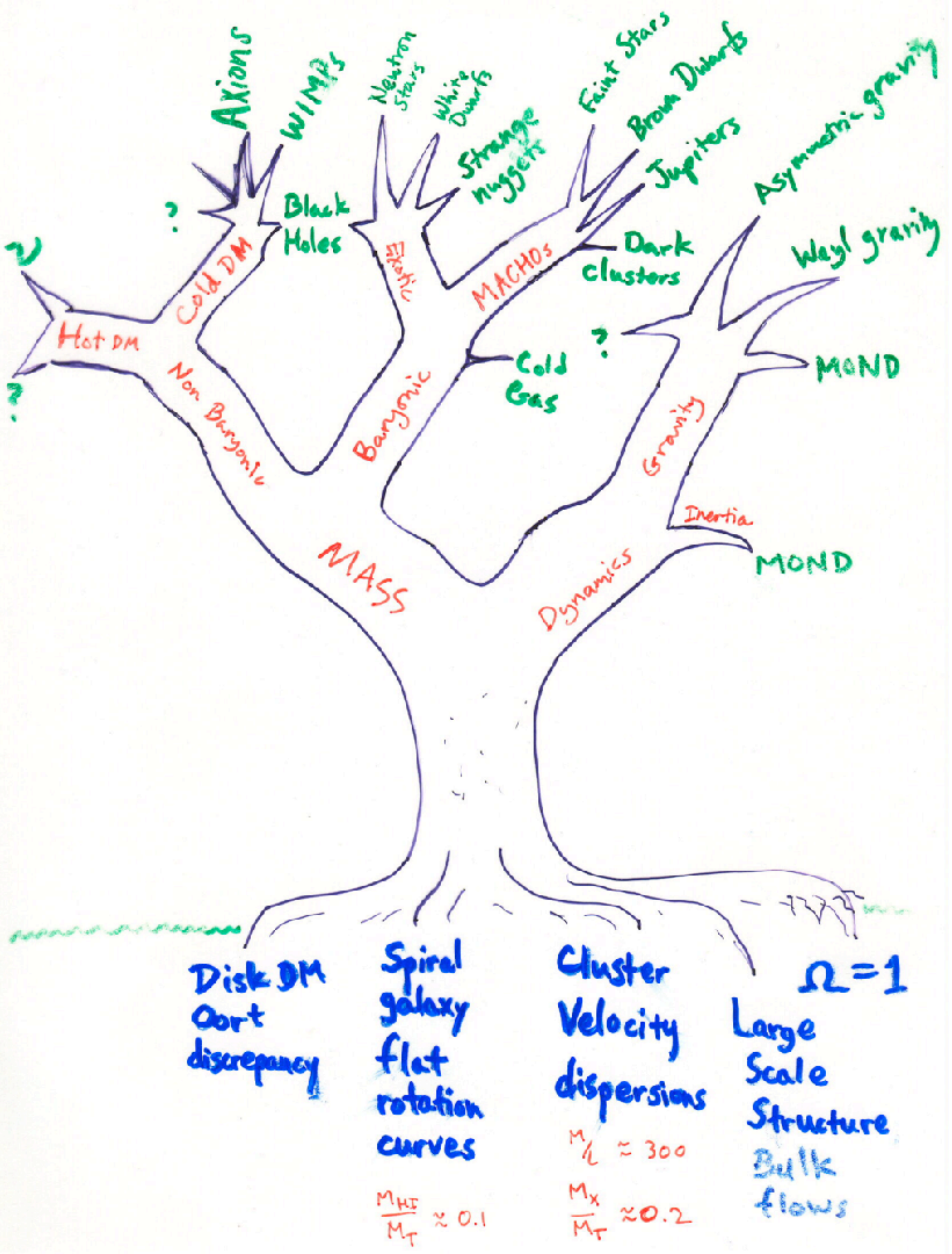
# DARK MATTER

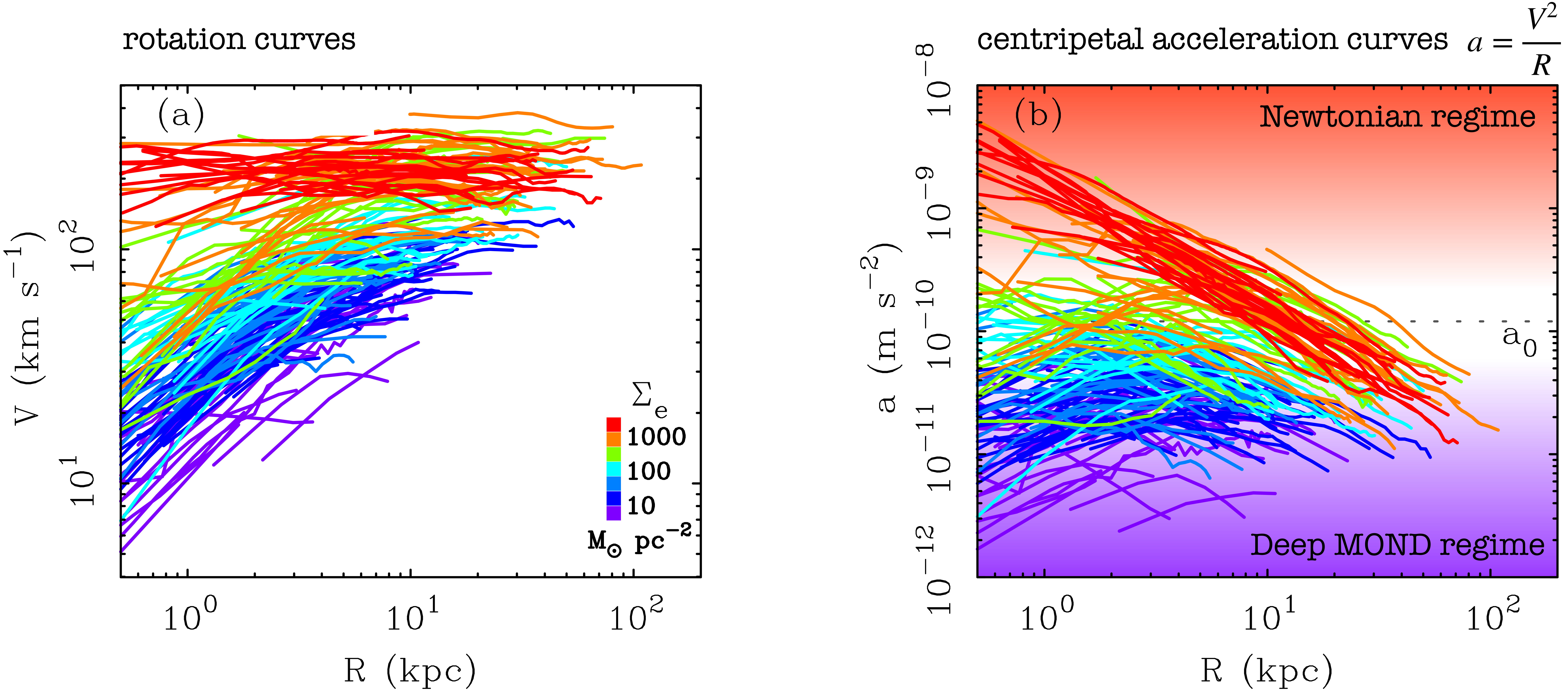
ASTR 333/433
SPRING 2024
TR 11:30AM–12:45PM
SEARS 552

http://astroweb.case.edu/ssm/ASTR333/

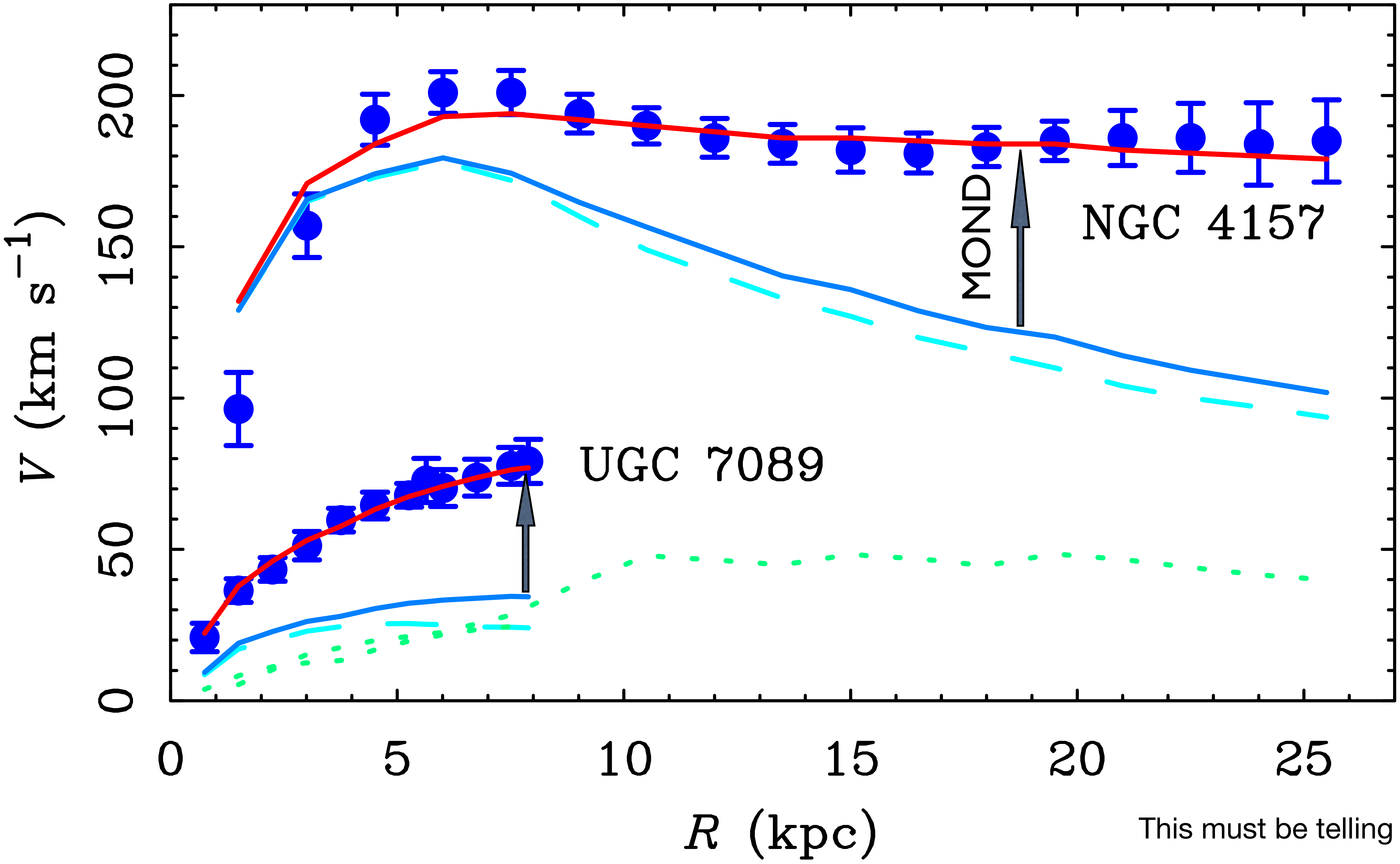
PROF. STACY MCGAUGH
SEARS 558
368-1808
stacy.mcgaugh@case.edu

CASE WESTERN RESERVE
UNIVERSITY
EST. 1826



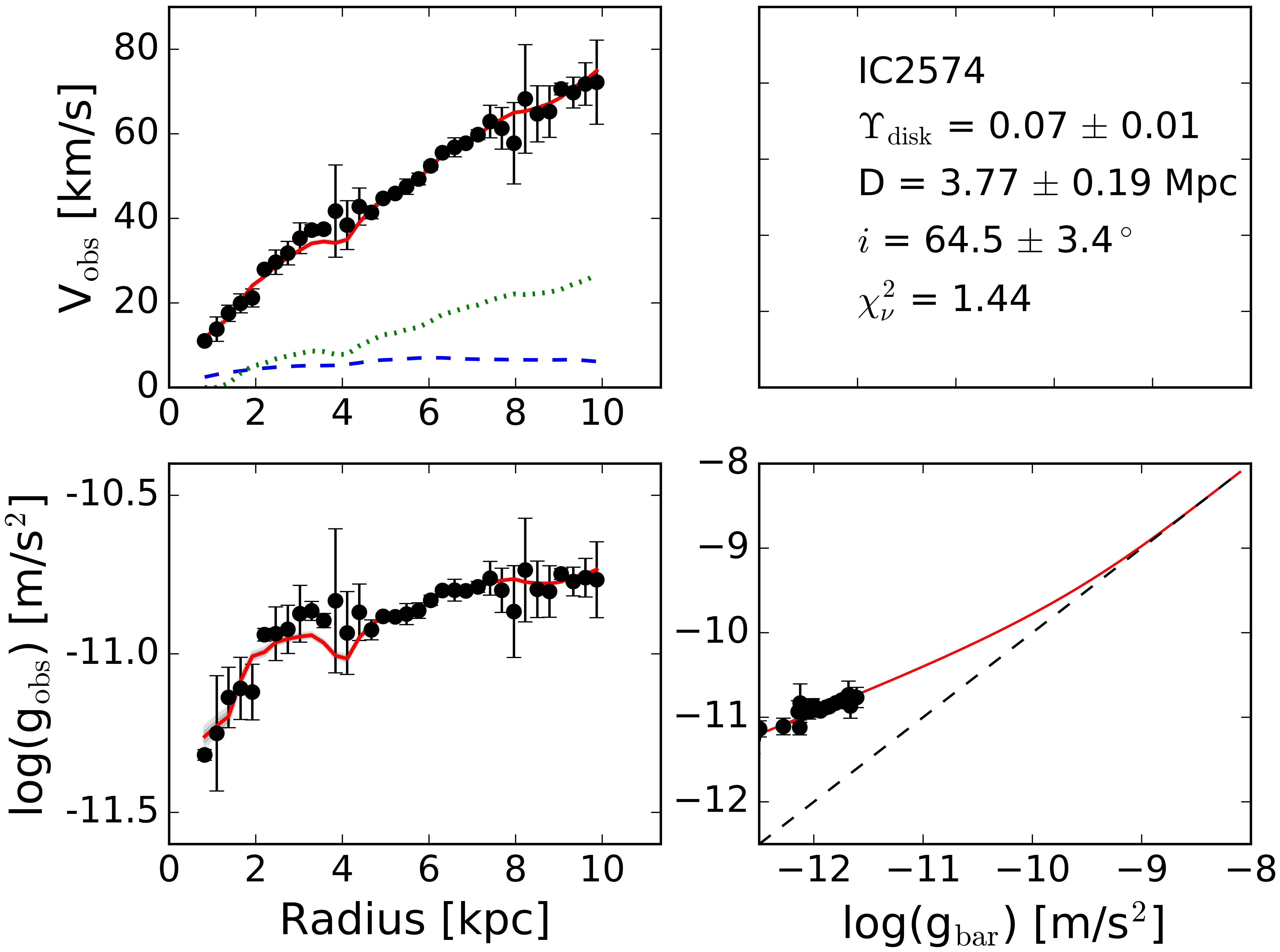

rotation curves
(a)
V (km s$^{-1}$)
$10^2$
$10^1$
R (kpc)
$10^0$
$10^1$
$10^2$
$\Sigma_e$
1000
100
10
$M_\odot$ pc$^{-2}$
centripetal acceleration curves $a = \frac{V^2}{R}$
(b)
Newtonian regime
Deep MOND regime
$a_0$
a (m s$^{-2}$)
$10^{-8}$
$10^{-9}$
$10^{-10}$
$10^{-11}$
$10^{-12}$
R (kpc)
$10^0$
$10^1$
$10^2$

MOND is a surprisingly effective algorithm for mapping what you see to what you get



