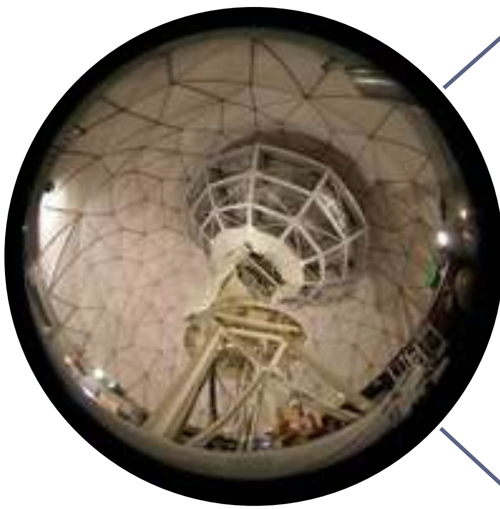
INTRODUCTION TO SPACE 18.3.2019

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

Boris Dmitriev

25.3. The Galaxy II: stars, gas, dust
1.4. Extragalactic & cosmology
12.4. 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?

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

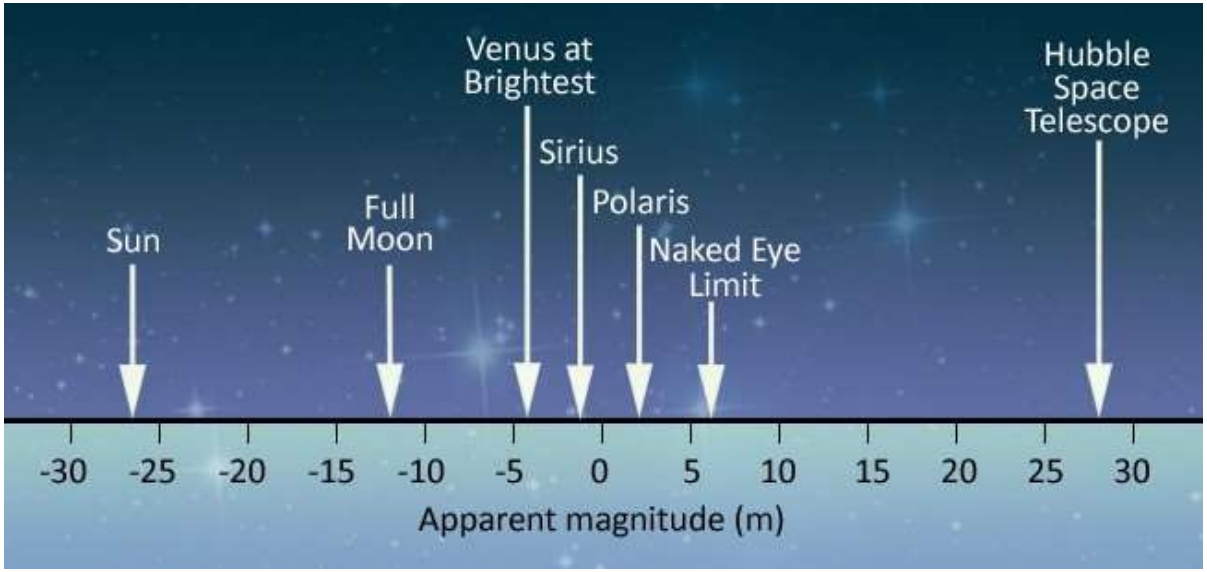
- **Absolute magnitude M**: $m - M = 5 \lg (r/10pc)$
- **Absolute bolometric magnitude**:

$M_{bol} - M_{bol,\odot} = -2.5 \lg L/L_\odot$

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

MAGNITUDES: EXAMPLES

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

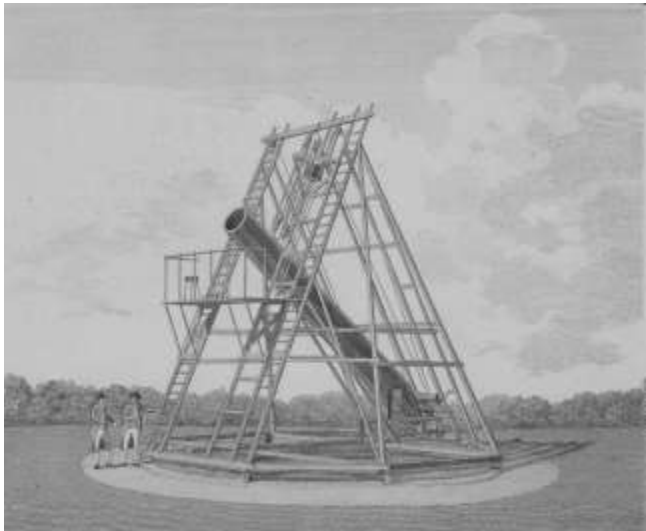


Tim Trott

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.)

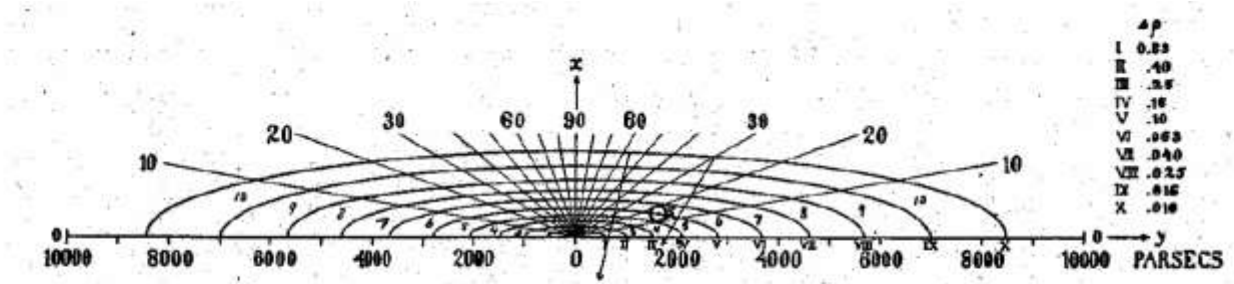
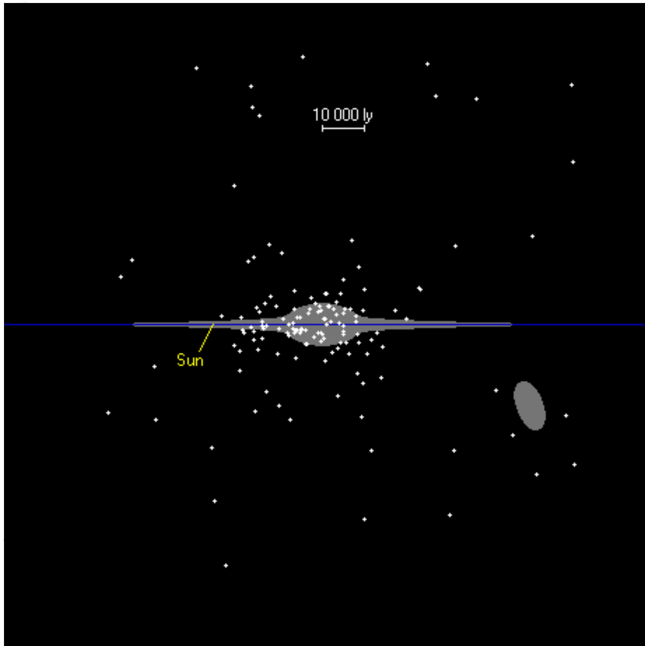


FIG. I

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

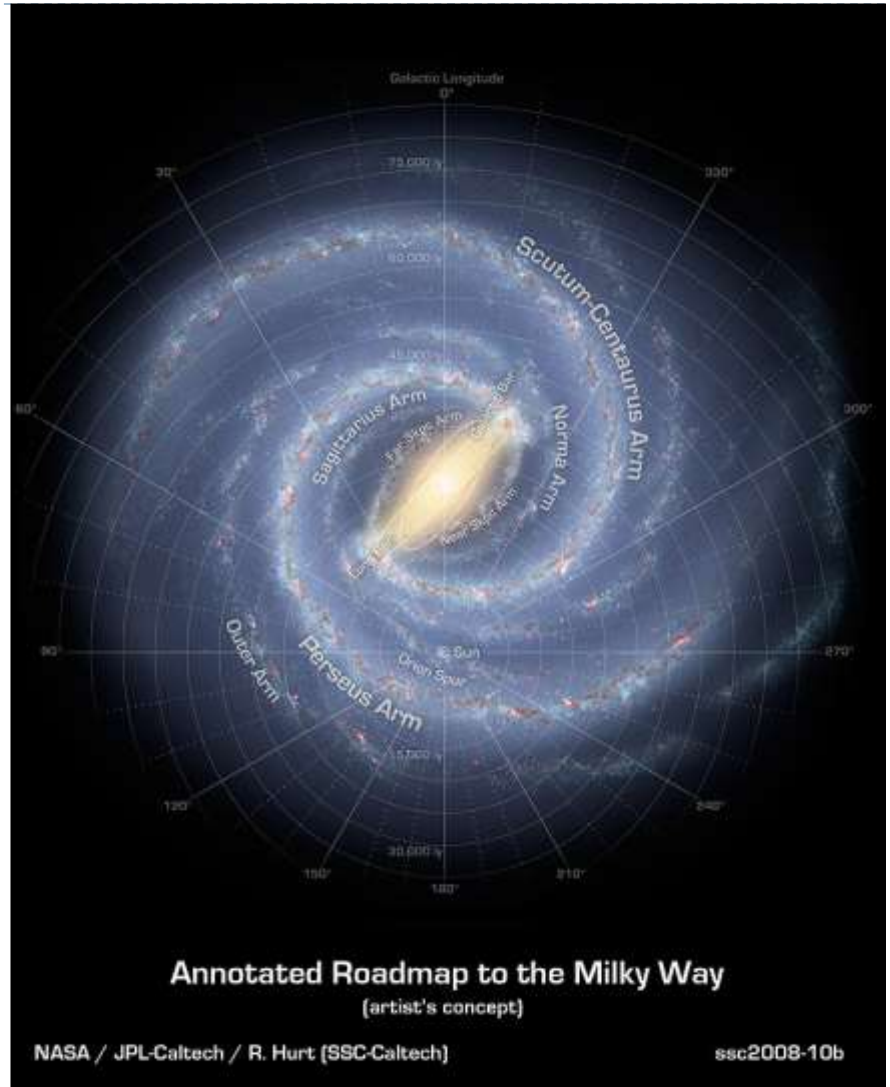


BUILDING BLOCKS OF THE GALAXY

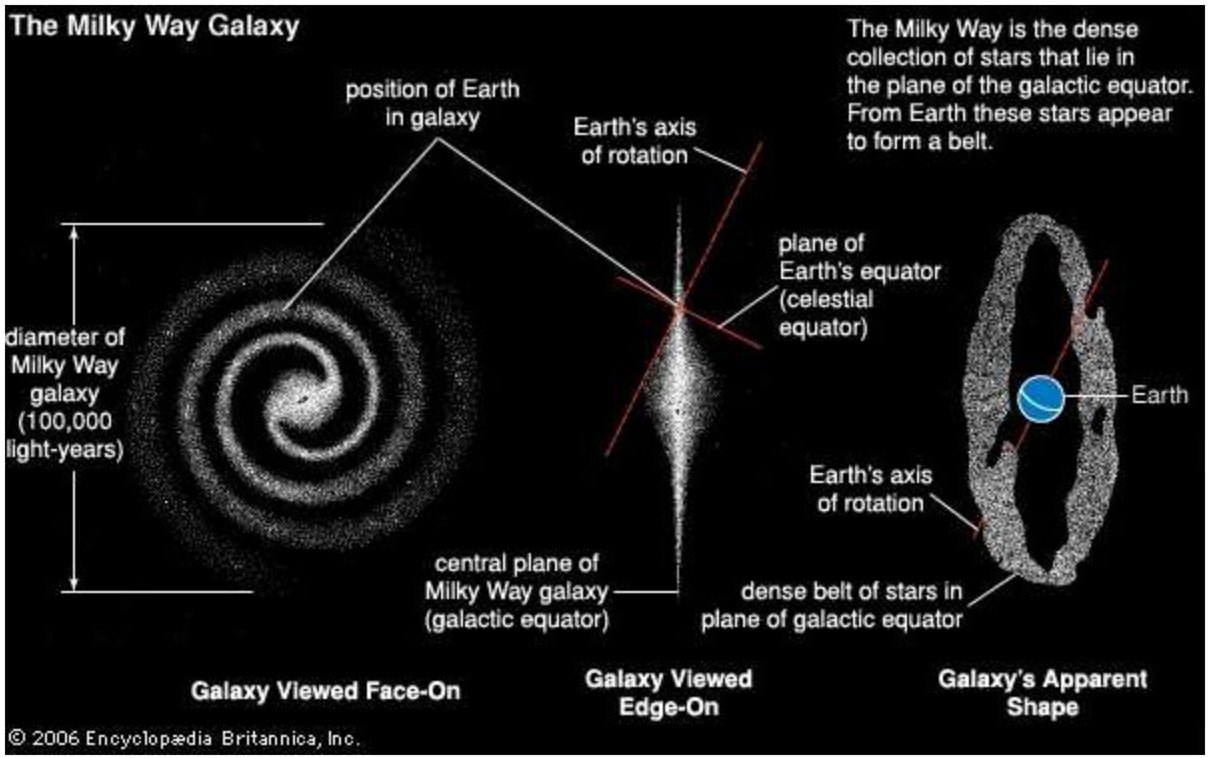
- stars & star formation regions
- dying stars
- supernova remnants
- molecular clouds
- neutral hydrogen, HI, and ionized hydrogen, HII
- masers
- dust
- cosmic rays
- magnetic field
- black hole ?
- dark matter ?

