SUGGESTIONS FROM THE DYNAMICS OF GALAXIES

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OUTLINE

Introduction

PART I – Spiral galaxies

PART II – Elliptical galaxies

PART III – The Fundamental Plane inspected
through a gravitational lens
(Bertin & Lombardi 2006, ApJL)

Conclusions

INTRODUCTION

General goals (distributions of luminous & dark matter, formation & evolution, the distant/early Universe).

“Constraints”?
Diagnostics vs. physical mechanisms.

Stellar dynamics, X-rays: dynamics of galaxies.

Not all topics covered; e.g., the Milky Way, central massive black holes…

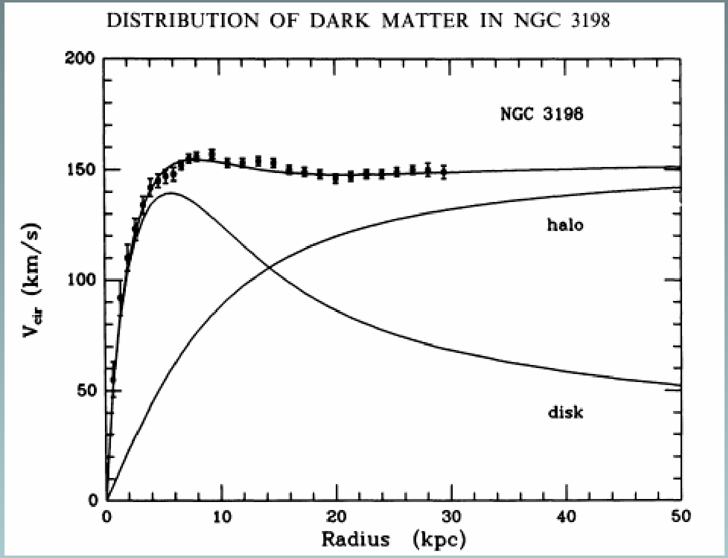
Key issues from the dynamics of galaxies that would be interesting in the context of Gravitational Lensing?

I. SPIRAL GALAXIES

- **“Direct” diagnostics**
- **Mechanisms: morphologies “in the disk plane”**
- **Mechanisms: morphologies “out of the disk plane” (and the flattening of dark halos)**

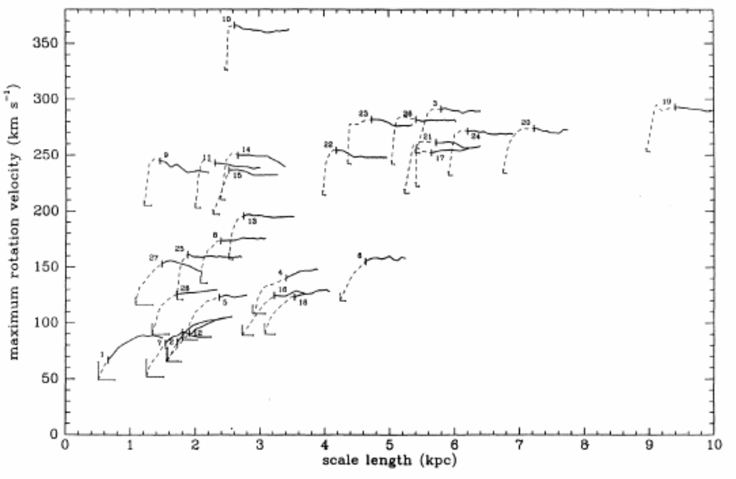
1.1 DIAGNOSTICS

DARK HALOS
IN SPIRAL GALAXIES



van Albada, Bahcall, Begeman, Sancisi 1985, ApJ

Dark halos are diffuse, with a “conspiracy”



Casertano, van Gorkom 1991, AJ

WHISP: "Westerbork observations of neutral Hydrogen in Irregular and SPiral galaxies"

Low Surface Brightness and Late Type Dwarfs

Swaters, R.A. 1999, PhD Thesis, Groningen; this conference
McGaugh, this conference

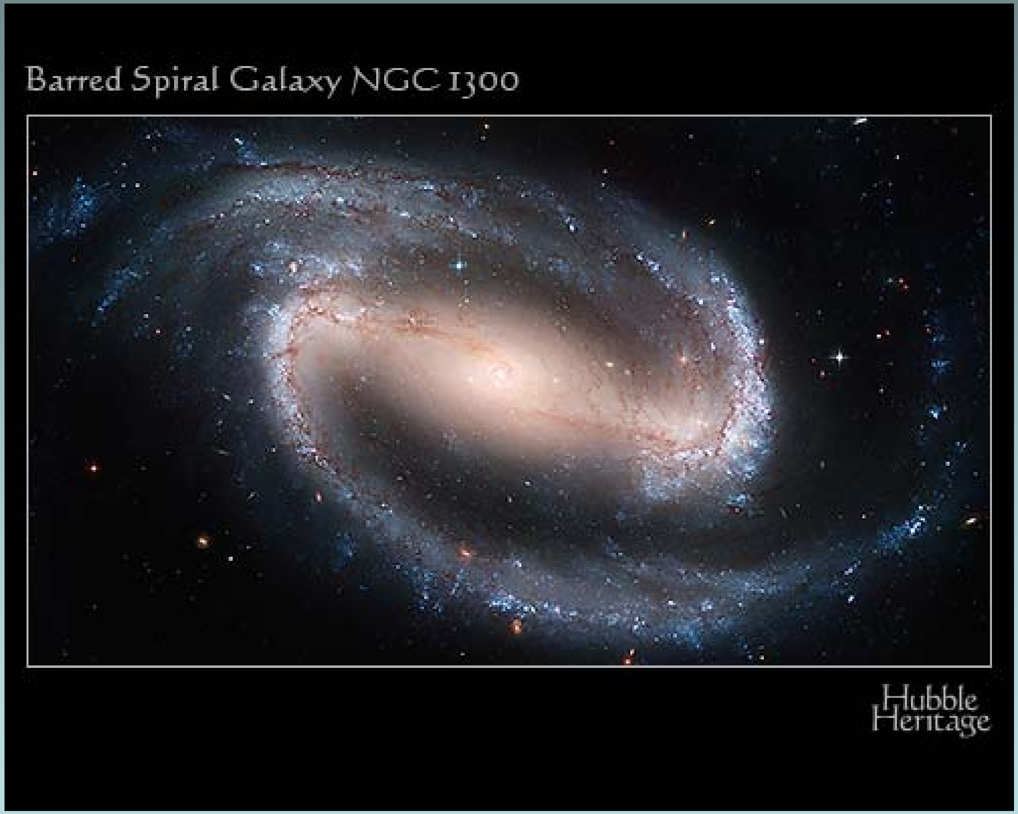
Bright Early Type Spiral galaxies Declining rotation curves

Noordermeer, van der Hulst, Sancisi, Swaters, van Albada 2005, A&A
Noordermeer, E. 2006, PhD Thesis, Groningen

1.2 MECHANISMS

MORPHOLOGY OF SPIRAL GALAXIES (I)

Barred spirals and Normal spirals



If all galaxy disks were embedded in massive dark halos, we would not see barred spiral galaxies.

