Constraining Dark Matter Halo Profiles and Galaxy Formation Models Using Spiral Arm Morphology

Marc Seigar

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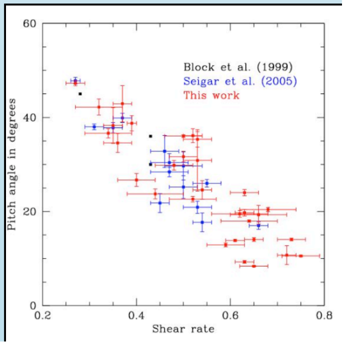
January 23rd, Berkeley



Collaborators

- Aaron Barth (UCI)
- James Bullock (UCI)
- Luis Ho (OCIW)

Phil James (Liverpool), David Block (Wits), Ivanio Puerari (INAOE)

Outline

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- Spiral arm morphology
- The connection with rotation curve shear
- Constraining mass profiles using spiral morphology
- Application to M31
- Nuclear spiral structure
- The Carnegie-Irvine Nearby Galaxies Survey (CINGS)

Why are we interested in DM Halo profiles?

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DM density profiles are very sensitive to our cosmology

- Cold Dark Matter (CDM) predicts cuspy DM profiles, e.g. the NFW profile.
- Observations of late-type galaxies highlight constant density cores, which are consistent with Warm Dark Matter (e.g. Zentner & Bullock 2003)
- Note that non-circular motions play an important role, and need to be highlighted using IFU spectra (see work by Josh Simon et al.)

Spiral Density Waves

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Density wave theory predicts a relationship between spiral arm pitch angle and central mass concentration

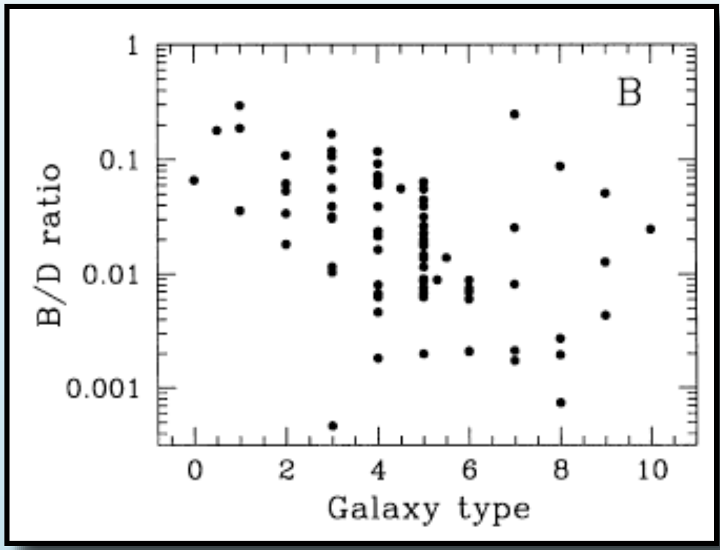
(e.g. Lin & Shu 1964, 1966; Bertin et al. 1989a, b; Bertin 1993; Bertin & Lin 1996).

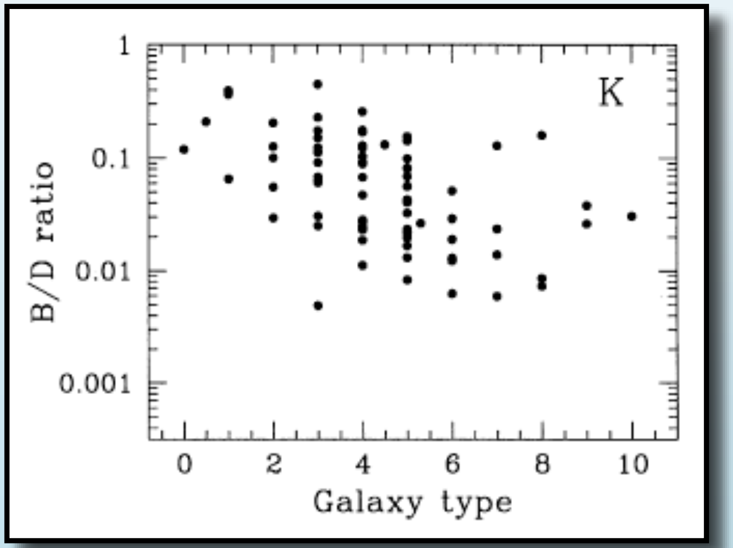
$$n(\theta - \theta_0) = -\int_{r_0}^{r} \frac{[\kappa^2 + \omega_i^2 + (\omega_r - n\Omega)^2]}{2\pi G \mu_0} dr$$

Lin & Shu (1964)

Spiral arm morphology I

There is a weak correlation between Hubbke type and B/D ratio (e.g. de Jong 1996; Seigar & James 1998a)





Spiral arm morphology II

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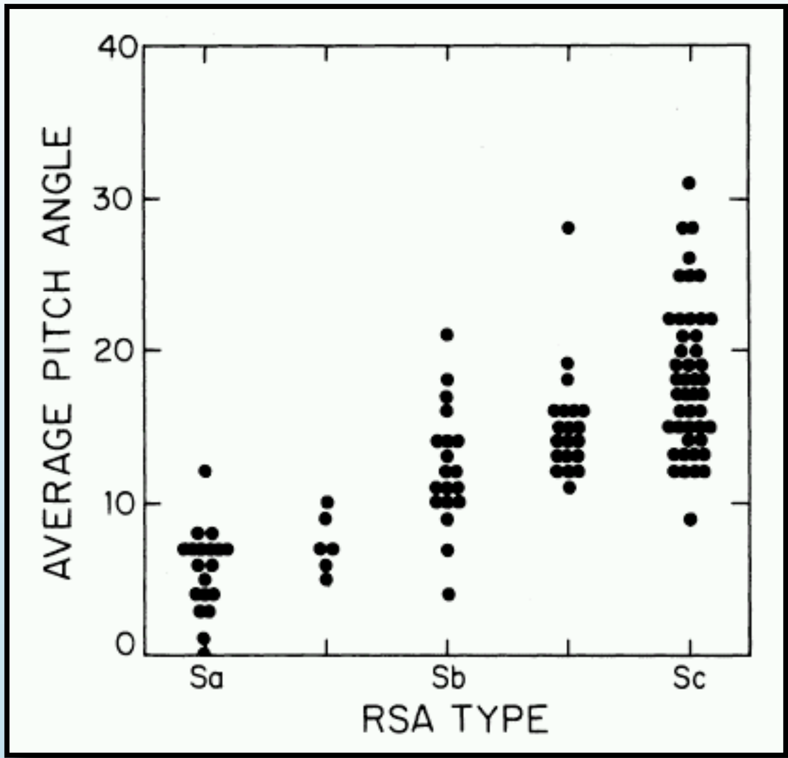
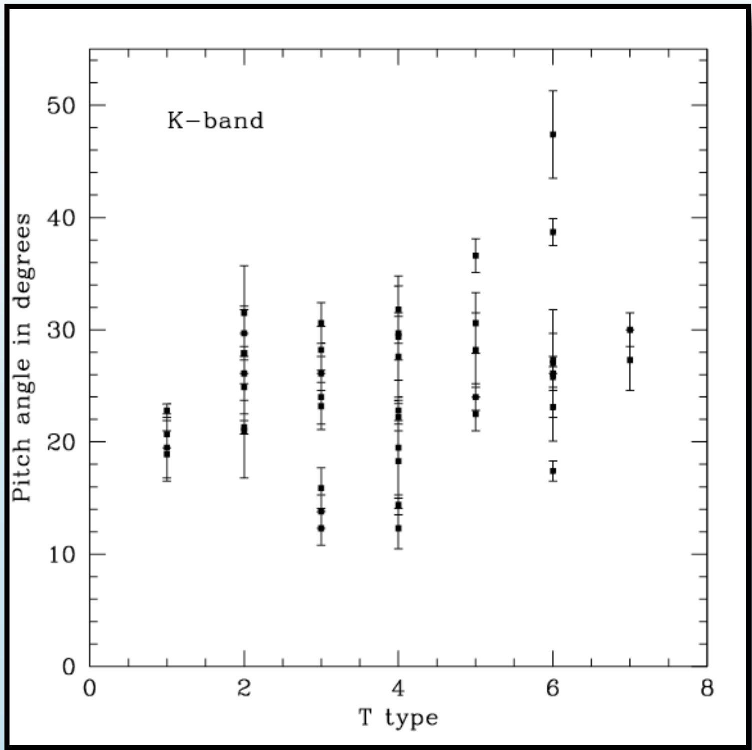
Also a weak correlation bewteen Hubble type and spiral arm pitch angle.



Kennicutt(1981)



Seigar & James (1998b)

Spiral arm morphology III

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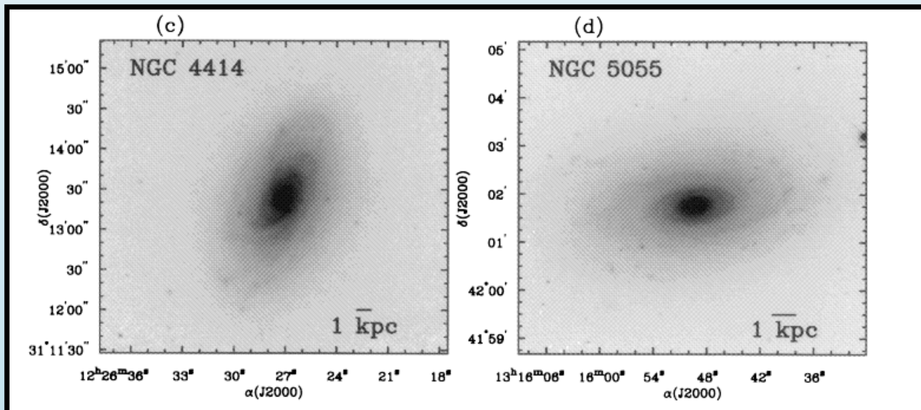
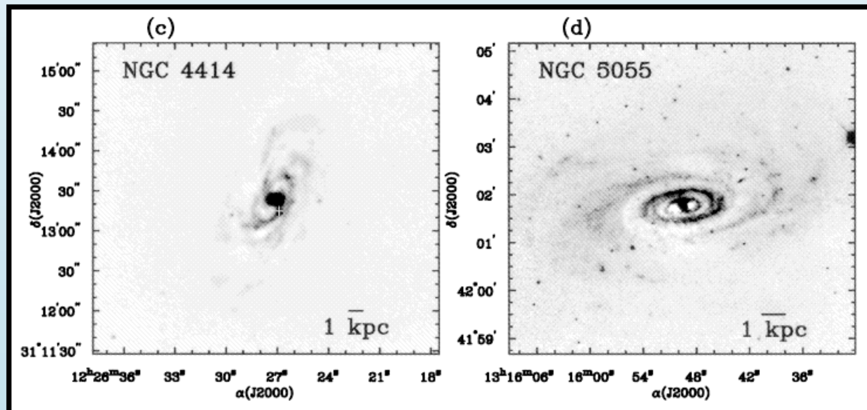
Galaxies with flocculent spiral structure in the optical sometimes have Grand-Design Spirals in the near-IR (Thornley 1996; Seigar et al. 2003)





Thornley (1996)

Spiral arm pitch angles and shear

Definition of shear, S, given by

$$S = \frac{A}{\omega} = \frac{1}{2}\left[1 - \frac{R}{V}\frac{dV}{dR}\right]$$

A is first Oort constant, ω is angular velocity

For a rising rotation curve S<0.5

For a flat rotation curve S=0.5

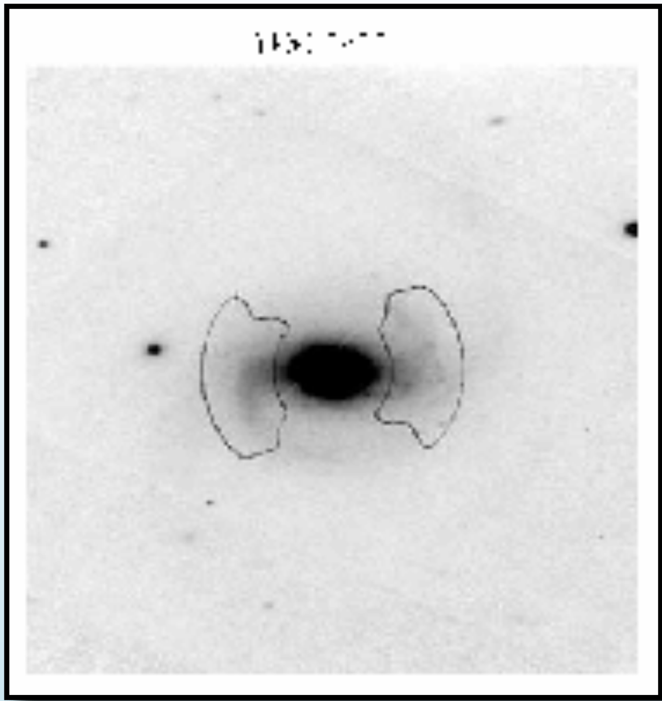
For a falling rotation curve S>0.5

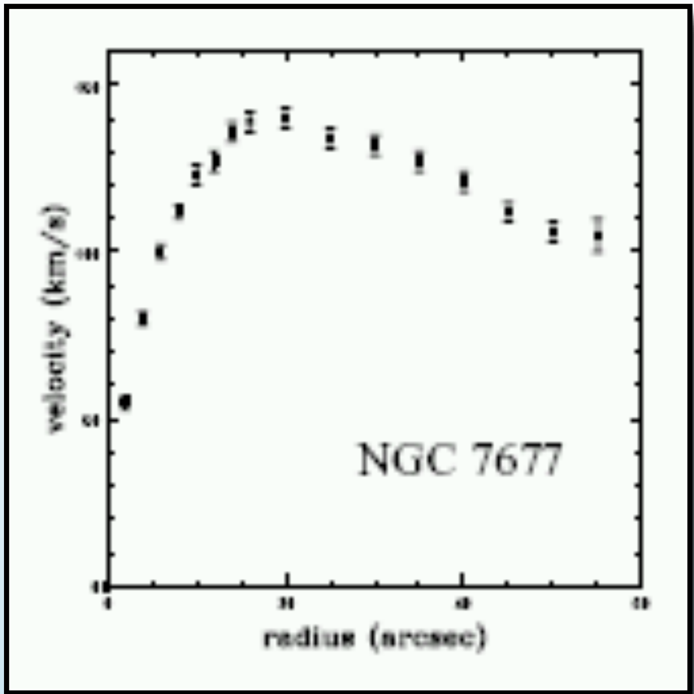
Spiral arm pitch angles and shear

Block et al. (1999) showed there is a hint of a correlation between spiral arm pitch angle and rotation curve shear, but only for 4 galaxies.