STRUCTURE OF THE GALAXY

(Barred) spiral galaxy



STRUCTURE OF THE GALAXY



STRUCTURE OF THE GALAXY

- **Central area:**
  - Dense, contains both new and old stars
  - 5 - 10 % of the total mass of the Galaxy

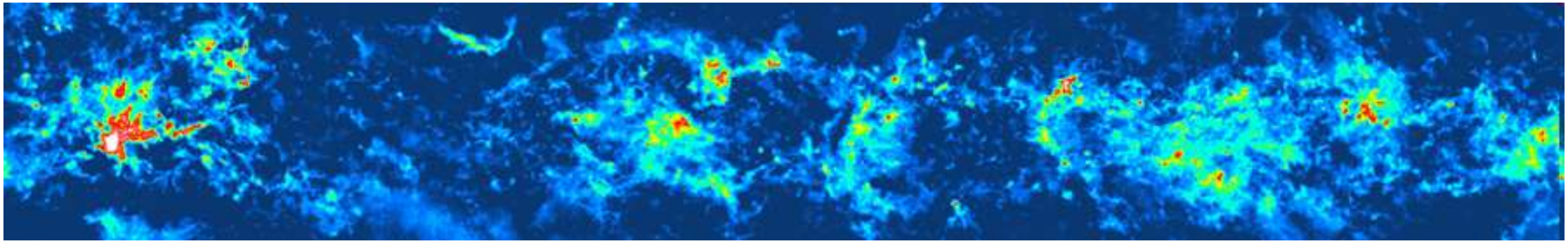
  - The other side of the central area has an asymmetrical bulge: a bar the longitudinal axis of which is close to the viewing angle
    - more evidence for a bar: carbon stars (old red giants) aligned along the axis
  - The bar at a 30° angle, 15 000 x 5 000 ly (best guess)

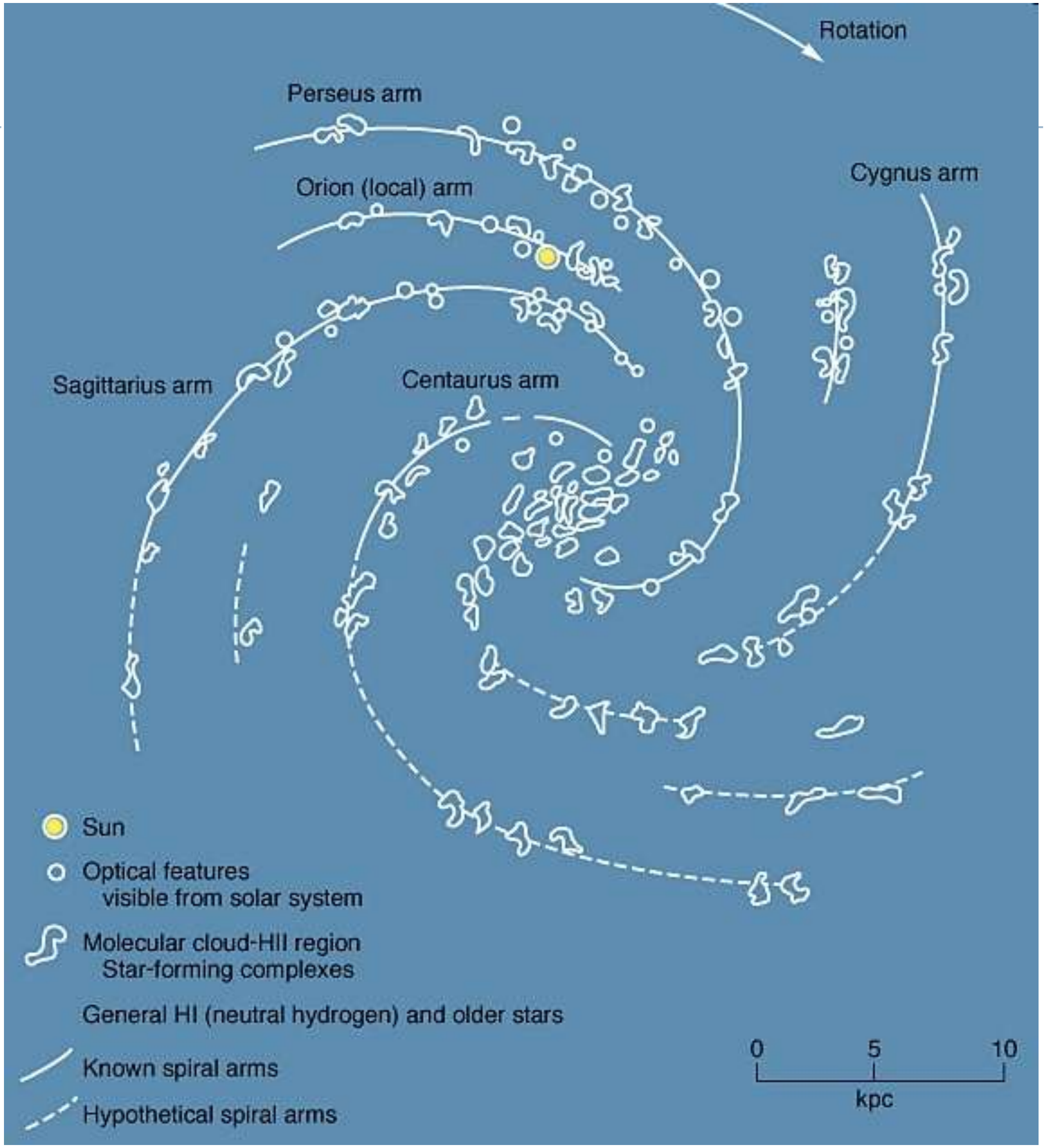
STRUCTURE OF THE GALAXY

- 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!

- **Disc and spiral arms:**
  - The spiral arms mapped at radio frequencies, with the help of star clusters and hydrogen clouds + pulsars

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



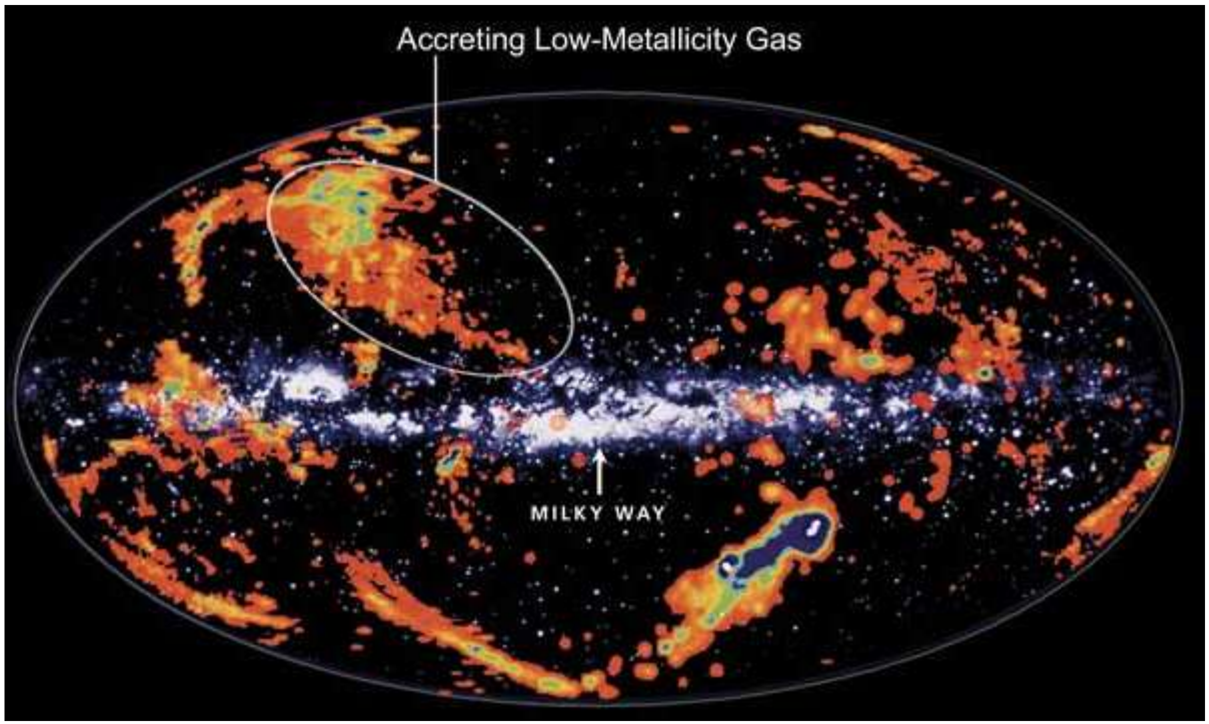


Rotation
Perseus arm
Orion (local) arm
Cygnus arm
Sagittarius arm
Centaurus arm
Sun
Optical features visible from solar system
Molecular cloud-HII region Star-forming complexes
General HI (neutral hydrogen) and older stars
Known spiral arms
Hypothetical spiral arms
0
5
10
kpc

STRUCTURE OF THE GALAXY

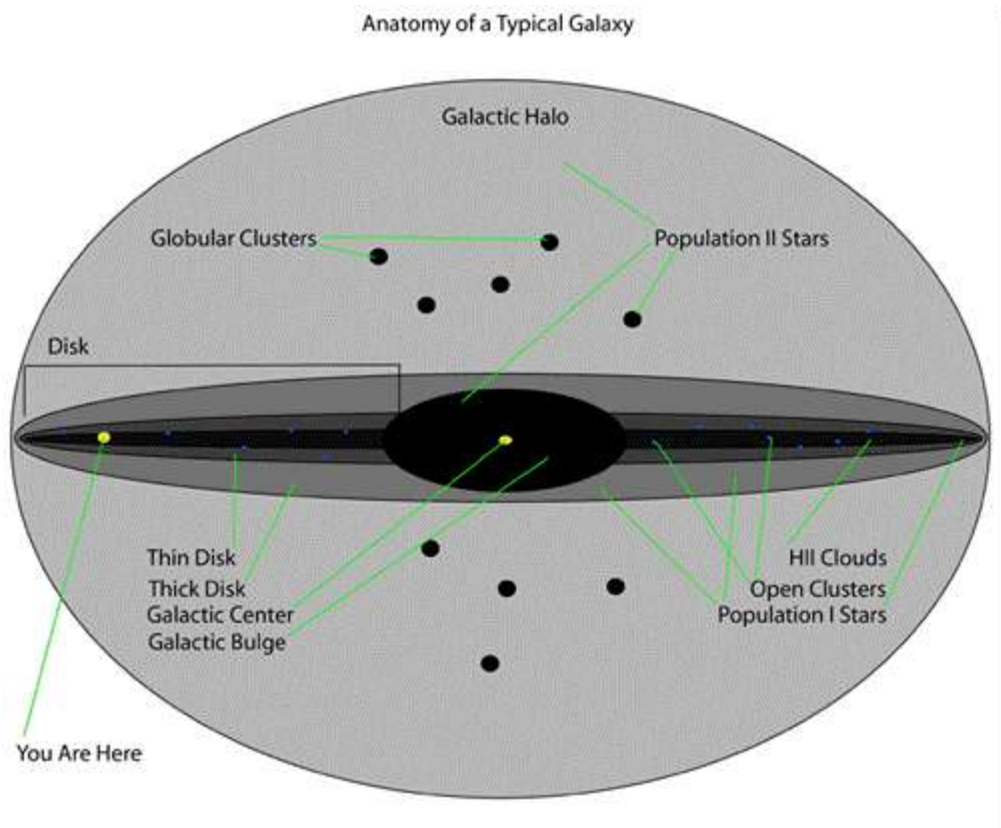
- Newly formed and young stars in the galactic plane in circular orbits (in one year ~1 $M_{\odot}$ new stars).
- The metallicity of young stars increases.

- 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


Accreting Low-Metallicity Gas
MILKY WAY

STRUCTURE OF THE GALAXY

- **Halo:**
  - old stars (up to ~13.5 billion years)
  - 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?
  - size (possibly) up to hundreds of kiloparsecs (>100 000 ly)


Anatomy of a Typical Galaxy
Galactic Halo
Globular Clusters
Population II Stars
Disk
Thin Disk
Thick Disk
Galactic Center
Galactic Bulge
HII Clouds
Open Clusters
Population I Stars
You Are Here

STAR CLUSTERS

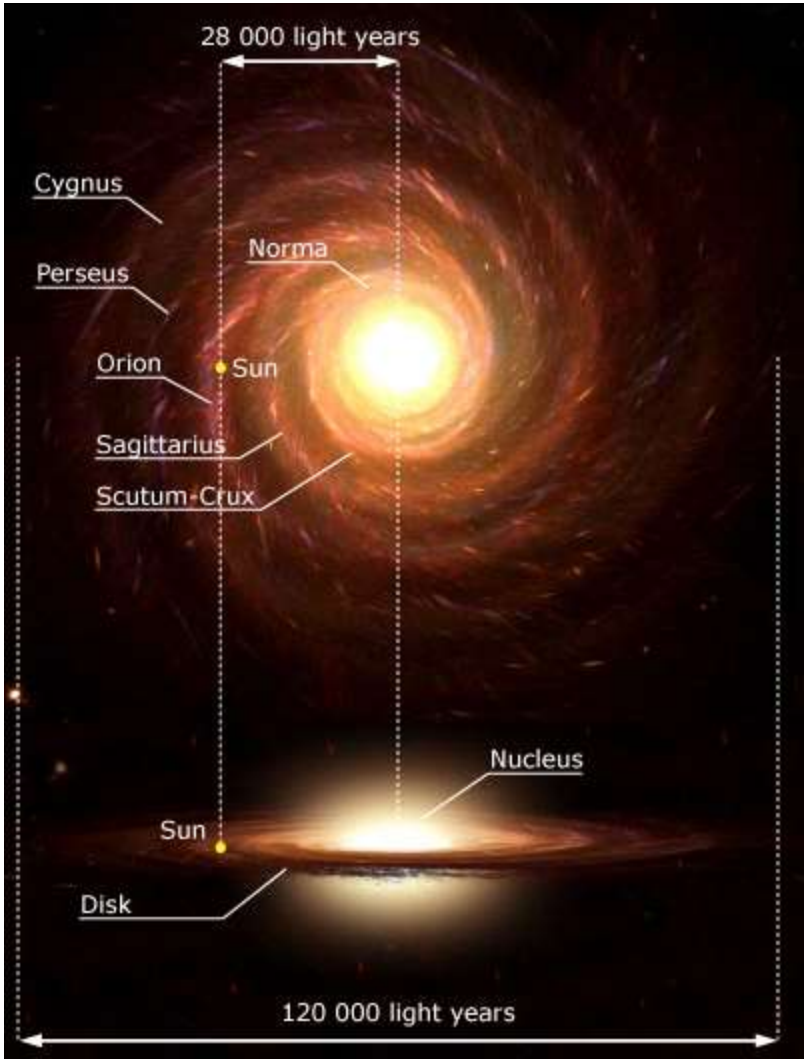
- A group of stars of roughly the same age, evolved from the same interstellar cloud

