Elliptical Galaxies Scaling Relations

Dylan Gavron and Jacqueline Beran

Overview

Paper 1: "The ATLAS3D project – VII. A new look at the morphology of nearby galaxies: the kinematic morphology–density relation" (Cappellari et al. 2011)

- *Revision of Hubble Tuning Fork*
- *Morphology-Environmental Density Relation*

Paper 2: "The ATLAS3D project – XV. Benchmark for early-type galaxies scaling relations from 260 dynamical models: mass-to-light ratio, dark matter, Fundamental Plane and Mass Plane" (Cappellari et al. 2013)

- *Fundamental plane*
- *Scaling relations*

Paper 1: Core Ideas

- Revision to Hubble diagram using kinematic classification scheme

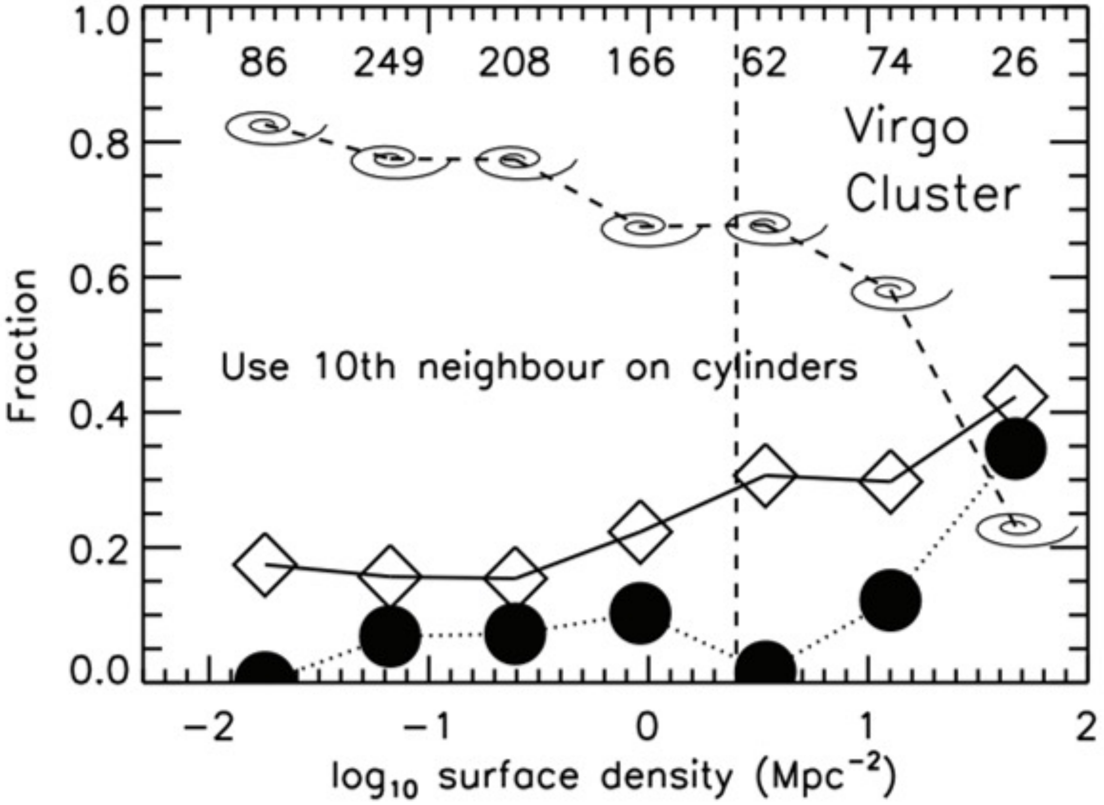
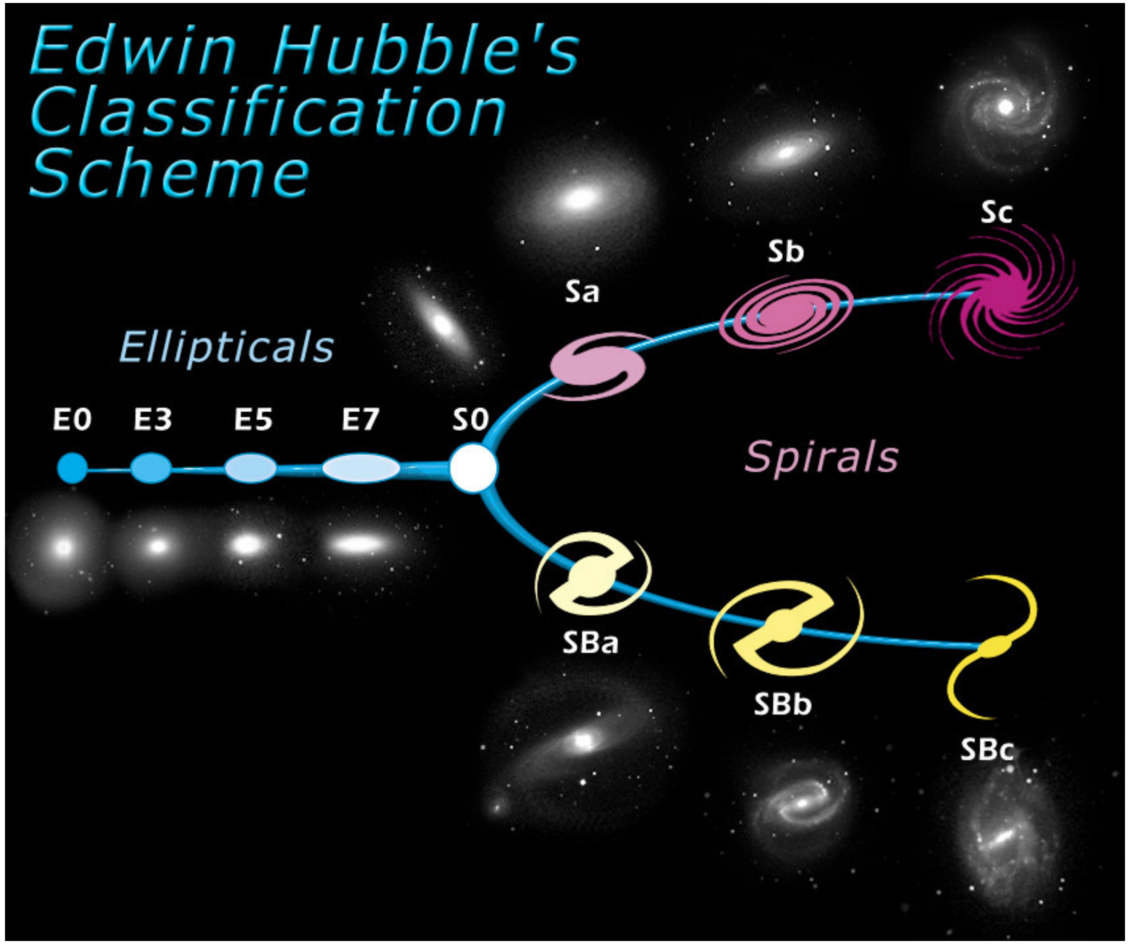


Figure 9. Morphology versus density for elliptical (black filled circles), lenticular (open diamonds) and spiral galaxies (spirals), versus the local surface density Σ_{10}. The numbers above the symbols represent the number of galaxies included in each of the seven density bins.

