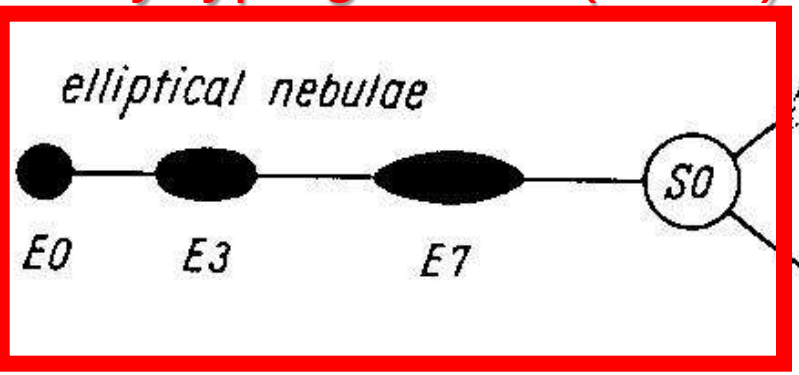
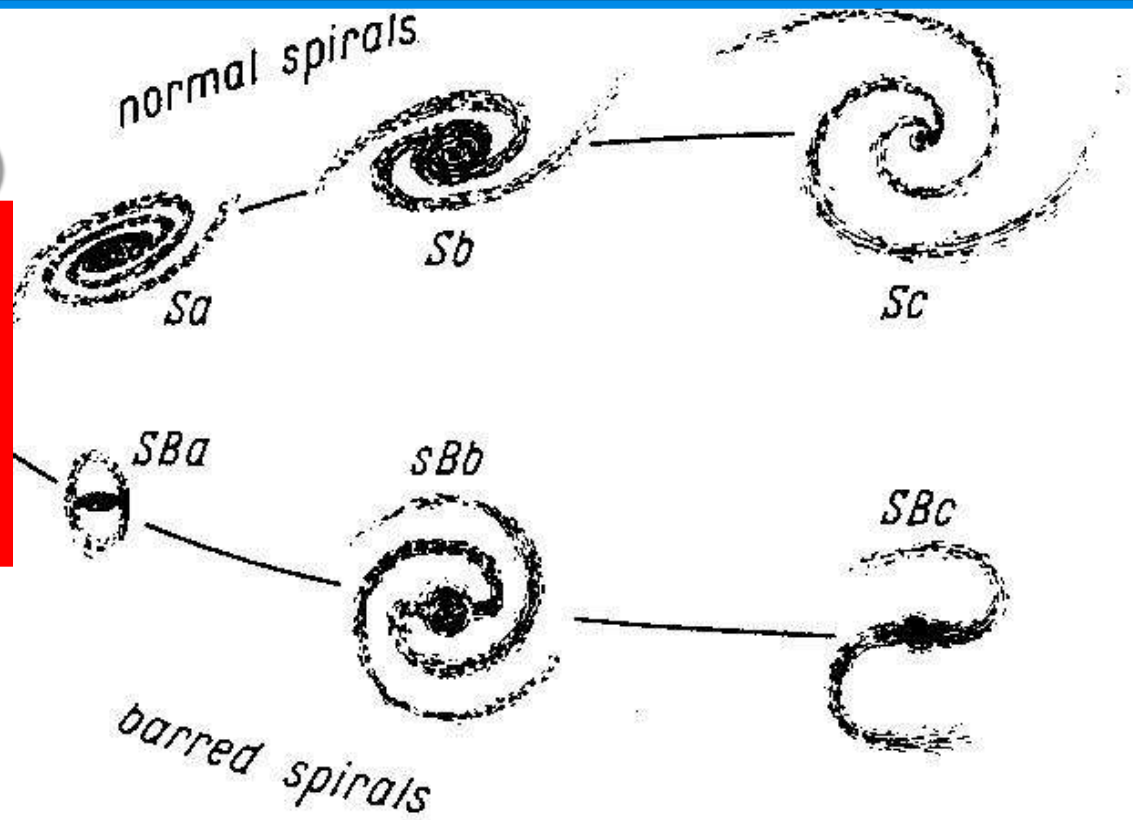
Observations and modelling of early-type galaxy dynamics

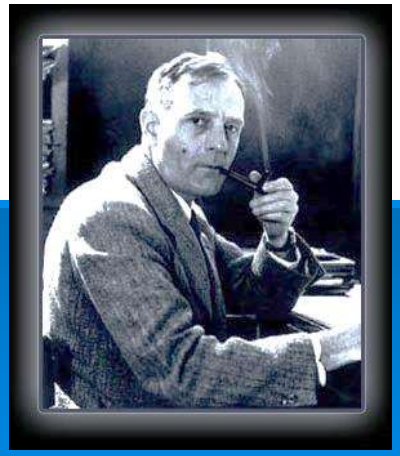
Michele Cappellari

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

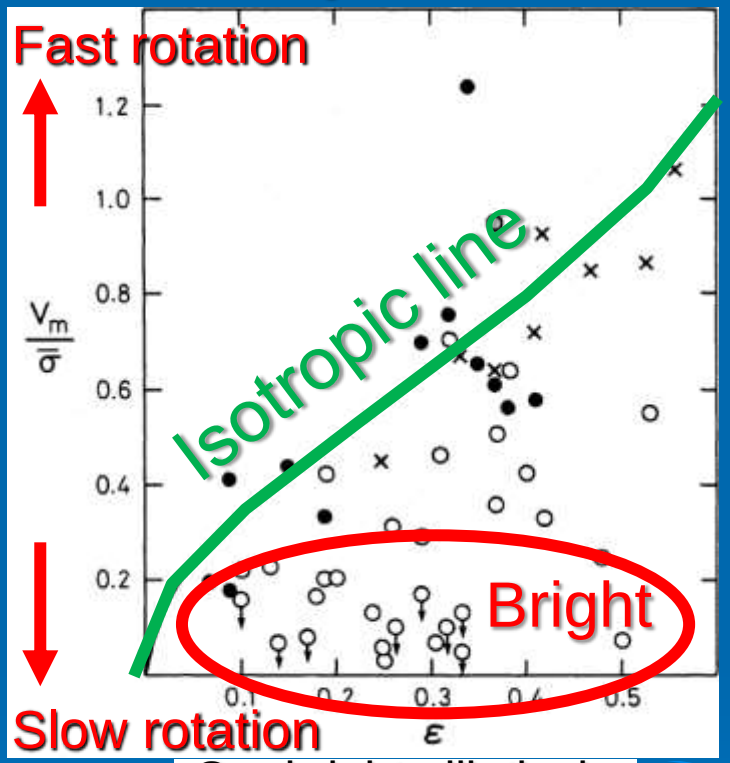
  (Bertola+Capaccioli75; Illingworth77; Binney78)

- Result of major disk mergers

  (Toomre+Toomre72; Barnes+Hernquist96)

