

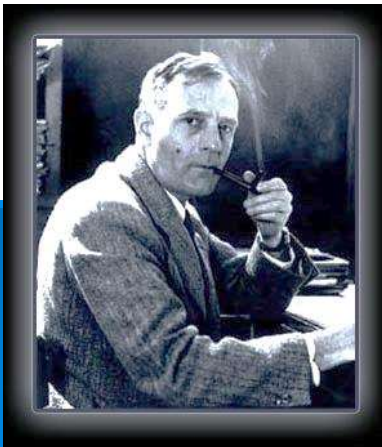
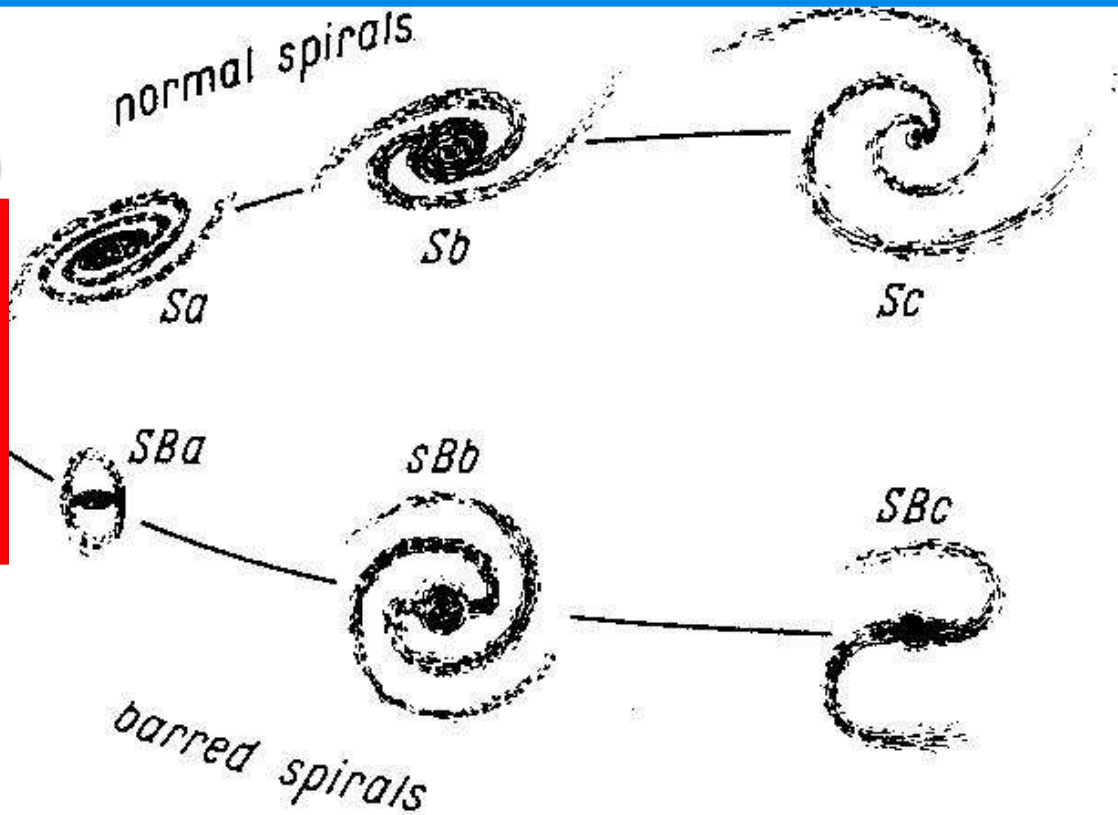
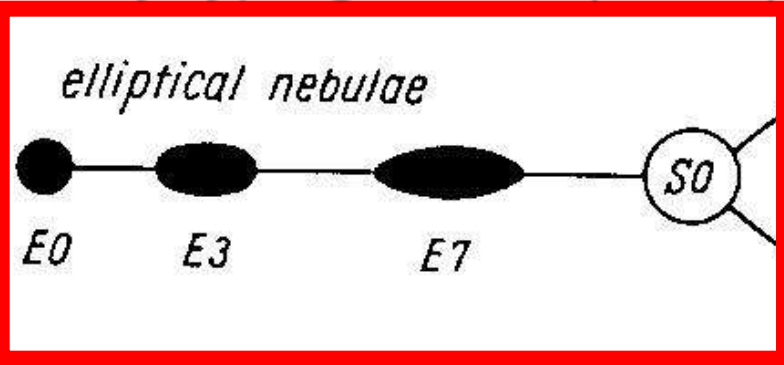
Observations and modelling of early-type galaxy dynamics

Michele Cappellari



ETG structure: 1936-1975

early-type galaxies (ETGs)



Edwin Hubble (1889-1953)

- Ellipticals supported by rotation (=isotropic) (e.g. Gott75)
- Shape dictated by angular momentum

Bright ellipticals anisotropic?

- Bright ellipticals rotate slowly: anisotropic and triaxial

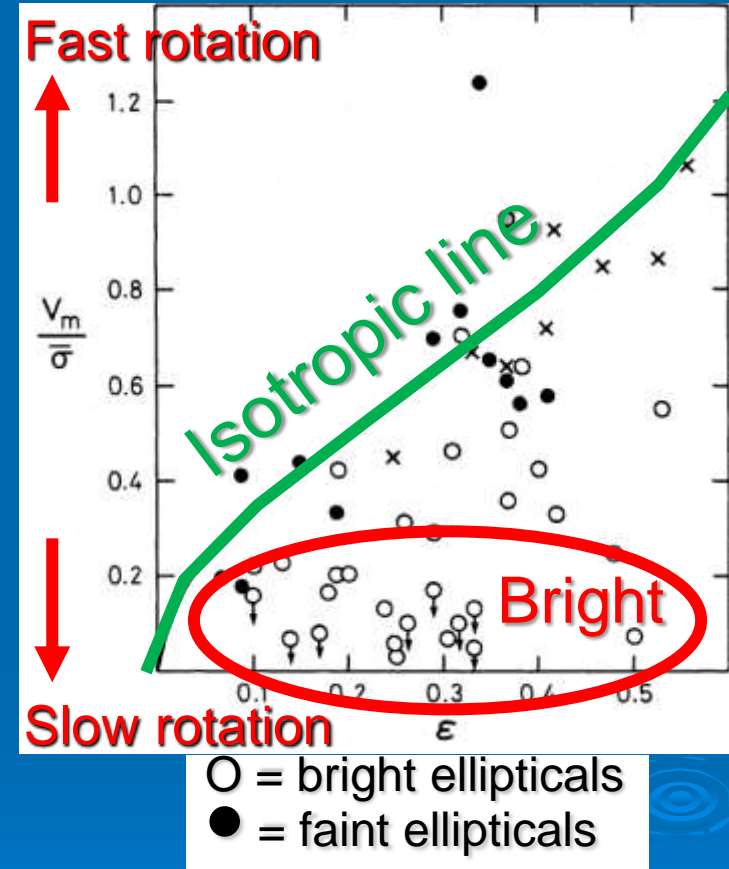
(Bertola+Capaccioli75; Illingworth77; Binney78)

- Result of major disk mergers

(Toomre+Toomre72; Barnes+Hernquist96)