Cappellari 2011



ESA

Kinematic Classification scheme

$$\lambda_R \equiv \frac{\langle R\,|V|\,\rangle}{\langle R\,\sqrt{V^2 + \sigma^2}\rangle} = \frac{\sum_{n=1}^{N} F_n\, Rn\, |Vn|}{\sum_{n=1}^{N} F_n\, Rn\sqrt{V^2 + \sigma^2}}$$

- F_n is the flux in the nth Voronoi bin
- V_n is the measured line-of-sight mean stellar velocity
- σ_n the velocity dispersion

Slow rotators ⟶ $\lambda_R\,(\mathrm{Re}) < 0.31\sqrt{\epsilon}$

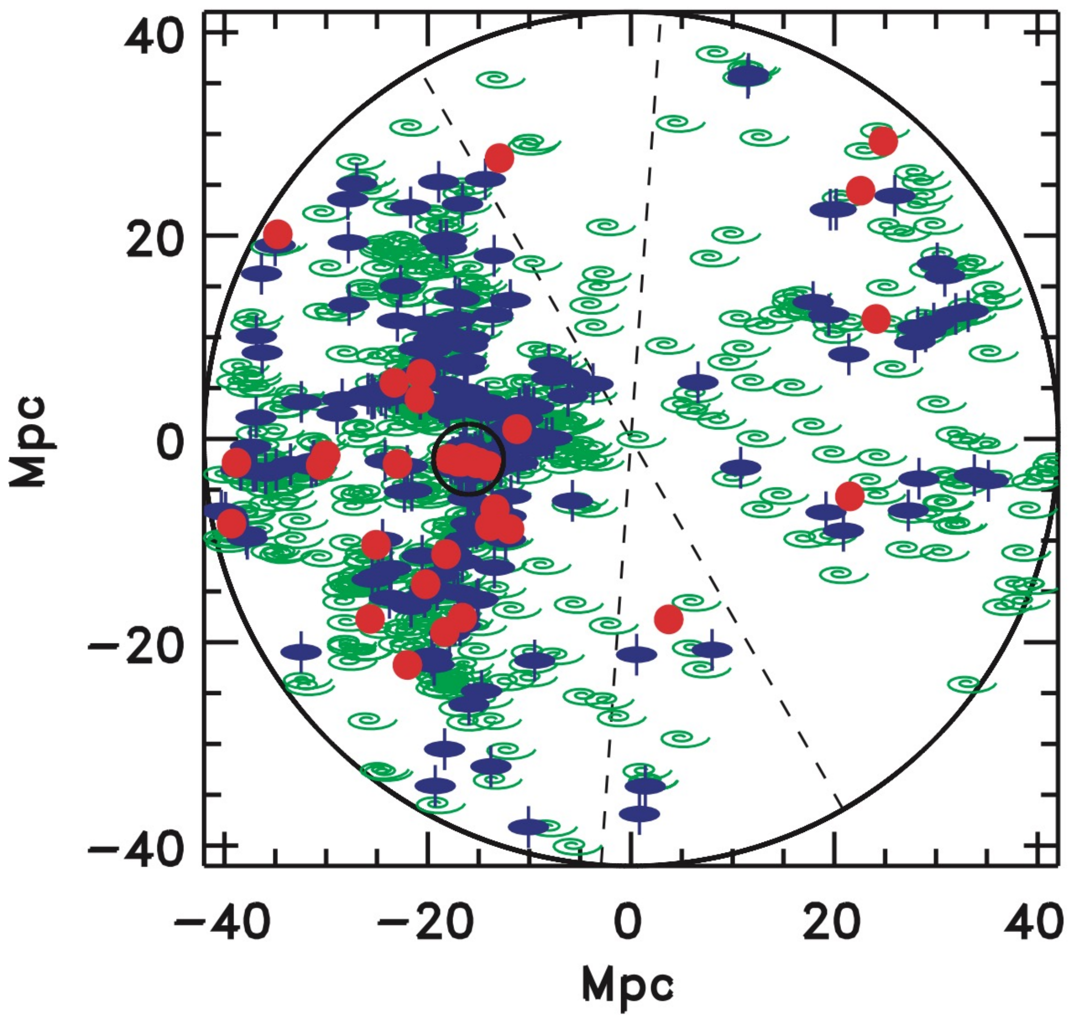
Fast rotators ⟶ $\lambda R\,(\mathrm{Re}) > 0.31\sqrt{\epsilon}$

R_e is the effective ***half light radius***
ϵ is the ***ellipticity*** within 1 R_e

Atlas^{3D} parent sample

- Survey volume: 1.16×10^5 [Mpc^3]
- K-band luminosity: $L > 8.2 \times 10^9$ L
- Total number of galaxies: $N_{gal} = 871$
  - Spiral and irregular: $N_{Sp} = 611$
  - S0 galaxies: $N_{S0} = 192$
  - E galaxies: $N_E = 68$

Cappellari 2011



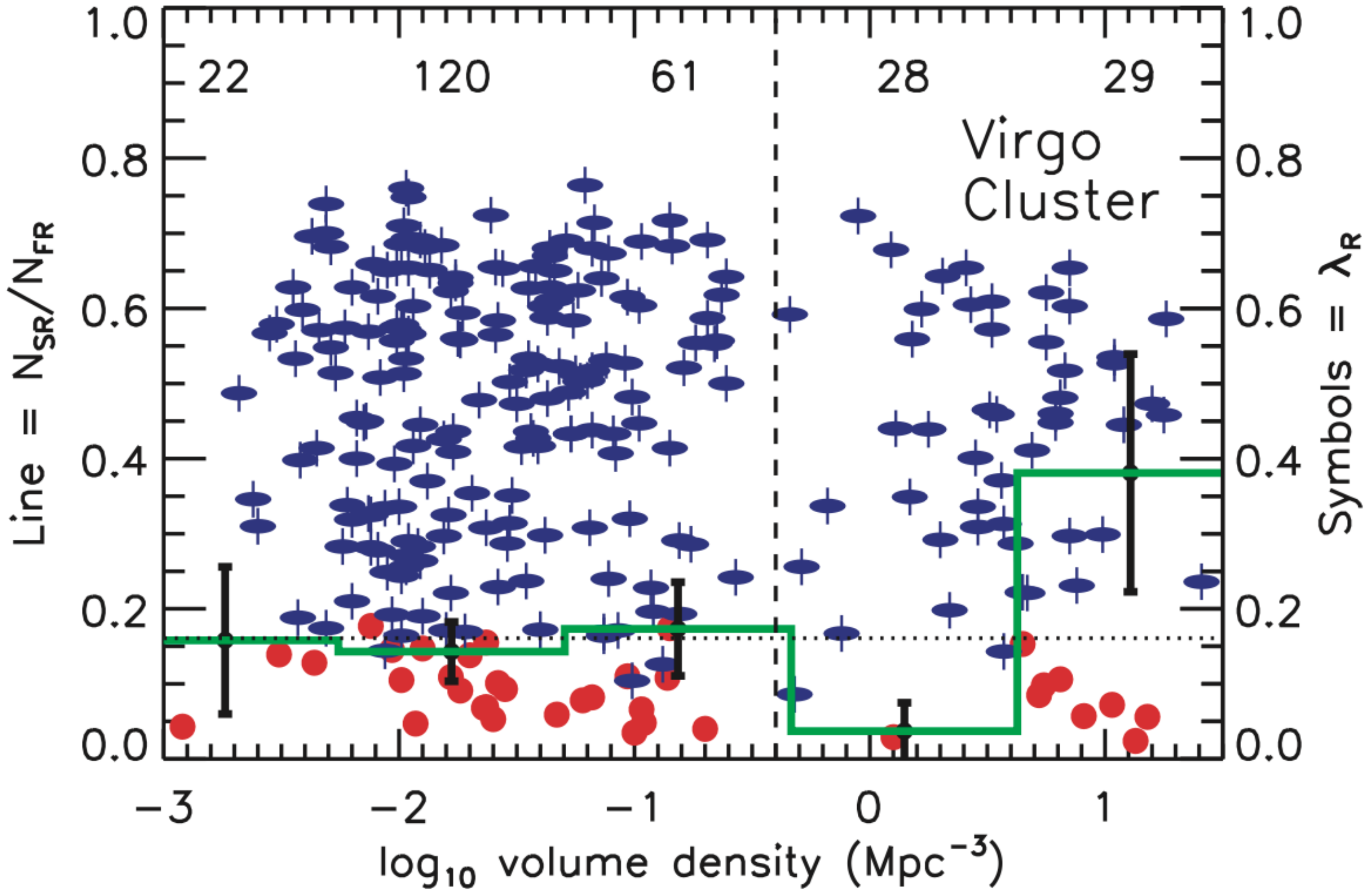
Blue ellipses = fast rotator ETGs
Red circles = slow rotator ETGs
Green spirals = spiral galaxies

Kinematic Classification scheme

- Volume density:
  - $\rho_{10} = Ngal \,/\, \left(\frac{4}{3}\,\pi\, r_{10}{}^{3}\right)$
- Surface brightness profile:
  - $\Sigma_{10} = N_{gal}/(\pi R_{10}^{2})$
  - $\Sigma_{3} = N_{gal}/(\pi R_{3}^{2})$

