Supermassive Black Holes: Their Relation to Galaxy Evolution

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Quiescent Galaxies (Nuker Group):
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S. Tremaine, T. Lauer, J. Magorrian, R. Green
A. Dressler, C. Grillmair, G. Bower, E. Ajhar
A. Filippenko, L. Ho, J. Pinkney

The Very Small (Globular Clusters):
C. Pryor, T. Williams, J. Hesser
J. Gerssen, R. van der Marel, P. Guhathakurta, R. Peterson

The Very Large (QUASARS):
G. Shields, B. Wills, S. Salviander, M. Yuan

Tremaine et al 2002, accepted

Table 1. Galaxy sample

Galaxy	Type	M_B	$M_\bullet$ (low,high) $M_\odot$	Method	σ_1 km s^{-1}	Distance Mpc	M/L, band	Ref
Milky Way	Sbc	−17.65	$1.8 \times 10^6(1.5, 2.2)$	s,p	103	0.008	1.0,K	1
N224=M31	Sb	−19.00	$4.5 \times 10^7(2.0, 8.5)$	s	160	0.76	5,V	2,3,4
N221=M32	E2	−15.83	$2.6 \times 10^6(2.4, 2.8)$	s,3I	75	0.81	1.85	5
N821	E4	−20.41	$3.7 \times 10^7(2.9, 6.1)$	s,3I	209	24.1	5.8,V	6
N1023	SB0	−18.40	$4.4 \times 10^7(3.8, 5.0)$	s,3I	205	11.6	4.9,V	7
N1068	Sb	−18.82	$1.7 \times 10^7(1.0, 3.0)$	m	151	15.0	···	8
N2787	SB0	−17.28	$4.1 \times 10^7(3.6, 4.5)$	g	140	7.5	···	9
N3031=M81	Sb	−18.16	$6.8 \times 10^7(5.5, 7.5)$	s,3I	170	3.9	2.0? V	10
N3245	S0	−19.65	$2.1 \times 10^8(1.6, 2.6)$	g	205	20.9	3.7,R	11
N3377	E5	−19.05	$1.1 \times 10^8(0.6, 2.5)$	s,3I	145	11.2	2.7,V	12
N3379	E1	−19.94	$1.0 \times 10^8(0.5, 1.6)$	s,3I	206	10.6	4.6,V	13
N3384	S0	−18.99	$1.6 \times 10^7(1.4, 1.7)$	s,3I	143	11.6	2.8,V	6
N3998	S0	−66.66	$5.6 \times 10^8(3.0, 8.0)$	s,3I	297	14.1		10
N3608	E2	−19.86	$1.9 \times 10^8(1.3, 2.9)$	s,3I	182	22.9	3.7,V	6
N4258	Sbc	−17.19	$4.2 \times 10^7(4.0, 4.4)$	m,a	130	7.3	···	14
N4261	E2	−21.09	$5.2 \times 10^8(4.1, 6.2)$	g	315	31.6	5.0,V	15
N4291	E2	−19.63	$3.1 \times 10^8(0.8, 3.9)$	s,3I	242	26.2	4.4,V	6
N4342	S0	−17.04	$3.0 \times 10^8(2.0, 4.7)$	s,3I	225	15.3	6.5,I	16
N4459	S0	−19.15	$7.0 \times 10^7(5.7, 8.3)$	g	167	16.1	···	9
N4473	E5	−19.89	$1.4 \times 10^8(0.31, 1.5)$	s,3I	190	15.7	6.3,V	6
N4486=M87	E0	−21.53	$3.0 \times 10^9(2.0, 4.0)$	g	375	16.1	4.0,V	17,18
N4564	E3	−18.92	$5.6 \times 10^7(4.8, 5.9)$	s,3I	162	15.0	1.9,I	6
N4596	SB0	−19.48	$7.8 \times 10^7(4.5, 12)$	g	136	16.8	···	9
N4649	E1	−21.30	$2.0 \times 10^9(1.4, 2.4)$	s,3I	385	16.8	9.0,V	6
N4697	E4	−20.24	$1.7 \times 10^8(1.6, 1.9)$	s,3I	177	11.7	4.8,V	6
N4742	E4	−18.94	$1.4 \times 10^7(0.9, 1.8)$		90	15.5	??	19
N5128	pec	−20.80	$2.4 \times 10^8(0.7, 6.0)$	g	150	4.2	···	20
N5845	E	−18.72	$3.7 \times 10^8(2.2, 5.4)$	s,3I	234	25.9	4.8,V	6
N6251	E2	−21.81	$6.0 \times 10^8(2.0, 8.0)$	g	290	106.0	8.5,V	21
N7052	E4	−21.31	$3.3 \times 10^8(2.0, 5.6)$	g	266	58.7	6.3,I	22
N7457	S0	−17.69	$3.5 \times 10^6(2.1, 4.6)$	s,3I	67	13.2	3.4,V	6
IC1459	E3	−21.39	$2.6 \times 10^9(1.5, 3.7)$	s,3I	350	30.3	3.1	23

Note. — Distances are taken from Tonry et al. (2001) for 80% of the galaxies; where these are not available the distance is determined from the recession velocity, assuming a Hubble constant of 80 km s^{-1} Mpc^{-1}. Methods: s=stellar radial velocities; p=stellar proper motions; m=maser radial velocities; a=maser accelerations; g=rotating gas disk from emission-line observations; 3I=general (i.e. up to three-integral) dynamical models. References: (1) Chakrabarty & Saha (2001); (2) Tremaine (1995); (3) Kormendy & Bender (1999); (4) Bacon et al. (2001); (5) Verlome et al. (2002); (6) Gebhardt et al. (2002); (7) Bower et al. (2001); (8) Greenhill et al. (1996); (9) Sarzi et al. (2000); (10) Bower et al. (2000); (11) Barth et al. (2001a); (12) Kormendy et al. (1998); (13) Gebhardt et al. (2000b); (14) Miyoshi... (15) Ferrarese, Ford, & Jaffe (1996); (16) Cretton & van den Bosch (1998); (17) Harms et al. (1994); (18) Macchetto et al. (1997); (19) Kaiser et al. (2002); (20) Marconi et al. (2001); (21) Ferrarese & Ford (1999); (22) van der Marel & van den Bosch (1998); (23) Capellari et al. (2002)

Measuring BH Masses

- Masers : excellent for measuring BH mass
  no information on orbital structure
  Rare!!
  (Miyoshi, Moran et al.)
- Gas : OK for BH mass
  assumption of circular motion in question
  no info on orbital structure
  (Sarzi, Ford, Ferrarese, many others)
- Proper Motion : the best way, only possible nearby
  (Ghez, Eckart : MW)
  (Meylan, King : GC)
- Reverberation : very good for BH mass if calibrated
  potentially useful for all AGNs
  new x–ray telescopes will do well
  (Wandel et al.)
- Photoionization : easy and quick to apply to AGN
- Stars : complicated modeling and need high S/N data
  determine BH and orbital properties!!
  ALL galaxies have stars!!
  (Kormendy, Dressler, many others)

Five Steps Towards Making a 3-Integral Model

Schwarzschild's orbit-based method for axisymmetry

1) observe $\Sigma(r,\theta) \longrightarrow \nu(r,\theta)$

   deprojection: unique for edge-on only

2) $\nu(r,\theta) \longrightarrow \rho(r,\theta)$

   need assumption of M/L
   (either constant or vary according to colors)

