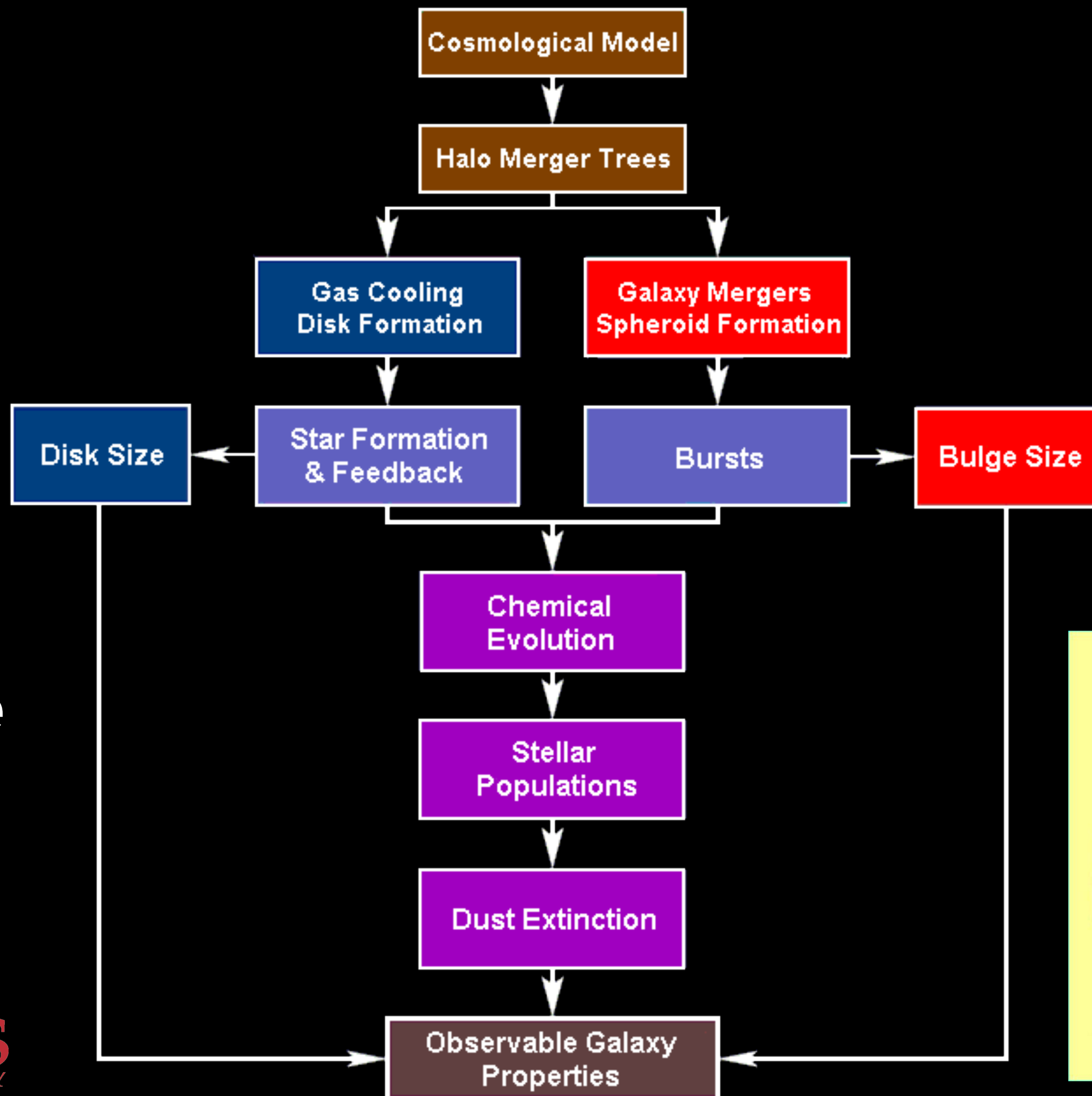
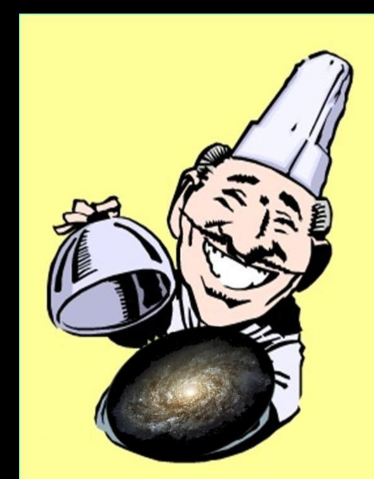
SCALING RELATIONS OF DISK GALAXIES

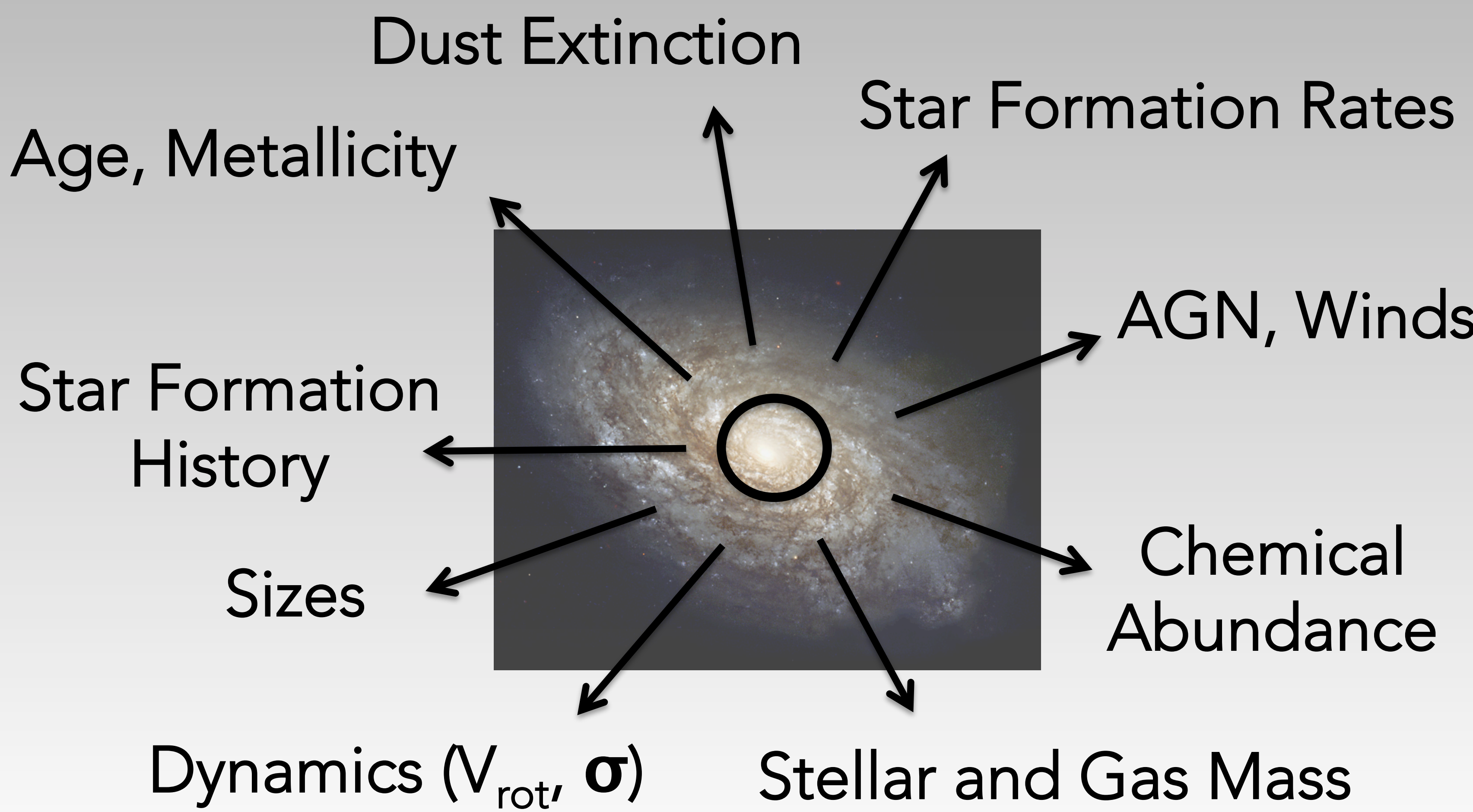


Stéphane
Courteau

Queen's
UNIVERSITY



Modern (SDSS) Structural Parameters and Relations



"Basic" Galaxy Scaling Relations with Dynamics

- Size (R), Velocity (V), Luminosity (L), Colour / Stellar Mass
- Velocity – Luminosity (VL) relation (aka Tully-Fisher Relation, or TFR)
- Size-Luminosity (RL)
- Size-Velocity (RV)
- Luminosity, Velocity/Mass Functions (SHMR) (predicted by ΛCDM)

