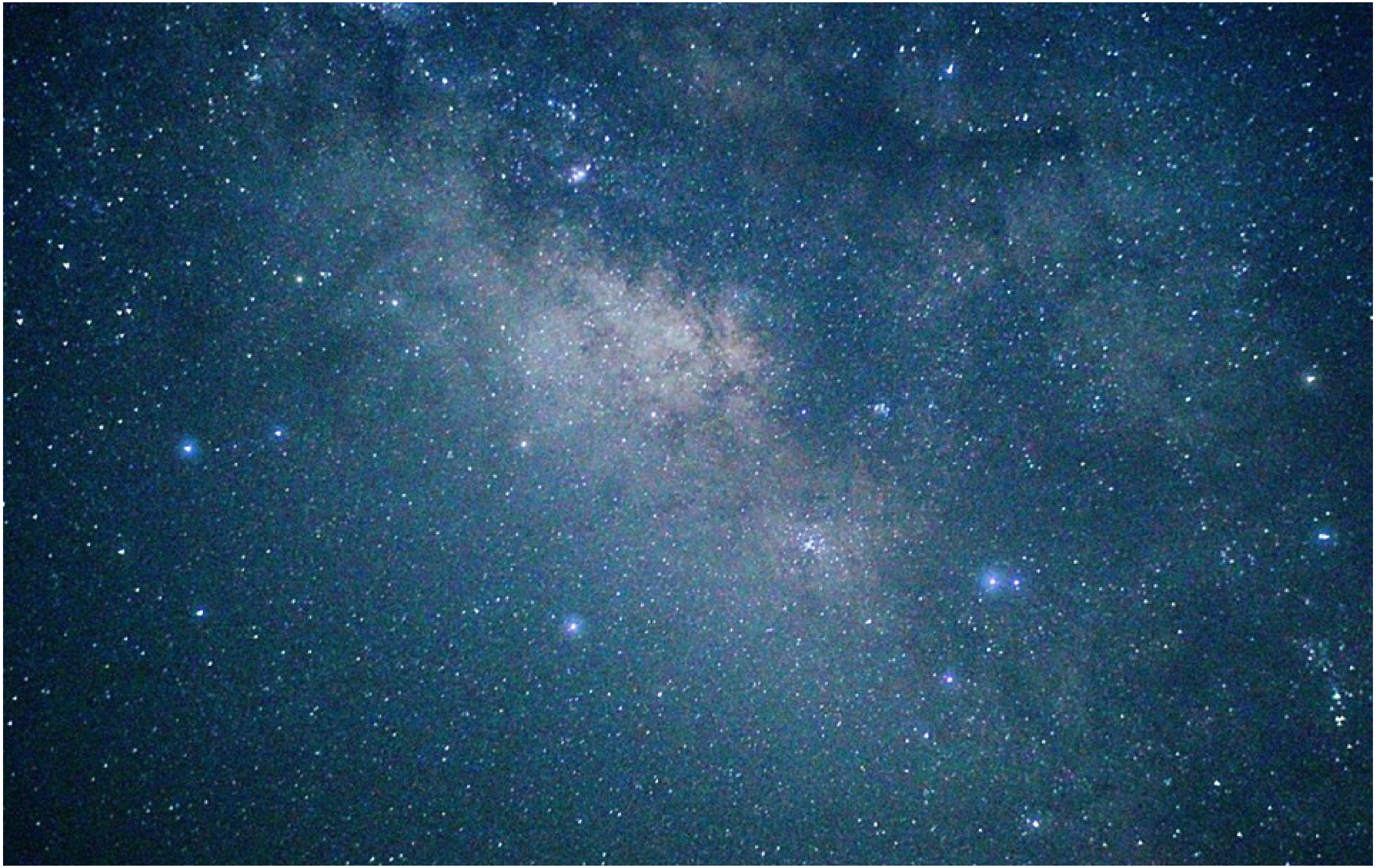
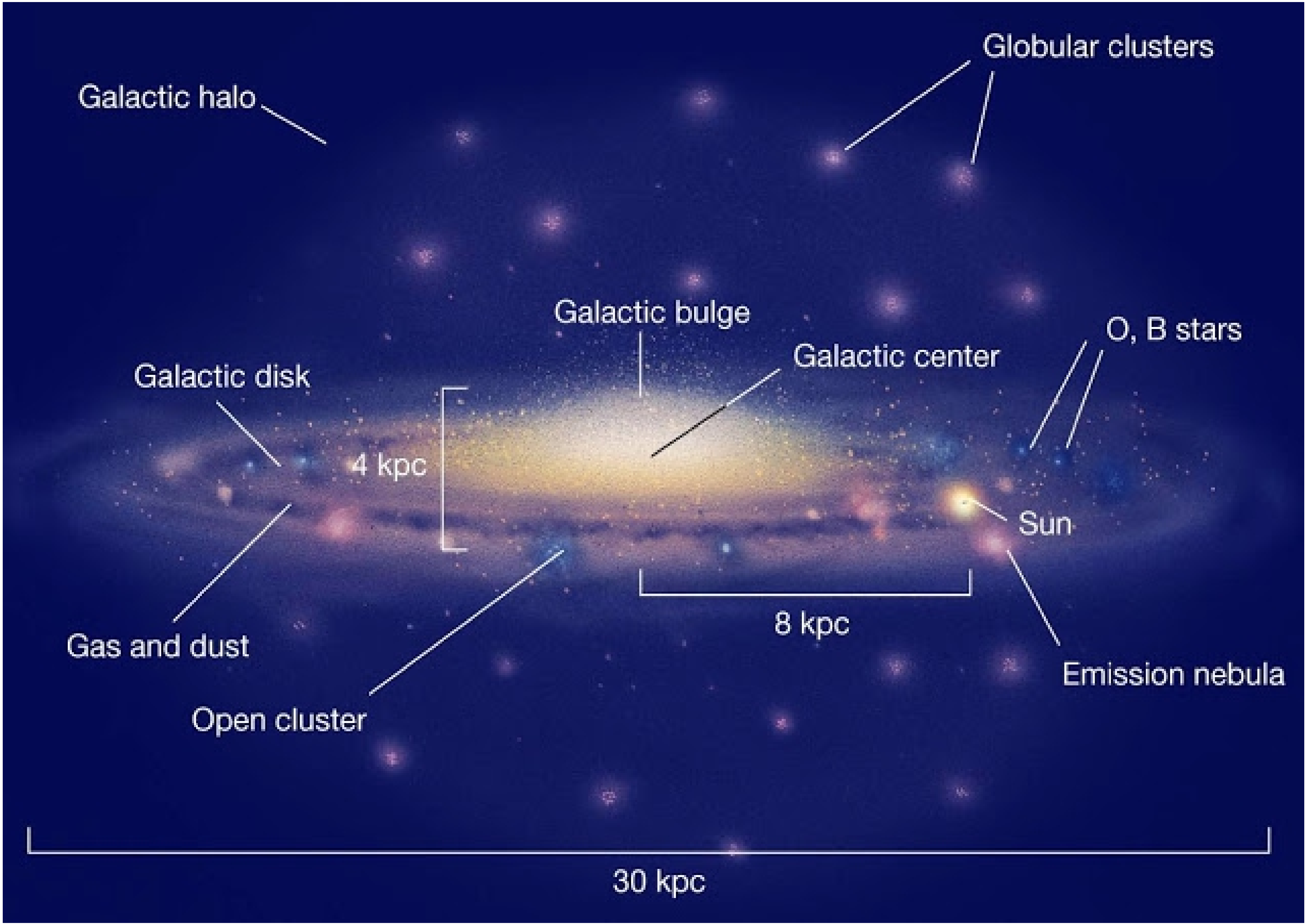
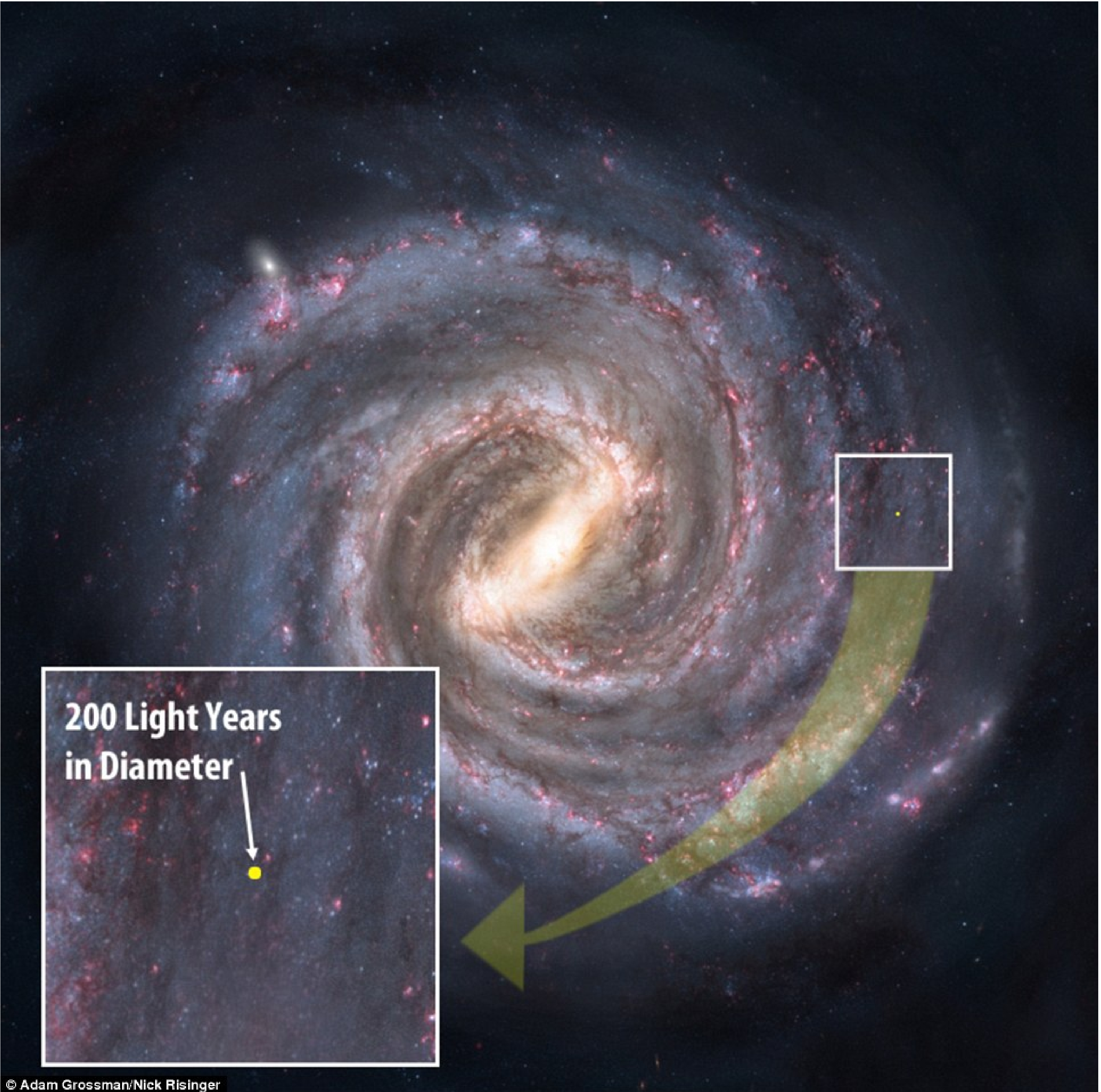
LECTURE 1: Introduction to Galaxies



The Milky Way on a clear night

VISIBLE COMPONENTS OF THE MILKY WAY

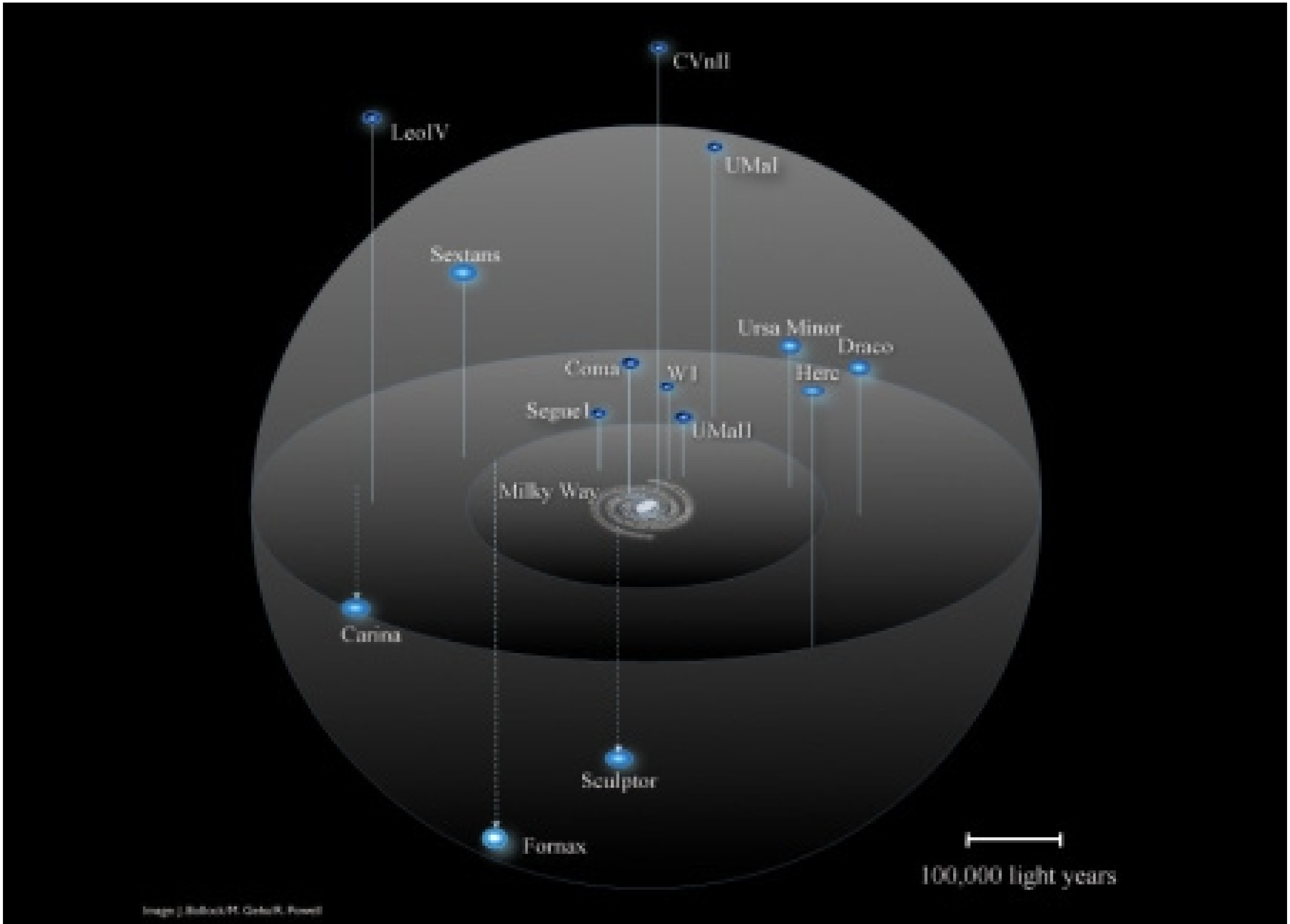




Our Sun is located 28,000 light years (8.58 kiloparsecs from the center of our Galaxy) in the Orion spiral arm.

One orbital period of the solar system is around 250 million years.

On large scales: Dwarf "satellite" galaxies embedded in a dark matter halo that is 10 times more massive than that of the visible component.



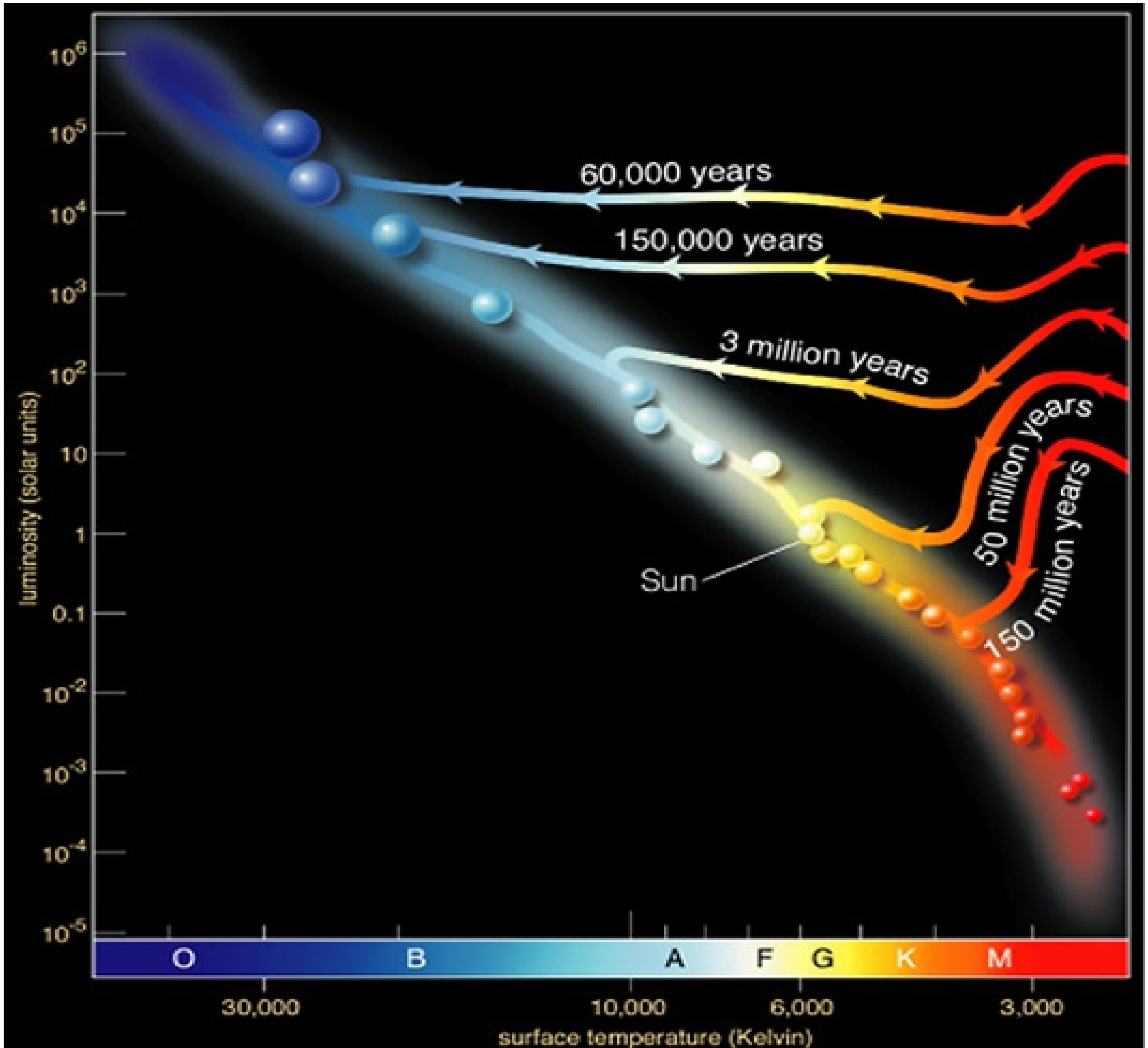
To first approximation, a star can be regarded as a **BLACK BODY**. A black body is an object that absorbs all the radiation it receives. It then heats up and emits its own radiation, with a spectrum that depends only on temperature.

