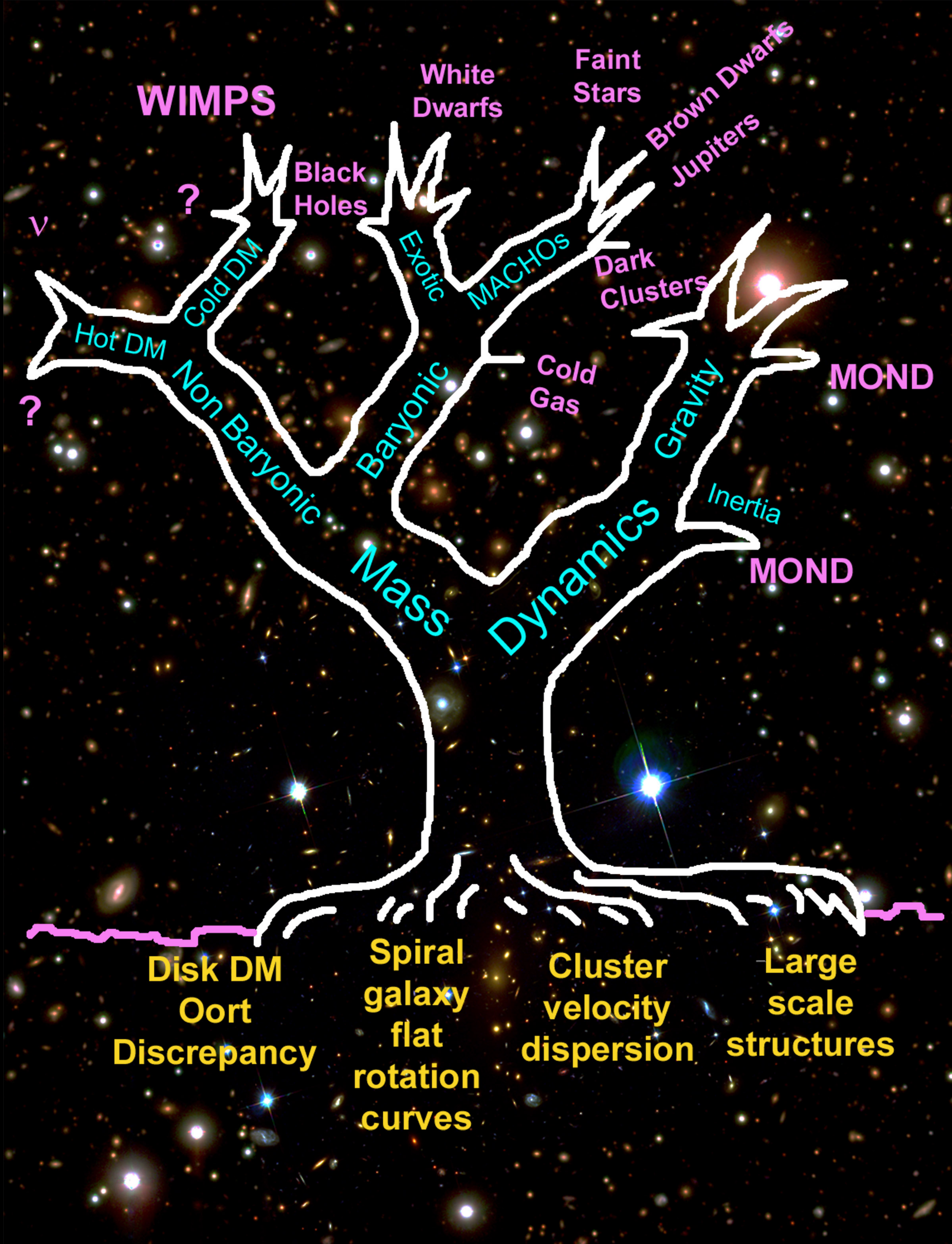
DARK MATTER

ASTR 333/433

<u>TODAY</u>

MOND



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.

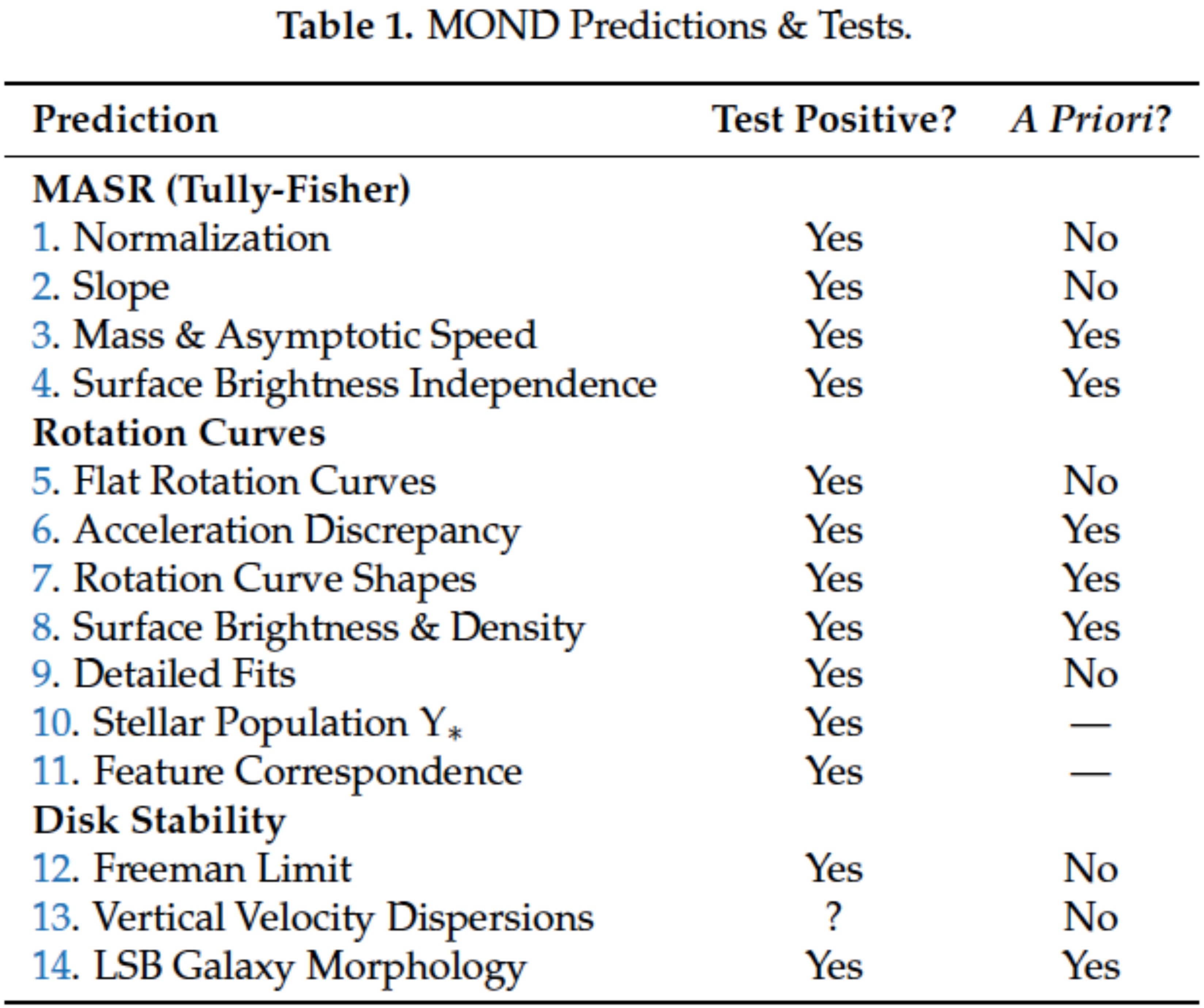


Table 1. MOND Predictions & Tests.

