Our galaxy & the interstellar medium

Topic 6

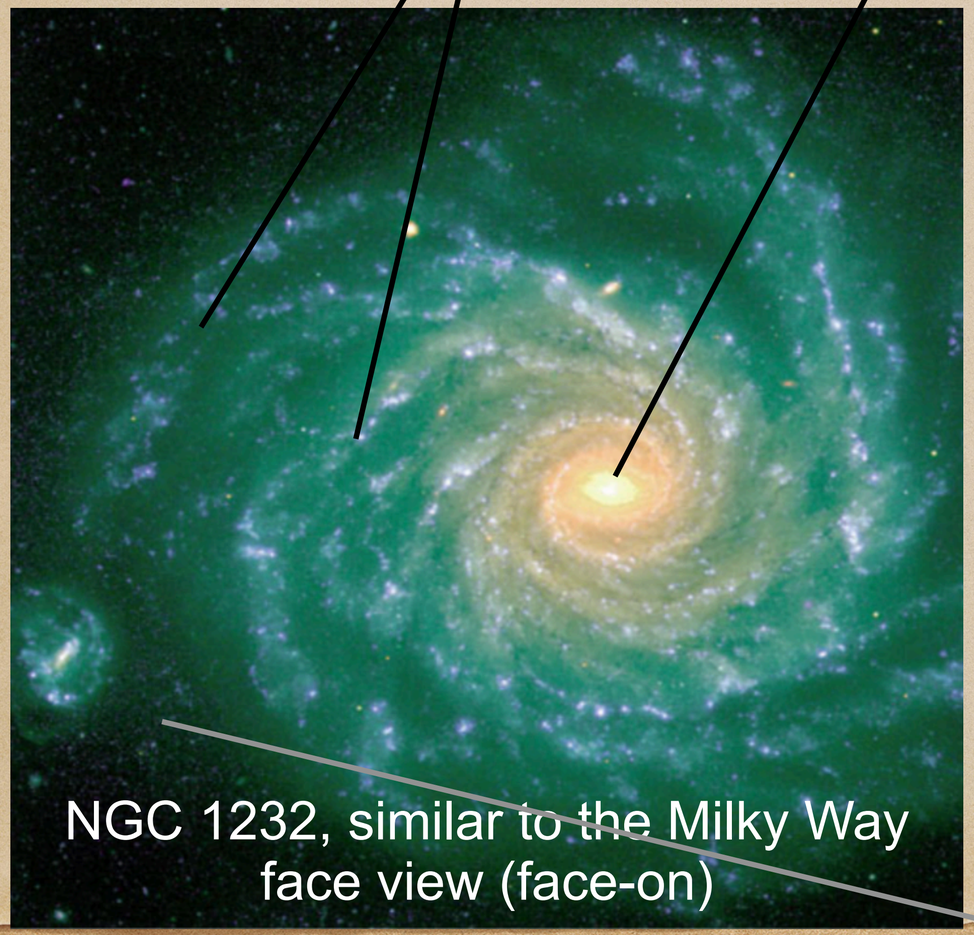
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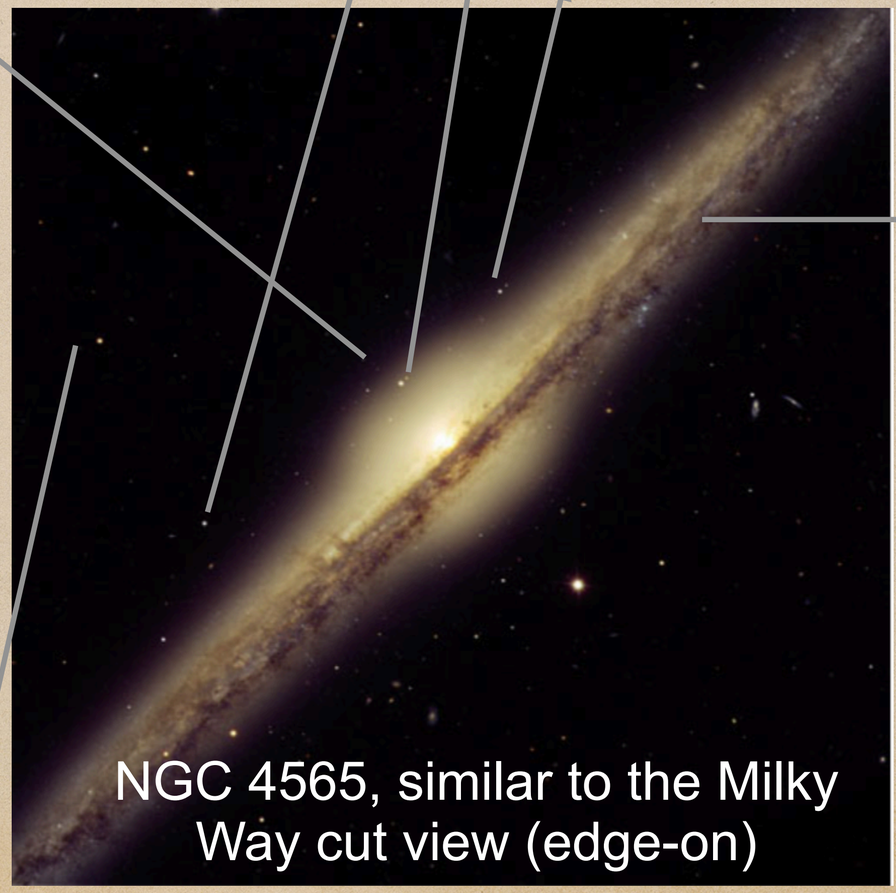
Chap. 19 “The cosmic perspective”, by J. O. Bennett, M. O. Donahue, N. Schneider & M. Voit

e Chap. 2 “Extragalactic Astronomy and Cosmology”, by P. Schneider, 2nd edition

(or Chap. 16&18 “Fundamental Astronomy” edition, by H. Karttunen, H. Oja, M. Poutanen, K. J. Donner)

Our galaxy





Halo

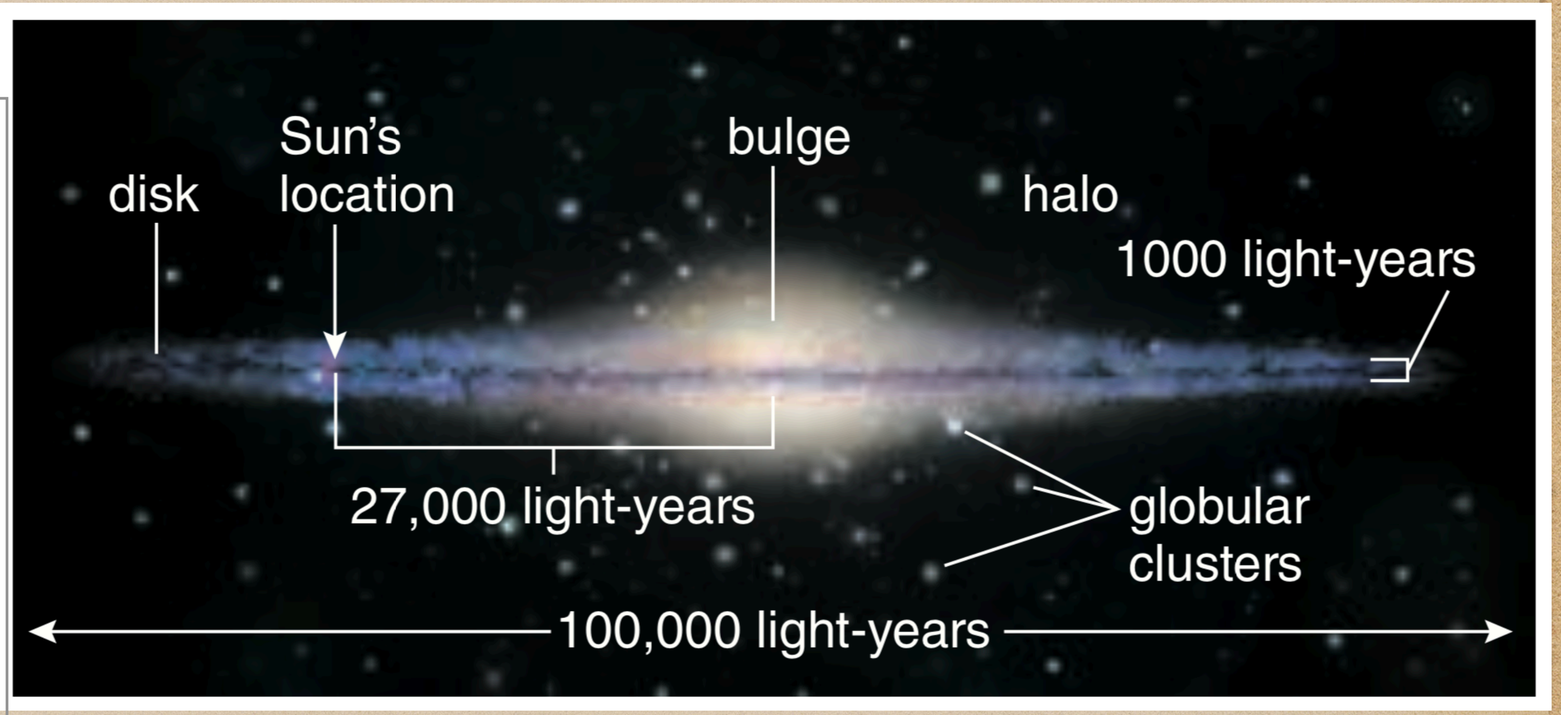
The real Milky way



- 6000 Stars visible to the naked eye
- A strip of dust

Our galaxy

- Our galaxy is a spiral, with extensive arms housed in the disk
- The bulge is a bright spheroid around the center
- The galaxy is immersed in the halo, very weak and spherical
- The globular clusters (about 200) are in the halo



- The galaxy contains 100 billion stars, its mass is ~$10^{11} M_\odot$
- It's just one of the 100 billion galaxies in the Universe

Some numbers

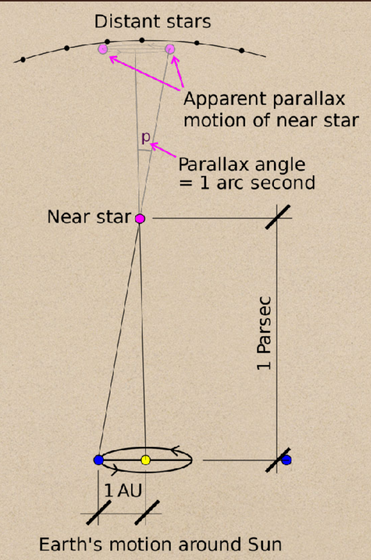
1 Light year [ly]=Distance traveled by light in a year

c=299 792 458 m/s

1 ly=?? km?

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1 parsec [pc]=Distance at which an AU underlies an arc of 1”



1 pc=206265 UA

1 kpc~ 3x10^16 km

1 UA = Earth-Sun distance

1 UA = 150 000 000 km

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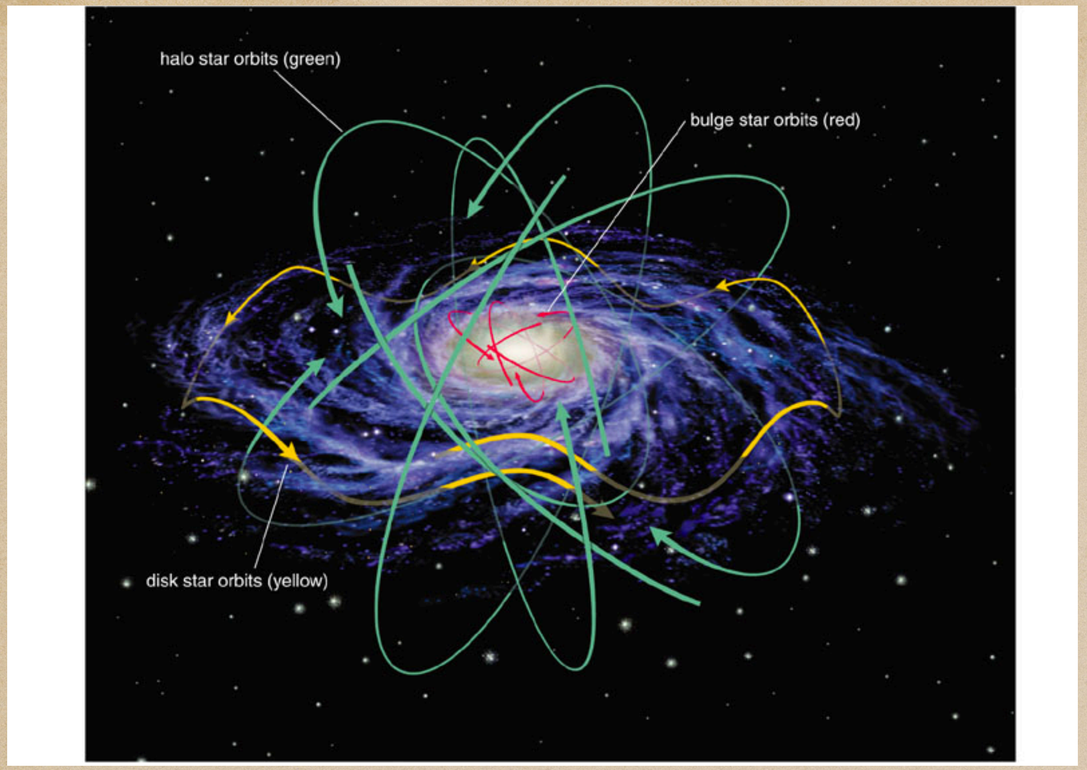
1 $M_\odot$ = Sun mass

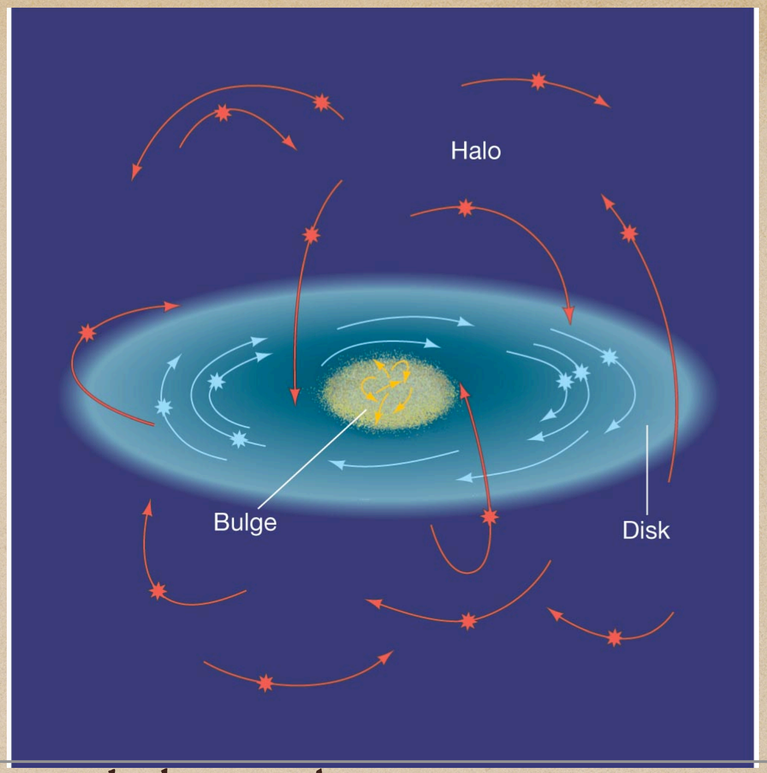
= 2×10^{30} kg

1 $L_\odot$ = Solar luminosity

= 3.8×10^{33} erg/s = 3.8×10^{26} Watt

Stellar Motions





- In the disc the motions are quasi-circular, around the galactic center.
- The Sun has a circular orbit of 27,000 light years radius, with speed 220 km/s
- In the halo the stars orbit around the galactic center, but the orbits are randomly oriented
- The bulge is intermediate, with some orbits randomly distributed, others aligned with the disk

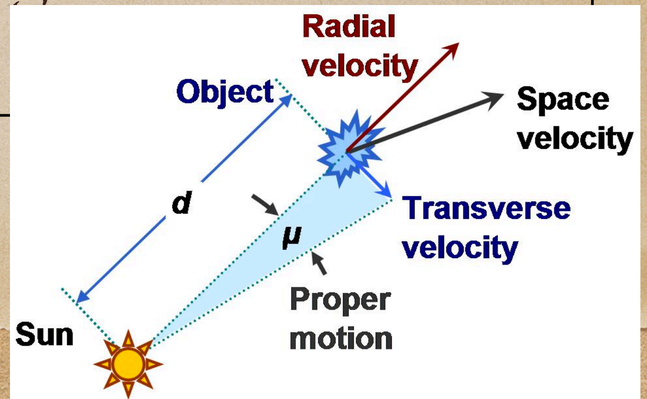
How do we know the structure of the Galaxy?