3) $\rho(r,\theta) \longrightarrow \Phi(r,\theta)$ + M_bh + M_halo

   add black hole and halo of various sizes

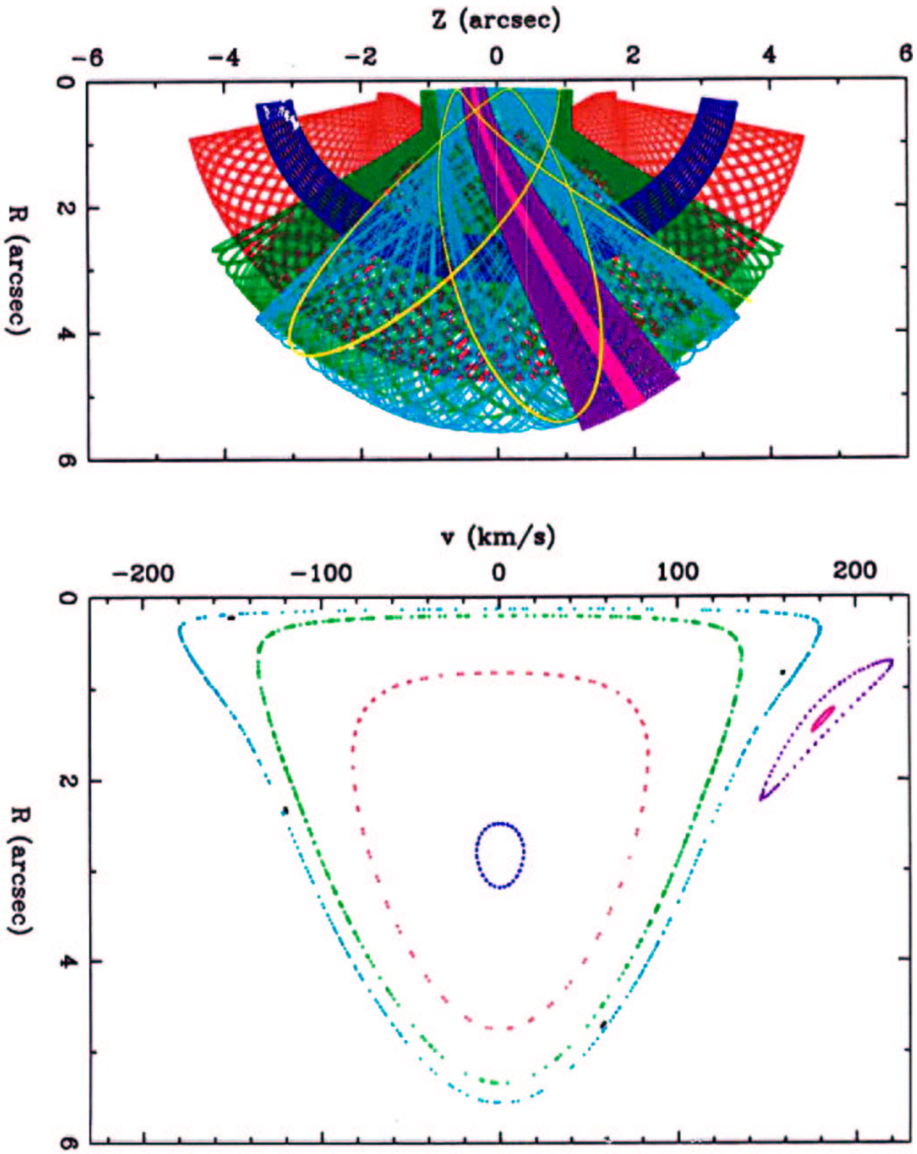
4) run orbits in Φ

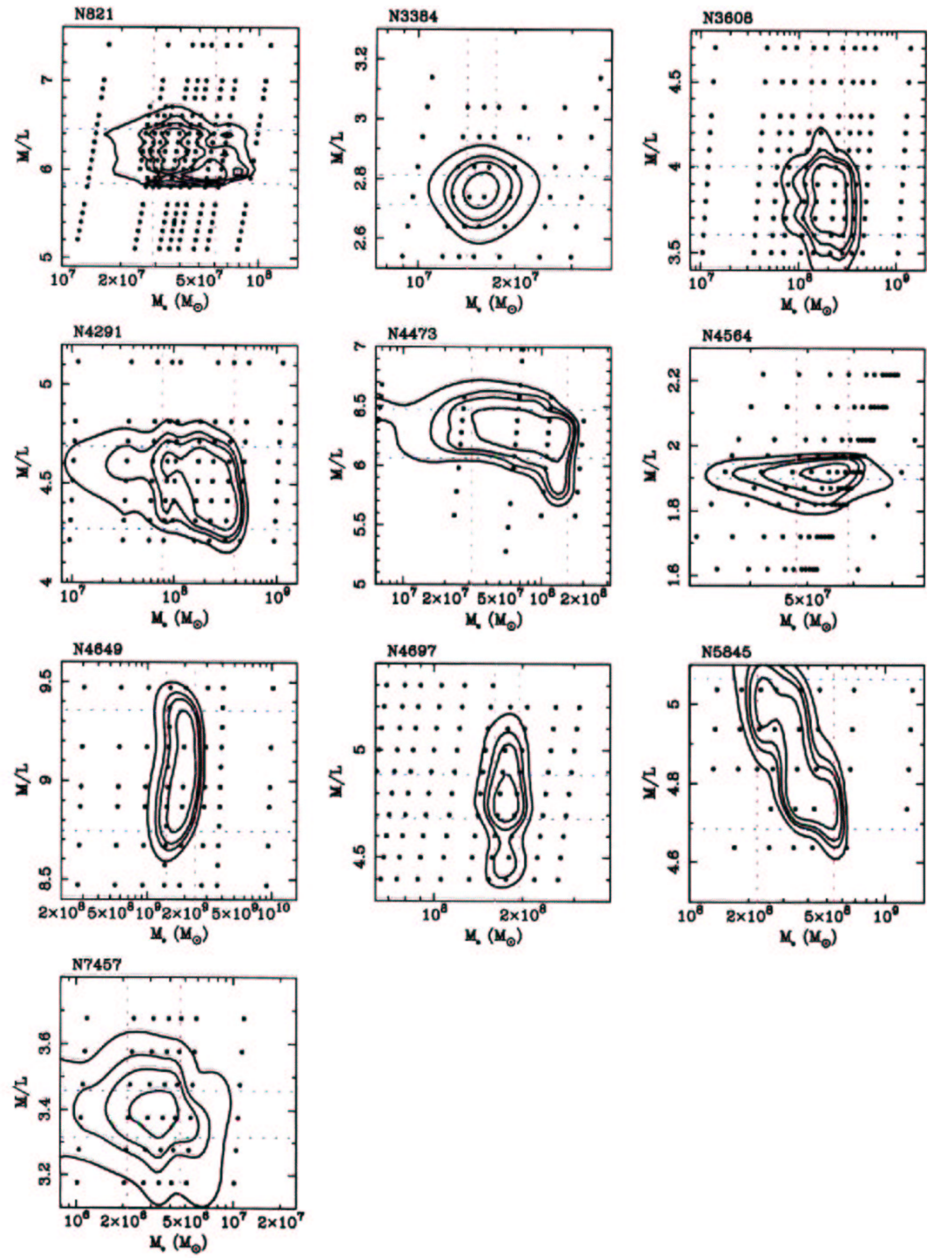
   track r, theta, and velocity (in projection and real)
   and store in bins for every orbit

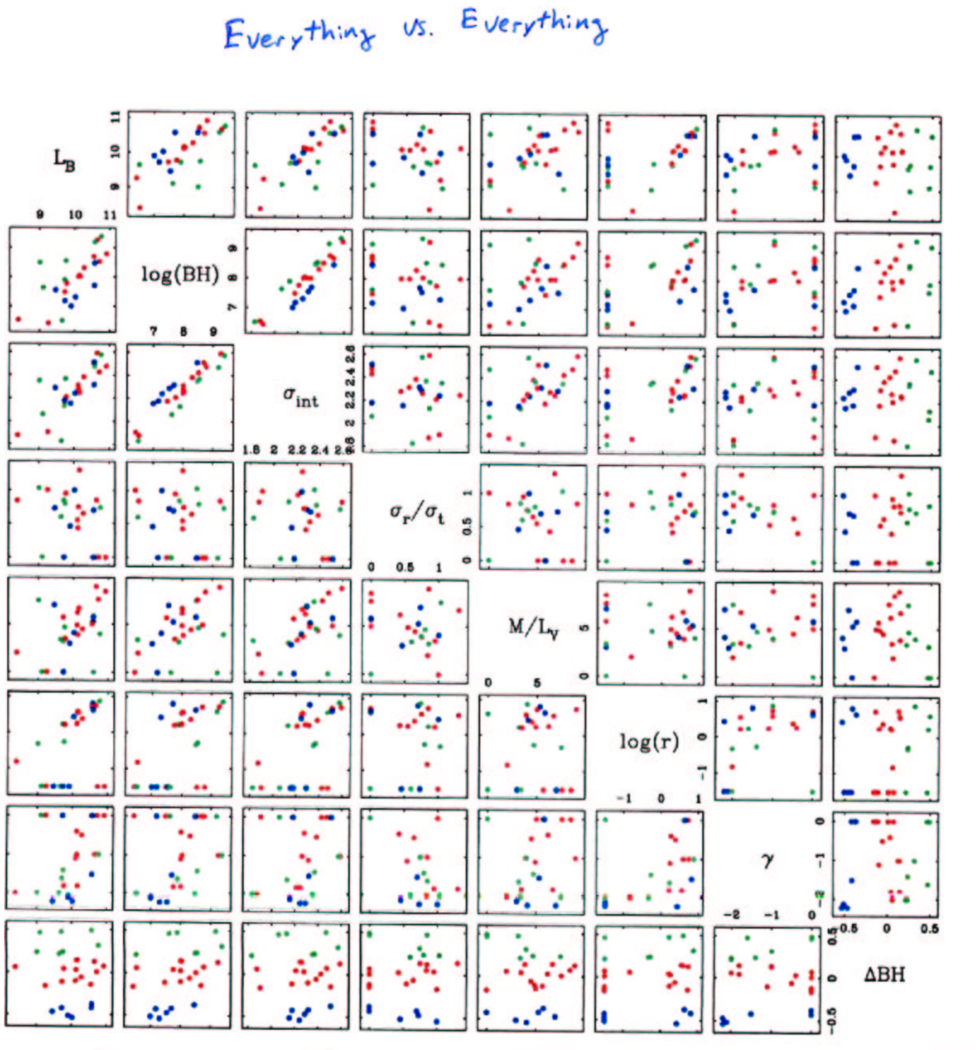
5) $M\_galaxy(r,\theta,v) = \sum_i \omega_i m_i(r,\theta,v)$

