Observational signatures of kinematic transformations

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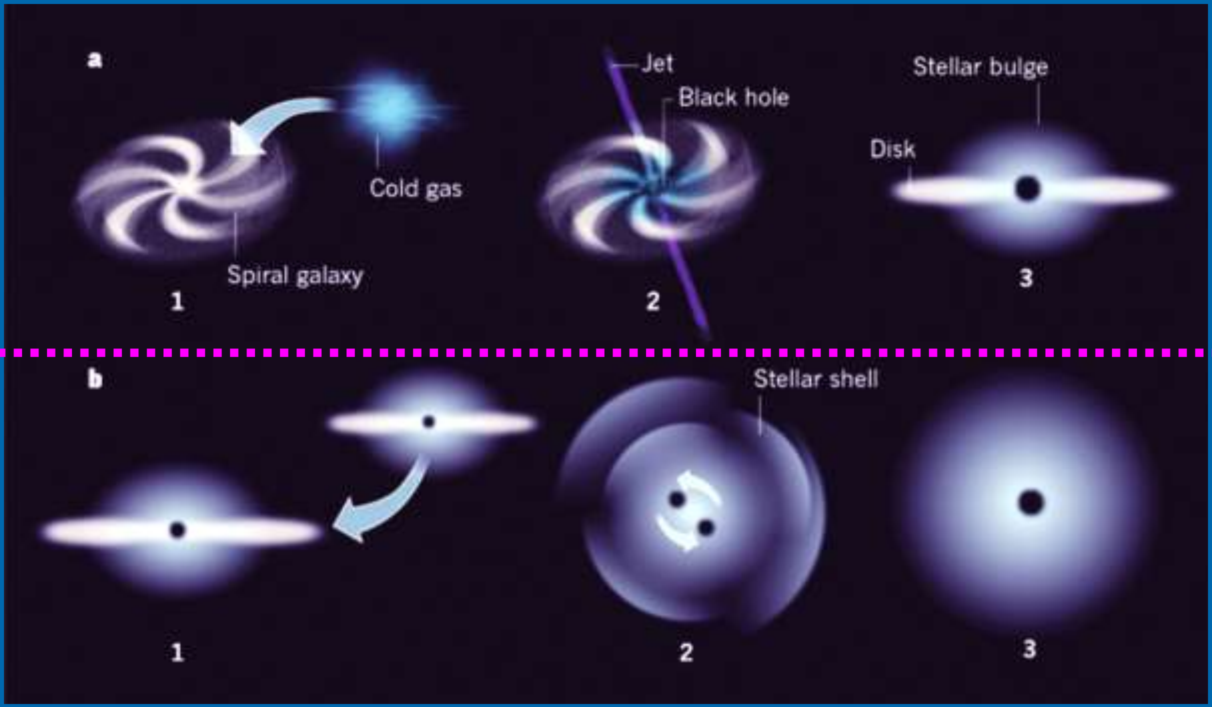
See Cappellari (2016, ARA&A, 54, 597)

What do we expect?

Gas accretion

Dry mergers

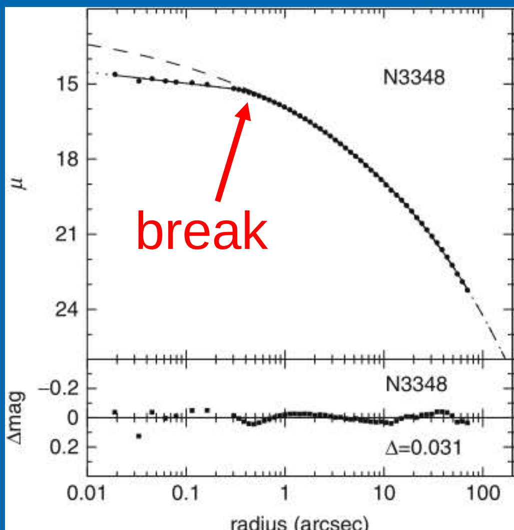


(Cappellari-11 Nature)

- Two main channels
  - a) Build up by gas accretion (+ quenching)
  - b) Build up by dry mergers
- What are their relative contributions?

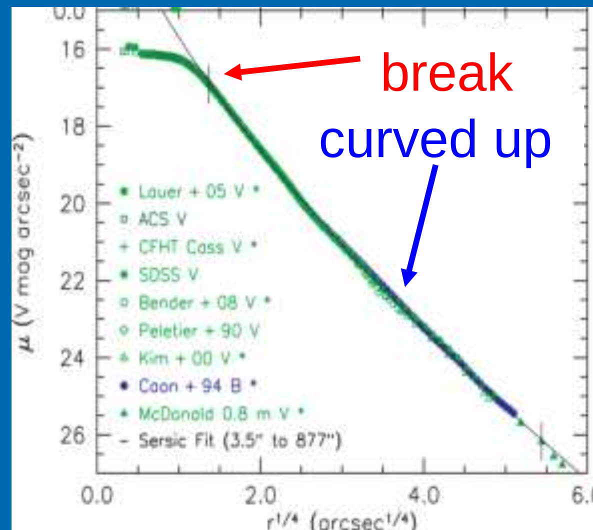
Relics of dry-merging channel

Core/break/deficit



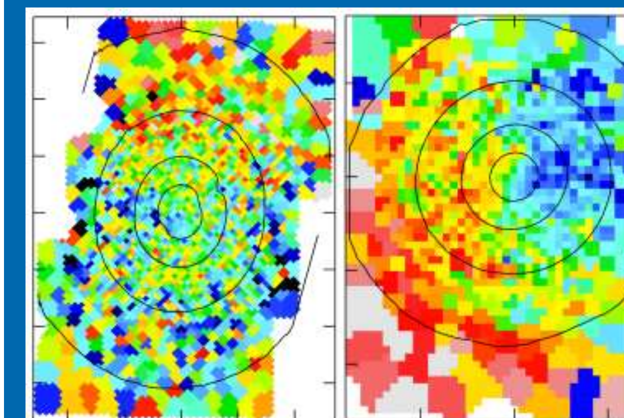
Graham+03

High Sersic n



Kormendy+09

Slow rotators

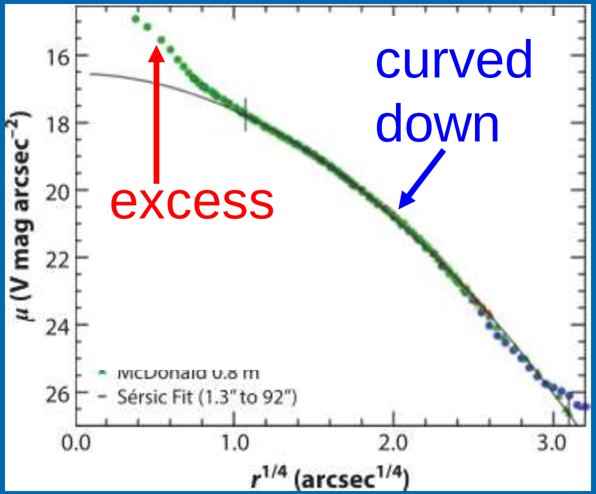


Emsellem+04

- Core scouring by SMBH (e.g. Faber+97; Milosavljevic+01)
- Multiple minor merging (Hilz+13, Naab+14)
- Disk destruction or lack of formation

