Studying galaxy formation with dynamical modelling

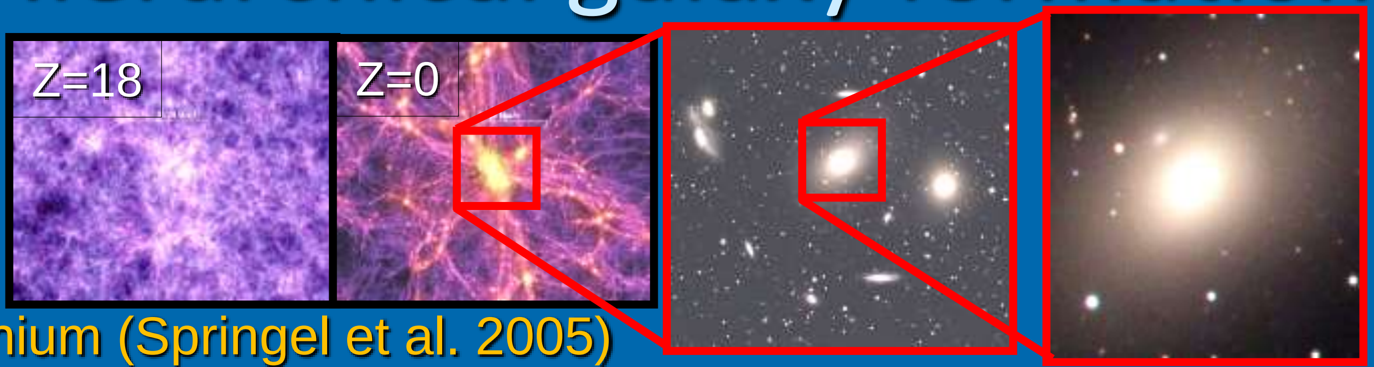
Michele Cappellari

UNIVERSITY OF OXFORD

THE ROYAL SOCIETY

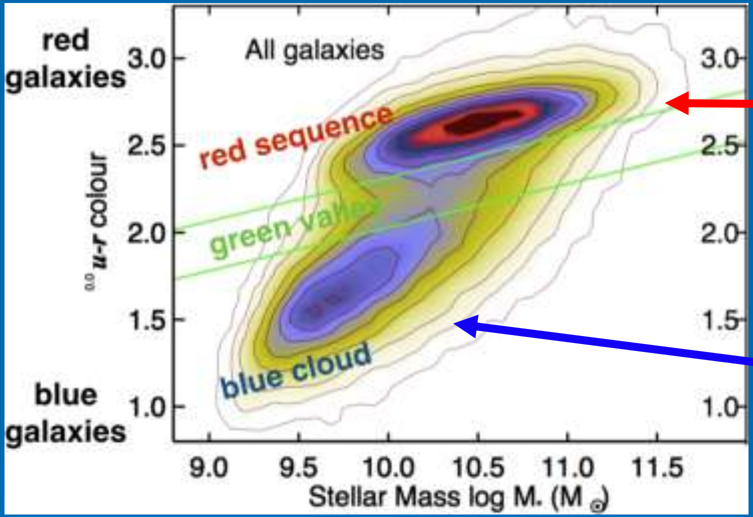
General framework

Hierarchical galaxy formation



Millennium (Springel et al. 2005)

(Schawinski+14)

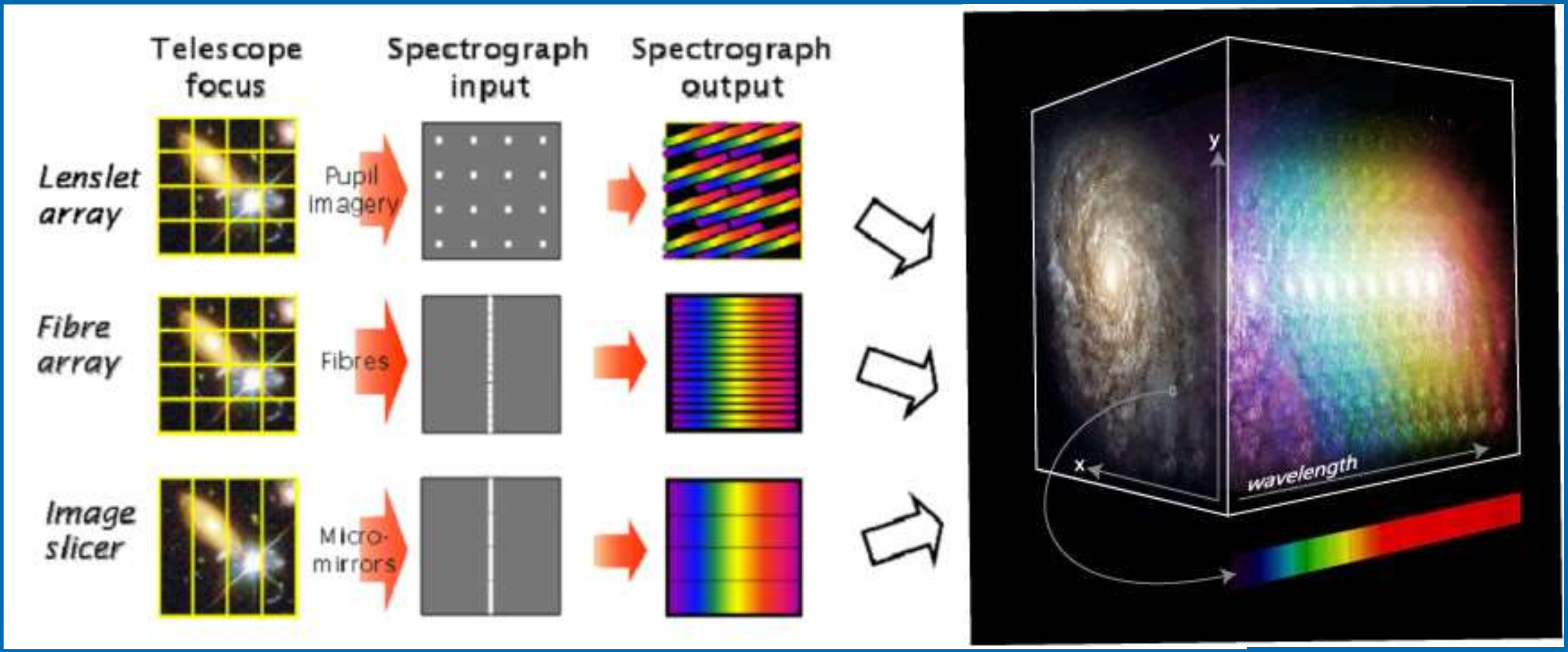


Early-type galaxy
= ETG

Spiral galaxy

- Bimodal galaxy colour distribution
- Mergers of blue galaxies → Red galaxies
- Feedback required for quick transition: Blue → Red
- Merger of red galaxies required to reach highest masses

What are the observables?

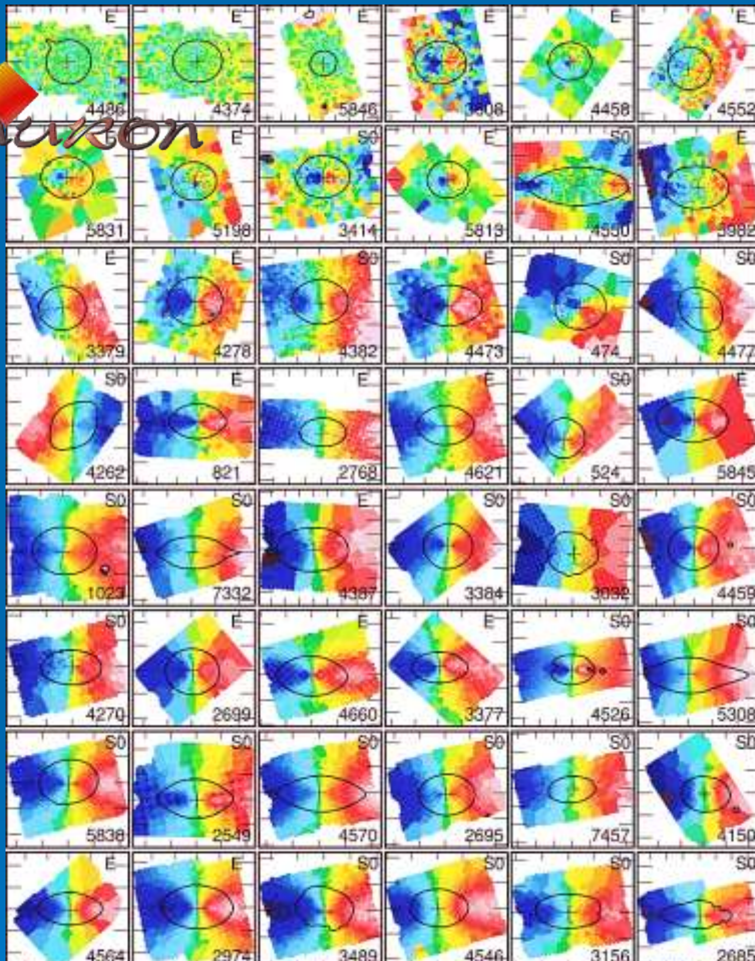


(Allington-Smith 2006)

- Integral-field spectroscopy (IFS)
- Various technical approaches
- All produce a three-dimensional data-cube

The revolution of IFS surveys

Stellar Kinematics

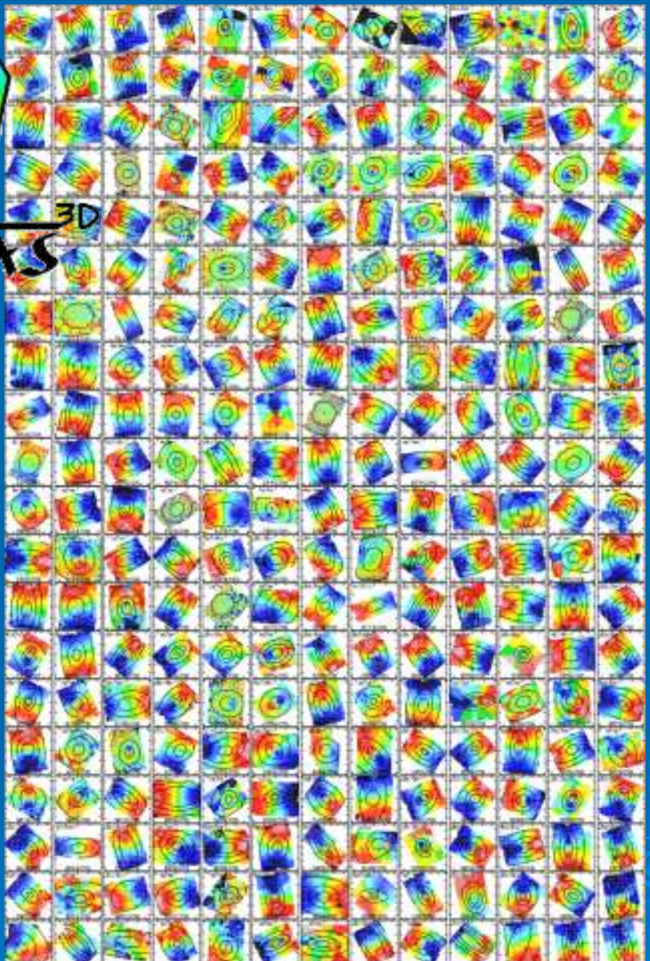


(Emsellem+04)

SAURON survey: deZeeuw+02

48 ETGs + 24 spirals

Stellar Kinematics



(Krajnovic+11)

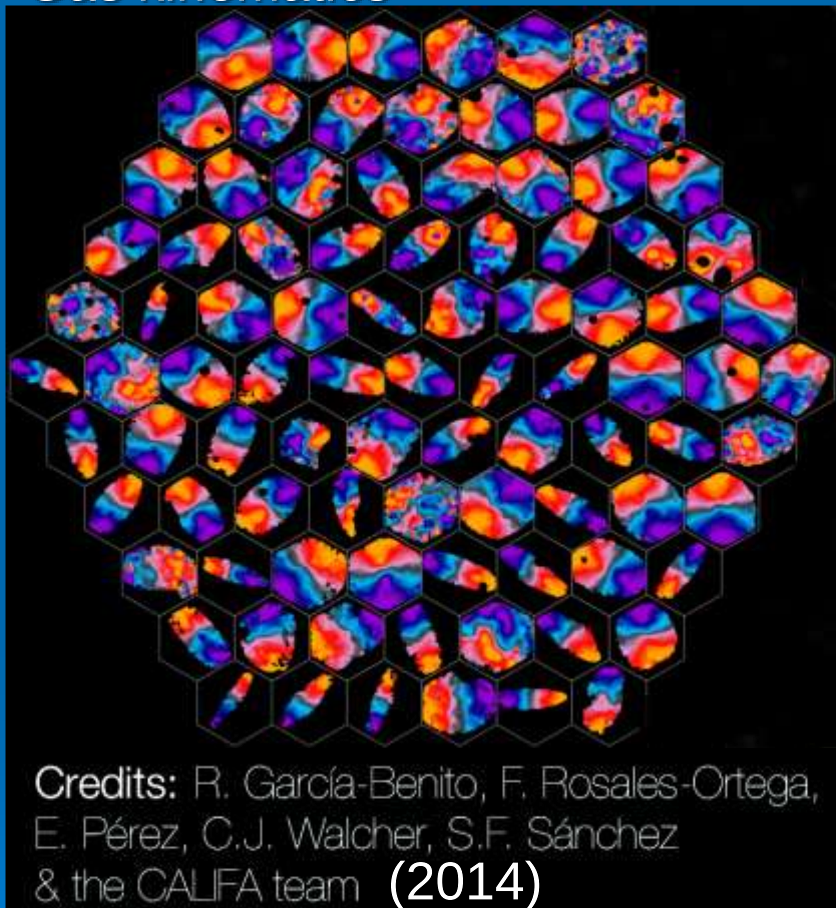
ATLAS^{3D} survey: Cappellari+11

260 ETGs volume-limited

http://purl.org/atlas3d

The race to large IFS samples

Gas kinematics



CALIFA survey: Sánchez+12
600 ETG + spiral galaxies planned, 200 in DR2
http://califaserv.caha.es/