From the Stefan-Boltzmann Law:

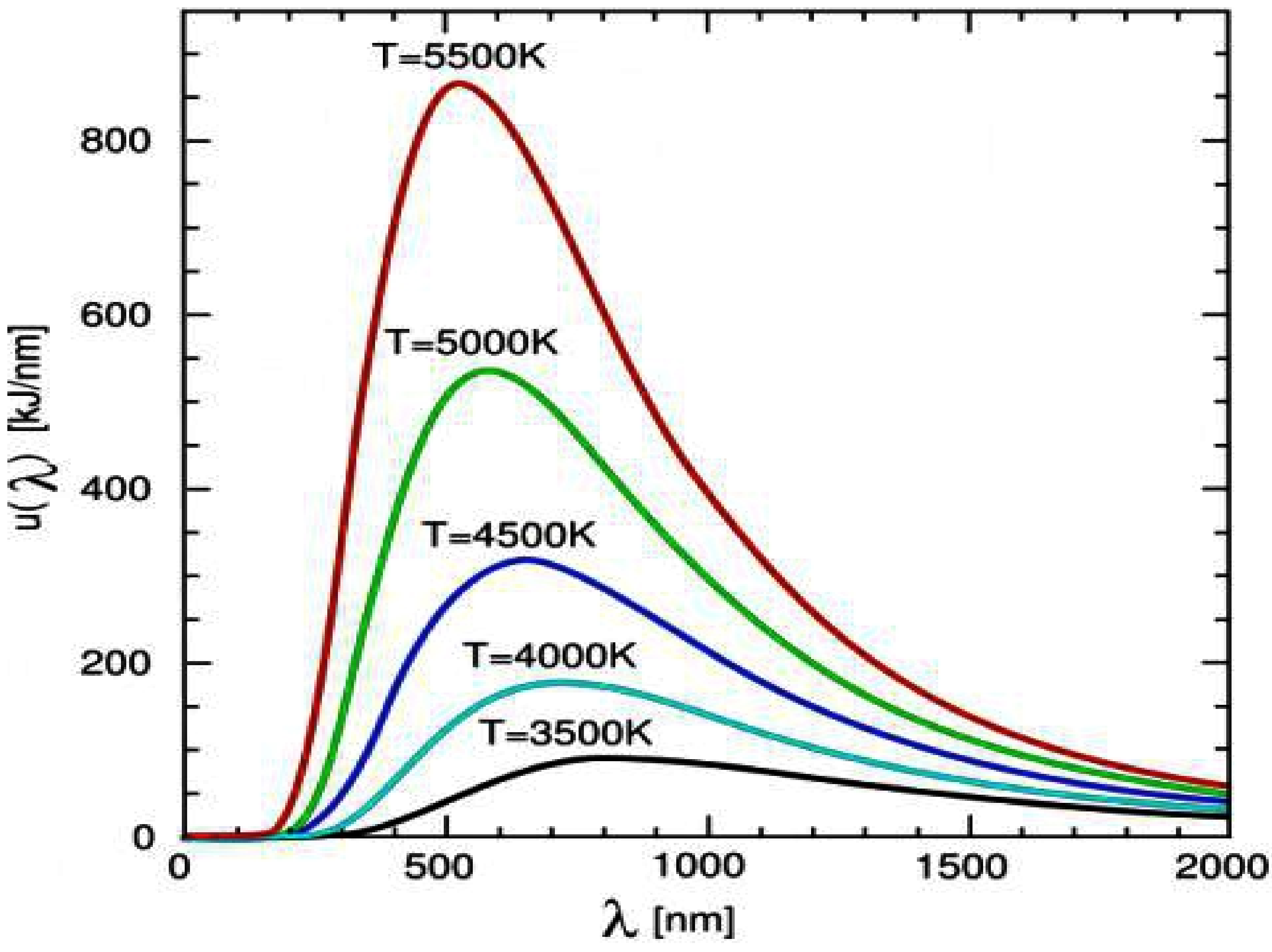
$E = \sigma T^4$

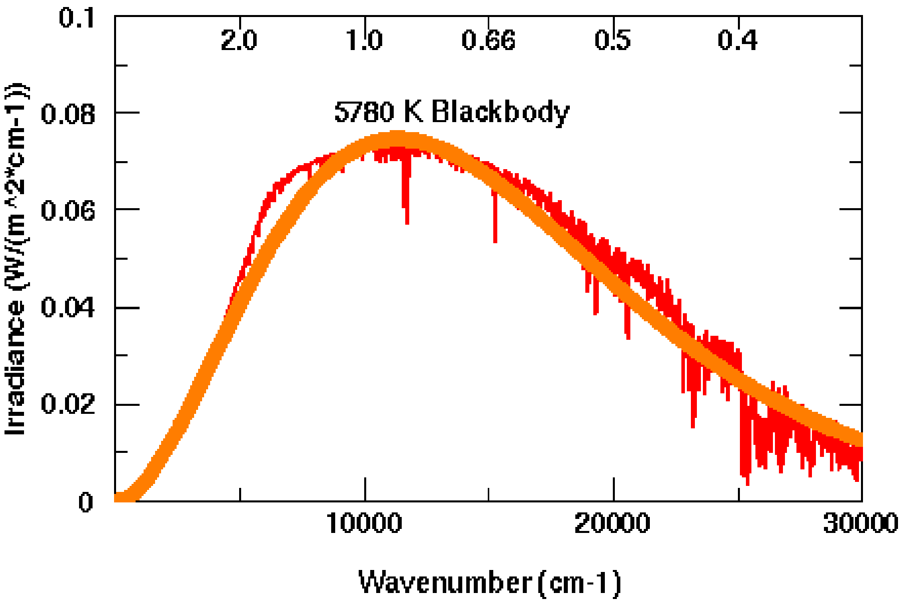
Total luminosity : $L = 4 \pi R^2 \sigma T^4$

Gravitational collapse of a gas cloud until this is halted by energy released by nuclear burning. Star joins the Main Sequence, at a given position in the luminosity/temperate plane (Hetzsprung-Russell diagram)

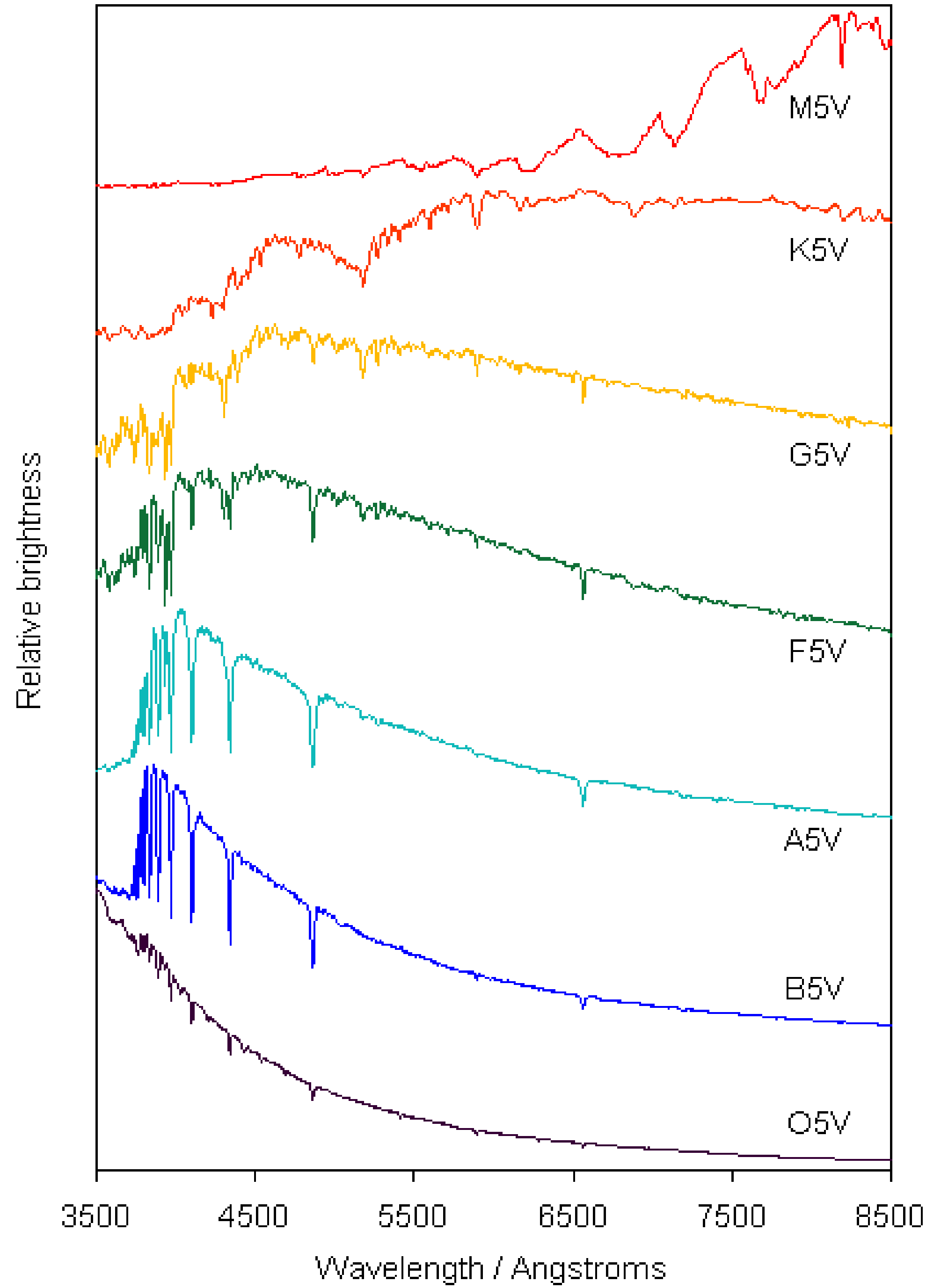


Wien's Law gives peak of blackbody radiation spectrum as Λ_{peak} T = 2.898 x 10 $^{-3}$ mK

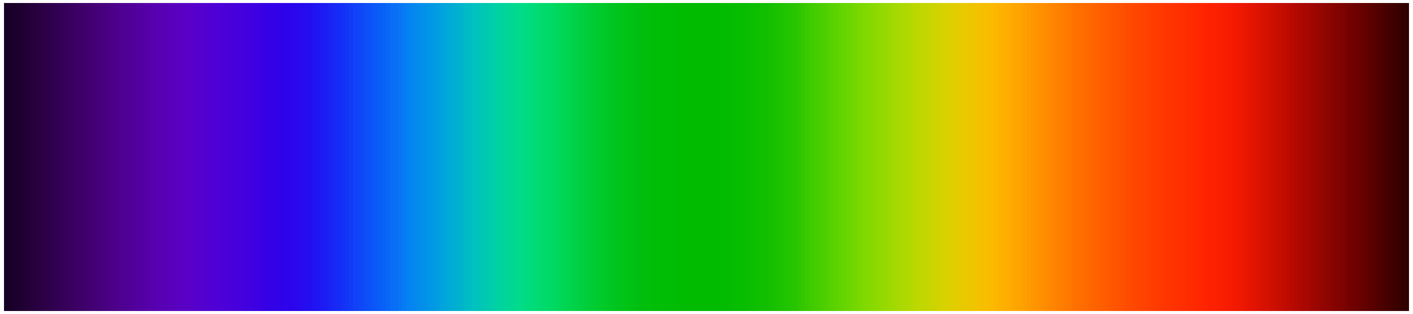




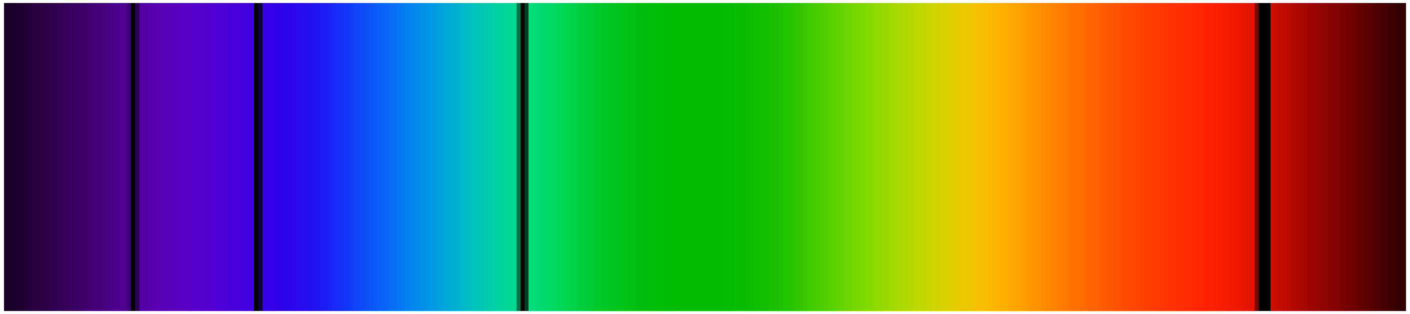
In practice, stars are not perfect black bodies!

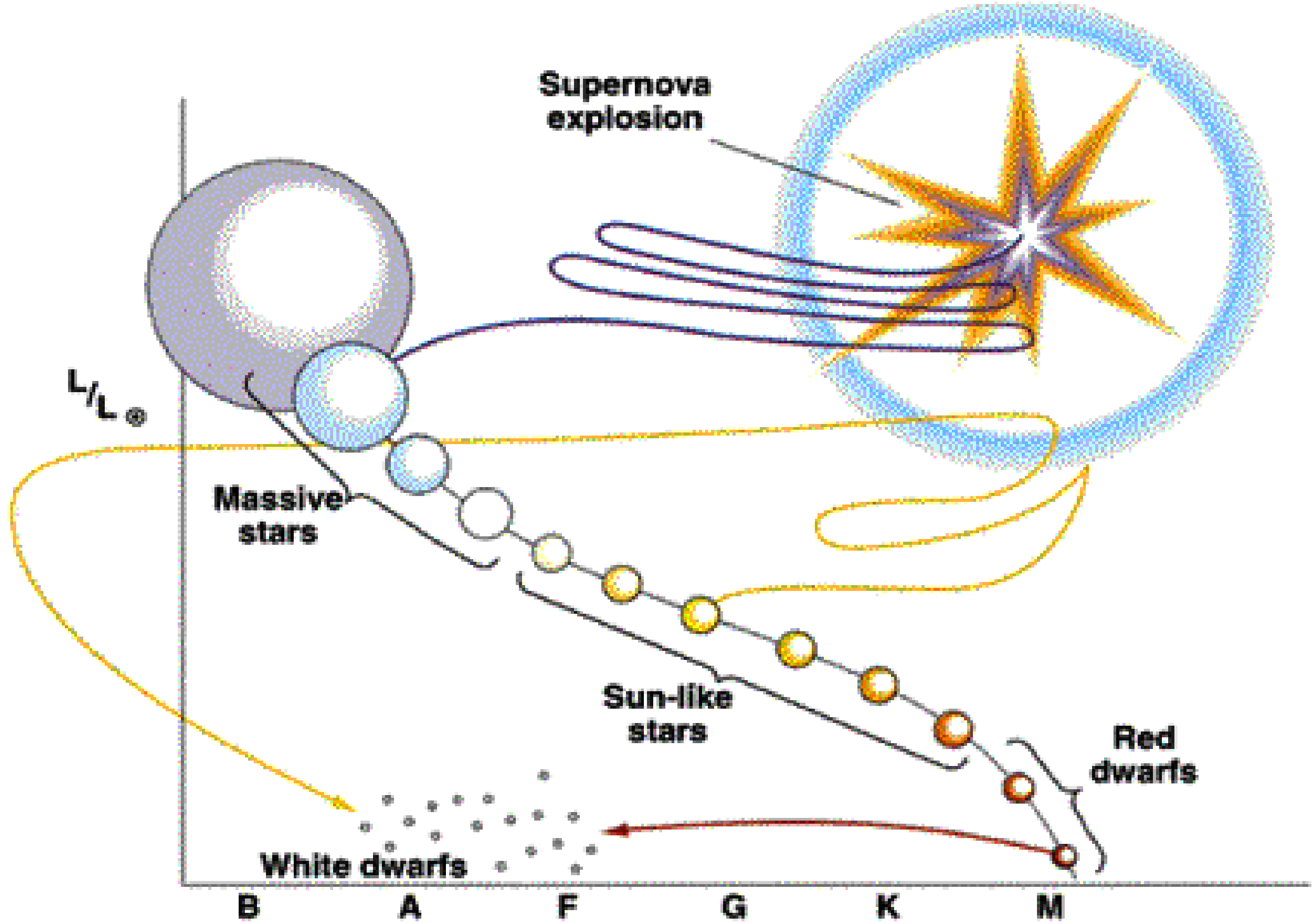


CONTINUOUS SPECTRUM



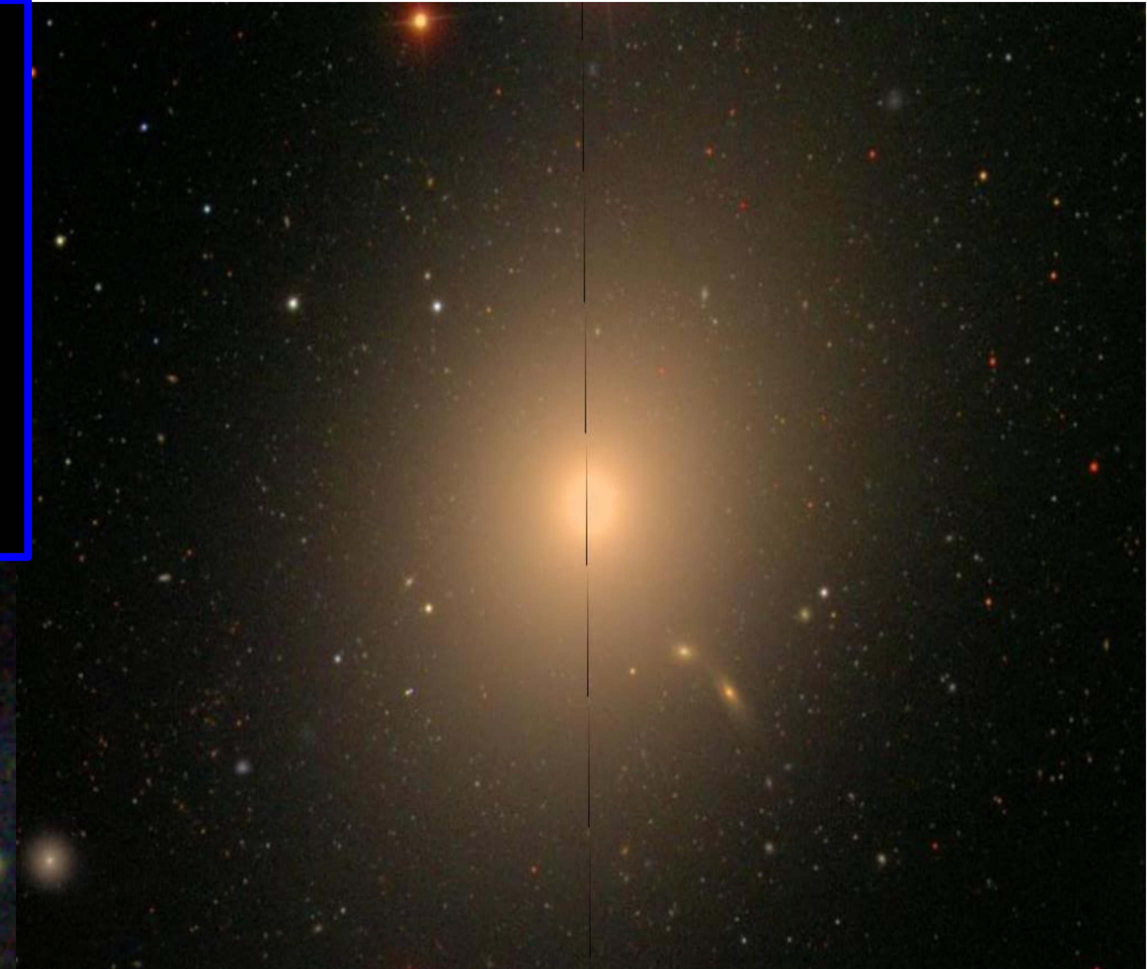
Absorption lines produced when a cold gas is present between a broad spectrum photon source and the detector. In this case a **decrease** in the intensity of light in the frequency of the incident photon is seen as the photons are absorbed, then re-emitted in random directions.





Luminous, blue stars end their lives quickly in Supernova explosions. Less luminous, red stars live longer. They finally go through a cool, red giant phase, before becoming white dwarfs.

