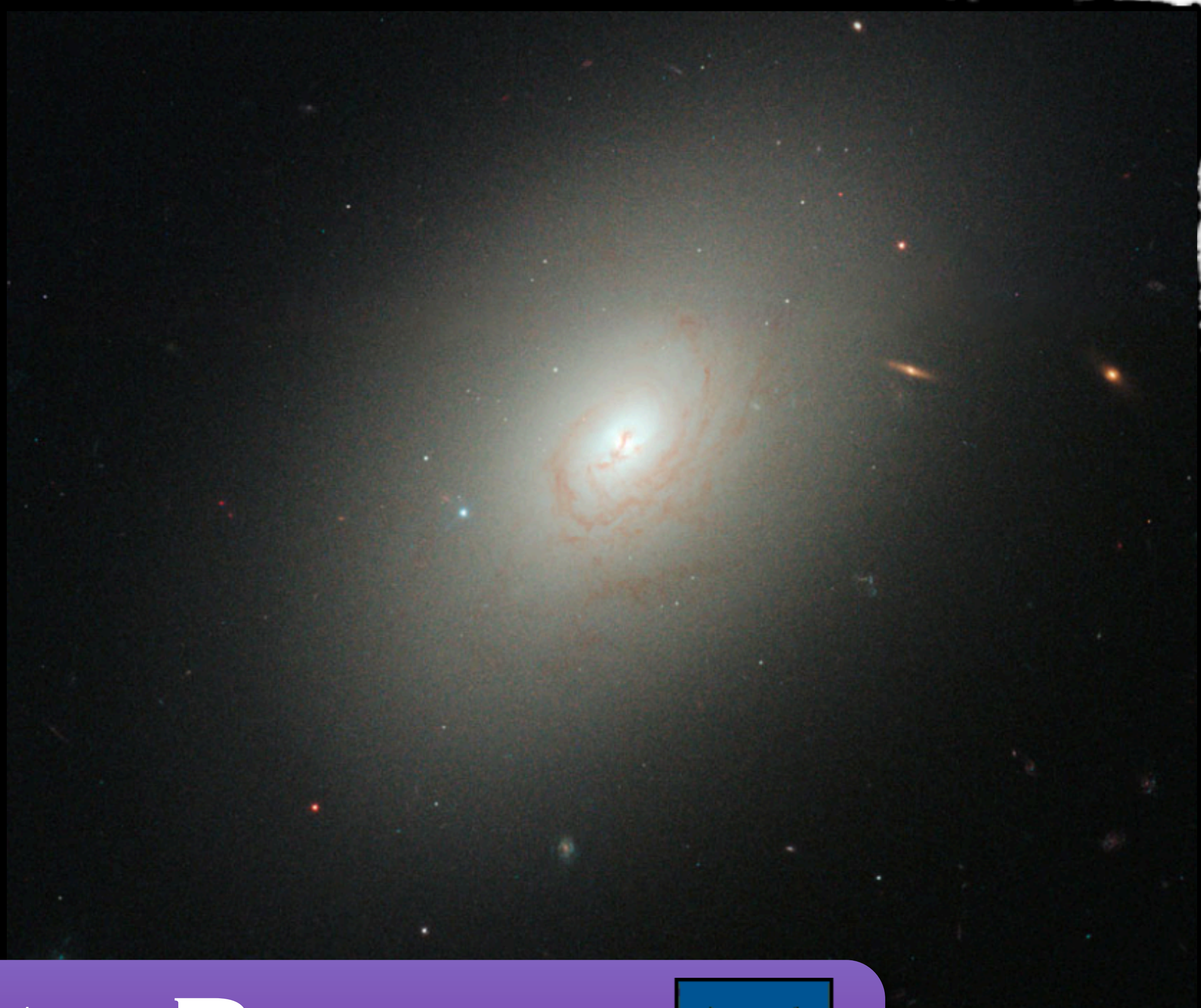
The Formation of Disk Galaxies

Insights from Disk Galaxy Scaling Relations and the Galaxy-Dark Matter Connection



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Main Collaborators: Aaron Dutton (MPIA) & Surhud More (IPMU)

Disk Formation: The Standard Picture

Disk galaxies are systems in centrifugal equilibrium.
Hence, their structure is governed by angular momentum content.

The Three Pillars of Disk Formation

- Angular momentum originates from cosmological torques
- Baryons & DM acquire identical angular momentum distributions
- During cooling, baryons conserve their specific angular momentum

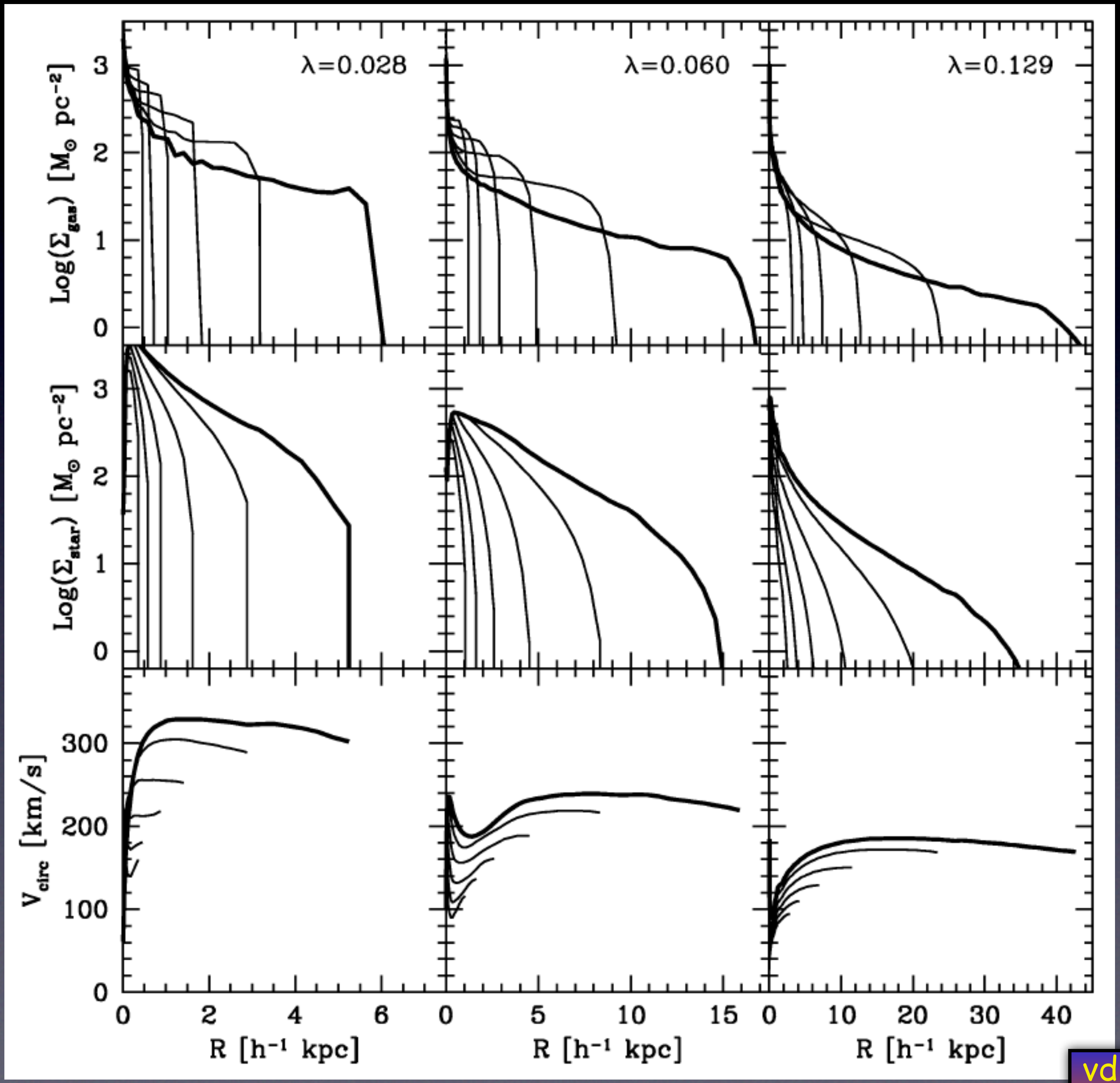
Gas settles in disk in centrifugal equilibrium

$$\Sigma_{\rm disk}(R) \leftrightarrow M_{\rm bar}(j_{\rm bar}) \leftrightarrow M_{\rm dm}(j_{\rm dm})$$

It is assumed that DM halo contracts in response to disk formation (AC)

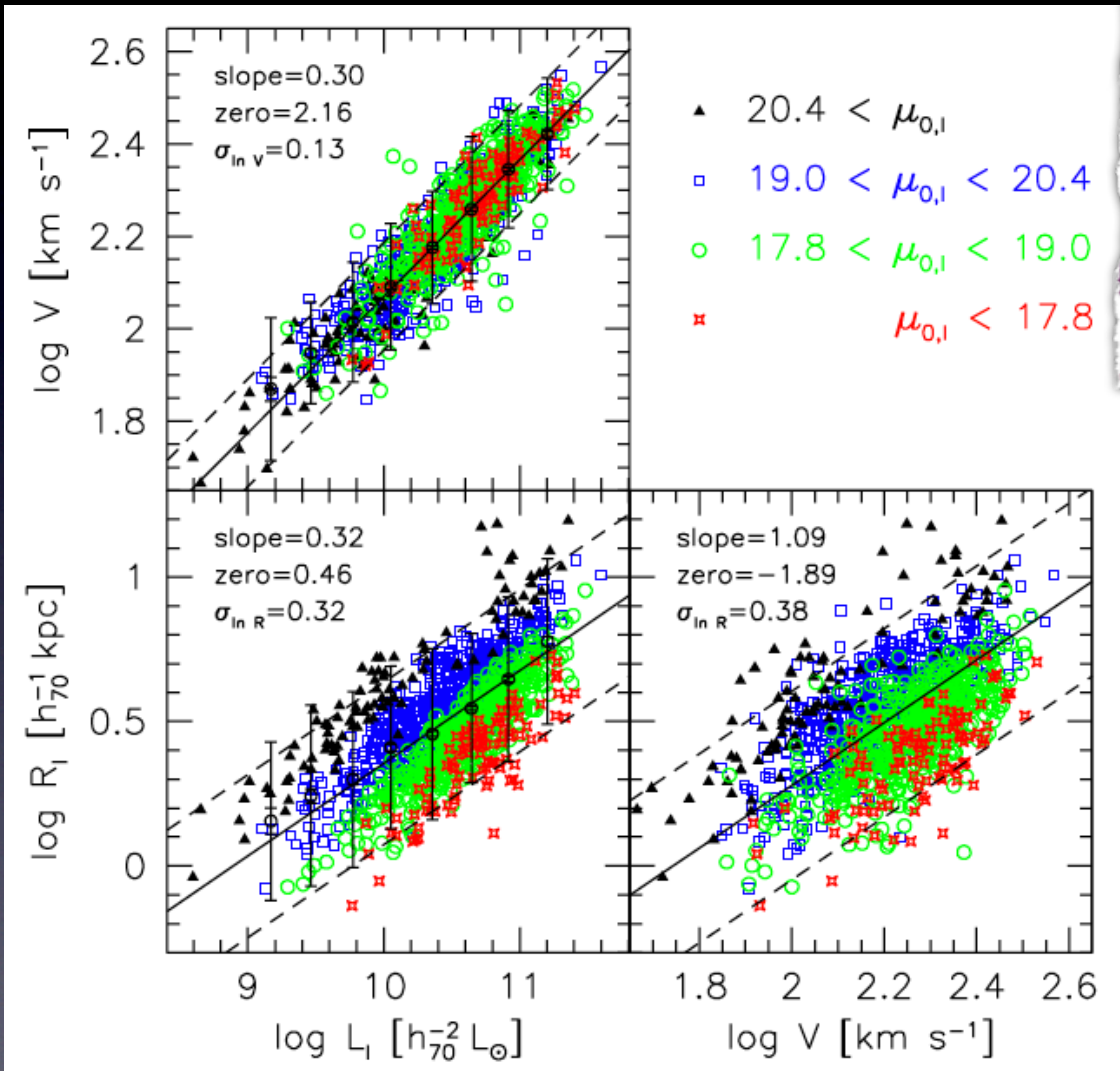
[e.g., Fall & Efstathiou 1980; Dalcanton, Spergel & Summers 1997; Mo, Mao & White 1998; vdBosch 2001, 2002]

Inside-Out Growth of Galactic Disks



vdBosch 2002

Disk Galaxy Scaling Relations



Sample of ~1300 disk galaxies with Hα rotation curves.

Rotation velocities measured at 2.2 disk scale lengths.

Uniform inclination & extinction corrections.

Courteau+07

NOTE: TF residuals are not correlated with surface brightness (size).

Galaxy Scaling Relations

Tully-Fisher (TF) Relation

$$L \propto V_{\rm rot}^{\alpha} \qquad (\alpha \sim 3.5)$$

scatter NOT correlated with size

Faber-Jackson (FJ) Relation

$$L \propto \sigma^{\beta} \qquad (\beta \sim 4)$$

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Fundamental Plane: $L \propto \sigma^{\beta} R_e^{\gamma}$

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This scaling is similar to observed stellar mass TF & FJ relations

$$V_{2.2} \propto M_{*}^{0.28}$$

[Dutton et al. 2010]

$V_{2.2}$ is disk rotation velocity at 2.2 disk scale lengths

$$\sigma_{\rm e} \propto M_{*}^{0.29}$$

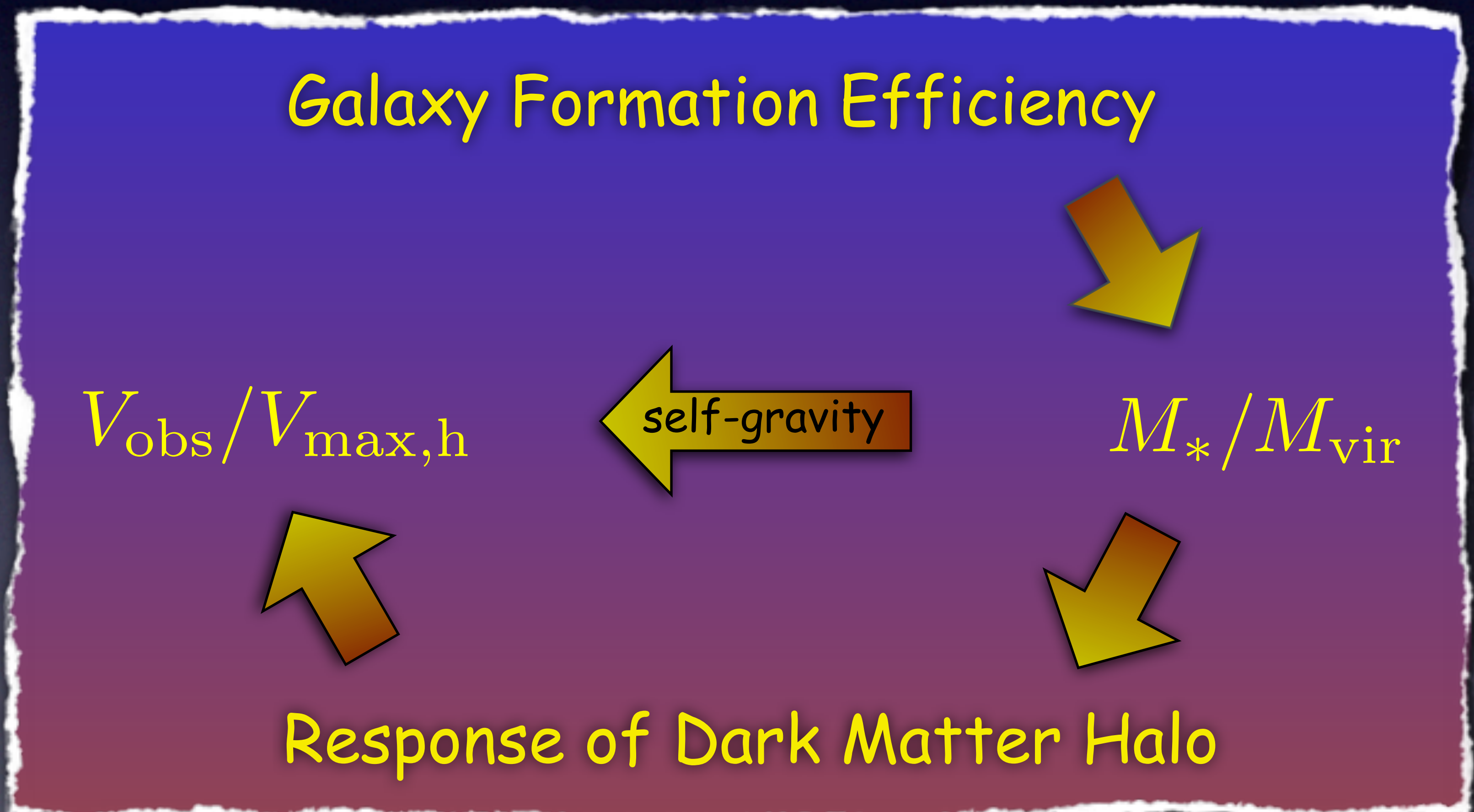
[Gallazzi et al. 2006]

$\sigma_{\rm e}$ is velocity dispersion inside effective radius

The Origin of Galaxy Scaling Relations

For the $V_{\rm max,h} - M_{\rm vir}$ relation to be the direct origin of the TF & FJ relations requires that $V_{\rm obs}/V_{\rm max,h}$ and $M_*/M_{\rm vir}$ are both constants!✣

These requirements are neither "natural" nor consistent with observations



✣ Here $V_{\rm obs} = V_{2.2}$ for late-types, and $V_{\rm obs} = \sigma_{\rm e}$ for early-types

Tully-Fisher Relation in Semi-Analytical Models

Simultaneously matching LF & TF has been long-standing problem for CDM-based models

(White & Frenk 1991; Kauffmann et al. 1993; Cole et al. 2000; and many more...)