MaNGA

sami galaxy survey

- Multiplexed surveys:
- SAMI 13 IFUs: Bryan+15
  - 3,400 galaxies planned
- MaNGA 17 IFUs: Bundy+15
  - 10,000 galaxies planned
- Hector: Bland-Hawthorn+15
  - 100,000 galaxies planned
  - Aims for end of the decade

Galaxy kinematics from data cubes

(Kinematics: Emsellem+04)

- Galaxy image gives 0^{th} velocity moment →Σ
- Each spectrum in data cube is Doppler shifted
- Spectrum shift gives 1^{st} velocity moment → V
- Lines broadening gives 2^{nd} moment → σ …

Dynamical modelling techniques

Main dynamical methods

- Orbit-superposition (Schwarzschild 1979)
  - Spherical: Richstone & Tremaine (1988)
  - Axisymmetric: van der Marel et al. (1998)
  - Triaxial: van den Bosch et al. (2008)
- Velocity moments (Jeans 1922)
  - Isotropic: Binney et al. (1990)
  - Anisotropic: Cappellari (2008)

Schwarzschild's (1979) method

- Assume steady state (Jeans theorem)

$$DF = f\left(x, y, z, v_x, v_y, v_z\right) = f(\boldsymbol{I})$$

- Find complete set of basis functions for DF

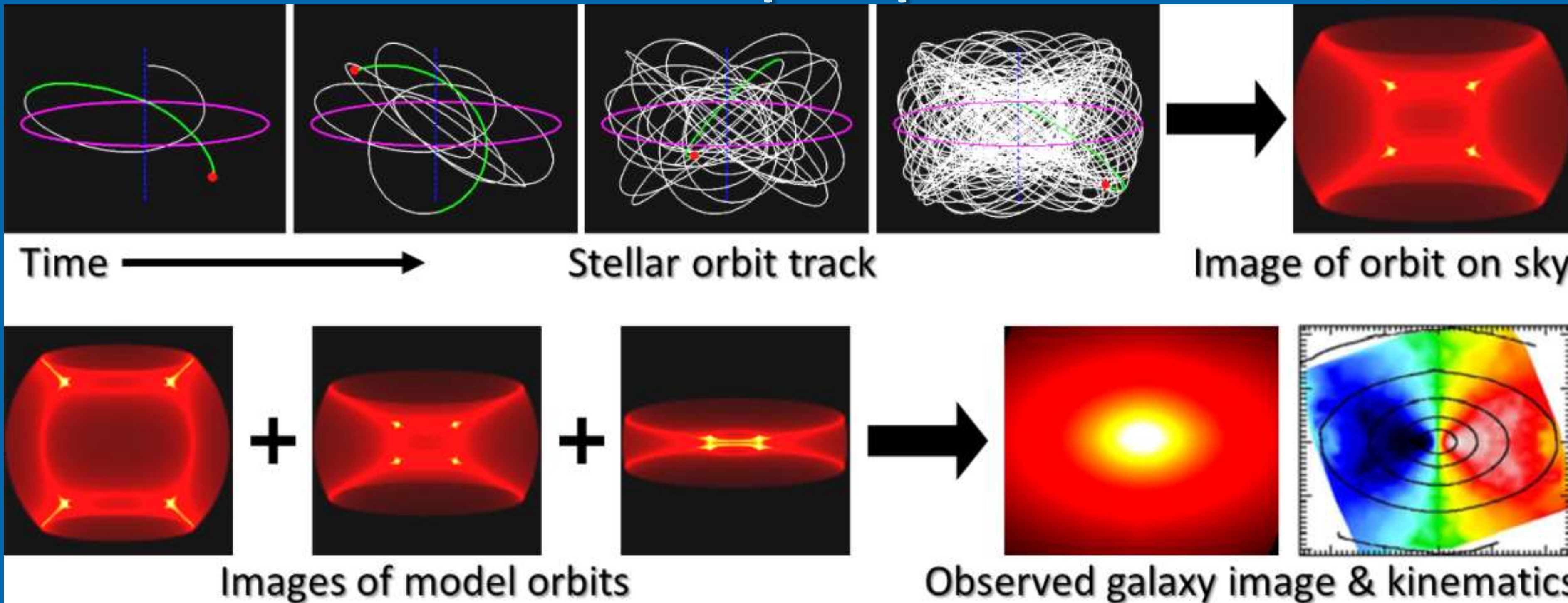
$$DF = \sum_j w_j F_j(\boldsymbol{I})$$

- Linear superposition of observables

$$O_\alpha(x', y') = \sum_j G_\alpha[F_j(\boldsymbol{I})]$$

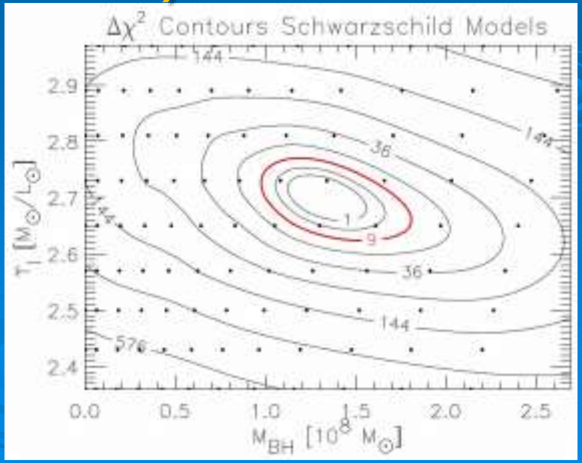
- Key idea: basis functions F_j are stellar orbits

Orbital superposition



(Cappellari 2015)

- Orbital set changes with gravitational potential (e.g. black hole or dark matter)
- Find the set of orbits that better fits the data



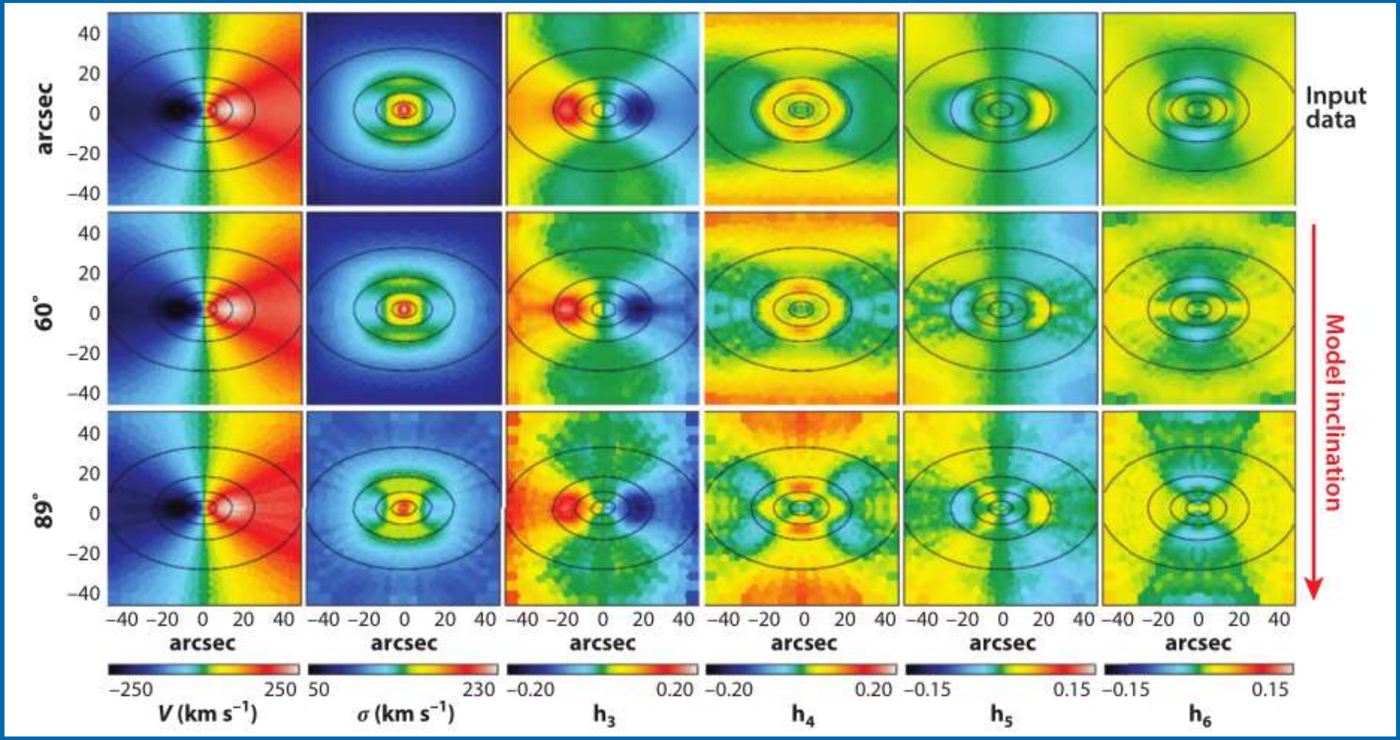
Fit orbits to observables

- With *N* orbits and *M* observables to fit
- Problem to solve in the least-squares sense:

$$\begin{pmatrix} p_{1,1} & \cdots & p_{1,N} \\ \vdots & \ddots & \vdots \\ p_{M,1} & \cdots & p_{M,N} \end{pmatrix} \begin{pmatrix} w_1 \\ \vdots \\ w_N \end{pmatrix} = \begin{pmatrix} o_1 \\ \vdots \\ o_M \end{pmatrix}$$

- $\min_{x}\{||\boldsymbol{A}x - b||\}\ \mathit{with}\ x > 0$
- Is a Non-Negative Least-Squares problem
- Has a unique (possibly degenerate) minimum
- Efficient algorithms exist (NNLS or quadratic prog.)