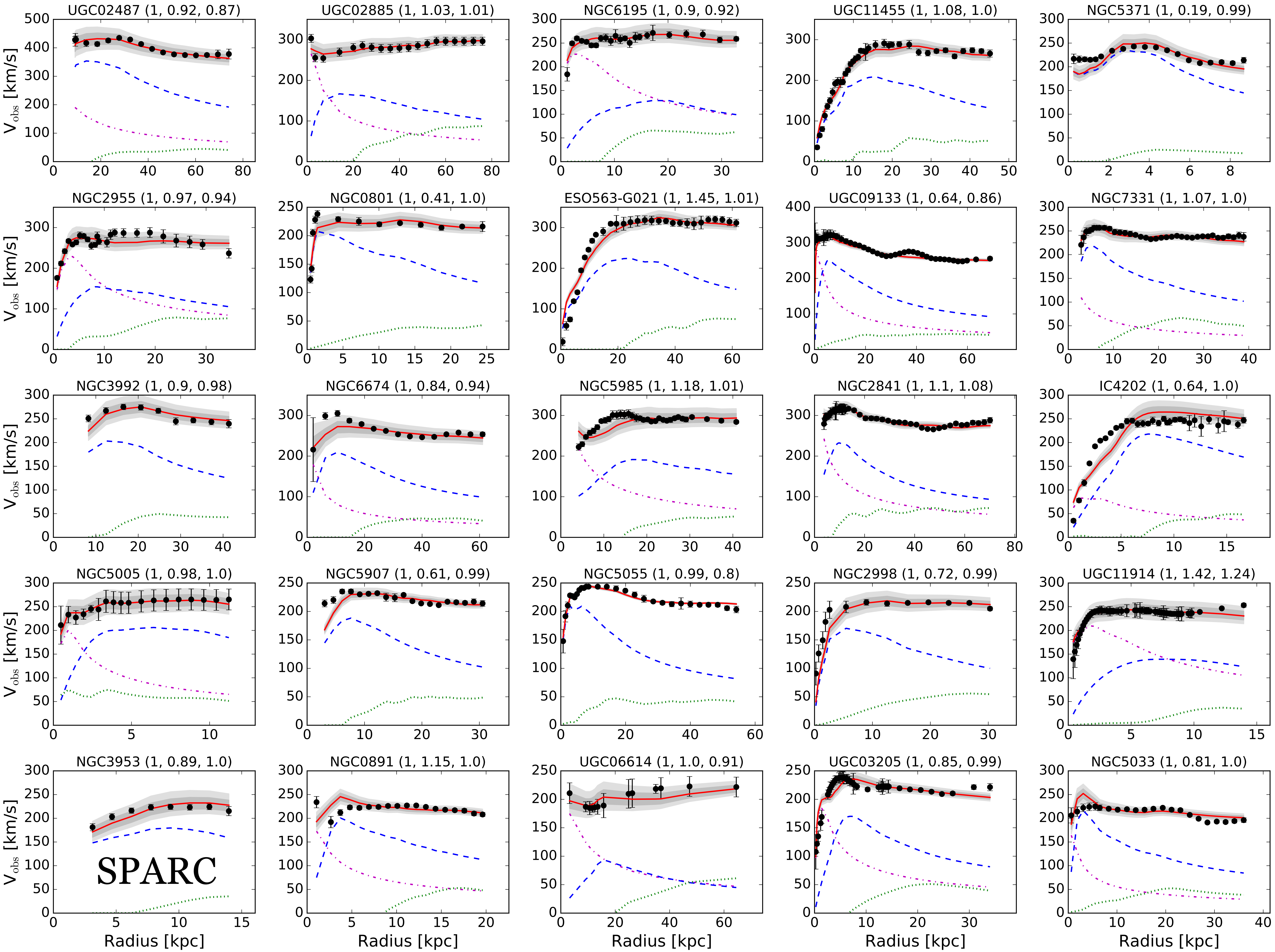
This must be telling us something

# MOND fits are equivalent to choosing M*/L to place galaxies on the RAR (Li et al. 2018)

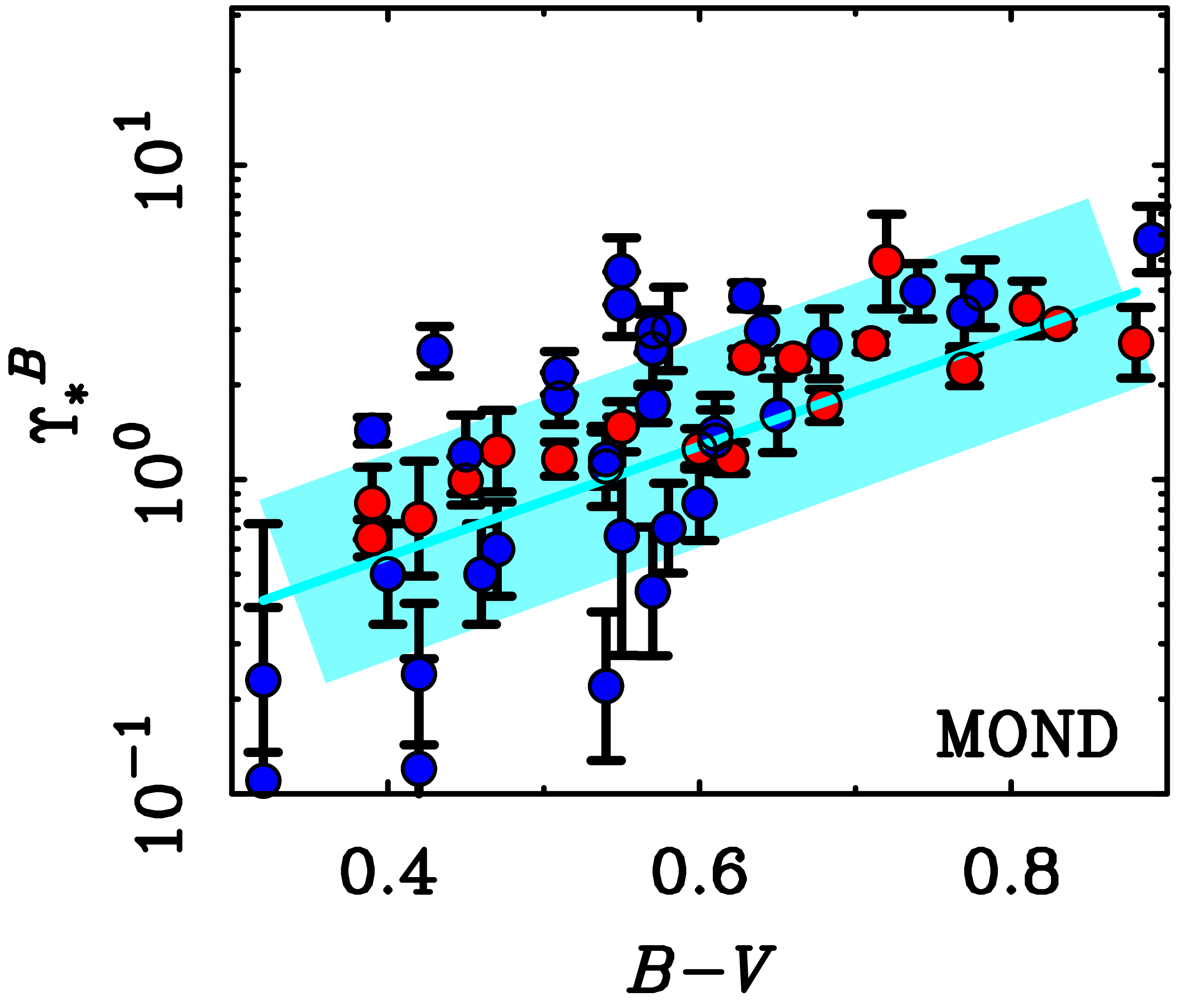


Distance and inclination are nuisance parameters in Bayesian fits.

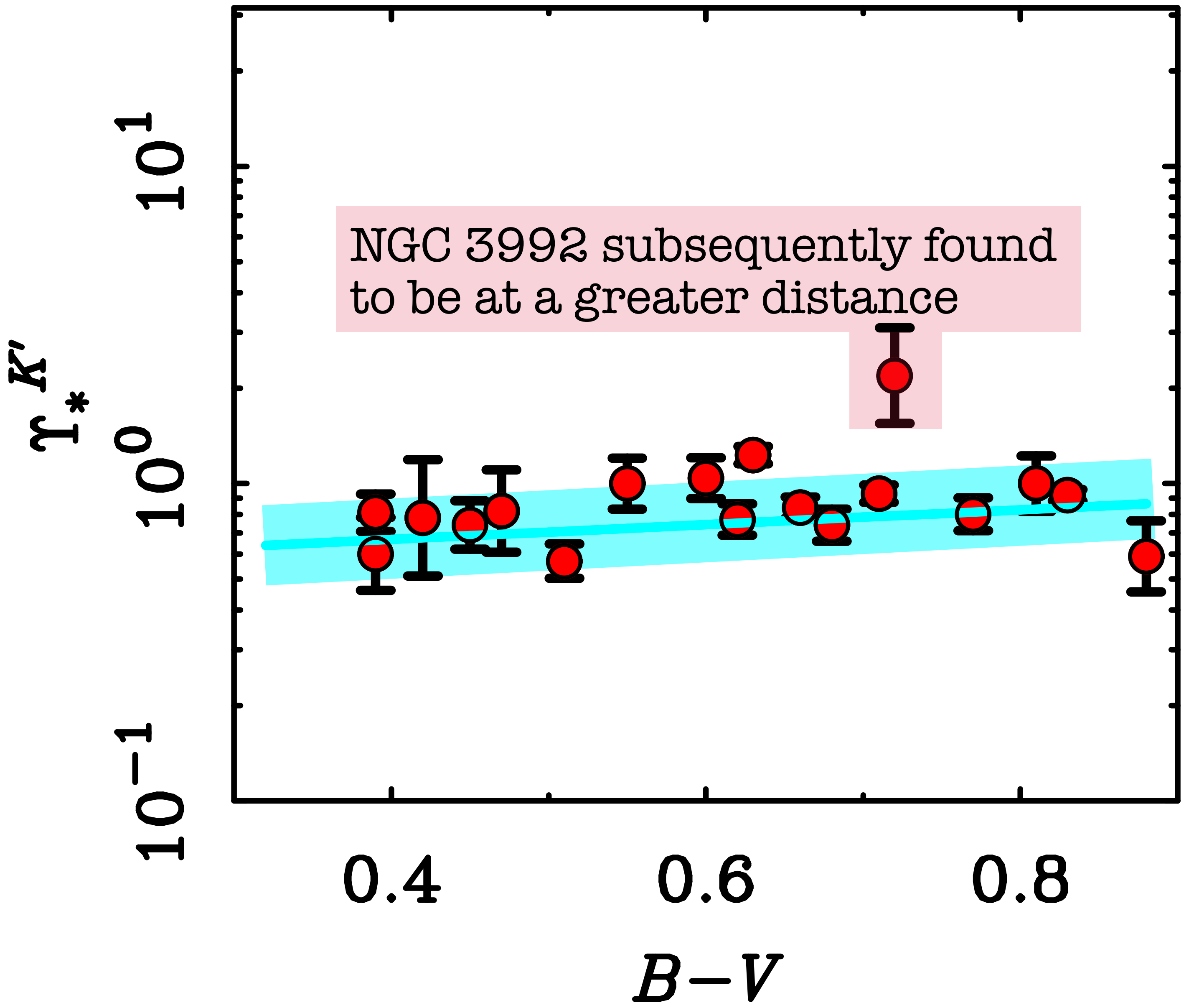
Low surface density galaxies reside entirely in the low acceleration regime.


UGC02487 (1, 0.92, 0.87)
UGC02885 (1, 1.03, 1.01)
NGC6195 (1, 0.9, 0.92)
UGC11455 (1, 1.08, 1.0)
NGC5371 (1, 0.19, 0.99)
NGC2955 (1, 0.97, 0.94)
NGC0801 (1, 0.41, 1.0)
ESO563-G021 (1, 1.45, 1.01)
UGC09133 (1, 0.64, 0.86)
NGC7331 (1, 1.07, 1.0)
NGC3992 (1, 0.9, 0.98)
NGC6674 (1, 0.84, 0.94)
NGC5985 (1, 1.18, 1.01)
NGC2841 (1, 1.1, 1.08)
IC4202 (1, 0.64, 1.0)
NGC5005 (1, 0.98, 1.0)
NGC5907 (1, 0.61, 0.99)
NGC5055 (1, 0.99, 0.8)
NGC2998 (1, 0.72, 0.99)
UGC11914 (1, 1.42, 1.24)
NGC3953 (1, 0.89, 1.0)
NGC0891 (1, 1.15, 1.0)
UGC06614 (1, 1.0, 0.91)
UGC03205 (1, 0.85, 0.99)
NGC5033 (1, 0.81, 1.0)
$V_{obs}$ [km/s]
Radius [kpc]
SPARC

# MOND predictions



Best-fit mass-to-light ratio in good agreement with stellar population models in amplitude, color dependence, and scatter.

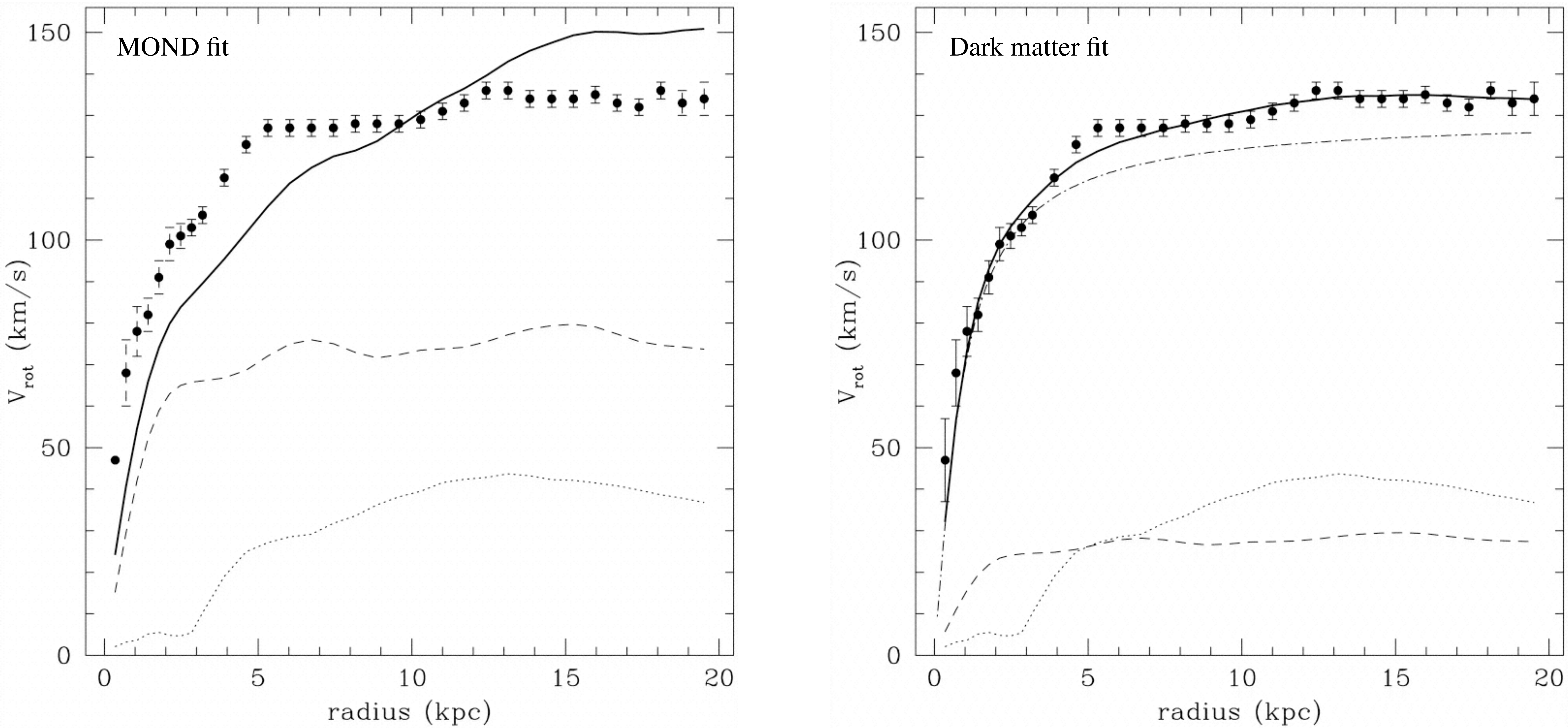


NGC 3992 subsequently found to be at a greater distance

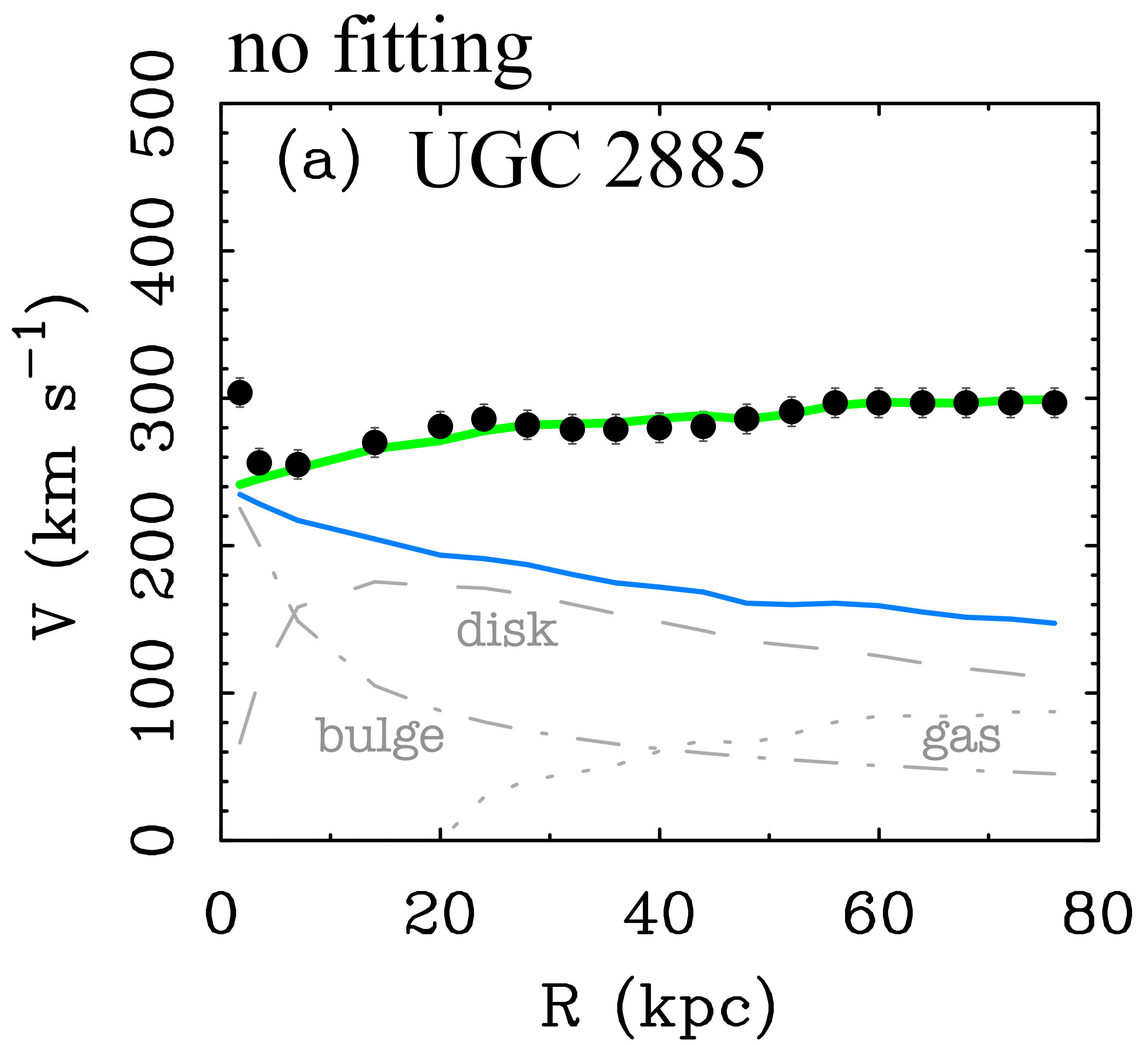
- The Tully-Fisher Relation
  - ✓ Slope = 4
  - ✓ Normalization = $1/(a_0G)$
  - ✓ Fundamentally a relation between Disk Mass and $V_{flat}$
  - ✓ No Dependence on Surface Brightness
- ✓ Dependence of conventional M/L on radius and surface brightness
- ✓ Rotation Curve Shapes
- ✓ Surface Density ~ Surface Brightness
- ✓ Detailed Rotation Curve Fits
- ✓ Stellar Population Mass-to-Light Ratios