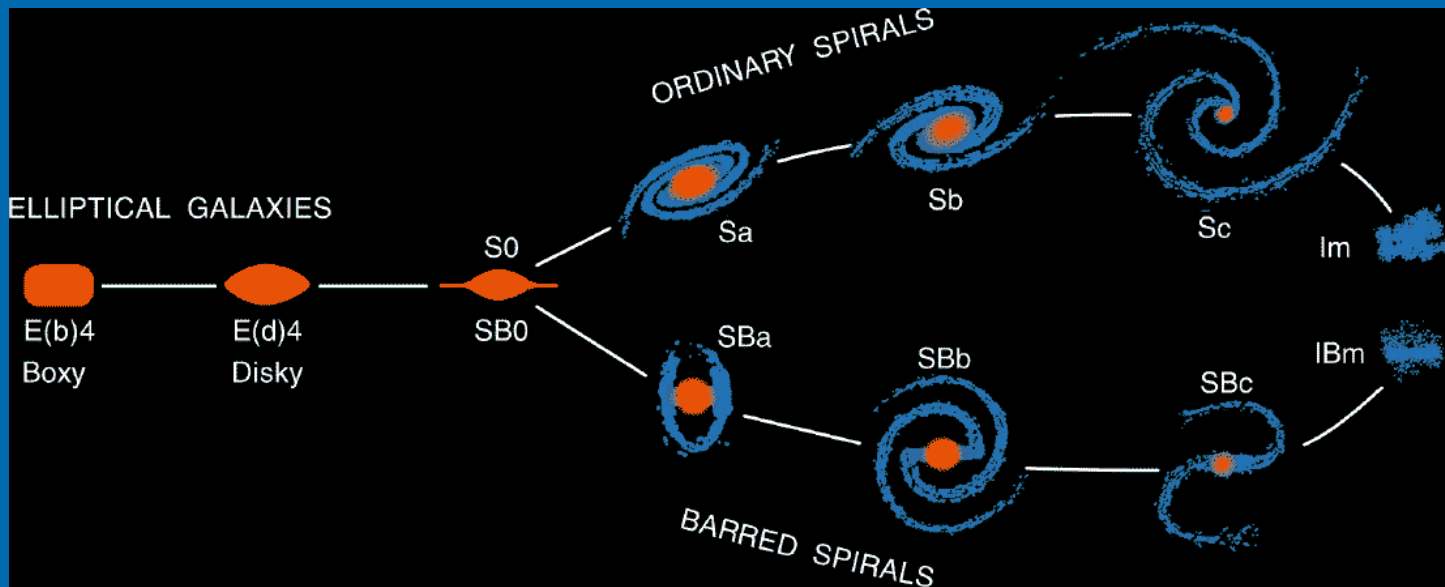
- Faint ellipticals rotate fast: isotropic

(Kormendy+Illingworth82; Davies+83)



(Davies+83)

Only faint ellipticals are disky



(Kormendy+Bender96)

- Disky isophotes only in faint E

(Bender88, Bender+89)

- Do they actually contain disks?

(Rix+White90; vanDenBergh90; Jorgensen+Franx94; Michard94)

- Disky ellipticals: transition between bright E and S0

(Kormendy+Bender96)

Limits of photometric classification

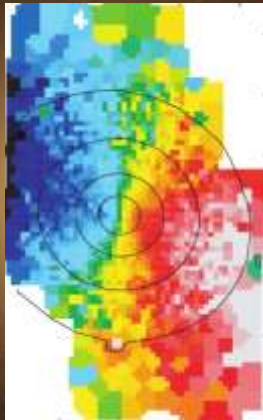
(Kinematic maps from Emsellem+04 and Krajnovic+11: P2)

NGC3379 (E1)

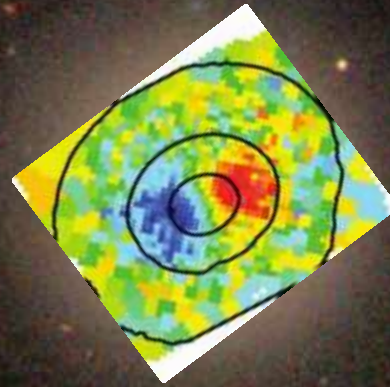
NGC5631 (S0)

NGC4374 (E1)

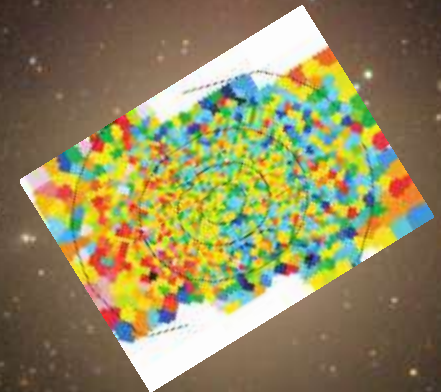
SDSS



Fast-rotator



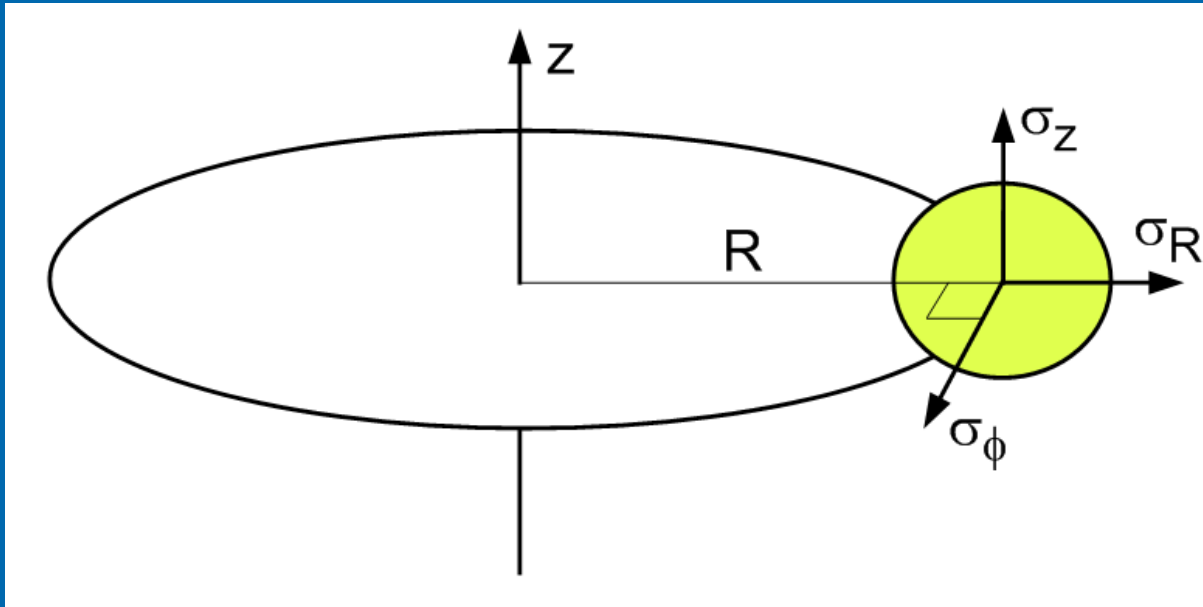
Slow-rotators



- Genuine ellipticals \rightarrow spheroids from all directions
- Lenticulars \rightarrow look elliptical close to face-on
- Kinematics provide basis for new classification

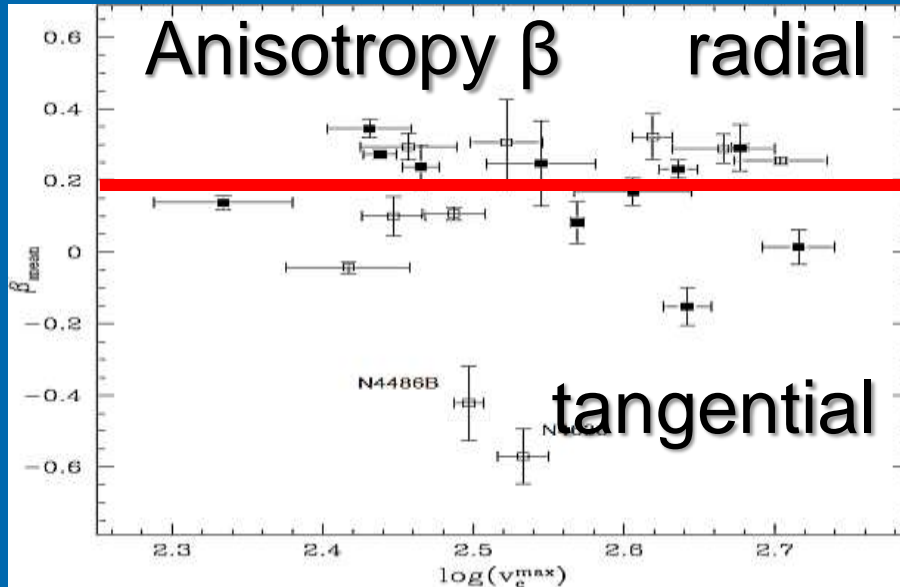
(Emsellem+07; Cappellari+07)

