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A580: Topics in Extragalactic Astronomy - Galaxy Disks

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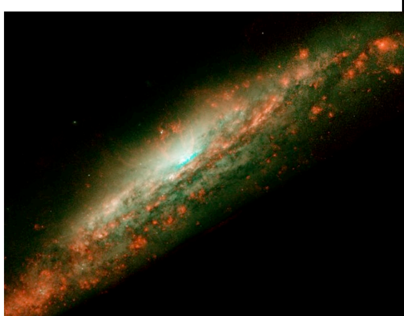
October 9, 16 2008

Beauty in Rotation!



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Why study disks?

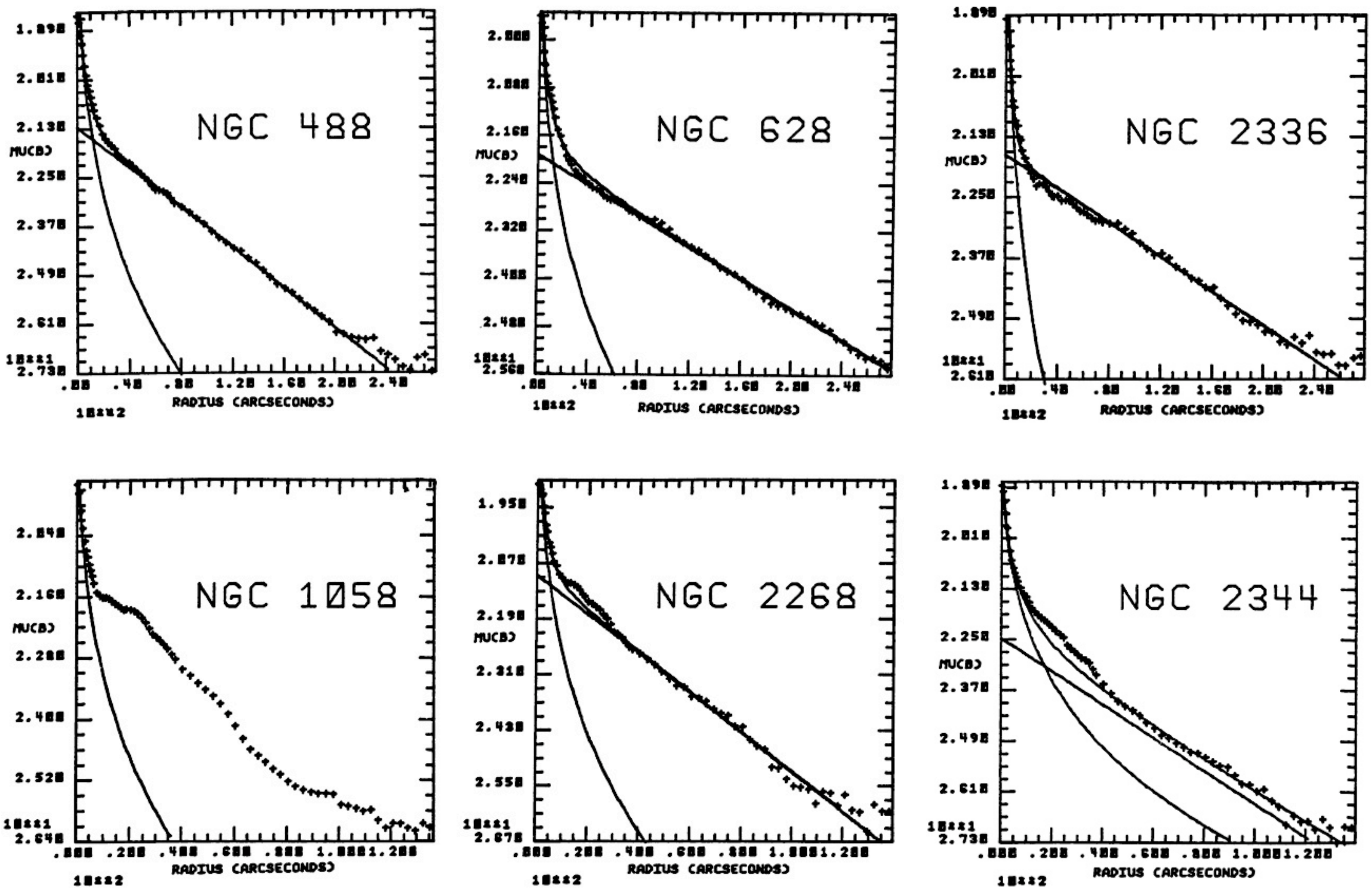
- Disks are thought to be inherently fragile. If so, how did a violent universe of hierarchical mergers produce a local galaxy population greatly dominated by disks?
- Why do galaxies rotate? How do they acquire angular momentum? Why do disks and dark matter haloes do not seem to exchange angular momentum?
- What did the first disks look like? Are they large? Are they cold? Is mass assembly efficient enough in the early Universe?
- They are beautiful!!

Outline

- Photometric properties
- Kinematics/dynamics
- Scaling Relations
- Formation Models
- Disks at high redshifts

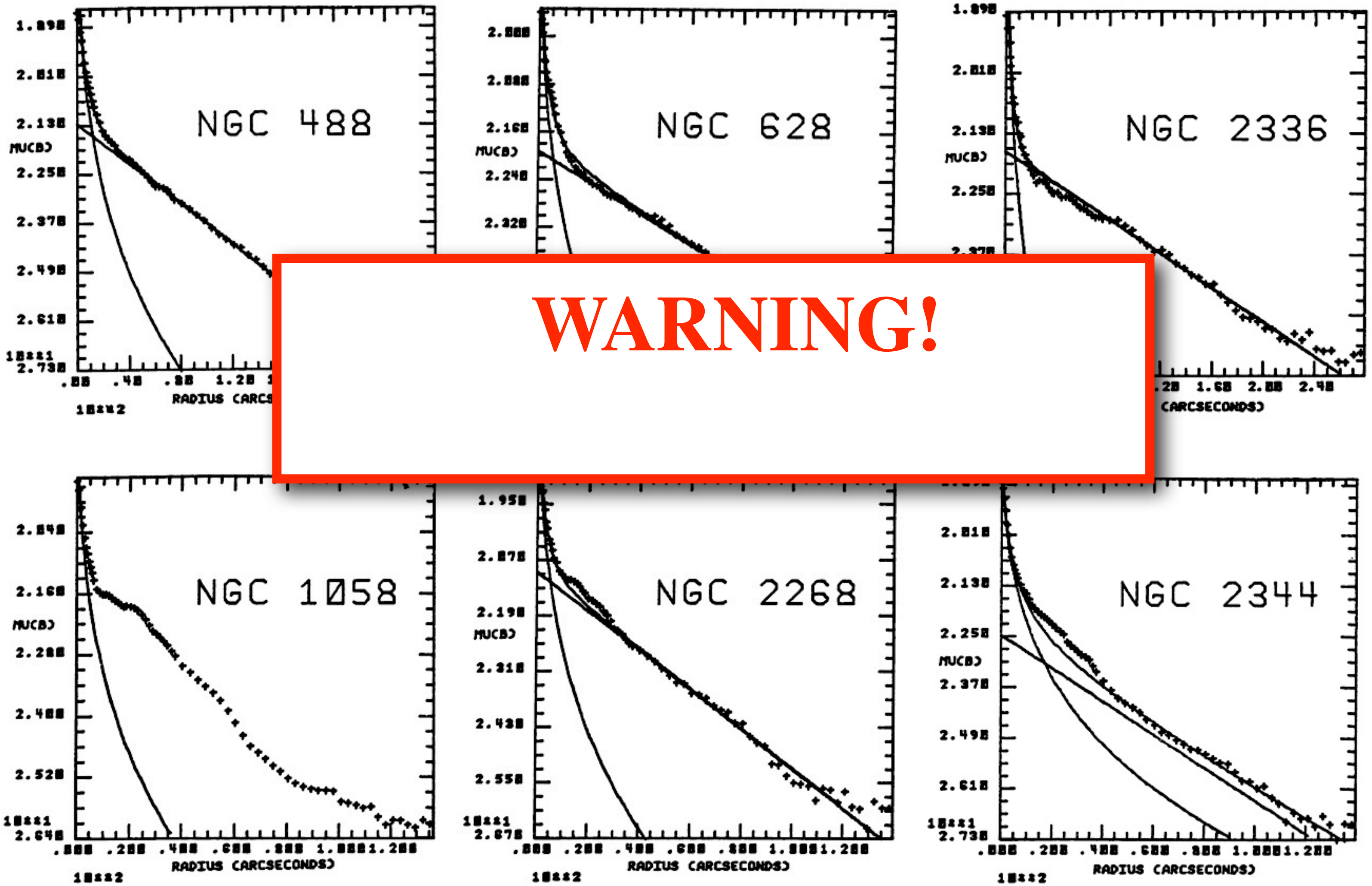
Photometric Properties

Radial Profiles



(Boroson 1981, ApJS, 46,177)

Radial Profiles



WARNING!

(Boroson 1981, ApJS, 46,177)

Exponential Law

Disk radial profile follows:

$$\Sigma(r) = \Sigma_0 \exp(-r/r_d)$$

The total disk luminosity is obtained by integrating

$$L_{tot} = 2\pi \int_0^{2\pi} \int_0^{\infty} \Sigma_0 \exp(-r/r_d) r dr d\theta$$

which gives

$$L_{tot} = 2\pi r_d^2 \Sigma_0$$

Exponential Law

Disk radial profile follows:

$$\Sigma(r) = \Sigma_0 \exp(-r/r_d)$$

Disk central surface brightness

The total disk luminosity is obtained by integrating

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Exponential Law

Disk radial profile follows:

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Disk scale length (often simply called "size")

The total disk luminosity is obtained by integrating

$$L_{tot} = 2\pi \int_0^{2\pi} \int_0^{\infty} \Sigma_0 \exp(-r/r_d) r dr d\theta$$

which gives

$$L_{tot} = 2\pi r_d^2 \Sigma_0$$

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The total disk luminosity is obtained by integrating

$$L_{tot} = 2\pi \int_0^{2\pi} \int_0^{\infty} \Sigma_0 \exp(-r/r_d) r dr d\theta$$

Infinite disks are not real of course!

which gives

$$L_{tot} = 2\pi r_d^2 \Sigma_0$$

Exponential Law

Disk radial profile follows:

$$\Sigma(r) = \Sigma_0 \exp(-r/r_d)$$

The total disk luminosity is obtained by integrating

$$L_{tot} = 2\pi \int_0^{2\pi} \int_0^{\infty} \Sigma_0 \exp(-r/r_d) r dr d\theta$$

which gives

$$L_{tot} = 2\pi r_d^2 \Sigma_0$$

Extended UV Disks

(Thilker et al. 2007)

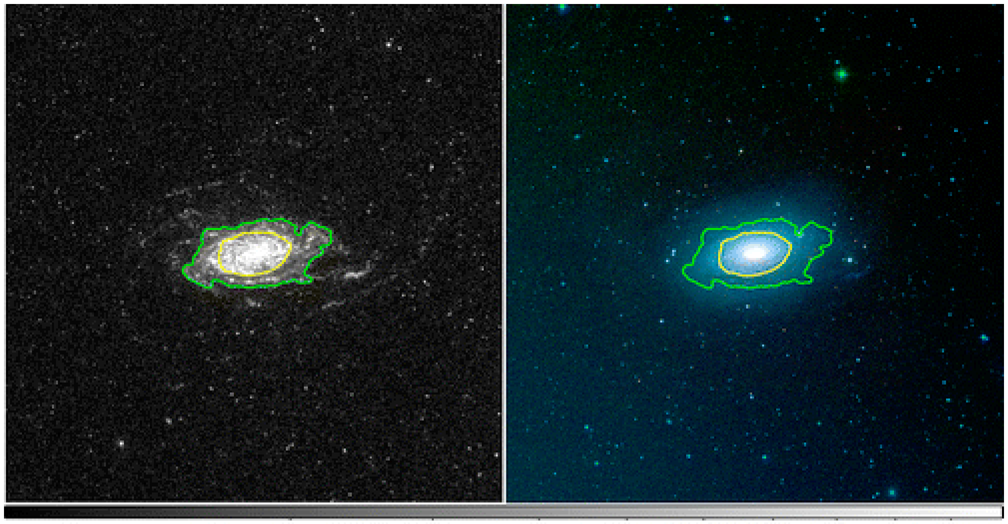
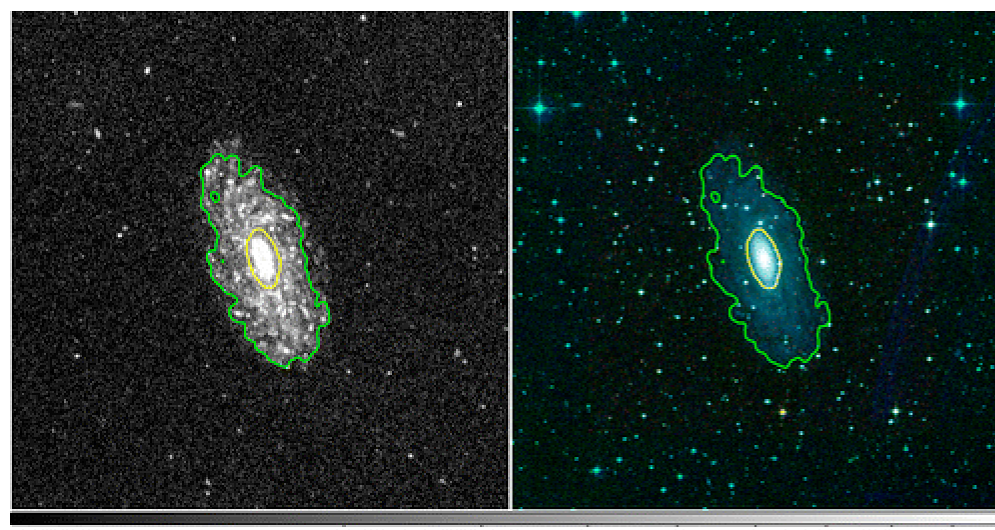


Fig. 3.— FUV-NIR imagery and classification contours for XUV-disk galaxy NGC 5055 (M63), a prototype for our Type 1 class. On the left we show the GALEX FUV image of the galaxy. On the right we show the 2MASS K_{s} -band, DSS2-red, and DSS2-blue imaging (as RGB channels) for an identical field of view ($3D_{25}=37.5^{\prime }=89.4$ kpc at 8.2 Mpc). Contours are the same on both images. At the green line, the FUV surface brightness (corrected for Galactic foreground extinction and measured at 1 kpc resolution) is $\mu _{\mathrm{F}\,\mathrm{UV}\,}=27.25$ AB mag arcsec−2. This is the position at which (apparent?) star formation threshold mechanisms are thought to become important. The yellow contour encloses 80% of the K_{s} -band luminosity of the galaxy, defining the effective extent for the old stellar population. Note the structured UV-bright emission features beyond the green (UV) contour, which give this galaxy the Type 1 XUV-disk designation.

Fig. 4.— FUV-NIR imagery and classification contours for Type 2 XUV-disk galaxy NGC 2090. We observe a rather large blue LSB zone, which dominates the spatial extent of the galaxy despite being of low (optical) surface brightness. The image passbands and contour types are identical to those of Fig. 3. The field of view spans $3D_{25}=12.9^{\prime }=42.4$ kpc at 11.3 Mpc.



Outer Disk Profiles

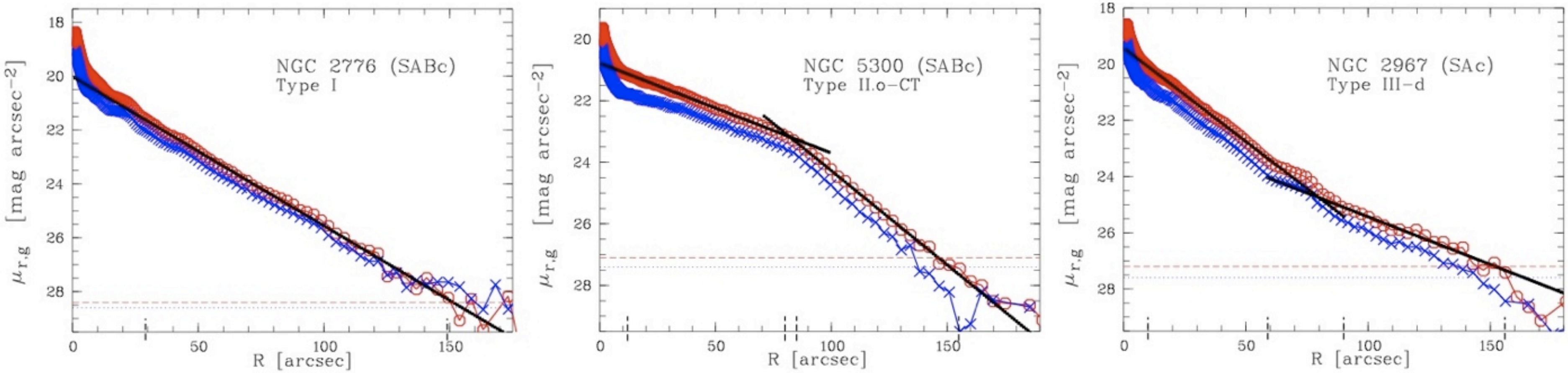


Figure 1. The three main disk types: Type I, Type II, and Type III (from left to right). Azimuthally averaged, radial SDSS surface brightness profiles in the g'- (*triangles*) and r'-band (*circles*) overlaid by r'-band exponential fits to the individual regions: single disk; inner and outer disk.

(Pohlen et al. 2008, ASP Conf. Series, Vol. 390, 247)

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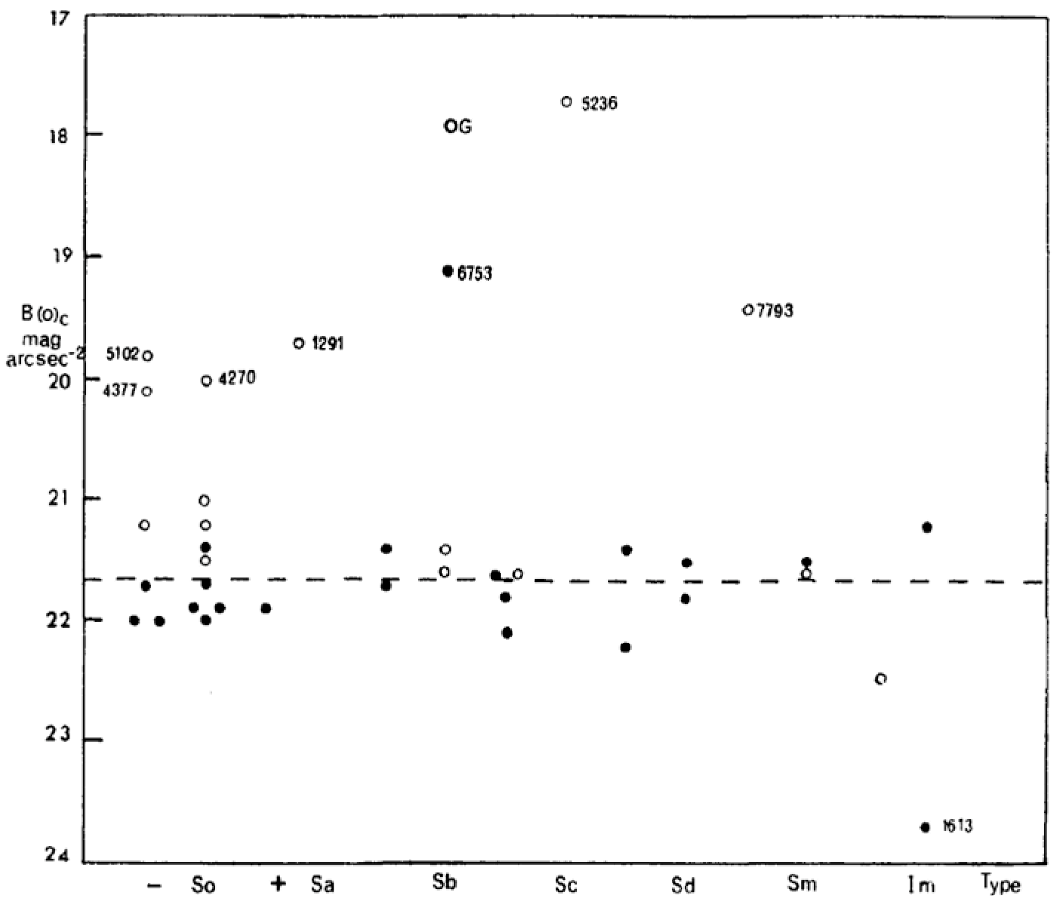
"Freeman's Law" For Galaxy Disks

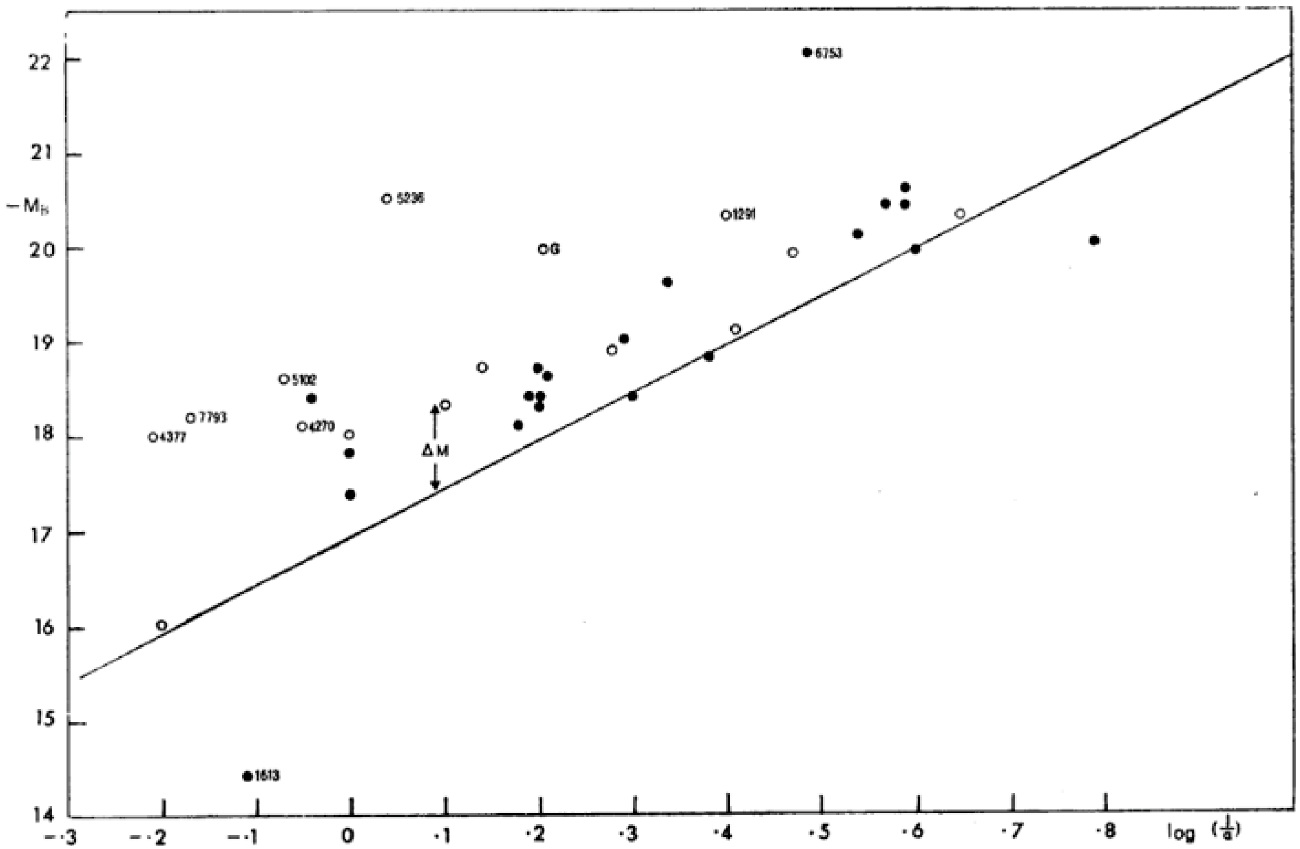


B-band central surface brightness of disks is constant

$\mu_B(0)$ ~ 21.65 mag/ arcsec^2

(Freeman 1970)

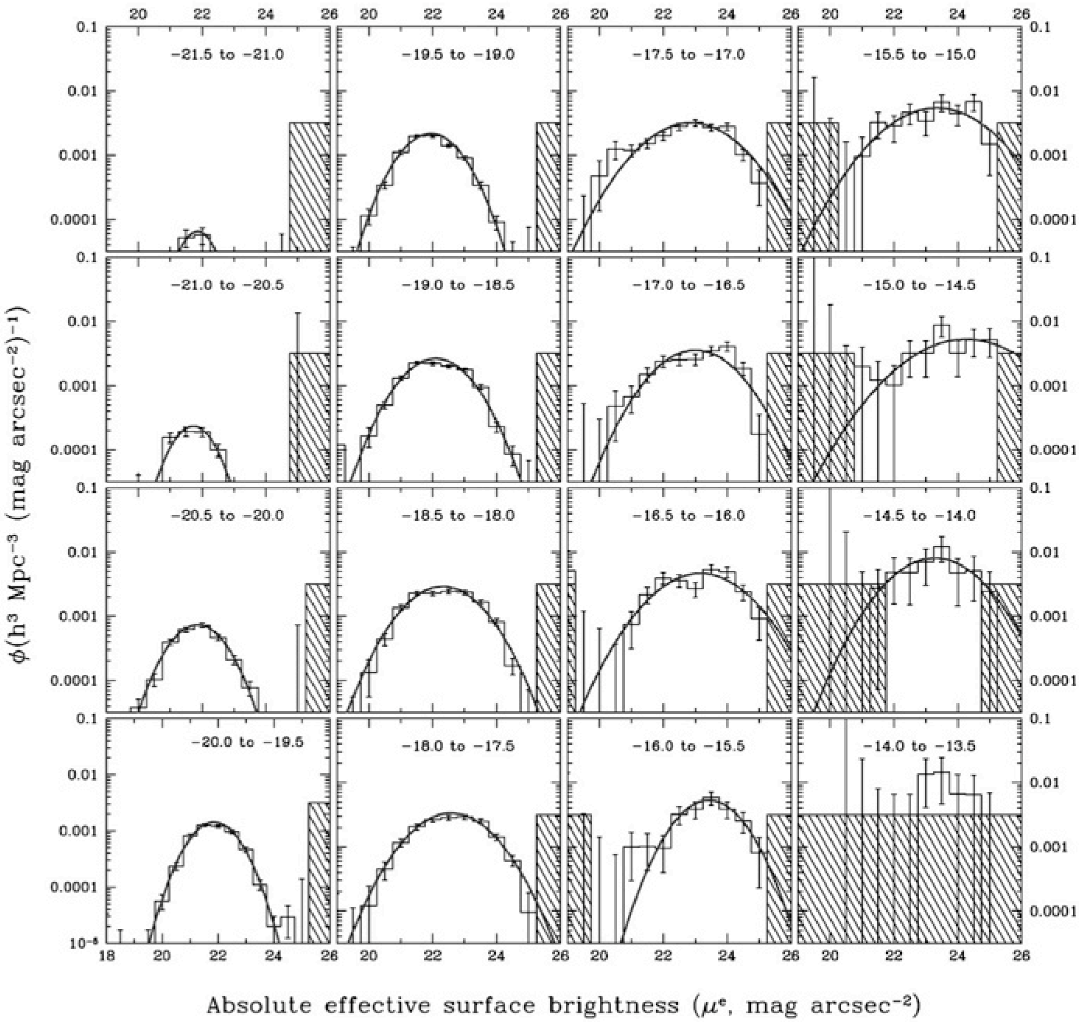
"Freeman's Law" For Galaxy Disks



Disk luminosity and size are correlated

(Freeman 1970)

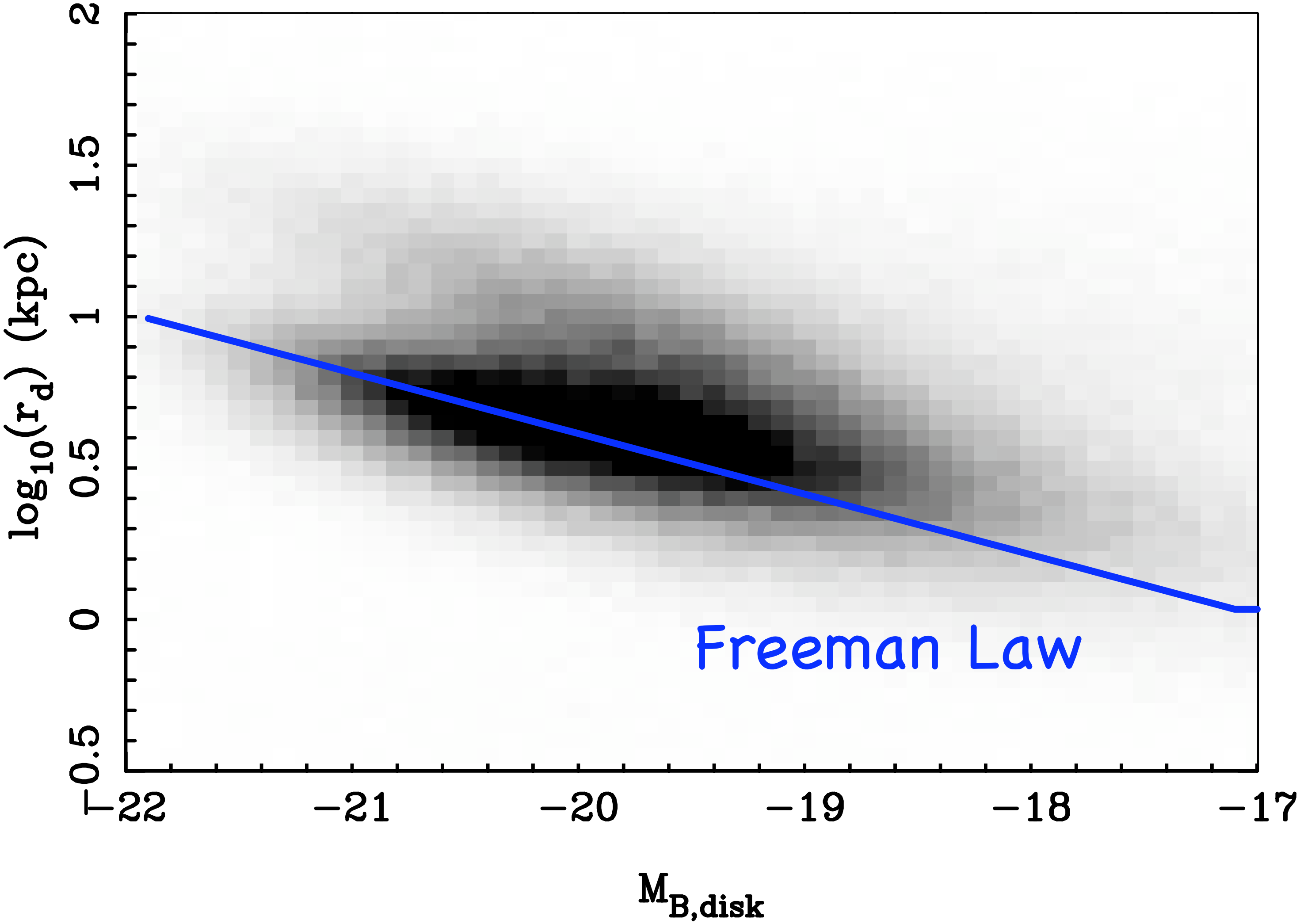
Millenium Galaxy Catalog Surface Brightness Distribution



Note change in μ with absolute magnitude

(Driver et al. 2005, MNRAS, 360, 81)

SDSS Disk Luminosity-Size Relation



Disk surface brightness is <u>not</u> constant

No curvature (e.g., Shen et al. 2003)

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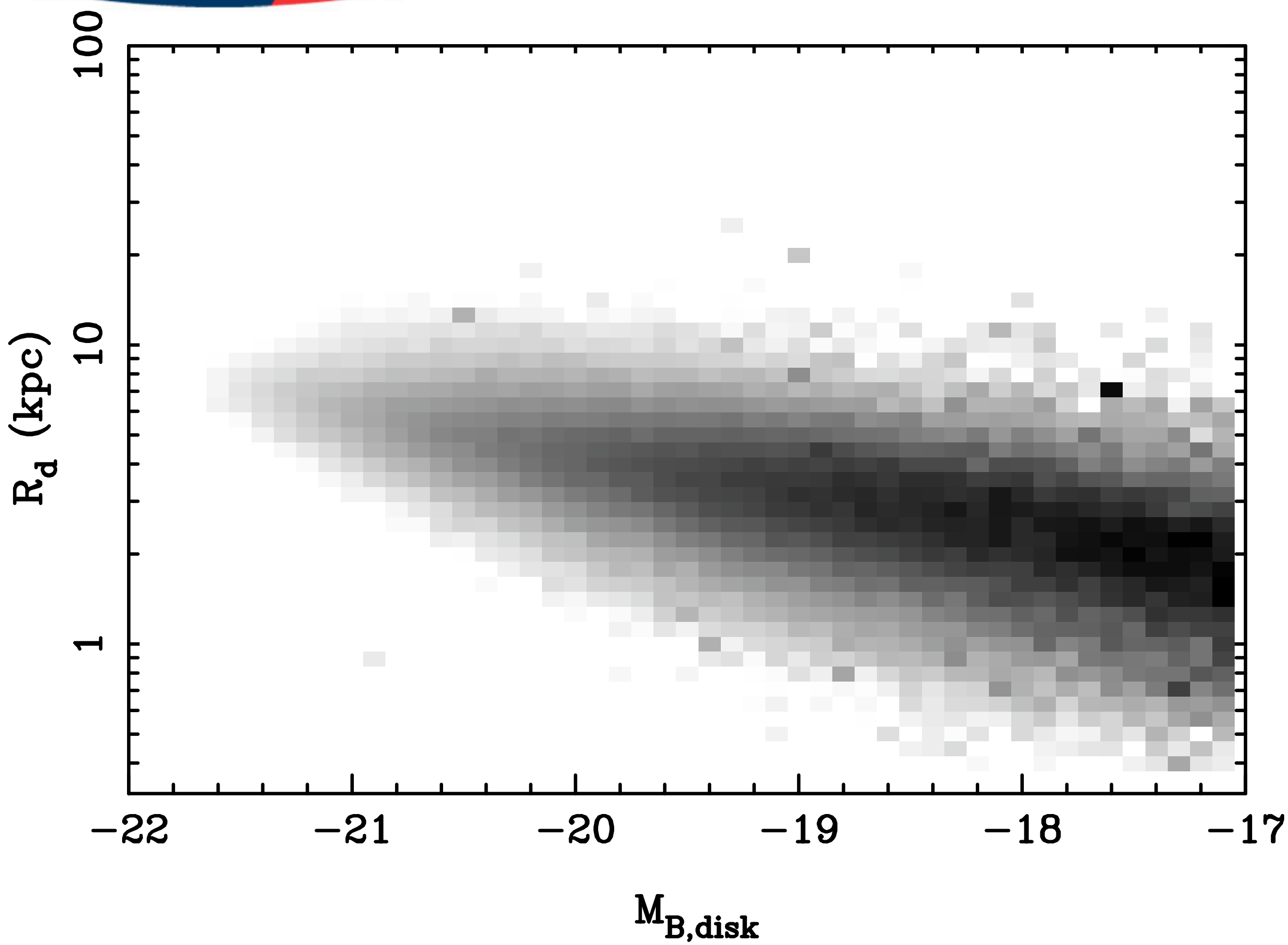
SDSS Disk Luminosity-Size Relation

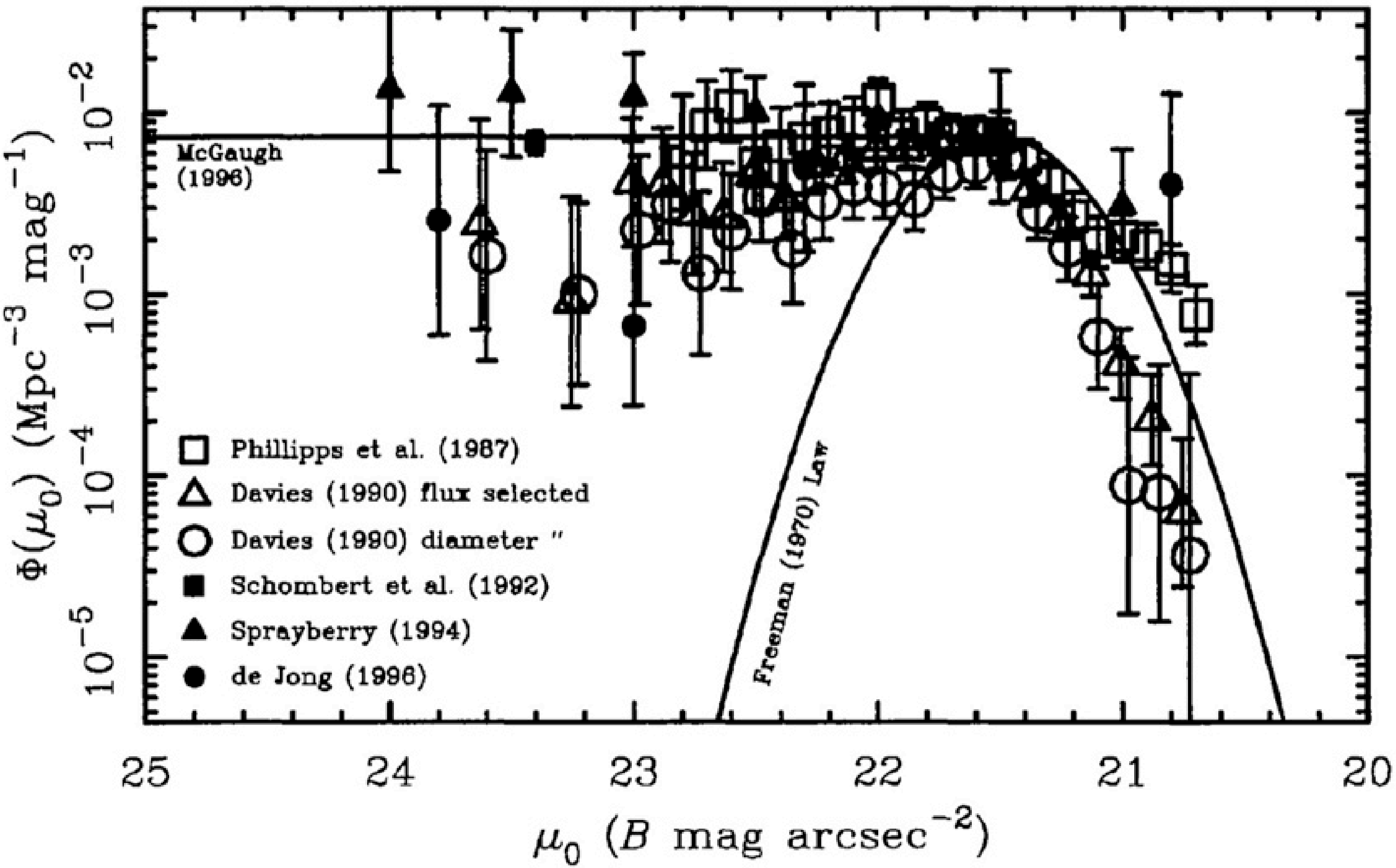


(Simard 2008, ApJ, in prep.)

