Stellar Halos of Early-Type Galaxies

Wide-field spectroscopy with the Mitchel Spectrograph

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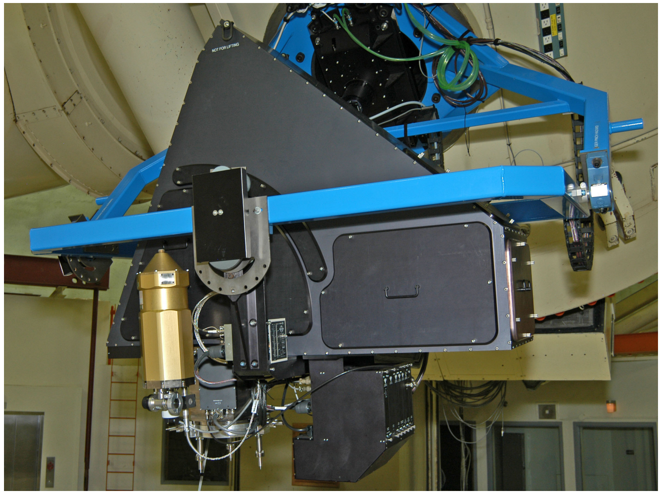
Outline

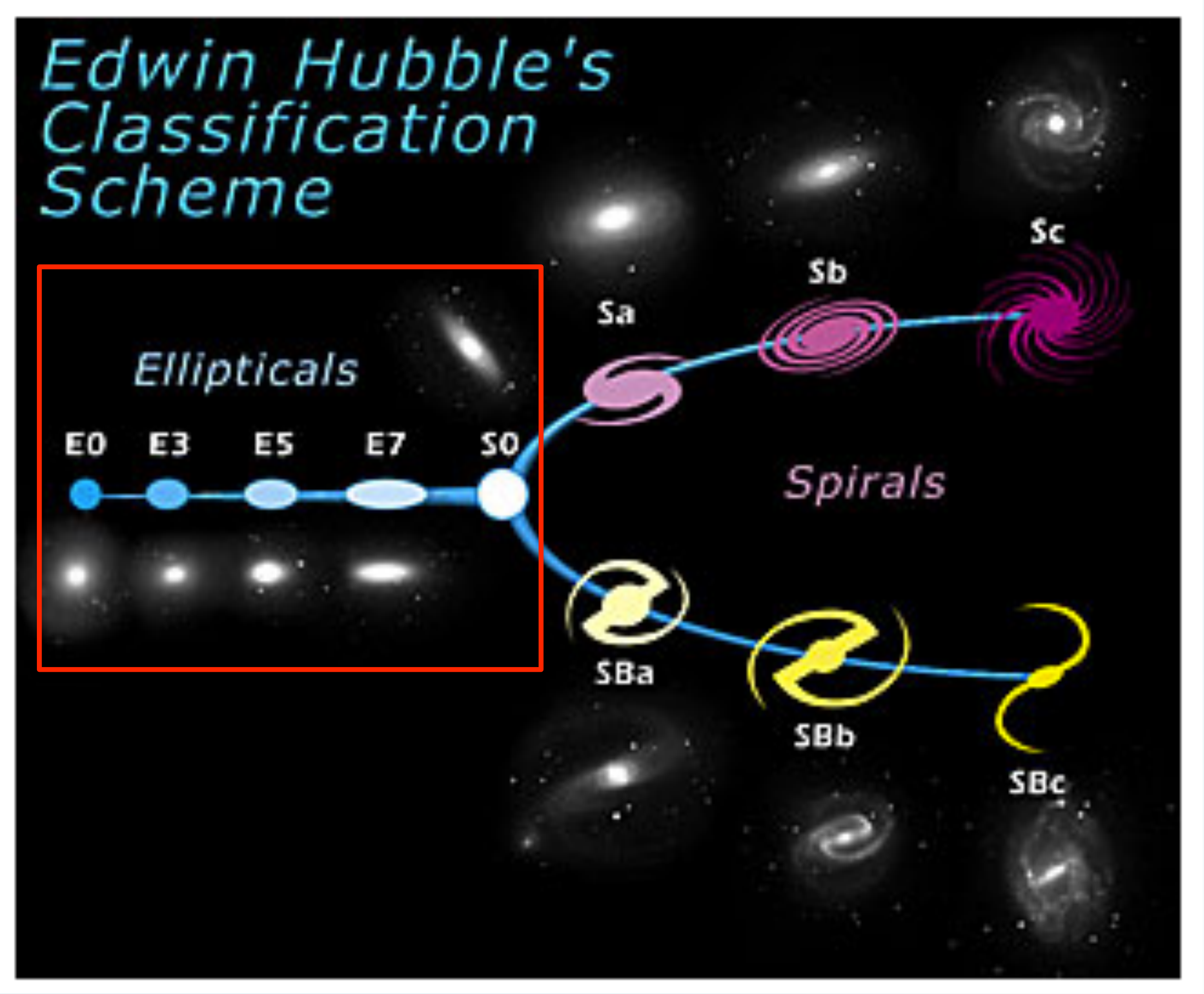
- Background
- Sample & Instrument
- First results



NGC 3998. From SDSS.

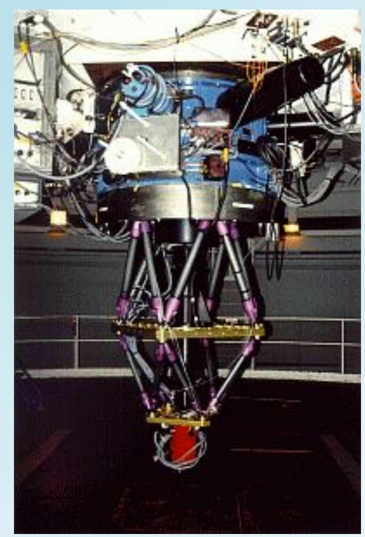
Galaxy Classification

“Early-type galaxies”



Galaxy Classification

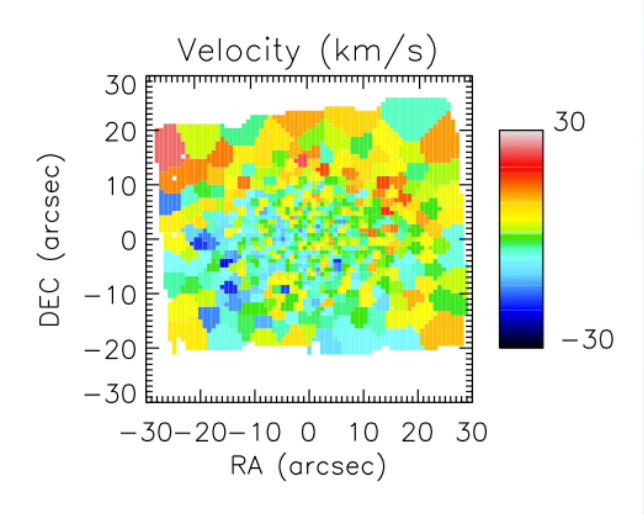
- ATLAS3D (Cappellari et al. 2011)
  - Large, volume-limited survey; 260 nearby ETGs
  - Includes IFU observations with SAURON
  - Observations out to ~1 half-light radius (R_e)
  - Early-type galaxies "fast rotators" (FRs) or "slow rotators" (SRs) (Emsellem et al. 2007; 2011)



