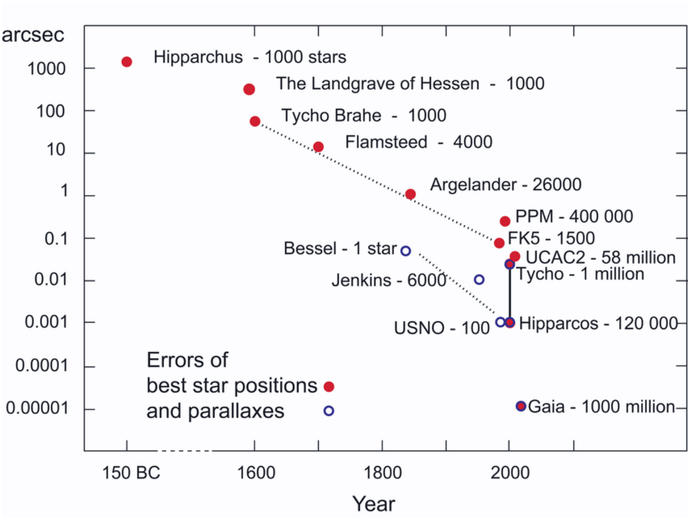
Galaxies: Structure, formation and evolution

Lecture 12

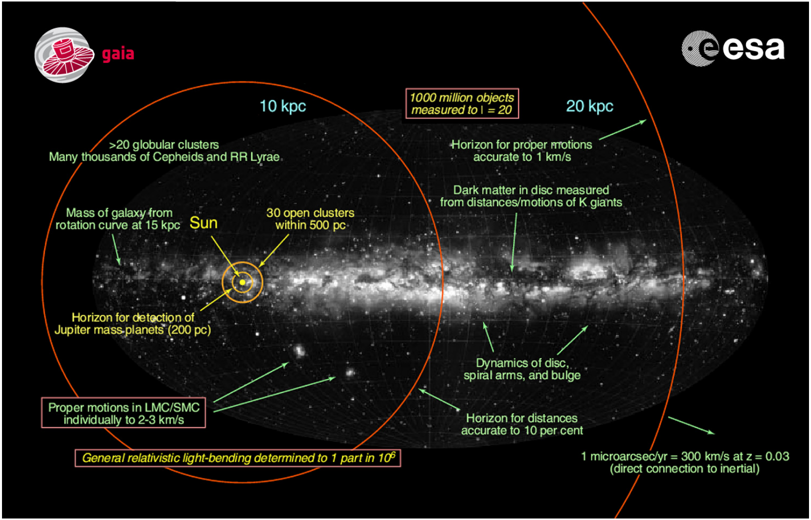
Yogesh Wadadekar

Mar-Apr 2022

Gaia Astrometric Accuracy and sample size



GAIA mission



DR3 scheduled for 13 June 2022

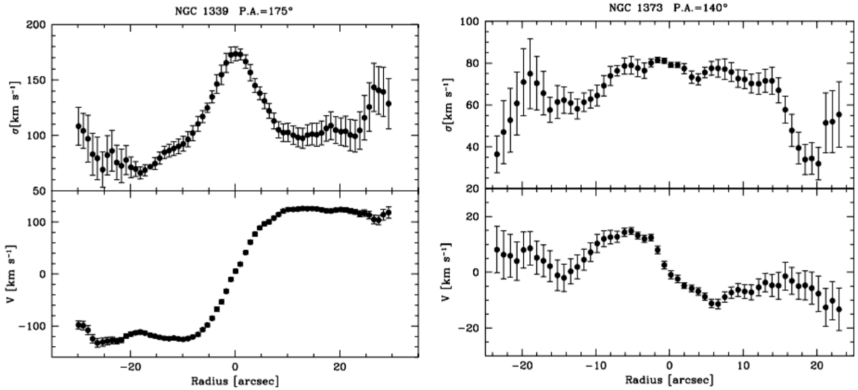
Question

I mentioned that Gaia will measure the phase space distribution of stars in 6 dimensions - i.e. it will measure x, y, z, v_x, v_y, v_z for each star. Gaia will measure transverse velocity (via proper motion) and radial velocity for each star. How can we determine three numbers v_x, v_y, v_z from only two measurements?