Young, star-forming galaxy

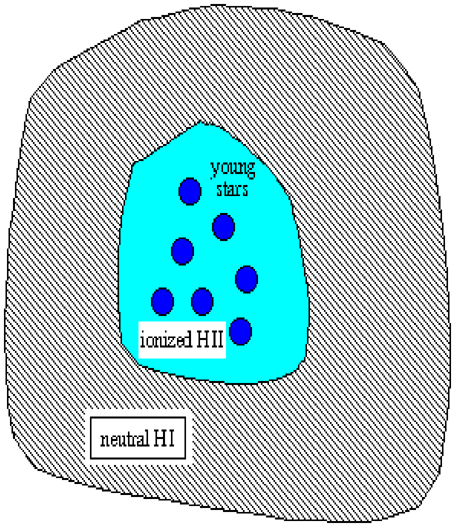


Old, red galaxy

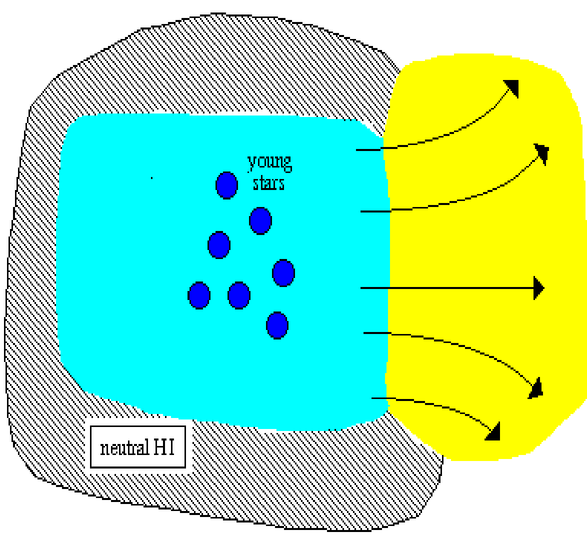
The Hubble Classification Scheme for Galaxies

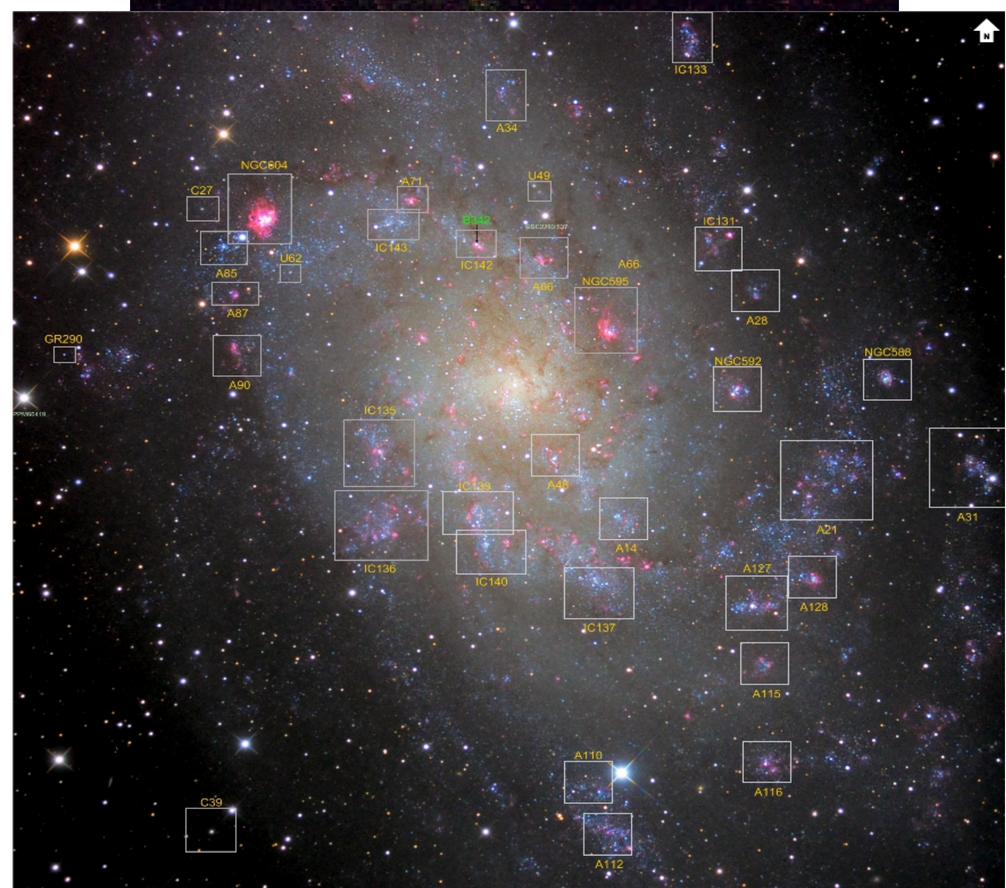
HII region

Young stars will heat and ionize a region inside the molecular cloud where they are born.



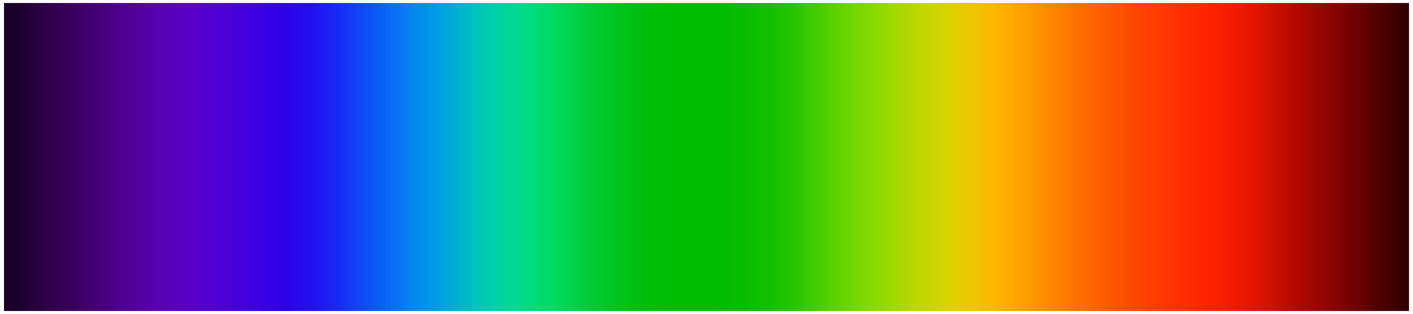
As the heated region grows, it will eventual breakthrough the clouds exterior to become a visible HII region.





Hydrogen ions (which is the main constituent of galaxies) have no electrons, so they can not absorb radiation

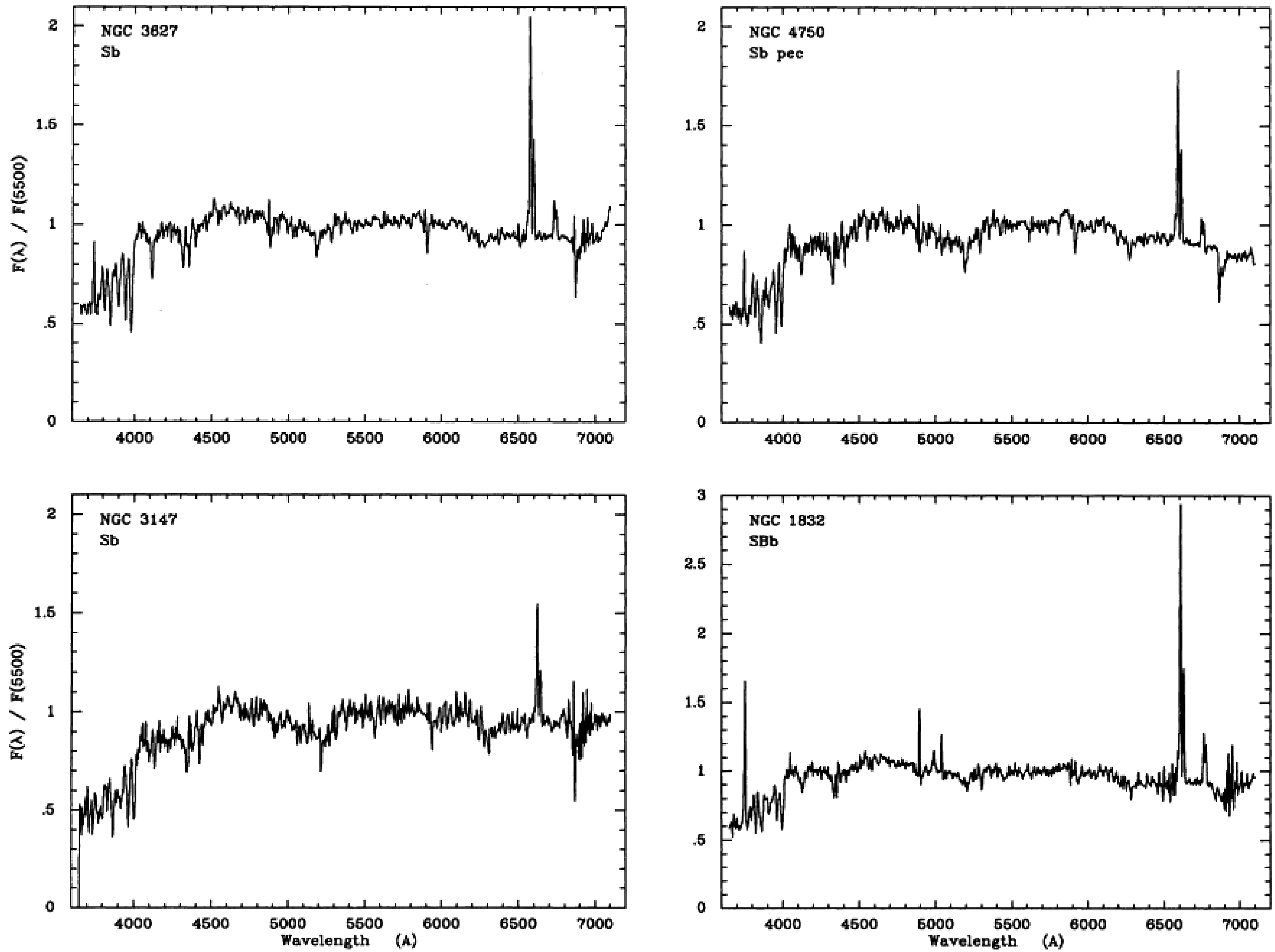
CONTINUOUS SPECTRUM



If the detector sees photons emitted directly from a (hot) glowing gas, then the detector often sees photons emitted in a narrow frequency range by quantum emission processes in atoms in the gas, and this results in an emission line.

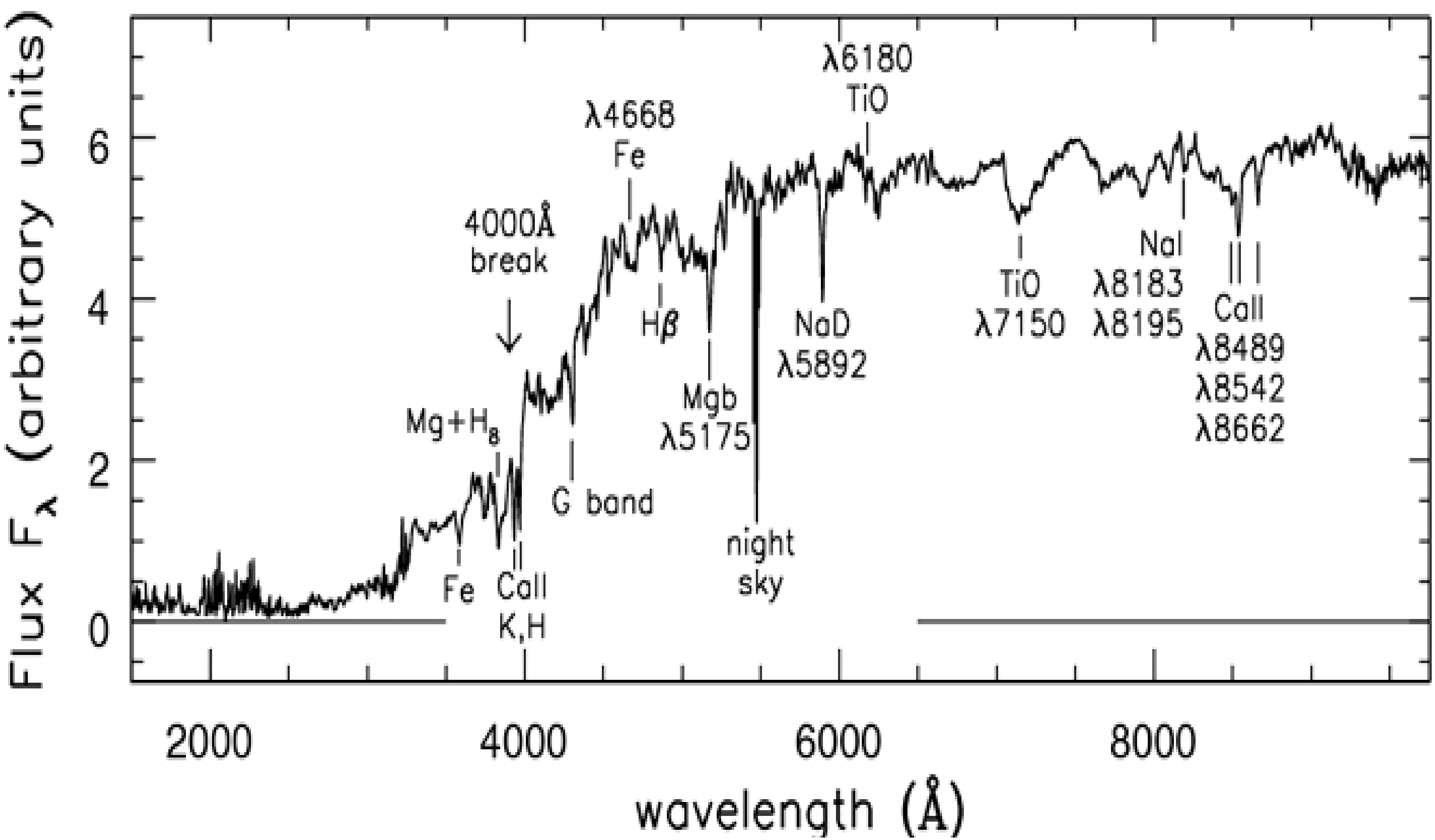
Optical spectra of blue, star-forming galaxies:

Absorption and emission lines from transitions of other elements

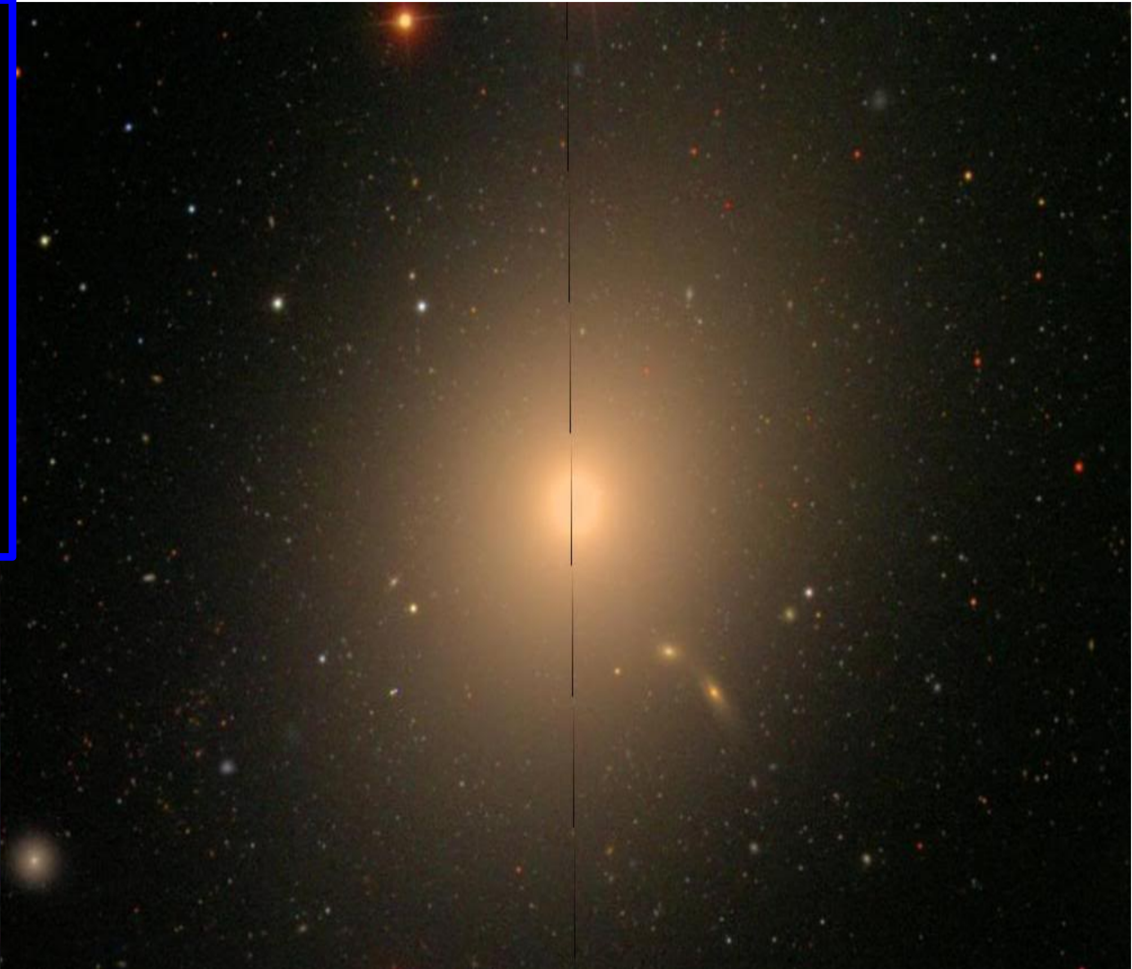


Optical spectrum of an old, red, elliptical galaxy:

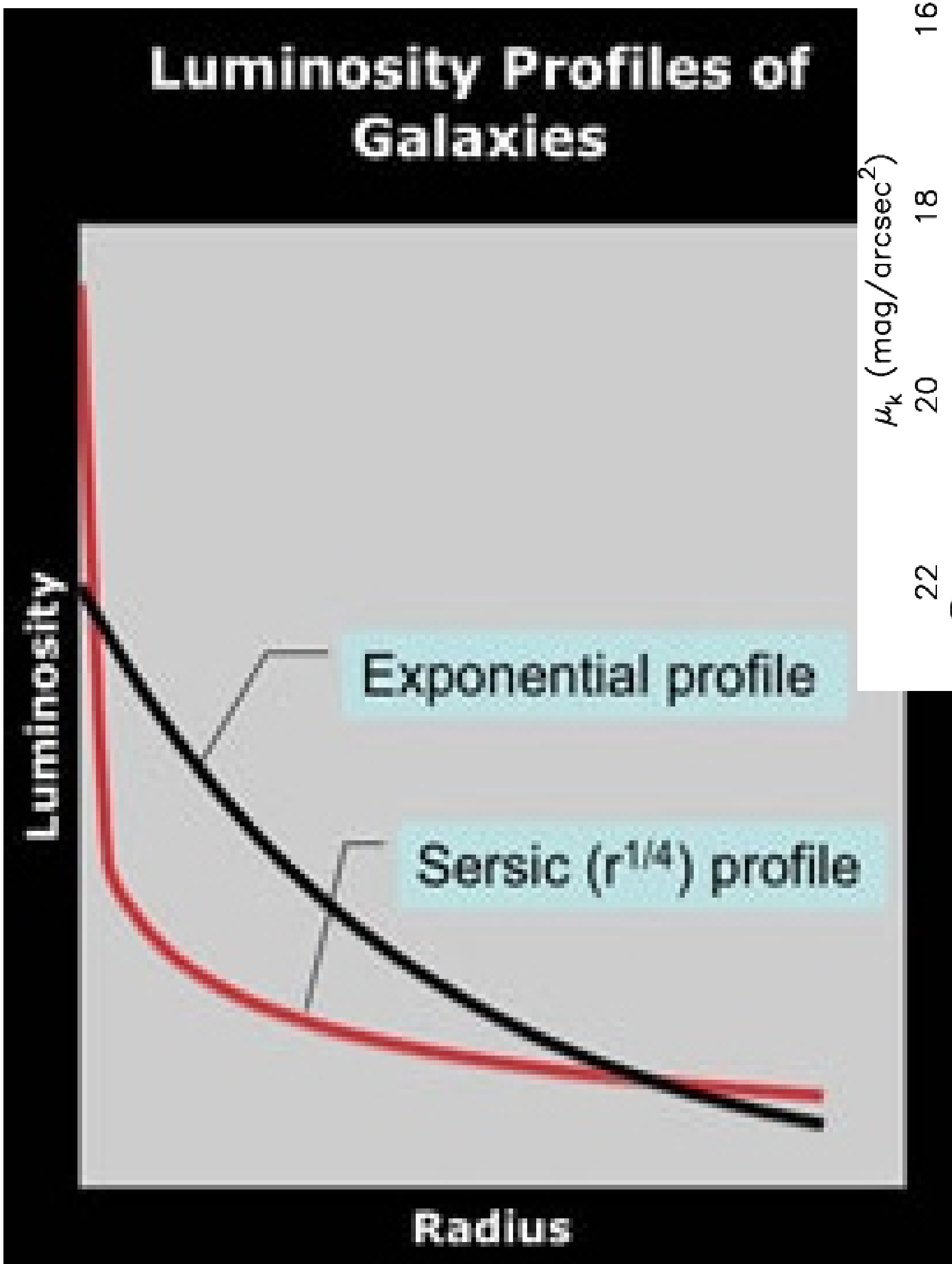
Only absorption features as radiation generated at the center of the star is absorbed at the outer atmosphere are visible

