# Pattern Speed Estimates of Barred Galaxies from CINGS: A Connection Between Central Dark Halo Concentration and SMBH Mass?

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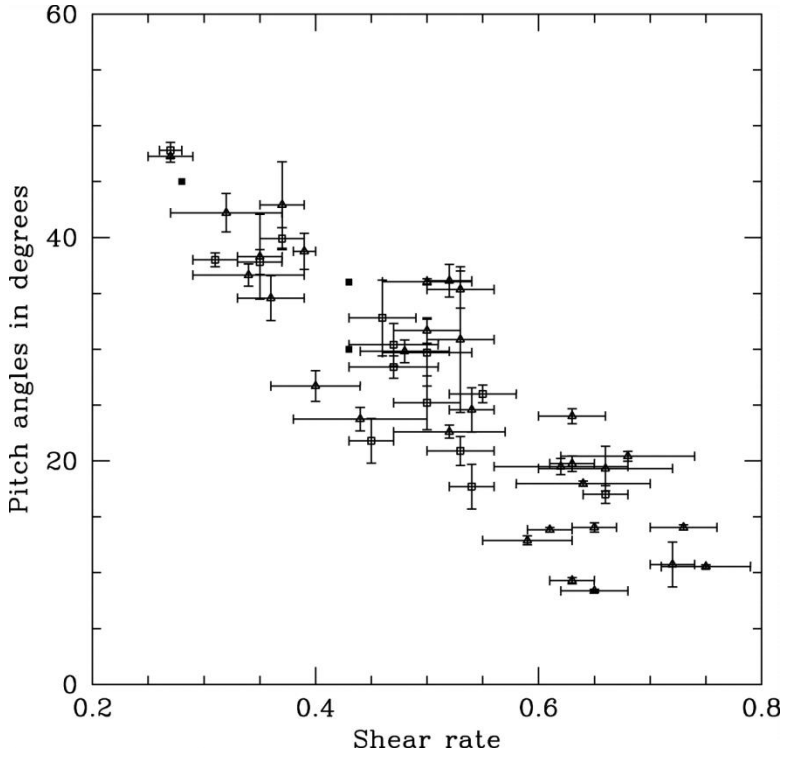
# Outline

- Introduction
- Sample
- Pitch Angle Measurements
- Gravitational Potentials
- Simulations
- Results
- Conclusion

# Introduction

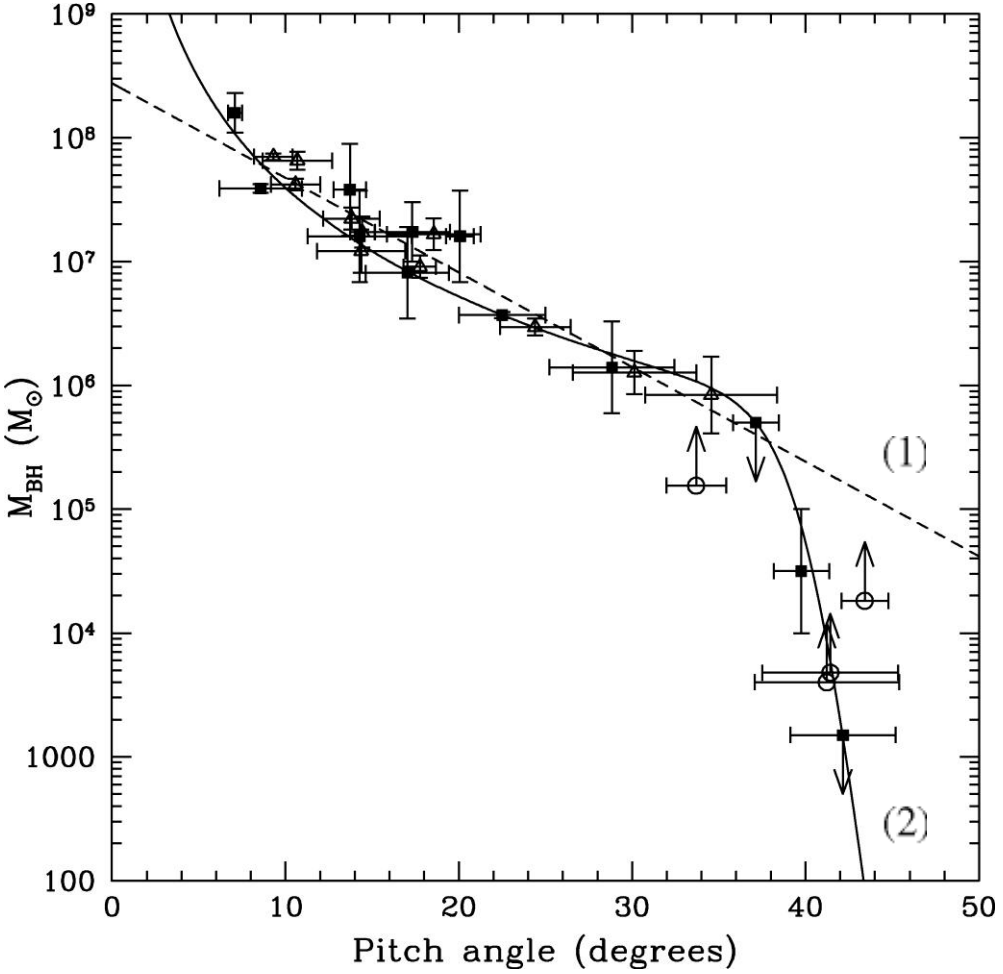
(Seigar et al. 2006)




- Useful relations to estimate SMBH mass
  - $M_{BH}$-$M_{bulge}$ (Magorrian et al. 1998)
  - $M_{BH}$-σ (i.e. Gebhardt et al. 2000)
  - $M_{BH}$-P (Seigar et al. 2008)
    - Rotation curve shear is related to P (Seigar et al. 2004, 2005, 2006)

# Introduction

- Dark matter (DM) halo mass appears linked to SMBH mass (Ferrarese 2002).
- Late-type galaxies, with little or no bulge, have been found to harbor SMBHs (Satyapal et al. 2007, 2008).
  - Suggests DM halo concentration may be linked to SMBH mass (Satyapal et al. 2007, Seigar et al. 2008)
    - Fast bars exist in DM halos of low central concentration (Debattista & Sellwood 2000).
      - Fast: $1 \leq R_{CR}/R_{bar} \leq 1.4$
      - Slow: $R_{CR}/R_{bar} > 1.4$




(Seigar et al. 2008)