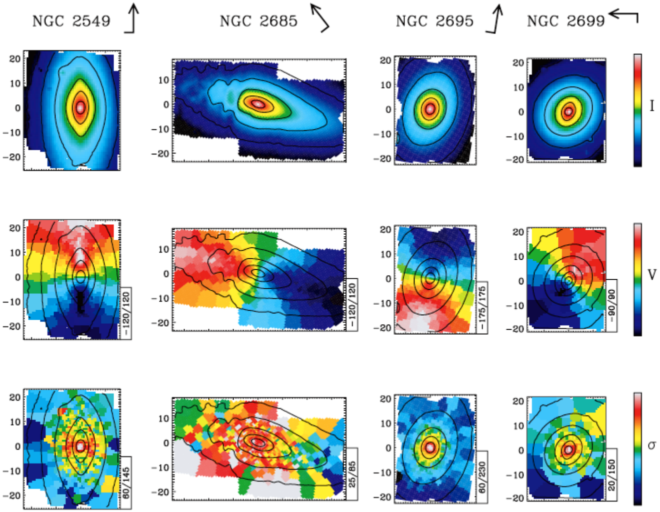
Stars in elliptical galaxies

Stars in E galaxies have some ordered motions (e.g., rotation), but most of their kinetic energy is in the form of random orbits. Thus, we say that ellipticals are **pressure-supported** systems To measure the kinematics within galaxies we use absorption lines. Each star emits a spectrum which is Doppler shifted in wavelength according to its motion. Random distribution of velocities then broadens the spectral lines relative to those of an individual star. Systemic motions (rotation) shift the line centroids.

Rotation and dispersion in elliptical galaxies



Intensity,Velocity,Dispersion



How to measure velocity dispersion?

In ellipticals, one often measures the **central velocity dispersion.** Why measuring this is easier? Why is it not useful for spiral disks?

Velocity anisotropy in elliptical galaxies

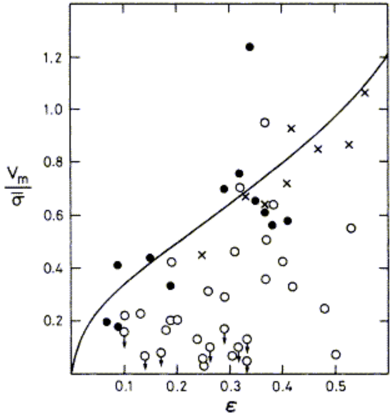


FIG. 3.—The quantity $V_m/\bar{\sigma}$ against ellipticity. Ellipticals with $M_B^{UH} > -20.5$ are shown as filled circles; ellipticals with $M_B^{UH} < -20.5$, as open circles; and the bulges of disk galaxies, as crosses. The solid line shows the $(V/\sigma, \epsilon)$-relation for oblate galaxies with isotropic velocity dispersions (Binney 1978).

Ellipticals are not rotationally supported.

Anisotropy parameter and dependence on luminosity

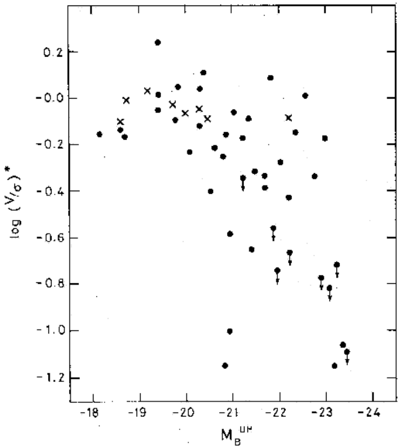


FIG. 4.—Log $(V/\sigma)^*$ against absolute magnitude. Ellipticals are shown as filled circles and the bulges as crosses; $(V/\sigma)^*$ is defined in § III*b*.