We now apply this to a larger sample of galaxies.

NGC 7677





SABbc; P=17.0±0.8

S=0.66±0.02

ESO 576 -G51

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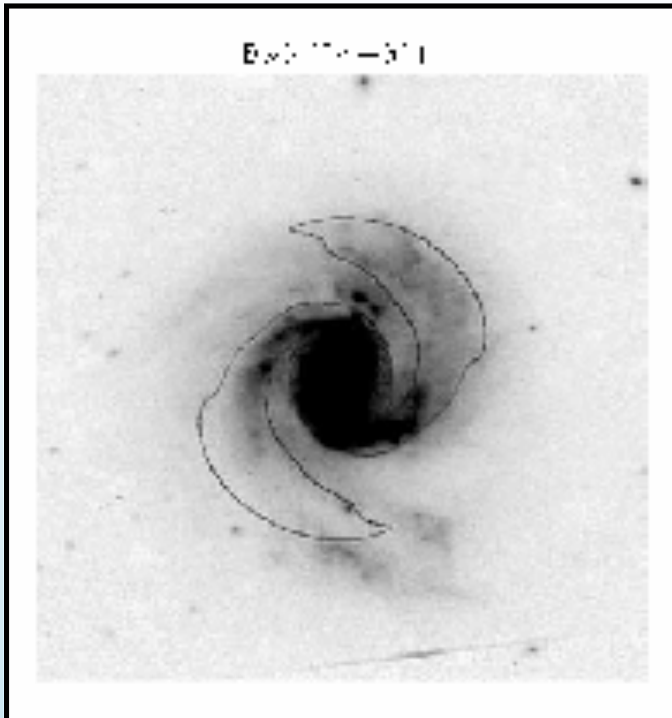

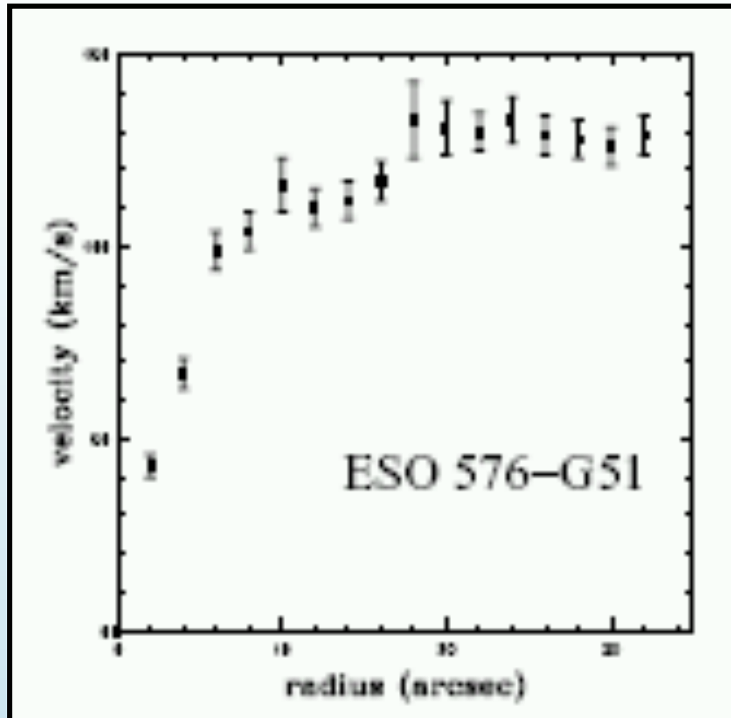

SBbc; P=30.4±1.9

S=0.47±0.04

NGC 3456

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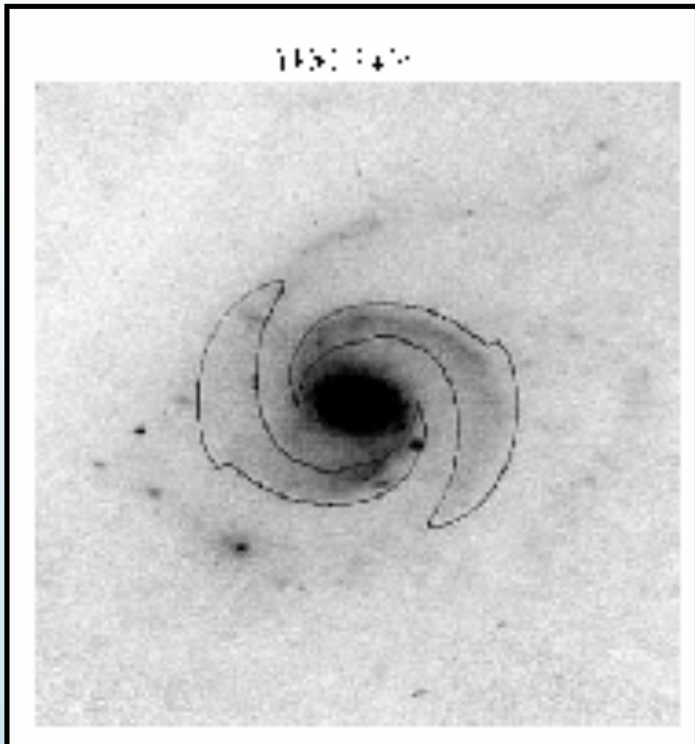
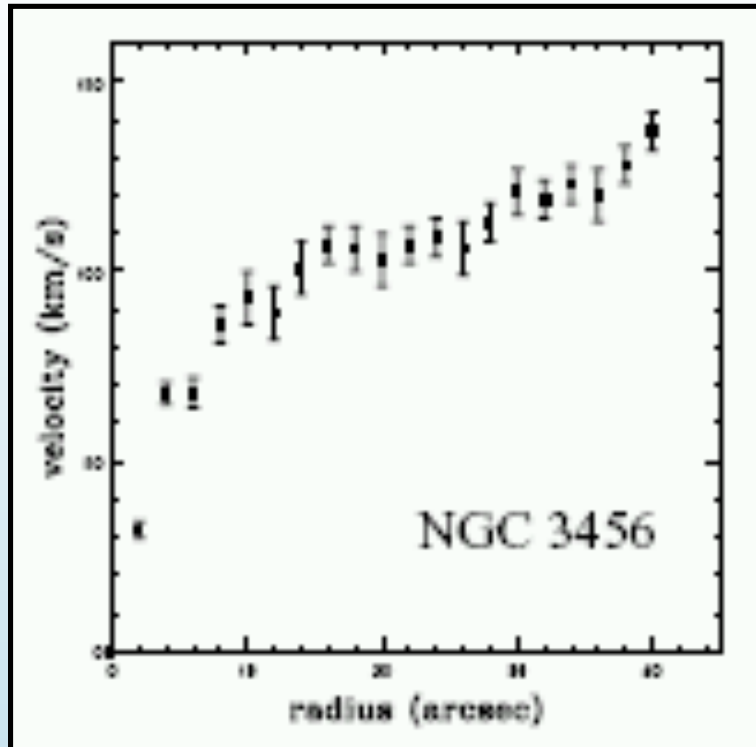
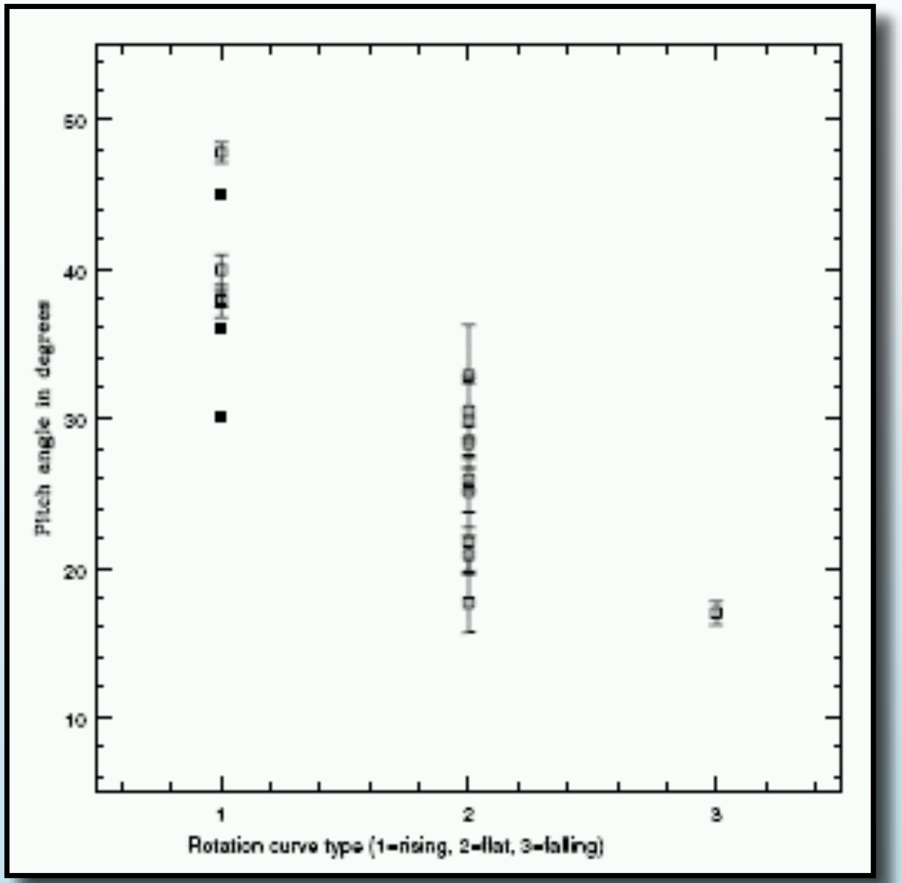




SBc; P=38.0±0.6

S=0.31±0.02

Spiral arm pitch angle vs rotation curve type



Seigar et al. (2005)

Spiral arm pitch angle vs rotation curve shear

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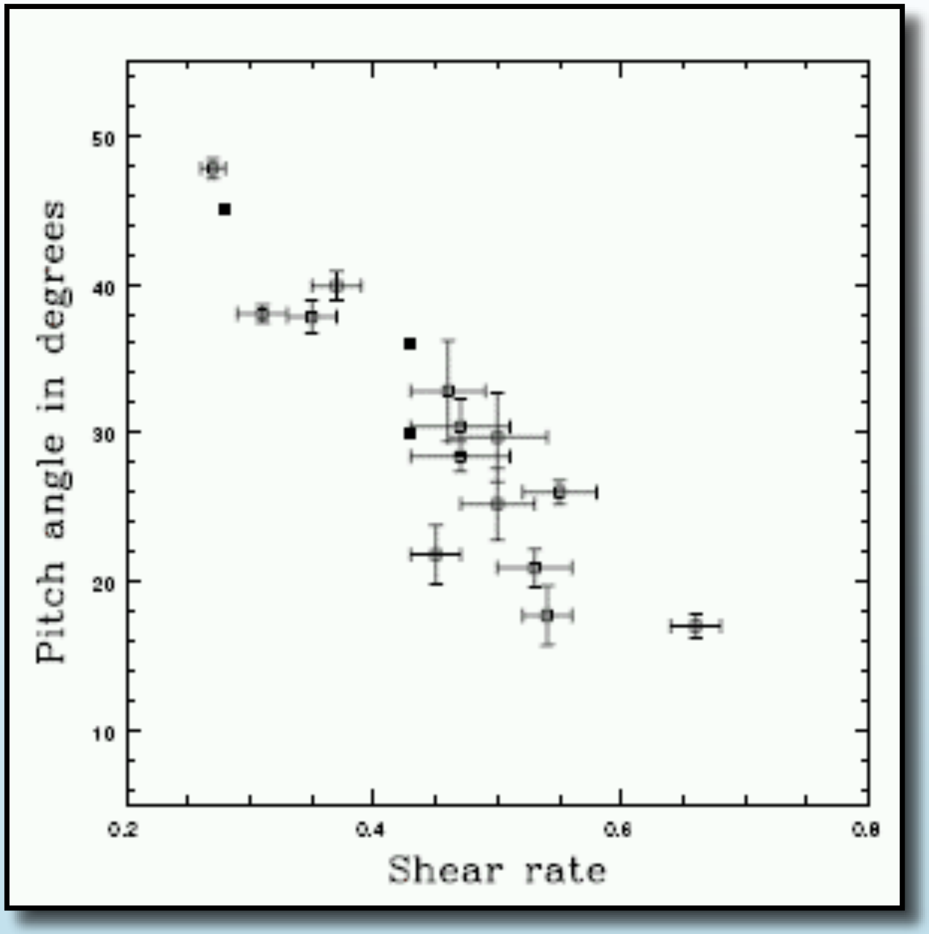
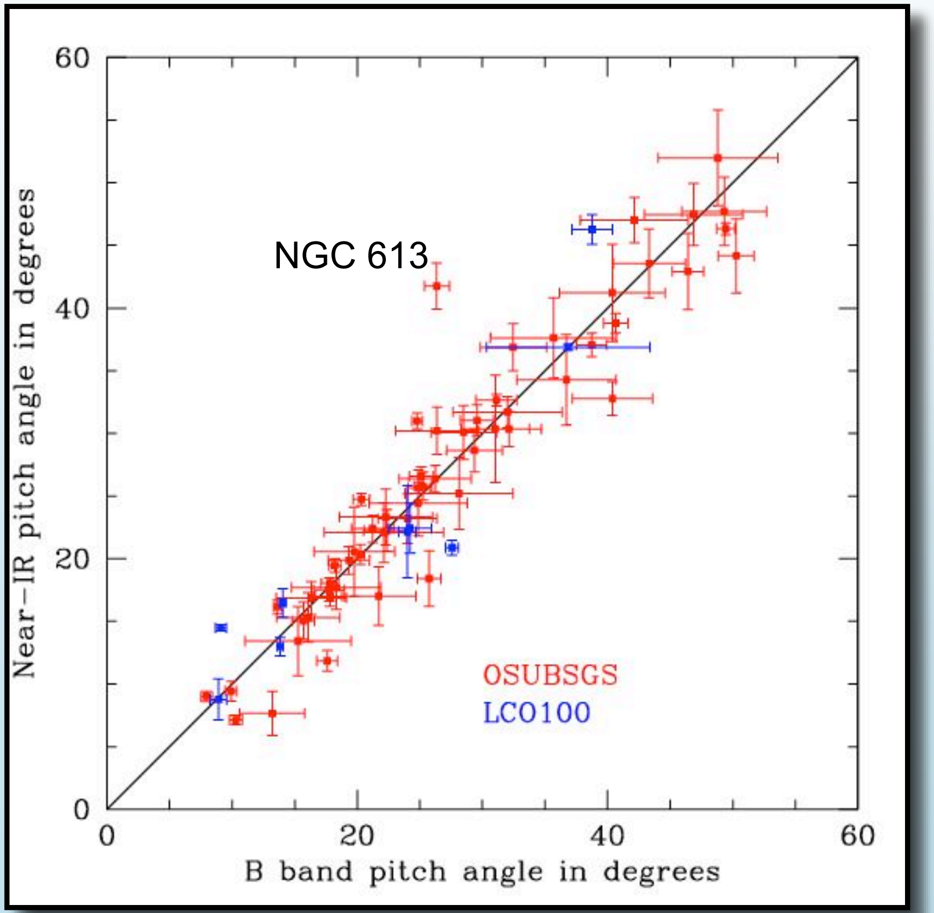