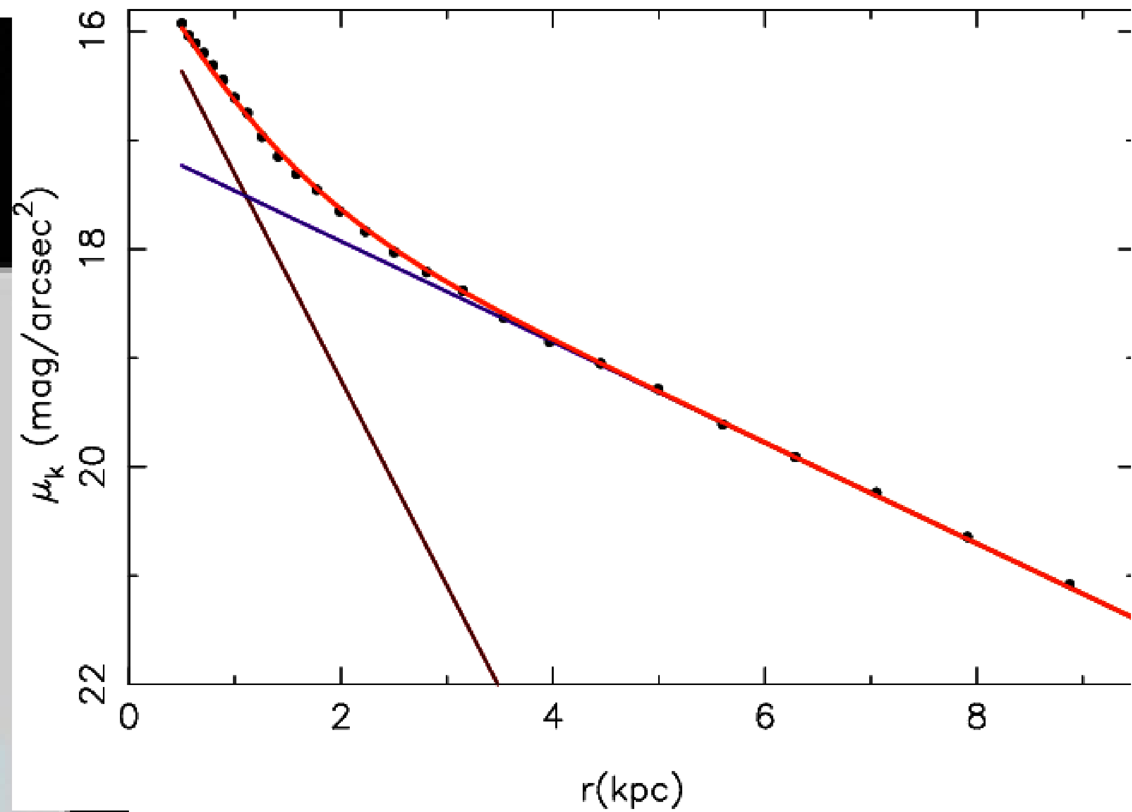


Young, star-forming galaxy



Old, red galaxy





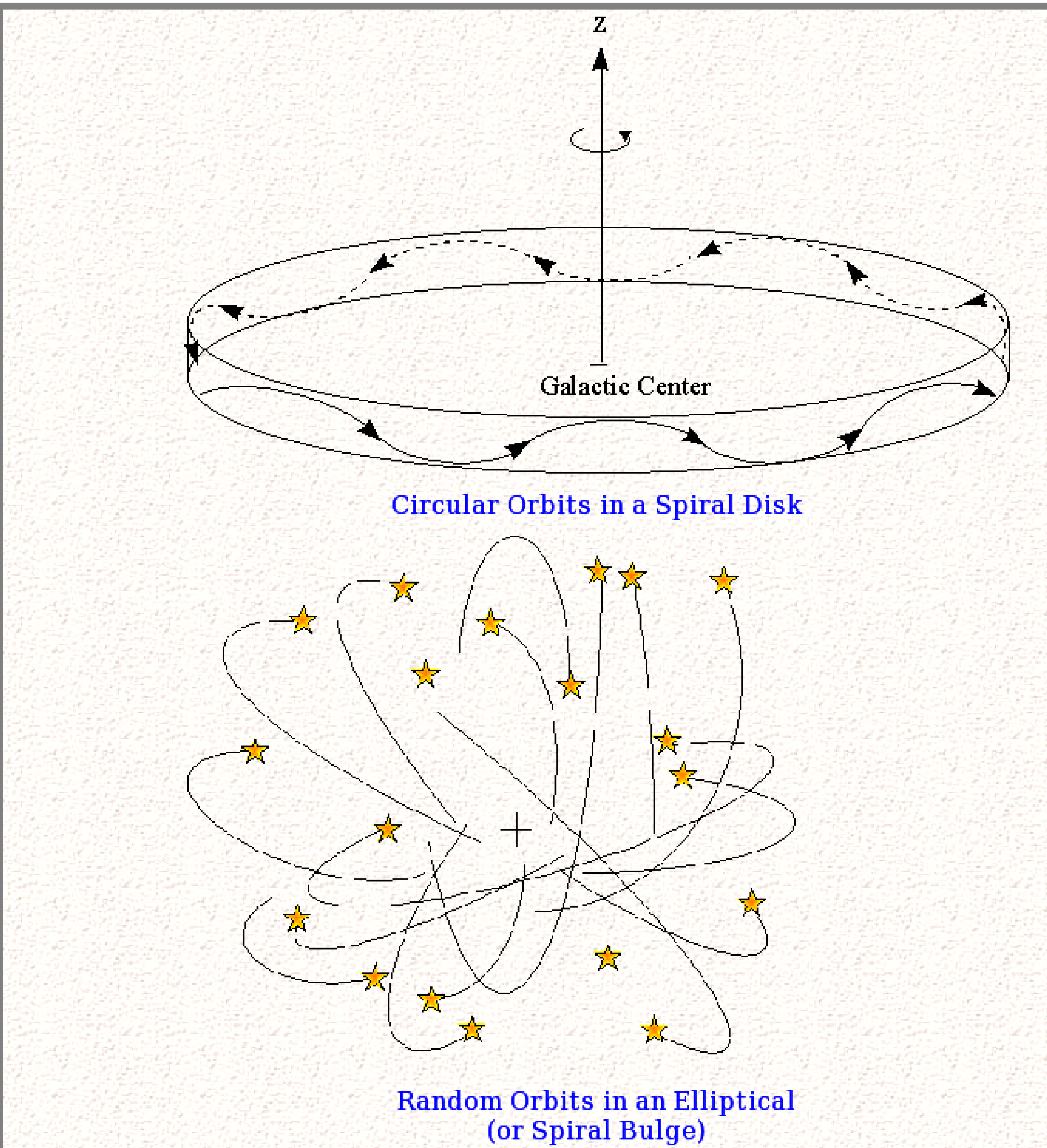
$$I(r) = I_0\, e^{-r/h}$$

(exponential describes pure disks, I represents the surface brightness, i.e. Luminosity per unit area)

$$I(r)= I_0\, e^{-(r/r0)^{1/n}}$$

(sersic, n=4, describes ellipticals and bulges)

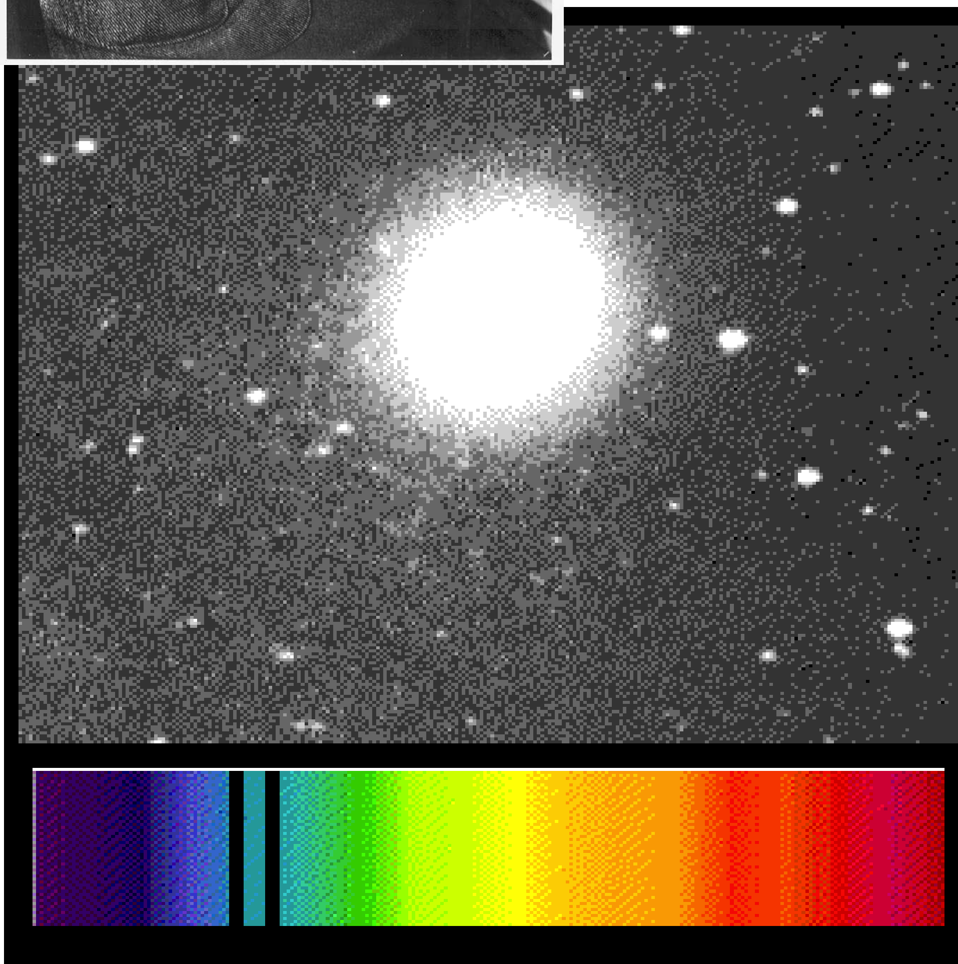
Motions of stars in spiral and elliptical galaxies are different

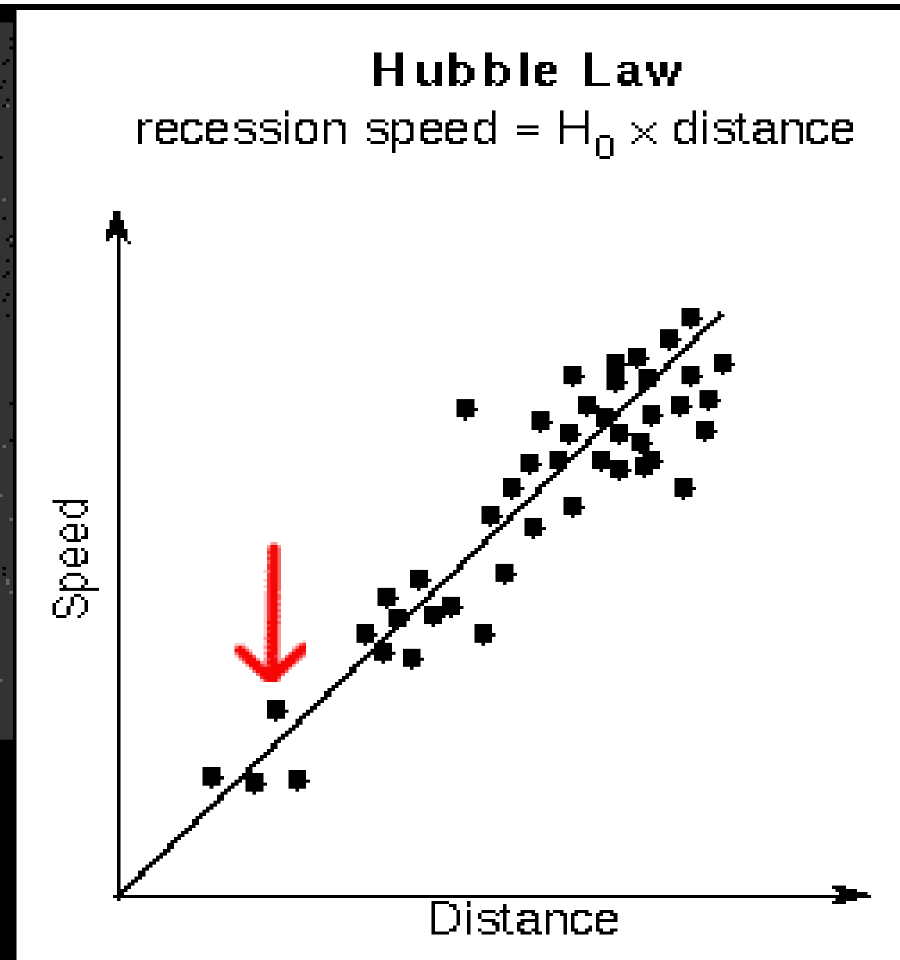


Spiral galaxies appear flattened when viewed "edge on", whereas elliptical galaxies are always close to round.

How to Measure the Distance to a Galaxy?

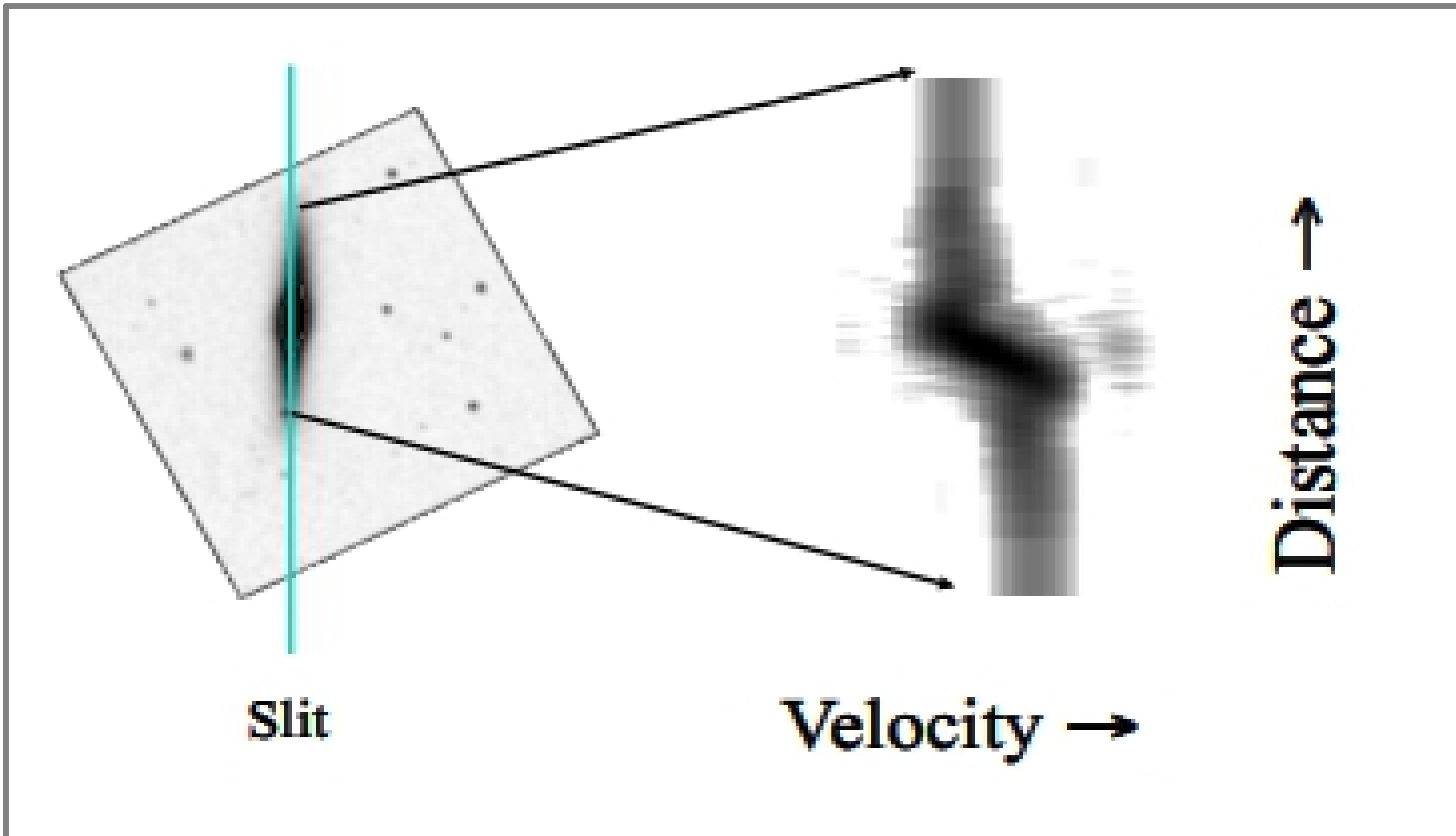
The Hubble “law” was predicted by Georges Lemaitres in 1927; he proposed the Universe is expanding and derived an estimate of the expansion from equations of GR (next lecture) . The expansion should be visible as a Doppler shift of the light.



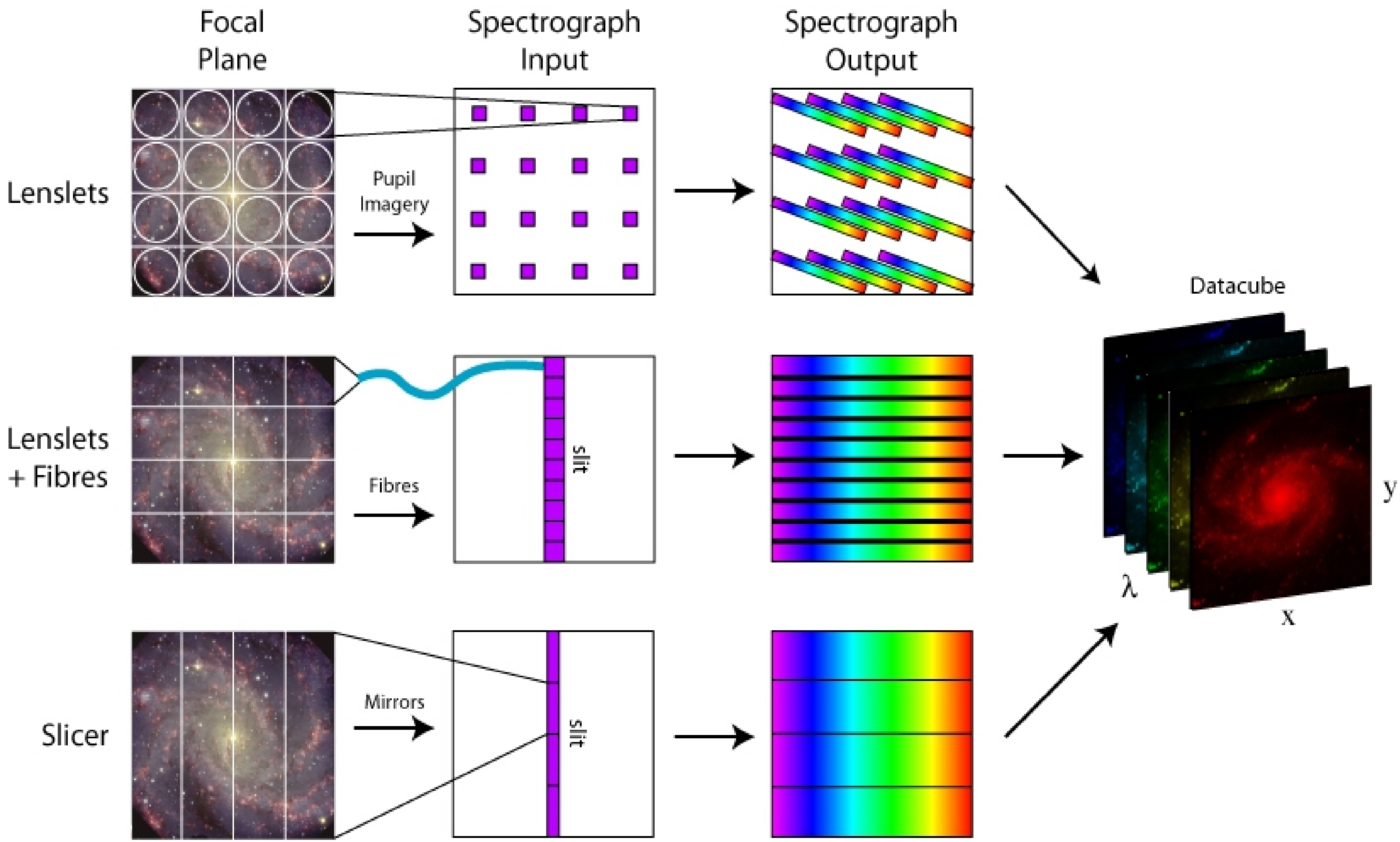


How do we measure the rotation of a galaxy?