With survey volume correction:

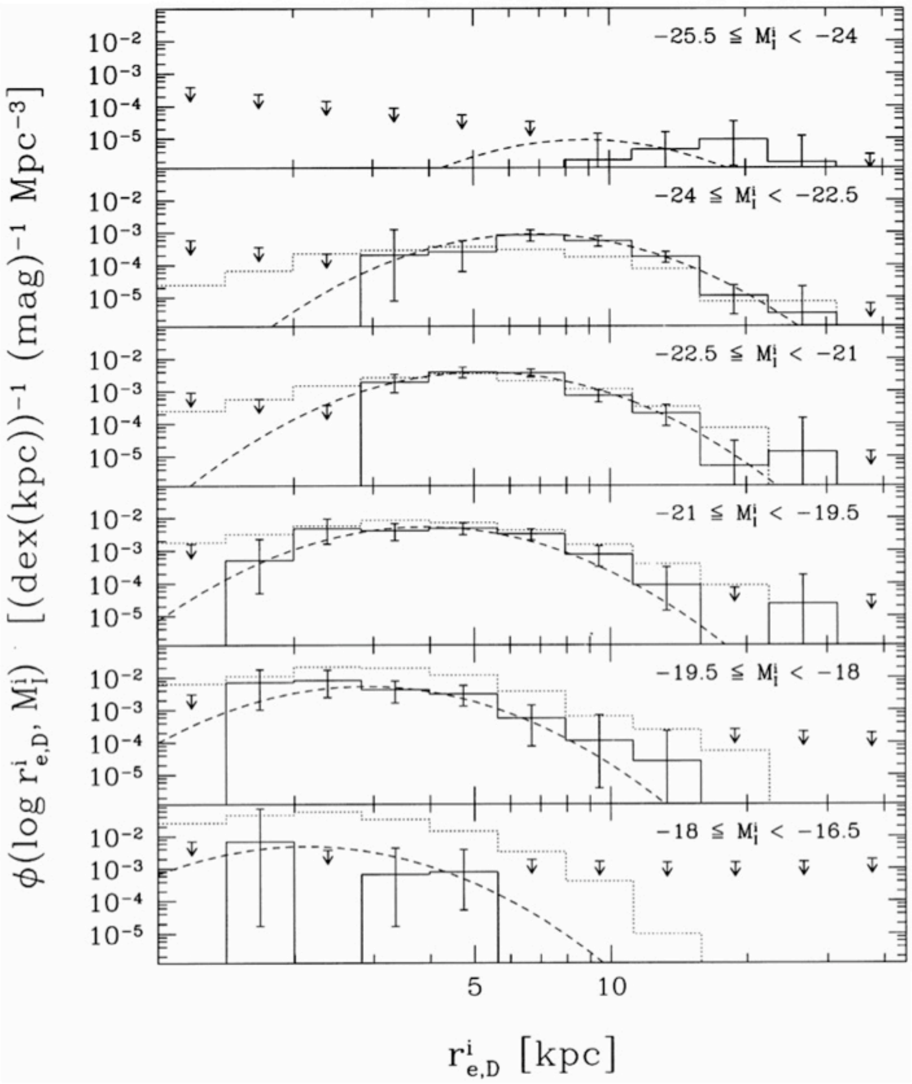
$$V_{max} = \frac{1}{4\pi}\int d\Omega f(\theta,\phi)\int_{z_{min}(\theta,\phi)}^{z_{max}(\theta,\phi)} \frac{d_A^2(z)}{H(z)(1+z)}cdz$$

Low Surface Brightness Disks



(Bothun 1997, PASP, 109, 745)

Disk Size Function

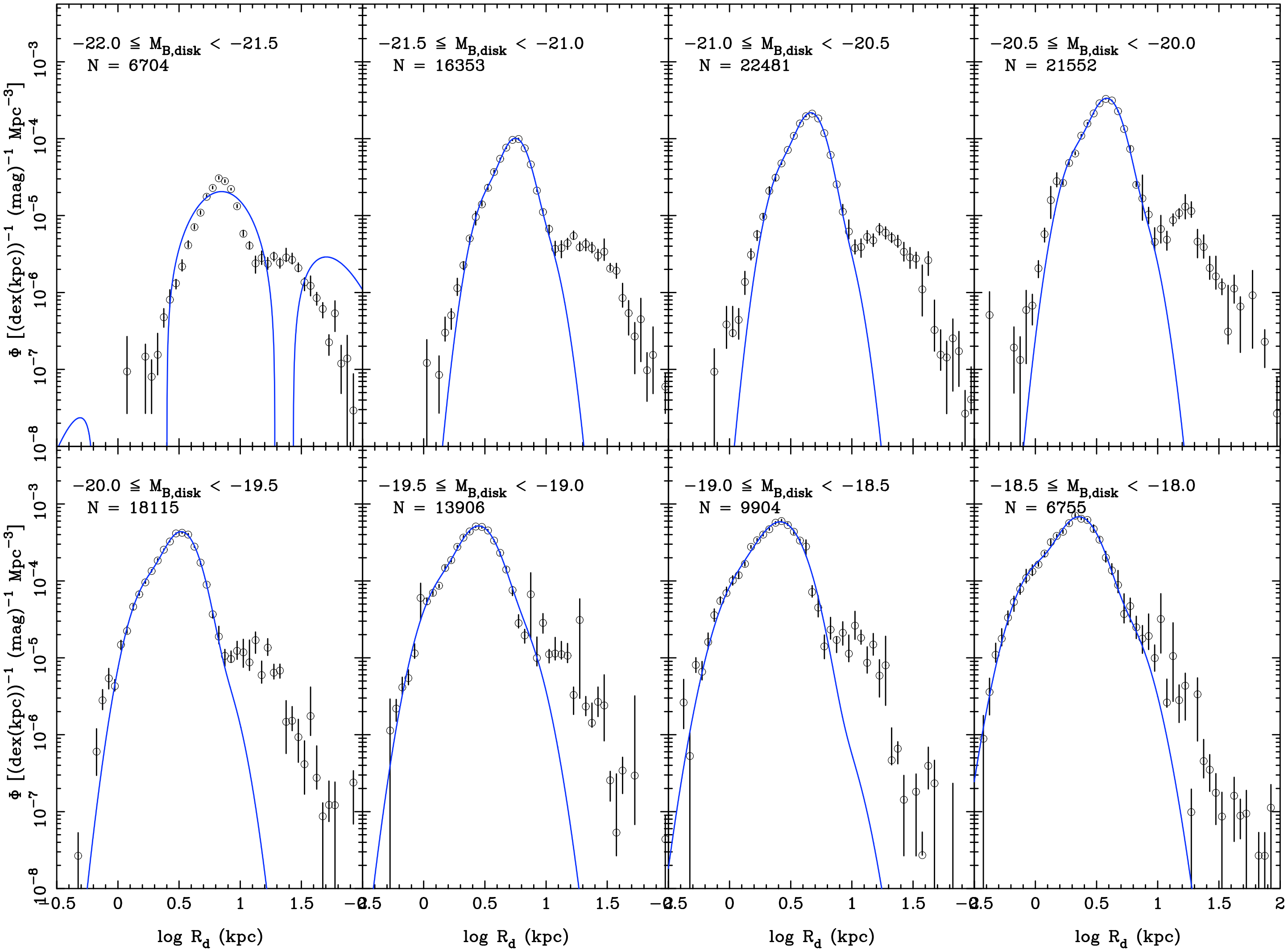


$$\Phi(M, \log R_d) dM d\log R_d = \sum_{i=1}^{N} \frac{1}{V_{max,i}}$$

1000 Sb - Sdm galaxies

(de Jong & Lacey 2000, ApJ, 545, 781)

Disk Size Function



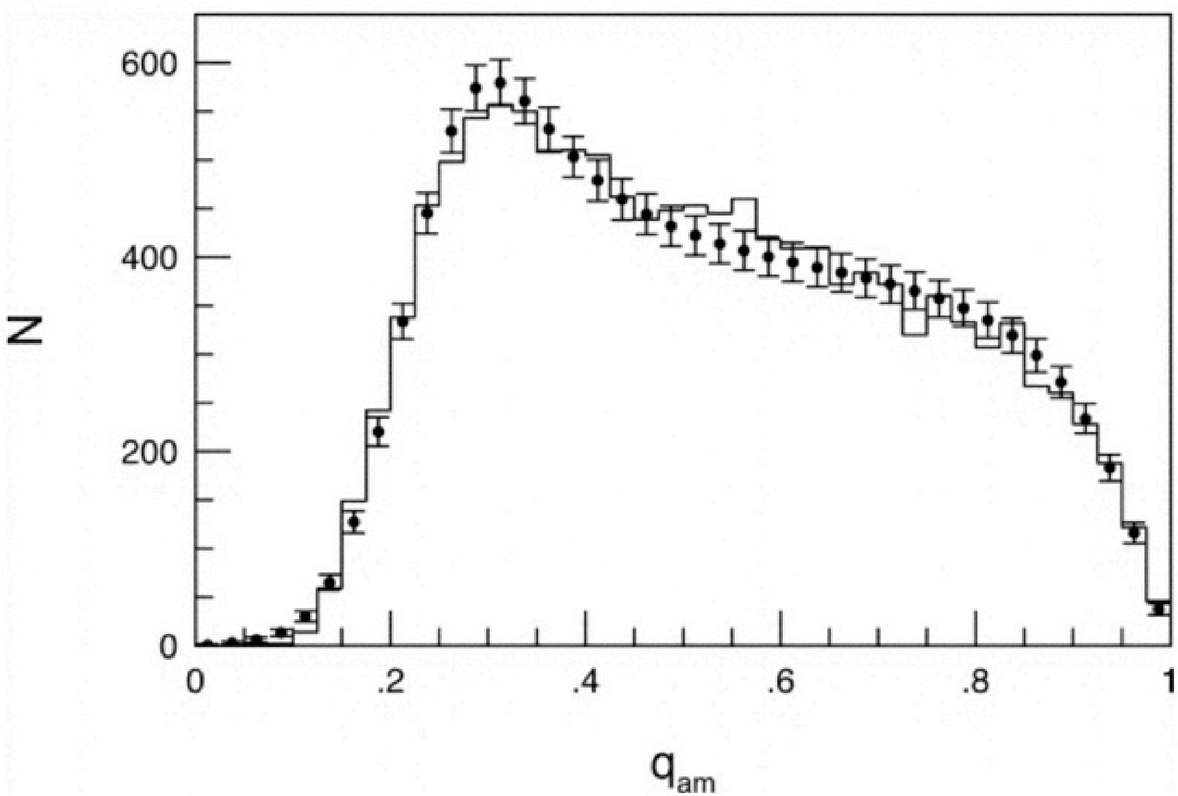
115,000 disks in SDSS

(Simard 2008, ApJ, in prep.)

Are Disks Circular?

First compute distribution of apparent axial ratios using:

$$q_{am} = \left(\frac{1-e}{1+e}\right)^{1/2} \qquad e \equiv (e_+^2 + e_\times^2)^{1/2}$$



12,000 galaxies in SDSS

(Ryden 2005, ApJ, 601 214)

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Are Disks Circular?

Assume disk thickness follows a Gaussian distribution:

$$f(\gamma) \propto \exp\left[-\frac{(\gamma-\mu_\gamma)^2}{2\sigma_\gamma^2}\right]$$

Assume disk ellipticity follows a lognormal distribution:

$$f(\epsilon) \propto \frac{1}{\epsilon}\exp\left[-\frac{(ln\epsilon-\mu)^2}{2\sigma^2}\right]$$

Pick values for (μ_γ, σ_γ, μ and σ), compute resulting apparent axial ratio, repeat to build a distribution and compare with observed distribution. Repeat. Best values:

$$\mu_\gamma = 0.222 \quad \sigma_\gamma = 0.057 \qquad \mu = -1.85 \qquad \sigma = 0.89$$

$$\Rightarrow \quad e(\text{mode}, \text{median}, \text{mean}) = (0.071, 0.16, 0.21)$$

Vertical Disk Profile

Consider the luminosity density of 3D disk of the form:

$$L(R,z) = L_0 e^{-R/h_R} f(z)$$

$$f(z) = \text{sech}^{2/N}(Nz/z_0)$$

(Yoachim & Dalcanton 2006, AJ, 131, 226)

where N = 1 for a self-gravitating, isothermal sheet. For N $\rightarrow \infty$,

$$f(z) \propto e^{-z/h_z}$$ where $$h_z = z_0/2$$

N ≈ 2 seems to reproduce real disks (van der Kruit 1988).

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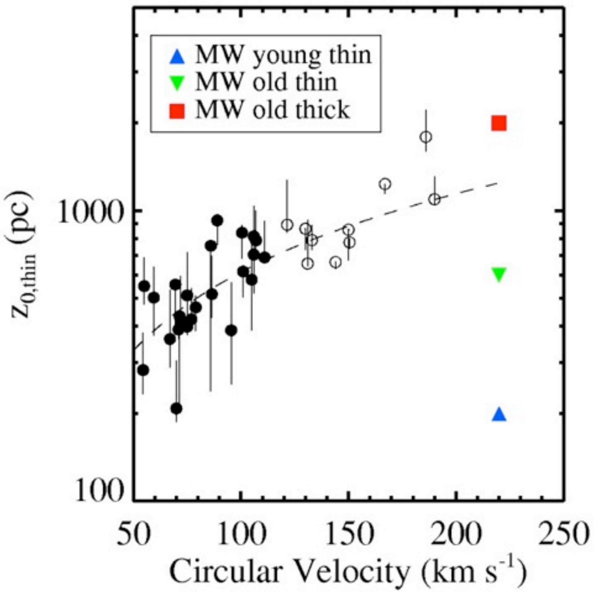
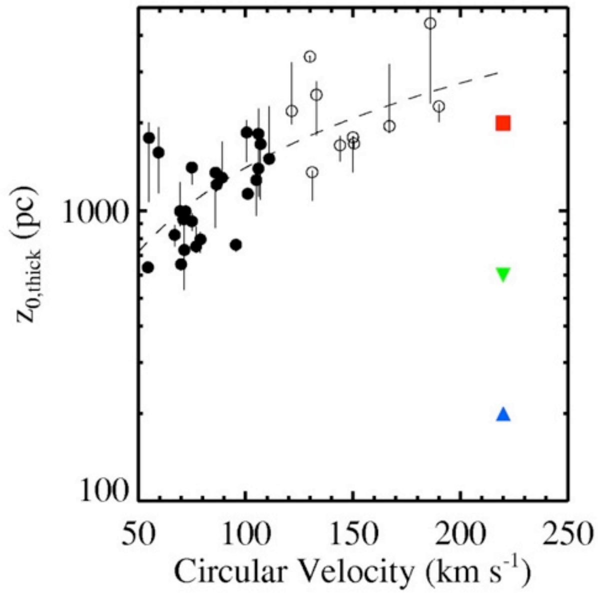
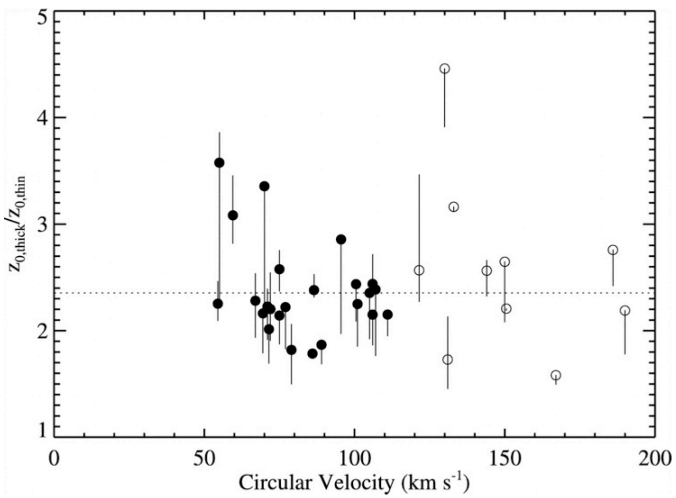
Thin and Thick Disks





(Yoachim & Dalcanton 2006)



- **Major mergers?**
- **Stochastic heating?**
- **Accretion?**

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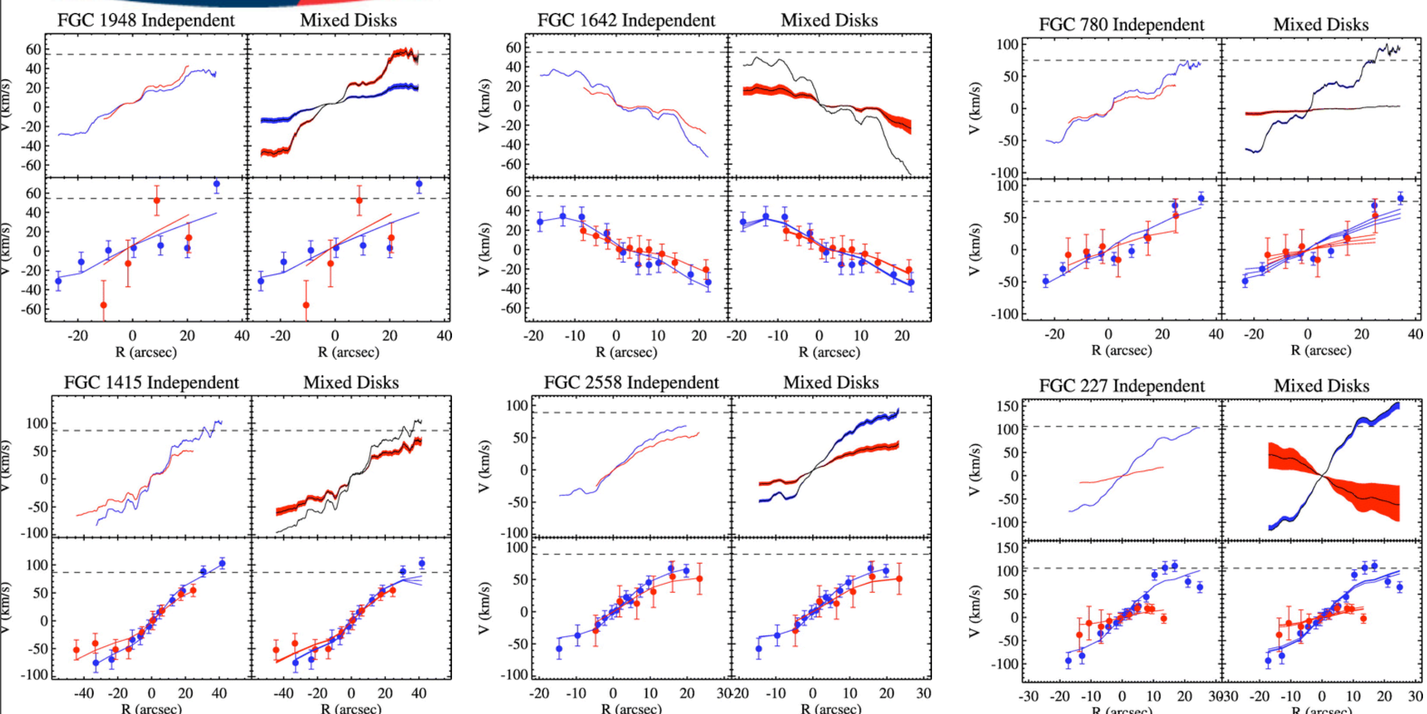
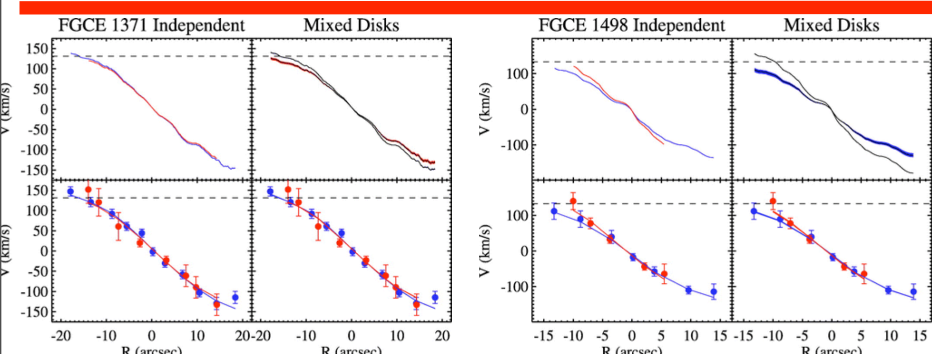
Thick Disks Form Through Accretion?



Diversity of thick disk kinematics below V_c = 120 km/s

V_c = 120 km/s



(Yoachim & Dalcanton 2006)

How Can Thin Disks Even Exist?

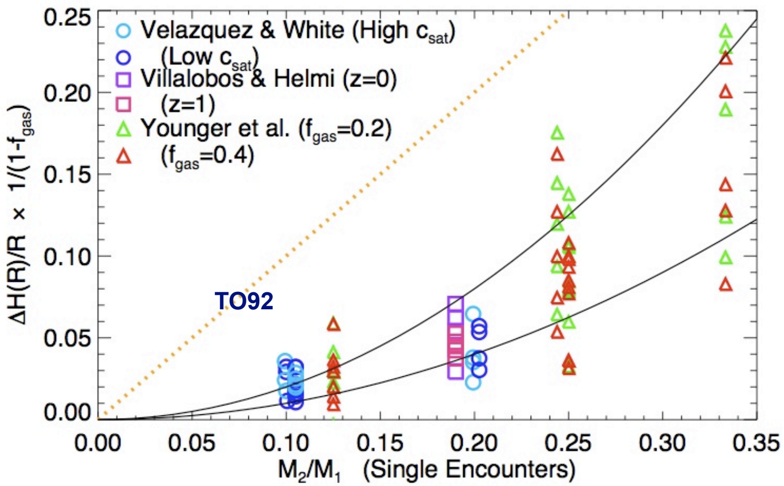
An interesting question (Tóth & Ostriker 1992, ApJ, 389, 5):

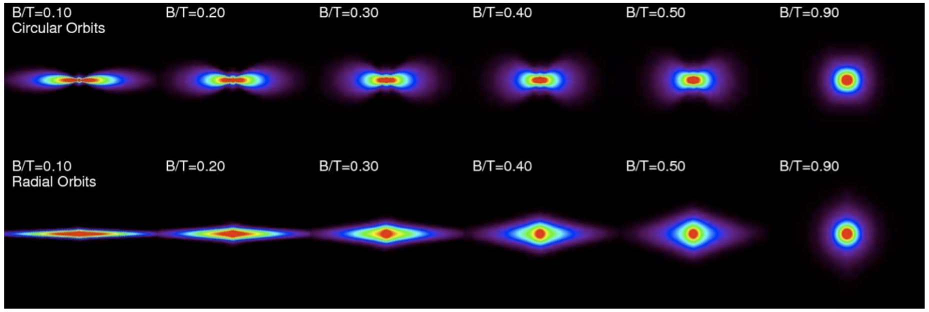
Given the thinness and coldness of disks, what kind of limit does this put on the current rate of infall of satellites onto spiral galaxies?

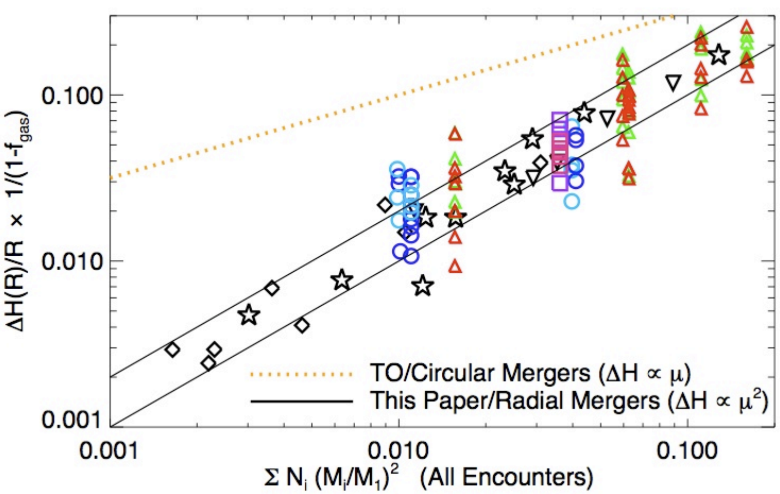
Answer: No more than 4% of the mass inside the solar radius can have been accreted within the last 5 Gyrs (expect > 28% in $\Omega = 1$)

THIS CANNOT BE RIGHT! What is the solution? (An open universe with Λ is part of the answer ...)

How Can Thin Disks Even Exist?







Satellites come in on radial orbits → efficient angular momentum shedding + mass stripping →

$$\Delta H \propto (M_{sat}/M_{disk})^2$$

and not the TO92 regime of

$$\Delta H \propto (M_{sat}/M_{disk})$$

(Hopkins et al. 2008, astro-ph/0806.2861)

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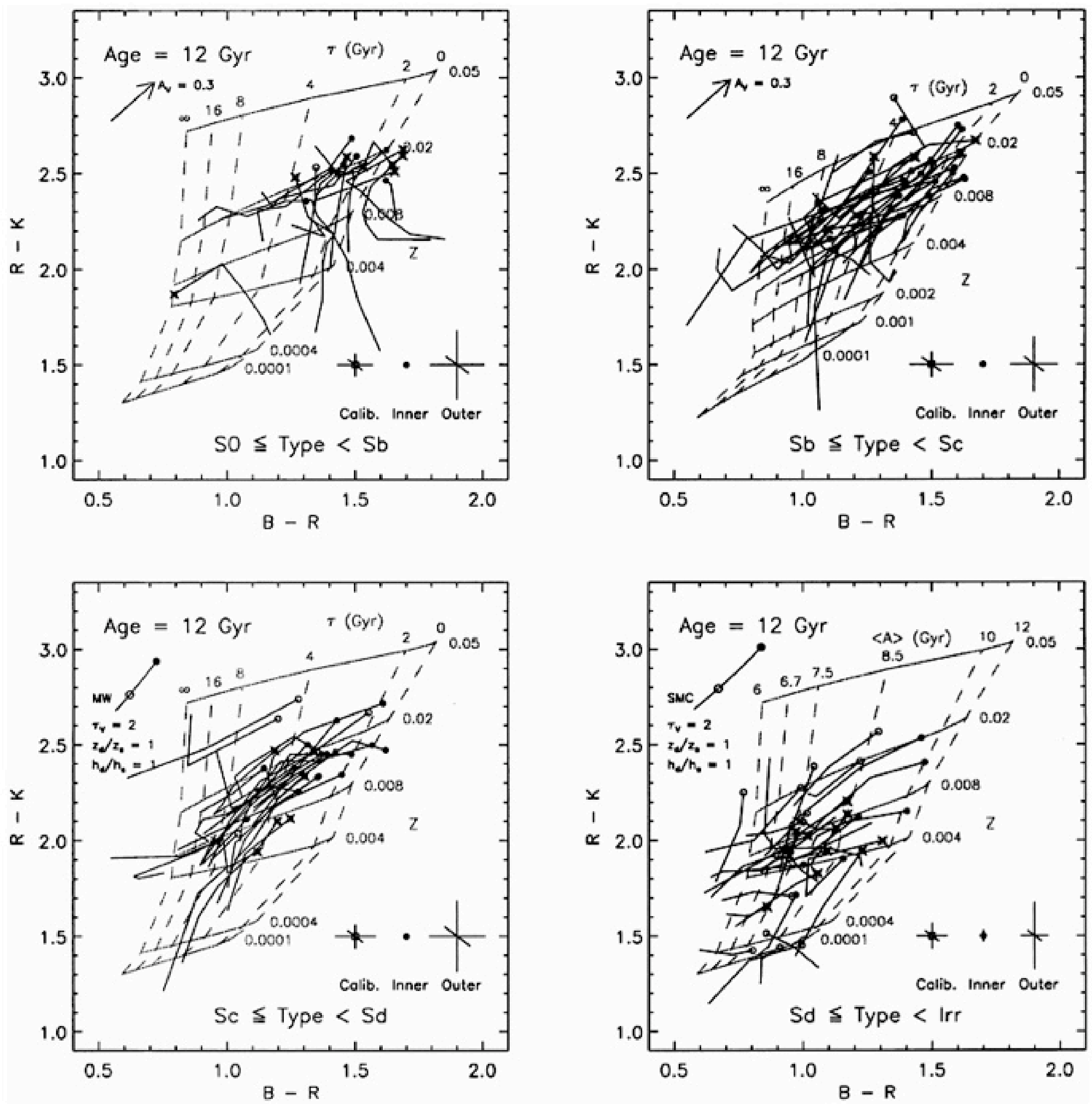
Color Distribution

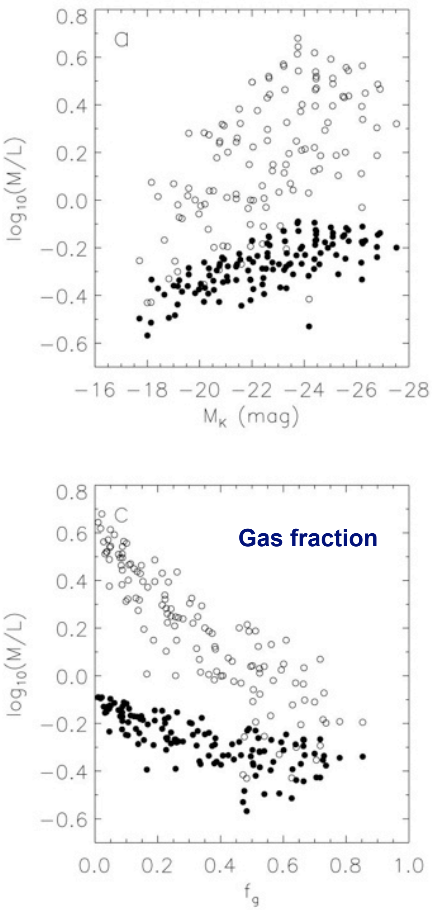


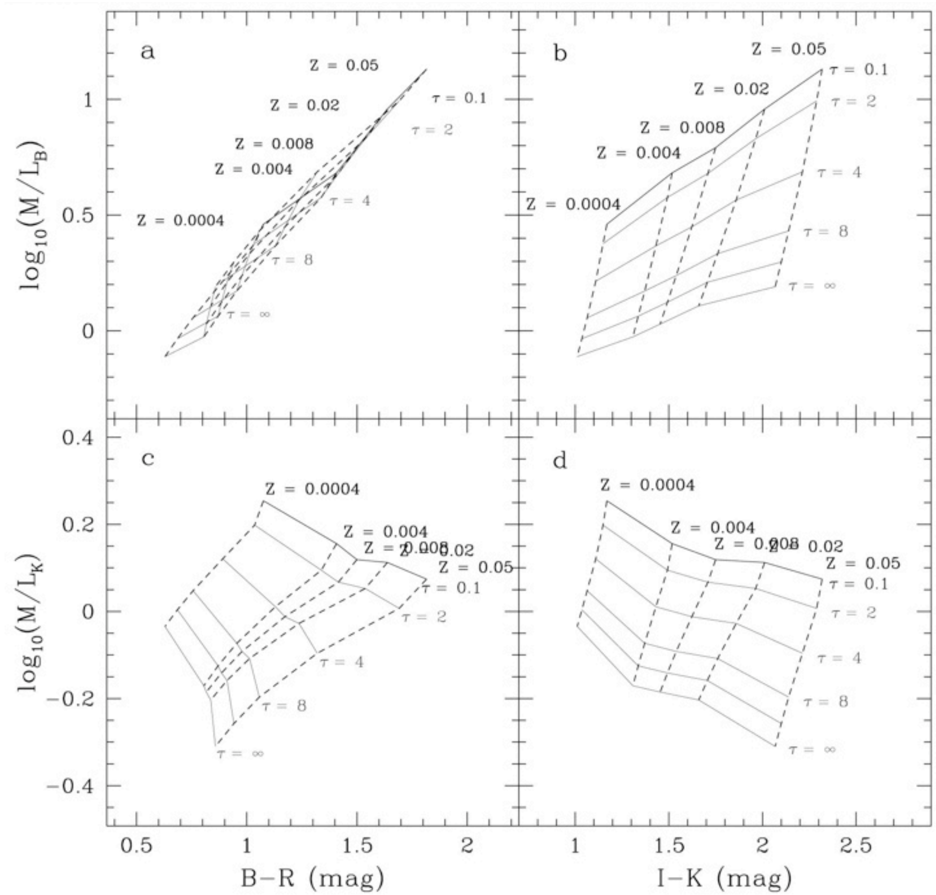
Optical-nearIR colors + Bruzual-Charlot Stellar Population Models

(Bell & de Jong 2000, MNRAS, 312, 497)

Mass-to-Light Ratios

(Bell & de Jong 2001, ApJ, 550, 212)





B-band (open) and K-band (open)

Single metallicity, exponentially declining star formation rate and Salpeter IMF

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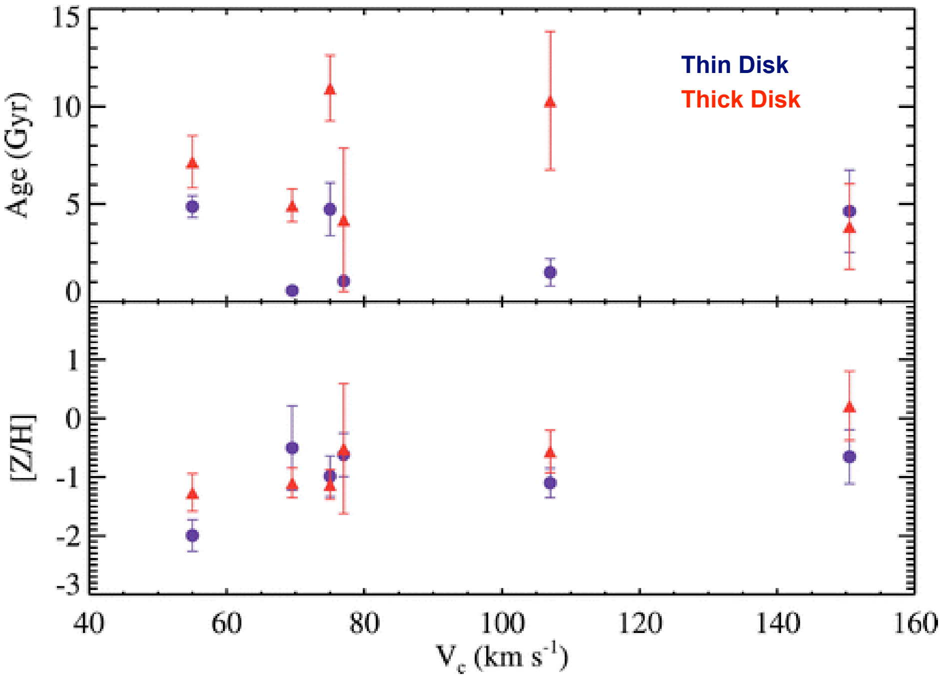
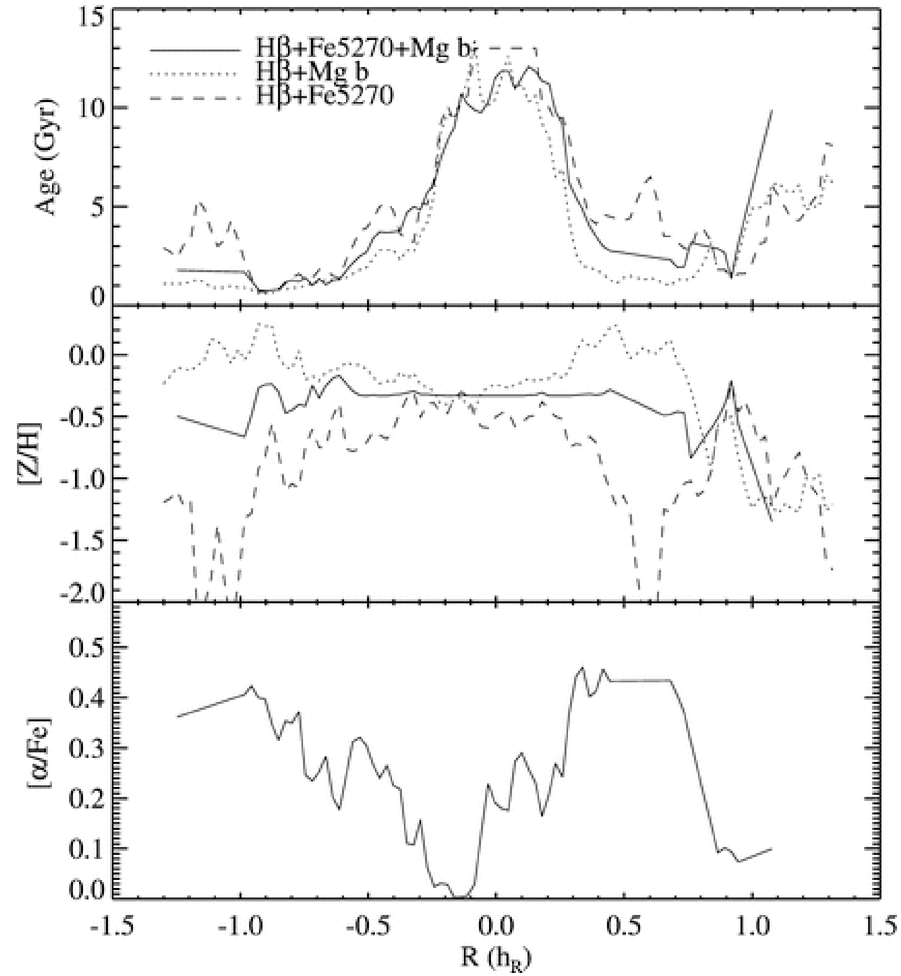
Metallicity Trends