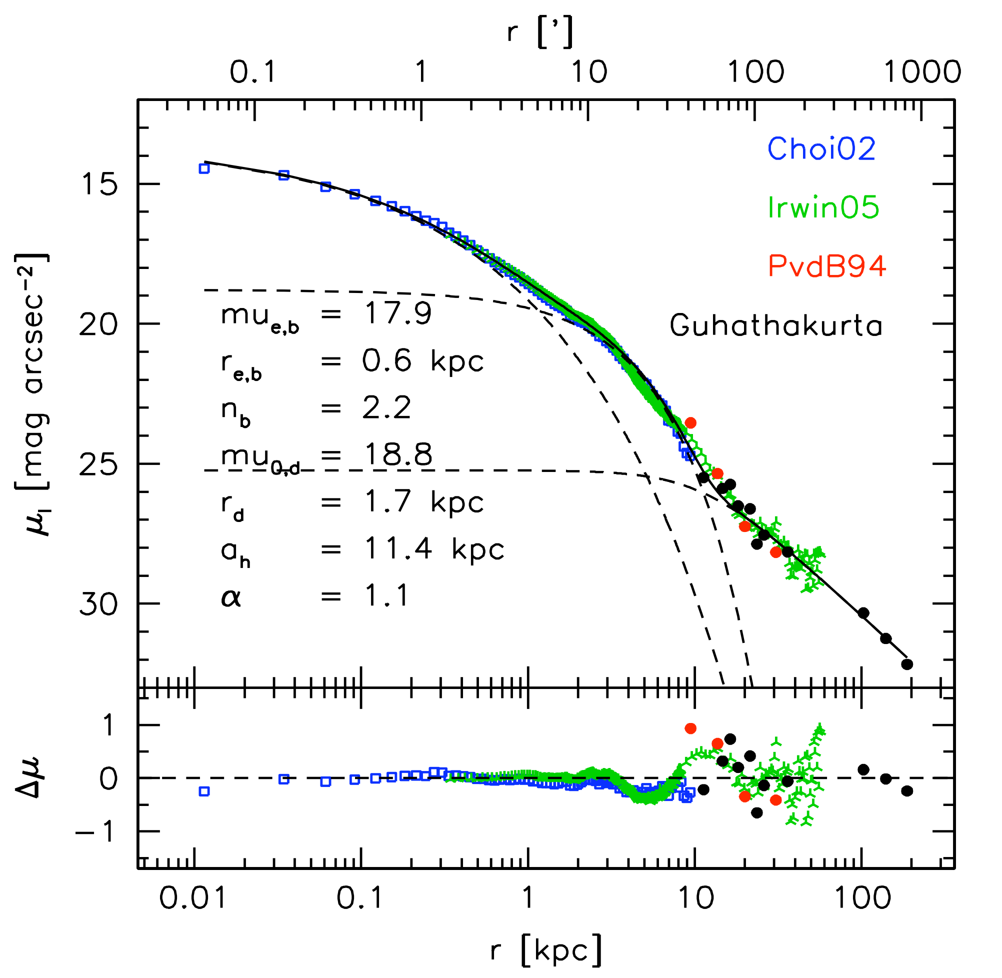
must skip stellar pops, metallicity, outer profiles, environment, … *See vdKruit & Freeman (2011)*

CAVEATS: B/D decompositions

E.g. with M31

Courteau+11

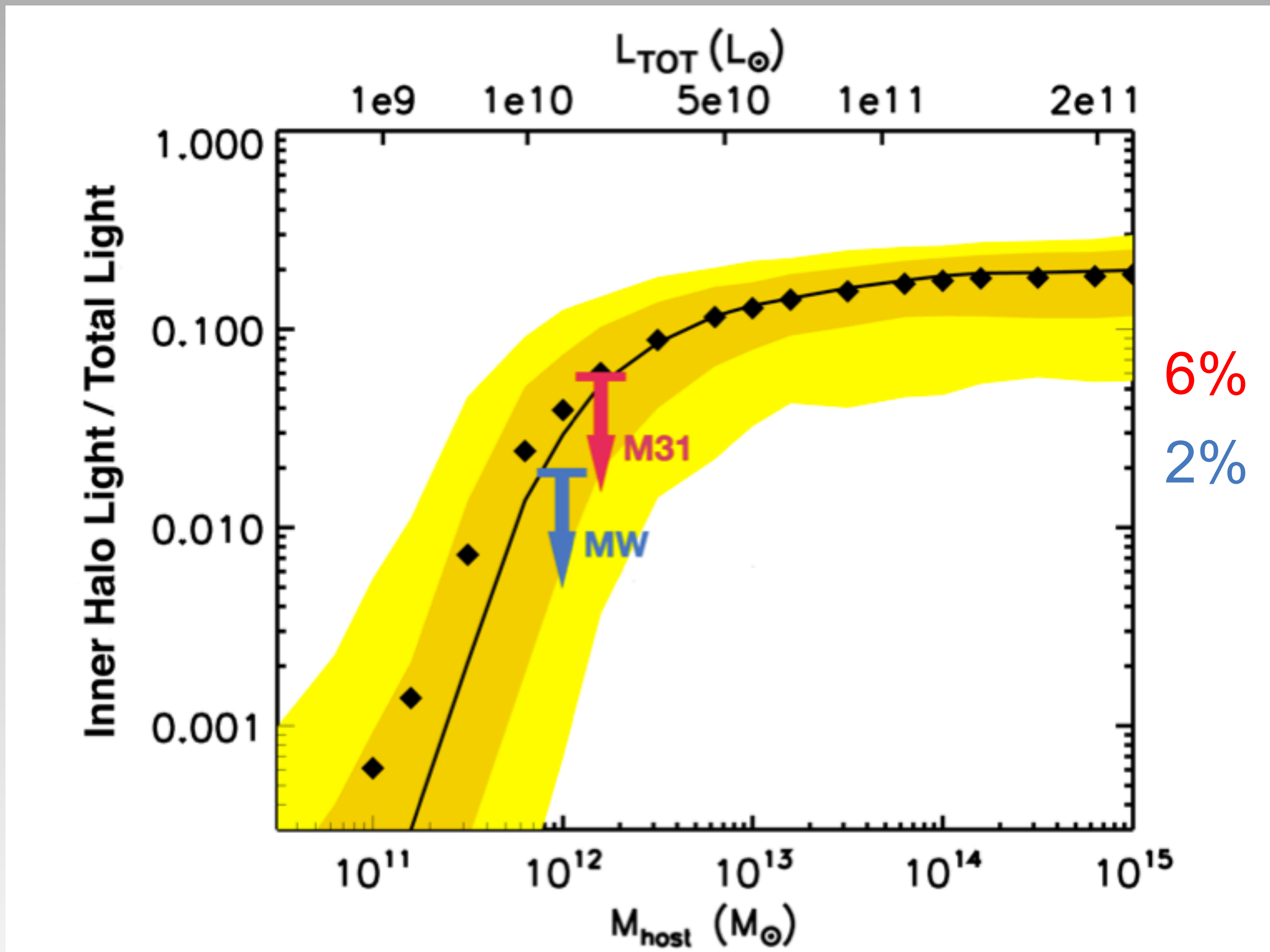
Spectroscopic evidence: Saglia+11, Dorman+13



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

CAVEATS: B/D decompositions

- B/D decompositions: de Jong 1996 series – spectacular!
- Byun+94 (ApJ, 432, 114: Dust Opacity in Spiral Galaxies)
  Byun+95 (ApJ, 448, 563: 2D B/D Decompositions)
- Sersic model fine for ETGs: for LTGs, careful about ill-motivated bells and whistles (esp. w/ monochromatic data). At the very least, do B/D decomp with multi-band data
- 1D/2D B/D decomps, I(R), should NOT be attempted for edge-on galaxies ➔ I(z); also problems with Freeman Type II, dust, …
- Use non-parametric estimates (from isophotal fits)
- Need spectroscopy (~IFU) to properly separate structural components (e.g. ATLAS3D, CALIFA, MaNGA)

- IMAGING (LIGHT WEIGHTED) and SPECTRA (MASS WEIGHTED) MAY TELL YOU ORTHOGONAL PICTURES:

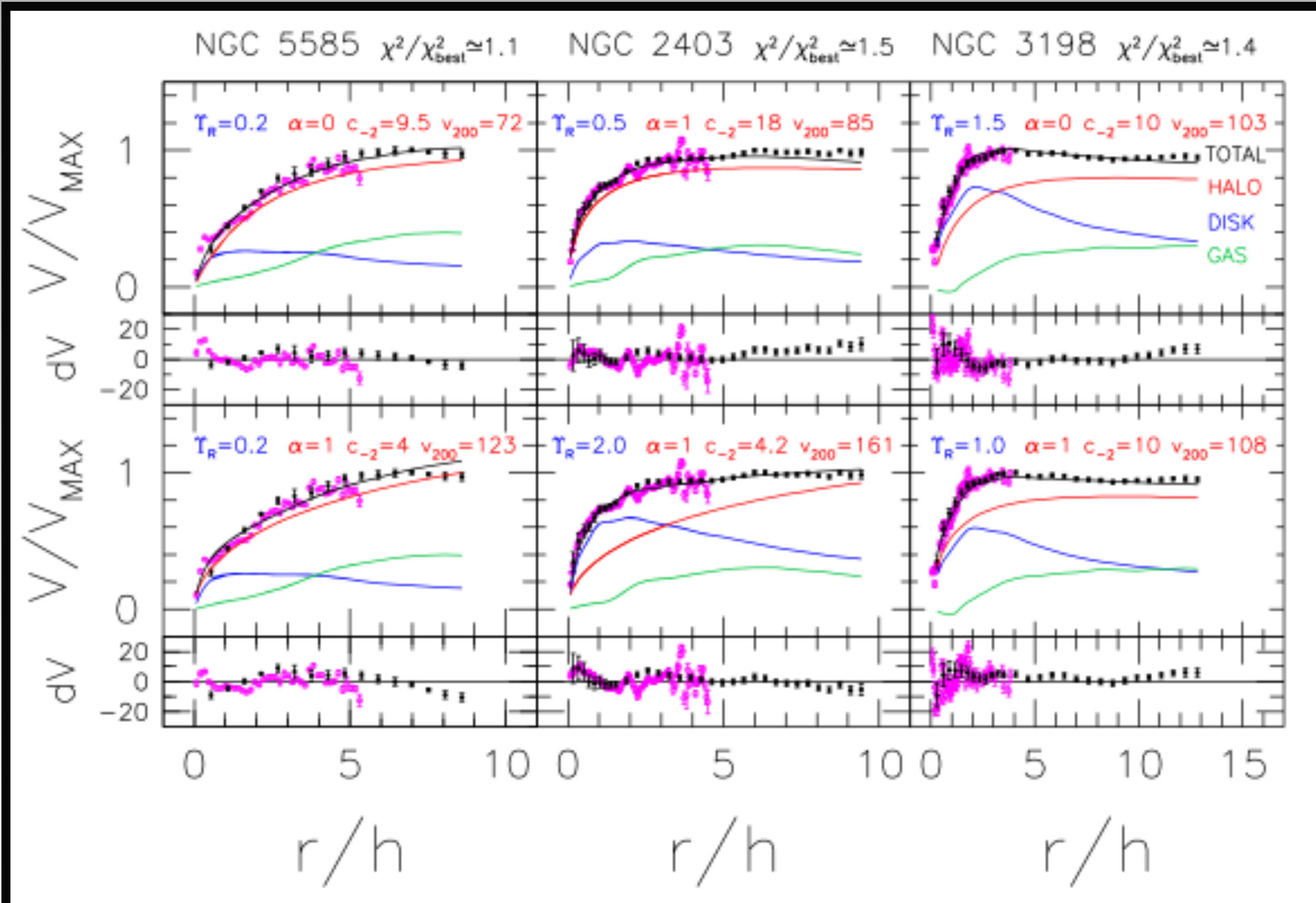
MacArthur+09: Light vs Mass Weighted

- Need moderate spectral resolution, good λ coverage, and high S/N/Å (>50), measurement of light- and mass-weighted ages, metallicities, & dust for late-type galaxies is feasible with full spectrum fitting
- Details are critical: calibration (flux & λ), resolution, velocity dispersion, & rotation must be treated self-consistently (within data & models)
- Bulges follow similar trends to ellipticals in age/Z *at a given mass* (also true at $0.1 < z < 1$; see MacArthur etal. 2008, ApJ 680, 70)
- All bulges are dominated by OLD stellar pops (>~80% by mass)
- Secular contribution increases in weight with decreasing σ_0
- Spheroid formation dominated by processes common to all spheroids, whether or not they currently reside in disks
- Dominant formation mechanism occurred on shorter timescales for more massive spheroids

See also Sánchez-Blázquez+11

CAVEATS: Mass Models (Dutton+05)

fixed M/L α = 1 (NFW) fixed c

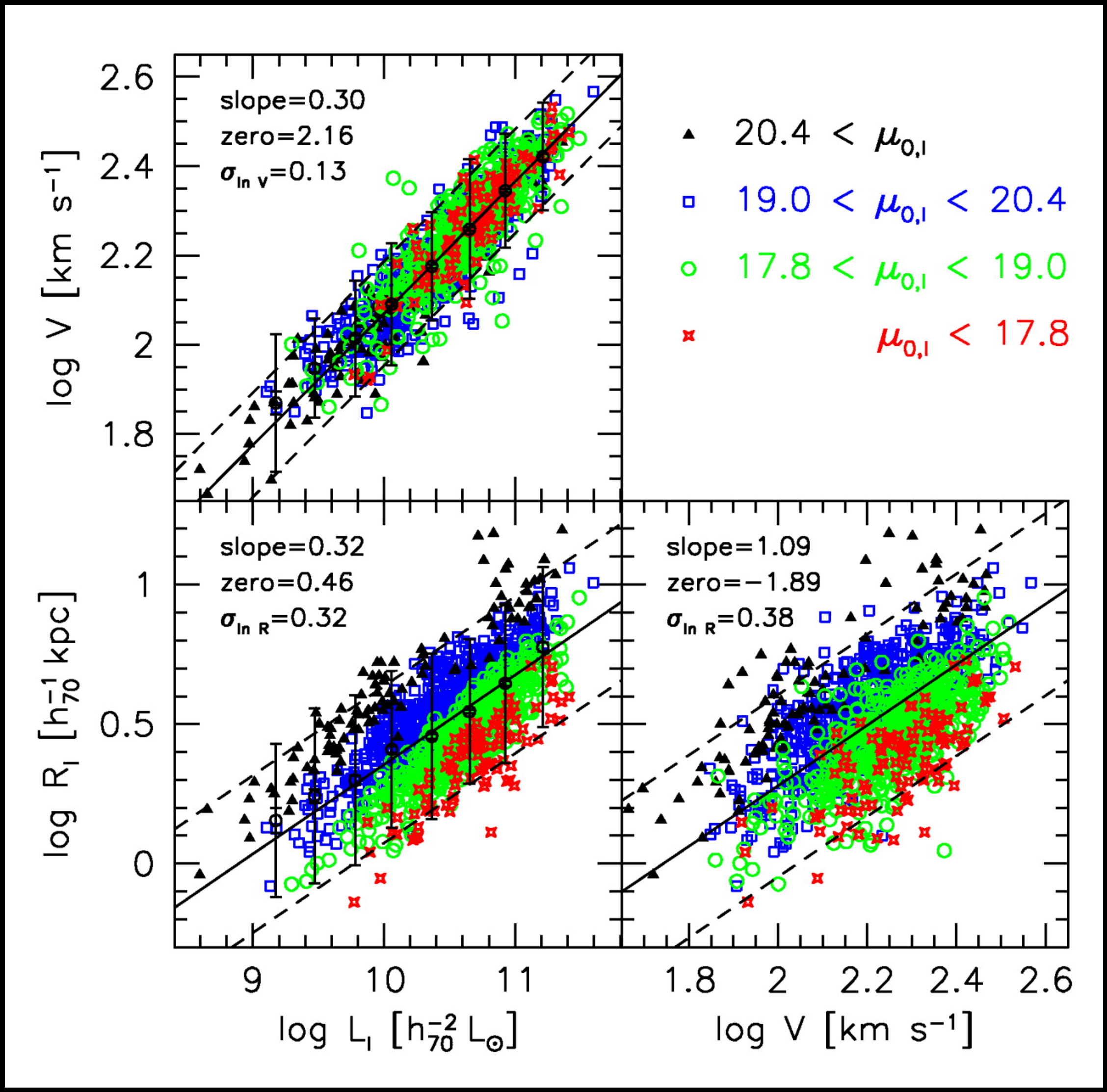


Galaxy Masses: Courteau+14 (RMP)

Global Disk Galaxy Scaling Relations

Tully & Fisher (1977)

$L \sim V^3$



Courteau+07;
also Hall+12

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

On the choice of scaling parameters

Hall et al (2012, MNRAS, 425, 2741)

"An Investigation of Sloan Digital Sky Survey imaging data and multiband scaling relations of (3041) spiral galaxies"

Compare SDSS DR7 Petrosian R and L with similar values from isophotal fits to the SDSS galaxy images.

Scatter degradation VL by ~8% and RV by ~30% with SDSS Petrosian parameters.

