ASTR 610
Theory of Galaxy Formation

Lecture 19: Elliptical Galaxies

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Yale University, Fall 2020

Structure & Formation of Ellitpical Galaxies

In this lecture we discuss the structure and formation of elliptical galaxies. After a very brief overview of some of the main observational properties of ellipticals, we discuss two `competing' pictures for the formation of ellipticals.

Topics that will be covered include:

- Dichotomy of elliptical
- Fundamental Plane
- Intrinsic Shapes
- Monolithic collapse picture
- Sizes & the Merger picture
- Formation Scenarios

Observational Facts

Surface Brightness Profiles

Elliptical galaxies have surface brightness profiles that are well described by a Sersic profile:

$$I(R) = I_0 \exp\left[-\beta_n \left(\frac{R}{R_e}\right)^{1/n}\right]$$

$$\beta_n \simeq 2n - 0.324$$

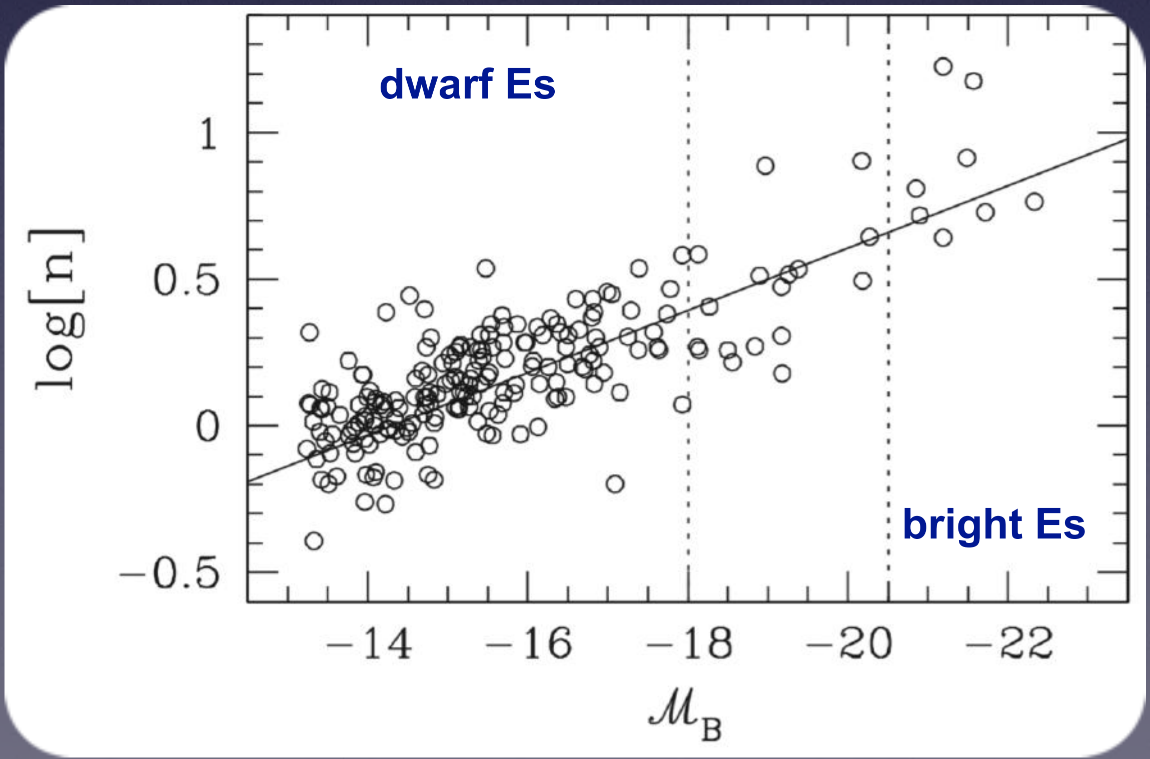
follows from definition of R_e

$$L = 2\pi \int_0^\infty I(R)\, R\, \mathrm{d}R = \frac{2\pi n \Gamma(2n)}{(\beta_n)^{2n}}\, I_0\, R_e^2$$

n: Sersic index
R_e: effective radius that encloses half of the total light

For n=4 this is known as the `de Vaucouleurs' profile, while n=1 corresponds to an exponential profile

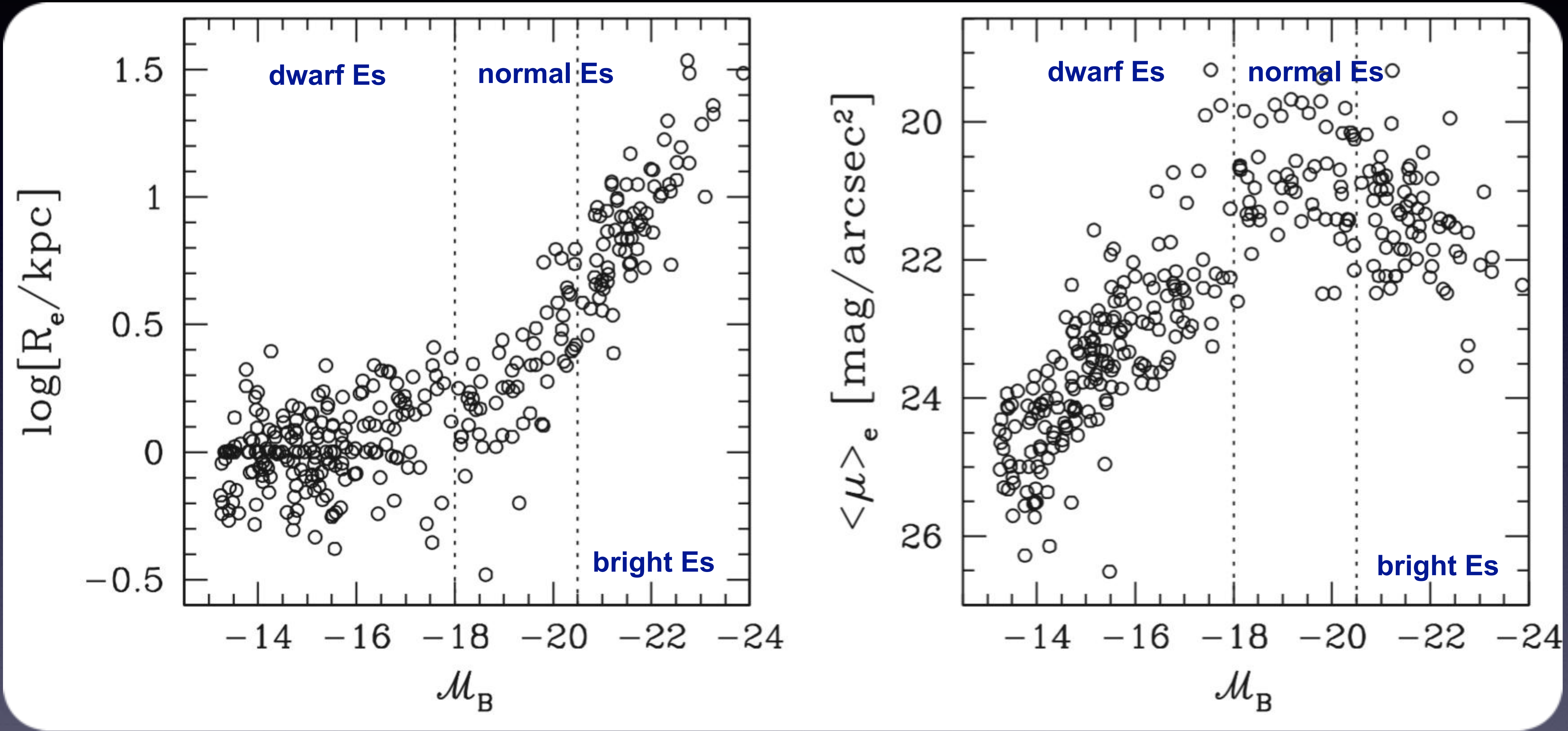
MBW, Fig. 2.13



Typically, brighter ellipticals have a larger Sersic index
Faintest ellipticals (dwarf spheroidals) have n~1, corresponding to an exponential profile

Observational Facts

Surface Brightness Profiles

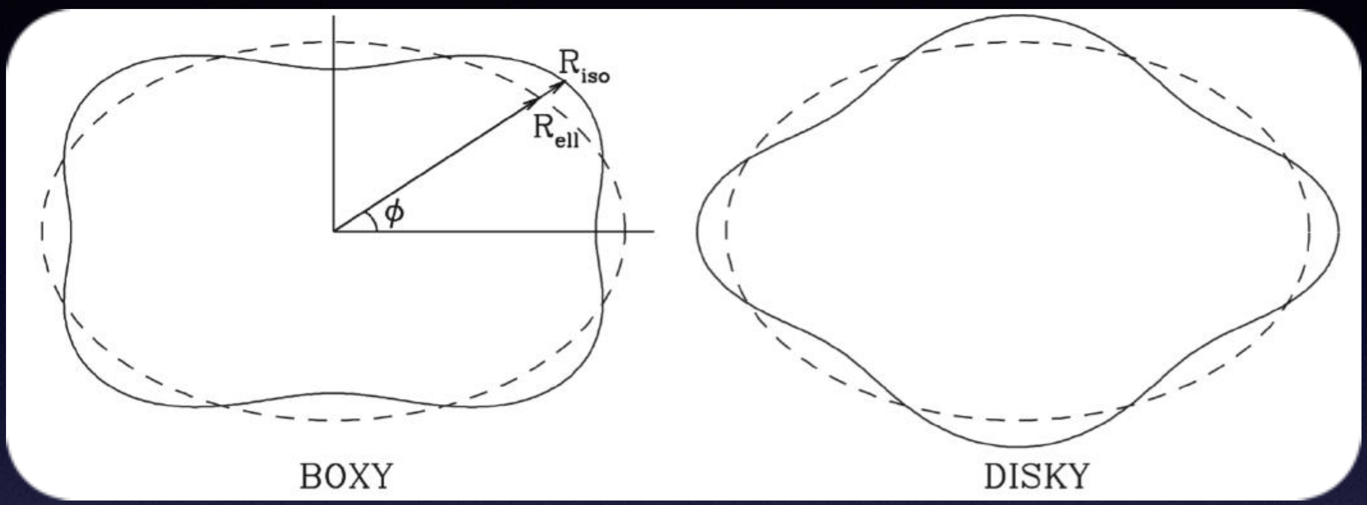


MBW, Fig. 2.14

Brighter ellipticals are larger and have higher surface brightness
But, trends are not continuous: for $M_B < -20.5$ surface brightess decreases with increasing luminosity, while there is little to no magnitude-size trend for dwarfs…

Isophotal Shapes

The isophotes of elliptical galaxies are elliptical, but not perfectly so. They show deviations that are typically either 'disky' or 'boxy'



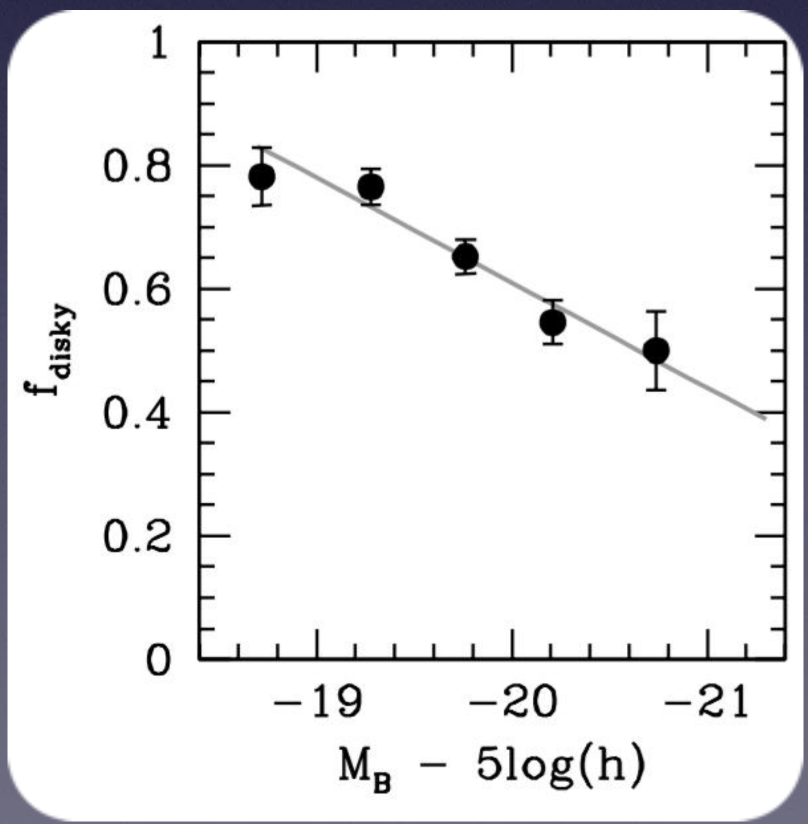
best fit elliptical

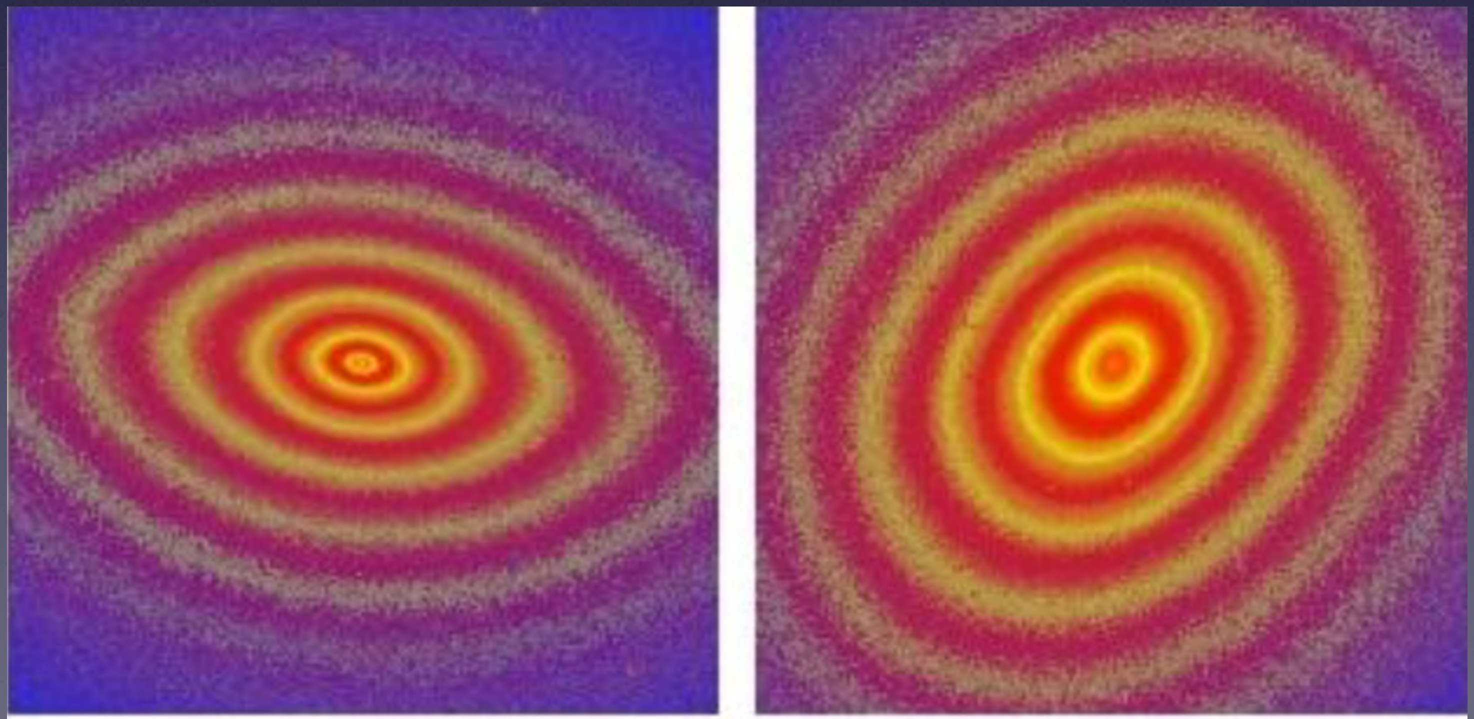
$$\Delta\phi \equiv R_{\rm iso}(\phi) - R_{\rm ell}(\phi)$$
$$= \sum_{n=3}^{\infty} [a_n \cos(n\phi) + b_n \sin(n\phi)]$$

disky and boxy correspond to $a_4>0$ and $a_4<0$, respectively

Brighter ellipticals are more likely boxy (disky fraction decreases with luminosity)