Intrinsic dynamical degeneracy



(Krajnovic+05)

- Orbital distribution is 3D → 3D data (=IFU) needed
- But even 3D data not sufficient to constrain both DF and potential (two 3D functions)
- Degeneracies are expected! See inclination above ↑

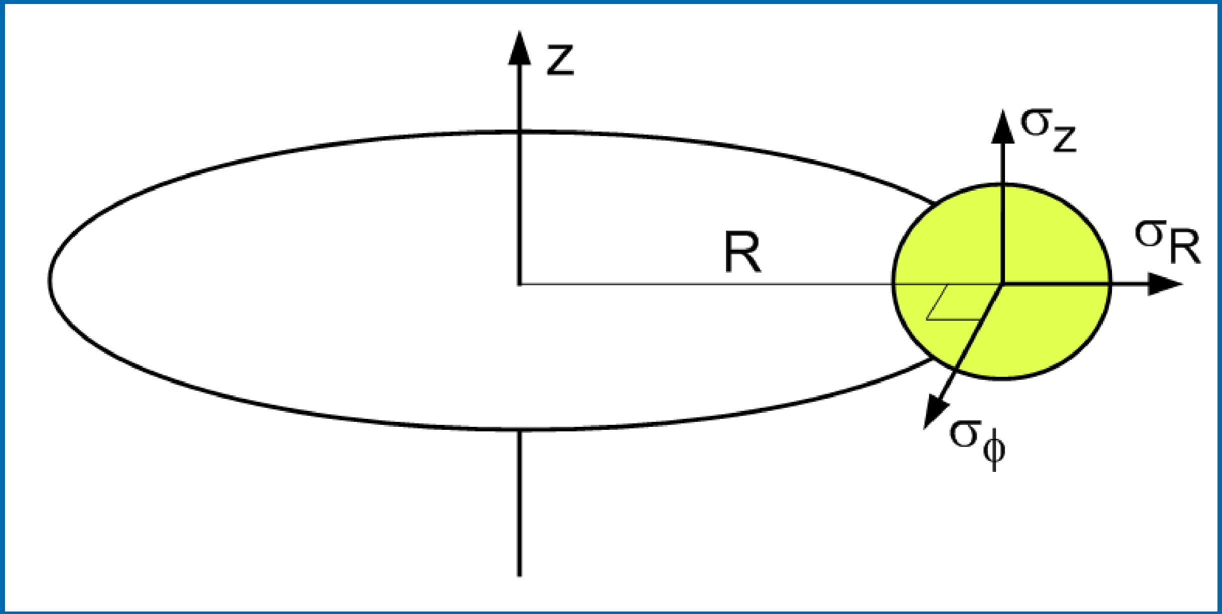
Spherical Jeans (1922) equations

- Think hydrodynamics: pressure → σ
- Gravity balanced by σ (velocity 2nd moment)
- Simplest spherical form

$$\nu \frac{GM(r)}{r^2} = \frac{d}{dr}\left[\nu\sigma^2(r)\right] \rightarrow \rho g(z) = -\frac{d}{dz}P(z)$$

- Infer $\nu(r)$ from photometry $\Sigma(R)$
- Adopt parametrization for total mass
- Calculate PSF-convolved $\sigma_{los}(R)$
- Fit model to data

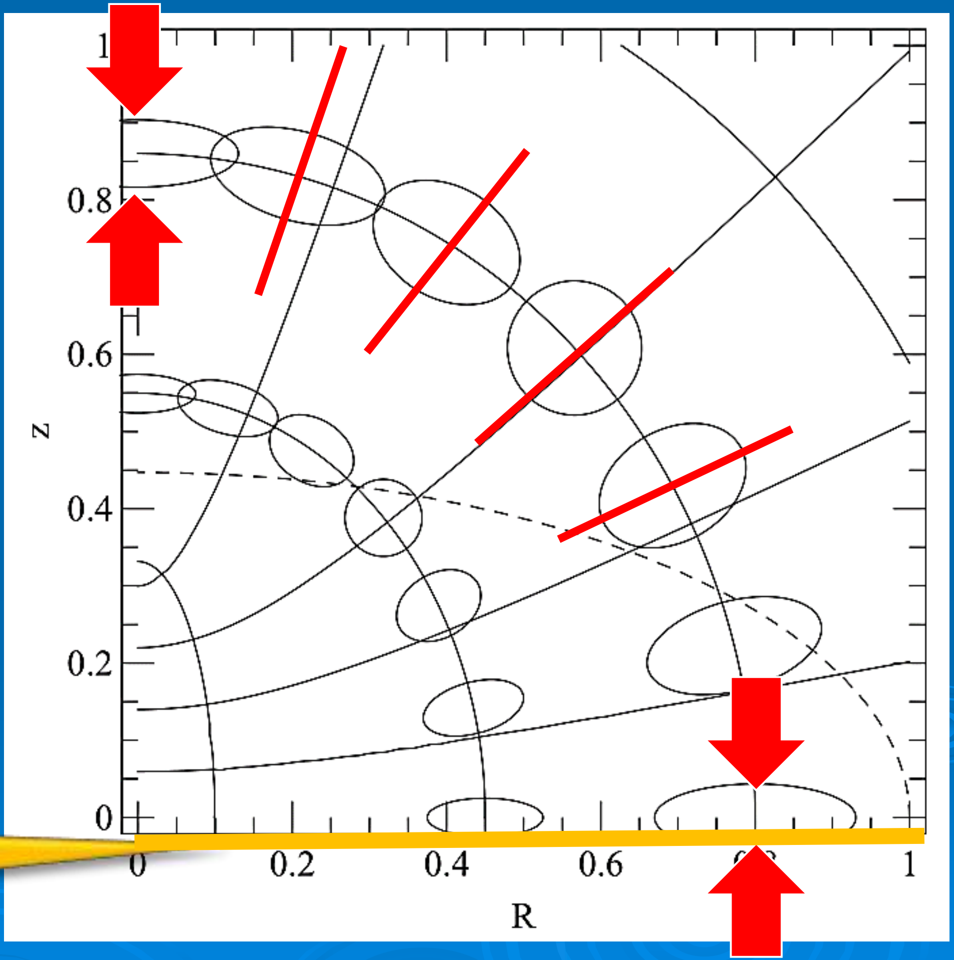
Solving axisymmetric Jeans eq.



- Focus on velocity second moments $\langle v_{jk}^2 \rangle$ only
- Assume shape of velocity ellipsoid (2 ratios)
- Solve hydrostatic equilibrium equations
- Can this simple model describe real galaxies?

Velocity ellipsoid in regular rotators

- Velocity ellipsoid from Schwarzschild's models
- Nearly spherically aligned beyond 1Re
- $\sigma_R \approx \sigma_\phi$
- $\sigma_z < \sigma_R$ on equatorial plane & symmetry axis (Cappellari+07; Thomas+09)



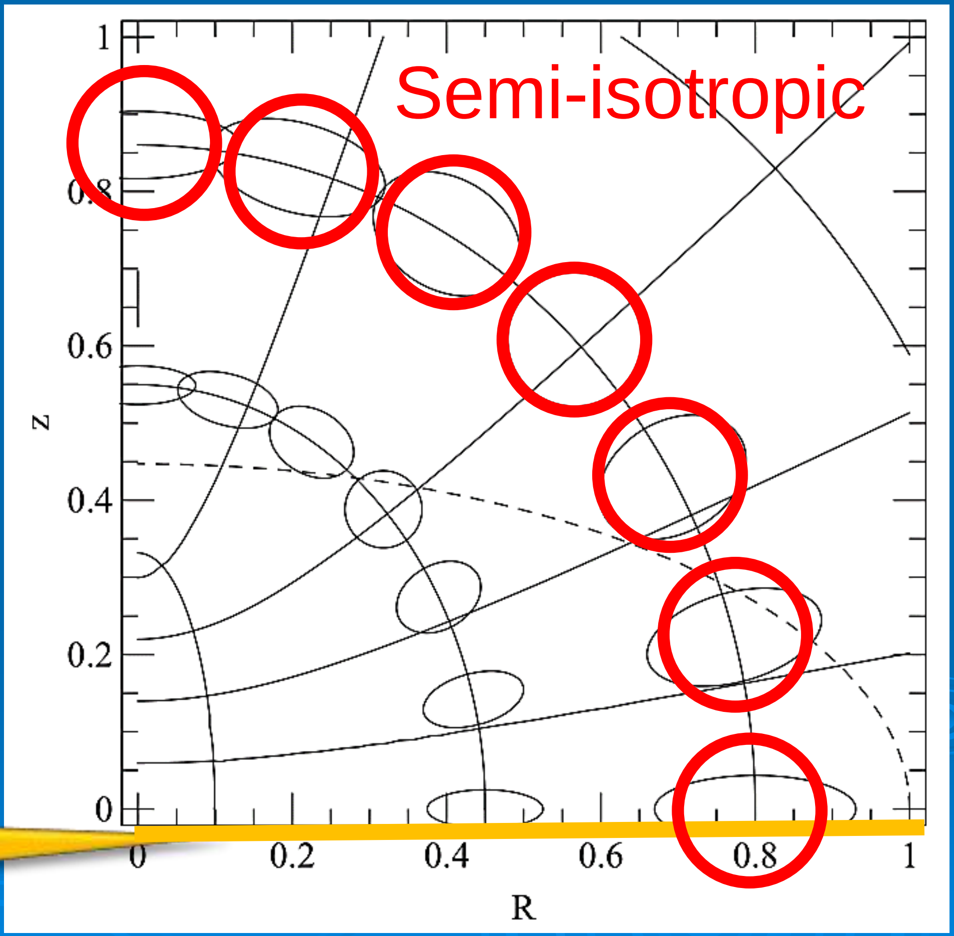
Maximum density along line-of-sight

(Cappellari 2008)

Velocity ellipsoid in regular rotators

- Velocity ellipsoid from Schwarzschild's models
- Nearly spherically aligned beyond 1Re
- $\sigma_R \approx \sigma_\phi$
- $\sigma_z < \sigma_R$ on equatorial plane & symmetry axis (Cappellari+07; Thomas+09)

Maximum density along line-of-sight

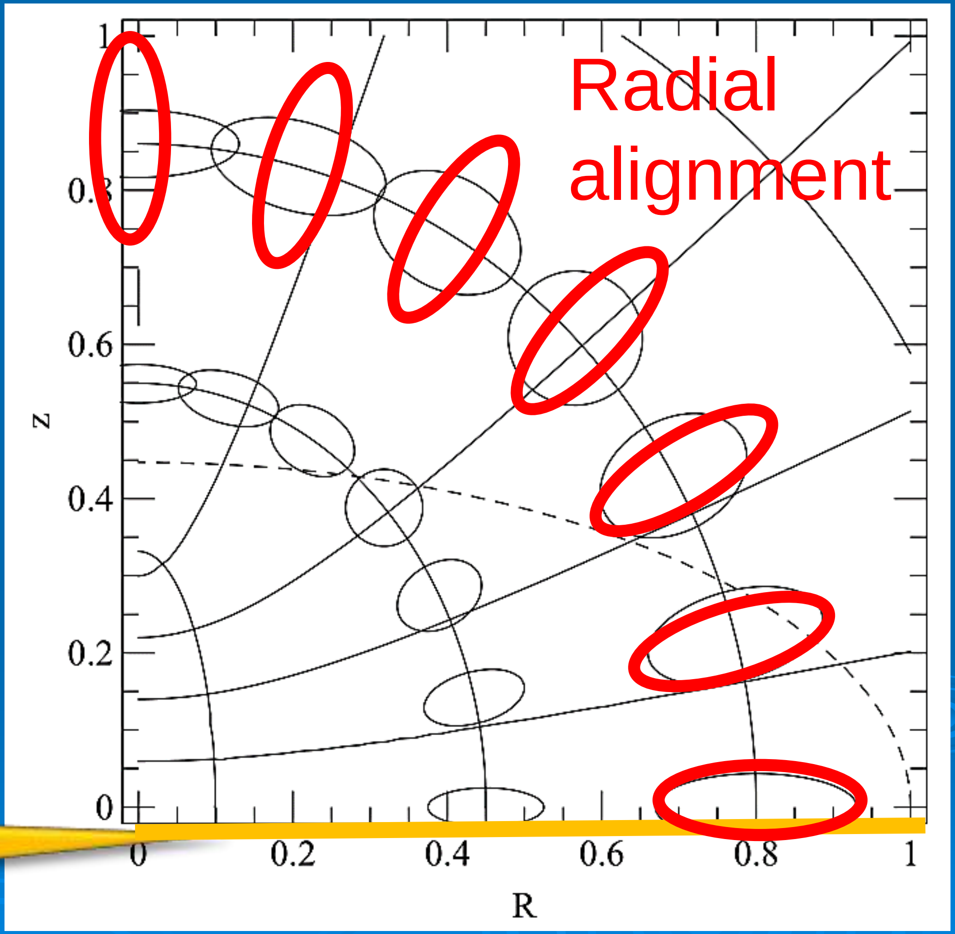


(Cappellari 2008)

Velocity ellipsoid in regular rotators

- Velocity ellipsoid from Schwarzschild's models
- Nearly spherically aligned beyond 1Re
- $\sigma_R \approx \sigma_\phi$
- $\sigma_z < \sigma_R$ on equatorial plane & symmetry axis (Cappellari+07; Thomas+09)

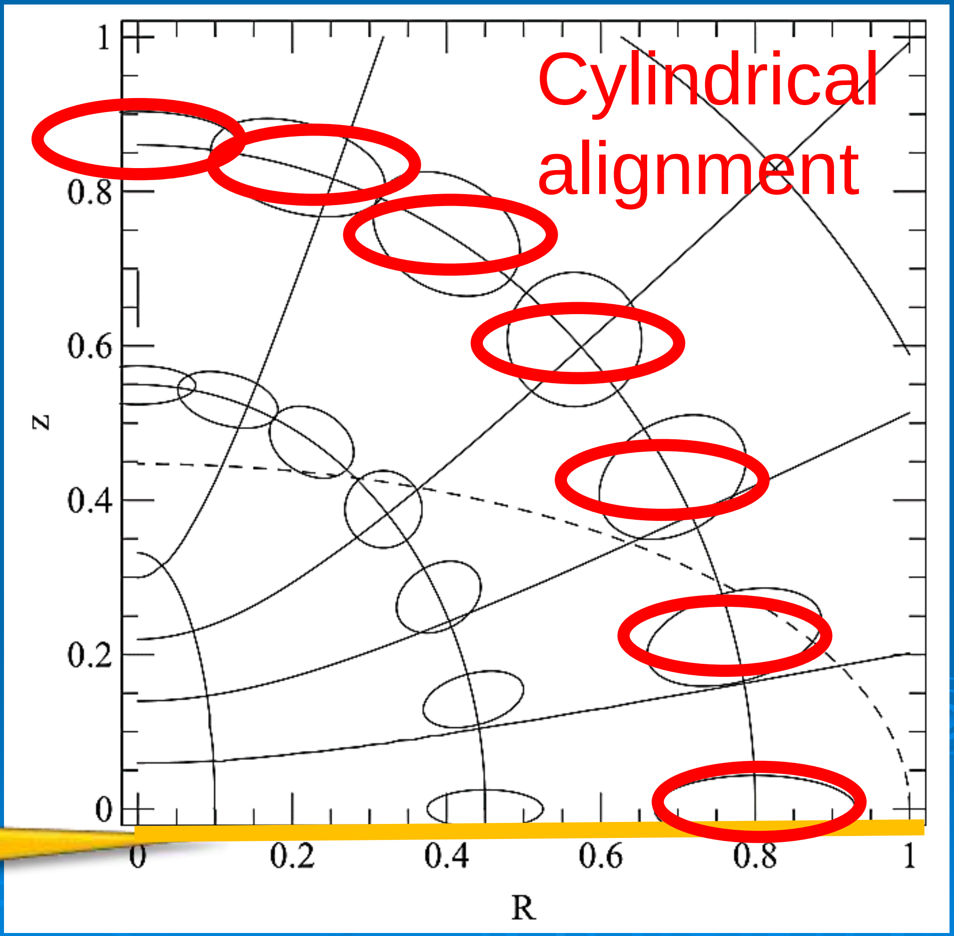
Maximum density along line-of-sight



(Cappellari 2008)