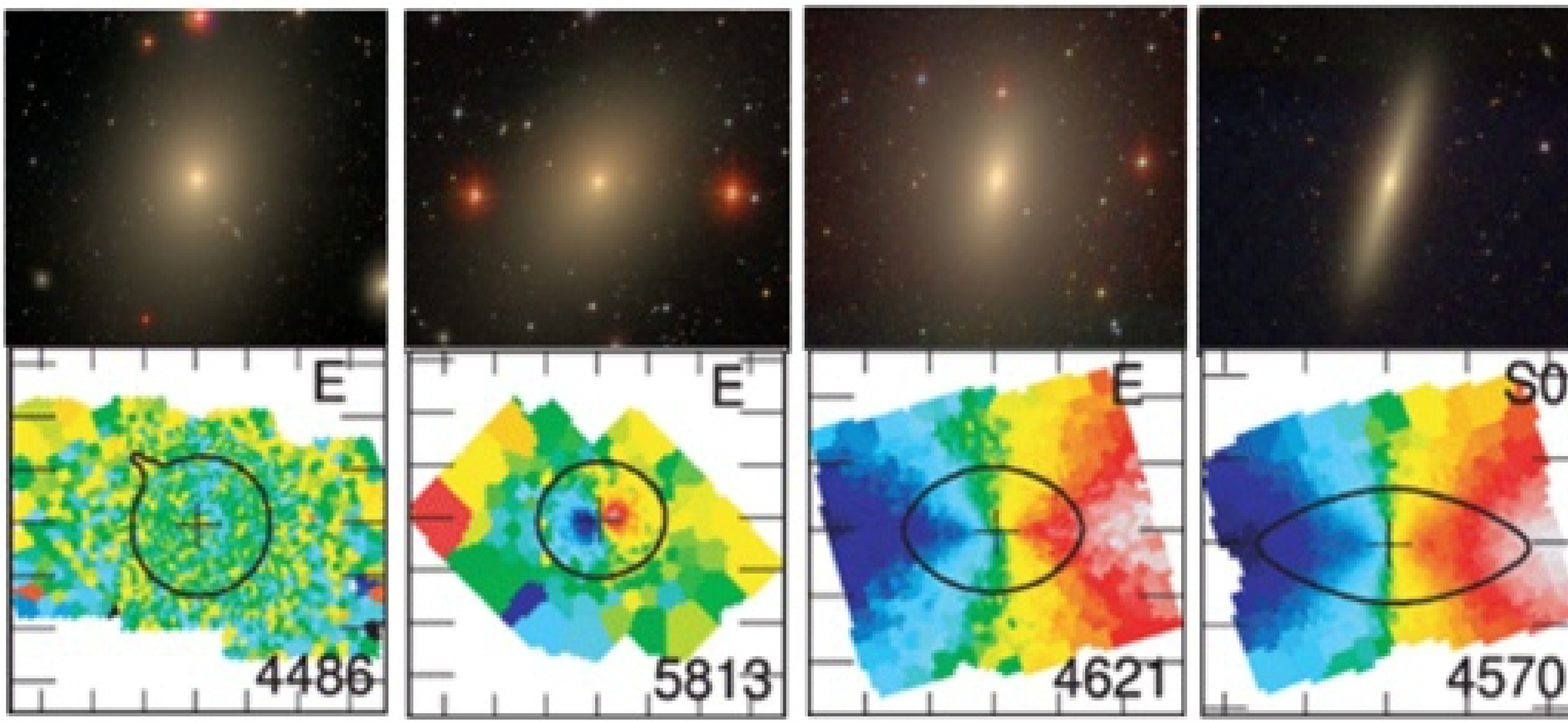
Once we correct for the Doppler shift of the spectral lines caused by the expansion of the Universe, we find that the lines are shifted by +Δλ on one side of the galaxy and by -Δλ on the other side.



Integral Field Unit (IFU) Spectrographs



Examples of Velocity Maps



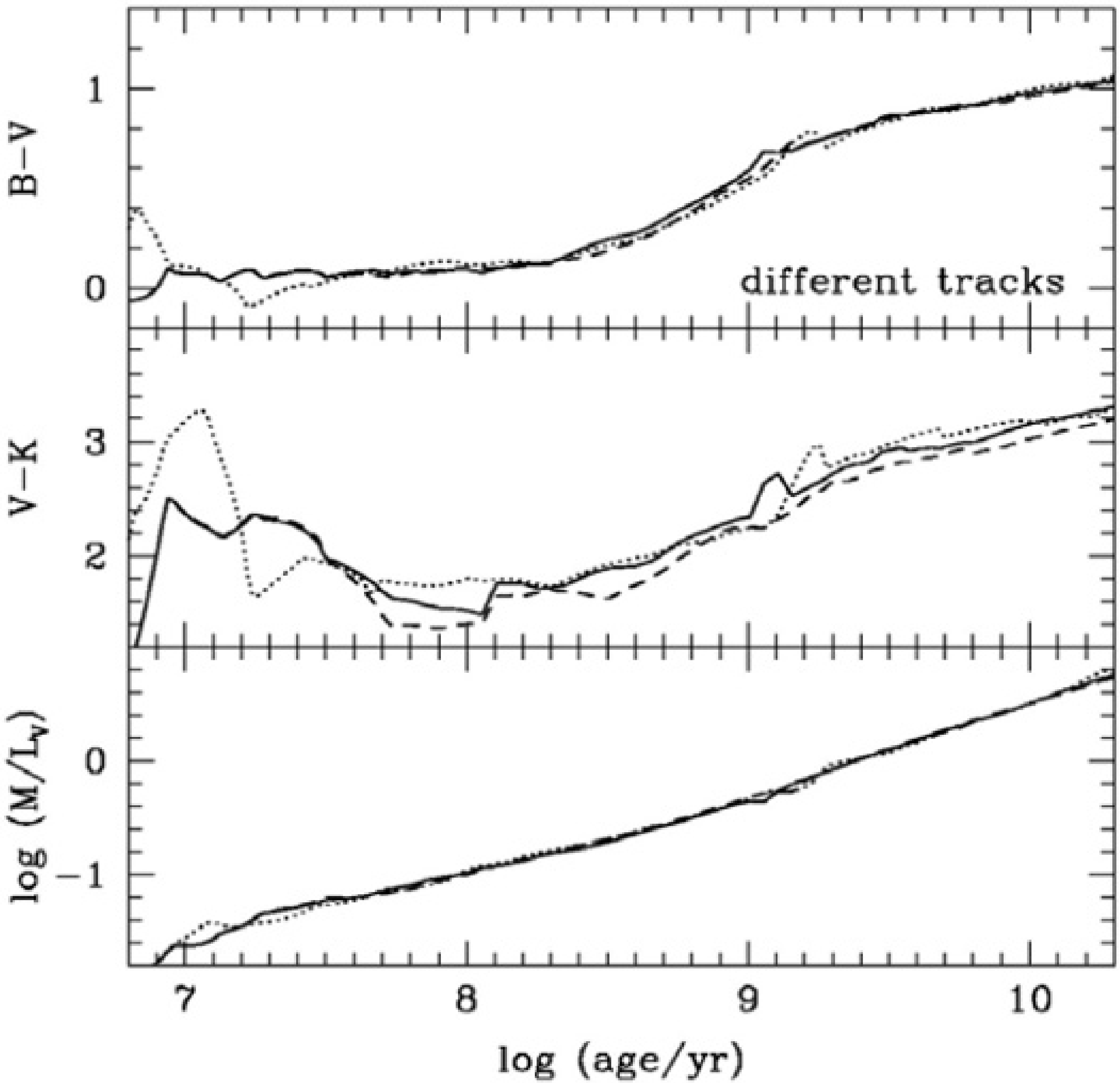
Random orbits

Rotating central component

The whole galaxy is rotating

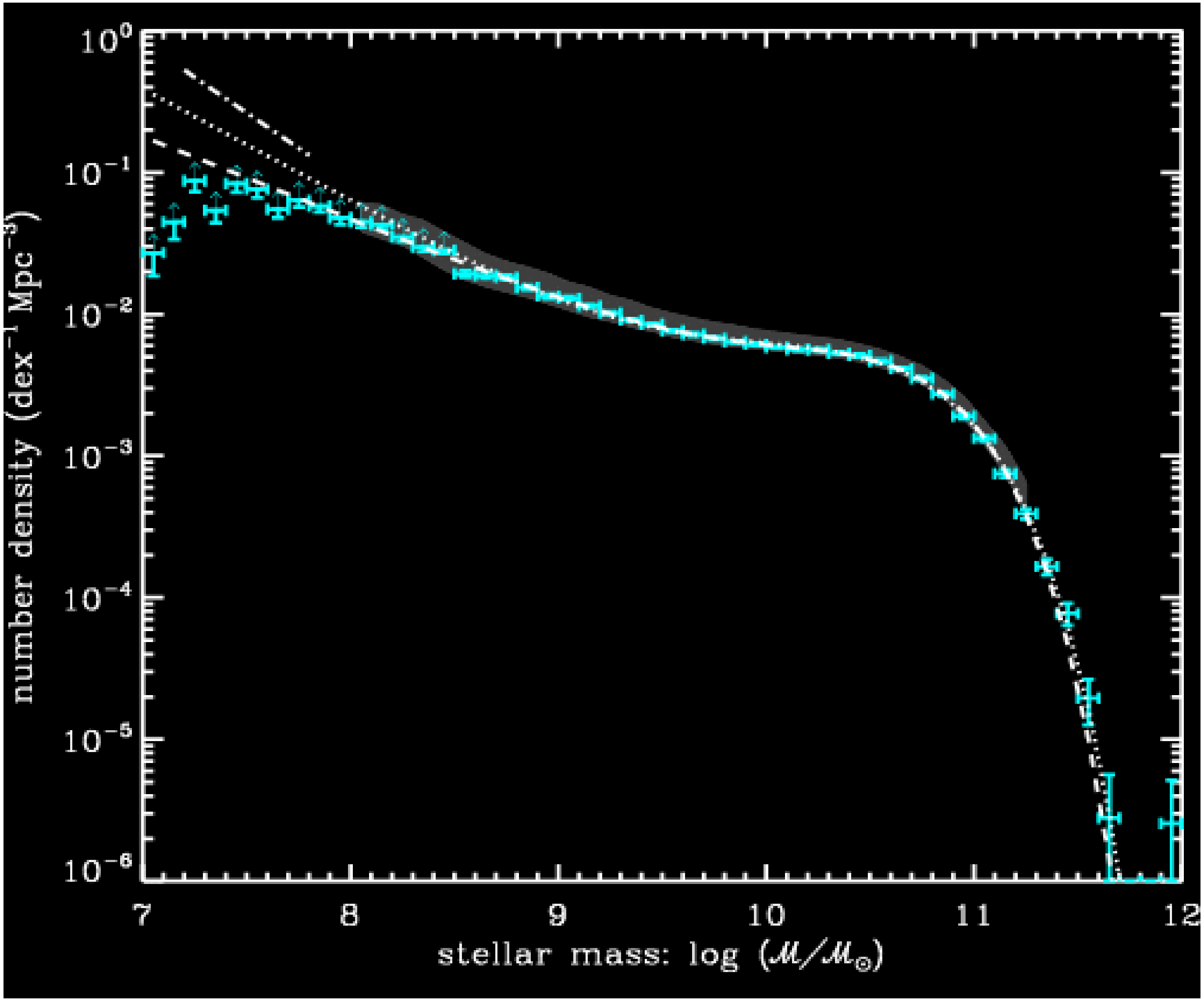
Mass-to-light ratio of a group of stars “born” on the Main Sequence at the same time as a function of their age:

it increases with time because the most luminous stars die and expel their mass first.



Empirical fitting function for the mass function of galaxies
(Schechter function)

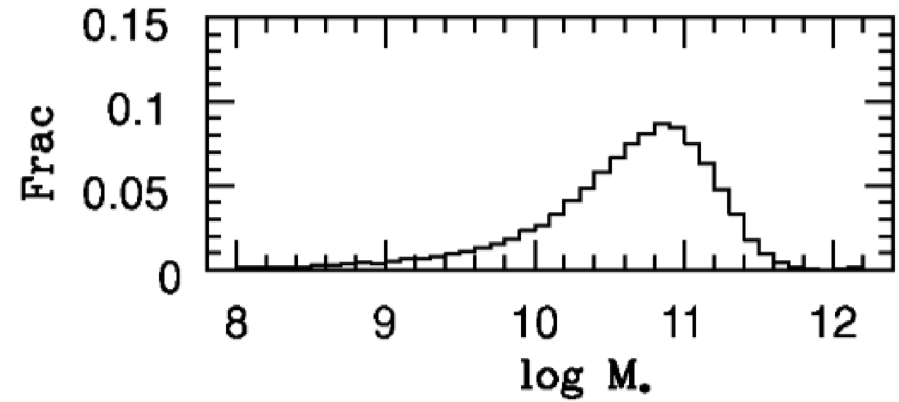
$$\Phi(L)\,dL = n_* \left(\frac{L}{L_*}\right)^{\alpha} exp\left(-\frac{L}{L_*}\right)\, d\left(\frac{L}{L_*}\right)$$



L*, the characteristic luminoisity/mass that separates the low and high luminosity/mass parts.

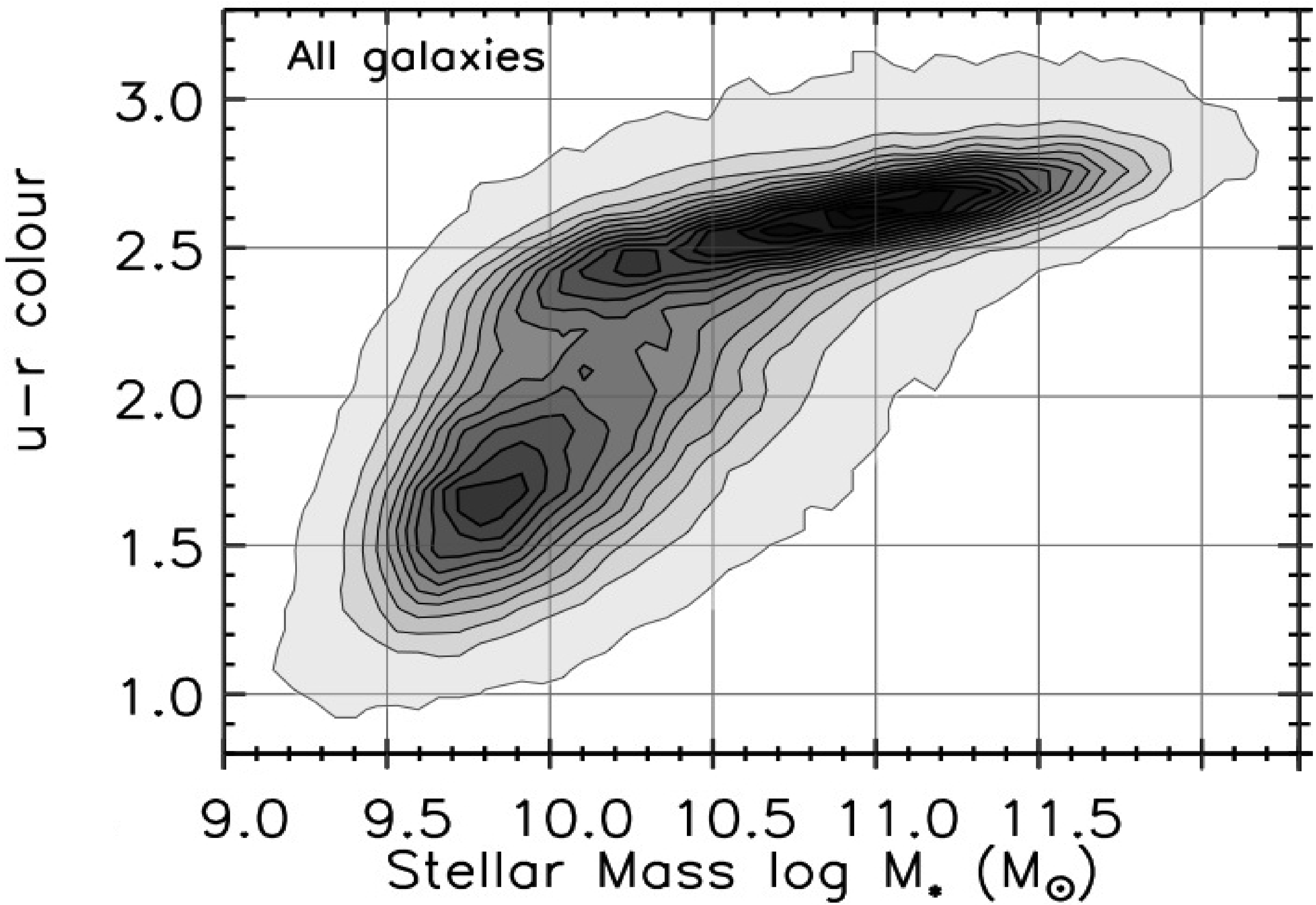
At low luminosity/mass: Power law with alpha=-1.2 (low luminosity galaxies are more common)

At high luminosit/ mass: exponential cut-off (very massive galaxies are rare)



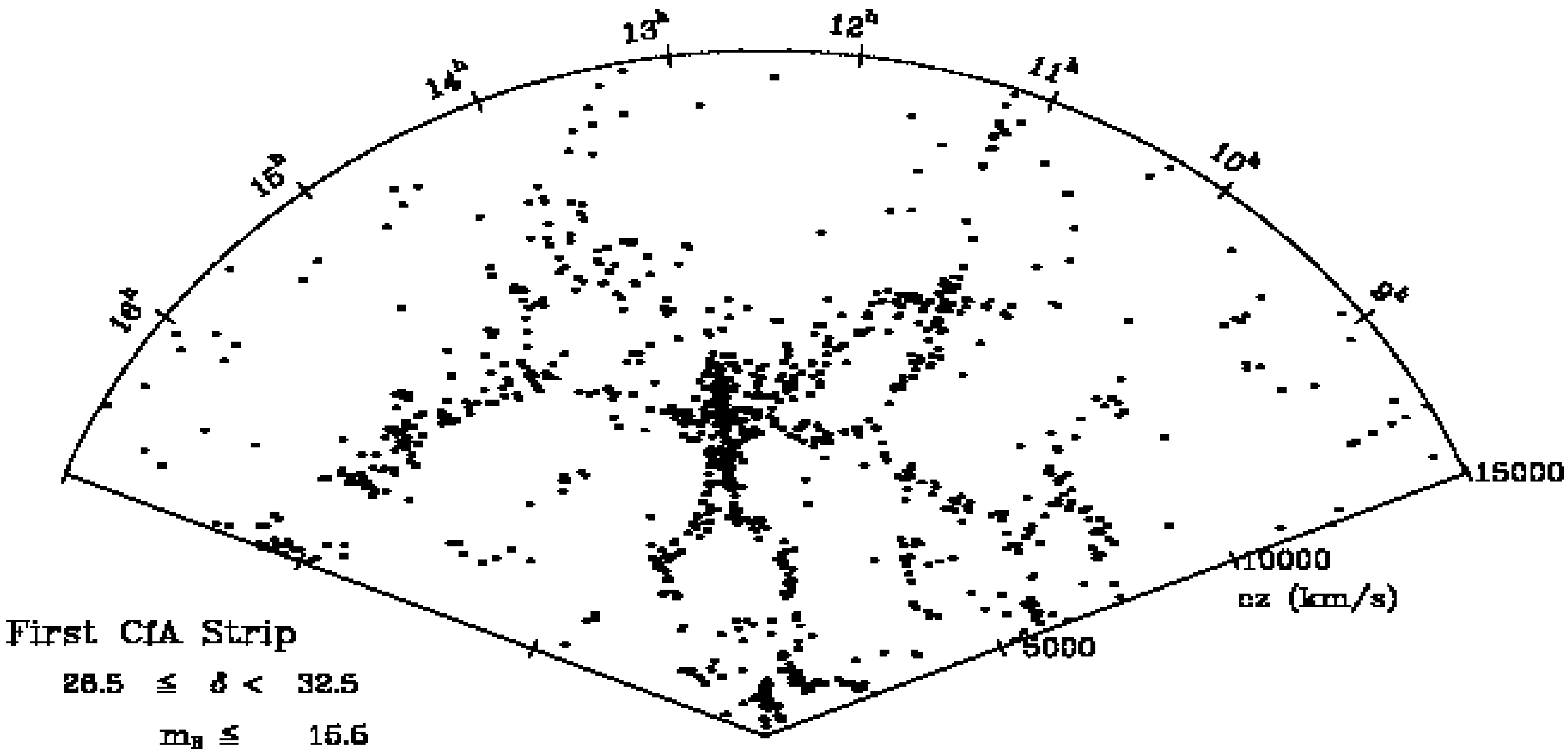
Integrate the galaxy mass function to obtain the total stellar mass density in the local Universe, and then plot the fraction of total as a function of galaxy mass. It peaks at around 5×10^{10} solar masses, very close the the mass of the Milky Way!