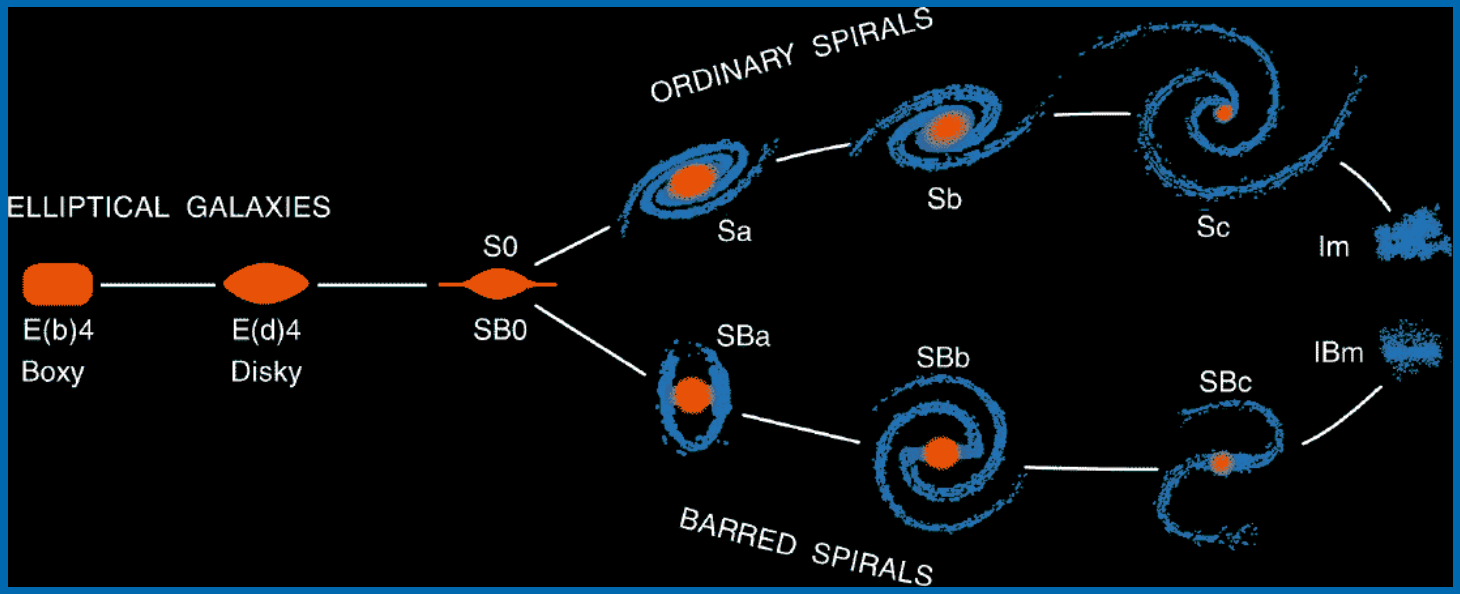
- Faint ellipticals rotate fast: isotropic

  (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)

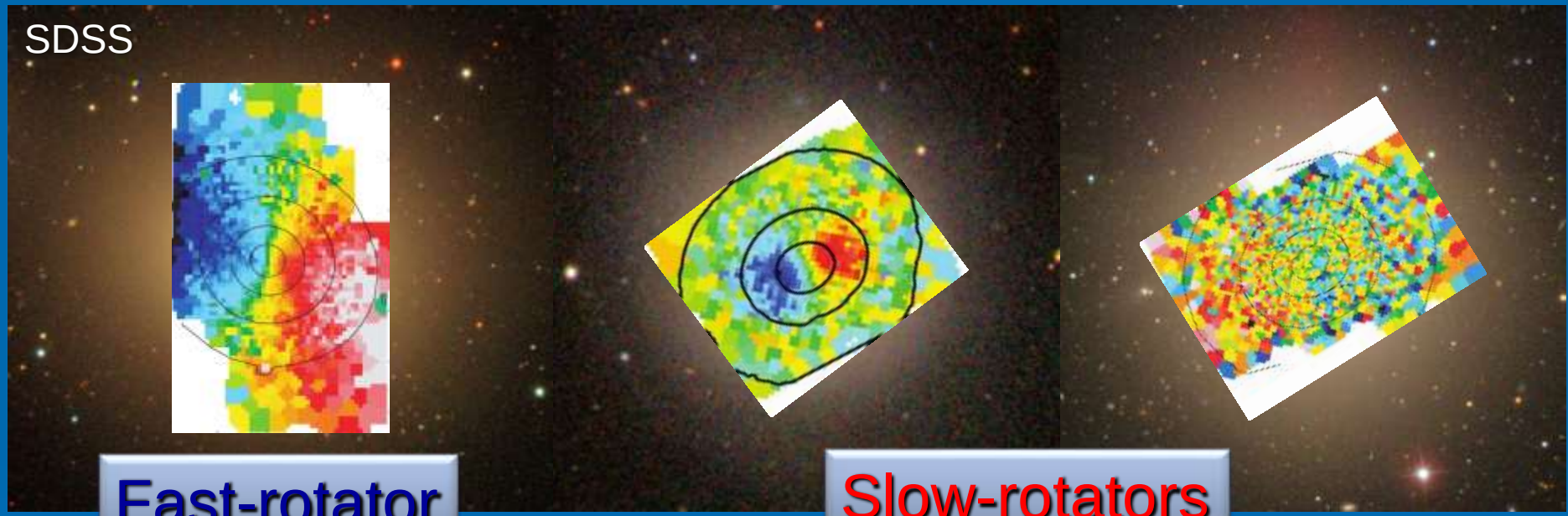
- Disky ellipticals: transition between bright E and S0

  (Kormendy+Bender96)

Limits of photometric classification

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

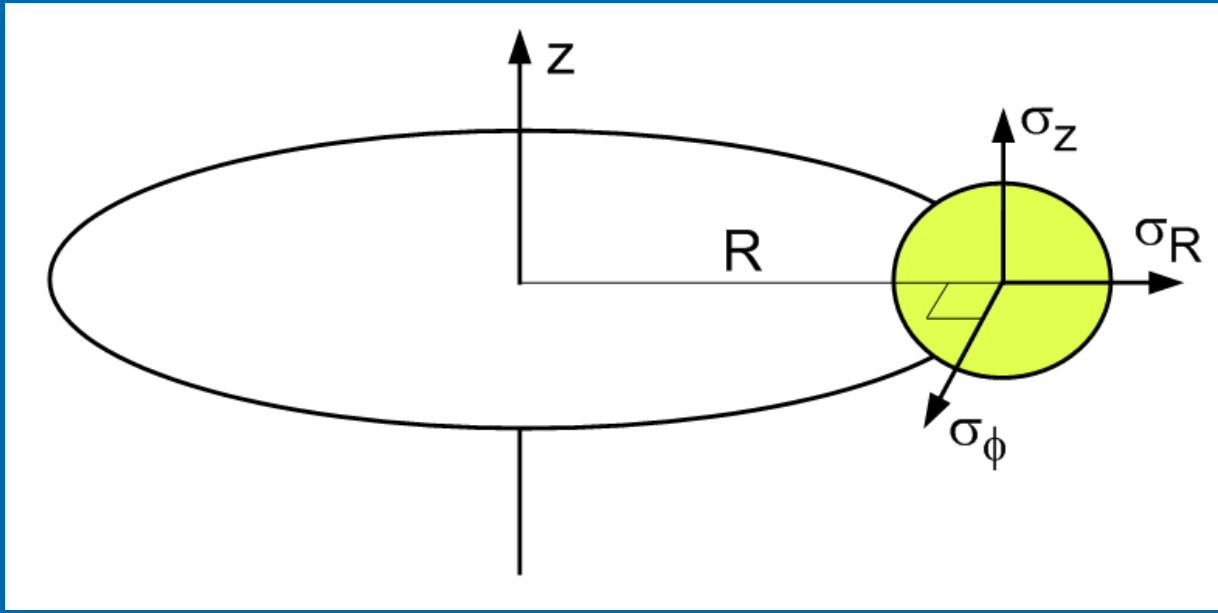
NGC3379 (E1) NGC5631 (S0) NGC4374 (E1)



