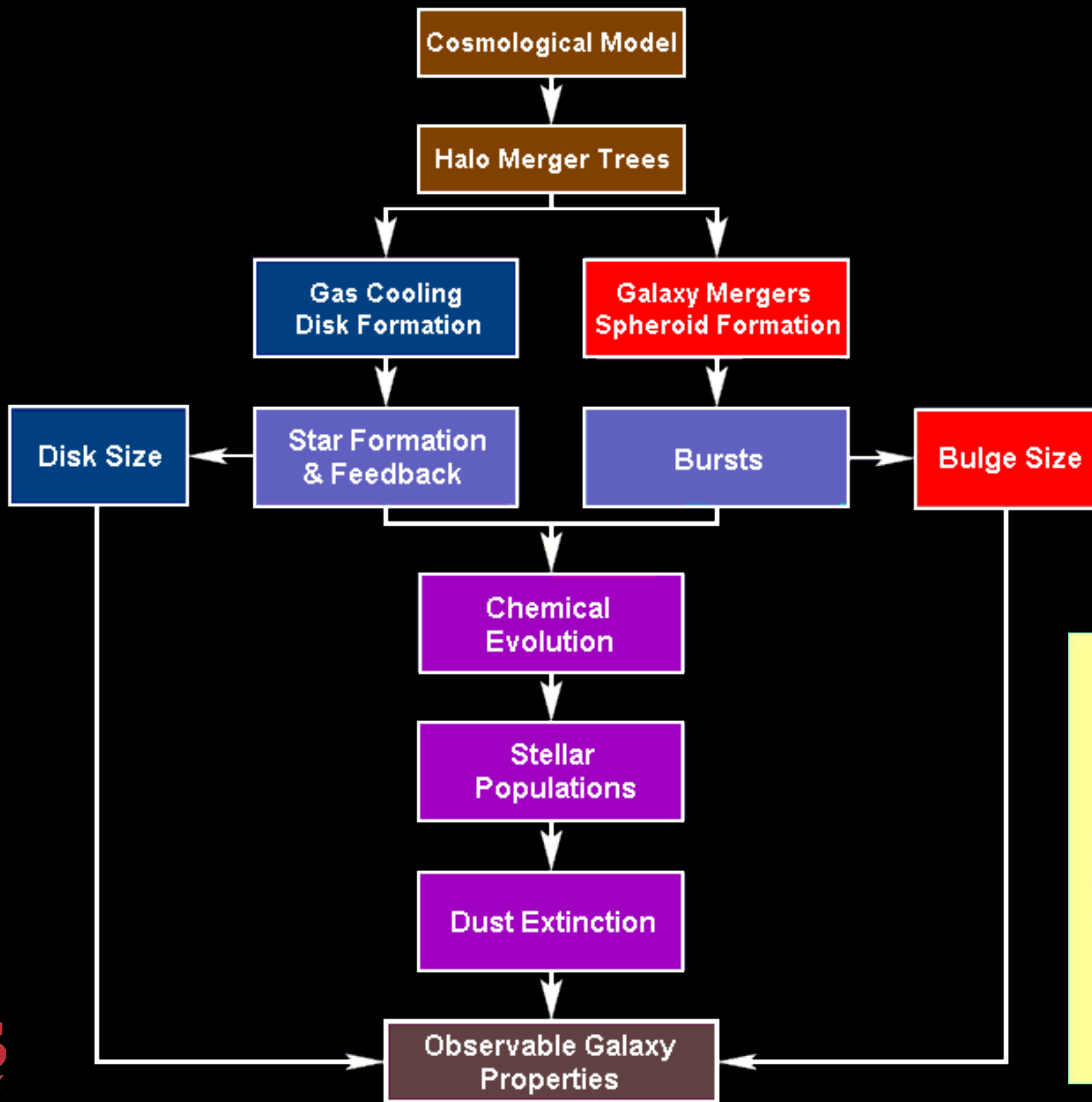
STÉPHANE COURTEAU

Puzzles in Galaxy Scaling Relations

Queen's University

SCALING RELATIONS OF DISK GALAXIES



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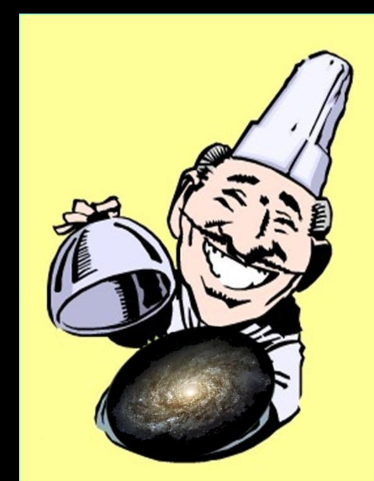
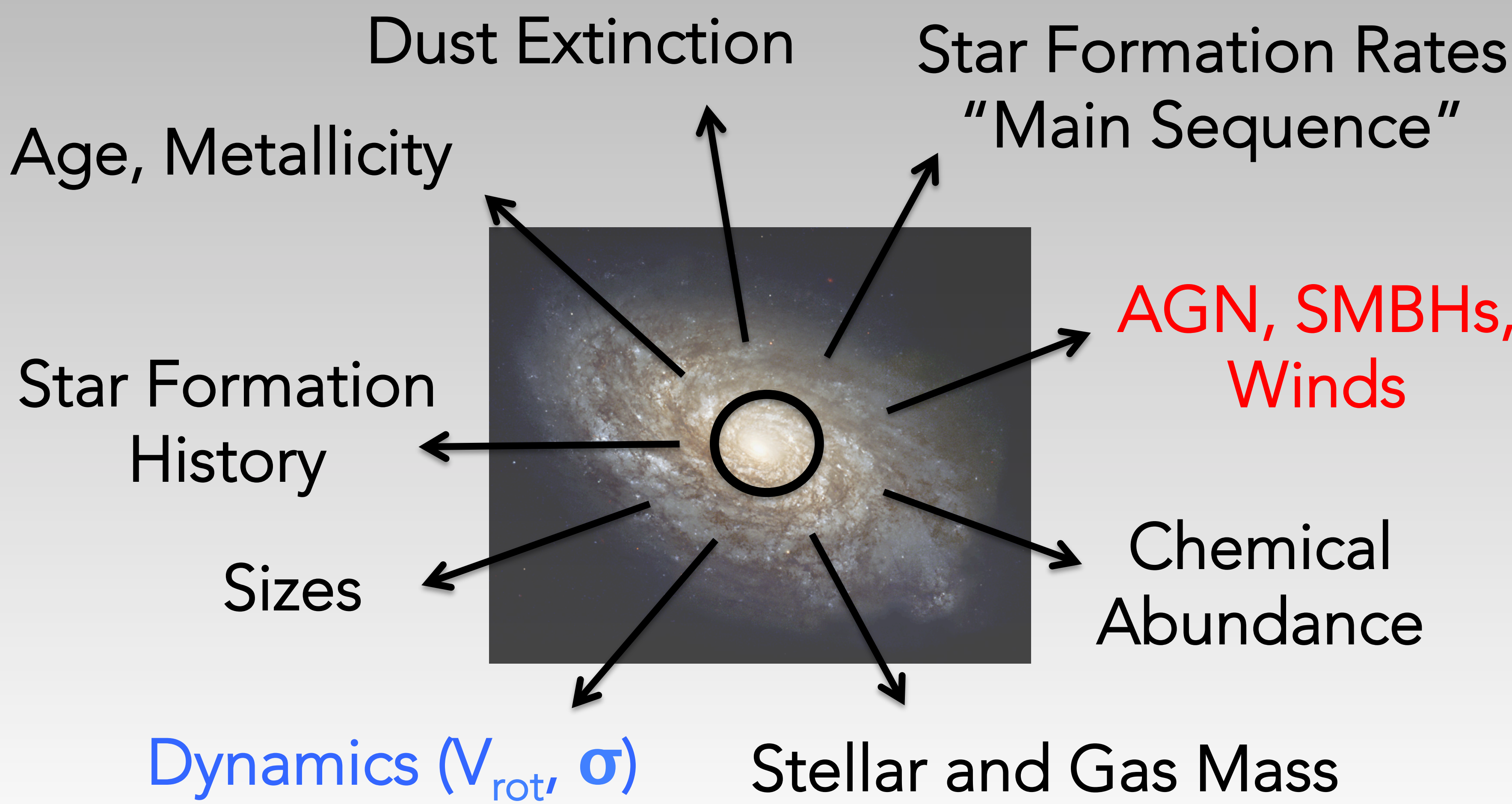


Modern Structural Parameters and Scaling Relations



“Basic” Properties of Disk Galaxies and Scaling Relations with Dynamics

- Size (R), Velocity (V), Luminosity (L), Colour / Stellar Mass
- Velocity – Luminosity (VL) relation (aka Tully-Fisher Relation, or [S/B]TFR)
- Size-Luminosity (RL)
- Size-Velocity (RV)
- Luminosity, ΛCDM Velocity/Mass Functions (Stellar-to-Halo Mass Relation: SHMR)

Use of (Disk) Scaling Relations

- Originally, TFRs used to determine galaxy distance for cosmic flow studies Tully & Fisher 1977; Courteau+93; Strauss & Willick 1995; Giovanelli+97; Masters+06; Springob+09
- TFRs assembled over broad range of types Courteau+03[bars]; Vogt+04[env.]; Courteau+07; Pizagno+07
  for testing galaxy formation models Navarro & Benz 1991; Dalcanton+97; MMW-99; Navarro & Steinmetz-00; Dutton+07; Gnedin+07; Avila-Reese+08; Governato+07,10; Brook+12; Aumer+13;
- Connecting ET and LT galaxies with their haloes through dynamics / velocity function (SHMR) Dutton+11; Trujillo-Gomez+11; Papastergis+11; Reyes+12; Hudson+15; Ouellette+16
- Evolution of Scaling Relations with time Ziegler+02; Barden04; Kassin+07; Trujillo+09; Dutton+11b; Miller+13; Tiley+16

Philosophy and methods

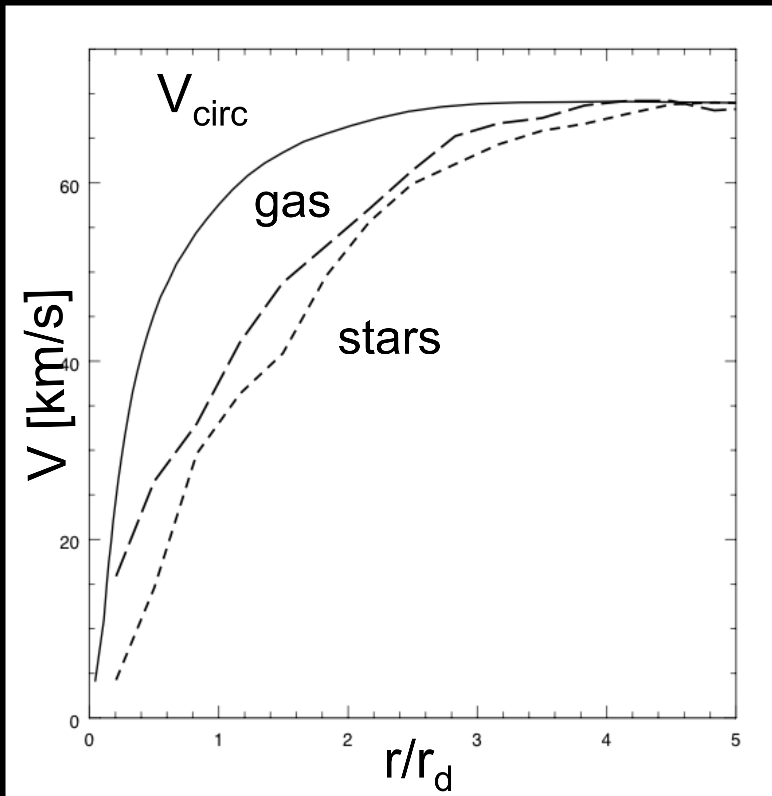
- Scaling relations philosophy: model slope, intercept, and scatter <u>and</u> fit all known scaling relations *simultaneously*