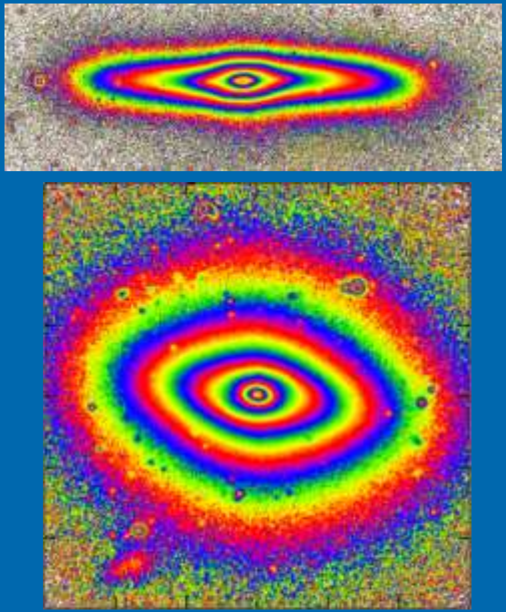
Relics of gas-accretion channel

Light Excess

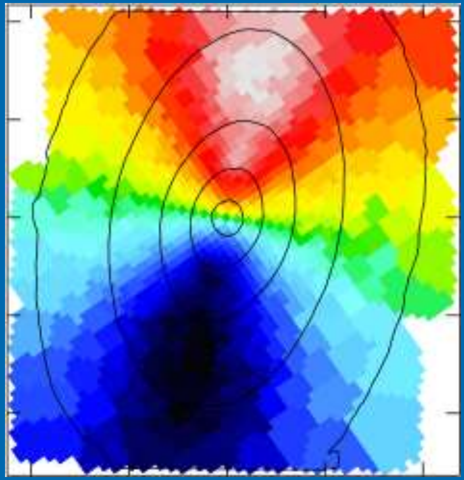


Kormendy+09

Disks



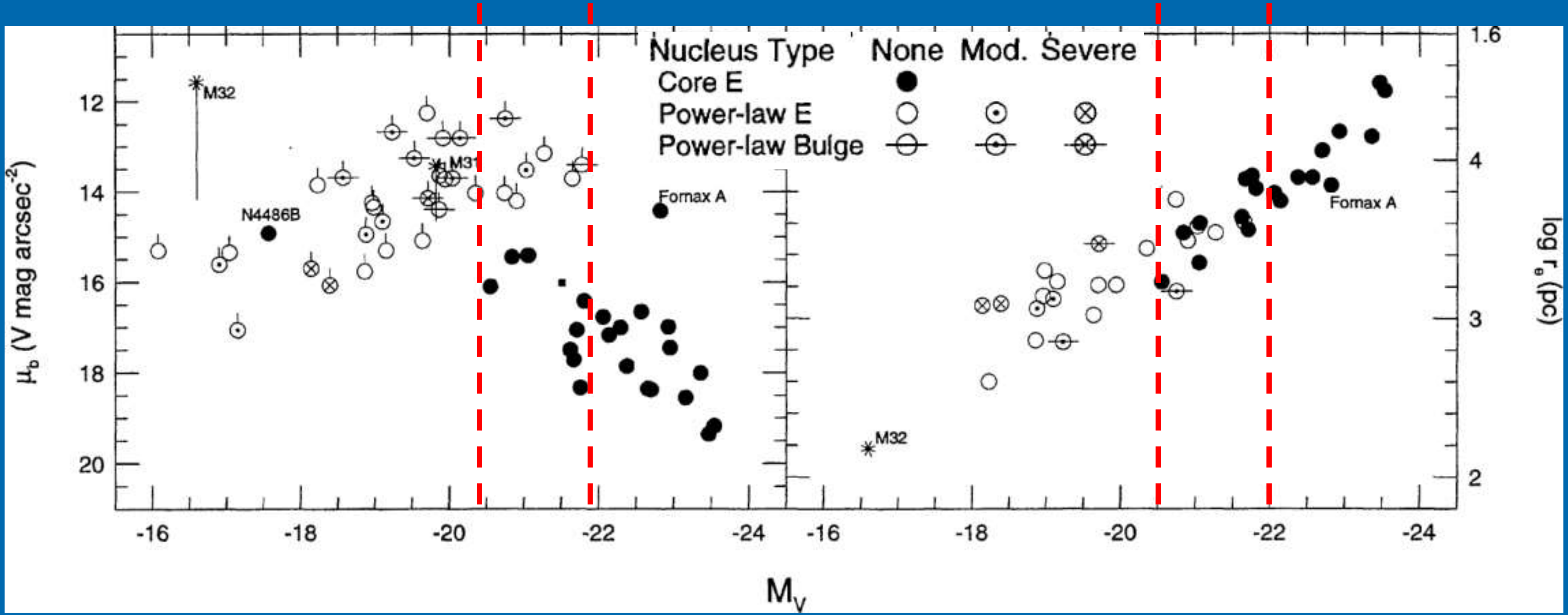
Fast rotators



Emsellem+04

- Central light excess (Mihos-Hernquist94)
- Gas dissipation: disk growth or preservation
- Fast rotation like spiral galaxies (Emsellem+07; Cappellari+07)
- Axisymmetric shapes

Nuclear profiles and luminosity



(Faber+97)

(Also e.g. Graham-Guzman03, Ferrarese+06, Kormendy+09)