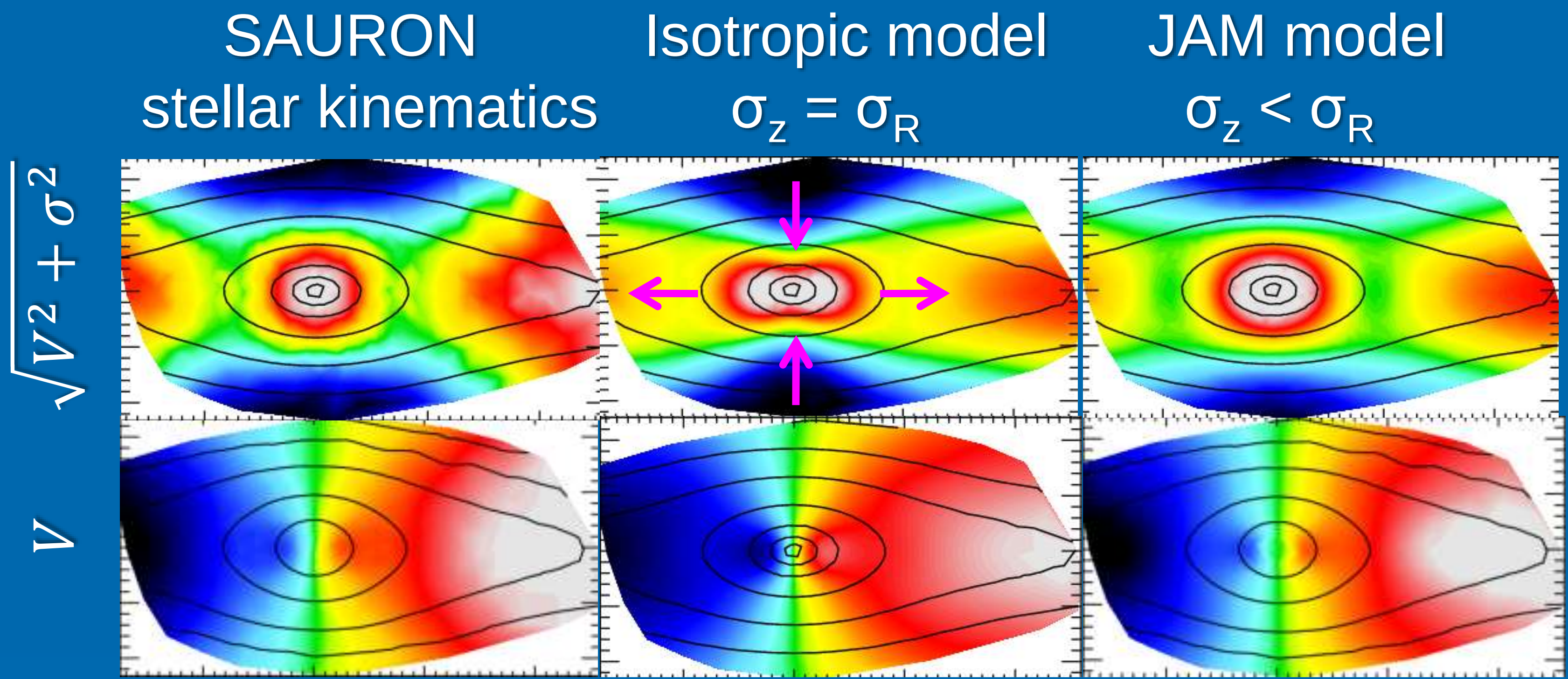
Velocity ellipsoid in regular rotators

- Velocity ellipsoid from Schwarzschild's models
- Nearly spherically aligned beyond 1Re
- $\sigma_R \approx \sigma_\phi$
- $\sigma_z < \sigma_R$ on equatorial plane & symmetry axis (Cappellari+07; Thomas+09)



(Cappellari 2008)

Jeans Anisotropic Models (JAM)

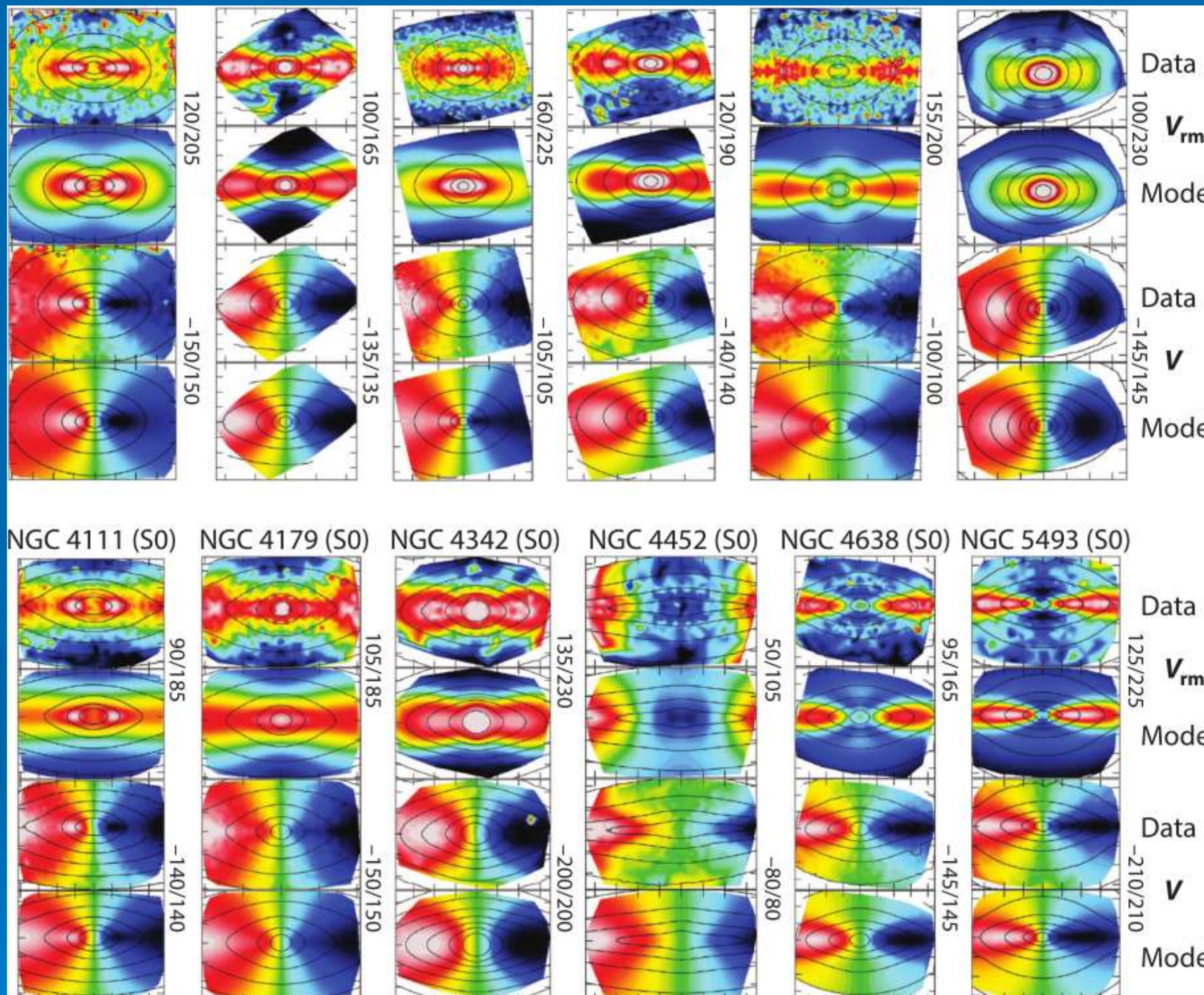


- Use Multi-Gaussian fit to images (Emsellem+94; Cappellari-02)
- Efficient Jeans solution with $\sigma_z \neq \sigma_R \neq \sigma_\phi$ (Cappellari-08)
- Just two parameters $(i, \sigma_z/\sigma_R)$ fit shape of both V_{rms} and V! (http://purl.org/cappellari/software)