How do we know the structure?

- The stars visible at night seem to be evenly distributed around the Sun: is the Sun the center of the galaxy?
- No: the absorption by dust prevents us from seeing the stars of the disk far from us
- Globular clusters appear spherically distributed around a point 27,000 light years from Earth (Shapley): this point is the center of the Galaxy
- The observations of dust and gas (line 21cm in the radio) allows to establish the spiral structure of the disc

How do we know about stellar orbits?

- Studying the motion of many stars with respect to the Sun. How?
  - Doppler effect: radial motion
  - Tangential motion: through proper motions, the apparent motion of the stars in the sky at a distance of a long time
  - To convert your own motions into speed you need to know the distance
- The speed with respect to the sun is the vector sum of the tangential and radial velocity

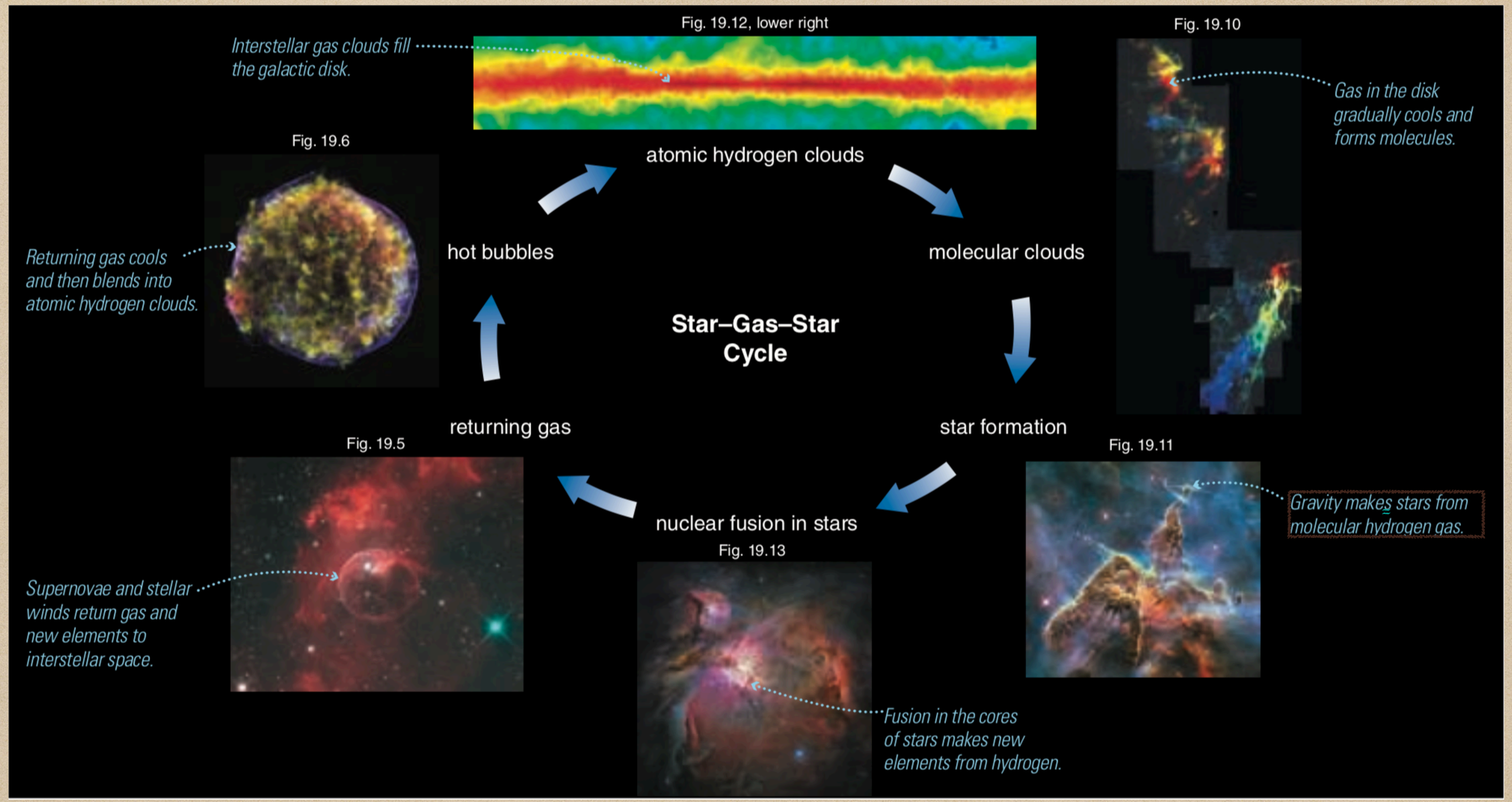


Milky Way: a star-forming galaxy



- The Milky Way is a galaxy that forms stars constantly over time
- On average, it produces 1-2 $M_\odot$ of new stars per year, so it has a modest star formation rate
- If it continued to form stars with the same rate, it would employ 100 Gyr to double its mass ($M_{gal}=10^{11}M_\odot$; To produce the same number of stars it would take 10^{11} yr=100 Gyr)
- Which mechanism allows the galaxy to continue forming stars at this constant rate?

The gas cycle in the galaxy

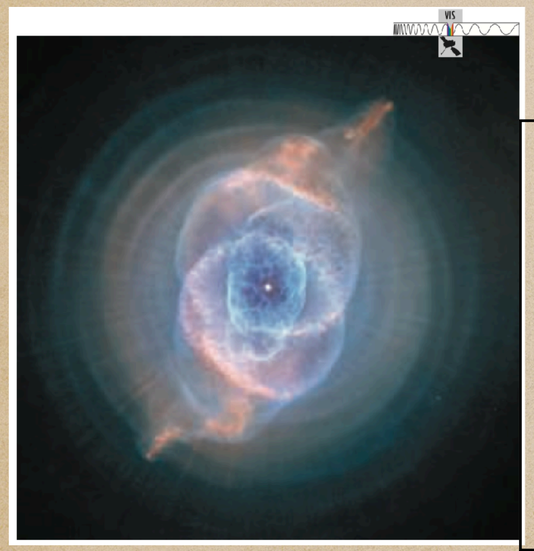


Keeps the formation of stars active in the galaxy

The gas cycle in the galaxy

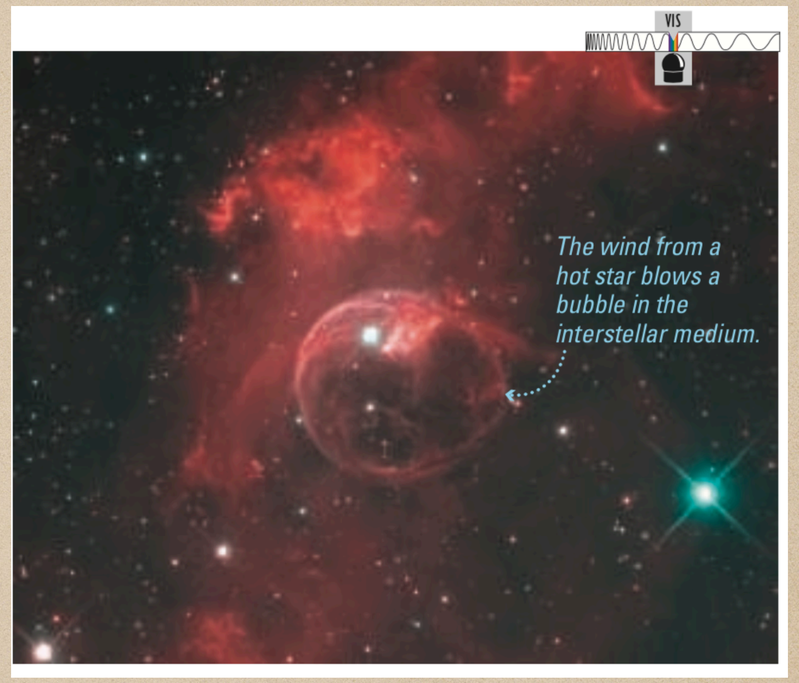
Phase 1: gas expelled from stars

All stars return much of their original mass to interstellar space, through stellar winds (during their lifetime) or catastrophic events: planetary nebulae (for small-mass stars) or supernovae (for large-mass stars)

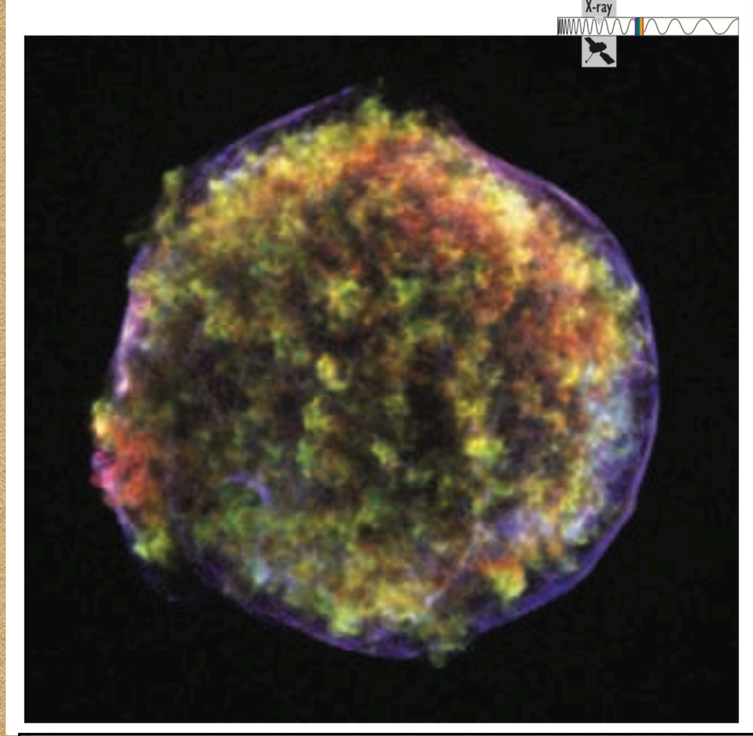


The death of a small mass star: about 50% of its original mass is returned to interstellar space

Planetary nebula

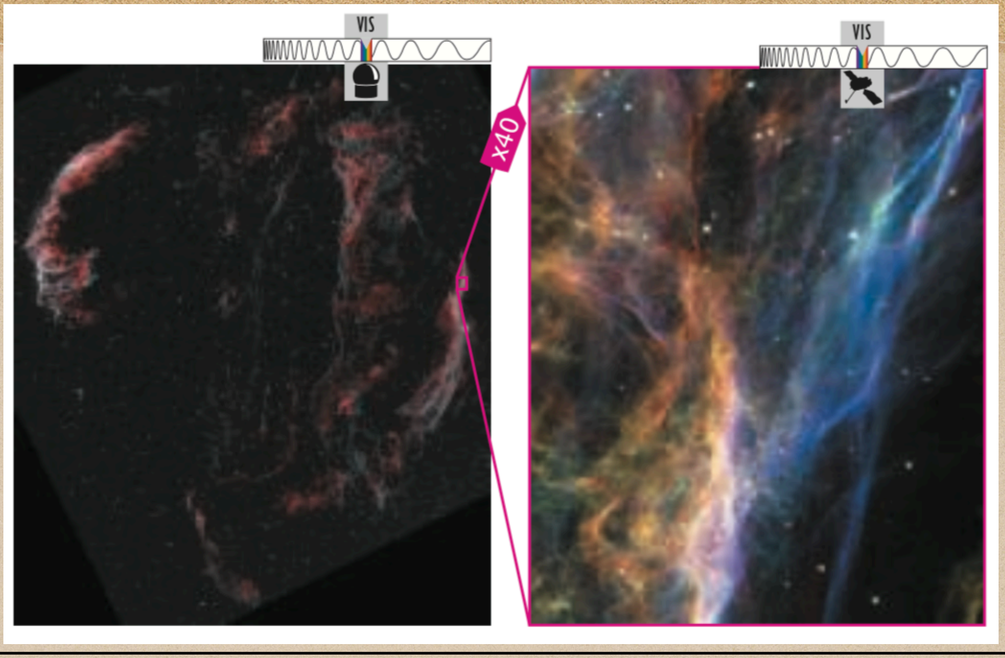


Expanding hot gas shell



Young remnant of supernova

- Explosion of massive stars $M>8M_{\odot}$
- blue: gas at 20,000,000 °K, shock front
- Green/red: gas at 10,000,000 °K, product of the explosion, heated by the shock front



Remnant of evolved supernova

- Colder, because the shock front expanded, swept more material and cooled
- In the end the gas heated by the shock cools (it radiates all the thermal energy) and mixes with the surrounding interstellar medium

Heavy elements such as C, O, Fe, ... are created in the nucleus of the stars and transferred to the interstellar medium with this kind of events

