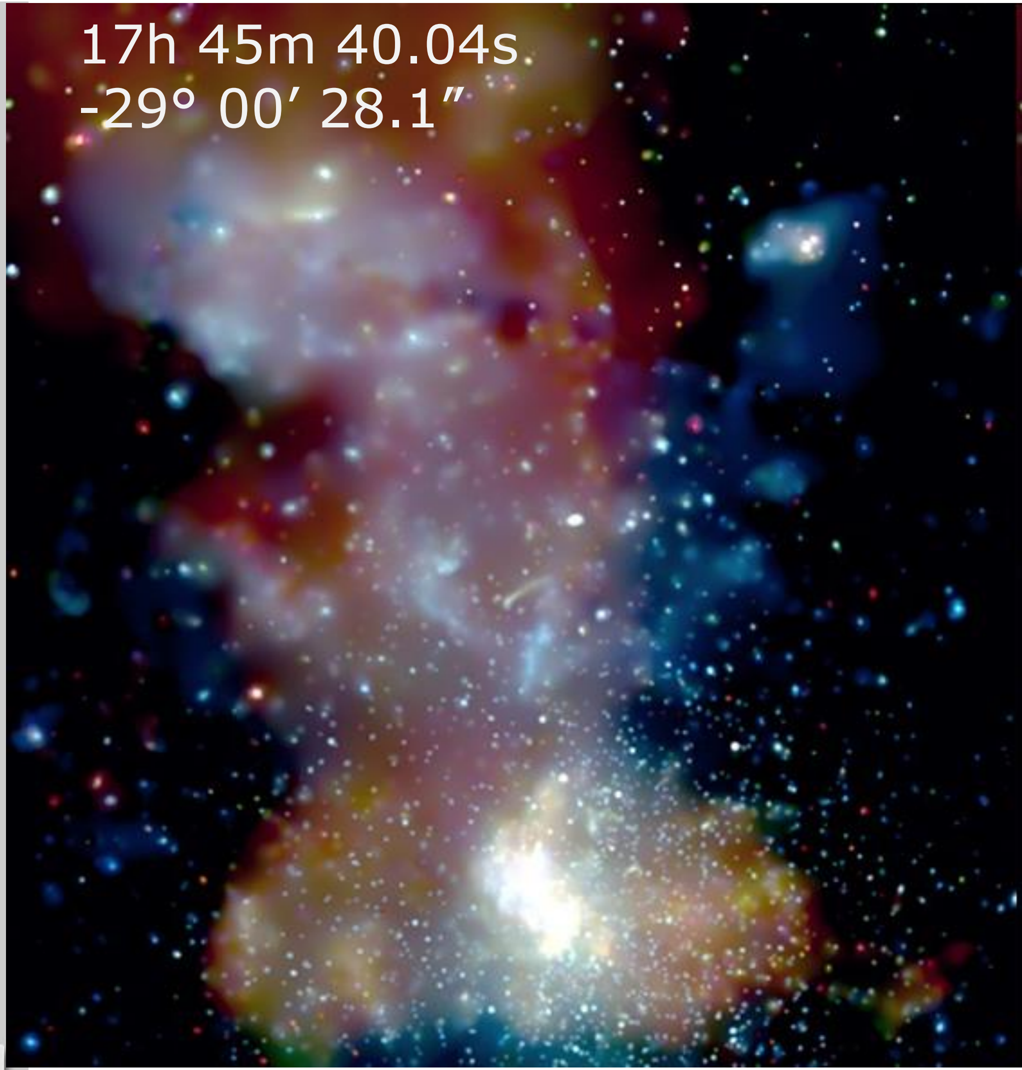
ESO

- We cannot see the Galactic centre here in Finland as it is in the southern celestial hemisphere. It can be seen in the previous slide, as a distinctly brighter area in the Galactic plane –even though it is mostly covered by heavy dust.

- In the next slide on the left there is a 2 micron image (notice the reddining) and on the right an X-ray image, with the coordinates of the Galactic centre.

THE GALACTIC CENTRE





Chandra X-rays

THE GALACTIC CENTRE

Where is it ?

- At a distance of 28 000 ly (8.5 kpc) from the Sun.
- Dust hides the centre that could otherwise be seen as a bright ”cloud” in the southern sky (optical extinction 28 mag!). However, we can perform
  - X-ray observations (for example, hot gas, x-ray binaries, supernovae)
  - IR observations (for example, hot stars)
  - Radio observations from the constellation of Sagittarius, Sgr A (an offset of 25° from the site fixed optically)

Remember, radio emission propagates freely (nonthermal!)

THE GALACTIC CENTRE

What's there ?

- Stellar density increases towards the centre.
- A dense gas disc in the core (5000 ly or 1.5 kpc) .
- Most of the mass in the molecular area surrounding the core (1000 ly or 300 pc).