Globular cluster

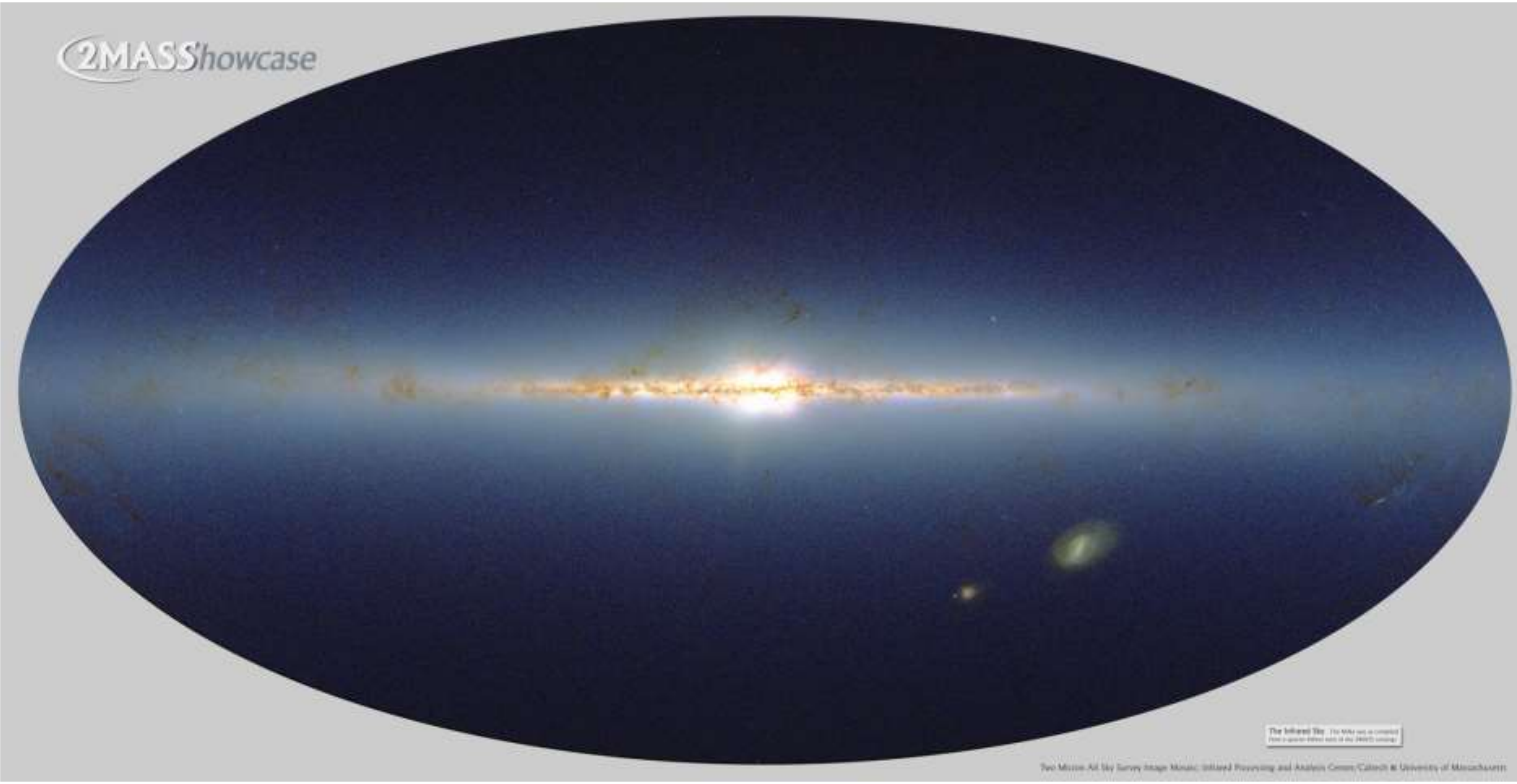
Open cluster

STRUCTURE OF THE GALAXY

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



The Galaxy @ 2μm

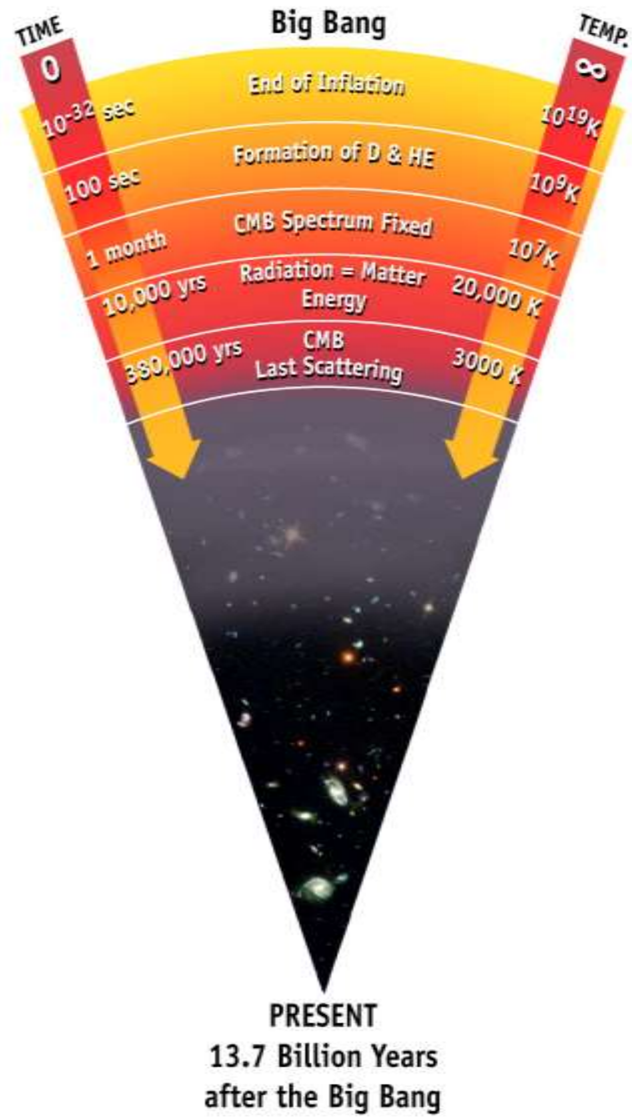


BARRED SPIRAL GALAXIES

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

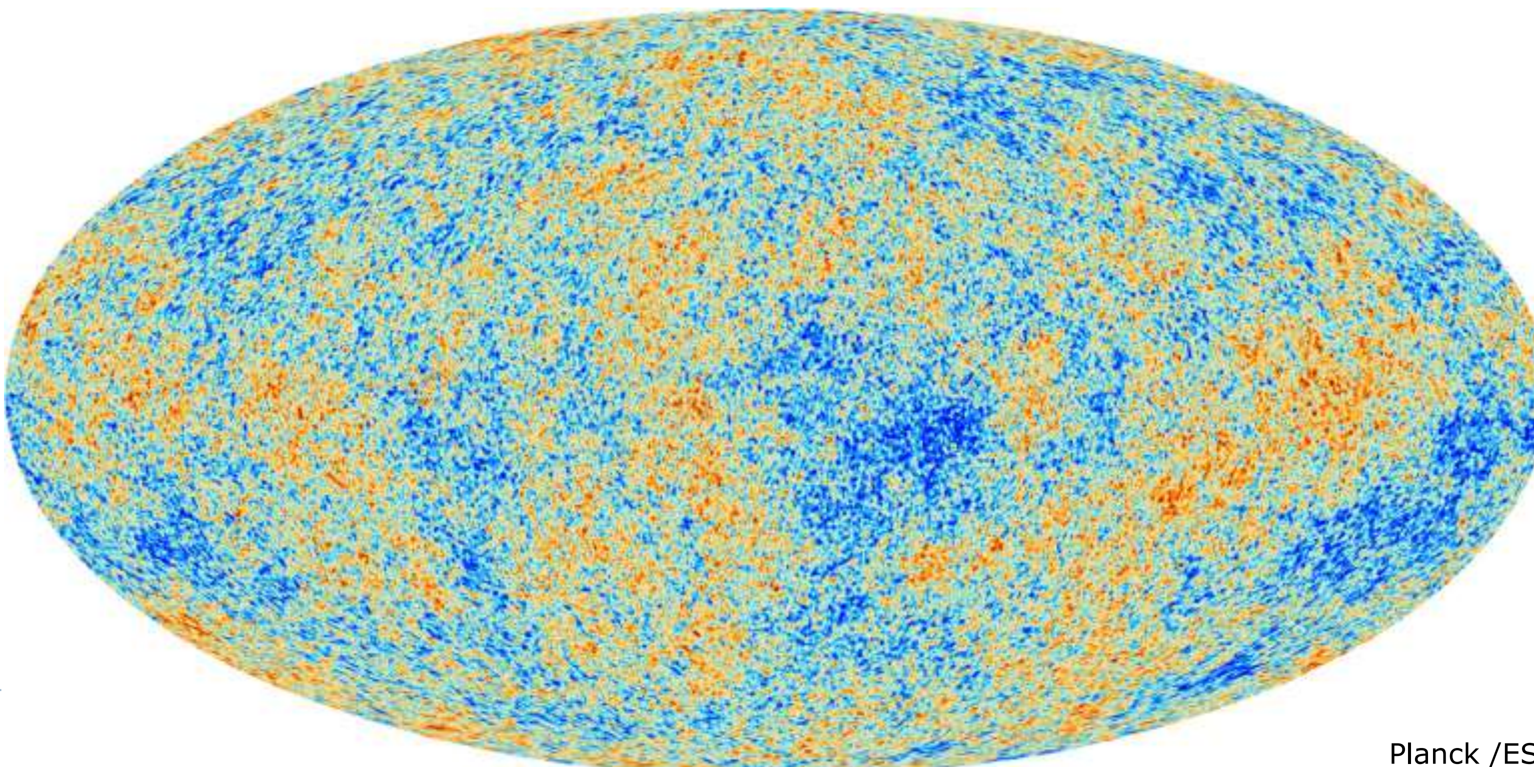
IT ALL STARTED WITH A BANG

- In the beginning opaque photon-baryon plasma until…
- Photons scattered from matter for the last time
  - 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.