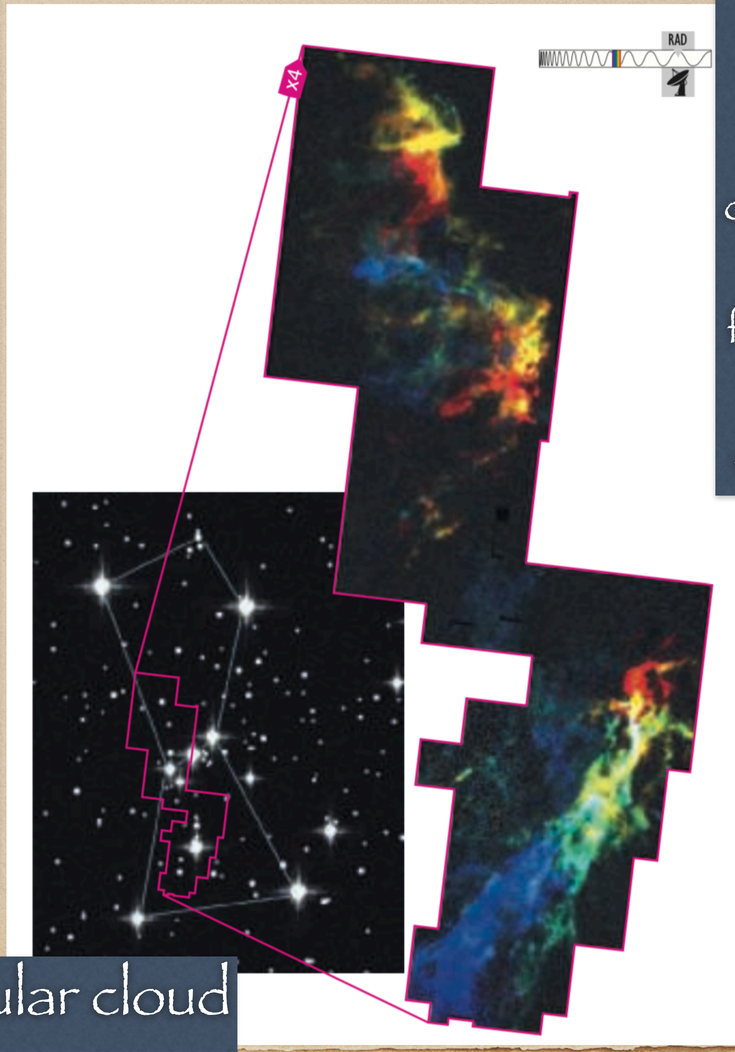
Phase 2: gas cooling and molecular cloud formation

- Once the gas expelled from the stars cools, it mixes with the interstellar atomic hydrogen
- Atomic hydrogen is found in 2 forms:

Low density clouds of warm gas (warm, 10,000 °K)

Denser clouds of cold gas (cold, 100 °K)

- With the passage of time (millions of years) the gas condenses, and in doing so it cools
- This phase is very long, so most of the gas in a galaxy is in this state
- As it cools further, atomic hydrogen combines into molecular hydrogen, forming molecular clouds (about 5% of the galaxy's mass is in this form)



molecular cloud

The colors indicate the Doppler displacement: red going further away, blue approaching

Phase 3: Star formation

- Once formed, the molecular cloud fragments and forms a stellar cluster Stars of different masses are formed; the most massive and hot (O, B) ionize and heat the surrounding gas, the winds sweep away the gas

- Feedback prevents most of the molecular gas from forming stars



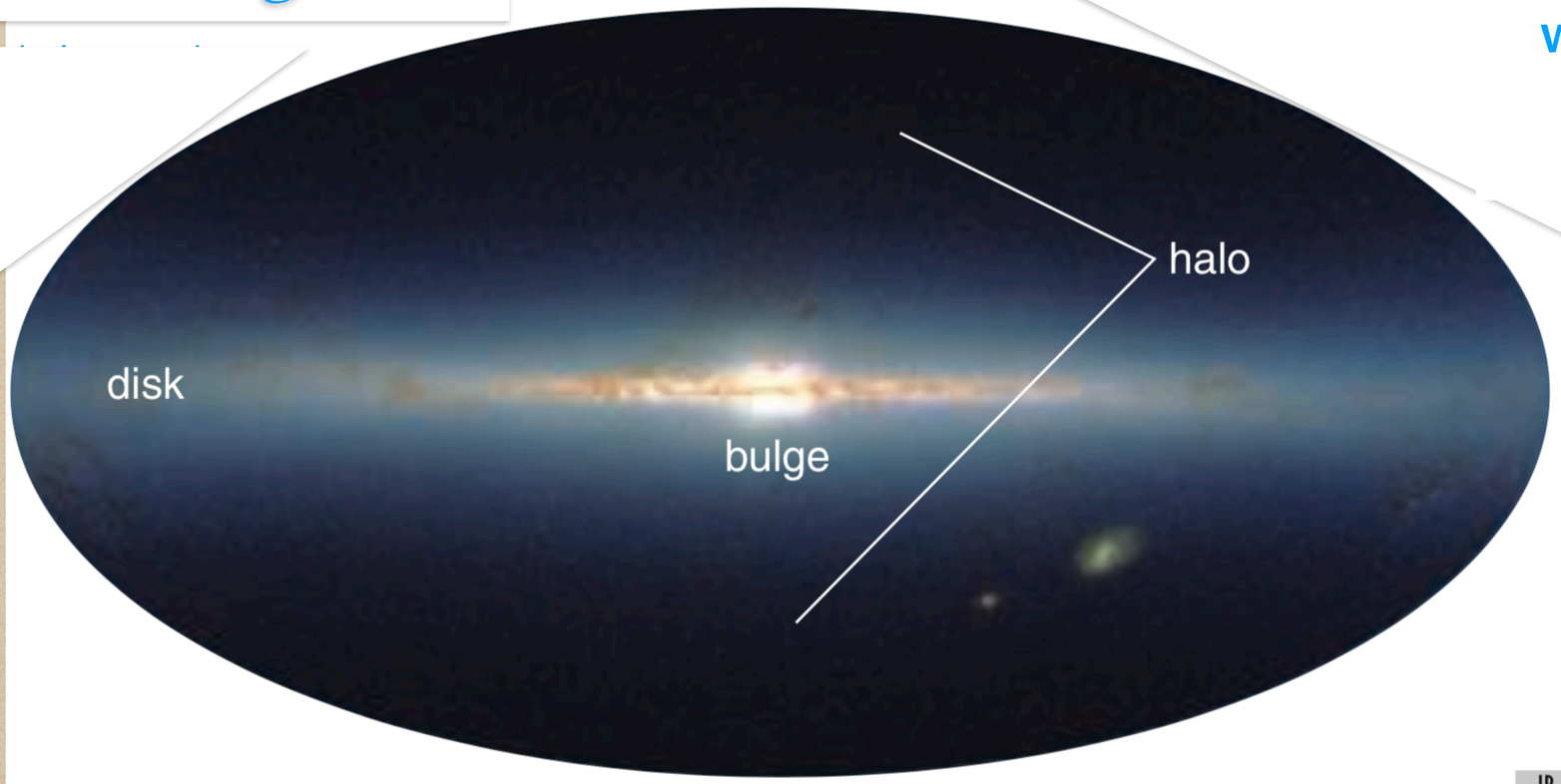
Carina nebula

Distribution of gas and stars in our galaxy

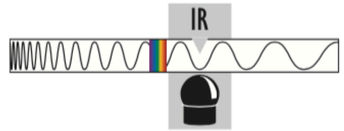
These images are all sky

They show the Galactic disk edge on

Near infrared wavelengths show the spatial distribution of stars



infrared (short wavelength)



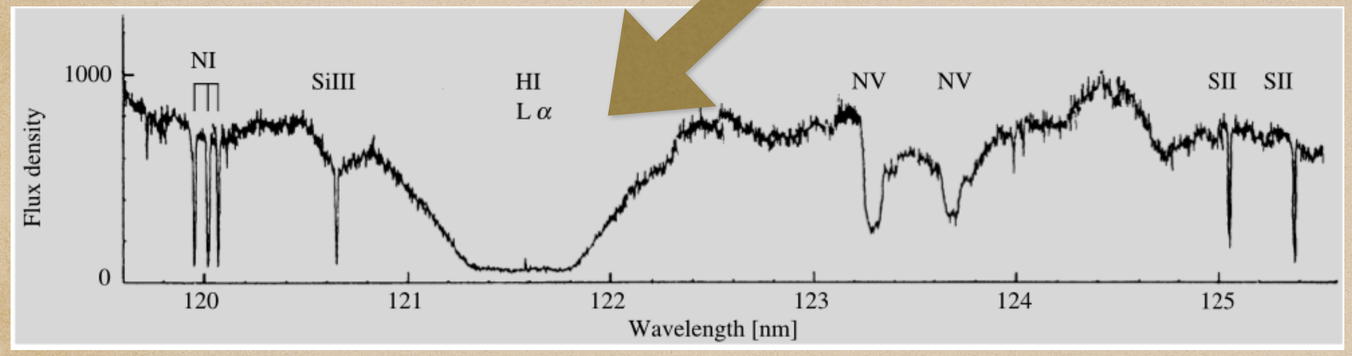
Interstellar medium components

Table 16.1 Main properties of interstellar gas and dust

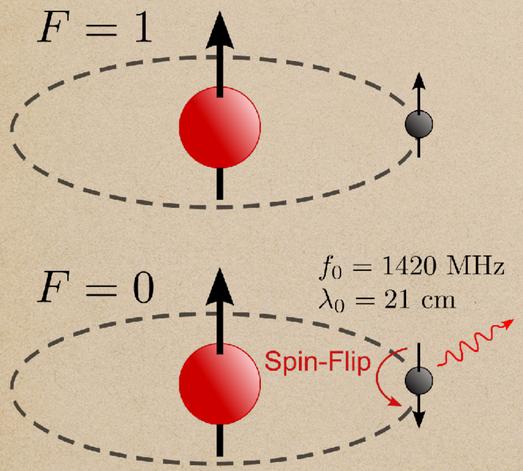
Property	Gas	Dust
Mass fraction	10 %	0.1 %
Composition	H I, H II, H_2 (70 %) He (28 %) C, N, O, Ne, Na, Mg, Al, Si, S, … (2 %)	Solid particles $d \approx 0.1$–1 μm H_2O (ice), silicates, graphite + impurities
Particle density	1 /cm^3	10^{-13} /cm^3 = 100 /km^3
Mass density	10^{-21} kg/m^3	10^{-23} kg/m^3
Temperature	100 K (H I), 10^4 K (H II) 50 K (H_2)	10–20 K
Method of study	Absorption lines in stellar spectra. Optical: Ca I, Ca II, Na I, K I, Ti II, Fe I, CN, CH, CH^+ Ultraviolet: H_2, CO, HD Radio lines: hydrogen 21 cm emission and absorption; H II, He II, C II recombination lines; molecular emission and absorption lines OH, H_2CO, NH_3, H_2O, CO, H_2C_2HCN, C_2H_5OH	Absorption and scattering of starlight. Interstellar reddening Interstellar polarisation Thermal infrared emission

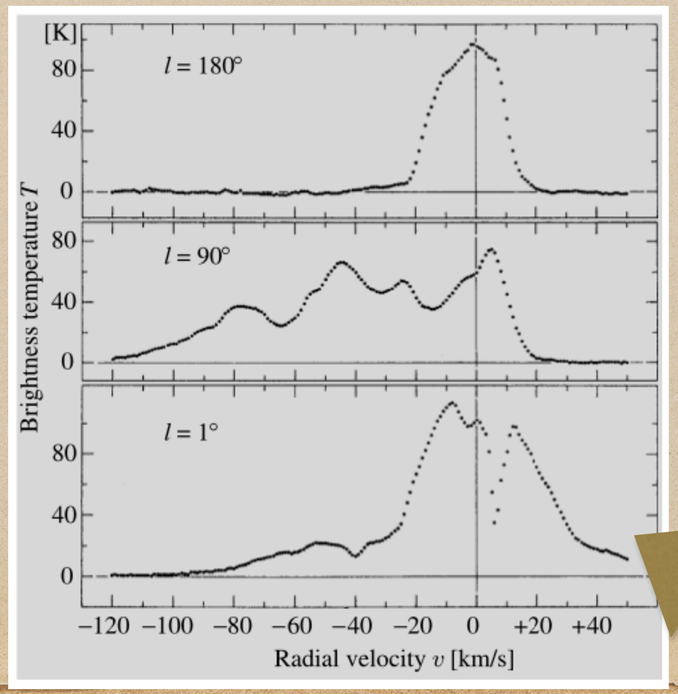
Neutral hydrogen

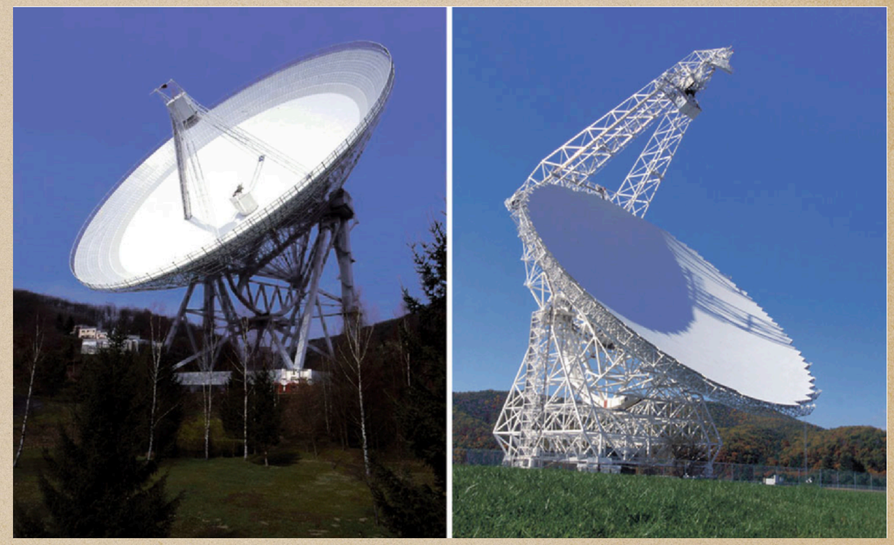
In absorption











In emission

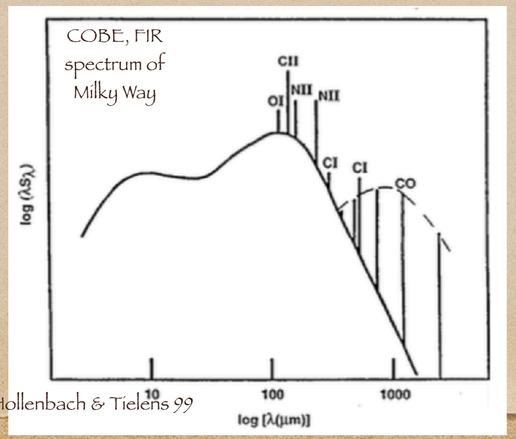
Molecular gas

Table 16.4 Some molecules observed in the interstellar medium

Molecule	Name	Year of discovery
Discovered in the optical and ultraviolet region:		
CH	methylidyne	1937
CH^+	methylidyne ion	1937
CN	cyanogen	1938
H_2	hydrogen molecule	1970
CO	carbon monoxide	1971
Discovered in the radio region:		
OH	hydroxyl radical	1963
CO	carbon monoxide	1970
CS	carbon monosulfide	1971
SiO	silicon monoxide	1971
SO	sulfur monoxide	1973
H_2O	water	1969
HCN	hydrogen cyanide	1970
NH_3	ammonia	1968
H_2CO	formaldehyde	1969
HCOOH	formic acid	1975
HCCNC	isocyanoacetylene	1991
C_2H_4O	vinyl alcohol	2001

