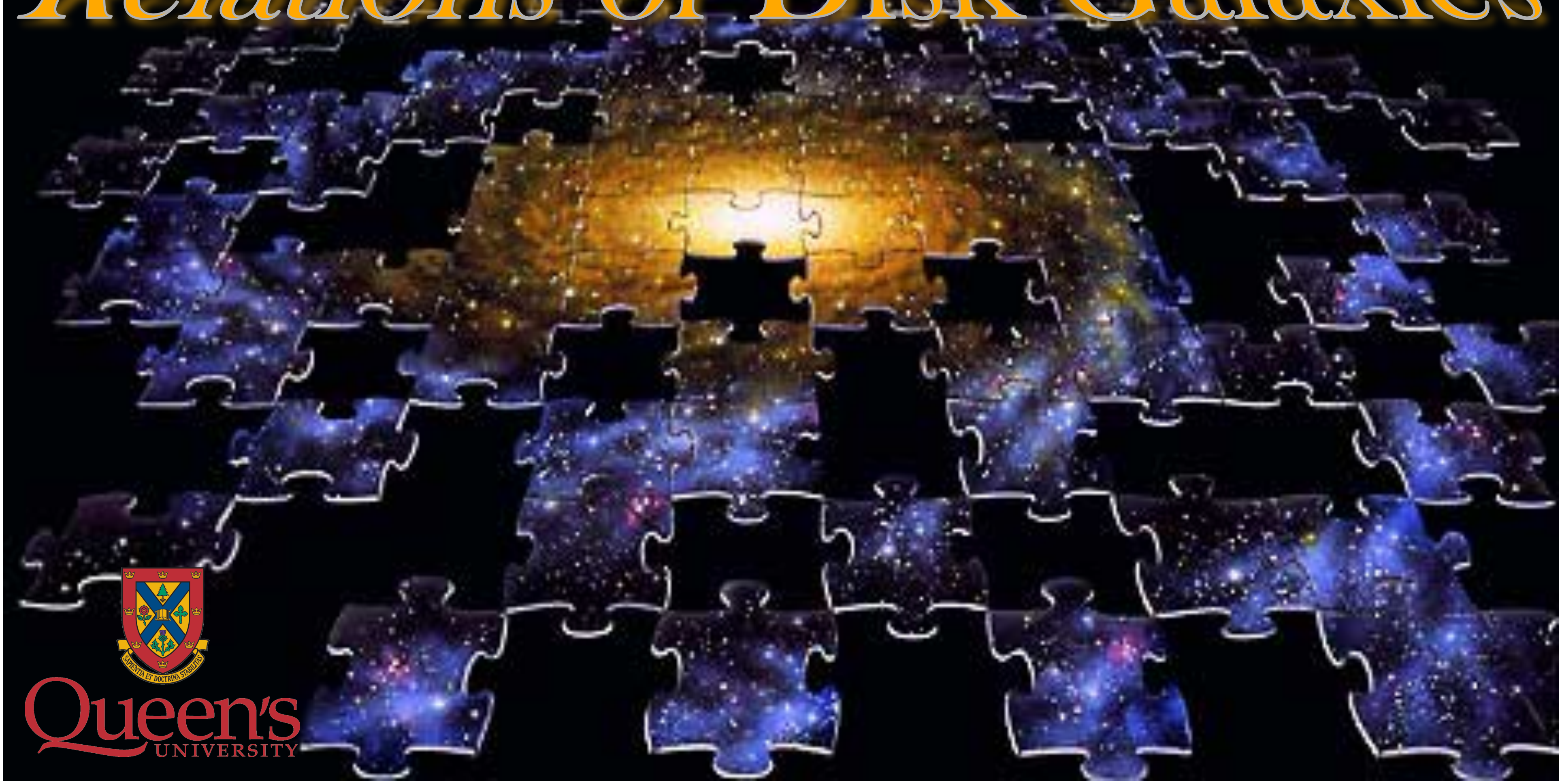
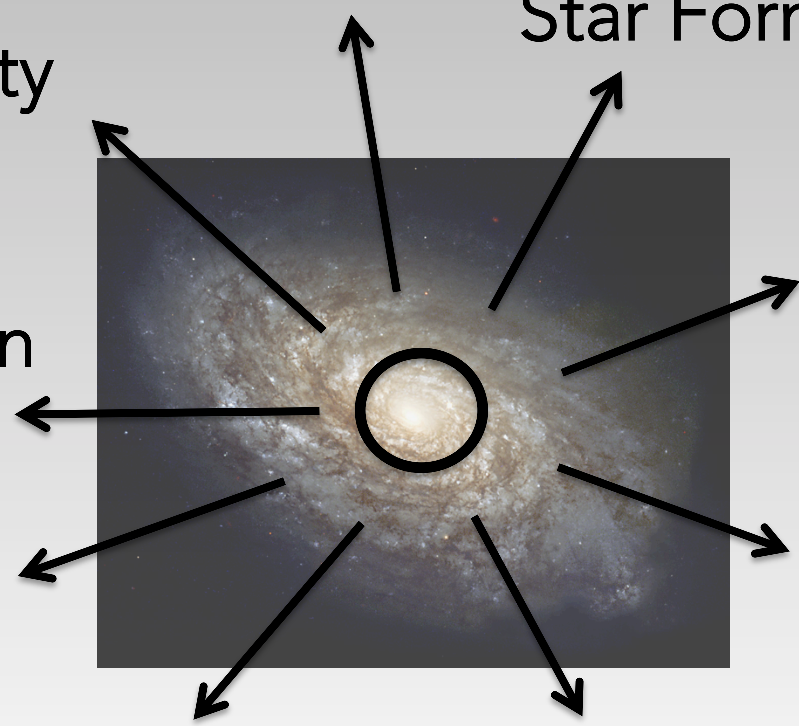
STÉPHANE COURTEAU

The Puzzling Scaling Relations of Disk Galaxies



Queen's
UNIVERSITY

Modern Structural Parameters and Relations



“Basic” Galaxy Scaling Relations with Dynamics (no populations)

- Galaxy Masses Review
- Tully-Fisher Relation: Halo Contraction, IMF
- Structural Bimodality of Galaxy Disks
- Light Profile Decompositions : e.g. M31
- Velocity/Mass Functions (SHMR)
  (predicted by ΛCDM)

must skip stellar pops, metallicity, globular clusters, SMBH,
outer profiles (disk breaks), environment, …
See vdKruit & Freeman (2011)

REVIEWS OF MODERN PHYSICS, VOLUME 86, JANUARY–MARCH 2014

Galaxy masses

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(published 14 January 2014)

Courteau etal 2014, Reviews of Modern Physics, 86, 47-119

Goal: map M/L as a function of R

I. Modeling the Stellar M*/L Ratio
II. Masses of Gas-Rich Galaxies
III. The Milky Way
IV. Masses of Gas-Poor Galaxies
V. Weak Lensing by Galaxies
VI. Strong Lensing by Galaxies

For gas-rich systems:

$$M(<R) = \alpha V_c^2 R / G$$

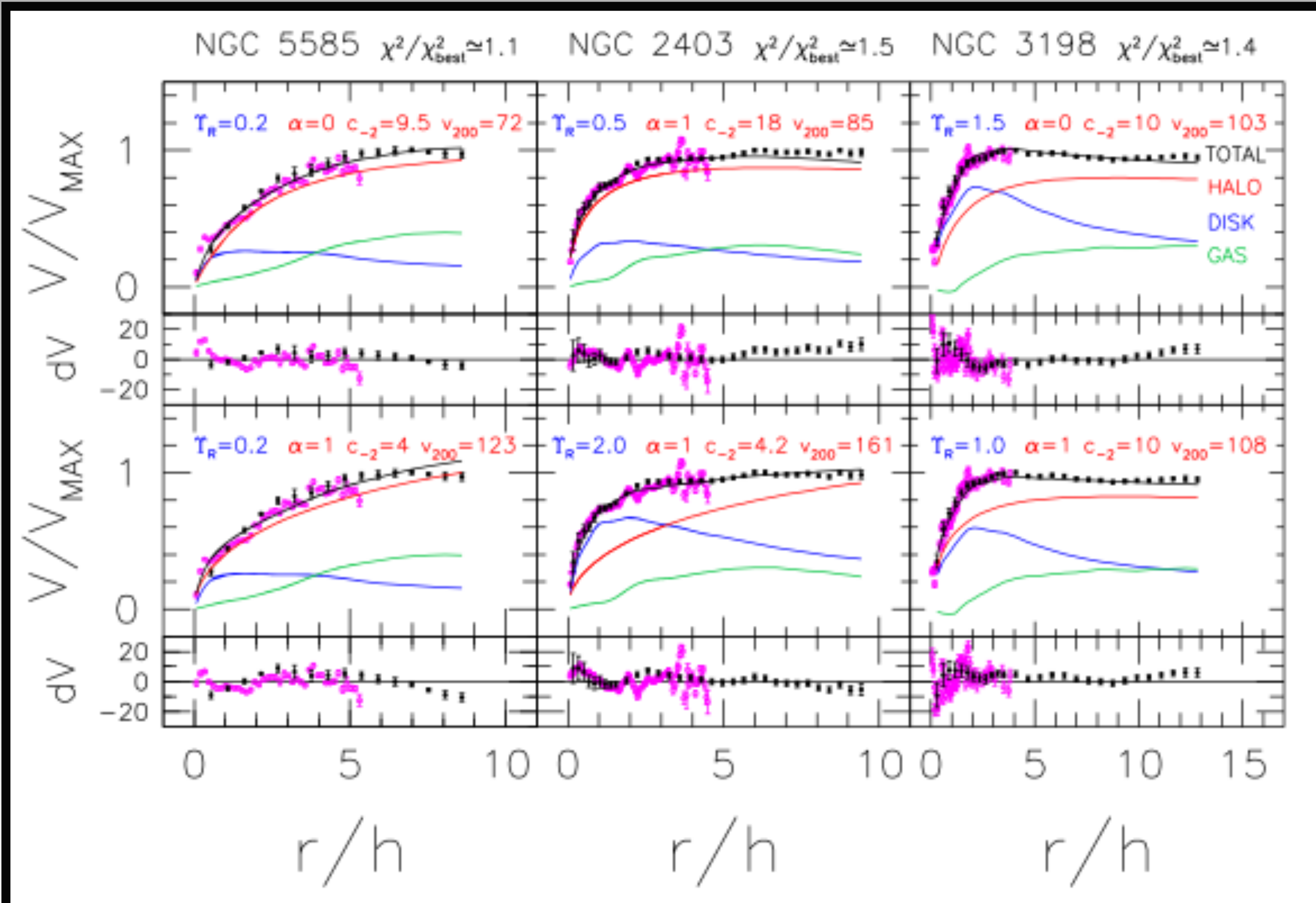
- $\alpha \approx 0.7 - 1$ (Binney & Tremaine: flattened potential; see An & Evans 2011 for theory of mass estimators)

- Problems: measure V_{los}
  non-circular velocities
  baryons/DM degeneracies
  dynamical stability
  (e.g. Widrow & Dubinski 2005; M2M)

- Mass modeling decompositions assume $\left(\frac{M}{L}\right)$

CAVEATS: Mass Models (Dutton+05)