From near-IR imaging

Seigar et al. (2005)

Spiral arm pitch angles in the near-IR versus the optical



Seigar et al. (2006)

The new correlation

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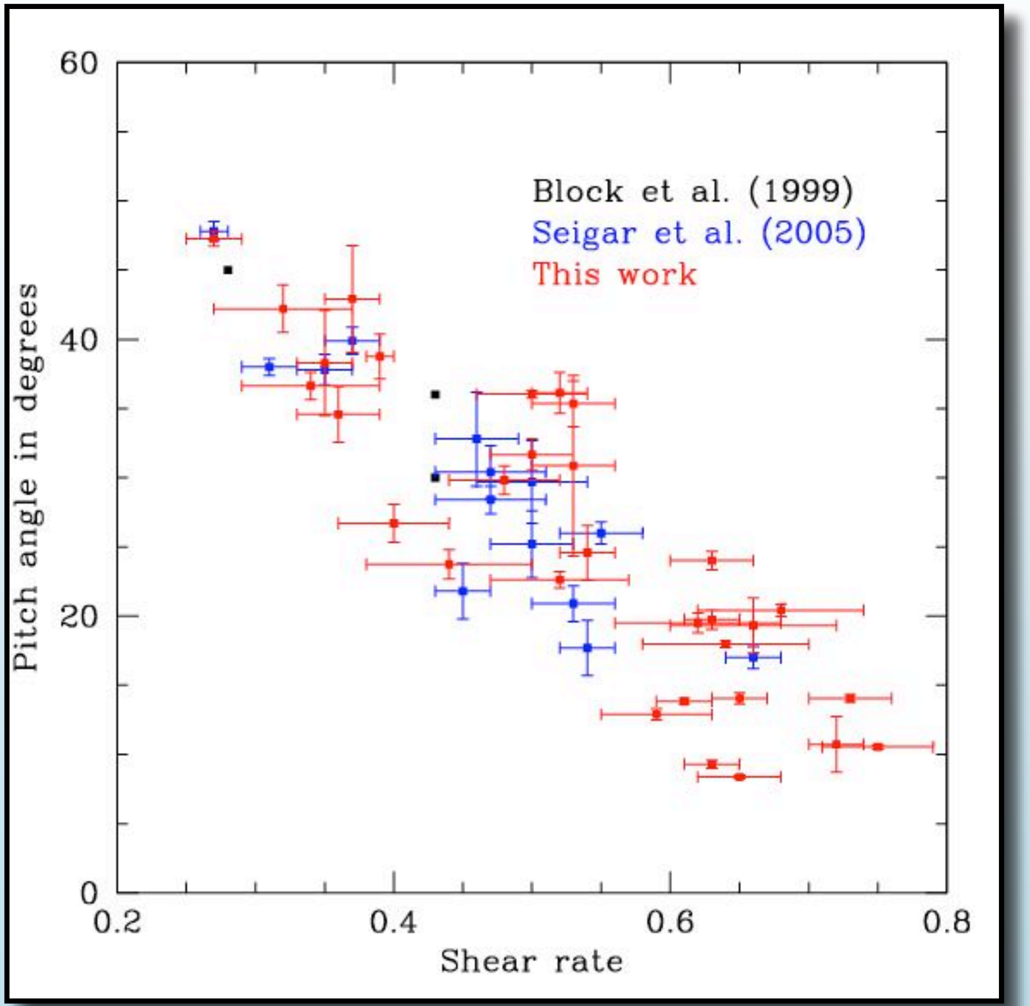

Seigar et al. (2006)

The connection with central mass concentration

- Low shear ➙ low central mass concentration
- High shear ➙ high central mass concentration

We can use spiral arm morphology to determine how mass concentrations in disk galaxies.

Use adiabatic contraction models (e.g. Blumenthal et al. 1986; Gnedin et al. 2004) to model this.

Adiabatic Contraction

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- Expected in the accepted theory of disk galaxy formation (e.g. Fall & Efstathiou 1980; Blumenthal et al. 1986)
- Baryons cool and fall to the center of a halo

  → much slower than one orbital period of halo

  → halo responds to baryonic infall and contracts
- Confirmed in N-body simulations (Gnedin et al. 2004)

The NFW Profile

- Start with the NFW profile:

$$\frac{\rho(r)}{\rho_{\mathrm{crit}}} = \frac{\delta_c}{(r/r_s)(1 + r/r_s)^2}$$

Where r_s is a scale-length and δ_c is defined as:

$$\delta_c = \frac{200}{3} \frac{c^3}{[\ln(1 + c) - c/(1 + c)]}$$

Where $c=r_{vir}/r_s$, or the NFW concentration

Our models

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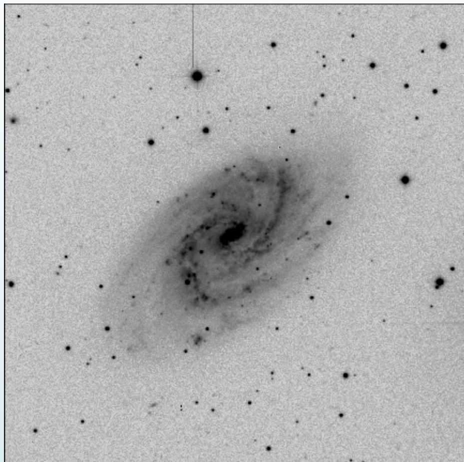
- We start with an NFW profile and contract it according the B86 AC recipe (e.g. Bullock et al. 2001)
- We also use a pure NFW model
- We estimate the rotation curve slope using shear/spiral arms and normalize it using the $V_{2.2}$

Model Inputs

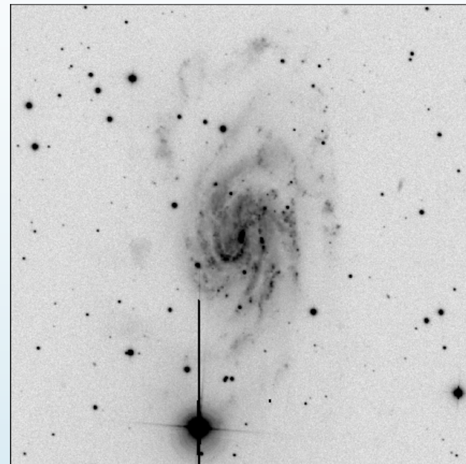
- Disk scale-length in kpc and its 1-σ error
- B/D and its1-σ error
- Disk mass, calculated using the disk luminosity and a typical M/L ratio. We use M/L values of 1.0, 1.3 and 1.6 in B-band solar units (Bell et al. 2003)
- The rotation velocity at 2.2 disk scale-lengths, $V_{2.2}$ in km/s

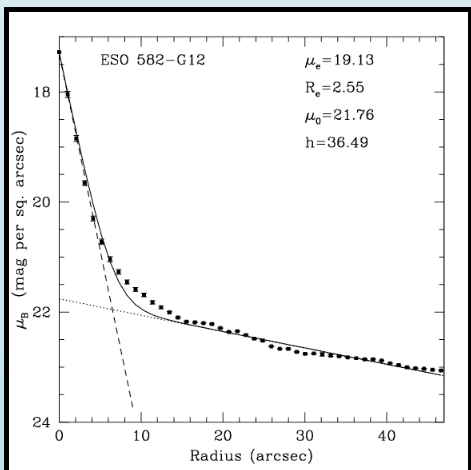
1-D Bulge/Disk Decomposition

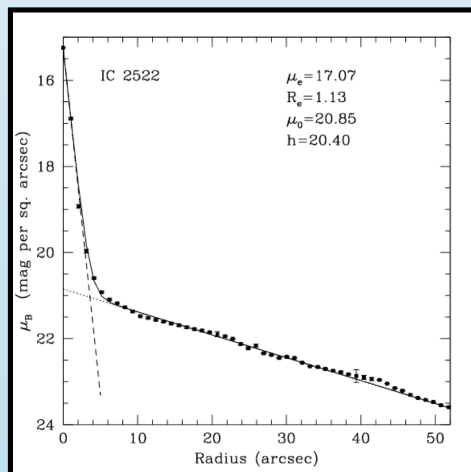
ESO 582 -G12



IC 2522







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Results of the B/D Decomposition

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ESO 582 -G12:

- h=36.5±3.8 arcsec
- h=5.48±0.57 kpc
- B/D=0.11
- L_{disk}=(1.27±0.11)x10^{10} $L_{\odot}$
- $V_{2.2}$=145 km/s

IC2522:

- h=20.4±2.1 arcsec
- h=3.98±0.41 kpc
- B/D=0.16
- L_{disk}=(1.55±0.14)x10^{10} $L_{\odot}$
- $V_{2.2}$=216 km/s

ESO 582 -G12

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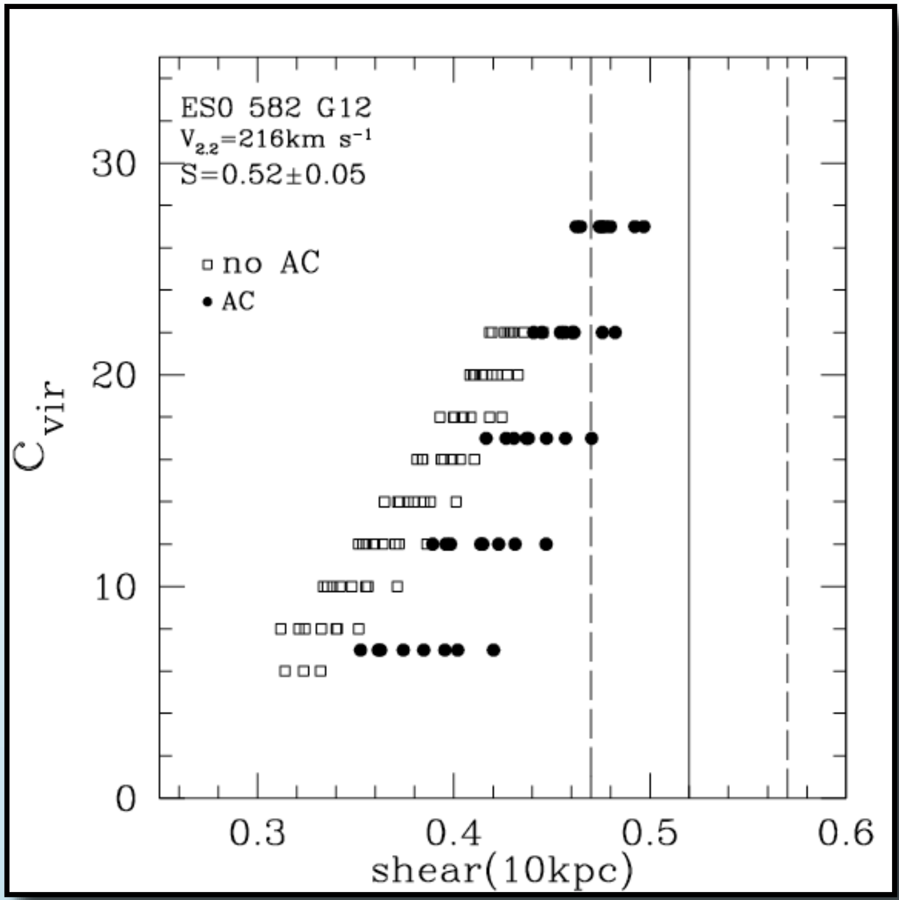
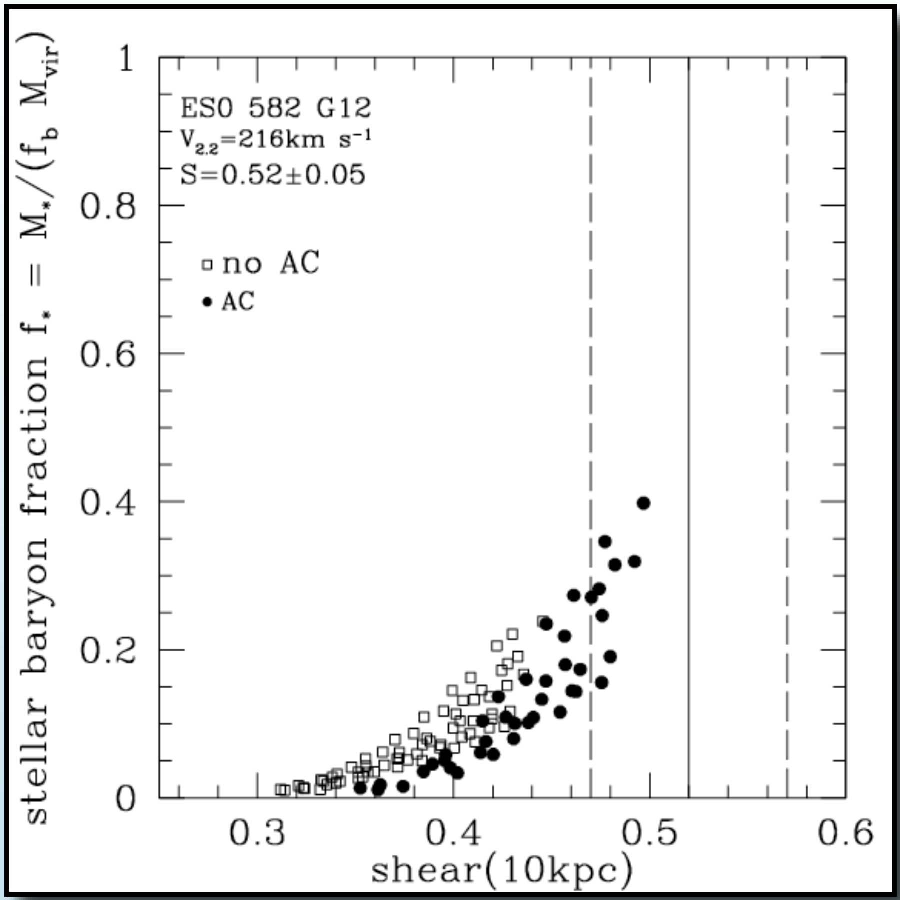