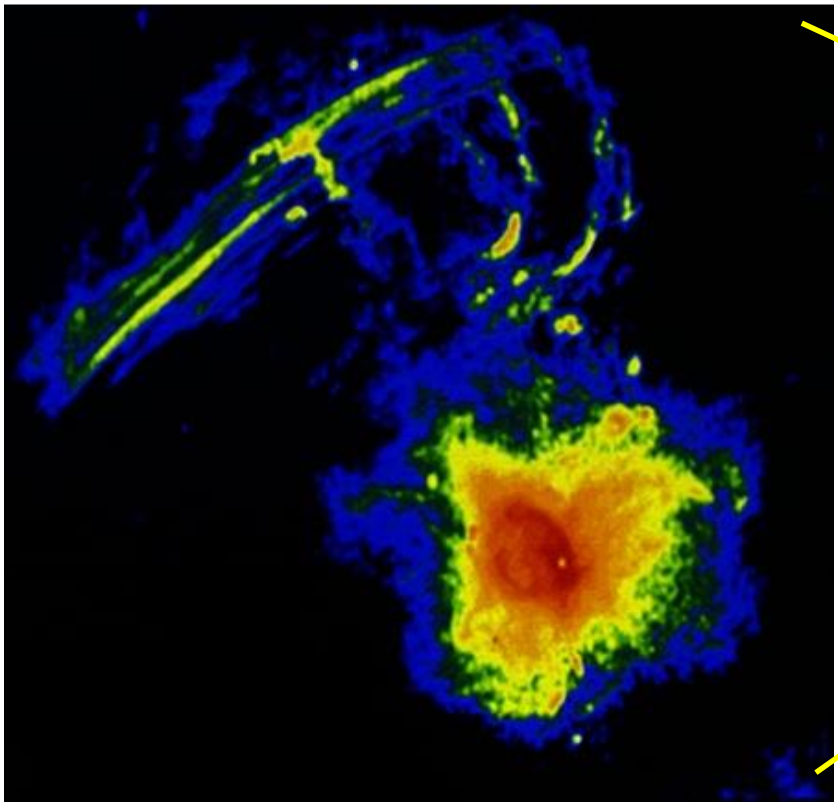
Innermost 30 ly (10 pc)

- Streamers of ionized gas and dust, threads, other features.
- Star formation regions, supernova remnants etc.
- Enigmatic radio source Sagittarius A
- Sgr A* (= *"Sagittarius A star"*) is the bright and compact central point.