Prediction	Test Positive?	*A Priori*?
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 Υ_*	Yes	—
11. Feature Correspondence	Yes	—
Disk Stability		
12. Freeman Limit	Yes	No
13. Vertical Velocity Dispersions	?	No
14. LSB Galaxy Morphology	Yes	Yes

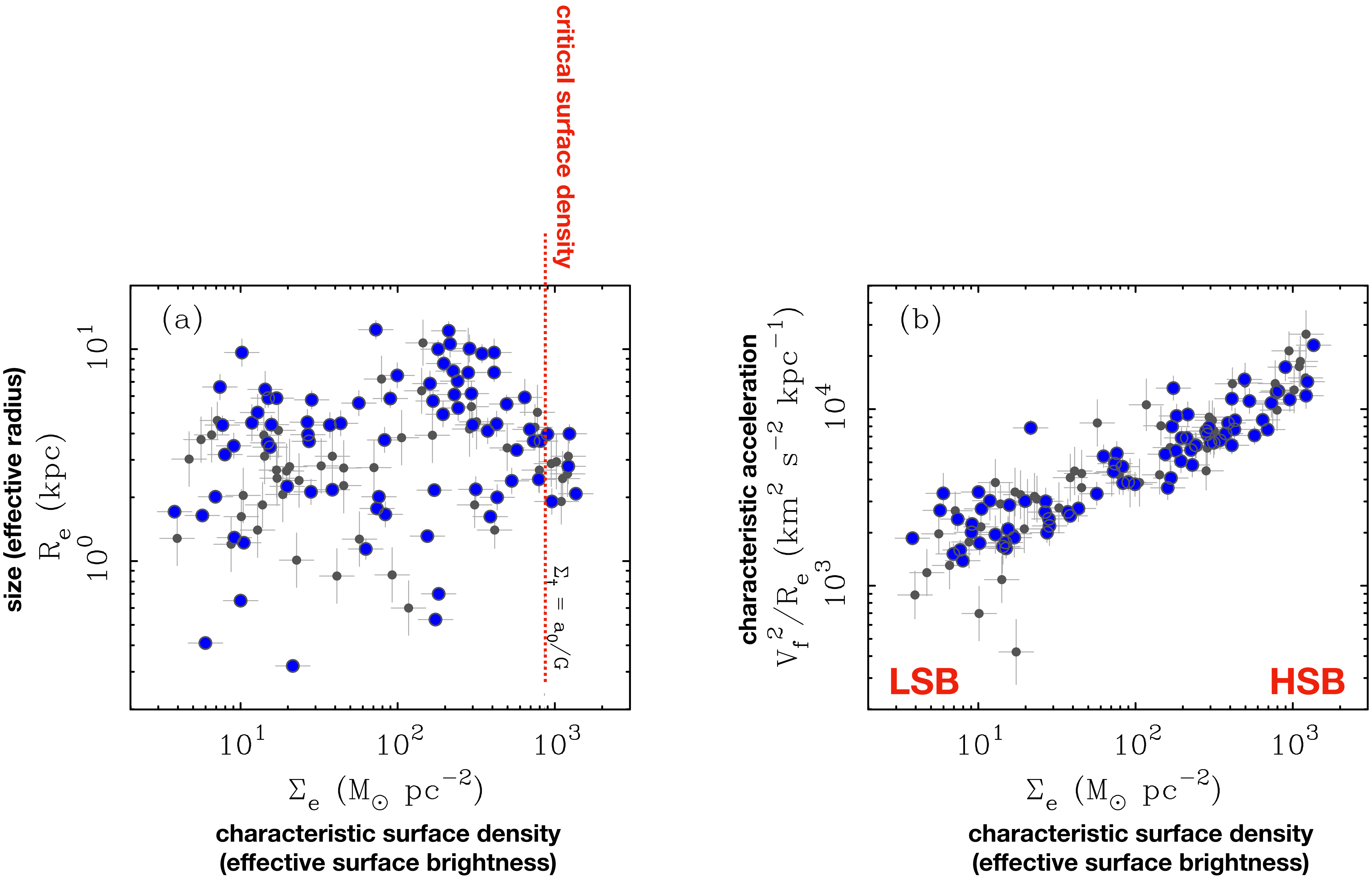
Invited review for *Galaxies* (2020), in press

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

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 $t = \dfrac{T}{|W|} \approx 0.14$
  - less added stability at low surface brightness (low acceleration)

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


critical surface density
(a)
size (effective radius)
R_e (kpc)
10^0
10^1
$\Sigma_+ = a_0/G$
10^1
10^2
10^3
Σ_e ($M_\odot$ pc^{-2})
characteristic surface density
(effective surface brightness)
(b)
characteristic acceleration
V_f^2/R_e (km^2 s^{-2} kpc^{-1})
10^3
10^4
LSB
HSB
10^1
10^2
10^3
Σ_e ($M_\odot$ pc^{-2})
characteristic surface density
(effective surface brightness)

Tiret & Combes (2007, 2008)

MOND numerical simulations of galaxy morphology

real galaxies simulated galaxies

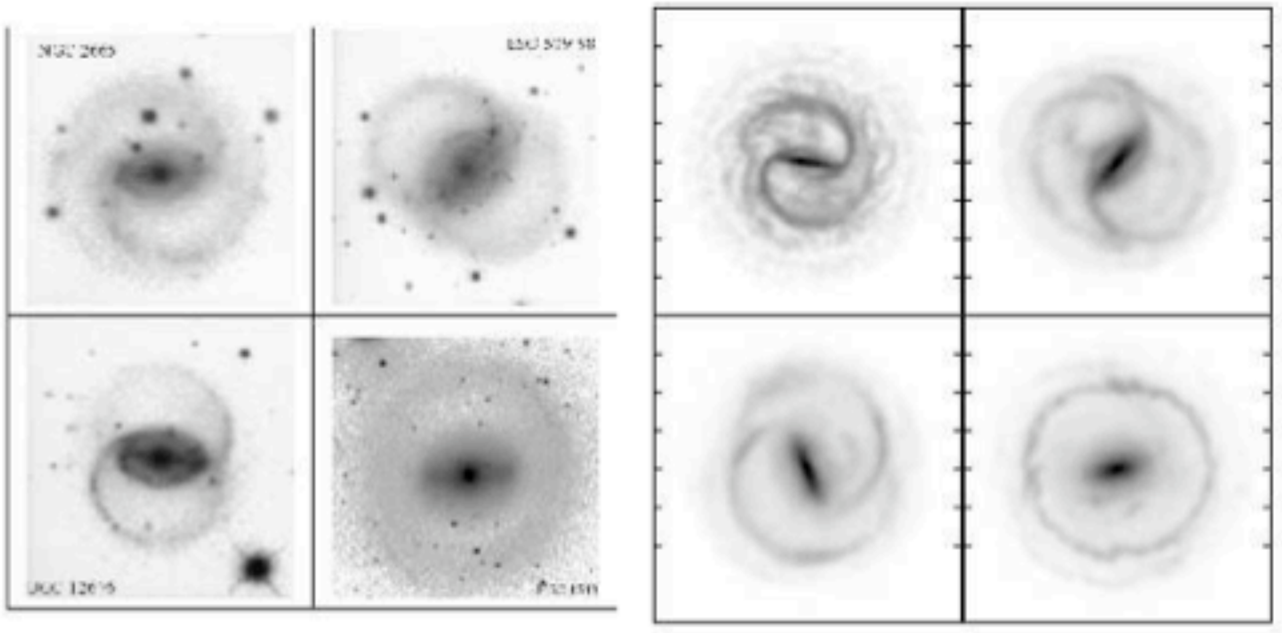
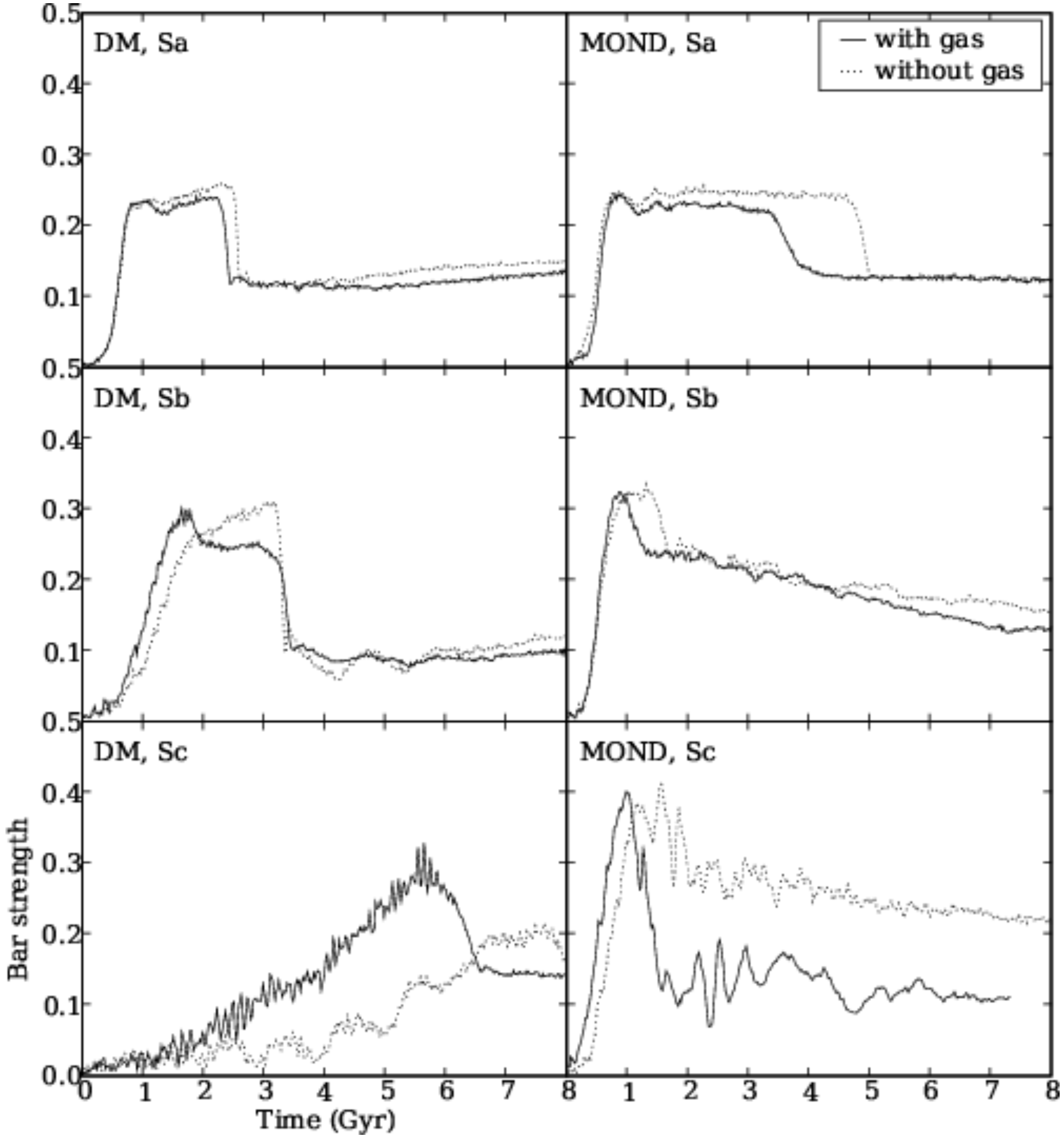