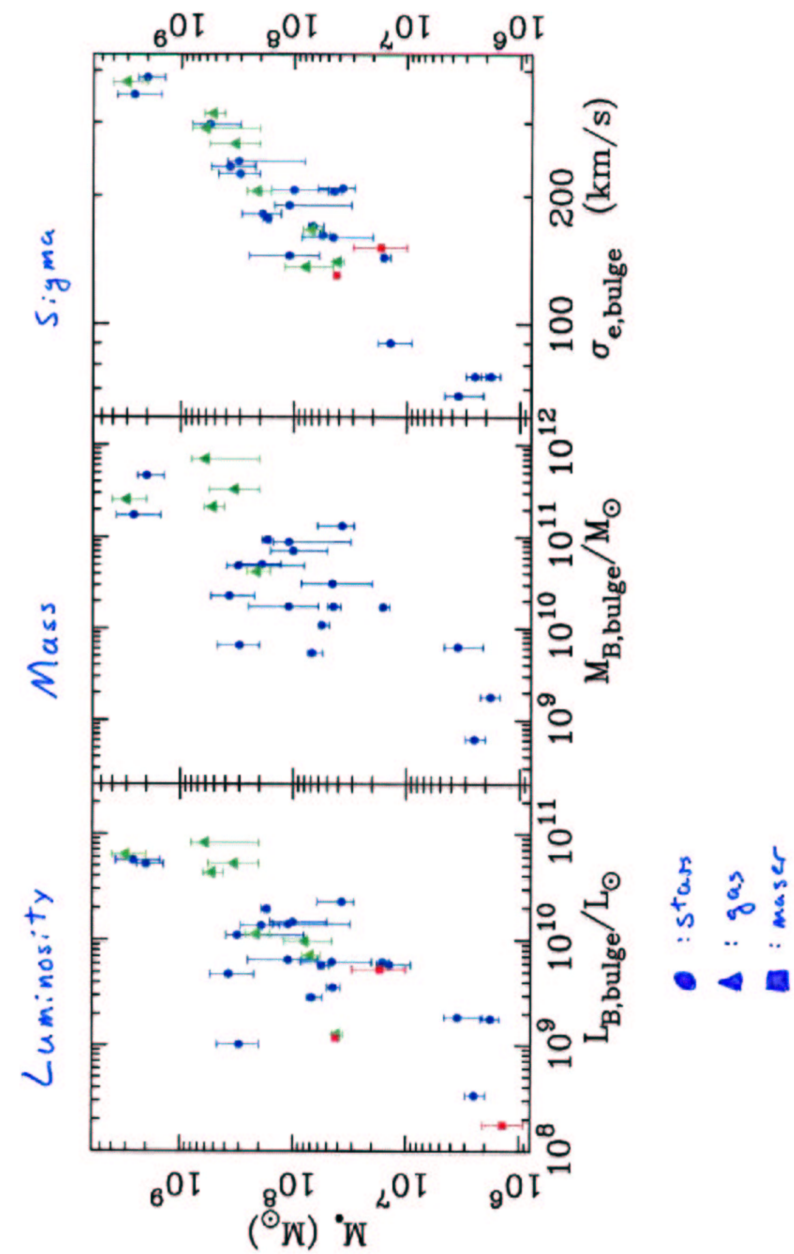
   find weights using Lagrangian constraints
   by maximizing entropy

   Entropy = dE x dLz x dI_3


Z (arcsec)
R (arcsec)
v (km/s)
R (arcsec)


N821
N3384
N3608
N4291
N4473
N4564
N4649
N4697
N5845
N7457
M/L
$M_\bullet$ ($M_\odot$)

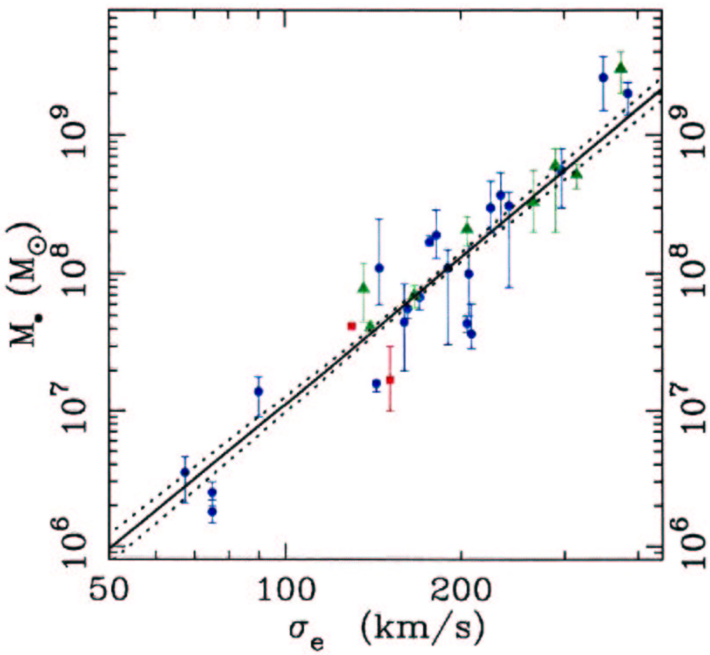

Everything vs. Everything
L_B
log(BH)
σ_int
σ_r/σ_t
M/L_V
log(r)
γ
ΔBH


Sigma
Mass
Luminosity
σ_e,bulge (km/s)
M_B,bulge/M⊙
L_B,bulge/L⊙
M• (M⊙)
: stars
: gas
: maser

Tremaine et al 2002

$$M_{BH} = 1.4\,(\pm .2) \times 10^8 \left(\frac{\sigma}{220}\right)^{3.92 \pm .3}$$

● : stars
▲ : gas
■ : masers



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HST luminosity profiles

Gebhardt et al. '96

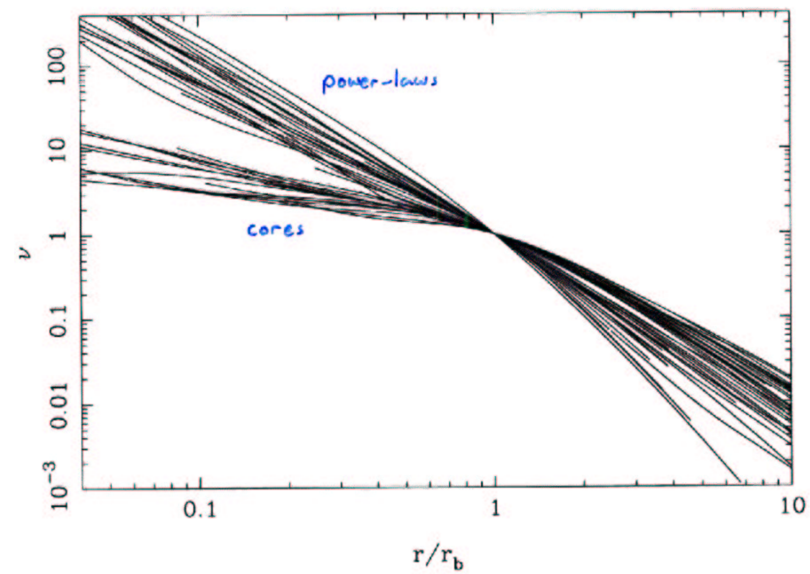


Fig. 3.— Luminosity density profiles of all galaxies in the sample scaled to the radius and the luminosity at the radius of maximum curvature in the surface brightness

Black Hole Formation Models

Silk and Rees (98) : slope = 5

Ostriker (00) : slope from 4–4.5

Haehnelt and Kauffmann (00) : slope < 3.8

Nulsen and Fabian (00) : slope = 5

Blandford (99) : slope = 2

Adams, Graff, Richstone (01): slope = 4

Burkert and Silk (01): slope from 4–5

many others in progress.....