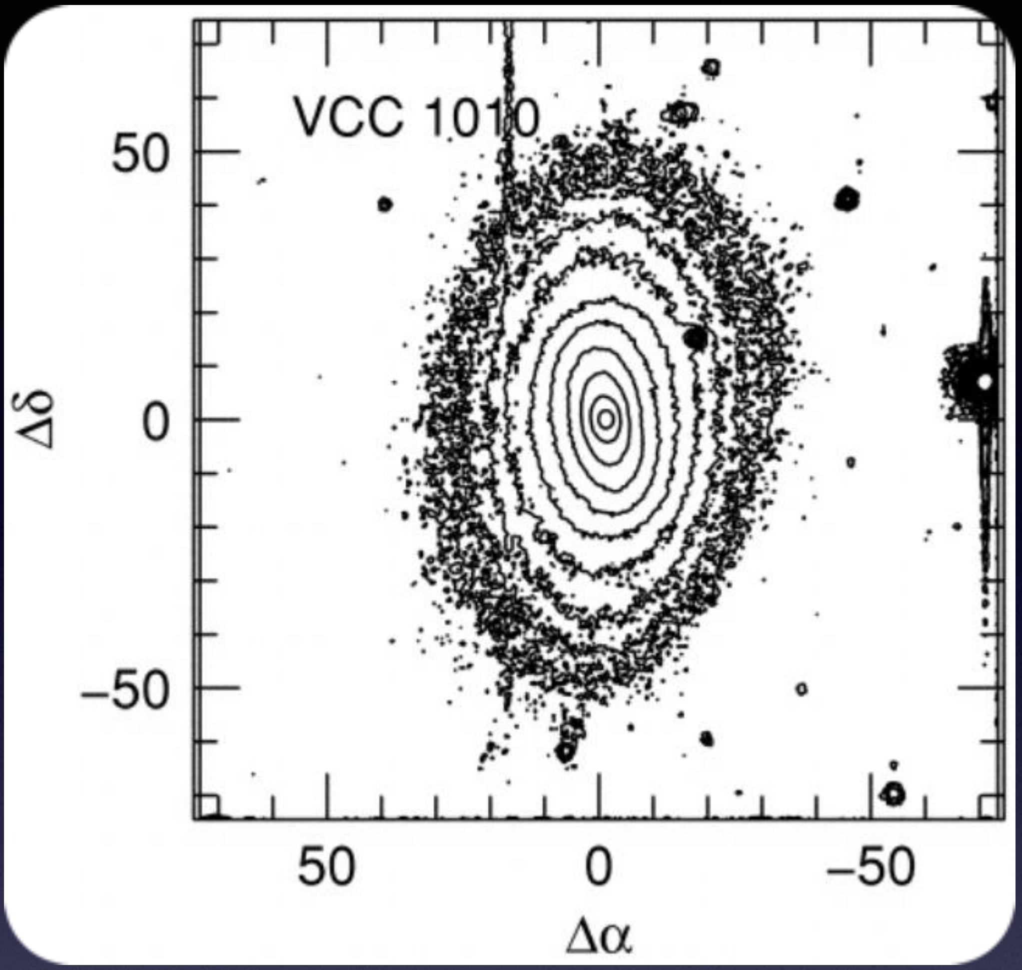
Pasquali, vdBosch & Rix, 2007, ApJ, 664, 738





NGC 821: $a_4/a \sim +0.02$, disky NGC 2300: $a_4/a \sim -0.02$, boxy

Isophotal Twist

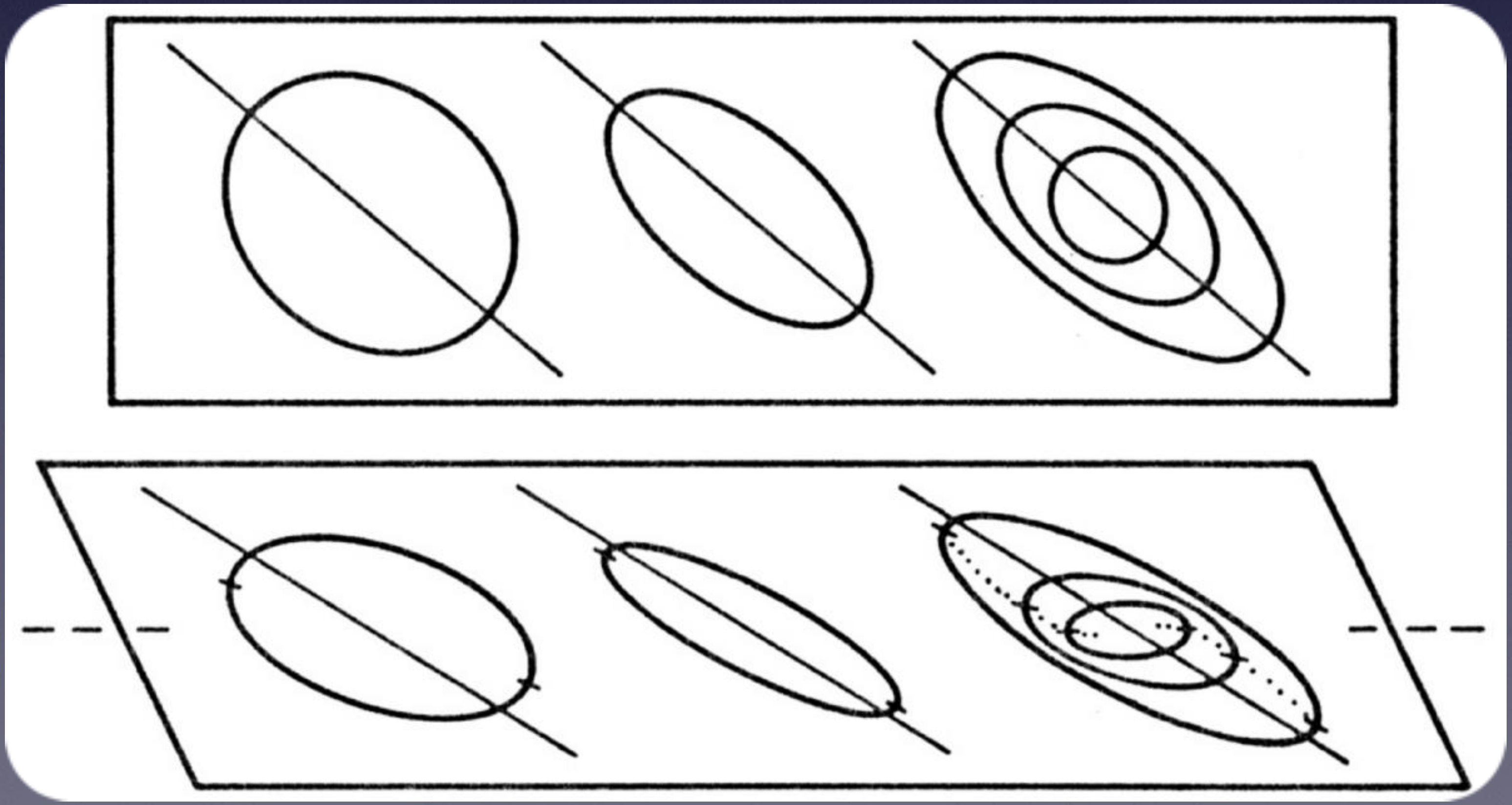


Some ellipticals reveal isophotal twists, with direction of major axis of isophote changing with isophotal level

Most of these ellipticals are boxy

The simplest explanation is that (these) elliptical galaxies are triaxial (rather than oblate/prolate), and have their intrinsic axis ratios change with radius.

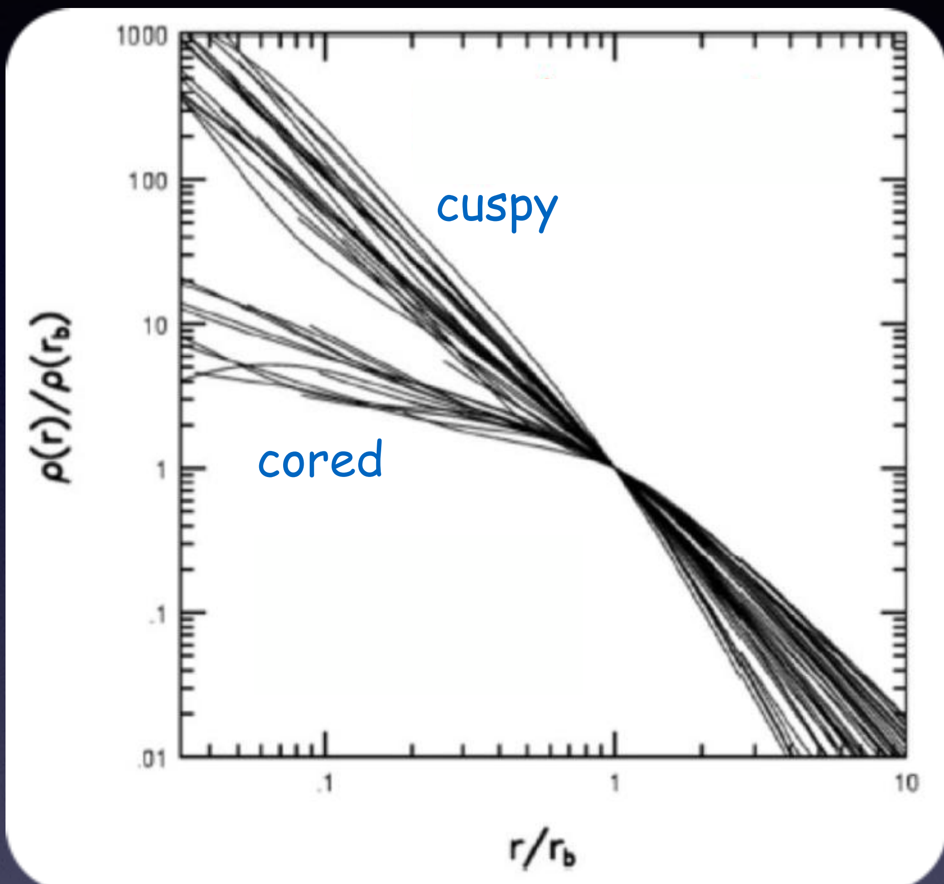
Such a system in projection will reveal isophote twist

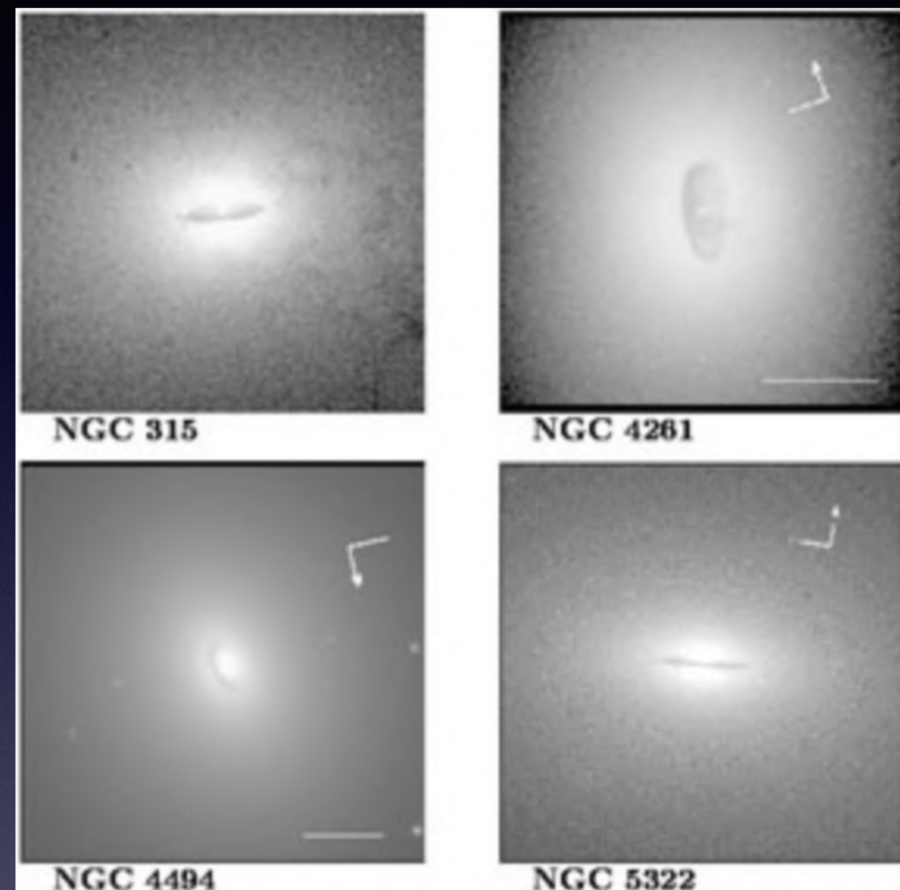


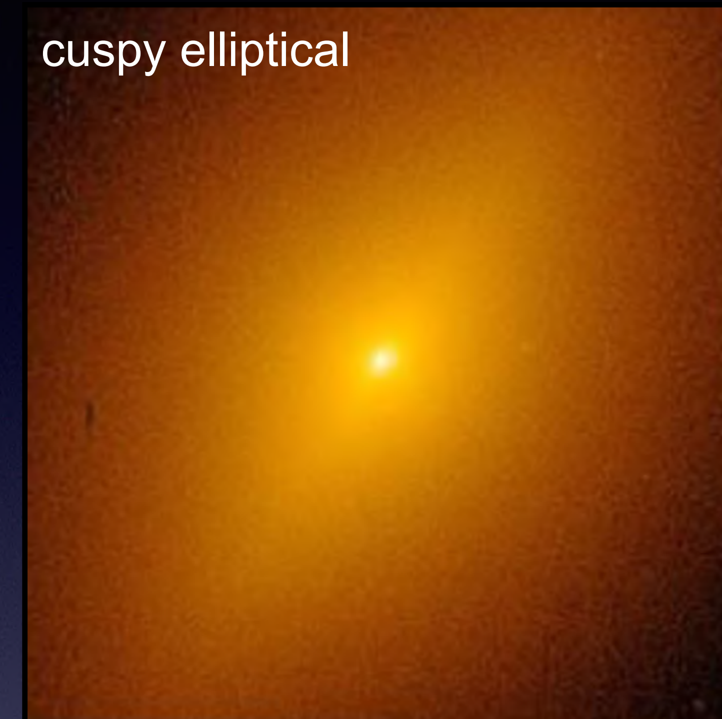
The presence of isophote twists among (bright/boxy) ellipticals is often taken as evidence that, as a class, they must be triaxial.