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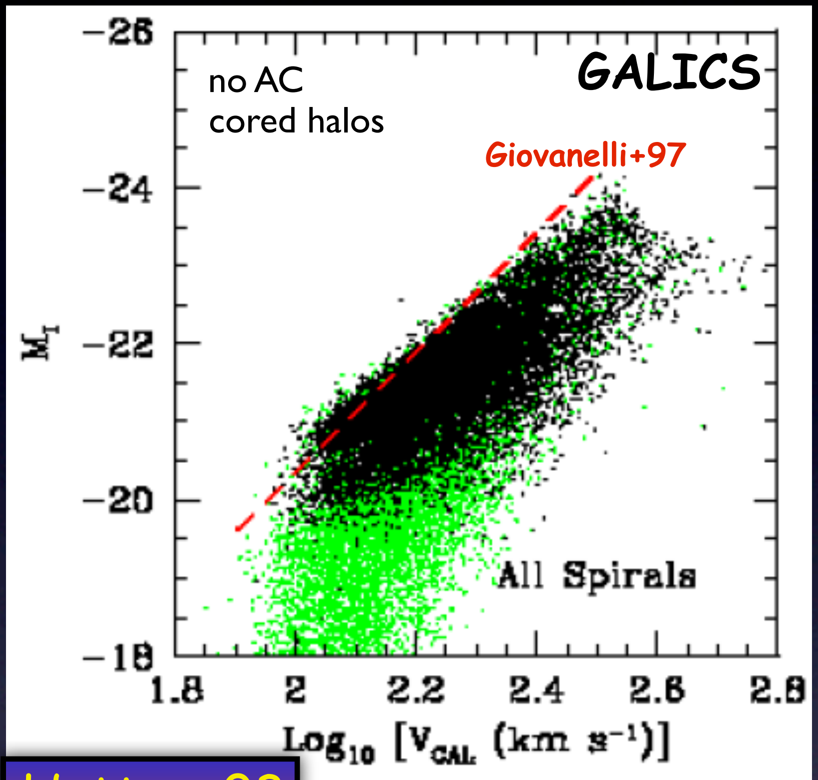

Hatton+03

GALICS: fail, despite ignoring AC and even assuming cored halos (Hatton et al. 2003)

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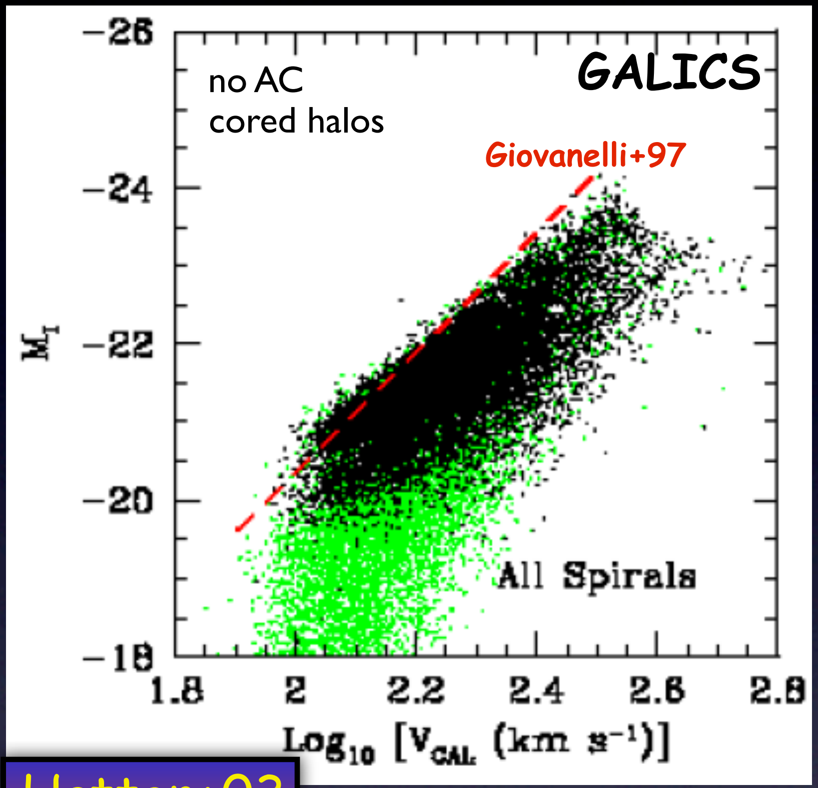

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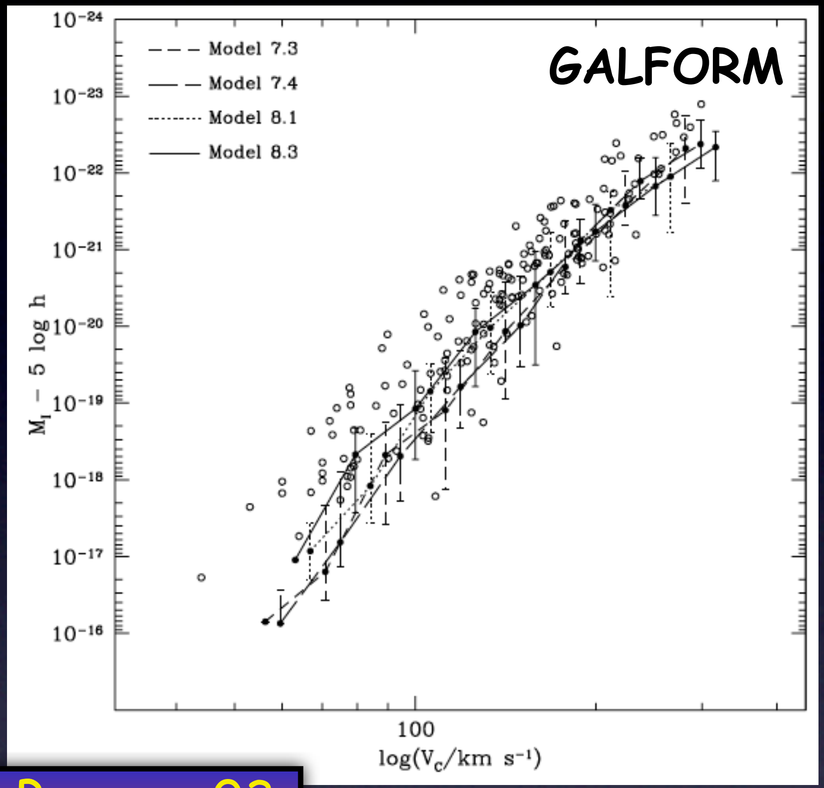

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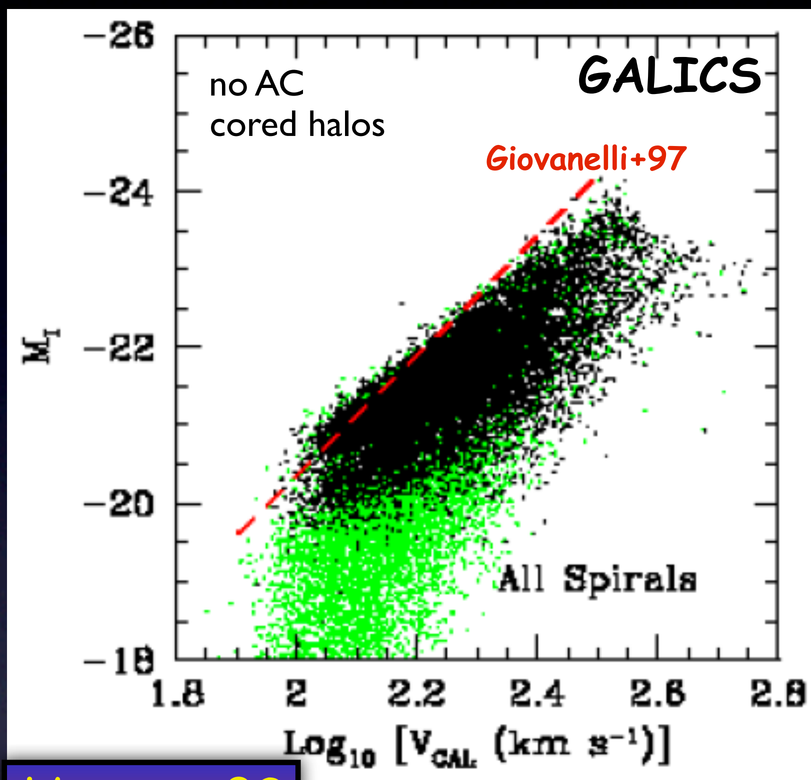

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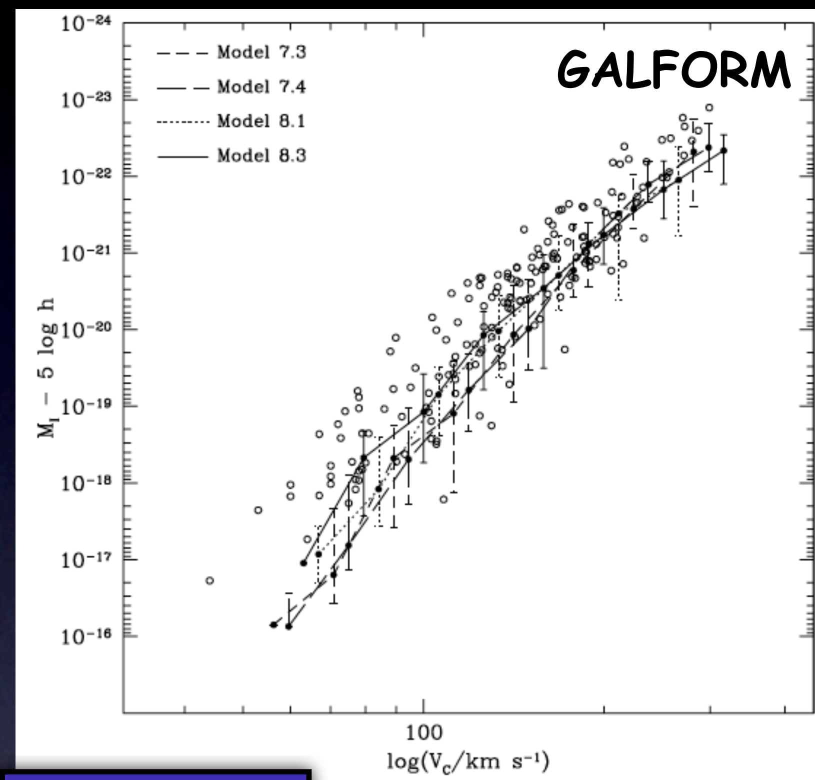

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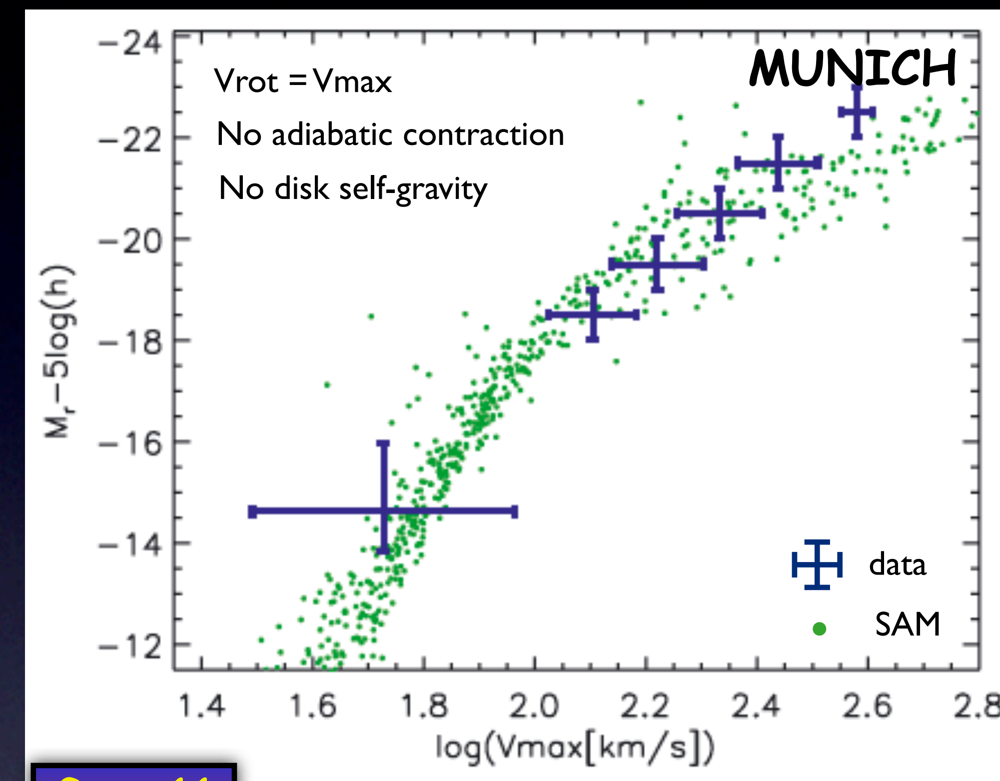

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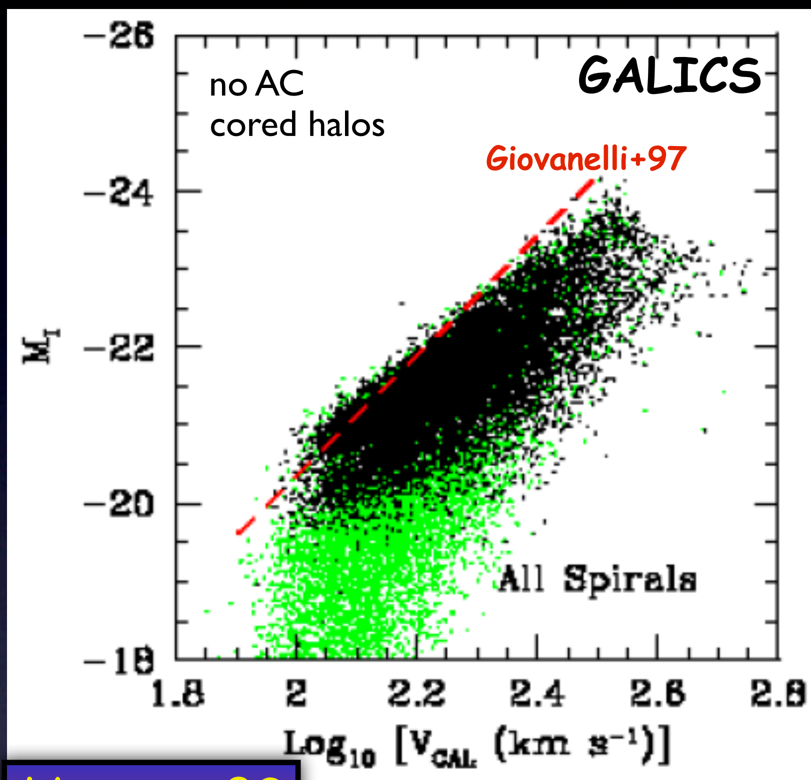

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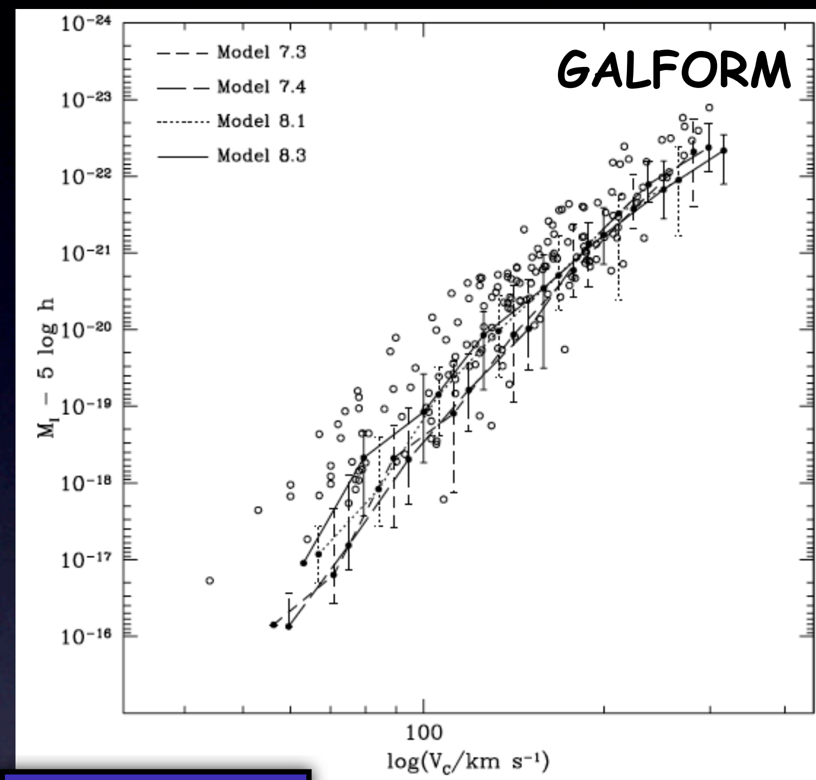

