Extragalactic Astronomy

Overview

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Extragalactic Astronomy

I. The Milky Way
II. Galaxies
III. Galaxy evolution

II. Galaxies

II. Galaxies

a) Galaxy morphology: Hubble sequence

b) Galaxy types: luminosity-color diagram

c) Surface brightness profiles

d) Galaxy groups and clusters

e) Observation: Rotation curves & gravitational lensing

f) Dark Matter

Spiral Galaxies

M101: face-on galaxy

NGC 4414: slight tilt

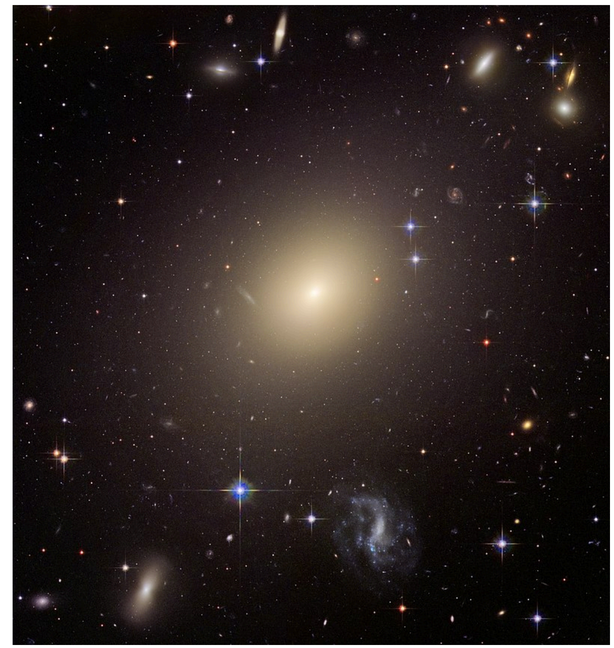
NGC 891: edge-on

Spiral Galaxies

- They have a flat rotating disk with stars, gas and dust
- They have a central stellar concentration: the bulge. Can be shaped like a bar
- They have a halo of stars with many globular clusters
- Many young stars and star formation in the spiral arms
- Stars orbit the disk in circles and more randomly in bulge and halo
- Supermassive black hole

Elliptical Galaxies

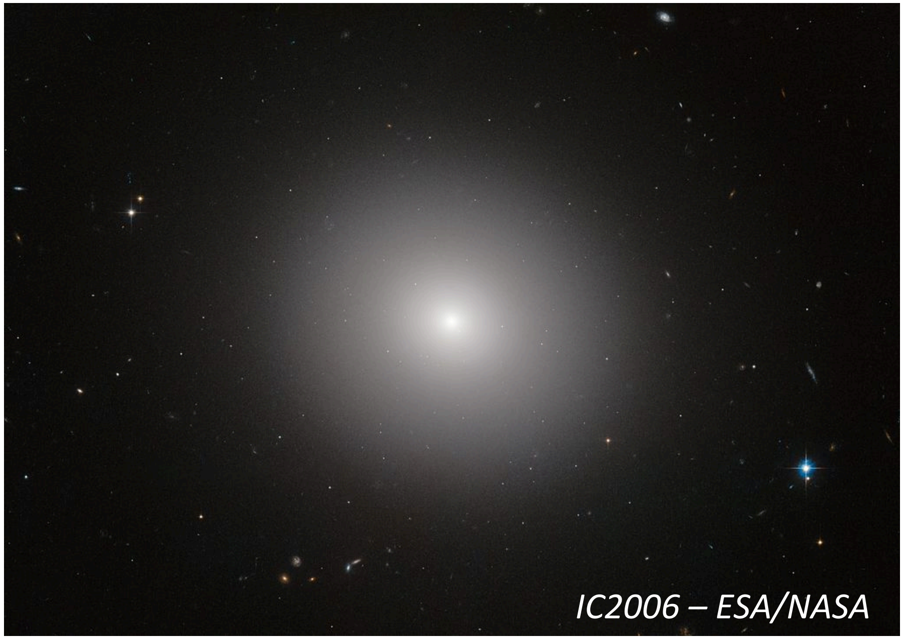
M87: part of Virgo cluster



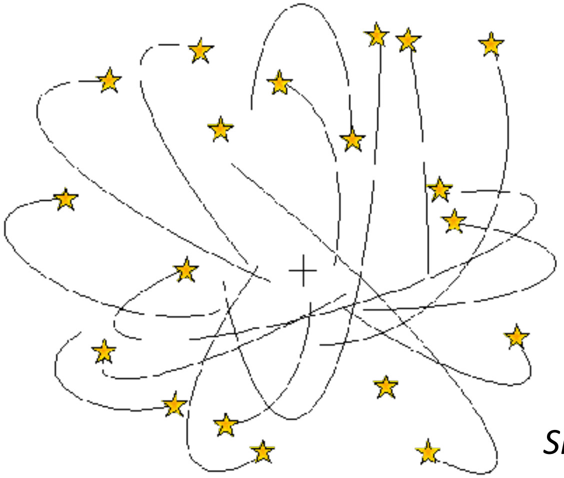
ES0325-G004: part of Abell S0740 cluster

Elliptical Galaxies

- Ellipsoidal shape with less structure: no disk
- Random star orbits around center
- Stars are on average older (less massive) than in spirals, so they look redder
- Less presence of interstellar medium (cool gas and dust) and less star formation
- Span many sizes
- Supermassive black hole in the center

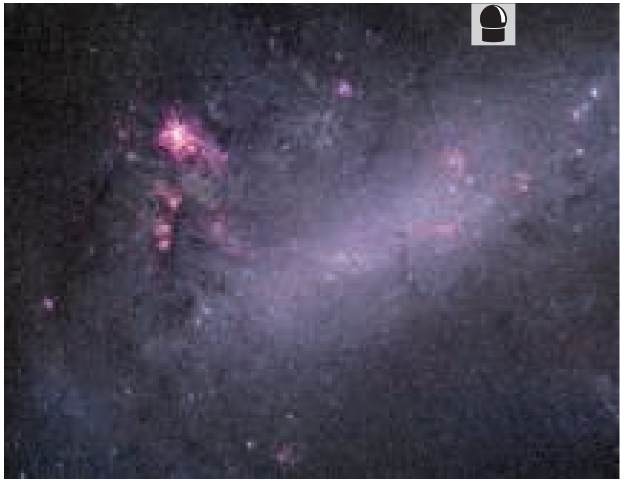


IC2006 – ESA/NASA



Smith, UCal

Irregular Galaxies

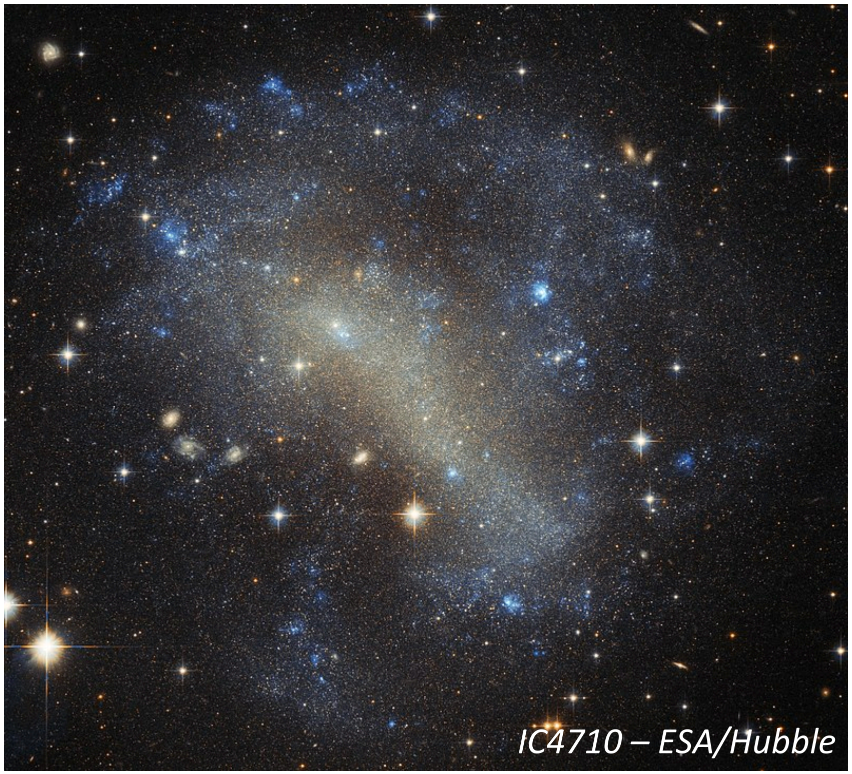


Large Magellanic Cloud

Small Magellanic Cloud

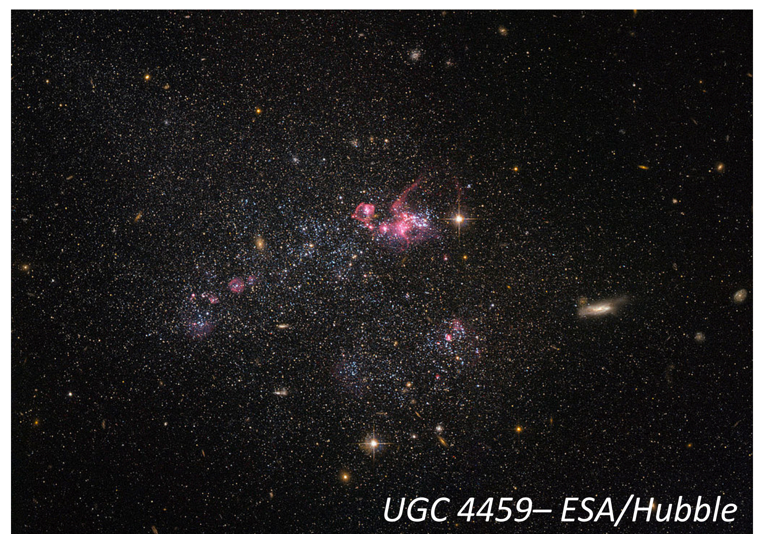
NGC 1427A

Irregular Galaxies

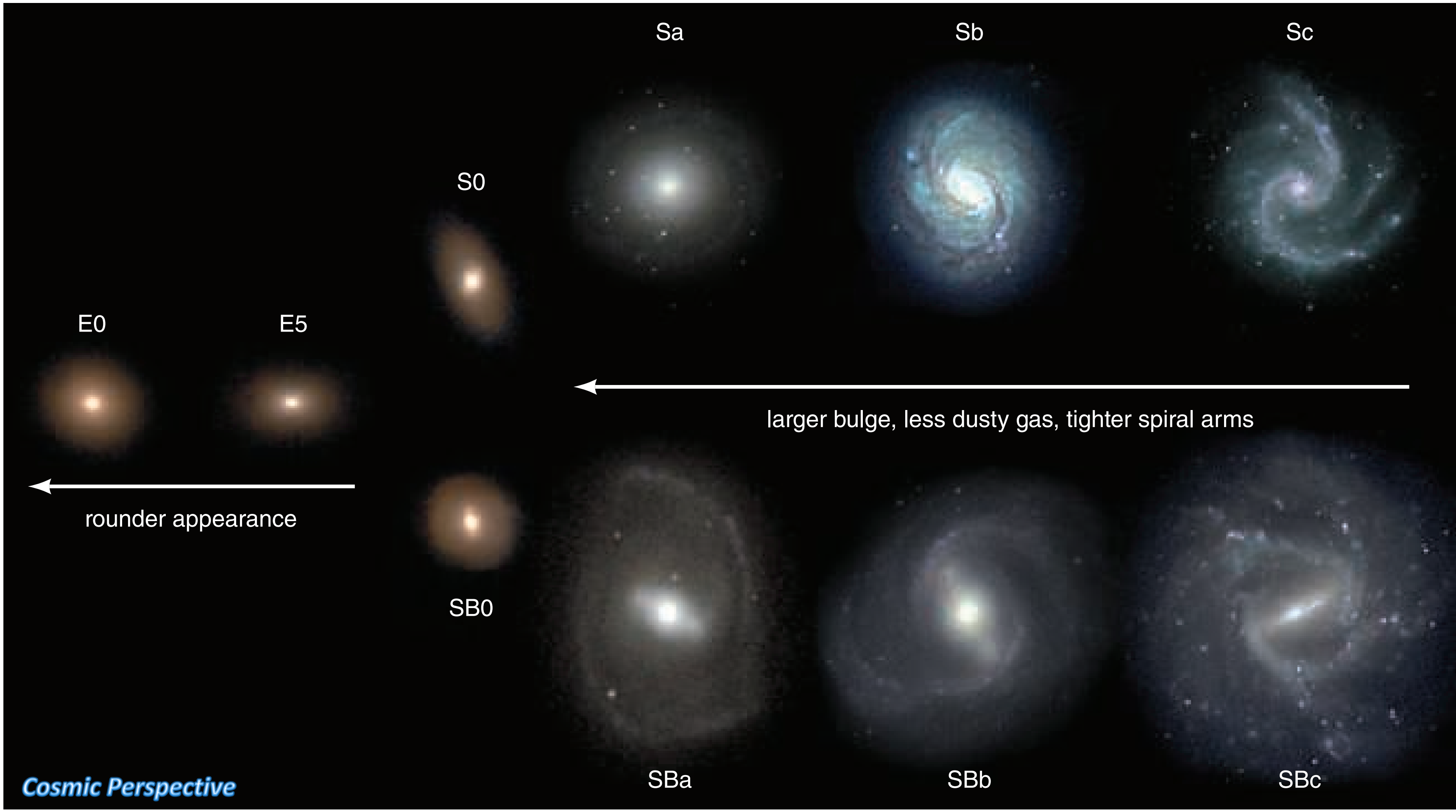

IC4710 – ESA/Hubble

- No regular shape
- No bulge, no spiral arms
- Normally small (1/10 of Milky Way's mass)

- Abundant gas and dust
- Young massive stars


UGC 4459– ESA/Hubble

Hubble's tuning fork



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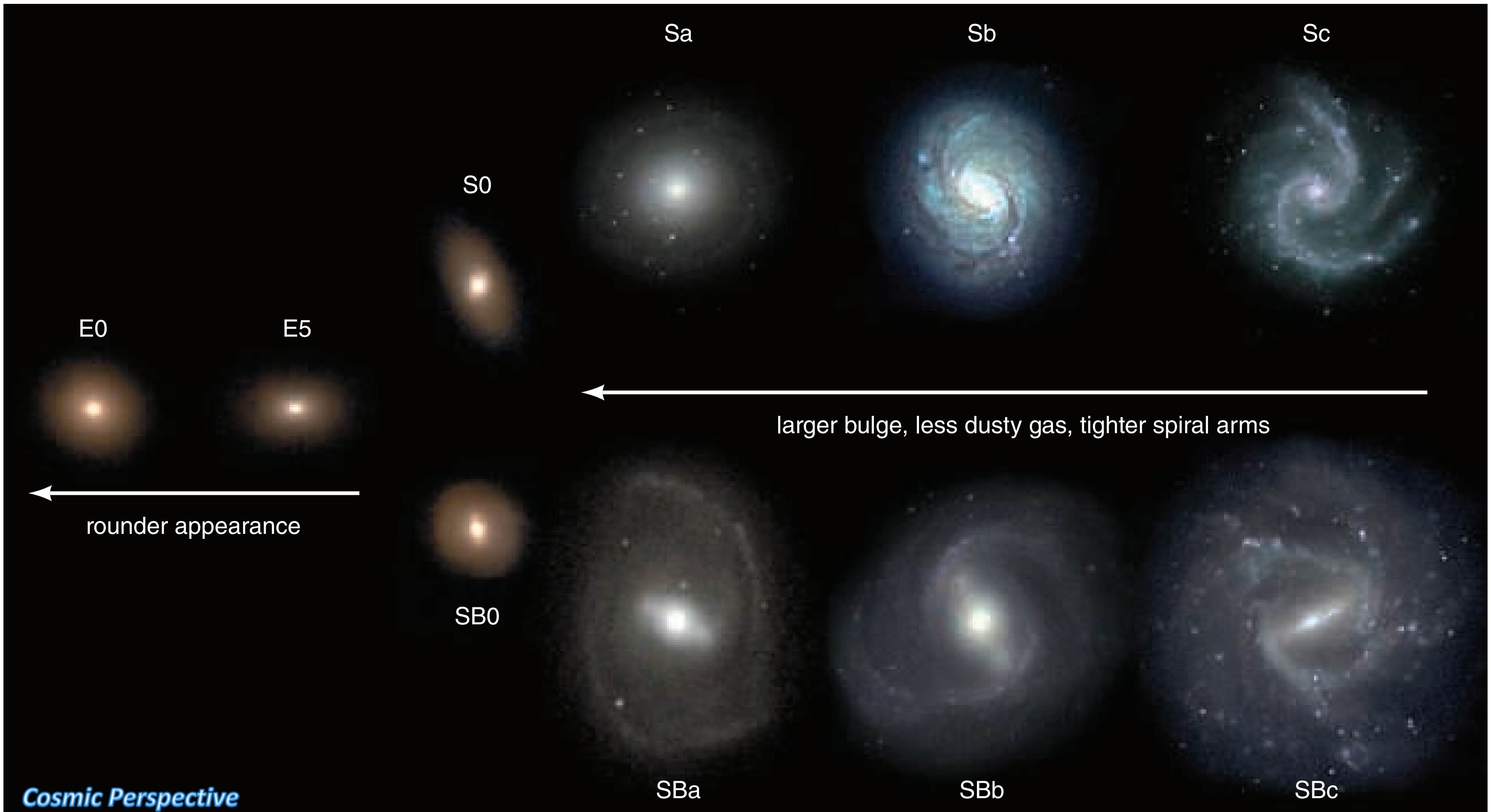


No bar

Bar

Elliptical galaxies

Spiral galaxies

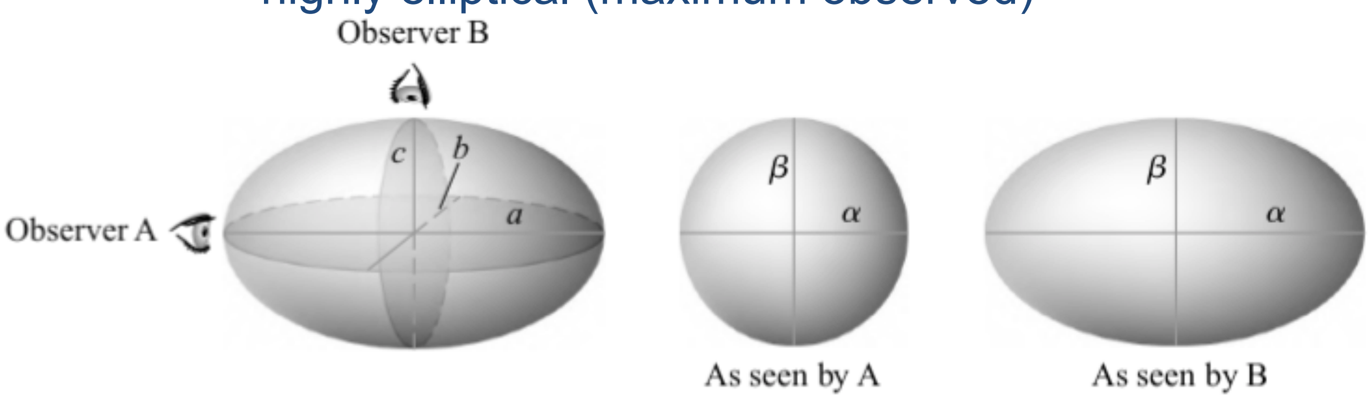
Elliptical galaxies

Hubble made a division based on the **ellipticity** of a galaxy $\epsilon \equiv 1 - \beta/\alpha$