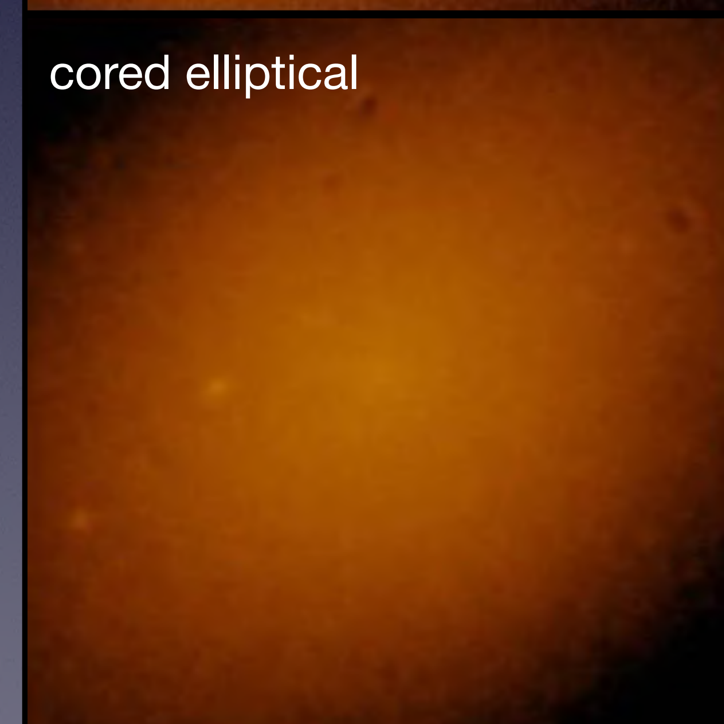
The Nuclei of Elliptical Galaxies

High resolution imaging with the HST revealed that the central regions of ellipticals reveal a dichotomy in their central surface brightness profile; ‘cusps’ vs ‘cores’







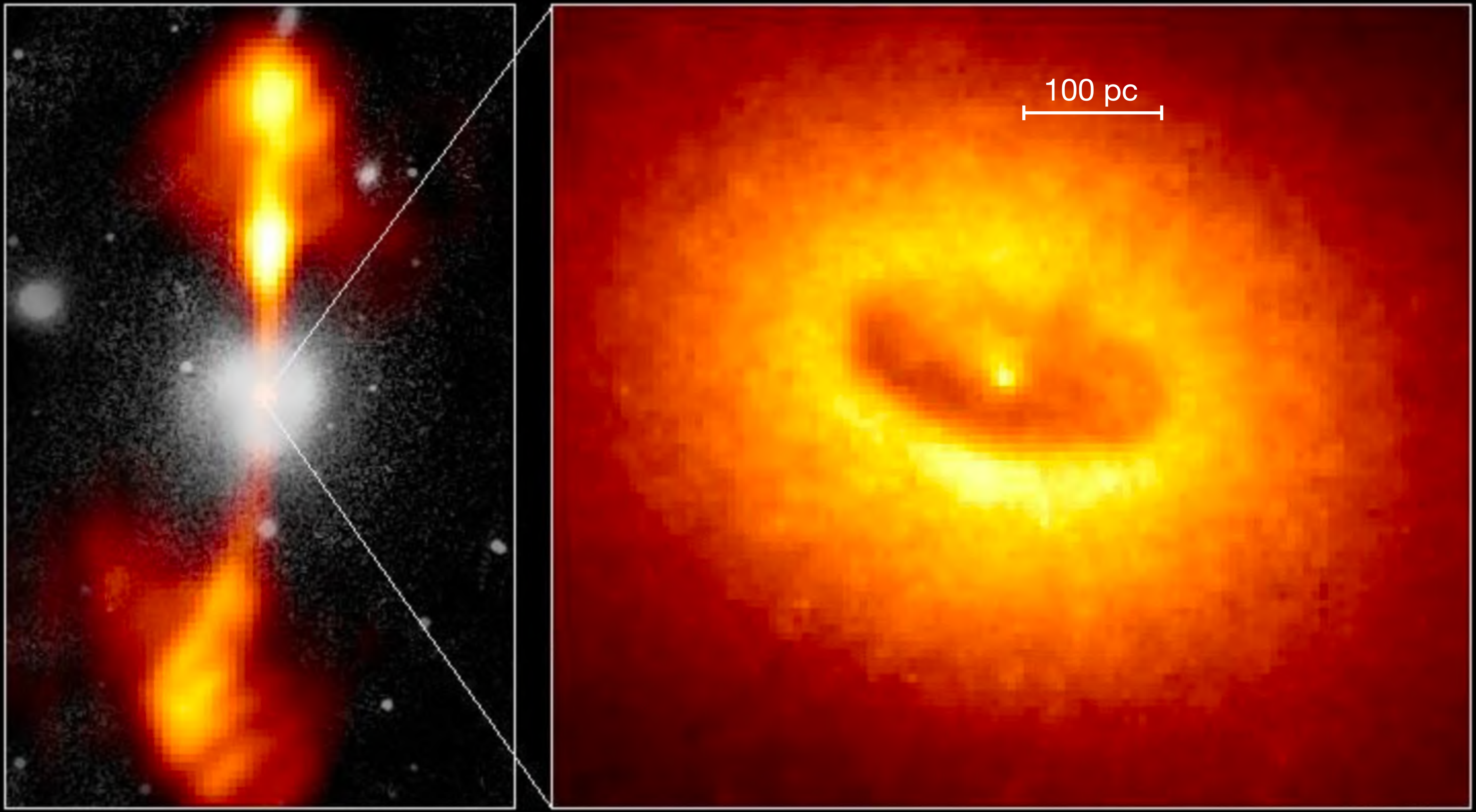


Typically cored ellipticals are bright ($M_B \lesssim -20.5$) and boxy, while cuspy ellipticals are fainter and disky.

Whether this is a true \`dichotomy’ or not is still debated…

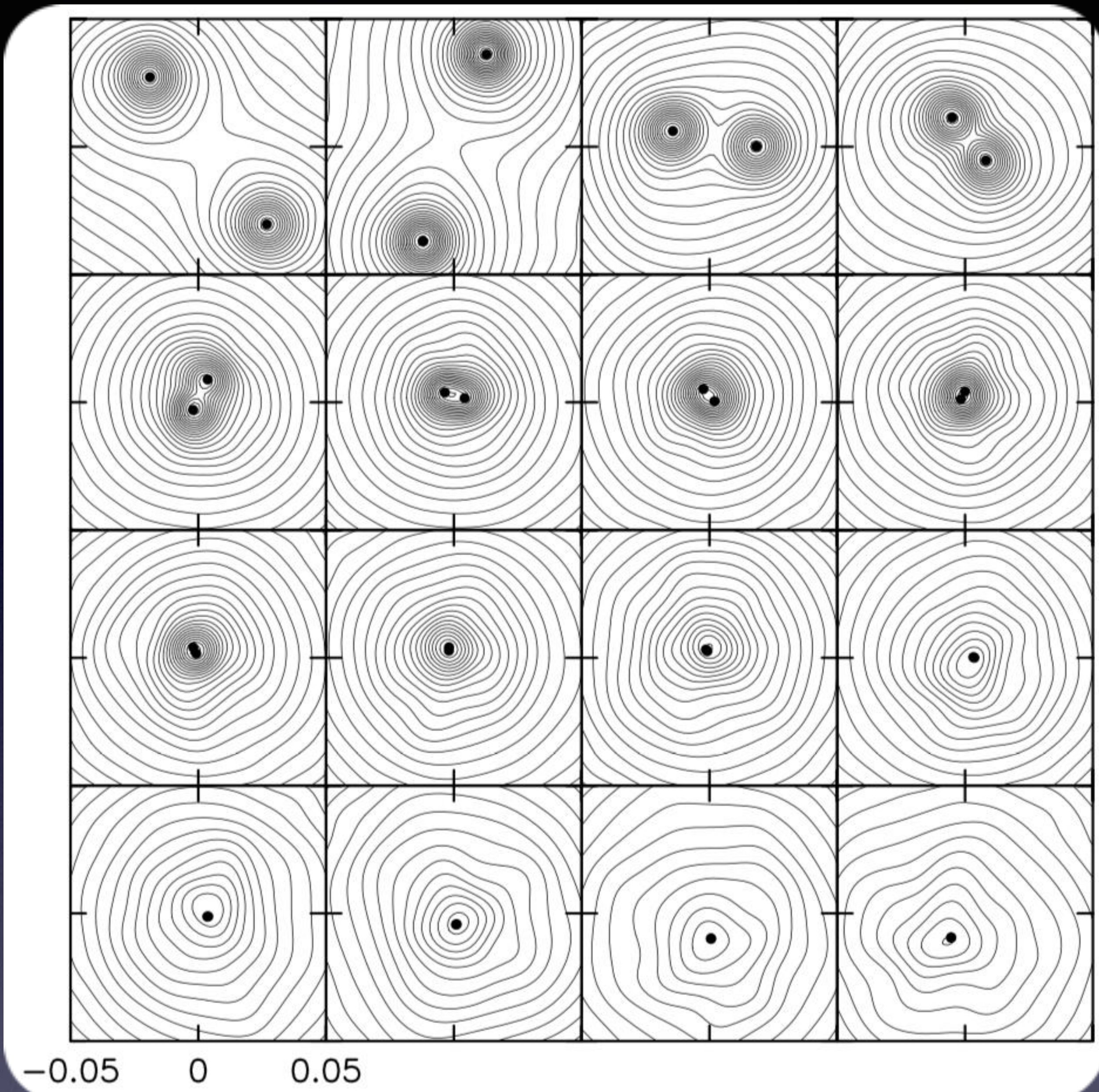
Nuclei of elliptical galaxies also often harbour small (few 100pc) disks of gas/dust and/or stars

The Nuclear Dust Disk of NGC 4261



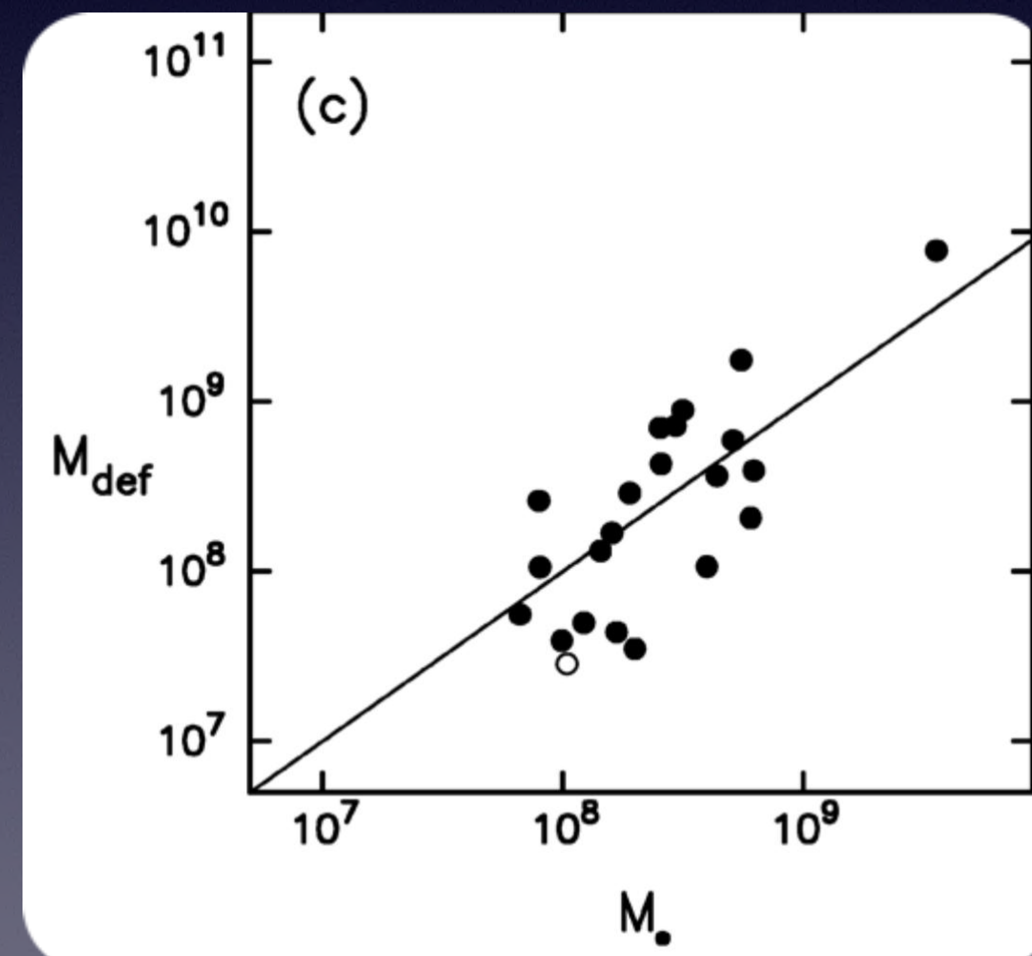
Dust disk ~100 pc size, oriented perpendicular to radio jets; is this the material that feeds the accretion disk surrounding the SMBH at the center?

Creating Cores with Scouring SMBH Binaries



Milosavljevic & Merritt, 2001, ApJ, 563, 34

Cores can be created due to scouring by a SMBH binary. Dynamical friction acting on the SMBHs tightens the binary, and transfers momentum to the cusp stores, thereby creating a core. This process becomes inefficient once gravitational wave radiation becomes important..



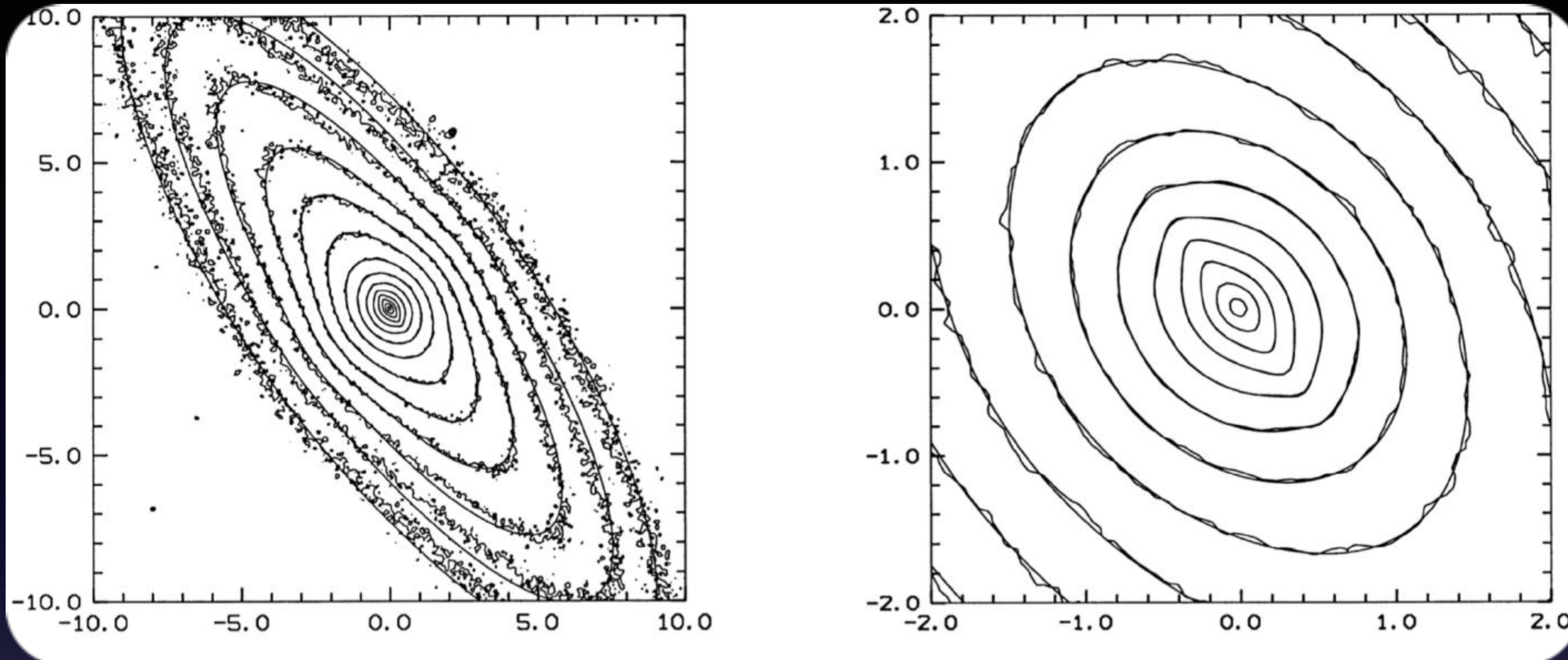
Milosavljevic, Merritt, Rest & vdBosch, 2002, MNRAS, 331, L51