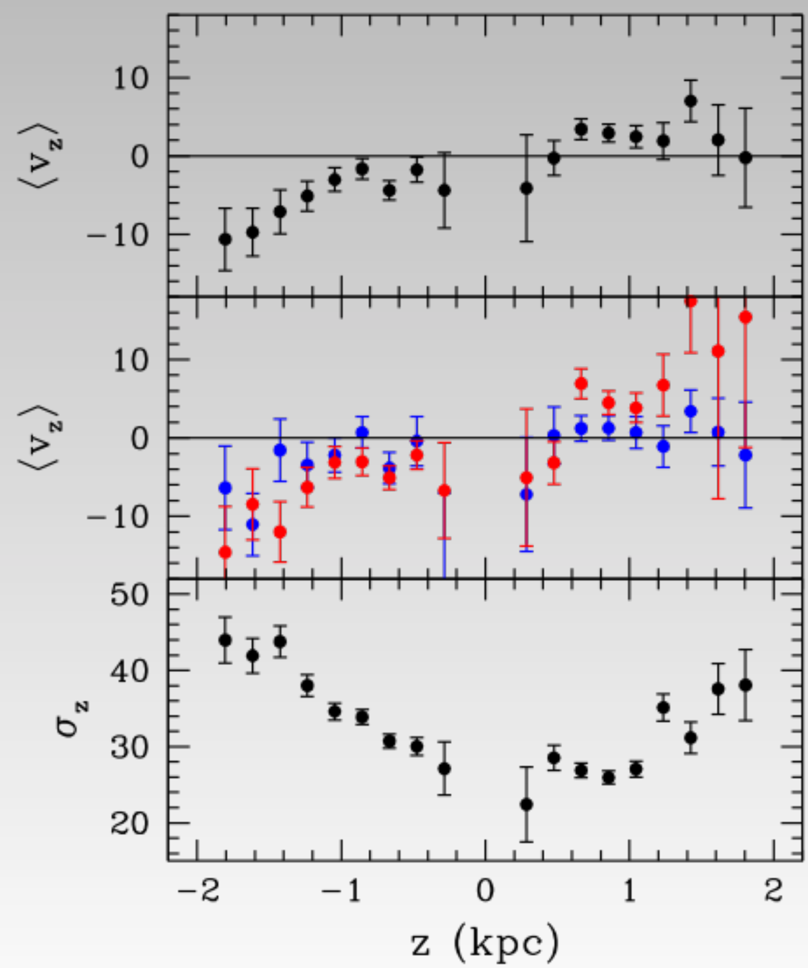
fixed M/L α = 1 (NFW) fixed c

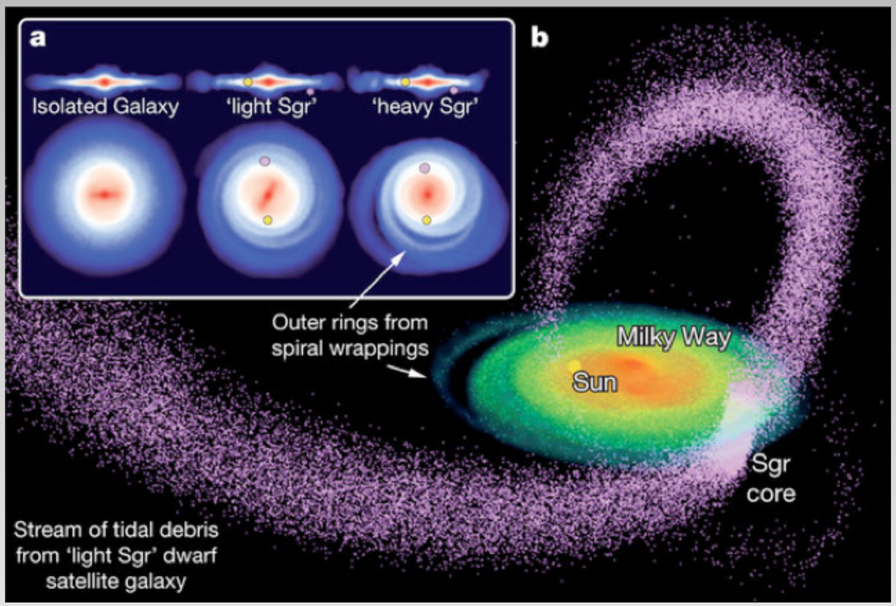


Need statistical treatments!

Halo substructure

provokes bars, spiral structure and vertical oscillations





Galactoseismology: Discovery of Vertical Waves in the Galactic Disk
➔ Widrow et al. (2012)

see also Debattista (1405.6345)

Velocity profile from SEGUE (see also RAVE papers)

For Gas-Poor Galaxies:
"Virial Estimator" $M(r_M) = c r_r \sigma_{ap}^2 (R_\sigma)/G$

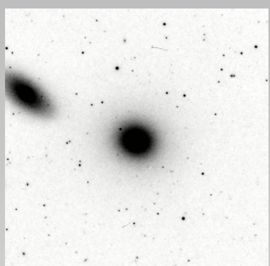
TABLE II. Structural constant $c = GM(r_M)/r_r\sigma_{\rm ap}^2(R_\sigma)$.

	Spitzer	Cappellari	Wolf	$3R_e$
r_M	∞	$r_{1/2}^{\rm light}$	$r_{1/2}^{\rm light}$	$3R_e$
r_r	$r_{1/2}$	R_e	R_e	R_e
R_σ	∞	R_e	$r_{\rm vir}$	$3R_e$
Predicted	7.5	2.5	4.0	···
Hernquist	7.46	3.31	4.84	5.74
$n = 1.0$ Sérsic	7.19	3.79	4.78	8.56
$n = 2.0$ Sérsic	7.23	3.63	4.85	7.22
$n = 4.0$ Sérsic	6.59	2.96	4.44	5.36
$n = 5.5$ Sérsic	5.91	2.49	3.96	4.37
$n = 1.0$ Sérsic + Einasto DM	112	3.78	4.63	9.53
$n = 2.0$ Sérsic + Einasto DM	112	3.74	4.67	8.38
$n = 4.0$ Sérsic + Einasto DM	103	3.20	4.33	6.70
$n = 5.5$ Sérsic + Einasto DM	94	2.76	3.95	5.70

Cappellari, Wolf & Mamon agree within 20%

Dark Matter Fractions:
Deep, homogeneous sampling needed

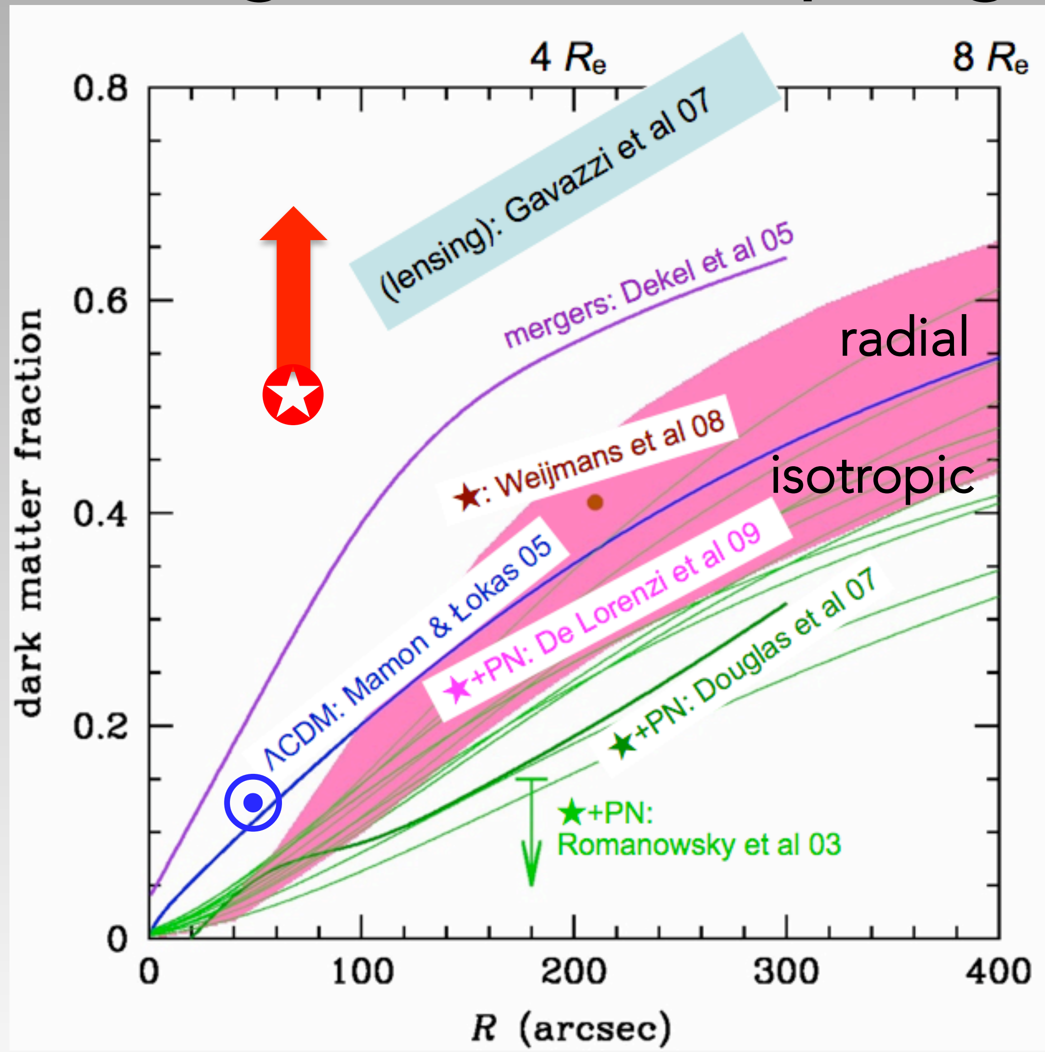
M105; E1



⊙ Cappellari (2013)