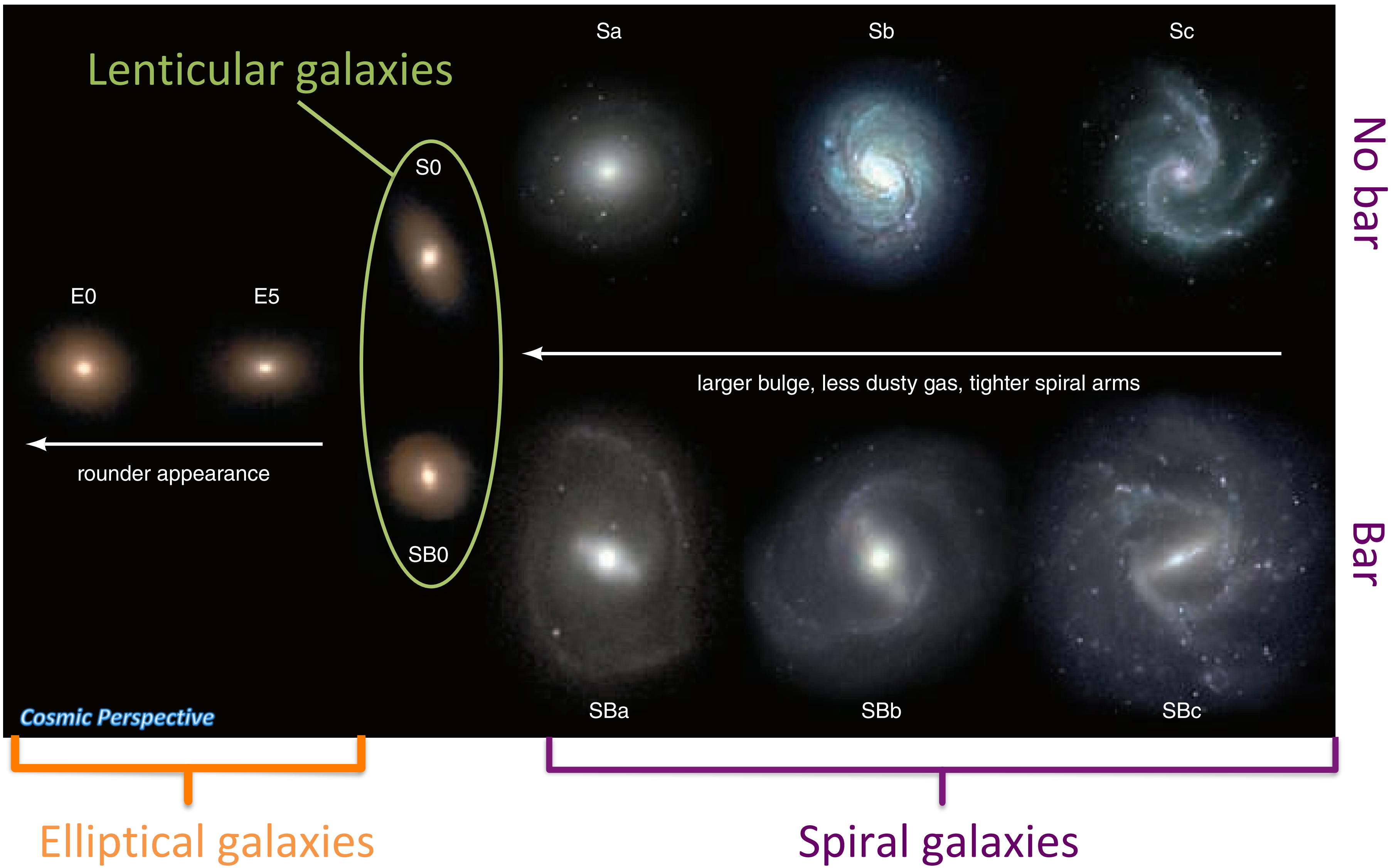
α, β $\longrightarrow$ apparent major and minor axes of the ellipsoid projection on the plane of the sky

E0 $\epsilon = 0$ spherical

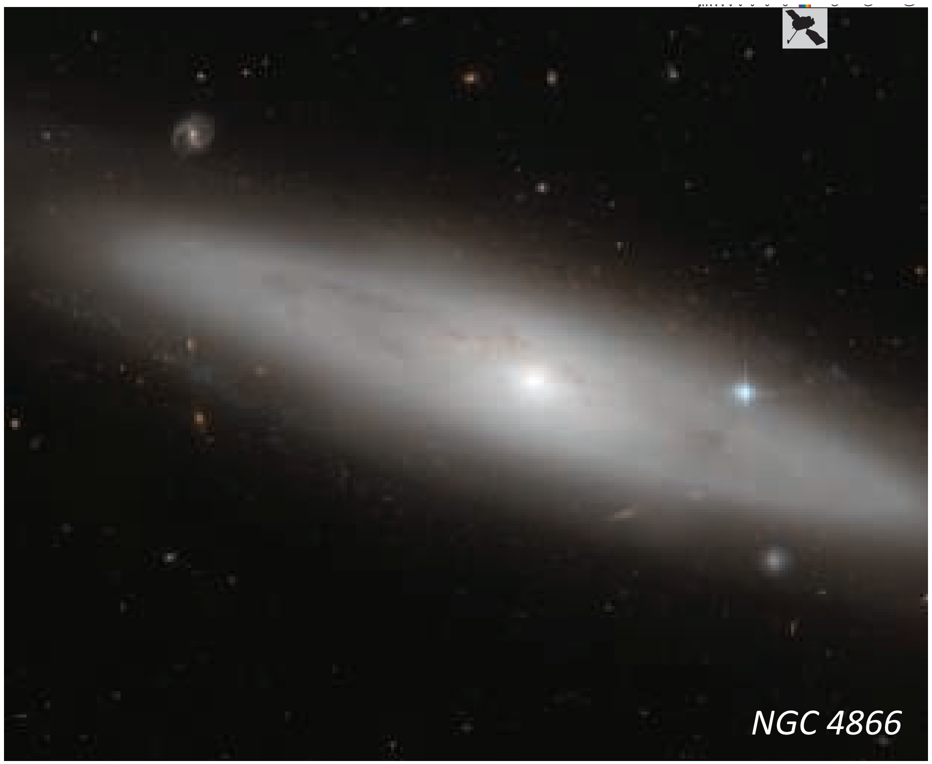
E7 $\epsilon = 0.7$ highly elliptical (maximum observed)



Hubble's tuning fork

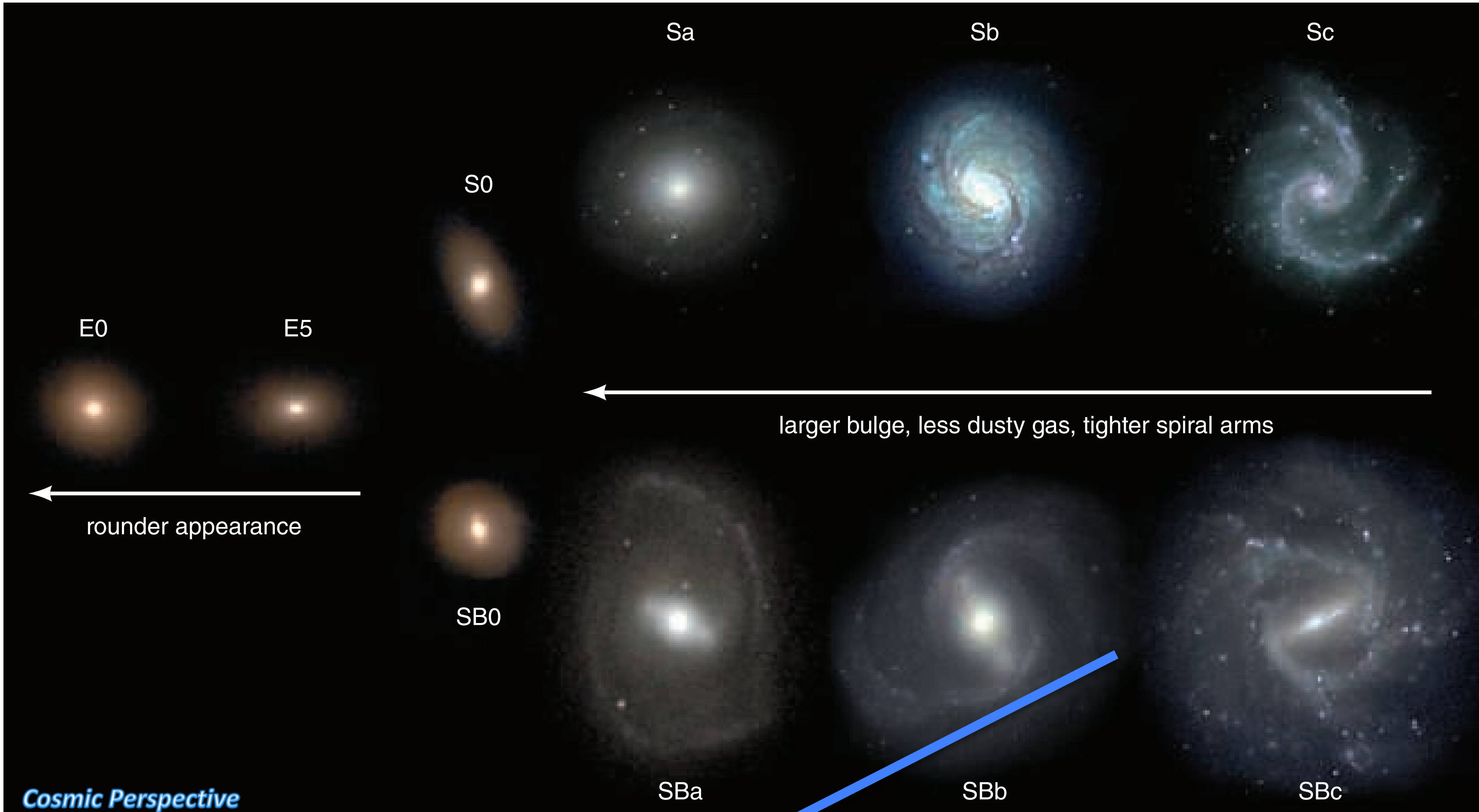


Lenticular Galaxies



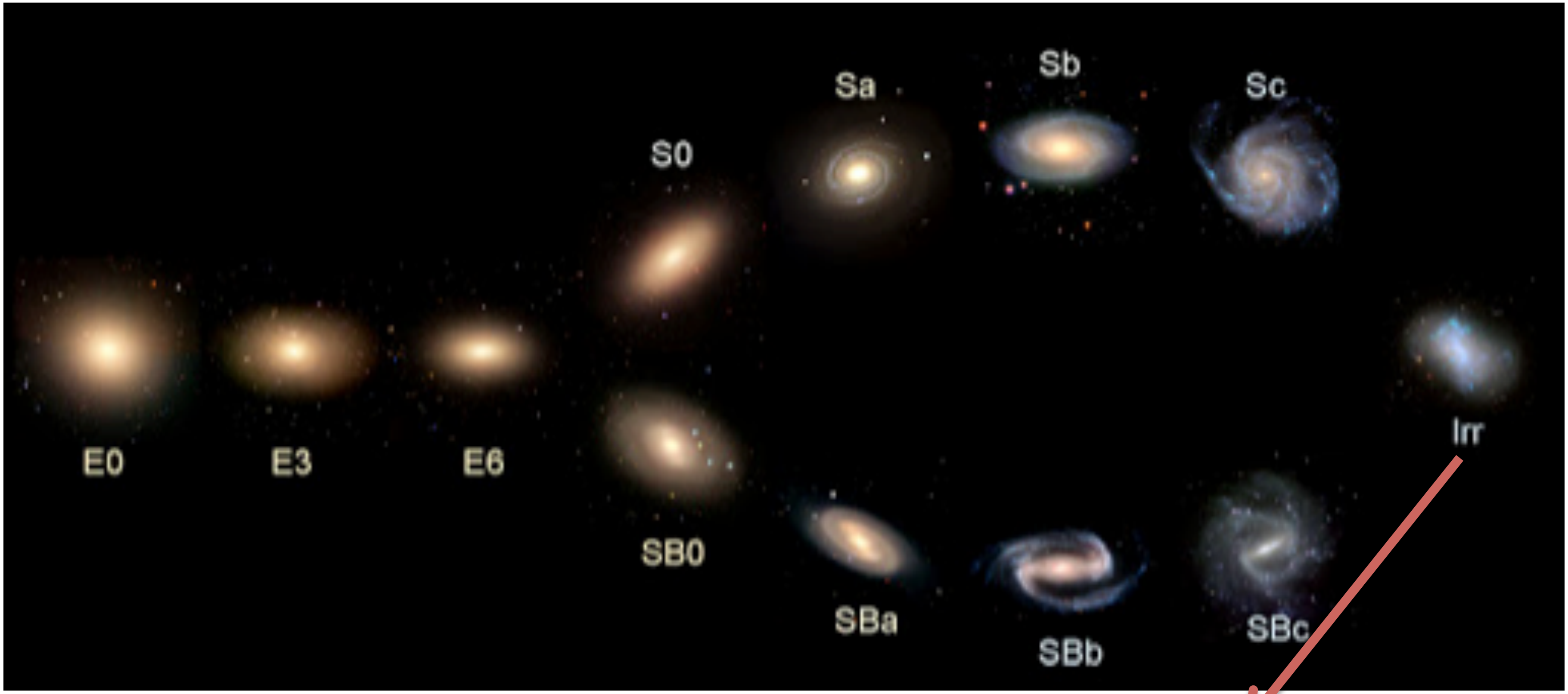
- They have disks and bulge components like spirals but no arms
- Less cool gas than spirals but more than elliptical
- Intermediate between spirals and galaxies

Hubble's tuning fork



Milky Way is believed to be a barred spiral galaxy

Hubble's tuning fork



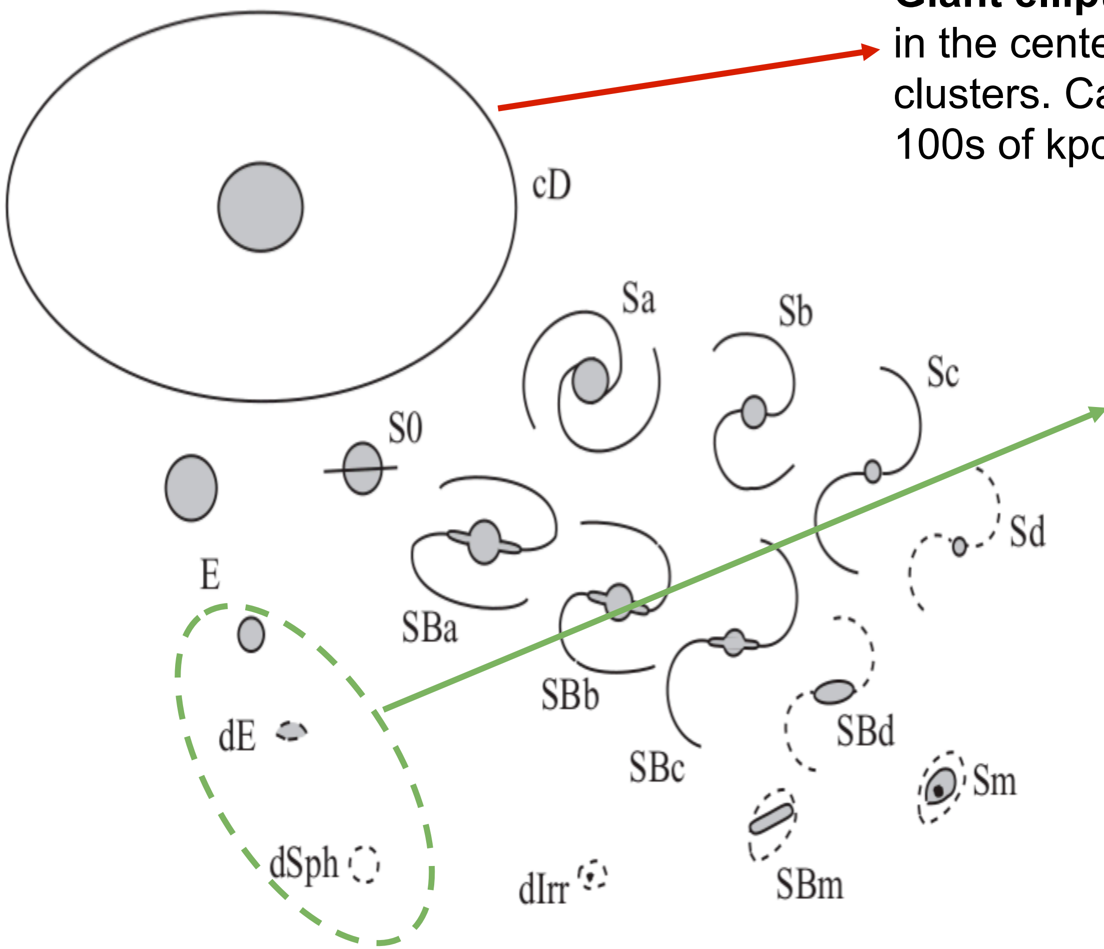
Irregular galaxies

Dwarf Spheroidal Galaxies

- Similar to elliptical galaxies but smaller and spheroidal
- Much fainter
- Millions of stars (compared to trillions in giants)
- Lower metallicity
- Very old population
- Most common in the universe although difficult to detect: ten in Local Group


NGC 147: Local Group - *Nielsen*

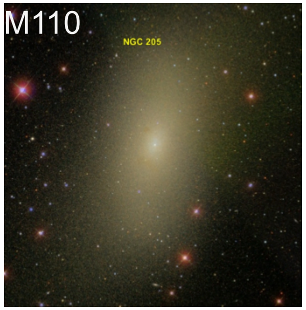
Beyond Hubble: a modified galaxy classification scheme

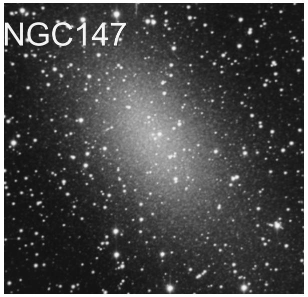


Giant ellipticals, found in the centers of galaxy clusters. Can stretch 100s of kpc

Faint ellipticals:

- Compact
- Diffuse:
    - Dwarf ellipticals (dE) < 10 kpc
    - Dwarf spheroidals (dSph) < 0.5 kpc





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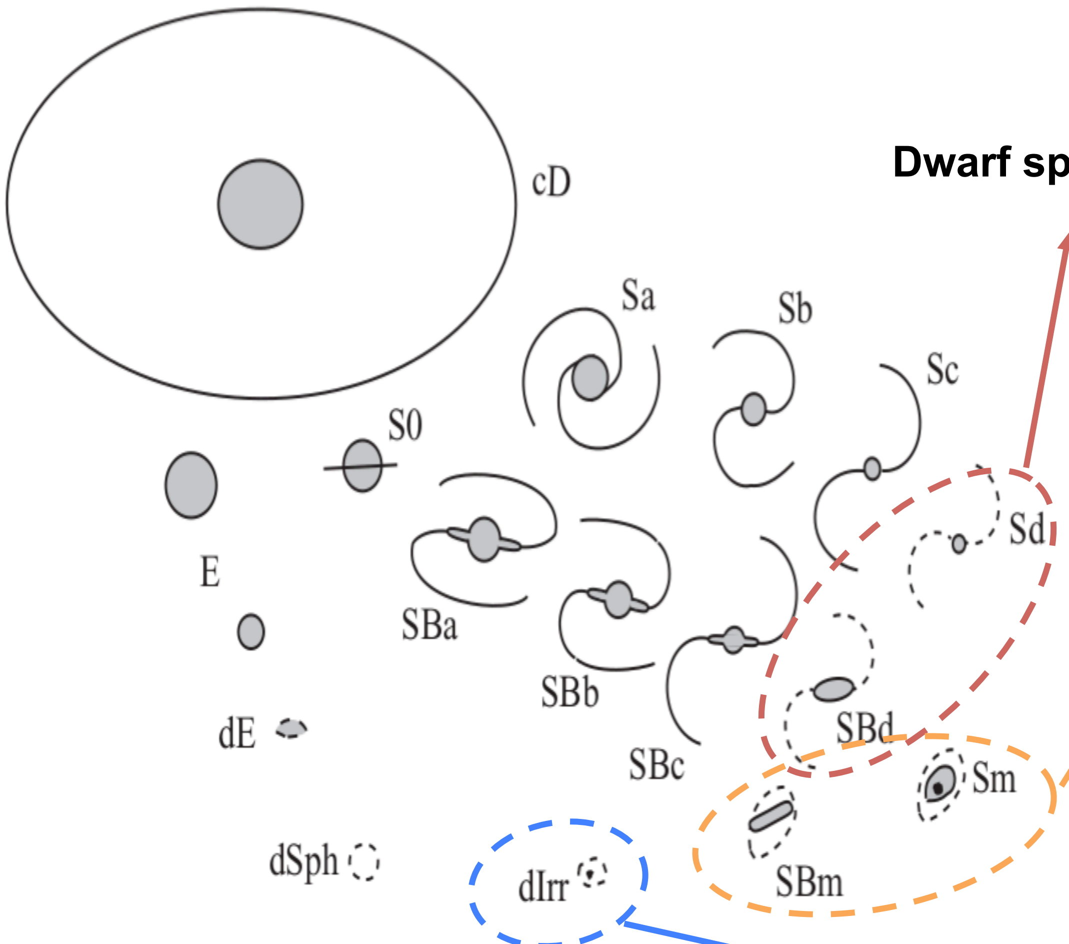
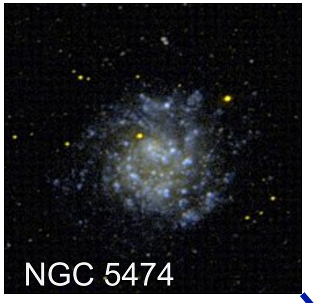