# Misconceptions Abound

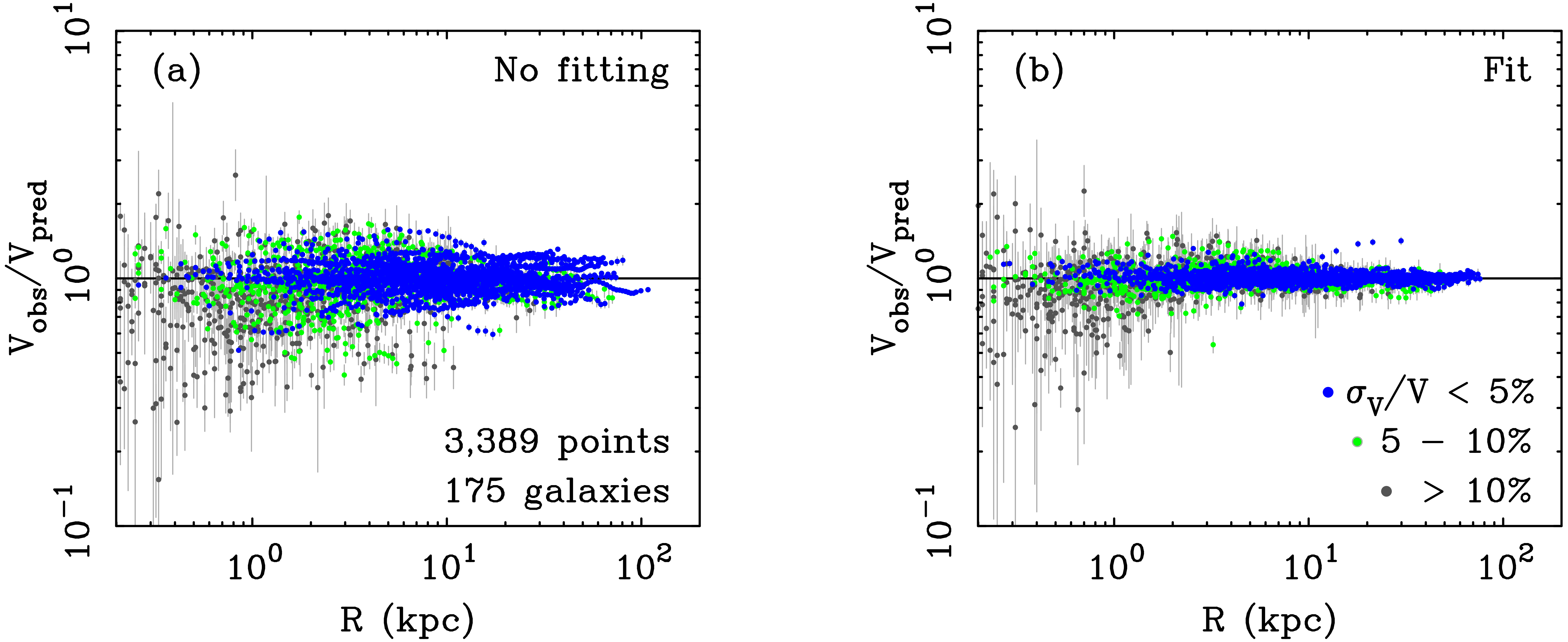
## “MOND was designed to fit rotation curves, so it is guaranteed to fit.”



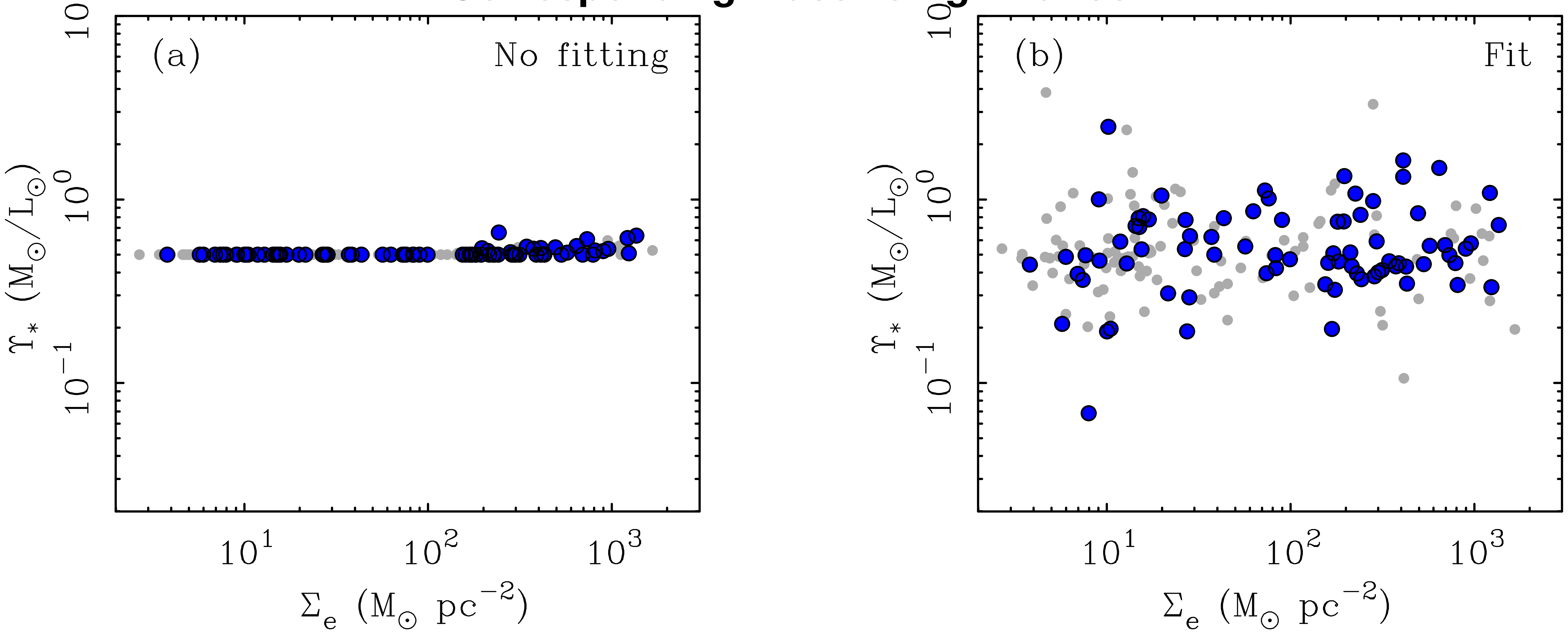
Fits of a hybrid NGC 2403/UGC 128 galaxy. This galaxy was constructed by using the NGC 2403 rotation curve data, but replacing its surface photometry by that of UGC 128.