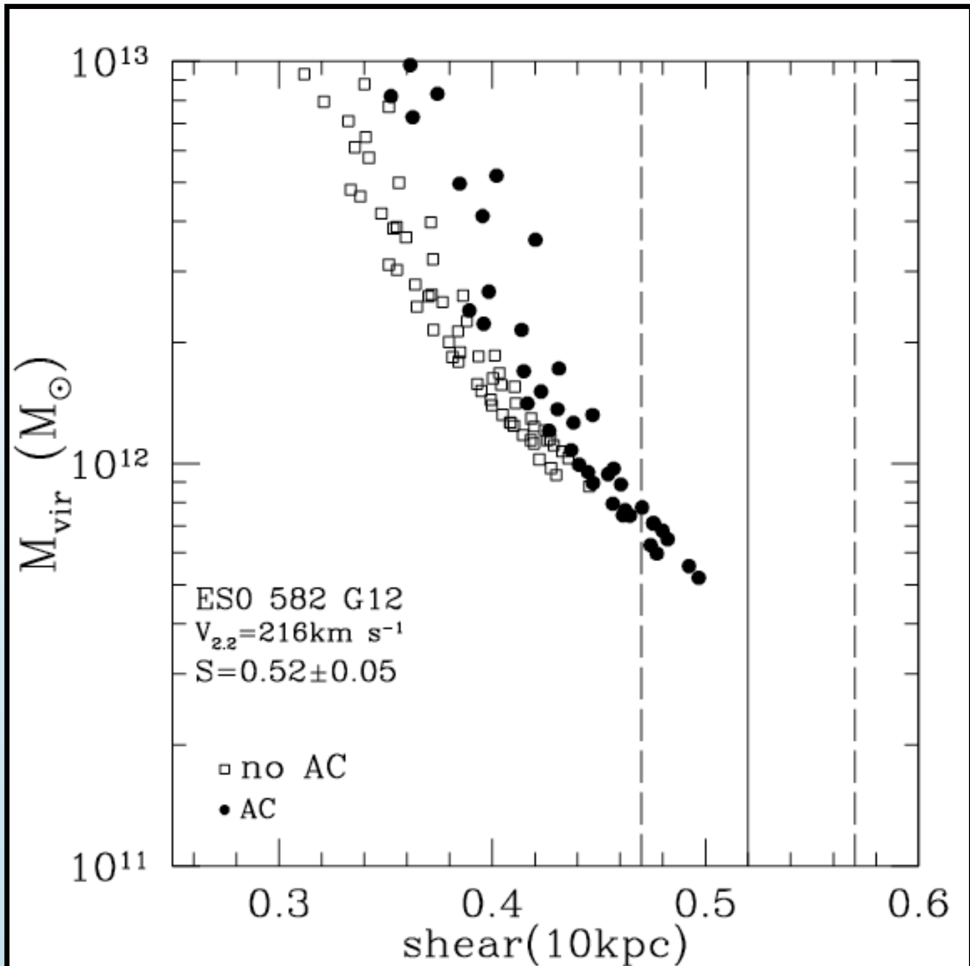


C_{vir}=16-30

f_*=0.15-0.40

Seigar et al. (2006)

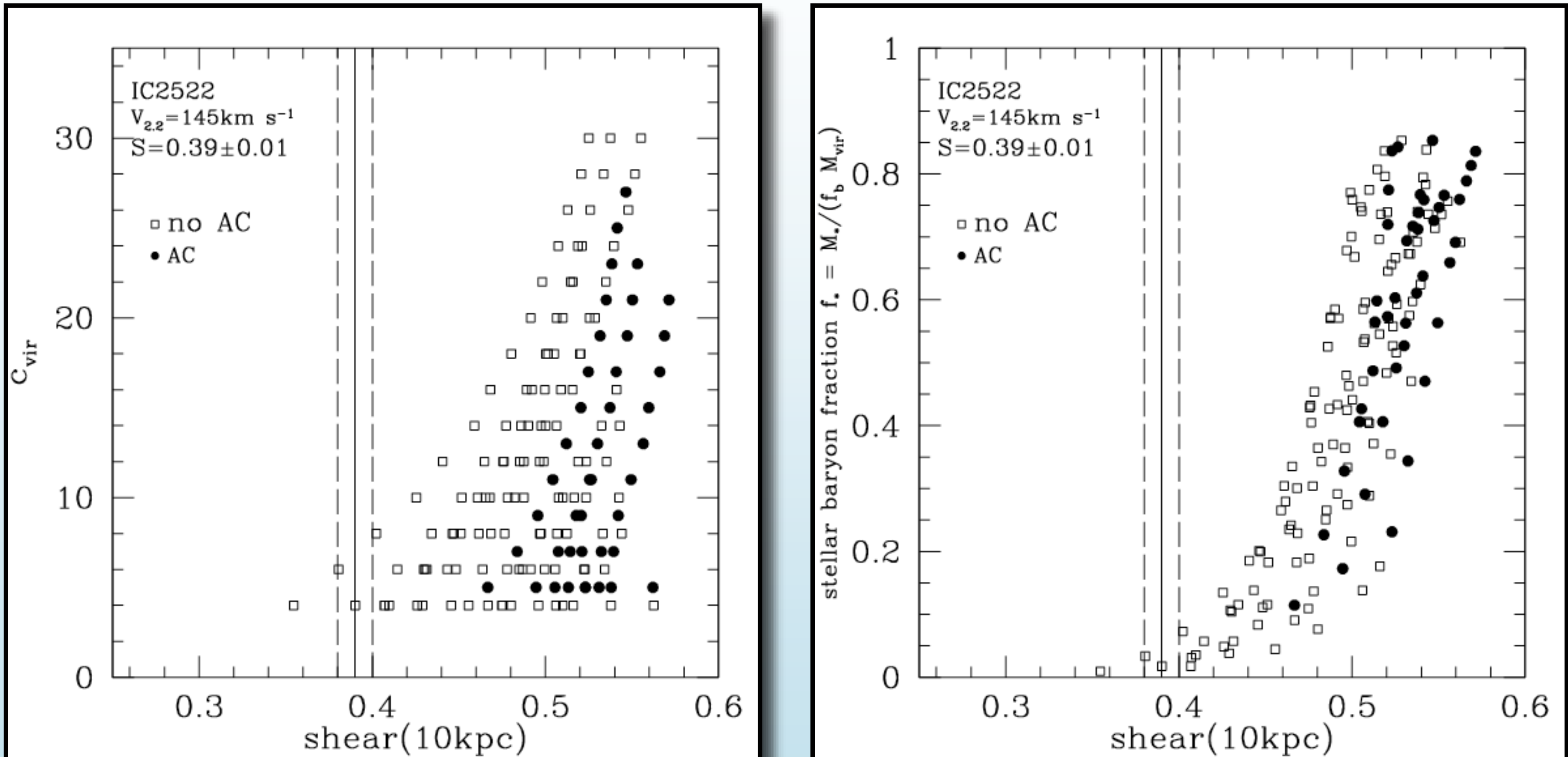
ESO 582 -G12



M_{vir}=5-9x10^{11} $M_\odot$

Seigar et al. (2006)

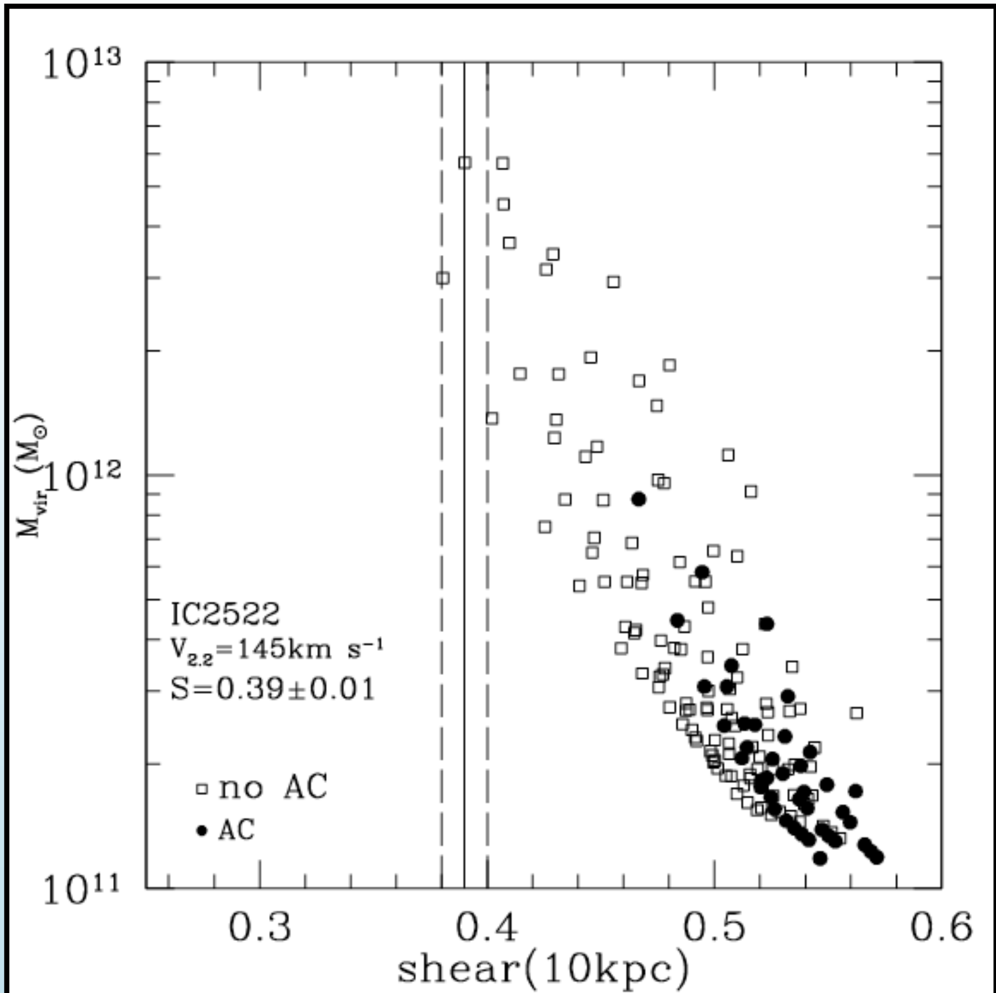
IC 2522



C_{vir}<8 f_*<0.10

Seigar et al. (2006)