(Bertin & Lin 1996 “Spiral structure in galaxies: A density wave theory”, The MIT Press; see Ostriker & Peebles, 1973, ApJ)

MODE PROTOTYPES

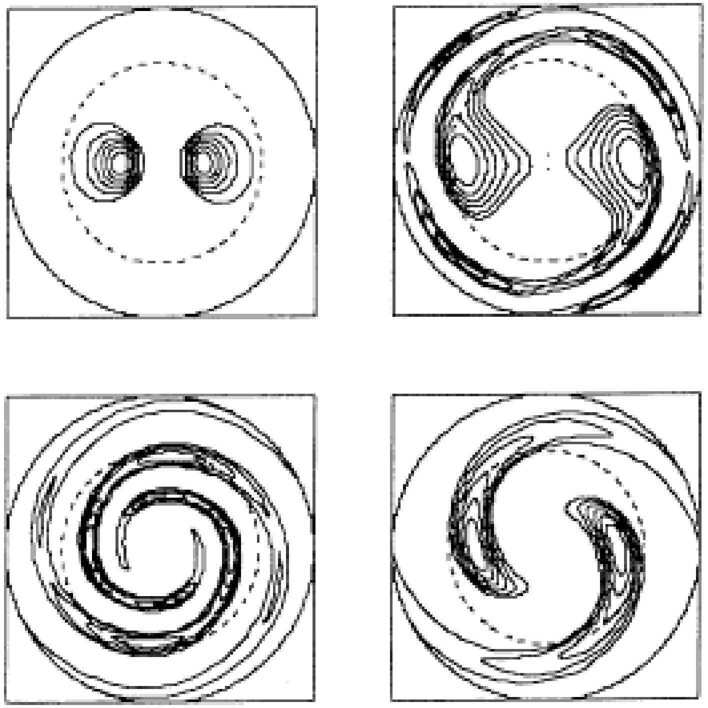
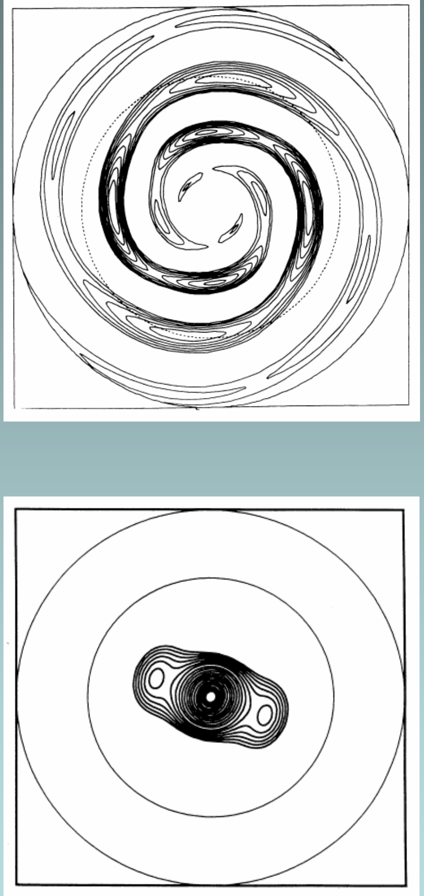


FIG. 11.—Mode prototypes. Four key morphological types are compared: SB0, SB(s), and S, all with moderate growth; a violently unstable S mode at the low right corner. The dynamical properties of these modes are discussed in Paper II.



(Bertin, Lin, Lowe & Thurstans, 1989, ApJ)

BARRED MODES, AMPLITUDE MODULATION, COROTATION RADIUS

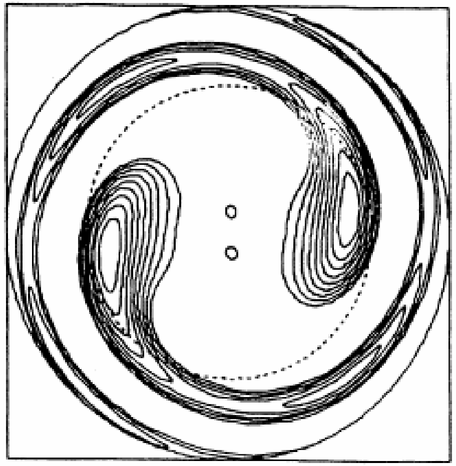
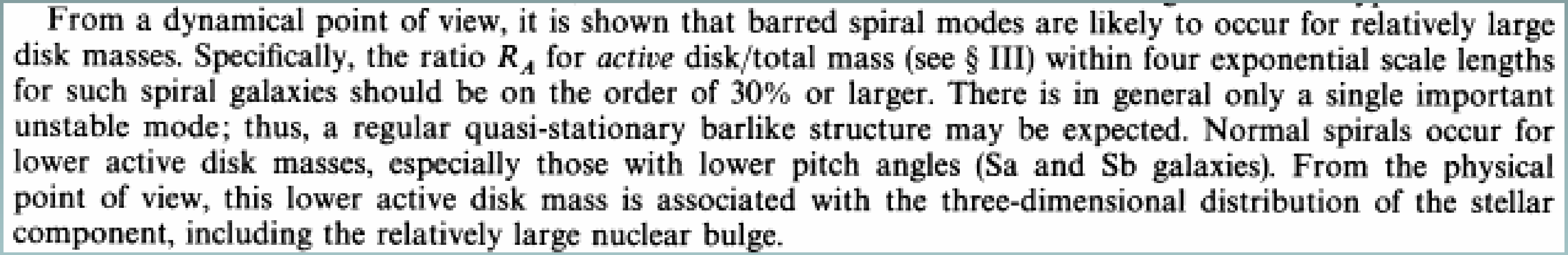


FIG. 1——Positive density contours for a barred mode from the survey reported by Bertin et al. (1989a). The structure of the mode (pitch angle, gaps, and arm shape) closely resembles the barred spiral structure found in NGC 1300 [compare with Fig. 1(f) of Elmegreen et al. 1992a]. The dotted circle is the corotation circle.



From a dynamical point of view, it is shown that barred spiral modes are likely to occur for relatively large disk masses. Specifically, the ratio R_A for *active* disk/total mass (see § III) within four exponential scale lengths for such spiral galaxies should be on the order of 30% or larger. There is in general only a single important unstable mode; thus, a regular quasi-stationary barlike structure may be expected. Normal spirals occur for lower active disk masses, especially those with lower pitch angles (Sa and Sb galaxies). From the physical point of view, this lower active disk mass is associated with the three-dimensional distribution of the stellar component, including the relatively large nuclear bulge.

