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GALAXY FORMATION AND EVOLUTION

PAP 318, 5 op, autumn 2022
B119, Exactum

Lecture 12: Formation of elliptical galaxies

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TODAY WE WILL COVER

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.**

The lecture notes correspond to:

- **MBW: pages 574-602 (§13.1-13.3)**

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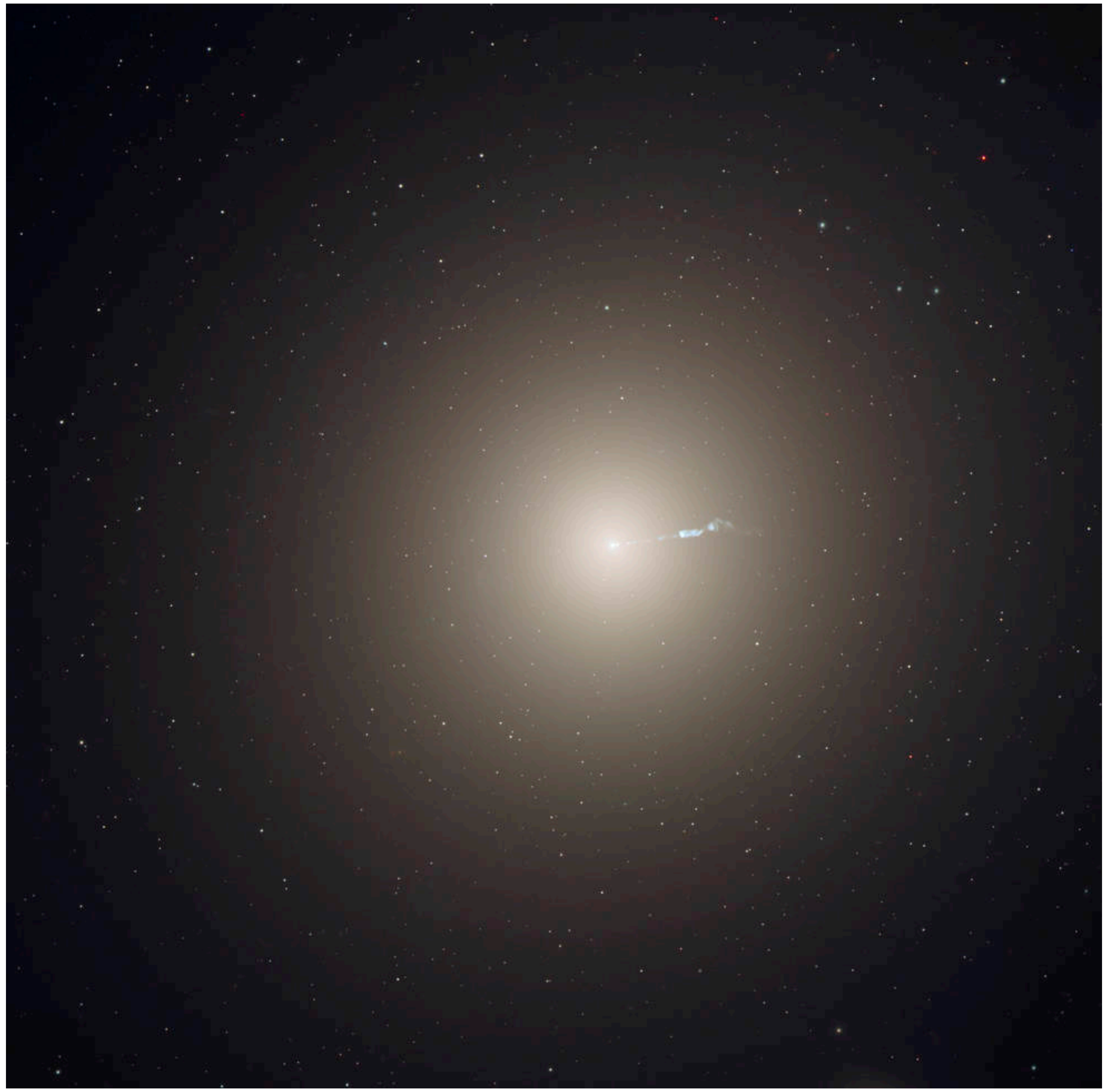
12.1 ELLIPTICALS: PROPERTIES

- Before the first observations in the 1970s, it was assumed that ellipticals are ***oblate*** systems, flattened by rotation and with isotropic velocity distributions. However, now we know that ellipticals are far more complex systems.

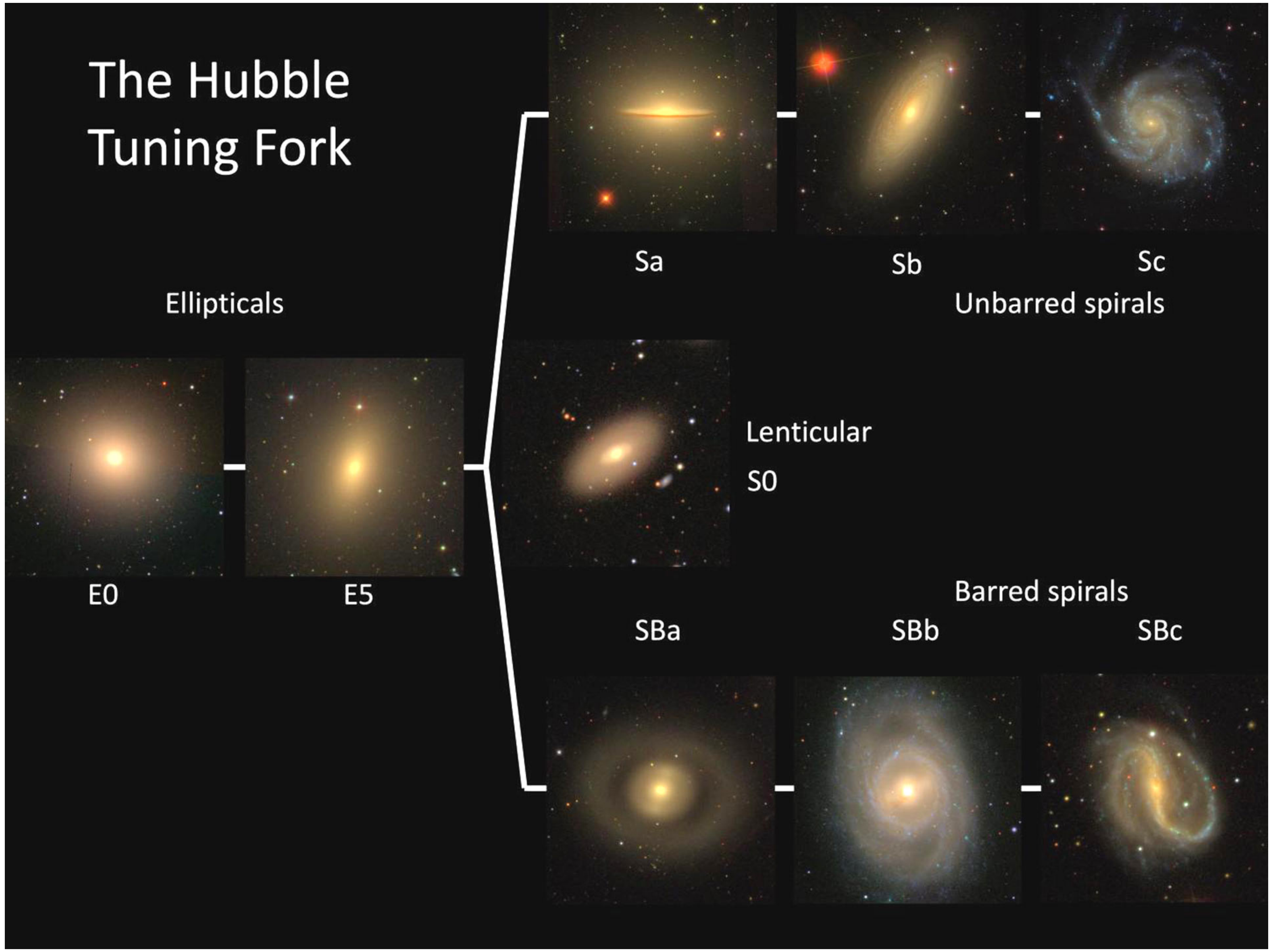
- Elliptical galaxies can be divided into 3 classes:
  - Bright Es ($M_B \leq -20.5$) are dominated by systems with little rotation, typically boxy isophotes and relatively shallow central surface brightness profiles.
  - Intermediate luminosity Es ($-20.5 \leq M_B \leq -18$) seem to be supported by rotation, have disky isophotes and steep central surface brightness profiles.
  - Faint Es ($M_B \geq -18$) reveal no, or very little rotation, and have roughly exponential surface brightness profiles.