*Calculated for M_K < -21.5 mag

Cappellari 2011



Blue ellipses = fast rotator ETGs
Red circles = slow rotator ETGs

Three estimators of galaxies' environment

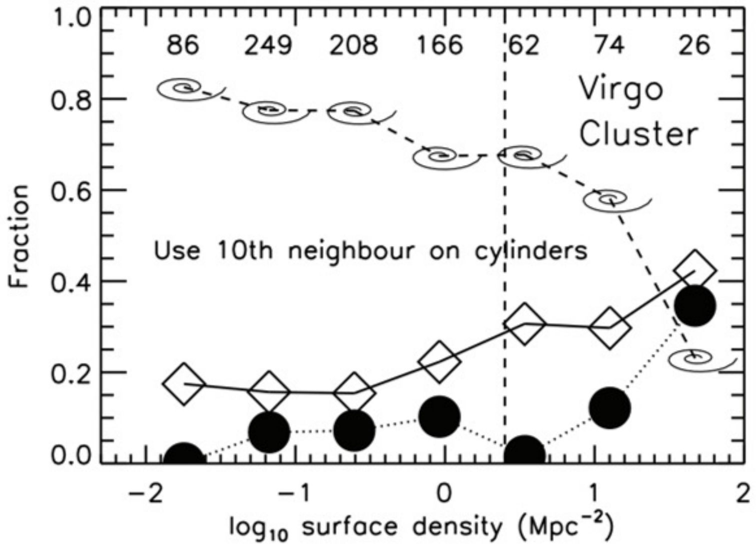
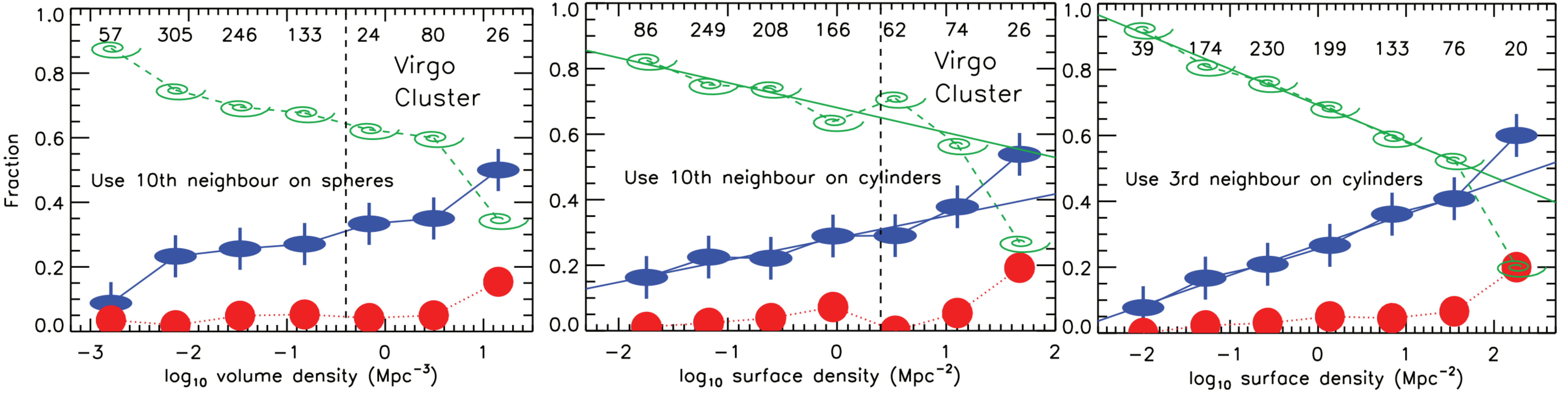


Figure 9. Morphology versus density for elliptical (black filled circles), lenticular (open diamonds) and spiral galaxies (spirals), versus the local surface density Σ_{10}. The numbers above the symbols represent the number of galaxies included in each of the seven density bins.

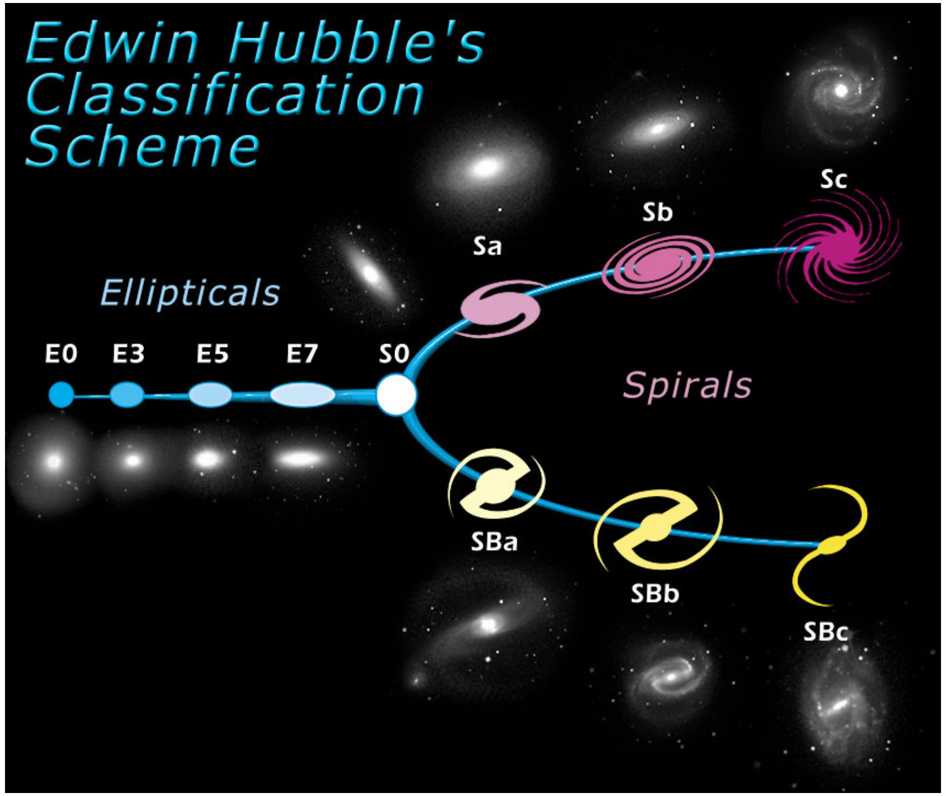
Cappellari 2011

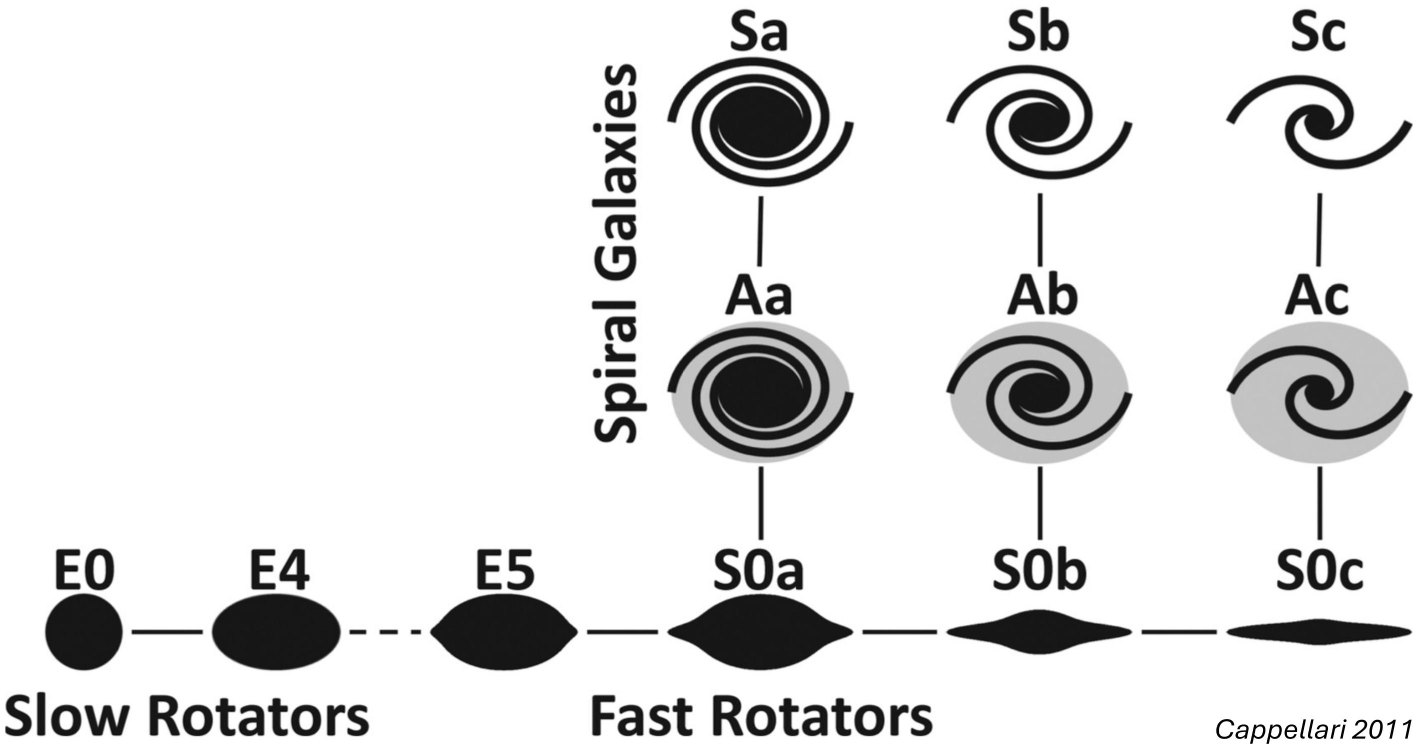
Blue ellipses = fast rotator ETGs
Red circles = slow rotator ETGs
Green spirals = spiral galaxies