(From the Abstract of Bertin, Lin, Lowe & Thurstans 1989, ApJ, 338, 78)

MORPHOLOGY CLASSIFICATION

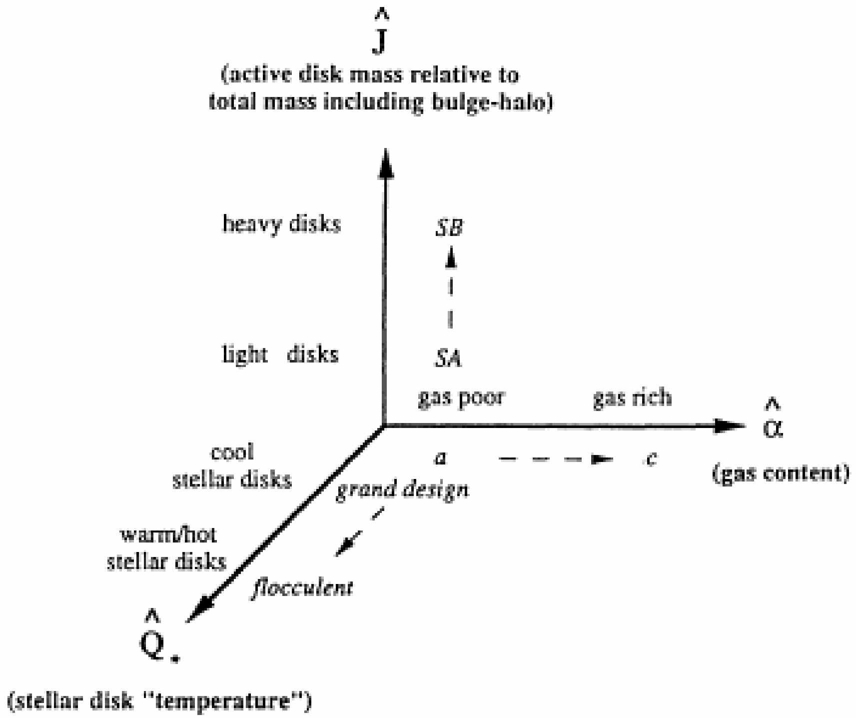


Fig. 1. Framework for the classification of the morphologies of spiral galaxies on the basis of their intrinsic modal characteristics (see Bertin 1991)

But, with the help of a rotating prolate dark halo

(J. Navarro, this conference) …

Traditional measurements of dark matter in barred galaxies are difficult to make and may be controversial.

Could Gravitational Lensing help provide a decisive measurement here?

MORPHOLOGY OF SPIRAL GALAXIES (II)

- **Warps as probes of the outer regions**

- **Anomalous HI gas “halos”**

Edge-on views

ESO 510-G13

NGC 5907

NGC 4565

NGC 891

- **Dark halos have been considered to resolve the problem of differential precession (Tubbs & Sanders 1979; see also Sparke & Casertano 1988), or to excite or damp bending perturbations, depending on their pattern speed (Bertin & Mark 1980), through disk-halo interactions; dark halos resolve the apparent stability paradox posed by earlier studies (Hunter & Toomre 1969).**

- **Anomalous extraplanar cold gas found recently in deep HI studies – NGC2403 Fraternali et al. 2002; UGC7321 Matthews & Wood 2003; NGC4559 Barbieri et al. 2005; NGC891 Swaters et al. 1997; see Barnabe' et al. 2006.**

The three-dimensional morphology of galaxy disks is very interesting and carries important information about the dark matter halos (<u>and their shapes</u>). Unfortunately, a coherent theory of the development of the observed morphologies is still lacking.

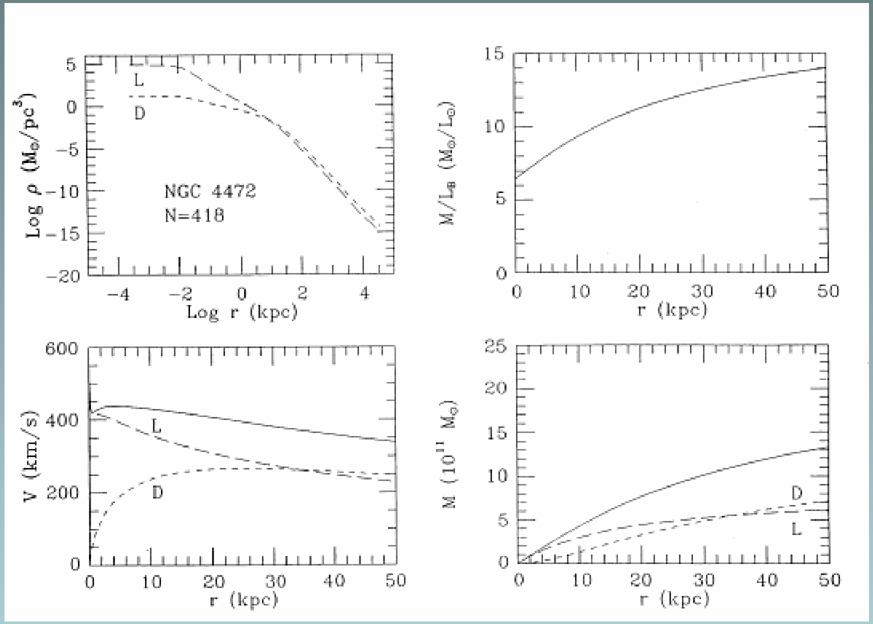
II. ELLIPTICAL GALAXIES

- **Diagnostics, X-rays**
- **Modeling**
- **Dynamical evolution**

2.1 DIAGNOSTICS

DARK HALOS IN ELLIPTICAL GALAXIES

Stellar dynamics



Saglia, Bertin, Stiavelli 1992, ApJ

For many bright ellipticals, dark halos are diffuse, with a "conspiracy" of a flat circular velocity curve