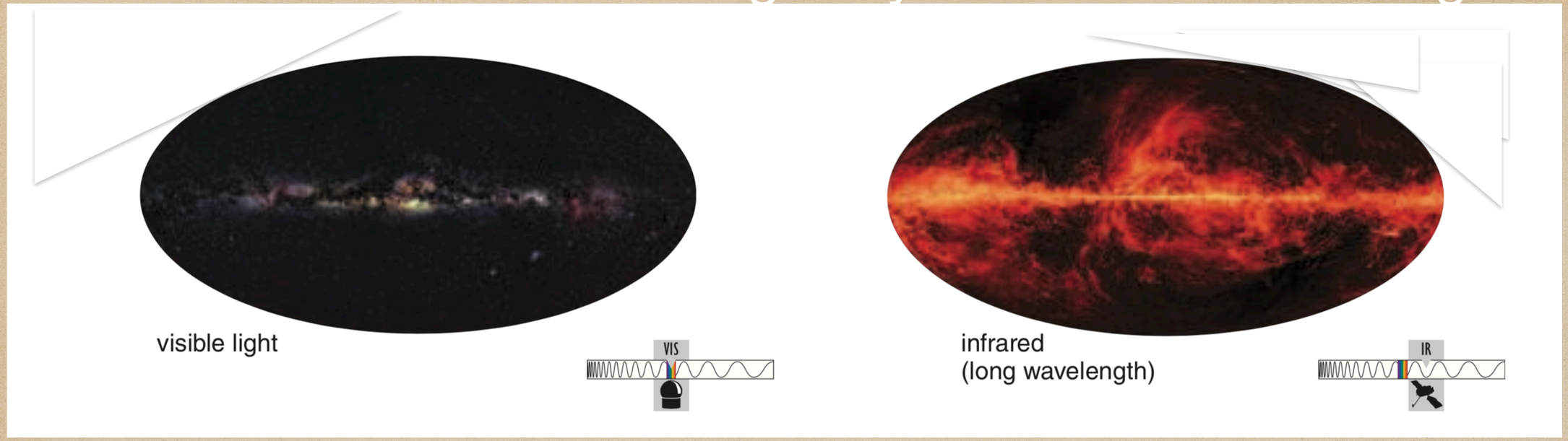
- It is the most common molecule
- It contains most of the hydrogen mass of the interstellar mediumM_{H2}/M_{HI}≈2
- Practically not observable, it has no dipole moment

- It is the second most common molecule
- Observable in the FIR (for example ALMA)
- It is used to trace H_2





The galaxy at different wavelengths



Visible light

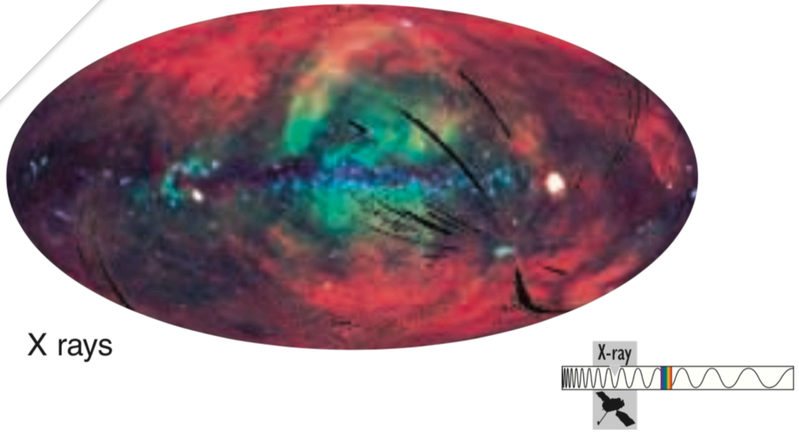
- Solar-type stars emit most of the light at these wavelengths
- But the dust in the galactic disk absorbs stellar light
- What you see are lines of sight casually not blocked by dust

Far infrared

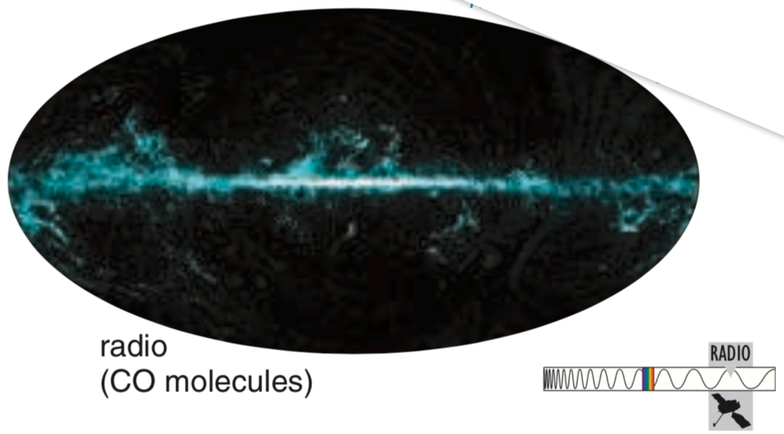
- Galactic dust absorbs UV and visible light, heating up
- Dust emits the energy absorbed in the form of black body thermal energy
- What you see are the regions of active star formation, rich in dust

The galaxy at different wavelengths

At X rays wavelengths the halo is brighter than the disc: it is filled with hot ionized gas



At radio wavelengths we see cold molecular gas

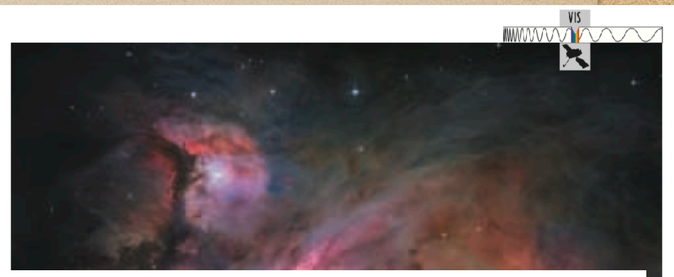


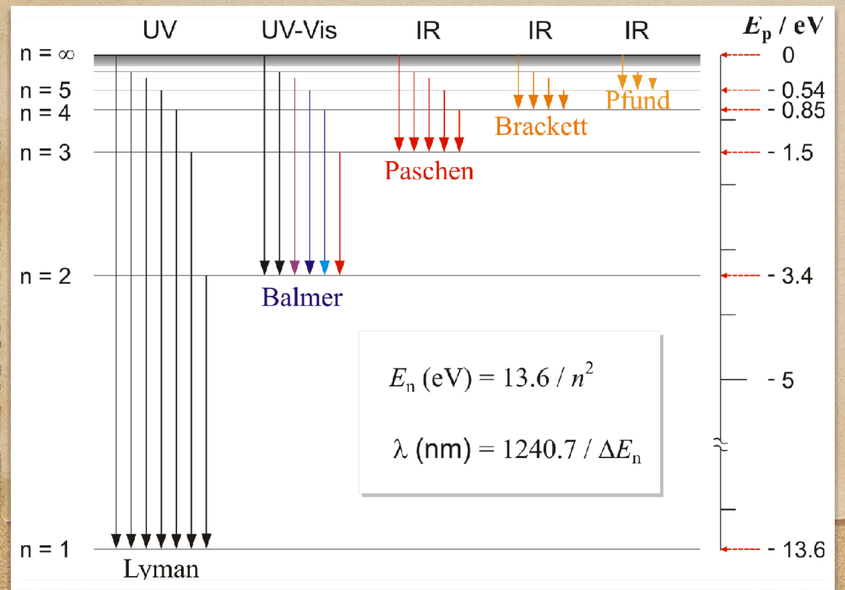
	State of Gas		
	Hot bubbles	**Atomic Hydrogen Clouds**	Molecular clouds
Primary Constituent	≈	Atomic hydrogen	Molecular hydrogen
Approximate Temperature	1,000,000 K	100–10,000 K	30 K
Approximate Density (atoms per cm^3)	0.01	1–100	300
Description	Pockets of gas heated by stellar winds or supernovae	The most common form of gas, filling much of the galactic disk	Regions of star formation

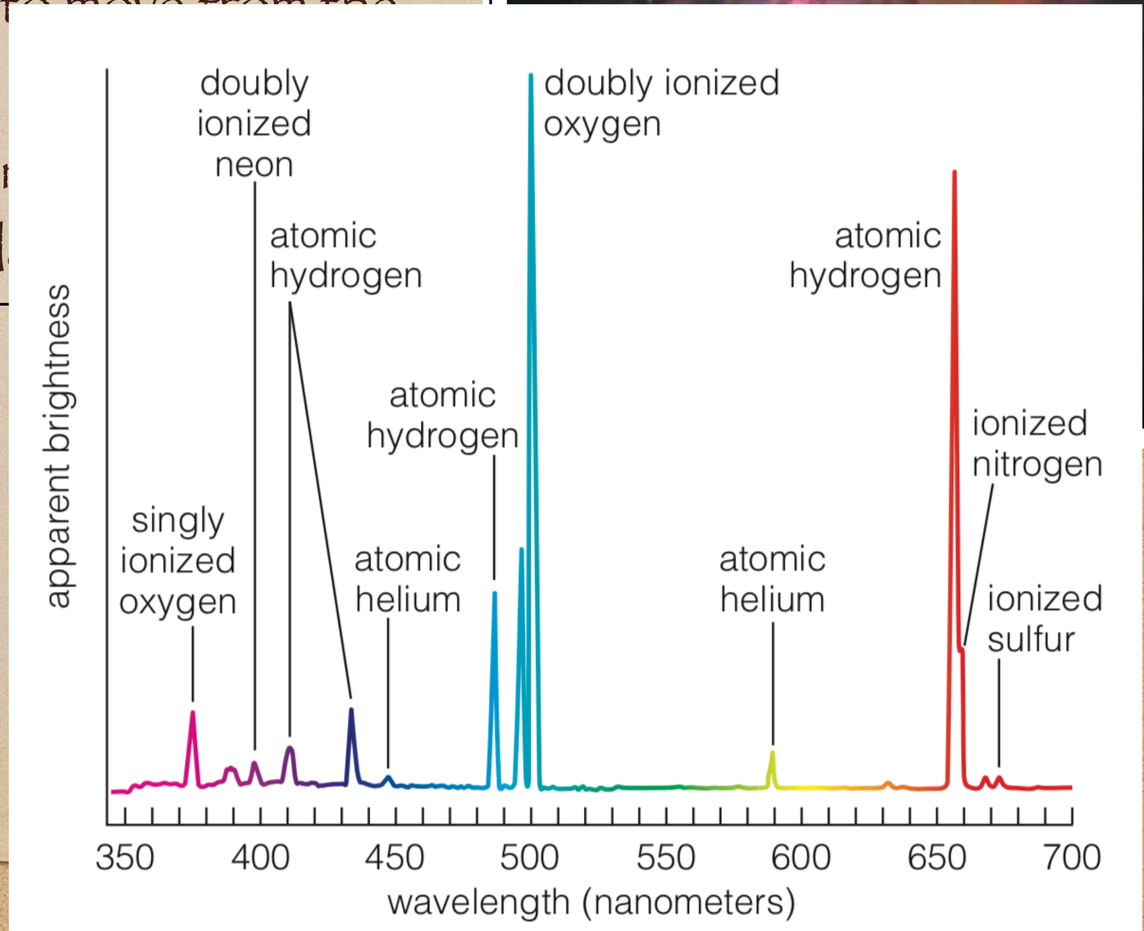
Distribution of star formation in our galaxy

How to identify regions of recent star formation?

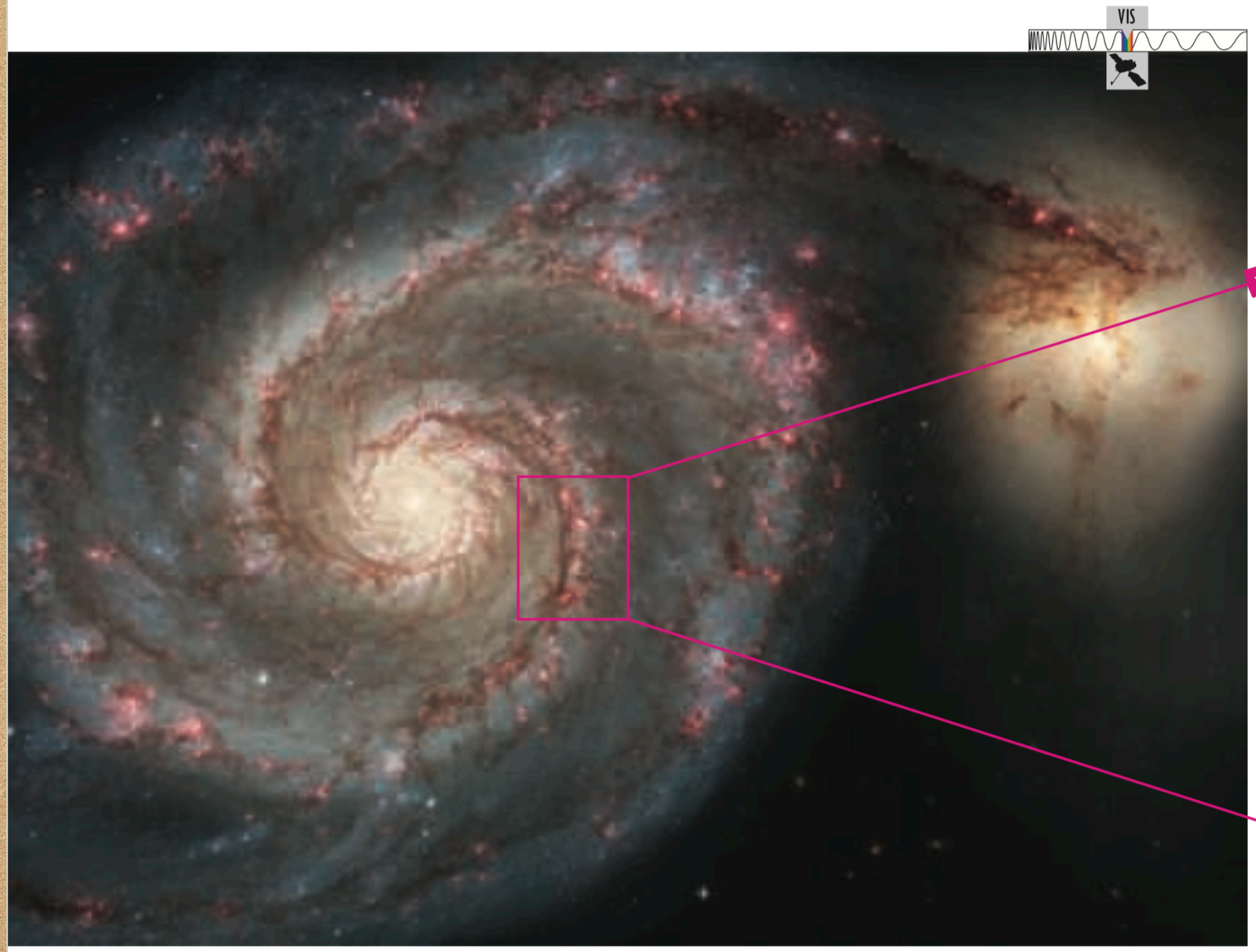
- Stars form in molecular clouds, which are dark (UV/optical light is absorbed by dust)
- Hot and blue stars are excellent indicators of places of stellar formation: stars O and B live for a short time, they do not have time to move from the formation area
- UV radiation from hot and young stars ionizes the surrou excited/ionized by emitting light when it is recombinant/d