Anisotropy and velocity ellipsoid

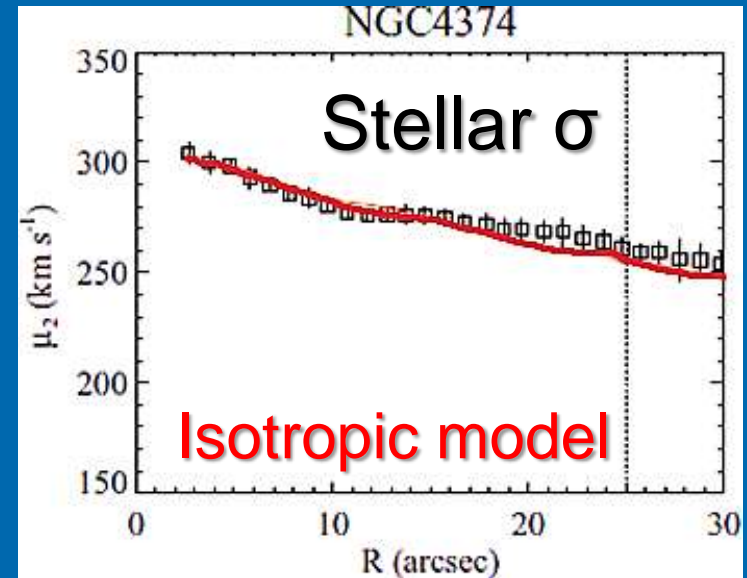


- $\beta = 1 - \frac{\sigma_z^2}{\sigma_R^2}; \gamma = 1 - \frac{\sigma_\phi^2}{\sigma_R^2}; \delta = 1 - \frac{2\sigma_z^2}{\sigma_R^2 + \sigma_\phi^2}$ (Cappellari+07)
- δ is measured by the $(V/\sigma, \epsilon)$ diagram (Binney78,05)
- β, γ require dynamical models
- $\sigma_R = \sigma_\phi \rightarrow (\delta = \beta; \gamma = 0)$: Oblate velocity ellipsoid

Bright slow rotators isotropic!



(Gerhard+01)

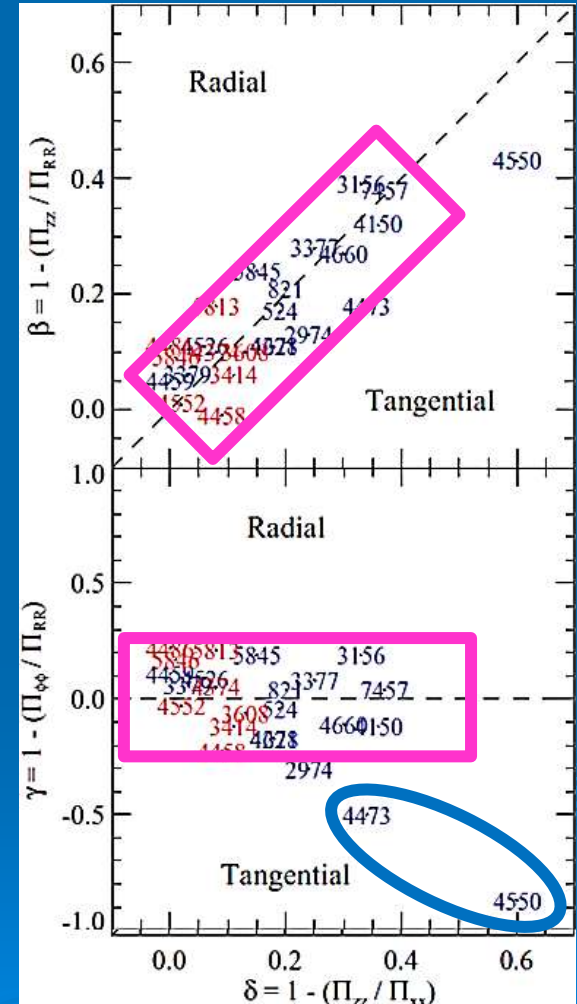


(Cappellari+07)

- Spherical dynamical models (Kronawitter+00)
- $\beta \approx 0.2$ within $1R_e$ (just 10% from isotropic)
- Consistent with Jeans models \rightarrow OK

Faint fast rotators anisotropic!

- SAURON integral-field data
- Schwarzschild's axisymmetric models
- 24 galaxies (Cappellari+07)
- $\delta \approx \beta$ and $\gamma \approx 0$
(2 important exceptions)
- **Oblate velocity ellipsoid!**
- Independently confirmed in Coma cluster (Thomas+09)

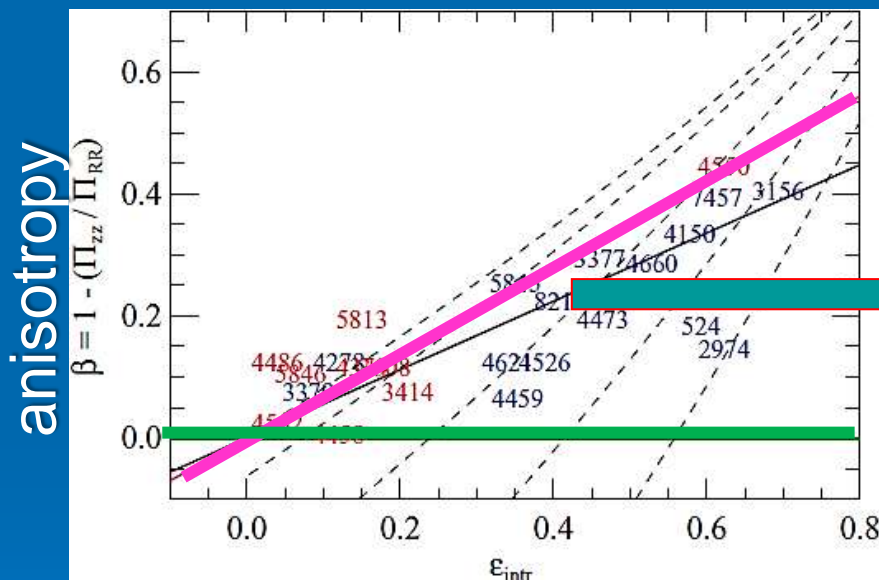


(Cappellari+07)