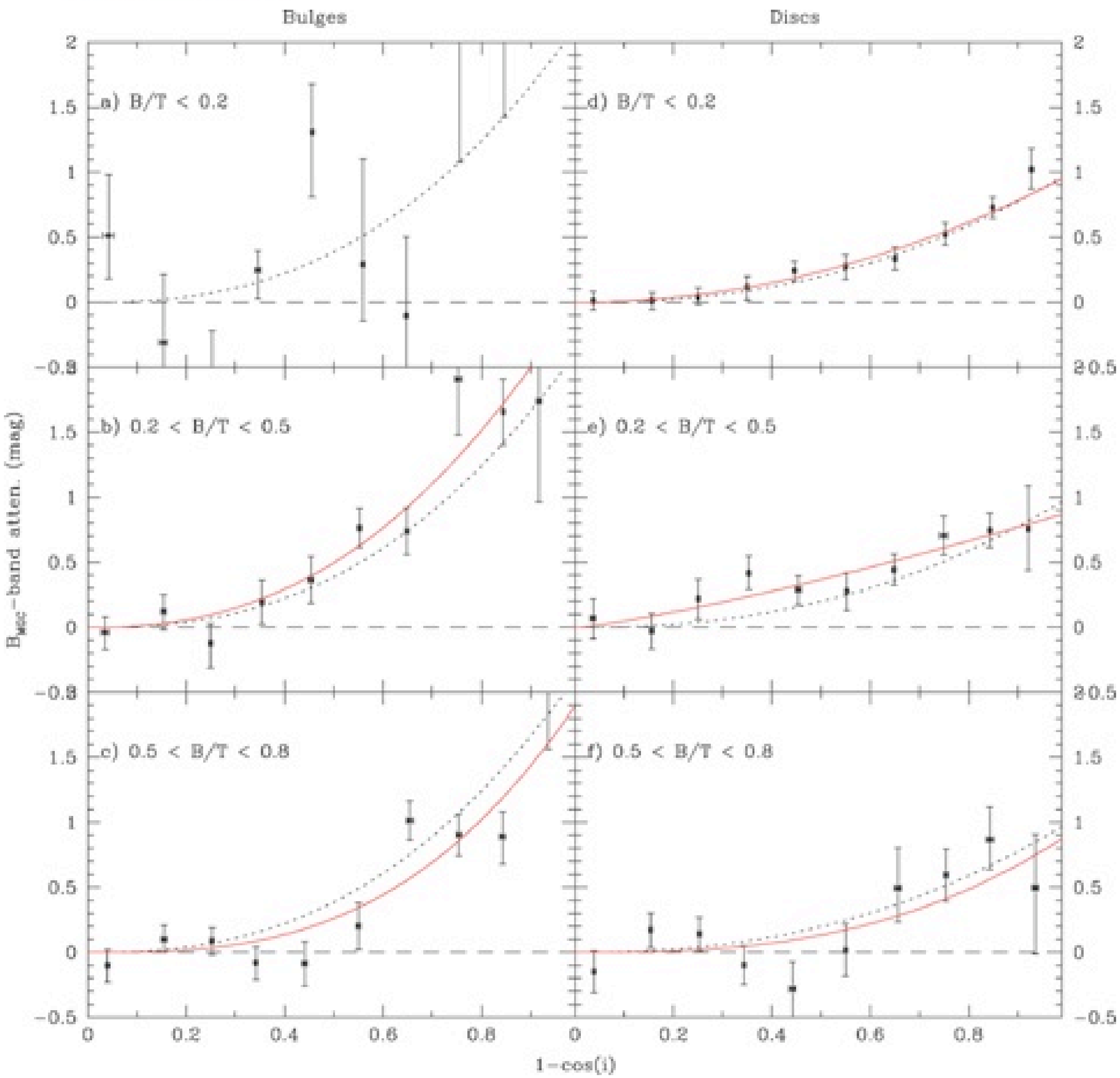
Age and metallicity from Lick indices

(Yoachim & Dalcanton 2008, ApJ, 683, 707)

In the midplane (thin disk)



Dust in Disks



Dotted line = full sample

Solid line = B/T cut

(Driver et al. 2007, MNRAS, 379, 1022)

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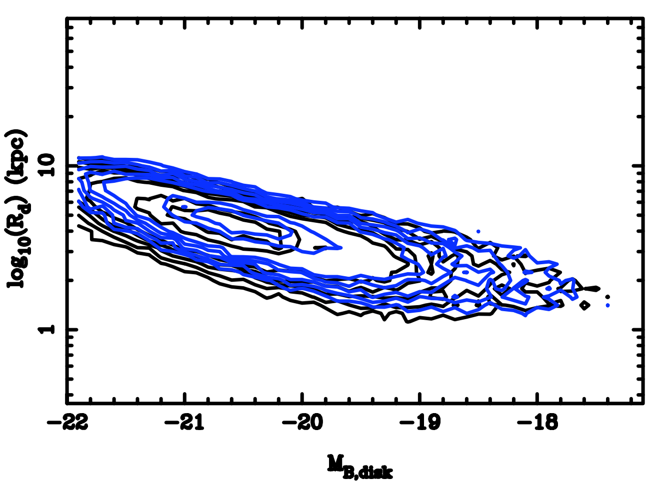
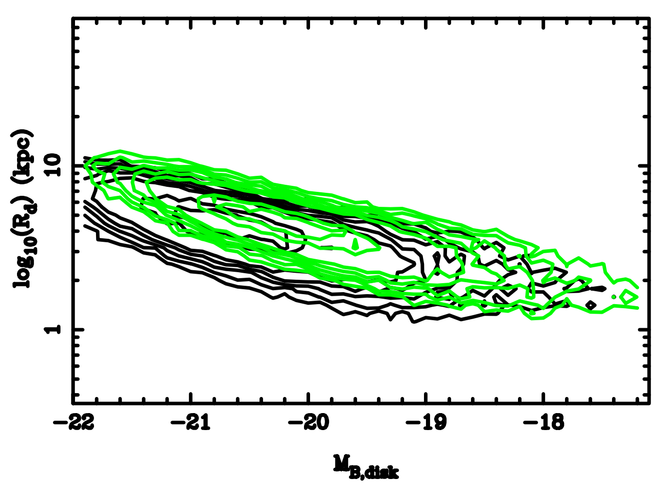
Internal Absorption in Late-Type Disks

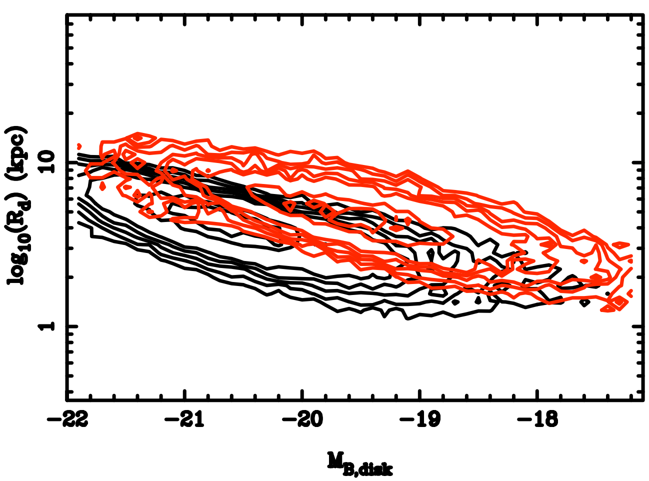
Disk (B/T < 0.3) Luminosity–Size versus Disk b/a



Disk (B/T < 0.3) Luminosity–Size versus Disk b/a



Disk (B/T < 0.3) Luminosity–Size versus Disk b/a



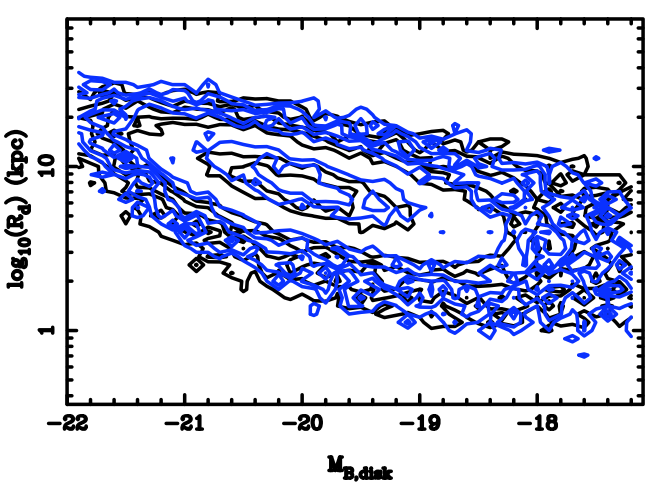
B/T < 0.3

$$M_d(b/a) \approx M_d(1) + (2.5)(0.6)\log_{10}(b/a)$$

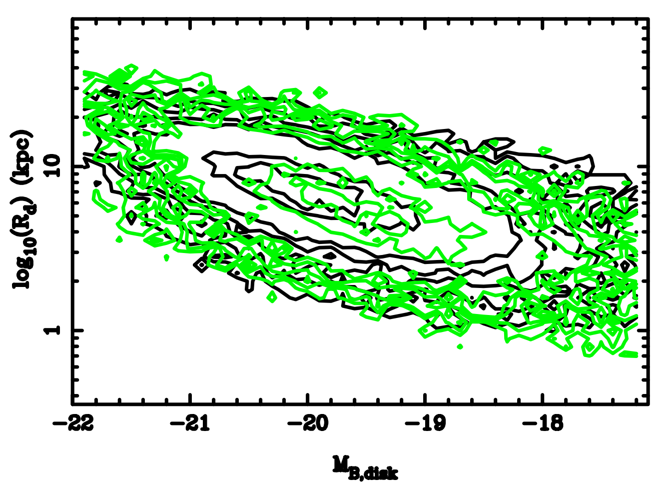
$$R_d(b/a) \approx R_d(1)/[1.0-(0.2)\log_{10}(b/a)]$$

Internal Absorption in Early-Type Disks

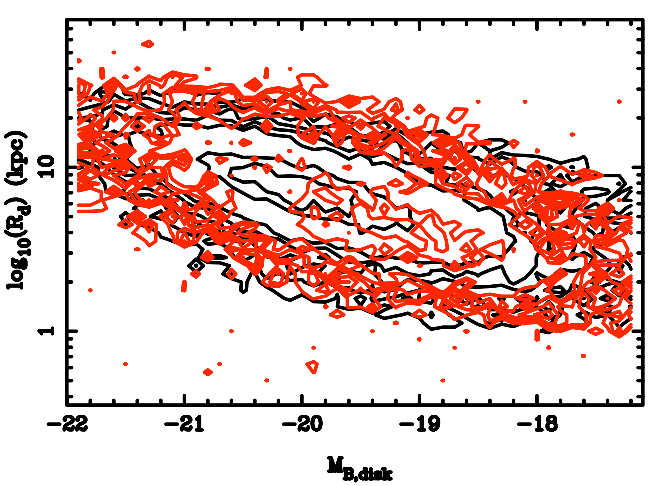
Disk (B/T > 0.5) Luminosity–Size versus Disk b/a



Disk (B/T > 0.5) Luminosity–Size versus Disk b/a



Disk (B/T > 0.5) Luminosity–Size versus Disk b/a

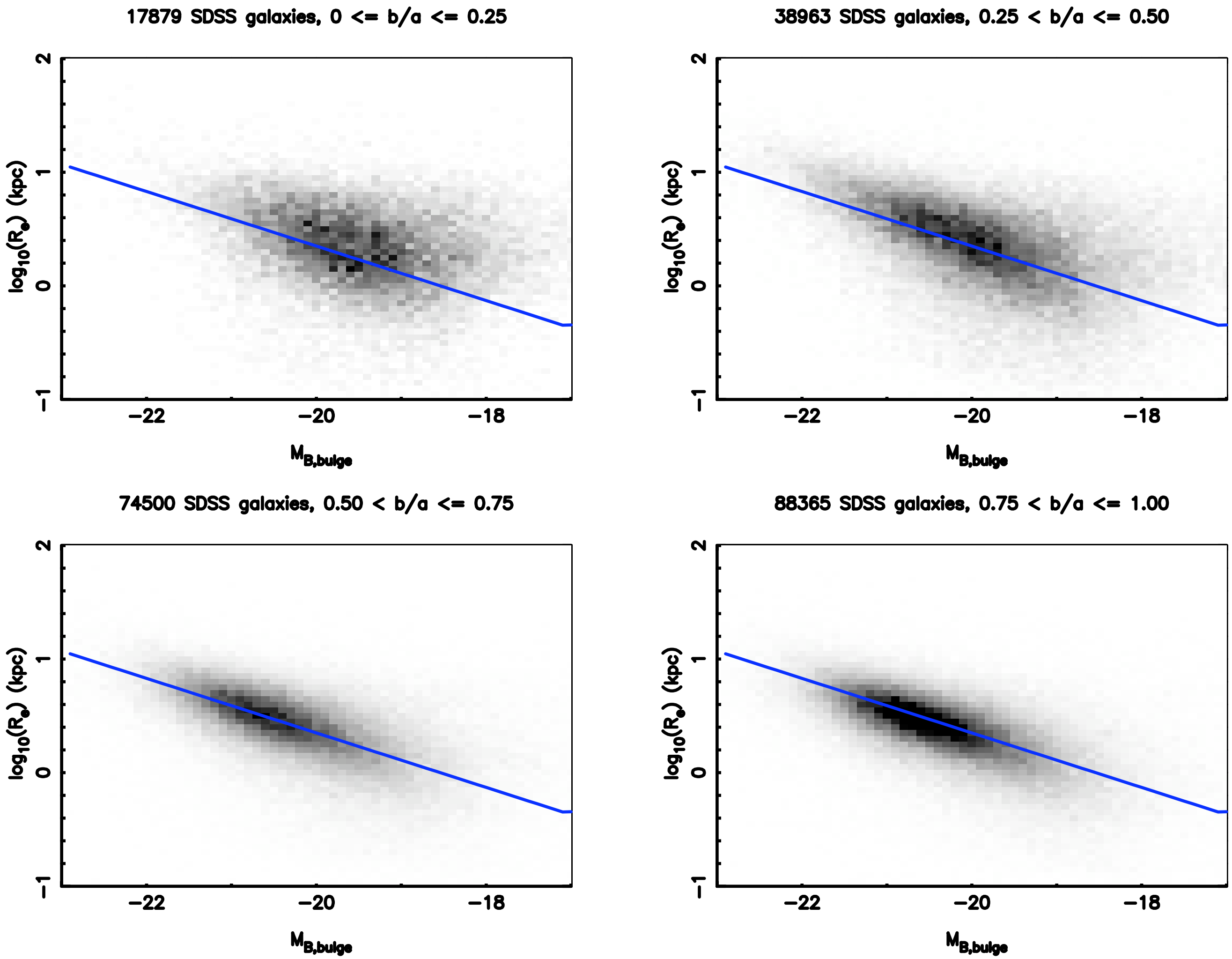


B/T > 0.5

$M_d(b/a) \approx M_d(1) + (2.5)(0.0)\log_{10}(b/a)$

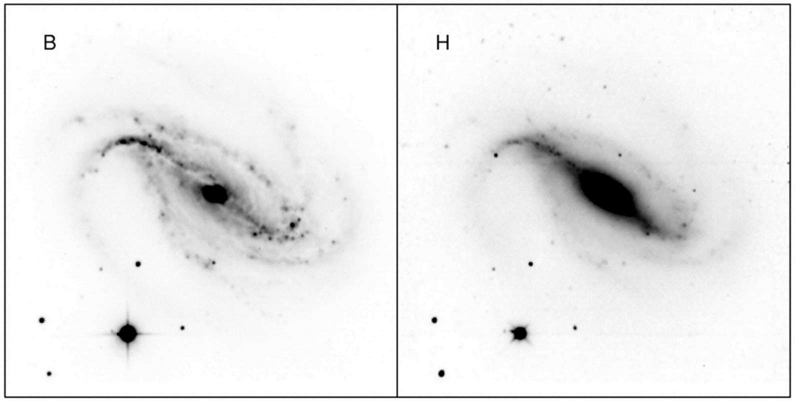
$R_d(b/a) \approx R_d(1)/[1.0-(0.0)\log_{10}(b/a)]$

Dust in Disks



(Simard 2008, in prep.)

Bars in Disks



BAR FRACTION IN THE *H* BAND AND OPTICAL CATALOGS

	H BAND		RC3		CAG	
BAR CLASS (1)	Fraction (%) (2)	Number (3)	Fraction (%) (4)	Number (5)	Fraction (%) (6)	Number (7)
SB..............	56	105	35	65	27	44
SAB............	16	30	30	56	4	6
SB+SAB......	73	135	65	121	30	50
SA	27	51	35	65	70	116
SA+SAB......	44	81	66	121	74	122

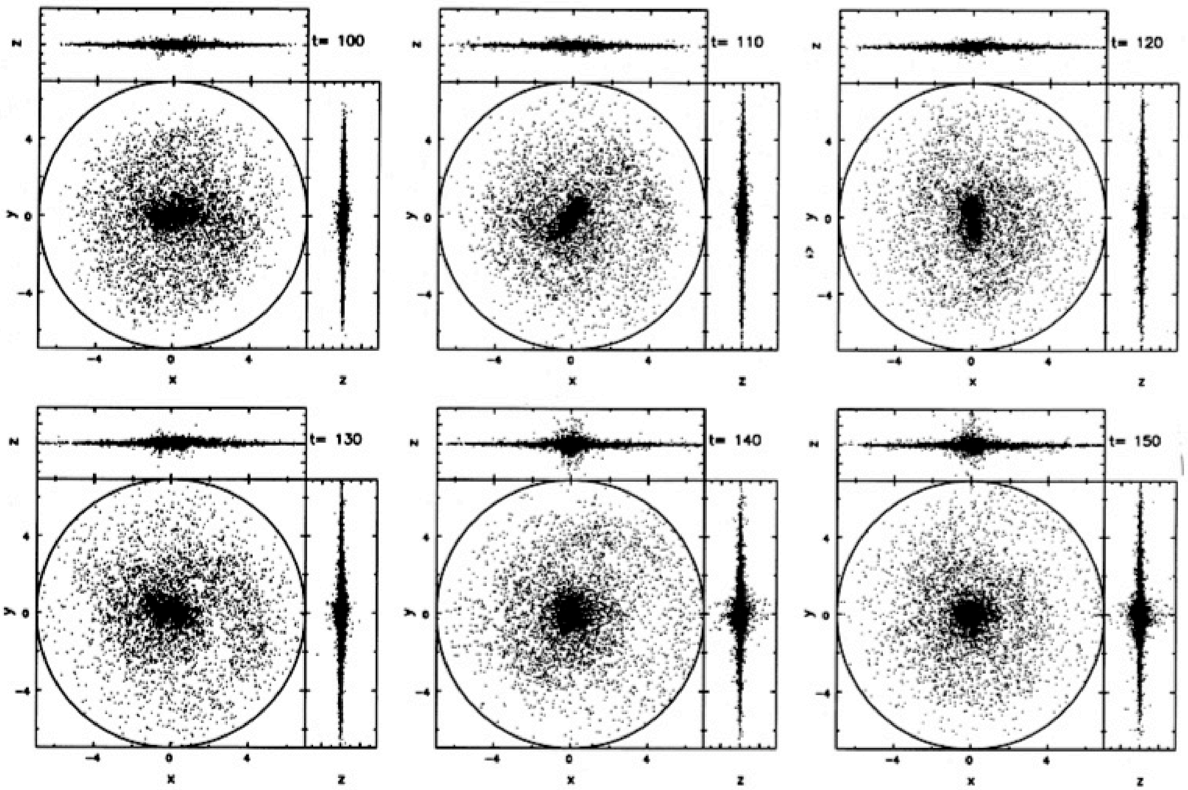
Eskridge et al. 2000, AJ, 119, 536

Cold disks are very unstable

Disks with large radial velocity dispersion are immune to bars

Bars are transient phenomena

Bar Dissolution and Bulge Formation



(Norman et al. 2006, ApJ, 462, 114)

Gas is funneled to the center of the disk, it triggers a starburst, forms a bulge. Once bulge is formed, stars on radial orbits in the bar scatter off and bar dissolves.

Warps in Disks

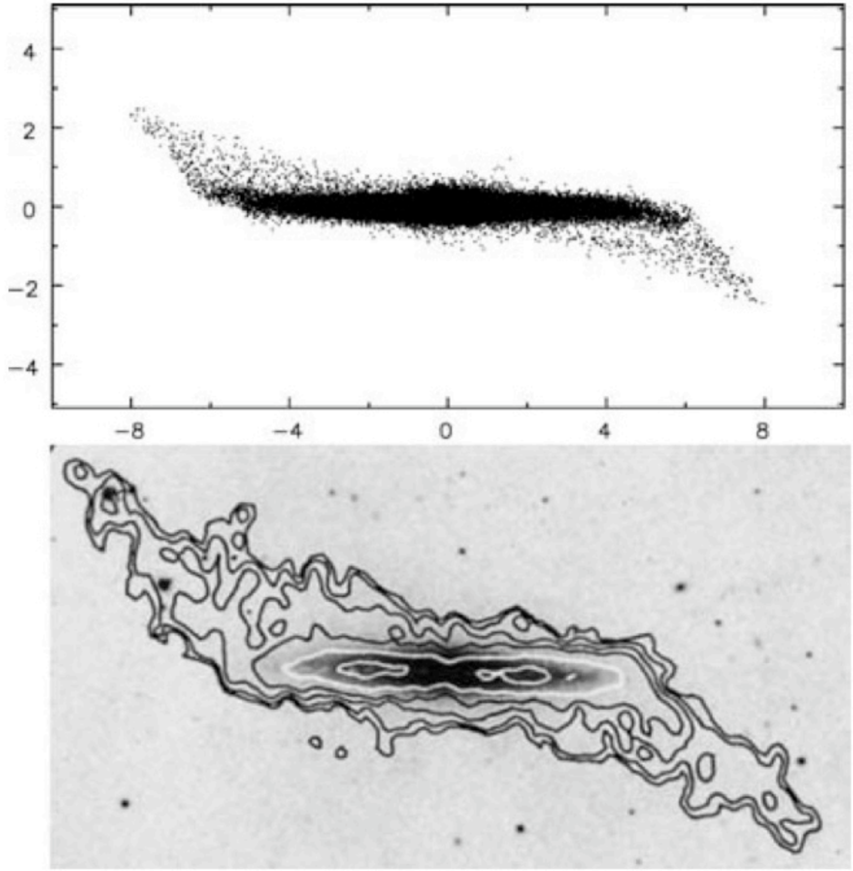
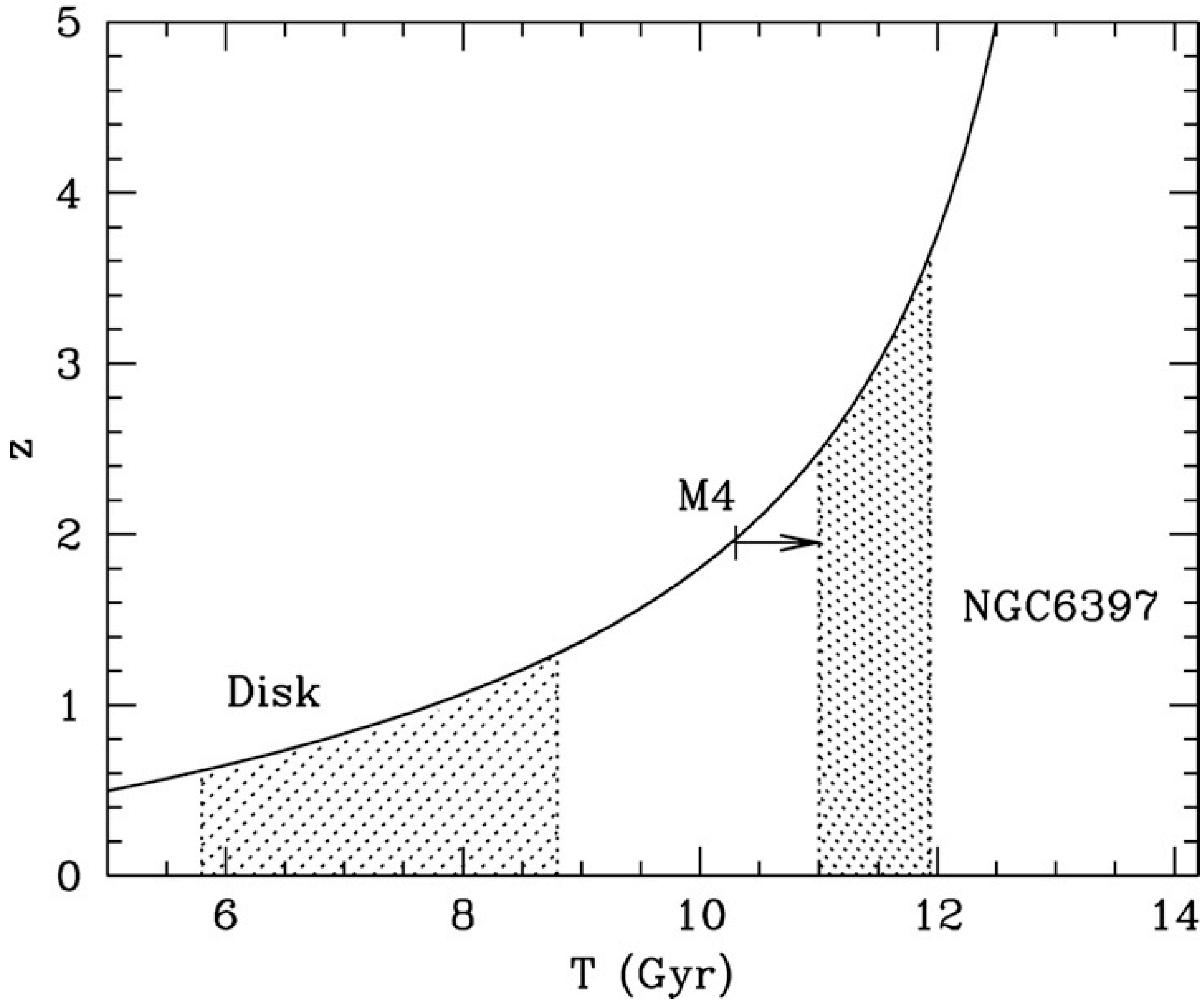


Figure 2. (a) The warp at $t = 400$ in our simulation; its morphology closely resembles the observed H I warp of NGC 4013 (reproduced with permission Bottema 1996) shown in (b). The length unit shown is the scalelength R_d of the exponential disc. Note that, we have oriented the model so that the inner ($R < 3R_d$) disc lies in the x–y plane, which is perpendicular to the paper.

Evolving halo due to cosmic infall creates different torques on inner and outer disks

(Shen & Sellwood 2006, MNRAS, 370, 2)

Age of MW Disk in Cosmological Context



Age determination based on white dwarf cooling sequence

(Hansen et al. 2007, ApJ, 671, 380)

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Kinematics / Dynamics

Internal Kinematics - Observations

- Challenges
  - Sensitivity
  - Spatial coverage
  - Spatial resolution (“beamwidth”)
  - Spectral resolution

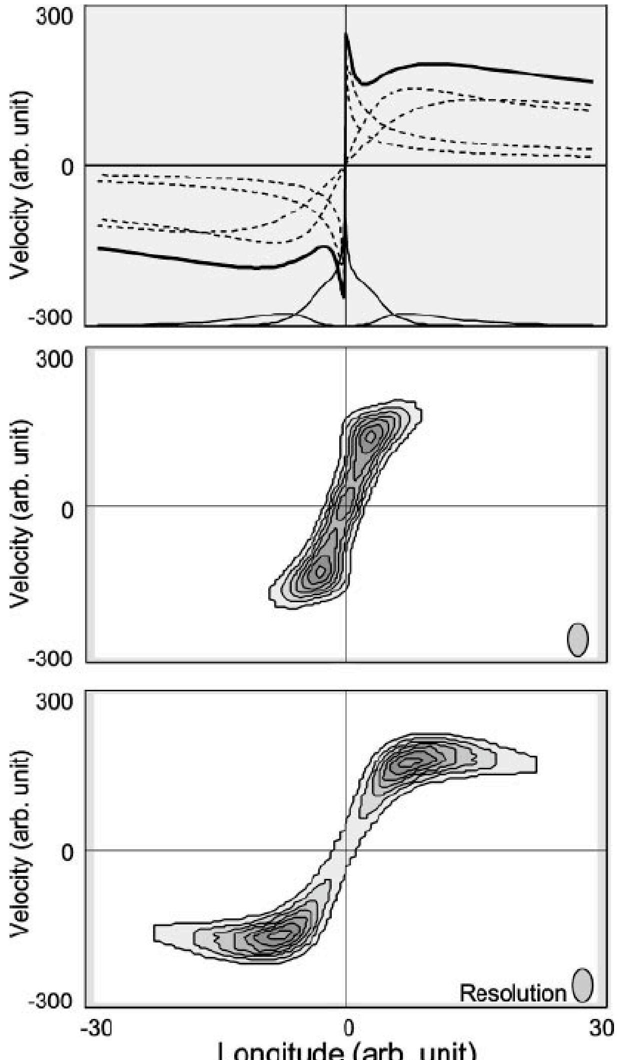
- Optical
  - Slitless
  - Slit Spectroscopy
    - Long (minor/major axis, drift-scan)
    - Multi
  - Integral Field Spectroscopy
    - Fabry-Perot
    - Fiber bundles
    - Image slicers
- Radio
  - Single dish
  - Interferometry

Internal Kinematics - Observations

Assumed true velocity curve

Observed P-V diagram in CO

Observed P-V diagram in HII



Example of an observational challenge :

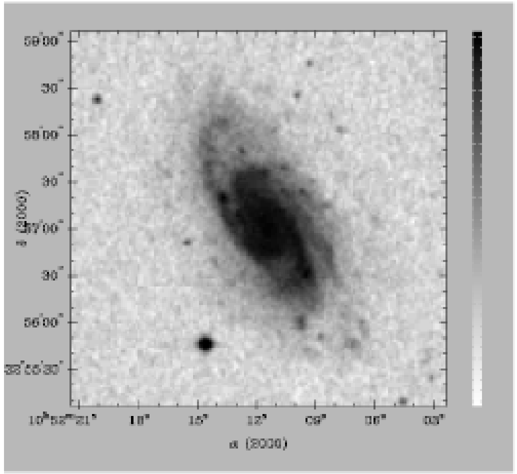
The subtle effects of beamwidth smearing

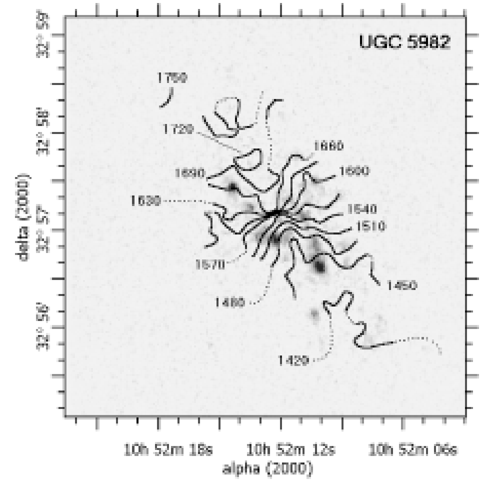
Sofue & Rubin 2001, ARAA, 39, 137

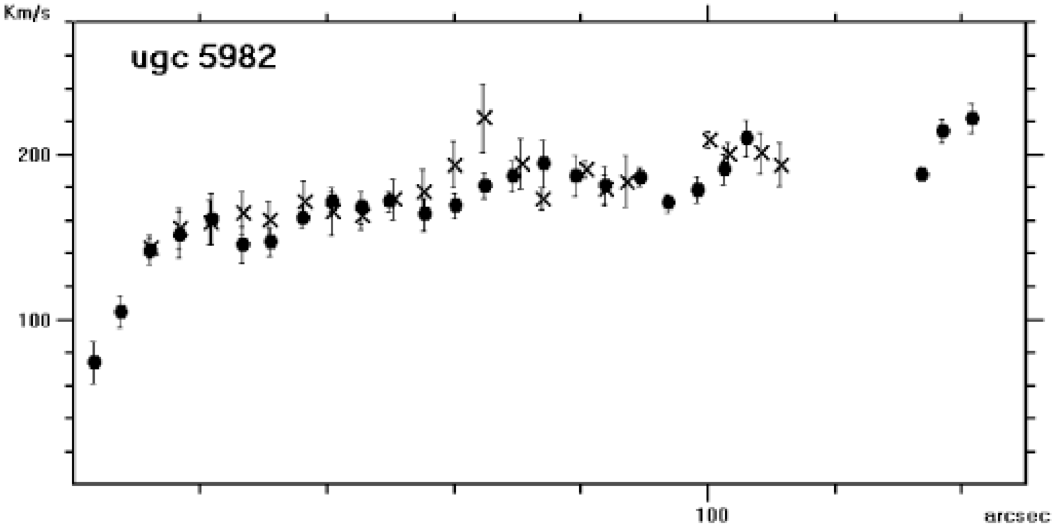
Internal Kinematics - Tracers

- **Optical**
  - Emission-lines (gaseous)
    - [OII] 3727,3729
    - Hb 4861
    - [OIII] 4959,5007
    - Ha 6562
    - NII
  - Absorption-line (stellar)
    - Mg triplet 5167,5173,5184
    - G-band 4300
    - Ca triplet 8498, 8542, 8662
    - Ca H + K 3934, 3968
  - Planetary nebulae ([OIII] 5007)
- **Radio**
  - Neutral hydrogen (HI)
  - Carbon Monoxide (CO)
  - SiO, OH and H_2O Masers in circumstellar envelopes

Internal Kinematics - Tracers





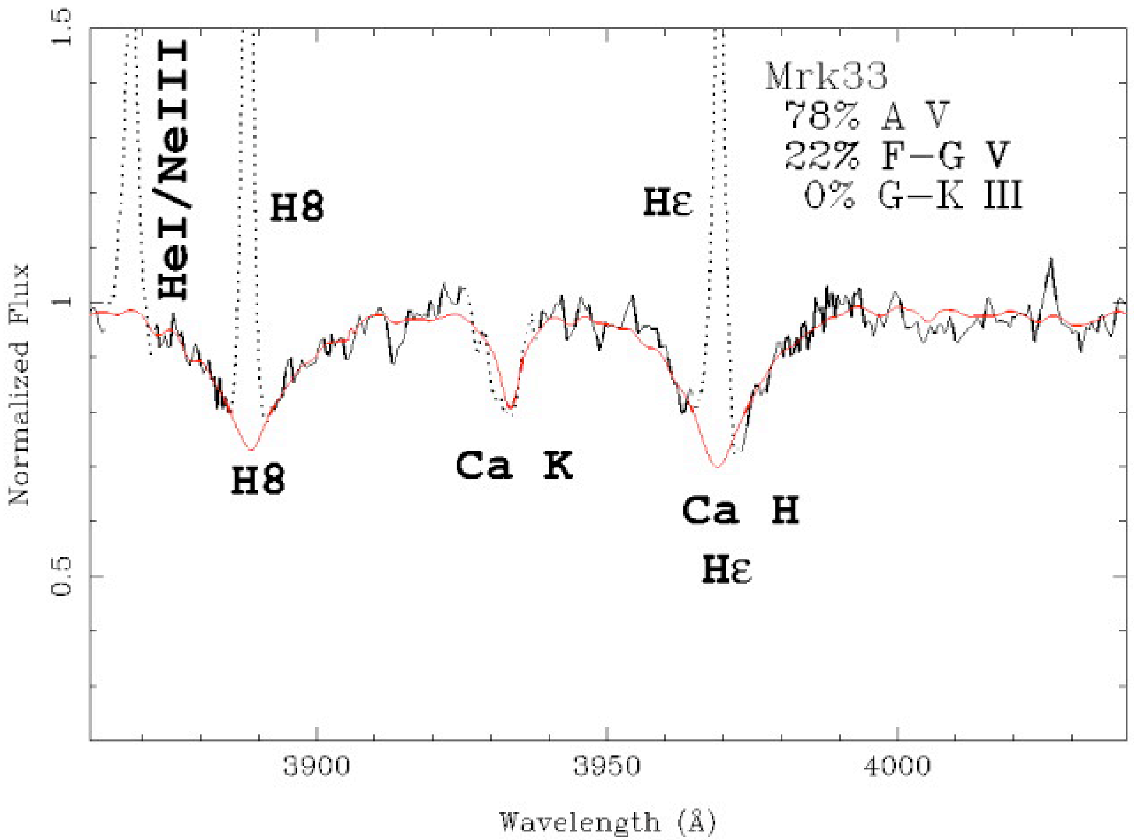


Hα emission line
(high spatial resolution)