Paper 1: Core Ideas

- Revision to Hubble diagram using kinematic classification scheme





Cappellari 2011

Paper 2: Core Ideas

- Origin of tilt in ***Fundamental Plane***
- Build axisymmetric dynamical models to reproduce observables for subset of Atlas^{3D} sample:
  - ***Integral-field stellar kinematics*** (out to 1R_e)

- Use dynamical models to measure ***scaling relations*** parameters
  - R_e and L
  - σ_e

Revisit Atlas^{3D} sample

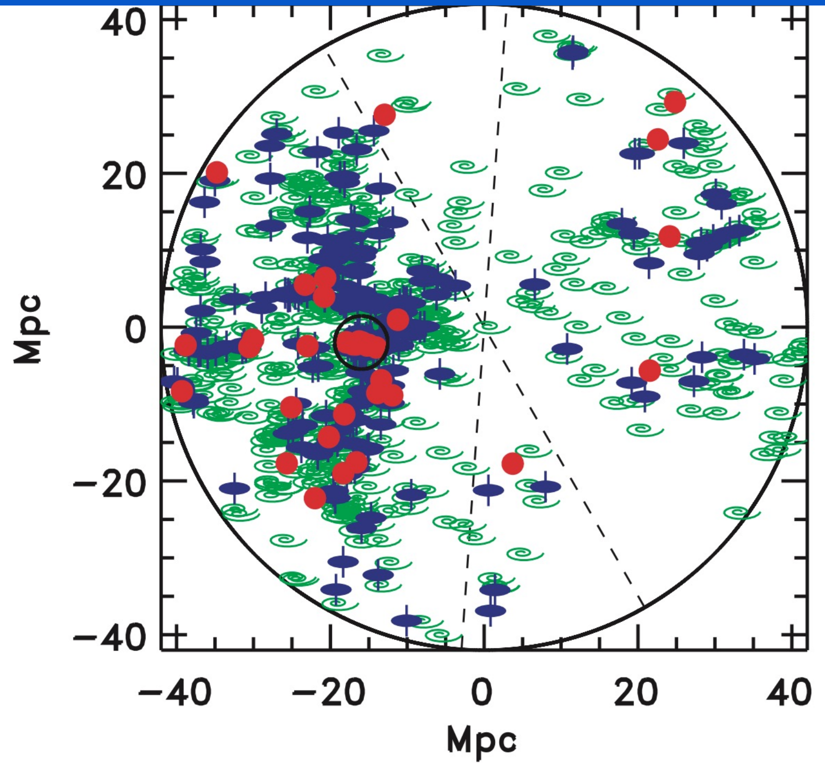
Atlas^{3D} sample

- Survey volume: 1.16×10^5 [Mpc^3]
- K-band luminosity: $L > 8.2 \times 10^9$ L
- ~~Total number of galaxies: N_{gal} = 871~~
  - ~~Spiral and irregular: N_{Sp} = 611~~
  - S0 galaxies: N_{S0} = 192
  - E galaxies: N_E = 68 +

N_{gal} = 260

→SAURON integral-field stellar kinematics within 1R_e

→SDSS photometry



Blue ellipses = fast rotator ETGs
Red circles = slow rotator ETGs
Green spirals = spiral galaxies

Fundamental Plane

- σ , R_e and L are correlated
- L re-written in terms of surface brightness:

$$\Sigma_e \equiv L / (2\pi Re^2)$$

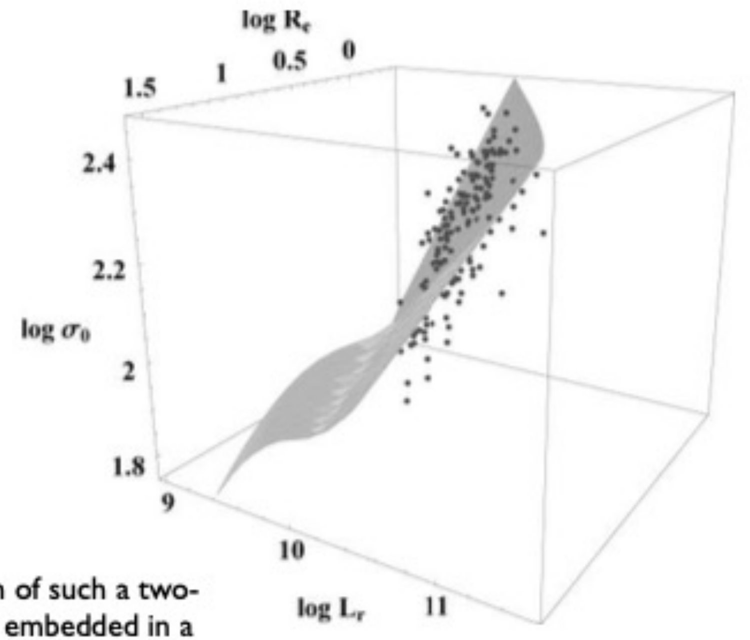
- From studies, plane can be written as:

$$R_e \propto \sigma^{1.33} \Sigma_e^{-0.82}$$

Which differs from the viral prediction

$$R_e \propto \sigma^2 \Sigma_e^{-1}$$

The properties of galaxies occupy a two dimensional plane in the three dimensional parameter space.



Here is an illustration of such a two-dimensional surface embedded in a three-dimensional space.

***Recall from Lecture 7**

Jeans Anisotropic Multi-Gaussian Expansion (JAM) Model

Axisymmetric Jeans equations

$$\frac{\nu\overline{v_R^2} - \nu\overline{v_\phi^2}}{R} + \frac{\partial(\nu\overline{v_R^2})}{\partial R} + \frac{\partial(\nu\overline{v_R v_z})}{\partial z} = -\nu\frac{\partial\Phi}{\partial R}$$

Jeans-1
(continuity eqn.)

$$\frac{\nu\overline{v_R v_z}}{R} + \frac{\partial(\nu\overline{v_z^2})}{\partial z} + \frac{\partial(\nu\overline{v_R v_z})}{\partial R} = -\nu\frac{\partial\Phi}{\partial z}$$

Jeans-2
(force eqn.)

where: $\nu\overline{v_k v_j} \equiv \int v_k v_j f \, \mathrm{d}^3\mathbf{v}$

Axisymmetric anisotropic Jeans equations

$$\nu\overline{v_\phi^2}(R,z) = b\left[R\frac{\partial(\nu\overline{v_z^2})}{\partial R} + \nu\overline{v_z^2}\right] + R\nu\frac{\partial\Phi}{\partial R}.$$

Jeans Anisotropic Multi-Gaussian Expansion (JAM) Model

MGE

Approx. observed SDSS r-band surface brightness distribution using MGE parametrization

$$\Sigma(x', y') = \sum_{j=1}^{M} \Sigma_j \exp\left[-\frac{1}{2\sigma_j^2}\left(x'^2 + \frac{y'^2}{q_j'^2}\right)\right]$$

Estimates the first two velocity moments (V and σ)

JAM

Use V and σ in anisotropic Jeans MGE

Return LOS second velocity moments $\langle \mathrm{vlos}^2 \rangle^{1/2}$

Jeans Anisotropic Multi-Gaussian Expansion (JAM) Models

Six models tested in this paper:

(A) Self-consistent JAM model
(B) JAM + ***NFW*** dark halo
(C) JAM + contracted NFW dark halo
(D) JAM + general dark halo (gNFW)
(E) JAM + fixed NFW dark halo
(F) JAM + fixed contracted dark halo

Free parameters:

- Vertical anisotropy, $\beta_z = 1 - \sigma_z^2 / \sigma_R^2$
- Inclination, *i*
- \+ more

NFW profile from Lecture 8

Navarro-Frenk-White Density Profiles

Simulations show that collapsed halos approximately have the following density profile:

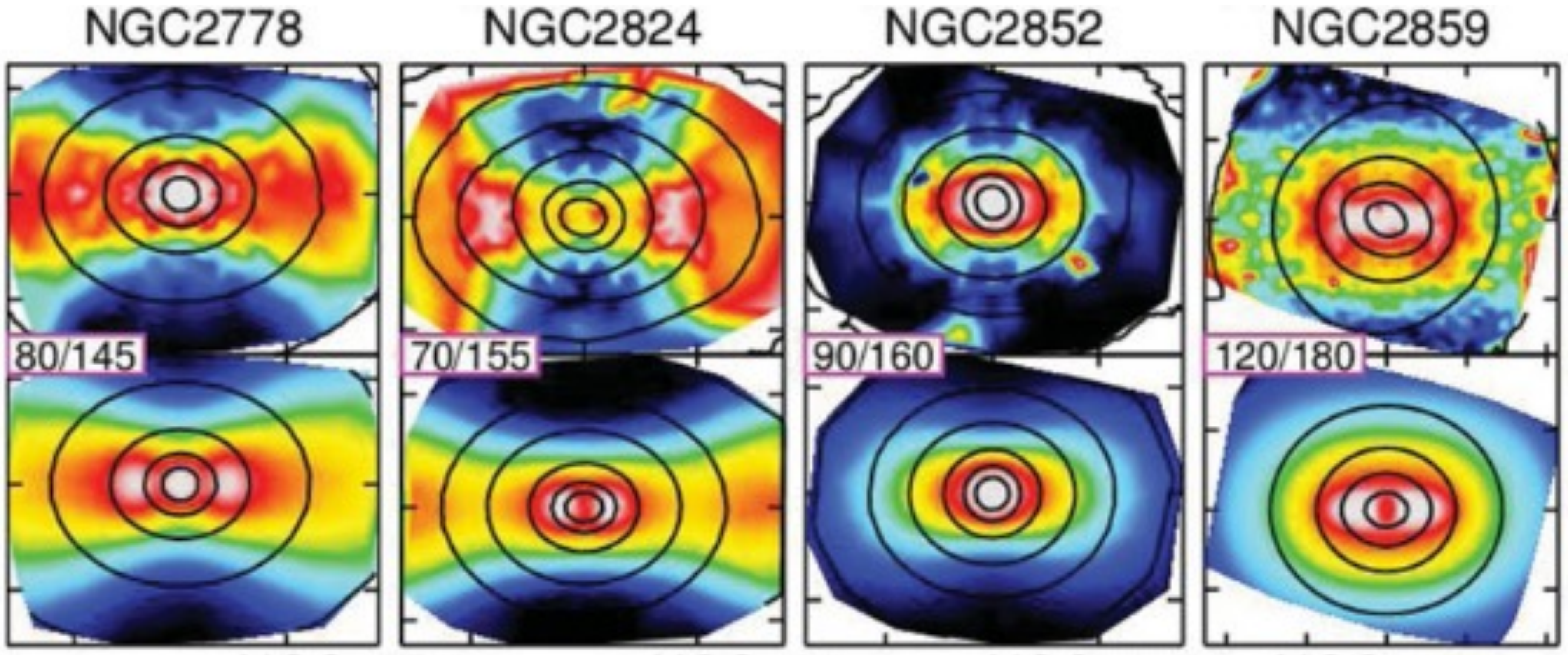
$$\rho(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}$$

where r_s and ρ_s are some scaling parameters.

Mass follows light *JAM* models

SAURON observation

Best fitting JAM model



*$V_{rms} \equiv \sqrt{V^2 + \sigma^2}$

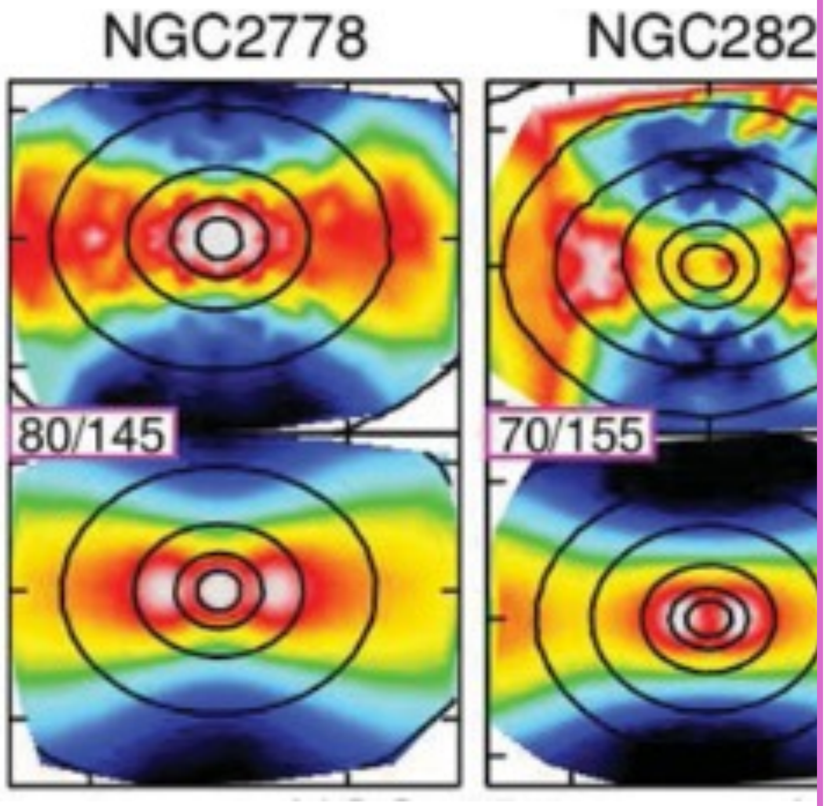
*Ticks are separated by 10 arcsec

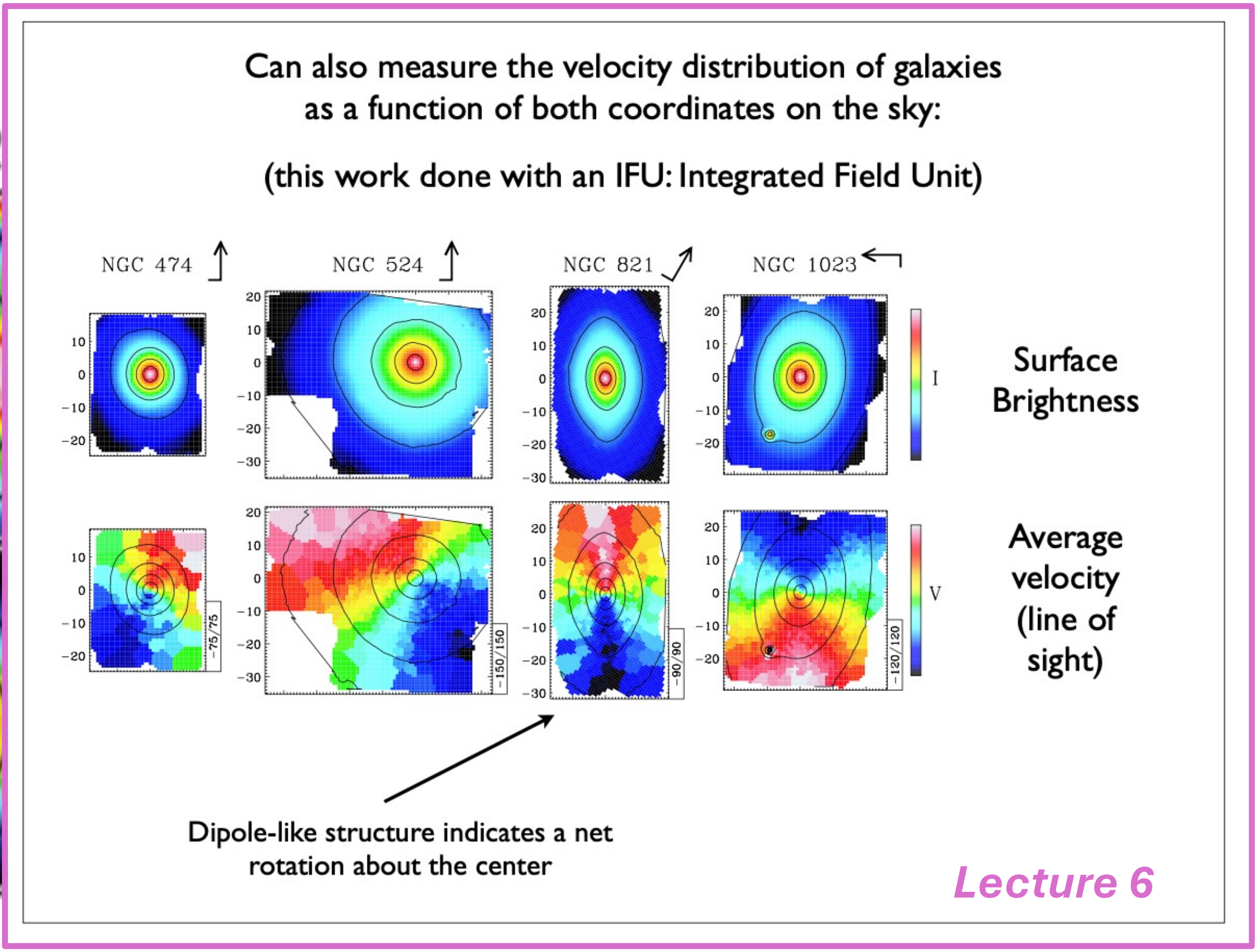
*Surface brightness overlaid, in steps of 1 mag.