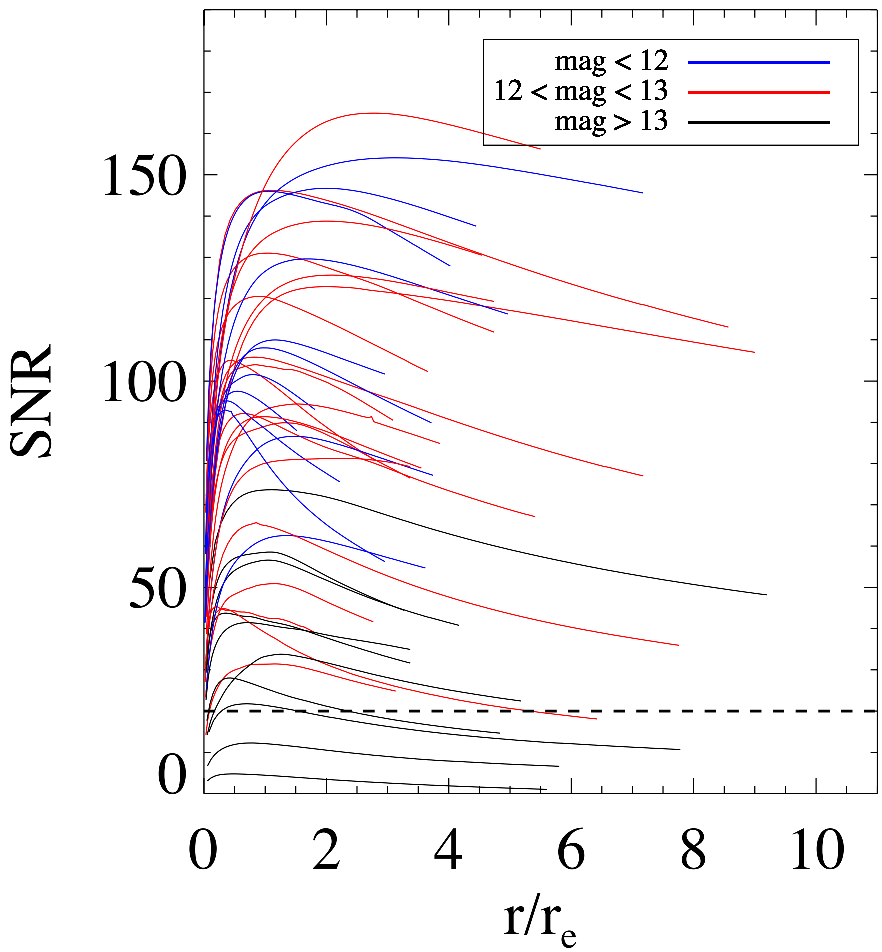
✪ Spirals

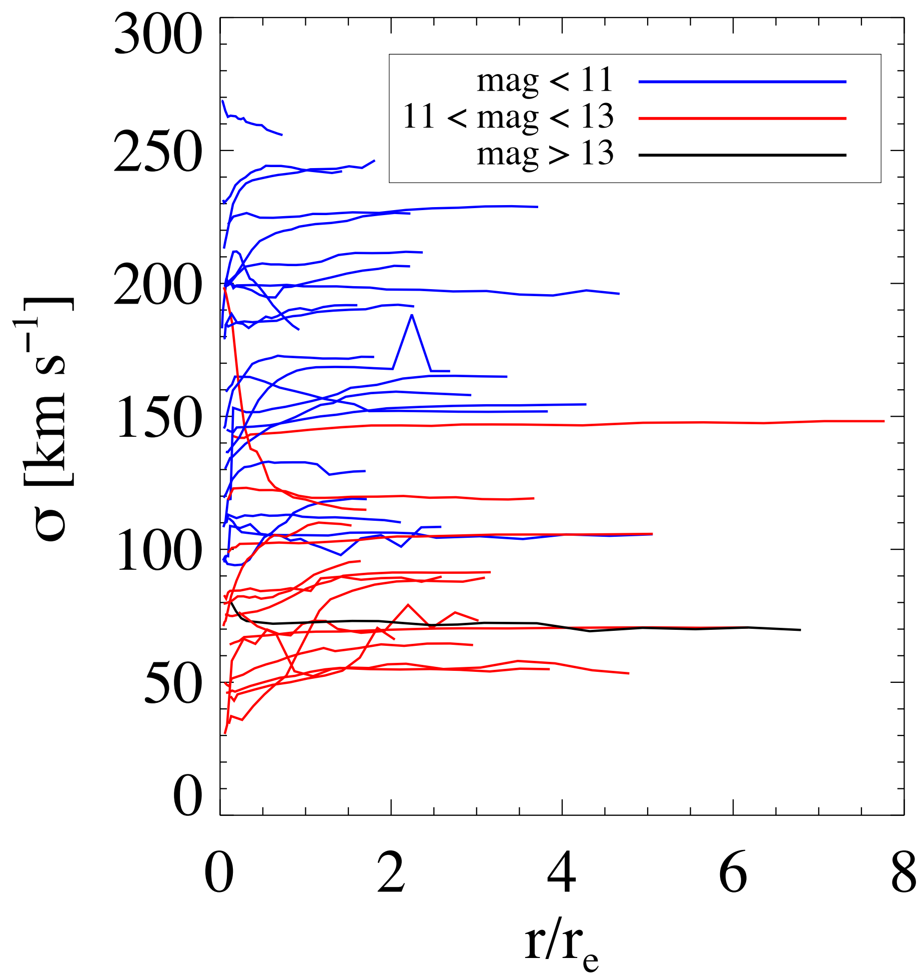
Courteau+14
Reviews of Modern Physics



Dark matter content @ 1,2,3,4… R_e still uncertain!

Extended Egals Dispersion Profiles
(PNS [Arnaboldi/Gerhard], SHIVir [Ouellette/Courteau], SLUGGS [Brodie/Romanowsky/Foster], …)





Ouellette etal 2014 (SHIVir)

Looking forward to…

Galaxy Masses Review (RMP) – Courteau+14

arXiv:1309.3276 – ask me for the latest copy

IAU Symposium 311

Galaxy Masses as Constraints of Formation Models

21–25 (Mon–Fri) July 2014, Oxford UK

This IAU Symposium will also be an opportunity to celebrate the career of Prof. Roger Davies

www.physics.ox.ac.uk/iau311

“Basic” Galaxy Scaling Relations with Dynamics (no populations)

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- Structural Bimodality of Galaxy Disks
- Light Profile Decomposition: e.g. M31
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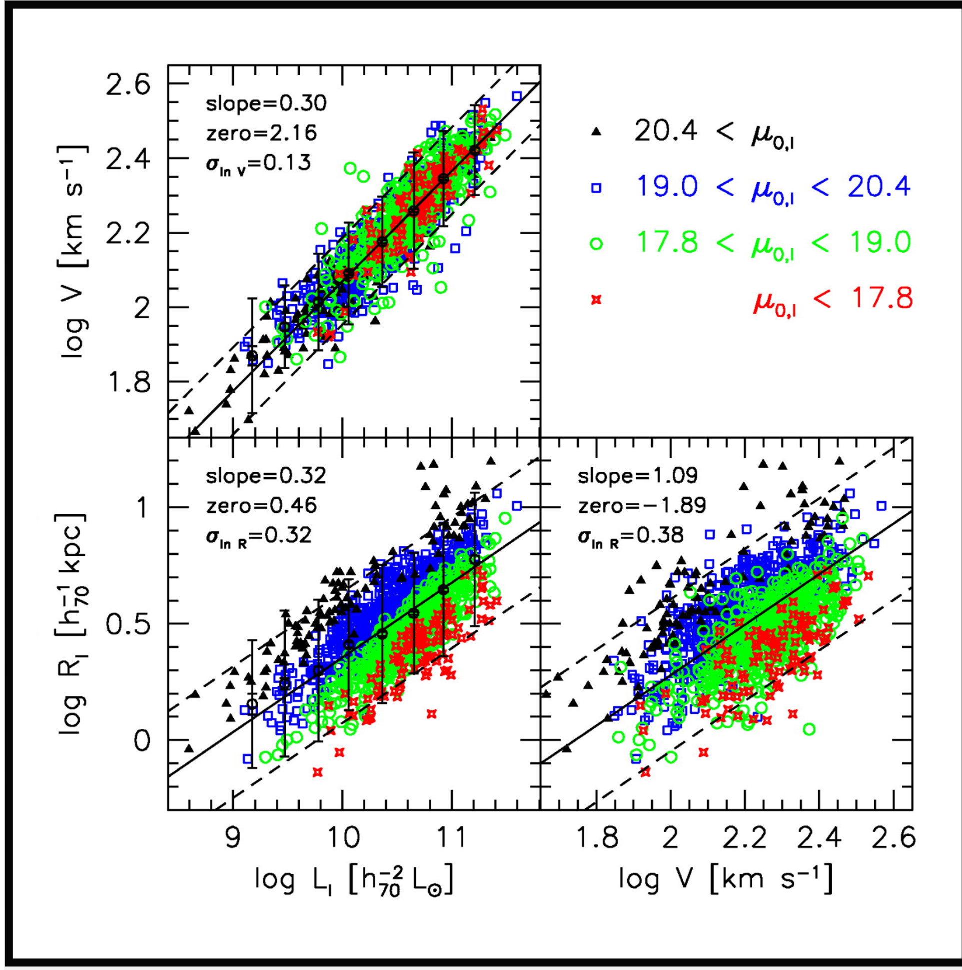
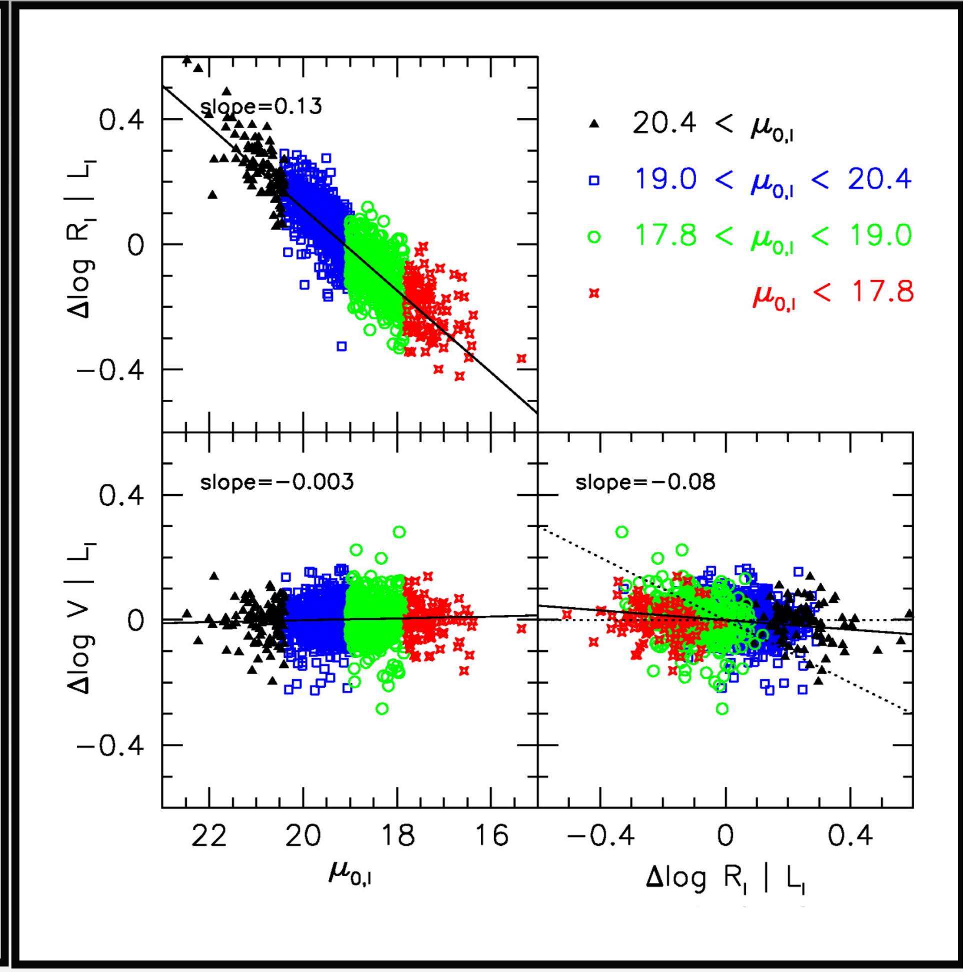
must skip stellar pops, metallicity, globular clusters, SMBH, outer profiles (disk breaks), environment, …
See vdKruit & Freeman (2011)

Use of (Disk) Scaling Relations

- Originally, TFRs used to determine galaxy distance for cosmic flow studies [Marseille '13]
  e.g. Tully-Fisher+77; Courteau+93; Strauss & Willick 1995; Giovanelli+97; Masters+06; Springob+09
- TFRs assembled over broad range of types
  e.g. Courteau+03[bars]; Vogt+04[env.]; Courteau+07; Pizagno+07
  for testing galaxy formation models e.g. Dalcanton+97; MMW-99; Navarro & Steinmetz-00; Dutton+07; Gnedin+07
- Connecting ET and LT galaxies with their haloes through dynamics / velocity function
  e.g. Dutton+11; Trujillo-Gomez+11; Papastergis+11; Reyes+12
- Evolution of Scaling Relations with time
  Ziegler+02; Barden04; Kassin+07; Trujillo+09; Dutton+11b; Miller+13
  Oxford IAUS 311 21-25 July 2014

Global Disk Galaxy Scaling Relations





Courteau+07; see also Reyes+11, Hall+12

Tully-Fisher Residuals Argument
(Courteau and Rix 1999)

- For pure exponential stellar disks $$V^2 \sim \frac{(M/L)L}{R_{exp}}$$
- For a given luminosity $$V^2 \sim \frac{(M/L)}{R_{exp}}$$
- and if *M/L* vs r is self-similar in bright spirals $$V \sim R_{exp}^{-1/2}$$

Therefore

$$\boxed{\frac{\partial \log V(L)}{\partial \log R_{exp}(L)} = -0.5}$$

TFR as a Tracer of DM

(Courteau and Rix 1999)

Pure self-gravitating exponential disks should have

$$\boxed{\frac{\partial \log V(L)}{\partial \log R_{exp}(L)} = -0.5}$$

Empirically, we find:

$$\boxed{\frac{\partial \log V_{2.2}}{\partial \log R_{exp}} = -0.08 \pm 0.05}$$

Galaxy scaling relations

Pure Disk

Pure DM

Calibrated Tully–Fisher relations 2379

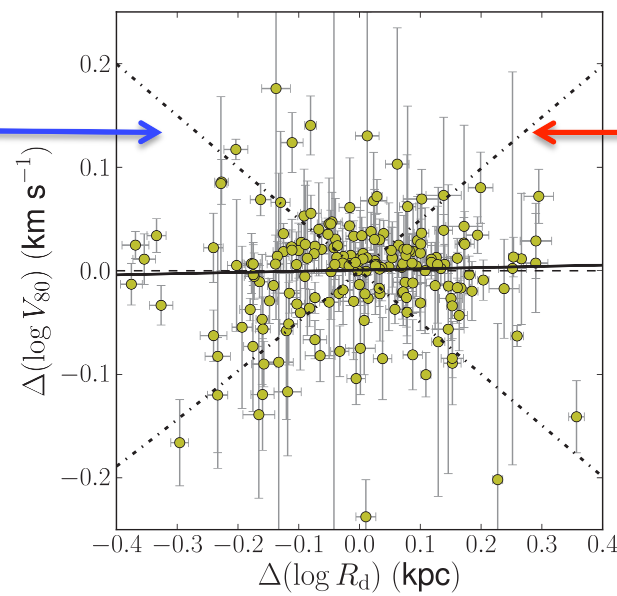


Figure 28. Correlation between velocity residuals from the $M_\star$ ITFR, $\Delta(\log V_{80})$, and disc size offsets $\Delta(\log R_{\rm d})$, defined relative to the mean relation $\log \bar{R}_{\rm d}(M_\star)$ (given by equation 35). The best-fitting linear relation has a slope consistent with zero (solid line). Predicted trends for a pure self-gravitating disc model (slope = −0.5) and a pure NFW DM halo model (slope = +0.5) are also shown (dot-dashed lines).