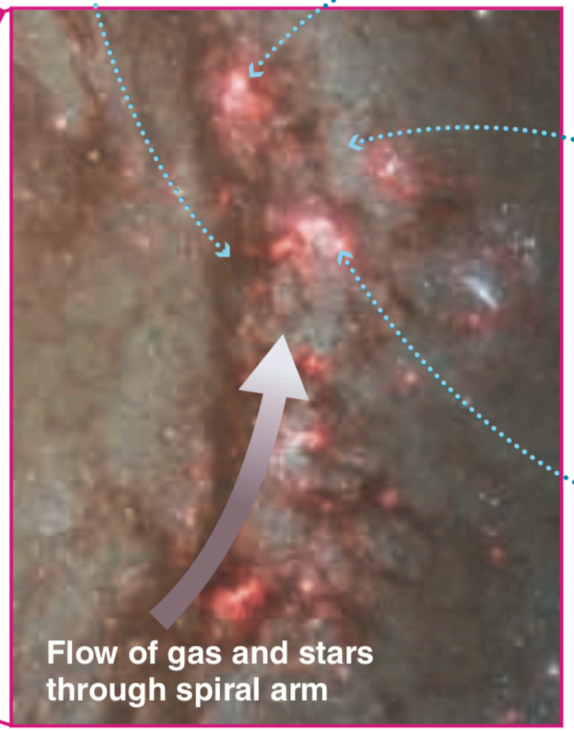




Stellar formation: mainly in the spiral arms



x4



Dark patches on inner edge of spiral arm show where gas clouds are packing together . . .

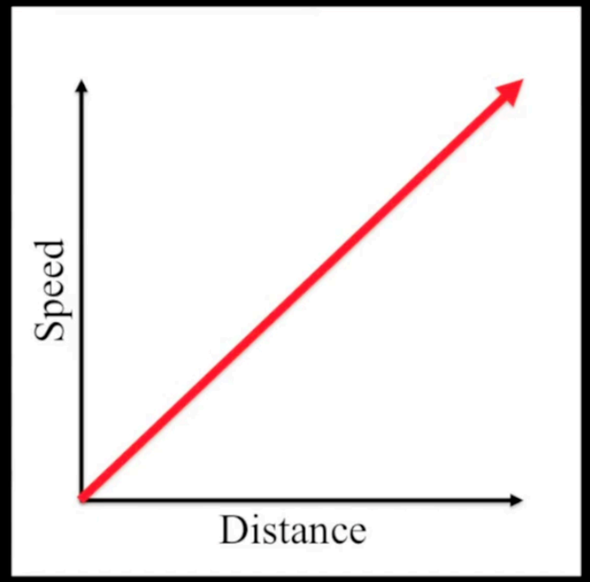
. . . and compression of these clouds triggers star formation in the arm.

Blue specks are young stars that formed in the spiral arm.

Red patches are ionization nebulae around the hottest, youngest stars.

Rotation Curve – solid disc





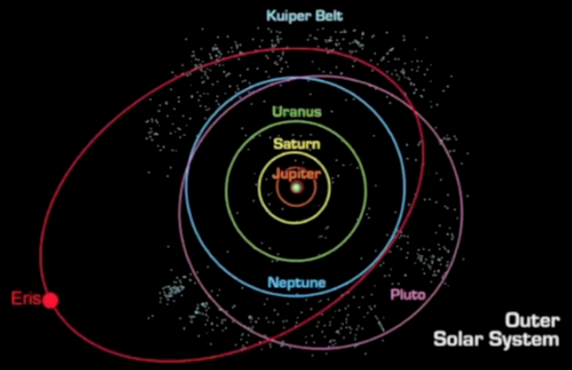
Rotation Curve – Orbits

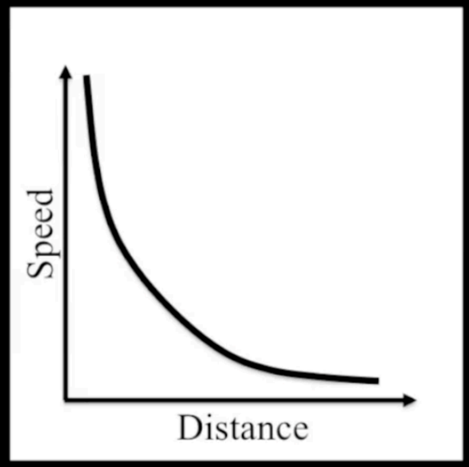
- Gravity holds objects in orbits.
- Speed of orbits depends on the amount of mass interior to the orbit.

More interior mass ➔ higher orbital speed

- If mass is mainly concentrated at the center of system, then speed will decrease with distance.
  - Example: our solar system

Solar System rotation curve

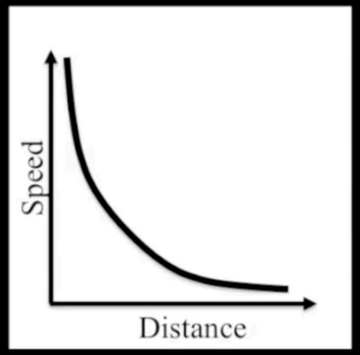




But what about the Galaxy?

- Assuming mass is where the luminous matter is, the Galaxy's rotation curve should be similar to the solar system's.

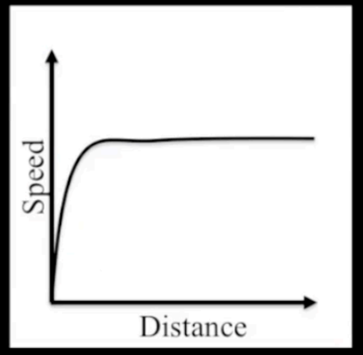




But what about the Galaxy?

- What is actually measured is quite different!
- Speeds are essential constant with increasing distance.





How is this rotation curve possible?

- To keep speeds constant at increasing distance, there needs to be mass distributed throughout the system, not just at the center.
- But the Galaxy is brightest at the center!

Maybe all the mass doesn't give off light!

DARK MATTER

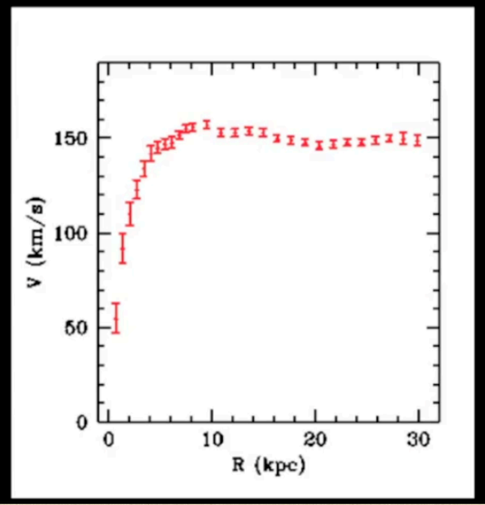
OK, but what ***is*** Dark Matter?

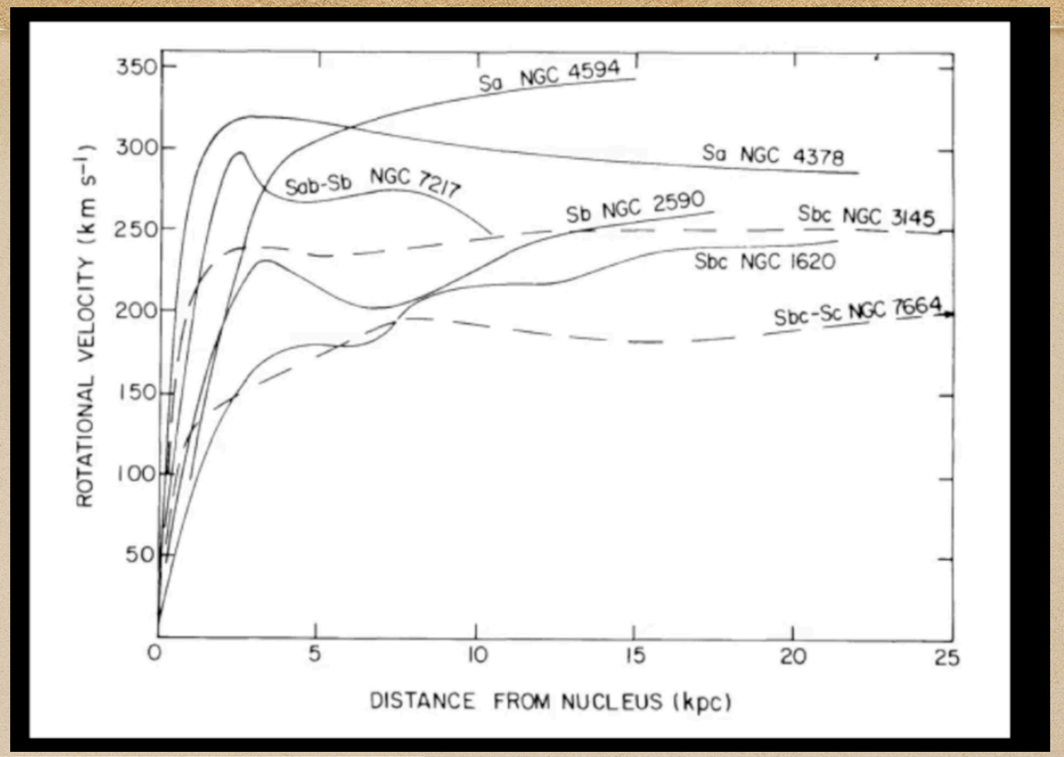
- Dark Matter is material that is non-luminous, has gravitational effects, but doesn't interact with electromagnetic forces.
- "Dark Matter" is just a place-holding term.
- We don't know yet what makes up the Dark Matter.

Other galaxies have similar rotation curves!

- For example, NGC 3198









Vera Rubin 70's

Other Evidence for Dark Matter?

- "Bullet Cluster"
- Result of two galaxy clusters colliding
- Pink/red is X-ray emission from gas/ plasma
- Mass distribution is shown in blue





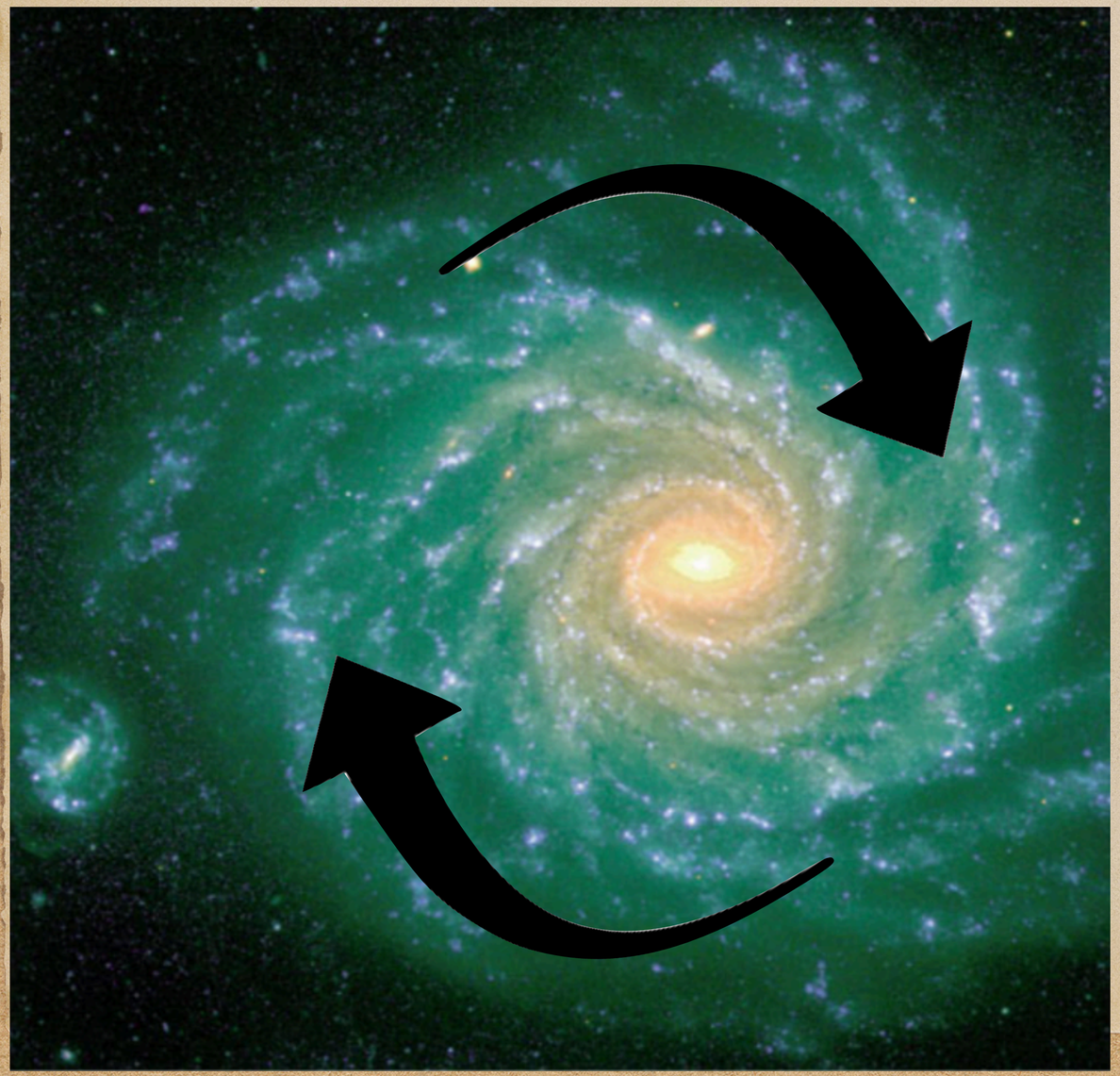
Galaxy Cluster PLCK G165.7+67.0
NIRCam/JWST



This side-by-side image shows galaxy cluster Abell S1063 as imaged with JWST (L) and Hubble (rotated, R). The longer wavelength coverage and greater exposure time with JWST reveals features that Hubble never could have hoped to see. (Credit: ESA/Webb, NASA & CSA, H. Atek, M. Zamani (ESA/Webb); Acknowledgement: R. Endsley (L); NASA, ESA, and J. Lotz (STScI) (R))