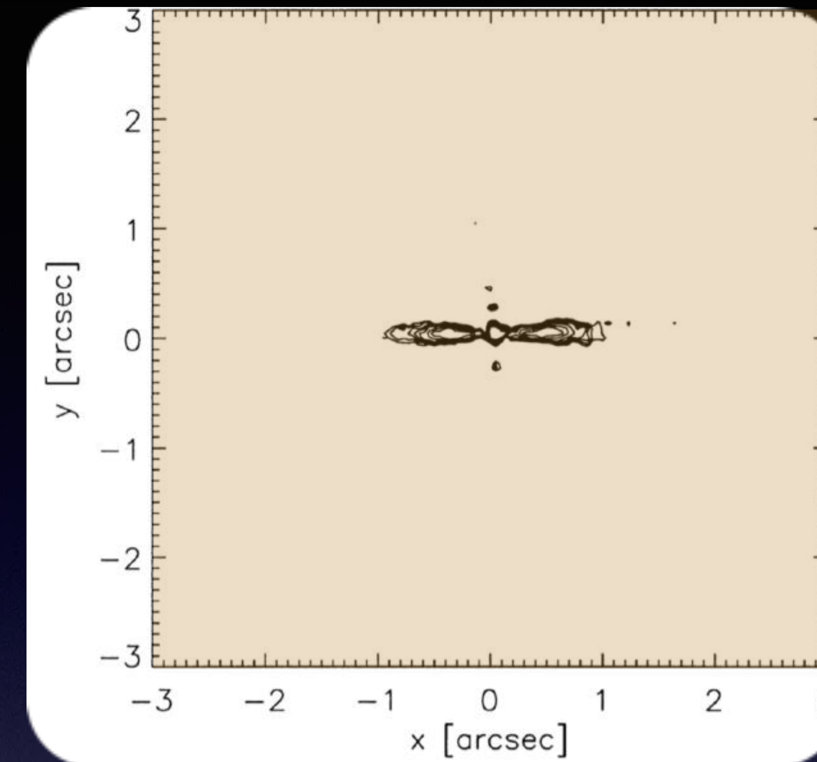
Rule of thumb $M_{ej} \sim 0.5\,(M_{\bullet,1} + M_{\bullet,2})\,\ln(a_h/a_{gr})$

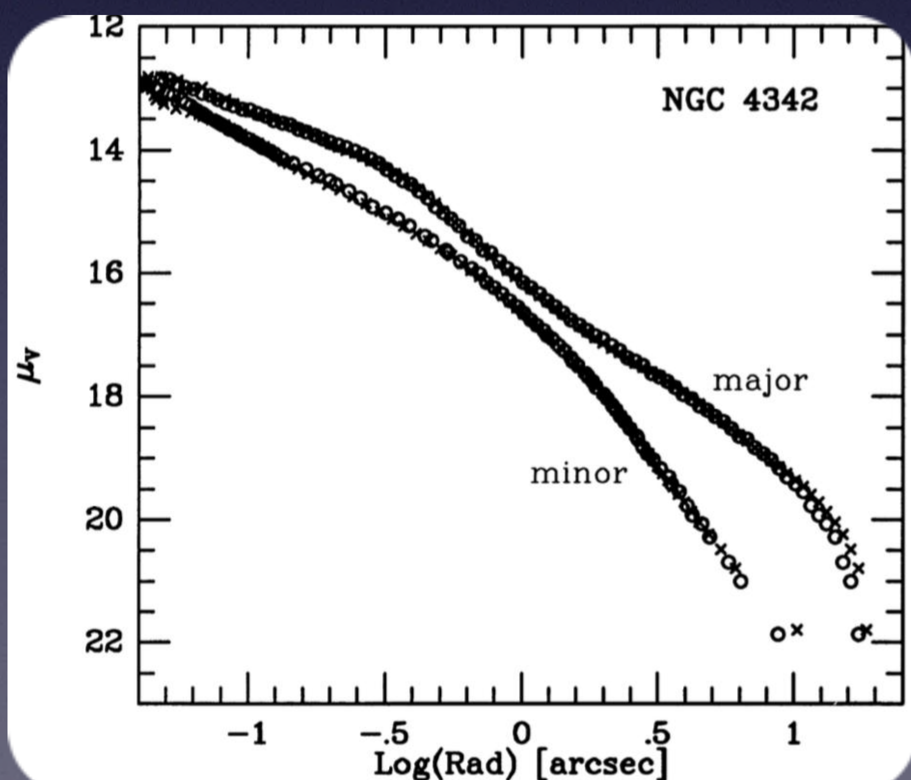
a_h = semi-major axis of SMBH binary when binary first becomes hard

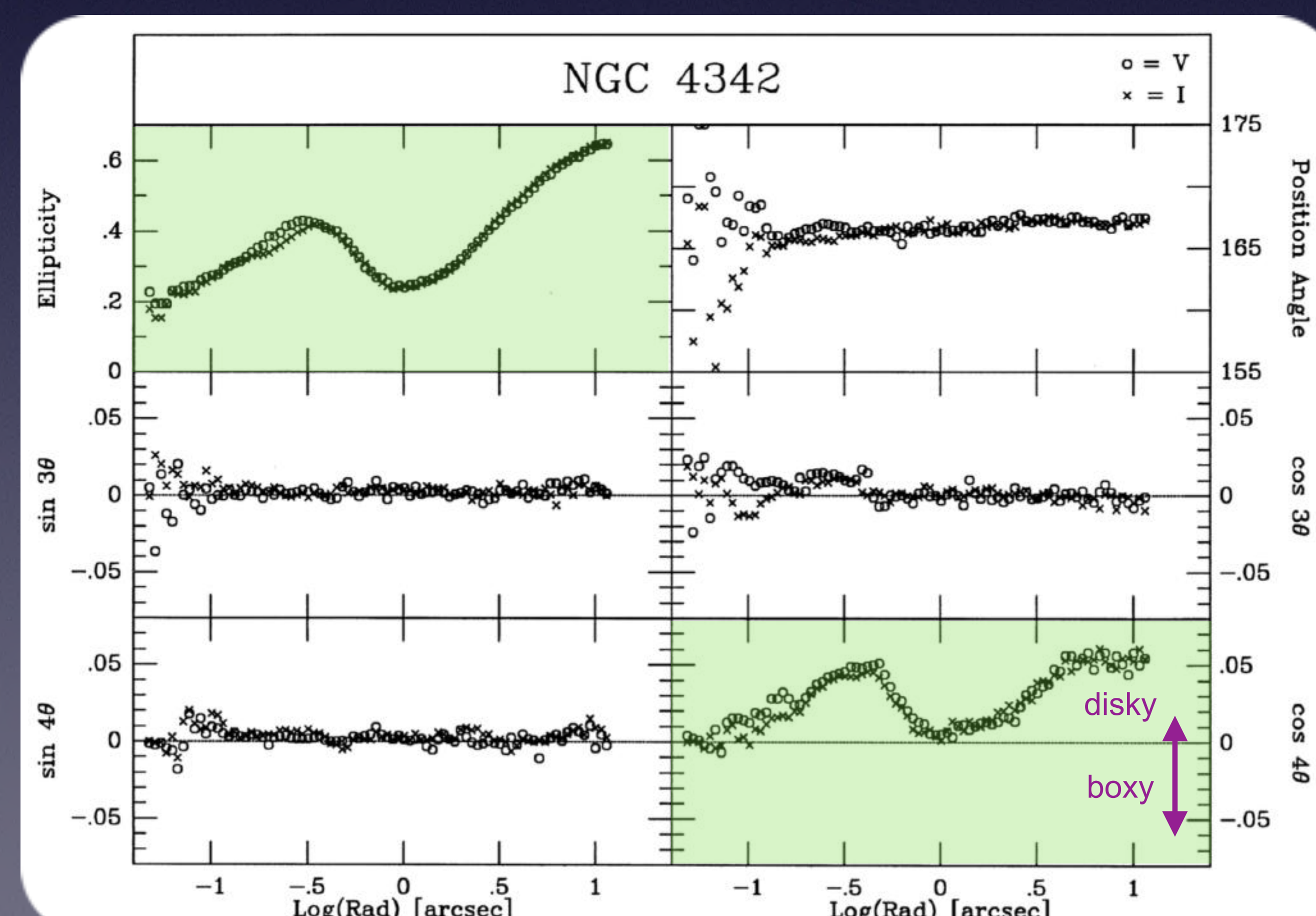
a_h = semi-major axis of SMBH binary when gravitational radiation starts to dominate

The Nuclear Stellar Disk of NGC 4342









SOURCE: vdBosch, Jaffe & vdMarel, 1998, MNRAS, 293, 343

Kinematics

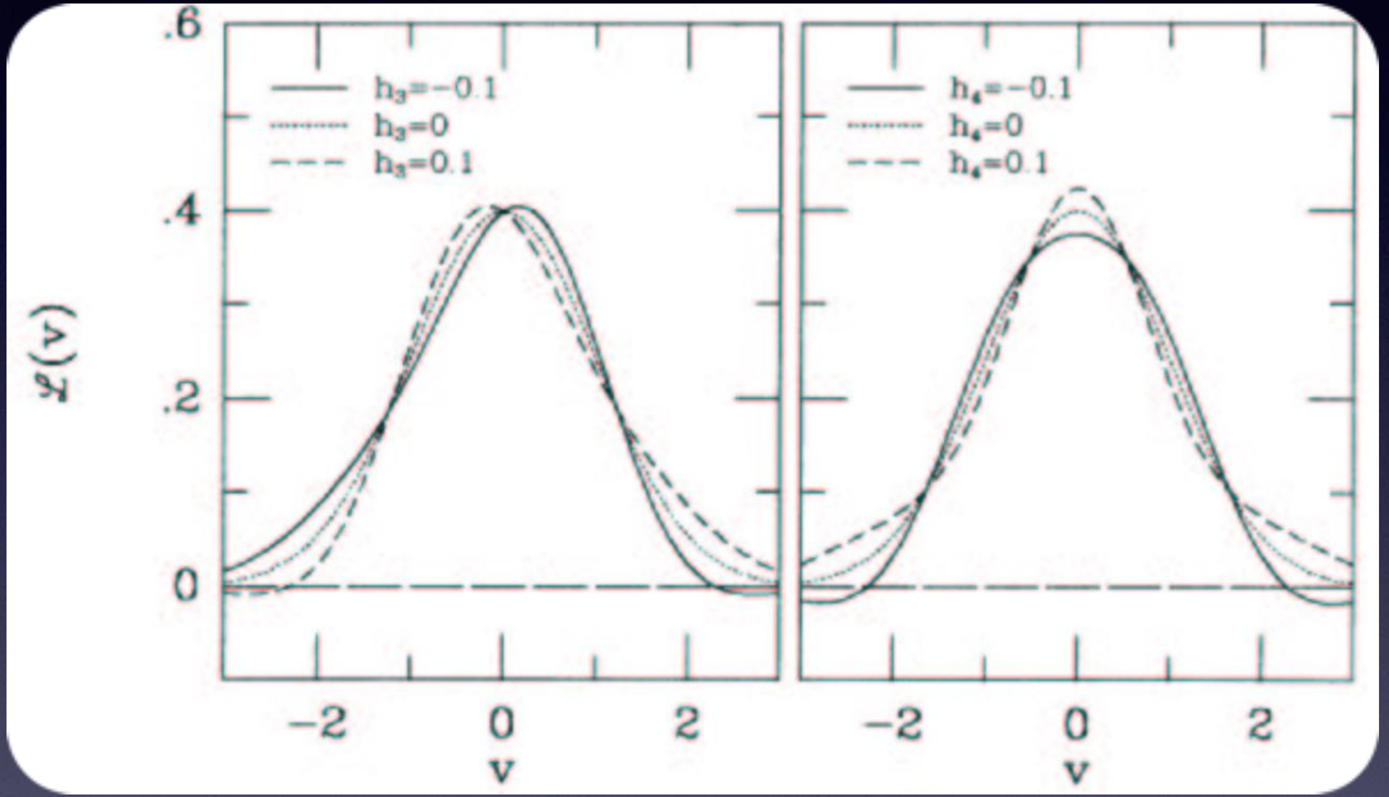
The observed spectrum of an elliptical galaxy is a convolution of the template spectrum, which is the luminosity weighted spectrum of all the various stars along the line-of-sight (LOS) and a broadening function, which is a combination of an instrumental broadening function an the line-of-sight velocity distribution (LOSVD)

A typical functional form for the LOSVD is a simple Gaussian.

$$\mathcal{L}(v) = \frac{1}{\sqrt{2\pi}\sigma} \mathrm{e}^{-\frac{1}{2}w^2} \qquad w = (v - V)/\sigma$$

However, the LOSVD is generally not Gaussian and is has become standard practice to adopt a Gauss-Hermite series

$$\mathcal{L}(v) = \frac{1}{\sqrt{2\pi}\sigma} \mathrm{e}^{-\frac{1}{2}w^2} \left[1 + \sum_{j=3}^{N} h_j H_j(w) \right]$$