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

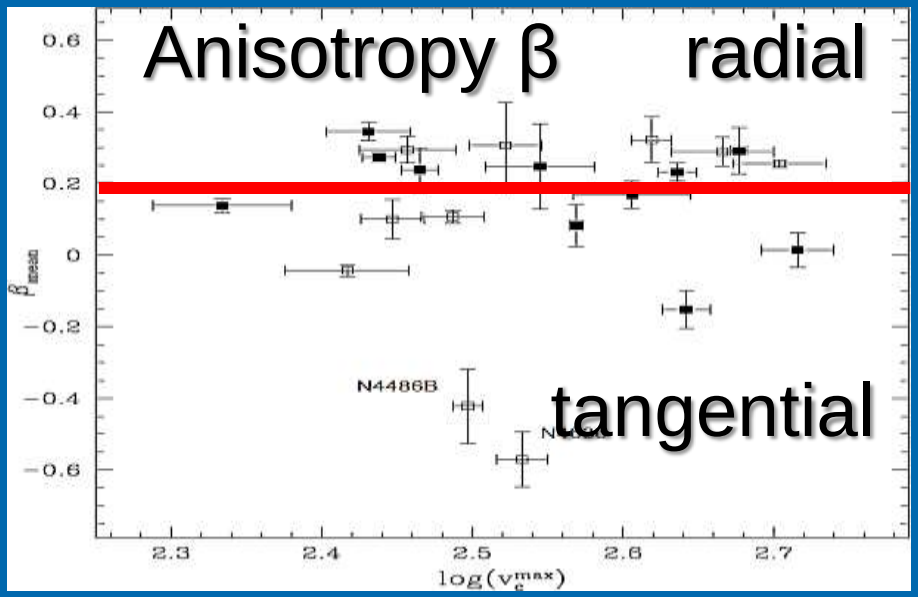
(Emsellem+07; Cappellari+07)

Anisotropy and velocity ellipsoid

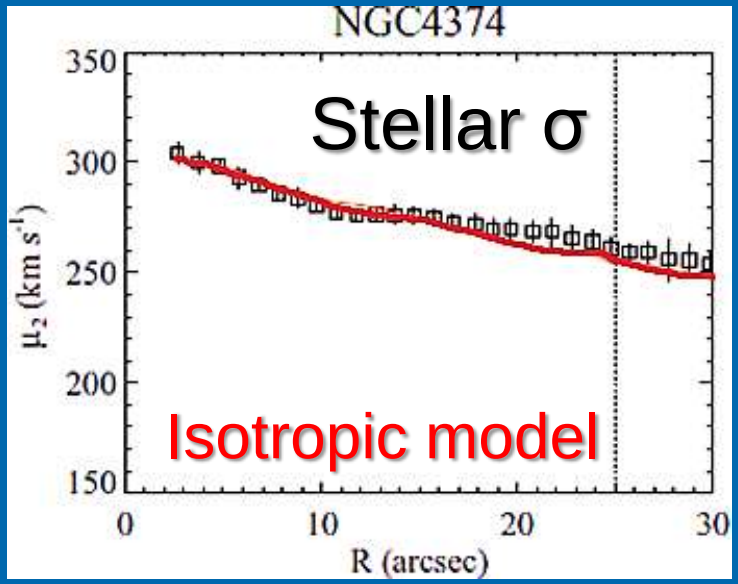


- $\beta = 1 - \frac{\sigma_z^2}{\sigma_R^2}; \gamma = 1 - \frac{\sigma_\phi^2}{\sigma_R^2}; \delta = 1 - \frac{2\sigma_z^2}{\sigma_R^2 + \sigma_\phi^2}$ (Cappellari+07)
- δ is measured by the (V/σ,ε) diagram (Binney78,05)
- β, γ require dynamical models
- $\sigma_R = \sigma_\phi \rightarrow (\delta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

Bright slow rotators isotropic!



(Gerhard+01)



(Cappellari+07)

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

Faint fast rotators anisotropic!

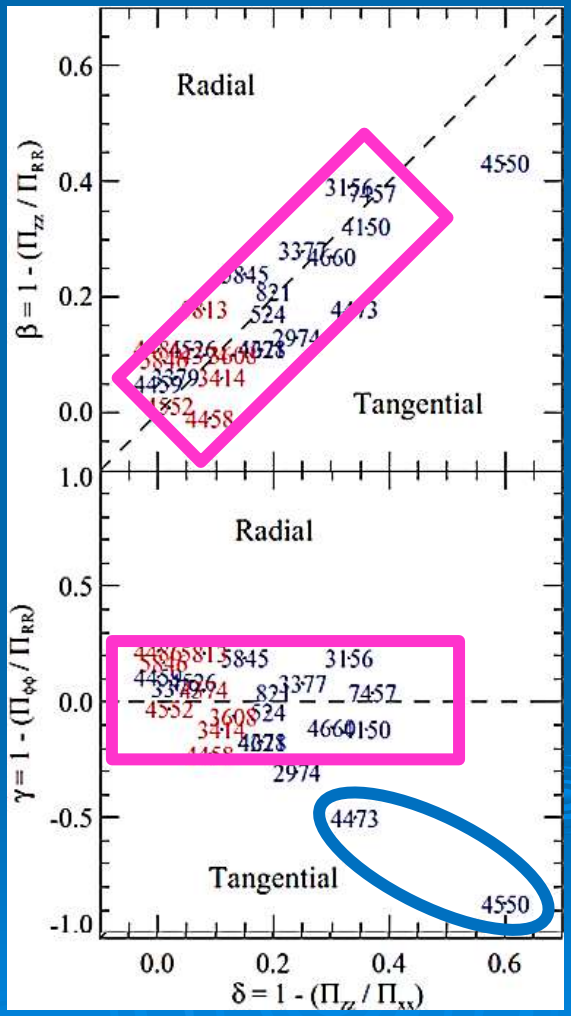
- SAURON integral-field data
- Schwarzschild's axisymmetric models
- 24 galaxies (Cappellari+07)

→ $\delta \approx \beta \; and \; \gamma \approx 0$

(2 important exceptions)

→ Oblate velocity ellipsoid!

- Independently confirmed in Coma cluster (Thomas+09)

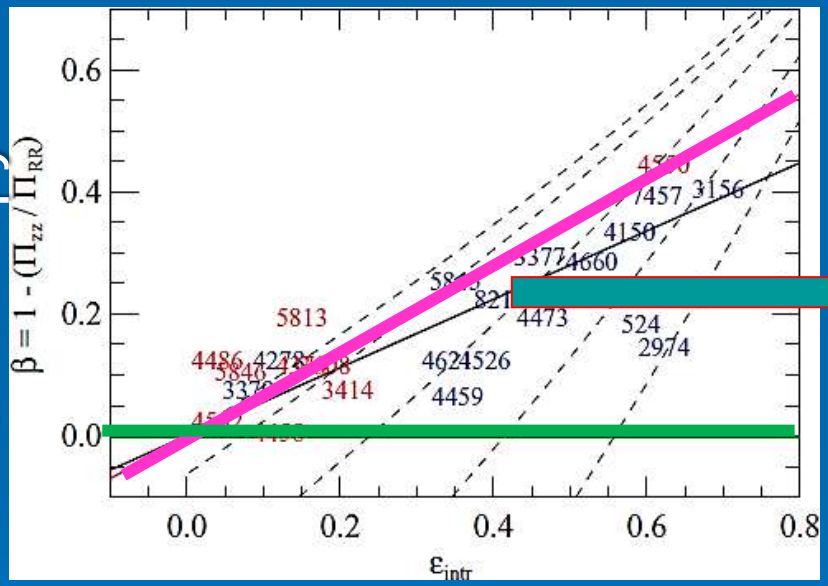


(Cappellari+07)