Dwarf spirals, < 5kpc

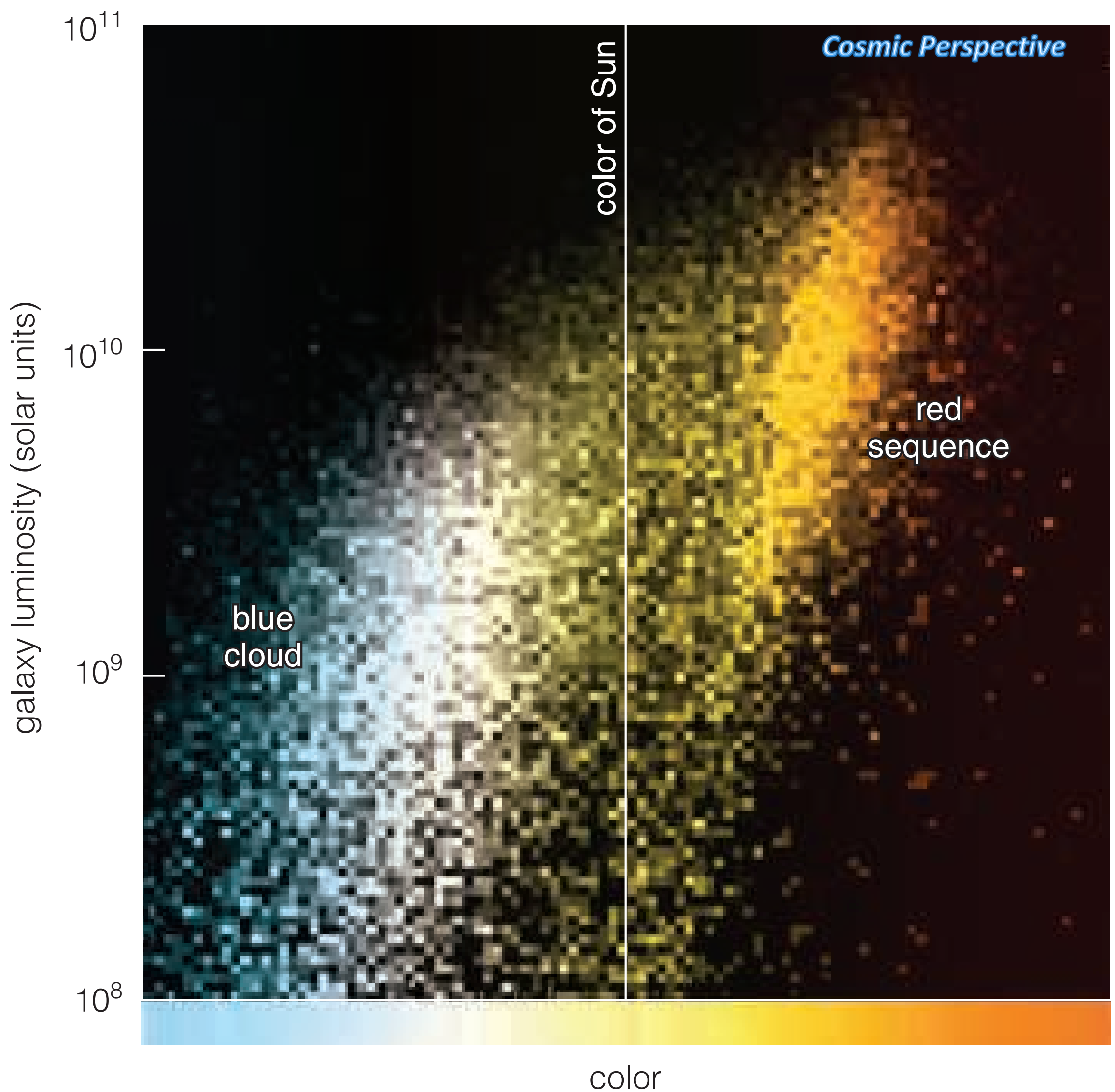


Hubble's Irr

Magellanic spirals

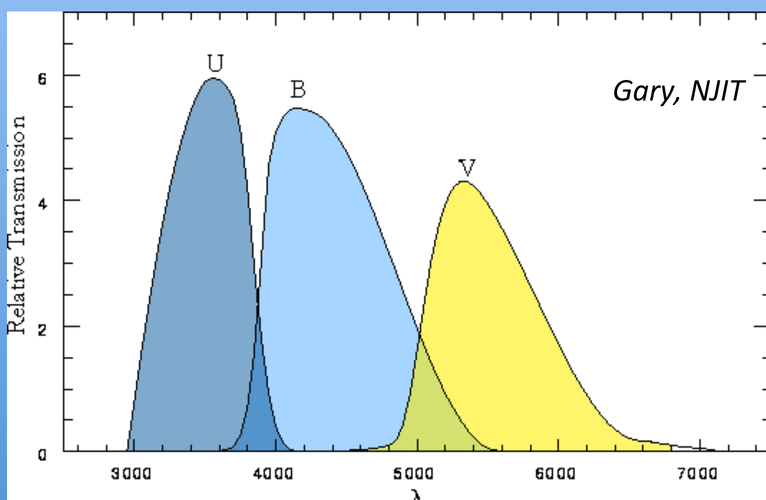
Dwarf Irregulars

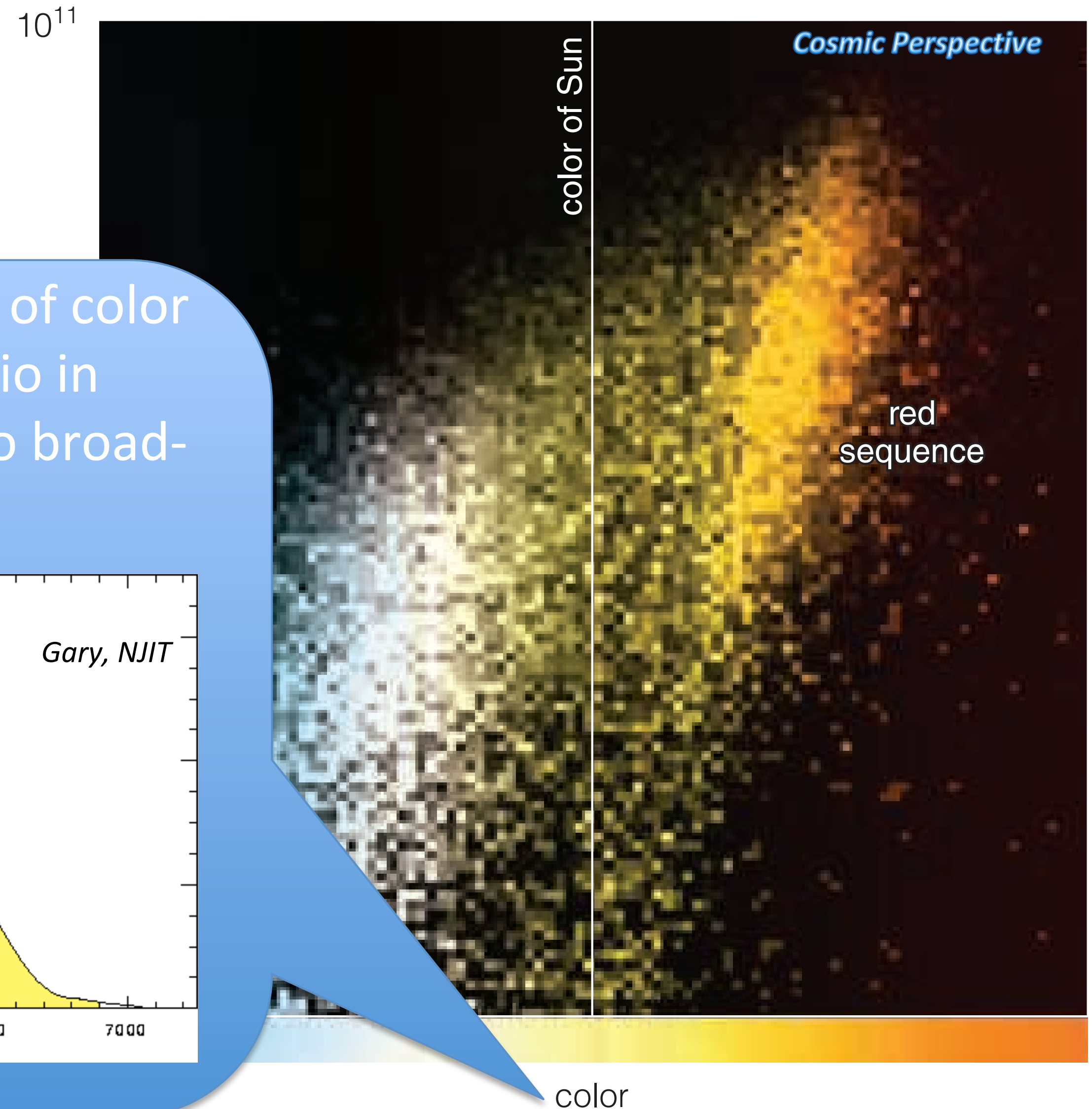
Galaxy luminosity vs color



Galaxy luminosity vs color

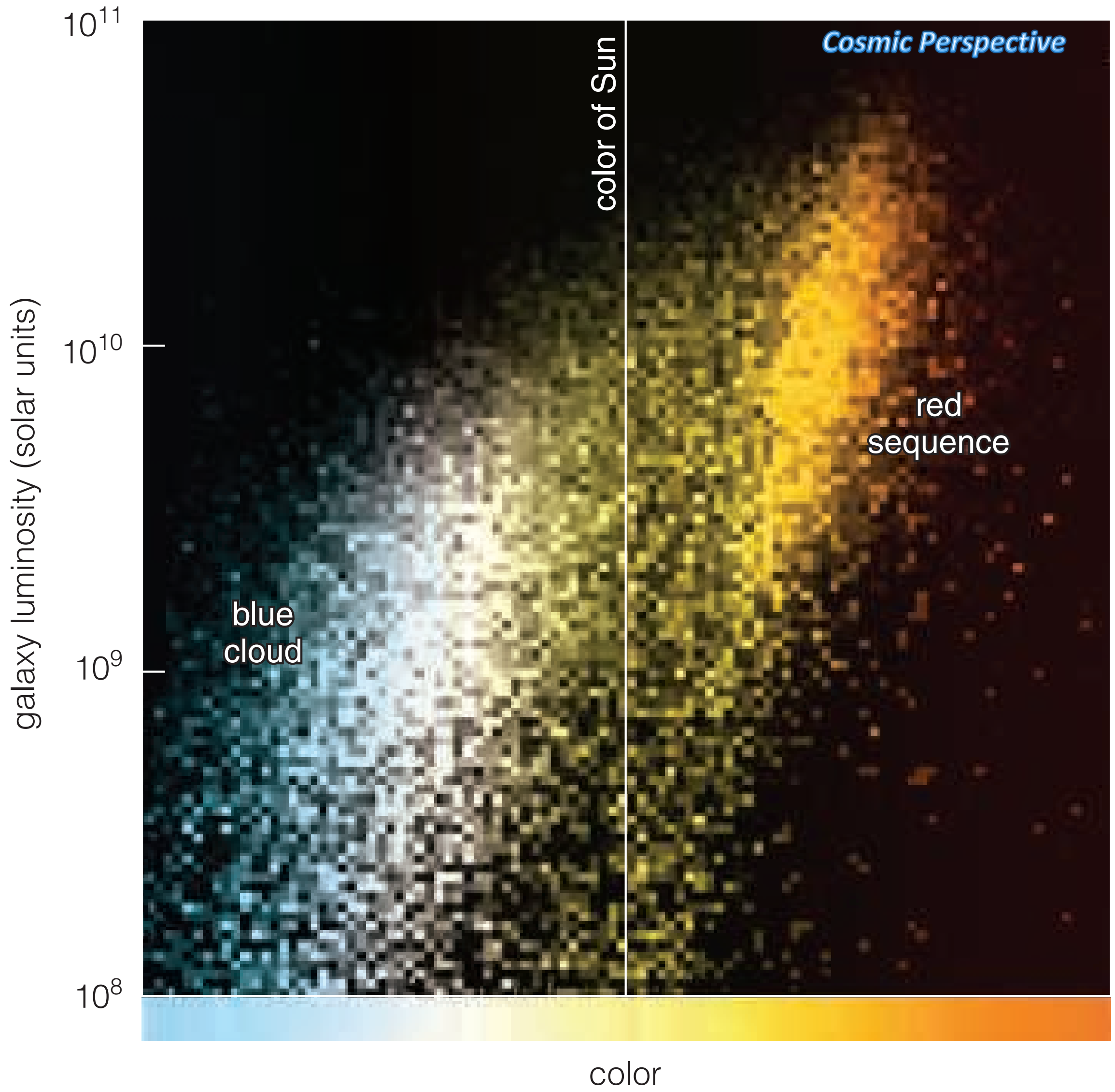
A quantitative measure of color is defined as the ratio in brightness between two broad-band filters





Galaxy luminosity vs color

- Blue cloud: spiral and irregular galaxies with many hot young stars
- Red sequence: elliptical galaxies with old stars



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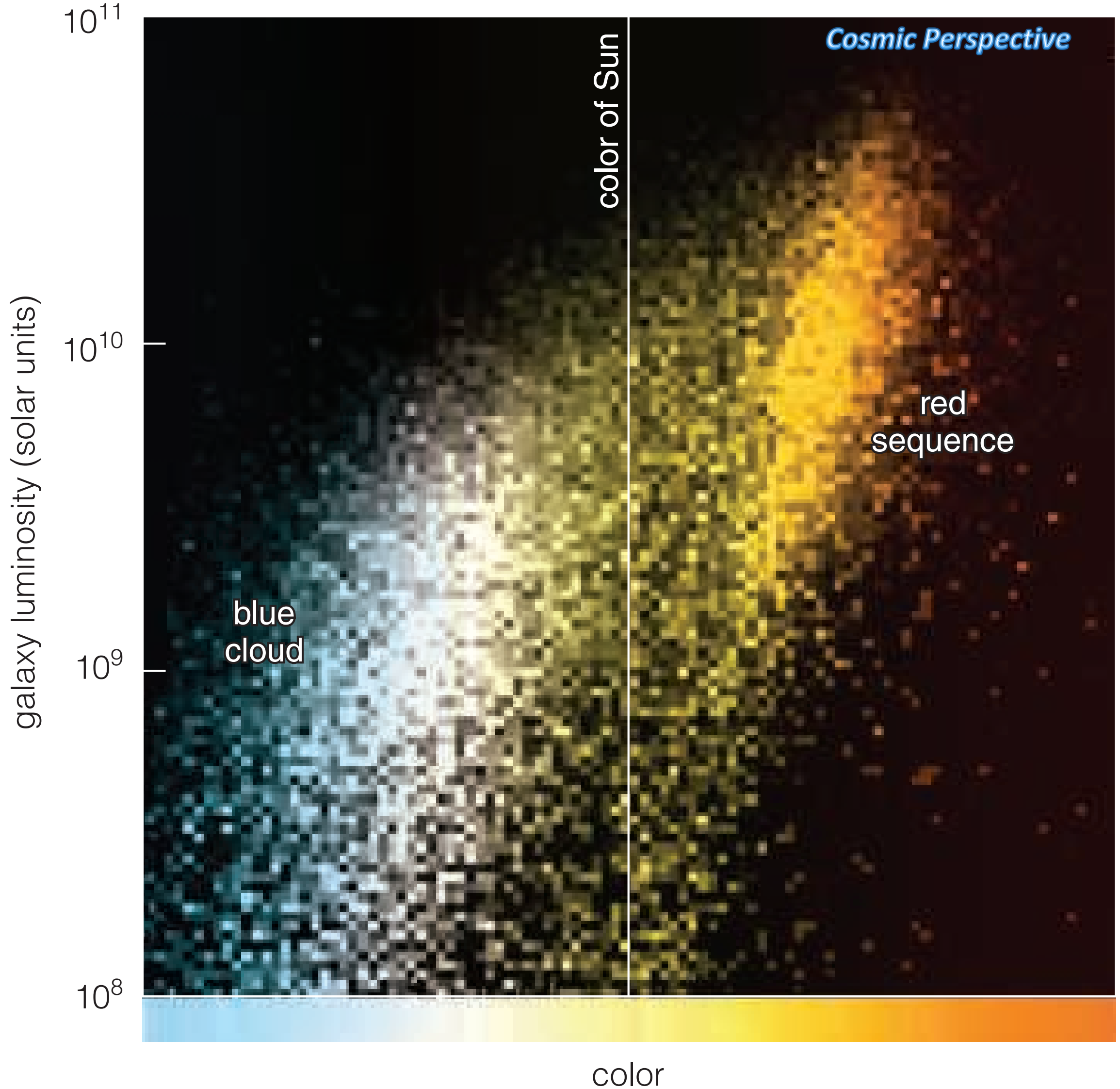
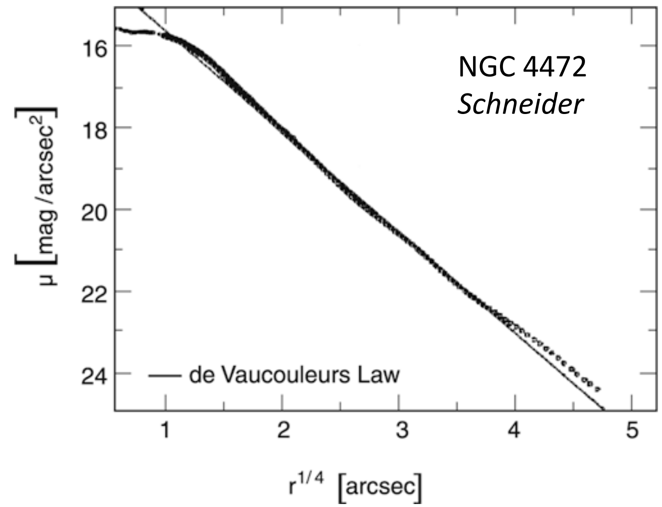


➔ Evolution from blue cloud to red sequence?

Galaxy brightness profiles

- **Elliptical galaxies approximately follow the *de Vaucouleurs* profile (like the Milky Way bulge)**

$$\boxed{I(R) = I_{\rm e}\,\exp\left(-7.669\left[(R/R_{\rm e})^{1/4} - 1\right]\right)}$$



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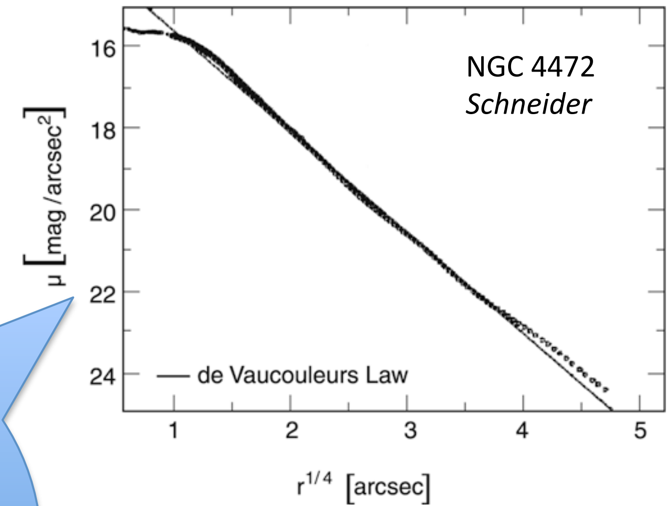

Magnitude is an inverse logarithmic brightness of an object on a given band

Galaxy brightness profiles

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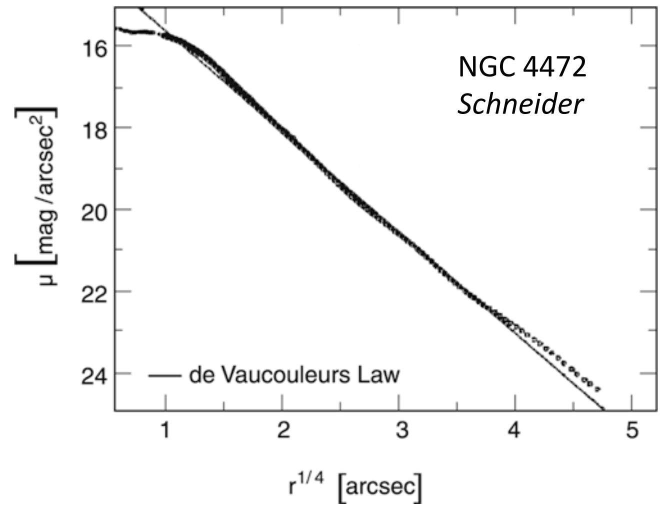
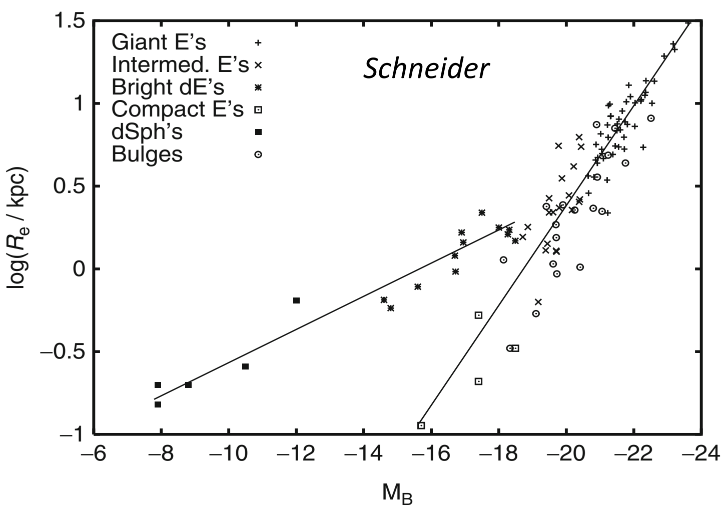
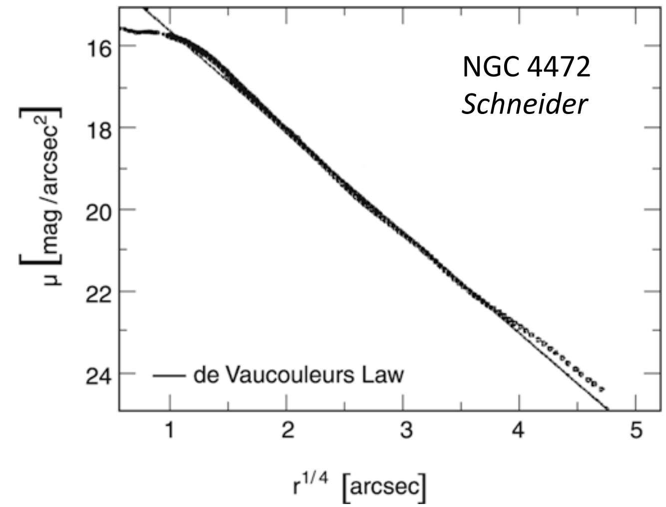