Examples

- NGC 4733 – slow rotator

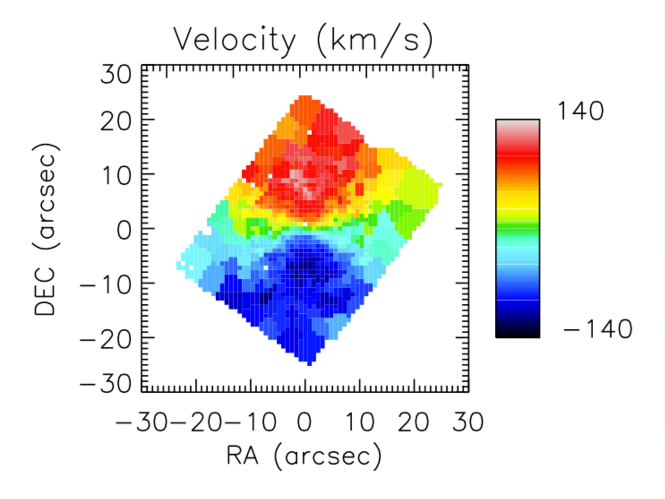
SDSS



Cappellari et al. 2011

- NGC 680 – fast rotator

SDSS



Cappellari et al. 2011

How do they form?

- Rapid size evolution observed for $z < \sim 2$
  - Eg: van Dokkum et al. 2010
- FR/SR dichotomy observed in local ETGs

Suggests a two-phase formation process

Eg: Oser et al. 2010, Oser et al. 2012, Wu et al. 2014

Two-phase formation model

- 1st phase: formation of central bulge
  - Gas-rich major mergers, gas inflows, etc
  - $z > 2$
- 2nd phase: slow growth of galaxy
  - Largely from dry minor mergers
  - $z < \sim 3$
- Precise histories vary between galaxies
- Evidence from both simulations (eg: Oser et al. 2010) and observations (eg: Forbes et al. 2011)

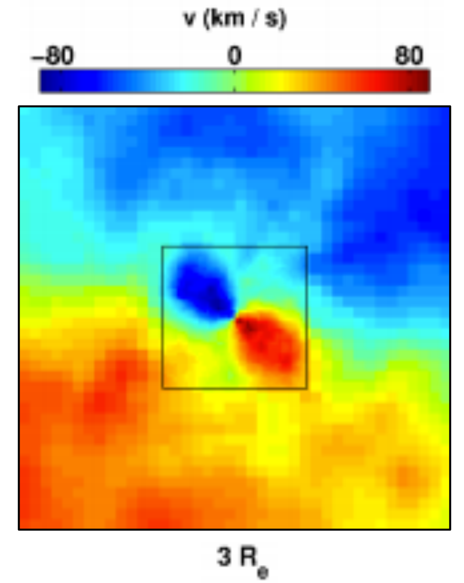
Some problems

- Distant and local ETGs assumed to be from *same population*
  - Not necessarily true…
- Apparent connection between FRs and spirals
  - Eg: Van den Bergh, 1976, Kormendy & Bender 2012, Cappellari 2013
  - Suggests passive evolution from spirals to FRs

Further observations needed

Two-phase model - predictions

- **<u>Transitions expected past ~1 R_e</u>**
  - Stellar kinematics, populations
- Formation of bulge; affects inner parts
  - Rotational orbits
  - Stellar population gradients
  - Eg, Hoffman et al. 2010
- Dissipationless accretion; affects outer parts
  - Radial orbits
  - "Washing out" of population gradients
  - Eg, Oser et al. 2010



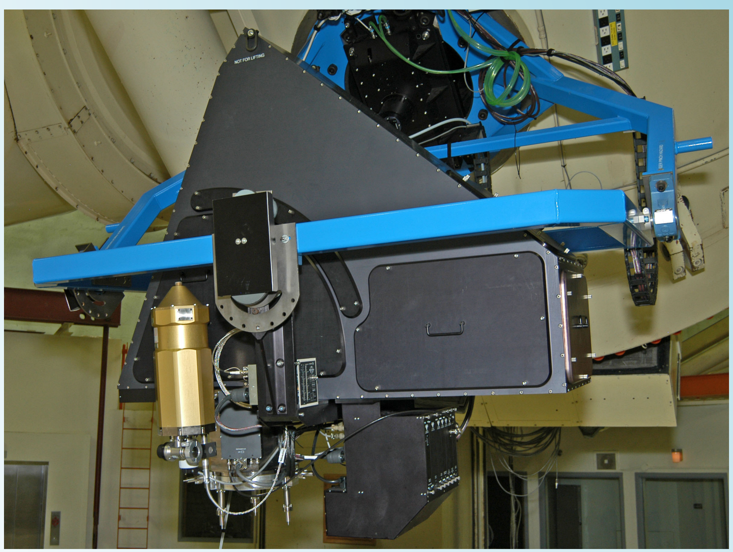
Hoffman et al. 2010

Two-phase model - predictions

- ATLAS3D provides high-quality IFU data out to ~1R_e
- To probe for expected transitions, must look beyond this.
- Wide-field spectroscopy needed