GHASP Survey

Garrido et al. 2002, A+A, 387, 821

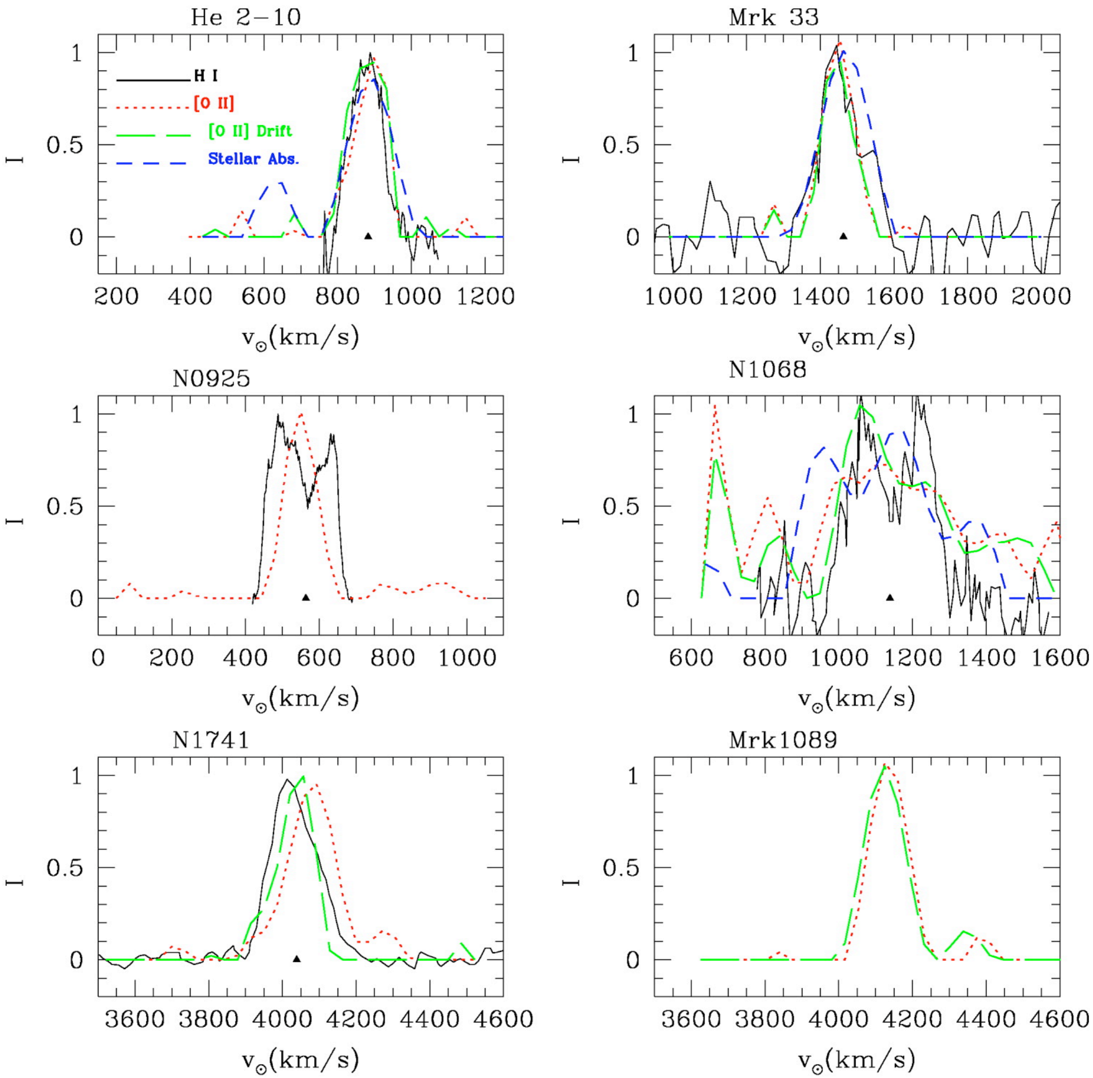
Internal Kinematics - Tracers



Ca H and K lines (Stellar velocity dispersion)

Kobulnicky & Gebhardt 2002, AJ, 119, 1608

Internal Kinematics - Tracers

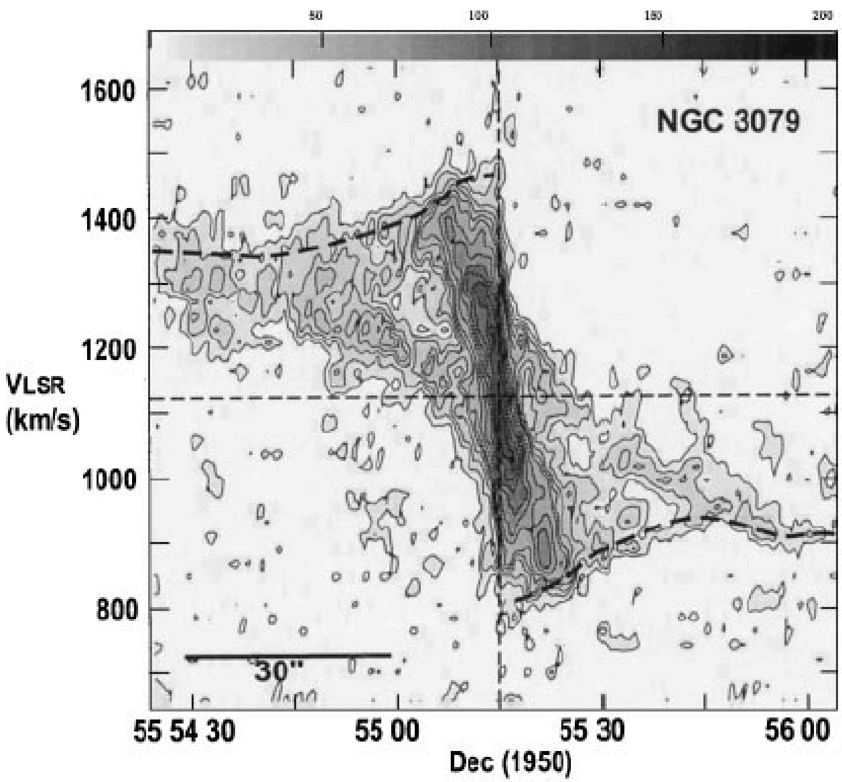


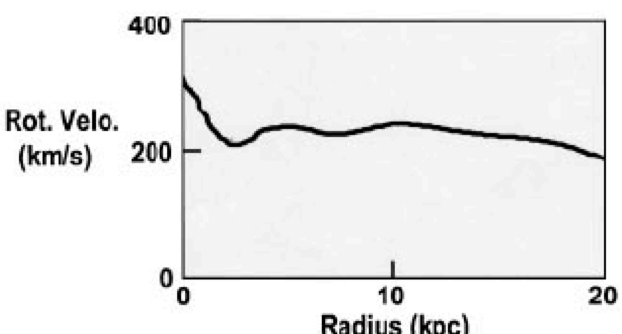
Neutral Hydrogen (HI)

Kobulnicky & Gebhardt

2002, AJ, 119, 1608

Internal Kinematics - Tracers





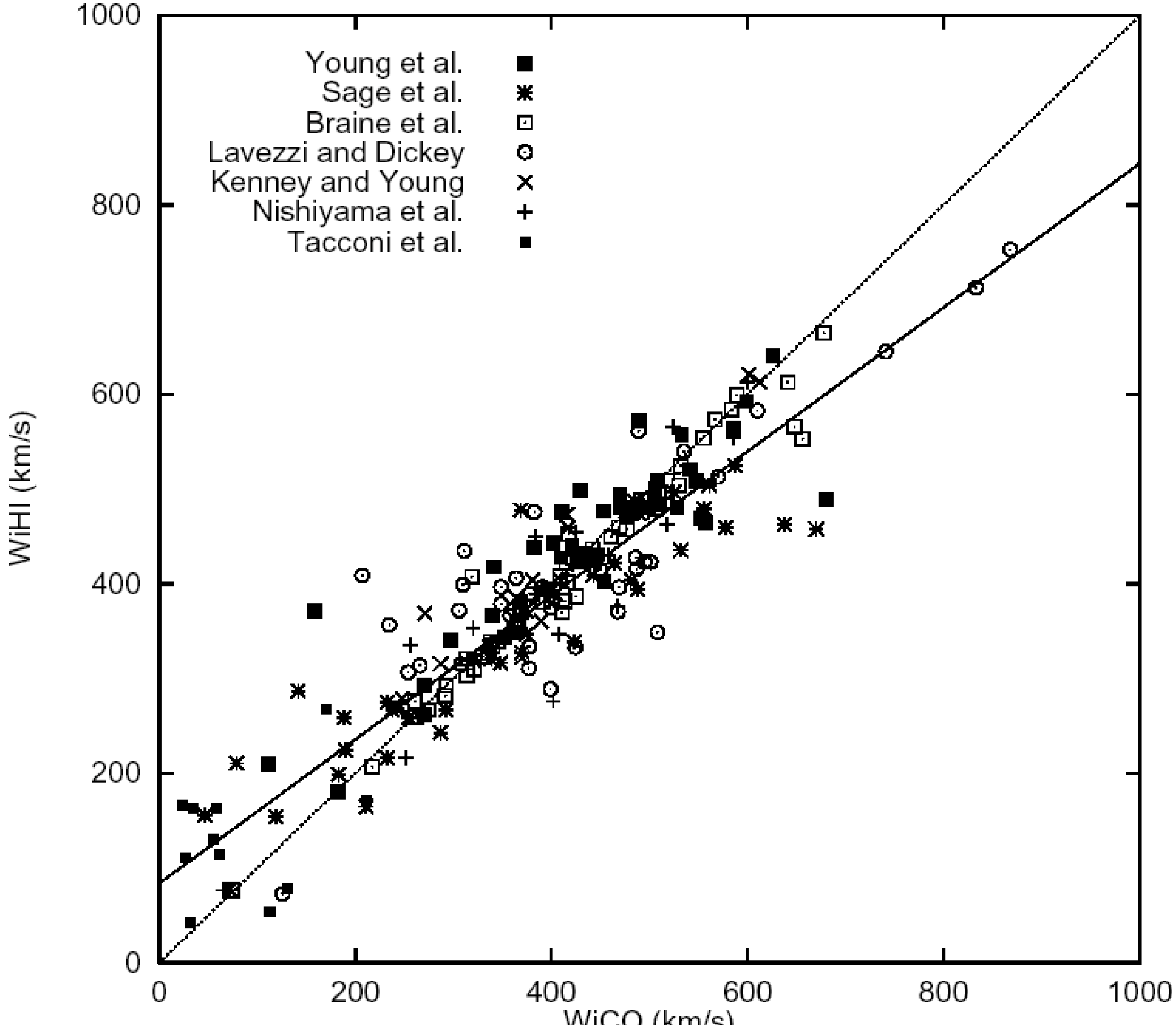
Carbon Monoxide (CO)

"arctan velocity field"

(Think ALMA ...)

Sofue et al.
1999, ApJ, 523, 136

Internal Kinematics - Tracer Comparison



HI versus CO (atomic versus molecular)

Tutui & Sofue 1999, A&A, 351, 467

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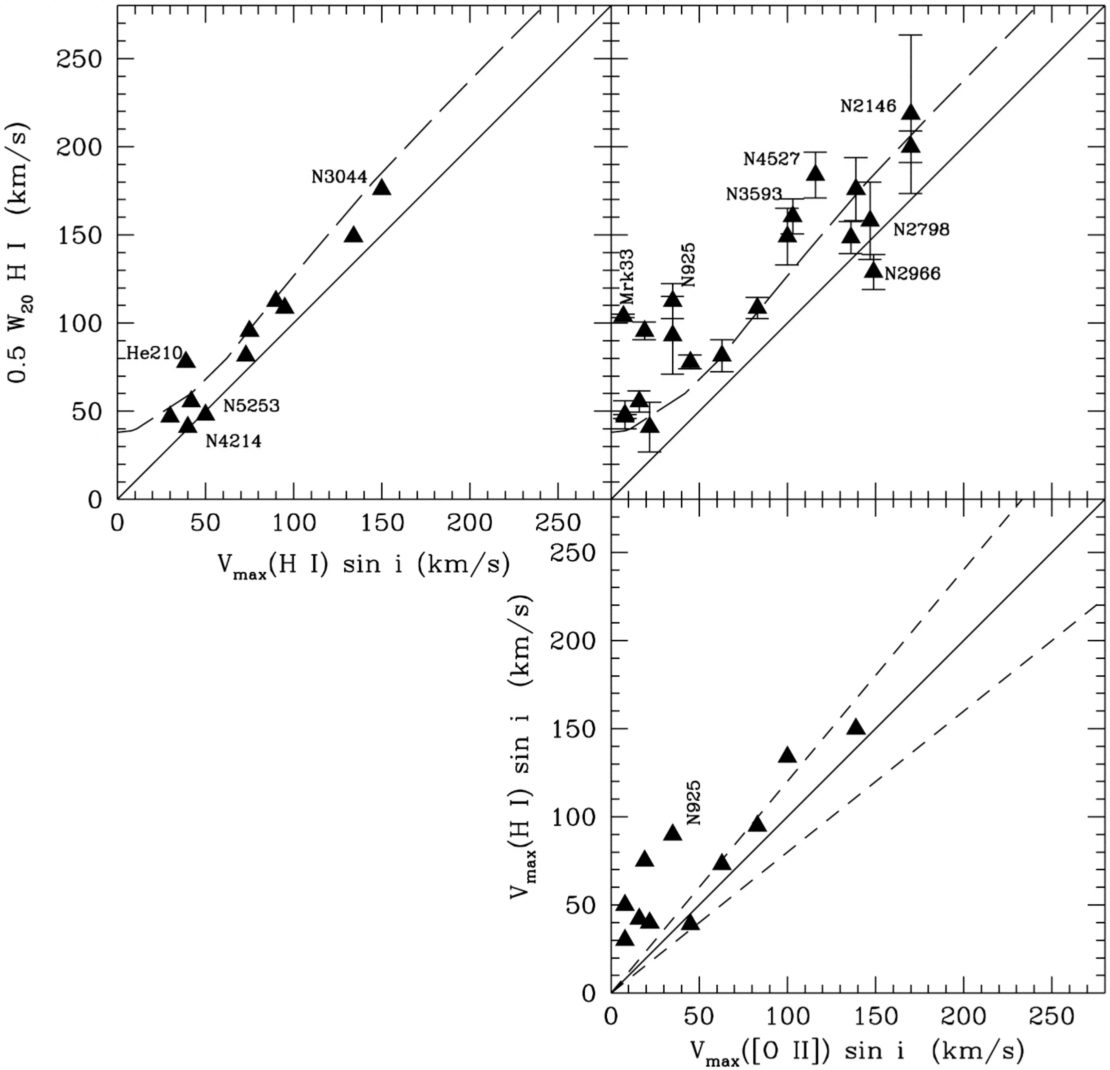
Internal Kinematics - Tracer Comparison



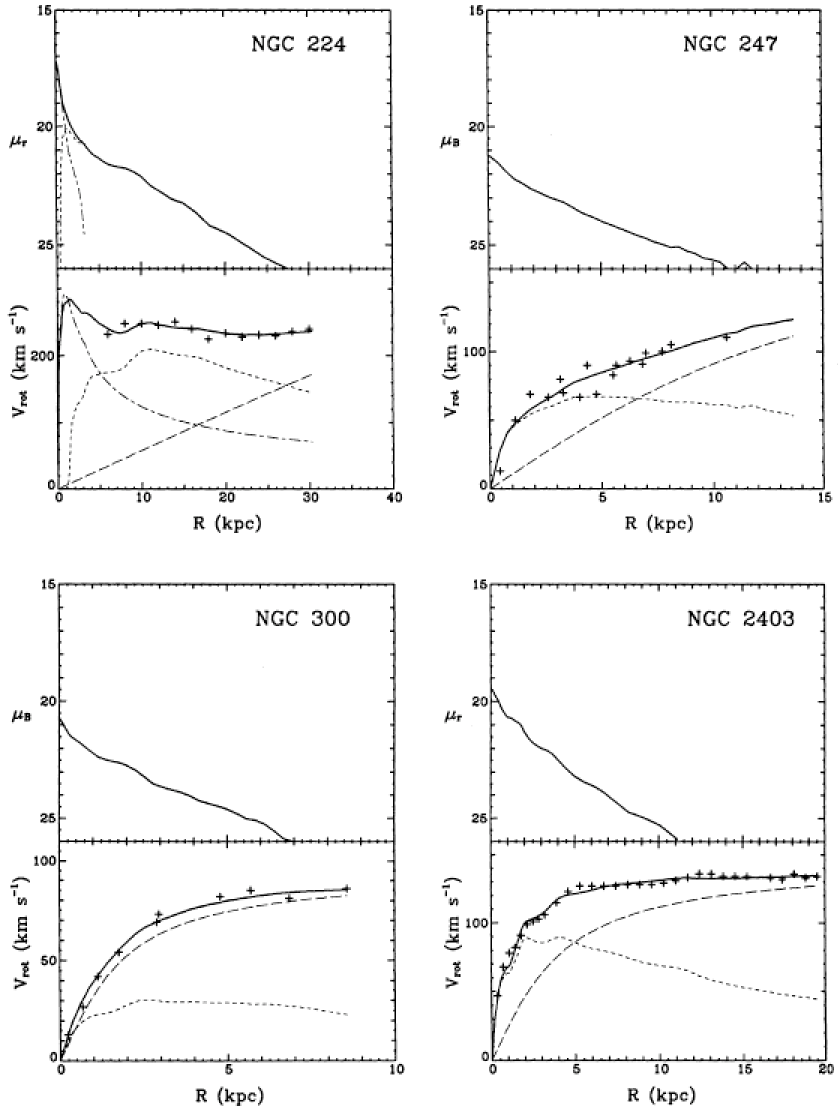
[OII] versus HI (very different spatial resolutions)

Kobulnicky & Gebhardt 2002, AJ, 119, 1608

Internal Kinematics - Types of Motion

- Basic components ("Easier to measure")
  - Rotation (V_c or V_{rot})
  - Dispersion (σ)
- Peculiar motions ("Hard to measure")
  - Massive black holes and circumnuclear rotation
  - Counter-rotation
    - Nuclear disks
    - Extended disks
    - Decoupled cores
  - Resonance rings
  - Lopsided gas
  - Bars, warps, supershells
  - Interactions and mergers

Internal Kinematics - Rotation Curves

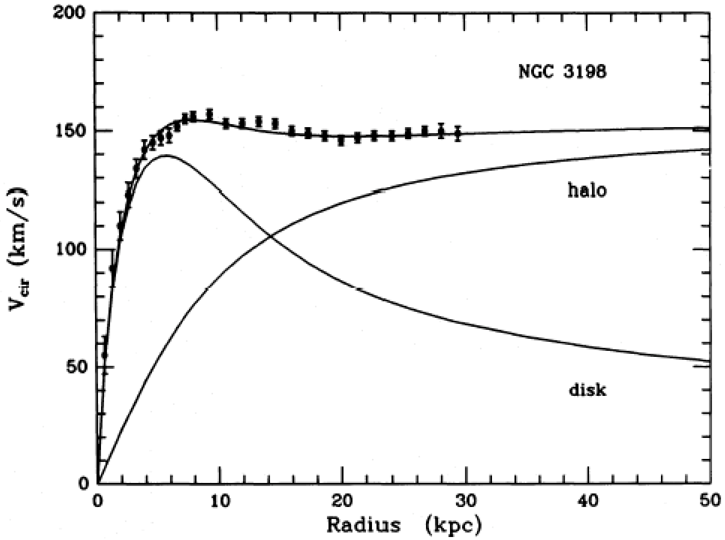


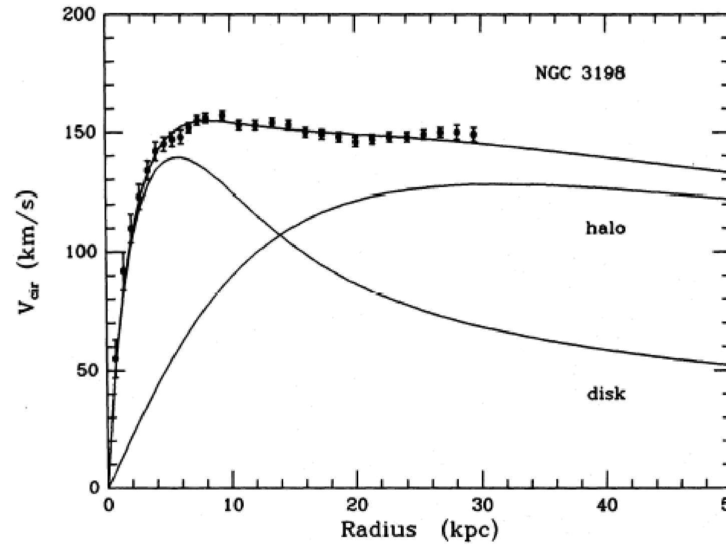
The outer parts of disk galaxy rotation curves are “flat”, i.e., M(r) α r

One of the best pieces of evidence
for the existence of dark matter

Kent 1987, AJ, 93, 816

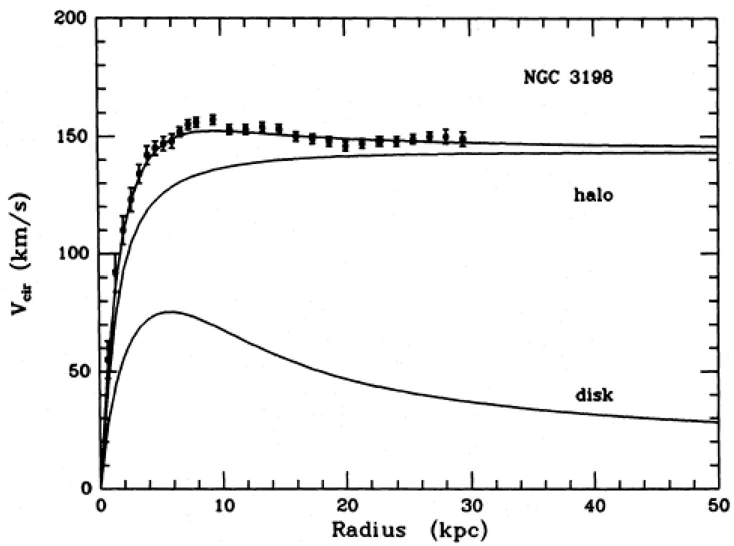
Mass-Halo Degeneracy

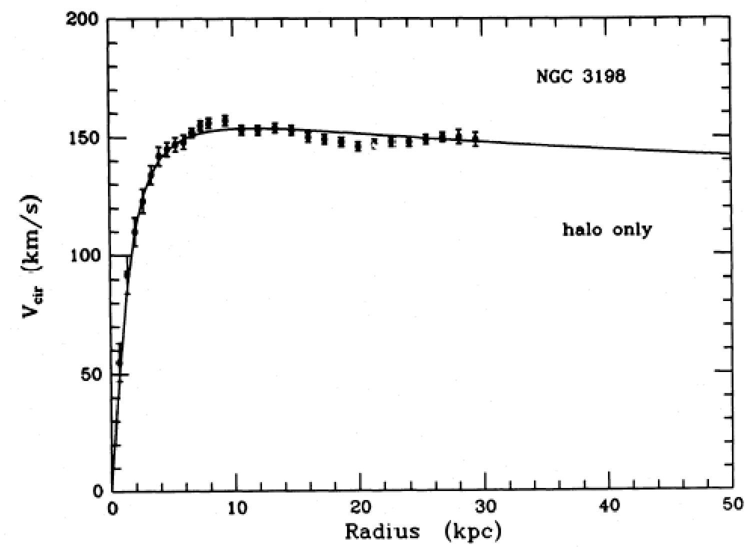




Mass decompositions are <u>degenerate</u>

Are disks "maximal"?





van Albada et al. 1985, ApJ, 295, 305

Rotation Curves - Cores

Can rotation curves help us determine the shape of dark matter halos?

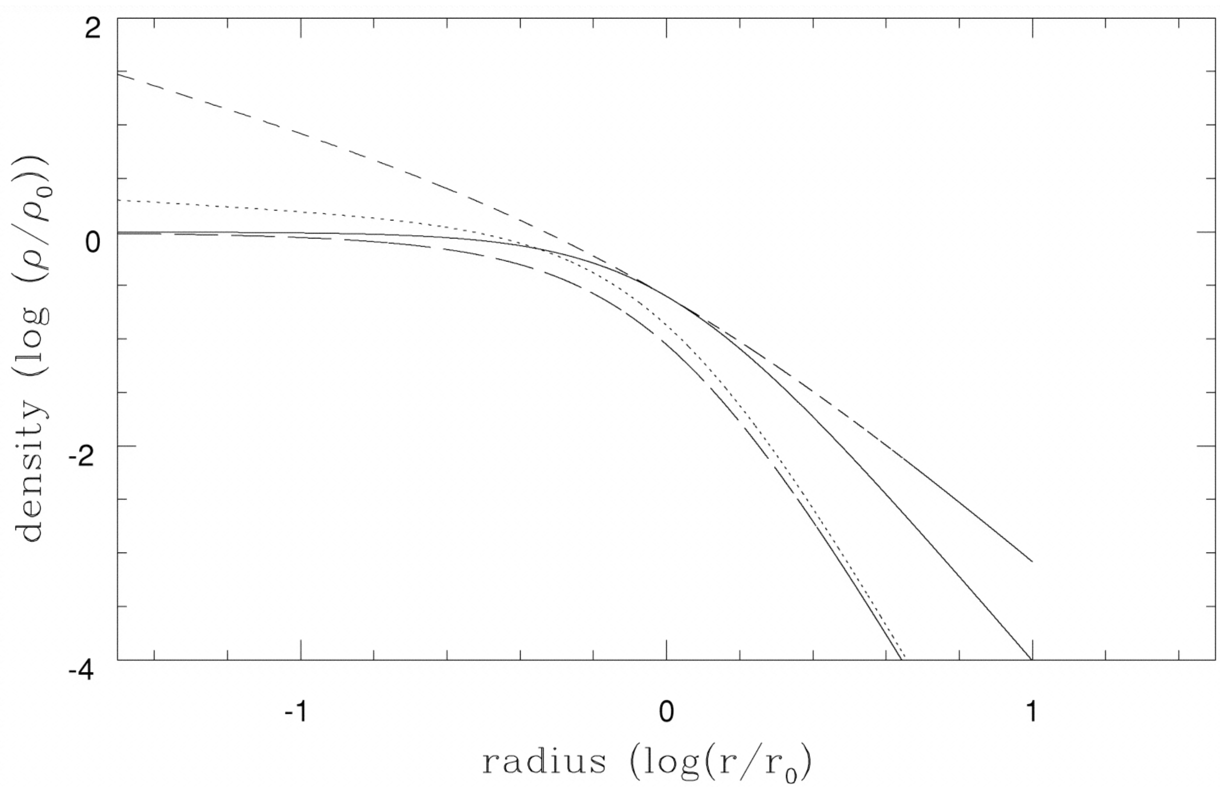
$$\rho(r) = \frac{\rho_0}{[c + (r/r_0)^{\gamma}][1 + (r/r_0)^{\alpha}]^{(\beta-\gamma)/\alpha}},$$

where ρ_0 and r_0 are characteristic density and radius. The constant c forces the presence of a flat core. The parameters, α, β, and γ, determine the shape of the halo profile.

Four different models for (c, α, β, γ):

1. **Pseudo-isothermal sphere (1, α != 0, 2, 2)**
2. **Navarro-Frenk-White (0, 1, 3, 1)**
3. **Burkert (1, 2, 3,1)**
4. **Klypin et al. (0, 2, 3, 0.2)**

Rotation Curves - Cores



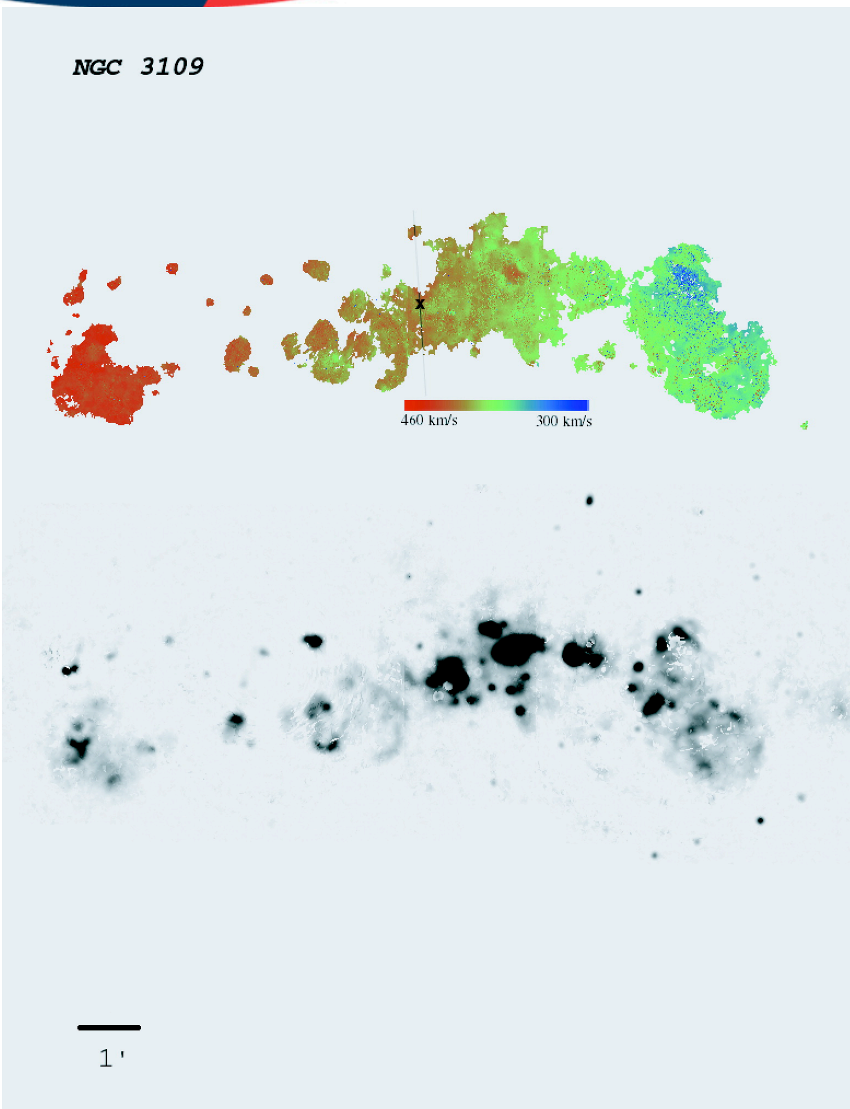
Pseudo-isothermal (solid)

Klypin (dotted)

Burkert (long-dashed)

NFW (short-dashed)

Rotation Curves - Cores



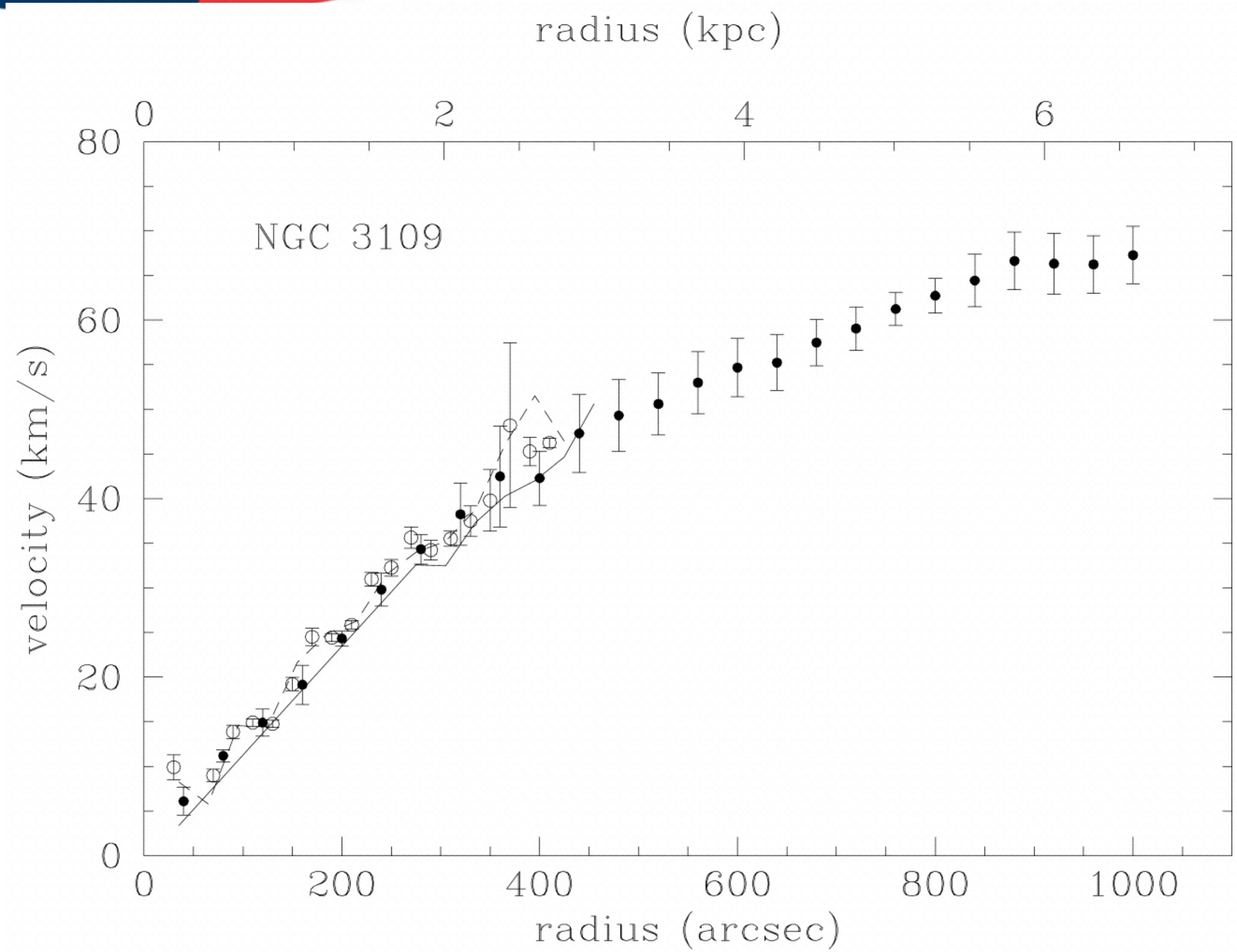
<u>Very</u> inhomogenous emission-line gas distribution

Slit observations are not adequate

Use Integral Field Spectroscopy

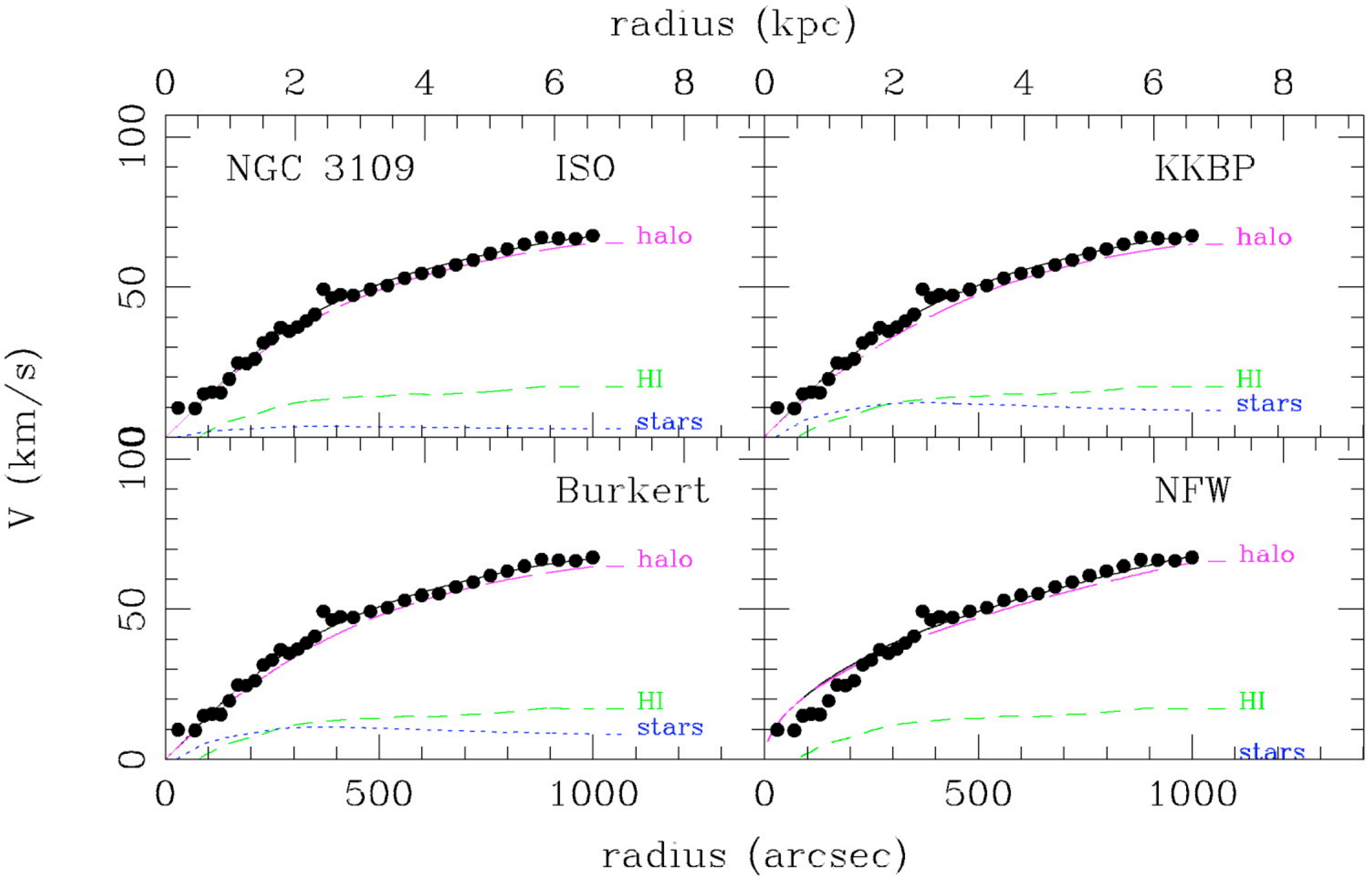
Blais-Ouellette et al. 2001, AJ, 121, 1952