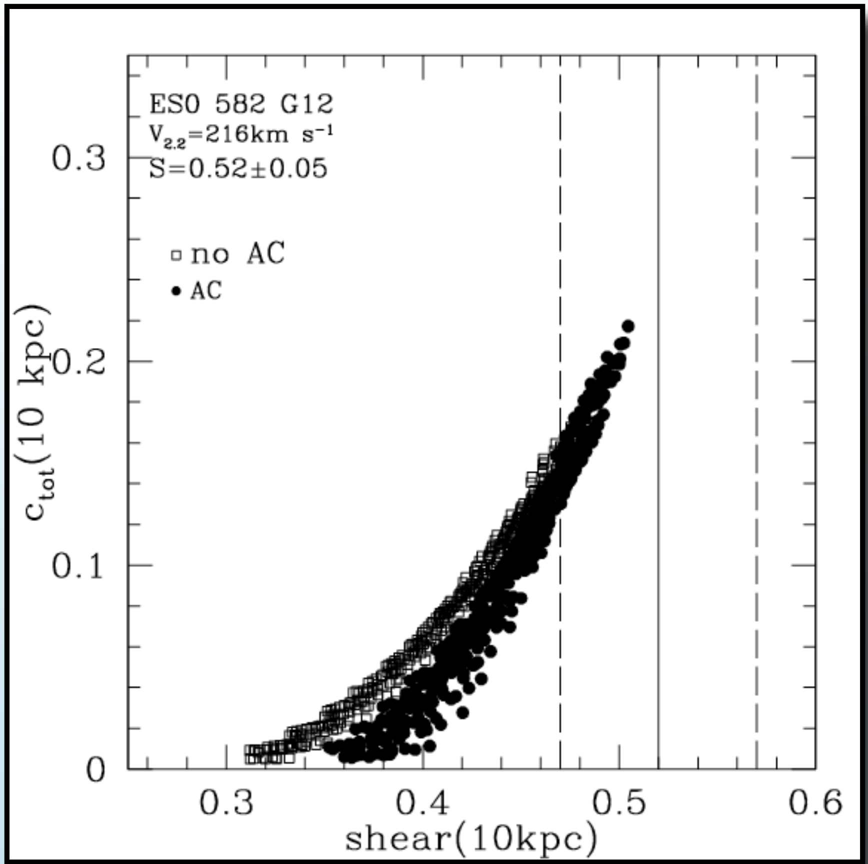
IC 2522

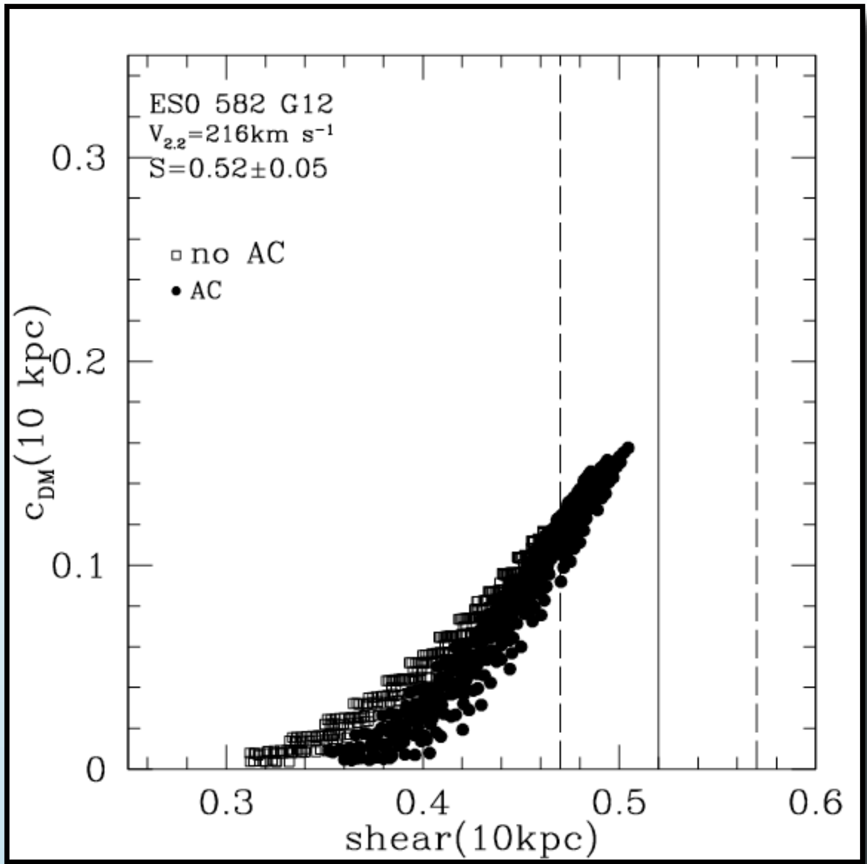


M_{vir}=1-6x10^{12} $M_\odot$

Seigar et al. (2006)

ESO 582 -G12 mass concentrations





c_{tot}=0.12-0.22

c_{DM}=0.08-0.16

Seigar et al. (2006)

IC 2522 mass concentrations

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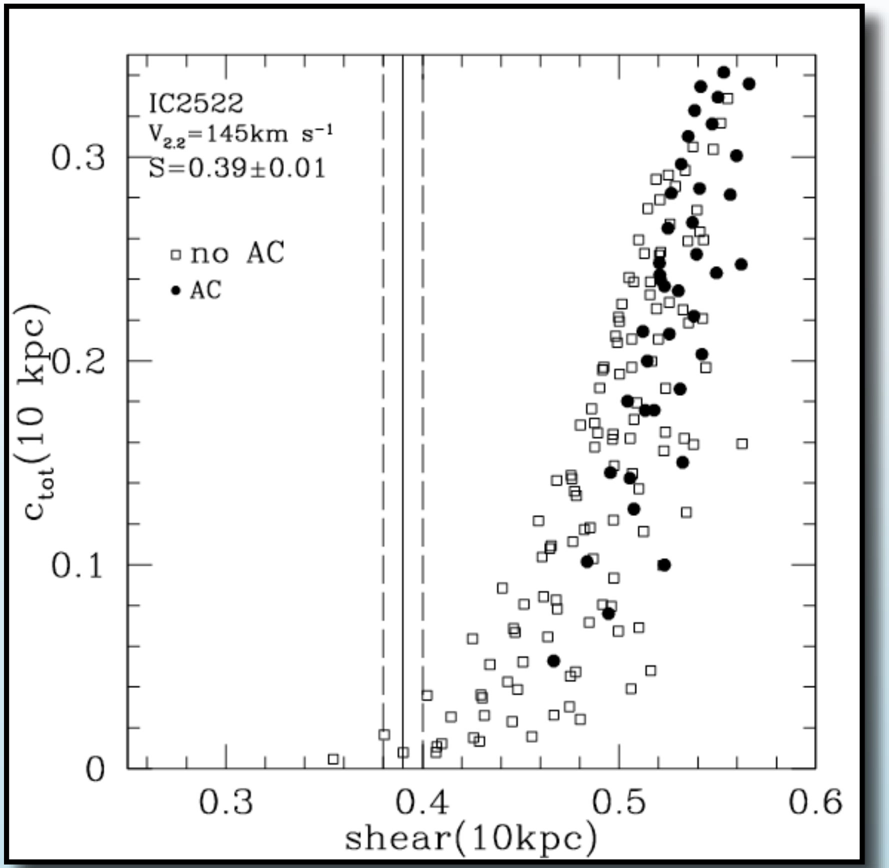
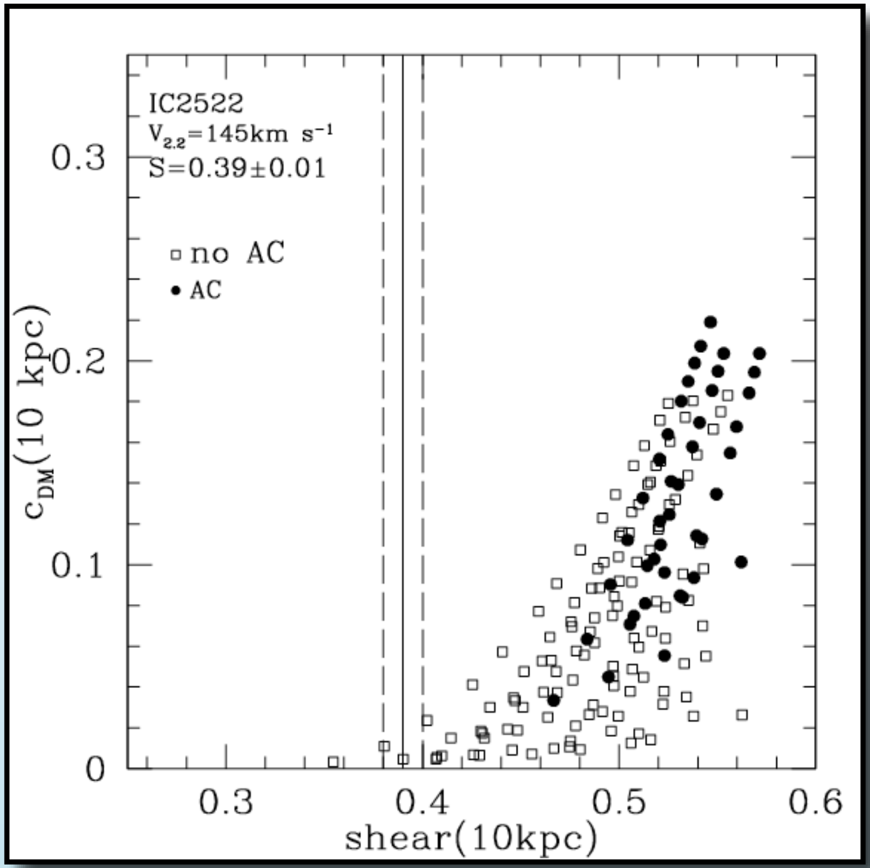




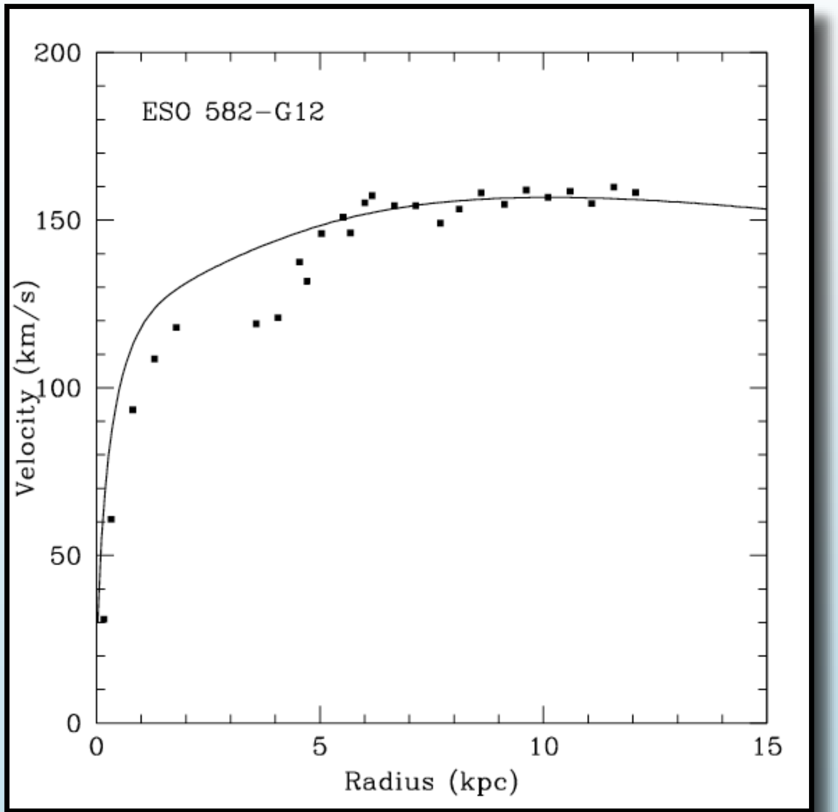
$c_{tot}<0.04$ $c_{DM}<0.02$

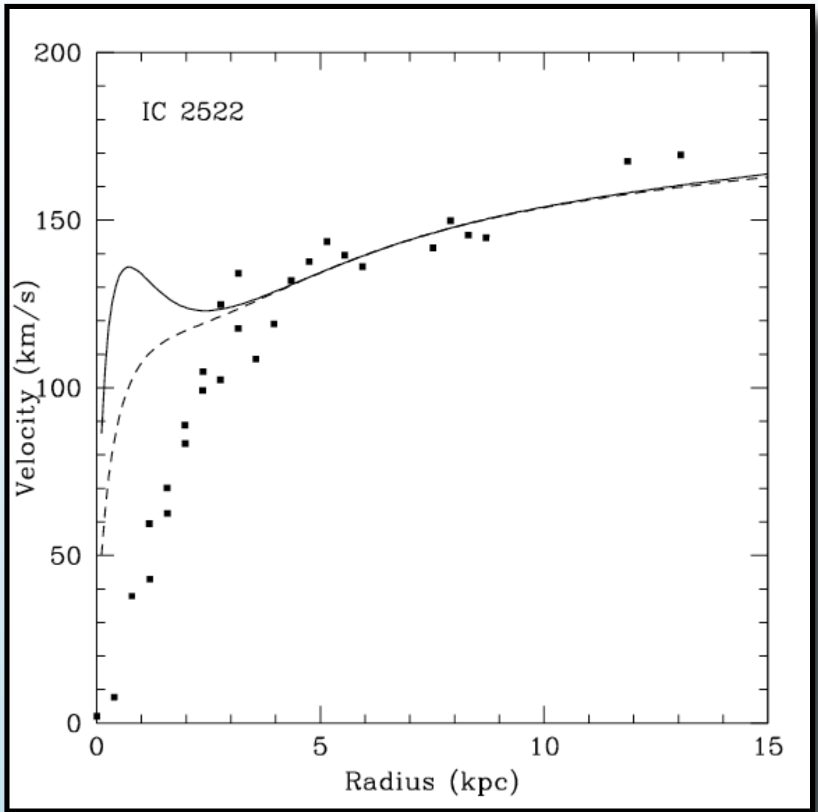
Seigar et al. (2006)