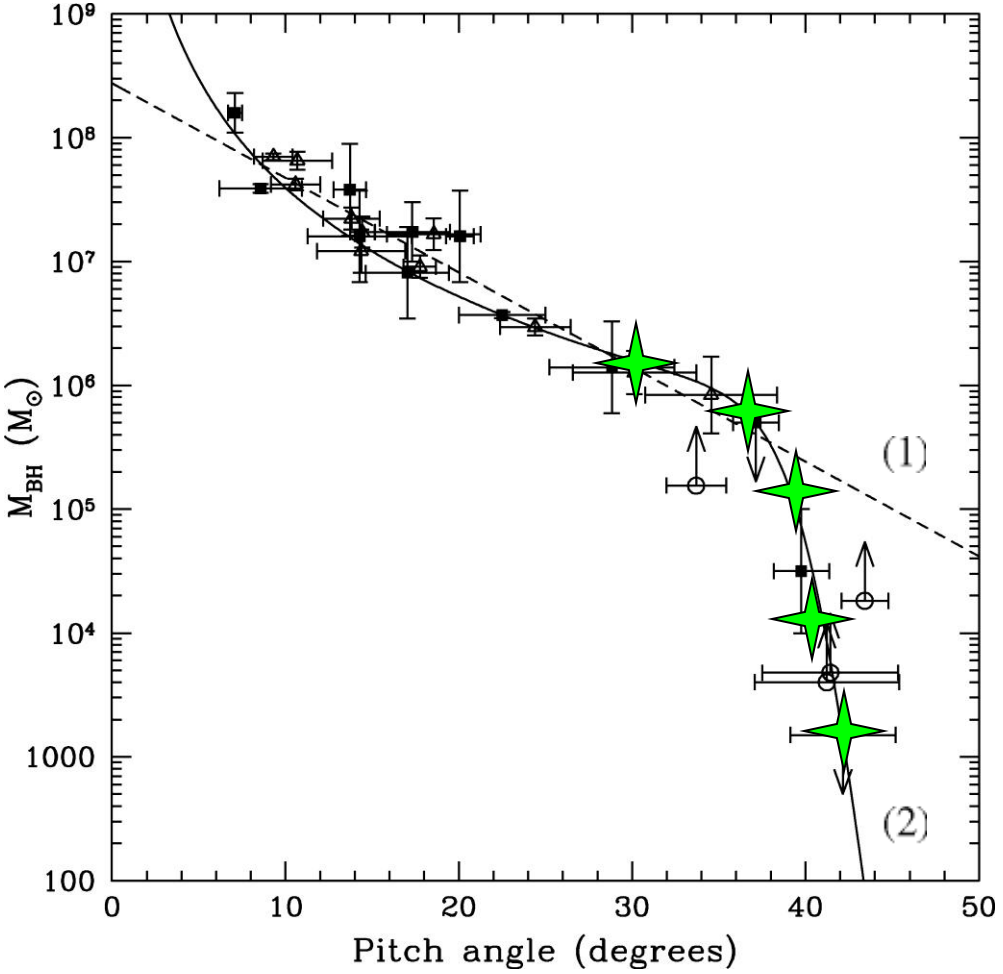
$$(1) \quad \log_{10} M_{\rm BH} = (8.44 \pm 0.10) - (0.076 \pm 0.005)P.$$

$$(2) \quad M_{\rm BH} = 2^{(\beta-\gamma/\alpha)} M_{{\rm BH}_b} \left(\frac{P_b}{P}\right)^{\gamma} \left[1 + \left(\frac{P}{P_b}\right)^{\alpha}\right]^{(\gamma-\beta/\alpha)}$$

$\alpha = 23.5$ $\quad M_{{\rm BH}_b} = 1.72 \times 10^4\, M_\odot$

$\beta = 126.1$ $\quad P_b = 40.8^\circ$

$\gamma = 2.92$




Fast bar

(Seigar et al. 2008)

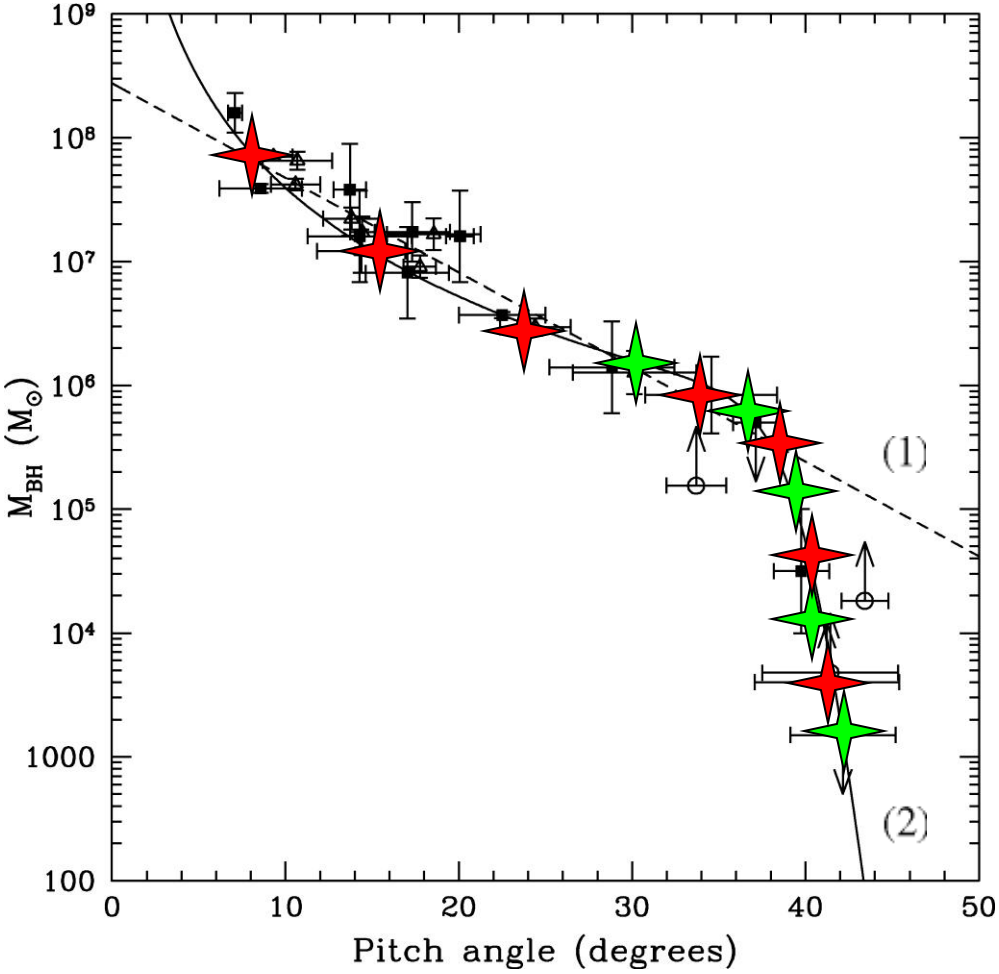
(1) $\log_{10} M_{\rm BH} = (8.44 \pm 0.10) - (0.076 \pm 0.005)P.$

(2) $$M_{\rm BH} = 2^{(\beta-\gamma)/\alpha} M_{{\rm BH}_b} \left(\frac{P_b}{P}\right)^{\gamma} \left[1 + \left(\frac{P}{P_b}\right)^{\alpha}\right]^{(\gamma-\beta)/\alpha}$$

$\alpha = 23.5$ $\quad M_{{\rm BH}_b} = 1.72 \times 10^4\, M_\odot$

$\beta = 126.1$ $\quad P_b = 40.8^\circ$

$\gamma = 2.92$




Fast bar

Slow bar

(Seigar et al. 2008)

(1) $\log_{10} M_{\rm BH} = (8.44 \pm 0.10) - (0.076 \pm 0.005)P.$

(2) $M_{\rm BH} = 2^{(\beta-\gamma)/\alpha} M_{{\rm BH}_b} \left(\frac{P_b}{P}\right)^{\gamma} \left[1 + \left(\frac{P}{P_b}\right)^{\alpha}\right]^{(\gamma-\beta)/\alpha}$