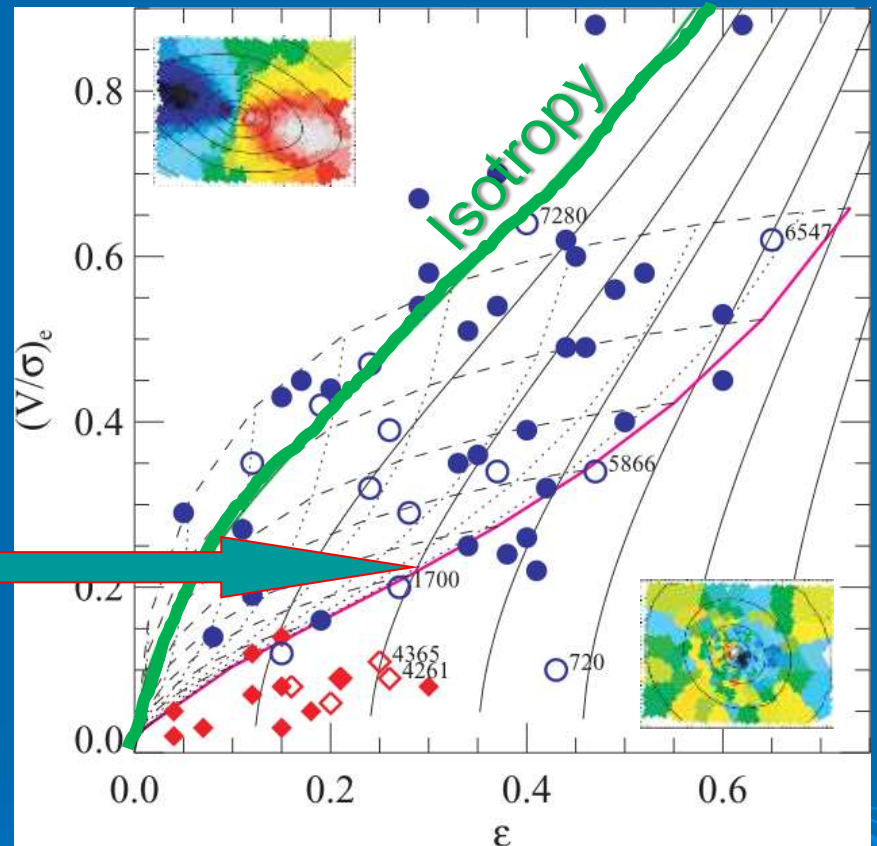
Revisiting the $(V/\sigma, \epsilon)$ diagram

Use integral-field kinematics

$$\left(\frac{V}{\sigma}\right)_e \equiv \frac{\langle V^2 \rangle}{\langle \sigma^2 \rangle} \quad (\text{Binney05})$$



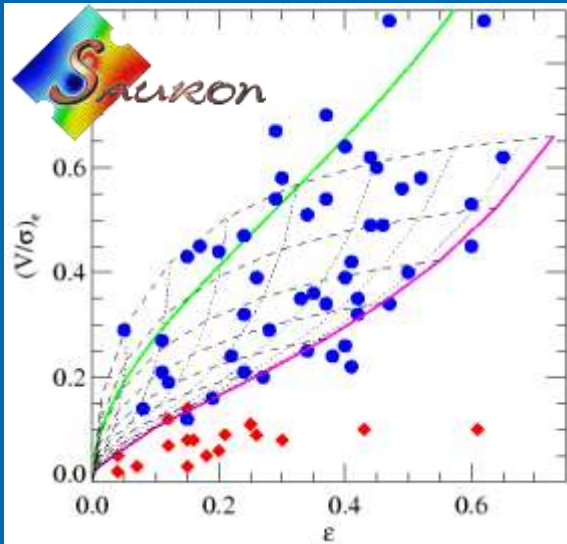
24 models



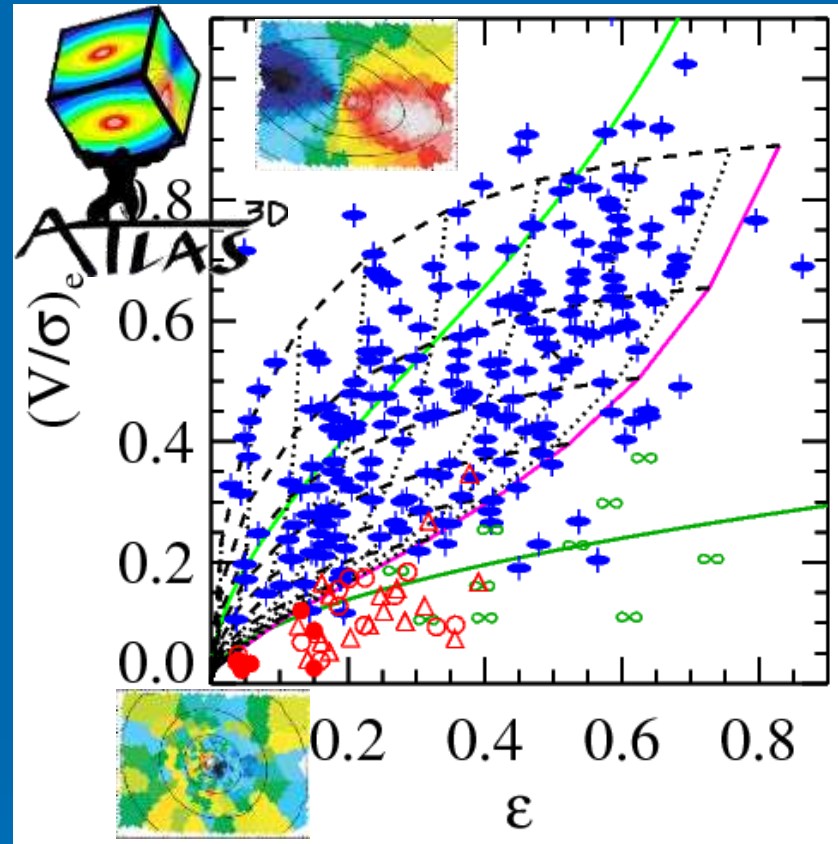
Entire sample (Cappellari+07)

- **Fast rotators:** inclined anisotropic disks
- **Slow rotators:** nearly isotropic weakly triaxial

From SAURON to ATLAS^{3D}



(Cappellari+07)

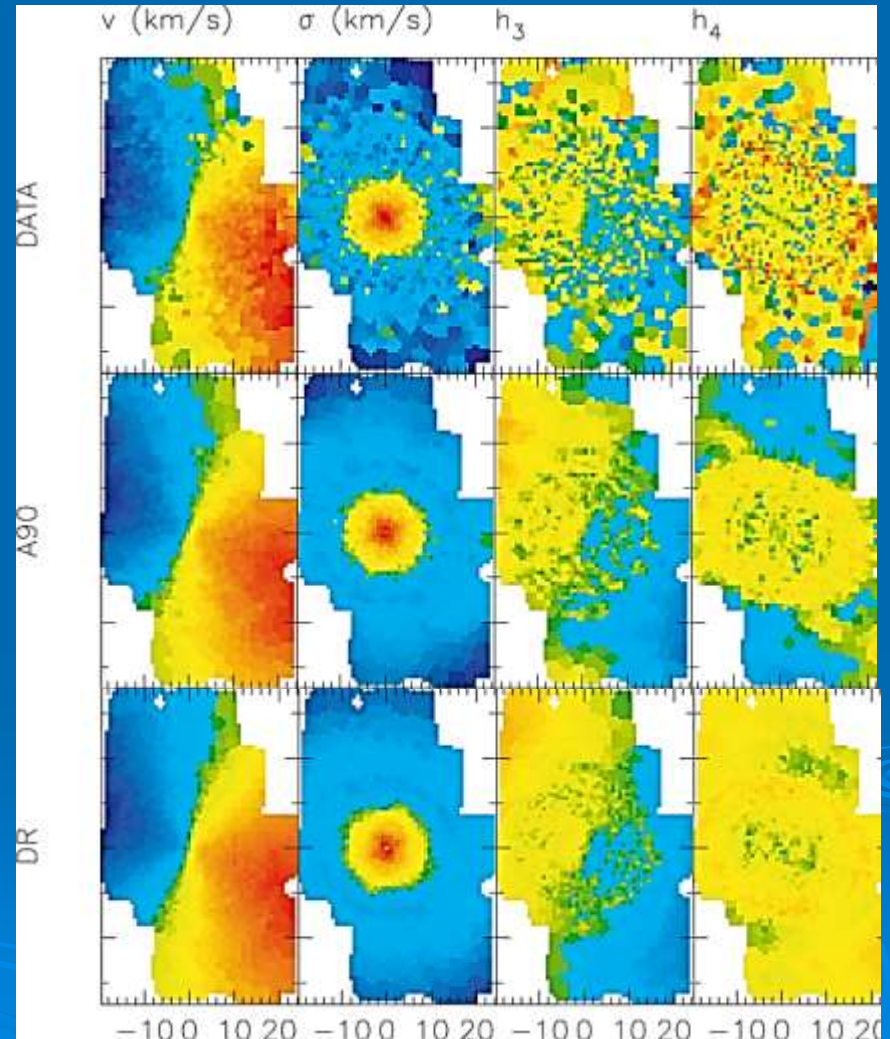


(Emsellem+11)