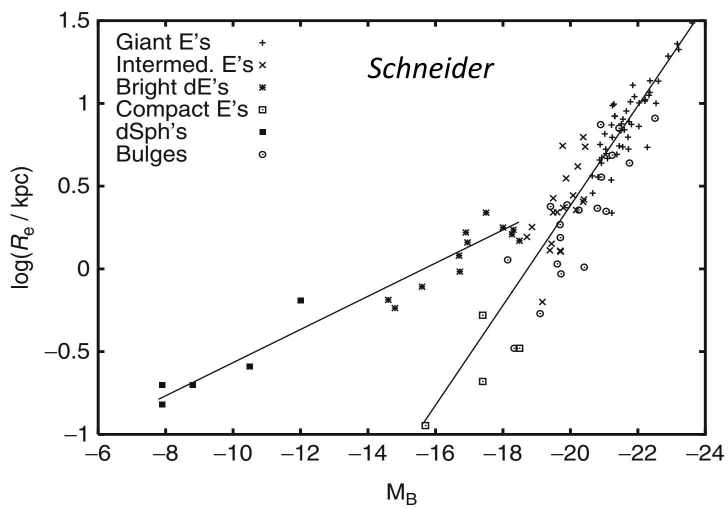


- **Effective radius (1/2 of light is emitted) correlates with brightness**

Galaxy brightness profiles

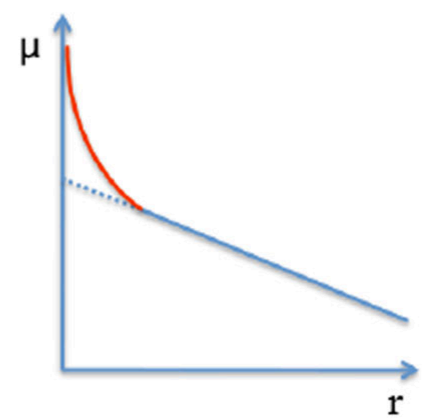
- Elliptical galaxies approximately follow the *de Vaucouleurs* profile (like the Milky Way bulge)

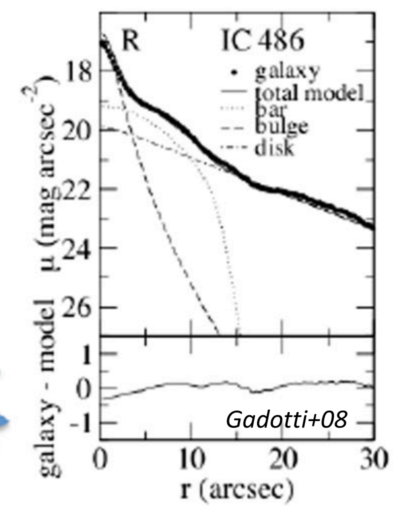




- Effective radius (1/2 of light is emitted) correlates with brightness

- Spiral galaxy bulges also follow the *de Vaucouleurs* profile whereas its disks follow *exponential* brightness profiles

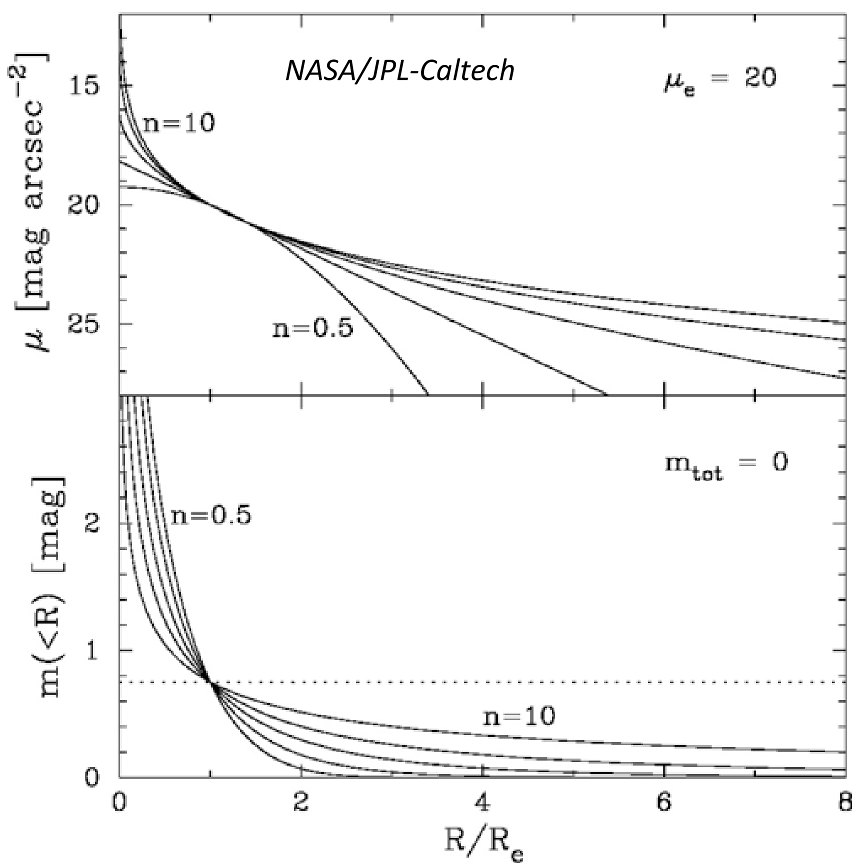




Brightness profiles: Sérsic profiles

$$\log\left(\frac{I(R)}{I_e}\right) = -b_n\left[\left(\frac{R}{R_e}\right)^{1/n} - 1\right]$$

- Sérsic profiles: *useful* parameterization of brightness profiles of multiple galaxies in terms of Sérsic index n, b_n and R_e
- $n=1$ is exponential, $n=4$ is de Vaucouleurs profile
- Larger n means more central concentration of light
- May not fit all galaxies and some need multiple components



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Sérsic index

Surface brightness (lum/area)

Surface brightness at Re

Effective radius at which half of the light is emitted

- Sérsic profiles: useful parameterization of brightness profiles of multiple galaxies in terms of Sérsic index n, b_n and R_e
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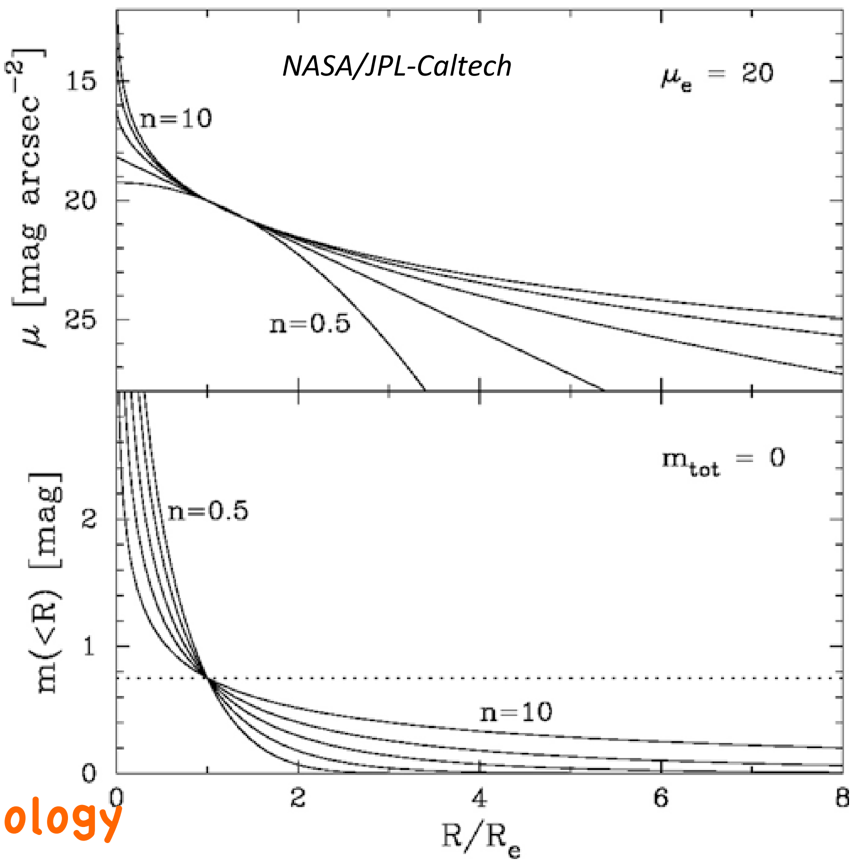
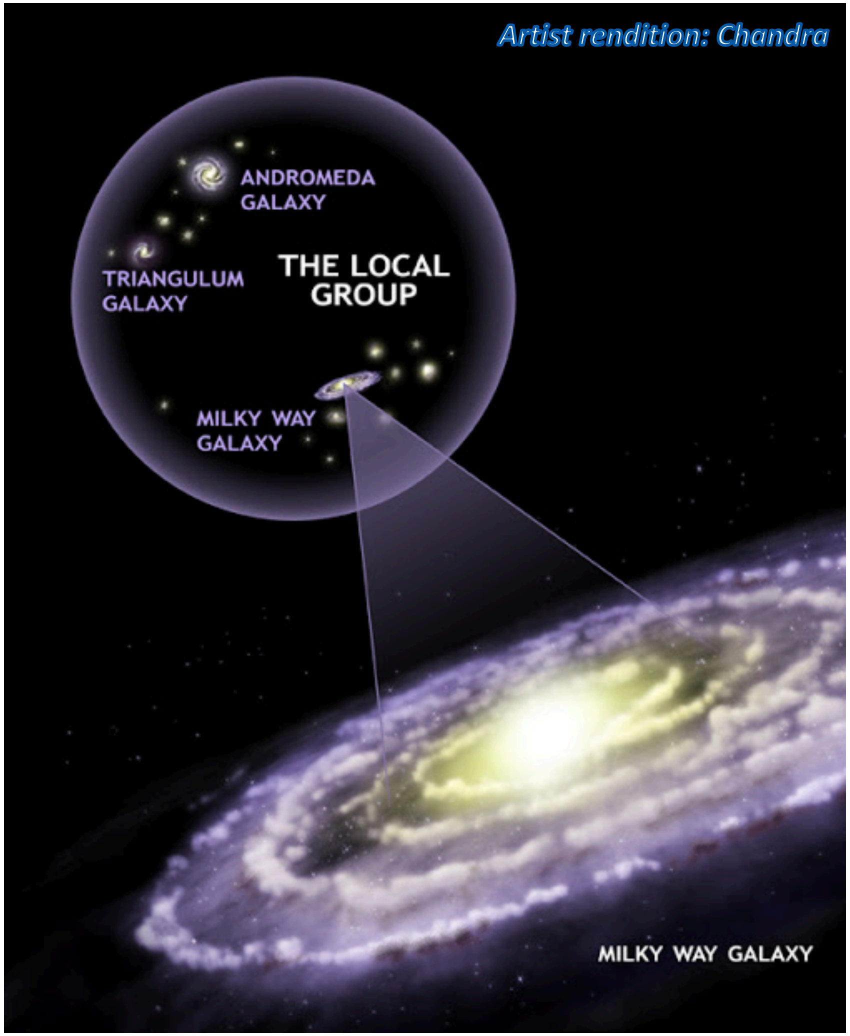


→ Sérsic parameters relate to morphology type and color/brightness

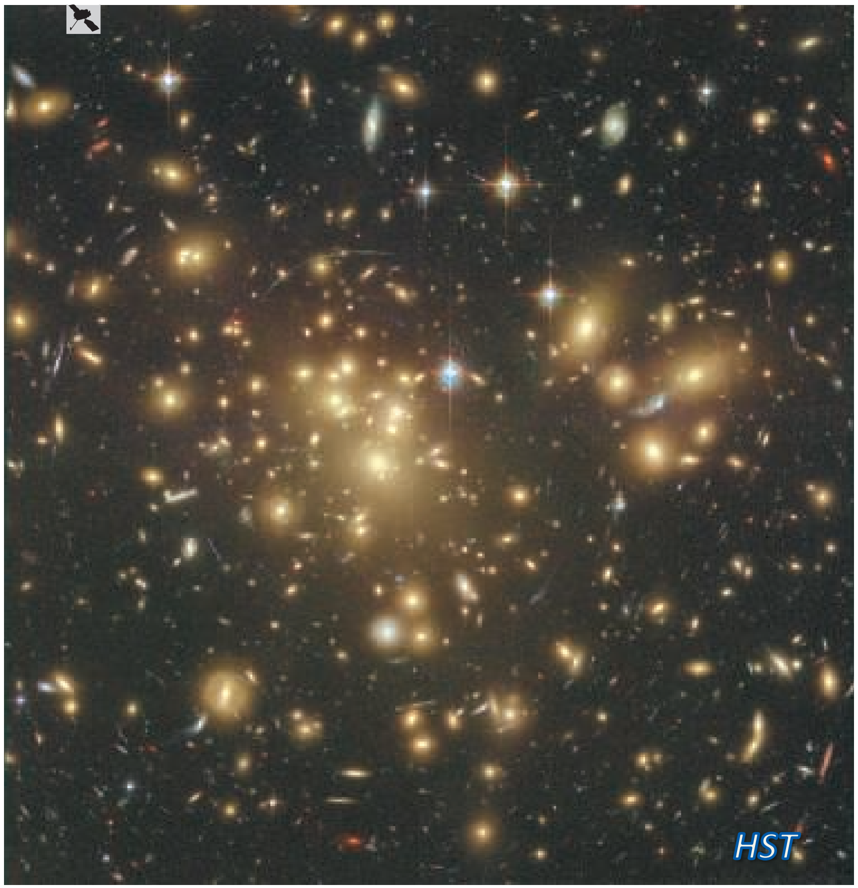
Groups of galaxies



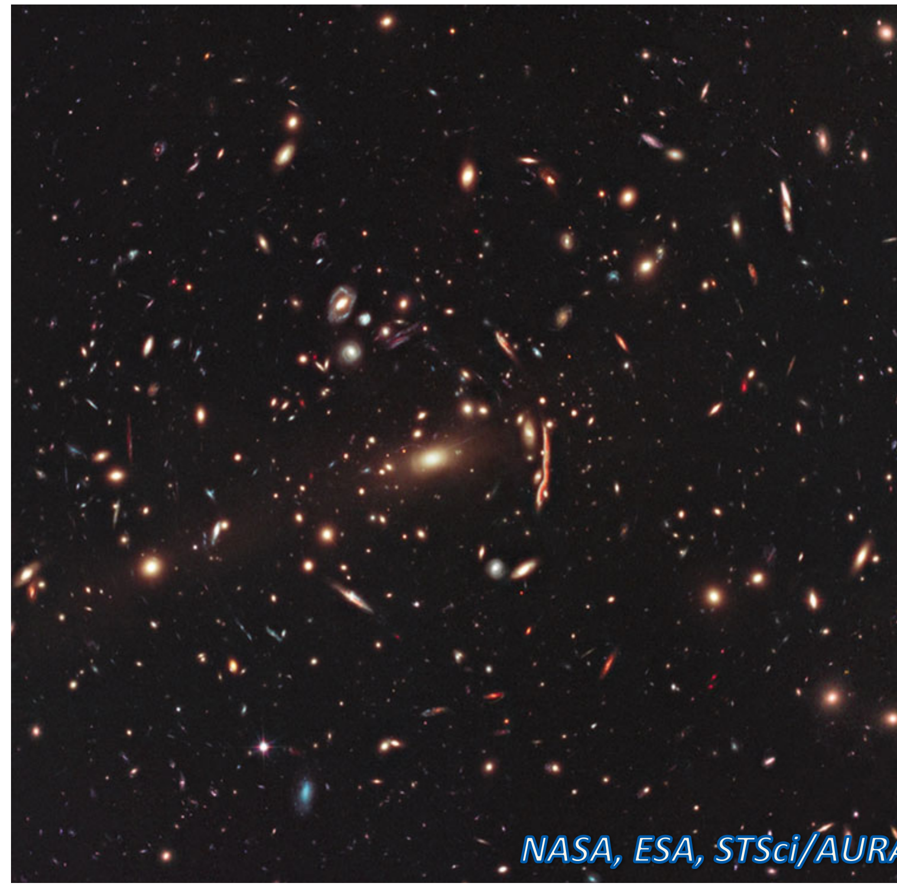
Local Group: Milky Way,
Andromeda and 70 small galaxies

Hickson Compact Group 87:
3 spirals, 1 elliptical

Clusters of galaxies

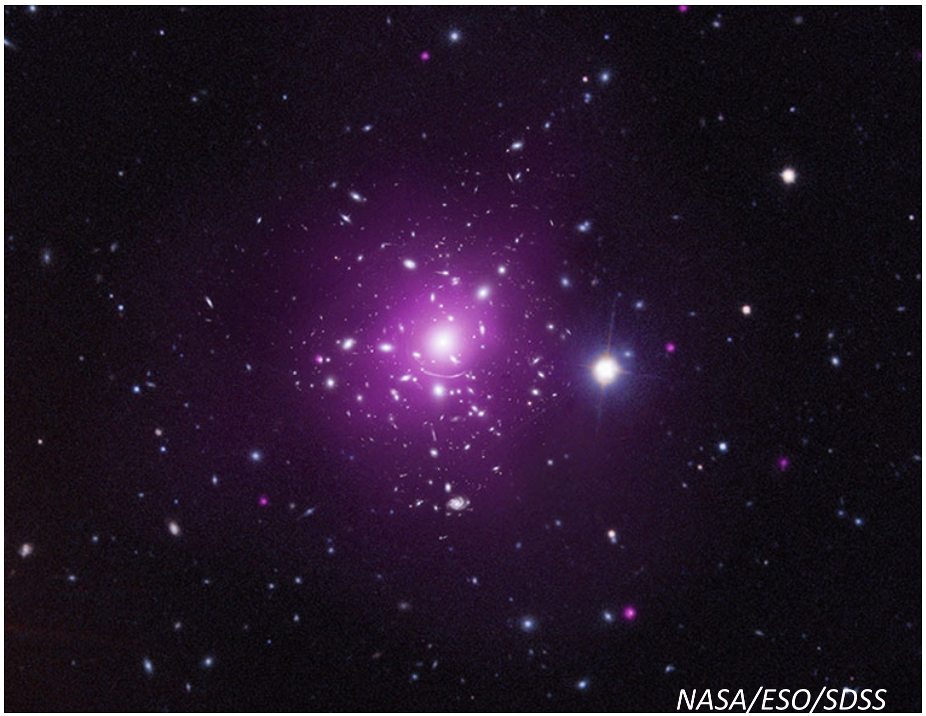


Abell 1689



MACS J1206.2-0847

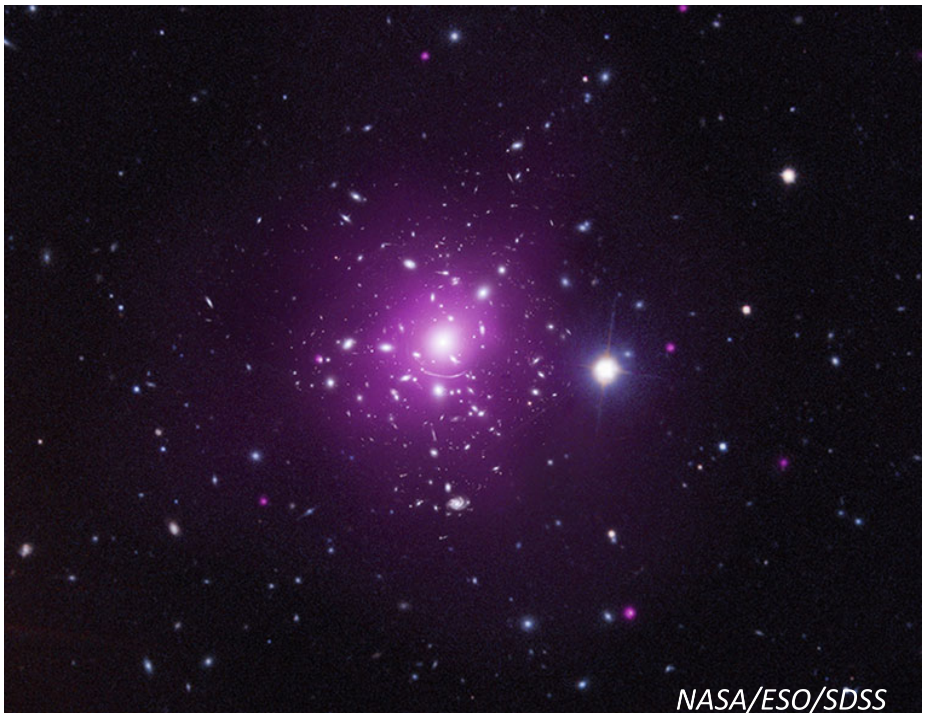
Clusters of galaxies



Abell 383 –X-ray/optical

- Galaxies gravitationally bound in *groups* (tens) or *clusters* (hundreds to thousands)
- Elliptical galaxies make up more than half of central concentration
- Most luminous galaxies are in the center

Clusters of galaxies



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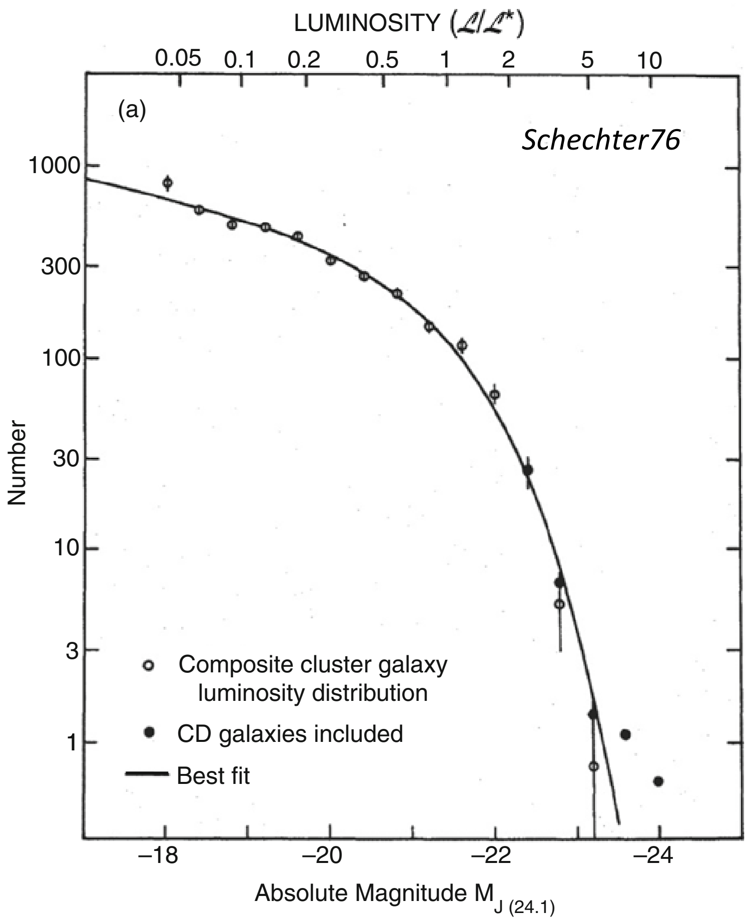
➔ Environment help to determine galaxy type?