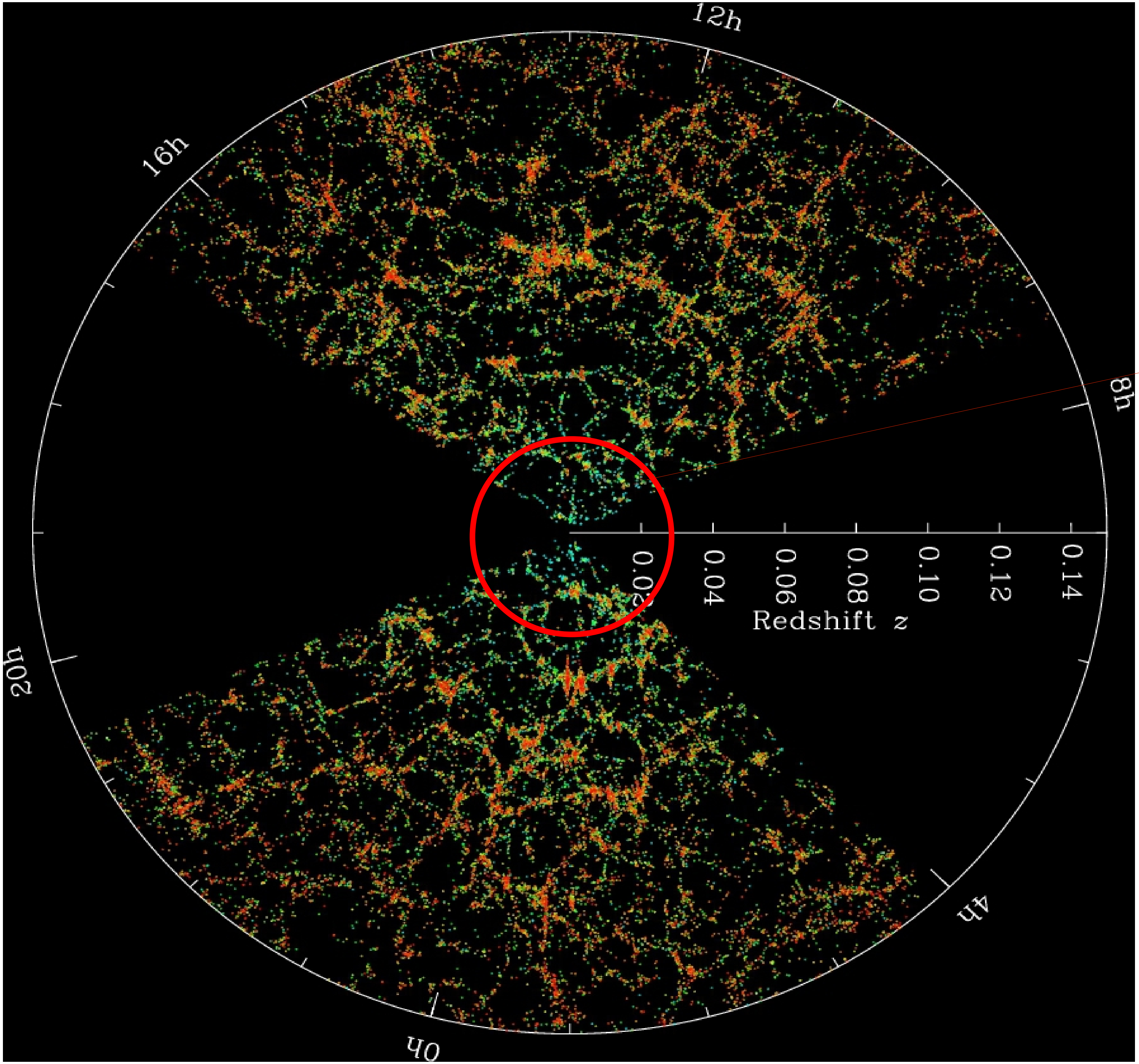
Binggeli's 1987 cartoon of Paul Schechter and his function. Quite why it has this form buried details underfoot....



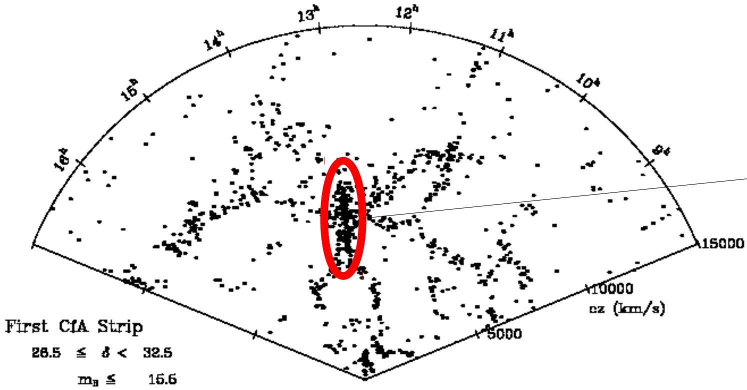
Low mass galaxies are blue and massive galaxies are red.
The red and the blue populations are disjoint (bimodal)

Map of the Galaxy Distribution Showing that Galaxies are not Distributed Randomly in Space



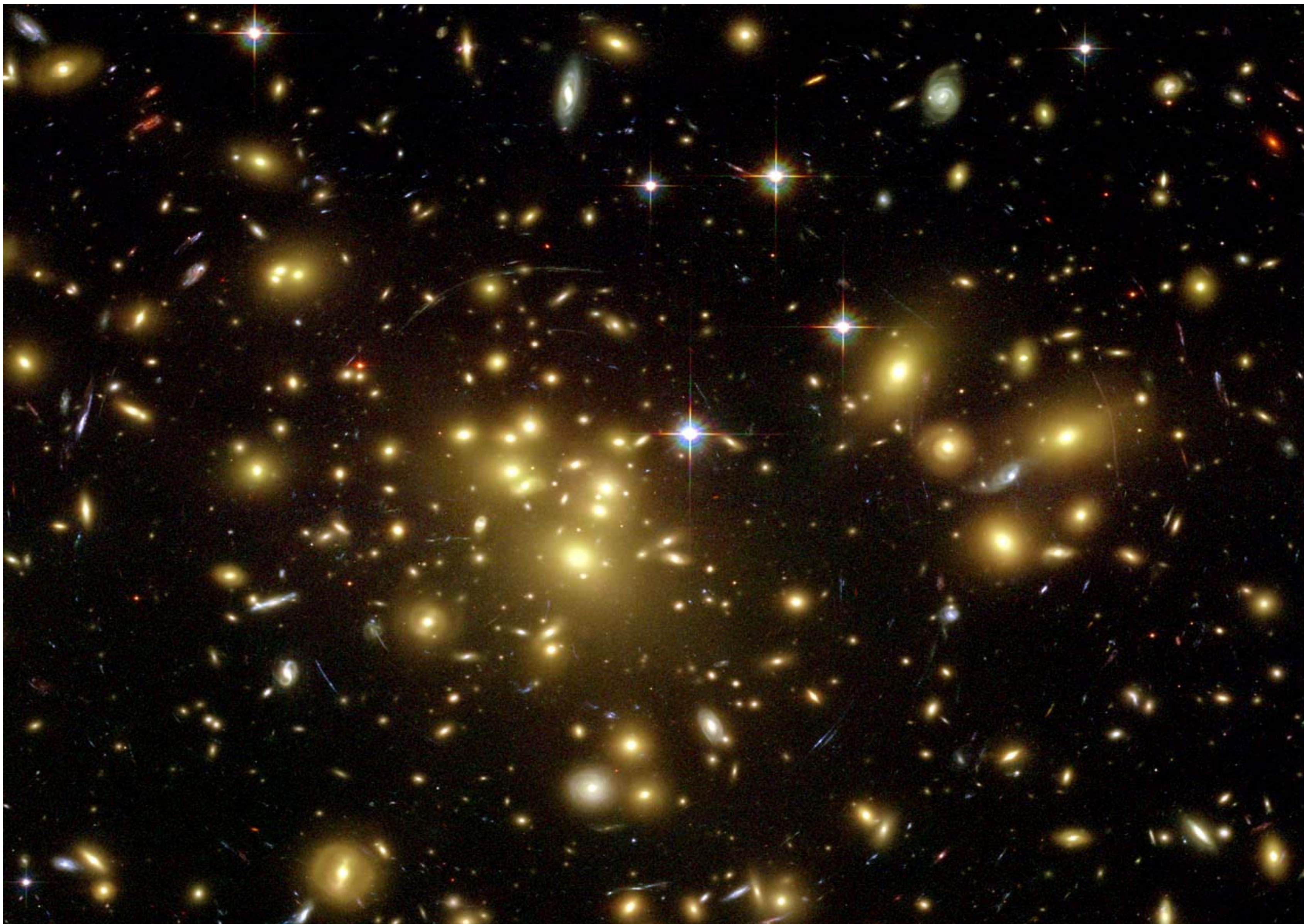


Size of the original CfA Survey compared the present-day State-of the art (Sloan Digital Sky survey main sample)



Coma Cluster of galaxies

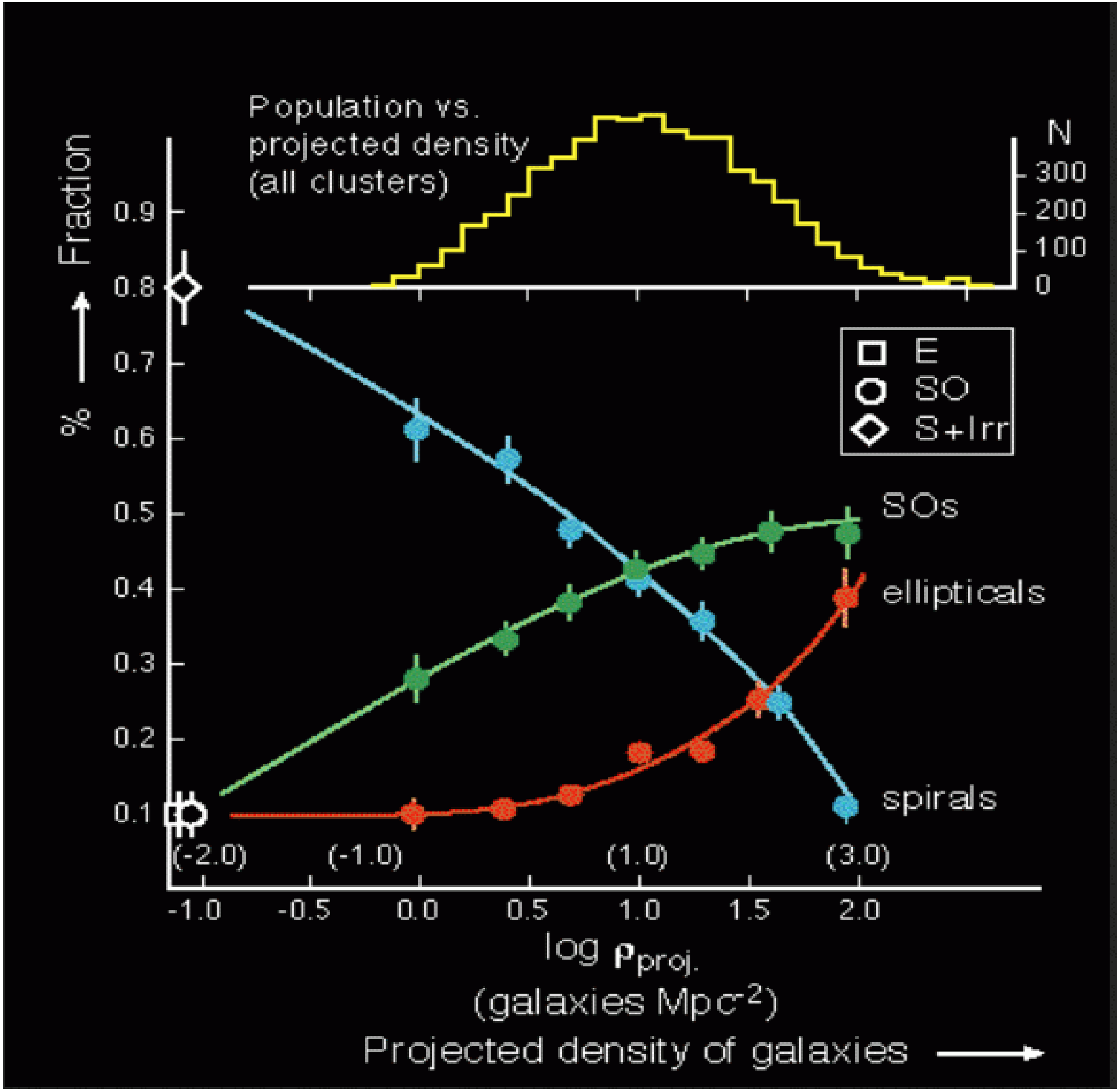
Abell 1989 , one of the most massive galaxy clusters know: It acts as a gravitational lens, stretching and bending the images of background galaxies (one of the predictions of Einstein's theory of general relativity)



Some galaxies live in smaller groups



Examples of Interacting Galaxies



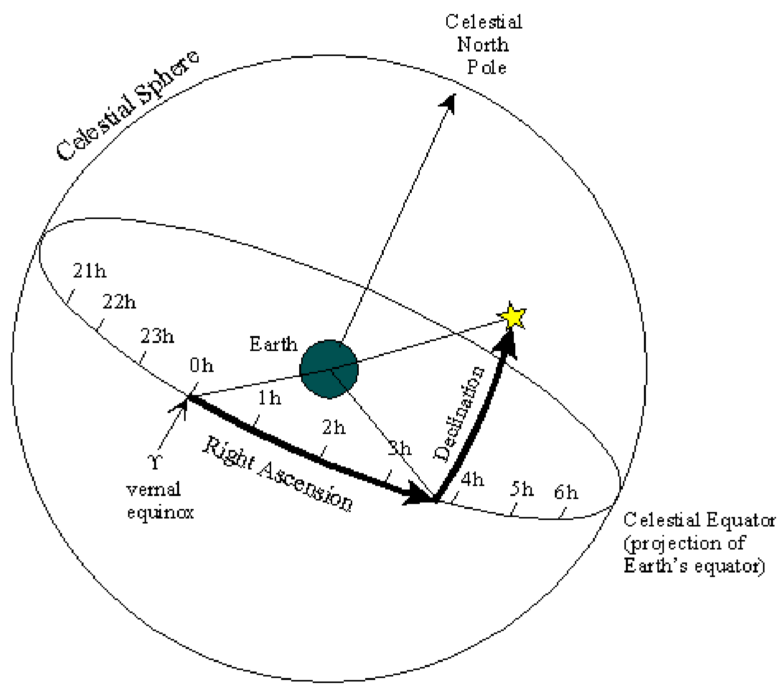
Morphology
-Density
Relation

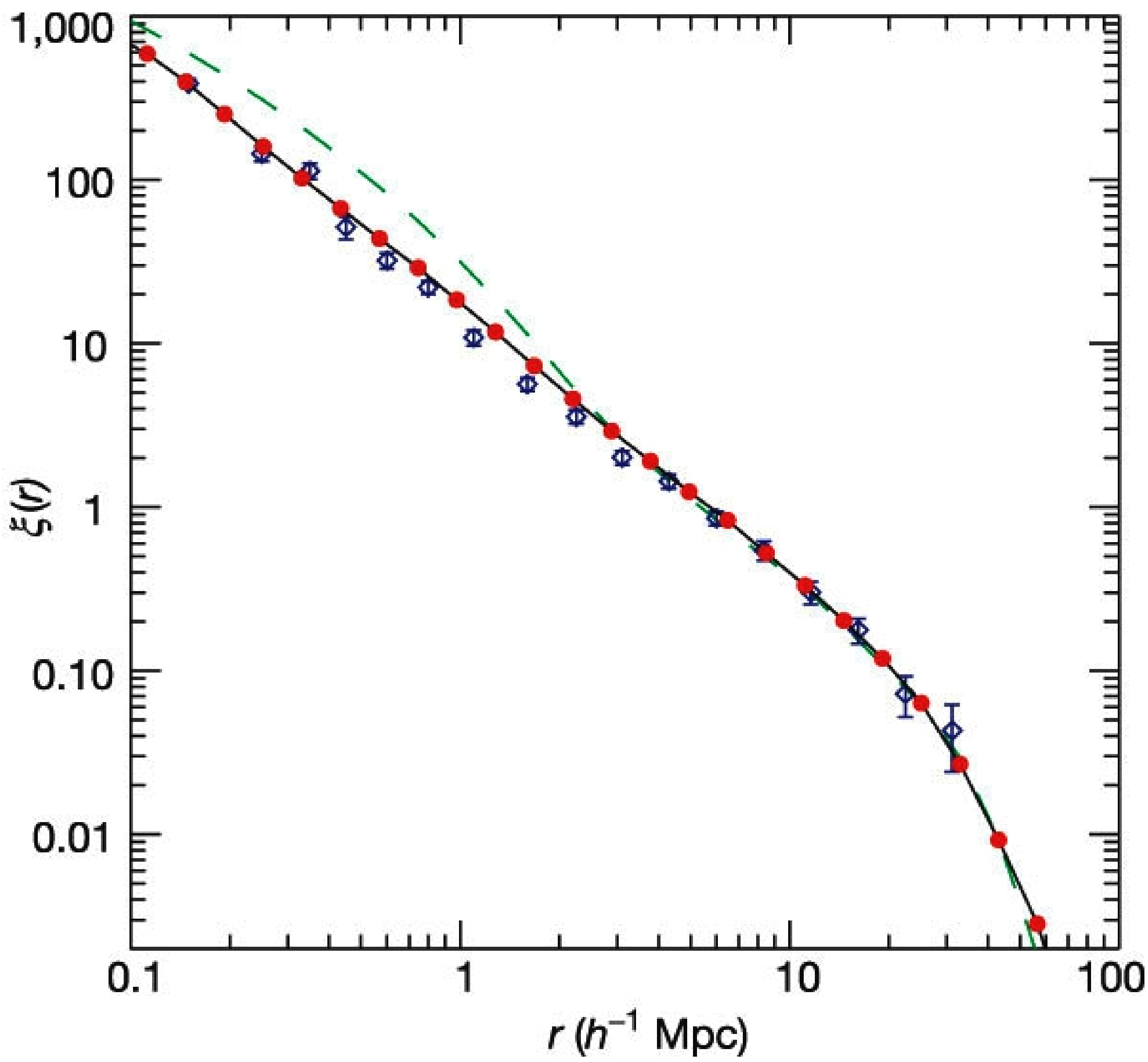
In cosmology, the 2-point galaxy correlation function is defined as a measure of the excess probability, relative to a Poisson distribution, of finding two galaxies at the volume elements dV1 and dV2 separated by a vector distance **r** :

$$dP_{12} = n^2 \, [\, 1 + \xi\,(\mathbf{r})]\, dV_1\, dV_2$$

n is the number density of the sample. Assuming homogeneity and isotropy means that **r** = |r|. The conditional probability that a galaxy lies at dV at a distance r from another galaxy is then

$$dP = n\,[\, 1 + \xi(r)]\, dV$$



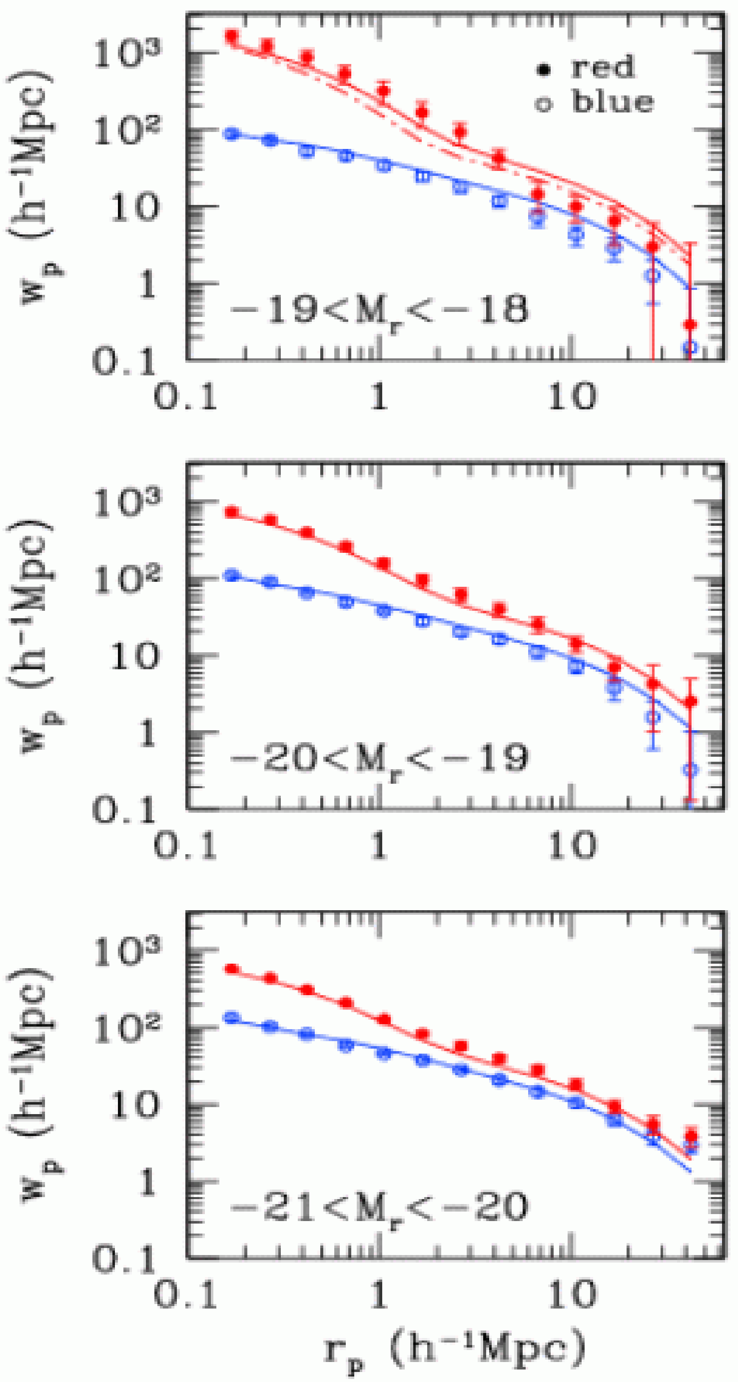


$\xi(r) =$

$(r / 8 \text{ Mpc})^{-1.8}$

Power-law over a factor of 30 in scale!