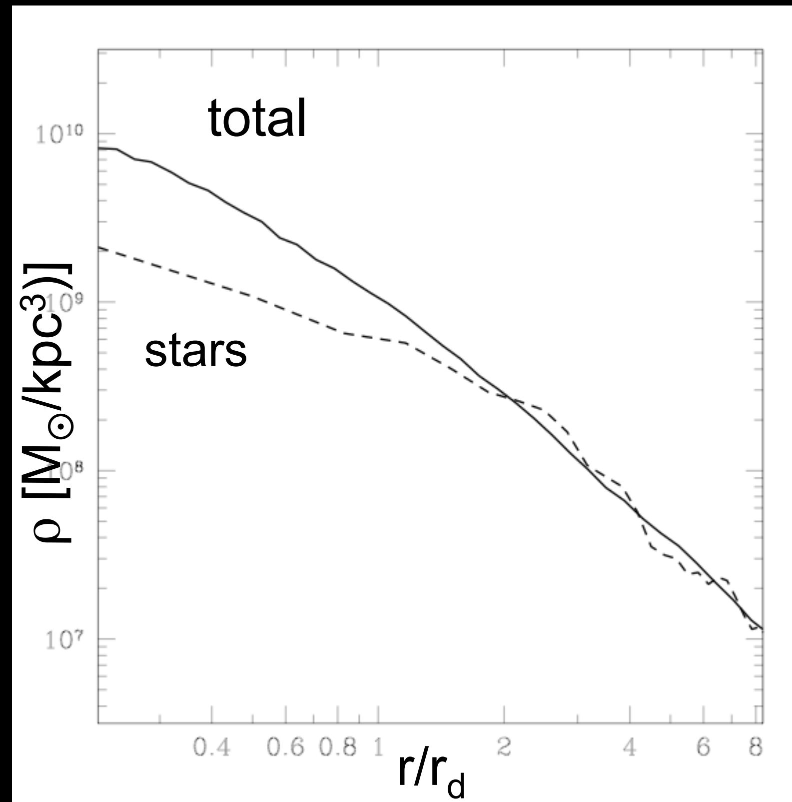
  Courteau+07; **Dutton**+07,11,13; Avila-Reese+08; Trujillo-Gomez+11; Reyes+11; **Brook**+12; Brook+14

- Scaling relations depend sensitively on the nature of the measurement: model fitting (bisector/orthogonal), selection bias, $W_{20,50,}$ $V_{2.2}$, $V_{flat,}$ R_d, $R_{23.5}$, SDSS/R_{pet}

  Courteau 1996,1997; Willick+99; Giovanelli+99; Courteau+03,07; Saintonge & Spekkens 2011; Hall+12; Bradford+16; Brook and Shankar 2016; Békeraité+16; Gilhuly+16

Choice of velocities





For $r>3r_d$, $V_{obs} \sim V_{circ}$

More relaxed constraint for higher V_{max}

Rhee et al 2004 ; Valenzuela et al 2007

Sellwood & Spekkens (2007) – non-circular motions

Defining Scale Parameters: Sizes and Scale Lengths

Radial profile breaks

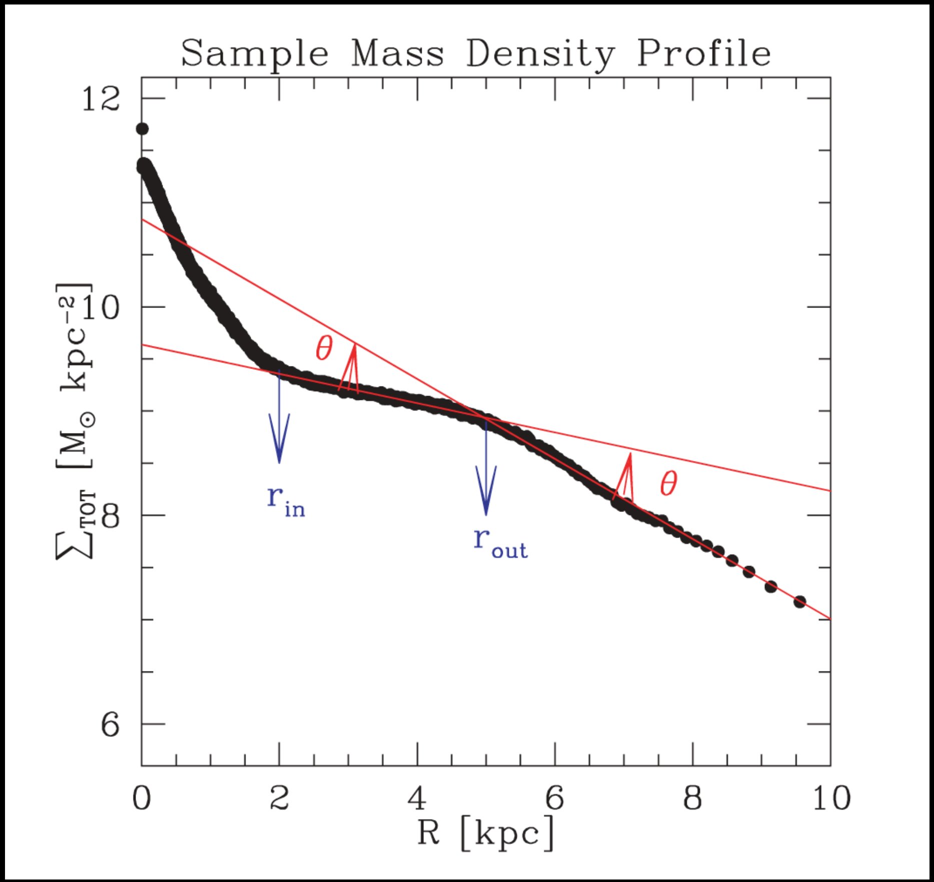
Pohlen&Trujillo+06; Debattista+06; **Foyle+08**; Roškar+08; Roediger+12

Problem for Freeman Type II disks: fit the inner (A4 > 0) or outer disk?

Use <u>non-parametric</u>:

R_e or $R_{23.5}$

(Colleen Gihuly's talk)

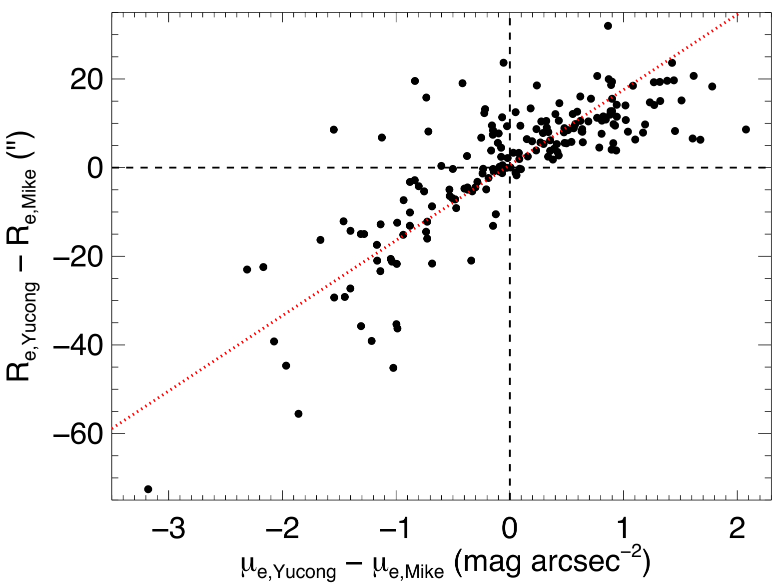


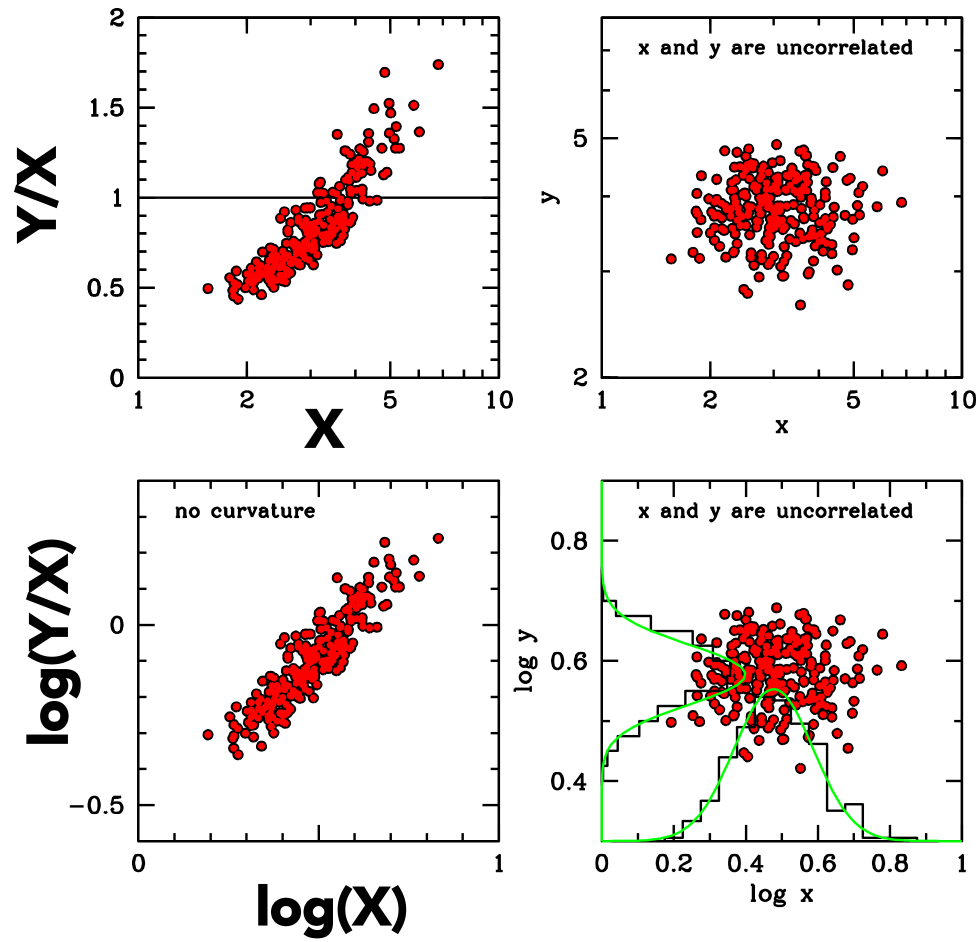
Foyle+08

Basic Parameter Uncertainties

Typical errors on:

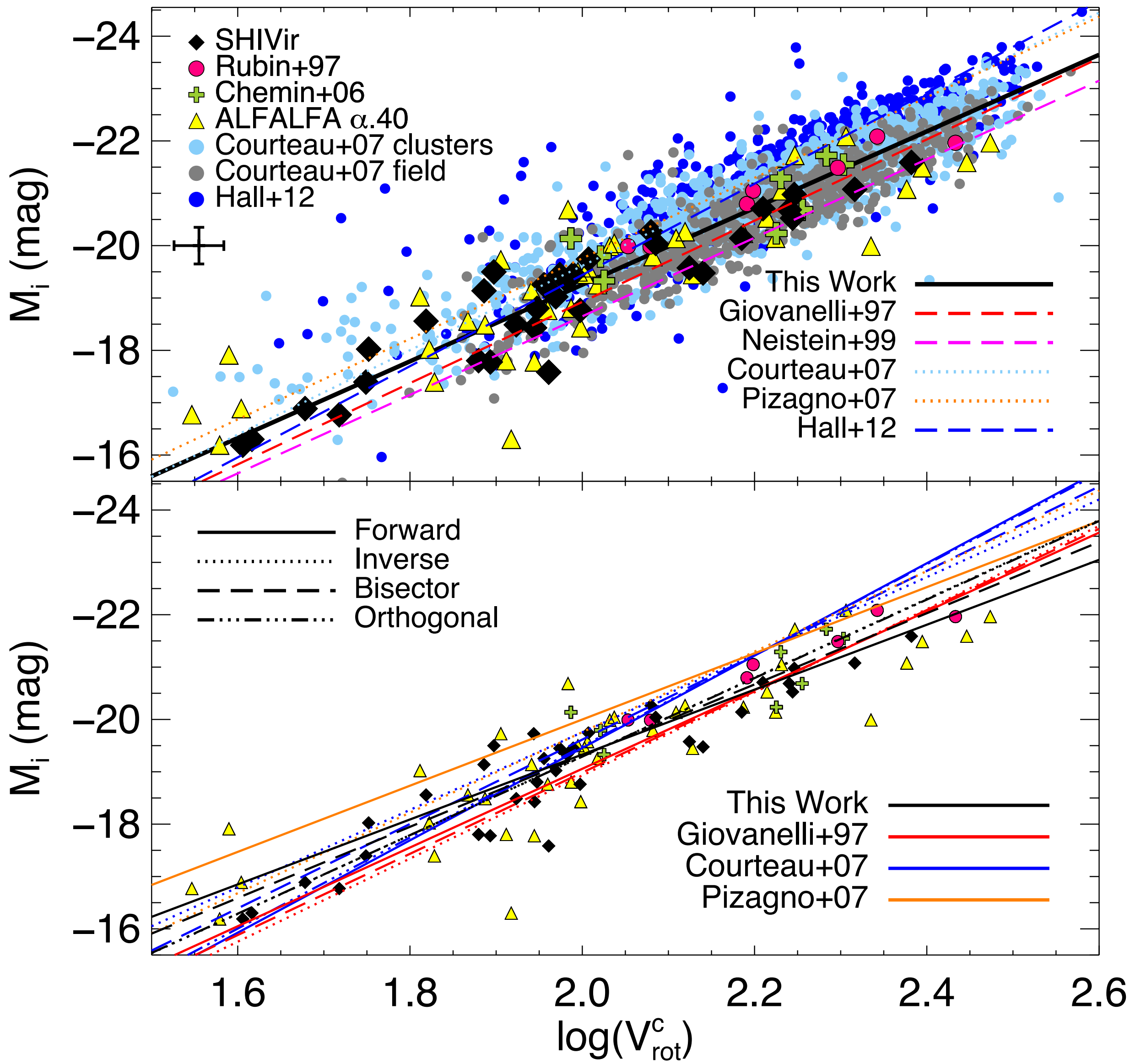
R_d, R_e ~ 15-20%
V_{circ},$\boldsymbol{\sigma}$ ~ 15%
C_{28} ~ 12%
SB_e ~ 5%





Random variables look correlated!

Disk Galaxy Scaling Relations

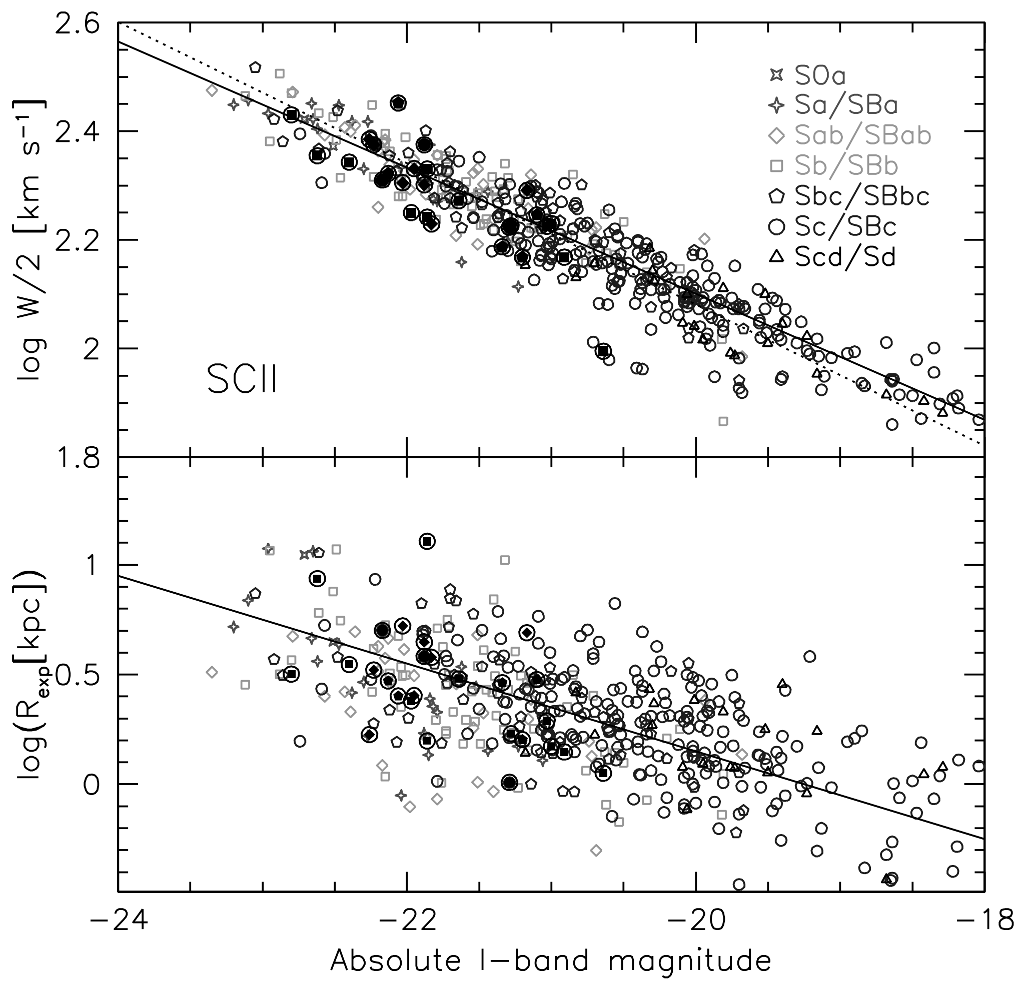


Data for Virgo cluster (SHIVir) contributed by McDonald, Roediger, Ouellette

BTFR scatter depends on environment/MAHs

Galaxy Scaling Relations: TFR for Barred Galaxies

Barred / unbarred galaxies share same TFR*;
bars share no link to LSS of the universe



Courteau+03; Sheth+12; Cervantes-Sodi+15

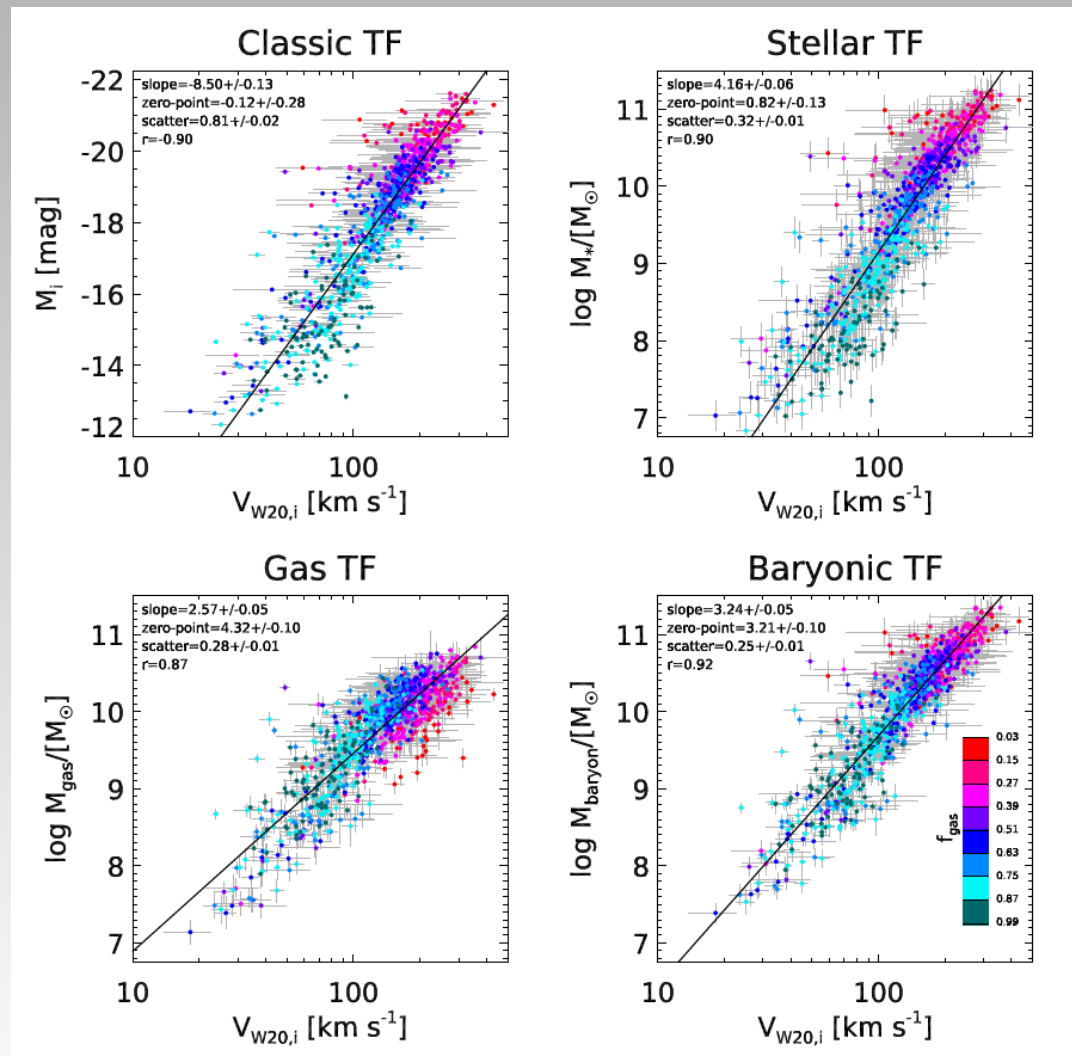
* May not hold for dwarf systems

Disk Galaxy Scaling Relations

TFR → STFR → BTFR

$M_{bar} \sim V_{cir}^{\ \alpha}$
where
α =3-4.3
and scatter
~0.2-0.4 dex

Bradford+16



BTFR: McGaugh 2000; Hall+12; Brook+16

Global Scaling Relations of Galaxies (Mo, Mao, White 1999)

- For a virialized DM halo: $$V_{\rm Vir}^2 \propto \frac{M_{\rm Vir}}{R_{\rm Vir}}$$
- At early times, with: $$a = (1+z)^{-1}$$

$$\frac{M_{\rm Vir}}{R_{\rm Vir}^3} \propto a^{-3} \Rightarrow V_{\rm Vir} \propto a^{-1/2} M_{\rm Vir}^{1/3} \qquad R_{\rm Vir} \propto a M_{\rm Vir}^{1/3}$$

- Constant M/L : $$L \propto M_{\rm Vir}$$
- N-body simul : $$R_{\rm disk} \cong \lambda R_{\rm Vir} \qquad V_{\rm obs} \cong V_{\rm Vir}$$