Galaxy luminosity function



Based on 13 clusters

- Distribution of galaxies as a function of luminosity
- Less luminous galaxies are more frequent
- Well modeled by Schechter function:

Slope (free)

$$\Phi(L) = \left(\frac{\Phi^*}{L^*}\right)\left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-L/L^*\right)$$

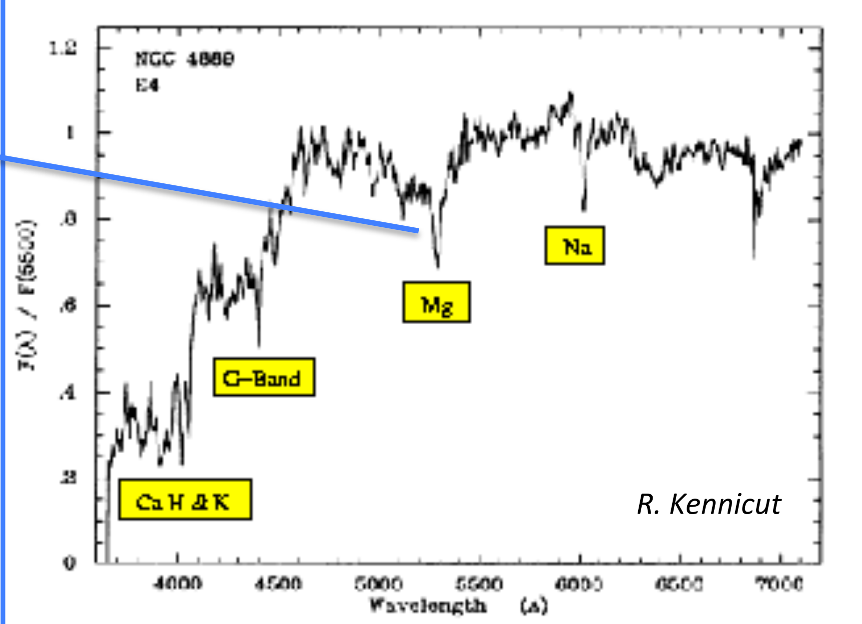
Normalization factor (free)

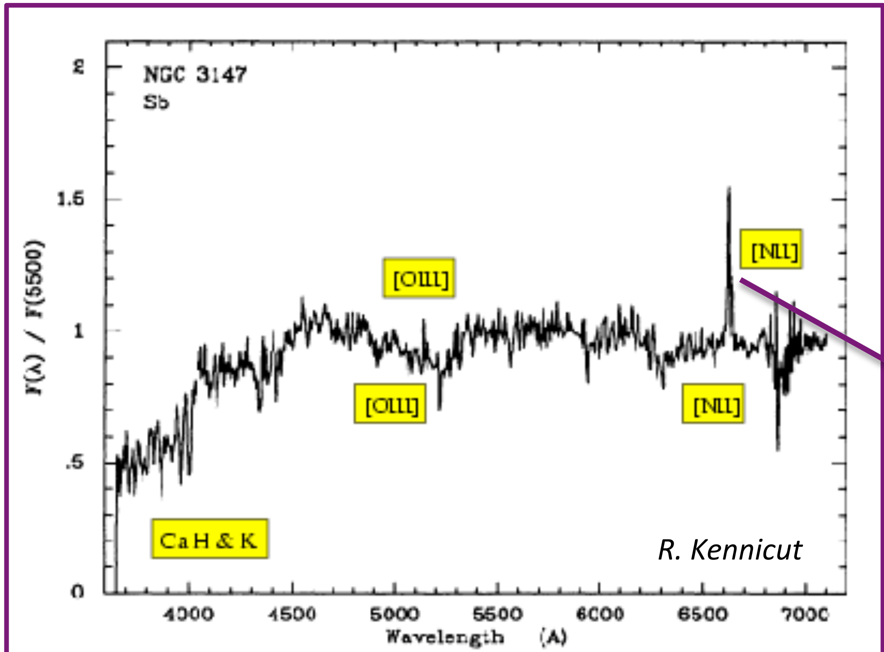
Luminosity at which distribution decays exponentially (free)

OBSERVATION: spectroscopy

- Decomposition of light through e.g. prism
- Reveals chemical composition, temperature, velocity…
- In galaxies: ensemble of stars and ISM

➢ Elliptical galaxies have strong absorption lines from atmospheres of stars

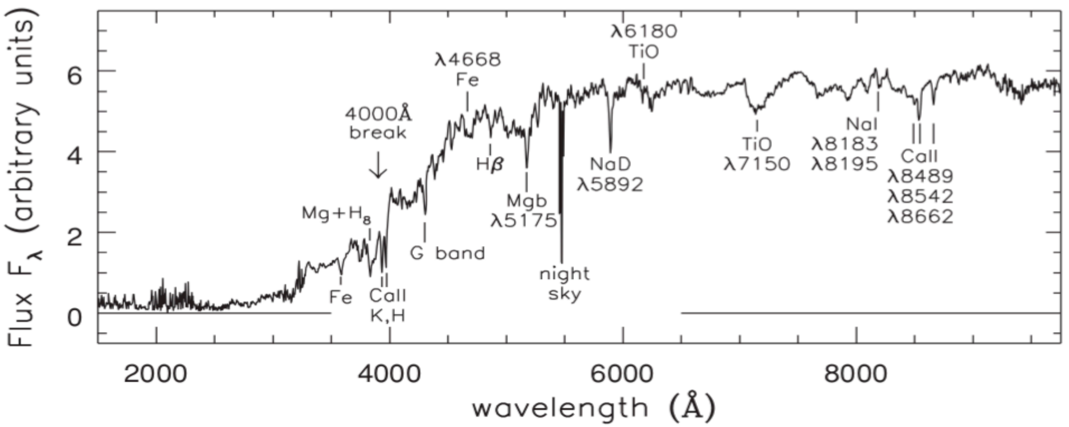


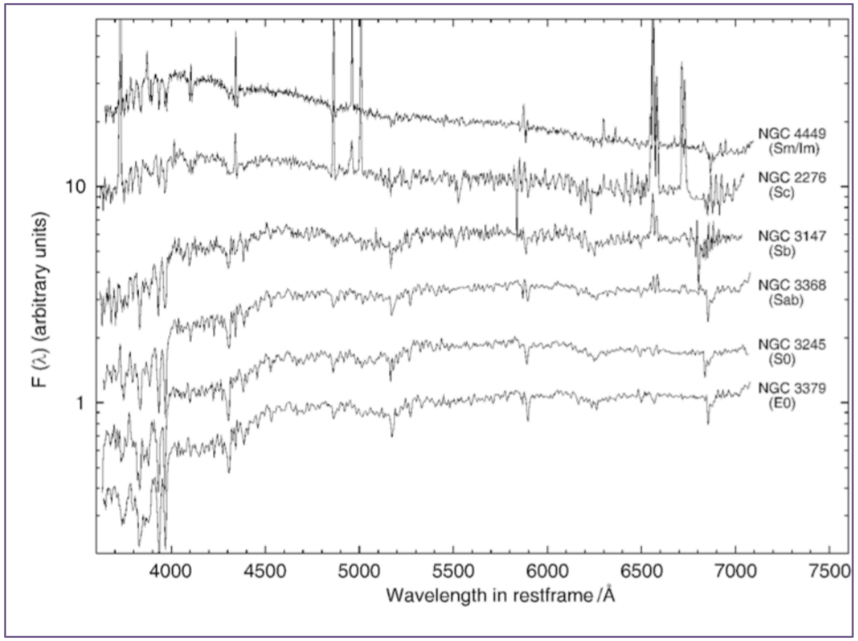


➢ Spiral galaxies have emission lines from gas heated by young stars

OBSERVATION: spectroscopy

- Absorption lines from stellar atmospheres and/or cold gas from the interstellar medium -OLD (ellipticals, lenticulars, spiral bulges

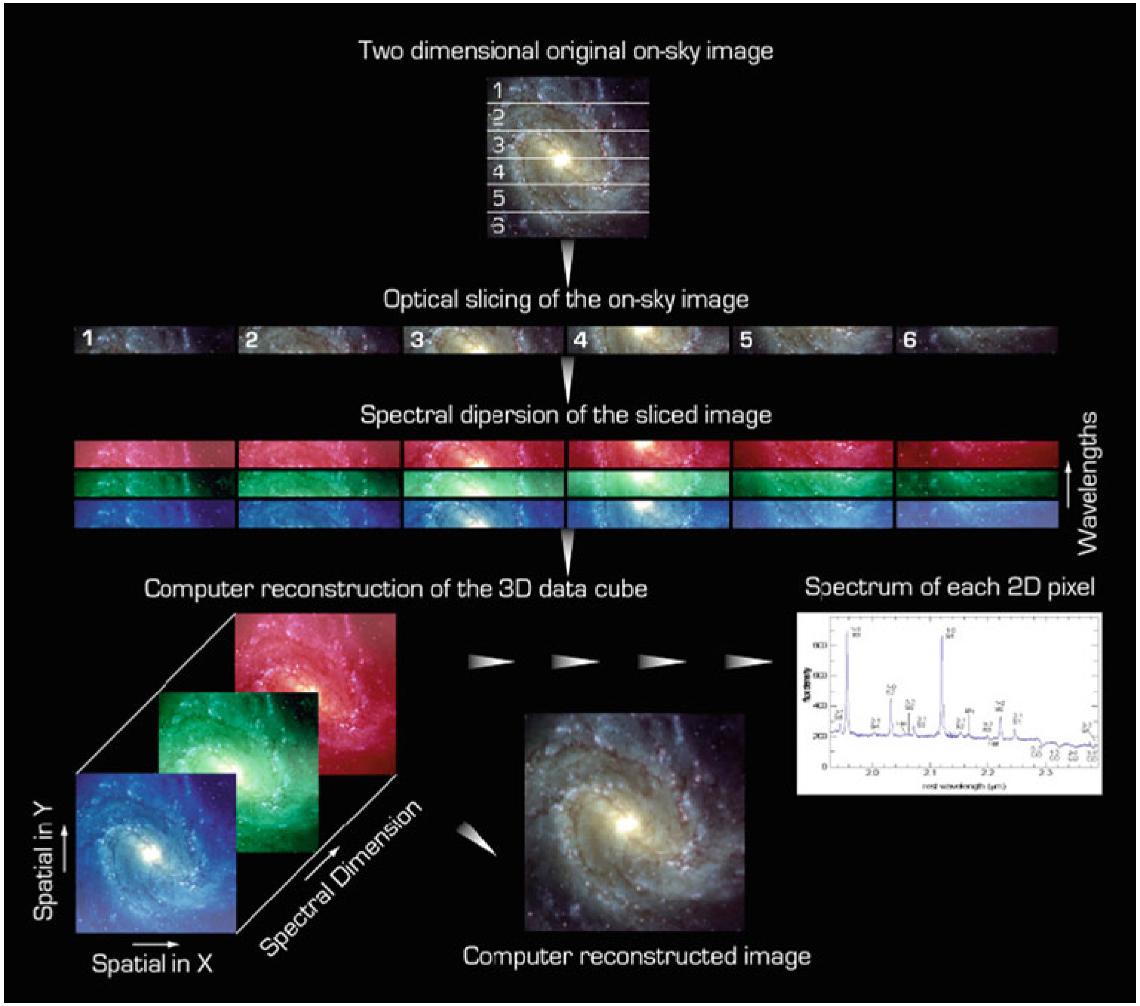




- Emission lines from hot gas around young massive stars - YOUNG (irregulars, spirals)

OBSERVATION: integral field spectroscopy

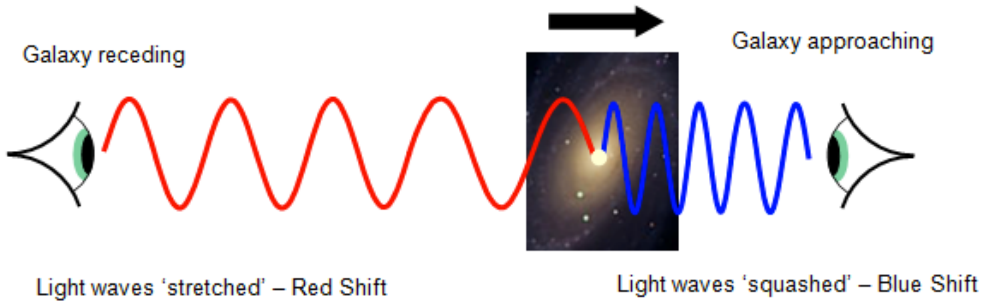
- Simultaneous imaging and spectral coverage
- Very useful to study galaxies!

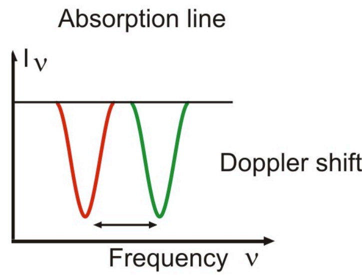


OBSERVATION: galaxy rotation maps

Velocity can be measured from Doppler shift:

$$\frac{v_{\rm rad}}{c} = \frac{\lambda_{\rm shift} - \lambda_{\rm rest}}{\lambda_{\rm rest}}$$





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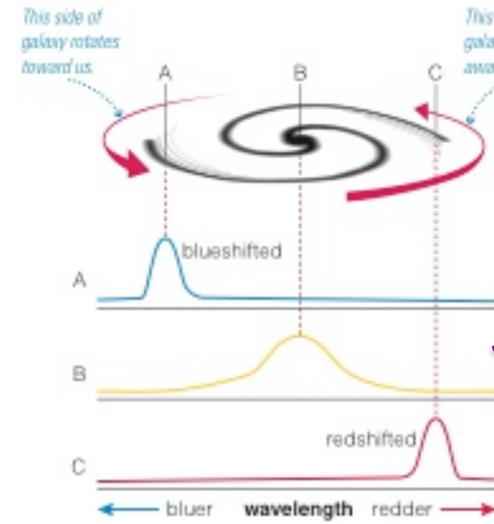
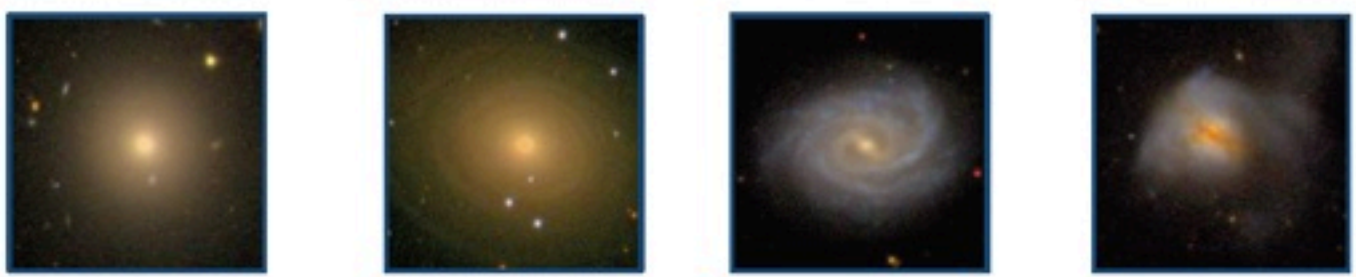
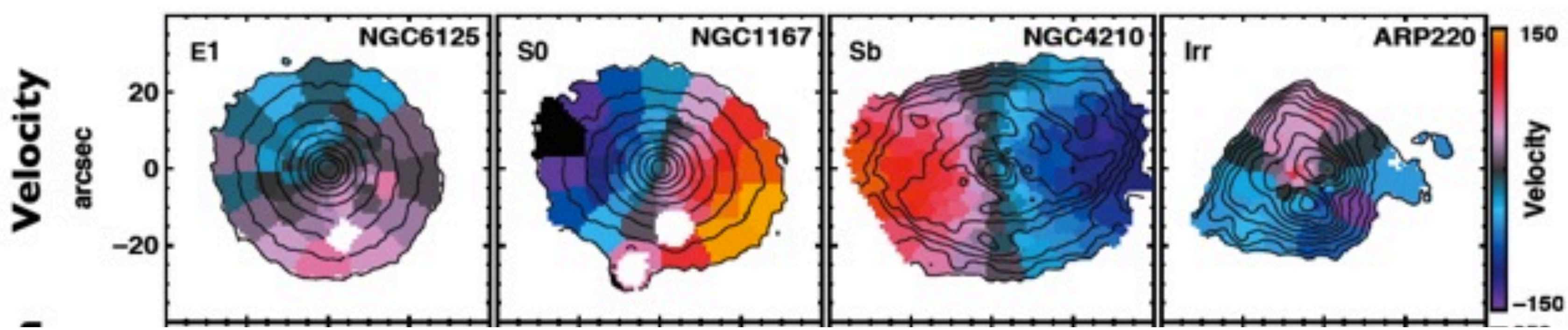


Emission from Hα



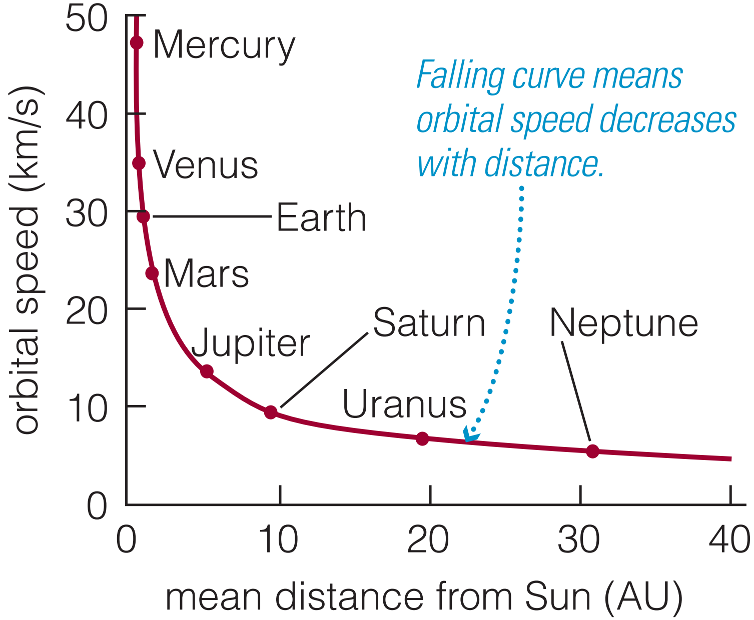


CALIFA

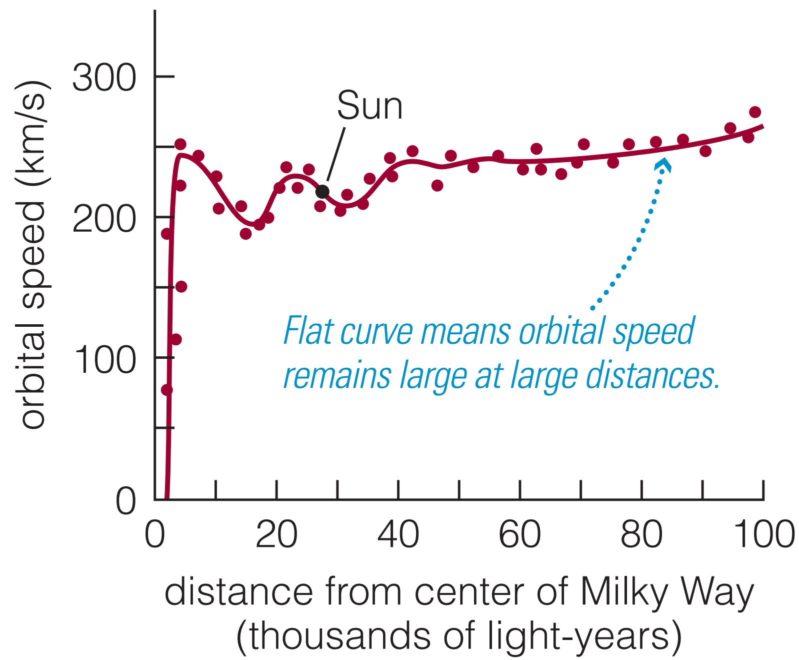
Galaxy rotation curves

$$v^2 = G \times M / r$$

Solar System



Milky Way



Most mass in the Solar system is concentrated in the Sun

Mass density does not drop off!