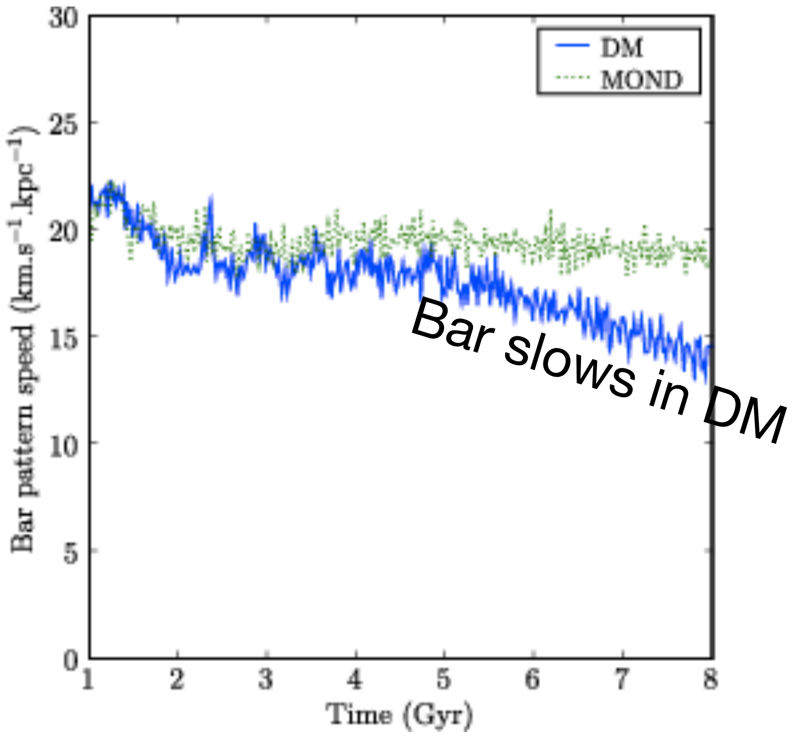
Fig. 3. Several examples showing the morphological structures of NGC 2665, ESO 509-98, UGC 12646 and NGC 1543 (top panel) compared to simulated galaxies in MOND (bottom panel). Rings and pseudo-rings structures are well reproduced with modified gravity.

Tiret & Combes (2007, 2008)

Bar strength



Bar pattern speed



Bar slows in DM

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.

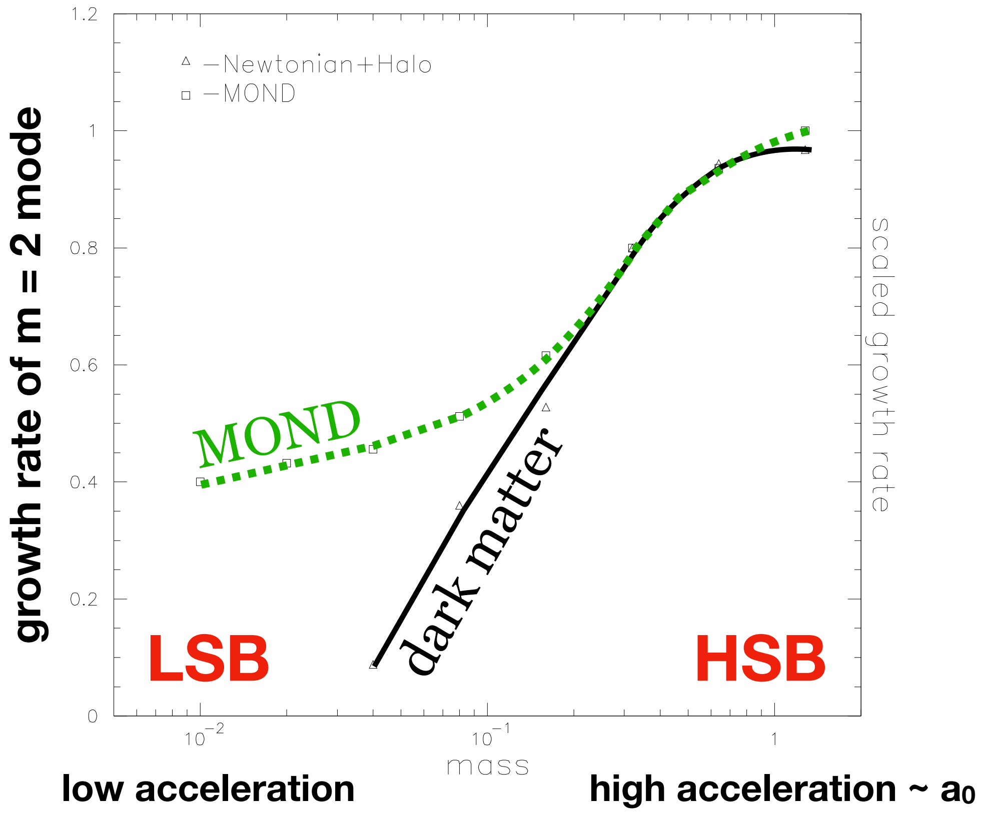
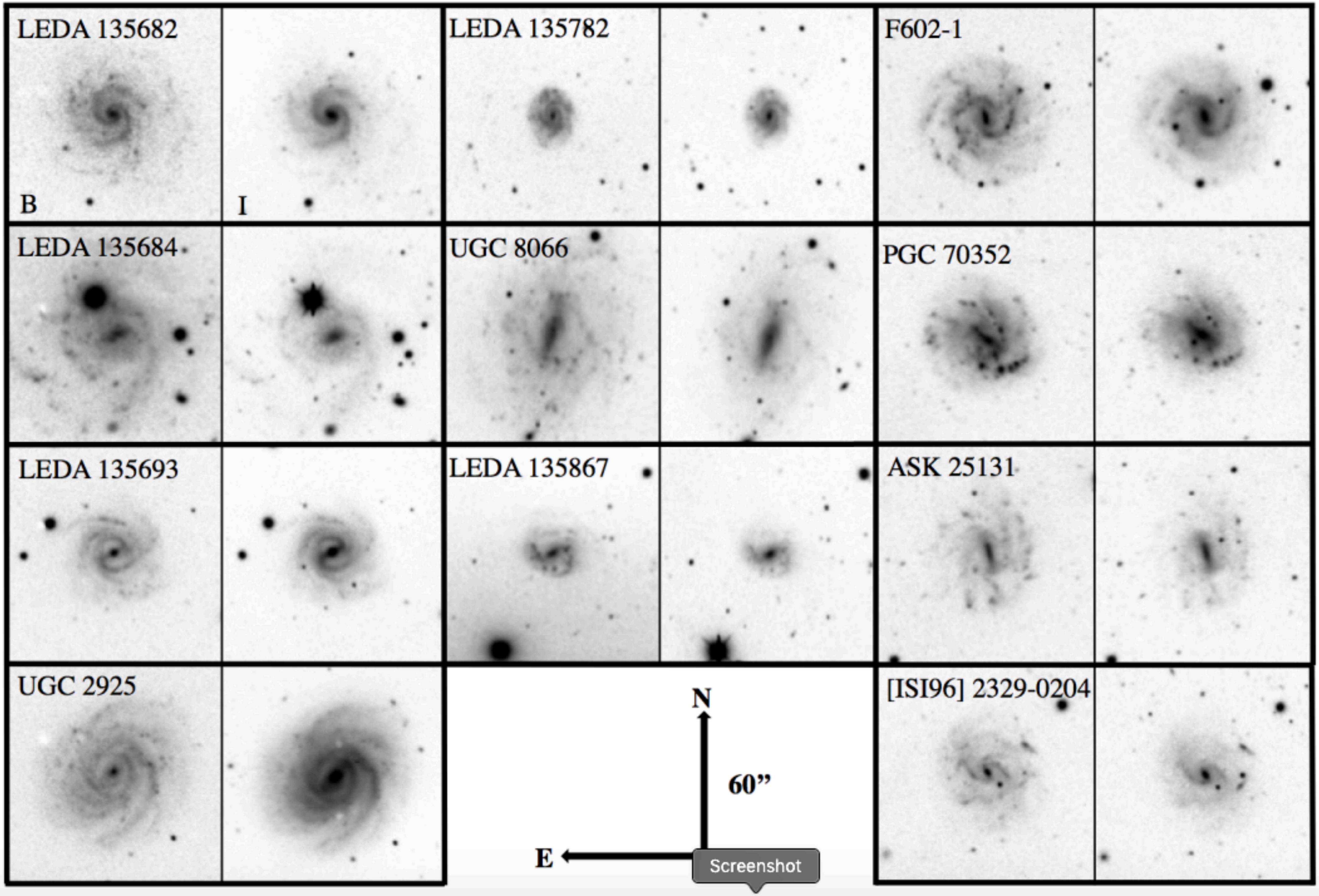