Galaxy structure from kinematics/dynamics

Fast kinematics very homogeneous

E



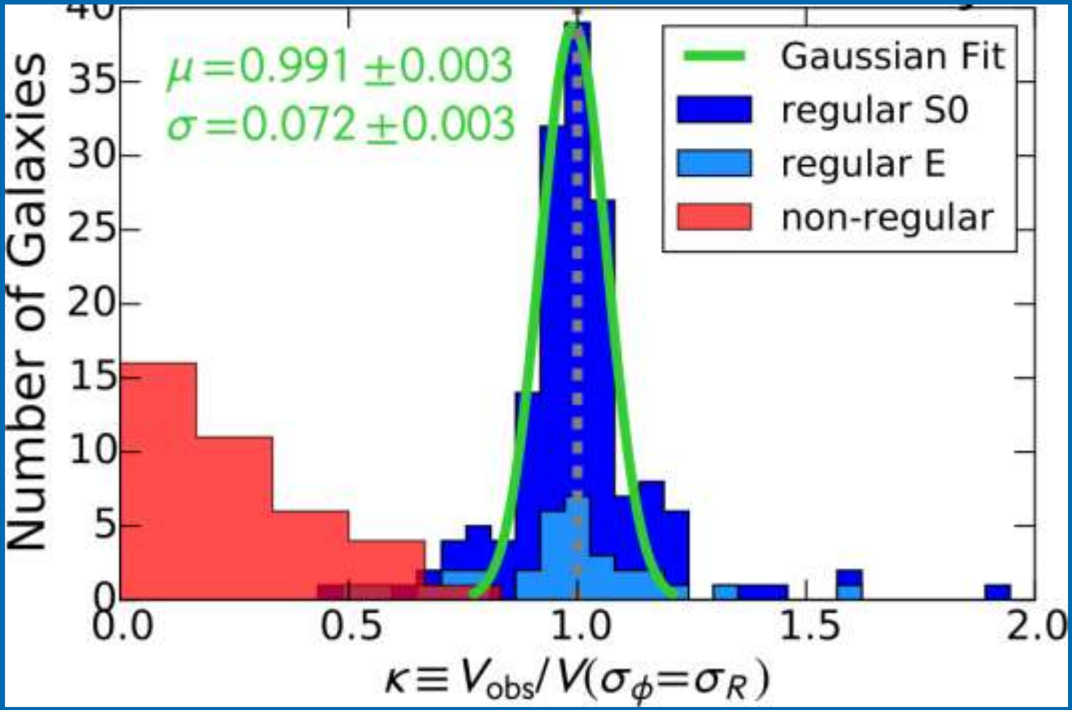
S0

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

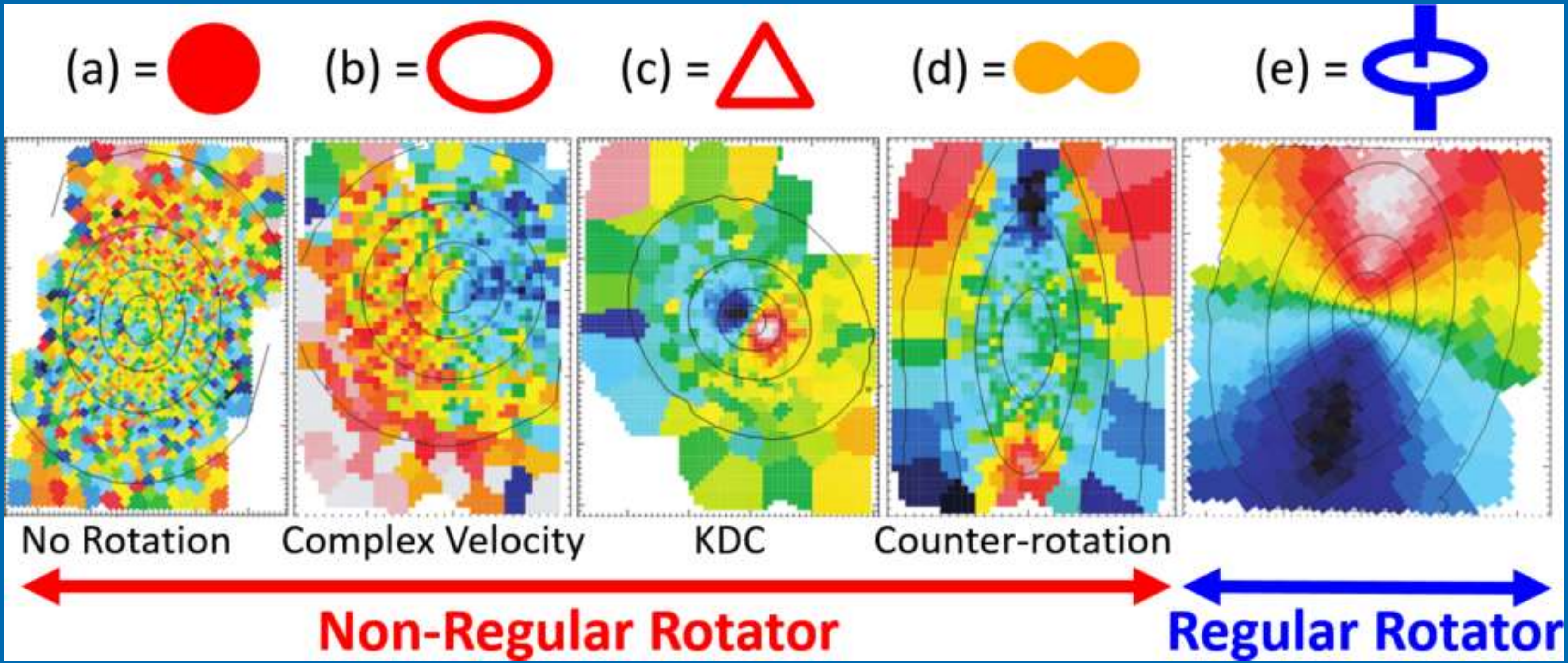
Fast/slow: rotation dichotomy



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

Kinematic Morphology



(From Krajnovic+11)

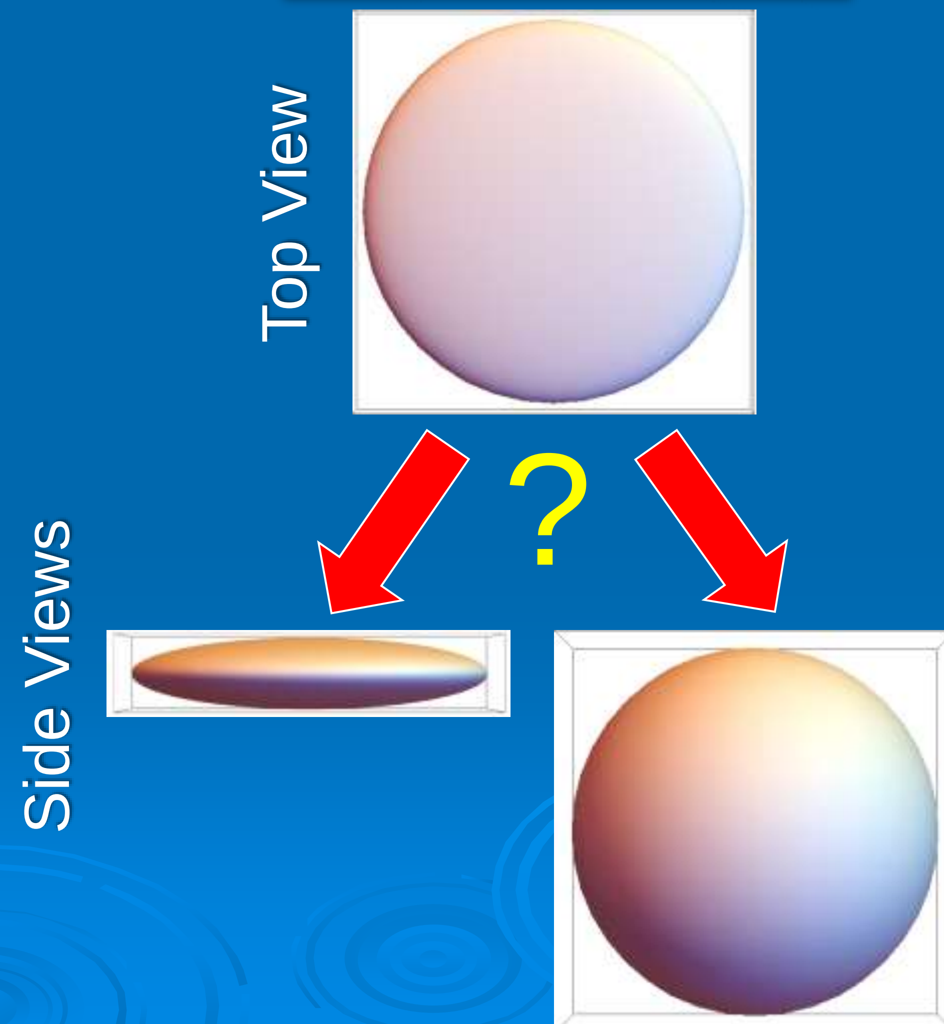
- Variety of kinematic maps
- But two major classes: non-regular/regular

What is the shape of ellipticals?

Credit: SDSS

- Trivial concept
- Difficult solution
- Profound implications

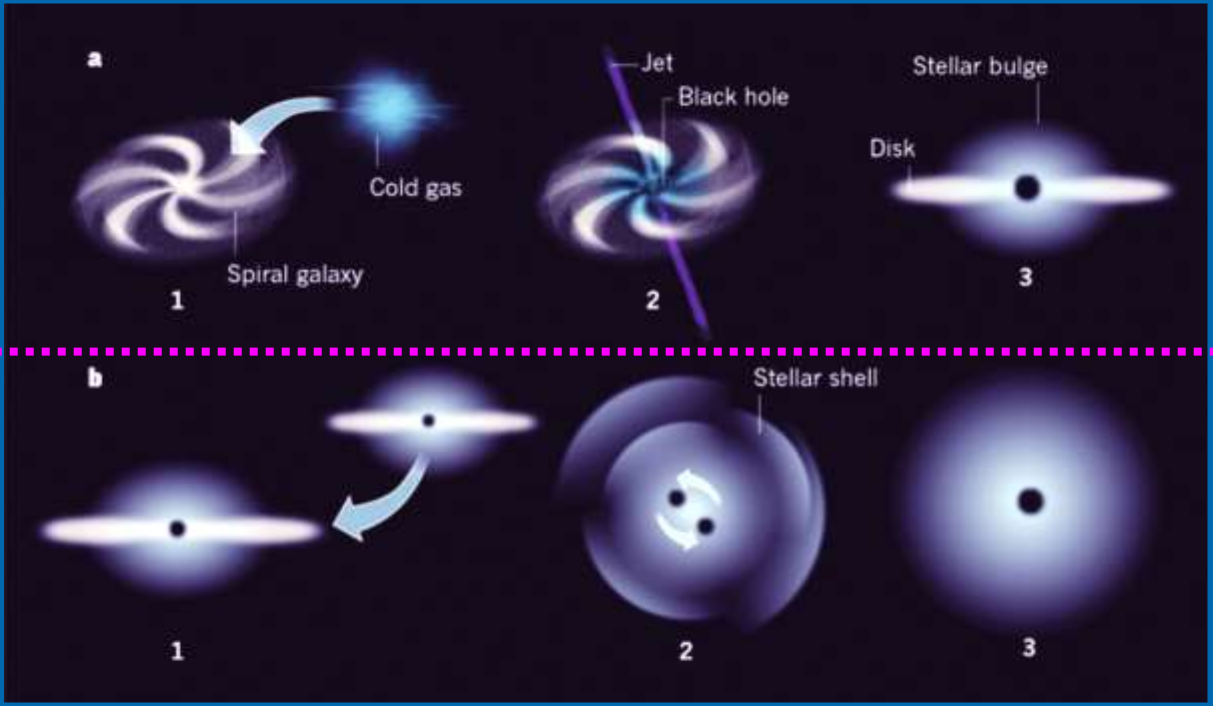
Sphere or disk?



Key accretion processes

Gas accretion

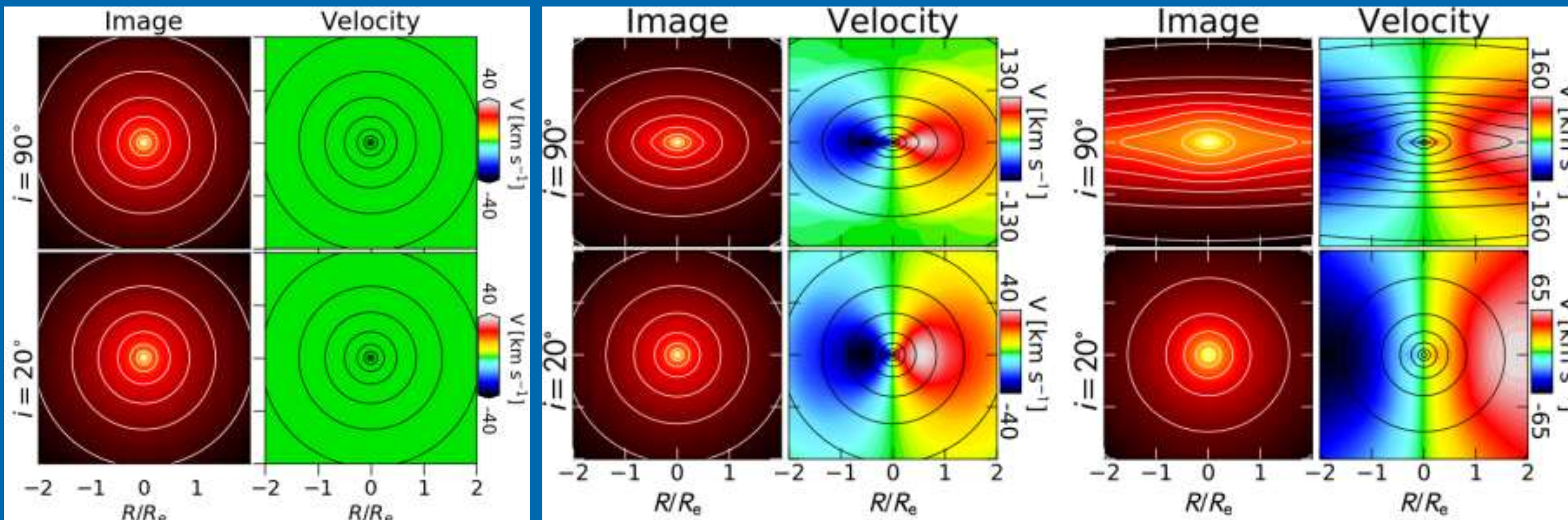
Dry mergers



(Cappellari-11 Nature)

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

Recognizing disks using dynamics



Spherical Galaxy | Disky Elliptical | S0

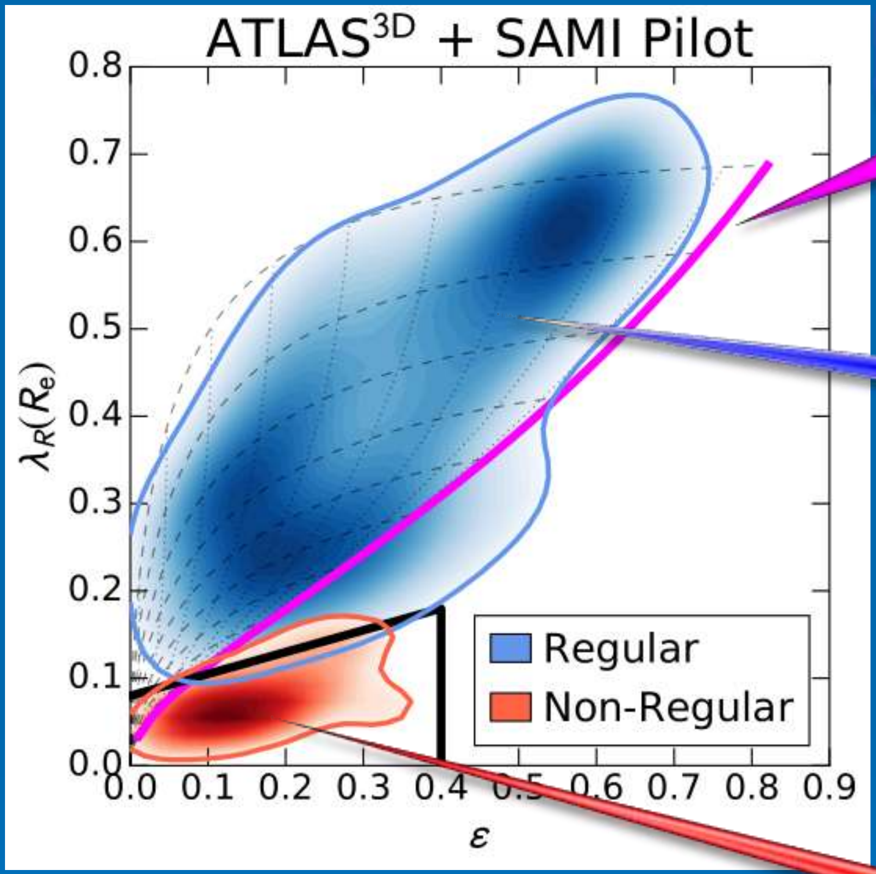
(Cappellari-16 ARA&A)