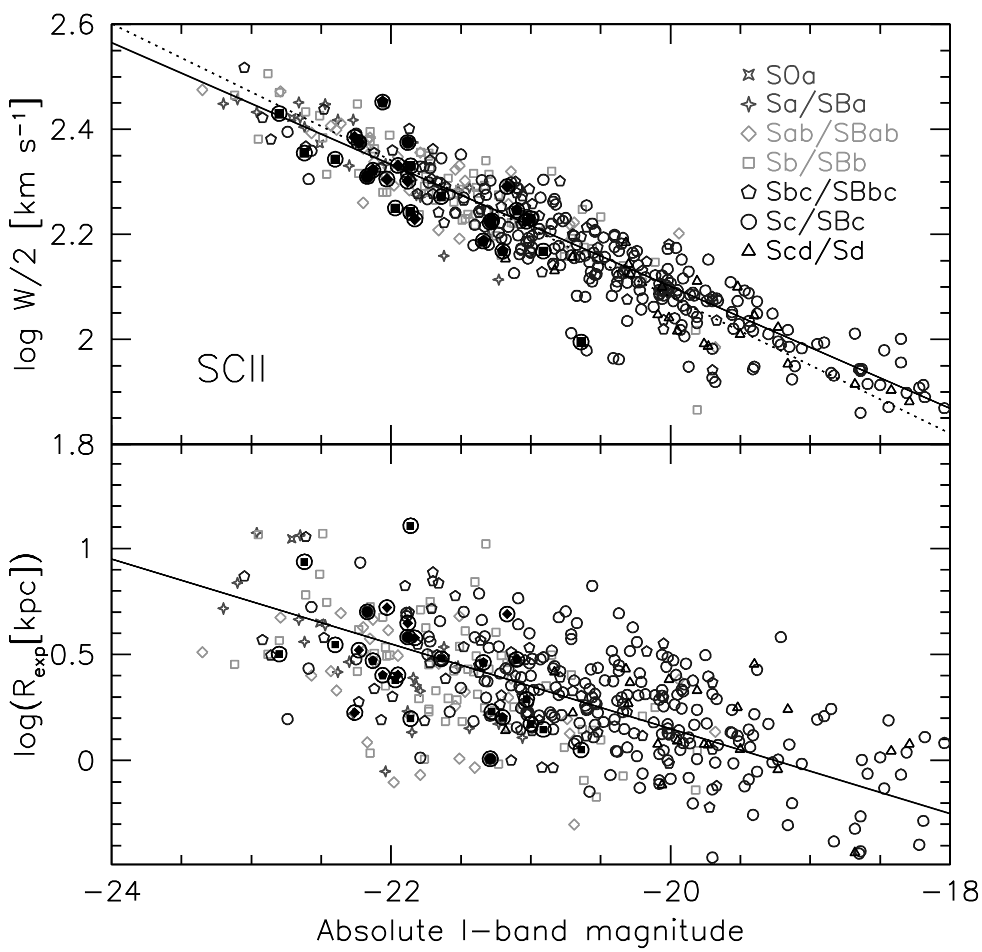
Largest (Baryonic) TFR to date: Hall et al (2012)

Ask me for the data.
Web site coming soon!

Galaxy Scaling Relations: TFR for Barred Galaxies

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

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

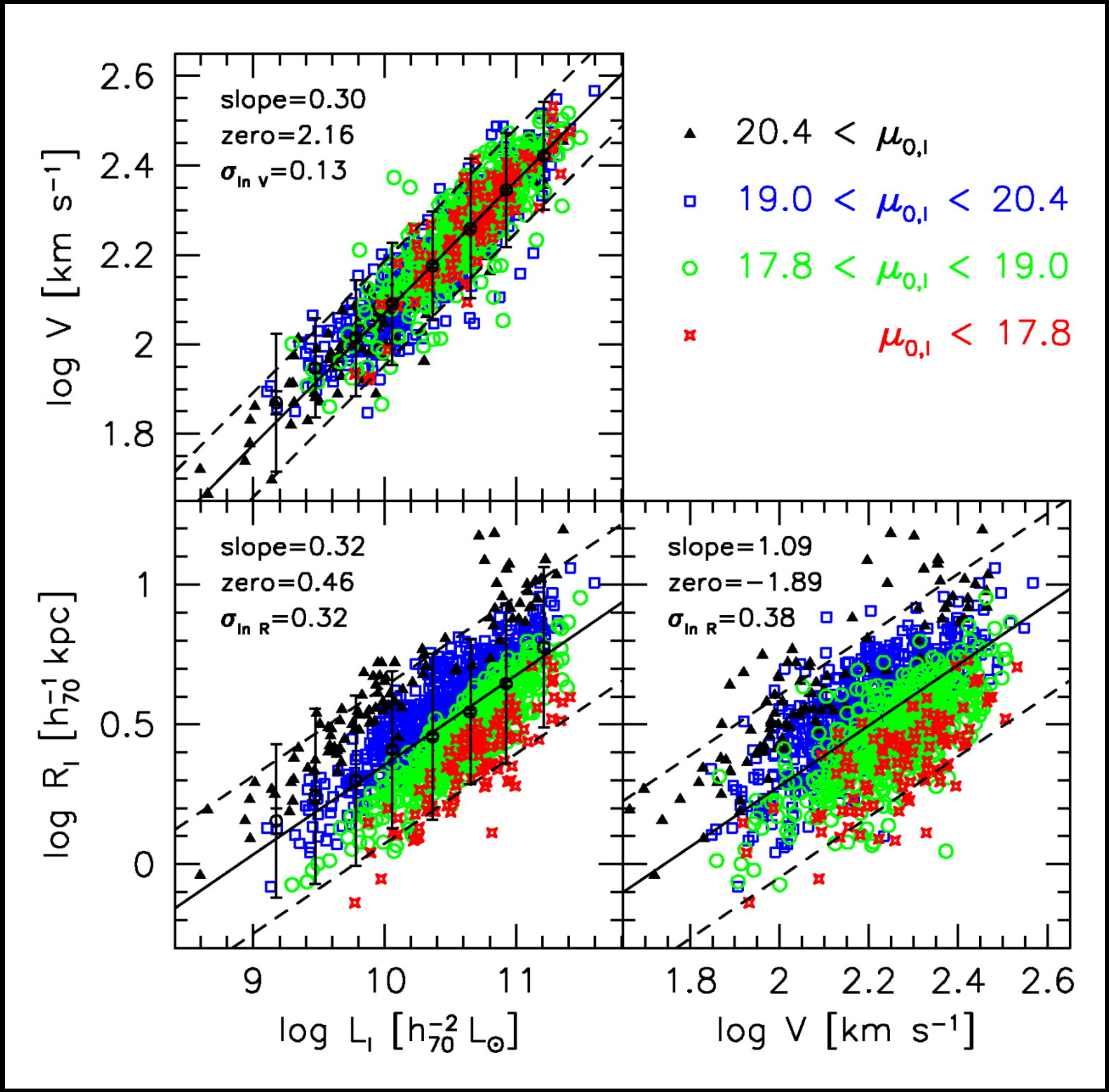


Courteau+03

Global Disk Galaxy Scaling Relations

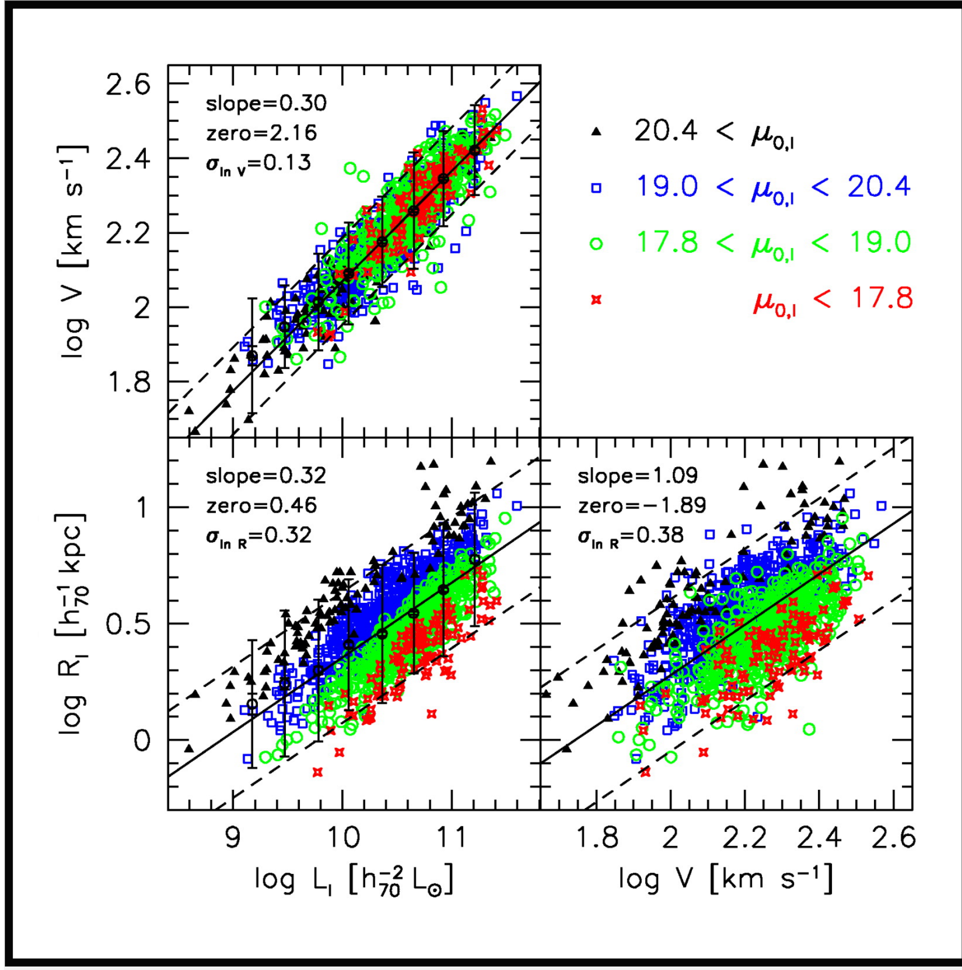
Tully & Fisher (1977)