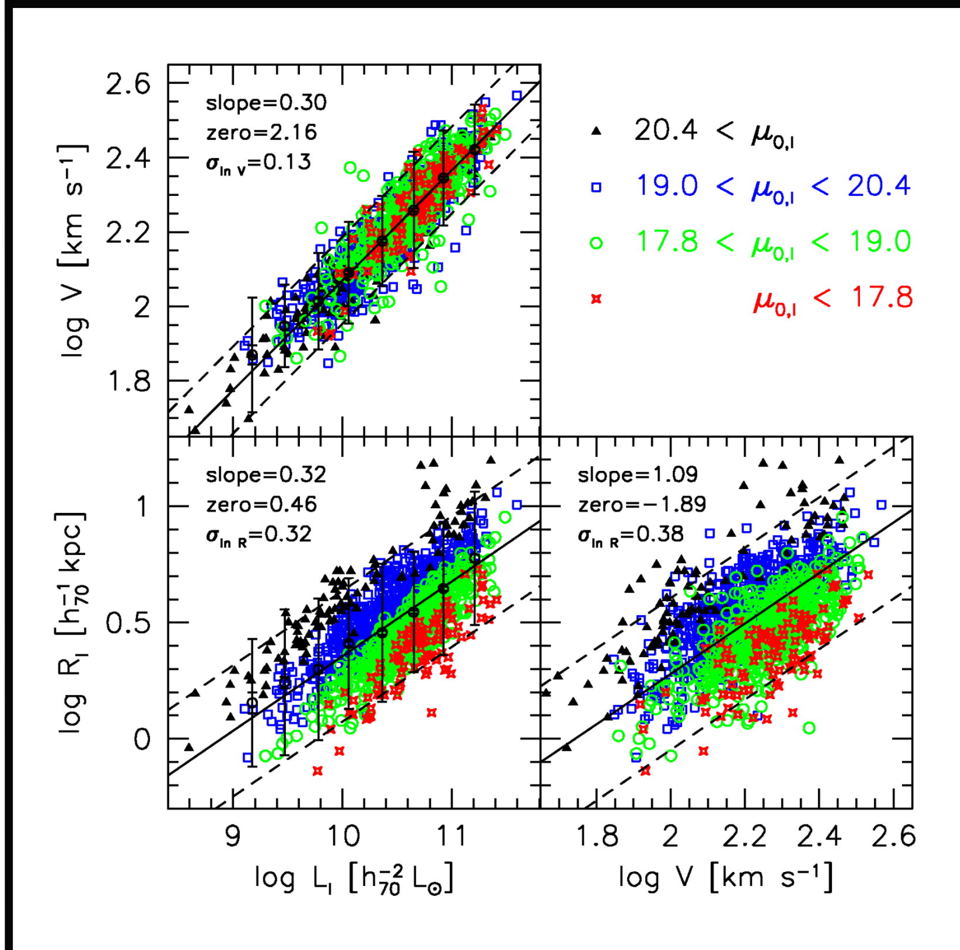
$$\Rightarrow V_{\rm obs} \propto a^{-1/2} L^{0.33} \qquad R_{\rm disk} \propto a L^{0.33}$$

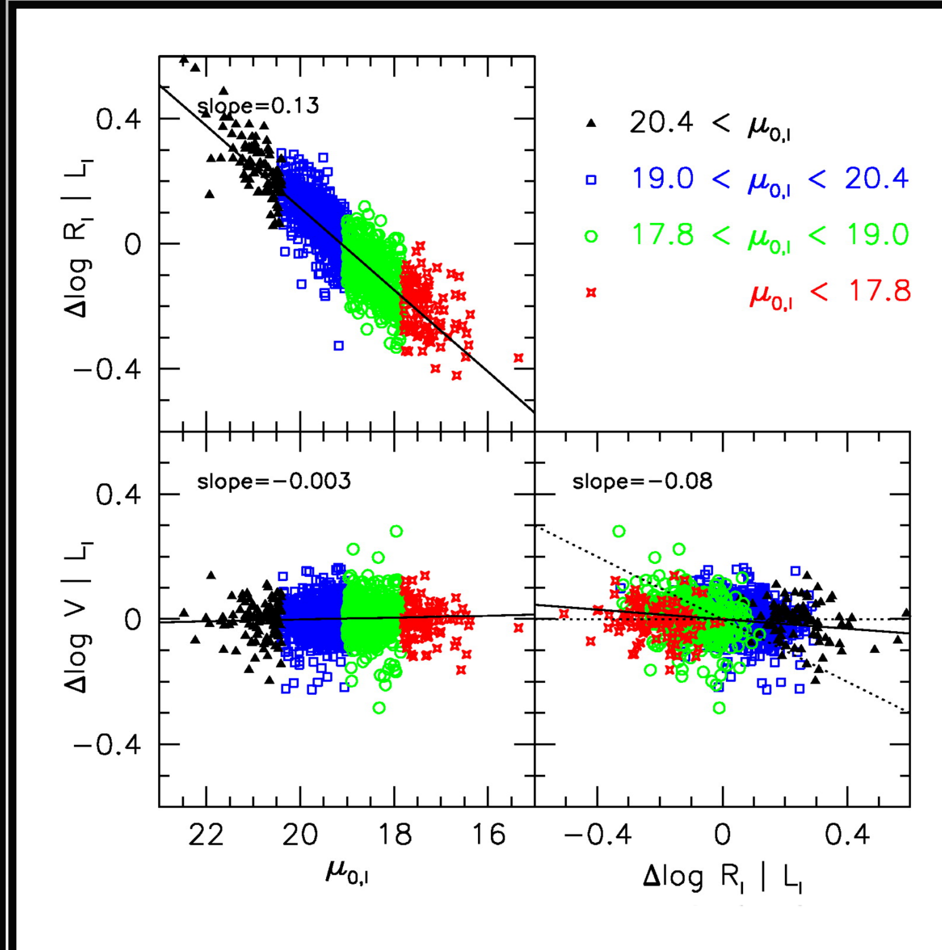
Observed: $$V_{\rm obs} \propto L_I^{0.30\pm0.02} \qquad R_{\rm disk} \propto L^{0.32\pm0.02}$$

Courteau et al. 2007 (Appendices B,C; why this is not quite right)

Disk Galaxy Scaling Relations

VL scatter independent of surface brightness (RL) and colour; theory must reproduce slope, scatter, intercept





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

Tully-Fisher Residuals Argument
(Courteau and Rix 1999)

- For pure exponential stellar disks

$$\mathrm{V}^2 \sim \frac{(M/L)L}{\mathrm{R}_{\mathrm{exp}}}$$

- For a given luminosity

$$\mathrm{V}^2 \sim \frac{(M/L)}{\mathrm{R}_{\mathrm{exp}}}$$

- and if *M/L* vs r is self-similar in bright spirals

$$\mathrm{V} \sim \mathrm{R}_{\mathrm{exp}}^{-1/2}$$

Therefore

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

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

Calibrated Tully–Fisher relations 2379

Pure Disk

Pure DM

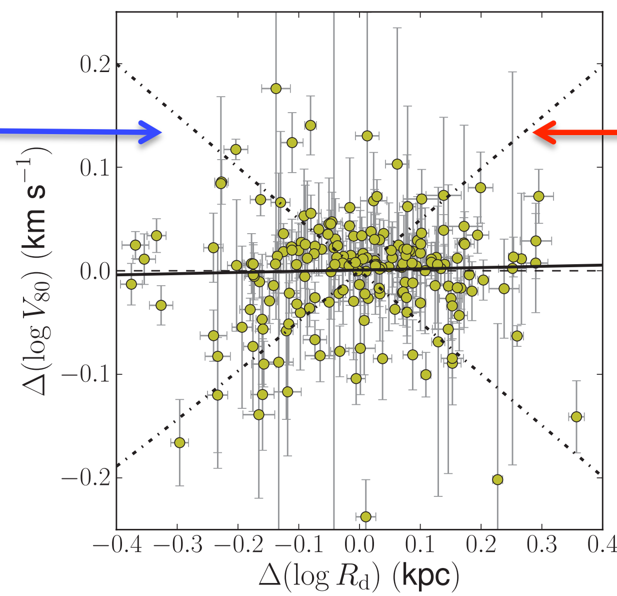


Figure 28. Correlation between velocity residuals from the $M_\star$ ITFR, $\Delta(\log V_{80})$, and disc size offsets $\Delta(\log R_{\rm d})$, defined relative to the mean relation $\log \bar{R}_{\rm d}(M_\star)$ (given by equation 35). The best-fitting linear relation has a slope consistent with 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

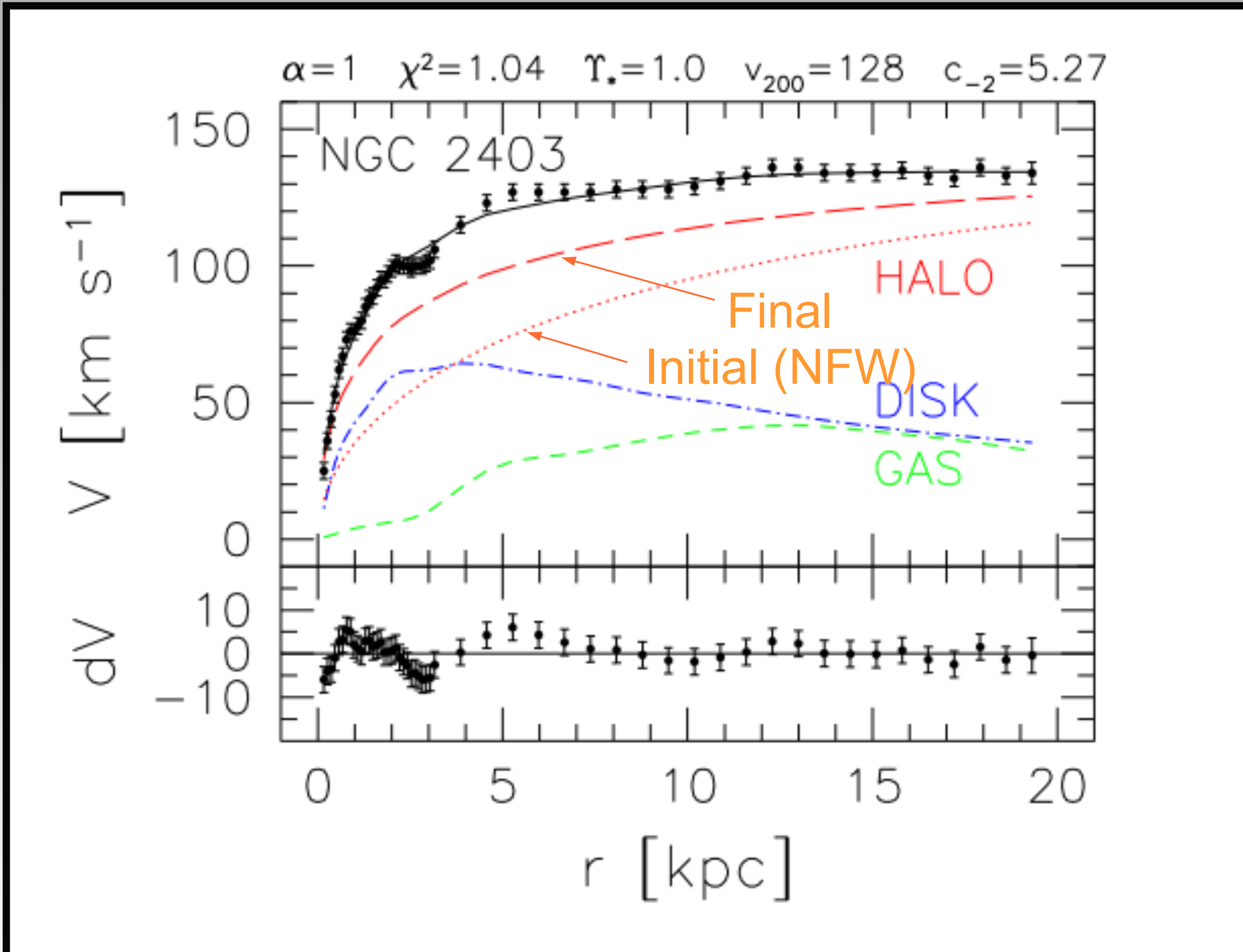
Courteau & Rix (1999)

- 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. Constrains LF.