Figure 11: The growth rate, in units of the dynamical time, for the m=2 mode as a function of the total mass of the disk. □ MOND, △ Newtonian + Halo.

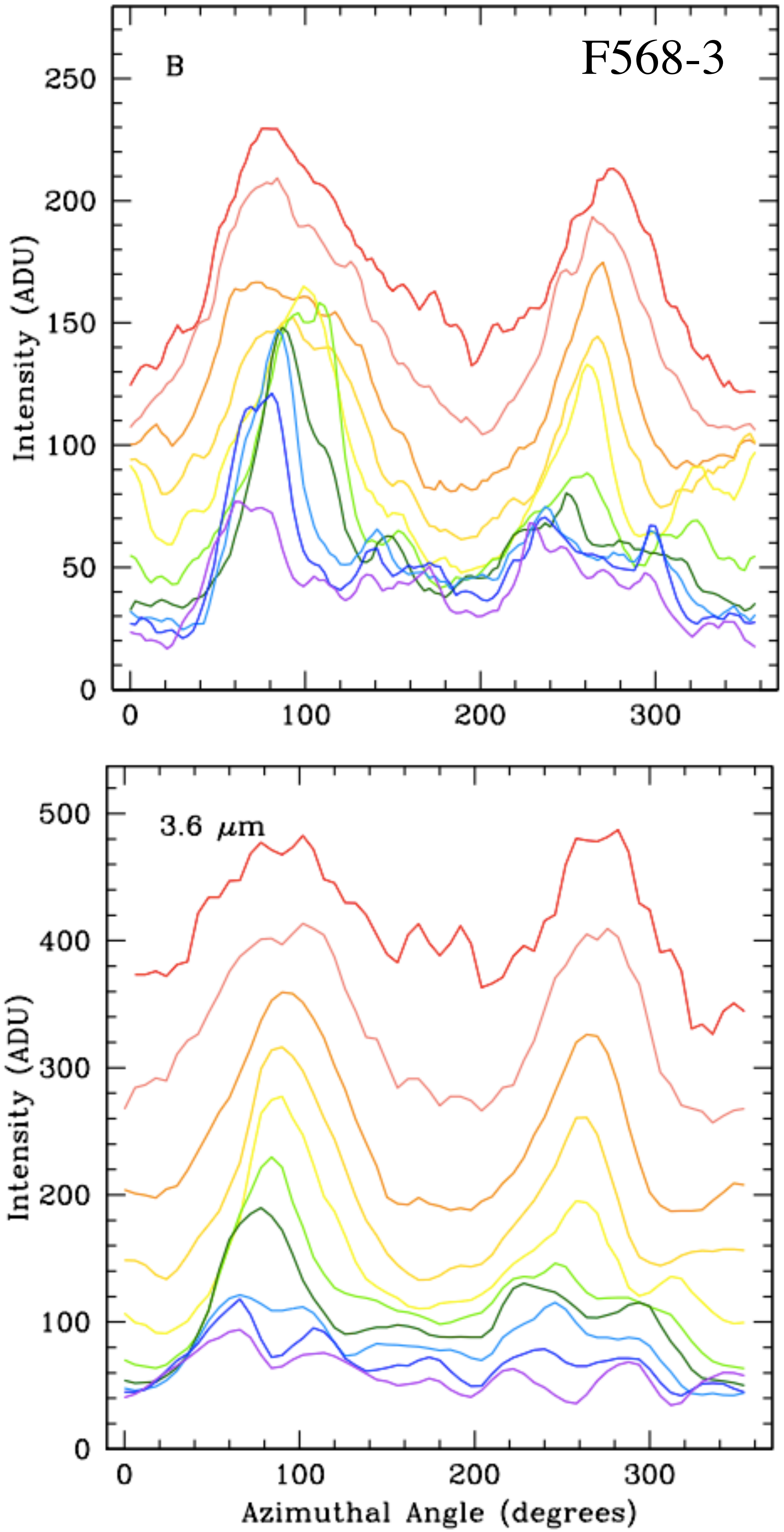
m	Q	time step scaling	Growth rate MOND	Growth rate Newt+DM	halo mass at R=1
0.005	2.55	1			
0.01	2.5	0.84	0.4		
0.02	2.4	0.7	0.43		
0.04	2.25	0.58	0.46	0.09	0.18
0.08	2.0	0.48	0.51	0.36	0.23
0.16	1.79	0.39	0.62	0.53	0.28
0.32	1.62	0.3	0.8	0.8	0.31
0.64	1.53	0.22	0.94	0.94	0.31
1.28	1.5	0.16	1.0	0.97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

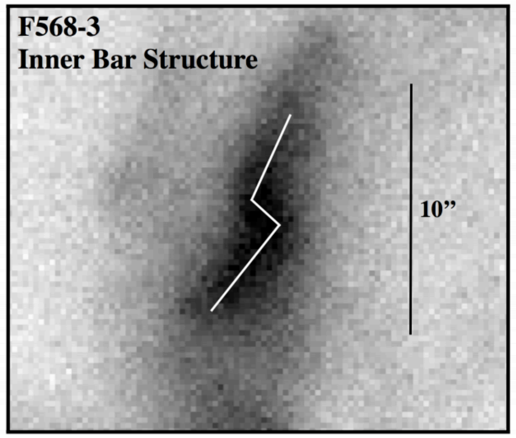
Table 1: The growth rate, in units of dynamical time, for the $m = 2$ mode, and model parameters for the different mass models.