Credits: NASA, ESA, HST

12.1.1 ELLIPTICALS: MORPHOLOGY

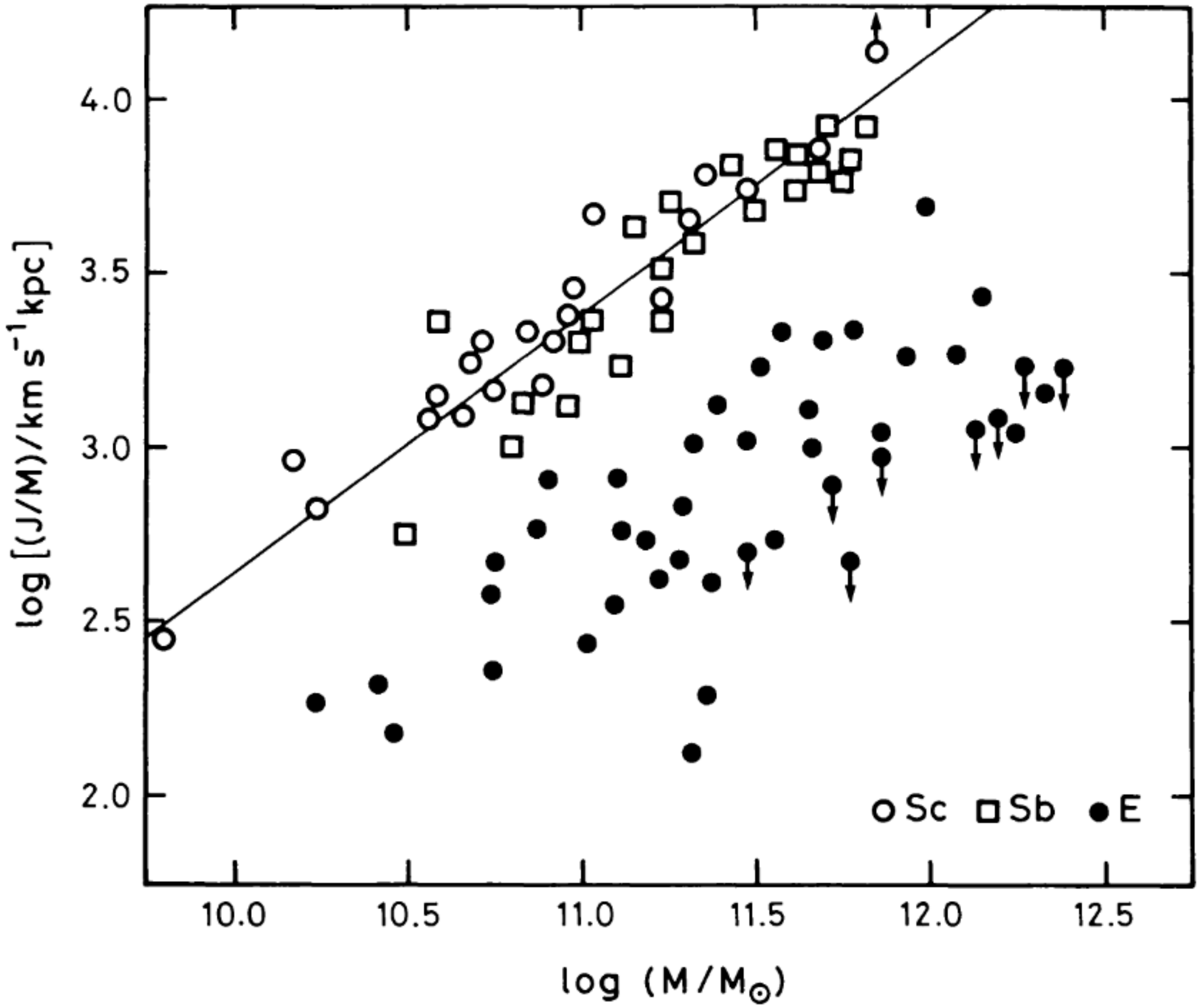
- **Ellipticals belong in the 'early-type' morphology group and have in general red colours with low cold gas fractions.**



Credits: Masters+19, 1904.11436

12.1.2 ELLIPTICALS: ANGULAR MOMENTUM

- **Ellipticals have also lower specific angular momentum than spiral galaxies at a given mass.**



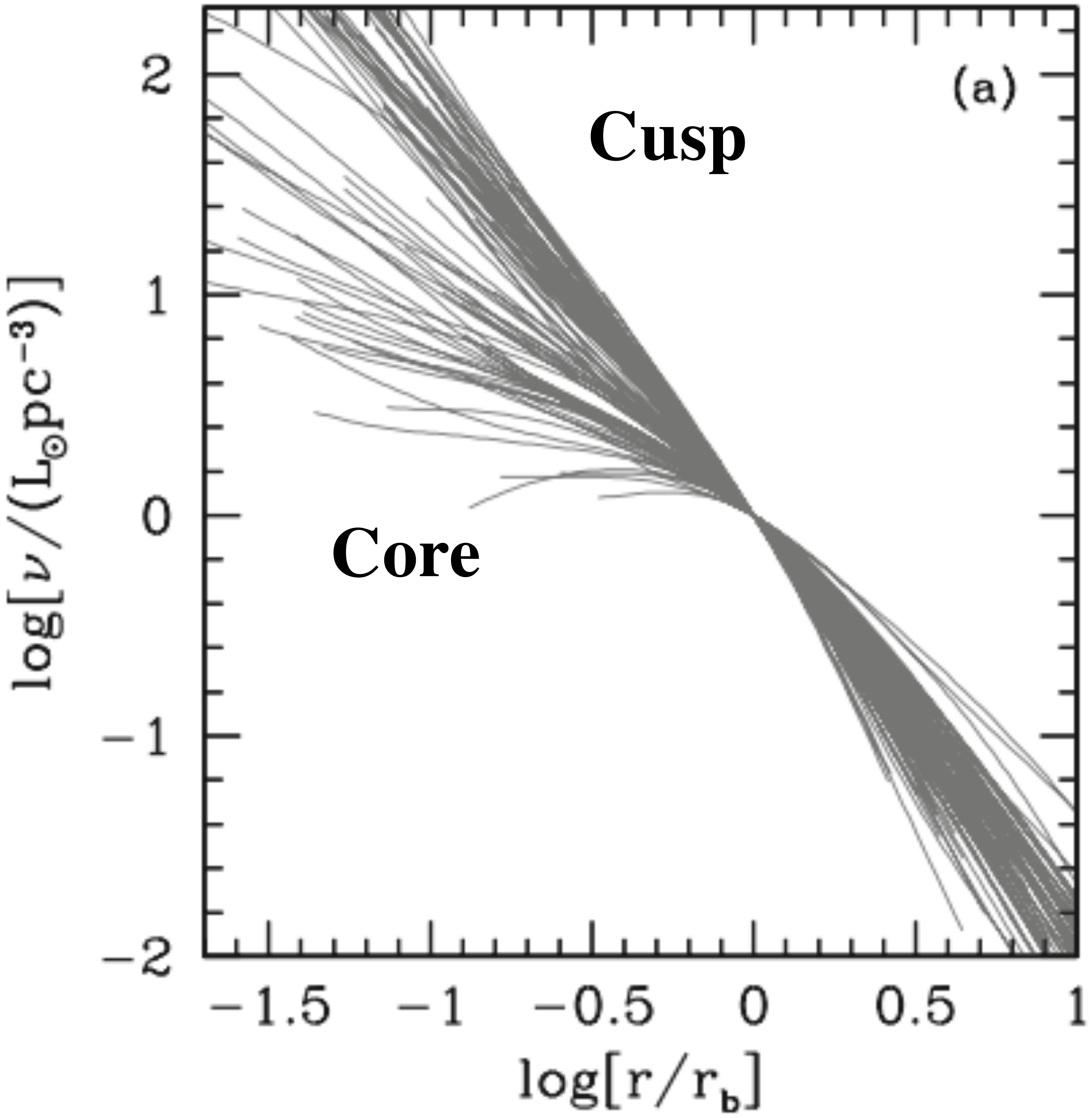
Credits: Fall83, 1983IAUS..100..391F

12.1.3 ELLIPTICALS: STRUCTURE

- **The *observed diskiness* in intermediate luminosity ellipticals is often interpreted as due to an embedded stellar disc.**