$\alpha = 23.5$ $\quad M_{{\rm BH}_b} = 1.72 \times 10^4\, M_\odot$

$\beta = 126.1$ $\quad P_b = 40.8^\circ$

$\gamma = 2.92$

# Sample

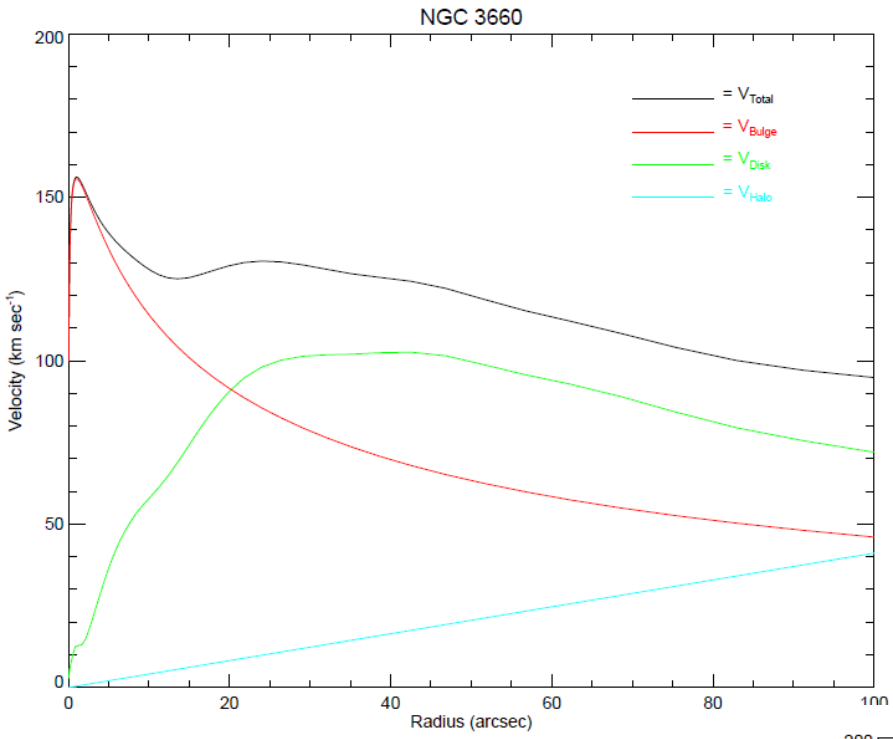
- Carnegie-Irvine Nearby Galaxies Survey (CINGS) sample
  - 603 brightest southern hemisphere galaxies
    - $B_T < 12.9$
  - Observed in *B*, *V*, *R*, *I*, $K_s$
- We used a subsample of 40 barred spiral galaxies
  - Morphology range
    - $0.8 \pm 0.5 \leq T \leq 6.7 \pm 0.8$ (HyperLeda)

# Pitch Angle Measurements

- *B*-band images were deprojected
- Pitch angles were measured using a 2D FFT assuming logarithmic spirals (Schröder et al. 1994).
  - Radial range was selected to exclude the bar and extend to the outer limits of the visible arms.

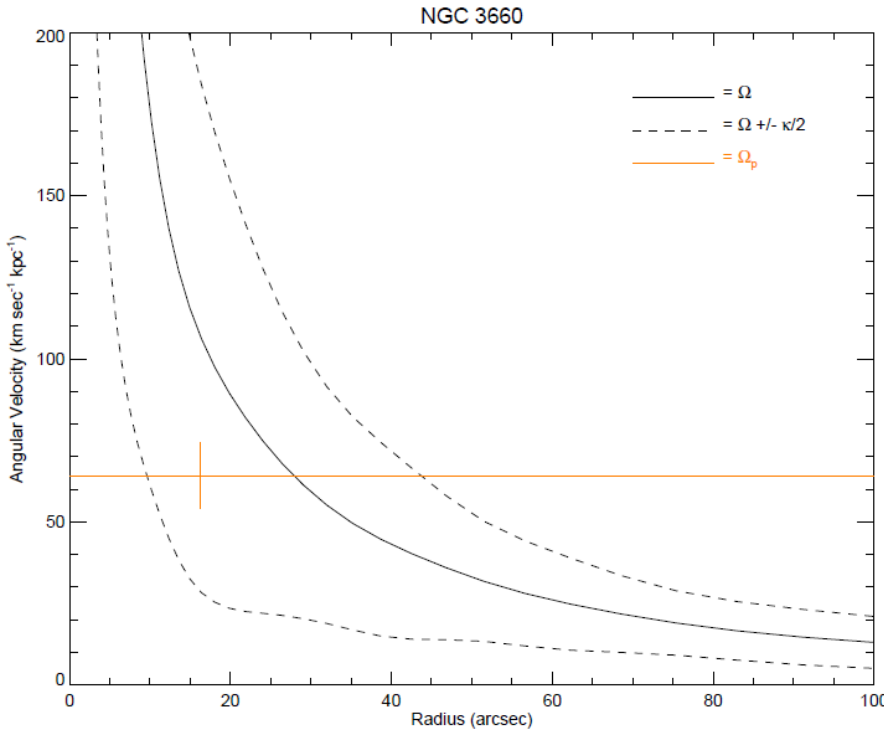
# Gravitational Potentials

- $K_s$-band image
  - Surface mass density determined by assuming a M/L from *B*-*V* color gradient (Bell et al. 2003).
  - 2D bulge-disk-bar decomposition
    - Bulge: Sérsic $r^{1/n}$ function
    - Disk: exponential function
    - Bar: Ferrers function
  - Fourier decomposition of deprojected image
    - Even components ($0 \leq m \leq 8$)
  - Typical $h_z/h_r$ values were assumed for the disk components (de Grijs 1998).




Azimuthally averaged rotation curve derived from the mass model based on the M/L-corrected $K_s$-band image.

The halo component is assumed to be an isothermal sphere and is based on the universal rotation curve of Persic et al. (1996).




Lindblad precession frequency curves derived from the mass model rotation curve.