HI

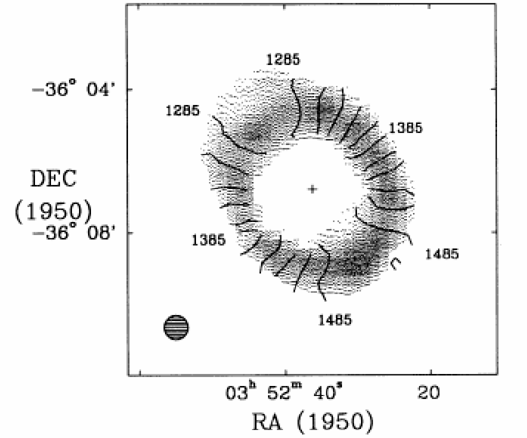
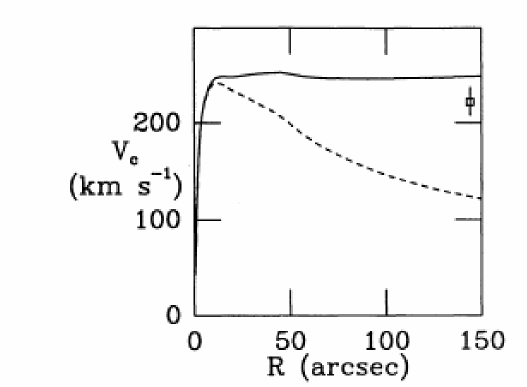
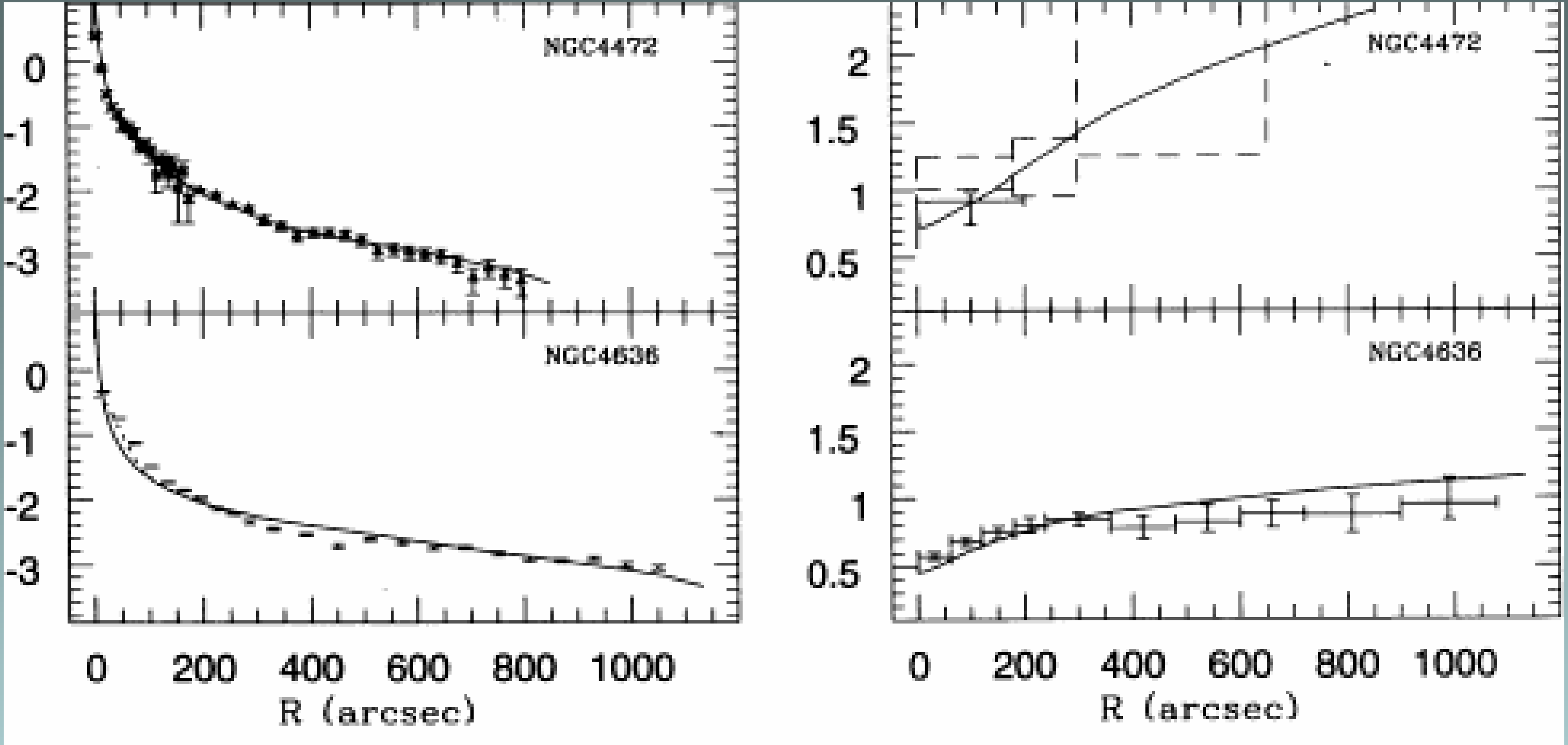


FIG. 5.—The intensity-weighted mean H I velocities in IC 2006. The contours are spaced by 20 km s^{-1}, and some of the velocities are marked. The systemic velocity of the galaxy is 1385 km s^{-1}. The gray-scale map represents the total H I flux distribution.



Franx, van Gorkom, de Zeeuw 1994, ApJ



Bertin & Toniazzo 1995, ApJ
Temperature for NGC4636: ROSAT PSPC, Trinchieri et al. 1994

NGC 4472 vs. NGC 3198

(large elliptical vs. small spiral)

TYPE	E0	Sc	TYPE
Distance	20 Mpc	9.2 Mpc	Distance
M/L_B	14-47	18	$(M/L\_B)\|_{11h}$
M_L/L_B	6.5	4.7	M_L/L_B
$(M\_D/M\_L)\|_{Re}$	0.5	0.5	$(M\_D/M\_L)\|_{4h}$
M_L	6-8.4	0.41	M_L
M	17-57	1.54	M

(Bertin, Elba Conference 1992)