- **The central regions of disky Es typically have steep cusps, while many boxy (α_4<0), bright Es have gently rising inner luminosity profiles (i.e. cores of "missing light").**

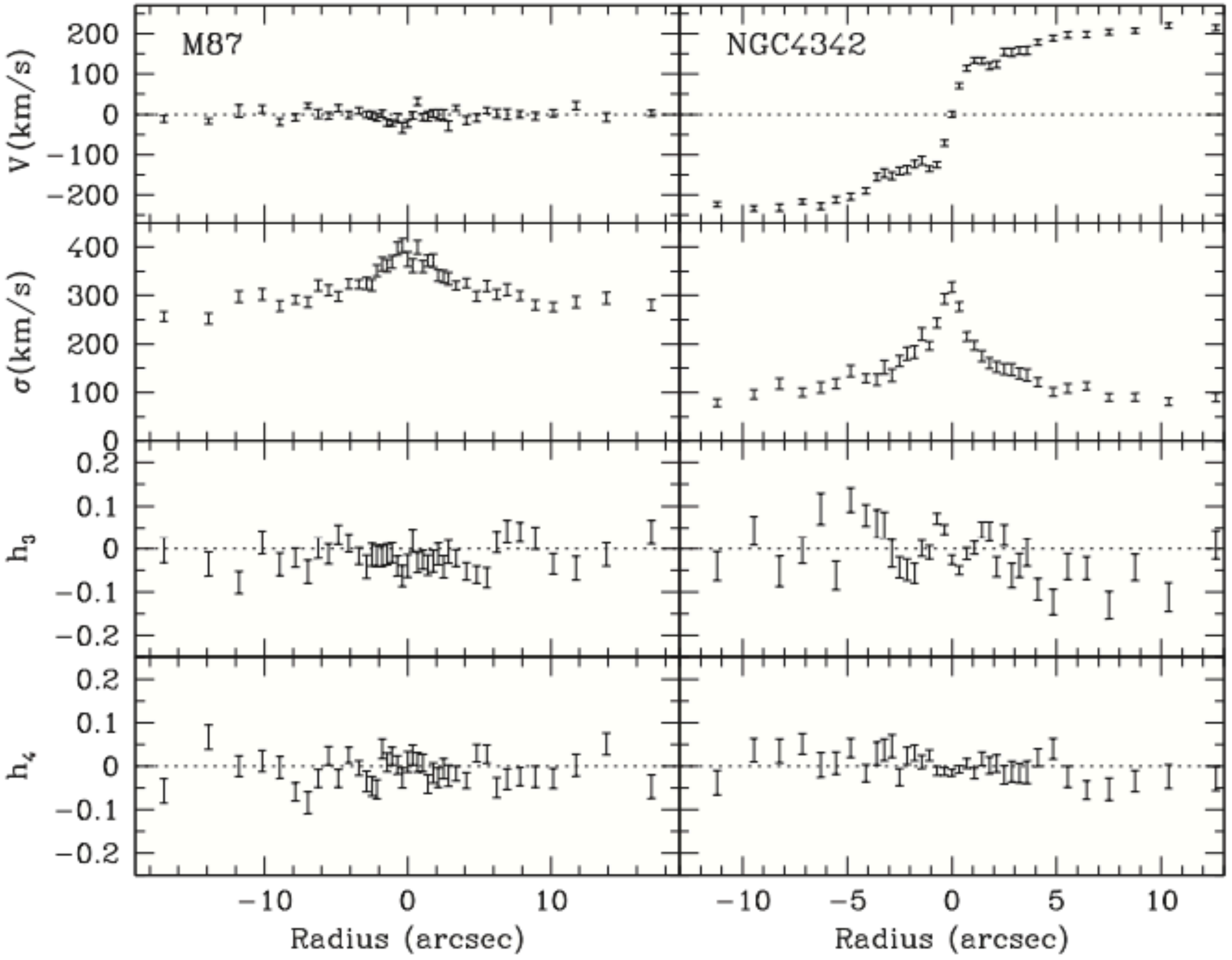
- **A significant fraction of bright Es show isophotal twisting. This is strong evidence for a triaxial structure where the intrinsic axis ratios change with radius**



Credits: Fig 13.1, MBW

12.1.4 ELLIPTICALS: DYNAMICS

- **Bright, boxy Es are slow rotators, supported by anisotropic velocity dispersions and are triaxial.**
- **Fainter, disky Es typically have much higher rotation velocities and are often consistent with being purely rotationally flattened.**
- **Line-of-sight velocity dispersions (σ) are close to Gaussian and the departure from the Gaussian profiles can be quantified using the Gauss-Hermite moments h_3 and h_4.**



Slow rotator **Fast rotator**

Credits: Fig 13.2, MBW

12.1.5 ELLIPTICALS: KINEMATICS

- 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.
- Kinematic misalignments (angle Y) 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 ELLIPTICALS: DARK MATTER

- Compared to disc 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 there are 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.

12.3 ELLIPTICALS: 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**

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

- **Many ellipticals have centrally rising velocity dispersions (see Fig 13.1 in 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.**

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12.4 ELLIPTICALS: MODELLING

- **Modelling the dynamics of elliptical galaxies and comparing them with observed ellipticals has two main scientific goals:**
  - **Constrain the mass-to-light ratio which reveals the properties of stars, dark matter and supermassive black holes**
  - **Constrain the orbital structure, which can be used to study different formation scenarios.**

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12.4.1 ELLIPTICALS: MODELLING

- **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 β(r)**

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

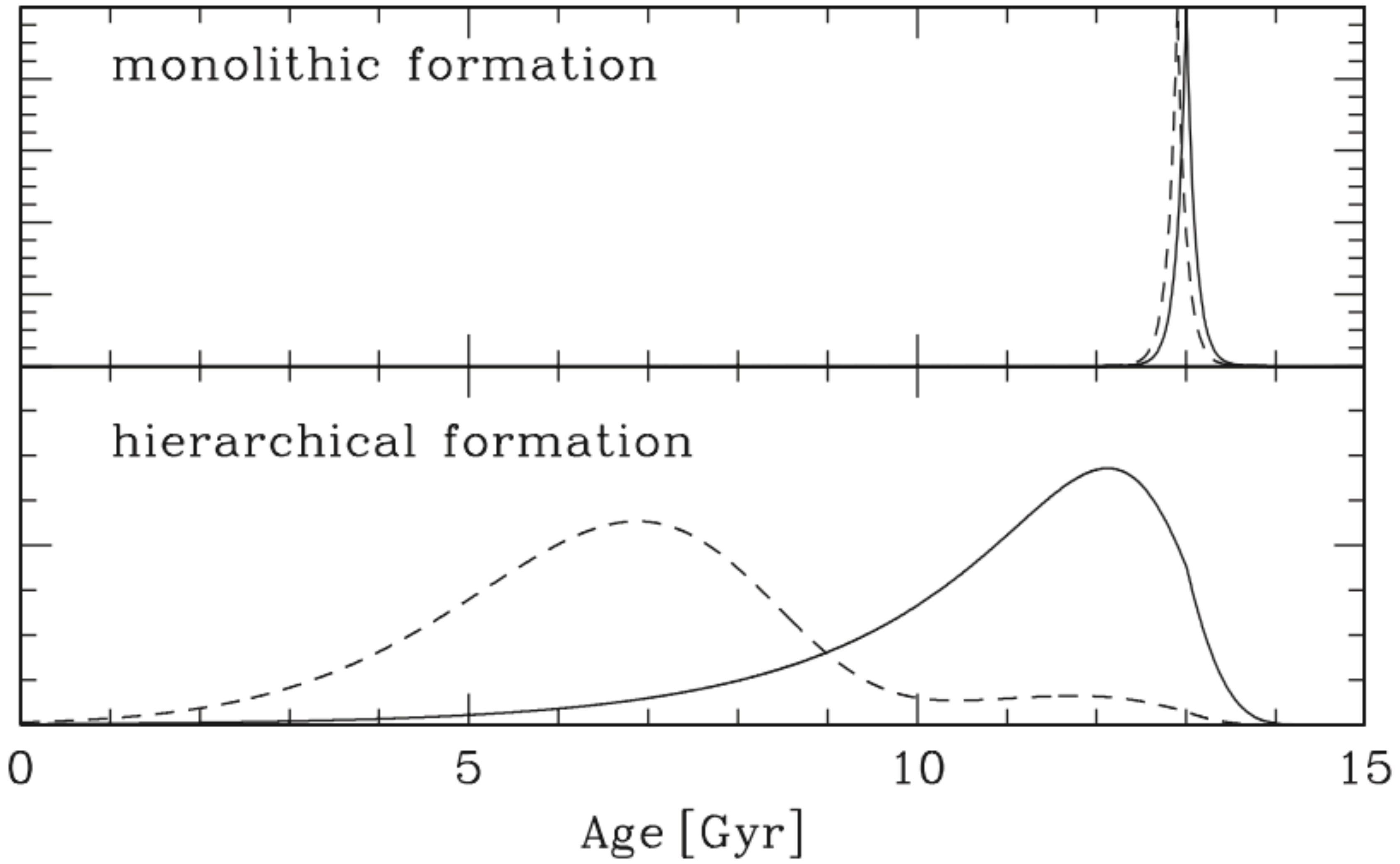
- **Schwarzschild orbit models: Assuming a stellar-mass-to-light ratio the deprojected light distribution is transformed into a stellar mass distribution. Then a large number of orbits are calculated by numerical integration in order to find the orbit model that best fits the derived gravitational potential.**