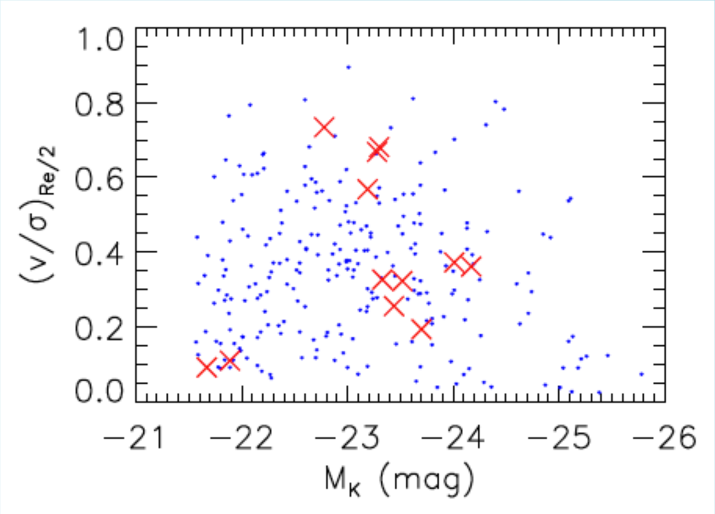
The Instrument

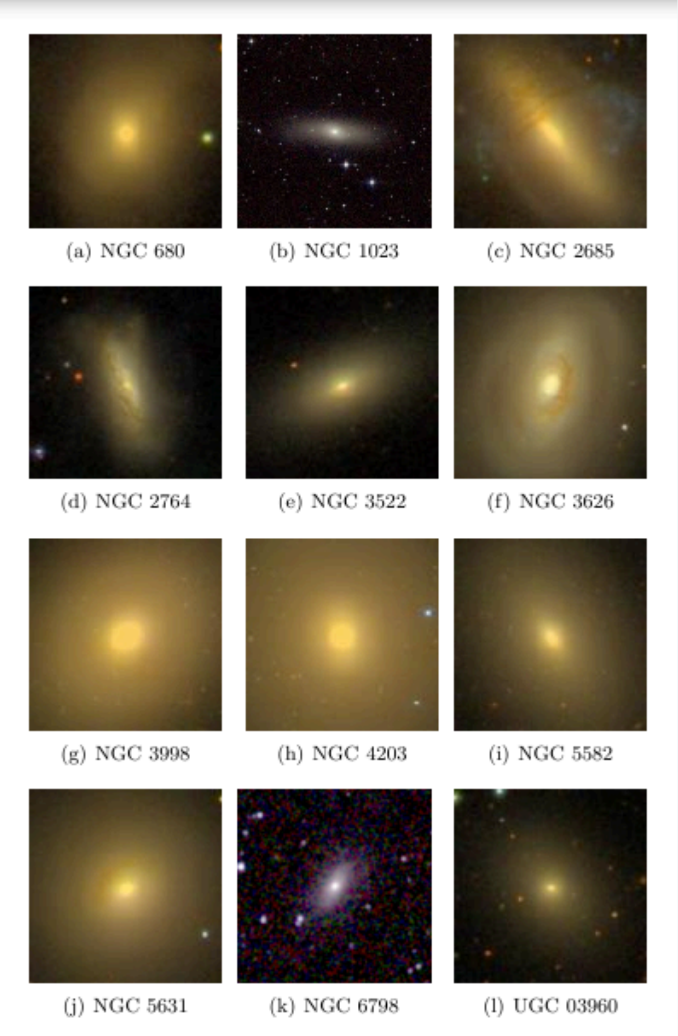
- The Mitchell Spectrograph, formerly VIRUS-P
- 246 fibres (diameter 4’’), covering a 107’’ X 107’’ field of view
- **<u>Ideal</u>** for studying galaxies’ faint outer regions



The sample

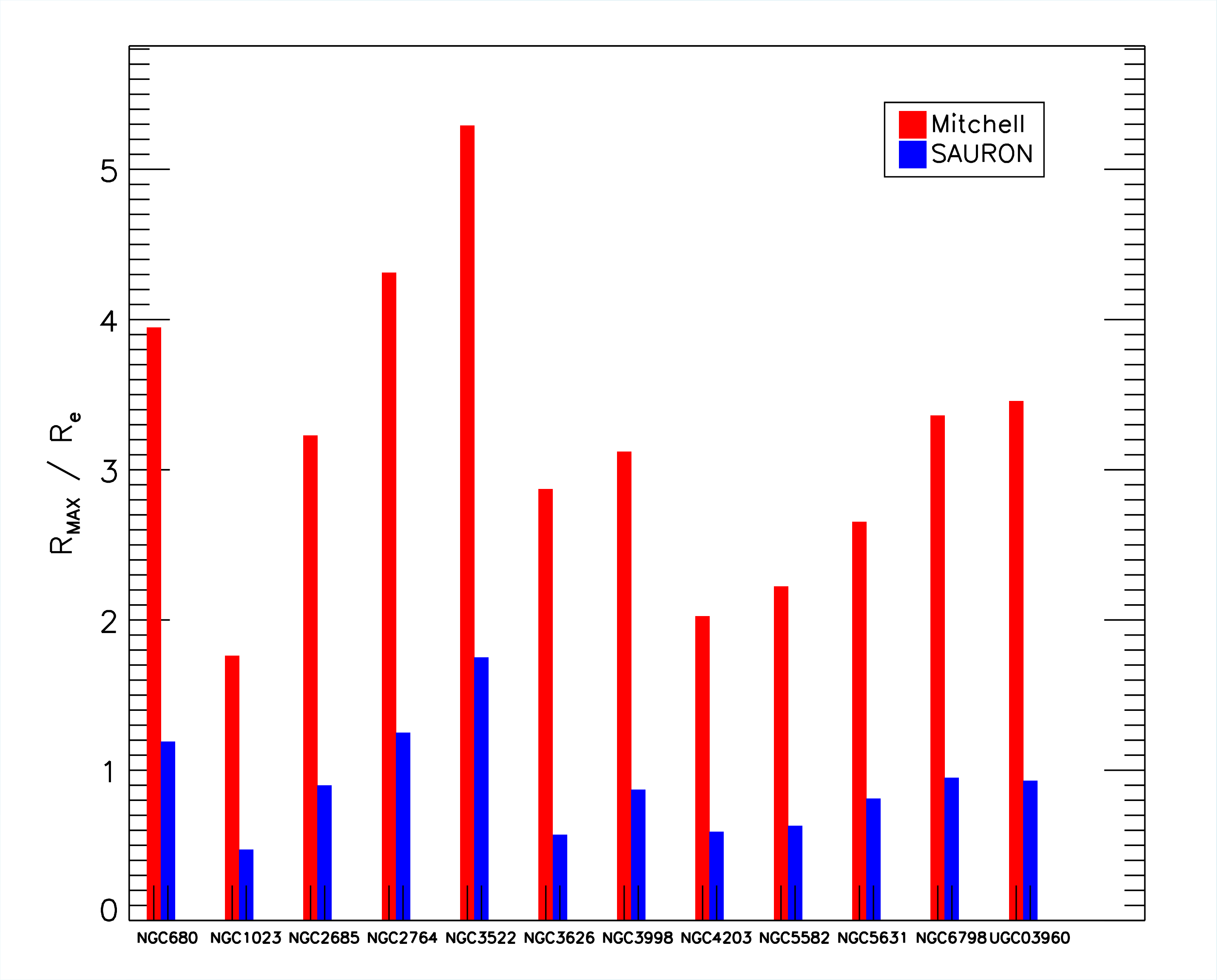
- 12 ETGs from ATLAS3D sample
- Selected for detection in HI
  - For dark matter work
- Observed with Mitchell Spectrograph
  - Wavelength range of 4800-5400Å
  - Average spectral resolution 1.4Å FWHM