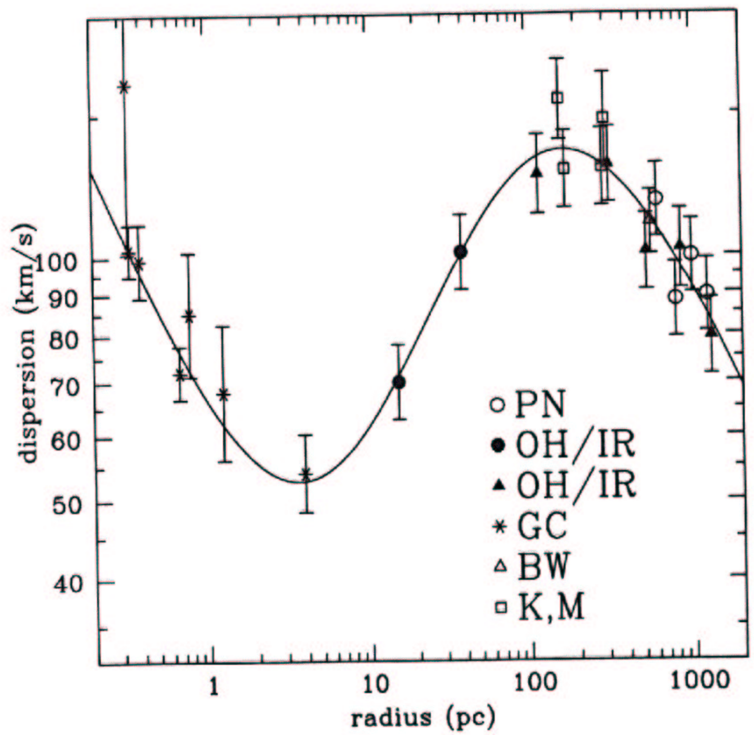
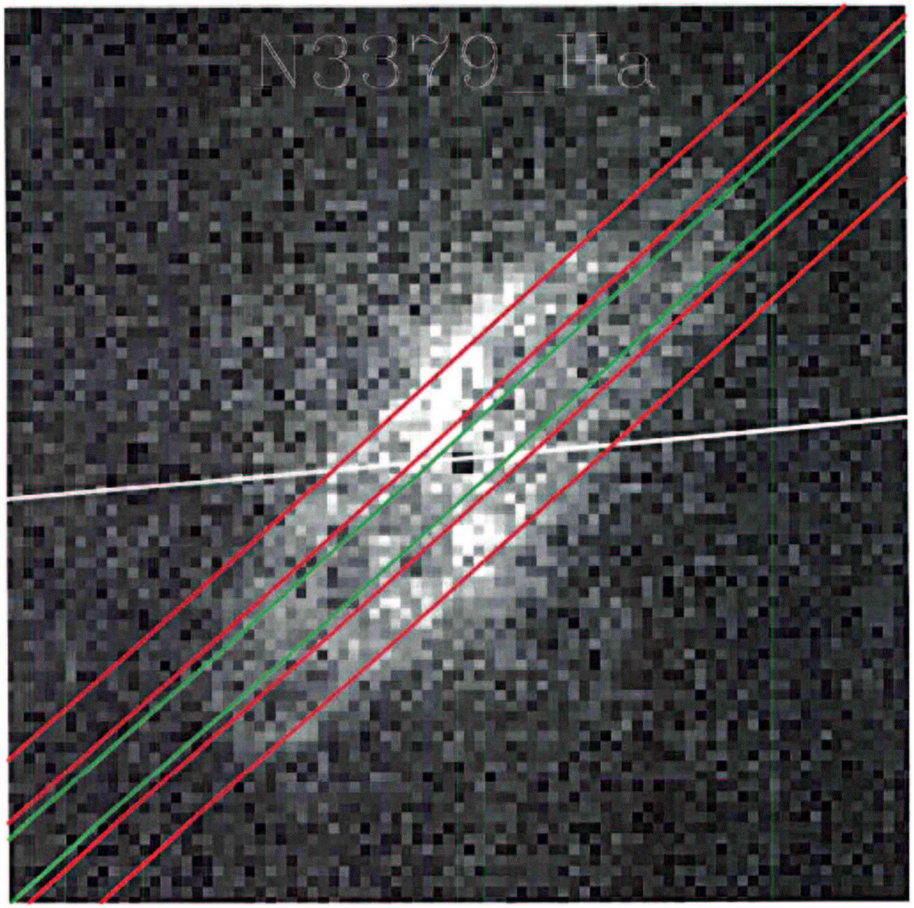


Fig. 6.— The velocity dispersion of the bulge of the Milky Way as a function of radius. PN = planetary nebulae (Beaulieu, Dopita, & Freeman 1999); OH/IR = OH/IR stars (Lindqvist et al. 1992a; Lindqvist, Habing, & Winnberg 1992b; Sevenster et al. 1997); BW = giant stars in Baade's window (Terndrup, Sadler, & Rich 1995); K,M = giant stars (Blum et al. 1994, 1995); GC = stars near the Galactic center (Genzel et al. 2000). Filled symbols denote observations biased towards the Galactic plane, and open symbols denote observations biased away from the plane.



Black Hole Formation Models

Adiabatic BH Growth (Quinlan, Hernquist, Sigurdsson 95)

Slow accumulation of gas

$\beta = -0.3$
$\gamma = -1.5$

BH Infall Models (Nakano and Makino 99)