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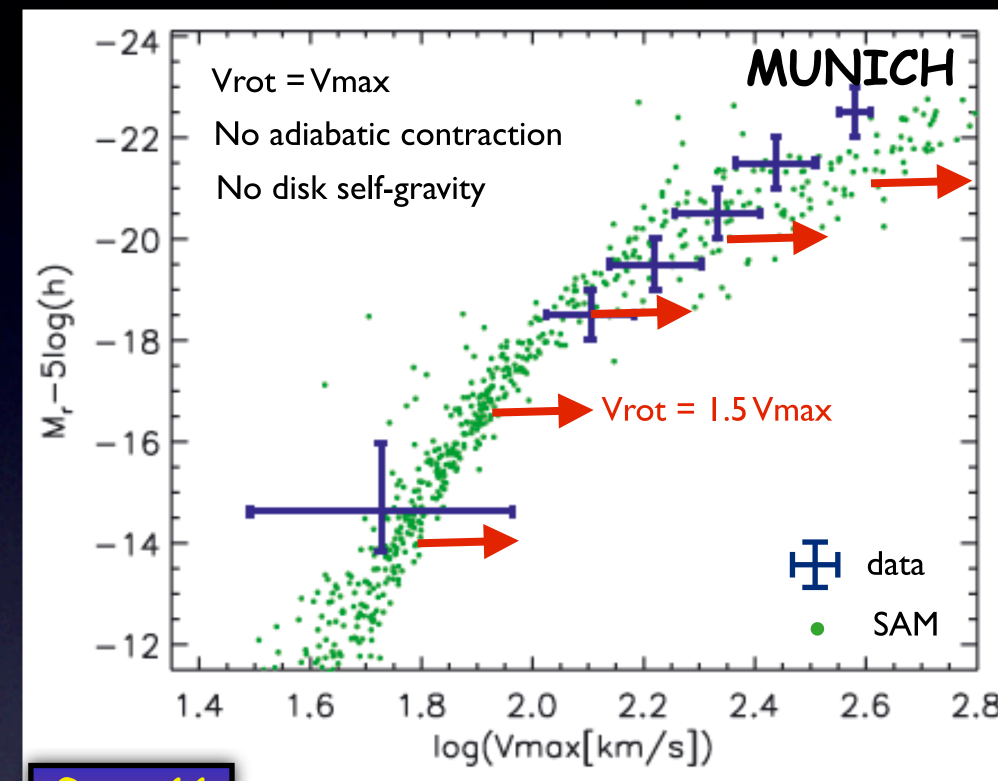

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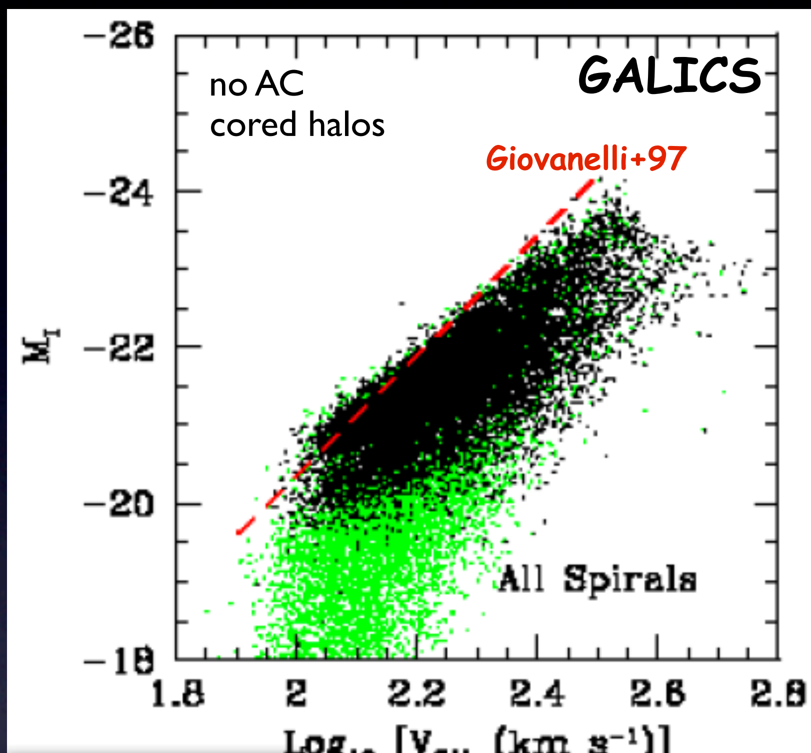

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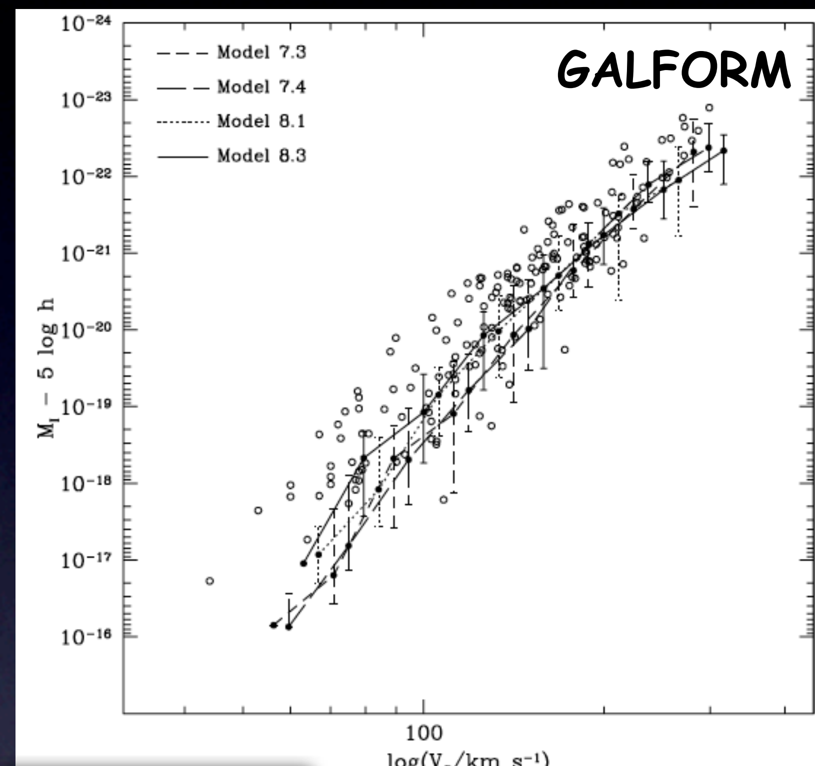

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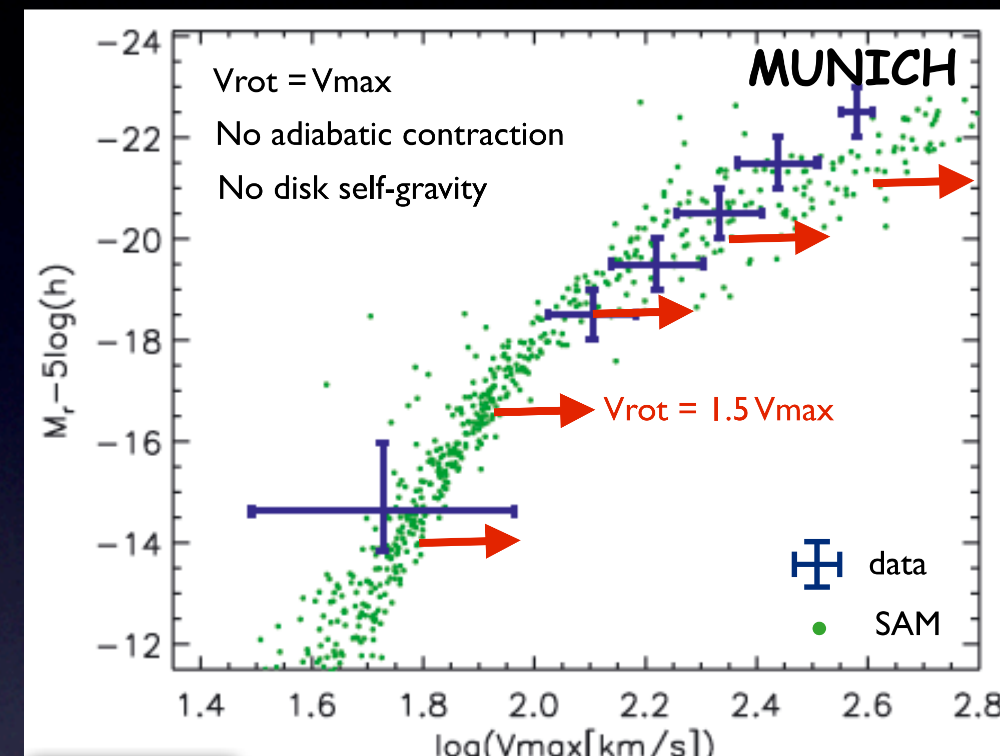

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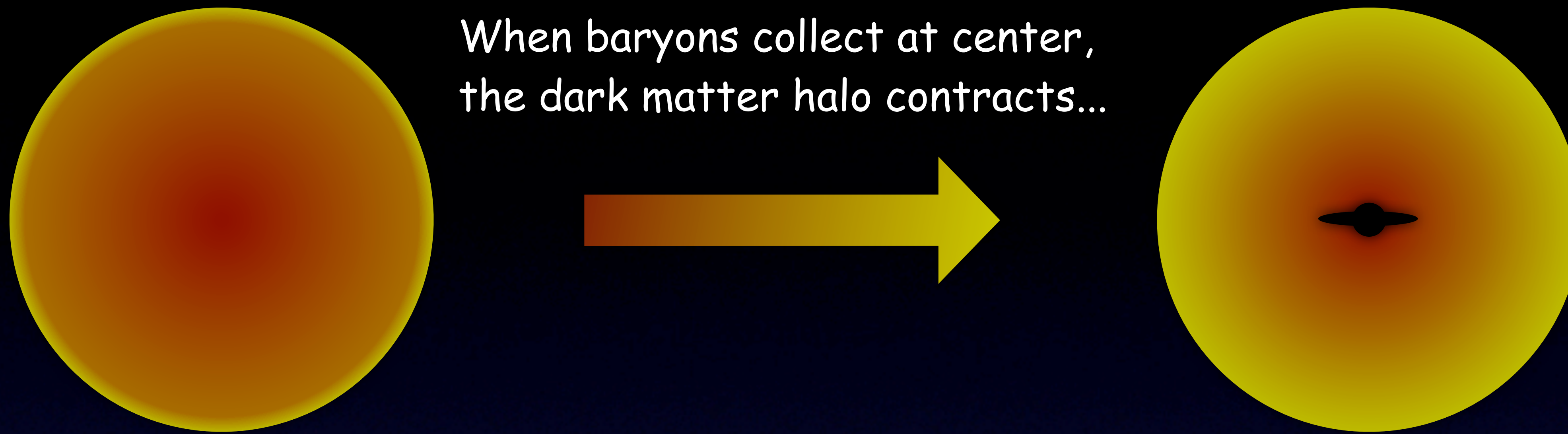
GALACTICUS: sophisticated model including disk self-gravity and AC; "fails to predict correct sizes and velocities of disk galaxies" (Benson & Bower 2010)

Dark Halo Response

When baryons collect at center,
the dark matter halo contracts...



In the limit where the process is slow, the response is adiabatic

spherical symmetry: $r_\mathrm{i}\, M_\mathrm{i}(r_\mathrm{i}) = r_\mathrm{f}\, M_\mathrm{f}(r_\mathrm{f})$

no shell crossing: $M_\mathrm{h,i}(r_\mathrm{i}) = M_\mathrm{h,f}(r_\mathrm{f})$

initially well mixed: $M_\mathrm{b,i}(r_\mathrm{i}) = f_\mathrm{b} M_\mathrm{h,i}(r_\mathrm{i})$

$$\frac{r_\mathrm{f}}{r_\mathrm{i}} = \Gamma_\mathrm{AC} = \frac{M_\mathrm{h,i}(r_\mathrm{i})}{M_\mathrm{b,f}(r_\mathrm{f}) + (1 - f_\mathrm{b}) M_\mathrm{h,i}(r_\mathrm{i})}$$

Blumenthal et al. (1986)

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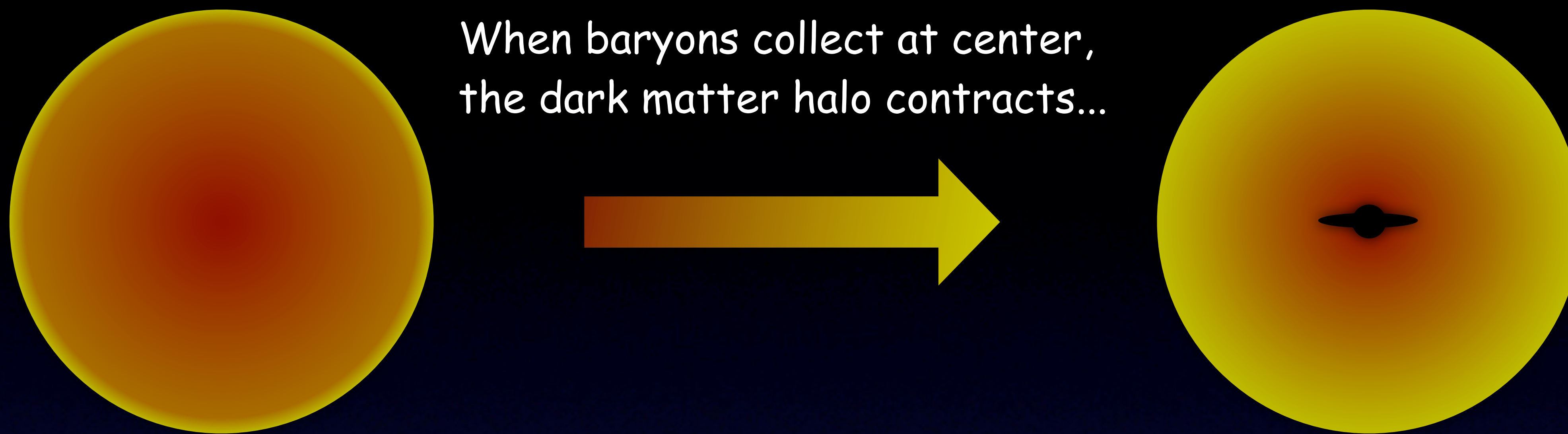

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In general, system is not spherically symmetric and the process of galaxy formation may not be adiabatic. It is useful to adopt the more general form:

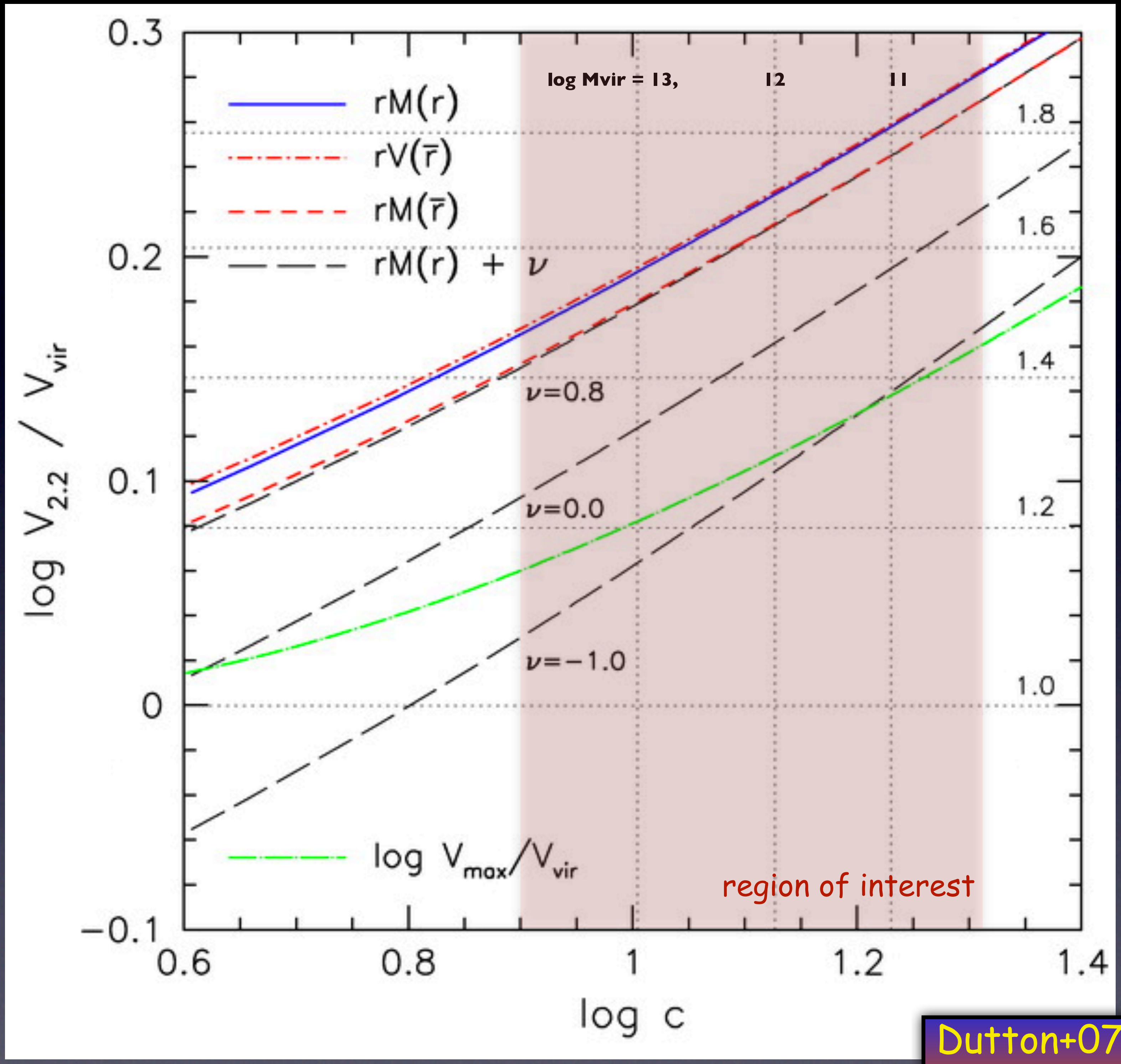
$$\frac{r_\mathrm{f}}{r_\mathrm{i}} = \Gamma_\mathrm{AC}^{\nu}$$

Here ν is a free parameter, to be constrained by the data:

- $\nu = 1$ standard AC
- $\nu = 0$ no contraction
- $\nu < 0$ expansion

[Based on hydro-simulations, Gnedin+04 suggest $\nu \simeq 0.8$, while Abadi+10 find $\nu \simeq 0.4$]