# Simulations

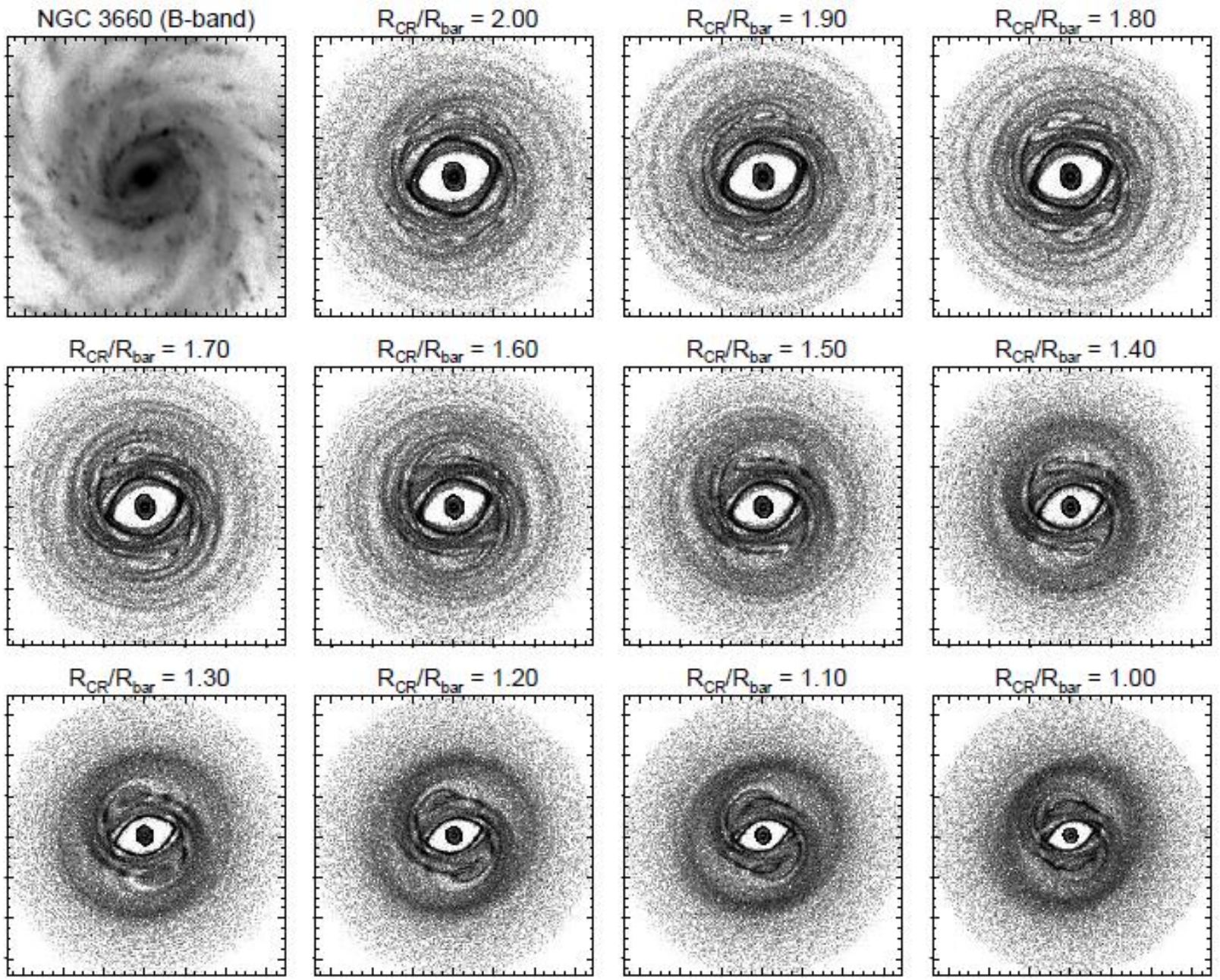
- Code written by H. Salo
- Simulated the behavior of 20,000 inelastically colliding gas particles in the determined potentials.
  - Exponential initial particle distribution
  - Aligned and coadded particle snapshots within ±0.2 bar rotation periods for increased S/N
    - The net result is a 100,000 particle snapshot.
- Nonaxisymmetric potential component was turned on gradually.
  - Full strength at two bar rotations

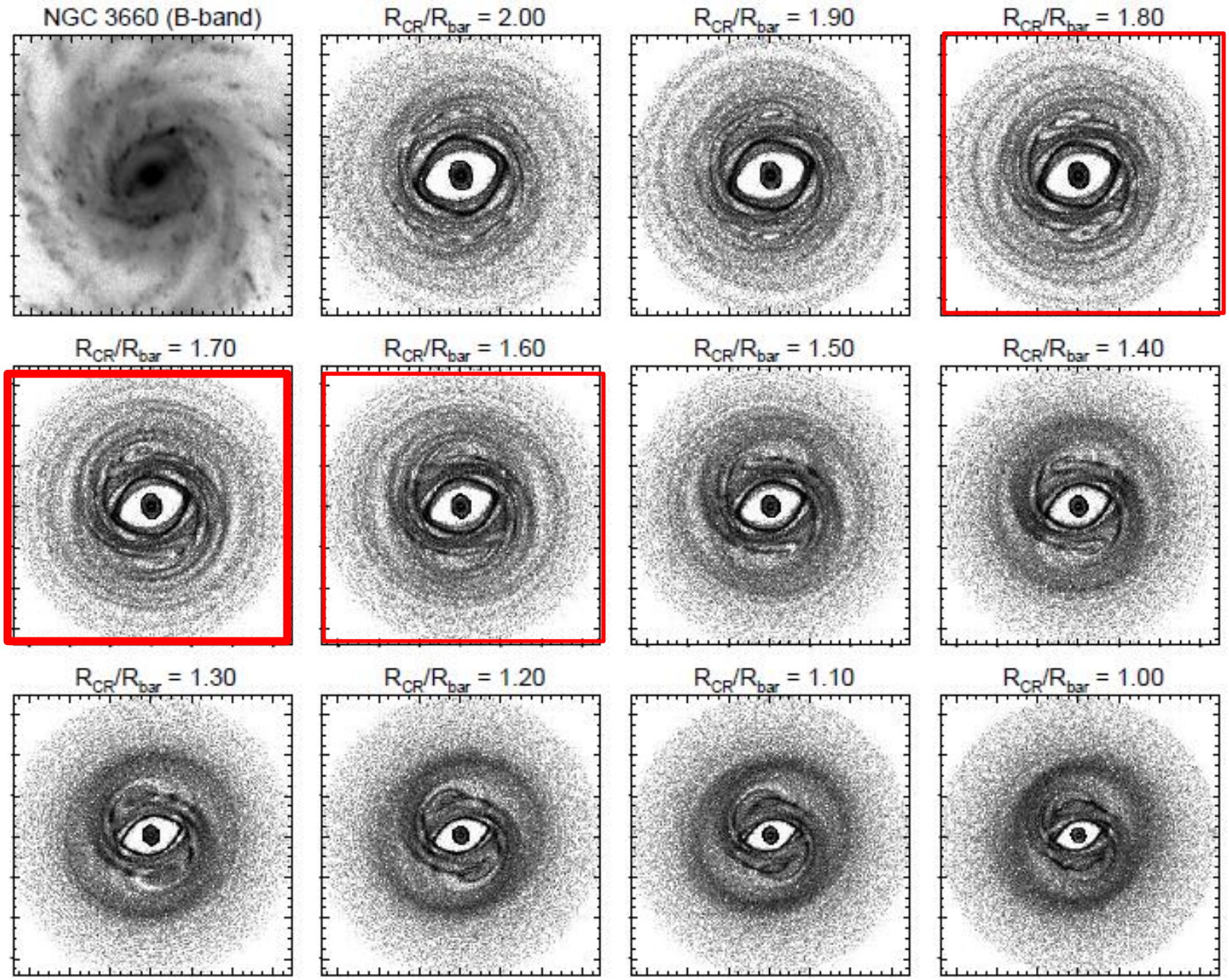
# Simulations

- The bar pattern speed was the main parameter that was varied.
  - $2.0 \geq R_{CR}/R_{bar} \geq 1.0$ in increments of 0.1.
    - $R_{bar}$ was estimated by fitting ellipses to *B*-band isophotes
      - Looked for a minimum in q=b/a in the radius region of the visible ends of the bar.