Single Black Hole falls into Galaxy Center

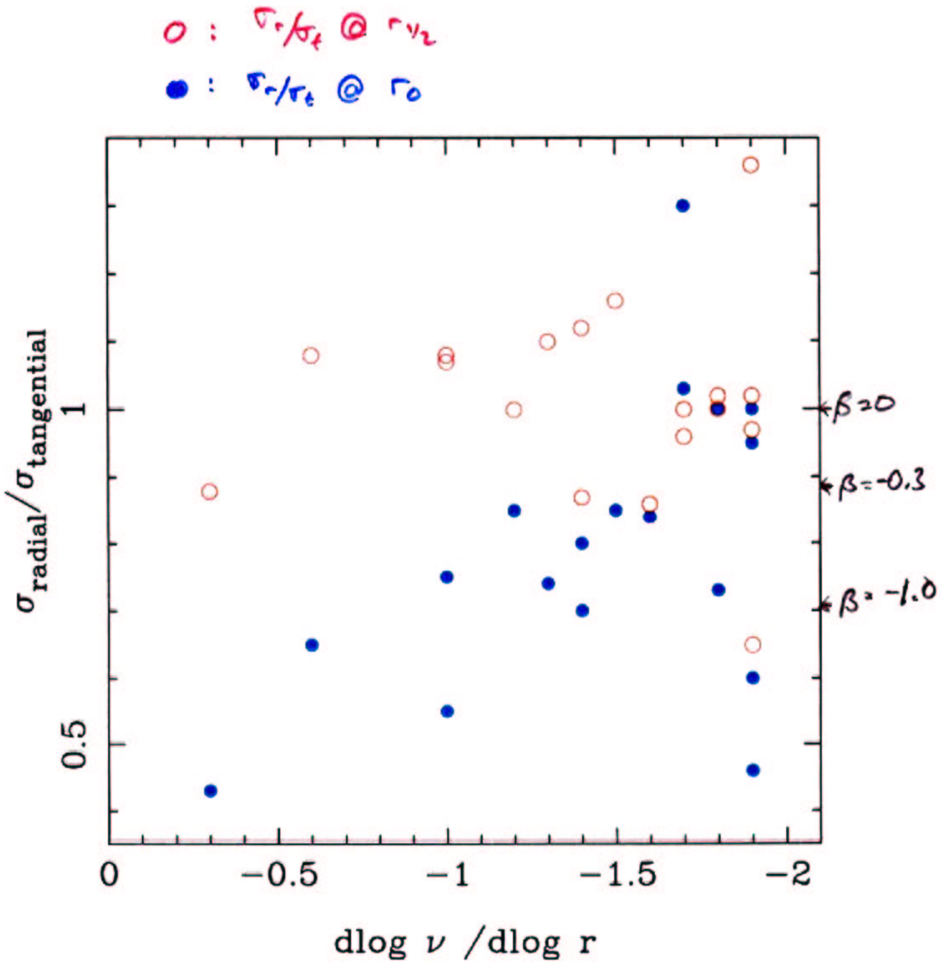
$0. > \beta > -0.3$
$\gamma = -0.5$

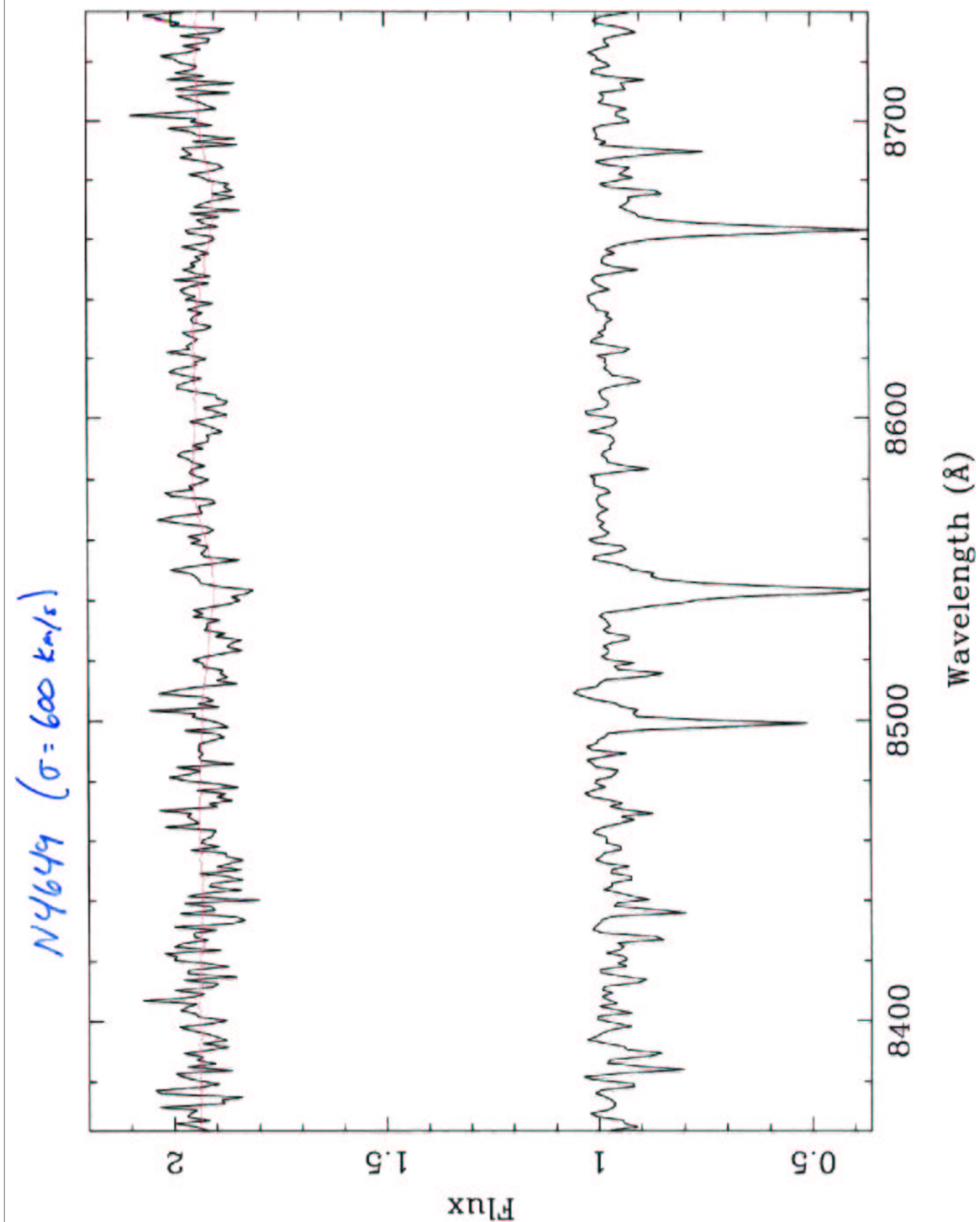
BH Binary/Merger Models (Quinlan and Hernquist 97)

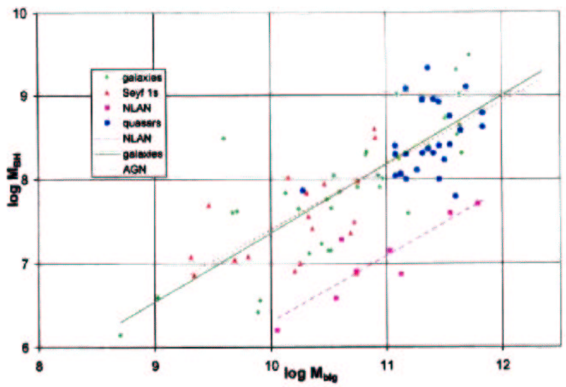
Black Hole falls in and forms a binary
with the present Black Hole; binary hardens

$\beta = -1.0$
$0. > \gamma > -1.0$

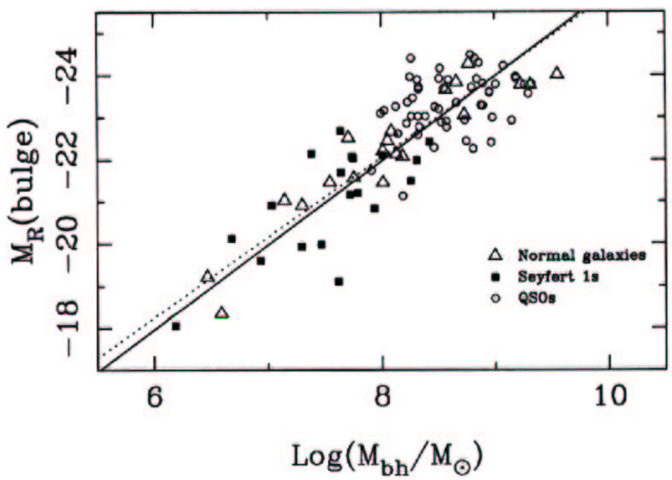
$\beta = 1. - v_t^2 / v_r^2$ $\gamma = d \log \rho / d \log r$


o : σr/σt @ r1/2
• : σr/σt @ r0
σradial/σtangential
dlog ν /dlog r
0
−0.5
−1
−1.5
−2
0.5
1
β=0
β=-0.3
β=-1.0


N4649 (σ = 600 km/s)
Wavelength (Å)
Flux
8400
8500
8600
8700
2
1.5
1
0.5

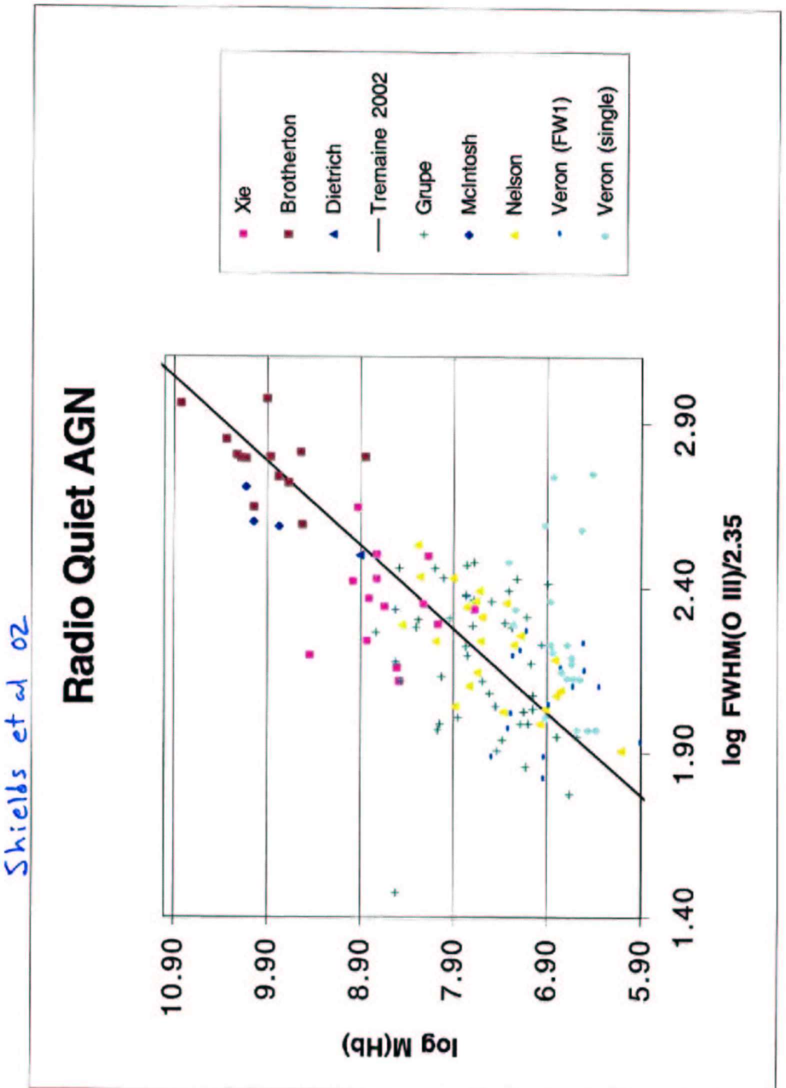


Wandel
(astroph/0108461)