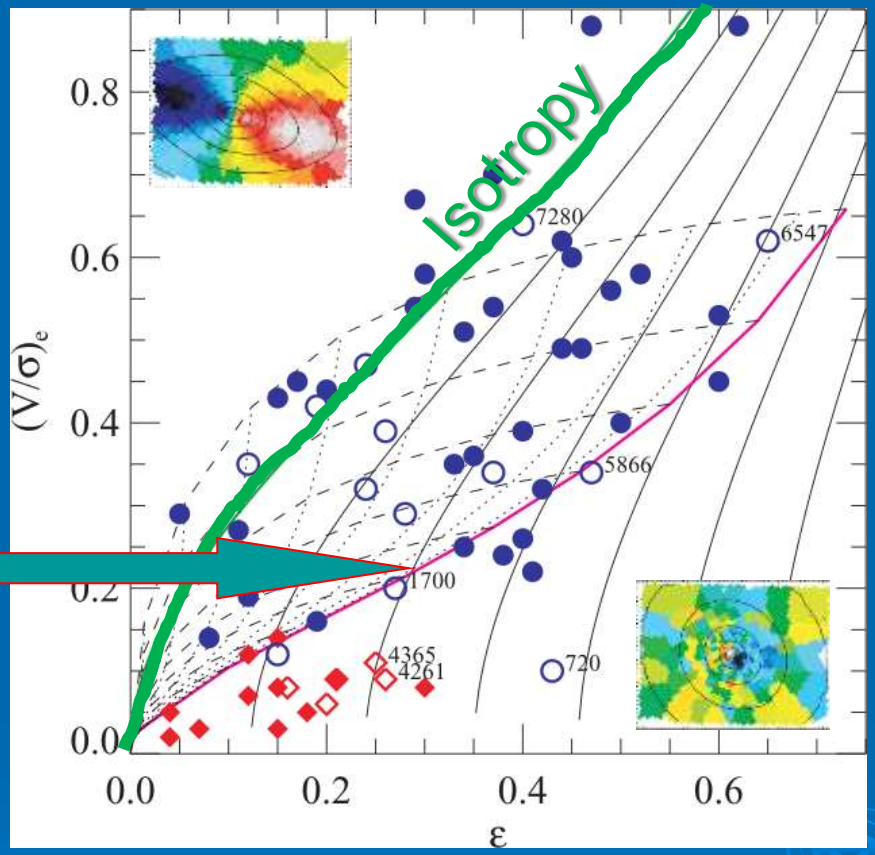
Revisiting the (V/σ,ε) diagram

Use integral-field kinematics

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



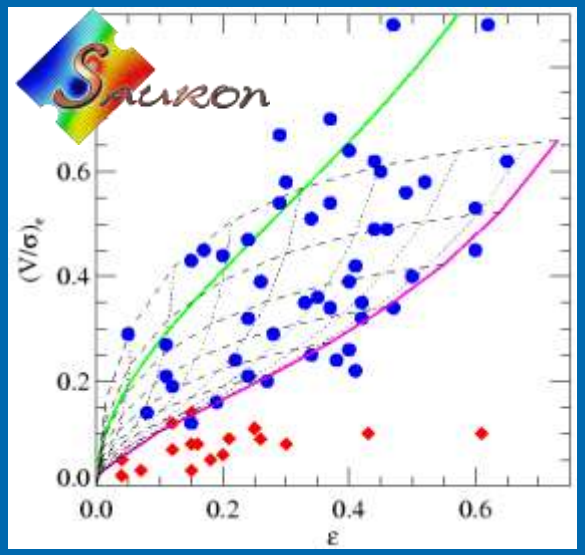
24 models



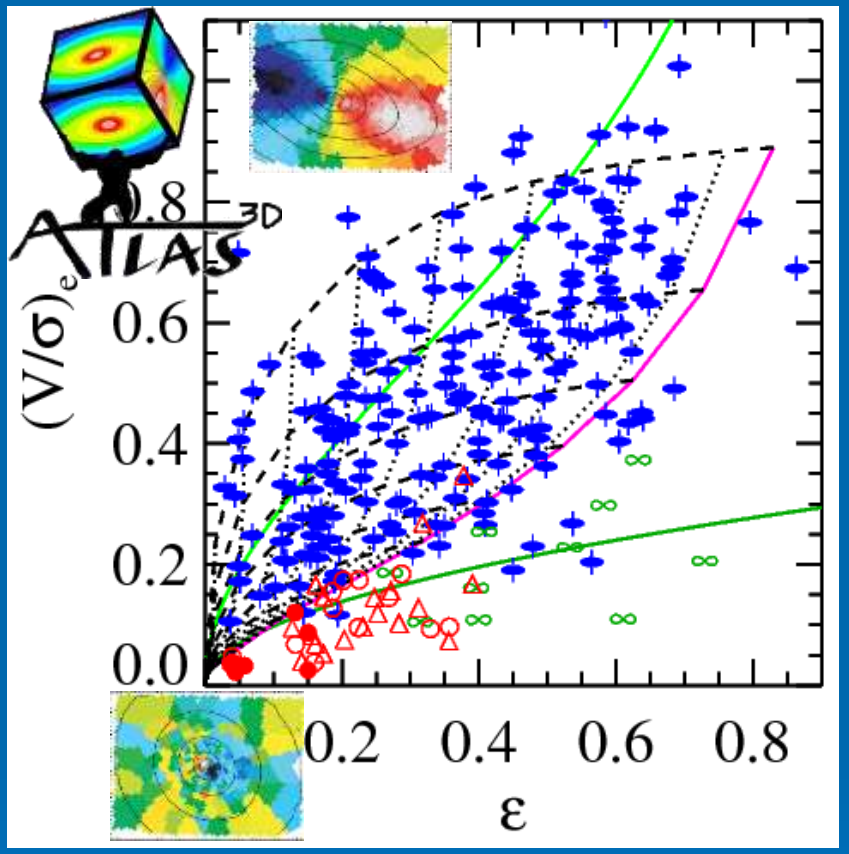
Entire sample (Cappellari+07)

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

From SAURON to ATLAS^{3D}



(Cappellari+07)