Bars in LSB galaxies



Bars in LSB galaxies





Bar lengths/pattern speeds

Bars in LSBs fast; no sign of dynamical friction

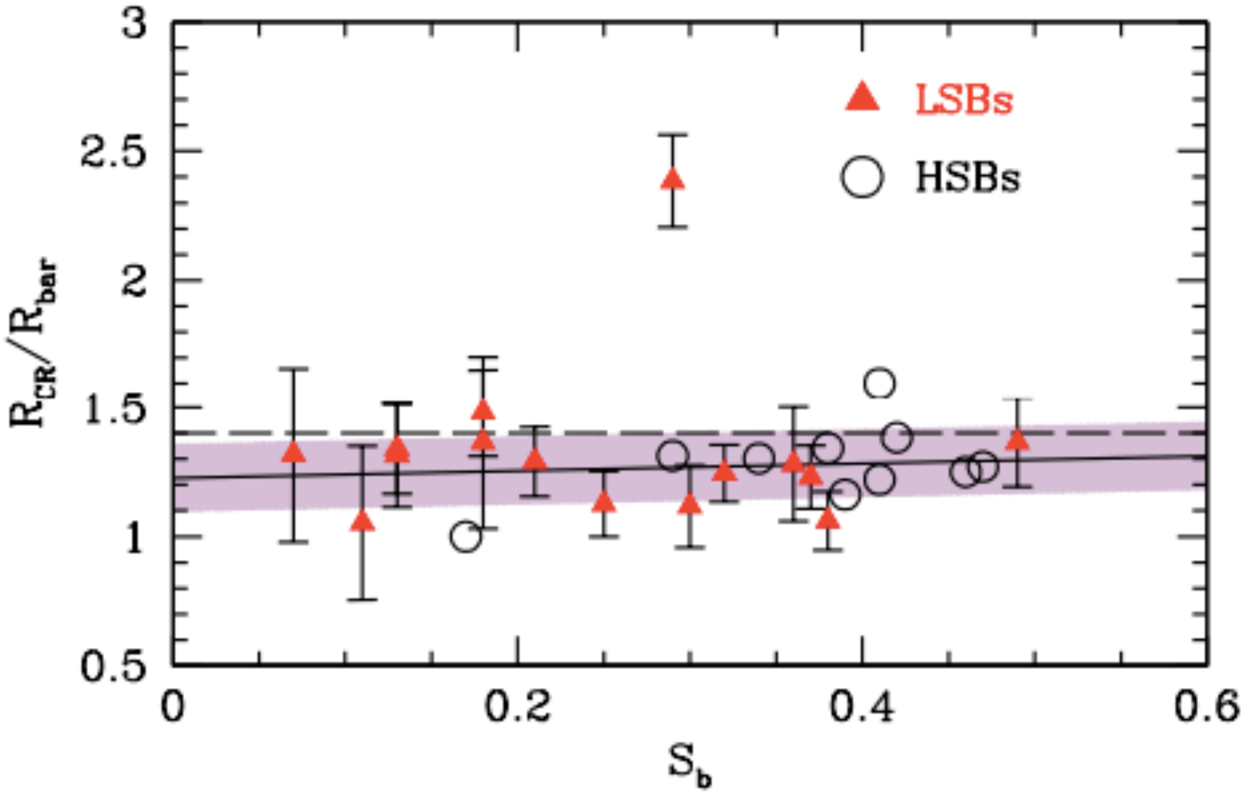


Figure 10. Relative bar pattern speed ($\mathcal{R} = R_{\rm CR}/R_{\rm bar}$) as a function of bar strength (S_b) for our sample (red triangles) and HSBs from Aguerri et al. (1998) (open circles). The solid line indicates the fit to the HSBs and LSBs, excluding the outlier discussed in the text: $\mathcal{R} = 1.23 + 0.14 S_b$. 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)

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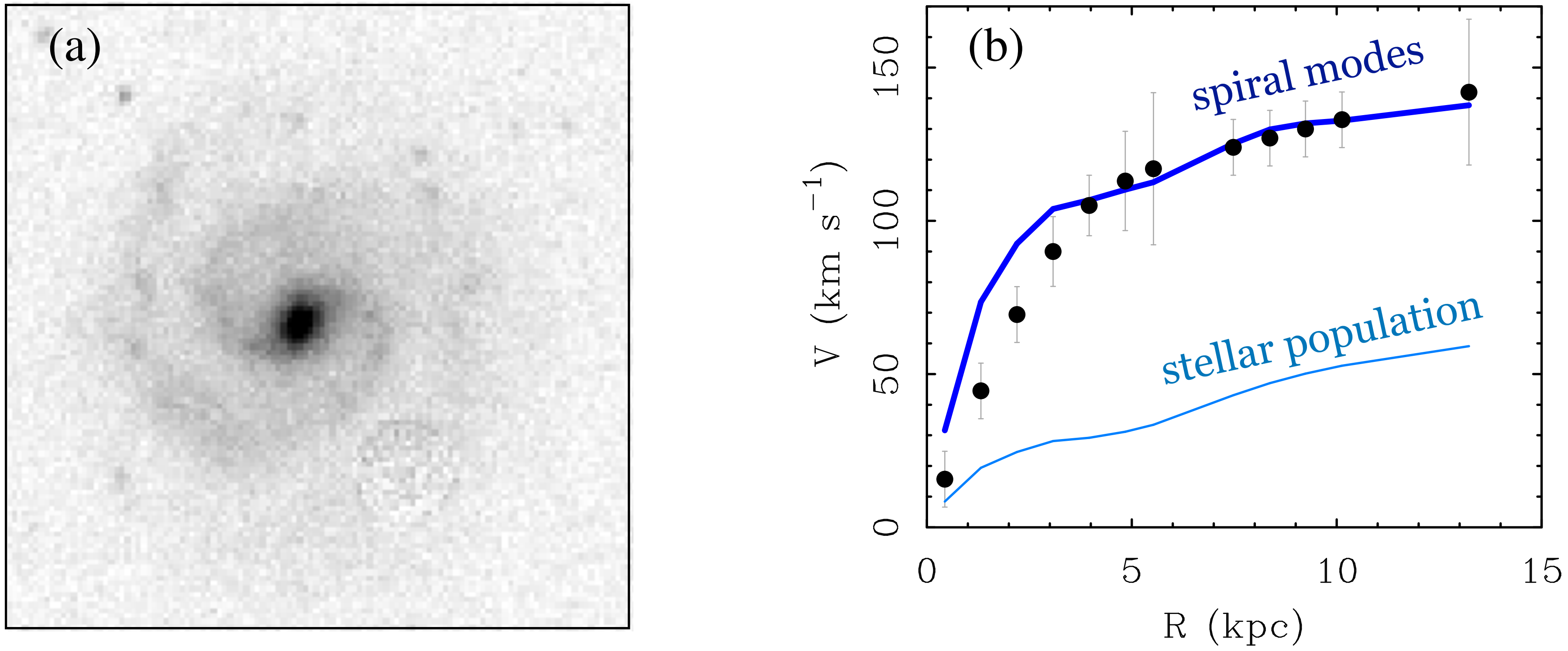
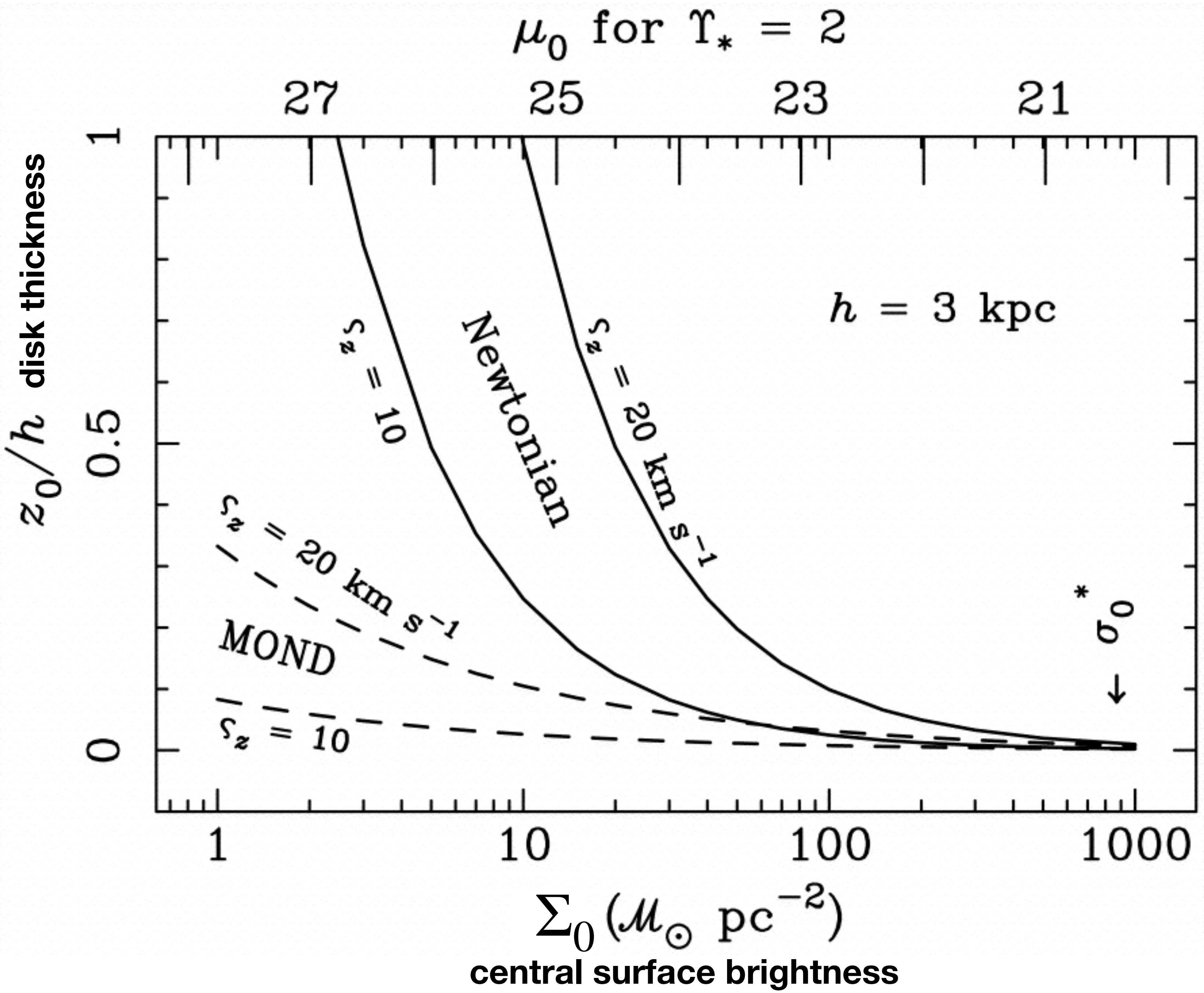