- ATLAS^{3D} volume-limited sample (Cappellari+11)
- SAURON result strongly confirmed
- But ATLAS^{3D} gives proper statistics: 12% are slow

Dynamical degeneracy

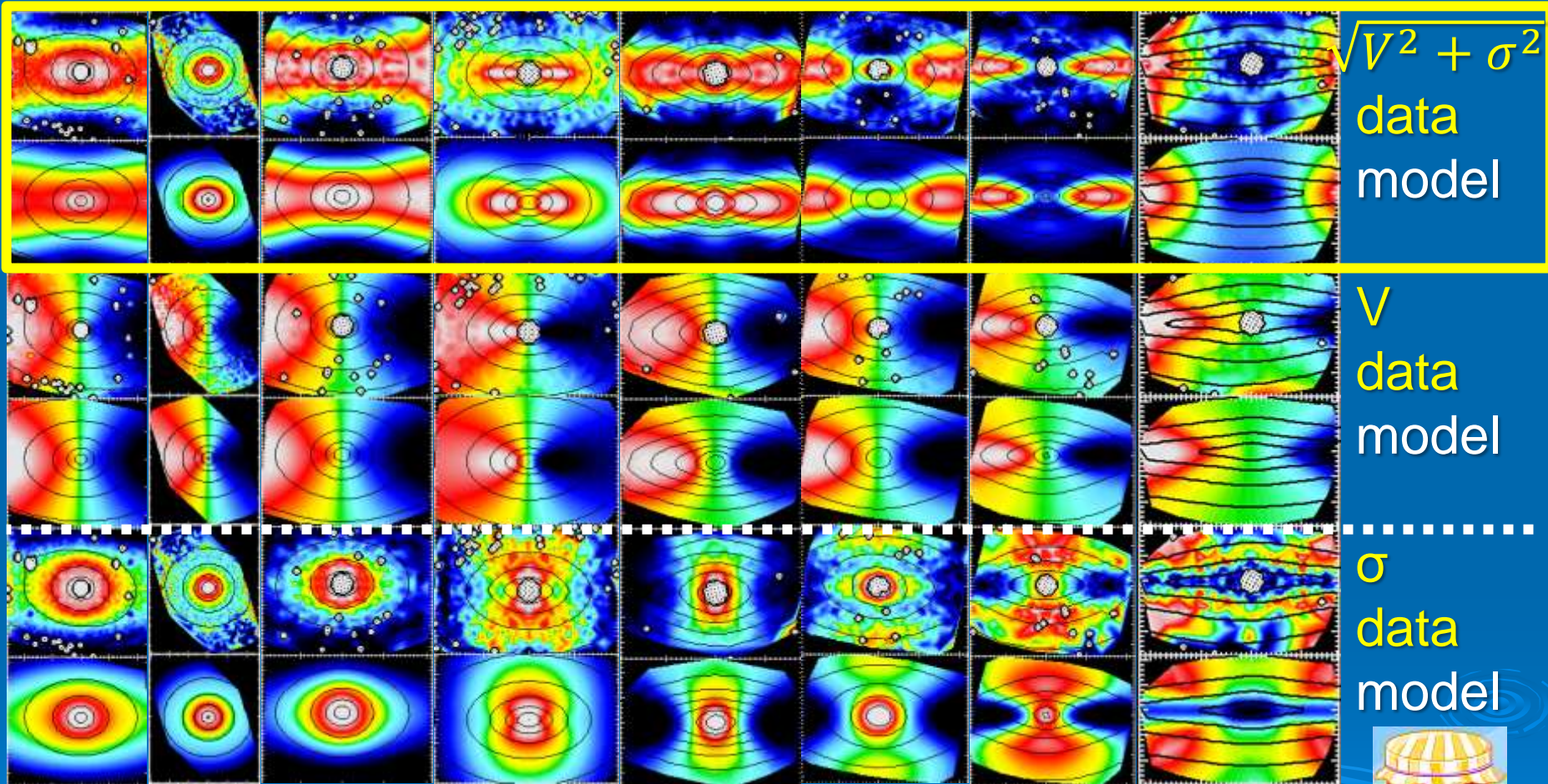
- 3-dim orbital distribution (Jeans15; Lynden-Bell62)
- Even IFU cannot constrain both orbits and potential (Dejonghe+Merritt92; Gerhard+98; Valluri+04)
- Total $(M/L)(r)$ robust (Thomas+05; Cappellari+13a)
- But vast degeneracy in shape and DM recovery (Krajnovic+05; deLorenzi+09; Morganti+Gerhard12)
- Difficult to progress with full generality



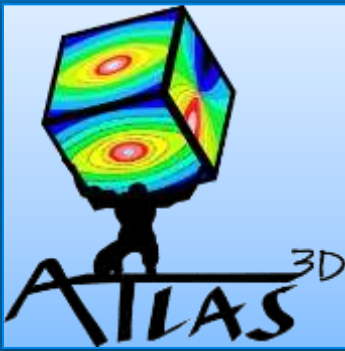
(deLorenzi09)

Triax+Halo Axi no halo SAURON

Oblate velocity ellipsoid models



- Nature does not use allowed generality
- Kinematics 'predicted' using just two parameters (i, β_z)!
(**JAM models**: Cappellari 2008; purl.org/cappellari/idl)



260 dynamical models



Volume-limited sample ETGs ($M_{\star} \gtrsim 6 \times 10^9 M_{\odot}$)

M. Cappellari et al.

The ATLAS^{3D} project – XV. Dynamical models 78 M. Cappellari et al.