- Core/deficit dominate for $M_V < -22$
- Core-cusp overlap $-22 < M_V < -20.5$

Recognizing relics in large surveys

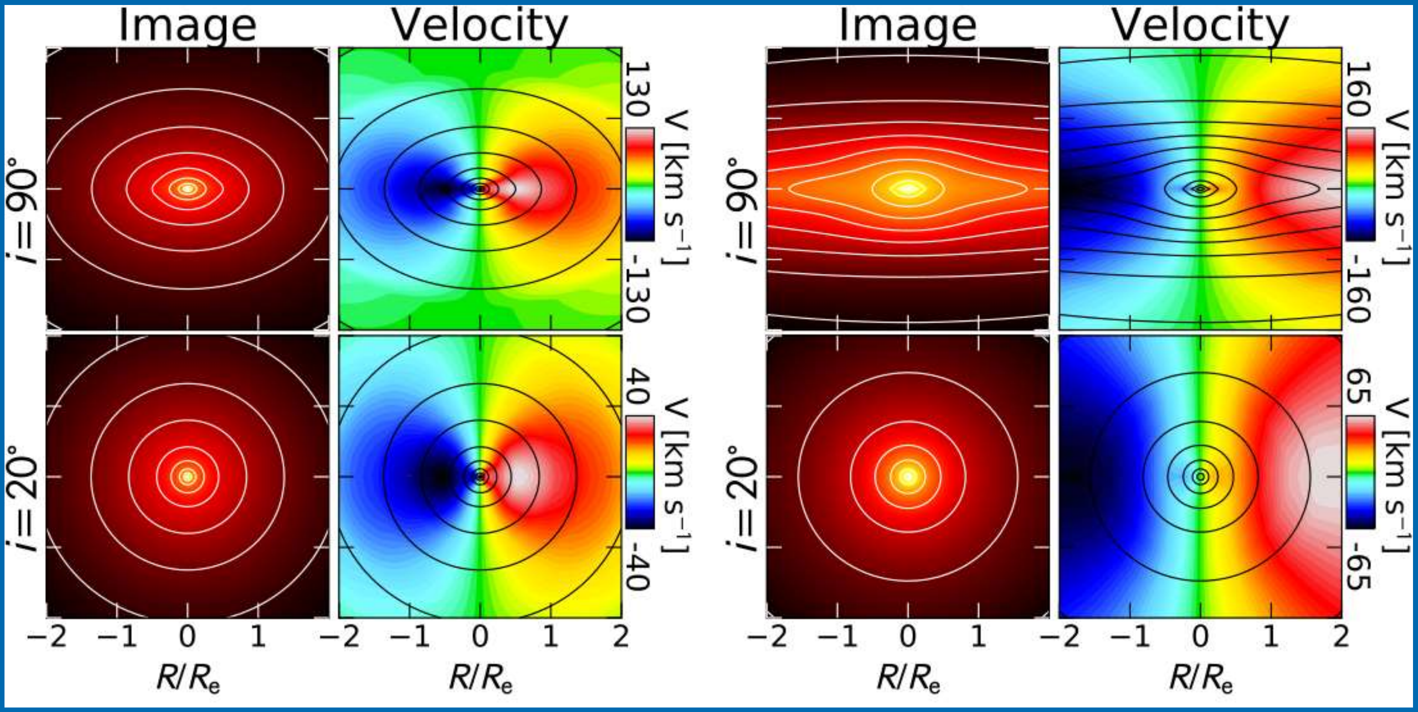
- Core/deficit measurement requires HST/JWST
- Bulge/disk decomp. depends on inclination
- Isophotal shape depends on inclination
- Sersic n is a weaker indicator

→ Stellar kinematics solves these problems

Bryant+15

Bundy+15

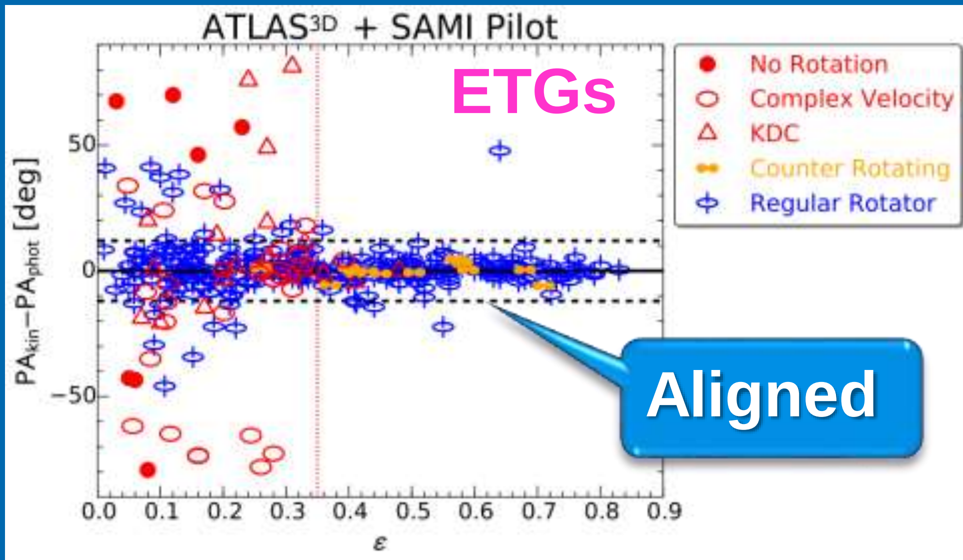
Recognizing face on disks

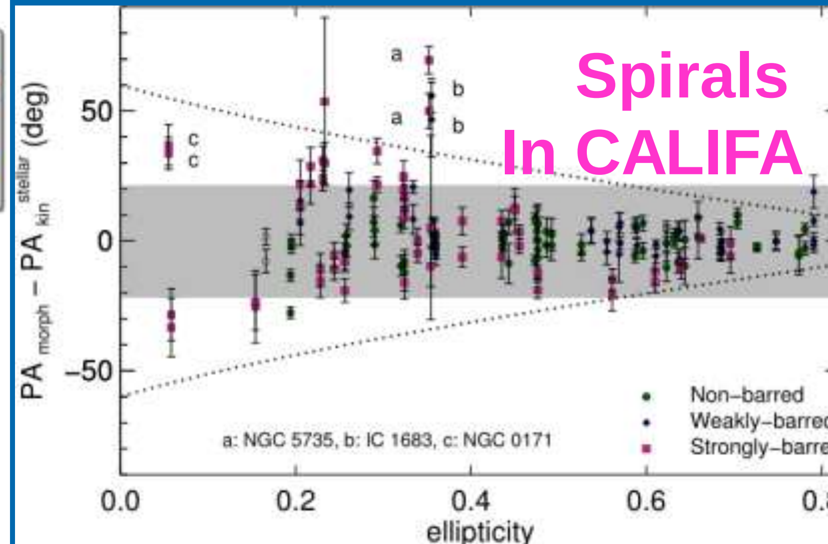


Disky Elliptical S0 (Cappellari-16 ARA&A)