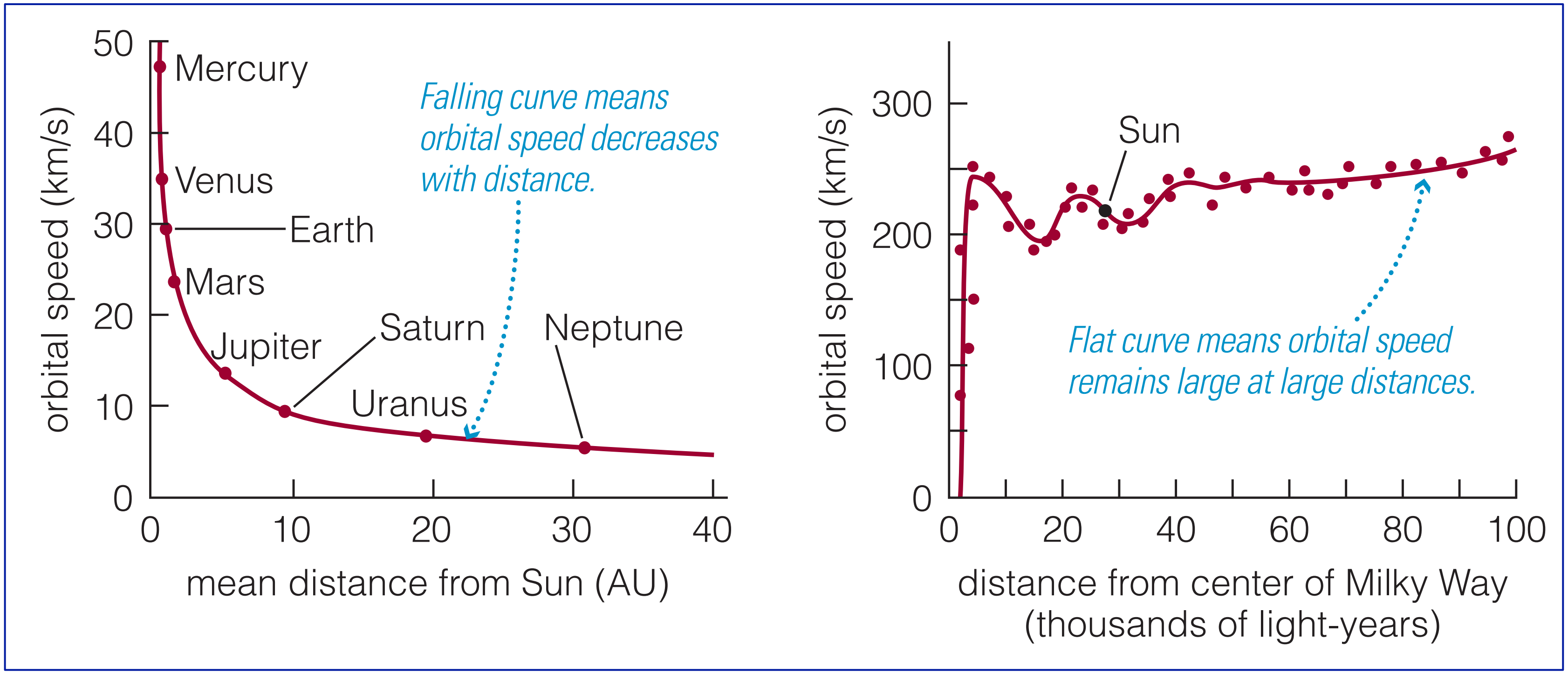
Galaxy rotation c

For a spherical distribution of objects, virial theorem:

$$E_{\text{kin}} = \frac{1}{2}\left|E_{\text{pot}}\right|$$

$$v^2 = G \times M / r$$

Solar System **Milky Way**



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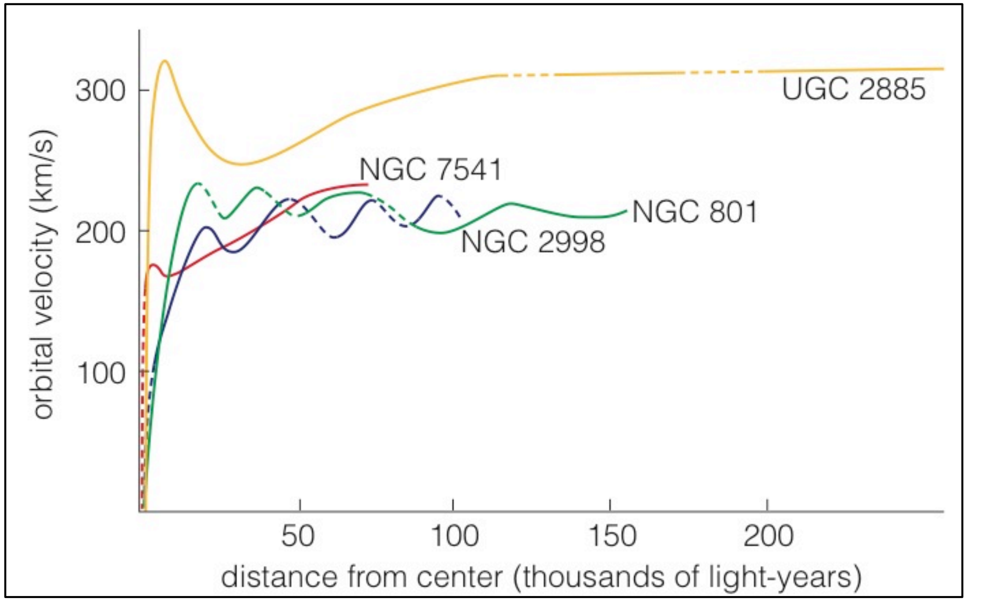
Galaxy rotation curves: dark matter

- Rotation curves are flat in all spiral galaxies
- Mass is distributed in the spherical halo
- The mass goes beyond what is seen in stars, globular clusters…
- This mass is 10 times more than what we observe in stars



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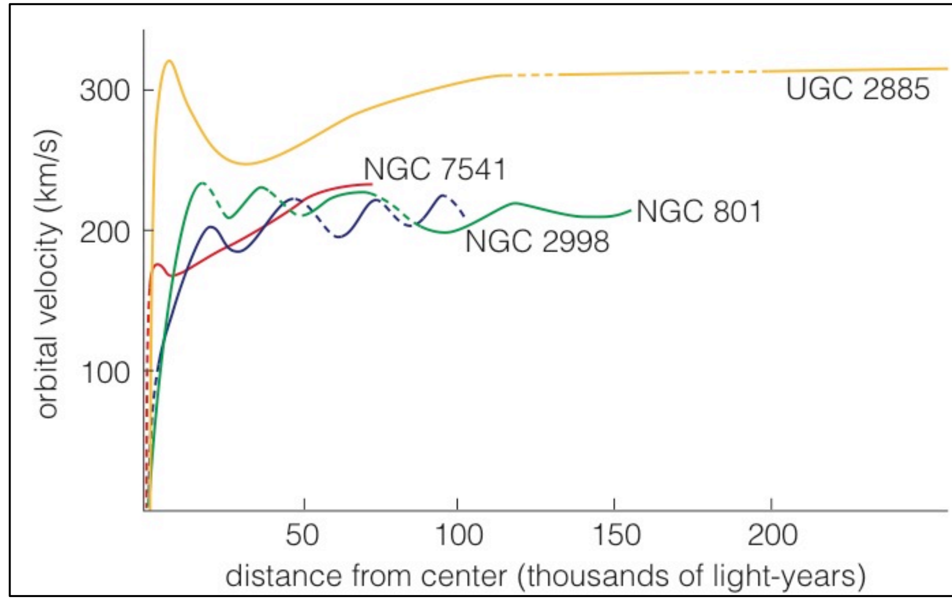

Mass-to-light ratio (M/L): total mass divided by visible luminosity

Galaxy rotation curves: dark matter

- Rotation curves are flat in all spiral galaxies
- Mass is distributed in the spherical halo
- The mass goes beyond what is seen in stars, globular clusters…
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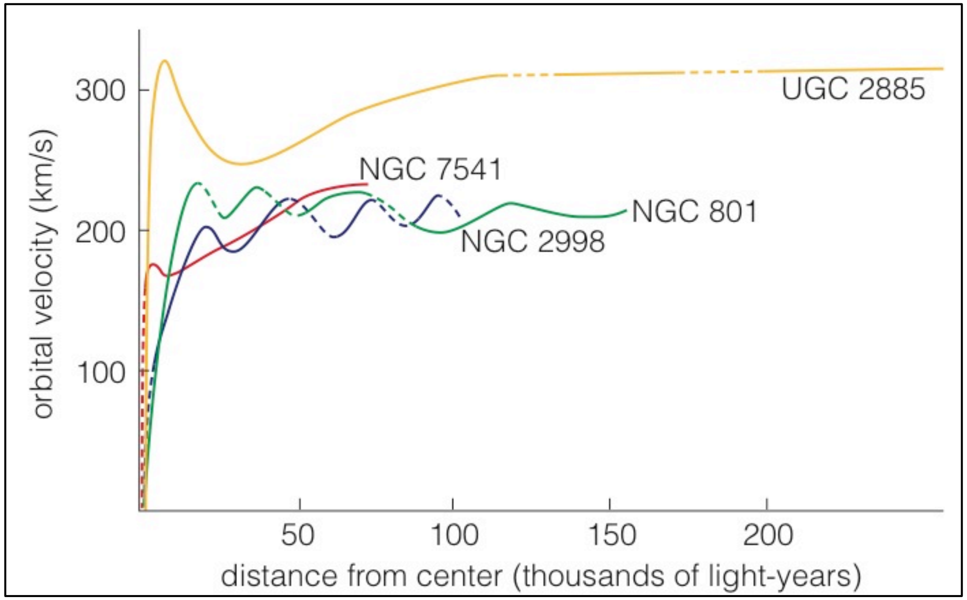
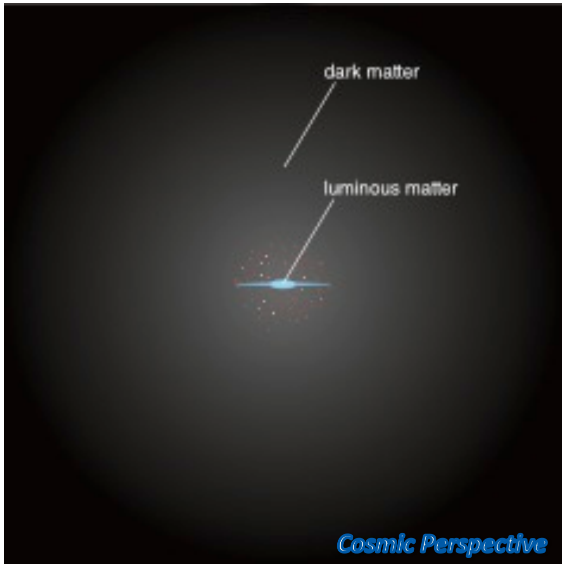


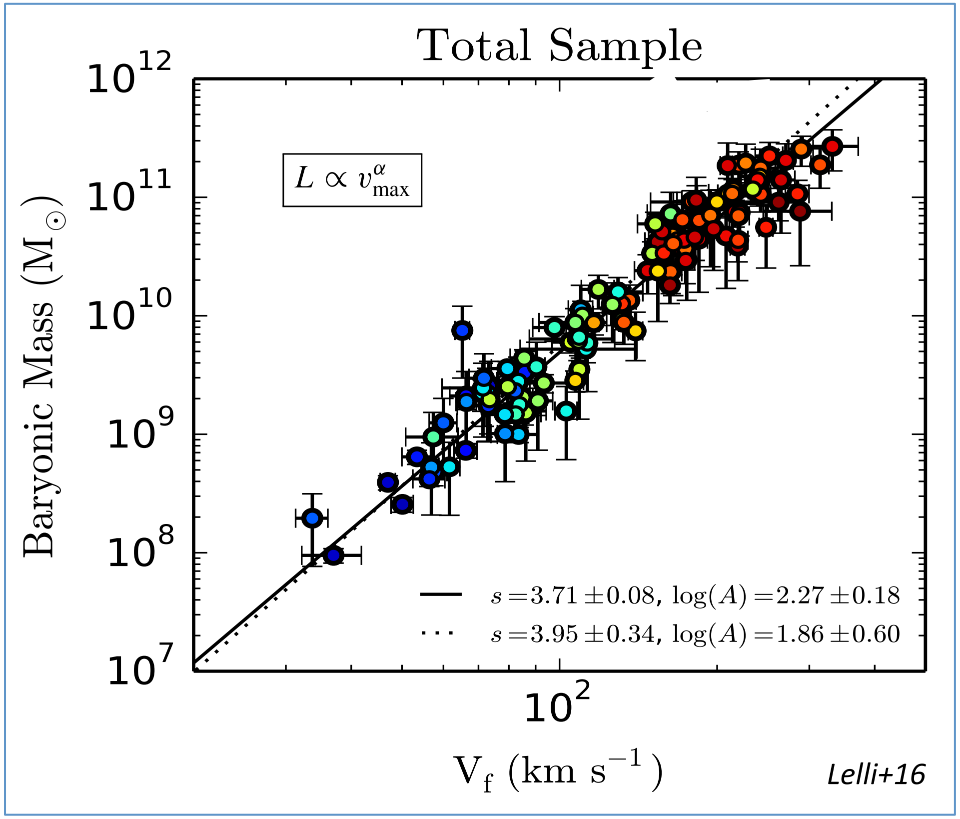


→ ***Dark Matter***

Unknown invisible matter component (ubiquitous and making up 85% of matter in universe)

Dark matter in spiral galaxies: Tully-Fisher relation

Tully-Fisher: Observational dependence between galaxy luminosity and max. stars velocity for many galaxies



Dark matter in spiral galaxies: Tully-Fisher relation

Tully-Fisher: Observational dependence between galaxy luminosity and max. stars velocity for many galaxies

Flat rotation curve:

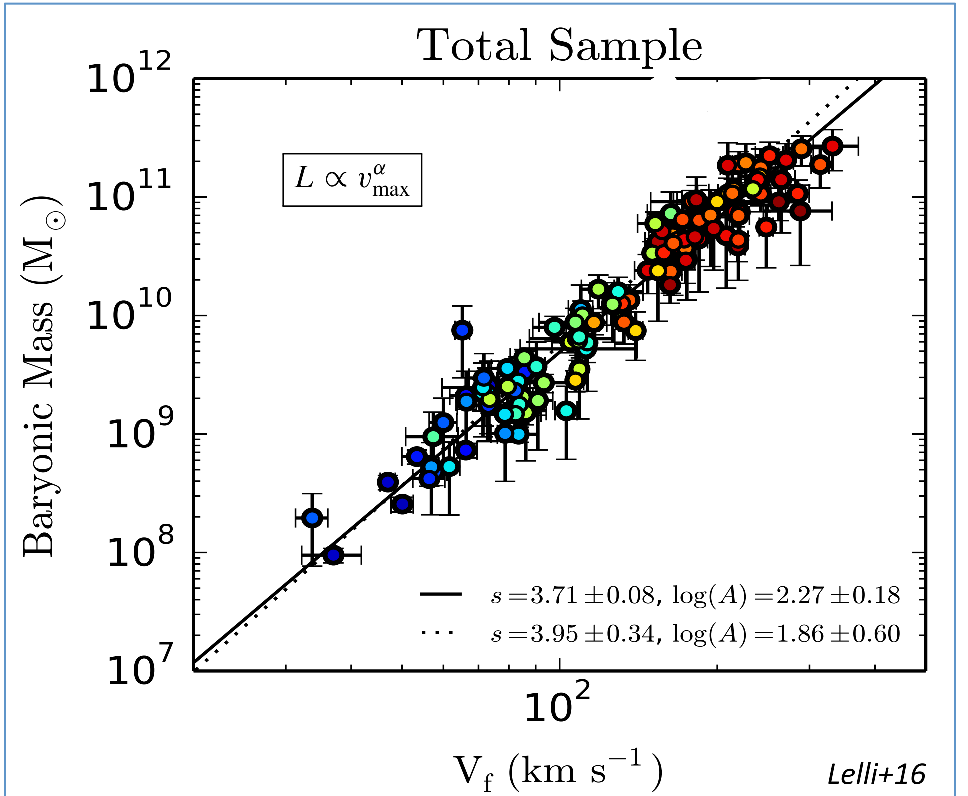
$$\boxed{M = \frac{v_{\max}^2 R}{G}}$$

Using mass-to-light ratio (M/L):

$$L = \left(\frac{M}{L}\right)^{-1} \frac{v_{\max}^2 R}{G}$$

Using mean surface brightness, $I=L/R^2$:

$$\boxed{L = \underbrace{\left(\frac{M}{L}\right)^{-2}}_{\sim\text{constant}} \left(\frac{1}{G^2 \langle I \rangle}\right) v_{\max}^4}$$



Lelli+16

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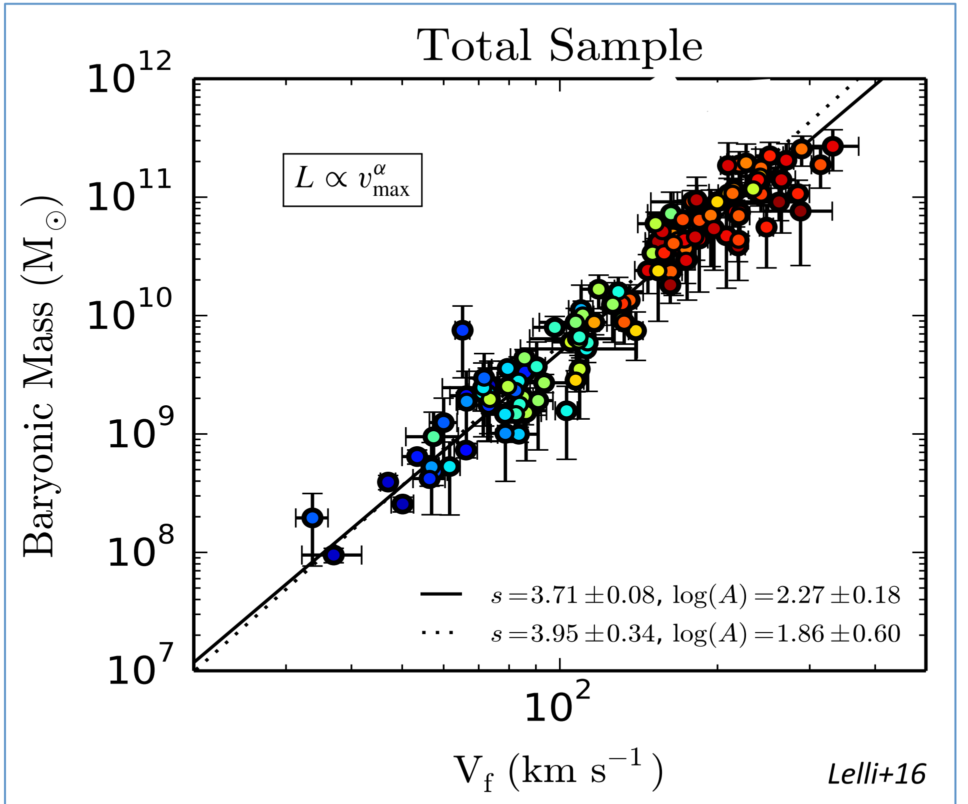
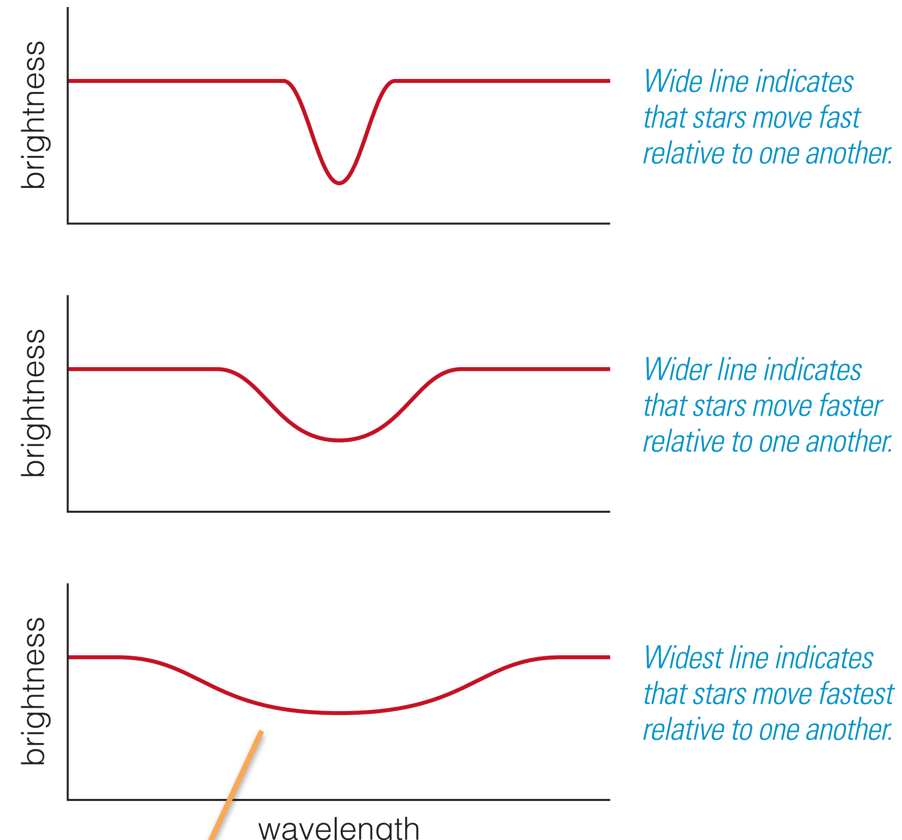
~constant



Lelli+16

➔ Useful to measure distances!