Rotational Properties of Elliptical Galaxies:

Anisotropy parameter:

$$\left(\frac{v}{\sigma}\right)^* \equiv \frac{v/\sigma}{\sqrt{\frac{1-b/a}{b/a}}} = \frac{(v/\sigma)_{\text{observed}}}{(v/\sigma)_{\text{rot. flattened}}}$$

see: Davies et al. (1983) *ApJ*, **266**, 41

This trend does not continue to fainter levels. Dwarf Es hardly rotate.

Violent relaxation

Stars in galaxies are collisionless systems. In steady state, stars will continue in steady state orbits without perturbing each other. However, the situation can be very different in a system that is not in equilibrium. A changing gravitational potential will cause the orbits of the stars to change. Because the stars determine the overall potential, the change in their orbits will change the potential. This process of changes in the dynamics of stars caused by changes in their net potential is called **violent relaxation**. Galaxies experienced violent relaxation during their formation. Can violent relaxation occur later?

Violent relaxation

Stars in galaxies are collisionless systems. In steady state, stars will continue in steady state orbits without perturbing each other. However, the situation can be very different in a system that is not in equilibrium. A changing gravitational potential will cause the orbits of the stars to change. Because the stars determine the overall potential, the change in their orbits will change the potential. This process of changes in the dynamics of stars caused by changes in their net potential is called **violent relaxation**. Galaxies experienced violent relaxation during their formation. Can violent relaxation occur later? Interactions between galaxies can also bring about violent relaxation. The process takes place relatively quickly (10^8 yr) and redistributes the motions of stars.

Crossing time or dynamical timescale

$T_{cross} \equiv \frac{R}{v}$.
For a spherically symmetric system it can be shown that:
$T\mathrm{cross} \sim \frac{1}{\sqrt{G\rho}}$. Even for non-spherically symmetric systems, this gives a rough value for crossing time. Plugging in numbers for a typical galaxy, one gets a crossing time of $\sim 10^8$ years.

Measuring dynamical mass via virial theorem

The virial theorem can be applied to any system of stars that is in a steady state such as:

- elliptical galaxies
- evolved star clusters, e.g. globular clusters
- evolved clusters of galaxies (with the galaxies acting as the particles, not the individual stars)

Measuring dynamical mass via virial theorem

The virial theorem can be applied to any system of stars that is in a steady state such as:

- elliptical galaxies
- evolved star clusters, e.g. globular clusters
- evolved clusters of galaxies (with the galaxies acting as the particles, not the individual stars)

It obviously cannot be used for:

- merging galaxies
- newly formed star clusters
- clusters of galaxies that are still forming/still have infalling galaxies

Can it be applied in the solar system today?

Measuring dynamical mass via virial theorem

Consider a spherical elliptical galaxy of radius R that has uniform density and which consists of N stars each of mass m having typical velocities v. Can we measure typical velocity of stars in an elliptical galaxy?

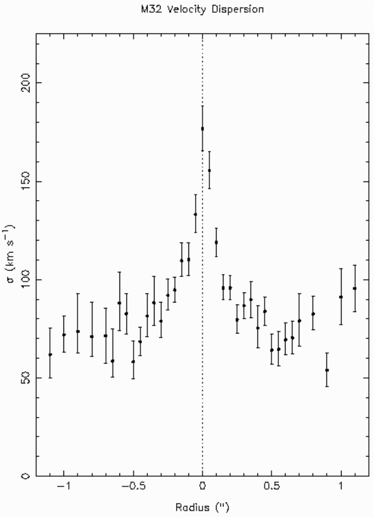
Measuring dynamical mass via virial theorem

Consider a spherical elliptical galaxy of radius R that has uniform density and which consists of N stars each of mass m having typical velocities v. Can we measure typical velocity of stars in an elliptical galaxy?