Rotation Curves - Cores



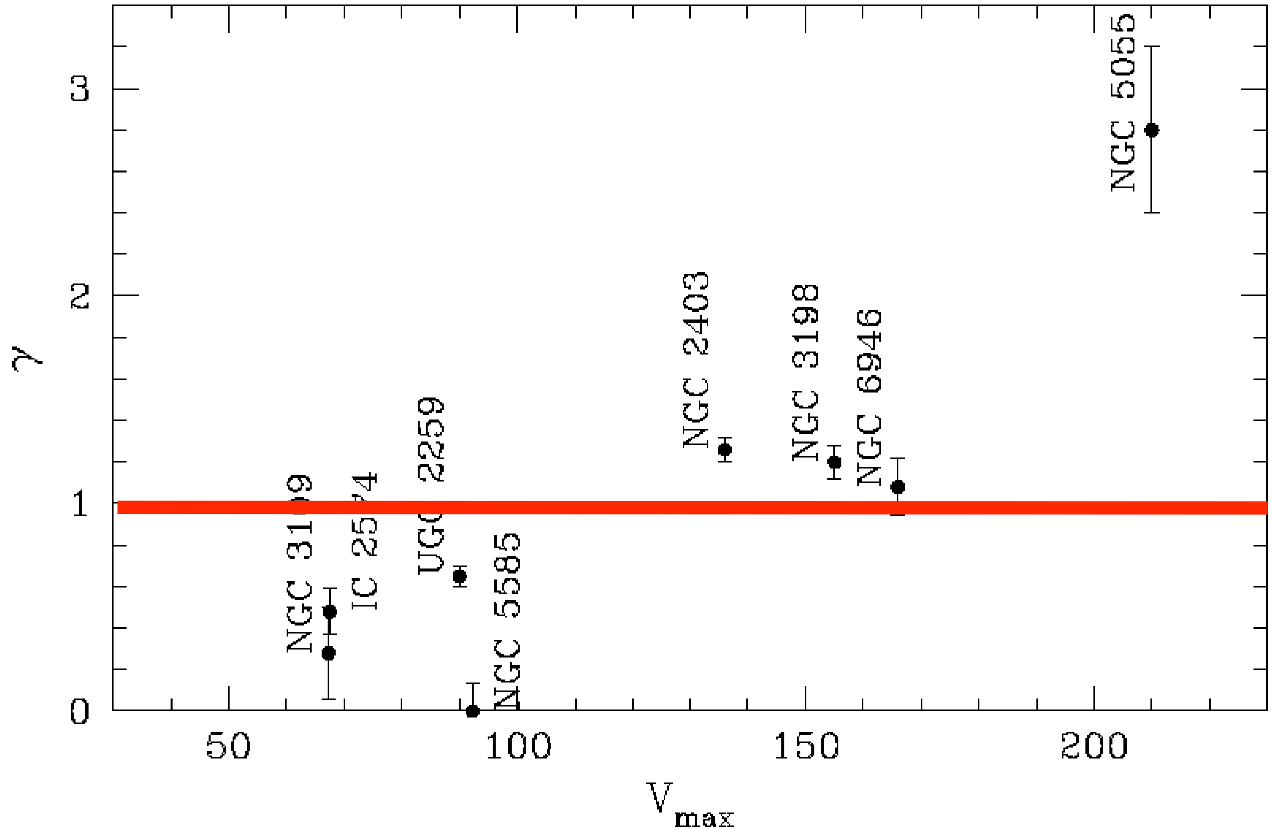
Blais-Ouellette et al. 2001, AJ, 121, 1952

Rotation Curves - Cores



Blais-Ouellette et al. 2001, AJ, 121, 1952

Rotation Curves - Cores

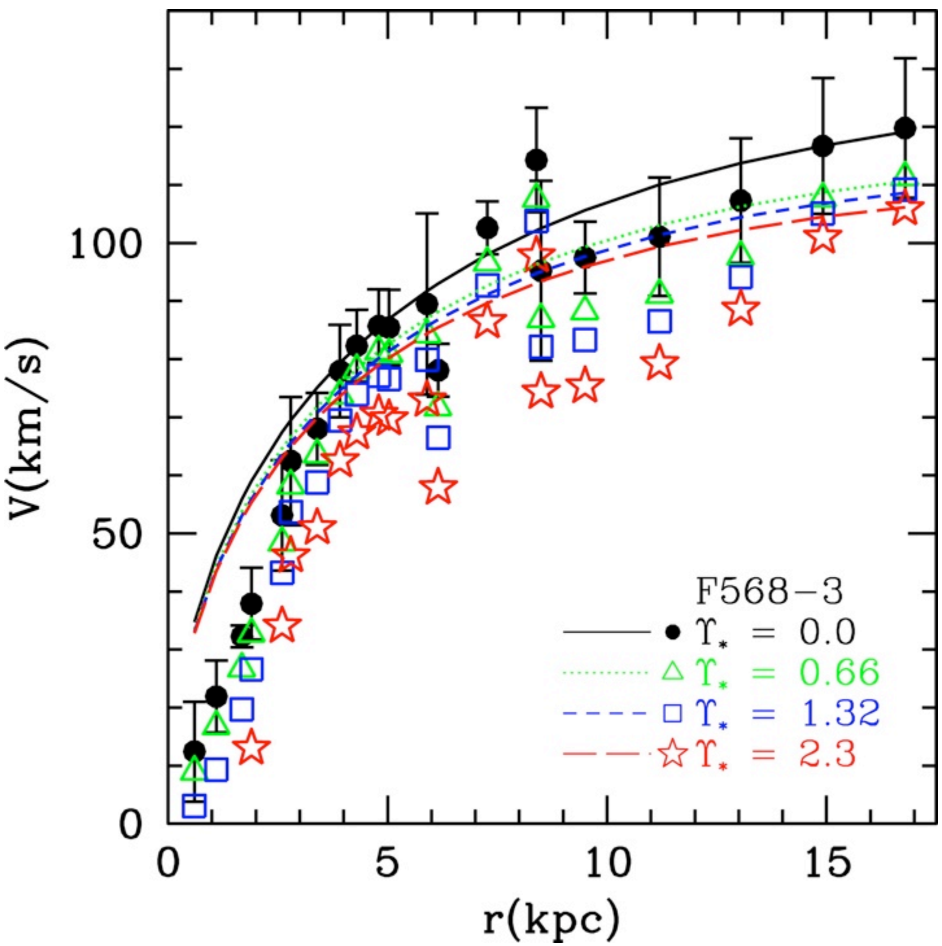


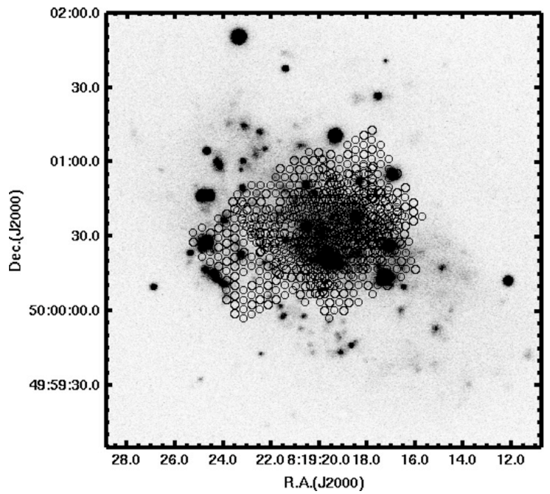
``Cuspy" profiles

Figure 3. Inner logarithmic slope (γ) of the CDM halos. Note that N-body simulations give $\gamma \geq 1$.

Blais-Ouellette et al. 2002, astro-ph/0203146

Velocity Fields - Cores





More mass in the core of NFW profiles than allowed in full 2D IFU velocity fields

Kuzio de Naray et al. 2008, ApJ, 676, 920

Scaling Relations

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Scaling Relations

- Galaxies have a fundamental set of physical properties
  - Mass
  - Size
  - Angular momentum

- These physical properties translate into observables
  - Luminosity or mass-to-light ratio
  - Velocity (rotation and/or dispersion)
  - Size
    - Half-light radius (R_{hl} or R_e)
    - Disk scale length (R_d or h)

- Basic questions : What are the underlying relations (if any) among galaxy properties and what do they tell us about galaxy formation?

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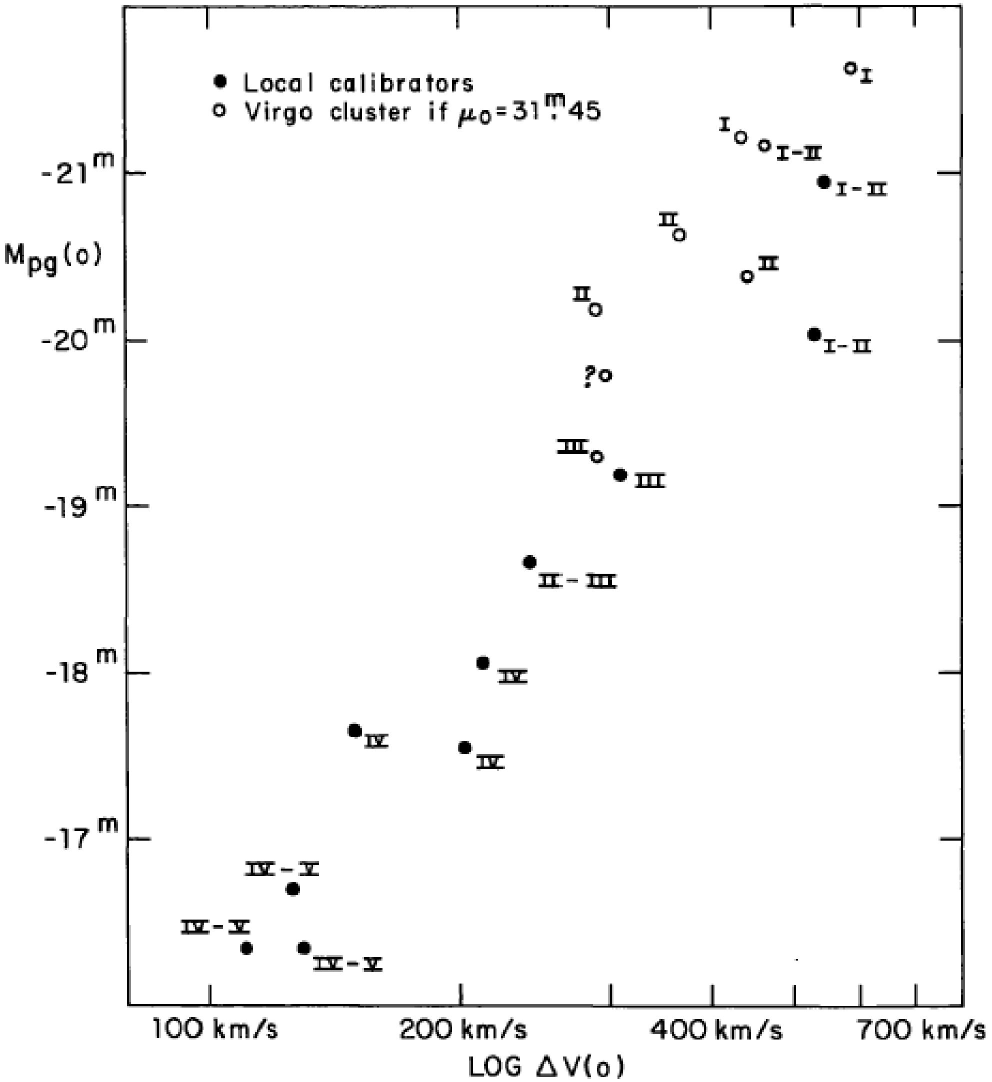
Scaling Relations - Observables

- Luminosity
  - Integrated
  - Disk-only (model dependent)
  - Choice of bandpass
- Velocity
  - Integrated?
  - Rotation curve: where do you measure V_c ?
    - Peak
    - Flat region
    - Intermediate radius (~ 2.2 R_d)
- Size
  - Half-light radius
  - Disk scale length (model dependent)

Tully-Fisher Relation - History

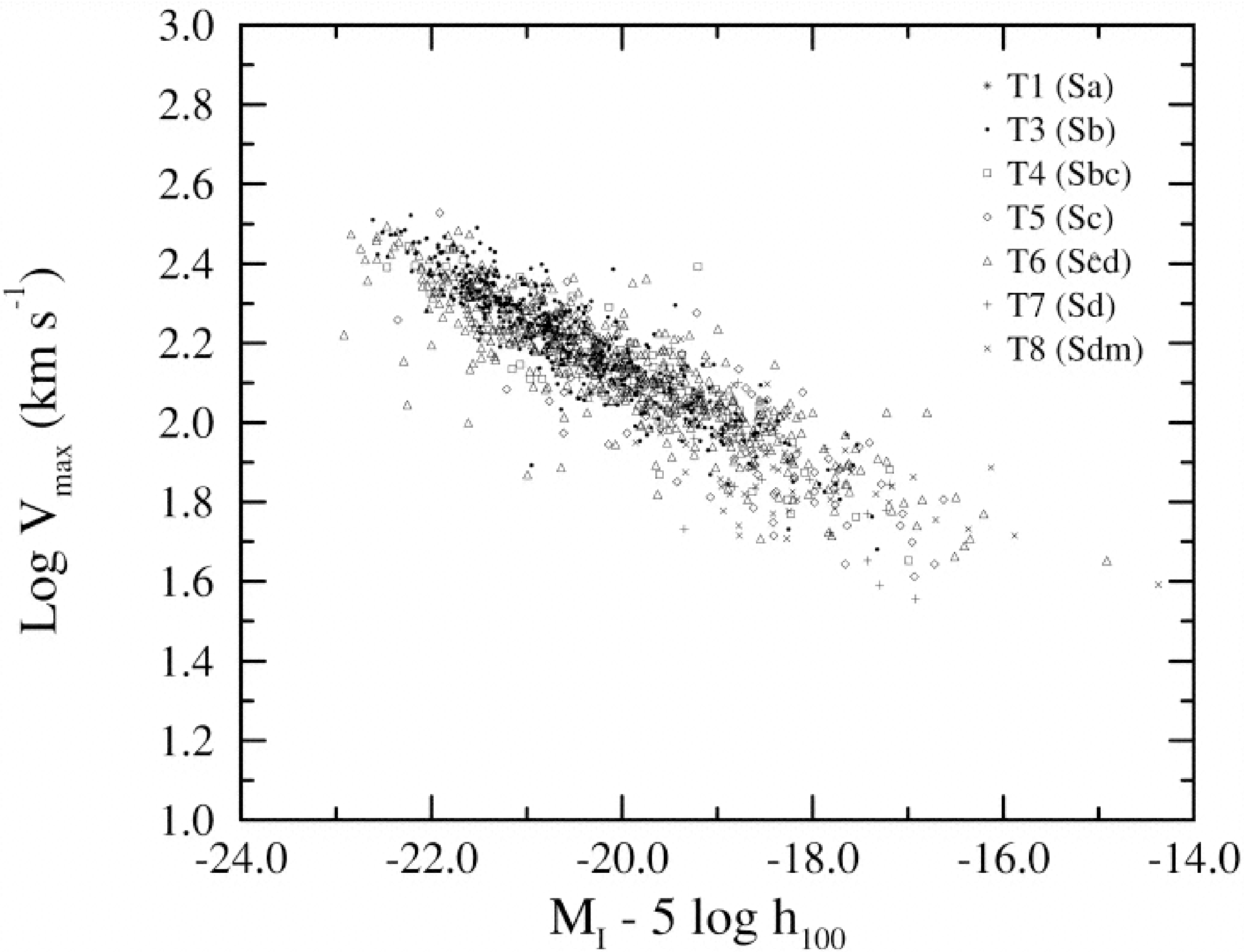
- Opik (1922) : Assume all spiral nebulae have same M/L => distance to M31 of 450 kpc (!!!)
  - (We know $V^2 = GM/R$. Assume $L \sim R^2$, then $L \propto V^4$)
- Hubble (1936) : Failed to recognize use as a distance indicator
- Roberts (1962)
- Balkowski et al. (1974) : HI width is correlated with luminosity
- Tully & Fisher (1977): Hey! Please use correlation as a distance indicator!!!

Tully-Fisher Relation - History



Tully & Fisher 1977, A&A, 54, 66

Tully-Fisher Relation - Modern Version



Simard & Pritchet 1998, ApJ, 505, 96

Using data for 1355 galaxies from Mathewson et al. 1992, ApJS, 81, 413

Tully-Fisher Relation - Biases and Corrections

- Inclination measurements from direct optical images
  - Disks may not be circular (q_0 = 0.11- 0.20)
  - Disks may not have constant ellipticity
  - Disks are not infinitely thin (+seeing)

$$i = \cos^{-1}\sqrt{\frac{(b/a)^2 - q_0^2}{1 - q_0^2}} ,$$

- Spectral resolution : $W^2_{raw} = W^2_{gal} + W^2_{res}$

- Internal extinction

$$A_i^\lambda = \gamma_\lambda \log\left(\frac{a}{b}\right) ,$$

- Turbulence (HI)

$$W_R^2 = W_{20}^2 + W_t^2 - 2W_t W_{20}\left(1 - e^{-W_{20}^2/W_c^2}\right) - 2W_t^2 e^{-W_{20}^2/W_c^2} + 4W_{\rm dwarf}^2 ,$$

- Malmquist bias

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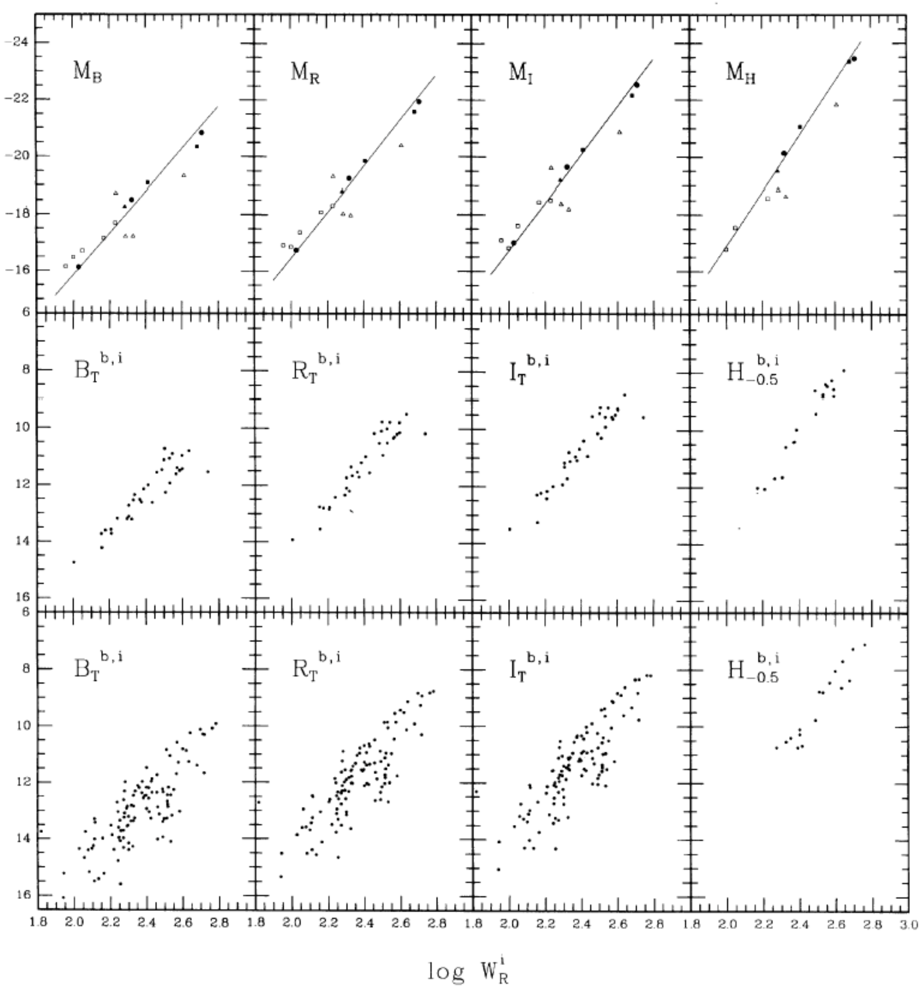
Tully-Fisher Relation - Slope

Local

Ursa Major

Virgo



Slope steepens towards redder bandpasses (real?)

Jacoby et al. 1992, PASP, 104, 599

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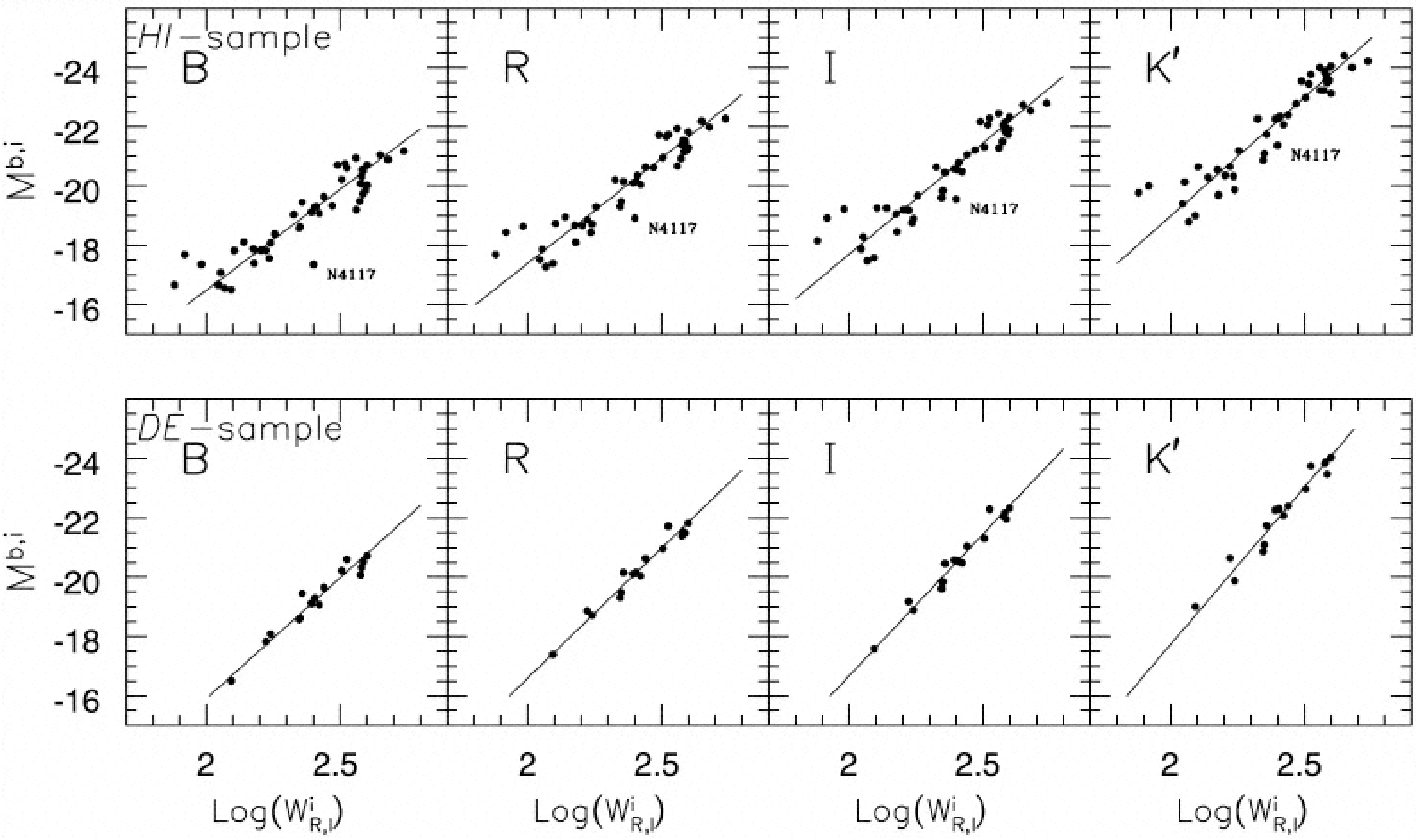
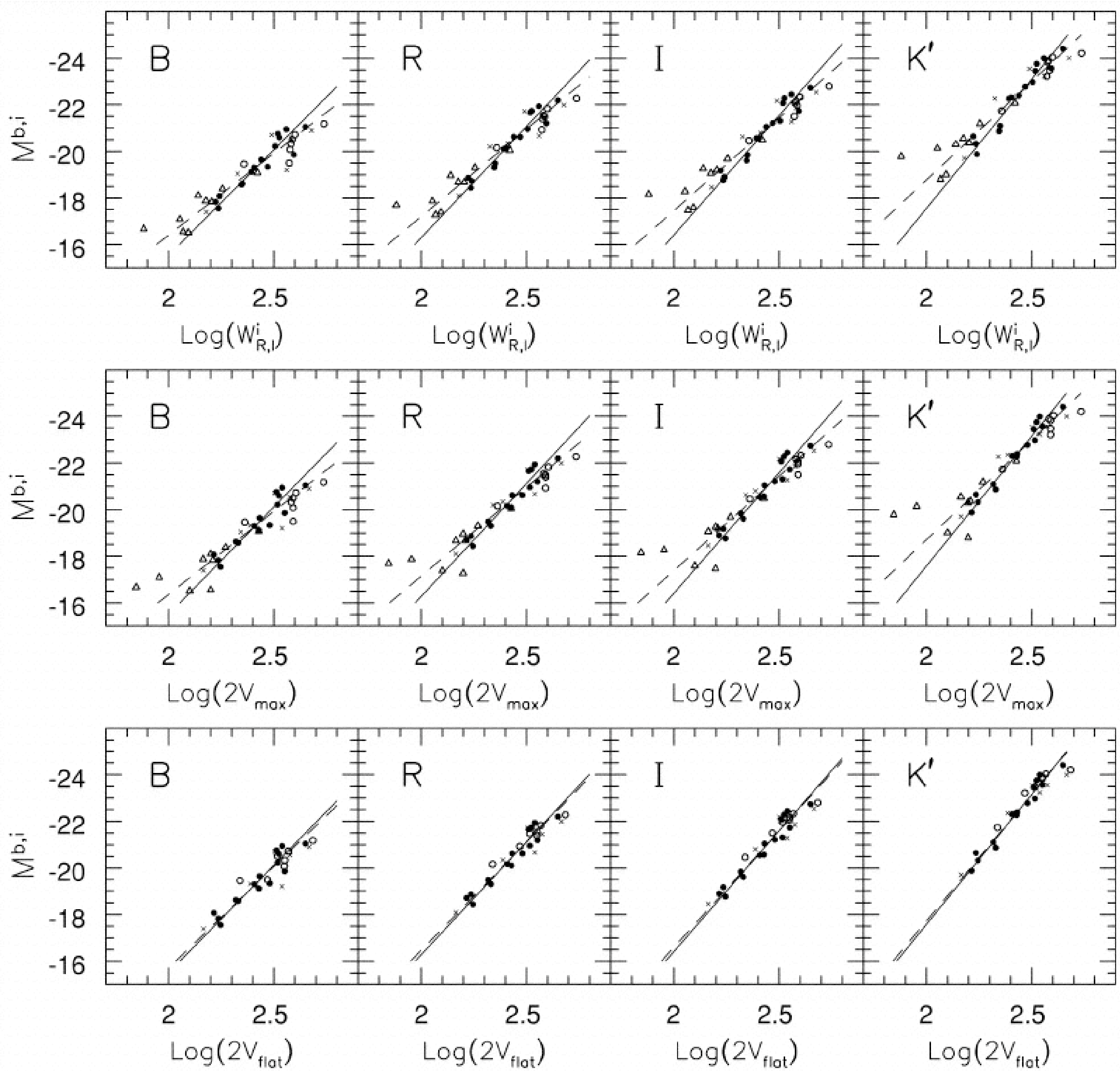
Tully-Fisher Relation - Slope



"Pruning"

Verheijen 2001
ApJ, 563, 694

Tully-Fisher Relation - Scatter



Which radius should be used for V?

Verheijen 2001 ApJ, 563, 694

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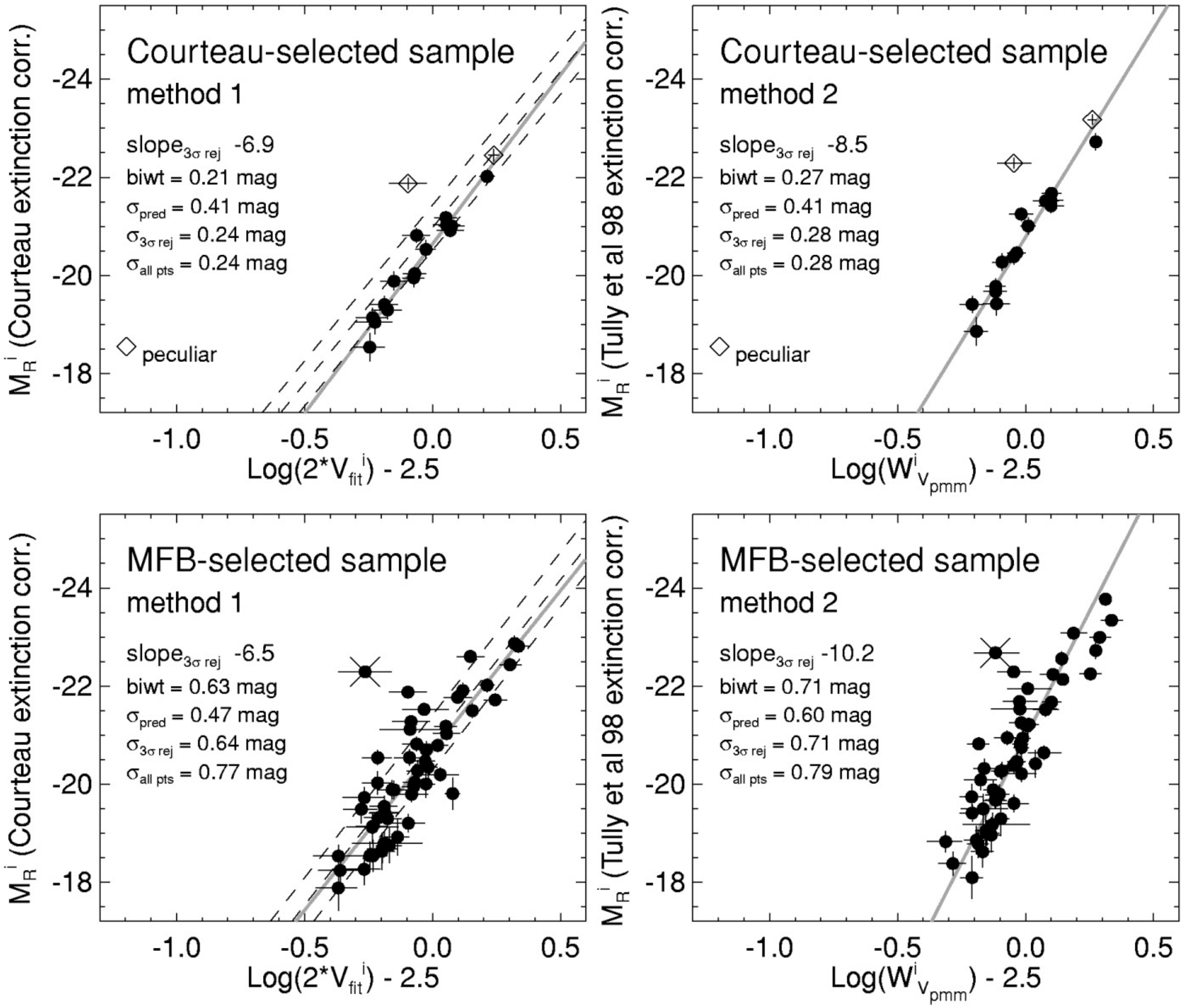
Tully-Fisher Relation - Scatter

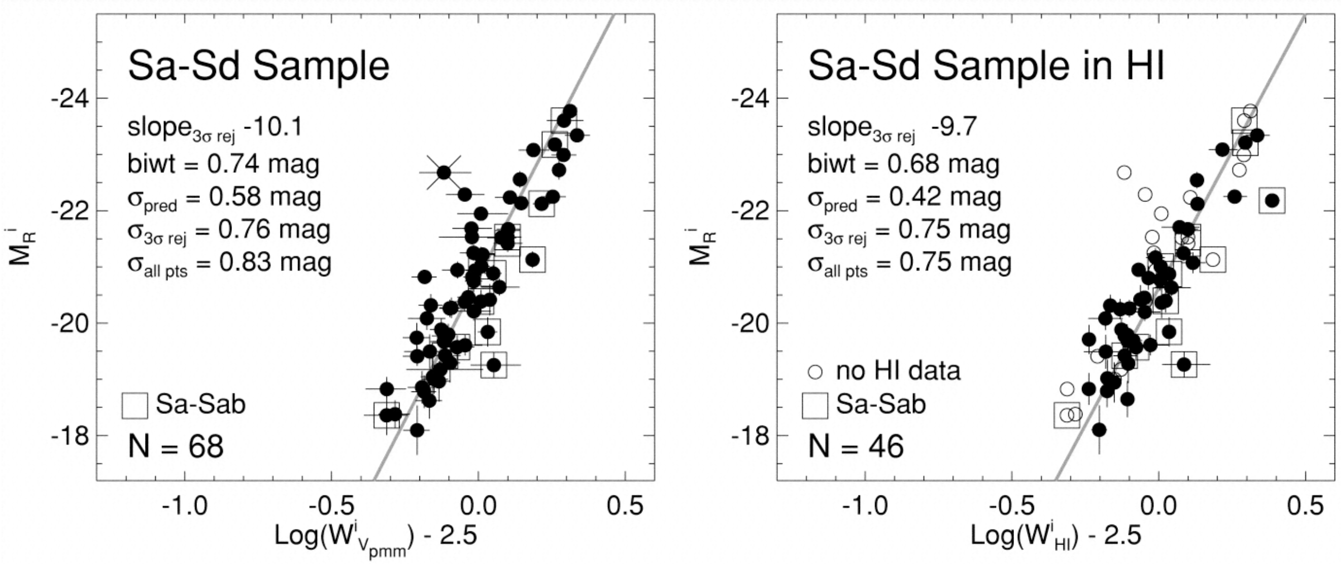


Samples for TF distances are "pruned"

Choice of internal extinction and fitting method can change results dramatically

Kannappan et al. 2002, AJ, 123, 2358

Tully-Fisher Relation - Scatter



Sa galaxies exhibit offsets:

0.76 mag in R
0.95 mag in B
1.20 mag in U

Kannappan et al. 2002
AJ, 123, 2358

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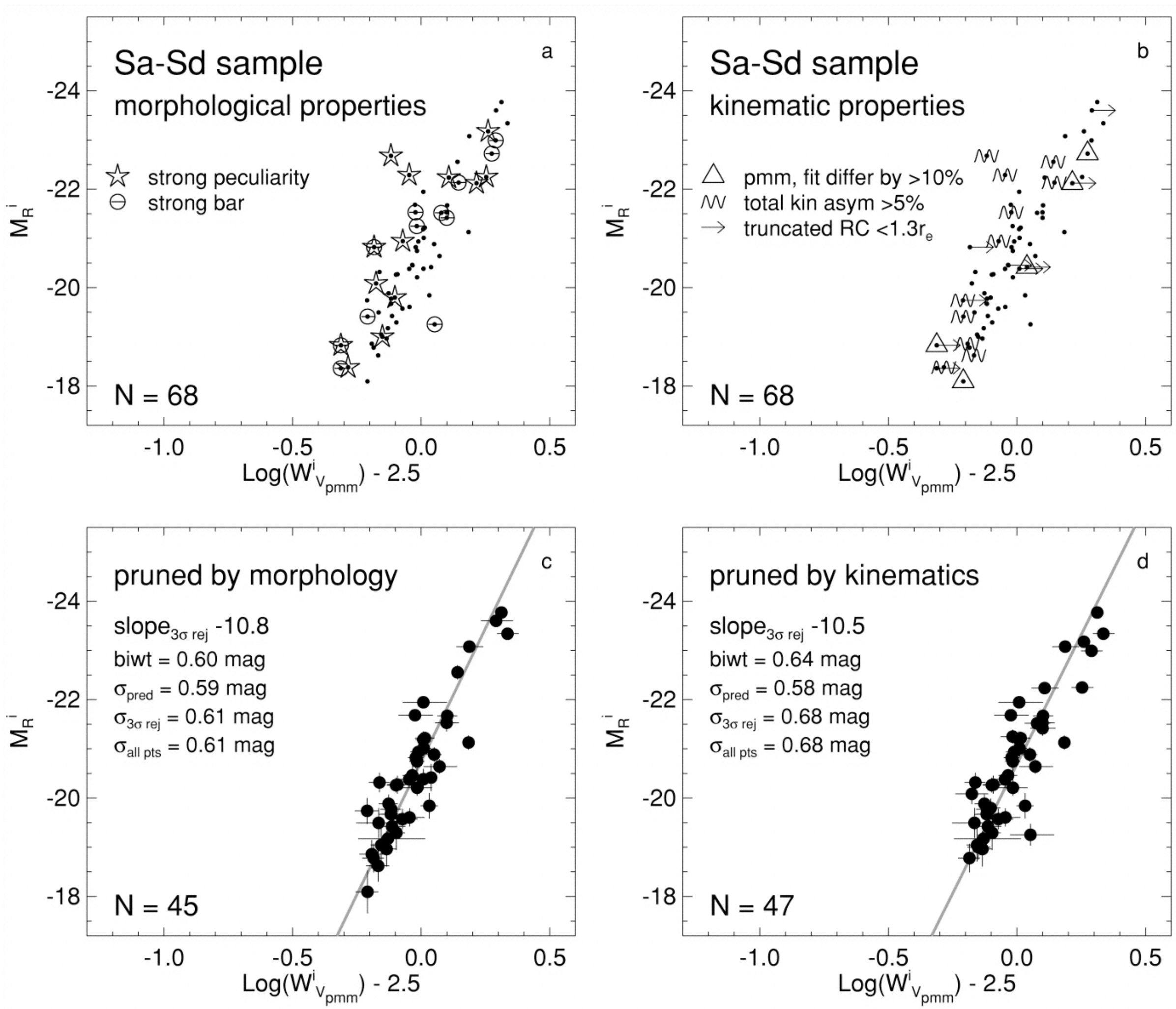
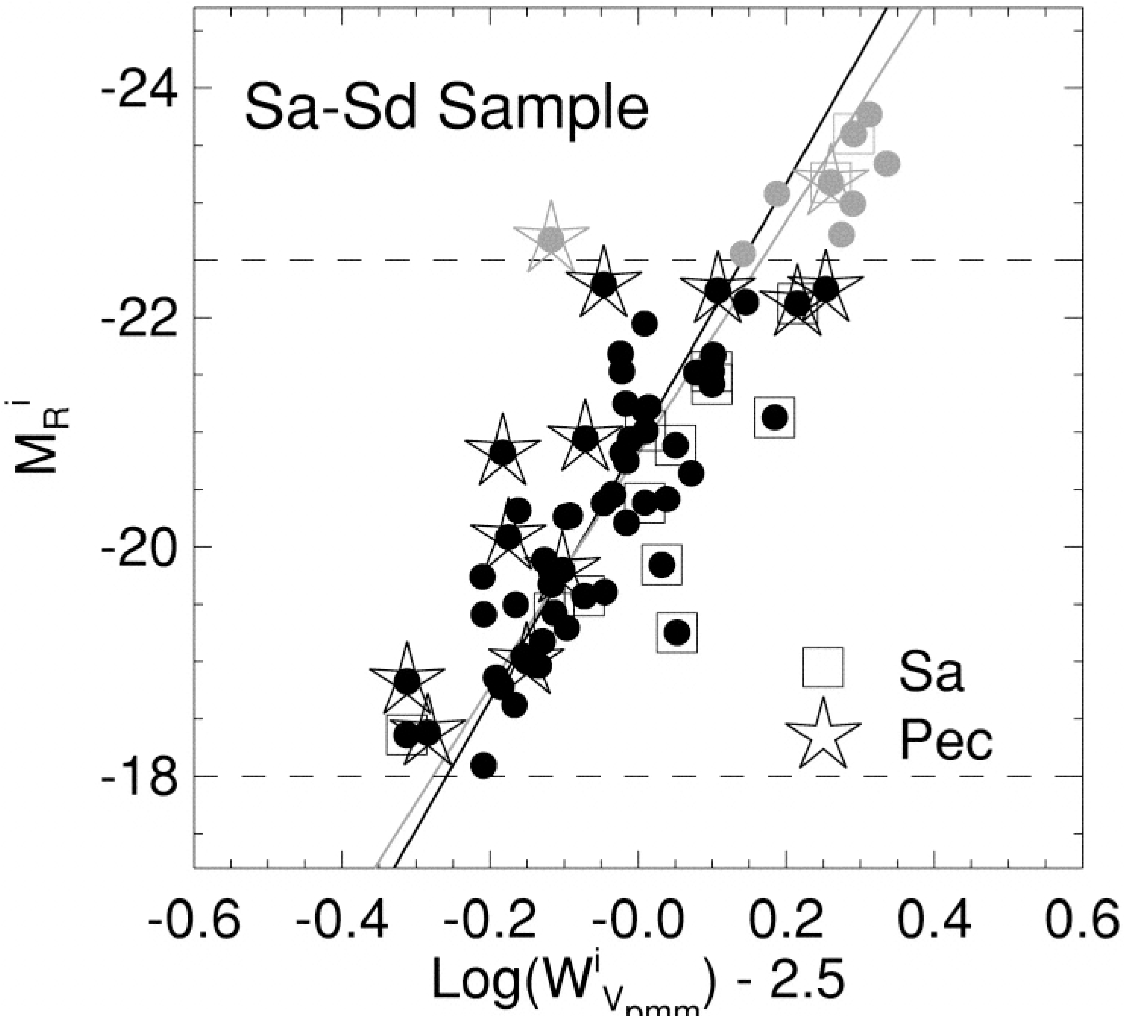
Tully-Fisher Relation - Scatter



