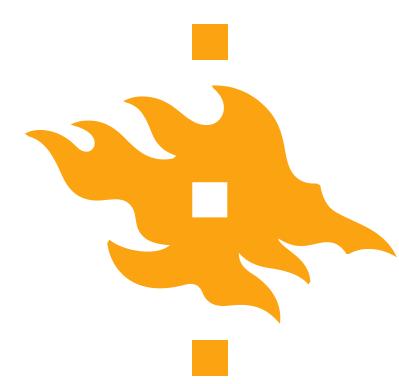


# **Galaxy formation and evolution**

**PAP 318, 5 op, autumn 2020**  
on Zoom

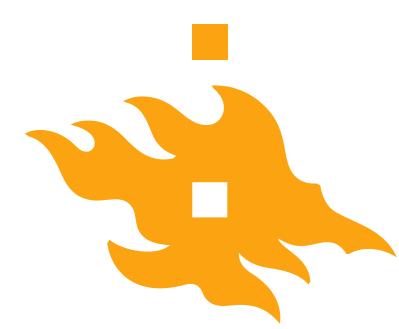
**Lecture 12: Formation of elliptical galaxies,  
27/11/2020**



# On this lecture we will discuss

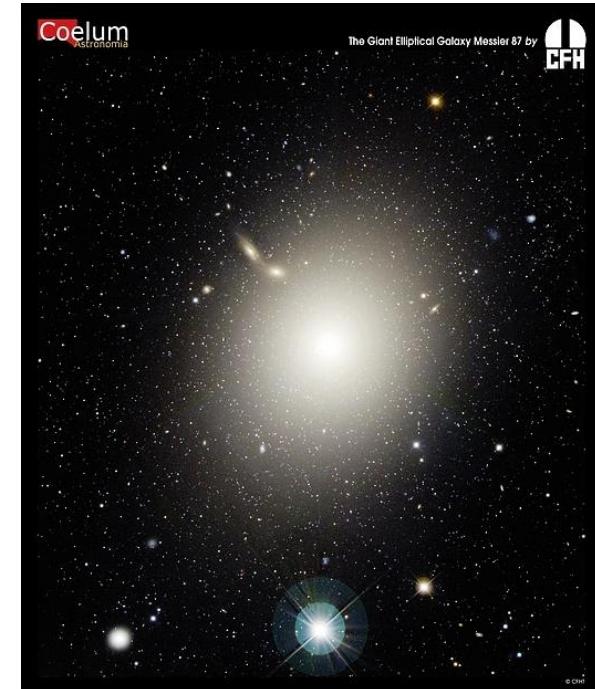
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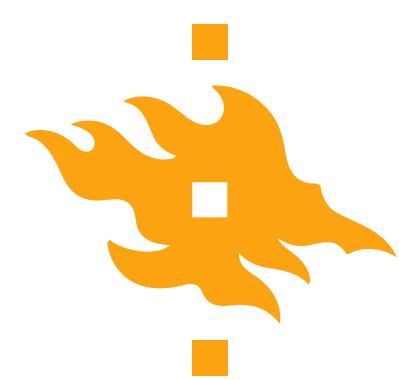
1. Photometric and kinematic properties of elliptical galaxies.
2. Dynamical modelling and the evidence for dark matter and black holes in elliptical galaxies.
3. The formation of elliptical galaxies. 1) The monolithic collapse scenario and 2) The merger scenario.
4. Observational tests of the formation scenarios. The sizes of elliptical galaxies.
5. Observational constraints. The phase-space densities of ellipticals and their merger rates.
6. The lecture notes correspond to: **MBW: pages 574-602 (§13.1-13.3)**



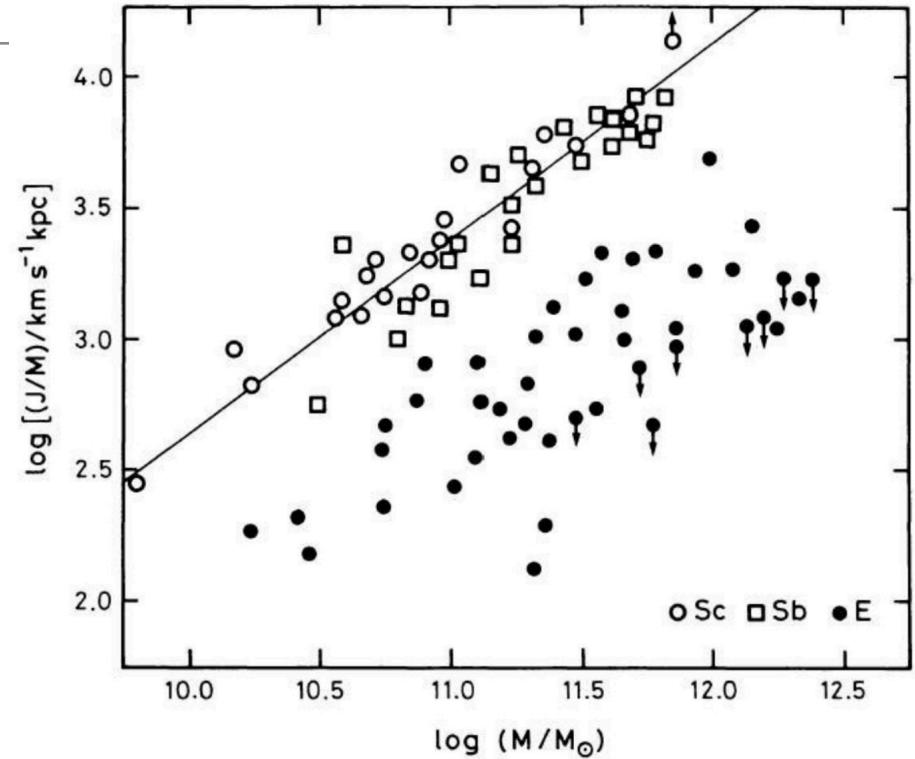
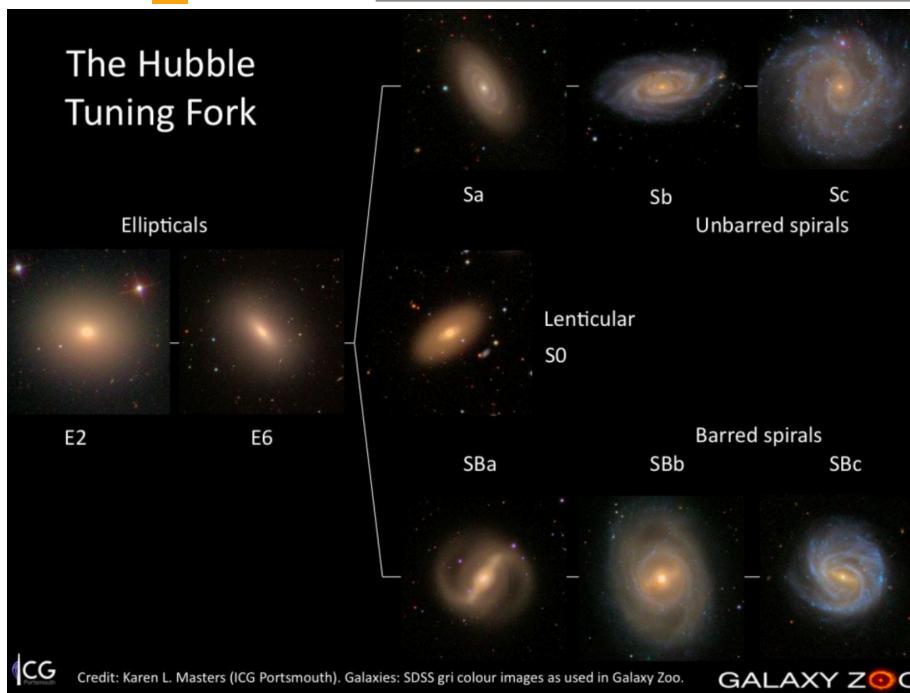
# 12.1 Ellipticals: Basic properties I