Courteau+Rix 99

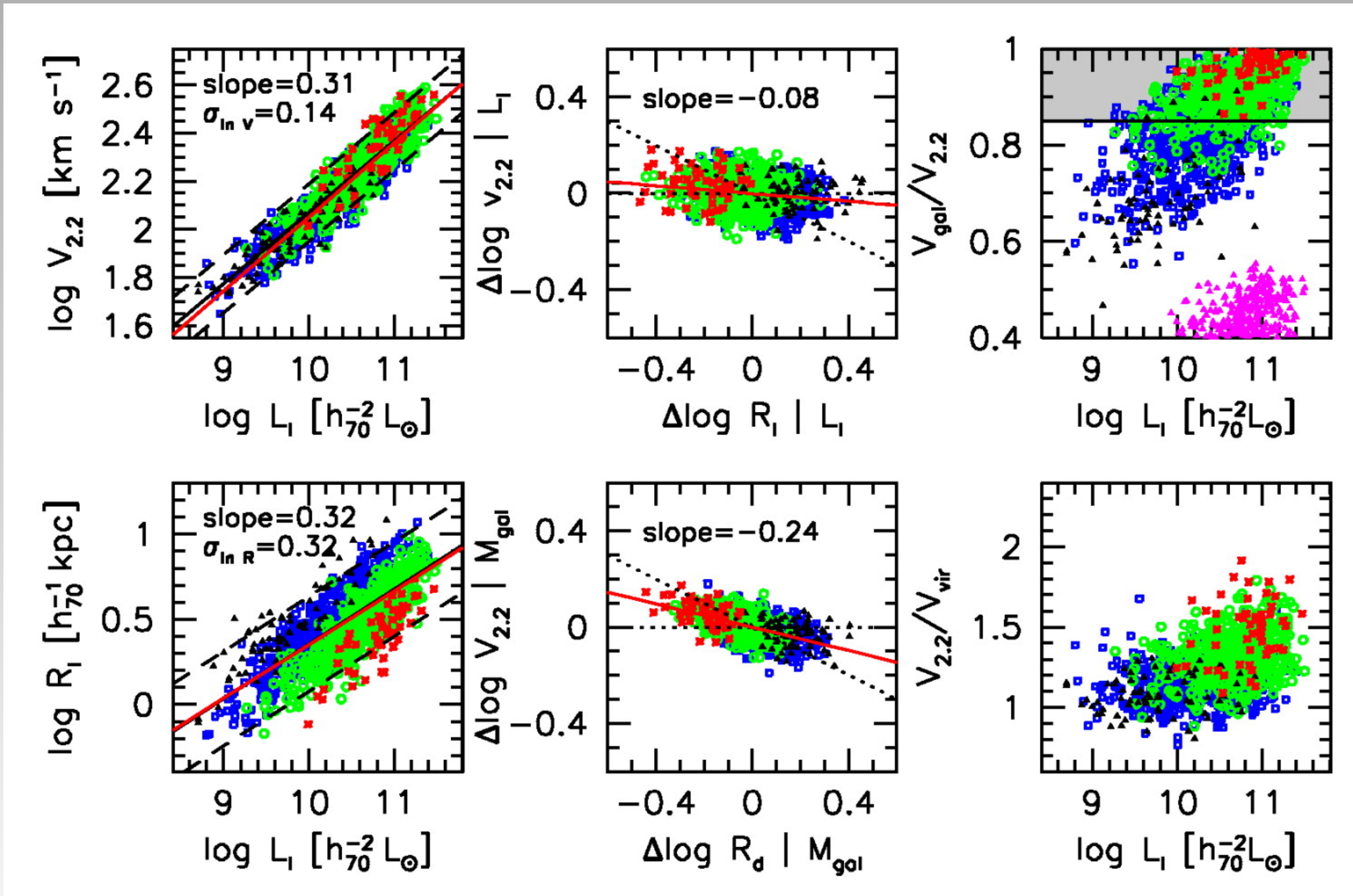
Reyes+11

dlogV/dlogR = -0.5 for self-gravitating disk

+0.5 for pure NFW DM halo model

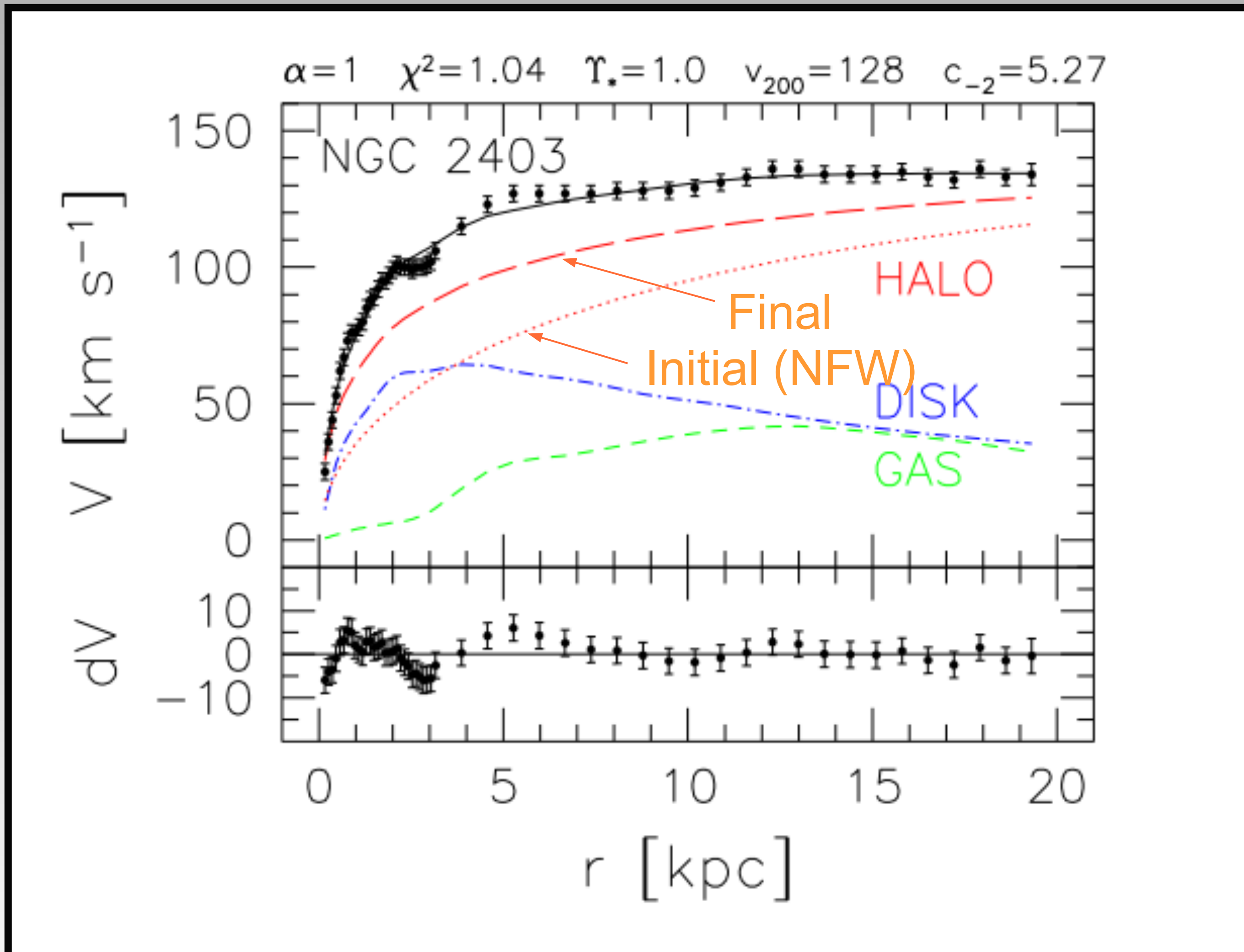
Estimate Baryons/DM fraction in galaxies!

Galaxy scaling relations



Allow for halo expansion **Dutton etal 2007, 2011**

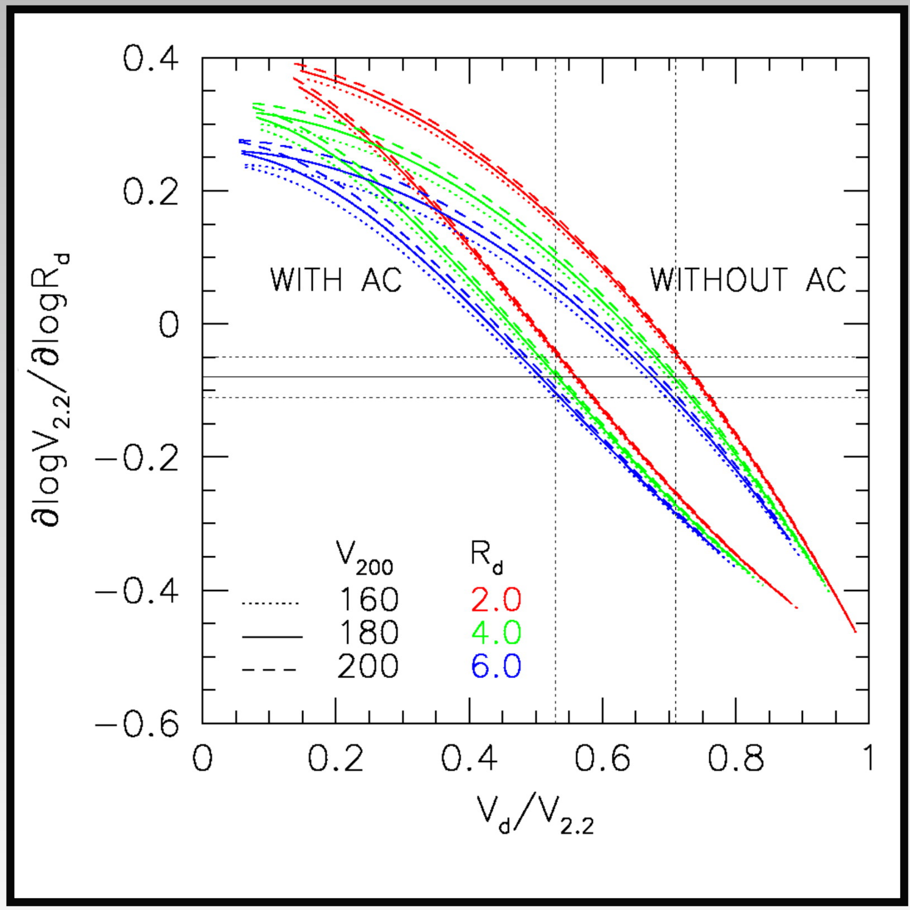
Caveat: adiabatic contraction



Without adiabatic contraction, $\chi^2 = 1.7$, $v_{200} = 91$, $c = 14.8$

Comparison With Models

→ $V_{\mathbf{disk}} / V_{\mathbf{tot}}$ = 0.72 ± 0.05 at R = 2.2R_{exp} without AC



Dutton etal 2007

→ $V_{\mathbf{disk}} / V_{\mathbf{tot}}$ < 0.6 at R = 2.2R_{exp} with AC *(Courteau & Rix 1999)*

Evidence for Sub-Maximal Disks (at 2.2R_d)

- Kuijken & Gilmore (1989): local stellar density
- Predicted by analytical models of galaxy formation (e.g., Mo et al. 1998; Dutton et al 2007) (Assumes AC)
- stellar kinematics of galactic disks Bottema (1997); DiskMass project (Bershady, Verheijen + 11)
- TF residuals: Courteau & Rix (1999); Dutton+07
- gas kinematics and structure of spiral arms Kranz, Slyz & Rix (2002); Foyle etal (2008):
- Kregel et al. (2005): disk flattening of edge-on galaxies
- Trott & Webster (2010): lensing + rotation curve constraints

$$\boxed{V_{disk}/V_{tot} \leq 0.6} \Rightarrow \boxed{M_{DM}/M_{tot} \geq 0.7}$$