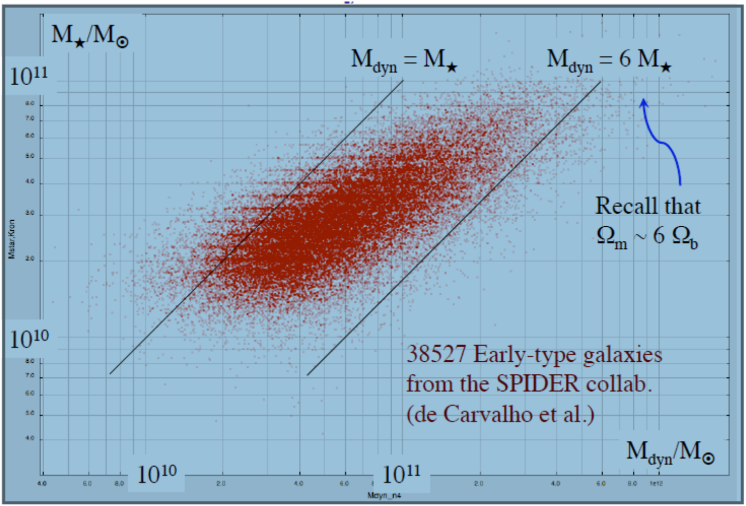
$$2T + U = 2\left(\frac{1}{2}Nm\sigma^2\right) - \frac{3}{5}\frac{GM^2}{r} = 0$$

where the gravitational PE is for uniform sphere of mass M and radius R. This implies: $M \simeq \frac{\sigma^2 R}{G}$ Can we measure the mass of supermassive black holes using this?

Even black holes in small galaxies can be measured!



Baryonic mass versus dynamical mass



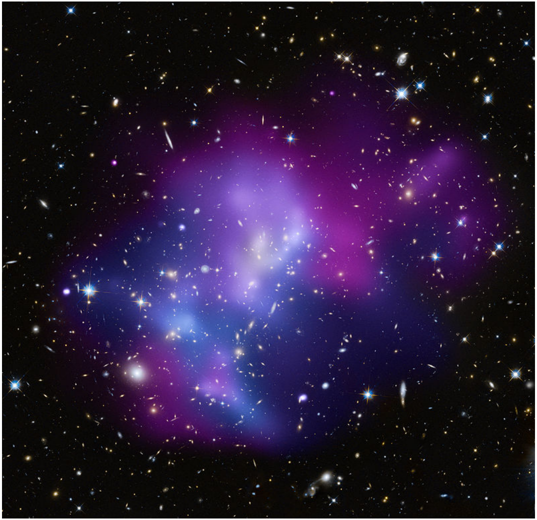
Question

How would you use the Virial Theorem to estimate the mass of a virialised cluster? Before that, how will you determine if a cluster is virialised or not?

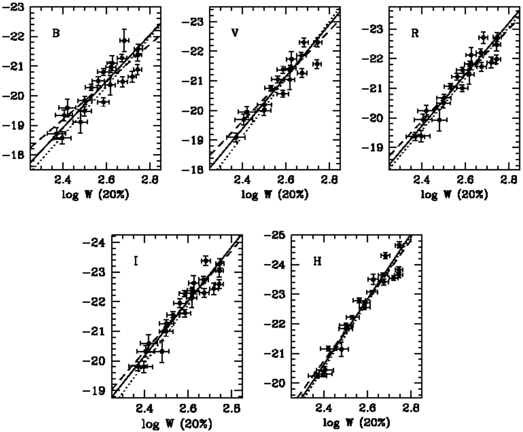
Question

How would you use the Virial Theorem to estimate the mass of a virialised cluster? Before that, how will you determine if a cluster is virialised or not? Zwicky's 1937 measurement was $M/L = 300$ for the Coma cluster.

Cluster: Virialised or not?