Pruning by morphology and kinematics

Kannappan et al. 2002, AJ, 123, 2358

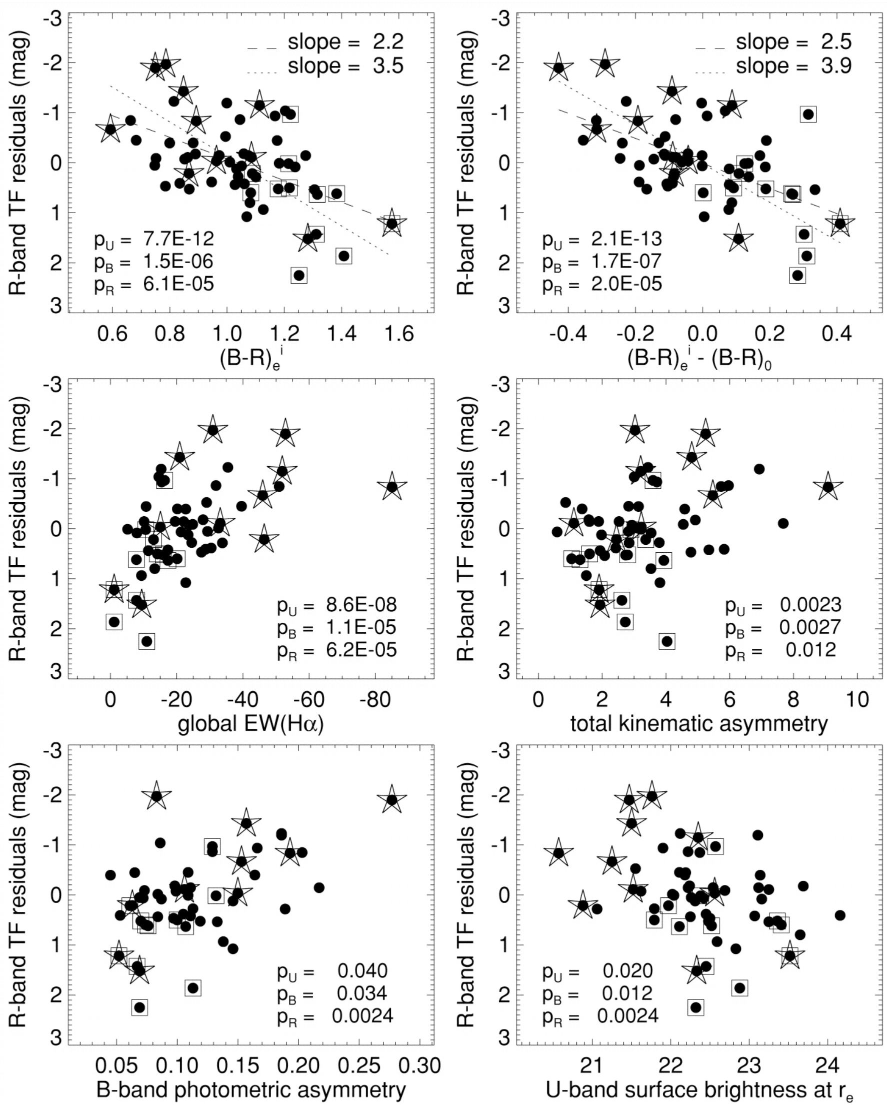
Tully-Fisher Relation - Scatter



Scatter depends on morphology

Kannappan et al. 2002, AJ, 123, 2358

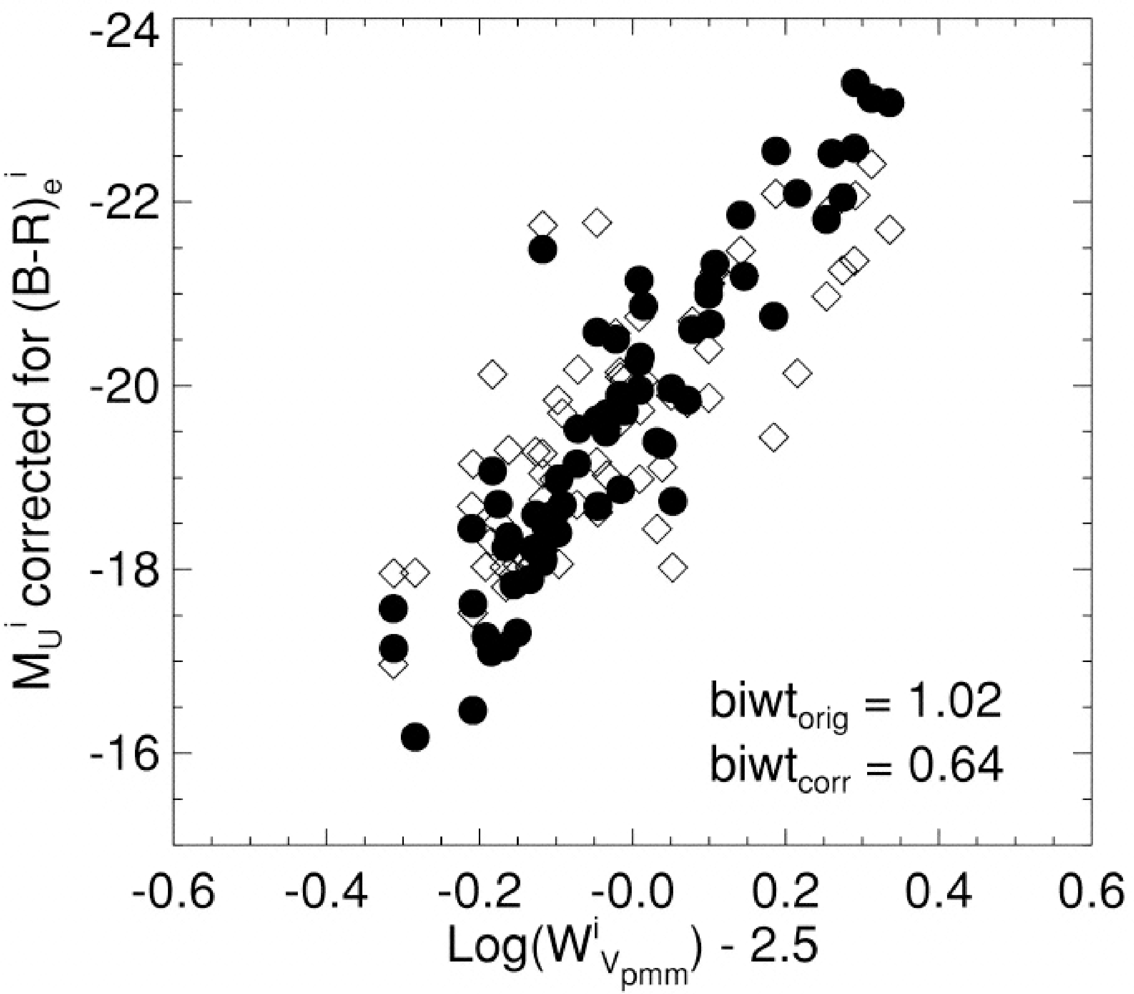
Tully-Fisher Relation - Scatter



Systematic dependence of residuals on color and EW(Hα)

Kannappan et al. 2002 AJ, 123, 2358

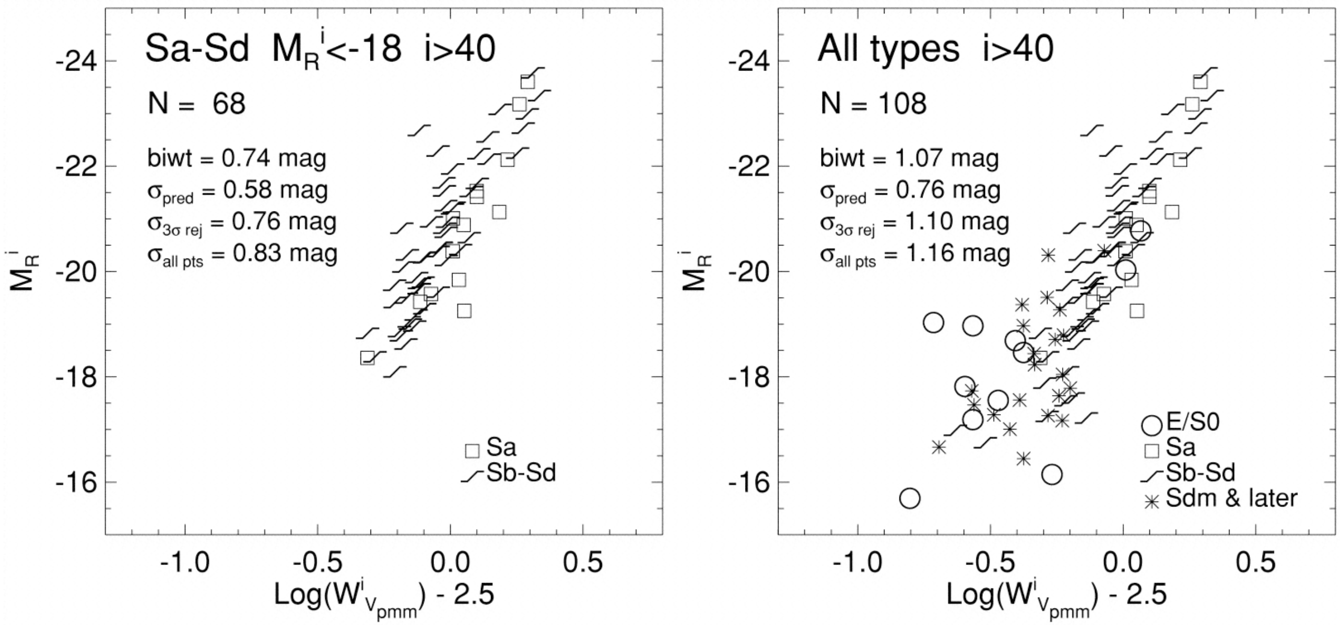
Tully-Fisher Relation - Scatter



Color correction reduces scatter

Kannappan et al. 2002, AJ, 123, 2358

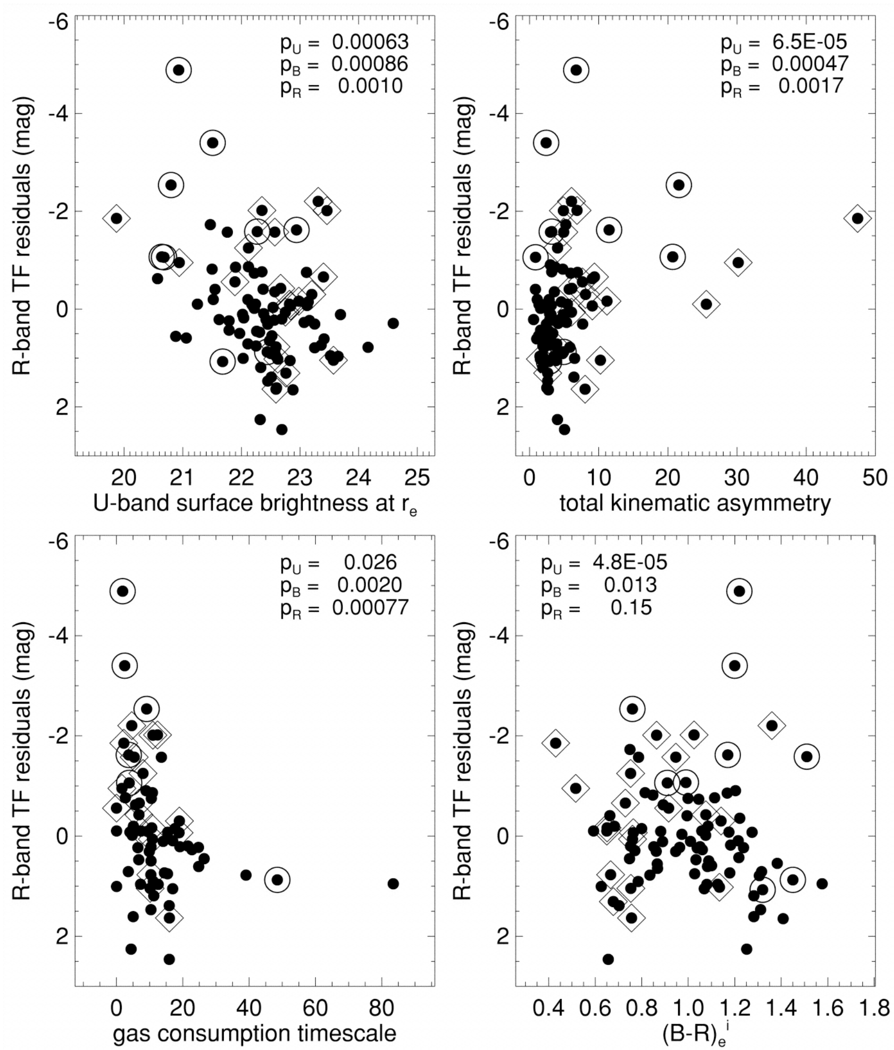
Tully-Fisher Relation - Scatter



Including all types and luminosities increases scatter

Kannappan et al. 2002, AJ, 123, 2358

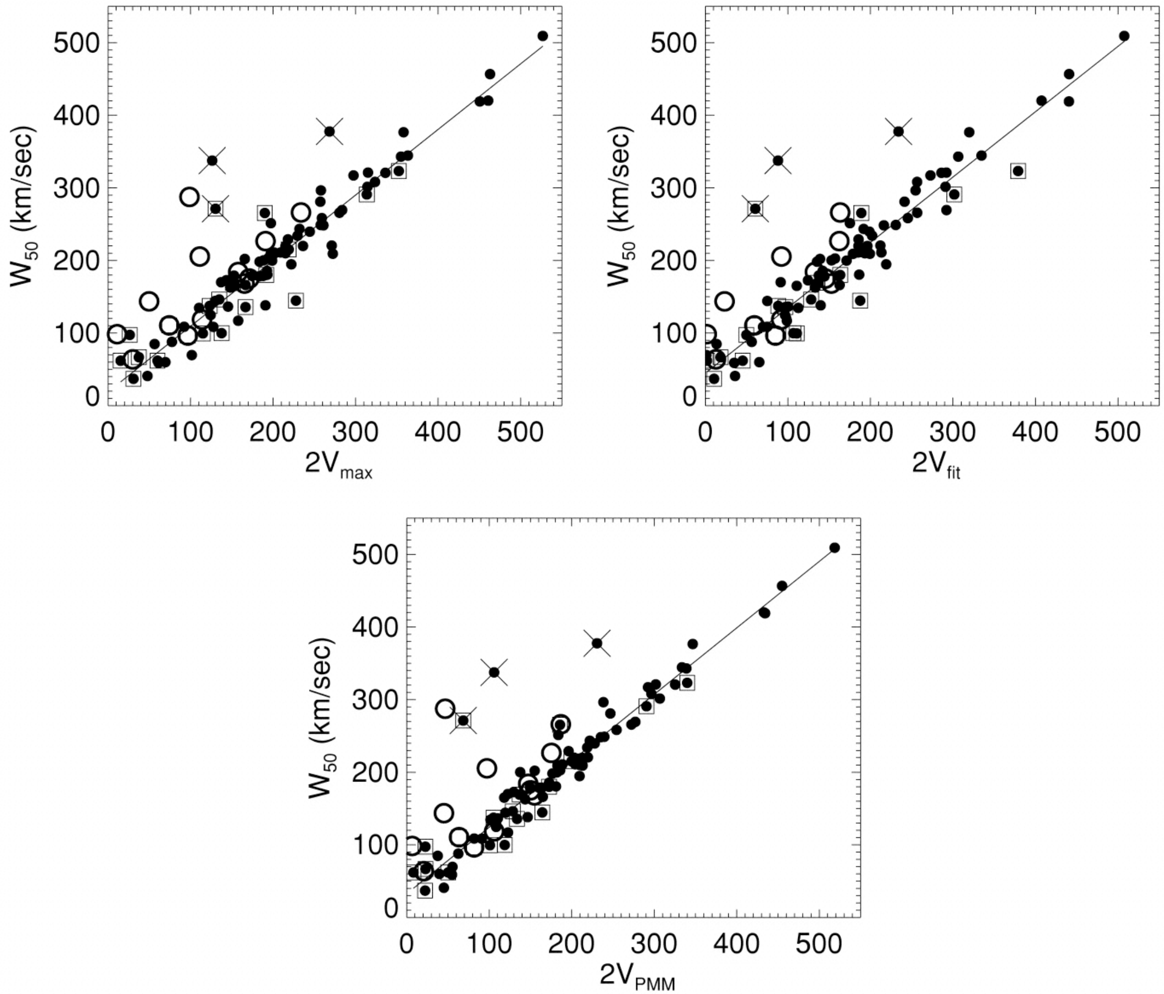
Tully-Fisher Relation - Scatter



Scatter is neither correlated with surface brightness nor with gas consumption

Kannappan et al. 2002, AJ, 123, 2358

Tully-Fisher Relation - Turbulence



Turbulence introduces an offset

Kannappan et al. 2002, AJ, 123, 2358

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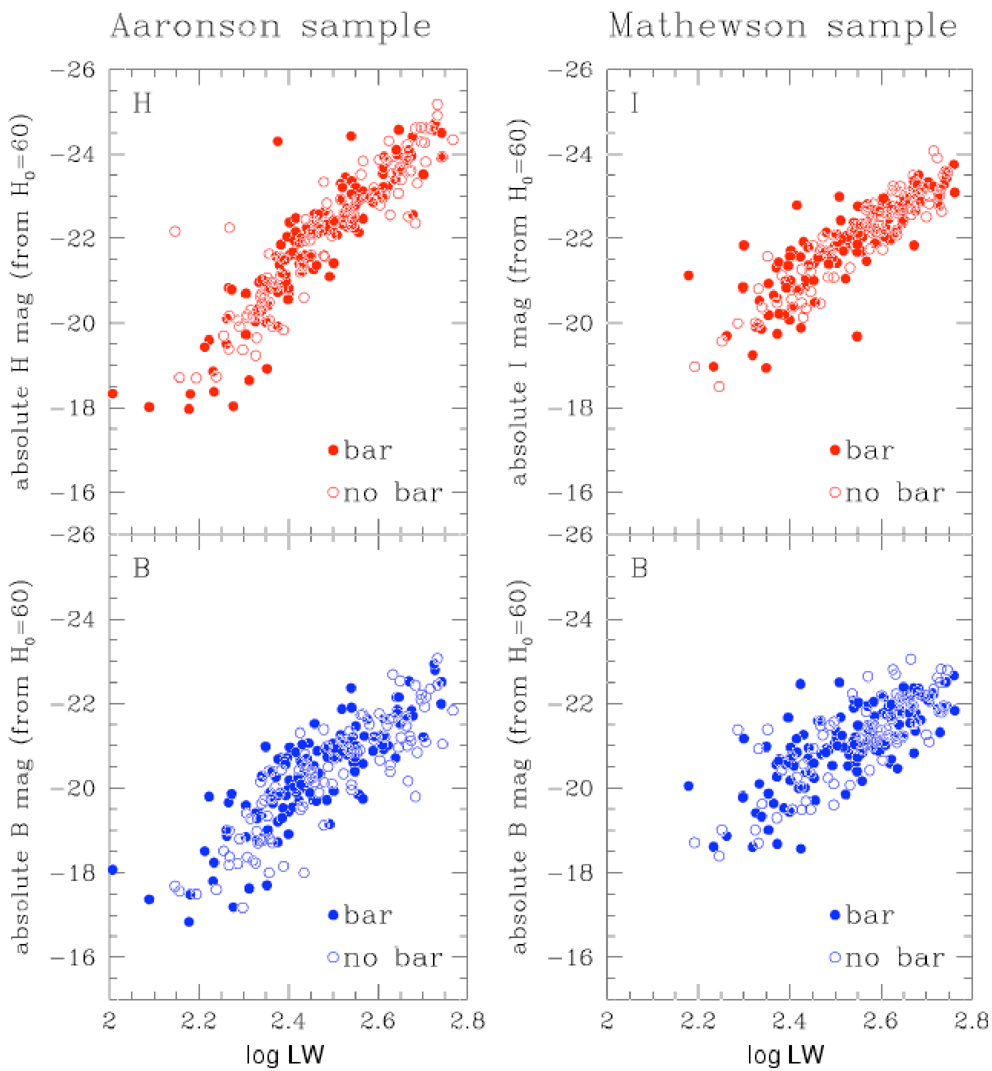
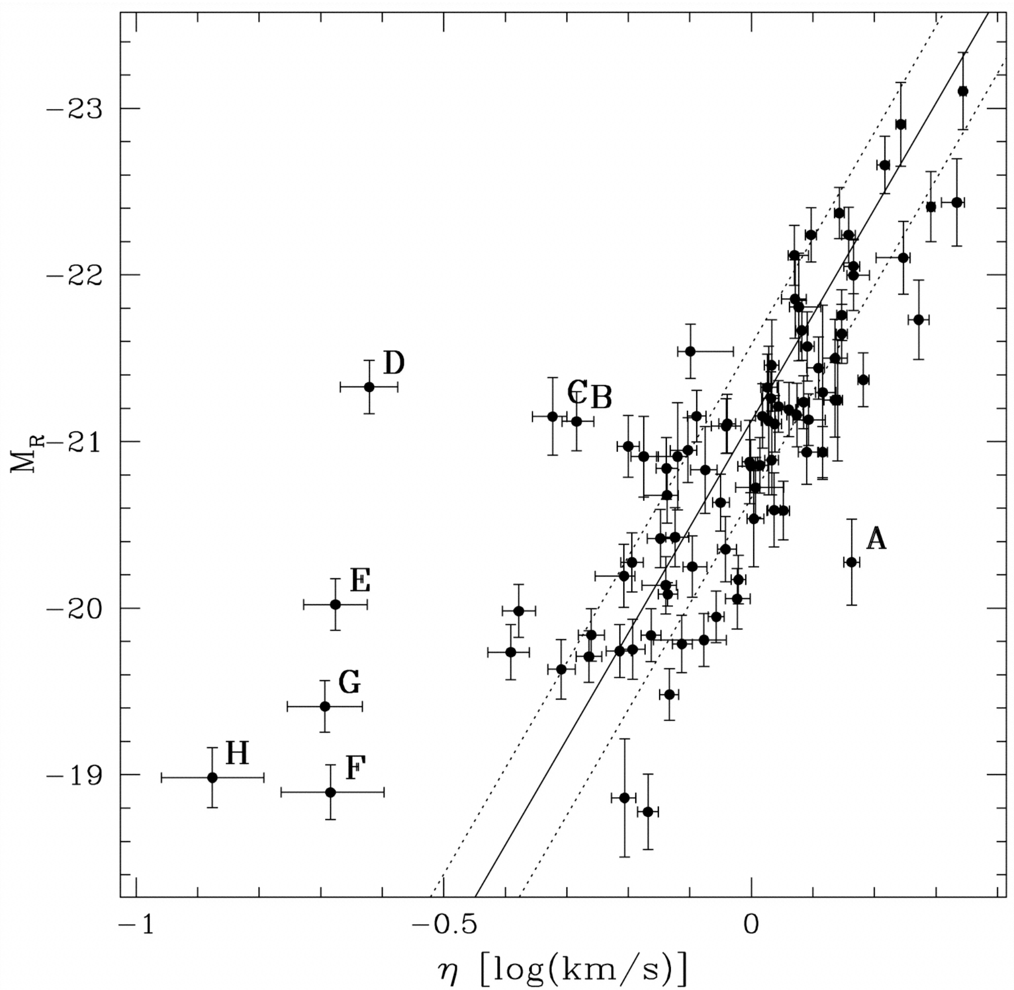
Tully-Fisher Relation - Barred Galaxies



Barred galaxies follow same TFR as “normal” galaxies

Federspiel 1999 Ph.D. Thesis

Tully-Fisher Relation - Galaxy Pairs



Galaxy pairs follow same TFR as "normal" galaxies except for a few outliers

Barton et al. 2001, AJ, 121, 625

Tully-Fisher Relation - Surface Brightness

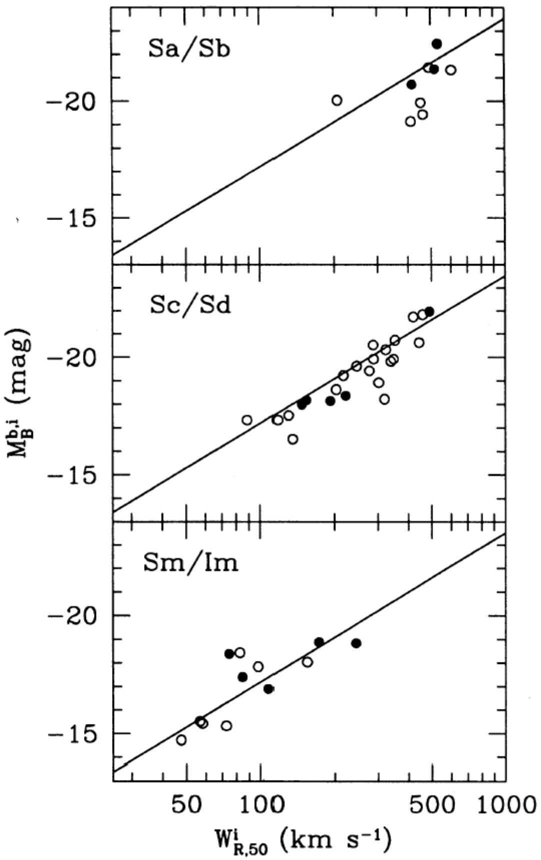


Figure 2. Tully–Fisher relations binned according to morphological type. The solid circles are LSB galaxies, and the open circles are HSB galaxies from Broeils. The line is a fit to all LSB galaxies.

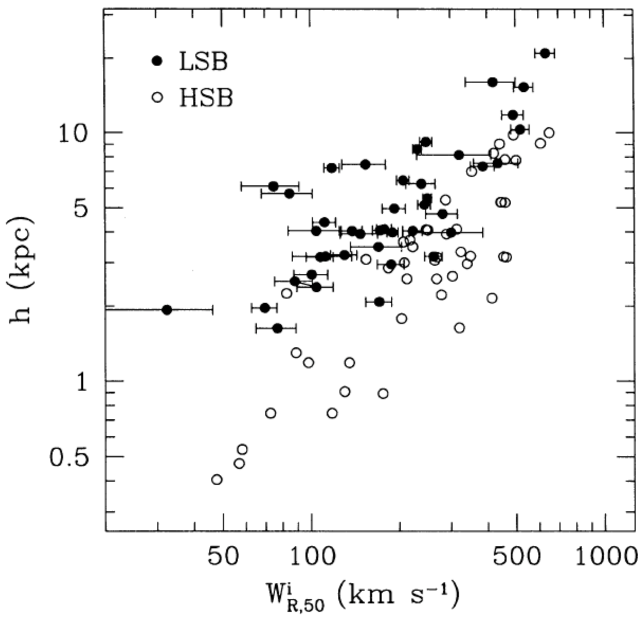


Figure 3. Scalelength versus velocity width, where solid circles are LSB galaxies, and open circles are HSB galaxies from Broeils.

LSB galaxies follow same TFR as HSB galaxies -

$(M/L)_{LSB} \sim 2\ (M/L)_{HSB}$

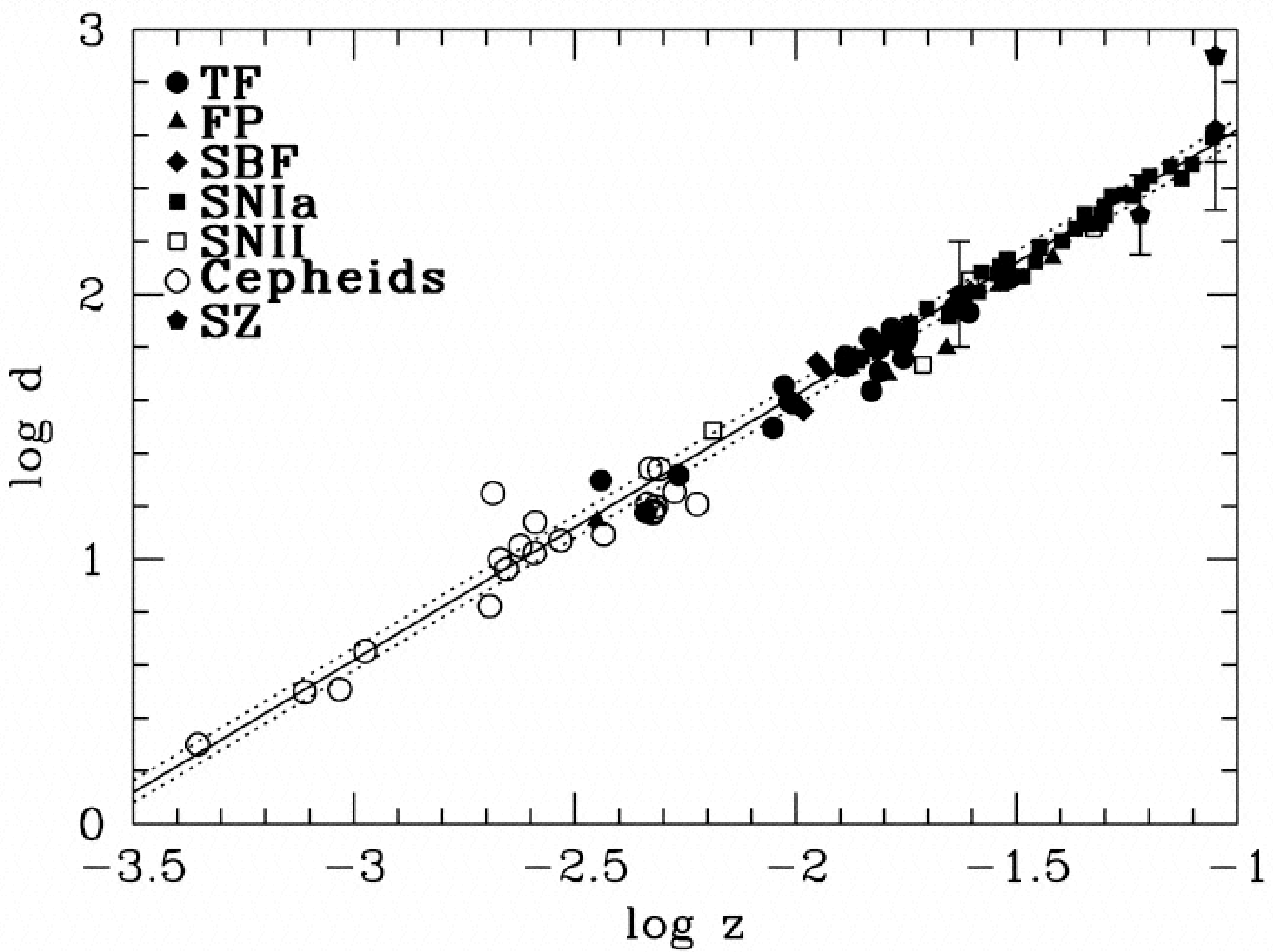
Since $M \sim V^2 h$, then $h_{LSB} \sim 2h_{HSB}$

Zwaan et al. 1995 MNRAS, 273, L35

Tully-Fisher Relation - Summary

- Slope steepens towards redder bandpasses (internal extinction?)
- Sa galaxies exhibit a systematic offset
- TFR scatter depends on:
  - Radius at which V_c is measured
  - Bandpass (internal extinction)
  - Morphology
  - Galaxy color
  - Star formation rate
- LSB galaxies follow the same relation as HSB galaxies
- Galaxies in pairs follow the same relation as “normal” galaxies
- Barred galaxies follow same relation as “normal galaxies”

Tully-Fisher Relation - A Distance Indicator



Final results of HST H_0 Key Project

TFR is a <u>secondary</u> distance indicator

Freedman et al. 2001, ApJ, 553, 47

Formation Models

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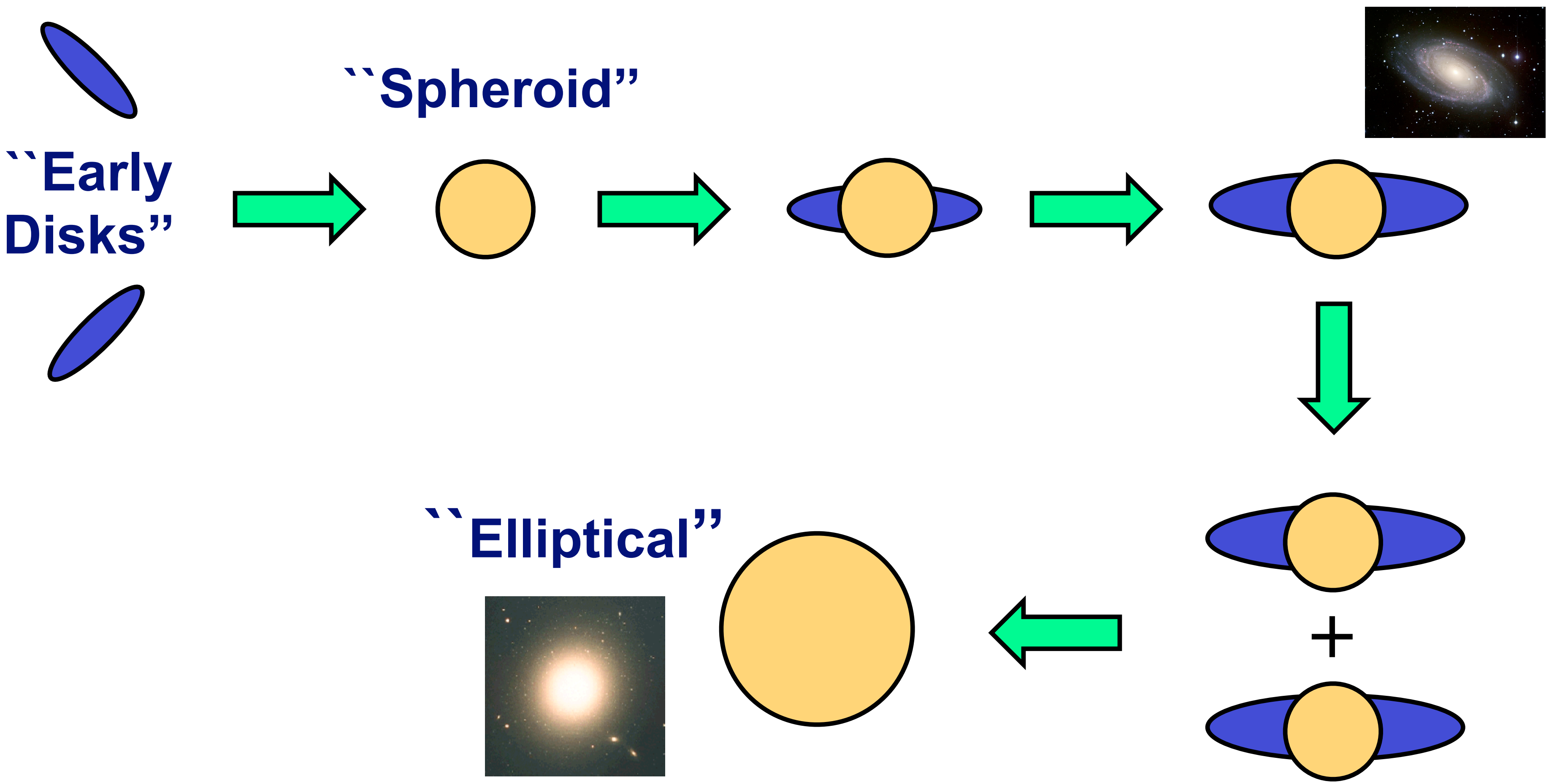
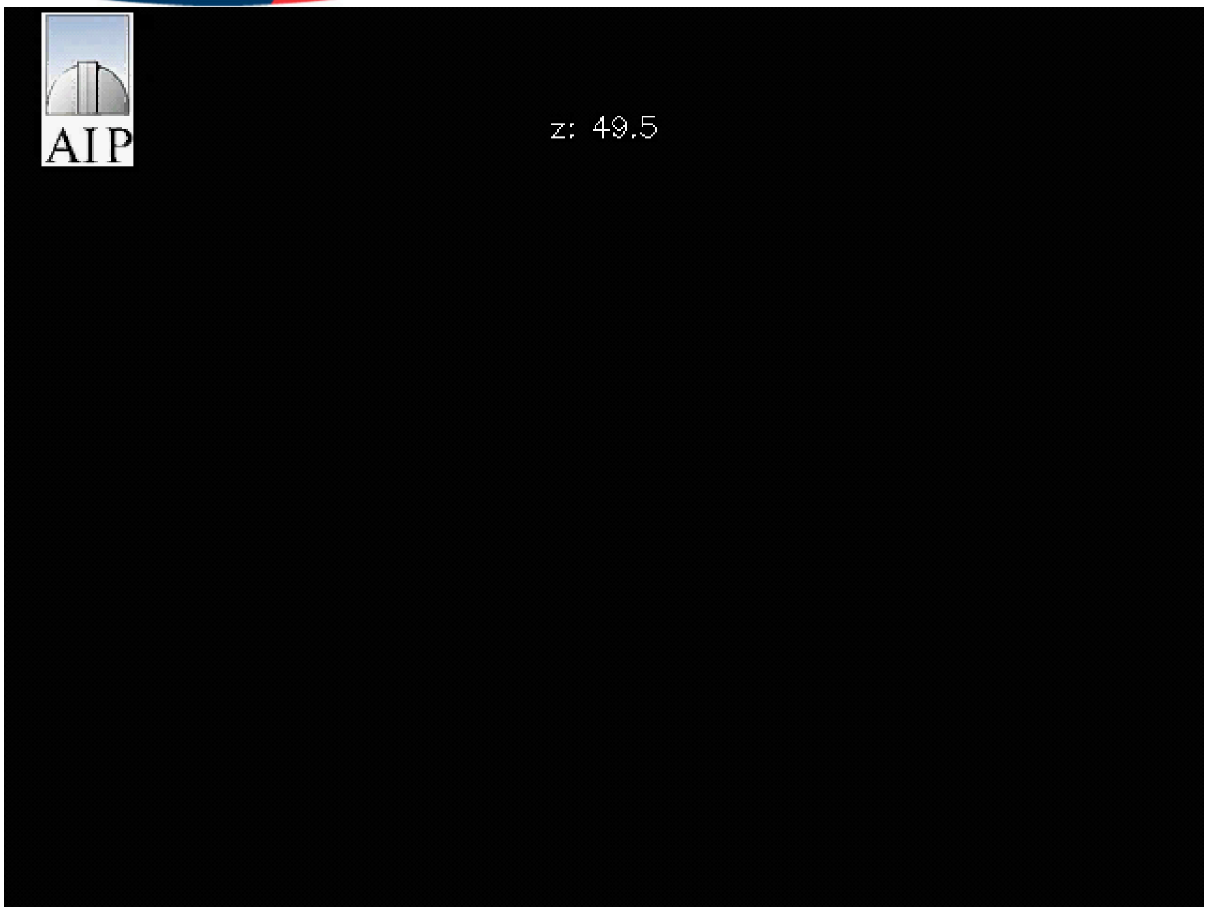
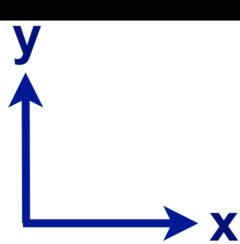
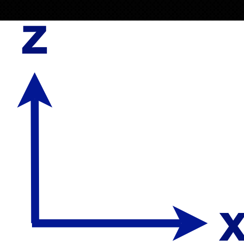
Galaxy Morphology Through Hierarchical Assembly