The Optical-to-Virial Velocity Ratio



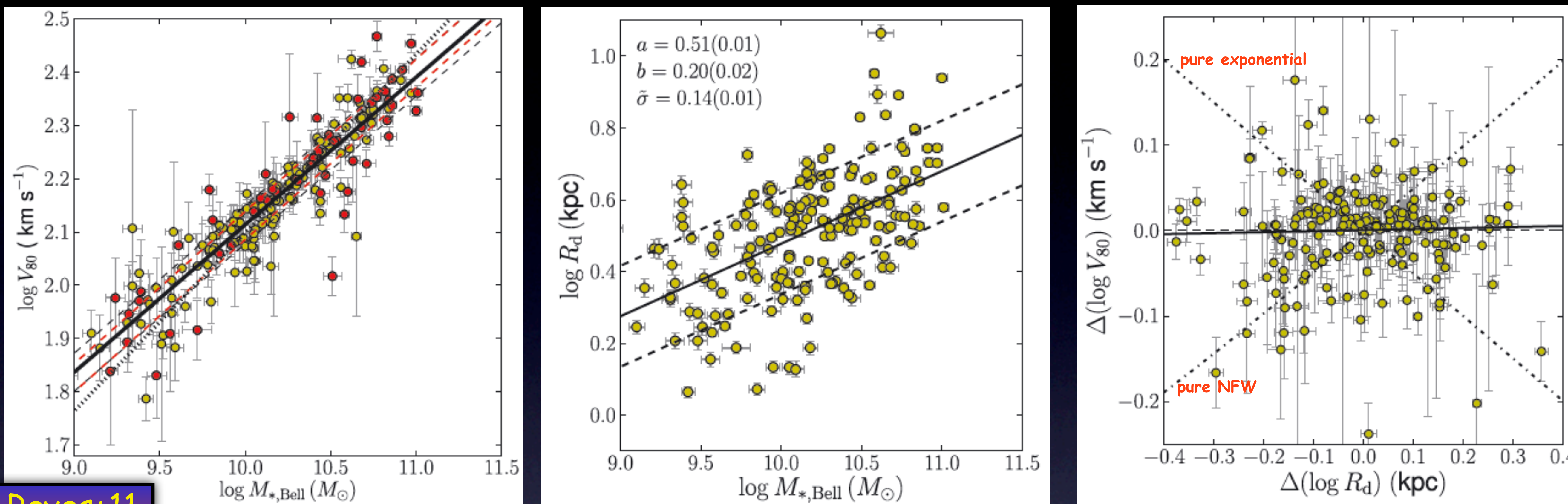
$M_*/M_h = 0.05$

$\lambda_{gal} = 0.048$

Dutton+07

NOTE: assuming $V_{2.2} = V_{max}$ is equivalent to assuming <u>halo expansion</u>

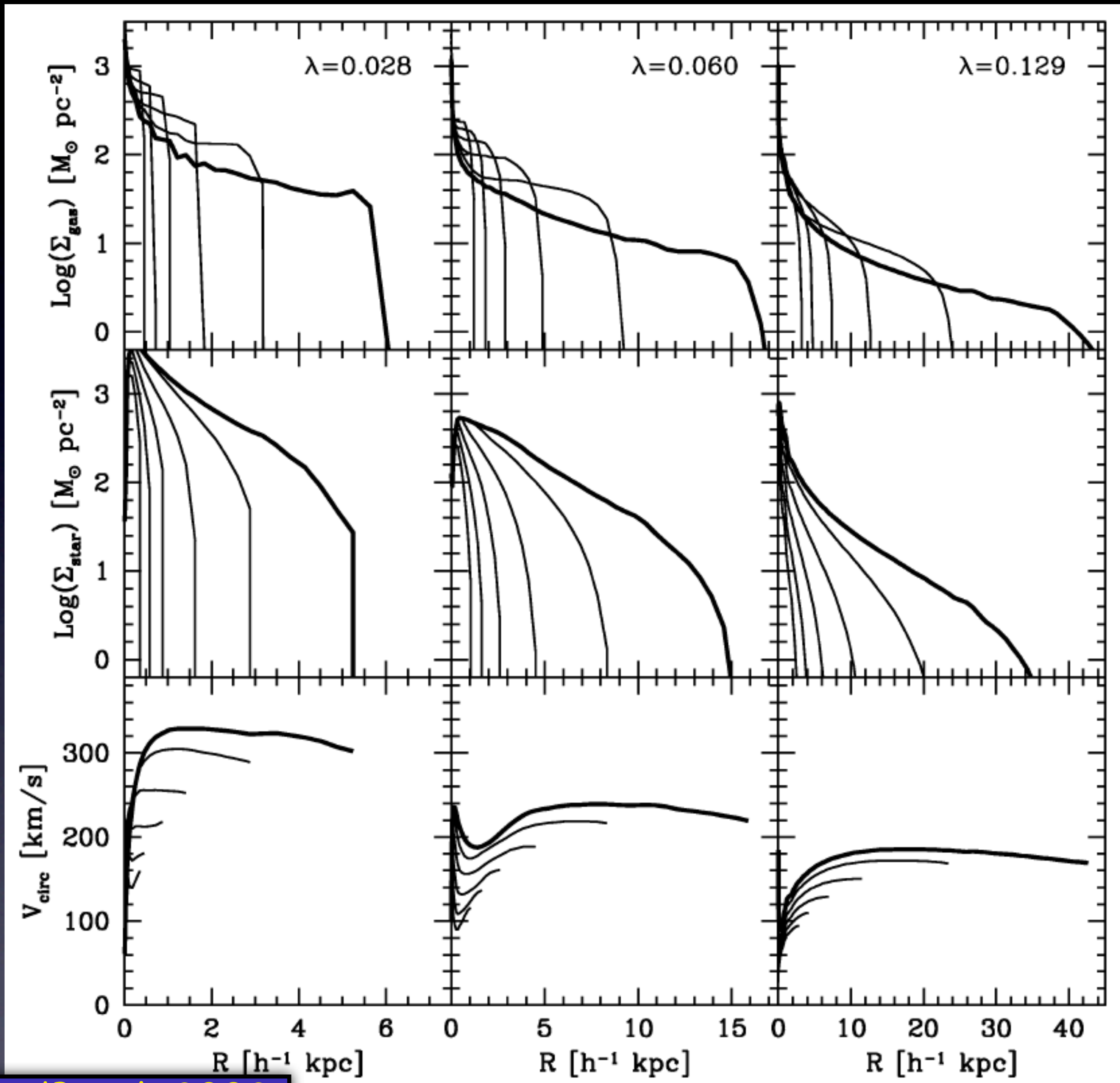
Disk Galaxy Scaling Relations



Reyes+11

- TFR has min. scatter (0.036 ± 0.005 dex) when using $M_{*,\rm Bell}$ and V_{80} (Reyes et al. 2011)
- The velocity-mass (TF) and size-mass residuals are uncorrelated; this constrains the contribution of the disk to the measured rotation velocity (Courteau & Rix 1999)
- When using M_{bar} and R_{bar}, instead of M_* and R_*, the slope of the residual correlation is -0.15. Hence, R_{bar} is a third parameter in the <u>baryonic</u> TFR (Avila-Reese et al. 2008)

Model Predictions



vdBosch 2002

Naive prediction:

If haloes of same mass yield disk galaxies of same M_*, then scatter in spin parameter can yield large scatter in V_{rot}. This scatter is anti-correlated with disk size....

NOTE: model assumes flat LCDM cosmology with σ_8=1 and no feedback (illustration only)

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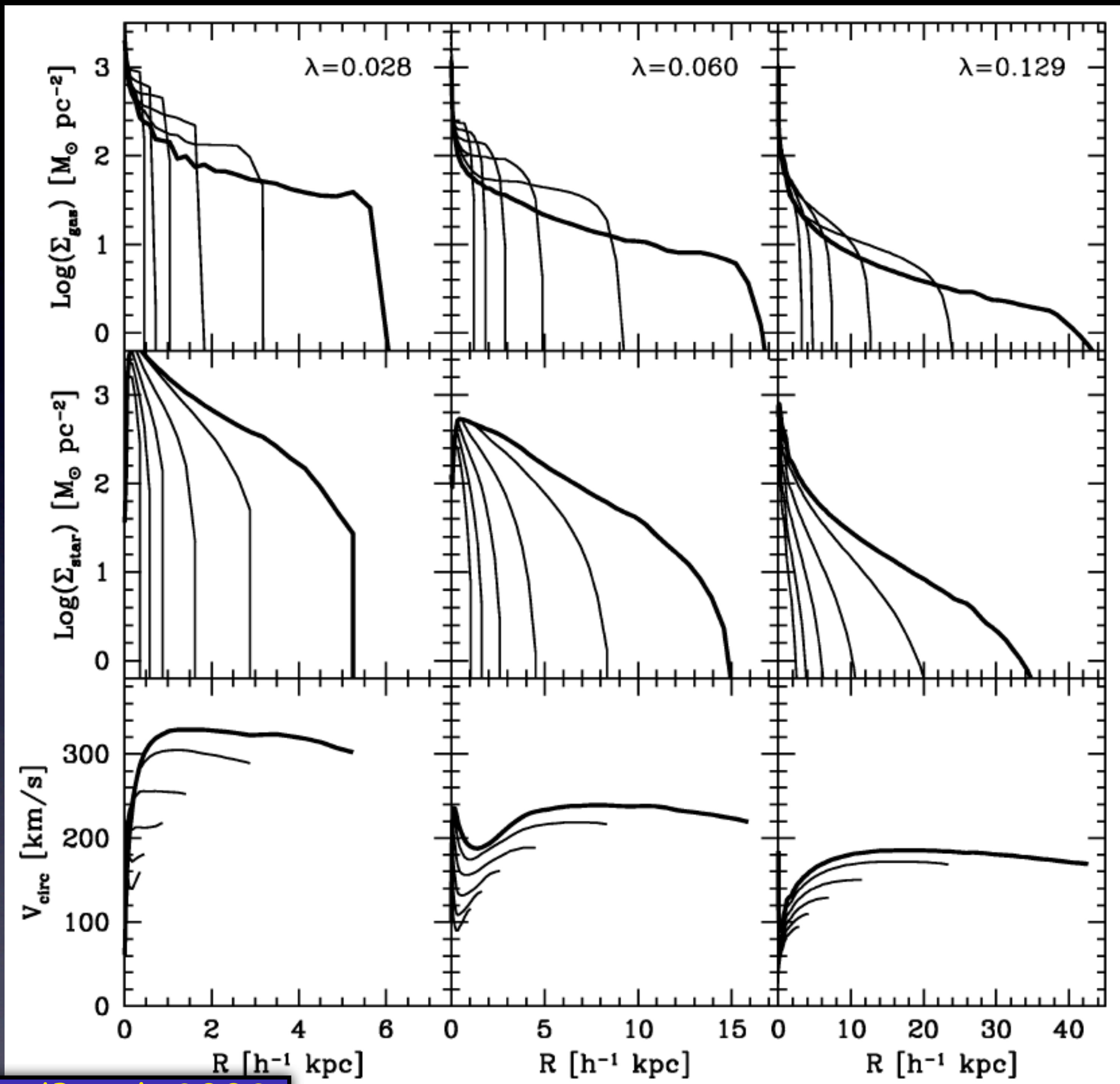

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Ways out:

- M_* is correlated with spin parameter. Natural outcome of SF threshold
  Firmani & Avila-Reese (2000)
  van den Bosch (2000)
- Self-gravity of disk is reduced (add feedback)
- Adiabatic contraction does not happen or is counter-acted Dutton et al. (2007)

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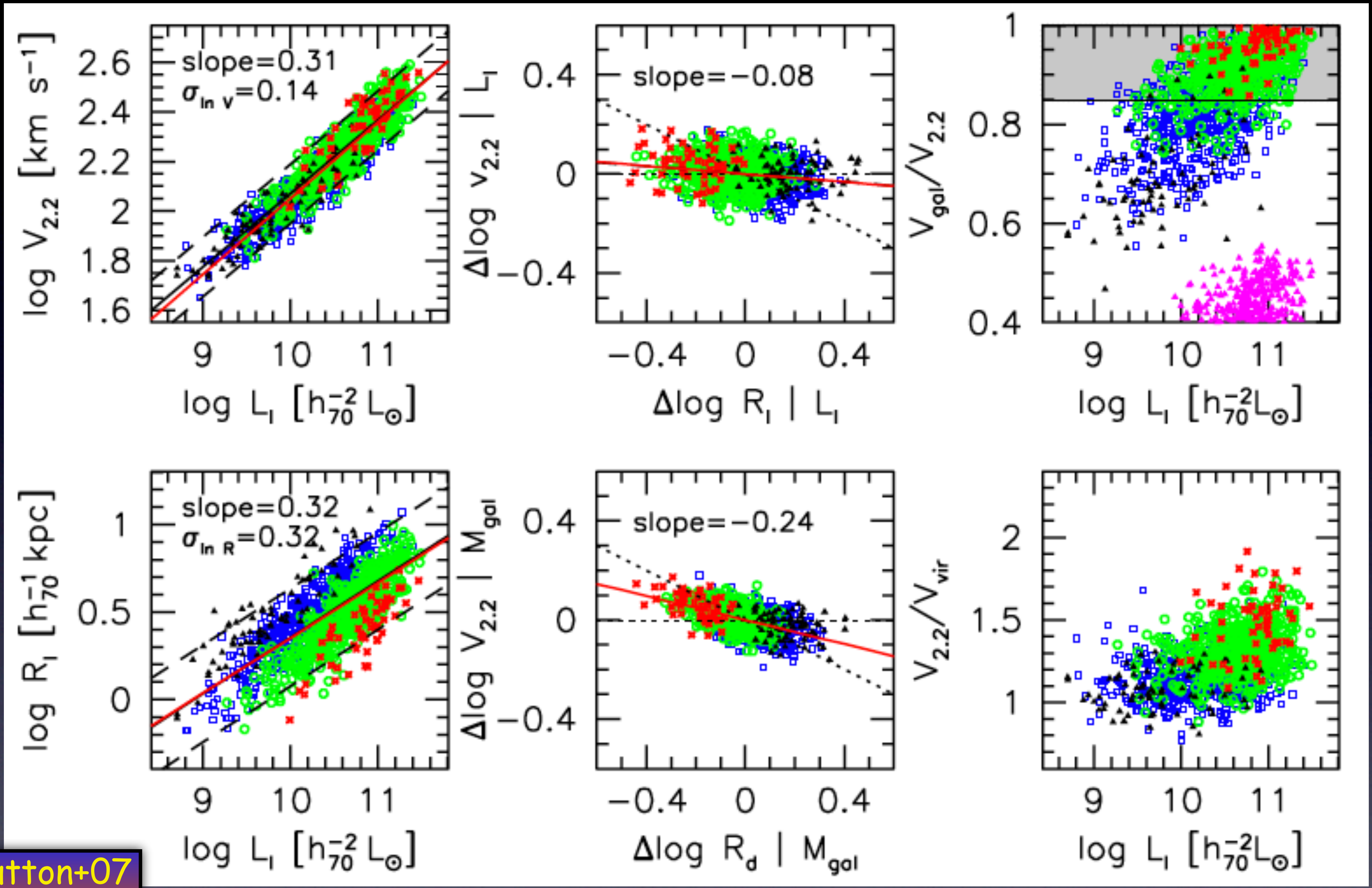
Towards a Working Model...



Dutton+07

Matching data requires <u>halo expansion</u> (ν =-1) and <u>low spin parameters</u> ($\lambda_{gal} \approx \lambda_{halo}/2$)
Note that this model predicts a significant correlation in the residual plot for the baryonic relations, which has since been confirmed by Avila-Reese+08.