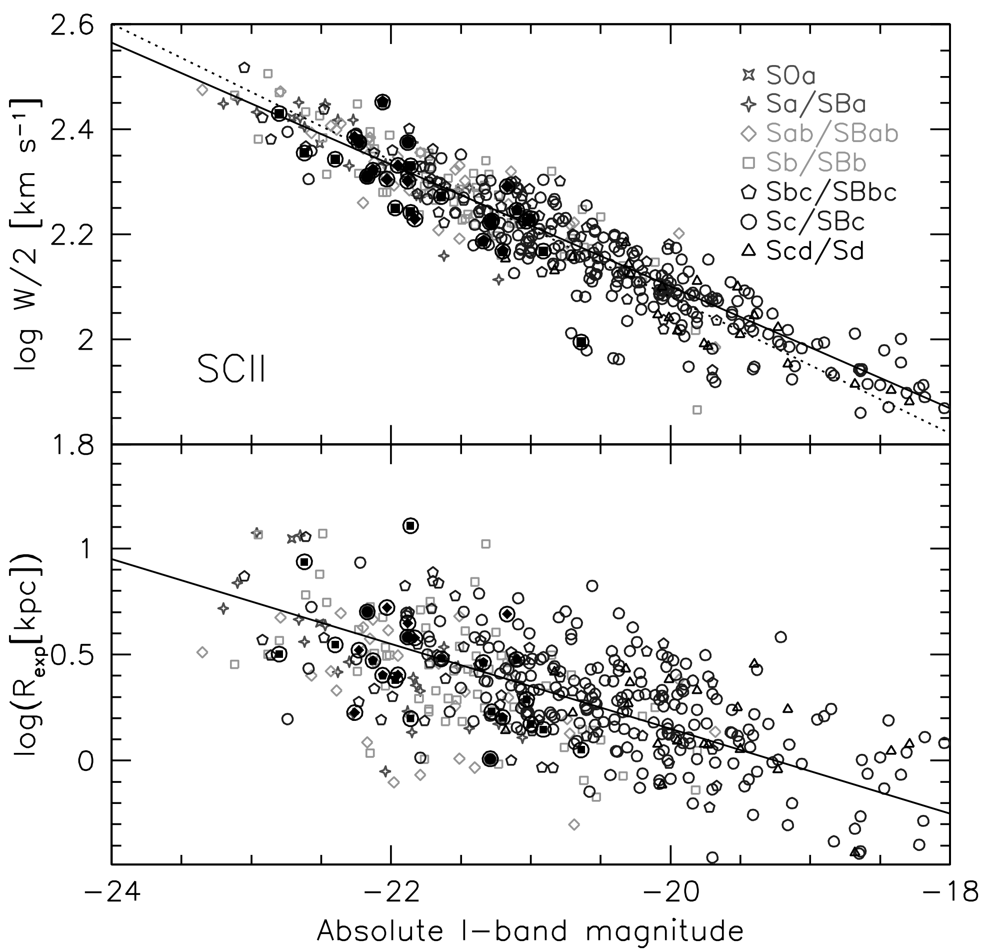
(on average at 2.2 disk scale lengths)

van den Kruit & Freeman (2011; ARAA) Courteau etal (2014; RMP)

Galaxy Scaling Relations: TFR for Barred Galaxies

TFR: Courteau+03; Sheth+12; Aguerri+13

FJR/FP/Kappa Space: Gadotti & Kauffman+09; Gadotti-09



Courteau+03

SDSS Study: Dark halo response and the stellar IMF in early- and late-type galaxies (Dutton+11)

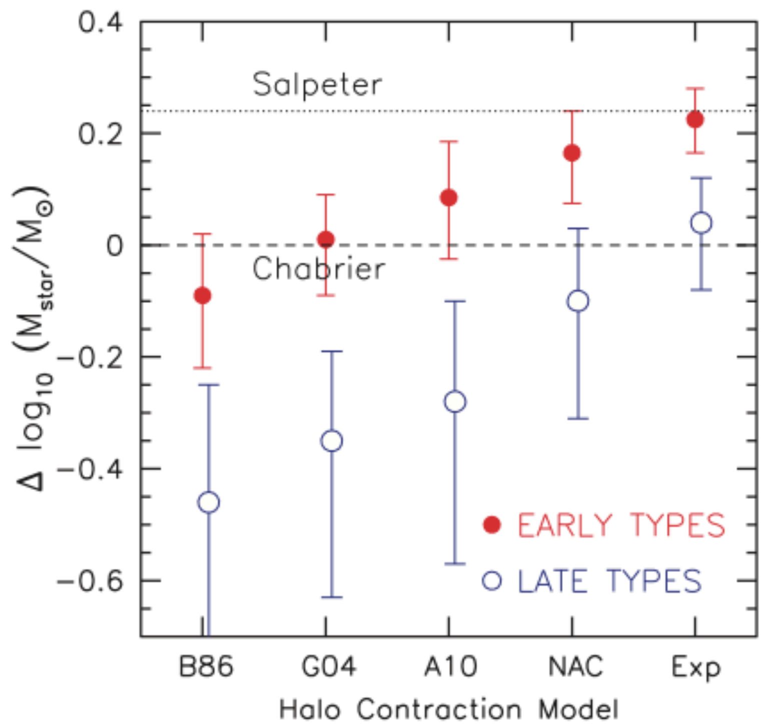


Figure 17. Offset in stellar masses required to match the zero-point of the VM relations as a function of halo response model, calculated at $\log_{10}(V_{opt}/\mathrm{km\,s^{-1}}) = 2.30$, for early-type (red filled symbols) and late-type (blue open symbols) galaxies. The models correspond to the following: B86 – Blumenthal et al. (1986); G04 – Gnedin et al. (2004); A10 – Abadi et al. (2010); NAC – no halo contraction; Exp – halo expansion with $\nu = -0.5$ in equation (17). The error bars show the effects of 2σ systematic errors on the zero-points of the VM and M_{200}–M_{star} relations. For fixed IMF (i.e. horizontal lines) early-type galaxies require stronger contraction than late-type galaxies, while for fixed halo response (vertical direction) early-type galaxies require heavier IMFs than late-type galaxies.

- $V_c = 1.54\,\sigma$ for ETGs

Courteau+07b; Catinella+12; Cappellari+13; Courteau+14

- $V_{opt}/V_{200} = 1.3$

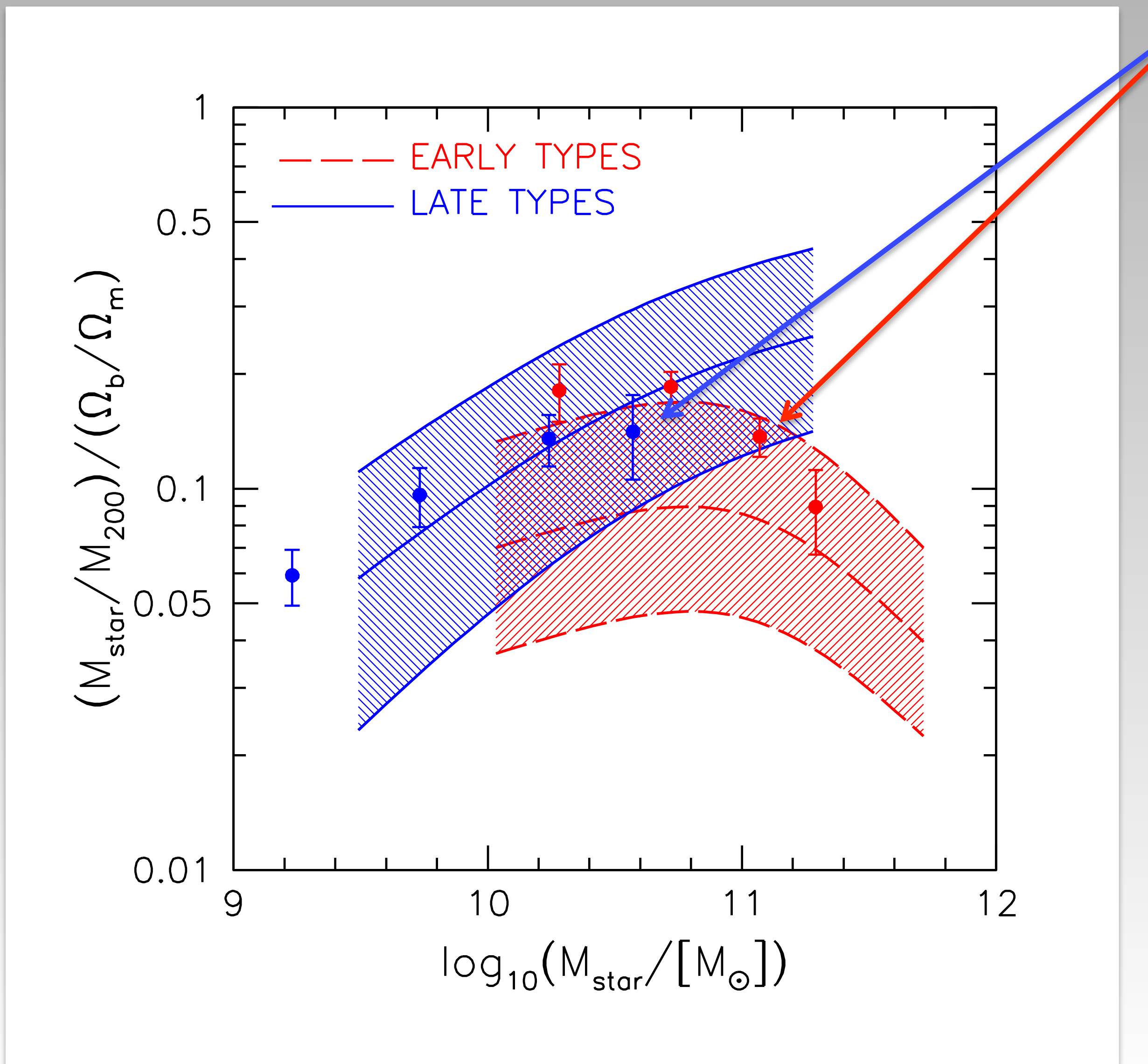
Lensing: Dutton+10; Reyes+11

- $\rho \approx r^{-2}$

("Disk/Halo conspiracy"; see Remus+13)

Dutton+11; see also Trujillo-Gomez+11

SDSS Study: Dark halo response and the stellar IMF in early- and late-type galaxies (Dutton+11)