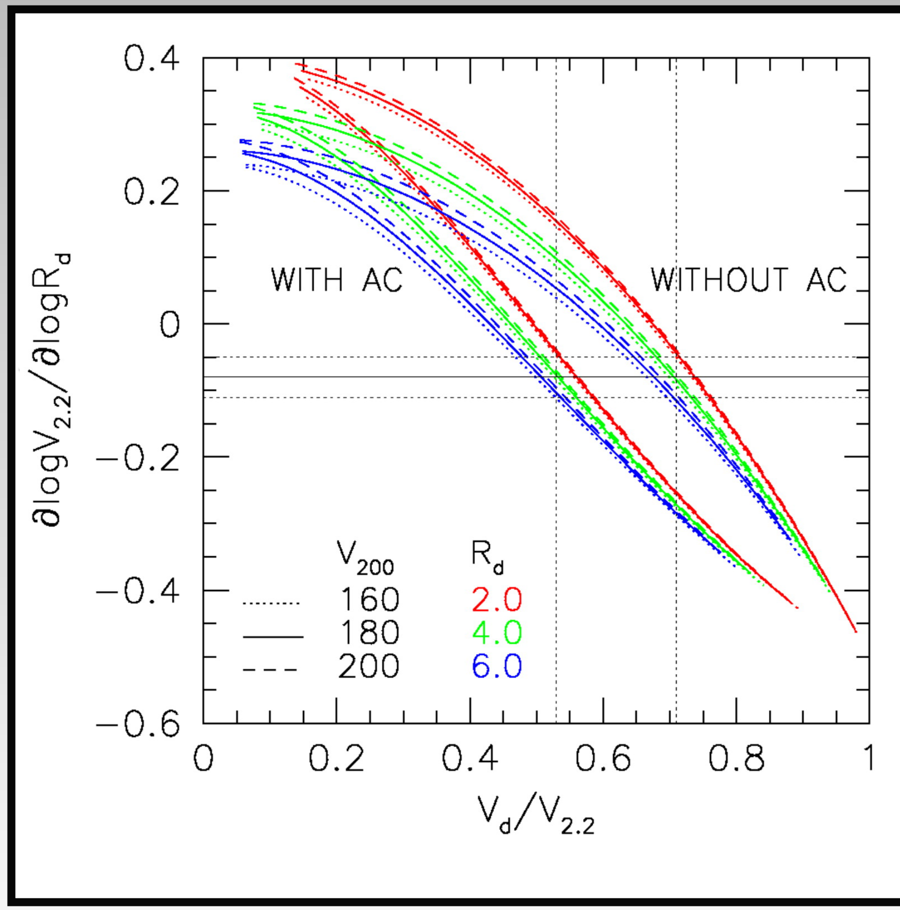
Caveat: adiabatic contraction



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)*

Mass fraction at 2.2R_d (1.3R_e)

- 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 etal 2011,2013)
- TF residuals: Courteau & Rix (1999); Dutton etal 2007
- gas kinematics and structure of spiral arms Kranz, Slyz & Rix (2002); Foyle etal (2008):
- disk flattening of edge-on galaxies: Kregel et al. (2005)
- lensing + rotation curve constraints Trott & Webster (2010)
- local stellar density: Bovy & Rix (2013): MW is *maximal*

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

(on average at 2.2 disk scale lengths)

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

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

Galaxy masses

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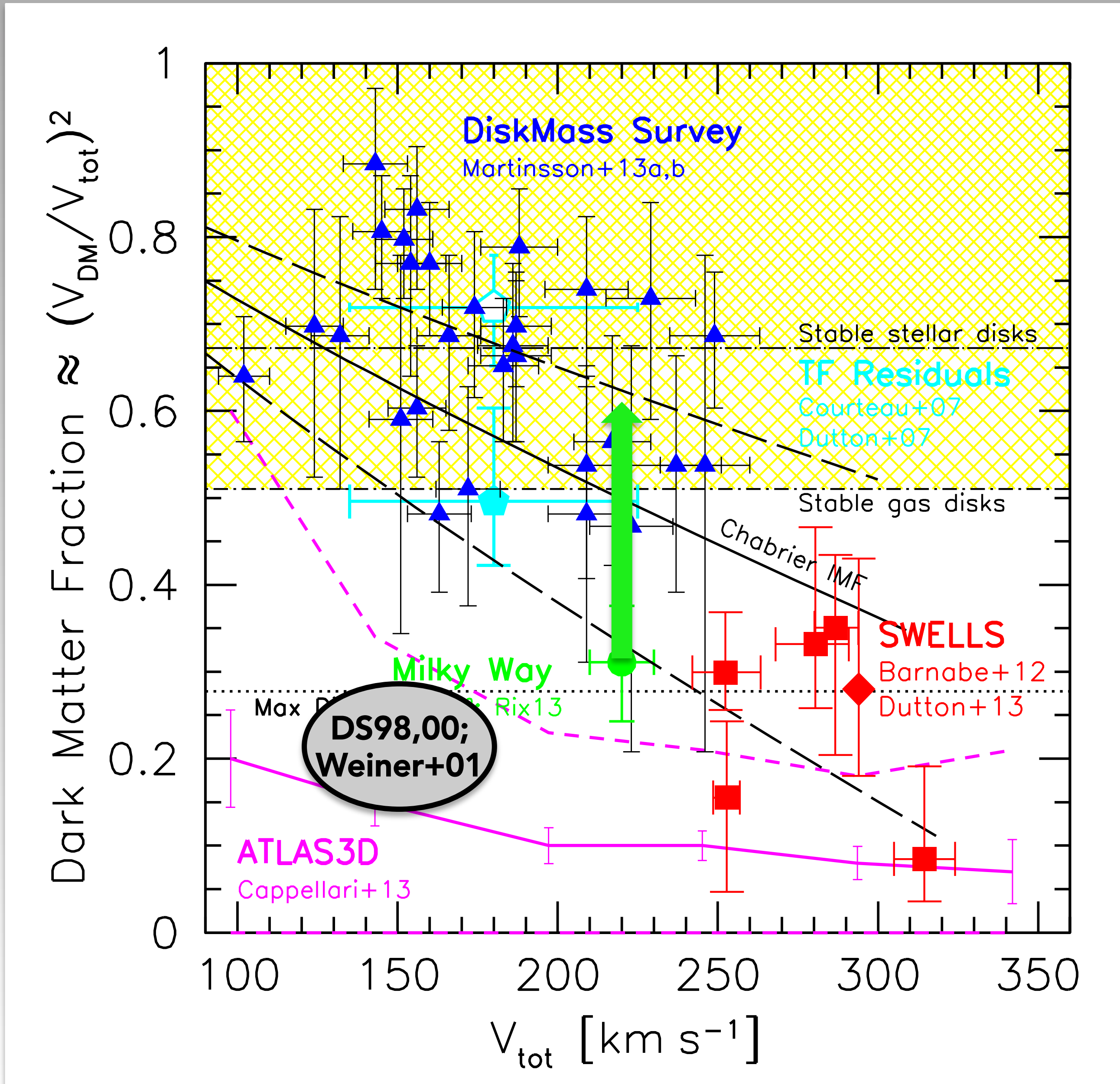
(published 14 January 2014)

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

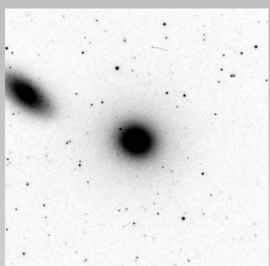
Mass fraction at ~2.2R_d in LTGs and ETGs