Projected Two Point Correlation function for nearby galaxies

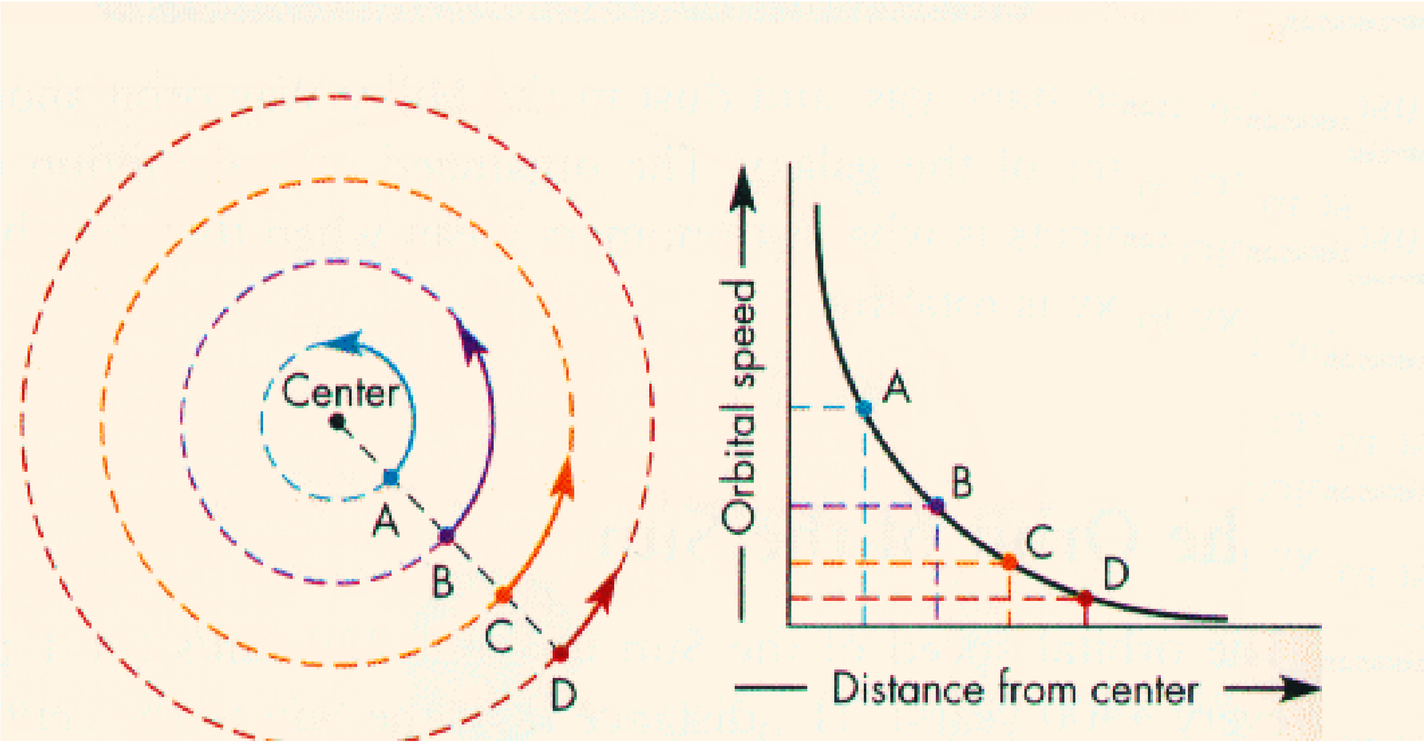


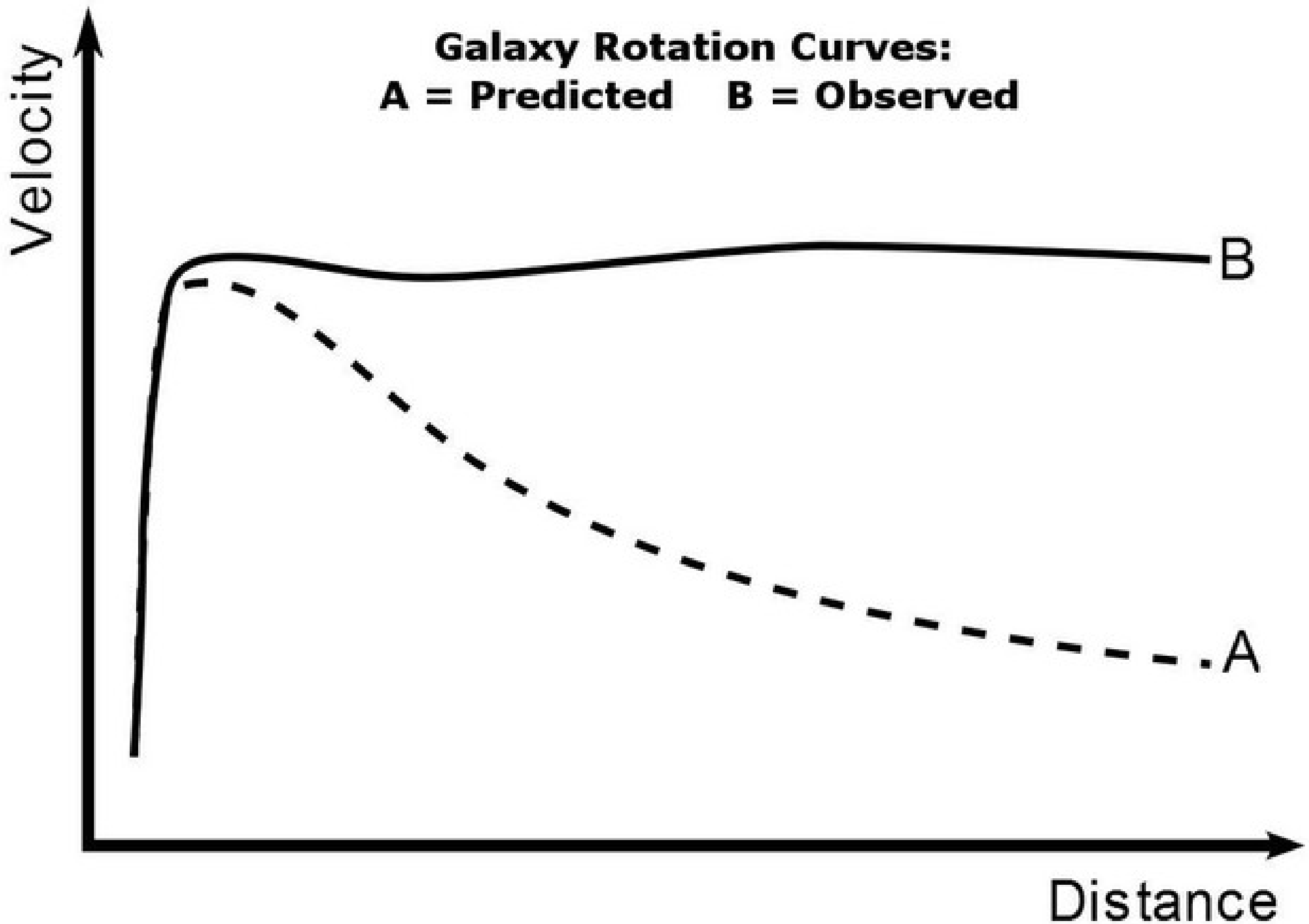
The two-point correlation function of red galaxies is steeper than that of blue galaxies: red galaxies have a significantly higher probability of having a close neighbor (consistent with higher fraction of red galaxies in clusters)

Other components of galaxies

1) Dark components: dark matter and supermassive black holes

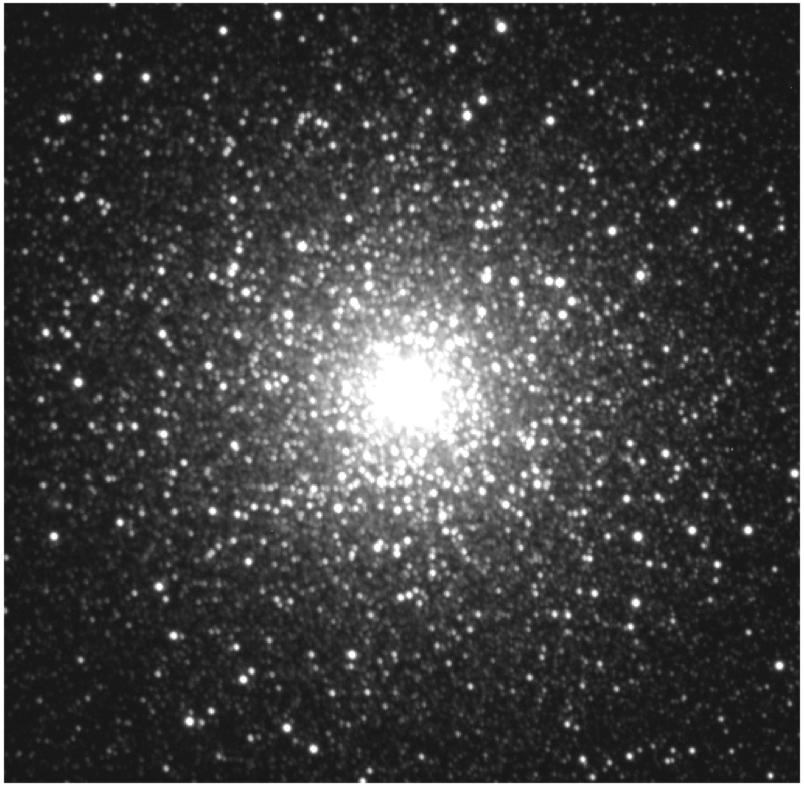
Recall Kepler's 3rd law: the orbital period of the planet at distance R yields a measure of the central mass





A is the rotation curve predicted by the observed distribution of mass in stars and gas in the galaxy.

B is what is observed



In mechanics, the **virial theorem** provides a general equation that relates the average over time of the total kinetic energy, of a stable system consisting of N particles, bound by potential forces, with that of its total potential energy.

This means we can estimate the MASS of a system from the average motions of its constituent particles.

The Virial Theorem

This section follows Zwicky's derivation [1]. Consider a system of mutually interacting masses. Let $\mathbf{r}_i$ be the position of mass m_i with respect to the system center of mass. Furthermore, let $\mathbf{F}_i$ be the total force acting on this mass as a result of its interaction with all of the other masses in the system. Then, by Newton's second law,

$$\boldsymbol{F}_i = m_i \frac{d^2 \boldsymbol{r}_i}{dt^2}$$

Scalar multiplication of this equation by $\mathbf{r}_i$ then yields

$$\frac{1}{2}\frac{d^2}{dt^2}\left(m_i r_i^2\right) = \boldsymbol{r}_i \cdot \boldsymbol{F}_i + m_i \left(\frac{d\boldsymbol{r}_i}{dt}\right)^2$$

Summing over all of the masses, time averaging, and letting v_i be the velocity of the ith mass, we find

$$\overline{\frac{1}{2}\frac{d^2}{dt^2}\left(\sum_i m_i r_i^2\right)} = \overline{\sum_i \boldsymbol{r}_i \cdot \boldsymbol{F}_i} + \overline{\sum_i m_i v_i^2}$$

If we further assume that the overall mass distribution (specifically $\sum m_i r_i^2$) fluctuates about some equilibrium value, then the time average of the derivative on the left must be zero, leaving

$$\overline{\sum_i \frac{1}{2} m_i v_i^2} = -\frac{1}{2}\overline{\sum_i \boldsymbol{r}_i \cdot \boldsymbol{F}_i}$$

This is the virial theorem, which relates a system's total kinetic energy (on the left) to its virial (the sum on the right)

The virial for a system of masses interacting gravitationally can be simplified using Newton's third law, $\mathbf{F}_{ij} = -\mathbf{F}_{ji}$, where $\mathbf{F}_{ji}$ is the force from mass j on mass i (and $\mathbf{r}_{ji}$ is the displacement from mass j to mass i). We get

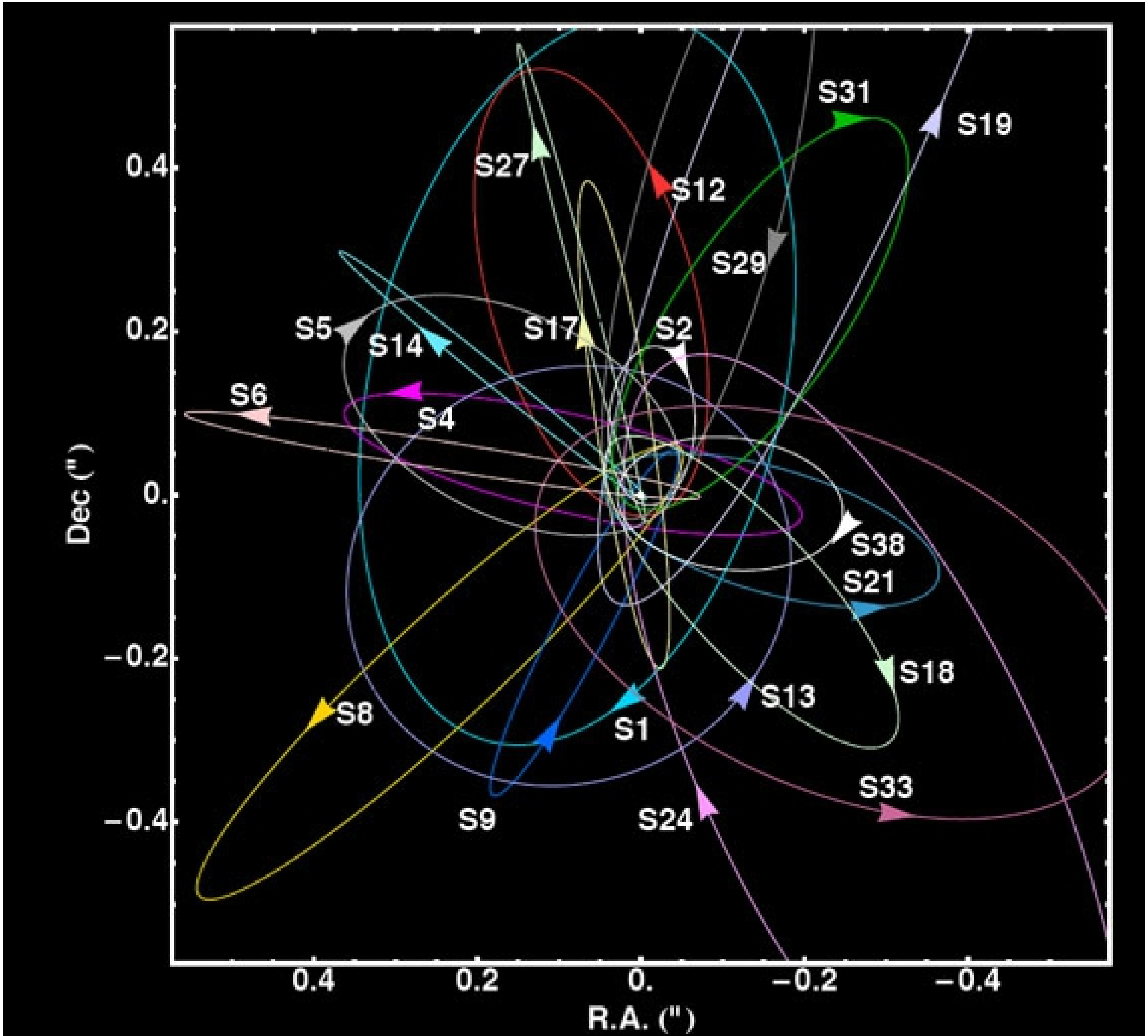
$$\begin{aligned}\sum_i \boldsymbol{F}_i \cdot \boldsymbol{r}_i &= \sum_i \left(\sum_{j \neq i} \boldsymbol{F}_{ji} \right) \cdot \boldsymbol{r}_i \\ &= \sum_i \sum_{j<i} \boldsymbol{F}_{ji} \cdot (\boldsymbol{r}_i - \boldsymbol{r}_j) \\ &= \sum_i \sum_{j<i} \boldsymbol{F}_{ji} \cdot \boldsymbol{r}_{ji} \\ &= -\sum_i \sum_{j<i} \left(\frac{G m_i m_j}{r_{ij}^3} \boldsymbol{r}_{ji} \right) \cdot \boldsymbol{r}_{ji}\end{aligned}$$

Here, the third law has been used in the second step to reduce the number of terms in the sum by a factor of two and the final step has been achieved by explicitly writing the universal law of gravitation. Thus, for a system of gravitationally interacting masses, the virial theorem states that

$$\overline{\sum_i m_i v_i^2} = \overline{\sum_i \sum_{j<i} \frac{G m_i m_j}{r_{ij}}}$$

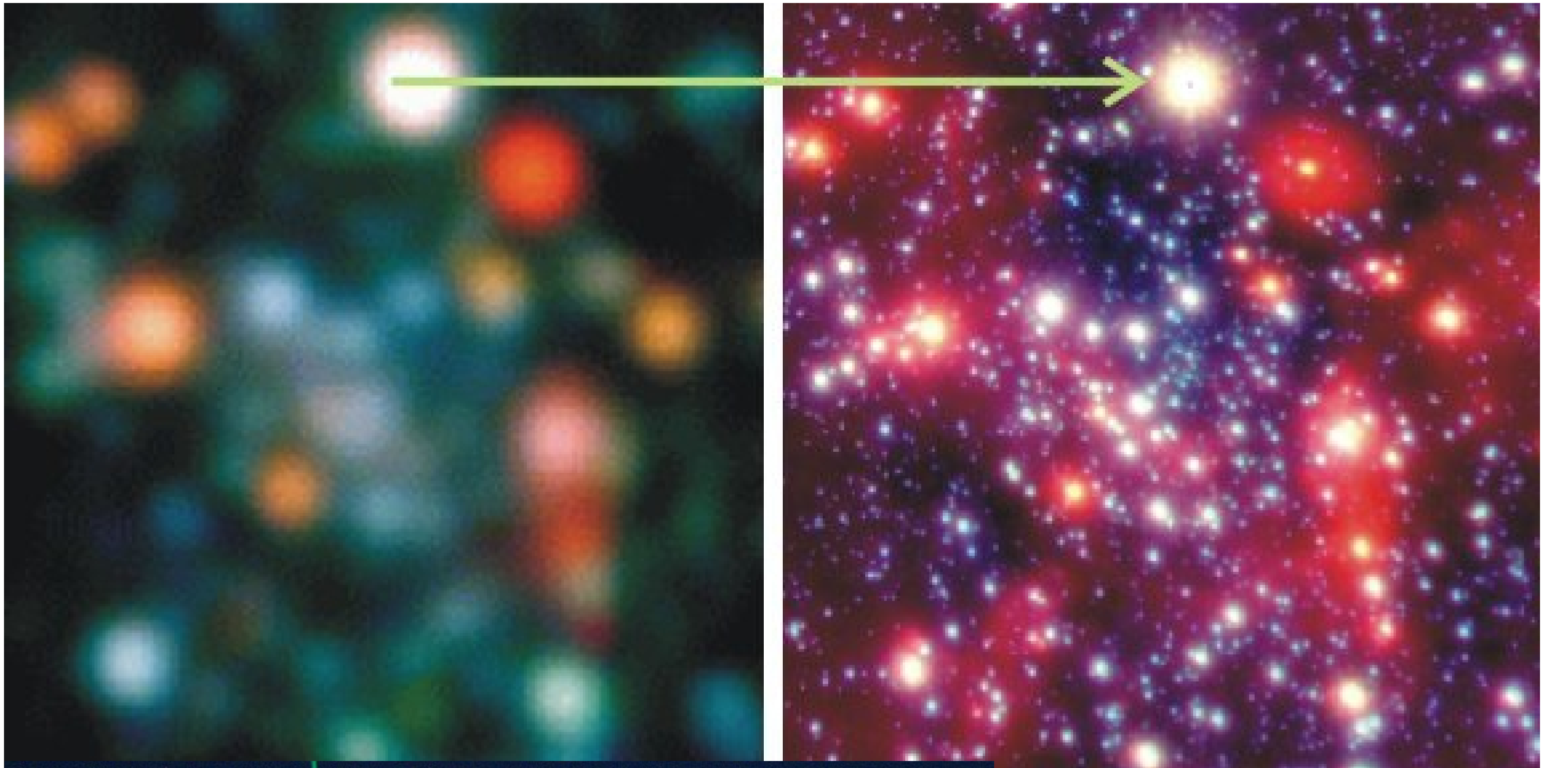
The left side of this equation is just the total mass, M, of the galaxy cluster multiplied by the time *and* mass averaged squared velocity. The right side can be approximated to within constants of order unity as $G{*}M^2/R$, where G is the gravitational constant and R is the radius of the galaxy cluster. (This can be obtained by assuming a uniform distribution of mass over a sphere of radius R. Zwicky discusses the applicability of this order of magnitude calculation even if the mass distribution varies significantly from uniformity.) To within constants of order unity, then, the total mass of the galaxy cluster is just the cluster radius times the mean squared velocity, divided by the gravitational constant.