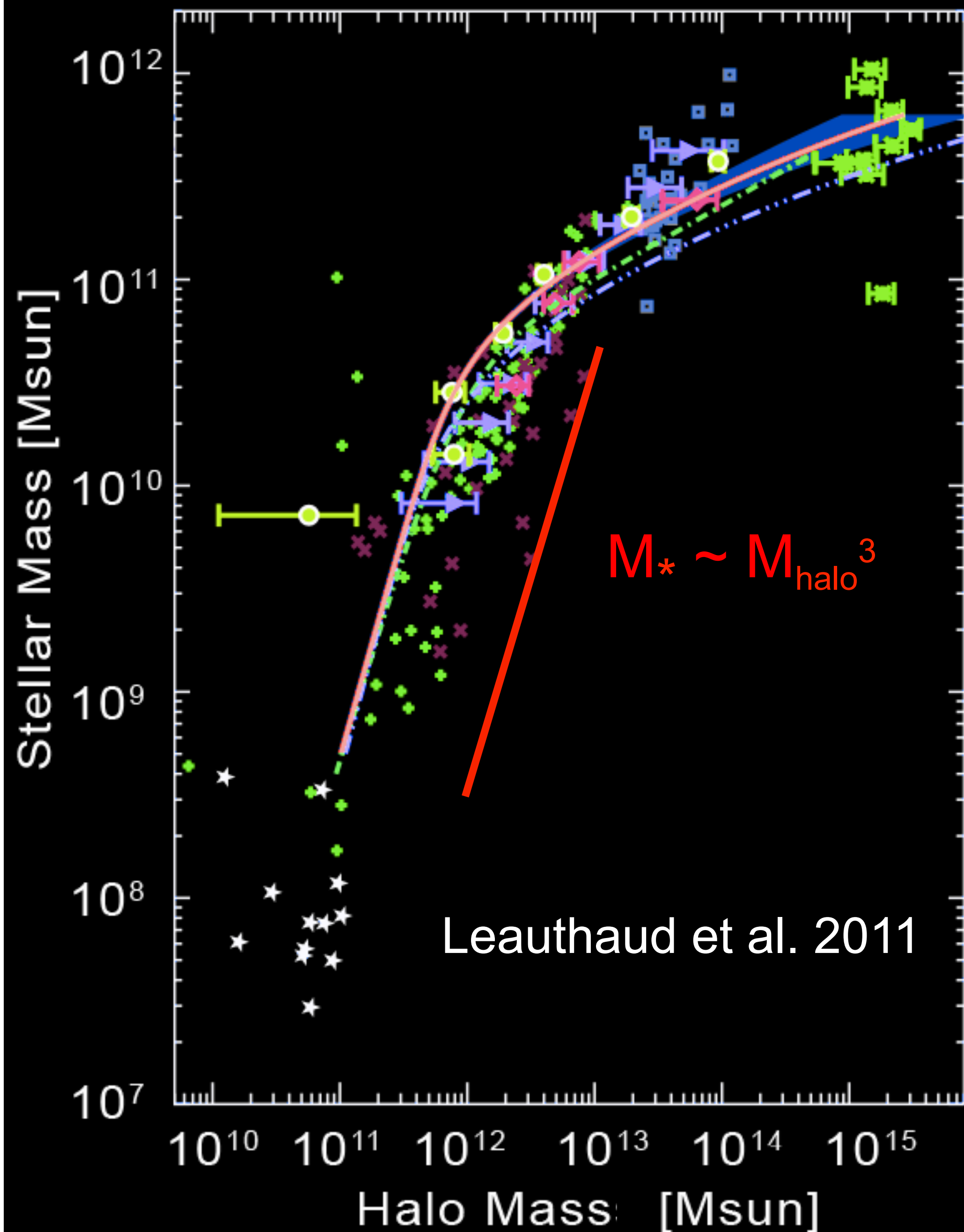


Hudson etal 2014 weak lensing: central + satellites at z=0.3

IMF change with [Fe/H], α, age, DM contributions?

- e.g. Spiniello, Barnabè, R. Smith

Stellar Mass-Halo Mass Relation



4 Methods: consistent results

Halo Matching- rank order halos from simulations and stellar masses from surveys

Weak Lensing

Satellite Kinematics

Tully-Fisher (caveats)

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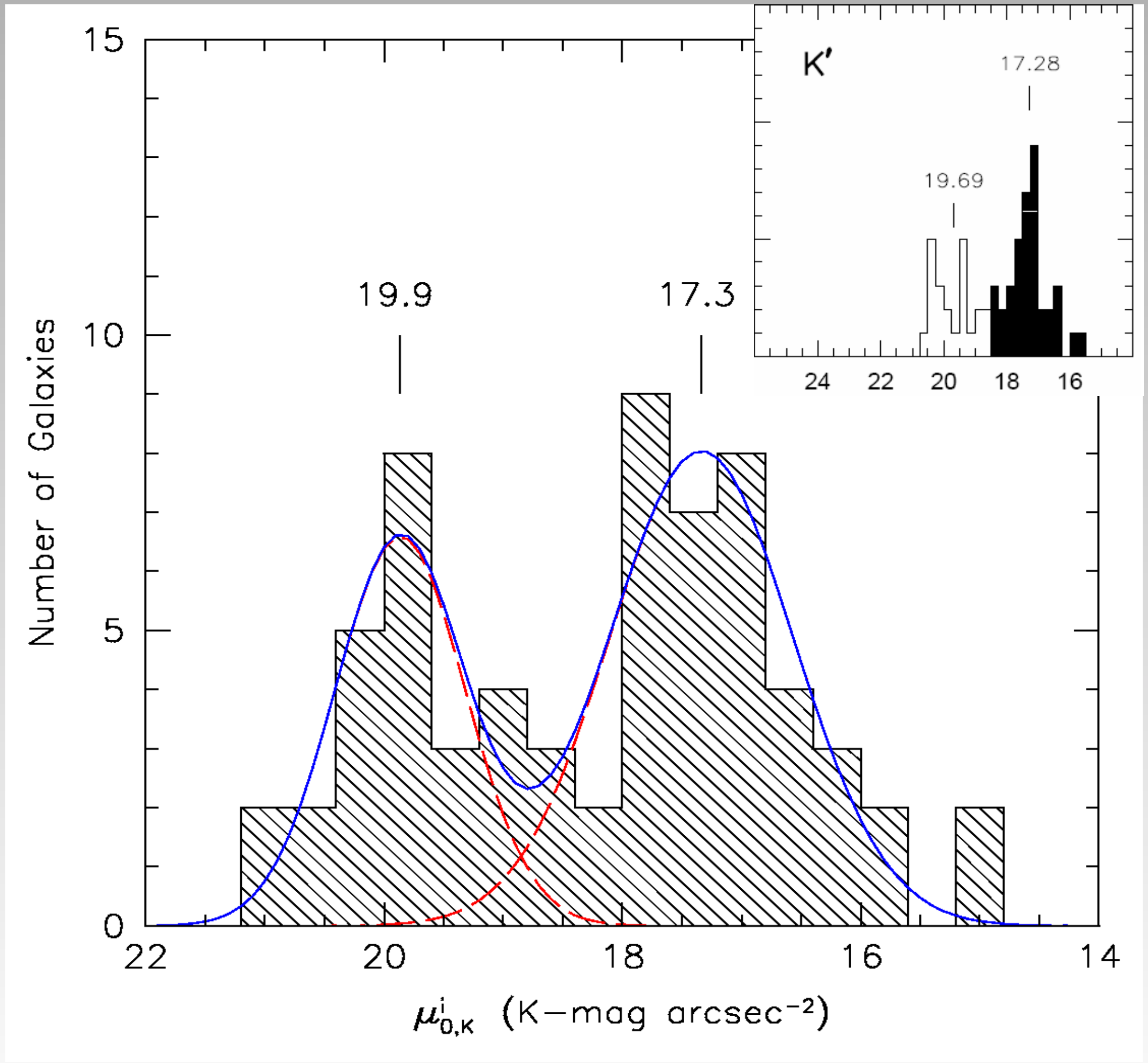
must skip stellar pops, metallicity, globular clusters, SMBH, outer profiles (disk breaks), environment, …
See vdKruit & Freeman (2011)

Intro – UMa revisited

- B/D decompositions on K'-band profiles for the 63 UMa galaxies confirmed Tully & Vereijhen (1997)'s result to within 0.2 K-mag arcsec^{-2}.
- Observed bimodality is not due to systematic bias by TV97.
- Bimodality not seen at optical wavelengths

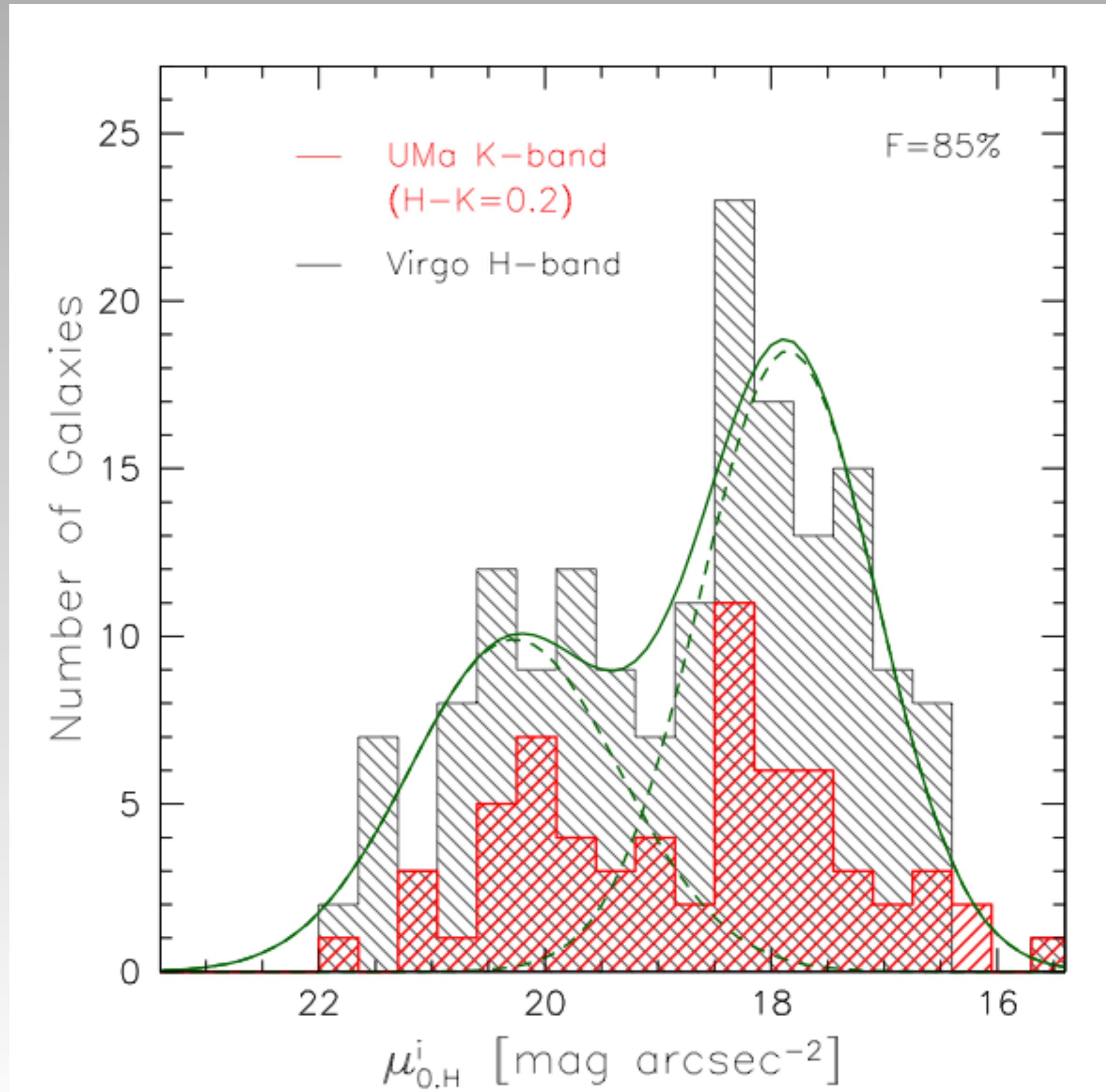


McDonald, Courteau & Tully 2009a

Results – now Virgo

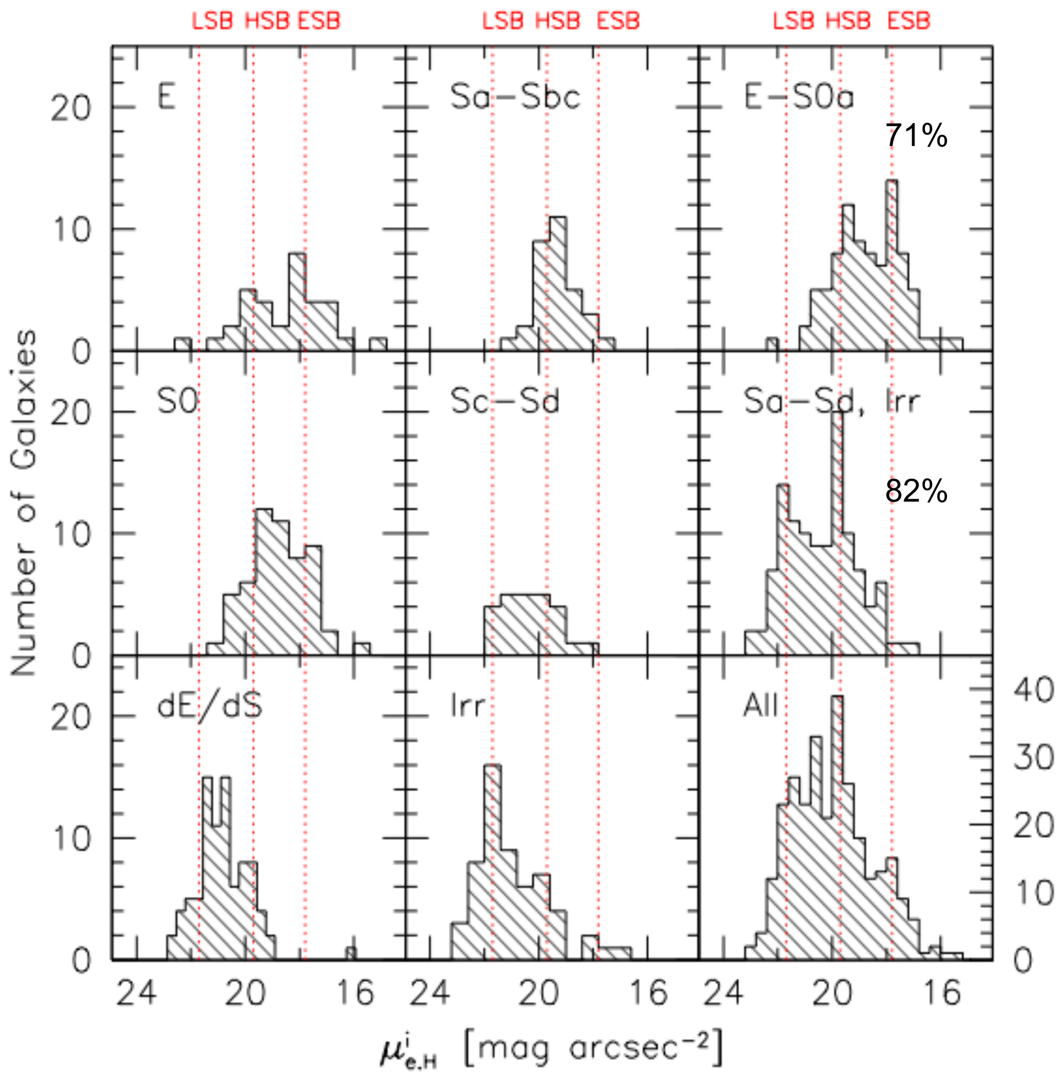
B/D decompositions for 161 VCC disk galaxies