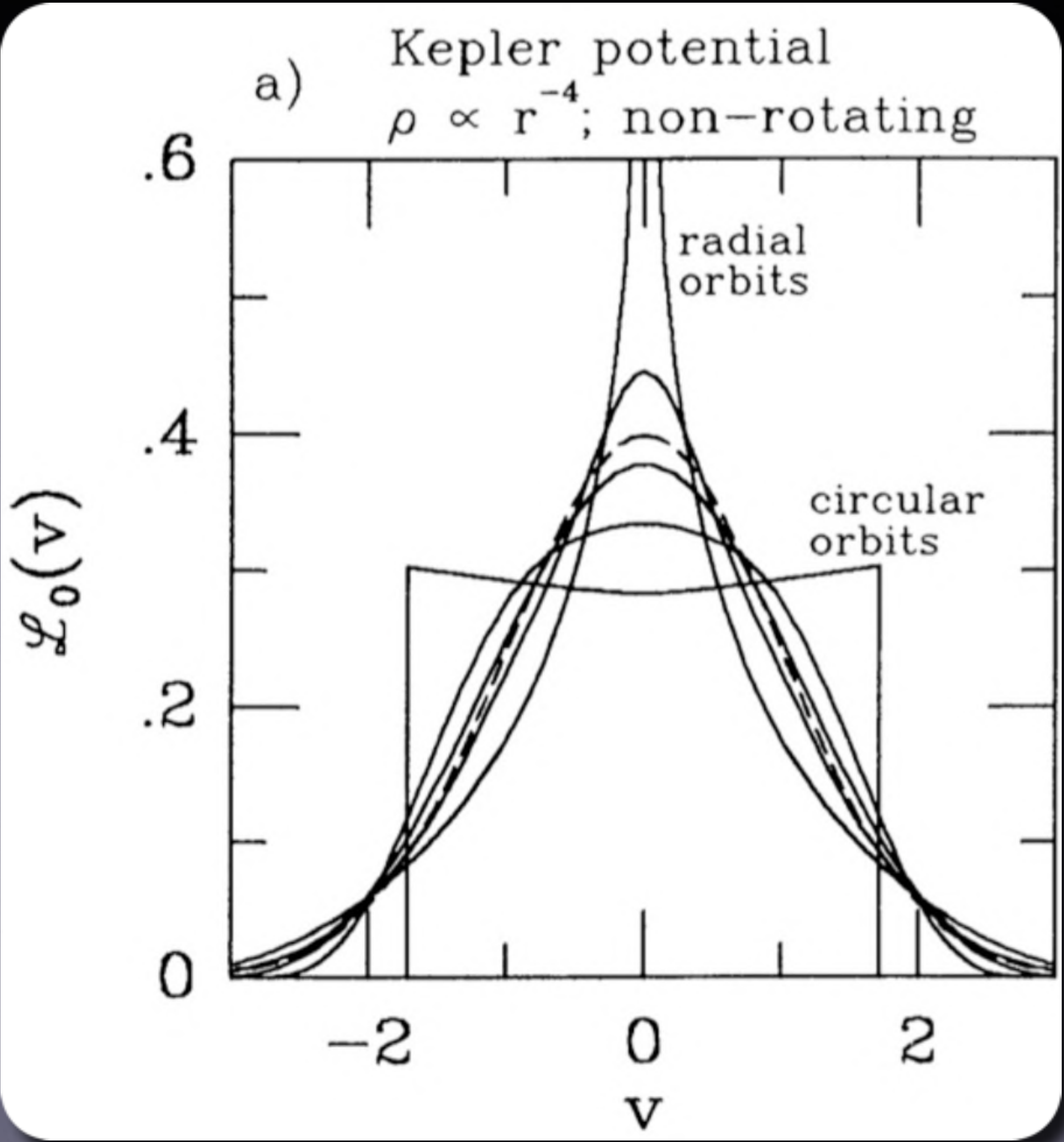
van der Marel & Franx 1993

Typically one truncates the series at N=4, such that LOSVD is described by four parameters: V, σ, h_3, h_4

related to skewness

related to kurtosis

Kinematics

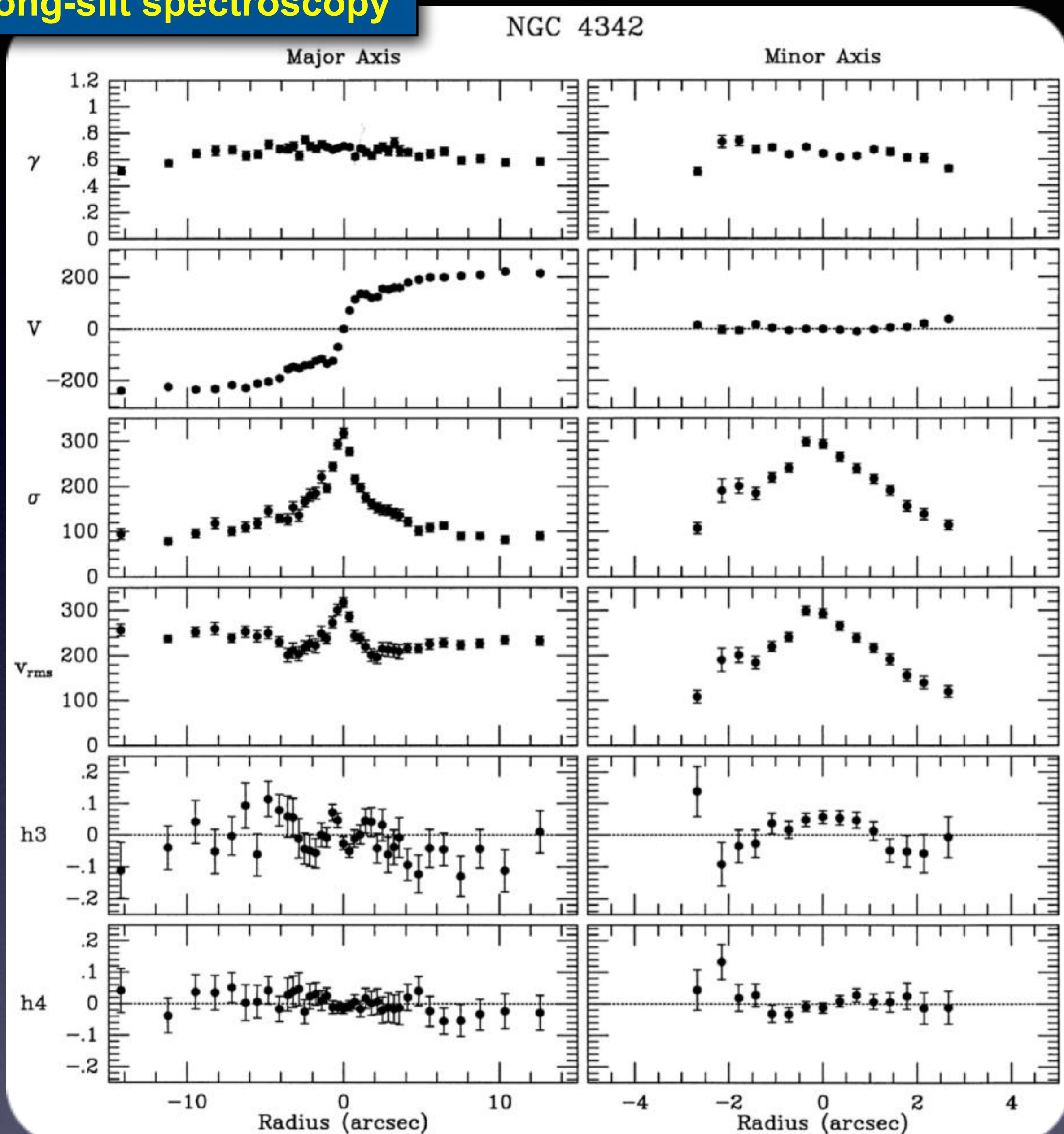


van der Marel & Franx 1993

The h_4 Gauss-Hermite moment is especially powerful as it is sensitive to the orbital distribution of the galaxy, and can therefore be used to break the mass-anisotropy degeneracy that hampers kinematic models.

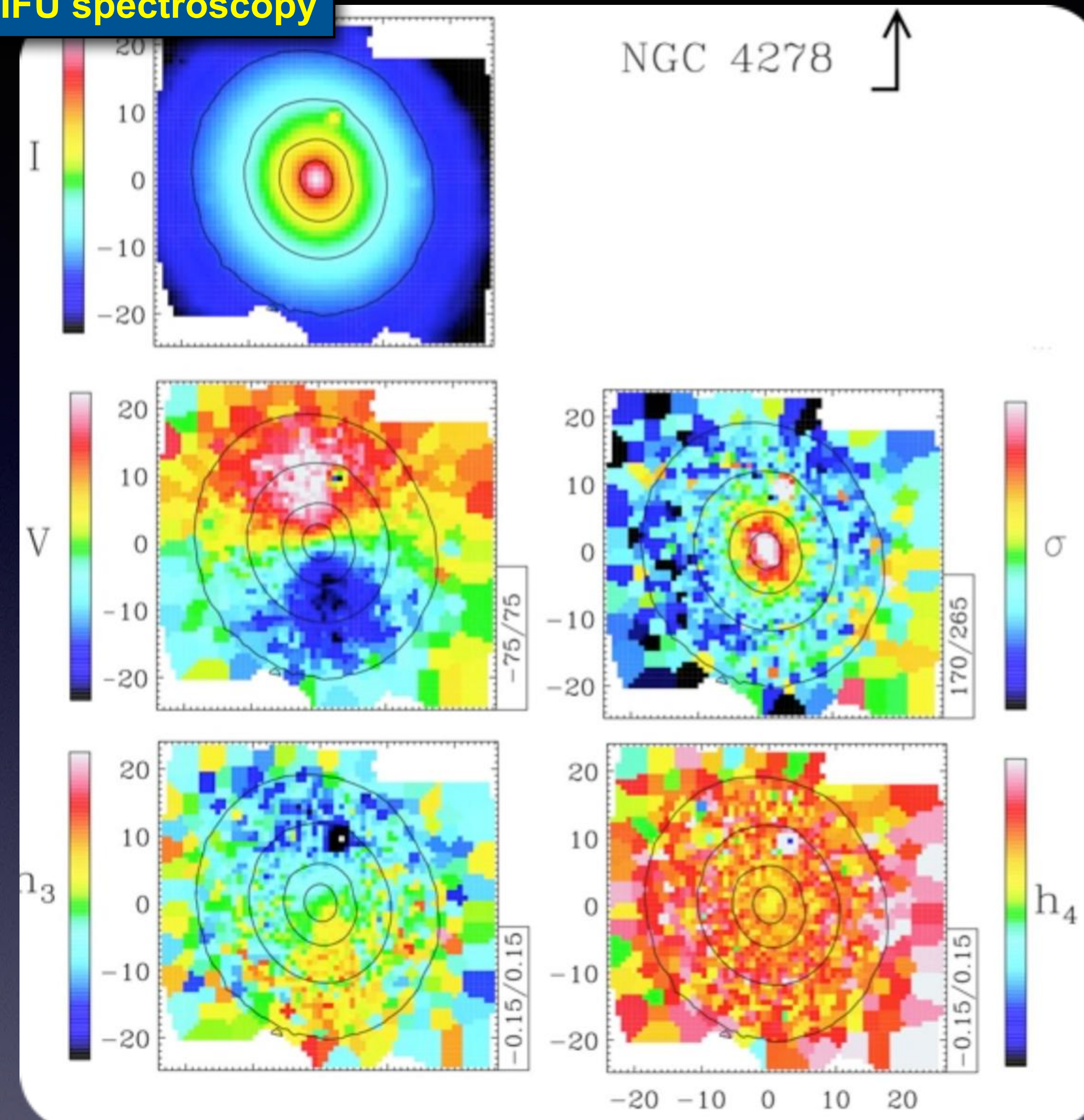
Kinematics

long-slit spectroscopy



vdBosch, Jaffe & vdMarel, 1998, MNRAS, 293, 343

IFU spectroscopy

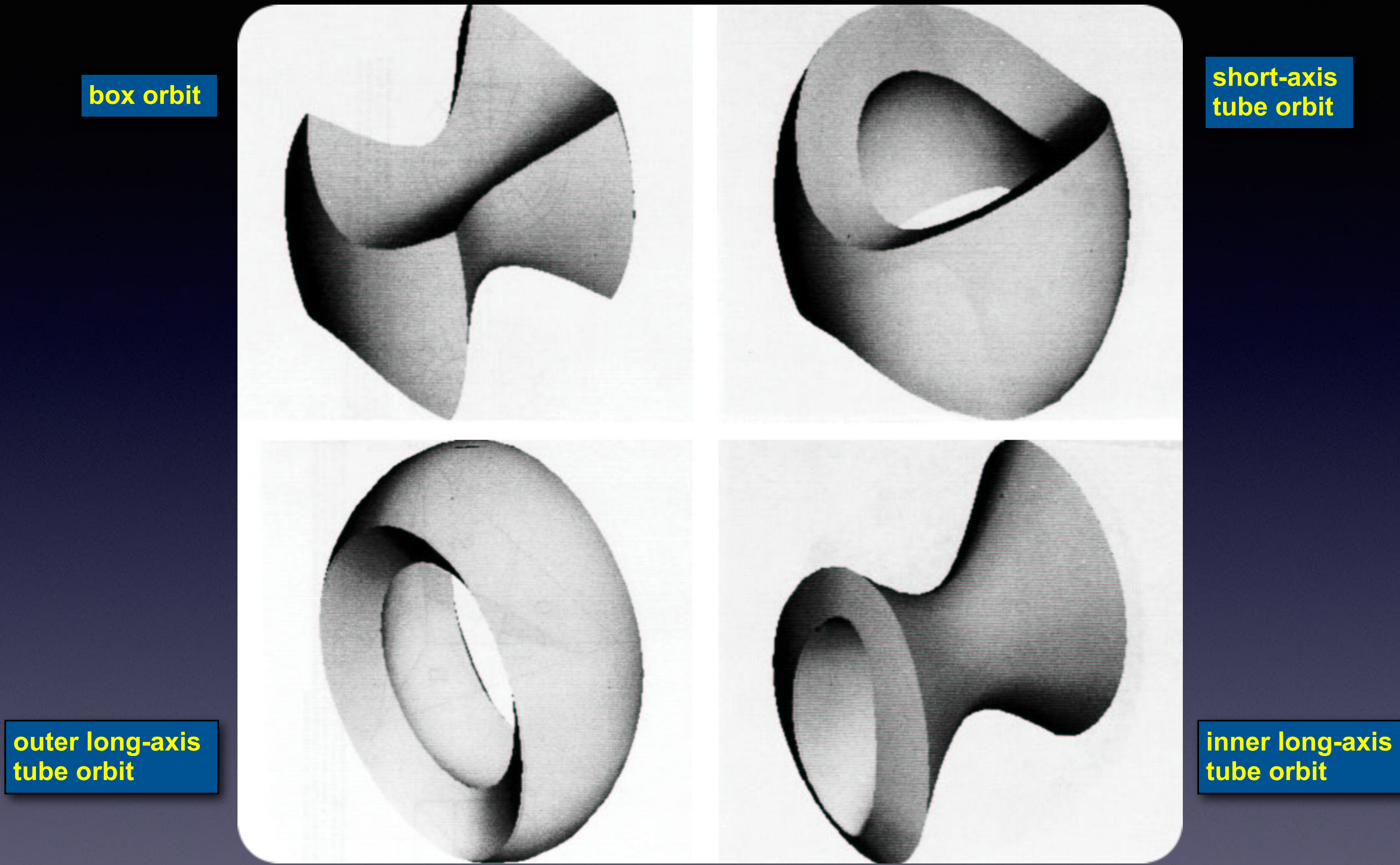


Emsellem et al. 2004

Disky ellipticals typically reveal strong rotation along major axis, consistent with them being `oblate rotators' (oblate in shape, with flattening due to rotation)

Boxy ellipticals reveal little rotation, and occasionaly rotation along the minor axis. Latter is a clear sign that (boxy) ellipticals are triaxial

Orbital Families in Triaxial Potentials



In triaxial potentials, there are four families of regular orbits.

Box orbit have no net angular momentum; the orbit comes arbitrarily close to the centre. Tube orbits, on the other hand, have an angular momentum barrier

The Tensor Virial Theorem

We now examine how the structure of elliptical galaxies relates to their kinematics.