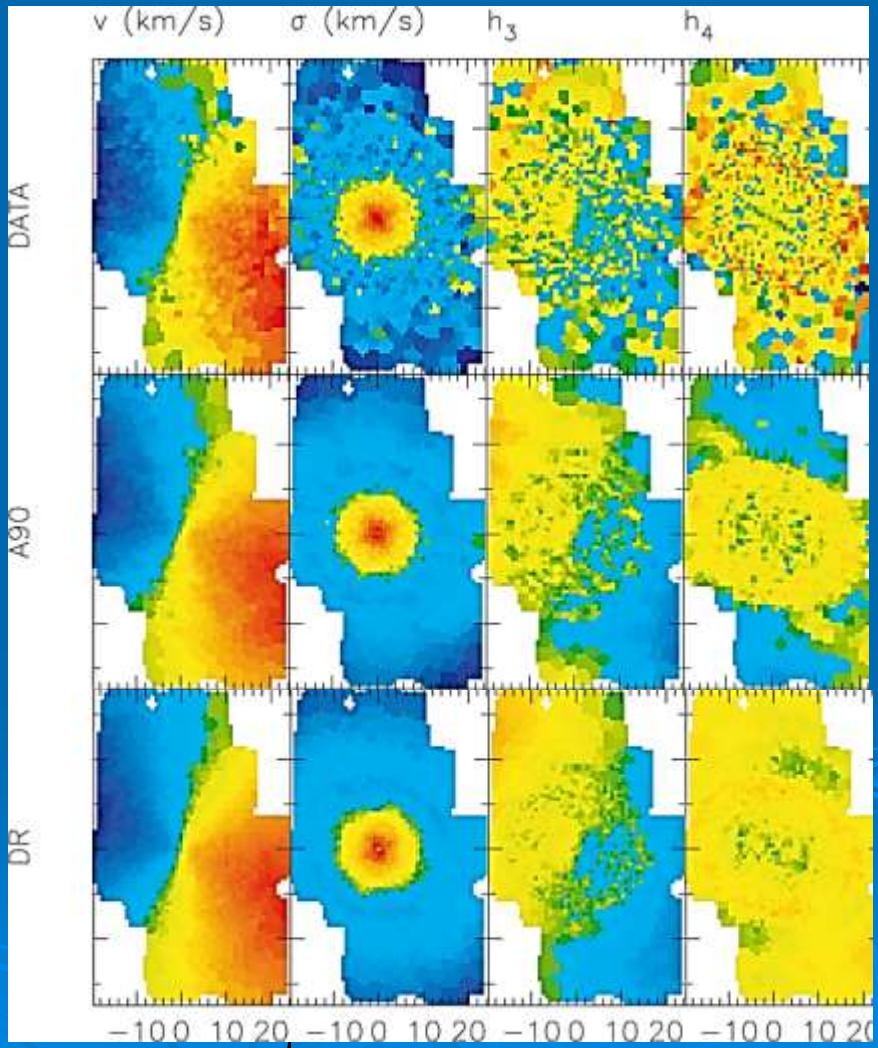


(Emsellem+11)

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

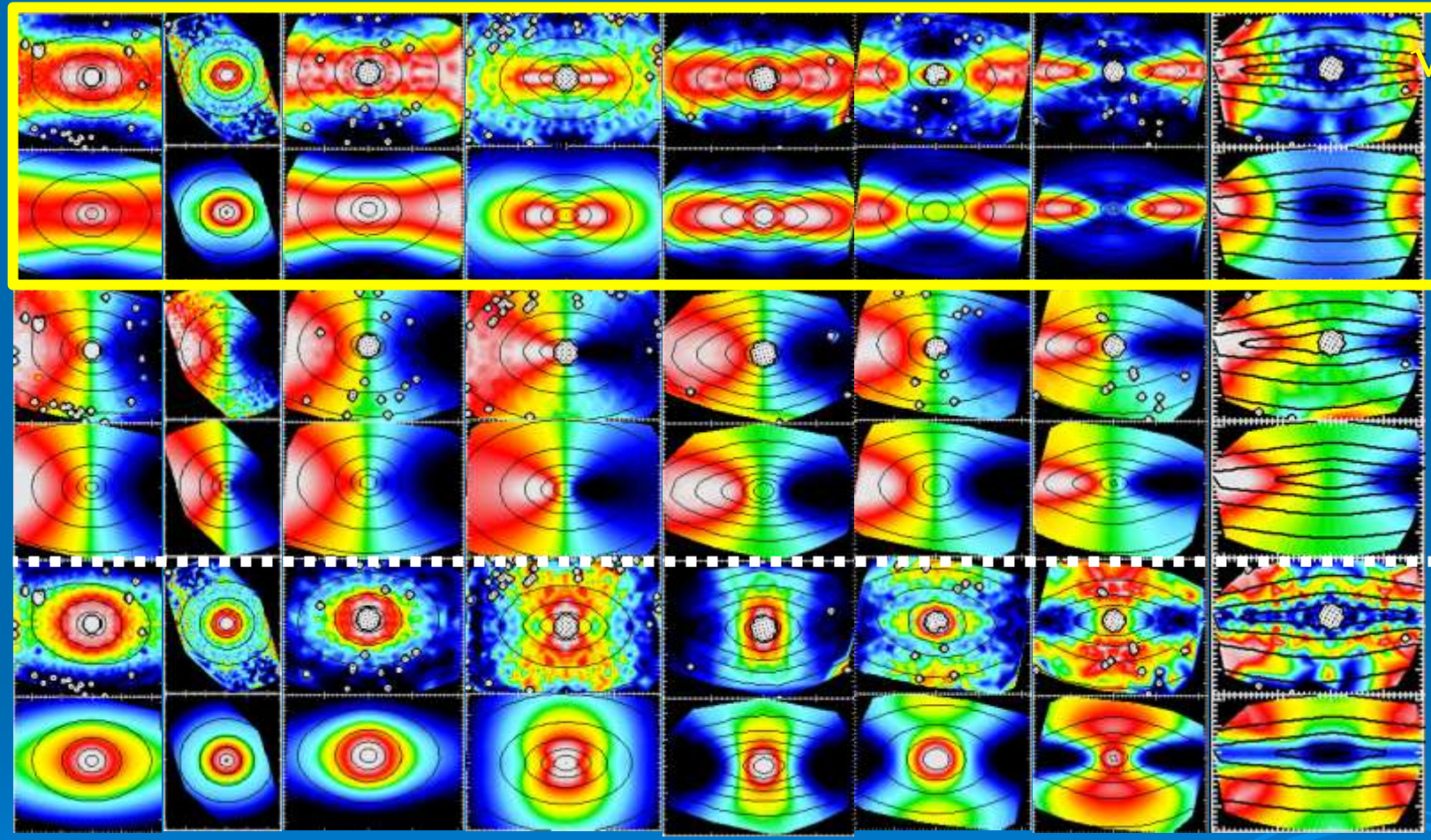
Dynamical degeneracy

- 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)