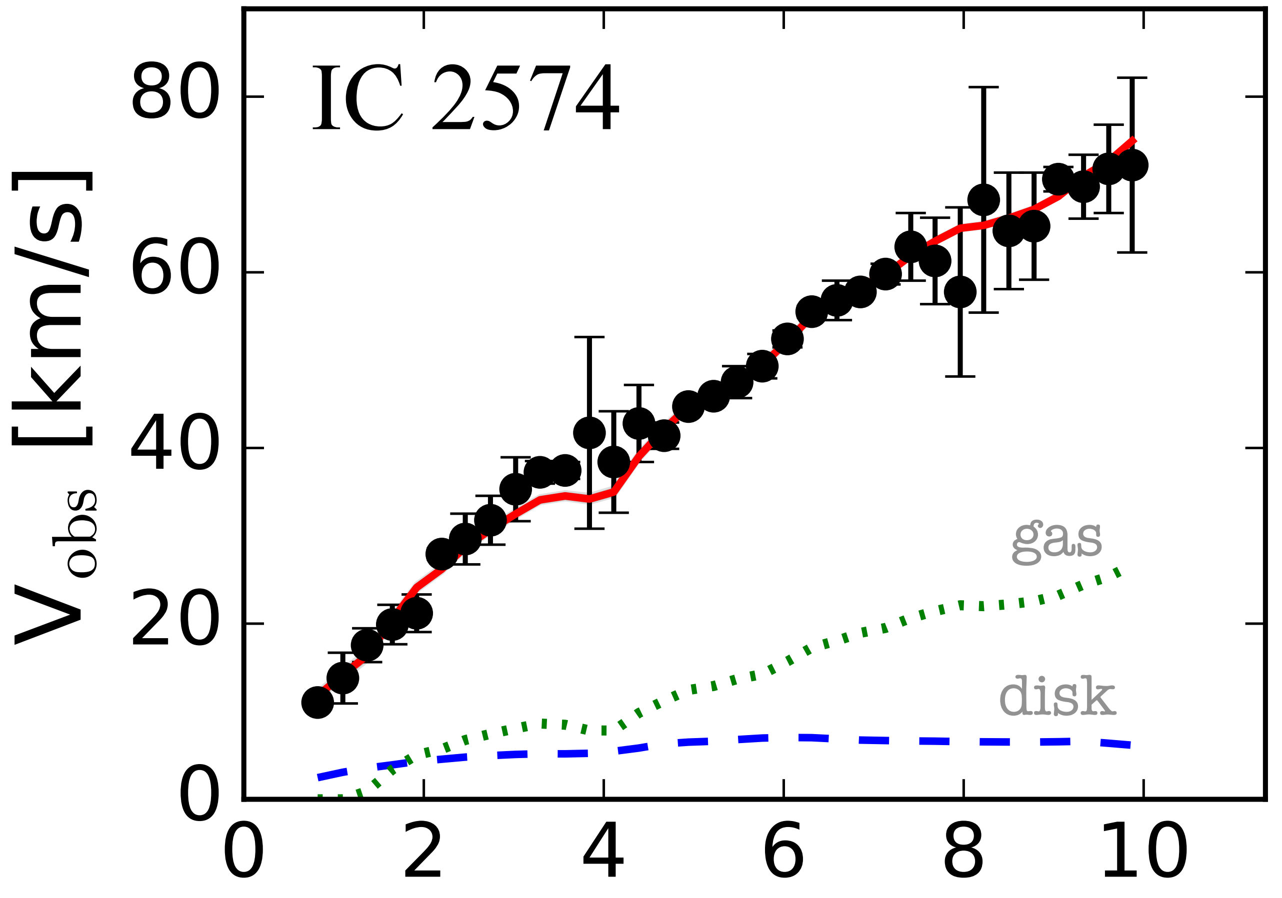
## Residuals from rotation curves



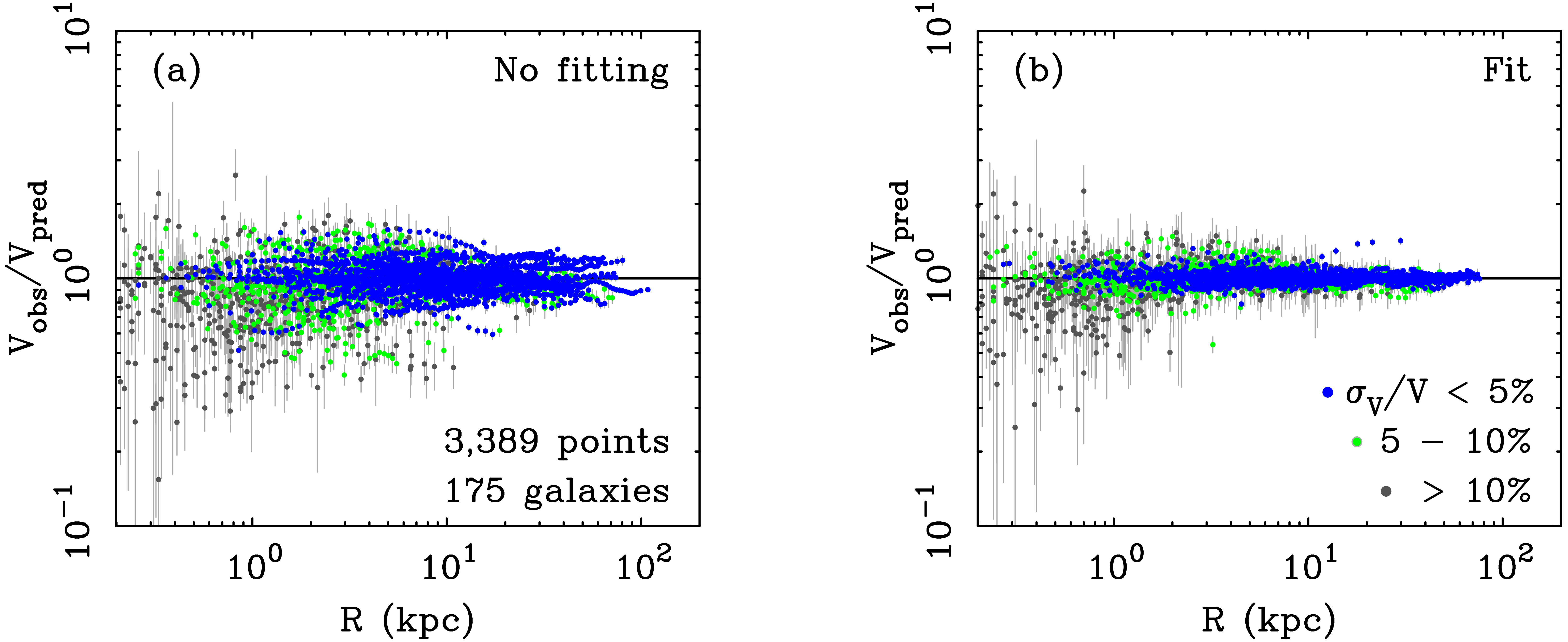
## Corresponding mass-to-light ratios



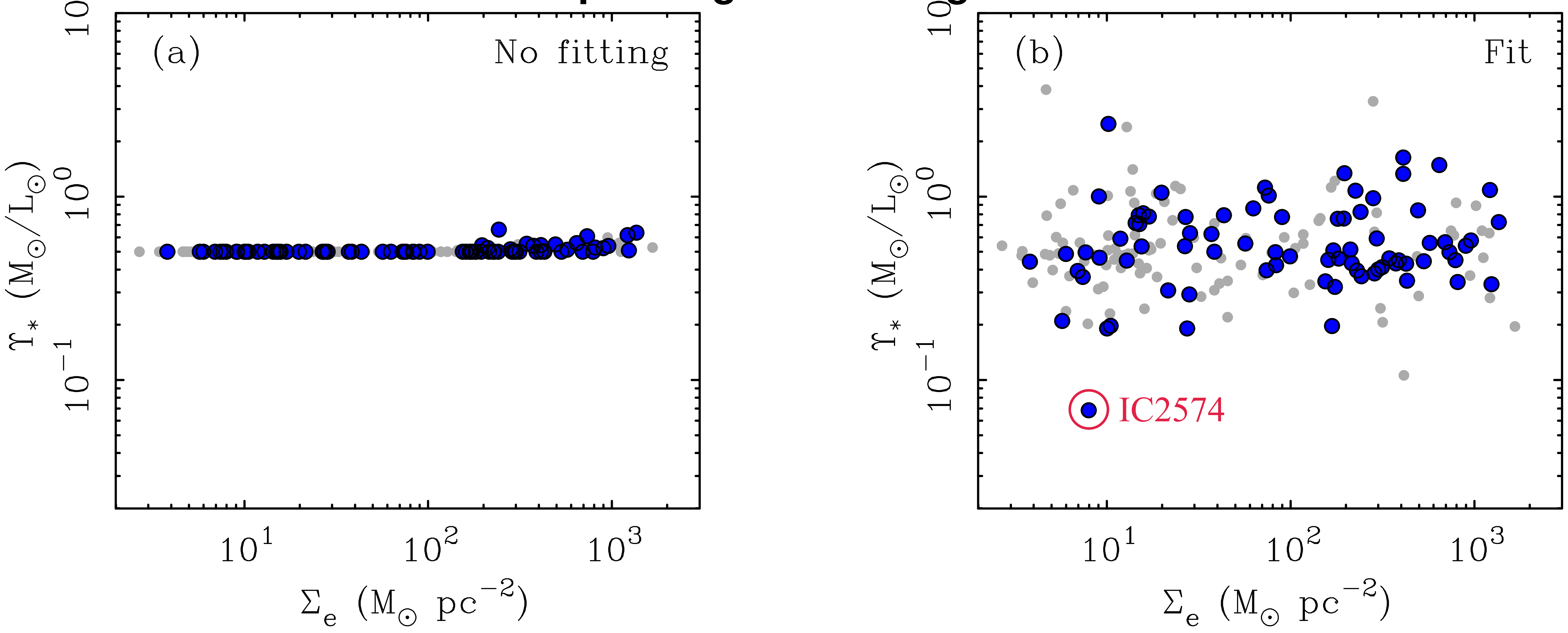
fitting - low M*/L



## Residuals from rotation curves



## Corresponding mass-to-light ratios



# Distance

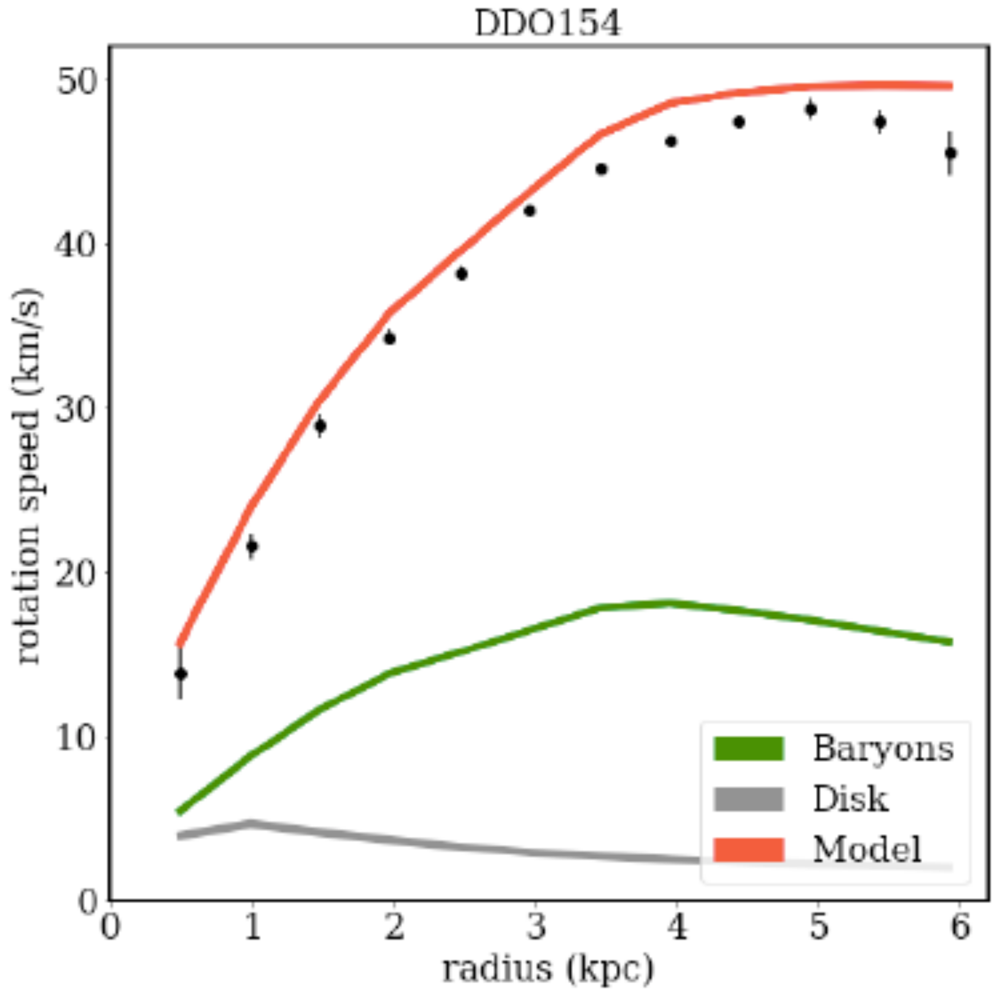
$$a \sim \frac{V^2}{R}$$

Distance and inclination play subtle but important roles in MOND fits. Make a good application of Bayesian statistics with the mass-to-light ratio as the one physical fit parameter and distance and inclination as nuisance parameters.

## Fixed distance

TRGB distance

$D = 4.04 \pm 0.08$ Mpc

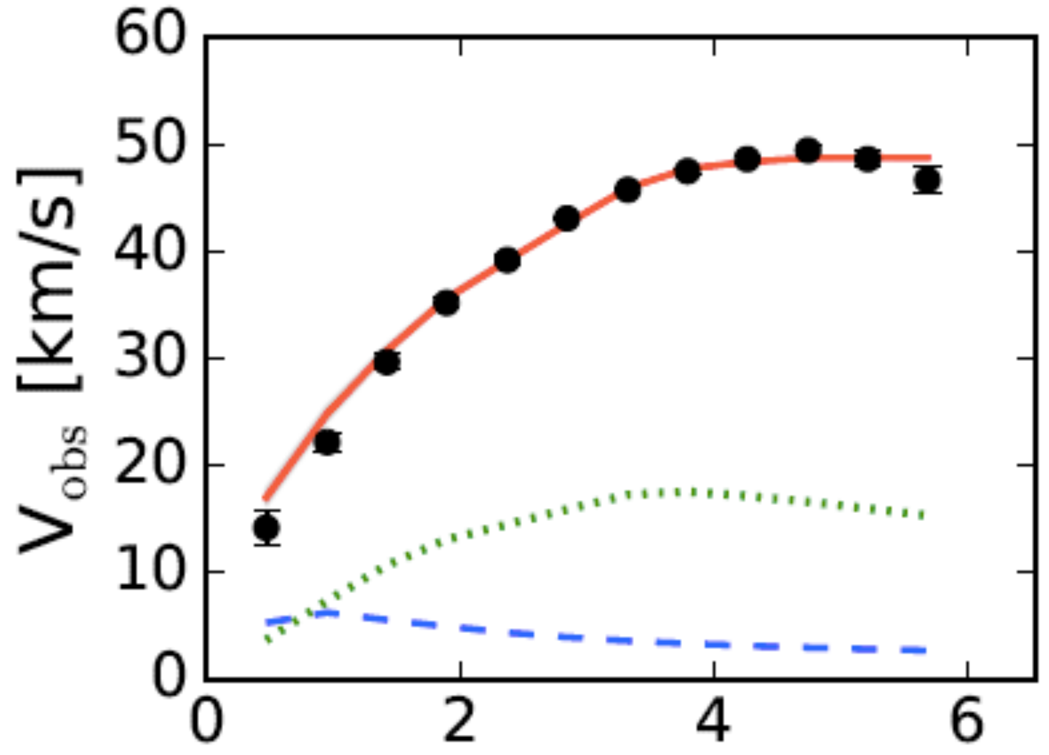


The MOND fit to DDO 154 from Ren et al. (2018).

## Distance treated as nuisance parameter

Bayesian fitted distance

$D = 3.87 \pm 0.16$ Mpc



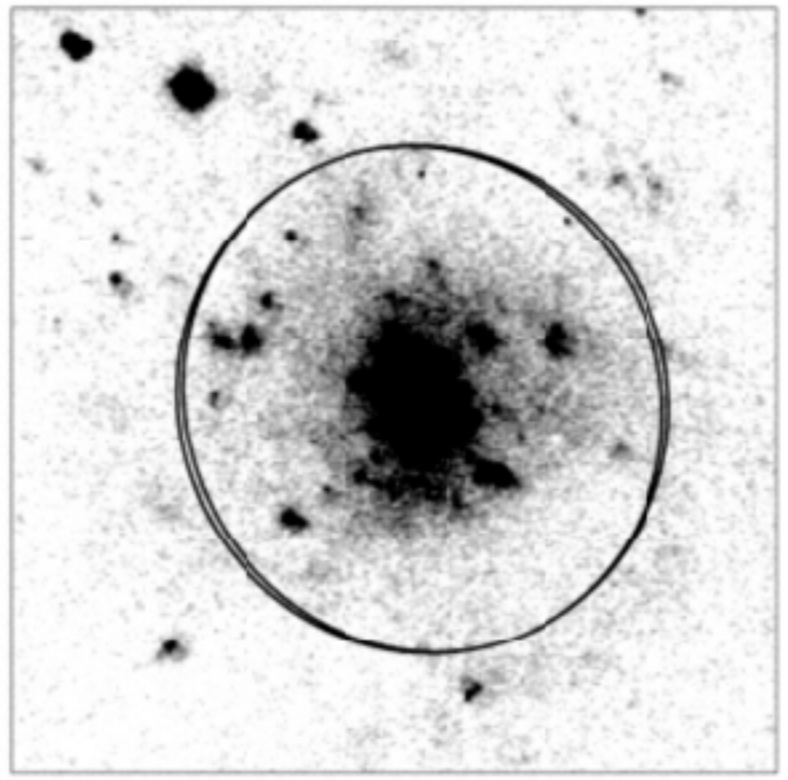
The MOND fit to DDO 154 from Li et al. (2018) using the same data.

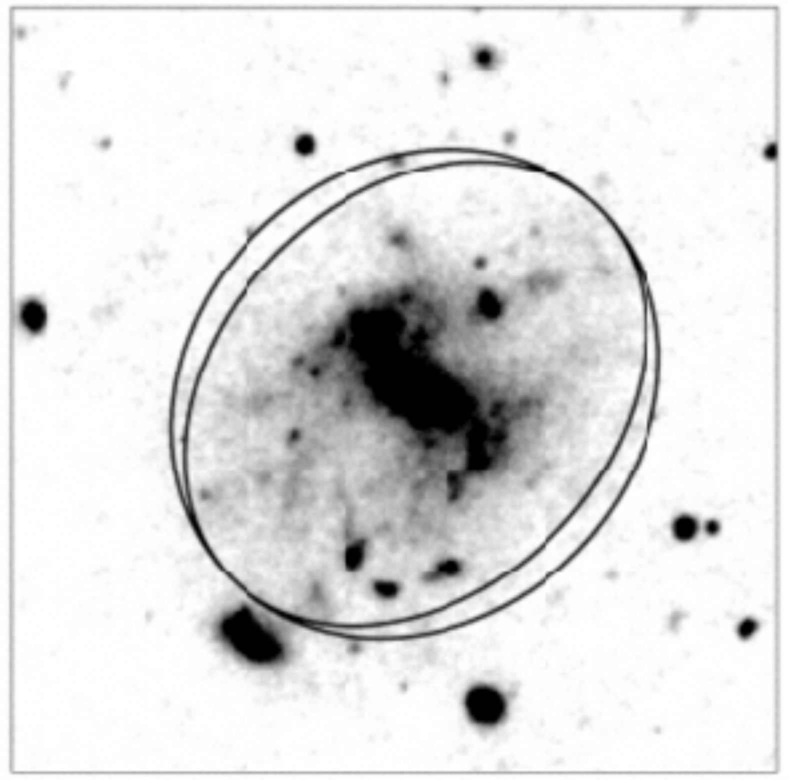
# Inclination

$$M \sim V^4 \sim \frac{v_{obs}^4}{\sin^4(i)}$$

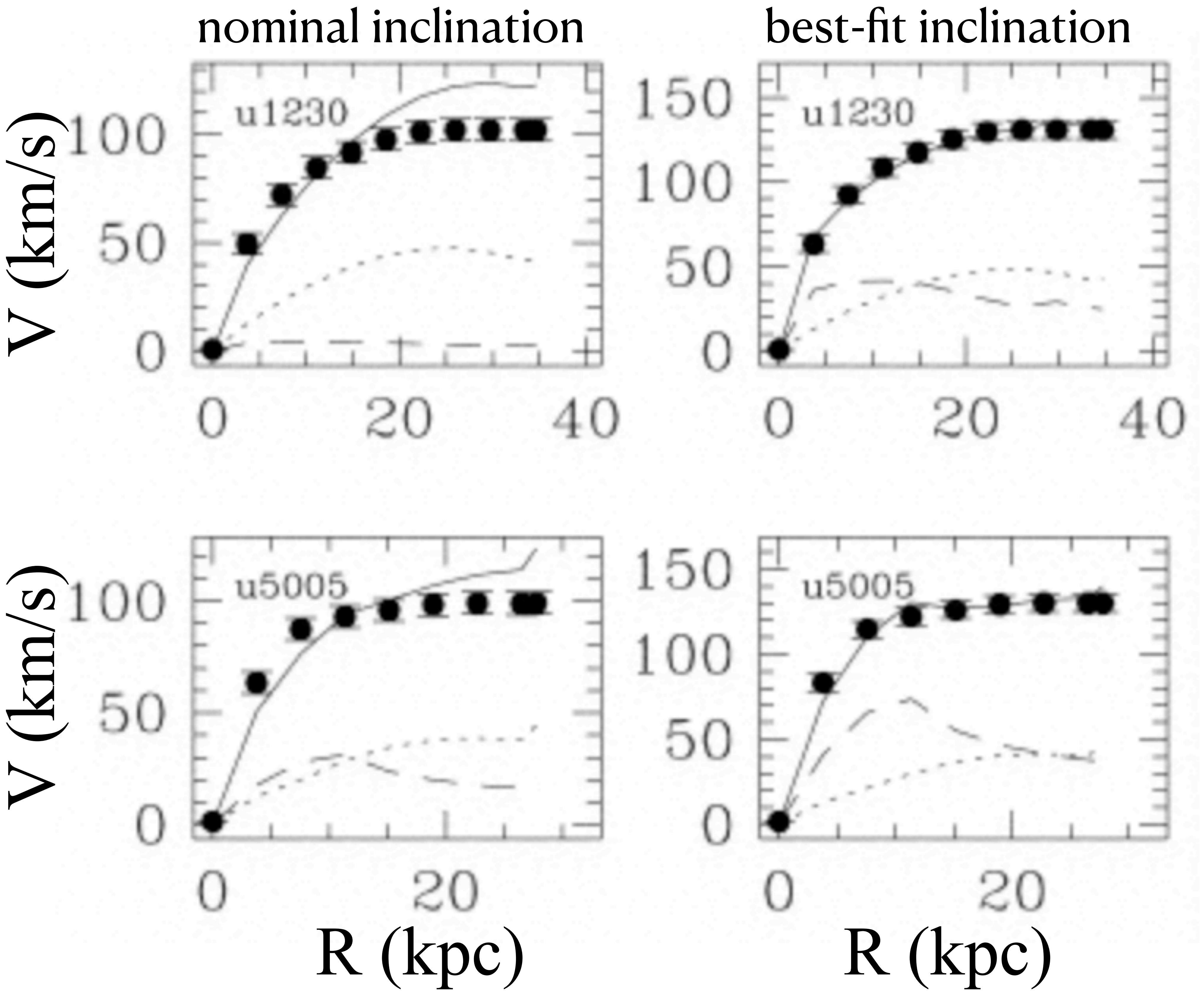
Distance and inclination play subtle but important roles in MOND fits. Make a good application of Bayesian statistics with the mass-to-light ratio as the one physical fit parameter and distance and inclination as nuisance parameters.

UGC 1230



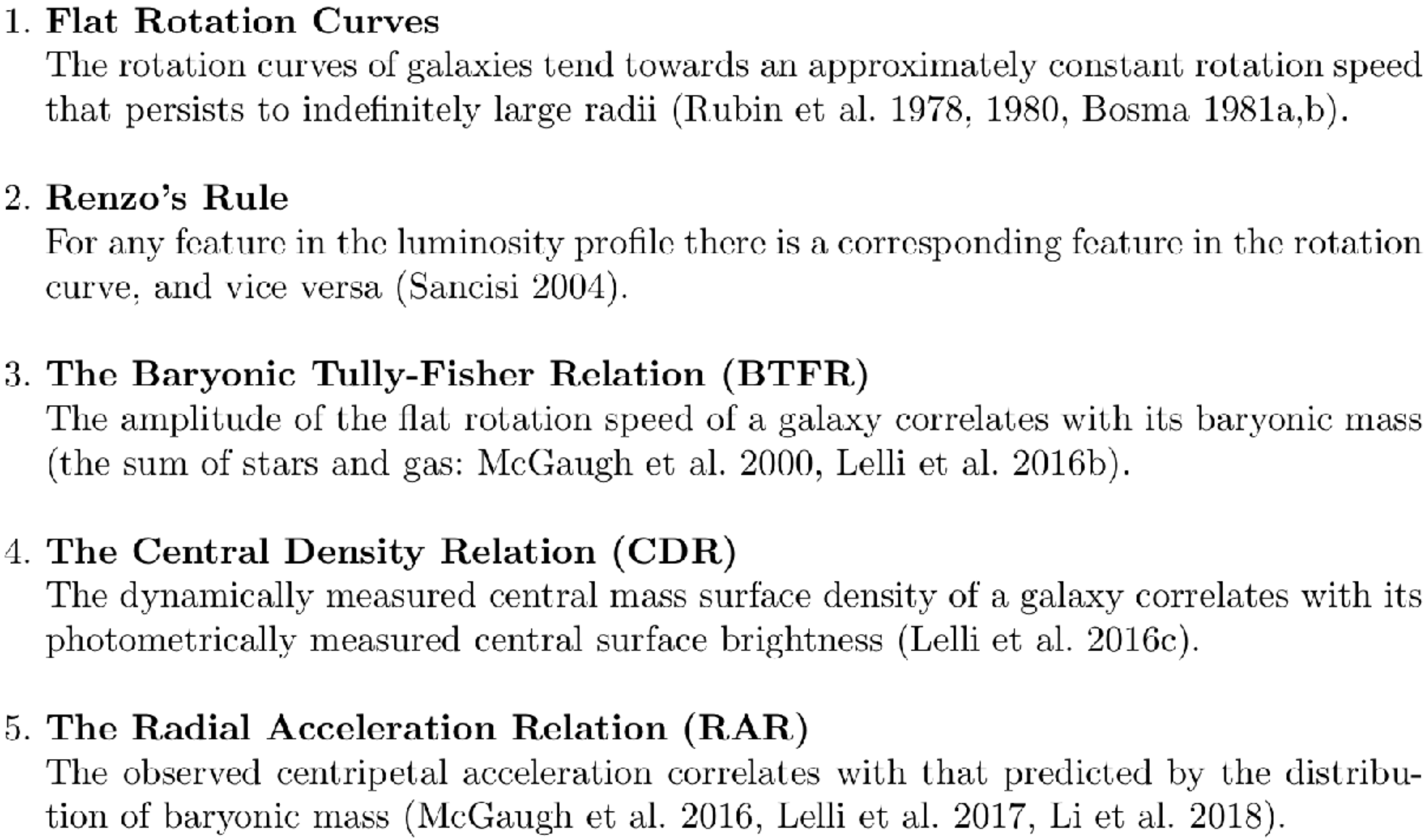


UGC 5005



de Blok & McGaugh 1998, ApJ, 508, 132

## Recall our empirical laws - these are true in the data irrespective of their interpretation



1. **Flat Rotation Curves**
   The rotation curves of galaxies tend towards an approximately constant rotation speed that persists to indefinitely large radii (Rubin et al. 1978, 1980, Bosma 1981a,b).