Gravitational lensing in clusters of galax

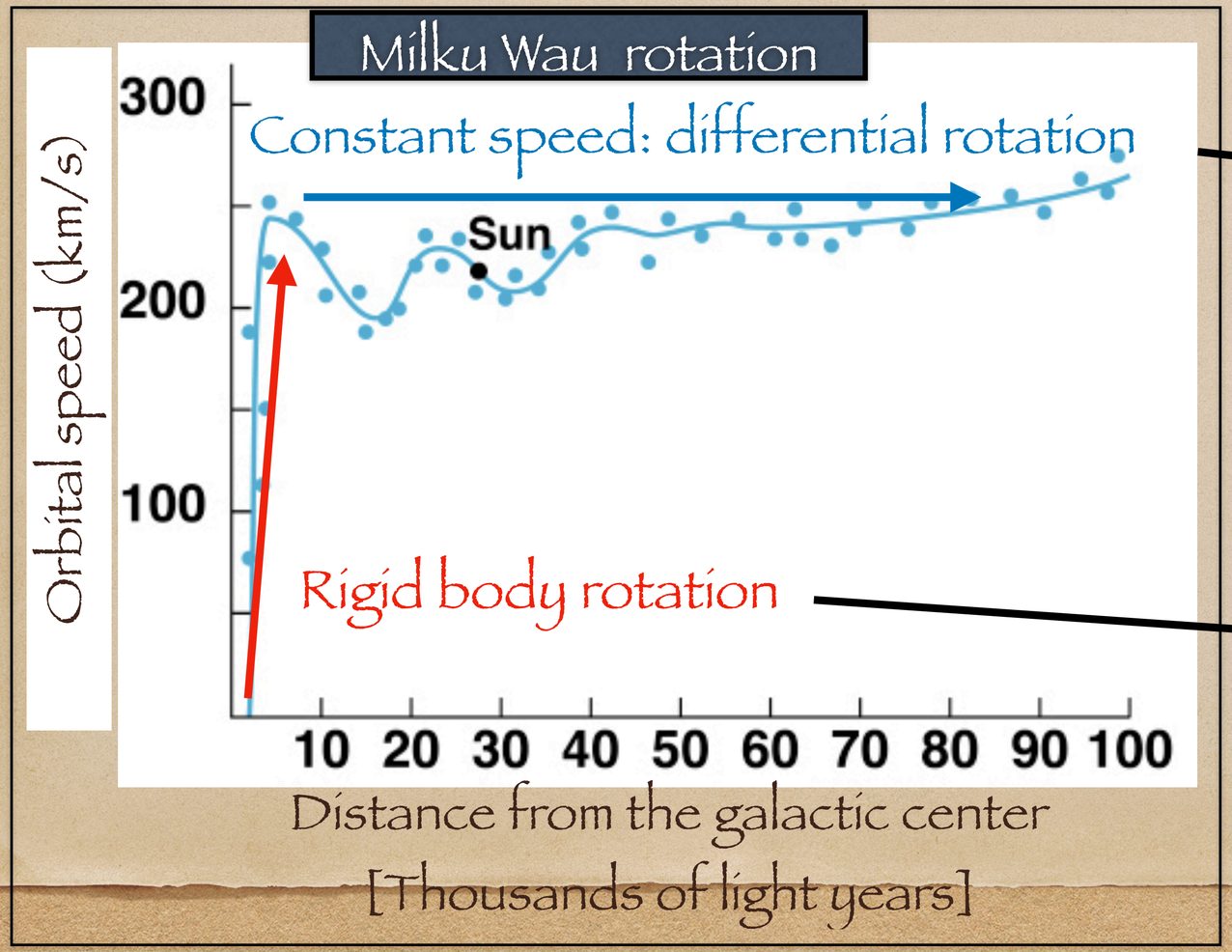
Galaxy kinematics



Do the spiral arms rotate together with the stars?

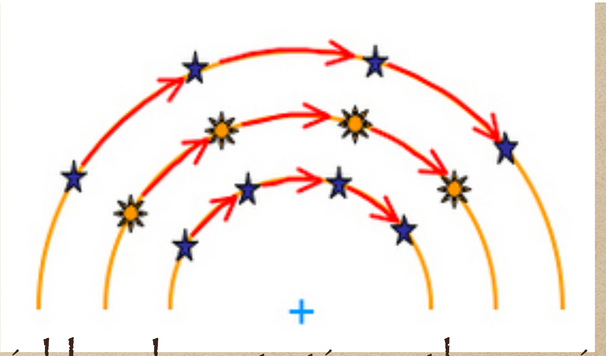
Do the spiral arms rotate together with the stars?

It might seem that the spiral arms rotate around the center of the galaxy along with the stars. Is that so?

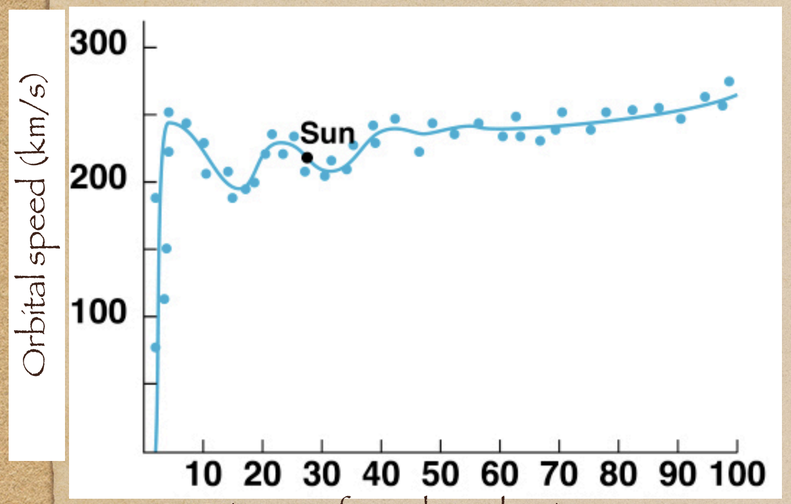


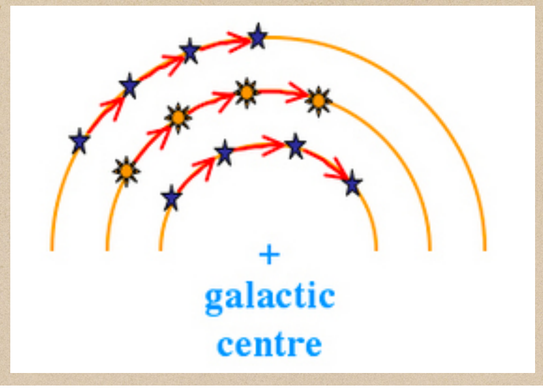
If the linear speed is constant, objects close to the center have a shorter orbital period; those far away "remain behind"



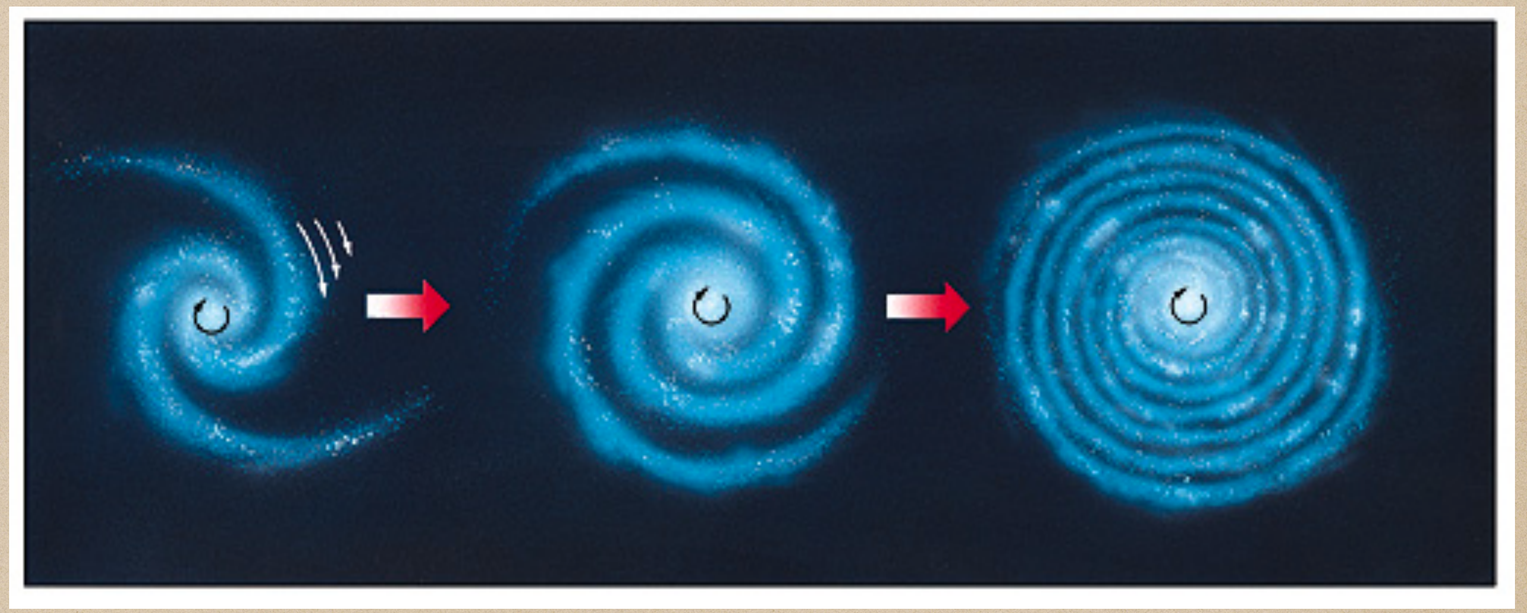


In a rigid body rotation, the points maintain the same position: the orbital speed increases with the distance





The outer part of the arms, further away from the center, would remain "backward" with respect to the inner part; the arms would "wround" very quickly around the center, and then dissolve.



We don't see galaxies with many concentric circles of arms, but we see that most galaxies have few arms

The arms do not rotate in differential rotation together with the stars

- Centripetal force required to keep it on a circle:

$$F_{\text{cent}} = \frac{mv^2}{r}$$

where m is the particle mass and v its orbital speed.

- Gravitational force exerted by mass M (Newtonian gravity, spherical symmetry or point mass):

$$F_{\text{grav}} = \frac{GMm}{r^2}$$

Set them equal for a stable circular orbit:

$$\frac{mv^2}{r} = \frac{GMm}{r^2}$$

Cancel m and multiply both sides by r:

$$v^2 = \frac{GM}{r}$$

Take the positive square root:

$$v = \sqrt{\frac{GM}{r}}$$

This is the standard Keplerian circular velocity.

First proof of the existence of dark matter

The Milky Way rotates...

Kepler 3rd law

$$\frac{4\pi^2}{T^2} = \frac{Gm}{a^3}$$

$$V_0 = \sqrt{\frac{G\,M(R_0)}{R_0}}$$

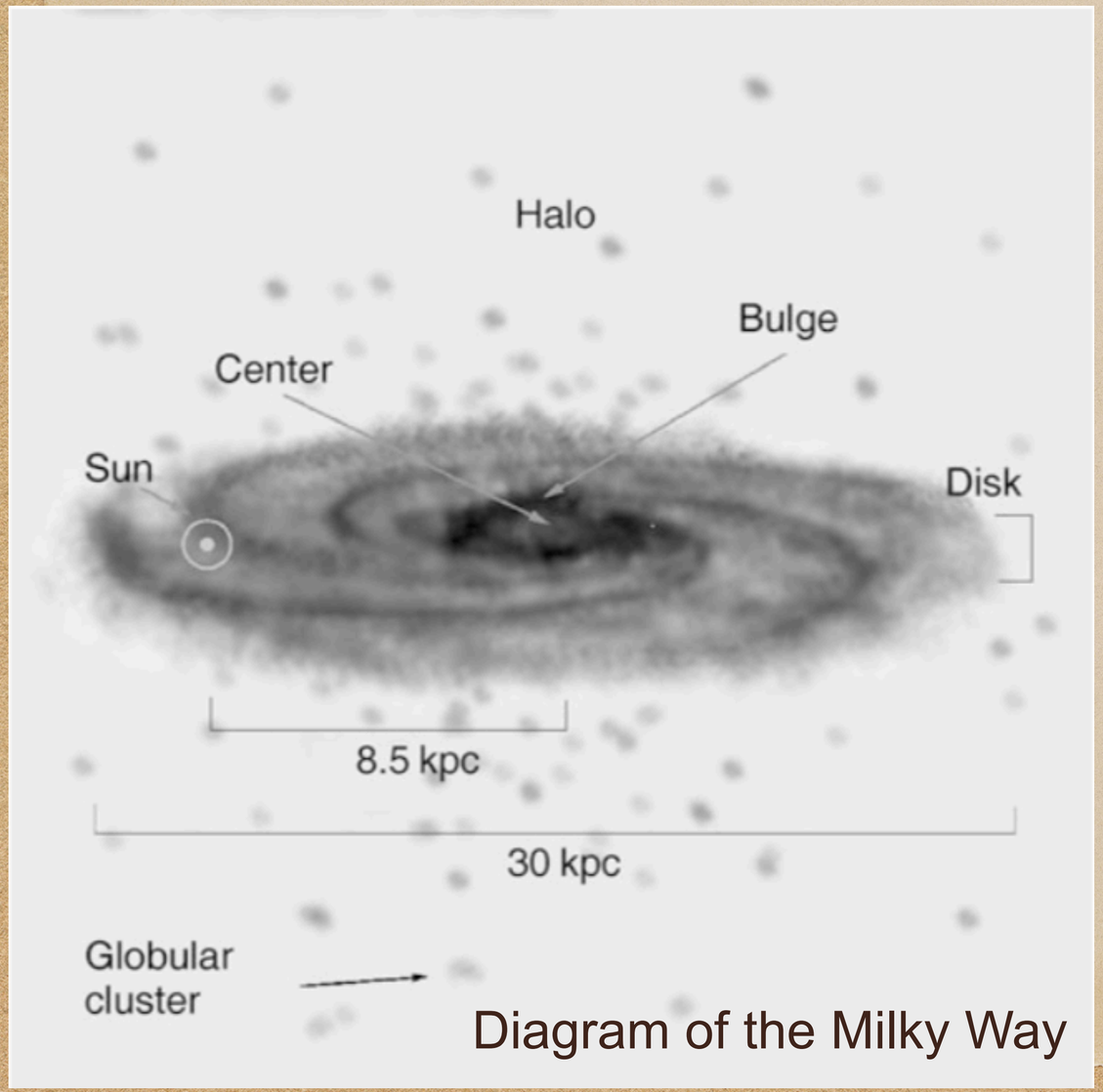
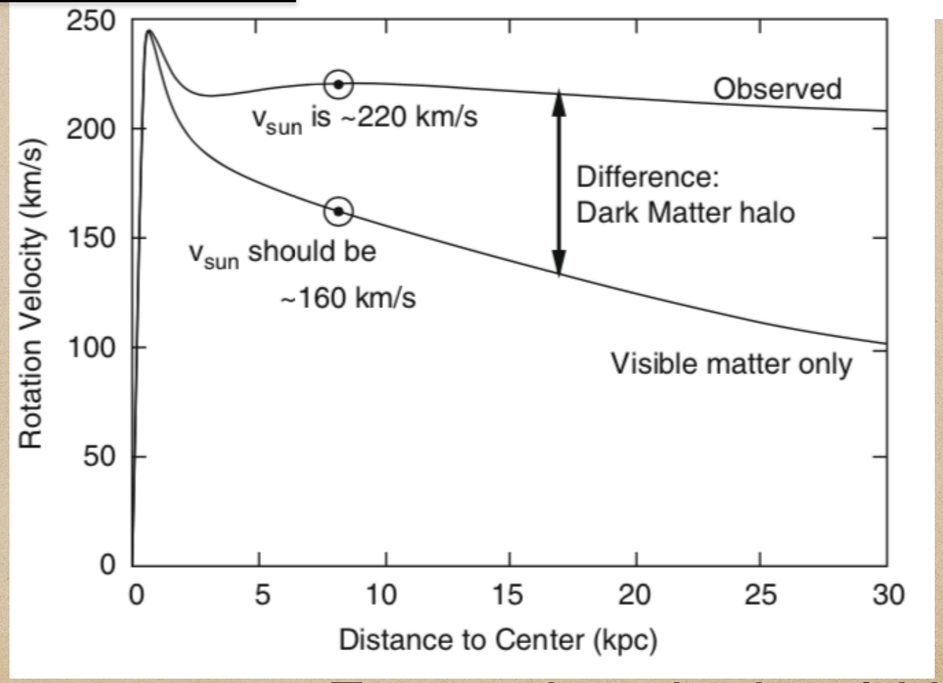