Mass follows light *JAM* models

SAURON observation

Best fitting JAM model





*$V_{rms} \equiv \sqrt{V^2 + \sigma^2}$

*Ticks are separated by 10 arcsec

*Surface brightness overlaid, in steps of 1 mag.

Jeans Anisotropic Multi-Gaussian Expansion (JAM) Model

MGE

Approx. observed SDSS r-band surface brightness distribution using MGE parametrization

$$\Sigma(x', y') = \sum_{j=1}^{M} \Sigma_j \exp\left[-\frac{1}{2\sigma_j^2}\left(x'^2 + \frac{y'^2}{q_j'^2}\right)\right]$$

Estimates the first two velocity moments (V and σ) → L, R_e

↓

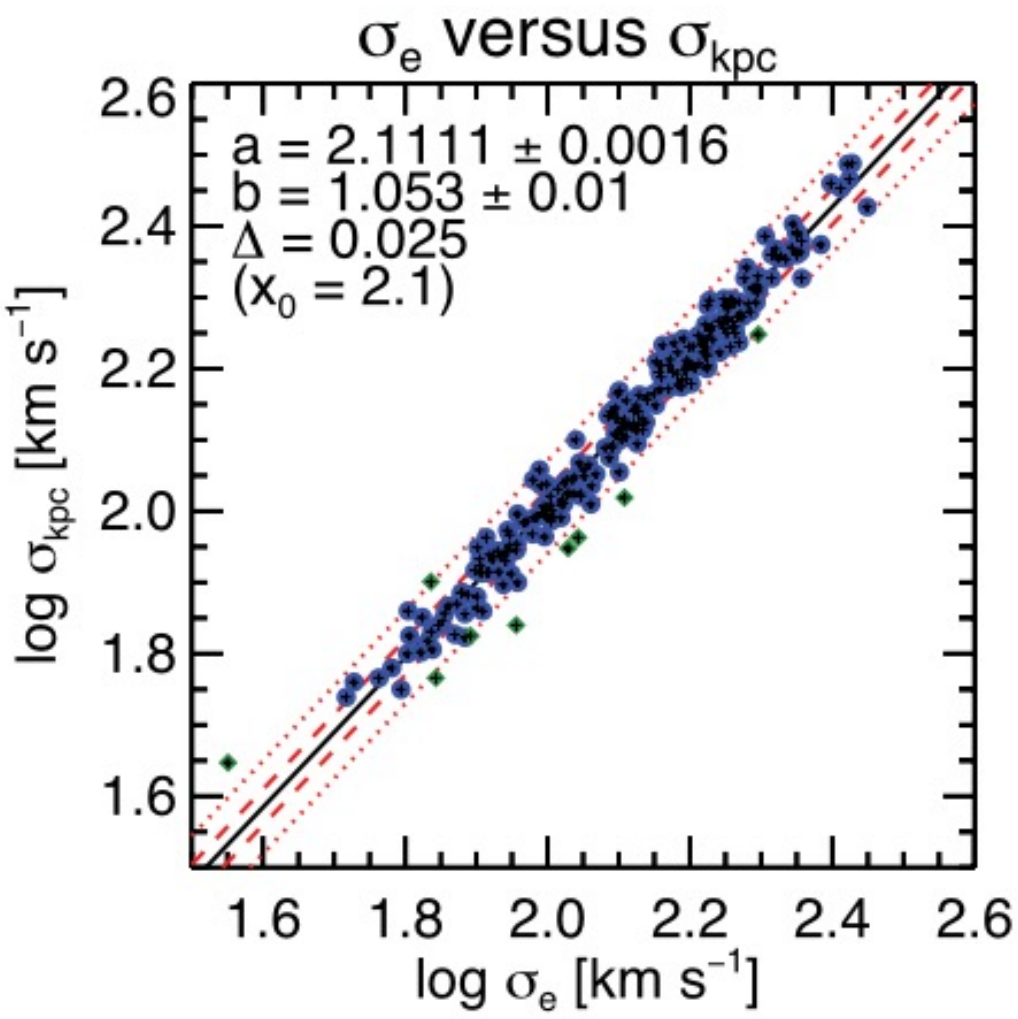
JAM

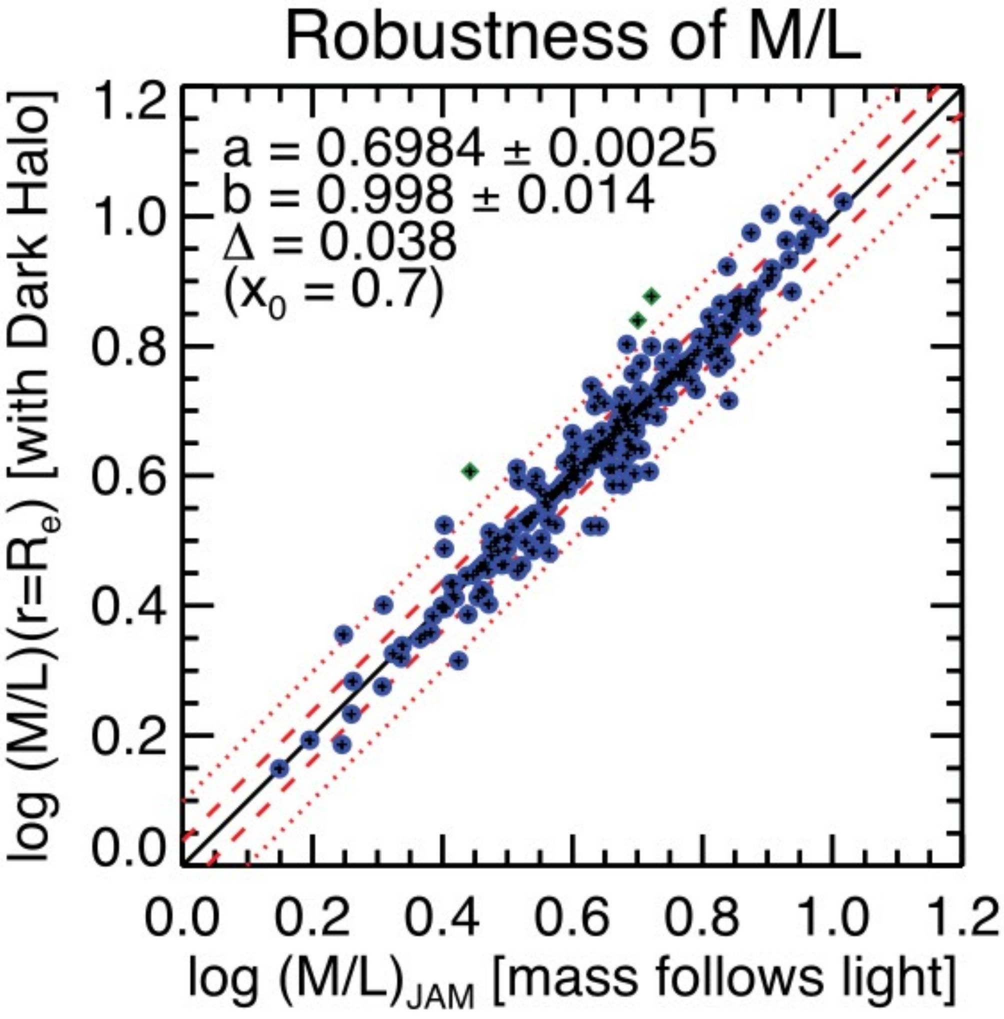
Use V and σ in anisotropic Jeans equations