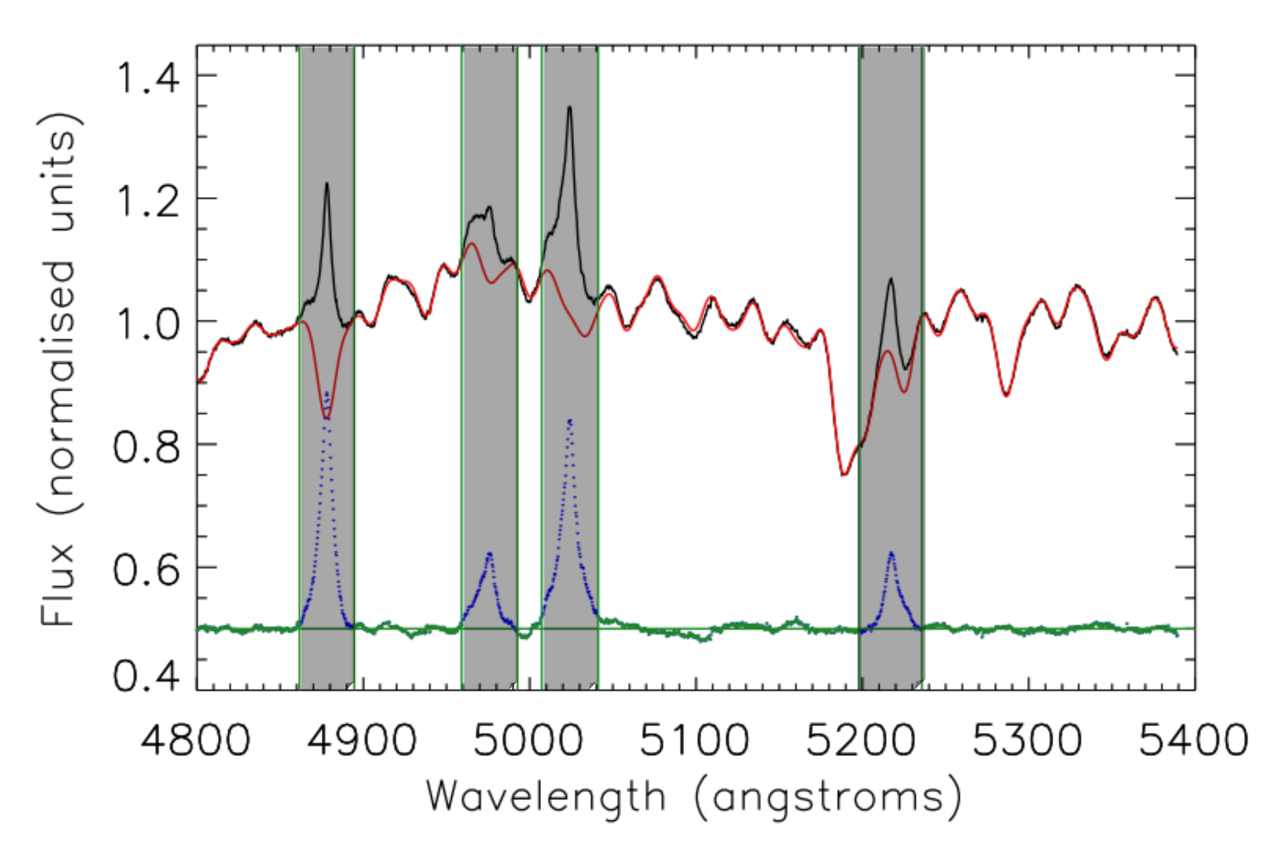
SDSS, 2MASS

Coverage


Mitchell
SAURON
R_{MAX} / R_e
0
1
2
3
4
5
NGC680
NGC1023
NGC2685
NGC2764
NGC3522
NGC3626
NGC3998
NGC4203
NGC5582
NGC5631
NGC6798
UGC03960

Stellar Kinematics

- Obtained using penalized PiXel Fitting (pPXF; Cappellari & Emsellem, 2004)
- Galaxy spectra fitted using sets of template stars