Dark matter in elliptical galaxies

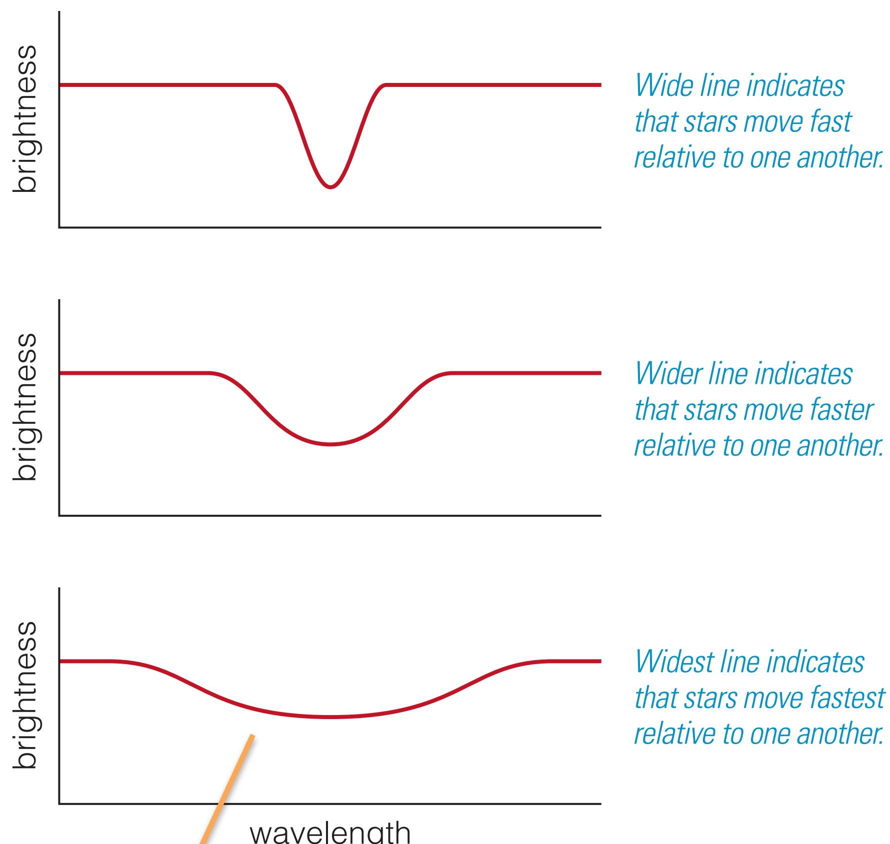


Velocity dispersion (σ): statistical dispersion of velocities of objects in a group around mean

Dark matter in elliptical galaxies

- Orbits of stars are more random and no hydrogen clouds to produce emission lines
- Multiple Doppler shifts create a *broadening* of the line
- Line width remains constant as a function of galaxy radius

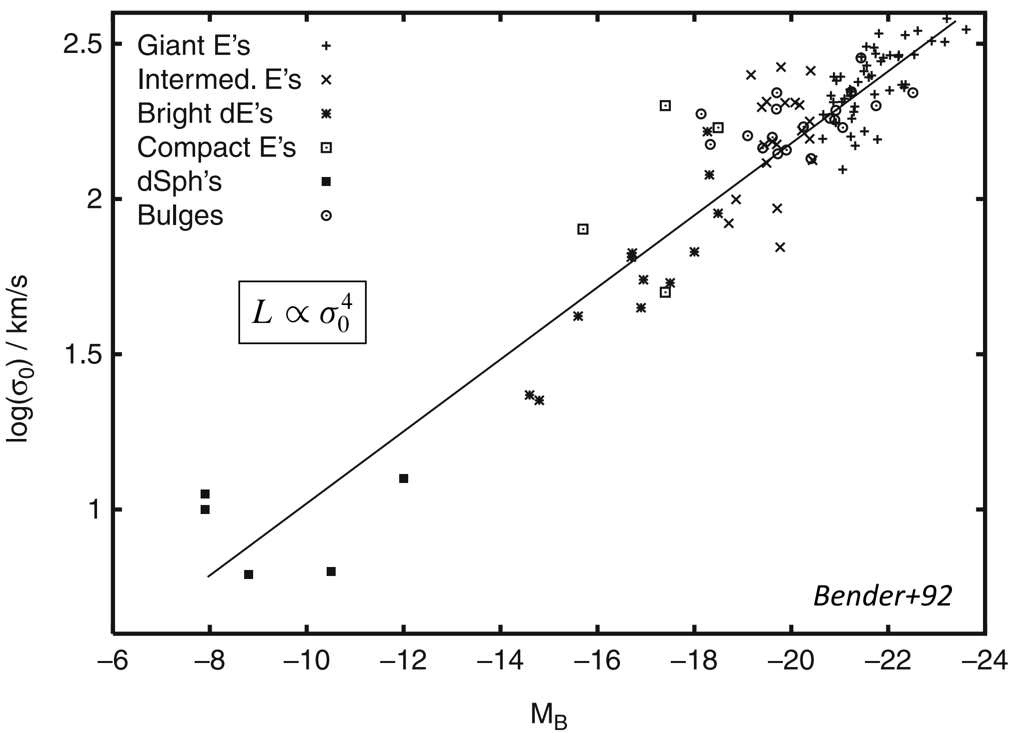
→ Dark matter, ten times more than luminous matter



Velocity dispersion (σ): statistical dispersion of velocities of objects in a group around mean

Dark matter in elliptical galaxies: Faber-Jackson relation

Faber-Jackson: Analogous to spiral galaxies, observational dependence between galaxy luminosity and velocity dispersion in center of ellipticals (*also M-σ relation*)



- Similar derivation than Tully-Fisher
- Larger dispersions, so not used for distances

Dark matter in galaxy clusters

1) Speeds of outer galaxies orbiting the center of the cluster

Dark matter in galaxy clusters

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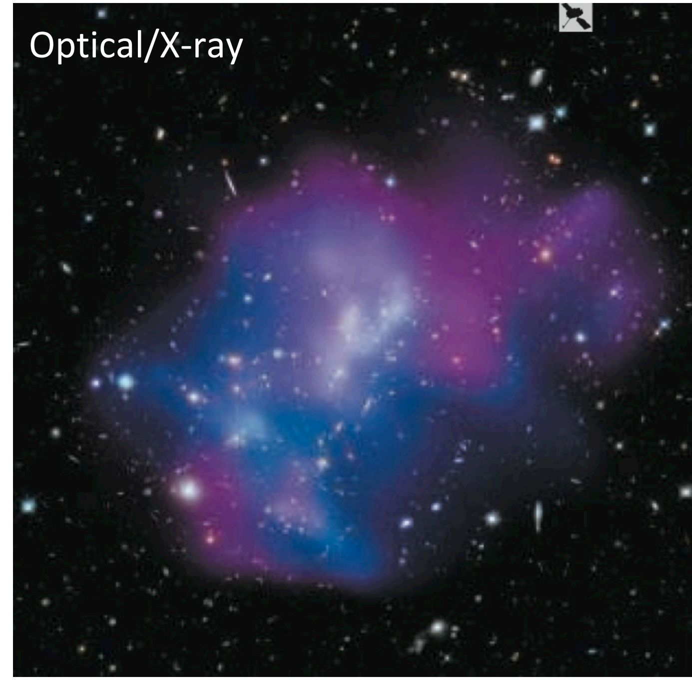

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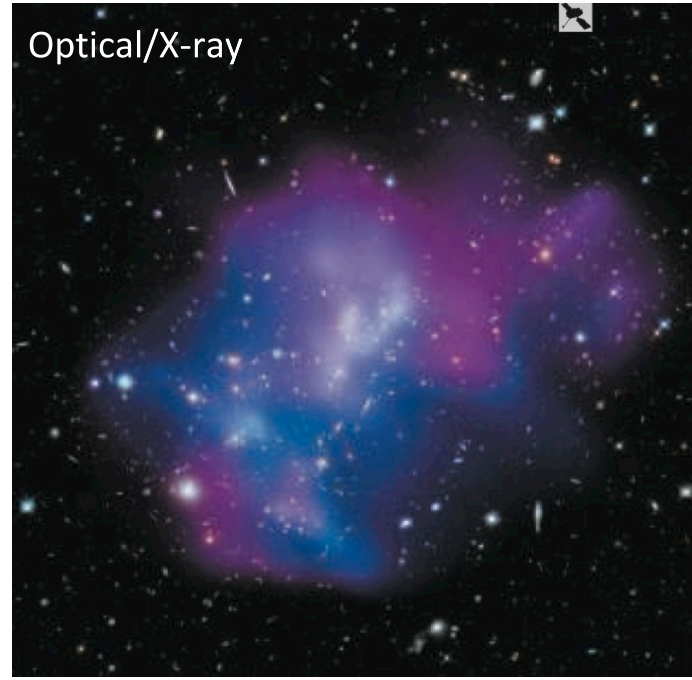
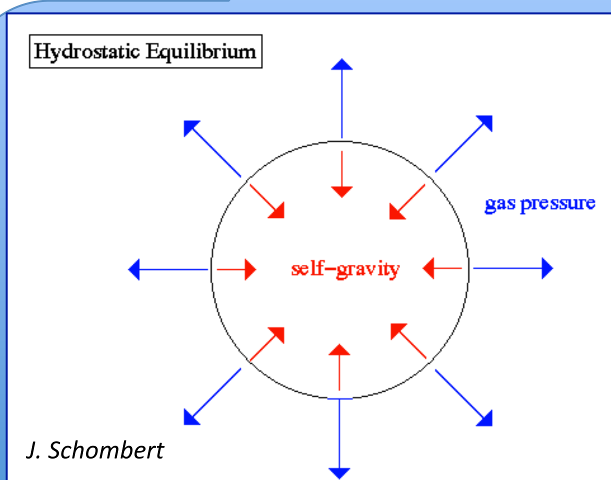




buoyancy = gravitational force:

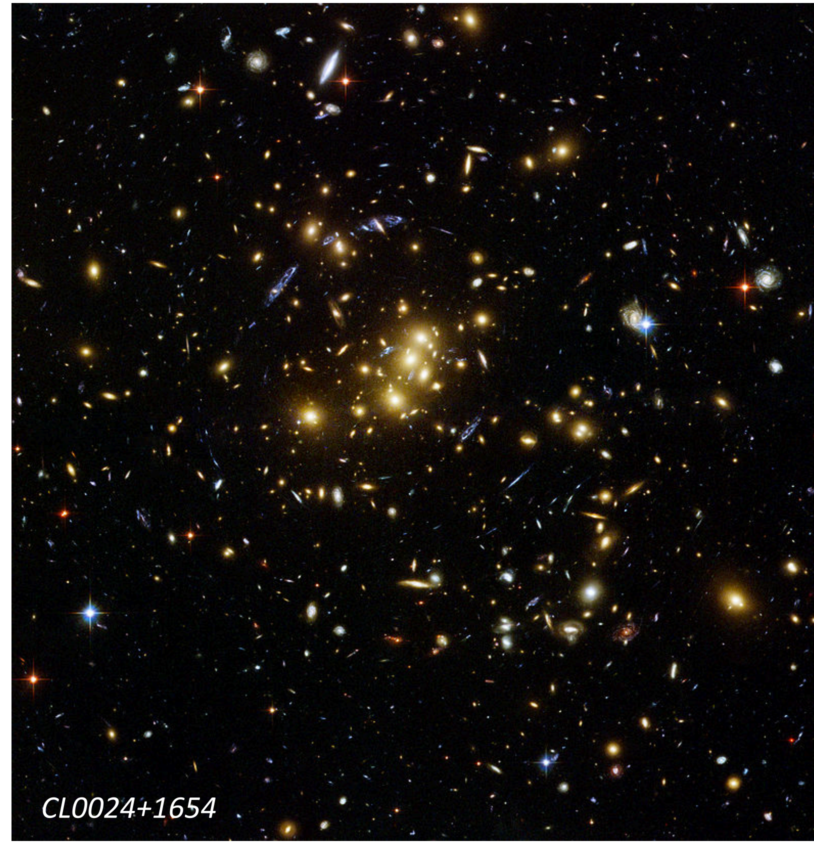
$$dF_p + dF_g = 0$$

$$-dPdA - g\rho dAdr = 0$$

$$\boxed{\frac{dP}{dr} = -g\rho(r)}$$

Dark matter in galaxy clusters

1) Speeds of outer galaxies orbiting the center of the cluster
2) X-ray emission from hot gas within galaxies: *intergalactic medium*. The hotter, the more massive
3) In general relativity, masses curve space-time and light gets bent: gravitational lensing



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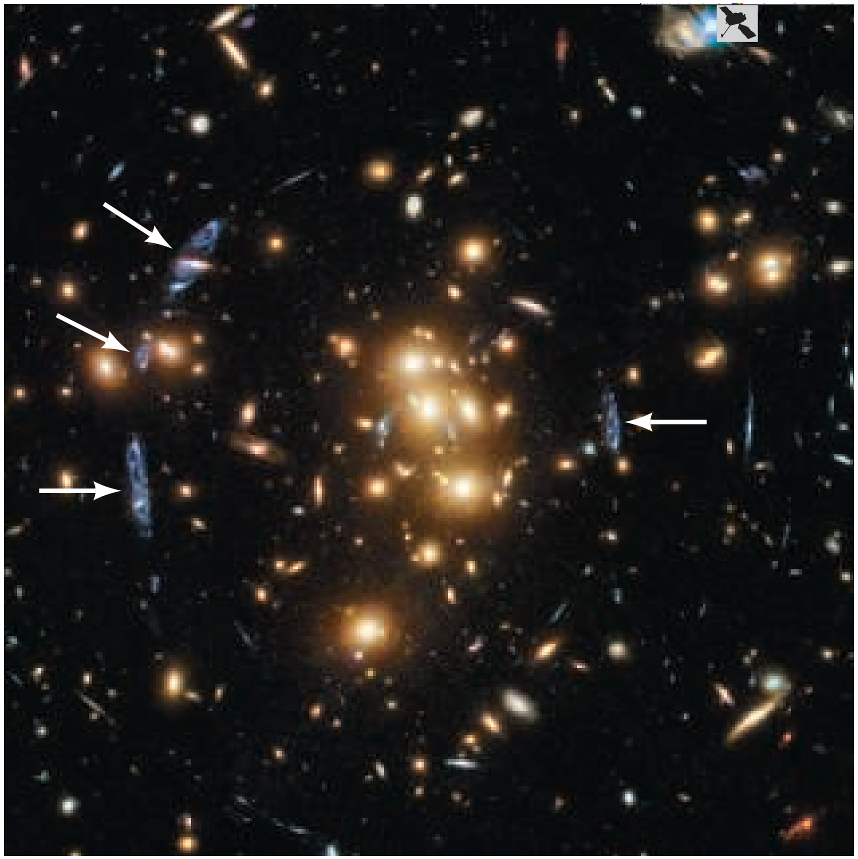

Yellow elliptical galaxies of the cluster act as a lens. Multiple images of the same spiral galaxy (lying in the back) appear

Dark matter in galaxy clusters

1)

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2)

more

3)

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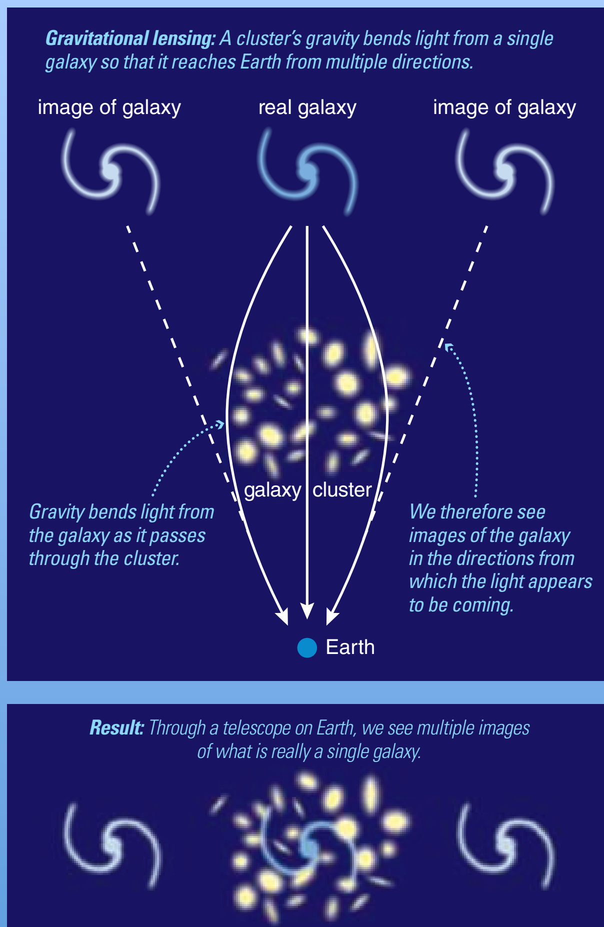
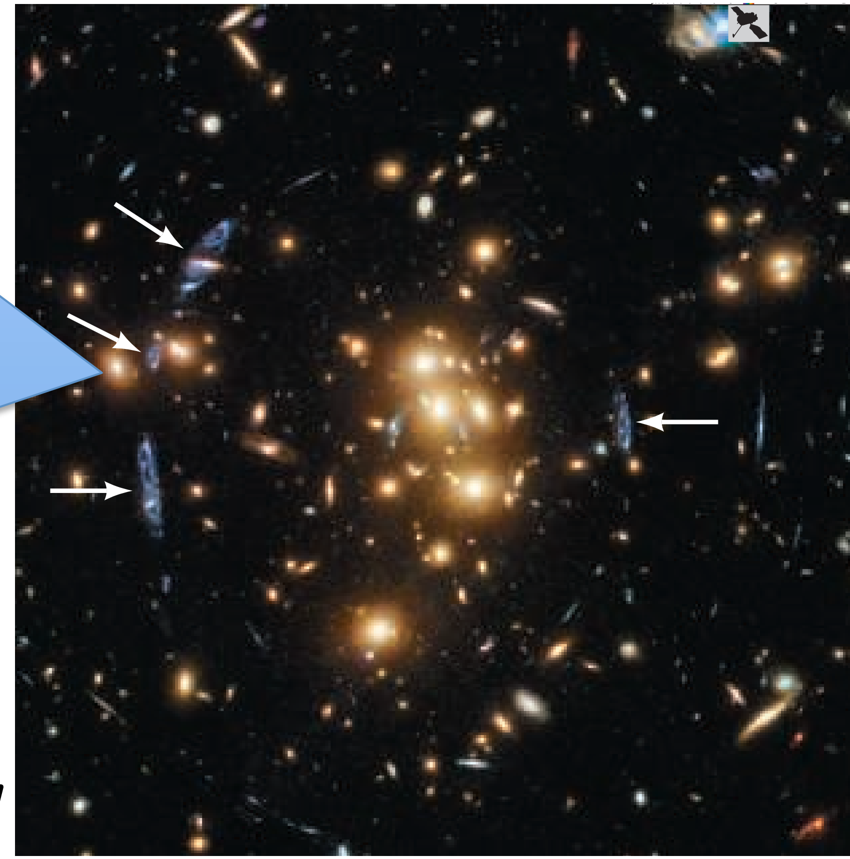