Rotation curves

ESO 582 -G12

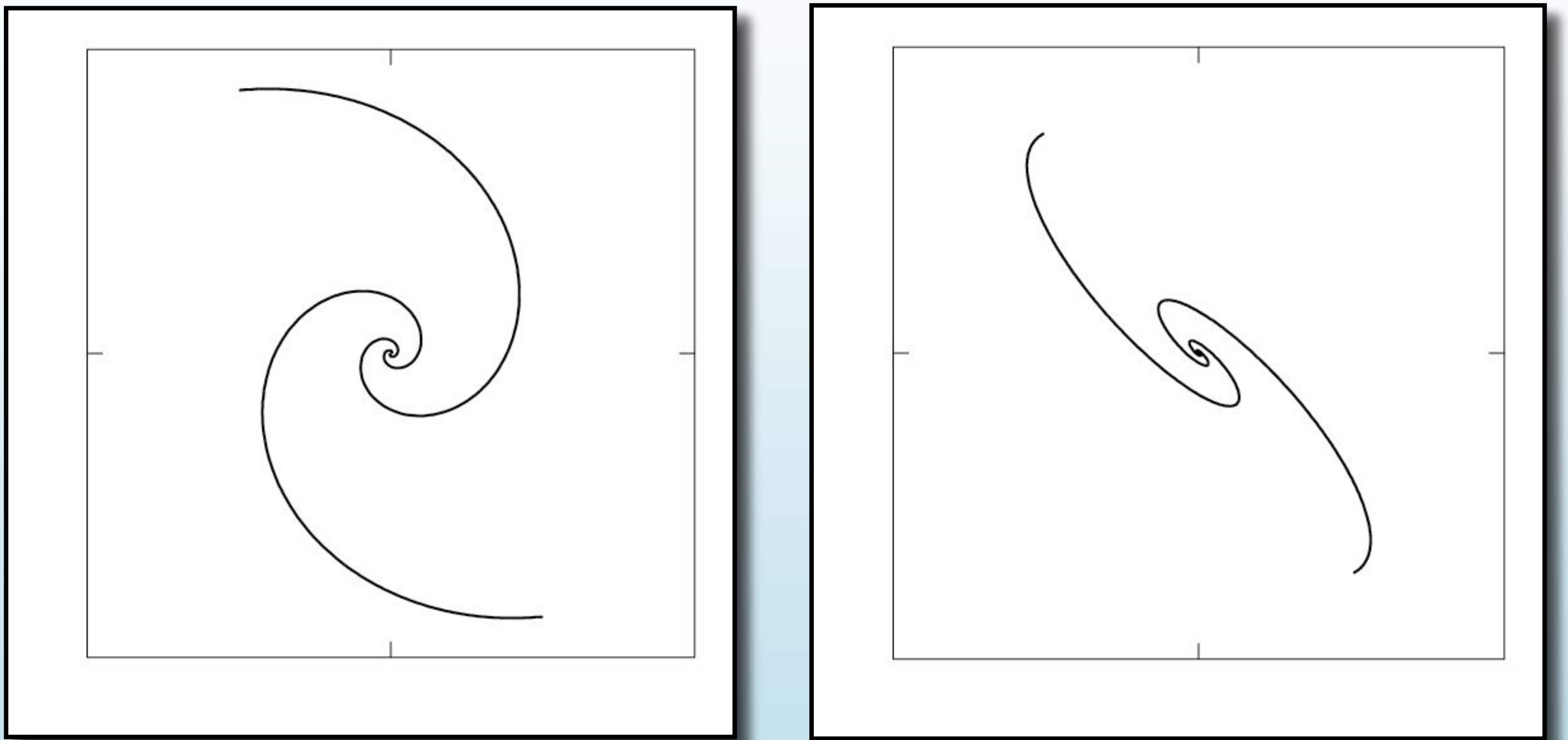
IC 2522





Seigar et al. (2006)

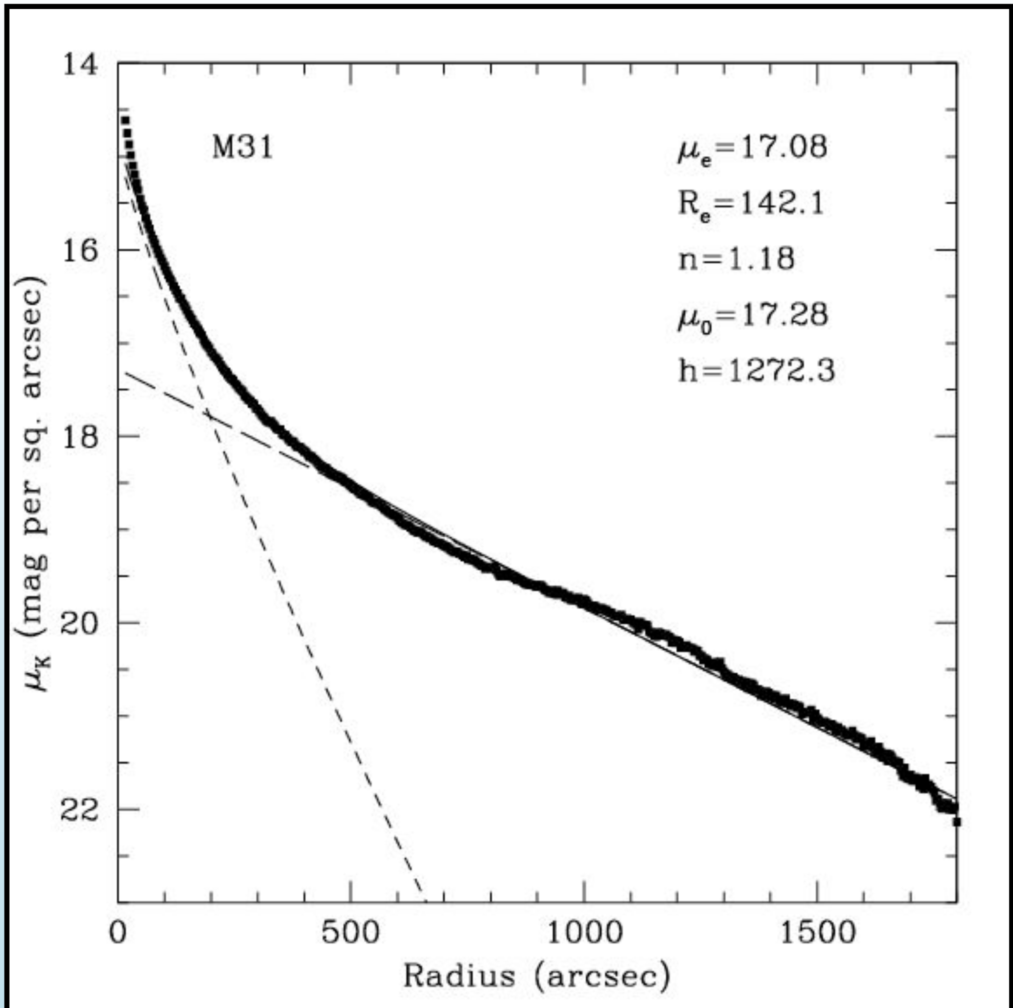
Application to M31: Spiral arm morphology



P=24.7±4.4

Seigar, Barth & Bullock (2007, ApJ, submitted)

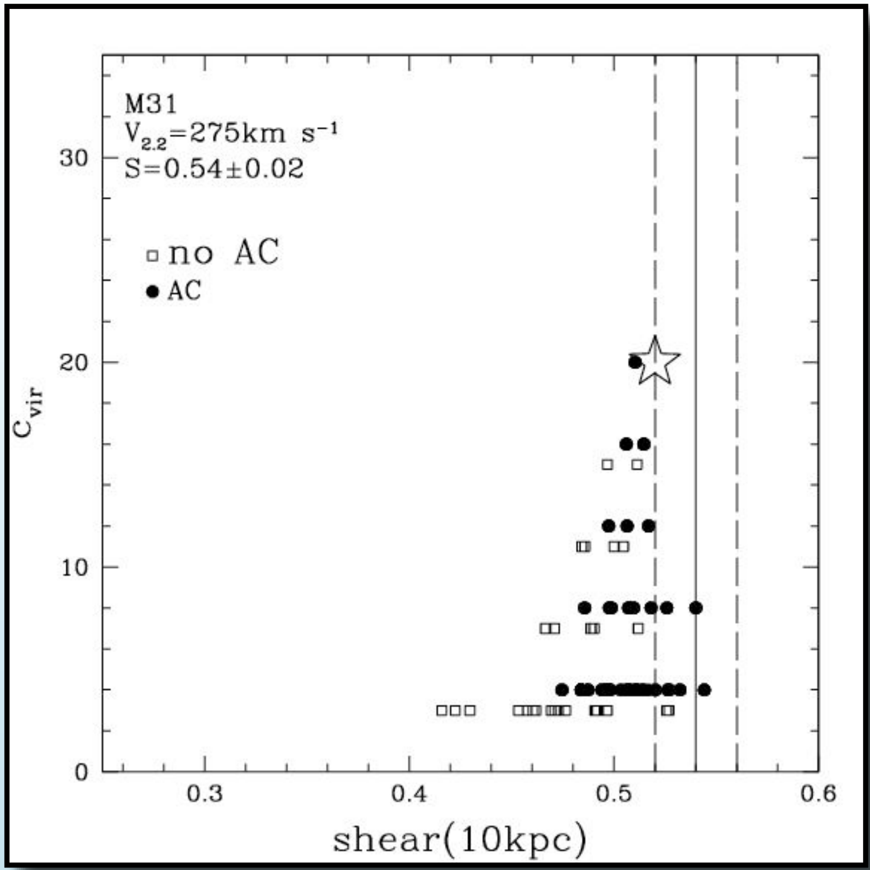
M31 Bulge/Disk decomposition



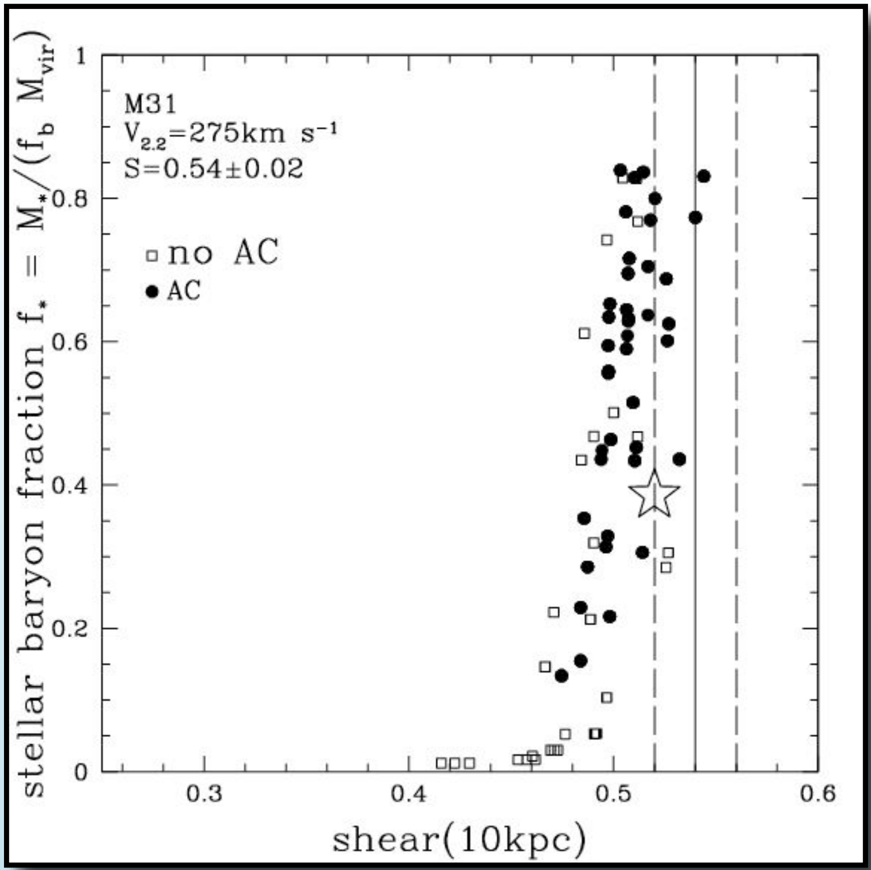
2MASS K_s-band image of M31

Seigar et al. (2007)

M31



C_{vir}<20



f_*=0.3-0.9

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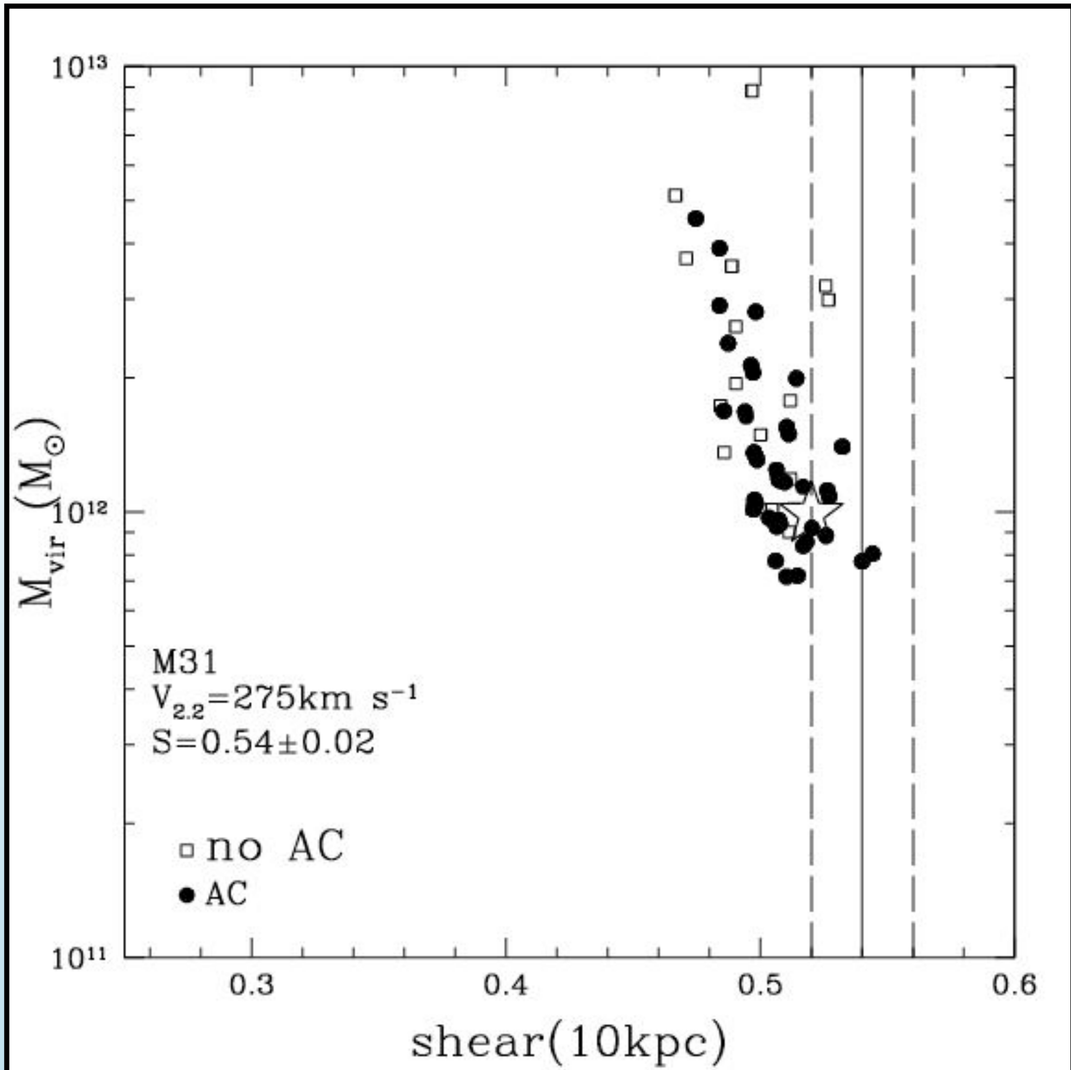
M31