2. **Renzo's Rule**
   For any feature in the luminosity profile there is a corresponding feature in the rotation curve, and vice versa (Sancisi 2004).

3. **The Baryonic Tully-Fisher Relation (BTFR)**
   The amplitude of the flat rotation speed of a galaxy correlates with its baryonic mass (the sum of stars and gas: McGaugh et al. 2000, Lelli et al. 2016b).

4. **The Central Density Relation (CDR)**
   The dynamically measured central mass surface density of a galaxy correlates with its photometrically measured central surface brightness (Lelli et al. 2016c).

5. **The Radial Acceleration Relation (RAR)**
   The observed centripetal acceleration correlates with that predicted by the distribution of baryonic mass (McGaugh et al. 2016, Lelli et al. 2017, Li et al. 2018).

# Predicted by MOND?

1. **Flat Rotation Curves**

*Unanticipated observation. No prediction.*

☆ 2. **Renzo's Rule**

*Match between features natural and inevitable*

★ ☆ 3. **The Baryonic Tully-Fisher Relation (BTFR)**

★ *TF known when MOND proposed, but not the specific BTFR*

☆ *Specifically predicted lack of surface brightness residuals*

☆ 4. **The Central Density Relation (CDR)**

*Specifically predicted surface brightness-acceleration connection*

☆ 5. **The Radial Acceleration Relation (RAR)**

*Just MOND's interpolation function*

*A priori* prediction is the gold standard of the scientific method.
MOND was the only theory to correctly predict many of these observations in advance.

# Explained by dark matter?

1. **Flat Rotation Curves**

   *Unanticipated observation. No prediction.*
   *Dark matter halos do not automatically make for flat rotation curves.*

2. **Renzo's Rule**

   *Match between features should only occur where baryons dominate.*

3. **The Baryonic Tully-Fisher Relation (BTFR)**

   *CDM predicted wrong slope; still struggles to match data*
   *There should be surface brightness residuals*

4. **The Central Density Relation (CDR)**

   *Not explained. Never seems to get explicitly addressed.*

5. **The Radial Acceleration Relation (RAR)**

   *No satisfactory explanation.*

Review for *Galaxies* (2020)

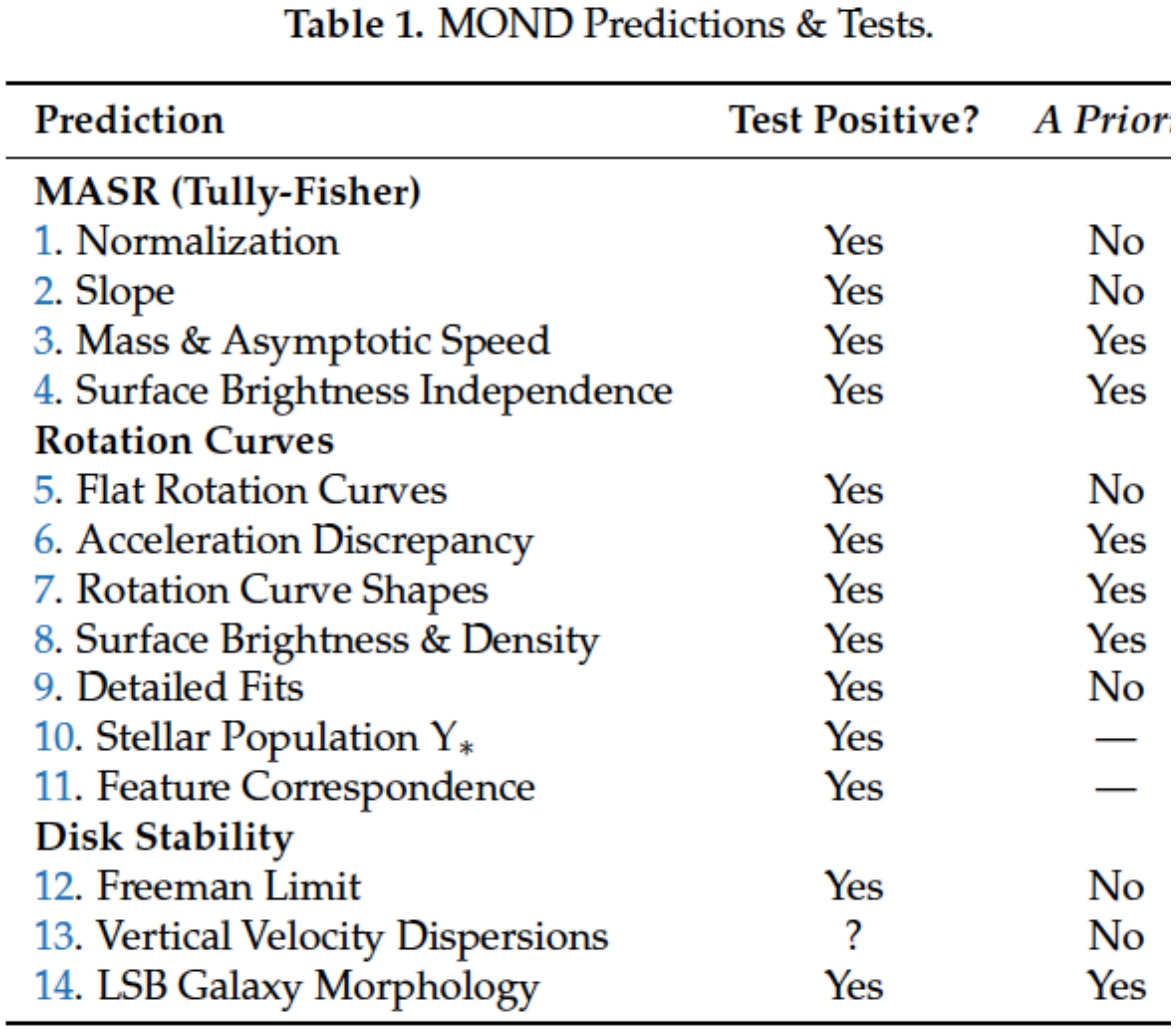
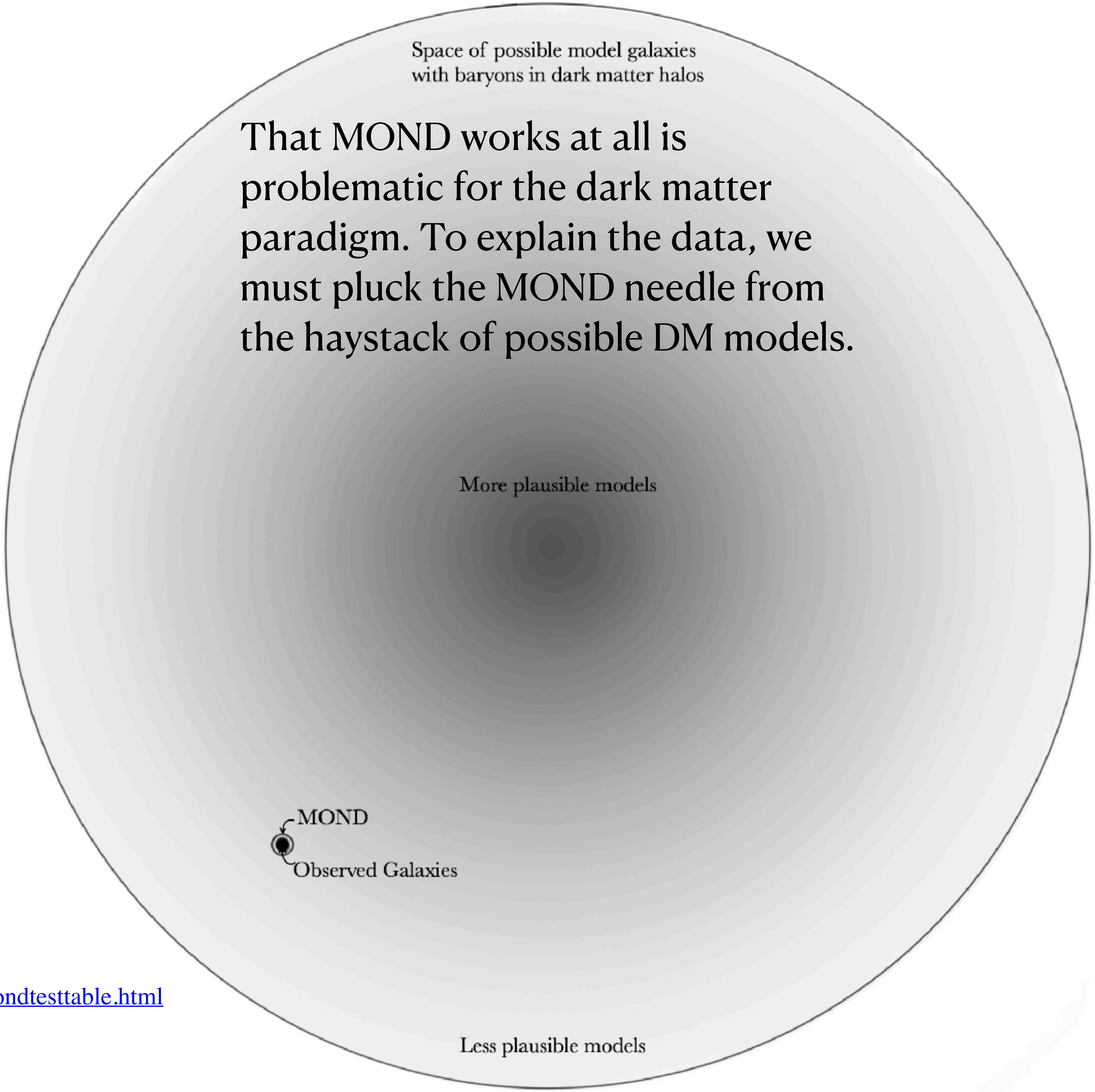


**Table 1.** MOND Predictions & Tests.

| Prediction | Test Positive? | *A Prior* |
|---|---|---|
| **MASR (Tully-Fisher)** | | |
| 1. Normalization | Yes | No |
| 2. Slope | Yes | No |
| 3. Mass & Asymptotic Speed | Yes | Yes |
| 4. Surface Brightness Independence | Yes | Yes |
| **Rotation Curves** | | |
| 5. Flat Rotation Curves | Yes | No |
| 6. Acceleration Discrepancy | Yes | Yes |
| 7. Rotation Curve Shapes | Yes | Yes |
| 8. Surface Brightness & Density | Yes | Yes |
| 9. Detailed Fits | Yes | No |
| 10. Stellar Population $\Upsilon_*$ | Yes | — |
| 11. Feature Correspondence | Yes | — |
| **Disk Stability** | | |
| 12. Freeman Limit | Yes | No |
| 13. Vertical Velocity Dispersions | ? | No |
| 14. LSB Galaxy Morphology | Yes | Yes |

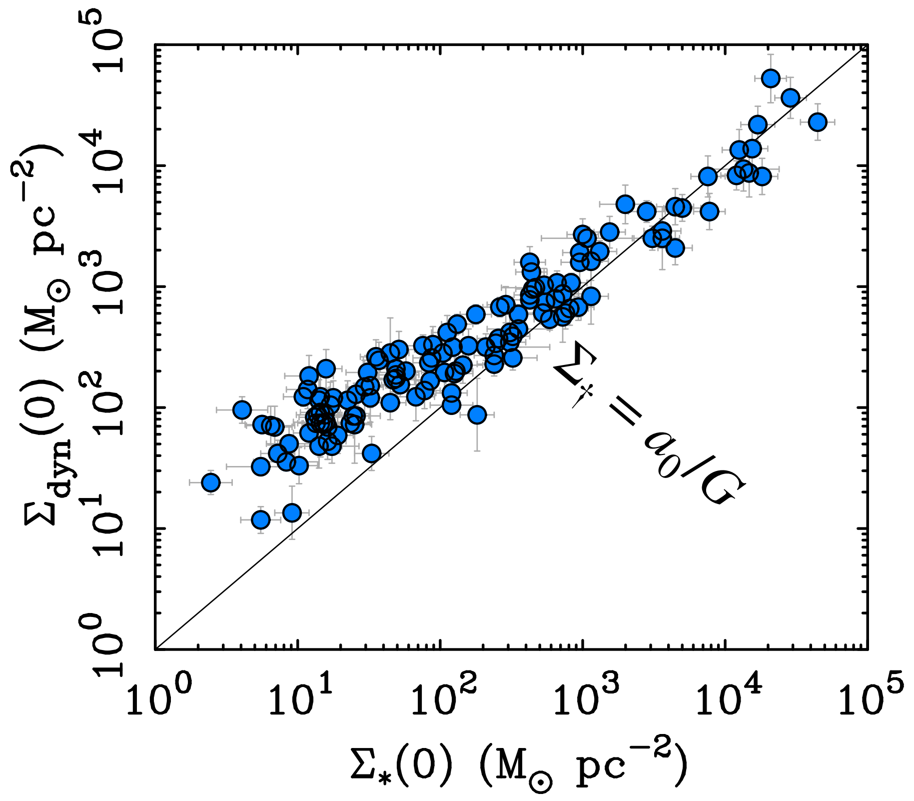
A more exhaustive list can be found at [http://astroweb.case.edu/ssm/mond/LCDMmondtesttable.html](http://astroweb.case.edu/ssm/mond/LCDMmondtesttable.html)



That MOND works at all is problematic for the dark matter paradigm. To explain the data, we must pluck the MOND needle from the haystack of possible DM models.

# Disk Stability

- MOND stabilizes disk in the low acceleration regime
  - High acceleration objects suffer usual Newtonian instabilities
- Predicts upper limit to disk surface brightness
  - Freeman’s surface brightness marks transition between stable and unstable regimes $\Sigma \lesssim \Sigma_\dagger = a_0/G$



- Stability properties differ from DM case
  - similar at high surface brightness $t = \frac{T}{|W|} \approx 0.14$
  - less added stability at low surface brightness (low acceleration)

$$t = \frac{T}{|W|} \ll 0.14$$

# **Disk Stability in MOND**

Brada (1998)
Brada & Milgrom (1999, 2000)

MOND adds stability roughly comparable to that added by a dark matter halo of ~3 times the disk mass, enclosed by the disk radius.

- Stability properties
    - similar to DM at high surface brightness
    - less added stability at low surface brightness (low acceleration)