Simplified Einstein's deflection angle:

$$\boxed{\hat{\alpha} = \frac{4\,G\,M}{c^2\,\xi}}$$



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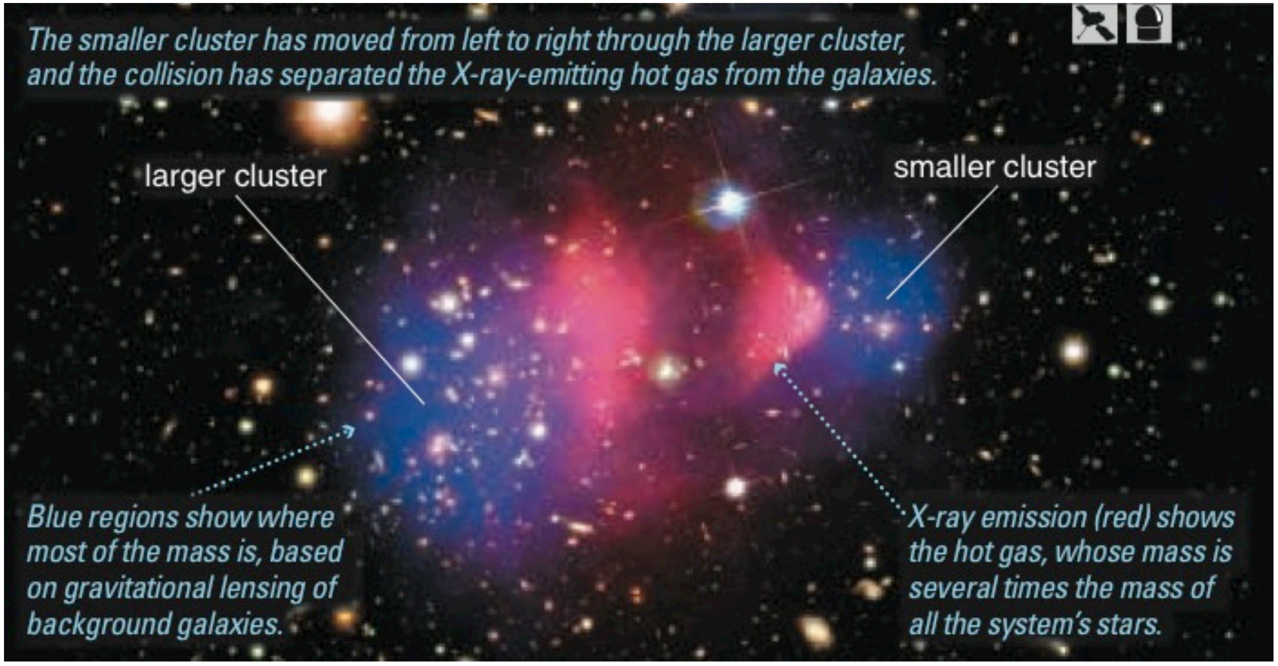
Dark Matter Hypothesis

- Dark matter always inferred through gravitation (Newton or Einstein): it means there is much more matter we do not see OR alternatively there is an extension to our laws of gravity (e.g. MOND)



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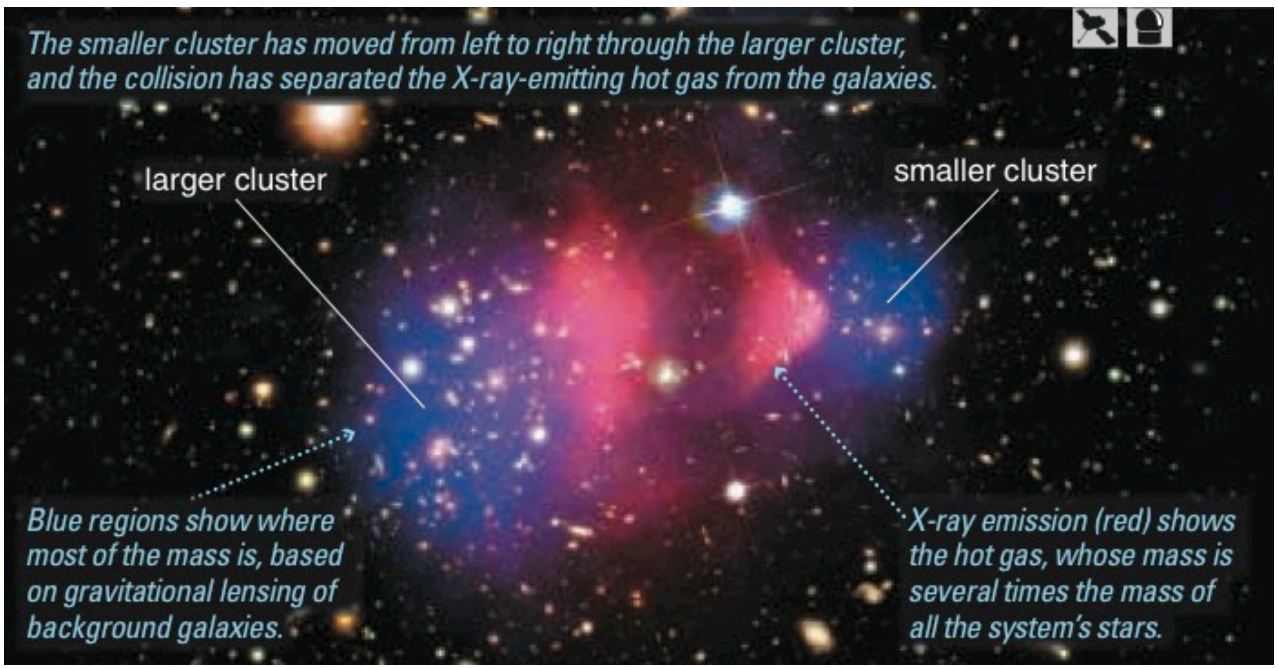


→ Dark Matter is the leading hypothesis!!

Dark Matter candidates

- *Ordinary matter* (baryonic matter) too dark to be seen:

  Planets, brown dwarfs, faint red stars, black holes

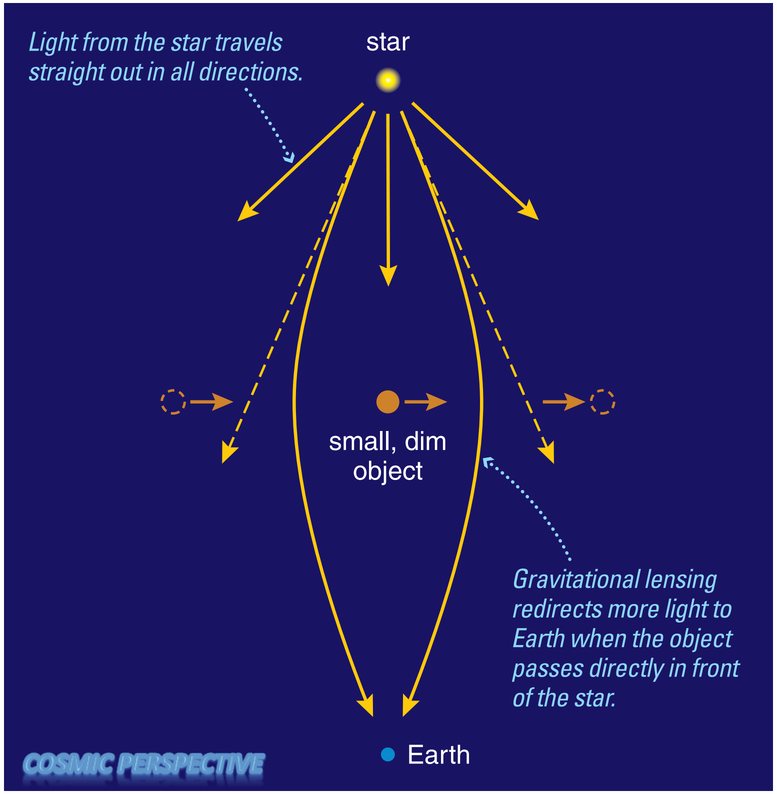
- *Exotic matter* (non-baryonic matter) that does not interact with light:

  Weakly interacting massive particles (similar to neutrinos with no charge nor bound but more massive)

Dark Matter search

1. *Ordinary Matter*

   Galactic Microlensing: the light of a star is temporarily magnified by a moving foreground massive object



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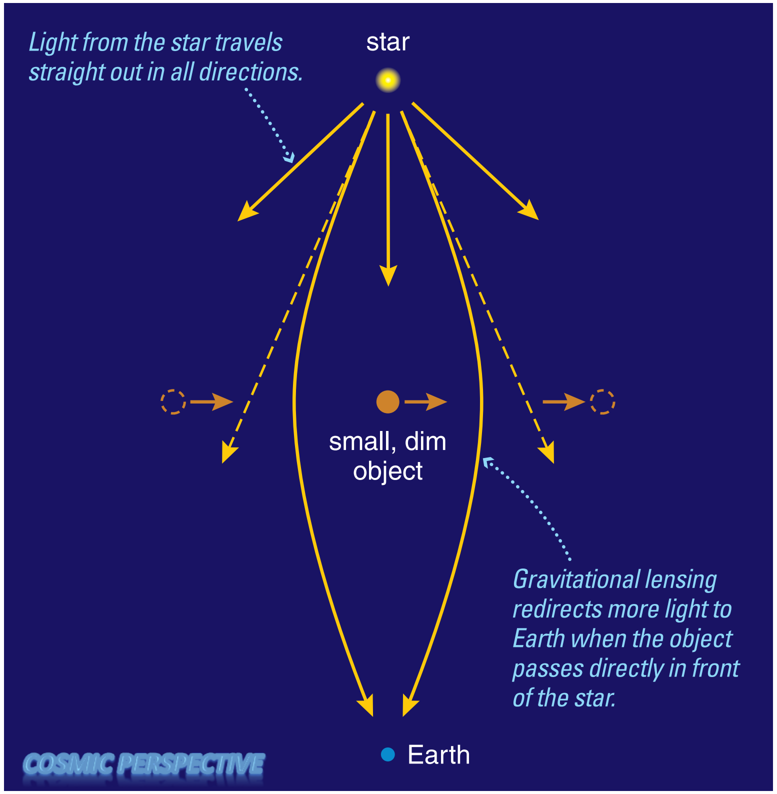
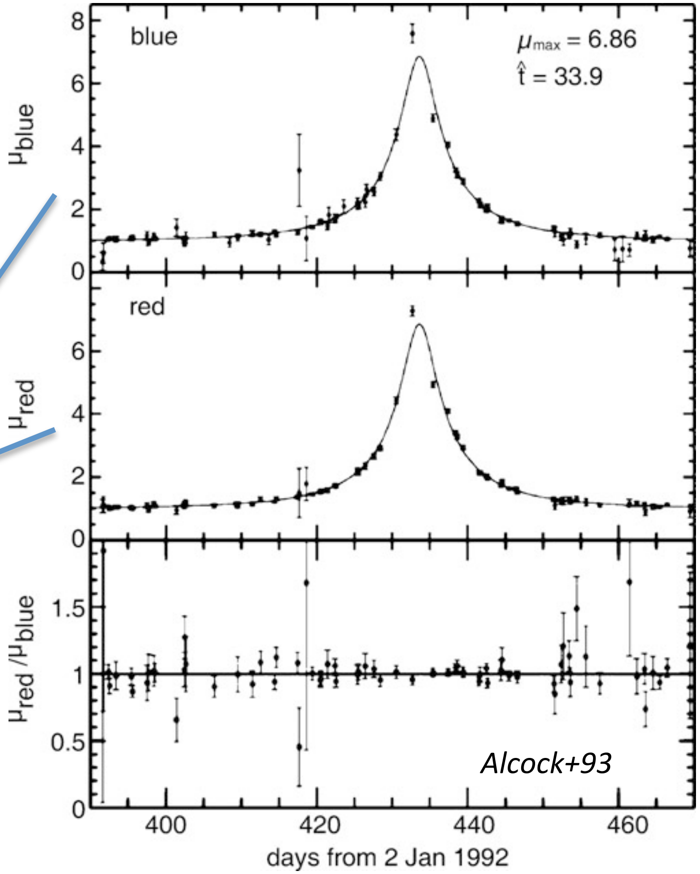
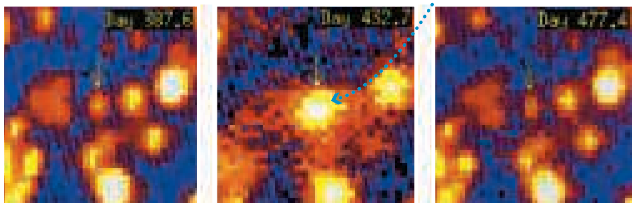


Wavelength-independent



Detection of exoplanets and others (100s/yr)



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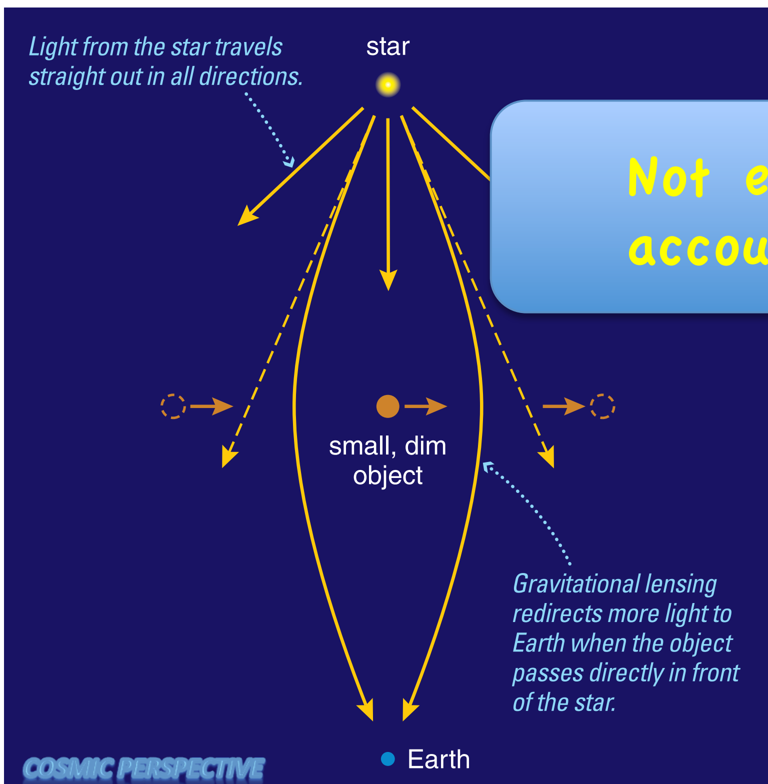
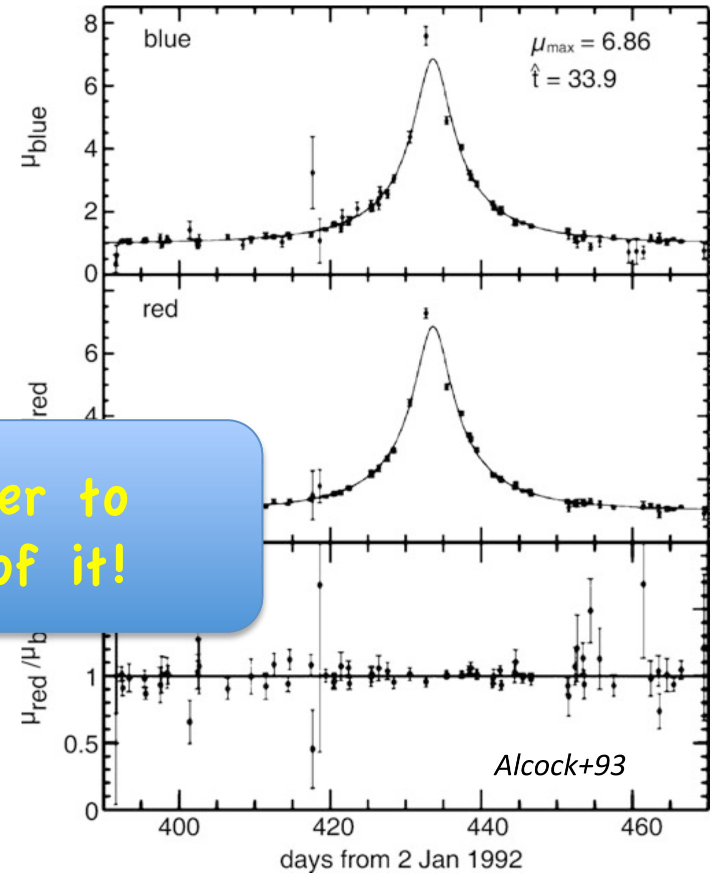
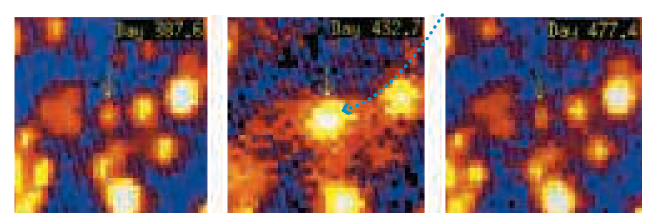




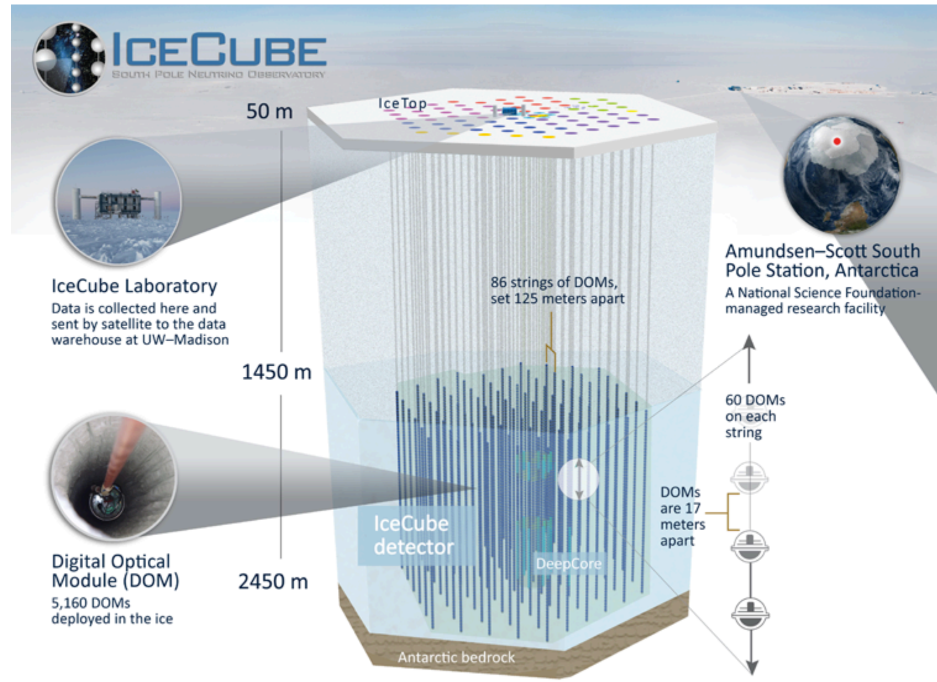


Not enough matter to account for all of it!

Dark Matter search

2. Exotic Matter

- *Production in the laboratory*
- *Direct detection:* scattering of dark matter nuclei interactions
- *Indirect detection:* products of dark matter annihilation/decay like cosmic rays (anomalous flux of neutrinos, photons…)




Large Hadron Collider

- Particle accelerators
- Underground detectors

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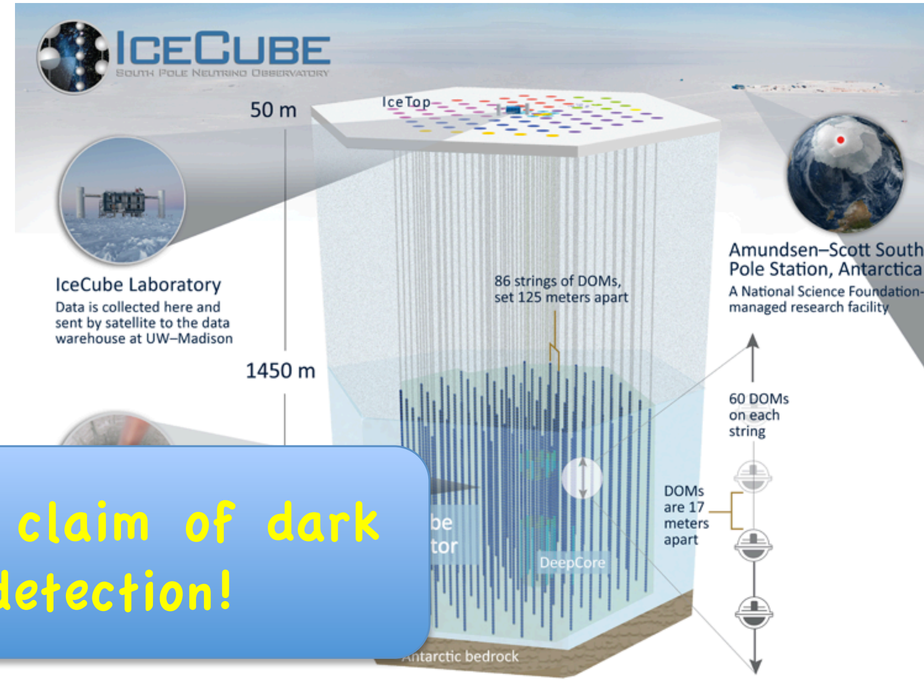

No conclusive claim of dark matter detection!


Large Hadron Collider

- Particle accelerators
- Underground detectors

Summary

- Galaxies come as spirals, ellipticals, lenticulars, irregulars, dwarfs
- Luminous galaxies can be organized in the Hubble sequence or magnitude-color diagram
- Elliptical galaxies have less dust and cool gas, less star formation and older stellar populations
- Brightness profiles of galaxies can be modeled with Sérsic profiles
- Galaxies coexist in groups and clusters
- Rotational curves of galaxies/galaxy clusters reveal invisible mass: dark matter
- Tully-Fisher and Faber-Jackson relations relate galaxy's luminosity with stars' velocity and dispersion