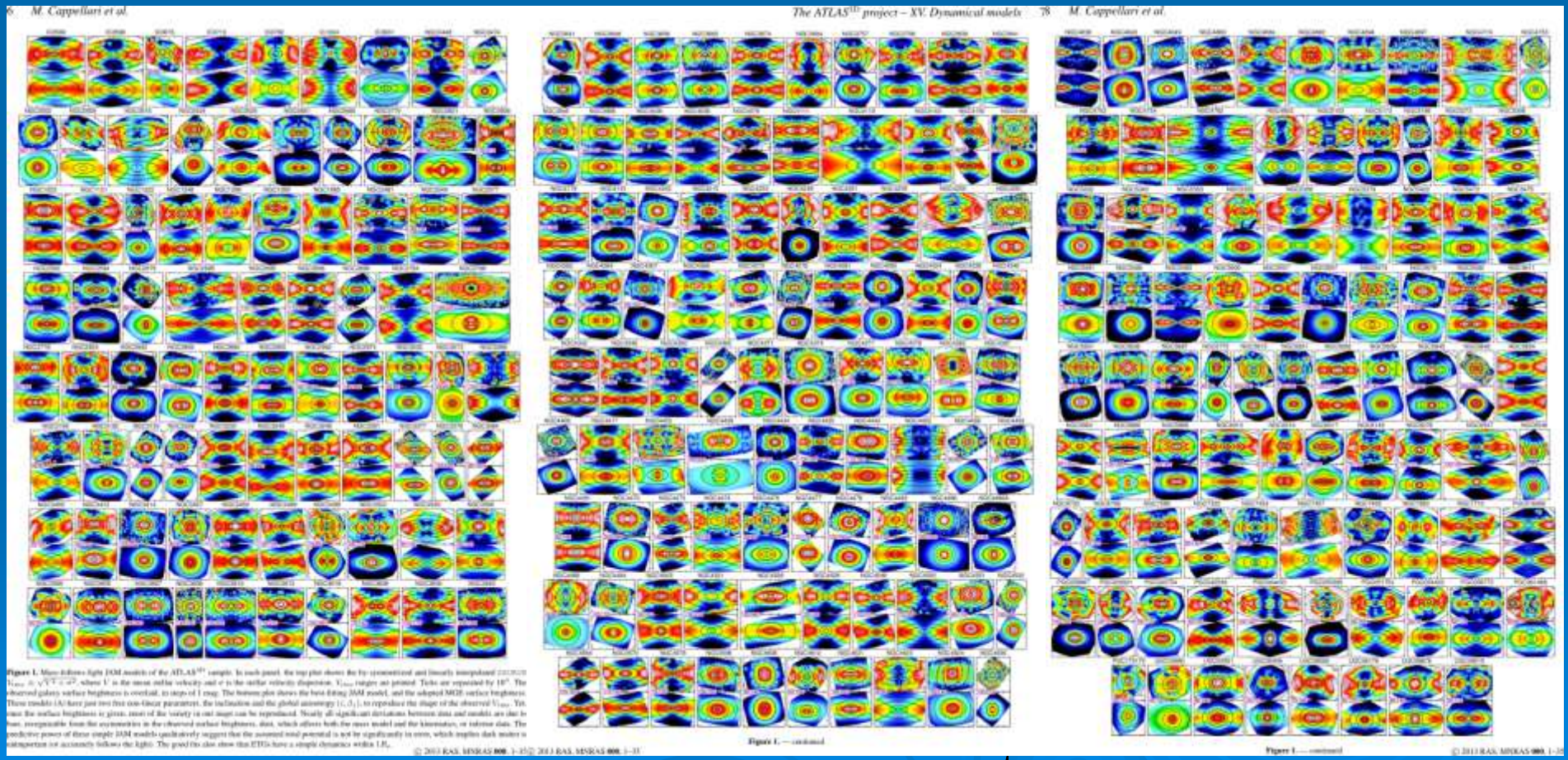
Oblate velocity ellipsoid models



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

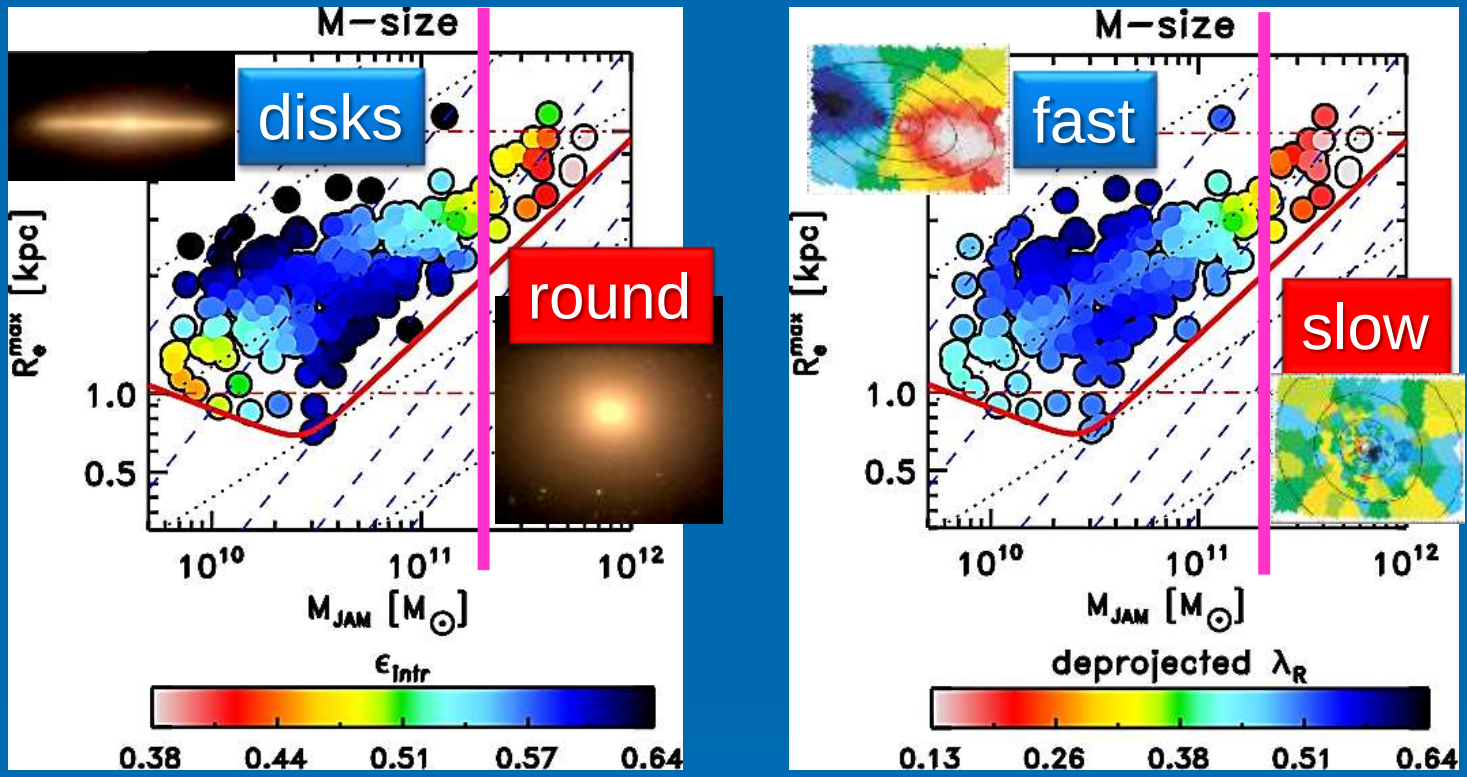
260 dynamical models

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



(Cappellari+13a: P15)