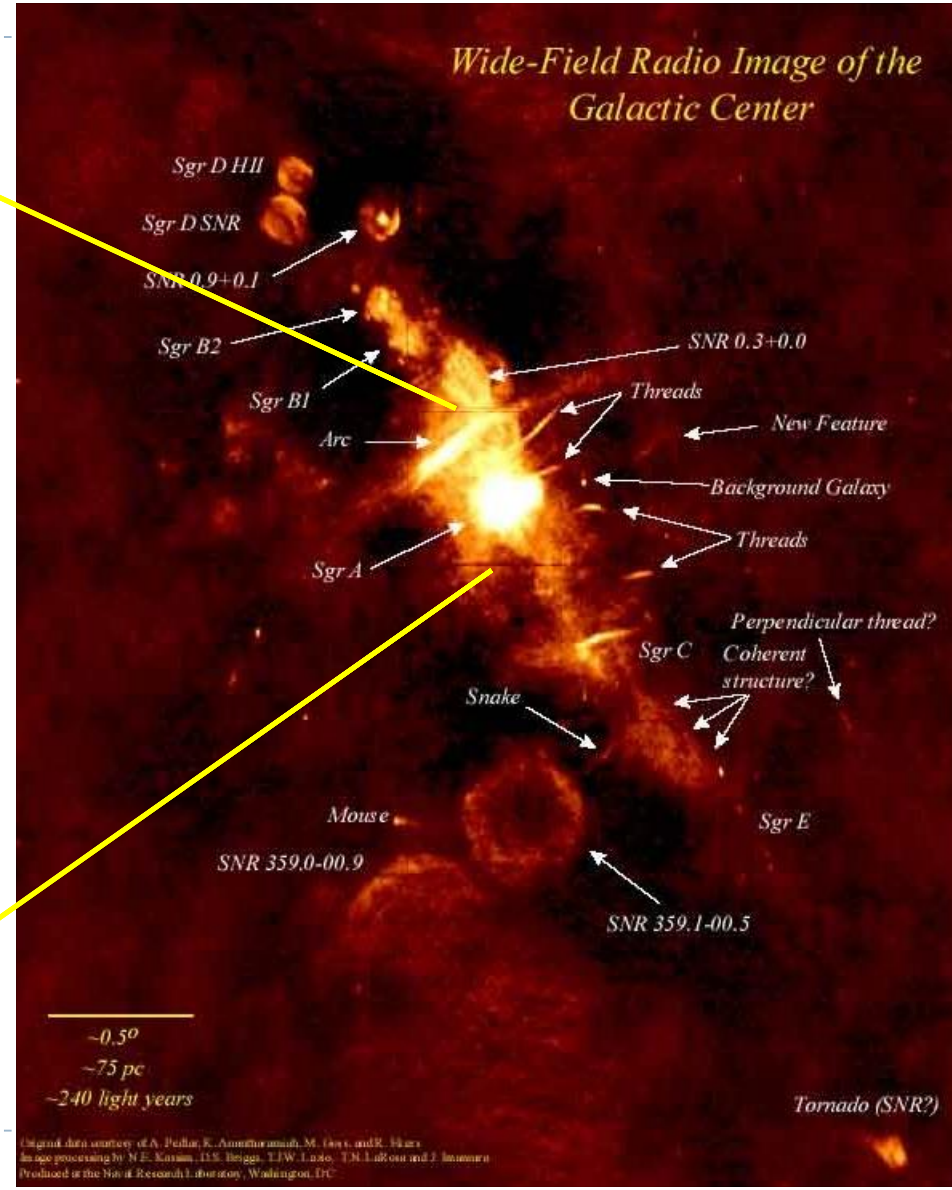
THE GALACTIC CENTRE

- in IR: bright source IRS 16, contains hot gas with extremely high velocities, and hot giant stars
- in X-rays: bright stars
- in gamma-rays: strong electron-positron annihilation (511 keV), "The Great Annihilator" (x-ray binary system?)

- Something in the middle makes the surrounding material move fast.