The dynamics of (elliptical) galaxies are governed by the CBE: df/dt = 0

Mutiplying the CBE with velocity, and integrating over velocity-space yields the Jeans equations (which are momentum equations)

$$\frac{\partial(\rho\langle v_j\rangle)}{\partial t} + \frac{\partial(\rho\langle v_i v_j\rangle)}{\partial x_i} + \rho\frac{\partial\Phi}{\partial x_j} = 0$$

Multiplying all terms with x_k and integrating over all of configuration space yields

$$\frac{\partial}{\partial t}\int \rho x_k\langle v_j\rangle\,\mathrm{d}^3\vec{x} = -\int x_k\frac{\partial(\rho\langle v_i v_j\rangle)}{\partial x_i}\,\mathrm{d}^3\vec{x} - \int \rho x_k\frac{\partial\Phi}{\partial x_j}\mathrm{d}^3\vec{x}$$

Using integration by parts, the first terms on the rhs can be written as

$$\int x_k\frac{\partial(\rho\langle v_i v_j\rangle)}{\partial x_i}\,\mathrm{d}^3\vec{x} = -\int \rho\langle v_k v_j\rangle \mathrm{d}^3\vec{x} \equiv -2\mathcal{K}_{kj}$$

where we have defined the kinetic energy tensor, $\mathcal{K}_{kj}$

Centrifugal Support vs. Pressure Support

We split kinetic energy tensor into contributions from ordered and random motions:

$$\mathcal{K}_{ij} \equiv \mathcal{T}_{ij} + \frac{1}{2}\Pi_{ij}$$

$$\mathcal{T}_{ij} \equiv \frac{1}{2}\int \rho\langle v_i\rangle\,\langle v_j\rangle\,\mathrm{d}^3\vec{x}$$

$$\Pi_{ij} \equiv \int \rho\sigma_{ij}^2\,\mathrm{d}^3\vec{x}$$

In addition to the kinetic energy tensor, we also define the potential energy tensor:

$$\mathcal{W}_{ij} \equiv -\int \rho x_i \frac{\partial\Phi}{\partial x_j}\,\mathrm{d}^3\vec{x}$$

Combining the above, and using that both $\mathcal{K}$ and $\mathcal{W}$ are symmetric, we have that

$$\frac{1}{2}\frac{\mathrm{d}}{\mathrm{d}t}\int \rho\left[x_k\langle v_j\rangle + x_j\langle v_k\rangle\right]\mathrm{d}^3\vec{x} = 2\mathcal{K}_{jk} + \mathcal{W}_{jk}$$

The Tensor Virial Theorem

Finally, we define the moment of inertia tensor

$$\boxed{\mathcal{I}_{ij} \equiv \int \rho x_i x_j \mathrm{d}^3\vec{x}}$$

Differentiating wrt time and using the continuity equation (i.e., zeroth moment of CBE):

$$\boxed{\frac{\mathrm{d}\mathcal{I}_{jk}}{\mathrm{d}t} = \int \frac{\partial \rho}{\partial t} x_j x_k \, \mathrm{d}^3\vec{x} = -\int \frac{\partial \rho \langle v_i \rangle}{\partial x_i} x_j x_k \mathrm{d}^3\vec{x} = \int \rho \left[x_j \langle v_k \rangle + x_k \langle v_j \rangle \right] \mathrm{d}^3\vec{x}}$$

students: try this at home

so that

$$\boxed{\frac{1}{2}\frac{\mathrm{d}}{\mathrm{d}t} \int \rho \left[x_j \langle v_k \rangle + x_k \langle v_j \rangle \right] \mathrm{d}^3\vec{x} = \frac{1}{2}\frac{\mathrm{d}^2\mathcal{I}_{jk}}{\mathrm{d}t^2}}$$

which allows us to write the Tensor Virial Theorem as

$$\boxed{\frac{1}{2}\frac{\mathrm{d}^2\mathcal{I}_{jk}}{\mathrm{d}t^2} = 2\mathcal{T}_{jk} + \Pi_{jk} + \mathcal{W}_{jk}}$$

which relates the gross kinematic and structural properties of gravitational systems

The Tensor Virial Theorem

If the system is in a steady state, the moment of inertia tensor is stationary, and the tensor virial theorem reduces to

$$\boxed{2\mathcal{K}_{jk} + \mathcal{W}_{jk} = 0}$$

The common (scalar) virial theorem (2K+W=0) is simply the trace of this tensor equation.

We now use this tensor virial theorem, to relate the flattening of an elliptical to its kinematics. Consider an oblate system with it's symmetry axis along the z-direction. Because of symmetry considerations we have that

$$\boxed{\langle v_R \rangle = \langle v_z \rangle = 0 \qquad\qquad \langle v_R v_\phi \rangle = \langle v_z v_\phi \rangle = 0}$$

If we write $\langle v_x \rangle = \langle v_\phi \rangle \, \sin\phi$ and $\langle v_y \rangle = \langle v_\phi \rangle \, \cos\phi$ then we obtain

$$\mathcal{T}_{xy} = \frac{1}{2} \int \rho \langle v_x \rangle \, \langle v_y \rangle \, \mathrm{d}^3\vec{x} = \frac{1}{2} \int_0^{2\pi} \mathrm{d}\phi \sin\phi \, \cos\phi \int_0^{\infty} \mathrm{d}R \int_{-\infty}^{+\infty} \mathrm{d}z \, \rho(R,z) \, \langle v_\phi \rangle^2 (R,z) = 0$$

A similar analysis shows that all other non-diagonal elements of $\mathcal{T}, \Pi$ and $\mathcal{W}$ have to be zero

In addition, because of symmetry considerations we must also have that $\mathcal{T}_{xx} = \mathcal{T}_{yy}$, and similar for Π and $\mathcal{W}$

The Tensor Virial Theorem

Given these symmetries, the only independent, non-trivial virial equations are

$$\boxed{2\mathcal{T}_{xx} + \Pi_{xx} + \mathcal{W}_{xx} = 0 \qquad\qquad 2\mathcal{T}_{zz} + \Pi_{zz} + \mathcal{W}_{zz} = 0}$$

If the only streaming motion is rotation about the z-axis, then $\mathcal{T}_{zz} = 0$ and

$$2\mathcal{T}_{xx} = \frac{1}{2}\int \rho \, \langle v_\phi \rangle^2 \mathrm{d}^3\vec{x} = \frac{1}{2} M v_0^2$$

where v_0 is the mass-weighted rotation velocity. Similarly we can write

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

where $\sigma_0^2 \equiv (1/M) \int \rho \sigma_{xx}^2 \mathrm{d}^3\vec{x}$ is the mass-weighted velocity dispersion along los,

and $\delta \equiv 1 - \Pi_{zz}/\Pi_{xx} < 1$ is a measure of the anisotropy of the velocity dispersion

Taking the ratio between the two non-trivial virial equations above then yields

$$\boxed{\frac{\mathcal{W}_{xx}}{\mathcal{W}_{zz}} = \frac{1}{1-\delta}\left(1 + \frac{1}{2}\frac{v_0^2}{\sigma_0^2}\right)}$$

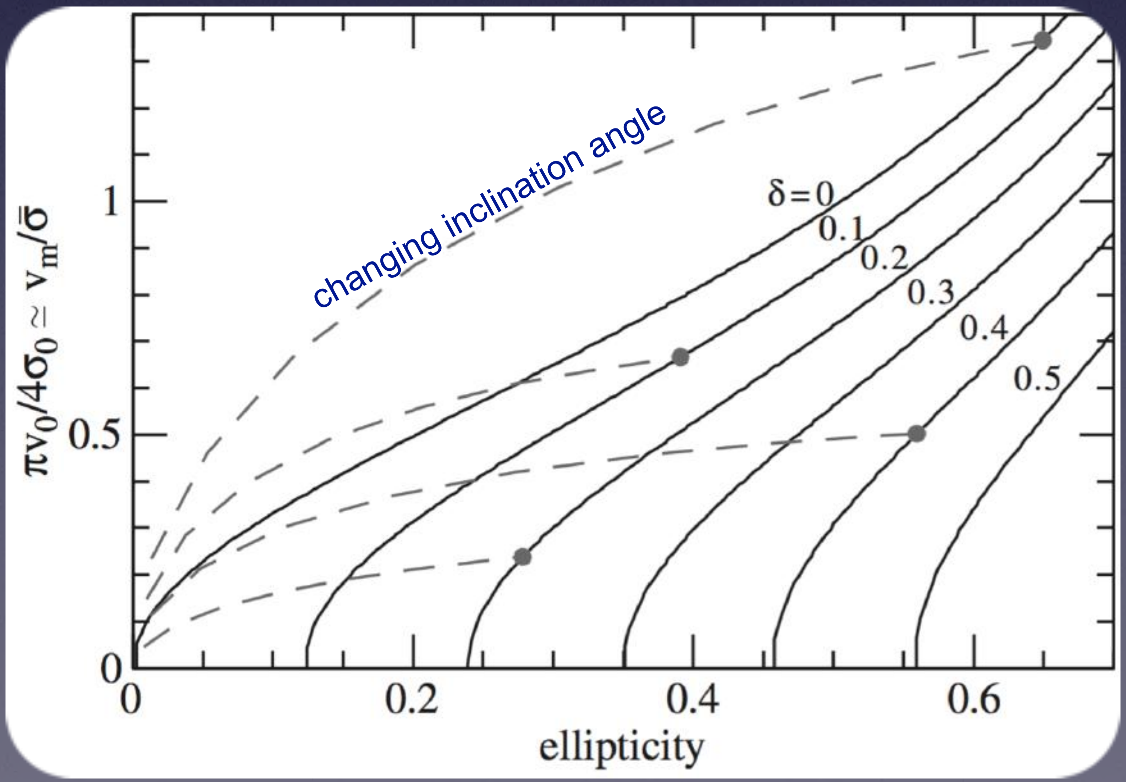
The Tensor Virial Theorem

As shown by Roberts (1962), for systems stratified on similar coaxial oblate ellipsoids, the ratio $\mathcal{W}_{xx}/\mathcal{W}_{zz}$ depends only on the ellipticity ε

$$\boxed{\frac{\mathcal{W}_{xx}}{\mathcal{W}_{zz}} = \frac{1}{1-\delta}\left(1+\frac{1}{2}\frac{v_0^2}{\sigma_0^2}\right)}$$

The above expression therefore makes it clear that a stellar system can be flattened either by rotation, or by anisotropic velocity dispersion (i.e., $\delta > 0$)

It is customary to identify σ_0 with $\bar{\sigma}$, the mean velocity dispersion interior to half the effective radius, and v_0 with $4v_{\rm m}/\pi$, with $v_{\rm m}$ the maximum rotation velocity (Binney 2005)

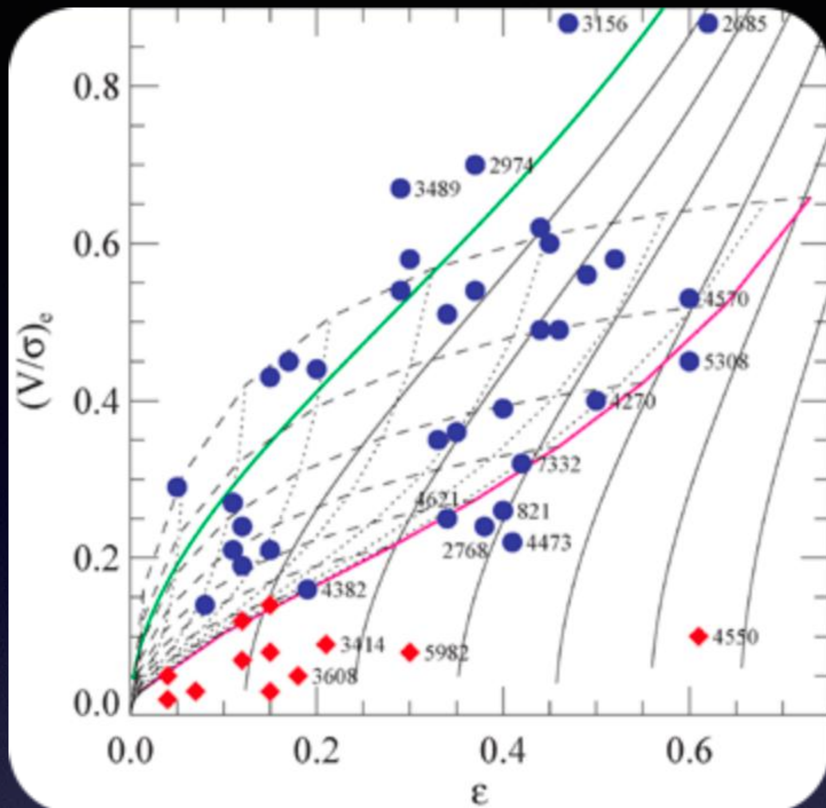


Solid lines are for edge-on system; dashed lines show impact of projection for decreasing inclination angle.

For isotropic case, to good approximation we have

$$\boxed{\frac{v_{\rm m}}{\bar{\sigma}} \approx \sqrt{\frac{\varepsilon}{1-\varepsilon}}}$$

Fast vs. Slow Rotators

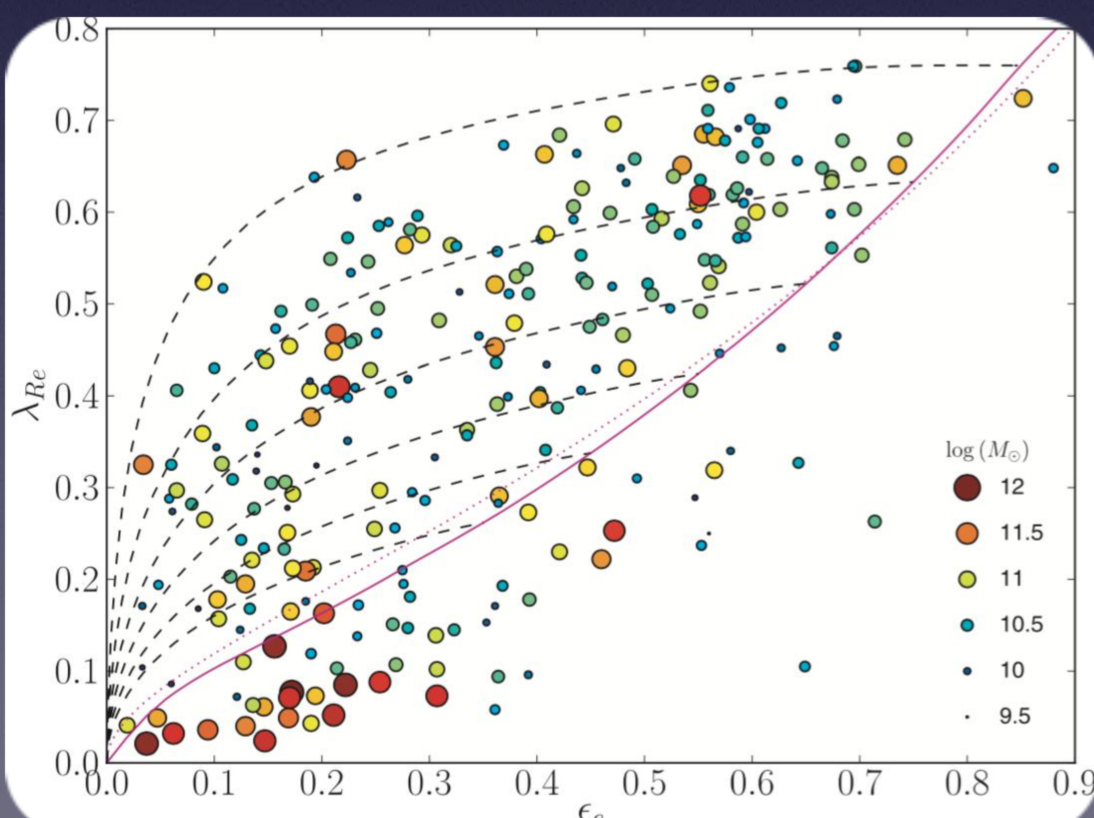


One can split ellipticals in two kinematic classes:

Fast rotators; kinematics consistent with oblate rotators, shape is flattened by rotation

Slow rotators; very little rotation; shape is due to anisotropic pressure support