↓

Return LOS second velocity moments $\langle \mathrm{vlos}^2 \rangle^{1/2}$ → M/L, M_{DM}/L, f_{DM}

Results from *JAM* modelling

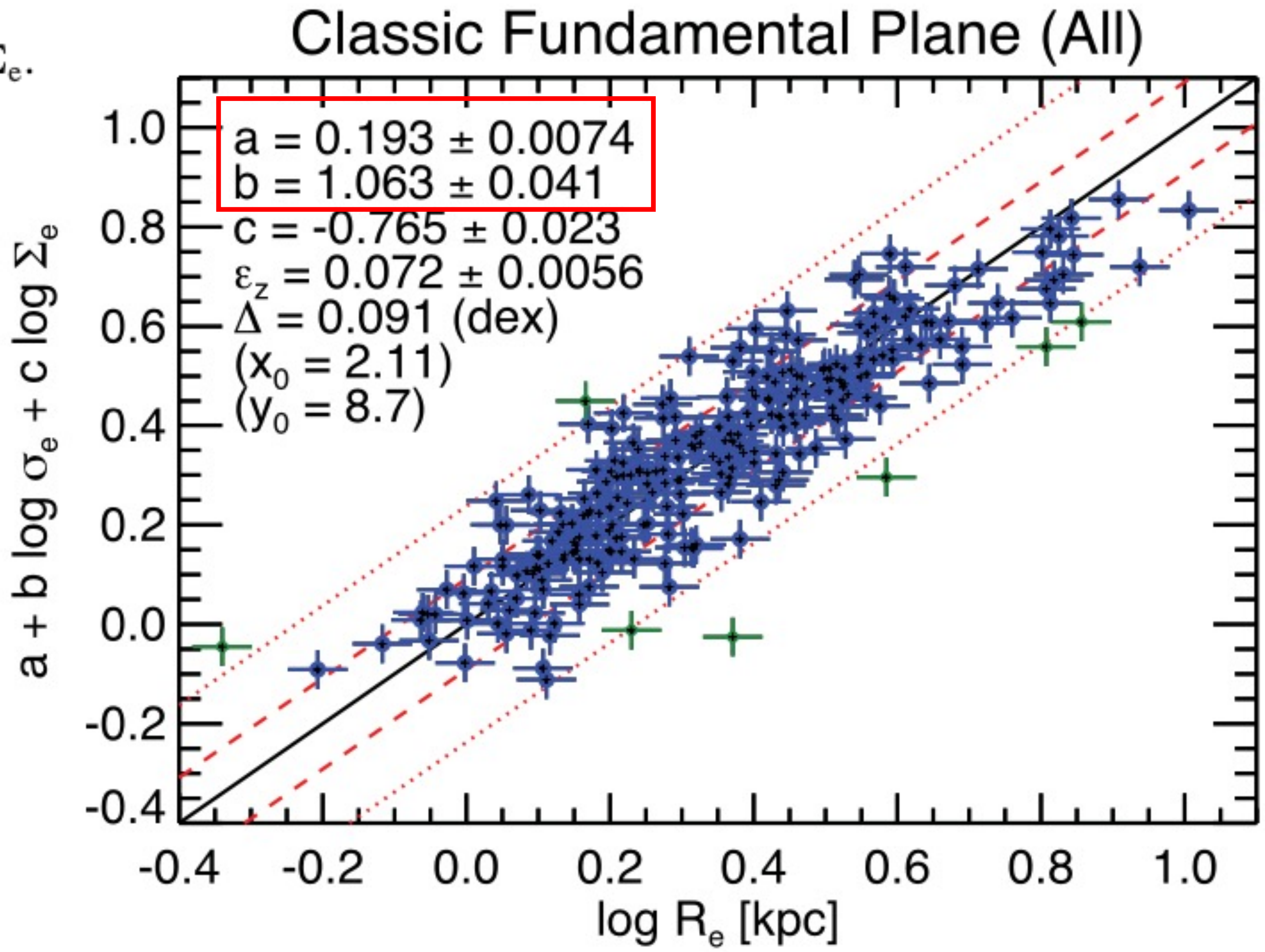




Fundamental plane from models

$$\log R_e = a + b \log \sigma + c \log \Sigma_e.$$

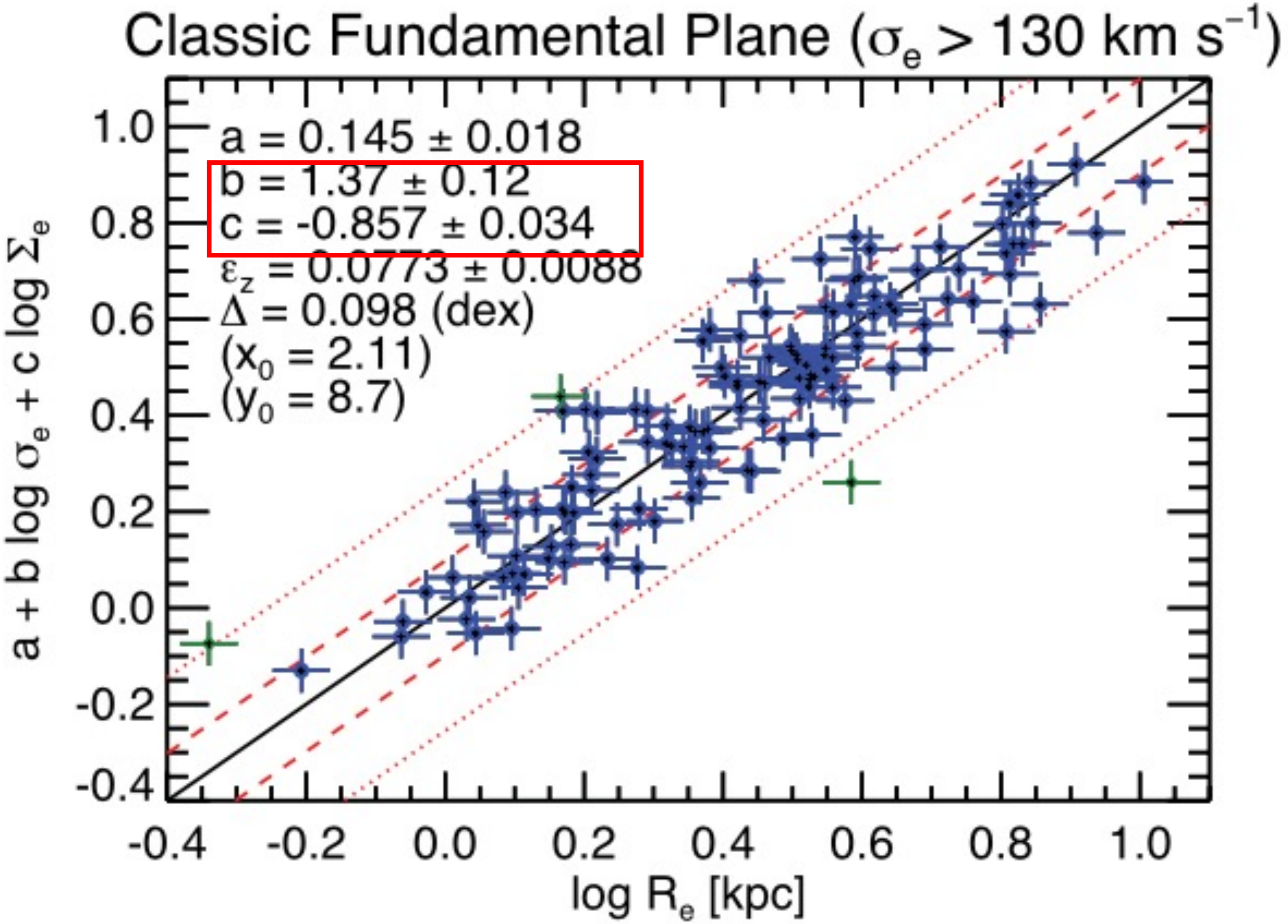
Other studies yield:
b = 1.33 , c = -0.82