TRENDS

An ESO Key Programme

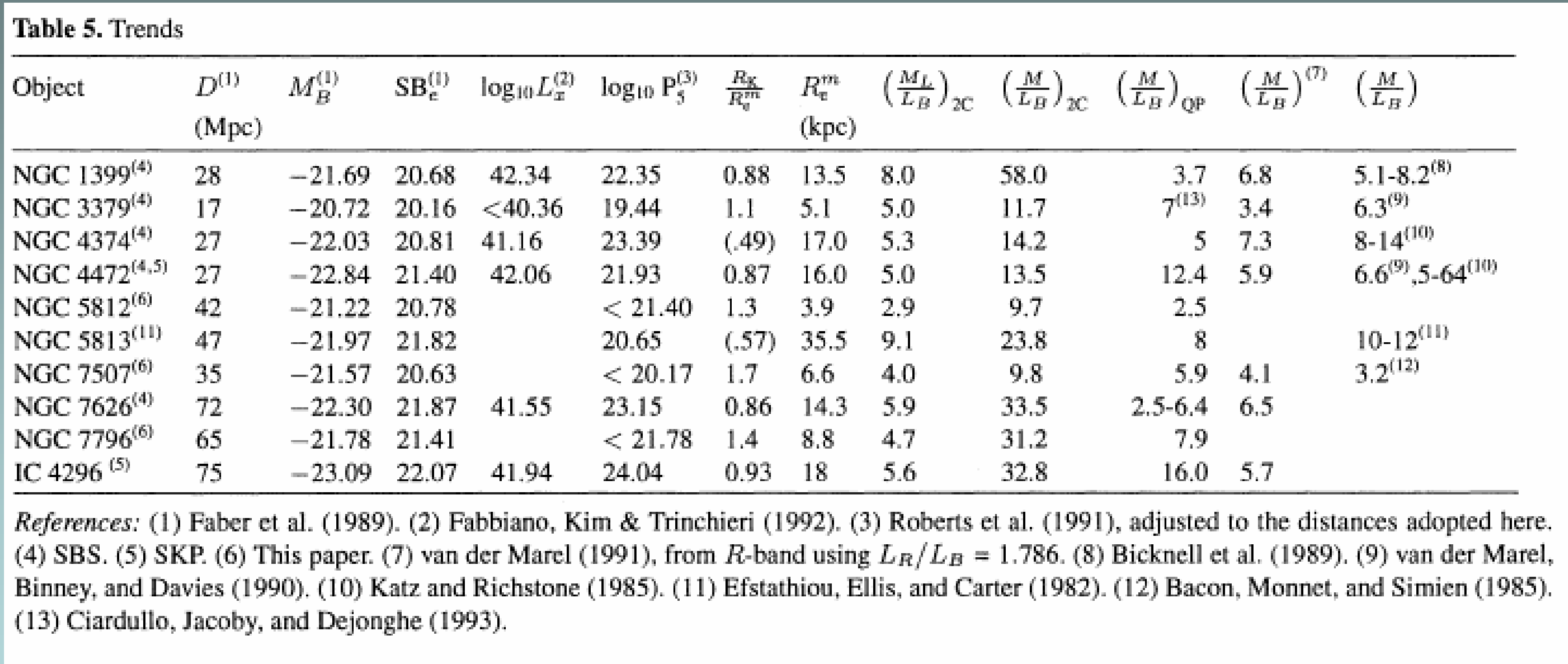


Table 5. Trends

Object	$D^{(1)}$ (Mpc)	$M_B^{(1)}$	$\mathrm{SB}_e^{(1)}$	$\log_{10} L_x^{(2)}$	$\log_{10} \mathrm{P}_5^{(3)}$	$\frac{R_K}{R_e^m}$	R_e^m (kpc)	$\left(\frac{M_L}{L_B}\right)_{2C}$	$\left(\frac{M}{L_B}\right)_{2C}$	$\left(\frac{M}{L_B}\right)_{QP}$	$\left(\frac{M}{L_B}\right)^{(7)}$	$\left(\frac{M}{L_B}\right)$
• NGC 1399[4]	28	−21.69	20.68	42.34	22.35	0.88	13.5	8.0	58.0	3.7	6.8	5.1-8.2[8]
NGC 3379[4]	17	−20.72	20.16	<40.36	19.44	1.1	5.1	5.0	11.7	7[13]	3.4	6.3[9]
• NGC 4374[4]	27	−22.03	20.81	41.16	23.39	(.49)	17.0	5.3	14.2	5	7.3	8-14[10]
• NGC 4472[4,5]	27	−22.84	21.40	42.06	21.93	0.87	16.0	5.0	13.5	12.4	5.9	6.6[9],5-64[10]
NGC 5812[6]	42	−21.22	20.78		< 21.40	1.3	3.9	2.9	9.7	2.5		
• NGC 5813[11]	47	−21.97	21.82		20.65	(.57)	35.5	9.1	23.8	8		10-12[11]
NGC 7507[6]	35	−21.57	20.63		< 20.17	1.7	6.6	4.0	9.8	5.9	4.1	3.2[12]
• NGC 7626[4]	72	−22.30	21.87	41.55	23.15	0.86	14.3	5.9	33.5	2.5-6.4	6.5	
• NGC 7796[6]	65	−21.78	21.41		< 21.78	1.4	8.8	4.7	31.2	7.9		
• IC 4296 [5]	75	−23.09	22.07	41.94	24.04	0.93	18	5.6	32.8	16.0	5.7	

References: (1) Faber et al. (1989). (2) Fabbiano, Kim & Trinchieri (1992). (3) Roberts et al. (1991), adjusted to the distances adopted here. (4) SBS. (5) SKP. (6) This paper. (7) van der Marel (1991), from *R*-band using $L_R/L_B = 1.786$. (8) Bicknell et al. (1989). (9) van der Marel, Binney, and Davies (1990). (10) Katz and Richstone (1985). (11) Efstathiou, Ellis, and Carter (1982). (12) Bacon, Monnet, and Simien (1985). (13) Ciardullo, Jacoby, and Dejonghe (1993).

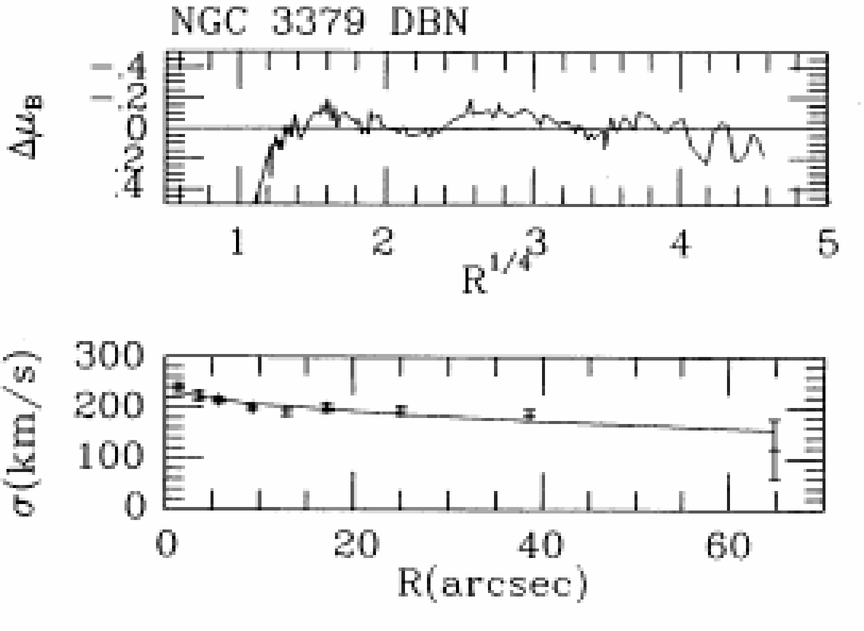
NGC3379, NGC5812, NGC7507 (small R_e) no real evidence for a dark halo; ellipticals with evidence for a dark halo are typically X-ray bright objects.