M_{vir}=0.7-2.0x10^{12} $M_\odot$ (Seigar et al. 2007)

c.f. M_{vir}=8-9x10^{11} $M_\odot$

From satellite kinematics & halo stars by Chapman et al. (2006) and Fardal et al. (2006)

M31 mass concentrations

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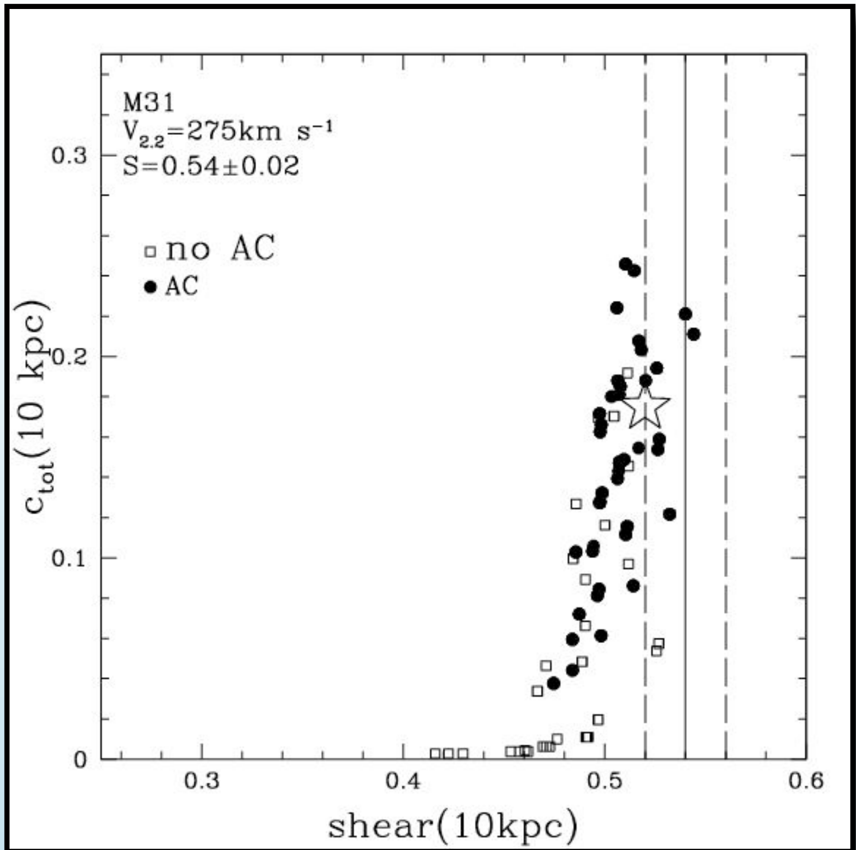
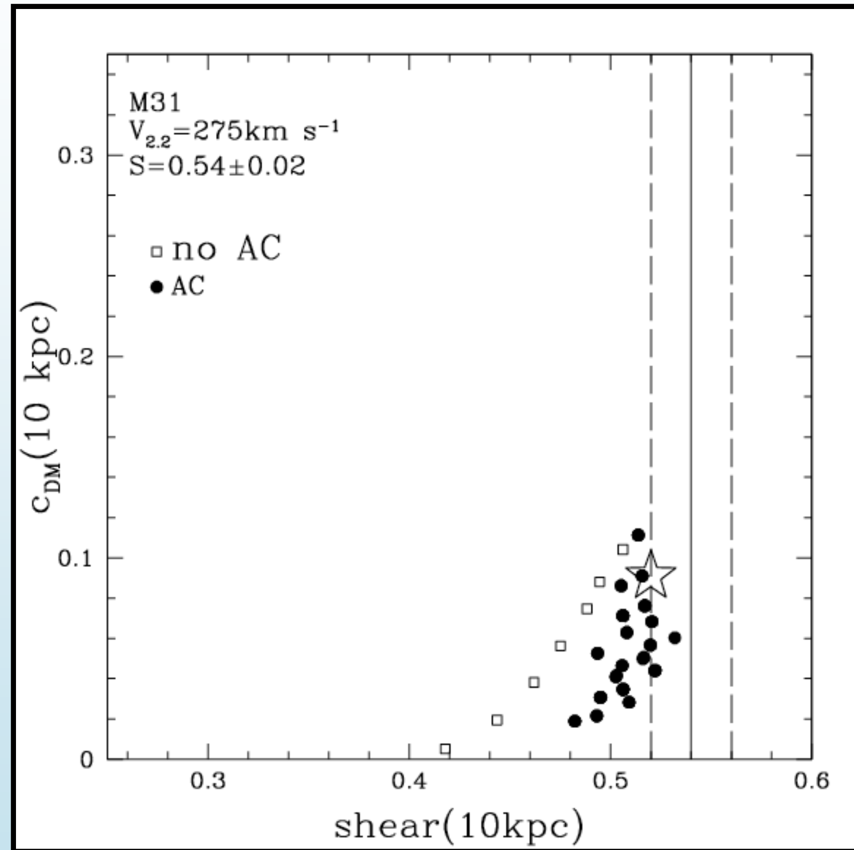
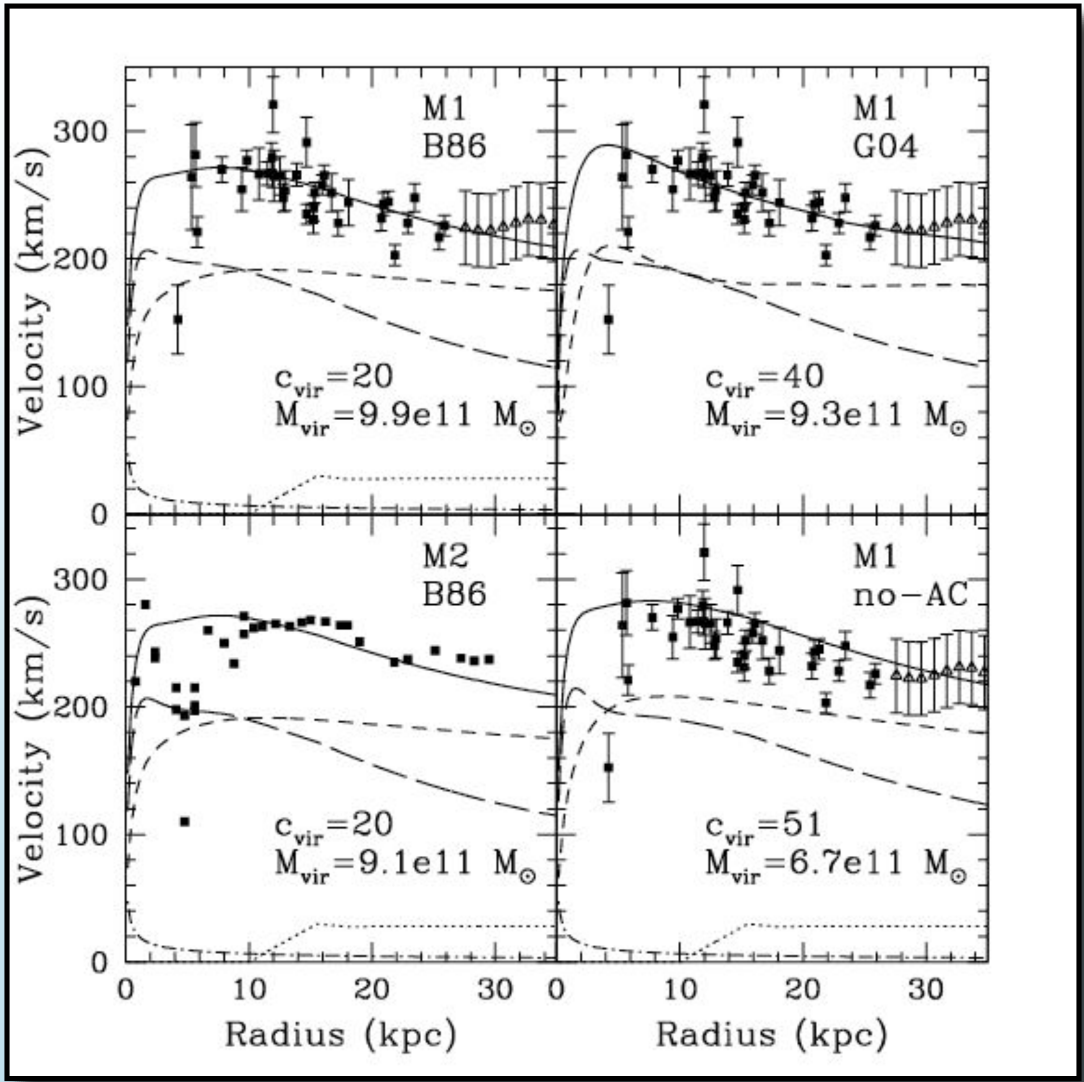




c_{tot}=0.06-0.25

c_{DM}=0.04-0.11

M31 model rotation curves



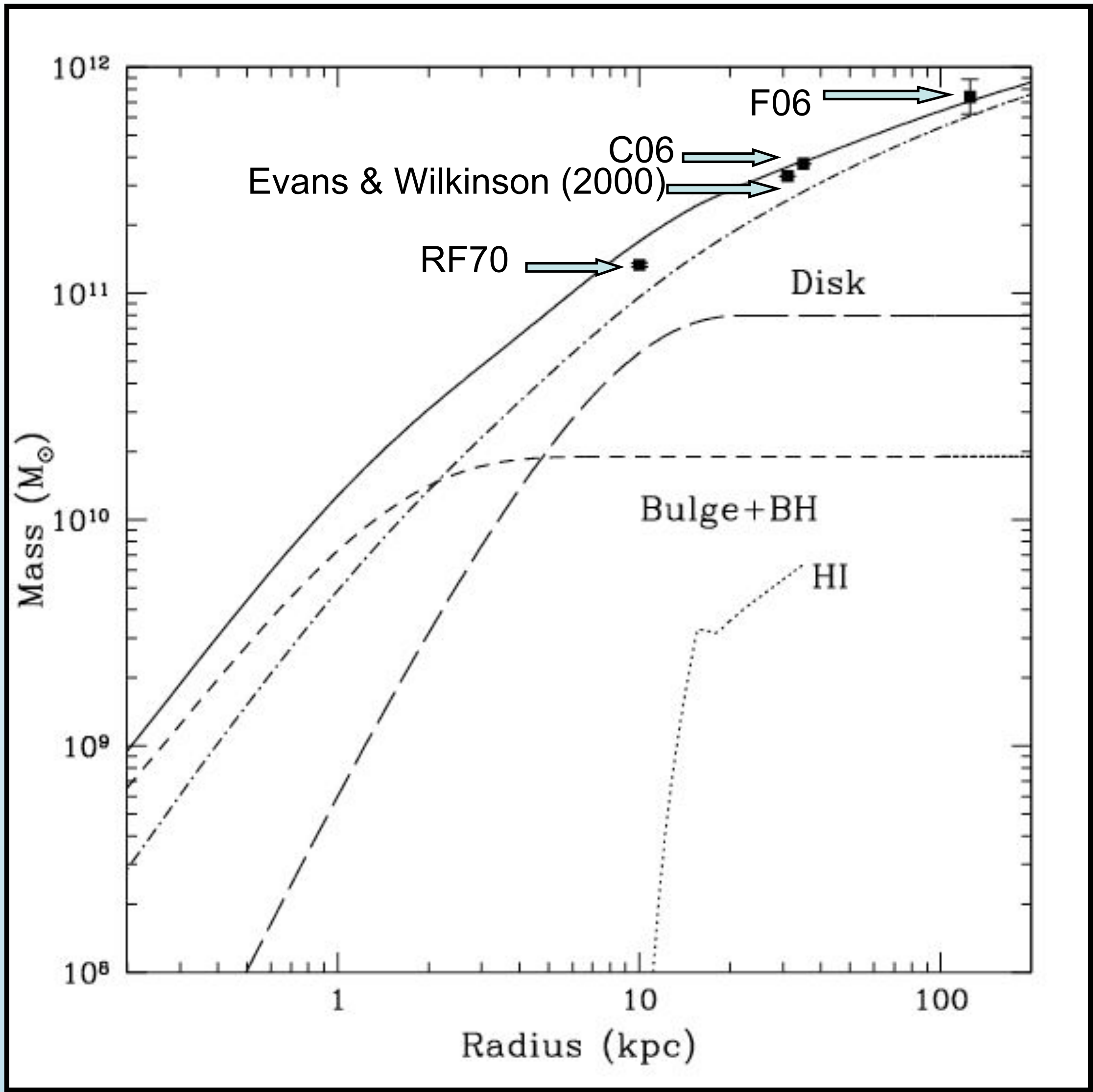
All models provide reasonable fits.