- NGC 3998
- Central fiber
- S/N = 336

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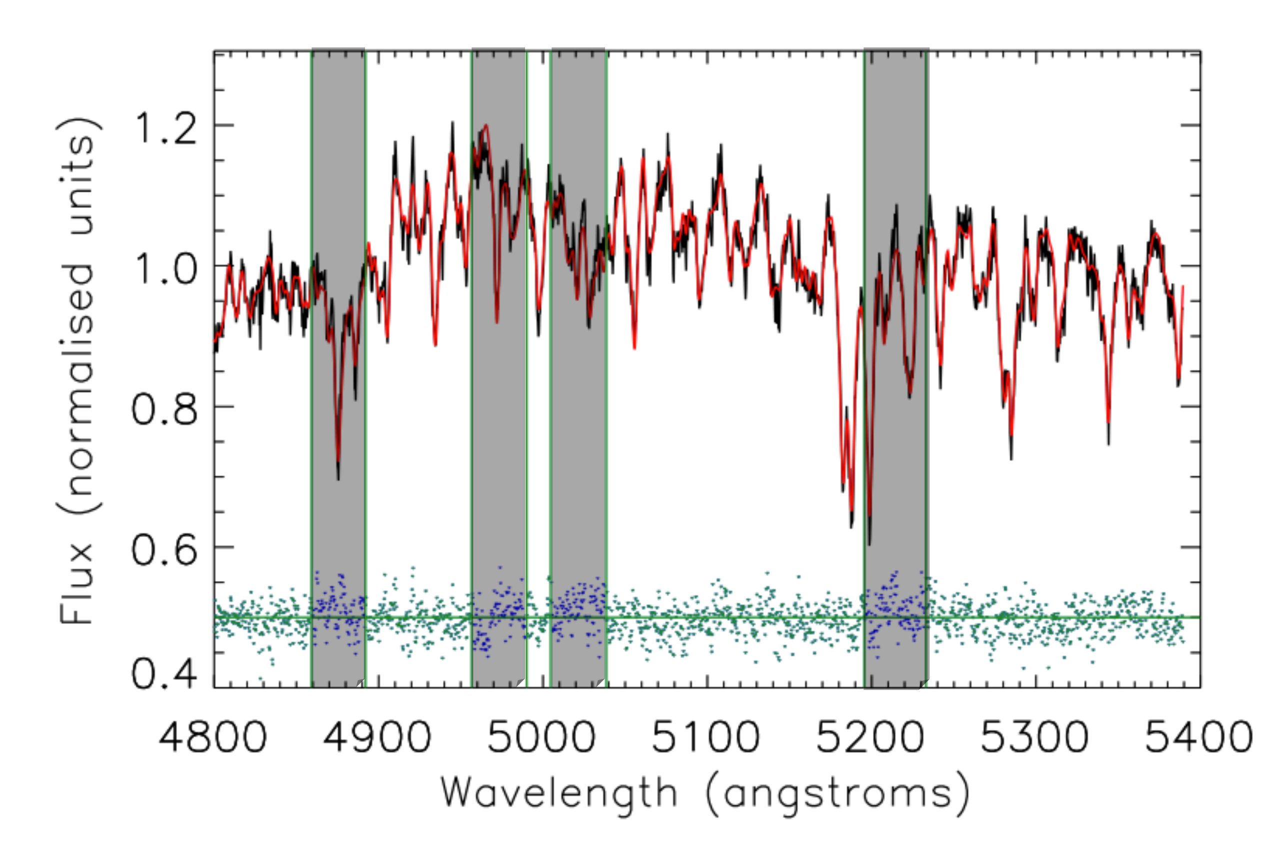
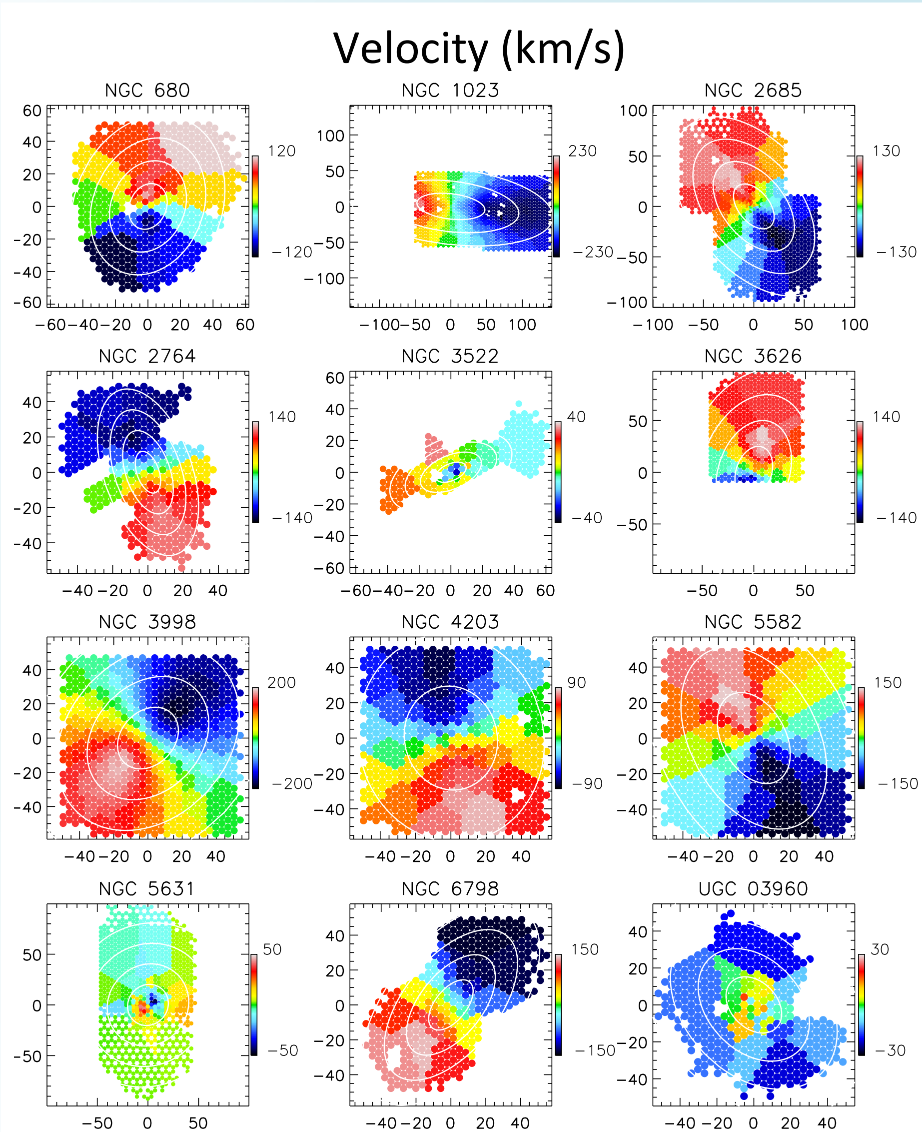
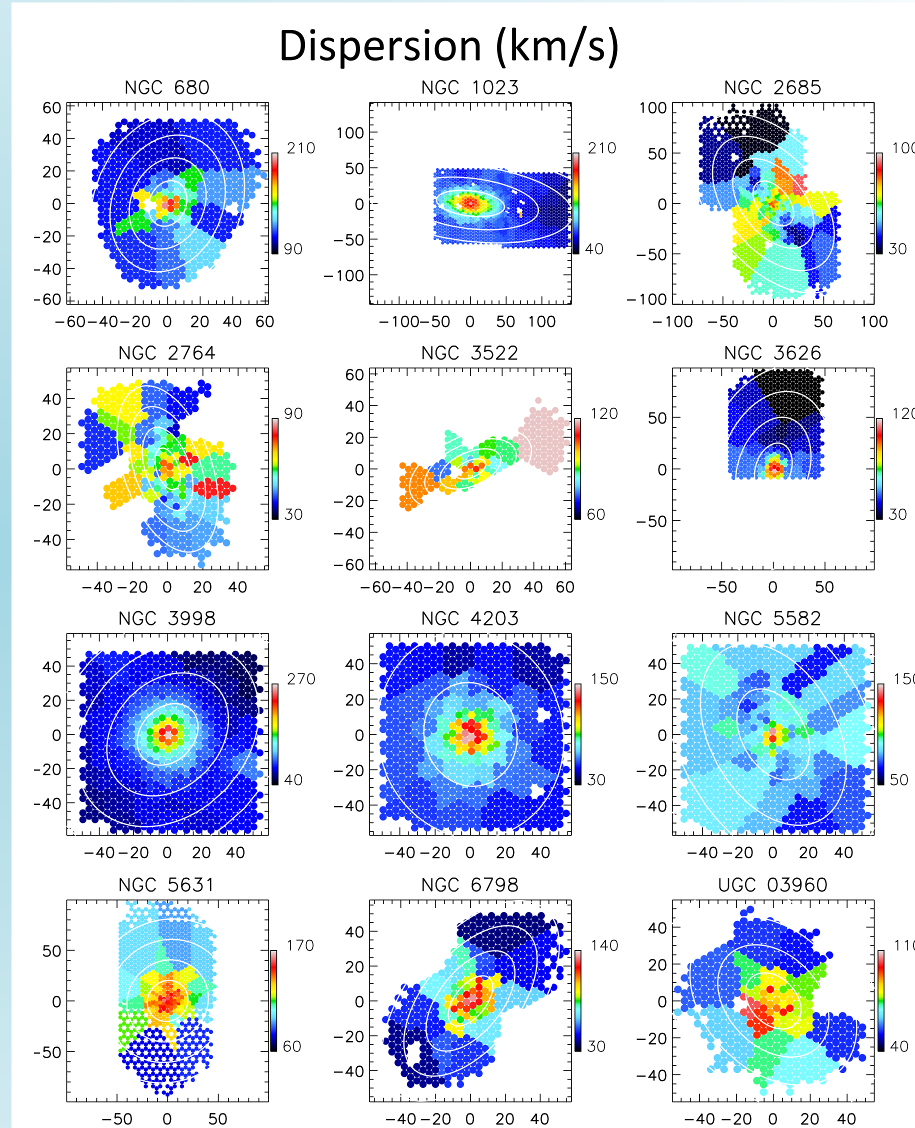