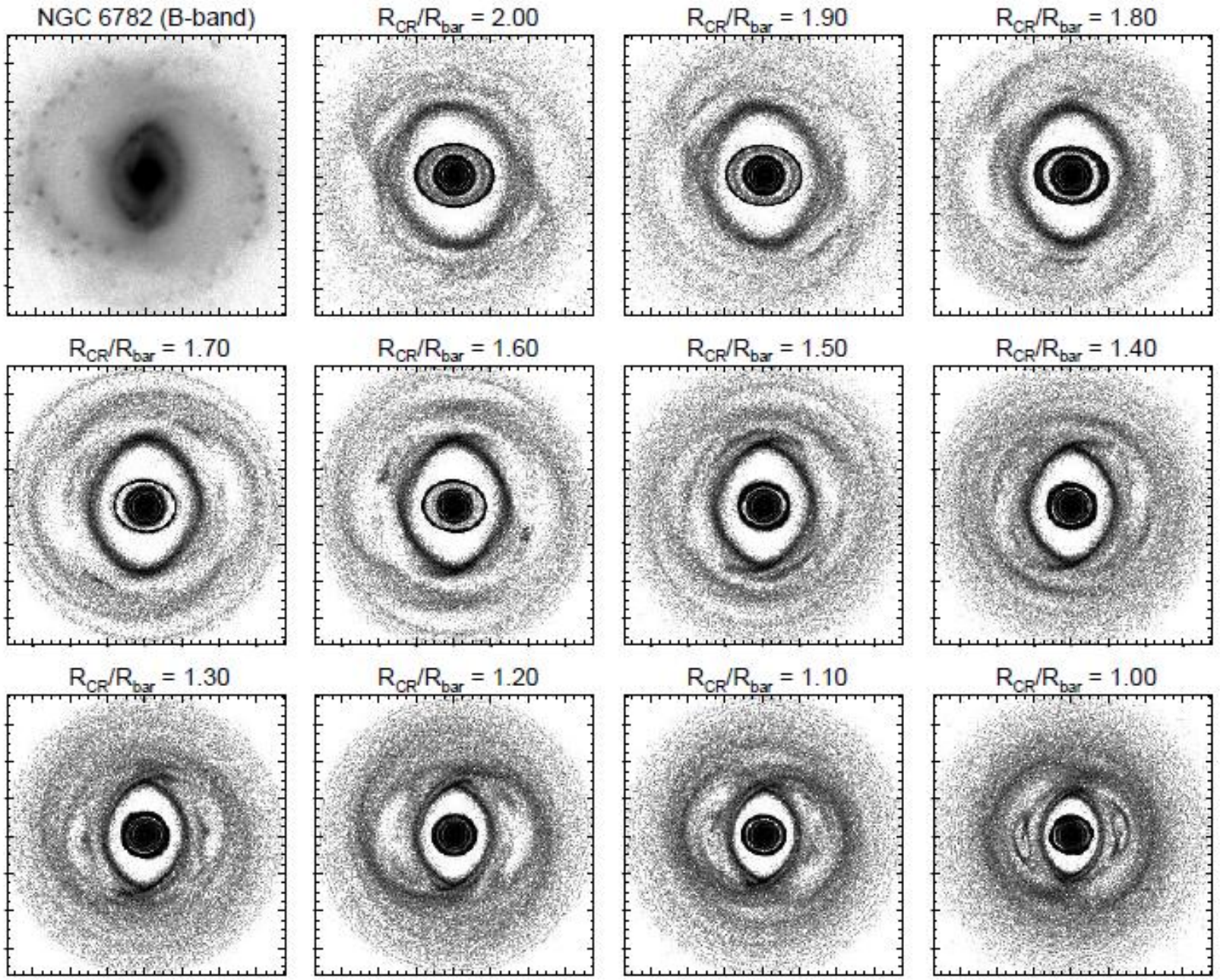
# Simulations

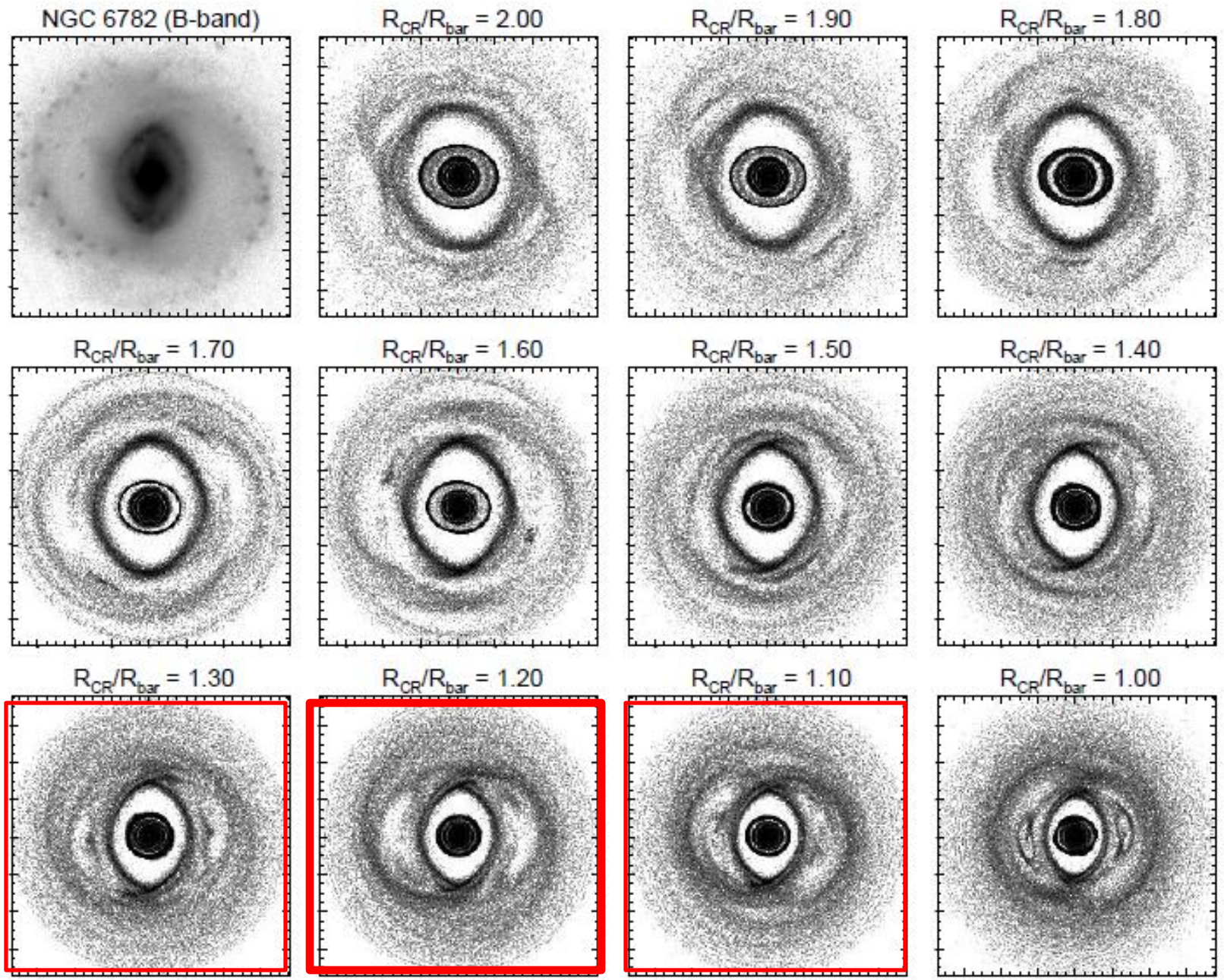
- Compared the morphologies of the simulated gas distribution to the observed *B*-band image of each galaxy.
  - Compared the inner ring size, when applicable.
  - Compared the overall structure outside of this ring.
  - Best matches and errors were determined from four independent evaluations.