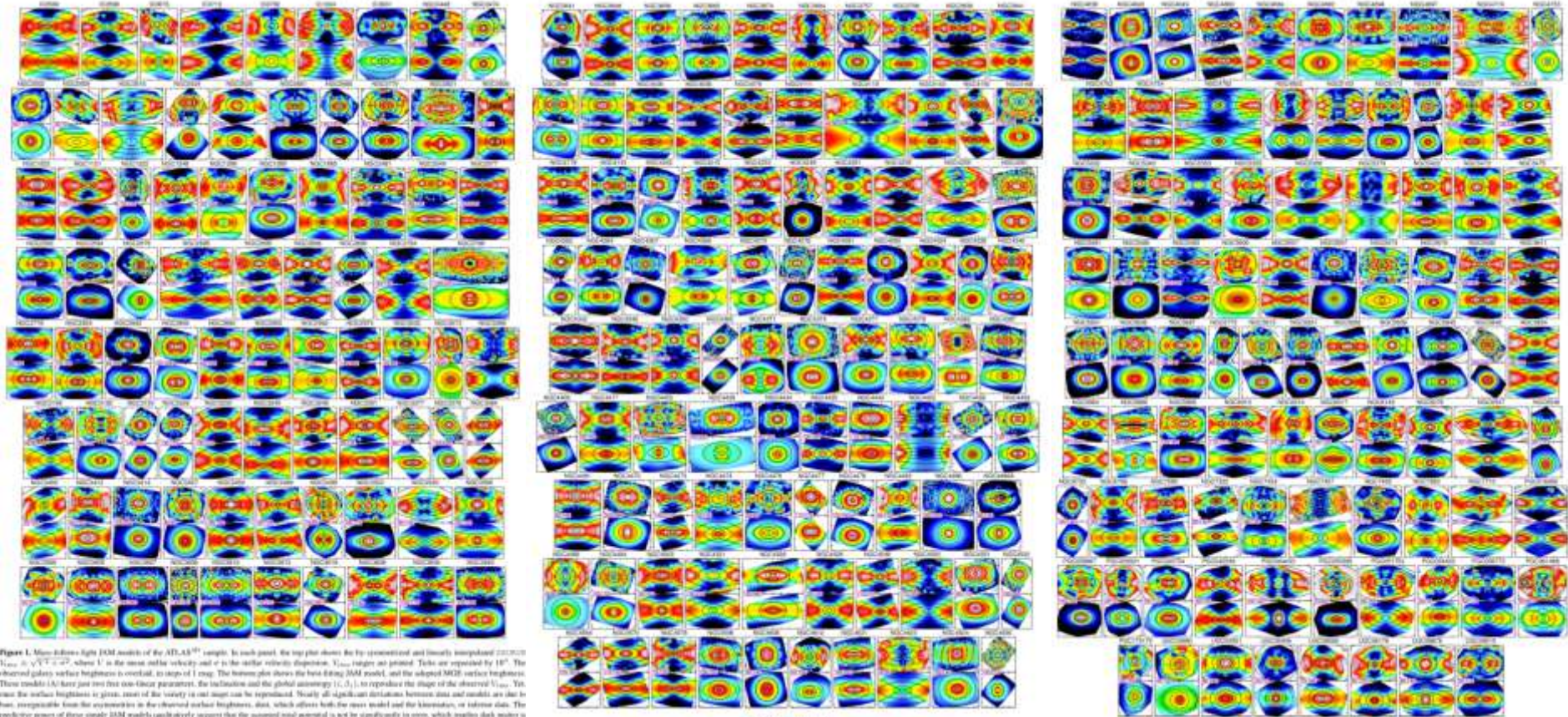


Figure 1. Mass-follows-light IJM models of the ATLAS^{3D} sample. In each panel, the top plot shows the fit (parameterized and linearly interpolated) $\rho(r, \theta, \phi) \propto \sqrt{V(r) + \sigma^2}$, where V is the most outer velocity and σ is the outer velocity dispersion. V_{max} (right axis printed) is the observed galaxy surface brightness is overlaid, in steps of 1 mag. The bottom plot shows the best-fitting IJM model, and the adopted MGE surface brightness. These models fit have just two free non-linear parameters, the inclination and the global anisotropy $(\beta, \beta_{\text{an}})$, to reproduce the shape of the observed V_{max} . Yet, since the surface brightness is given, most of the velocity is not longer can be reproduced. Usually all significant distortions between data and models are due to bias, responsible for the asymmetries in the observed surface brightness, data, which affects both the mass model and the kinematics, or intrinsic data. The predictive power of these simple IJM models qualitatively suggest that the assumed total potential is not by significantly in error, which implies dark matter is not important or accurately follows the light. The grid also show that ETGs have a simple dynamics within 1 kpc.

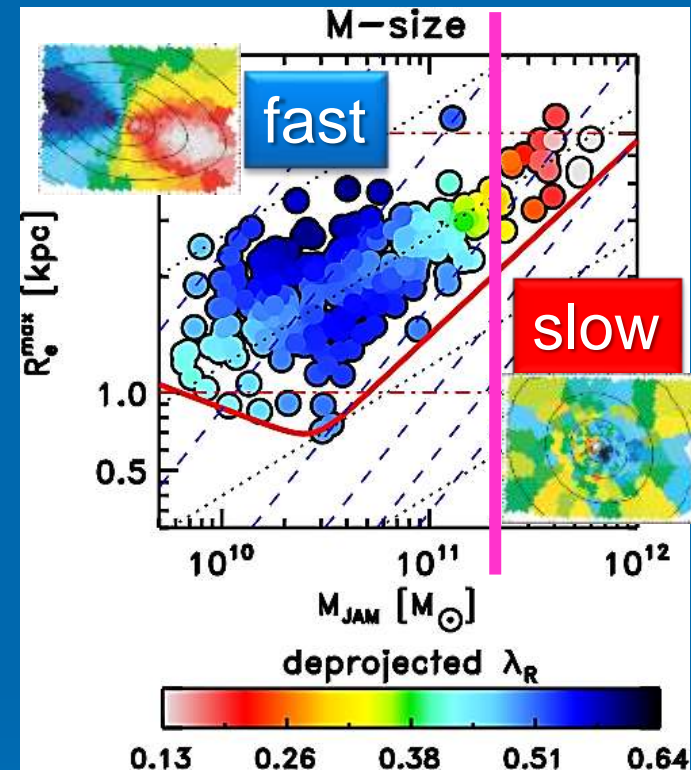
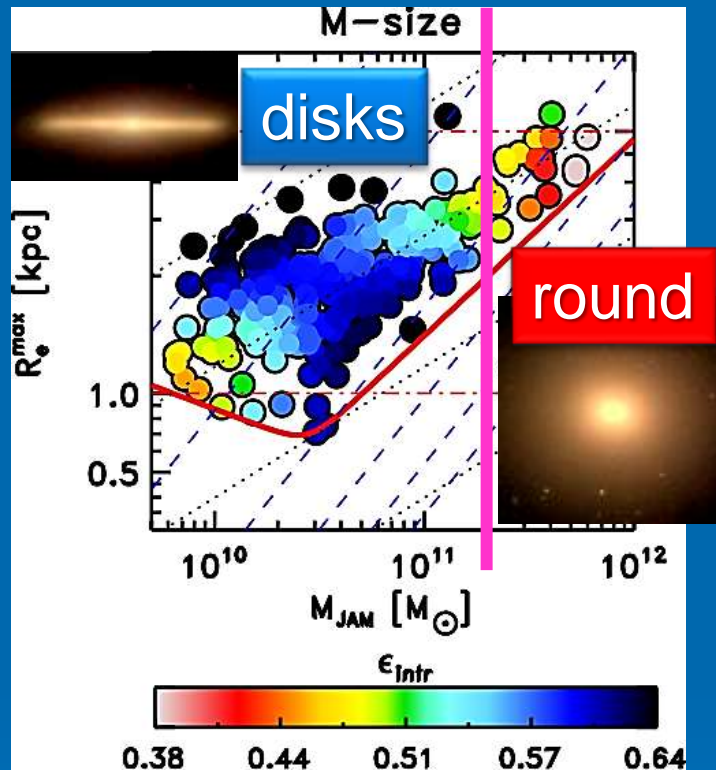
Figure 1. — continued

Figure 1. — continued

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(Cappellari+13a: P15)