M1 B86 is preferred due to its concentration

Fit to Rubin & Ford (1970) rotation curve

Seigar et al. (2007)

Mass profile of M31



M_{vir}=(9.9±0.7)x10^{11} $M_{\odot}$

Similar to masses found through kinematics of satellites, Andromeda stream etc (e.g. Fardal et al. 2006; Chapman et al. 2006)

Seigar et al. (2007)

Summary I

- There is a tight 1:1 correlation between optical and near-IR spiral arm pitch angles
- There is a strong correlation between spiral arm pitch angle and rotation curve shear
- Using this we have determined the mass concentrations/distributions of 3 galaxies (including M31)

Summary II

- Using the correlation between shear and pitch angle we have shown that ESO 582 -G12 needs AC to reproduce its shear. IC 2522 has a shear value that is inconsistent with AC
- The rotation curve of M31 is consistent with a halo that has undergone AC. Its halo virial mass of is consistent with estimated derived using satellite kinematics and the Andromeda Stream

Future Work

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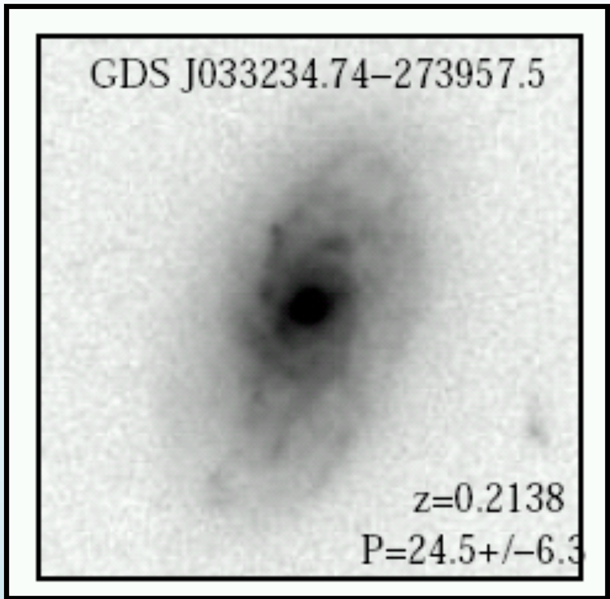
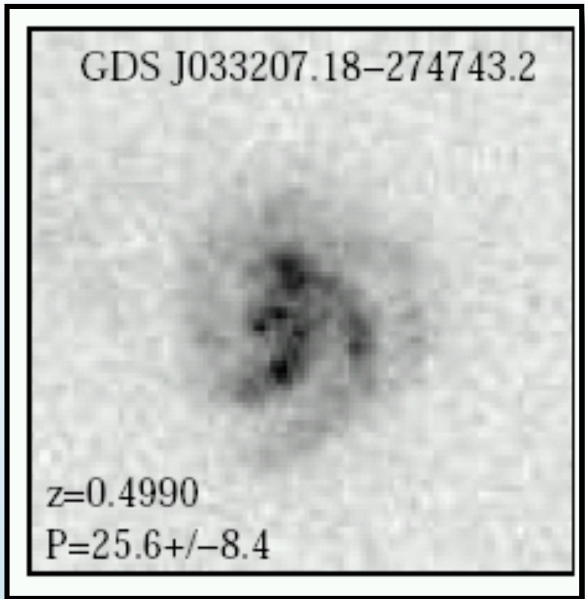
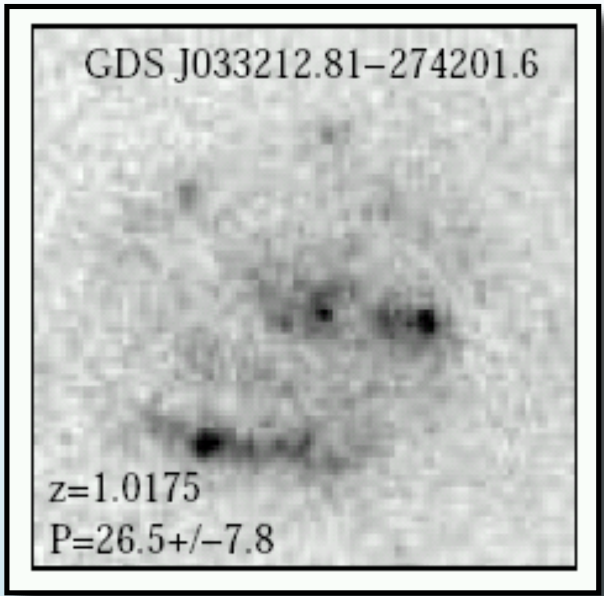
- We have ~150 face-on galaxies from the Carnegie-Irvine Nearby Galaxies Survey (CINGS; PI: Luis Ho) to which we can apply these methods for estimating mass profiles
- Apply these methods to galaxies which have little or no kinematic information, e.g. galaxies at higher redshift in the GOODS or DEEP2 fields

Galaxies in the GOODS fields







Some example galaxies in the GOODS-S field

Nuclear spirals I

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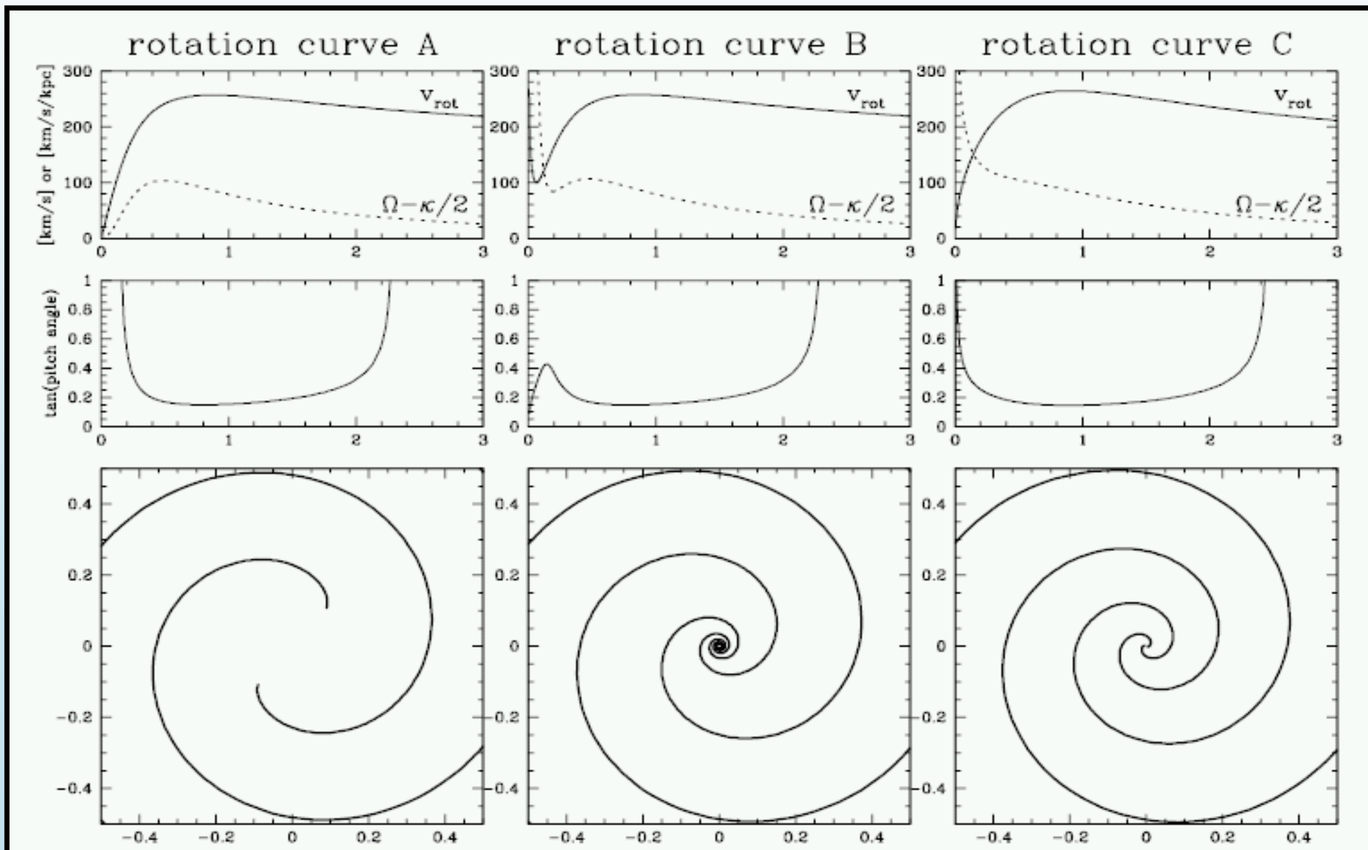
Models of nuclear spiral structure from Maciejewski (2004a, b):



Nuclear spirals II

NGC 3362: Spiral arms traced to 120 pc - constant density core

NGC 1530: Spiral arms wind up within 60 pc - SMBH

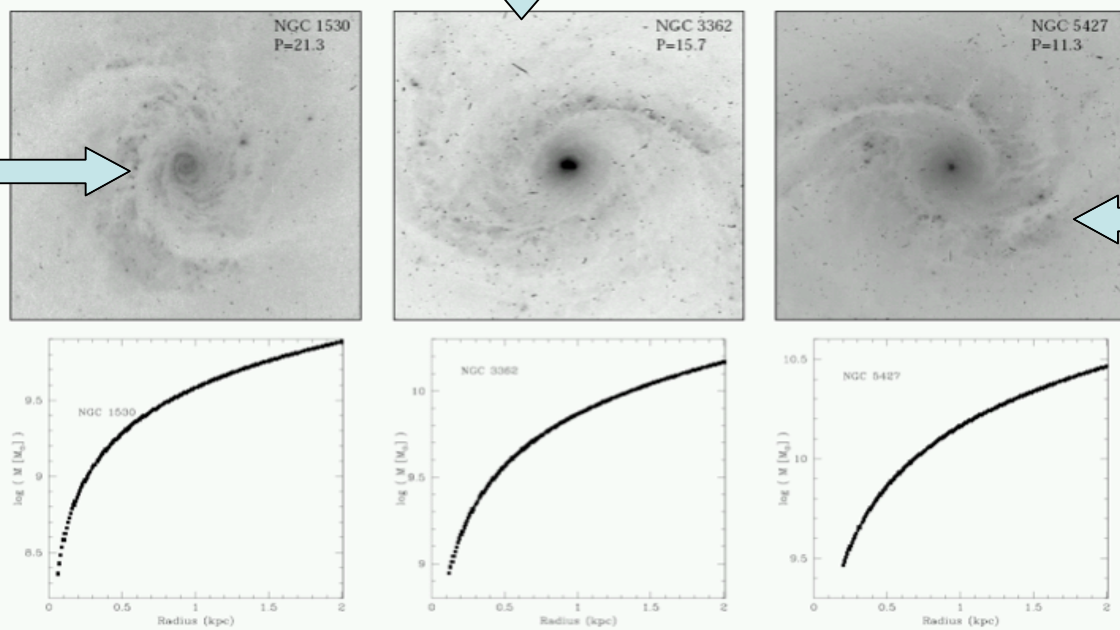
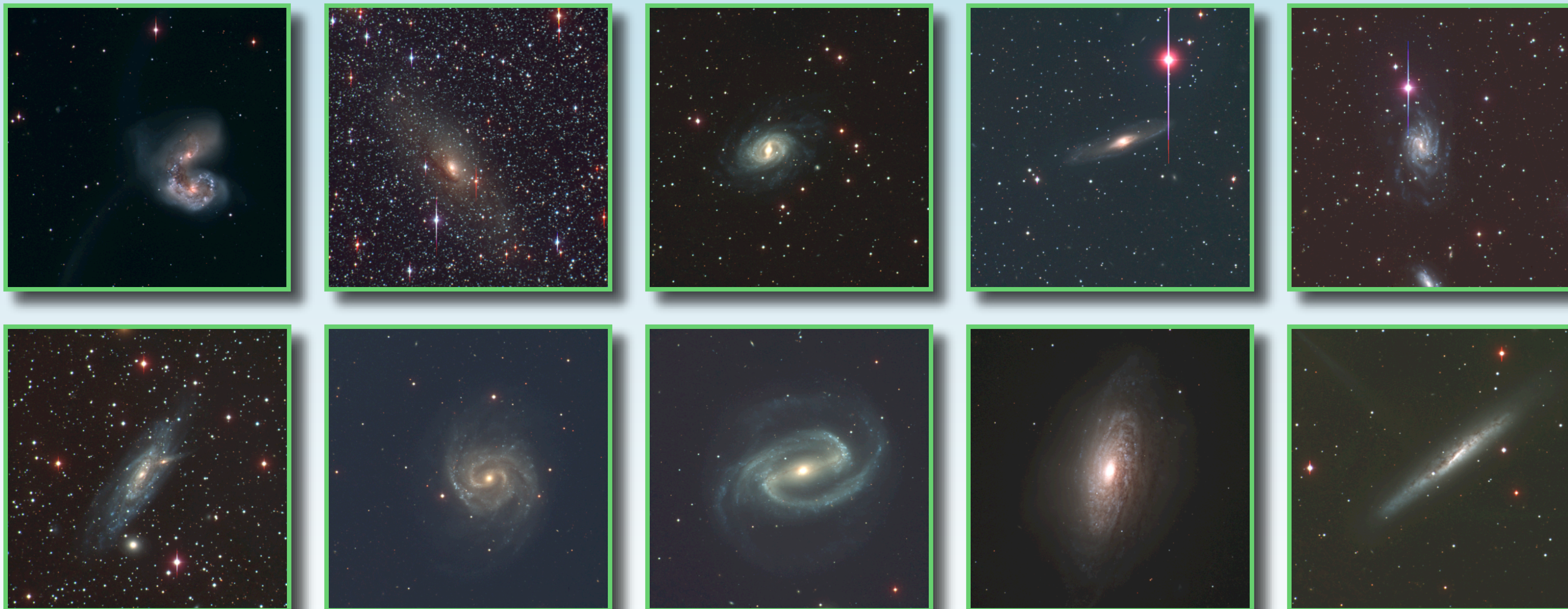


Fig 1. *Top row:* PC1 images of three example galaxies with their measured spiral arm pitch angle. *Bottom row:* Enclosed mass as a function of radius out to 2 kpc calculated using the models of Maciejewski (2004a).

NGC 5427: Spiral arms traced to 200 pc - constant density core

The Carnegie-Irvine Nearby Galaxies Survey (CINGS)



http://www.ociw.edu/~lho/projects/CINGS/CINGS.html

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