N-Body Simulation - circa 2000







Stars color-coded according to age with blue (young) and red (old)

Navarro & Steinmetz 2000, ApJ, 538, 477

Theoretical Disk Formation

For a singular isothermal sphere the density profile is just

$$\rho(r) = \frac{V_c^2}{4\pi G r^2}, \tag{1}$$

$$r_{200} = \frac{V_c}{10H(z)}; \qquad M = \frac{V_c^2 r_{200}}{G} = \frac{V_c^3}{10GH(z)}, \tag{2}$$

We assume that the mass which settles into the disc is a fixed fraction m_d of the halo mass. The disc mass is then

$$M_d = \frac{m_d V_c^3}{10GH(z)} \approx 1.7 \times 10^{11} h^{-1} \, M_\odot \left(\frac{m_d}{0.05}\right) \left(\frac{V_c}{250\,\mathrm{km\,s^{-1}}}\right)^3 \left[\frac{H(z)}{H_0}\right]^{-1}. \tag{4}$$

Fall & Efstathiou 1980, MNRAS, 193, 189;
Mo et al. 1998, MNRAS, 295, 319

Theoretical Disk Formation (cont'd)

$$\Sigma(R) = \Sigma_0 \exp\left(-R/R_\mathrm{d}\right). \tag{5}$$

Here R_d and Σ_0 are the disc scalelength and central surface density, and are related to the disc mass through

$$M_\mathrm{d} = 2\pi\Sigma_0 R_\mathrm{d}^2. \tag{6}$$

If the gravitational effect of the disc is neglected, its rotation curve is flat at the level V_c and its angular momentum is just

$$J_\mathrm{d} = 2\pi \int V_\mathrm{c}\Sigma(R)R^2 \mathrm{d}R = 4\pi\Sigma_0 V_\mathrm{c} R_\mathrm{d}^3 = 2M_\mathrm{d} R_\mathrm{d} V_\mathrm{c}. \tag{7}$$

We assume this angular momentum to be a fraction j_d of that of the halo, i.e.

$$J_\mathrm{d} = j_\mathrm{d} J, \tag{8}$$

Theoretical Disk Formation (cont'd)

and we relate J to the spin parameter λ of the halo through the definition

$$\lambda = J|E|^{1/2}G^{-1}M^{-5/2}, \tag{9}$$

where E is the total energy of the halo. Equations (7) and (8) then imply that

$$R_{\rm d} = \frac{\lambda G M^{3/2}}{2V_{\rm c}|E|^{1/2}}\left(\frac{j_{\rm d}}{m_{\rm d}}\right). \tag{10}$$

The total energy of a truncated singular isothermal sphere is easily obtained from the virial theorem by assuming all particles to be on circular orbits:

$$E = -\frac{GM^2}{2r_{200}} = -\frac{MV_{\rm c}^2}{2}. \tag{11}$$

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Theoretical Disk Formation (cont'd)

$$R_d = \frac{1}{\sqrt{2}} \left(\frac{j_d}{m_d} \right) \lambda r_{200}$$

$$\approx 8.8 h^{-1}\,\mathrm{kpc} \left(\frac{\lambda}{0.05} \right) \left(\frac{V_c}{250\,\mathrm{km\,s^{-1}}} \right) \left[\frac{H}{H_0} \right]^{-1} \left(\frac{j_d}{m_d} \right), \quad (12)$$

$$P(\lambda) d\lambda = \frac{1}{\sqrt{2\pi}\sigma_\lambda} \exp\left[-\frac{\ln^2(\lambda/\lambda_{\mathrm{med}})}{2\sigma_\lambda^2} \right] \frac{d\lambda}{\lambda}. \quad (5)$$

The median λ_{med} and dispersion (in $\ln\lambda$) σ_λ are found to depend remarkably weakly on the cosmology, halo mass, or initial spectrum of density fluctuations (e.g., Barnes & Efstathiou 1987; Warren et al. 1992; Cole & Lacey 1996), with typical values $\lambda_{\mathrm{med}} \approx 0.04$ and $\sigma_\lambda \approx 0.5$–$0.6$.

$\sigma(\ln\lambda)_{\mathrm{theo}} \approx$

$1.5\mathrm{x}\ \sigma(\ln\lambda)_{\mathrm{obs}}$

Theoretical Disk Formation (cont'd)

$$R_{\rm d} = \frac{1}{\sqrt{2}}\left(\frac{j_{\rm d}}{m_{\rm d}}\right)\lambda r_{200}$$

$$\approx 8.8h^{-1}\,{\rm kpc}\left(\frac{\lambda}{0.05}\right)\left(\frac{V_{\rm c}}{250\,{\rm km\,s^{-1}}}\right)\left[\frac{H}{H_0}\right]^{-1}\left(\frac{j_{\rm d}}{m_{\rm d}}\right), \qquad (12)$$

?

$$P(\lambda)d\lambda = \frac{1}{\sqrt{2\pi}\sigma_\lambda}\exp\left[-\frac{\ln^2(\lambda/\lambda_{\rm med})}{2\sigma_\lambda^2}\right]\frac{d\lambda}{\lambda}. \qquad (5)$$

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$\sigma(\ln\lambda)_{\rm theo} \approx$

$1.5{\rm x}\ \sigma(\ln\lambda)_{\rm obs}$

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Observed Width of Disk Size Distribution

$M_{B,disk}$	N	$\langle \log_{10} R_d \rangle$	$\sigma(\log_{10} R_d)$
[-22.0,-21.5]	6246	0.82	0.12
[-21.5,-21.0]	12497	0.73	0.12
[-21.0,-20.5]	15061	0.64	0.12
[-20.5,-20.0]	13186	0.56	0.12
[-20.0,-19.5]	9593	0.48	0.13
[-19.5,-19.0]	6212	0.40	0.15
[-19.0,-18.5]	3588	0.36	0.16
[-18.5,-18.0]	2132	0.30	0.18

(Simard 2008, in prep.)

SDSS Disk subsample:
$B/T \lesssim 0.3$
$b/a \gtrsim 0.5$

Predicted $\sigma(\log_{10} R_d) \approx$ 0.20-0.25

Feedback at high λ? Secular instability at low λ?

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Tully-Fisher Relation - Origin

$$M_{\rm d} = \frac{m_{\rm d} V_{\rm c}^3}{10 G H(z)} \approx 1.7 \times 10^{11} h^{-1}\,{\rm M}_\odot \left(\frac{m_{\rm d}}{0.05}\right) \left(\frac{V_{\rm c}}{250\,{\rm km\,s^{-1}}}\right)^3 \left[\frac{H(z)}{H_0}\right]^{-1}$$

et al. 1998
MNRAS, 295, 319

$$\Upsilon_{\rm d} \equiv M_{\rm d}/L_{\rm d} \text{ (in solar units)}$$

$$L_{\rm d} = A \left(\frac{V_{\rm c}}{250\,{\rm km\,s^{-1}}}\right)^{\alpha},$$

where $\alpha = 3$ is the slope, and

$$A = 1.7 \times 10^{11} h^{-1} {\rm L}_\odot \Upsilon_{\rm d}^{-1} \left(\frac{m_{\rm d}}{0.05}\right) \left[\frac{H(z)}{H_0}\right]^{-1}$$

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Tully-Fisher Relation - Origin

$$M_{\mathrm{d}} = \frac{m_{\mathrm{d}} V_{\mathrm{c}}^3}{10 G H(z)} \approx 1.7 \times 10^{11} h^{-1}\,\mathrm{M}_{\odot} \left(\frac{m_{\mathrm{d}}}{0.05}\right) \left(\frac{V_{\mathrm{c}}}{250\,\mathrm{km\,s^{-1}}}\right)^3 \left[\frac{H(z)}{H_0}\right]^{-1}$$

et al. 1998
MNRAS, 295, 319

$$\Upsilon_{\mathrm{d}} \equiv M_{\mathrm{d}}/L_{\mathrm{d}} \text{ (in solar units)}$$

But why?
And recall LSB galaxies ...

$$L_{\mathrm{d}} = A \left(\frac{V_{\mathrm{c}}}{250\,\mathrm{km\,s^{-1}}}\right)^{\alpha},$$

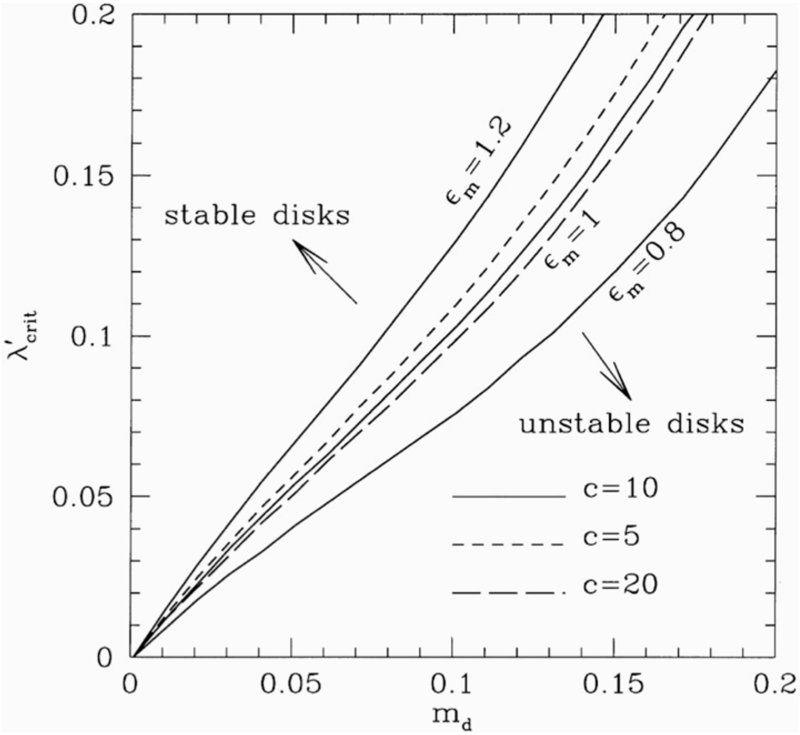
where $\alpha = 3$ is the slope, and

$$A = 1.7 \times 10^{11} h^{-1} \mathrm{L}_{\odot} \Upsilon_{\mathrm{d}}^{-1} \left(\frac{m_{\mathrm{d}}}{0.05}\right) \left[\frac{H(z)}{H_0}\right]^{-1}$$

A Disk Stability Criterion

$$\epsilon \equiv \frac{V_{max}}{(GM_d/R_d)^{1/2}} \leq 1.1$$

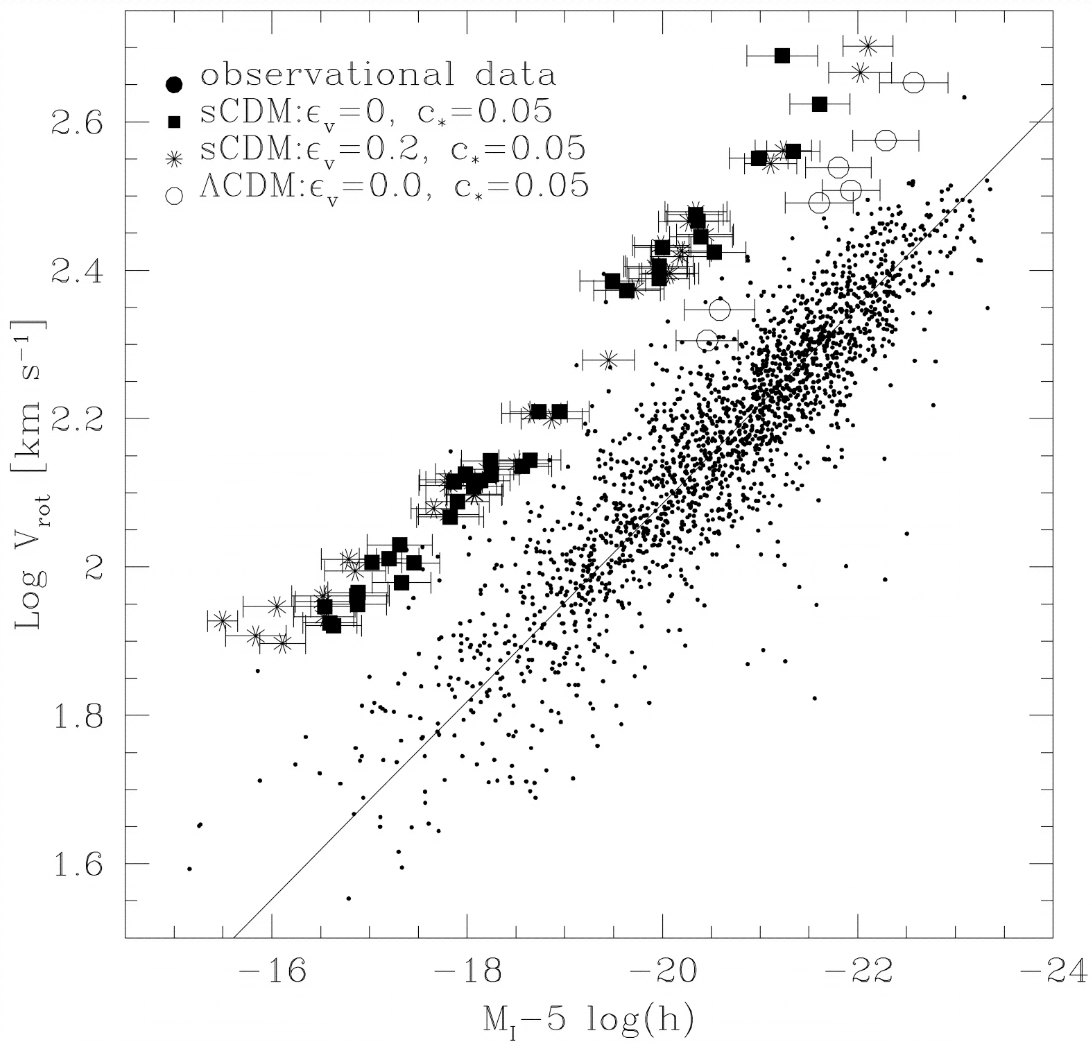
If self-gravity of disk dominates rotational support, then disk will be unstable leading to the formation of a bar or a bulge



$$\lambda' \equiv \lambda j_d/m_d$$

(Efstathiou et al. 1982, MNRAS, 199, 1069)

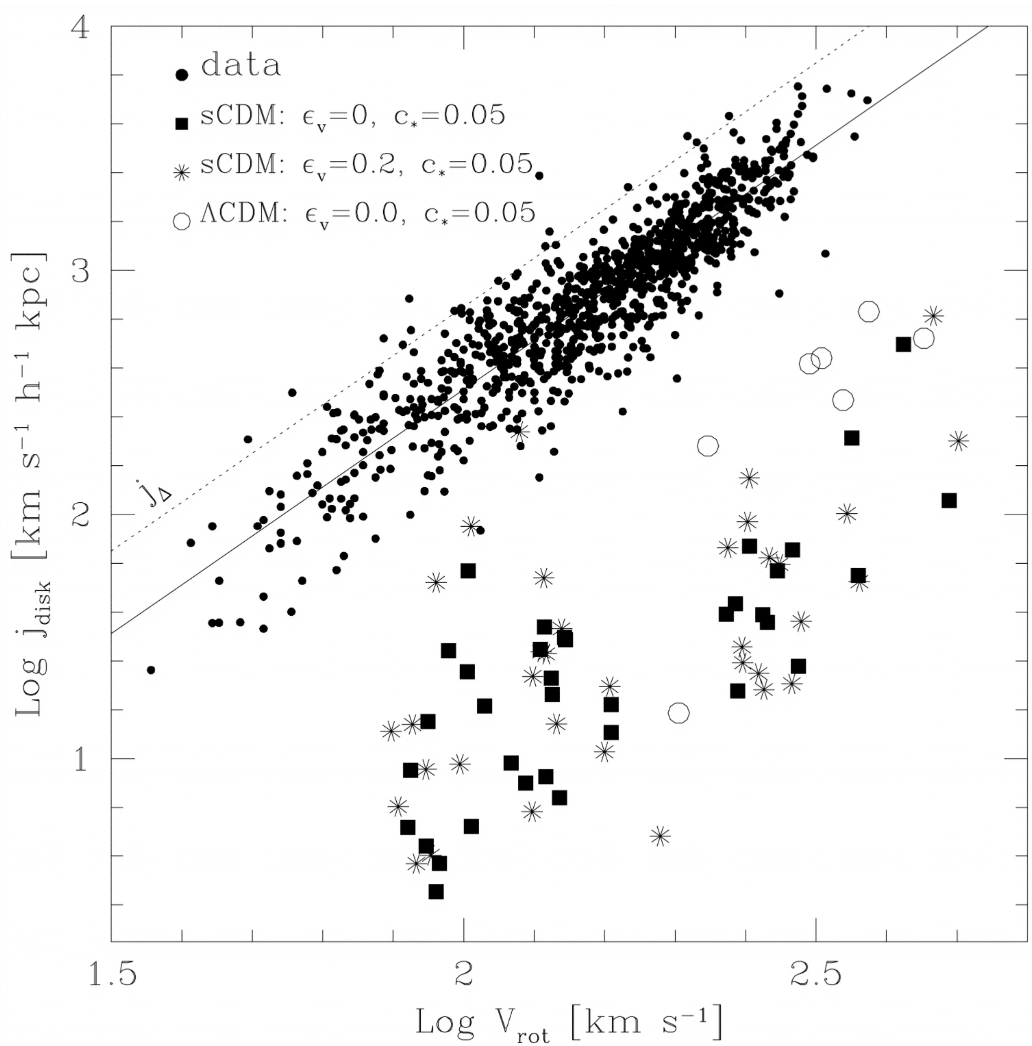
``Angular Momentum Catastrophe”



Simulations reproduce slope but not zero-point

Navarro & Steinmetz 2000, ApJ, 538, 477

``Angular Momentum Catastrophe”

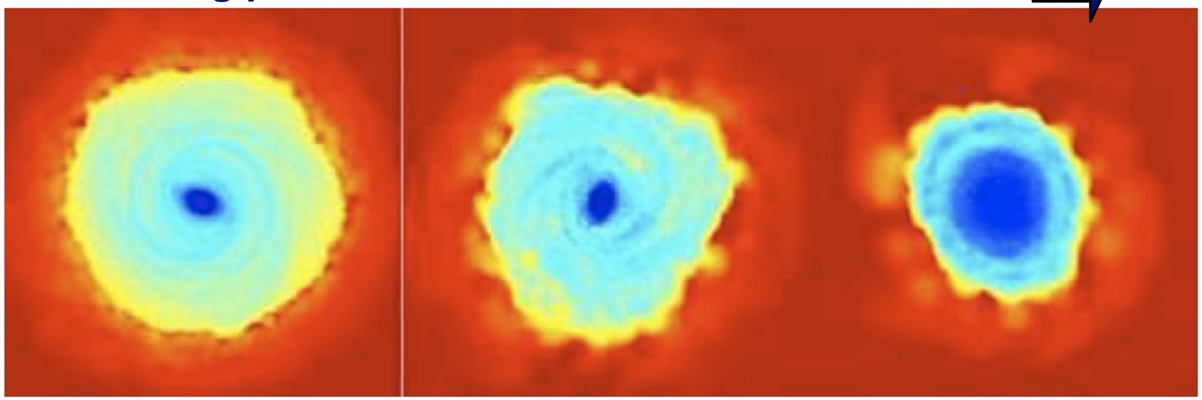


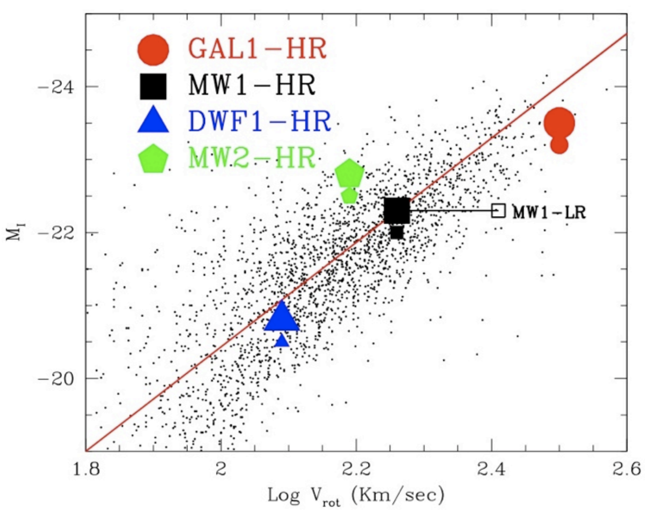
Specific angular momenta of simulated disks are too low

Navarro & Steinmetz 2000, ApJ, 538, 477

Angular Momentum Catastrophe - Resolved?

Decreasing particle resolution in isolated CDM halo

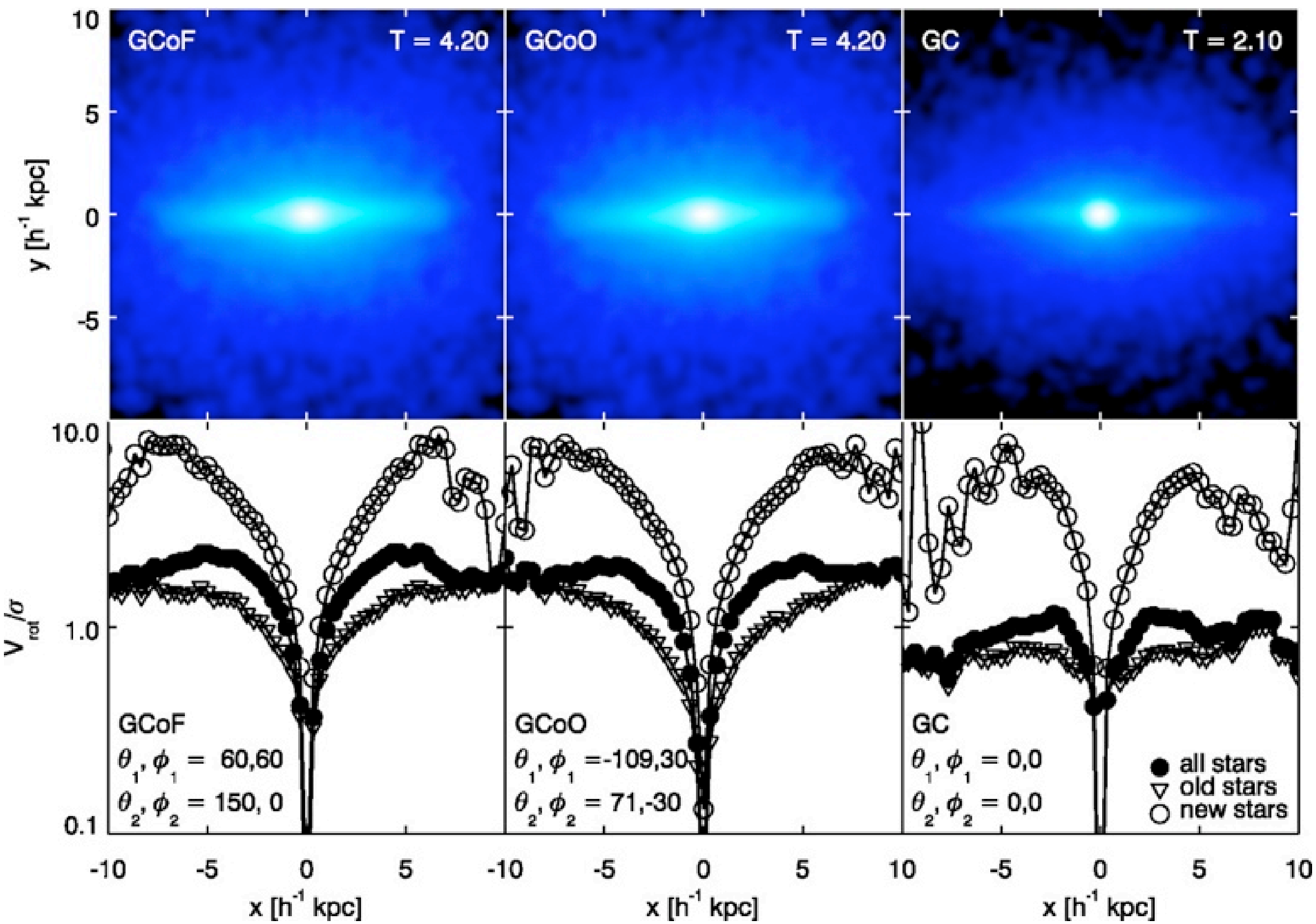




Disk-halo transfer due to halo clumpiness?

(Mayer et al. 2008, arXiv: 0801.3845; Governato et al. 2008, arXiv: 0801.1707)

Disks in Mergers

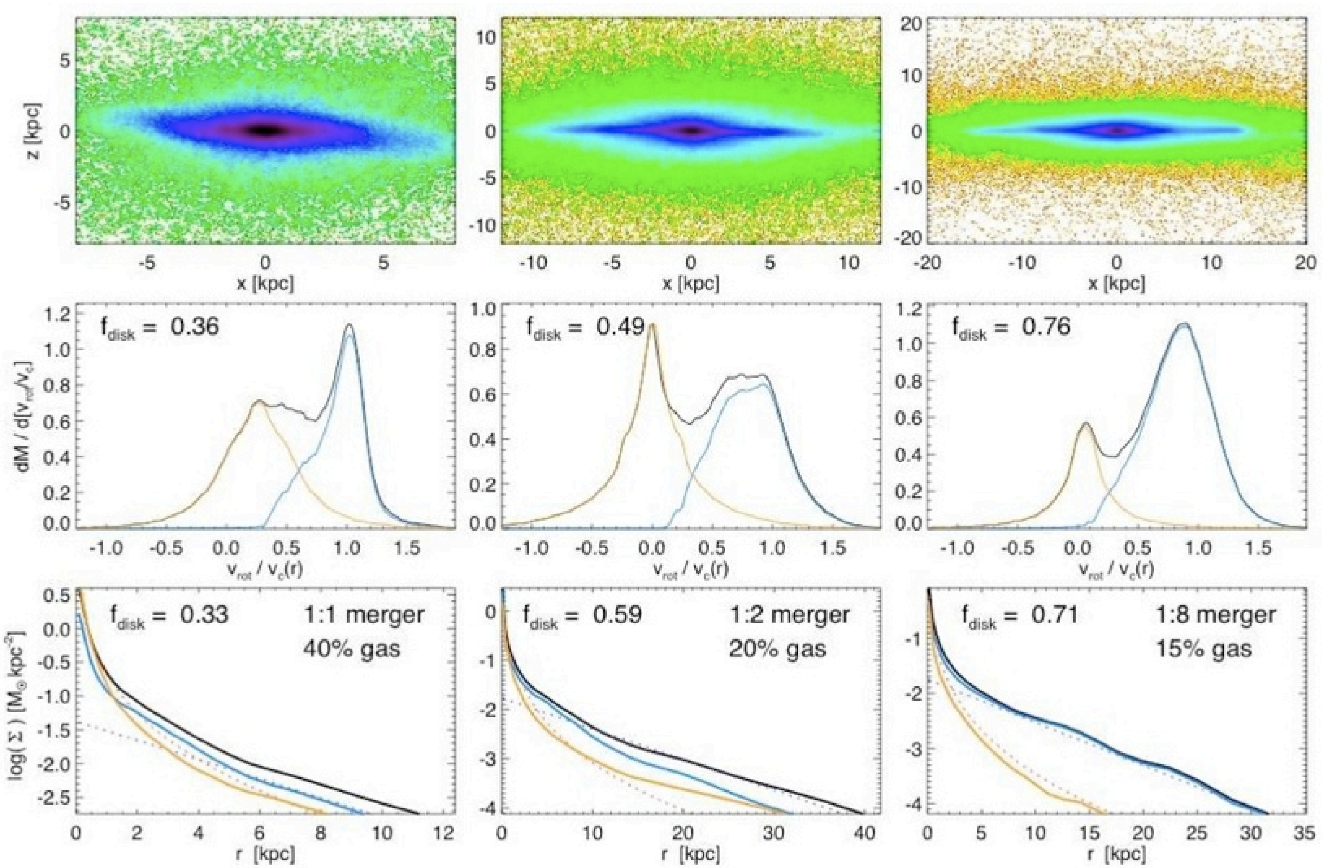


Gas-rich mergers actually produce disks!

(Robertson et al. 2006, ApJ, 645, 986)

Three different types of pre-merger orbits

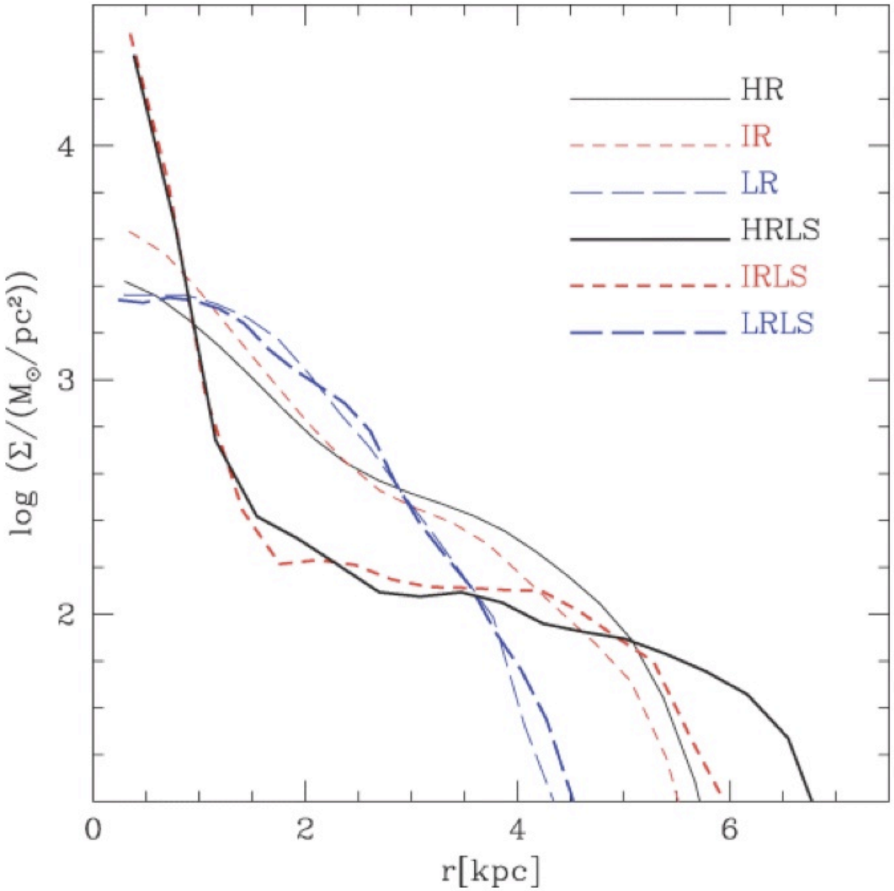
Disks in Mergers



Significant disk component in mergers (f_{disk} = 0.76)

(Hopkins et al. 2008, arXiv: 0806.1739)

Origin of Exponential Disks



Resulting surface density of gas disks is not exponential ...

Angular momentum transport?

Initially,

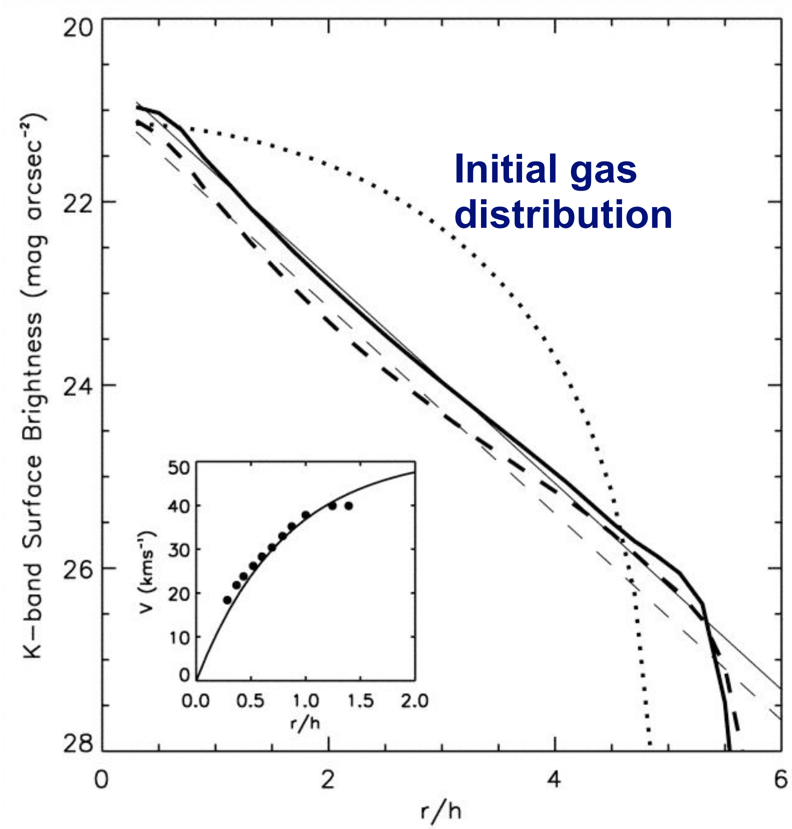
$j_{gas} \propto r^{1.0}$

$j_{DM} \sim 0$

(Mayer et al. 2007, MNRAS, 375, 53)

Origin of Exponential Disks

$$\frac{\partial \Sigma_g}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}\left[\frac{(\partial/\partial r)(\nu \Sigma_g r^3 d\Omega/dr)}{d/dr(r^2\Omega)}\right] - \psi_*$$



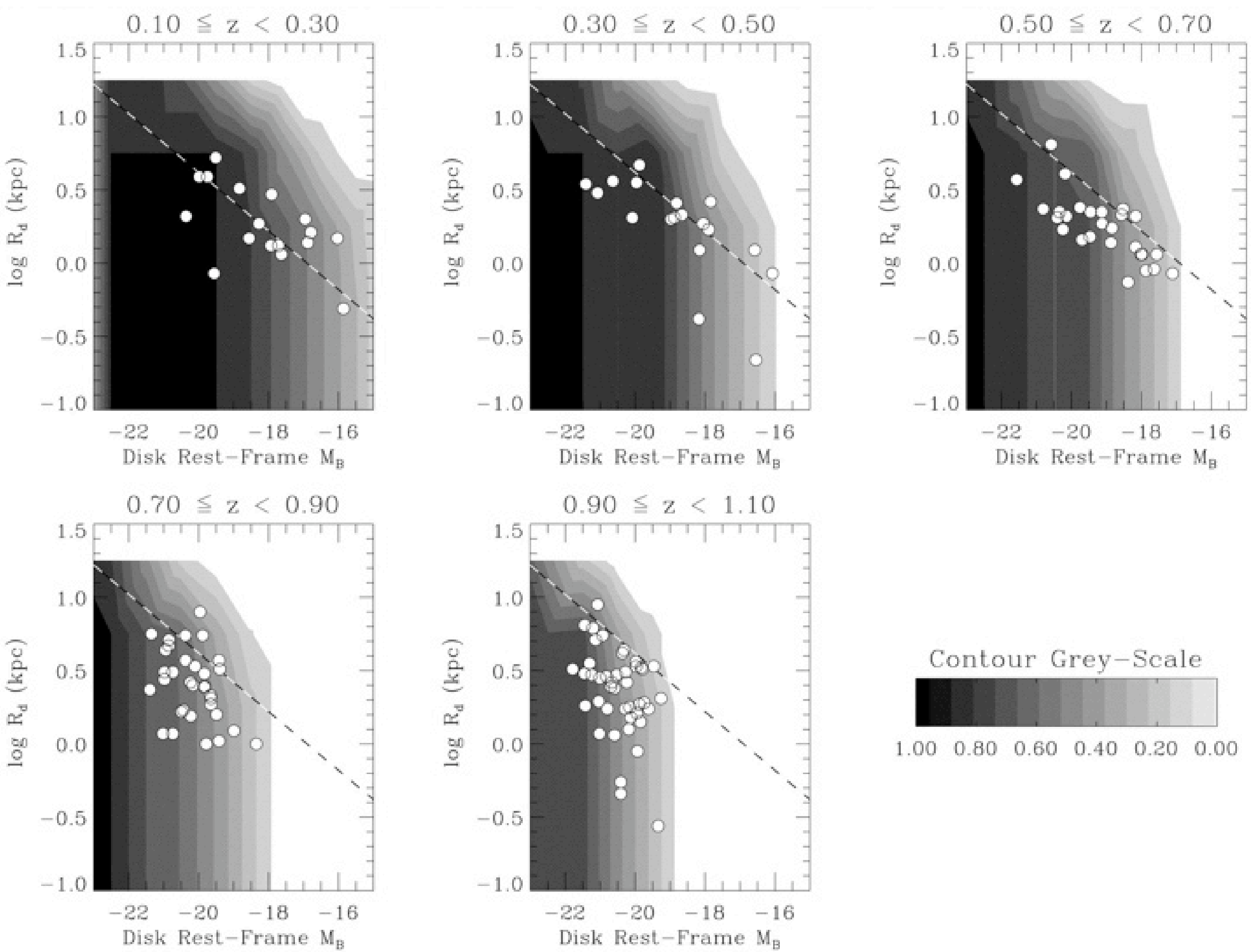
Viscous evolution?