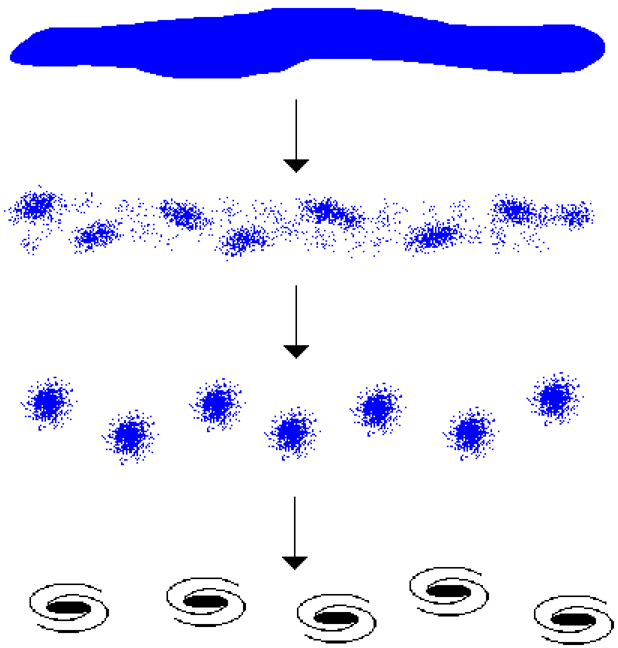


Planck /ESA

FORMATION OF STRUCTURE

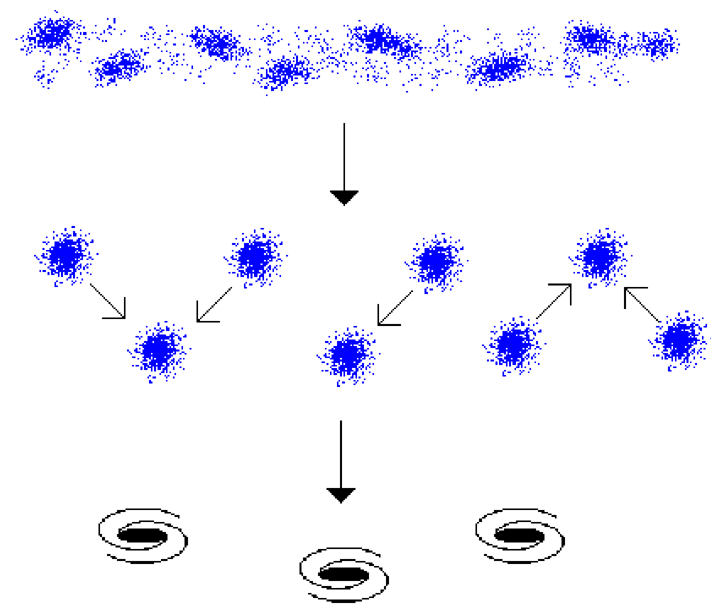
Top–Down Structure Formation

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



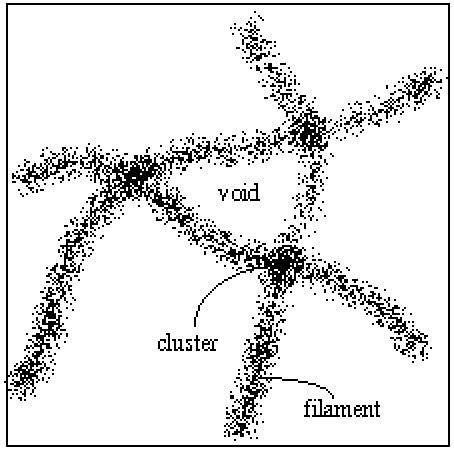
Bottom–Up Structure Formation

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

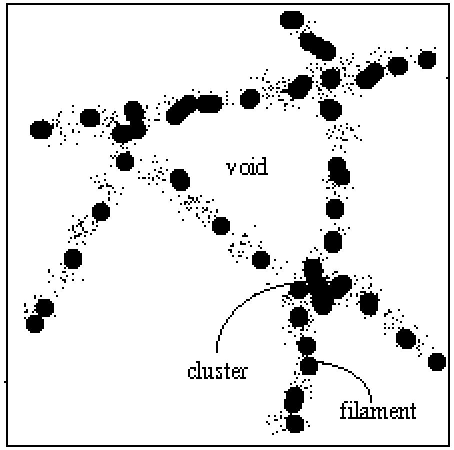


Large Scale Structure

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

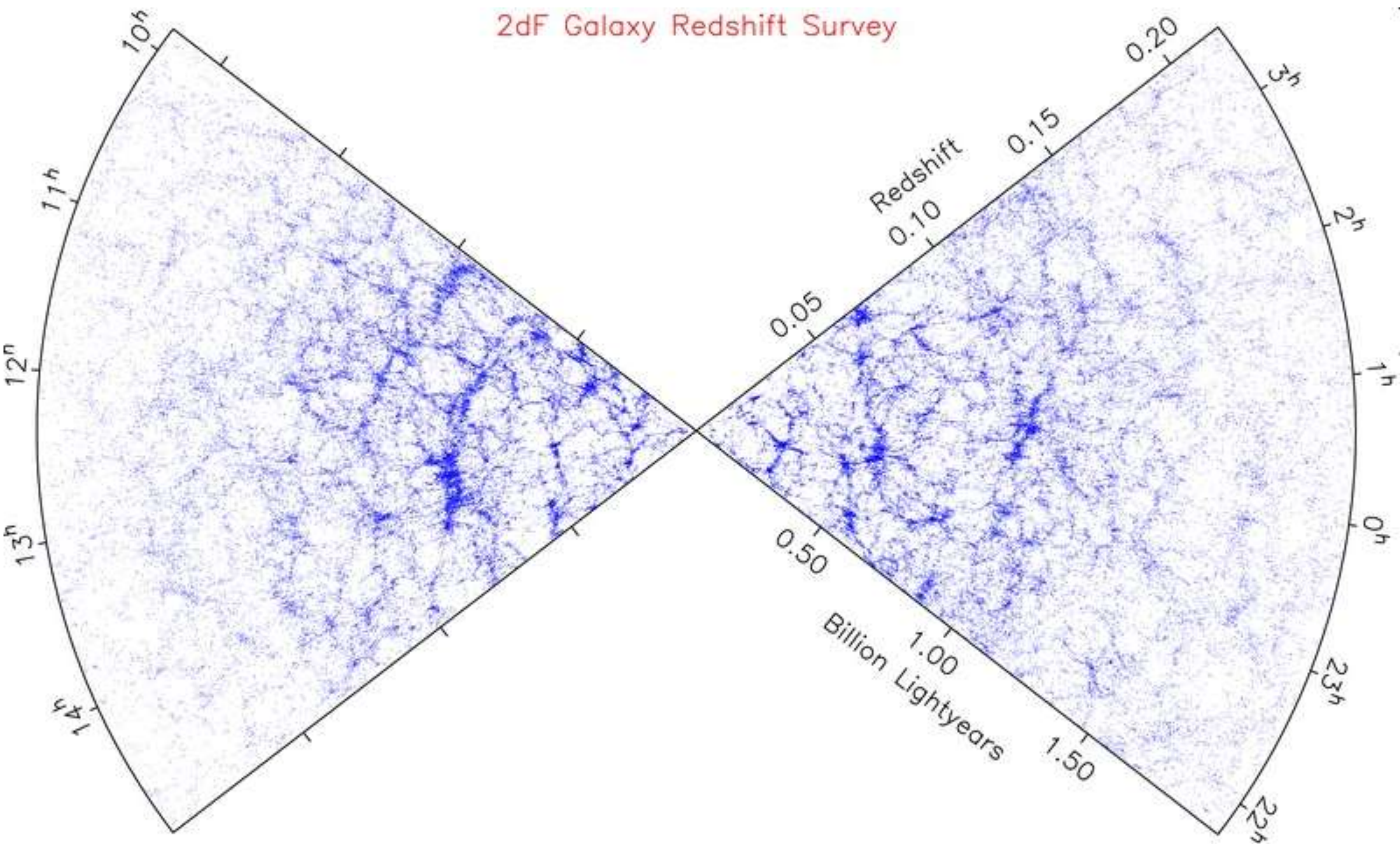


HDM

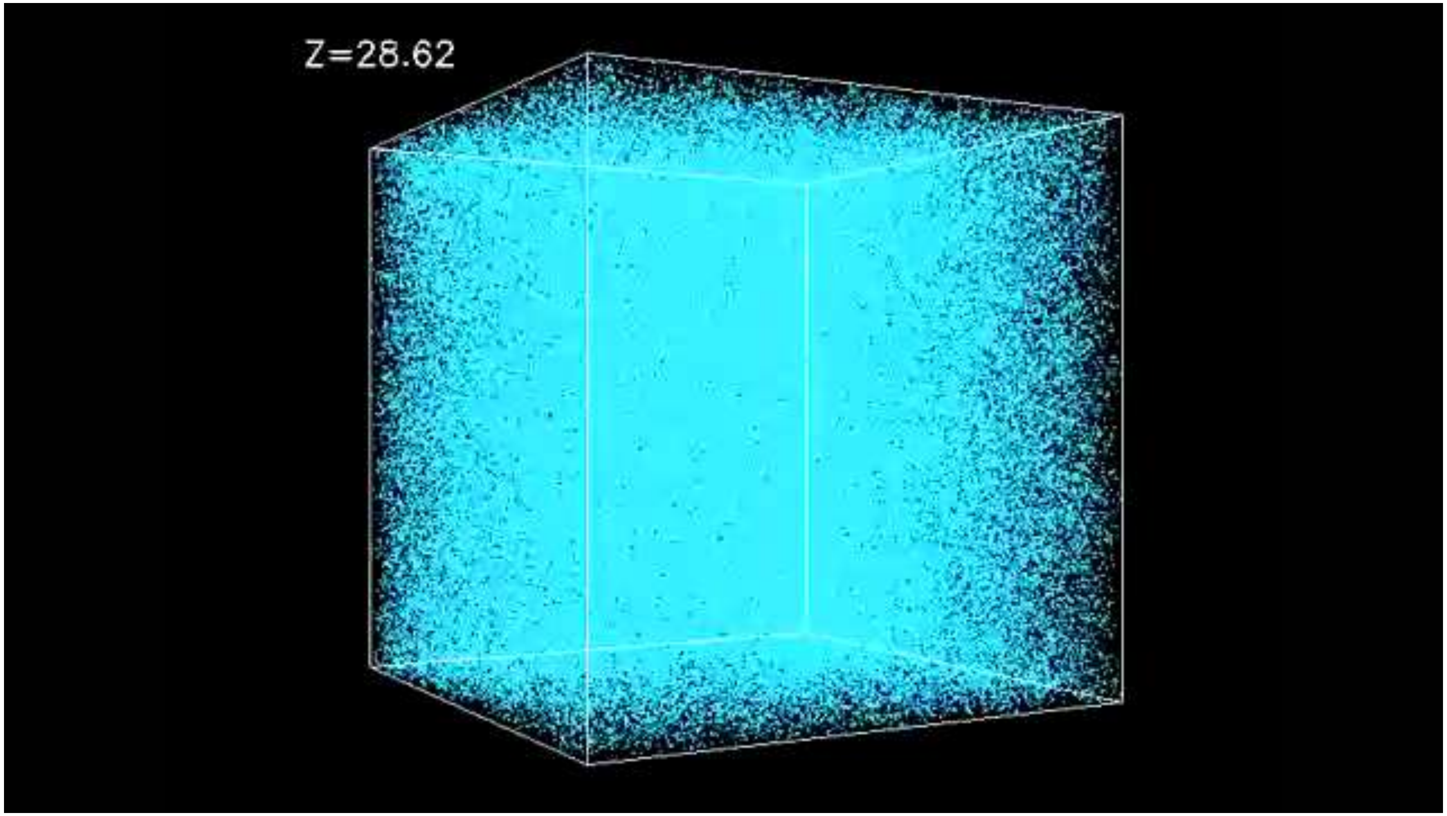


CDM

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


2dF Galaxy Redshift Survey
10h
11h
12h
13h
14h
Redshift
0.05
0.10
0.15
0.20
3h
2h
1h
0h
23h
22h
0.50
1.00
1.50
Billion Lightyears

FORMATION OF LARGE SCALE STRUCTURE



http://cosmicweb.uchicago.edu/sims.html

HOW THE GALAXY FORMED

HOW THE GALAXY FORMED

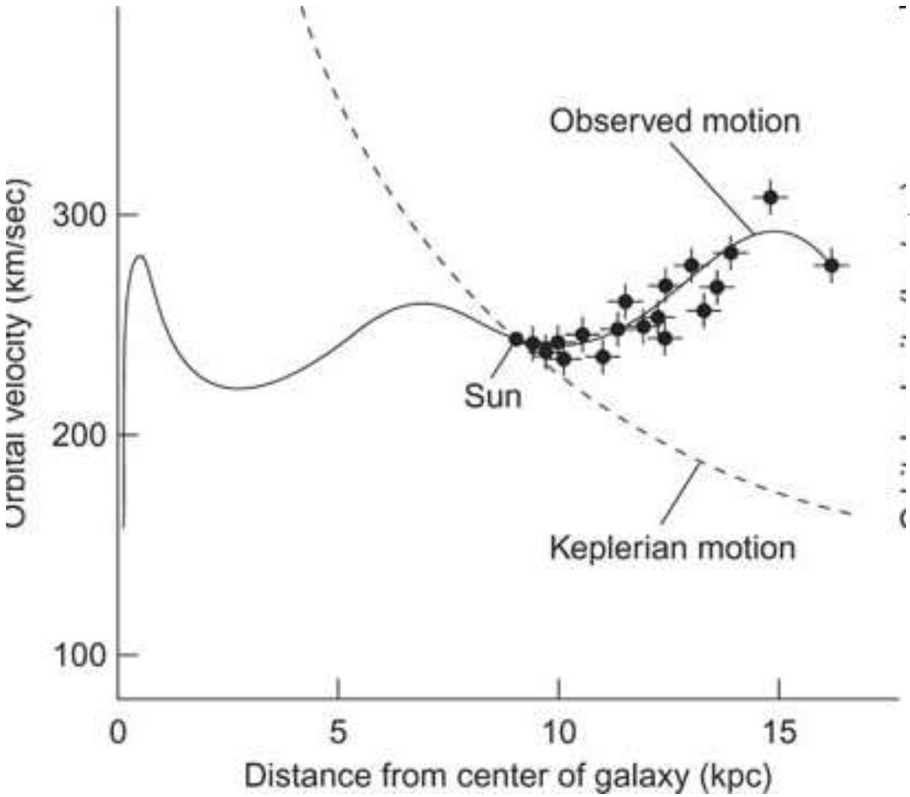
- Approx. 13.5 billion years ago the Galaxy was a large turbulent cloud made of hydrogen and helium.
  - The first very massive stars formed (fast evolution, heavier elements, supernova explosions).
  - Shock waves accelerated the formation of further generations of stars.

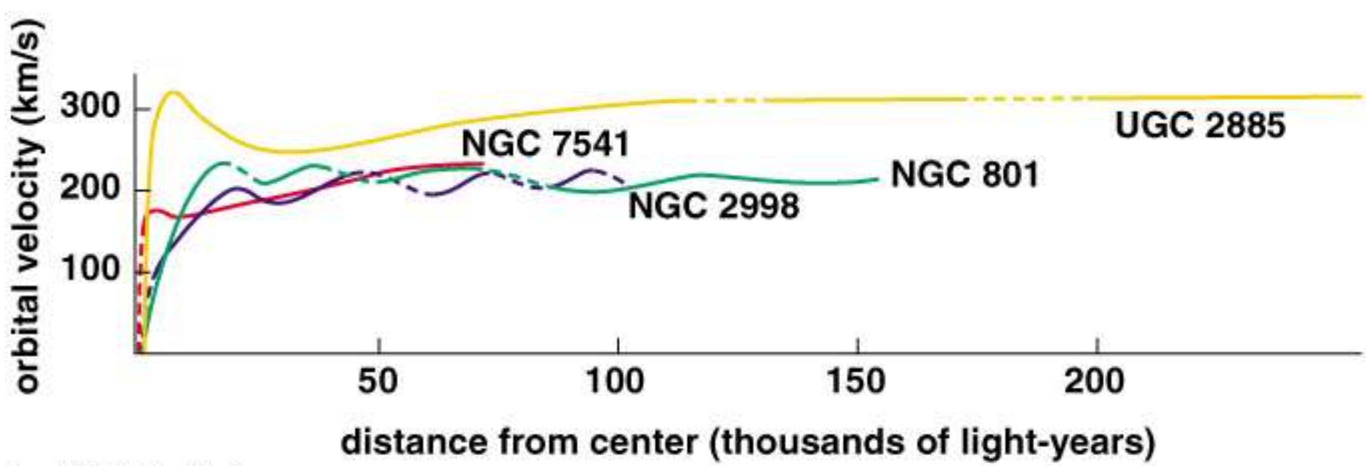
- The Galaxy contracted under its internal gravity, the originally slow rotation accelerated.
- After a couple of billion years the cloud collapsed along its rotational axis and a disc was formed.

DIFFERENTIAL ROTATION

- The angular velocity of the rotation depends on the distance to the galactic centre (the velocity decreases as the distance increases).
- Studies of stars and interstellar matter to measure the rotation curve
  - "flat" $\Rightarrow$ dark matter?