Independent Determination of V_{opt}/V_{vir}

- Use satellite kinematics (or other methods) to infer $M_* - M_h$ relation.
- Convert halo mass to V_{vir}.
- Use stellar mass TFR to convert stellar mass to V_{opt}.
- This yields V_{opt}/V_{vir} as function of M_* [Dutton+10, Reyes+12]

Satellite Kinematics

We use satellite kinematics in the SDSS to probe the relation between stellar mass and halo mass. Using virial equilibrium and spherical collapse:

$$\sigma^2 \propto \frac{GM_{\rm h}}{r_{\rm h}} \qquad M_{\rm h} \propto r_{\rm h}^3 \qquad \sigma \propto M_{\rm h}^{1/3}$$

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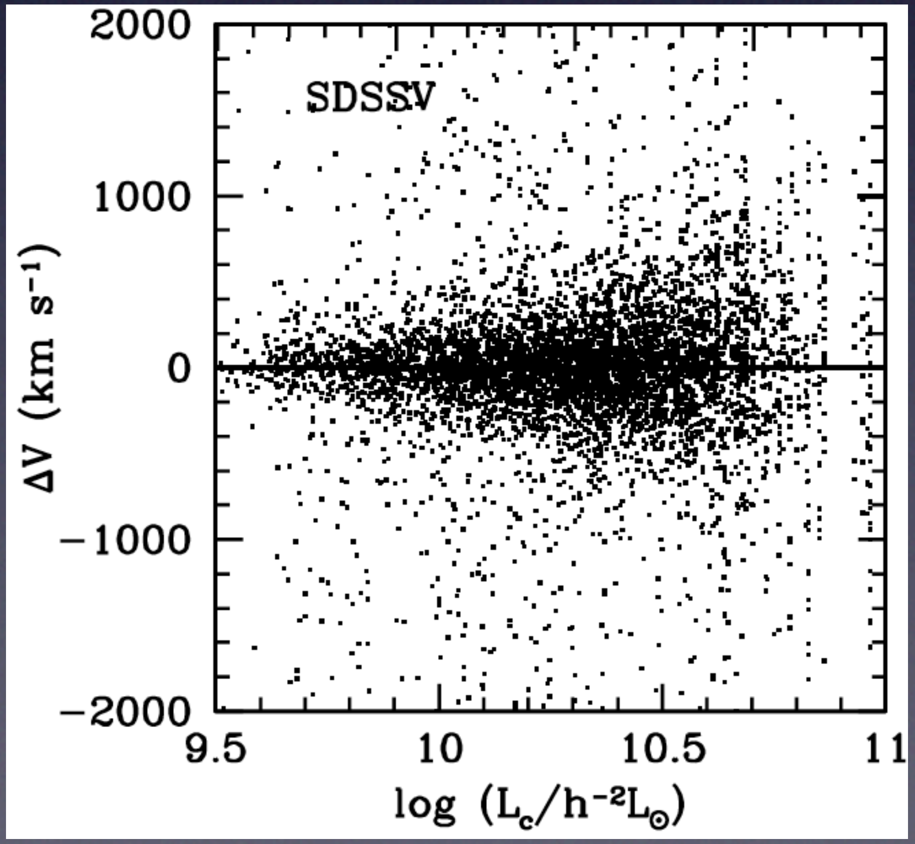
On average, only ~2 satellites per central: → **stacking**

- select centrals and satellites from SDSS
- using redshifts, measure $\Delta V = V_{\rm sat} - V_{\rm cen}$ as function of M_*



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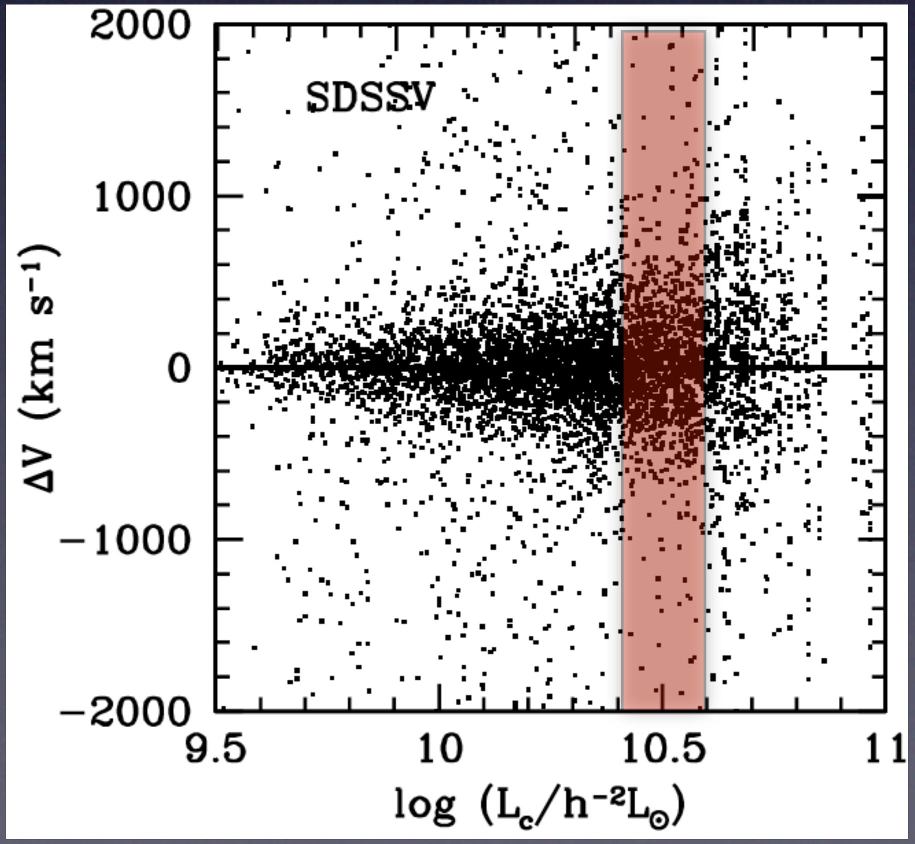
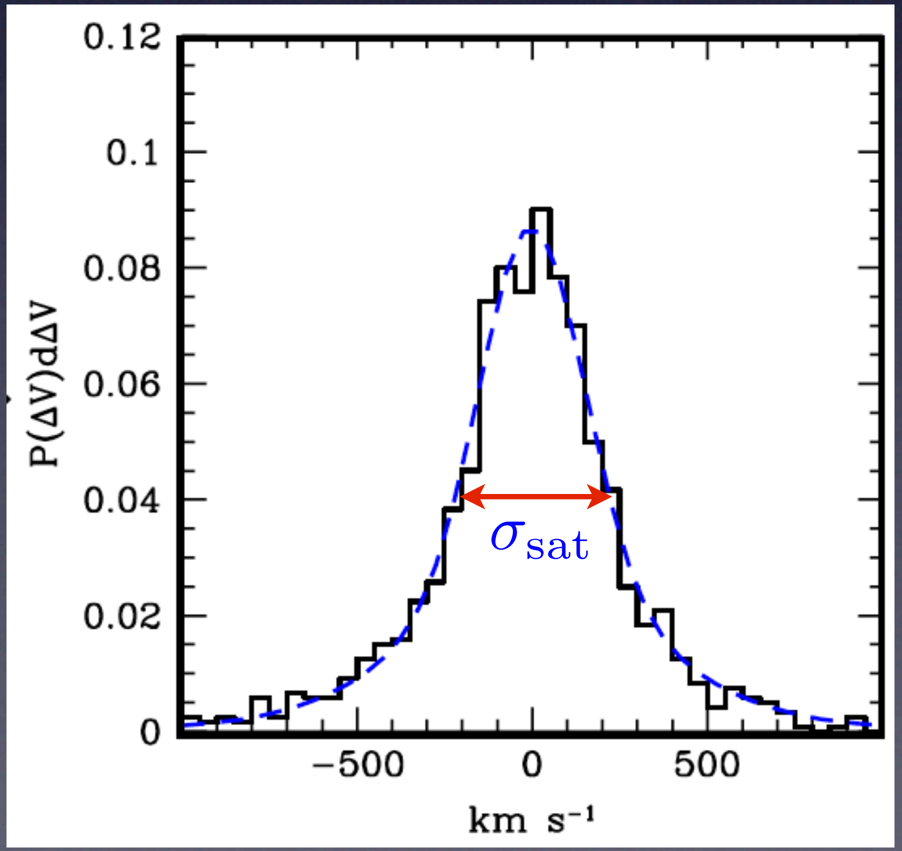




Satellite Kinematics

Unless $P(M_{\rm h}|M_*)$ is a Dirac Delta function, stacking implies combining haloes of different masses. Consequently, distinguish two schemes:

satellite weighting:

$$\sigma^2_{\rm sw}(M_*) = \frac{\int P(M_{\rm h}|M_*)\,\langle N_{\rm s}|M_{\rm h}\rangle\,\sigma^2_{\rm sat}(M_{\rm h})\,{\rm d}M_{\rm h}}{\int P(M_{\rm h}|M_*)\,\langle N_{\rm s}|M_{\rm h}\rangle\,{\rm d}M_{\rm h}}$$

host weighting:

$$\sigma^2_{\rm hw}(M_*) = \frac{\int P(M_{\rm h}|M_*)\,\sigma^2_{\rm sat}(M_{\rm h})\,{\rm d}M_{\rm h}}{\int P(M_{\rm h}|M_*)\,{\rm d}M_{\rm h}}$$

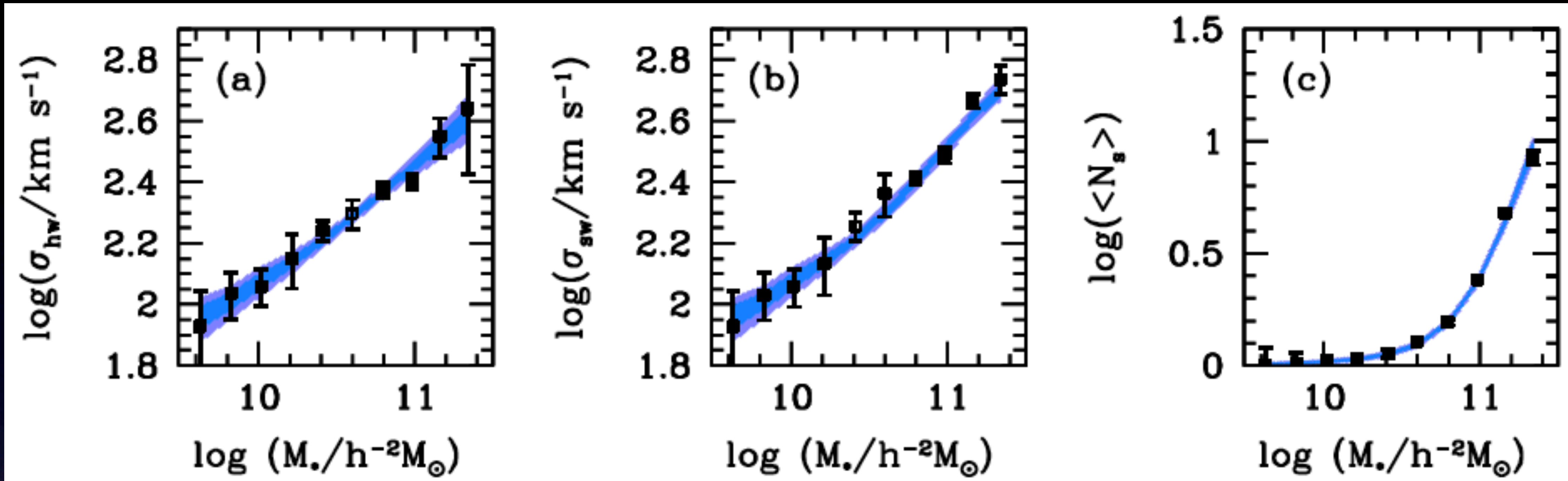
satellites per host:

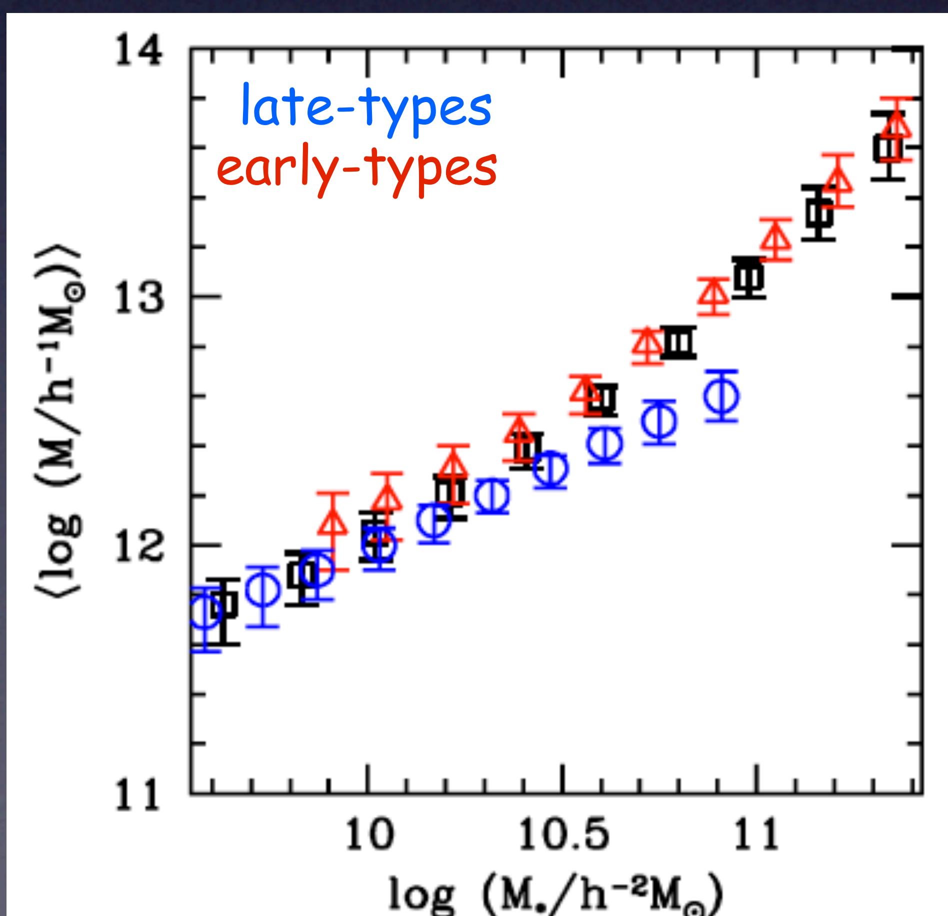
$$\langle N_{\rm sat}\rangle(M_*) = \frac{\int P(M_{\rm h}|M_*)\,\langle N_{\rm s}|M_{\rm h}\rangle\,{\rm d}M_{\rm h}}{\int P(M_{\rm h}|M_*)\,{\rm d}M_{\rm h}}$$

From the measurements of $\sigma^2_{\rm sw}(M_*)$, $\sigma^2_{\rm hw}(M_*)$, and $\langle N_{\rm sat}\rangle(M_*)$ one can determine $P(M_{\rm h}|M_*)$.

[More, vdB & Cacciato 2009]

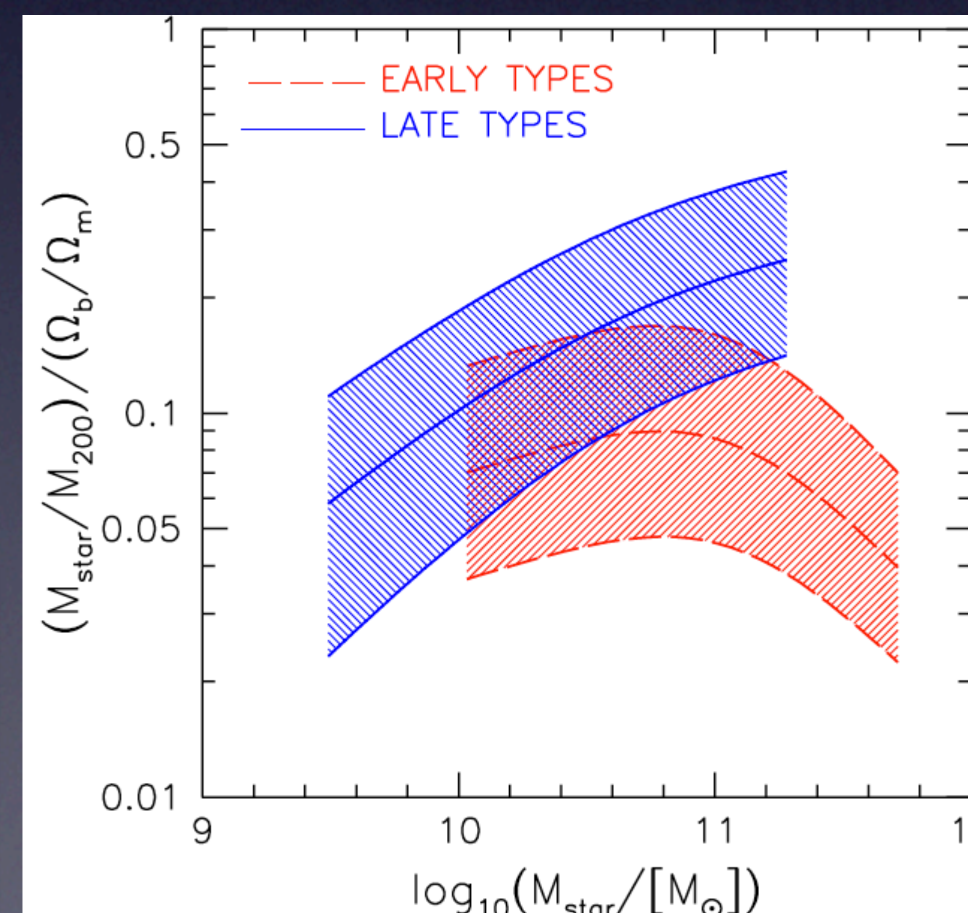
Satellite Kinematics: results





based on ~6300 satellites around ~3800 centrals

[More et al. 2011]



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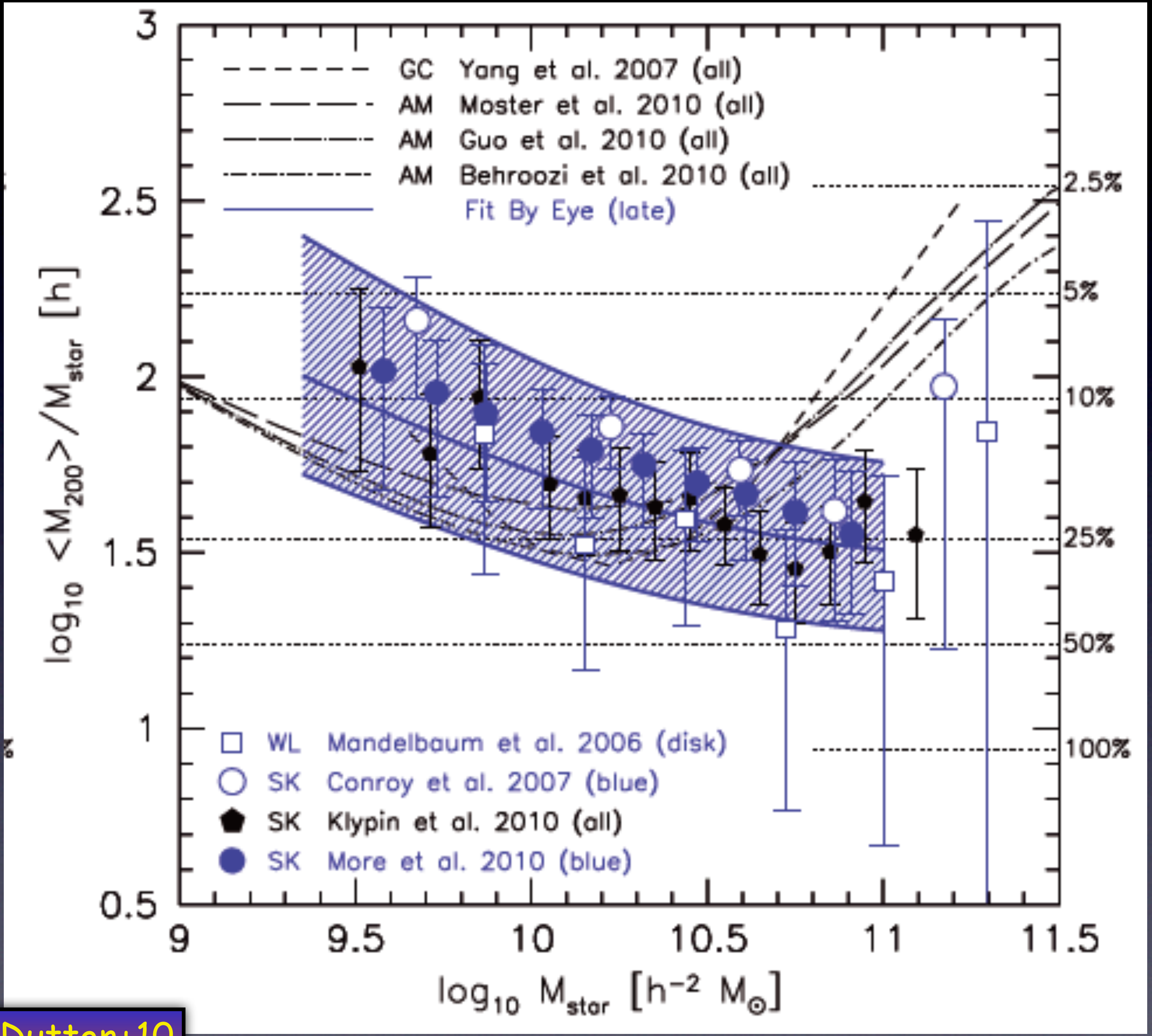