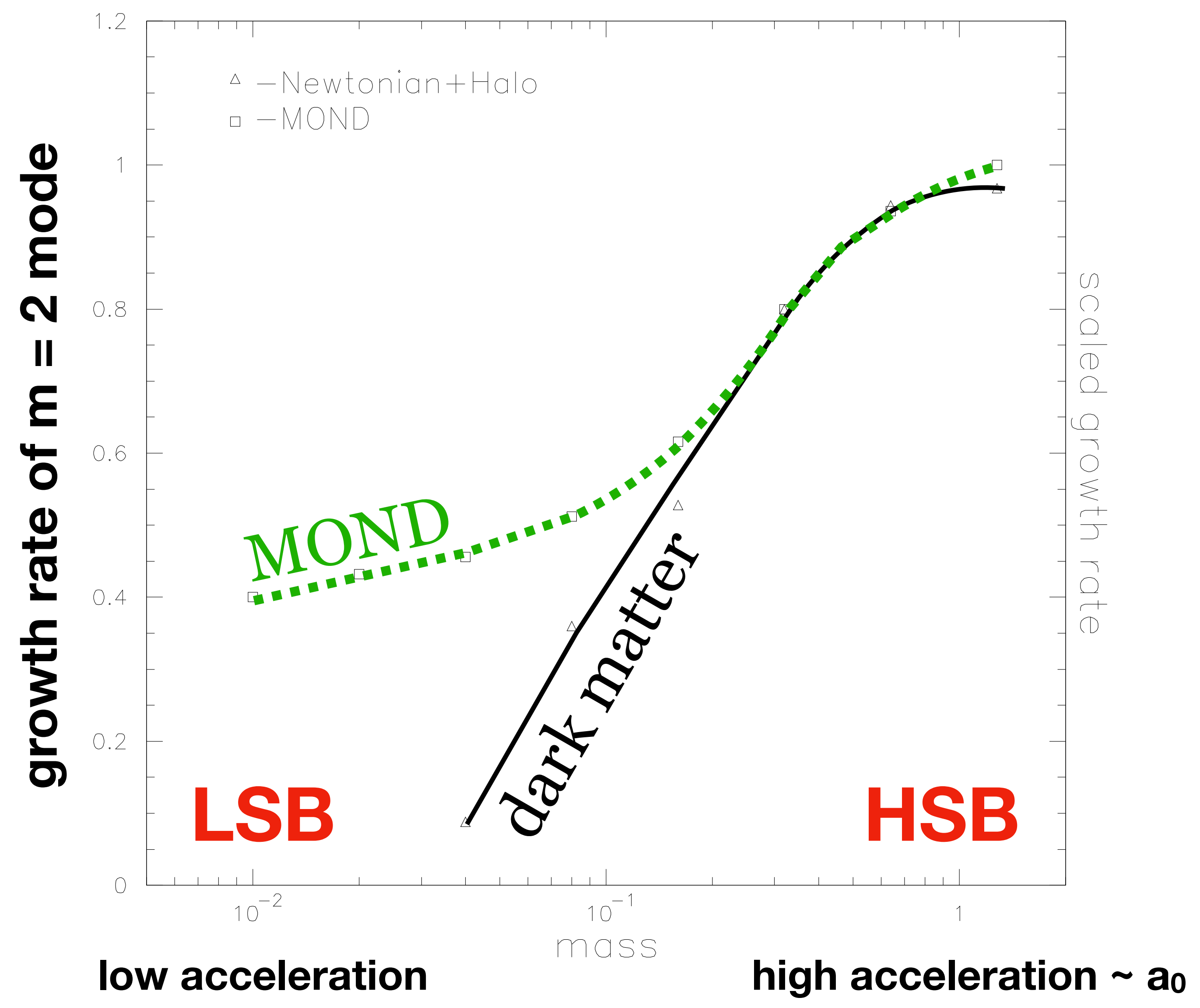


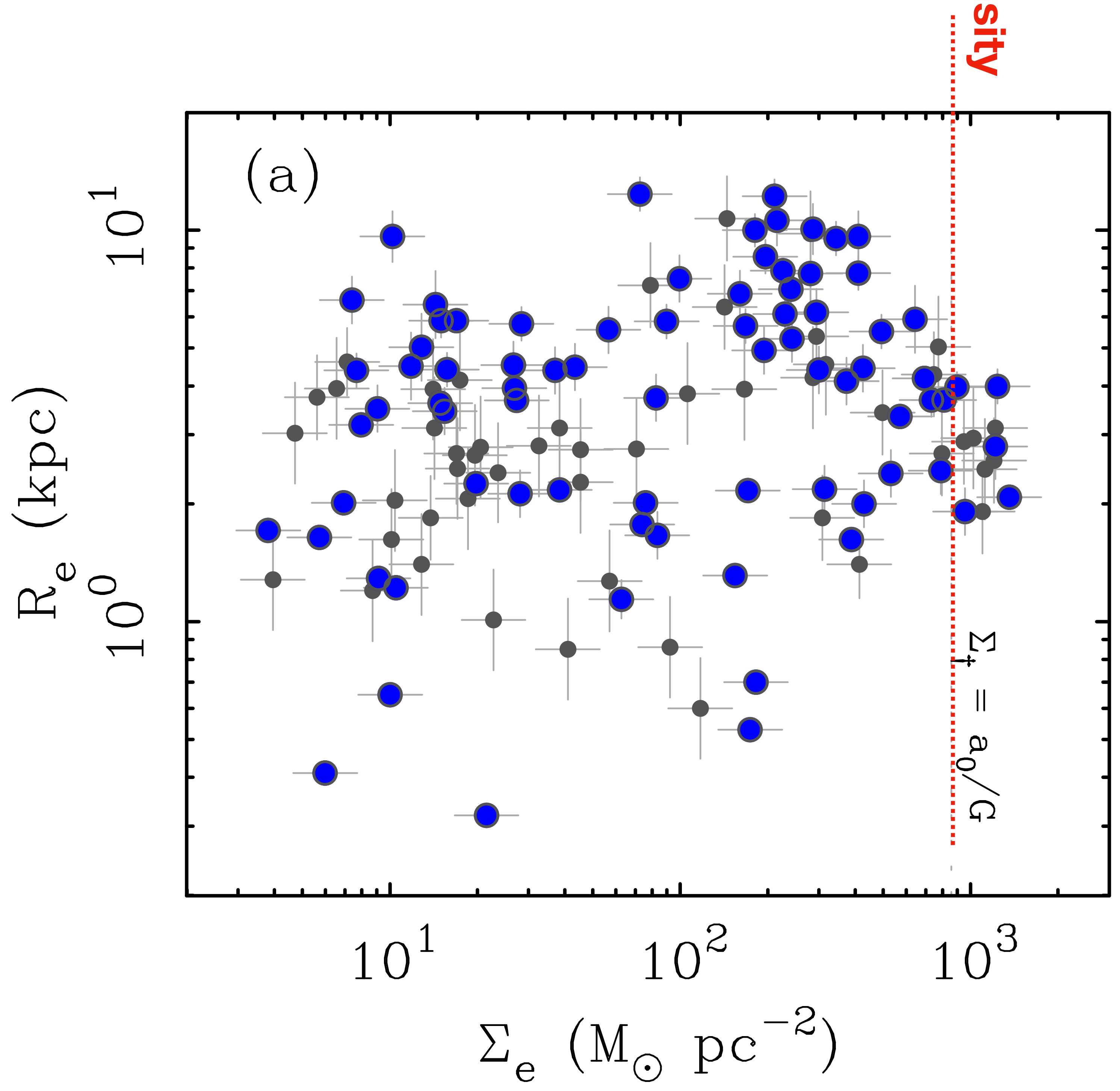
Figure 11: The growth rate, in units of the dynamical time, for the m=2 mode as a function of the total mass of the disk. □ MOND, △ Newtonian + Halo.

| m | Q | time step scaling | Growth rate | | halo mass at R=1 |
|---|---|---|---|---|---|
| | | | MOND | Newt+DM | |
| 0.005 | 2.55 | 1 | | | |
| 0.01 | 2.5 | 0.84 | 0.4 | | |
| 0.02 | 2.4 | 0.7 | 0.43 | | |
| 0.04 | 2.25 | 0.58 | 0.46 | 0.09 | 0.18 |
| 0.08 | 2.0 | 0.48 | 0.51 | 0.36 | 0.23 |
| 0.16 | 1.79 | 0.39 | 0.62 | 0.53 | 0.28 |
| 0.32 | 1.62 | 0.3 | 0.8 | 0.8 | 0.31 |
| 0.64 | 1.53 | 0.22 | 0.94 | 0.94 | 0.31 |
| 1.28 | 1.5 | 0.16 | 1.0 | 0.97 | 0.27 |

Table 1: The growth rate, in units of dynamical time, for the $m = 2$ mode, and model parameters for the different mass models.

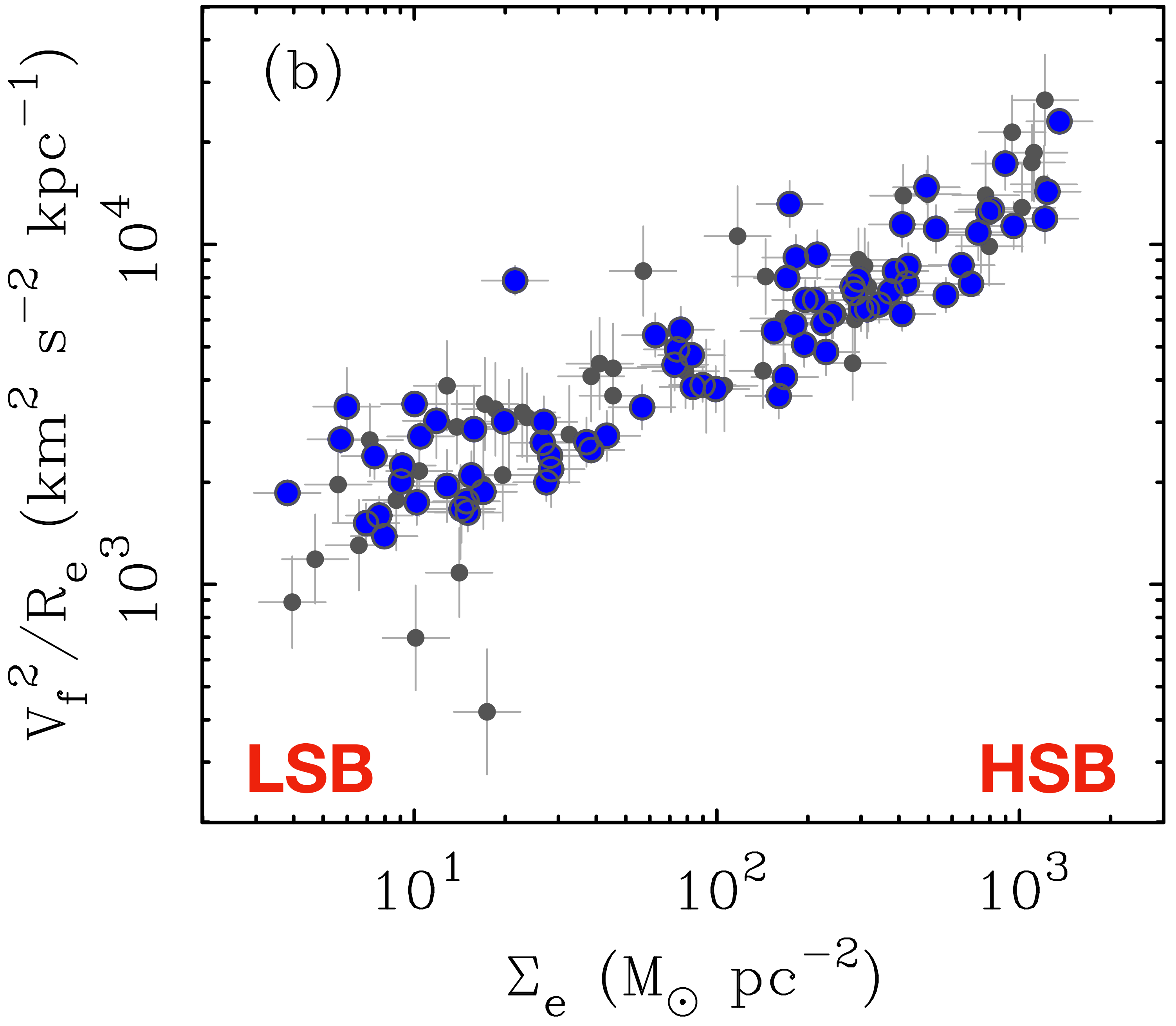
**critical surface density**

**size (effective radius)**



**characteristic surface density**
**(effective surface brightness)**

**characteristic acceleration**



**LSB**

**HSB**

**characteristic surface density**
**(effective surface brightness)**

**Tiret & Combes** (2007, 2008)

MOND numerical simulations of galaxy morphology

real galaxies simulated galaxies

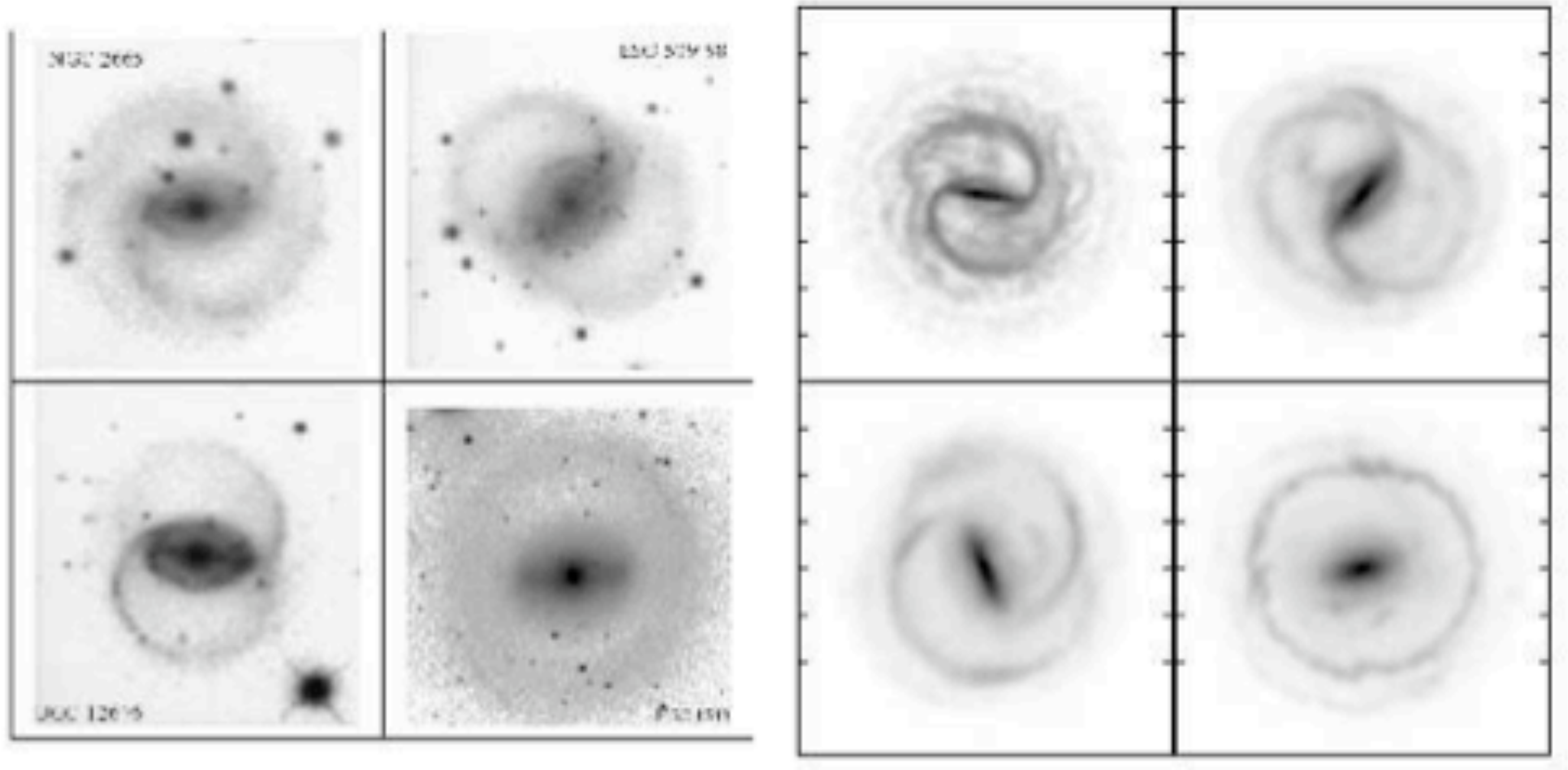
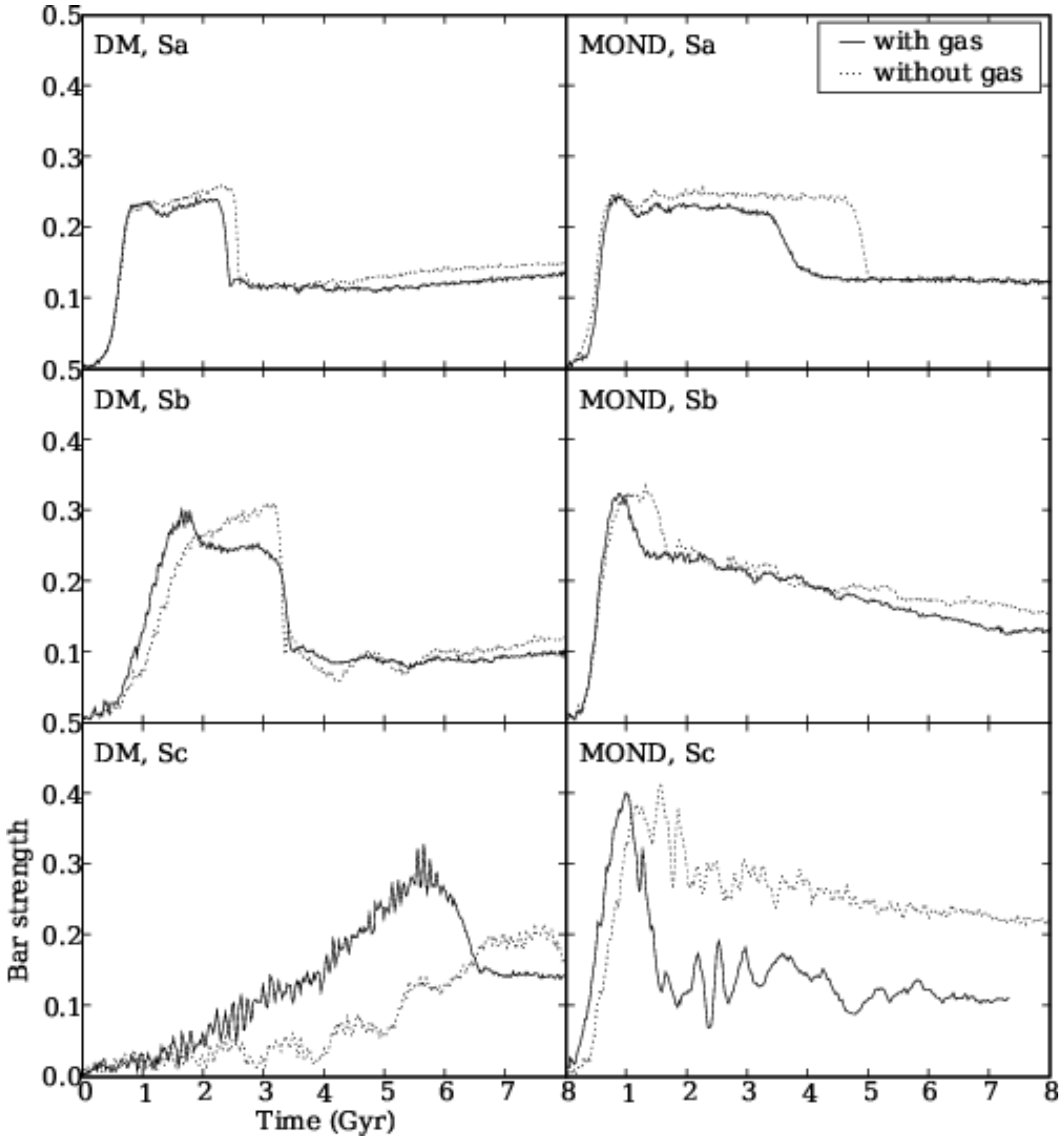