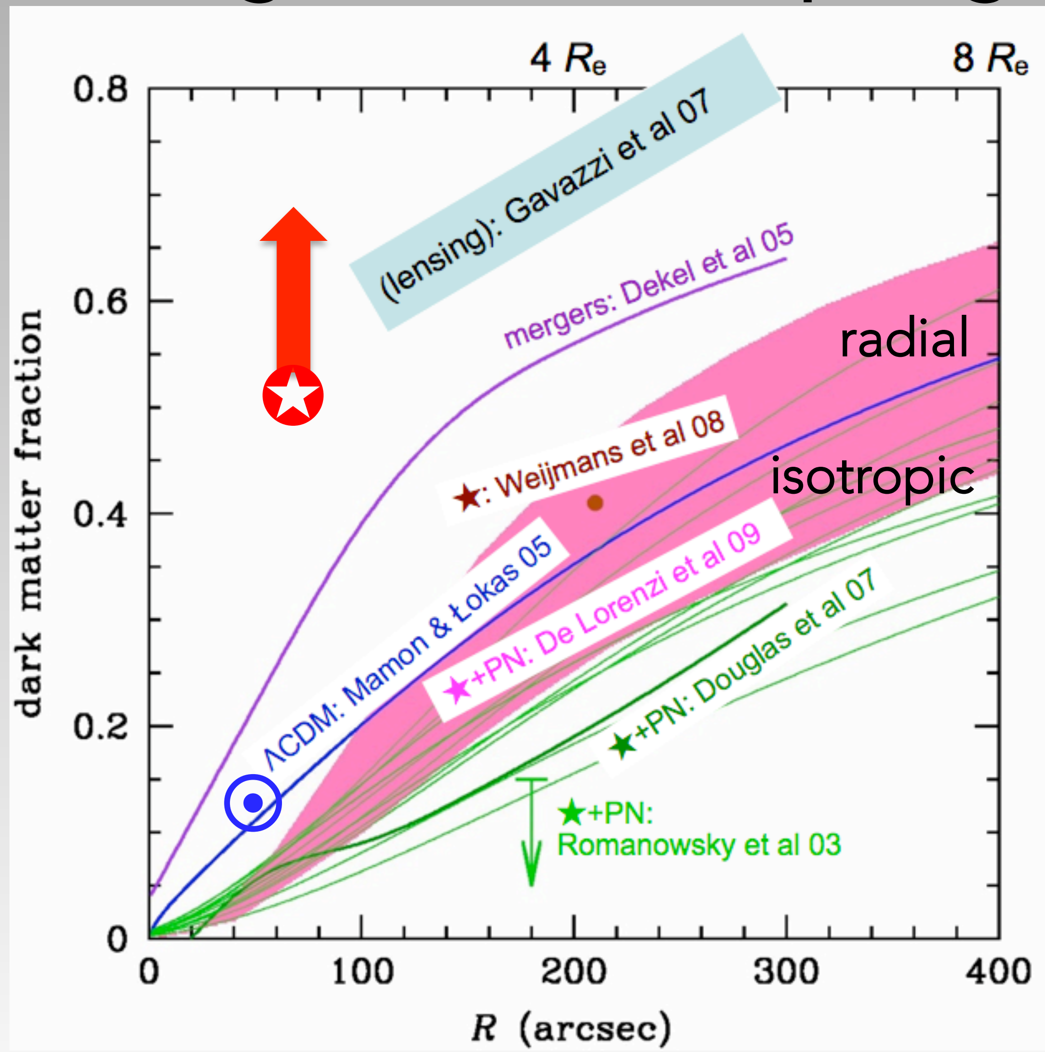


Courteau and Dutton 2015

Dark Matter Fractions:
Deep, homogeneous sampling needed

M105; E1



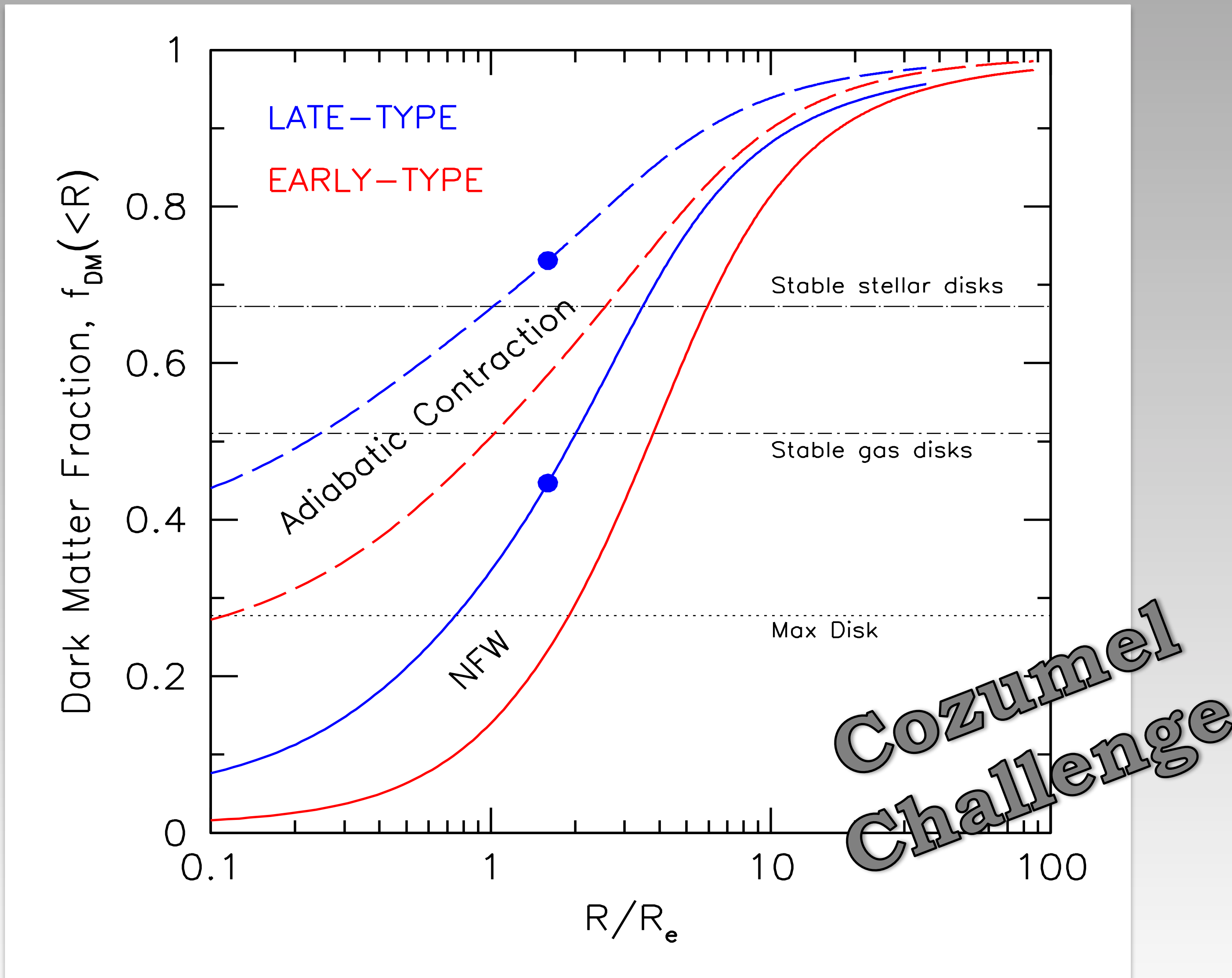


- Cappellari (2013)
- Spirals

Courteau+14
Reviews of Modern Physics

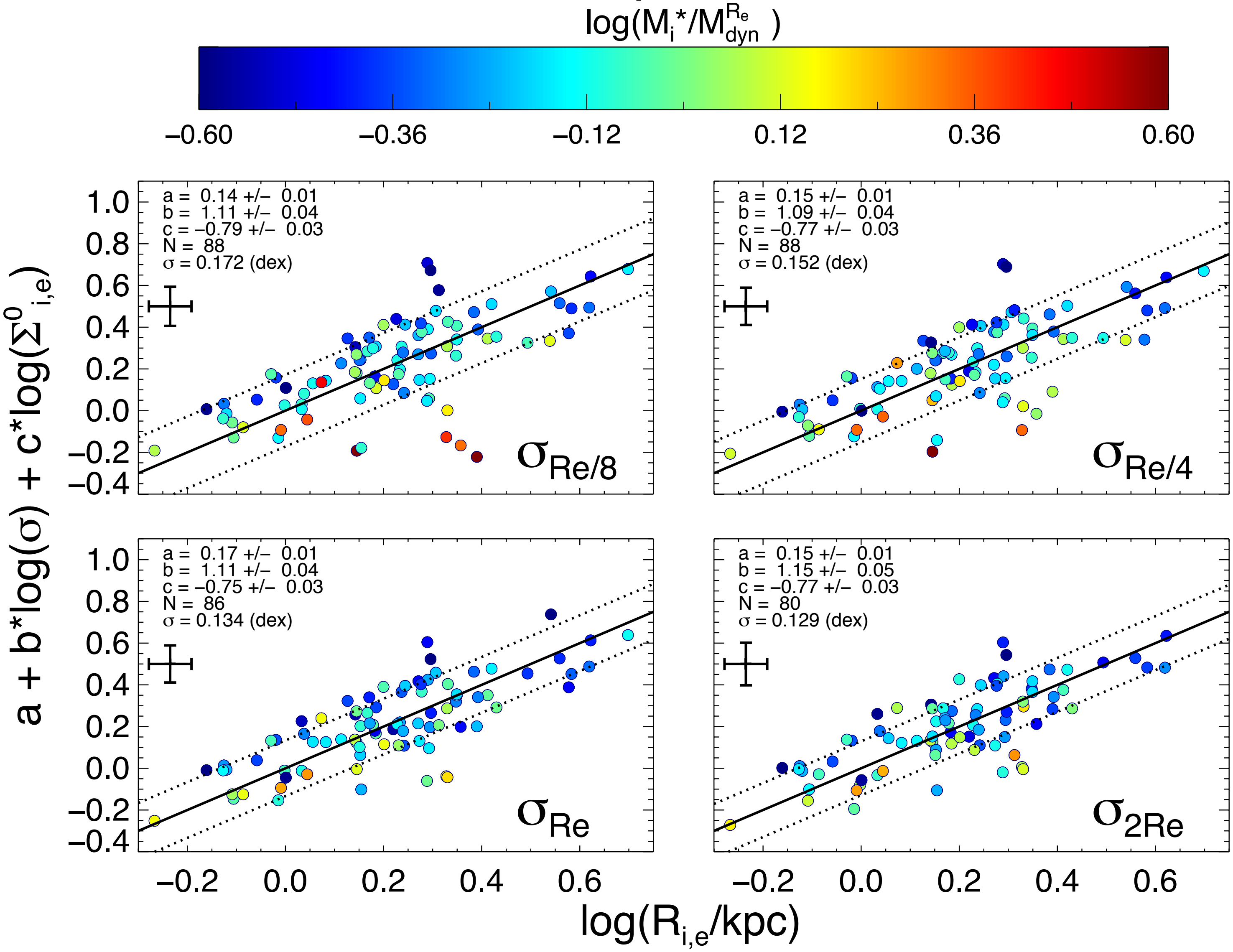
Dark matter content @ 1,2,3,4… R_e still uncertain!