Dutton+10

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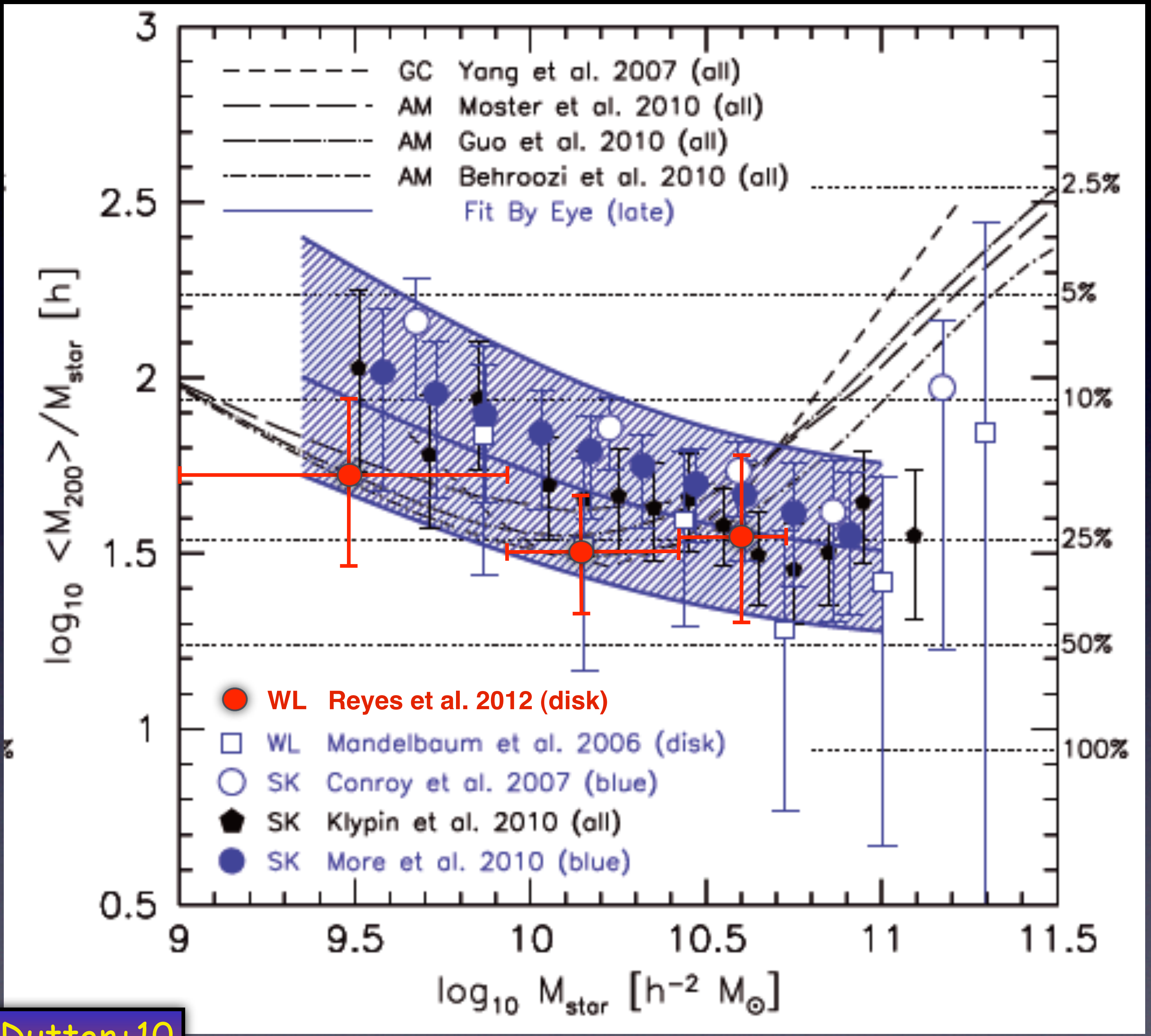
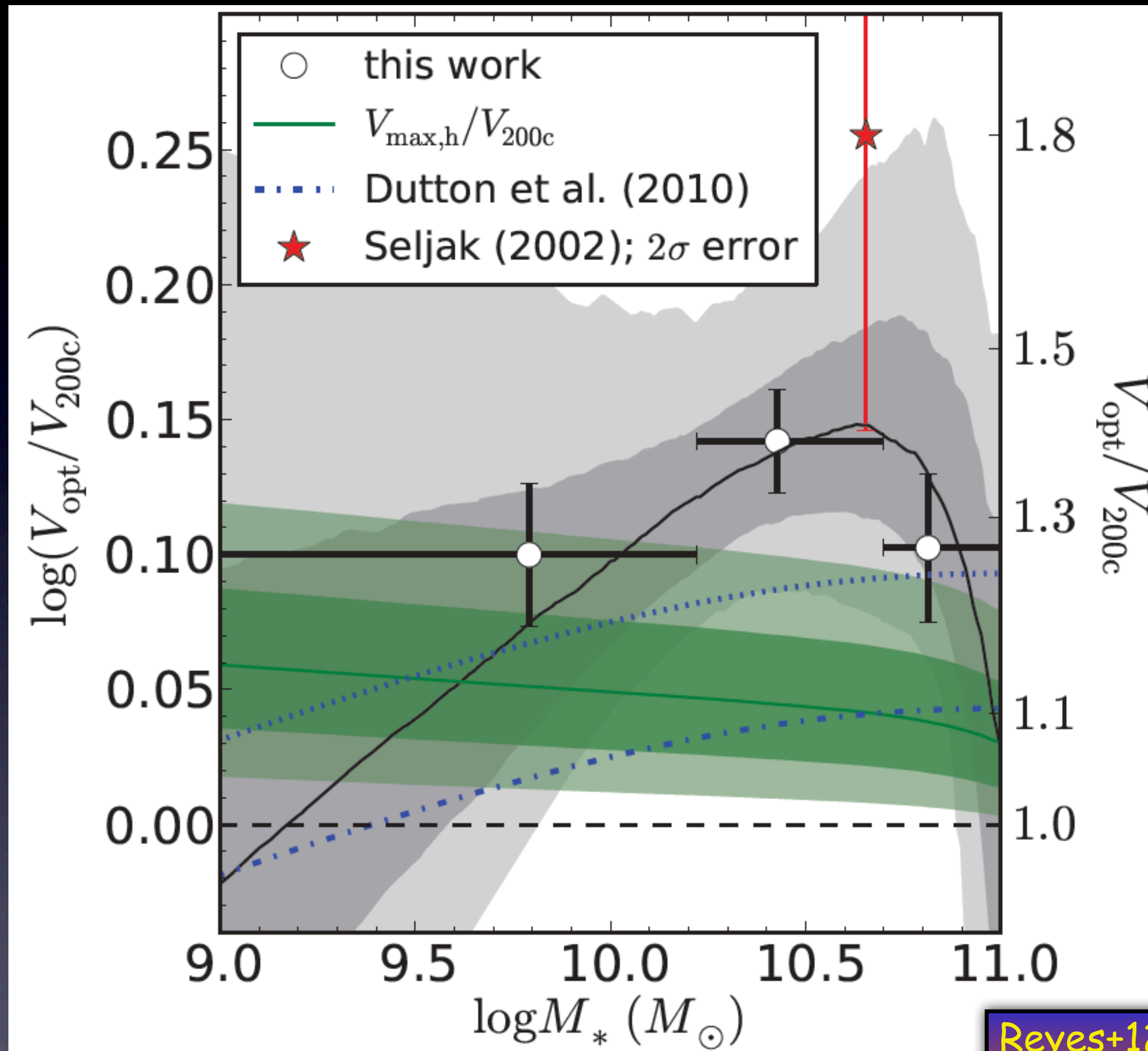


Dutton+10

Optical-to-Virial Velocities



Reyes+12

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Error bars still too large to place firm constraints: dominated by errors on M_*/M_{vir}

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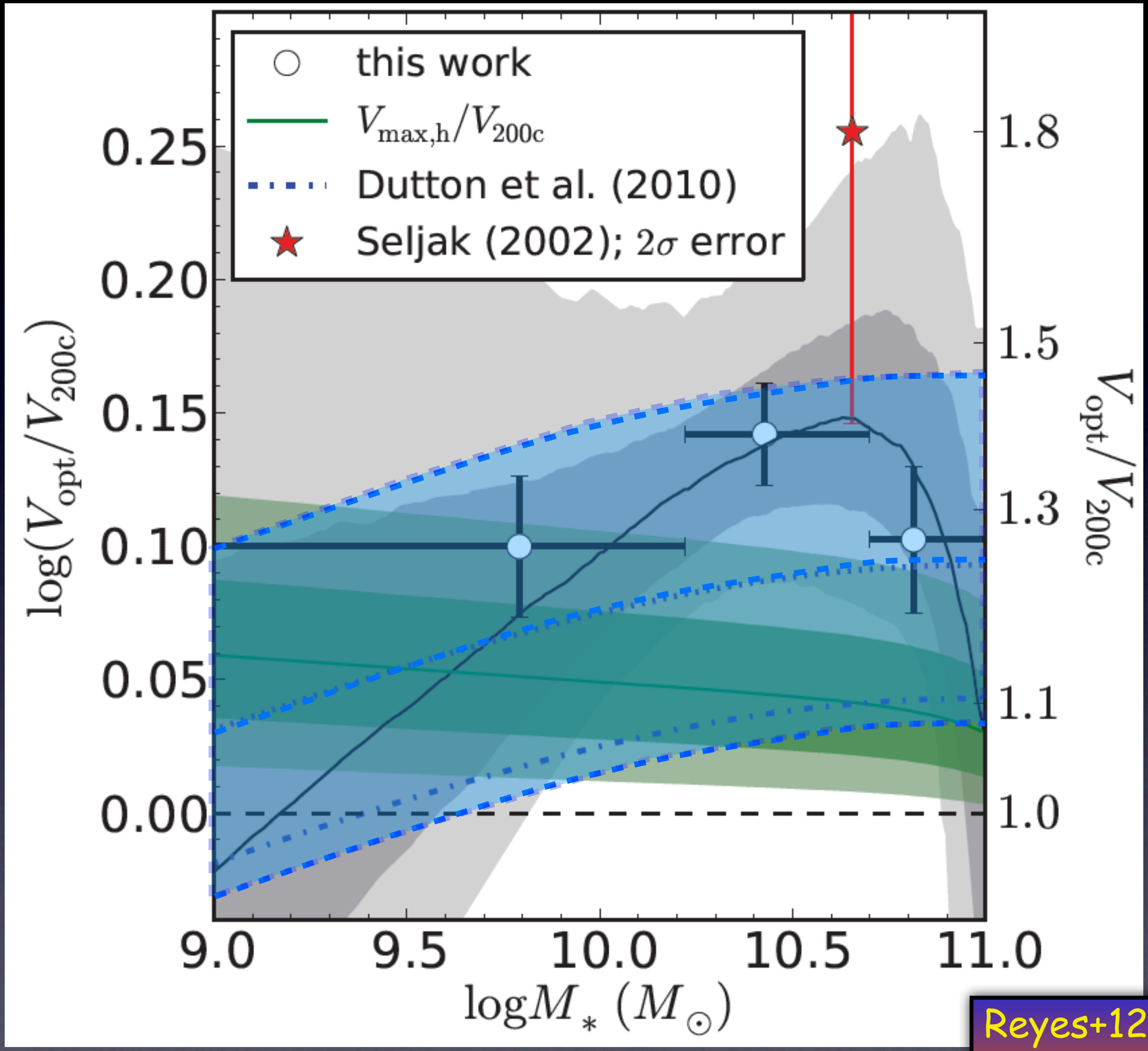

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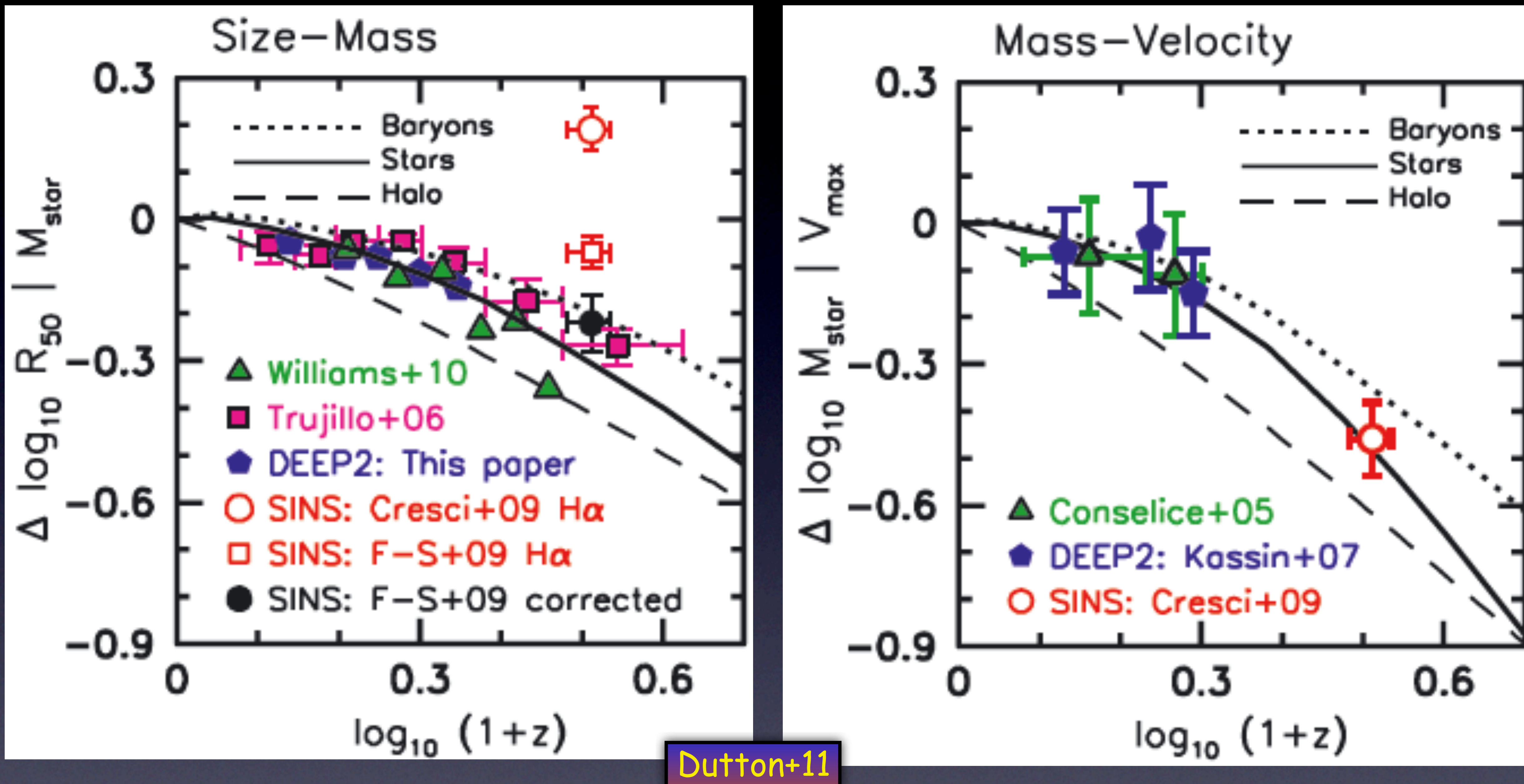
Redshift Evolution



The `standard' picture of disk formation can nicely explain the evolution in the scaling relations of disk galaxies. See also Firmani & Avila-Reese (2009)

Scaling relations & angular momentum

Structure of disk galaxies is governed by their angular momentum distribution

In ‘standard model’, this angular momentum arises from cosmological torques, and is conserved during cooling....

As shown by Mo, Mao & White (1998), in this case one has that

$$R_{\rm d} = \frac{1}{\sqrt{2}}\,\lambda\,\left(\frac{j_{\rm d}}{m_{\rm d}}\right)\,R_{\rm vir}\,F_R^{-1}\,F_E^{-1/2}$$

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halo spin parameter

halo profile

adiabatic contraction

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In 'standard model', this angular momentum arises from cosmological torques, and is conserved during cooling....