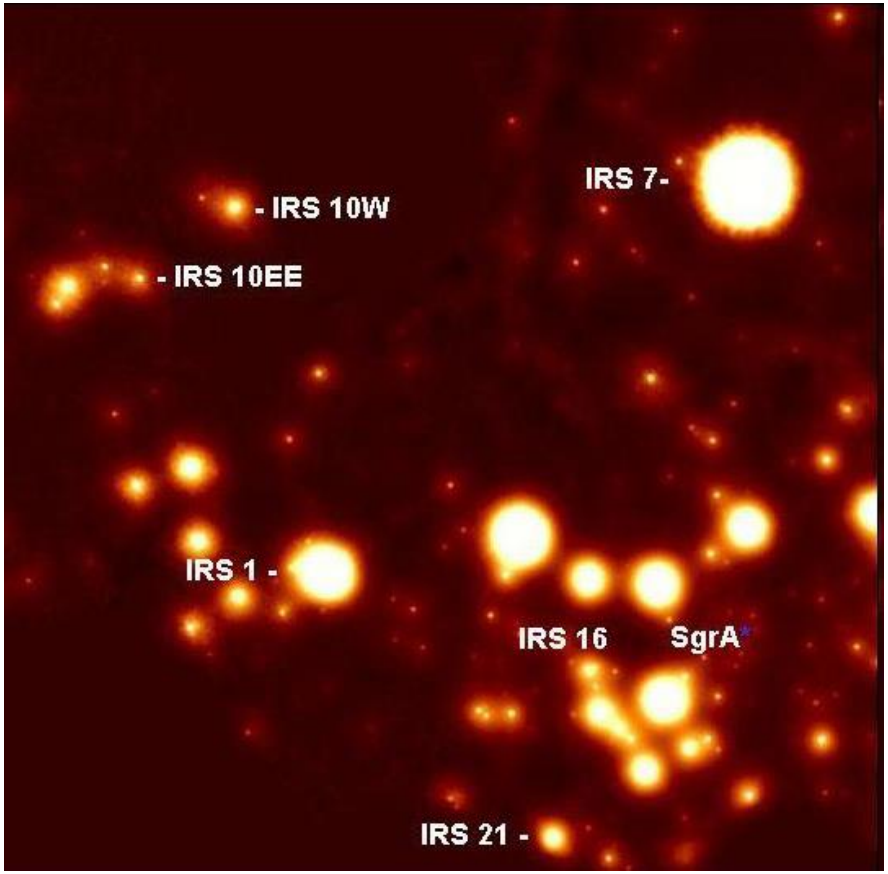


Sgr A at 1.4 GHz

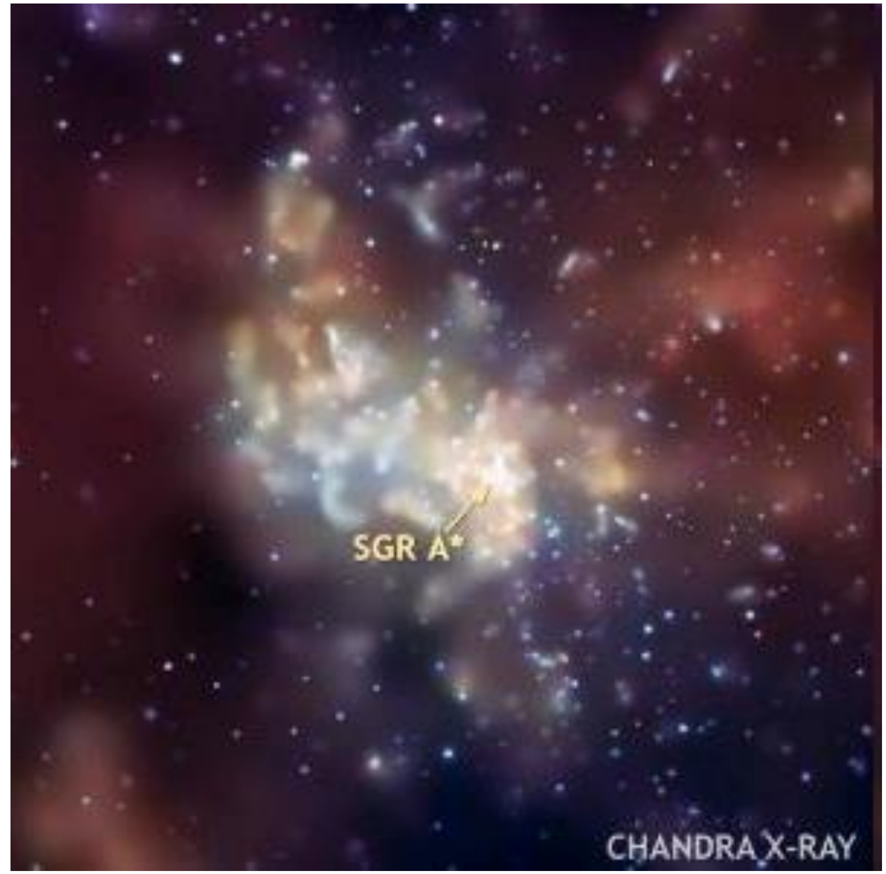


The Galactic centre region at 0.3 GHz

IR & X-rays



IRS 7-
- IRS 10W
- IRS 10EE
IRS 1 -
IRS 16
SgrA*
IRS 21 -



SGR A*
CHANDRA X-RAY

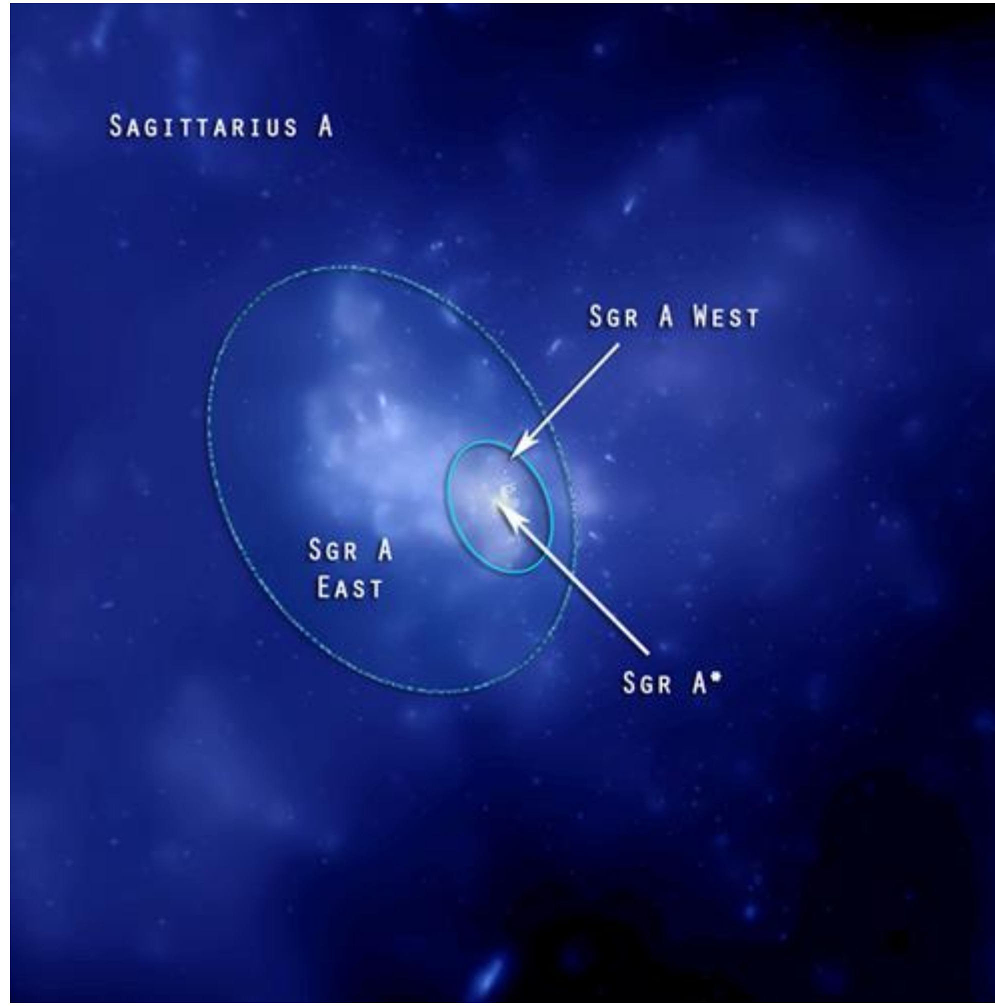
