Scaling Relations of late-type galaxies

- an observational perspective -

- Lecture I Trends along the Hubble sequence
- Lecture II Galaxy rotation curves
- Lecture III Tully-Fisher relations

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Bertinoro, May 2006

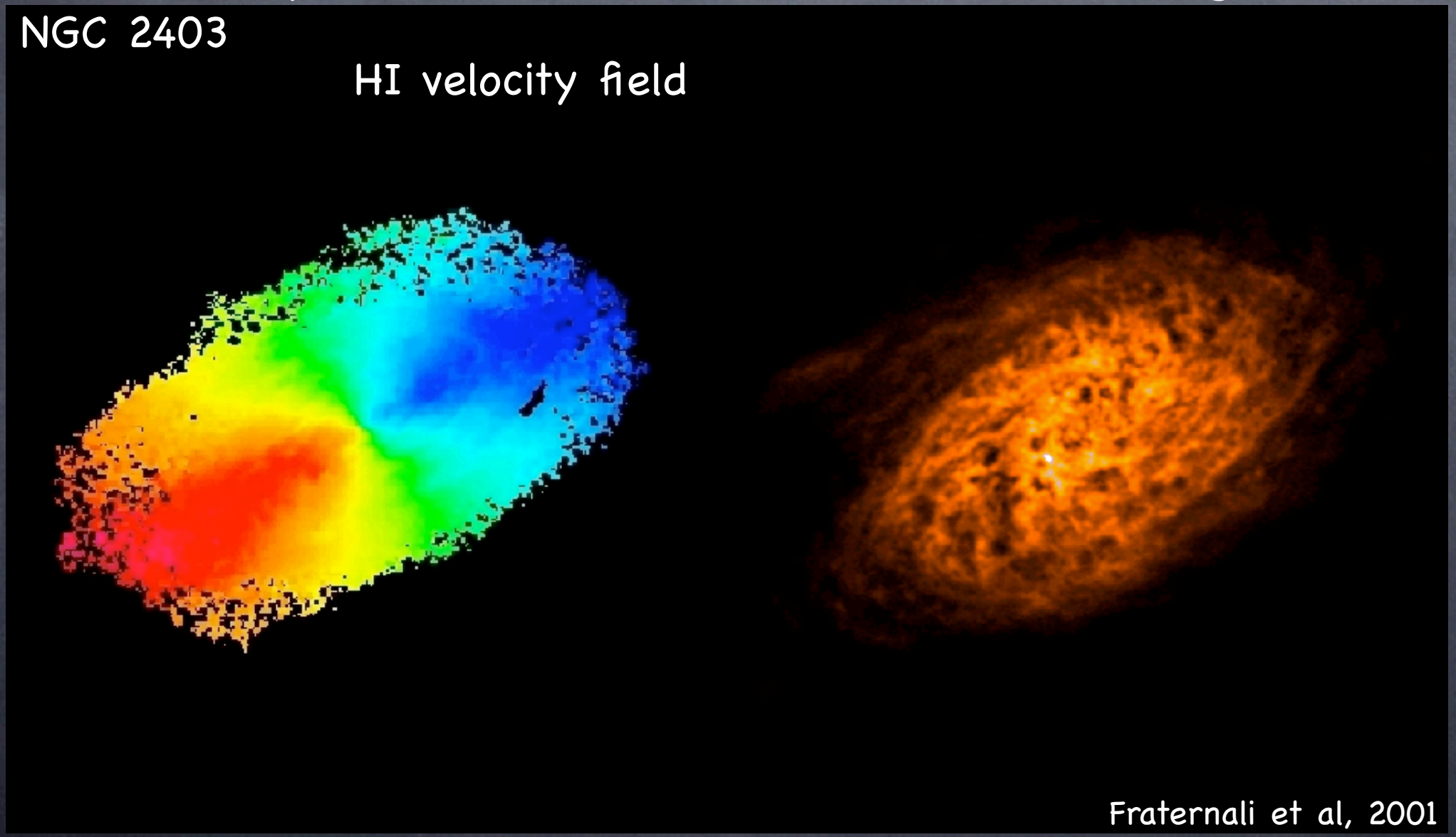
II. Galaxy Rotation Curves

- observed shapes of rotation curves
- mass components & RC decompositions
- disk-halo degeneracy & Maximum Disk hypothesis
- mass-to-light ratios
- imprint of luminous matter on RC shape
- dark matter scaling relations

Gas content

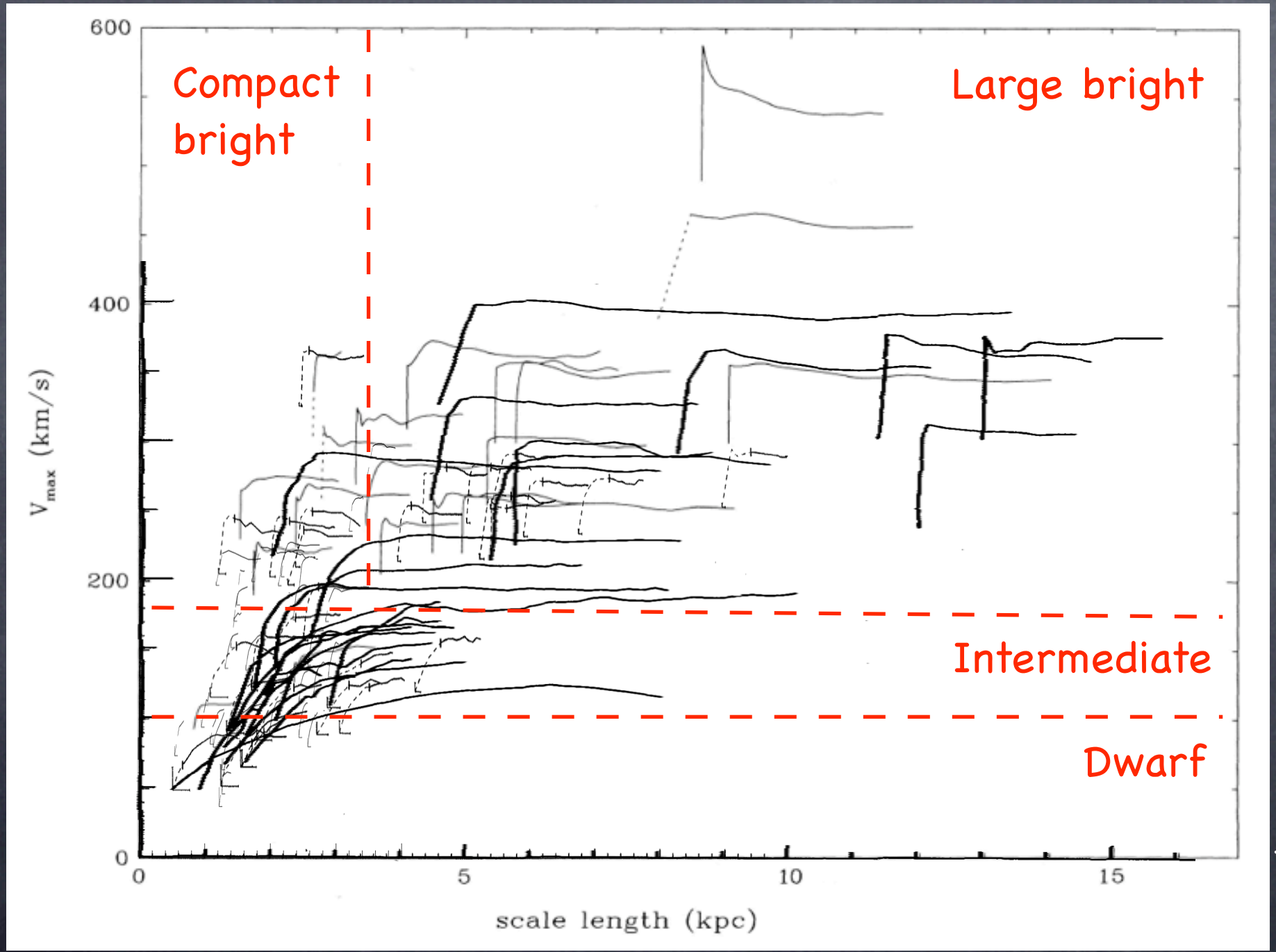
optical

atomic hydrogen



same scale!

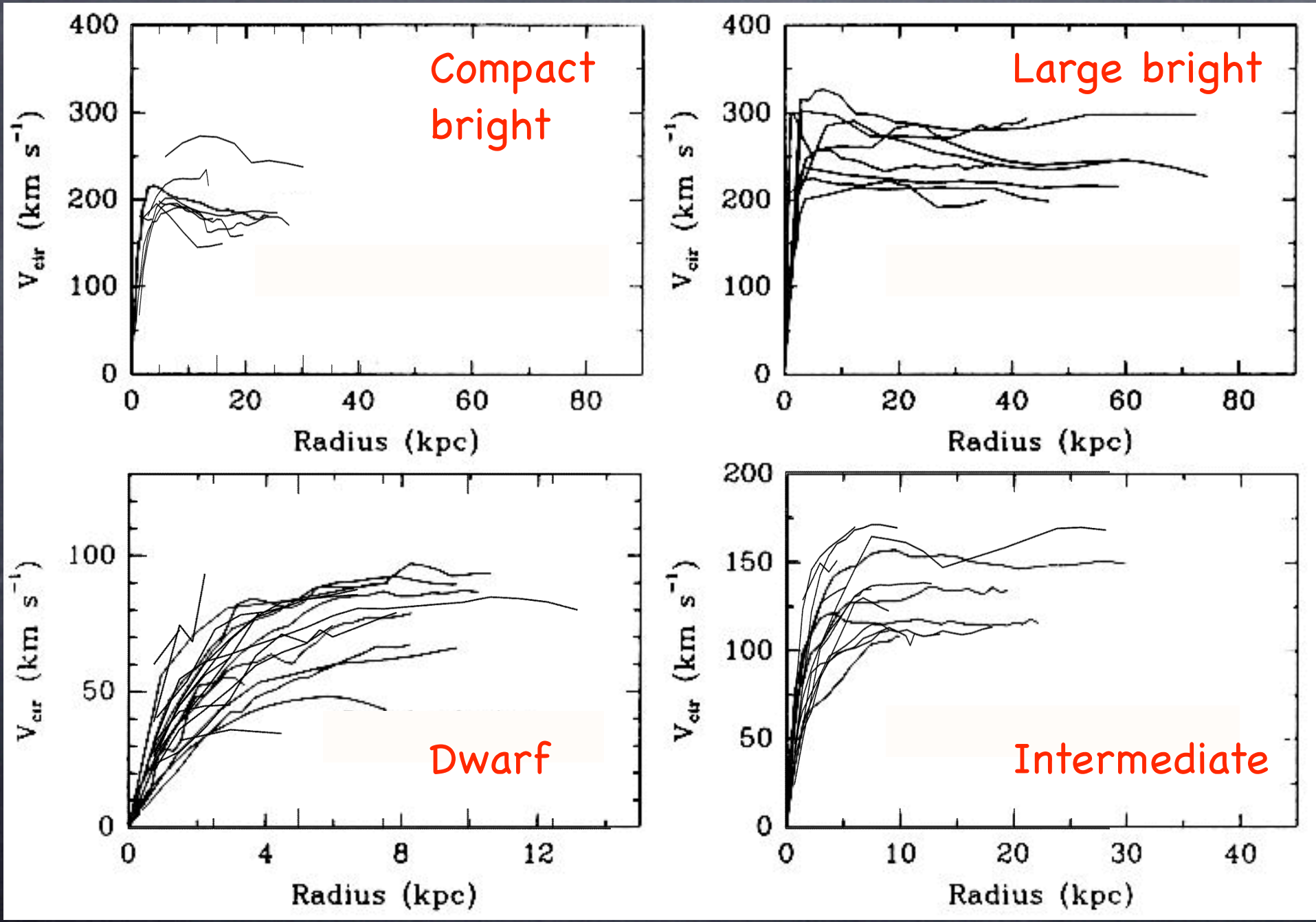
Kinematics - galaxy rotation curves



Casertano & van Gorkom, 1996

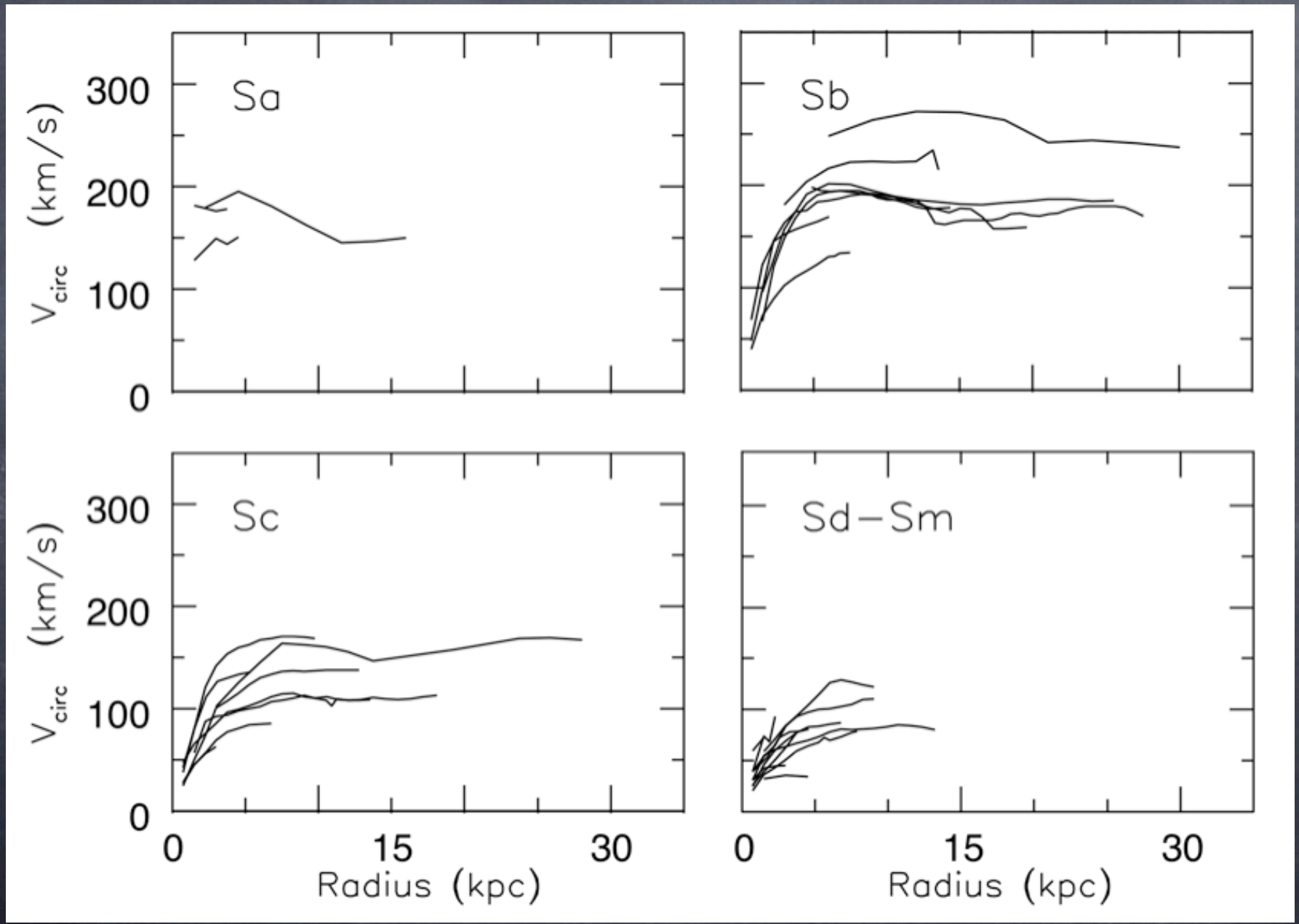
Verheijen, 1997 Broeils, 1992 Noordermeer, 2006