NGC 3660 (B-band)
$R_{CR}/R_{bar}$ = 2.00
$R_{CR}/R_{bar}$ = 1.90
$R_{CR}/R_{bar}$ = 1.80
$R_{CR}/R_{bar}$ = 1.70
$R_{CR}/R_{bar}$ = 1.60
$R_{CR}/R_{bar}$ = 1.50
$R_{CR}/R_{bar}$ = 1.40
$R_{CR}/R_{bar}$ = 1.30
$R_{CR}/R_{bar}$ = 1.20
$R_{CR}/R_{bar}$ = 1.10
$R_{CR}/R_{bar}$ = 1.00

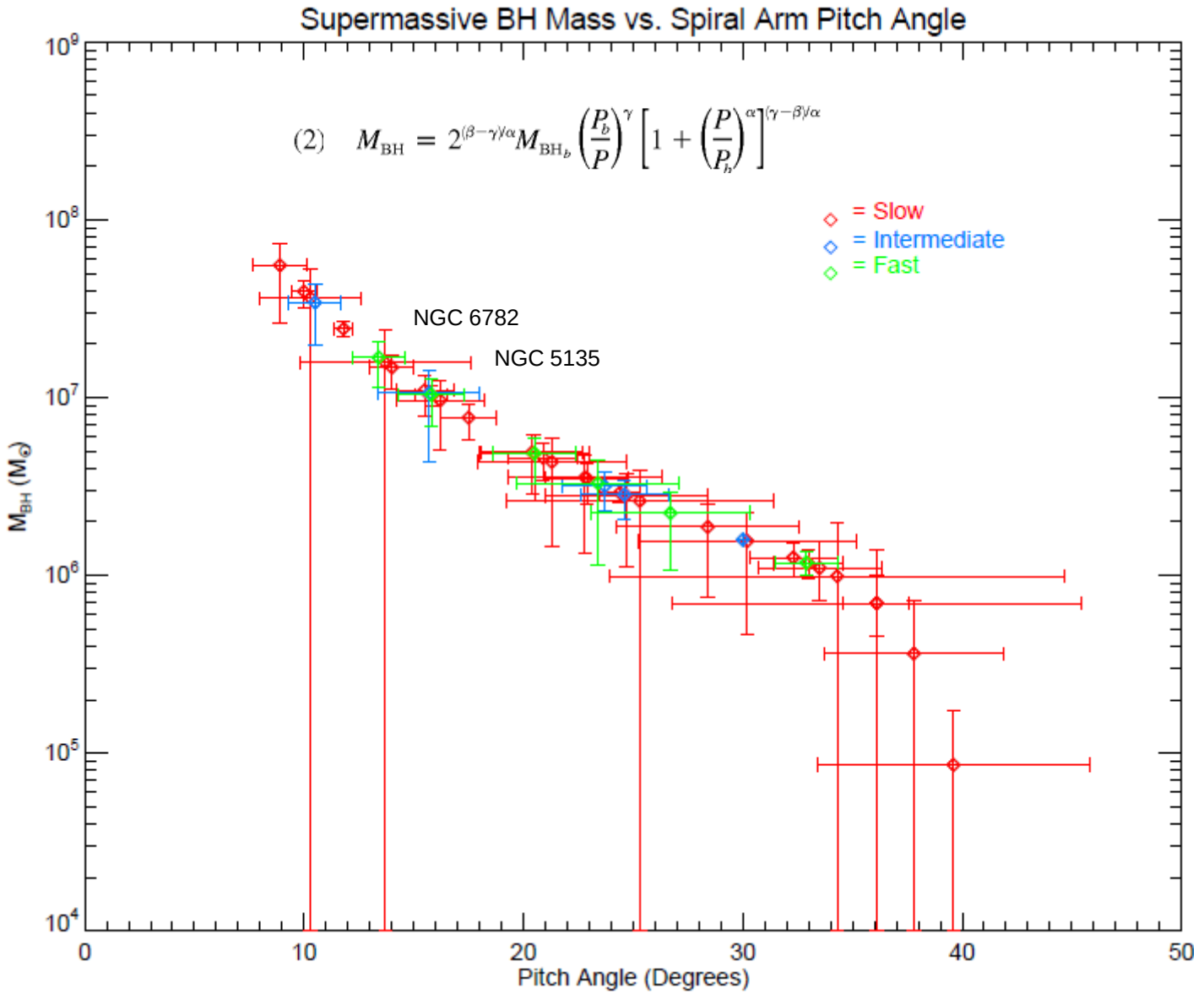


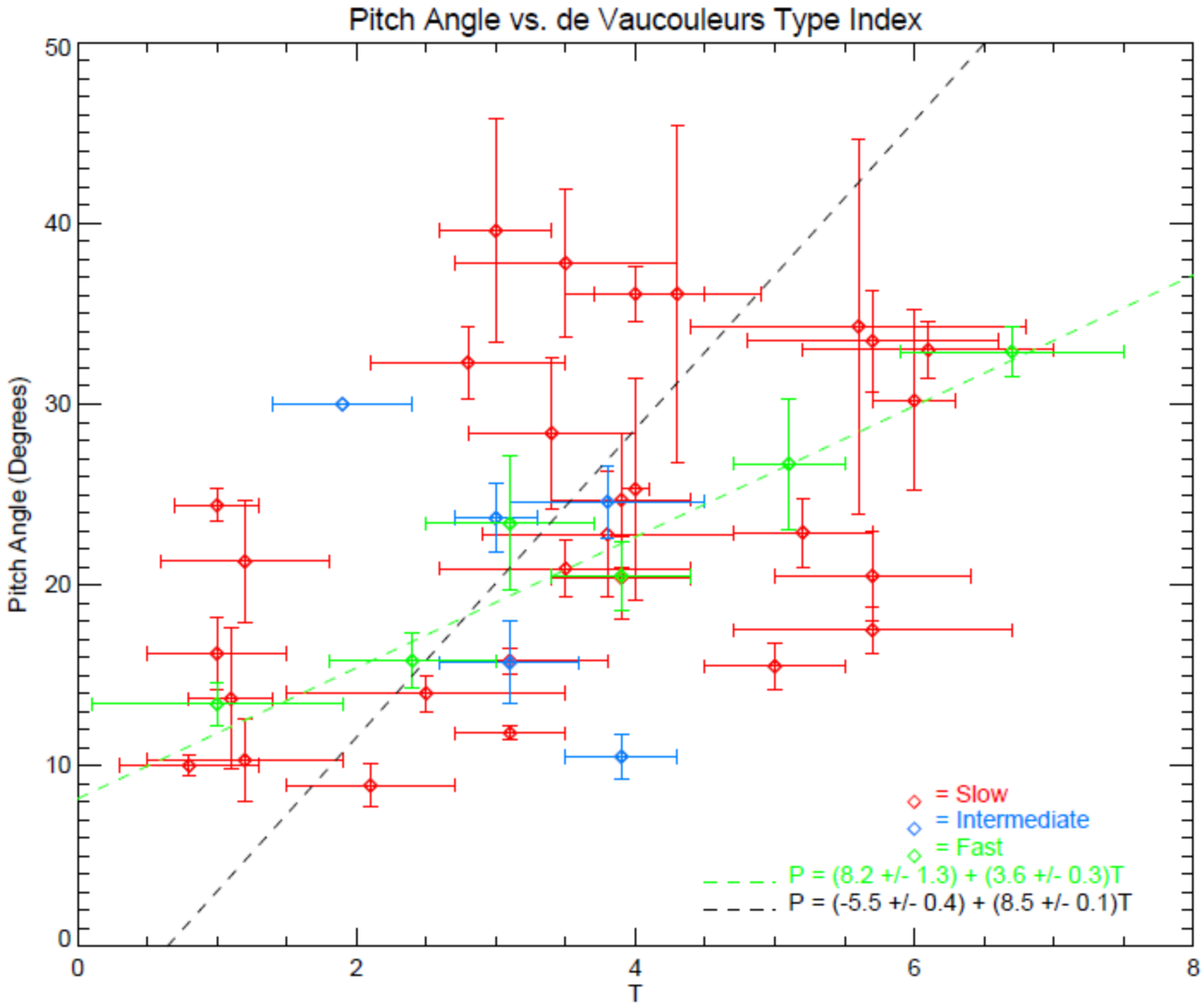

$R_{CR}/R_{bar} = 1.75 \pm 0.10$

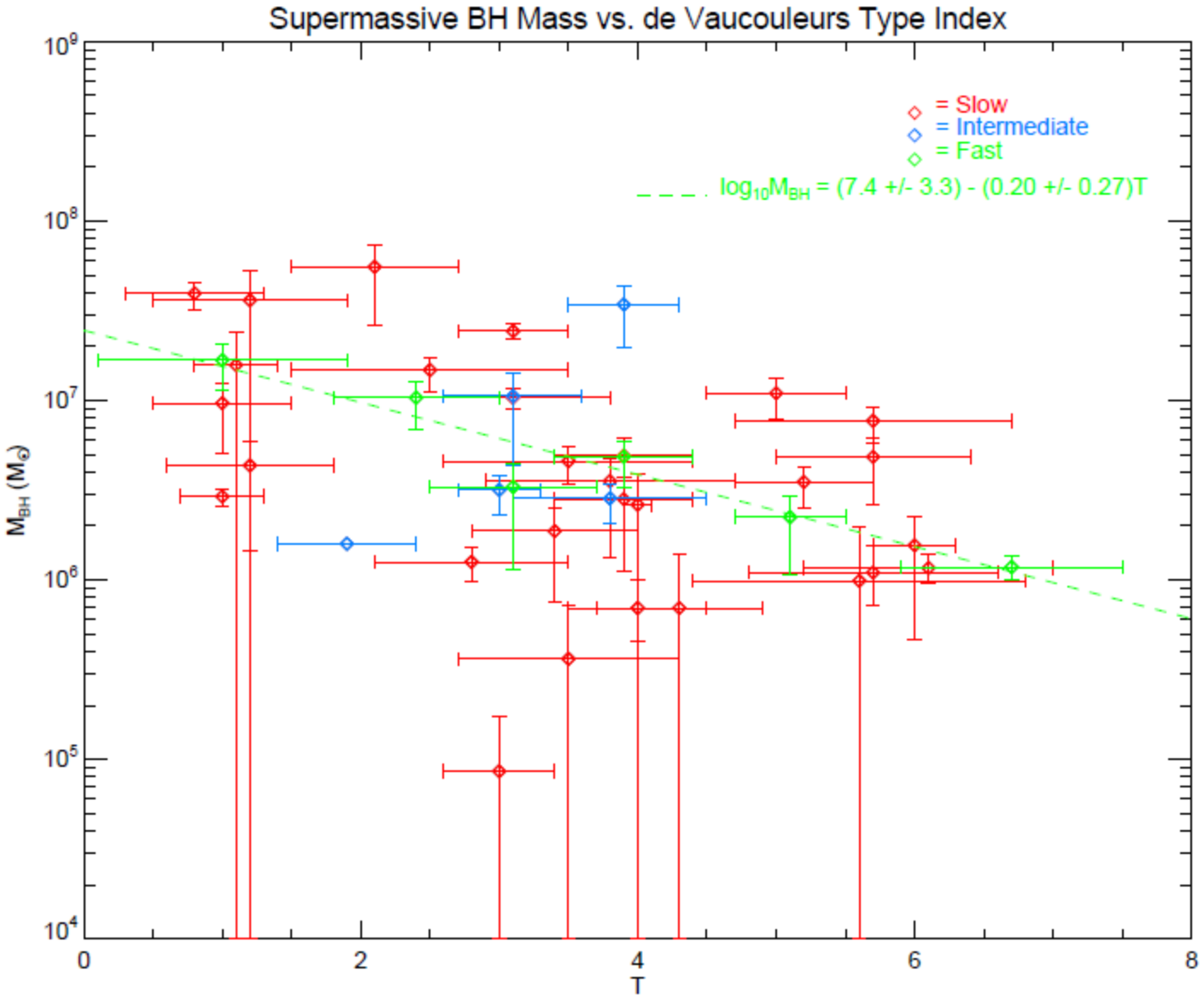

NGC 6782 (B-band)
$R_{CR}/R_{bar}$ = 2.00
$R_{CR}/R_{bar}$ = 1.90
$R_{CR}/R_{bar}$ = 1.80
$R_{CR}/R_{bar}$ = 1.70
$R_{CR}/R_{bar}$ = 1.60