12.4 ELLIPTICALS: FORMATION

- **The fact that the dynamical structure of elliptical galaxies is less ordered than that of disc 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:**
  - **The monolithic collapse scenario.**
  - **The hierarchical scenario.**



Credits: Fig 13.4, MBW

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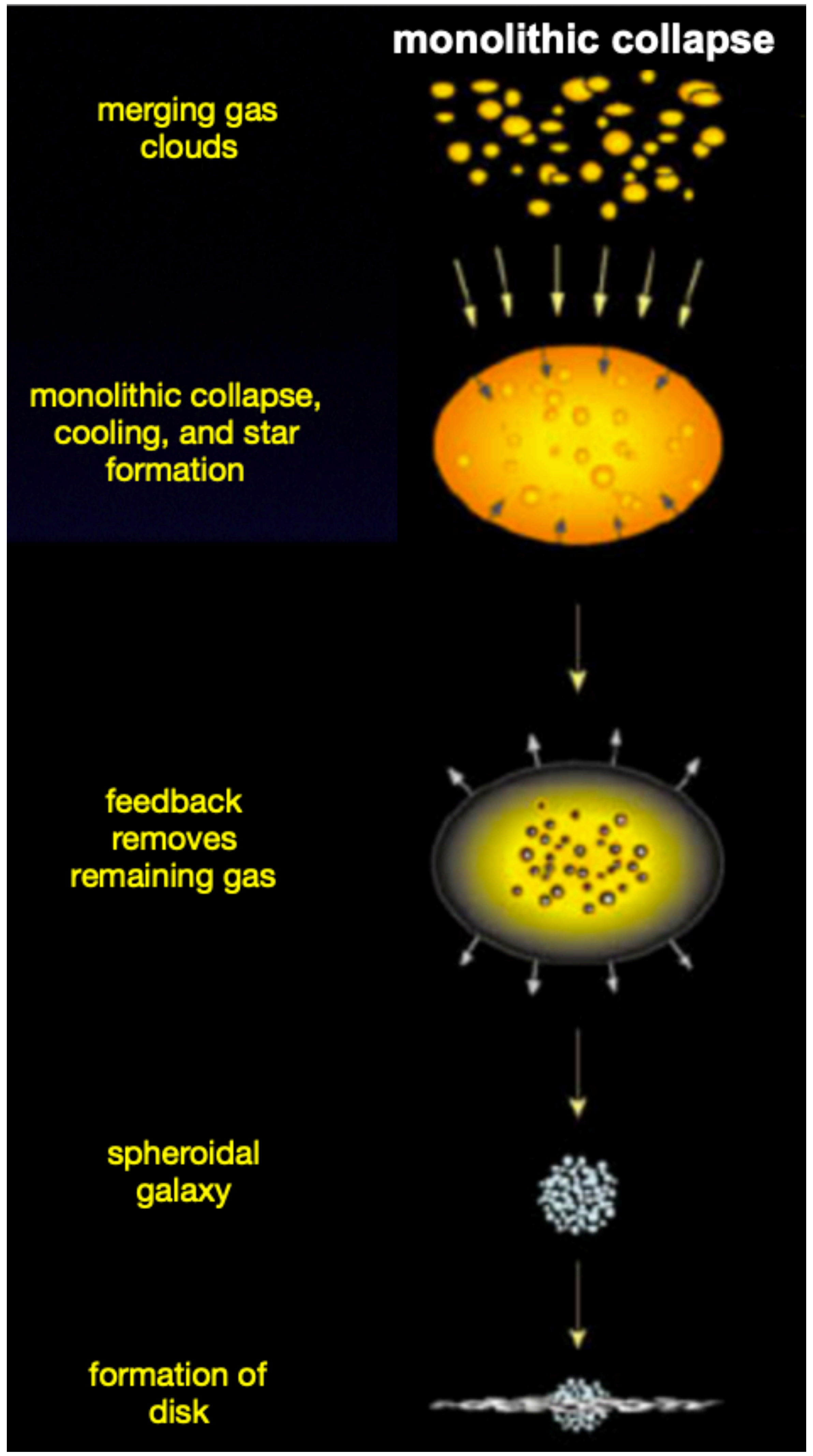
12.4.1 ELLIPTICALS: MONOLITHIC

- 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.



Credits: vdB

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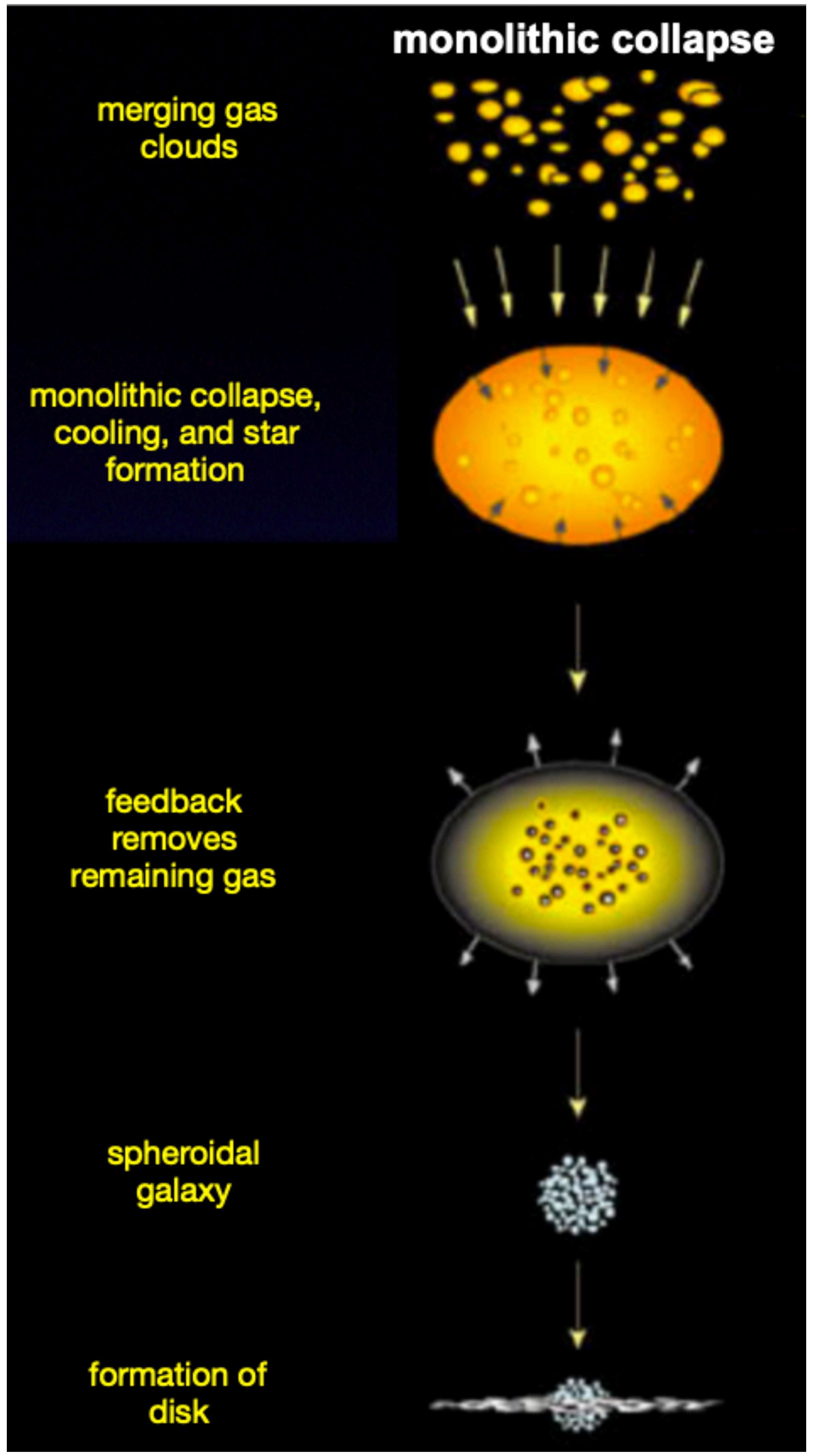
12.4.2 ELLIPTICALS: MONOLITHIC