- Kinematics identifies nearly face-on disks
- Only $\lesssim$ 2% of disk can be missed (Jesseit+09)

Fast rotators/spirals are axisymmetric



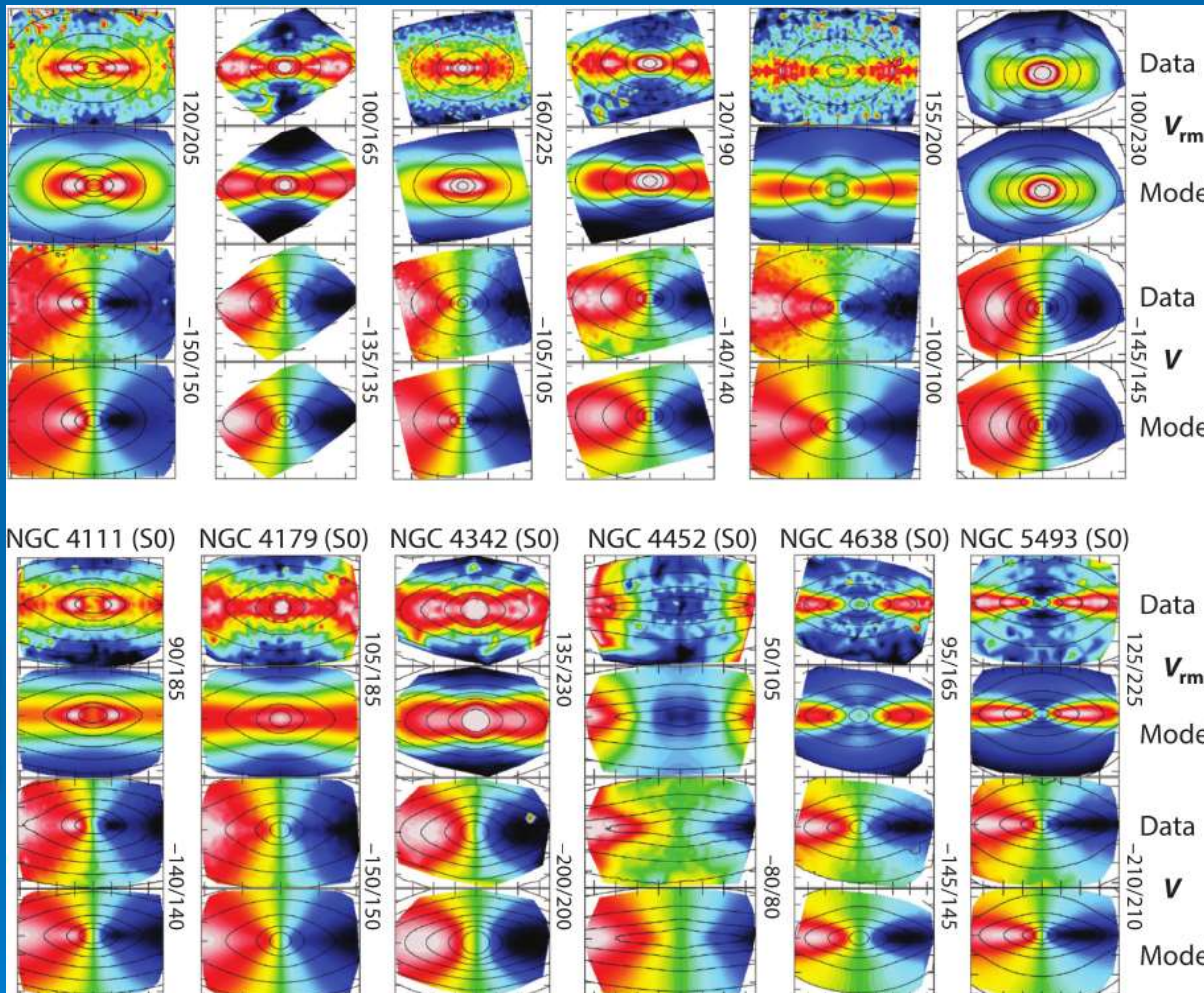


(Krajnovic+11 & Fogarty+15) (Barrera-Ballesteros+14)

- 90% of all fast rotators aligned within ≈ 5°
- Better aligned than spiral galaxies
- Only exceptions are bars and interactions
- Axisymmetric out to the stellar halo $\sim 3R_e$