shapes of rotation curves



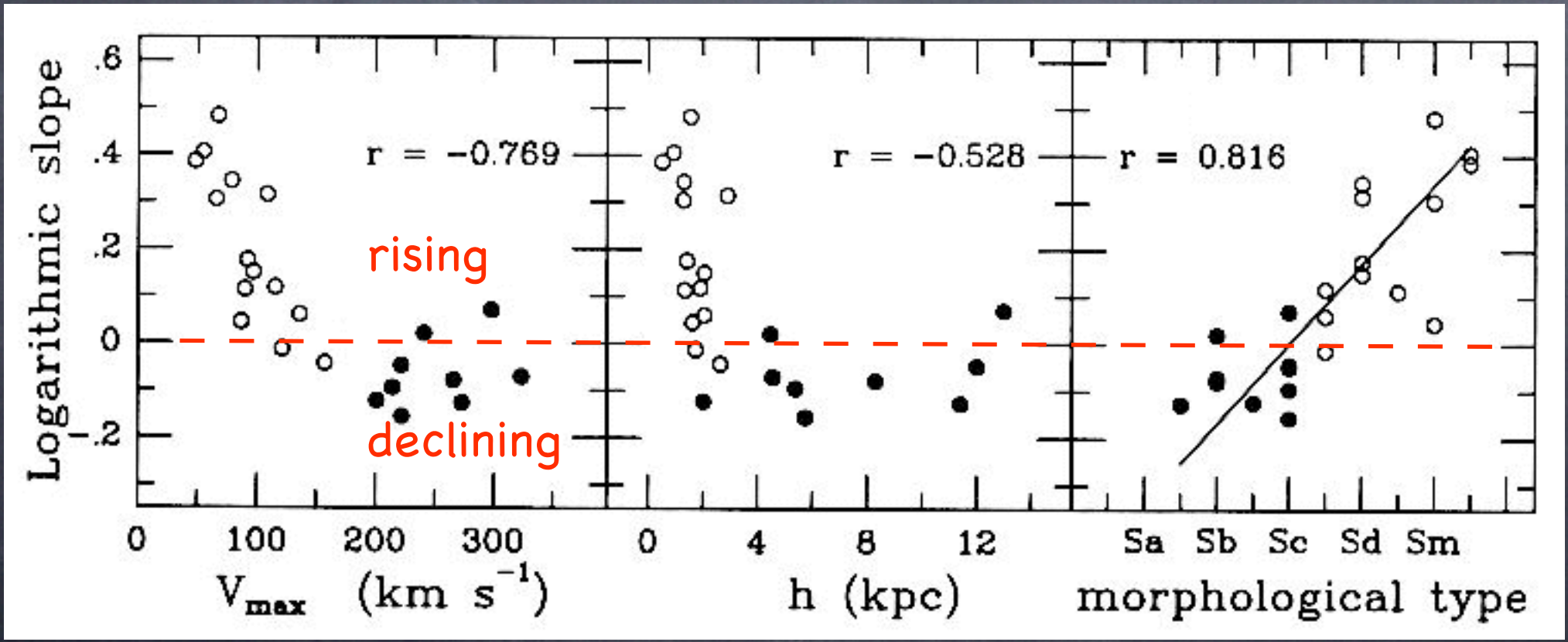
Broeils, 1992 Verheijen, 1997

shapes of rotation curves



Verheijen, 1997

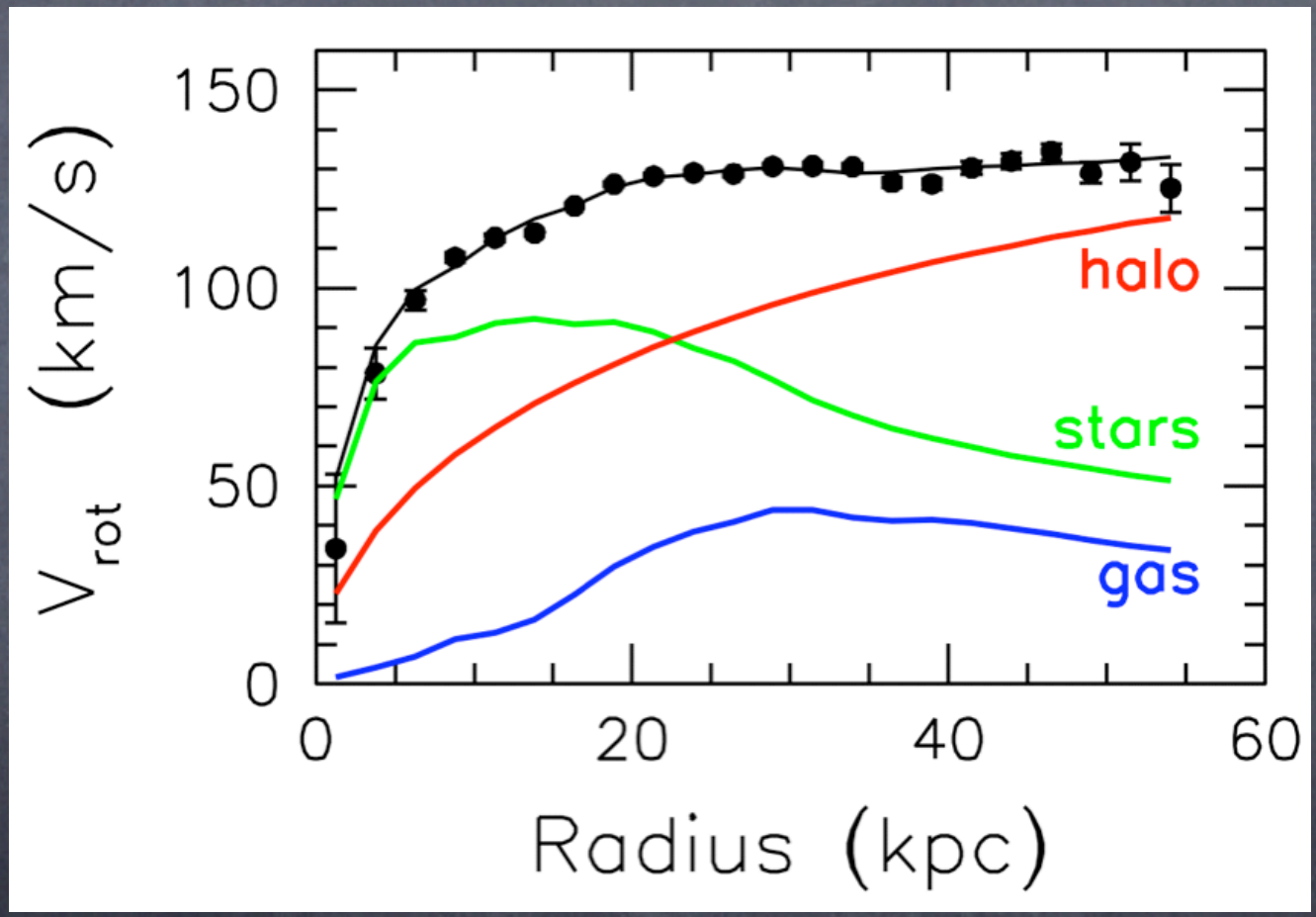
slopes of rotation curves



Broeils, 1992

Rotation curve decompositions

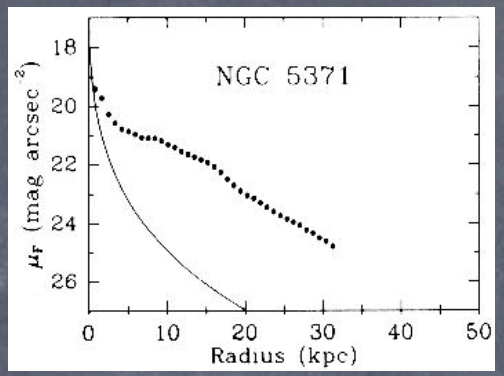
Deriving the distribution of Dark Matter

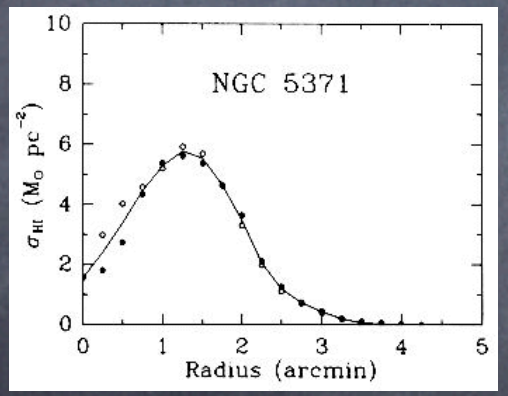


$$V_{obs} = \sqrt{(V_{stars}^2 + V_{gas}^2 + V_{halo}^2)}$$

Rotation curves of stars and gas

- shapes of radial light and HI profiles
  → shapes of the stellar and gas rotation curves

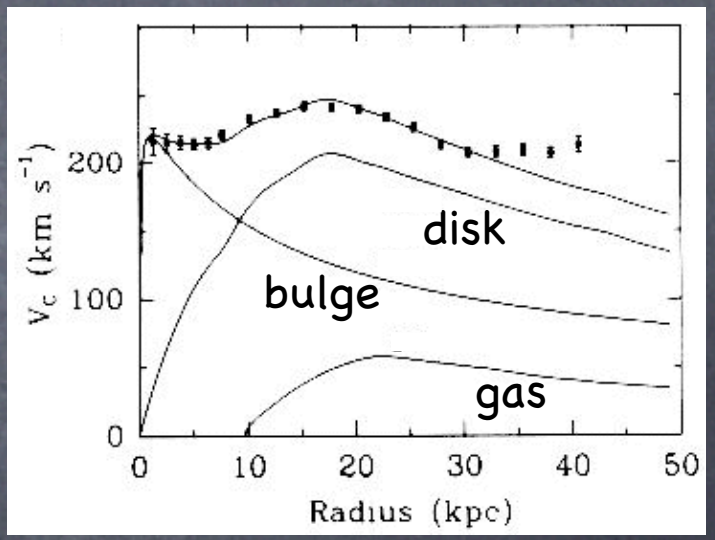




spherical bulge
+
flattened disk

calculate
potential

thin gas disk



Begeman, 1987

- mass or mass-to-light ratio $\mathcal{M}/\mathcal{L}$ of the stars
  → amplitude of the stellar rotation curve
- mass of gas, corrected for He fraction, is well known

Halo mass models

- Pseudo-isothermal sphere:

$$\rho(R) = \frac{\rho_o}{1+(R/R_c)^2} \qquad V_{halo}^2(R) = 4\pi G\rho_o R_c^2 \left[1 - \frac{R_c}{R} \arctan\left(\frac{R}{R_c}\right) \right]$$

$$V_{halo}^{max} = R_c\sqrt{4\pi G\rho_o}$$

- Hernquist profile:

$$\rho(R) = \frac{M_o}{2\pi R_o^2} \frac{1}{R[1+(R/R_o)]^3} \qquad V_{halo}(R) = \frac{\sqrt{GM_oR_o}}{R + R_o}$$

$$V_{halo}^{max} = 1039\sqrt{M_o/R_o}$$

- NFW profile: motivated by numerical simulations

→ similar to Hernquist profile at small radius

(Navarro, Frenk & White, 1996)

NFW halo model

$$\rho(R) = \frac{\rho_{crit}\ \delta_c}{(R/R_s)[1+(R/R_s)]^2}$$

ρ_{crit} = critical density = $3H^2/8\pi G$

R_s = scale radius = r_{200}/c

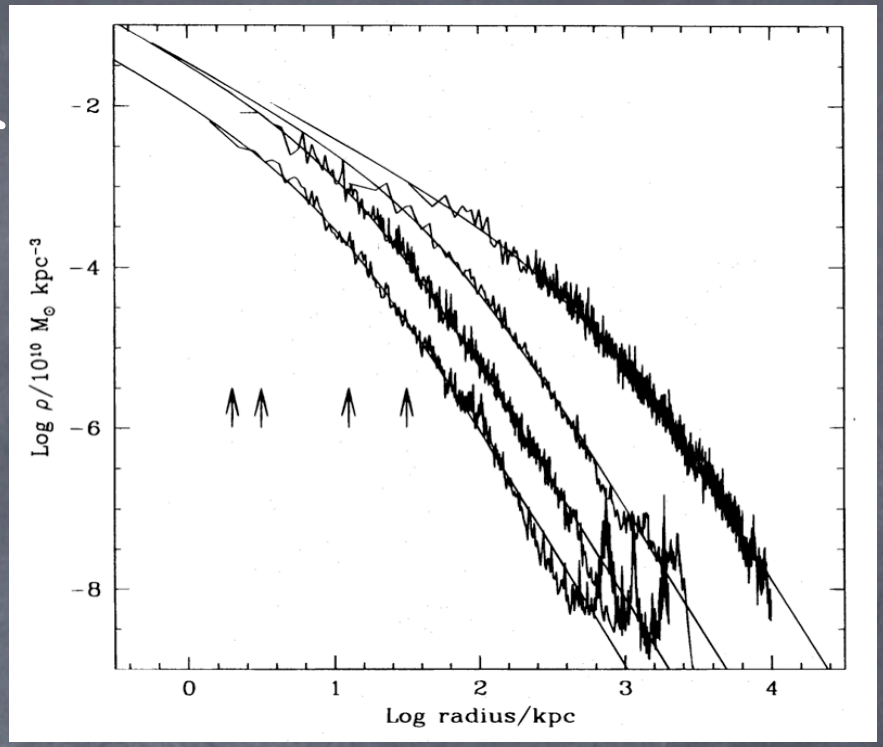
$M_{200} = 200\rho_{crit}(4\pi/3)r_{200}^3$