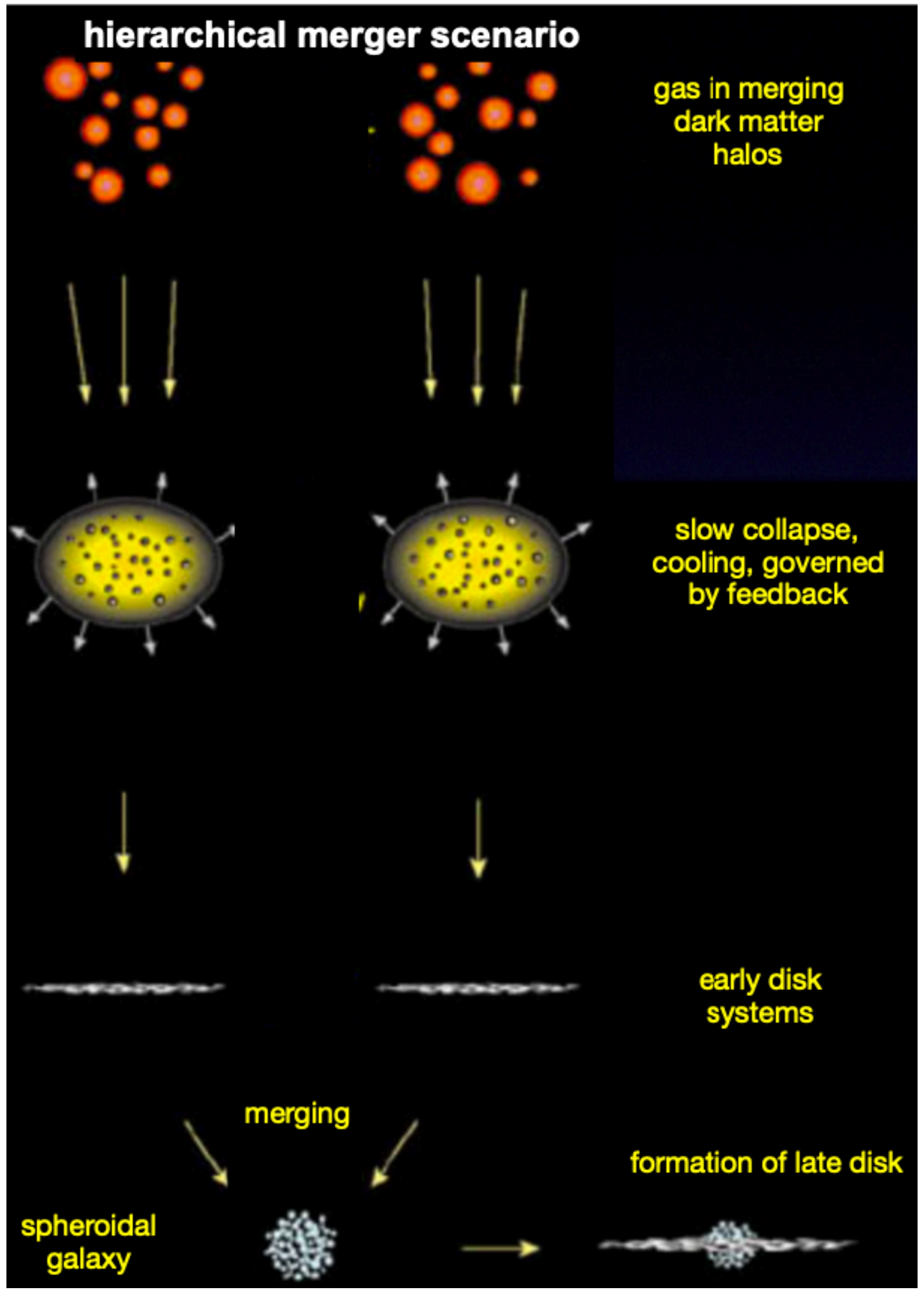
- In the dissipationless extreme, all the gas associated with the object is turned into stars prior to the collapse. The collapse then effectively conserves energy and given the observed sizes and large masses of elliptical galaxies they must have formed at redshifts greater than z~20 in stark conflict 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~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~2 until the present day, clearly contradicting monolithic collapse and passive stellar evolution.



Credits: vdB

12.4.3 ELLIPTICALS: HIERARCHICAL

- In this scenario, an elliptical galaxy 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.
- Issues: 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.



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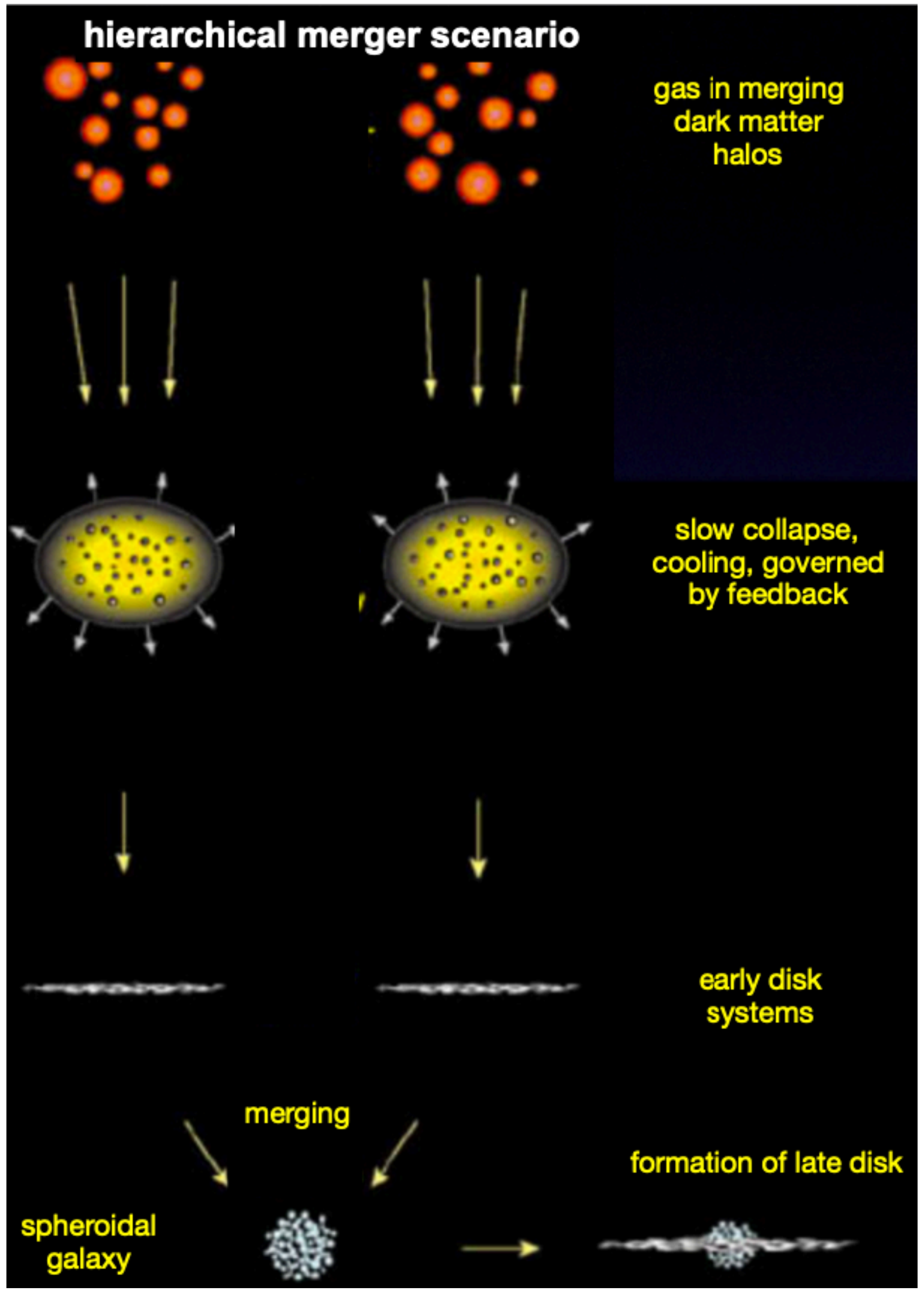
12.4.4 ELLIPTICALS: HIERARCHICAL