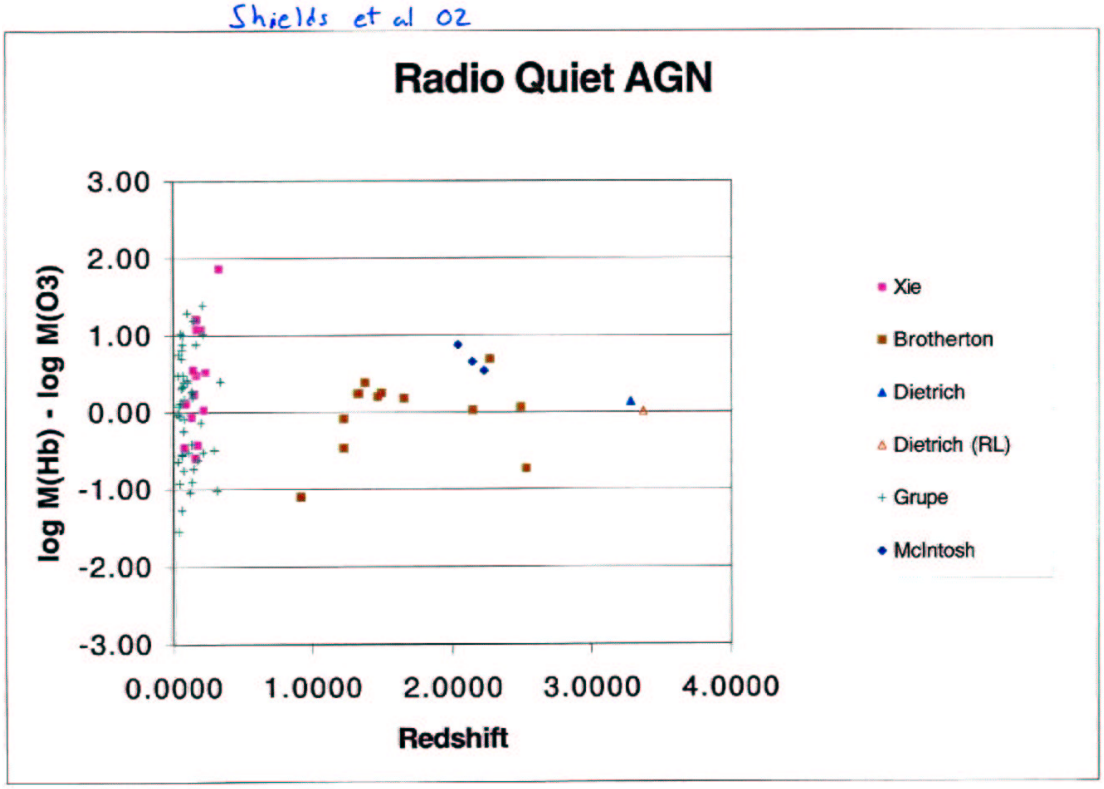


McLure and Dunlop
(astroph/0201081)