Bertin, Bertola, Buson, Danziger, Dejonghe, Sadler, Saglia, de Zeeuw, Zeilinger 1994, A&A

NGC3379

$$f(E, J^2) = A(-E)^{3/2} \exp\left[-aE - cJ^2/2\right] = f_\infty$$

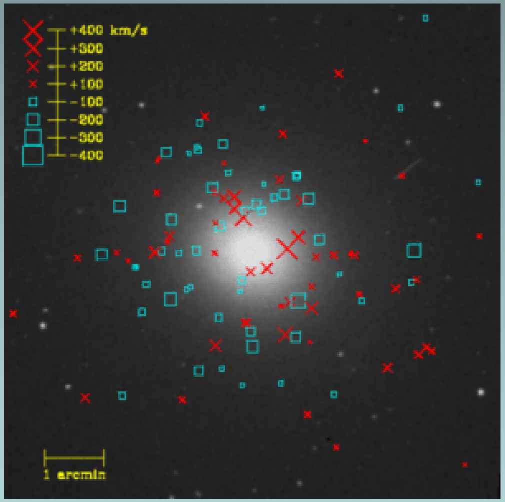
Bertin, Stiavelli A&A 1984; see Rep. Progr. Phys. 1993



Saglia, Bertin, Stiavelli ApJ 1992

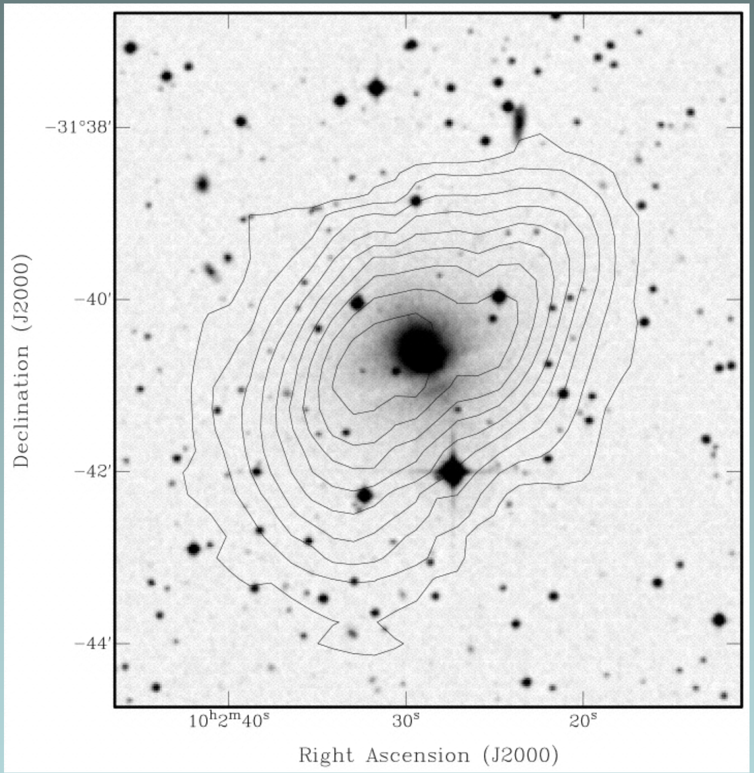
Stellar dynamics

Planetary nebulae



Romanowsky et al. Science 2003
For Pne & g.c.'s, see also Peng et al. 2004, Teodorescu et al. 2005, Pierce et al. 2006

Low luminosity HI disks



NGC 3108 Oosterloo, Morganti, Sadler, Vergani, Caldwell 2002, AJ

STRUCTURE OF ELLIPTICALS

In large ellipticals there is evidence for moderate halos on the scale of their effective radius; a simple $1/r^2$ density distribution for the total (luminous + dark) mass appears to be a reasonable model both in the nearby Universe and at relatively high z (see Gerhard et al. 2001; Magorrian & Ballantyne 2001; Koopmans & Treu 2003, ApJ; Rusin et al. 2003; Treu & Koopmans 2004, ApJ; Koopmans, this conf.; Rusin, this conf.; Treu, this conf.). In some cases significant angular momentum may be stored in their outer parts.

Small ellipticals appear to be rotation supported (Davies et al. 1983; Rix et al. 1999) and do not exhibit hard evidence for dark halos.

Intermediate cases remain puzzling (e.g., NGC3379; see also NGC4494, NGC4697;see Romanowski et al. 2003).

X-RAYS

In stellar dynamics, great attention has been given to the so-called dark matter – pressure anisotropy degeneracy. In turn, the justification of the hydrostatic equilibrium conditions for the hot coronal gas in ellipticals has frequently been accepted as undisputed. In addition, the possibility of sampling larger radial ranges (several Re's) makes X-ray diagnostics highly appealing. Therefore, it is often thought that X-ray diagnostics leads to more reliable mass measurements.

In practice, some claims of discoveries of dark halos around ellipticals from X-rays turned out to be unjustified, as was immediately apparent from inconsistencies with stellar dynamical data inside Re (e.g., see the history of X-ray analysis of NGC 4472). In turn, X-ray data appeared to be of only little help in resolving the uncertainties associated with stellar dynamics (Bertin et al. 1993).