Components of Sagittarius A

Sgr A East

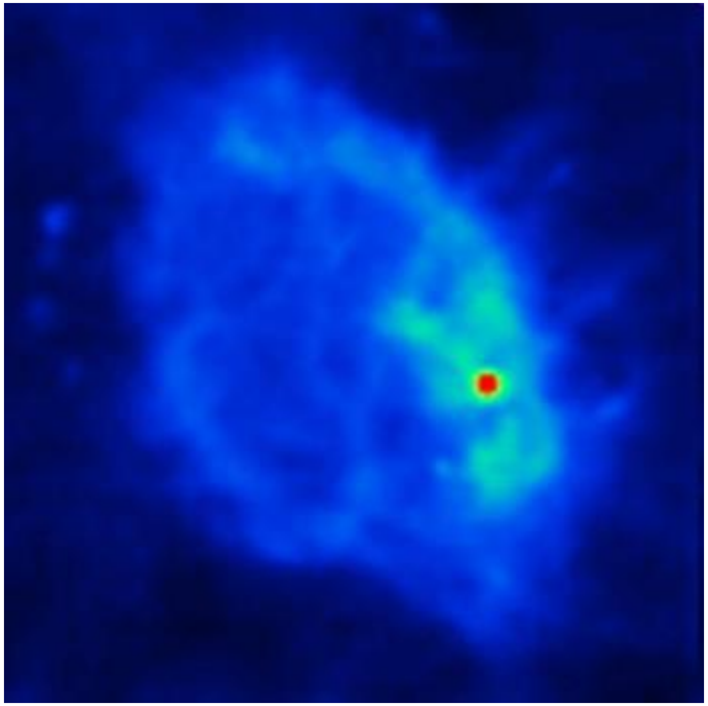
- probably a supernova remnant.

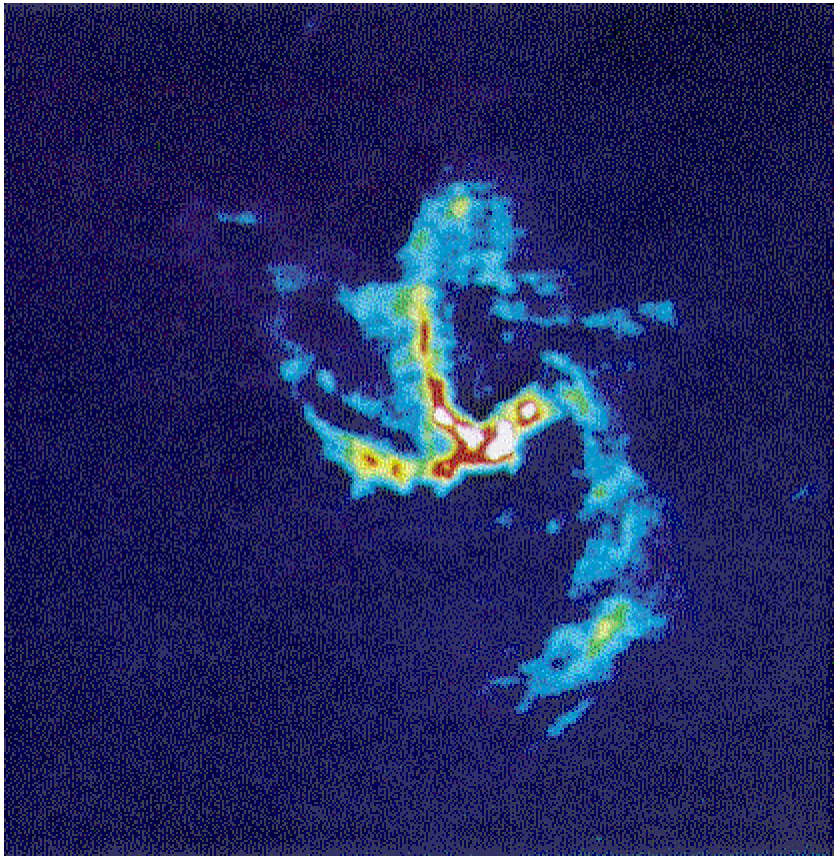
Sgr A West

- a ”spiral-shaped” hydrogen region.
- surrounded by unusually hot gas and a molecule ring (5–25 ly or 2–8 pc) that contains denser gas.