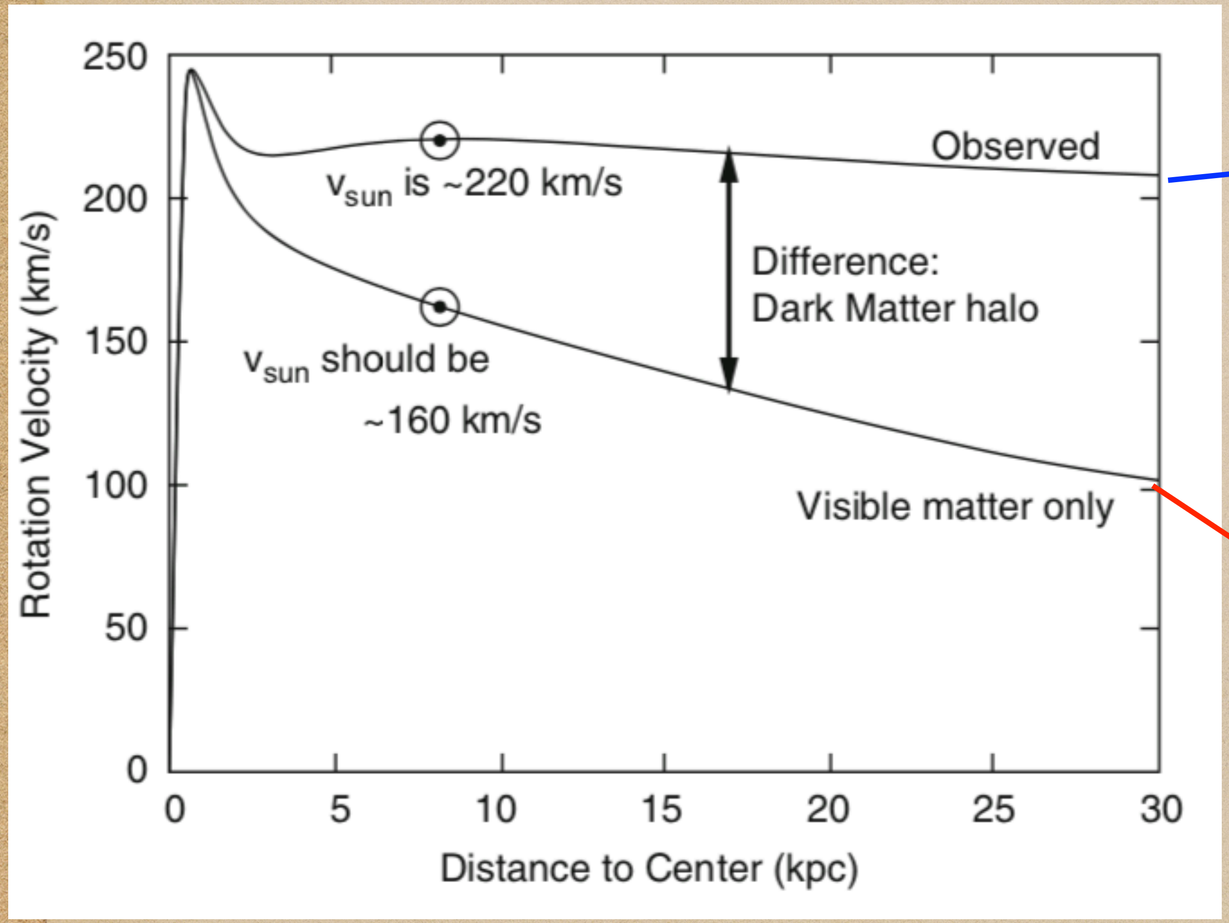
Diagram of the Milky Way



...Faster than it should be, based on visible light (matter)

- If $M(r)$ becomes roughly constant beyond some radius (i.e. no extra mass outside), $v(r)$ falls as $v \propto r^{-1/2}$ (Keplerian decline).
- If $M(r) \propto r$ (enclosed mass growing linearly with radius) then $v(r)$ is constant with radius — this explains observed **flat rotation curves** of spiral galaxies and motivates dark matter halos.

Dark matter



Observed

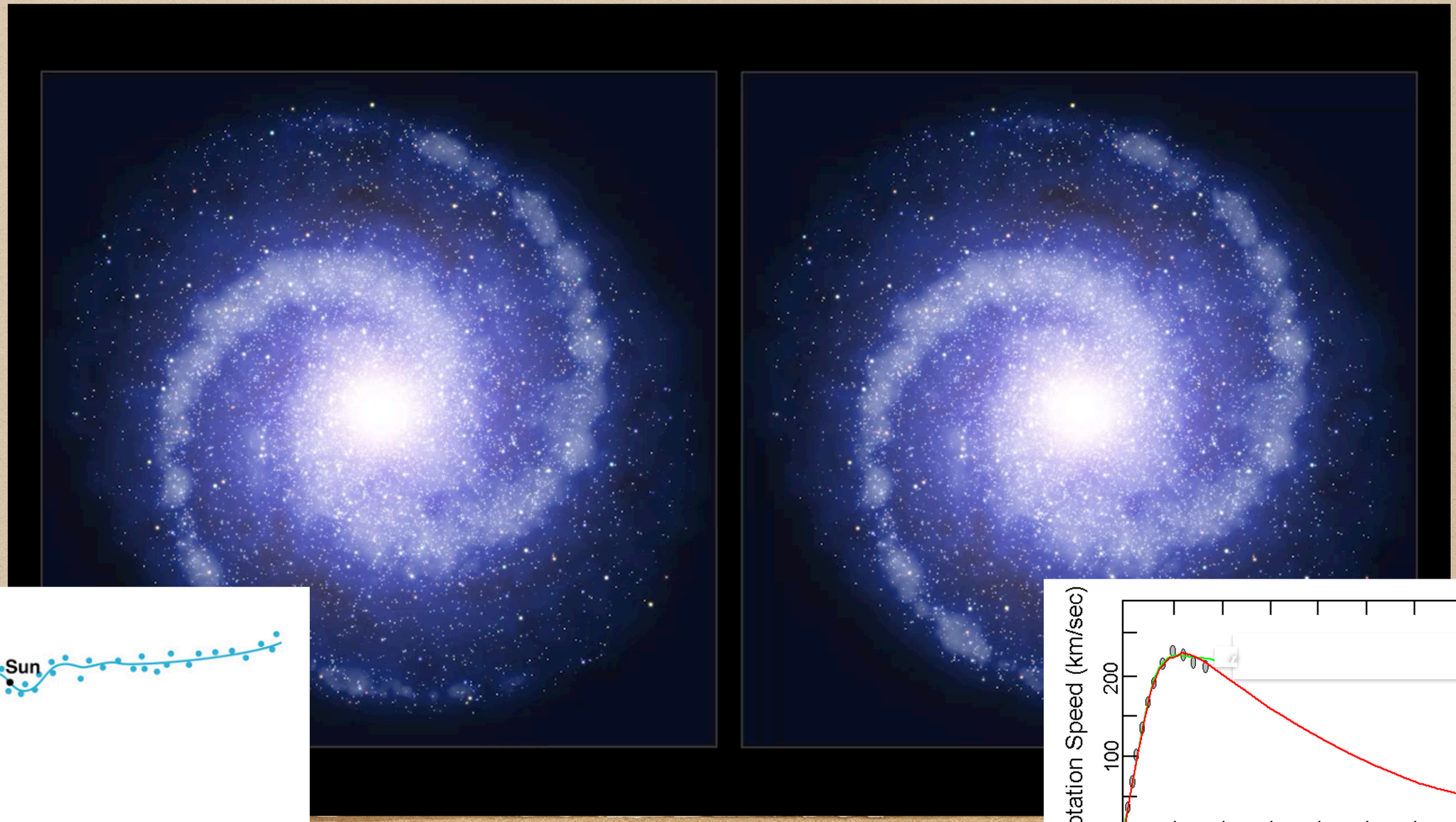
$$v^2(R) = GM(R)/R$$

Dark matter

$$v^2_{\mathrm{lum}}(R) = GM_{\mathrm{lum}}(R)/R$$

What would it be like if there was only visible matter

Dark matter



orbital speed (km/sec)
300
200
100
Sun

Rotation Speed (km/sec)
0
100
200
0
10
20
30
40
50
Keplerian
Prediction

History of the Milky way

The properties of the Milky Way give us information about its history

Evidences:

- The stars in the halo have disordered orbits
- The stars in the disk have orderly and circular orbits
- There are no young stars in the halo
- Halo stars have few heavy elements (metals)

Population I stars

- Disk population
- Young and old stars
- All with a metal content of 2% (like the Sun)

Population II stars

- Spheroidal population
- Bulge and halo stars
- Old stars (therefore not very massive)
- All with few metals (up to 0.02%, 100 times less than the Sun)

Possible theory



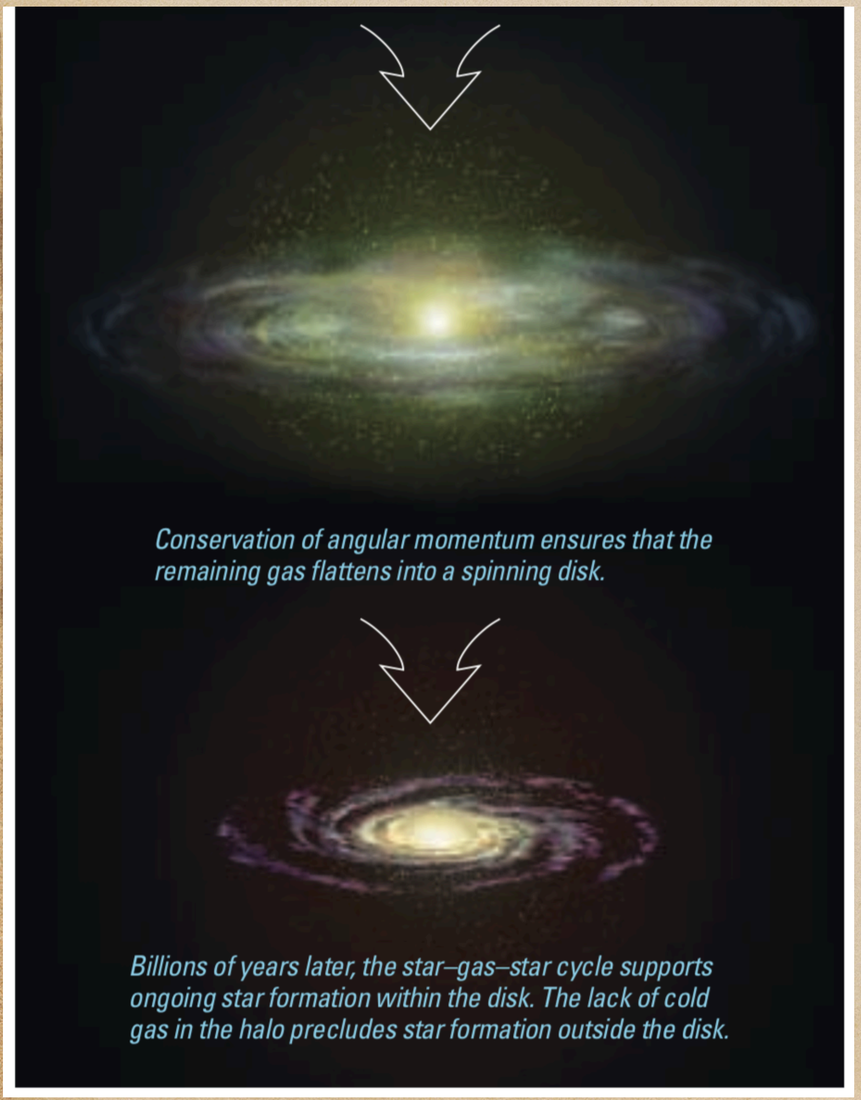
The theory must explain the observations, in particular that:

- Halo stars are old
- They have very few metals
- The orbits are oriented in a disorderly way

1. The protogalactic cloud from which halo stars are formed has a primordial composition (no metals, old stars)

2. Stars are formed until the gas has spherical distribution without rotation (random orientation of the orbit)

Possible theory



The theory must explain the observations, in particular that:

- Disk stars are young
- They are rich in metals
- The orbits are oriented in an orderly manner

3. The residual gas of the protogalactic cloud collapses, for the preservation of the angular momentum a disk is formed (young stars in disk)

4. In the disk, the gas-star-gas cycle helps to keep the formation of new stars active and regulated, which will be enriched with metals from previous generations

Possible theory



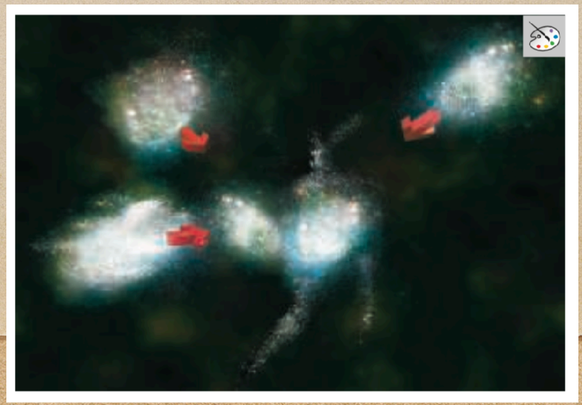
This simple theory explains most of the observations, but it's a little too simplistic