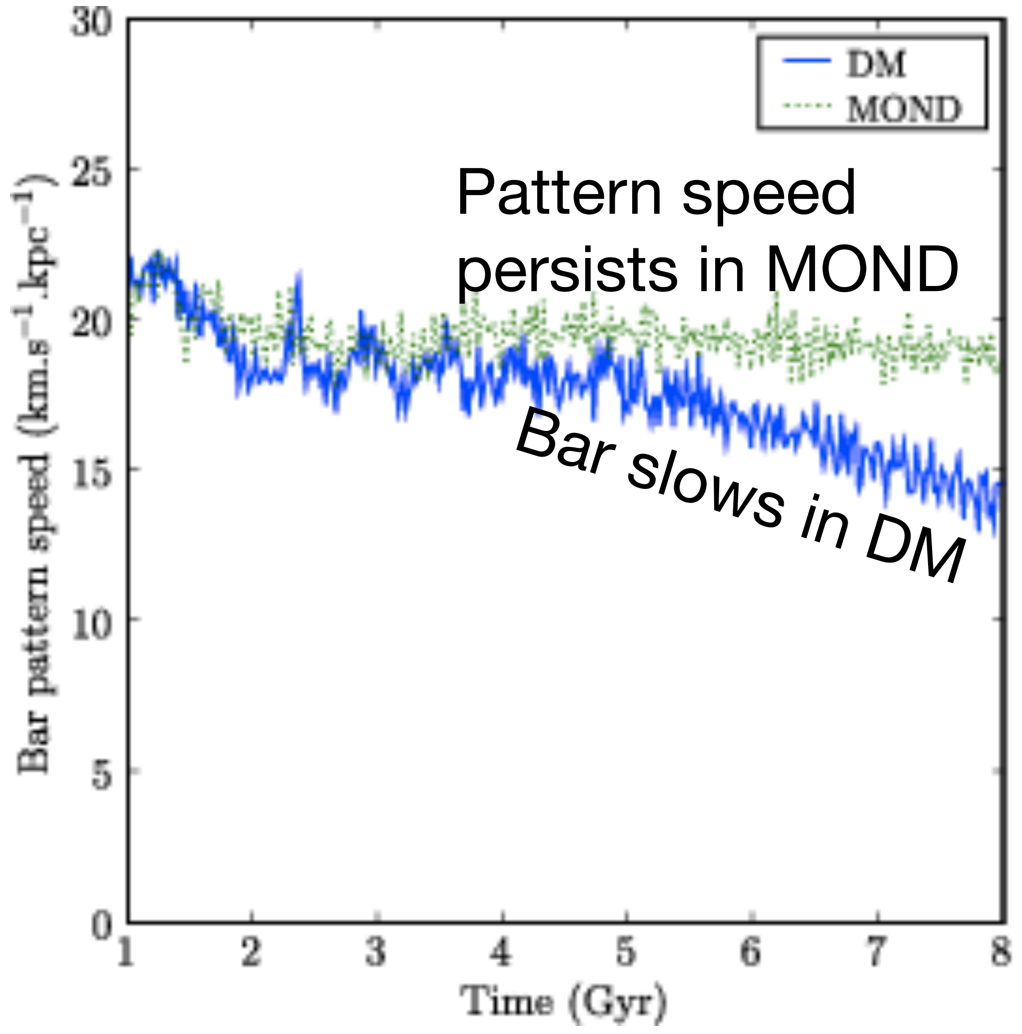
**Fig. 3.** Several examples showing the morphological structures of NGC 2665, ESO 509-98, UGC 12646 and NGC 1543 (top panel) compared to simulated galaxies in MOND (bottom panel). Rings and pseudo-rings structures are well reproduced with modified gravity.