Sgr A East (1.4 GHz) & West (5 GHz)





The compact centre point

Sgr A*

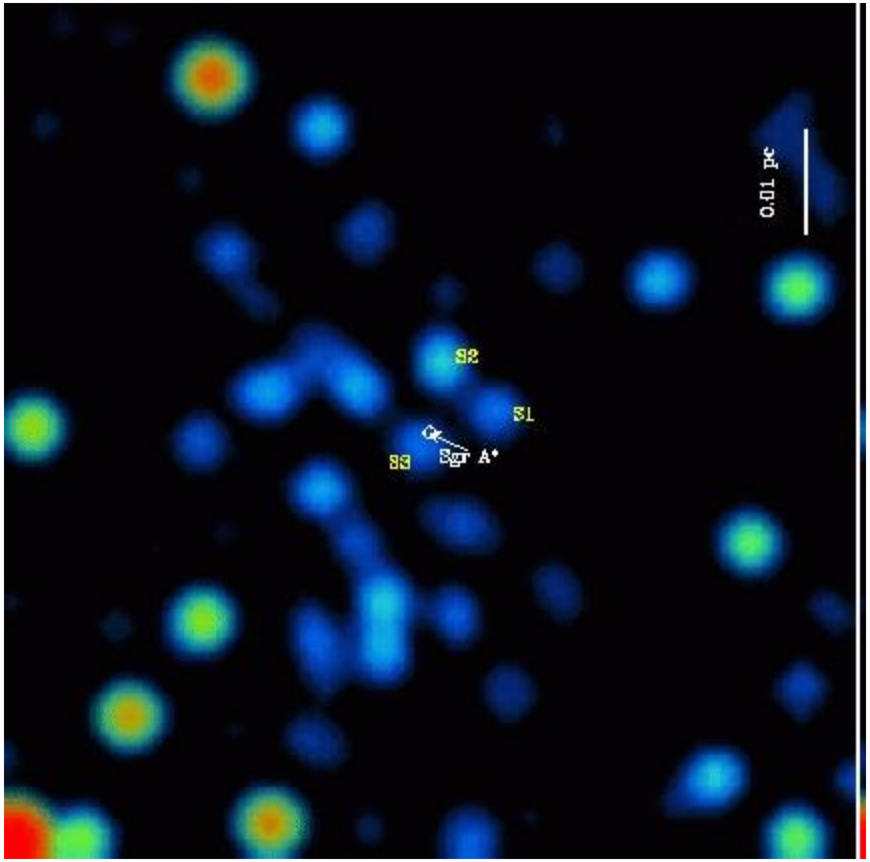
- Point-like, compact source (< 1 AU)
- Does not move, very massive ($4 \times 10^6\ M_\odot$)
- Flat spectrum, variable radio emission

  $\Rightarrow$ a black hole ?
- The black holes in the centres of galaxies are usually larger, why is the one in the Galaxy so ”small” and why is it so ”faint” ?

  $\Rightarrow$ “starving” black hole?
- How has the black hole formed? Formation and growth of black holes are still mostly unknown.