δ_c = characteristic overdensity

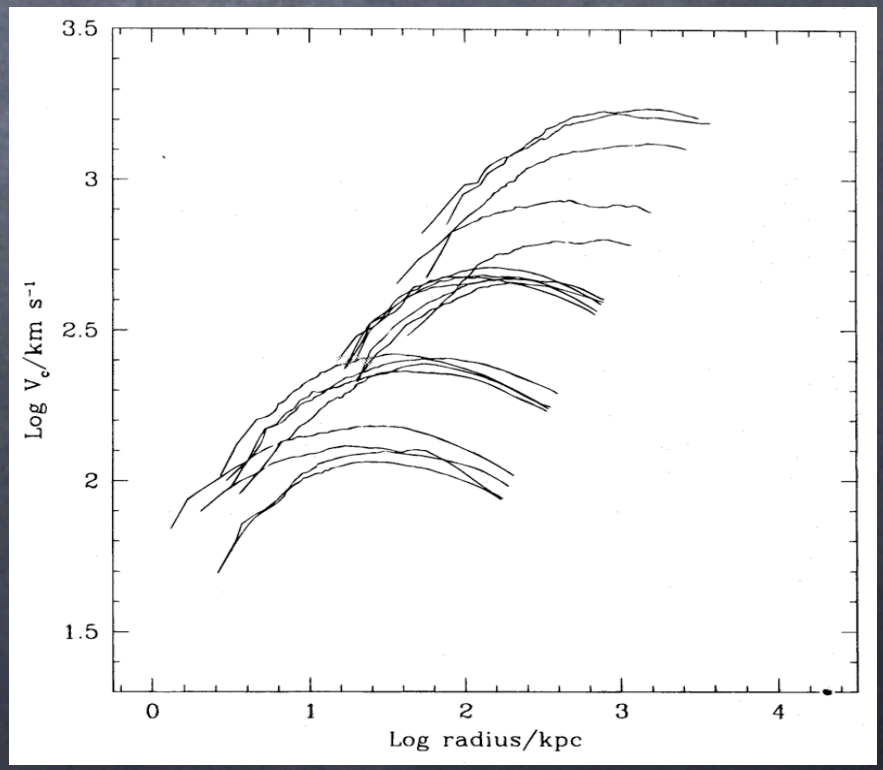
$$= \frac{200}{3}\frac{c^3}{\ln(1+c) - c/(1+c)}$$

c = concentration index

halo density



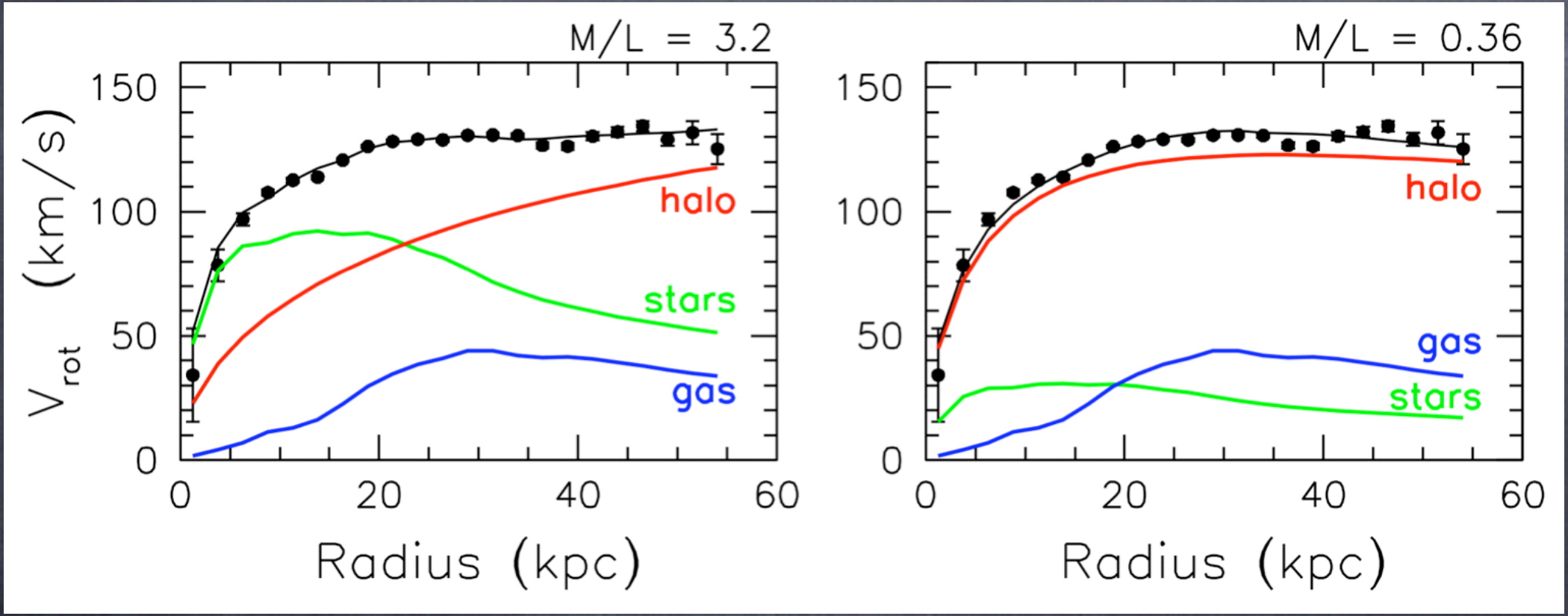
halo rotation curve



a severe disk-halo degeneracy

maximum disk

maximum halo



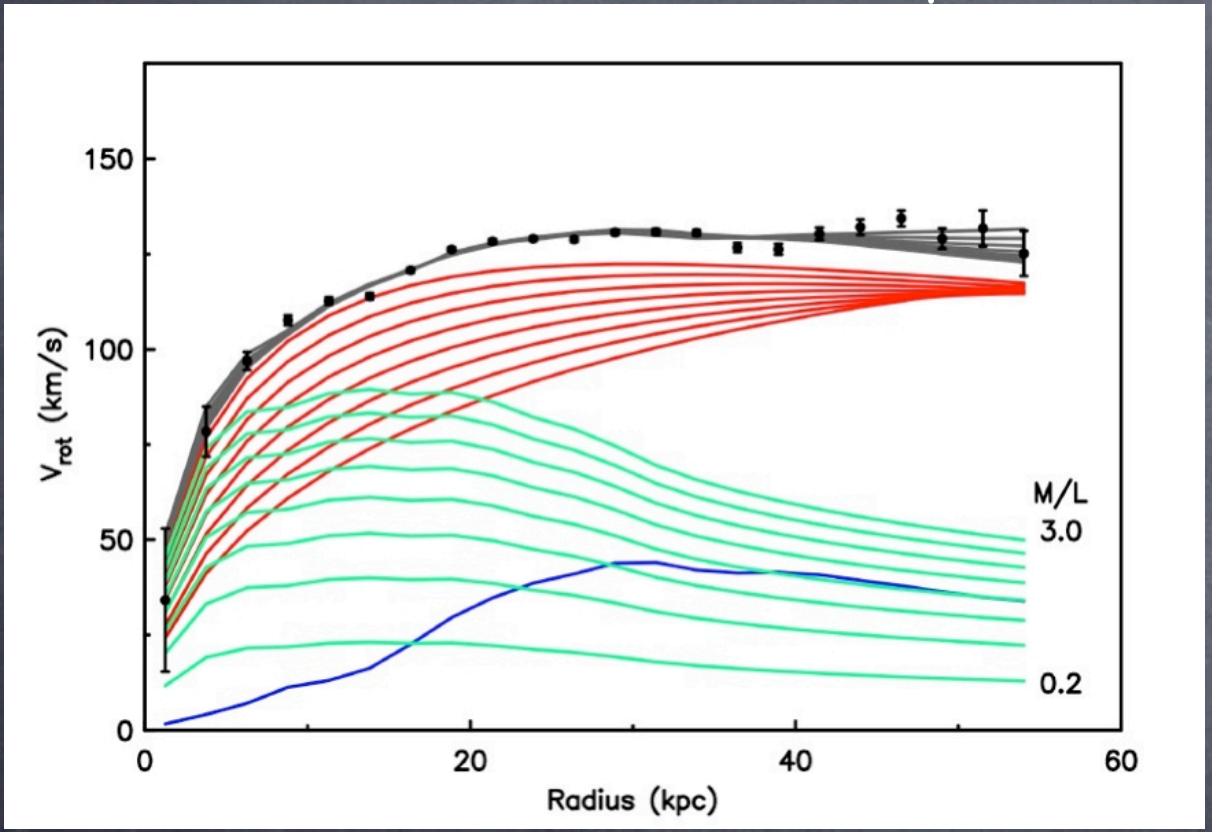
UGC 128 (LSB) - Hernquist halo

Halo properties depend on $V_{disk}^{max} \propto \sqrt{(\mathcal{M}/\mathcal{L})}$

M/L and halo parameters

UGC 128

Hernquist halo



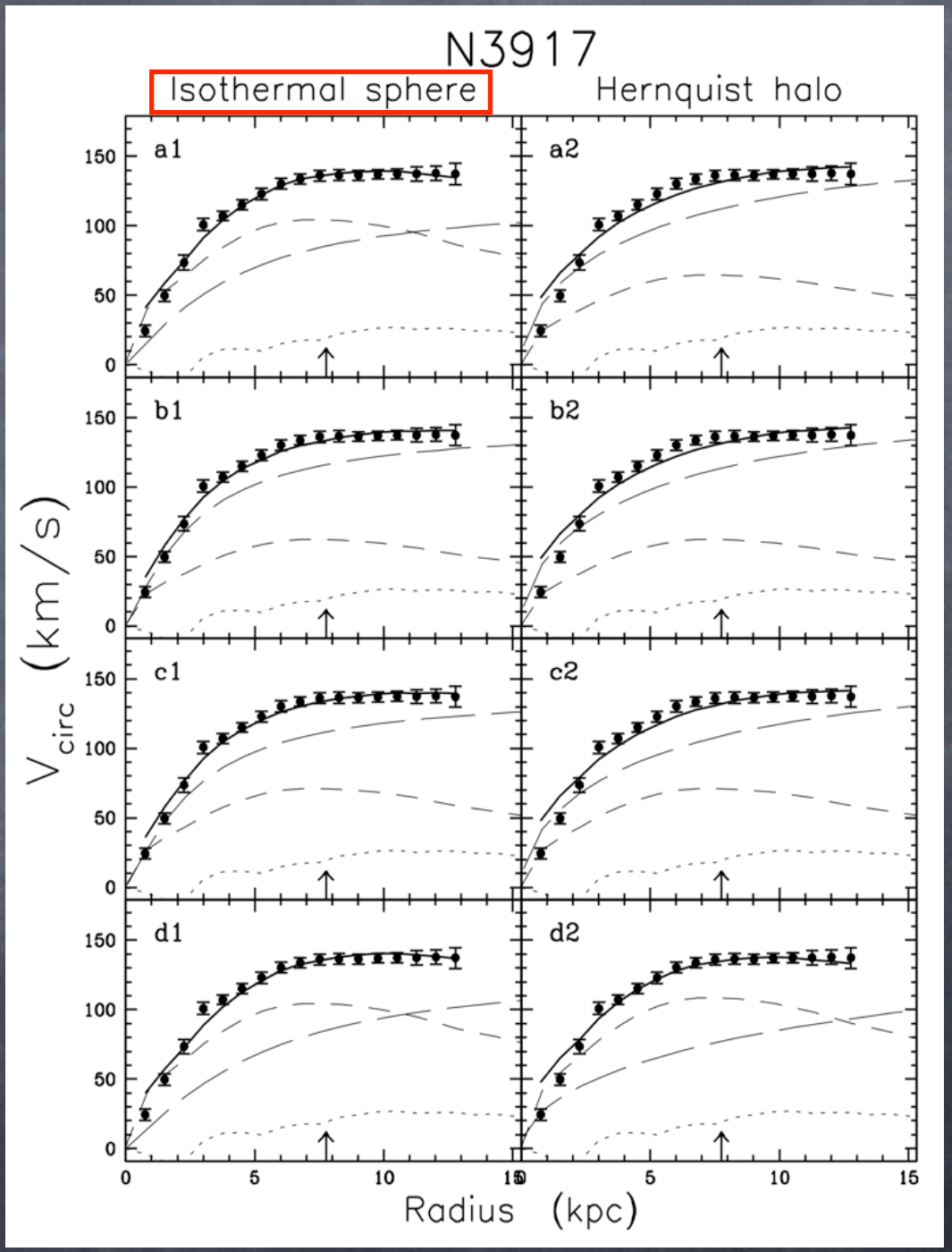
$\mathcal{M}/\mathcal{L}$	R_0	M_0	χ^2_{red}
4.0	1180	8541	8.25
3.8	1023	6910	4.91
3.6	764	4157	3.43
3.4	325	871	2.85
3.2	203	395	2.54
3.0	147	236	2.42
2.8	114	164	2.42
2.6	93	124	2.49
2.4	79	100	2.61
2.2	68	84	2.75
2.0	60	73	2.88
1.8	54	66	3.01
1.6	49	60	3.13
1.4	45	55	3.23
1.2	41	52	3.31
1.0	38	49	3.38
0.8	36	47	3.45
0.6	34	45	3.50
0.4	32	43	3.55
0.2	30	42	3.61
0.0	29	41	3.67

Maximum Disk Hypothesis

van Albada & Sancisi, 1986

M/L	R_c (kpc)	ρ_o ($M_\odot/pc^{-3}$)	V_∞ (km/s)
1.30	3.6	0.022	124
0.46	2.3	0.078	147
0.60	2.4	0.067	143
1.30	4.5	0.017	135

Isothermal sphere



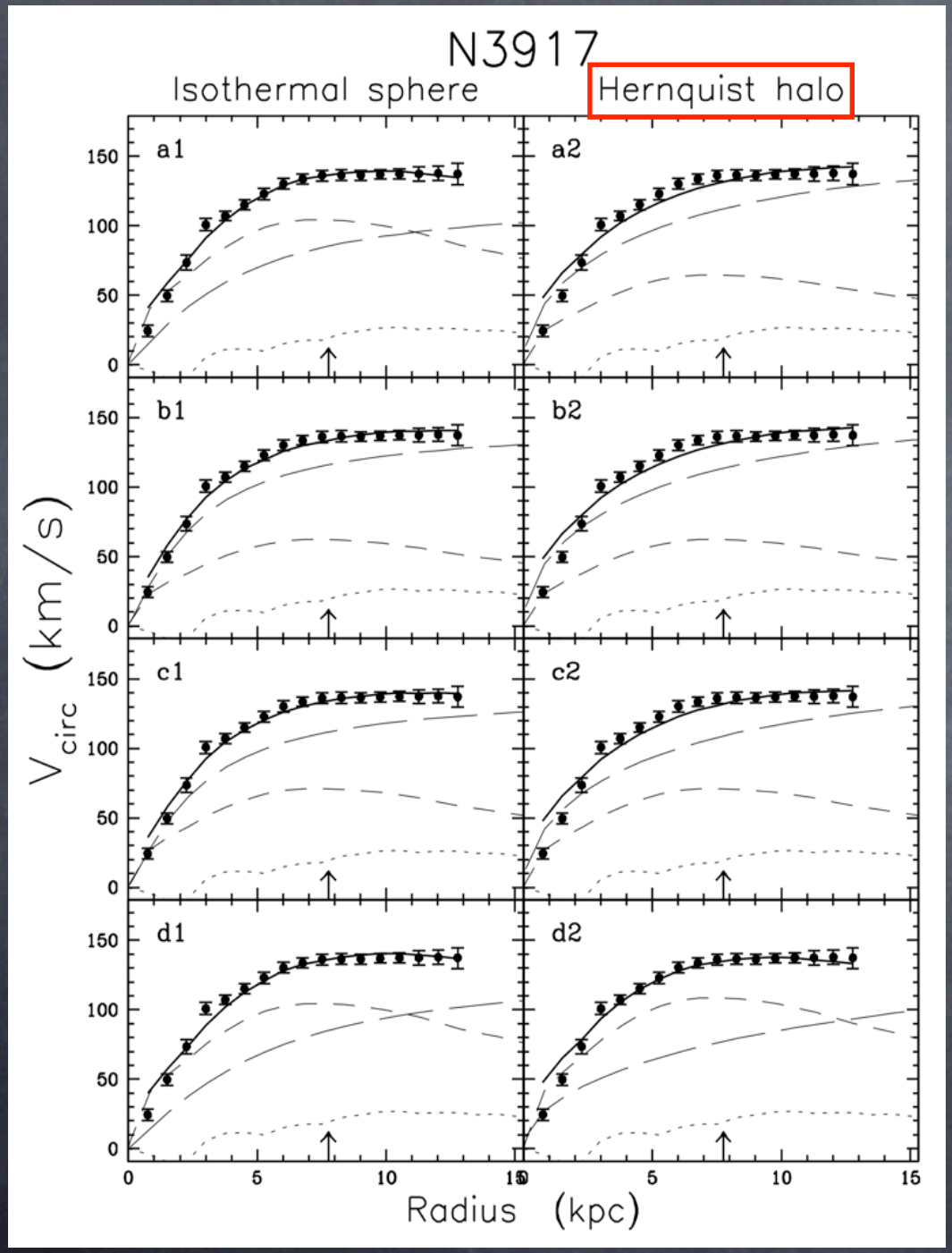
maximum 'Bottema' disk
disk M/L=0.6
constrained halo