- In the 1970s it was assumed that ellipticals are relaxed systems, flattened by rotation and with isotropic velocity distributions. However, now we know that ellipticals are far more complex systems.
- Elliptical galaxies can be divided into 3 classes:
  1. Bright Es ( $M_B \leq -20.5$ ) are dominated by systems with little rotation, typically boxy isophotes and relatively shallow central surface brightness profiles.
  2. Intermediate Es ( $-20.5 \leq M_B \leq -18$ ) seem to be supported by rotation, have disk-like isophotes and steep central surface brightness profiles.
  3. Faint Es ( $M_B \geq -18$ ) reveal no, or very little rotation, and have roughly exponential surface brightness profiles.

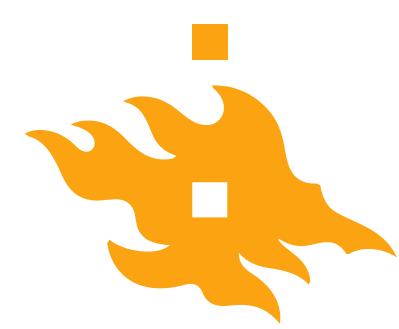




# Ellipticals: Basic properties II



- Ellipticals are early-type galaxies that have in general red colours with low cold gas fractions. Ellipticals have also lower specific angular momentum than spiral galaxies at a given mass.



# Observables of ellipticals

- The observables of a galaxy, such as the surface brightness, rotation velocity and velocity dispersion at a position  $(x,y)$  are line-of-sight projections of the corresponding three-dimensional quantities.
- The surface brightness at a position  $(x,y)$  is then given by:

$$I(x, y) = \frac{\Sigma(x, y)}{\Upsilon} = \frac{1}{\Upsilon} \int \rho(\vec{x}) dz$$

- Here  $\Sigma(x, y)$  is the projected surface mass density and  $\Upsilon$  is the stellar mass-to-light ratio. Similarly the normalized line-of-sight velocity (LOSVD) is given by:

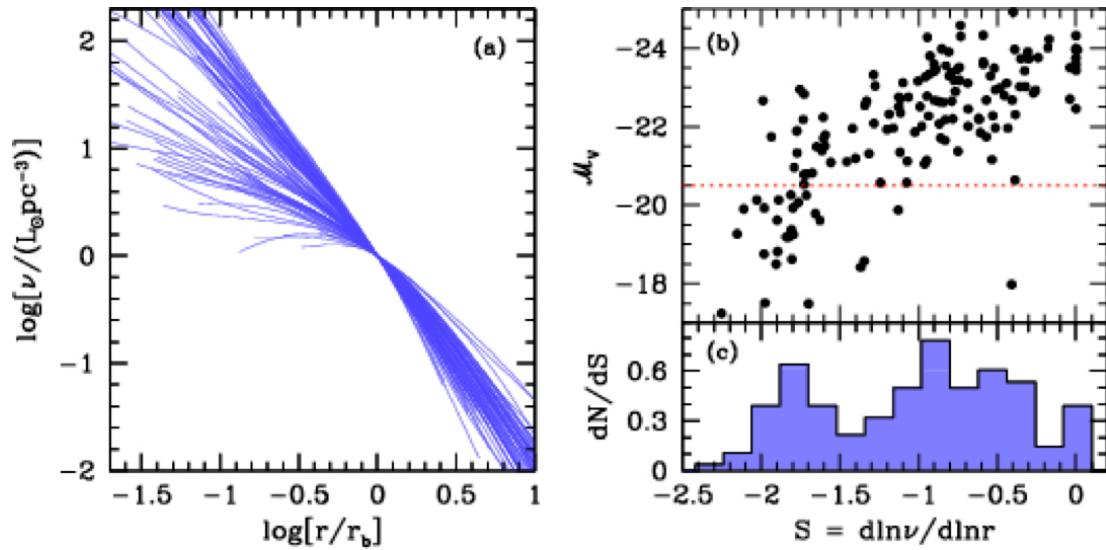
$$\mathcal{L}(x, y, v_z) = \frac{1}{\Sigma(x, y)} \int \int \int f(\vec{x}, \vec{v}) dv_x dv_y dz$$

- Here  $f(\mathbf{x}, \mathbf{v})$  is the 6D phase-space distribution function. Observationally the LOSVDs can be obtained by analysing the profiles of spectral absorption lines.