Shields et al 02

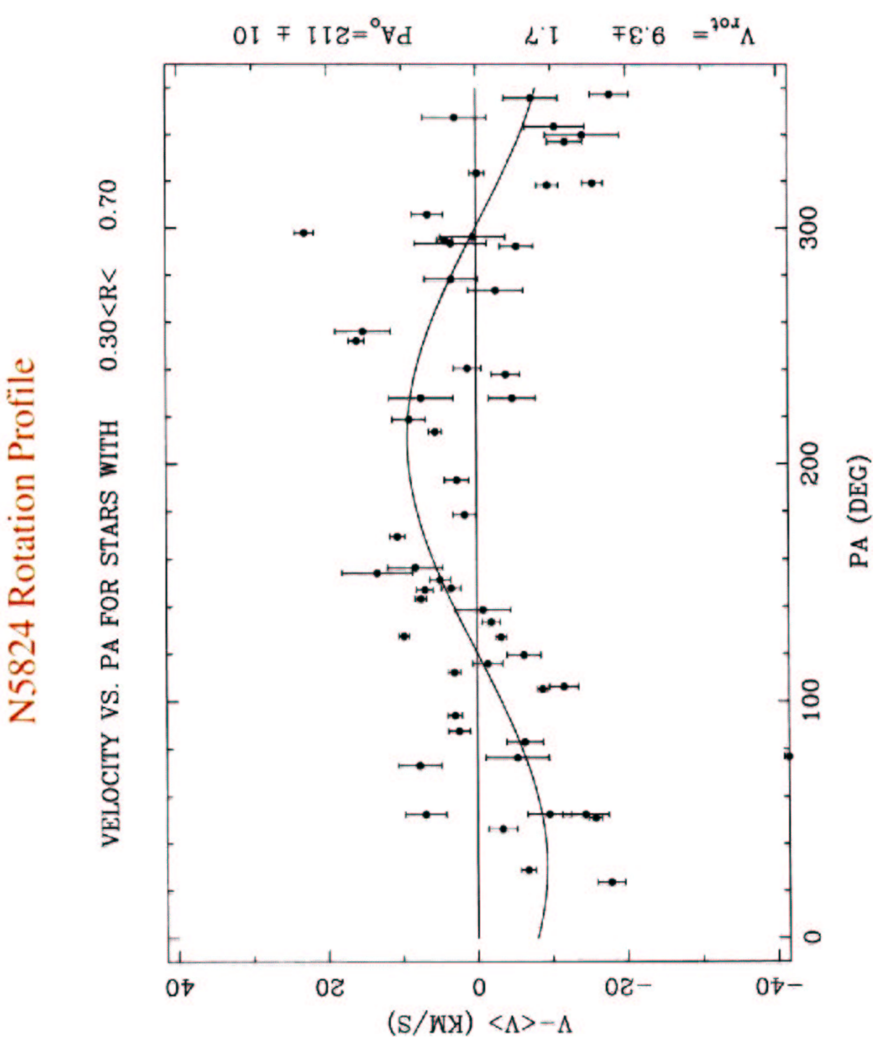


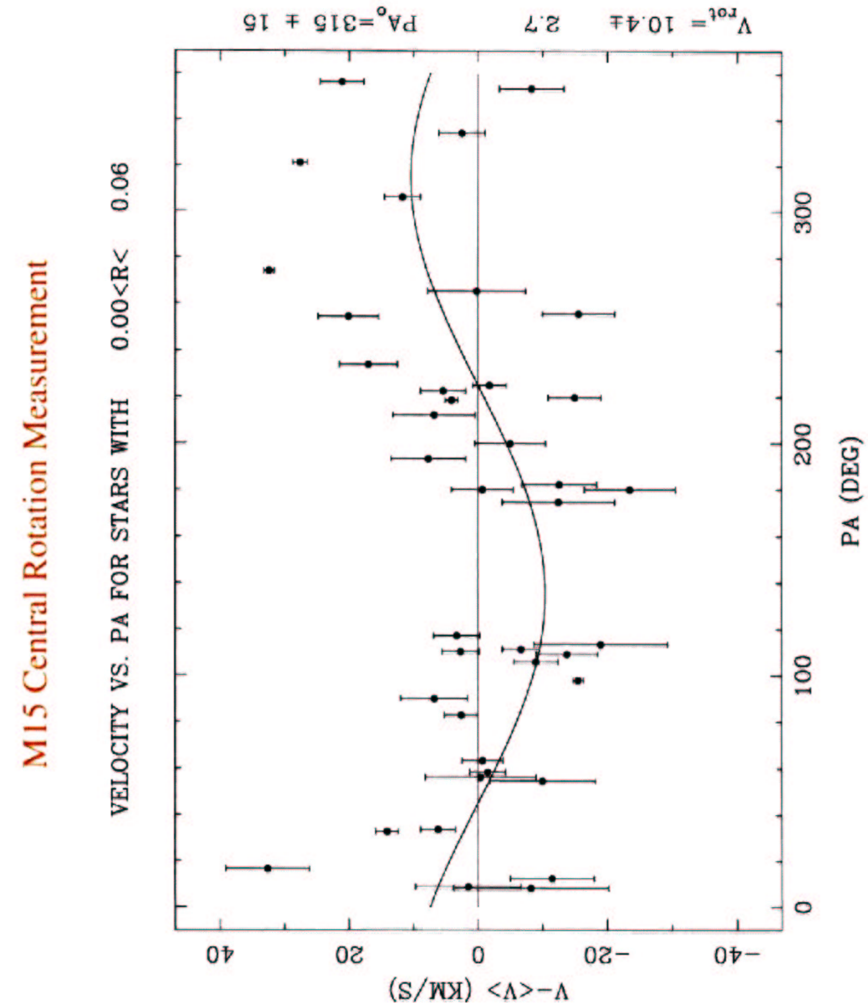
Shields et al 02

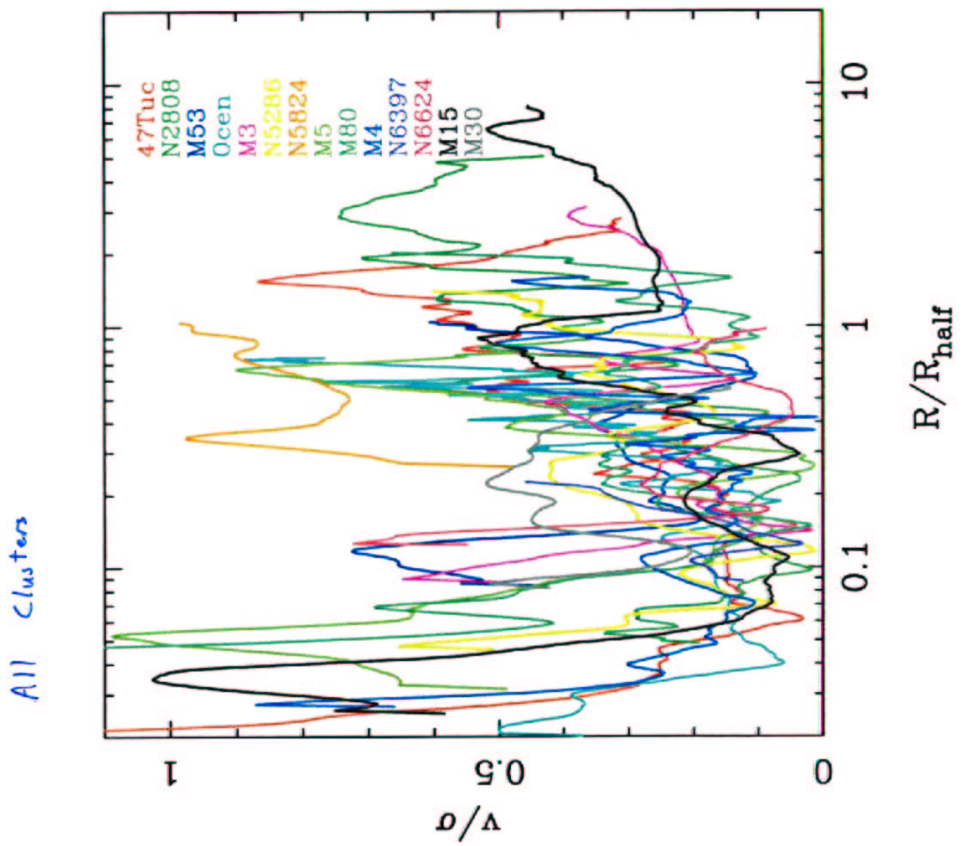


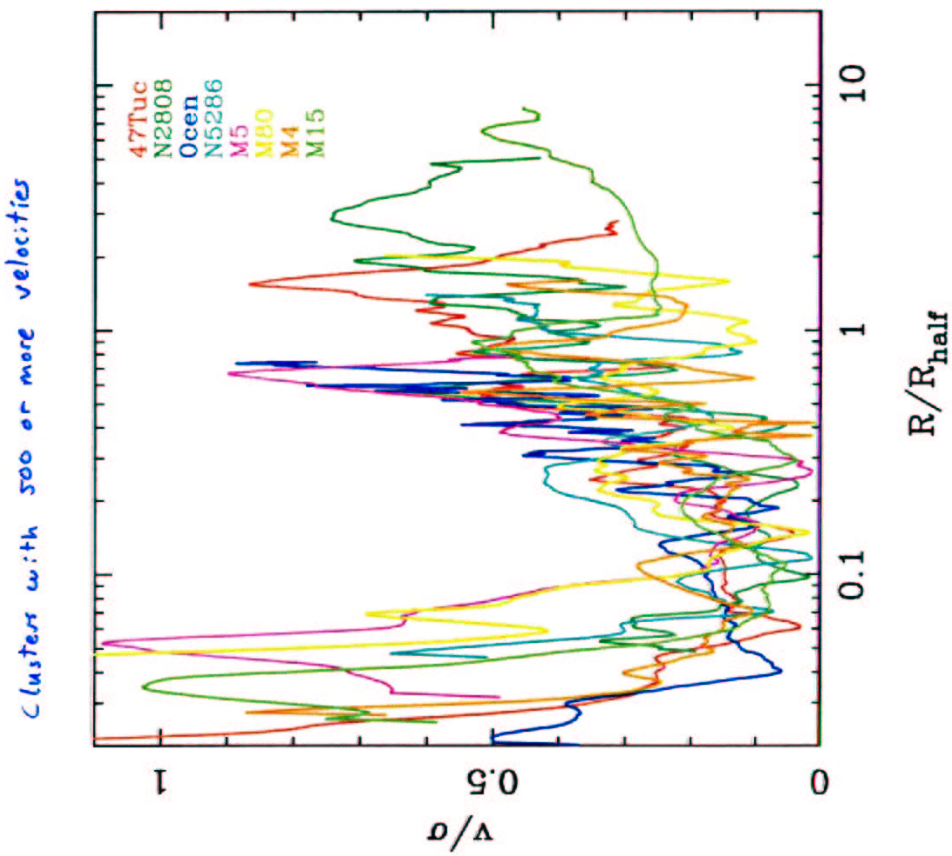
Fabry–Perot Velocity Samples

47Tuc : 5600 radial velocities
N2808 : 3695
M53 : 464
Ocen : 7000
M3 : 474
N5286 : 1165
N5824 : 108
M5 : 1068
M80 : 744
M4 : 1896
N6397 : 115
N6624 : 289
M15 : 1781
M30 : 127
N3201 : 561
N362 : 265
M55 : 173
N6752 : 469
N1783 : 208
N2157 : 102

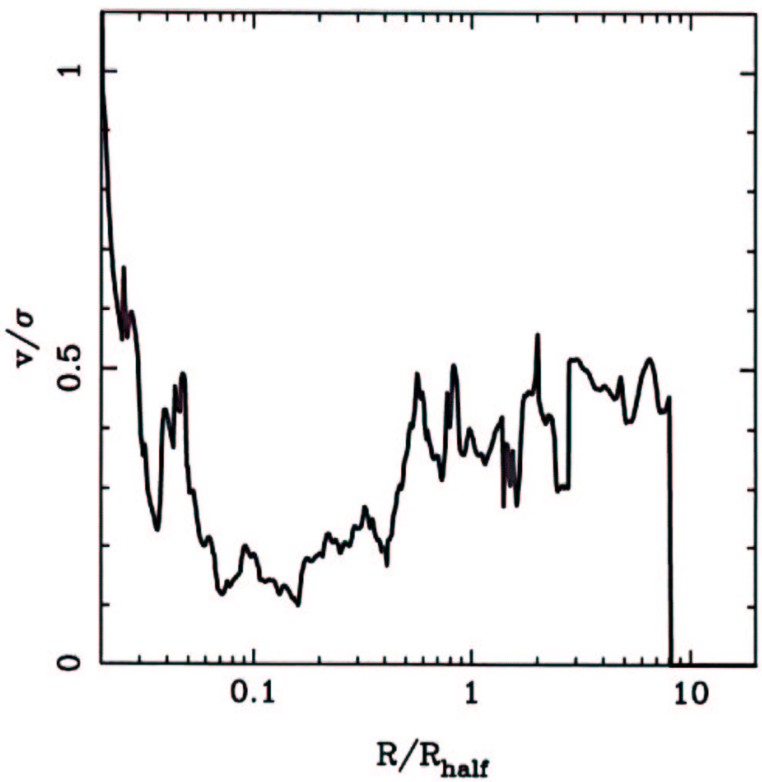

N5824 Rotation Profile
VELOCITY VS. PA FOR STARS WITH 0.30<R< 0.70
V$_{rot}$= 9.3± 1.7 PA$_o$=211 ± 10
V−<V> (KM/S)
PA (DEG)
40
20
0
−20
−40
0
100
200
300


M15 Central Rotation Measurement
VELOCITY VS. PA FOR STARS WITH 0.00<R< 0.06
V$_{rot}$= 10.4± 2.7 PA$_o$=315 ± 15
V−<V> (KM/S)
PA (DEG)
40
20
0
−20
−40
0
100
200
300