Verheijen, 1997

'Bottema' maximum disk

M/L=0.6

constrained halo

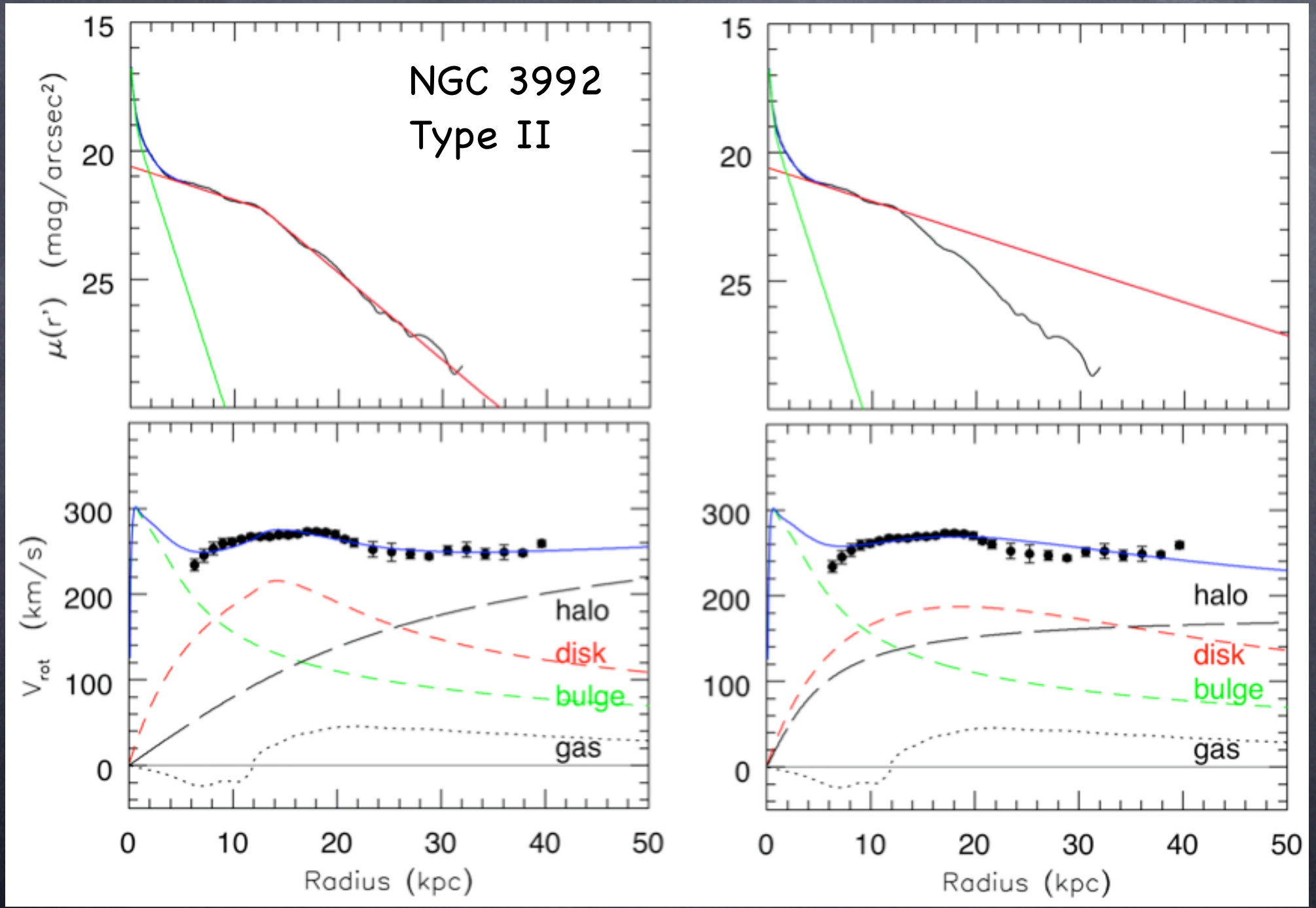


Verheijen, 1997

M/L	M_o ($10^{12} M_\odot$)	R_o (kpc)	V_{max} (km/s)
0.50	0.63	33	143
0.46	0.61	32	144
0.60	0.67	36	143
1.41	1.32	78	135

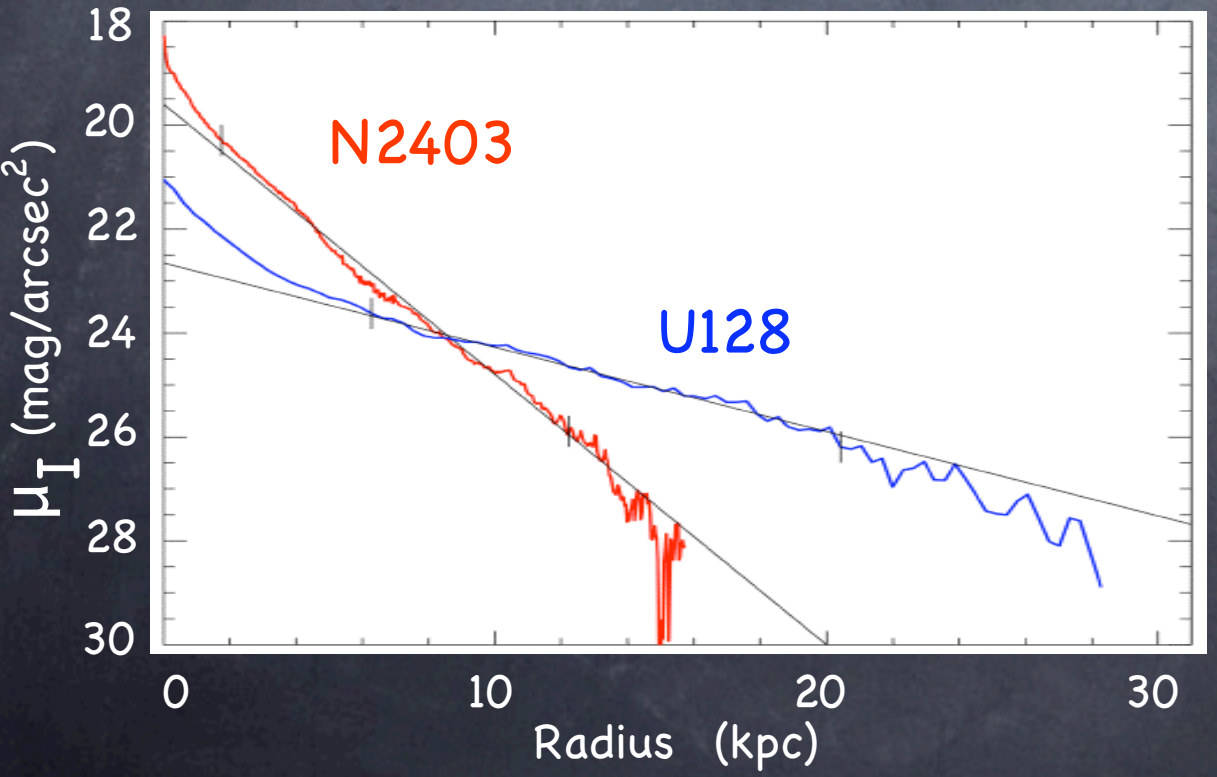
Hernquist profile

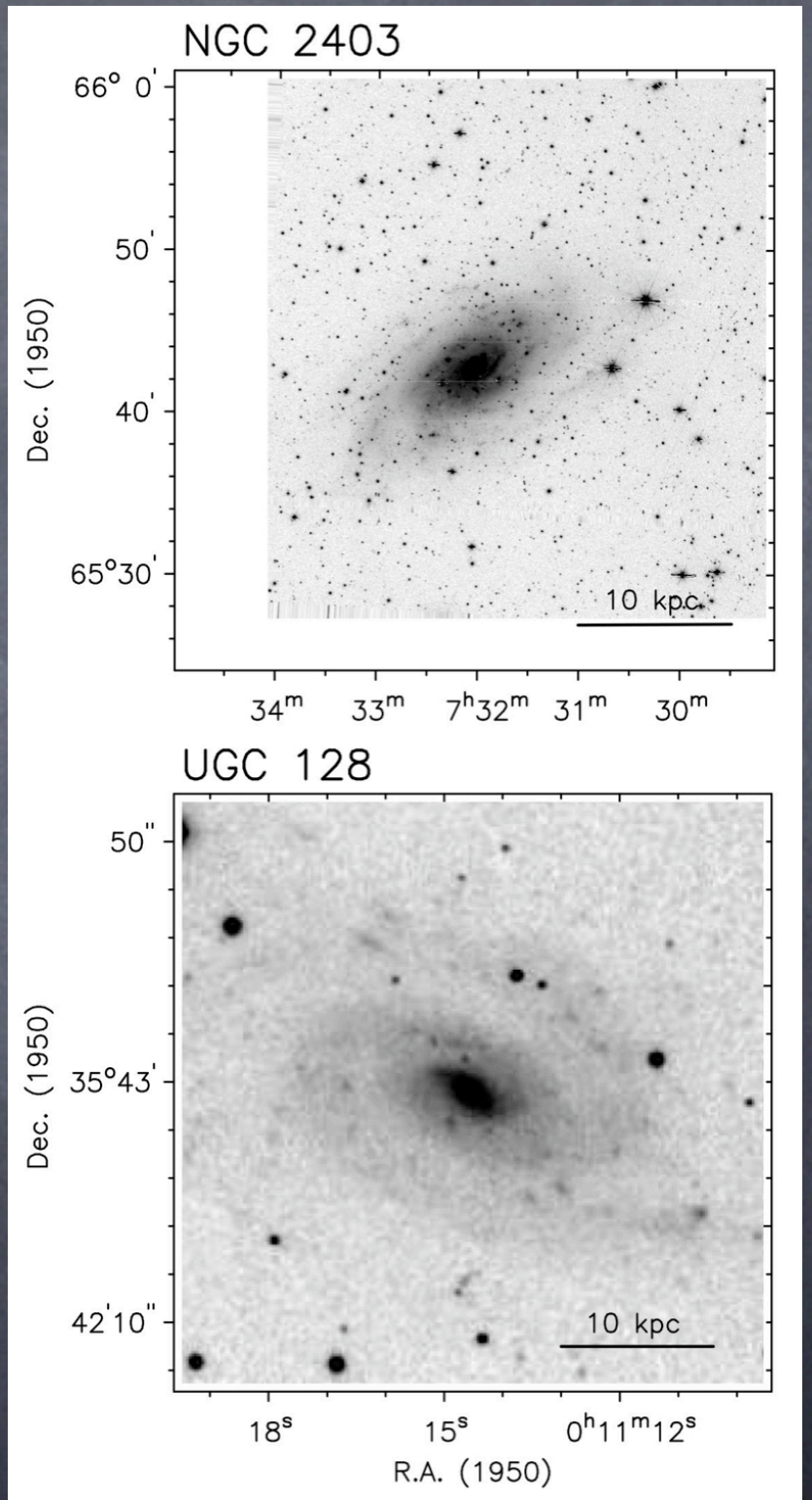
Kinematic effect of stellar disk truncation



HSB-LSB pair

	N2403	U128
Distance (Mpc)	3.6	64.8
$\mu_0^i(I)$ (mag/$''^2$)	19.60	22.65
h_{disk} (kpc)	2.09	6.70
$M_{tot}(I)$ (mag)	-20.69	-20.16
$L_{tot}(I)$ ($L_\odot$)	7.7×10^9	4.7×10^9