- Mergers of disc 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 (≥3:1) result in more disky and rapidly rotating ellipticals.
- The amount of gas in the merger results in distinctly different ellipticals. Gas-rich mergers produce more disky 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.



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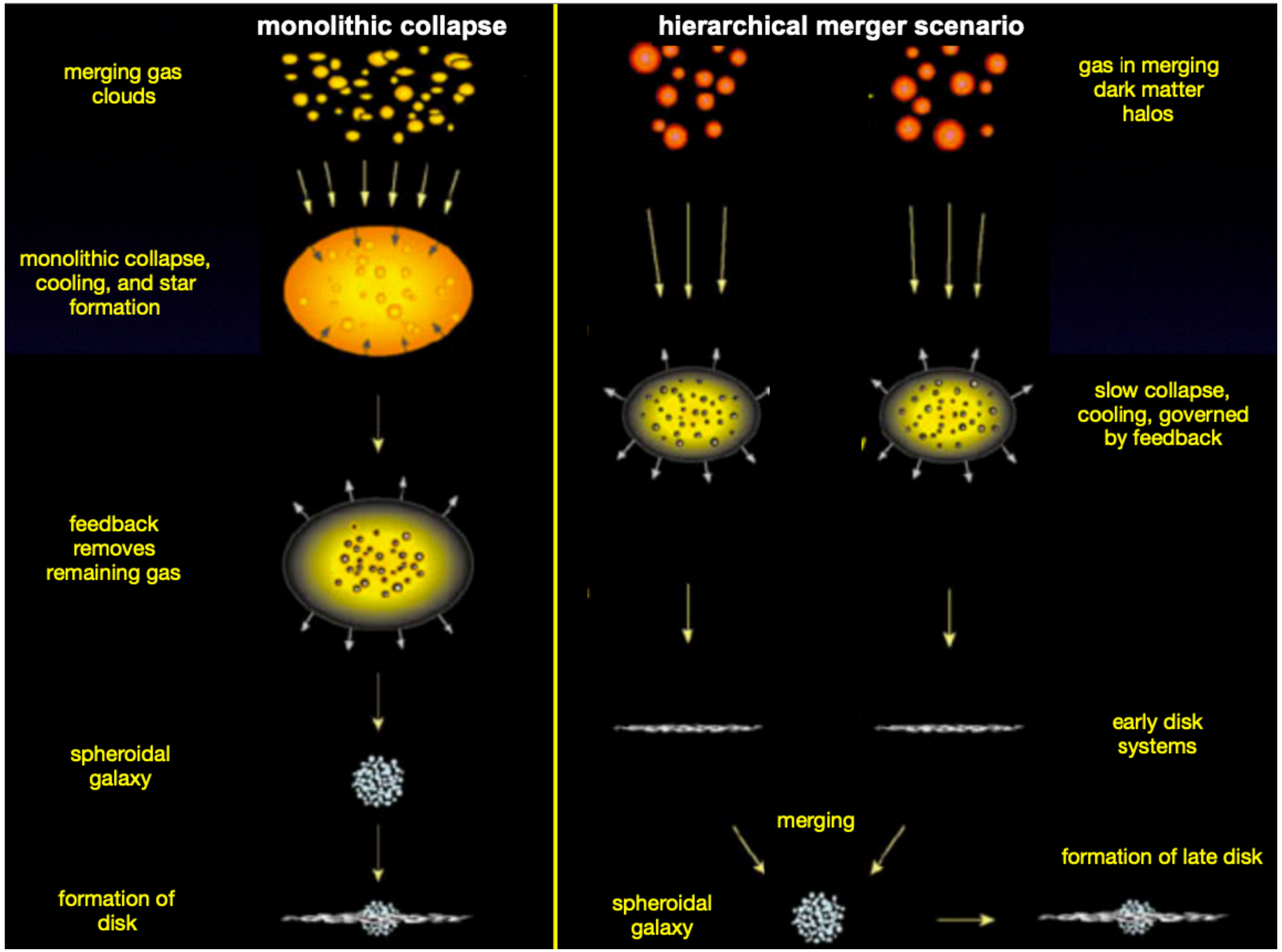
12.4.5 ELLIPTICALS: TWO-PHASE MODEL

- **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 ($z\sim4$-6) in dissipational collapse and multiple mergers. The later assembly ($z\leq2$-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 $z\sim2$**