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

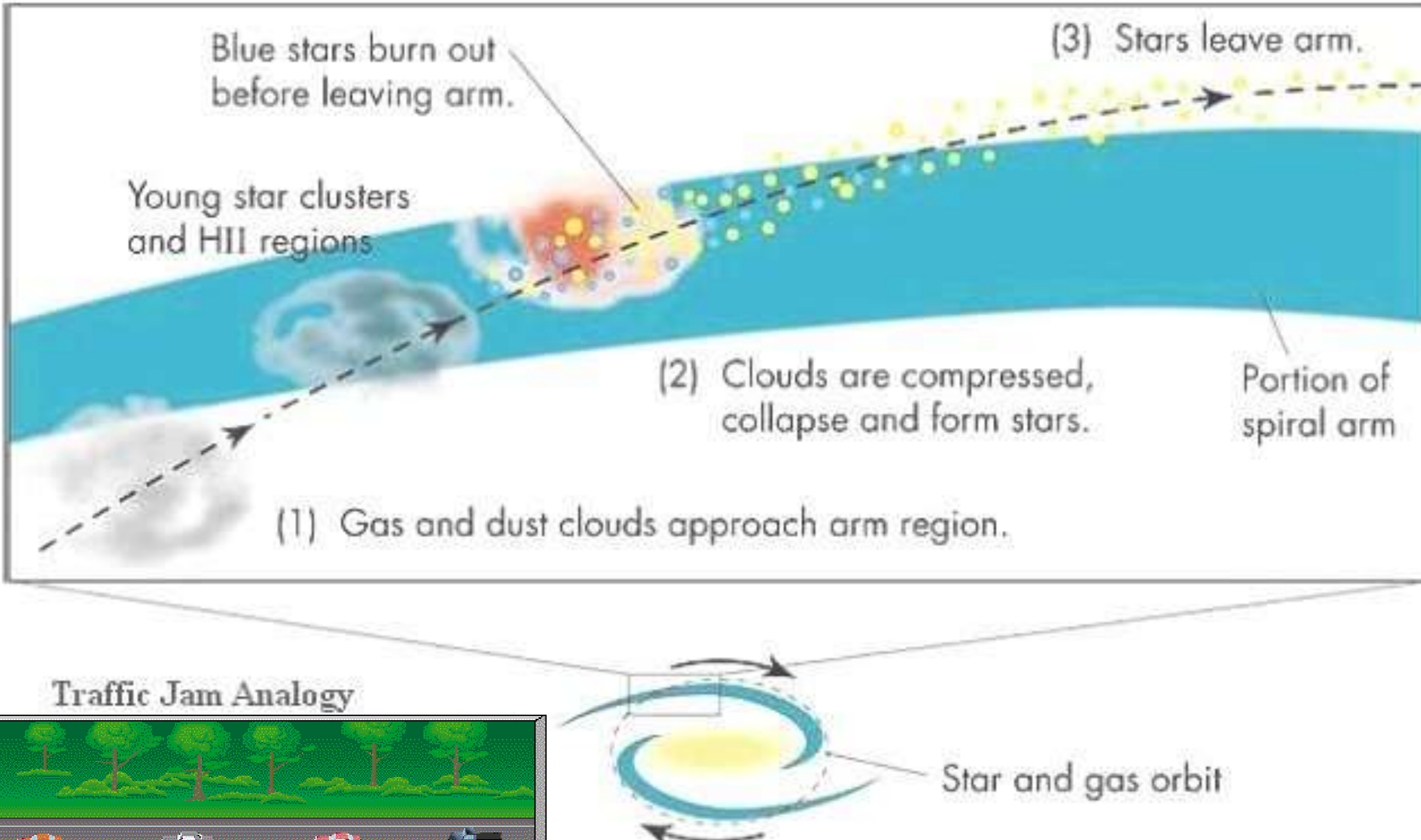

Observed motion
Orbital velocity (km/sec)
300
200
100
Sun
Keplerian motion
0
5
10
15
Distance from center of galaxy (kpc)


orbital velocity (km/s)
300
200
100
UGC 2885
NGC 7541
NGC 801
NGC 2998
50
100
150
200
distance from center (thousands of light-years)

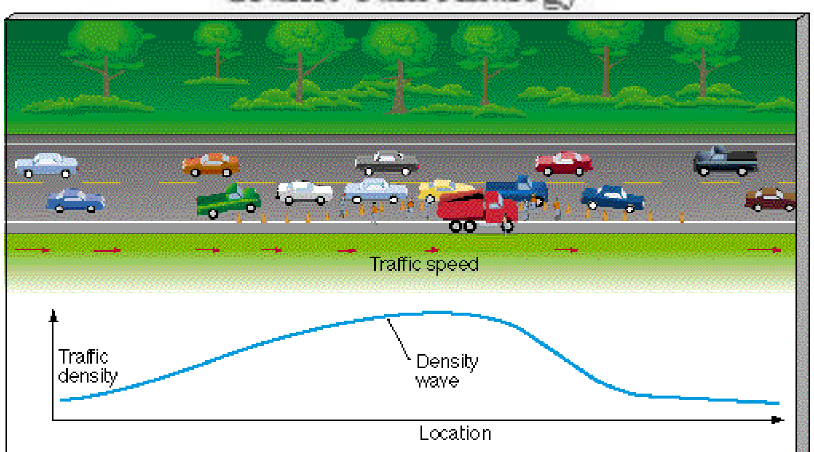
FORMATION OF SPIRAL STRUCTURE

1. Density wave theory

- "Grand Design" spiral galaxies
- Spiral arms are not solid.
- A spiral-shaped gravitational disturbance i.e. density wave is formed. It rotates around the centre with constant radial velocity.
  - At the distance of the Sun: half of the radial velocity of matter.



Traffic Jam Analogy



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/stars in the density wave

  $\Rightarrow$ spiral arm
- Young objects in the spiral arms, e.g., 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 ?

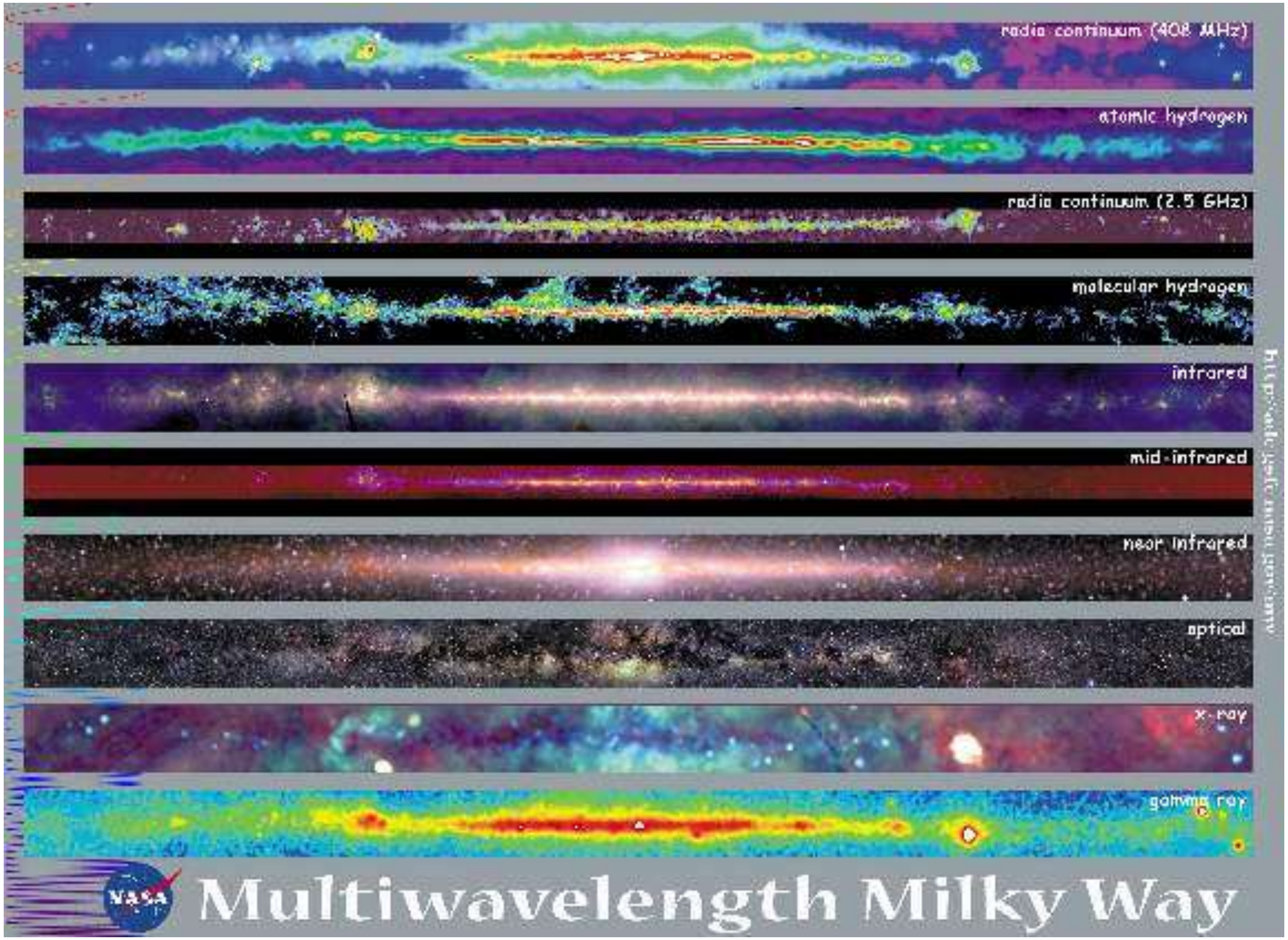
FORMATION OF SPIRAL STRUCTURE

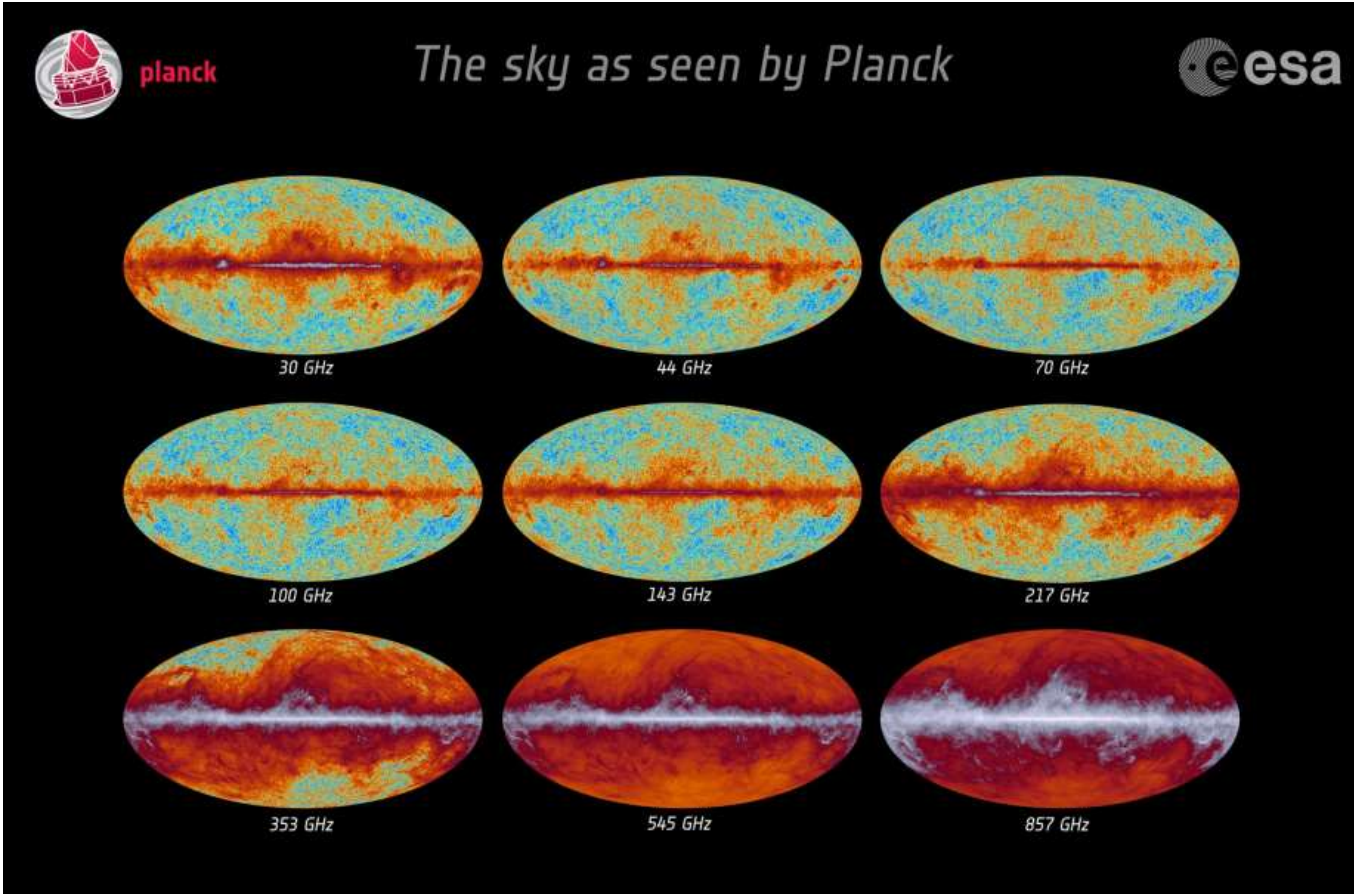
2. Stochastic Self-Propagative Star Formation

- Flocculent spiral galaxies

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

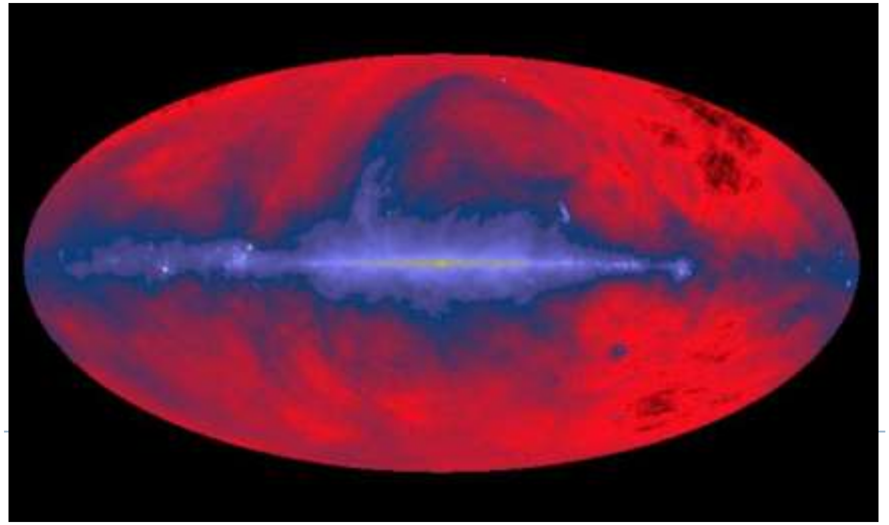
THE GALACTIC CONTINUUM




planck
The sky as seen by Planck
esa
30 GHz
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz

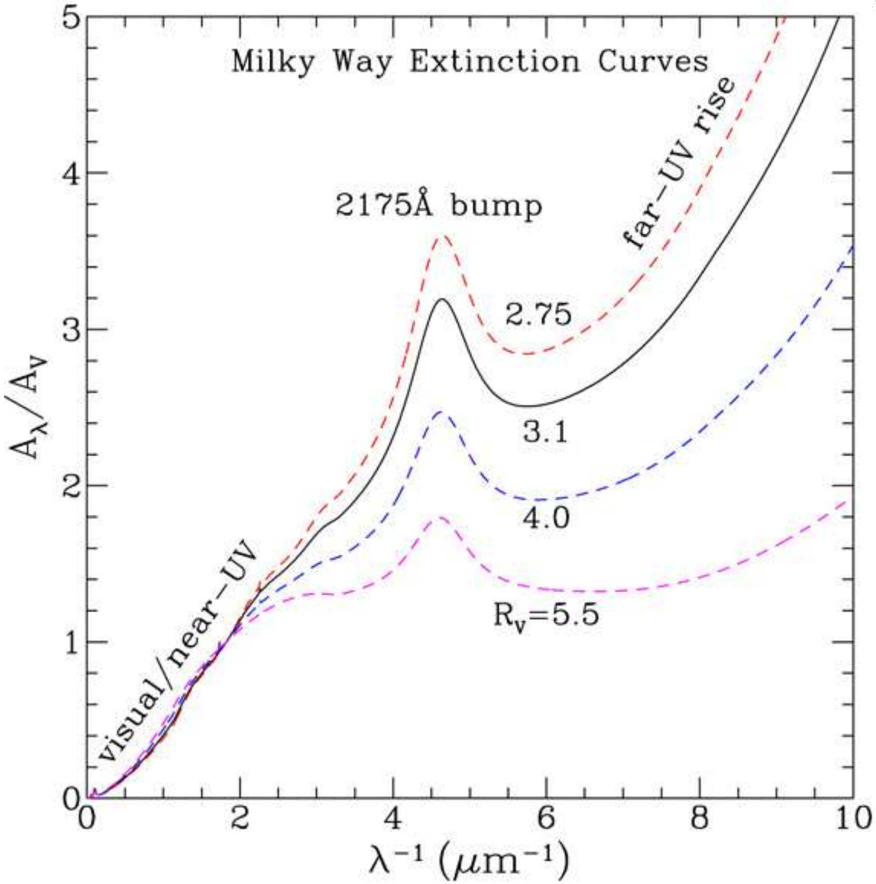
THE GALACTIC CONTINUUM

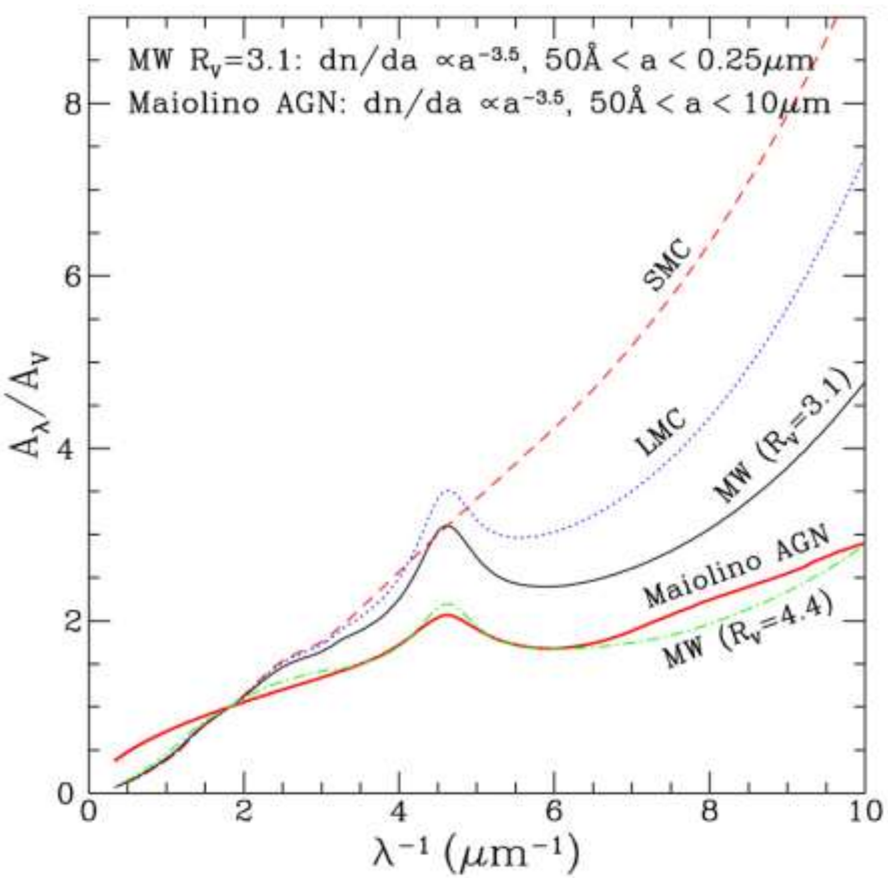
- Interstellar space is not empty, optical and shorter wavelength radiation is absorbed (and re-emitted, scattered…).
- Radiation decreases as the distance increases.
- Dust (and gas) block observations at short wavelengths $\Rightarrow$ radio astronomy!



THE GALACTIC CONTINUUM

- **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


Milky Way Extinction Curves
far-UV rise
2175Å bump
2.75
3.1
4.0
R_V=5.5
visual/near-UV
A_λ/A_V
λ^{-1} (μm^{-1})


MW R_v=3.1: dn/da $\propto a^{-3.5}$, 50Å < a < 0.25μm
Maiolino AGN: dn/da $\propto a^{-3.5}$, 50Å < a < 10μm
SMC
LMC
MW (R_v=3.1)
Maiolino AGN
MW (R_v=4.4)
A_λ/A_V
λ^{-1} (μm^{-1})

THE GALACTIC CONTINUUM

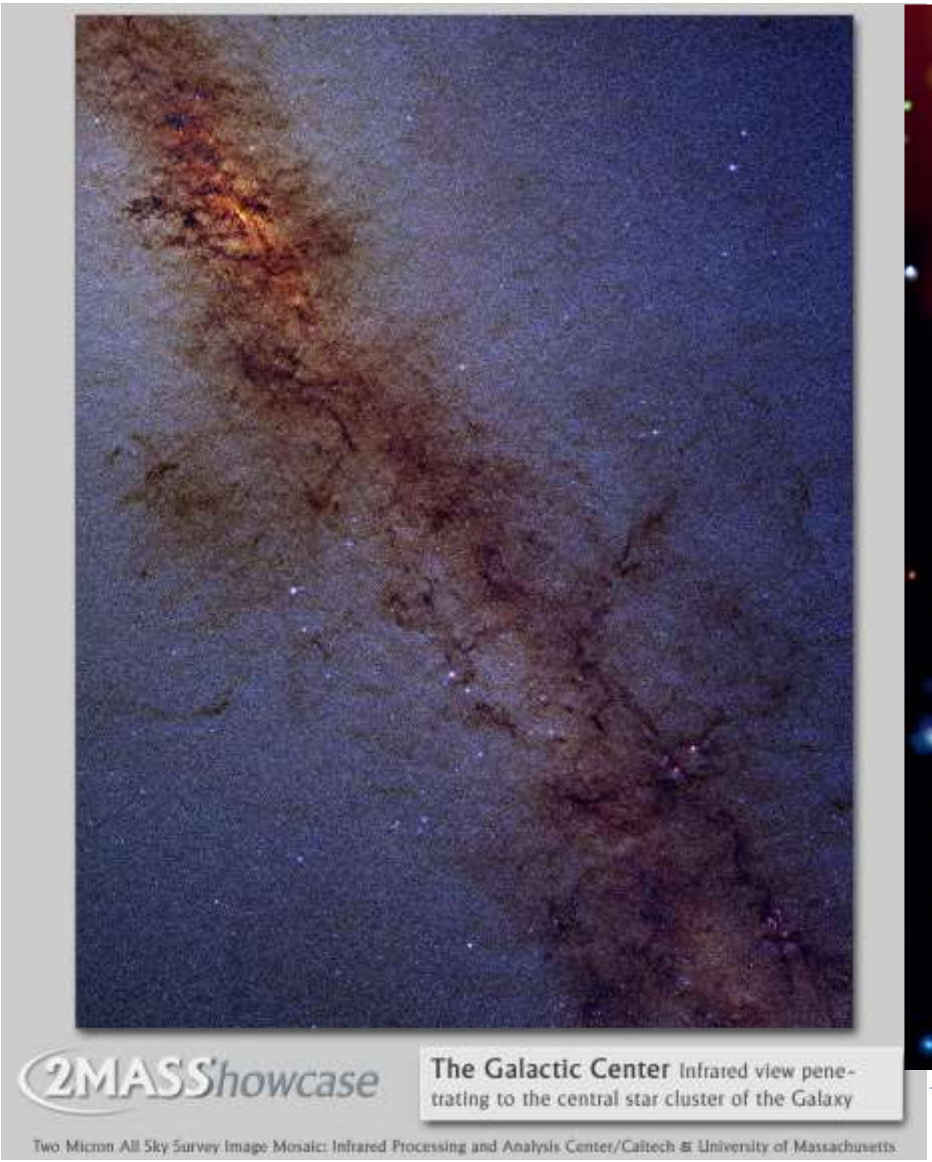
- **Reddening**
  - Blue light is scattered and absorbed (by dust) more than red (amount of extinction is larger for shorter λ).
  - The light of distant stars is redder than would be expected on the basis of their spetral class.

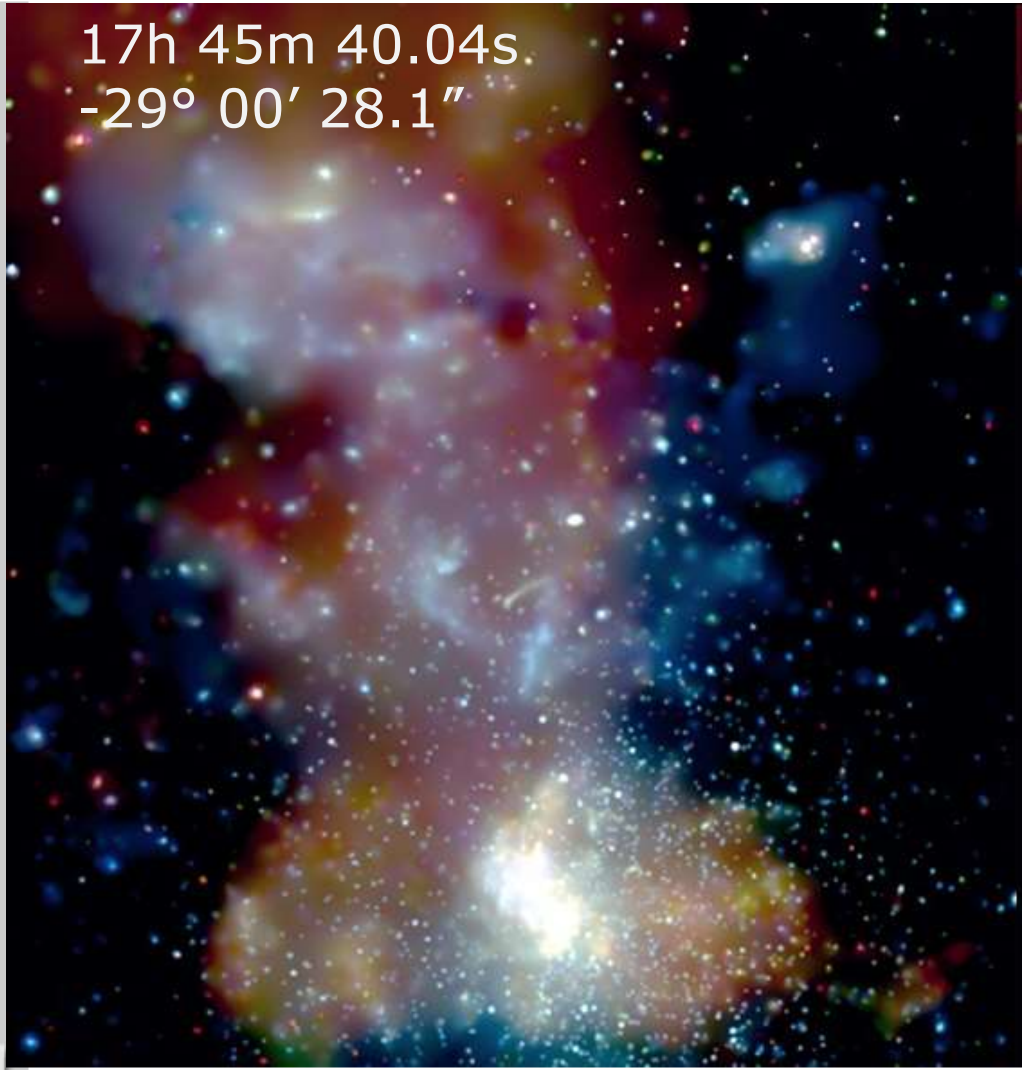
- **Polarization**
  - Nonspherical dust particles aligned by the interstellar magnetic field:
    - properties of the dust particles.
    - mapping of structure of the galactic magnetic field.

THE GALACTIC CENTRE?

ESO

THE GALACTIC CENTRE





Chandra X-rays

THE GALACTIC CENTRE

Where is it ?

- At a distance of 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!).
- 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)

radio emission propagates freely (nonthermal!)

THE GALACTIC CENTRE

What's there ?