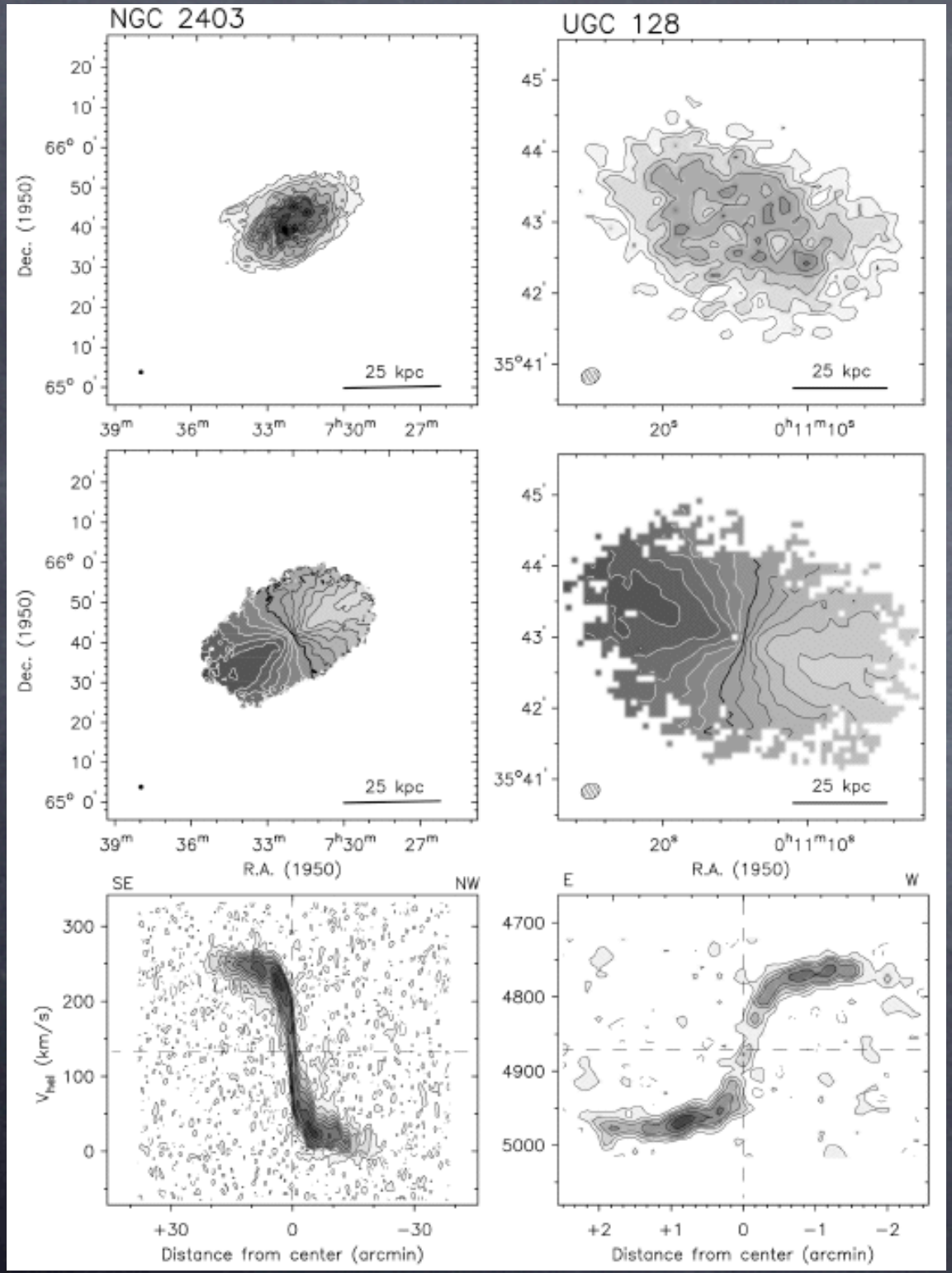




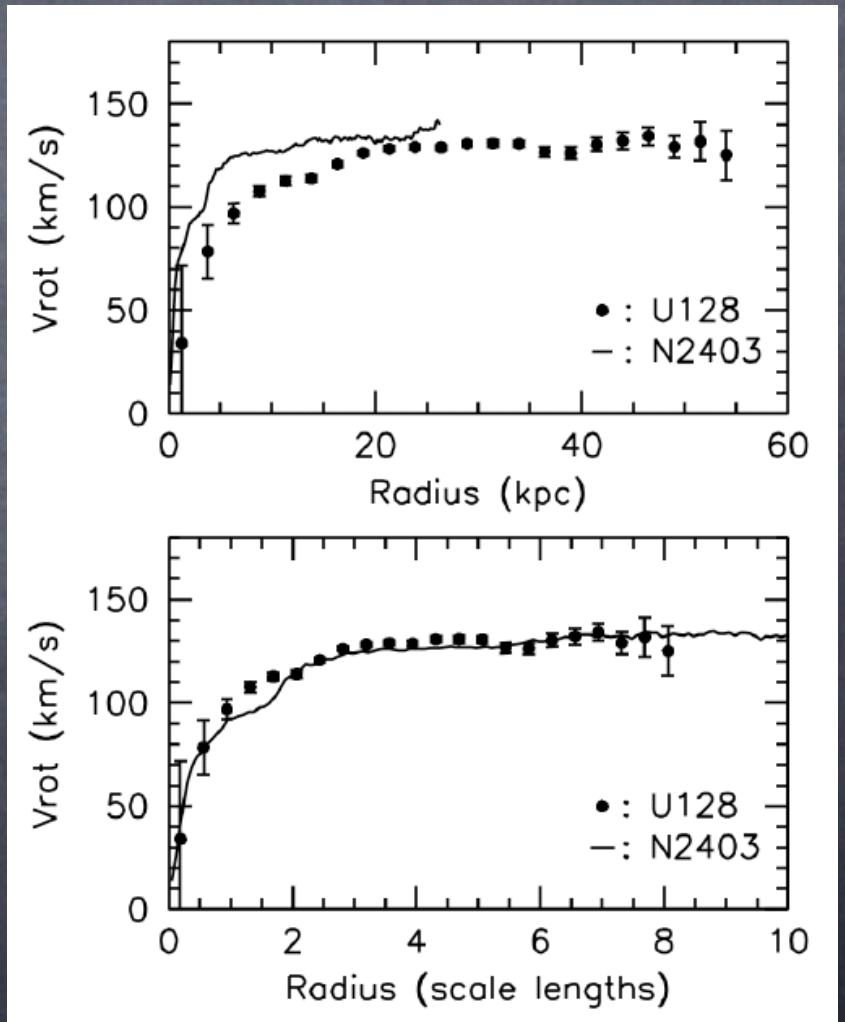
HI map

HI velocity field

XV-diagram

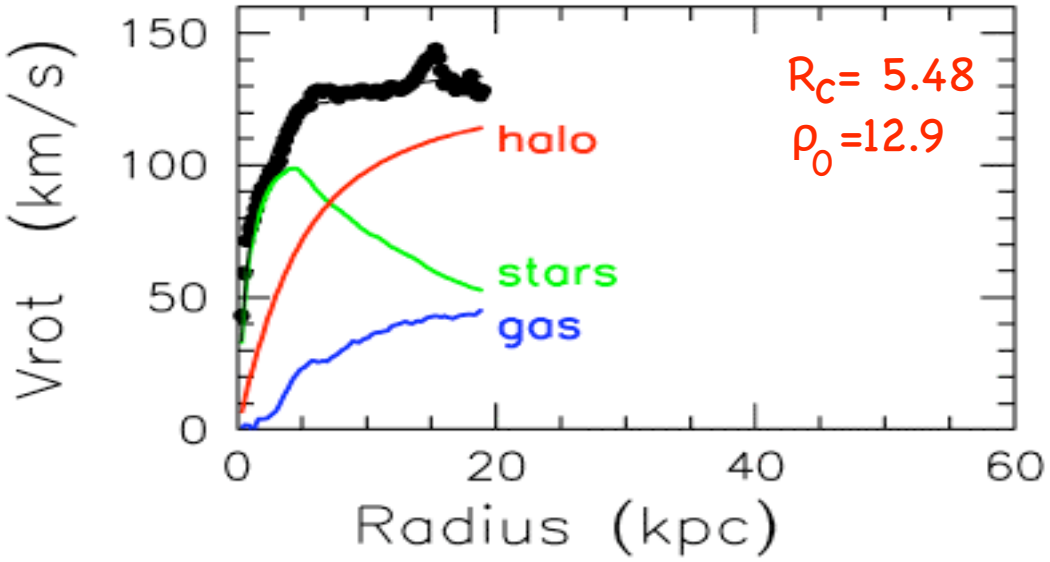


	N2403	U128
M_{HI} ($M_\odot$)	3.8×10^9	7.5×10^9
M_{HI}/L_I	0.50	1.59
M_{bar}($M_\odot$)	1.3×10^{10}	1.5×10^{10}

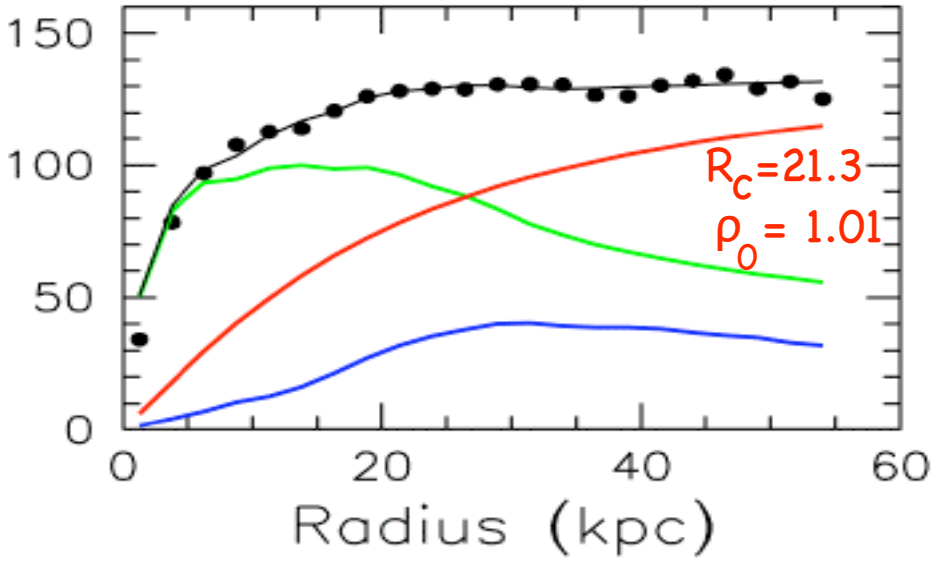


Rotation Curve decompositions

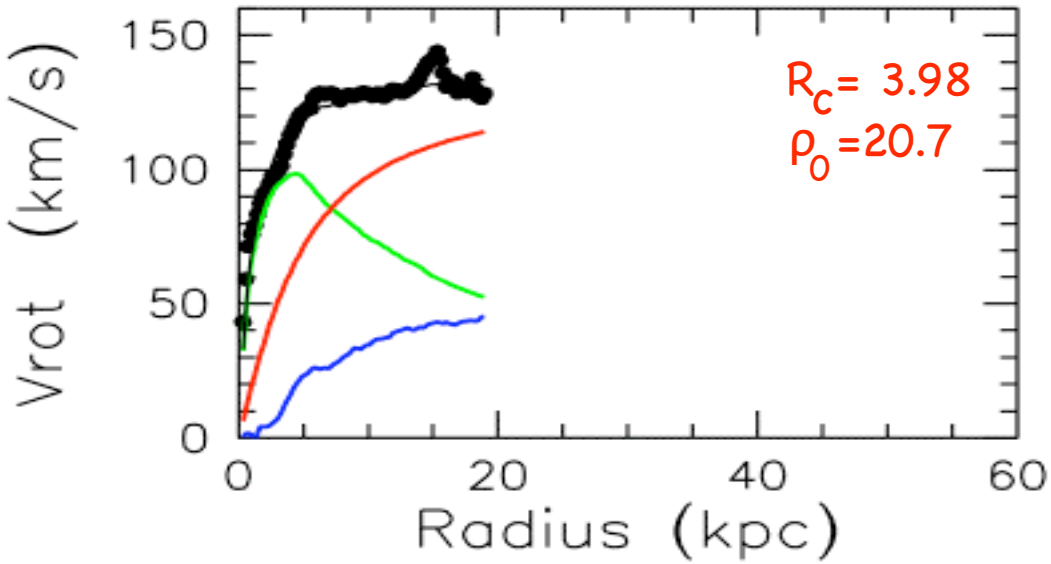
Maximum Disk M_*/L_I = 1.22



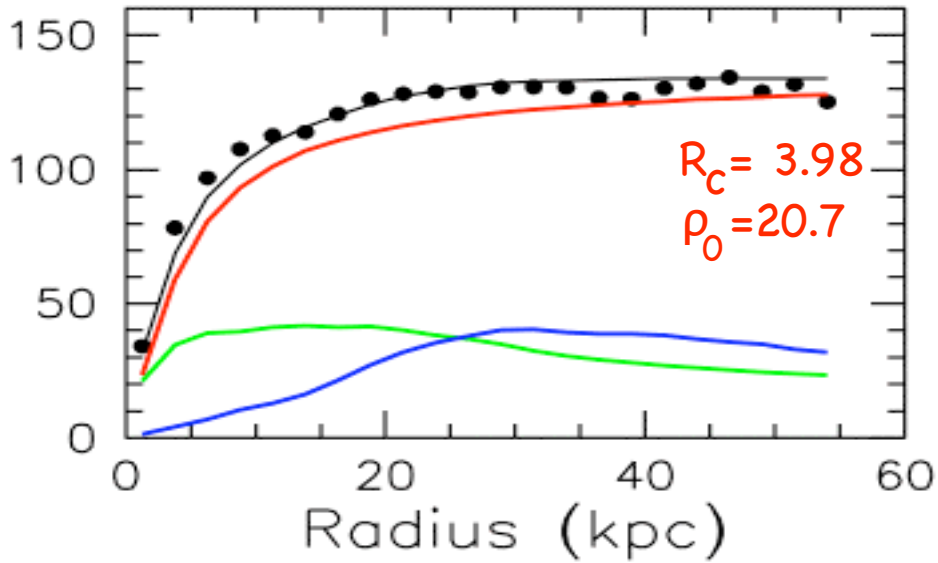
M_*/L_I = 3.98



Same Halo M_*/L_I = 1.11

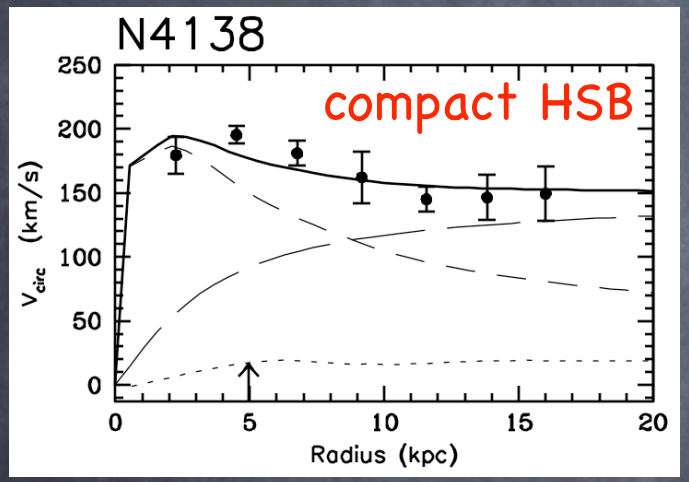


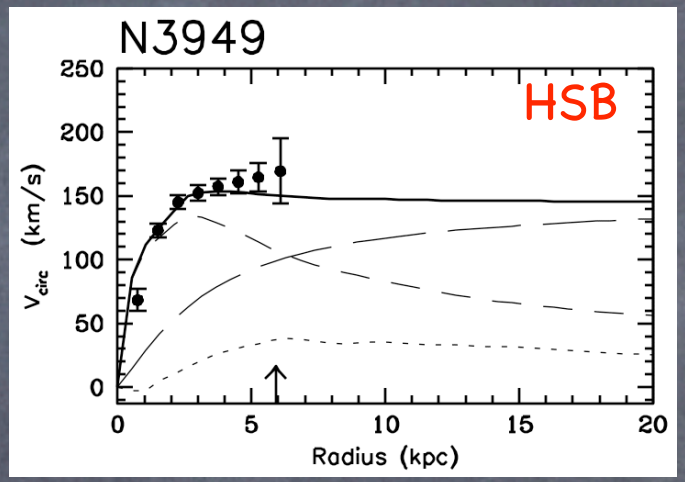
M_*/L_I = 0.73

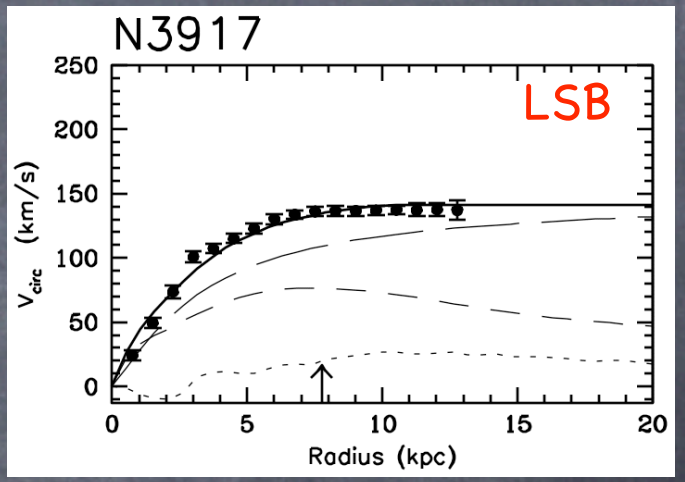


three of a kind

M_K	(mag)	-22.79	-22.56	-21.97
μ_o	(mag/$''^2$)	16.48	17.08	18.66
h_{disk}	(kpc)	1.2	1.4	2.6