- Distribution of μ_0 identical to that found by TV97 and McDonald+09 for UMa galaxies



McDonald, Courteau & Tully 2009b

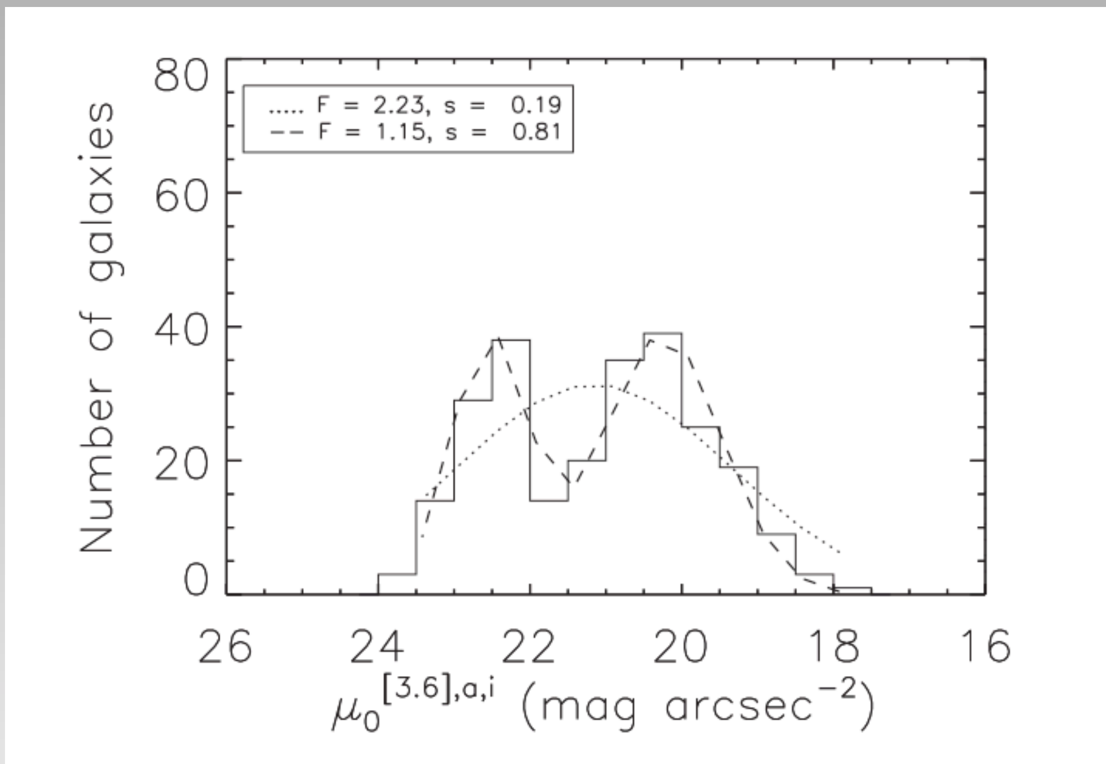
Results – SB Distribution



- Model independent μ_e for 286 VCC galaxies
  - HSB-ESB=1.61
  - LSB-HSB=1.61

McDonald, Courteau & Tully 2009b, MNRAS, 394, 2022

Scorce etal (2013)



- Model (disk-only fits) μ_0 for 438 ***S*^{4}*G*** galaxies
  - LSB-HSB=2.0 mag at 3.6μm in the AB system

Corroborate Tully & Verheijen 1997 and McDonald etal 2009ab.
Hypothesis: Two stable modes? LSBs where DM dominates everywhere; HSB where baryons dominate the center? Lack of ISB galaxies due to galaxies avoid staying in a mode where baryons and DM are co-dominant in the central parts? Test using dynamics / simulations (Illustris?)

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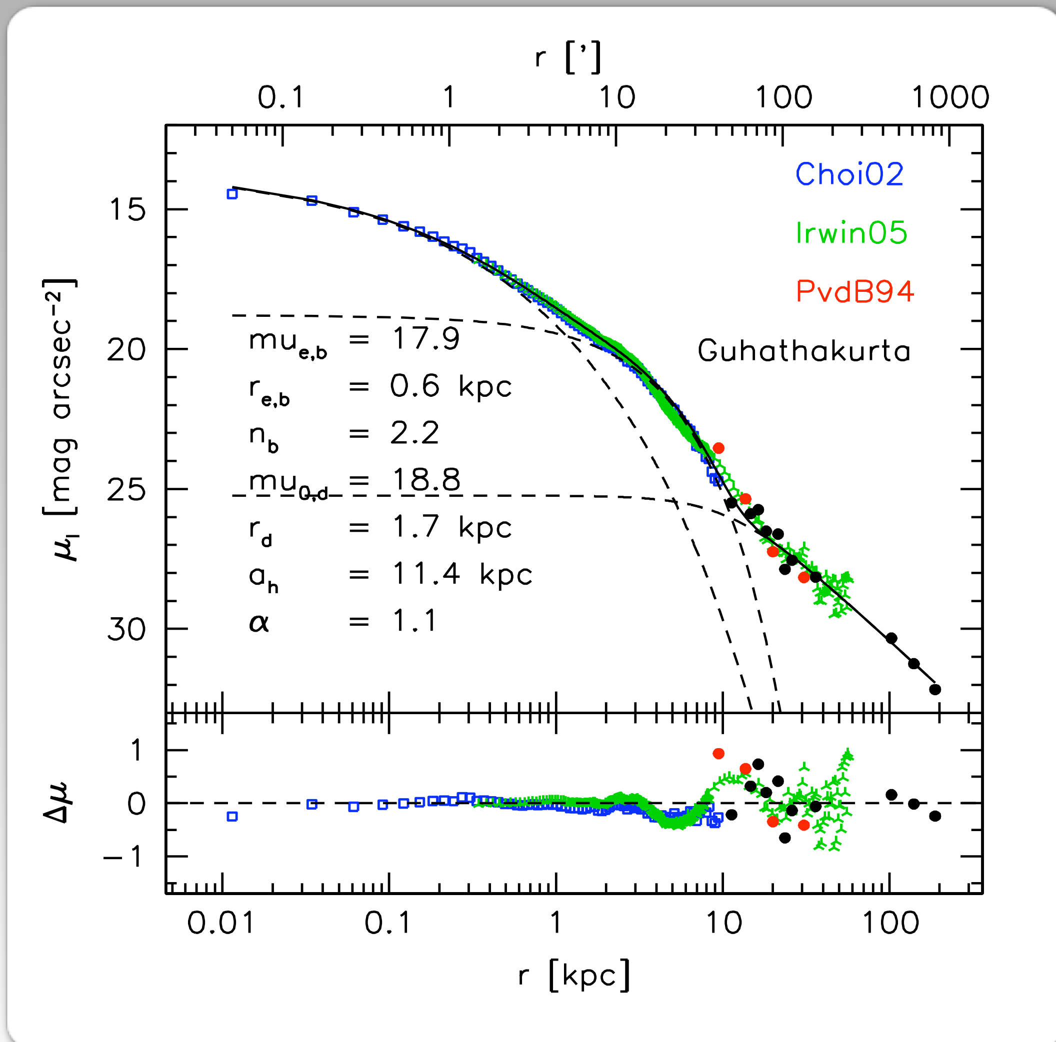
CAVEATS: B/D decompositions

E.g. with M31

Courteau+11

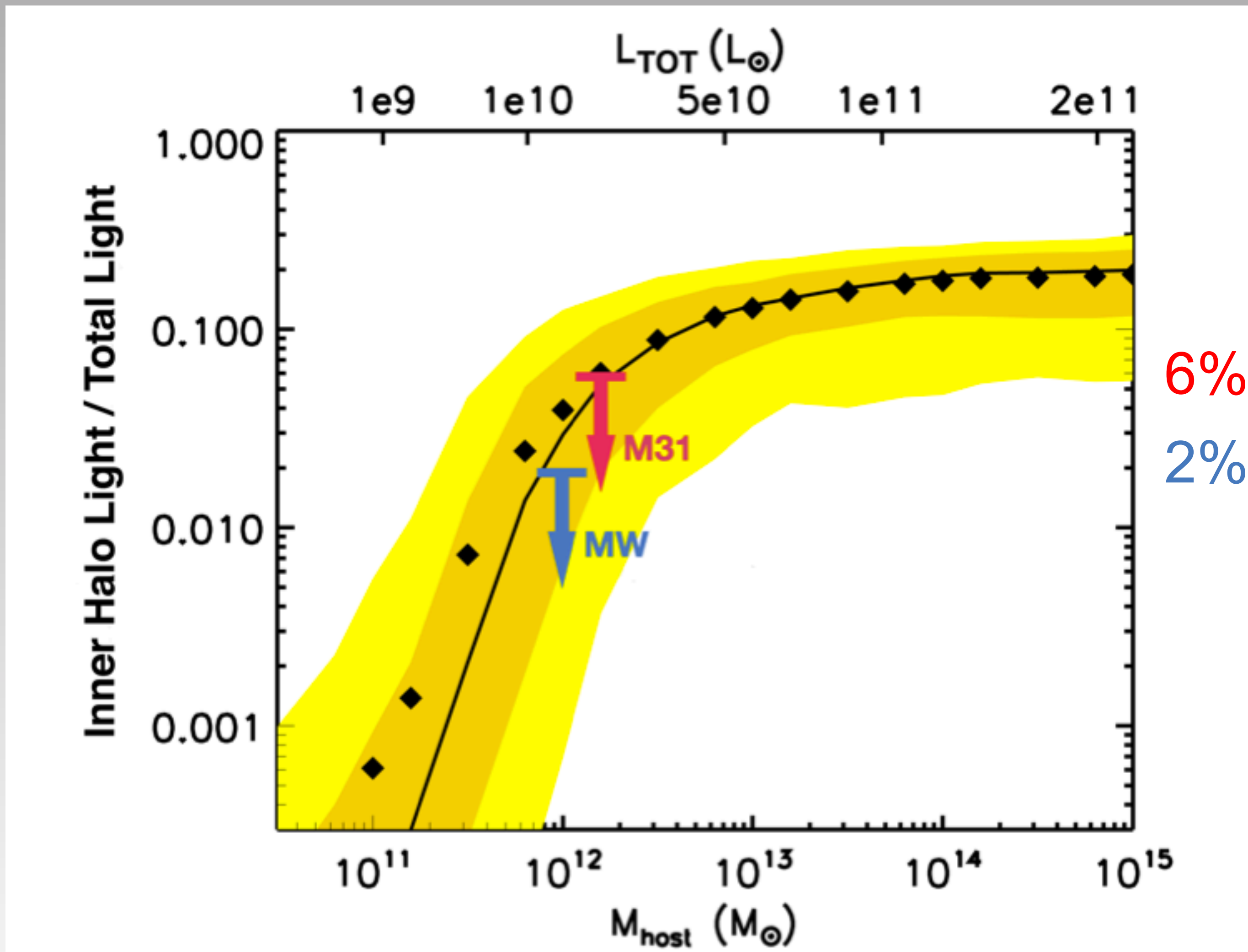
Spectroscopic evidence: Saglia+11, Dorman+13