- NGC 3998
- Outer spectral bin
- r ~ 2.5 R_e
- S/N = 38

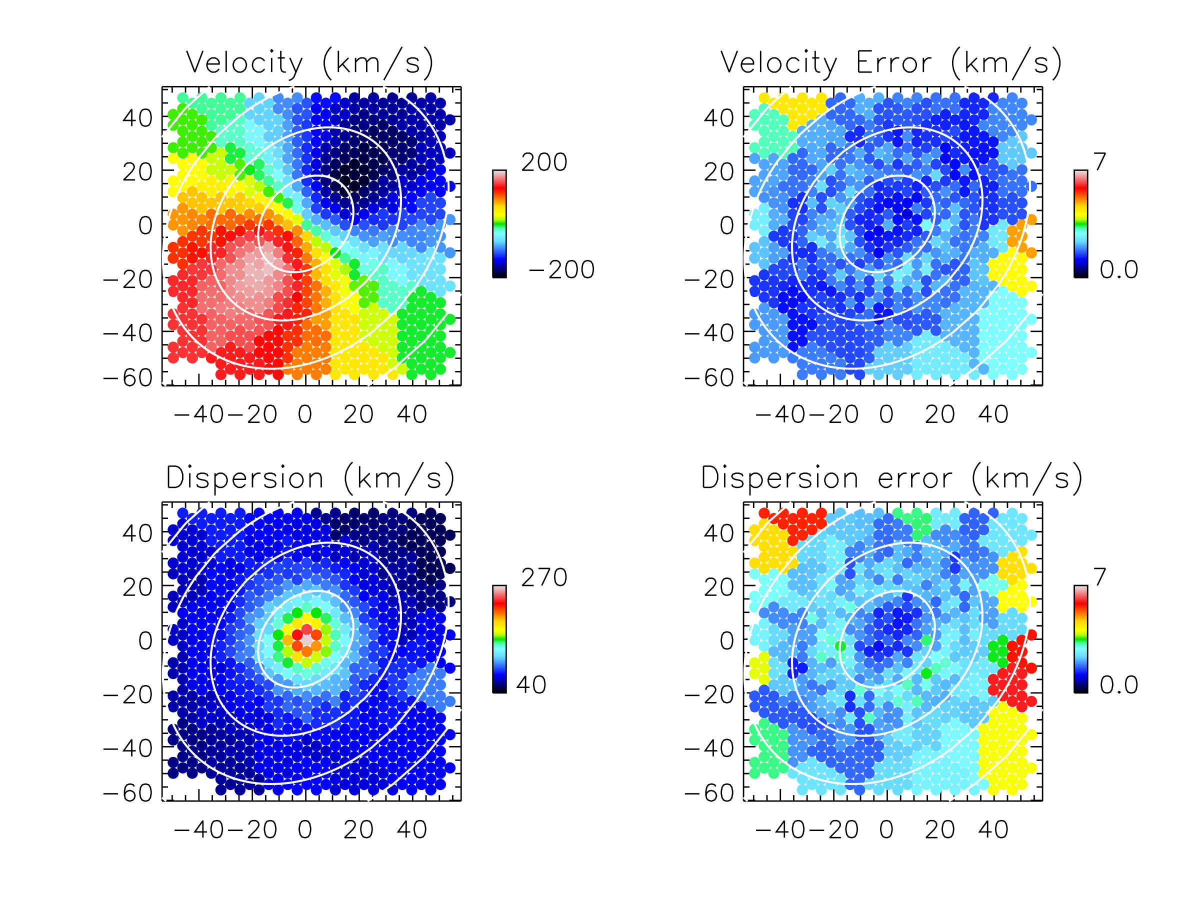
Stellar Kinematics





Kinematics errors

- Obtained using re-simulations with random noise
- Example: NGC 3998

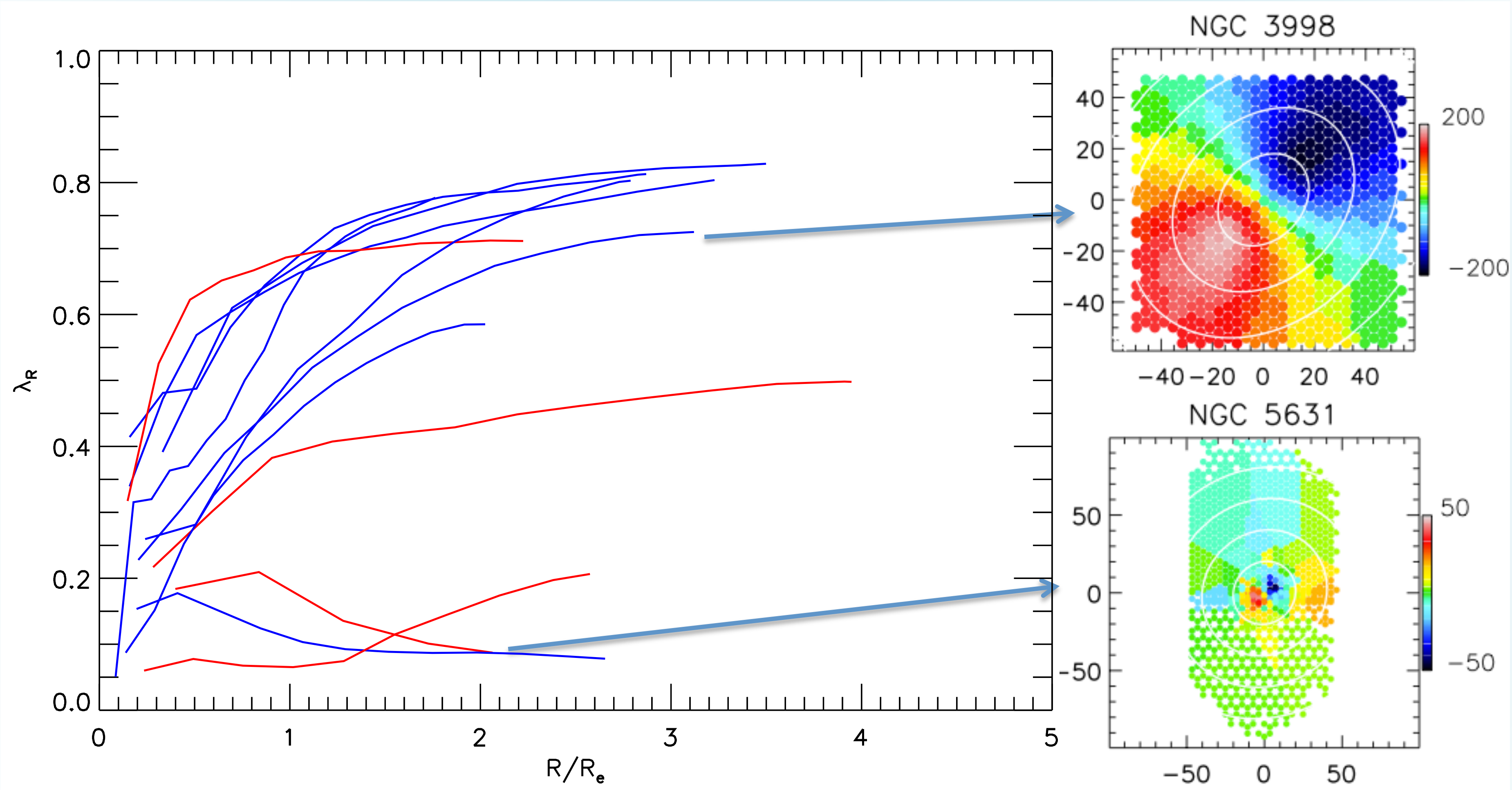


Angular momentum

- Use λ_R parameter as a proxy,
- Describes velocity structure (Emsellem et al. 2007)
  - Fast rotators/slow rotators
- Differentiates between between small and large kinematic structures