# Photometric properties

- The observed diskiness ( $a_4 > 0$  Lect 2.) in intermediate luminosity ellipticals is often interpreted as due to an embedded stellar disk.
- The central regions of disky Es typically have steep cusps, while many boxy ( $a_4 < 0$ ), bright Es have gently rising inner luminosity profiles (i.e. cores of “missing light”).
- A significant fraction of bright Es show isophotal twisting. This is strong evidence for a triaxial structure.

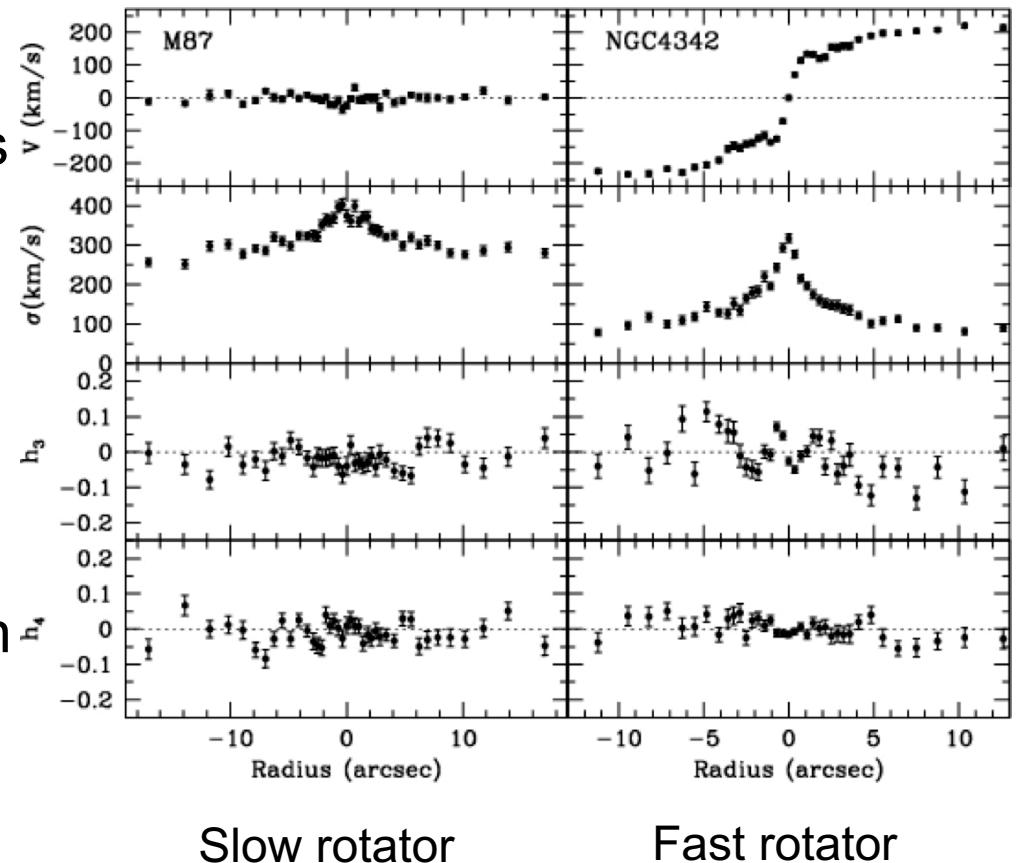


- The bimodality in the photometric properties is partly due to sample selections. The transition between the two populations is actually smoother, as seen in the right panel.



# Kinematic properties I

- Bright, boxy Es are slow rotators, supported by anisotropic velocity dispersions and are triaxial.
- Fainter, disk-like Es typically have much higher rotation velocities and are often consistent with being purely rotationally flattened.
- LOSVDs are close to Gaussian and the departure from the Gaussian profiles can be quantified using the Gauss-Hermite moments  $h_3$  and  $h_4$ .

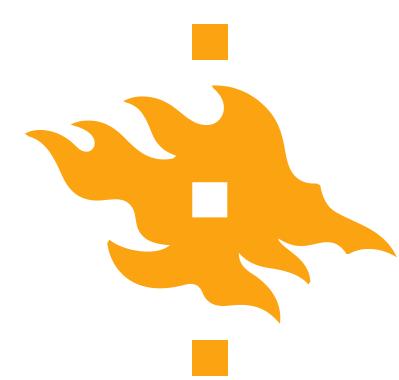




# Kinematic properties II

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- For an oblate rotator, the kinematic axis, defined as the axis along which the observed rotation velocity is zero, is aligned with the minor axis of the photometry.
- A number of ellipticals, however, are observed to have rotation along both the major and minor axes. Thus, their kinematic and photometric axes do not coincide.  $\Psi = |\theta_{\text{kin}} - \theta_{\text{phot}}|$
- Kinematic misalignments (angle  $\Psi$ ) are more common among the bright, velocity-dispersion supported ellipticals. Rapidly rotating ellipticals, on the other hand, rarely reveal kinematic misalignment.
- Finally, about ~25% of all ellipticals have kinematically decoupled cores, for which the angular momentum vector is misaligned with respect of the that of the bulk of the galaxy.



## 12.2 Dynamical modelling

- Modelling the dynamics of elliptical galaxies has two primary goals:  
1) Constrain the mass-to-light ratio and 2) Constrain the orbital structure, or equivalently, the phase-space distribution functions of the elliptical.
1. Jeans Models: One way to constrain the mass distribution from the observed kinematics is to solve the Jeans equation relating the gravitational potential to the various intrinsic velocity moments. The largest uncertainty lies in the velocity anisotropy  $\beta(r)$ :

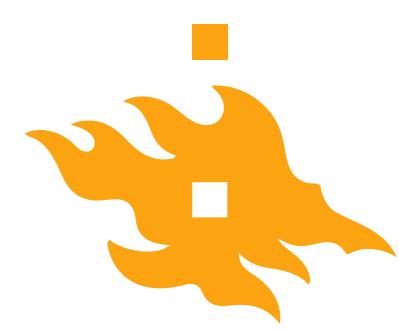
$$\frac{1}{\rho} \frac{d(\rho \langle v_r^2 \rangle)}{dr} + 2\beta \frac{\langle v_r^2 \rangle}{r} = -\frac{d\Phi}{dr}, \quad \beta(r) = 1 - \langle v_\theta^2 \rangle / \langle v_r^2 \rangle$$

2. Schwarzschild orbit models: Assuming a stellar-mass-to-light ratio the deprojected light distribution is transformed into a stellar mass distribution. Then a large number of orbits are calculated by numerical integration in order to find the orbit model that best fits the derived gravitational potential.