Bulge: 22%
Disk: 72%
Halo: 6%

Scale Parameters rarely determined to better than 20%

Fractional Halo Light

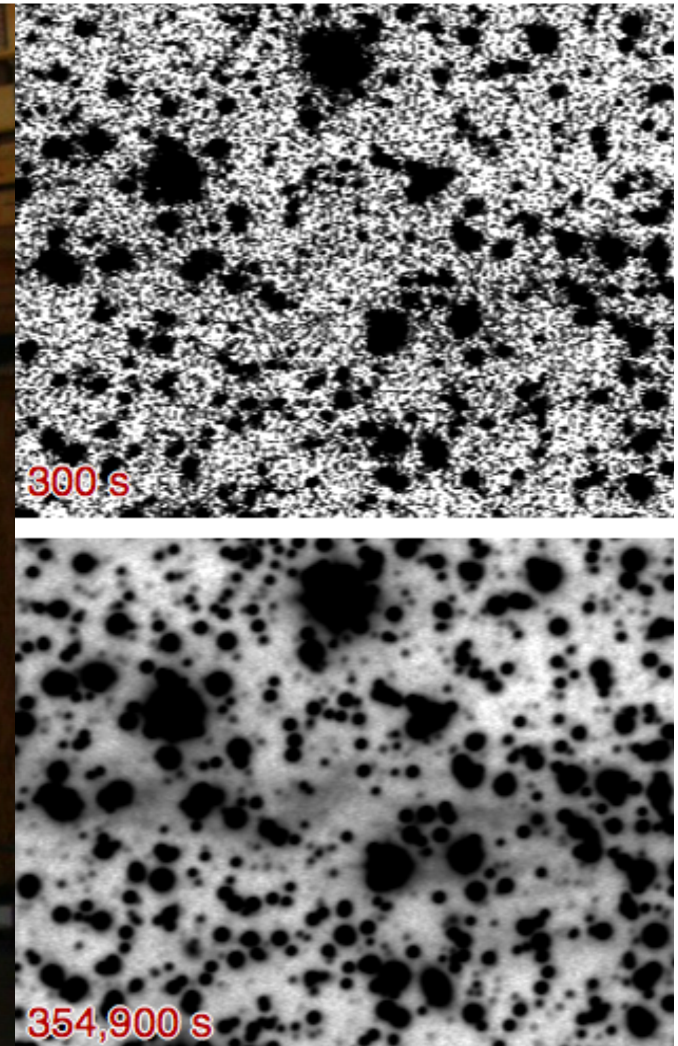


Purcell, Bullock, Zentner (2008)
Courteau & van den Bergh (1999)

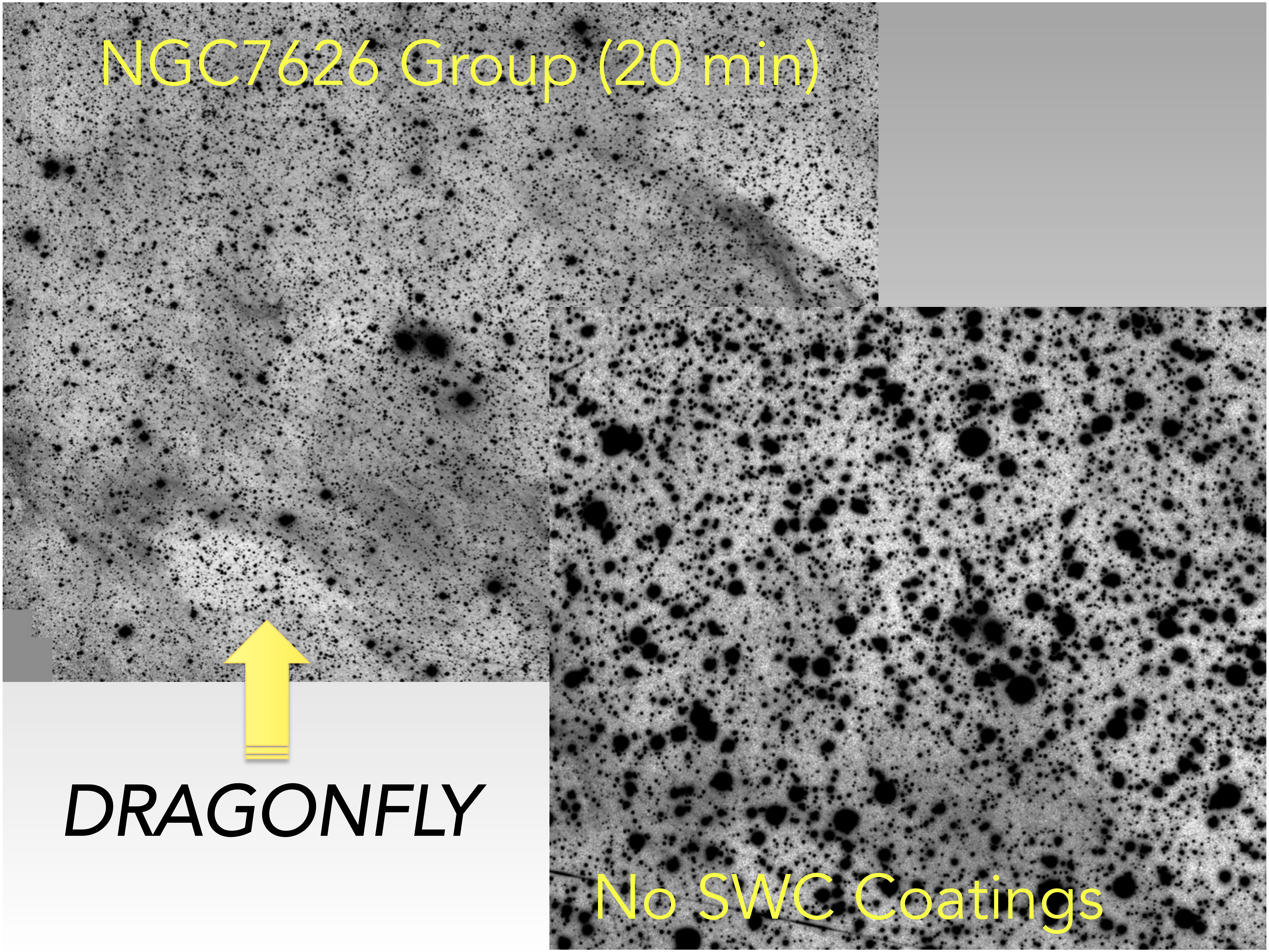
Courteau+11

DRAGONFLY:
an f/1.0 refractor

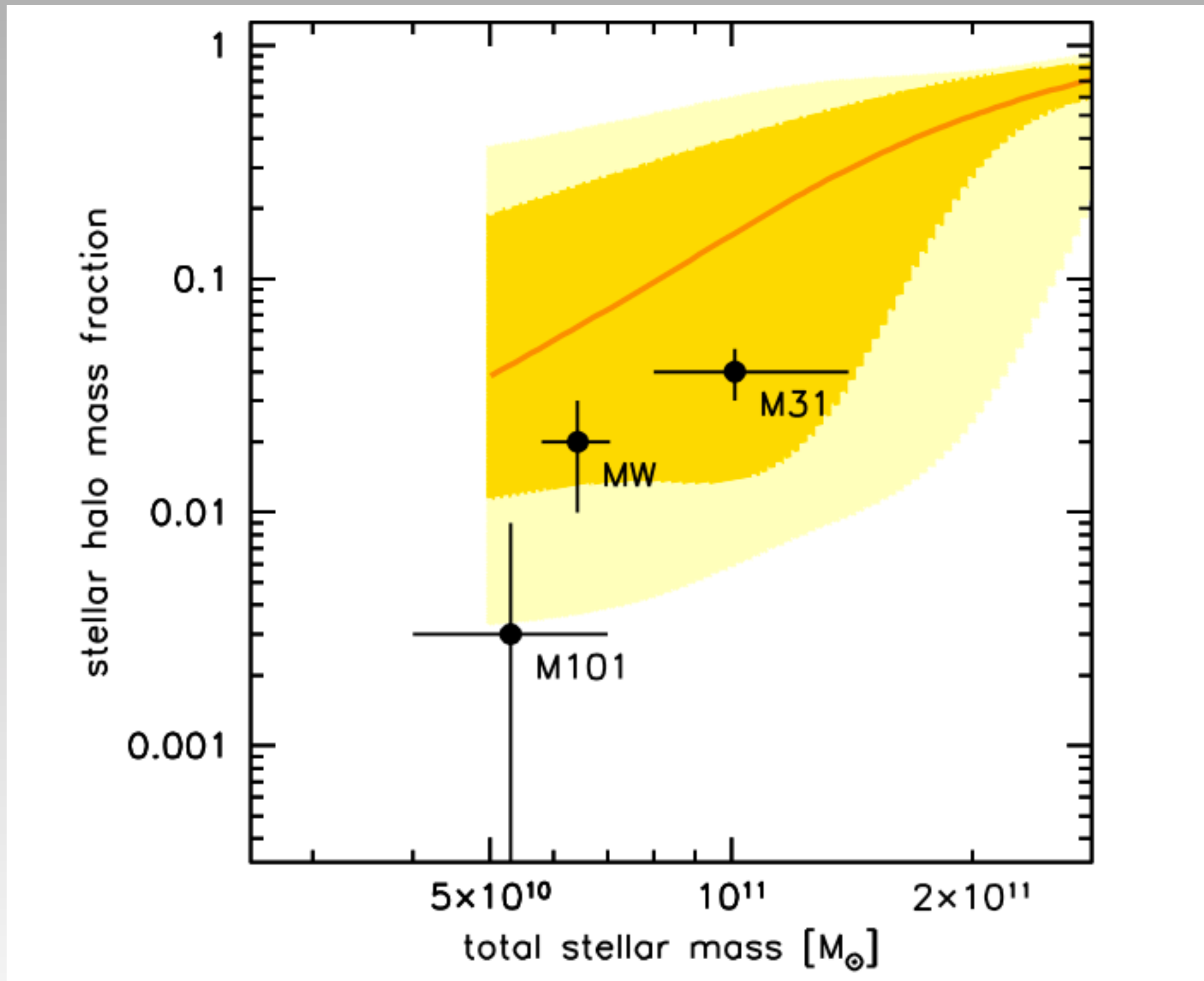
Systematics no longer set a limit on integration time…



PIs: Roberto Abraham (UT)
Pieter van Dokkum (Yale University)


NGC7626 Group (20 min)
DRAGONFLY
No SWC Coatings

Halo Mass Fraction



van Dokkum+14: DRAGONFLY

Wish list (Obs.)

- **General:** must determine biases and applicability of structural parameters (V_{rot}, σ, $R_{23.5}$, accurate D, …) Measure V(r) and σ(r) as <u>deeply and homogeneously</u> as possible.

- BTF/FP analysis for <u>*tens of thousands*</u> of LTGs and ETGs: need *deep* dynamics (V, σ), PNe, GCs, lensing, X-ray maps, multi-wavelength imaging, gas fractions E.g. Atlas3D, ALFALFA, CALIFA, MaNGA, SAMI, SLACS, SLUGGS, **SHIVir**, … (bias on dynamics)

- **VL/RL/LF** analysis for LTGs/ETGs: must constrain stellar population models, metallicities, IMF and AC. *Slope, zero-point and scatter of scaling relations must be matched <u>simultaneously</u>:* Dutton+11; Papastergis+11; Trujillo-Gomez+11; Reyes+12

Key Science Questions

1. How was angular momentum distributed among baryonic and non-baryonic components as the galaxy formed?
2. How do various mass components assemble and influence one another? Must understand AC and feedback (SN + AGN) and baryons/DM cross-talk: **need M^*/M_{tot} vs R!**
3. How does gas accretion drive the growth of galaxies?
4. What are the relative roles of stellar accretion, minor and major mergers, and instabilities in forming galactic bulges and ellipticals?
5. What quenches star formation? What external forces affect star formation in groups and clusters?

Time for Questions?