Fundamental plane with velocity dispersion selection

$$\log R_e = a + b \log \sigma + c \log \Sigma_e.$$

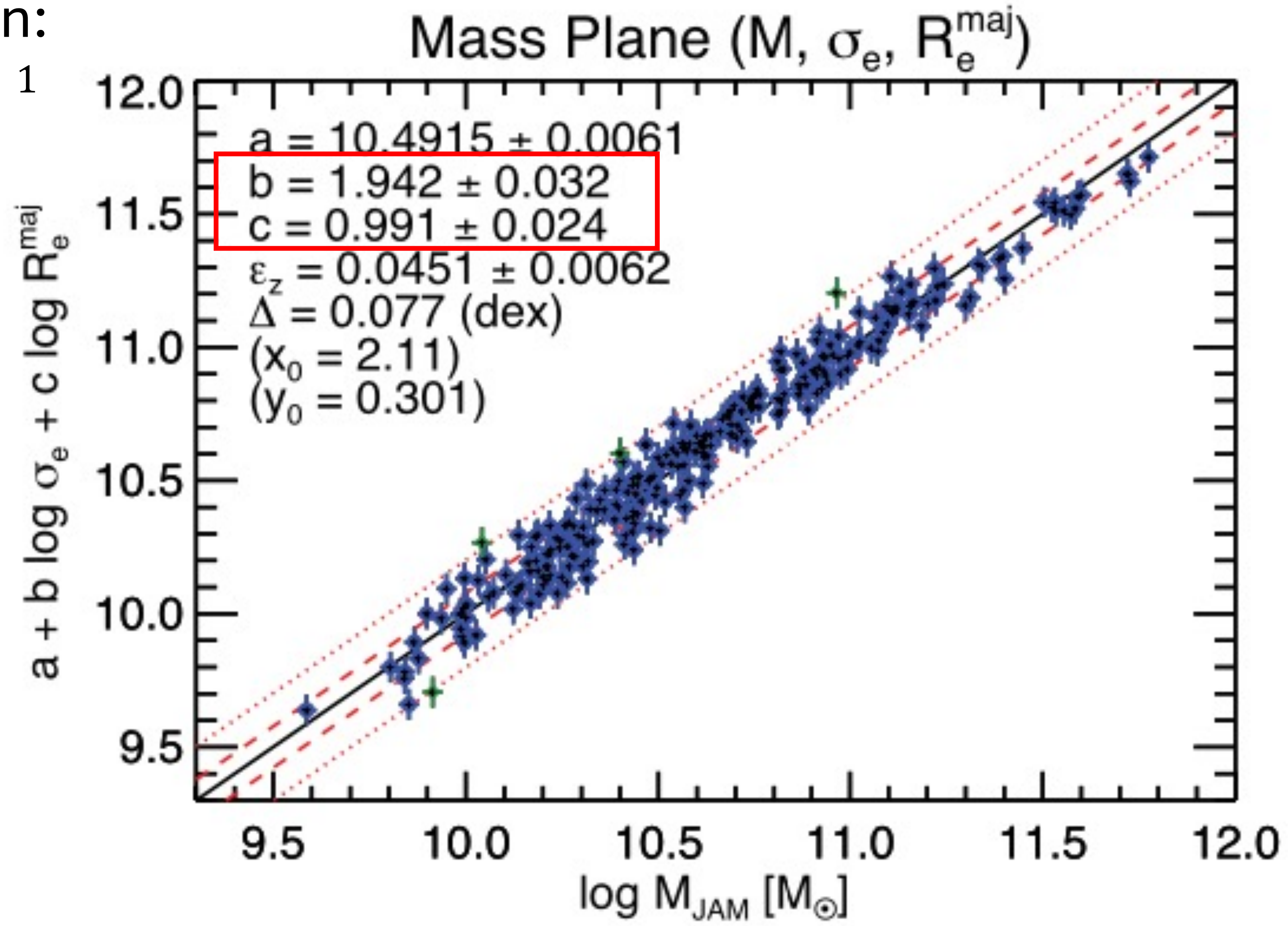
Other studies yield:
b = 1.33 , c = -0.82

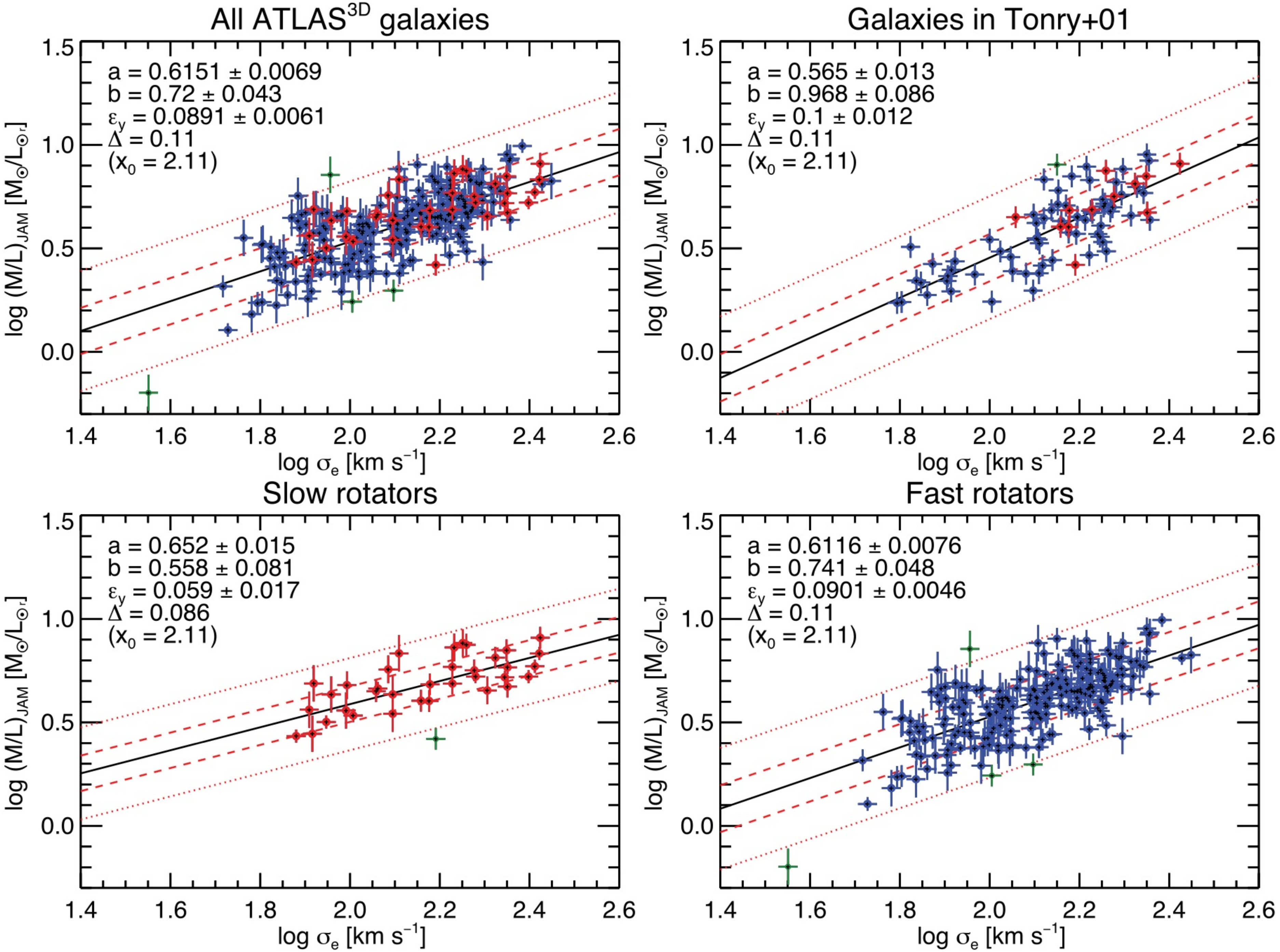


Mass plane

*Virial relation:

$R_e \propto \sigma^2 \Sigma_e^{-1}$




All ATLAS^{3D} galaxies
a = 0.6151 ± 0.0069
b = 0.72 ± 0.043
ε_y = 0.0891 ± 0.0061
Δ = 0.11
(x_0 = 2.11)
Galaxies in Tonry+01
a = 0.565 ± 0.013
b = 0.968 ± 0.086
ε_y = 0.1 ± 0.012
Δ = 0.11
(x_0 = 2.11)
Slow rotators
a = 0.652 ± 0.015
b = 0.558 ± 0.081
ε_y = 0.059 ± 0.017
Δ = 0.086
(x_0 = 2.11)
Fast rotators
a = 0.6116 ± 0.0076
b = 0.741 ± 0.048
ε_y = 0.0901 ± 0.0046
Δ = 0.11
(x_0 = 2.11)
log $(M/L)_{JAM}$ [$M_\odot/L_{\odot r}$]
log σ_e [km s^{-1}]
1.5
1.0
0.5
0.0
1.4
1.6
1.8
2.0
2.2
2.4
2.6