Fast kinematics very homogeneous

E



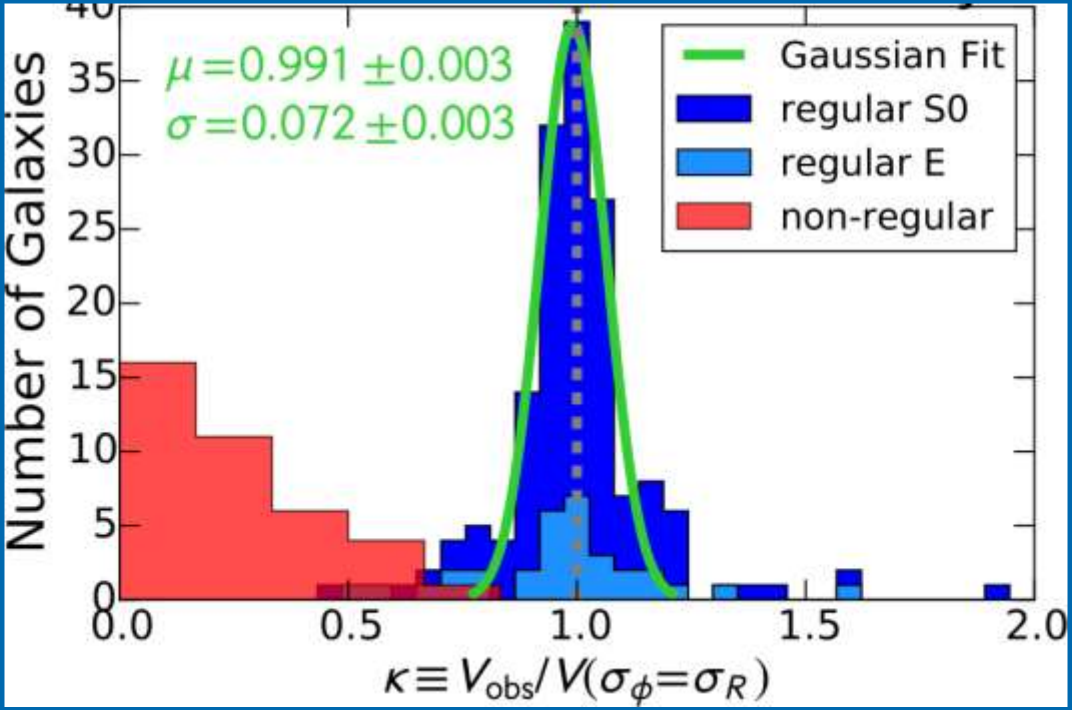
S0

JAM models of ATLAS^{3D} kinematics

Cappellari-16 ARA&A

- Kinematics encoded by <u>one</u> number $\beta_z = 1 - \sigma_z^2/\sigma_R^2$
- Differences entirely due to bulge/disk fraction

Fast/slow: rotation dichotomy



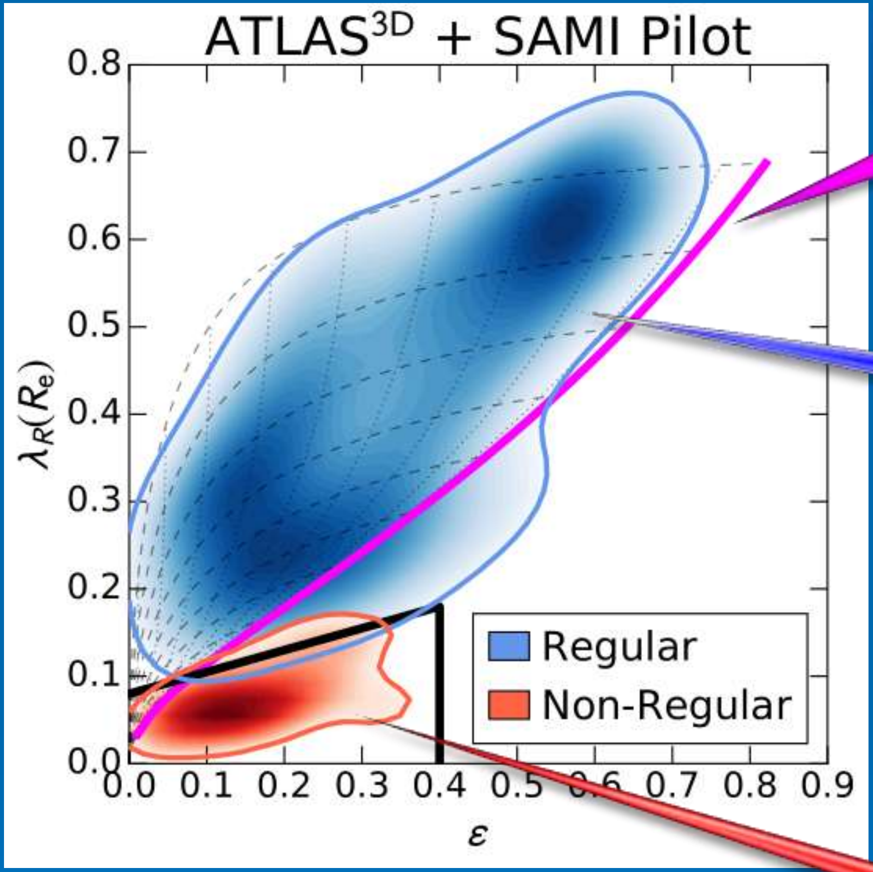
Cappellari-16 ARA&A

- Fast rotators have oblate velocity ellipsoid
  - Observed scatter of 7% including models errors!
  - Consistent distribution for both E and S0 galaxies
- Slow rotators follow different distribution

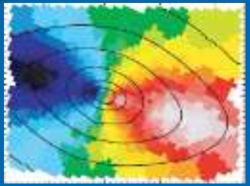
Stellar angular momentum

Cappellari-16
ARA&A

Data from:
Emsellem+11
Fogarty+15



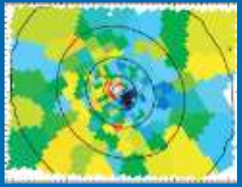
Cappellari+07



Fast ETGs

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

(Emsellem+07)