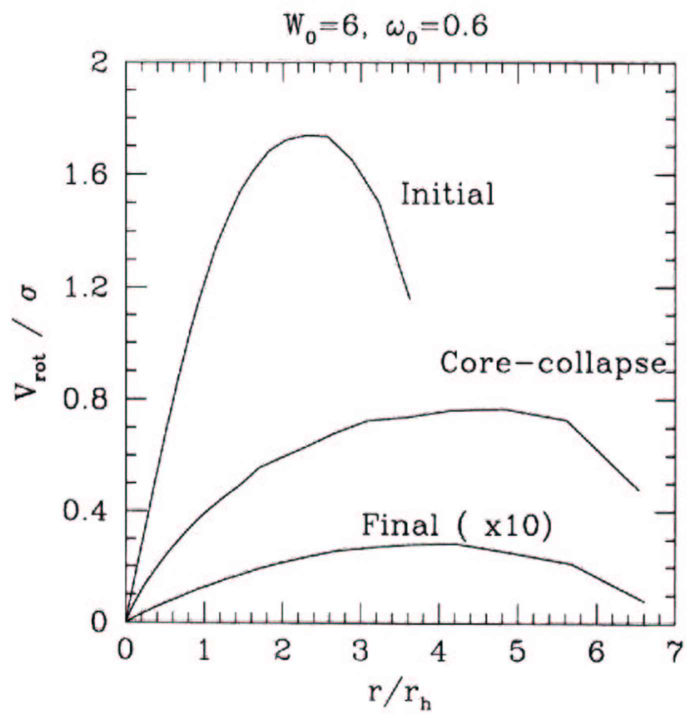

All Clusters
47Tuc
N2808
M53
Ocen
M3
N5286
N5824
M5
M80
M4
N6397
N6624
M15
M30
R/R_half
v/σ
0.1
1
10
0
0.5
1

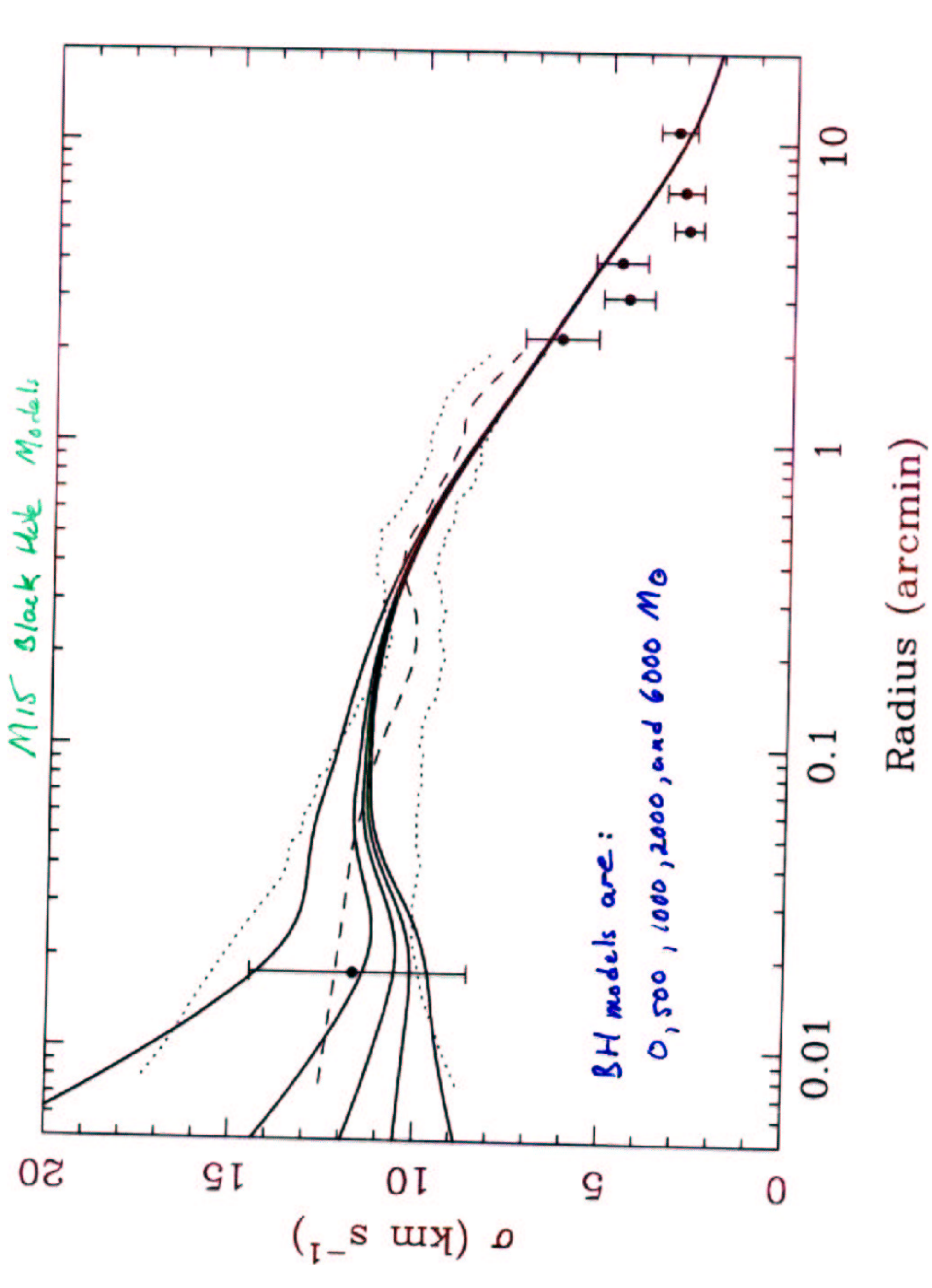

Clusters with 500 or more velocities
47Tuc
N2808
Ocen
N5286
M5
M80
M4
M15
R/R_half
v/σ
0.1
1
10
0
0.5
1

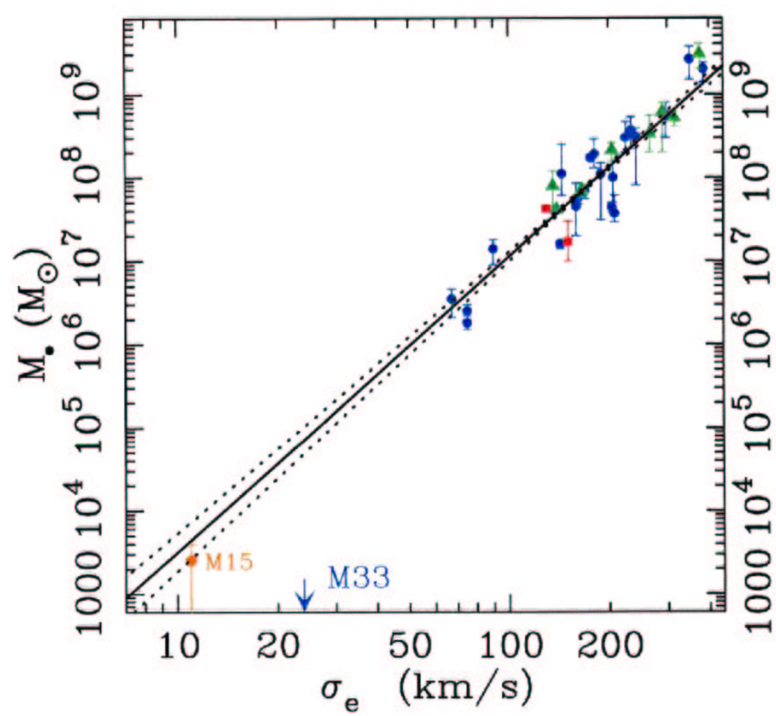
Average Rotation Profile for all clusters with over 500 radial velocities (8 total)



Fokker–Planck results from
Kim, Einsel, Lee, and Spurzem (2001)
Einsel and Spurzem (1999)




M15 Black Hole Models
BH models are:
0, 500, 1000, 2000, and 6000 M⊙
Radius (arcmin)
σ (km s−1)


M15
M33
σe (km/s)
M• (M⊙)

Prospects for Quiescent Galaxies

In a year, we will have about another 50 BH measurements

Many galaxies will have multiple techniques used in order to find potential biases (IC342: Capellari et al, N3379: Gebhardt et al N4697: Pinkney et al)

Explore the low and high mass end from resolved kinematics

Look for other parameters (e.g., environment)

Prospects for Globular Clusters

M15 STIS results soon to come (Gerssen et al.)
G1 in M31 " (Rich et al)

Combine HST imaging with ground−based velocities to study about 15 clusters (Noyola & Gebhardt)

Major obstacle is understanding role of stellar remnants

Prospects for Quasars

Easy to obtain large samples of BH masses in AGN

Calibration of reverberation and photoionization techniques

Provides constraints on AGN physics

Evolution of BHs and Galaxies; soon we will have 10,000 BHs over a large range of redshifts