Caused by non-circular motions and turbulence in differentially rotating disks - no shear = no viscous evolution

(Lin & Pringle 1987, ApJ, 320, L87; Bell 2002, ApJ, 581, 1013

Disks at High Redshifts

Luminosity-Size Relation at z < 1

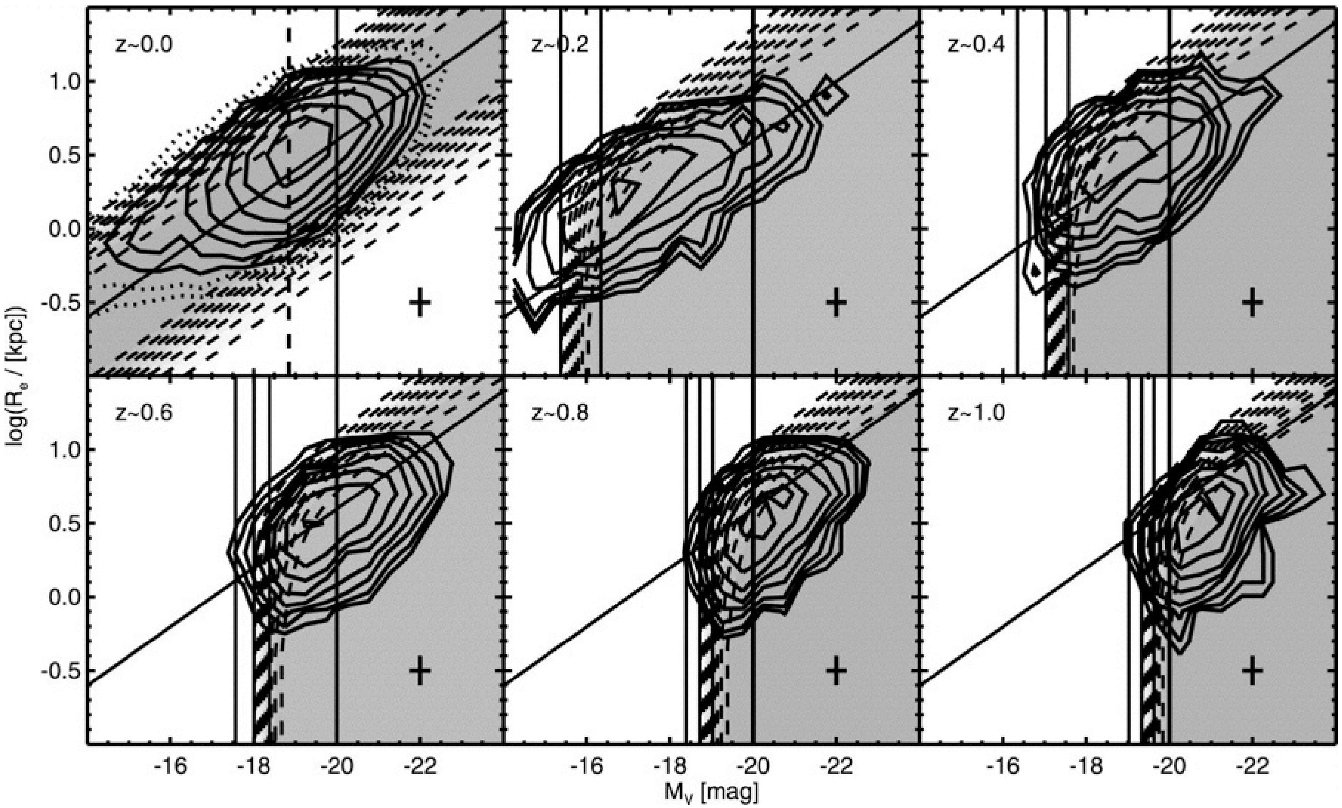


Selection effects are very significant

No surface brightness evolution?

(Simard et al. 1999, ApJ, 519, 563)

Luminosity-Size Relation at z < 1

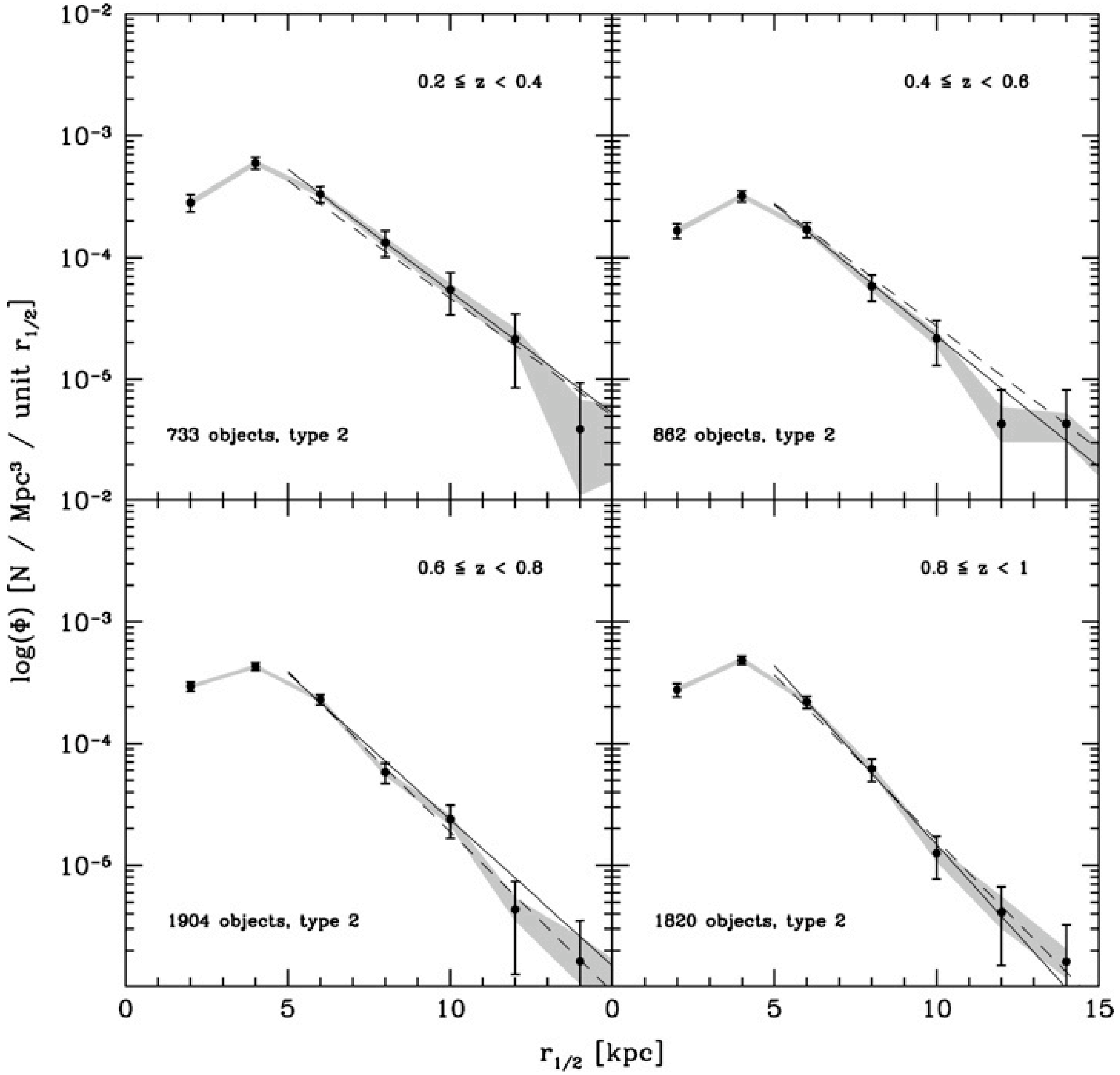


Selection effects are very significant

~ 1 mag brighter in V-band surface brightness at z ~ 1

(Barden et al. 2005, ApJ, 635, 959)

Disk Size Function at z < 1

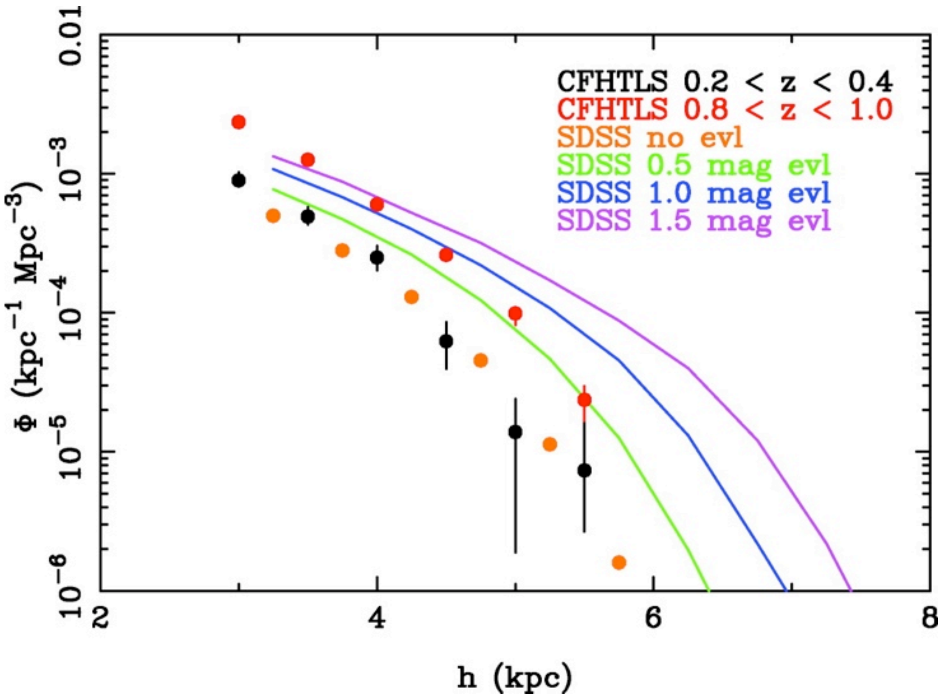


Size function remains constant out to z ~ 1 if selection window is shifted by ~1 mag with z.

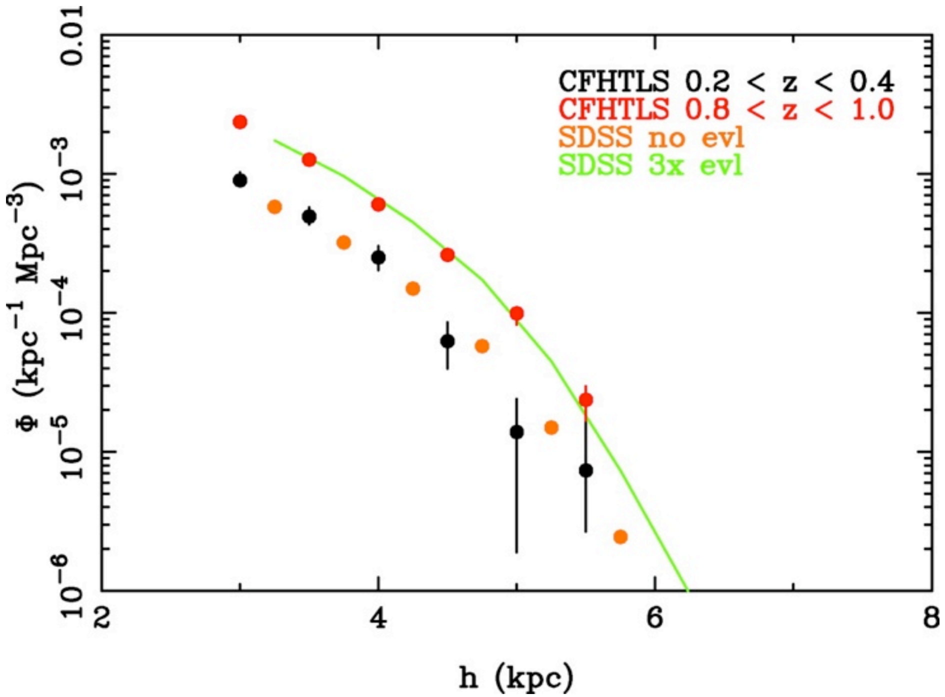
(Sargent et al. 2007, ApJ, 172, 434)

Disk Size Function at z < 1

Are selection effects "Lagrangian" or "Eulerian"?



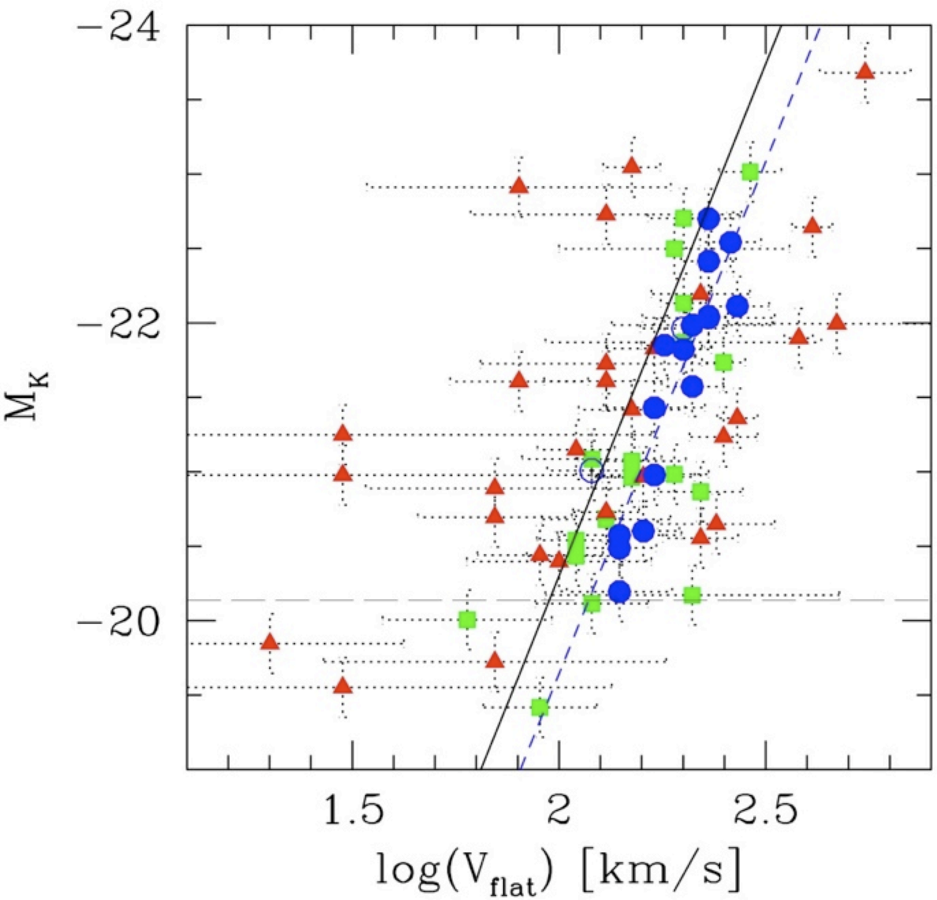
Pure Luminosity Evolution



Pure Number Evolution

(Kanwar et al. 2008, ApJ, 682, 907)

Tully-Fisher Relation at z < 1



Blue = Rotating disks
Green = Perturbed rotators
Red = "Kinematically complex"

IMAGES Survey

2D velocity fields with VLT/GIRAFFE

(Puech et al. 2008, A&A, 484, 173)

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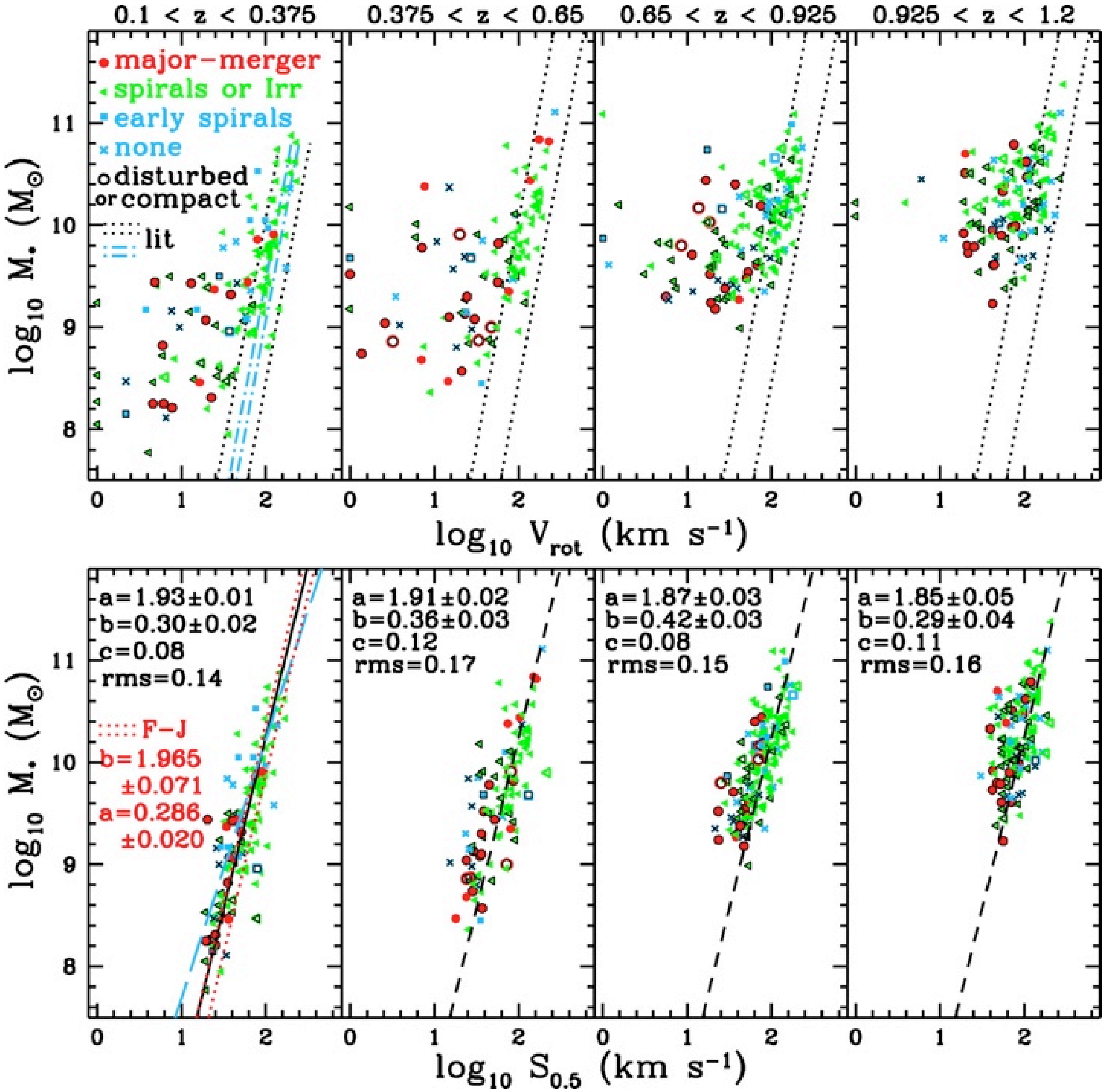
Tully-Fisher Relation at z < 1



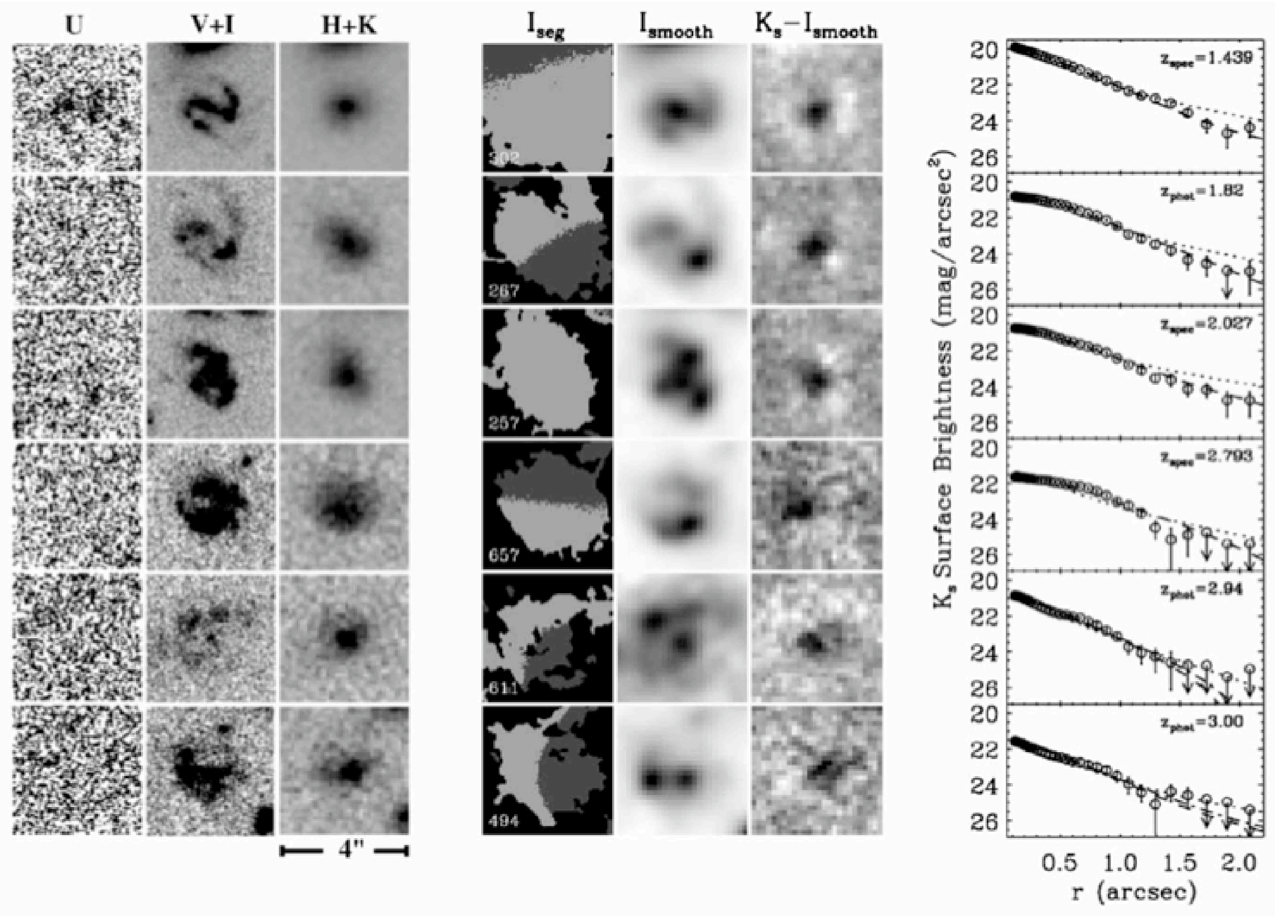
DEEP2 Survey

Multi-slits with Keck/DEIMOS

Galaxies are "settling down" onto a fundamental TF relation

(Kassin et al. 2007, ApJ, 660, L35)

Very Large Disks



HDF-South
FIRES

z = 2 - 3

(Labbé et al. 2003, 591, L95)

Very Large Disks

TABLE 1

Properties of High-Redshift Disk Galaxies in the HDF-S

Galaxy (1)	$K_{s,\,tot}$ (2)	z (3)	$M_{B,\,rest}$ (4)	$\mu_{0,\,B,\,rest}$ (5)	$r_{e,\,K}$ (arcsec) (6)	$r_{1/2,\,K}$ (arcsec) (7)	$r_{1/2,\,I}$ (arcsec) (8)	ϵ (9)
302	19.70	1.439[a]	−22.70	19.70	0.89	0.70	0.86	0.46
267	19.98	1.82	−22.88	19.92	0.75	0.74	0.88	0.37
257	20.25	2.027[a]	−23.08	19.53	0.74	0.74	0.84	0.36
657	20.68	2.793[a]	−23.56	19.33	0.76	0.70	0.74	0.18
611	20.53	2.94	−23.59	18.51	0.65[b]	0.52	0.97	0.27
494	21.14	3.00	−23.31	18.84	0.75[b]	0.56	0.86	0.47

Note.—Col. (1): Catalog identification numbers (see Labbé et al. 2003). Col. (2): K_s-band total magnitudes. Col. (3): Redshift. Col. (4): Rest-frame absolute B-band magnitudes. Col. (5): Face-on rest-frame B-band central surface brightnesses. Col. (6): Face-on best-fit effective radii. Col. (7): K_s half-light radii. Col. (8): I_{814} half-light radii, PSF-matched to K_s. Col. (9): Ellipticity.

[a] Spectroscopic redshifts.

[b] Two-component models (point+exponential).

HDF-South FIRES

z = 2 - 3 (7.83 kpc per arcsec)

(Labbé et al. 2003, ApJ, 591, L95)

- **Sizes comparable to Milky Way**
- **Large Stellar Masses**
- **Regular K morphologies, knotty in V**
- **Constitute half of the most rest-frame luminous galaxies**
- **Number density is at least a factor of two above model predictions**

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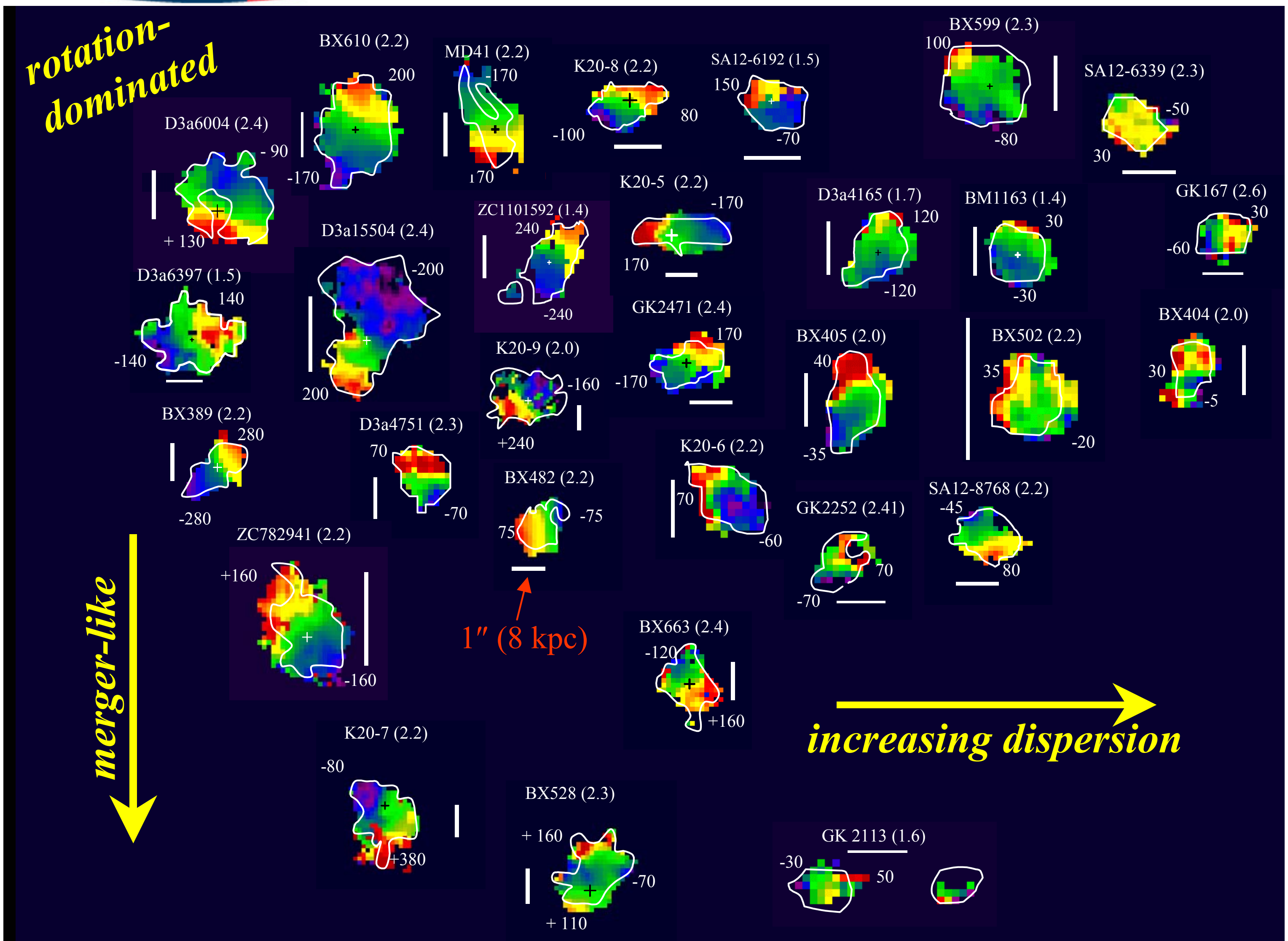
Rotation or Mergers?



“SINS” Survey

Forster-Schreiber et al. 2006, ApJ, 645, 1062

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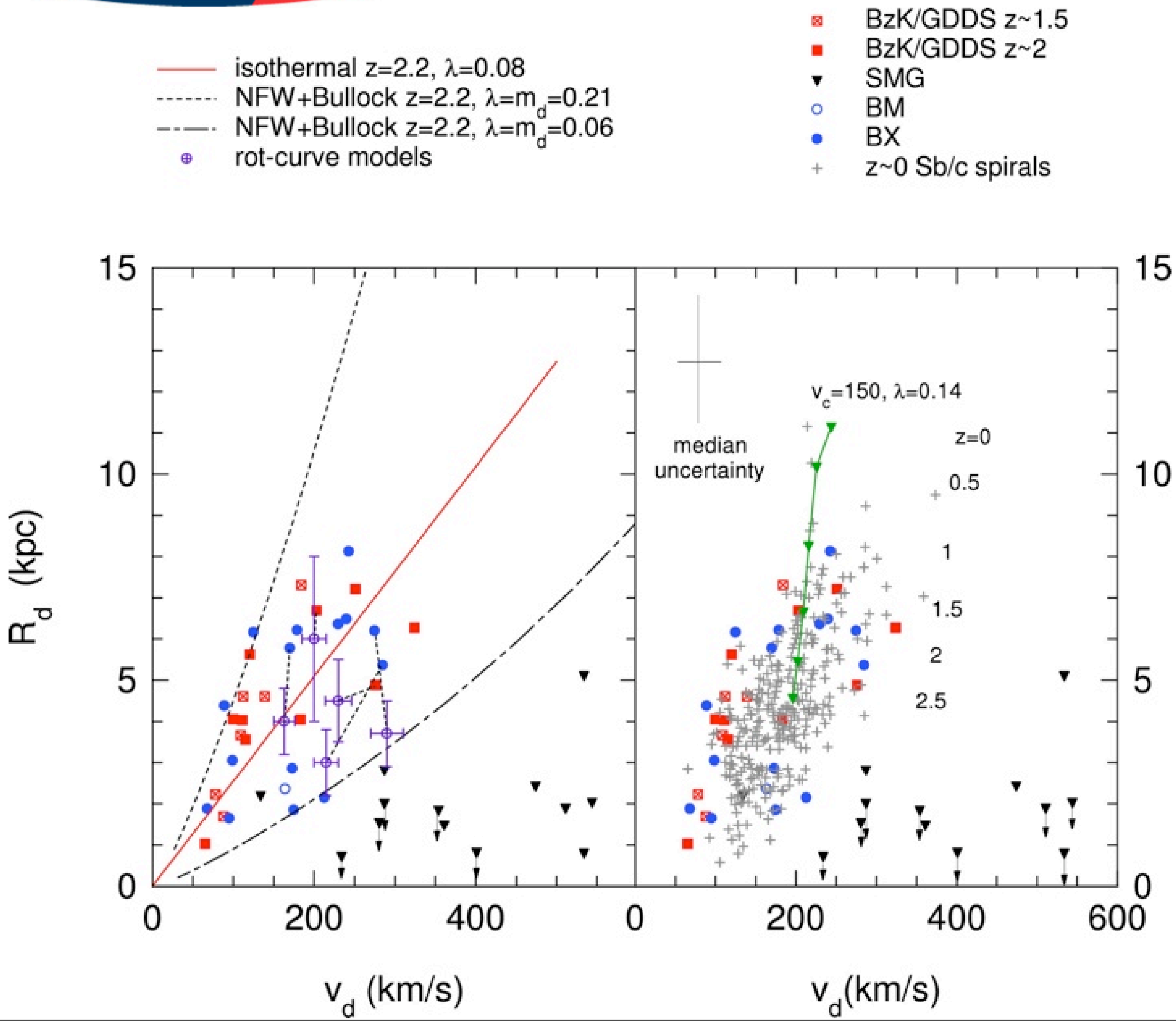
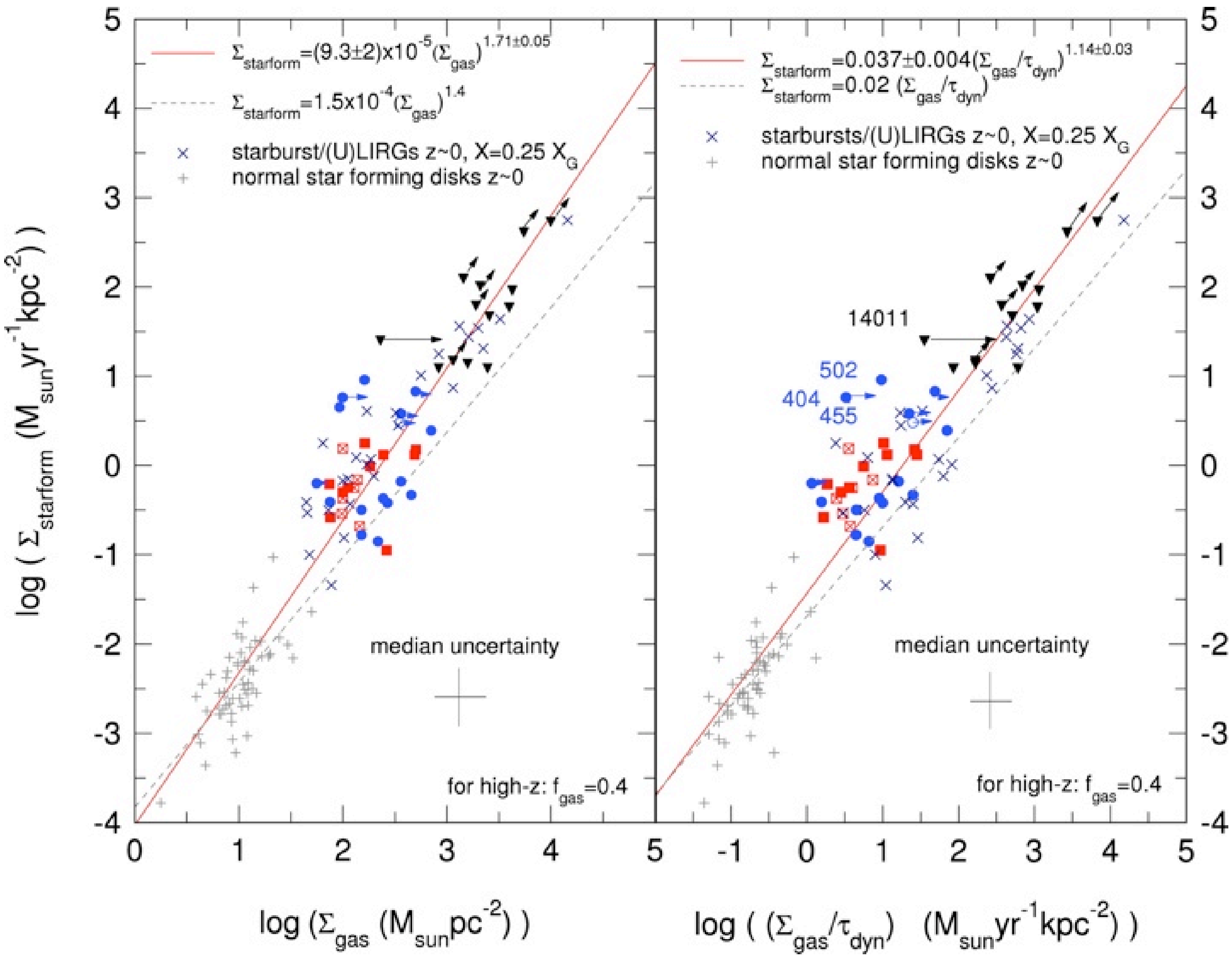
Size-Velocity Relation at z ~ 2



Same as the local relation (!)

(Bouché et al. 2007, ApJ, 671, 303)

Schmidt-Kennicutt Law at z ~ 2



Same as the local relation (!)

(Bouché et al. 2007, ApJ, 671, 303)

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The End!