# Evidence for dark matter haloes

- Compared to disk galaxies it is harder to detect dark matter in elliptical galaxies because of the lack of suitable and easily interpretable tracers at large radii. For detecting dark matter in Ellipticals the following techniques have been used:
  - The stellar kinematics obtained from absorption line spectroscopy can be used in principle. However, the surface brightness drops rapidly beyond one effective radius and the velocity measurements can also be contaminated by velocity anisotropy ( $\beta \neq 0$ ).
  - Use discrete dynamical tracers, such as globular clusters, planetary nebulae and/or satellite galaxies. Can be observed to large radii, but uncertainties in the underlying dynamics of the tracer population.
  - X-ray mapping of the hot gas and direct mass measurements using gravitational lensing have also been used for ellipticals.

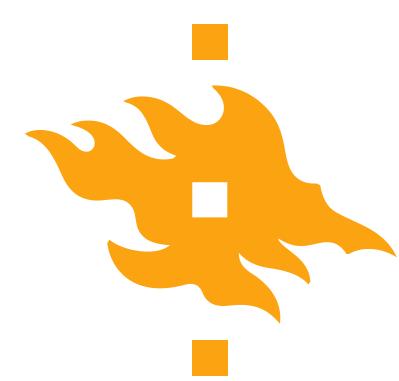


# Evidence for supermassive black holes

- In searching for supermassive black holes in galaxies, one attempts to find evidence for an increase in the mass-to-light ratio towards the centre to values that cannot be explained by normal stellar populations.
- A massive BH at the centre of a galaxy only significantly influences the dynamics inside its radius of influence:

$$r_{\text{BH}} = \frac{GM_{\text{BH}}}{\sigma^2} = 10.8\text{pc} \left( \frac{M_{\text{BH}}}{10^8 M_{\odot}} \right) \left( \frac{\sigma}{200 \text{km s}^{-1}} \right)^{-2}$$

- Many ellipticals have centrally rising velocity dispersions (see Fig on slide 7). However, the observed rise can also be due to a radially anisotropic velocity field and not necessarily a BH.
- The black hole masses correlate with the stellar velocity dispersion, important result for galaxy formation studies (see next lecture 13).

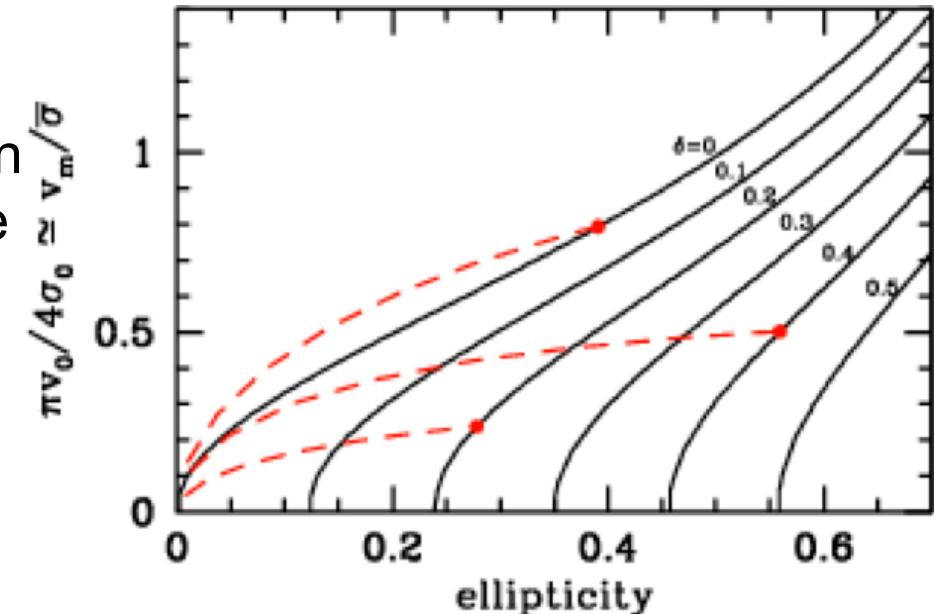


# Shapes of elliptical galaxies

- The positions of ellipticals can be plotted in an anisotropy diagram, which shows the relationship between the kinematic parameter  $v_m/\sigma$  and the ellipticity  $\epsilon$  of the galaxy.
- The position of ellipticals in this diagram depends on the anisotropy parameter  $\delta$  and projection effects (dashed red lines):

$$\Pi_{xx} = M\sigma_0^2, \quad \Pi_{zz} = (1 - \delta)M\sigma_0^2$$

- For an oblate system with isotropic velocity dispersion, i.e.  $\delta=0$  we get:

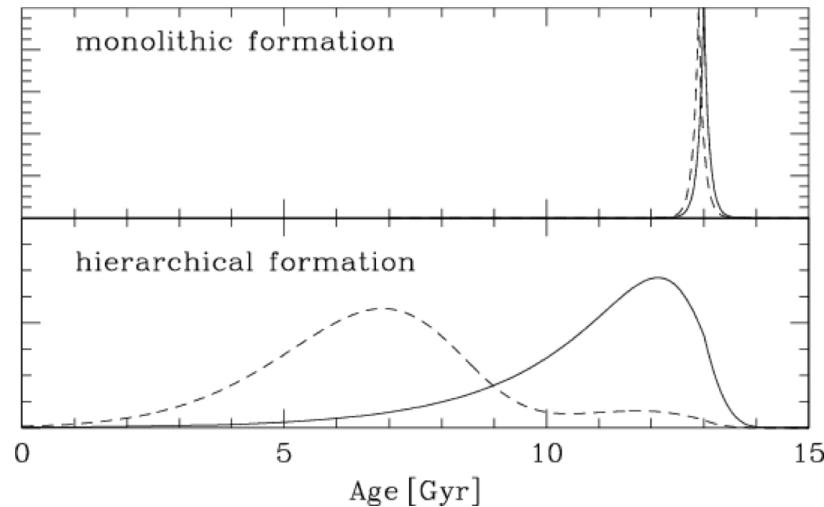


$$\frac{v_m}{\sigma} \approx \sqrt{\frac{\epsilon}{1 - \epsilon}}$$



## 12.3 The formation of elliptical galaxies

- The fact that the dynamical structure of elliptical galaxies is less ordered than that of disk galaxies immediately suggests that their formation was more violent.
- It is thus believed that violent relaxation in which the potential fluctuates rapidly played an important role in their formation
- The role of angular momentum (low for ellipticals) and the initial density (high for ellipticals) has also been invoked in elliptical formation models.
- The two main formation mechanisms are:
  1. The monolithic collapse scenario.
  2. The merger scenario.



Formation age is plotted in solid and the assembly age in dashed.

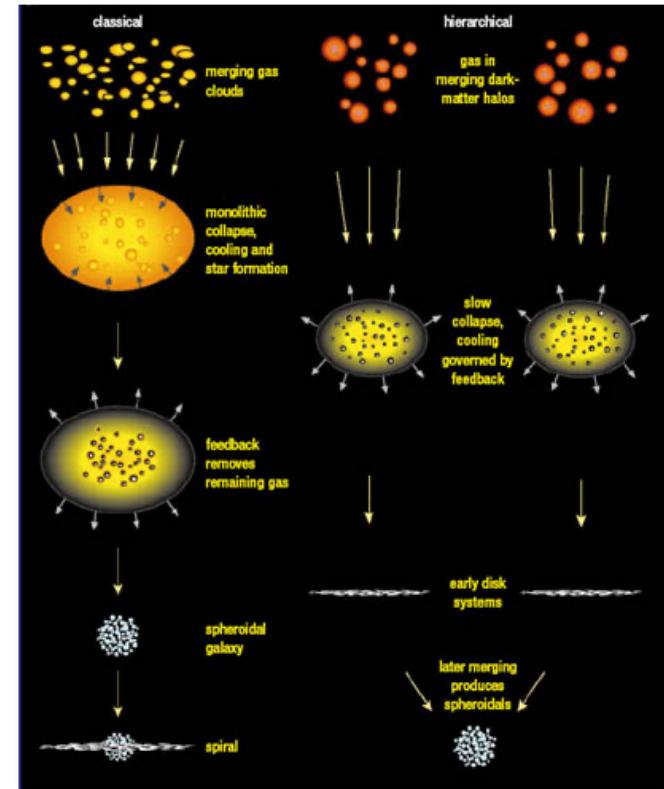
**Formation age ≠ Assembly age**

Formation of stars →  
Assembly of galaxies.



# Monolithic collapse

- In this scenario ellipticals form on a short time scale through collapse and virialisation from idealised uncollapsed initial conditions.
- If the star-formation time scale is short compared to the free-fall time scale the collapse is effectively dissipationless.
- The main characteristic of this scenario is that the stars form simultaneously with the assembly of the final galaxy.
- This scenario was inspired by the fact that elliptical galaxies appear to be a remarkably homogeneous class of objects with uniformly old stellar populations.



**Figure 1:** The two competing models of galaxy formation and evolution that could produce the galaxies we observe today. The classical 'top-down' or monolithic model is shown on the left. This involves the collapse of a large cloud over time. The hierarchical or 'bottom-up' model is shown on the right and involves successive mergers of small bodies.<sup>4</sup>



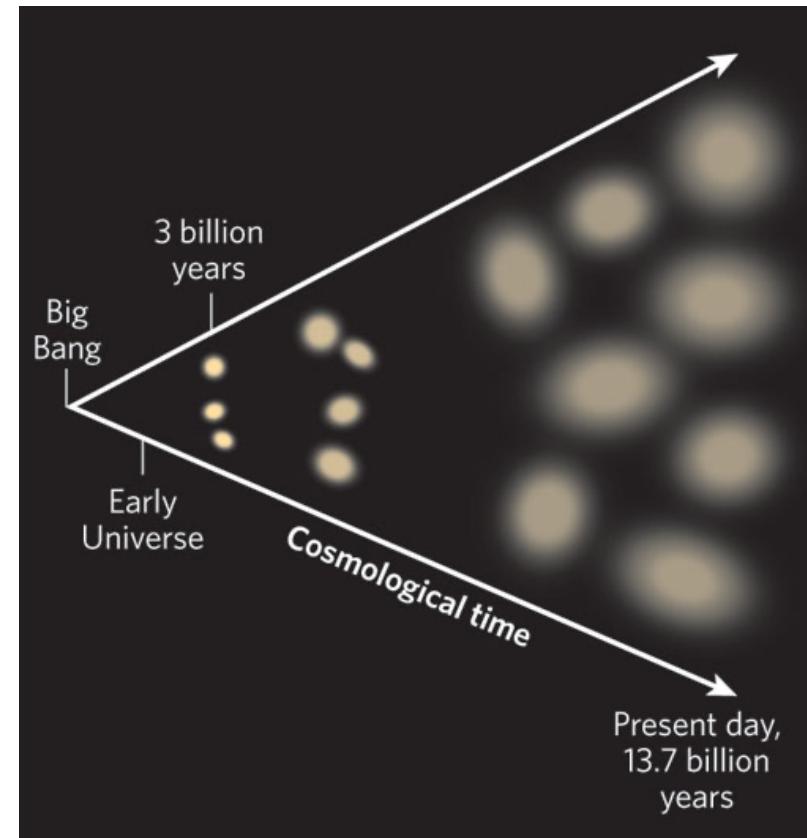
# Monolithic collapse: Problems

- In the dissipationless extreme, all the gas associated with the object is turned into stars prior to the collapse. The collapse then effectively conserves energy and given the observed sizes and large masses of elliptical galaxies they must have formed at redshifts greater than  $z \sim 20$  in stark conflict with observations.
- Violent relaxation does not differentiate between stars and dark matter, but elliptical galaxies are clearly differentiated with the baryons strongly concentrated in the centres of the galaxies.
- The great majority of ellipticals have old stellar populations, but the total mass density of ellipticals is a factor of 3-4 lower at  $z \sim 1$  than today. Thus ellipticals had to either form or assemble stars at later redshifts.
- There is also evidence of substantial size growth of ellipticals since  $z \sim 2$  until the present day, clearly contradicting monolithic collapse and passive stellar evolution.