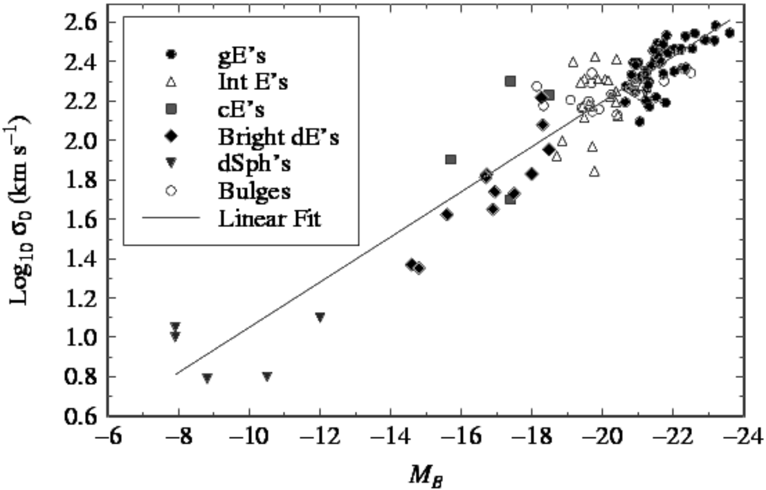
The Tully Fisher relation



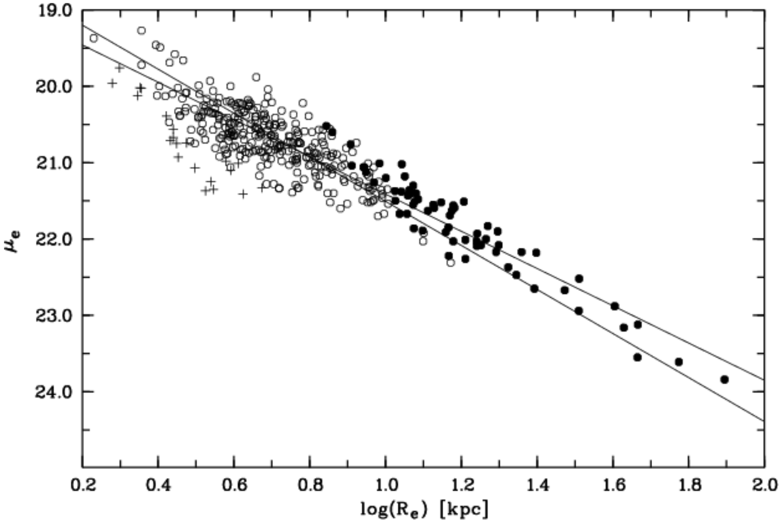
Why is the TF relation so special?

- it connects a property of the dark halo - the maximum circular speed - with the product of the net integrated star formation history, i.e., the luminosity of the disk. This implies: Halo-regulated galaxy formation/evolution?
- The scatter is remarkably low. There is some important feedback mechanism involved, which we do not understand yet. The TFR offers some important insights into the physics of disk galaxy formation.

Faber Jackson relation



Kormendy relation



This relation tells us something about galaxy formation!

Dissipationless less merging or dissipational collapse?

From virial theorem, the dynamical $M \propto R\sigma^2$.
Luminosity $L \propto IR^2$ where I is the mean surface brightness
If M/L is constant, then $M \propto IR^2 \propto R\sigma^2$ and $IR \propto \sigma^2$
If ellipticals formed via dissipationless (dry) merging, kinetic energy per unit mass ($\sim \sigma^2$ remains constant), implying $R \propto I^{-1}$
If ellipticals formed via dissipative collapse of gas, then $I \propto MR^{-2}$, implying $R \propto I^{-0.5}$
Kormendy relation gives $R \propto I^{-0.8}$. What does this imply?

For elliptical galaxies

- $L = f(\sigma)$
- $\mu_e = g(r_e)$
- $L = h(\mu_e, r_e)$

Could these correlations be projections of a higher dimensional correlation?