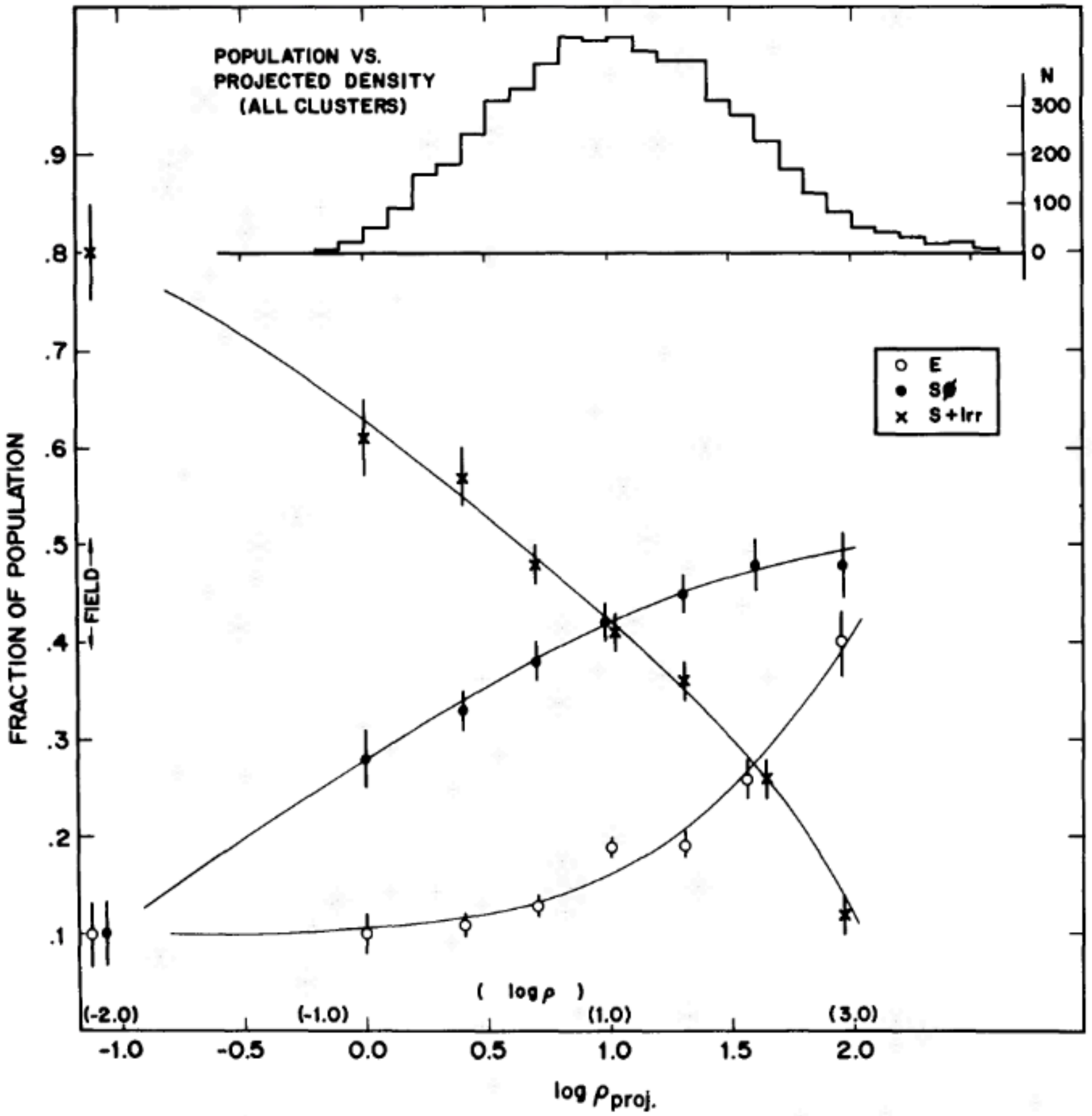
Credits: vdB

12.5 ELLIPTICALS: OBSERVATIONAL CONSTRAINTS

- **The theories for the formation of elliptical galaxies can be tested in the following main areas:**
  - **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.**
  - **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.**
  - **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)**

12.5.1 ELLIPTICALS: OBSERVATIONAL CONSTRAINTS

- **The Morphology-Density Relation shows that galaxy morphologies depend on the environment.**
- **Disc 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**



Credits: Dressler, 1980ApJ…236..351D

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12.5.2 ELLIPTICALS: OBSERVATIONAL CONSTRAINTS

- 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.
- 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 $z \sim 1$

12.6 ELLIPTICALS: SIZES

- **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 potential energy can be expressed as:** $$W = \zeta \frac{GM_s^2}{r_e}$$
- **Here r_e is some characteristic size of the system and ζ 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 ($f_{gas} = M_{gas}/M_{vir}$ and r_t is the turnaround radius, $r_t \sim 2r_{vir}$)**

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

12.6.1 ELLIPTICALS: SIZES

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

$$r_e = 0.98h^{-1}\mathrm{kpc}\left(\frac{M_*}{10^{10}h^{-1}M_\odot}\right)^{0.56}$$

Shen+03

$$\eta = 6.9\left(\frac{f_{\mathrm{gas}}}{0.15}\right)^{0.44}\left(\frac{M_{\mathrm{vir}}}{10^{12}h^{-1}M_\odot}\right)^{-0.23}$$

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

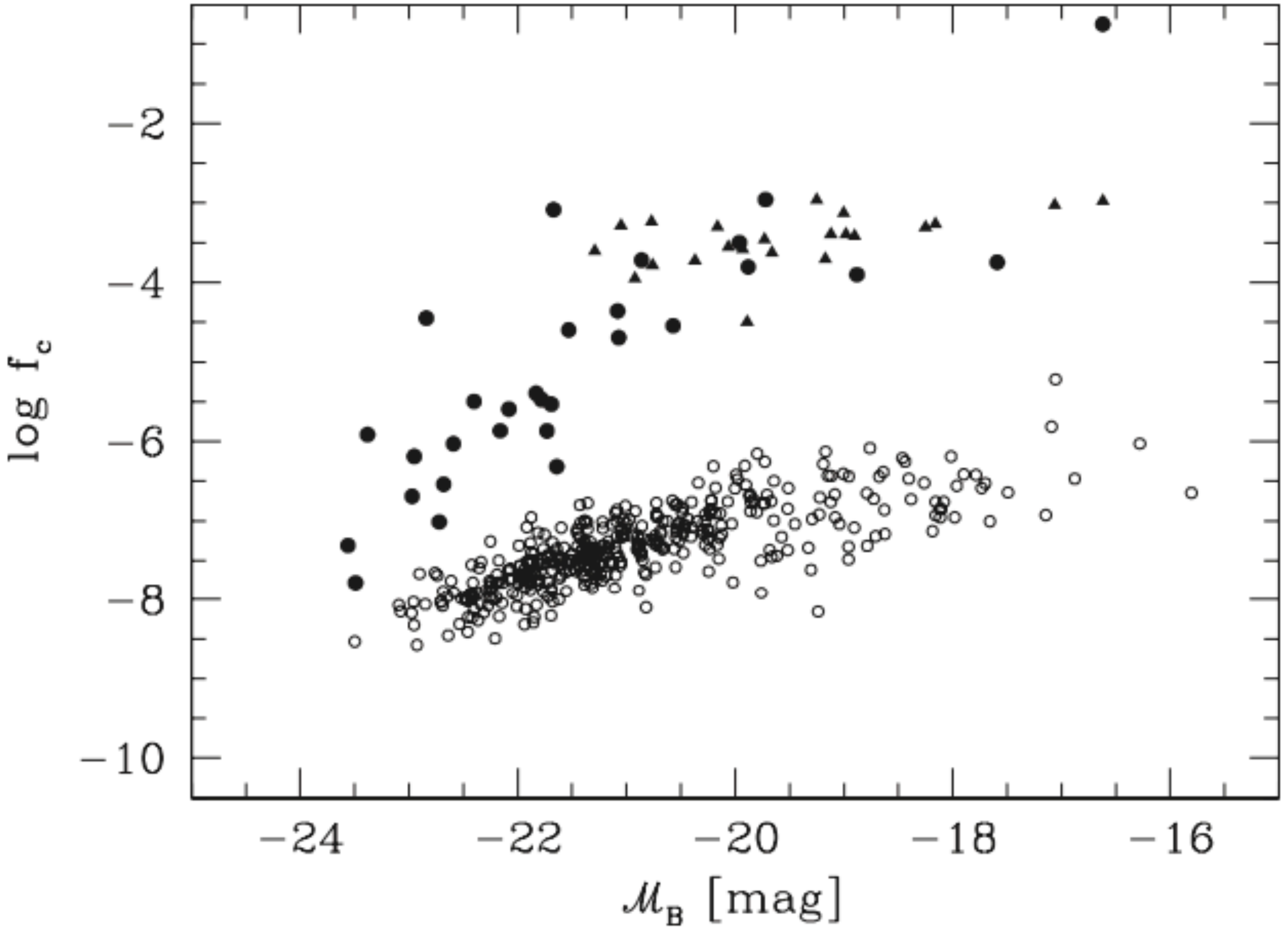
12.6.2 ELLIPTICALS: SIZES

- 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 $f_{tot}=f_{orb}+f_{tr}+f_{ej}$ is the total fraction of the orbital, transferred (from the stars to the DM component) and ejected energies:

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

12.6.3 ELLIPTICALS: PHASE-SPACE DENSITY

- **The maximum value of the coarse-grained phase-space density of a collisonless system cannot increase during its evolution (see §5.4)**
- **The central phase-space densities of $M_B \geq -22$ Es are more than three orders of magnitude higher than those of observed discs.**
- **If giant elliptical galaxies are produced by collisionless mergers of stellar discs, then their maximum phase-space densities should not exceed those of their disc progenitors!**
- **However, high-*z* discs were more compact/dense than low-*z*. Also, mergers with significant amounts of gas can easily enhance the central phase-space densities to the observed values, since gas can lose energy through radiation before it turns into stars**



Credits: Fig. 13.6, MBW

12.6.4 ELLIPTICALS: GLOBULAR CLUSTERS

- **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.**

- **If 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**

12.6.5 ELLIPTICALS: 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)

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

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

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

- The result is uncertain, but in general the merger rate increases with increasing redshift:

$$f_{\rm mrg} \propto (1+z)^m, \quad 0 \lesssim m \lesssim 4$$

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WHAT HAVE WE LEARNT?