$R_{CR}/R_{bar}$ = 1.50
$R_{CR}/R_{bar}$ = 1.40
$R_{CR}/R_{bar}$ = 1.30
$R_{CR}/R_{bar}$ = 1.20
$R_{CR}/R_{bar}$ = 1.10
$R_{CR}/R_{bar}$ = 1.00



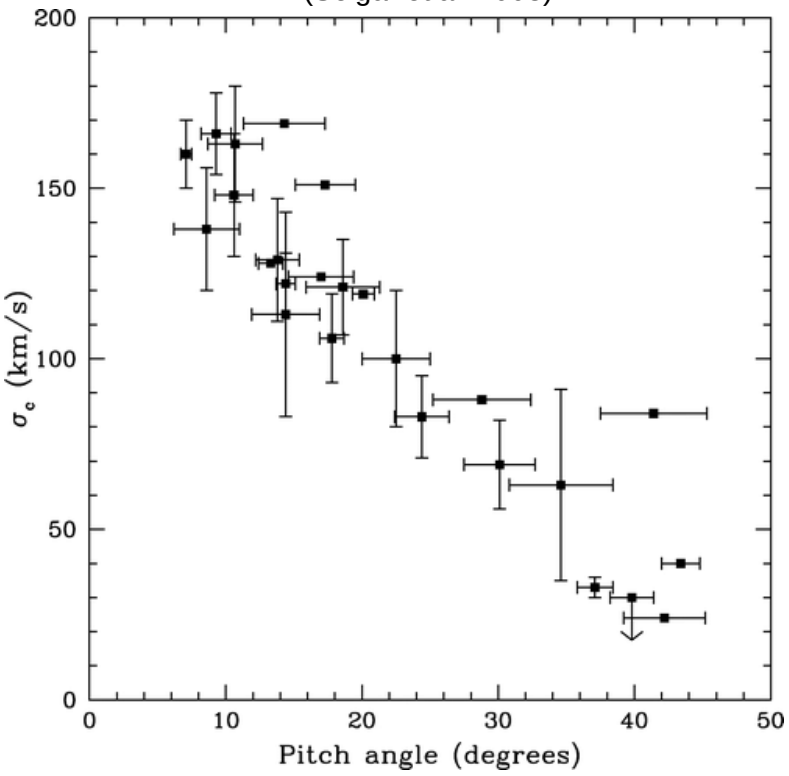

$R_{CR}/R_{bar} = 1.20 \pm 0.06$


Supermassive BH Mass vs. Spiral Arm Pitch Angle
$(2) \quad M_{\mathrm{BH}} = 2^{(\beta-\gamma/\alpha}M_{\mathrm{BH}_b}\left(\frac{P_b}{P}\right)^{\gamma}\left[1+\left(\frac{P}{P_b}\right)^{\alpha}\right]^{(\gamma-\beta)/\alpha}$
= Slow
= Intermediate
= Fast
NGC 6782
NGC 5135
$M_{BH}$ ($M_\odot$)
$10^9$
$10^8$
$10^7$
$10^6$
$10^5$
$10^4$
0
10
20
30
40
50
Pitch Angle (Degrees)