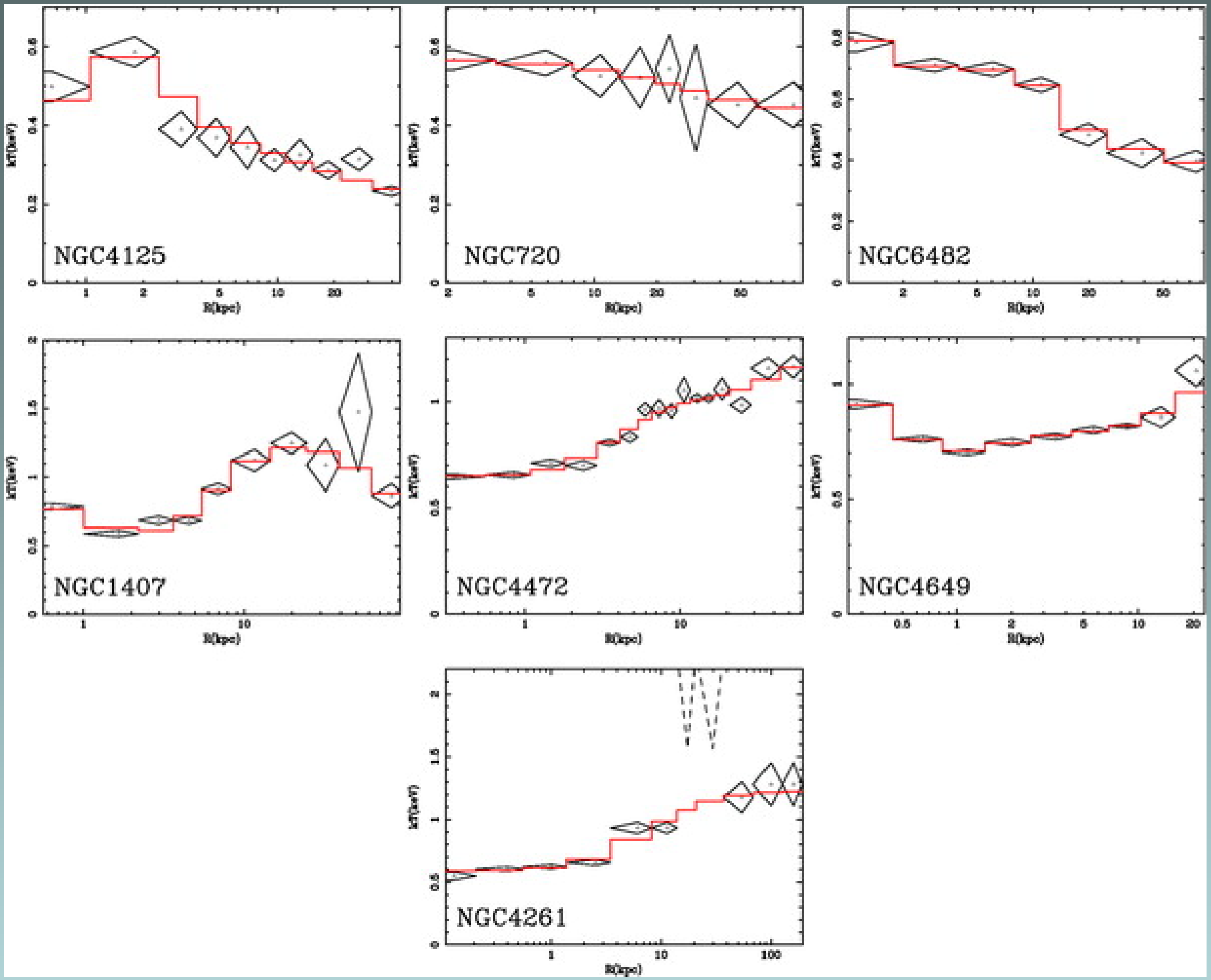
X-RAYS: RECENT STUDIES

- **For M 87, a reported apparent discrepancy (detection of <u>less</u> mass) with respect to optical measurements has been argued to be due to an improper use of a single-phase model for the hot coronal gas (Tsai 1994). <u>Less</u> mass may result from application of hydrostatic equilibrium in the presence of <u>inflows</u> (Ciotti & Pellegrini 2004). <u>Turbulence</u> in the hot gas may also be a factor (Rasia et al. 2006).**

- **A study of NGC3379 (Fukazawa et al. 2003, a sample of 53 early type galaxies; Chandra data). The reported apparent discrepancy (detection of <u>more</u> mass) with studies based on stellar dynamics and PNe may be due to a failure of the hydrostatic model in the presence of <u>outflows</u> (Pellegrini & Ciotti 2006; see also Ciotti & Pellegrini 2004).**

- **Cf. scatter of L_X – L_B relation, inflow-outflow models (Ciotti et al. 1991)**

- **An interesting Chandra study of NGC720, NGC1407, NGC4125, NGC4261, NGC4472, NGC4649, NGC6482 (Humphrey et al. 2006), arguing in favor of application of hydrostatic equilibrium.**



Humphrey et al. 2006

For NGC 720 (Chandra) see also Buote et al. 2002; for M 87 (XMM) see Matsushita et al. 2002

Great progress will be made by a joint diagnostics based on stellar dynamics, globular clusters and planetary nebulae, X-rays, HI, and gravitational lensing: each of these diagnostics, if taken separately, may present significant limitations.

2.2 MODELING

Interest in the dynamics of ellipticals came in the 70s from the surprisingly low rotation found in bright objects; now that surprising behavior is "explained", but we are left with many open questions about the structure of low luminosity ellipticals. Note that low luminosity ellipticals follow the Fundamental Plane, but are structurally different from bright ellipticals, for which the FP is commonly interpreted on the basis of structural homology.

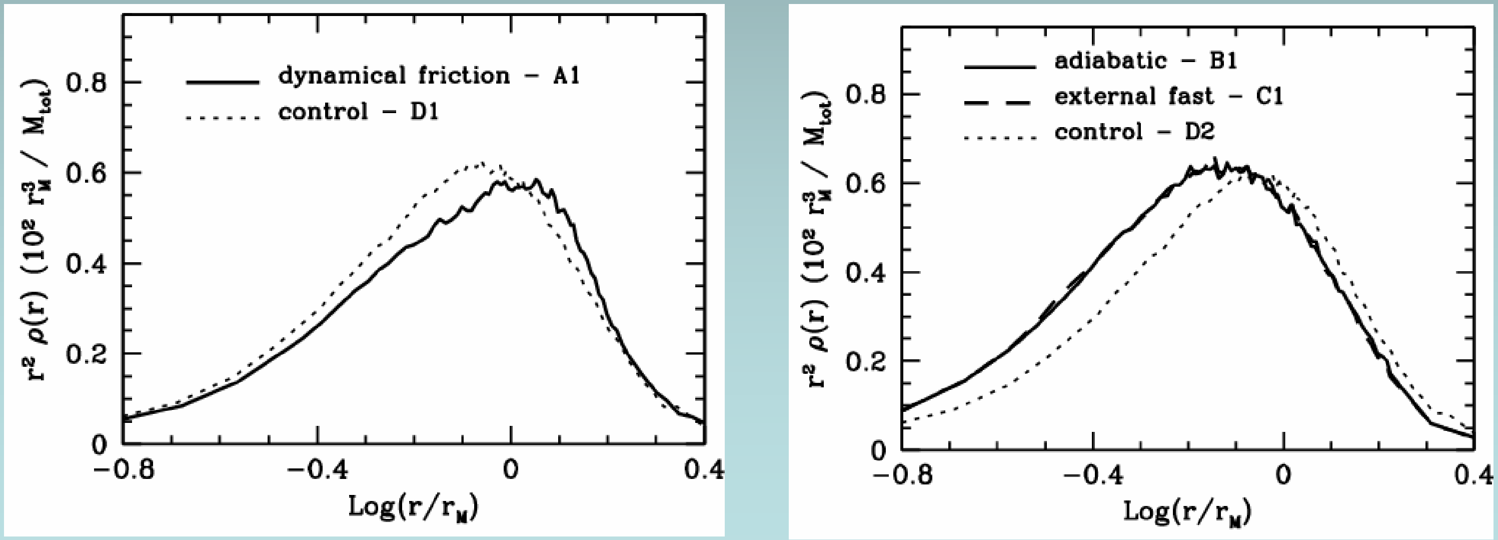
The so-called dark matter – anisotropy degeneracy has turned out to be a nuisance rather than a problem: many elliptical galaxies appear to be characterized by regular distribution functions and conform to the picture of violent relaxation (relaxed and isotropic inside R_e, radially anisotropic outside; see Bertin & Stiavelli 1993, Rep. Prog. Phys.; Winsall & Freeman 1993, A&A; Gerhard et al. 2001, AJ).