Slow rotators: $M_{\star} \gtrsim 2 \times 10^{11} M_{\odot}$

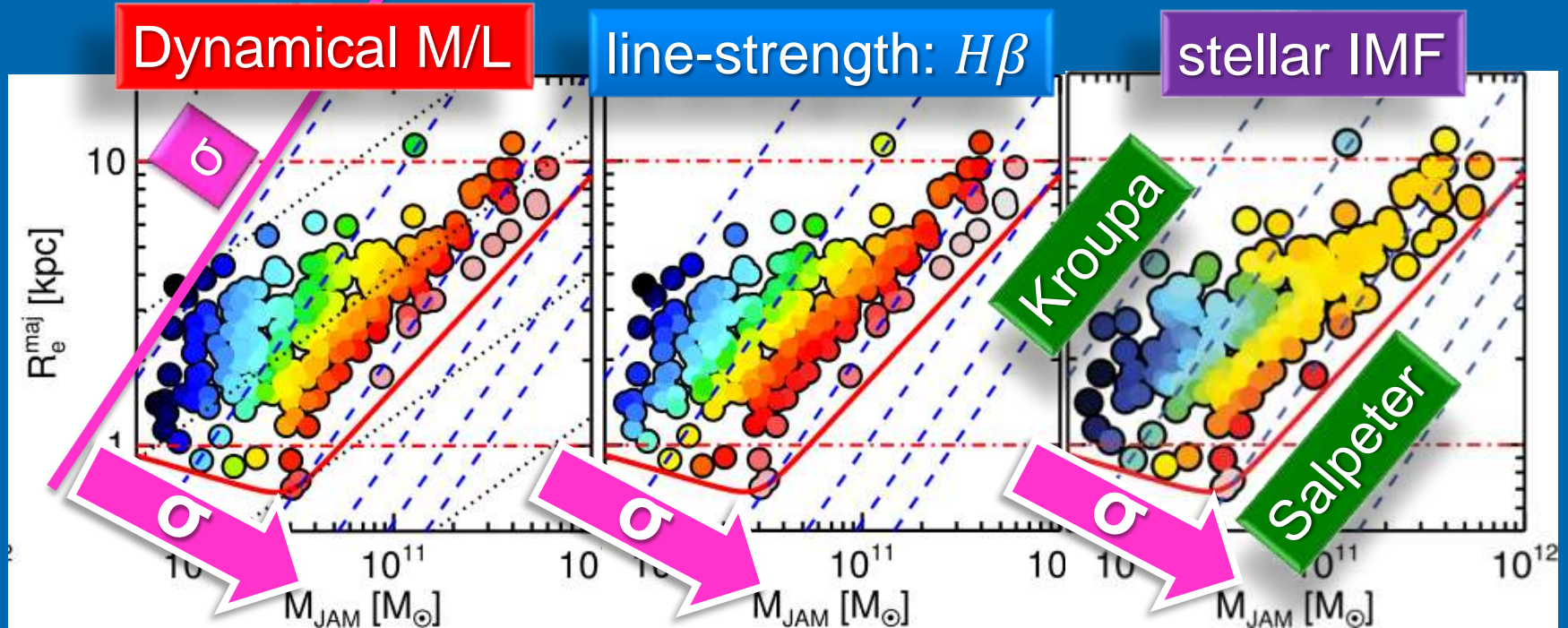


(Cappellari+13b: P20)

- Galaxy model inclination allows deprojection
- Characteristic mass $M_{\star} \approx 2 \times 10^{11} M_{\odot}$
- Separates flat/round galaxies (vanDerWel+09; Bernardi+11)
- Separates fast/slow rotators

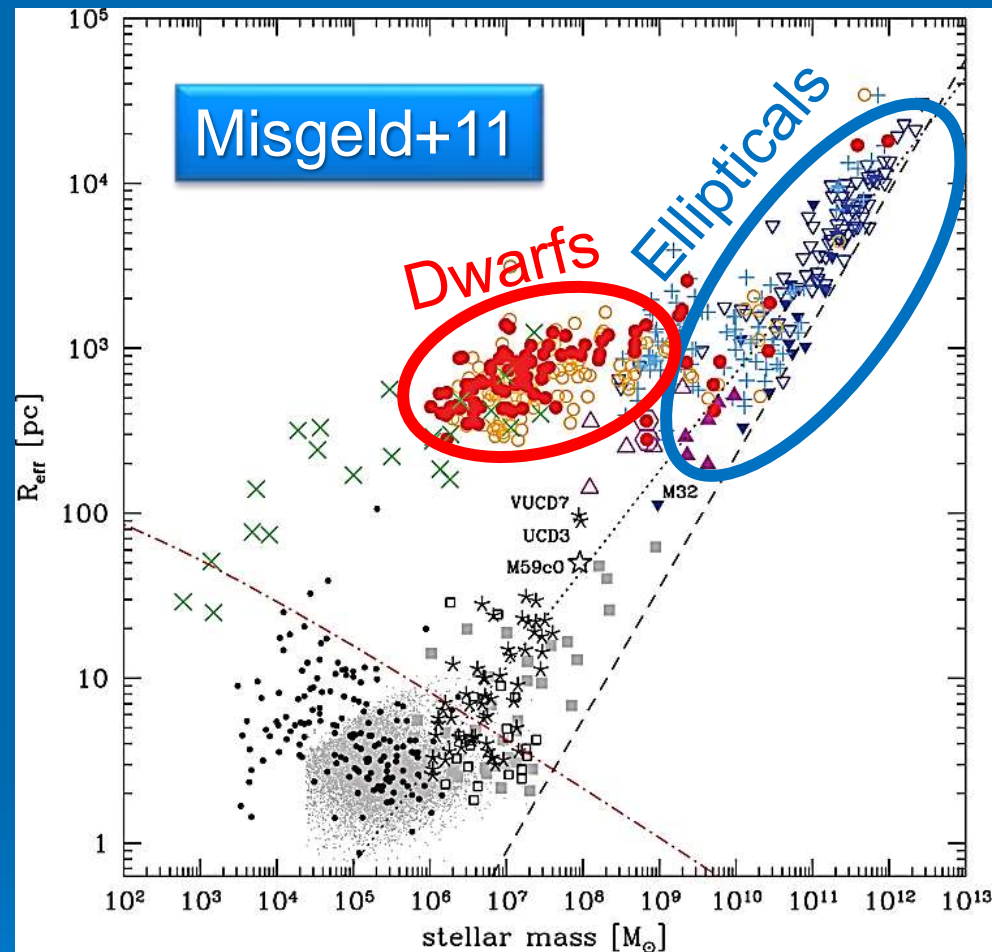
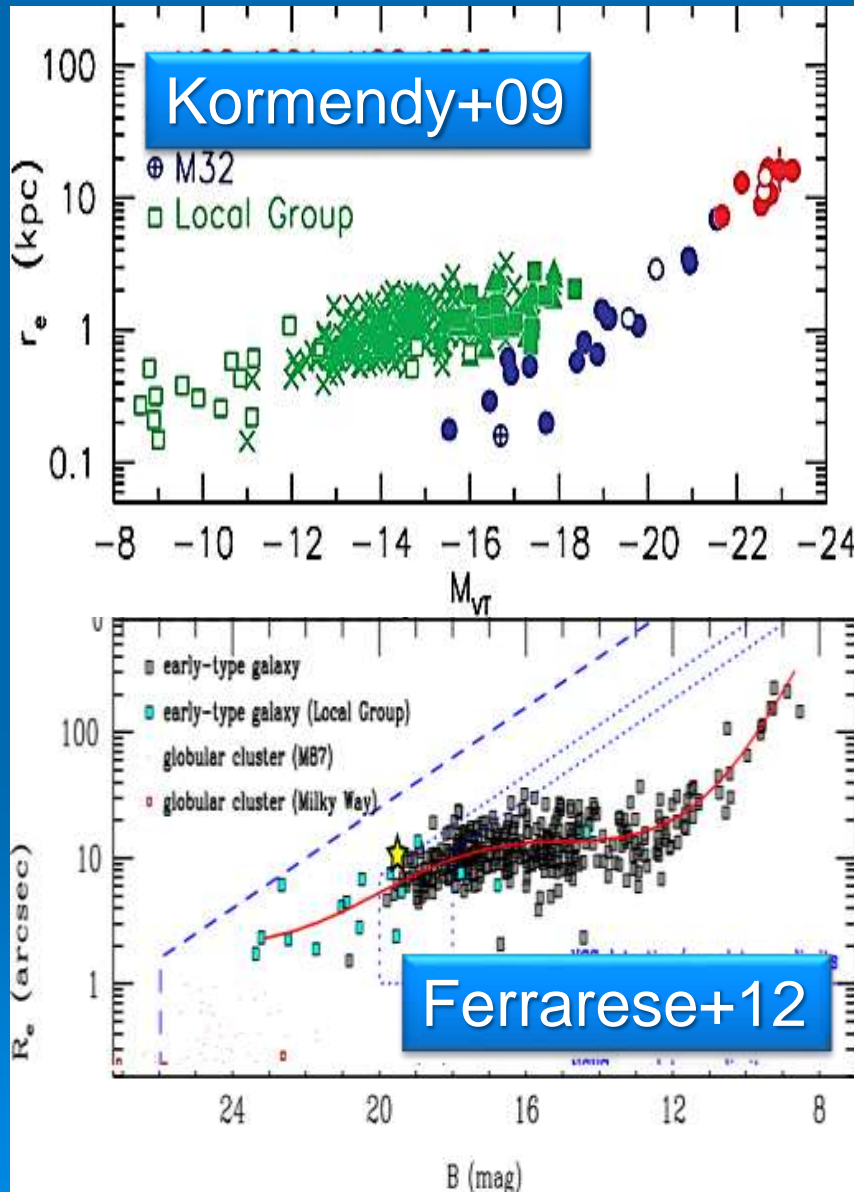
M/L, population and IMF follow σ