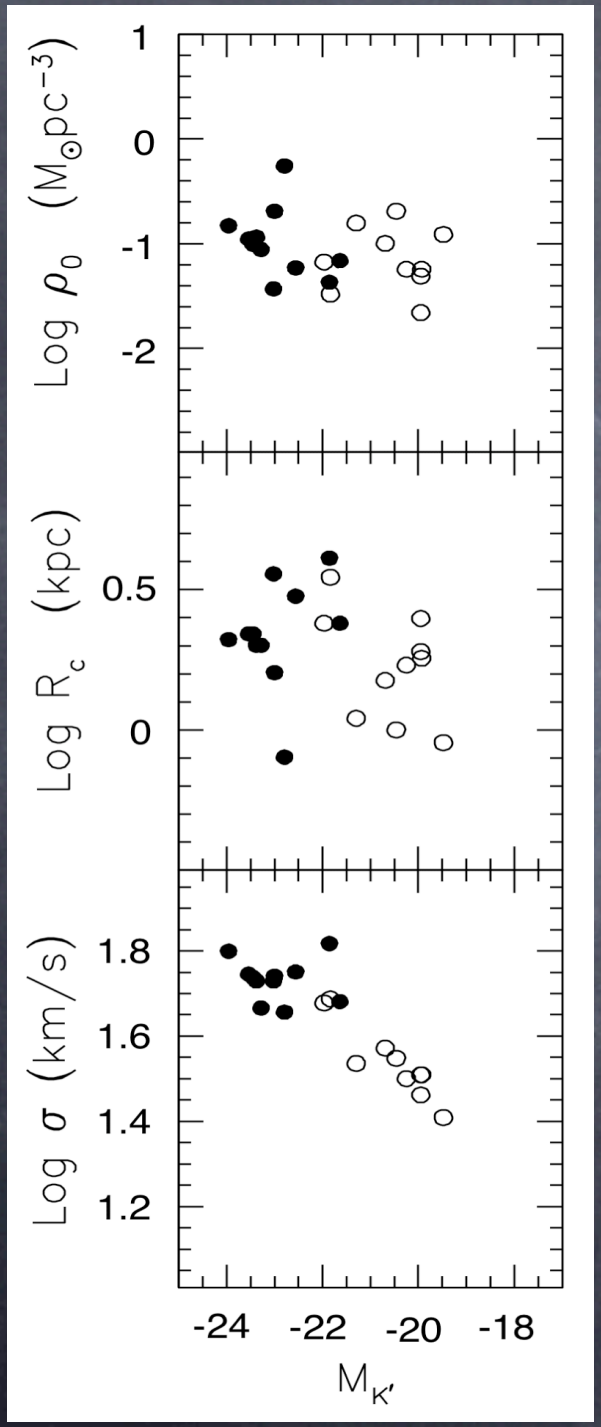


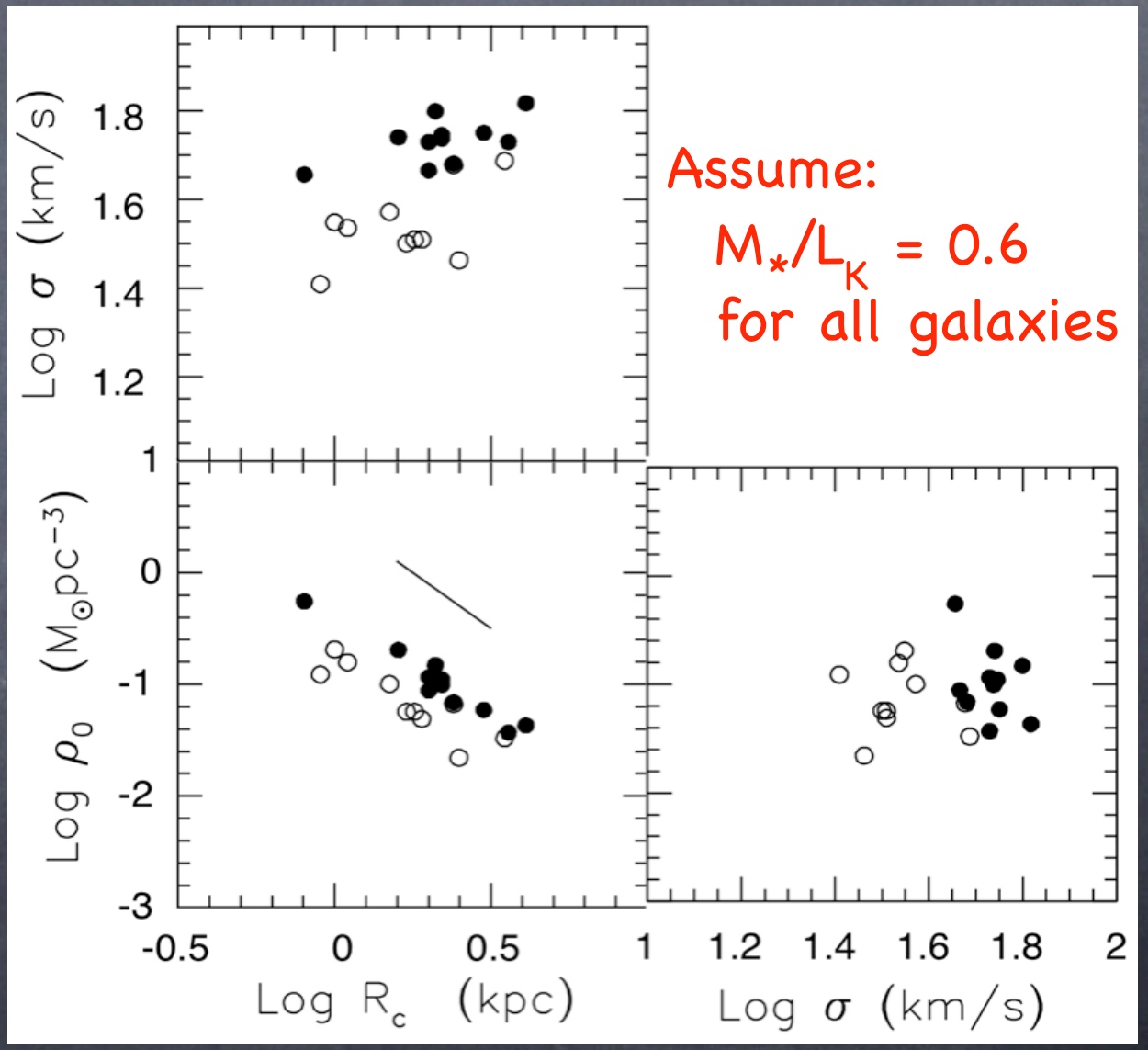
decompositions with identical halos (R_c=3 kpc, V_{halo}=149 km/s)

$(\mathcal{M}_*/\mathcal{L}_K)$	0.8	0.6	0.7

Galaxies of similar luminosity but different μ_o and h_{disk} could have similar halos.

Dark Matter scaling relation (?)



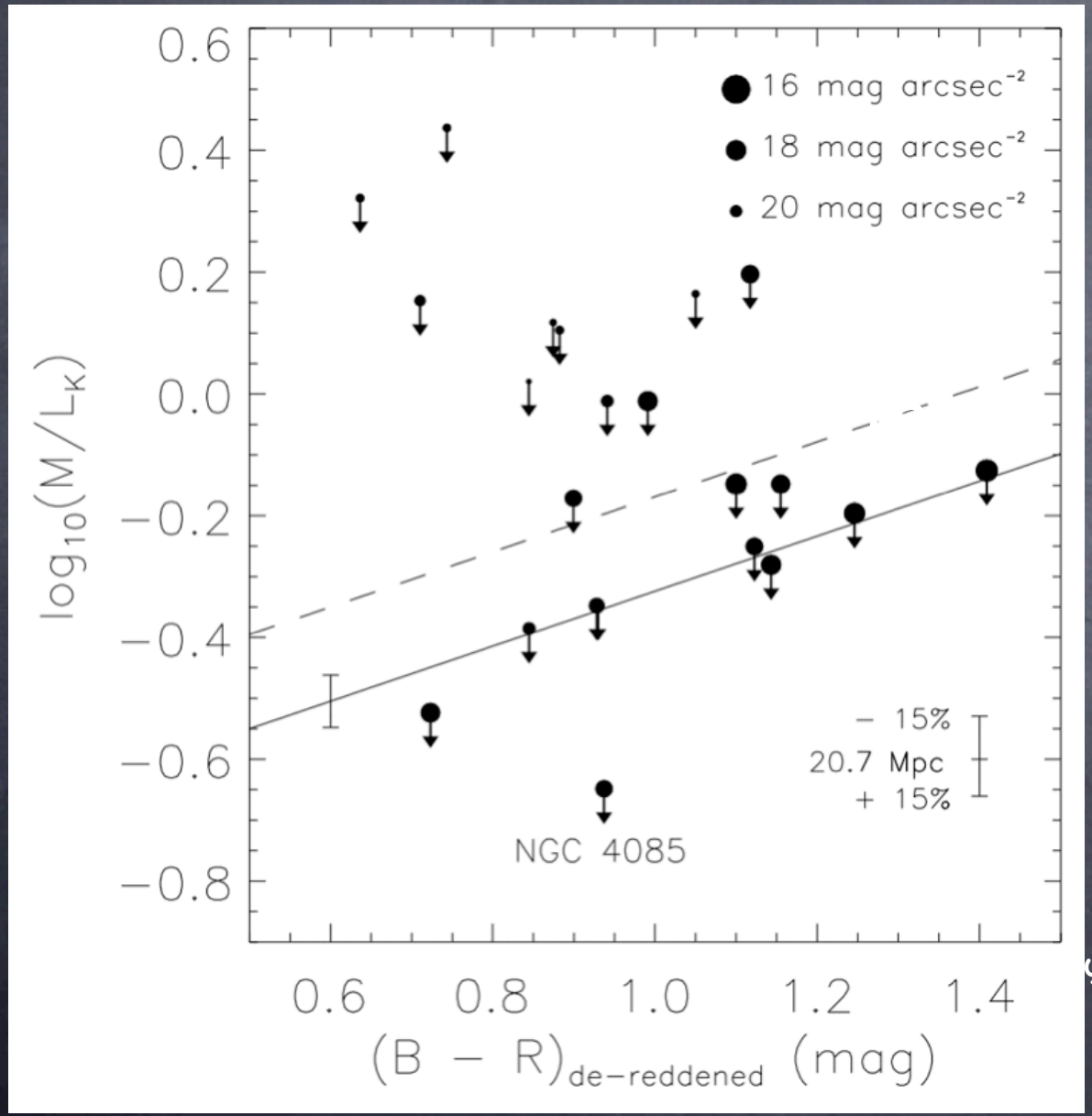


Assume:
$M_*/L_K = 0.6$
for all galaxies

Verheijen, 1997

Calibrating stellar population models

Maximum Disk M_*/L_K



Bell & de Jong, 2001

→ Salpeter IMF

→ `scaled down' Salpeter IMF

photometric M/L are relative, not absolute

Disk-Halo degeneracy must be broken!

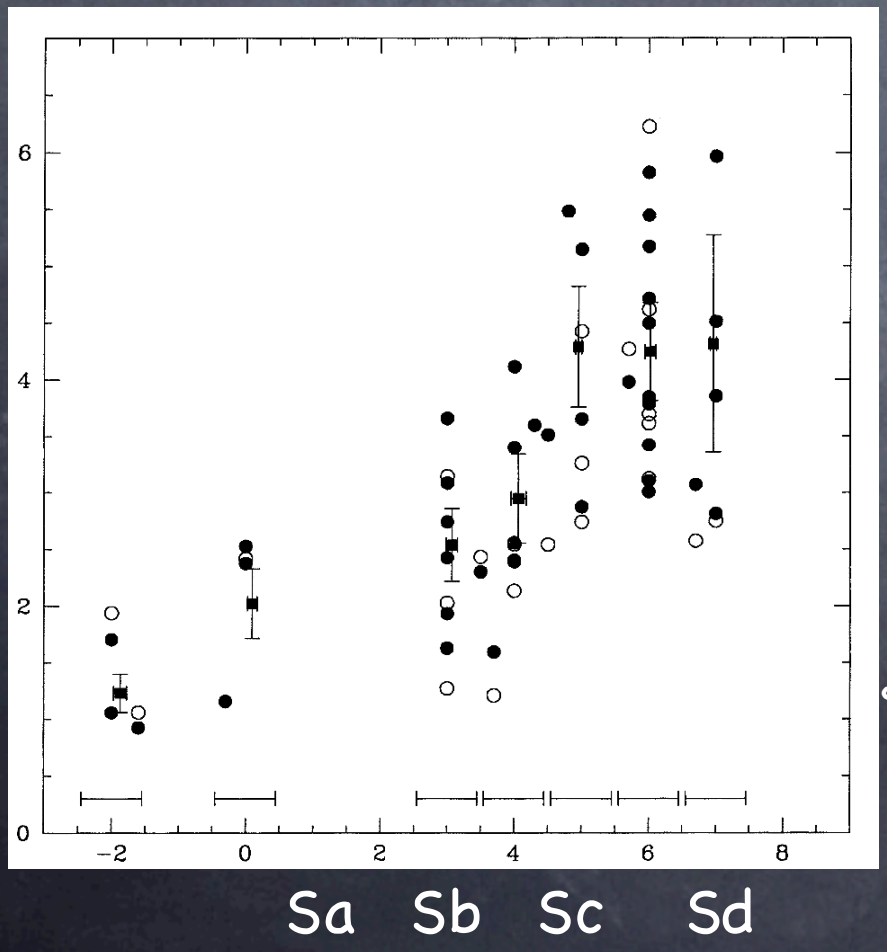
Needed: independent measurement of
stellar ($\mathcal{M}/\mathcal{L}$) or disk surface density Σ.

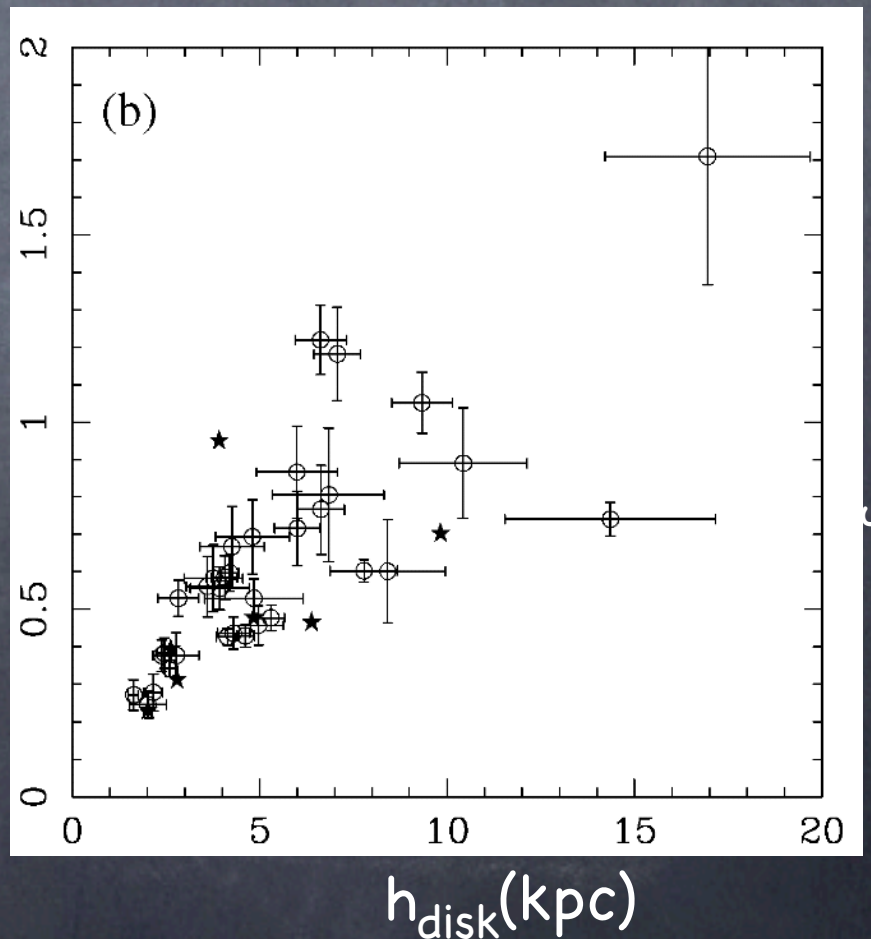
- Obtain $\mathcal{M}/\mathcal{L}$ via stellar population synthesis models
- Measure Σ directly via stellar dynamics
  → the Disk Mass Project

For a sech^2 disk in equilibrium with scale height z_0:

$$\sigma_z = \sqrt{\pi\, G\, \Sigma\, z_0} = \sqrt{\pi\, G\, (M/L)\, \mu\, z_0} \qquad (z_0 = 2h_z)$$