As shown by Mo, Mao & White (1998), in this case one has that

$$R_{\rm d} = \frac{1}{\sqrt{2}} \lambda \left(\frac{j_{\rm d}}{m_{\rm d}} \right) R_{\rm vir} F_R^{-1} F_E^{-1/2}$$

halo spin parameter

halo profile

adiabatic contraction

But what about j_d/m_d (almost always assumed to be unity) ???

j_d: fraction of angular momentum that ends up in disk

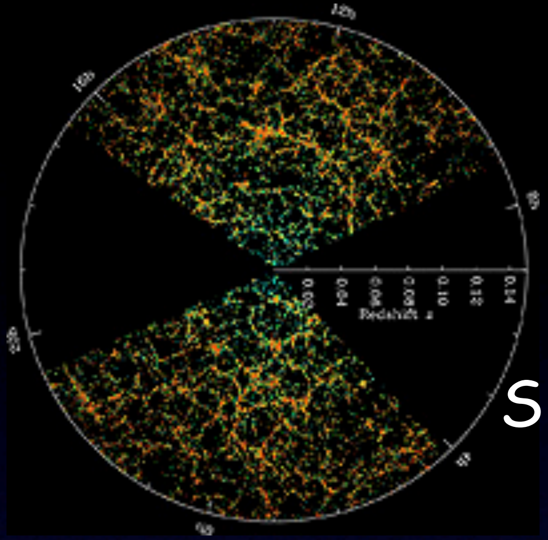
m_d: fraction of baryonic matter that ends up in disk

Methodology

Dutton+11

Observed Scaling Relations

M_h *vs.* M_*	R_d *vs.* M_*	B/D *vs.* M_*
M_g *vs.* M_*	R_b *vs.* M_*	R_g *vs.* R_d



SDSS

Model Parameters

$M_\mathrm{h}, M_\mathrm{d}, M_\mathrm{b}, M_\mathrm{g}$

$R_\mathrm{d}, R_\mathrm{b}, R_\mathrm{g}$

Δ_IMF ν

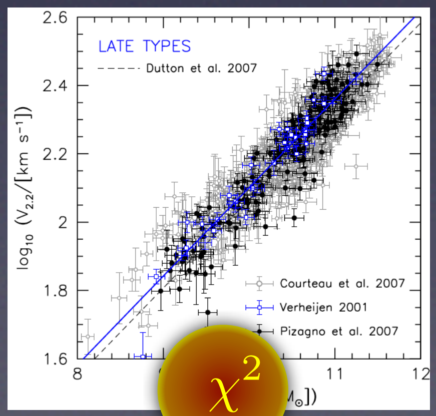
Rotation Curve

$$V_c(r) = \sqrt{V_\mathrm{h}^2 + V_\mathrm{d}^2 + V_\mathrm{b}^2 + V_\mathrm{g}^2}$$

$V_{2.2}$

Sampling of M_h

TF relation



χ^2

compare to data

Constrain

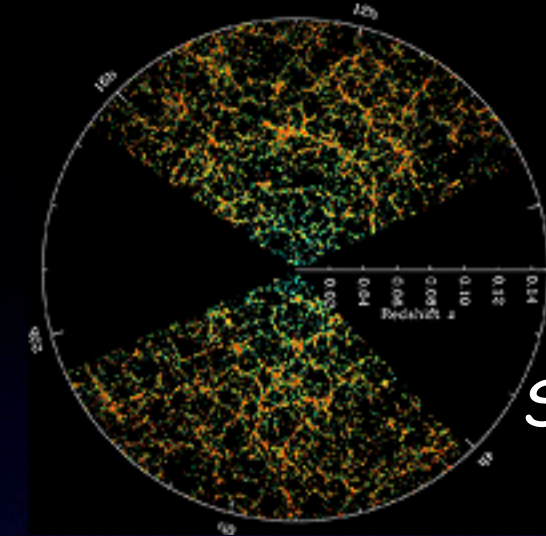
Δ_IMF & ν

Methodology

Dutton+11

Observed Scaling Relations

$M_{\rm h}$ *vs.* M_*	$R_{\rm d}$ *vs.* M_*	B/D *vs.* M_*
$M_{\rm g}$ *vs.* M_*	$R_{\rm b}$ *vs.* M_*	$R_{\rm g}$ *vs.* $R_{\rm d}$



SDSS

Model Parameters

$M_{\rm h}, M_{\rm d}, M_{\rm b}, M_{\rm g}$
$R_{\rm d}, R_{\rm b}, R_{\rm g}$
$\Delta_{\rm IMF}$ ν

Rotation Curve

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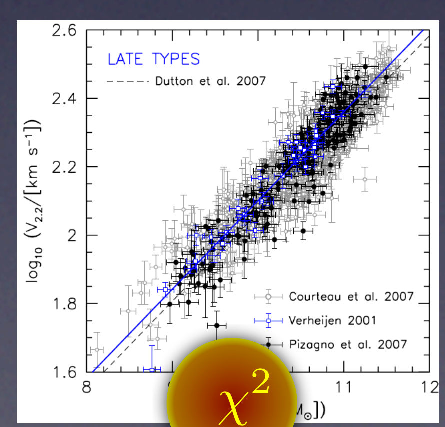
$V_{2.2}$

Sampling of $M_{\rm h}$

TF relation

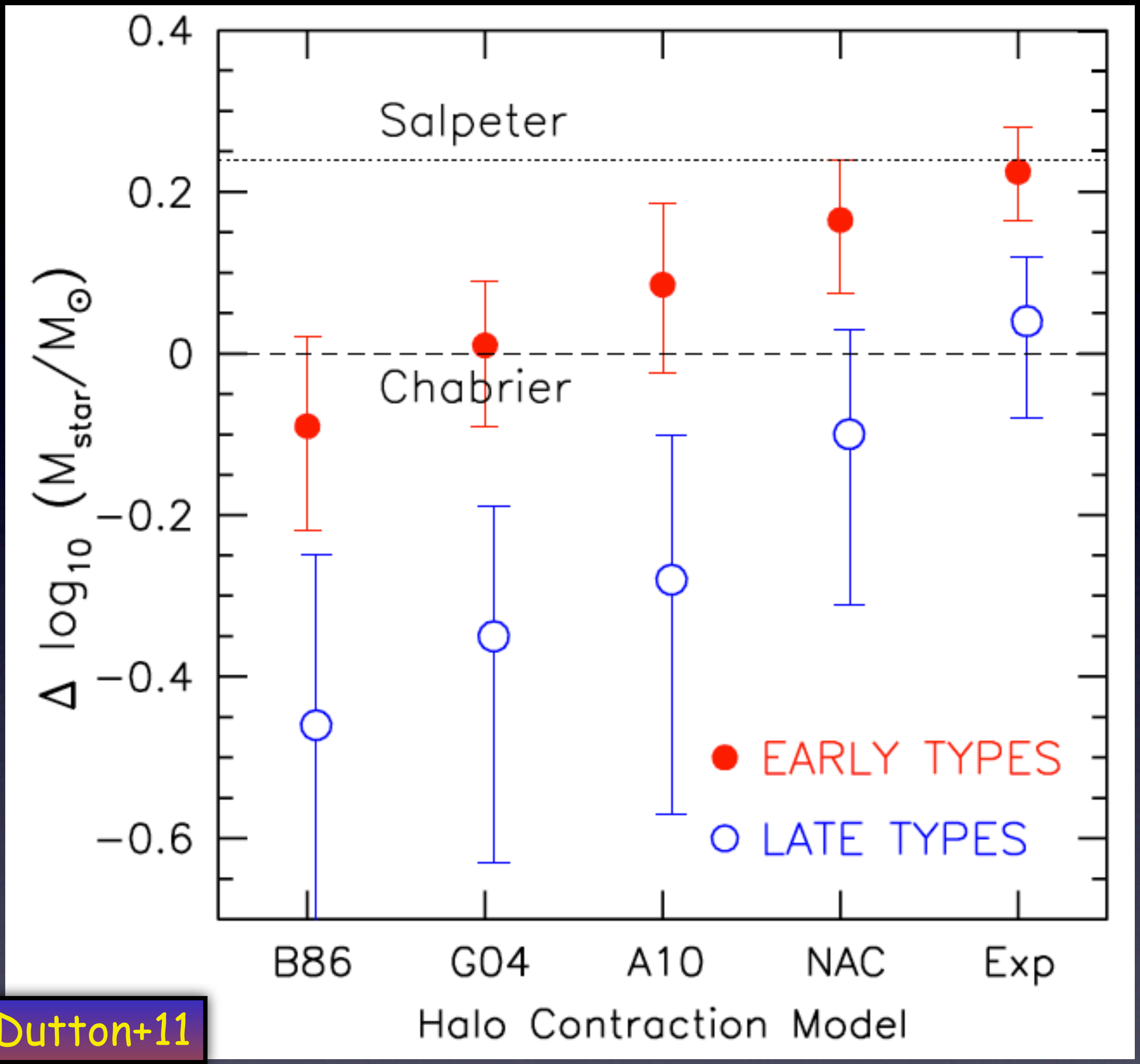


χ^2

compare to data

Constrain $\Delta_{\rm IMF}$ & ν

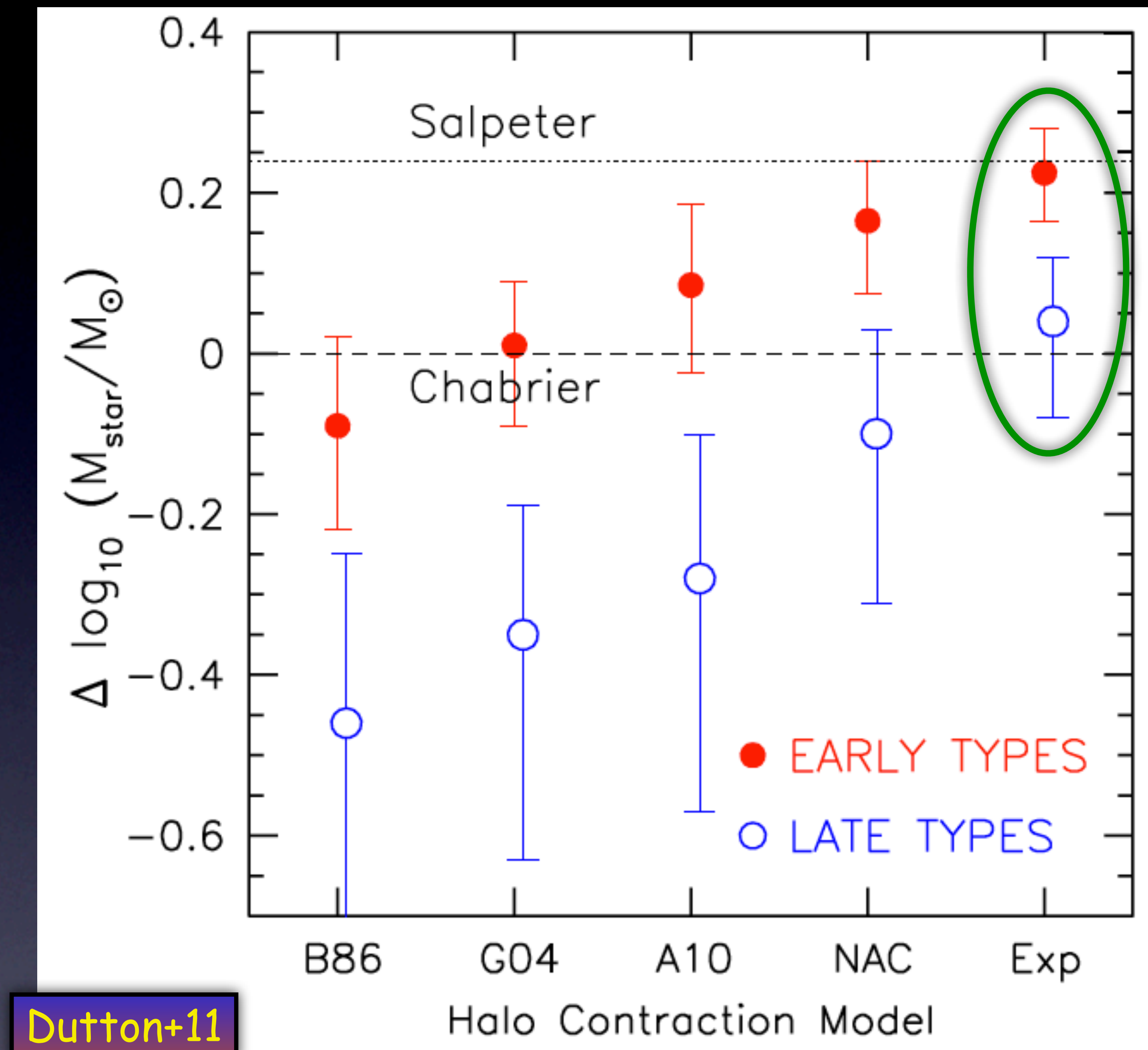
Dark Halo Response vs. Stellar IMF



Dutton+11

- With `standard' adiabatic contraction (B86; ν=1), the stellar IMF needs to be significantly more top-heavy than a Chabrier IMF (unrealistic).
- With Chabrier IMF, disk scaling relations suggest halo expansion...

Dark Halo Response vs. Stellar IMF



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Methodology

Dutton+vdB 2012

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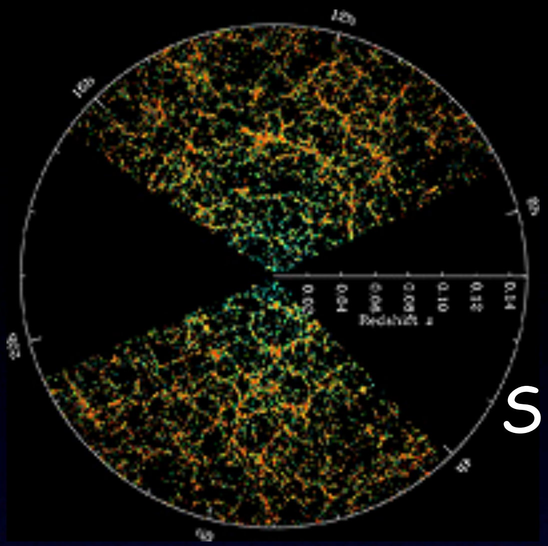
$M_{\rm g}$ *vs.* M_*	$R_{\rm b}$ *vs.* M_*	$R_{\rm g}$ *vs.* $R_{\rm d}$



SDSS

Model Parameters

$M_{\rm h}, M_{\rm d}, M_{\rm b}, M_{\rm g}$

$R_{\rm d}, R_{\rm b}, R_{\rm g}$

$\Delta_{\rm IMF}$ ν

Methodology

Dutton+vdB 2012

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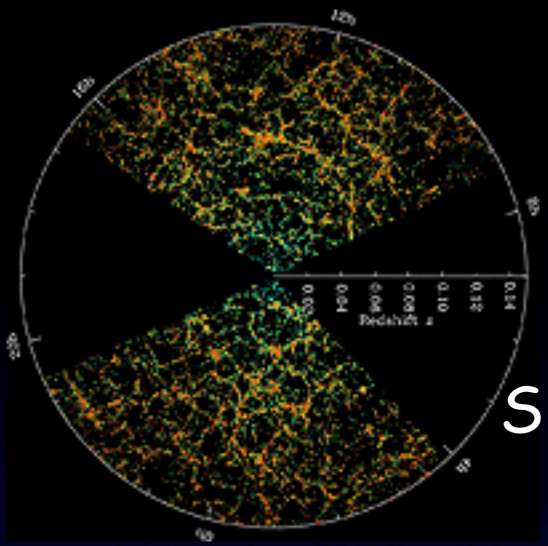

SDSS

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$M_{\rm gal}/M_{\rm vir}$

Methodology

Dutton+vdB 2012

Observed Scaling Relations

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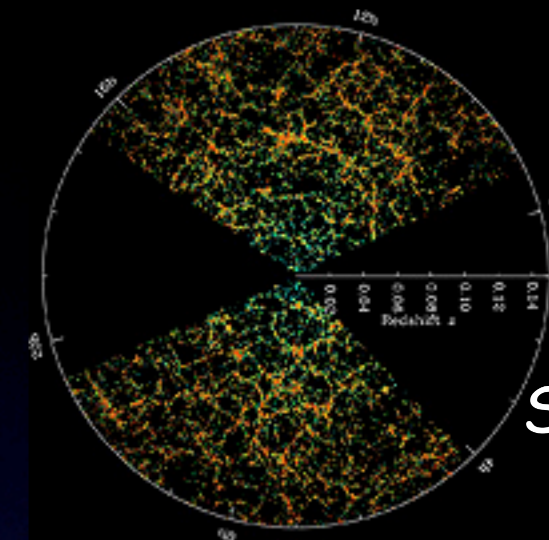


SDSS

Model Parameters

$M_{\rm h}, M_{\rm d}, M_{\rm b}, M_{\rm g}$

$R_{\rm d}, R_{\rm b}, R_{\rm g}$

$\Delta_{\rm IMF}$ ν

Rotation Curve

$$V_c(r) = \sqrt{V_{\rm h}^2 + V_{\rm d}^2 + V_{\rm b}^2 + V_{\rm g}^2}$$

$M_{\rm gal}/M_{\rm vir}$

$J_{\rm gal}/J_{\rm vir}$

$\lambda'_{\rm vir} = 0.031$

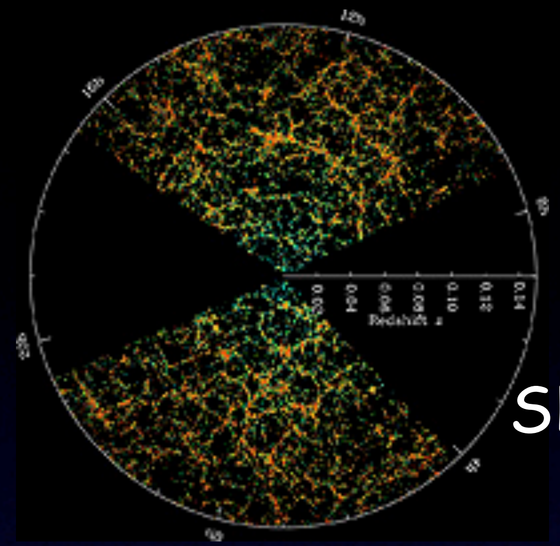
Methodology

Dutton+vdB 2012

Observed Scaling Relations

$M_{\rm h}$ *vs.* M_* $R_{\rm d}$ *vs.* M_* B/D *vs.* M_*

$M_{\rm g}$ *vs.* M_* $R_{\rm b}$ *vs.* M_* $R_{\rm g}$ *vs.* $R_{\rm d}$



SDSS

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$R_{\rm d}, R_{\rm b}, R_{\rm g}$