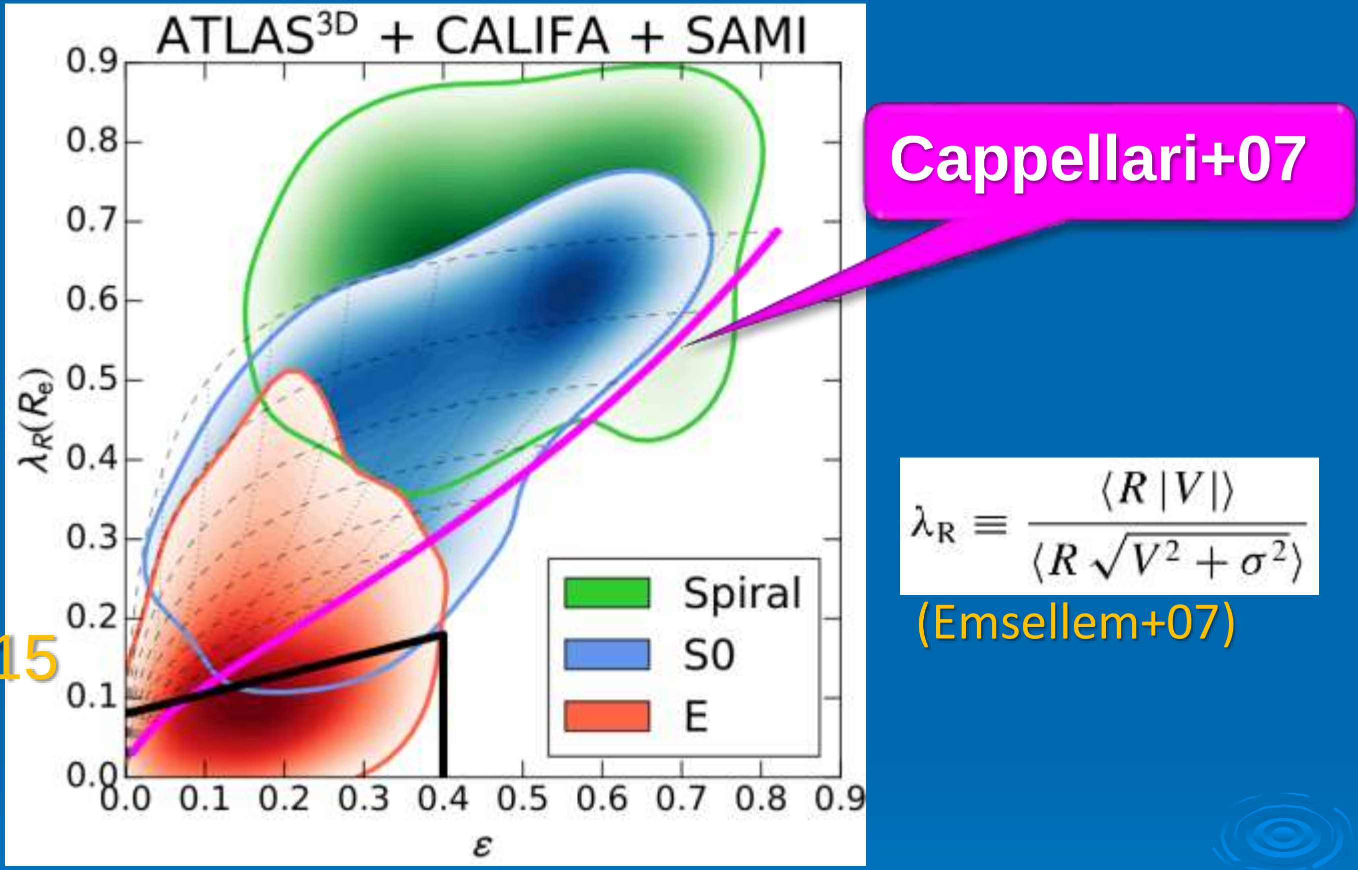
Slow ETGs

- Fast rotator → inclined disk galaxies
- Consistent with anisotropy trend from dynamics
- Slow rotator → weakly triaxial $c/a > 0.6$

E class is poor proxy for kinematics

Cappellari-16 ARA&A

Data from:
Emsellem+11
Fogarty+15
Falcon-Barroso-15

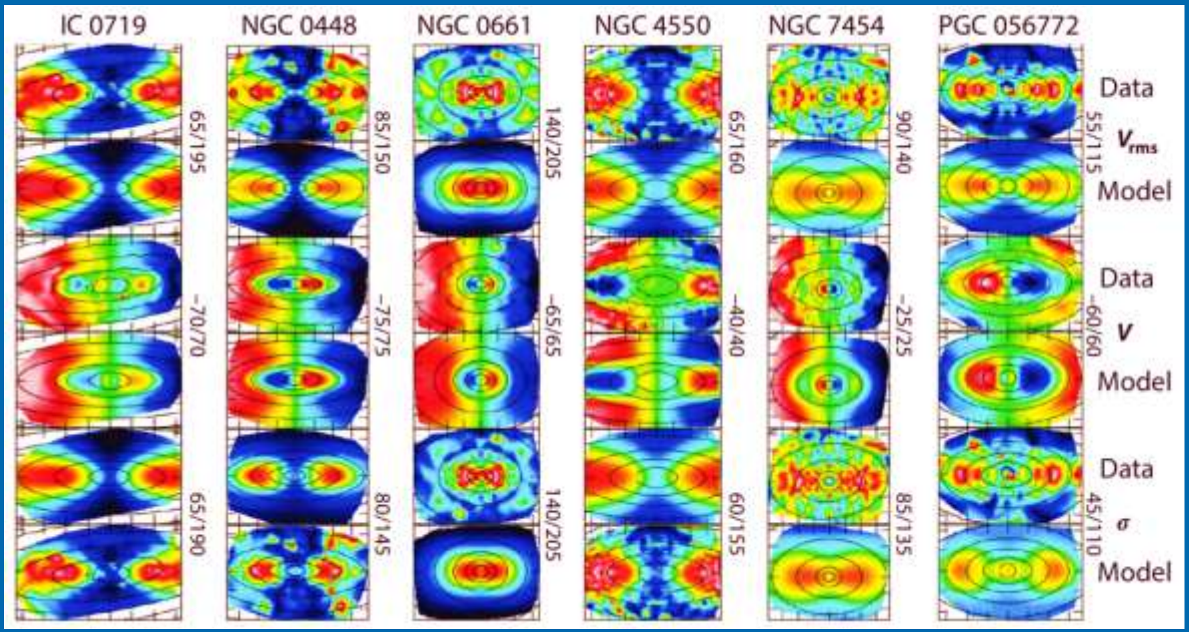


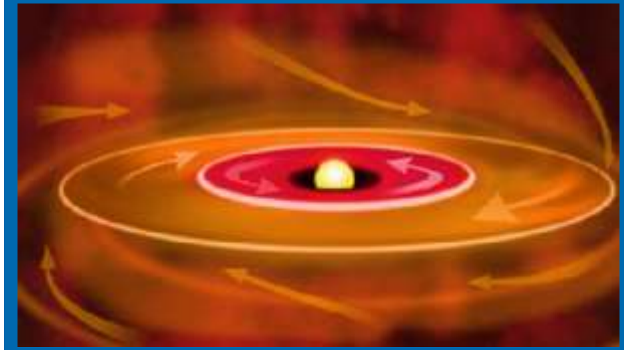
$$\lambda_R \equiv \frac{\langle R\,|V|\rangle}{\langle R\sqrt{V^2+\sigma^2}\rangle}$$

(Emsellem+07)

- Expected trend angular momentum vs. morphology
- Explained by variation in bulge fraction (e.g. Cortese+16)
- 2/3 of classic ellipticals from RC3 are fast rotators!

Beware of counter-rotating disks!