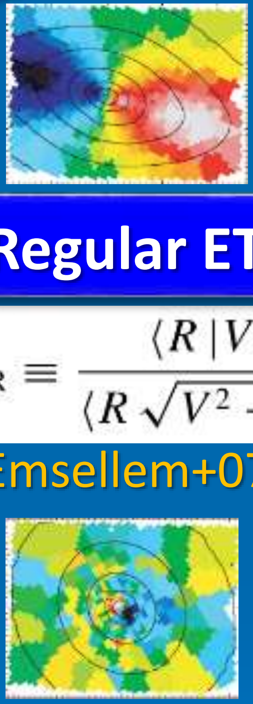
- Dynamics identifies nearly face-on disks
- Only $\lesssim$ 2% of disk can be missed

Stellar angular momentum

Cappellari-16 ARA&A

Data from:
Emsellem+11
Fogarty+15





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

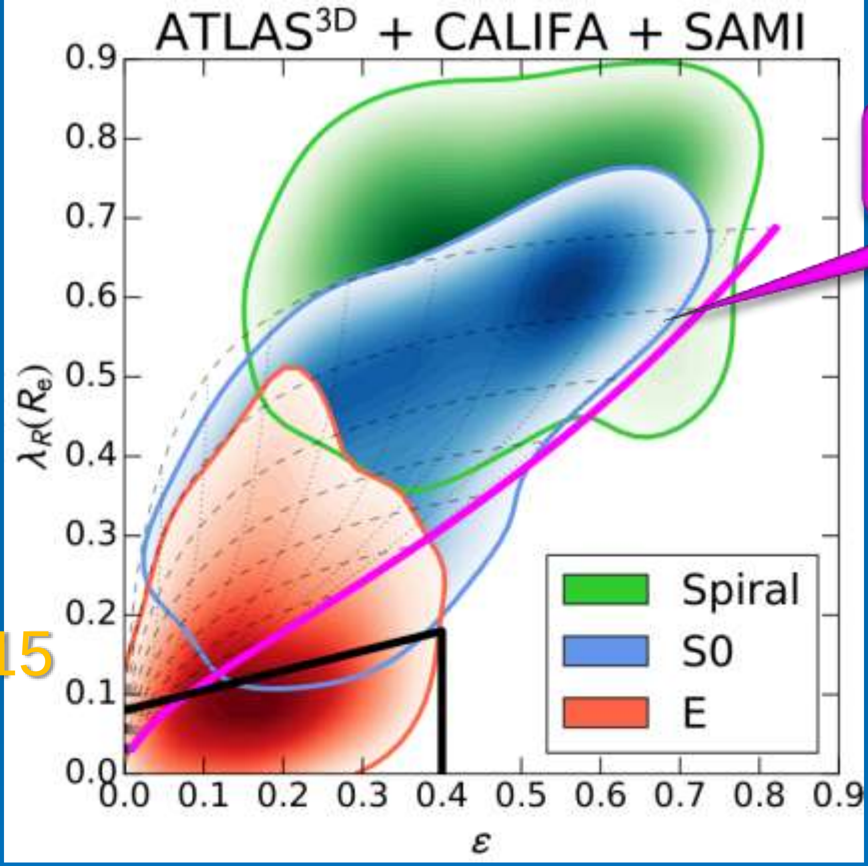
(Emsellem+07)

- Fast rotator → inclined disk galaxies
- Consistent with anisotropy trend from dynamics
- Slow rotator → weakly triaxial $c/a > 0.75$

E/S0 are poor proxy for kinematics

Cappellari-16
ARA&A

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



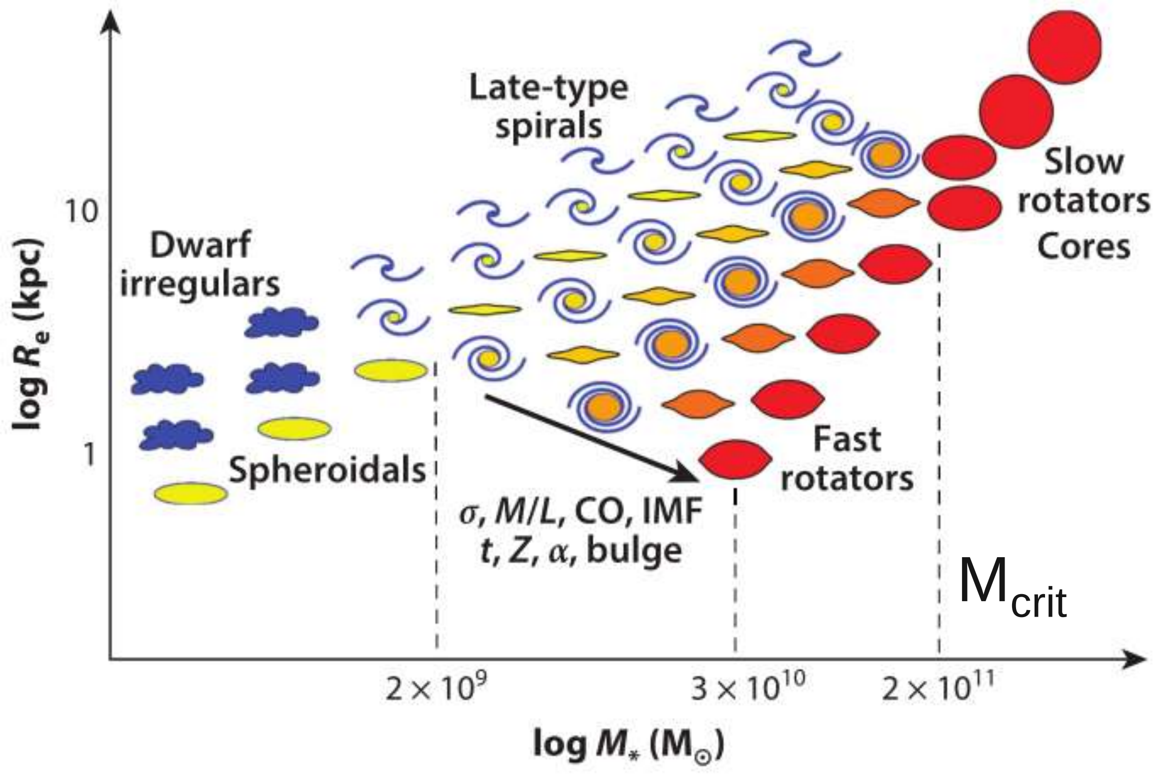
Cappellari+07

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

(Emsellem+07)

- Expected trend angular momentum vs. morphology
- Explained by variation in bulge fraction
- 2/3 of classic ellipticals from RC3 are fast rotators!

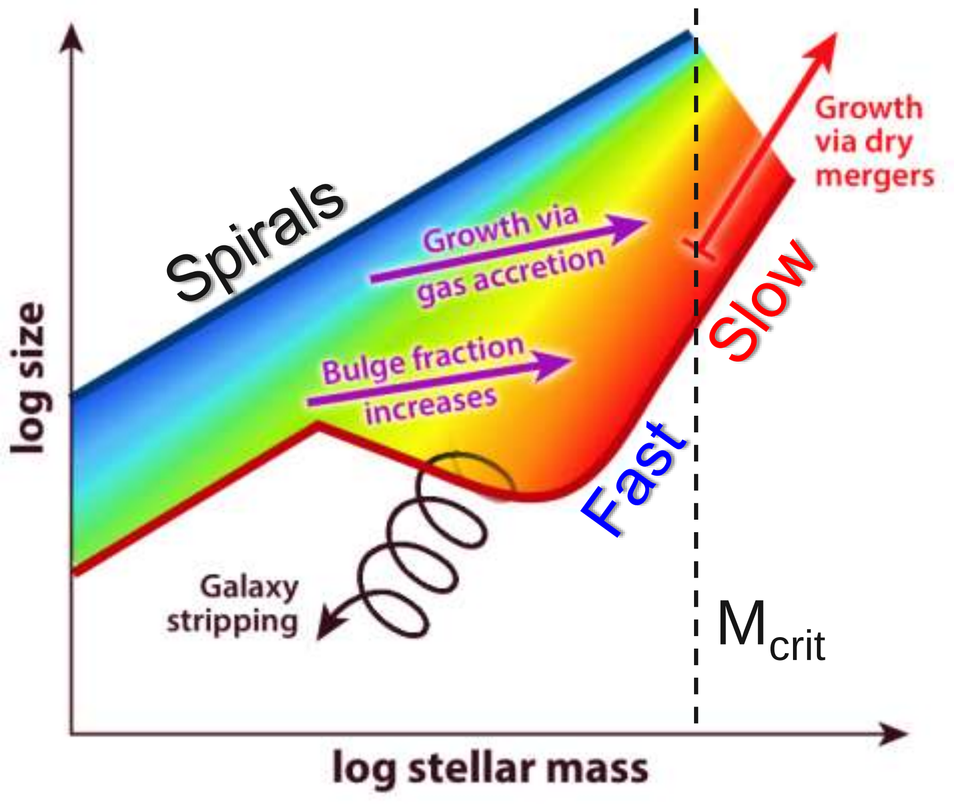
Summary of galaxy structure



(Cappellari+13b)

- Bulge fraction linked to quenching of star formation
  (see Cappellari+11b; Kauffmann+12; Bell+12; Cheung+12; Fang+12)
- Three characteristic galaxy stellar masses
  (cfr. Davies+83; Faber+97; Kauffmann+03; van der Wel+09; Geha+12)

Summary of galaxy evolution

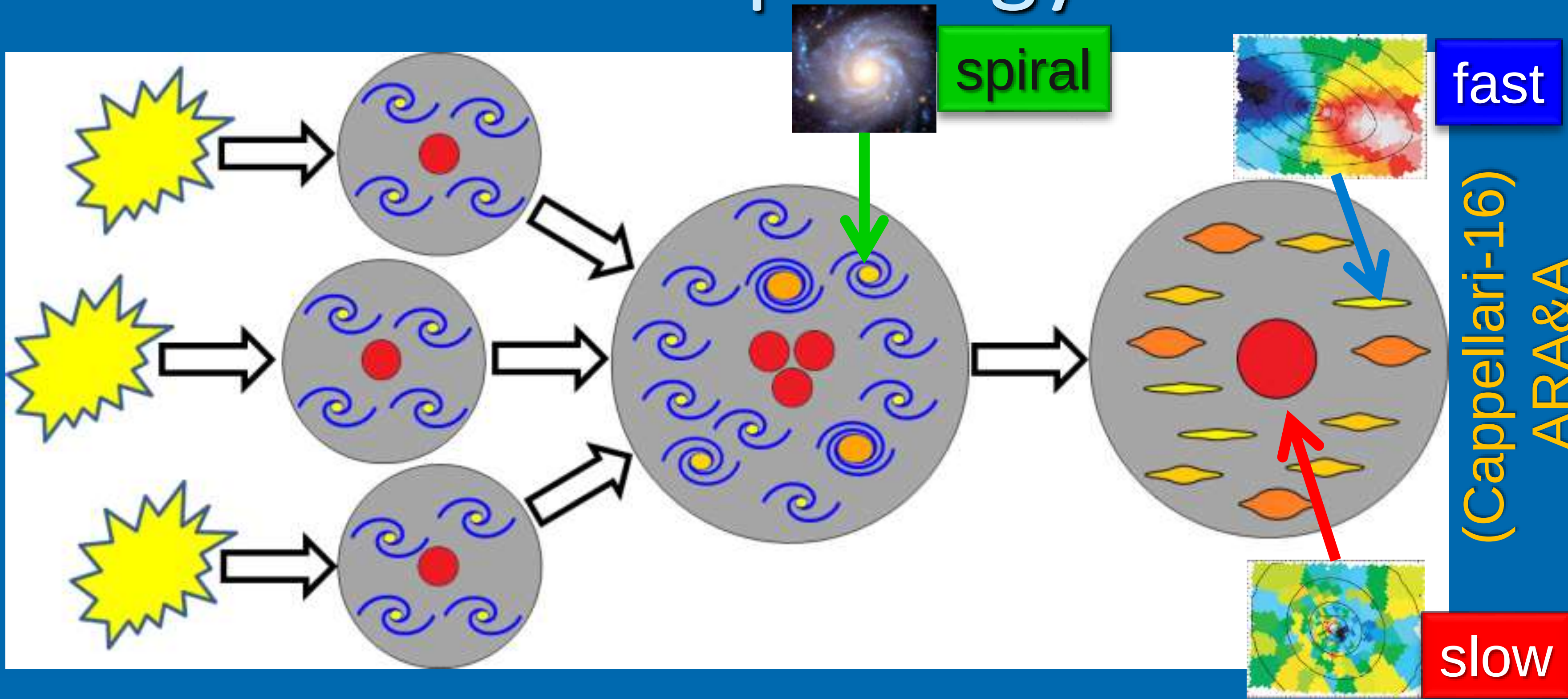


Cappellari-16 ARA&A

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

- Two channels of galaxy formation (e.g. Khochfar+11)
- Also explains observed black hole scaling relations (e.g. Kormendy-Ho 13, Grahm-Scott13, Krajnovic+17)
- But galaxies do not follow both in sequence!