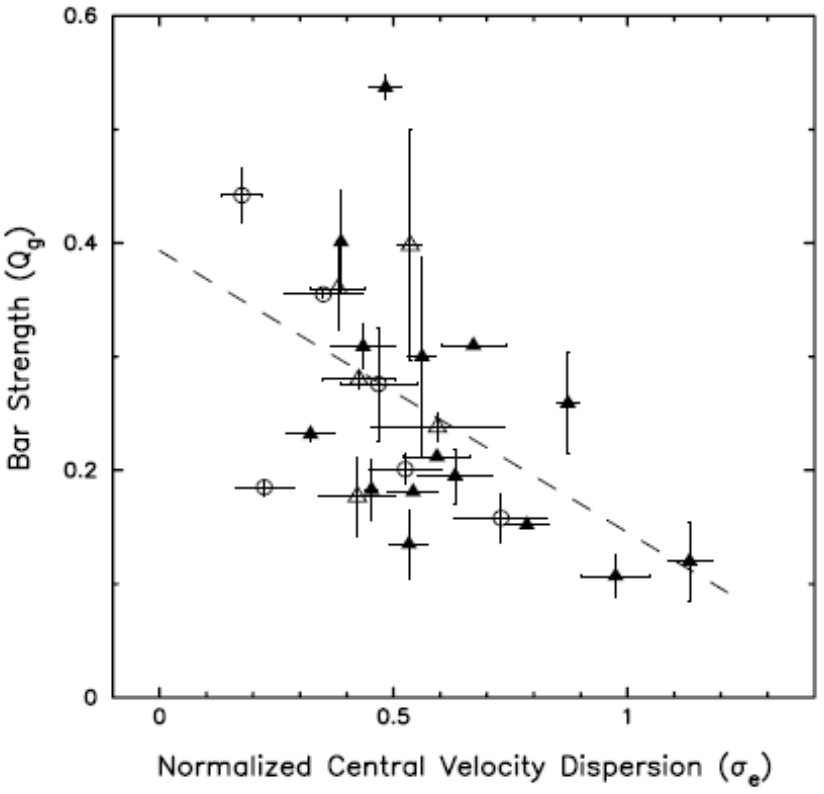

Pitch Angle vs. de Vaucouleurs Type Index
Pitch Angle (Degrees)
T
0
10
20
30
40
50
0
2
4
6
8
= Slow
= Intermediate
= Fast
P = (8.2 +/- 1.3) + (3.6 +/- 0.3)T
P = (-5.5 +/- 0.4) + (8.5 +/- 0.1)T

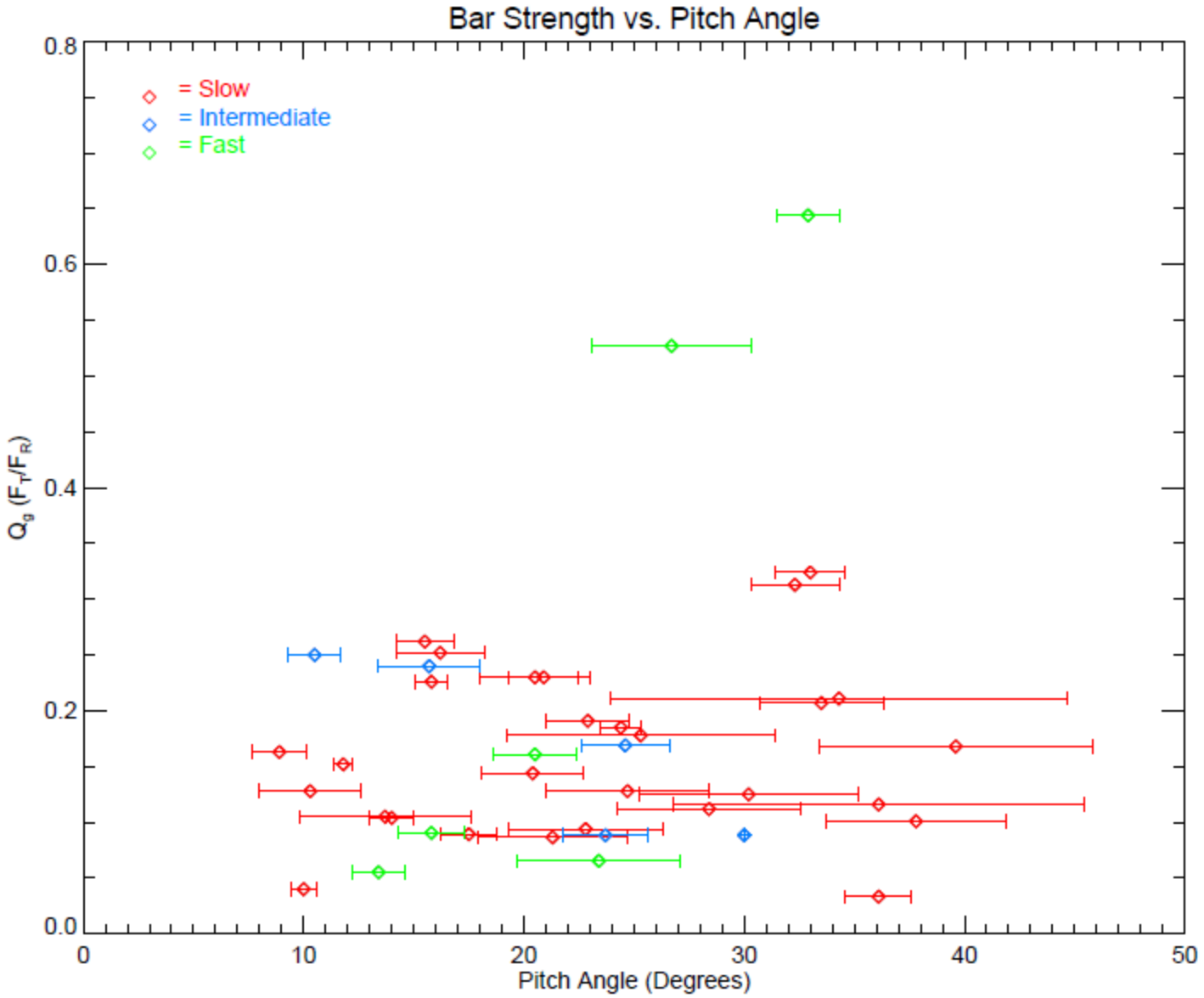

Supermassive BH Mass vs. de Vaucouleurs Type Index
= Slow
= Intermediate
= Fast
log10MBH = (7.4 +/- 3.3) - (0.20 +/- 0.27)T
MBH (M⊙)
T
10^9
10^8
10^7
10^6
10^5
10^4
0
2
4
6
8

(Seigar et al. 2008)




(Das et al. 2008)




Bar Strength vs. Pitch Angle
= Slow
= Intermediate
= Fast
$Q_g (F_T/F_R)$
0.0
0.2
0.4
0.6
0.8
0
10
20
30
40
50
Pitch Angle (Degrees)

# Conclusion

- “A connection between central dark halo concentration and SMBH mass?”
  - Probably not.
    - Outer spiral structure of NGC 6782 and NGC 5135 appear to be resonance features.
- Fast bars seem to have a connection between spiral arm pitch angle (P) and de Vaucouleurs type index (T).
  - Also SMBH mass and T
- Fast bars may have a tenuous connection between $Q_g$ and P, or T.

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