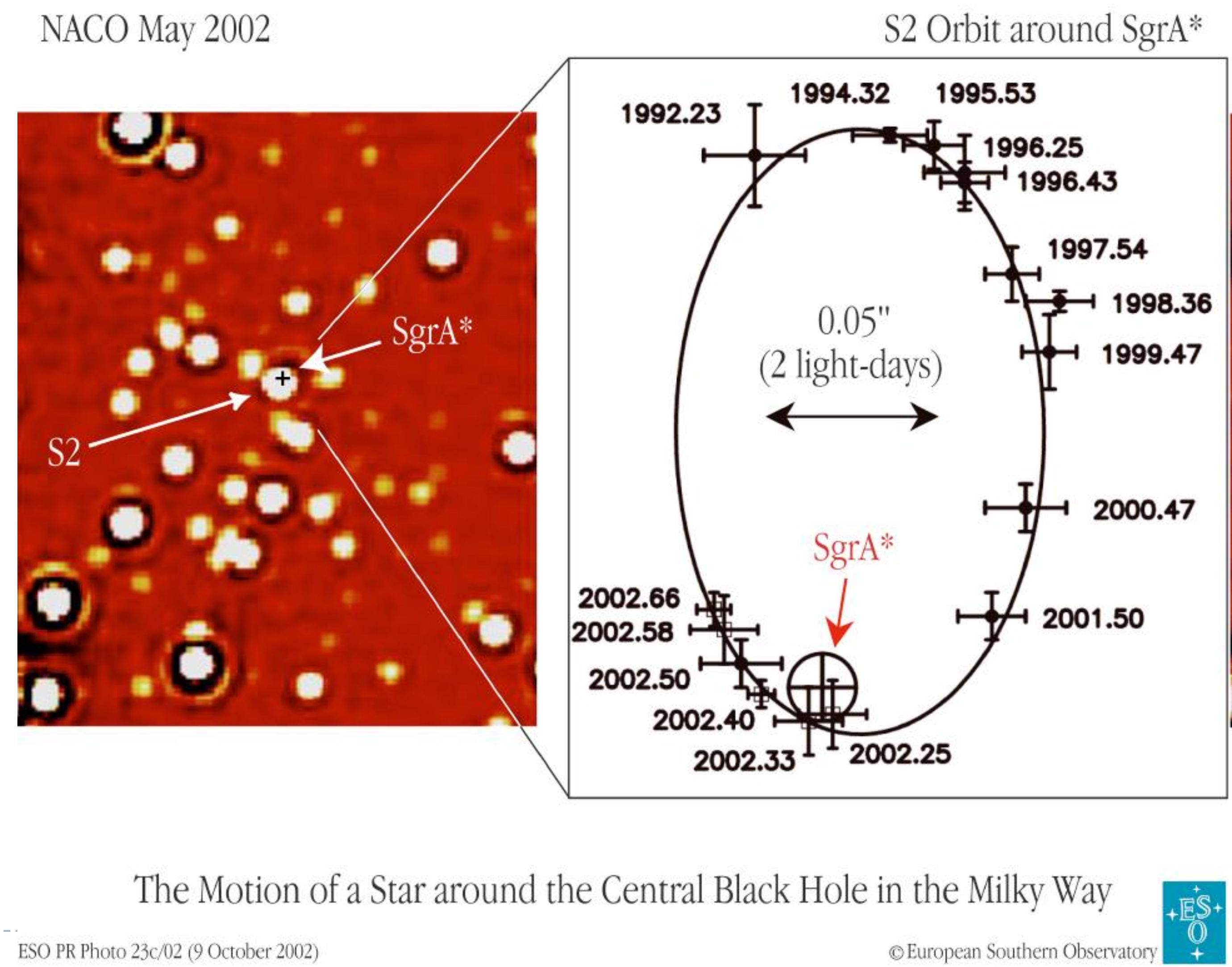
How close can we see?