Some trends noted for ellipticals go in the opposite direction (in particular, evidence for and importance of dark halos in small ellipticals vs. large ellipticals) with respect to those noted for spiral galaxies (in particular, evidence for and importance of dark halos in small vs. large spirals).

Could Gravitational Lensing help clarify the situation?

2.3 DYNAMICAL EVOLUTION OF ELLIPTICAL GALAXIES

Dynamical evolution via dynamical friction leads to broadening of the relevant density distribution, in contrast with expectations from the adiabatic scenario (Bertin, Liseikina, Pegoraro 2004; Ma & Boylan-Kolchin 2004; Nipoti, Treu, Ciotti, Stiavelli 2004).



Arena, Bertin, Liseikina, Pegoraro 2006

III. LOOKING AT THE FUNDAMENTAL PLANE THROUGH A GRAVITATIONAL LENS

(Bertin & Lombardi, ApJL, 2006)

$$\log R_e = \log r_e + \log D_A(z)$$
$$= \alpha \log \sigma_0 + \beta SB_e + \gamma$$

The Fundamental Plane as a “standard rod”

$$\log r_e + \log D_A(z) =$$
$$\alpha \log \sigma_0 + \beta SB_e + \gamma - \frac{1}{2} \log |\det A|$$

The Fundamental Plane seen through a lens

$$0.4343\kappa \approx$$

$$\log r_e + \log D_A(z) - \alpha \log \sigma_0 - \beta SB_e - \gamma$$

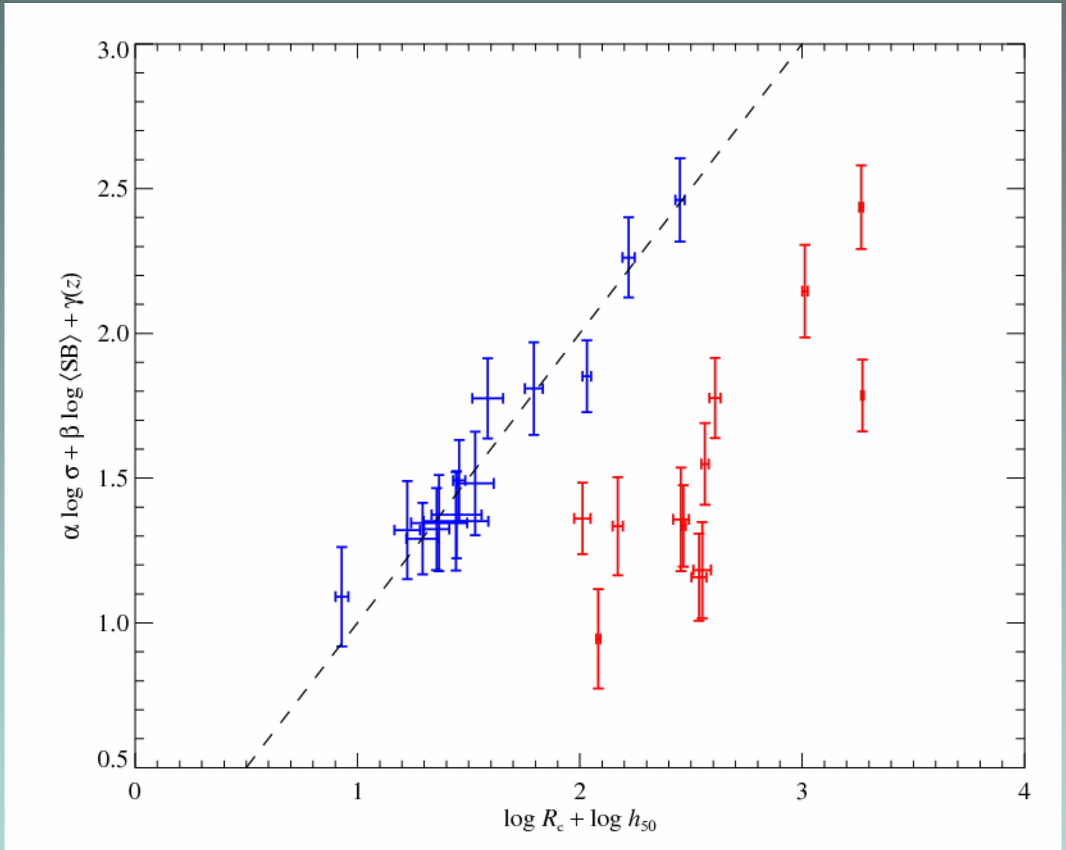
[γ(z) : see Treu et al. (2002, 2005), van der Wel et al. (2005)]

- **This new method breaks the mass-sheet degeneracy (cf. the difficult to measure magnification effect; Taylor et al. 1998, Schneider et al. 2000).**

- **It provides a measurement of κ on the small "pencil beams" that characterize the size of the background galaxies.**

- **Merits with respect to lensing of Tully-Fisher or SNe Ia ("standard candles")**

(A simulated case, prepared by M. Lombardi, under realistic conditions, for a sample of early-type galaxies behind a strong lensing cluster)



An error of 15% in R_e implies an absolute error of 0.15 in κ.

[For the scatter of the FP in the nearby Universe, see Jørgensen et al. (1996); at higher z, see Jørgensen et al. (1999), Treu et al. (1999, 2002), Bernardi et al. (2003), di Serego et al. (2005), Rusin & Kochanek (2005), …]

CONCLUSIONS (1)

For galaxies, especially bright galaxies, with the help of stellar dynamics and other diagnostics (HI, for spirals, or X-rays, for ellipticals), dark and luminous distributions have been disentangled on the scale of the galaxy effective radius and beyond. Dark halos appear to be diffuse. This picture is now finding support from Gravitational Lensing. [The case of some intermediate luminosity ellipticals (see NGC3379) remains puzzling.]

Some important general issues in relation to the structure of galaxies (the origin of barred spiral structure, the basic state of low luminosity ellipticals) depend on a decisive measurement about the relative distribution of dark and luminous matter that traditional diagnostics have so far been unable to make.
Could Gravitational Lensing help in this respect?

CONCLUSIONS (2)

A simple idea based on the joint use of dynamics and lensing is proposed (looking at the Fundamental Plane through a gravitational lens), with interesting diagnostic potential.