CREDIT: Bill Saxton
NRAO/AUI/NSF

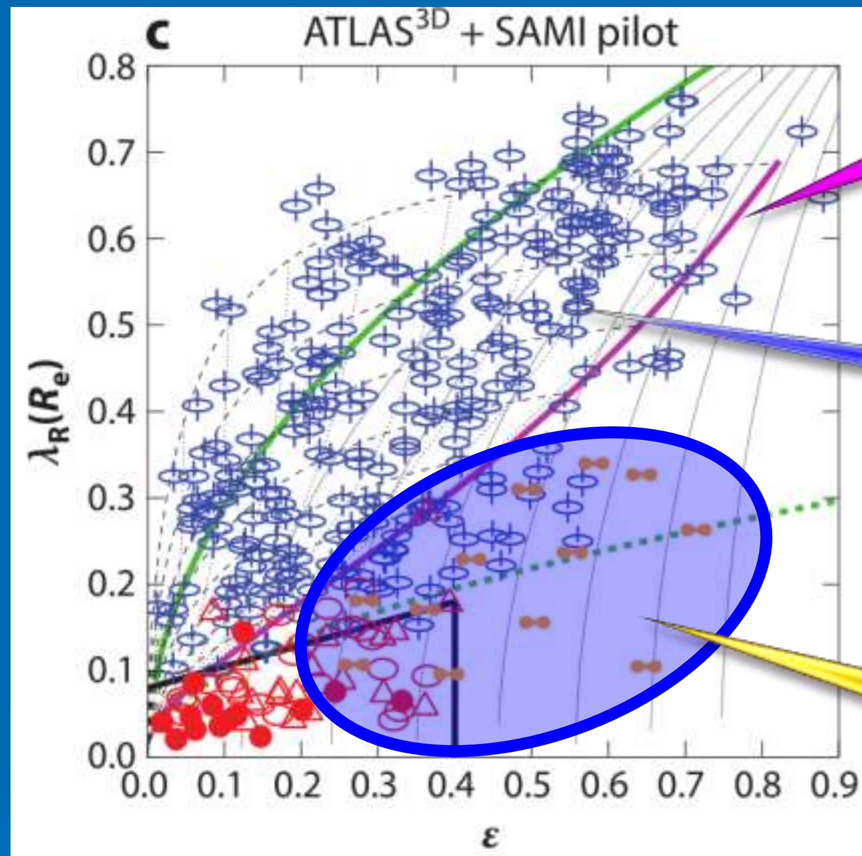
JAM dynamical models (Cappellari-16 ARA&A)

- Velocity reversal along major axis
- Double peak of velocity dispersion (2σ: Krajnovic+11)
- Low projected angular momentum
- But belong to the class of ETGs with disks

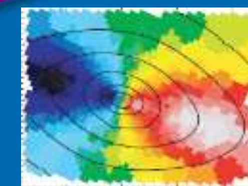
Counter-rotating disks on (λ_R, ϵ)

Cappellari-16 ARA&A

Data from:
Emsellem+11
Fogarty+15



Cappellari+07



Fast ETGs

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

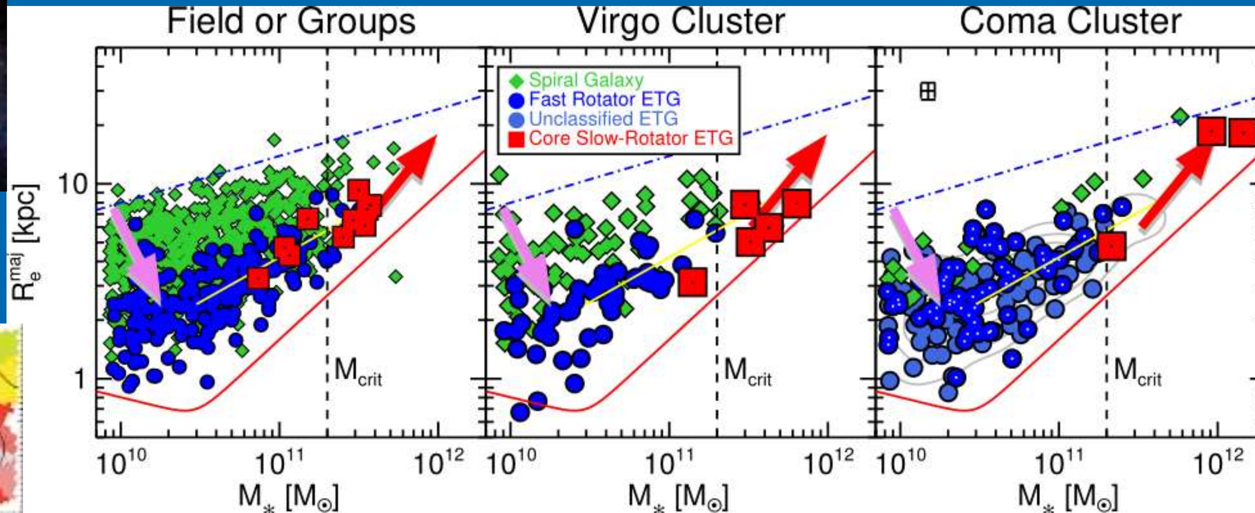
(Emsellem+07)

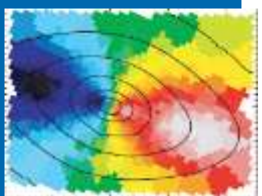
Counter Rotating

- Overlap with slow rotators on (λ_R, ϵ)
- But physically distinct and different mass distribution
- ‘Blind’ classification can affect conclusions

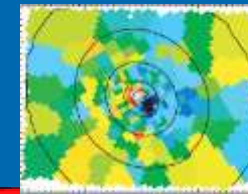
Two channels of galaxy evolution

spiral





fast ETG



slow ETG

Coma dark halo: $M \approx 1.4 \times 10^{15}\ M_\odot$ (Lokas+Mamon03)

$\Delta \log \Sigma_3 \sim 3$ increase in number density

Number Density or Halo Mass →

Kinematic classification from IFS (Cappellari-13 ApJL)