Radial Mass Fractions in LTGs and ETGs



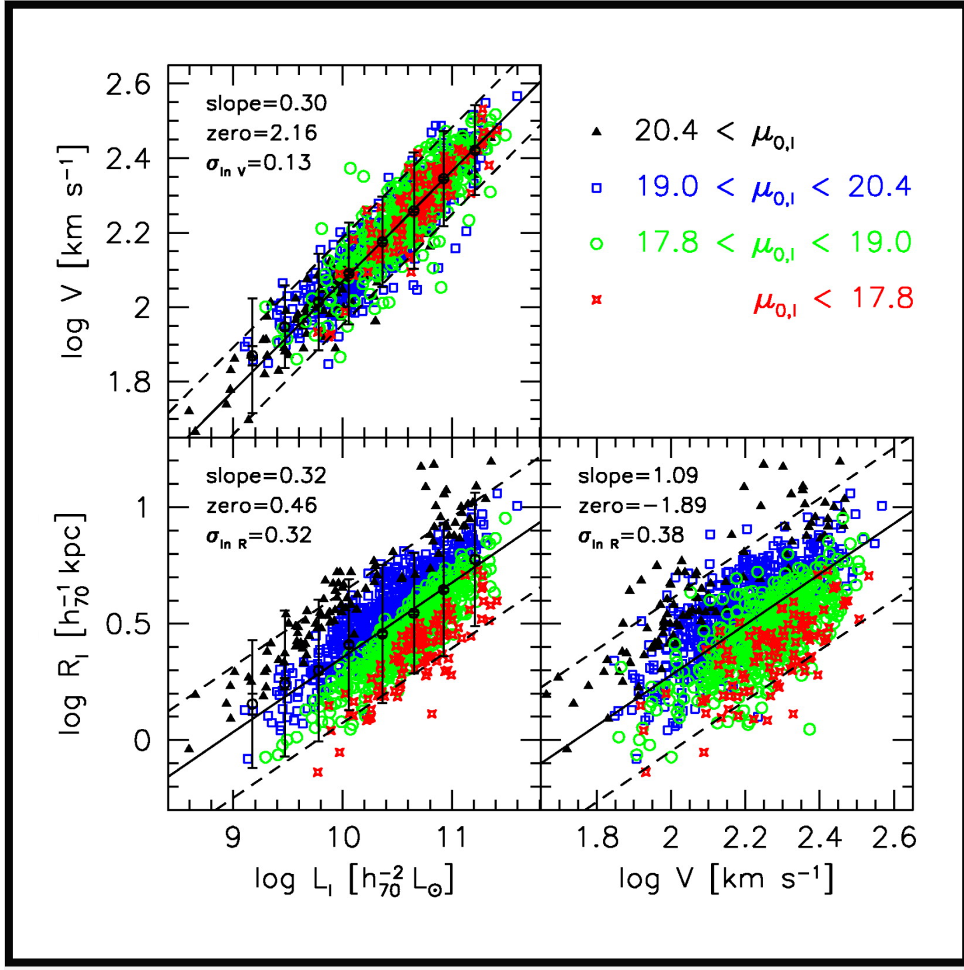
Courteau and Dutton 2015

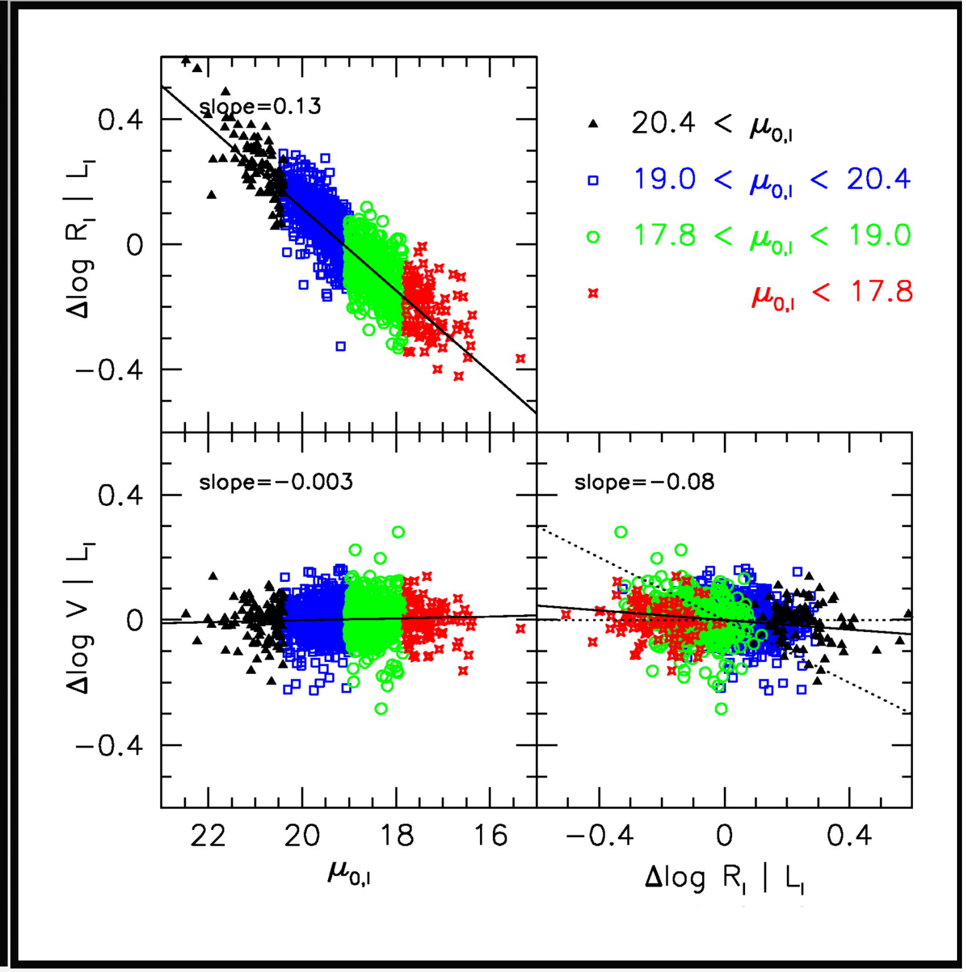
FP Analysis: tilt depends on M^*/M_{bar}



Ouellette+16; also Cappellari ARAA 2016

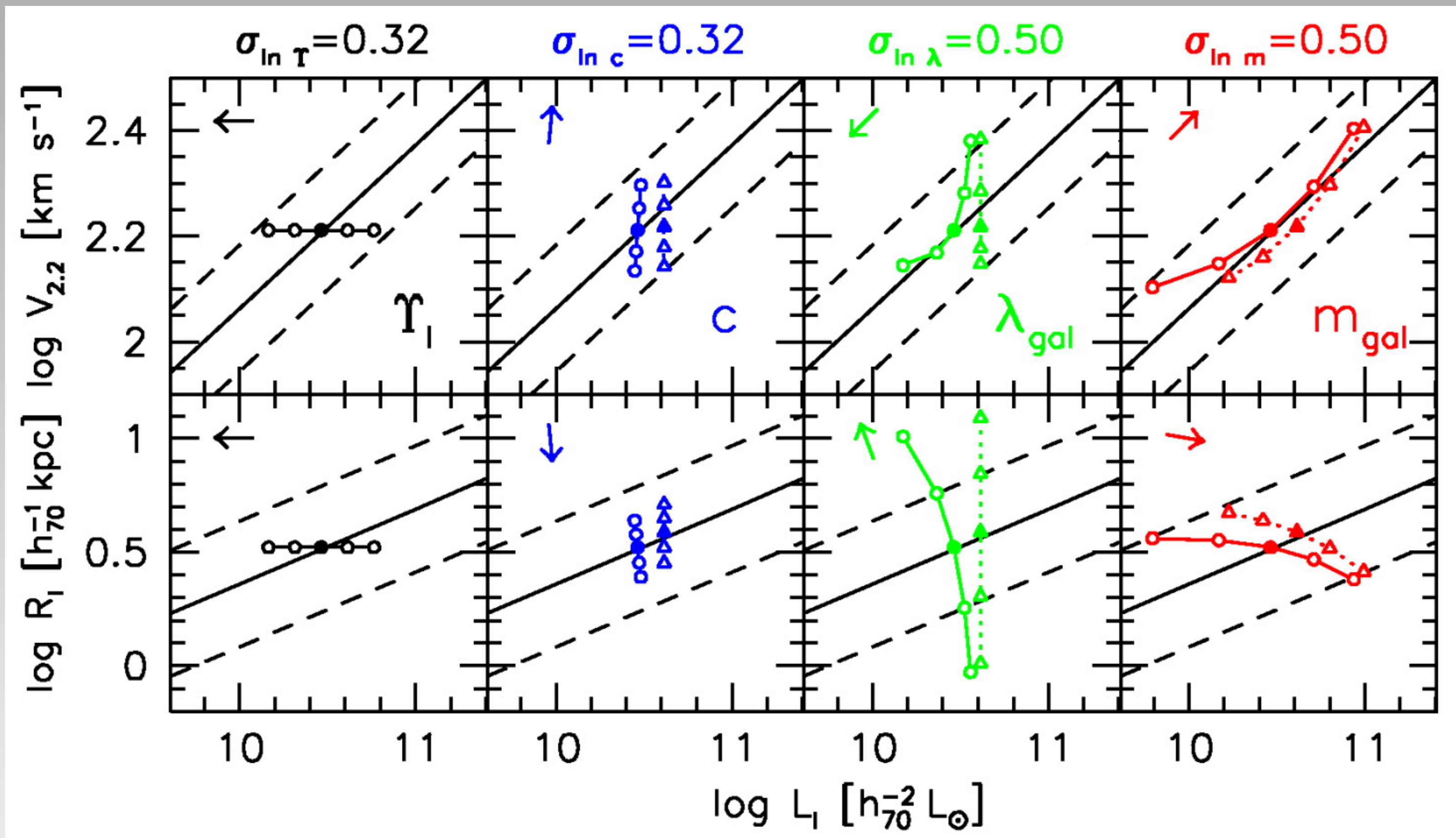
Global Disk Galaxy Scaling Relations





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

Semi-Analytic Models of Disk Galaxies



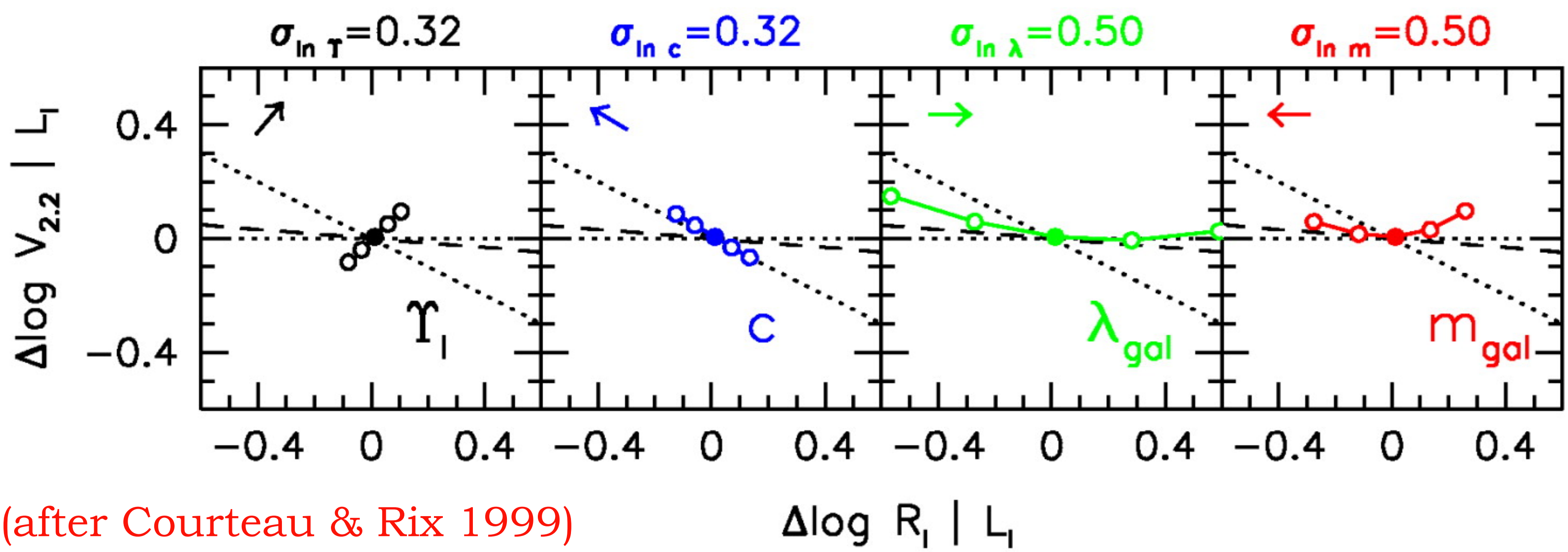
λ = halo spin c = halo conc.

m_g = disk mass Υ_I = disk M/L

Assumes log-normal scatter

Dutton+07,11

Semi-Analytic Models of Disk Galaxies



(after Courteau & Rix 1999)

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

Dutton+07,11

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?

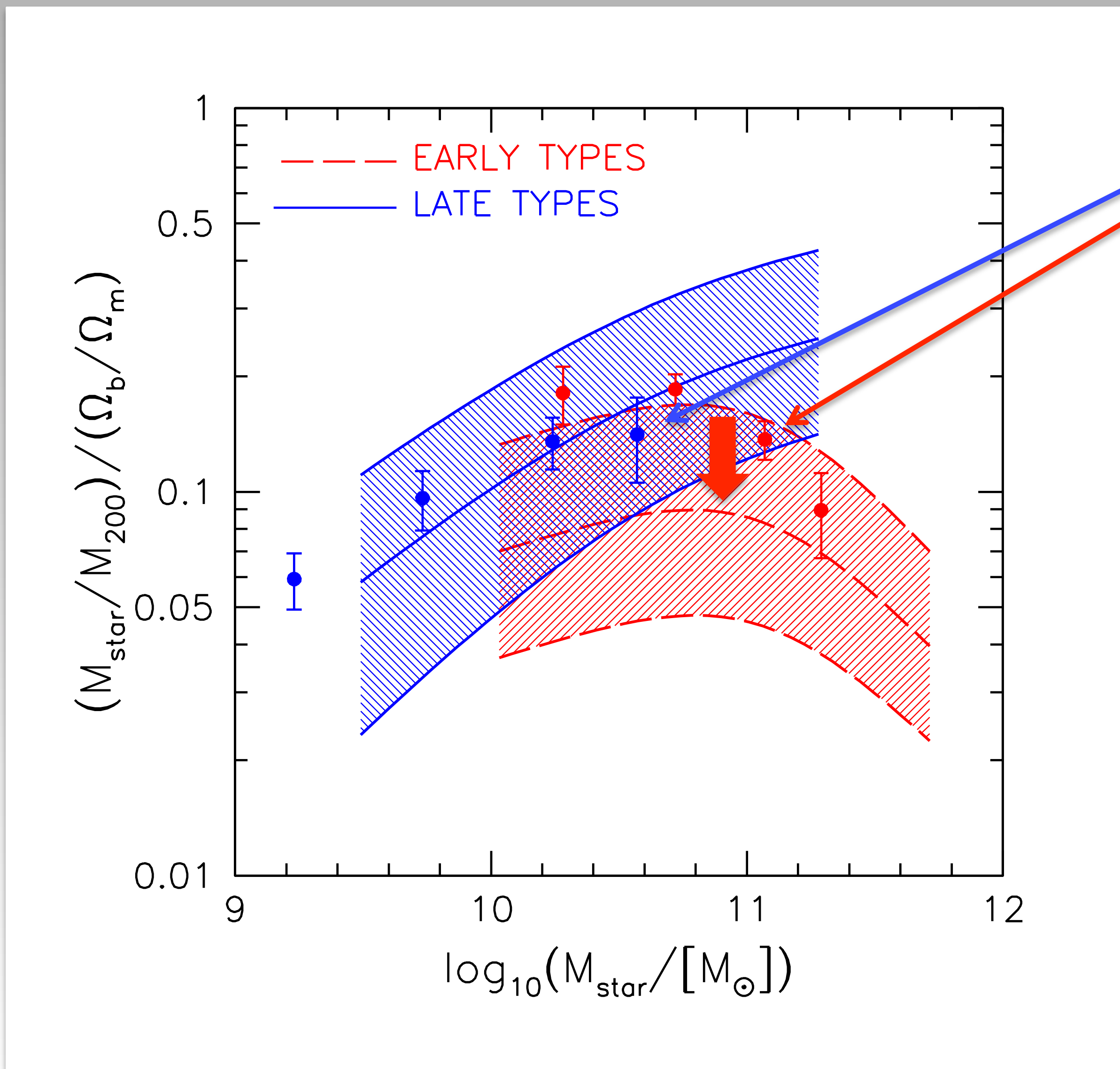
- Lower initial halo concentration

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: **Feedback compensates for halo contraction**

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



Hudson etal 2015 weak lensing: central + satellites at z=0.3 (at z~0).