If it were true, halo stars that orbit far from the galactic center should be older and poorer in metals than those that orbit closer, but that's not what you see

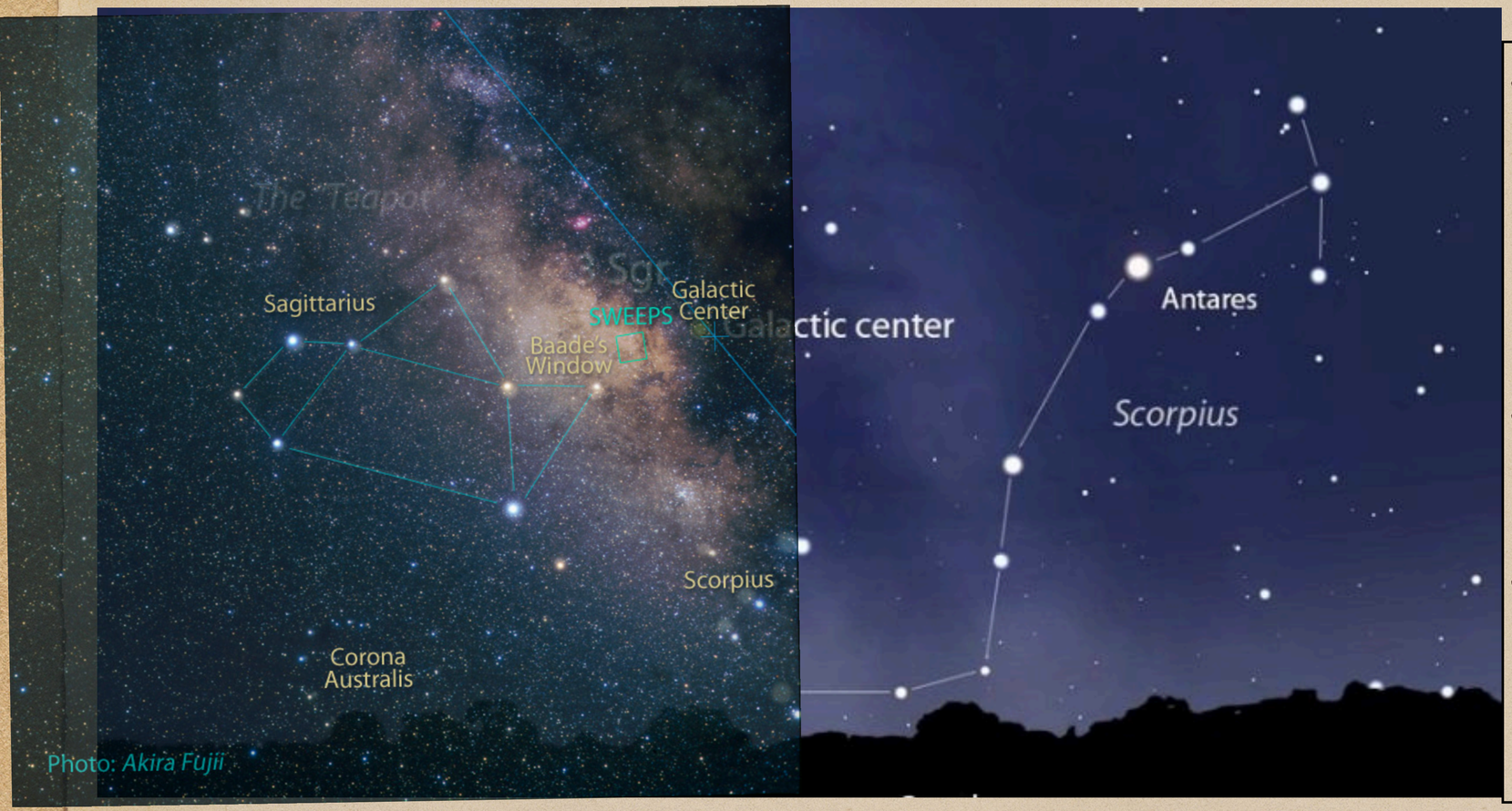
There are differences in metal content, but not depending on the distance



It is more plausible that the halo was formed by collision of various protogalactic clouds



The galactic center



- The galactic center is located in the constellation of Sagittarius, near that of Scorpio
- It is visible in summer, low on the horizon, not easy to see
- Apparently it is a very ordinary region, rich in dust and therefore dark

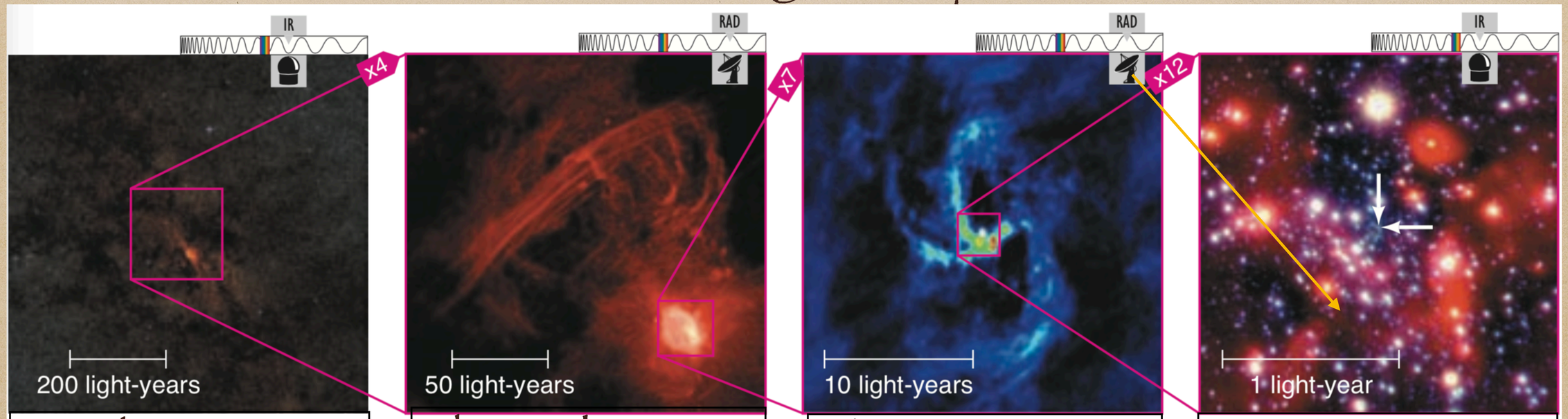
However, what would we see if we could lift the curtain of dust?

Try to think: how can I observe through the dust?

The Galactic center

Just move to infrared or radio wavelengths, which are less absorbed by dust

Sgr A*: Super-massive black hole



The near-infrared image

This radio image shows streams

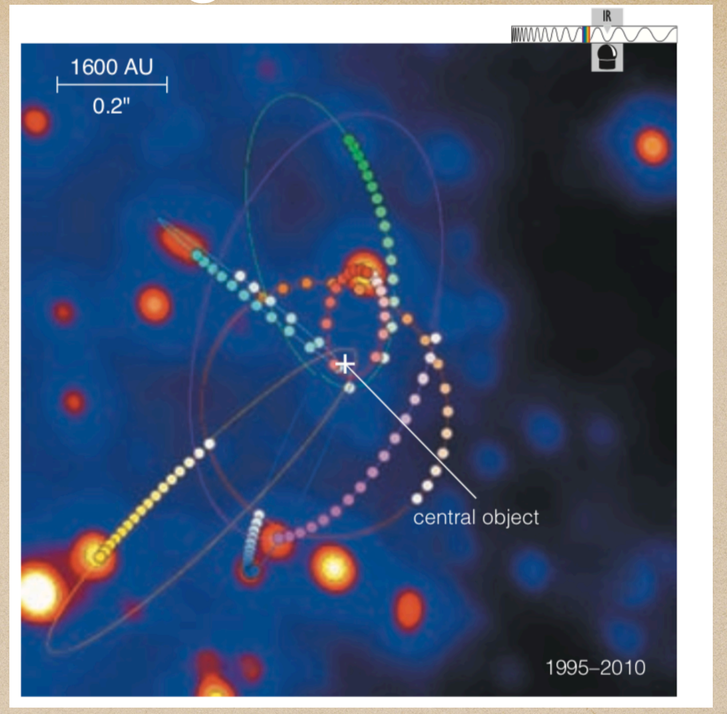
This radio image shows the gas flowing towards

This near infrared image

The galactic center



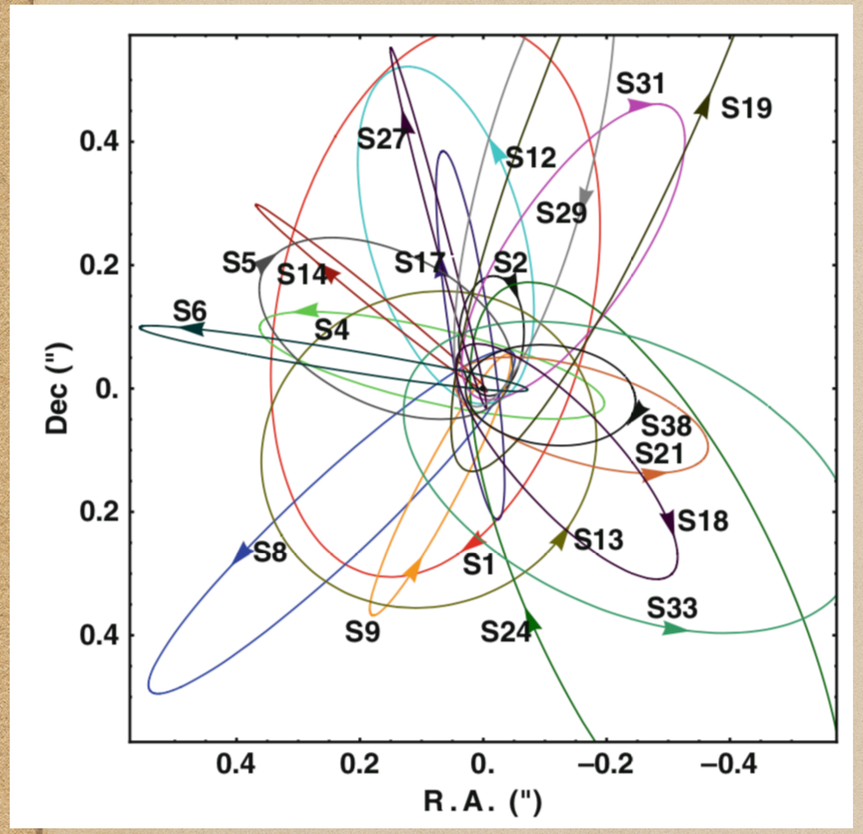
This X ray image shows the 60 light years around the galactic center: the presence of hot gas is highlighted, accelerated until it falls towards the black hole. The central emission is intermittent: when a bubble of material approaches the black hole, there is an "explosion" of light



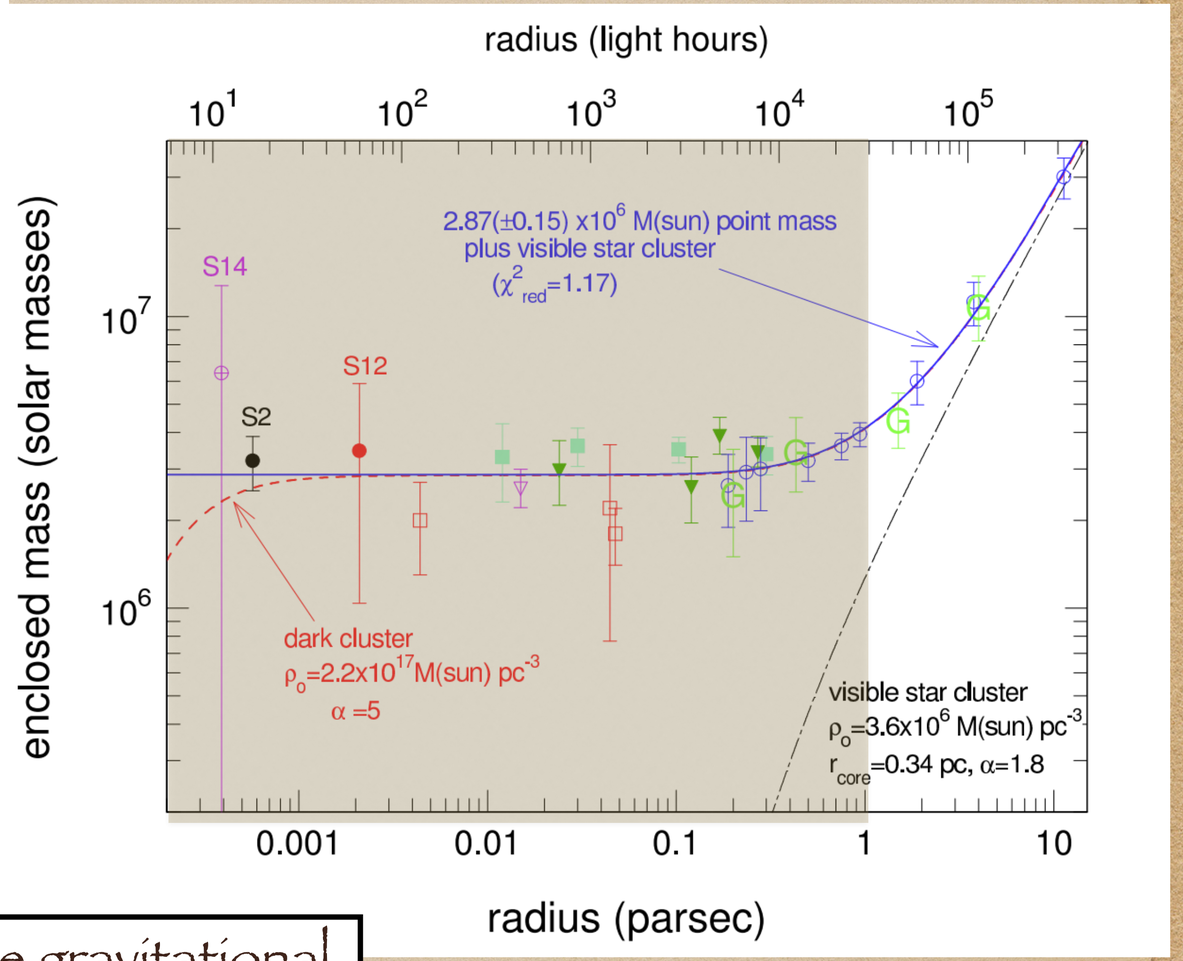
Proof of the existence of a black hole in the center of our galaxy (at Sgr A*): each set of colored dots shows the positions of a star, separated by a year, in an interval of 15 years. Applying Newton's version of Kepler's third law, we get that the central object has a mass 4 million times that of our sun, concentrated in a region so small that it must necessarily be a black hole

The galactic center

$$\frac{4\pi^2}{T^2} = \frac{Gm}{a^3}$$



~25 stars orbiting in the central arcsecond around the galactic center.



Only in this region the gravitational field of the black hole dominates (it is measurable)