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

Angular momentum



- For FRs: no clear difference between S0s (blue) and Es (red)
- No sudden drops beyond 1 R_e
  - No clear transitions

Summary

- Two-phase formation model; expect evidence beyond ~1R_e
- Observed 12 ETGs with Mitchell Spectrograph
- Data reaches 3 R_e in many cases
- No evidence of two-phase formation from velocity or dispersion
- Next steps: orbit modelling (van den Bosch et al. 2008), stellar populations, dark matter

Some problems

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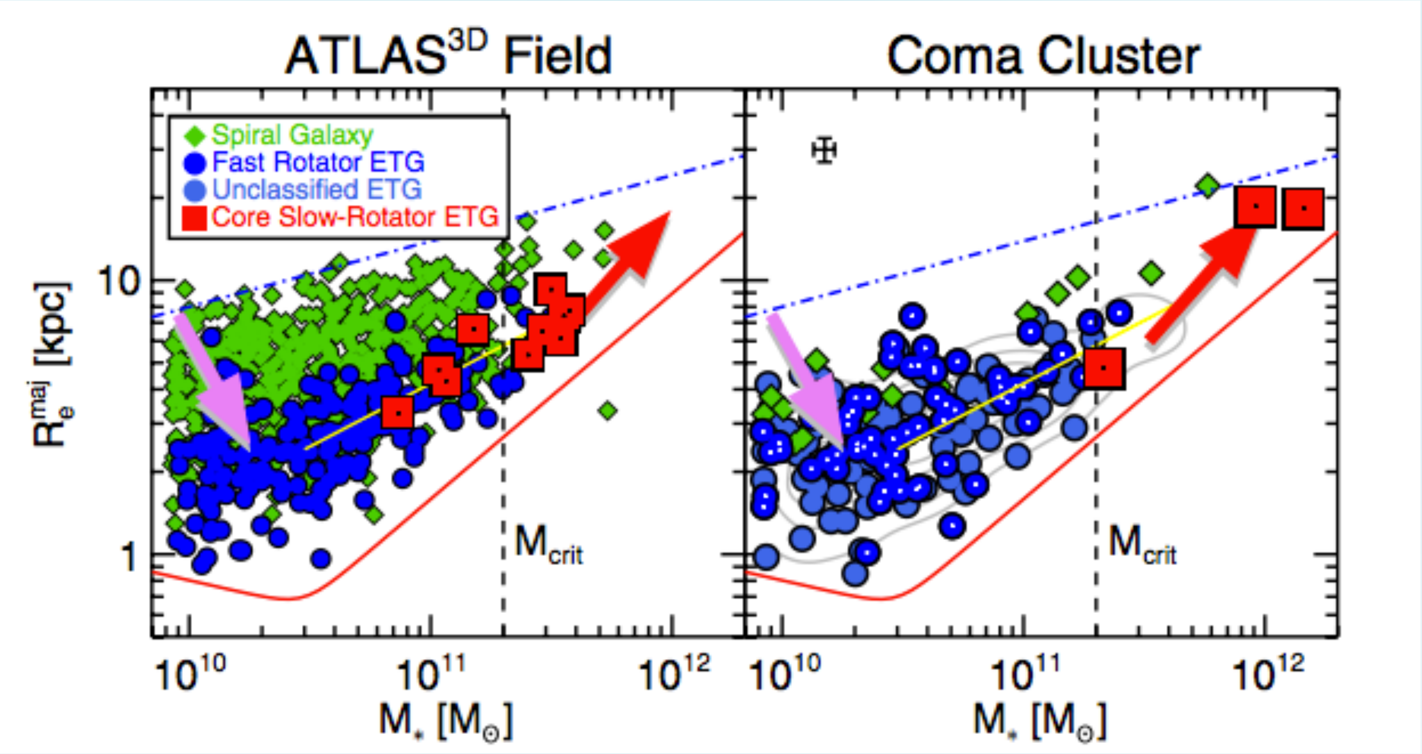
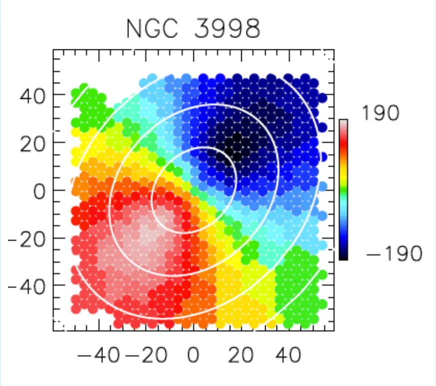
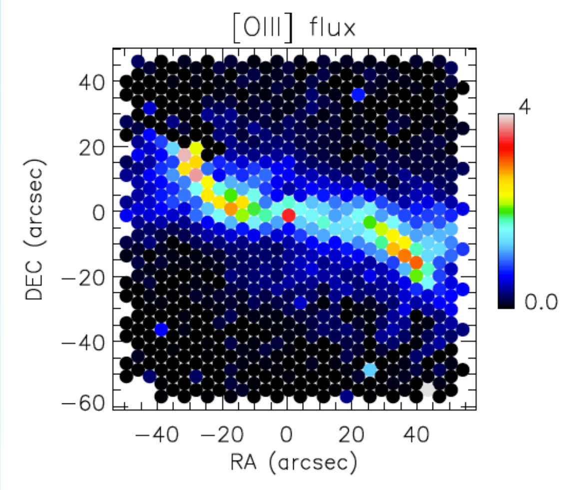


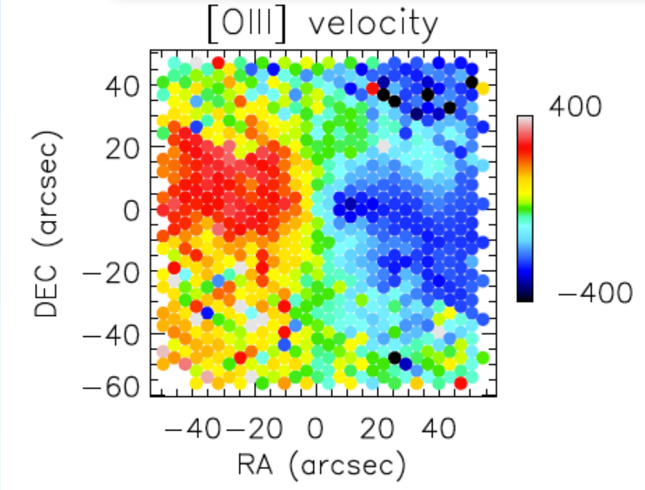
Cappellari, 2013

Gas kinematics

- Ionised gas intensity/kinematics from IFU data
- Extracted with GANDALF code (Sarzi et al, 2006)
- Doesn't always follow stellar distribution
- Example: NGC 3998