Spirals → Fast rotators

- Slow mass increase
- Environment quenching
- Bulge quenching

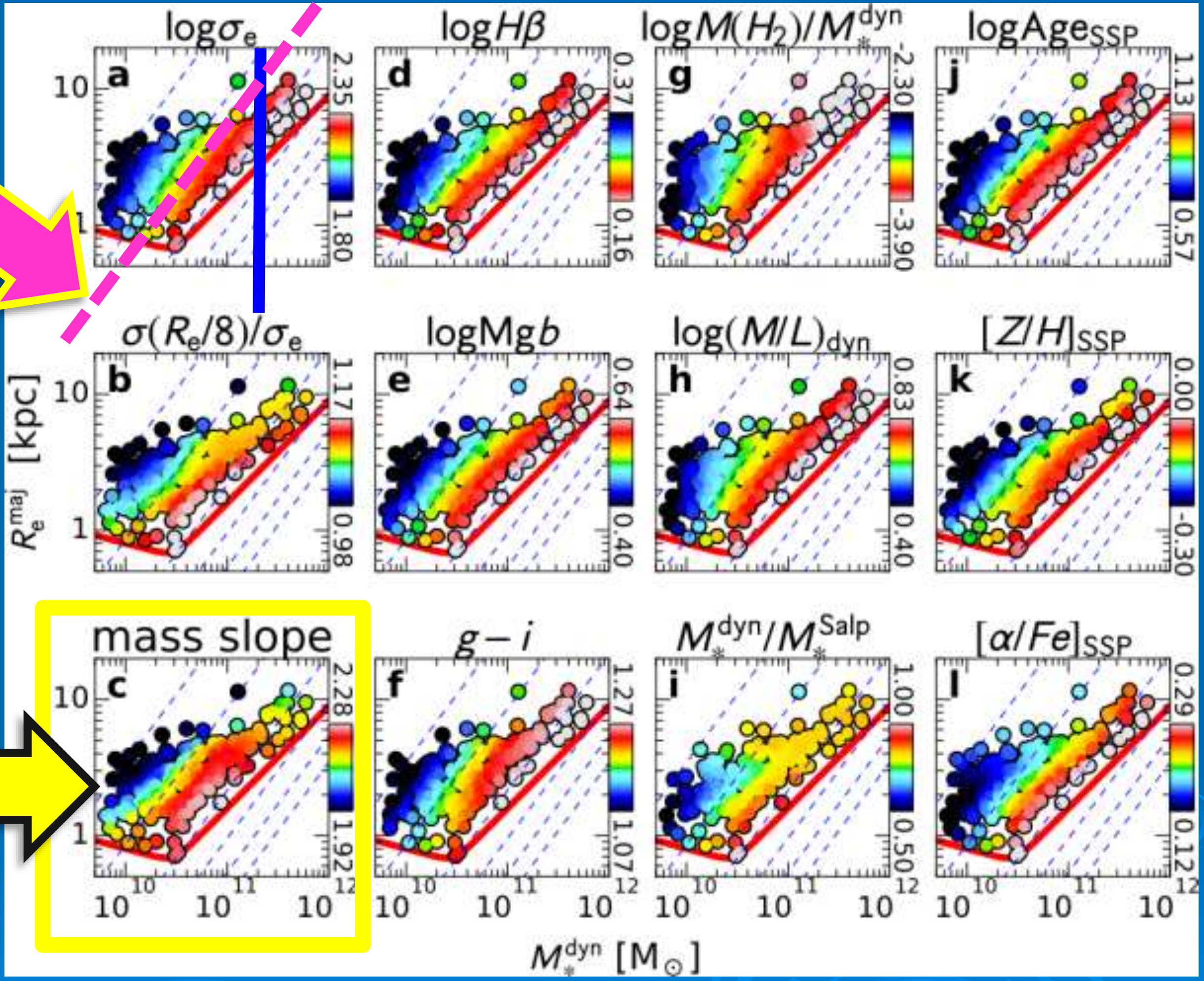
Core slow rotators →

- Mass growth $M \propto R_e$
- Halo quenching
- Dominate above $M_{\rm crit} \approx 2 \times 10^{11} M_\odot$

Properties driven by bulge fraction

- Bulge Fraction
- Density Slope

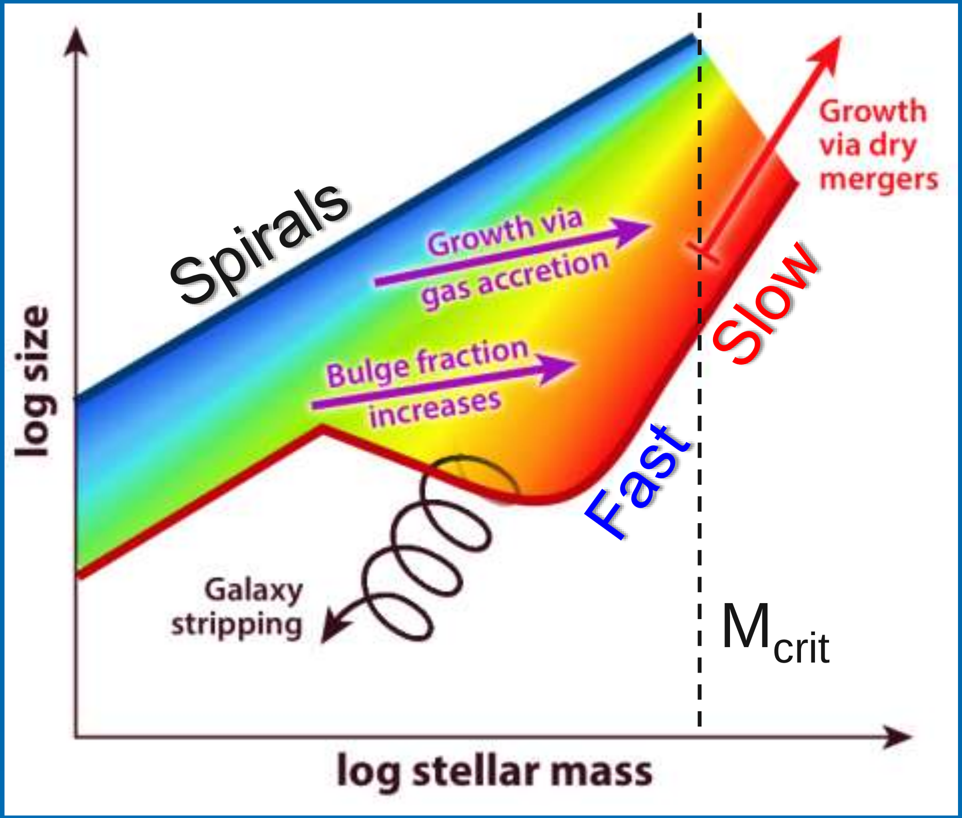
σ



- Below stellar mass $M_{\rm crit} \lesssim 2 \times 1011$
- Stellar population
- Molecular gas frac.
- Follow <u>total mass</u> slope
- Parallel to σ
- Traces bulge mass fraction

Cappellari-16 ARA&A
(data from Cappellari+13b & McDermid+15)

Summary of galaxy evolution



Cappellari-16 ARA&A

Based on:
Cappellari+11,13b
Van Dokkum+15

- Two channels of galaxy formation
- Also explains observed black hole scaling relations
  (e.g. Kormendy-Ho 13, Grahm-Scott13, van den Bosch-16)
- But galaxies do not follow both in sequence!