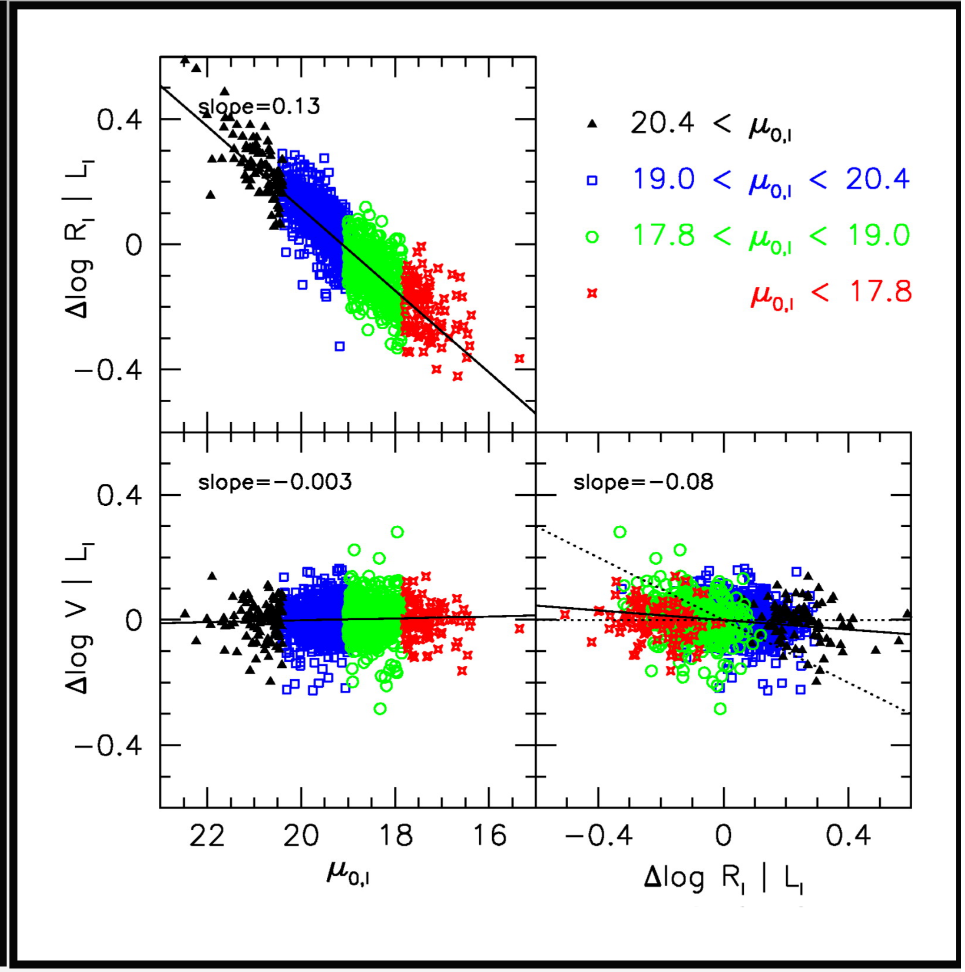
L~V3



Courteau+07;
also Hall+12

Galaxy scaling relations





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

Galaxy scaling relations

Pure Disk

Pure DM

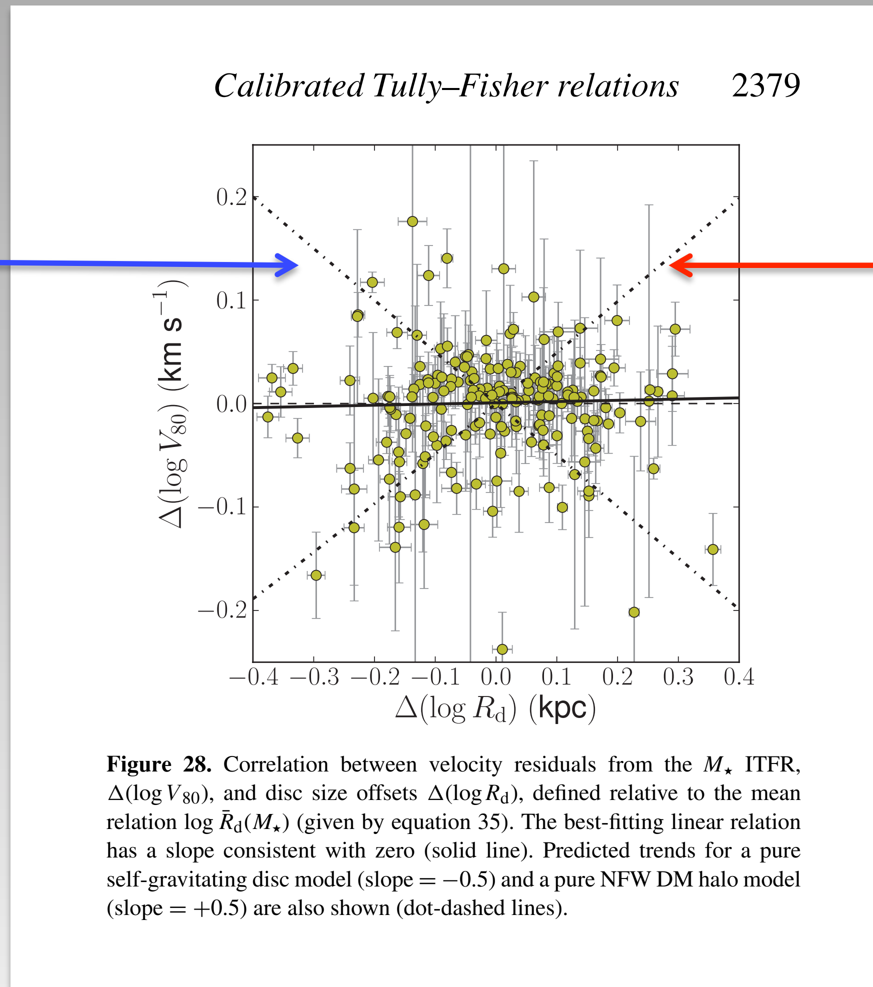

Calibrated Tully–Fisher relations 2379

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!

SAMs: Models against Data

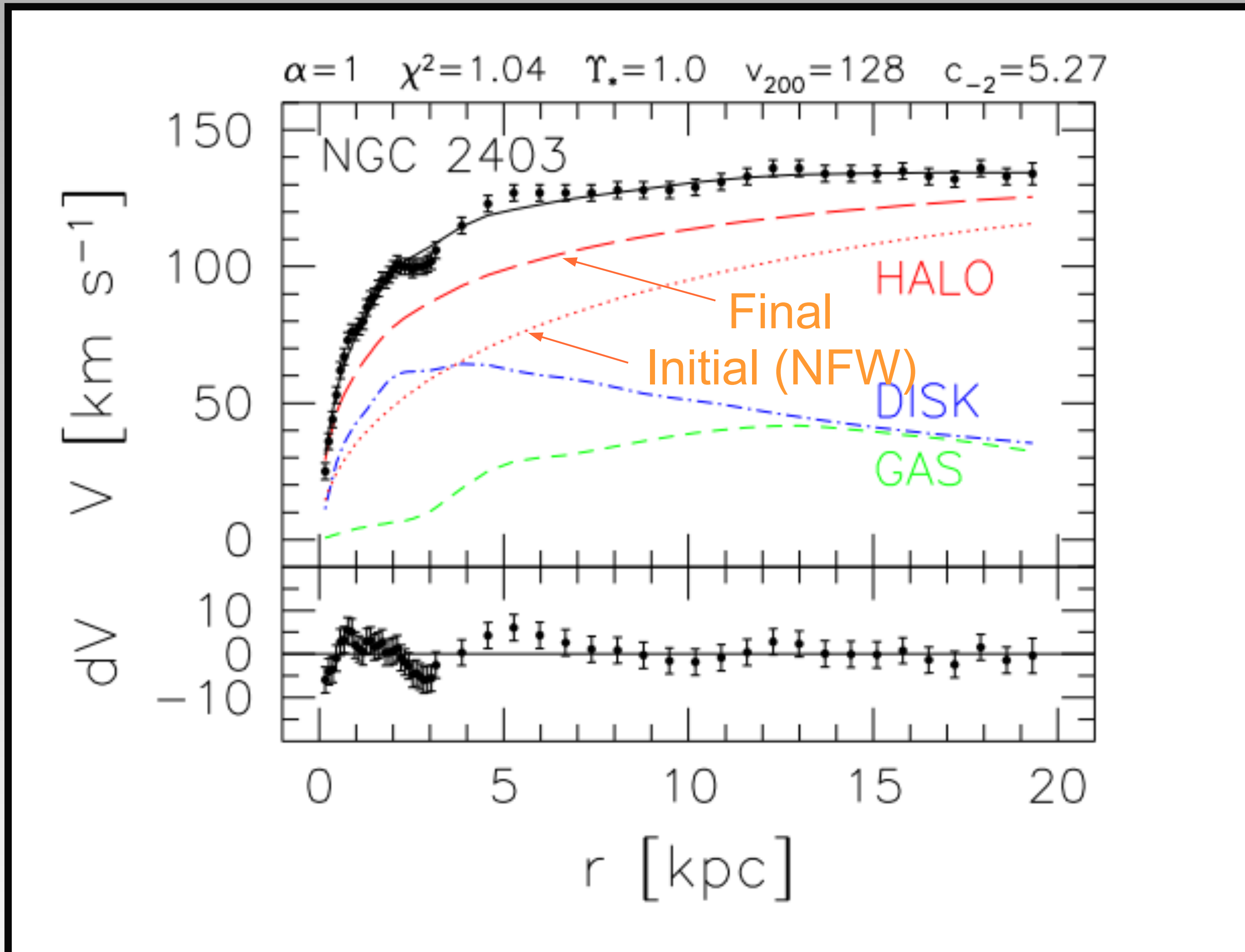
Courteau & Rix (1999)