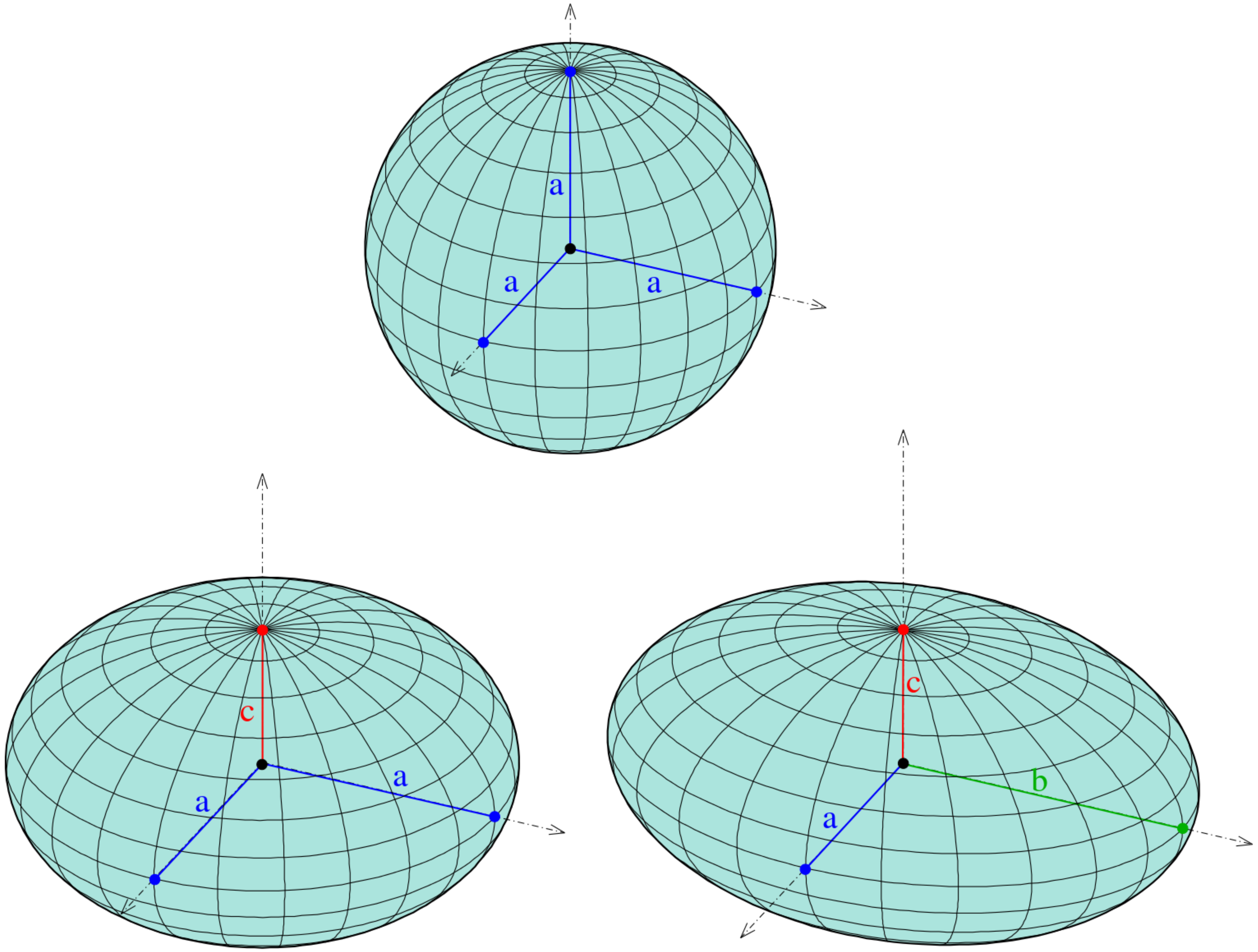
- The population of elliptical galaxies is bimodal, with bright ($M_B \leq -20.5$) ellipticals being slow rotators, with anisotropic velocity dispersions, boxy isophotes and central cores. Intermediate ellipticals ($-20.5 \leq M_B \leq -18$) are fast rotators, supported by rotation and they have disky isophotes and cuspy inner light profiles.

- 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.

- 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 assembly hierarchically, but the most massive ellipticals form very rapidly at high redshifts.

EXTRA SLIDES

- **Sphere: a=b=c**
- **Oblate: a=b>c**
- **Prolate: a=b<c**
- **Triaxial: a≠b≠c**



EXTRA SLIDES

- **Observed properties, 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.**
- **For example, the surface brightness at a position (x,y) is given by**

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

- **where Σ(x,y) is the projected surface mass density, Y is the stellar mass-to-light ratio, ϱ is the 3D density and z is the distance along the line-of-sight.**

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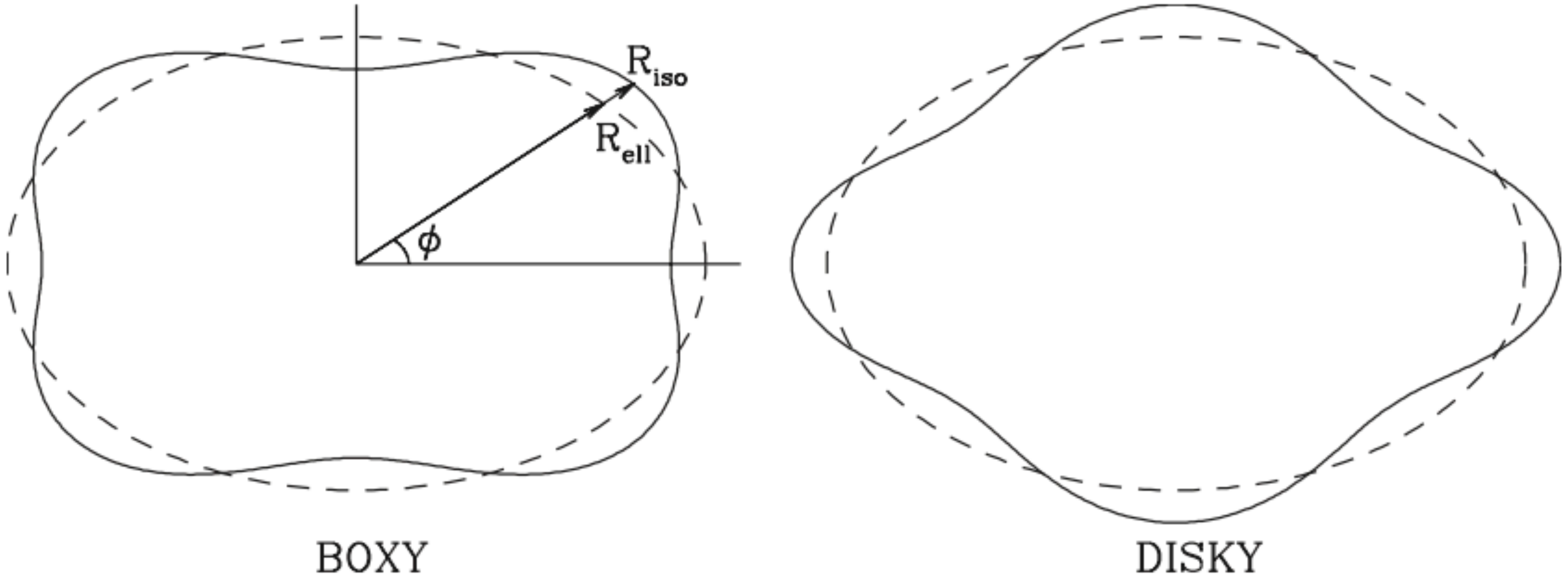
EXTRA SLIDES

- **The Fourier coefficients of isophotes can quantify deviations from perfect ellipses**

$$\Delta(\phi) \equiv R_{\rm iso}(\phi) - R_{\rm ell}(\phi) = a_0 + \sum_{n=1}^{\infty} (a_n \cos n\phi + b_n \sin n\phi)$$

- **Isophotes are 'disky' if $a_4 > 0$ and 'boxy' if $a_4 < 0$**



Credits: Fig 2.15, MBW