# The merger scenario I

- In this scenario, an elliptical forms when two or more pre-existing and fully formed galaxies merge together.
- The main difference with respect to the monolithic collapse scenario is that the formation of the stars occurs before, and effectively independently of, the assembly of the final galaxy.
- The outstanding issues are 1) whether mergers of observed galaxies (not necessarily  $z=0$  galaxies) can produce ellipticals and 2) whether the integrated merger rate as a function of progenitor properties and environment can reproduce the  $z=0$  population.





# The merger scenario II

- Mergers of disk galaxies when including extensive dark matter haloes are able to produce relatively slowly rotating ( $v/\sigma \sim 0.2$ ) ellipticals, with isophotal shapes that are roughly consistent with observed ellipticals.
- The merger mass ratio plays an important role, equal-mass mergers result in more boxy and slowly rotating remnants whereas unequal-mass mergers ( $\geq 3:1$ ) result in diskier and more rapidly rotating ellipticals.
- The amount of gas in the merger results in distinctly different ellipticals. Gas-rich mergers produce more disk-like fast-rotating ellipticals, whereas gas-poor mergers produce more boxy slowly-rotating ellipticals.
- Although a large range of ellipticals can be explained by the merger scenario, binary mergers are unable to produce the most massive slowly-rotating ellipticals, found especially in galaxy clusters.



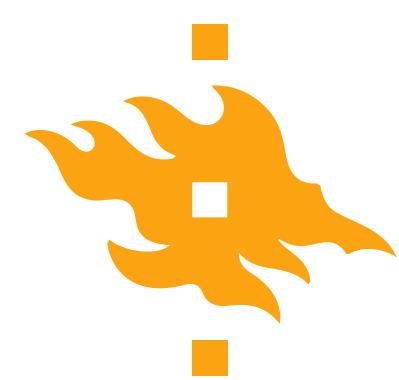
# The two-phased model of elliptical galaxy formation

- In the two-phased model of elliptical galaxy formation developed by Naab, Johansson & Ostriker the formation of elliptical galaxies is explained as a combination of the monolithic and merger scenarios.
- The core ( $r<1$  kpc) of ellipticals is assembled rapidly at high redshifts ( $z\sim 4-6$ ) in dissipational collapse and multiple mergers. The later assembly ( $z\leq 2-3$ ) proceeds then by the accretion of gas-poor minor galaxies that build the outer envelope of the ellipticals.
- In this scenario the formation time and the assembly time of the elliptical is not equal.
- The scenario can potentially explain the observed bimodality in the galaxy population, the downsizing of massive ellipticals and the observed size growth of elliptical galaxies since  $z\sim 2$ .