- Simple exponential disk embedded in a DM halo
- Use density profile for collisionless ΛCDM simulations of halo formation (NFW)
- **Assume *adiabatic contraction***
- Use stellar disks of various M/L ratios and R_{exp} = 3 kpc, and compute the disk-halo contributions to the rotation curve
- Get $\partial \log(V_{2.2}) / \partial \log(R_{exp})$ for each value of V_{disk} / V_{tot}
- Test with bulge and isothermal halos

Dutton+07

- Include baryonic effects: feedback, self-regulating bulge for disk stability, generalised adiabatic contraction, SFR w/ threshold surface density, IMFs, etc.

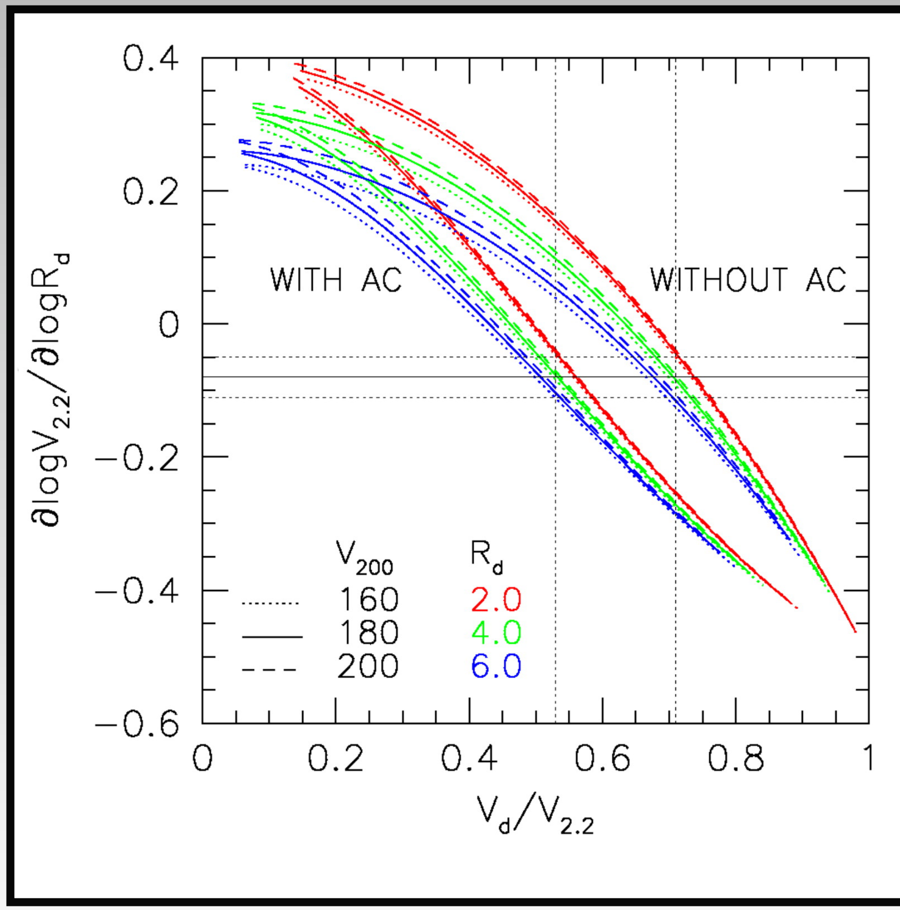
Caveat: adiabatic contraction



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

Comparison With Models

→ $V_{\mathbf{disk}} / V_{\mathbf{tot}} = 0.72 \pm 0.05$ 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 $2.2R_d$)

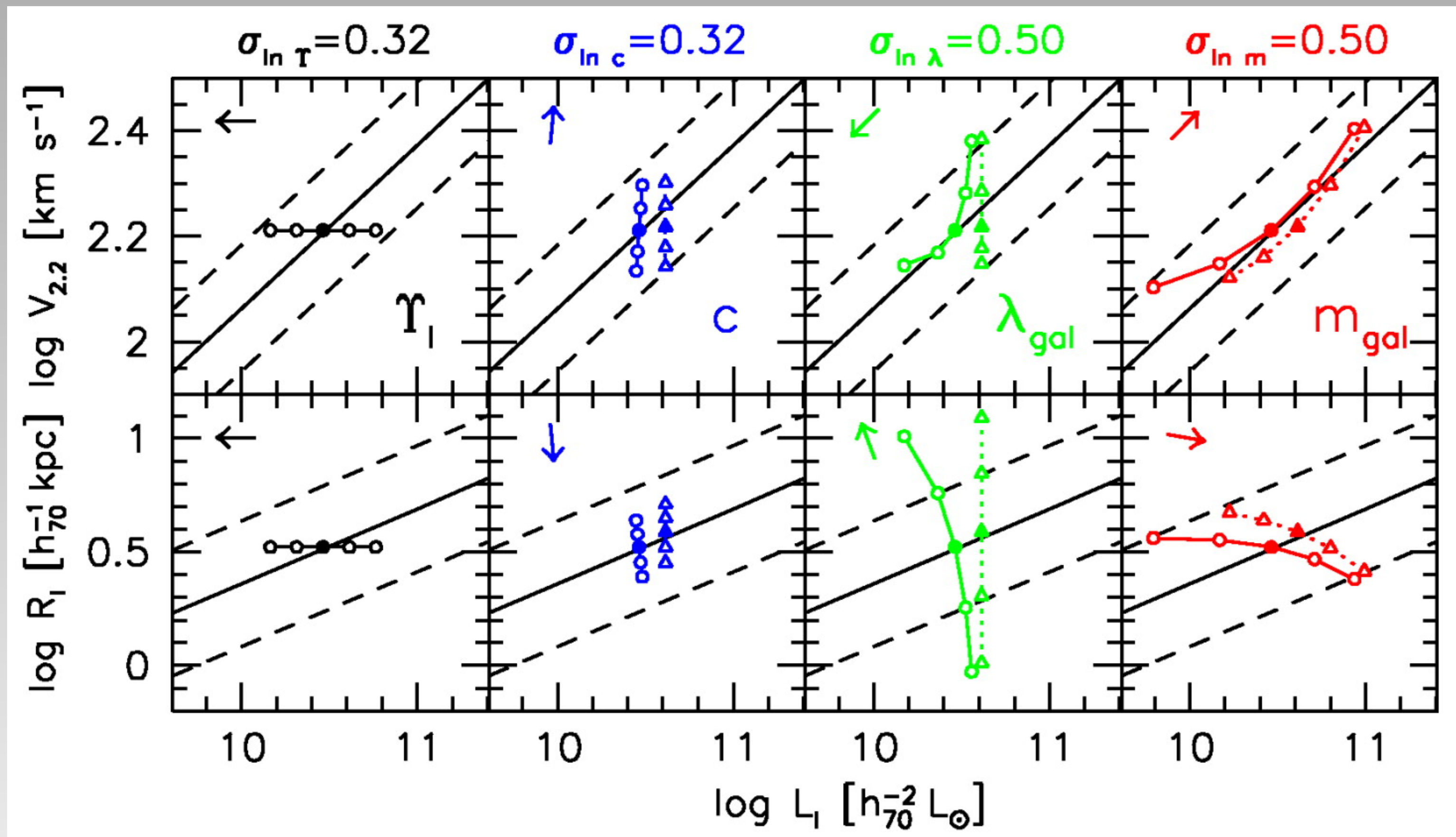
- Kuijken & Gilmore (1989): local stellar density
- Predicted by analytical models of galaxy formation (e.g., Mo et al. 1998; Dutton et al 2007) (Assumes AC)
- stellar kinematics of galactic disks Bottema (1997); DiskMass project (Bershady, Verheijen + 11)
- TF residuals: Courteau & Rix (1999); Dutton+07
- 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

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

(on average at 2.2 disk scale lengths)

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

Semi-Analytic Models of Disk Galaxies



λ = halo spin

c = halo conc.