**Tiret & Combes** (2007, 2008)

## Bar strength



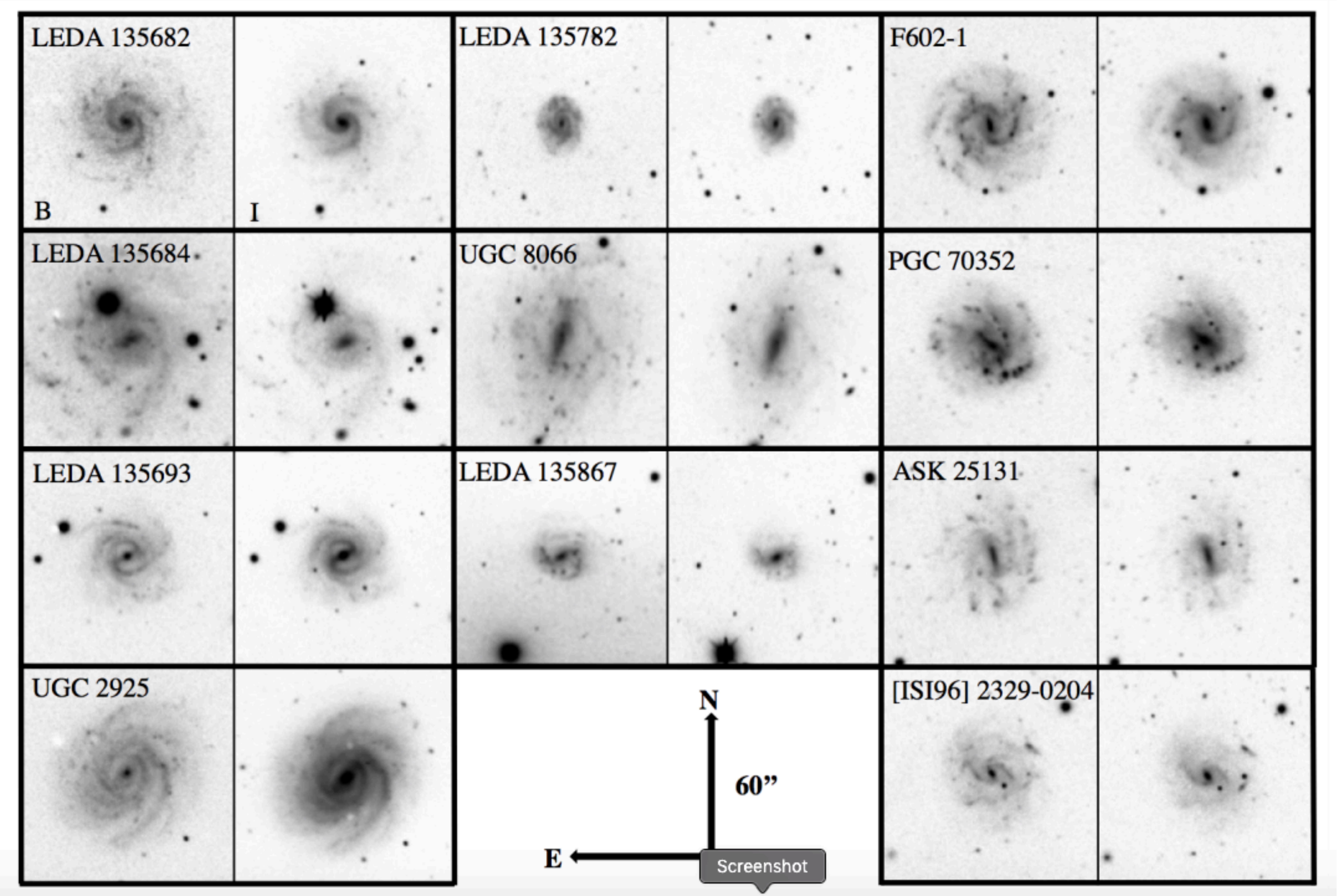
## Bar pattern speed



Pattern speed persists in MOND

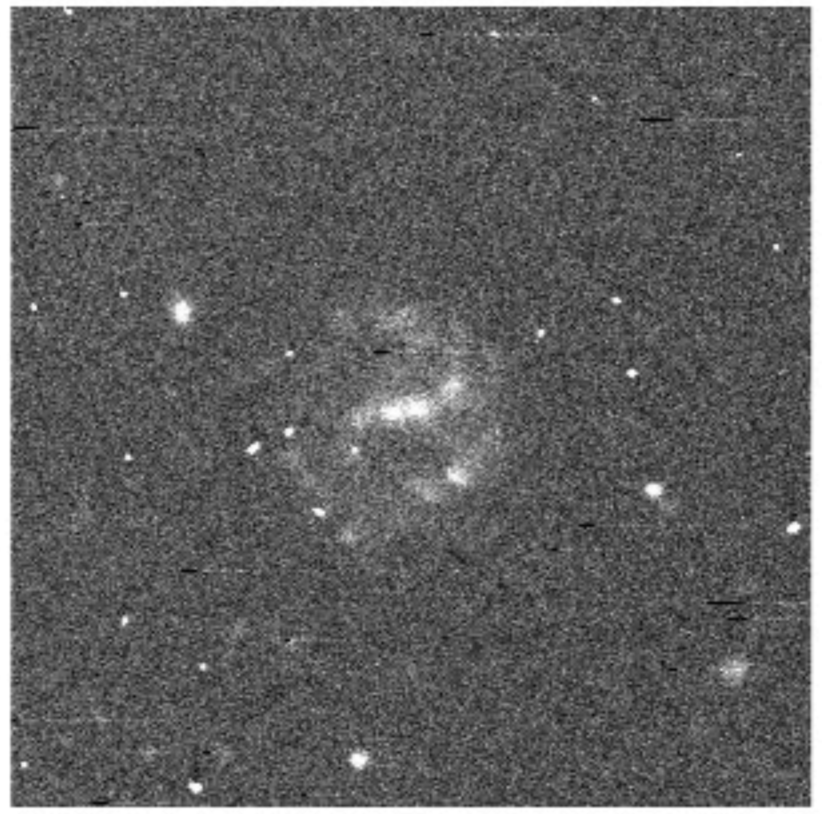
Bar slows in DM

# Bars in LSB galaxies

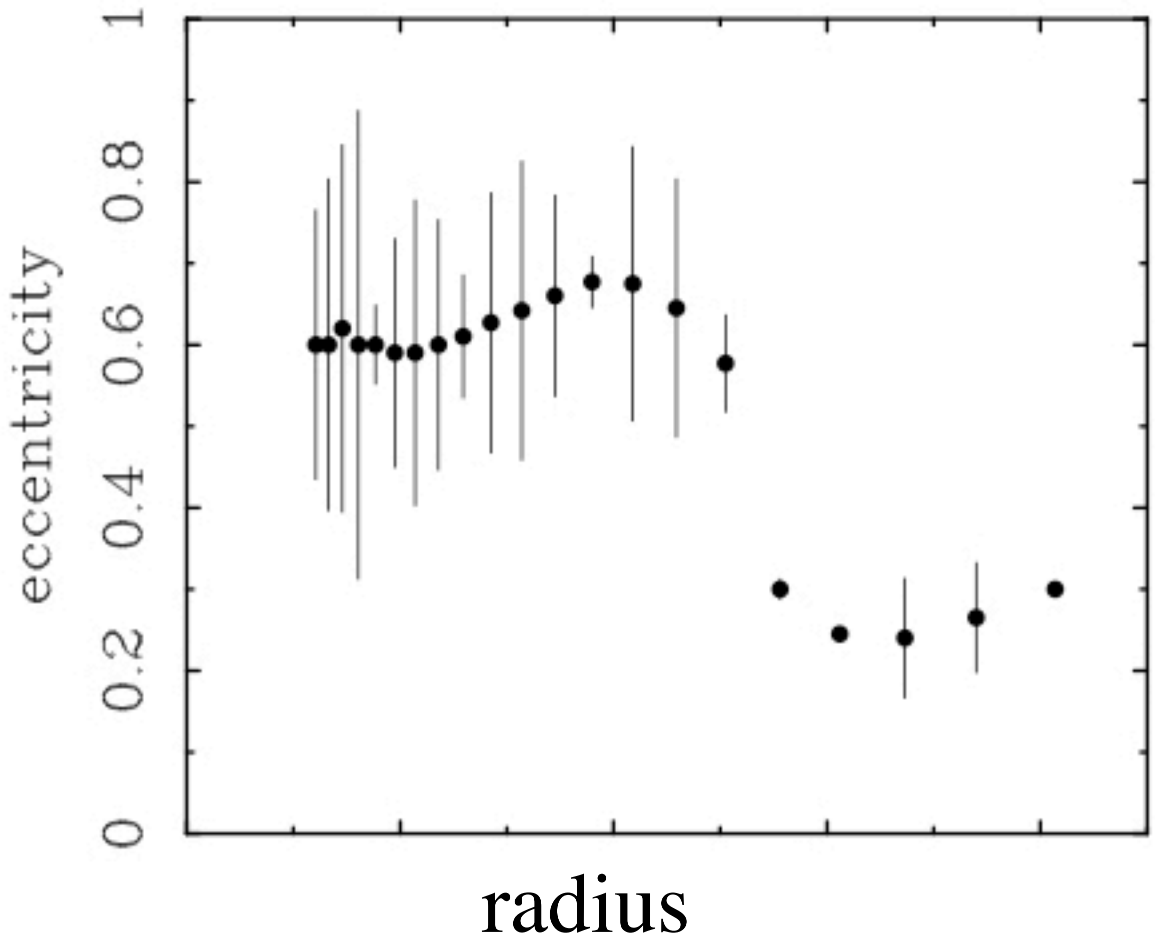


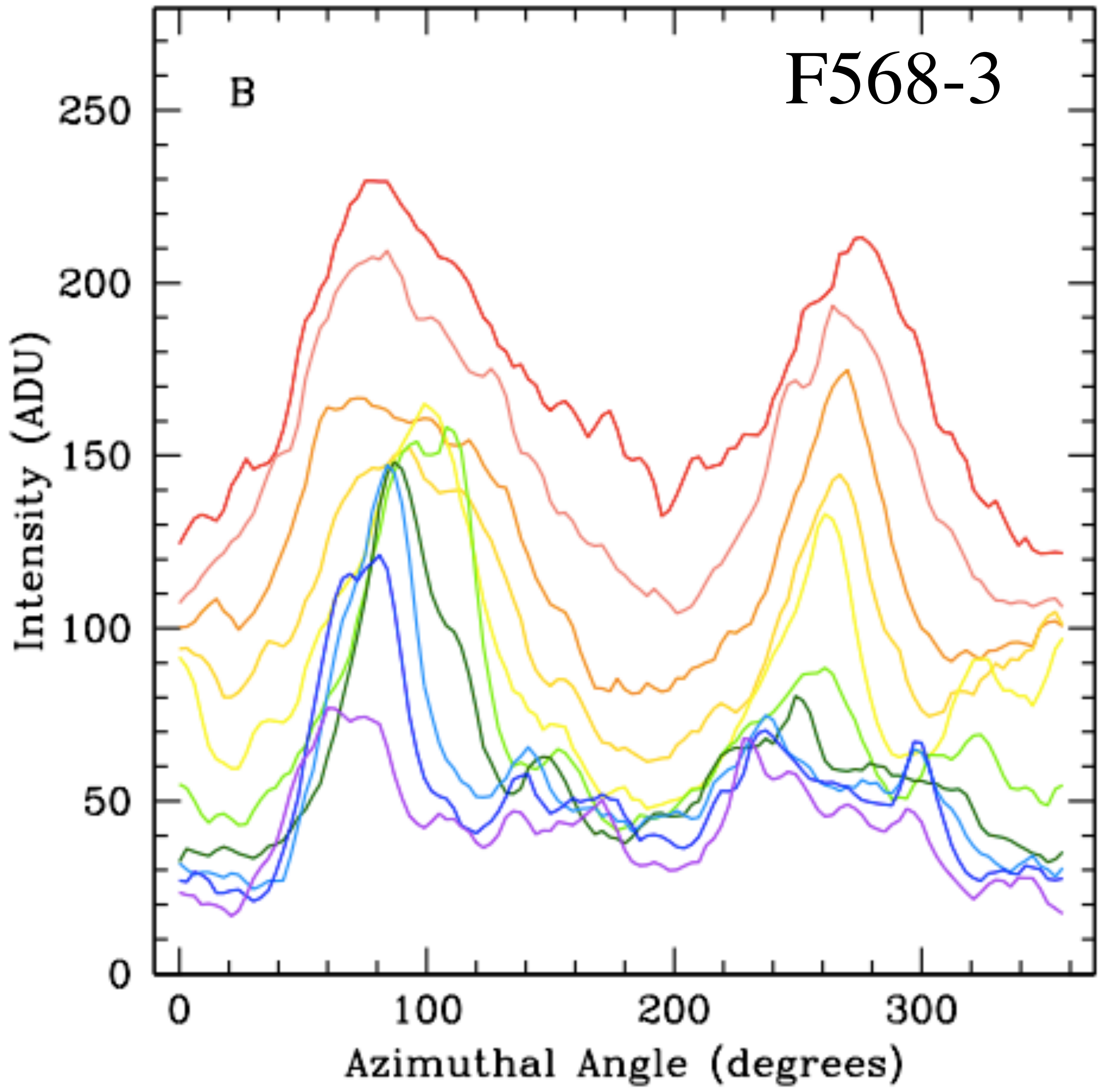
# Bars in LSB galaxies

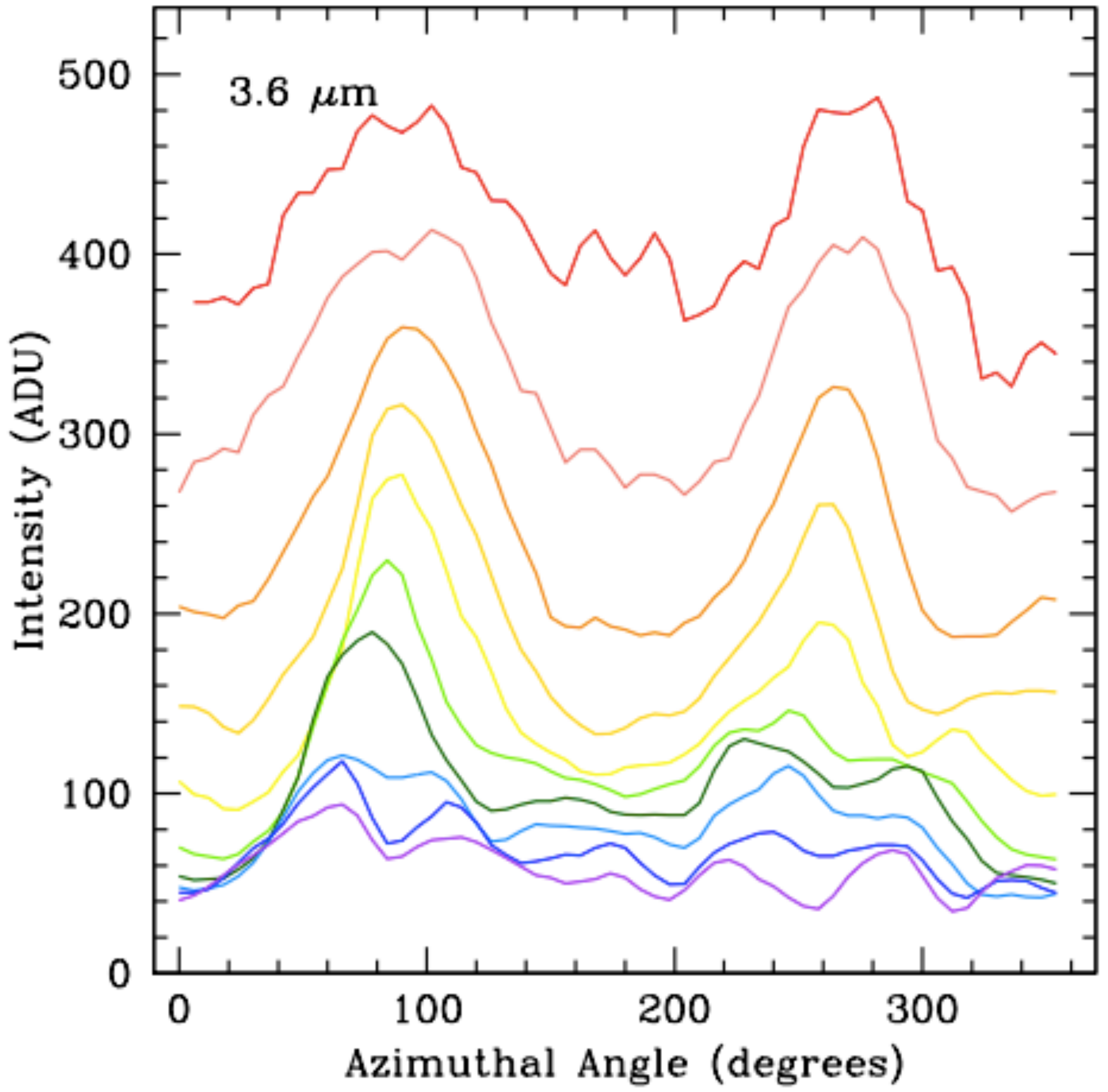
F577-V1

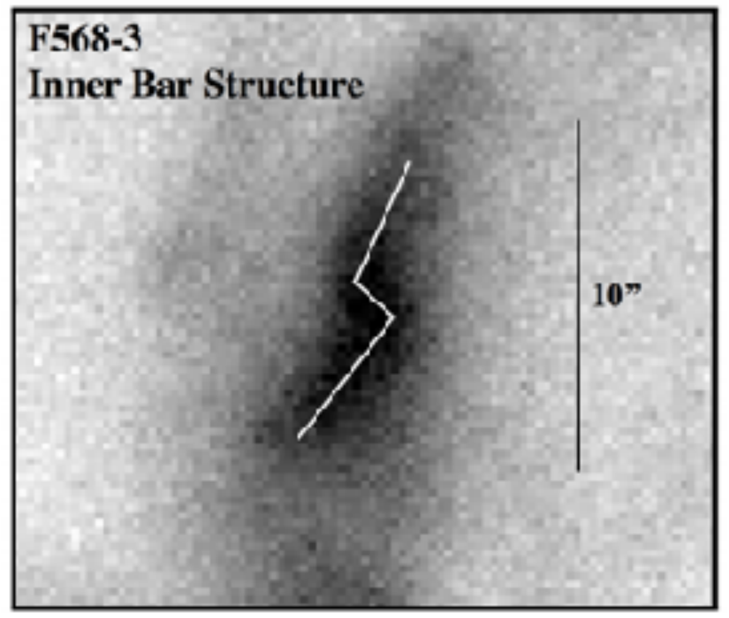


Eccentricity changes suddenly at the end of the bar









Bar lengths/pattern speeds

Bars in LSBs fast; no sign of dynamical friction

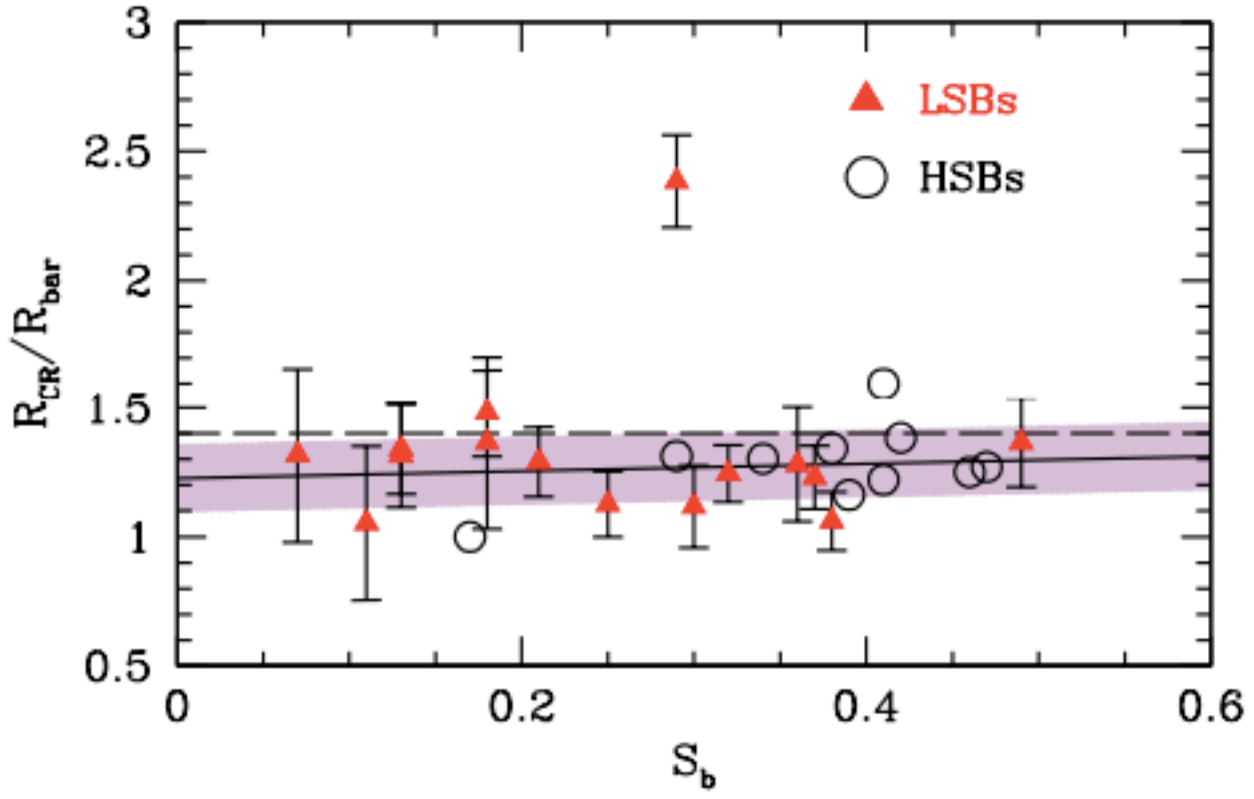
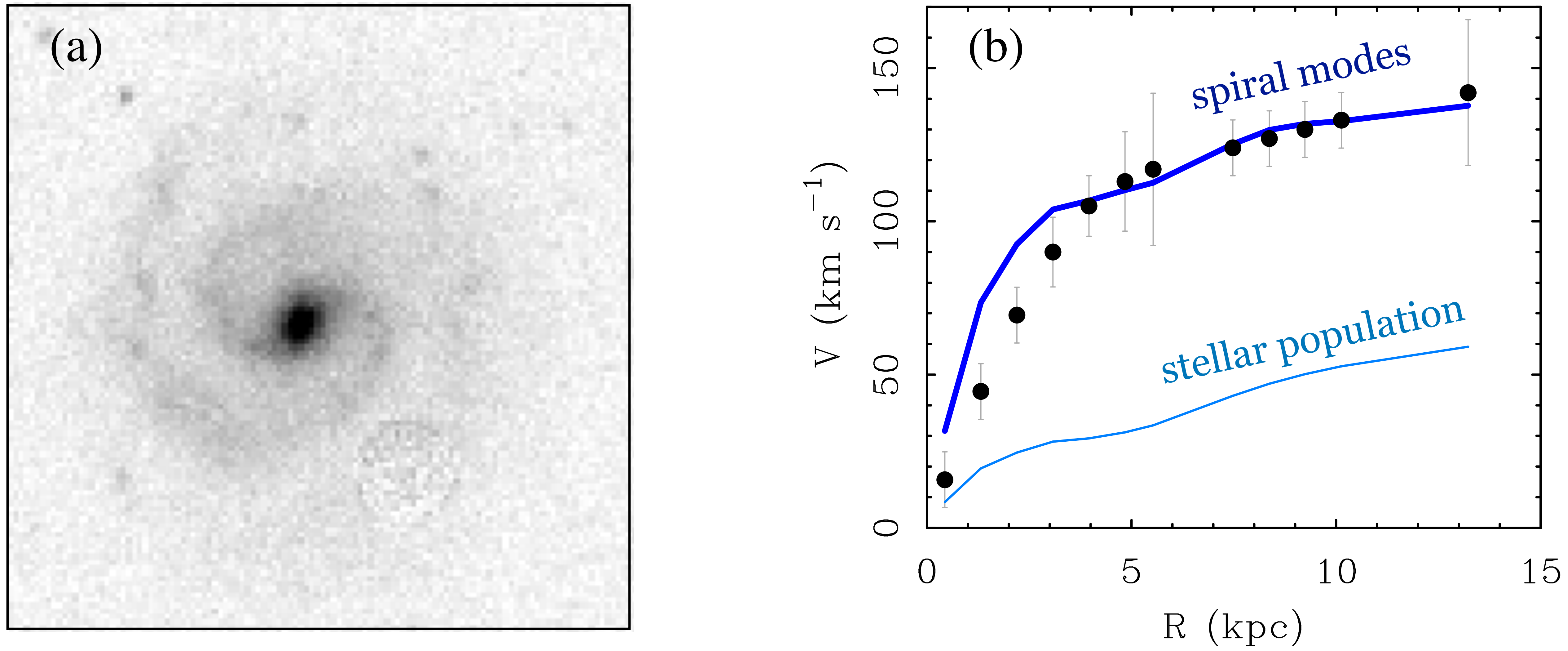


**Figure 10.** Relative bar pattern speed ($\mathcal{R} = R_{\rm CR}/R_{\rm bar}$) as a function of bar strength ($S_b$) for our sample (red triangles) and HSBs from Aguerri et al. (1998) (open circles). The solid line indicates the fit to the HSBs and LSBs, excluding the outlier discussed in the text: $\mathcal{R} = 1.23+0.14S_b$. The shaded region shows the scatter in the relation: $\sigma = 0.13$. The horizontal dashed line is the separator between fast and slow bars (i.e. $\mathcal{R} = 1.4$).

The different stability properties at high and low surface brightness predict different morphologies. In DM, bars and spiral modes should be strongly suppressed. To generate them will require increasing the disk mass over that expected for ordinary stellar populations.

“In LSB disks, it is conceivable that the minimum disk mass required to generate spiral arms might exceed the maximum disk mass allowed by the rotation curve.” (McGaugh & de Blok 1998)

F568-1



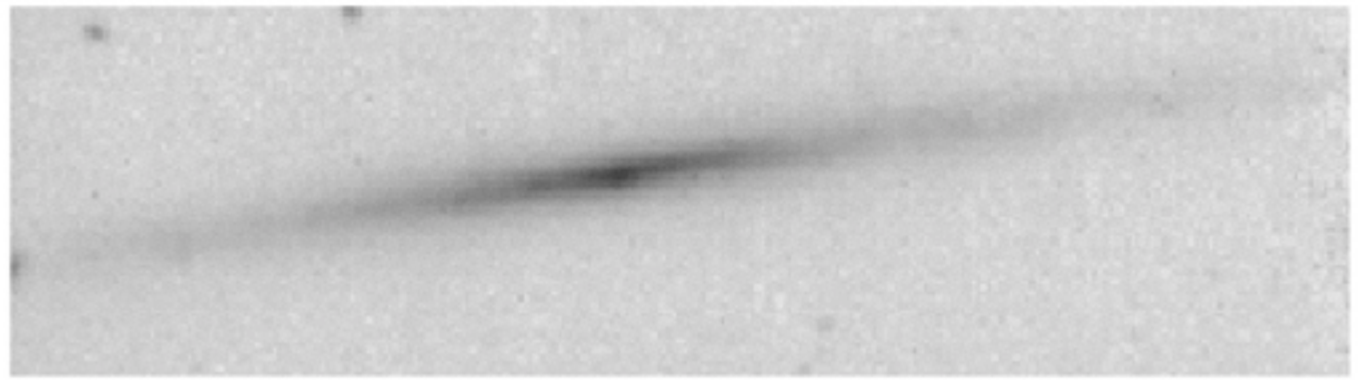
The disk mass required to drive the observed spiral arms is much larger than that expected for the stellar population.

*In this case, more disk mass is required than is allowed by the rotation curve. Taken at face value, this is a contradiction to the existences of dark matter.*

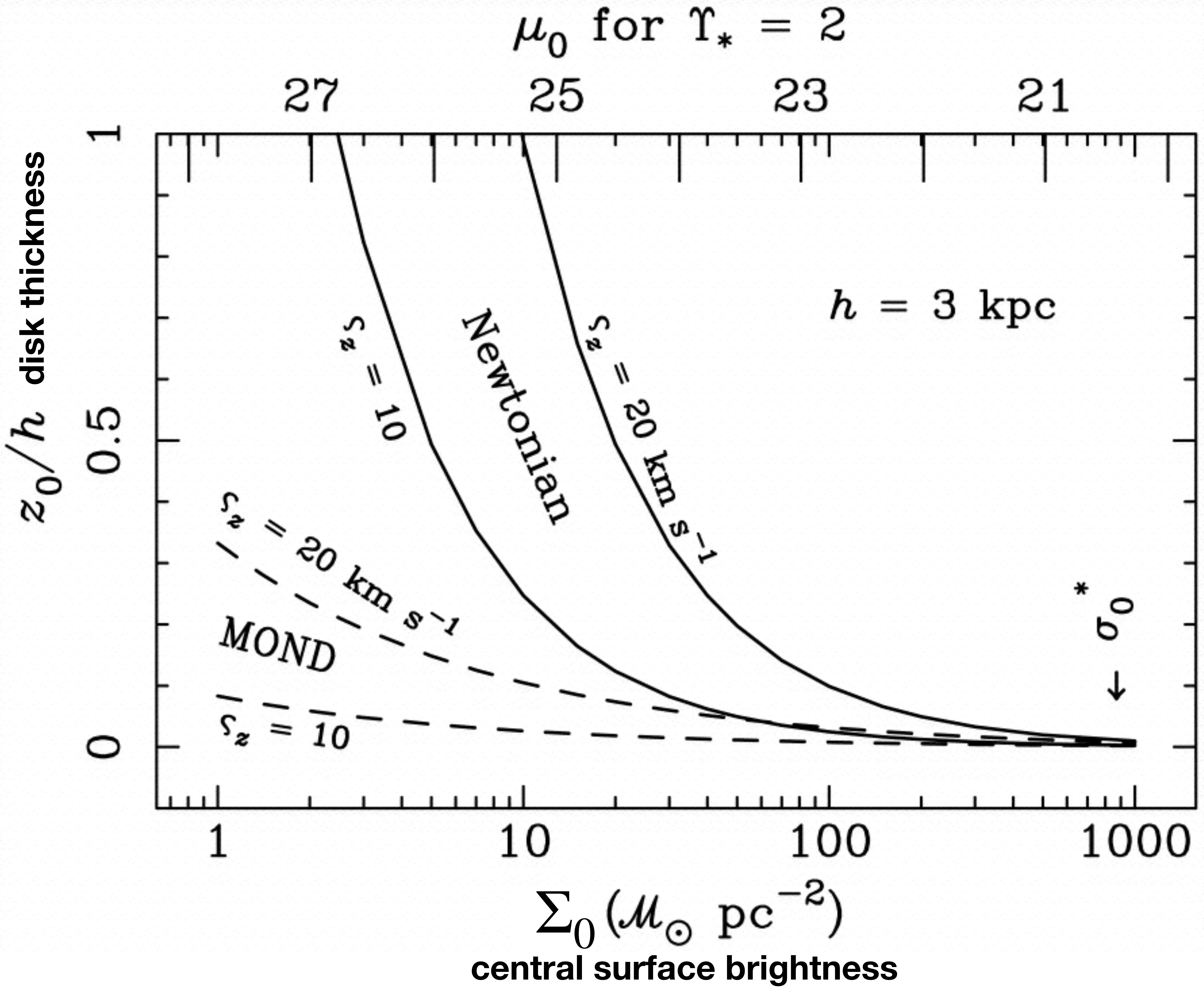
Galaxy disks should flare less in MOND than in Newtonian dynamics.

Equivalently, they can sustain higher velocity dispersions without become unduly thick.

Superthin galaxyUGC 7321



Matthews, Gallagher, & van Driel (1999)



McGaugh & de Blok (1998)

The outer, LSB regions of disks should have velocity dispersions of ~2 km/s conventionally; ~7 km/s is typically observed.

Conventionally, non-gravitational forces are invoked to explain the difference. These are not necessary in MOND.