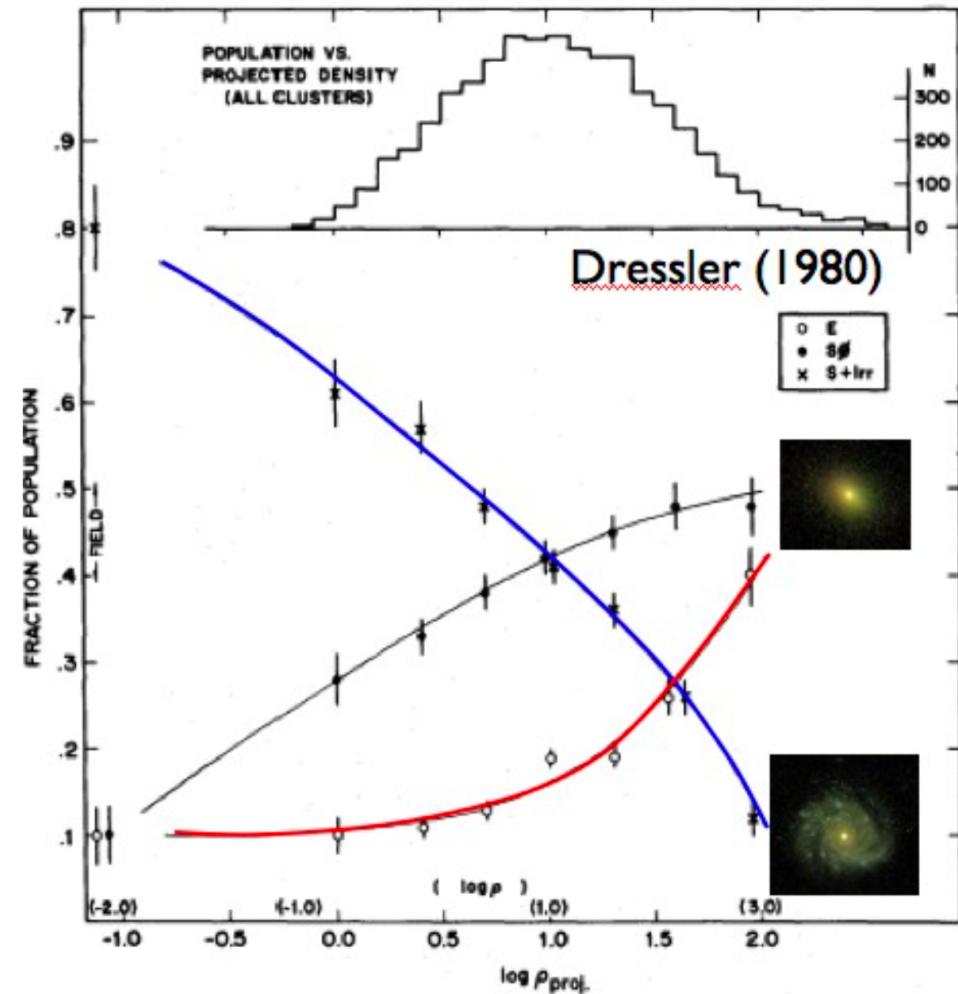
## 12.4 Observational tests

- The theories for the formation of elliptical galaxies can be tested in the following main areas:
  1. Star formation history: The monolithic collapse model assumes that the stars form in a single burst, whereas hierarchical merging predicts star formation in several different sites and over a more extended period.
  2. Assembly history: In the monolithic collapse model the assembly of an elliptical is coeval with the formation of its stars, while in the merger scenario, most of the stars form in progenitor galaxies well before the assembly of the final elliptical.
  3. Progenitor properties: In the monolithic picture the progenitor of the elliptical is a single star-bursting gas cloud, while in the hierarchical picture ellipticals have diverse progenitors (spirals and ellipticals).



# Morphology-density relation

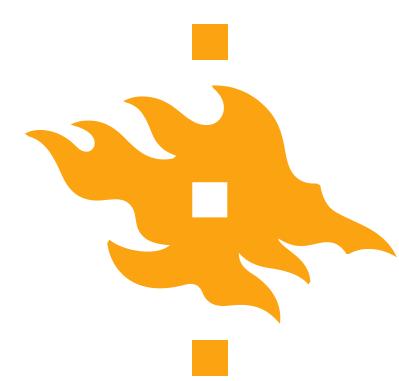
- The Morphology-Density Relation shows that galaxy morphologies depend on the environment.
- Disk galaxies are more prominent in the field (low density), whereas elliptical galaxies are more prominent in galaxy clusters (high density). This observation supports the merger scenario.





# Evolution of number densities

- An important difference between the monolithic and merger scenarios is the number density of ellipticals.
- In the monolithic scenario the present population of ellipticals must be present throughout the cosmic epoch, whereas the merger scenario predicts that the comoving number density above any given stellar mass should decrease with increasing redshift.
- Recent observations seem to indicate that the stellar mass in galaxies of all types at redshift  $1.3 < z < 2$  seems to be a factor of several below the current value of ellipticals.
- However, the situation for the most massive ellipticals is unclear, with some papers claiming that the number density of the most massive ellipticals change little if at all back to  $z \sim 1$ : -> **Downsizing**.



# The sizes of ellipticals I

- In general, the size of an equilibrium galaxy is related to its mass and binding energy via the scalar virial theorem, which states that  $E=W/2$ .
- The energy can be expressed as:  $W = \zeta \frac{GM_s^2}{r_e}$
- Here  $r_e$  is some characteristic size of the system and  $\zeta$  is a form factor that depends on the density distributions of the stars and dark matter. From numerical simulations we get for typical galaxies with realistic dark matter profiles:  $\zeta \sim 0.6 \pm 0.1$ .
- For a monolithic collapse the relationship between the final energy and initial energy of the gas can be parameterized as:  $|E_f| = \eta |E_i|$ , where for a spherical system ( $f_{\text{gas}} = M_{\text{gas}}/M_{\text{vir}}$  and  $r_t$  is the turnaround radius,  $r_t \sim 2r_{\text{vir}}$ ):

$$E_i = W_i = -\frac{3}{5} \frac{GM_{\text{gas}}^2}{f_{\text{gas}} r_t} \quad E_f = \frac{W_f}{2} = -\zeta_f \frac{GM_{\text{gas}}^2}{2r_e}$$

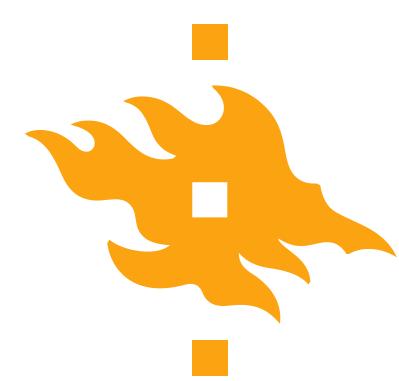


# The sizes of ellipticals II

- Relating the two energies for  $\zeta \sim 0.6$  we obtain  $\eta_{\text{gas}} = f_{\text{gas}}(r_{\text{vir}}/r_e)$  and inserting the following observational result for the sizes of ellipticals we finally obtain an expression for  $\eta$ :

$$r_e = 0.98 h^{-1} \text{kpc} \left( \frac{M_*}{10^{10} h^{-1} M_\odot} \right)^{0.56}$$
$$\eta = 6.9 \left( \frac{f_{\text{gas}}}{0.15} \right)^{0.44} \left( \frac{M_{\text{vir}}}{10^{12} h^{-1} M_\odot} \right)^{-0.23}$$

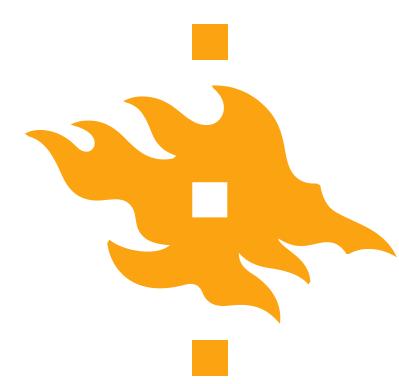
- Thus in the monolithic collapse scenario the binding energy of the gas has to become more negative by a factor of  $\sim 7$  before it forms stars, in order to explain the observed sizes of elliptical galaxies.