The disk mass required to drive the observed spiral arms is much larger than that expected for the stellar population.

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.



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.

McGaugh & de Blok (1998)

The External Field Effect in MOND

Subtly different effects occur in non-isolated systems

- At high accelerations, everything is Newtonian $a_{in} \gg a_0$ or $a_{in} < a_0 < a_{ext}$
- The deep MOND regime occurs for isolated systems in the limit of low acceleration $a_{ext} < a_{in} < a_0$
- The external field effect comes into play for low acceleration systems exposed to a stronger external field $a_{in} < a_{ext} < a_0$
- Tidal effects become strong when the external field dominates

http://astroweb.case.edu/ssm/mond/EFE.html

http://astroweb.case.edu/ssm/mond/milgromonefe.html

Newtonian regime

$g_{in} > a_0$

$$M = \frac{RV^2}{G}$$

e.g., surface of the Earth

MOND regime

$g_{in} < a_0$

$$M = \frac{V^4}{a_0 G}$$

e.g., remote dwarf Leo I

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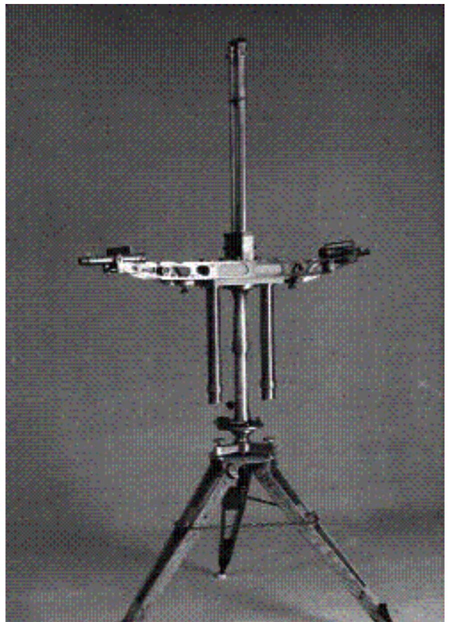
External Field dominant Newtonian regime

$g_{in} < a_0 < g_{ex}$

$$M = \frac{RV^2}{G}$$



e.g., Eotvos-type experiment on the surface of the Earth

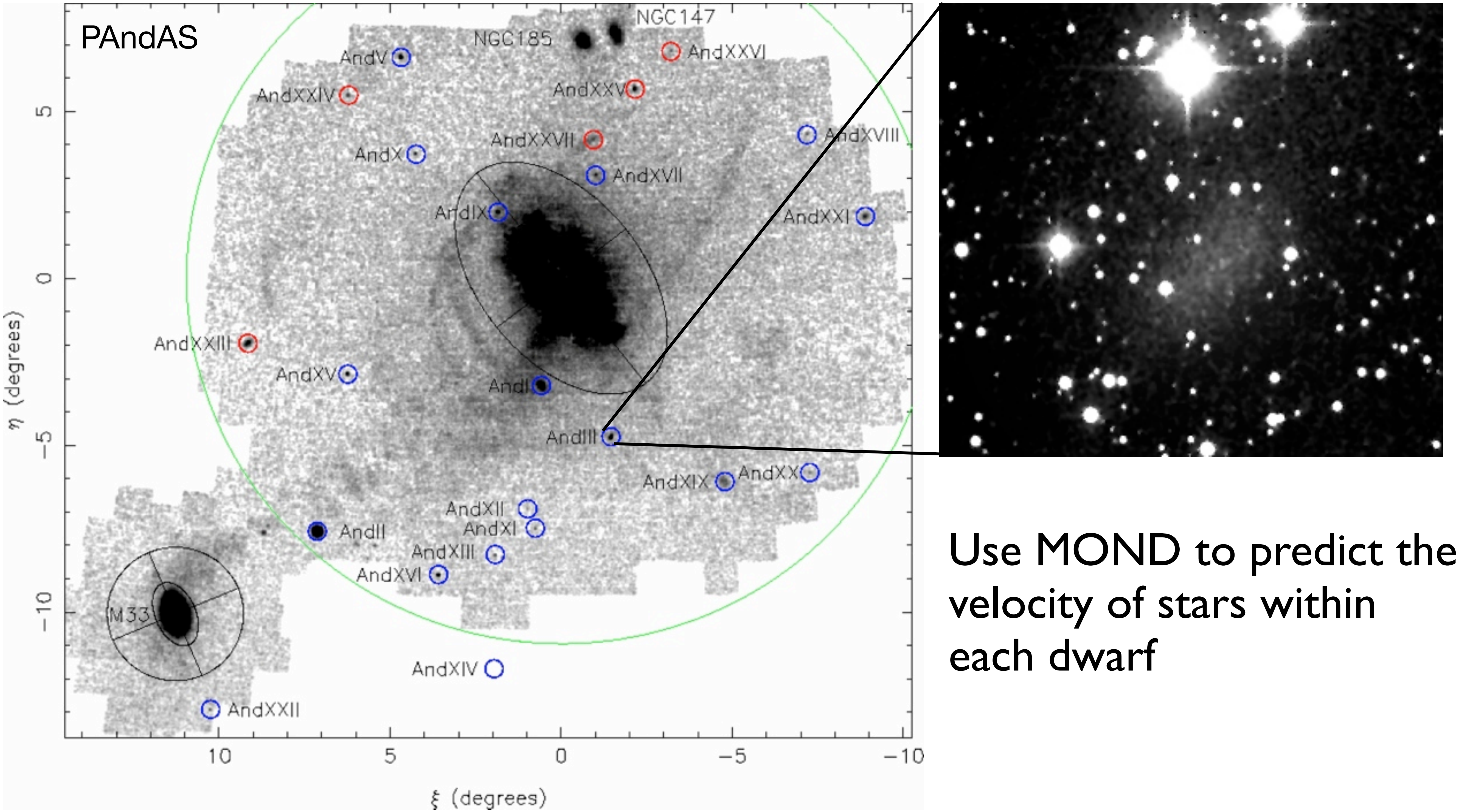
External Field dominant quasi-Newtonian regime