Emsellem et al. 2011, MNRAS, 414, 888

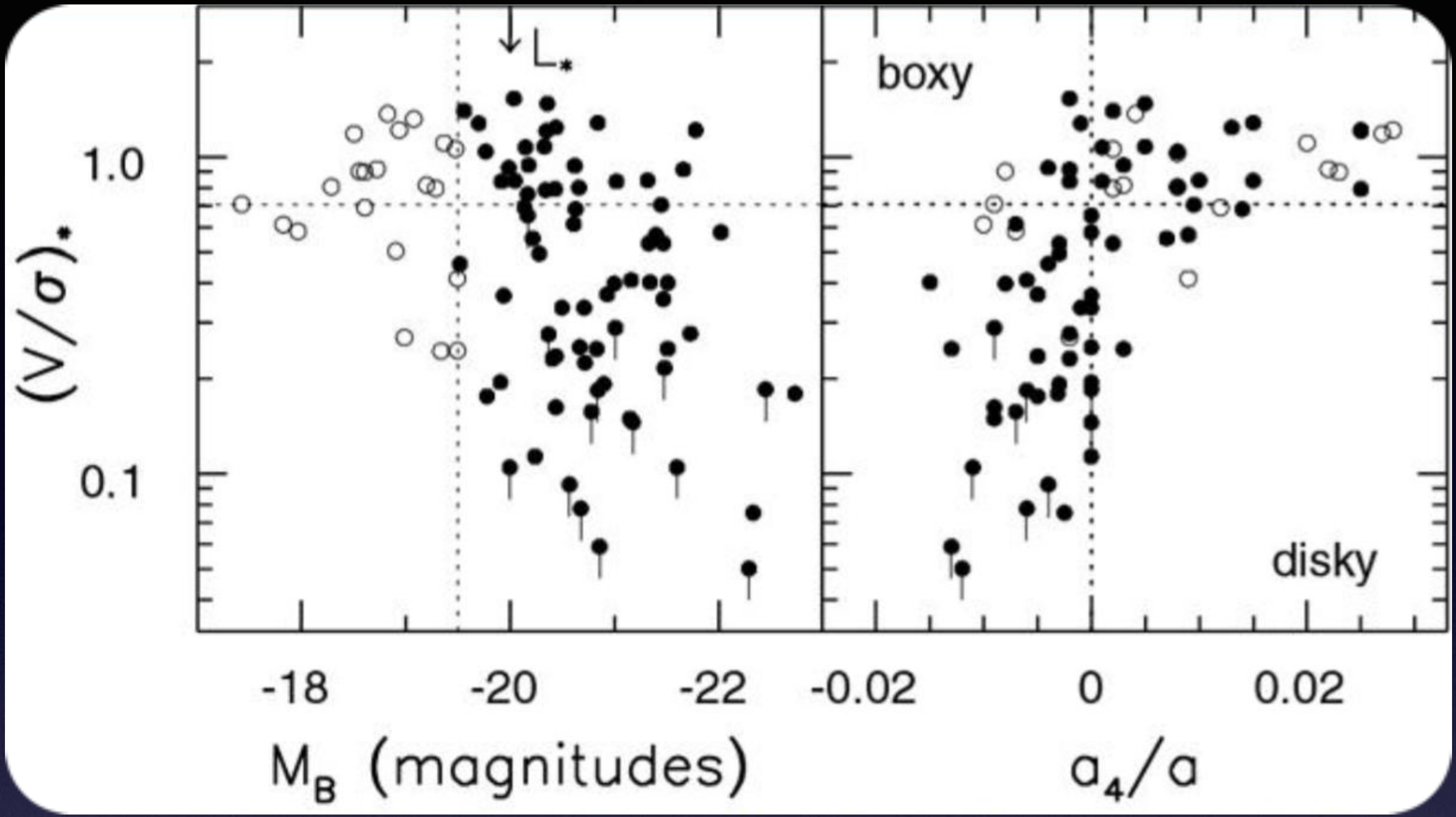


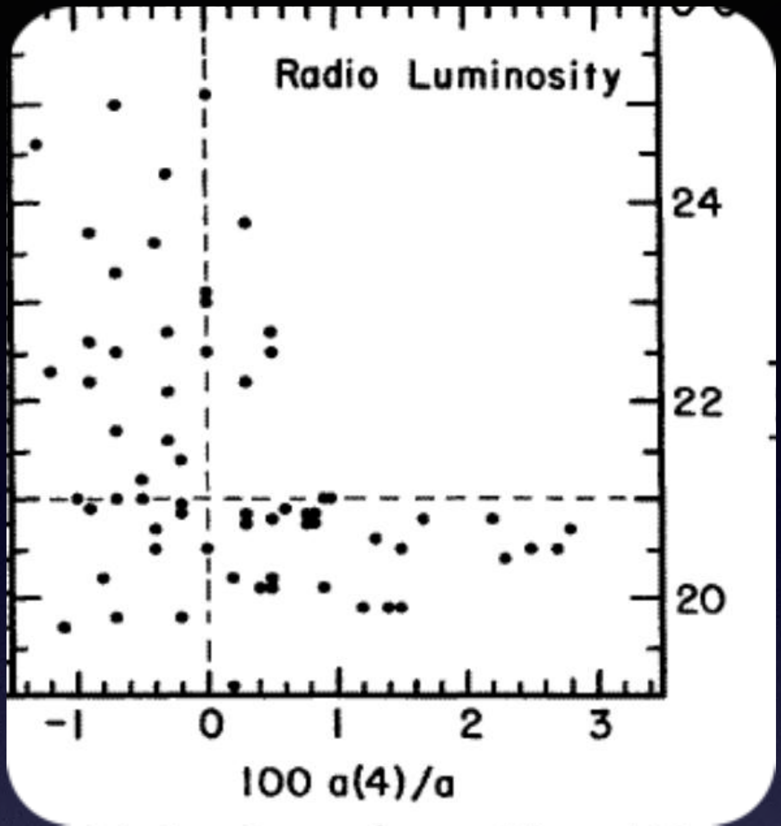
Typically, slow rotators are more massive, and are often boxy. Fast rotators are disky ellipticals or S0s, and are often less luminous.

$$\lambda_R = \frac{\langle R\,|V|\rangle}{\langle R\sqrt{V^2+\sigma^2}\rangle}$$

a modern replacement for $v_{\rm m}/\bar{\sigma}$

The Dichotomy among Ellipticals

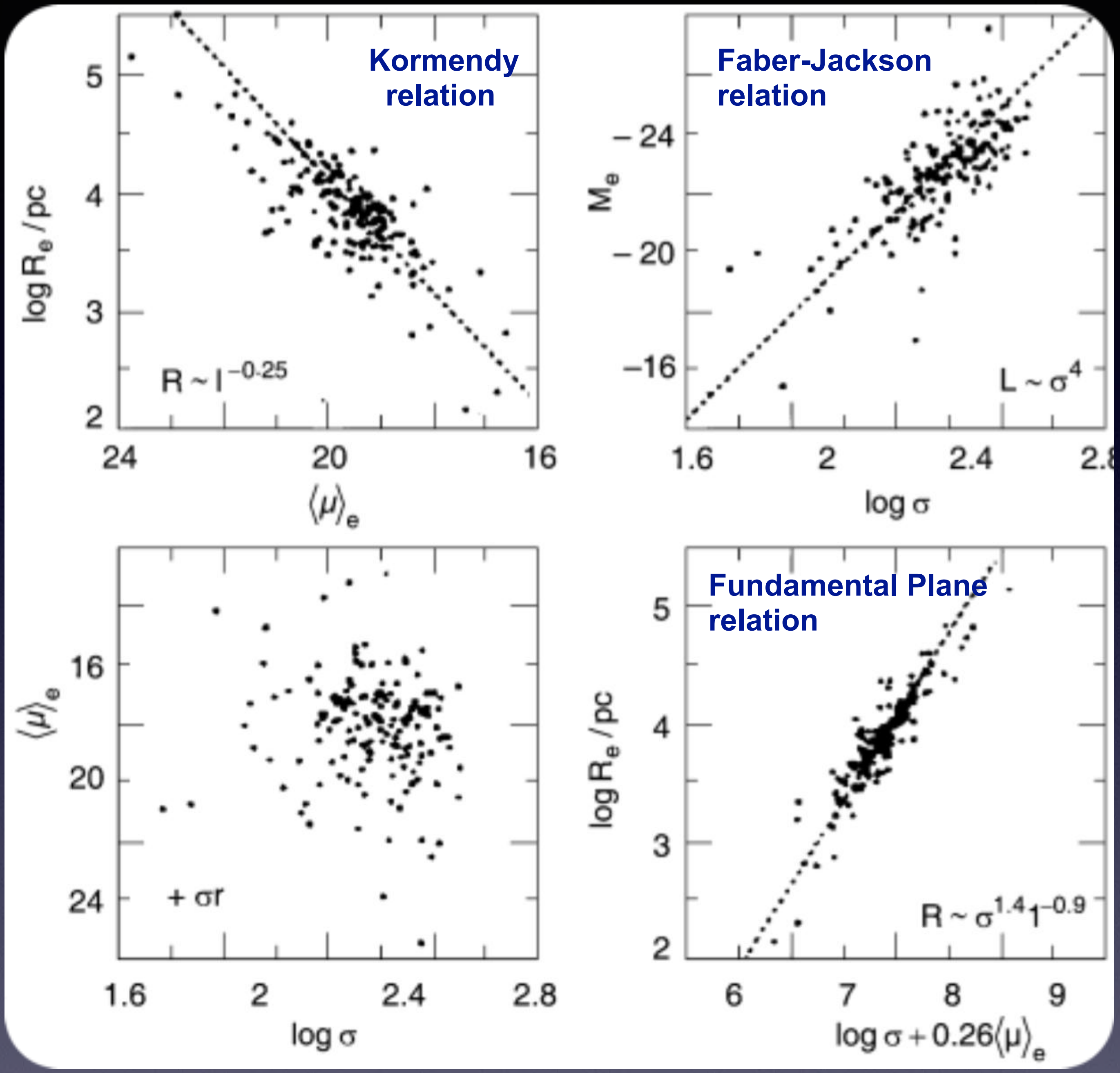




Faint ellipticals ($M_B \gtrsim -20.5$)	Bright ellipticals ($M_B \lesssim -20.5$)
disky isophotes cuspy SB profile fast rotator weak in radio/X-ray isophotal twists rare	boxy isophotes cored SB profile slow rotator often strong radio/X-ray emittor isophotal twists common

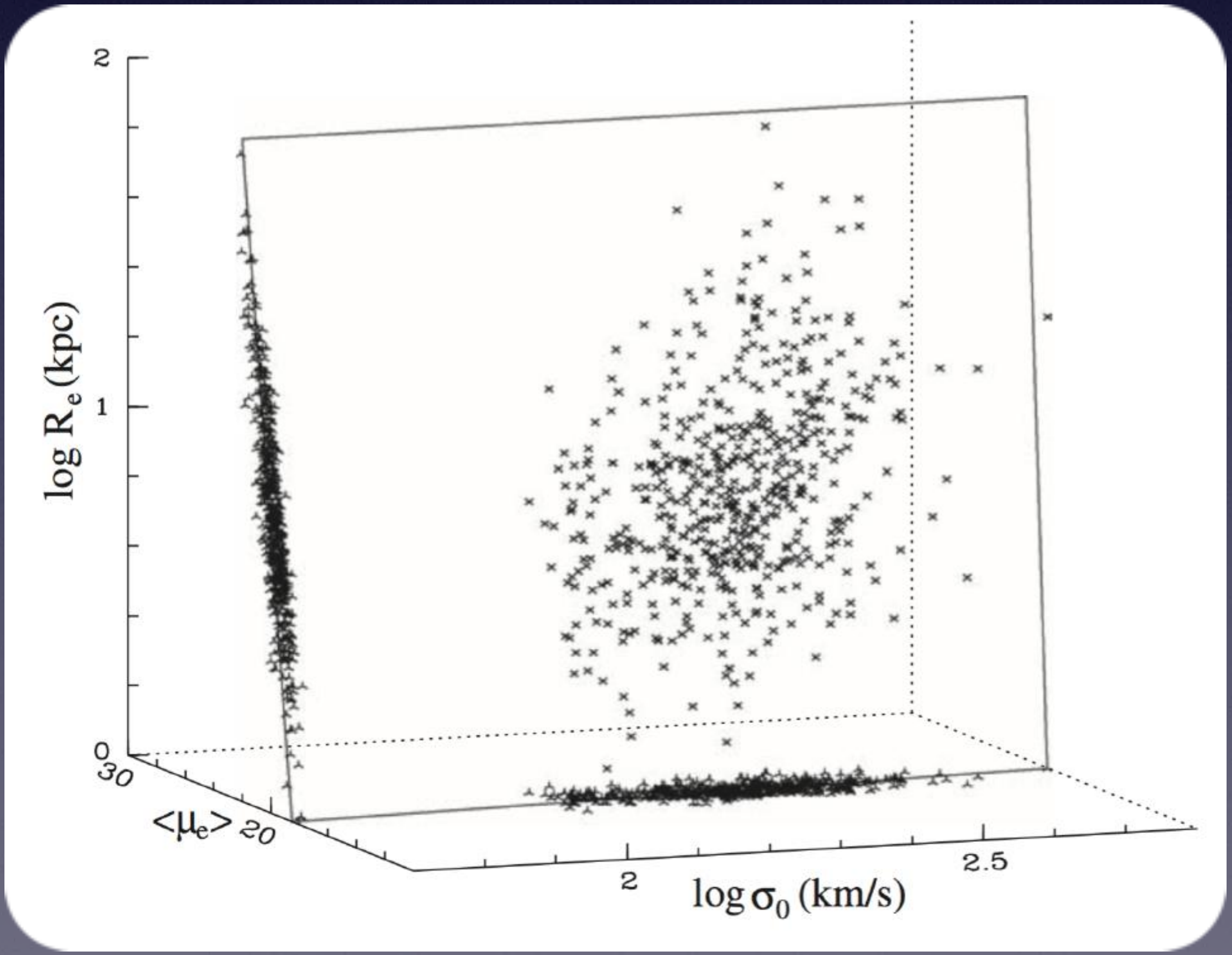
Disky ellipticals are consistent with being more bulge-dominated versions of S0 galaxies.

The Fundamental Plane



Similar to the TF-relation for disk galaxies, ellipticals reveal a scaling relation between luminosity and velocity dispersion, known as the Faber-Jackson (FJ) relation:

However, unlike the TF, the scatter in FJ *is* correlated with size, giving rise to a three-parameter Fundamental Plane relation.



The Fundamental Plane

The FP-relation is generally written in the form $\boxed{\log R_{\rm e} = a \log \sigma_0 + b \log \langle I \rangle_{\rm e} + \mathrm{cst}}$

Best-fit parameters are a ~ 1.2 to 1.5 (depending on waveband), and b ~ -0.8

The FP-relation is usually interpreted in terms of the Virial Theorem

$$\boxed{\frac{G\,M}{\langle R \rangle} = \langle v^2 \rangle}$$

$\langle R \rangle =$ average radius,such that lhs is abs. value of mean potential energy per unit mass

$\langle v^2 \rangle =$ average rms velocity, such that half that value is mean kinetic energy per unit mass

Let
$$R_{\rm e} = \kappa_R \langle R \rangle$$
$$\sigma_0 = \kappa_V \sqrt{\langle v^2 \rangle}$$
$$\Rightarrow \quad R_{\rm e} = \frac{1}{2\pi G\, \kappa_R\, \kappa_V^2}\, \sigma_0^2\, \langle I \rangle_{\rm e}^{-1}\, (M/L)^{-1}$$

If ellipticals are homologous (i.e. $\kappa_{\rm R}$ and $\kappa_{\rm V}$ constant), and the mass-to-light ratio is constant, then the Virial Theorem predicts a FP-relation with a=2 and b=-1

The deviation from this prediction is called the 'tilt' of the fundamental plane, and reflects that ellipticals as a class are not homologous, and/or that $(M/L) \propto L^{\alpha} \langle I \rangle_{\rm e}^{\beta}$ with $(\alpha, \beta) \neq 0$.

although still debated, the latter option seems to explain most of the tilt.