Hierarchical morphology evolution



Fast rotators

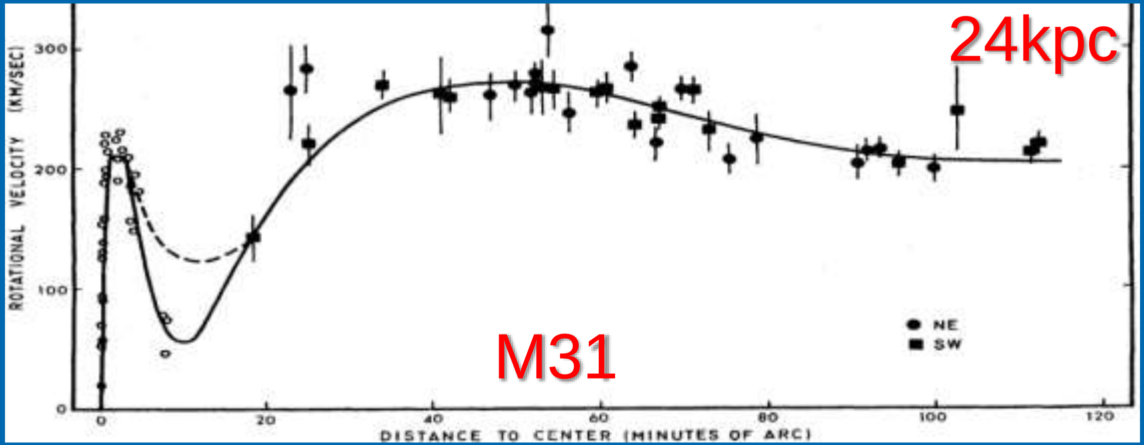
- Generally satellites or isolated
- Quenched by environment
- Or by internal processes
- Bulge grows with quenching

Core slow rotators

- Generally near halo centre
- Sink by dynamical friction
- Mass grows by dry mergers
- Halo quenching

Galaxy density profiles and dark matter

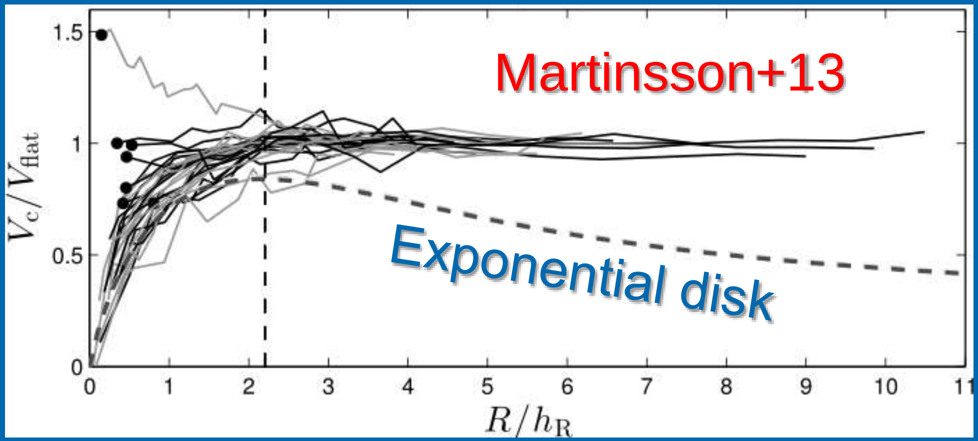
Spirals rotation from ionized gas

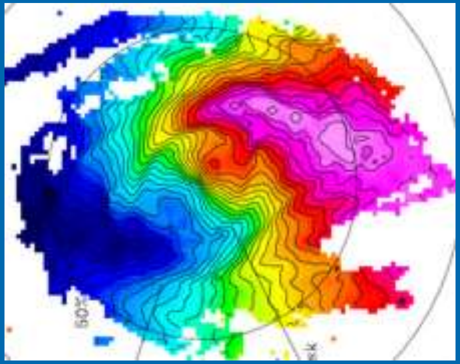


- Extended curves from ionized gas (Rubin-Ford70; Roberts-Whitehurst75; Rubin+80)
- Outer curves remain flat
- Limited to optical disk
- No connection to dark matter made
- Need to estimate baryonic mass

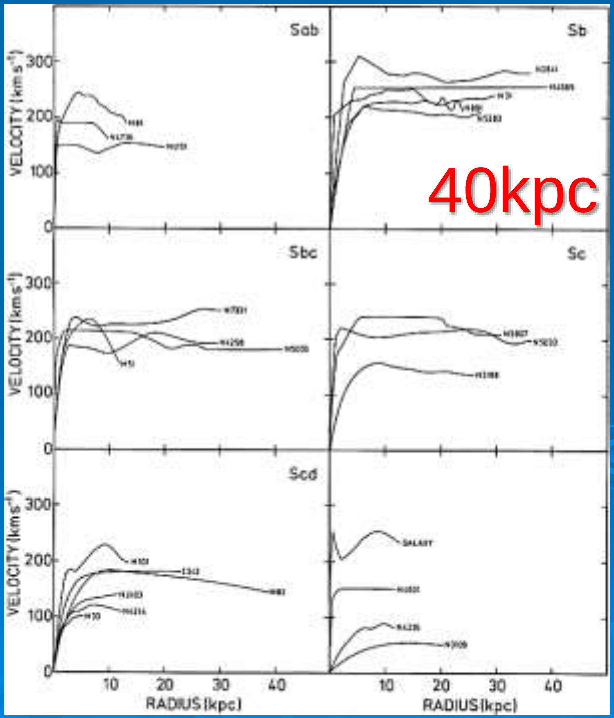
At Lowell Observatory
© Bob Rubin

Spirals rotation from HI





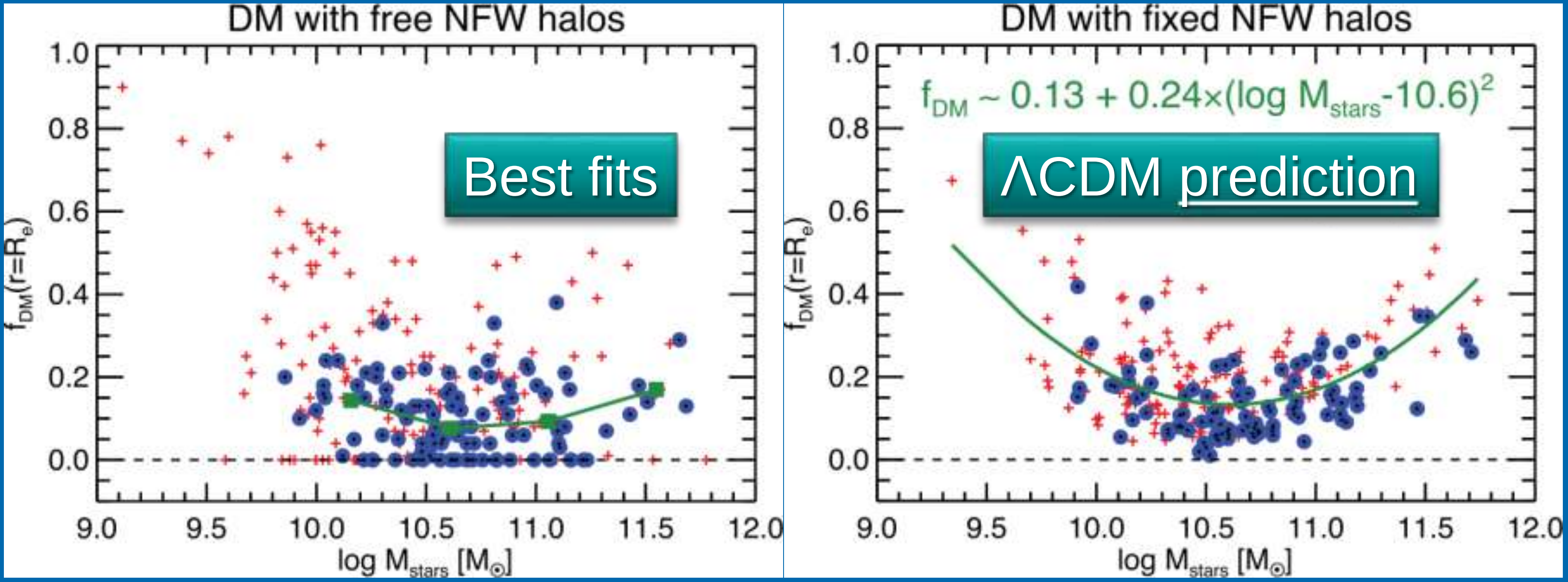
Miller+09



Bosma78

- Radio HI observations
- Extend well beyond images
- Rotation curves still flat
- "it seems relatively certain that dark material is being detected"
  (Faber+Gallager79 ARA&A)

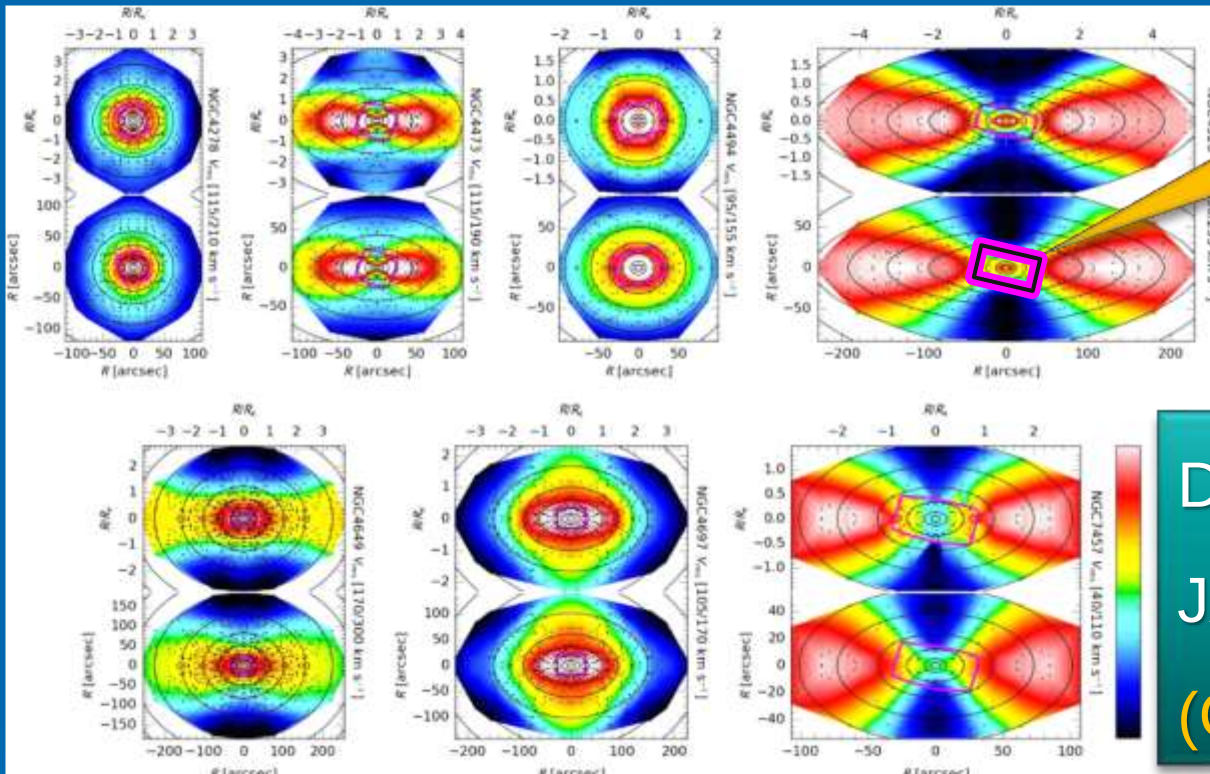
Little dark matter in ETGs centres (1R_e)