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

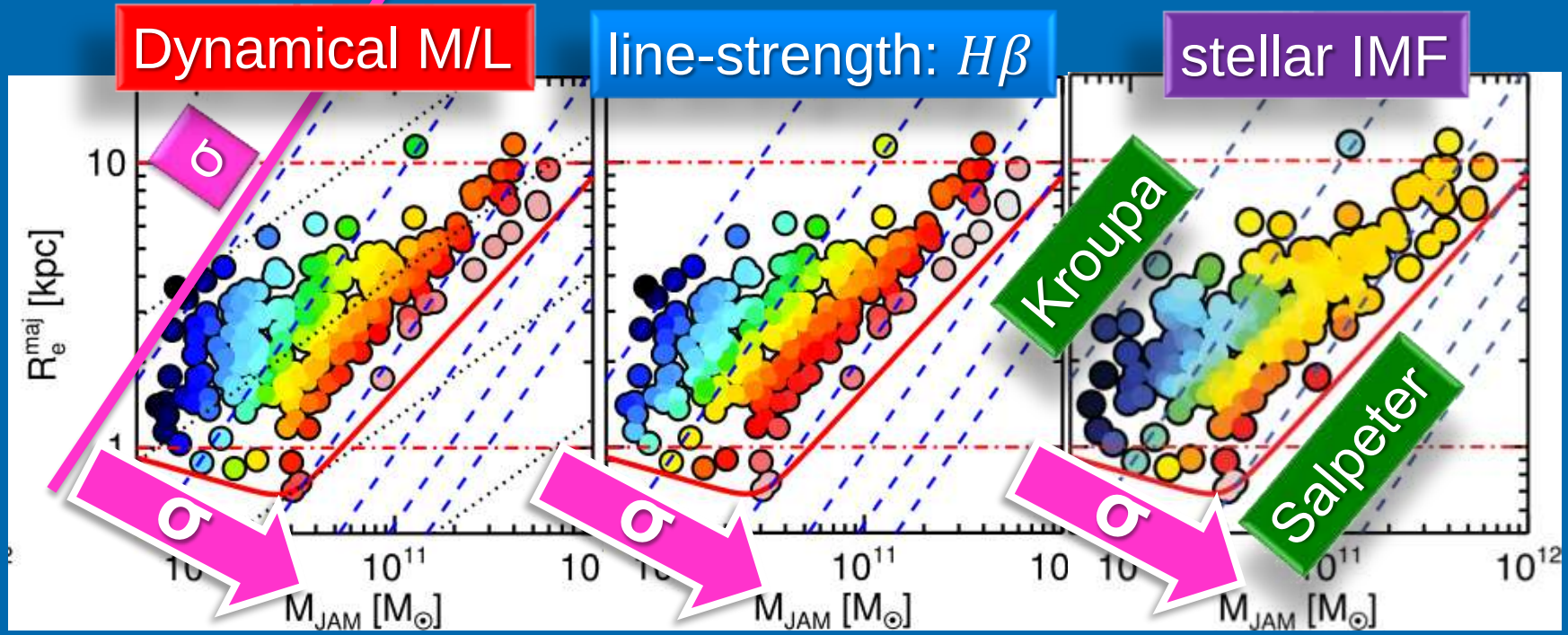


(Cappellari+13b: P20)

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

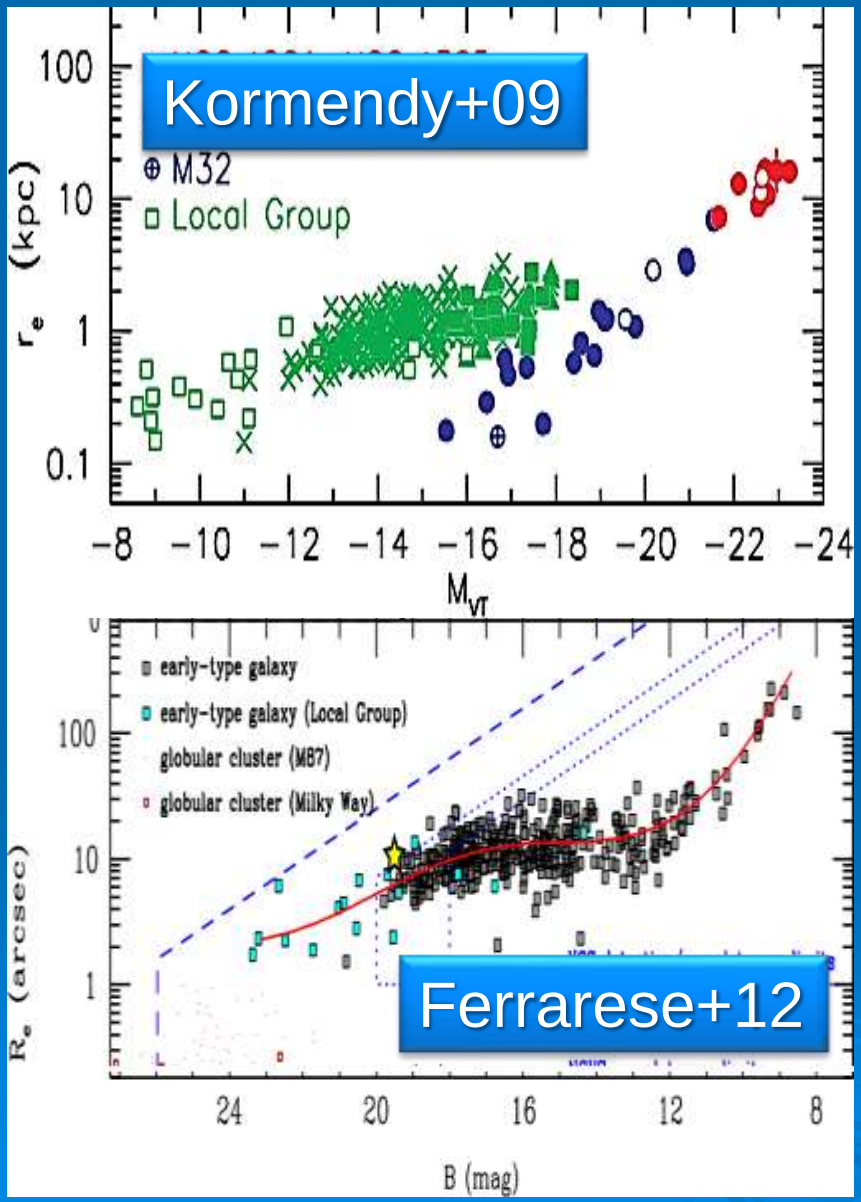
M/L, population and IMF follow σ

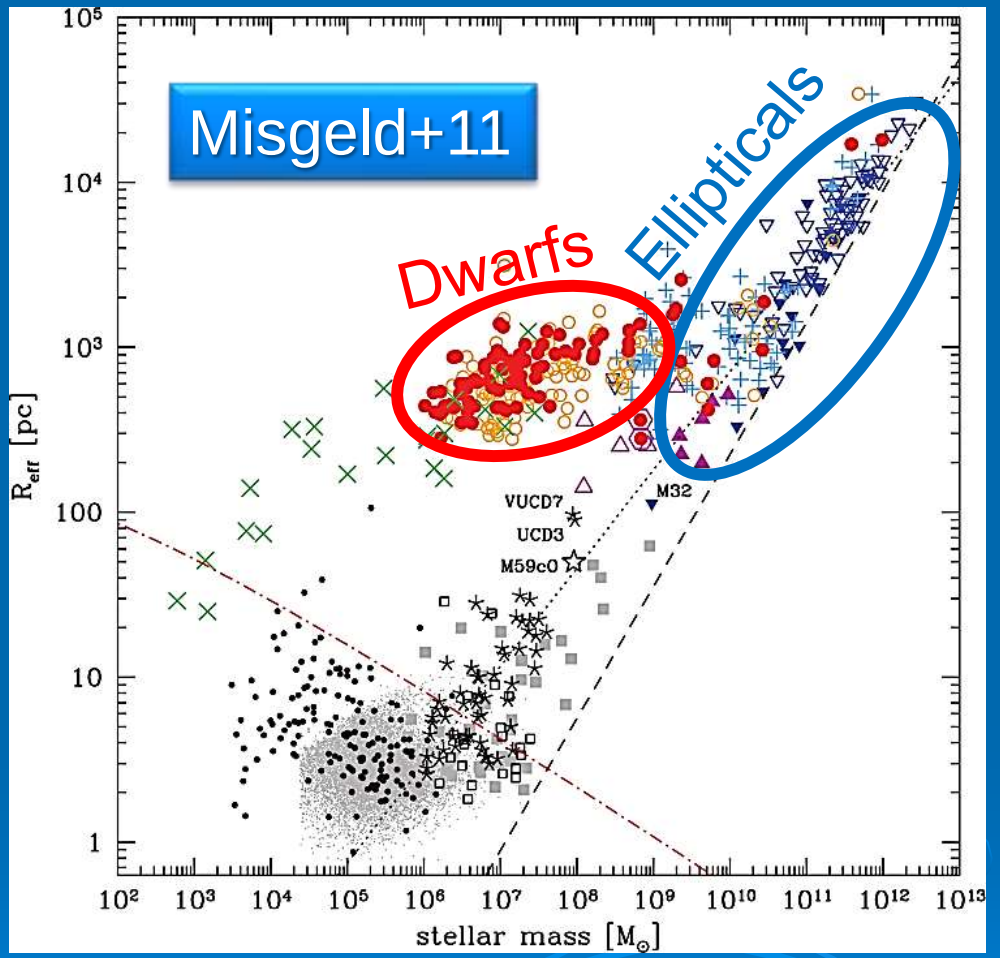
(Cappellari+13b P20)