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

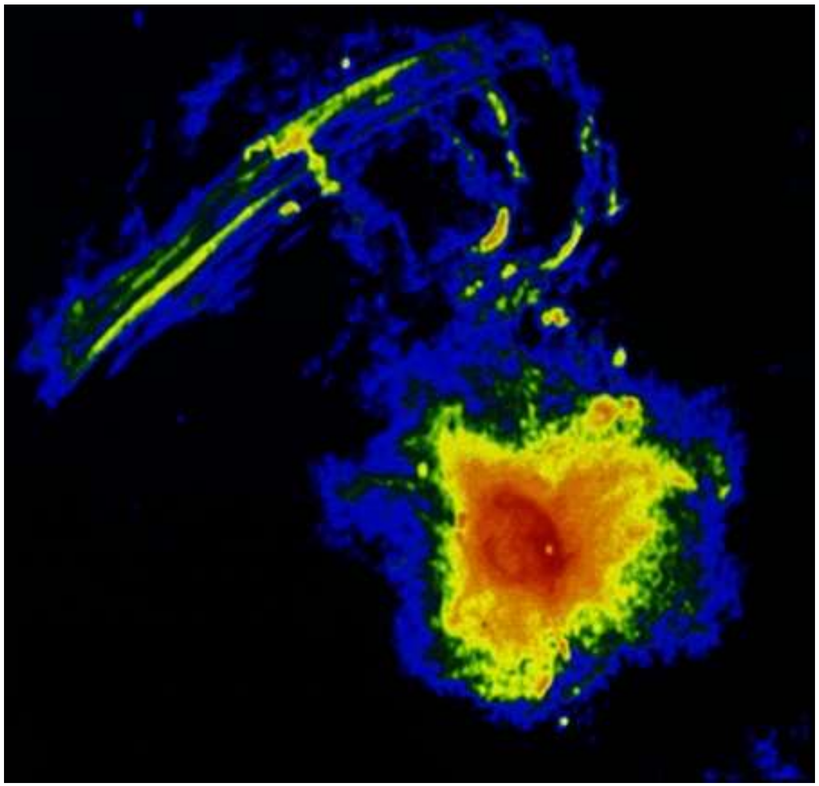
Innermost 10 pc

- Streamers of ionized gas and dust, threads, other features.
- Enigmatic radio source Sagittarius A (Sgr A*).

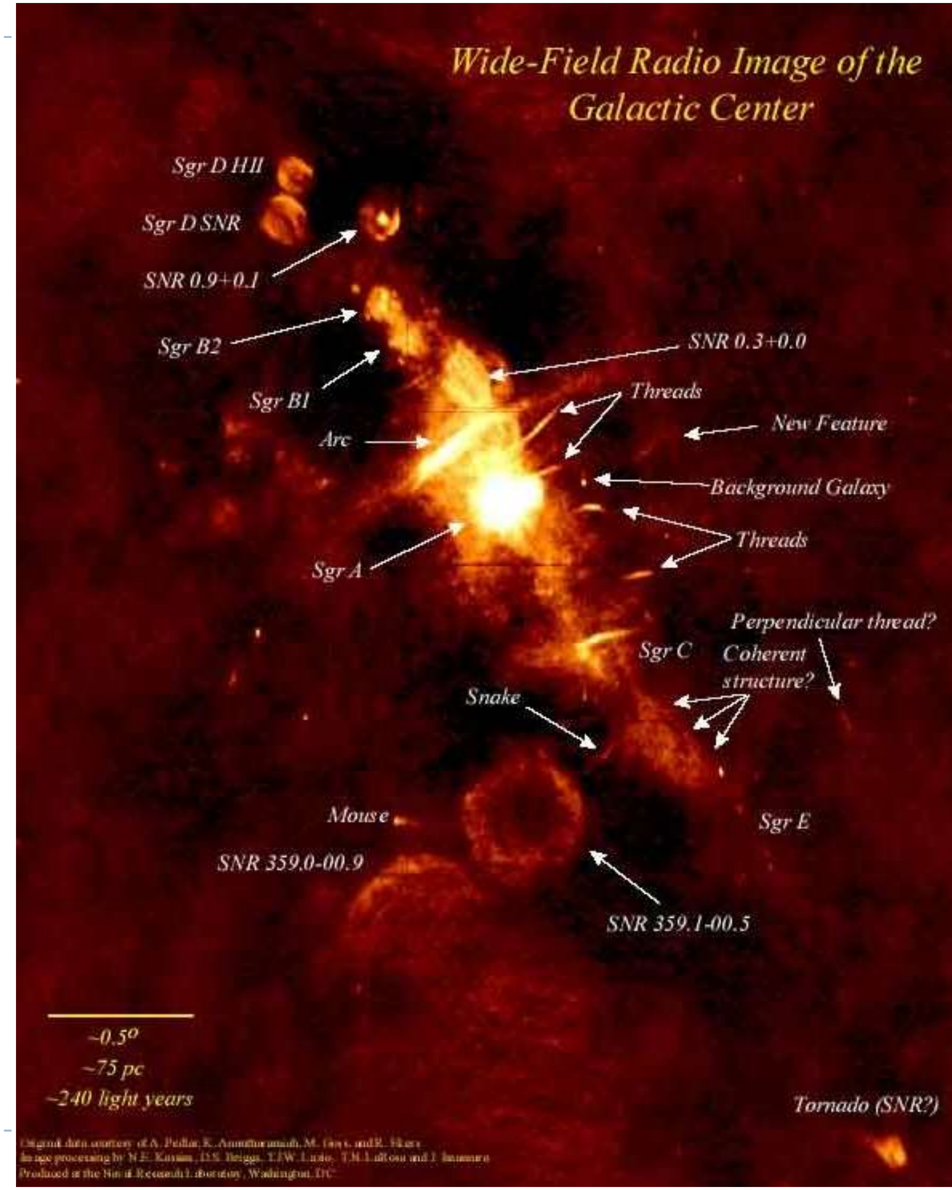
THE GALACTIC CENTRE

- Star formation regions, supernova remnants etc.
- 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?)

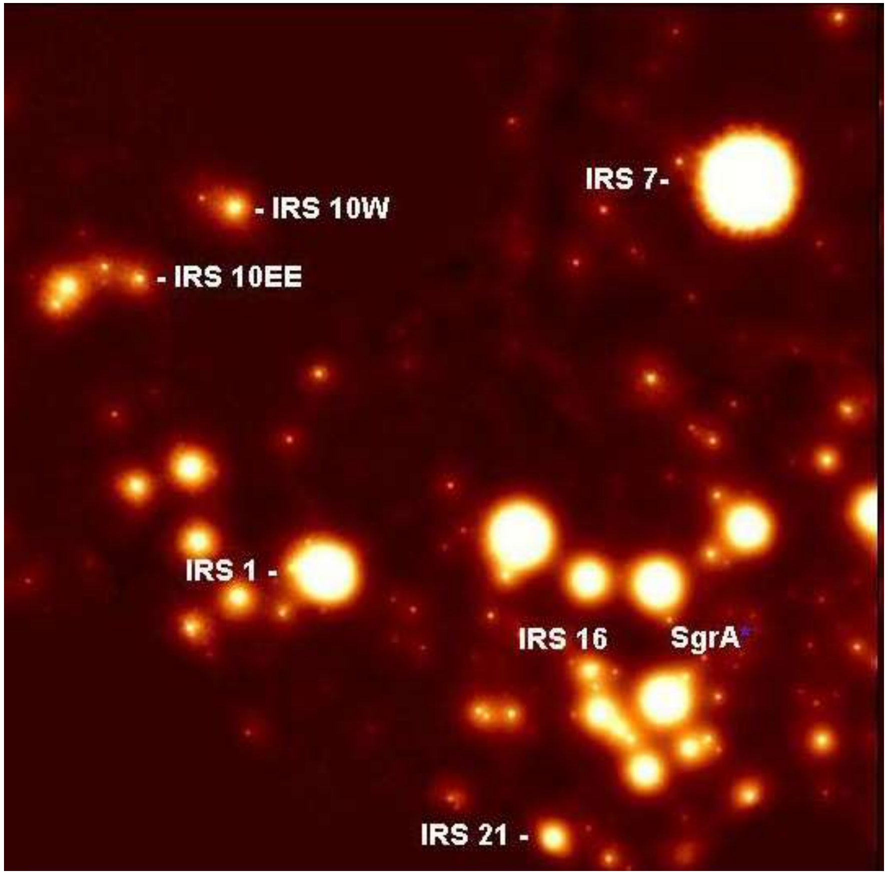
- Something in the middle makes the surrounding material move fast.



Sgr A: 1.4 GHz (VLA)



IR & X-rays


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


SGR A*
CHANDRA X-RAY

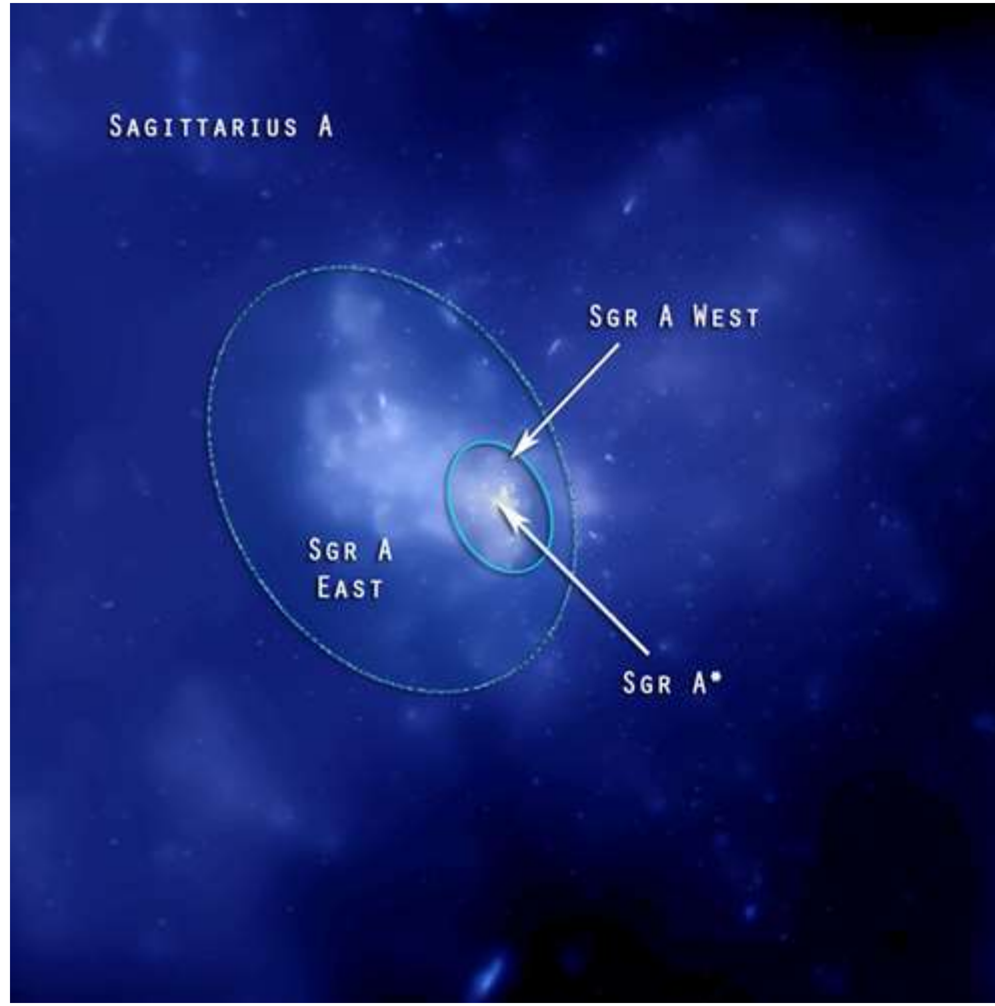
THE GALACTIC CENTRE

Sgr A East

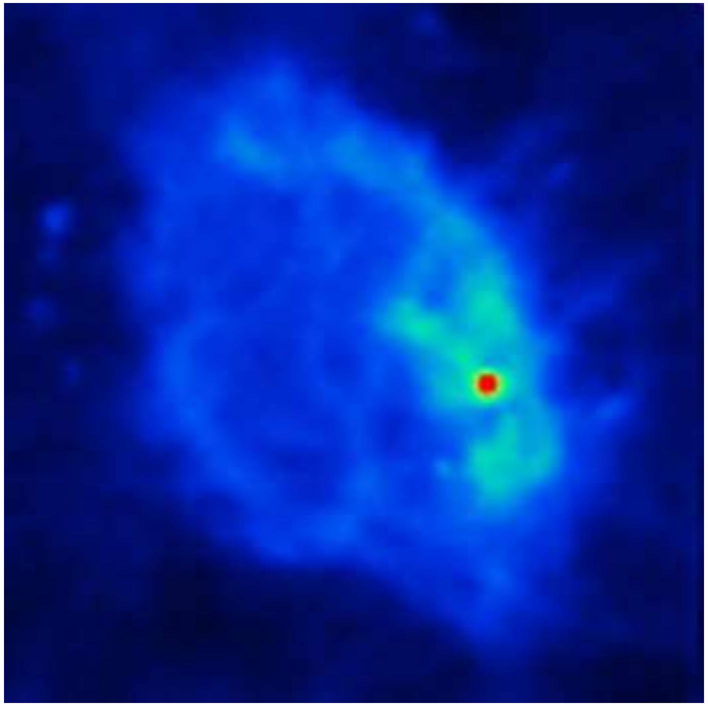
- probably a supernova remnant.