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

- e.g. Cappellari, Trager, Smith, Spiniello…

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

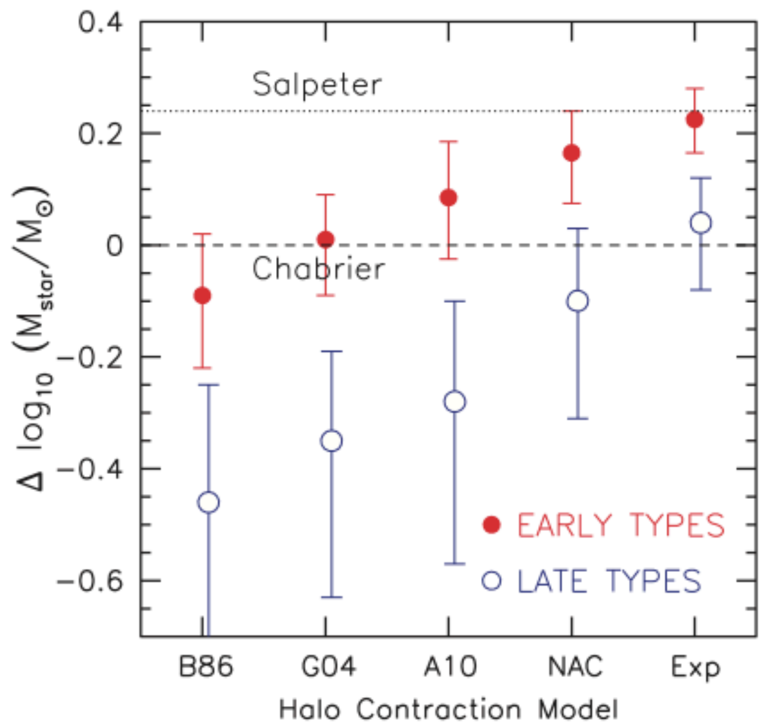


Figure 17. Offset in stellar masses required to match the zero-point of the VM relations as a function of halo response model, calculated at $\log_{10}(V_{opt}/\mathrm{km\,s^{-1}}) = 2.30$, for early-type (red filled symbols) and late-type (blue open symbols) galaxies. The models correspond to the following: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

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

Lensing: Dutton+10; Reyes+11

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

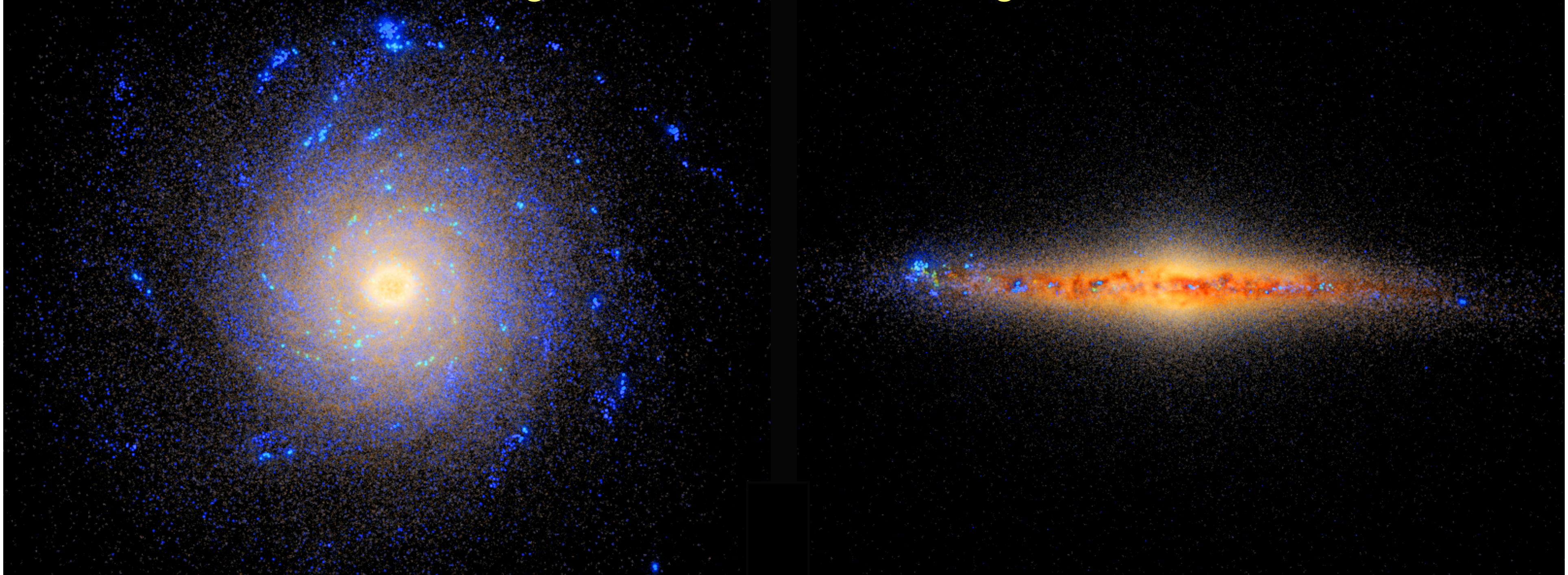
("Disk/Halo conspiracy"; see Remus+13)

Dutton+11; see also Trujillo-Gomez+11

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

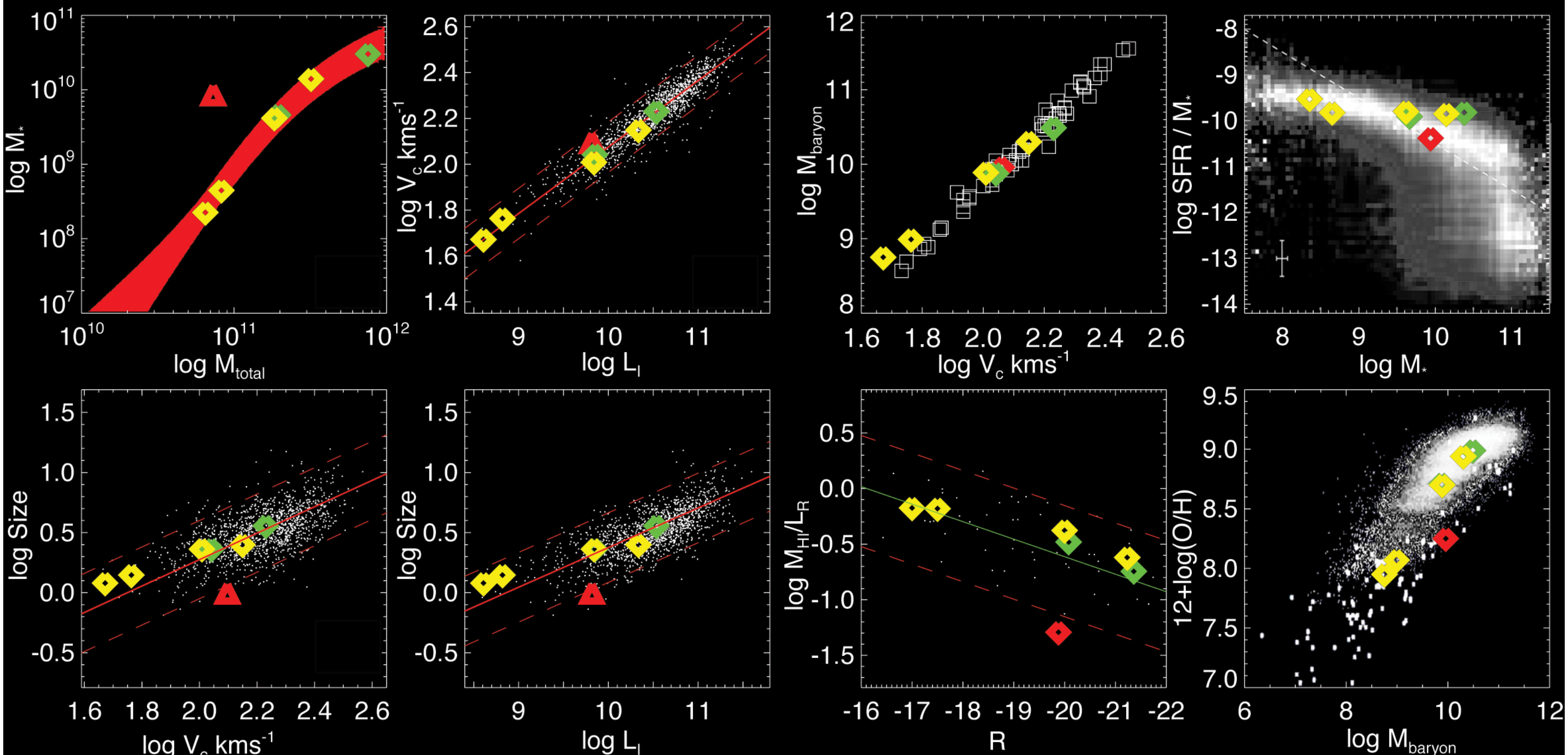
(Brook etal 2012, MNRAS, 424, 1275-1283)

* Making Galaxies in a Cosmological Context



Avila-Reese+Mancillas; Genel; Gibson; Naab; Remus (Magneticum); Stevens;Teklu; Teyssier; Tissera;Torrey;
Aquino; van de Ven; van den Bosch

Stellar-Mass, Halo-Mass
Size (S), Rotation Velocity (Vc), Luminosity (L), M_{HI},
Specific SFR, Colour, M_{bar}, 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

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 (esp, at baryon/DM transition).

- BTF/FP analysis for ***tens of thousands*** of LTGs and ETGs: need *deep* and *extended* dynamical profiles, X-ray maps, multi-wavelength imaging, gas fractions E.g. Atlas3D, ALFALFA, CALIFA, MaNGA, SAMI, SLACS, SLUGGS, SHIVir, … (bias on dynamics)

Wish List (Obs/Theory)

- **Baryon/DM fraction vs radius: need accurate stellar pop models**
- **Velocity function of galaxies**
- **Theory:** Must understand AC, IMF variations, feedback (SN + AGN) and baryons/DM cross-talk:

  Viable models must require strong SN feedback at low masses and strong AGN feedback at high masses to match observed LFs

  Most galaxy scaling relations depend on the feedback model. But there is no substitute to extensive, homogeneous data!