$g_{in} < g_{ex} < a_0$

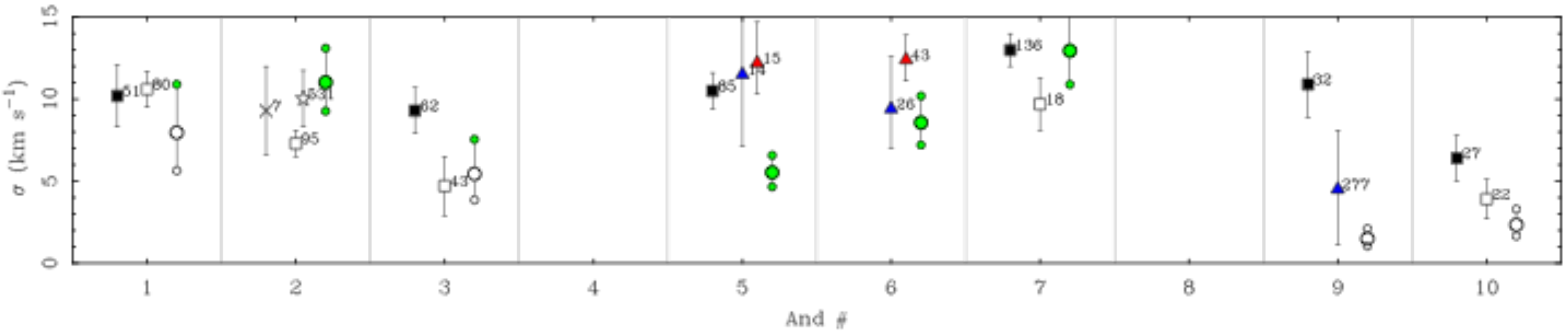
$$M = \frac{a_0}{g_{ex}} \frac{RV^2}{G}$$

e.g., nearby Sgr dwarf

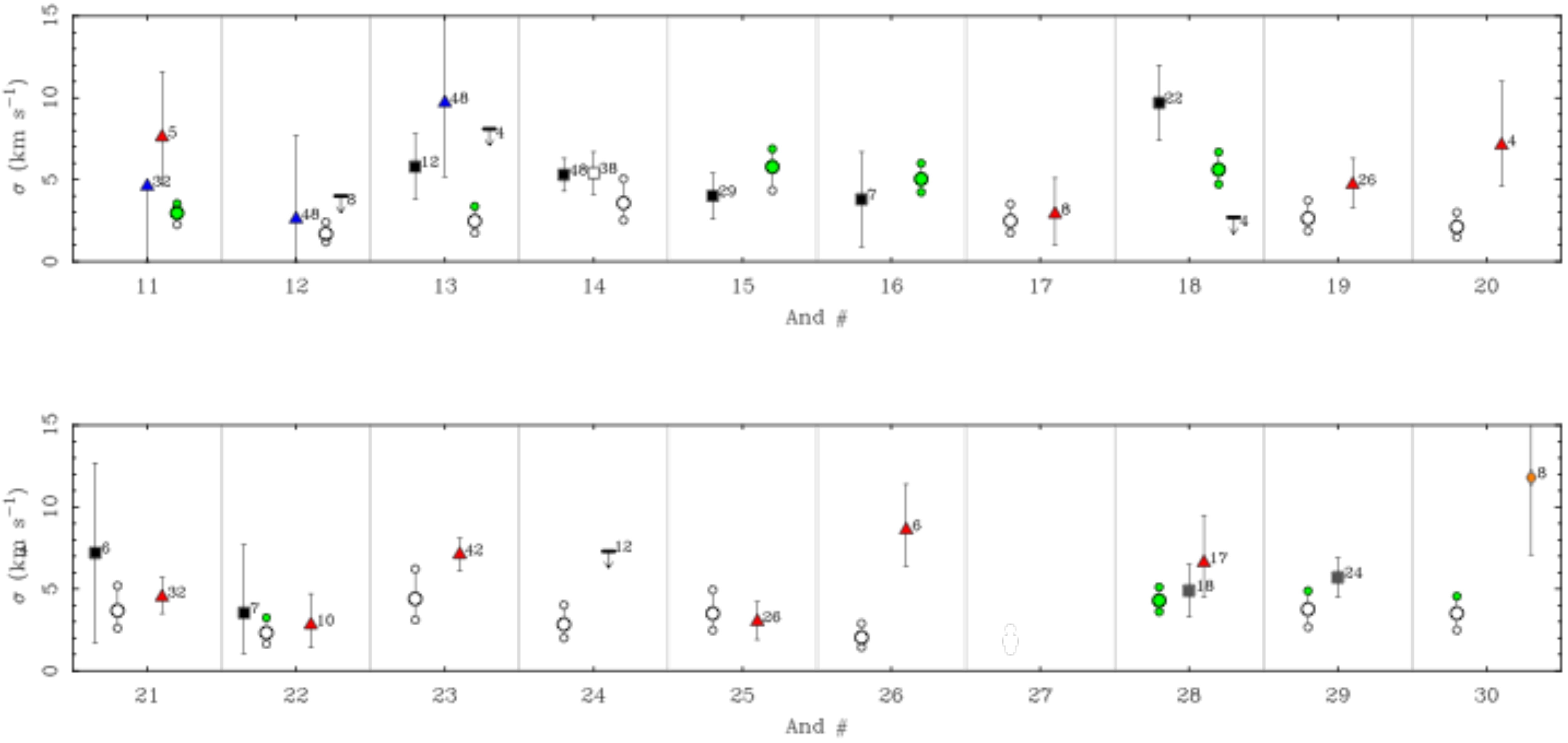
A test with the dwarf satellites of Andromeda