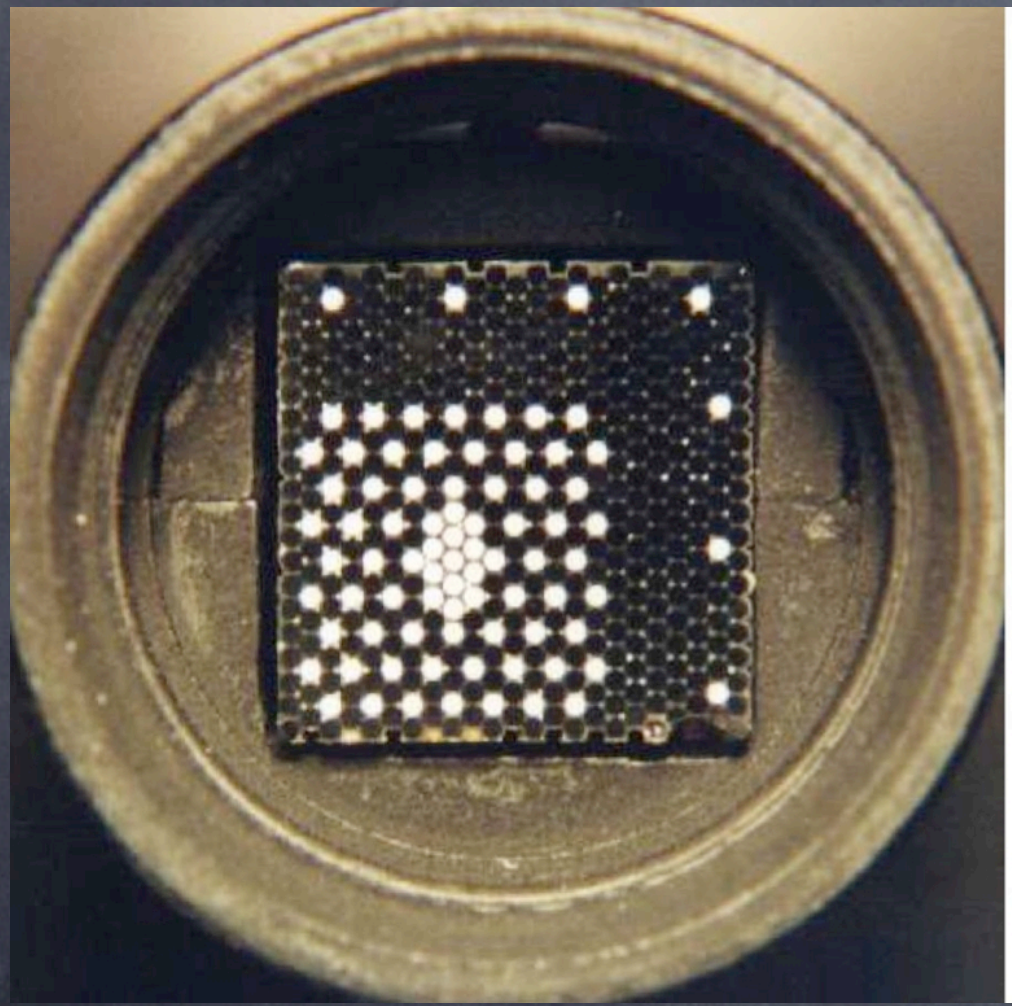
$$\Sigma = \frac{\sigma_z^2}{\pi\, G\, z_0} \qquad \text{or} \qquad (M/L) = \frac{\sigma_z^2}{\pi\, G\, \mu\, z_0}$$





SparsePak

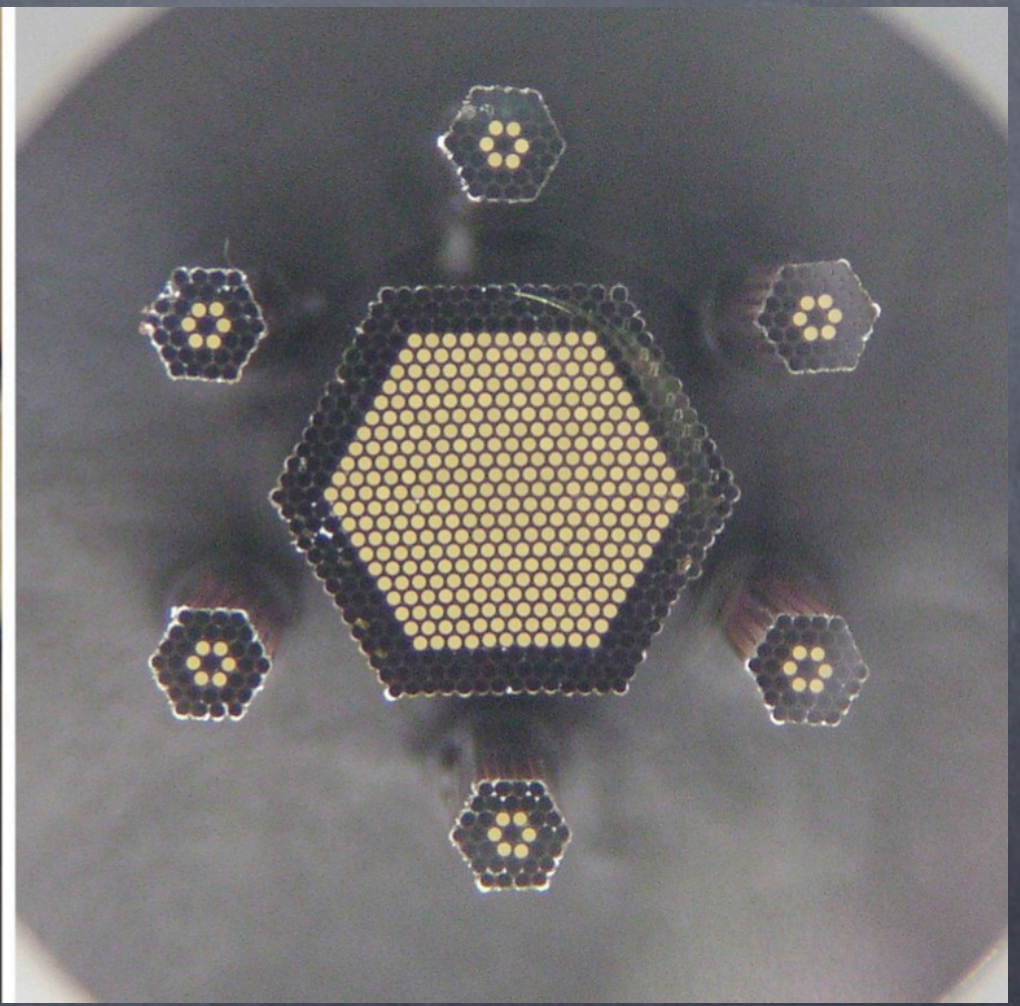
UW - Madison



3.5m WIYN, Kitt Peak
71"x72" field of view
82 fibers (4.7" ∅)
75 science, 7 sky
R≈10.000 (Hα, MgIb, CaII)

P-Pak

AIP - Potsdam



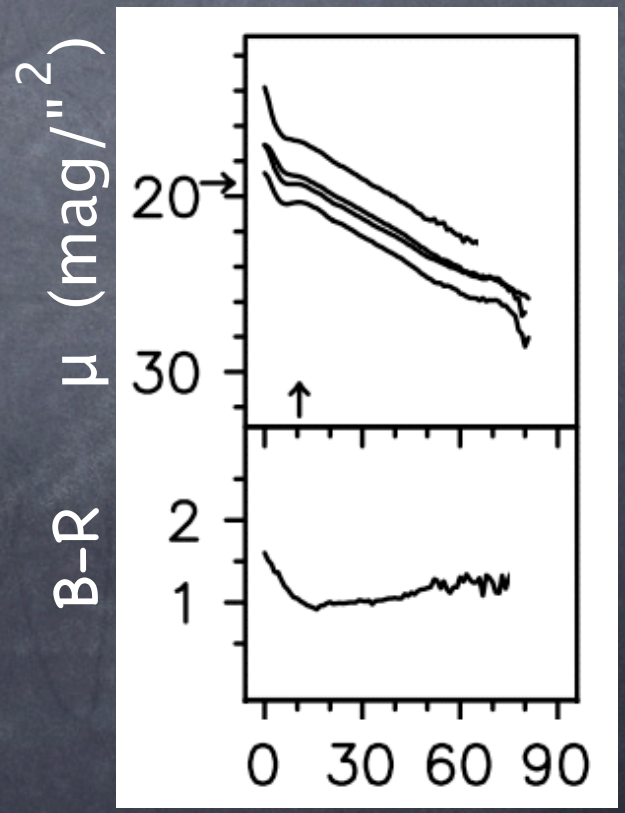
3.5m CAHA, Calar Alto
64"x74" field of view
382 fibers (2.7" ∅)
331 science, 36 sky, 15 calib.
R≈8.000 (MgIb, Hα/Hβ/Hγ)

Measuring σ_z – an example

NGC 3982

HST/WFPC-2

D	=	18.6	Mpc
$M_{K'}$	=	-22.8	mag
V_{max}	=	195	km/s
h_{disk}	=	0.96	kpc
$\mu_0(B)$	=	19.27	mag/"^{2}
incl	=	26±2	deg



Measuring σ_z – an example

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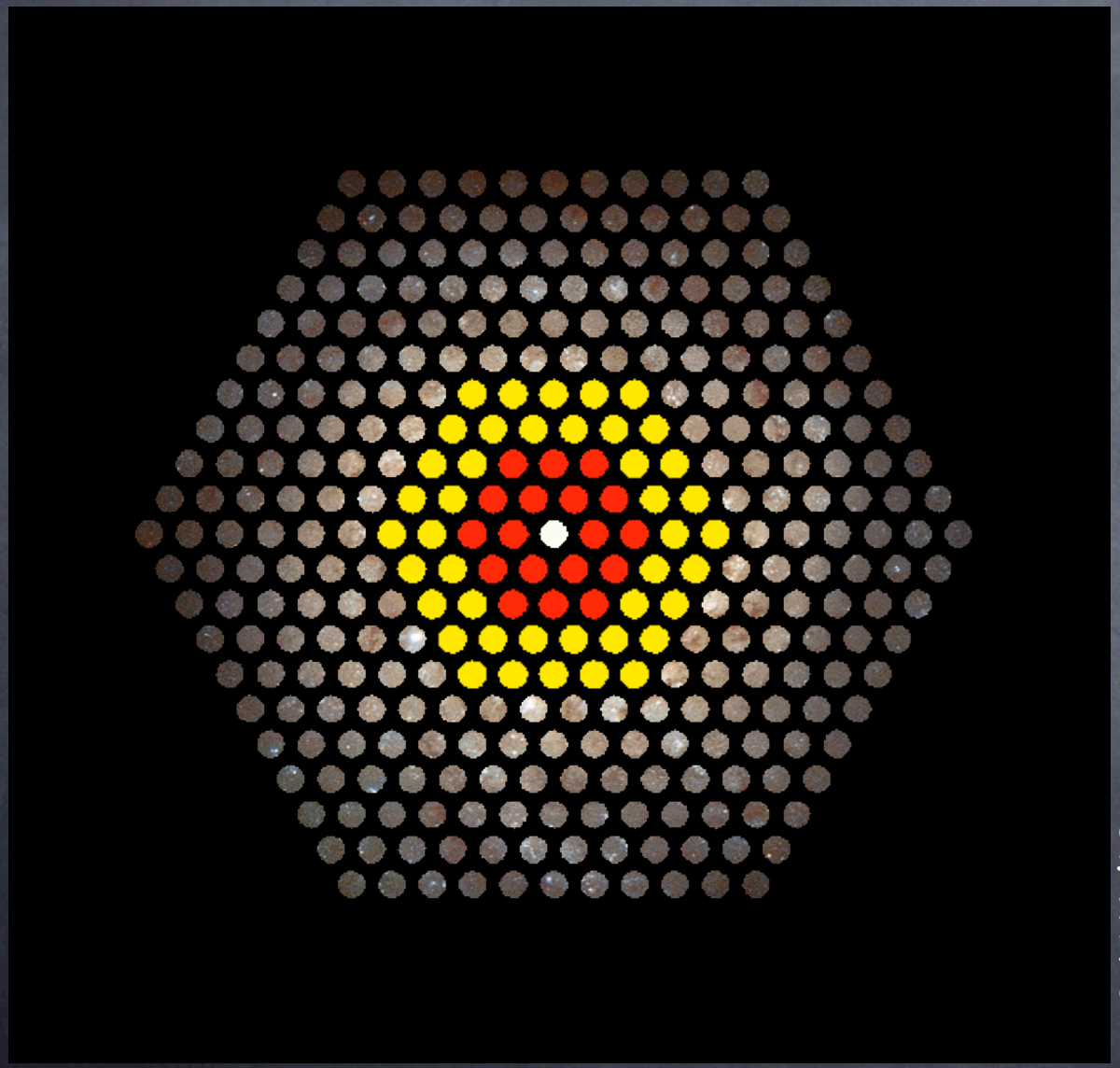