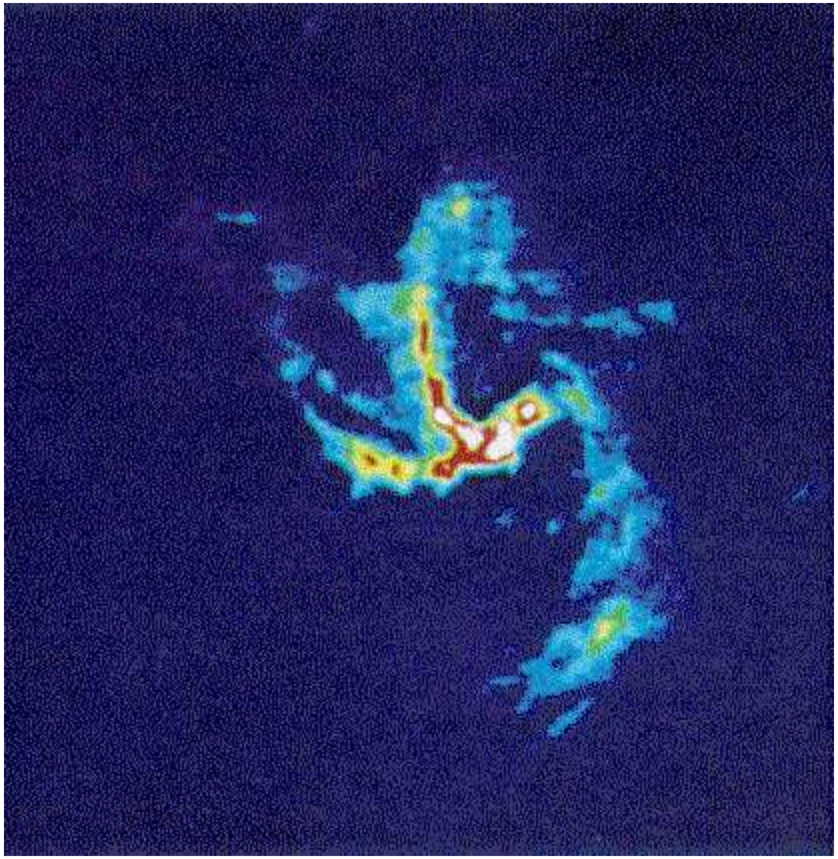
Sgr A West

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



Sgr A East & West





THE GALACTIC CENTRE

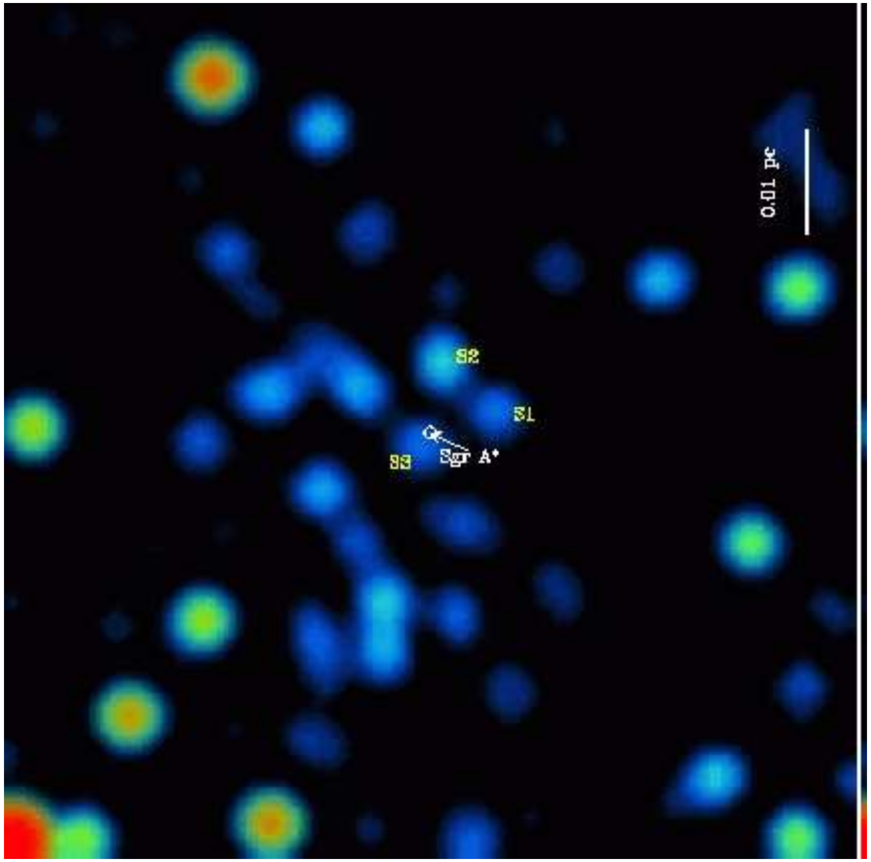
Sgr A*

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

  ⇒ 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” ?

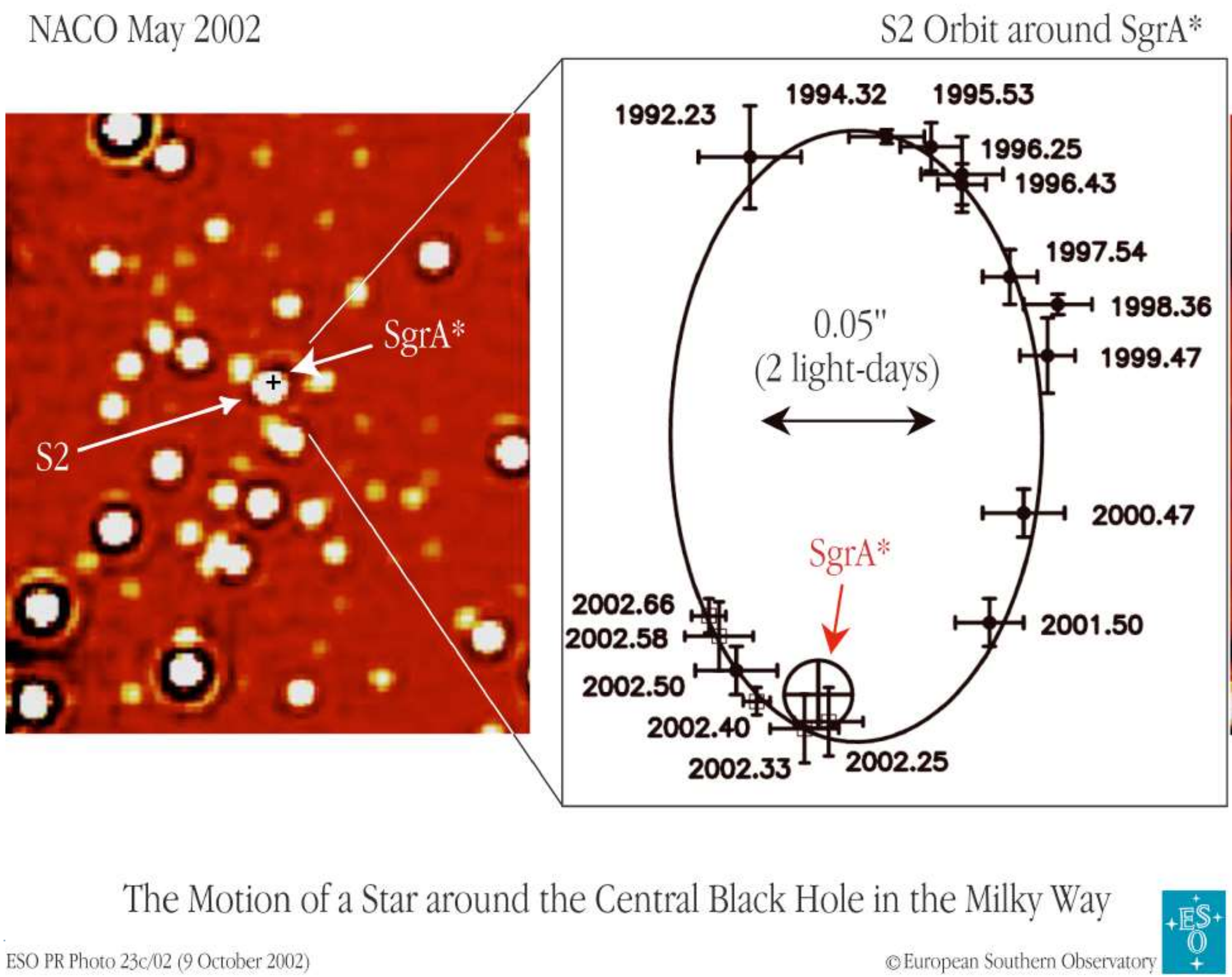
  ⇒ “starving” black hole?
- How has the black hole formed?

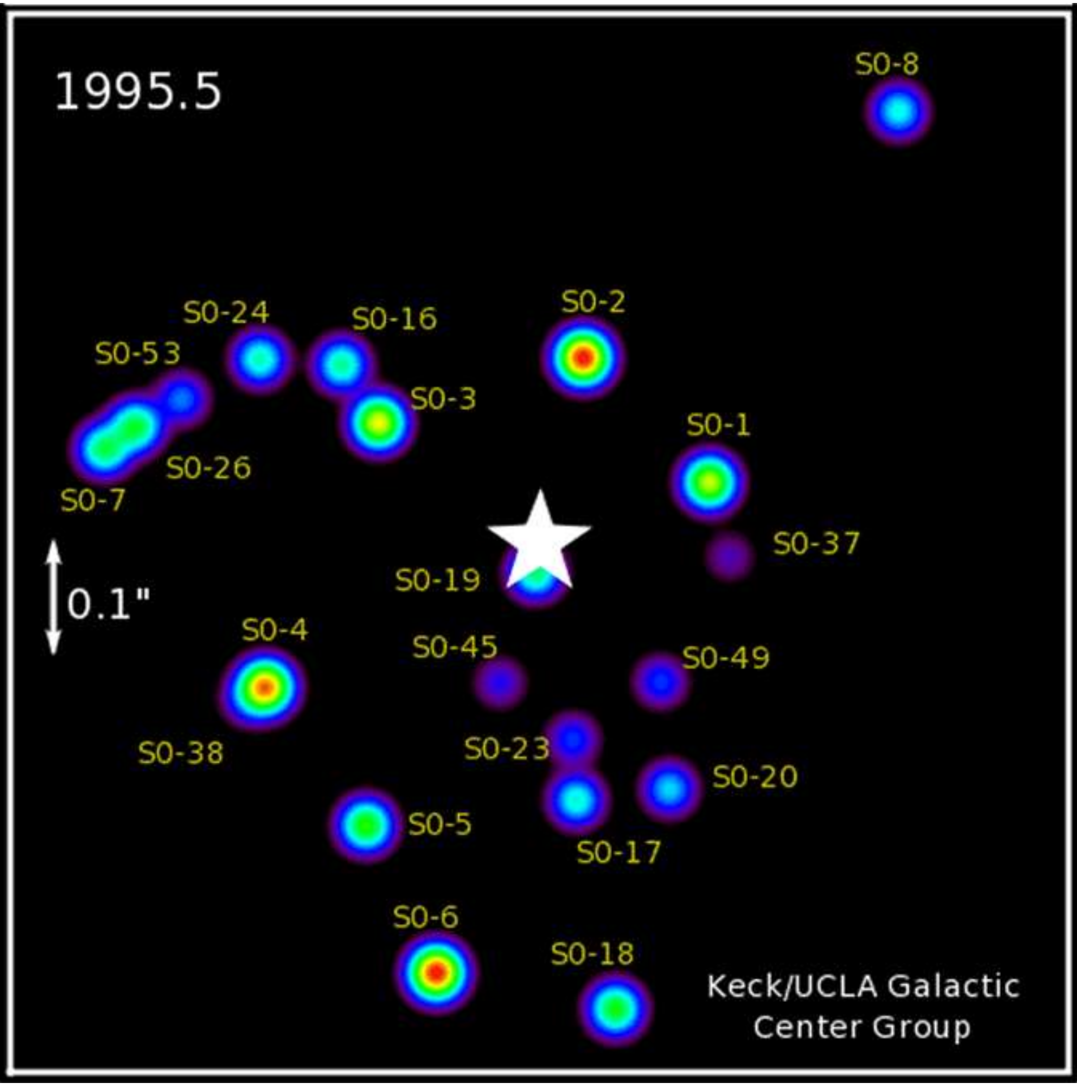
How close can we see?



IR

Stellar orbits in the central parsec
→ the mass of the black hole

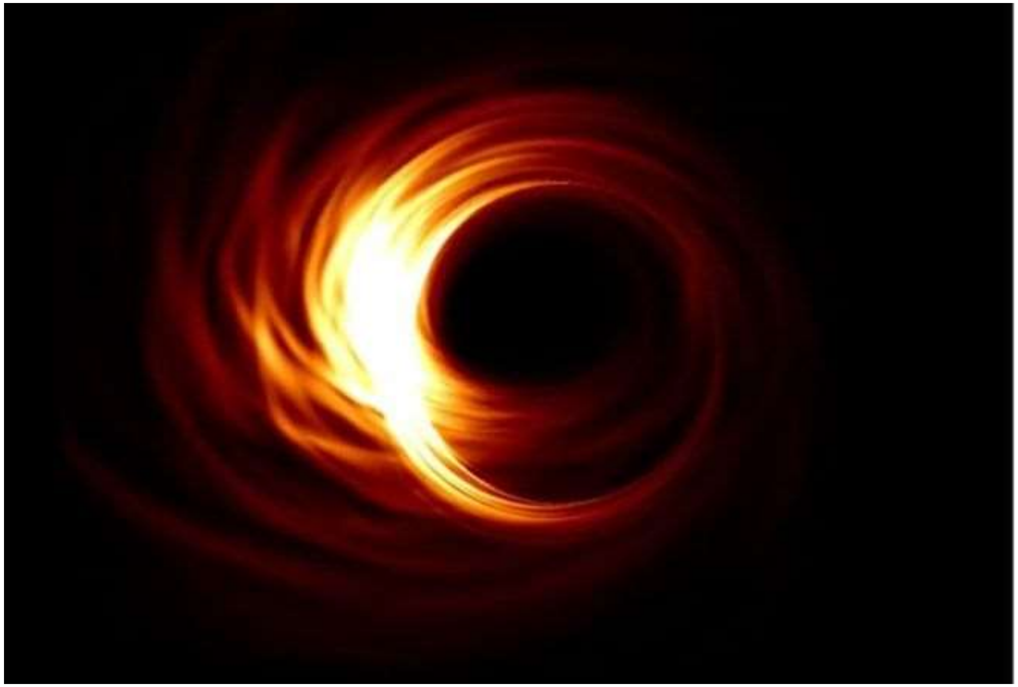




Orbital period of S0-2 is 15.78 years.
Distance of S0-16 from the black hole only 90 AU.

eventhorizontelescope.org

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



Hotaka Shiokawa/CFA/HARVARD

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