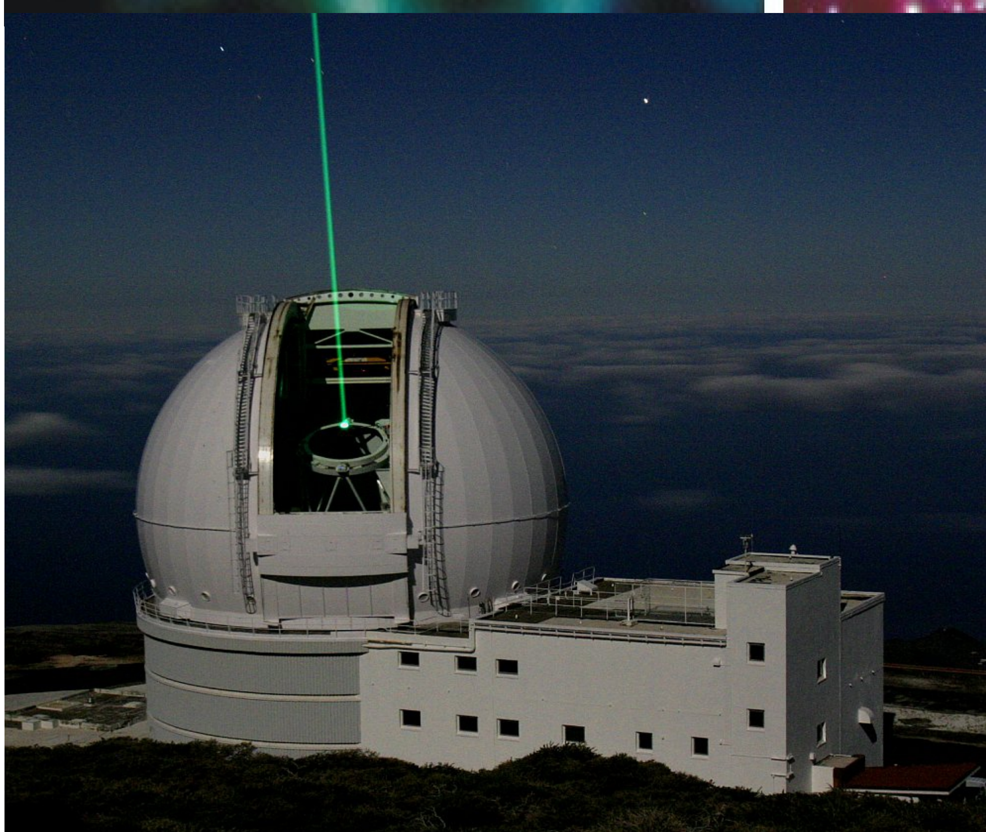
Zwicky knew the radius of the Coma cluster to be $2{*}10^6$ lightyears. The true galaxy velocities cannot be determined, but the line of sight velocities could be found via redshift. Using the mean squared line of sight velocity instead of the mean squared total velocity only introduces a factor of three (assuming spherical symmetry), so the result is not changed to within order of magnitude. Zwicky took $5{*}10^{15}$ cm^2s^{-2} as the value for the time and mass averaged squared velocity. The total cluster mass is then about $7{*}10^{13}$ solar masses. Since the cluster contains about 1000 galaxies, this yields an average galactic mass of $7{*}10^{10}$ solar masses. However, the average galactic luminosity in the Coma cluster is found to be only $8.5{*}10^7$ solar luminosities. Thus, the average mass to light ratio, in solar units, of the galaxies in the Coma cluster is approximately 800. This is several orders of magnitude greater than what one would expect if the mass of the Coma galaxies is mostly in stars (which should have mass to light ratios of order unity in solar units) [1]. One plausible explanation for this discrepancy is dark matter, which contributes mass without increasing the galactic luminosity.



Another application of Kepler's third law to measure the mass of the dark mass at the center of our Galaxy.

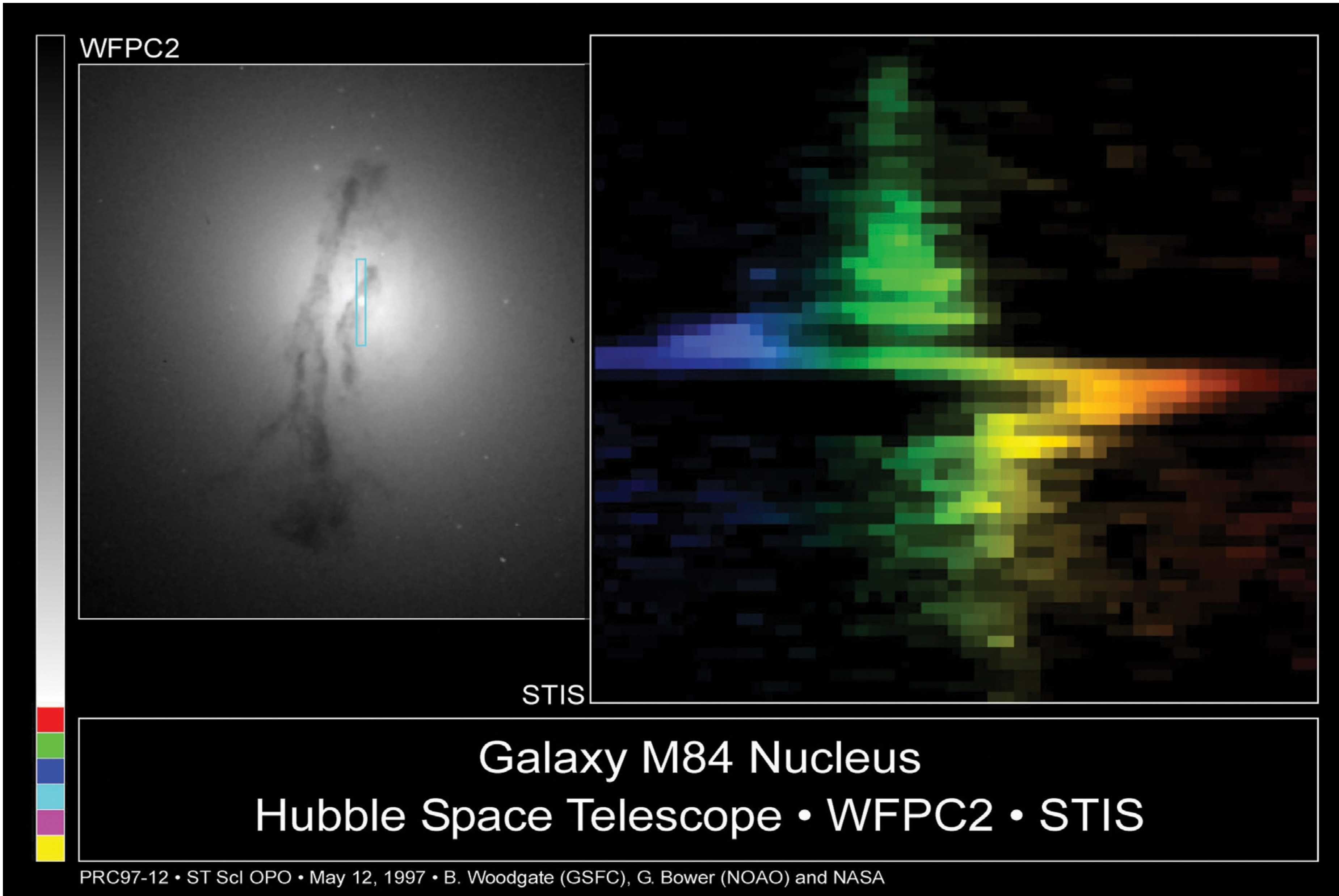
4.1 million solar masses within a radius of 6.25 light hours -comparable to diameter of Uranus' orbit.
--> larger than Schwarzschild radius, but almost all forms of matter other than black hole are excluded.





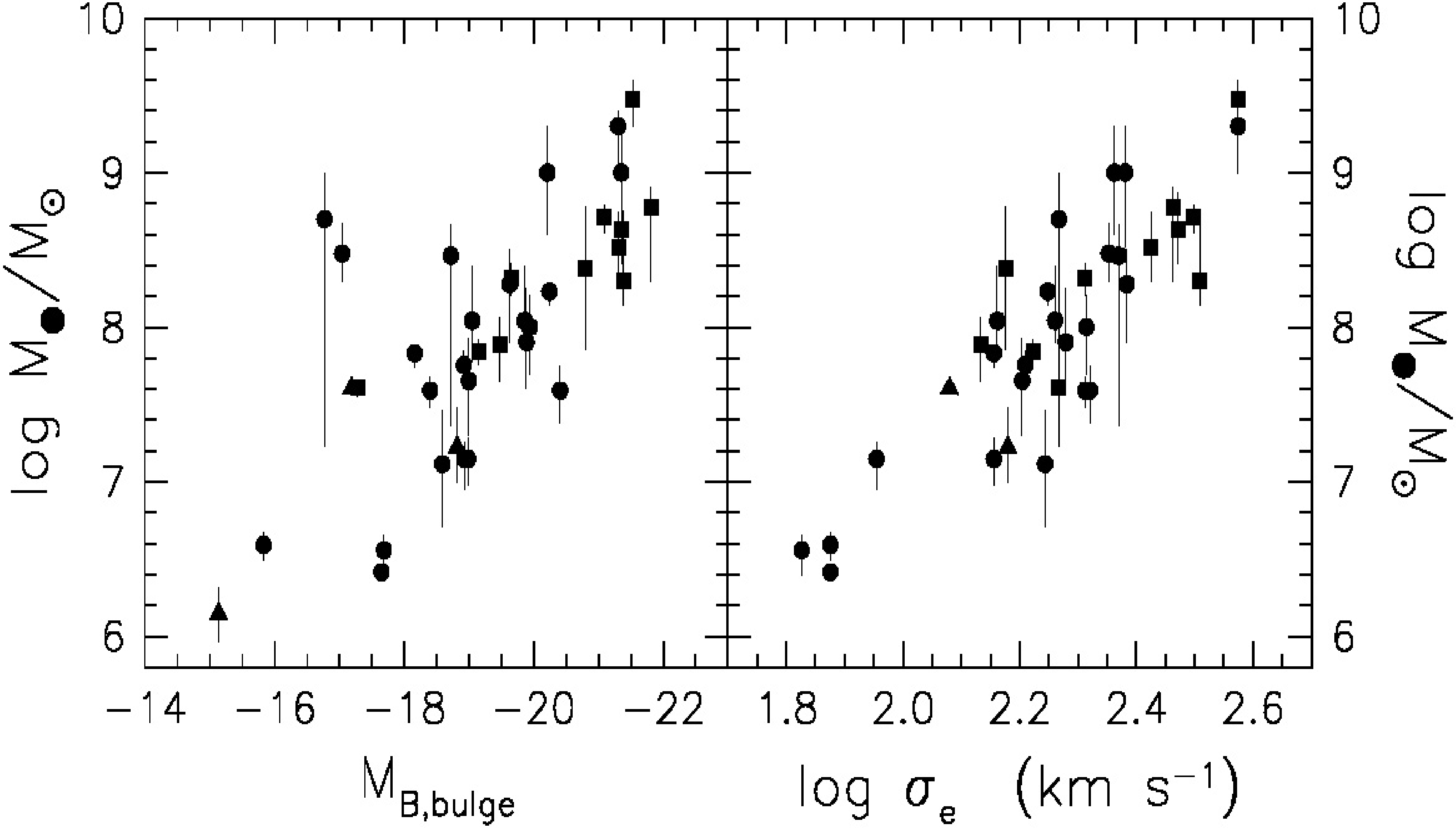
Enabled by a technique called adaptive optics

Black hole mass measurements in other galaxies come from spectroscopy of their nuclear regions --> evaluated at much larger scales



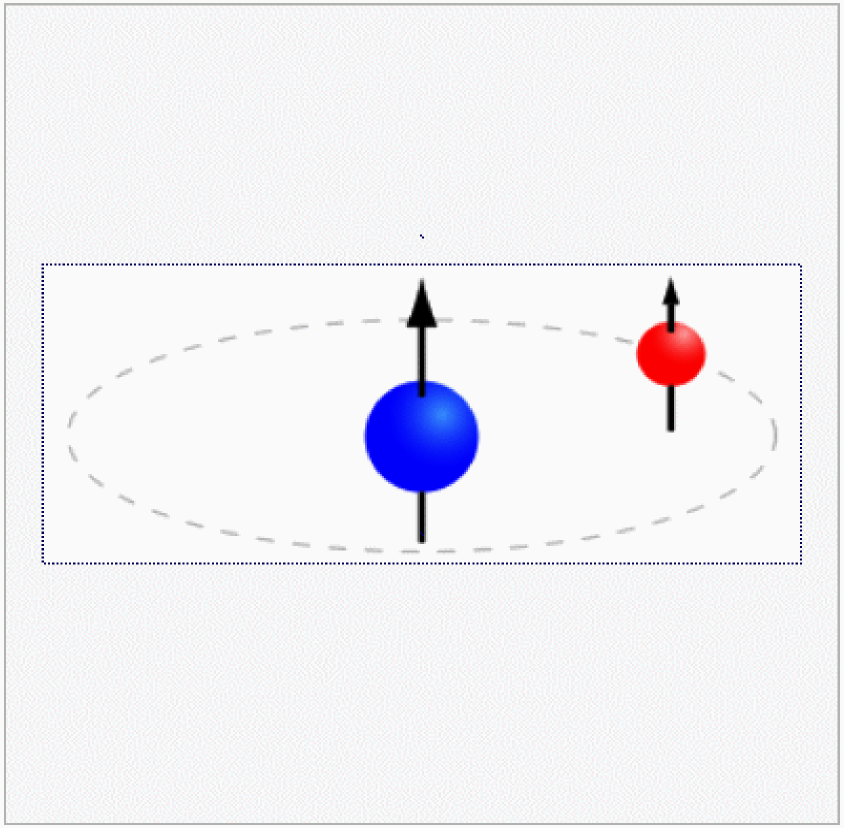
The plot below shows all current measurements of black hole masses in galaxies interior to a radius where the mass of the black hole contributes significantly more to the motions of the stars than the mass of the observed stars.

A remarkably tight correlation is observed with properties of the galactic bulge!! Black hole and bulge Formation must be linked...

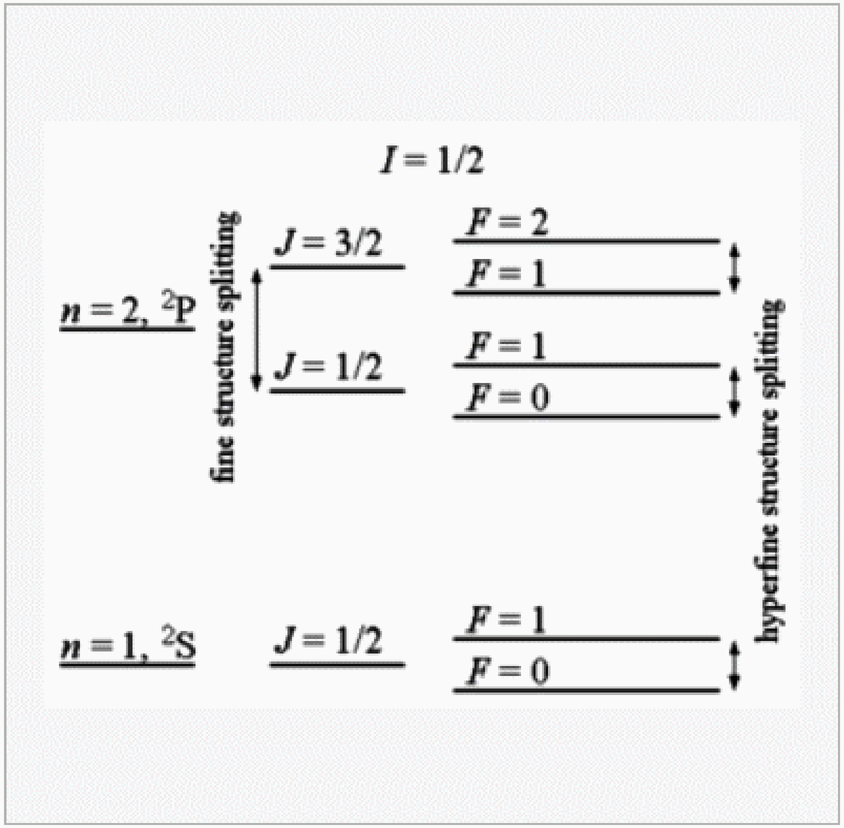


2) Neutral hydrogen in galaxies
(can only be observed at radio wavelengths)

Origin of neutral hydrogen emission



An electron orbiting a proton with parallel spins (pictured) has higher energy than if the spins were anti-parallel.

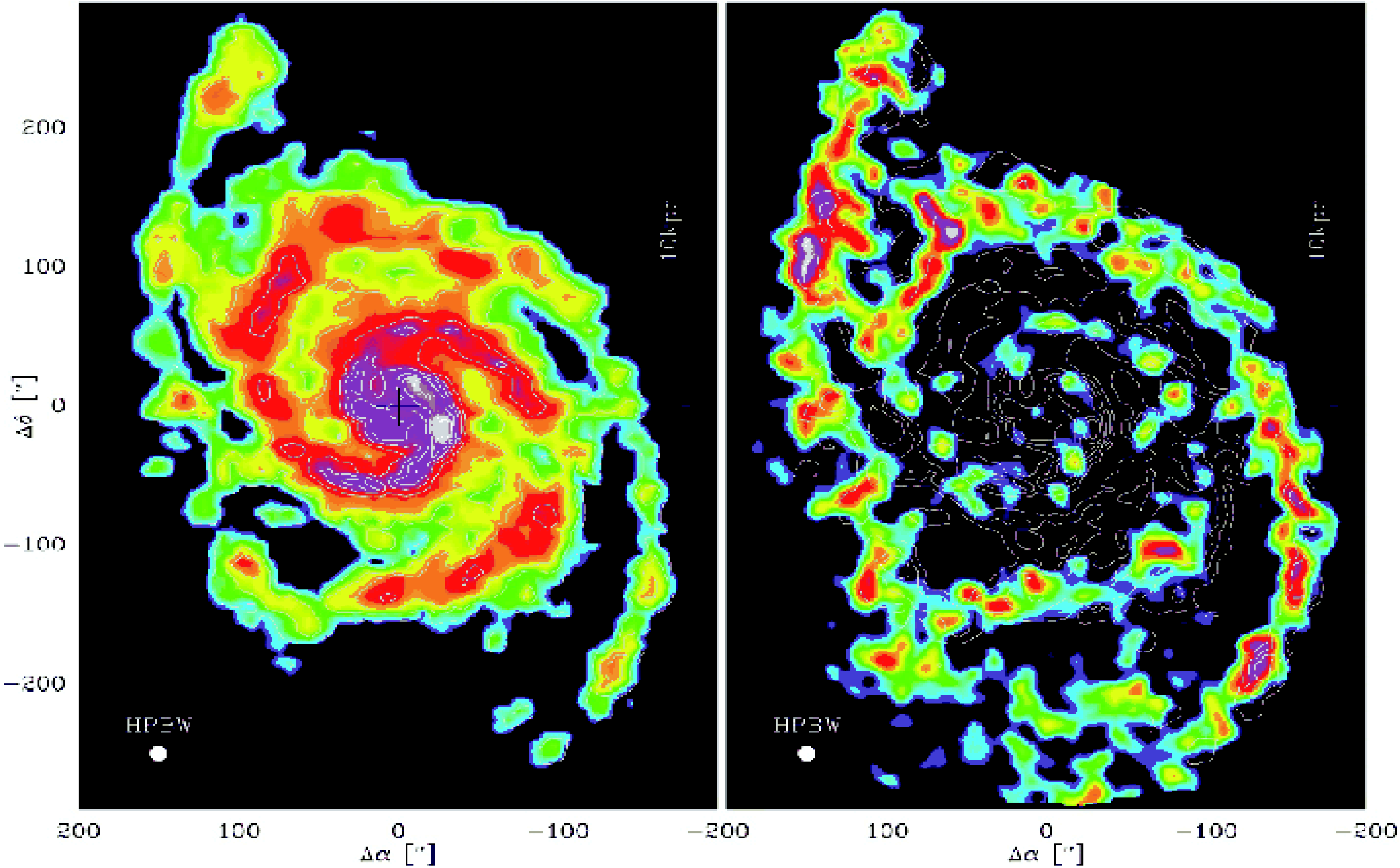


Fine and hyperfine structure in hydrogen. The hyperfine splitting of the ground ^2S state is the source of the 21 cm hydrogen line.

Molecular Clouds

A type of interstellar cloud whose density and size permits the formation of molecules, most commonly molecular hydrogen (H_2), In general molecules are found in cool astrophysical environments where dust will absorb high-energy ultraviolet photons that can destroy molecular bonds.

H_2 is difficult to detect, so the molecule used to infer the presence of H2 is carbon monoxide (CO). The ratio of CO luminosity and H2 mass may vary from one galaxy to another.



The distribution of the CO emission (left) and the 21cm line emission (right) in the nearby galaxy M51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GENERAL OUTLINE OF THE LECTURES

2) COSMOLOGICAL FRAMEWORK: evidence for the Hot Big Bang and an expanding Universe, the Friedmann equations

3) OBSERVATIONAL TESTS: distances and sizes in an expanding Universe, Evidence for a cosmological constant from "standard candles"

4) Thermal history of the Universe, early growth of fluctuations

5) Growth of fluctuations into the non-linear regime, N-body simulations

6) Analysis of N-body simulations: structure and assembly of dark matter halos

7) The behaviour of gas in dark matter halos

8) The formation and evolution of stars in galaxies TBD

COURSE MATERIAL

Slides from lecture available online

Lecture material drawn from a mixture of sources (textbooks, research papers, review articles, web-based material). I will provide a list of background reading to go with every lecture.