# The sizes of ellipticals III

- In the merger scenario, the size of the remnant depends on those of the progenitors as well as on the amount of dissipation and star formation during the merger and in general numerical merger simulations must be performed to make realistic predictions for the sizes of merger remnants.
- In special circumstances, however, simple predictions are still possible. In particular we can estimate the sizes of the merger remnant in the case of a merger between two galaxies with no gas (a dissipationless or **dry merger**).
- For an equal-mass dry merger we can derive the following formula (see MBW pages 596-597 for details), where  $f_{\text{tot}} = f_{\text{orb}} + f_{\text{tr}} + f_{\text{ej}}$  is the total fraction of the orbital, transferred (from the stars to the DM component) and ejected energies:

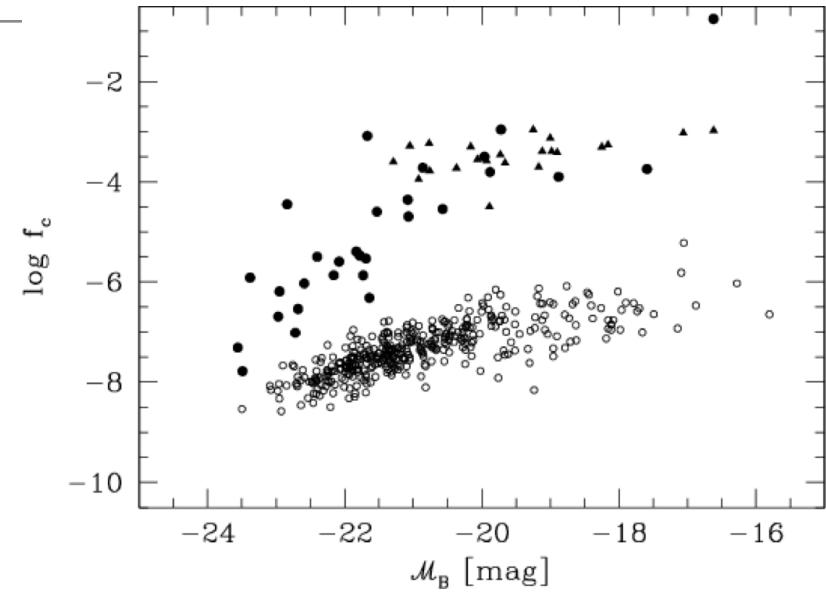
$$\frac{r_f}{r_1} = \frac{4}{2 + f_{\text{tot}}/\zeta} \left(1 - \frac{M_{\text{ej}}}{M_1 + M_2}\right)^2$$



# 12.5 Observational constraints: The phase-space density

- The maximum value of the coarse-grained phase-space density of a collisionless system cannot increase during its evolution.
- The phase-space density in the central region of a galaxy can be estimated by dividing the central mass density by the volume occupied by an ellipsoid with its axes equal to the three velocity dispersions.
- The central phase-space densities of  $M_B \geq -22$  Es are more than three orders of magnitude higher than those of observed disks.

Solid symbols: ellipticals  
Open symbols: spirals



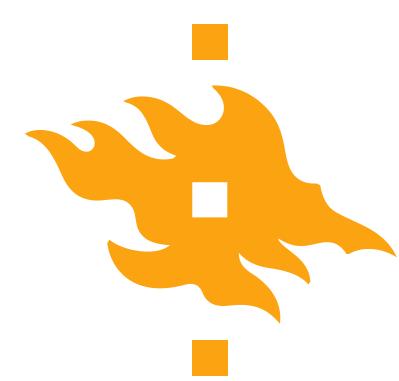
- Higher redshift disks were more compact (bulges). But most importantly mergers with **significant amounts of gas** can easily enhance the central phase-space densities to the observed values.



# Globular clusters and merging signatures

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- Elliptical galaxies have more globular clusters per unit stellar mass than spirals (by a factor of 3-5 for a unit of galaxy luminosity of  $M_V=-15$ ). At first this seems to be a serious challenge to the merger scenario.
- The globular cluster population is bimodal, with red metal-rich clusters and blue metal-poor clusters. The metal-poor clusters formed at high  $z$  and the metal-rich clusters in somewhat later gas-rich mergers.
- In many elliptical galaxies formed through mergers we would expect to find observational signatures, such as clearly distorted morphologies, shells, ripples and plumes. Observational merger signatures are not created in the merger of dynamically hot systems such as ellipticals.
- The observed number of distorted morphologies in local galaxies and the number of elliptical galaxies are consistent with the merger scenario.



# Merger rates

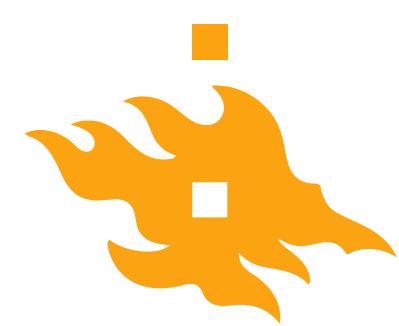
- What is the rate of major mergers as a function of redshift and of galaxy properties?
- The number of mergers can be observed directly by observing galaxies in the process of merging (in practise difficult due to cosmological redshift dimming):

$$\dot{n}_{\text{mrg}}(z) = \frac{f_{\text{mrg}}(z)n_{\text{gal}}(z)}{\tau_{\text{mrg}}(z)}$$

- Alternatively we can observe the number of galaxy pairs and use the dynamical timescale to estimate the merger timescale:

$$\dot{n}_{\text{mrg}}(z) = \frac{1}{2} \frac{f_{\text{pair}}(z)n_{\text{gal}}(z)}{\tau_{\text{df}}(z)}$$

- The result is uncertain, but in general the merger rate increases with increasing redshift:  $f_{\text{mrg}} \propto (1 + z)^m$ ,  $0 \lesssim m \lesssim 4$



# What have we learned?

1. The population of elliptical galaxies is bimodal, with bright ( $M_B \leq -20.5$ ) ellipticals being slow rotators, with anisotropic velocity dispersions, boxy isophotes and central cores. Intermediate ellipticals ( $-20.5 \leq M_B \leq -18$ ) are fast rotators, supported by rotation and they have disk-like isophotes and cuspy inner light profiles.
2. Traditionally the main formation mechanisms of ellipticals include the monolithic collapse in which the elliptical is assembled in a single burst at high redshift and the merger scenario in which ellipticals are formed from the merger of pre-existing galaxies.
3. The formation age and assembly age of an elliptical is in general not the same. Observations indicate significant evolution in the elliptical galaxy population with redshift ruling out the monolithic collapse scenario. A successful model of elliptical galaxy formation is most probably a mixture of both formation scenarios, i.e. ellipticals assemble hierarchically, but the most massive ellipticals form very rapidly at high redshifts.