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$$V_c(r) = \sqrt{V_{\rm h}^2 + V_{\rm d}^2 + V_{\rm b}^2 + V_{\rm g}^2}$$

$\lambda'_{\rm vir} = 0.031$

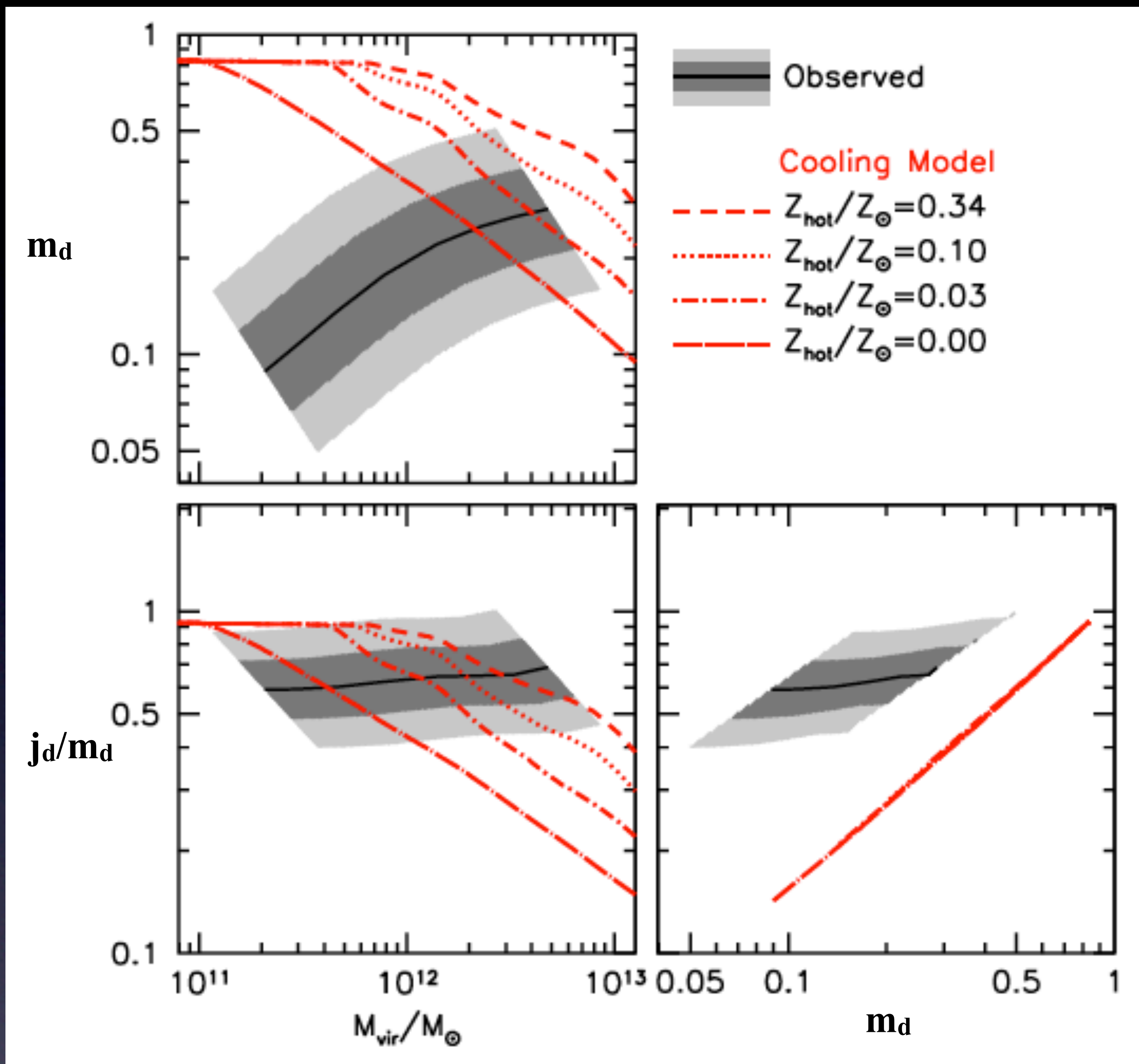
$M_{\rm gal}/M_{\rm vir}$

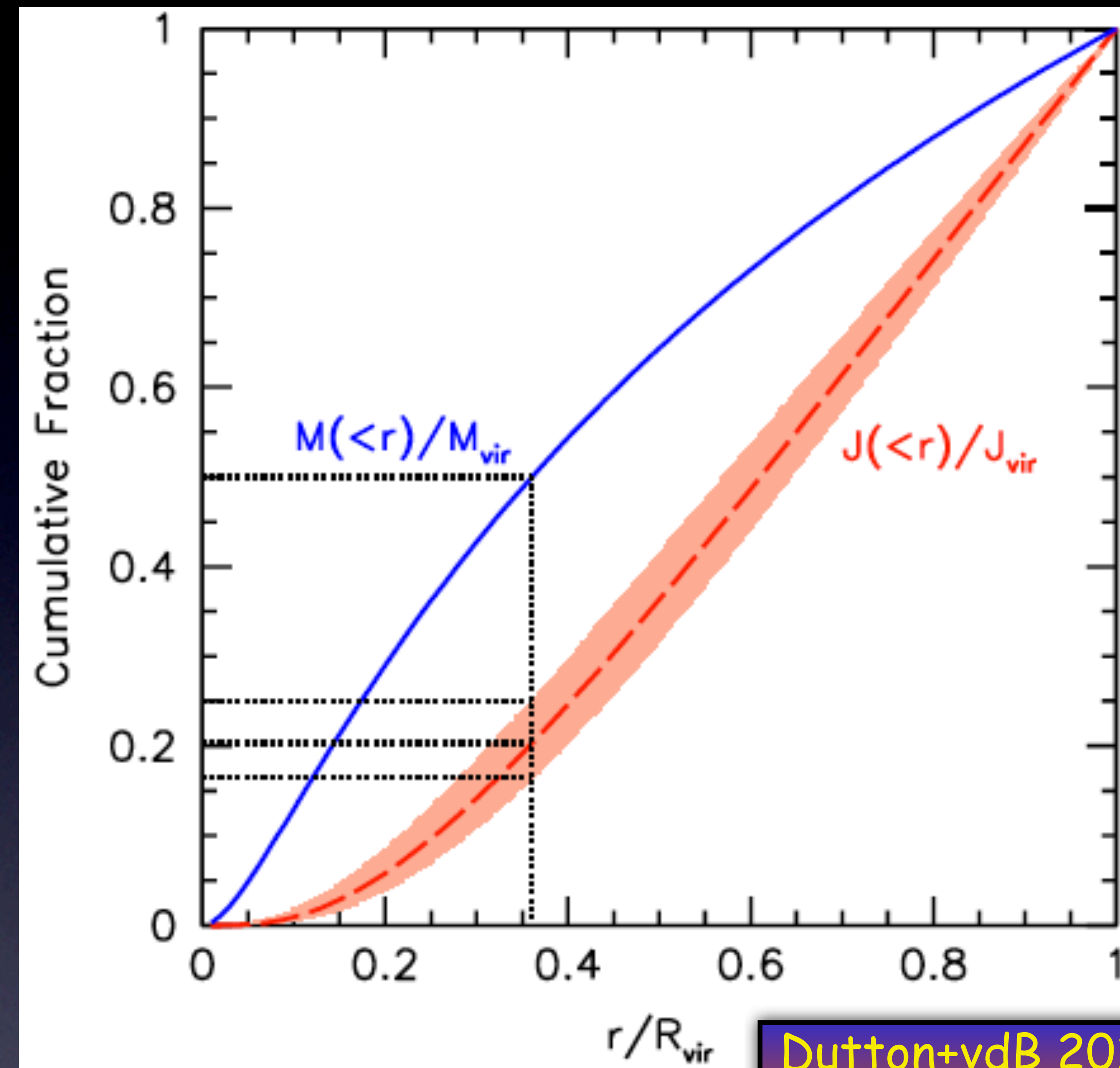
$J_{\rm gal}/J_{\rm vir}$

$$m_{\rm d} \equiv \frac{M_{\rm gal}/M_{\rm vir}}{\Omega_{\rm b}/\Omega_{\rm m}}$$

$$\frac{j_{\rm d}}{m_{\rm d}} \equiv \frac{J_{\rm gal}/J_{\rm vir}}{M_{\rm gal}/M_{\rm vir}}$$

The Assembly of Mass and Angular Momentum

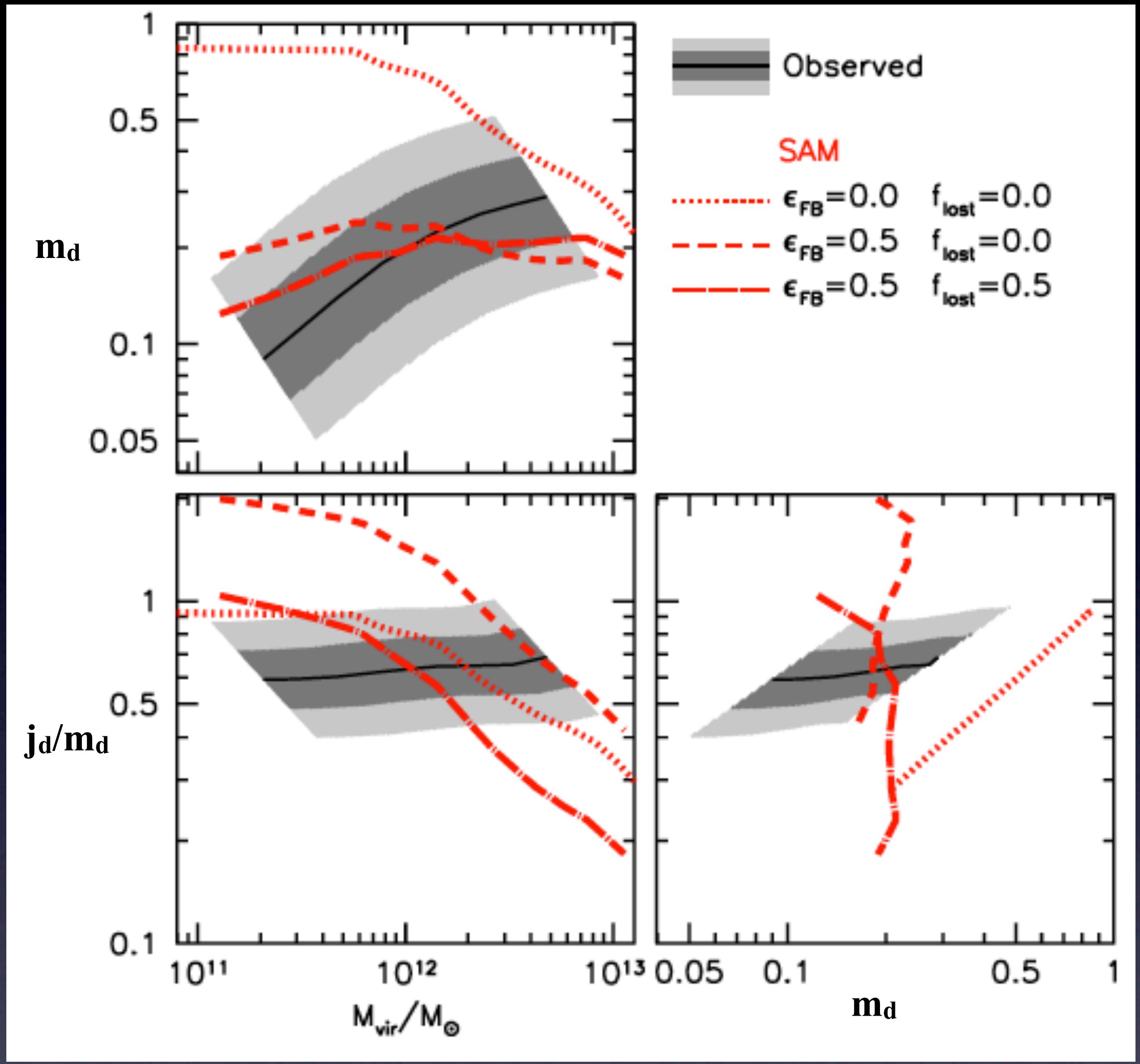


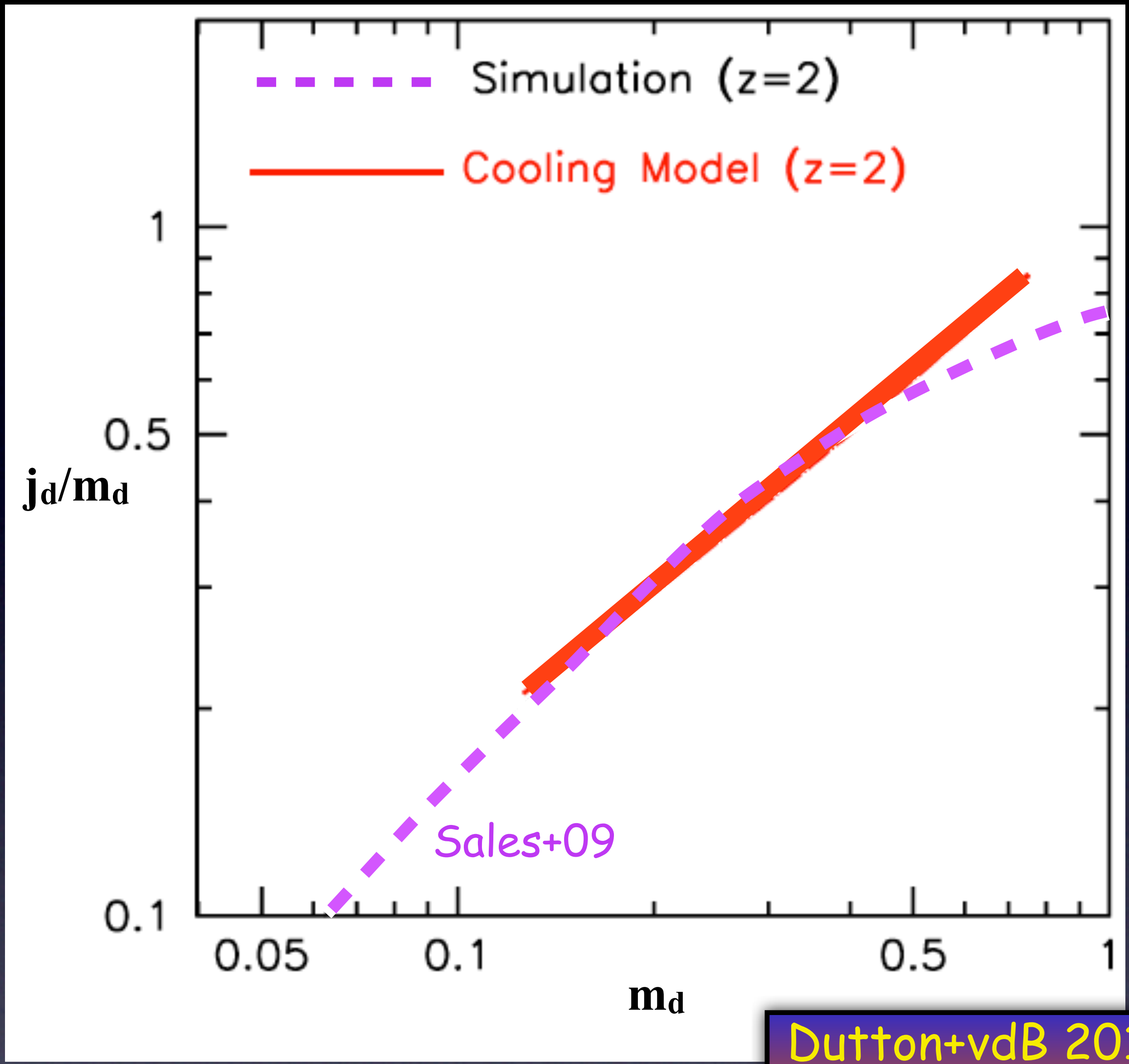


Dutton+vdB 2012

- The gray-shaded areas mark region in `galaxy-formation-space' that are required in order to yield disks with the observed scaling relations.
- m_d has strong halo-mass dependence, j_d/m_d does not.
- This is NOT a `natural' outcome of a scenario in which disks form `inside-out'

The Assembly of Mass and Angular Momentum





Dutton+vdB 2012

- More sophisticated models with SN feedback and angular momentum transfer (disk-->halo) fair only slightly better; no 'natural' explanation within standard 'framework' of disk formation
- Hydro-simulations of Sales et al. (2009) predict relation between j_d/m_d and m_d similar to that of naive `inside-out-cooling-model'; outflows in simulations preserve rank-order of $E_{binding}$

Conclusions & Outstanding Issues

Are Disk Galaxy Scaling Relations a `success' for the LCDM paradigm?

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Are Disk Galaxy Scaling Relations a `failure' for the LCDM paradigm?

NO We now know what is needed to make it work, although this is not `natural'

- The formation of disk galaxies causes the central regions of dark matter halos to expand (or at least, not to contract). HOW?
- The small fraction of baryons that end up in disk have a disproportionate fraction of the specific angular momentum. WHY?
- Do we need to modify models for disk formation to account for
  cold flow feeding of disks ? [e.g, Kimm+11; Power+11; Pichon+11]
  secular redistribution of angular momentum ? [e.g.,Tonini+11; Minchev+12; Roškar+12]