(Cappellari+13b P20)



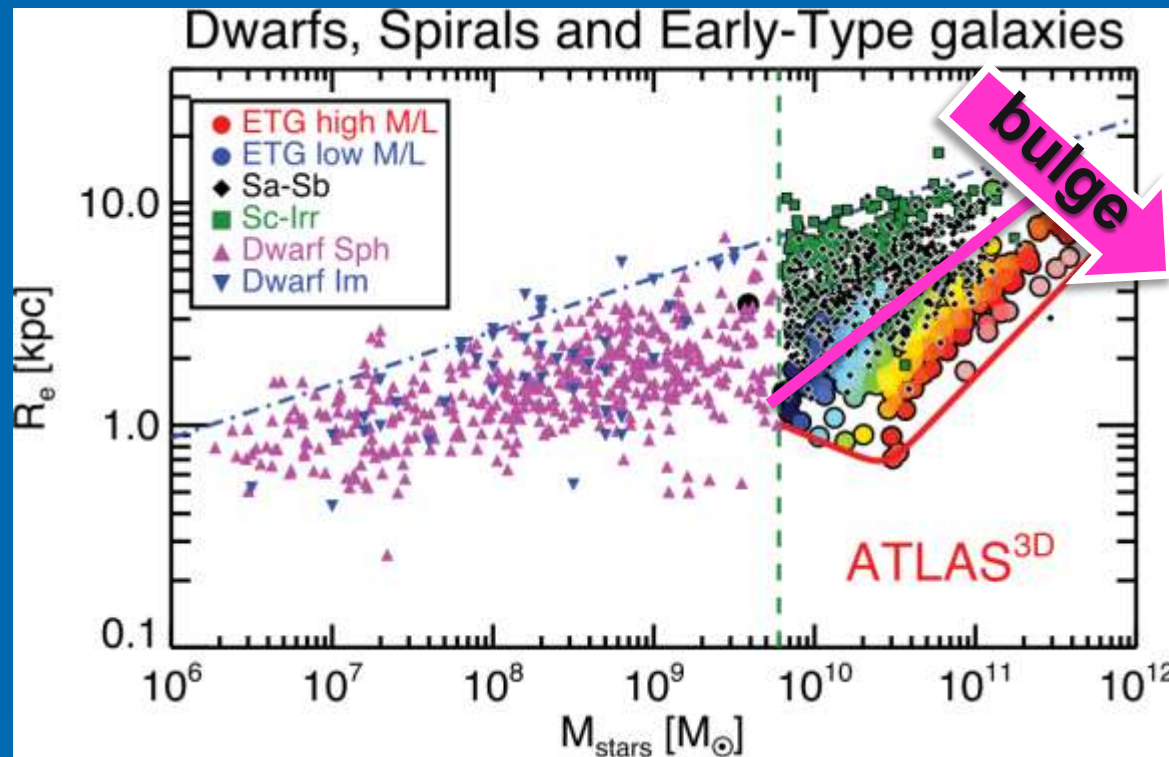
- IMF traces dynamical M/L and stellar pop.
- Variation along lines of constant σ
- IMF contributes $\frac{1}{2}$ of (M/L)- σ relation

The ellipticals – dwarfs debate



- Two sequences?
- Single S-shape trend?

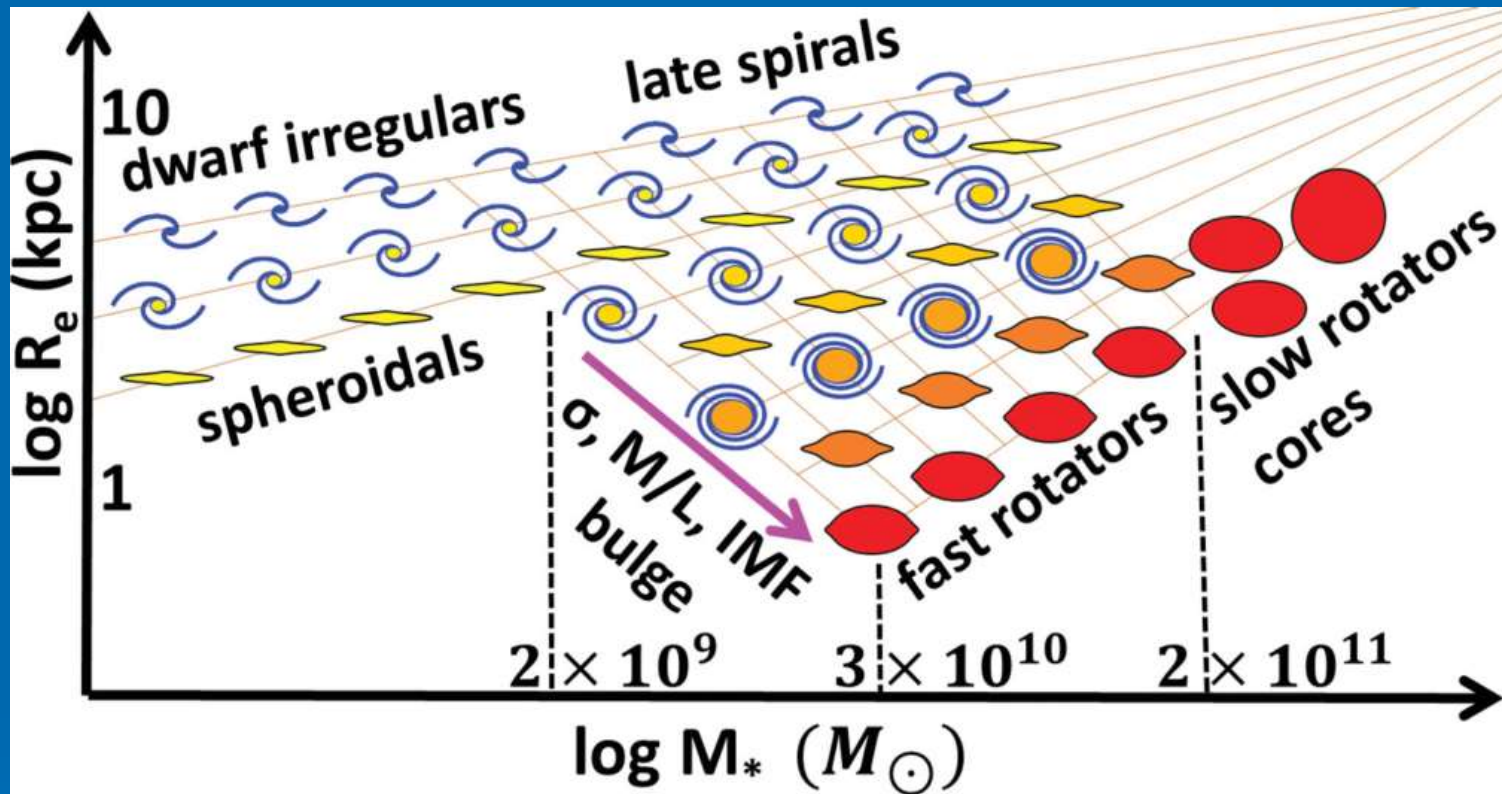
Importance of global picture



(Cappellari+13b: P20)

- Parallel sequence spirals—fast rotator
(Cappellari+11; Kormendy+Bender12)
- Galaxy properties driven by $\sigma \rightarrow$ bulge fraction
- Dwarfs naturally extend trends to lower masses

New view of legendary relations



(Cappellari+13b: P20)

- $(V/\sigma, \varepsilon)$, disky E, Kormendy rel. , Faber-Jackson, $M/L-\sigma$, color- σ , SFR-size, IMF- σ ,... all explained by plot above
- Spirals essential to understand the pictures
- 3 characteristic masses (Faber+97; Kauffmann+03; Bernardi+11)