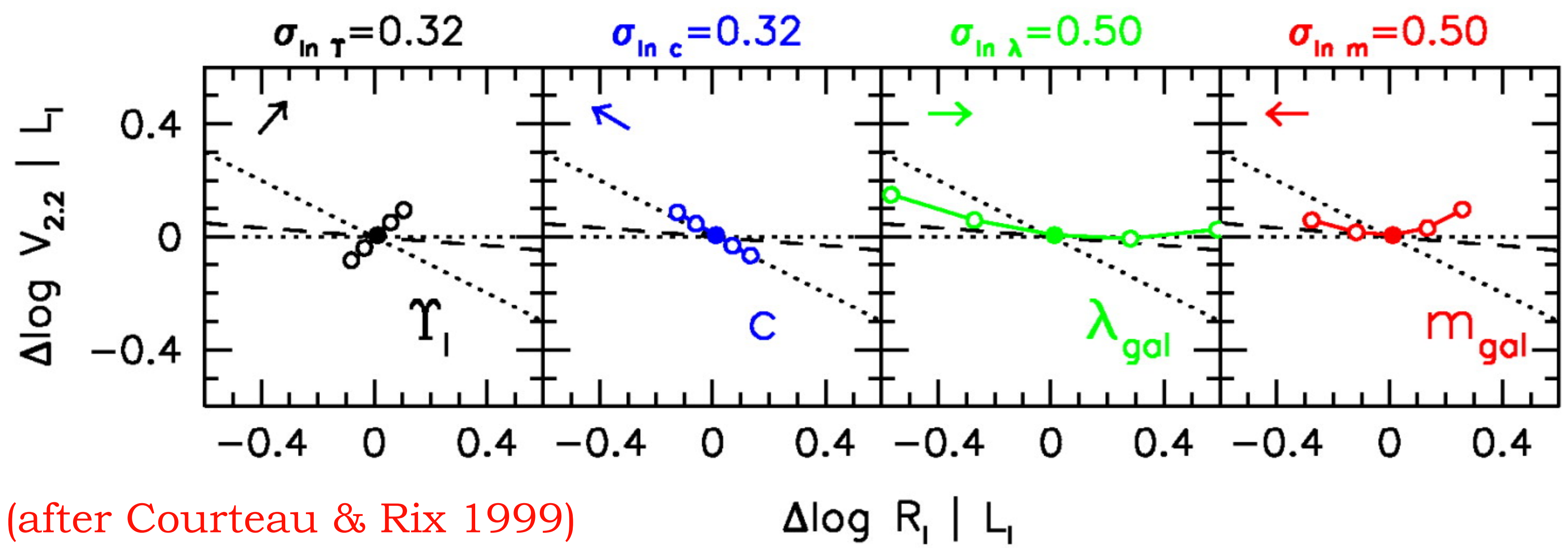
m_g = disk mass

Υ_I = disk M/L

Assumes log-normal scatter

Dutton et al 2007

Semi-Analytic Models of Disk Galaxies



λ = halo spin
c = halo conc.
m_g = disk mass
Υ_I = disk M/L
Assumes log-normal scatter

Dutton+07

Three problems for three solutions

- Lower stellar mass-to-light ratio

  But need an extreme top-heavy IMF, or maybe lots of dust. IMF likely universal on Galactic scales. But not on extragalactic scales?

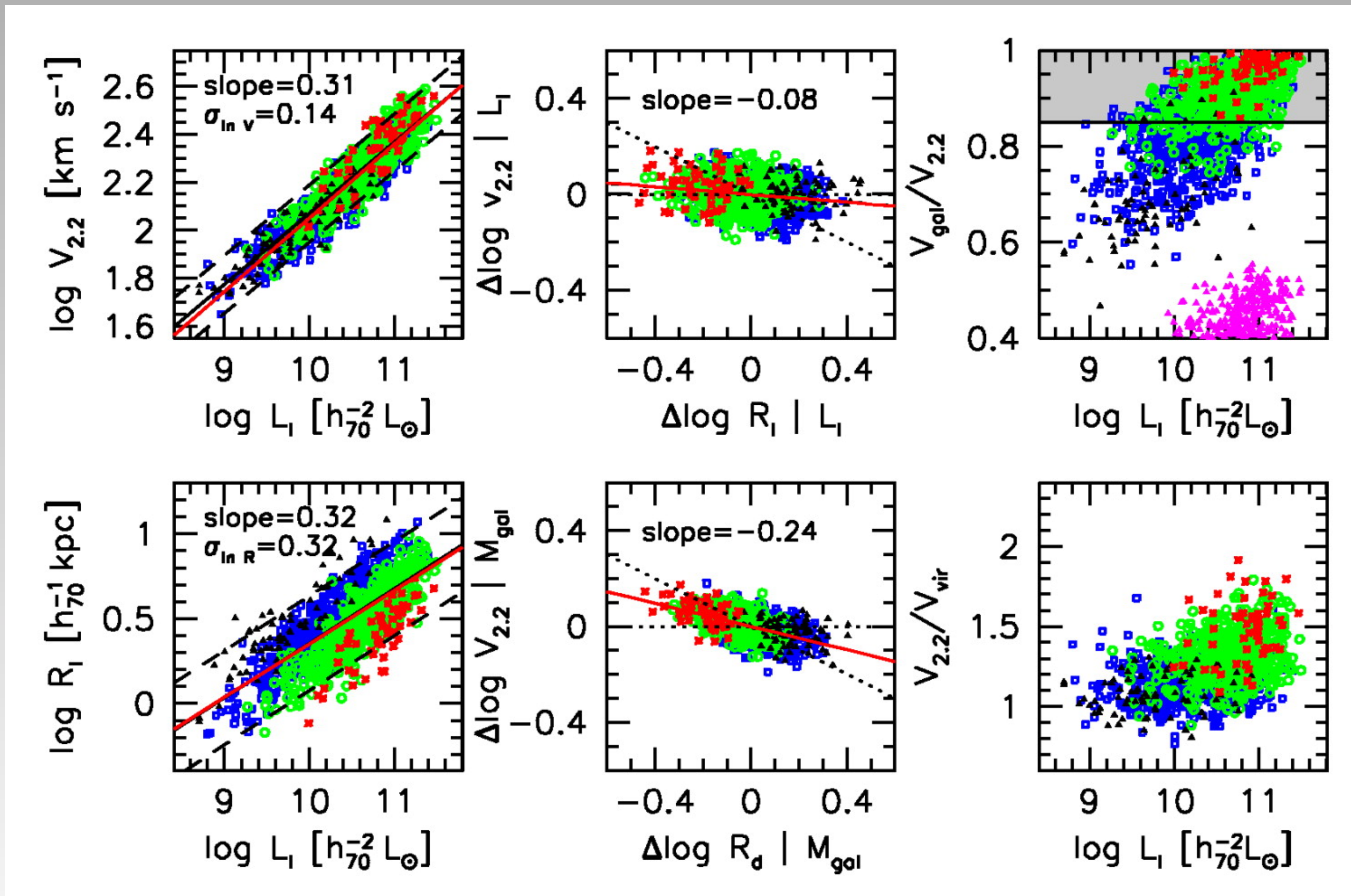
- Lower initial halo concentration

  need *uncontracted* $z=0$ $c_{200}\approx 3$, which seems inconsistent with ΛCDM (e.g. Gao etal 2008)

- Turn off halo contraction

  All fitting conditions are met if disk formation causes the DM halo to expand

Galaxy scaling relations



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

Reversing Halo Contraction is not so Crazy

For galaxies w/o a major merger, dark halo expansion due to:

- Feedback

  SN/stellar wind driven mass outflows

  (e.g., Navarro+96; Gnedin&Zhao 2000;
  Read & Gilmore 2005; Governato+10; Brook+12
  Pontzen & Governato 2012; DiCintio+13)

  Also explains the small fraction (~20%) of the universal baryons in galaxies.
- Angular Momentum Exchange:

  baryon clumps lose AM to halo through dynamical friction (bars, mergers)

  (e.g. Weinberg & Katz 2002; El Zant+04; Elmegreen+08)