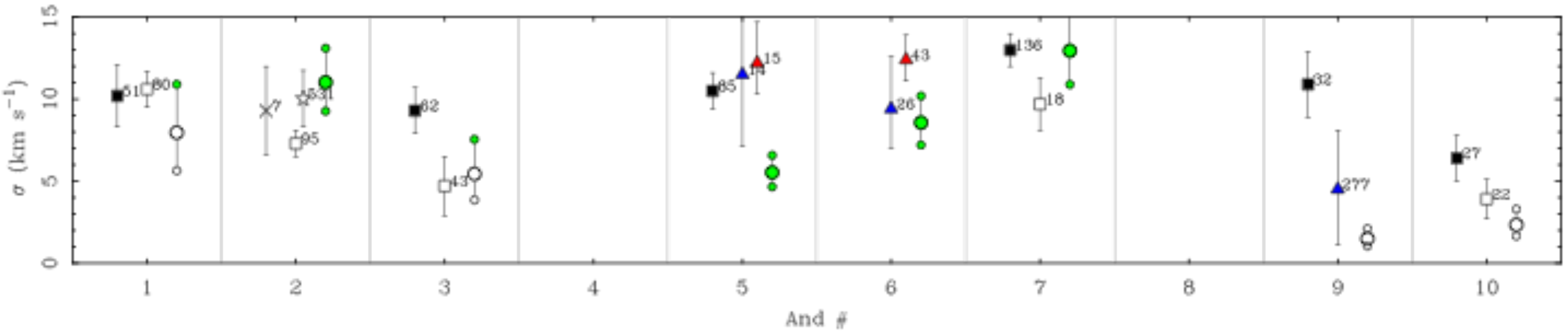


Use MOND to predict the velocity of stars within each dwarf

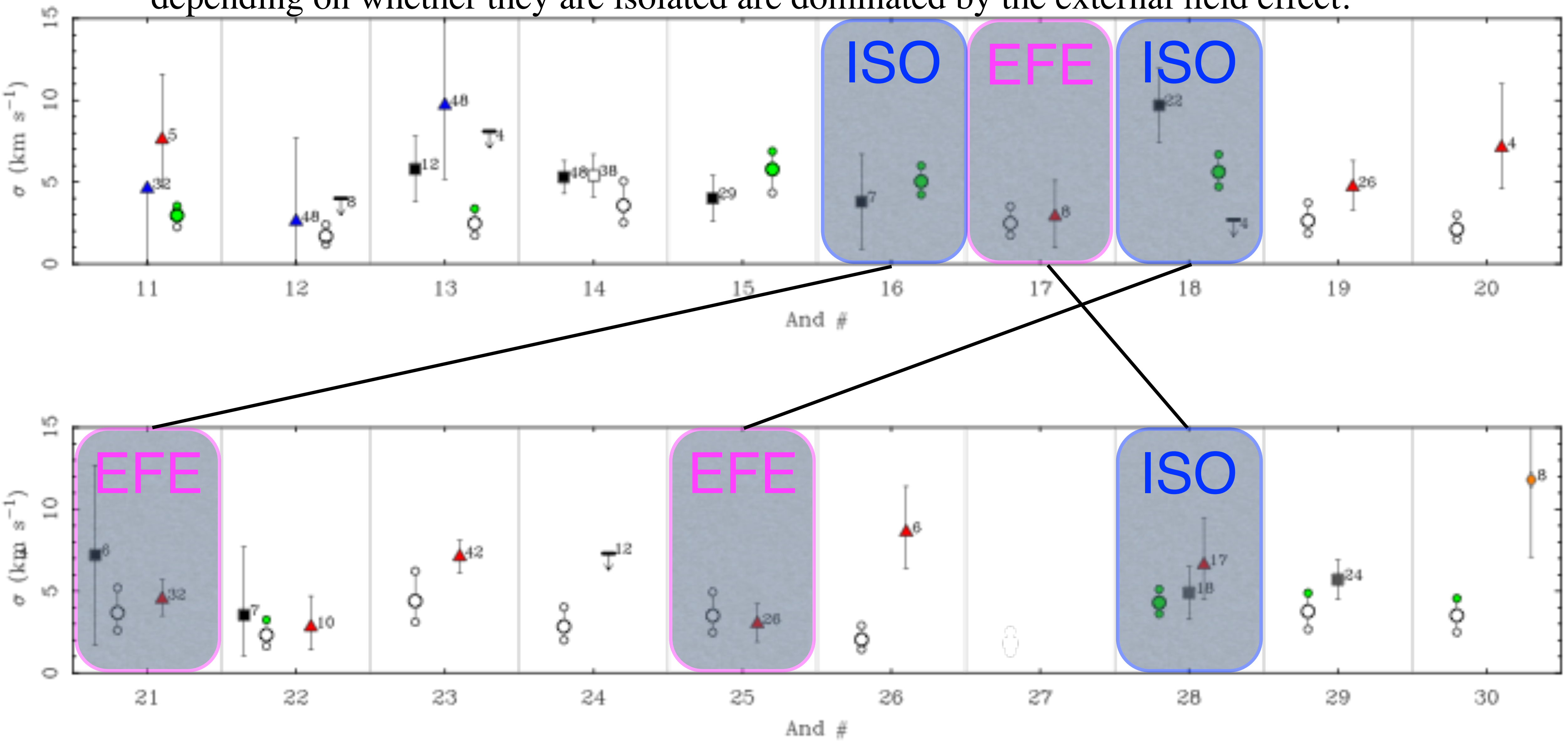


Velocity dispersions of the dwarf satellites of Andromeda





Pairs of photometrically identical dwarfs should have different velocity dispersion depending on whether they are isolated are dominated by the external field effect.



There is no EFE in dark matter - this is a unique signature of MOND.

MOND

Crater 2 - a clear example of the EFE

Crater 2

The recently discovered, ultra-diffuse Crater 2 provides another test.

$$L_V = 1.6 \times 10^5 \ \mathrm{L}_\odot$$
$$r_h = 1066 \ \mathrm{pc}$$

LCDM anticipates 10 - 17 km/s
(abundance matching; size-v. disp. rel'n)
but makes no concrete prediction

MOND predicts 2.1 +0.9/-0.6 km/s
(in EFE regime: McGaugh 2016, ApJ, 832, L8)

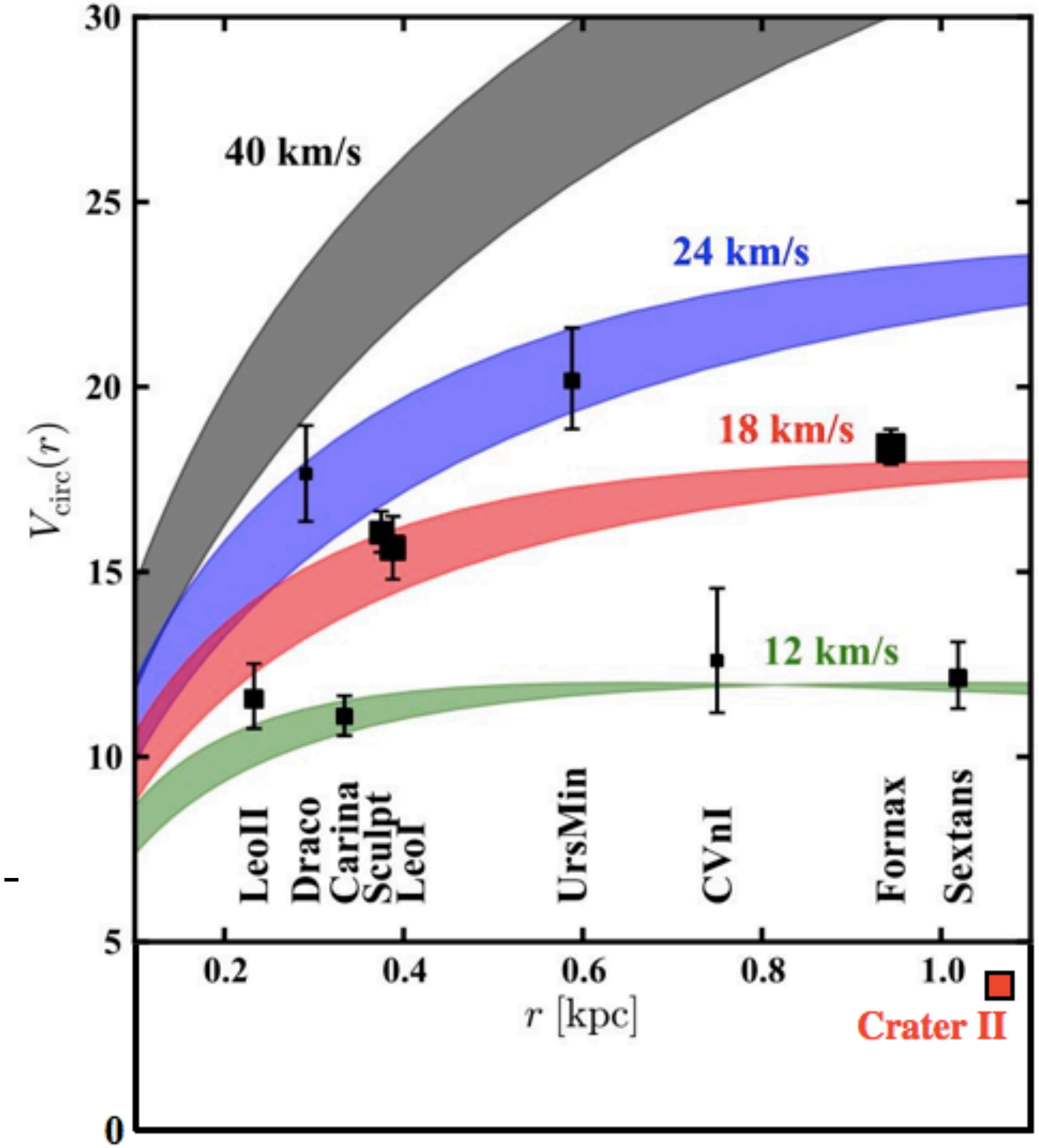
Subsequently observed: 2.7 ± 0.3 km/s
(Caldwell et al. 2017, ApJ, 839, 20)

Consistent with a priori MOND prediction

Very hard to understand in the context of ΛCDM - incredibly low velocity at a very large radius.

Boylan-Kolchin et al. (2012) MNRAS, 422, 1203

"Too Big To Fail"



Predictions made in advance of observation are the gold standard in science.
MOND has had *many* more successful *a priori* predictions than dark matter based theories.

I find your lack of faith disturbing.

- You don’t know the Power of the Dark Side
- Can MOND explain large scale structure?
- Can it provide a satisfactory cosmology?
- Can it be reconciled with General Relativity?