- Scale: ~12 light days or 0.033 ly
- S1, S2 and S3 are stars close to SgrA*

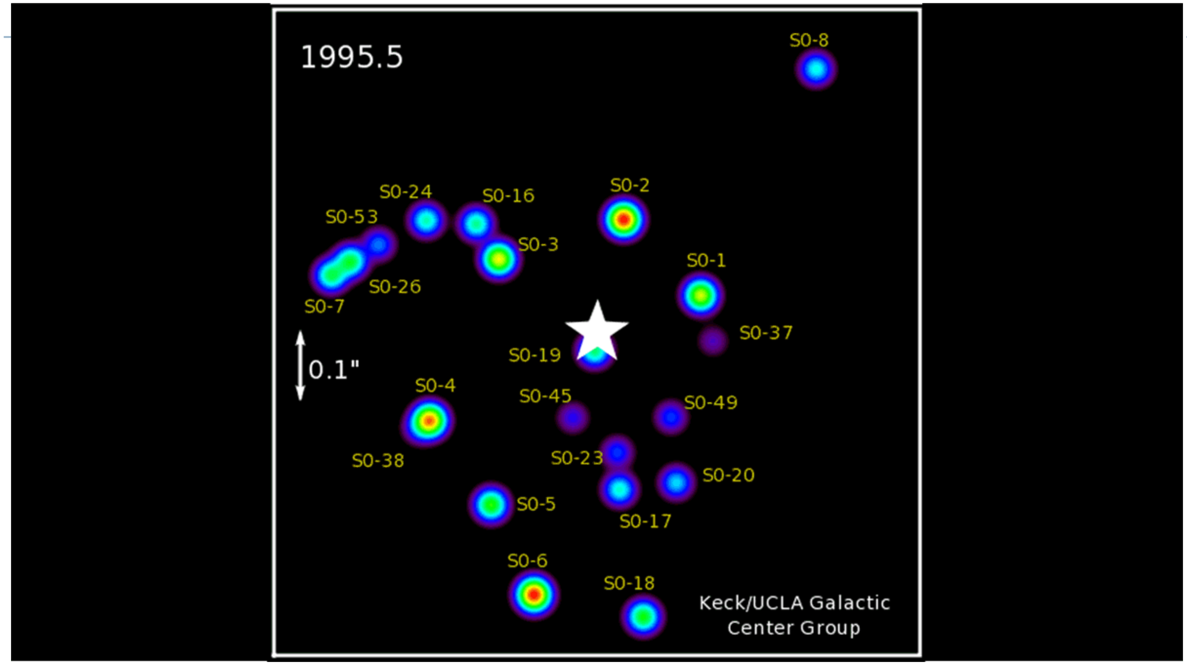


IR

From the stellar orbits in the central parsec we can get the mass of the black hole



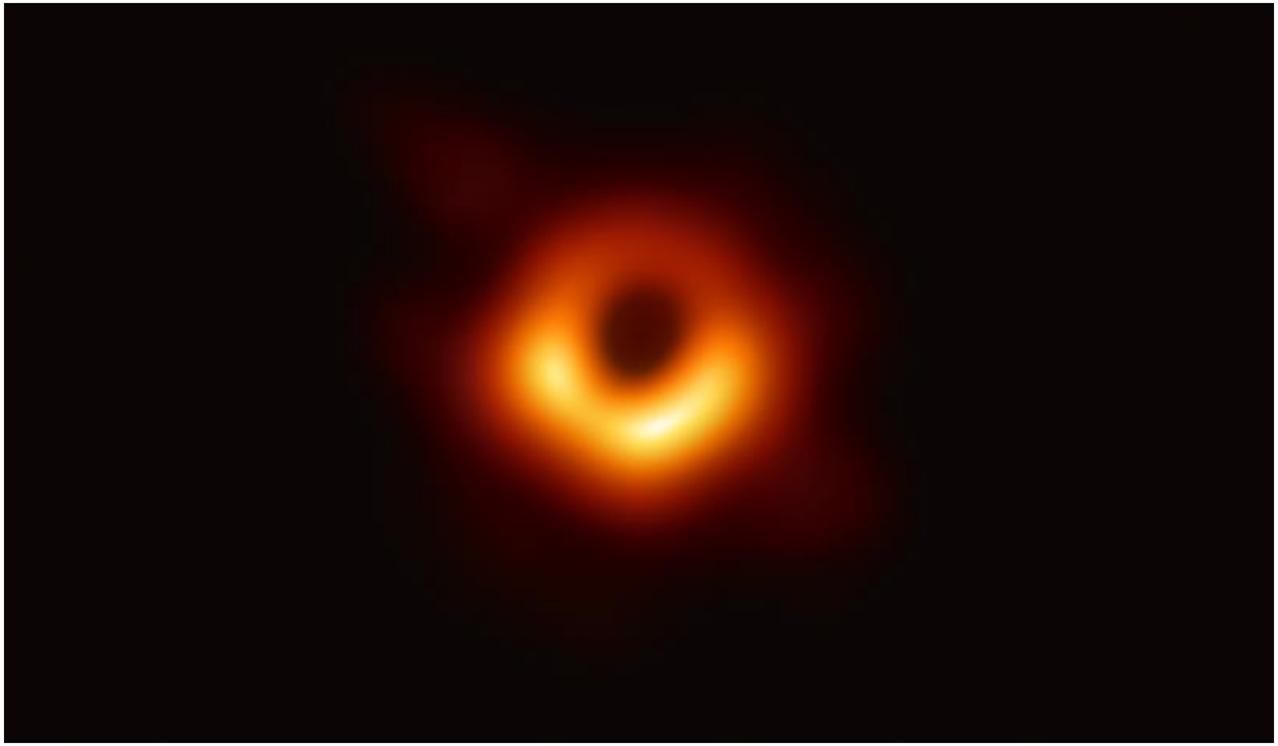
The orbital period of star S0-2 is 16.05 years. The distance of S0-16 from the black hole is only 90 AU. S62 is the closest, 16 AU.



- To see an animation how the stars orbit the Galactic black hole, go to http://www.astro.ucla.edu/~ghezgroup/gc/animations.html
- They also have other materials about the Galactic Centre at
- http://www.astro.ucla.edu/~ghezgroup/gc/multimedia.html

eventhorizontelescope.org

- Imaging supermassive black holes in the centres of galaxies: Sgr A* and M87



TODAY

- The Galaxy I:
  - Magnitude systems
  - Structure, rotation, spiral arms
  - Evolution
  - Galactic continuum
  - Galactic centre

Boris Dmitriev

NEXT WEEK

- The Galaxy II:
  - Stars:
    - Classification and evolution
    - Various types of stars
  - Interstellar matter: dust, gas
  - Dark matter