Dutton et al. 2007, 2011

Dark halo response and the stellar IMF in early-type and late-type galaxies

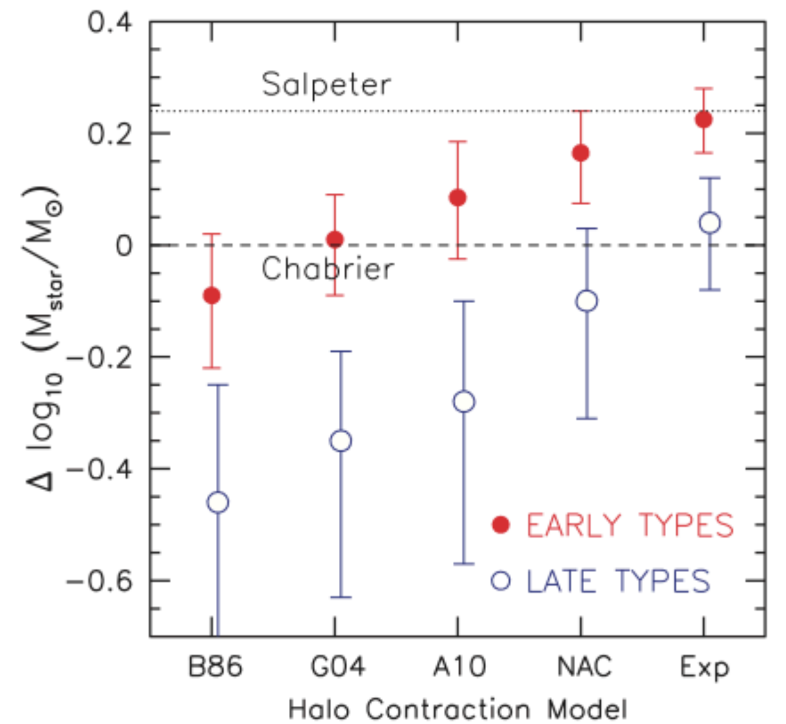


Figure 17. Offset in stellar masses required to match the zero-point of the VM relations as a function of halo response model, calculated at $\log_{10}(V_{opt}/\mathrm{km\,s^{-1}}) = 2.30$, for early-type (red filled symbols) and late-type (blue open symbols) galaxies. The models correspond to the following: 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

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

Dutton+10; Reyes+11

Dutton+11; $\rho \approx r^{-2}$

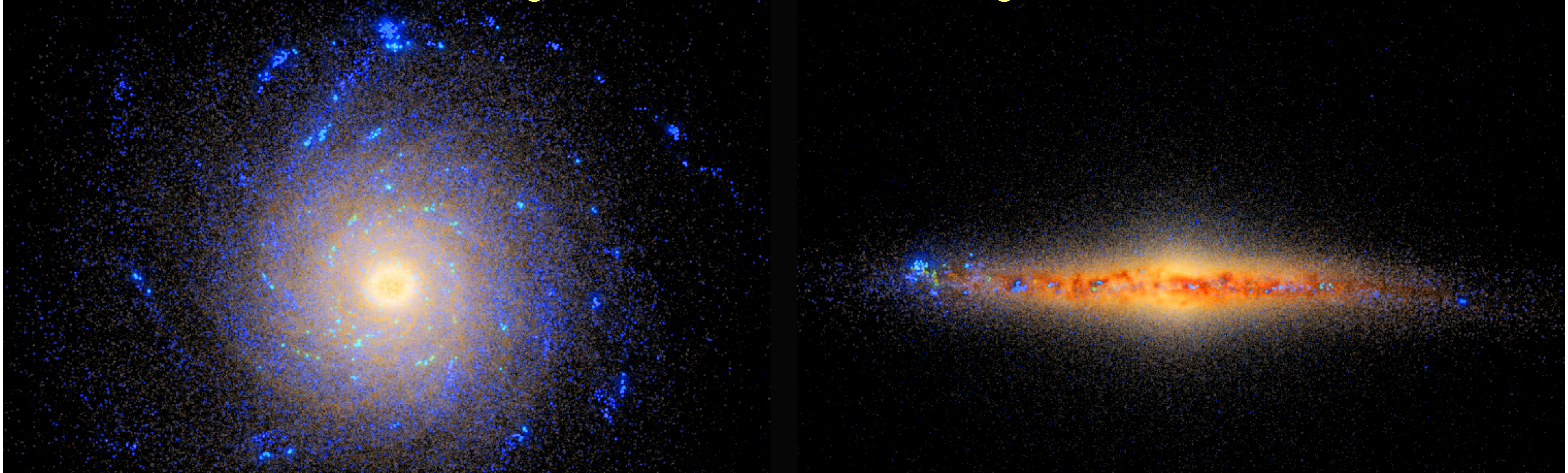
("B/D/H conspiracy", as also found by Remus+13)

Dutton+11; see also Trujillo-Gomez+11

MaGICC* disks: matching observed galaxy relationships over a wide stellar mass range

(MNRAS, 2012, 424, 1275-1283)

* Making Galaxies in a Cosmological Context



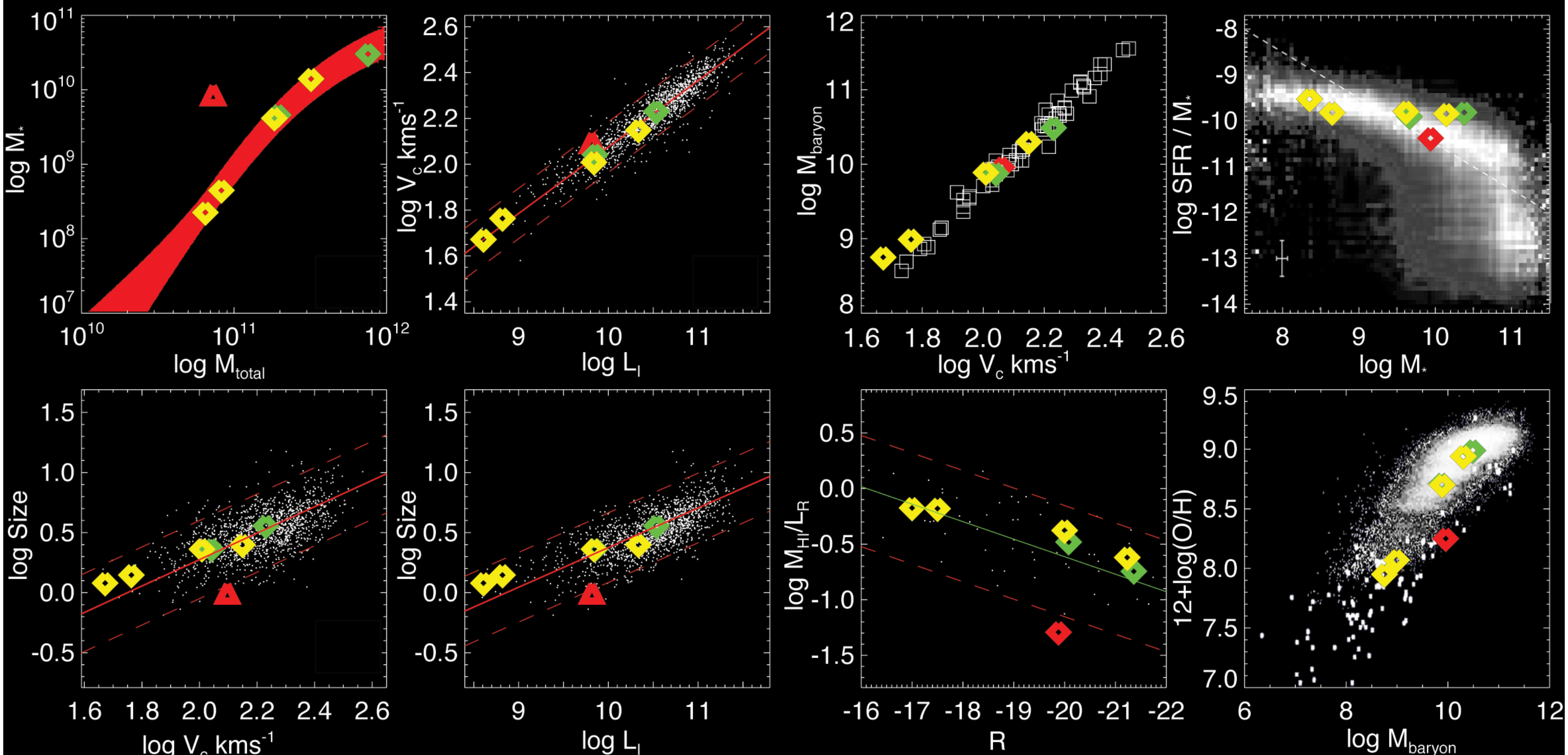
Chris Brook

Universidad Autonoma de Madrid

with Greg Stinson, B.K. Gibson,

James Wadsley, Tom Quinn

Stellar-Mass, Halo-Mass
Size (S), Rotation Velocity (Vc), Luminosity (L), M_{HI},
Specific SFR, Colour, Mbaryons, Metallicity (log O/H)



same resolution
same physics
same feedback

low resolution
same physics
same feedback
C* adjusted

old feedback
Stinson et al 2010
Scannepieco et al. 2012

Data from
Courteau+07
McGaugh+05

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?
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?

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, **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

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