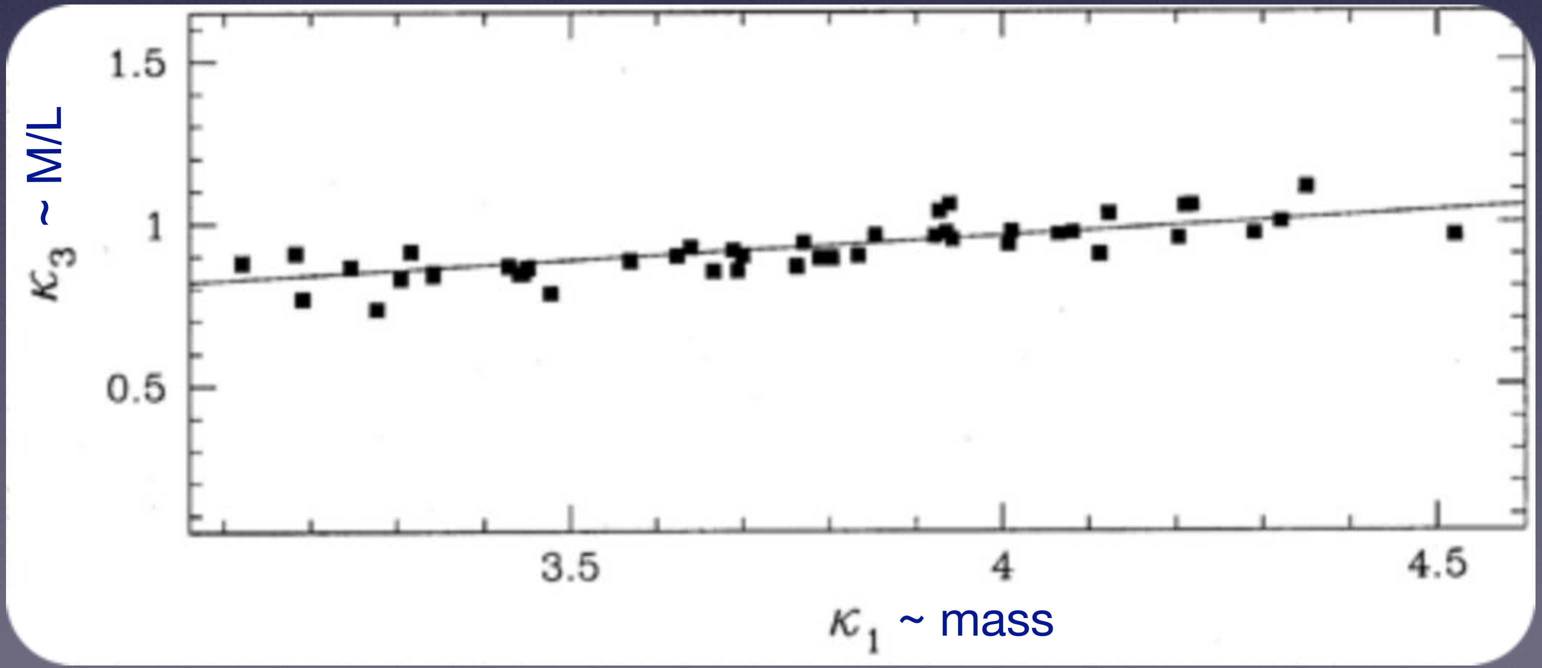
The Fundamental Plane

As originally proposed by Bender+92, it is useful to use an orthogonal combination of the three observables that enter the FP-relation, which facilitates interpretation.

$$\kappa_1 \equiv (\log \sigma_0^2 + \log R_e)/\sqrt{2}$$
$$\kappa_2 \equiv (\log \sigma_0^2 + 2\log\langle I\rangle_e - \log R_e)/\sqrt{6}$$
$$\kappa_3 \equiv (\log \sigma_0^2 - \log\langle I\rangle_e - \log R_e)/\sqrt{3}$$

$$\kappa_1 \propto \log(\sigma_0^2 R_e) \propto \log M$$
$$\kappa_3 \propto \log(\sigma_0^2 R_e/\langle I\rangle_e R_e^2) \propto \log(M/L)$$

In this 'κ-space', the κ_1-κ_2 projection is very close to a face-on projection of the FP, while the κ_1-κ_3 projection shows the FP nearly edge-on. In fact, if ellipticals are homologous, and $(M/L) \propto M^\gamma$, the virial theorem implies that $\kappa_3 = \sqrt{2/3}\gamma\kappa_1 + \mathrm{cst}$



Formation of Ellitpical Galaxies

One ‘obvious’ scenario for why some galaxies are ellipticals and others are spirals is to assume this is governed by angular momentum….

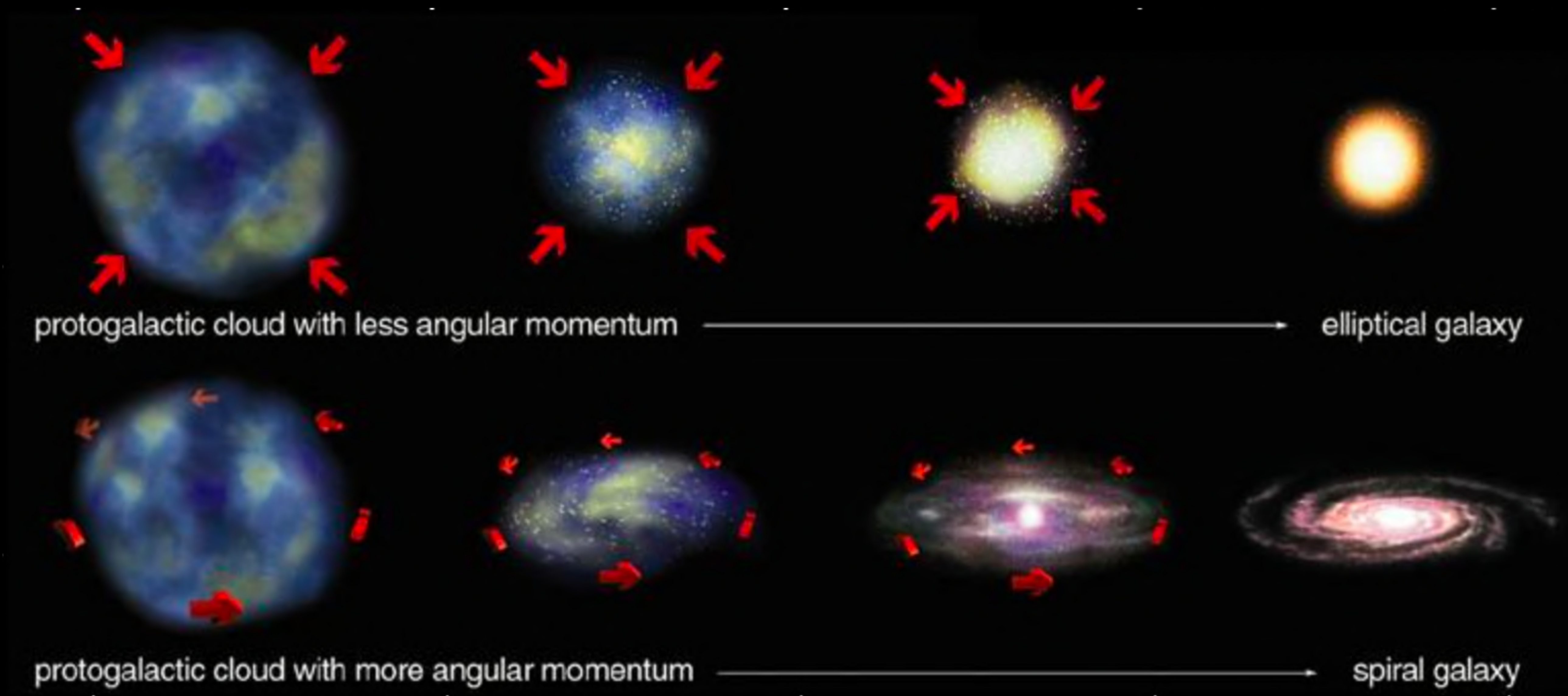


Fig. credit: 2004, Pearson Education, publishing as Addison-Wesley

Formation of Ellitpical Galaxies

an alternative is to assume that the difference relates to the density of the proto-galaxy

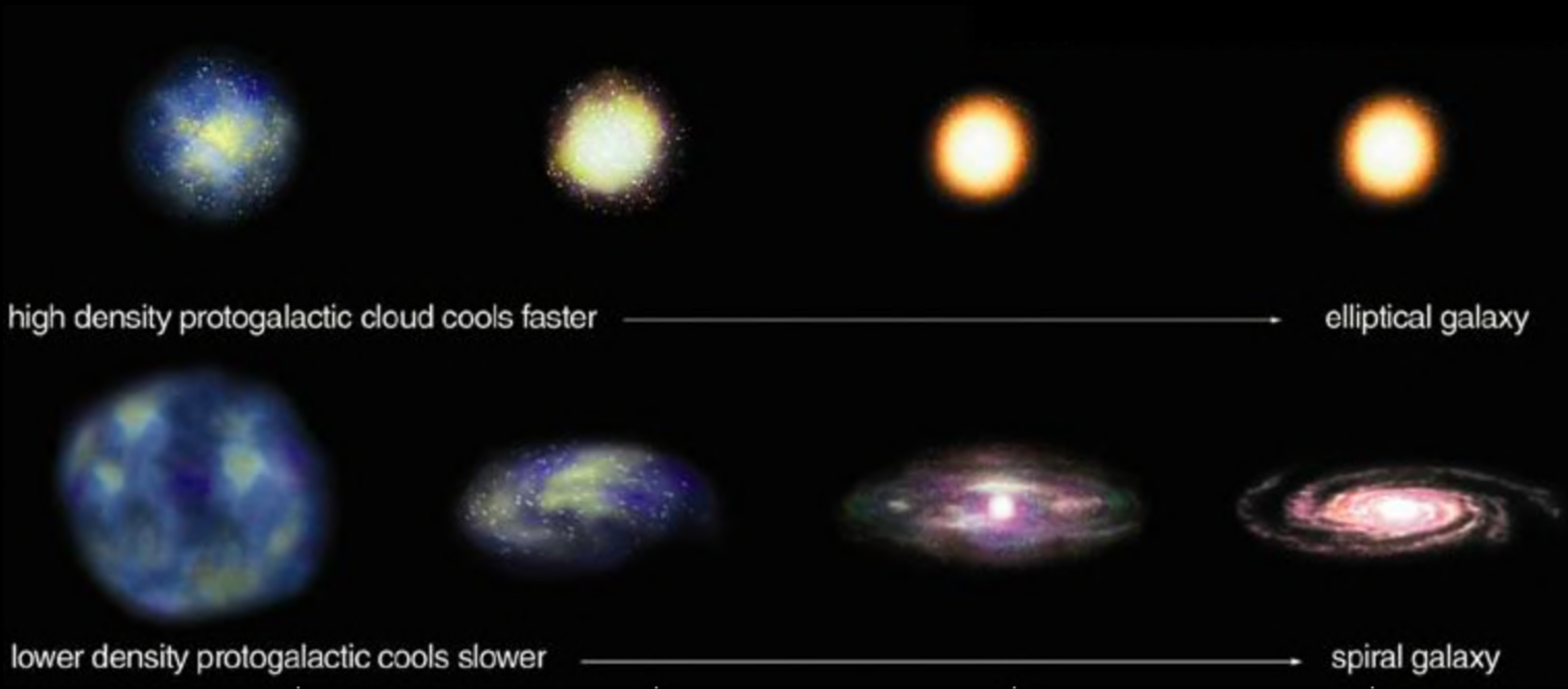
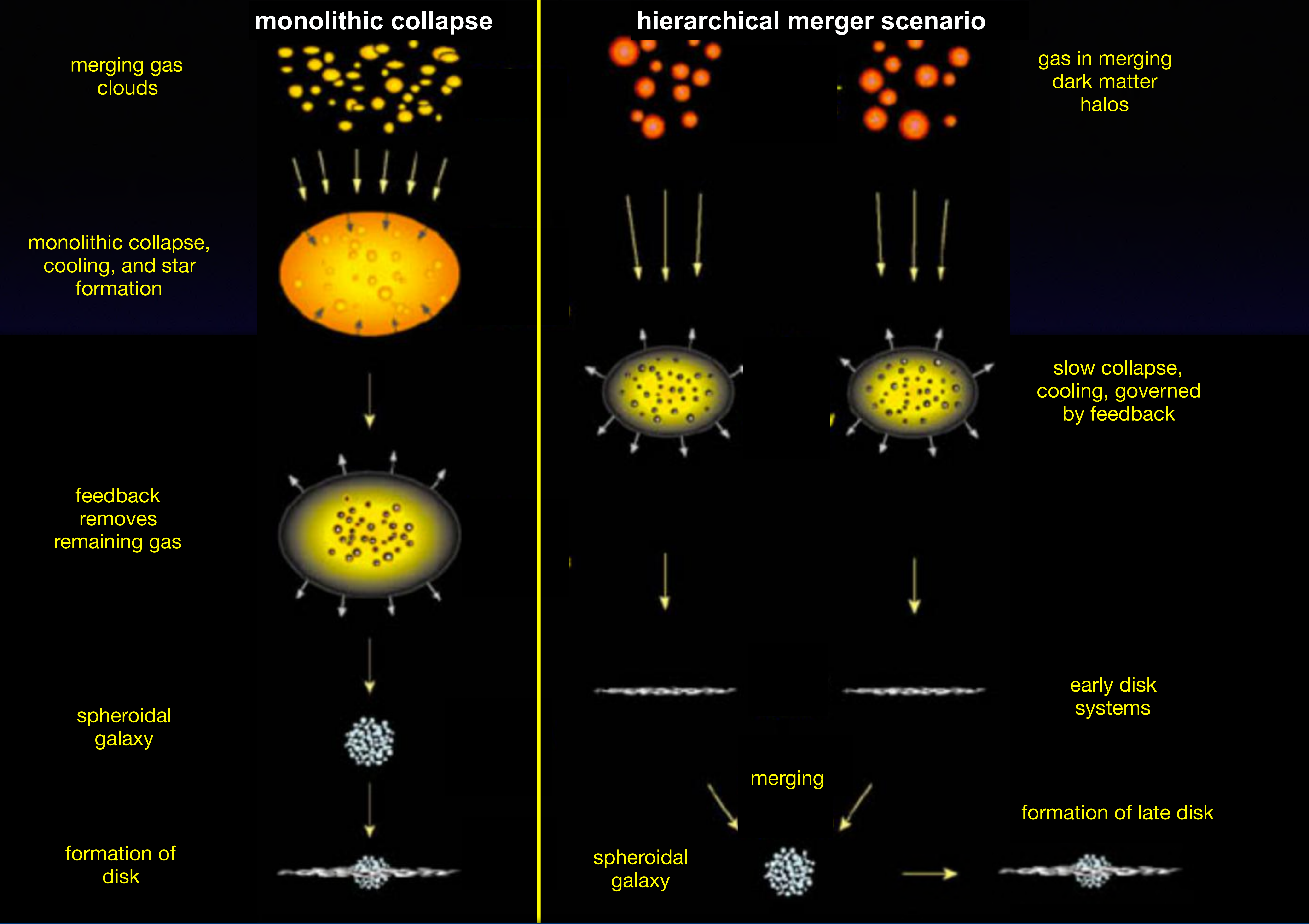


Fig. credit: 2004, Pearson Education, publishing as Addison-Wesley


monolithic collapse
hierarchical merger scenario
merging gas clouds
monolithic collapse, cooling, and star formation
feedback removes remaining gas
spheroidal galaxy
formation of disk
gas in merging dark matter halos
slow collapse, cooling, governed by feedback
early disk systems
merging
formation of late disk
spheroidal galaxy