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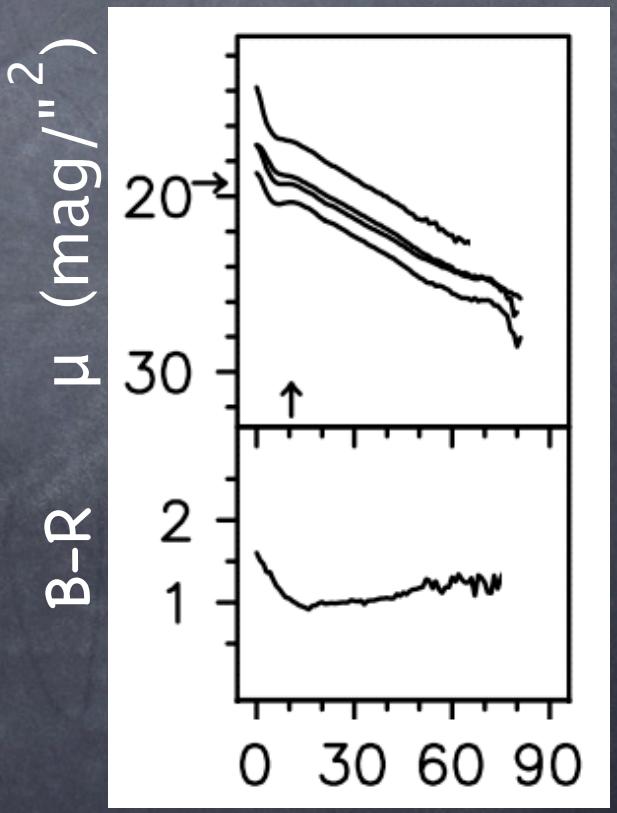
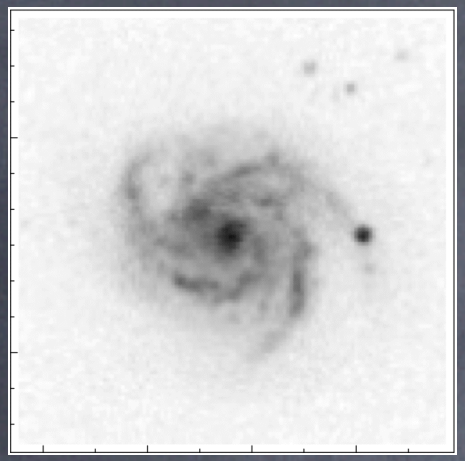
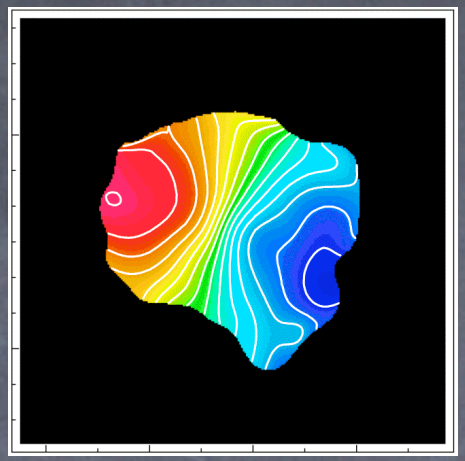
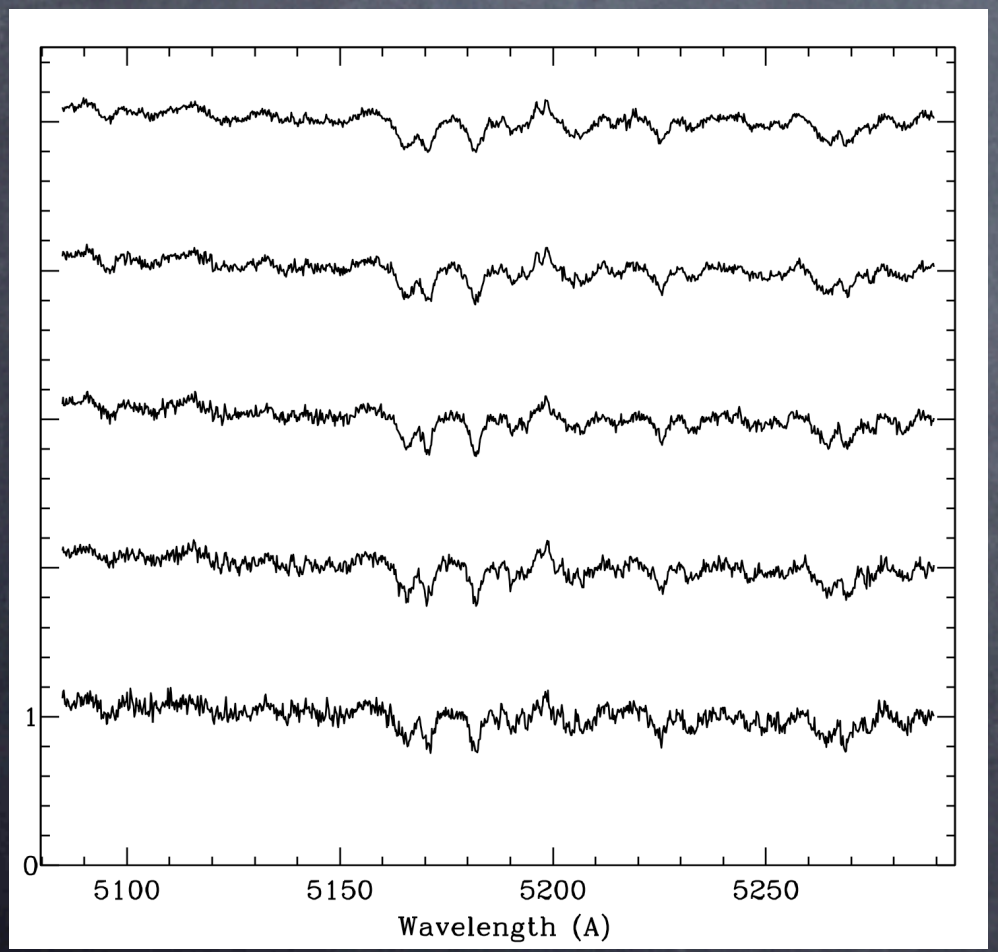


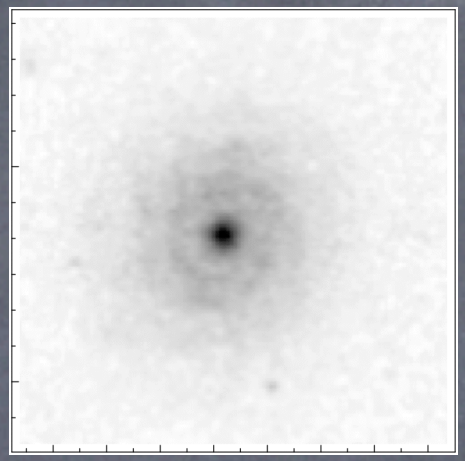
UGC 463

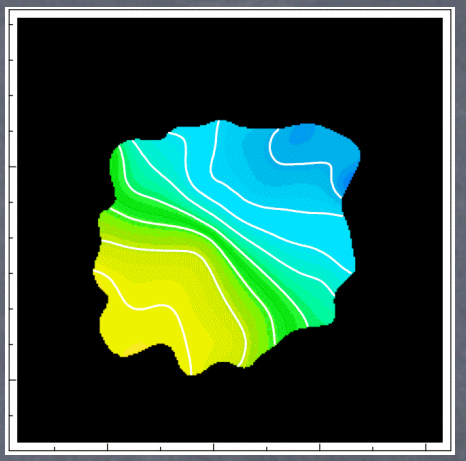


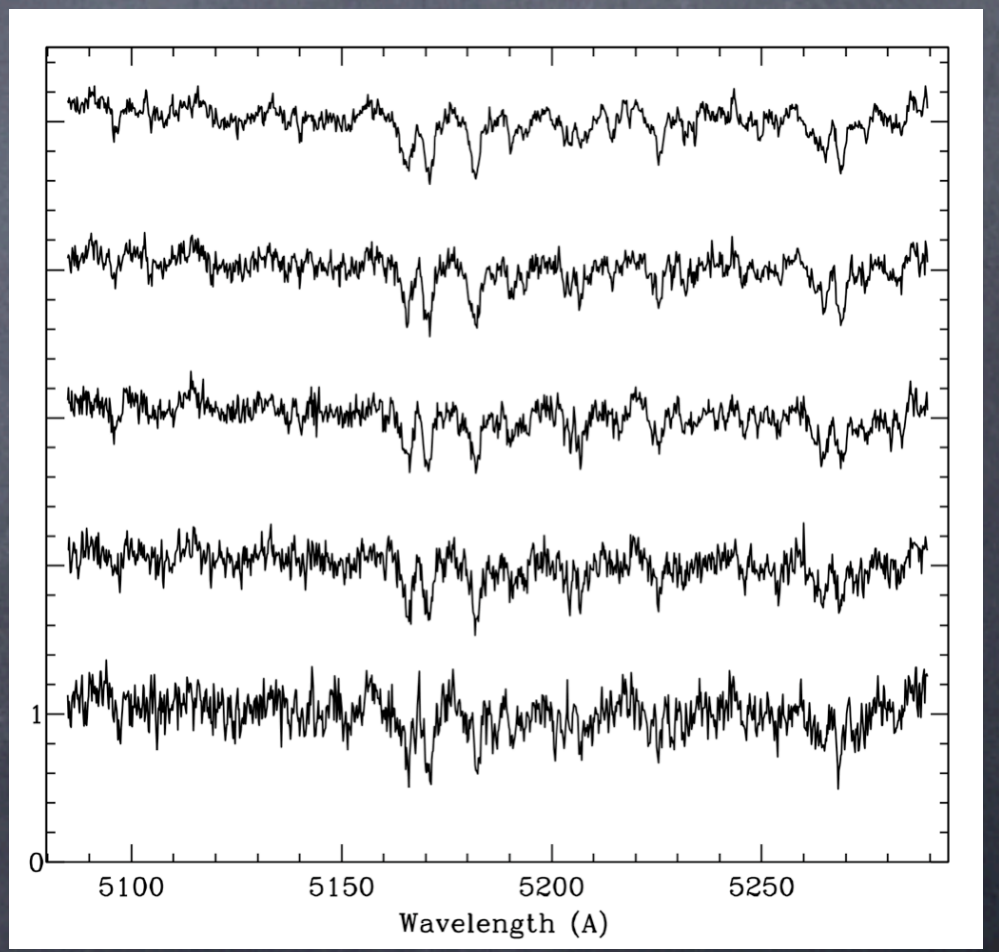




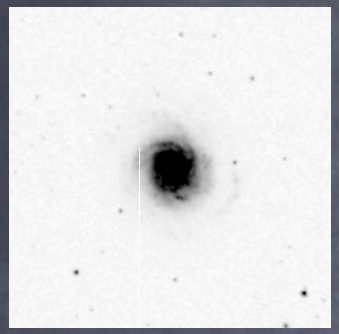
UGC 1635



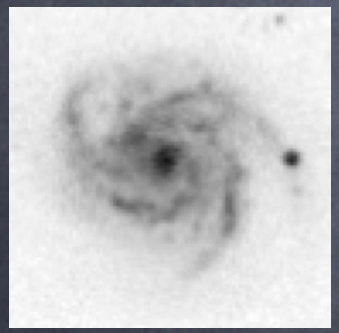




N3982



U463



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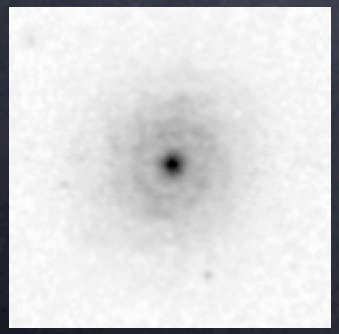
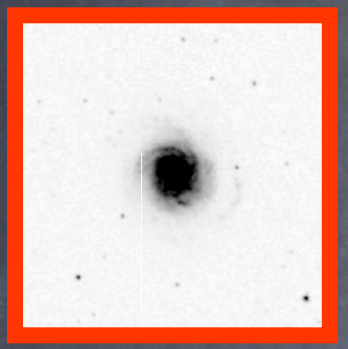


r/h_{disk}	$\mu(B)$	σ_z km/s	Σ $M_\odot/pc^2$	M/L_B	M/L_K
1.0	20.4	59	1074	2.6	0.73
1.7	21.1	44	598	2.7	0.78
2.0	21.4	41	519	3.1	0.97
2.6	22.1	26	209	2.4	0.74
3.5	23.1	12	44	1.3	0.43
0.5	21.4	81	520	3.2	0.43
1.1	21.9	67	356	3.4	0.64
1.7	22.2	58	267	3.4	0.73
2.3	22.7	52	214	4.1	1.02
2.9	23.3	38	114	4.0	1.01
0.4	22.5	49	219	3.7	0.66
0.9	23.1	41	153	4.4	0.80
1.5	23.7	35	112	5.6	1.01
2.0	24.3	26	62	5.4	0.97
2.6	24.9	15	21	3.2	0.57

r/h_{disk} $\mu(B)$ σ_z km/s Σ $M_\odot/pc^2$ M/L_B M/L_K

N3982



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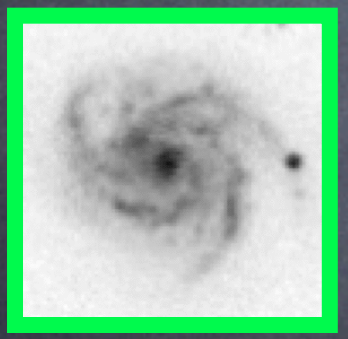

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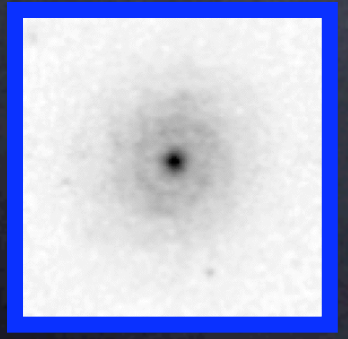

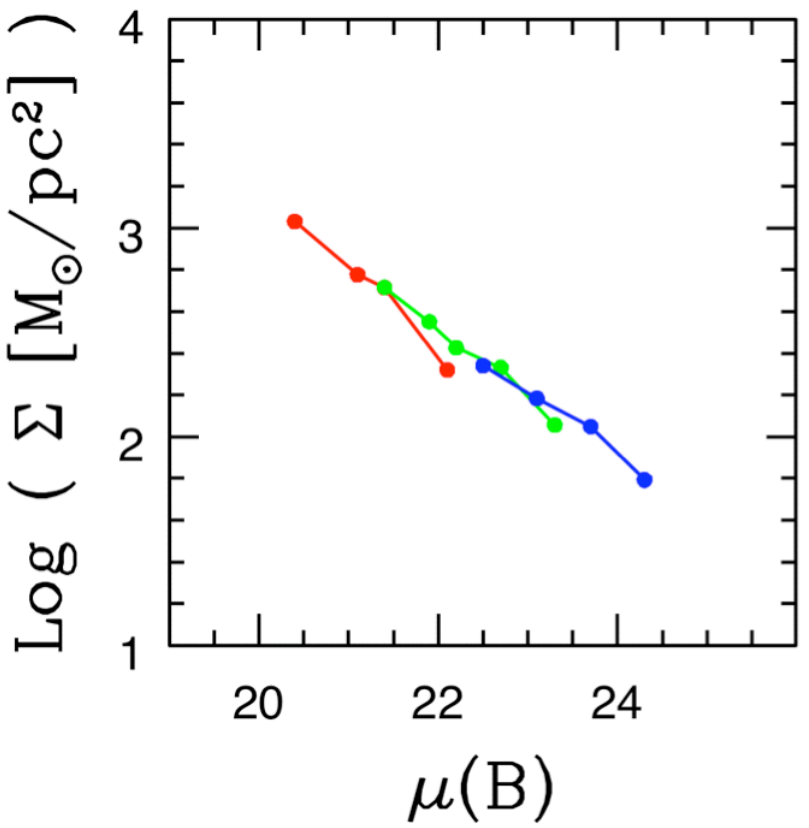

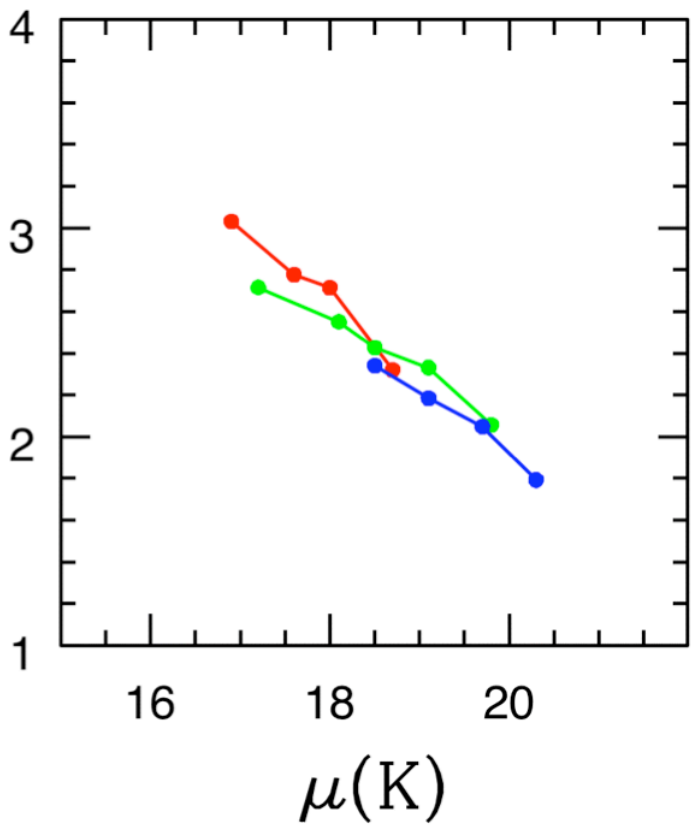

Summary - rotation curves

- low-mass galaxies show rising rotation curves
- massive and compact galaxies show declining rotation curves
- some rotation curves reflect the distribution of luminous matter
- galaxies with similar baryonic mass live in similar halos
- HSB galaxies are close to Maximum Disk