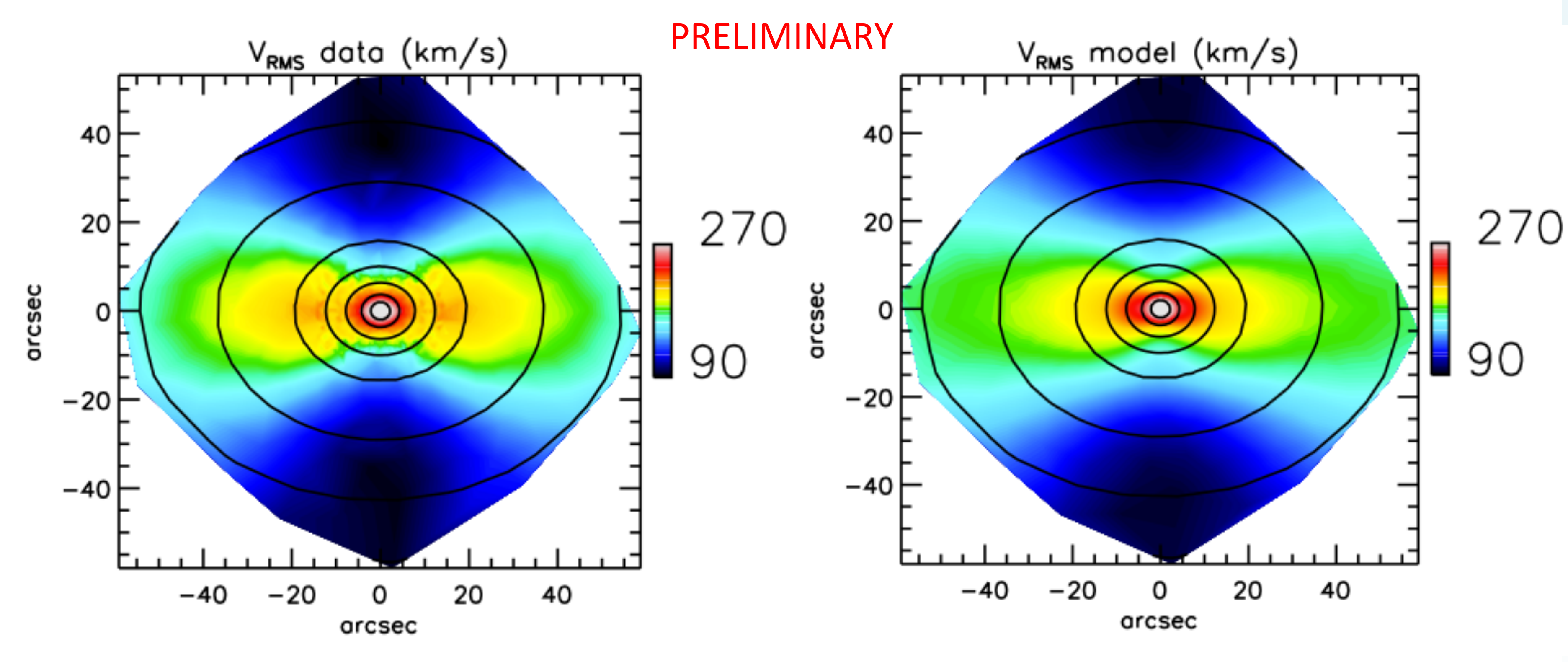


Dark matter

- Dark matter constrained via Jeans Anisotropic MGE modelling (JAM; Cappellari, 2008)
- Uses velocity and velocity dispersion

$$V_{RMS} = \sqrt{V^2 + \sigma^2}$$

- NGC 3998



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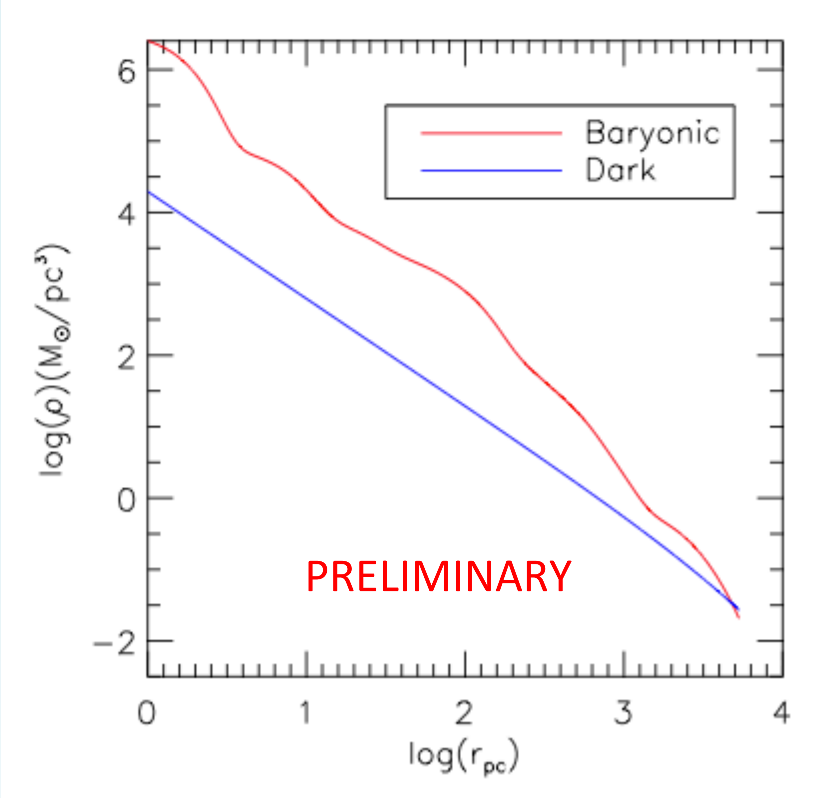

(Baryonic component obtained from Walsh et al. 2012)

What next?

- No obvious transitions in velocity or dispersion beyond ~$1R_e$
- Next step: higher kinematic moments.
- Example: kurtosis (h_4)

h4 = 0 plot here

  - $h_4 = 0$
- Will use triaxial Schwarzschild modelling
  - van den Bosch, 2008.

What next?

- No obvious transitions in velocity or dispersion beyond $\sim 1R_e$
- Next step: higher kinematic moments.
- Example: kurtosis (h_4)

h4 > 0 plot here

  - $h_4 > 0$; excess of radial orbits
- Will use triaxial Schwarzschild modelling
  - van den Bosch, 2008.

What next?

- No obvious transitions in velocity or dispersion beyond ~$1R_e$
- Next step: higher-order kinematics and orbit modelling
- Example: kurtosis (h_4)

h4 < 0 plot here

  - $h_4 < 0$; excess of tangential orbits
- Will use triaxial Schwarzschild modelling
  - van den Bosch, 2008.