- IMF traces dynamical M/L and stellar pop.
- Variation along lines of constant σ
- IMF contributes ½ of (M/L)-σ relation

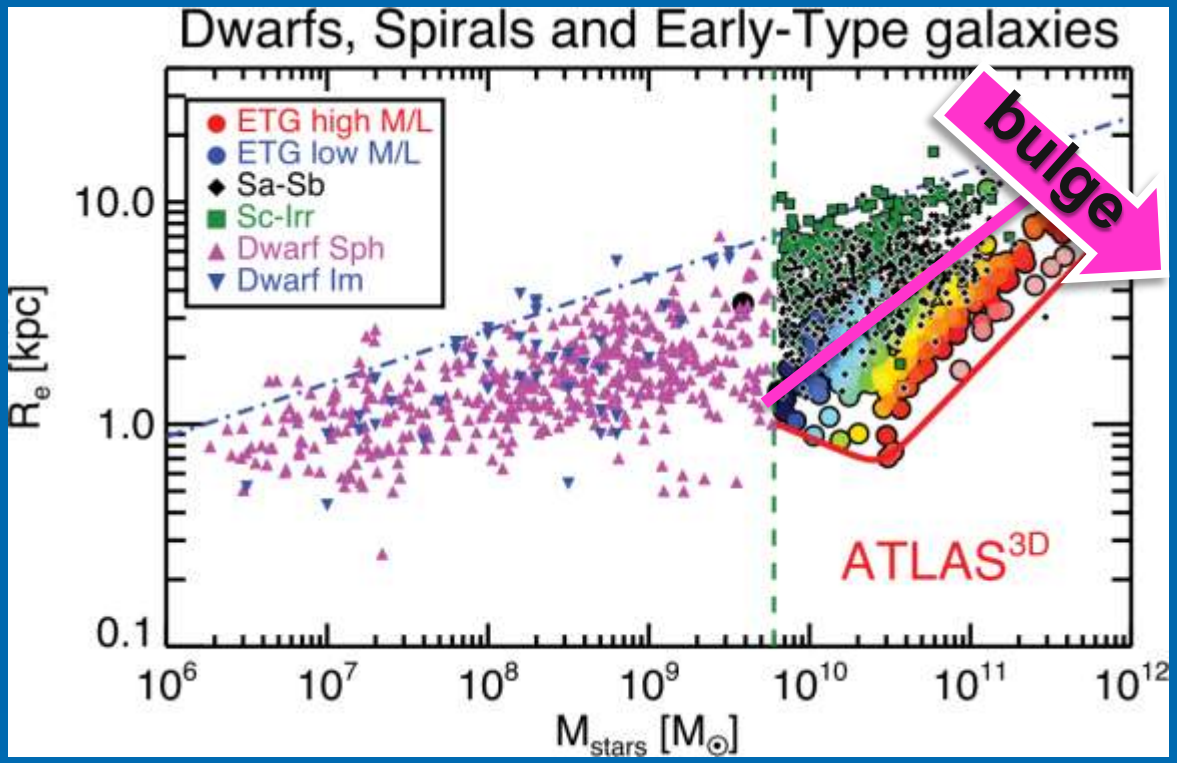
The ellipticals – dwarfs debate





- Two sequences?
- Single S-shape trend?

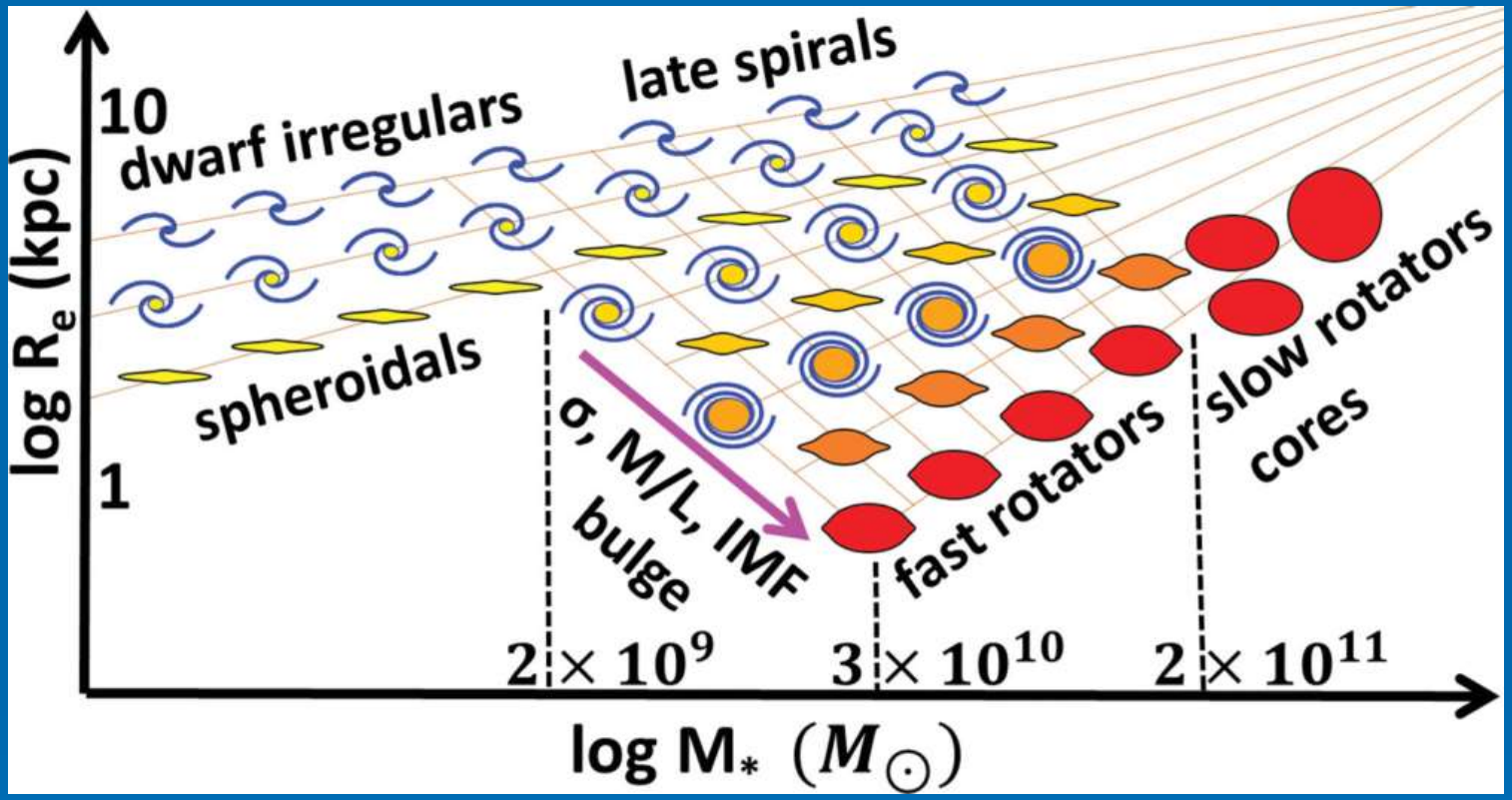
Importance of global picture



(Cappellari+13b: P20)

- Parallel sequence spirals–fast rotator
  (Cappellari+11; Kormendy+Bender12)
- Galaxy properties driven by σ → 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-σ, 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)