(Cappellari+13a)

- Best fitting median $f_{DM}(R_e) = 13\%$
- Fully consistent with ΛCDM prediction
  - Fixed-halo models fitted to real ATLAS^{3D} galaxies
  - Use NFW following $M_{200} - M_\star$ and $M_{200} - c_{200}$ (Moster+10, Behroozi+10, Guo+10)

ETGs 2-dim dynamics to $4R_e$



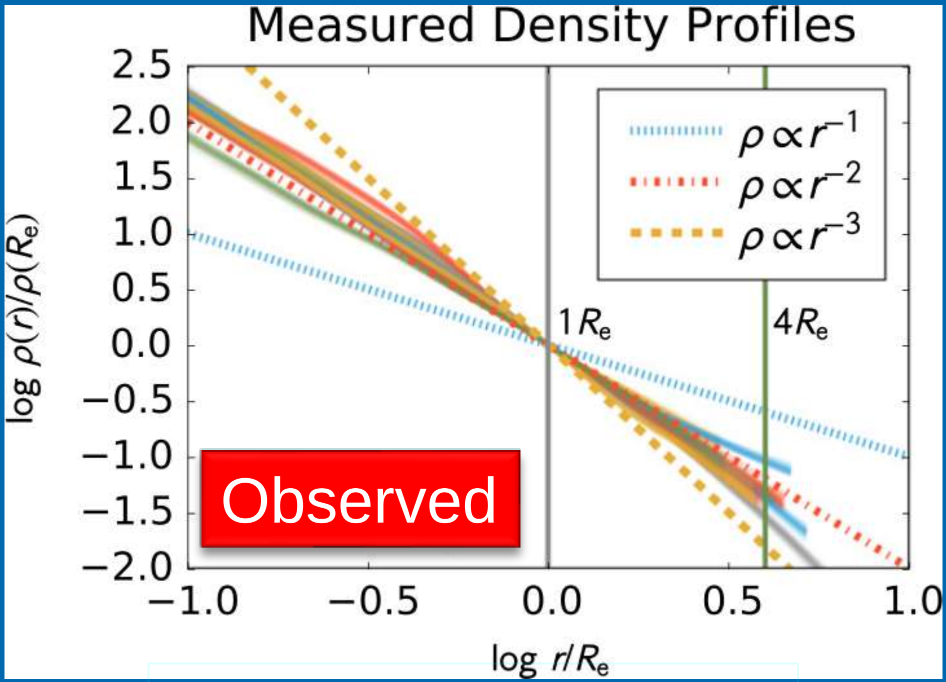
This is the tiny SAURON FoV!

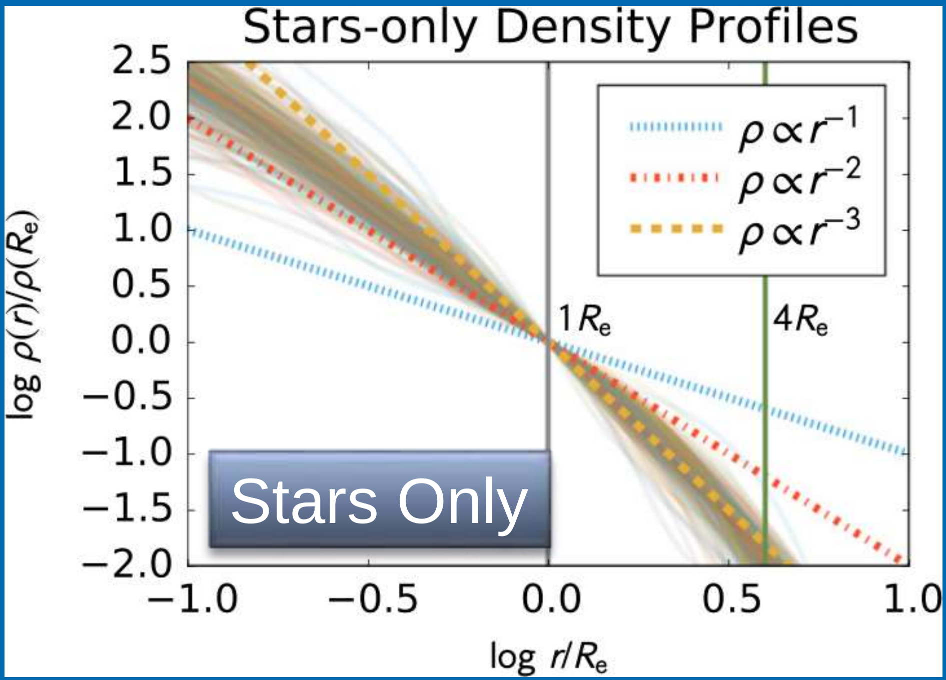
Data versus JAM  Models V_{rms}

(Cappellari+15 ApJL)

- 14 fast rotator ETGs ($10.2 < \log M_*/M_\odot < 11.7$)
- Model ATLAS^{3D} + SLUGGS stellar kinematics
- Median coverage of 4Re (2.0-6.2R_e)
- Sample dynamics where dark matter dominates

ETG profiles are like in spirals

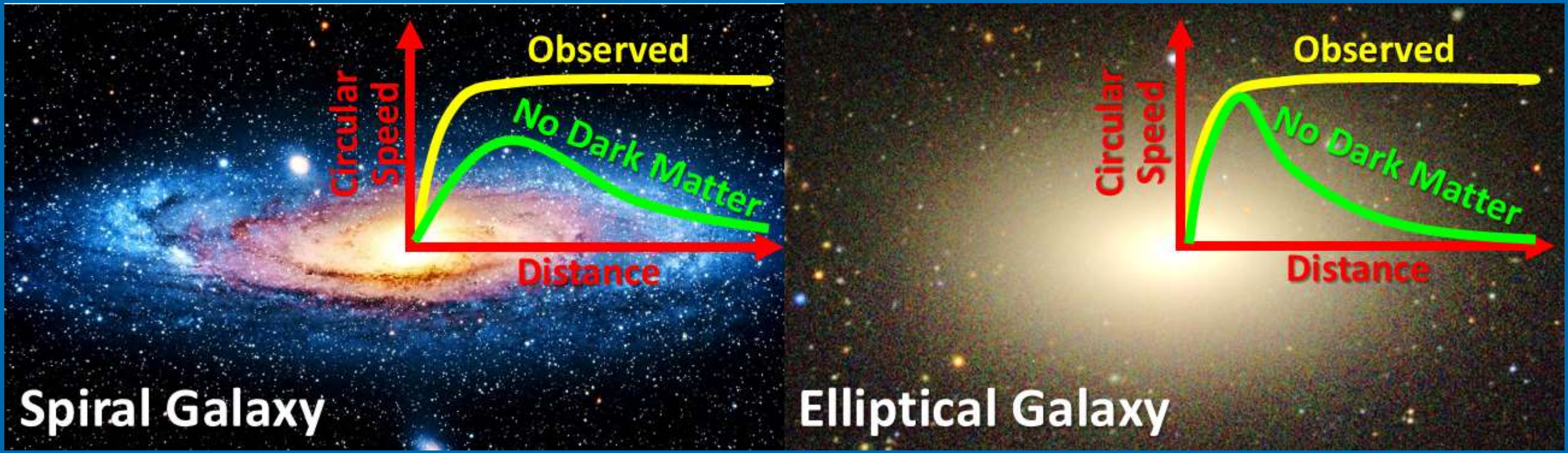




(Cappellari+15 ApJL)

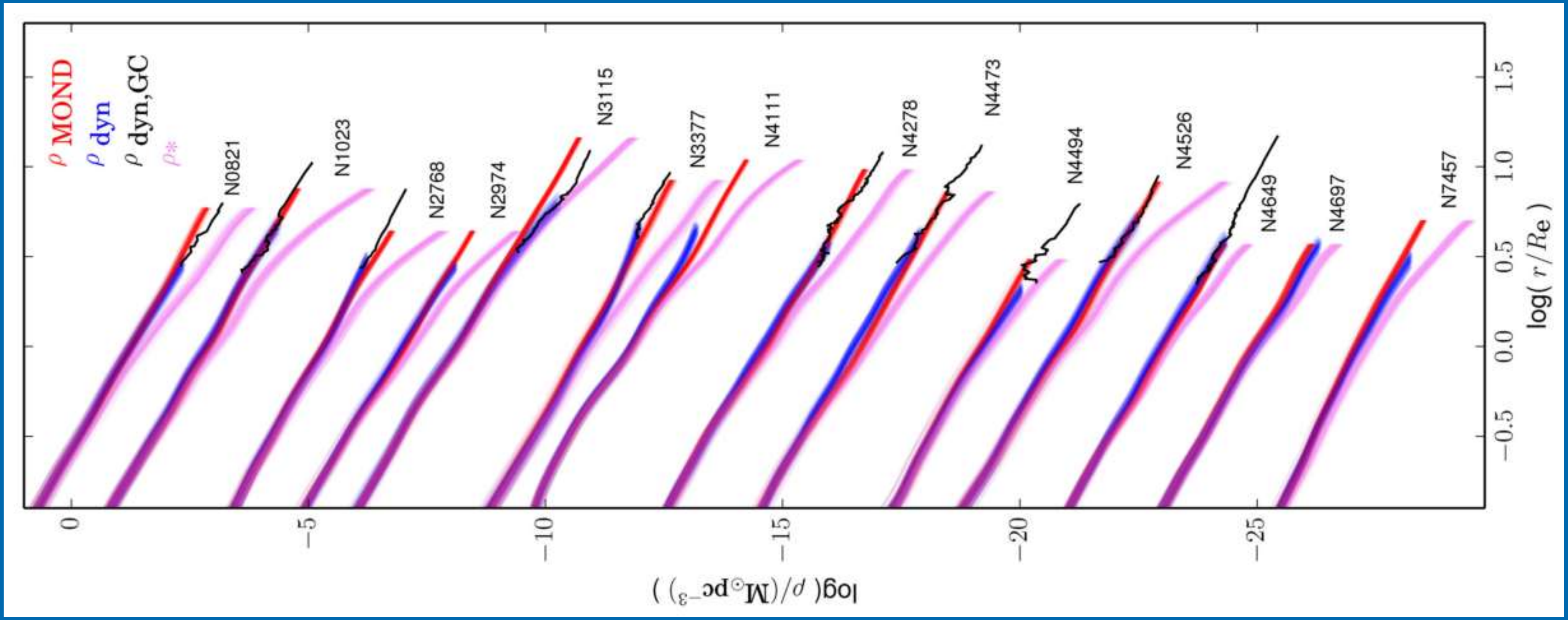
- Universal total mass profile to $4R_e$: $\rho_{tot} \propto r^{-2.2}$
- Observed rms scatter 0.11 in logarithmic slope
- Same as strong lensing studies near $R_e/2$ (Auger+10)

Rotation curves in spirals and ETGs



- Similar total density profiles
- Evidence for dark matter
- Slopes consistent with ΛCDM predictions
- Consistent with evolution spirals → ellipticals

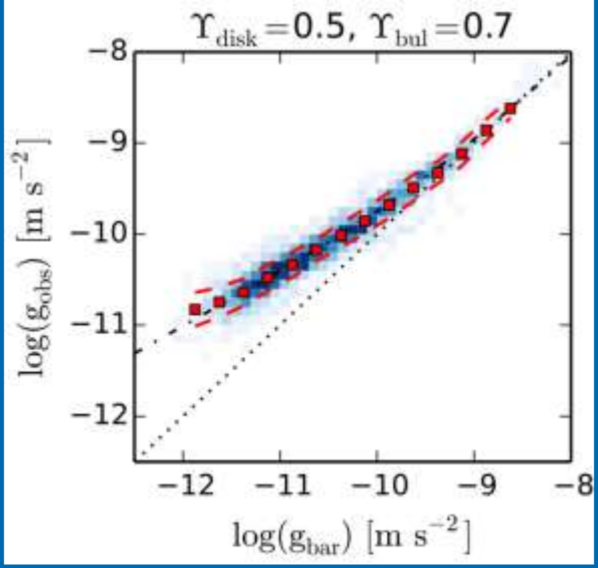
Can we rule out alternative gravity?



(Janz+16)

- Use Modified Newtonian Dynamics (MOND)
- Try to predict observed accelerations
- Predictions consistent with the data!

The Radial Acceleration Relation



(Lelli+17)

- 240 galaxies; 9 dex in stellar mass
- Empirical relation between
  - Predicted acceleration from baryons + models
  - Measured acceleration from kinematics
- Support modified gravity? MOND (Milgrom 1983)

Summary

- Galaxy dynamical models
  - Based on integral-field stellar kinematics
- Demonstrate dichotomy of galaxy properties
  - Indicative of two evolutionary channels
- Measure nearly universal density profiles
  - Consistent with ΛCDM paradigm
  - But surprising link of baryons and dark matter